EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP), located near Carlsbad, New Mexico, is a deep geologic repository for the disposal of transuranic (TRU) wastes generated by atomic energy defense activities. The WIPP Land Withdrawal Act (LWA) requires the Department of Energy (DOE) to submit to EPA documentation of WIPP's continuing compliance with the Agency's disposal regulations, 40 CFR Part 191, Subparts B and C, not later than five years after initial receipt of TRU waste for disposal at the repository, and every five years thereafter until the decommissioning of the facility is completed. The first five-year period ends on March 27, 2004. This Compliance Recertification Application (CRA) demonstrates WIPP's continuing compliance and requests that EPA recertify the repository.

Background

DOE estimates that approximately 115,000 m^3 of defense TRU wastes are stored at DOE sites across the country. Ongoing decommissioning and dismantlement work at these sites will generate more TRU wastes, as will continuing operations to maintain the nation's nuclear arsenal. Disposal of these wastes in the WIPP repository will ensure their isolation from the accessible environment for at least 10,000 years.

Waste disposal operations at the WIPP began on March 26, 1999, after the Environmental Protection Agency (EPA) certified WIPP's compliance with the disposal regulations. EPA's certification of WIPP in May 1998 followed submittal by DOE of the Compliance Certification Application (CCA) in October 1996. The first application demonstrated how the geological, hydrological, physical, chemical, and environmental characteristics of the site, along with engineered features of the facility, would comply with EPA's requirements for at least 10,000 years.

Content of the CRA

As required by 40 CFR Parts 191 and 194, this CRA addresses a wide range of topics. It incorporates portions of the CCA and provides updates in those areas where approved changes occurred. It also presents new data and associated analyses. In addition, it responds to specific requests from EPA for new or expanded information or analyses. Topics addressed in this CRA include (but are not limited to) the following:

- Natural and engineered features of the disposal system**,** including geology, geophysics, and hydrogeology of the repository and its environs, as well as the geochemistry of interactions between the disposal system and the wastes placed in it**;**

- Assessments of the disposal system's long-term performance**,** including the input parameters used in those assessments**;**

- Criteria for accepting waste at WIPP and the programs and activities that ensure adherence to those criteria**;**

- Information concerning the inventory of TRU waste emplaced in the repository, stored at DOE sites, and the waste DOE expects to generate at those sites in the future**;**

- Reassessments of WIPP-relevant features, events, and processes (FEPs) that are important to the repository's performance, in light of data acquired since WIPP's original certification**;**

- Individual and groundwater protection standards and DOE's analyses demonstrating that WIPP will meet or exceed those standards; and

- Assurance requirements**,** including active and passive institutional controls, monitoring and impact of natural resource extraction.

The CRA follows the format of the CCA, but is modified to include new information and to respond to the guidance given by EPA on the content of this first CRA. As approved by EPA, portions of the original CCA were modified for this application; other portions of the CCA are incorporated by reference. Should EPA approve of DOE's request for recertification of WIPP, the CRA would establish an updated compliance baseline for the repository.

Changes Since the CCA

This application incorporates information about, and assessments of, several changes proposed by DOE and approved by EPA (or requested by EPA itself) since the original certification. These changes involve many aspects of the repository and the systems and processes associated with it. The most important of these changes include:

- ***Inventory:*** DOE updated estimates used in the CCA describing the TRU waste the Department may dispose of at WIPP. In addition, DOE compiled information about the waste already emplaced at WIPP. The updated waste information is incorporated into performance assessments (PAs) conducted for and described in this CRA.

- ***Repository Configuration:*** DOE requested approval from EPA for a small change in the horizon at which the repository is mined to facilitate ground control and provide greater protection to workers underground.

- ***Panel Closure:*** In its original certification, EPA stipulated that panel closures should be constructed using a specific design (known as "Option D"). The performance of this design is modeled in the 2004 PA, rather than the generic panel closure design modeled in the 1996 PA.

- ***Disposal Operations:*** Considering the extensive creep closure of excavations in Panel 1, DOE requested approval from EPA to not use certain rooms for waste disposal.

- ***Engineered Barrier:*** DOE requested approval from EPA to eliminate emplacement of so-called magnesium oxide (MgO) "mini-sacks" among the stacks of waste containers in the repository, while retaining the bulk of the MgO in "supersacks" placed on top of stacks of waste containers.

- ***Waste Characterization:*** DOE requested approval from EPA for updates to the WIPP Waste Acceptance Criteria (WAC). EPA approved the updates with conditions, which DOE fulfilled.

- ***Performance Assessment:*** DOE modified its approach to assessing the long-term performance of the repository in a number of aspects.

  – To make the representation of the shafts and of the repository geometry more appropriate for modeling the repository's performance, and to explicitly include the Option D panel closure system, DOE modified 3 of the 24 conceptual models employed in PA: disposal system geometry, repository fluid flow, and disturbed rock zone. A peer review panel extensively examined these changes and found them to be reasonable and appropriate.

  – Responding to EPA's guidance that another conceptual model needed modification, DOE developed a new model to predict possible spall releases and submitted it to a peer review. That review judged the new model to be reasonable and appropriate.

  – DOE implemented a single PA parameter set for this CRA, rather than maintaining two – one used in the creation of the CCA and the other resulting from PA verification tests mandated by EPA as part of its evaluation of the CCA.

  – DOE updated PA computing hardware and key software components of the PA system, including operating systems and database software, to improve computational performance. These upgrades also prolong the capabilities of the PA computing environment.

Results

DOE requested and EPA approved the changes described above at various times since EPA's original certification of WIPP. This CRA assesses the combined effect of these changes on the compliance of the facility and demonstrates that the combined effect does not adversely impact performance or compliance.

The predicted releases from the repository remain well below the limits specified in 40 CFR Part 191, Subpart B. Similarly, compliance analyses performed on the undisturbed repository result in a single postulated release whose value is significantly smaller than even the very small release estimated by the same analyses in the CCA**.** Taken together, the CCA and the CRA compliance analyses demonstrate that WIPP complies with the individual and groundwater protection standards promulgated in 40 CFR Part 191, Subpart C. When considered with information in this CRA pertaining to other aspects of TRU waste characterization and disposal, the PA and compliance analysis results amply demonstrate WIPP's continued compliance with EPA's requirements.

Therefore, WIPP continues to comply with the governing laws and regulations for the disposal of transuranic waste and the repository should be recertified by EPA.

ACRONYMS AND ABBREVIATIONS

Note: The following acronyms are carried forward from the initial certification application. Some acronyms appear in both the initial application and this recertification application. Acronyms that are unique to this application appear in bold, blue, italicized text**.**

ACA	Agency for Conservation Archaeology
ACNFS	Advisory Committee on Nuclear Facility Safety
AEC	Atomic Energy Commission
AECL	Atomic Energy of Canada Limited
AG	Attorney General
AIC	Active Institutional Controls
AIS	air intake shaft
AK	acceptable knowledge
Al	aluminum
ALARA	as low as reasonably achievable
Am	americium
amsl	above mean sea level
AMWTF	Advanced Mixed Waste Treatment Facility
AMWTP	Advanced Mixed Waste Treatment Project
ANL-E	Argonne National Laboratory-East
ANL-W	Argonne National Laboratory-West
ANSI	American National Standards Institute
APD	Application for Permission to Drill
API	American Petroleum Institute
ARCO	ARCO Medical Products Company
ASER	Annual Site Environmental Report
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
B&W-NES	Babcock & Wilcox-Nuclear Engineering Services
BAB	butyric acid bacteria
BAPL	Bettis Atomic Power Laboratory
BCL	Battelle Columbus Laboratories
BCLDP	Battelle Columbus Laboratories Decommissioning Project
BGR	Bundesanstalt fur Geowissenschaften und Rohstoffe
BIR	Baseline Inventory Report
BLM	U.S. Bureau of Land Management
BMP	Best Management Practice
BNL	Brookhaven National Laboratory
BP	branch procedure
BRAGFLO	brine and gas flow
BRP	Blue Ribbon Panel
BSEP	Brine Sampling and Evaluation Program
CAG	Compliance Application Guidance
CAO	Carlsbad Area Office *(former designation)*
CAR	Corrective Action Report

CARD	Compliance Application Review Document
CAST	CAST Transportation, Inc.
CB	Cabin Baby
CBFO	Carlsbad Field Office (DOE)
CBP	Central Basin Platform
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CCP	Central Characterization Project
CDA	corrected during the audit
CDF	cumulative distribution function
CDR	Conceptual Design Report
CEMRC	Carlsbad Environmental Monitoring and Research Center
Cf	californium
CFR	Code of Federal Regulations
CH	Contact-Handled
Ci	curie
Cm	curium
CMM	Coordinate Measurement Machine
CMP	Compliance Monitoring Plan
CMPR	Conceptual Model Peer Review
CMPRP	Conceptual Models Peer Review Panel
CMUG	Conceptual Model Uncertainty Group
Co	cobalt
CO_2	carbon dioxide
COMP	compliance monitoring parameter
CPR	cellulosic, plastic, and rubber
CRA	Compliance Recertification Application
Cs	cesium
CTAC	Carlsbad Field Office Technical Assistance Contractor
CTEN	Combined Thermal-Epithermal Neutron
CU	Culebra unit
D&D	decontamination and decommissioning
D/H	deuterium/hydrogen
DA	Data Administrator
DAC	Drum Age Criteria
DAM	Design Analysis Model
DAS	data acquisition software
DBDSP	Delaware Basin Drilling Surveillance Program
DBE	Design Basis Earthquake
DBT	Design Basis Tornado
DCCA	Draft Compliance Certification Application
DDZ	Drilling Damage Zone
DEIS	Draft Environmental Impact Statement
DFR	driving force ratio
DNAG	Decade of North American Geology
DOE	U.S. Department of Energy

DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
DP	disturbed performance
DQO	Data Quality Objective
DR/CT	dry rod construction technology
DRXS	Data Review Expert System
DRZ	disturbed rock zone
DSCR	Draft Site Characterization Report
EA	engineered alternative
EACBS	Engineered Alternatives Cost/Benefit Study
EATF	Engineered Alternatives Task Force
EDTA	ethylenediaminetetracetate
EEG	Environmental Evaluation Group
EIS	Environmental Impact Statement
EM	emergency management
EMP	Environmental Monitoring Plan
EMPEIS	Environmental Management Programmatic Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
EPD	Engineered Products Department
EPs	events and processes
ER	environmental restoration
ERDA	U.S. Energy Research and Development Administration
ERMS	Electronic Record Management System
ES&H	Environment, Safety, and Health
ESHAP	Exhaust Shaft Hydraulic Assessment Program
ESPR	Engineered Systems Peer Review
ETC	Engineering Training Center
ETEC	Energy Technology Engineering Center
EXP	exponent
FB	FB Line, Savannah River Site
Fe	iron
FEIS	Final Environmental Impact Statement
FEPs	features, events, and processes
FGE	fissile gram equivalent
FLAC	Fast Lagrangian Analysis of Continua
FLPMA	Federal Land Policy and Management Act
FMT	Fracture-Matrix Transport (calculation)
FR	Federal Register
FRP	fiberglass-reinforced polyethylene
FSAR	Final Safety Analysis Report
FSEIS	Final Supplement Environmental Impact Statement
FSU	Florida State University
FWS	U.S. Fish and Wildlife Service
FxG	Fracture Expert Group
GCR	Geological Characterization Report
GE-VNC	General Electric Vallecitos Nuclear Center

GGTP	gas generation testing process
GTP	Generic Technical Position
GTSD	*Government Technical Services Division*
GWMP	groundwater monitoring plan
HANF	Hanford Site
Hanford-RL	Hanford Site - Richland Operations Office
Hanford-ORP	Hanford Site – Office of River Protection
also	
Hanford-RP	Hanford Site – Office of River Protection
HB	HB Line, Savannah River Site H-canyon
HC	historical and current human activities
HCN	historic, current, and near future human activities
HEPA	high-efficiency particulate air
HLW	high-level waste
HMHWA	New Mexico Hazardous Waste Act
HSG	headspace gas
HWFP	Hazardous Waste Facility Permit
IA	Internal Audit
IAEA	International Atomic Energy Agency
ICP/MS	inductively coupled plasma-mass spectrometry
ICV	inner containment vessel
IMC	International Mining Consultants
INEEL	Idaho National Engineering and Environmental Laboratory
INEL	Idaho National Engineering Laboratory
IRG	International Review Group
IRT	independent review team
ITC	International Technology Corporation
ITR	Independent Technical Review
K	potassium
KAPL-NFS	*Knolls Atomic Power Laboratory-Nuclear Fuel Services*
L/ILW	low- and intermediate-level waste
LANL	Los Alamos National Laboratory
LANL-CO	Los Alamos National Laboratory-Carlsbad
LBNL	Lawrence Berkeley National Laboratory
LCM	lost circulation material
LCS	laboratory-controlled sample
LHS	Latin hypercube sampling
LLD	lower limit of detection
LLNL	Lawrence Livermore National Laboratory
LMP	Land Management Plan
LQS	large quantity site
LWA	Land Withdrawal Act
LWB	Land Withdrawal Boundary
M&OC	Management and Operating Contractor
M&TE	measuring and test equipment
MB	marker bed

MCS	Mobile Characterization Systems
MDC	Minimal Detectable Concentration
MDL	minimum detection level
MgO	magnesium oxide
MIP	Monitoring Implementation Plan
MIT	Massachusetts Institute of Technology
MOA	Memorandum of Agreement
MOU	memorandum of understanding
MP	management procedure
MPCC	multipurpose crate counter
MPI	Mississippi Potash Inc.
MREs	Measures of Relative Effectiveness
MSD	matrix spike duplicate
MSGP	Multi-Sector General Permit
MSL	mean sea level
MSP	matrix spike
MTHM	metric tons heavy metal
MURR	University of Missouri Research Center
Na	sodium
NAGRA	National Cooperative for the Storage of Radioactive Waste
NAS	National Academy of Sciences
NBPR	Natural Barriers Peer Review
NDA	nondestructive assay
NDE	nondestructive examination
NEA	Nuclear Energy Agency
NEPA	National Environmental Policy Act
NHPA	National Historic Preservation Act
Ni	nickel
NIREX	UK Nuclear Industry Radioactive Waste Executive
NIST	National Institute of Standards and Technology
NMAC	New Mexico Administrative Code
NMBMMR	New Mexico Bureau of Mines and Mineral Resources
NMD	no-migration determination
NMDG&F	New Mexico Department of Game and Fish
NMED	New Mexico Environment Department
NMERI	New Mexico Engineering Research Institute
NMMA	nuclear material management area
NMOCD	New Mexico Oil Conservation Division
NON-PA SES	nonperformance assessment scientific and engineering software
NORM	naturally occurring radioactive material
Np	Neptunium
NP	nuclear waste management QA procedure
NPDES	National Pollutant Discharge Elimination System
NQA	nuclear quality assurance
NRC	Nuclear Regulatory Commission
NTP	National TRU Program

NTS	Nevada Test Site
NUTS	Nuclide Transport System
NWMP	Nuclear Waste Management Program
OCA	Office of Cultural Affairs
OECD	Organization for Economic Cooperation and Development
OJT	on-the-job training
ORC	Office of Regulatory Compliance
ORNL	Oak Ridge National Laboratory
OSR	Off-Site Source Recovery
OSW	Office of Solid Waste
PA	performance assessment
PA Non-SES	performance assessment nonscientific and engineering software
PA SES	performance assessment scientific and engineering software
PAN	Passive-Active Neutron
PAPRP	Performance Assessment Peer Review Panel
PART	Performance Assessment Review Team
PAVT	Performance Assessment Verification Test
Pb	lead
PCB	polychlorinated biphenyl
Pd	palladium
PDF	probability distribution function
PDP	Performance Demonstration Program
PE	protective equipment
PFP	Plutonium Finishing Plant
PGDP	Paducah Gaseous Diffusion Plant
PIC	Passive Institutional Controls
PMP	probable maximum precipitation
PRMP	Peer Review Management Plan
PTF	passive institutional controls task force
P-TGS	portable-tomographic gamma scanner
Pu	plutonium
PZ	piezometer
QA	quality assurance
QAI	Quality Assurance Instruction
QAO	quality assurance objective
QAP	Quality Assurance Procedure
QAPD	Quality Assurance Program Document (CAO)
QAPjP	Quality Assurance Project Plan
QAPP	Quality Assurance Program Plan
QC	quality control
QED	qualification of existing data
R&D	research and development
Ra	radium
RBP	Radiological Baseline Program
RCRA	Resource Conservation and Recovery Act
RFETS	Rocky Flats Environmental Technology Site

RH	Remote-Handled
ROR	rest of repository
RP	review panel
RPD	relative percent difference
RRF	risk-reduction factor
RSD	relative standard deviations
RSI	Institute for Regulatory Science
RTC	Response to Comments Document
RTR	real-time radiography
SA	Scientific Advisor
SAR	Safety Analysis Report
SARP	Safety Analysis Report for Packaging
SCMS	Software Configuration Management System
SDWA	Safe Drinking Water Act
SEIS	Supplemental Environmental Impact Statement
SGRS	SWEPP gamma-ray spectrometer
SGS	segmented gamma scanner
SHPO	State Historic Preservation Officer
SHS	salt-handling shaft
SKB	SKI & Swedish Nuclear Fuel and Waste Management Company
SKI	*Statens Kärnkraftinspektion*
SLB	standard large box
SMC	Salado Mass Concrete
SMP	Subsidence Monitoring Program
SNL	Sandia National Laboratories
SNM	special nuclear material
SO-C	regulatory consequence
SOP	standard operating procedure
SO-P	regulatory probability
SO-R	regulatory exclusions
SPDV	Site and Preliminary Design Validation
SPE	Society of Petroleum Engineers
SPRU	Separations Process Research Unit
SQS	small-quantity site
Sr	strontium
SRS	Savannah River Site
SVOC	semi-volatile organic compound
SWB	standard waste box
SWCF	Sandia WIPP Central Files
SWEPP	Stored Waste Examination Pilot Plant
SWTS	Standard Waste Treatment System
T	transmissivity
TB	Teledyne Brown Engineering
TBM	Technical Baseline Migration
TCP/IP	Transmission Control Protocol/Internet Protocol
TDD	Technology Development Description

TDEM	time-domain electromagnetic
TDOP	Ten Drum Overpack
TDS	total dissolved solids
Th	thorium
TMU	total measurement uncertainties
TOB	Technical Oversight Board
TP	Team Procedure
TRAMPAC	TRUPACT-II Authorized Methods for Payload Control
TRIPS	Transuranic Reporting, Inventory, and Processing System
TRU	transuranic
TRUPACT	Transuranic Package Transporter
TSG	Technical Support Group
TSMT	Tri-State Motor Transit
TSP	total suspended particulate
TSR	technical safety requirements
TWBID	Transuranic Waste Baseline Inventory Database
TWBIR	Transuranic Waste Baseline Inventory Report
TWCP	TRU Waste Characterization Project
TZ	transition zone
UCL	upper confidence limit
UNM	University of New Mexico
UP	undisturbed performance
USAMC	U.S. Army Material Command
USDW	underground source of drinking water
USGS	United States Geological Survey
UVP/ENRESA	Universidad del País Vasco/Enresa Nacional de Residuos Radicactivos S.A.
V&V	verification and validation
VCMP	VOC Confirmatory Monitoring Plan
VE	visual examination
VOC	volatile organic compound
VSP	Vertical Seismic Profiling
WAC	Waste Acceptance Criteria
WAGS	Waste Assay Gamma Ray Spectrometer
WAP	Waste Analysis Plan
WCPIP	Waste Characterization Program Implementation Plan
WCPR	Waste Characterization Peer Review
WCRR	Waste Characterization, Reduction, and Repackaging (facility)
WEMS	Waste and Environmental Management System
WERC	Waste-Management Education and Research Consortium
WFDR	Waste Form and Disposal Room
WG	weapons grade
WID	Westinghouse Waste Isolation Division
WIPP	Waste Isolation Pilot Plant
WLMP	Water Level Monitoring Plan
WMC	waste matrix code
WMP	waste material parameter

WP	WIPP procedure
WQSP	Water Quality Sampling Program
WRAC	Waste Removal After Closure
WSPF	Waste Stream Profile Form
WTS	Washington TRU Solutions
WUF	waste unit factor
WVDP	West Valley Demonstration Project
WWIS	WIPP Waste Information System

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GLOSSARY OF TERMS

40 CFR Part 191. *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes.* This regulation sets environmental radiation protection standards for management (Subpart A) and disposal (Subparts B and C) of spent nuclear fuel and high-level and transuranic radioactive wastes.

40 CFR Part 194. This regulation provides EPA's *Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with 40 CFR Part 191 Disposal Regulations.*

40 CFR Part 261. *Identification and Listing of Hazardous Waste.* This part identifies those solid wastes which are subject to regulation as hazardous wastes under Parts 262B, 265, 268, 270, 271, and 124 of Title 40 of the Code of Federal Regulations.

40 CFR Part 264. *Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities.* This subpart establishes minimum national standards which define the acceptable management of hazardous waste.

40 CFR Part 264, Subpart G. This subpart of 40 CFR Part 264 defines closure and post-closure requirements pertaining to hazardous waste management units.

40 CFR Part 264, Subpart X. This subpart specifies requirements that apply to owners and operators of facilities that treat, store, or dispose of hazardous waste in miscellaneous hazardous waste management units.

40 CFR Part 268. This regulation restricts the land disposal of hazardous waste and specifies treatment standards and/or treatment technologies that must be met or applied before hazardous wastes may be land disposed. Section 268.6 provides for petitioning to allow land disposal of untreated hazardous waste if it can be demonstrated to a reasonable degree of certainty that there will be no migration of hazardous constituents from the disposal unit for as long as the waste remains hazardous.

40 CFR Part 270. This regulation establishes provisions for the Hazardous Waste Permitting Program under Subtitle C of the Resource Conservation and Recovery Act. This regulation and the associated State of New Mexico regulation require the permitting of the WIPP as a hazardous waste facility.

abscissa. The horizontal coordinate (x coordinate) of a point plotted in Cartesian (x, y) coordinates.

absolute temperature. Temperature measured in degrees Celsius from absolute zero. -273.18 °C. Absolute temperatures are given either as "degrees absolute" (for example, 150°A) or as degrees kelvin (for example, 150K).

absorption. The process by which a fluid penetrates or is drawn into and held in the inner structure of another (solid or liquid) material. The word also appears in contexts such as absorbed energy and absorbed radiation dose, in which case it refers to internal energy imparted to the absorbing material. Absorbed radiation dose refers specifically to the energy imparted by ionizing radiation per unit mass of irradiated material at a particular location.

accessible environment. "(1) [T]he atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all of the lithosphere that is beyond the controlled area." (40 CFR § 191.12)

acid rain. Any form of precipitation having a pH of 5.6 or less. Major components contributing to the acid rain are sulfur dioxide and oxides of nitrogen.

actinide intrinsic colloids. Macromolecules or aggregations of actinide compounds which form by exsolution of dissolved actinide compounds and remain in suspension, thereby acting as colloids.

actinide source term. Modeling terminology denoting the fraction of total actinide inventory of a disposal room or the repository that can be mobilized for transport.

active institutional control. (1) Controlling access to a disposal site by any means other than passive institutional controls, (2) performing maintenance operations or remedial actions at a site, (3) controlling or cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance. (40 CFR § 191.12)

activity. A measure of the rate at which a material emits nuclear radiation, usually given in terms of the number of nuclear disintegrations occurring in a given length of time. The unit of activity used in this document is the curie (Ci).

adsorption. (1) The net accumulation of matter at the interface between a solid phase and an aqueous solution through the formation of two-dimensional (that is, noncrystallographic) molecular structures. The accumulated matter is the *adsorbate*. The solid surface is the *adsorbent*. (2) Adherence of gas molecules to the surface of solids in which they are in contact.

advection. The transport of matter (for example, a trace contaminant) by motion of the medium in which it is contained. The most common transport medium is the flow of a fluid.

aeolian. Also spelled eolian. Applies to the erosional action of wind, and to deposits which are due to the transporting action of wind.

aerobic degradation. The microbial degradation of organic (that is, cellulosic, rubber, plastic, etc.) wastes using oxygen (O_2) as the electron acceptor and producing carbon dioxide (CO_2) and water (H_2O).

aeromagnetic survey. Refers to the geomagnetic observations using a magnetometer from an airborne craft.

air lock. An intermediate chamber between zones of different static pressure.

alluvial. Pertaining to or composed of alluvium, or deposited by a stream or running water. For example, an alluvial clay or an alluvial divide.

algal features. Features created by the secretion of calcium carbonate from algae.

alkalophilic bacteria. Bacteria that can grow and reproduce well in an alkaline (high pH) environment.

alpha emitter. A radioactive isotope that decays through the emission of alpha particles.

alpha particle. (α-particle). A positively charged particle emitted in the radioactive decay of certain nuclides. Made up of two protons and two neutrons bound together, it is identical to the nucleus of a helium atom. It is the least penetrating of the three common types of ionizing radiation—alpha, beta, and gamma radiation.

alternative conceptual models. Alternative sets of assumptions that describe the same system for the same purpose and are consistent with the existing information.

Advanced Mixed Waste Treatment Project. A project designed to retrieve, characterize, prepare and store CH-TRU waste at the INEEL for shipment to the WIPP. The CH-TRU waste at INEEL consists of debris and non-debris wastes. The debris wastes will be processed through a sort, size, and volume reduction (supercompaction) process (i.e., treated AMWTP waste). The non-debris waste also will be retrieved, characterized, prepared and stored for shipment to WIPP, but will not be supercompacted. The DOE expects that the AMWTP will ship both supercompacted and uncompacted waste concurrently.

anaerobic. The microbial degradation of organic (that is, cellulosic, rubber, plastic, etc.) wastes in the absence of oxygen (O_2), usually consuming nitrate (NO_3) as the electron acceptor and producing carbon dioxide (CO_2), nitrous oxide (N_2O), and nitrogen (N_2).

angular velocity. The rate of rotation of the drill stem, to which the drill bit is attached.

anhydrite. A mineral consisting of anhydrous calcium sulfate ($CaSO_4$). It is gypsum without water and is denser, harder, and less soluble.

anhydrite lithologies. The description of a rock type, in this case an anhydrous calcium sulfate.

annual committed effective dose. The committed effective dose resulting from a one-year intake of radionuclides released plus the annual effective dose caused by direct radiation from facilities or activities subject to Subparts B and C of 40 CFR Part 191. (40 CFR § 191.12)

annulus. The area between the borehole wall and the outside of the drill pipe in rotary drilling operations. Rotary drilling is used for scientific investigation studies, such as the WIPP project, and the exploration for natural resources (that is, oil and gas).

anoxic. Describes a process that occurs in the absence of oxygen (O_2). Anoxic corrosion of steels, iron-base alloys, and other metal wastes use water (H_2O) or hydrogen sulfide (H_2S) and produces hydrogen gas (H_2).

anthropogenic. Resulting from the influence of human beings on nature (that is, acid rain, greenhouse effect, and man-made organic material).

anticline. A fold of rocks whose core contains the stratigraphically older rocks; it is generally convex upward.

Anticipated Waste Inventory. The sum of the stored and projected TRU waste inventories at currently listed DOE TRU waste sites that have not been emplaced at WIPP.

aquifer. An underground geological formation or part of a formation that is capable of yielding a significant amount of water to a well or spring. (40 CFR § 191.12)

arenaceous. Of the texture or character of sand.

argillaceous rocks. A group of detrital sedimentary rocks with a grain or particle size less than 1/16 millimeter. Commonly comprised of clay minerals and including shales, mudstones, siltstones, and marls.

artesian. Adjective that refers to groundwater confined under pressure so that it will rise in a well. Sometimes the word is used to mean that the water flows out at the surface, but that, strictly speaking, is “flowing artesian.”

assurance requirements. Qualitative requirements in 40 CFR § 191.14 that specify actions and procedures to increase confidence that the probabilistic release events in the containment requirements (40 CFR § 191.13) will be met.

Atoka. The Early-Middle Pennsylvanian rocks, assigned to the Atokan or Derryan Stage, consist of dark-colored sandstones, shales and limestones, which attain a maximum thickness of about 1,000 feet.

atomic weights. Atomic weight is the total mass of an atom and is almost, but not exactly, the sum of the masses of its constituent protons, neutrons and electrons.

attenuation. (1) A reduction in the amplitude or energy of a signal, such as might be produced by passage through a filter. (2) A reduction in the amplitude of seismic waves, as produced by divergence, reflection and scattering, and absorption. (3) That portion of the decrease in seismic or sonar signal strength with distance that is not dependent on geometrical divergence, but on the physical characteristics of the transmitting medium.

authigenic. Formed or generated in place of rock constituents and minerals that have not been transported or that crystallized locally at the spot where they are now found, and of minerals that came into existence at the same time as, or subsequently to, the formation of

the rock of which they constitute a part. The term often refers to a mineral (such as quartz or feldspar) formed after deposition of the original sediment.

backfill. Material placed around or above the waste containers, filling the open space in the disposal room.

background (radiation). Radiation in the human environment from naturally occurring elements, fallout, and from cosmic radiation.

bacterioruberin. A carotenoid pigment excreted during growth and multiplication of various strains of bacteria that may be involved in waste decomposition.

barrier. "Any material or structure that prevents or substantially delays movement of water and/or radionuclides toward the accessible environment. For example, a barrier may be a geologic structure, a canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around waste, provided that the material or structure substantially delays movement of water or radionuclides." (40 CFR § 191.12) Barriers also prevent or delay the movement of hazardous constituents.

Baseline Inventory Report. Also known as the Transuranic Waste Baseline Inventory Report. This document provides the total DOE transuranic waste inventory. The Baseline Inventory Report establishes a methodology for grouping wastes of similar physical and chemical properties from across the DOE transuranic waste system into a series of waste profiles.

bedding plane. A flat or near-flat bedding surface that visibly separates the individual layers, beds, or strata in sedimentary or stratified rocks from the preceding or following layers.

Bell Canyon Formation. A sequence of rock strata that form the uppermost formation of the Delaware Mountain Group (Early Permian). It is immediately below the Castile Formation and about 4,000 feet below the surface at the WIPP. May contain some oil and gas.

bentonite. A commercial term applied to expansive clay materials containing montmorillonite (smectite) as the essential mineral.

beta particle. (β-particle). A negatively charged particle emitted in the radioactive decay of certain radioactive elements (nuclides). A beta particle is identical to an electron. It is not a strong penetrating radiation and can be stopped by an inch of wood or a thin sheet of aluminum.

biodegradation. The process of consumption by microbial substances—usually organic materials such as cellulosics.

bioelectric activity. The electric phenomena associated with organic matter (plants and animals).

biofilm ecosystem. An ecosystem composed of substrates and nutrients developed on surfaces containing one or more layers of cells with extra cellular polymeric material.

biological half-life. The time required for an organism to eliminate half the amount of a radionuclide ingested or inhaled. See definition for half-life.

bleb. A small, usually rounded inclusion of one mineral in another.

blowout. An unexpected volume of gas or fluid released from subsurface pressurized zones that flows upwards to the land surface and into the atmosphere during the drilling of a borehole.

Boltzmann Constant. The ideal gas constant per molecule is the ratio of the molar gas constant to the number of molecules per gram of a substance. Boltzman's Constant is defined as having a value of approximately 1.380×10^{-23}Joules/Molecule K.

borehole. (1) A hole drilled from the surface for purposes of geologic or hydrologic testing, injection, or exploration and subsequent production of resources; sometimes referred to as a drillhole or well bore. (2) A man-made hole in the wall, floor, or ceiling of a subsurface room used for verifying geology, making observations, or emplacing canisters of remote-handled transuranic waste.

brackish. Water with between one and ten parts per thousand salinity. This places the saline content of brackish waters between that of streams and sea water. See saline and brine.

BRAGFLO. The name of the computer model the DOE uses to simulate brine and gas flow in the disposal system.

breccia. Fragmented rock whose components are angular and cemented together by a mineral cement or a fine-grained matrix. May be sedimentary (for example, carbonate or evaporite karst features) or formed by crushing or grinding along faults. There are friction or fault breccias, talus breccias, eruptive breccias, and large-scale collapse sinks (for example, breccia pipes). Breccia pipes are vertical or near vertical cylindrical features filled with collapse debris.

brine. Water with greater than 100 parts per thousand salinity. Brines are often found in deep sedimentary basins and contain calcium (Ca), sodium (Na), potassium (K), chloride (Cl), sulfate (SO_4), and minor amounts of other elements.

brine pocket. See brine reservoir.

brine reservoir. A volume of brine of limited extent trapped within fractures and/or intergranular pore spaces of a host rock and usually pressurized relative to normal formation fluids. Such pockets may exist under various conditions of stress and solute concentration. Pressurized brine pockets have been observed in the Castile Formation in the Delaware Basin.

Brushy Canyon Formation. The basal unit of the Guadalupian Series or Delaware Mountain Group within the Delaware Basin. The formation is dominated by submarine channel sandstones with minor limestones and shales, and its structural features are indicative of deposition in agitated water. This formation terminates northward against the Bone Spring flexure at the basin margin.

Bureau of Land Management. An agency of the federal government, within the Department of the Interior, which among other land management duties, reviews environmental assessments, environmental impact statements, land acquisition procedures, and any other plans to site waste management facilities on federal lands over which it has jurisdiction.

calcareous remnant. Commonly used with reference to organisms that use calcium compounds to form endo- or exoskeletal structures. The calcareous remnant is that which remains after the soft tissues have disappeared.

calcic. Said of minerals and igneous rocks containing a relatively high proportion of calcium; the proportion required to warrant use of the term depends on circumstances.

calcite. A crystalline mineral composed of calcium carbonate ($CaCO_3$).

calibrate. To vary parameters of an applied computational model within a reasonable range until differences between observed data and computed values are minimized.

caliche. A calcareous material commonly found in layers on or within the surface of stony soils of arid or semiarid regions. It occurs in the form of gravels, sands, silts, and clays cemented together by calcium carbonate or as crusts at the surface of the soil.

Cambrian. The oldest period of the Paleozoic Era, and the corresponding system of rocks. It is subsequent to the Precambrian Period and followed by the Ordovician Period, between approximately 570 and 505 million years ago.

canister. As used in this document, a container, usually cylindrical, for remotely handled transuranic waste. The waste remains in this canister during and after burial. A canister affords physical containment but not shielding; shielding is provided during shipment by a cask.

capillary pressure. The difference in pressure across the interface between two immiscible fluid phases jointly occupying the interstices of a rock. It is due to the tension of the interfacial surface, and its value depends on the curvature of that surface.

Capitan Limestone. Also referred to as the Capitan Reef and/or Capitan Formation. The Capitan Limestone or Reef is a light colored, fossiliferous and vuggy limestone and breccia which almost completely surrounds the Delaware Basin. The reef was formed in the Early to Mid-Permian Period, between approximately 286 and 260 million years ago. It is a time-stratigraphic equivalent of the Bell Canyon Formation in the Delaware Basin. The reef is a major part of the Guadalupe Mountains from the west to the northwest of the WIPP site,

the Apache Mountains and Davis Mountains to the south, and the Glass Mountains to the southeast.

Capitan Reef. See Capitan Limestone.

carbonate mudstone. A nonfissile mud shale consisting mainly of carbonate minerals.

carbonates. Compounds containing the carbonate radical, CO_3^{-2}, primarily applies to rock formations composed of carbonate minerals.

Carlsbad potash district. The area east of Carlsbad formally designated by the U.S. Geological Survey as having potentially economic grades of potash mineralization.

carotenoid pigment. A yellow-to-red color found in microbes and associated biofilms (plants and animals) observed in WIPP microbial gas generation experiments.

cask. A massive shipping container providing shielding for highly radioactive materials and holding one or more canisters.

$CaSO_4$. Calcium sulfate.

Castile Formation. A formation of evaporite rocks (mainly anhydrite with a few halite interbeds) of Permian age that immediately underlies the Salado Formation.

catalytic surface. Referring to a substance on a surface that initiates a reaction and enables it to take place at lower temperature or activation energy than in the absence of the catalyst.

cation-anion. A cation is a positively charged ion whereas an anion is a negatively charged ion. A cation in an electrolyzed solution migrates to the cathode (negative terminal); an anion in an electrolyzed solution migrates to the anode (positive terminal).

cavings. During rotary drilling, material that erodes from the borehole wall in response to the upward-flowing drilling fluid within the annulus formed by the drill pipe and the borehole wall.

cellulosic. Those materials derived from high polymer plant carbohydrates. Examples are paper, cardboard, wood, cellophane, cloth, etc.

cementitious. A mineral agent, natural or man-made, usually emplaced by hydration or exsolution, that serves to bind together grains of another material, thereby acting as or resembling cement. May also be used to describe a geologic deposit containing a significant amount of cementitious material that was formed by this mechanism.

Cenozoic. An era of geologic time, from the beginning of the Tertiary period to the present (Some authors do not include the Quatenary, considering it a separate era). It is characterized paleontologically by the evolution and abundance of mammals, advanced mollusks, and birds; paleobotanically, by angiosperms. The Cenozoic is considered to have begun about 66 million years ago.

Central Basin Platform. The geological region known as the High Plains, covering an area of several hundreds of square miles separating the Delaware and Midland basins.

certification. Any action taken by the Administrator of the U.S. Environmental Protection Agency under Section 8(d) of the WIPP Land Withdrawal Act.

certifier. In the context of 40 CFR Part 191, the "certifier" is the U.S. Environmental Protection Agency, which must certify whether the Department of Energy has demonstrated that the Waste Isolation Pilot Plant is in compliance with the requirements of the standard.

chelating agents. A particular category of complexant that increases solubility by forming a cage around the complexed (or chelated) substance.

chemical retardation. Refers to retardation effects (see retardation) that are attributable to chemical mechanisms. Chemical reactions with constituents of a rock, precipitation, and sorption of contaminants are examples of chemical retardation.

chemical source term. The fraction of the hazardous constituents inventory that can be mobilized for transport.

chemisorption. The immobilization of a gas, liquid, or material in solution or suspension by the formation of bonds with the surface molecules of a solid material. The strength of these bonds is comparable to that of ordinary chemical bonds.

Cherry Canyon Formation. The center sandstone of the Delaware Mountain Group consisting of a fine-grained sandstone to siltstone that is very finely laminated.

chert. A hard, extremely dense or compact, dull to semivitreous, microcrystalline or cryptocrystalline sedimentary rock, consisting dominantly of interlocking crystals of silica (SiO_2) less than about 30 μm in diameter.

chronostratigraphic boundaries. The boundary of a rock stratum that is characterized by having been formed during a specific interval of geologic time.

clastic sedimentation. A sediment formed by the accumulation of fragments derived from preexisting rocks or minerals and transported as separate particles to their places of deposition by purely mechanical agents (such as water, wind, ice, and gravity).

clastics. Pertaining to a rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals and that have been transported some distance from their places of origin; also said of the texture of such a rock. The term has been used to indicate sources both within and outside the depositional basin.

Clayton Basin. Northeast of the WIPP site by eight miles. It contains Quaternary alluvium.

climate. The average condition of the weather at a place over a period of years as exhibited by temperature, wind velocity, precipitation and other factors.

climax vegetation. The vegetation that would exist if an area was undisturbed.

Code of Federal Regulations. A codification of the general and permanent rules published in the Federal Register by the departments and agencies of the Federal government. The Code is divided into 50 titles that represent broad areas subject to Federal regulation. It is issued quarterly and revised annually.

collapse block. A gravity-induced collapsed rock unit resulting from the formation of sink holes.

colloid. Refers to a suspended particulate in a colloidal suspension or to a particle that is small enough that it could be placed in colloidal suspension. A colloidal suspension is a dispersion of extremely fine particles in a fluid with the characteristic size of the particles (in at least one dimension) being so small that the behavior differs from that of more common suspensions. The maximum size range for particles which may be regarded as "colloidal" is subject to some variation, depending on context and application.

CCDFGF. The CCDFGF code assembles the release estimates from all other components of the WIPP Performance Assessment system to generate cumulative complementary distribution functions (CCDFs) of releases.

complementary cumulative distribution function. Mathematically, a complementary cumulative distribution function is equal to one minus a cumulative distribution function. A cumulative distribution function is the sum (or integral) of the probability of those values or variables that are less than or equal to a specified value. Complementary cumulative distribution functions are a graphical display of the probability (the ordinate) that the value of the variable will be greater than a specified value (the abscissa). For the WIPP, the complementary cumulative distribution function displays the probability that 10,000-year cumulative radionuclide releases from the disposal system for the scenarios considered will exceed calculated values. Radionuclide releases are normalized as stipulated in 40 CFR Part 191, Appendix A, and the complementary cumulative distribution function is compared to the quantitative release limits specified in 40 CFR § 191.13(a).

complexing agents. Complexing agents increase the solubility of the complexed substance; the aqueous solubility. They are often referred to as complexants.

complexants. Complexing agents increase the solubility of the complexed substance; the aqueous solubility. They are often referred to as complexing agents.

compliance assessment. The analysis conducted to determine compliance with the Individual Protection requirements in 40 CFR § 191.15 and the Groundwater Protection Requirements in Subpart C.

computational model. The computational model is the implementation of the mathematical model. (See definition of mathematical model below). The implementation may be through analytical or numerical means. Often, the analytical solution is numerically evaluated (for example, numerical integration or evaluation of complex functions); hence,

both solution techniques are typically coded on the computer. Consequently, the computational model is often called a computer model.

computer model. A computer code or set of codes that are used together to make calculations for a corresponding mathematical description for a process or system (for example, movement of groundwater through a geologic formation).

conceptual model. A set of qualitative assumptions used to describe a system or subsystem for a given purpose. At a minimum, these assumptions concern the geometry and dimensionality of the system, initial and boundary conditions, time dependence, and the nature of the relevant physical and chemical processes. The assumptions should be consistent with one another and with existing information within the context of the given purpose.

conductivity. A material property describing the ease with which something can be transferred through that material. Examples of conductivity are electrical conductivity (electricity), thermal conductivity (heat transfer), or hydraulic conductivity (groundwater flow).

confirmation. For the purposes of this document, a term used to indicate support or establishment of certainty and/or validity of models used in reference to specific performance issues of the repository over any specific time frame of interest. In general, laboratory and field experiments at the WIPP and elsewhere are conducted to provide data in support of this type of activity, such as for the gas generation model. Confirmation is used in a mechanistic sense and is not intended to have specific legal implications.

consequence analysis. The analysis used to examine the effects of processes and events on performance of the disposal system. (See Performance Assessment).

conservative assumption. Assumptions that result in the overestimation (rather than underestimation) of any phenomenon that could contribute to the release of radionuclides from the disposal system.

Consultation and Cooperation Agreement. An agreement that affirms the intent of the Secretary of Energy to consult and cooperate with the State of New Mexico with respect to State public health and safety concerns. The term “Agreement” means the July 1, 1981, Agreement for Consultation and Cooperation, as amended by the November 30, 1984, “First Modification,” the August 4, 1987, “Second Modification,” and the March 22, 1988, modification to the Working Agreement.

contact-handled transuranic waste. Packaged transuranic waste that has a measured external surface dose rate less than 200 millirems per hour at the surface of the container.

containment. The retention of radioactivity within prescribed boundaries, such as within a waste package. In this document, containment refers to retention within a system to prevent releases in unacceptable quantities or concentrations during handling and storage, or to containment within the disposal system.

contamination. Introduction of radionuclides into the repository's immediate surroundings, such as into the brine via a breach of the containment system.

controlled area. The controlled area means (1) a surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than 5 kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location. (40 CFR § 191.12). For WIPP, the controlled area is defined by the area withdrawn by the Land Withdrawal Act.

convection. The circulatory motion that occurs in a fluid at a nonuniform temperature. The transfer of heat by automatic circulation of fluids.

corrosivity. The tendency of a metal to deteriorate by chemical decomposition.

creep. A very slow, usually continuous, time-dependent movement of soil or rock; refers to the geologic phenomenon experienced as the gradual flow of salt under differential stress.

creep closure. Closure of underground openings, especially openings in salt, by plastic flow of the surrounding rock under lithostatic pressure.

Cretaceous. The final period of the Mesozoic era (after the Jurassic and before the Tertiary period of the Cenozoic era), thought to have covered the span of time between 135 and 66 million years ago; also, the corresponding system of rocks. It is named after the Latin word for chalk (creta) because of the English chalk beds of this age.

crustal processes. Any processes that occur within the earth's crust. Usually refers to igneous, metamorphic, or tectonic activity.

crystallographic. This term deals with the system of forms among crystals, their structures, and their physical properties.

CSH gel. A cementitious material containing calcium-silicate-hydrate gel.

cubic law. The cubic law states that for a given change in gradient of the hydraulic head, flow through a fracture is proportional to the cube of the fracture opening.

cuesta. A hill or ridge with a gentle slope on one side and a steep slope on the other, specifically an asymmetric ridge (as in the southwest United States) with one face (dip slope) long and gentle and conforming with the dip of the resistant bed or beds that form it, and the opposite face (scarp slope) steep or even cliff-like and formed by the outcrop of the resistant rocks, the formation of the ridge being controlled by the differential erosion of the gently inclined strata.

Culebra. The Culebra Dolomite Member, also referred to as Culebra, is the lower of two rock units of dolomite within the Rustler Formation and was formed in the late Permian Period between approximately 258 and 245 million years ago. It is a brown, finely crystalline,

argillaceous dolomite or dolomitic limestone with solution cavities. The Culebra is the principal water-bearing unit of the Rustler Formation and has been identified as the most likely pathway for release of radionuclides to the subsurface accessible environment.

cultural resource sites. Human-associated ruins of archaeological significance.

Cumulative Distribution Function. A cumulative distribution function is the sum (or integral) of the probability of those values of variable that are less than or equal to a specific value.

curie. A quantitative measure of radioactivity equal to 3.7×10^{10} disintegrations per second.

curie load. The number of curies in a particular location or in a container such as a radioactive waste drum. The curie load of a waste drum may be broken down into alpha, beta, and gamma curie loads to describe the amount of total radioactivity that is contributed by disintegrations yielding alpha, beta, or gamma radiation.

cuttings. During rotary drilling, material contained in the cylindrical volume created by the cutting action of the drill bit. In terms of releases from the WIPP through inadvertent human intrusion, the maximum potential waste volume that could form cuttings is equal to the cross-sectional area of the drill bit multiplied by the repository thickness.

CUTTINGS_S. The CUTTINGS_S code was written to calculate the quantity of material (in m^3) brought to the surface from a radioactive waste disposal repository as a consequence of an inadvertent human intrusion through drilling.

Darcy's Law. A mathematical equation that can be used to compute the quantity of water flowing through an aquifer. $Q = KA(h_A - h_B/L)$. Q is the discharge, A is the cross-sectional area, $h_A - h_B$ is the difference in the height of the water (hydraulic head), L is the flow length, and K is a coefficient, which is dependent upon the nature of the porous medium.

daughter product. A nuclide that results from radioactive decay. Thus radium-226 decays to radon-220, which in turn decays to polonium-216. The radon is the daughter of the radium, and the polonium is the daughter of the radon.

Davis Mountains. A mountain range in Texas south of the WIPP site making up the southern-most part of the Capitan Reef.

decay, radioactive. The decrease in the number of radioactive nuclei present in a radioactive material due to their spontaneous transmutation. Also, the transmutation of a radionuclide into another nuclide by the emission of a charged particle.

decommissioning. Actions taken upon closure of the repository to reduce potential environmental, health, and safety impacts, including repository sealing as well as activities to stabilize, reduce, or remove radioactive materials or demolish surface structures.

decommissioning phase. The term "decommissioning phase" refers to the period of time beginning with the end of the disposal phase and ending when all shafts at the WIPP repository have been sealed.

decontamination. With respect to operational activities, decontamination is the removal of unwanted material (especially radioactive material) from the surface of or from within another material.

defense waste. Nuclear waste deriving from the manufacture of nuclear weapons and the operation of naval reactors. Associated activities, such as the research carried on in the weapons laboratories, also produce defense waste.

deformation. Any change in the original form or volume of rock masses. Folding, faulting, solid flow, and dissolution and subsequent collapse are examples of deformation.

degradation. The wearing down or away of a material or the earth's surface, whether on a large or small scale, and the products it produces. Examples of degradation include the wearing down of drill casing from corrosion, and the wearing down of organics in the waste materials from microorganisms.

Delaware Basin. Those surface and subsurface features that lie inside the boundary formed to the north, east, and west of the disposal system by the innermost edge of the Capitan Reef, and formed to the South by a straight line drawn from the southeastern point of the Davis Mountains to the most southwestern point of the Glass Mountains.

Delaware Mountain Group. A set of three formations that underlie the Castile Formation at the Los Medaños site. The uppermost of these is the Bell Canyon Formation.

demography. The statistical study of human population with response to sizes and density, distribution, and vital statistics.

density. Mass per unit volume (that is, kilograms per cubic meter).

denudation. The sum total of processes that results in the general lowering of the land surface.

Design Basis Earthquake. An earthquake that is the most severe design basis accident of this type and that produces the vibratory ground motion for which safety class items are designed to remain functional.

Design Basis Tornado. A tornado that is the most severe design basis accident of that type applicable to the area under consideration.

detritivores. Organisms that eat organic debris.

deviatoric stress. Refers to a state of stress disequilibrium in the subsurface, in which at least one of the three perpendicular (normal) axes used to characterize stress at a point differs in magnitude from the other two. The stress tensor used to characterize subsurface stress can be written as the sum of two tensors. The first tensor represents a hydrostatic state with all

shear stresses equal to zero. The components of the second tensor are shear stresses - these are deviatonic stresses and are independent of hydrostatic stress.

Devonian. A period of the Paleozonic Era (after the Silurian and before the Mississippian) spanning the time between 400 and 345 million years ago; also, the corresponding system of rocks. It is named after Devonshire, England, where rocks of this age were first studied.

Devonian Woodford Shale. This is a Devonian-age geological marker about 15,600 feet deep at the WIPP that separates rocks of the Silurian era from rocks of the Mississippian era.

Dewey Lake Redbeds. A formation of the Permian Period that overlies the Rustler Formation and is composed of reddish brown marine mudstone and siltstones interbedded with fine grained sandstone.

diapirism. The formation of an intrusion or diapir that penetrates through overlying layers of more brittle rock and domes the overlying rock cover. Diapirs are commonly formed from mobile igneous intrusions or from plastic salt bodies. The development of narrow necks at depth often gives diapirs a balloon-like form.

diagenetic. Pertaining to or caused by diagenesis; for example, a “diagenetic change” resulting from compaction, a “diagenetic structure” (such as a stylolite) formed after deposition, a “diagenetic deposit” (such as dolomitized limestone or consisting of manganese nodules), or a “diagenetic environment” of rock consolidation.

diffusion, molecular. Transport of material (particularly the spread of a contaminant) through the random motion of molecules in a fluid or solid. Diffusion results in the slow transfer of material from regions of high concentration to regions of lower concentration even when there is no net fluid flow.

dike. A tabular body of igneous rock that cuts across the structure of adjacent rocks or cuts massive rocks. Most dikes result from the intrusion of magma. Some dikes occur in a set of numerous parallel structures identified as dike swarms. Present in the vicinity of the WIPP site are lamprophyre dikes. (See Lamprophyre)

discharge point (or area). In groundwater hydraulics, the point (or area) where water comes out of an aquifer onto the surface.

Disposal Inventory. The inventory volume defined for waste emplacement in the WIPP to be used for CRA-2004 PA calculations. The Land Withdrawal Act (LWA; Public Law 102-579) identifies the total amount of TRU waste allowed in the WIPP as 175,564 m^3 (6,200,000 ft^3). The “Agreement for Consultation and Cooperation” limits the RH-TRU inventory to 7,079 m^3 (250,000 ft^3).

dispersion. Signifies the tendency for a sharp change in fluid properties (for example, temperature, contaminant concentration) to become broader and less abrupt as flow progresses. For example, if a volume of contaminated water is injected into an aquifer, the contact between the contaminated and uncontaminated water will initially be sharply

defined by a very steep gradient in contaminant concentration. As the water flows away from the injection point, however, natural variations in the rock allow contaminated water to move quickly through some large pores while nearby smaller pores will retain uncontaminated water for a longer period. This, and other similar effects, will cause contaminated and uncontaminated water to intermingle, resulting in dispersion of the contaminant "front."

disposal. The term "disposal" means permanent isolation of transuranic waste from the accessible environment with no intent of recovery, whether or not such isolation permits the recovery of such waste. Disposal of waste in a mined geologic repository occurs when the waste has been emplaced and all the shafts to the repository are sealed.

disposal phase. The term "disposal phase" means the period of time during which transuranic waste is disposed of at the WIPP, beginning with the initial emplacement of transuranic waste for disposal and ending when the last container of transuranic waste is emplaced for disposal and the shafts are sealed.

disposal room. An excavated cavity in the WIPP repository in which transuranic waste will be emplaced during disposal operations.

disposal system. The disposal system is any combination of engineered and natural barriers that isolate transuranic waste after disposal. For the purposes of the WIPP, this will include the combination of the repository/shaft system and the controlled area.

disposal system performance. Disposal system performance is measured in Section 6.5. It is compared with the EPA requirements in the complementary cumulative distribution function.

dissolution. (1) The process whereby a space or cavity in or between rocks is formed by the solution of part of the rock material. (2) The solution of material by a solvent (for example, dissolution of waste by brine at the WIPP).

disturbed rock zone. That portion of the geologic barrier in which the physical and/or chemical properties may have changed significantly as a result of underground construction activities.

Dockum Group. The Triassic Dockum Group consists of three formations. In ascending order, they are (1) the Tecovas Formation, which consists of up to 300 ft of red shale, siltstone, and fine-grained sandstone; (2) the Santa Rosa Sandstone, which is composed of 100 to 650 ft of red, brown, and gray sandstone; and (3) the Chinle Formation equivalent, which consists of up to 1,300 ft of red, maroon, and purple shales and siltstones with lenses of fine-grained red-to-gray sandstone. The group is present only as a thin wedge in Eddy County, thickening to the east in Lea County and in Texas.

dolomite. A sedimentary rock consisting mostly of the mineral dolomite: $CaMg(CO_3)_2$. It is commonly found with limestone.

dome (breccia pipe). A type of hill found near the Los Medaños site; under at least a few of these hills lies a roughly cylindrical volume of breccia (rock reconstituted of coarse rock fragments).

dome, salt. A diapiric or piercement structure with a central, nearly circular salt plug, generally 1 to 2 km in diameter, that has risen through the enclosing sediments from a deep mother bed of salt. In the continental U.S., salt domes are located primarily in the Gulf Coast states.

dose. A general term indicating the amount of energy absorbed per unit mass from incident radiation.

dose conversion factor. A numerical factor used in converting radionuclide uptake (curies) in the body to the resultant radiation dose or dose commitment (rem or man-rem).

dose equivalent. The product of absorbed dose and appropriate factors to account for differences in biological effectiveness due to the quality of radiation and its spatial distribution in the body; the unit of dose equivalent is the rem (sievert in System of International units). (40 CFR § 191.12)

downdip. To move in the direction at which a rock layer or any planar feature is inclined (dip) from the horizontal.

drift. A horizontal passageway in a mine away from the main shaft.

drilling fluids. A suspension fluid used in drilling. The fluid is pumped through the inside of the drill pipe and out through the jets of the drilling bit. It is used to lubricate the drilling bit, seal off porous zones, and to counter-balance the pressure of oil, gas, or water. The fluids consist of various substances in a finely divided state among which bentonite and barite are common. Oil may also be used as a base instead of water.

Driving Force Ratio. A ratio established to assess the effects of density gradient when examining hydraulic effects of fluid density variations in the Salado interbeds and the Culebra. It is given by driving force ratio = $(\Delta\rho\rho\ \nabla E)/(\rho f\ \Delta Hf)$, where ΔHf is the gradient of freshwater head, $\Delta\rho$ is the difference between actual fluid density and reference fluid density, ρf is the density of freshwater, and ∇E is the gradient of elevation.

DRSPALL. The DRSPALL code is written to calculate the spallings release, defined as a mass of waste subject to tensile failure during an inadvertent drilling intrusion into a high-pressure WIPP repository.

E1, E2. These are potential human intrusion scenarios used in computer modeling for compliance purposes.

effective dose. The sum over specified tissues of the products of the dose equivalent received following an exposure of, or an intake of radionuclides into, specified tissues of the body, multiplied by appropriate weighting factors. This allows the various tissue-specific health

risks to be summed into an overall health risk. The method used to calculate effective dose is described in Appendix B of 40 CFR Part 191. (40 CFR § 191.12)

effective porosity. Porosity is defined as the ratio of volume to bulk volume. Effective porosity is connected porosity, through which fluids may move; that is, it has permeability.

effluent. Wastewater or airborne emissions discharged into the environment.

Eh. The oxidation potential is a measure of the oxidizing or reducing tendency of a solution. It is written as a reduction reaction using the standard hydrogen reaction, Eh (volts) = E_h^0 + RT/nF ln (oxidized species/reduced species).

elasticity. The ability of rocks to recover in size and shape (no long-term changes in rock properties) resulting from minor deformation (for example, minor deflection of anhydrite beds, deformation of rock due to passage of seismic wave, etc.). The property by virtue of which a body resists and recovers from deformation produced by force.

electrochemical. Refers to chemical effects or reactions that produce, are mediated by, or significantly influenced by electrical currents or accumulations of electrical charge.

electrolytes. A substance that will provide ionic conductivity when dissolved in water or when in contact with water. The term is also used to designate solutions of such substances.

electromechanical. Mechanical processes or effects that are driven by or produce electricity.

electron acceptors. Atoms or molecules that will readily accept an additional electron to form an ionic or covalent bond. The availability of such chemical species is necessary for some bacterial processes involving the decomposition of complex organic molecules.

electrophoresis. Migration of colloidal or other particles in a liquid suspension that responds to applications of an electric field.

empirical. Methods that rely on experience or observation alone without regard for system and theory. They are capable of being verified or disproved by observation or experiments.

emplacement. At the WIPP, the placing of radioactive wastes in the repository.

Emplaced Waste Inventory. Waste that has been disposed at the WIPP as of the inventory date (September 30, 2002).

engineered alternatives. Potential modifications to the design or operation of the WIPP or to waste forms that, if adopted, will provide increased assurance that the WIPP will perform in compliance with environmental protection and safety requirements.

engineered barriers. Backfill, seals, and any other man-made barrier components of the disposal system.

enthalpy. The sum of the internal energy (heat) generated or absorbed when a reaction takes place.

eolian. Pertaining to the wind. Also spelled aeolian.

EPA unit. The EPA unit is a measure of radioactivity that has been normalized by the inventory of the disposal system in question and by the release limits specified by the EPA in Appendix B, Table 1, of 40 CFR Part 191. Specifically, a quantity of radioactivity of any radionuclide (expressed in curies) may be expressed in dimensionless EPA units by dividing it by the product of the waste unit factor and the EPA release limit for that radionuclide. The containment requirements of 40 CFR § 191.13(a) establish release limits for the disposal system in terms of the probability that 10,000 year cumulative releases will exceed 1 and 10 EPA units.

EPAUNI. The EPAUNI code is used for estimating the probability distribution of EPA unit loading in the WIPP repository.

epicenter. The point on the earth's surface directly above the focus of an earthquake.

equilibrium. A state of balance between opposing forces or actions that is either static (as in a body acted on by forces whose resultant is zero) or dynamic (as in a reversible chemical reaction when the velocities in both directions are equal).

erosion. The processes whereby earthy or rock material is loosened or dissolved and removed from any part of the earth's surface. It includes the processes of weathering, solution, corrosion, and transportation.

estuarine. The seaward end of the widened tidal mouth of a river where fresh water comes into contact with seawater.

evaporite. A sedimentary rock composed primarily of minerals produced by precipitation from a solution that has become concentrated by the evaporation of a solvent, especially salts deposited from a restricted or enclosed body of seawater or from the water of a salt lake. In addition to halite (NaCl), these salts include potassium, calcium, and magnesium chlorides and sulfates.

event. A phenomenon that occurs instantaneously or within a short time interval relative to the time frame of interest.

excavation. The action of cutting, digging, or mining a cavity in the earth and the removal of that mined material. The WIPP repository excavated in solid salt rock is an example of excavation.

exothermic. The release of heat from a (chemical) reaction.

extraction. The withdrawal of natural resources with no provision for replenishment.

fast Langrangian analysis of continua. A two-dimensional finite-difference code used for the WIPP to estimate subsidence above the repository for conditions ranging from no backfill to emplacement of a highly compacted crushed salt backfill.

fault. A surface or zone of rock fracture along which there has been displacement.

fault tree. A tree-like cause-and-effect diagram of hypothetical events. Analysis of fault trees is used to investigate failures in a system or concept.

fauna. An entire animal population of a given region, environment, formation, or time span.

features, events, and processes. Features, events, and processes (FEPs) that are potentially important to long-term performance of the disposal system. A comprehensive set of FEPs relevant to the WIPP was considered in applying a screening methodology to evaluate compliance with the numerical performance requirements provided in 40 CFR Part 191.

Federal Facilities Compliance Act. An amendment, promulgated in 1992, to the Solid Waste Disposal Act. Title I of the act grants the EPA administrative enforcement authority against any department, agency, or instrumentality of the executive, legislative, or judicial branch of the federal government. In regard to mixed wastes, sovereign immunity for federal agencies is waived, consistent with a schedule provided in the act. In addition, the act requires that the DOE prepare an inventory of mixed wastes and mixed waste treatment capacities and technologies. For those mixed wastes for which treatment capacities or technologies do not exist, the Department must prepare plans for the development of the capacities or technologies.

Fick's Law. Mathematical equation in which steady-state diffusion through solids is represented. J is the flux or diffusion current density, D is the diffusion coefficient, c is the volume concentration of atoms, and x is the distance along the direction in which diffusion occurs.

filter bank. An arrangement of air filters in series and/or parallel.

final safety analysis report. A safety document providing a concise but complete description and safety evaluation of the site, the design, normal and emergency operations, potential accidents, and predicted consequences of such accidents, and the means proposed to prevent such accidents or to mitigate the consequences of such accidents. A final safety analysis report documents the adequacy of safety analysis for a nuclear facility to ensure that the facility can be constructed, operated, maintained, shut down, and decommissioned safely and in compliance with applicable laws and regulations.

Final Waste Form. The expected final physical form of a waste stream. The use of the final waste form helps to group waste streams that are expected to have similar physical and chemical properties at the time of disposal. Waste is assigned to 1 of 11 final waste forms: solidified inorganics, salt, solidified organics, soils, uncategorized metal, lead/cadmium metal, inorganic non-metal, combustible, graphite, heterogeneous, and filter.

fissile material. Fissile material means any material consisting of or containing one or more fissile radionuclides. Examples of fissile radionuclides are plutonium-238, plutonium-239, plutonium-241, uranium-233, and uranium-235.

fission. The splitting of a heavy nucleus into two approximately equal parts, each the nucleus of a lighter element, accompanied by the release of a large amount of energy and generally one or more neutrons. Fission can occur spontaneously, but it usually follows the absorption of neutrons.

fissionable. A nuclide that is available to undergo fission on absorption of a neutron with energy over some threshold energy.

flowpath. The path traveled by a zero-charged, floating particle released into a groundwater flow field.

fluid. A substance that is able to flow freely as liquids and gases do.

fluvial. Produced by or pertaining to a river or rivers. Applies to erosion (fluvial erosion) by rivers or streams and deposition (fluvial deposition) by the accumulation of sediments in a depositional environment associated with rivers or streams.

flux. The rate of transfer of heat, mass, electricity, groundwater, etc., across a unit surface area in a unit time.

formation (geologic). The basic rock-stratigraphic unit in the local classification of rocks. It consists of a body of rock (usually sedimentary) generally characterized by some degree of internal lithologic homogeneity or distinctive features.

Forty-niner Member. Upper most member of the Rustler Formation formed in the Late Permian Period, between approximately 250 and 245 million years ago. It consists of upper and lower sulfates separated by claystone or halite. The member is about 60 ft (18 m) thick around the WIPP site.

fracture porosity. Porosity resulting from the presence of openings or fractures produced by the breaking or shattering of an otherwise less porous rock.

fractures. A general term for any break in a rock, whether or not it has an associated displacement. Fractures are the result of mechanical failure by stress. Fractures include cracks, joints, and faults. Fracture porosity is the resulting opening produced by the breaking or shattering of an otherwise less pervious rock.

fugacities. The pressures of vapors assumed to behave as ideal gases.

galvanic coupling. Refers to the establishment of an electrical current through chemical processes. Galvanic coupling could lead to the establishment of potential gradients between metals in the waste form, canisters, and other metals external to the waste form.

gamma rays. (X-rays) Short wavelength electromagnetic radiation emitted in the radioactive decay of certain nuclides. Gamma rays are the same as gammas or gamma particles.

gas generation. Three gas generation processes are expected to be factors in the degradation of transuranic waste in the WIPP repository. The generation of gaseous species is expected to occur through chemical (that is, corrosion), microbial, and radiolytic processes.

gas generation model. A computational model that can simulate and/or predict the rate and quantity of gases generated by waste transformation processes in a disposal room of the decommissioned repository.

gas generation rate. The combined gas production rate from all species of gases produced as a result of transuranic waste transformations such as corrosion, and/or microbial degradation, at any given time. The rate of gas production throughout the history of the repository is expected to vary depending on repository conditions with respect to humidity, total or partial brine inundation, competitive reactions that absorb specific gases, and the ability of the repository to retain the gases generated. The term is also applied to individual gases.

gastropod. Any of a large class (Gastropoda) of mollusks with a univalve shell or none, usually with distinct head-bearing sensory organs.

Gatuña Formation. A geologic formation covering the Permian Dewey Lake Formation, or the Santa Rosa Formation of the late Pliocene Period. Considered to be fluvial in origin, the Gatuña Formation varies in thickness and is overlain by the Mescalero Caliche.

generator and/or storage sites. Refers to the DOE sites nationwide where transuranic wastes are generated and/or stored as a result of activities associated with nuclear weapons production.

geochemistry. The study of the relative and absolute abundances of elements found on the earth, and the chemical distribution and migration of individual elements located in various parts of the earth (the atmosphere, hydrosphere, etc.).

geomechanical. The response of natural earth materials to the application of deforming forces. These forces would include the excavation and subsequent deformational response of the WIPP disposal rooms and drifts.

geomorphology. The description and interpretation of landforms on the earth's surface.

geophysical log. A graphic record of the measured or computed physical characteristics of the rock section encountered in a well, plotted as a continuous function of depth. Measurements are made by a sonde as it is withdrawn from the borehole by a wireline. Several measurements are usually made simultaneously, and the resulting curves are displayed side by side on the common depth scale. Both the full display and the individual curves are called logs. Well logs are commonly referred to by generic type.

geophysical techniques. The methods used to obtain geophysical data (that is, values of the physical parameters of the earth). The methods of techniques generally involve the study of ambient fields (gravitational, magnetic, electrical, temperature) or the study of the effects of applied fields (seismics through the application of shock waves, electrical through the direct application of electrical currents — resistivity methods — and by electromagnetic induction.)

geostatistics. A branch of statistics used to describe and interpret spatial data.

geothermal. The internal energy of the earth, available from heat sources produced at depth within the earth's crust.

getters. Substances that sorb gases, such as carbon dioxide (CO_2), and may be added with other materials to mitigate the pressure buildup in the repository and radionuclide mobility.

Gibbs Free Energy. A thermodynamic quantity defined as H - TS. H is enthalpy, S is absolute entropy, and T is temperature. The magnitude of the change in Gibbs Free Energy for a reaction determines whether it is reversible or will occur spontaneously at given temperature and pressure.

glaciation. Applies to both the formation, progression, and recession of glaciers and the resulting alteration of the earth's ground surface through erosion and deposition.

glove box. A sealed box in which workers, remaining outside and using gloves attached to and passing through openings in the box, can safely handle and work with radioactive materials under controlled conditions.

Goat Seep. The Goat Seep was a reef that grew primarily upward and formed a barrier around a considerable portion of the western side of the Delaware Basin. The lower portion of the Goat Seep is thick-bedded, and the upper portion is a massive light gray, fine-crystalline to saccharoidal, and in places very porous, dolomite.

graben. An elongate, relatively depressed crustal unit or block that is bounded by roughly parallel faults on its long sides. It is a structural form that may or may not be geomorphologically expressed as a rift valley.

gradient. Spatial changes in the value of a variable. Changes are along vertical, inclined, or horizontal distances, such as the groundwater pressure gradient of the Culebra Dolomite changing in the vicinity of the WIPP site.

greenhouse effect. Warming of the earth's surface and the lower layers of atmosphere that tends to increase with increasing atmospheric carbon dioxide and other gases, and is caused by conversion of solar radiation into heat.

groundwater. Water below the land surface in a zone of saturation. (40 CFR § 191.12)

grout. A mortar of cement slurry (of high water content) used to plug potential fluid-flow paths in geologic or engineered structures.

Guadalupian. Geological group of rocks below the Castile about 4,100 ft to about 8,000 ft below the surface at the WIPP. Contains the Bell Canyon, Brushy Canyon, and Cherry Canyon formations.

gypsite. An earthy variety of gypsum containing dirt and sand, found only in arid regions.

gypsum. A mineral consisting of hydrous calcium sulfate: $CaSO_4$ $ $2H_2O$. It is soft and, when pure, white.

half-life. The time required for the activity of a group of identical radioactive nuclei to decay to half its initial value. (See biological half-life).

halite. The mineral rock salt: NaCl.

halophilic. A type of organism that flourishes in a salty environment, such as salt lakes and marshes. Halophilic microorganisms may be present in WIPP's disposal environment at the time of closure.

halotolerant. A type of organism that is tolerant of salty environments but does not prefer them. Halotolerant microorganisms may be introduced into the waste before disposal from semi-salty environments, such as the skin of humans.

health physics. The science concerned with the recognition, evaluation, and control of health hazards from ionizing radiation.

heavy metal. All uranium, plutonium, or thorium placed into a nuclear reactor. (40 CFR § 191.12)

HEPA filter. A high-efficiency particulate air filter usually capable of 99.7 percent efficiency as measured by a standard photometric test using 0.3-micron droplets (aerodynamic equivalent diameter) or dioctylphthalate.

high-level waste. Radioactive waste resulting from the reprocessing of spent fuel. Discarded, unreprocessed spent fuel is also high-level waste. It is characterized by intense, penetrating radiation and by high heat-generation rates. Even in protective canisters, high-level waste must be handled remotely.

horizon. In geology, an interface indicative of a particular position in a stratigraphic sequence. For instance, the waste-emplacement horizon in the Salado Formation at the WIPP is the level about 650 m (2,150 ft) deep where openings are mined for waste disposal.

host rock. The rock unit, in this case the Salado Formation, in which the radioactive waste is to be emplaced.

hot cell. A heavily shielded compartment in which highly radioactive material can be handled, generally by remote control.

human intrusion. (See Inadvertent Human Intrusion).

humics. Matter that is derived from humus, which is a brown or black complex of variable material resulting from partial decomposition of plant or animal matter and forming the organic portion of soil.

hummocky. Containing rounded knolls or small hills.

hydration. The uptake of water by a substance, generally involving reactions in which the H-OH bond of the water molecules is not broken. (See hydrolysis.)

hydraulic conductivity. A quantity defined in the study of groundwater hydraulics that describes the ability of rock to transmit groundwater. It is measured in feet per day or equivalent units. It is equal to the hydraulic transmissivity divided by the thickness of the aquifer.

hydraulic gradient. A quantity defined in the study of groundwater hydraulics that describes the rate of change of hydraulic head with distance.

hydraulic potential (or hydraulic head). Hydraulic pressure corrected for the potential energy of elevation. In an aquifer it is equivalent to the highest level of a column of water that the pressure in the aquifer will support. It is measured relative to a specified level, which in this document is the mean sea level.

hydraulic transmissivity. A rate at which water is transmitted through a unit width of aquifer. It is measured in square meters per second or equivalent units. (See transmissivity).

hydraulic transport. The transport of dissolved or suspended substances by groundwater.

hydraulics, hydrology. These two terms tend to be used interchangeably, but they are not the same. Hydraulics is an engineering discipline; hydrology is the related science. Hydraulics deals with the flow of water. Hydrology deals with water: its properties, circulation, and distribution, from the time it falls as rainwater until it is returned to the atmosphere through evapotranspiration or flows into the ocean.

hydrocarbon. An organic compound (as acetylene or benzene) containing only carbon and hydrogen and often occurring in petroleum, natural gas, coal, and bitumens.

hydrolysis. A chemical reaction between water and another material in which two or more new species are formed, implying that the H-OH bond in the water molecules is broken.

hydrostatic. The pressure and equilibrium of liquids such as the pressure exerted by water at any given point in a body of water at rest. The hydrostatic pressure of groundwater is generally due to the weight of water in higher levels in the zone of saturation.

igneous. Rocks that are formed by solidification from a molten or partially molten state. For convenience, igneous rocks are divided into two major classes, plutonic and volcanic, which describe igneous rocks formed at depth and at or near the land surface, respectively.

inadvertent human intrusion. The accidental violation of the disposal system through human activity such as mining or exploration drilling. Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario (40 CFR § 194.33[b][1]).

infiltration. The penetration of water through the ground surface into subsurface soil.

ingestion. The uptake of materials taken into the body by way of the digestive tract.

ingrowth. The process in which a nuclide results from the radioactive disintegration of a radionuclide. The nuclide can be formed directly or as the results of successive transformations in a radioactive series. A decay product may be either radioactive or stable.

injection well. A well into which fluids are injected.

in situ. In the natural or original position. The phrase is used in this document to distinguish in-place experiments, rock properties, and so on, from those measured in the laboratory.

insoluble. Unable to be dissolved.

intensity, earthquake. A measure of the effects of an earthquake on humans and structures at a particular place. Not to be confused with magnitude.

interbed. A usually thin layer of rock, typically of one kind of rock material, occurring between or alternating with layers of another rock type. The Salado Formation in the vicinity of the WIPP site contains layers of anhydrite that are interbedded between more massive layers of halite.

interfacial energy. Energy associated with an interface between two materials (surfaces). Changes in interfacial energy control effects such as the wetting of a solid surface by a liquid.

intergranular. The porosity or spaces occurring between the grains of granular or crystalline rocks in which the void space usually contains a liquid.

interpreted data sets. Data sets derived from a surrogate data source where direct measurement is not possible.

interstitial brine. Brine distributed in the pore space (voids) of a rock mass.

intragranular. The porosity or spaces occurring within a grain or crystal, especially within skeletal material of a carbonate sedimentary rock in which the void space may or may not contain a liquid.

intraplate rifting. Rifting of the continental or oceanic crust within a crustal plate. Typically applies to areas that have shown regional extensional tectonic activity away from the plate boundaries and where igneous rocks have formed intrusive sill, dikes, volcanic plugs, and other intrusive bodies. Intraplate rifting has taken place along the Rio Grande valley, 120 miles (200 kilometers) west of the WIPP site during the Tertiary and Quaternary Periods. (See Rio Grande Rift).

Inventory Date. September 30, 2002. The cutoff date for determining the emplaced waste inventory included in CRA-2004 and the date TRU waste sites have used as the basis for their revised stored waste and projected waste inventory estimates.

ion exchange. A phenomenon in which chemical species in one phase or material exchange with similar species in another phase.

isopach. A line drawn on a map through points of equal true thickness of a designated stratigraphic unit or group of stratigraphic units.

isotope. Any of two or more species of atoms of a chemical element with the same atomic number but with differing atomic mass.

Jurassic. The second period of the Mesozoic era (after the Triassic and before the Cretaceous), thought to have covered the span of time between 190 and 135 million years ago; also, the corresponding system of rocks.

K-Ar. Determination of the age of a mineral or rock in years, based on measurement of the ratio of radiogenic argon-40 to potassium-40 and the known radioactive decay rate of potassium-40 to argon-40.

karst. A type of topography that is formed on limestone, gypsum, and other rocks by dissolution, and that is characterized by sinkholes, caves, and underground drainage.

K_d. A symbol used to designate a coefficient used in calculating chemical retardation.

kelvin. The name of the absolute temperature scale generally used in scientific measurements and calculations. The unit of temperature is also designated a kelvin.

kinetic. An adjective referring to motion and, by extension, to changing conditions. In chemistry, kinetic behavior refers to the performance of a system in which ongoing chemical reactions are changing the quantities or character of the substances present in the system at a certain rate and are thereby moving towards equilibrium.

lacustrine. The term is used to identify sediments formed by deposition in lakes and to identify chemical and biological processes that typically occur in lakes.

Lamar Limestone. A limestone member at the top of the Bell Canyon Formation, known as the Lamar limestone, is recognizable over a considerable part of the Delaware Basin.

lamprophyre. A group of dark-colored intermediate igneous rocks characterized by unrestricted crystal structures and a high percentage of mafic minerals (that is, biotite, hornblende, and pyroxene). Lamprophyre igneous rocks commonly occur in the form of dikes. (See Dike) This type of dike is present in the vicinity of the WIPP site and is identified by the dark minerals that occur both as phenocrysts and in the groundmass and light minerals occurring only in the groundmass.

Land Withdrawal Act. Public Law 102-579, which withdraws the land at the WIPP site from "entry, appropriation, and disposal," transfers jurisdiction of the land from the Secretary of the Interior to the Secretary of Energy, reserves the land for activities associated with the development and operation of the WIPP, and includes many other requirements and provisions pertaining to the protection of public health and the environment.

langbeinite. A mineral, $K_2Mg_2(SO_4)_3$, used in the fertilizer industry as a source of potassium sulfate present in economic quantities in the McNutt Potash Zone.

Latin hypercube sampling. A Monte Carlo sampling technique that divides the range of each variable into intervals of equal probability and samples from each interval.

leachate. Any liquid, including any suspended components in the liquid, that has percolated through or drained from waste.

leaching. The process of extracting a soluble component from a solid by the percolation of a solvent (in this report, water) through the solid.

Leonardian. The geologic formation from 8,000 feet to 11,400 feet below the surface at the WIPP. Middle of the Permian Period.

level-line survey. A cross-country survey in which changes in elevation with respect to sea level are very carefully measured.

LHS. The LHS program samples distributions of input parameters using normal Monte Carlo sampling or efficient Latin Hypercube Sampling.

ligands. A molecule, ion, or atom that is attached to the central atom of a coordination compound. Ligands are also called complexing agents.

lithofacies. A lateral, mappable subdivision of a designated stratigraphic unit, distinguished from adjacent subdivisions on the basis of lithology, including all mineralogic and petrographic characters and those paleontologic characters that influence the appearance, composition, or texture of the rock.

lithology. The study and examination of the physical characteristics (color, mineralogic composition, grain size, etc.) of rocks, generally determined from a hand specimen with the aid of a low-powered magnifier.

lithosphere. The outer solid shell of the earth considered to be about 50 miles (80 kilometers) in thickness. Composed of the rocks that include both the earth's crust and upper mantle.

lithostatic pressure. The vertical pressure at a point in the Earth's crust, equal to the pressure caused by the weight of the overlying rocks.

Livingston Ridge. Topographic feature marking the eastern boundary of Nash Draw.

long term. Refers to the first 10,000 years after shaft sealing for which performance assessment calculations and models assess the behavior of the repository with respect to compliance with 40 CFR Part 191 and 40 CFR § 268.6.

Los Medaños. In this report, the area in southeastern New Mexico surrounding the site proposed for the WIPP repository. In Spanish it means "dune country."

Los Medaños Member. The lowest member of the Rustler formation, formerly known as the unnamed lower member.

lower explosive limit. The minimum concentration of gas or vapor in air below which a substance does not burn when exposed to an ignition source.

macromolecule. A very large molecule (such as proteins, cellulosics, and rubbers) that contains hundreds or thousands of atoms.

Magenta Dolomite Member. The upper of two layers of dolomite within the Rustler Formation that are locally water-bearing. Also called the Magenta Member.

magma. Naturally occurring molten rock material which is generated within the earth. This material is capable of intrusion and extrusion, from which igneous rocks are derived through solidification and related processes.

magnitude, earthquake. A measure of the total energy released by an earthquake. Not to be confused with intensity.

Malaga Bend. A sharp bend in the Pecos River 20 miles southeast of Carlsbad, New Mexico, and directly east of the town of Malaga.

man-rem. A unit of population dose (see population dose).

marker beds. Marker beds are well-defined layers of rock that mark distinct divisions in major geological strata or geological time frames.

mathematical model. In the context of the WIPP, mathematical formulations developed to represent the processes at the WIPP site. The conceptual models provide the context

within which these mathematical models must operate and define the processes they must characterize. The mathematical models are predictive in the sense that, once provided with the known or assumed properties of the system and possible perturbations to the system, they predict the response of the system. The processes represented by these mathematical models include fluid flow, mechanical deformation, radionuclide transport in groundwater, and removal of waste through intruding boreholes.

matrix porosity. The porosity of the matrix or finer parts of a rock, as opposed to the porosity imparted to a rock through fractures, vugs, and voids.

maximally exposed person. A hypothetical person who is exposed to a release of radioactivity in such a way that the person receives the maximum possible individual dose or dose commitment. For instance, if the release is a puff of contaminated air, the maximally exposed person is the individual at the point of largest ground-level concentration who stays there during the whole time of the cloud passage. The use of this term is not meant to imply that there is such a person, but only that thought is being given to the maximum exposure a person could receive.

maximum individual dose. The highest dose delivered to the whole body or to an individual organ that a person can receive from a release of radioactivity. The hypothetical person who receives this dose, the maximally exposed person, is one whose location and activities maximize the dose. For instance, the person may be at the point of maximum concentration of a radioactive cloud for the whole time it takes to pass.

MB 139. A marker bed located one m below the WIPP site and is on average one m thick. It consists mostly of anhydrite and clay.

mCi. Abbreviation for millicurie. One one-thousandth (0.001) of a curie.

McNutt Potash Zone or Member. The middle member of the Salado Formation measuring 348 to 413 ft (106 to 126 m) thick in the vicinity of the WIPP site. This member contains reddish-orange and brown halite with deposits of sylvite and langbeinite from which potassium salts are mined. The McNutt Potash Member was deposited in the Late Permian Period between approximately 258 and 250 million years ago.

mean. The average value. For a given set of *n* values, the mean is the sum of their values divided by *n*.

median. The median of a set of data is the value such that half of the observations are less than that value and half are greater than that value.

megapascal. 10^6 pascals.

Mercalli intensity. A scale of measurement of earthquake intensity.

Mescalero Caliche. An informal name for a layer of caliche of varying thickness found in the WIPP area.

Mescalero Plain. The Plain is composed of the ground surface east of the Pecos River valley and is one of the principal geomorphic features associated with the WIPP site. It consists of a poorly drained surface covered by gravels, eolian sand, and caliche. The plain has developed since the Early to Middle Pleistocene time (approximately 1.6 million year ago).

Mesozoic. An era of geologic time from the end of the Paleozonic Era, 245 million years ago, to the beginning of the Cenozoic era, 66 million years ago. It comprises the Triassic, Jurassic, and Cretaceous period.

metabolized. Refers to a material which has been consumed or transformed by the life processes of an organism.

metamorphic. Metamorphism is changes in rocks brought on by the effects of temperature, pressure and/or the introduction of new chemical substances. It requires deep burial below the zones of weathering and cementation.

methanogenesis. The generation of methane through the decomposition of organic matter in wastes.

microbial. The action of microbes or microorganisms. In the context of the WIPP, the term is mainly applied to the waste degradation and gas generation activity of microorganisms.

mineralization. The process whereby minerals are precipitated out of a solution into a porous or fracture zone. For example, if the Salado Formation brine is transported to the Culebra Dolomite, cooling may cause the precipitation of salt minerals.

Miocene. The fourth of five epochs into which the Tertiary Period is divided; also, the corresponding system of rocks. It is subsequent to the Oligocene Epoch and precedes the Pliocene Epoch (approximately 23.7 to 5.3 million years ago).

miscellaneous hazardous waste management unit. A waste management unit where hazardous waste is treated, stored, or disposed of, and that is not a container, tank, surface impoundment, pile, land treatment unit, landfill, incinerator, boiler, industrial furnace, underground injection well, or unit eligible for a research, development, and demonstration permit (40 CFR § 260.10).

Mississippian. Third youngest period of the Paleozonic Era and the corresponding system of rocks. Prior to the Pennsylvanian and representing approximately the interval from 360 to 320 million years ago. Mississippian rocks are present from 15,000 to 15,600 feet below the surface at the WIPP.

Mississippian Limestone. The limestone is light gray to brown, finely crystalline and commonly cherty, with a basal dark gray organic-rich shale unit. The limestone partially grades to shale southeastward from the northern margin of the Delaware Basin.

mixed waste. Mixed waste contains both radioactive and hazardous components, as defined by the Atomic Energy Act and the Resource Conservation and Recovery Act, respectively.

model. An investigative technique using a mathematical or physical representation of a system that accounts for all or some of its known parameters. Models are often used to test the effect of changes of system components on the overall performance of the system.

model validation. The process of ensuring (through sufficient testing of a model using actual site data), that a conceptual model, and corresponding mathematical and computer models, correctly simulate a physical process with sufficient accuracy.

model verification. The process of ensuring (for example, through tests on ideal problems) that a computer code (computational model) correctly performs the necessary functional operations (such as solving the mathematical model). Given that a computer code correctly solves the mathematical model, the physical assumptions of the mathematical model must then be checked through validation.

MODFLOW. A computer program that numerically solves the three-dimensional groundwater flow equation for a porous medium by using a finite-difference method.

molality. The molality of a solution is the number of moles of solute in 1,000 g of solvent. A solution which contains one mole of solute in 1,000 g of solvent is called a one-molal solution.

molarity. The molarity of a solvent is the number of moles of solute per liter of solution. A solution containing one gram formula weight, or mole, of the solute in one liter of solution is a one-molar solution.

Monte Carlo Analysis/Technique. A technique that obtains distribution of approximate solutions to a problem by using statistical sampling techniques and computer simulations. For the WIPP PA, the method is used to evaluate the distribution of the consequence results and thereby approximate the uncertainty in the results.

Morrow Formation. This formation was formed in the Early Pennsylvanian Period approximately 320 million years ago. It consists of fine to coarse grain sandstones with dark gray shales and some thin limestones layers present in the upper section. It is approximately 14,000 ft (4,200 m) below the surface at the WIPP and 1,200 ft (366 m) in thickness. The Morrowan sandstones are a source of natural gas production north of the WIPP site.

MTHM. Metric tons of heavy metal; used in the release limit described in Appendix A of 40 CFR Part 191.

mudstone. An indurated mud having the texture and composition of shale, but lacking its fine lamination or fissility; a blocky or massive, fine-grained sedimentary rock in which the proportions of clay and silt are approximately equal; a nonfissile mud shale.

multi-mechanism deformation model. A simulation model developed to help predict the behavior, particularly the rate of room closure, of WIPP underground openings.

Nash Draw. A shallow valley, approximately five miles wide, open to the southwest, and located to the west of the WIPP site.

natural background radiation. Radiation in the human environment from naturally occurring elements and from cosmic radiation. See background (radiation).

natural barriers. The repository host rock and surrounding geologic structures and formations. The natural barriers extend from the engineered barrier to the compliance boundary.

near future. Defined for any activity that is initiated prior to shaft sealing (preclosure), even if the completion will occur after shaft sealing (postclosure). The demarcation between near future and future is the date of shaft sealing. All activities initiated after shaft sealing are "future" activities. Any activity initiated prior to shaft sealing is a "near future" activity and is part of the undisturbed performance.

neutron. An elementary particle that has approximately the same mass as the proton but lacks electric charge, and is a constituent of all nuclei having mass number greater than one.

New Mexico Bureau of Mines and Mineral Resources. The New Mexico Bureau of Mines and Mineral Resources is a division of the New Mexico Institute of Mine Technology.

nitrates. The salts from nitric acid generating sodium nitrate and potassium nitrate. These salts are used in the agricultural industry as fertilizers. When used as a fertilizer, nitrates can be a cause for groundwater chemistry changes.

nondestructive assay. The remote determination of the radionuclide content inside a waste package.

non-Salado. In this report, non-Salado refers to the hydrological aspects of all geologic formations above and below the Salado Formation. It pertains to the conceptual models used for flow and transport of radionuclides within these formations.

nuclear criticality. A self-sustaining nuclear chain reaction from sufficient mass of a fissionable material.

Nuclear Energy Agency. The Nuclear Energy Agency was established on February 1, 1958 under the name of OEEC European Nuclear Energy Agency. Nuclear Energy Agency membership today consists of all the European member countries of Organisation for Economic Cooperation and Development as well as Australia, Canada, Japan, the Republic of Korea, Mexico and the United States. The primary objective of Nuclear Energy Agency is to promote cooperation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable, and economic energy source.

nucleation. The process by which the formation of a crystal or some other particulate from the liquid state, vapor, or solution is begun. Often a minute particle of a foreign substance provides the initial nucleus for crystal growth.

nuclide. A species of atom characterized by the number of protons and neutrons in its nucleus.

nuclide inventory (radionuclide inventory). A list of the kinds and amounts of radionuclides in a container or a source. Amounts are usually expressed in activity units: curies or curies per unit volume.

nutrient. Applies to any substance assimilated by living things that promotes growth. The term generally applies to nitrogen and phosphorus in waste water, but is also applied to other essential and trace elements.

NUTS. NUTS is a radioisotope transport code that is used for the analysis in Chapter 6.0. Its principal capabilities are (1) to decay the inventory, using Bateman's equations, and (2) to transport radionuclide through porous or fractured media. NUTS is capable of resolving and tracking many individual radioisotopes.

Ochoan. The Late Permian Ochoan series consists primarily of evaporites that were deposited during recurrent retreats of a shallow sea restricted by the Guadalupian reefs. The lower three formations in the series, the Castile, Salado and Rustler, comprise what is perhaps the thickest and most extensive evaporite rock sequence in North America.

Ogallala Formation. Deposition of the Ogallala began about 12 million years ago, in Miocene time. The Ogallala represents the first preserved sedimentary record in the vicinity of the Delaware Basin since Cretaceous deposition. The Ogallala formed a thick mantle throughout the Permian Basin, producing the even surface of the High Plains, called the Llano Estacado in western Texas and eastern New Mexico. Locally, eolian activity played a part in deposition, and periodically, widespread soils formed.

one hundred-year storm. A storm that, on a statistical basis, is expected to recur only once every hundred years.

oolite. A sedimentary rock, usually a limestone, made up chiefly of ooliths cemented together. Synonym for roestone and eggstone. An oolith is a spherical or subspherical rock particle that has grown by accretion around a nucleus. The most common type of oolith is calcareous, although primary ooliths of iron minerals are also found.

order of magnitude. A factor of ten. When a measurement is made with a result such as 3×10^7, the exponent of 10 (here 7) is the order of magnitude of that measurement. To say that this result is known to "within an order of magnitude" is to say that the true value lies between (in this example) 3×10^6 and 3×10^8.

Ordovician. The second oldest period of the Paleozoic Era and also the corresponding system of rocks. It is represented by the rock units between 16,900 ft and 18,200 ft below the surface in the vicinity of the WIPP. The Ordovician Period is subsequent to the Cambrian Period and followed by the Silurian Period, between approximately 505 and 438 million years ago.

orthogonal reactions. Chemical reactions that do not affect or interfere with each other.

osmotic. The passage of pure liquid from a region of higher solute concentration to a region of lower solute concentration, usually through some intervening solid or liquid barrier such as a membrane, which restricts mixing. Thus, if a volume of dilute salt water is separated from a volume of concentrated brine by a semi-permeable membrane, water is passed by osmosis through the membrane from the dilute solution to the high-salinity brine.

overpack. A container put around another container. In the WIPP, overpacks would be used on damaged or otherwise contaminated drums, boxes, and canisters that it would not be practical to decontaminate.

oxic. Describes a process that occurs in the presence of oxygen (O_2), such as the corrosion of steels, iron-base alloys, and other metal wastes, using O_2 and water (H_2O) to produce iron oxide and hydrogen gas (H_2).

oxidation. The chemical process whereby electrons are removed from an atom or ion. Originally referring to chemical reactions involving oxygen, the term is also used to designate any chemical reaction in which the reactant gives up one or more electrons. Thus, when hydrogen (H_2) and chlorine (Cl_2) react to form 2H+Cl, the hydrogen is "oxidized" by the chlorine. The oxidation state of an ion is expressed as a positive or negative number representing the ionic or effective charge.

oxides. Minerals in which cationic atoms are bonded to oxygen atoms.

packaging. The assembly of components necessary to ensure compliance with packaging requirements. It may consist of one or more receptacles, absorbent materials, spacing structures, thermal insulation, radiation shielding, and devices for cooling or absorbing mechanical shocks. The vehicle, tie-down system, and auxiliary equipment may be designated as part of the packaging.

Paleozoic. Major geological era from 245 million years to 570 million years. Denotes a wide range of geological strata from different geological periods (that is, Permian, Pennsylvanian, Mississippian, etc).

panel. A group of several underground rooms connected by drifts. Within the WIPP, a panel consists of seven rooms connected by drifts at each end.

PANEL. Sandia National Laboratory computer program which simulates the process of waste mobilization.

parameter. The underlying elements ($x = x_1, ..., x_n, ..., x_{nV}$) of a computational model. As x changes so does the model result. The individual parameters, x_n, may be vectors, tensors, higher order quantities, or even functions, but are usually scalar quantities. Furthermore, the individual parameters are usually coefficients of the mathematical model, but they may also relate to scenario uncertainty or model form uncertainty.

Pascal. A unit of pressure obtained by dividing force (in Newtons) by area (in meters squared).

passive/active neutron analysis. An assaying technique used to determine the amount of fissionable material in a container of waste. Background neutrons are counted as well as neutrons from artificially-induced fissioning in the waste. The analysis assumes that the isotopic composition is already known.

passive institutional controls. "(1) [P]ermanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system." (40 CFR § 191.12)

Pennsylvanian. Second-youngest period of the Paleozonic Era and also the corresponding system of rocks. Pennsylvanian rocks are found about 12,800 to 15,000 ft below the Los Medaños surface in the vicinity of the WIPP site and may contain oil and natural gas. Subsequent to the Mississipian Period and followed by the Permian Period, between approximately 320 and 286 million years ago.

percolate. The movement of liquid (usually water) through unsaturated or saturated solid and rock.

performance assessment (PA). An analysis that (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events.

performance modeling. A process of building models of the factors affecting the containment of nuclear waste to project into the future how the WIPP facility will respond to probabilistic events and processes.

permafrost. Permanently frozen ground which occurs at different depths below the ground surface in frigid climates.

permeability. In hydrology, the capacity of a rock, sediment, or soil to transmit fluids under specified conditions. It is given by the hydraulic conductivity (K) times the fluid dynamic viscosity (μ) divided by the fluid density (ρ) times acceleration due to gravity (g); $k = \mu K/\rho g$.

Permian Basin. A region in the Central U.S. where, during Permian times 286 and 245 million years ago, there were many shallow seas that laid down vast beds of evaporites. The Delaware basin is a part of the Permian basin.

Permian Period. This period is the last of seven periods of the Paleozonic Era, subsequent to the Pennsylvanian Period; also, the corresponding system of rocks (between approximately 286 and 245 million years ago).

PEST. The parameter estimation program that can be used with other models to quickly calibrate parameters using a set of known observations.

petrological. Relating to the general study of rocks in all their aspects, including their mineralogies, textures, structures, origins, field occurrences, alterations, and their relationships to other rocks.

pH. The symbol used to designate a standard measure of the acidity of a solution. pH is defined as the negative logarithm (base 10) of the activity of hydrogen ion in the solution. Pure water, which is regarded as neutral, has a pH of 7. A lower value of pH would indicate acidity, and a higher value would indicate that a solution is basic (alkaline).

phenols. Organic compounds that are by-products of petroleum refining, tanning, and textile, dye, and resin manufacturing. Low concentrations cause taste and odor problems in water; higher concentrations can kill aquatic life and humans.

physicochemical. Describes chemically related processes studied for performance assessment purposes that have potential to influence the transport of contaminants throughout the disposal system. These physicochemical processes include alpha recoil, chemical gradients and osmotic activity.

physiography. A description of the natural features of the surface of the earth.

Pipe Overpack. The standard pipe overpack consists of a pipe component surrounded by cane fiberboard and plywood dunnage within a standard 55-gallon drum with a rigid polyethylene liner and lid. It is designed to be used for the shipment of specific contact-handled transuranic waste forms in the TRUPACT-II.

pisolitic. Pertaining to pisolite [sed], or to the texture of a rock made up of pisoliths or pealike grains; for example, pisolitic bauxite or pisolitic limestone.

Pitzer Formalisms. A semi-empirical formalism for calculating activity coefficients, particularly in saline aqueous systems.

plasticity. The property of a material that enables it to undergo permanent deformation without appreciable volume change or elastic rebound, and without rupture.

Pleistocene. This is the first epoch of the Quaternary Period of the Upper-Cenozoic Era; also, the corresponding system of rocks. It is subsequent to the Pliocene Epoch of the Tertiary Period and precedes the Holocene Epoch of the Quaternary Period (between approximately 1.6 million to 10,000 years ago). Climatic changes during this period are used as an analog in estimating future climatic extremes for the WIPP.

Pliocene. The last epoch of the Tertiary Period of the Middle-Cenozoic Era; also, the corresponding system of rocks. It is subsequent to the Miocene Epoch of the Tertiary Period and preceded by the Pleistocene Epoch of the Quaternary Period (between approximately 5.3 and 1.6 million years ago).

plug. A watertight or gastight seal installed in a borehole or well to prevent movement of fluids or gas. Also used to fill in or seal off fractures, cavities, or other porosity in the walls of a

borehole. Commonly a cement plug is used in the sealing of boreholes or wells associated with oil, gas, or water exploration.

plutonium. A metallic, radioactive actinide, symbol Pu, atomic number 94, in the transuranium series of elements; used as a nuclear fuel and as the fissile agent in nuclear weapons.

plutonium equivalent curie. A term developed to provide a uniform basis among various radioactive wastes to perform comparative human health consequence analyses resulting from inhalation. The plutonium equivalent curie concept has strict limits of applicability. It is utilized herein as a means of expressing the transuranic activity content of transuranic waste packages.

pmH. The symbol used to designate a standard measure of the acidity of a solution. pmH is defined as the negative logarithm of the molal concentration of hydrogen ion in solution.

Poços de Caldas. A location in Brazil where two uranium deposits were investigated for the possibility that the flow of fluids might lead to the development and migration of a large-scale redox front.

point data. Discrete actual data collected by directly observing and recording a measurable event or attribute.

point source. A source of effluents that is small enough in dimensions that it can be treated as if it were a point. The converse (not used in this document) is a diffuse source. A point source can be either a continuous source or a source that emits effluents only in pulses or for a short time.

polyelectrolyte. A substance of high molecular weight (as a protein or a nuclide).

polyhalite. An evaporite mineral: $K_2MgCa_2\ (SO_4)_4 \cdot 2H_2O$. It is a hard, nearly insoluble mineral with no economic value.

Polypropylene "supersacks." Sacks containing 4,000 pounds of magnesium oxide which are placed on top of the three high seven-packs of containerized waste that has been placed underground.

population dose. The sum of the radiation doses received by the individual members of a population.

porosity. The ratio of the void volume in a rock or soil to its total volume. It may be stated as a percentage or as a decimal.

process. A physical, natural, or anthropogenic phenomenon that occurs continuously or over a significant portion of the time frame of interest. In other words, a "long-term" phenomenon.

portlandite. An ingredient of Portland cement [$Ca(OH)_2$].

possible futures. The set of all possible occurrences within the 10,000-year regulatory time frame.

postclosure phase. A designated period of time beginning with the end of the decommissioning phase and extending through the end of the regulatory time frame of 10,000 years. PA modeling of repository behavior addresses this time frame.

potash. A potassium compound used in agriculture and industry.

potassium. A silver-white metallic element of the alkali metal group. It occurs abundantly in the McNutt Potash Zone in the vicinity of the WIPP site.

potentiometric surface. A subsurface map of the hydraulic potentials of an aquifer. It is usually represented in figures as a contour map, each point estimating how high the water would rise in a well tapping that aquifer at that point.

Precambrian. Applies to all geologic time, and its corresponding rocks, before the beginning of the Paleozonic Era, 570 million years ago. The Precambrian basement is approximately 18,000 feet (5,486 meters) below the surface in the vicinity of the WIPP site.

probabilistic analysis. Analysis that arose from statistical investigations is referred to as probabilistic analysis. This analysis is characterized by the fact that, although specific outcomes of an experiment cannot be predicted with certainty, relative frequencies for various possible outcomes are predictable. Monte Carlo analysis is used for probabilistic analysis of the WIPP.

Project Gnome. The Plowshare Project Gnome Test, an underground nuclear test, took place on December 10, 1961, at a location approximately 8 mi (13 km) southwest of the WIPP site. Its primary purpose was to study the effects of a nuclear explosion in salt. The site was decommissioned in 1979, but continues to be monitored by the EPA for radioactive contamination.

Projected Inventory. The part of the TRU inventory that has not been generated, but is estimated to be generated at some time in the future, by the TRU waste sites. The projected inventory is the same as the to-be-generated waste referred to in 40 CFR 194.24(a).

promulgation. Referring to the process of putting regulations into law.

Public Law 96-164. The U.S. Department of Energy National Security and Military Applications of Nuclear Energy Act of 1980. Public Law 96-164 directed the DOE to proceed with the design and development of the WIPP.

Public Law 102-579. See Land Withdrawal Act.

quality assurance. The planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service.

Quality Assurance Project Plans. This document identifies the quality of data necessary, and the techniques designed to attain and ensure the required data quality objectives associated with the WIPP waste characterization program.

quality control. Those quality assurance activities that provide a means to control and measure the characteristics of a structure, system, or component to established requirements.

Quaternary. The last period of the Cenozoic Era; also, the corresponding system of rocks. It is subsequent to the Tertiary Period, beginning approximately 1.6 million years ago and extends to the present.

rad. See radiation absorbed dose.

radially. The term "radial" is the adjective of "radius" and is used to describe forces that act in directions parallel to some radius or to designate lines, fractures, flow paths, etc., that are oriented parallel to radii. "Radially" is the corresponding adverb. Effects that act outward from a single point or inward toward a point (for example, flow of groundwater toward a borehole) may be radial in form.

radiation absorbed dose (rad). The special unit of absorbed dose of ionizing radiation. One rad of absorbed dose is equal to the absorption of 100 ergs of radiation energy per gram of absorbing material. See also rem.

radioactive decay. A process whereby the nucleus of an atom spontaneously emits excess energy by emitting particles and/or rays (alpha, beta, gamma, or neutrons).

radioactive material. Matter composed of or containing radionuclides, with radiological half-lives greater than 20 years, subject to the Atomic Energy Act of 1954, as amended. (40 CFR § 191.12)

radiographic examination. The nondestructive technique that enables a qualitative evaluation of the contents of a waste container.

radiolysis. Chemical decomposition by the action of radiation.

radiometric. Pertaining to the measurement of geologic time by the study of parent and/or daughter isotopic abundances and known disintegration rates of the radioactive parent isotopes, for example, radiometric dating.

radionuclide. An isotope having an unstable nucleus that is subject to spontaneous decay.

reactant. A substance that enters into a chemical reaction and is altered. For example, metal waste reacts with oxygen and water to produce hydrogen and metal oxides.

real-time radiography. A type of remote Non-Destructive Test that uses a luminescent screen to form a moving image from x-rays that have passed through a rotating test object. Real-time radiography is relied on for detection of waste form shapes and the presence of liquids inside the waste package.

reasonable. (1) Not conflicting with reason; (2) not extreme or excessive; (3) having the faculty of reason; or (4) possessing sound judgment.

recharge. The amount of water and the processes involved in the addition of water to an aquifer.

recharge point (or area). In groundwater hydraulics, the point (or area) where surface water enters an aquifer.

recovery. The process of getting something back. The term "resource recovery" is often used to indicate the mining of minerals or the withdrawal of oil or natural gas from beneath the surface of the Earth through wells.

recrystallization. The formation, initially in the solid state, of new crystalline mineral grains in a rock. The new grains are generally larger than the original grains and may have a different mineralogical composition. It is usually caused by increased temperatures and pressures exerted on a rock formation.

regulatory time frame. As defined in 40 CFR Part 194, the regulatory time frame means the time period beginning with disposal and ending 10,000 years after disposal.

release. Movement of regulated substances into the accessible environment as defined in 40 CFR Part 191 or beyond the unit boundary as defined for 40 CFR § 268.6.

rem. Roentgen equivalent in man—a special unit of dose equivalent which is the product of absorbed dose, a quality factor which rates the biological effectiveness of the radiation types producing the dose, and other modifying factors (usually equal to one). If the quality and modifying factors are unity, 1 rem is equal to 1 rad: 100 rem = 1 Sievert (SI units). Also expressed in terms of millirem (mrem): 1 rem = 1,000 mrem.

remote-handled transuranic waste. Packaged transuranic waste that has a measured external surface dose rate at or greater than 200 millirems per hour at the surface of the container.

repository. The portion of the WIPP underground system within the Salado Formation, including the access drifts, waste panels, and experimental areas, but excluding the shafts.

repository/shaft system. The WIPP repository underground workings, including the shafts, all engineered and natural barriers, and the altered zones within the Salado Formation and overlying units resulting from construction of the underground workings.

repressurization. The increase in pressure in a previously depleted volume that might be associated with a fluid injection.

reserves. Mineral resources that can be extracted profitably by existing techniques and under present economic conditions.

reservoir. A subsurface volume of rock that has sufficient porosity and permeability to permit the accumulation of oil, gas, or water under adequate trap conditions. Also applies to any natural or artificial surface holding area used to store, regulate, or control water.

residuum. An accumulation of rock debris formed by weathering and remaining essentially in place after all but the least soluble constituents have been removed, usually forming a comparatively thin surface layer concealing the unweathered or partly altered rock below.

resistivity. Measure of electrical resistance in a fluid such as brine.

resources. Mineralization that is concentrated enough, in large enough quantity, and in a physical and chemical form such that its extraction is currently or potentially feasible and profitable.

retardation. Attenuation of contaminant concentration with migration distance. There are a variety of physical and chemical processes that can contribute to retardation.

retrievable. Describes storage of radioactive waste in a manner designed for potential recovery without loss of control or release of radioactivity.

Richter scale. A logarithmic scale expressing the magnitude of a seismic disturbance (as an earthquake) in terms of the energy dissipated in it with 2 being the lowest and 8.5 being the largest earthquakes yet recorded.

Rio Grande Rift. The rift system of the Rio Grande valley in which the crustal plate has split and a series of grabens have formed in New Mexico and Southern Colorado. It is a product of extensional tectonics.

room. An excavated cavity within a panel in the underground portion of the WIPP, a room is about 10 meters wide, 4 meters high, and 91 meters long.

rubidium-strontium age. Determination of an age for a mineral or rock in years based on the ratio of radiogenic strontium-87 to rubidium-87 and the known radioactive decay rate of rubidium-87. If ratios are measured for more than one phase of a single rock, or for a number of related rocks that differ in rubidium content, an isochron may be drawn.

Rustler Formation. The evaporite beds, including mudstones, of probable Permian age that immediately overlie the Salado Formation.

Salado Formation. A geologic formation of Late Permian age in southeastern New Mexico. At the WIPP site, it is composed of salt beds with minor amounts of anhydrite (45 numbered anhydrite marker beds: Marker Bed 101 through Marker Bed 145) and clay. It is the host unit for the WIPP repository.

saline. Waters are considered saline when they contain between 10 and 100 parts per thousand salinity. See brackish and brine.

saline intrusion. A human-induced coastal process whereby subsurface seawater progressively replaces freshwater withdrawn from an aquifer being pumped close to the shoreline.

Sandia National Laboratories. A multiprogram laboratory located in Albuquerque, NM, and Livermore, CA. SNL is operated and managed for the DOE by the Sandia Corporation. From 1949 until October 1993, Sandia Corporation was a wholly owned subsidiary of AT&T. Sandia Corporation is currently a wholly owned subsidiary of Lockheed-Martin Corp.

San Simon Sink. The central, most depressed area of San Simon Swale.

San Simon Swale. A broad depression about 15 miles east of the Los Medaños site, open to the southeast.

Santa Rosa Formation. The Santa Rosa Sandstone is a principal aquifer in several areas, particularly in Winkler and Ward Counties, Texas. It produces both fresh and saline water, depending on location. The westernmost extent of the Santa Rosa Sandstone is just into Eddy County. Wells completed in the Santa Rosa Sandstone have low yields with specific capacities of 0.14-0.2 gpm per foot of drawdown; the formation porosity is about 13 percent.

SANTOS. A finite element program designed to compute the quasistatic, large deformation, inelastic response of two-dimensional planar or axisymmetric solids or engineering structures.

saturated. A condition in which all connected pores in a given volume of material contain fluid.

scarp. A line of cliffs produced by faulting or by erosion. The term is an abbreviated form of escarpment, and the two terms commonly have the same meaning, although “scarp” is more often applied to cliffs formed by faulting.

Scaled Inventory. Synonymous with Disposal Inventory. The scaled inventory is the inventory volume that fills WIPP capacity and is used for PA calculations. This volume is calculated as the sum of the disposal volumes for all WIPP-eligible waste streams after application of RH-TRU and CH-TRU scaling computations to each WIPP-eligible projected TRU waste stream.

scenario. A combination of naturally occurring or human-induced events and processes that represent realistic future changes to the WIPP repository, geologic, and geohydrologic systems that could cause or promote the escape of radionuclides and/or hazardous constituents from the WIPP repository.

screening argument. Regulatory Guidance, Probability of Occurrence, and Consequence are three criteria used to eliminate from scenario development those events and processes that are not applicable to a specific disposal system or that do not have the potential of contributing significantly to the performance measure (for example, integrated radionuclide releases).

seal. An engineered barrier designed to isolate the waste and to impede groundwater flow in the shafts.

sealing system. Includes all components of the WIPP seal design program.

SECOTP2D. A computer program that simulates single or multiple component radionuclide transport in fractures or granular aquifers.

sedimentary. A descriptive term for rocks formed of sediment, such as clastic rocks (sandstones and shales), secretions of organisms, limestones, and precipitation from solution, rock salts and gypsums.

sedimentation. The process of accumulating sediment into layers of solid rock which includes the generation of rock particles, the transportation and the deposition of these particles, and the consolidation of these particles into solid rock.

seismic. Applies to the activity of naturally- or artificially-induced earthquakes or earth vibrations, where the seismic waves are the elastic waves produced by these vibrations.

seismic risk zone. A designation of a geographic region expressing the maximum intensity of earthquakes that could be expected there.

sensitivity analysis. Methods for computing the effect of changes in the input parameters on the model predictions.

seral. Relating to a series of ecological communities formed in ecological succession.

sequestration. To hold (as a metallic ion) in solution.

shaft. A man-made hole, either vertical or steeply inclined, that connects the surface with the underground workings of a mine.

shaft pillar. The cylindrical volume of rock around a shaft from which major underground openings are excluded in order that they do not weaken the shaft.

shallow-dissolution zone. A zone of residual material at the interface of the Rustler and Salado formations left after dissolution of salt. It is highly permeable and often contains brine.

SI unit. See System of International Units.

Sievert. The SI unit of effective dose. It is equal to 100 rem or one joule per kilogram. (40 CFR § 191.12)

siliciclastic. Pertaining to clastic noncarbonate rocks which are almost exclusively silicon-bearing, either as forms of quartz or as silicates.

siltstone. An indurated silt having the texture and composition of shale but lacking its fine lamination or fissility; a massive mudstone in which the silt predominates over clay; a nonfissile silt shale.

Silurian. Third-oldest period of the Paleozonic Era, and also the corresponding system of rocks. Subsequent to the Ordovician Period and followed by the Devonian Period, between approximately 438 and 400 million years ago. The Silurian of the southeast New Mexico - west Texas area consists of the Fusselman limestone and the carbonates and shales of an Upper Silurian unit, both of which were deposited in the broad subsiding area named the Tobosa Basin.

Simpson. In the Delaware basin, the Simpson consists of three main layers of limestone, alternating with thinner green, brown, and black shale, black shale with rounded quartz grain inclusions, and sandstone.

site characterization. The process of making geologic and environmental studies to identify potential sites for mined geologic repositories. Detailed site characterization goes further: additional data are collected that would be necessary if a license application were to be submitted.

SKI (Statens Kärnkraftinspection). An abbreviation for the Swedish Nuclear Power Inspectorate, Statens Kärnkraftinspection. A list of potentially relevant features, events, and processes developed by SKI was considered to be the best documented and most comprehensive starting point for the WIPP scenario development process.

sludge. Refers to de-watered contact-handled transuranic wastes containing both organic and inorganic constituents that must meet the Waste Acceptance Criteria for shipment and disposal at the WIPP repository. High sludges are contact-handled transuranic waste where the sludge component constitutes 50 percent or more of the waste volume; low sludges are the same type of waste containing less than 50 percent by volume of sludge.

SO-C. Screened-out on the basis of consequence. The term applies to the elimination of features, events, and processes from PA and compliance assessment calculations for WIPP compliance efforts on the basis of consequence.

solifluction. The slow downslope flow of waterlogged soil that is commonly active in periglacial regions underlain by frozen ground that acts as a downward barrier to water percolation.

SO-P. Screened-out on the basis of low probability. The term applies to the elimination of features, events, and processes from PA and compliance assessment calculations for WIPP compliance efforts on the basis of low probability of occurrence.

SO-R. Screened-out on the basis of regulations. The term applies to the elimination of features, events, and processes from PA calculations used for WIPP compliance efforts on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR Part 194.

solubility. The ability or tendency of one substance to blend uniformly with another (for example, solid in liquids, liquid in liquid, gas in liquid, and gas in gas). Solids vary from 0 to 100 percent in their degree of solubility in liquids depending on the chemical nature of the substance(s); to the extent that they are soluble, they lose their crystalline form and become molecularly or ionically dispersed in the solvent to form a true solution. Liquids and gases are often said to be miscible in other liquids and gases rather than soluble.

solute. A substance which is dissolved in another substance called the solvent. The solute is uniformly dispersed in the solvent either molecularly or ionically.

solution. A mixture, liquid, solid, or gaseous, in which the components are uniformly distributed throughout the mixture.

solution subsidence. Gradual subsidence of nonsoluble strata due to the dissolution of underlying rock.

solvent. A substance capable of dissolving another substance (solute) to form a uniform dispersed mixture (solution) at the molecular or ionic level. Solvents are, accordingly, characterized as either polar or non-polar. Water is strongly polar; hydrocarbon solvents are non-polar.

soret effect. The principle that asserts when temperature differences are induced in a solution of common salt or other substance in water, the dissolved material will become relatively concentrated in those portions in which the temperature is lowest.

sorption. The binding on a microscopic scale of one substance to another, such as by adsorption or ion exchange. In this document, the word is especially used in the sorption of solutes onto aquifer solids.

source term. The kinds and amounts of radionuclides that make up the source of a potential release of radioactivity. See nuclide inventory.

spallings. During exploratory drilling, waste surrounding the eroded borehole that is transported by waste-generated gas escaping to the lower pressure borehole.

specific activity. Radioactivity per unit weight of radioactive material.

standard waste box. A waste container measuring approximately 6 by 4.5 by 3 feet high, with rounded ends.

steady-state. A state or condition of a system or process that does not change over time; a condition that changes only negligibly over a specified time.

stochastic uncertainty. As used in probabilistic risk assessment, stochastic uncertainty characterizes uncertainty involving conceptual models and/or the future.

Stored Inventory. Also referred to as “retrievably stored” inventory. The part of the anticipated waste inventory that is stored in such a fashion that it can be readily retrieved.

Retrievably stored waste includes waste stored at the TRU waste sites since approximately 1970 in buildings or berms with earthen cover and does not include any waste generated prior to 1970. Retrievably stored waste also includes waste that is stored in underground storage tanks, ponds, and as decontamination and decommissioning material identified for disposal that requires retrieval at the TRU waste sites.

strata. Geologic term for layers of the earth's crust. The crust was generally laid down in layers during geological epochs.

stratigraphy. The science and study of the origin, composition, and proper sequence in which various rock strata were layered during various geological ages.

strike slip fault. A fault on which the movement is parallel to the fault's strike.

structure map. A map that portrays subsurface configuration by means of structure contour lines.

subduction zone. A long, narrow belt in which subduction takes place. For example, along the Peru-Chile trench, where the Pacific plate descends the South American plate.

study area. The region about the Los Medaños site studied in the evaluation of that site.

subjective uncertainty. Subjective uncertainty derives from a lack of knowledge about quantities, attributes, or properties believed to have a single or certain range of values.

subsidence. The downward settling of the earth's surface with little or no horizontal motion. Subsidence may be caused by natural geological processes or by man-made activities.

substrate. The surface and/or nutrient on which an organism will live and grow.

subsurface. The rock and soil below the ground surface whose geological features, principally stratigraphy and structure, are interpreted primarily on the basis of drilling activities and geophysical evidence.

subvertical. Used to describe planar features oriented within approximately 15 degrees of vertical.

sulfates. Mineral compounds characterized by the sulfate radical $S0_4$. Anhydrous sulfates, such as barite, $BaS0_4$, have divalent cations linked to the sulfate radical; hydrous and basic sulfates, such as gypsum, $CaSO_4$-$2H_20$, contains water molecules.

supersaturation. A solution, such as the Salado Formation brine, that contains more of a solute (radioactive isotope) than is normally present when equilibrium is established.

swipe samples. The presence of radioactive contaminants may be ascertained by applying a Kim-wipe™ or equivalent to the surface of the potentially contaminated item and measuring the radioactivity of the Kim-wipe™.

sylvite. A mineral, KCl, used in the manufacture of fertilizer.

syndeposition. Processes occurring during deposition of a sedimentary rock, and contributing to the formation of the sedimentary framework.

System of International units. The version of the metric system which has been established by the International Bureau of Weights and Measures and is administered in the United States by the National Institute of Standards and Technology. The abbreviation for this system is "SI." (40 CFR § 191.12)

Tamarisk Member. The middle anhydrite layer of the Rustler Formation.

Tansill Formation. The Tansill Formation is the uppermost formation of the Artesia Group, developing in the Mid-Permian Period, between approximately 280 and 260 million years ago. The Artesia Group represents the shelf region of the Goat Seep Formation and the Capitan Limestone. To the south of the Delaware Basin the Tansill Formation consists of dolomites and sandstones. Toward the northern part of the basin, gypsum and anhydrite along with siltstones and dolomites increase in the Tansill Formation. The Tansill Formation is time correlative to the Capitan Reef at the basin margin and the Bell Canyon Formation in the Delaware Basin.

tectonics. The branch of geology dealing with regional structural or deformational features.

tensile. Refers to tension in the mechanical sense. A material is under tension when the stress exerted on it (tensile stress) acts "outward" such that the effect is to increase the length or volume of the body.

Tertiary Period. The first of two periods in the Cenozoic Era and the corresponding system of rocks. It is subsequent to the Cretaceous Period of the Mesozoic Era and is followed by the Quaternary Period of the Cenozoic Era. The Tertiary Period dates between approximately 66.4 and 1.6 million years ago.

thermal effect. The effects of naturally occurring heat on groundwater flow.

thermal field. The field or set of temperatures throughout a volume. Use of the term usually connotes temperatures that differ from point to point.

thermal gradient. The rate of change of temperature in the direction of increasing temperature.

thermodynamic. A term that deals with the relations between heat and other forms of energy. A system is at thermodynamic equilibrium when there is no tendency for change in the free energy of the system,

thief zone. A rock unit responsible for excessive fluid loss from boreholes during drilling or production operations.

topographic/topography. Relating to or concerning the configuration of a surface that includes relief and the position of its natural and man-made features.

transient. This term is used to describe changing state or condition as in ground motion due to seismic activity, or groundwater flow resulting from changing fluid densities.

transmissivity. The rate at which water is transmitted through a unit thickness of an aquifer. It is considered a property of the aquifer. The contained liquid is transmissible.

transport. For regulatory purposes relating to moving waste to the repository. The movement of radioactive wastes across public routes via the use of packaging as the transportation container and the movement of a hazardous substance by any mode, including pipeline (as defined in the Pipeline Safety Act). In the case of a hazardous substance that has been accepted for transportation by a common or contract carrier, the term “transport” or “transportation” shall include any stoppage in transit that is temporary, incidental to the transportation movement, and at the ordinary operating convenience of a common or contract carrier, and any such stoppage shall be considered as a continuity of movement and not as the storage of a hazardous substance. When addressing the performance of the geologic repository, “transport” refers to the movement of material by mechanisms such as solution, or association with colloids, in groundwater or water from other sources flowing through the repository, seepage of gas through fractured or porous media, or entrainment in drilling fluid, brine, or gas flowing in a borehole.

transuranic. See Transuranic Waste.

transuranic nuclide. A nuclide with an atomic number greater than that of uranium (92). All transuranic nuclides are produced artificially and are radioactive.

Transuranic Package Transporter-II. A package designed to transport contact-handled transuranic mixed waste to the WIPP site. It is a cylinder with a flat bottom and a domed top that is transported in the upright position. Also called TRUPACT-II.

transuranic waste. The term “transuranic waste” means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for: (1) high-level radioactive waste; (2) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations; or (3) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR 61.

treatment. Any method, technique, or process, including neutralization, designed to change the physical, chemical, or biological character or composition of any hazardous waste so as to neutralize such waste, or so as to recover energy or material resources from the waste, or so as to render such waste non-hazardous, or less hazardous; safe to transport, store, or dispose of; or amenable for recovery, amenable for storage, or reduced in volume.

Triassic. The first period of the Mesozoic era (after the Permian of the Paleozonic Era, and before the Jurassic), thought to have covered the span of time between 225 and 190 million years ago; also, the corresponding system of rocks. The Triassic is so named because of its threefold division in the rocks of Germany.

true solution. A uniformly dispersed mixture at the molecular or ionic level, of one or more substances (solute) in one or more substances (solvent). Solutions that exhibit no change of internal energy upon mixing and have complete uniformity of cohesive forces are considered true.

TRUPACT-II TDOP (ten drum overpack). A container that is designed for use either with the TRUPACT II Shipping Package or as a stand-alone Department of Transportation (DOT) 7A Type A packaging. The container was designed to hold ten 55-gallon drums, loose homogenous materials, or one Standard Waste Box (SWB).

TRU Waste Inventory Update. Los Alamos National Laboratory (LANL), Carlsbad Office performed an inventory update of TRU Waste planned for disposal at WIPP. LANL collected updated inventory data from each of the generator sites which will be shipping TRU Waste to the WIPP. The inventory will not replace the Baseline Inventory Report (BIR), Rev. 3 it will be a stand-alone document representing the best estimate of TRU Waste remaining to be shipped.

Type A Packaging. A packaging designed to retain the integrity of containment and shielding required by this part under normal conditions of transport as demonstrated by the tests set forth in 49 CFR § 173.465 or 173.466, as appropriate.

uncertainty analysis. (1) An evaluation to determine the uncertainty in model predictions that results from imprecisely known input variables; or (2) Determination of the degree of uncertainty in the results of a calculation based on uncertainties in the input parameters and underlying assumptions. Such an analysis requires definition of a system, description of the uncertainties in the factors that are to be investigated, and the characteristics of the system that are to be simulated.

underpressurized. A zone or rock formation (Culebra Dolomite or perhaps units underlying the Salado Formation) that falls below the expected pressure gradient as depth increases.

undisturbed performance. "[T]he predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." (40 CFR § 191.12)

uninterruptible power supply. A power supply that provides automatic, instantaneous power, without delay or transients, on failure of normal power. It can consist of batteries or full-time operating generators. It can be designated as standby or emergency power depending on the application. Emergency installations must meet the requirements specified for emergency.

unit boundary. In the context of 40 CFR § 268.6, the unit boundary is that point at which migration occurs if hazardous constituents pass that point in concentrations exceeding health-based levels.

uplift. A structurally high area in the crust, produced by positive movements that raise or upthrust the rocks, as in a dome or arch.

Upper Devonian Woodford Shale. The Woodford is a dark brown to black, fissile, bituminous, spore-bearing shale which becomes [arenaceous] northward and contains black [chert] to the south and west.

U.S. Department of Energy. The cabinet-level U.S. Government agency responsible for weapons production, energy research, and for the subsequent cleanup of hazardous and radioactive waste sites. It was created from the Energy Research and Development Administration and other federal government functions in 1977. DOE is also responsible for the construction and oversight of WIPP primarily through its Carlsbad Area Office.

U.S. Environmental Protection Agency. (1) An independent agency of the Federal government formed in 1970 by Presidential executive order, bringing together parts of various government agencies involved with the control of pollution, and responsible for pollution abatement and control programs, including programs in air and water pollution control, water supply and radiation protection, solid and toxic waste management, pesticides control, and noise abatement; (2) The Agency for those implementation responsibilities for the Waste Isolation Pilot Plant, given to the Agency by the Waste Isolation Pilot Plant Land Withdrawal Act (Pub. L. 102-579, 106, Stat. 4777) which are:

(i) Determinations by the Agency that the Waste Isolation Pilot Plant is in compliance with Subpart A of this part;
(ii) Issuance of criteria for the certifications of compliance with subparts B and C of this part of the Waste Isolation Pilot Plant's compliance with subparts B and C of this part;
(iii) Certifications of compliance with subparts B and C of this part of the Waste Isolation Pilot Plant's compliance with subparts B and C of this part;
(iv) If the initial certification is made, periodic recertification of the Waste Isolation Pilot Plant's continued compliance with subparts B and C of this part;
(v) Review and comment on performance assessment reports of the Waste Isolation Pilot Plant; and,
(vi) Concurrence by the Agency with the Department's determination under § 191.02(i) that certain wastes do not need the degree of isolation required by subparts B and C.

U.S. Energy Research and Development Agency. Energy Research and Development Agency, a forerunner of the DOE that was formed in 1974 (Pub. L. 93-438).

U.S. Geological Survey. U.S. Geological Survey, Department of Interior.

valence state. The degree of oxidation (oxidation state) of an element or atom. It is usually expressed as a positive or negative number representing the ionic charge or effective charge of the element of atom.

Van Horn Sandstone. Clastics of the late Precambrian age that crop out near Van Horn, Texas and are overlain by the Bliss Sandstone.

varve. In its broadest sense, a varve is a usually thin layer of sedimentary rock that was deposited in a single year. The term is most commonly used to describe sediments deposited in glacial meltwater lakes that exhibit a sequence of alternating coarser and finer layers representing summer and winter deposition, respectively.

vector. A quantity or guide that requires a magnitude, direction and sense. It is commonly represented by a line, but also includes the direction of a substance (or activity) such as the flow of water in a general direction. As used in PA, the term is also used to describe model results from one set of parameters selected through statistical techniques.

viscosity. A property of fluids which is displayed by definite resistance to change of form. Many solids show a gradual yielding to forces tending to change their form. This property, a sort of internal friction, is also called viscosity.

volatile organic compounds. An organic compound that evaporates (volatilizes) readily at room temperature.

vug. Small open cavity in a rock.

Waste Acceptance Criteria. A set of conditions established for permitting transuranic wastes to be packaged, shipped, managed, and disposed of at the WIPP.

waste characterization. Sampling, monitoring, and analysis activities to determine the nature of the waste to be emplaced at the WIPP.

Waste characteristic. 40 CFR § 194.2 includes a regulatory definition of waste characteristic: Waste characteristic means a property of the waste that has an impact on the containment of waste in the disposal system.

Waste component. 40 CFR § 194.2 includes a regulatory definition of waste component: Waste component means an ingredient of the total inventory of the waste that influences a waste characteristic.

waste disposal panels. A collection of disposal rooms in the WIPP repository. Each panel will be sealed as a unit.

waste form. A term used to emphasize the physical and chemical properties of the waste.

Waste Isolation Pilot Plant. (1) The project authorized under § 213 of the DOE National Security and Military Application of Nuclear Energy Authorizations Act of 1980 (Public Law 96-164; Stat. 1259, 1265) to demonstrate the safe disposal of radioactive waste materials generated by atomic defense activities; (2) A research and development facility, located near Carlsbad, New Mexico, to be used for demonstrating the safe disposal of transuranic wastes from DOE activities.

waste matrix. The material that surrounds and contains the waste and to some extent protects it from being released into the surrounding rock and groundwater. Only material within the canister (or drum or box) that contains the waste is considered part of the waste matrix.

waste stream. A grouping of waste materials with specific definable characteristics that remain the same throughout the process generating the waste stream. A waste stream is produced by a single process or subprocess or may be combined to produce a single output waste stream.

waste unit factor. The waste unit factor is the normalizing factor used to determine the release limits for 40 CFR § 191.13(a). The term is the same as the "unit of waste" defined in 40 CFR Part 191 Appendix B, Table 1, note e, as "an amount of transuranic wastes containing one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years." For the WIPP, the overall quantity of radionuclides that apply to the waste unit is 4.07×10^6 curies, and the waste unit factor is therefore 4.07.

wicking. The mechanism by which a liquid can migrate through an unsaturated zone against the forces of gravity and surface tension in the soil. Also called capillary rise.

Wink Sink. Wink Sink is located 100 mi (160 km) southeast of the WIPP site outside the Delaware Basin. The surface impression is 360 ft (110 m) in width and 110 ft (34 m) deep. It is the result of dissolution of the Salado Formation caused by percolation of shallow groundwater through abandoned boreholes. Subsequent subsidence of the rock units overlying the Salado Formation led to the collapse feature present on the surface.

WIPP site boundary. The boundary that defines the outer limits of the 16-section land withdrawal area. For the purposes of this application, this boundary defines the controlled area.

Wolfcampian. Lower member of Permian age in Southeastern New Mexico.

working agreement. Appendix B of the Agreement of Consultation and Cooperation, which sets forth the working details of that Agreement.

X-ray. Any of the electromagnetic radiations of the same nature as visible radiation but of extremely short wavelength (less than 100 angstroms). X-rays are produced by bombarding a metallic target with fast electrons in vacuum or by transition of atoms to lower energy states, and have the properties of ionizing a gas upon passage through it, of penetration various thicknesses of all solids, of producing secondary radiations by impinging on materials bodies, of acting on photographic films and plates as light does, and of causing fluorescent screens to emit light.

Yates Formation. The Yates Formation is one of five formations in the Artesia Group developing in the Mid-Permian Period, between approximately 280 and 260 million years ago. It is subsequent to the Seven Rivers Formation and is preceded by the Tansill Formation. The Tansill Formation, Seven Rivers Formation, and the Yates Formation represent the shelf region of the Capitan Limestone at the margin of the Delaware Basin.

To the south it consists of dolomites and sandstones. Siltstones, mudstones, and dolomites increase toward the northern part of the basin. The Yates Formation is time correlative to the Capitan Reef at the basin margin and the Bell Canyon Formation in the Delaware Basin.

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GLOSSARY OF TERMS

40 CFR Part 191. *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes.* This regulation sets environmental radiation protection standards for management (Subpart A) and disposal (Subparts B and C) of spent nuclear fuel and high-level and transuranic radioactive wastes.

40 CFR Part 194. This regulation provides EPA's *Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with 40 CFR Part 191 Disposal Regulations.*

40 CFR Part 261. *Identification and Listing of Hazardous Waste.* This part identifies those solid wastes which are subject to regulation as hazardous wastes under Parts 262B, 265, 268, 270, 271, and 124 of Title 40 of the Code of Federal Regulations.

40 CFR Part 264. *Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities.* This subpart establishes minimum national standards which define the acceptable management of hazardous waste.

40 CFR Part 264, Subpart G. This subpart of 40 CFR Part 264 defines closure and post-closure requirements pertaining to hazardous waste management units.

40 CFR Part 264, Subpart X. This subpart specifies requirements that apply to owners and operators of facilities that treat, store, or dispose of hazardous waste in miscellaneous hazardous waste management units.

40 CFR Part 268. This regulation restricts the land disposal of hazardous waste and specifies treatment standards and/or treatment technologies that must be met or applied before hazardous wastes may be land disposed. Section 268.6 provides for petitioning to allow land disposal of untreated hazardous waste if it can be demonstrated to a reasonable degree of certainty that there will be no migration of hazardous constituents from the disposal unit for as long as the waste remains hazardous.

40 CFR Part 270. This regulation establishes provisions for the Hazardous Waste Permitting Program under Subtitle C of the Resource Conservation and Recovery Act. This regulation and the associated State of New Mexico regulation require the permitting of the WIPP as a hazardous waste facility.

abscissa. The horizontal coordinate (x coordinate) of a point plotted in Cartesian (x, y) coordinates.

absolute temperature. Temperature measured in degrees Celsius from absolute zero. -273.18 °C. Absolute temperatures are given either as "degrees absolute" (for example, 150°A) or as degrees kelvin (for example, 150K).

absorption. The process by which a fluid penetrates or is drawn into and held in the inner structure of another (solid or liquid) material. The word also appears in contexts such as absorbed energy and absorbed radiation dose, in which case it refers to internal energy imparted to the absorbing material. Absorbed radiation dose refers specifically to the energy imparted by ionizing radiation per unit mass of irradiated material at a particular location.

accessible environment. "(1) [T]he atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all of the lithosphere that is beyond the controlled area." (40 CFR § 191.12)

acid rain. Any form of precipitation having a pH of 5.6 or less. Major components contributing to the acid rain are sulfur dioxide and oxides of nitrogen.

actinide intrinsic colloids. Macromolecules or aggregations of actinide compounds which form by exsolution of dissolved actinide compounds and remain in suspension, thereby acting as colloids.

actinide source term. Modeling terminology denoting the fraction of total actinide inventory of a disposal room or the repository that can be mobilized for transport.

active institutional control. (1) Controlling access to a disposal site by any means other than passive institutional controls, (2) performing maintenance operations or remedial actions at a site, (3) controlling or cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance. (40 CFR § 191.12)

activity. A measure of the rate at which a material emits nuclear radiation, usually given in terms of the number of nuclear disintegrations occurring in a given length of time. The unit of activity used in this document is the curie (Ci).

adsorption. (1) The net accumulation of matter at the interface between a solid phase and an aqueous solution through the formation of two-dimensional (that is, noncrystallographic) molecular structures. The accumulated matter is the *adsorbate*. The solid surface is the *adsorbent*. (2) Adherence of gas molecules to the surface of solids in which they are in contact.

advection. The transport of matter (for example, a trace contaminant) by motion of the medium in which it is contained. The most common transport medium is the flow of a fluid.

aeolian. Also spelled eolian. Applies to the erosional action of wind, and to deposits which are due to the transporting action of wind.

aerobic degradation. The microbial degradation of organic (that is, cellulosic, rubber, plastic, etc.) wastes using oxygen (O_2) as the electron acceptor and producing carbon dioxide (CO_2) and water (H_2O).

aeromagnetic survey. Refers to the geomagnetic observations using a magnetometer from an airborne craft.

air lock. An intermediate chamber between zones of different static pressure.

alluvial. Pertaining to or composed of alluvium, or deposited by a stream or running water. For example, an alluvial clay or an alluvial divide.

algal features. Features created by the secretion of calcium carbonate from algae.

alkalophilic bacteria. Bacteria that can grow and reproduce well in an alkaline (high pH) environment.

alpha emitter. A radioactive isotope that decays through the emission of alpha particles.

alpha particle. (α-particle). A positively charged particle emitted in the radioactive decay of certain nuclides. Made up of two protons and two neutrons bound together, it is identical to the nucleus of a helium atom. It is the least penetrating of the three common types of ionizing radiation—alpha, beta, and gamma radiation.

alternative conceptual models. Alternative sets of assumptions that describe the same system for the same purpose and are consistent with the existing information.

Advanced Mixed Waste Treatment Project. A project designed to retrieve, characterize, prepare and store CH-TRU waste at the INEEL for shipment to the WIPP. The CH-TRU waste at INEEL consists of debris and non-debris wastes. The debris wastes will be processed through a sort, size, and volume reduction (supercompaction) process (i.e., treated AMWTP waste). The non-debris waste also will be retrieved, characterized, prepared and stored for shipment to WIPP, but will not be supercompacted. The DOE expects that the AMWTP will ship both supercompacted and uncompacted waste concurrently.

anaerobic. The microbial degradation of organic (that is, cellulosic, rubber, plastic, etc.) wastes in the absence of oxygen (O_2), usually consuming nitrate (NO_3) as the electron acceptor and producing carbon dioxide (CO_2), nitrous oxide (N_2O), and nitrogen (N_2).

angular velocity. The rate of rotation of the drill stem, to which the drill bit is attached.

anhydrite. A mineral consisting of anhydrous calcium sulfate ($CaSO_4$). It is gypsum without water and is denser, harder, and less soluble.

anhydrite lithologies. The description of a rock type, in this case an anhydrous calcium sulfate.

annual committed effective dose. The committed effective dose resulting from a one-year intake of radionuclides released plus the annual effective dose caused by direct radiation from facilities or activities subject to Subparts B and C of 40 CFR Part 191. (40 CFR § 191.12)

annulus. The area between the borehole wall and the outside of the drill pipe in rotary drilling operations. Rotary drilling is used for scientific investigation studies, such as the WIPP project, and the exploration for natural resources (that is, oil and gas).

anoxic. Describes a process that occurs in the absence of oxygen (O_2). Anoxic corrosion of steels, iron-base alloys, and other metal wastes use water (H_2O) or hydrogen sulfide (H_2S) and produces hydrogen gas (H_2).

anthropogenic. Resulting from the influence of human beings on nature (that is, acid rain, greenhouse effect, and man-made organic material).

anticline. A fold of rocks whose core contains the stratigraphically older rocks; it is generally convex upward.

Anticipated Waste Inventory. The sum of the stored and projected TRU waste inventories at currently listed DOE TRU waste sites that have not been emplaced at WIPP.

aquifer. An underground geological formation or part of a formation that is capable of yielding a significant amount of water to a well or spring. (40 CFR § 191.12)

arenaceous. Of the texture or character of sand.

argillaceous rocks. A group of detrital sedimentary rocks with a grain or particle size less than 1/16 millimeter. Commonly comprised of clay minerals and including shales, mudstones, siltstones, and marls.

artesian. Adjective that refers to groundwater confined under pressure so that it will rise in a well. Sometimes the word is used to mean that the water flows out at the surface, but that, strictly speaking, is “flowing artesian.”

assurance requirements. Qualitative requirements in 40 CFR § 191.14 that specify actions and procedures to increase confidence that the probabilistic release events in the containment requirements (40 CFR § 191.13) will be met.

Atoka. The Early-Middle Pennsylvanian rocks, assigned to the Atokan or Derryan Stage, consist of dark-colored sandstones, shales and limestones, which attain a maximum thickness of about 1,000 feet.

atomic weights. Atomic weight is the total mass of an atom and is almost, but not exactly, the sum of the masses of its constituent protons, neutrons and electrons.

attenuation. (1) A reduction in the amplitude or energy of a signal, such as might be produced by passage through a filter. (2) A reduction in the amplitude of seismic waves, as produced by divergence, reflection and scattering, and absorption. (3) That portion of the decrease in seismic or sonar signal strength with distance that is not dependent on geometrical divergence, but on the physical characteristics of the transmitting medium.

authigenic. Formed or generated in place of rock constituents and minerals that have not been transported or that crystallized locally at the spot where they are now found, and of minerals that came into existence at the same time as, or subsequently to, the formation of

the rock of which they constitute a part. The term often refers to a mineral (such as quartz or feldspar) formed after deposition of the original sediment.

backfill. Material placed around or above the waste containers, filling the open space in the disposal room.

background (radiation). Radiation in the human environment from naturally occurring elements, fallout, and from cosmic radiation.

bacterioruberin. A carotenoid pigment excreted during growth and multiplication of various strains of bacteria that may be involved in waste decomposition.

barrier. "Any material or structure that prevents or substantially delays movement of water and/or radionuclides toward the accessible environment. For example, a barrier may be a geologic structure, a canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around waste, provided that the material or structure substantially delays movement of water or radionuclides." (40 CFR § 191.12) Barriers also prevent or delay the movement of hazardous constituents.

Baseline Inventory Report. Also known as the Transuranic Waste Baseline Inventory Report. This document provides the total DOE transuranic waste inventory. The Baseline Inventory Report establishes a methodology for grouping wastes of similar physical and chemical properties from across the DOE transuranic waste system into a series of waste profiles.

bedding plane. A flat or near-flat bedding surface that visibly separates the individual layers, beds, or strata in sedimentary or stratified rocks from the preceding or following layers.

Bell Canyon Formation. A sequence of rock strata that form the uppermost formation of the Delaware Mountain Group (Early Permian). It is immediately below the Castile Formation and about 4,000 feet below the surface at the WIPP. May contain some oil and gas.

bentonite. A commercial term applied to expansive clay materials containing montmorillonite (smectite) as the essential mineral.

beta particle. (β-particle). A negatively charged particle emitted in the radioactive decay of certain radioactive elements (nuclides). A beta particle is identical to an electron. It is not a strong penetrating radiation and can be stopped by an inch of wood or a thin sheet of aluminum.

biodegradation. The process of consumption by microbial substances—usually organic materials such as cellulosics.

bioelectric activity. The electric phenomena associated with organic matter (plants and animals).

biofilm ecosystem. An ecosystem composed of substrates and nutrients developed on surfaces containing one or more layers of cells with extra cellular polymeric material.

biological half-life. The time required for an organism to eliminate half the amount of a radionuclide ingested or inhaled. See definition for half-life.

bleb. A small, usually rounded inclusion of one mineral in another.

blowout. An unexpected volume of gas or fluid released from subsurface pressurized zones that flows upwards to the land surface and into the atmosphere during the drilling of a borehole.

Boltzmann Constant. The ideal gas constant per molecule is the ratio of the molar gas constant to the number of molecules per gram of a substance. Boltzman's Constant is defined as having a value of approximately 1.380×10^{-23}Joules/Molecule K.

borehole. (1) A hole drilled from the surface for purposes of geologic or hydrologic testing, injection, or exploration and subsequent production of resources; sometimes referred to as a drillhole or well bore. (2) A man-made hole in the wall, floor, or ceiling of a subsurface room used for verifying geology, making observations, or emplacing canisters of remote-handled transuranic waste.

brackish. Water with between one and ten parts per thousand salinity. This places the saline content of brackish waters between that of streams and sea water. See saline and brine.

BRAGFLO. The name of the computer model the DOE uses to simulate brine and gas flow in the disposal system.

breccia. Fragmented rock whose components are angular and cemented together by a mineral cement or a fine-grained matrix. May be sedimentary (for example, carbonate or evaporite karst features) or formed by crushing or grinding along faults. There are friction or fault breccias, talus breccias, eruptive breccias, and large-scale collapse sinks (for example, breccia pipes). Breccia pipes are vertical or near vertical cylindrical features filled with collapse debris.

brine. Water with greater than 100 parts per thousand salinity. Brines are often found in deep sedimentary basins and contain calcium (Ca), sodium (Na), potassium (K), chloride (Cl), sulfate (SO_4), and minor amounts of other elements.

brine pocket. See brine reservoir.

brine reservoir. A volume of brine of limited extent trapped within fractures and/or intergranular pore spaces of a host rock and usually pressurized relative to normal formation fluids. Such pockets may exist under various conditions of stress and solute concentration. Pressurized brine pockets have been observed in the Castile Formation in the Delaware Basin.

Brushy Canyon Formation. The basal unit of the Guadalupian Series or Delaware Mountain Group within the Delaware Basin. The formation is dominated by submarine channel sandstones with minor limestones and shales, and its structural features are indicative of deposition in agitated water. This formation terminates northward against the Bone Spring flexure at the basin margin.

Bureau of Land Management. An agency of the federal government, within the Department of the Interior, which among other land management duties, reviews environmental assessments, environmental impact statements, land acquisition procedures, and any other plans to site waste management facilities on federal lands over which it has jurisdiction.

calcareous remnant. Commonly used with reference to organisms that use calcium compounds to form endo- or exoskeletal structures. The calcareous remnant is that which remains after the soft tissues have disappeared.

calcic. Said of minerals and igneous rocks containing a relatively high proportion of calcium; the proportion required to warrant use of the term depends on circumstances.

calcite. A crystalline mineral composed of calcium carbonate ($CaCO_3$).

calibrate. To vary parameters of an applied computational model within a reasonable range until differences between observed data and computed values are minimized.

caliche. A calcareous material commonly found in layers on or within the surface of stony soils of arid or semiarid regions. It occurs in the form of gravels, sands, silts, and clays cemented together by calcium carbonate or as crusts at the surface of the soil.

Cambrian. The oldest period of the Paleozoic Era, and the corresponding system of rocks. It is subsequent to the Precambrian Period and followed by the Ordovician Period, between approximately 570 and 505 million years ago.

canister. As used in this document, a container, usually cylindrical, for remotely handled transuranic waste. The waste remains in this canister during and after burial. A canister affords physical containment but not shielding; shielding is provided during shipment by a cask.

capillary pressure. The difference in pressure across the interface between two immiscible fluid phases jointly occupying the interstices of a rock. It is due to the tension of the interfacial surface, and its value depends on the curvature of that surface.

Capitan Limestone. Also referred to as the Capitan Reef and/or Capitan Formation. The Capitan Limestone or Reef is a light colored, fossiliferous and vuggy limestone and breccia which almost completely surrounds the Delaware Basin. The reef was formed in the Early to Mid-Permian Period, between approximately 286 and 260 million years ago. It is a time-stratigraphic equivalent of the Bell Canyon Formation in the Delaware Basin. The reef is a major part of the Guadalupe Mountains from the west to the northwest of the WIPP site,

the Apache Mountains and Davis Mountains to the south, and the Glass Mountains to the southeast.

Capitan Reef. See Capitan Limestone.

carbonate mudstone. A nonfissile mud shale consisting mainly of carbonate minerals.

carbonates. Compounds containing the carbonate radical, CO_3^{-2}, primarily applies to rock formations composed of carbonate minerals.

Carlsbad potash district. The area east of Carlsbad formally designated by the U.S. Geological Survey as having potentially economic grades of potash mineralization.

carotenoid pigment. A yellow-to-red color found in microbes and associated biofilms (plants and animals) observed in WIPP microbial gas generation experiments.

cask. A massive shipping container providing shielding for highly radioactive materials and holding one or more canisters.

$CaSO_4$. Calcium sulfate.

Castile Formation. A formation of evaporite rocks (mainly anhydrite with a few halite interbeds) of Permian age that immediately underlies the Salado Formation.

catalytic surface. Referring to a substance on a surface that initiates a reaction and enables it to take place at lower temperature or activation energy than in the absence of the catalyst.

cation-anion. A cation is a positively charged ion whereas an anion is a negatively charged ion. A cation in an electrolyzed solution migrates to the cathode (negative terminal); an anion in an electrolyzed solution migrates to the anode (positive terminal).

cavings. During rotary drilling, material that erodes from the borehole wall in response to the upward-flowing drilling fluid within the annulus formed by the drill pipe and the borehole wall.

cellulosic. Those materials derived from high polymer plant carbohydrates. Examples are paper, cardboard, wood, cellophane, cloth, etc.

cementitious. A mineral agent, natural or man-made, usually emplaced by hydration or exsolution, that serves to bind together grains of another material, thereby acting as or resembling cement. May also be used to describe a geologic deposit containing a significant amount of cementitious material that was formed by this mechanism.

Cenozoic. An era of geologic time, from the beginning of the Tertiary period to the present (Some authors do not include the Quatenary, considering it a separate era). It is characterized paleontologically by the evolution and abundance of mammals, advanced mollusks, and birds; paleobotanically, by angiosperms. The Cenozoic is considered to have begun about 66 million years ago.

Central Basin Platform. The geological region known as the High Plains, covering an area of several hundreds of square miles separating the Delaware and Midland basins.

certification. Any action taken by the Administrator of the U.S. Environmental Protection Agency under Section 8(d) of the WIPP Land Withdrawal Act.

certifier. In the context of 40 CFR Part 191, the "certifier" is the U.S. Environmental Protection Agency, which must certify whether the Department of Energy has demonstrated that the Waste Isolation Pilot Plant is in compliance with the requirements of the standard.

chelating agents. A particular category of complexant that increases solubility by forming a cage around the complexed (or chelated) substance.

chemical retardation. Refers to retardation effects (see retardation) that are attributable to chemical mechanisms. Chemical reactions with constituents of a rock, precipitation, and sorption of contaminants are examples of chemical retardation.

chemical source term. The fraction of the hazardous constituents inventory that can be mobilized for transport.

chemisorption. The immobilization of a gas, liquid, or material in solution or suspension by the formation of bonds with the surface molecules of a solid material. The strength of these bonds is comparable to that of ordinary chemical bonds.

Cherry Canyon Formation. The center sandstone of the Delaware Mountain Group consisting of a fine-grained sandstone to siltstone that is very finely laminated.

chert. A hard, extremely dense or compact, dull to semivitreous, microcrystalline or cryptocrystalline sedimentary rock, consisting dominantly of interlocking crystals of silica (SiO_2) less than about 30 μm in diameter.

chronostratigraphic boundaries. The boundary of a rock stratum that is characterized by having been formed during a specific interval of geologic time.

clastic sedimentation. A sediment formed by the accumulation of fragments derived from preexisting rocks or minerals and transported as separate particles to their places of deposition by purely mechanical agents (such as water, wind, ice, and gravity).

clastics. Pertaining to a rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals and that have been transported some distance from their places of origin; also said of the texture of such a rock. The term has been used to indicate sources both within and outside the depositional basin.

Clayton Basin. Northeast of the WIPP site by eight miles. It contains Quaternary alluvium.

climate. The average condition of the weather at a place over a period of years as exhibited by temperature, wind velocity, precipitation and other factors.

climax vegetation. The vegetation that would exist if an area was undisturbed.

Code of Federal Regulations. A codification of the general and permanent rules published in the Federal Register by the departments and agencies of the Federal government. The Code is divided into 50 titles that represent broad areas subject to Federal regulation. It is issued quarterly and revised annually.

collapse block. A gravity-induced collapsed rock unit resulting from the formation of sink holes.

colloid. Refers to a suspended particulate in a colloidal suspension or to a particle that is small enough that it could be placed in colloidal suspension. A colloidal suspension is a dispersion of extremely fine particles in a fluid with the characteristic size of the particles (in at least one dimension) being so small that the behavior differs from that of more common suspensions. The maximum size range for particles which may be regarded as "colloidal" is subject to some variation, depending on context and application.

CCDFGF. The CCDFGF code assembles the release estimates from all other components of the WIPP Performance Assessment system to generate cumulative complementary distribution functions (CCDFs) of releases.

complementary cumulative distribution function. Mathematically, a complementary cumulative distribution function is equal to one minus a cumulative distribution function. A cumulative distribution function is the sum (or integral) of the probability of those values or variables that are less than or equal to a specified value. Complementary cumulative distribution functions are a graphical display of the probability (the ordinate) that the value of the variable will be greater than a specified value (the abscissa). For the WIPP, the complementary cumulative distribution function displays the probability that 10,000-year cumulative radionuclide releases from the disposal system for the scenarios considered will exceed calculated values. Radionuclide releases are normalized as stipulated in 40 CFR Part 191, Appendix A, and the complementary cumulative distribution function is compared to the quantitative release limits specified in 40 CFR § 191.13(a).

complexing agents. Complexing agents increase the solubility of the complexed substance; the aqueous solubility. They are often referred to as complexants.

complexants. Complexing agents increase the solubility of the complexed substance; the aqueous solubility. They are often referred to as complexing agents.

compliance assessment. The analysis conducted to determine compliance with the Individual Protection requirements in 40 CFR § 191.15 and the Groundwater Protection Requirements in Subpart C.

computational model. The computational model is the implementation of the mathematical model. (See definition of mathematical model below). The implementation may be through analytical or numerical means. Often, the analytical solution is numerically evaluated (for example, numerical integration or evaluation of complex functions); hence,

both solution techniques are typically coded on the computer. Consequently, the computational model is often called a computer model.

computer model. A computer code or set of codes that are used together to make calculations for a corresponding mathematical description for a process or system (for example, movement of groundwater through a geologic formation).

conceptual model. A set of qualitative assumptions used to describe a system or subsystem for a given purpose. At a minimum, these assumptions concern the geometry and dimensionality of the system, initial and boundary conditions, time dependence, and the nature of the relevant physical and chemical processes. The assumptions should be consistent with one another and with existing information within the context of the given purpose.

conductivity. A material property describing the ease with which something can be transferred through that material. Examples of conductivity are electrical conductivity (electricity), thermal conductivity (heat transfer), or hydraulic conductivity (groundwater flow).

confirmation. For the purposes of this document, a term used to indicate support or establishment of certainty and/or validity of models used in reference to specific performance issues of the repository over any specific time frame of interest. In general, laboratory and field experiments at the WIPP and elsewhere are conducted to provide data in support of this type of activity, such as for the gas generation model. Confirmation is used in a mechanistic sense and is not intended to have specific legal implications.

consequence analysis. The analysis used to examine the effects of processes and events on performance of the disposal system. (See Performance Assessment).

conservative assumption. Assumptions that result in the overestimation (rather than underestimation) of any phenomenon that could contribute to the release of radionuclides from the disposal system.

Consultation and Cooperation Agreement. An agreement that affirms the intent of the Secretary of Energy to consult and cooperate with the State of New Mexico with respect to State public health and safety concerns. The term “Agreement” means the July 1, 1981, Agreement for Consultation and Cooperation, as amended by the November 30, 1984, “First Modification,” the August 4, 1987, “Second Modification,” and the March 22, 1988, modification to the Working Agreement.

contact-handled transuranic waste. Packaged transuranic waste that has a measured external surface dose rate less than 200 millirems per hour at the surface of the container.

containment. The retention of radioactivity within prescribed boundaries, such as within a waste package. In this document, containment refers to retention within a system to prevent releases in unacceptable quantities or concentrations during handling and storage, or to containment within the disposal system.

contamination. Introduction of radionuclides into the repository's immediate surroundings, such as into the brine via a breach of the containment system.

controlled area. The controlled area means (1) a surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than 5 kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location. (40 CFR § 191.12). For WIPP, the controlled area is defined by the area withdrawn by the Land Withdrawal Act.

convection. The circulatory motion that occurs in a fluid at a nonuniform temperature. The transfer of heat by automatic circulation of fluids.

corrosivity. The tendency of a metal to deteriorate by chemical decomposition.

creep. A very slow, usually continuous, time-dependent movement of soil or rock; refers to the geologic phenomenon experienced as the gradual flow of salt under differential stress.

creep closure. Closure of underground openings, especially openings in salt, by plastic flow of the surrounding rock under lithostatic pressure.

Cretaceous. The final period of the Mesozoic era (after the Jurassic and before the Tertiary period of the Cenozoic era), thought to have covered the span of time between 135 and 66 million years ago; also, the corresponding system of rocks. It is named after the Latin word for chalk (creta) because of the English chalk beds of this age.

crustal processes. Any processes that occur within the earth's crust. Usually refers to igneous, metamorphic, or tectonic activity.

crystallographic. This term deals with the system of forms among crystals, their structures, and their physical properties.

CSH gel. A cementitious material containing calcium-silicate-hydrate gel.

cubic law. The cubic law states that for a given change in gradient of the hydraulic head, flow through a fracture is proportional to the cube of the fracture opening.

cuesta. A hill or ridge with a gentle slope on one side and a steep slope on the other, specifically an asymmetric ridge (as in the southwest United States) with one face (dip slope) long and gentle and conforming with the dip of the resistant bed or beds that form it, and the opposite face (scarp slope) steep or even cliff-like and formed by the outcrop of the resistant rocks, the formation of the ridge being controlled by the differential erosion of the gently inclined strata.

Culebra. The Culebra Dolomite Member, also referred to as Culebra, is the lower of two rock units of dolomite within the Rustler Formation and was formed in the late Permian Period between approximately 258 and 245 million years ago. It is a brown, finely crystalline,

argillaceous dolomite or dolomitic limestone with solution cavities. The Culebra is the principal water-bearing unit of the Rustler Formation and has been identified as the most likely pathway for release of radionuclides to the subsurface accessible environment.

cultural resource sites. Human-associated ruins of archaeological significance.

Cumulative Distribution Function. A cumulative distribution function is the sum (or integral) of the probability of those values of variable that are less than or equal to a specific value.

curie. A quantitative measure of radioactivity equal to 3.7×10^{10} disintegrations per second.

curie load. The number of curies in a particular location or in a container such as a radioactive waste drum. The curie load of a waste drum may be broken down into alpha, beta, and gamma curie loads to describe the amount of total radioactivity that is contributed by disintegrations yielding alpha, beta, or gamma radiation.

cuttings. During rotary drilling, material contained in the cylindrical volume created by the cutting action of the drill bit. In terms of releases from the WIPP through inadvertent human intrusion, the maximum potential waste volume that could form cuttings is equal to the cross-sectional area of the drill bit multiplied by the repository thickness.

CUTTINGS_S. The CUTTINGS_S code was written to calculate the quantity of material (in m^3) brought to the surface from a radioactive waste disposal repository as a consequence of an inadvertent human intrusion through drilling.

Darcy's Law. A mathematical equation that can be used to compute the quantity of water flowing through an aquifer. $Q = KA(h_A - h_B/L)$. Q is the discharge, A is the cross-sectional area, $h_A - h_B$ is the difference in the height of the water (hydraulic head), L is the flow length, and K is a coefficient, which is dependent upon the nature of the porous medium.

daughter product. A nuclide that results from radioactive decay. Thus radium-226 decays to radon-220, which in turn decays to polonium-216. The radon is the daughter of the radium, and the polonium is the daughter of the radon.

Davis Mountains. A mountain range in Texas south of the WIPP site making up the southern-most part of the Capitan Reef.

decay, radioactive. The decrease in the number of radioactive nuclei present in a radioactive material due to their spontaneous transmutation. Also, the transmutation of a radionuclide into another nuclide by the emission of a charged particle.

decommissioning. Actions taken upon closure of the repository to reduce potential environmental, health, and safety impacts, including repository sealing as well as activities to stabilize, reduce, or remove radioactive materials or demolish surface structures.

decommissioning phase. The term "decommissioning phase" refers to the period of time beginning with the end of the disposal phase and ending when all shafts at the WIPP repository have been sealed.

decontamination. With respect to operational activities, decontamination is the removal of unwanted material (especially radioactive material) from the surface of or from within another material.

defense waste. Nuclear waste deriving from the manufacture of nuclear weapons and the operation of naval reactors. Associated activities, such as the research carried on in the weapons laboratories, also produce defense waste.

deformation. Any change in the original form or volume of rock masses. Folding, faulting, solid flow, and dissolution and subsequent collapse are examples of deformation.

degradation. The wearing down or away of a material or the earth's surface, whether on a large or small scale, and the products it produces. Examples of degradation include the wearing down of drill casing from corrosion, and the wearing down of organics in the waste materials from microorganisms.

Delaware Basin. Those surface and subsurface features that lie inside the boundary formed to the north, east, and west of the disposal system by the innermost edge of the Capitan Reef, and formed to the South by a straight line drawn from the southeastern point of the Davis Mountains to the most southwestern point of the Glass Mountains.

Delaware Mountain Group. A set of three formations that underlie the Castile Formation at the Los Medaños site. The uppermost of these is the Bell Canyon Formation.

demography. The statistical study of human population with response to sizes and density, distribution, and vital statistics.

density. Mass per unit volume (that is, kilograms per cubic meter).

denudation. The sum total of processes that results in the general lowering of the land surface.

Design Basis Earthquake. An earthquake that is the most severe design basis accident of this type and that produces the vibratory ground motion for which safety class items are designed to remain functional.

Design Basis Tornado. A tornado that is the most severe design basis accident of that type applicable to the area under consideration.

detritivores. Organisms that eat organic debris.

deviatoric stress. Refers to a state of stress disequilibrium in the subsurface, in which at least one of the three perpendicular (normal) axes used to characterize stress at a point differs in magnitude from the other two. The stress tensor used to characterize subsurface stress can be written as the sum of two tensors. The first tensor represents a hydrostatic state with all

shear stresses equal to zero. The components of the second tensor are shear stresses - these are deviatonic stresses and are independent of hydrostatic stress.

Devonian. A period of the Paleozonic Era (after the Silurian and before the Mississippian) spanning the time between 400 and 345 million years ago; also, the corresponding system of rocks. It is named after Devonshire, England, where rocks of this age were first studied.

Devonian Woodford Shale. This is a Devonian-age geological marker about 15,600 feet deep at the WIPP that separates rocks of the Silurian era from rocks of the Mississippian era.

Dewey Lake Redbeds. A formation of the Permian Period that overlies the Rustler Formation and is composed of reddish brown marine mudstone and siltstones interbedded with fine grained sandstone.

diapirism. The formation of an intrusion or diapir that penetrates through overlying layers of more brittle rock and domes the overlying rock cover. Diapirs are commonly formed from mobile igneous intrusions or from plastic salt bodies. The development of narrow necks at depth often gives diapirs a balloon-like form.

diagenetic. Pertaining to or caused by diagenesis; for example, a “diagenetic change” resulting from compaction, a “diagenetic structure” (such as a stylolite) formed after deposition, a “diagenetic deposit” (such as dolomitized limestone or consisting of manganese nodules), or a “diagenetic environment” of rock consolidation.

diffusion, molecular. Transport of material (particularly the spread of a contaminant) through the random motion of molecules in a fluid or solid. Diffusion results in the slow transfer of material from regions of high concentration to regions of lower concentration even when there is no net fluid flow.

dike. A tabular body of igneous rock that cuts across the structure of adjacent rocks or cuts massive rocks. Most dikes result from the intrusion of magma. Some dikes occur in a set of numerous parallel structures identified as dike swarms. Present in the vicinity of the WIPP site are lamprophyre dikes. (See Lamprophyre)

discharge point (or area). In groundwater hydraulics, the point (or area) where water comes out of an aquifer onto the surface.

Disposal Inventory. The inventory volume defined for waste emplacement in the WIPP to be used for CRA-2004 PA calculations. The Land Withdrawal Act (LWA; Public Law 102-579) identifies the total amount of TRU waste allowed in the WIPP as 175,564 m^3 (6,200,000 ft^3). The “Agreement for Consultation and Cooperation” limits the RH-TRU inventory to 7,079 m^3 (250,000 ft^3).

dispersion. Signifies the tendency for a sharp change in fluid properties (for example, temperature, contaminant concentration) to become broader and less abrupt as flow progresses. For example, if a volume of contaminated water is injected into an aquifer, the contact between the contaminated and uncontaminated water will initially be sharply

defined by a very steep gradient in contaminant concentration. As the water flows away from the injection point, however, natural variations in the rock allow contaminated water to move quickly through some large pores while nearby smaller pores will retain uncontaminated water for a longer period. This, and other similar effects, will cause contaminated and uncontaminated water to intermingle, resulting in dispersion of the contaminant "front."

disposal. The term "disposal" means permanent isolation of transuranic waste from the accessible environment with no intent of recovery, whether or not such isolation permits the recovery of such waste. Disposal of waste in a mined geologic repository occurs when the waste has been emplaced and all the shafts to the repository are sealed.

disposal phase. The term "disposal phase" means the period of time during which transuranic waste is disposed of at the WIPP, beginning with the initial emplacement of transuranic waste for disposal and ending when the last container of transuranic waste is emplaced for disposal and the shafts are sealed.

disposal room. An excavated cavity in the WIPP repository in which transuranic waste will be emplaced during disposal operations.

disposal system. The disposal system is any combination of engineered and natural barriers that isolate transuranic waste after disposal. For the purposes of the WIPP, this will include the combination of the repository/shaft system and the controlled area.

disposal system performance. Disposal system performance is measured in Section 6.5. It is compared with the EPA requirements in the complementary cumulative distribution function.

dissolution. (1) The process whereby a space or cavity in or between rocks is formed by the solution of part of the rock material. (2) The solution of material by a solvent (for example, dissolution of waste by brine at the WIPP).

disturbed rock zone. That portion of the geologic barrier in which the physical and/or chemical properties may have changed significantly as a result of underground construction activities.

Dockum Group. The Triassic Dockum Group consists of three formations. In ascending order, they are (1) the Tecovas Formation, which consists of up to 300 ft of red shale, siltstone, and fine-grained sandstone; (2) the Santa Rosa Sandstone, which is composed of 100 to 650 ft of red, brown, and gray sandstone; and (3) the Chinle Formation equivalent, which consists of up to 1,300 ft of red, maroon, and purple shales and siltstones with lenses of fine-grained red-to-gray sandstone. The group is present only as a thin wedge in Eddy County, thickening to the east in Lea County and in Texas.

dolomite. A sedimentary rock consisting mostly of the mineral dolomite: $CaMg(CO_3)_2$. It is commonly found with limestone.

dome (breccia pipe). A type of hill found near the Los Medaños site; under at least a few of these hills lies a roughly cylindrical volume of breccia (rock reconstituted of coarse rock fragments).

dome, salt. A diapiric or piercement structure with a central, nearly circular salt plug, generally 1 to 2 km in diameter, that has risen through the enclosing sediments from a deep mother bed of salt. In the continental U.S., salt domes are located primarily in the Gulf Coast states.

dose. A general term indicating the amount of energy absorbed per unit mass from incident radiation.

dose conversion factor. A numerical factor used in converting radionuclide uptake (curies) in the body to the resultant radiation dose or dose commitment (rem or man-rem).

dose equivalent. The product of absorbed dose and appropriate factors to account for differences in biological effectiveness due to the quality of radiation and its spatial distribution in the body; the unit of dose equivalent is the rem (sievert in System of International units). (40 CFR § 191.12)

downdip. To move in the direction at which a rock layer or any planar feature is inclined (dip) from the horizontal.

drift. A horizontal passageway in a mine away from the main shaft.

drilling fluids. A suspension fluid used in drilling. The fluid is pumped through the inside of the drill pipe and out through the jets of the drilling bit. It is used to lubricate the drilling bit, seal off porous zones, and to counter-balance the pressure of oil, gas, or water. The fluids consist of various substances in a finely divided state among which bentonite and barite are common. Oil may also be used as a base instead of water.

Driving Force Ratio. A ratio established to assess the effects of density gradient when examining hydraulic effects of fluid density variations in the Salado interbeds and the Culebra. It is given by driving force ratio = $(\Delta\rho\rho\ \nabla E)/(\rho f\ \Delta Hf)$, where ΔHf is the gradient of freshwater head, $\Delta\rho$ is the difference between actual fluid density and reference fluid density, ρf is the density of freshwater, and ∇E is the gradient of elevation.

DRSPALL. The DRSPALL code is written to calculate the spallings release, defined as a mass of waste subject to tensile failure during an inadvertent drilling intrusion into a high-pressure WIPP repository.

E1, E2. These are potential human intrusion scenarios used in computer modeling for compliance purposes.

effective dose. The sum over specified tissues of the products of the dose equivalent received following an exposure of, or an intake of radionuclides into, specified tissues of the body, multiplied by appropriate weighting factors. This allows the various tissue-specific health

risks to be summed into an overall health risk. The method used to calculate effective dose is described in Appendix B of 40 CFR Part 191. (40 CFR § 191.12)

effective porosity. Porosity is defined as the ratio of volume to bulk volume. Effective porosity is connected porosity, through which fluids may move; that is, it has permeability.

effluent. Wastewater or airborne emissions discharged into the environment.

Eh. The oxidation potential is a measure of the oxidizing or reducing tendency of a solution. It is written as a reduction reaction using the standard hydrogen reaction, Eh (volts) = E_h^0 + RT/nF ln (oxidized species/reduced species).

elasticity. The ability of rocks to recover in size and shape (no long-term changes in rock properties) resulting from minor deformation (for example, minor deflection of anhydrite beds, deformation of rock due to passage of seismic wave, etc.). The property by virtue of which a body resists and recovers from deformation produced by force.

electrochemical. Refers to chemical effects or reactions that produce, are mediated by, or significantly influenced by electrical currents or accumulations of electrical charge.

electrolytes. A substance that will provide ionic conductivity when dissolved in water or when in contact with water. The term is also used to designate solutions of such substances.

electromechanical. Mechanical processes or effects that are driven by or produce electricity.

electron acceptors. Atoms or molecules that will readily accept an additional electron to form an ionic or covalent bond. The availability of such chemical species is necessary for some bacterial processes involving the decomposition of complex organic molecules.

electrophoresis. Migration of colloidal or other particles in a liquid suspension that responds to applications of an electric field.

empirical. Methods that rely on experience or observation alone without regard for system and theory. They are capable of being verified or disproved by observation or experiments.

emplacement. At the WIPP, the placing of radioactive wastes in the repository.

Emplaced Waste Inventory. Waste that has been disposed at the WIPP as of the inventory date (September 30, 2002).

engineered alternatives. Potential modifications to the design or operation of the WIPP or to waste forms that, if adopted, will provide increased assurance that the WIPP will perform in compliance with environmental protection and safety requirements.

engineered barriers. Backfill, seals, and any other man-made barrier components of the disposal system.

enthalpy. The sum of the internal energy (heat) generated or absorbed when a reaction takes place.

eolian. Pertaining to the wind. Also spelled aeolian.

EPA unit. The EPA unit is a measure of radioactivity that has been normalized by the inventory of the disposal system in question and by the release limits specified by the EPA in Appendix B, Table 1, of 40 CFR Part 191. Specifically, a quantity of radioactivity of any radionuclide (expressed in curies) may be expressed in dimensionless EPA units by dividing it by the product of the waste unit factor and the EPA release limit for that radionuclide. The containment requirements of 40 CFR § 191.13(a) establish release limits for the disposal system in terms of the probability that 10,000 year cumulative releases will exceed 1 and 10 EPA units.

EPAUNI. The EPAUNI code is used for estimating the probability distribution of EPA unit loading in the WIPP repository.

epicenter. The point on the earth's surface directly above the focus of an earthquake.

equilibrium. A state of balance between opposing forces or actions that is either static (as in a body acted on by forces whose resultant is zero) or dynamic (as in a reversible chemical reaction when the velocities in both directions are equal).

erosion. The processes whereby earthy or rock material is loosened or dissolved and removed from any part of the earth's surface. It includes the processes of weathering, solution, corrosion, and transportation.

estuarine. The seaward end of the widened tidal mouth of a river where fresh water comes into contact with seawater.

evaporite. A sedimentary rock composed primarily of minerals produced by precipitation from a solution that has become concentrated by the evaporation of a solvent, especially salts deposited from a restricted or enclosed body of seawater or from the water of a salt lake. In addition to halite (NaCl), these salts include potassium, calcium, and magnesium chlorides and sulfates.

event. A phenomenon that occurs instantaneously or within a short time interval relative to the time frame of interest.

excavation. The action of cutting, digging, or mining a cavity in the earth and the removal of that mined material. The WIPP repository excavated in solid salt rock is an example of excavation.

exothermic. The release of heat from a (chemical) reaction.

extraction. The withdrawal of natural resources with no provision for replenishment.

fast Langrangian analysis of continua. A two-dimensional finite-difference code used for the WIPP to estimate subsidence above the repository for conditions ranging from no backfill to emplacement of a highly compacted crushed salt backfill.

fault. A surface or zone of rock fracture along which there has been displacement.

fault tree. A tree-like cause-and-effect diagram of hypothetical events. Analysis of fault trees is used to investigate failures in a system or concept.

fauna. An entire animal population of a given region, environment, formation, or time span.

features, events, and processes. Features, events, and processes (FEPs) that are potentially important to long-term performance of the disposal system. A comprehensive set of FEPs relevant to the WIPP was considered in applying a screening methodology to evaluate compliance with the numerical performance requirements provided in 40 CFR Part 191.

Federal Facilities Compliance Act. An amendment, promulgated in 1992, to the Solid Waste Disposal Act. Title I of the act grants the EPA administrative enforcement authority against any department, agency, or instrumentality of the executive, legislative, or judicial branch of the federal government. In regard to mixed wastes, sovereign immunity for federal agencies is waived, consistent with a schedule provided in the act. In addition, the act requires that the DOE prepare an inventory of mixed wastes and mixed waste treatment capacities and technologies. For those mixed wastes for which treatment capacities or technologies do not exist, the Department must prepare plans for the development of the capacities or technologies.

Fick's Law. Mathematical equation in which steady-state diffusion through solids is represented. J is the flux or diffusion current density, D is the diffusion coefficient, c is the volume concentration of atoms, and x is the distance along the direction in which diffusion occurs.

filter bank. An arrangement of air filters in series and/or parallel.

final safety analysis report. A safety document providing a concise but complete description and safety evaluation of the site, the design, normal and emergency operations, potential accidents, and predicted consequences of such accidents, and the means proposed to prevent such accidents or to mitigate the consequences of such accidents. A final safety analysis report documents the adequacy of safety analysis for a nuclear facility to ensure that the facility can be constructed, operated, maintained, shut down, and decommissioned safely and in compliance with applicable laws and regulations.

Final Waste Form. The expected final physical form of a waste stream. The use of the final waste form helps to group waste streams that are expected to have similar physical and chemical properties at the time of disposal. Waste is assigned to 1 of 11 final waste forms: solidified inorganics, salt, solidified organics, soils, uncategorized metal, lead/cadmium metal, inorganic non-metal, combustible, graphite, heterogeneous, and filter.

fissile material. Fissile material means any material consisting of or containing one or more fissile radionuclides. Examples of fissile radionuclides are plutonium-238, plutonium-239, plutonium-241, uranium-233, and uranium-235.

fission. The splitting of a heavy nucleus into two approximately equal parts, each the nucleus of a lighter element, accompanied by the release of a large amount of energy and generally one or more neutrons. Fission can occur spontaneously, but it usually follows the absorption of neutrons.

fissionable. A nuclide that is available to undergo fission on absorption of a neutron with energy over some threshold energy.

flowpath. The path traveled by a zero-charged, floating particle released into a groundwater flow field.

fluid. A substance that is able to flow freely as liquids and gases do.

fluvial. Produced by or pertaining to a river or rivers. Applies to erosion (fluvial erosion) by rivers or streams and deposition (fluvial deposition) by the accumulation of sediments in a depositional environment associated with rivers or streams.

flux. The rate of transfer of heat, mass, electricity, groundwater, etc., across a unit surface area in a unit time.

formation (geologic). The basic rock-stratigraphic unit in the local classification of rocks. It consists of a body of rock (usually sedimentary) generally characterized by some degree of internal lithologic homogeneity or distinctive features.

Forty-niner Member. Upper most member of the Rustler Formation formed in the Late Permian Period, between approximately 250 and 245 million years ago. It consists of upper and lower sulfates separated by claystone or halite. The member is about 60 ft (18 m) thick around the WIPP site.

fracture porosity. Porosity resulting from the presence of openings or fractures produced by the breaking or shattering of an otherwise less porous rock.

fractures. A general term for any break in a rock, whether or not it has an associated displacement. Fractures are the result of mechanical failure by stress. Fractures include cracks, joints, and faults. Fracture porosity is the resulting opening produced by the breaking or shattering of an otherwise less pervious rock.

fugacities. The pressures of vapors assumed to behave as ideal gases.

galvanic coupling. Refers to the establishment of an electrical current through chemical processes. Galvanic coupling could lead to the establishment of potential gradients between metals in the waste form, canisters, and other metals external to the waste form.

gamma rays. (X-rays) Short wavelength electromagnetic radiation emitted in the radioactive decay of certain nuclides. Gamma rays are the same as gammas or gamma particles.

gas generation. Three gas generation processes are expected to be factors in the degradation of transuranic waste in the WIPP repository. The generation of gaseous species is expected to occur through chemical (that is, corrosion), microbial, and radiolytic processes.

gas generation model. A computational model that can simulate and/or predict the rate and quantity of gases generated by waste transformation processes in a disposal room of the decommissioned repository.

gas generation rate. The combined gas production rate from all species of gases produced as a result of transuranic waste transformations such as corrosion, and/or microbial degradation, at any given time. The rate of gas production throughout the history of the repository is expected to vary depending on repository conditions with respect to humidity, total or partial brine inundation, competitive reactions that absorb specific gases, and the ability of the repository to retain the gases generated. The term is also applied to individual gases.

gastropod. Any of a large class (Gastropoda) of mollusks with a univalve shell or none, usually with distinct head-bearing sensory organs.

Gatuña Formation. A geologic formation covering the Permian Dewey Lake Formation, or the Santa Rosa Formation of the late Pliocene Period. Considered to be fluvial in origin, the Gatuña Formation varies in thickness and is overlain by the Mescalero Caliche.

generator and/or storage sites. Refers to the DOE sites nationwide where transuranic wastes are generated and/or stored as a result of activities associated with nuclear weapons production.

geochemistry. The study of the relative and absolute abundances of elements found on the earth, and the chemical distribution and migration of individual elements located in various parts of the earth (the atmosphere, hydrosphere, etc.).

geomechanical. The response of natural earth materials to the application of deforming forces. These forces would include the excavation and subsequent deformational response of the WIPP disposal rooms and drifts.

geomorphology. The description and interpretation of landforms on the earth's surface.

geophysical log. A graphic record of the measured or computed physical characteristics of the rock section encountered in a well, plotted as a continuous function of depth. Measurements are made by a sonde as it is withdrawn from the borehole by a wireline. Several measurements are usually made simultaneously, and the resulting curves are displayed side by side on the common depth scale. Both the full display and the individual curves are called logs. Well logs are commonly referred to by generic type.

geophysical techniques. The methods used to obtain geophysical data (that is, values of the physical parameters of the earth). The methods of techniques generally involve the study of ambient fields (gravitational, magnetic, electrical, temperature) or the study of the effects of applied fields (seismics through the application of shock waves, electrical through the direct application of electrical currents — resistivity methods — and by electromagnetic induction.)

geostatistics. A branch of statistics used to describe and interpret spatial data.

geothermal. The internal energy of the earth, available from heat sources produced at depth within the earth's crust.

getters. Substances that sorb gases, such as carbon dioxide (CO_2), and may be added with other materials to mitigate the pressure buildup in the repository and radionuclide mobility.

Gibbs Free Energy. A thermodynamic quantity defined as H - TS. H is enthalpy, S is absolute entropy, and T is temperature. The magnitude of the change in Gibbs Free Energy for a reaction determines whether it is reversible or will occur spontaneously at given temperature and pressure.

glaciation. Applies to both the formation, progression, and recession of glaciers and the resulting alteration of the earth's ground surface through erosion and deposition.

glove box. A sealed box in which workers, remaining outside and using gloves attached to and passing through openings in the box, can safely handle and work with radioactive materials under controlled conditions.

Goat Seep. The Goat Seep was a reef that grew primarily upward and formed a barrier around a considerable portion of the western side of the Delaware Basin. The lower portion of the Goat Seep is thick-bedded, and the upper portion is a massive light gray, fine-crystalline to saccharoidal, and in places very porous, dolomite.

graben. An elongate, relatively depressed crustal unit or block that is bounded by roughly parallel faults on its long sides. It is a structural form that may or may not be geomorphologically expressed as a rift valley.

gradient. Spatial changes in the value of a variable. Changes are along vertical, inclined, or horizontal distances, such as the groundwater pressure gradient of the Culebra Dolomite changing in the vicinity of the WIPP site.

greenhouse effect. Warming of the earth's surface and the lower layers of atmosphere that tends to increase with increasing atmospheric carbon dioxide and other gases, and is caused by conversion of solar radiation into heat.

groundwater. Water below the land surface in a zone of saturation. (40 CFR § 191.12)

grout. A mortar of cement slurry (of high water content) used to plug potential fluid-flow paths in geologic or engineered structures.

Guadalupian. Geological group of rocks below the Castile about 4,100 ft to about 8,000 ft below the surface at the WIPP. Contains the Bell Canyon, Brushy Canyon, and Cherry Canyon formations.

gypsite. An earthy variety of gypsum containing dirt and sand, found only in arid regions.

gypsum. A mineral consisting of hydrous calcium sulfate: $CaSO_4$ $ $2H_2O$. It is soft and, when pure, white.

half-life. The time required for the activity of a group of identical radioactive nuclei to decay to half its initial value. (See biological half-life).

halite. The mineral rock salt: NaCl.

halophilic. A type of organism that flourishes in a salty environment, such as salt lakes and marshes. Halophilic microorganisms may be present in WIPP's disposal environment at the time of closure.

halotolerant. A type of organism that is tolerant of salty environments but does not prefer them. Halotolerant microorganisms may be introduced into the waste before disposal from semi-salty environments, such as the skin of humans.

health physics. The science concerned with the recognition, evaluation, and control of health hazards from ionizing radiation.

heavy metal. All uranium, plutonium, or thorium placed into a nuclear reactor. (40 CFR § 191.12)

HEPA filter. A high-efficiency particulate air filter usually capable of 99.7 percent efficiency as measured by a standard photometric test using 0.3-micron droplets (aerodynamic equivalent diameter) or dioctylphthalate.

high-level waste. Radioactive waste resulting from the reprocessing of spent fuel. Discarded, unreprocessed spent fuel is also high-level waste. It is characterized by intense, penetrating radiation and by high heat-generation rates. Even in protective canisters, high-level waste must be handled remotely.

horizon. In geology, an interface indicative of a particular position in a stratigraphic sequence. For instance, the waste-emplacement horizon in the Salado Formation at the WIPP is the level about 650 m (2,150 ft) deep where openings are mined for waste disposal.

host rock. The rock unit, in this case the Salado Formation, in which the radioactive waste is to be emplaced.

hot cell. A heavily shielded compartment in which highly radioactive material can be handled, generally by remote control.

human intrusion. (See Inadvertent Human Intrusion).

humics. Matter that is derived from humus, which is a brown or black complex of variable material resulting from partial decomposition of plant or animal matter and forming the organic portion of soil.

hummocky. Containing rounded knolls or small hills.

hydration. The uptake of water by a substance, generally involving reactions in which the H-OH bond of the water molecules is not broken. (See hydrolysis.)

hydraulic conductivity. A quantity defined in the study of groundwater hydraulics that describes the ability of rock to transmit groundwater. It is measured in feet per day or equivalent units. It is equal to the hydraulic transmissivity divided by the thickness of the aquifer.

hydraulic gradient. A quantity defined in the study of groundwater hydraulics that describes the rate of change of hydraulic head with distance.

hydraulic potential (or hydraulic head). Hydraulic pressure corrected for the potential energy of elevation. In an aquifer it is equivalent to the highest level of a column of water that the pressure in the aquifer will support. It is measured relative to a specified level, which in this document is the mean sea level.

hydraulic transmissivity. A rate at which water is transmitted through a unit width of aquifer. It is measured in square meters per second or equivalent units. (See transmissivity).

hydraulic transport. The transport of dissolved or suspended substances by groundwater.

hydraulics, hydrology. These two terms tend to be used interchangeably, but they are not the same. Hydraulics is an engineering discipline; hydrology is the related science. Hydraulics deals with the flow of water. Hydrology deals with water: its properties, circulation, and distribution, from the time it falls as rainwater until it is returned to the atmosphere through evapotranspiration or flows into the ocean.

hydrocarbon. An organic compound (as acetylene or benzene) containing only carbon and hydrogen and often occurring in petroleum, natural gas, coal, and bitumens.

hydrolysis. A chemical reaction between water and another material in which two or more new species are formed, implying that the H-OH bond in the water molecules is broken.

hydrostatic. The pressure and equilibrium of liquids such as the pressure exerted by water at any given point in a body of water at rest. The hydrostatic pressure of groundwater is generally due to the weight of water in higher levels in the zone of saturation.

igneous. Rocks that are formed by solidification from a molten or partially molten state. For convenience, igneous rocks are divided into two major classes, plutonic and volcanic, which describe igneous rocks formed at depth and at or near the land surface, respectively.

inadvertent human intrusion. The accidental violation of the disposal system through human activity such as mining or exploration drilling. Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario (40 CFR § 194.33[b][1]).

infiltration. The penetration of water through the ground surface into subsurface soil.

ingestion. The uptake of materials taken into the body by way of the digestive tract.

ingrowth. The process in which a nuclide results from the radioactive disintegration of a radionuclide. The nuclide can be formed directly or as the results of successive transformations in a radioactive series. A decay product may be either radioactive or stable.

injection well. A well into which fluids are injected.

in situ. In the natural or original position. The phrase is used in this document to distinguish in-place experiments, rock properties, and so on, from those measured in the laboratory.

insoluble. Unable to be dissolved.

intensity, earthquake. A measure of the effects of an earthquake on humans and structures at a particular place. Not to be confused with magnitude.

interbed. A usually thin layer of rock, typically of one kind of rock material, occurring between or alternating with layers of another rock type. The Salado Formation in the vicinity of the WIPP site contains layers of anhydrite that are interbedded between more massive layers of halite.

interfacial energy. Energy associated with an interface between two materials (surfaces). Changes in interfacial energy control effects such as the wetting of a solid surface by a liquid.

intergranular. The porosity or spaces occurring between the grains of granular or crystalline rocks in which the void space usually contains a liquid.

interpreted data sets. Data sets derived from a surrogate data source where direct measurement is not possible.

interstitial brine. Brine distributed in the pore space (voids) of a rock mass.

intragranular. The porosity or spaces occurring within a grain or crystal, especially within skeletal material of a carbonate sedimentary rock in which the void space may or may not contain a liquid.

intraplate rifting. Rifting of the continental or oceanic crust within a crustal plate. Typically applies to areas that have shown regional extensional tectonic activity away from the plate boundaries and where igneous rocks have formed intrusive sill, dikes, volcanic plugs, and other intrusive bodies. Intraplate rifting has taken place along the Rio Grande valley, 120 miles (200 kilometers) west of the WIPP site during the Tertiary and Quaternary Periods. (See Rio Grande Rift).

Inventory Date. September 30, 2002. The cutoff date for determining the emplaced waste inventory included in CRA-2004 and the date TRU waste sites have used as the basis for their revised stored waste and projected waste inventory estimates.

ion exchange. A phenomenon in which chemical species in one phase or material exchange with similar species in another phase.

isopach. A line drawn on a map through points of equal true thickness of a designated stratigraphic unit or group of stratigraphic units.

isotope. Any of two or more species of atoms of a chemical element with the same atomic number but with differing atomic mass.

Jurassic. The second period of the Mesozoic era (after the Triassic and before the Cretaceous), thought to have covered the span of time between 190 and 135 million years ago; also, the corresponding system of rocks.

K-Ar. Determination of the age of a mineral or rock in years, based on measurement of the ratio of radiogenic argon-40 to potassium-40 and the known radioactive decay rate of potassium-40 to argon-40.

karst. A type of topography that is formed on limestone, gypsum, and other rocks by dissolution, and that is characterized by sinkholes, caves, and underground drainage.

K_d. A symbol used to designate a coefficient used in calculating chemical retardation.

kelvin. The name of the absolute temperature scale generally used in scientific measurements and calculations. The unit of temperature is also designated a kelvin.

kinetic. An adjective referring to motion and, by extension, to changing conditions. In chemistry, kinetic behavior refers to the performance of a system in which ongoing chemical reactions are changing the quantities or character of the substances present in the system at a certain rate and are thereby moving towards equilibrium.

lacustrine. The term is used to identify sediments formed by deposition in lakes and to identify chemical and biological processes that typically occur in lakes.

Lamar Limestone. A limestone member at the top of the Bell Canyon Formation, known as the Lamar limestone, is recognizable over a considerable part of the Delaware Basin.

lamprophyre. A group of dark-colored intermediate igneous rocks characterized by unrestricted crystal structures and a high percentage of mafic minerals (that is, biotite, hornblende, and pyroxene). Lamprophyre igneous rocks commonly occur in the form of dikes. (See Dike) This type of dike is present in the vicinity of the WIPP site and is identified by the dark minerals that occur both as phenocrysts and in the groundmass and light minerals occurring only in the groundmass.

Land Withdrawal Act. Public Law 102-579, which withdraws the land at the WIPP site from "entry, appropriation, and disposal," transfers jurisdiction of the land from the Secretary of the Interior to the Secretary of Energy, reserves the land for activities associated with the development and operation of the WIPP, and includes many other requirements and provisions pertaining to the protection of public health and the environment.

langbeinite. A mineral, $K_2Mg_2(SO_4)_3$, used in the fertilizer industry as a source of potassium sulfate present in economic quantities in the McNutt Potash Zone.

Latin hypercube sampling. A Monte Carlo sampling technique that divides the range of each variable into intervals of equal probability and samples from each interval.

leachate. Any liquid, including any suspended components in the liquid, that has percolated through or drained from waste.

leaching. The process of extracting a soluble component from a solid by the percolation of a solvent (in this report, water) through the solid.

Leonardian. The geologic formation from 8,000 feet to 11,400 feet below the surface at the WIPP. Middle of the Permian Period.

level-line survey. A cross-country survey in which changes in elevation with respect to sea level are very carefully measured.

LHS. The LHS program samples distributions of input parameters using normal Monte Carlo sampling or efficient Latin Hypercube Sampling.

ligands. A molecule, ion, or atom that is attached to the central atom of a coordination compound. Ligands are also called complexing agents.

lithofacies. A lateral, mappable subdivision of a designated stratigraphic unit, distinguished from adjacent subdivisions on the basis of lithology, including all mineralogic and petrographic characters and those paleontologic characters that influence the appearance, composition, or texture of the rock.

lithology. The study and examination of the physical characteristics (color, mineralogic composition, grain size, etc.) of rocks, generally determined from a hand specimen with the aid of a low-powered magnifier.

lithosphere. The outer solid shell of the earth considered to be about 50 miles (80 kilometers) in thickness. Composed of the rocks that include both the earth's crust and upper mantle.

lithostatic pressure. The vertical pressure at a point in the Earth's crust, equal to the pressure caused by the weight of the overlying rocks.

Livingston Ridge. Topographic feature marking the eastern boundary of Nash Draw.

long term. Refers to the first 10,000 years after shaft sealing for which performance assessment calculations and models assess the behavior of the repository with respect to compliance with 40 CFR Part 191 and 40 CFR § 268.6.

Los Medaños. In this report, the area in southeastern New Mexico surrounding the site proposed for the WIPP repository. In Spanish it means "dune country."

Los Medaños Member. The lowest member of the Rustler formation, formerly known as the unnamed lower member.

lower explosive limit. The minimum concentration of gas or vapor in air below which a substance does not burn when exposed to an ignition source.

macromolecule. A very large molecule (such as proteins, cellulosics, and rubbers) that contains hundreds or thousands of atoms.

Magenta Dolomite Member. The upper of two layers of dolomite within the Rustler Formation that are locally water-bearing. Also called the Magenta Member.

magma. Naturally occurring molten rock material which is generated within the earth. This material is capable of intrusion and extrusion, from which igneous rocks are derived through solidification and related processes.

magnitude, earthquake. A measure of the total energy released by an earthquake. Not to be confused with intensity.

Malaga Bend. A sharp bend in the Pecos River 20 miles southeast of Carlsbad, New Mexico, and directly east of the town of Malaga.

man-rem. A unit of population dose (see population dose).

marker beds. Marker beds are well-defined layers of rock that mark distinct divisions in major geological strata or geological time frames.

mathematical model. In the context of the WIPP, mathematical formulations developed to represent the processes at the WIPP site. The conceptual models provide the context

within which these mathematical models must operate and define the processes they must characterize. The mathematical models are predictive in the sense that, once provided with the known or assumed properties of the system and possible perturbations to the system, they predict the response of the system. The processes represented by these mathematical models include fluid flow, mechanical deformation, radionuclide transport in groundwater, and removal of waste through intruding boreholes.

matrix porosity. The porosity of the matrix or finer parts of a rock, as opposed to the porosity imparted to a rock through fractures, vugs, and voids.

maximally exposed person. A hypothetical person who is exposed to a release of radioactivity in such a way that the person receives the maximum possible individual dose or dose commitment. For instance, if the release is a puff of contaminated air, the maximally exposed person is the individual at the point of largest ground-level concentration who stays there during the whole time of the cloud passage. The use of this term is not meant to imply that there is such a person, but only that thought is being given to the maximum exposure a person could receive.

maximum individual dose. The highest dose delivered to the whole body or to an individual organ that a person can receive from a release of radioactivity. The hypothetical person who receives this dose, the maximally exposed person, is one whose location and activities maximize the dose. For instance, the person may be at the point of maximum concentration of a radioactive cloud for the whole time it takes to pass.

MB 139. A marker bed located one m below the WIPP site and is on average one m thick. It consists mostly of anhydrite and clay.

mCi. Abbreviation for millicurie. One one-thousandth (0.001) of a curie.

McNutt Potash Zone or Member. The middle member of the Salado Formation measuring 348 to 413 ft (106 to 126 m) thick in the vicinity of the WIPP site. This member contains reddish-orange and brown halite with deposits of sylvite and langbeinite from which potassium salts are mined. The McNutt Potash Member was deposited in the Late Permian Period between approximately 258 and 250 million years ago.

mean. The average value. For a given set of *n* values, the mean is the sum of their values divided by *n*.

median. The median of a set of data is the value such that half of the observations are less than that value and half are greater than that value.

megapascal. 10^6 pascals.

Mercalli intensity. A scale of measurement of earthquake intensity.

Mescalero Caliche. An informal name for a layer of caliche of varying thickness found in the WIPP area.

Mescalero Plain. The Plain is composed of the ground surface east of the Pecos River valley and is one of the principal geomorphic features associated with the WIPP site. It consists of a poorly drained surface covered by gravels, eolian sand, and caliche. The plain has developed since the Early to Middle Pleistocene time (approximately 1.6 million year ago).

Mesozoic. An era of geologic time from the end of the Paleozonic Era, 245 million years ago, to the beginning of the Cenozoic era, 66 million years ago. It comprises the Triassic, Jurassic, and Cretaceous period.

metabolized. Refers to a material which has been consumed or transformed by the life processes of an organism.

metamorphic. Metamorphism is changes in rocks brought on by the effects of temperature, pressure and/or the introduction of new chemical substances. It requires deep burial below the zones of weathering and cementation.

methanogenesis. The generation of methane through the decomposition of organic matter in wastes.

microbial. The action of microbes or microorganisms. In the context of the WIPP, the term is mainly applied to the waste degradation and gas generation activity of microorganisms.

mineralization. The process whereby minerals are precipitated out of a solution into a porous or fracture zone. For example, if the Salado Formation brine is transported to the Culebra Dolomite, cooling may cause the precipitation of salt minerals.

Miocene. The fourth of five epochs into which the Tertiary Period is divided; also, the corresponding system of rocks. It is subsequent to the Oligocene Epoch and precedes the Pliocene Epoch (approximately 23.7 to 5.3 million years ago).

miscellaneous hazardous waste management unit. A waste management unit where hazardous waste is treated, stored, or disposed of, and that is not a container, tank, surface impoundment, pile, land treatment unit, landfill, incinerator, boiler, industrial furnace, underground injection well, or unit eligible for a research, development, and demonstration permit (40 CFR § 260.10).

Mississippian. Third youngest period of the Paleozonic Era and the corresponding system of rocks. Prior to the Pennsylvanian and representing approximately the interval from 360 to 320 million years ago. Mississippian rocks are present from 15,000 to 15,600 feet below the surface at the WIPP.

Mississippian Limestone. The limestone is light gray to brown, finely crystalline and commonly cherty, with a basal dark gray organic-rich shale unit. The limestone partially grades to shale southeastward from the northern margin of the Delaware Basin.

mixed waste. Mixed waste contains both radioactive and hazardous components, as defined by the Atomic Energy Act and the Resource Conservation and Recovery Act, respectively.

model. An investigative technique using a mathematical or physical representation of a system that accounts for all or some of its known parameters. Models are often used to test the effect of changes of system components on the overall performance of the system.

model validation. The process of ensuring (through sufficient testing of a model using actual site data), that a conceptual model, and corresponding mathematical and computer models, correctly simulate a physical process with sufficient accuracy.

model verification. The process of ensuring (for example, through tests on ideal problems) that a computer code (computational model) correctly performs the necessary functional operations (such as solving the mathematical model). Given that a computer code correctly solves the mathematical model, the physical assumptions of the mathematical model must then be checked through validation.

MODFLOW. A computer program that numerically solves the three-dimensional groundwater flow equation for a porous medium by using a finite-difference method.

molality. The molality of a solution is the number of moles of solute in 1,000 g of solvent. A solution which contains one mole of solute in 1,000 g of solvent is called a one-molal solution.

molarity. The molarity of a solvent is the number of moles of solute per liter of solution. A solution containing one gram formula weight, or mole, of the solute in one liter of solution is a one-molar solution.

Monte Carlo Analysis/Technique. A technique that obtains distribution of approximate solutions to a problem by using statistical sampling techniques and computer simulations. For the WIPP PA, the method is used to evaluate the distribution of the consequence results and thereby approximate the uncertainty in the results.

Morrow Formation. This formation was formed in the Early Pennsylvanian Period approximately 320 million years ago. It consists of fine to coarse grain sandstones with dark gray shales and some thin limestones layers present in the upper section. It is approximately 14,000 ft (4,200 m) below the surface at the WIPP and 1,200 ft (366 m) in thickness. The Morrowan sandstones are a source of natural gas production north of the WIPP site.

MTHM. Metric tons of heavy metal; used in the release limit described in Appendix A of 40 CFR Part 191.

mudstone. An indurated mud having the texture and composition of shale, but lacking its fine lamination or fissility; a blocky or massive, fine-grained sedimentary rock in which the proportions of clay and silt are approximately equal; a nonfissile mud shale.

multi-mechanism deformation model. A simulation model developed to help predict the behavior, particularly the rate of room closure, of WIPP underground openings.

Nash Draw. A shallow valley, approximately five miles wide, open to the southwest, and located to the west of the WIPP site.

natural background radiation. Radiation in the human environment from naturally occurring elements and from cosmic radiation. See background (radiation).

natural barriers. The repository host rock and surrounding geologic structures and formations. The natural barriers extend from the engineered barrier to the compliance boundary.

near future. Defined for any activity that is initiated prior to shaft sealing (preclosure), even if the completion will occur after shaft sealing (postclosure). The demarcation between near future and future is the date of shaft sealing. All activities initiated after shaft sealing are "future" activities. Any activity initiated prior to shaft sealing is a "near future" activity and is part of the undisturbed performance.

neutron. An elementary particle that has approximately the same mass as the proton but lacks electric charge, and is a constituent of all nuclei having mass number greater than one.

New Mexico Bureau of Mines and Mineral Resources. The New Mexico Bureau of Mines and Mineral Resources is a division of the New Mexico Institute of Mine Technology.

nitrates. The salts from nitric acid generating sodium nitrate and potassium nitrate. These salts are used in the agricultural industry as fertilizers. When used as a fertilizer, nitrates can be a cause for groundwater chemistry changes.

nondestructive assay. The remote determination of the radionuclide content inside a waste package.

non-Salado. In this report, non-Salado refers to the hydrological aspects of all geologic formations above and below the Salado Formation. It pertains to the conceptual models used for flow and transport of radionuclides within these formations.

nuclear criticality. A self-sustaining nuclear chain reaction from sufficient mass of a fissionable material.

Nuclear Energy Agency. The Nuclear Energy Agency was established on February 1, 1958 under the name of OEEC European Nuclear Energy Agency. Nuclear Energy Agency membership today consists of all the European member countries of Organisation for Economic Cooperation and Development as well as Australia, Canada, Japan, the Republic of Korea, Mexico and the United States. The primary objective of Nuclear Energy Agency is to promote cooperation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable, and economic energy source.

nucleation. The process by which the formation of a crystal or some other particulate from the liquid state, vapor, or solution is begun. Often a minute particle of a foreign substance provides the initial nucleus for crystal growth.

nuclide. A species of atom characterized by the number of protons and neutrons in its nucleus.

nuclide inventory (radionuclide inventory). A list of the kinds and amounts of radionuclides in a container or a source. Amounts are usually expressed in activity units: curies or curies per unit volume.

nutrient. Applies to any substance assimilated by living things that promotes growth. The term generally applies to nitrogen and phosphorus in waste water, but is also applied to other essential and trace elements.

NUTS. NUTS is a radioisotope transport code that is used for the analysis in Chapter 6.0. Its principal capabilities are (1) to decay the inventory, using Bateman's equations, and (2) to transport radionuclide through porous or fractured media. NUTS is capable of resolving and tracking many individual radioisotopes.

Ochoan. The Late Permian Ochoan series consists primarily of evaporites that were deposited during recurrent retreats of a shallow sea restricted by the Guadalupian reefs. The lower three formations in the series, the Castile, Salado and Rustler, comprise what is perhaps the thickest and most extensive evaporite rock sequence in North America.

Ogallala Formation. Deposition of the Ogallala began about 12 million years ago, in Miocene time. The Ogallala represents the first preserved sedimentary record in the vicinity of the Delaware Basin since Cretaceous deposition. The Ogallala formed a thick mantle throughout the Permian Basin, producing the even surface of the High Plains, called the Llano Estacado in western Texas and eastern New Mexico. Locally, eolian activity played a part in deposition, and periodically, widespread soils formed.

one hundred-year storm. A storm that, on a statistical basis, is expected to recur only once every hundred years.

oolite. A sedimentary rock, usually a limestone, made up chiefly of ooliths cemented together. Synonym for roestone and eggstone. An oolith is a spherical or subspherical rock particle that has grown by accretion around a nucleus. The most common type of oolith is calcareous, although primary ooliths of iron minerals are also found.

order of magnitude. A factor of ten. When a measurement is made with a result such as 3×10^7, the exponent of 10 (here 7) is the order of magnitude of that measurement. To say that this result is known to "within an order of magnitude" is to say that the true value lies between (in this example) 3×10^6 and 3×10^8.

Ordovician. The second oldest period of the Paleozoic Era and also the corresponding system of rocks. It is represented by the rock units between 16,900 ft and 18,200 ft below the surface in the vicinity of the WIPP. The Ordovician Period is subsequent to the Cambrian Period and followed by the Silurian Period, between approximately 505 and 438 million years ago.

orthogonal reactions. Chemical reactions that do not affect or interfere with each other.

osmotic. The passage of pure liquid from a region of higher solute concentration to a region of lower solute concentration, usually through some intervening solid or liquid barrier such as a membrane, which restricts mixing. Thus, if a volume of dilute salt water is separated from a volume of concentrated brine by a semi-permeable membrane, water is passed by osmosis through the membrane from the dilute solution to the high-salinity brine.

overpack. A container put around another container. In the WIPP, overpacks would be used on damaged or otherwise contaminated drums, boxes, and canisters that it would not be practical to decontaminate.

oxic. Describes a process that occurs in the presence of oxygen (O_2), such as the corrosion of steels, iron-base alloys, and other metal wastes, using O_2 and water (H_2O) to produce iron oxide and hydrogen gas (H_2).

oxidation. The chemical process whereby electrons are removed from an atom or ion. Originally referring to chemical reactions involving oxygen, the term is also used to designate any chemical reaction in which the reactant gives up one or more electrons. Thus, when hydrogen (H_2) and chlorine (Cl_2) react to form 2H+Cl, the hydrogen is "oxidized" by the chlorine. The oxidation state of an ion is expressed as a positive or negative number representing the ionic or effective charge.

oxides. Minerals in which cationic atoms are bonded to oxygen atoms.

packaging. The assembly of components necessary to ensure compliance with packaging requirements. It may consist of one or more receptacles, absorbent materials, spacing structures, thermal insulation, radiation shielding, and devices for cooling or absorbing mechanical shocks. The vehicle, tie-down system, and auxiliary equipment may be designated as part of the packaging.

Paleozoic. Major geological era from 245 million years to 570 million years. Denotes a wide range of geological strata from different geological periods (that is, Permian, Pennsylvanian, Mississippian, etc).

panel. A group of several underground rooms connected by drifts. Within the WIPP, a panel consists of seven rooms connected by drifts at each end.

PANEL. Sandia National Laboratory computer program which simulates the process of waste mobilization.

parameter. The underlying elements ($x = x_1, ..., x_n, ..., x_{nV}$) of a computational model. As x changes so does the model result. The individual parameters, x_n, may be vectors, tensors, higher order quantities, or even functions, but are usually scalar quantities. Furthermore, the individual parameters are usually coefficients of the mathematical model, but they may also relate to scenario uncertainty or model form uncertainty.

Pascal. A unit of pressure obtained by dividing force (in Newtons) by area (in meters squared).

passive/active neutron analysis. An assaying technique used to determine the amount of fissionable material in a container of waste. Background neutrons are counted as well as neutrons from artificially-induced fissioning in the waste. The analysis assumes that the isotopic composition is already known.

passive institutional controls. "(1) [P]ermanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system." (40 CFR § 191.12)

Pennsylvanian. Second-youngest period of the Paleozonic Era and also the corresponding system of rocks. Pennsylvanian rocks are found about 12,800 to 15,000 ft below the Los Medaños surface in the vicinity of the WIPP site and may contain oil and natural gas. Subsequent to the Mississipian Period and followed by the Permian Period, between approximately 320 and 286 million years ago.

percolate. The movement of liquid (usually water) through unsaturated or saturated solid and rock.

performance assessment (PA). An analysis that (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events.

performance modeling. A process of building models of the factors affecting the containment of nuclear waste to project into the future how the WIPP facility will respond to probabilistic events and processes.

permafrost. Permanently frozen ground which occurs at different depths below the ground surface in frigid climates.

permeability. In hydrology, the capacity of a rock, sediment, or soil to transmit fluids under specified conditions. It is given by the hydraulic conductivity (K) times the fluid dynamic viscosity (μ) divided by the fluid density (ρ) times acceleration due to gravity (g); $k = \mu K/\rho g$.

Permian Basin. A region in the Central U.S. where, during Permian times 286 and 245 million years ago, there were many shallow seas that laid down vast beds of evaporites. The Delaware basin is a part of the Permian basin.

Permian Period. This period is the last of seven periods of the Paleozonic Era, subsequent to the Pennsylvanian Period; also, the corresponding system of rocks (between approximately 286 and 245 million years ago).

PEST. The parameter estimation program that can be used with other models to quickly calibrate parameters using a set of known observations.

petrological. Relating to the general study of rocks in all their aspects, including their mineralogies, textures, structures, origins, field occurrences, alterations, and their relationships to other rocks.

pH. The symbol used to designate a standard measure of the acidity of a solution. pH is defined as the negative logarithm (base 10) of the activity of hydrogen ion in the solution. Pure water, which is regarded as neutral, has a pH of 7. A lower value of pH would indicate acidity, and a higher value would indicate that a solution is basic (alkaline).

phenols. Organic compounds that are by-products of petroleum refining, tanning, and textile, dye, and resin manufacturing. Low concentrations cause taste and odor problems in water; higher concentrations can kill aquatic life and humans.

physicochemical. Describes chemically related processes studied for performance assessment purposes that have potential to influence the transport of contaminants throughout the disposal system. These physicochemical processes include alpha recoil, chemical gradients and osmotic activity.

physiography. A description of the natural features of the surface of the earth.

Pipe Overpack. The standard pipe overpack consists of a pipe component surrounded by cane fiberboard and plywood dunnage within a standard 55-gallon drum with a rigid polyethylene liner and lid. It is designed to be used for the shipment of specific contact-handled transuranic waste forms in the TRUPACT-II.

pisolitic. Pertaining to pisolite [sed], or to the texture of a rock made up of pisoliths or pealike grains; for example, pisolitic bauxite or pisolitic limestone.

Pitzer Formalisms. A semi-empirical formalism for calculating activity coefficients, particularly in saline aqueous systems.

plasticity. The property of a material that enables it to undergo permanent deformation without appreciable volume change or elastic rebound, and without rupture.

Pleistocene. This is the first epoch of the Quaternary Period of the Upper-Cenozoic Era; also, the corresponding system of rocks. It is subsequent to the Pliocene Epoch of the Tertiary Period and precedes the Holocene Epoch of the Quaternary Period (between approximately 1.6 million to 10,000 years ago). Climatic changes during this period are used as an analog in estimating future climatic extremes for the WIPP.

Pliocene. The last epoch of the Tertiary Period of the Middle-Cenozoic Era; also, the corresponding system of rocks. It is subsequent to the Miocene Epoch of the Tertiary Period and preceded by the Pleistocene Epoch of the Quaternary Period (between approximately 5.3 and 1.6 million years ago).

plug. A watertight or gastight seal installed in a borehole or well to prevent movement of fluids or gas. Also used to fill in or seal off fractures, cavities, or other porosity in the walls of a

borehole. Commonly a cement plug is used in the sealing of boreholes or wells associated with oil, gas, or water exploration.

plutonium. A metallic, radioactive actinide, symbol Pu, atomic number 94, in the transuranium series of elements; used as a nuclear fuel and as the fissile agent in nuclear weapons.

plutonium equivalent curie. A term developed to provide a uniform basis among various radioactive wastes to perform comparative human health consequence analyses resulting from inhalation. The plutonium equivalent curie concept has strict limits of applicability. It is utilized herein as a means of expressing the transuranic activity content of transuranic waste packages.

pmH. The symbol used to designate a standard measure of the acidity of a solution. pmH is defined as the negative logarithm of the molal concentration of hydrogen ion in solution.

Poços de Caldas. A location in Brazil where two uranium deposits were investigated for the possibility that the flow of fluids might lead to the development and migration of a large-scale redox front.

point data. Discrete actual data collected by directly observing and recording a measurable event or attribute.

point source. A source of effluents that is small enough in dimensions that it can be treated as if it were a point. The converse (not used in this document) is a diffuse source. A point source can be either a continuous source or a source that emits effluents only in pulses or for a short time.

polyelectrolyte. A substance of high molecular weight (as a protein or a nuclide).

polyhalite. An evaporite mineral: $K_2MgCa_2\ (SO_4)_4 \cdot 2H_2O$. It is a hard, nearly insoluble mineral with no economic value.

Polypropylene "supersacks." Sacks containing 4,000 pounds of magnesium oxide which are placed on top of the three high seven-packs of containerized waste that has been placed underground.

population dose. The sum of the radiation doses received by the individual members of a population.

porosity. The ratio of the void volume in a rock or soil to its total volume. It may be stated as a percentage or as a decimal.

process. A physical, natural, or anthropogenic phenomenon that occurs continuously or over a significant portion of the time frame of interest. In other words, a "long-term" phenomenon.

portlandite. An ingredient of Portland cement [$Ca(OH)_2$].

possible futures. The set of all possible occurrences within the 10,000-year regulatory time frame.

postclosure phase. A designated period of time beginning with the end of the decommissioning phase and extending through the end of the regulatory time frame of 10,000 years. PA modeling of repository behavior addresses this time frame.

potash. A potassium compound used in agriculture and industry.

potassium. A silver-white metallic element of the alkali metal group. It occurs abundantly in the McNutt Potash Zone in the vicinity of the WIPP site.

potentiometric surface. A subsurface map of the hydraulic potentials of an aquifer. It is usually represented in figures as a contour map, each point estimating how high the water would rise in a well tapping that aquifer at that point.

Precambrian. Applies to all geologic time, and its corresponding rocks, before the beginning of the Paleozonic Era, 570 million years ago. The Precambrian basement is approximately 18,000 feet (5,486 meters) below the surface in the vicinity of the WIPP site.

probabilistic analysis. Analysis that arose from statistical investigations is referred to as probabilistic analysis. This analysis is characterized by the fact that, although specific outcomes of an experiment cannot be predicted with certainty, relative frequencies for various possible outcomes are predictable. Monte Carlo analysis is used for probabilistic analysis of the WIPP.

Project Gnome. The Plowshare Project Gnome Test, an underground nuclear test, took place on December 10, 1961, at a location approximately 8 mi (13 km) southwest of the WIPP site. Its primary purpose was to study the effects of a nuclear explosion in salt. The site was decommissioned in 1979, but continues to be monitored by the EPA for radioactive contamination.

Projected Inventory. The part of the TRU inventory that has not been generated, but is estimated to be generated at some time in the future, by the TRU waste sites. The projected inventory is the same as the to-be-generated waste referred to in 40 CFR 194.24(a).

promulgation. Referring to the process of putting regulations into law.

Public Law 96-164. The U.S. Department of Energy National Security and Military Applications of Nuclear Energy Act of 1980. Public Law 96-164 directed the DOE to proceed with the design and development of the WIPP.

Public Law 102-579. See Land Withdrawal Act.

quality assurance. The planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service.

Quality Assurance Project Plans. This document identifies the quality of data necessary, and the techniques designed to attain and ensure the required data quality objectives associated with the WIPP waste characterization program.

quality control. Those quality assurance activities that provide a means to control and measure the characteristics of a structure, system, or component to established requirements.

Quaternary. The last period of the Cenozoic Era; also, the corresponding system of rocks. It is subsequent to the Tertiary Period, beginning approximately 1.6 million years ago and extends to the present.

rad. See radiation absorbed dose.

radially. The term "radial" is the adjective of "radius" and is used to describe forces that act in directions parallel to some radius or to designate lines, fractures, flow paths, etc., that are oriented parallel to radii. "Radially" is the corresponding adverb. Effects that act outward from a single point or inward toward a point (for example, flow of groundwater toward a borehole) may be radial in form.

radiation absorbed dose (rad). The special unit of absorbed dose of ionizing radiation. One rad of absorbed dose is equal to the absorption of 100 ergs of radiation energy per gram of absorbing material. See also rem.

radioactive decay. A process whereby the nucleus of an atom spontaneously emits excess energy by emitting particles and/or rays (alpha, beta, gamma, or neutrons).

radioactive material. Matter composed of or containing radionuclides, with radiological half-lives greater than 20 years, subject to the Atomic Energy Act of 1954, as amended. (40 CFR § 191.12)

radiographic examination. The nondestructive technique that enables a qualitative evaluation of the contents of a waste container.

radiolysis. Chemical decomposition by the action of radiation.

radiometric. Pertaining to the measurement of geologic time by the study of parent and/or daughter isotopic abundances and known disintegration rates of the radioactive parent isotopes, for example, radiometric dating.

radionuclide. An isotope having an unstable nucleus that is subject to spontaneous decay.

reactant. A substance that enters into a chemical reaction and is altered. For example, metal waste reacts with oxygen and water to produce hydrogen and metal oxides.

real-time radiography. A type of remote Non-Destructive Test that uses a luminescent screen to form a moving image from x-rays that have passed through a rotating test object. Real-time radiography is relied on for detection of waste form shapes and the presence of liquids inside the waste package.

reasonable. (1) Not conflicting with reason; (2) not extreme or excessive; (3) having the faculty of reason; or (4) possessing sound judgment.

recharge. The amount of water and the processes involved in the addition of water to an aquifer.

recharge point (or area). In groundwater hydraulics, the point (or area) where surface water enters an aquifer.

recovery. The process of getting something back. The term "resource recovery" is often used to indicate the mining of minerals or the withdrawal of oil or natural gas from beneath the surface of the Earth through wells.

recrystallization. The formation, initially in the solid state, of new crystalline mineral grains in a rock. The new grains are generally larger than the original grains and may have a different mineralogical composition. It is usually caused by increased temperatures and pressures exerted on a rock formation.

regulatory time frame. As defined in 40 CFR Part 194, the regulatory time frame means the time period beginning with disposal and ending 10,000 years after disposal.

release. Movement of regulated substances into the accessible environment as defined in 40 CFR Part 191 or beyond the unit boundary as defined for 40 CFR § 268.6.

rem. Roentgen equivalent in man—a special unit of dose equivalent which is the product of absorbed dose, a quality factor which rates the biological effectiveness of the radiation types producing the dose, and other modifying factors (usually equal to one). If the quality and modifying factors are unity, 1 rem is equal to 1 rad: 100 rem = 1 Sievert (SI units). Also expressed in terms of millirem (mrem): 1 rem = 1,000 mrem.

remote-handled transuranic waste. Packaged transuranic waste that has a measured external surface dose rate at or greater than 200 millirems per hour at the surface of the container.

repository. The portion of the WIPP underground system within the Salado Formation, including the access drifts, waste panels, and experimental areas, but excluding the shafts.

repository/shaft system. The WIPP repository underground workings, including the shafts, all engineered and natural barriers, and the altered zones within the Salado Formation and overlying units resulting from construction of the underground workings.

repressurization. The increase in pressure in a previously depleted volume that might be associated with a fluid injection.

reserves. Mineral resources that can be extracted profitably by existing techniques and under present economic conditions.

reservoir. A subsurface volume of rock that has sufficient porosity and permeability to permit the accumulation of oil, gas, or water under adequate trap conditions. Also applies to any natural or artificial surface holding area used to store, regulate, or control water.

residuum. An accumulation of rock debris formed by weathering and remaining essentially in place after all but the least soluble constituents have been removed, usually forming a comparatively thin surface layer concealing the unweathered or partly altered rock below.

resistivity. Measure of electrical resistance in a fluid such as brine.

resources. Mineralization that is concentrated enough, in large enough quantity, and in a physical and chemical form such that its extraction is currently or potentially feasible and profitable.

retardation. Attenuation of contaminant concentration with migration distance. There are a variety of physical and chemical processes that can contribute to retardation.

retrievable. Describes storage of radioactive waste in a manner designed for potential recovery without loss of control or release of radioactivity.

Richter scale. A logarithmic scale expressing the magnitude of a seismic disturbance (as an earthquake) in terms of the energy dissipated in it with 2 being the lowest and 8.5 being the largest earthquakes yet recorded.

Rio Grande Rift. The rift system of the Rio Grande valley in which the crustal plate has split and a series of grabens have formed in New Mexico and Southern Colorado. It is a product of extensional tectonics.

room. An excavated cavity within a panel in the underground portion of the WIPP, a room is about 10 meters wide, 4 meters high, and 91 meters long.

rubidium-strontium age. Determination of an age for a mineral or rock in years based on the ratio of radiogenic strontium-87 to rubidium-87 and the known radioactive decay rate of rubidium-87. If ratios are measured for more than one phase of a single rock, or for a number of related rocks that differ in rubidium content, an isochron may be drawn.

Rustler Formation. The evaporite beds, including mudstones, of probable Permian age that immediately overlie the Salado Formation.

Salado Formation. A geologic formation of Late Permian age in southeastern New Mexico. At the WIPP site, it is composed of salt beds with minor amounts of anhydrite (45 numbered anhydrite marker beds: Marker Bed 101 through Marker Bed 145) and clay. It is the host unit for the WIPP repository.

saline. Waters are considered saline when they contain between 10 and 100 parts per thousand salinity. See brackish and brine.

saline intrusion. A human-induced coastal process whereby subsurface seawater progressively replaces freshwater withdrawn from an aquifer being pumped close to the shoreline.

Sandia National Laboratories. A multiprogram laboratory located in Albuquerque, NM, and Livermore, CA. SNL is operated and managed for the DOE by the Sandia Corporation. From 1949 until October 1993, Sandia Corporation was a wholly owned subsidiary of AT&T. Sandia Corporation is currently a wholly owned subsidiary of Lockheed-Martin Corp.

San Simon Sink. The central, most depressed area of San Simon Swale.

San Simon Swale. A broad depression about 15 miles east of the Los Medaños site, open to the southeast.

Santa Rosa Formation. The Santa Rosa Sandstone is a principal aquifer in several areas, particularly in Winkler and Ward Counties, Texas. It produces both fresh and saline water, depending on location. The westernmost extent of the Santa Rosa Sandstone is just into Eddy County. Wells completed in the Santa Rosa Sandstone have low yields with specific capacities of 0.14-0.2 gpm per foot of drawdown; the formation porosity is about 13 percent.

SANTOS. A finite element program designed to compute the quasistatic, large deformation, inelastic response of two-dimensional planar or axisymmetric solids or engineering structures.

saturated. A condition in which all connected pores in a given volume of material contain fluid.

scarp. A line of cliffs produced by faulting or by erosion. The term is an abbreviated form of escarpment, and the two terms commonly have the same meaning, although “scarp” is more often applied to cliffs formed by faulting.

Scaled Inventory. Synonymous with Disposal Inventory. The scaled inventory is the inventory volume that fills WIPP capacity and is used for PA calculations. This volume is calculated as the sum of the disposal volumes for all WIPP-eligible waste streams after application of RH-TRU and CH-TRU scaling computations to each WIPP-eligible projected TRU waste stream.

scenario. A combination of naturally occurring or human-induced events and processes that represent realistic future changes to the WIPP repository, geologic, and geohydrologic systems that could cause or promote the escape of radionuclides and/or hazardous constituents from the WIPP repository.

screening argument. Regulatory Guidance, Probability of Occurrence, and Consequence are three criteria used to eliminate from scenario development those events and processes that are not applicable to a specific disposal system or that do not have the potential of contributing significantly to the performance measure (for example, integrated radionuclide releases).

seal. An engineered barrier designed to isolate the waste and to impede groundwater flow in the shafts.

sealing system. Includes all components of the WIPP seal design program.

SECOTP2D. A computer program that simulates single or multiple component radionuclide transport in fractures or granular aquifers.

sedimentary. A descriptive term for rocks formed of sediment, such as clastic rocks (sandstones and shales), secretions of organisms, limestones, and precipitation from solution, rock salts and gypsums.

sedimentation. The process of accumulating sediment into layers of solid rock which includes the generation of rock particles, the transportation and the deposition of these particles, and the consolidation of these particles into solid rock.

seismic. Applies to the activity of naturally- or artificially-induced earthquakes or earth vibrations, where the seismic waves are the elastic waves produced by these vibrations.

seismic risk zone. A designation of a geographic region expressing the maximum intensity of earthquakes that could be expected there.

sensitivity analysis. Methods for computing the effect of changes in the input parameters on the model predictions.

seral. Relating to a series of ecological communities formed in ecological succession.

sequestration. To hold (as a metallic ion) in solution.

shaft. A man-made hole, either vertical or steeply inclined, that connects the surface with the underground workings of a mine.

shaft pillar. The cylindrical volume of rock around a shaft from which major underground openings are excluded in order that they do not weaken the shaft.

shallow-dissolution zone. A zone of residual material at the interface of the Rustler and Salado formations left after dissolution of salt. It is highly permeable and often contains brine.

SI unit. See System of International Units.

Sievert. The SI unit of effective dose. It is equal to 100 rem or one joule per kilogram. (40 CFR § 191.12)

siliciclastic. Pertaining to clastic noncarbonate rocks which are almost exclusively silicon-bearing, either as forms of quartz or as silicates.

siltstone. An indurated silt having the texture and composition of shale but lacking its fine lamination or fissility; a massive mudstone in which the silt predominates over clay; a nonfissile silt shale.

Silurian. Third-oldest period of the Paleozonic Era, and also the corresponding system of rocks. Subsequent to the Ordovician Period and followed by the Devonian Period, between approximately 438 and 400 million years ago. The Silurian of the southeast New Mexico - west Texas area consists of the Fusselman limestone and the carbonates and shales of an Upper Silurian unit, both of which were deposited in the broad subsiding area named the Tobosa Basin.

Simpson. In the Delaware basin, the Simpson consists of three main layers of limestone, alternating with thinner green, brown, and black shale, black shale with rounded quartz grain inclusions, and sandstone.

site characterization. The process of making geologic and environmental studies to identify potential sites for mined geologic repositories. Detailed site characterization goes further: additional data are collected that would be necessary if a license application were to be submitted.

SKI (Statens Kärnkraftinspection). An abbreviation for the Swedish Nuclear Power Inspectorate, Statens Kärnkraftinspection. A list of potentially relevant features, events, and processes developed by SKI was considered to be the best documented and most comprehensive starting point for the WIPP scenario development process.

sludge. Refers to de-watered contact-handled transuranic wastes containing both organic and inorganic constituents that must meet the Waste Acceptance Criteria for shipment and disposal at the WIPP repository. High sludges are contact-handled transuranic waste where the sludge component constitutes 50 percent or more of the waste volume; low sludges are the same type of waste containing less than 50 percent by volume of sludge.

SO-C. Screened-out on the basis of consequence. The term applies to the elimination of features, events, and processes from PA and compliance assessment calculations for WIPP compliance efforts on the basis of consequence.

solifluction. The slow downslope flow of waterlogged soil that is commonly active in periglacial regions underlain by frozen ground that acts as a downward barrier to water percolation.

SO-P. Screened-out on the basis of low probability. The term applies to the elimination of features, events, and processes from PA and compliance assessment calculations for WIPP compliance efforts on the basis of low probability of occurrence.

SO-R. Screened-out on the basis of regulations. The term applies to the elimination of features, events, and processes from PA calculations used for WIPP compliance efforts on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR Part 194.

solubility. The ability or tendency of one substance to blend uniformly with another (for example, solid in liquids, liquid in liquid, gas in liquid, and gas in gas). Solids vary from 0 to 100 percent in their degree of solubility in liquids depending on the chemical nature of the substance(s); to the extent that they are soluble, they lose their crystalline form and become molecularly or ionically dispersed in the solvent to form a true solution. Liquids and gases are often said to be miscible in other liquids and gases rather than soluble.

solute. A substance which is dissolved in another substance called the solvent. The solute is uniformly dispersed in the solvent either molecularly or ionically.

solution. A mixture, liquid, solid, or gaseous, in which the components are uniformly distributed throughout the mixture.

solution subsidence. Gradual subsidence of nonsoluble strata due to the dissolution of underlying rock.

solvent. A substance capable of dissolving another substance (solute) to form a uniform dispersed mixture (solution) at the molecular or ionic level. Solvents are, accordingly, characterized as either polar or non-polar. Water is strongly polar; hydrocarbon solvents are non-polar.

soret effect. The principle that asserts when temperature differences are induced in a solution of common salt or other substance in water, the dissolved material will become relatively concentrated in those portions in which the temperature is lowest.

sorption. The binding on a microscopic scale of one substance to another, such as by adsorption or ion exchange. In this document, the word is especially used in the sorption of solutes onto aquifer solids.

source term. The kinds and amounts of radionuclides that make up the source of a potential release of radioactivity. See nuclide inventory.

spallings. During exploratory drilling, waste surrounding the eroded borehole that is transported by waste-generated gas escaping to the lower pressure borehole.

specific activity. Radioactivity per unit weight of radioactive material.

standard waste box. A waste container measuring approximately 6 by 4.5 by 3 feet high, with rounded ends.

steady-state. A state or condition of a system or process that does not change over time; a condition that changes only negligibly over a specified time.

stochastic uncertainty. As used in probabilistic risk assessment, stochastic uncertainty characterizes uncertainty involving conceptual models and/or the future.

Stored Inventory. Also referred to as “retrievably stored” inventory. The part of the anticipated waste inventory that is stored in such a fashion that it can be readily retrieved.

Retrievably stored waste includes waste stored at the TRU waste sites since approximately 1970 in buildings or berms with earthen cover and does not include any waste generated prior to 1970. Retrievably stored waste also includes waste that is stored in underground storage tanks, ponds, and as decontamination and decommissioning material identified for disposal that requires retrieval at the TRU waste sites.

strata. Geologic term for layers of the earth's crust. The crust was generally laid down in layers during geological epochs.

stratigraphy. The science and study of the origin, composition, and proper sequence in which various rock strata were layered during various geological ages.

strike slip fault. A fault on which the movement is parallel to the fault's strike.

structure map. A map that portrays subsurface configuration by means of structure contour lines.

subduction zone. A long, narrow belt in which subduction takes place. For example, along the Peru-Chile trench, where the Pacific plate descends the South American plate.

study area. The region about the Los Medaños site studied in the evaluation of that site.

subjective uncertainty. Subjective uncertainty derives from a lack of knowledge about quantities, attributes, or properties believed to have a single or certain range of values.

subsidence. The downward settling of the earth's surface with little or no horizontal motion. Subsidence may be caused by natural geological processes or by man-made activities.

substrate. The surface and/or nutrient on which an organism will live and grow.

subsurface. The rock and soil below the ground surface whose geological features, principally stratigraphy and structure, are interpreted primarily on the basis of drilling activities and geophysical evidence.

subvertical. Used to describe planar features oriented within approximately 15 degrees of vertical.

sulfates. Mineral compounds characterized by the sulfate radical $S0_4$. Anhydrous sulfates, such as barite, $BaS0_4$, have divalent cations linked to the sulfate radical; hydrous and basic sulfates, such as gypsum, $CaSO_4$-$2H_20$, contains water molecules.

supersaturation. A solution, such as the Salado Formation brine, that contains more of a solute (radioactive isotope) than is normally present when equilibrium is established.

swipe samples. The presence of radioactive contaminants may be ascertained by applying a Kim-wipe™ or equivalent to the surface of the potentially contaminated item and measuring the radioactivity of the Kim-wipe™.

sylvite. A mineral, KCl, used in the manufacture of fertilizer.

syndeposition. Processes occurring during deposition of a sedimentary rock, and contributing to the formation of the sedimentary framework.

System of International units. The version of the metric system which has been established by the International Bureau of Weights and Measures and is administered in the United States by the National Institute of Standards and Technology. The abbreviation for this system is "SI." (40 CFR § 191.12)

Tamarisk Member. The middle anhydrite layer of the Rustler Formation.

Tansill Formation. The Tansill Formation is the uppermost formation of the Artesia Group, developing in the Mid-Permian Period, between approximately 280 and 260 million years ago. The Artesia Group represents the shelf region of the Goat Seep Formation and the Capitan Limestone. To the south of the Delaware Basin the Tansill Formation consists of dolomites and sandstones. Toward the northern part of the basin, gypsum and anhydrite along with siltstones and dolomites increase in the Tansill Formation. The Tansill Formation is time correlative to the Capitan Reef at the basin margin and the Bell Canyon Formation in the Delaware Basin.

tectonics. The branch of geology dealing with regional structural or deformational features.

tensile. Refers to tension in the mechanical sense. A material is under tension when the stress exerted on it (tensile stress) acts "outward" such that the effect is to increase the length or volume of the body.

Tertiary Period. The first of two periods in the Cenozoic Era and the corresponding system of rocks. It is subsequent to the Cretaceous Period of the Mesozoic Era and is followed by the Quaternary Period of the Cenozoic Era. The Tertiary Period dates between approximately 66.4 and 1.6 million years ago.

thermal effect. The effects of naturally occurring heat on groundwater flow.

thermal field. The field or set of temperatures throughout a volume. Use of the term usually connotes temperatures that differ from point to point.

thermal gradient. The rate of change of temperature in the direction of increasing temperature.

thermodynamic. A term that deals with the relations between heat and other forms of energy. A system is at thermodynamic equilibrium when there is no tendency for change in the free energy of the system,

thief zone. A rock unit responsible for excessive fluid loss from boreholes during drilling or production operations.

topographic/topography. Relating to or concerning the configuration of a surface that includes relief and the position of its natural and man-made features.

transient. This term is used to describe changing state or condition as in ground motion due to seismic activity, or groundwater flow resulting from changing fluid densities.

transmissivity. The rate at which water is transmitted through a unit thickness of an aquifer. It is considered a property of the aquifer. The contained liquid is transmissible.

transport. For regulatory purposes relating to moving waste to the repository. The movement of radioactive wastes across public routes via the use of packaging as the transportation container and the movement of a hazardous substance by any mode, including pipeline (as defined in the Pipeline Safety Act). In the case of a hazardous substance that has been accepted for transportation by a common or contract carrier, the term “transport” or “transportation” shall include any stoppage in transit that is temporary, incidental to the transportation movement, and at the ordinary operating convenience of a common or contract carrier, and any such stoppage shall be considered as a continuity of movement and not as the storage of a hazardous substance. When addressing the performance of the geologic repository, “transport” refers to the movement of material by mechanisms such as solution, or association with colloids, in groundwater or water from other sources flowing through the repository, seepage of gas through fractured or porous media, or entrainment in drilling fluid, brine, or gas flowing in a borehole.

transuranic. See Transuranic Waste.

transuranic nuclide. A nuclide with an atomic number greater than that of uranium (92). All transuranic nuclides are produced artificially and are radioactive.

Transuranic Package Transporter-II. A package designed to transport contact-handled transuranic mixed waste to the WIPP site. It is a cylinder with a flat bottom and a domed top that is transported in the upright position. Also called TRUPACT-II.

transuranic waste. The term “transuranic waste” means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for: (1) high-level radioactive waste; (2) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations; or (3) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR 61.

treatment. Any method, technique, or process, including neutralization, designed to change the physical, chemical, or biological character or composition of any hazardous waste so as to neutralize such waste, or so as to recover energy or material resources from the waste, or so as to render such waste non-hazardous, or less hazardous; safe to transport, store, or dispose of; or amenable for recovery, amenable for storage, or reduced in volume.

Triassic. The first period of the Mesozoic era (after the Permian of the Paleozonic Era, and before the Jurassic), thought to have covered the span of time between 225 and 190 million years ago; also, the corresponding system of rocks. The Triassic is so named because of its threefold division in the rocks of Germany.

true solution. A uniformly dispersed mixture at the molecular or ionic level, of one or more substances (solute) in one or more substances (solvent). Solutions that exhibit no change of internal energy upon mixing and have complete uniformity of cohesive forces are considered true.

TRUPACT-II TDOP (ten drum overpack). A container that is designed for use either with the TRUPACT II Shipping Package or as a stand-alone Department of Transportation (DOT) 7A Type A packaging. The container was designed to hold ten 55-gallon drums, loose homogenous materials, or one Standard Waste Box (SWB).

TRU Waste Inventory Update. Los Alamos National Laboratory (LANL), Carlsbad Office performed an inventory update of TRU Waste planned for disposal at WIPP. LANL collected updated inventory data from each of the generator sites which will be shipping TRU Waste to the WIPP. The inventory will not replace the Baseline Inventory Report (BIR), Rev. 3 it will be a stand-alone document representing the best estimate of TRU Waste remaining to be shipped.

Type A Packaging. A packaging designed to retain the integrity of containment and shielding required by this part under normal conditions of transport as demonstrated by the tests set forth in 49 CFR § 173.465 or 173.466, as appropriate.

uncertainty analysis. (1) An evaluation to determine the uncertainty in model predictions that results from imprecisely known input variables; or (2) Determination of the degree of uncertainty in the results of a calculation based on uncertainties in the input parameters and underlying assumptions. Such an analysis requires definition of a system, description of the uncertainties in the factors that are to be investigated, and the characteristics of the system that are to be simulated.

underpressurized. A zone or rock formation (Culebra Dolomite or perhaps units underlying the Salado Formation) that falls below the expected pressure gradient as depth increases.

undisturbed performance. "[T]he predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." (40 CFR § 191.12)

uninterruptible power supply. A power supply that provides automatic, instantaneous power, without delay or transients, on failure of normal power. It can consist of batteries or full-time operating generators. It can be designated as standby or emergency power depending on the application. Emergency installations must meet the requirements specified for emergency.

unit boundary. In the context of 40 CFR § 268.6, the unit boundary is that point at which migration occurs if hazardous constituents pass that point in concentrations exceeding health-based levels.

uplift. A structurally high area in the crust, produced by positive movements that raise or upthrust the rocks, as in a dome or arch.

Upper Devonian Woodford Shale. The Woodford is a dark brown to black, fissile, bituminous, spore-bearing shale which becomes [arenaceous] northward and contains black [chert] to the south and west.

U.S. Department of Energy. The cabinet-level U.S. Government agency responsible for weapons production, energy research, and for the subsequent cleanup of hazardous and radioactive waste sites. It was created from the Energy Research and Development Administration and other federal government functions in 1977. DOE is also responsible for the construction and oversight of WIPP primarily through its Carlsbad Area Office.

U.S. Environmental Protection Agency. (1) An independent agency of the Federal government formed in 1970 by Presidential executive order, bringing together parts of various government agencies involved with the control of pollution, and responsible for pollution abatement and control programs, including programs in air and water pollution control, water supply and radiation protection, solid and toxic waste management, pesticides control, and noise abatement; (2) The Agency for those implementation responsibilities for the Waste Isolation Pilot Plant, given to the Agency by the Waste Isolation Pilot Plant Land Withdrawal Act (Pub. L. 102-579, 106, Stat. 4777) which are:

(i) Determinations by the Agency that the Waste Isolation Pilot Plant is in compliance with Subpart A of this part;
(ii) Issuance of criteria for the certifications of compliance with subparts B and C of this part of the Waste Isolation Pilot Plant's compliance with subparts B and C of this part;
(iii) Certifications of compliance with subparts B and C of this part of the Waste Isolation Pilot Plant's compliance with subparts B and C of this part;
(iv) If the initial certification is made, periodic recertification of the Waste Isolation Pilot Plant's continued compliance with subparts B and C of this part;
(v) Review and comment on performance assessment reports of the Waste Isolation Pilot Plant; and,
(vi) Concurrence by the Agency with the Department's determination under § 191.02(i) that certain wastes do not need the degree of isolation required by subparts B and C.

U.S. Energy Research and Development Agency. Energy Research and Development Agency, a forerunner of the DOE that was formed in 1974 (Pub. L. 93-438).

U.S. Geological Survey. U.S. Geological Survey, Department of Interior.

valence state. The degree of oxidation (oxidation state) of an element or atom. It is usually expressed as a positive or negative number representing the ionic charge or effective charge of the element of atom.

Van Horn Sandstone. Clastics of the late Precambrian age that crop out near Van Horn, Texas and are overlain by the Bliss Sandstone.

varve. In its broadest sense, a varve is a usually thin layer of sedimentary rock that was deposited in a single year. The term is most commonly used to describe sediments deposited in glacial meltwater lakes that exhibit a sequence of alternating coarser and finer layers representing summer and winter deposition, respectively.

vector. A quantity or guide that requires a magnitude, direction and sense. It is commonly represented by a line, but also includes the direction of a substance (or activity) such as the flow of water in a general direction. As used in PA, the term is also used to describe model results from one set of parameters selected through statistical techniques.

viscosity. A property of fluids which is displayed by definite resistance to change of form. Many solids show a gradual yielding to forces tending to change their form. This property, a sort of internal friction, is also called viscosity.

volatile organic compounds. An organic compound that evaporates (volatilizes) readily at room temperature.

vug. Small open cavity in a rock.

Waste Acceptance Criteria. A set of conditions established for permitting transuranic wastes to be packaged, shipped, managed, and disposed of at the WIPP.

waste characterization. Sampling, monitoring, and analysis activities to determine the nature of the waste to be emplaced at the WIPP.

Waste characteristic. 40 CFR § 194.2 includes a regulatory definition of waste characteristic: Waste characteristic means a property of the waste that has an impact on the containment of waste in the disposal system.

Waste component. 40 CFR § 194.2 includes a regulatory definition of waste component: Waste component means an ingredient of the total inventory of the waste that influences a waste characteristic.

waste disposal panels. A collection of disposal rooms in the WIPP repository. Each panel will be sealed as a unit.

waste form. A term used to emphasize the physical and chemical properties of the waste.

Waste Isolation Pilot Plant. (1) The project authorized under § 213 of the DOE National Security and Military Application of Nuclear Energy Authorizations Act of 1980 (Public Law 96-164; Stat. 1259, 1265) to demonstrate the safe disposal of radioactive waste materials generated by atomic defense activities; (2) A research and development facility, located near Carlsbad, New Mexico, to be used for demonstrating the safe disposal of transuranic wastes from DOE activities.

waste matrix. The material that surrounds and contains the waste and to some extent protects it from being released into the surrounding rock and groundwater. Only material within the canister (or drum or box) that contains the waste is considered part of the waste matrix.

waste stream. A grouping of waste materials with specific definable characteristics that remain the same throughout the process generating the waste stream. A waste stream is produced by a single process or subprocess or may be combined to produce a single output waste stream.

waste unit factor. The waste unit factor is the normalizing factor used to determine the release limits for 40 CFR § 191.13(a). The term is the same as the "unit of waste" defined in 40 CFR Part 191 Appendix B, Table 1, note e, as "an amount of transuranic wastes containing one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years." For the WIPP, the overall quantity of radionuclides that apply to the waste unit is 4.07×10^6 curies, and the waste unit factor is therefore 4.07.

wicking. The mechanism by which a liquid can migrate through an unsaturated zone against the forces of gravity and surface tension in the soil. Also called capillary rise.

Wink Sink. Wink Sink is located 100 mi (160 km) southeast of the WIPP site outside the Delaware Basin. The surface impression is 360 ft (110 m) in width and 110 ft (34 m) deep. It is the result of dissolution of the Salado Formation caused by percolation of shallow groundwater through abandoned boreholes. Subsequent subsidence of the rock units overlying the Salado Formation led to the collapse feature present on the surface.

WIPP site boundary. The boundary that defines the outer limits of the 16-section land withdrawal area. For the purposes of this application, this boundary defines the controlled area.

Wolfcampian. Lower member of Permian age in Southeastern New Mexico.

working agreement. Appendix B of the Agreement of Consultation and Cooperation, which sets forth the working details of that Agreement.

X-ray. Any of the electromagnetic radiations of the same nature as visible radiation but of extremely short wavelength (less than 100 angstroms). X-rays are produced by bombarding a metallic target with fast electrons in vacuum or by transition of atoms to lower energy states, and have the properties of ionizing a gas upon passage through it, of penetration various thicknesses of all solids, of producing secondary radiations by impinging on materials bodies, of acting on photographic films and plates as light does, and of causing fluorescent screens to emit light.

Yates Formation. The Yates Formation is one of five formations in the Artesia Group developing in the Mid-Permian Period, between approximately 280 and 260 million years ago. It is subsequent to the Seven Rivers Formation and is preceded by the Tansill Formation. The Tansill Formation, Seven Rivers Formation, and the Yates Formation represent the shelf region of the Capitan Limestone at the margin of the Delaware Basin.

To the south it consists of dolomites and sandstones. Siltstones, mudstones, and dolomites increase toward the northern part of the basin. The Yates Formation is time correlative to the Capitan Reef at the basin margin and the Bell Canyon Formation in the Delaware Basin.

ACRONYMS AND ABBREVIATIONS

Note: The following acronyms are carried forward from the initial certification application. Some acronyms appear in both the initial application and this recertification application. Acronyms that are unique to this application appear in bold, blue, italicized text**.**

ACA	Agency for Conservation Archaeology
ACNFS	Advisory Committee on Nuclear Facility Safety
AEC	Atomic Energy Commission
AECL	Atomic Energy of Canada Limited
AG	Attorney General
AIC	Active Institutional Controls
AIS	air intake shaft
AK	acceptable knowledge
Al	aluminum
ALARA	as low as reasonably achievable
Am	americium
amsl	above mean sea level
AMWTF	Advanced Mixed Waste Treatment Facility
AMWTP	Advanced Mixed Waste Treatment Project
ANL-E	Argonne National Laboratory-East
ANL-W	Argonne National Laboratory-West
ANSI	American National Standards Institute
APD	Application for Permission to Drill
API	American Petroleum Institute
ARCO	ARCO Medical Products Company
ASER	Annual Site Environmental Report
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
B&W-NES	Babcock & Wilcox-Nuclear Engineering Services
BAB	butyric acid bacteria
BAPL	Bettis Atomic Power Laboratory
BCL	Battelle Columbus Laboratories
BCLDP	Battelle Columbus Laboratories Decommissioning Project
BGR	Bundesanstalt fur Geowissenschaften und Rohstoffe
BIR	Baseline Inventory Report
BLM	U.S. Bureau of Land Management
BMP	Best Management Practice
BNL	Brookhaven National Laboratory
BP	branch procedure
BRAGFLO	brine and gas flow
BRP	Blue Ribbon Panel
BSEP	Brine Sampling and Evaluation Program
CAG	Compliance Application Guidance
CAO	Carlsbad Area Office *(former designation)*
CAR	Corrective Action Report

CARD	Compliance Application Review Document
CAST	CAST Transportation, Inc.
CB	Cabin Baby
CBFO	Carlsbad Field Office (DOE)
CBP	Central Basin Platform
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CCP	Central Characterization Project
CDA	corrected during the audit
CDF	cumulative distribution function
CDR	Conceptual Design Report
CEMRC	Carlsbad Environmental Monitoring and Research Center
Cf	californium
CFR	Code of Federal Regulations
CH	Contact-Handled
Ci	curie
Cm	curium
CMM	Coordinate Measurement Machine
CMP	Compliance Monitoring Plan
CMPR	Conceptual Model Peer Review
CMPRP	Conceptual Models Peer Review Panel
CMUG	Conceptual Model Uncertainty Group
Co	cobalt
CO_2	carbon dioxide
COMP	compliance monitoring parameter
CPR	cellulosic, plastic, and rubber
CRA	Compliance Recertification Application
Cs	cesium
CTAC	Carlsbad Field Office Technical Assistance Contractor
CTEN	Combined Thermal-Epithermal Neutron
CU	Culebra unit
D&D	decontamination and decommissioning
D/H	deuterium/hydrogen
DA	Data Administrator
DAC	Drum Age Criteria
DAM	Design Analysis Model
DAS	data acquisition software
DBDSP	Delaware Basin Drilling Surveillance Program
DBE	Design Basis Earthquake
DBT	Design Basis Tornado
DCCA	Draft Compliance Certification Application
DDZ	Drilling Damage Zone
DEIS	Draft Environmental Impact Statement
DFR	driving force ratio
DNAG	Decade of North American Geology
DOE	U.S. Department of Energy

DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
DP	disturbed performance
DQO	Data Quality Objective
DR/CT	dry rod construction technology
DRXS	Data Review Expert System
DRZ	disturbed rock zone
DSCR	Draft Site Characterization Report
EA	engineered alternative
EACBS	Engineered Alternatives Cost/Benefit Study
EATF	Engineered Alternatives Task Force
EDTA	ethylenediaminetetracetate
EEG	Environmental Evaluation Group
EIS	Environmental Impact Statement
EM	emergency management
EMP	Environmental Monitoring Plan
EMPEIS	Environmental Management Programmatic Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
EPD	Engineered Products Department
EPs	events and processes
ER	environmental restoration
ERDA	U.S. Energy Research and Development Administration
ERMS	Electronic Record Management System
ES&H	Environment, Safety, and Health
ESHAP	Exhaust Shaft Hydraulic Assessment Program
ESPR	Engineered Systems Peer Review
ETC	Engineering Training Center
ETEC	Energy Technology Engineering Center
EXP	exponent
FB	FB Line, Savannah River Site
Fe	iron
FEIS	Final Environmental Impact Statement
FEPs	features, events, and processes
FGE	fissile gram equivalent
FLAC	Fast Lagrangian Analysis of Continua
FLPMA	Federal Land Policy and Management Act
FMT	Fracture-Matrix Transport (calculation)
FR	Federal Register
FRP	fiberglass-reinforced polyethylene
FSAR	Final Safety Analysis Report
FSEIS	Final Supplement Environmental Impact Statement
FSU	Florida State University
FWS	U.S. Fish and Wildlife Service
FxG	Fracture Expert Group
GCR	Geological Characterization Report
GE-VNC	General Electric Vallecitos Nuclear Center

GGTP	gas generation testing process
GTP	Generic Technical Position
GTSD	*Government Technical Services Division*
GWMP	groundwater monitoring plan
HANF	Hanford Site
Hanford-RL	Hanford Site - Richland Operations Office
Hanford-ORP	Hanford Site – Office of River Protection
also	
Hanford-RP	Hanford Site – Office of River Protection
HB	HB Line, Savannah River Site H-canyon
HC	historical and current human activities
HCN	historic, current, and near future human activities
HEPA	high-efficiency particulate air
HLW	high-level waste
HMHWA	New Mexico Hazardous Waste Act
HSG	headspace gas
HWFP	Hazardous Waste Facility Permit
IA	Internal Audit
IAEA	International Atomic Energy Agency
ICP/MS	inductively coupled plasma-mass spectrometry
ICV	inner containment vessel
IMC	International Mining Consultants
INEEL	Idaho National Engineering and Environmental Laboratory
INEL	Idaho National Engineering Laboratory
IRG	International Review Group
IRT	independent review team
ITC	International Technology Corporation
ITR	Independent Technical Review
K	potassium
KAPL-NFS	*Knolls Atomic Power Laboratory-Nuclear Fuel Services*
L/ILW	low- and intermediate-level waste
LANL	Los Alamos National Laboratory
LANL-CO	Los Alamos National Laboratory-Carlsbad
LBNL	Lawrence Berkeley National Laboratory
LCM	lost circulation material
LCS	laboratory-controlled sample
LHS	Latin hypercube sampling
LLD	lower limit of detection
LLNL	Lawrence Livermore National Laboratory
LMP	Land Management Plan
LQS	large quantity site
LWA	Land Withdrawal Act
LWB	Land Withdrawal Boundary
M&OC	Management and Operating Contractor
M&TE	measuring and test equipment
MB	marker bed

MCS	Mobile Characterization Systems
MDC	Minimal Detectable Concentration
MDL	minimum detection level
MgO	magnesium oxide
MIP	Monitoring Implementation Plan
MIT	Massachusetts Institute of Technology
MOA	Memorandum of Agreement
MOU	memorandum of understanding
MP	management procedure
MPCC	multipurpose crate counter
MPI	Mississippi Potash Inc.
MREs	Measures of Relative Effectiveness
MSD	matrix spike duplicate
MSGP	Multi-Sector General Permit
MSL	mean sea level
MSP	matrix spike
MTHM	metric tons heavy metal
MURR	University of Missouri Research Center
Na	sodium
NAGRA	National Cooperative for the Storage of Radioactive Waste
NAS	National Academy of Sciences
NBPR	Natural Barriers Peer Review
NDA	nondestructive assay
NDE	nondestructive examination
NEA	Nuclear Energy Agency
NEPA	National Environmental Policy Act
NHPA	National Historic Preservation Act
Ni	nickel
NIREX	UK Nuclear Industry Radioactive Waste Executive
NIST	National Institute of Standards and Technology
NMAC	New Mexico Administrative Code
NMBMMR	New Mexico Bureau of Mines and Mineral Resources
NMD	no-migration determination
NMDG&F	New Mexico Department of Game and Fish
NMED	New Mexico Environment Department
NMERI	New Mexico Engineering Research Institute
NMMA	nuclear material management area
NMOCD	New Mexico Oil Conservation Division
NON-PA SES	nonperformance assessment scientific and engineering software
NORM	naturally occurring radioactive material
Np	Neptunium
NP	nuclear waste management QA procedure
NPDES	National Pollutant Discharge Elimination System
NQA	nuclear quality assurance
NRC	Nuclear Regulatory Commission
NTP	National TRU Program

NTS	Nevada Test Site
NUTS	Nuclide Transport System
NWMP	Nuclear Waste Management Program
OCA	Office of Cultural Affairs
OECD	Organization for Economic Cooperation and Development
OJT	on-the-job training
ORC	Office of Regulatory Compliance
ORNL	Oak Ridge National Laboratory
OSR	Off-Site Source Recovery
OSW	Office of Solid Waste
PA	performance assessment
PA Non-SES	performance assessment nonscientific and engineering software
PA SES	performance assessment scientific and engineering software
PAN	Passive-Active Neutron
PAPRP	Performance Assessment Peer Review Panel
PART	Performance Assessment Review Team
PAVT	Performance Assessment Verification Test
Pb	lead
PCB	polychlorinated biphenyl
Pd	palladium
PDF	probability distribution function
PDP	Performance Demonstration Program
PE	protective equipment
PFP	Plutonium Finishing Plant
PGDP	Paducah Gaseous Diffusion Plant
PIC	Passive Institutional Controls
PMP	probable maximum precipitation
PRMP	Peer Review Management Plan
PTF	passive institutional controls task force
P-TGS	portable-tomographic gamma scanner
Pu	plutonium
PZ	piezometer
QA	quality assurance
QAI	Quality Assurance Instruction
QAO	quality assurance objective
QAP	Quality Assurance Procedure
QAPD	Quality Assurance Program Document (CAO)
QAPjP	Quality Assurance Project Plan
QAPP	Quality Assurance Program Plan
QC	quality control
QED	qualification of existing data
R&D	research and development
Ra	radium
RBP	Radiological Baseline Program
RCRA	Resource Conservation and Recovery Act
RFETS	Rocky Flats Environmental Technology Site

RH	Remote-Handled
ROR	rest of repository
RP	review panel
RPD	relative percent difference
RRF	risk-reduction factor
RSD	relative standard deviations
RSI	Institute for Regulatory Science
RTC	Response to Comments Document
RTR	real-time radiography
SA	Scientific Advisor
SAR	Safety Analysis Report
SARP	Safety Analysis Report for Packaging
SCMS	Software Configuration Management System
SDWA	Safe Drinking Water Act
SEIS	Supplemental Environmental Impact Statement
SGRS	SWEPP gamma-ray spectrometer
SGS	segmented gamma scanner
SHPO	State Historic Preservation Officer
SHS	salt-handling shaft
SKB	SKI & Swedish Nuclear Fuel and Waste Management Company
SKI	*Statens Kärnkraftinspektion*
SLB	standard large box
SMC	Salado Mass Concrete
SMP	Subsidence Monitoring Program
SNL	Sandia National Laboratories
SNM	special nuclear material
SO-C	regulatory consequence
SOP	standard operating procedure
SO-P	regulatory probability
SO-R	regulatory exclusions
SPDV	Site and Preliminary Design Validation
SPE	Society of Petroleum Engineers
SPRU	Separations Process Research Unit
SQS	small-quantity site
Sr	strontium
SRS	Savannah River Site
SVOC	semi-volatile organic compound
SWB	standard waste box
SWCF	Sandia WIPP Central Files
SWEPP	Stored Waste Examination Pilot Plant
SWTS	Standard Waste Treatment System
T	transmissivity
TB	Teledyne Brown Engineering
TBM	Technical Baseline Migration
TCP/IP	Transmission Control Protocol/Internet Protocol
TDD	Technology Development Description

TDEM	time-domain electromagnetic
TDOP	Ten Drum Overpack
TDS	total dissolved solids
Th	thorium
TMU	total measurement uncertainties
TOB	Technical Oversight Board
TP	Team Procedure
TRAMPAC	TRUPACT-II Authorized Methods for Payload Control
TRIPS	Transuranic Reporting, Inventory, and Processing System
TRU	transuranic
TRUPACT	Transuranic Package Transporter
TSG	Technical Support Group
TSMT	Tri-State Motor Transit
TSP	total suspended particulate
TSR	technical safety requirements
TWBID	Transuranic Waste Baseline Inventory Database
TWBIR	Transuranic Waste Baseline Inventory Report
TWCP	TRU Waste Characterization Project
TZ	transition zone
UCL	upper confidence limit
UNM	University of New Mexico
UP	undisturbed performance
USAMC	U.S. Army Material Command
USDW	underground source of drinking water
USGS	United States Geological Survey
UVP/ENRESA	Universidad del País Vasco/Enresa Nacional de Residuos Radicactivos S.A.
V&V	verification and validation
VCMP	VOC Confirmatory Monitoring Plan
VE	visual examination
VOC	volatile organic compound
VSP	Vertical Seismic Profiling
WAC	Waste Acceptance Criteria
WAGS	Waste Assay Gamma Ray Spectrometer
WAP	Waste Analysis Plan
WCPIP	Waste Characterization Program Implementation Plan
WCPR	Waste Characterization Peer Review
WCRR	Waste Characterization, Reduction, and Repackaging (facility)
WEMS	Waste and Environmental Management System
WERC	Waste-Management Education and Research Consortium
WFDR	Waste Form and Disposal Room
WG	weapons grade
WID	Westinghouse Waste Isolation Division
WIPP	Waste Isolation Pilot Plant
WLMP	Water Level Monitoring Plan
WMC	waste matrix code
WMP	waste material parameter

WP	WIPP procedure
WQSP	Water Quality Sampling Program
WRAC	Waste Removal After Closure
WSPF	Waste Stream Profile Form
WTS	Washington TRU Solutions
WUF	waste unit factor
WVDP	West Valley Demonstration Project
WWIS	WIPP Waste Information System

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EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP), located near Carlsbad, New Mexico, is a deep geologic repository for the disposal of transuranic (TRU) wastes generated by atomic energy defense activities. The WIPP Land Withdrawal Act (LWA) requires the Department of Energy (DOE) to submit to EPA documentation of WIPP's continuing compliance with the Agency's disposal regulations, 40 CFR Part 191, Subparts B and C, not later than five years after initial receipt of TRU waste for disposal at the repository, and every five years thereafter until the decommissioning of the facility is completed. The first five-year period ends on March 27, 2004. This Compliance Recertification Application (CRA) demonstrates WIPP's continuing compliance and requests that EPA recertify the repository.

Background

DOE estimates that approximately 115,000 m^3 of defense TRU wastes are stored at DOE sites across the country. Ongoing decommissioning and dismantlement work at these sites will generate more TRU wastes, as will continuing operations to maintain the nation's nuclear arsenal. Disposal of these wastes in the WIPP repository will ensure their isolation from the accessible environment for at least 10,000 years.

Waste disposal operations at the WIPP began on March 26, 1999, after the Environmental Protection Agency (EPA) certified WIPP's compliance with the disposal regulations. EPA's certification of WIPP in May 1998 followed submittal by DOE of the Compliance Certification Application (CCA) in October 1996. The first application demonstrated how the geological, hydrological, physical, chemical, and environmental characteristics of the site, along with engineered features of the facility, would comply with EPA's requirements for at least 10,000 years.

Content of the CRA

As required by 40 CFR Parts 191 and 194, this CRA addresses a wide range of topics. It incorporates portions of the CCA and provides updates in those areas where approved changes occurred. It also presents new data and associated analyses. In addition, it responds to specific requests from EPA for new or expanded information or analyses. Topics addressed in this CRA include (but are not limited to) the following:

- Natural and engineered features of the disposal system**,** including geology, geophysics, and hydrogeology of the repository and its environs, as well as the geochemistry of interactions between the disposal system and the wastes placed in it**;**

- Assessments of the disposal system's long-term performance**,** including the input parameters used in those assessments**;**

- Criteria for accepting waste at WIPP and the programs and activities that ensure adherence to those criteria**;**

- Information concerning the inventory of TRU waste emplaced in the repository, stored at DOE sites, and the waste DOE expects to generate at those sites in the future**;**

- Reassessments of WIPP-relevant features, events, and processes (FEPs) that are important to the repository's performance, in light of data acquired since WIPP's original certification**;**

- Individual and groundwater protection standards and DOE's analyses demonstrating that WIPP will meet or exceed those standards; and

- Assurance requirements**,** including active and passive institutional controls, monitoring and impact of natural resource extraction.

The CRA follows the format of the CCA, but is modified to include new information and to respond to the guidance given by EPA on the content of this first CRA. As approved by EPA, portions of the original CCA were modified for this application; other portions of the CCA are incorporated by reference. Should EPA approve of DOE's request for recertification of WIPP, the CRA would establish an updated compliance baseline for the repository.

Changes Since the CCA

This application incorporates information about, and assessments of, several changes proposed by DOE and approved by EPA (or requested by EPA itself) since the original certification. These changes involve many aspects of the repository and the systems and processes associated with it. The most important of these changes include:

- ***Inventory:*** DOE updated estimates used in the CCA describing the TRU waste the Department may dispose of at WIPP. In addition, DOE compiled information about the waste already emplaced at WIPP. The updated waste information is incorporated into performance assessments (PAs) conducted for and described in this CRA.

- ***Repository Configuration:*** DOE requested approval from EPA for a small change in the horizon at which the repository is mined to facilitate ground control and provide greater protection to workers underground.

- ***Panel Closure:*** In its original certification, EPA stipulated that panel closures should be constructed using a specific design (known as "Option D"). The performance of this design is modeled in the 2004 PA, rather than the generic panel closure design modeled in the 1996 PA.

- ***Disposal Operations:*** Considering the extensive creep closure of excavations in Panel 1, DOE requested approval from EPA to not use certain rooms for waste disposal.

- ***Engineered Barrier:*** DOE requested approval from EPA to eliminate emplacement of so-called magnesium oxide (MgO) "mini-sacks" among the stacks of waste containers in the repository, while retaining the bulk of the MgO in "supersacks" placed on top of stacks of waste containers.

- ***Waste Characterization:*** DOE requested approval from EPA for updates to the WIPP Waste Acceptance Criteria (WAC). EPA approved the updates with conditions, which DOE fulfilled.

- ***Performance Assessment:*** DOE modified its approach to assessing the long-term performance of the repository in a number of aspects.

  – To make the representation of the shafts and of the repository geometry more appropriate for modeling the repository's performance, and to explicitly include the Option D panel closure system, DOE modified 3 of the 24 conceptual models employed in PA: disposal system geometry, repository fluid flow, and disturbed rock zone. A peer review panel extensively examined these changes and found them to be reasonable and appropriate.

  – Responding to EPA's guidance that another conceptual model needed modification, DOE developed a new model to predict possible spall releases and submitted it to a peer review. That review judged the new model to be reasonable and appropriate.

  – DOE implemented a single PA parameter set for this CRA, rather than maintaining two – one used in the creation of the CCA and the other resulting from PA verification tests mandated by EPA as part of its evaluation of the CCA.

  – DOE updated PA computing hardware and key software components of the PA system, including operating systems and database software, to improve computational performance. These upgrades also prolong the capabilities of the PA computing environment.

Results

DOE requested and EPA approved the changes described above at various times since EPA's original certification of WIPP. This CRA assesses the combined effect of these changes on the compliance of the facility and demonstrates that the combined effect does not adversely impact performance or compliance.

The predicted releases from the repository remain well below the limits specified in 40 CFR Part 191, Subpart B. Similarly, compliance analyses performed on the undisturbed repository result in a single postulated release whose value is significantly smaller than even the very small release estimated by the same analyses in the CCA**.** Taken together, the CCA and the CRA compliance analyses demonstrate that WIPP complies with the individual and groundwater protection standards promulgated in 40 CFR Part 191, Subpart C. When considered with information in this CRA pertaining to other aspects of TRU waste characterization and disposal, the PA and compliance analysis results amply demonstrate WIPP's continued compliance with EPA's requirements.

Therefore, WIPP continues to comply with the governing laws and regulations for the disposal of transuranic waste and the repository should be recertified by EPA.

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1.0 INTRODUCTION

This Compliance Recertification Application (CRA) documents the U.S. Department of Energy's (DOE's) demonstration of the continuing compliance of the Waste Isolation Pilot Plant (WIPP) with the long-term disposal regulations in Title 40 of the Code of Federal Regulations (CFR) Part 191, Subparts B and C (U.S. Environmental Protection Agency [EPA], Volume 50 Federal Register (FR) 38084, Sept. 19, 1985, as amended at 50 FR 40003, Oct. 1, 1985. Redesignated at 58 FR 66414, Dec. 20, 1993). The information provided in this application has been developed in accordance with the criteria established by the EPA (40 CFR Part 194) (61 FR 5235, Feb. 9, 1996).

The DOE is responsible for the disposition of transuranic (TRU) waste generated in whole or in part by atomic energy defense activities. It is estimated that approximately 115,000 cubic meters of these wastes have been generated and are currently stored at government installations across the country. The U.S. Congress established criteria for the management and operation of the WIPP in 1992 by its passage of the WIPP Land Withdrawal Act (LWA [Public Law 102-579, 106 Stat. 4777, 1992; as amended by Public Law 104-201, 110 Stat. 2422, 1996]). The LWA required that, prior to opening the WIPP for the disposal of TRU waste, the EPA certify that the WIPP facility will comply with the final disposal regulations. The DOE submitted the Compliance Certification Application (CCA) in October 1996. This compliance application documented the suitability of the geological, hydrological, physical, chemical, and environmental characteristics of the WIPP site, located near Carlsbad, New Mexico, and demonstrated how these characteristics, along with engineered features of the facility, lead to a reasonable expectation that compliance will be maintained for the required 10,000-year regulatory period. The EPA reviewed the CCA, requested additional information and studies, and also performed independent analyses during its evaluation of compliance. Public input was solicited throughout this process. Information developed through the certification process is available for review by the public in EPA WIPP dockets A-93-02 and A-98-49. On May 18, 1998 (63 FR 27405), the EPA certified that the WIPP did comply with the final disposal regulations and criteria of 40 CFR Parts 191 and 194, and on March 26, 1999, disposal operations began.

Section 8(f) of the LWA requires that the DOE submit to the EPA and the State of New Mexico documentation of continued compliance with the final disposal regulations not later than five years after the initial receipt of waste for disposal at WIPP and every five years thereafter until the end of the decommissioning phase of the project. Based on the DOE submittal, the EPA must determine whether the WIPP facility continues to be in compliance with the final disposal regulations. This recertification application has been prepared by the DOE and submitted to the EPA in accordance with these provisions of the law.

This application builds upon material presented in the CCA. The CCA included a performance assessment (PA) to demonstrate that, under the stringent conditions dictated by the disposal standards and certification criteria, the WIPP will comply with quantitative release limits, individual exposure standards, and groundwater protection standards over the 10,000-year regulatory period. The performance assessment provided in this recertification application updates the original performance assessment for the CCA with new waste inventory information, with changes made to the WIPP facilities, and with experience gained during the first years of

repository operation. The CRA-2004 PA demonstrates that the WIPP continues to comply with all requirements mandated in 40 CFR Part 191 Subparts B and C. In addition, this application documents the measures that the DOE has taken, or is required to take, at the time of facility closure to provide further assurance that the quantitative limits will be met.

The criteria established for selection of a site for the safe disposal of TRU waste were developed to ensure that a disposal location had certain favorable characteristics that were thought to be desirable for long-term waste isolation. The WIPP site meets these criteria. For example, the site has favorable geological characteristics in that:

- the host rock formation behaves plastically and will therefore encapsulate buried waste;
- the effects of dissolution at the site are minimal and predictable;
- excavation of the repository is relatively easy;
- future resource development is predictable and minimal; and
- the repository host rock is relatively uncomplicated lithologically and structurally.

Hydrologically, the site exhibits:

- a host rock that contains little interstitial brine and is very impermeable (i.e., transmits the brine very poorly);
- a location where the effects of groundwater flow are minimal and predictable;
- an area where probable future groundwater use is low and where there are no permanent surface waters; and
- a repository host rock that will not likely be affected by potential long-term climate changes within 10,000 years.

Finally, the WIPP site:

- maximized the use of federal lands while avoiding existing drill holes and minimizing the impacts on potash deposits;
- avoided endangered species and critical habitats; and
- is in a seismically stable area.

All of these favorable factors contribute to the WIPP's ability to comply with the long-term disposal regulations and more than compensate for less favorable features such as nearby hydrocarbon production and potash mining.

The information presented in the CCA and this recertification application is the culmination of over 25 years of scientific work specifically dedicated to evaluating TRU waste isolation in the

WIPP repository. Throughout this process, the DOE and its predecessor agencies have ensured that qualified individuals were available to address the technical questions surrounding the long-term performance of the disposal system. These experts have included members of federal and state government agencies, several national laboratories, academia, and industry. In addition, the DOE has ongoing technical oversight of the project by the National Academy of Sciences (NAS), the Environmental Evaluation Group (EEG), and the New Mexico Governor's Consultation Task Force on Radioactive Waste. Frequent consultation with these organizations has served to identify and resolve important issues in a timely manner. In addition, the DOE has involved the public in the decision-making process throughout the compliance demonstration process. Finally, the DOE has maintained a documented Quality Assurance program to ensure that objective evidence exists to support the quality of the work that has been performed.

The remainder of this chapter provides an overview of the recertification application, including a summary of the 1998 EPA certification decision conditions and the regulatory basis for the application, a discussion of the WIPP mission, a summary of the site selection process, a summary of the approach taken in this recertification application to demonstrate continued compliance with the performance standards, a summary of major changes since the CCA, and a brief description of the contents of the remaining chapters.

1.1 EPA Certification Decision Conditions

The EPA certified that the WIPP complied with the final disposal regulations and criteria of 40 CFR Parts 191 and 194 on May 18, 1998 (63 FR 27405). The certification of compliance was made subject to the following conditions:

> Condition 1: § 194.14(b), Disposal system design, panel closure system. The Department shall implement the panel seal design designated as Option D in Docket A-93-02, Item II-G-1 (October 29, 1996, Compliance Certification Application submitted to the Agency). The Option D design shall be implemented as described in Appendix PCS of Docket A-93-02, Item II-G-1, with the exception that the Department shall use Salado mass concrete (consistent with that proposed for the shaft seal system, and as described in Appendix SEAL of Docket A-93-02, Item II-G-1) instead of fresh water concrete.
>
> Condition 2: § 194.22: Quality Assurance. The Secretary shall not allow any waste generator site other than the Los Alamos National Laboratory to ship waste for disposal at the WIPP until the Agency determines that the site has established and executed a quality assurance program, in accordance with §§ 194.22(a)(2)(i), 194.24(c)(3) and 194.24(c)(5) for waste characterization activities and assumptions. The Agency will determine compliance of site-specific quality assurance programs at waste generator sites using the process set forth in § 194.8.
>
> Condition 3: § 194.24: Waste Characterization. The Secretary may allow shipment for disposal at the WIPP of legacy debris waste at the Los Alamos National Laboratory ("LANL") that can be characterized using the systems and processes inspected by the Agency and documented in Docket A-93-02, Item II-I-70. The Secretary shall not allow shipment of any waste from any additional LANL waste stream(s) or from any waste generator site other than LANL for disposal at the WIPP until the Agency has approved the processes for characterizing those waste streams for shipment using the process set forth in § 194.8.
>
> Condition 4: § 194.43, Passive institutional controls.

(a) Not later than the final recertification application submitted prior to closure of the disposal system, the Department shall provide, to the Administrator or the Administrator's authorized representative:

(1) a schedule for implementing passive institutional controls that has been revised to show that markers will be fabricated and emplaced, and other measures will be implemented, as soon as possible following closure of the WIPP. Such schedule should describe how testing of any aspect of the conceptual design will be completed prior to or soon after closure, and what changes to the design of passive institutional controls may be expected to result from such testing.

(2) documentation showing that the granite pieces for the proposed monuments and information rooms described in Docket A-93-02, Item II-G-1, and supplementary information may be: quarried (cut and removed from the ground) without cracking due to tensile stresses from handling or isostatic rebound; engraved on the scale required by the design; transported to the site, given the weight and dimensions of the granite pieces and the capacity of existing rail cars and rail lines; loaded, unloaded, and erected without cracking based on the capacity of available equipment; and successfully joined.

(3) documentation showing that archives and record centers will accept the documents identified and will maintain them in the manner identified in Docket A-93-02, Item II-G-1.

(4) documentation showing that proposed recipients of WIPP information other than archives and record centers will accept the information and make use of it in the manner indicated by the Department in Docket A-93-02, Item II-G-1 and supplementary information.

(b) Upon receipt of the information required under paragraph (a) of this condition, the Agency will place such documentation in the public dockets identified in § 194.67. The Agency will determine if a modification to the compliance certification in effect is necessary. Any such modification will be conducted in accordance with the requirements at §§ 194.65 and 194.66.

The DOE has proposed a modification to Condition 1 and a new panel closure design which is equally protective but simpler to construct; however, the EPA has stated that it will not consider the proposal until after WIPP recertification. In the interim, waste emplacement in Panel 1 has been completed, and the Option D explosion wall has been constructed in each of the access-ways to the panel. The EPA has agreed that construction of the remainder of the panel closure system in Panel 1 can be delayed until a decision has been made regarding the proposed new design. As discussed in Chapter 6.0, the PA representation of the repository has been modified to represent the Option D panel closure.

All sites planning to ship TRU waste to WIPP are required to comply with Conditions 2 and 3. Prior to shipment of waste, the EPA, using the process set forth in 40 CFR § 194.8, must determine that the site has established and executed a quality assurance program, in accordance with 40 CFR §§ 194.22(a)(1), 194.22(a)(2)(i), 194.24(c)(3) and 194.24(c)(5) for waste characterization activities and assumptions. The EPA must also approve the processes for characterizing those waste streams for shipment. During the period covered by this recertification application, the EPA has conducted numerous audits or inspections of DOE audits to ensure the quality and efficacy of waste characterization programs prior to a site gaining approval to ship a particular waste stream to WIPP. Further details are provided in Chapter 4.0 and in Appendix TRU WASTE of this application.

The DOE has initiated activities as part of the Passive Institutional Controls (PICs) program to ensure that the permanent markers, archiving, and awareness triggers can be fully implemented and submitted to the EPA for final approval. As mandated by Condition 4, the DOE will provide the required information no later than the final recertification application (prior to closure). Chapter 7.0 provides more information on the PICs program and activities.

1.2 Applicable Regulations

The regulatory framework for demonstrating the continued compliance of the WIPP with the disposal standards is primarily provided in 40 CFR Part 191, Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, and in 40 CFR Part 194, Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations; Final Rule.

In addition to the applicable regulations cited above, the EPA has provided guidance in the implementation of 40 CFR 191 and 40 CFR 194; i.e., the Compliance Application Guidance for 40 CFR Part 194 and in the Guidance to the U.S. Department of Energy on Preparation for Recertification of the Waste Isolation Pilot Plant with 40 CFR Parts 191 and 194.

1.2.1 40 CFR Part 191

The EPA is responsible for developing environmental standards for the protection of the public and the environment from radioactivity. The statutory authority cited by EPA for establishing and implementing the regulatory standards applicable to the operation, closure, and long-term performance of the WIPP facility are found in the LWA Atomic Energy Act of 1954, and the Reorganization Plan Number 3 of 1970. The regulations affecting the radioactive waste disposal operations at the WIPP are found in 40 CFR Part 191.

Since the mid-1970s, the EPA has been developing guidance and standards for the management and disposal of radioactive waste. The EPA's final rule, 40 CFR Part 191, was published on September 19, 1985. This standard was vacated and remanded to the EPA by a Federal Court of Appeals in 1987. The LWA of 1992 reinstated the 1985 disposal standard Subpart B of 40 CFR 191 except for the three aspects of 40 CFR § 191.15 and 40 CFR § 191.16 that were specifically questioned by the court. On December 20, 1993, the EPA promulgated effective January 19, 1994, final disposal standards.

Title 40 CFR Part 191 contains three subparts. Subpart A addresses radiation doses during the operational phase (i.e., management and storage) of WIPP. Subparts B and C establish long-term (apply to a 10,000-year period) standards for the disposal of radioactive waste. Specifically, Title 40 CFR Part 191 Subparts B and C establish standards and measures of performance for the following aspects of a disposal system:

- isolation of radionuclides sufficient to meet the containment requirements of the disposal system.

- protection of individuals from radiation exposures for a period of 10,000 years, and

- protection of groundwater from radioactive contamination for 10,000 years.

To demonstrate that a disposal system will comply with 40 CFR Part 191, the DOE must show a reasonable expectation that each performance measure will be satisfied.

In addition to numeric requirements, the qualitative assurance standards set out in 40 CFR § 191.14 were promulgated in order to provide the confidence needed for long-term compliance with the containment requirements in 40 CFR § 191.13. They include (1) active and passive institutional controls to preclude or mitigate the potential for human disturbance of the repository for an extended period of time, (2) the concept of multiple (natural and engineered) barriers, and (3) other measures taken to enhance confidence in the disposal system performance.

The DOE demonstrated that the WIPP complies with the disposal standards in 40 CFR Part 191 in the original 1996 certification process. As required by the LWA, this application documents that the WIPP continues to comply with the disposal standards of 40 CFR Part 191 Subparts B and C. A regulatory cross reference of compliance for each of the requirements in 40 CFR Part 191 Subparts B and C is provided at the end of this chapter in Table 1-1. The final mean complementary cumulative distribution function (CCDF), which is the measure of compliance for containment, is shown in Figure 1-1. Based on this CCDF, the DOE has a reasonable expectation that the disposal system will perform in compliance with the containment requirements of 40 CFR Part 191.

1.2.2 40 CFR Part 194

The EPA was mandated by the LWA to issue criteria for evaluating the DOE's compliance demonstrations. The EPA met this requirement on February 9, 1996, with the publication of 40 CFR Part 194. In the summary of the rule, the EPA states that

> The Environmental Protection Agency (EPA) is promulgating criteria for determining if the Waste Isolation Pilot Plant (WIPP) will comply with EPA's environmental radiation protection standards for the disposal of radioactive waste. If the Administrator of EPA determines that the WIPP will comply with the standards for disposal, then the Administrator will issue to the Secretary of Energy a certification of compliance which will allow the emplacement of transuranic waste in the WIPP to begin, provided that all other statutory requirements have been met. If a certification is issued, EPA will also use this final rule to determine if the WIPP has remained in compliance with EPA's environmental radiation protection standards, once every five years after the initial receipt of waste for disposal at the WIPP. (61 FR 5224)

In its preamble to the rule, the EPA stated that "[w]ith today's rulemaking, the Agency establishes criteria by which to judge whether the WIPP is in compliance with the 'disposal regulations' and sets forth procedural requirements for this determination." To this end, the rule contains four subparts.

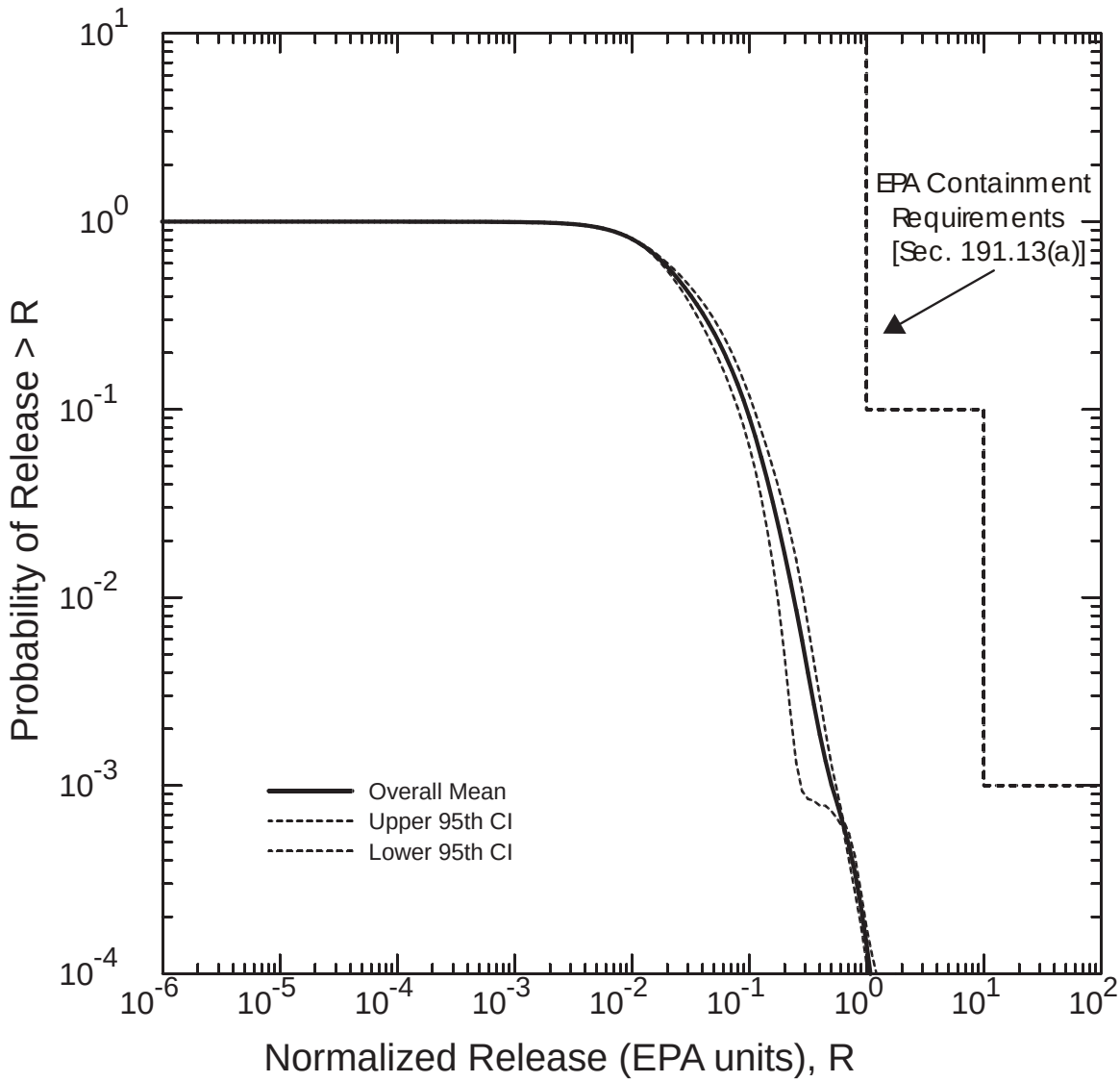

Figure 1-1. Final WIPP CCDF

- Subpart A establishes provisions related to the structure of the 40 CFR Part 194, including purpose, scope and applicability; definitions; substitution of alternative provisions for those promulgated in the final rule; and procedures that shall be followed in communications and written reports submitted by the DOE to EPA.

- Subpart B sets forth requirements for the submission format and content of compliance applications.

- Subpart C establishes the requirements that apply to the performance assessments and compliance assessments that will be used to demonstrate compliance with the requirements of the disposal regulations.

- Subpart D establishes procedures that the EPA will use to involve the public in the decisions on certification and recertification and requires the EPA to publish notices of its actions in the Federal Register.

In its certification decision for the WIPP (63 FR 27654), the EPA acknowledged that the DOE met all of the criteria established by the EPA in 40 CFR Part 194. The documentation for demonstrating continued compliance, as defined in the criteria in 40 CFR Part 194, is contained in this application. A crosswalk relating the criteria to the various sections of the application is provided in Table 1-1.

Criteria specific to the development of a recertification application are included in 40 CFR 194.15, which states:

> §194.15 Content of Compliance Re-Certification Application(s).
>
> (a) In submitting documentation of continued compliance pursuant to section 8(f) of the WIPP LWA, the previous compliance application shall be updated to provide sufficient information for the Administrator to determine whether or not the WIPP continues to be in compliance with the disposal regulations. Updated documentation shall include:
>
> (1) All additional geologic, geophysical, geochemical, hydrologic, and meteorologic information;
>
> (2) All additional monitoring data, analyses and results;
>
> (3) All additional analyses and results of laboratory experiments conducted by the Department or its contractors as part of the WIPP program;
>
> (4) An identification of any activities or assumptions that deviate from the most recent compliance application;
>
> (5) A description of all waste emplaced in the disposal system since the most recent compliance certification or re-certification application. Such description shall consist of a description of the waste characteristics and waste components identified in §194.24(b)(1) and §194.24(b)(2);
>
> (6) Any significant information not previously included in a compliance certification or re-certification application related to whether the disposal system continues to be in compliance with the disposal regulations; and
>
> (7) Any additional information requested by the Administrator or the Administrator's authorized representative.
>
> (b) To the extent that information required for a re-certification of compliance remains valid and has been submitted in previous certification or re-certification application(s), such information need not be duplicated in subsequent applications; such information may be summarized and referenced.

This recertification application contains the required information, and the WIPP continues to comply with the provisions of 40 CFR Parts 191 and 194.

1.2.3 Compliance Application Guidance for 40 CFR Part 194

Following the issuance of 40 CFR Part 194, the EPA issued guidance for implementation entitled "Compliance Application Guidance for 40 CFR Part 194" (EPA 1996b). The Compliance Application Guidance (CAG) is a companion to 40 CFR 194 and summarizes and explains EPA's expectations of the format and content of compliance certification applications based on a section-by-section discussion of the requirements of 40 CFR 194 and how they can be met.

1.2.4 Guidance to the U.S. Department of Energy on Preparation for Recertification of the Waste Isolation Pilot Plant with 40 CFR Parts 191 and 194

After its certification decision, and in anticipation of the initial recertification application, the EPA issued additional guidance specific to the recertification process entitled "Guidance to the U.S. Department of Energy on Preparation for Recertification of the Waste Isolation Pilot Plant with 40 CFR Parts 191 and 194" (EPA 2000). In this document, the EPA provided specific guidance to the DOE for the preparation and submission of a CRA. The guidance provides suggestions regarding the content and format of the CRA document and discusses the time frames and evaluation process that EPA will utilize to review this application. The purpose of this guidance is to assist DOE with the preparation of recertification applications, first by identifying the regulatory requirements pertinent to recertification and second by describing EPA's own approach to planning for recertification.

1.3 Project Background

The DOE began the development of the WIPP facility by selecting a site. Several alternative sites were evaluated, and the present site was selected as the best alternative based on a considerable amount of existing geotechnical information that was confirmed by extensive research and testing. Subsequent research and review have increased the understanding of the geologic, hydrologic, geochemical, and mechanical properties of the host rock and surrounding strata of the site. A Final Environmental Impact Statement (FEIS) (DOE 1980), which evaluated alternatives for the safe, long-term isolation of TRU waste, was completed by DOE in 1980. In its Record of Decision for the FEIS, the DOE concluded that the phased development of the WIPP facility was appropriate (DOE 1981).

The site preliminary design and validation phase followed the selection of the repository location. During this validation, the DOE constructed two shafts, excavated an underground testing area, and investigated various geologic, hydrologic, and other geotechnical features, further increasing understanding of the site's characteristics. In addition, the DOE evaluated methods for assessing the long-term performance of the WIPP facility. A series of geologic and hydrologic studies were conducted in accordance with an agreement between the DOE and the state of New Mexico.

The construction of the WIPP facility followed the site preliminary design and validation phase. Surface structures for receiving waste were built and underground excavations were mined, including one panel for waste emplacement and numerous areas for in-situ experiments. The data collected from these experiments and investigations were used to evaluate the potential short-term and long-term impacts of the WIPP facility.

The WIPP facility began waste disposal operations in 1999. During the disposal operations, which the DOE assumes for the purposes of this application to last 25 years, the DOE will receive, handle, and emplace TRU and TRU mixed waste in the repository.

Decommissioning of the WIPP facility will follow the operational period. At that time, the repository will be prepared for permanent closure, i.e., surface facilities will be decontaminated and decommissioned, underground excavations will be closed, and shaft seals will be emplaced. Decommissioning is expected to require about 10 years to complete.

Active and passive institutional controls will be implemented following the operating period. Active institutional controls include activities such as control of access to the site, maintenance, clean-up, and monitoring. Such controls will be implemented in a manner that is consistent with applicable regulations and requirements. Consistent with 40 CFR Part 191, 40 CFR Part 194, and the WIPP certification decision, only the first 100 years of active institutional controls have been included in the assessment of the disposal system's performance. Passive institutional controls include notification devices such as permanent markers and archives. These controls have been designed to reduce the likelihood of inadvertent human intrusion to the extent practicable, but no credit has been taken for these controls in the performance assessment for this recertification.

1.4 Site Selection Process

In 1957, the NAS National Research Council recognized salt as a medium well suited for radioactive waste disposal. Salt has favorable plastic (creep) properties, which allow significant deformation without fracturing. The existence of large salt deposits demonstrates isolation from circulating groundwaters for long periods of geologic time. Similarly, the depositional nature and preservation of large intact salt deposits demonstrate that the region has been stable for long periods of time.

The site selection process for the WIPP began in 1973 with a review of information on potential disposal media. This work focused on salt beds and salt domes. The preliminary selection criteria used in the initial stage of the process emphasized radiation and mine safety, hydrologic isolation, and ease of construction. In addition to salt lithological factors, the criteria specified the following conditions: 305 to 762 meters (1,000 to 2,500 feet) depth to salt, 61 meters (200 feet) minimum of salt thickness, lateral extent of salt sufficient to protect against dissolution, favorable tectonics (low historical seismicity and no salt-flow structures nearby), minimal groundwater, low resource potential, minimal number of existing boreholes, low population density, and maximum use of federal lands. The U.S. Geological Survey (USGS) and the Oak Ridge National Laboratory (ORNL) selected eastern New Mexico as the area with bedded salt that best satisfied the preliminary selection criteria.

During the second stage of the selection process, two of the three locations in this region were determined to be inadequate: the Clovis-Portales site because shallow salt formations had a significant clay content and the purer salt formations were too deep, and the Mescalero Plains area because of extensive oil field development. After shifting the potential site twice (in order to avoid borehole penetrations of the salt within 3.2 kilometers [2 miles] of the repository border), ORNL selected a site in the Delaware Basin for extensive characterization.

In the final stage of the process, eight areas in the Delaware Basin in Eddy and Lea counties were evaluated. Exploratory drilling at the first site recommended for characterization indicated unsuitable geology (see Chapter 2.0), and in 1975 the USGS and SNL reexamined the Delaware Basin for a more favorable location. This reexamination led to the selection of the Los Medaños site. Selection criteria considered at this stage of the process included:

1. the site should be at least 10 kilometers (6 miles) from the Capitan Limestone to avoid any possible deformation hazard related to the nearness of this reef structure;

2. to minimize potential conflicts with exploration of mineral resources, the central 10 square kilometers (4 square miles) of the repository itself should not be in the known Potash District, and as little as possible of the surrounding buffer zone should be in the district;

3. no part of the central area should be less than 1.6 kilometers (1 mile) away from holes drilled through the Castile Formation (hereafter referred to as the Castile) into underlying rocks in order to avoid dissolution by water flowing upward through an inadequately plugged borehole;

4. known oil and gas stratigraphic trends should be avoided;

5. the nearest dissolution front in the Salado Formation should be at least 1.6 kilometers (1 mile) from the site;

6. the bedding of geological strata should be as nearly flat as can be determined by surface geophysical investigations to ensure mine safety and ease of construction and to avoid the need for numerous exploratory holes that could pose a subsequent risk to the integrity of the repository;

7. salt of high purity should be available at depths between 305 and 914 meters (1,000 and 3,000 feet) to ensure mine safety and ease of construction. In addition, a salt thickness of 61 meters (200 feet) or more is preferred to confine thermal and mechanical effects to the salt; and

8. the use of state and private land should be minimized, especially in the central area, to simplify land acquisition and to avoid any relocation of residents.

The FEIS provided the basis for making the final decision regarding siting the WIPP facility at the Los Medaños site (the present WIPP location). This decision weighed the numerous advantages of the location and its suitability against potentially adverse environmental impacts. The WIPP site (Figure 1-2) was selected as the best of the alternatives. The specific horizon in the bedded salt was selected because of its desirable stratigraphic features. The stratigraphy is continuous throughout a large geographic area and major clay seams and interbeds of anhydrite or polyhalite are absent from the repository horizon. The facility has been constructed at a horizon such that operational and rock-support problems are minimized. Subsequent validation and construction activities have confirmed that the site's features are suitable for the long-term isolation of TRU waste. The DOE has concluded, based on the information in this application,

that these favorable features continue to offset any enhanced risk of human intrusion associated with extraction of resources in the vicinity.

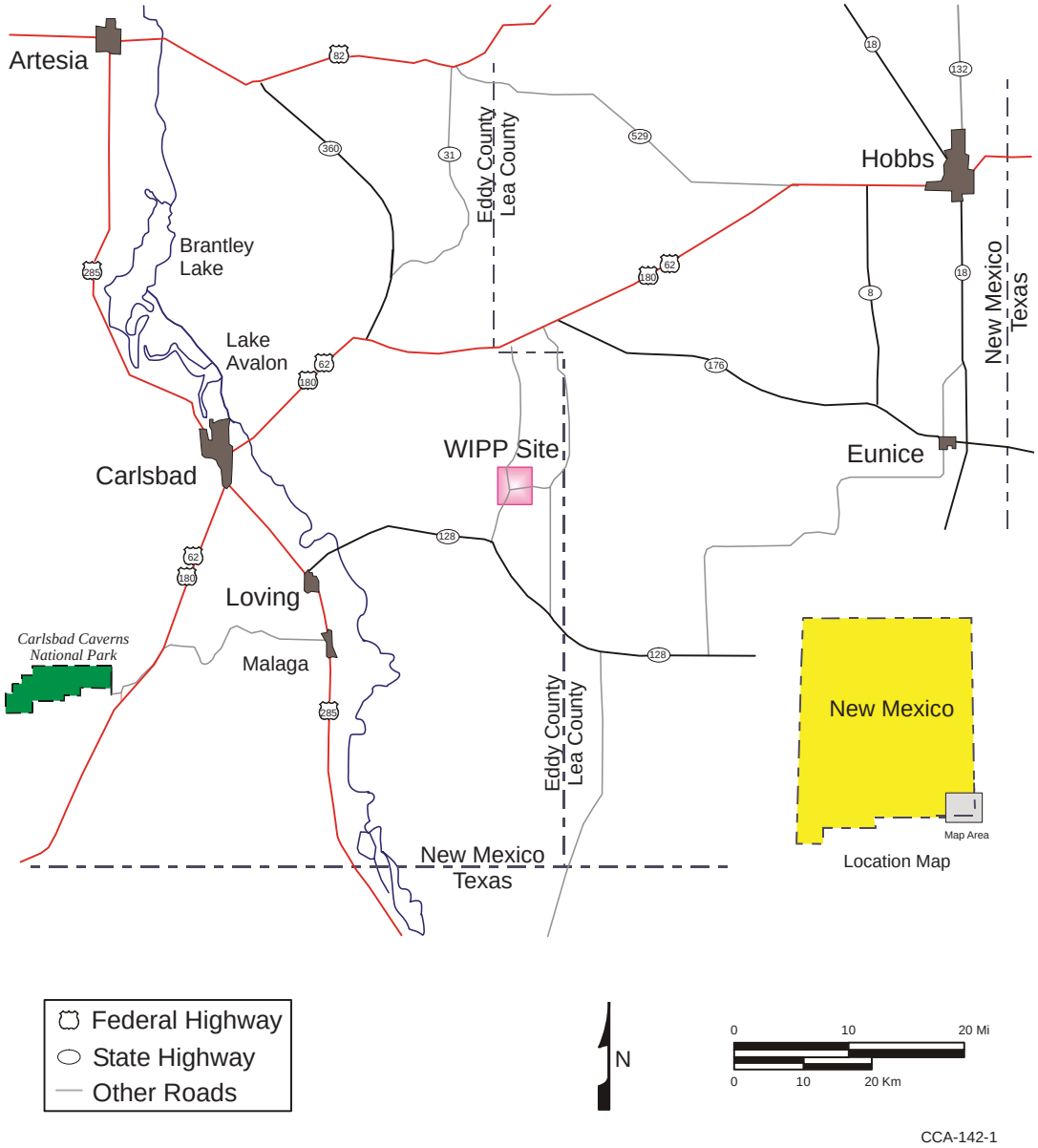

Figure 1-2. WIPP Location in Southeastern New Mexico

1.5 Program for Evaluating Long-Term Performance

When ORNL scientists recommended siting criteria for selecting a waste disposal location in salt, they had a general understanding of how a salt disposal system should perform, given the nature of the waste to be managed. Siting criteria emphasized stratigraphic factors to take full advantage of: creep properties of salt, purity to minimize the presence of complicating or unfavorable properties, isolation from aquifers to minimize impacts of circulating groundwaters, tectonic stability to ensure long-term isolation of waste, minimizing the presence of existing boreholes that could become conduits for release or dissolution, and minimizing resource activity

that could disrupt the disposal system. This understanding was, in a broad sense, a conceptual model that linked waste isolation to key features and processes that describe or affect the disposal system (ORNL 1973).

As site selection and site characterization proceeded, emphasis was placed on obtaining additional information on those features, events, and processes (FEPs) that define disposal system performance. For the CCA, about 240 FEPs that could operate on the WIPP disposal system were identified and addressed by the DOE (see CCA Appendix SCR). This information led to (1) the development of detailed conceptual models of various disposal system components such as salt creep, salt hydrology, groundwater hydrology, and waste degradation, as well as investigations to determine regional processes such as tectonism; and (2) scenarios of disposal system performance to be addressed by the modeling. The development of conceptual models required that several detailed laboratory and field experimental and investigation programs be conducted to answer questions about parameter values and uncertainty. Ultimately, the interaction between the various components of the disposal system was modeled to produce estimates of expected disposal system performance. CCA Appendix MASS contains a historical discussion of the evolutionary process that led to the conceptual model of the disposal system that is used in this application. This recertification application updates and refines that model. The FEPs baseline was assessed to evaluate the potential impacts that new information and operational changes had on the original screening decisions. The assessment concluded that no substantive changes to the FEPs baseline or conceptual models are necessary for this recertification application (see Appendix PA, Attachments SCR and MASS).

To evaluate the long-term performance of the disposal system, the DOE uses a technique developed especially for predicting the behavior of geologic repositories over the thousands of years required for waste isolation. This technique is performance assessment. Performance assessment is a multidisciplinary, iterative, analytical process that uses available information about the waste and the disposal system (the design of the repository, the repository seals, and the natural barriers provided by the host rock and the surrounding formations). Performance assessment is used to estimate the releases of radionuclides, based on the probabilities of relevant FEPs occurring, a knowledge of the system and the conceptual models developed to represent the system. Sensitivity analyses are used to determine which characteristics of the disposal system exert the greatest effect on performance. The results of sensitivity analyses are provided in this application in Appendix PA. The results of performance assessment are used in the 40 CFR Part 191 compliance program to assess disposal system behavior and possible environmental releases.

The WIPP performance assessment uses relevant information about the disposal system and the waste to simulate performance over the regulatory time periods. The WIPP PA process has been reviewed by the NAS and experts inside and outside of the United States. This process is schematically represented by the flow diagram in Figure 1-3, which shows how information describing the disposal system is used to develop scenarios, scenario probabilities, the consequence models used to estimate performance, and where these items are discussed in this application.

Uncertainty associated with the WIPP disposal system has been addressed through careful site, facility, and waste characterization. Remaining uncertainty is incorporated into the

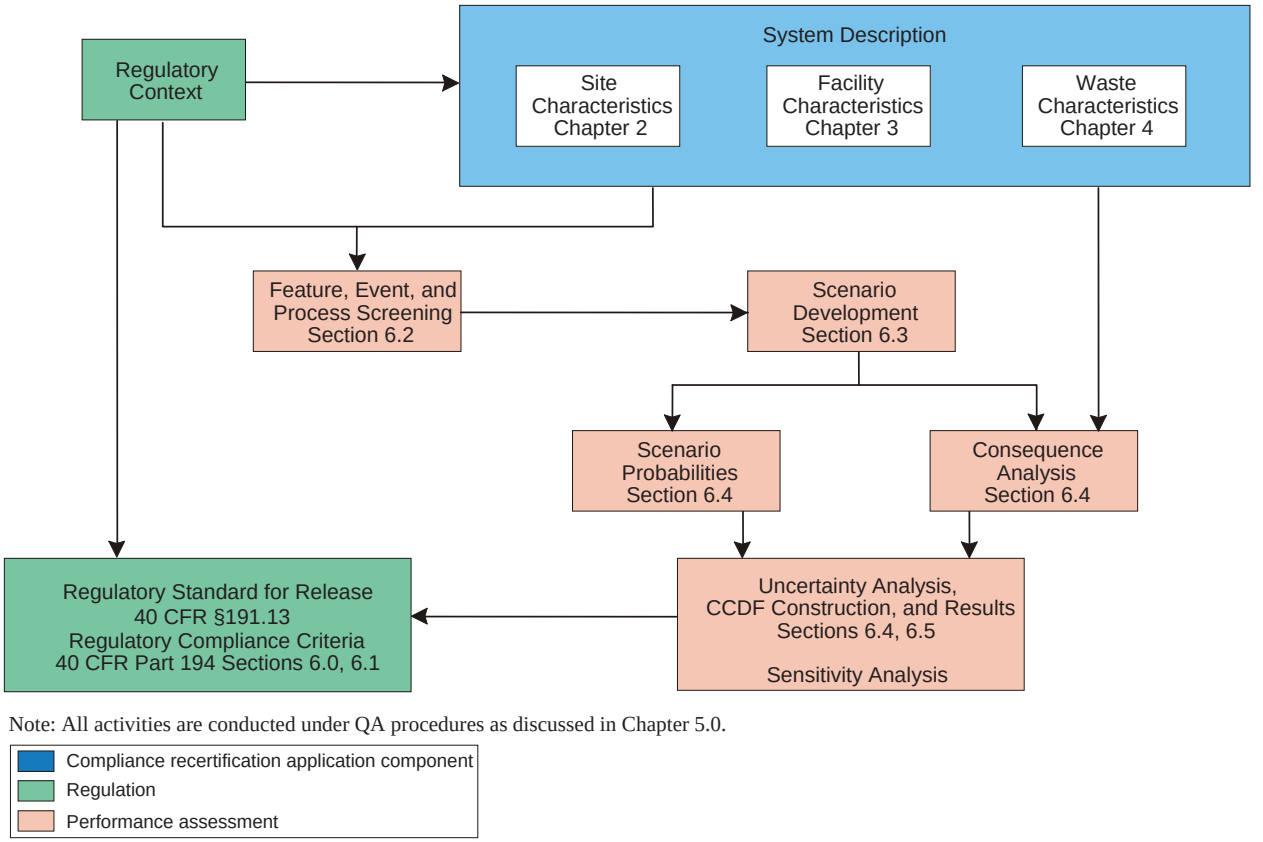

Figure 1-3. Methodology for Performance Assessment of the WIPP

performance assessment through the use of reasonable assumptions about models and parameter values. Uncertainty, and how it is handled in the analysis, plays a major role in the formulation of a performance assessment strategy. The EPA anticipates that uncertainty in long-term predictions will be inevitable and substantial (see 40 CFR § 191.13[b]). Because of this, the EPA applies a reasonableness test to the outcome of performance assessments. In other words, the EPA examines the information provided to determine if there is a reasonable expectation that compliance will be achieved.

This uncertainty is incorporated in the probabilistic nature of the complementary cumulative distribution function (CCDF). In this application, the mean CCDF, which is the measure of compliance for containment, displays the probability that radionuclide releases from the WIPP disposal system will exceed the regulatory requirements. In general, an attempt has not been made to include conservative assumptions that might bias the outcome of performance assessment. The mean CCDF represents a best estimate of the expected (and in the case of human intrusion, prescribed) performance of the disposal system. However, where realistic approaches to incorporating uncertainty are unavailable or impractical, and where the impact of the uncertainty on performance is small, the analysis has often been simplified by implementing

conservative assumptions.[1] The conservatism in the analysis is reviewed in Section 6.5.4 and discussed in Appendix PA, Attachment MASS, Table MASS-1. The review concludes that the conservatism does not significantly affect the location of the mean CCDF in Figure 1-1.

The format of this application is consistent with the process discussed in Section 6.1 and depicted in Figure 1-3. Basic input information is discussed in Chapters 2.0 through 5.0. Subsequent chapters use the input information to predict compliance as discussed in the following section.

1.6 Compliance Recertification Application Synopsis

This document contains the information necessary to demonstrate WIPP's continuing compliance with EPA requirements. Guidance provided by the EPA was used in preparing this application. All chapters and appendices provided in this application are described in Table 1-1 and are related to their CCA counterparts.

This application contains new information, and it references previously submitted information that is required for a recertification application. Where required information contained in the CCA remains valid, that information is referenced as provided by 40 CFR 194.15(b) and is not physically included in this recertification application. The information necessary to demonstrate compliance is included in a number of chapters, the contents of which are summarized below. Supporting, and more detailed, information is included in a series of appendices and attachments that are needed to make the application complete; therefore the appendices and attachments are integral parts of this application.

Chapter 2.0 describes the site and surrounding area as it existed prior to construction of the WIPP repository. Geological descriptions include both regional and local geology including structure, subsurface geology, geomorphology, geologic stability, soils, and topography. This chapter's purpose is to (1) explain the characteristics of the site, (2) describe background environmental quality, and (3) discuss features of the site that are important for inclusion in a quantitative performance assessment. The information in Chapter 2.0 has been used to develop and screen FEPs (see Appendix PA, Attachment SCR) to determine which ones are important to repository performance and to develop conceptual, mathematical, and computational models to evaluate the efficacy of the natural barriers in meeting the environmental performance standards (see Section 6.4). Numerical values have been derived for key parameters used to describe characteristics of the natural system. Information that supports these characteristics is discussed in Chapter 2.0; however, the specific parameter values used in the performance assessment are provided in Appendix PA, Attachment PAR.

Chapter 2.0 is supported by several appendices. These include basic site characterization reports, which were contained in the CCA (Appendices GCR, HYDRO, SUM, DEF, CLI, RBP, SER, and FAC). These appendices are included by reference in this recertification application and are summarized in Table 1-1. Other appendices, including Appendix PA (Attachments SCR, MASS

[1] Conservative assumptions are defined in this document as assumptions that result in the overestimation, rather than the underestimation, of any phenomenon that could contribute to the release of radionuclides from the disposal system.

and TFIELD) and Appendix DATA, were prepared specifically for this application and are also discussed in Table 1-1.

Chapter 3.0 provides technical information about those engineered systems at the WIPP that are important in meeting the disposal standards of 40 CFR Part 191. Descriptions relevant to long-term containment are provided for underground waste disposal and support facilities, and engineered barriers. In addition, details are provided for systems that significantly impede the movement of radionuclides to the accessible environment. These systems include shaft and borehole seals, panel closures, and an engineered barrier. Chapter 3.0 is supported by CCA Appendices SEAL, PCS, DVR, and EBS, that are included in the CRA by reference, and by Appendices PA (Attachment SCR), BARRIERS and QAPD, that are included with this recertification application.

Chapter 4.0 describes the wastes to be managed and disposed of at the WIPP facility. The waste description includes the definition, sources, types, components, and characteristics of TRU waste planned for emplacement in the repository. Those physical, chemical, and radiological characteristics of the waste that may singly or in combination affect the ability of the WIPP disposal system to meet the environmental performance standards in 40 CFR Part 191 are identified. An analysis of the waste inventory has been performed to determine those components of the waste that are important to the performance of the disposal system. This analysis is described in Appendix PA, Attachment SOTERM, and Appendix TRU WASTE and is supported by CCA Appendix WCA (included by reference). Inventory estimates of waste components are used as input into the PA to determine acceptable ranges for those components. Ranges determined acceptable based on the waste parameter values used in the CRA-2004 PA are imposed as limits through the waste acceptance process. Inventory estimates of TRU waste and specific information regarding the waste already emplaced in the repository are provided in Appendix DATA.

Chapter 5.0 describes the WIPP QA program. The certification criteria in 40 CFR Part 194 emphasize QA because a strong QA program can provide significant confidence in measured data and in complex computational models. The chapter provides the information required by 40 CFR § 194.22 and confirms that the DOE has had a QA program that is consistent with the requirements of the American Society of Mechanical Engineers (ASME)-Nuclear Quality Assurance (NQA)-1 for many years at the WIPP facility. The Carlsbad Field Office (CBFO) QAPD also mandates, in addition to NQA-1, the ASME NQA-2a-1990 addenda to NQA-2-1989, Part 2.7, and ASME NQA-3-1989 requirements. All WIPP participants who perform work that affects quality are required to have QA programs that meet the requirements of the CBFO QAPD to ensure that the data used in the performance assessment and compliance assessments meet the EPA requirements. All QA records (including many technical documents) related to this application are available for inspection in records facilities in Carlsbad, Albuquerque, and at other WIPP participant sites. Chapter 5.0 is supported by Appendix AUD and Appendix QAPD.

Chapter 6.0 discusses compliance with the containment requirements of 40 CFR § 191.13. The chapter includes a description of the overall system performance assessment methodology used to evaluate the performance of the WIPP disposal system; a list of FEPs that might affect the disposal system performance, the screening methodology applied to that list, and the result of the screening process; a summary of the development of the scenarios used in the PA; details of the

conceptual and computational models used in the PA, the overall flow of information in the PA, and the construction of the performance measure for comparison to the disposal standards; and a discussion of the results and the reliability of the performance assessment.

Chapter 6.0 is supported by numerous appendices and attachments including Appendices PA, BARRIERS, and DATA, which describe or support major numerical codes used in the analysis. Performance assessment parameters are provided in Appendix PA, Attachment PAR. Modeling assumptions used in the construction of the conceptual models and the implementation of the mathematical models are presented in Appendix PA, Attachment MASS. Justification for the source term used in the analysis is discussed in Appendix PA, Attachment SOTERM. In addition, Appendix PA, Attachment SCR, and CCA Appendices SEAL, CLI, and DEL support Chapter 6.0.

Chapter 7.0 describes the implementation of each of the 40 CFR Part 191 assurance requirements. This chapter and associated appendices describe plans, programs and/or analyses for compliance with active institutional control, passive institutional control, multiple barrier, monitoring, resource disincentives, and waste removal requirements. Chapter 7.0 is supported with numerous appendices. Appendix MON describes the rationale for the monitoring program and addresses the criteria for an analysis of sensitive disposal system parameters. Other supporting appendices include CCA Appendices AIC, D&D, DMP, EBS, EMP, EPIC, GTMP, LMP, GWMP, PIC, SMP, VCMP and WRAC. Supporting information provided in this recertification application includes Appendices MON, BARRIERS, and DATA.

Chapter 8.0 describes the DOE's compliance with the individual and groundwater protection requirements in 40 CFR Part 191. Chapter 8.0 is supported by CCA Appendix USDW, which identifies underground sources of drinking water in the vicinity of the controlled area.

Chapter 9.0 summarizes the results of peer reviews relevant to this application. The certification criteria mandated that the DOE perform peer reviews of the conceptual models, the waste characteristics analysis, and the engineered barrier study. In addition, the DOE conducted other peer reviews. The peer reviews related to waste characterization, engineered barriers, and conceptual models are found in Appendix PEER of the CCA. Additional peer reviews, including reviews by oversight and scientific organizations, performed since the certification are also discussed in Chapter 9.0 of this recertification application. Complete reports of peer reviews and scientific/oversight reviews, and associated documents, are included in Appendix PEER-2004 of this application.

1.7 Summary of Changes Since the CCA

Several changes have occurred to the WIPP facility and its operations since the CCA was developed and submitted to the EPA. These changes involve many aspects of the repository and the associated systems and processes. Changes relevant to this application include:

- TRU waste inventory estimates have been updated and are provided in this application, in addition to information about waste already emplaced in WIPP. This updated waste inventory information has been incorporated into the WIPP performance assessment conducted for and described in this CRA.

- A small change in the excavated horizon (elevated 2.4 m) for part of the repository was made to facilitate ground control and enhance worker safety.

- Waste was not emplaced in the main portions of Rooms 4, 5 and 6 of Panel 1 because of the advanced age of Panel 1, and no RH-TRU wastes were emplaced in Panel 1.

- The practice of attaching magnesium oxide “mini-sacks” in the waste containers in the repository was discontinued in order to enhance worker safety and improve operational efficiency.

- Three of the 24 conceptual models employed in the original performance assessments of the repository were modified to better represent the panel closure system selected by the EPA in the original certification of WIPP. These changes were examined by a peer review panel and were found to be reasonable and appropriate.

- A new spallings model was developed and underwent peer review. The peer review panel judged the revised model to be reasonable and appropriate for use in performance assessment of the WIPP.

- A single PA parameter set was adopted from a combination of the performance assessment parameters used in the CCA and in the EPA performance assessment verification test.

- Computing hardware and key software were upgraded to optimize computational performance and avoid obsolescence of the performance assessment computing environment.

These changes were evaluated and approved by the EPA and are discussed in more detail in this recertification application.

Table 1-1. Description of CRA-2004 Content Compared to the CCA

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Site Characterization – Describes the site and surrounding area. Descriptions include both regional and local geology including structure, subsurface geology, geomorphology, geologic stability, soils, and topography.	Ch. 2	Ch. 2
Facility Description – Technical information on engineered systems important in meeting the radioactive waste disposal standards. Descriptions relevant to long-term containment provided for underground waste disposal system, supporting facilities, and engineered barriers are included.	Ch. 3	Ch. 3
Waste Description – Summary description of the TRU wastes to be managed and emplaced in the disposal system. The waste description includes sources, types, components, and characteristics of TRU waste. This chapter identifies the principal waste aspects that may be important to long-term behavior of the disposal system, as well as the methods used to characterize and track these during pre-closure period.	Ch. 4	Ch. 4
Quality Assurance – Describes the DOE, WIPP participant, and TRU waste site QA programs, their implementation and applicability to activities described in this application.	Ch. 5	Ch. 5
Containment Requirements – Describes the overall system performance assessment (PA) methodology used to evaluate the performance of the WIPP disposal system. Includes a list of considered features, events, and processes (FEPs), the screening methodology applied to that list, and the result of the screening process; a summary of the scenarios used in PA; descriptions of the conceptual and computational models, the overall flow of information, and the construction of the performance measure for comparison to the disposal standards; and the overall PA results along with a discussion of the reliability of those results.	Ch. 6	Ch. 6
Assurance Requirements – Describes the assurance measures required by the disposal standards, and the implementation, plans and/or investigations for ensuring that active institutional control, pre-closure and post-closure monitoring, passive institutional control, multiple barrier, resource disincentives, and waste removal requirements are satisfied.	Ch. 7	Ch. 7
Individual and Groundwater Protection Requirements – Describes the approach and compliance basis of meeting the individual and groundwater protection requirements in 40 CFR Part 191 Subpart C.	Ch. 8	Ch. 8
Peer Review – Summarizes the results of NUREG-1297 peer reviews, and other reviews relevant to this compliance application. Previous information from the CCA is also summarized in this chapter.	Ch. 9	Ch. 9

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Active Institutional Controls – This CCA appendix includes the DOE's plans for active institutional controls that will be used following facility closure. The appendix provides the rationale and details of the various measures that the DOE intends to implement for the 100-year period of active controls. Active institutional controls are summarized in Chapter 7.0.	AIC	No update of this appendix needed for this application.
Audits – Descriptions of the QA assessments (audits and surveillances) of WIPP participants and TRU waste sites. Information is provided to demonstrate compliance with the requirements of NQA-1, NQA-2, Part 2.7, and NQA-3. The AUD-2004 appendix is a supplement to the information provided in the CCA. Documentation in this application applies to audits and surveillances conducted between November 1998 and May 2003.	AUD	AUD-2004
Barriers, Engineered – Description of the use and effectiveness of magnesium oxide and the related long-term performance aspects of the disposal system.	BACK	BARRIERS
Barriers (Multiple) – Description of engineered and disposal system barriers. Compilation of the salient information tied to continued compliance, and to satisfy the certification criteria of 40 CFR § 194.44.	Information not applicable to CCA.	BARRIERS
Environmental Compliance (general) – Biennial report summarizing WIPP compliance with a wide range of environmental requirements. No longer part of the compliance certification basis.	BECR	This portion of CCA eliminated from this and future compliance recertification applications.
Boreholes – Technical descriptions of existing boreholes drilled in the WIPP vicinity. Numerous boreholes have been drilled around the WIPP site for characterization purposes and for monitoring. These include holes for geological, hydrological, potash and soil investigations. A compendium of these holes, along with summary physical and geological information is provided, along with reference tables for non-WIPP holes (such as oil wells) that have been used in both site and regional studies by various investigators.	BH	DATA, Attachment G
TRU Waste Inventory – Original reports (TWBIR 2 and 3) established the baseline of TRU waste inventory data. The updated inventory data is provided in Appendix DATA, Attachment F.	BIR	DATA, Attachment F
Brine and Gas Flow – The CCA provided a description of the purpose of BRAGFLO and "Users manual" describing the codes that calculate brine flow estimates. The description of the BRAGFLO code has been updated in Appendix PA, and the user manual and other software and hardware documentation are referenced.	BRAGFLO	PA

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
CCDF – Description of the program designed to construct complementary cumulative distribution functions (CCDFs) from Monte Carlo sampling of PA modeling output. CCDFGF is used to calculate and present statistical performance assessment results. CCDFGF scales BRAGFLO and SECOTP2D results to match radionuclide outputs calculated by NUTS and PANEL. Use of the program results in CCDF plots of the overall predicted performance of the disposal system by combining the calculated release data and simulating many different repository histories, generating random sequences of future events, and calculating the probabilities associated with those random sequences.	CCDFGF	PA
Climate (long-term) – Technical study that was performed to determine climate changes in the recent past as a means of anticipating further changes in the next 10,000 years. Climate variation is modeled as part of the PA system.	CLI	No update of this appendix needed for this application.
Codes Links – Describes the conceptual links between computer codes for PA, overviews of and backgrounds for the principal codes, and the principal code-linkage sequences that support the 1996 performance assessment. Updated information on the relationships between codes is described in Appendix PA.	CODELINK	PA
Cuttings – This computer code estimates the direct removal of radionuclides from the repository as the result of penetration by a borehole drilled into the disposal system at some time in the future. These mechanically based releases to the surface are modeled to occur at the time of drilling.	CUTTINGS	PA
Data – Extensive supporting numerical and descriptive information, including monitoring and TRU waste inventory data collected since the development of the CCA.	Information not applicable to CCA.	DATA
Decommissioning – Post-operational plan that describes the activities planned for the decontamination and decommissioning and closure phase.	D&D	No update of this appendix needed for this application.
Deformation – Description of conclusions from investigating the effect of salt dissolution and evaporite deformation. DOE conducted numerous investigations to resolve the issues surrounding deformation of the evaporites and dissolution of salt. This CCA appendix summarizes those investigations and the conclusions reached as the result. This information is referenced in Chapter 2.0.	DEF	No update of this appendix needed for this application.
Delaware Basin Study – Historical drilling evaluation and prediction of future drilling rates. This information includes a summary of historical and current drilling practices, current well-plugging practices, presents an inventory of deep and shallow wells, and proposes assumptions for the inadvertent human intrusion scenarios in the performance assessment. This information is considered in the performance assessment parameters and calculations.	DEL	MON-2004 and DATA

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Delaware Basin Drilling Surveillance Plan – Summary of the Delaware Basin drilling activity surveillance program. This program will focus on drilling activities whose changes over time may impact the disposal system. These may include drilling rates, drill diameters, and borehole plugging practices.	DMP	MON-2004 and DATA
Disposal System Design – Description of the analysis used to validate the design of the disposal system. This is a compliance certification basis document, and is not replicated in the CRA-2004.	DVR	No update of this appendix needed for this application.
Selection of Barriers – The DOE performed an evaluation of potential engineered barriers in accordance with the certification criteria. Both natural and engineered barriers were considered with a multitude of alternatives. This information supports the concept of multiple barriers in Chapter 7.0. The final report is part of the compliance basis documentation and is not reproduced in this application.	EBS	No update of this appendix needed for this application.
Environmental Monitoring – This plan describes the activities of the environmental monitoring performed at and around the WIPP site. Portions applicable to the general and assurance requirements are provided in this application.	EMP	MON-2004
Evaluation of Passive Institutional Controls – Analysis of the effectiveness of the Passive Institutional Controls.	EPIC	No update of this appendix needed for this application.
Deposition – The WIPP shafts provided the opportunity to study the sediments and evaporites at the WIPP site. This report provides in-depth interpretations of the geological evidence in the shafts and proposes depositional theories for the rocks of the site region. This report is referenced as part of the detailed lithological information in Chapter 2.0.	FAC	No update of this appendix needed for this application.
Geological Characterization – A compendium of the geological studies that characterized the WIPP site. This 1978 Geological Characterization Report was prepared by Sandia National Laboratories (SNL) as a summary of the investigations performed for the WIPP. It includes a summary of work performed in the area by numerous other scientists, as well as studies designated for selecting a radioactive waste disposal facility site. The basic geological features such as stratigraphy, lithology, geomorphology, physiography are established in this report. This information remains as part of the compliance certification basis, and is not replicated in this application.	GCR	No update of this appendix needed for this application.
Dose Estimate (undisturbed path) – The method of calculating dose from undisturbed release pathways was through utilization of a computer code. The CCA provided the user's manual describing the exposure/dose computer code in an appendix. The CRA-2004 describes a simplified method utilized to quantify the dose for this type of release.	GENII	PA
Geotechnical Monitoring Plan – Describes the program established to monitor the behavior of surface and subsurface strata, within and near the disposal system.	GTMP	MON-2004

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Groundwater Monitoring Plan – Describes the program established to monitors the groundwater behavior of the Culebra Formation.	GWMP	MON-2004
Geology and Hydrology – A comprehensive discussion of studies conducted by the U.S. Geological Service (USGS) and other organizations of the formations near the location of the WIPP disposal system.	HYDRO	No update of this appendix needed for this application.
Resource Disincentive – An evaluation of the potential resources surrounding the WIPP site.	IRD	No update of this appendix needed for this application.
Statistical Sampling – Intermediate results and description of a statistical analysis of time-dependent parameters.	IRES	PA
Land Management – Required by the Land Withdrawal Act, this plan details the land management practices implemented throughout the 16-square miles of the WIPP site boundary. This portion of the CCA has been eliminated from this and future compliance applications	LMP	This portion of CCA eliminated from this and future compliance recertification applications.
Modeling Assumptions – Description of the assumptions used in the PA modeling applicable to numerical, mathematical, computational, and conceptual models.	MASS	PA, Attachment MASS
Pre- and Post-Closure Monitoring Plan – Description of surveillance and monitoring programs that the DOE has implemented to demonstrate compliance with 40 CFR 194.42.	MON	MON-2004
Radionuclide Transport (in fractured media) – A summary and users' manual describing the code used to calculate radionuclide decay and transport through fractured media.	NUTS	PA
Radionuclide Transport (in brine) – Descriptive summary and users' manual describing the code used to calculate radionuclide decay and transport in a brine mixture.	PANEL	PA
Performance Assessment (Total System) – A comprehensive appendix and set of attachments that provide descriptions of the performance assessment basis, conceptual models, methodology, and related supporting information provided in attachments. This is the primary appendix supporting the information in Chapter 6.0.	Information not applicable to CCA.	PA
Parameters – Description and rationalization of the parameters selected and used in the performance assessment calculations.	PAR	PA, Attachment PAR
Panel Closure System – Reproduction of an engineering report that describes the systems of panel closures available to close individual waste panels. The CRA-2004 captures the applicable portions of the similar information in a new appendix.	PCS	BARRIERS
Peer Reviews – Reproduction of NUREG-1297 peer review reports, and related documents published by independent organizations. Each report captures evaluations of specific topics associated with WIPP compliance. Two NUREG-1297-compliant peer reviews were performed in support of this application.	PEER	PEER-2004

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Passive Institutional Controls – Documentation consisting of the conceptual designs and plans for awareness triggers, archiving, and permanent markers. This document has not been updated since the CCA, though the current status of this endeavor is summarized in Chapter 7.0.	PIC	No update of this appendix needed for this application.
Salado (Repository) Behavior – Creep closure of the excavation and the presence of either brine or gas in the waste disposal region both influence the time-dependent changes in void volume in the waste disposal region. In order to vary them in a computationally efficient manner, a porosity surface is generated. This surface is used by the BRAGFLO code to indirectly couple mechanical closure of the excavation and gas generation to the two-phase fluid flow calculations.	PORSURF	PA
Quality Assurance Program – The Quality Assurance Program Document (QAPD) defines the QA requirements that are applicable to WIPP and TRU waste site activities. The QAPD establishes the foundation for which all WIPP-related QA programs must adhere, and outlines the approach used to demonstrate compliance with 40 CFR, Section 194.22.	QAPD	QAPD
Radiological Baseline (background) – This CCA appendix was provided as reference information describing the effort to establish a WIPP radiological baseline, with the first five years of environmental radiological sampling (1985-1989). The background radiation data for air, soil, water, biota, and fauna were complied to establish the radiological baseline (described in Chapter 2.0). Future sampling data will be compared to the baseline.	RBP	No update of this appendix needed for this application.
Sensitivity Analysis – The 1996 application provided limited descriptions of the post-processing evaluation of modeling sensitivities and uncertainties within the system PA. Since then, extensive analyses have been performed for both the CCA PA and PA verification test. The discussion of the sensitivity analyses is provided in this application as part of the overall PA system description.	SA	PA
Features, Events, and Processes (FEPs) screening – A description of the basis for the modeling foundation and all inputs considered for scenario and model development. SCR documents the screening process and decisions. Those that are retained (not screened out) are included in the conceptual models of repository performance as described in Chapter 6.0.	SCR	PA, Attachment SCR
Shaft Seals – Description of the plan and design of the repository shaft seals expected to be used in the D&D and closure phase. The CCA provides the complete description of designs and plans, while the CRA-2004 summarizes this information.	SEAL	BARRIERS
Culebra Flow – The CCA described the use of users' manual describing the computer code that calculates the groundwater flow-field of the Culebra. For the CRA-2004, the mathematical and computation models are executed through use of MODFLOW-2000. Information on the implementation is provided in Appendix PA.	SECOFL2D	PA and PA, Attachment TFIELD

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Culebra Transport – The CCA provided a description and users' manual for the computer code used to estimate material transport within the Culebra. The CRA-2004 provides updated information within the PA appendix and related attachment TFIELD	SECOTP2D	PA and PA, Attachment TFIELD
Annual Environmental Report – Annual report that describes the results of the environmental monitoring for the reporting year. The CCA provided a copy of the 1995 report as an appendix. The applicable information for this application is captured in Chapter 2.0 and the appendices shown.	SER	MON-2004 and DATA
Subsidence Monitoring – Description of the subsidence surveillance program that DOE implements to gage the surface movement in response to the excavated portions of the disposal system. Subsidence predictions will be compared to actual measurements to investigate any potential deviations that may indicate a change in repository performance.	SMP	MON-2004
Actinide Source Term – Explanation of the actinide source term for the WIPP performance calculations. The source term is defined by the sum of dissolved actinide species and mobile colloidal actinide species. Estimates of the mobile concentration of actinides that may be released from the repository are provided.	SOTERM	PA, Attachment SOTERM
Site Characterization – Compilation of the findings related to site-specific testing and studies ranging over a period from 1977 to 1987. Following the final selection of the site in 1980 and a review by the NAS and the EEG, numerous additional studies were identified to resolve specific site-related issues. These investigations included regional studies, site studies, and underground tests. DOE prepared a summary of the findings and offered interpretations of geological relationships. These results were definitive in developing conceptual models for the WIPP disposal system.	SUM	No update of this appendix needed for this application.
Culebra Transmissivity – Hydrological transmissivity of the Culebra is highly variable. Numerous measurements have been made to characterize this parameter. These data have been processed geo-statistically to produce an array of transmissivity fields for use in the transport calculations that are part of the performance assessment. The process for generating these fields and the results themselves are included in this application.	TFIELD	PA, Attachment TFIELD
Underground Sources of Drinking Water – Evaluation of potential drinking water sources (groundwater) in the WIPP and surrounding area. This appendix includes a description of available groundwater information and concludes that there are three possible underground sources of drinking water near the WIPP-controlled area. Theses sources are within the Dewey Lake Formation, the Santa Rosa Formation, and the Culebra Member of the Rustler Formation. Updated information in Chapter 8.0 supplements this baseline appendix.	USDW	No update of this appendix needed for this application.

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Volatile Organic Compounds – In 1996, DOE included a plan that described the program established to monitor potential VOCs. This information is no longer part of the compliance certification basis, and will not be addressed in this or future applications.	VCMP	This portion of CCA eliminated from this and future compliance recertification applications.
Waste Characterization – Descriptions of sampling and analysis techniques, and reference to documentation that establishes the data quality objectives for characterization. This portion also summarizes the methodology for collecting and using acceptable knowledge in the characterization process.	WAP	TRU WASTE
Waste Characterization Analysis – Identification of TRU waste characteristics and components expected to be important to disposal system performance.	WCA	TRU WASTE
Waste Component Limits – Based on identification of key waste components, this portion describes the limits established for each. In calculating the performance of the disposal system, the DOE has set bounding values for each waste component. Within these values, the analyses are valid, and the WIPP can be reasonably expected to comply with the disposal standards.	WCL	TRU WASTE
Waste Removal – Plan that describes the future removal of the repository waste This appendix contains a feasibility study for the removal of most of the waste from the disposal system at some time in the future. Conventional mining techniques, coupled with remote-handled (RH) technology, are discussed to show that, even with current technology, such removal would be possible at any time after facility closure.	WRAC	No update of this appendix needed for this application.
Reference citations – Specific list of reference citations used in the CCA. This information has not been replicated for the CRA-2004.	XRE	No update of this appendix needed for this application.

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2.0 SITE CHARACTERIZATION

The U.S. Department of Energy (DOE) uses the performance assessment (PA) methodology described in Chapter 6.0 to demonstrate that the Waste Isolation Pilot Plant (WIPP) disposal system will meet the environmental performance standards of Title 40 of the Code of Federal Regulations (CFR) Part 191 Subparts B and C. In order to effectively use PA, three inputs are necessary: What can happen to the disposal system? What are the chances of it happening? What are the consequences if it happens? The answers to these questions are derived from many sources, including field studies, laboratory evaluations, experiments, and, in the case of some features not amenable to direct characterization, professional judgment. The information used in PA is described in terms of features of the disposal system that can be used to describe its isolation capability, events that can affect the disposal system, and processes that are reasonably expected to act on the disposal system.

The DOE selected the Los Medaños region and present site for the WIPP based on certain defined siting criteria. The site selection process, which was focused on sites that contained certain favorable features while other unfavorable features were excluded, was applied by the DOE with the intent of finding the area that best met the siting criteria. The siting process is discussed in CCA Appendix GCR. Chapters 3.0, 4.0, and 6.0 and several appendices provide additional information supporting this chapter.

Conceptual models of the WIPP disposal system simulate the interaction between the natural environment (described in this chapter), the engineered structures (described in Chapter 3.0) and the waste (described in Chapter 4.0). One starting point in developing conceptual models of the WIPP disposal system is an understanding of the natural characteristics of the site and of the region around the site. Site characterization and model development is an interactive process that the DOE has used for many years. Basic site information leads to initial models. Initial model sensitivity studies indicate the need for more detailed information. More site characterization then leads to improved models. In addition, an assessment of the impacts of uncertainty inherent in the parameters used to numerically simulate geological features and processes has also led the DOE to conduct more in-depth investigations of the natural system. These investigations generally proceeded until uncertainty was sufficiently reduced or to the point where no further information could be reasonably obtained.

The discussion of conceptual models and initial and boundary conditions is in Section 6.4 and Appendix PA, Attachment MASS. Conceptual models implement scenarios about the future. Scenario development is discussed in Section 6.3. Scenario development requires as inputs information about the natural features, events, and processes (FEPs) that can reasonably be expected to act on the disposal system. While the list of possible FEPs is derived independently of the disposal system, their screening (in Section 6.2 and Appendix PA, Attachment SCR) is based on an understanding of the geology, hydrology, and climatology of the region and the site in particular. The screening methodology follows U.S. Environmental Protection Agency (EPA) criteria on the Scope of Performance Assessments (40 CFR § 191.32). This basic understanding is provided in this chapter and its associated appendices.

Table 2-1 shows the tie between the list of natural FEPs that were identified and screened for the WIPP and the sections of this chapter or Appendix PA, Attachment SCR. Those FEPs that have

been retained for inclusion in the modeling are shown in bold in Table 2-1. These generally receive a greater level of detail in the following discussions and are supported by additional discussion in Chapter 6.0, Appendix PA, Attachments MASS and SCR. In addition, parameter values that have been derived for these FEPs are included in Appendix PA, Attachment PAR.

In this chapter, the DOE describes the WIPP site geology, hydrology, climatology, air quality, ecology, and cultural and natural resources. This chapter's purpose is to (1) explain characteristics of the site, (2) describe background environmental quality, and (3) discuss features of the site that might be important for inclusion in a quantitative PA. The DOE has used this information to develop and screen FEPs and to develop conceptual, mathematical, and computational models to evaluate the efficacy of natural and engineered barriers in meeting environmental performance standards (Chapter 6.0). Results of these predictive models are used by the DOE to demonstrate that the DOE has a reasonable expectation that compliance with applicable regulations will be achieved. This chapter has been prepared to describe the site prior to excavating the repository. Excavation of the repository and its associated effects, such as the disturbed rock zone (DRZ), are discussed in Chapter 3.0.

The DOE located the WIPP site 42 km (26 mi) east of Carlsbad, New Mexico, in Eddy County (Figure 2-1). Additional details related to the location of the WIPP site can be found in Section 2.1.4.2 and in Figure 3-1 (see Chapter 3.0). The latitude of the WIPP site center is 32°22' 11" N and the longitude is 103°47' 30" W. The region surrounding the WIPP site has been studied for many years, and exploration of both potash and hydrocarbon deposits has provided extensive knowledge of the geology of the region. Two exploratory holes were drilled by the federal government in 1974 at a location northeast of the present site; that location was abandoned in 1975 as a possible repository site after U.S. Energy Research and Development Administration (ERDA) 6 borehole was drilled and unacceptable structure and pressurized brine were encountered. The results of these investigations are reported in Powers et al. (1978, 2 – 6; included in CCA Appendix GCR). During late 1975 and early 1976, the ERDA identified the current site, and an initial exploratory hole (ERDA-9) was drilled. By the time an initial phase of site characterization was completed in August 1978, 47 holes had been or were being drilled for various hydrologic and geologic purposes. Geophysical techniques were applied to augment data collected from boreholes. Since 1978, the DOE has drilled additional holes to support hydrologic studies, geologic studies, and facility design. Geophysical logs, cores, basic data reports, geochemical sampling and testing, and hydrological testing and analyses are reported by the DOE and its scientific advisor, Sandia National Laboratories (SNL), in numerous public documents. Many of those documents form the basis for the DOE's positions in this application. As necessary, specific references from these documents are cited to reinforce statements being made.

Biological studies of the site began in 1975 to gather information for the Environmental Impact Statement (DOE 1980). Meteorological studies began in 1976, and economic studies were initiated in 1977. Baseline environmental data were initially reported in 1977 and are now updated annually by the DOE.

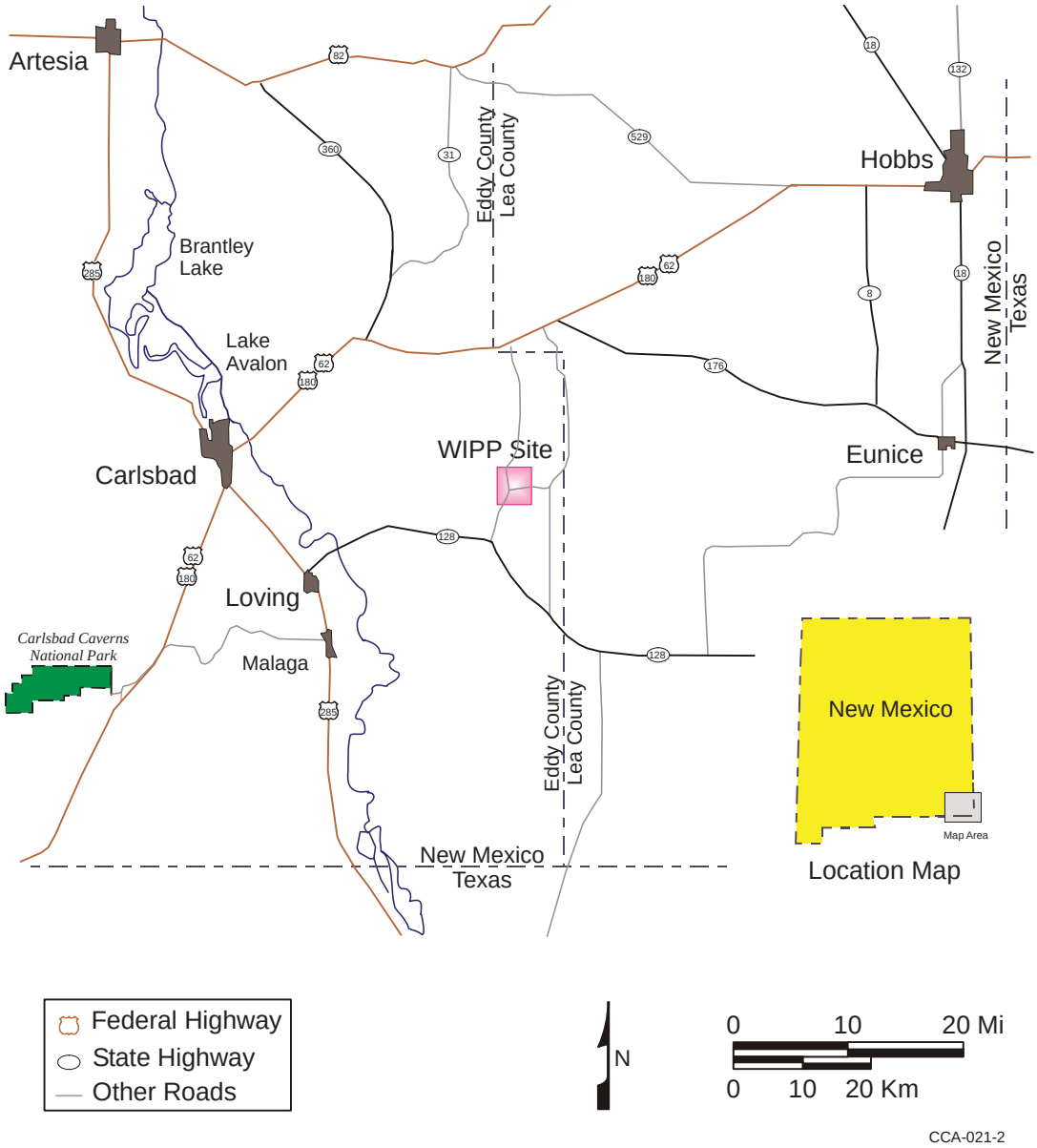

Figure 2-1. WIPP Site Location in Southeastern New Mexico

Table 2-1. Issues Related to the Natural Environment That Were Evaluated for the WIPP PA Scenario Screening

Features, Events, and Processes (FEPs)	EPA FEP No.	Discussion
NATURAL FEPs		
Stratigraphy		
Stratigraphy	N1	Section 2.1.3
Brine reservoirs	N2	Section 2.2.1.2.2
Tectonics		
Changes in regional stress	N3	Section 2.1.5.1
Regional tectonics	N4	Section 2.1.5.1
Regional uplift and subsidence	N5	Section 2.1.5.1
Structural FEPs		
Deformation		
Salt deformation	N6	Section 2.1.6.1
Diapirism	N7	Appendix PA, Attachment SCR
Fracture development		
Formation of fractures	N8	Section 2.1.5
Changes in fracture properties	N9	Section 2.1.5
Fault movement		
Formation of new faults	N10	Section 2.1.5
Fault movement	N11	Section 2.1.5.3
Seismic activity		
Seismic activity	N12	Section 2.6
Crustal processes		
Igneous activity		

Table 2-1. Issues Related to the Natural Environment That Were Evaluated for the WIPP PA Scenario Screening — Continued

Features, Events, and Processes (FEPs)	EPA FEP No.	Discussion
Volcanic activity	N13	Section 2.1.5.4
Magmatic activity	N14	Appendix PA, Attachment SCR
Metamorphic activity		
Metamorphism	N15	Appendix PA, Attachment SCR
Geochemical FEPs		
Dissolution		
Shallow dissolution	N16	Section 2.1.6.2
Lateral dissolution	N17	Section 2.1.6.2
Deep dissolution	N18	Section 2.1.6.2
Solution chimneys	N19	Section 2.1.6.2
Breccia pipes	N20	Section 2.1.6.2
Collapse breccias	N21	Section 2.1.6.2
Mineralization		
Fracture infills	N22	Section 2.1.3.5.2
SUBSURFACE HYDROLOGICAL FEPs		
Groundwater characteristics		
Saturated groundwater flow	N23	Section 2.2.1
Unsaturated groundwater flow	N24	Section 2.2.1
Fracture flow	N25	Section 2.2.1
Density effects on groundwater flow	N26	Section 2.2.1
Effects of preferential pathways	N27	Section 2.2.1
Changes in groundwater flow		
Thermal effects on groundwater flow	N28	Appendix PA, Attachment SCR
Saline water intrusion	N29	Appendix PA, Attachment SCR
Freshwater intrusion	N30	Appendix PA, Attachment SCR
Hydrological effects of seismic activity	N31	Appendix PA, Attachment SCR
Natural gas intrusion	N32	Appendix PA, Attachment SCR
SUBSURFACE GEOCHEMICAL FEPs		
Groundwater geochemistry		
Groundwater geochemistry	N33	Section 2.2.1.4.1.2
Changes in groundwater geochemistry		
Saline water intrusion	N34	Appendix PA, Attachment SCR
Freshwater intrusion	N35	Appendix PA, Attachment SCR
Changes in groundwater Eh	N36	Appendix PA, Attachment SCR
Changes in groundwater pH	N37	Appendix PA, Attachment SCR

Table 2-1. Issues Related to the Natural Environment That Were Evaluated for the WIPP PA Scenario Screening — Continued

Features, Events, and Processes (FEPs)	EPA FEP No.	Discussion
Effects of dissolution	N38	Appendix PA, Attachment SCR
GEOMORPHOLOGICAL FEPs		
Physiography		
Physiography	N39	Section 2.1.4
Meteorite impact		
Impact of a large meteorite	N40	Appendix PA, Attachment SCR
Denudation		
Weathering		
Mechanical weathering	N41	Appendix PA, Attachment SCR
Chemical weathering	N42	Appendix PA, Attachment SCR
Erosion		
Eolian erosion	N43	Section 2.1.3.10
Fluvial erosion	N44	Section 2.1.3.6
Mass wasting	N45	Appendix PA, Attachment SCR
Sedimentation		
Eolian deposition	N46	Appendix PA, Attachment SCR
Fluvial deposition	N47	Appendix PA, Attachment SCR
Lacustrine deposition	N48	Appendix PA, Attachment SCR
Mass wasting (deposition)	N49	Appendix PA, Attachment SCR
Soil development		
Soil development	N50	Section 2.1.3.10
SURFACE HYDROLOGICAL FEPs		
Fluvial		
Stream and river flow	N51	Section 2.2.2
Lacustrine		
Surface water bodies	N52	Section 2.2.2
Groundwater recharge and discharge		
Groundwater discharge	N53	Section 2.2.1
Groundwater recharge	N54	Section 2.2.1
Infiltration	N55	Section 2.1.3 Section 2.2.1
Changes in surface hydrology		
Changes in groundwater recharge and discharge	N56	Section 2.2.1
Lake formation	N57	Section 2.2.2
River flooding	N58	Section 2.2.2

Table 2-1. Issues Related to the Natural Environment That Were Evaluated for the WIPP PA Scenario Screening — Continued

Features, Events, and Processes (FEPs)	EPA FEP No.	Discussion
CLIMATIC FEPs		
Climate		
Precipitation (for example, rainfall)	N59	Section 2.5.2.3
Temperature	N60	Section 2.5.2.2
Climate change		
Meteorological		
Climate change	N61	Section 2.5
Glaciation		
Glaciation	N62	Section 2.5.1
Permafrost	N63	Appendix PA, Attachment SCR
MARINE FEPs		
Seas		
Seas and oceans	N64	Appendix PA, Attachment SCR
Estuaries	N65	Appendix PA, Attachment SCR
Marine sedimentology		
Coastal erosion	N66	Appendix PA, Attachment SCR
Marine sediment transport and deposition	N67	Appendix PA, Attachment SCR
Sea level changes		
Sea level changes	N68	Appendix PA, Attachment SCR
ECOLOGICAL FEPs		
Flora and fauna		
Plants	N69	Section 2.4.1
Animals	N70	Section 2.4.1
Microbes	N71	Appendix PA, Attachment SCR
Changes in flora and fauna		
Natural ecological development	N72	Section 2.4.1

*NOTE: Additional information for FEPs N1-N72 is located in Appendix PA, Attachment SCR.

The DOE located the WIPP disposal horizon within a rock salt deposit known as the Salado Formation at a depth of 650 m (2,150 ft) below the ground surface. The Salado is regionally extensive, includes continuous beds of salt without complicated structure, is deep with little potential for dissolution in the immediate vicinity of the WIPP, and is near enough to the surface to make access reasonable. Particular site selection criteria narrowed the choices when the present site was located during 1975 and 1976, as is discussed in CCA Appendix GCR and summarized by Weart (1983).

2.1 Geology

The DOE and its predecessor agencies determined at the outset of the geological disposal program that the geological characteristics of the disposal system are extremely important because the natural barriers provided by the geological units have a significant impact on the performance of the disposal system. Among the DOE's site selection criteria was the intent to maximize the beneficial impacts of the geology. This was accomplished when the DOE selected (1) a host formation that behaves plastically, thereby creeping closed to encapsulate buried waste, (2) a location where the effects of dissolution are minimal and predictable, (3) an area where deformation of the rocks is low, (4) an area where excavation is relatively easy, (5) an area where future resource development is predictable and minimal, and (6) a repository host rock that is relatively uncomplicated lithologically and structurally. Therefore, a thorough and accurate description of the WIPP facility's natural environmental setting is considered crucial by the DOE for a demonstration of compliance with the disposal standards and is an EPA certification criterion in 40 CFR § 191.14(a). The DOE is providing the detail necessary to assess the achievable degree of waste isolation. In this chapter, the DOE addresses environmental factors and long-term environmental changes that are important for assessing the waste isolation potential of the disposal system. The first of these environmental factors is geology.

Geological data have been collected from the WIPP site and surrounding area to evaluate the site's suitability as a radioactive waste repository. These data have been collected principally by the DOE, the DOE's predecessor agencies, the United States Geological Survey (USGS), the New Mexico Bureau of Mines and Mineral Resources (NMBMMR), and private organizations engaged in natural resource exploration and extraction. The DOE has analyzed the data and has determined that the data support the DOE's position that the WIPP site is suitable for the long-term isolation of radioactive waste.

Many issues have been discussed, investigated, and resolved in order for the DOE to conclude that the site is suitable. The DOE discusses these issues in the following sections. Most of the data collected have been reported or summarized in CCA Appendices GCR, SUM, HYDRO, and FAC. These appendices represent the majority of the site characterization results for the WIPP site which ended in 1988. A number of more focused geological and hydrological studies continued after this date. These latter studies provided detailed information needed to construct the conceptual models for disposal system performance that are discussed in Section 6.4. An example of these studies is the H-19 multiwell tracer test that was completed in early 1996. Results of this test were incorporated into the discussions in this chapter and into the conceptual models described in Section 6.4.6. Model parameters derived from the data are displayed in Appendix PA, Attachment PAR. A discussion of the data is included in CCA Appendix MASS; and Appendix PA, Attachment MASS.

Geological field studies designed to collect data pertinent to the WIPP PA continue. The Culebra Dolomite Member and Magenta Dolomite Members are the two carbonates in the Rustler Formation, the youngest evaporite-bearing formation in the Delaware Basin. Geologic data related to the Culebra and Magenta remain of particular interest, as these members are the most significant transmissive units at the WIPP site.

The EPA's December 19, 1996 letter (A-93-02, Docket II-I-01) made a request to the DOE for recent studies that had provided detailed information used in developing conceptual models for disposal system performance. In a response letter to EPA dated February 26, 1997 (Docket A-93-02, Item II-I-10), the DOE cited Holt (1997) for detailed information on the recent enhancement of the conceptual model for transport in the Culebra. Holt (1997) discusses interpretation and conceptual insights obtained from field and laboratory tracer tests and core studies that support the double-porosity conceptual model of the Culebra, in which Culebra porosity is divided into advective and diffusive components.

Geological data provide the basis for a different approach to estimating the transmissivity field for modeling fluid flow and transport in the Culebra (Beauheim 2002). Geological data correlate strongly with Culebra transmissivity (Holt and Yarbrough 2002), and they are available from many more locations, such as industry (oil, gas, potash) drillholes, than are transmissivity data. With this correlation, Culebra properties can be inferred over a wide area, leading to an improved computational model of the spatial distribution of Culebra transmissivity. Initial results from this computational model of the spatial distribution of Culebra transmissivity have been incorporated in the PA; they are discussed in more detail in Section 2.2.1.4.1.2, and are incorporated in Appendix PA, Attachment TFIELD. Additional data in support of this modeling are being collected through field activities, including drilling and testing of new wells, to improve understanding of the Culebra and to assess the causes(s) of rising water levels (see Section 2.2.1.4.1.2).

2.1.1 Data Sources

The geology of southeastern New Mexico has been of great interest for more than a century. The Guadalupe Mountains have become a common visiting and research point for geologists because of the spectacular exposures of Permian-age reef rocks and related facies (see Shumard 1858, Crandall 1929, Newell et al. 1953, and Dunham 1972 in the CCA bibliography). Because of intense interest in both hydrocarbon and potash resources in the region, a large volume of data exists as background information for the WIPP site, though some data are proprietary. Finally, there is the geological information developed directly and indirectly by studies sponsored by the DOE for the WIPP project; it ranges from raw data to interpretive reports.

Elements of the geology of southeastern New Mexico have been discussed or described in professional journals or technical documents from many different sources. These types of articles are an important source of information, and where there is consistency among the technical community, the information in these articles is referenced when subject material is relevant. Implicit rules of professional conduct for research and reporting have been assumed, as have journal and editorial review. Elements of the geology presented in such sources have been deemed critical to the WIPP and have been the subject of specific DOE-sponsored WIPP studies.

The geological data that the DOE has developed explicitly for the WIPP project have been produced over a 25-year period by different organizations and contractors using applicable national standards (Quality Assurance Program history is described in Section 5.1.2). During a rulemaking in 1988 related to the underground injection of hazardous wastes, the EPA addressed the use of older geological data in making a long-term demonstration of repository performance. In response to comments on a proposed rule regarding the permitting of underground injection

wells, the EPA concluded that "[e]xcluding historical data or information which might have been gathered off-site by methods not consistent with certain prescribed procedures may be counterproductive." The EPA further stated that such data should be used as long as their limitations are accounted for. In the final rule, the EPA stipulated "that only measurements pertaining to the waste or that result from testing performed to gather data for the petition demonstration comply with prescribed procedures." Further, the EPA stated that "the concerns about the accuracy of geologic data are addressed more appropriately by requiring that the demonstration identify and account for the limits on data quality rather than by excluding data from consideration" (EPA 1988).

As site characterization activities progressed, the DOE, along with independent review groups such as the National Academy of Sciences (NAS), the Environmental Evaluation Group (EEG), and the state of New Mexico acting through the Governor's Radioactive Waste Consultation Task Force, identified natural FEPs that required additional detailed investigation. Because these investigations, in many cases, were to gather data that would either be used in developing conceptual models or in the prediction of disposal system performance, the quality assurance (QA) standards applied to these investigations were more stringent, thereby ensuring accuracy and repeatability to the extent possible for geologic investigations.

Geological data from site characterization have been developed by the DOE through a variety of WIPP-sponsored studies using drilling, mapping or other direct observation, geophysical techniques, and laboratory work. Most of the techniques and statistics of data acquisition will be incorporated by specific discussion. The processes used in deriving modeling parameters from field and laboratory data are discussed in records packages which support the conceptual models in Section 6.4 and the parameters in Appendix PA, Attachment PAR. Pointers to these records packages are provided principally in Appendix PA, Attachment PAR. Records packages are stored in the Sandia WIPP Records Center in Carlsbad. Access to review of these records packages can be obtained by contacting the person designated in Table 1-10. Borehole investigations are a major source of geological data for the WIPP and surrounding area. Borehole studies provide raw data (for example, depth measurements, amount of core, geophysical logs) that support point data and interpreted data sets. These data sets are used in developing other analysis tools such as structure maps for selected stratigraphic horizons or isopachs (thicknesses) of selected stratigraphic intervals.

The borehole data set that was used specifically for obtaining WIPP geologic information is included as reference information in CCA Appendix BH. A map of some borehole locations in the data set is provided in Figure 2-2. Figure 2-3 shows Culebra monitoring wells within the site boundary as of December 2002, including well C-2737, which was drilled and completed in 2001 (Powers 2002c). Figure 2-4 shows Culebra monitoring wells outside the WIPP site as of December 2002; plugged and abandoned wells formerly monitored are not included in this figure. Figure 2-5 shows the locations of wells configured to monitor the Magenta, including well C-2737. Other hydrostratigraphic units are monitored in wells shown in Figure 2-6, including well C-2811, which was drilled and completed in 2001 to monitor a shallow saturated zone developed since the WIPP surface structures were constructed (Powers and Stensrud 2003). Other holes are not shown because they were not of sufficient depth, were not cored, or were not drilled for purposes of site characterization. A more comprehensive drillhole database of the

entire Delaware Basin is addressed in Section 2.3.1.2 and is presented in Appendix DATA. This database includes all drillholes used in evaluating human intrusion rates for the WIPP PA.

2.1.2 Geologic History

In this section, the DOE summarizes the more important points of the area's geologic history within about 320 km (200 mi) of the WIPP site, with emphasis on more recent or nearby events. Figure 2-7 shows the major elements of the area's geological history from the end of the Precambrian Period.

The geologic time scale that the DOE uses for WIPP is based on the compilation by Palmer (1983, pp. 503 – 504) for *The Decade of North American Geology* (DNAG). There are several compiled sources of chronologic data related to different reference sections or methods (see, for example, Harland et al. 1989 and Salvador 1985. Although most of these sources show generally similar ages for chronostratigraphic boundaries, there is no consensus on either reference boundaries or most-representative ages. The DNAG scale is accepted by the DOE as a standard that is useful and sufficient for WIPP purposes, as no known critical performance assessment parameters require more accurate or precise dates.

The geologic history in this region can be conveniently subdivided into three general phases:

- A Precambrian Period, represented by metamorphic and igneous rocks ranging in age from about 1.5 to 1.1 billion years;
- A period from about 1.1 to 0.6 billion years ago, from which no rocks are preserved. Erosion may have been the dominant process during much of this period; and
- An interval from 0.6 billion years ago to the present represented by a more complex set of mainly sedimentary rocks and shorter periods of erosion and dissolution.

This latter phase is the main subject of the DOE's detailed discussion in this text.

Only a few boreholes in the WIPP region have bored deep enough to penetrate Precambrian crystalline rocks, and, therefore, relatively little petrological information is available. Foster (1974, Figure 3) extrapolated the elevation of the Precambrian surface under the area of WIPP as being between 4.42 km (14,500 ft) and 4.57 km (15,000 ft) below sea level; the site surface at WIPP is about 1,036 m (3,400 ft) above sea level. Keesey (1976, Vol. II, Exhibit No. 2) projected a depth of about 5,545 m (18,200 ft) from the surface to the top of Precambrian rocks in the vicinity of the WIPP. The depth projection is based on the geology of the nearby borehole in Section 15, T22S, R31E.

Precambrian rocks of several types crop out in the following locations: the Sacramento Mountains northwest of WIPP; around the Sierra Diablo and Baylor Mountains near Van Horn, Texas; west of the Guadalupe Mountains at Pump Station Hills; and in the Franklin Mountains

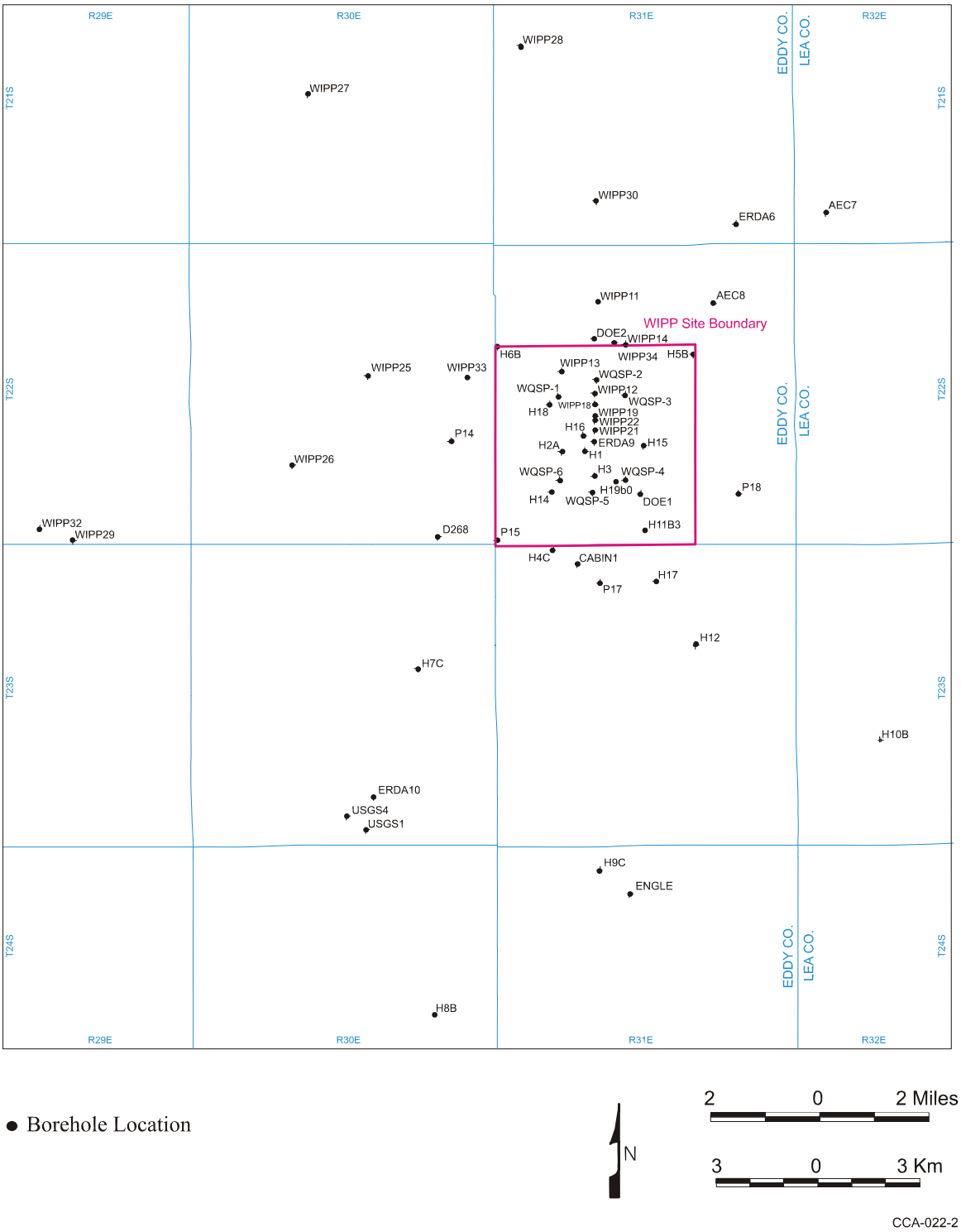

● Borehole Location

Figure 2-2. WIPP Site and Vicinity Borehole Location Map (partial)

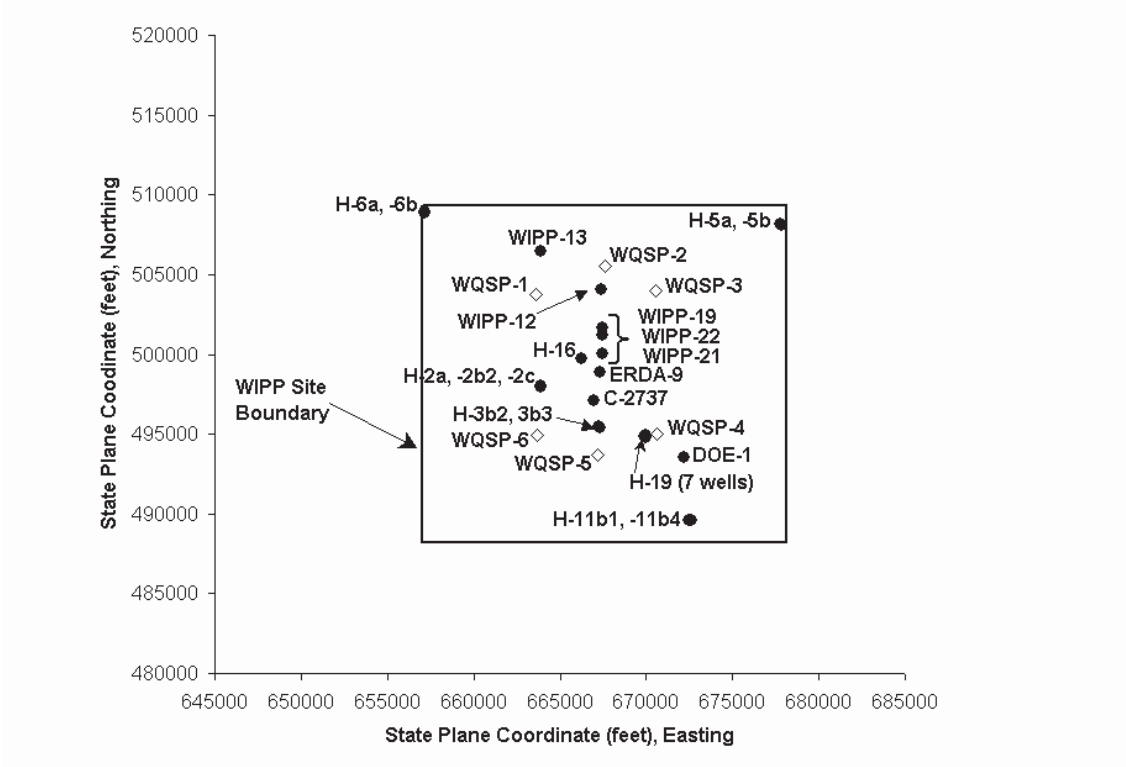

Figure 2-3. Locations of Culebra Monitoring Wells Inside the WIPP Site Boundary

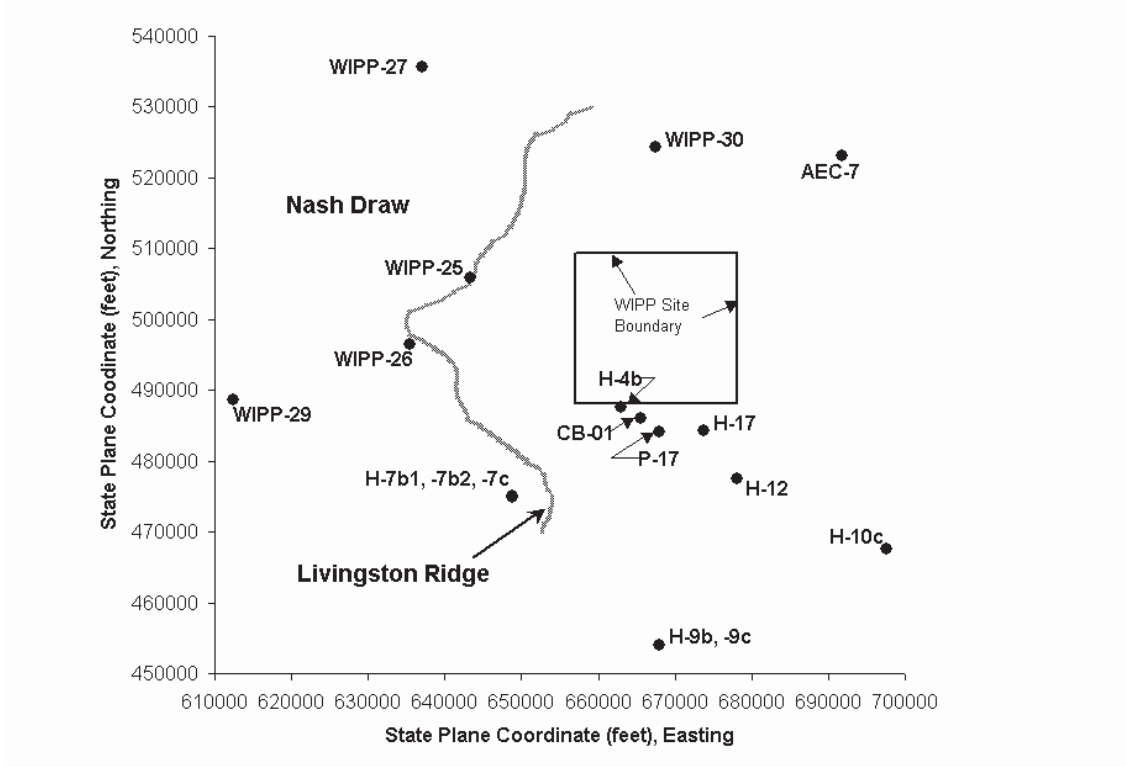

Figure 2-4. Locations of Culebra Monitoring Wells Located Outside the WIPP Site Boundary

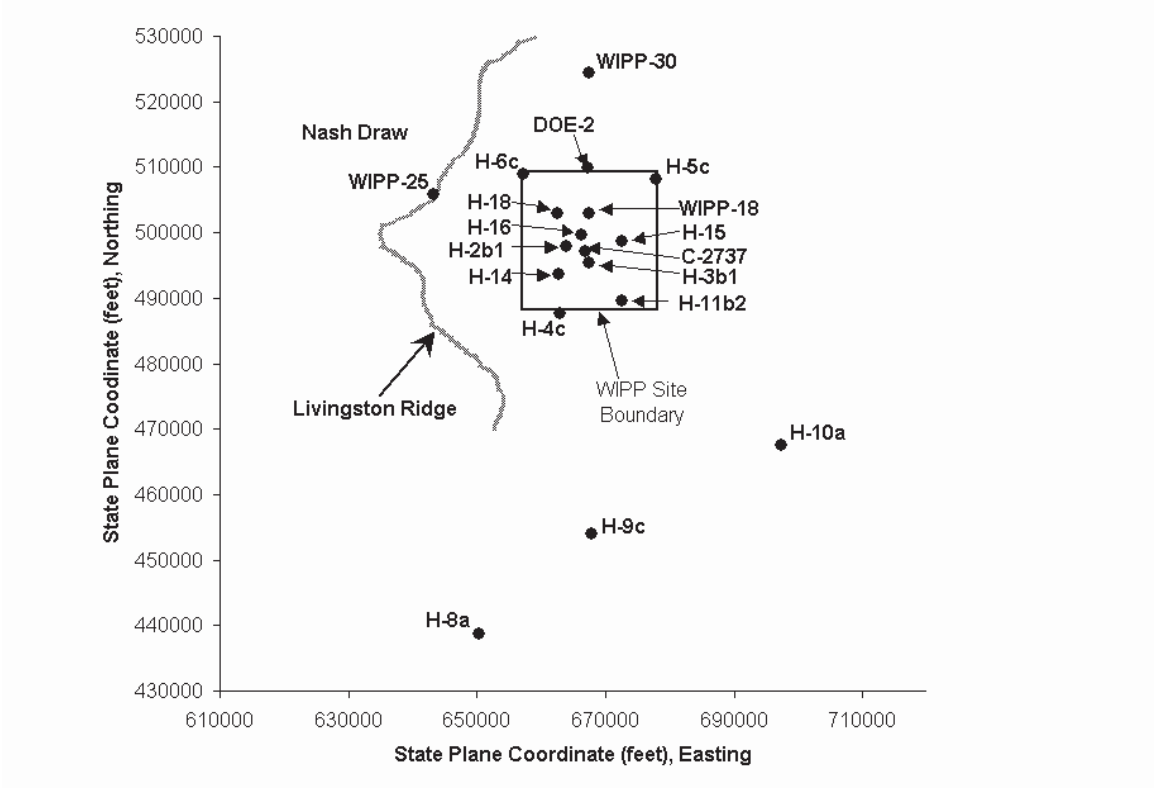

Figure 2-5. Locations of Magenta Monitoring Wells

near El Paso, Texas. East of the WIPP, a relatively large number of boreholes on the Central Basin Platform have penetrated the top of the Precambrian (Foster 1974, Figure 3). As summarized by Foster (1974, 10), Precambrian rocks in the area considered similar to those in the vicinity of the site range in age from about 1.14 to 1.35 billion years.

For about 500 million years (1.1 to 0.6 billion years ago), there is no certain rock record in the region around the WIPP. The most likely rock record for this period may be the Van Horn sandstone (McGowan and Groat 1971), but there is no conclusive evidence that it represents part of this time period (CCA Appendix GCR, Section 3.3.1). The region is generally thought to have been subject to erosion for much of the period until the Bliss sandstone began to accumulate during the Cambrian.

There is additional geologic history information contained in the EPA Technical Support Document for Section 194.14: Content of Compliance Certification Application, Section IV (Docket A-93-02, Item V-B-3).

2.1.3 Stratigraphy and Lithology in the Vicinity of the WIPP Site

The conceptual model of the disposal system uses information about the geometry of the various rock layers as a model input as described in Section 6.4.2.1. This means that stratigraphic information (thickness and lateral extent) provided in the following sections are important inputs.

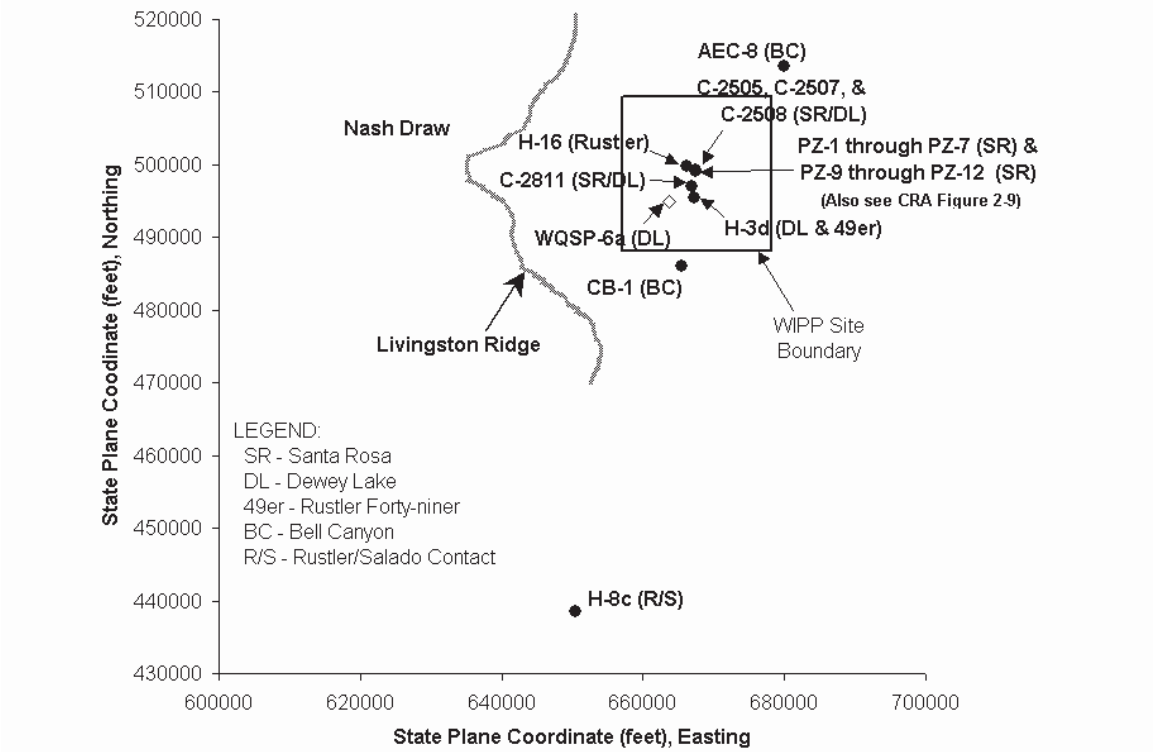

Figure 2-6. Locations of Monitoring Wells Completed to Hydrostratigraphic Units Other Than the Culebra and Magenta Dolomite Members (See also Figure 2-39).

In addition, less important features such as the lithology and the presence of geochemically significant minerals are provided to support screening arguments in Appendix PA, Attachment SCR. Consequently, this discussion has focused on the general properties of the various rock units as determined from field studies. Specific parameters used in the modeling described in Sections 6.4.5 and 6.4.6 are summarized in Appendix PA, Attachment PAR. Stratigraphy-related parameters are input as constants. Stratigraphic thicknesses of units considered in modeling are compiled in Appendix PA, Attachment PAR, Table PAR-49.

This section describes the stratigraphy and lithology of the Paleozoic and younger rocks underlying the WIPP site and vicinity (Figure 2-8), emphasizing the units nearer the surface. After briefly describing pre-Permian rocks, the section provides detailed information on the Permian (Guadalupian) Bell Canyon Formation (hereafter referred to as the Bell Canyon)—the upper unit of the Delaware Mountain Group—because this is the uppermost transmissive formation below the evaporites. The principal stratigraphic data are the chronologic sequence, age, and extent of rock units, including some of the nearby relevant facies changes. For deeper rocks, characteristics such as thickness and depth are summarized from published sources, and for shallower rocks, they are mainly based on data sets presented in CCA Appendix BH (above the Bell Canyon). The lithologies of upper formations and some formation members are described. A comprehensive discussion of stratigraphy in the WIPP area is presented in CCA Appendix GCR. Detailed referencing to original investigations by the USGS and others is included.

ERA	PERIOD	EPOCH	YEARS DURATION	YEARS BEFORE PRESENT	MAJOR GEOLOGIC EVENTS - SOUTHEAST NEW MEXICO REGION
CENOZOIC	Quaternary	Holocene	10,000		Eolian and erosion/solution activity. Development of present landscape.
		Pleistocene	1,590,000	1,600,000	Continued deposition of Gatuña sediments.
	Tertiary	Pliocene	3,700,000		Deposition of Gatuña sediments. Formation of caliche caprock. Regional uplift and east-southeastward tilting; Basin-Range uplift of Sacramento and Guadalupe-Delaware Mountains.
		Miocene	18,400,000		
		Oligocene	12,900,000		Erosion dominant. No Early to Mid-Tertiary rocks present.
		Eocene	21,200,000		
		Paleocene	8,600,000	66,400,000	Laramide revolution. Uplift of Rocky Mountains. Mild tectonism and igneous activity to west and north.
MESOZOIC	Cretaceous		77,600,000	144,000,000	Submergence. Intermittent shallow seas. Thin limestone and clastics deposited.
	Jurassic		64,000,000	208,000,000	Emergent conditions. Erosion, formation of rolling terrain.
	Triassic		37,000,000	245,000,000	Deposition of fluvial clastics. Erosion. Broad flood plain develops.
PALEOZOIC	Permian		41,000,000	286,000,000	Deposition of evaporite sequence followed by continental redbeds. Sedimentation continuous in Delaware, Midland, Val Verde basins and shelf areas.
	Pennsylvanian		34,000,000	320,000,000	Massive deposition of clastics. Shelf, margin, basin pattern of deposition develops.
	Mississippian		40,000,000	360,000,000	Regional tectonic activity accelerates, folding up Central Basin platform. Matador arch, ancestral Rockies. Regional erosion. Deep, broad basins to east and west of platform develop.
	Devonian		48,000,000	408,000,000	Renewed submergence. Shallow sea retreats from New Mexico; erosion. Mild epeirogenic movements. Tobosa basin subsiding. Pedernal landmass and Texas Peninsula emergent until Middle Mississippian.
	Silurian		30,000,000	438,000,000	
	Ordovician		67,000,000	505,000,000	Marathon-Quachita geosyncline, to south, begins subsiding. Deepening of Tobosa basin area; shelf deposition of clastics, derived partly from ancestral Central Basin platform and carbonates.
	Cambrian		65,000,000	570,000,000	Clastic sedimentation - Bliss sandstone.
	PRECAMBRIAN				Erosion to a nearly level plain. Mountain building, igneous activity, metamorphism, erosional cycles.

Figure 2-7. Major Geologic Events - Southeast New Mexico Region

SYSTEM/ Series		Group	Formation	Members
QUATER-NARY	Holocene		surficial deposits	
TERTIARY	Pleisto-cene		Mescalero caliche	
	Pliocene		Gatuña	
	Miocene			
TRIASSIC		Dockum	Santa Rosa	
	Ochoan		Dewey Lake	
PERMIAN			Rustler	*Forty-niner* *Magenta Dolomite* *Tamarisk* *Culebra Dolomite* *Los Medaños*
			Salado	*upper* *Vaca Triste Sandstone* *McNutt potash zone* *lower*
			Castile	
	Guadalupian	Delaware Mountain	Bell Canyon	
			Cherry Canyon	
			Brushy Canyon	

Figure 2-8. Partial Site Geologic Column

2.1.3.1 General Stratigraphy and Lithology below the Bell Canyon

As stated previously, the Precambrian basement near the site is projected to be about 5,545 m (18,200 ft) below the surface (Keesey 1976, Vol. II, Exhibit No. 2), consistent with information presented by Foster in 1974. Ages of similar rock suites in the region range from about 1.14 to 1.35 billion years.

A detailed discussion of the distribution of Precambrian rocks in southeastern New Mexico and Texas can be found in CCA Appendix GCR. Figure 3.4-2 in CCA Appendix GCR provides a structure contour map of the Precambrian. The basal Paleozoic units overlying Precambrian rocks are clastic rocks commonly attributed either to the Cambrian Bliss sandstone or the Ellenberger Group (Foster 1974, p. 10), considered most likely to be Ordovician in age in this area. The Ordovician System comprises the Ellenberger, Simpson, and Montoya Groups in the northern Delaware Basin. Carbonates are predominant in these groups, with sandstones and shales common in the Simpson Group. Foster (1974, Figure 4) reported 297 m (975 ft) of Ordovician-age rocks north of the site area and extrapolated a thicker section of about 396 m (1,300 ft) at the present site (Foster 1974, Figure 5). Keesey (1976, Vol. II, Exhibit No. 2) projected a thickness of 366 m (1,200 ft) for the Ordovician System within the site boundaries.

Silurian-Devonian rocks in the Delaware Basin are not stratigraphically well defined, and there are various notions for extending nomenclature into the basin. Common drilling practice is not to differentiate, though the Upper Devonian Woodford shale at the top of the sequence is frequently distinguished from the underlying dolomite and limestone (Foster 1974, p. 18). Foster (1974, Figure 6) showed a reference thickness of 384 and 49 m (1,260 and 160 ft) for the carbonates and the Woodford shale, respectively; he estimated thickness of these units at the present WIPP site to be about 351 m (1,150 ft) (Foster 1974, Figure 7) and 52 m (170 ft) (Foster 1974, Figure 8), respectively. Keesey (1976, Vol. II, Exhibit No. 2) projected 381 m (1,250 ft) of carbonate and showed 25 m (82 ft) of the Woodford shale.

The Mississippian System in the northern Delaware Basin is commonly attributed to Mississippian limestone and the overlying Barnett shale (Foster 1974, p. 24), but the nomenclature is not consistently used. At the reference well used by Foster (1974, 25), the limestone is 165 m (540 ft) thick and the shale is 24 m (80 ft); isopachs at the WIPP are 146 m (480 ft) (Foster 1974, Figure 10) and less than 61 m (200 ft). Keesey (1976, Vol. II, Exhibit No. 2) indicates 156 m (511 ft) and 50 m (164 ft), respectively, within the site boundaries.

The nomenclature of the Pennsylvanian System applied within the Delaware Basin is both varied and commonly inconsistent with accepted stratigraphic rules. Chronostratigraphic, or time-stratigraphic, names are applied from base to top of these lithologic units: the Morrow, Atoka, and Strawn (Foster 1974, p. 31). Foster (1974, Figure 13) extrapolated thicknesses of about 671 m (2,200 ft) for the Pennsylvanian at the WIPP site. Keesey (1976, Vol. II, Exhibit No. 2) reports 636 m (2,088 ft) for these units. The Pennsylvanian rocks in this area are mixed clastics and carbonates, with carbonates more abundant in the upper half of the sequence.

The Permian is the thickest system in the northern Delaware Basin, and it is divided into four series from the base to top: Wolfcampian, Leonardian, Guadalupian, and Ochoan. According to Keesey (1976, Vol. II, Exhibit No. 2), the three lower series total 2,647 m (8,684 ft) near the site.

Foster (1974, Figures 14, 16, and 18) indicates a total thickness for the lower three series of 2,336 m (7,665 ft) for a reference well north of WIPP. Foster's isopach maps of these series (Foster 1974, Figures 15, 17, and 19) indicate about 2,591 m (8,500 ft) for the WIPP site area. The Ochoan Series at the top of the Permian is considered in more detail later because the formations host and surround the WIPP repository horizon. Its thickness at DOE-2, about 3.2 km (2 mi) north of the site center, is 1,200 m (3,938 ft), according to Mercer et al. (1987, p. 23).

The Wolfcampian Series is also referred to as the Wolfcamp Formation (hereafter referred to as the Wolfcamp) in the Delaware Basin. In the site area, the lower part of the Wolfcamp is dominantly shale with carbonate and some sandstone, according to Foster (1974, Figure 14); carbonate increases to the north (Foster 1974, p. 36). Clastics increase to the east toward the margin of the Central Basin Platform. Keesey (1976, Vol. II, Exhibit No. 2) reports the Wolfcamp to be 455 m (1,493 ft) thick at a well near the WIPP site.

The Leonardian Series is represented by the Bone Spring Limestone or Formation (hereafter referred to as the Bone Spring). According to Foster (1974, pp. 35 - 36), the lower part of the formation is commonly interbedded carbonate, sandstone, and some shale, while the upper part is dominantly carbonate. Near the site the Bone Spring is 990 m (3,247 ft) thick, according to Keesey (1976, Vol. II, Exhibit No. 2).

The Guadalupian Series is represented in the general area of the site by a number of formations exhibiting complex facies relationships (Figure 2-9). The Guadalupian Series is known in considerable detail west of the site from outcrops in the Guadalupe Mountains, where numerous outcrops are present and subsurface studies have been undertaken. (See, for example, King 1948, Newell et al. 1953, and Dunham 1972 in the CCA bibliography.)

Within the Delaware Basin, the Guadalupian Series, known as the Delaware Mountain Group, comprises three formations: Brushy Canyon, Cherry Canyon, and Bell Canyon, from base to top. These formations are dominated by submarine channel sandstones with interbedded limestone and some shale. The Lamar limestone generally tops the series, immediately underneath the Castile Formation (hereafter referred to as the Castile). Around the margin of the Delaware Basin, reefs developed when the Cherry Canyon and Bell Canyon were being deposited. These massive reef limestones, the Goat Seep and Capitan Limestones, are equivalent in time to the basin sandstone formations but were developed topographically much higher around the basin margin. A complex set of limestone-to-sandstone and evaporite beds was deposited further away from the basin, behind the reef limestones. The Capitan Reef and back-reef limestones are well known because numerous caves, including the Carlsbad Caverns, are partially developed in these rocks.

2.1.3.2 The Bell Canyon

As will be discussed in Section 2.1.3.3, the Castile is a 427-to-487m (1,400-to-1,600ft) thick layer of nearly impermeable anhydrites and halites that isolate the Salado from the

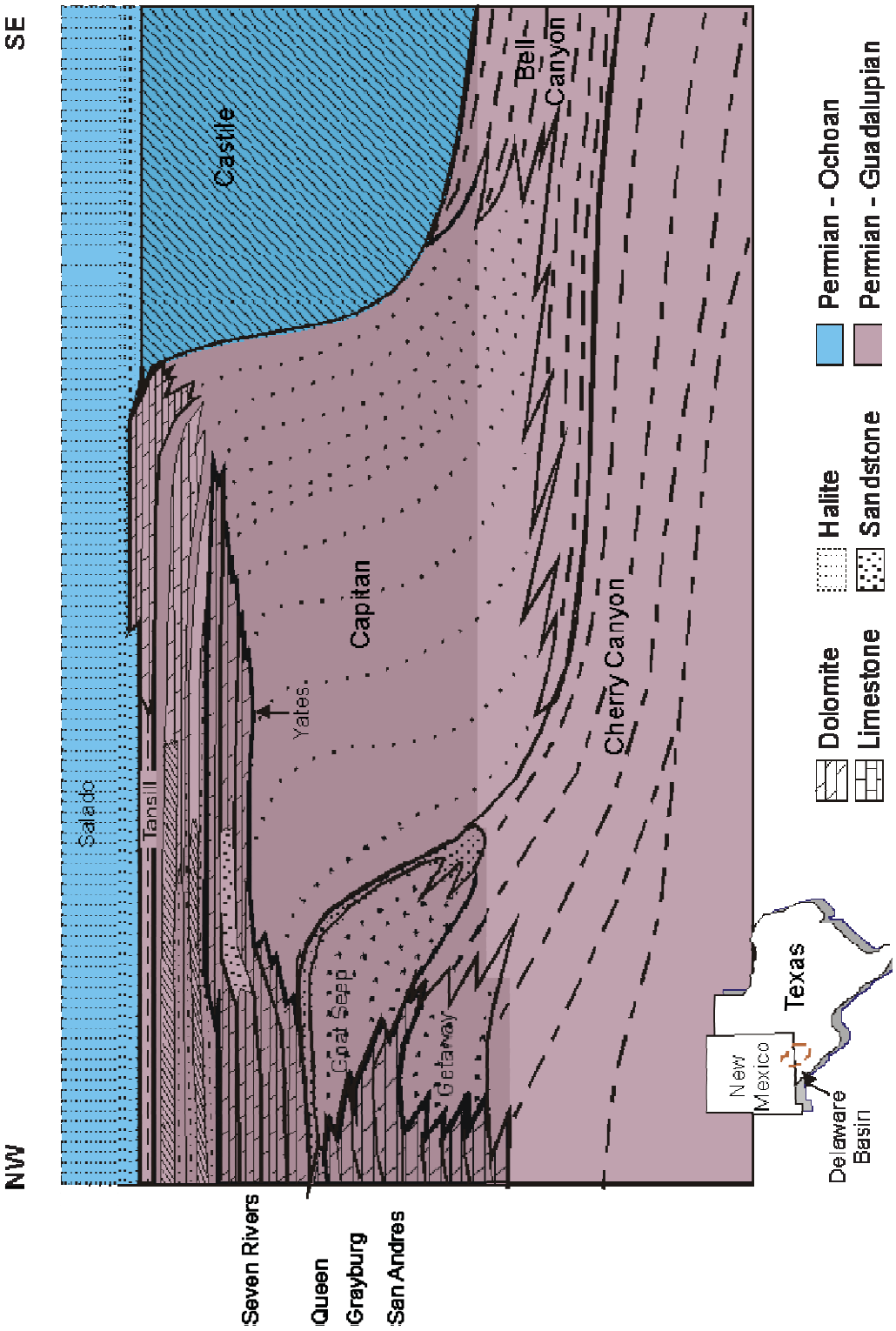

Figure 2-9. Schematic Cross-Section from Delaware Basin (southeast) through Marginal Reef Rocks to Back-Reef Facies (based on King 1948)

deeper water-bearing rocks. This notwithstanding, the DOE is interested in the Bell Canyon because it is the first laterally continuous transmissive unit below the WIPP repository. The significance of this unit is related to the FEP in Table 2-1 for deep dissolution. In evaluating this FEP, the DOE considers the potential for groundwater to migrate from the Bell Canyon or lower units into the repository and cause dissolution. The following discussion summarizes the basic understanding of the Bell Canyon lithology. Dissolution is discussed in Section 2.1.6. Bell Canyon hydrology is presented in Section 2.2.1.2. A thorough discussion of dissolution is in CCA Appendix DEF.

The Bell Canyon is known from outcrops on the west side of the Delaware Basin and from subsurface intercepts for oil and gas drilling. Several informal lithologic units are commonly named during such drilling. Mercer et al. (1987, p. 28) stated that DOE-2 penetrated the Lamar limestone, the Ramsey sand, the Ford shale, the Olds sand, and the Hays sand. This informal nomenclature is used for the Bell Canyon in some other WIPP reports.

The Clayton Williams Badger Federal borehole (Section 15, T22S, R31E) intercepted 961 feet (293 meters) of Bell Canyon, including the Lamar limestone, according to Keesey (1976, Vol. II, Exhibit No. 2). Reservoir sandstones of the Bell Canyon were deposited in channels that are straight to slightly sinuous. In their 1988 paper, Harms and Williamson proposed that density currents flowed from shelf regions, cutting channels and depositing the sands.

Within the basin, the Bell Canyon (Lamar limestone) Castile contact is distinctive on geophysical logs because of the contrast in low natural gamma of the basal Castile anhydrite compared to the underlying limestone. Density or acoustic logs are also distinctive because of the massive and uniform lithology of the anhydrite compared to the underlying beds. In cores, the transition is sharp, as described by Mercer et al. (1987, 312) for DOE-2. A structure contour map of the top of the Bell Canyon is shown in Figure 2-10. Also see CCA Appendix MASS, MASS Attachment 18-6, Figure 5.3-3. According to Powers et al. (1978) (CCA Appendix GCR, 4–59), this structure does not reflect the structure of deeper formations, suggesting different deformation histories. The rootless character of at least some of the normal faulting in the lower Permian suggests these are shallow-seated features.

2.1.3.3 The Castile

The Castile is the lowermost lithostratigraphic unit of the Late Permian Ochoan Series (Figure 2-11) and is part of the thick layer of evaporites within the WIPP disposal system. It was originally named by Richardson (1904, p. 43) for outcrops in Culberson County, Texas.

The Castile crops out along a lengthy area of the western side of the Delaware Basin. The two distinctive lithologic sequences now known as the Castile and the Salado were separated into the Upper and Lower Castile by Cartwright (1930). Lang (1939) clarified the nomenclature by restricting the Castile to the lower unit and naming the upper unit the Salado. By defining an anhydrite resting on the marginal Capitan limestone as part of the Salado, Lang in 1939 effectively restricted the Castile to the Delaware Basin inside the reef rocks.

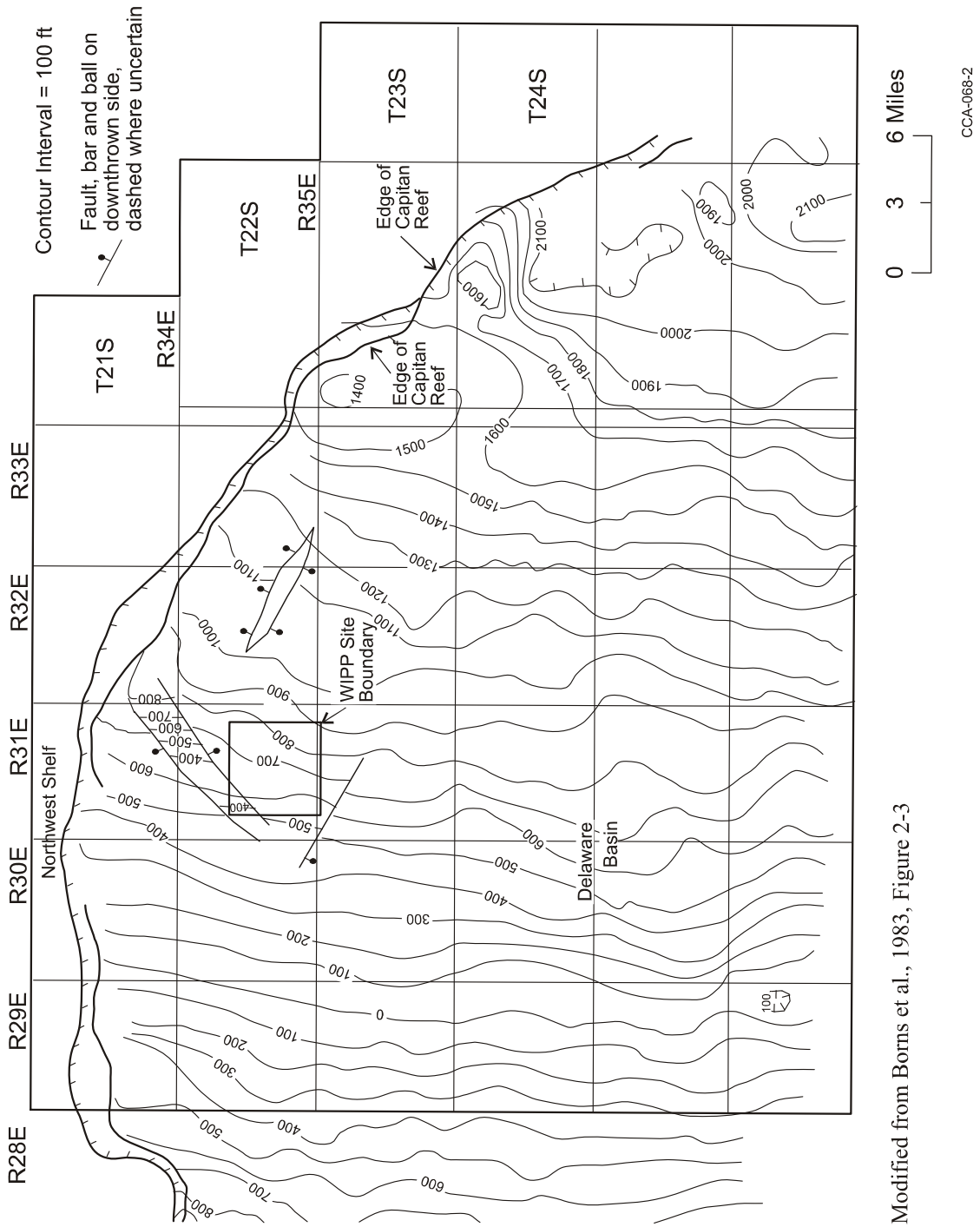

Modified from Borns et al., 1983, Figure 2-3

Figure 2-10. Structure Contour Map of Top of Bell Canyon

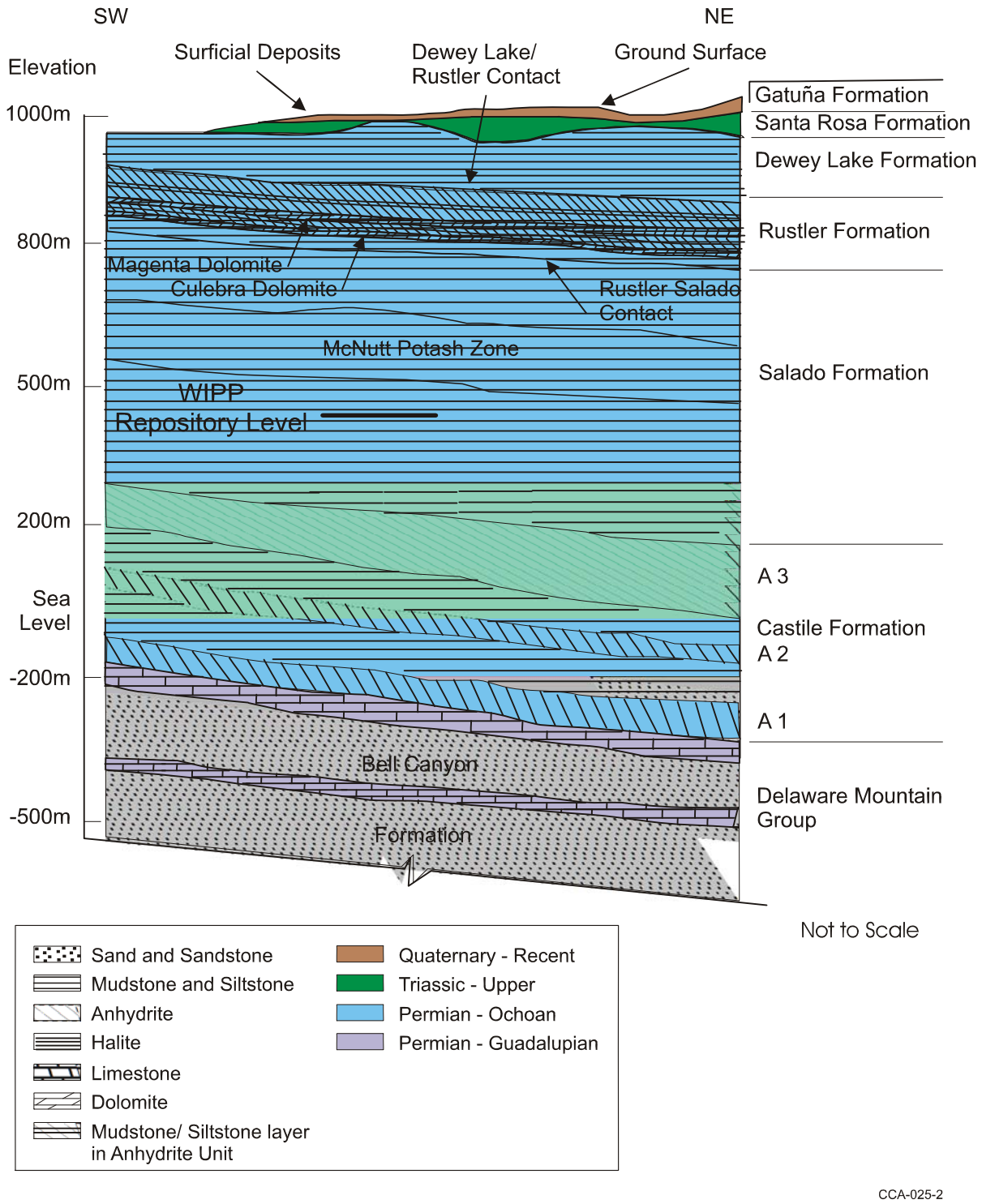

Figure 2-11. Generalized Stratigraphic Cross Section above Bell Canyon Formation at WIPP Site

Through detailed studies of the Castile, Anderson et al. (1972) introduced an informal system of names that is widely used and included in many WIPP reports. The units are named from the base as anhydrite I (A1), halite I (H1), anhydrite II (A2), etc. The informal nomenclature varies through the basin from A3 up because of complexity of the depositional system. The Castile consists almost entirely of thick beds of two lithologies: (1) interlaminated carbonate and anhydrite, and (2) high-purity halite.

In the eastern part of the Delaware basin, the Castile thickness ranges from about 299 to 616 m (980 to 2,022 ft) (derived from Powers et al. 1996, Figure 5.3-1; see also Borns and Shaffer 1985, Figures 9, 11, and 16 for an earlier range based on fewer drillholes). At DOE-2, the Castile is 301 m (989 ft) thick. The Castile is thinner in the western part of the Delaware Basin, and it lacks halite units.

Anderson et al. (1978) and Anderson (1978, Figures 1, 3, 4, and 5) correlated geophysical logs throughout the WIPP region, interpreting thin zones equivalent to halite units as dissolution residues. Anderson et al. (1972, p. 81) further attributed the lack of halite in the basin to its removal by dissolution. A structure contour map of the top of the Castile is reported in Figure 4.4-6, CCA Appendix GCR based on seismic data gathered for site characterization. In addition, Borns et al. (1983) prepared a seismic time structure of the middle Castile for identifying deformation. This map is shown in Figure DEF-2.2 in CCA Appendix DEF. Powers et al. (1996; Figures 5.2-1, 5.2-2, and 5.2-3) provide comparative figures of the elevations of the top of the Bell Canyon, top of Anhydrite 2 (of the Castile), and top of Anhydrite 3 (of the Castile), respectively, based on geophysical log data from oil and gas wells.

For borehole DOE-2, a primary objective was to ascertain whether a series of depressions in the Salado 3.3 km (2 mi) north of the site center was from dissolution in the Castile and related processes, as proposed by Davies (1984, p. 175) in his doctoral thesis. Studies have suggested that these depressions were not from dissolution but from halokinesis in the Castile (see, for example, Borns 1987). Robinson and Powers (1987, pp. 22 and 78) interpreted one deformed zone in the Castile in the western part of the Delaware Basin as partly caused by synsedimentary, gravity-driven, clastic deposition and suggested that the extent of dissolution may have been overestimated by previous workers. No Castile dissolution is known to be present in the immediate vicinity of the WIPP site. The process of dissolution and the resulting features are discussed later in this chapter. See CCA Appendix DEF, Section DEF.3 for a more in-depth discussion of the study of dissolution in the Castile.

In Culberson County, Texas, the Castile hosts major native sulfur deposits. The outcrops of Castile on the Gypsum Plain south of White's City, New Mexico, have been explored for native sulfur without success, and there is no reported indication of native sulfur anywhere in the vicinity of the WIPP.

In part of the area around the WIPP, the Castile has been significantly deformed and there are pressurized brines associated with the deformed areas; borehole ERDA-6 encountered both deformation and pressurized brine. WIPP-12, 1.6 km (1 mi) north of the site center, revealed lesser Castile structure, but it also encountered a zone of pressurized brine within the Castile. Castile deformation is described and discussed in Section 2.1.5 and in CCA Appendix DEF,

which detail structural features. Pressurized brine is described in Section 2.2.1, which details the area's hydrology.

Where they exist, Castile brine reservoirs in the northern Delaware Basin are believed to be fractured systems, with high-angle fractures spaced widely enough that a borehole can penetrate through a volume of rock containing a brine reservoir without intersecting any fractures and therefore not produce brine. They occur in the upper portion of the Castile (Popielak et al. 1983). Appreciable volumes of brine have been produced from several reservoirs in the Delaware Basin, but there is little direct information on the areal extent of the reservoirs or the interconnection between them. The presence of a pressurized brine pocket is treated in the conceptual model of WIPP as discussed in Section 6.4.8.

The Castile continues to be an object of research interest unrelated to the WIPP program as an example of evaporites supposedly deposited in deep water. Anderson (1993, pp. 12-13) discusses alternatives and contradictory evidence. Becker et al. (2002) presented a data set yielding a total Pb/U isochron age of 251.5 ± 2.8 million years (Ma) for calcite from the Castile and inferred that the Permo-Triassic boundary could be younger than this date. This discussion contrasts with other data regarding age of the Salado, Rustler, and Dewey Lake Formations (see later sections), including evidence that later formations yield slightly older radiometric ages. Although these discussions and a resolution might eventually affect some concepts of Castile deposition and dissolution, this issue is largely of academic interest and bears no impact on the suitability of the Los Medaños region for the WIPP site. Additional discussion of Castile deformation and the associated WIPP studies appears in Section 2.1.6.1 and CCA Appendix DEF. The Castile is included in the conceptual model as described in Section 6.4.8. As shown in Appendix PA, Attachment PAR, Table PAR-43, no stratigraphic or lithologic parameters are of importance for this unit. Important hydrological parameters are discussed subsequently.

The EPA questioned DOE's geologic and geophysical basis for the probability (i.e., eight percent probability) of intercepting pressurized brine in the Castile Formation beneath the WIPP disposal panels, and therefore required this distribution to be revised (to a uniform distribution with a range of 0.01 to 0.6) in Performance Assessment Verification Testing (PAVT) (Docket A-93-02, Item II-I-25). The formation of Castile brine pockets as a result of Castile deformation was described in the CCA, and although DOE's discussion of the distribution and nature of fractures in the Castile was limited, parameters were modified to include larger Castile brine pockets in the PAVT. Further information on this topic is contained in EPA Technical Support Document for Section 194.14: Content of Compliance Certification Application, Section IV.C (Docket A-93-02, Item V-B-3), EPA Technical Support Document for Section 194.23: Parameter Justification Report (Docket A-93-02, Item V-B-14), and EPA Technical Support Document for Section 194.23: Review of TDEM Analysis of WIPP Brine Pockets (Docket A-93-02, Item V-B-30).

2.1.3.4 The Salado

The Salado is of interest because it contains the repository horizon and provides the primary natural barrier for the long-term containment of radionuclides. The following section provides basic information regarding the genesis and lithology of the Salado. Subsequent sections discuss

Salado deformation, Salado dissolution, and Salado hydrology. CCA Appendix GCR provides detailed information about the Salado from early site characterization studies.

The Salado is dominated by halite, in contrast to the underlying Castile. The Salado extends well beyond the Delaware Basin, and Lowenstein (1988, p. 592) has termed the Salado a saline "giant."

While the Fletcher Anhydrite Member, which is deposited on the Capitan Reef rocks, is defined by Lang (1939; 1942) as the base of the Salado, some investigators consider that the Fletcher Anhydrite Member may interfinger with anhydrites normally considered part of the Castile. The Castile-Salado contact is not uniform across the basin, and whether it is conformable is unresolved. Around the WIPP site, the Castile-Salado contact is commonly placed at the top of a thick anhydrite informally designated A3; the overlying halite is called the infra-Cowden salt and is included within the Salado. Bodine (1978, pp. 28 - 29) suggests that the clay mineralogy of the infra-Cowden in ERDA-9 cores changes at about 4.6 m (15 ft) above the lowermost Salado and that the lowermost clays are more like Castile clays. At the WIPP site, the DOE recognizes the top of the thick A3 anhydrite as the local contact for differentiating the Salado from the Castile and notes that the distinction is related only to nomenclature and has no relevance to the performance of the WIPP disposal system.

The Salado in the northern Delaware Basin is broadly divided into three informal members. The middle member is known locally as the McNutt Potash Zone (hereafter referred to as McNutt) or Member, and it includes 11 defined potash zones, 10 of which are of economic significance in the Carlsbad Potash District. The lower member and the upper member remain unnamed. The WIPP repository level is located below the McNutt in the lower member. Figure 2-12 shows details of the Salado stratigraphy near the excavated regions. Elements of this stratigraphy are important to the conceptual model. The conceptual model for the Salado is discussed in Section 6.4.5. The thicknesses used in the model are given in Appendix PA, Attachment PAR, Table PAR-49.

Within the Delaware Basin, a system is used for numbering the more significant sulfate beds within the Salado, designating these beds as marker beds (MBs) from MB 100 (near the top of the formation) to MB 144 (near the base). The system is generally used within the Carlsbad Potash District as well as at and around the WIPP site. The repository is located between MB 139 and MB 138.

In the central and eastern part of the Delaware Basin, the Salado is at its thickest, ranging up to about 600 m (2,000 ft) thick and consisting mainly of interbeds of sulfate minerals and halite, with halite dominating. The thinnest portions of the Salado consist of a brecciated residue of insoluble material a few tens-of-feet thick, which is exposed in parts of the western Delaware Basin. The common sulfate minerals are anhydrite ($CaSO_4$), gypsum ($CaSO_4 \cdot 2H_2O$) near the surface, and polyhalite ($K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$). They form interbeds and are also found along halite grain boundaries. Isopach maps of various intervals of the Salado above the repository horizon have been provided to assist in understanding regional structure. These are Figures 4.3-4 to 4.3-7 in CCA Appendix GCR. A structure contour map of the Salado can be found in CCA Appendix GCR (Figure 4.4-10).

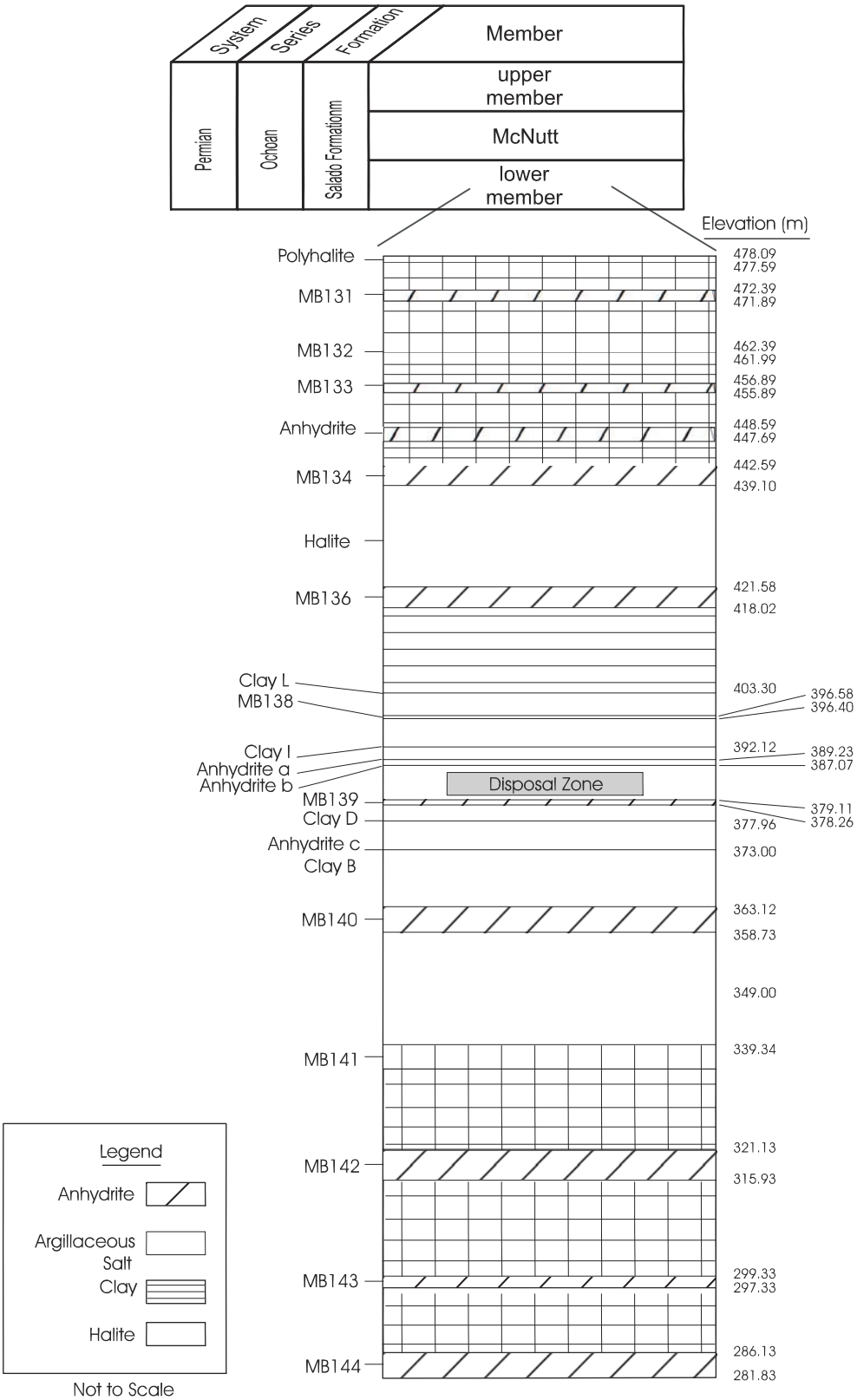

Figure 2-12. Salado Stratigraphy in the Vicinity of the WIPP Disposal Zone

Table 2-2. Chemical Formulas, Distributions, and Relative Abundances of Minerals in the Castile, Salado, and Rustler Formations

Mineral	Formula	Occurrence and Abundance
Amesite	$(Mg_4Al_2)(Si_2Al_2)O_{10}(OH)_8$	S, R
Anhydrite	$CaSO_4$	CCC, SSS, RRR (rarely near surface)
Calcite	$CaCO_3$	S, RR
Carnallite	$KMgCl_3 \bullet 6H_2O$	SS
Chlorite	$(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$	S, R
Corrensite	mixed-layer chlorite and smectite	S, R
Dolomite	$CaMg(CO_3)_2$	RR
Feldspar	$(K,Na,Ca)(Si,Al)_4O_8$	C, S, R
Glauberite	$Na_2Ca(SO_4)_2$	C, S (never near surface)
Gypsum	$CaSO_4 \bullet 2H_2O$	CCC (only near surface), S, RRR
Halite	NaCl	CCC, SSS, RRR (rarely near surface)
Illite	$K_{1-1.5}Al_4[Si_{7-6.5}Al_{1-1.5}O_{20}](OH)_4$	S, R
Kainite	$KMgClSO_4 \bullet 3H_2O$	SS
Kieserite	$MgSO_4 \bullet H_2O$	SS
Langbeinite	$K_2Mg_2(SO_4)_3$	S
Magnesite	$MgCO_3$	C, S, R
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \bullet 2H_2O$	SS, R (never near surface)
Pyrite	FeS_2	C, S, R
Quartz	SiO_2	C, S, R
Serpentine	$Mg_3Si_2O_5(OH)_4$	S, R
Smectite	$(Ca_{1/2},Na)_{0.7}(Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4 \bullet nH_2O$	S, R
Sylvite	KCl	SS

Legend:

C = Castile
S = Salado
R = Rustler
3 letters = abundant
2 letters = common
1 letter = rare or accessory

In the vicinity of the repository, authigenic quartz (SiO_2) and magnesite ($MgCO_3$) are also present as accessory minerals. Interbeds in the salt are predominantly anhydrite with seams of clay. The clays within the Salado are enriched in magnesium and depleted in aluminum (Bodine 1978, p. 1). The magnesium enrichment probably reflects the intimate contact of the clays with brines derived from evaporating sea water, which are relatively high in magnesium.

Powers et al. (Chapter 7 of CCA Appendix GCR) studied the geochemistry of the rocks in the vicinity of the disposal system. A partial list of minerals found in the Delaware Basin evaporites, together with their chemical formulas, is given in Table 2-2. The table also indicates the relative abundances of the minerals in the evaporite rocks of the Castile, Salado, and Rustler. Minerals found either only at depth, removed from influence of weathering, or only near the surface, as weathering products, are also identified.

Although the most common Delaware Basin evaporite mineral is halite, the presence of less soluble interbeds (dominantly anhydrite, polyhalite, and claystone) and more soluble admixtures (for example, sylvite, glauberite, kainite) has resulted in chemical and physical properties of the bulk Salado that are significantly different from those of pure halite layers contained within it. In particular, the McNutt, between MB 116 and MB 126, is locally explored and mined for potassium-bearing minerals of economic interest. Under differential stress, interbeds (anhydrite, polyhalite, magnesite, dolomite) may fracture while, under the same stress regime, pure halite would undergo plastic deformation. Fracturing of relatively brittle beds, for example, has locally enhanced the permeability, allowing otherwise nonporous rock to carry groundwater. Some soluble minerals incorporated in the rock salt can be radiometrically dated, and their dates indicate the time of their formation. The survival of such minerals is significant, in that such dating is impossible in pure halite or anhydrite.

Liquids were collected from fluid inclusions in the Salado halite and from seeps and boreholes within the WIPP drifts. Analysis of these samples indicated that there is compositional variability in the fluids that shows the effects of various phase transformations on brine composition. The fluid inclusions belong to a different chemical population than do the fluids emanating from the walls. It was concluded that much of the brine is completely immobilized within the salt and that the free liquid emanating from the walls is present as a fluid film along intergranular boundaries, mainly in clays and in fractures in anhydrites. Additional information can be found in CCA Appendix GCR, Sections 7.5 and 7.6.

Early investigators of the Salado recognized a repetitious vertical succession or cycle of beds in the Salado: clay - anhydrite - polyhalite - halite and minor polyhalite - halite. Later investigators described the cyclical units as clay - magnesite - anhydrite or polyhalite or glauberite - halite - argillaceous halite capped by mudstone. Lowenstein (1988, pp. 592 - 608) defined a depositional cycle (Type I) consisting of (1) basal mixed siliciclastic and carbonate (magnesite) mudstone, (2) laminated to massive anhydrite or polyhalite, (3) halite, and (4) halite with mud. Lowenstein also recognized repetitious sequences of halite and halite with mud as incomplete Type I cycles and termed them Type II cycles. Lowenstein (1988, pp. 592 - 608) interpreted the Type I cycles as having formed in a shallowing upward, desiccating basin beginning with a perennial lake or lagoon of marine origin and evaporating to saline lagoon and salt pan environments. Type II cycles are differentiated because they do not exhibit features of prolonged subaqueous deposition and also have more siliciclastic influx than do Type I cycles.

From detailed mapping of the Salado in the air intake shaft (AIS) at WIPP, Holt and Powers (1990a, pp. 2-26) interpreted depositional cycles of the Salado in terms of modern features such as those at Devil's Golf Course at Death Valley National Monument, California. The evaporative basin was desiccated, and varying amounts of insoluble residues had collected on the surface through surficial dissolution, eolian sedimentation, and some clastic sedimentation from temporary flooding caused from surrounding areas. The surface developed local relief that could be mapped in some cycles, while the action of continuing desiccation and exposure increasingly concentrated insoluble residues. Flooding, most commonly from marine sources, reset the sedimentary cycle by depositing a sulfate bed.

The details available from the shaft demonstrated the important role of syndepositional water level to water table changes that created solution pits and pipes within the halitic beds while they

were at the surface. Holt and Powers (1990a, Appendix F) concluded that passive halite cements filled the pits and pipes, as well as less dramatic voids, as the water table rose. Early diagenetic to synsedimentary cements filled the porosity early and rather completely with commonly clear and coarsely crystalline halite, reducing the porosity to a very small volume according to Casas and Lowenstein (1989).

Although Holt and Powers (1990a) found no evidence for postdepositional halite dissolution in the AIS, dissolution of the upper Salado halite has occurred west of the WIPP. Effects of dissolution are visible in Nash Draw and at other localities where gypsum karst has formed, where units above the Salado such as the Rustler Formation, Dewey Lake Redbeds, and post-Permian rocks have subsided. Dissolution studies are summarized in CCA Appendix DEF, Section DEF.3. The dissolution margin of upper Salado halite (see Figure 2-13), based on changes in thickness of the interval from the Culebra dolomite to the Vaca Triste Sandstone Member of the Salado, has been interpreted in detail by Powers (2002a, 2002b, 2003a), Holt and Powers (2002), and Powers et al. (2003). Powers (2002a, 2002b, 2003a) examined data from additional drillholes and noted that the upper Salado dissolution margin appears relatively narrow in many areas, and it directly underlies much of Livingston Ridge. The hydraulic properties of the Culebra correlate in part with dissolution of halite from the upper Salado (Holt and Yarbrough 2002; Powers et al. 2003), and the relationships are further described in Section 2.2.1.4.1.2.

Within Nash Draw, Robinson and Lang (1938, pp. 87-88) recognized a zone equivalent to the upper Salado but lacking halite. Test wells in southern Nash Draw produced brine from this interval, and it has become known as the brine aquifer. Robinson and Lang (1938) considered this zone a residuum from dissolution of Salado halite (see Section 2.1.6.2). Jones et al. (1960) remarked that the residuum should be considered part of the Salado, though in geophysical logs it may resemble the lower Rustler. The approximate eastern limit of the residuum and brine aquifer lies near Livingston Ridge (the eastward margin of Nash Draw) and is marked by a thickening of the Salado (see Section 2.1.6.2.2).

At the center of the site, Holt and Powers (1984, pp. 4-9) recognized clasts of fossil fragments and mapped channeling in siltstones and mudstones above the halite; they considered these beds to be a normal part of the transition from the shallow evaporative lagoons and desiccated salt pans of the Salado to the saline lagoon of the lower Rustler. Although some Salado halite dissolution at the WIPP may have occurred before deposition of the Rustler clastics, this process was quite different from the subsurface removal of salt from the Salado in more recent time that caused the residuum and associated brine aquifer in Nash Draw.

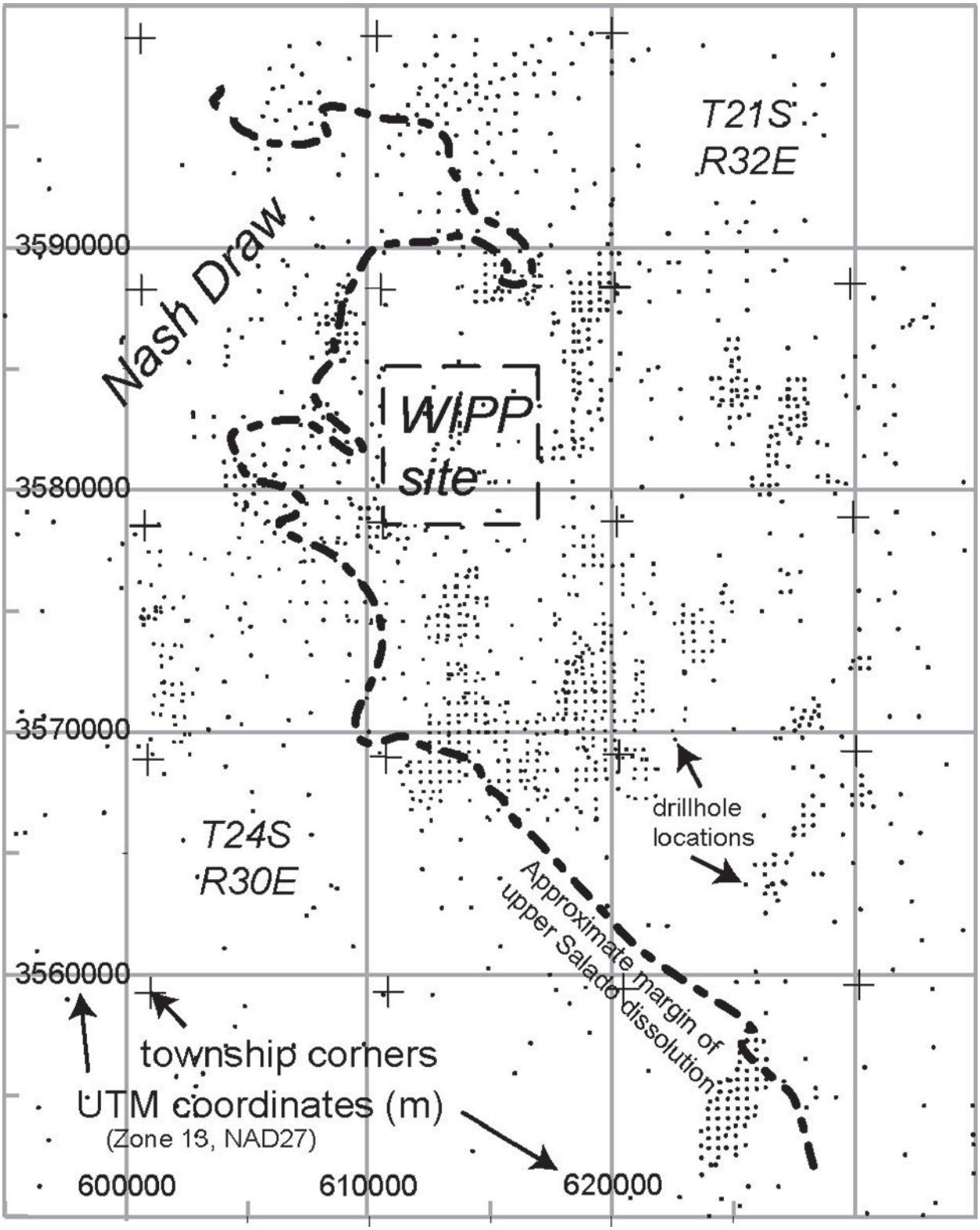

Figure 2-13. Dissolution Margin for the Upper Salado

Geochronological investigations provide a means to confirm the physical evidence indicating that little or no rock-water interactions have occurred in the Salado at the WIPP since the Late Permian Period. Radiometric techniques provide a means of determining the approximate time of the latest episode of regional recrystallization of evaporite minerals, which can be inferred as the approximate time of the latest episode of freely circulating groundwater. Radiometric dates for minerals of the Salado are available from mines and boreholes in the vicinity of the WIPP (Register and Brookins, 1980, pp. 30-42; Brookins, 1980, pp. 29-31; Brookins, et al. 1980, pp. 635-637; Brookins, 1981; and Brookins and Lambert, 1987, pp. 771-780). The distribution of dates shows that many of the rubidium-strontium (Rb-Sr) isochron determinations on evaporite minerals, largely sylvite (214 ± 14 million years ago), are in good agreement with potassium-argon (K-Ar) determinations on pure polyhalites (198 to 216 million years ago). (Potassium-argon ages for sylvite are significantly younger than Rb-Sr ages for the same rocks because of the loss of radiogenic argon. Radiogenic strontium, as a solid, is less mobile than argon and therefore the Rb-Sr isochron method is preferred for sylvite.) Renne et al. (1998) sampled langbeinite crystals from the Salado and obtained Ar-39/Ar-40 plateau ages of 251 ± 0.2 Ma and 251 ± 0.4 Ma. Clay minerals have both Rb-Sr and K-Ar ages significantly older (390 ± 77 million years [Register, 1981]) than the evaporite minerals, presumably reflecting the detrital origin of the clays.

One significantly younger recrystallization event has been identified in evaporites in the WIPP region and is a contact phenomenon associated with the emplacement of an Oligocene igneous dike (see Section 2.1.5.4). Polyhalite near the dike yields a radiometric age of 21 million years, compared to the 32- to 34-million-year age determined for the dike (Brookins, 1980, pp. 29-31; and Calzia and Hiss, 1978, p. 44) (this number was recalculated to 34.8 ± 0.8 million years; CCA Appendix GCR, pp. 3 - 80). This exception notwithstanding, the results of radiometric determinations argue for the absence of pervasive recrystallization of the evaporites in the Salado in the last 200 million years. This conclusion is supported by the number of replicate determinations, the wide distribution of similarly dated minerals throughout the Delaware Basin, and the concordance of dates obtained by various radiometric methods.

The notion of extensive recrystallization of Salado evaporites has been raised again since the CCA was submitted. Hazen and Roedder (2001), reiterating some arguments presented by Roedder (1984) and O'Neill et al. (1986), suggested that halite has been extensively recrystallized by water moving through the Salado at unknown times. Stable isotope data from fluid inclusions within coarse, clear halite crystals were interpreted as signifying that modern meteoric water constituted part of the fluid inclusion. O'Neill et al. (1986) noted as well that the stable isotope data are consistent with meteoric water falling on a desiccated Salado salt pan surface. Powers and Hassinger (1985) and Holt and Powers (1990a, 1990b) interpret syndepositional dissolution pipes as a common feature of the Salado, with coarse, clear halite with large fluid inclusions formed on a desiccated salt pan. Powers et al. (2001) summarized the arguments against extensive recrystallization of Salado halite. Stein and Krumhansl (1988) found variable compositions of large fluid inclusions, and show that inclusion chemistry differs significantly from intercrystalline brines, indicating that fluid movement is very limited. Satterfield et al. (2002) also concluded that the coarse halite cements found in certain beds of the Salado are synsedimentary, based on ionic concentrations in fluid inclusions. Moreover, Beauheim and Roberts (2002) find extremely low permeability in Salado halite, showing that fluid movement, especially vertically, through the Salado is too limited and slow to create the

purported recrystallization. These findings are also consistent with indications that salt pan deposits are cemented quickly and thoroughly at shallow depths of burial (Casas and Lowenstein 1989). The conclusion that Salado halite has not been pervasively recrystallized remains sound.

The Salado is of primary importance to the containment of waste. Because it is the principal natural barrier, many of the properties of the Salado have been characterized by the DOE, and numerical codes are used by the DOE to simulate the natural processes within the Salado that affect the disposal system performance.

Two conceptual models of the Salado are used in the performance assessment. One models the creep closure properties of the Salado and the other, the hydrological properties. The creep closure of the Salado is discussed in Appendix PA, Attachment PORSURF. This model uses key parameters derived from both in-situ measurements and laboratory testing on Salado core samples. Summaries of these parameters are in Butcher (1997). Appendix PORSURF Attachment 1, Table 2.

The second conceptual model is titled the Salado conceptual model and is discussed in Section 6.4.5. This model divides the Salado into two lithologic units: impure halite and Salado interbeds. The impure halite in this conceptual model is characterized entirely by its hydrological parameters as shown in Table 6-16. The interbeds are characterized by both hydrological parameters in Table 6-17 and fracture properties in Table 6-19. This latter information is needed since the model in Section 6.4.5.2 incorporates the possibility of interbed fracturing should pressures in the repository become high enough. The modeling assumptions surrounding the fracturing model are discussed in Appendix PA, Attachment MASS, Section MASS-13.

2.1.3.5 The Rustler

The Rustler is the youngest evaporite-bearing formation in the Delaware Basin. It was originally named by Richardson in 1904 for outcrops in the Rustler Hills of Culberson County, Texas. Adams (1944, p. 1614) first used the names Culebra Member and Magenta Member to describe the two carbonates in the formation, indicating that Lang favored the names, although Lang did not use these names to subdivide the Rustler in his 1942 publication. Vine (1963, p. B1) extensively described the Rustler in Nash Draw and proposed the four formal names and one informal term that were used for the stratigraphic subdivisions of the Rustler. These are as follows (from the base): unnamed lower member, Culebra Dolomite Member, Tamarisk Member, Magenta Dolomite Member, and Forty-niner Member (Figure 2-14). Powers and Holt (1999) formalized the nomenclature for the lower Rustler, naming the Los Medaños Member for the exposures of the former “unnamed lower member” in the WIPP shafts and in boreholes in the vicinity of Los Medaños near the WIPP site. Four studies of the Rustler since Vine’s 1963 work contribute important information about the stratigraphy, sedimentology, and regional relationships while examining more local details as well. Eager (1983) published a report on relationships of the Rustler observed in the southern Delaware Basin as part of sulfur exploration in the area. Holt and Powers (1988, Section 5.0), reproduced

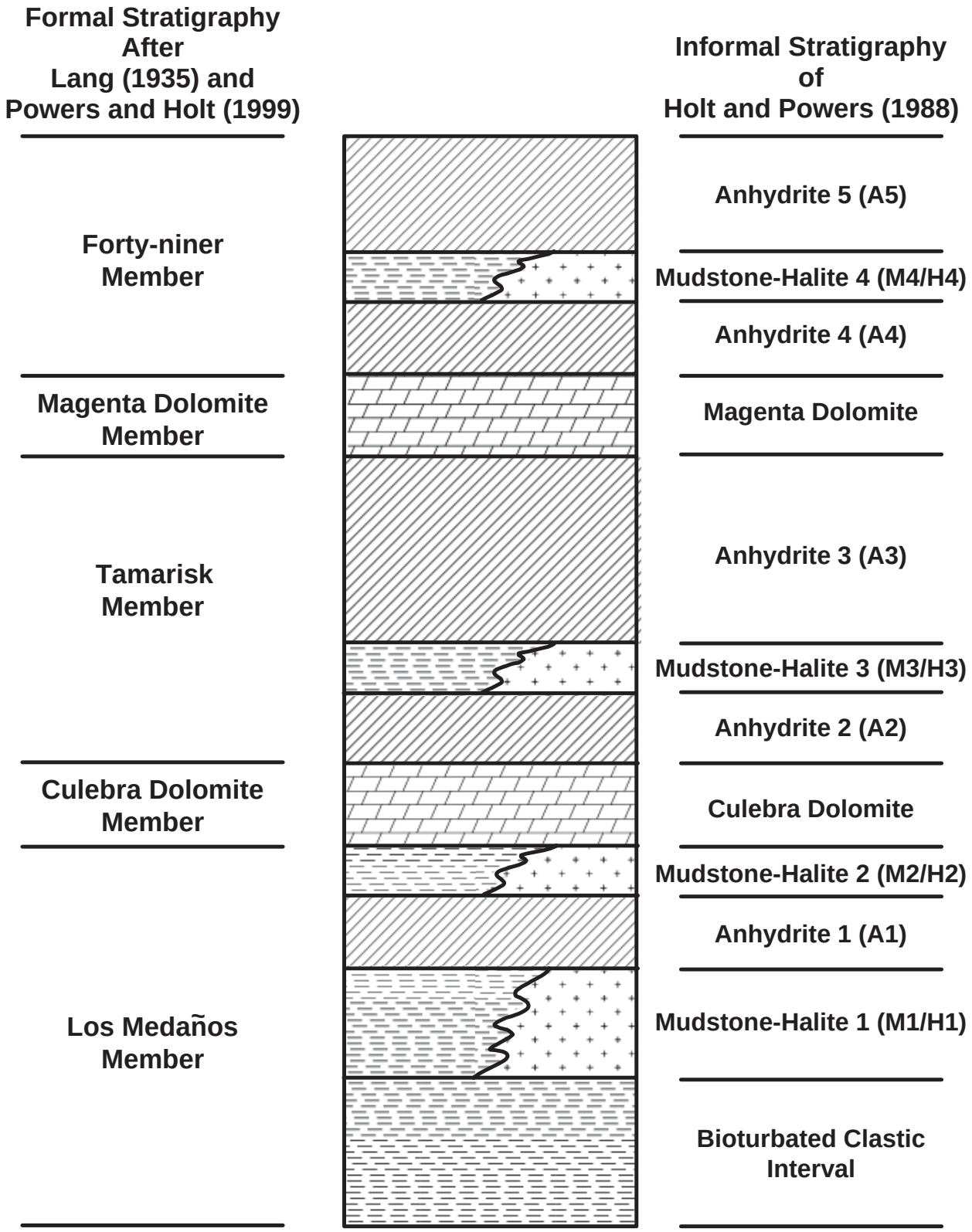

Figure 2-14. Rustler Stratigraphy

as CCA Appendix FAC, reported the details of sedimentologic and stratigraphic studies of WIPP shafts and cores as well as of geophysical logs from about 600 boreholes in southeastern New Mexico. Their work resulted in the more detailed subdivisions of the Rustler indicated in the right-hand column of Figure 2-14.

The Rustler is regionally extensive; a similar unit in the Texas panhandle is also called the Rustler. Within the area around WIPP, evaporite units of the Rustler are interbedded with significant siliciclastic beds and the carbonates. Both the Magenta and the Culebra extend regionally beyond areas of direct interest to the WIPP. In the general area of the WIPP, both the Tamarisk and the Forty-niner have similar lithologies: lower and upper sulfate beds and a middle unit that varies principally from mudstone to halite from west to east (Figure 2-14). In a general sense, halite in the Los Medaños broadly persists to the west of the WIPP site, and halite is found east of the center of the WIPP in the Tamarisk and the Forty-niner (Figure 2-15).

Two different explanations have been proposed over the history of the project to account for the observed distribution of halite in the non-dolomite members of the Rustler. The earliest researchers (e.g., Bachman [1985] and Snyder [1985]) assumed that halite had originally been present in all the non-sulfate intervals of the Forty-niner, Tamarisk, and Los Medaños Members, and that its present-day absence reflected post-depositional dissolution.

An alternative interpretation was presented by Holt and Powers (1988) following detailed mapping of the Rustler exposed in the WIPP ventilation (now waste) and exhaust shafts in 1984. Fossils, sedimentological features, and bedding relationships were identified in units that had previously been interpreted from boreholes as dissolution residues. Cores from existing boreholes, outcrops, geophysical logs, and petrographic data were also reexamined to establish facies variability across the area.

As a result of these studies, the Rustler was interpreted to have formed in variable depositional environments, including lagoon and saline playas, with two major episodes of marine flooding which produced the carbonate units. Sedimentary structures were interpreted to indicate synsedimentary dissolution of halite from halitic mudstones around a saline playa and fluvial transport of more distal clastic sediments. The halite in the Rustler, by this interpretation, has a present-day distribution similar to that at the time the unit was deposited. Some localized dissolution of halite may have occurred along the depositional margins, but not over large areas. Hence, the absence of halite in Rustler members at the WIPP site more generally reflects non-deposition than dissolution.

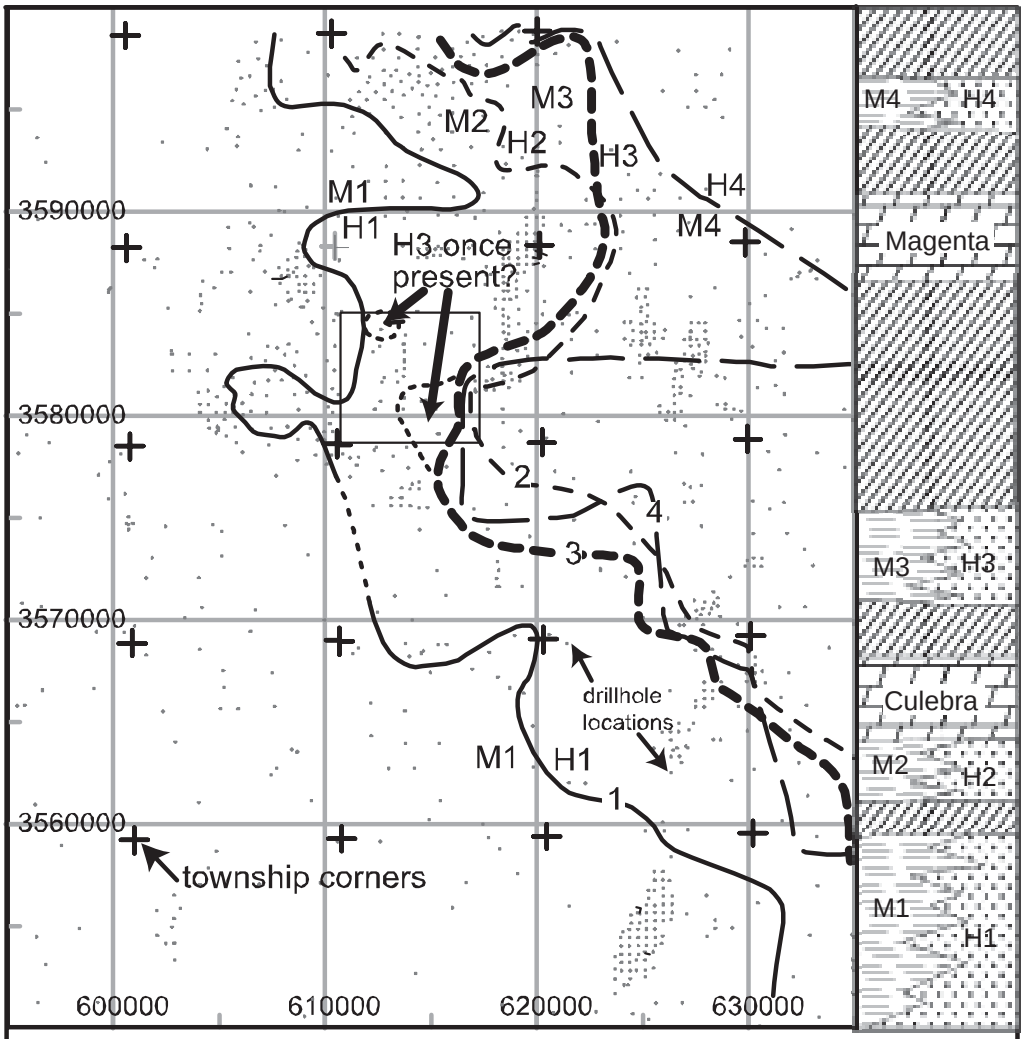

Explanation

M#, H# indicate mudstone and halitic facies on each side of estimated halite margin (numbered line on map) for stratigraphic intervals as indicated in the column to the right (key on Figure 2-14).

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.

Two zones within the WIPP site boundary ("H3 once present?") indicate where halite may have been present west of the current boundary of H3 (marked by ▬▬▬▬).

Figure 2-15. Halite Margins for the Rustler Formation Members

This hypothesis was tested and refined by subsequent investigations (e.g., Powers and Holt 1990, 1999, 2000; Holt and Powers 1990a) and is now considered the accepted explanation for the present-day distribution of halite in the Rustler. Powers and Holt (1999) thoroughly described the sedimentary structures and stratigraphy of the Los Medaños as part of the procedure for naming the unit. This shows the basis for interpreting the depositional history of the member and for rejecting significant post-burial dissolution of halite in that unit. Powers and Holt (2000) further describe the lateral facies relationships in other Rustler units, especially the Tamarisk, developed on sedimentologic grounds, and rejected the concept of broad, lateral dissolution of halite from the Rustler across the WIPP site area.

As discussed in Section 2.2.1.4, regional Culebra transmissivity shows about six orders of magnitude variation across the area around the site and about three orders of magnitude across the site itself. Although some investigators have called attention to the broad relationship between the distribution of halite in the Rustler and variations in Culebra transmissivity and have attributed the variation to fracturing resulting from postdepositional dissolution of Rustler halite (see, for example, Snyder 1985, p. 10; and CCA Appendix DEF, Section DEF-3.2), CCA Appendix FAC and Powers and Holt 1990, 1999, 2000) largely rule out this explanation. Variations in transmissivity of the Culebra were correlated qualitatively to the thickness of overburden above the Culebra (see discussion in Section 2.1.5.2), the amount of dissolution of the upper Salado, and the distribution of gypsum fillings in fractures in the Culebra (Beauheim and Holt 1990). Subsequently, Holt and Yarbrough (2002) and Powers et al. (2003) related the variation in Culebra transmissivity more quantitatively to overburden thickness and dissolution of upper Salado halite. The DOE believes that variations in Culebra transmissivity are primarily caused by the relative abundance of open fractures in the unit, which may be related to each of these factors. As discussed in Section 6.4.6.2 and Appendix PA, Attachment TFIELD, uncertainty in spatial variability in the transmissivity of the Culebra has been incorporated in the PA.

In the region around the WIPP, the Rustler reaches a maximum thickness of more than 152 m (500 ft) (Figure 2-16), while it is about 91 to 107 m (300 to 350 ft) thick within most of the WIPP site. Much of the difference in Rustler thickness can be attributed to variations in the amount of halite contained in the formation. Variation in Tamarisk thickness accounts for a larger part of thickness changes than do variations in either the Los Medaños or the Forty-niner. Details of the Rustler thickness can be found in CCA Appendix GCR, 4-39 to 4-42 and Figure 4.3-8. See also CCA Appendix FAC.

Much project-specific information about the Rustler is contained in CCA Appendix FAC. The WIPP shafts were a crucial element in Holt and Powers' 1988 study, exposing features not previously reported. Cores were available from several WIPP boreholes, and their lithologies were matched to geophysical log signatures to extend the interpretation throughout a larger area in southeastern New Mexico. These data are included in CCA Appendix FAC, Appendix II.

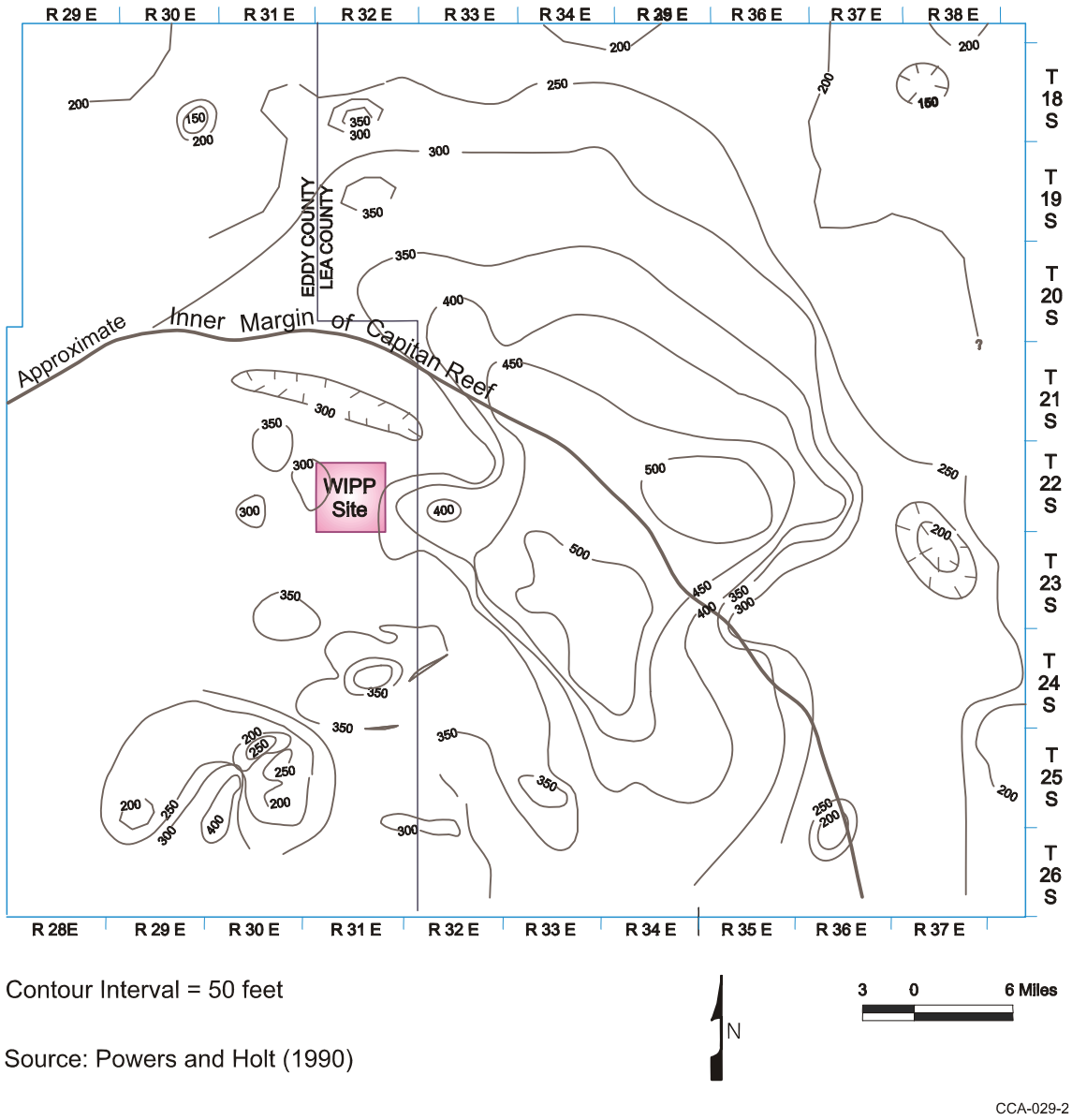

Figure 2-16. Isopach Map of the Entire Rustler

2.1.3.5.1 Los Medaños Member

The unit formerly referred to as the unnamed lower member has been named the Los Medaños Member. The Los Medaños rests on the Salado with apparent conformity at the WIPP site. It consists of significant proportions of bedded and burrowed siliciclastic sedimentary rocks with cross-bedding and fossil remains. These beds record the transition from strongly evaporative environments of the Salado to saline lagoonal environments. The upper part of the Los Medaños includes halitic and sulfatic beds within clastics. CCA Appendix FAC, pp. 6-8 and Powers and Holt (1999) interpret these as facies changes within a saline playa or lagoon environment, not dissolution residues from postdepositional dissolution.

According to CCA Appendix FAC, Figure 4-4, the Los Medaños ranges in thickness from about 29 to 38 m (96 to 126 ft) within the site boundaries. The maximum thickness recorded during that study was 63 m (208 ft) southeast of the WIPP site. An isopach of the Los Medaños is shown as Figure 4-7 in CCA Appendix FAC.

Halite is present in the M1/H1 unit of the Los Medaños west of most of the site area (see Figure 2-15 for an illustration of the halite margins). The drilling initiated during CRA-2004 preparation to investigate Culebra transmissivity variations based on overburden and Salado dissolution will develop additional detailed information about distribution of halite in the Los Medaños. Cross-sections based on geophysical log interpretations by Holt and Powers (CCA Appendix FAC) and Powers and Holt (2000) show that the unit is thicker to the east where the halite is more abundant. The Los Medaños is incorporated into the conceptual model as described in Section 6.4.6.1. Model parameters are in Appendix PA, Attachment PAR, Table PAR- 27.

2.1.3.5.2 The Culebra Dolomite Member

The Culebra rests with apparent conformity on the Los Medaños, though the underlying unit ranges from claystone to its lateral halitic equivalent in the site area. West of the WIPP site, in Nash Draw, the Culebra is disrupted from dissolution of underlying halite. Holt and Powers (CCA Appendix FAC, Section 8.9.3) principally attribute this to dissolution of Salado halite, noting the presence of sedimentologic features in the lower Rustler (see also Powers and Holt 1999). Culebra hydrology and its significance to disposal system performance are discussed in detail in Section 2.2.1.4.1.2.

The Culebra was described by Robinson and Lang (1938, p. 83) as a dolomite 11 m (35 ft) in thickness. The Culebra is generally brown, finely crystalline, locally argillaceous and arenaceous dolomite with rare to abundant vugs with variable gypsum and anhydrite filling; Adams (1944, p. 1614) noted that oölites are present in some outcrops as well. Holt and Powers (CCA Appendix FAC, pp. 5 - 11) describe the Culebra features in detail, noting that most of the Culebra is microlaminated to thinly laminated, while some zones display no depositional fabric. Holt and Powers (1984) described an upper interval of the Culebra consisting of medium brown, microlaminated carbonate that thickens up to 0.6 m (2 ft) in the vicinity of dome structures and is of probable algal origin. This is underlain by a 0.64-to 2.54-cm (0.25-to-1-in) thick bed of cohesive black claystone. Because of the unique organic composition of this thin layer, Holt and Powers (1988) did not include it in the Culebra for thickness computations, and this will be

factored into discussions of Culebra thickness. Based on core descriptions from the WIPP project, Holt and Powers (CCA Appendix FAC) concluded that there is very little variation of depositional sedimentary features throughout the Culebra.

Vugs are an important part of Culebra porosity. They are commonly zoned parallel to bedding. In outcrop, vugs are commonly empty. In the subsurface, vugs range from open to partially filled or filled with anhydrite, gypsum, or clay (Holt and Powers 1990a, pp. 3-18 to 3-20). Lowenstein (1987, pp. 19 - 20) noted similar features. Holt and Powers (CCA Appendix FAC) attributed vugs partly to syndepositional growth as nodules and partly as later replacive textures. Lowenstein (1987, pp. 29 - 31) also described textures related to later replacement and alteration of sulfates. Vug or pore fillings vary across the WIPP site and contribute to the porosity structure of the Culebra. As pointed out by Holt and Powers (see CCA Appendix FAC, Section 8.8), natural fractures filled with gypsum are common east of the WIPP site center and in a smaller area west of the site center (Figure 2-17). Section 2.1.5.2 discusses Culebra fracture mechanisms. Additional discussion of Culebra fractures and their role in groundwater flow and transport is in Section 2.2.1.4.1.1, Appendix PA, Attachment MASS, Sections MASS.14.4 and MASS.15.

Holt (1997) reexamined geological and hydrological data for the Culebra and developed a conceptual model for transport processes. In this document, Holt (1997) recognized several porosity types for the Culebra, and separated four Culebra units (CU) informally designated CU-1 through CU-4 from top to bottom. CU-1 differs from underlying units because it has been disrupted very little by syndepositional processes. Microvugs and interbeds provide most of the porosity, and the permeability of CU-1 is relatively limited. CU-2 and CU-3 likely contribute most of the flow in the Culebra, and the significant difference is that CU-2 includes more persistent silty dolomite interbeds. CU-2 and CU-3 include “small-scale bedding-plane fractures, networks of randomly oriented small-scale fractures and microfractures, discontinuous silty dolomite interbeds, large vugs hydraulically connected with microfractures and small-scale fractures, microvugs hydraulically connected with microfractures and intercrystalline porosity, blebs of silty dolomite interconnected with microfractures and intercrystalline porosity, and intercrystalline porosity” (Holt 1997, p. 2-19). Bedding-plane fractures dominate CU-4 at the base of the Culebra, and the unit shows some brittle deformation. CU-4 has not been isolated for hydraulic testing.

Holt (1997, p. I) also related porosity and solute transport, conceptualizing the medium “as consisting of advective porosity, where solutes are carried by the groundwater flow, and fracture-bounded zones of diffusive porosity, where solutes move through slow advection or diffusion.” Holt (1997) noted that length or time scales will govern how each porosity type will contribute to solute transport.

Sewards et al. (1991, pp. IX-1) report that the Culebra is primarily dolomite with some quartz and clay. Clay minerals include corrensite, illite, serpentine, and chlorite. Clay occurs in bulk

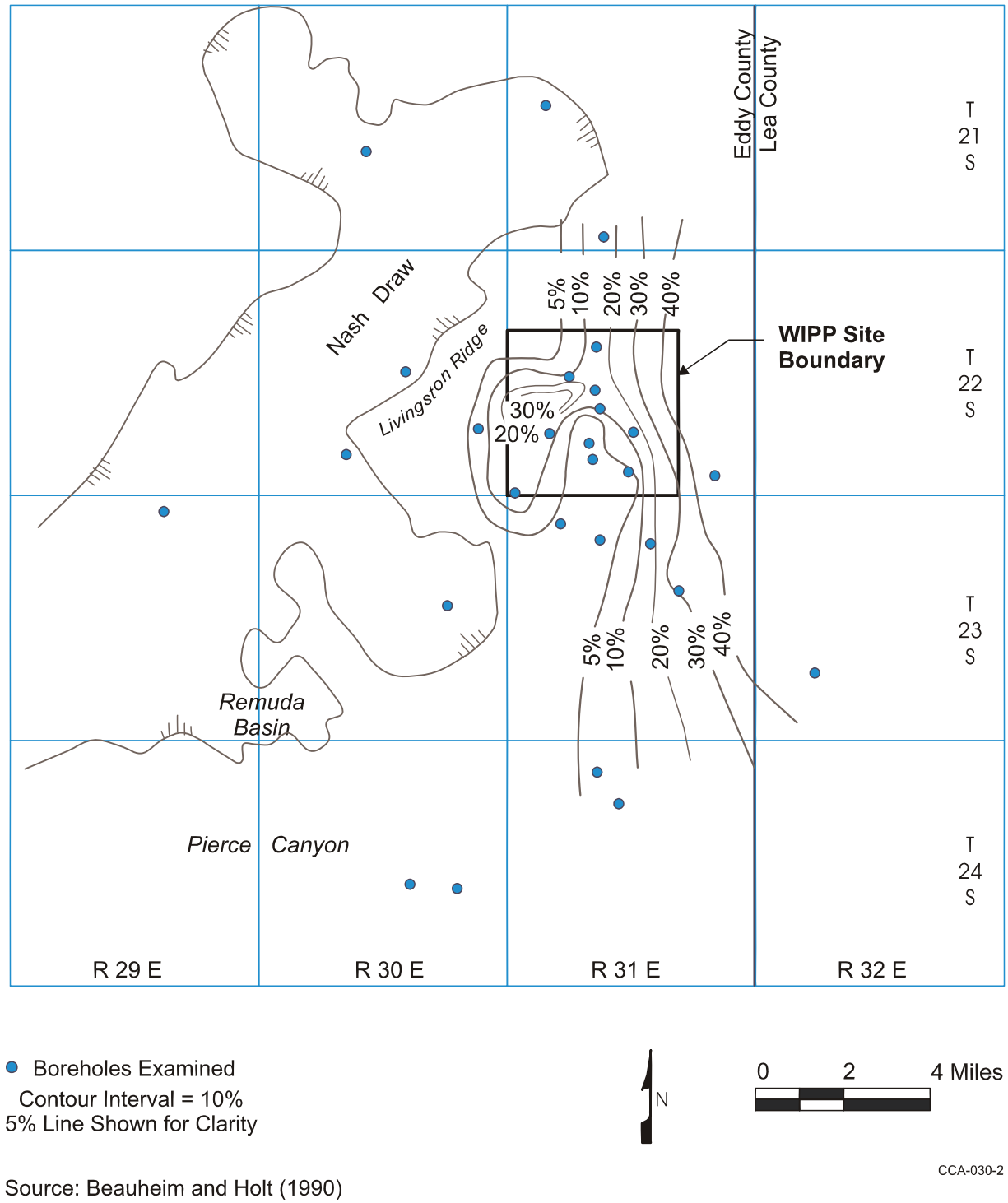

Source: Beauheim and Holt (1990)

Figure 2-17. Percentage of Natural Fractures in the Culebra Filled with Gypsum

rock and on fracture surfaces. Even though these clays occur, the conceptual model discussed in Section 6.4.6.2.1 takes no credit for their presence.

In the WIPP area, the Culebra varies in thickness. Depending on the area considered and the horizons chosen for the upper and lower boundaries of the Culebra, different data sources provide varying estimates (Table 2-3). Holt and Powers (CCA Appendix FAC, p. 4-4) considered the organic-rich layer at the Culebra-Tamarisk contact separately from the Culebra in interpreting geophysical logs.

Comparing data sets, Holt and Powers (CCA Appendix FAC) typically interpret the Culebra as being about 1 m (about 3 ft) thinner than do other interpretations. In general, this reflects the difference between including or excluding the unit at the Culebra-Tamarisk contact. The isopach of the Culebra is shown as Figure 4.8 in CCA Appendix FAC.

LaVenue et al. (1988, Table B.1) calculated a mean thickness of 7.7 m (25 ft) for the Culebra within their model domain based on thicknesses measured in 78 boreholes. Mercer (1983, reproduced as CCA Appendix HYDRO) reported a data set similar to that of LaVenue et al. The borehole database for the region of interest is provided in CCA Appendix BH.

The treatment of the Culebra in the conceptual model is discussed in Section 6.4.6.2 and associated parameter values in Table 6-20. A more thorough discussion of Culebra features, such as fractures, is provided in Appendix PA, Attachment MASS, Section MASS.15.

Table 2-3. Culebra Thickness Data Sets

Source	Data Set Location								
	T22S, R31E			T21-23S, R30-32E			Entire Set		
	n	ave	std dev	n	ave	std dev	n	ave	std dev
Richey (1989)	7	7.5 m	1.04 m	115	7.9 m	1.45 m	633	7.7 m	1.65 m
CCA Appendix FAC	35	6.4 m	0.59 m	122	7.0 m	1.26 m	508	6.5 m	1.89 m
LaVenue et al. (1988)							78	7.7 m	
Source	**WIPP Potash Drillholes**								
Jones (1978)				21	7.5 m	0.70 m			
CCA Appendix FAC				21	6.3 m	0.50 m			

Legend:

n	number of boreholes or data points
ave	average or mean
std dev	standard deviation
m	meters

2.1.3.5.3 The Tamarisk Member

Vine (1963, B14) named the Tamarisk for outcrops near Tamarisk Flat in Nash Draw. Outcrops of the Tamarisk are distorted, and subsurface information was used to establish member

characteristics. Vine reported two sulfate units separated by a siltstone, about 1.5 m (5 ft) thick, interpreted by Jones et al. in 1960 as a dissolution residue.

The Tamarisk is generally conformable with the underlying Culebra. The transition is marked by an organic-rich unit interpreted as being present over most of southeastern New Mexico. The Tamarisk around the WIPP site consists of lower and upper sulfate units separated by a unit that varies from mudstone (generally to the west) to mainly halite (to the east). Near the center of the WIPP site, the lower anhydrite was partially eroded during deposition of the middle mudstone unit, as observed in the WIPP waste-handling and exhaust shafts. The lower anhydrite was completely eroded at WIPP-19. Before shaft exposures were available, the lack of the Lower Tamarisk anhydrite at WIPP-19 was interpreted as the result of dissolution and the mudstone was considered a cave filling.

Jones (1978) interprets halite to be present east of the center of the WIPP site based on geophysical logs and drill cuttings. Based mainly on cores and cuttings records from the WIPP potash drilling program, Snyder prepared a map showing the halitic areas of each of the noncarbonate members of the Rustler (Snyder 1985, Figure 4). A very similar map based on geophysical log characteristics was prepared by Holt and Powers (1988).

CCA Appendix FAC describes the mudstones and halitic facies in the middle of the Tamarisk and postulate that the unit formed in a salt-pan-to-mudflat system. Powers and Holt (2000) cited sedimentary features and the lateral relationships as evidence of syndepositional dissolution of halite in the marginal mudflat areas.

The Tamarisk thickness varies greatly in southeastern New Mexico, principally as a function of the thickness of halite in the middle unit. Within T22S, R31E, the thickness ranges from 26 to 56 m (84 to 184 ft) for the entire Tamarisk and from 2 to 34 m (6 to 110 ft) for the interval of mudstone-halite between lower and upper anhydrites (CCA Appendix FAC, Figures 4-9 and 4-11). Expanded geophysical logs with corresponding lithology illustrate some of the lateral relationships for this interval (Figure 2-18; see also Powers and Holt 2000).

The Tamarisk is modeled as discussed in Section 6.4.6.3. Tamarisk parameter values are given in Appendix PA, Attachment PAR, Table PAR-24.

2.1.3.5.4 The Magenta Dolomite Member

Adams (1944, p. 1614) attributes the name Magenta Member to Lang, based on a feature named Magenta Point north of Laguna Grande de la Sal. According to CCA Appendix FAC the Magenta is a gypsiferous dolomite with abundant primary sedimentary structures and well-developed algal features. It does not vary greatly in sedimentary features

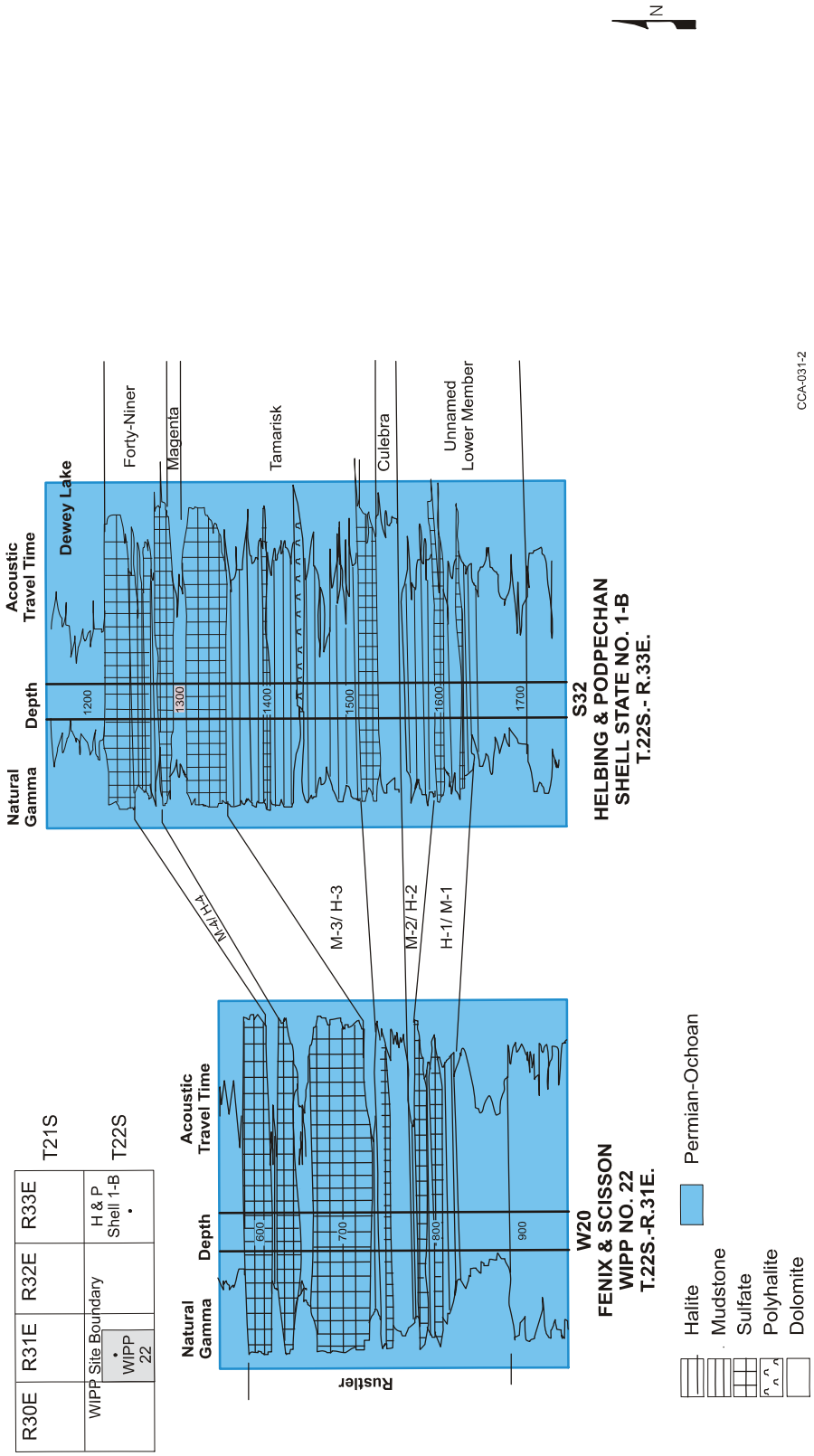

Figure 2-18. Log Character of the Rustler Emphasizing Mudstone-Halite Lateral Relationships

across the site area. CCA Appendix FAC, 5-22 reported that the Magenta varies from 7.0 to 8.5 m (23 to 28 ft) around the WIPP site. CCA Appendix FAC did not include a regional Magenta isopach. Additional detail on the Magenta can be found in Section 4.3.2 of CCA Appendix GCR and in Sections 4.1.4, 4.2.4, and 5.4 of CCA Appendix FAC. The Magenta is included in the conceptual model as discussed in Section 6.4.6.4. Modeling values are in Table 6-24.

2.1.3.5.5 The Forty-niner Member

Vine (1963) named the Forty-niner for outcrops at Forty-niner Ridge in eastern Nash Draw, but the unit is poorly exposed there. In the subsurface around the WIPP, the Forty-niner consists of basal and upper sulfates separated by a mudstone. It is conformable with the underlying Magenta. As with other members of the Rustler, geophysical log characteristics can be correlated with core and shaft descriptions to extend geological inferences across a large area (Holt and Powers 1988).

The Forty-niner varies from 13 to 23 m (43 to 77 ft) thick within T22S, R31E. East and southeast of the WIPP, the Forty-niner exceeds 24 m (80 ft), and some of the geophysical logs from this area indicate that halite is present in the beds between the sulfates. A regional isopach map of the Forty-niner is in CCA Appendix FAC (Figure 4-13). See also Powers and Holt (2000).

Within the waste-handling shaft, the Forty-niner mudstone displayed sedimentary features and bedding relationships indicating sedimentary transport. These beds are not known to have been described in detail prior to mapping in the waste-handling shaft at WIPP, and the features found there led Holt and Powers (CCA Appendix FAC) to reexamine the available evidence for, and interpretations of, dissolution of halite in Rustler units.

The inclusion of the Forty-niner in the conceptual model is discussed in Section 6.4.6.5.

2.1.3.6 The Dewey Lake

The nomenclature for rocks included in the Dewey Lake Formation was introduced during the 1960s to clarify relationships between these rocks assigned to the Upper Permian and the Cenozoic Gatuña Formation.

There are three main sources of data about the Dewey Lake in the area around WIPP. Miller reported the petrology of the unit in 1955 and 1966. Schiel (1988) described outcrops in the Nash Draw areas and interpreted geophysical logs of the unit in southeastern New Mexico and west Texas to infer the depositional environments and stratigraphic relationships in 1988 and 1994. Holt and Powers (1990a) were able to describe the Dewey Lake in detail at the AIS for WIPP in 1990, confirming much of Schiel's (1988) information and adding data regarding the Lower Dewey Lake.

The Dewey Lake overlies the Rustler conformably, though local examples of the contact (for example, the AIS described by Holt and Powers (1990a) show minor disruption by dissolution of some of the upper Rustler sulfate. The formation is predominantly reddish-brown fine sandstone to siltstone or silty claystone with greenish-gray reduction spots. Thin bedding, ripple cross-

bedding, and larger channeling are common features in outcrops, and additional soft sediment deformation features and early fracturing from the lower part of the formation are described by Holt and Powers (1990a). Schiel (1988, p. 143; 1994, p. 9) attributed the Dewey Lake to deposition on "a large, arid fluvial plain subject to ephemeral flood events."

There is no direct faunal or radiometric evidence of the age of the Dewey Lake in the vicinity of the WIPP site. It is assigned to the Ochoan Series, considered historically to be Late Permian in age, and it is regionally correlated with units of similar lithology and stratigraphic position. Schiel (1988, 1994) reviewed the limited radiometric data from lithologically similar rocks (Quartermaster Formation) and concluded that much of the unit could be Early Triassic in age. Renne et al. (1996) resampled tephra from the Quartermaster in the Texas panhandle area and found that radiometric data support the idea that the Quartermaster is mainly Triassic in age rather than Permian. Others have begun to infer as well that the Dewey Lake in the vicinity of the WIPP may be mostly Triassic (e.g., Powers and Holt 1999). These age relationships continue to be of academic interest because of the geologic significance of the Permo-Triassic boundary, but there is no significance for waste isolation at the WIPP.

Near the center of the WIPP site, Holt and Powers (1990a, Figure 5) mapped 152 m (498 ft) of the Dewey Lake (Figure 2-19). The formation is thicker to the east (Schiel 1994, Figure 2) of the WIPP site, in part because western areas were eroded before the overlying Triassic rocks were deposited.

The Dewey Lake contains fractures, which are filled with minerals to varying degrees. Both cements and fracture fillings have been examined and used to infer groundwater infiltration. Holt and Powers (1990a, pp. 3-10) described the Dewey Lake as cemented by carbonate above 50 m (164.5 ft) in the AIS; some fractures in the lower part of this interval were also filled with carbonate, and the entire interval surface was commonly moist. Below this point, the cement is harder and more commonly anhydrite (Powers 2003b), the shaft is dry, and fractures are filled with gypsum. Powers (2002c; 2003b) reports core and geophysical log data supporting these vertical changes in natural mineral cements in the Dewey Lake over a larger region at a horizon that is believed to underlie known natural groundwater occurrences in the Dewey Lake. In areas where the Dewey Lake has been exposed to weathering after erosion of the overlying Santa Rosa, this cement boundary tends to generally parallel the eroded upper surface of the Dewey Lake, suggesting that weathering has affected the location of the boundary. Where the Dewey Lake has been protected by overlying rocks of the Santa Rosa, the cement change appears to be stratigraphically controlled but the data points are too few to be certain. Holt and Powers (1990a, pp. 3 - 11, Figure 16) suggested that the cement change might be related to infiltration of meteoric water. They also determined that some of the gypsum-filled fractures are syndepositional. Dewey Lake fractures include horizontal to subvertical trends, some of which were mapped in detail (Holt and Powers 1986, Figures 6, 7, and 8).

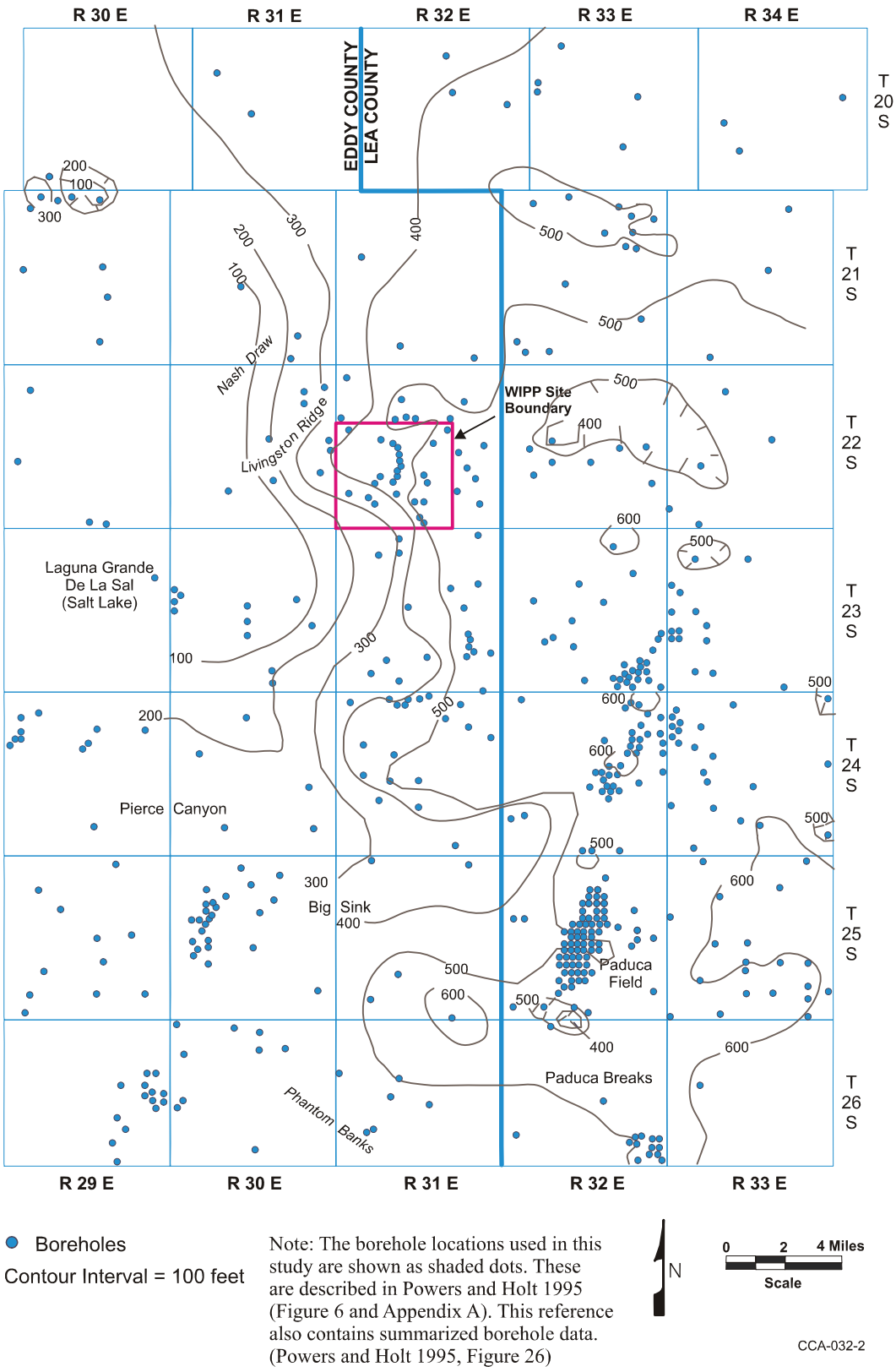

Figure 2-19. Isopach of the Dewey Lake

Lambert (1991, pp. 5 - 65) analyzed the deuterium/hydrogen (D/H) ratios of gypsum in the Rustler and gypsum veins in the Dewey Lake. He suggest that none of the gypsum formed from evaporitic fluid such as Permian seawater but that the D/H ratios all show influence of meteoric water. Furthermore, Lambert (1991, 5 – 66) infers that the gypsum D/H ratio is not consistent with modern meteoric water; it may, however, be consistent with older meteoric fluids. There is no obvious correlation with depth to indicate infiltration. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) indicate no intermixing or homogenization of fluids between the Rustler and the Dewey Lake, but there may have been lateral movement of water within the Dewey Lake (Lambert 1991, pp. 5 - 54). Dewey Lake carbonate-vein material shows a broader range of strontium ratios than does surface caliche, and the ratios barely overlap.

The treatment of the Dewey Lake in the conceptual model can be found in Section 6.4.6.6. Dewey Lake parameter values are in Table 6-25.

2.1.3.7 The Santa Rosa

There have been different approaches to the nomenclature of rocks of Triassic age in southeastern New Mexico. Bachman (1974) generally described the units as “Triassic, undivided” or as the Dockum Group, without dividing it. Vine (1963) used “Santa Rosa Sandstone,” and Santa Rosa has become common usage. Lucas and Anderson (1993a, 1993b) import other formation names that are unlikely to be useful for WIPP.

The Santa Rosa has been called disconformable over the Dewey Lake by Vine (1963, B25). These rocks have more variegated hues than the underlying uniformly colored Dewey Lake. Coarse-grained rocks, including conglomerates, are common, and the formation includes a variety of cross-bedding and sedimentary features (Lucas and Anderson 1993a, pp. 231 - 235).

Within the WIPP site boundary, the Santa Rosa is relatively thin to absent (Figure 2-20). At the AIS, Holt and Powers (1990a, Figure 5) attributed about 0.6 m (2 ft) of rock to the Santa Rosa. The Santa Rosa is a maximum of 78 m (255 ft) thick in potash holes drilled for WIPP east of the site boundary. The Santa Rosa is thicker to the east. The geologic data from design studies (Sergent et al. 1979) were incorporated with data from drilling to investigate shallow subsurface water in the Santa Rosa to provide structure and thickness maps of the Santa Rosa in the vicinity of the WIPP surface structures area (Powers 1997). These results are consistent with the broader regional distribution of the Santa Rosa.

The Santa Rosa and younger rocks are modeled in the WIPP PA as a single region as discussed in Section 6.4.6.7. The model parameters for this supra-Dewey Lake region are given in Table 6-26.

2.1.3.8 The Gatuña

Lang (in Robinson and Lang 1938, p. 84) named the Gatuña for outcrops in the vicinity of Gatuña Canyon in the Clayton Basin. Rocks now attributed to the Gatuña in Pierce Canyon were once included in the Pierce Canyon Formation with rocks now assigned to the Dewey Lake. The

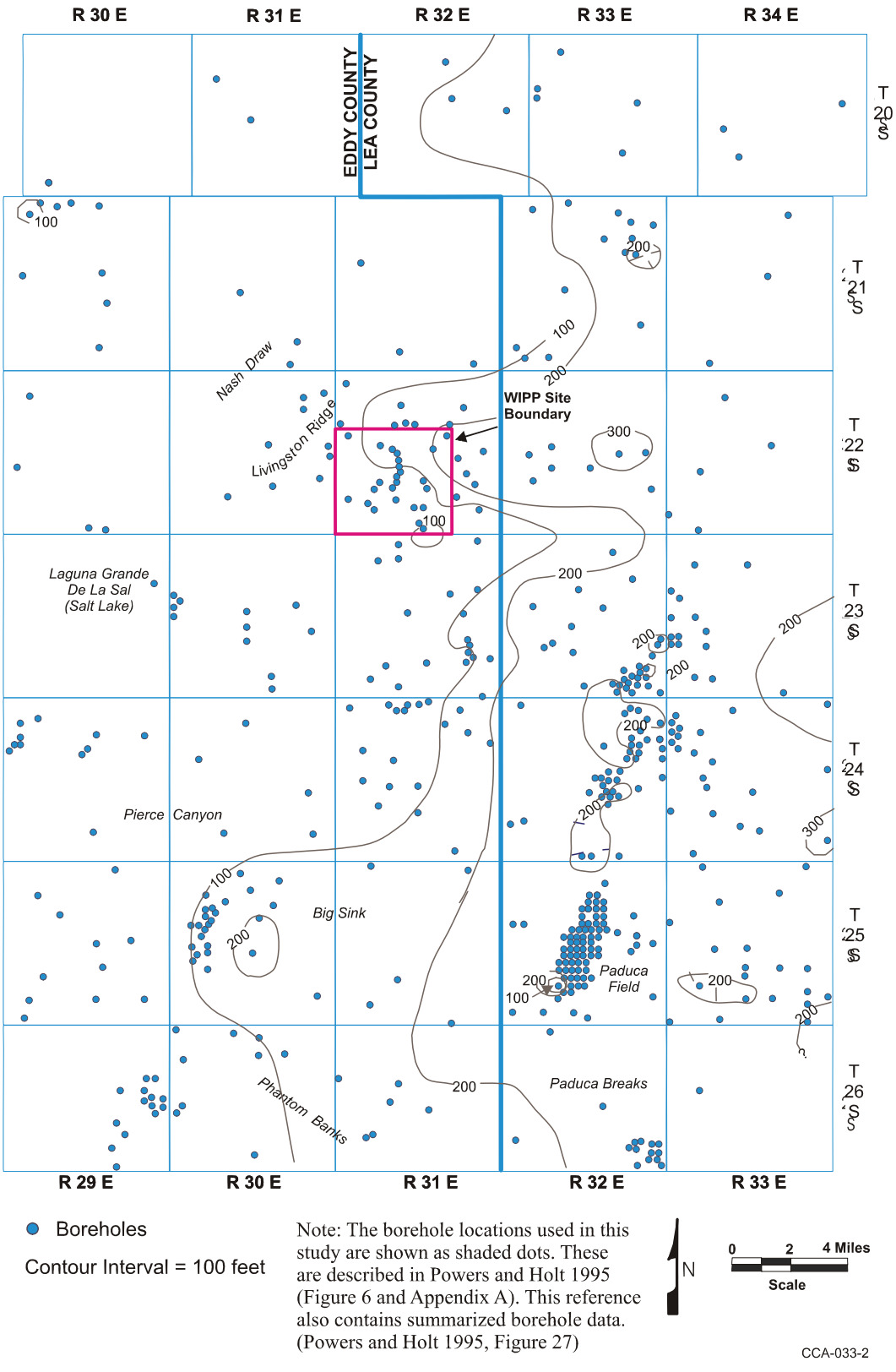

Figure 2-20. Isopach of the Santa Rosa

formation has been mapped from the Santa Rosa, New Mexico, area south to the vicinity of Pecos, Texas. It is unconformable with underlying units.

Vine (1963) and Bachman (1974) provided some limited description of the Gatuña. The most comprehensive study of the Gatuña is based on WIPP investigations and landfill studies for the City of Carlsbad and Eddy County (Powers and Holt 1993). Much of the formation is colored light reddish-brown. It is broadly similar to the Dewey Lake and the Santa Rosa, though the older units have more intense hues. The formation is highly variable, ranging from coarse conglomerates to claystones with some highly gypsiferous sections. Sedimentary structures are abundant. Analysis of lithofacies indicates that the formation is dominantly fluvial in origin with areas of low-energy deposits and evaporitic minerals.

The thickness of the Gatuña is not very consistent regionally, as shown in Figure 2-21. The thickness of the Gatuña ranges up to 91 m (300 ft) at Pierce Canyon, with thicker areas generally subparallel to the Pecos River. To the east, the Gatuña is thin or absent. Holt and Powers (1990a) reported about 2.7 m (9 ft) of undisturbed Gatuña in the AIS at WIPP. Powers (1997) integrated data from facility design geotechnical work (Sergent et al. 1979) and drilling to investigate shallow water to develop maps of the Gatuña in the vicinity of the WIPP surface facility. These maps are consistent with the broader regional view of the distribution of the Gatuña.

The Gatuña has been considered Pleistocene in age based on a volcanic glass in the Upper Gatuña along the eastern margin of Nash Draw that has been identified as the Lava Creek B ash, dated at 0.6 million years by Izett and Wilcox (1982). This upper-limit age is corroborated by the age determinations from the Mescalero caliche (hereafter referred to as the Mescalero) that overlies the Gatuña (see Section 2.1.3.9). An additional volcanic ash from the Gatuña in Texas yields consistent K-Ar and geochemical data, indicating that it is about 13 million years old at that location (Powers and Holt 1993, p. 271). Thus, the Gatuña ranges in age over a period of time that may be greater than that spanned by the Ogallala Formation (hereafter referred to as the Ogallala) on the High Plains east of WIPP.

2.1.3.9 Mescalero Caliche

The Mescalero caliche is an informal stratigraphic unit apparently first differentiated by Bachman in 1974, though Bachman (1973, p. 17, p. 27) described the caliche on the Mescalero Plain. He differentiated the Mescalero from the older, widespread Ogallala caliche or caprock on the basis of textures, noting that breccia and pisolitic textures are much more common in the Ogallala caliche. The Mescalero has been noted over significant areas in the Pecos drainage, including the WIPP area, and it has been formed over a variety of substrates. Bachman (1973) described the Mescalero as a two-part unit: (1) an upper dense laminar caprock and (2) a basal, earthy-to-firm, nodular calcareous deposit. Machette (1985, p. 5) classified the Mescalero as having Stage V morphologies of a calcic soil (the more mature Ogallala caprock that occurs east of the WIPP site reaches Stage VI).

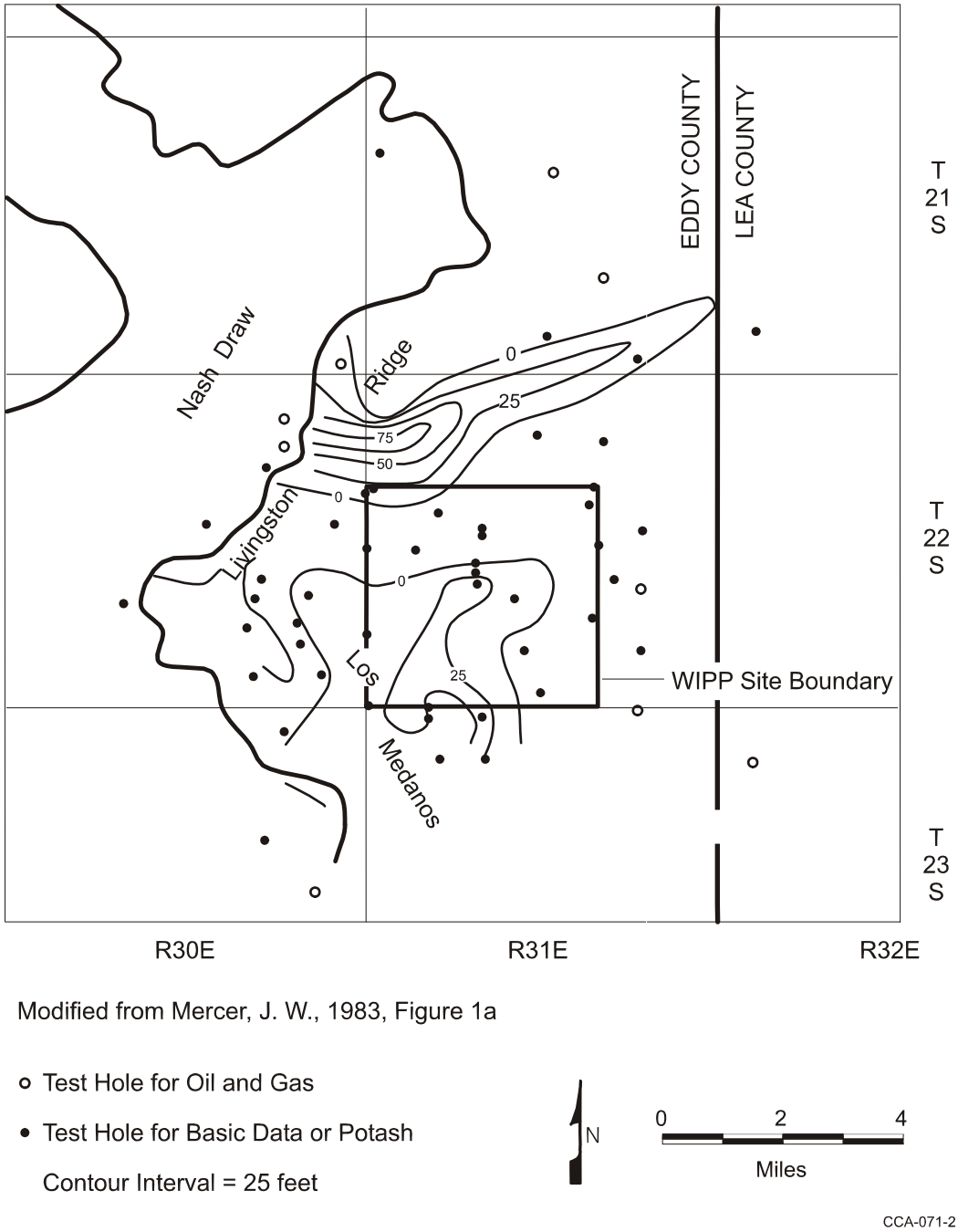

Figure 2-21. Isopach of the Gatuña

Bachman (1976, Figure 8) provided structure contours on the Mescalero caliche for a large area of southeastern New Mexico, including the WIPP site. From the contours and Bachman's discussion of the Mescalero as a soil, it is clear that the Mescalero is expected to be continuous over large areas. Explicit WIPP data are limited mainly to boreholes, though some borehole reports do not mention the Mescalero. The unit may be as much as 3 m (10 ft) thick.

The Mescalero overlies the Gatuña and was interpreted by Bachman (1976) on basic stratigraphic grounds as having accumulated during the early-to-middle Pleistocene. Samples of the Mescalero from the vicinity of the WIPP were studied using uranium-trend methods.

Based on early written communication from Rosholt, Bachman (1985, p. 20) reports that the basal Mescalero began to form about 510,000 years ago and the upper part began to form about 410,000 years ago; these ages are commonly cited in WIPP literature. The samples are interpreted by Rosholt and McKinney (1980, Table 5) in the formal report as indicating ages of 570,000 ± 110,000 years for the lower part of the Mescalero and 420,000 ± 60,000 years for the upper part.

According to Bachman (1985, p. 19), where the Mescalero is flat-lying and not breached by erosion, it is an indicator of stability or integrity of the land surface over the last 500,000 years. An additional discussion of the Mescalero caliche can be found in CCA Appendix GCR, Section 4.2.2.

2.1.3.10 Surficial Sediments

Soils of the region have developed mainly from Quaternary and Permian parent material. Parent material from the Quaternary System is represented by alluvial deposits of major streams, dune sand, and other surface deposits. These are mostly loamy and sandy sediments containing some coarse fragments. Parent material from the Permian System is represented by limestone, dolomite, and gypsum bedrock. Soils of the region have developed in a semiarid, continental climate with abundant sunshine, low relative humidity, erratic and low rainfall, and a wide variation in daily and seasonal temperatures. Subsoil colors are normally light brown to reddish brown but are often mixed with lime accumulations (caliche) that result from limited, erratic rainfall and insufficient leaching.

A soil association is a landscape with a distinctive pattern of soil types (series). It normally consists of one or more major soils and at least one minor soil. There are three soil associations within 8.3 km (5 mi) of the WIPP site: the Kermit-Berino, the Simona-Pajarito, and the Pyote-Maljamar-Kermit. Of these three associations, only the Kermit-Berino soil series has been mapped across the WIPP site by Chugg et al. (1952, Sheet No. 113). These are sandy soils developed on eolian material. The Kermit-Berino soils include active dune areas. The Berino soil has a sandy A horizon; the B horizons include more argillaceous material and weak-to-moderate soil structures. A and B horizons are described as noncalcareous, and the underlying C horizon is commonly caliche. Bachman (1980, p. 44) interpreted the Berino soil as a paleosol that is a remnant B horizon of the underlying Mescalero. Rosholt and McKinney (1980, Table 5) applied uranium-trend methods to samples of the Berino soil from the WIPP site area. Rosholt and McKinney (1980) interpreted the age of formation of the Berino soil as 330,000 ± 75,000 years.

Generally, the Berino Series, which covers about 50 percent of the site, consists of deep, noncalcareous, yellow-red to red sandy soils that developed from wind-worked material of mixed origin. These soils are described as undulating to hummocky and gently sloping (zero to three percent slopes). The soils are the most extensive of the deep, sandy soils in the Eddy County area. Berino soils are subject to continuing wind and water erosion. If the vegetative

cover is seriously depleted, the water-erosion potential is slight, but the wind-erosion potential is very high. These soils are particularly sensitive to wind erosion in the months of March, April, and May, when rainfall is minimal and winds are highest. These soil characteristics are a consideration for the design of long-term passive controls such as monuments and markers (see CCA Appendix PIC, Section III).

The Kermit Series consists of deep, light-colored, noncalcareous, excessively drained loose sands, typically yellowish-red fine sand. The surface is undulating to billowy (from 0 to 3 percent slopes) and consists mostly of stabilized sand dunes. Kermit soils are slightly to moderately eroded. Permeability is very high, and, if vegetative cover is removed, the water-erosion potential is slight, but the wind-erosion potential is very high.

Surface soils appear to play a role in the infiltration of precipitation. Mercer (CCA Appendix HYDRO) points out that where surface deposits are thickest, they may contain localized perched zones of groundwater. A more thorough discussion of this topic can be found in CCA Appendix HYDRO.

2.1.3.11 Summary

The stratigraphy and lithology at the WIPP site has been summarized from the lowermost pre-Cambrian units to the surface soils. While these are important for an understanding of the site and its stability, not all of these units are important to the performance of the disposal system. As a result, the DOE has developed a conceptual model that describes the lithology as 13 discrete model regions ranging from the Castile to a region that generally includes units above the Dewey Lake. In this model, emphasis is placed on the Castile, the Salado, the five members of the Rustler, the Dewey Lake, and the supra-Dewey Lake units. The Salado is divided into five stratigraphic units to capture the variations in properties near the horizon of the repository (see Figure 6-14). The identification and definition of the appropriate modeling units is based on the identification of FEPs that can impact the performance of the disposal system. Details of the conceptual model can be found in Section 6.4.2.

2.1.4 Physiography and Geomorphology

In this section, the DOE presents a discussion of the physiography and geomorphology of the WIPP site and surrounding area. This information is taken from DOE 1980 (pp. 7-21 to 7-23). Geomorphology and physiography are determined by the DOE (1980) to be features that are potentially important to disposal system performance. They are included in the consequence analysis through consideration of the topography and its influence on the regional water table. (See discussion of regional water table characteristics in Section 2.2.1.) Consequently, topographic information is presented in this section. In addition, several geomorphological processes have been screened out on the basis of either low consequence or low probability, as discussed in Appendix PA, Attachment SCR. These include weathering, erosion, sedimentation, and soil development. Information is presented in this section to support this screening. In order to perform this screening, such factors as slopes, proximity to watercourses, dissection, and historic and existing processes are important. These are presented in this section in terms of the regional and local physiographic and geomorphological characteristics. Tectonic processes that may alter the physiography of the region or site area are discussed in Section 2.1.5. In addition,

Section 2.1.6 presents more specific details on nontectonic processes identified during site characterization as having the potential for affecting the repository over the longer term and as requiring detailed investigation. These include halite deformation and dissolution.

2.1.4.1 Regional Physiography and Geomorphology

The WIPP site is in the Pecos Valley section of the southern Great Plains physiographic province (Figure 2-22), a broad, highland belt sloping gently eastward from the Rocky Mountains and the Basin and Range Province to the Central Lowlands Province. The Pecos Valley section itself is dominated by the Pecos River Valley, a long north-south trough that is from 8.3 to 50 km (5 to 30 mi) wide and as much as 305 m (1,000 ft) deep in the north. The Pecos River System has evolved from the south, cutting headward through the Ogallala sediments and becoming entrenched some time after the Middle Pleistocene. It receives almost all the surface and subsurface drainage of the region; most of its tributaries are intermittent because of the semiarid climate. The surface locally has a karst terrain containing sinkholes, dolines, and solution-subsidence troughs from both surface erosion and subsurface dissolution. The valley has an uneven rock- and alluvium-covered floor with widespread solution-subsidence features, the result of dissolution in the underlying Upper Permian rocks. The terrain varies from plains and lowlands to rugged canyonlands, and contains such erosional features as scarps, cuestas, terraces, and mesas. The surface slopes gently eastward, reflecting the underlying rock strata. Elevations vary from more than 1,829 m (6,000 ft) in the northwest to about 610 m (2,000 ft) in the south.

The Pecos Valley section is bordered on the east by the virtually uneroded plain of the Llano Estacado. The Llano Estacado is part of the High Plains section of the Great Plains physiographic province and is a poorly drained eastward-sloping surface covered by gravels, wind-blown sand, and caliche that has developed since early-to-middle Pleistocene time. Few and minor topographic features are present in the High Plains section, formed when more than 152 m (500 ft) of Tertiary silts, gravels, and sands were laid down in alluvial fans by streams draining the Rocky Mountains. In many areas, the nearly flat surface is cemented by a hard caliche layer.

To the west of the Pecos Valley section are the Sacramento Mountains and the Guadalupe Mountains, part of the Sacramento section of the Basin and Range Province. The Capitan escarpment along the southeastern side of the Guadalupe Mountains marks the boundary between the Basin and Range and the Great Plains provinces. The Sacramento section has large basinal areas and a series of intervening mountain ranges (DOE 1980).

2.1.4.2 Site Physiography and Geomorphology

The land surface in the area of the WIPP site is a semiarid, wind-blown plain sloping gently to the west and southwest, and is hummocky with sand ridges and dunes. A hard caliche layer (Mescalero rocks) is typically present beneath the sand blanket and on the surface of the underlying Gatuña. Figure 2-23 is a topographic map of the area. Elevations at the site range from 1,088 m (3,570 ft) in the east to 990 m (3,250 ft) in the west. The average east-to-west slope is 9.4 m per kilometer (50 ft/mi).

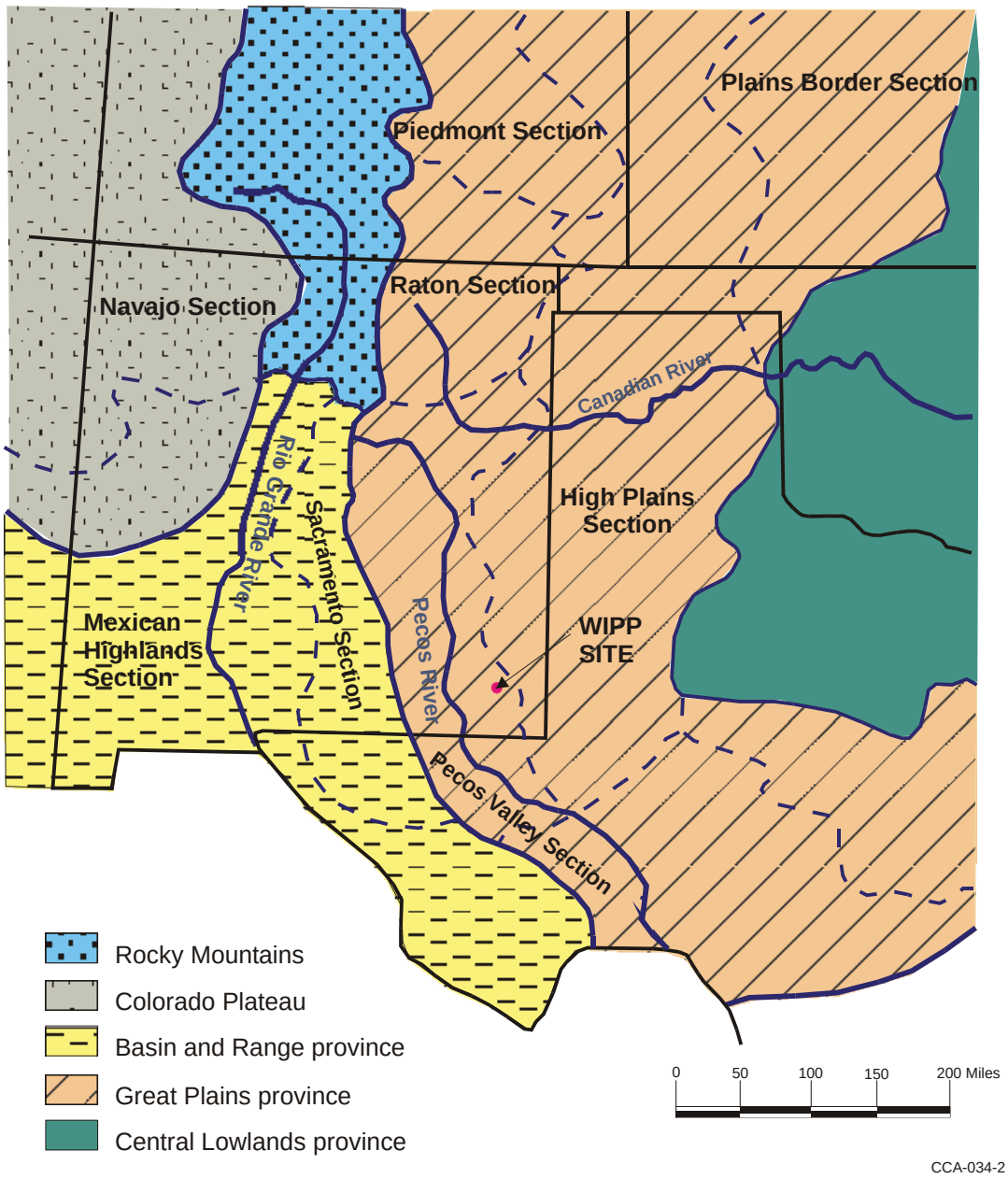

Figure 2-22. Physiographic Provinces and Sections

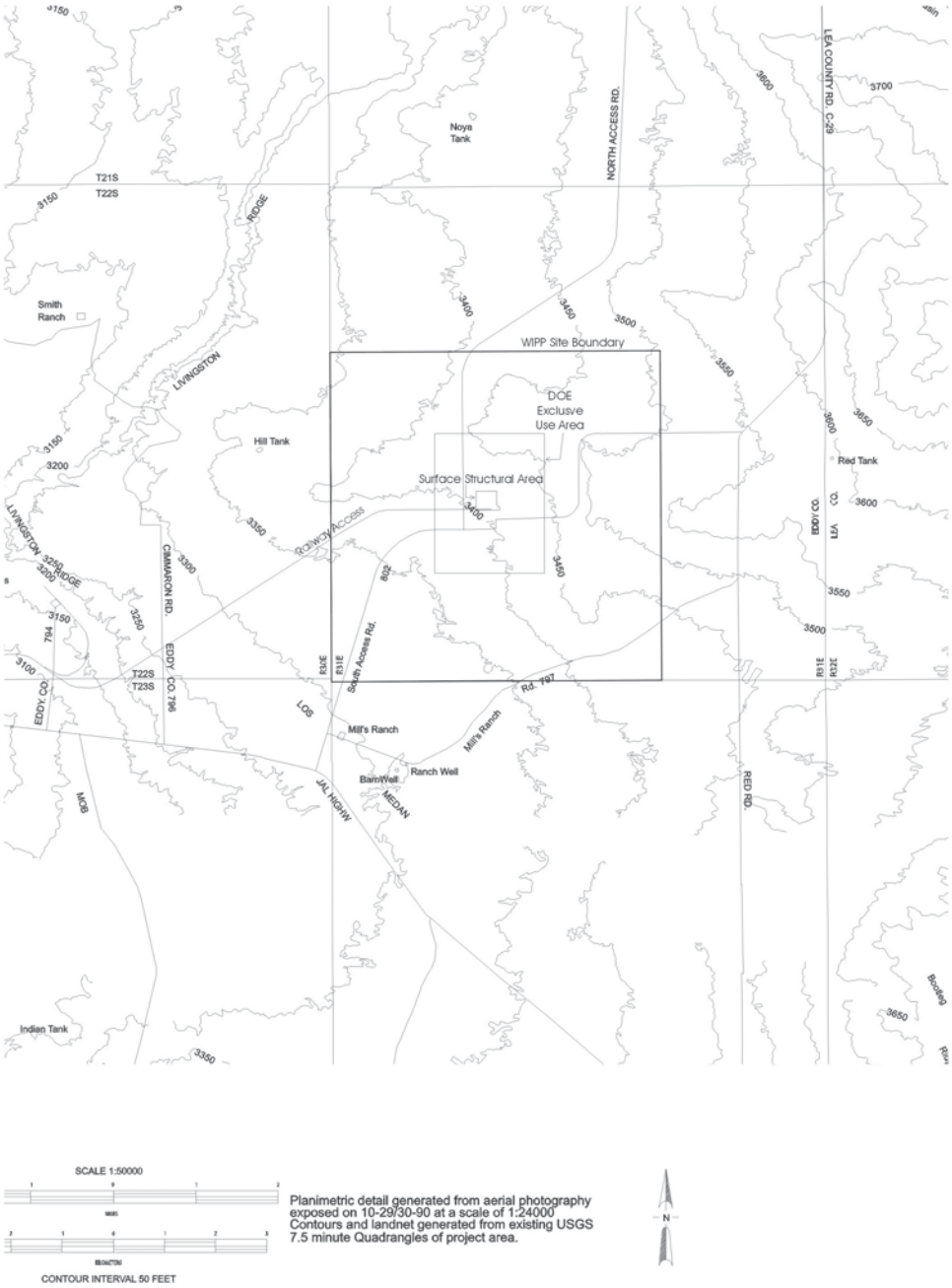

Figure 2-23 Topographic Map of the Area Around the WIPP Site

Livingston Ridge is the most prominent physiographic feature near the site. It is a west-facing escarpment that has about 23 m (75 ft) of topographic relief and marks the eastern edge of Nash Draw, the drainage course nearest to the site (see Figure 2-23). Nash Draw is a shallow 8-km-wide (5-mi-wide) basin, 61 to 91 m (200 to 300 ft) deep and open to the southwest. It was caused, at least in part, by subsurface dissolution and the accompanying subsidence of overlying sediments. Livingston Ridge is the approximate boundary between terrain that has undergone erosion and/or solution collapse to the west and terrain that has been little affected to the east.

About 24 km (15 mi) east of the site is the southeast-trending San Simon Swale, a depression caused, at least in part, by subsurface dissolution. Between San Simon Swale and the site is a broad, low mesa named the Divide. Lying about 9.7 km (6 mi) east of the site and about 30 m (100 ft) above the surrounding terrain, it is a boundary between southwest drainage toward Nash Draw and southeast drainage toward San Simon Swale. The Divide is capped by the Ogallala and the overlying caliche, upon which have formed small, elongated depressions similar to those in the adjacent High Plains section to the east.

Surface drainage is intermittent; the nearest perennial stream is the Pecos River, 19 km (12 mi) southwest of the WIPP site boundary. The site's location near a natural divide protects it from flooding and serious erosion caused by heavy runoff. Should the climate become more humid, any perennial streams should follow the present basins, and Nash Draw and San Simon Swale would be the most eroded, leaving the area of the Divide relatively intact.

2.1.5 Tectonic Setting and Site Structural Features

The DOE has screened out, on the basis of either probability or consequence or both, all tectonic, magmatic, and structural related processes. The screening discussions can be found in Appendix PA, Attachment SCR. The information needed for this screening is included here and covers regional tectonic processes such as subsidence and uplift and basin tilting, magmatic processes such as igneous intrusion and events such as volcanism, and structural processes such as faulting and loading and unloading of the rocks because of long-term sedimentation or erosion. Discussions of structural events, such as earthquakes, are considered to the extent that they may create new faults or activate old faults. The seismicity of the area is considered in Section 2.6 for the purposes of determining seismic design parameters for the facility.

2.1.5.1 Tectonics

The processes and features included in this section are those more traditionally considered part of tectonics, processes that develop the broad-scale features of the earth. Salt dissolution is a different process that can develop some features resembling those of tectonics.

Most broad-scale structural elements of the area around the WIPP developed during the Late Paleozoic (CCA Appendix GCR, pp. 3-58 to 3-77). There is little historical or geological evidence of significant tectonic activity in the vicinity, and the level of stress in the region is low. The entire region tilted slightly during the Tertiary, and activity related to Basin and Range tectonics formed major structures southwest of the area. Seismic activity is specifically addressed in a separate section.

Broad subsidence began in the area as early as the Ordovician, developing a sag called the Tobosa Basin. By Late Pennsylvanian to Early Permian time, the Central Basin Platform developed (Figure 2-24), separating the Tobosa Basin into two parts: the Delaware Basin to the west and the Midland Basin to the east. The Permian Basin refers to the collective set of depositional basins in the area during the Permian Period. Southwest of the Delaware Basin, the Diablo Platform began developing either in the Late Pennsylvanian or Early Permian. The Marathon Uplift and Ouachita tectonic belt limited the southern extent of the Delaware Basin.

According to Brokaw et al. (1972, p. 30), pre-Ochoan sedimentary rocks in the Delaware Basin show evidence of gentle downwarping during deposition, while Ochoan and younger rocks do not. A relatively uniform eastward tilt, generally from about 14 to 19 m/per km (75 to 100 ft/mi), has been superimposed on the sedimentary sequence.[1] King (1948, pp. 108 and 121) generally attributes the uplift of the Guadalupe and Delaware mountains along the west side of the Delaware Basin to the later Cenozoic, though he also notes that some faults along the west margin of the Guadalupe Mountains have displaced Quaternary gravels.

[1] Local dip of the Salado has been determined by mapping in the WIPP underground excavations. This dip is modeled as one degree to the south, as discussed in Section 6.4.2.1.

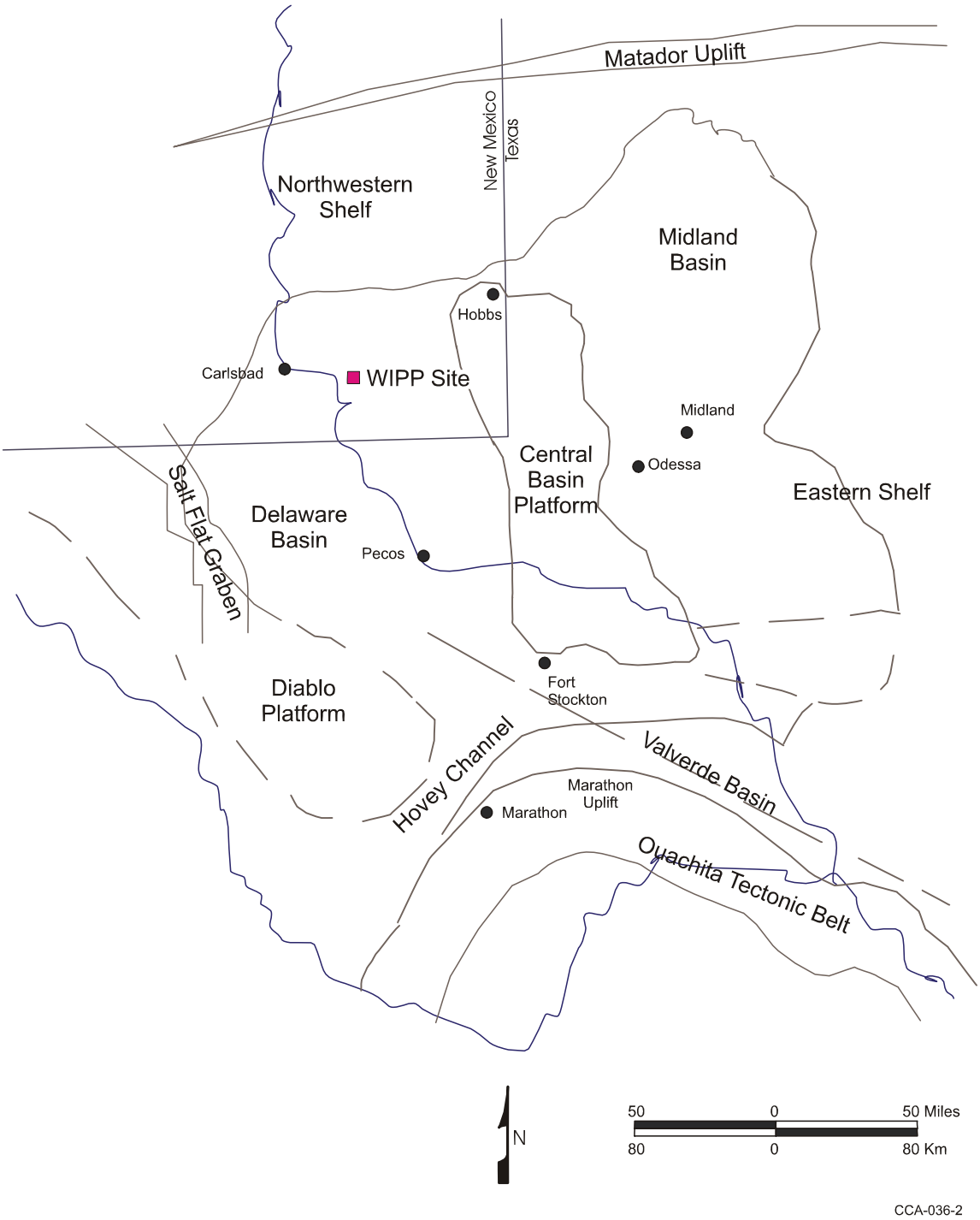

Figure 2-24. Structural Provinces of the Permian Basin Region

King (1948, p. 144) also infers the uplift from the Pliocene-age deposits of the Llano Estacado. Subsequent studies of the Ogallala of the Llano Estacado show that it varies in age from Miocene (about 12 million years before present) to Pliocene (Hawley 1993). This is the most likely range for uplift of the Guadalupe Mountains and broad tilting to the east of the Delaware Basin sequence.

Analysis of the present regional stress field indicates that the Delaware Basin lies within the Southern Great Plains stress province. This province is a transition zone between the extensional stress regime to the west and the region of compressive stress to the east. An interpretation by Zoback and Zoback (1991, p. 350) of the available data indicates that the level of stress in the Southern Great Plains stress province is low. Changes to the tectonic setting, such as the development of subduction zones and a consequent change in the driving forces, would take much longer than 10,000 years to occur.

To the west of the Southern Great Plains province is the Basin and Range province, or Cordilleran Extension province, where according to Zoback and Zoback (1991, pp. 348 - 351), normal faulting is the characteristic style of deformation. The eastern boundary of the Basin and Range province is marked by the Rio Grande Rift. Sanford et al. (1991, p. 230) note that, as a geological structure, the rift extends beyond the relatively narrow geomorphological feature seen at the surface, with a magnetic anomaly at least 500 km (300 mi) wide. On this basis, the Rio Grande Rift can be regarded as a system of axial grabens along a major north-south trending structural uplift (a continuation of the Southern Rocky Mountains). The magnetic anomaly extends beneath the Southern Great Plains stress province, and regional-scale uplift of about 1,000 m (3,300 ft) over the past 10 million years also extends into eastern New Mexico.

To the east of the Southern Great Plains province is the large Mid-Plate province that encompasses central and eastern regions of the conterminous United States and the Atlantic basin west of the Mid-Atlantic Ridge. The Mid-Plate province is characterized by low levels of paleo- and historic seismicity. Where Quaternary faulting has occurred, it is generally strike-slip and appears to be associated with the reactivation of older structural elements.

Zoback et al. (1991) report no stress measurements from the Delaware Basin. The stress field in the Southern Great Plains stress province has been defined from borehole measurements in west Texas and from volcanic lineaments in northern New Mexico. These measurements were interpreted by Zoback and Zoback (1991, p. 353) to indicate that the least principal horizontal stress is oriented north-northeast and south-southwest and that most of the province is characterized by an extensional stress regime.

There is an abrupt change between the orientation of the least principal horizontal stress in the Southern Great Plains and the west-northwest orientation of the least principal horizontal stress characteristic of the Rio Grande Rift. In addition to the geological indications of a transition zone as described above, Zoback and Zoback (1980, p. 6134) point out that there is also evidence for a sharp boundary between these two provinces. This is reinforced by the change in crustal thickness from about 40 km (24 mi) beneath the Colorado Plateau to about 50 km (30 mi) or more beneath the Southern Great Plains east of the Rio Grande Rift. The base of the crust within the Rio Grande Rift is poorly defined but is shallower than that of the Colorado Plateau (Thompson and Zoback 1979, p. 152). There is also markedly lower heat flow in the Southern

Great Plains (typically < 60 mWm^{-2}) reported by Blackwell et al. (1991, p. 428) compared with that in the Rio Grande Rift (typically > 80 mWm^{-2}) reported by Reiter et al. (1991, p. 463).

On the eastern boundary of the Southern Great Plains province, there is only a small rotation in the direction of the least principal horizontal stress. There is, however, a change from an extensional, normal faulting regime to a compressive, strike-slip faulting regime in the Mid-Plate province. According to Zoback and Zoback (1980, p. 6134), the available data indicate that this change is not abrupt and that the Southern Great Plains province can be viewed as a marginal part of the Mid-Plate province.

2.1.5.2 Loading and Unloading

Loading and unloading during the geological history since deposition is considered an influence on the hydrology of the Permian units because of its possible effect on the development of fractures.

The sedimentary loading, depth of total burial, and erosion events combine in a complex history reconstructed here from regional geological trends and local data. The history is presented in Figure 2-25 with several alternatives, depending on the inferences that are drawn, ranging from minimal to upper-bound estimates (Powers and Holt 1995, Section 5.3). Borns (1987) also made a generalized estimate of loading that is similar. The estimates are made with a reference point and depth to the Culebra at the AIS.

Given the maximum local thickness of the Dewey Lake, the maximum load at the end of the Permian was no more than approximately 240 m (787 ft). Given the present depth to the Culebra from the top of the Dewey Lake in the AIS, approximately 35 m (115 ft) of Dewey Lake might have been eroded during the Early Triassic before additional sediments were deposited. The Triassic thickness at the AIS is approximately 8 m (26 ft). Northeast of the WIPP site (T21S, R33E), Triassic rocks (Dockum Group) have a maximum local thickness of approximately 373 m (1,233 ft). This thickness is a reasonable estimate of the maximum thickness also attained at the WIPP site prior to the Jurassic Period. At the end of the Triassic, the total thickness at the WIPP site may have then attained approximately 586 m (1,863 ft) in two similar loading stages of a few million years each, over a period of approximately 50 million years.

The Jurassic outcrops nearest to the WIPP site are in the Malone Mountains of west Texas. There is no evidence that Jurassic rocks were deposited at or in the vicinity of the WIPP site.

As a consequence, the Jurassic is considered a time of erosion or nondeposition at the site, though erosion is most likely.

Widespread erosion during the Jurassic obviously cannot be broadly inferred for the area or there would not be thick Triassic rocks still preserved. Triassic rocks of this thickness are preserved nearby, indicating either pre-Jurassic tilting or that erosion did not occur until later (but still after tilting to preserve the Triassic rocks near the WIPP site). It is also possible that the immediate site area had little Triassic deposition or erosion, but very limited Triassic deposition (that is, 8 m [26 ft]) at the WIPP site seems unlikely.

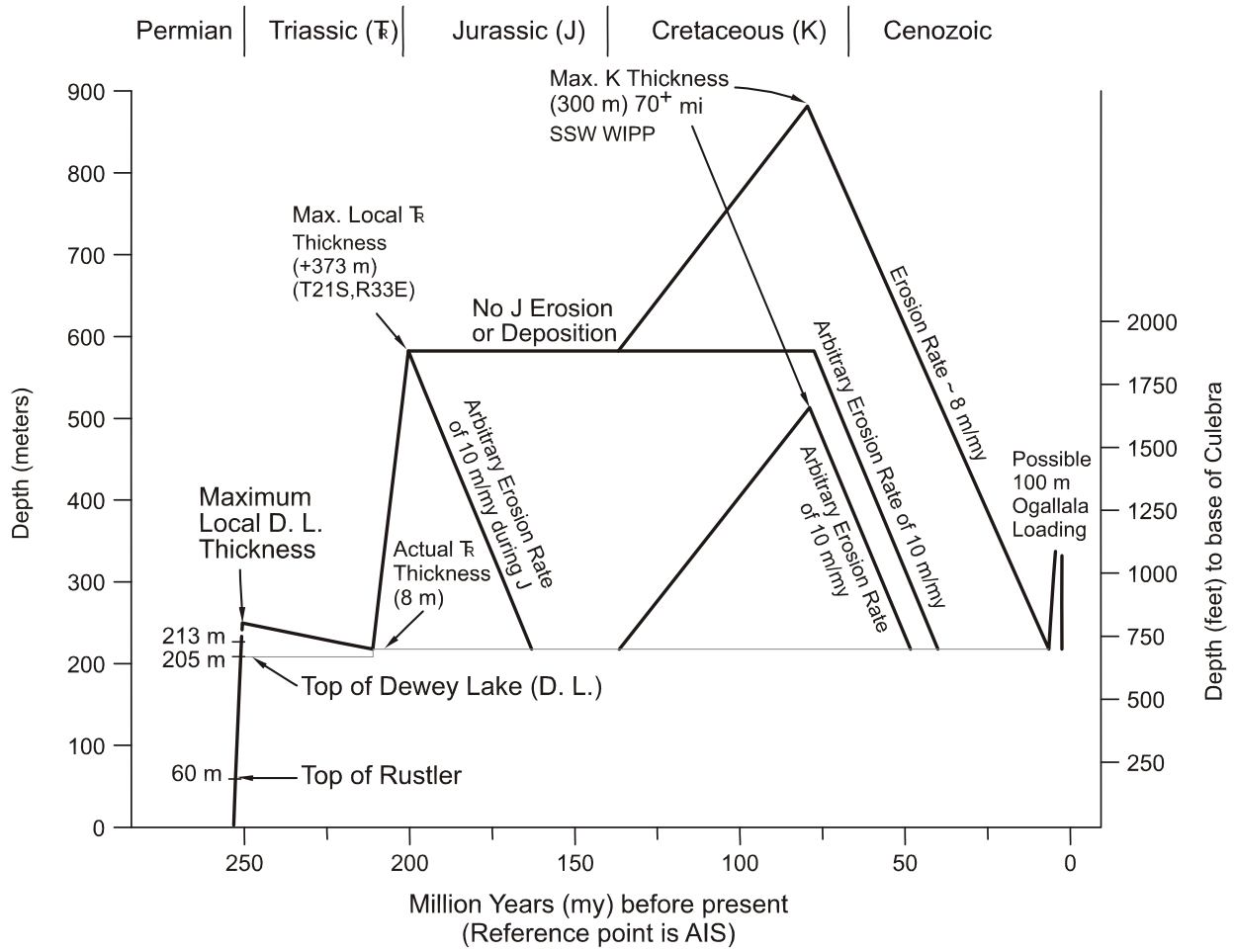

Note: The estimates are made with a reference point and depth to the base of the Culebra at the AIS. Source: Powers and Holt 1995, Figure 34.

Figure 2-25. Loading and Unloading History Estimated to the Base of the Culebra

Lang (1947) reported fossils from Lower Cretaceous rocks in the Black River Valley southwest of the WIPP site. Bachman (1980, p. 28) also reported similar patches of probable Cretaceous rocks near Carlsbad and south of White's City. From these reports, it is likely that some Cretaceous rocks were deposited at the WIPP site. Approximately 110 km (70 mi) south-southwest of the WIPP site, significant Cretaceous outcrops of both Early and Late Cretaceous age have a total maximum thickness of approximately 300 m (1,000 ft). Southeast of the WIPP, the nearest Cretaceous outcrops are thinner and represent only the Lower Cretaceous. Based on outcrops, a maximum thickness of 300 m (1,000 ft) of Cretaceous rocks could be estimated for the WIPP site. Compared to the estimate of Triassic rock thickness, it is less likely that Cretaceous rocks were this thick at the site. The uppermost lines of Figure 2-25 summarize the assumptions of maximum thickness of these units.

A more likely alternative is that virtually no Cretaceous rocks were deposited, followed by erosion of remaining Triassic rocks during the Late Cretaceous to the Late Cenozoic. Such erosion may also have taken place over an even longer period, beginning with the Jurassic Period. Ewing (1993) favors Early Cretaceous uplift and erosion for the Trans-Pecos Texas area, but does not analyze later uplift and erosional patterns.

In the general vicinity of the WIPP site, there are outcrops of Cenozoic rock from the Late Miocene (Gatuña and Ogallala Formations). There is little reason to infer any significant Early Cenozoic sediment accumulation at the WIPP site. Erosion is the main process inferred to have occurred during this period and an average erosion rate of approximately 10 m (33 ft) per million years is sufficient during the Cenozoic to erode the maximum inferred Triassic and Cretaceous thickness prior to Gatuña and Ogallala deposition. Significant thicknesses of Cretaceous rocks may not have been deposited, however, and average erosion rates could have been lower.

Maximum-known Gatuña thickness in the area around the WIPP is approximately 100 m (330 ft); at the WIPP site, the Gatuña is very thin to absent. Ogallala deposits are known from the Divide east of the WIPP site, as well as from the High Plains further east and north. On the High Plains northeast of the WIPP, the upper Ogallala surface slopes to the southeast at a rate of approximately 4 m/km (20 feet per mile). A straight projection of the 1,250-m (4,100-ft) contour line from this High Plains surface intersects the site area, which is at an elevation slightly above 1,036 m (3,400 ft). This difference in elevation of 213 m (700 ft) represents one estimate, probably near an upper bound, of possible unloading subsequent to deposition of the Ogallala Formation.

Alternatively, the loading and unloading of the Ogallala could have been closer to 100 m (330 ft). In any case, it would have occurred as a short-lived pulse over a few million years at most.

While the above inferences about greater unit thicknesses and probable occurrence are permissible, a realistic assessment suggests a more modest loading and unloading history (Powers and Holt 1995). It is likely that the Dewey Lake accumulated to near local maximum thickness of approximately 240 m (787 ft) before being slightly eroded prior to the deposition of Triassic rocks. It also is most probable that the Triassic rocks accumulated at the site to near local maximum thickness. In two similar cycles of rapid loading, the Culebra was buried to a depth of approximately 650 m (2,132 ft) by the end of the Triassic.

It also seems unlikely that a significant thickness of Cretaceous rock accumulated at the WIPP site. Erosion probably began during the Jurassic, slowed or stopped during the Early Cretaceous as the area was nearer or at base level, and then accelerated during the Cenozoic, especially in response to uplift as Basin and Range tectonics encroached on the area and the basin was tilted more. Erosional beveling of Dewey Lake and Santa Rosa suggest considerable erosion since tilting in the mid-Cenozoic. Erosion rates for this shorter period could have been relatively high, resulting in the greatest stress relief on the Culebra and surrounding units. Some filling occurred during the Late Cenozoic as the uplifted areas to the west formed an apron of Ogallala sediment across much of the area, but it is not clear how much Gatuña or Ogallala sediment was deposited in the site area. From general reconstruction of Gatuña history in the area (Powers and Holt 1993, p. 281), the DOE infers that Gatuña or Ogallala deposits likely were not much thicker at

the WIPP site than they are now. The loading and unloading spike (Figure 2-25) representing Ogallala thickness probably did not occur. Cutting and headward erosion by the Pecos River has created local relief and unloading by erosion.

At the WIPP site, this history is a little complicated by dissolution, though locally (for example, Nash Draw) the effects of erosion and dissolution are more significant. The underlying evaporites have responded to foundering of anhydrite in less dense halite beds. These have caused local uplift of the Culebra (as at ERDA 6) but little change in the overburden at the WIPP. Areas east of the WIPP site are likely to have histories similar to that of the site. West of the site, the final unloading is more complicated by dissolution and additional erosion leading to exposure of the Culebra along stretches of the Pecos River Valley.

2.1.5.3 Faulting

Fault zones are well known along the Central Basin Platform, east of WIPP, from extensive drilling for oil and gas, as reported by Hills (1984). Holt and Powers performed an analysis in 1988 (CCA Appendix FAC, p. 4-14) of geophysical logs from oil and gas wells to examine the regional geology for the Rustler. This analysis showed that faults along the margin of the Central Basin Platform displaced Rustler rocks of at least Late Permian age. The overlying Dewey Lake shows marked thinning along the same trend, according to Schiel (1988, Figure 21), but the structure contours of the top of the Dewey Lake are not clearly offset. Schiel (1988) concluded that the fault was probably reactivated during the Dewey Lake's deposition, but movement ceased at least by the time the Santa Rosa was deposited. No surface displacement or fault has been reported along this trend.

Muehlberger et al. (1978) mapped Quaternary fault scarps along the Salt Basin graben west of both the Guadalupe and Delaware mountains. These are the nearest known Quaternary faults of tectonic origin to the WIPP. Kelley (1971) inferred the Carlsbad and Barrera faults along the eastern escarpment of the Guadalupe Mountains based mainly on vegetative lineaments. Hayes and Bachman (1979) reexamined the field evidence for these faults in 1979 and concluded that they were nonexistent. Figure 2-26 illustrates major regional structures, including faults.

On a national basis, Howard et al. (1971, sheets 1 and 2) assessed the location and potential for activity of young faults. For the region around the WIPP site, Howard et al. (1971, sheet 1) located faults along the western escarpment of the Delaware and Guadalupe mountain trend. These faults were judged to be Late Quaternary (approximately the last 500,000 years) or older.

In summary, there are no known Quaternary or Holocene faults of tectonic origin that offset rocks at the surface nearer to the site than the western escarpment of the Guadalupe Mountains. A significant part of the tilt of basin rocks is attributed to a mid-Miocene to Pliocene uplift trend along the Guadalupe-Sacramento Mountains that is inferred on the basis of High Plains sediments of the Ogallala.

2.1.5.4 Igneous Activity

Within the Delaware Basin, only one feature of igneous origin is known to have formed since the Precambrian. An igneous lamprophyre dike or series of dikes occurs along a linear trace about

120 km (75 mi) long from the Yeso Hills south of White's City to the northeast of the WIPP site

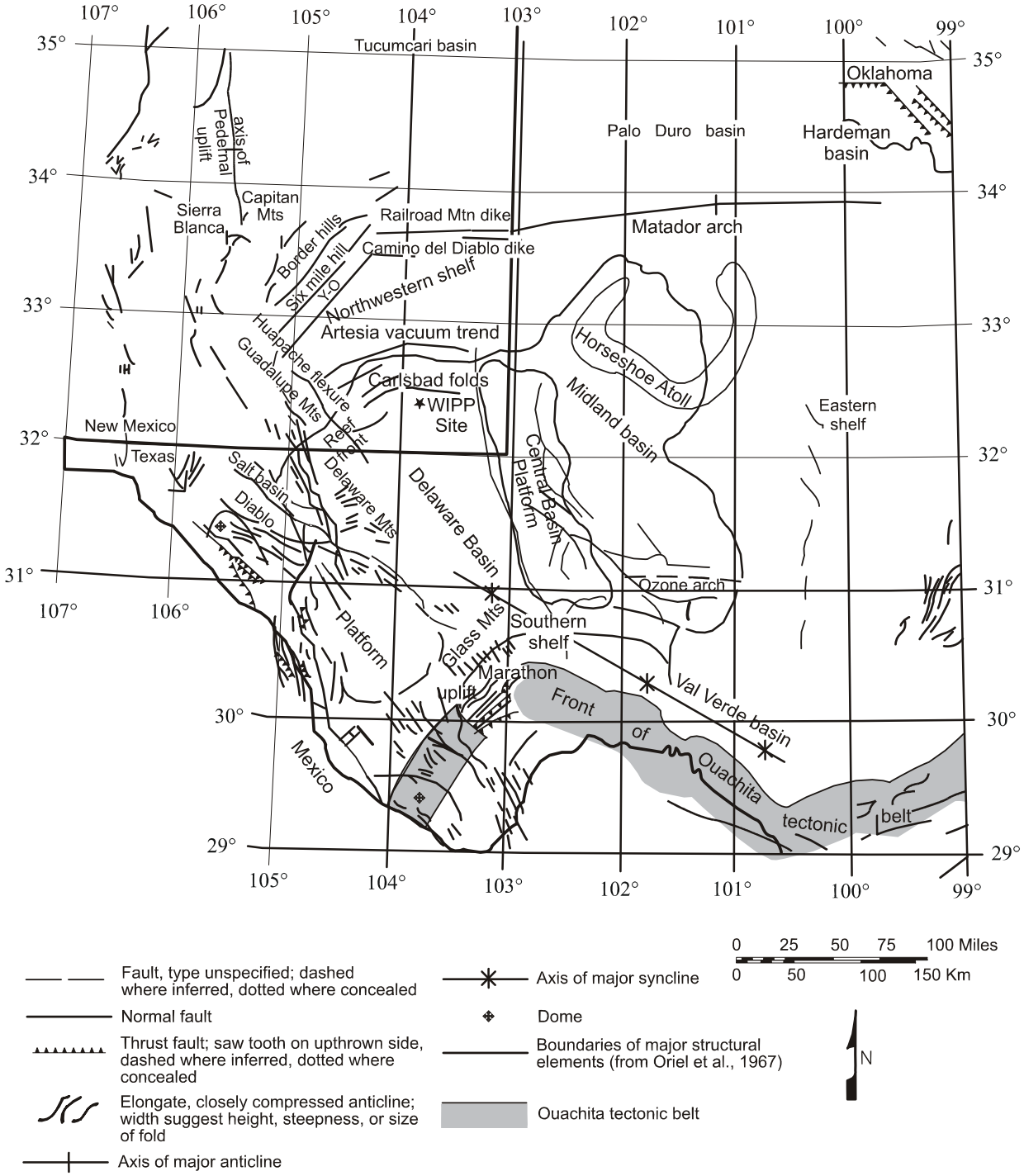

Figure 2-26. Regional Structures

(Elliot Geophysical Company 1976). At its closest, the dike trend passes about 13 km (8 mi) northwest of the WIPP site center, as shown in Figure 2-27. Evidence for the extent of the dike includes outcroppings at Yeso Hills, subsurface intercepts in boreholes and mines, and airborne magnetic responses.

An early radiometric determination for the dike by Urry (1936) yielded an age of 30 ± 1.5 million years. Work on dike samples by Calzia and Hiss (1978) is consistent with earlier work, indicating an age of 34.8 ± 0.8 million years.[2] Work by Brookins (1980) on polyhalite samples in contact with the dike indicated an age of about 21.4 million years. Volcanic ashes found in the Gatuña (Section 2.1.3.8) were airborne from distant sources and do not represent volcanic activity at the WIPP site.

2.1.6 Nontectonic Processes and Features

Nontectonic processes and features, which include evaporite deformation and dissolution of strata, are known to be active in the Delaware Basin. These processes are of interest because they represent mechanisms that are potentially disruptive to the repository in the long term. Both processes have been investigated extensively. The conclusions from these investigations are summarized in this section.

Halite in evaporite sequences is relatively plastic, which can lead to the process of deformation; it is also highly soluble, which can lead to the process of dissolution. Both processes (deformation and dissolution) can produce structural features similar to those produced by tectonic processes. The features developed by dissolution and deformation can be distinguished from similar-looking tectonic features where the underlying units do not reflect the same feature as do the evaporites. As an example, the evaporite deformation commonly does not affect the underlying Bell Canyon. Beds underlying areas of dissolved salt are not affected, but overlying units to the surface may be affected. The deformation in the Castile and Salado also tends to die out in overlying units, and the Rustler or the Dewey Lake may show little, if any, effects from deformed evaporites.

2.1.6.1 Evaporite Deformation

The most recent review of evaporite deformation in the northern Delaware Basin and original work to evaluate deformation is summarized here. More detail is provided in CCA Appendix DEF.

2.1.6.1.1 Basic WIPP History of Deformation Investigations

The Castile has been known for many years to be deformed in parts of the Delaware Basin, especially along the northern margin. Jones et al. (1973) clearly showed the Castile to be thicker from the northwestern to northern part of the basin margin, just inside the Capitan Reef. A dissertation by Snider (1966, Figures 11 and 14) and a paper by Anderson et al. (1972, Figure 10) also presented maps showing some evidence of thicker sections of Castile next to the

[2] Calzia and Hiss (1978, p. 44) reported 32.2 to 33.9 million years. However, Powers et al. 1978 (CCA Appendix GCR, p. 3-80) reported a recalculated value of 34.8 ± 0.8 million years based on a change in measured decay constant.

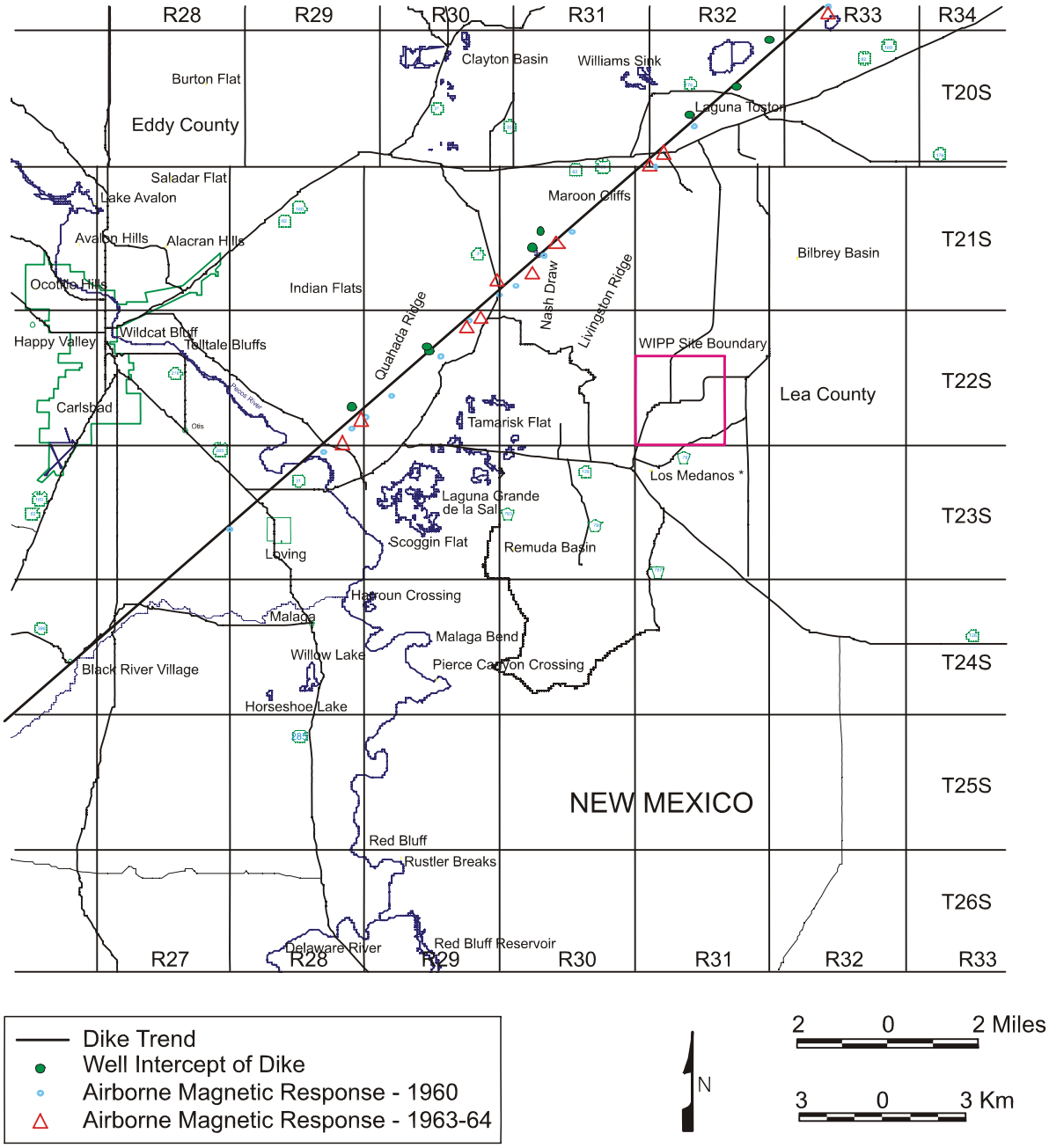

Source: Elliot (1976)

CCA-076-2

Figure 2-27. Igneous Dike in the Vicinity of the WIPP Site

Capitan. ERDA-6 was drilled during 1975 as part of the program to characterize an initial site for WIPP. The borehole penetrated increasingly deformed beds through the Salado into the Castile, and, at 826 m (2,711 ft) depth, the borehole began to produce pressurized brine and gas. Anderson and Powers (1978, p. 79) and Jones (1981a) interpreted beds to have been displaced structurally by as much as 289.5 m (950 ft). Some of the lower beds may have pierced overlying beds. The beds were considered too structurally deformed to mine reasonably along single horizons for a repository. Therefore, the site was abandoned in 1975, and the current site was located in 1976 (CCA Appendix GCR). The deformed beds around ERDA-6 were considered part of a deformed zone within about 10 km (6 mi) of the inner margin of the Capitan Reef. As a consequence, the preliminary selection criteria were revised to prohibit locating a new site within 10 km (6 mi) of the Capitan margin.

General criteria for the present site for the WIPP appeared to be met based on initial data from drilling (ERDA-9) and geophysical surveys. Beginning in 1977, the new site was more intensively characterized through geophysical surveys, including seismic reflection and drilling. Extensive seismic reflection work revealed good reflector quality in the southern part of the site and poor-quality or disturbed reflectors in a sector of the northern part of the site (see CCA Appendix DEF, Figure DEF-2.2). The area of disturbed reflectors became known as the disturbed zone, the area of anomalous seismic reflectors, or the zone of anomalous seismic reflection data. (The disturbed zone based on poor Castile seismic reflectors is completely different from the DRZ that describes the deformation around mined underground openings at the WIPP.)

Powers et al., in CCA Appendix GCR, Figures 4.4, 4.5, and 4.6, generally shows the disturbed zone beginning about 1.6 km (1 mi) north of the WIPP site center. Borns et al. (1983), included two areas south of the WIPP site as showing the same features of the disturbed zone. Neill et al.(1983) summarized the limits of the disturbed zone based on differing interpretations and included the area less than 1.6 km (1 mi) north of the site center, where the dip in the Castile begins to steepen. WIPP-11 was drilled in early 1978 about 5 km (3 mi) north of the site center over part of the disturbed zone where proprietary petroleum company data had also indicated significant seismic anomalies. The borehole encountered highly deformed beds within the Castile and altered thicknesses of halite units, but no pressurized brine and gas were found.

Less than 1.6 km (1 mi) north of the site center, seismic data indicated possible faulting of the upper Salado and the lower Rustler over the area of steepening Castile dips. Four boreholes (WIPP-18, -19, -21, -22) were drilled into the upper Salado and demonstrated neither faulting nor significant deformation of the Rustler-Salado contact. Lateral changes in the seismic velocity of the upper sections contributed to the interpretation of a possible fault and thus complicated interpretations of deeper structure.

WIPP-12 was located about 1.6 km (1 mi) north of the center of the site and drilled during 1978 to a depth of 850 m (2,785 ft) in the upper Castile to determine the significance of structure on possible repository horizons. The top of the Castile was encountered at an elevation about 49 m (160 ft) above the same contact in ERDA-9 at the site center.

WIPP-12 was deepened during late 1981 to a depth of 1,200 m (3,925 ft) to test for possible brine and gas in the deformed Castile. The probability of encountering brine and gas was

considered low because ERDA-6 and other known brine reservoirs in the Castile occurred in areas with greater deformation. During drilling, fractured anhydrite in the upper Castile (lower A3) began to yield pressurized brine and gas. The borehole was deepened to the basal anhydrite (A1) of the Castile. Subsequent reservoir testing (Popielak et al. 1983) was conducted to estimate reservoir properties (see Section 2.2.1.2.2 and Section 6.4.8).

As a consequence of discovering pressurized brine and gas in WIPP-12, the EEG recommended that the design of the facility be changed and that proposed waste disposal areas in the north be moved or reoriented to the south. After additional drilling of DOE-1, the DOE concluded that the design change had advantages, and the disposal facilities were placed south of the site center.

A microgravity survey of the site was designed to delineate further the structure within the disturbed zone, based on the large density differences between halite and anhydrite. The gravity survey was unsuccessful in yielding any improved resolution of the Castile structure.

DOE-2 was the last WIPP borehole to examine structure within the Castile. Potash drillhole data suggested a low point in Salado units about 3.3 km (2 mi) north of the site center. It was proposed by Davies (1984, p. 175) that the Salado low might indicate deeper dissolution of Castile halite, somewhat similar to the dissolution causing breccia pipes (see Section 2.1.6.2 on evaporite dissolution). The borehole demonstrated considerable Castile deformation, but there was no indication that halite had been removed by dissolution (Mercer et al. 1987; Borns 1987).

2.1.6.1.2 Extent of the Disturbed Zone at the Site

Nearby surface drilling, shafts, and underground drilling during early excavations at WIPP showed that the repository horizon varies modestly from the regional structure over the central part of the site; north of the site center, the beds dip gently to the south. Borns (1987) suggested that the south dip is probably related to the dip on the underlying Castile.

The upper surface of MB 139, under the repository horizon, exhibited local relief in the exploratory salt-handling shaft. Jarolimek et al. (1983, pp. 4 - 6) interpreted the relief as mainly caused by syndepositional growth of gypsum at the water-sediment interface to form mounds and by subsequent partial crushing. Jarolimek et al. (1983) concluded that the MB relief was not caused by deformation because the base of the MB showed no comparable relief. Based on concerns of the EEG, MB 139 was reevaluated. Borns (1985) found less relief on the upper surface of the MB in the areas they examined; he also concluded that depositional processes were responsible for the relief. In both cases, deformation is not thought to have caused the relief on MB 139.

For the investigation of geologic factors related to hydraulic properties of the Culebra, Powers (2002a; 2002b; 2003a) constructed elevation maps of the top of the Culebra for the region around the WIPP site. A simplified version (Figure 2-28) showing the elevations of the top of the Culebra in meters above mean sea level (m amsl) illustrates that deformation of the Castile propagated upward through the Culebra to the northeast of the WIPP site, forming a northwest-southeast trending anticline informally termed “the Divide anticline.” Across the

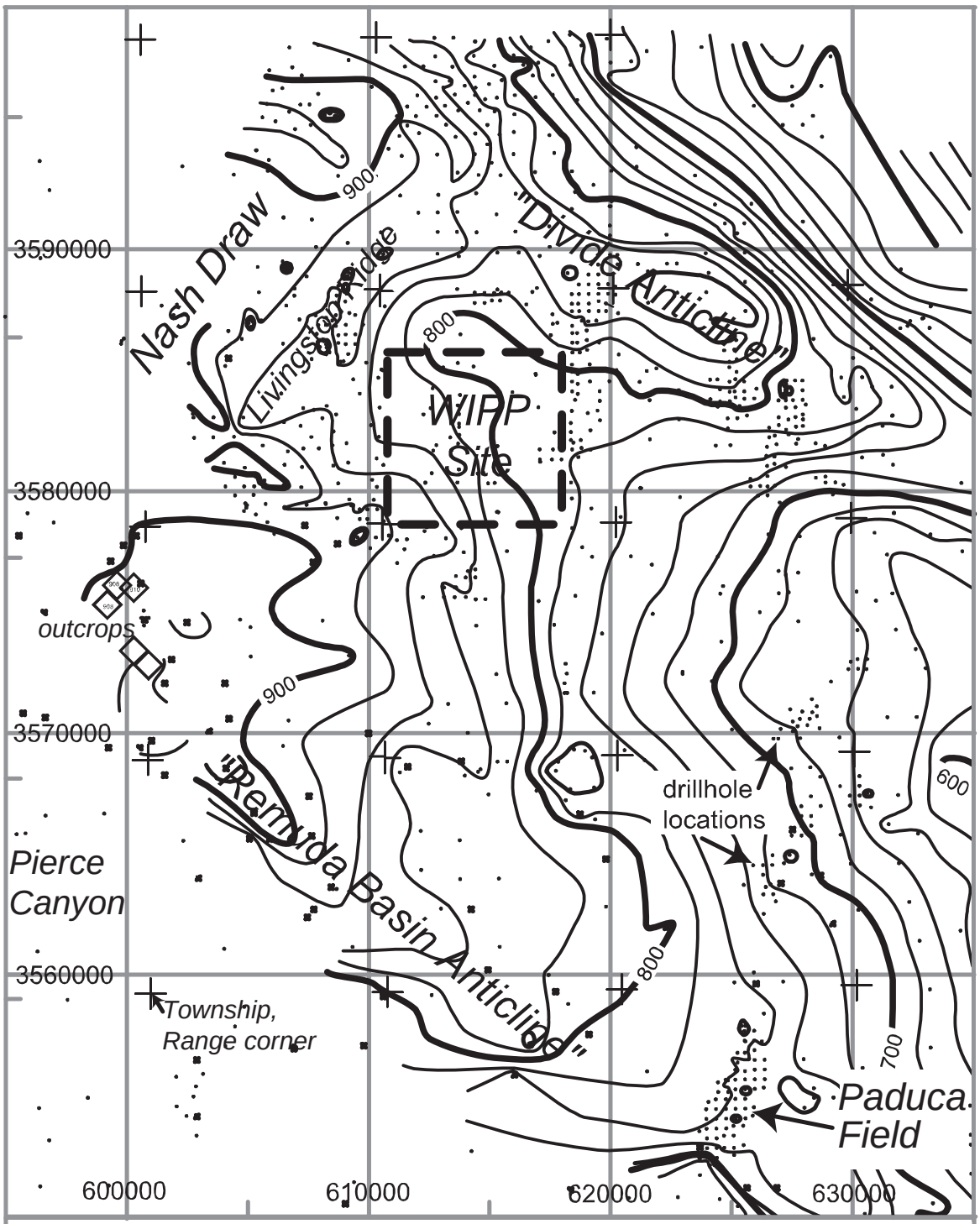

Explanation

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.
The contours for the elevation of the top of the Culebra are in meters (m) above mean sea level (amsl) (after Powers et al. 2003). Contour interval is 20 m.

Figure 2-28. Elevations of the Top of the Culebra Dolomite Member

WIPP site, the Culebra is slightly deformed by the deeper deformation, and the "disturbed zone" defined earlier geophysically is slightly evident at this horizon.

2.1.6.1.3 Deformation Mechanisms

In analyzing Castile structure in the northern Delaware Basin, Borns et al. (1983, p. 3) proposed five processes as the principal hypotheses to explain the structure: gravity foundering, dissolution, gravity sliding, gypsum dehydration, and depositional processes. Gravity foundering is the most comprehensive and best-accepted hypothesis of the five. It is based on the fact that anhydrite is much more dense (about 2.9 g/cm^3) than halite (about 2.1 g/cm^3), and anhydrite beds therefore have a potential for sinking into underlying halite. Regardless of which mechanism caused the disturbed zone, the important consideration is the long-term future effects. To evaluate this, Borns et al. (1983) postulated that both gravity-driven deformation mechanisms could be ongoing. The strain rates from such deformation are such that deformation would progress over the next 250,000 years and that such deformation would not directly jeopardize the disposal system.

2.1.6.1.4 Timing of Deformation of the Disturbed Zone at the Site

Jones (1981a, p. 18) estimated that deformation of the Castile and overlying rocks took place before the Ogallala Formation was deposited, as he believes the unit is undeformed. Anderson and Powers (1978, p. 79) inferred that data from ERDA-6 indicate that the Castile was deformed after the basin was tilted. Though these lines of evidence could be consistent with mid-Miocene deformation, there are other interpretations consistent with older deformation. There is no known evidence of surface deformation or other features to indicate recent deformation.

2.1.6.2 Evaporite Dissolution

Because evaporites are much more soluble than most other rocks, project investigators have considered it important to understand the dissolution processes and rates that occur within the site being considered for long-term isolation. These dissolution processes and rates constitute the limiting factor in any evaluation of the site. Over the course of the WIPP project, extensive resources have been committed to identify and study a variety of features in southeastern New Mexico interpreted to have been caused by dissolution. The subsurface distribution of halite for various units has been mapped. Several different kinds of surface features have been attributed to dissolution of salt or karst formation. The processes proposed or identified include point-source (brecciation), deep dissolution, shallow dissolution, and karst. These are each discussed in more detail in CCA Appendix DEF, Section DEF.3. Screening arguments relative to dissolution are presented in Appendix PA, Attachment SCR, FEPs N17 and N21 (including dissolution associated with abandoned boreholes in the discussion for FEP H34). These arguments are based principally on the observed rates and processes in the region. These are described below.

2.1.6.2.1 Brief History of Project Studies

Well before the WIPP project, several geologists recognized that dissolution is an important process in southeastern New Mexico, and that it contributed to the subsurface distribution of halite and to the surficial features. Early studies include those by Lee (1925), Maley and

Huffington (1953), and Olive (1957) Robinson and Lang (1938, p. 100) identified an area under Nash Draw where brine occurred at about the stratigraphic position of the upper Salado-basal Rustler and considered that salt had been dissolved to produce a dissolution residue. Vine (1963, p. B38 and B40) mapped Nash Draw and surrounding areas. Vine (1963) reported surficial domal structures, later called breccia pipes and identified as deep-seated dissolution and collapse features.

As the USGS and Oak Ridge National Laboratory (ORNL) began to survey southeastern New Mexico as an area in which to locate a repository site in salt, Brokaw et al. (1972) prepared a summary of the geology that included solution and subsidence as significant processes in creating the features of southeastern New Mexico. Brokaw et al. (1972) also recognized a solution residue at the top of the salt in the Salado in the Nash Draw area, and the unit commonly became known as the brine aquifer because it yielded brine. Brokaw et al. (1972) also interpreted the east-west decrease in thickness of the Rustler to be a consequence of removal by dissolution of halite and other soluble minerals.

During the early 1970s, the basic ideas about shallow dissolution of salt (generally from higher stratigraphic units and within a few hundred feet of the surface) were set out in a series of reports, as discussed in the following sections. Piper (1973; 1974) independently evaluated the geological survey data for ORNL. Claiborne and Gera (1974) concluded that salt was being dissolved too slowly from the near-surface units to affect a repository for several million years, at least.

By 1978, shallower drilling around the WIPP site to evaluate potash resources was interpreted by Jones (1978, p. 9), who felt that the Rustler included “dissolution debris, convergence of beds, and structural evidence for subsidence.” Halite in the Rustler has been reevaluated by the DOE, but there are only minor differences in inferred distributions among the various investigators. These investigators do have different explanations about how this distribution occurred (see Section 2.1.3.5 on Rustler stratigraphy): (1) through extensive dissolution of the Rustler’s halite after the Rustler was deposited, or (2) through syndepositional dissolution of halite from saline mud flat environments during Rustler deposition.

Anderson (1978) and Anderson et al. (1978) reevaluated halite distribution in deeper units, especially the Castile and Salado formations. They identified local anomalies proposed as features developed after deep dissolution of halite by water flowing upward from the underlying Bell Canyon. Anderson (1978) mapped geophysical log signatures of the Castile and interpreted lateral thinning and change from halite to non-halite lithology as evidence of lateral dissolution of deeper units (part of deep dissolution), and proposed that deep dissolution might threaten the WIPP site. In response to Anderson’s (1978) developing concepts, ERDA-10 was drilled south of the WIPP area during the latter part of 1977. ERDA-10 intercepted a stratigraphic sequence without evidence of solution residues in the upper Castile.

A set of annular or ring fractures is evident in the surface around San Simon Sink, about 30 km (18 mi) east of the WIPP site. Nicholson and Clebsch (1961, p. 14) suggested that San Simon Sink developed as a result of deep-seated collapse. WIPP-15 was drilled at about the center of the sink to a depth of 245 m (811 ft) to obtain samples for paleoclimatic data and stratigraphic data to interpret collapse. Anderson (1978) and Bachman (1980) both interpret San Simon Sink

as dissolution and collapse features, and the annular fractures are not considered evidence of tectonic activity.

Following the work by Anderson, Bachman (1980, 1981) mapped surficial features in the Pecos Valley, especially at Nash Draw, and differentiated between those surface features in the basin that were formed by karst and those that were formed by deep collapse features over the Capitan. WIPP-32, WIPP-33, and two boreholes over the Capitan Reef were eventually drilled. Their data, which demonstrated the concepts proposed by Bachman (1980, 1981), are documented in Snyder et al. (1982, p. 65).

A final program concerning dissolution and karst was initiated following a microgravity survey of a portion of the site during 1980. Based on localized low-gravity anomalies, Barrows et al. (1983) interpreted several areas within the site as locations of karst. WIPP-14 was drilled during 1981 at a low-gravity anomaly. It revealed normal stratigraphy through the zones proposed to be affected by karst. As a follow-up, Bachman (1985) also reexamined surface features around the WIPP and concluded that there was no evidence for active karst within the WIPP site. The nearest karst feature is northwest of the site boundaries at WIPP-33.

2.1.6.2.2 Extent of Dissolution

Within the Rustler, dissolution of halite is believed to have occurred only near the depositional margins, as discussed in Section 2.1.3.5. Figure 2-15 shows the only two areas where evidence has been found for halite dissolution from the M3/H3 horizon in the Tamarisk.

Upper intervals of the Salado thin dramatically west and south of the WIPP site (Figure 2-29) compared to deeper Salado intervals. There are no cores for further consideration of possible depositional variations. As a consequence, this zone of thinning is interpreted by the DOE as the edge of dissolution of the upper Salado.

2.1.6.2.3 Timing of Dissolution

The dissolution of Ochoan evaporites through the near-surface processes of weathering and groundwater recharge has been studied extensively (Anderson 1981; Lambert 1983a; Lambert 1983b; Bachman 1984; and CCA Appendix FAC). The work of Lambert (1983a) was specifically mandated by the agreement between the DOE and the state of New Mexico to evaluate in detail the conceptual models of evaporite dissolution proposed by Anderson (1981). There was no clear consensus among investigators on the volume of rock salt removed. Hence,

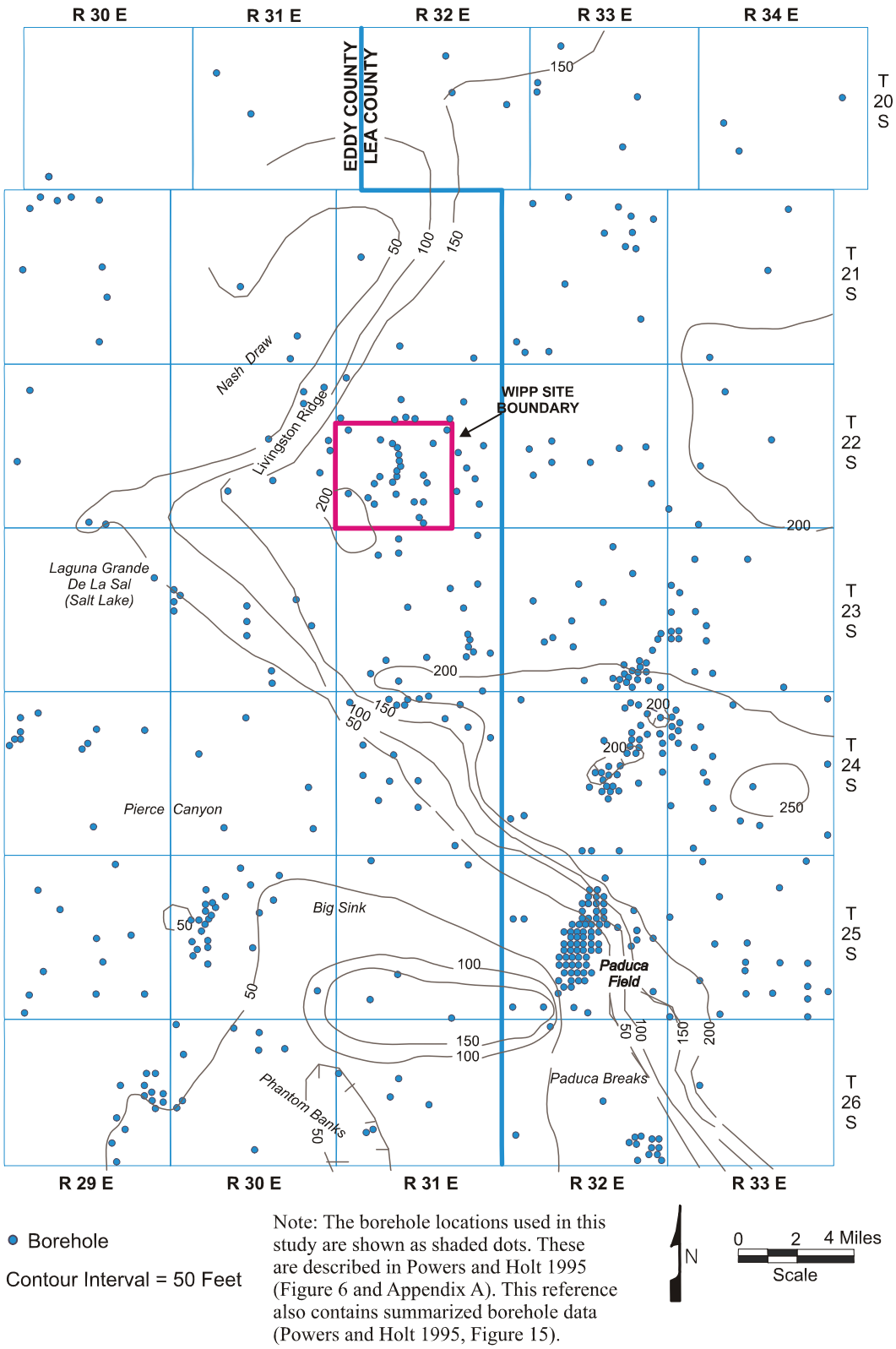

Figure 2-29. Isopach from the Base of MB 103 to the Top of the Salado

estimates of the instantaneous rate of dissolution vary significantly. Dissolution may have taken place as early as the Ochoan, during or shortly after deposition. For the Delaware Basin as a whole, Anderson (1981) proposed that up to 40 percent of the rock salt in the Castile and Salado formations was dissolved during the past 600,000 years. Lambert (1983b, p. 292) suggested that in many places the variations in salt-bed thicknesses inferred from borehole geophysical logs that were the basis for Anderson's (1981) calculation were depositional in origin, compensated by thickening of adjacent nonhalite beds, and were not associated with the characteristic dissolution residues. Borns and Shaffer (1985, p. 44 – 45) also suggested in 1985 a depositional origin for many apparent structural features attributed to dissolution.

Snyder (1985, p. 8), as well as earlier workers (for example, Vine 1963; Lambert 1983b; and Bachman 1984), attribute the variations in thickness in the Rustler, which crops out in Nash Draw, to postdepositional evaporite dissolution. Holt and Powers (CCA Appendix FAC, p. 9-2) have challenged this view and attribute the east-to-west thinning of salt beds in the Rustler to depositional facies variability rather than postdepositional dissolution. Bachman (1974, 1976, 1980) envisioned several episodes of dissolution since the Triassic, each dominated by greater degrees of evaporite exhumation and a wetter climate, interspersed with episodes of evaporite burial and/or a drier climate. Evidence for dissolution after deposition of the Salado and before deposition of the Rustler along the western part of the Basin was cited by Adams (1944, p. 1612). Others have argued that the evaporites in the Delaware Basin were above sea level and therefore potentially subject to dissolution, during the Triassic, Jurassic, Tertiary, and Quaternary periods. Because of discontinuous deposition, not all of these times are separable in the geological record of southeastern New Mexico. Bachman (1980) contends that dissolution was episodic during the past 225 million years as a function of regional base level, climate, and overburden.

There have been several attempts to estimate the rates of shallow dissolution in the basin. Bachman (1974) provided initial estimates of dissolution rates based on a reconstruction of Nash Draw relationships, including the observation that portions of the Gatuña were deposited over areas of active dissolution and subsidence of the underlying evaporites. Though these rates indicate no hazard to the WIPP related to Nash Draw dissolution, Bachman (1980, p. 85) later reconsidered the Nash Draw relationships and concluded that pre-Cenozoic dissolution had also contributed to salt removal. Thus, the initial estimated rates were too high.

With regard to deep dissolution, Anderson concluded in 1978 that the integrity of the WIPP to isolate radioactive waste would not be jeopardized by dissolution within about one million years. Anderson and Kirkland (1980, pp. 66 - 69) expanded on the concept of brine density flow proposed by Anderson (1978) as a means of dissolving evaporites at a point by circulating water from the underlying Bell Canyon. Wood et al. (1982, p. 100) examined the mechanism and concluded that, while it was physically feasible, it would not be effective enough in removing salt to threaten the ability of the WIPP to isolate transuranic (TRU) waste.

2.1.6.2.4 Features Related to Dissolution

Bachman (1980, p. 97) separated breccia pipes, formed over the Capitan Reef by dissolution and collapse of a cylindrical mass of rock, from evaporite karst features that appear similar to breccia pipes. There are surficial karst features, including sinks and caves, in large areas of the basin.

Nash Draw is the result of combined dissolution and erosion. Within the site boundaries, there are no known surficial features caused by dissolution or karst.

The subsurface structure of the Culebra is shown in Figure 2-28. South of the WIPP site, an antiformal structure informally called the "Remuda Basin anticline" has been created by dissolution of salt from the underlying Salado to the southwest of the anticline. Beds generally dip to the east, and salt removed to the west created the other limb of the structure. Units below the evaporites apparently do not show the same structure.

2.2 Surface Water and Groundwater Hydrology

The DOE has determined that the hydrological characteristics of the disposal system are important because contaminant transport via fluid flow has a potential to impact the performance of the disposal system. In addition, the EPA has provided numerous criteria related to groundwater in 40 CFR § 194.14(a). At the WIPP site, one of the DOE's selection criteria was to choose a location that would minimize this impact. This was accomplished when the DOE selected (1) a host formation that contains little groundwater and transmits it poorly, (2) a location where the effects of groundwater flow are minimal and predictable, (3) an area where groundwater use is low, (4) an area where there are no permanent surface waters, (5) an area where future groundwater use is unlikely, and (6) a repository host rock that will not likely be affected by anticipated possible long-term climate changes within 10,000 years.

The following discussion summarizes the characteristics of the groundwater and surface water at and around the WIPP site. This summary is based on data collection programs that were initiated with the WIPP program and that continue to some extent today. The purpose of these programs was to provide information sufficient for the development and use of predictive models of the groundwater movement at the WIPP site.

For a comprehensive understanding of the impact of groundwater and surface water on the disposal system, the following factors have been evaluated:

Groundwater

- Horizontal and vertical flow fluxes and velocities,
- Hydraulic interconnectivity between rock units,
- Hydraulic parameters (porosity, etc.),
- General groundwater use, and
- Chemistry (including, but not limited to, salinity, mineralization, age, Eh, and pH).

Surface Water

- Regional precipitation and evapotranspiration rates,
- Location and size of surface-water bodies,

- Water volume, flow rate, and direction,
- Drainage network,
- Hydraulic connection with groundwater,
- Soil hydraulic properties (infiltration), and
- General water chemistry and use.

Changes to the hydrological system due to human activity are evaluated in Chapter 6.0.

The specifics of groundwater modeling are found in Section 6.4.6, Appendix PA, Attachment MASS, Section MASS.14.2. The hydrological system is divided into four segments for the discussion in this chapter. These are: (1) the rock units below the Salado, which may impact the disturbed (human intrusion) performance of the disposal system, (2) the Salado, which mostly addresses the undisturbed performance of the disposal system, (3) the rock units above the Salado, which essentially impact only the disturbed (human intrusion) performance of the disposal system, and (4) the surface waters. The groundwater regime is discussed in Section 2.2.1, and the surface-water regime in Section 2.2.2.

The WIPP site lies within the Pecos River drainage area (Figure 2-23, see also Section 2.2.2, Figure 2-43). As discussed in the Final Environmental Impact Statement (FEIS) (DOE 1980, Section 7.1.1), the climate is semiarid, with a mean annual precipitation of about 0.33 m (13 in.), a mean annual runoff of 2.5 to 5 mm (0.1 to 0.2 in.), and a mean annual pan evaporation of more than 2.5 m (100 in.). Runoff is practically nonexistent and the WIPP does not have a well defined drainage pattern. The general movement of runoff can be inferred from the topography in Figure 2-23. Only one stream flow gaging station has been operated in the vicinity. This is at the location shown as Hill Tank in Figure 2-23. Observations at Hill Tank are discussed in Section 2.2.2.

Additional information about climatic conditions at the WIPP is given in Section 2.5.2. Brackish water with total dissolved solids (TDS) concentrations of more than 3,000 parts per million is common in the shallow wells near the WIPP site. Surface waters typically have high TDS concentrations, particularly of chloride, sulfate, sodium, magnesium, and calcium. Additional information about water quality is given in Section 2.4.2.

2.2.1 Groundwater Hydrology

At the WIPP site, the DOE has obtained groundwater hydrologic data from conventional and special-purpose test configurations in multiple surface boreholes. Geophysical logging of the boreholes has provided hydrologic information on the rock strata intercepted. Pressure measurements, fluid samples, and ranges of rock permeability have been obtained for selected formations through the use of standard and modified drill-stem tests. Slug injection or withdrawal tests and other flow-rate tests have provided data to aid in the estimation of transmissivity and storage. The hydraulic heads of groundwaters within many water-bearing zones in the region have been mapped from measured depths to water in the boreholes. Since the

CCA was submitted to the EPA in 1996, the DOE has implemented a number of monitoring programs (see Appendix MON-2004), including the Groundwater Monitoring Program, to meet the assurance requirements of 40 CFR § 191.14(b). In addition to the groundwater monitoring program, other hydrologic data gathered since the CCA come from logging of new or replacement wells, piezometers, special-purpose field investigations, and surveys of drilling practices in the Delaware Basin. A data summary of all these activities is provided in Appendix DATA.

Historically, the DOE has obtained hydrological data principally from a conventional well-monitoring network (Figures 2-3 through 2-6 are maps of the well locations) comprising 71 wells located on 45 separate wellpads (DOE 2003). Most of the 71 wells are completed only to a single hydrologic unit; however, six are multiple-completions to allow monitoring of two or more units in the same well. Hydrologic information (such as hydraulic head) is obtained at 80 completion intervals within the 71 wells. The focus of the hydrological monitoring is the Rustler (comprising 72 of the 80 monitored intervals) because this formation contains two of the most transmissive saturated units, the Culebra and Magenta Dolomites, which are important to the modeling of releases during various human intrusion scenarios. Limited hydrological monitoring of the Bell Canyon, Dewey Lake, and Santa Rosa also occurs.

Rock units that are shown in the conceptual models in Section 6.4 to be important to disposal system performance from a hydrological standpoint are the Castile, the Salado, the Rustler, and the Dewey Lake (Figures 2-30 and 2-31). However, other units which are discussed due to their significance in screening hydrological processes or because they are less important to the conceptual model include the Bell Canyon, the Capitan, the Rustler-Salado contact zone, and the supra-Dewey Lake units. These will also be discussed because they are features of the groundwater flow system of the WIPP region.

The Bell Canyon is of interest to the DOE because it is the first regionally continuous water-bearing unit beneath the WIPP and is the target stratigraphic horizon for salt-water injection by industry outside of the WIPP site boundary. The halite and anhydrite layers of the Castile provide a hydrologic barrier between the Salado and the underlying Bell Canyon. The Castile is of interest to PA because it contains isolated high-permeability zones containing pressurized brine. As discussed in Section 2.1.6.1, several such zones of pressurized brine have been intercepted by boreholes near the WIPP site, and one or more of these zones may exist at the WIPP site.

The Salado comprises low-permeability beds of variable composition. The low permeability of the Salado provides a hydrologic barrier in all directions between the repository and the accessible environment or more transmissive beds. At the repository horizon, a much higher

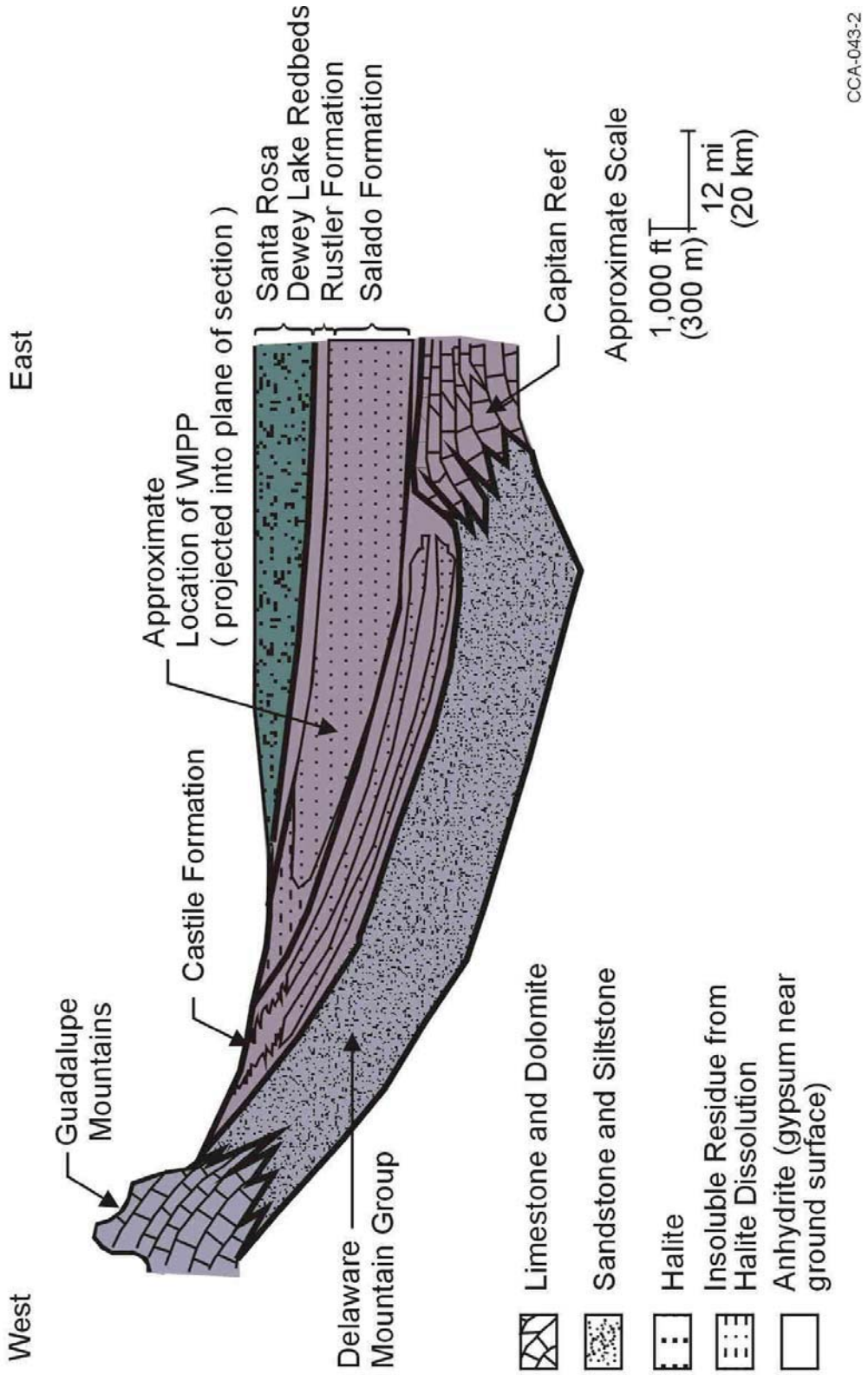

Figure 2-30. Schematic West-East Cross Section through the North Delaware Basin

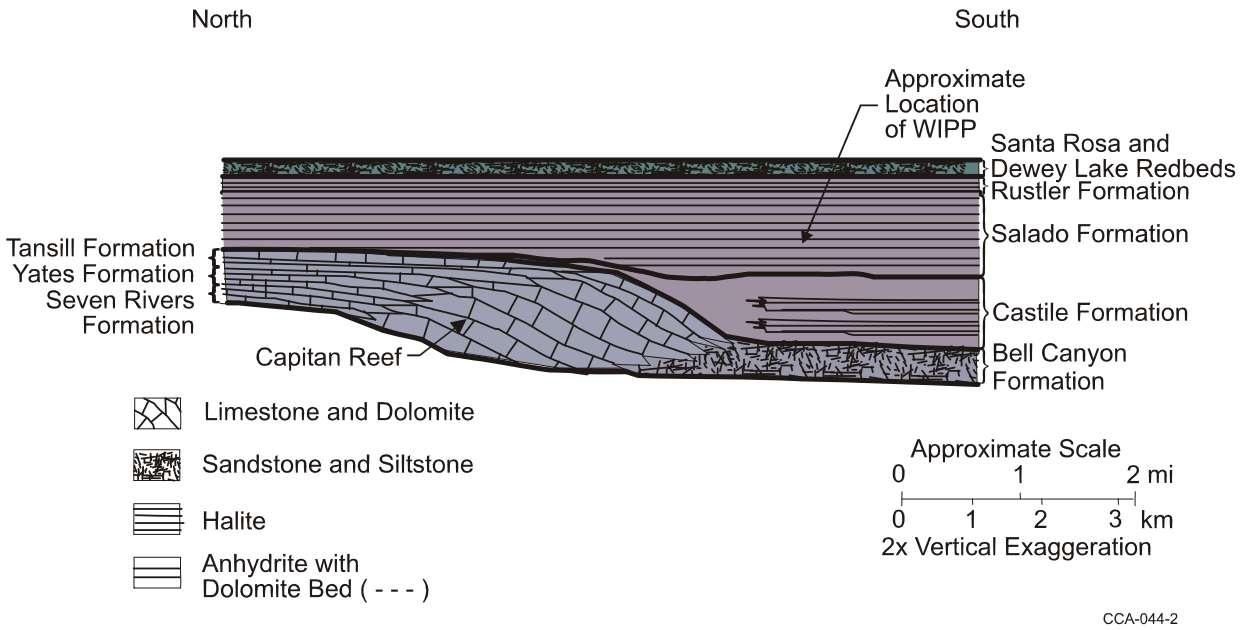

Figure 2-31. Schematic North-South Cross Section through the North Delaware Basin

permeability DRZ forms locally in the salt around the waste emplacement rooms and operational drifts. As described in Appendix DATA, the DRZ is of limited extent compared to the significant thickness of the Salado low-permeability beds surrounding the repository horizon.

The Rustler contains two laterally transmissive members. The Culebra is the first laterally continuous unit located above the WIPP underground facility to display hydraulic conductivity sufficient to warrant investigation for lateral contaminant transport. It is also the most transmissive continuously saturated unit above the WIPP repository. Therefore, except for a release directly to the surface, the Culebra provides the most direct pathway between the WIPP underground and the accessible environment. The hydrology and fluid geochemistry of the Culebra are complex and, as a result, have received a great deal of study (see, for example, LaVenue et al. 1988, 1990; Haug et al. 1987; and Siegel et al. 1991. The Magenta, although more transmissive than the anhydrite and claystone members of the Rustler, has lower transmissivity than the Culebra, and is unfractured at the WIPP.

There was no inflow of water from the Dewey Lake into the WIPP shafts after they were completed and prior to their lining, indicating unsaturated conditions or low transmissivity. However, since 1995, routine inspections of the WIPP exhaust shaft have revealed water entering the shaft at a depth of approximately 24 m (80 ft) at a location where no water had been observed during construction (the DOE is investigating the source and extent of this water; see Sections 2.2.1.4.2.1 and Appendix DATA). The quantity and quality of water in the Dewey Lake is also monitored in a deeper fractured zone in the Dewey Lake at well WQSP-6a (WIPP MOC 1995).

The Santa Rosa is shallow and unsaturated at the site (with the exception of a perched water table directly below the WIPP surface structures; see Section 2.2.1.4.2.2 and Appendix DATA), and apparently receives recharge only through infiltration.

In conclusion, at the WIPP site, the DOE recognizes the Salado as the most significant nontransmissive unit and the Culebra and the Magenta as the most significant transmissive units. Other units are considered to have less important roles. The DOE's sampling and analysis of non-Salado groundwater has focused on the Culebra and Magenta, and their hydrologic background, presented here, is more detailed than for other non-Salado rock units. Table 2-4 provides an overview of the hydrologic characteristics of the Rustler rock units at the WIPP site and the Rustler-Salado contact zone in Nash Draw. In developing this position on modeling the hydrology of the WIPP, the DOE considered several modeling approaches. These are summarized in CCA Appendix MASS, Section MASS.14.1 in general and Section MASS.15.1 for the Culebra. The DOE's conceptual models for hydrology are in Sections 6.4.5 and 6.4.6.

Table 2-4. Hydrologic Characteristics of the Rustler at the WIPP and in Nash Draw

Member	Thickness (meters)		Transmissivity (square meters per second)		Porosity	
	max	min	max	min	max	min
Forty-niner	23	13	8×10^{-8}	3×10^{-9}	—	—
Magenta	8.5	7	4×10^{-4}	1×10^{-9}	0.25	0
Tamarisk	56	26	2.7×10^{-11}	—	—	—
Culebra	11.6	4	1×10^{-3}	1×10^{-9}	0.30	0.03
Los Medaños	38	29	2.9×10^{-10}	2.2×10^{-13}	—	—
Rustler-Salado Contact Zone in Nash Draw	18	3	8.6×10^{-6}	3.2×10^{-11}	0.33	0.15

The EPA sought information supporting the conceptualization of the disposal system and the major site-related characteristics included in the PA modeling during the compliance review process for Section 194.14(a)(3). In general, the EPA concluded that the groundwater hydrology information for the various geologic and hydrostratigraphic units at the WIPP site identified the important characteristics of the PA and was therefore technically sufficient. The EPA also noted that the primary hydrogeologic units of concern relative to containment capability of the WIPP are the Castile, Salado, Rustler, and the Dewey Lake.

The EPA noted that the potential for fluid migration through Salado marker beds and the Culebra were acknowledged by DOE and included in the PA calculations. While the Dewey Lake is a potential underground source of drinking water (Section 8.2.2), DOE's modeling indicated that radionuclides will not reach the Dewey Lake, thus removing the formation as a unit needing consideration as a pathway (Docket A-93-02, Item II-G-26 and Docket A-93-02, Item II-G-28). The EPA concluded that Salado marker beds, and the Culebra were adequately identified and characterized to the level necessary for PA calculations.

2.2.1.1 Conceptual Models of Groundwater Flow

The DOE addresses issues related to groundwater flow and radionuclide transport within the context of a conceptual model of how the natural hydrologic system works on a large scale. The conceptual model of regional flow around the WIPP that is presented here is based on widely accepted concepts of regional groundwater flow in groundwater basins (see, for example, Hubbert 1940; Tóth 1963; and Freeze and Witherspoon 1967).

See CCA Appendix MASS, Sections MASS.14.1 and MASS.14.2 for a summary of the DOE's activities leading to the acceptance of the groundwater basin model as a reasonable representation of groundwater flow in the region.

An idealized groundwater basin is a three-dimensional closed hydrologic unit bounded on the bottom by an impermeable rock unit (units with much smaller permeability than the units above), on the top by the ground surface, and on the sides by groundwater divides. The water table is the upper boundary of the region of saturated liquid flow. All rocks in the basin are expected to have finite permeability; in other words, hydraulic continuity exists throughout the basin. This means that the potential for liquid flow from any unit to any other units exists, although the existence of any particular flow path is dependent on a number of conditions related to gradients and permeabilities. All recharge to the basin is by infiltration of precipitation to the water table and all discharge from the basin is by flow across the water table to the land surface.

Differences in elevation of the water table across an idealized basin provide the driving force for groundwater flow. The pattern of groundwater flow depends on the lateral extent of the basin, the shape of the water table, and the heterogeneity of the permeability of the rocks in the basin. Water flows along gradients of hydraulic head from regions of high head to regions of low head. The highest and lowest heads in the basin occur at the water table at its highest and lowest points, respectively. Therefore, groundwater flows from the elevated regions of the water table, downward across confining layers (layers with relatively small permeability), then laterally along more conductive layers, and finally upward to exit the basin in regions where the water table (and by association, the land surface) is at low elevations. Recharge is necessary to maintain relief on the water table, without which flow does not occur.

Groundwater divides are boundaries across which it is assumed that no groundwater flow occurs. In general, these are located in areas where groundwater flow is dominantly downward (recharge areas) or where groundwater flow is upward (discharge areas). Topography and surface-water drainage patterns provide clues to the location of groundwater divides. Ridges between creeks and valleys may serve as recharge-type divides, and rivers, lakes, or topographic depressions may serve as discharge-type divides.

In the groundwater basin model, rocks can be classified into hydrostratigraphic units. A hydrostratigraphic unit is a continuous region of rock across which hydraulic properties are similar or vary within described or stated limits. The definition of hydrostratigraphic units is a practical exercise to separate rock regions with similar hydrologic characteristics from rock regions with dissimilar hydrologic characteristics. Although hydrostratigraphic units often are defined to be similar to stratigraphic units, this need not be the case. Hydrostratigraphic unit boundaries can reflect changes in hydraulic properties related to differences in composition,

fracturing, dissolution, or a variety of other factors that may not be reflected in the definition of stratigraphic formations.

Confining layers in a groundwater basin model can be characterized as allowing vertical flow only. The amount of vertical flow occurring in a confining layer generally decreases in relation to the depth of the layer. Flow in conductive units is more complicated. In general, flow will be lateral through conductive units. The magnitude (in other words, volume flux) of lateral flow is related to the thickness, conductivity, and gradient present in the unit. Gradients generally decrease in deeper units. The direction of flow is generally related to the distance the unit is from the land surface. Near the land surface, flow directions are influenced primarily by the local slope of the land surface. In deeper conductive units, flow directions are generally oriented parallel to the direction between the highest and lowest points in a groundwater basin. Thus, flow rates, volumes, and directions in conductive units in a groundwater basin are generally not expected to be the same.

In the WIPP region, the Salado provides an extremely low-permeability layer that forms the base for a regional groundwater-flow basin in the overlying rocks of the Rustler, Dewey Lake, and Santa Rosa. The Castile and Salado together form their own groundwater system, and they separate flow in units above them from that in units below. Because of the plastic nature of halite and the resulting low permeability, fluid pressures in the evaporites are more related to lithostatic stress than to the shape of the water table in the overlying units, and regionally neither vertical nor horizontal flow will occur as a result of natural pressure gradients in time scales relevant to the disposal system. (On a repository scale, however, the excavations themselves create pressure gradients that may induce flow near the excavated region.) Consistent with the recognition of the Salado as the base of the groundwater basin of primary interest, the following discussion is divided into three sections: hydrology of units below the Salado, hydrology of the Salado, and hydrology of the units above the Salado. The DOE has implemented the groundwater basin model in the conceptual model for groundwater flow within the rocks above the Salado. The details of the model are discussed in Section 6.4.6. Key modeling assumptions associated with the implementation are provided in Appendix PA, Attachment MASS, Section MASS.14.2.

Technical issues related to the Castile brine, Salado marker bed permeability, and Culebra hydraulic properties (e.g., transmissivity variation) were raised by the EPA in a letter dated December 19, 1996 (Docket A-93-02, Item II-I-01). The DOE provided additional information regarding these issues in letters dated January 24, 1997; February 7, 1997; April 15, 1997; June 13, 1997; June 27, 1997; and July 3, 1997 (Docket A-93-02, Items II-I-03, II-I-07, II-I-24, II-H-44, II-H-45, and II-H-46, respectively).

A request was made in the December 19, 1996 EPA letter (Docket A-93-02, Item II-I-01) that DOE provide general hydraulic characteristic information for all geologic units within the disposal system by revising a partially complete table included in the letter. The DOE letter, dated February 14, 1997 (Docket A-93-02, Item II-I-08), transmitted the summary table providing the EPA with additional groundwater hydrology information related to hydraulic conductivity, storage coefficients, transmissivity, permeability, thickness, matrix and fracture characteristics, and hydraulic gradients for each of the geologic units in the WIPP disposal system. This information was reproduced as Figure IV-10 in EPA Technical Support Document

for Section 194.14: Content of Compliance Certification Application (Docket A-93-02, Item V-B-3).

In addition, the EPA in the December 19, 1996 EPA letter (Docket A-93-02, Item II-I-01) required the DOE to include the following in the discussion of conceptual models for groundwater flow: (1) the estimated infiltration at the surface and to the Dewey Lake, and (2) the estimated vertical flow of groundwater into other transmissive units within the area surrounding the WIPP. The DOE provided the estimates in a letter dated February 26, 1997 (Docket A-93-02, Item II-I-10) to EPA.

2.2.1.2 Units Below the Salado

Units of interest to the WIPP project below the Salado are the Bell Canyon and the Castile. These units have quite different hydrologic characteristics. Because of its potential to contain brine reservoirs below the repository, the hydrology of the Castile is regarded as having the most potential of all units below the Salado to impact the performance of the disposal system.

2.2.1.2.1 Hydrology of the Bell Canyon Formation

The Bell Canyon is considered for the purposes of regional groundwater flow to form a single hydrostratigraphic unit about 300 m (1,000 ft) thick. Tests at five boreholes (Atomic Energy Commission [AEC]-7, AEC-8, ERDA-10, DOE-2, and Cabin Baby [CB]-1) (CCA Appendix HYDRO, pp. 29-31; Beauheim et al. 1983, pp. 4-9 to 4-12; Beauheim 1986, p. 61-1]) indicate a range of hydraulic conductivities for the Bell Canyon from 1.7×10^{-7} to 3.5×10^{-12} m/s (5×10^{-2} ft/day to 1×10^{-6} ft/day). The pressure measured in the Bell Canyon at the DOE-2 and CB-1 boreholes at the time of the CCA ranged from 12.6 to 13.3 megapascals. Under the current groundwater-monitoring program, Bell Canyon water levels are measured in only two wells: CB-1 and AEC-8 (see locations in Figure 2-6).

After recovery from well work in 1999, the Bell Canyon water levels at CB-1 have remained steady for more that three years at 919 m (3,015 ft) above mean sea level (SNL 2003a). In contrast, since the beginning of 1994, the Bell Canyon water levels at AEC-8 have steadily risen by more than 32 m (106 ft) at a rate of approximately 0.5 m/month (1.6 ft/month) and stood at over 933.4 m (3,062 ft) above mean sea level (SNL 2003a) at the end of 2002. This water-level rise is hypothesized to be the result of deterioration of the well and not a response to actual Bell Canyon hydrologic conditions at this location. The well will be inspected and repaired or plugged and abandoned, as necessary, according to the requirements of DOE's groundwater monitoring program (see Appendix MON-2004).

Fluid flow in the Bell Canyon is markedly influenced by the presence of the extremely low-permeability Castile and Salado above it, which effectively isolate the Bell Canyon from interaction with overlying units except where the Castile is absent because of erosion or nondeposition, such as in the Guadalupe Mountains, or where the Capitan Reef is the overlying unit (Figures 2-30 and 2-31). Because of the isolating nature of the Castile and Salado, fluid flow directions in the Bell Canyon are sensitive only to gradients established over very long distances. At the WIPP, the brines in the Bell Canyon flow northeasterly under an estimated hydraulic gradient of 4.7 to 7.6 m/km (25 to 40 ft/mi) and discharge into the Capitan aquifer.

Velocities are on the order of tenths of feet per year, and groundwater yields from wells in the Bell Canyon are 2.3 to 5.8 liters (0.6 to 1.5 gallons) per minute. The fact that flow directions in the Bell Canyon under the WIPP are inferred to be almost opposite to the flow directions in units above the Salado (see Section 2.2.1.4) is not of concern because, as discussed above, the presence of the Castile and Salado makes the flow in the Bell Canyon sensitive to gradients established over long distances, whereas flow in the units above the Salado is sensitive to gradients established by more local variations in water table elevation.

As discussed in Appendix DATA, oil companies are currently involved in deep-well injection at several locations outside of the WIPP site boundary. Specifically, salt water (brine) produced during oil-field exploitation is injected into the Bell Canyon and Brushy Canyon Formations. For nearly four years, the DOE has monitored injection rates and pressures for a cluster of six of these salt water injection wells located approximately 1.6 to 2.4 km (1 to 1.5 mi) northeast of well H-9. Table 2-5 summarizes the depth intervals of the injection zones for each well. The cluster of six wells is currently injecting approximately 800 to 950 m^3 per day (5,000 to 6,000 barrels per day) of salt water; however, in previous years, injection has ranged from approximately 480 to 1270 m^3 per day (3,000 to 8,000 barrels per day) (SNL 2003a). Wellhead injection pressures typically range between 5.5 to 6.9 MPa (800 to 1,000 psi). Because only two Bell Canyon wells are currently being monitored, the effect of salt-water injection on Bell Canyon water levels is speculative, but water levels in the Bell Canyon monitoring well nearest the cluster (i.e., CB-1, Figure 2-6) indicate no response to the injection. Additional discussion on potential effects of salt-water injection on the WIPP hydrologic setting is provided below in Section 2.2.1.4.

2.2.1.2.2 Castile Hydrology

As described in Section 2.1.3, the Castile is dominated by low-permeability anhydrite and halite zones. However, fracturing in the upper anhydrite has generated isolated regions with much greater permeability than the surrounding intact anhydrite. These regions are located in the area of structural deformation, as discussed in Section 2.1.6.1.1. The higher-permeability regions of the Castile contain brine at pressures greater than hydrostatic and have been referred to as brine reservoirs (see Figure 2-32). The fluid pressure measured by Popielak et al. (1983) in the WIPP-12 borehole (12.7 megapascals) is greater than the nominal hydrostatic pressure for a column of equivalent brine at that depth (11.1 megapascals).

Therefore, under open-hole conditions, brine could flow upward to the surface through a borehole.

Results of hydraulic tests performed in the ERDA-6 and WIPP-12 boreholes suggest that the extent of the highly permeable portions of the Castile is limited. As discussed in Section 2.1.3.3 and modeled in Section 6.4.8, the vast majority of brine is thought to be stored in low-permeability microfractures; about five percent of the overall brine volume is stored in large

Table 2-5. Depth Intervals of the Injection Zones of Six Salt-Water Injection Wells Located Near Well H-9 (after SNL 2003a)

Injection Well	Depth Interval of Injection Zone, feet[1]
Cal Mon #5	4,484 – 5,780[2]
Sand Dunes 28F#1[3]	4,295 – 5,570[2]
Pure Gold B F#20[3]	7,740 – 7,774[4]
Todd 26F#2	4,460 – 5,134[2]
Todd 26F#3	4,390 – 6,048[2]
Todd 27F#16	4,694 – 5,284[2]

(1) Below ground surface, bgs
(2) Bell Canyon Formation
(3) Wells hydraulically connected to same manifold
(4) Brushy Canyon Formation

open fractures. The volumes of the ERDA-6 and WIPP-12 brine reservoirs were estimated by Popielak et al. (1983) to be 100,000 m^3 (3.5×10^6 ft^3) and 2,700,000 m^3 (9.5×10^7 ft^3), respectively. The conceptual model of the Castile brine region is discussed in Section 6.4.8. The model uses parameter values derived from the ERDA-6 and WIPP-12 tests for quantifying some reservoir characteristics. The derivation of some model parameters in Appendix PA, Attachment PAR, Table PAR-44 from the data discussed here is also given in CCA Appendix MASS, Section MASS.18.

A geophysical survey using time-domain electromagnetic (TDEM) methods was completed over the WIPP-12 brine reservoir and the waste disposal panels (The Earth Technology Corporation 1988). The TDEM measurements detected a conductor interpreted to be the WIPP-12 brine reservoir and also indicated that similar brine occurrences may be present within the Castile under a portion of the waste disposal panels. Powers et al. (1996) used 354 drill holes and 27 Castile brine occurrences to establish that there is an eight percent probability of a hole drilled into the waste panel region encountering brine in the Castile. This analysis was included as CCA Appendix MASS, Attachment 18-6.

Initially, the EPA found that DOE's discussion of the size, orientation, and repressurization potential of the Castile brine reservoirs was not well supported (Docket A-93-02, Item II-I-27). The EPA required the probability of encountering a brine reservoir to be sampled between a range of 1 and 60 percent in the PAVT (Docket A-93-02, Item II-G-26 and Docket A-93-02, Item II-G-28). In addition, the EPA modified the values for parameters such as bulk compressibility of Castile rock so that the brine reservoir sampling used in the PA would better represent the larger, higher-end possible brine volumes. Further information on the EPA review of these parameters may be found in CARD 23—Models and Computer Codes (EPA 1998f), EPA Technical Support Document for Section 23: Models and Computer Codes (Docket A-93-02, Item V-B-6), and EPA Technical Support Document for Section 23: Ground

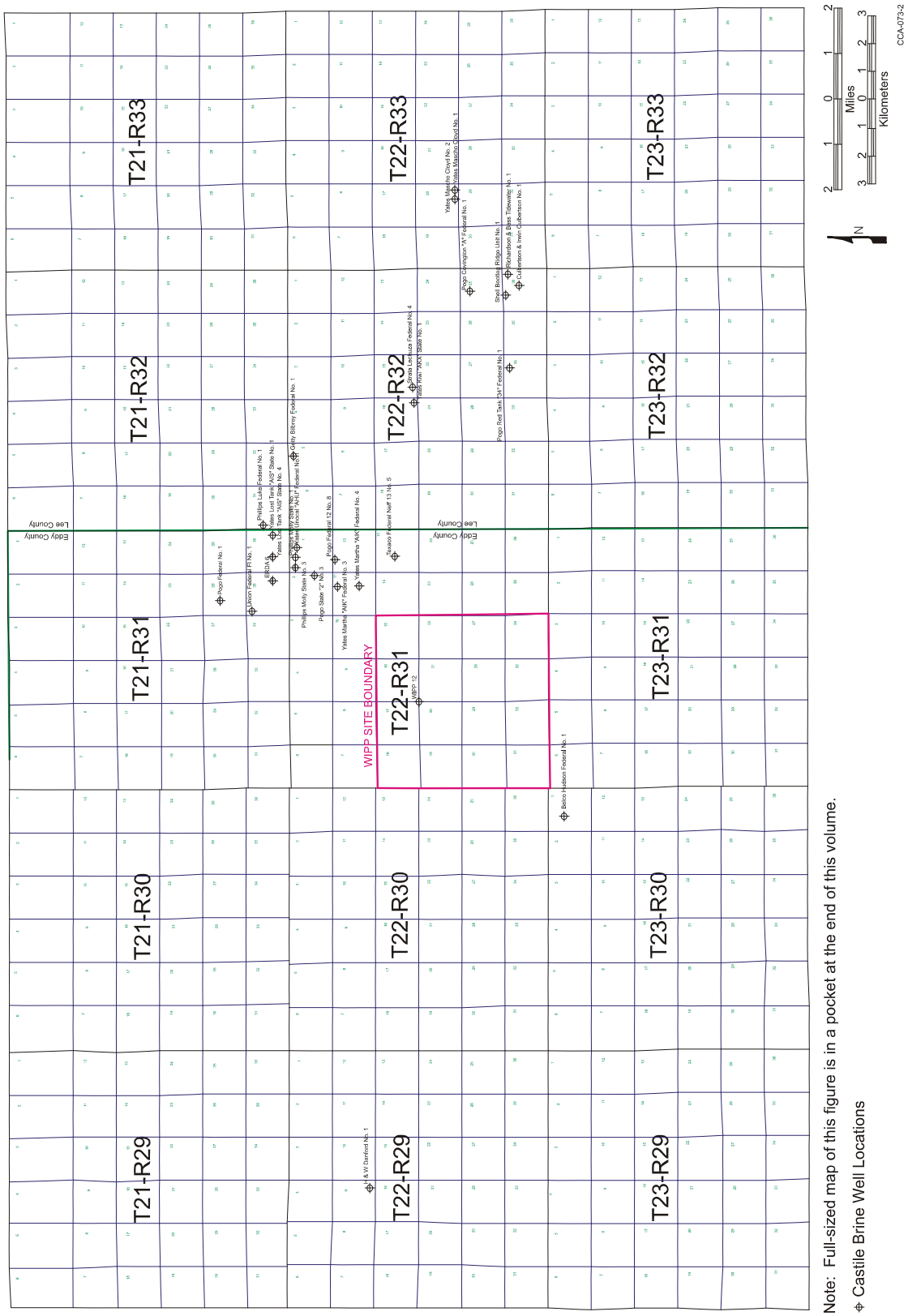

Note: Full-sized map of this figure is in a pocket at the end of this volume.

⌖ Castile Brine Well Locations

Figure 2-32. Recent Occurrences of Pressurized Brine in the Castile

Water Flow and Contaminant Transport Modeling at WIPP (Docket A-93-02, Item V-B-7). The PAVT used modified Castile brine reservoir characteristics and showed that the WIPP still meets the containment requirements (Docket A-93-02, Item II-G-26, Figure 7-2).

Based on these analyses, there was no significant impact on releases over the range of probabilities sampled. However, the DOE identified this parameter as a compliance monitoring parameter (see Appendix DATA) and conducts annual surveys as part of the Delaware Basin Monitoring Program (see Appendix MON-2004) to identify Castile brine encounters by drillers in the basin. Since the CCA, these surveys have identified five additional brine encounters. Appendix DATA provides extensive information pertinent to the brine reservoirs. The Delaware Basin Monitoring Annual Report (DOE 2002a), for example, documents three of the five Castile brine encounters. Two were located near well ERDA-6 northeast of the WIPP site and one was located to the southwest of the site. In the two encounters northeast of the site, reports indicated several hundred barrels of brine per hour were produced, but all brine was contained within the pits; thus, it was not necessary to file a report with the New Mexico Oil Conservation Division. In the other encounter, initial flows of from 64 to 79 m^3 (400 to 500 barrels) per hour were observed, but flow dissipated within hours of the encounter. Because of the relatively large number of boreholes (345 wells in the nine-township area drilled between 1996 and 2002), the five brine encounters that occurred do not substantially change the probability defined by Powers et al. (1996) and are unlikely to have any significant impact on PA given the large range of probabilities sampled in the PAVT analyses.

The origin of brine in the Castile has been investigated geochemically. Popielak et al. (1983, p. 2) concluded that the ratios of major and minor element concentrations in the brines indicate that these fluids originated from ancient seawater and that no evidence exists for fluid contribution from present meteoric waters. The Castile brine chemistries from the ERDA-6 and WIPP-12 reservoirs are distinctly different from each other and from local groundwaters. These geochemical data indicate that brine in reservoirs has not mixed to any significant extent with other waters and has not circulated. The brines are saturated, or nearly so, with respect to halite and, consequently, have little potential to dissolve halite. The chemical composition of Castile brine is given in Table 2-6. It's the use of the chemical composition of Castile brine as a parameter in the conceptual model of repository performance is discussed in Appendix PA.

2.2.1.3 Hydrology of the Salado

As described in Section 2.1.3, the Salado consists mainly of halite and anhydrite. A considerable amount of information about the hydraulic properties of these rocks has been collected through field and laboratory experiments. Appendix PA summarizes this information.

Hydraulic testing in the Salado in boreholes in the WIPP underground repository provided quantitative estimates of the hydraulic properties controlling brine flow through the Salado (Beauheim et al. 1991a; Beauheim et al. 1993; Domski et al. 1996; Roberts et al. 1999). This work was summarized by Beauheim and Roberts (2002). The stratigraphic intervals tested

Table 2-6. WIPP Salado and Castile Brine Compositions

	Salado Brine Average (n between 82 and 96)		Castile ERDA-6	Castile WIPP-12
Specific Gravity	1.22	± 0.01	1.216	1.215
pH	6.1		6.17	7.06
Sodium	79100	± 2,100	112000	138000
Potassium	15900	± 800	3800	2900
Calcium	282	± 38	490	350
Magnesium	22700	± 1,400	450	1600
Boron	1450	± 120	680	990
Lithium	nd		240	280
Silicon	1.6	± 0.7	21	27
Strontium	1.6	± 0.6	18	19
Ammonium	148	± 16	1119	476
Nitrate	0.8	(median)	2746	2436
Chloride	193000	± 4,000	170000	178000
Sulfate	17000	± 900	16000	18000
Bromide	1500	± 60	880	510
Iodide	14.8	± 3.1	28	24
Alkalinity (as HCO_3^- equivalent)[1]	883	± 123	2600	2700
Total Organic Carbon	54	± 50	nd	nd
Total Dissolved Solids	374000	± 13,000	330000	328000

[1] Alkalinity measured to an endpoint pH of 2.5 and expressed as equivalent bicarbonate.

Legend:

nd not determined

Note: All determinands reported in units of milligrams per liter (mg/L), except for pH and Specific Gravity. Only determinands with a concentration in excess of 10 mg/L in at least one of the brines are shown. Data taken from DOE (1994, Table 3-3) and Popeliak et al. (1983, Table C.2).

include both pure and impure halite, as well as anhydrite. Tests influence rock as far as 10 m (33 ft) distant from the test zone and therefore provide results representative of rock beyond the zone of mechanical disturbance associated with drilling of the test boreholes. Because tests close to the repository are within the DRZ that surrounds the excavated regions (see Section 3.2), results of the tests farthest from the repository are most representative of undisturbed conditions.

Fifty-nine intervals were isolated and monitored and/or tested in 27 boreholes. Thirty-five of the intervals isolated halite beds, and 24 isolated anhydrite beds. Permeability estimates were obtained from 14 of the halite intervals and 16 of the anhydrite intervals. Interpreted

permeabilities using a Darcy-flow model vary from 2×10^{-23} to 3×10^{-16} m^2 for impure halite intervals, with the lower values representing halite with few impurities and the higher values representing intervals within the DRZ of the excavations. Interpreted formation pore pressures vary from atmospheric to 9.8 MPa for impure halite, with the lower pressures showing the effects of the DRZ. Tests in pure halite show no observable response, indicating either extremely low permeability ($<10^{-23}$ m^2), or no flow whatsoever, even though appreciable pressures are applied to the test intervals.

Interpreted permeabilities using a Darcy-flow model vary from 2×10^{-20} to 9×10^{-18} m^2 for anhydrite intervals. Interpreted formation pore pressures vary from atmospheric to 14.8 MPa for anhydrite intervals (Beauheim and Roberts 2002 p. 82). Lower values are caused by depressurization near the excavation.

As discussed in Beauheim and Roberts (2002), permeabilities of some tested intervals have been found to be dependent on the pressures at which the tests were conducted, which is interpreted as the result of fracture apertures changing in response to changes in effective stress. Flow dimensions inferred from most test responses are subradial, meaning that flow to/from the test boreholes is not radially symmetric but is derived from a subset of the rock volume. The subradial flow dimensions are believed to reflect channeling of flow through fracture networks, or portions of fractures, that occupy a diminishing proportion of the radially available space, or through percolation networks that are not “saturated” (that is, fully interconnected). This is probably related to the directional nature of the permeability created or enhanced by excavation effects. Other test responses indicate flow dimensions between radial and spherical, which may reflect propagation of pressure transients above or below the plane of the test interval or into regions of increased permeability (e.g., closer to an excavation). The variable stress and pore-pressure fields around the WIPP excavations probably contribute to the observed non-radial flow dimensions.

The properties of anhydrite interbeds have also been investigated in the laboratory. Tests were performed on three groups of core samples from MB 139 as part of the Salado Two-Phase Flow Laboratory Program. The laboratory experiments provided porosity, intrinsic permeability, and capillary pressure data. Analysis of capillary pressure test results indicates a threshold pressure of less than 1 MPa. Both laboratory and field data were used to establish hydraulic parameters for the Salado for PA as summarized in CCA Appendix PAR (Tables PAR-6 and PAR-7).

The EPA believed the DOE’s initial information on anhydrite characteristics and response to high pressure was unclear. In response, the DOE provided the EPA with data on modeling implementation and anhydrite characterization clarifying DOE’s approach to anhydrite fracture properties under pressurized conditions. The EPA concluded that while fracture distribution and subsequent fluid flow in the Salado marker beds cannot be detailed, the general application of fracturing and subsequent fluid flow appears to be an adequate representation of overall site conditions. The EPA also concluded that DOE’s modeling of fractures within Salado anhydrite marker beds is acceptable. For further discussion on this topic, see CARD 23—Models and Computer Codes, Section 1.3.2.

Fluid pressure above hydrostatic is a hydrologic characteristic of the Salado (and the Castile) that plays a potentially important role in the repository behavior. It is difficult to measure natural

pressures in these formations accurately because the boreholes or repository excavations required to access the rocks decrease the stress in the region measured. Stress released instantaneously decreases fluid pressure in the pores of the rock, so measured pressures must be considered as a lower bound of the natural pressures. Stress effects related to test location and the difficulty of making long-duration tests in lower-permeability rocks result in higher pore pressures observed to date in anhydrites. The highest observed pore pressures in halite-rich units, near Room Q, are on the order of 9 MPa, whereas the highest pore pressures observed in anhydrite are approximately 12 MPa (Beauheim and Roberts 2002, p. 82). Far-field pore pressures in halite-rich and anhydrite beds in the Salado at the repository level are expected to be similar because the anhydrites are too thin and of too low permeabilities to have liquid pressures much different than those of the surrounding salt. For comparison, the hydrostatic pressure for a column of brine at the depth of the repository is about 7 MPa, and the lithostatic pressure calculated from density measurements in ERDA-9 is about 15 MPa.

Fluid pressures in sedimentary basins that are much higher or much lower than hydrostatic are referred to as abnormal pressures by the petroleum industry, where they have received considerable attention. In the case of the Delaware Basin evaporites, the high pressures are almost certainly maintained because of the large compressibility and plastic nature of the halite and, to a lesser extent, the anhydrite. The lithostatic pressure at a particular horizon must be supported by a combination of the stress felt by both the rock matrix and the pore fluid. In highly deformable rocks, the portion of the stress that must be borne by the fluid exceeds hydrostatic pressure but cannot exceed lithostatic pressure.

Brine content within the Salado is estimated at 1 to 2 percent by weight, although the thin clay seams have been inferred by Deal et al. (1993, pp. 4-3) to contain up to 25 percent brine by volume. Where sufficient permeability exists, this brine will move towards areas of lower hydraulic potential, such as a borehole or mined section of the Salado.

Observation of the response of pore fluids in the Salado to changes in pressure boundary conditions at walls in the repository, in boreholes without packers, in packer-sealed boreholes, or in laboratory experiments is complicated by low permeability and low porosity. Qualitative data on brine flow to underground workings and exploratory boreholes were collected routinely between 1985 and 1993 under the Brine Sampling and Evaluation Program (BSEP) and have been documented in a series of reports (Deal and Case 1987; Deal et al. 1987, 1989, 1991a, 1991b, 1993, and 1995). A discussion of alternative conceptual models for Salado fluid flow is given in Appendix PA, Attachment MASS, Section MASS.7. Additional data on brine inflow are available from the Large-Scale Brine Inflow Test (Room Q). Flow has been observed to move to walls in the repository, to boreholes without packers, and to packer-sealed boreholes. These qualitative and relatively short-term observations suggest that brine flow in the fractured DRZ is a complex process. In some locations, evidence for flow is no longer observed where it once was; in others, flow has begun where it once was not observed. In many cases, observations and experiments must last for months or years to obtain useful results.

For PA modeling, brine flow is a calculated term dependent on local hydraulic gradients and properties of the Salado units. Data on pore pressure and permeability of halite and anhydrite layers are available from the Room Q tests and other borehole tests as summarized in Beauheim

and Roberts (2002), and these data form the basis for the quantification of the material properties used in the PA. See Section 6.4.3.2 for a description of the repository fluid flow model.

Because brine is an important factor in repository performance, several studies of its chemistry have been conducted. Initial investigations were reported in Powers et al. (CCA Appendix GCR, Section 7.5) and were continued once access to the underground was established. The most comprehensive data were developed by the BSEP (Deal and Case 1987; Deal et al. 1987, 1989, 1991a, 1991b, 1993, 1995). Results are summarized in Table 2-6. CCA Appendix SOTERM discusses the role of brine chemistry in the conceptual model for actinide dissolution. The conceptual model is described in Section 6.4.3.5.

2.2.1.4 Units Above the Salado

In evaluating groundwater flow above the Salado, the DOE considers the Rustler, Dewey Lake, Santa Rosa, and overlying units to form a groundwater basin with boundaries coinciding with selected groundwater divides as discussed in Section 2.2.1.1. The model boundary follows Nash Draw and the Pecos River valley to the west and south and the San Simon Swale to the east (Figure 2-33). The boundary continues up drainages and dissects topographic highs along its northern part. These boundaries represent groundwater divides whose positions remain fixed over the past several thousand years and 10,000 years into the future. For reasons described in Section 2.2.1.2.1, the lower boundary of the groundwater basin is the upper surface of the Salado. Nash Draw and the Pecos River are areas where discharge to the surface occurs. Hunter (1985) described discharge at Surprise Spring and into saline lakes in Nash Draw. She reported groundwater discharge into the Pecos River between Avalon Dam north of Carlsbad and a point south of Malaga Bend as approximately 0.92 m^3/s (32.5 ft^3/s), mostly in the region near Malaga Bend.

Within this groundwater basin, hydrostratigraphic units with relatively high permeability are called conductive units, and those with relatively low permeability are called confining layers. The confining layers consist of halite and anhydrite and are perhaps five orders of magnitude less permeable than conductive units.

In a groundwater basin, the position of the water table moves up and down in response to changes in recharge. The amount of recharge is generally a very small fraction of the amount of rainfall; this condition is expected for the WIPP. Modeling of recharge changes within the groundwater basin as a function of climate variation is discussed in Section 6.4.9. The water table would stabilize at a particular position if the pattern of recharge remained constant for a long time. The equilibrated position depends, in part, on the distribution of hydraulic conductivity in all hydrostratigraphic units in the groundwater basin. However, the position of the water table depends mainly on the topography and geometry of the groundwater basin and the hydraulic conductivity of the uppermost strata. The position of the water table can adjust slowly to changes in recharge. Consequently, the water table can be at a position that is very much different from its equilibrium position at any given time. Generally, the water table drops

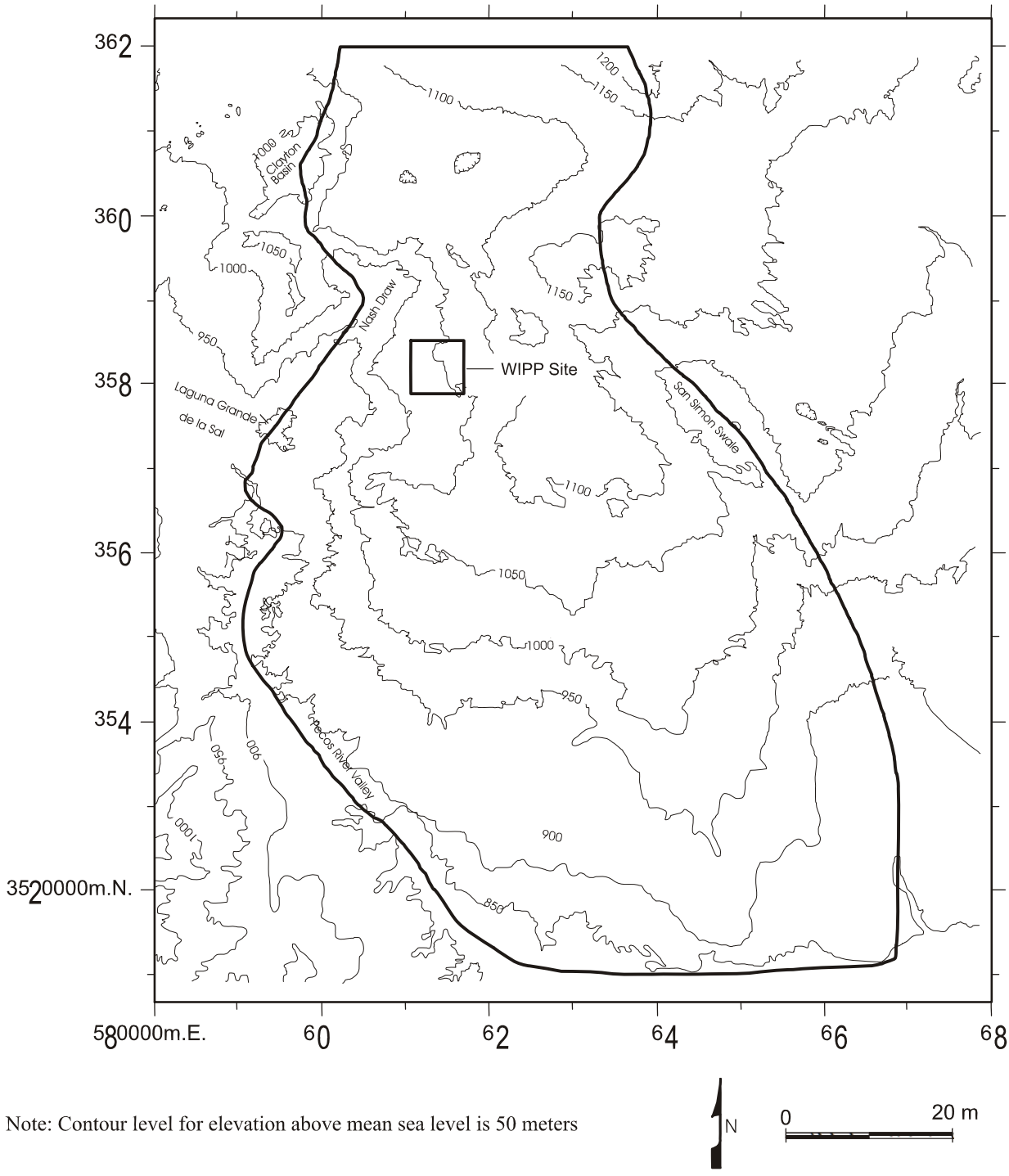

Note: Contour level for elevation above mean sea level is 50 meters

Figure 2-33. Outline of the Groundwater Basin Model Domain on a Topographic Map

very slowly in response to decreasing recharge but might rise rapidly in times of increasing recharge.

The asymmetry of response occurs because the rate at which the water table drops is limited by the rate at which water flows through the entire basin. In contrast, the rate at which the water table rises depends mainly on the recharge rate and the porosity of the uppermost strata. From groundwater basin modeling, the head distribution in the groundwater basin appears to equilibrate rapidly with the position of the water table.

The groundwater basin conceptual model (Corbet and Knupp 1996) described above has been implemented in a numerical model, as described in CCA Appendix MASS, Section MASS.14.2. This model has been used to simulate the interactive nature of flow through conductive layers and confining units for a variety of possible rock properties and climate futures. Thus, this model has allowed insight into the magnitude of flow through various units. The DOE has used this insight as a basis for model simplifications used in PA that are described here and in Chapter 6.

One conclusion from the regional groundwater basin modeling is pertinent here. In general, vertical leakage through confining layers is directed downward over all of the controlled area. This downward leakage uniformly over the WIPP site is the result of a well-developed discharge area, Nash Draw and the Pecos River, along the western and southern boundaries of the groundwater basin. This area acts as a drain for the laterally conductive units in the groundwater basin, causing most vertical leakage in the groundwater basin to occur in a downward direction. This conclusion is important in PA simplifications related to the relative importance of lateral flow in the Magenta versus the Culebra, which will be discussed later in this chapter and in Section 6.4.6.

Public concern was expressed that groundwater flow to the spring supplying brine to Laguna Grande de la Sal could be related to the presence of karst features. The EPA examined information regarding the hydrology of the units above the Salado and DOE's conceptualization of the groundwater flow model, including supplementary information submitted in letters dated May 2, 1997 (Docket A-93-02, Item V-B-6 (6)), and May 14, 1997 (Docket A-93-02, Item II-I-31), and the EPA concluded that the information was adequate.

The EPA concluded, based on WIPP field observations and site-specific hydrologic information, there is no indication that any cavernous or other karst-related flow is present within the WIPP site boundary. The EPA concurred with DOE's conceptualization of groundwater flow in the Culebra, which includes the presence of fractures within the Culebra and recharge and discharge areas for groundwater that are more consistent with potential discharge to areas south and west of the WIPP.

2.2.1.4.1 Hydrology of the Rustler Formation

The Rustler is of particular importance for WIPP because it contains the most transmissive units above the repository. Fluid flow in the Rustler is characterized by very slow rates of vertical leakage through confining layers and faster lateral flow in conductive units. To illustrate this point, regional modeling with the groundwater basin model indicates that lateral specific

discharges in the Culebra, for example, are perhaps two to three orders of magnitude greater than the vertical specific discharges across the top of the Culebra.

Because of its importance, the Rustler continues to be the focus of studies to understand better the complex relationship between hydrologic properties and geology, particularly in view of water-level rises observed in the Culebra and Magenta (e.g., SNL 2003a; also see Appendix DATA). An example of the complex nature of Rustler hydrology is the variation in Culebra transmissivity (T). Culebra T varies over three orders of magnitude on the WIPP site itself and over six orders of magnitude on the scale of the regional groundwater basin model with lower T east of the site and higher T west of the site in Nash Draw (e.g., Beauheim and Ruskauff 1998). As discussed below, site investigations and studies (e.g., Holt and Powers 1988; Beauheim and Holt 1990; Powers and Holt 1995; Holt 1997; Holt and Yarbrough 2002; Powers et al. 2003) suggest that the variability in Culebra T can be explained largely by the thickness of Culebra overburden, the location and extent of upper Salado dissolution, and the occurrence of halite in the mudstone units bounding the Culebra (see Section 2.1.3.5).

2.2.1.4.1.1 Los Medaños

The unnamed lower member was named the Los Medaños by Powers and Holt (1999). The Los Medaños is treated as a single hydrostratigraphic unit in WIPP models of the Rustler, although its composition varies. Overall, it acts as a confining layer. The basal interval of the Los Medaños, approximately 19.5 m (64 ft) thick, is composed of siltstone, mudstone, and claystone and contains the water-producing zones of the lowermost Rustler. Transmissivities of 2.9×10^{-10} m^2/s (2.7×10^{-4} ft^2/day) and 2.4×10^{-10} m^2/s (2.2×10^{-4} ft^2/day) were reported by Beauheim (1987a, p. 50) from tests at well H-16 that included this interval. The porosity of the Los Medaños was measured in 1995 as part of testing at the H-19 hydropad (TerraTek 1996). Two claystone samples had effective porosities of 26.8 and 27.3 percent. One anhydrite sample had an effective porosity of 0.2 percent. The transmissivity values correspond to hydraulic conductivities of 1.5×10^{-11} m/s (4.2×10^{-6} ft/day) and 1.2×10^{-11} m/s (3.4×10^{-6} ft/day). Hydraulic conductivity in the lower portion of the Los Medaños is believed by the DOE to increase to the west in and near Nash Draw, where dissolution at the underlying Rustler-Salado contact has caused subsidence and fracturing of the sandstone and siltstone.

The remainder of the Los Medaños contains mudstones, anhydrite, and variable amounts of halite. The hydraulic conductivity of these lithologies is extremely low. It is for this reason the Los Medaños is treated as a single hydrostratigraphic unit that overall acts as a confining unit. The conceptual model incorporating the Los Medaños is discussed in Section 6.4.6.1. Important hydrologic model properties of the Los Medaños are summarized in Appendix PA.

As described in Section 2.1.3.5, the Los Medaños contains two mudstone layers: one in the middle of the Los Medaños and one immediately below the Culebra. An anhydrite layer separates the two mudstones. The lower and upper Los Medaños mudstones have been given the designations M1/H1 and M2/H2, respectively, by Holt and Powers (1988). This naming convention is used to indicate the presence of halite in the mudstone at some locations at and near the WIPP site. Powers (2002a) has mapped (Figure 2-15) the margins delineating the occurrence of halite in both mudstone layers. Whereas early researchers (e.g., Snyder 1985) interpreted the absence of halite west of these margins as evidence of dissolution, Holt and

Powers (1988) interpreted it as reflecting changes in the depositional environment, not dissolution. However, Holt and Powers (1988) concluded that dissolution of Rustler halite may have occurred along the present-day margins. The presence of halite in the Los Medaños mudstones is likely to affect the conductivity of the mudstones, but its greater importance is the implications it has for the conductivity of the Culebra. As discussed in Section 2.2.1.4.1.2, the Culebra transmissivity in locations where halite is present in M2/H2 and M3/H3 (a mudstone in the lower Tamarisk Member of the Rustler) is assumed to be an order of magnitude lower than where halite does not occur (Holt and Yarbrough 2002).

Fluid pressures in the Los Medaños have been continuously measured at well H-16 since 1987. During this period, the fluid pressure has remained relatively constant at between 190 and 195 psi or a head of approximately 137 m (450 ft). Given the location of the pressure transducer (an elevation of 811.96 m amsl), the current elevation of the Los Medaños water level at H-16 is approximately 949 m amsl. No other wells in the WIPP monitoring network are completed to the Los Medaños. Thus, H-16 provides the only current head information for this member.

2.2.1.4.1.2 The Culebra Dolomite Member

The Culebra is of interest because it is the most transmissive saturated unit above the WIPP repository and hydrologic research has been concentrated on the unit for nearly two decades. Although it is relatively thin, it is an entire hydrostratigraphic unit in the WIPP hydrological conceptual model, and it is the most important conductive unit in this model. Implementation of the Culebra in the conceptual model is discussed in detail in Section 6.4.6.2. Model discussions cover groundwater flow and transport characteristics of the Culebra. These are supported by parameter values in Table 6-20, 6-21, 6-22, and 6-23. Additional background for the Culebra model is in CCA Appendix MASS, Sections MASS.14 and MASS.15.

The two primary types of field tests used to characterize the flow and transport characteristics of the Culebra are hydraulic tests and tracer tests.

The hydraulic testing consists of pumping, injection, and slug testing of wells across the study area (for example, Beauheim 1987a, p. 3). The most detailed hydraulic test data exist for the WIPP hydropads (for example, H-19). The hydropads generally comprise a network of three or more wells located within a few tens of meters of each other. Long-term pumping tests have been conducted at hydropads H-3, H-11, and H-19 and at well WIPP-13 (Beauheim 1987b; 1989; Beauheim et al. 1995; Meigs et al. 2000). These pumping tests provided transient pressure data at the hydropad and over a much larger area. Tests often included use of automated data-acquisition systems, providing high-resolution (in both space and time) data sets. In addition to long-term pumping tests, slug tests and short-term pumping tests have been conducted at individual wells to provide pressure data that can be used to interpret the transmissivity at that well (Beauheim 1987a). (Additional short-term pumping tests have been conducted in the WQSP wells [Beauheim and Ruskauff 1998]). Detailed cross-hole hydraulic testing has been conducted at the H-19 hydropad (Beauheim 2000).

The hydraulic tests are designed to yield pressure data for the interpretation of such characteristics as transmissivity, permeability, and storativity. The pressure data from long-term pumping tests and the interpreted transmissivity values for individual wells are used for the

generation of transmissivity fields in PA flow modeling (see Appendix PA, Attachment TFIELD, Sections TFIELD 5.0 and TFIELD-6.0). Some of the hydraulic test data and interpretations are also important for the interpretation of transport characteristics. For instance, information about the vertical distribution of permeability interpreted from the hydraulic tests at a given hydropad is needed for interpretations of tracer test data at that hydropad.

To evaluate transport properties of the Culebra, a series of tracer tests were conducted at six locations (the H-2, H-3, H-4, H-6, H-11, and H-19 hydropads) near the WIPP site. Tests at the first five of these locations consisted of two-well dipole tests and/or multiwell convergent flow tests and are described in detail in Jones et al. (1992). Tracer tests at the H-19 hydropad and additional tracer tests performed at the H-11 hydropad are described in Meigs et al. (2000). The 1995-1996 tracer test program consisted of single-well injection-withdrawal tests and multi-well convergent flow tests (Meigs and Beauheim 2001). Unique features of this testing program include the single-well test at both H-19 and H-11, the injection of tracers into six wells during the H-19 convergent-flow test, the injection of tracer into upper and lower zones of the Culebra at the H-19 hydropad, repeated injections under different convergent-flow pumping rates, and the use of tracers with different free-water diffusion coefficients. The 1995-1996 tracer tests were specifically designed to evaluate the importance of heterogeneity (both horizontal and vertical) and diffusion on transport processes.

The Culebra is a fractured dolomite with nonuniform properties both horizontally and vertically. Examination of core and shaft exposures has revealed that there are multiple scales of porosity within the Culebra including fractures ranging from microscale to potentially large, vuggy zones, and interparticle and intercrystalline porosity (Holt 1997). Porosity measurements made on core samples give porosity measurements ranging from 0.03 to 0.30 (Kelley and Saulnier 1990; TerraTek 1996). This large range in porosity for small samples is expected given the variety of porosity types within the Culebra. However, the effective porosity for flow and transport at larger scales will have a smaller range due to the effects of spatial averaging. The core measurements indicate that the Culebra has significant quantities of connected porosity.

Flow in the Culebra occurs within fractures, within vugs where they are connected by fractures, and to some extent within interparticle porosity where the porosity (and permeability) is high, such as chalky lenses. At any given location, flow will occur in response to hydraulic gradients in all places that are permeable. When the permeability contrast between different scales of connected porosity is large, the total porosity can effectively be conceptualized by dividing the system into advective porosity (often referred to as fracture porosity) and diffusive porosity (often referred to as matrix porosity). The advective porosity can be defined as the portion of the porosity where flow is the dominant process (for example fractures and to some extent vugs connected by fractures and interparticle porosity). Diffusive porosity can be defined as the portion of the porosity where diffusion is the dominant process (for example, intercrystalline porosity and to some extent microfractures, vugs and portions of the interparticle porosity.)

For the Culebra in the vicinity of the WIPP site, defining advective porosity is not a simple matter. In some regions the permeability of the fractures is inferred to be significantly larger than the permeability of the other porosity types, thus advective porosity can be conceptualized as predominantly fracture porosity (low porosity). In some regions, there appear to be no high permeability fractures. This may be due to a lack of large fractures or may be the result of

gypsum fillings in a portion of the porosity. Where permeability contrasts between porosity types are small, the advective porosity can be conceptualized as a combination of fractures, vugs connected by fractures, and permeable portions of the interparticle porosity. In each case, the diffusive porosity can be conceptualized as the porosity where advection is not dominant.

The major physical transport processes that affect actinide transport through the Culebra include advection (through fractures and other permeable porosity), diffusion from the advective porosity into the rest of the connected porosity (diffusive porosity) and dispersive spreading due to heterogeneity. Diffusion can be an important process for effectively retarding solutes by transferring mass from the porosity where advection (flow) is the dominant process into other portions of the rock. Diffusion into stagnant portions of the rock also provides access to additional surface area for sorption. Further discussion of transport of actinides in the Culebra as either dissolved species or as colloids is given in Section 6.4.6.2. Parameter values determined from tests of the Culebra are given in CCA Appendix PAR and are described in Section 6.4.6.2.2. A summary of input values to the conceptual model is in Tables 6-22 and 6-23.

Fluid flow in the Culebra is dominantly lateral and southward except in discharge areas along the west or south boundaries of the basin. Where transmissive fractures exist, flow is dominated by fractures but may also occur in vugs connected by microfractures and interparticle porosity. Regions where flow is dominantly through vugs connected by microfractures and interparticle porosity have been inferred from pumping tests and tracer tests. Flow in the Culebra may be concentrated along zones that are thinner than the total thickness of the Culebra. In general, the upper portion of the Culebra is massive dolomite with a few fractures and vugs, and appears to have low permeability. The lower portion of the Culebra appears to have many more vuggy and fractured zones and to have significantly higher permeability (Meigs and Beauheim 2001).

There is strong evidence that the permeability of the Culebra varies spatially and varies sufficiently that it cannot be characterized with a uniform value or range over the region of interest to the WIPP. The transmissivity of the Culebra varies spatially over six orders of magnitude from east to west in the vicinity of the WIPP (Figure 2-34). Over the site, Culebra transmissivity varies over three to four orders of magnitude. CCA Appendix TFIELD, Section TFIELD.2 contains the data used to develop Figure 2-34, which shows variation in transmissivity in the Culebra in the WIPP region. Attachment TFIELD to Appendix P provides the modeling rationale and addresses how data collected over a number of years were correlated for the generation of transmissivity fields.

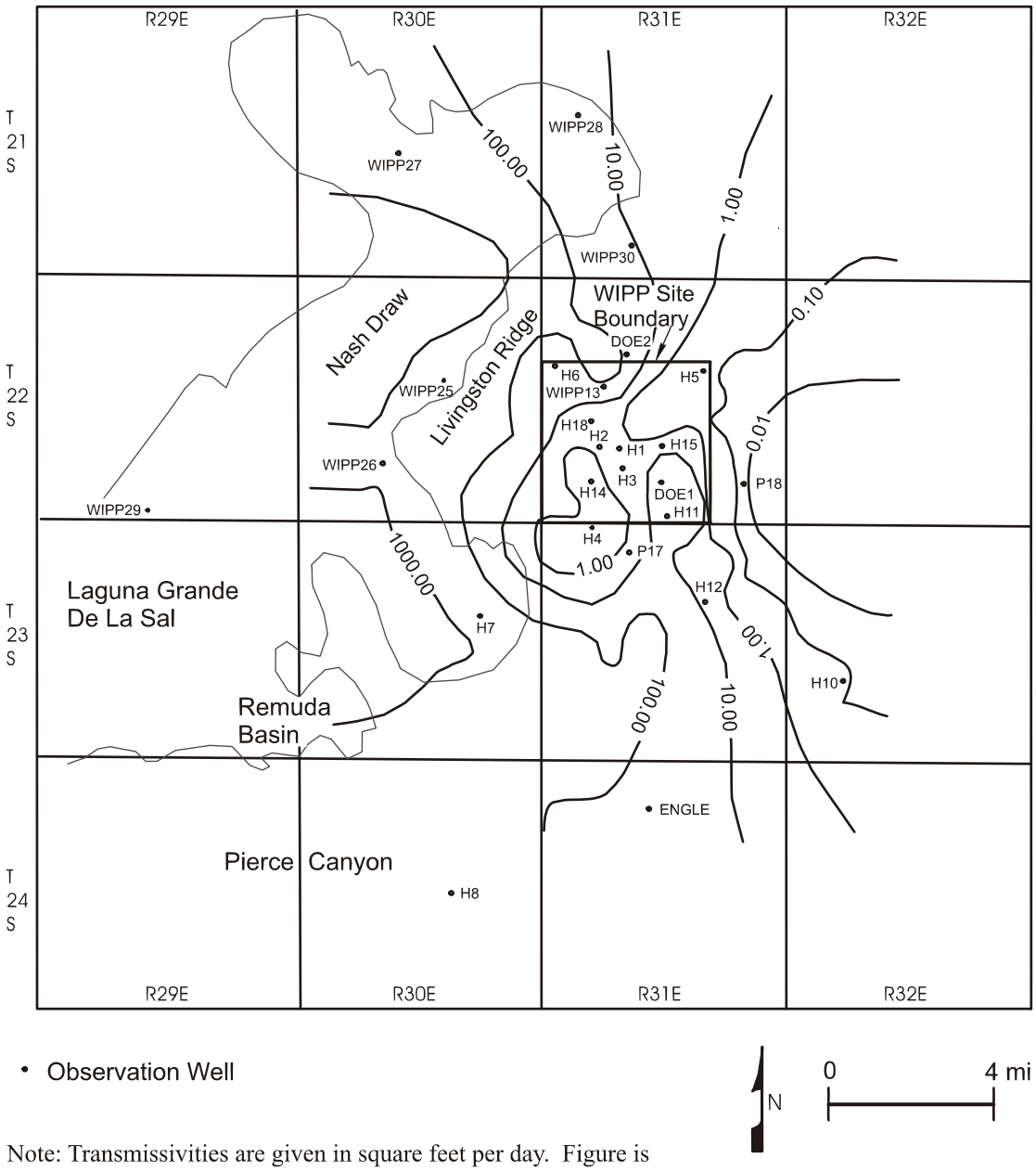

Note: Transmissivities are given in square feet per day. Figure is modified from Cauffman et al. 1990 (Figure 5.22a). See Appendix TFIELD for details of the performance assessment implementation.

Figure 2-34. Transmissivities of the Culebra

Transmissivities are from about 1×10^{-9} m^2/s (1×10^{-3} ft^2/day) at well P-18 east of the WIPP site to about 1×10^{-3} m^2/s (1×10^{3} ft^2/day) at well H-7 in Nash Draw (see Figure 2-2 for the locations of these wells and see Figure 4-8 in CCA Appendix FAC for a Culebra isopach map).

Transmissivity variations in the Culebra are believed to be controlled by the relative abundance of open fractures rather than by primary (that is, depositional) features of the unit. Lateral

variations in depositional environments were small within the mapped region, and primary features of the Culebra show little map-scale spatial variability, according to Holt and Powers (CCA Appendix FAC). Direct measurements of the density of open fractures are not available from core samples because of incomplete recovery and fracturing during drilling, but observation of the relatively unfractured exposures in the WIPP shafts suggests that the density of open fractures in the Culebra decreases to the east.

Recent investigations have made a significant contribution to the understanding of the large variability observed for Culebra transmissivity (e.g., Holt and Powers 1988; Beauheim and Holt 1990; Powers and Holt 1995; Holt 1997; Holt and Yarbrough 2002; Powers et al. 2003). The spatial distribution of Culebra transmissivity is believed to be due strictly to deterministic post-depositional processes and geologic controls (Holt and Yarbrough 2002). The important geologic controls include Culebra overburden thickness, dissolution of the upper Salado, and the occurrence of halite in the mudstone Rustler units (M2/H2 and M3/H3) above and below the Culebra (Holt and Yarbrough 2002). Culebra transmissivity is inversely related to thickness of overburden because stress relief associated with erosion of overburden (see Section 2.1.5.2) leads to fracturing and opening of preexisting fractures. Culebra transmissivity is high where dissolution of the upper Salado has occurred and the Culebra has subsided and fractured. Culebra transmissivity is observed to be low where halite is present in overlying and/or underlying mudstones. Presumably, high Culebra transmissivity leads to dissolution of nearby halite (if any). Hence, the presence of halite in mudstones above and/or below the Culebra can be taken as an indicator for low Culebra transmissivity. Details of the geologic-based transmissivity model for the Culebra are given in Attachment TFIELD (Section TFIELD-3.0) to Appendix PA and summarized below.

The Culebra has been tested hydraulically at 42 locations, yielding reliable transmissivity values. These values (log T) are plotted as a function of depth to Culebra (overburden thickness) in Figure 2-35. As shown, the Culebra transmissivities fall into two populations separated by a cutoff (termed ‘high-T’ cutoff) equal to -5.4 (log T [m^2/s]). These data suggest a bimodal distribution for transmissivity with one population having high transmissivity and the other low transmissivity, with the difference attributed to open, interconnected fractures (“fracture interconnectivity”) for the high-transmissivity population (Holt and Yarbrough 2002). Using these data, Holt and Yarbrough (2002) constructed a linear Culebra transmissivity model relating log T to the deterministic geologic controls described above. The linear model is expressed as follows:

$$Y(\mathbf{x}) = \beta_1 + \beta_2 d(\mathbf{x}) + \beta_3 I_f(\mathbf{x}) + \beta_4 I_D(\mathbf{x}), \tag{2.1}$$

where Y(x) is log T (x), β_i (I = 1 to 4) are regression coefficients, x is a two-dimensional location vector, d(x) is the overburden thickness at x (expressed in UTM coordinates and

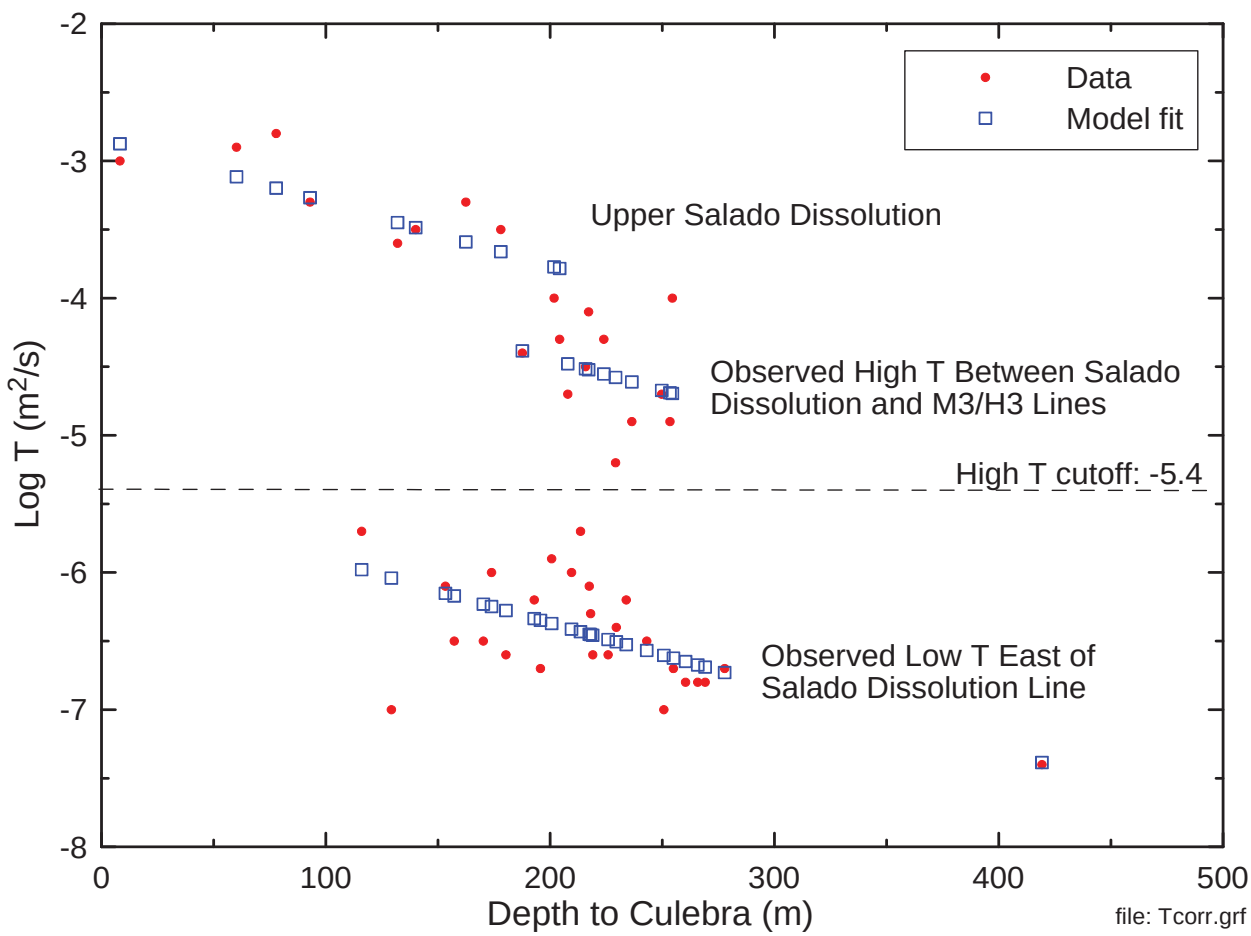

Figure 2-35. Correlation Between Culebra Transmissivity (log T (m^2/s)) and Overburden Thickness for Different Geologic Environments (after Holt and Yarbrough 2002)

meters), I_f (x) is the fracture-interconnectivity indicator at x (equal to 1 when log T (m^2/s) > -5.4 or 0 when log T (m^2/s) < -5.4), and I_D (x) is the dissolution indicator (equal to 1 when Salado dissolution has occurred at (x) and 0 when it has not). In this model, coefficient β_1 is the intercept value, β_2 is the slope of Y(x)/d(x), and β_3 and β_4 represent adjustments to the intercept for the occurrence of open, interconnected fractures and Salado dissolution, respectively. Based on linear-regression analysis, Holt and Yarbrough (2002) estimated the coefficients in Equation (2.1). These estimates are summarized in Table 2-7. Predictions of the Culebra transmissivity model represented by Equation (2.1) are shown in Figure 2-35.

The regression model expressed by Equation (2.1) cannot adequately predict transmissivity in the regions where halite is present both in M2/H2 and M3/H3. In these regions, Culebra

Table 2-7. Estimates of Culebra Transmissivity Model Coefficients

β_1	β_2	β_3	β_4
-5.441	-4.636 × 10-3	1.926	0.678

porosity is thought to be at least partially filled with halite, reducing transmissivity. For these regions, Equation (2.1) is modified as follows:

$$Y(\mathbf{x}) = \beta_1 + \beta_2 d(\mathbf{x}) + \beta_3 I_f(\mathbf{x}) + \beta_4 I_D(\mathbf{x}) + \beta_5 I_H(\mathbf{x}). \tag{2.2}$$

I_H (x) is a halite indicator function equal to 1 in locations where halite occurs in both the M2/H2 and M3/H3 intervals and 0 otherwise. The coefficient β_5 is equal to –1 to assure that the model in Equation (2.2) reduces the predicted transmissivity values by one order of magnitude where halite occurs in both the M2/H2 and M3/H3 intervals.

In the region east of the upper Salado dissolution margin and west of the M2/H2 and M3/H3 margins, high transmissivity depends, in part, on the absence of gypsum fracture fillings. No method has yet been determined for predicting whether fractures will or will not be filled with gypsum at a given location, so the distribution of high and low transmissivity is treated stochastically in this region. Predictions of transmissivity in this region make use of an isotropic spherical variogram model. Fitted parameters for the variogram model are described in Attachment TFIELD (Section TFIELD-4.3) of Appendix PA.

Geochemical and radioisotope characteristics of the Culebra have been studied. There is considerable variation in groundwater geochemistry in the Culebra. The variation has been described in terms of different hydrogeochemical facies that can be mapped in the Culebra (see Section 2.4.2). A halite-rich hydrogeochemical facies exists in the region of the WIPP site and to the east, approximately corresponding to the regions in which halite exists in units above and below the Culebra (Figure 2-15), and in which a large portion of the Culebra fractures are gypsum filled (Figure 2-17). An anhydrite-rich hydrogeochemical facies exists west and south of the WIPP site, where there is relatively less halite in adjacent strata and where there are fewer gypsum-filled fractures.

The Culebra groundwater geochemistry studies continue. Culebra water quality is evaluated semiannually at six wells, three north (WQSP-1, WQSP-2, and WQSP-3) and three south (WQSP-4, WQSP-5, and WQSP-6) (WIPP MOC 1995) of the surface structures area (see Figure 2-3 for well locations). Five rounds of semiannual sampling of water quality completed before the first receipt of waste at the WIPP were used to establish the initial Culebra water-quality baseline for major ion species including Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, and HCO_3^{2-} (Crawley and Nagy 1998). In 2000, this baseline was expanded to include five additional rounds of sampling that were completed before first receipt of RCRA-regulated waste (IT Corporation 2000). Table 2-8 gives the 95 percent confidence intervals presented in SNL (2001) for the major ion species determined from the 10 rounds (semiannual sampling for 5 years) of baseline sampling. Culebra water quality is extremely variable among the six sampling wells, as shown by the Cl^- concentrations that range from approximately 6,000 mg/L at WQSP-6 to 130,000 mg/L at WQSP-3.

Radiogenic isotopic signatures suggest that the age of the groundwater in the Culebra is on the order of 10,000 years or more (see, for example, Lambert 1987, Lambert and Carter 1987, and Lambert and Harvey 1987). The radiogenic ages of the Culebra groundwater and the geochemical differences provide information potentially relevant to the groundwater flow directions and groundwater interaction with other units and are important constraints on

Table 2-8. Ninety-Five Percent Confidence Intervals for Culebra Water-Quality Baseline

Well I.D.	Cl^- Conc. (mg/L)	SO_4^{2-} Conc. (mg/L)	HCO_3^- Conc. (mg/L)	Na^+ Conc. (mg/L)	Ca^{2+} Conc. (mg/L)	Mg^{2+} Conc. (mg/L)	K^+ Conc. (mg/L)
WQSP-1	31100-39600	4060-5600	45-54	15850-21130	1380-2030	940-1210	322-730
WQSP-2	31800-39000	4550-6380	43-53	14060-22350	1230-1730	852-1120	318-649
WQSP-3	113900-145200	6420-7870	23-51	62600-82700	1090-1620	1730-2500	2060-3150
WQSP-4	53400-63000	5620-7720	31-46	28100-37800	1420-1790	973-1410	784-1600
WQSP-5	13400-17600	4060-5940	42-54	7980-10420	902-1180	389-535	171-523
WQSP-6	5470-6380	4240-5120	41-54	3610-5380	586-777	189-233	113-245

conceptual models of groundwater flow. Previous conceptual models of the Culebra (see for example, Chapman 1986, Chapman 1988, LaVenue et al. 1990, and Siegel et al. 1991) have not been able to consistently relate the hydrogeochemical facies, radiogenic ages, and flow constraints (that is, transmissivity, boundary conditions, etc.) in the Culebra.

The groundwater basin modeling that was conducted, although it did not model solute transport processes, provides flow fields that can be used to develop the following concepts that help explain the observed hydrogeochemical facies and radiogenic ages. The groundwater basin model combines and tests three fundamental processes: (1) it calculates vertical leakage, which may carry solutes into the Culebra; (2) it calculates lateral fluxes in the Culebra (directions as well as rates); and (3) it calculates a range of possible effects of climate change. The presence of the halite-rich groundwater facies is explained by vertical leakage of solutes into the Culebra from the overlying halite-containing Tamarisk by advective or diffusive processes. Because lateral flow rates here are low, even slow rates of solute transport into the Culebra can result in high solute concentration. Vertical leakage occurs slowly over the entire model region, and thus the age of groundwater in the Culebra is old, consistent with radiogenic information. Lateral fluxes within the anhydrite zone are larger because of higher transmissivity, and where the halite and anhydrite facies regions converge, the halite facies signature is lost by dilution with relatively large quantities of anhydrite facies groundwater. Response of groundwater flow in the Culebra as the result of increasing recharge is modeled through the variation in climate, discussed in Section 6.4.9.

Groundwater levels in the Culebra in the WIPP region were measured prior to the CCA in numerous wells (Figure 2-2). The Culebra monitoring wells as of the end of 2002 are shown in Figures 2-3 and 2-4; plugged and abandoned wells are not shown in these figures. Beginning in 1989, a general

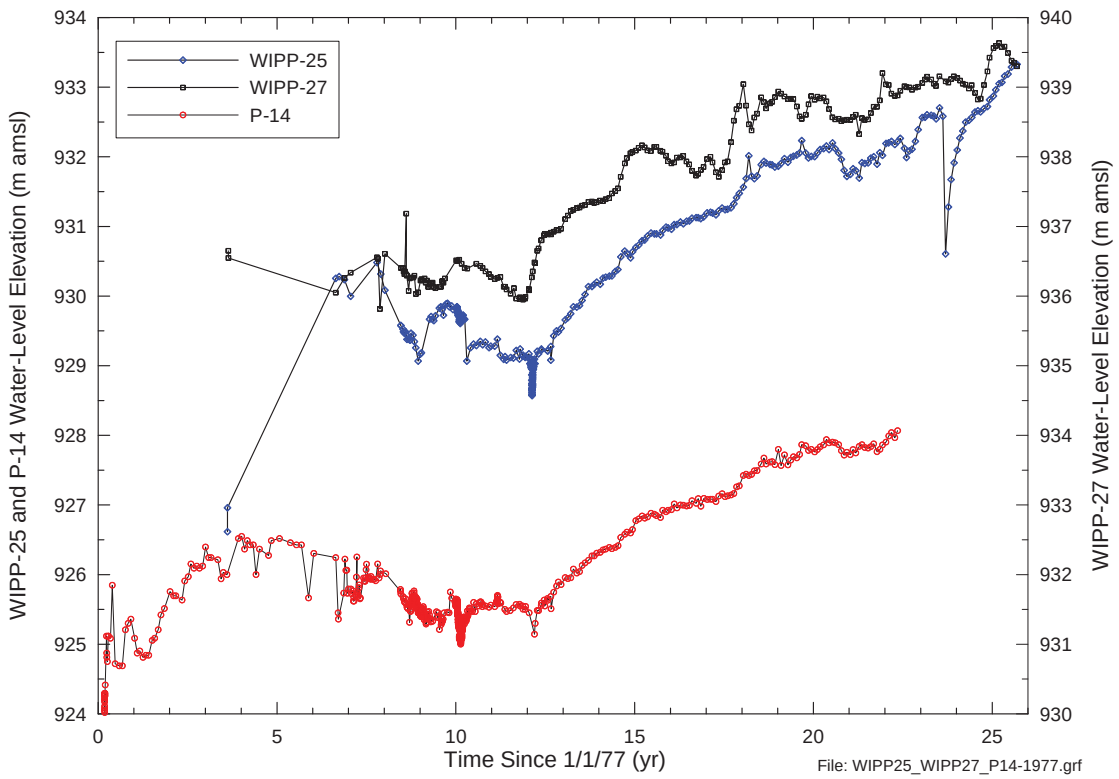

Figure 2-36. Water-level Trends in Nash Draw Wells and at P-14 (see Figure 2-2 for well locations)

long-term rise has been observed in both Culebra and Magenta water levels (Figure 2-36) over a broad area of the WIPP site including Nash Draw (SNL 2003a). At the time of the CCA this long-term rise was recognized, but was thought (outside of Nash Draw) to represent recovery from the accumulation of hydraulic tests that had occurred since the late 1970s and the effects of grouting around the WIPP shafts to limit leakage. Water levels in Nash Draw were thought to respond to changes in the volumes of potash mill effluent discharged into the draw (Silva 1996); however, correlation of these water levels with potash mine discharge cannot be proven because sufficient data on the timing and volumes of discharge are not available. As the rise in water levels has continued since 1996, observed heads have exceeded the ranges of uncertainty established for the steady-state heads in most of the 32 wells used in the calibration of the transmissivity fields described in CCA Appendix TFIELD. Although recovery from the hydraulic tests and shaft leakage has unquestionably occurred, the DOE has implemented a program to identify other potential causes for the water-level rises (SNL 2003b).

Potentiometric surface maps of the freshwater head in the Culebra in December 1998 and December 2002 are shown in Figures 2-37a, 2-37b and 2-37c, respectively. The maps are generally similar and indicate no changes in flow directions across the WIPP site over that period. Figure 2-37c shows the changes in heads at the wells monitored in both December 1998 and December 2002. Freshwater heads in most wells increased by 2-4 ft from 1998 to 2002. The largest rise was 4.84 ft at DOE-1. Only one well, AEC-7, showed a drop over this period (-0.85 ft) larger than potential measurement error.

Although Culebra heads have been rising, the head distribution in the Culebra (see Figures 2-37a, 2-37b and 2-37c) is consistent with groundwater basin modeling results (discussed in Appendix PA, Attachment MASS, Section MASS.14.2) indicating that the generalized direction of groundwater flow remains north to south. However, caution should be used when making assumptions based on groundwater-level data alone. Studies in the Culebra have shown that fluid density variations in the Culebra can affect flow direction (Davies 1989, p. 35). The fractured nature of the Culebra, coupled with variable fluid densities, can also cause localized flow patterns to differ from general flow patterns. Water-level rises in the vicinity of the H-9 hydropad, about 10.46 km (6.5 mi) south of the site, are not thought to be caused by either WIPP activities or potash mining discharge and have been included in the DOE program to investigate Culebra water-level rises in general. The DOE continues to monitor groundwater levels throughout the region, but only water-level changes at or near the site have the potential to impact the prediction of disposal system performance. The DOE has implemented water-level changes in its conceptual model through variations in climate as discussed in Section 6.4.9. These variations bring the water table to the surface for some calculations. The DOE has also used recent (late 2000) Culebra heads in flow and transport calculations for this recertification application, as discussed in Appendix PA, Attachment TFIELD, Section TFIELD-6.2.

Inferences about vertical flow directions in the Culebra have been made from well data collected by the DOE. Beauheim (1987a) reported flow directions toward the Culebra from both the Los Medaños and the Magenta over the WIPP site, indicating that the Culebra acts as a drain for the units around it. This indication is consistent with results of groundwater basin modeling. A more detailed discussion of Culebra flow and transport can be found in Appendix PA, Attachment TFIELD

In response to an EPA letter dated March 19, 1997 (Docket A-93-02, Item II-I-17), supplemental information to the CCA pertinent to groundwater flow and geochemistry within the Culebra was provided by the DOE in a letter dated May 14, 1997 (Docket A-93-02, Item II-I-31). In that letter, the DOE explained the conceptual model of Culebra groundwater flow used in the CCA. The CCA conceptual model, referred to as the groundwater basin model, offers a three-dimensional approach to treatment of supra-Salado rock units, and assumes that vertical leakage (albeit very slow) occurs between rock units of the Rustler (where hydraulic gradients exist). Flow in the Culebra is considered transient, but is not expected to change significantly over the next 10,000 years. This differs from previous interpretations, wherein no flow was assumed between the Rustler units.

In an attachment to the May 14, 1997 letter, the DOE concluded that the presence of anhydrite within the Rustler units did not preclude slow downward infiltration, as previously argued by the DOE, and that the observed geochemistry and flow directions can be explained with different recharge areas and Culebra travel paths. The EPA reviewed the groundwater flow and recharge conceptualization and concluded that it provides a realistic representation of site conditions.

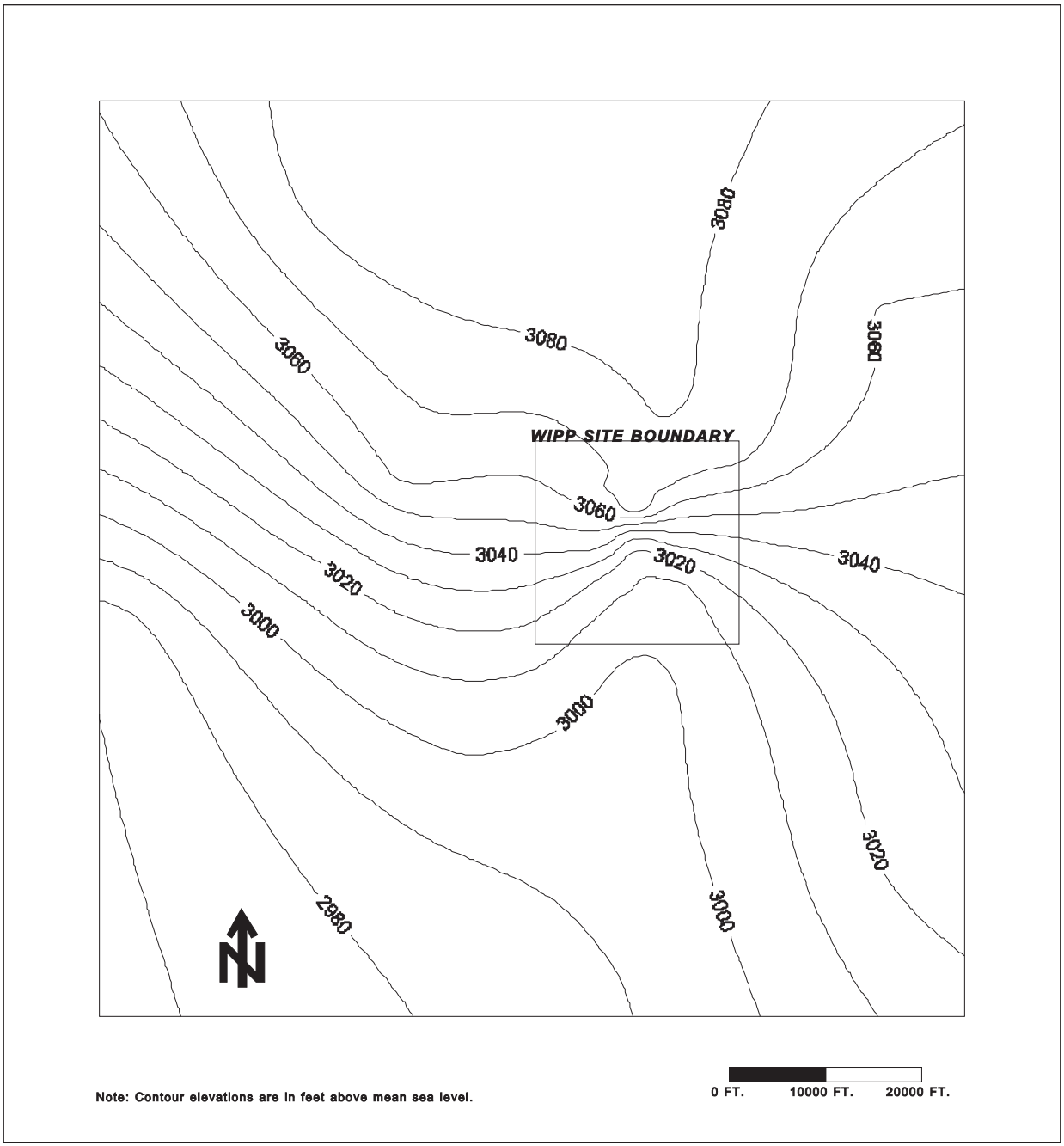

Figure 2-37. Hydraulic Heads in the Culebra

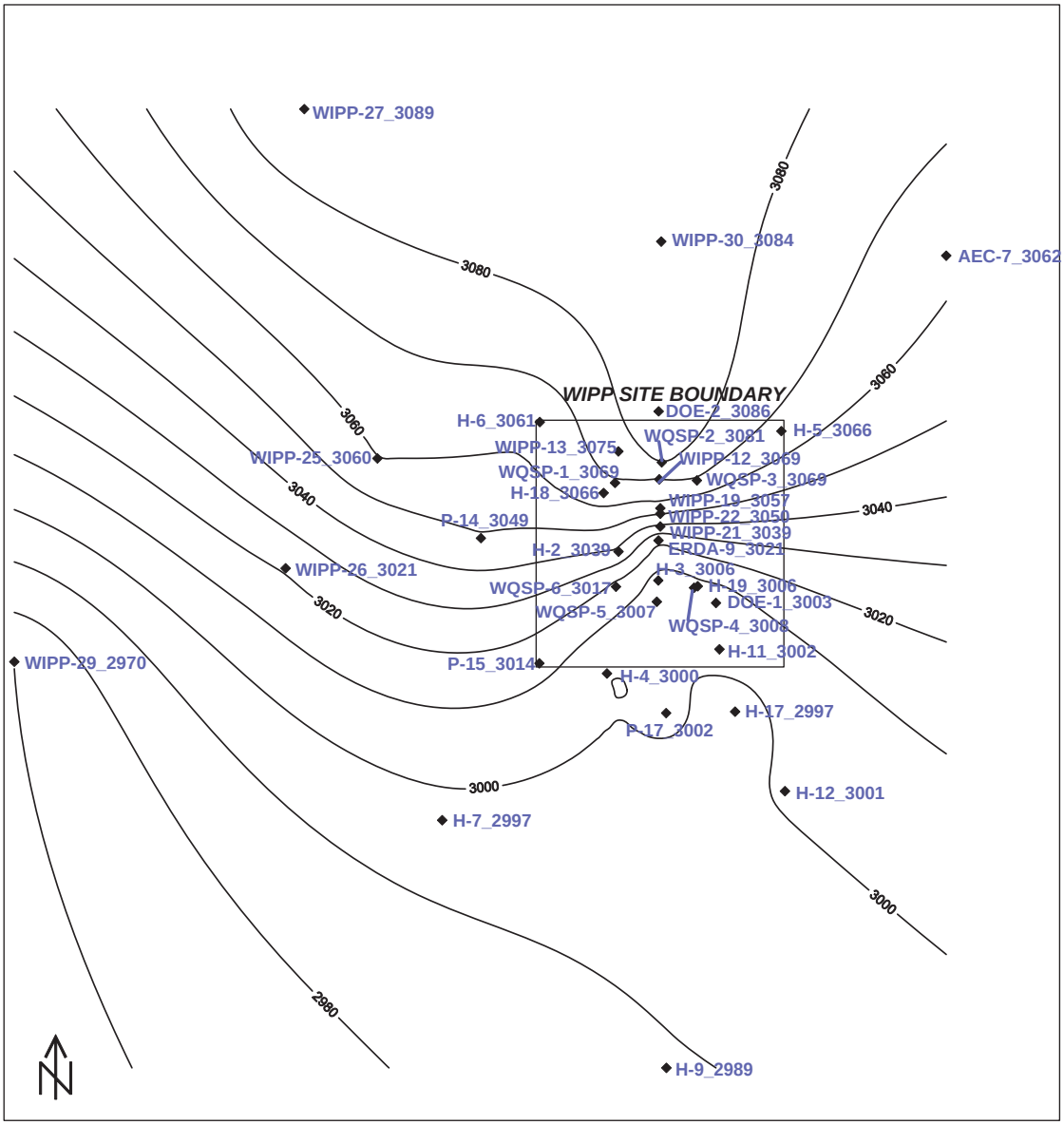

Note: Contour elevations are in feet above mean sea level,
Freshwater Head Elevations are given after the well ID

0 Ft 20000 Ft 40000 Ft

Figure 2-37a. Potentiometric Surface. Exprssesed as Equivalent Freshwater Head, of the Culebra in December 1998.

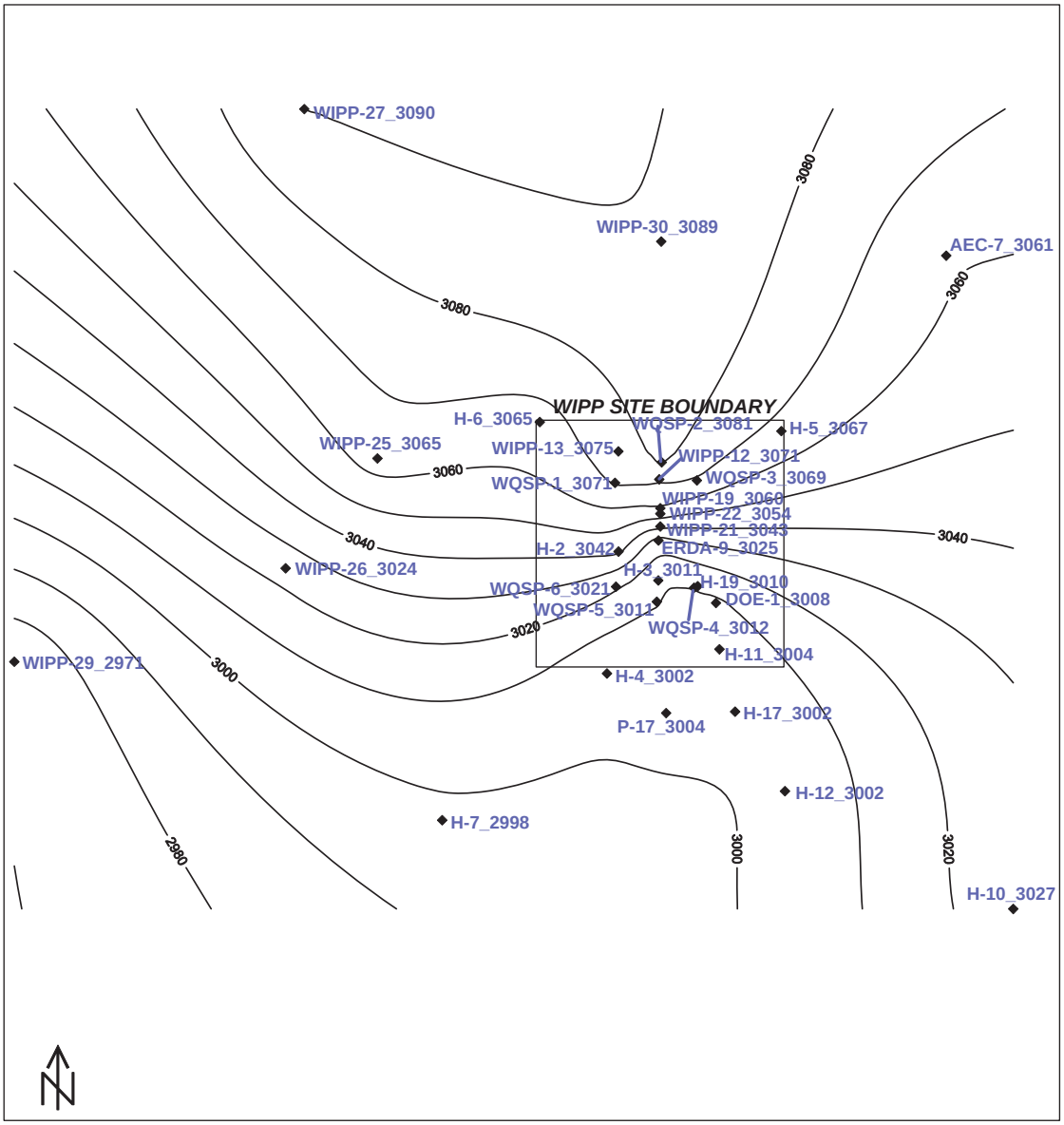

Note: Contour elevations are in feet above mean sea level
Freshwater Head Elevations are given after well ID

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Figure 2-37b. Potentiometric Surface, Expressed as Equivalent Freshwater Head, of the Culebra in December 2002.

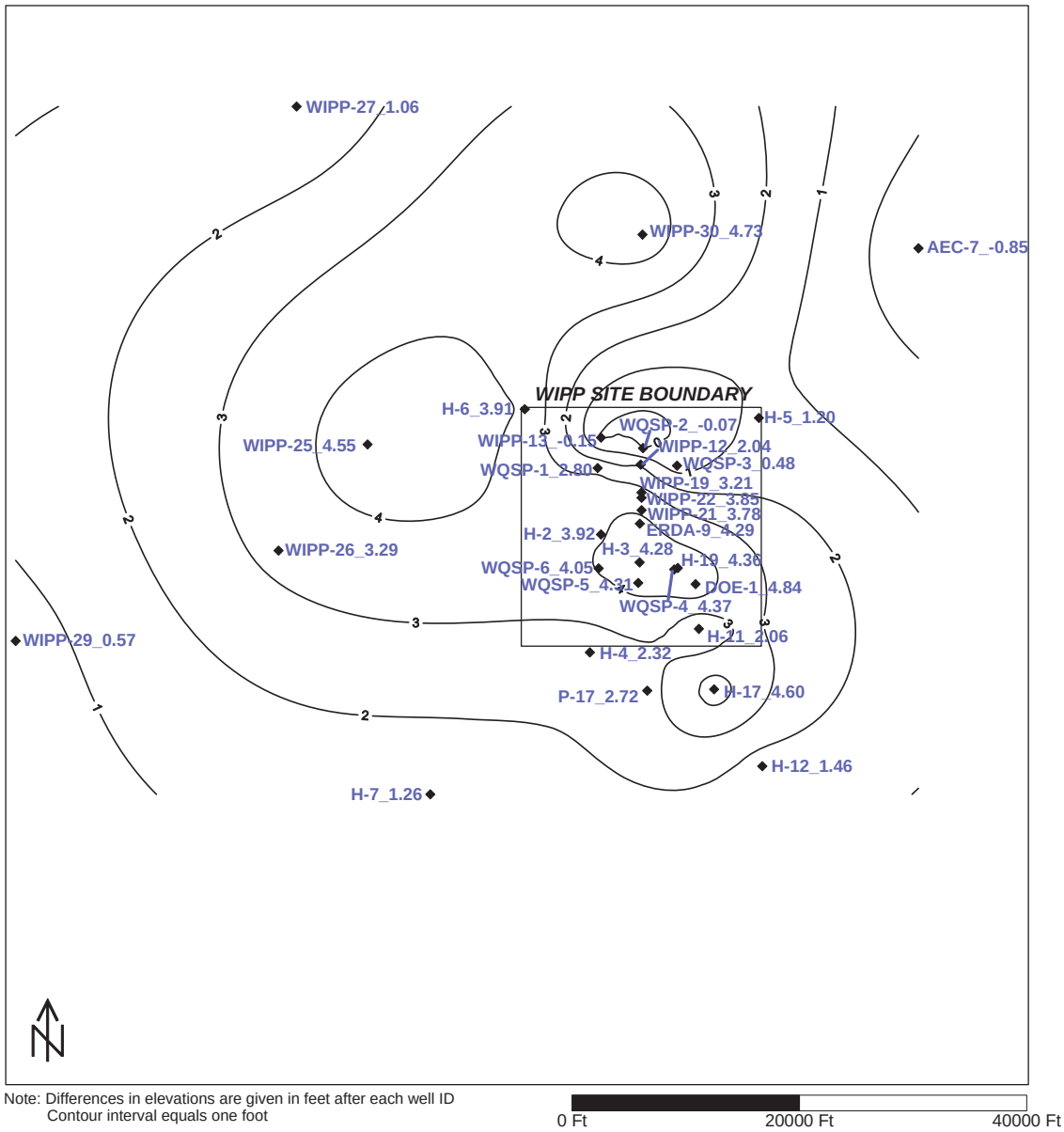

Figure 2-37c. Changes in Freshwater Heads in the Culebra Between December 1998 and December 2002.

During the CCA review, the EPA found that information on the Culebra in the CCA lacked a detailed discussion on the origin of the transmissivity variations relative to fracture infill/dissolution, integration of climatic change, and loading/unloading events. These are important aspects to understanding not only current transmissivity differences, but also potential future transmissivity variations that could affect PA calculations. The EPA's review stated, however, that the determination of the specific origin of fractures was not necessary because conditions were not expected to change during the regulatory period.

The DOE provided supplemental information in letters in 1997 (Docket A-93-02, Items II-I-03, II-I-24, II-I-31, II-H-44, and II-H-46) indicating that dissolution of fracture fill (which has the potential to alter fracture permeability) is unlikely to occur. The EPA accepted the DOE's position that infiltrating waters would most likely become saturated with calcium sulfate and consequently would not dissolve anhydrite or gypsum fracture fill. Further information on the EPA review of anhydrite and gypsum fracture fill dissolution is contained in EPA Technical Support Document for Section 194.14: Content of Compliance Certification Application, Section IV.C (Docket A-93-02, Item V-B-3).

The Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment reports the annual assessment of the Compliance Monitoring Parameters (COMPs) pursuant to the SNL Analysis Plan, AP-069. The first assessment, for calendar year 1998 (SNL 2000a), showed that changes in Culebra water levels were considered minor. During the assessment of the COMP 'changes in groundwater flow' for calendar year 2001 (SNL 2002), estimated freshwater Culebra heads in 15 wells were identified as above the ranges of uncertainty estimated for steady-state conditions at those wells. At 8 of the 15 wells, the measured water levels exceed the uncertainty range before being converted to freshwater head. In these cases, conversion to freshwater head using any feasible fluid density can only increase the deviation from the range. The freshwater head values from late 2000 were used to calibrate the Culebra transmissivity (T) fields used to simulate the transport of radionuclides through the Culebra (Appendix PA, Attachment TFIELD).

Because transport through the Culebra is a minor component of the total predicted releases from the repository, these changes in head values have little or no effect on the total releases to the accessible environment. The COMP assessment for the calendar year 2001 concluded that the current head values do not indicate a condition adverse to the predicted performance of the repository. However, because Culebra water levels are above expected values at most wells, work has been initiated to investigate the reason for the change and further evaluate the impact on performance.

Additional background for the Culebra model is in Appendix PA, Attachment TFIELD. Additional information on long-term pumping test data is documented in Meigs et al. (2000) and slug tests and short-term pumping tests are documented in Beauheim et al. (1991b) and Beauheim and Ruskauff (1998).

Several new publications on the Culebra updating the original CCA information have been released. Transport properties and tracer tests of the Culebra performed at the H-11 and H-19 hydropads are described in Meigs et al. (2000). The 1995-96 tracer test program, which consisted of single-well injection-withdrawal tests and multiwell convergent flow tests, is documented in Meigs and Beauheim (2001). The higher permeability of the lower Culebra has been addressed in Meigs and Beauheim (2001, p. 1116).

2.2.1.4.1.3 Tamarisk

The Tamarisk acts as a confining layer in the groundwater basin model. Attempts were made in two wells, H-14 and H-16, to test a 2.4-m (7.9-ft) sequence of the Tamarisk that consists of claystone, mudstone, and siltstone overlain and underlain by anhydrite. Permeability was too

low to measure in either well within the time allowed for testing; consequently, Beauheim (1987a, pp. 108-110) estimated the transmissivity of the claystone sequence to be one or more orders of magnitude less than that of the tested interval in the Los Medaños (that is, less than approximately 2.7×10^{-11} m^2/s [2.5×10^{-5} ft^2/day]). The porosity of the Tamarisk was measured in 1995 as part of testing at the H-19 hydropad (TerraTek 1996). Two claystone samples had an effective porosity of 21.3 to 21.7 percent. Five anhydrite samples had effective porosities of 0.2 to 1.0 percent.

Fluid pressures in the Tamarisk have been measured continuously at well H-16 since 1987. From 1998 through 2002, the pressures increased approximately 20 psi, from 80 to 100 psi (185 to 230 ft of water), probably in a continuing recovery response to shaft grouting conducted in 1993 to reduce leakage. Given the location of the pressure transducer, the elevation of Tamarisk water level has increased from 899 to 913 m amsl (2,950 to 2,995 ft amsl) during this period. Currently, no other wells in the WIPP monitoring network are completed to the Tamarisk. Thus, H-16 provides the only information on Tamarisk head levels.

Similar to the Los Medaños, the Tamarisk includes a mudstone layer (M3/H3) that contains halite in some locations at and around the WIPP site. This layer is considered to be important because of the effect it has on the spatial distribution of transmissivity of the Culebra as described in Section 2.2.1.4.1.2. The M3/H3 margin is described in Section 2.1.3.5 and mapped in Figure 2-15.

The Tamarisk is incorporated into the conceptual model as discussed in Section 6.4.6.3. The role of the Tamarisk in the groundwater basin model is in CCA Appendix MASS, Section MASS.14.1. Tamarisk hydrological model parameters are in Appendix PA, Attachment PAR, Table PAR-25.

2.2.1.4.1.4 Magenta

The Magenta is a conductive hydrostratigraphic unit about 7.9 m (26 ft) thick at the WIPP. The Magenta is saturated except near outcrops along Nash Draw, and hydraulic data are available from 22 wells including 7 wells recompleted to the Magenta between 1995 and 2002 (SNL 2003a). According to Mercer (CCA Appendix HYDRO, p. 65), transmissivity ranges over five orders of magnitude from 1×10^{-9} to 4×10^{-4} m^2/s (4×10^{-3} to 3.75×10^{2} ft^2/day). A slug test performed in H-9c, a recompleted Magenta well (see Figure 2-5 for well location), yielded a transmissivity of 6×10^{-7} m^2/s (0.56 ft^2/day), which is consistent with Mercer's findings (SNL 2003a). The porosity of the Magenta was measured in 1995 as part of testing at the H-19 hydropad (TerraTek 1996). Four samples had effective porosities ranging from 2.7 to 25.2 percent.

The hydraulic transmissivities of the Magenta, based on sparse data, show a decrease from west to east, with slight indentations of the contours north and south of the WIPP that correspond to the topographic expression of Nash Draw. In most locations, the hydraulic conductivity of the Magenta is one to two orders of magnitude less than that of the Culebra. The Magenta does not have hydraulically significant fractures in the vicinity of the WIPP. Treatment of the Magenta in the model is discussed in Section 6.4.6.4 with modeling parameters in Table 6-24.

Based on Magenta water levels measured in the 1980s (Lappin et al. 1989) when a wide network of Magenta monitoring wells existed, the hydraulic gradient in the Magenta across the site varies from 3 to 4 m/km (16 to 20 ft/mi) on the eastern side, steepening to about 6 m/km (32 ft/mi) along the western side near Nash Draw (Figure 2-38).

Regional modeling using the groundwater basin model indicates that leakage occurs into the Magenta from the overlying Forty-niner and out of the Magenta downward into the Tamarisk. Regional modeling also indicates that flow directions in the Magenta are dominantly westward, similar to the slope of the land surface in the immediate area of the WIPP. This flow direction is different than the dominant flow direction in the next underlying conductive unit, the Culebra. This difference is consistent with the groundwater basin conceptual model, in that flow in shallower units is expected to be more sensitive to local topography.

Inferences about vertical flow directions in the Magenta have been made from well data collected by the DOE. Beauheim (1987a, p. 137) reported flow directions downwards out of the Magenta over the WIPP site, consistent with results of groundwater basin modeling.

However, Beauheim (1987a, p. 139) concluded that flow directions between the Forty-niner and Magenta would be upward in the three boreholes from which reliable pressure data are available for the Forty-niner (H-3, H-14, and H-16), which is not consistent with the results of groundwater modeling. This inconsistency may be the result of local heterogeneity in rock properties that affect flow on a scale that cannot be duplicated in regional modeling.

As is the case for the Culebra, groundwater elevations in the Magenta have changed over the period of observation. The pattern of changes is similar to that observed for the Culebra (see Section 2.2.1.4.1.2), and is being investigated under the current DOE hydrology program (SNL 2003b).

2.2.1.4.1.5 Forty-niner

The Forty-niner is a confining hydrostratigraphic layer about 20 m (66 ft) thick throughout the WIPP area and consists of low-permeability anhydrite and siltstone. Tests by Beauheim (1987a, 119-123 and Table 5-2) in H-14 and H-16 yielded transmissivities of about 3×10^{-8} to 8×10^{-8} m^2/s (3×10^{-2} to 7×10^{-2} ft^2/day) and 3×10^{-9} to 6×10^{-9} m^2/s (5×10^{-3} to 6×10^{-3} ft^2/day), respectively, for the medial siltstone unit of the Forty-niner. Tests of the siltstone in H-3d provided transmissivity estimates of 3.8×10^{-9} to 4.8×10^{-9} m^2/s (3.5×10^{-3} to 4.5×10^{-3} ft^2/day) (Beauheim et al. 1991b, Table 5-1). The porosity of the Forty-niner was measured as part of testing at the H-19 hydropad (TerraTek 1996). Three claystone samples had effective porosities ranging from 9.1 to 24.0 percent. Four anhydrite samples had effective porosities ranging from 0.0 to 0.4 percent. Model consideration of the Forty-niner is in Section 6.4.6.5. Modeling parameters are in CCA Appendix PAR, Table PAR-27.

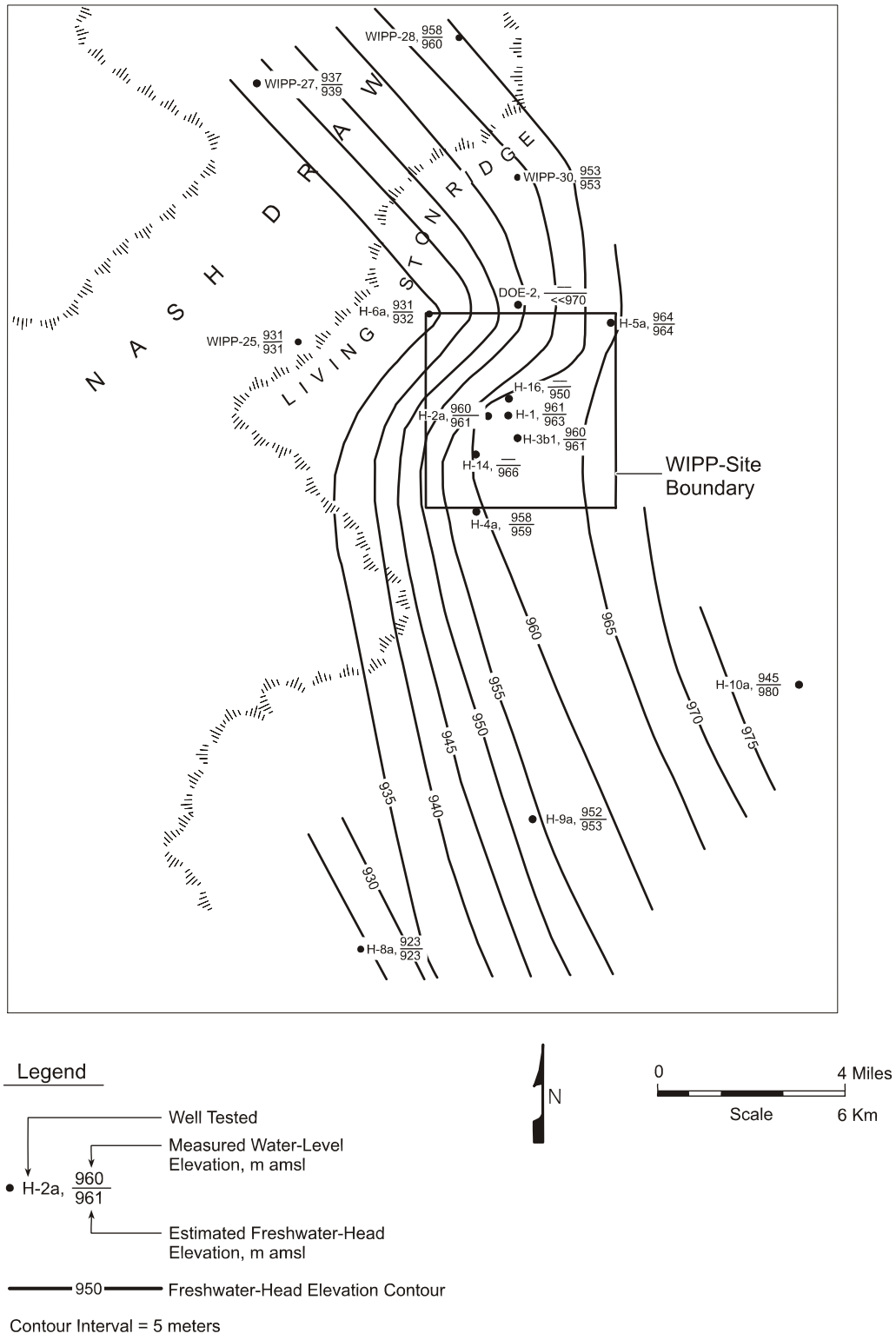

Figure 2-38. Hydraulic Heads in the Magenta (1980s)

Fluid pressures in the Forty-niner have been measured continuously at well H-16, approximately 13.9 m (45.6 ft) from the well of the AIS, since 1987. The pressures cycle in a sinusoidal fashion on an annual basis. These cycles correlate with cycles observed in rock bolt loads in the WIPP shafts (DOE 2002c), and presumably reflect seasonal temperature changes causing the rock around the shafts to expand and contract. From 1998 through 2002, the pressures have cycled between 40 and 70 psi (90 and 160 ft of fresh water). Given the location of the pressure transducer, the elevation of Forty-niner water level has varied between 899 to 920 m (2,950 to 3,020 ft) amsl during this period. Through April 2002, Forty-niner water levels were also measured monthly at H-3d as part of the WIPP groundwater monitoring program. Measurements were discontinued after April 2002 because of an obstruction in the well. The April 2002 Forty-niner water level elevation determined at H-3d was 942 m (3,092 ft) amsl. Differences in Forty-niner water levels at H-16 and H-3d are probably due, in part, to differences in the densities of the fluids in the wells. No other wells in the WIPP monitoring network are completed to the Forty-niner.

2.2.1.4.2 Hydrology of the Dewey Lake and the Santa Rosa

The Dewey Lake and the Santa Rosa, and surficial soils, overlie the Rustler and are the uppermost hydrostratigraphic units considered by the DOE. The Dewey Lake and overlying rocks are more permeable than the anhydrites at the top of the Rustler. Consequently, basin modeling indicates that most (probably more than 70 percent) of the water that recharges the groundwater basin (that is, percolates into the Dewey Lake from surface water) flows only in the rocks above the Rustler. As modeled, the rest leaks vertically through the upper anhydrites of the Rustler and into the Magenta or continues downward to the Culebra. More flow occurs into the Rustler units at times of greater recharge. Even though it carries most of the modeled recharge, lateral flow in the Dewey Lake is slow because of its low permeability in most areas.

A saturated, perched-water zone has been identified in the lower Santa Rosa directly below the operational area of the WIPP (DOE 1999; INTERA 1997a; INTERA 1997b; DES 1997). The zone occurred at a location that previously had been dry or only partially saturated. Details are provided in Appendix DATA and a summary provided in Section 2.2.1.4.2.2.

2.2.1.4.2.1 Dewey Lake

The Dewey Lake contains a productive zone of saturation, probably under water-table conditions, in the southwestern to south-central portion of the WIPP site and south of the site. Several wells operated by the J.C. Mills Ranch south of the WIPP site produce sufficient quantities of water from the Dewey Lake to supply livestock. Short-term production rates of 5.7 to 6.8 m^3/hr (25 to 30 gpm) were observed in boreholes P-9 (Jones 1978, Vol. 1., pp. 167- 168), WQSP-6, and WQSP-6a (see CCA Appendix USDW). Based on a single hydraulic test conducted at WQSP-6a (Figure 2-6), Beauheim and Ruskauff (1998) estimated the transmissivity of a 7.3m (24ft) fractured section of the Dewey Lake at 3.9×10^{-4} m^2/s (360 ft^2/day). The productive zone is typically found in the middle of the Dewey Lake, 55 to 81 m (180 to 265 ft) below ground surface and appears to derive much of its transmissivity from open fractures. Where present, the saturated zone may be perched or simply underlain by less transmissive rock. Fractures below the productive zone tend to be completely filled with gypsum. Open fractures

and/or moist (but not fully saturated) conditions have been observed at similar depths north of the zone of saturation, at the H-1, H-2, and H-3 boreholes (CCA Appendix HYDRO, p. 69).

Under the groundwater monitoring program (Appendix MON-2004), water levels are measured in two Dewey Lake wells, WQSP-6a and H-3d, located south of the WIPP site center (Figure 2-6). Water levels in these two wells are currently 975 and 937 m (3,198 and 3,075 ft) amsl, respectively. Water levels at WQSP-6a remain relatively constant. Over the past several years, water levels at H-3d have risen about 0.3 m/yr (1 ft/yr). Future changes in the Dewey Lake water table due to wetter conditions are part of the conceptual model discussed in Sections 6.4.6 and 6.4.9.

Similar to the six Culebra WQSP wells (WQSP-1 through WQSP-6), Dewey Lake water quality is determined semiannually at WQSP-6a. Baseline concentrations for major ion species have also been determined from ten rounds of sampling. The 95 percent confidence intervals for the major ion species presented in SNL (2001) are shown in Table 2-9 and indicate the Dewey Lake water at this location is relatively fresh. Major ion concentrations have been stable within the baseline 95 percent confidence intervals for all 14 rounds of sampling conducted through May 2002 (Kehrman 2002).

Table 2-9. Ninety-Five Percent Confidence Intervals for Dewey Lake Water-Quality Baseline

Well I.D.	Cl^- Conc. (mg/L)	SO_4^{2-} Conc. (mg/L)	HCO_3^- Conc. (mg/L)	Na^+ Conc. (mg/L)	Ca^{2+} Conc. (mg/L)	Mg^{2+} Conc. (mg/L)	K^+ Conc. (mg/L)
WQSP-6a	433-764	1610-2440	97-111	253-354	554-718	146-185	1.8-9.2

Powers (1997) suggests that what distinguishes the low-transmissivity lower Dewey Lake from the high-transmissivity upper Dewey Lake is a change in natural cements from carbonate (above) to sulfate (below). Resistivity logs correlate with this cement change and show a drop in porosity across the cement-change boundary. Similarly, porosity measurements made on eight core samples from the Dewey Lake from well H-19b4 showed a range from 14.9 to 24.8 percent for the four samples from above the cement change, and a range from 3.5 to 11.6 percent for the four samples from below the cement change (TerraTek 1996). In the vicinity of the surface structures area of the WIPP, Powers (1997) proposed the surface of the cement change is at a depth of approximately 50 to 55 m (165 to 180 ft), is irregular, and trends downward stratigraphically to the south and west of the site center.

During site characterization and initial construction of the WIPP shafts, the Dewey Lake did not produce water within the WIPP shafts or in boreholes in the immediate vicinity of the panels. However, since 1995, water has been observed leaking into the exhaust shaft at a depth of approximately 24.4 m (80 ft) at the location of the Dewey Lake/ Santa Rosa contact (Docket A-93-02, Item number 11-1-07, 1999; INTERA 1997a; INTERA 1997b). As described below in Section 2.2.1.4.2.2, the water is interpreted to be from an anthropogenic source, including infiltration from WIPP rainfall-runoff retention ponds and the WIPP salt storage area and

evaporation pond located at the surface. At the site center, thin cemented zones in the upper Dewey Lake retard, at least temporarily, downward infiltration of modern waters.

Saturation of the uppermost Dewey Lake was observed for the first time in 2001 as well C-2737 was being drilled (Powers 2002c). Well C-2811 was then installed nearby to monitor this zone (Powers and Stensrud 2003). Because of the proximity of these two wells to the WIPP surface structures area, and the absence of water at this horizon when earlier wells were drilled, the saturation is assumed to be an extension of the anthropogenic waters described in the following section.

For modeling purposes, the hydraulic conductivity of the Dewey Lake, assuming saturation, is estimated to be 10^{-8} m/sec (3×10^{-3} ft/day), corresponding to the hydraulic conductivity of fine-grained sandstone and siltstone (Davies 1989, p. 110).

The Dewey Lake is the uppermost important layer in the hydrological model. Its treatment is discussed in Section 6.4.6.6 and Appendix PA, Attachment MASS, Section MASS.14.2. Model parameters are in Table 6-25 and in Appendix PA, Attachment PAR, Table PAR-22.

2.2.1.4.2.2 Santa Rosa

The Santa Rosa ranges from 0 to 91 m (0 to about 300 ft) thick and is present over the eastern half of the WIPP site. It is absent over the western portion of the site. It crops out northeast of Nash Draw. The Santa Rosa near the WIPP site may have a naturalwater-saturated thickness of limited extent. It has a porosity of about 13 percent and a specific capacity of 0.029 to 0.041 L/s/m (0.14 to 0.20 gallons per minute per foot (gpm/ft) of drawdown, where it yields water in the WIPP region.

In May 1995, a scheduled inspection of the WIPP exhaust shaft revealed water emanating from cracks in the concrete liner at a depth of approximately 24.4 m (80 ft) below the shaft collar. Because little or no groundwater had been encountered at this depth interval previously (Bechtel 1979; DOE 1983; Holt and Powers 1984, 1986), the DOE implemented a program in early 1996 to investigate the source and extent of the water. The program included installation of wells and piezometers, hydraulic testing (pumping tests), water-quality sampling and analysis, and water-level and precipitation monitoring (Docket A-93-02, Item number 11-1-07, DOE 1999; INTERA 1997a; DES 1997; INTERA 1997b).

In the initial phases of the investigation, three wells (C-2505, C-2506, and C-2507) and 12 piezometers (PZ-1 through PZ-12) were installed within the surface structures area of the WIPP site (Figure 2-39). The three wells were located near the exhaust shaft and completed to the Santa Rosa/Dewey Lake contact (approximately 15 m [50 ft] below ground surface). Similarly, the piezometers were also completed to the Santa Rosa/Dewey Lake contact (approximately 16 to 23 m [55 to 75 ft] below ground surface). All wells and piezometers, with the exception of PZ-8, encountered a saturated zone just above the Santa Rosa/Dewey Lake contact, but water did not appear to have percolated significantly into the Dewey Lake. PZ-8, the piezometer located farthest to the east in the study area, was a dry hole.

Subsequent to the well and piezometer installations, water-level, water-quality, and rainfall data were collected. In addition, hydraulic tests were performed to estimate hydrologic properties and

water production rates. These data suggest that the water present in the Santa Rosa below the WIPP surface structures area represents an unconfined, water-bearing horizon perched on top of the Dewey Lake (DES 1997). Pressure data collected from instruments located in the exhaust shaft show no apparent hydrologic communication between the Santa Rosa and other formations located stratigraphically below the Santa Rosa.

A water-level-surface map of the Santa Rosa in the vicinity of the WIPPsurface structures area indicates that a potentiometric high is located near the salt water evaporation pond and PZ-7 (Figure 2-40). The water level at PZ-7 is approximately 1 m (3.3 ft) higher than the water levels in any other wells or piezometers. Water is presumed to move radially from this potentiometric high. The areal extent of the water is larger than the 80-acre investigative area shown in Figure 2-39 (DES 1997) as evidenced by drilling records of C-2737 (Powers 2002c) located outside of and south of the WIPP surface structures area that indicate a Santa Rosa/Dewey Lake perched-water horizon at a depth of approximately 18 m (60 ft). The study of this water is ongoing.

Water-quality data for the perched Santa Rosa waters are highly variable and appear to be dominated by two anthropogenic sources: (1) runoff of rainfall into and infiltration from the retention ponds located to the south of the WIPP surface facilities, and (2) infiltration of saline waters from the salt storage area, the salt storage evaporation pond, and perhaps remnants of the drilling and tailings pit used during the construction of the WIPP salt shaft. The total dissolved solids (TDS) in the perched water range from less than 3,000 mg/L at PZ-10 to more than 160,000 mg/L at PZ-3 (DES 1997). Concentration contours are known to shift with time. For example, the high-TDS zone centered at PZ-3 moved observably to the northeast toward PZ-9 between February 1997 and October 2000 (DOE 2002b).

Hydraulic tests (Docket A-93-02, Item number 11-1-07, DOE; INTERA 1997a; DES 1997) conducted in the three wells and 12 piezometers indicate that the Santa Rosa behaves as a low-permeability, unconfined aquifer perched on the Dewey Lake. Hydraulic conductivity ranges from 2.6×10^{-8} to 5.5×10^{-5} m/s (7.4×10^{-3} to 16 ft/day). The wells are capable of producing at rates of about 0.3 to 1.0 gpm. The estimated storativity value for the Santa Rosa is 1×10^{-2}.

2.2.1.5 Hydrology of Other Groundwater Zones of Regional Importance

The groundwater regimes in the Capitan Limestone, which is generally regarded as the northern boundary of the Delaware Basin, and Nash Draw have been evaluated by the DOE as part of the WIPP project because of their importance in some processes, notably dissolution features, that the DOE has determined to be of low probability at the WIPP site.

2.2.1.5.1 Capitan Limestone

The Capitan Limestone (hereafter referred to as the Capitan), which outcrops in the southern end of the Guadalupe Mountains, is a massive limestone unit that grades basinward into recemented, partly dolomitized reef breccia and shelfward into bedded carbonates and evaporites. A deeply incised submarine canyon near the Eddy-Lea county line has been identified (Hiss 1976). This

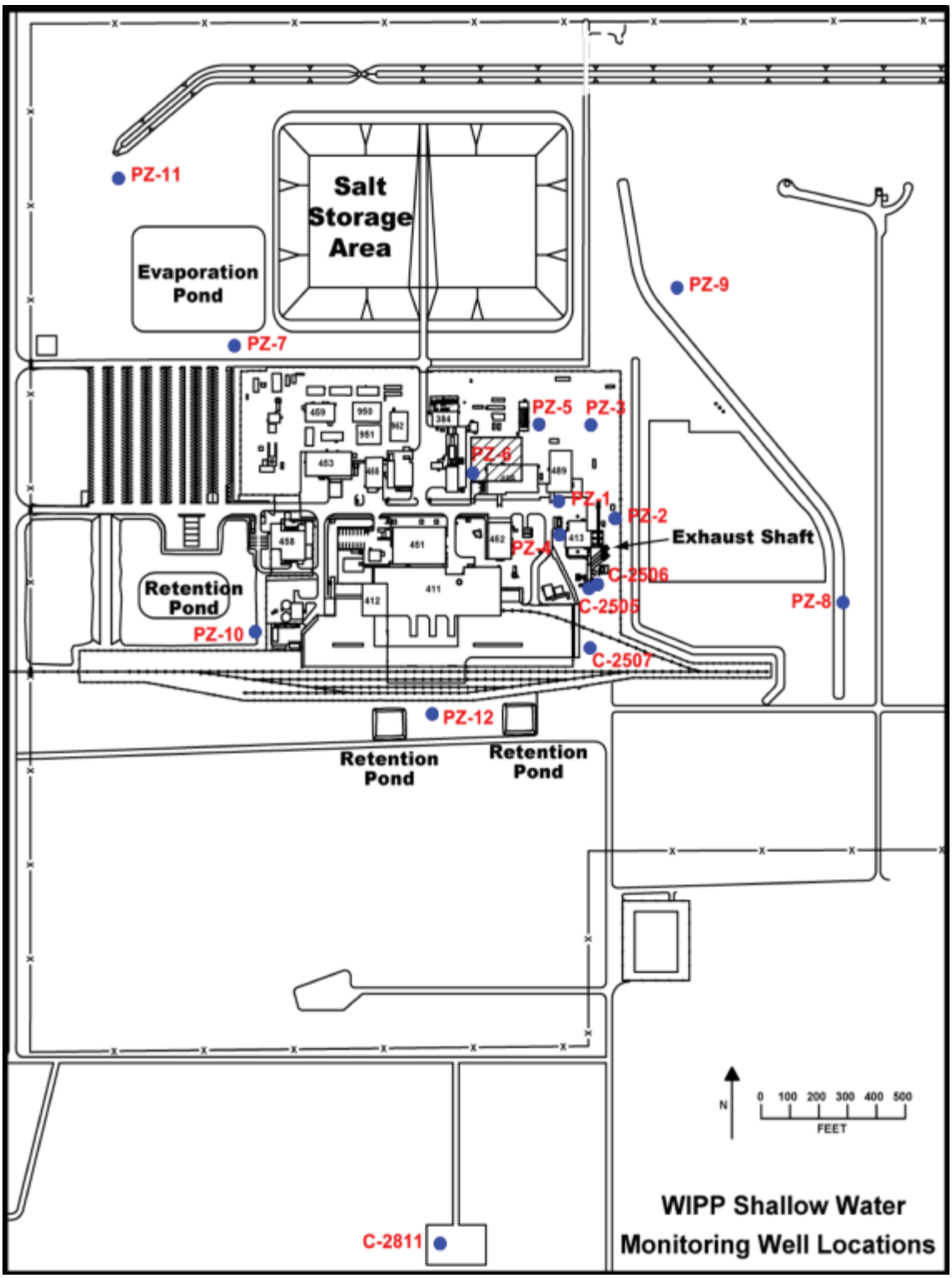

Figure 2-39. Site Map of WIPP Surface Structures Area Showing Location of Wells (e.g., C-2505) and Piezometers (e.g., PZ-1) (after INTERA 1997)

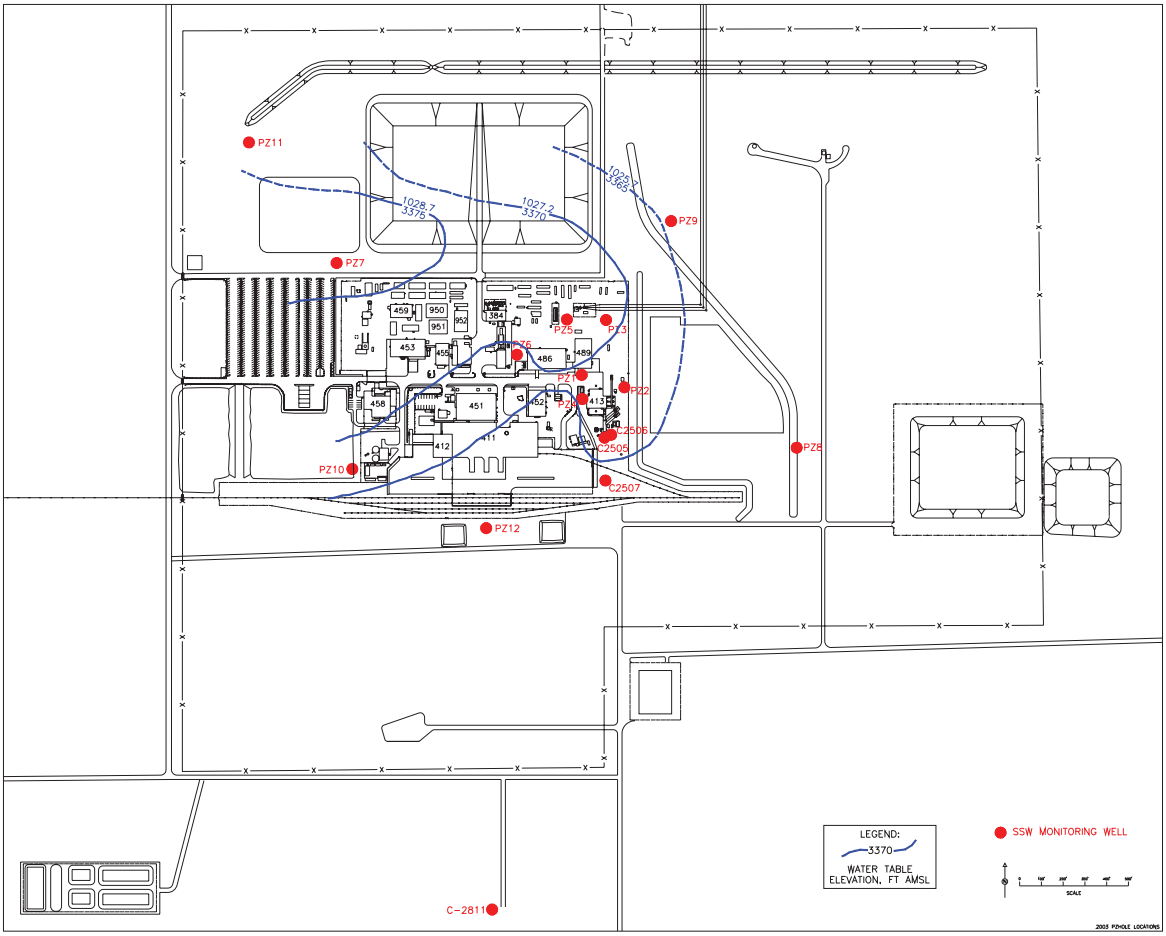

Figure 2-40. Santa Rosa Potentiometric Surface Map

canyon is filled with sediments of lower permeability than the Capitan and, according to Hiss (1975 p. 199), restricts fluid flow. The hydraulic conductivity of the Capitan ranges from 3×10^{-6} to 9×10^{-5} m/s (1 to 25 ft/day) in southern Lea County and is 1.7×10^{-5} m/s (5 ft/day) east of the Pecos River at Carlsbad (CCA Appendix HYDRO, p. 34). Hiss (1975, p. 199) reported in 1975 that average transmissivities around the northern and eastern margins of the Delaware Basin are 0.01 m^2/s (10,000 ft^2/day) in thick sections and 5.4×10^{-4} m^2/s (500 ft^2/day) in incised submarine canyons. Water table conditions are found in the Capitan aquifer southwest of the Pecos River at Carlsbad; however, artesian conditions exist to the north and east. The hydraulic gradient to the southeast of the submarine canyon near the Eddy-Lea county line has been affected by large oil field withdrawals. The Capitan is recharged by percolation through the northern shelf aquifers, by flow from the south and west from underlying basin aquifers (see information on the Bell Canyon, Section 2.2.1.2.1), and by direct infiltration at its outcrop in the Guadalupe Mountains. The Capitan is important in the regional hydrology because breccia pipes in the Salado have formed over it, most likely in response to the effects of dissolution by groundwater flowing in the Castile along the base of the Salado. See CCA Appendix DEF, Section DEF.3.1 for a more thorough discussion of breccia pipe formation.

2.2.1.5.2 Hydrology of the Rustler-Salado Contact Zone in Nash Draw

As discussed in Sections 2.1.3.4 and 2.1.6.2.1, in Nash Draw the contact between the Rustler and the Salado is an unstructured residuum of gypsum, clay, and sandstone created by the dissolution of halite and has been known as the brine aquifer, Rustler-Salado residuum, and residuum. The residuum is absent under the WIPP site. It is clear that dissolution in Nash Draw occurred after deposition of the Rustler (see CCA Appendix DEF, Section DEF.3.2 for a discussion of lateral dissolution of the Rustler-Salado contact). As described previously, the topographic low formed by Nash Draw is a groundwater divide in the groundwater basin conceptual model of the units above the Salado. The brine aquifer is shown in Figure 2-41.

Robinson and Lang (1938) described the brine aquifer (Section 2.1.3.4) and suggested that the structural conditions that caused the development of Nash Draw might control the occurrence of the brine; thus, the brine aquifer boundary may coincide with the topographic surface expression of Nash Draw, as shown in Figure 2-33. Their studies show brine concentrated along a strip from 3.3 to 13 km (2 to 8 mi) wide and about 43 km (26 mi) long. Data from the test holes that Robinson and Lang (1938) drilled indicate that the residuum (containing the brine) ranges in thickness from 3 to 18 m (10.5 to 60 ft) and averages about 24 feet (7 meters).

Hydraulic properties were determined by Hale et al. (1954) primarily for the area between Malaga Bend on the Pecos River and Laguna Grande de la Sal. They calculated a transmissivity value of 8.6×10^{-3} m^2/s (8,000 ft^2/day) and estimated the potentiometric gradient to be 0.27 m/km (1.4 ft/mi). In this area, the Rustler-Salado residuum apparently is part of a continuous hydrologic system, as evidenced by the coincident fluctuation of water levels in the test holes (as far away as Laguna Grande de la Sal) with pumping rates in irrigation wells along the Pecos River.

In the northern half of Nash Draw, the approximate outline of the brine aquifer as described by Robinson and Lang (1938) has been supported by drilling associated with the WIPP hydrogeologic studies. These studies also indicate that the main differences in areal extent occur along the eastern side where the boundary is very irregular and, in places (test holes P-14 and H-07), extends farther east than previously indicated by Robinson and Lang (1938).

Other differences from the earlier studies include the variability in thickness of residuum present in test holes WIPP-25 through WIPP-29. These holes indicate thicknesses ranging from 3.3 m (11 ft) in WIPP-25 to 33 m (108 ft) in WIPP-29 in Nash Draw, compared to 2.4 m (8 ft) in test hole P-14, east of Nash Draw. The specific geohydrologic mechanism that has caused dissolution to be greater in one area than in another is not apparent, although a general increase in chloride concentration in water from the north to the south may indicate the effects of movement down the natural hydraulic gradient in Nash Draw.

The average hydraulic gradient within the residuum in Nash Draw is about 1.9 m/km (10 ft/mi); in contrast, the average gradient at the WIPP site is 7.4 m/km (39 ft/mi) (CCA Appendix HYDRO, p. 50). This difference reflects the changes in transmissivity, which are as much as five orders of magnitude greater in Nash Draw. The transmissivity determined from aquifer tests in test holes completed in the Rustler-Salado contact residuum of Nash Draw ranges from

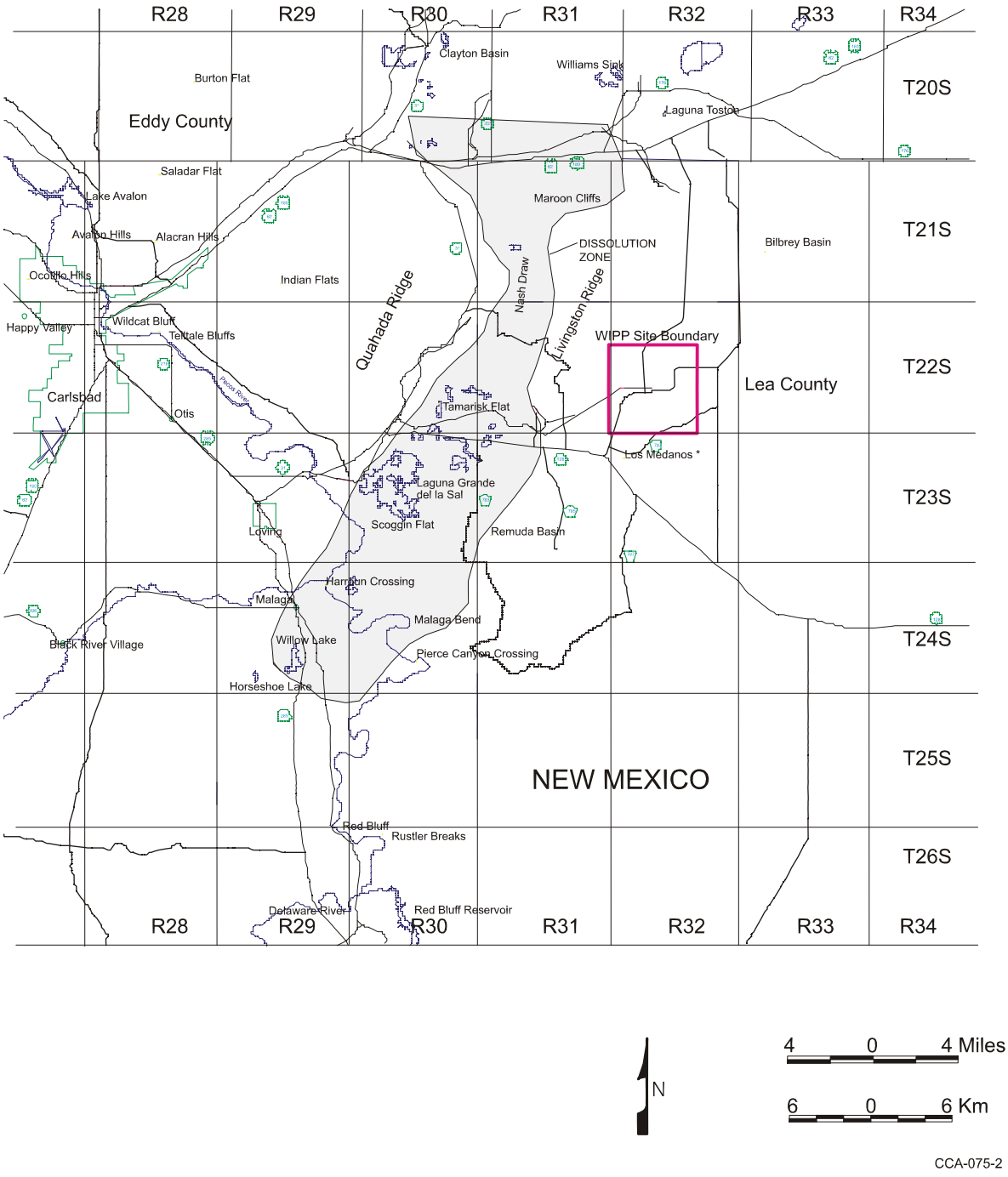

Figure 2-41. Brine Aquifer in the Nash Draw (Redrawn from CCA Appendix HYDRO, Figure 14)

2.1×10^{-10} m^2/s (2×10^{-4} ft^2/day) at WIPP-27 to 8.6×10^{-6} m^2/s (9 8 ft^2/day) at WIPP-29. This is in contrast to the WIPP site proper, where transmissivities range from 3.2×10^{-11} m^2/s (3×10^{-5} ft^2/day) at test holes P-18 and H-5c to 5.4×10^{-8} m^2/s (5×10^{-2} ft^2/day) at test hole P-14 (CCA Appendix HYDRO, p. 50). Locations and estimated hydraulic heads of these wells based on water-level measurements made in the 1980s (Lappin et al. 1989) are illustrated in Figure 2-42.

Hale et al. (1954) believed the Rustler-Salado contact residuum discharges to the alluvium near Malaga Bend on the Pecos River. Because the confining beds in this area are probably fractured because of dissolution and collapse of the evaporites, the brine (under artesian head) moves up through these fractures into the overlying alluvium and then discharges into the Pecos River.

According to CCA Appendix HYDRO, p. 55, water in the Rustler-Salado contact residuum in Nash Draw contains the largest concentrations of dissolved solids in the WIPP area, ranging from 41,500 mg/L in borehole H-1 to 412,000 mg/L in borehole H-5c. These waters are classified as brines. The dissolved mineral constituents in the brine consist mostly of sulfates and chlorides of calcium, magnesium, sodium, and potassium; the major constituents are sodium and chloride. Concentrations of the other major ions vary according to the spatial location of the sample, are probably directly related to the interaction of the brine and the host rocks, and reflect residence time within the rocks. Residence time of the brine depends upon the transmissivity of the rock. For example, the presence of large concentrations of potassium and magnesium in water is correlated with minimal permeability and a relatively undeveloped flow system.

The EPA's initial review of the CCA found the discussion of the Rustler/Salado contact to require clarification, particularly with respect to the possibility of the continued development and characteristics of a dissolution front along this contact, and the impact that continued dissolution within the brine aquifer residuum would have on the overlying units of the Rustler. The DOE discussed the rate and extent of dissolution processes further in supplemental information provided in a letter dated June 13, 1997 (Docket A-93-02, II-H-44). Based upon this information, the EPA concluded that, while dissolution may occur along the Rustler/Salado contact, it would not affect the WIPP's containment capabilities during the regulatory time period. Further discussion of this topic is contained in EPA Technical Support Document for Section 194.14: Content of Compliance Certification Application, Section IV.C.3 (Docket A-93-02, Item V-B-3).

2.2.2 Surface-Water Hydrology

The WIPP site is in the Pecos River basin, which contains about 50 percent of the drainage area of the Rio Grande Water Resources Region. The Pecos River headwaters are northeast of Santa Fe, and the river flows to the south through eastern New Mexico and western Texas to the Rio Grande. The Pecos River has an overall length of about 805 km (500 mi), a maximum basin width of about 209 km (130 mi), and a drainage area of about 115,301 km^2 (44,535 mi^2). (About 53,075 km^2 [20,500 mi^2] contained within the basin have no external surface drainage and their surface waters do not contribute to Pecos River flows.) Figure 2-43 shows the Pecos River drainage area.

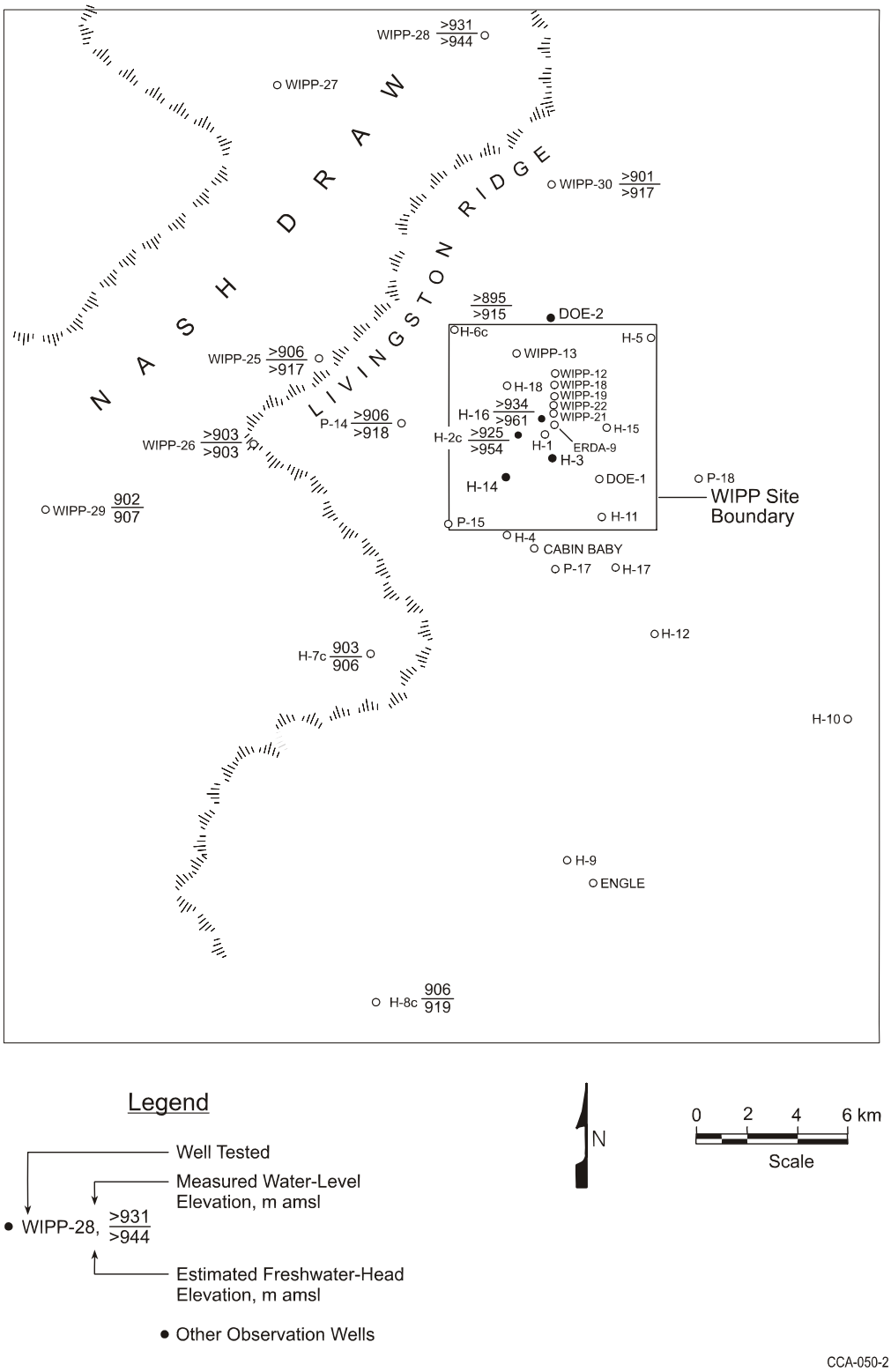

Figure 2-42. Measured Water Levels of the Los Medaños and Rustler-Salado Contact Zone (1980s)

The Pecos River generally flows year-round, except in the reach below Anton Chico where the low flows percolate into the stream bed. The main stem of the Pecos River and its major tributaries have low flows, and the tributary streams are frequently dry. About 75 percent of the total annual precipitation and 60 percent of the annual flow result from intense local thunderstorms between April and September.

There are no perennial streams at the WIPP site. At its nearest point, the Pecos River is about 19 km (12 mi) southwest of the WIPP site boundary. A few small creeks and draws are the only westward flowing tributaries of the Pecos River within 32 km (20 mi) north or south of the site. Nash Draw, the largest surface drainage feature east of the Pecos River in the WIPP region, is a closed depression and does not provide surface flow into the Pecos. Potash mining operations in and near Nash Draw likely contribute to the flow in Nash Draw. For example, the Mississippi Potash Inc. East operation located 11 to 13 km (7 to 8 mi) due north of the WIPP site disposes of mine tailings and refining-process effluent on its property and has done so since 1965. Records obtained from the New Mexico Office of the State Engineer show that since 1973, an average of 3×10^6 m^3 (2,400 acre-feet [ac-ft]) of water per year has been pumped from local aquifers (Ogallala and Capitan) for use in the potash-refining process at that location (SNL 2003b). Based on knowledge of the potash refining process, approximately 90 percent of the pumped water is estimated to be discharged to the tailings pile. Geohydrology Associates (1978) estimated that approximately half of the brine discharged onto potash tailings piles in Nash Draw seeps into the ground annually, while the remainder evaporates. The Black River (drainage area: 1,035 km^2 [400 mi^2]) joins the Pecos from the west about 25 km (16 mi) southwest of the site. The Delaware River (drainage area: 1,812 km^2 [700 mi^2]) and a number of small creeks and draws also join the Pecos River along this reach. The flow in the Pecos River below Fort Sumner is regulated by storage in Sumner Lake, Brantley Reservoir, Lake Avalon, and several other smaller irrigation dams.

Five major reservoirs are located on the Pecos River: Santa Rosa Lake, Sumner Lake, Brantley Reservoir, Lake Avalon, and the Red Bluff Reservoir, the last located just over the border in Texas (Figure 2-43). The storage capacities of these reservoirs and the Two Rivers Reservoir in the Pecos River Basin are shown in Table 2-10.

With regard to surface drainage onto and off of the WIPP site, there are no major natural lakes or ponds within 8 km (5 mi) of the site. Laguna Gatuña, Laguna Tonto, Laguna Plata, and Laguna Toston are playas more than 16 km (10 mi) north and are at elevations of 1,050 m (3,450 ft) or higher. Thus, surface runoff from the site (elevation 1,010 m [3,310 ft] above sea level) would not flow toward any of them. To the northwest, west, and southwest, Red Lake, Lindsey Lake, and Laguna Grande de la Sal are more than 8 km (5 mi) from the site, at elevations of 914 to 1,006 m (3,000 to 3,300 ft). A low-flow investigation has been initiated by the USGS within the Hill Tank Draw drainage area, the most prominent drainage feature near the WIPP site. The drainage area is about 10.3 km^2 (4 mi^2), with an average channel slope of 1 to 100, and the drainage is westward into Nash Draw. Two years of observations showed only four flow events. The USGS estimates that the flow rate for these events was under 0.057 m^3/s (2 ft^3/s) (DOE 1980, pp. 7- 74).

As discussed in Section 2.5.2.3, the mean annual precipitation in the region is 0.33 m (13 in.), and the mean annual runoff is 2.5 to 5 mm (0.1 to 0.2 in.). The maximum recorded 24-hour

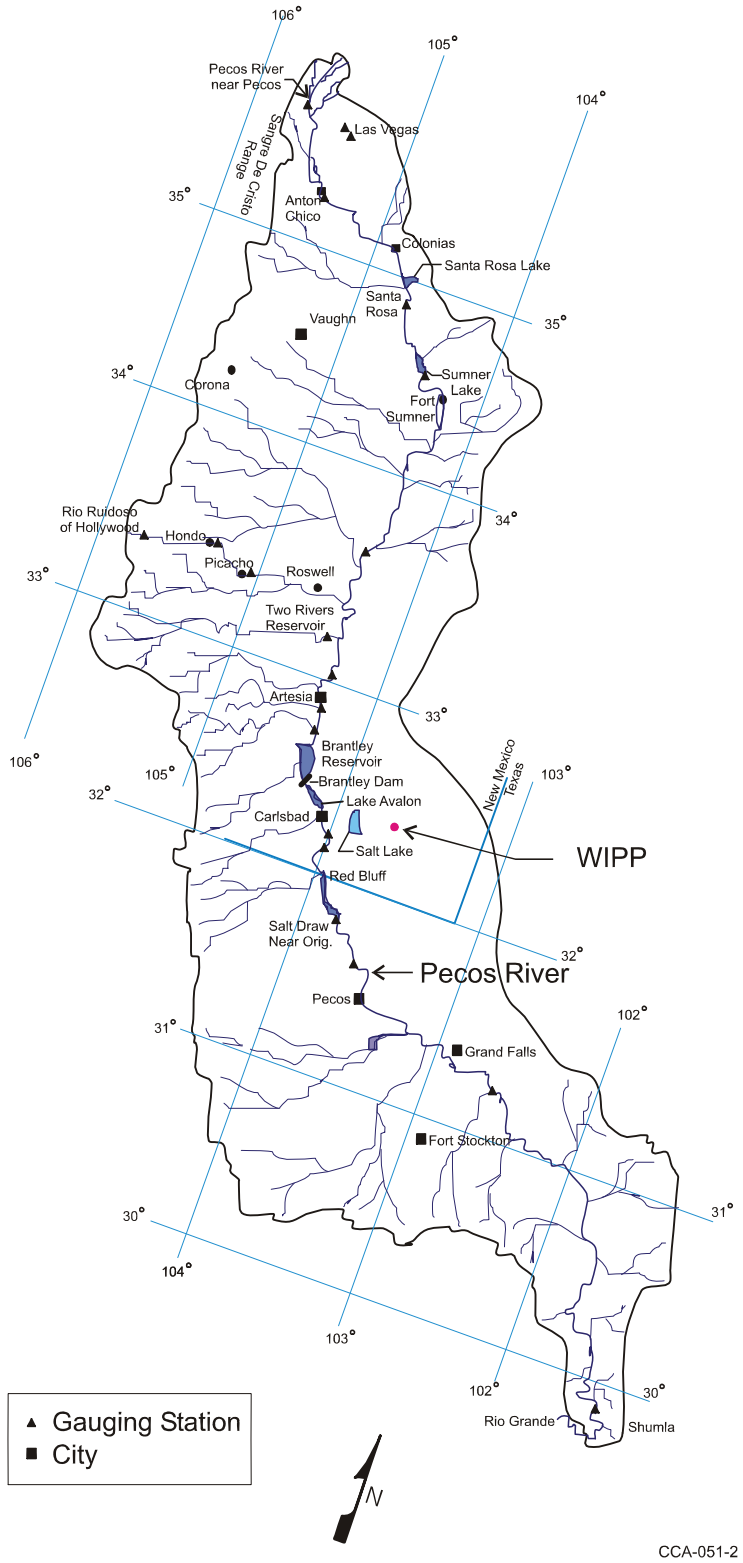

Figure 2-43. Location of Reservoirs and Gauging Stations in the Pecos River Drainage Area

Table 2-10. Capacities of Reservoirs in the Pecos River Drainage

Reservoir	River	Total Storage Capacity[a] (ac-ft)	Use[b]
Santa Rosa	Pecos	282000	FC
Sumner	Pecos	122100	IR, R
Brantley	Pecos	42000	IR, R, FC
Avalon	Pecos	5000	IR
Red Bluff	Pecos	310000	IR, P
Two Rivers	Rio Hondo	167900	FC

[a] Capacity below the lowest uncontrolled outlet or spillway.
[b] Legend:

FC flood control
IR irrigation
R recreation
P hydroelectric

precipitation at Carlsbad was 130 mm (5.12 in.) in August 1916. The predicted maximum 6-hour, 100-year precipitation event for the site is 91 mm (3.6 in.) and is most likely to occur during the summer. The maximum recorded daily snowfall at Carlsbad was 254 mm (10 in.) in December 1923.

The maximum recorded flood on the Pecos River occurred near the town of Malaga, New Mexico, on August 23, 1966, with a discharge of 3,396 m^3 (120,000 ft^3) per second and a stage elevation of about 895 m (2,938 ft) amsl. The minimum surface elevation at the WIPP is over 91 m (300 ft) above the elevation of this maximum historic flood (DOE 1980, Section 7.4.1).

As discussed in the FEIS (DOE 1980, pp. 7- 71), more than 90 percent of the mean annual precipitation at the site is lost by evapotranspiration. On a mean monthly basis, evapotranspiration at the site greatly exceeds the available rainfall; however, intense local thunderstorms may produce runoff and percolation.

Water quality in the Pecos River basin is affected by mineral pollution from natural sources and from irrigation return flows (see Section 2.4.2.2 for discussion of surface-water quality). At Santa Rosa, New Mexico, the average suspended-sediment discharge of the river is about 1,497 metric tons/day (1,650 tons/day). Large amounts of chlorides from Salt Creek and Bitter Creek enter the river near Roswell. River inflow in the Hagerman area contributes increased amounts of calcium, magnesium, and sulfate; and waters entering the river near Lake Arthur are high in chloride. Below Brantley Reservoir, springs flowing into the river are usually submerged and difficult to sample; springs that could be sampled had TDS concentrations of 3,350 to 4,000 mg/L. Concentrated brine entering at Malaga Bend adds an estimated 64 metric tons/day (370 tons/day) of chloride to the Pecos River (CCA Appendix GCR, pp. 6-7).

2.3 Resources

At the outset of the repository program, the DOE understood the importance of resources in the vicinity of a disposal system. Several of the siting criteria emphasized avoidance of resources that would impact the performance of the disposal system. In this regard, the DOE selected a site that (1) maximized the use of federal lands, (2) avoided known oil and gas trends, (3) minimized the impacts on potash deposits, and (4) avoided existing drill holes. While the DOE could not meet all these criteria totally, it is shown that the favorable characteristics of the location compensate for any increased risks due to the presence of resources. Consequently, the DOE has prepared this section to discuss resources that may exist at or beneath the WIPP site. The topic of resources is used to broadly define both economic (mineral and nonmineral) and cultural resources associated with the WIPP site. These resources are important because they (1) provide evidence of past uses of the area and (2) indicate potential future use of the area with the possibility that such use could lead to disruption of the closed repository. Because of the depth of the disposal horizon, it is believed that only the mineral resources are of significance in predicting the long-term performance of the disposal system. However, the nonmineral and cultural resources are presented for completeness because they are included in the FEP screening discussions in Chapter 6 and Appendix PA, Attachment SCR. Information needed to make screening decisions includes natural resource distributions, including potable groundwaters, the distribution of drillholes, mines, excavations, and other man-made features that exploit these resources, the distribution of drillholes and excavation used for disposal or injection purposes, activities that significantly alter the land surface, agricultural activities that may affect the disposal system, archaeological resources requiring deep excavation to exploit, and technological changes that may alter local demographics. This information is presented here or is referenced.

With respect to minerals or hydrocarbons, reserves are the portion of resources that are economic at today's market prices and with existing technology. For hydrocarbons, proved (proven) reserves are an estimated quantity that engineering and geologic data analysis demonstrates, with reasonable certainty, is recoverable in the future from discovered oil and gas pools. Probable resources (extensions) consist of oil and gas in pools that have been discovered but not yet developed by drilling. Their presence and distribution can generally be surmised with a high degree of confidence. Probable resources (new pools) consist of oil and gas surmised to exist in undiscovered pools within existing fields. (Definitions are from NMBMMR 1995, V-2 and V-3.)

Mineral resource discussions are focused principally on hydrocarbons and potassium salts, both of which have long histories of development in the region. Development of either resource potentially could be disruptive to the disposal system. The information regarding the mineral resources concentrates on the following factors:

- number, location, depth, and present state of development, including penetrations through the disposal horizon,
- type of resource,
- accessibility, quality, and demand, and

- mineral ownership in the area.

The specific impacts of resource development are discussed in Section 6.4.6.2.3, where scenarios related to mineral development are included for evaluation of disposal system performance. This discussion uses information presented in CCA Appendices DEL and MASS as indicated in the following text. The discussion of cultural and economic resources is focused on describing past and present land uses unrelated to the development of minerals. The archaeological record supports the observation that changes in land use are principally associated with climate and the availability of forage for wild and domestic animals. In no case does it appear that past or present land use has had an impact on the subsurface beyond the development of shallow groundwater wells to water livestock.

2.3.1 Extractable Resources

The geologic studies of the WIPP site included the investigation of potential natural resources to evaluate the impact of denying access to these resources and other consequences of their occurrence. Studies were completed in support of the FEIS to ensure knowledge of natural resources, and the impacts of denying access were included in the decision-making process for WIPP. Of the natural resources expected to occur beneath the site, five are of practical concern: the two potassium salts sylvite and langbeinite, which occur in the McNutt; and the three hydrocarbons, crude oil, natural gas, and distillate liquids associated with natural gas, all three of which occur elsewhere in strata below the Castile. Other mineral resources beneath the site are caliche, salt, gypsum, and lithium; enormous deposits of these minerals near the site and elsewhere in the country are more than adequate (and more economically attractive) to meet future requirements for these materials. In 1995, the NMBMMR performed a reevaluation of the mineral resources at and within 1.6 km (1 mi) around the WIPP site. The following discussion is based in part on information from NMBMMR (1995).

2.3.1.1 Potash Resources at the WIPP Site

Throughout the Carlsbad Potash District, commercial quantities of potassium salts are restricted to the middle portion of the Salado, locally called the McNutt. A total of 11 zones (or distinct ore layers) have been recognized in the McNutt. Horizon Number 1 is at the base, and Number 11 is at the top. The 11th ore zone is not mined.

The USGS uses three standard grades—low, lease, and high—to quantify the potash resources at the site. The USGS assumes that the lease and high grades comprise reserves because some lease-grade ore is mined in the Carlsbad Potash District. Most of the potash that is mined, however, is better typified as high-grade. Even the high-grade resources may not be reserves, however, if properties such as high clay content make processing uneconomical. The analysis in NMBMMR (1995) distinguishes between lease-grade ore and economically mineable ore.

The NMBMMR (1995) study contains a comprehensive summary of all previous potash resource evaluations. NMBMMR (1995, Chapter VII) used 40 existing boreholes drilled on and around the WIPP site to perform a reevaluation of potash resources. He selected holes that were drilled using brine so that the dissolution of potassium salts was inhibited. The conclusion reached is

that only the 4th and 10th ore zones contain economic potash reserves. The quantities are summarized in Table 2-11.

Table 2-11. Current Estimates of Potash Resources at the WIPP Site

		Recoverable Ore (10^6 tons)	
Mining Unit	**Product**	**Within the WIPP site**	**One-Mile Strip Adjacent to the WIPP site**
4th Ore Zone	Langbeinite	40.5 at 6.99%*	126.0 at 7.30%
10th Ore Zone	Sylvite	52.3 at 13.99%	105.0 at 14.96%

Source: NMBMMR 1995, Chapter VII.

* For example, read as 40.5×10^6 tons of ore at a grade of 6.99 percent or higher.

Within the Carlsbad Known Potash Leasing Area, exploration holes have been drilled to evaluate the grade of the various ore zones. These are included in the drillhole database in CCA Appendix DEL. None of the economically minable reserves identified by the NMBMMR lies directly above the waste panels. The known potash leases within the Delaware Basin are shown in Figure 2-44 and are detailed in CCA Appendix DEL, Figure DEL-8. From information in this figure and other data which is provided in CCA Appendix MASS, Attachment 15-5, DOE evaluates the extent of future mining outside the land withdrawal area. The extent of possible future mining within the controlled area is shown in Figure 2-45. The DOE also addresses this subject with respect to PA in Section 6.4.6.2.3.

The EPA concluded that neither the DOE's nor the Department of Interior's (DOI) estimate shows the area above the WIPP waste panels as containing mineable reserves. The DOE provided supplemental information in a letter dated May 14, 1997, indicating that potash solution mining and brine extraction do not need to be considered for the PA, based on low consequence to the containment capability of the repository (Docket A-93-02, Item II-I-31). The EPA reviewed the supplemental data and concurred with the DOE's conclusion. To obtain further discussion on this topic, CARD 32-Section 32.B, CARD 33-Section 33A, and CARD 32-Section 32 F (Docket A-93-02, item III-B-2) may be referenced. Additional information is found in FEPs screening discussions for solution mining for potash and solution mining for other resources (FEPs H58 and H59) in Appendix PA, Attachment SCR.

2.3.1.2 Hydrocarbon Resources at the WIPP Site

In 1974, Foster of the NMBMMR conducted a hydrocarbon resource study in southeastern New Mexico under contract to the ORNL. The study included an area of 3,914 km^2 (1,512 mi^2). At the time of that study, the proposed repository site was about 8 km (5 mi) northeast of the current site. The 1974 NMBMMR evaluation included a more detailed study of a four-township area centered on the old site; the present site is in the southwest quadrant of that area. The 1974 NMBMMR hydrocarbon resources study (Foster 1974) is presented in more detail in the FEIS (DOE 1980, Section 9.2.3.5). The reader is referred to the FEIS or the original study for additional information.

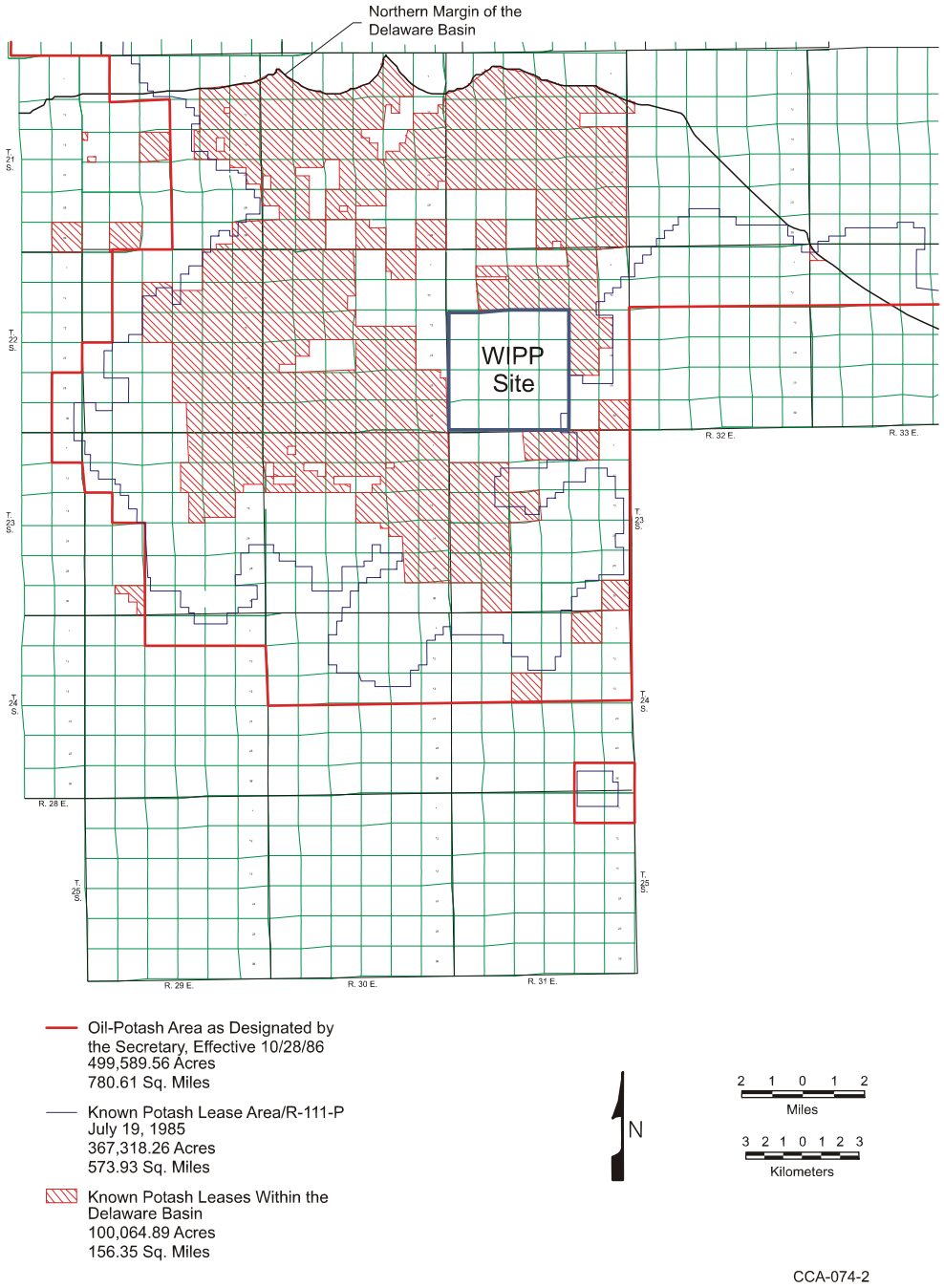

Figure 2-44. Known Potash Leases Within the Delaware Basin

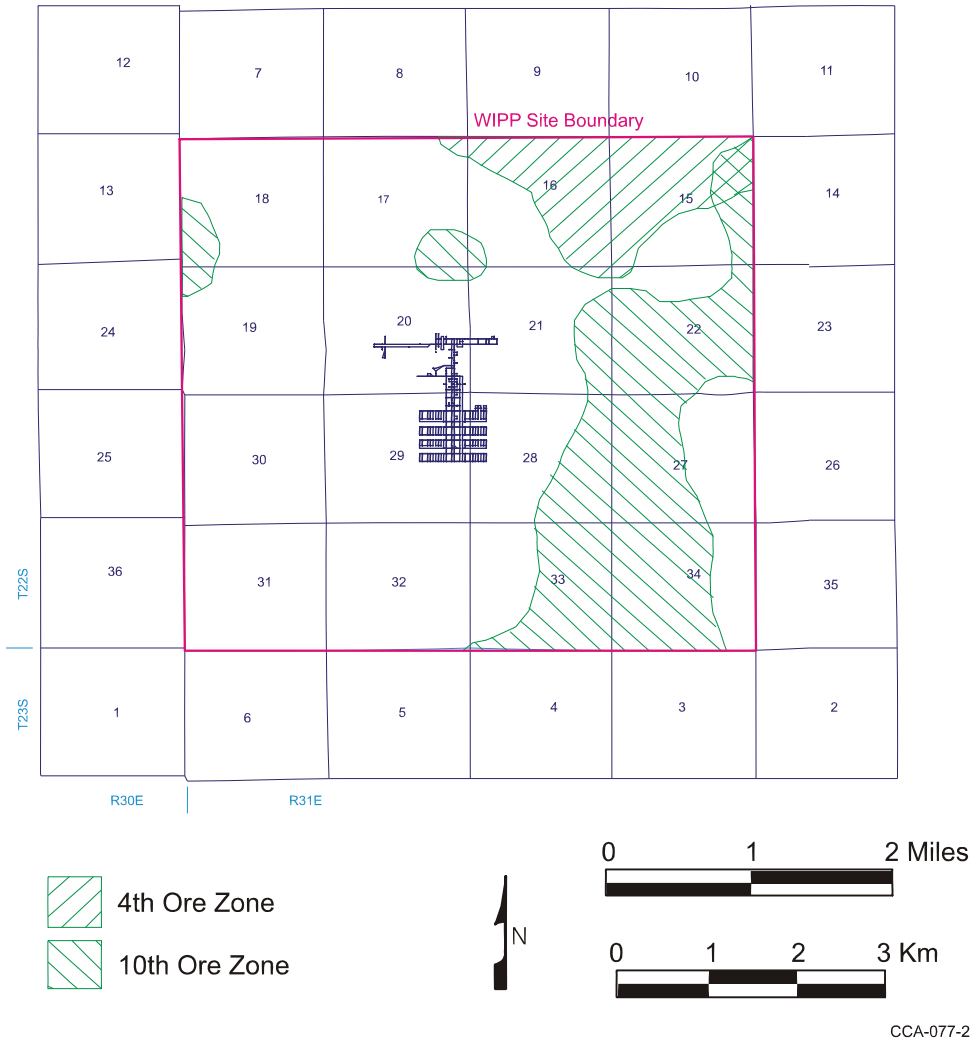

Figure 2-45. Extent of Economically Mineable Reserves Inside the Site Boundary (Based on NMBMMR Report)

The resource evaluation was based both on the known reserves of crude oil and natural gas in the region and on the probability of discovering new reservoirs in areas where past unsuccessful drilling was either too widely spread or too shallow to have allowed discovery. Potentially productive zones were considered in the evaluation; therefore, the findings may be used for estimating the total hydrocarbon resources at the site. A fundamental assumption in the study was that the WIPP area has the same potential for containing hydrocarbons as the larger region studied for which exploration data are available. Whether such resources actually exist can be satisfactorily established only by drilling at spacings close enough to give a high probability of discovery.

The NMBMMR 1995 mineral resource reevaluation contains a comprehensive summary of all previous evaluations. NMBMMR (1995, Chapter XI) provided a reassessment of hydrocarbon

resources within the WIPP site boundary and within the first mile adjacent to the boundary. Calculations were made for resources that are extensions of known, currently productive oil and gas resources that are thought to extend beneath the study area with reasonable certainty (called probable resources in the report). Qualitative estimates are also made concerning the likelihood that oil and gas may be present in undiscovered pools and fields in the area (referred to as possible resources). Possible resources were not quantified in the study. The results of the study are shown in Tables 2-12 and 2-13.

Table 2-12. In-Place Oil within Study Area

Formation	Within WIPP Site (10^6 bbl[a])	1-Mile Strip Adjacent to the WIPP Site (10^6 bbl)	Total (10^6 bbl)
Delaware	10.33	20.8	31.13
Bone Spring	0.44	0.8	1.25
Strawn	0.4	0.4	0.8
Atoka	1.1	0.1	0.2
Total	12.3	22.9	35.3

Source: NMBMMR (1995, Chapter XI)
a bbl = barrel = 42 gallons

Table 2-13. In-Place Gas within Study Area

Formation	Gas Reserves (Mcf)[a]	
	Within WIPP Site	1-Mile Strip Adjacent to the WIPP
Delaware	18176	32873
Bone Springs	956	1749
Strawn	9600	9875
Atoka	123336	94410
Morrow	32000	28780

Source: NMBMMR (1995, Chapter XI)
[a] Mcf = thousand cubic feet

The DOE compiled statistics on the historical development of hydrocarbon resources in the Delaware Basin and included them in CCA Appendix DEL. For these purposes, the Delaware Basin is described as the surface and subsurface features that lie inside the boundary formed to the north, east, and west by the innermost edge of the Capitan Reef and formed to the south by a straight line drawn from the southeastern point of the Davis Mountains to the southwestern point of the Glass Mountains (see Figure 2-46).

Several important modeling parameters result from the study of hydrocarbon resources and the history of their exploitation. These include parameters related to the number of human intrusions, the size of boreholes, the operational histories of such holes, the plugging of these

holes, and the use of such holes for other purposes, such as liquid disposal. Each of these topics is discussed in detail in CCA Appendix DEL and Appendix PA, Attachment MASS, Section MASS.16 and is addressed in Sections 6.4.7 and 6.4.12. The distribution of existing boreholes is shown in Figure DEL-4 (CCA Appendix DEL) for the entire Delaware Basin and Figure 2-47 for the vicinity of the WIPP site. In addition, CCA Appendix DEL includes an assessment of current drilling and plugging practices in the Delaware Basin. CCA Appendix DEL also discusses the regulatory constraints placed on the use of wells for injection.

2.3.1.3 Other Resources

While the focus of studies at the WIPP has been on potash and hydrocarbon, other resources are known to occur within the Delaware Basin and are considered in the screening. For example, sulfur is produced in the vicinity of Orla, Texas. Sulfur wells are included in CCA Appendix DEL; however, no sulfur resources have been identified in the vicinity of the WIPP; therefore, there are no projected impacts. Another resource that is extensively produced is groundwater. Potable water occurs in numerous places within the Delaware Basin. Several communities rely solely on groundwater sources for drinking water. CCA Appendix DEL includes a distribution of groundwater wells in the Delaware Basin. All such wells in the vicinity of the WIPP are shallow, generally no deeper than the Culebra. An evaluation of underground sources of drinking water in the vicinity of the disposal system is presented in CCA Appendix USDW. Figure USDW-4 shows the distribution of groundwater wells in the vicinity of the disposal system. Sand, gravel, and caliche are produced in numerous areas within the Delaware Basin. In all cases, these are surface quarries that are generally shallow (10s of feet). No impact to the disposal system is expected from these activities.

2.3.2 Cultural and Economic Resources

The demographics, land use, and history and archaeology of the WIPP site and its environs are characterized in the sections that follow.

2.3.2.1 Demographics

The WIPP facility is located 42 km (26 mi) east of Carlsbad in Eddy County in southeastern New Mexico and includes an area of 10,240 ac (approximately 41 km^2) (16 mi^2). The facility is located in a sparsely populated area with fewer than 30 permanent residents living within a 16-km (10-mi) radius of the facility. The area surrounding the facility is used primarily for grazing, potash mining, and hydrocarbon production. No resource development that would affect WIPP facility operations or the long-term integrity of the facility is allowed within the 10,240 ac that have been set aside for the WIPP project.

The permanent residence nearest to the WIPP site boundary is the J.C. Mills Ranch, which is 2 km (1.2 mi) to the south. The community nearest to the WIPP site is the town of Loving, New Mexico, 29 km (18 mi) west-southwest of the site center. The population of Loving increased from 1,243 in 1990 to 1,326 in 2000. The nearest population center is the city of Carlsbad, New Mexico, 42 km (26 mi) west of the site. The population of

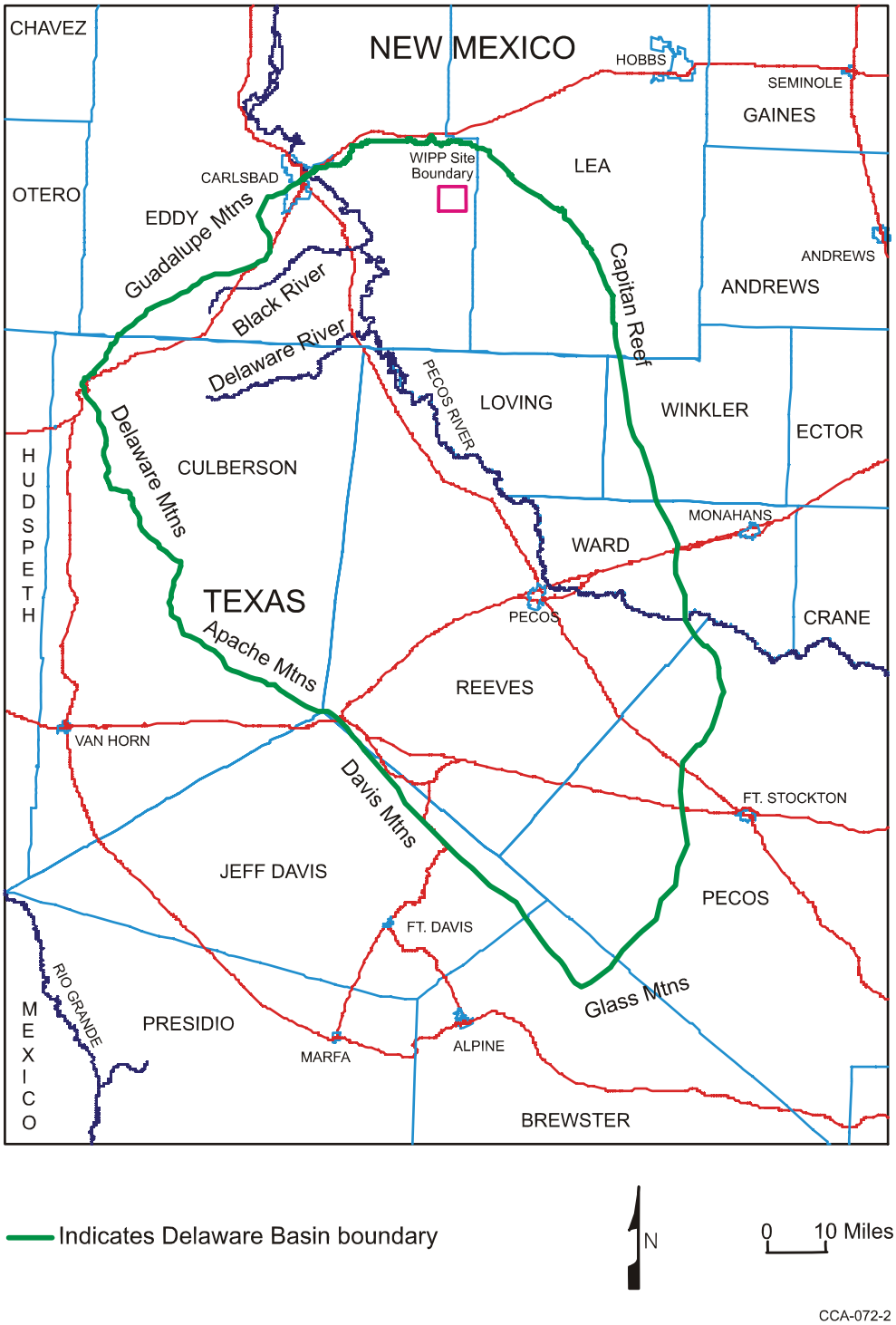

Figure 2-46. Delaware Basin Boundary

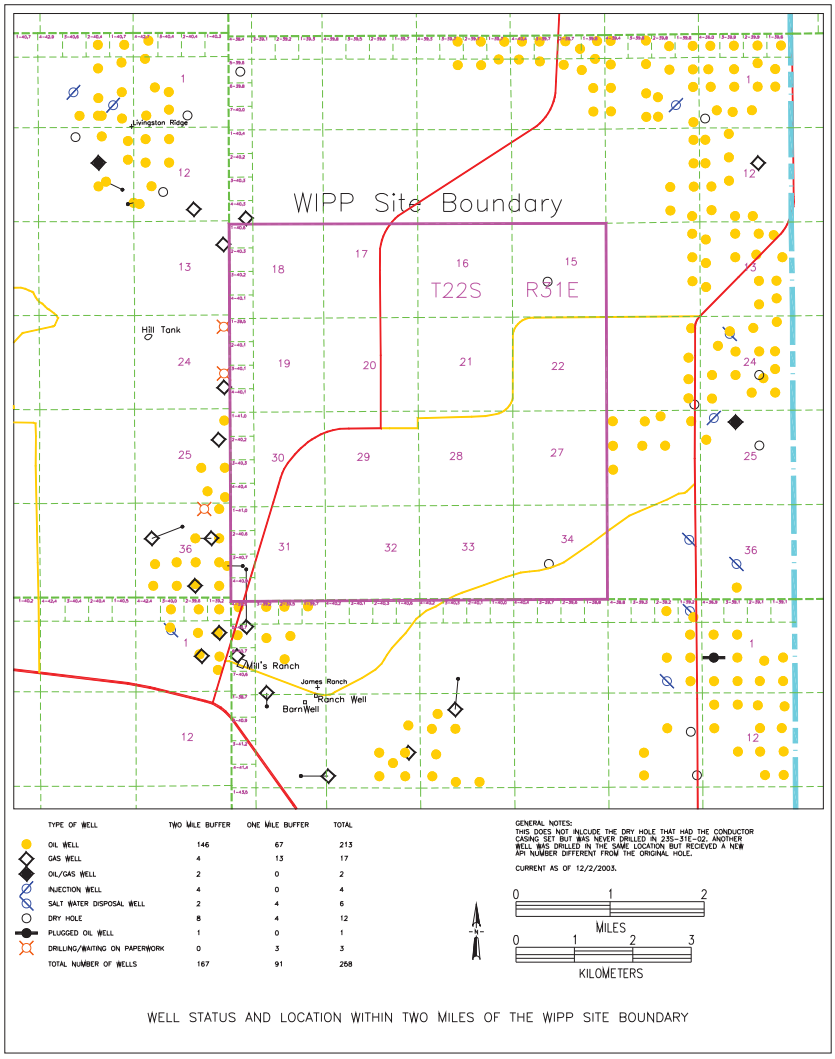

Figure 2-47. Distribution of Existing Petroleum Industry Boreholes Within Two Miles of the WIPP Site

Carlsbad increased from 24,896 in 1990 to 26,870 in 2000. Hobbs, New Mexico, 58 km (36 mi) to the east of the site, had a population decrease from 29,115 in 1990 to 28,657 in 2000. Eunice, New Mexico, 64 km (40 mi) east of the site, had a 1990 population of 2,731 decrease to 2,562 in 2000. Jal, New Mexico, 72 km (45 mi) southeast of the site, had a population of 2,153 in 1990 decrease to 1,996 in 2000.

The WIPP site is located in Eddy County near the border of Lea County, New Mexico. The Eddy County population increased from 48,605 in 1990 to 51,658 in 2000. The Lea County population decreased from 55,765 in 1990 to 55,511 in 2000. Population figures are taken from the 1990 census (U.S. Department of Commerce,1990) and the 2000 census (U.S. Census Bureau, 2000).

2.3.2.2 Land Use

At present, land within 16 km (10 mi) of the site is used for potash mining operations, active oil and gas wells, activities associated with hydrocarbon production, and grazing.

The WIPP Land Withdrawal Act (LWA) (U.S. Congress 1992) withdrew certain public lands from the jurisdiction of the Bureau of Land Management (BLM). The law provides for the transfer of the WIPP site lands from the DOI to the DOE and effectively withdraws the lands, subject to existing rights, from entry, sale, or disposition; appropriation under mining laws; or operation of the mineral and geothermal leasing laws. The LWA directed the Secretary of Energy to produce a management plan to provide for grazing, hunting and trapping, wildlife habitat, mining, and the disposal of salt and tailings.

Between 1978 and 1988, DOE acquired all active potash and hydrocarbon leases within the WIPP site boundary. These were acquired either through outright purchase or through condemnation. In one condemnation proceeding, the court awarded DOE the surface and top 1.82 km (6,000 ft) of Section 31 and allowed the leaseholder to retain the subsurface below 1.82 km (6,000 ft). This was allowed because analysis showed that wells developed within this lease below the 1.82-km (6,000ft) limit would be too far away from the waste panels to be of consequence to the WIPP (see, for example, Brausch et al. 1982). This is corroborated by the results of PA discussed in Section 6.2.5.1; and Appendix PA, Attachment SCR, FEP 56. Consequently, as the result of the DOE's acquisition activities, there are no producing hydrocarbon wells within the volumetric boundary defined by the land withdrawal (T22S, R31E, S15-22, 27-34). Two active wells were drilled to tap the oil and gas resources on the leases beneath Section 31. The James Ranch #13, drilled in 1982, is a gas well, and the James Ranch #27, drilled in 2000, is an oil well. Both wells are located on surface leases outside the WIPP site boundary. Both wells enter Section 31 below a depth of 1.82 km (6,000 ft) beneath ground level. Except for the leases in Section 31, the LWA prohibits all drilling into the controlled area unless such drilling is in support of the WIPP.

Grazing leases have been issued for all land sections immediately surrounding the WIPP facility. Grazing within the WIPP site lands occurs within the authorization of the Taylor Grazing Act of 1934, the Federal Land Policy and Management Act (FLPMA), the Public Rangelands Improvement Act of 1978, and the Bankhead-Jones Farm Tenant Act of 1973.

The responsibilities of DOE include supervision of ancillary activities associated with grazing (for example, wildlife access to livestock water development), tracking of water developments inside WIPP lands to ensure that they are configured according to the regulatory requirements, and ongoing coordination with respective allottees. Administration of grazing rights is in cooperation with the BLM according to the memorandum of understanding (MOU) and the coinciding Statement of Work through guidance established in the East Roswell Grazing Environmental Impact Statement. The WIPP site is composed of two grazing allotments administered by the BLM: the Livingston Ridge (No. 77027), and the Antelope Ridge (No. 77032) (see Figure 7-2).

2.3.2.3 History and Archaeology

From about 10,000 B.C. to the late 1800s, the WIPP site and surrounding region were inhabited by nomadic aboriginal hunters and gatherers who subsisted on various wild plants and animals. From about A.D. 600 onward, as trade networks were established with Puebloan peoples to the west, domesticated plant foods and materials were acquired in exchange for dried meat, hides, and other products from the Pecos Valley and Plains. In the late 1500s, the Spanish Conquistadors encountered Jumano and Apachean peoples in the region who practiced hunting and gathering and engaged in trade with Puebloans. After the Jumanos abandoned the southern Plains region, the Comanches became the major population of the area. Neighboring populations with whom the Comanches maintained relationships ranging from mutual trade to open warfare included the Lipan, or Southern Plains Apache, several Puebloan Groups, Spaniards, and the Mescalero Apaches.

The best documented indigenous culture in the WIPP region is that of the Mescalero Apaches, who lived west of the Pecos. The lifestyle of the Mescalero Apaches represents a transition between the full sedentism of the Pueblos and the nomadic hunting and gathering of the Jumanos. In 1763, the San Saba expedition encountered and camped with a group of Mescaleros in Los Medaños. Expedition records indicate the presence of both Lipan and Mescalero Apaches in the region.

A peace accord reached between the Comanches and the Spaniards in 1786 resulted in two historically important economic developments: (1) organized buffalo hunting by Hispanic and Puebloan ciboleros, and (2) renewal and expansion of the earlier extensive trade networks by Comancheros. These events placed eastern New Mexico in a position to receive a wide array of both physical and ideological input from the Plains culture area to the east and north and from Spanish-dominated regions to the west and south. Comanchero trade began to mesh with the Southwest American trade influence in the early nineteenth century. However, by the late 1860s, the importance of Comanchero trade was cut short by Texan influence.

The first cattle trail in the area was established along the Pecos River in 1866 by Charles Goodnight and Oliver Loving. By 1868, Texan John Chisum dominated much of the area by controlling key springs along the river. Overgrazing, drought, and dropping beef prices led to the demise of open-range cattle ranching by the late 1880s.

Following the demise of open-range livestock production, ranching developed using fenced grazing areas and production of hay crops for winter use. Herd grazing patterns were influenced by the availability of water supplies as well as by the storage of summer grasses for winter feeding.

The town of Carlsbad was founded as Eddy in 1889 as a health spa. In addition to ranching, the twentieth century brought the development of the potash, oil, and gas industries that have increased the population eightfold in the last 50 years.

Although technological change has altered some of the aspects, ranching remains an important economic activity in the WIPP region. This relationship between people and the land is still an important issue in the area. Ranch-related sites dating to the 1940s and 1950s are common in

parts of the WIPP area. These will be considered historical properties within the next several years, and thus will be treated as such under current law.

The National Historic Preservation Act (NHPA) (16 USC Part 470 et seq.) was enacted to protect the nation's cultural resources in conjunction with the states, local governments, Indian tribes, and private organizations and individuals. The policy of the federal government includes: (1) providing leadership in preserving the prehistoric and historic resources of the nation, (2) administering federally owned, administered, or controlled prehistoric resources for the benefit of present and future generations, (3) contributing to the preservation of nonfederally owned prehistoric and historic resources, and (4) assisting state and local governments and the national trust for historic preservation in expanding and accelerating their historic preservation programs and activities. The act also established the National Register of Historic Places (National Register). At the state level, the State Historic Preservation Officer (SHPO) coordinates the state's participation in implementing the NHPA. The NHPA has been amended by two acts: the Archeological and Historic Preservation Act (16 USC Part 469 et seq.), and the Archeological Resource Protection Act (16 USC Part 470aa et seq.).

To protect and preserve cultural resources found within the WIPP site boundary, the WIPP submitted a mitigation plan to the New Mexico SHPO describing the steps to either avoid or excavate archaeological sites. A site was defined as a place used and occupied by prehistoric people. In May 1980, the SHPO made a determination of "no adverse effect from WIPP facility activities" on cultural resources. The Advisory Council on Historic Preservation concurred that the WIPP Mitigation Plan is appropriate to protect cultural resources.

Known historical sites (more than 50 years old) in southeastern New Mexico consist primarily of early twentieth century homesteads that failed, or isolated features from late nineteenth century and early twentieth century cattle or sheep ranching, or military activities. To date, no Spanish or Mexican sites have been identified. Historic components are rare but are occasionally noted in the WIPP area. These include features and debris related to ranching.

Since 1976, cultural resource investigations have recorded 98 archaeological sites and numerous isolated artifacts within the 41km^2 (16mi^2) area enclosed by the WIPP site. In the central 10.4km^2 (4mi^2) area, 33 sites were determined to be eligible for inclusion on the National Register as archaeological districts. Investigations since 1980 have recorded an additional 14 individual sites outside the central 10.4km^2 (4mi^2) area that are considered eligible for inclusion on the National Register. The following major cultural resource investigations to date are broken out in the list that follows. Additional information can be found in the bibliography of CCA Chapter 2.

1977. The first survey of the area was conducted for SNL by Nielson of the Agency for Conservation Archaeology (ACA). This survey resulted in the location of 33 sites and 64 isolated artifacts.

1979. MacLennan and Schermer of ACA conducted another survey to determine access roads and a railroad right-of-way for Bechtel, Inc. The survey encountered two sites and 12 isolated artifacts.

1980. Schermer conducted another survey to relocate the sites originally recorded by Nielson. This survey redescribed 28 of the original 33 sites.

1981. Hicks (1981a, 1981b) directed the excavation of nine sites in the WIPP core area.

1982. Bradley (Lord and Reynolds 1985) recorded one site and four isolated artifacts in an archaeological survey for a proposed water pipeline.

1985. Lord and Reynolds (1985) examined three sites within the WIPP core area that consisted of two plant-collecting and processing sites and one base camp used between 1000 B.C. and A.D. 1400. The artifacts recovered from the excavations are in the Laboratory of Anthropology at the Museum of New Mexico in Santa Fe.

1987. Mariah Associates, Inc. identified 40 sites and 75 isolates in an inventory of 2,460 ac in 15 quarter-section units surrounding the WIPP site. In this investigation, 19 of the sites were located within the WIPP site's boundary. Sites encountered in this investigation tended to lack evident or intact features. Of the 40 new sites defined, 14 were considered eligible for inclusion in the National Register, 24 were identified as having insufficient data to determine eligibility, and 2 were determined to be ineligible for inclusion. The eligible and potentially eligible sites have been mapped and are avoided by DOE in its current activities at the WIPP site.

1988–1992. Several archaeological clearance reports have been prepared for seismic testing lines on public lands in Eddy County, New Mexico.

All archaeological sites are surface or near-surface sites, and no reasons exist (either geological or archeological) to suspect that deep drilling would uncover or investigate archaeological sites.

No artifacts were encountered during cultural resource surveys performed from 1992 until present. The following list provides examples of WIPP projects that required cultural resource surveys. All investigations were performed and reported in accordance with requirements established by the New Mexico Office of Cultural Affairs (OCA) and administered by the SHPO.

- SPDV site investigation into status of a previously recorded site (#LA 33175) to determine potential impacts from nearby reclamation activity. Assessment included minor surface excavation.

- WIPP well bore C-2737. Cultural resource investigation for well pad and access road.

- WIPP well bores WQSP 1-6 and 6a. Individual cultural resource investigations conducted for construction of each respective well pad and access road.

- WIPP well bores SNL 1, 2, 3, 9 and 12. Cultural resource investigations conducted for construction of each respective well pad and access road.

- WIPP well bore WTS 4. Cultural resource investigation conducted in support of siting and constructing reserve pits for well drilling and development.

- North Salt Pile Expansion. Cultural resource investigation conducted in support of the expansion of the North Salt Pile, a project designed to mitigate surface water infiltration.

All of the aforementioned archeological investigations received determinations of "No Adverse Affect" from the OCA and the SHPO. This determination serves as a clearance to proceed with work.

The Delaware Basin has been used in the past for an isolated nuclear test. This test, Project Gnome, took place in 1961 at a location approximately 13 km (8 mi) southwest of the WIPP. The primary objective of Project Gnome was to study the effects of an underground nuclear explosion in salt. The Gnome experiment involved the detonation of a 3.1-kiloton nuclear device at a depth of 361 m (1,200 ft) in the bedded salt of the Salado (Rawson et al. 1965). The explosion created a cavity of approximately 28,000 m^3 (1,000,000 ft^3) and caused surface displacements over an area of about a 360m (1,200ft) radius. Fracturing and faulting caused measurable changes in rock permeability and porosity at distances up to approximately 100 m (330 ft) from the cavity. No earth tremors were reported at distances over 40 km (25 mi) from the explosion. Project Gnome was decommissioned in 1979.

2.4 Background Environmental Conditions

Background environmental conditions at and near the WIPP site were characterized prior to the initiation of the operation of the facility and are described in CCA Section 2.4. Because background characterization focuses on environmental conditions existing prior to operations, it is not meaningful to redefine background environmental conditions after operations began. Accordingly, information presented in CCA Section 2.4 is not repeated and updated in this recertification application.

2.5 Climate and Meteorological Conditions

The DOE did not consider climate directly in its site selection process, although criteria such as low population density and large tracts of federally owned land tend to favor arid and semi-arid areas in the western United States. The semi-arid climate around the WIPP is beneficial since it is a direct cause of the lack of a near surface water table and the minimization of radiation exposure pathways that involve surface or groundwater. Data used to interpret paleoclimates in the American southwest come from a variety of sources and indicate alternating arid and subarid to subhumid climates throughout the Pleistocene. The information in this section was taken from Swift (1992), and included in CCA Appendix CLI and references therein.

2.5.1 Historic Climatic Conditions

Prior to 18,000 years ago, radiometric dates are relatively scarce, and the record is incomplete. From 18,000 years ago to the present, however, the climatic record is relatively well constrained by floral, faunal, and lacustrine data. These data span the transition from the last full-glacial maximum to the present interglacial period; given the global consistency of glacial fluctuations described below, they can be taken to be broadly representative of extremes for the entire Pleistocene.

Early and middle Pleistocene paleoclimatic data for the southwestern United States are incomplete and permit neither continuous reconstructions of paleoclimates nor direct correlations between climate and glaciation prior to the last glacial maximum, which occurred 22,000 to 18,000 years ago. Stratigraphic and soil data from several locations, however, indicate that cyclical alternation of wetter and drier climates in the Southwest had begun by the Early Pleistocene. Fluvial gravels in the Gatuña exposed in the Pecos River Valley of eastern New Mexico suggest wetter conditions 1.4 million years ago and again 600,000 years ago. The Mescalero caliche, exposed locally over much of southeastern New Mexico, suggests drier conditions 510,000 years ago, and loosely dated spring deposits in Nash Draw west of the WIPP imply wetter conditions occurring again later in the Pleistocene. The Blackwater Draw Formation of the southern High Plains of eastern New Mexico and western Texas, correlating in time to both the Gatuña Formation and the Mescalero caliche, contains alternating soil and eolian sand horizons that show at least six climatic cycles beginning more than 1.4 million years ago and continuing to the present.

Data used to construct the more detailed climatic record for the latest Pleistocene and Holocene come from six independent lines of evidence dated using carbon-14 techniques: plant communities preserved in packrat middens throughout the southwest, including sites in Eddy and Otero counties, New Mexico; pollen assemblages from lacustrine deposits in western New Mexico and other locations in the southwest; gastropod assemblages from western Texas; ostracod assemblages from western New Mexico; paleolake levels throughout the southwest; and faunal remains from caves in southern New Mexico.

Prior to the last glacial maximum 22,000 to 18,000 years ago, evidence from faunal assemblages in caves in southern New Mexico, including the presence of species such as the desert tortoise that are now restricted to warmer climates, suggests hot summers and mild, dry winters. Lacustrine evidence confirms the interpretation of a relatively dry climate prior to and during the glacial advance. Permanent water did not appear in what was later to become a major lake in the Estancia Valley in central New Mexico until some time before 24,000 years ago, and water depths in lakes at higher elevations in the San Agustin Plains in western New Mexico did not reach a maximum until sometime between 22,000 and 19,000 years ago. Ample floral and lacustrine evidence documents cooler, wetter conditions in the southwest during the glacial peak. These changes were not caused by the immediate proximity of glacial ice. None of the Pleistocene continental glaciations advanced farther southwest than northeastern Kansas, and the most recent, late-Wisconsinan ice sheet reached its limit in South Dakota, approximately 1,200 km (750 mi) from WIPP. Discontinuous alpine glaciers formed at the highest elevations throughout the Rocky Mountains, but these isolated ice masses were symptoms, rather than causes, of cooler and wetter conditions and had little influence on regional climate at lower elevations. The closest such glacier to WIPP was on the northeast face of Sierra Blanca Peak in the Sacramento Mountains, approximately 220 km (135 mi) to the northwest.

Global climate models indicate that the dominant glacial effect in the southwest was the disruption and southward displacement of the westerly jet stream by the physical mass of the ice sheet to the north. At the glacial peak, major Pacific storm systems followed the jet stream across New Mexico and the southern Rocky Mountains, and winters were wetter and longer than either at the present or during the previous interglacial period.

Gastropod assemblages at Lubbock Lake in western Texas suggest mean annual temperatures 5º C (9º F) below present values. Both floral and faunal evidence indicate that annual precipitation throughout the region was 1.6 to 2.0 times greater than today's values. Floral evidence also suggests that winters may have continued to be relatively mild, perhaps because the glacial mass blocked the southward movement of arctic air. Summers at the glacial maximum were cooler and drier than at present, without a strongly developed monsoon.

The jet stream shifted northward following the gradual retreat of the ice sheet after 18,000 years ago, and the climate responded accordingly. By approximately 11,000 years ago, conditions were significantly warmer and drier than previously, although still dominated by winter storms and still wetter than today. Major decreases in total precipitation and the shift toward the modern monsoonal climate did not occur until the ice sheet had retreated into northeastern Canada in the early Holocene.

By middle Holocene time, the climate was similar to that of the present, with hot, monsoon-dominated summers and cold, dry winters. The pattern has persisted to the present, but not without significant local variations. Soil studies show that the southern High Plains were drier from 6,500 to 4,500 years ago than before or since. Gastropod data from Lubbock Lake indicate the driest conditions from 7,000 to 5,000 years ago (precipitation, 0.89 times present values; mean annual temperature, 2.5º C [4.5º F] higher than present values), with a cooler and wetter period 1,000 years ago (precipitation, 1.45 times present values; mean annual temperature, 2.5º C [4.5º F] lower than present). Plant assemblages from southwestern Arizona suggest steadily decreasing precipitation from the middle Holocene to the present, except for a brief wet period approximately 990 years ago. Stratigraphic work at Lake Cochise (the present Willcox playa in southeast Arizona) shows two mid-Holocene lake stands, one near or before 5,400 years ago and one between or before 3,000 to 4,000 years ago; however, both were relatively short-lived, and neither reached the maximum depths of the Late Pleistocene high stand that existed before 14,000 years ago.

Inferred historical precipitation indicates that during the Holocene, wet periods were relatively drier and shorter in duration than those of the late Pleistocene. Historical records over the last several hundred years indicate numerous lower-intensity climatic fluctuations, some too short in duration to affect floral and faunal circulation. Sunspot cycles and the related change in the amount of energy emitted by the sun have been linked to historical climatic changes elsewhere in the world, but the validity of the correlation is uncertain. Correlations have also been proposed between volcanic activity and climatic change. In general, however, causes for past short-term changes are unknown.

The climatic record presented here should be interpreted with caution because its resolution and accuracy are limited by the nature of the data used to construct it. Floral and faunal assemblages change gradually and show only a limited response to climatic fluctuations that occur at frequencies that are higher than the typical life span of the organisms in question. For long-lived species such as trees, resolution may be limited to hundreds or even thousands of years. Sedimentation in lakes and playas has the potential to record higher-frequency fluctuations, including single-storm events, but only under a limited range of circumstances. Once water levels reach a spill point, for example, lakes show only a limited response to further increases in precipitation.

With these observations in mind, three significant conclusions can be drawn from the climatic record of the American southwest. First, maximum precipitation in the past coincided with the maximum advance of the North American ice sheet. Minimum precipitation occurred after the ice sheet had retreated to its present limits. Second, past maximum long-term average precipitation levels were roughly twice the present levels. Minimum levels may have been 90 percent of the present levels. Third, short-term fluctuations in precipitation have occurred during the present relatively dry, interglacial period, but they have not exceeded the upper limits of the glacial maximum.

Too little is known about the relatively short-term behavior of global circulation patterns to accurately predict precipitation levels over the next 10,000 years. The long-term stability of patterns of glaciation and deglaciation, however, do permit the conclusion that future climatic extremes are unlikely to exceed those of the late Pleistocene. Furthermore, the periodicity of glacial events suggests that a return to full-glacial conditions is highly unlikely within the next 10,000 years.

2.5.2 Recent Climatic Conditions

Recent climatic conditions are provided to allow for the assessment of impacts of these factors on the disposal unit and the site. Data are taken from the WIPP environmental monitoring reports (see WEC 1991a, 1991b, 1992, 1993, 1994, 1995, 1996, 1997, 1998; WGESC 1999; ESRF 2000, 2001, 2002; and WRES 2003).

2.5.2.1 General Climatic Conditions

The climate of the region is semiarid, with generally mild temperatures, low precipitation and humidity, and a high evaporation rate. Winds are mostly from the southeast and moderate. In late winter and spring, there are strong west winds and dust storms. During the winter, the weather is often dominated by a high-pressure system situated in the central portion of the western United States and a low-pressure system located in north-central Mexico. During the summer, the region is affected by a low-pressure system normally situated over Arizona.

2.5.2.2 Temperature Summary

Temperatures are moderate throughout the year, although seasonal changes are distinct. The mean annual temperature in southeastern New Mexico is 63º F (17º C). In the winter (December through February), nighttime lows average near 23º F (-5º C), and maxima average in the 50s. The lowest recorded temperature at the nearest Class-A weather station in Roswell was -29º F (-34º C) in February 1905. In the summer (June through August), the daytime temperature exceeds 90°F (32º C) approximately 75 percent of the time. The National Weather Service documented 122º F (50º C) at the WIPP site as the record high temperature for New Mexico. This temperature was recorded on June 27, 1994. Table 2-14 shows the annual average, maximum, and minimum temperatures from 1990 through 2002.

2.5.2.3 Precipitation Summary

Precipitation is light and unevenly distributed throughout the year, averaging 28.2cm (11.1in.) per year from 1995 through 2002. Winter is the season of least precipitation, averaging less than 1.5 cm (0.6 in.) of rainfall per month. Snow averages about 13 cm (5 in.) per year at the site and seldom remains on the ground for more than a day. Approximately half the annual precipitation comes from frequent thunderstorms in June through September. Rains are usually brief but occasionally intense when moisture from the Gulf of Mexico spreads over the region. Monthly average, maximum, and minimum precipitations recorded at the WIPP site from 1990 through 2002 are summarized in Figure 2-48.

2.5.2.4 Wind Speed and Wind Direction Summary

The frequencies of wind speeds and directions are depicted by wind roses in Figures 2-49 through 2-56 for the WIPP site.

Table 2-14. Annual Average, Maximum, and Minimum Temperatures

Year	Annual Average Temperature		Maximum Temperature		Minimum Temperature	
	(^oC)	(^oF)	(^oC)	(^oF)	(^oC)	(^oF)
1990	17.8	64	46.1	115	−13.9	7
1991	17.2	63	42.8	109	−7.8	18
1992	17.2	63	42.8	109	−10	14
1993	17.8	64	42.8	109	−18.9	−2
1994	17.8	64	50	122	−14.4	6
1995	17	63	42	107	-7	19
1996	17	63	41	106	-7	19
1997	16.3	61.4	38.6	101.5	-11.4	11.4
1998	18.3	64.9	41.6	106.9	-10.8	12.6
1999	18.1	64.6	40.9	105.6	-7.9	17.8
2000	17.4	63.3	40.2	104.4	-6.8	19.7
2001	17.5	63.5	39.5	103.2	-7.8	18.0
2002	17.5	63.5	39.8	103.7	-8.9	16.0
Average	17.5	63.5	42.2	107.9	-0.2	13.9

2.6 Seismology

The DOE used tectonic activity as a siting criterion. The intent was to avoid tectonic conditions such as faulting and igneous activity that would jeopardize waste isolation over the long term and to avoid areas where earthquake size and frequency could impact facility design and operations. The WIPP site met both aspects of this criterion fully. Long-term tectonic activity is discussed in Section 2.1.5. The favorable results of the seismic (earthquake) studies are discussed here. The purpose of the seismic studies is to build a basis from which to predict ground motions that the WIPP repository may be subjected to in the near and distant future. The concern about seismic effects in the near future, during the operational period, pertains mainly to the design requirements for surface and underground structures for providing containment during seismic events. The concern about effects occurring over the long term, after the repository has been decommissioned and sealed, pertains more to relative motions (faulting) within the repository and possible effects of faulting on the integrity of the salt beds and/or shaft seals. Updated seismic activity information is provided in Figures 2-57 and 2-58. In this discussion, the magnitudes are reported in terms of the Richter scale, and all intensities are based on the

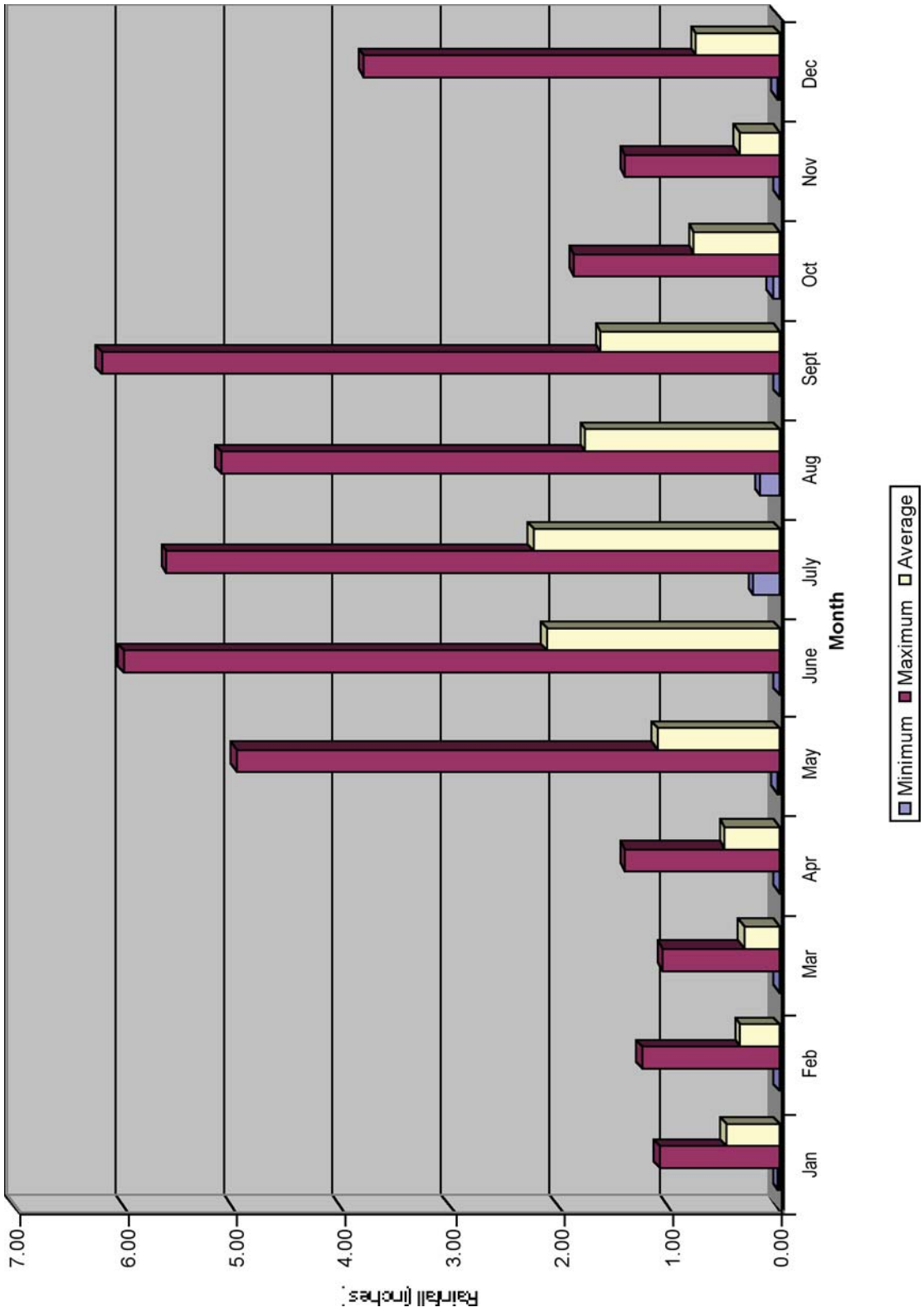

Figure 2-48. Monthly Precipitation for the WIPP Site from 1990-2002

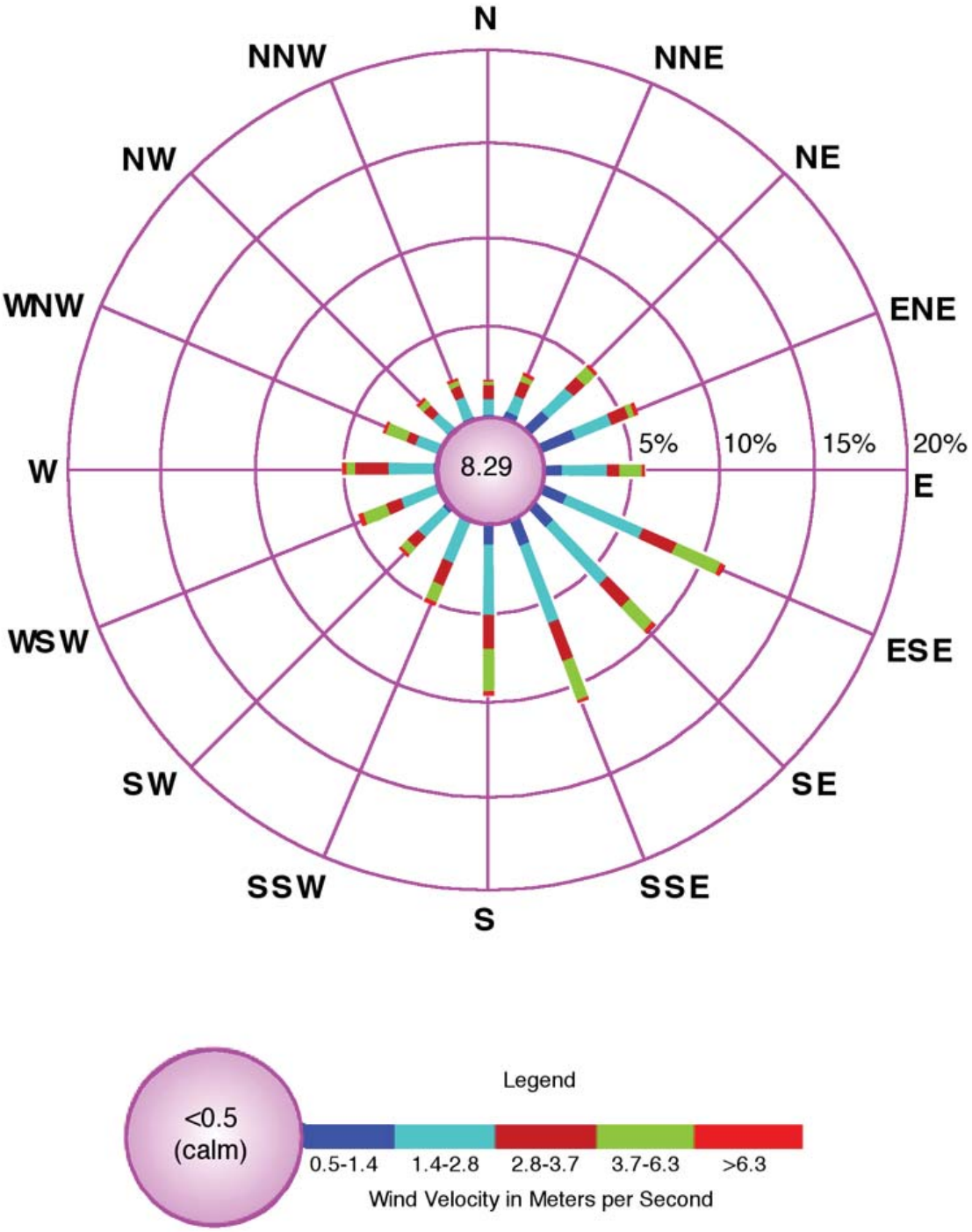

Figure 2-49. 1995 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

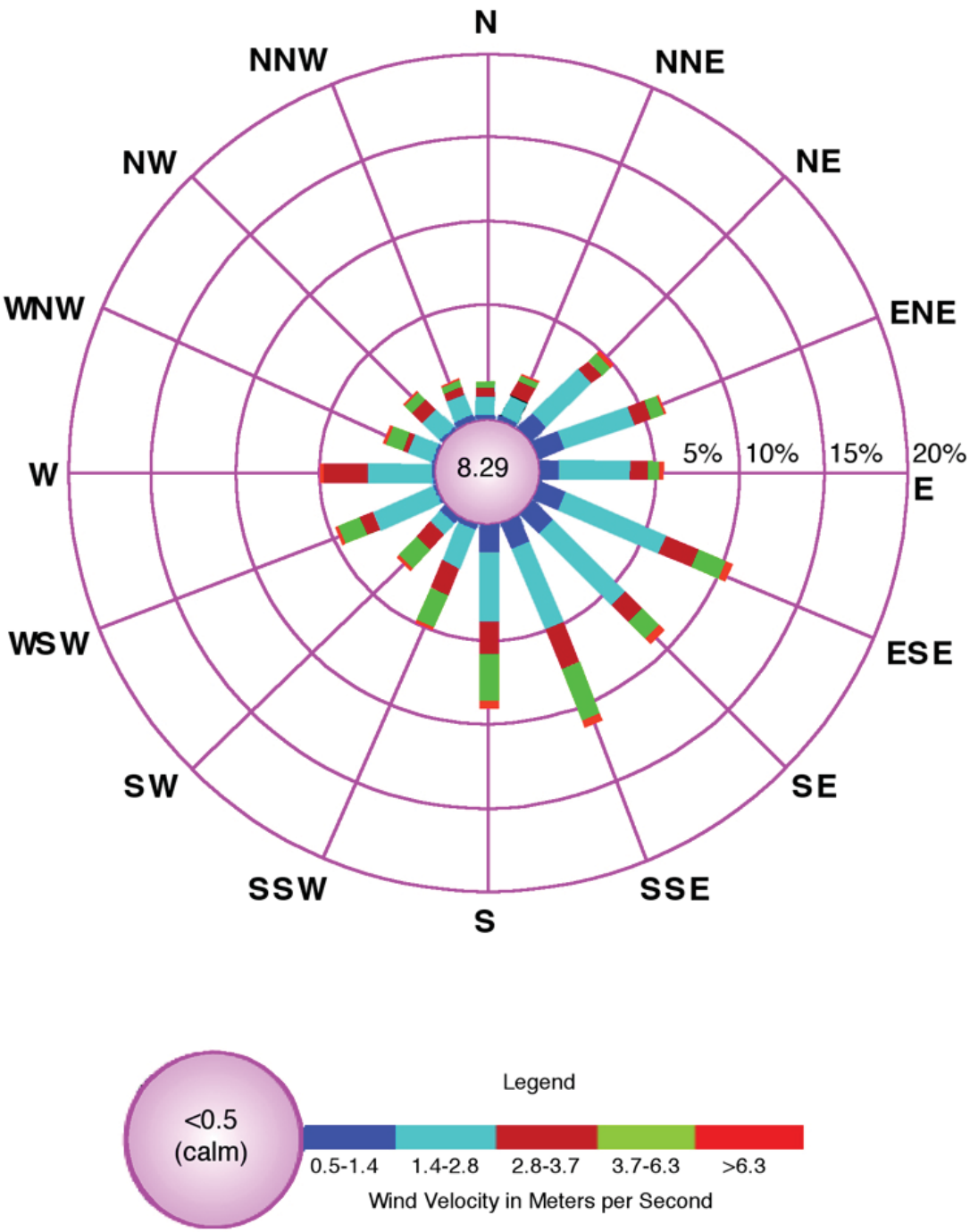

Figure 2-50. 1996 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

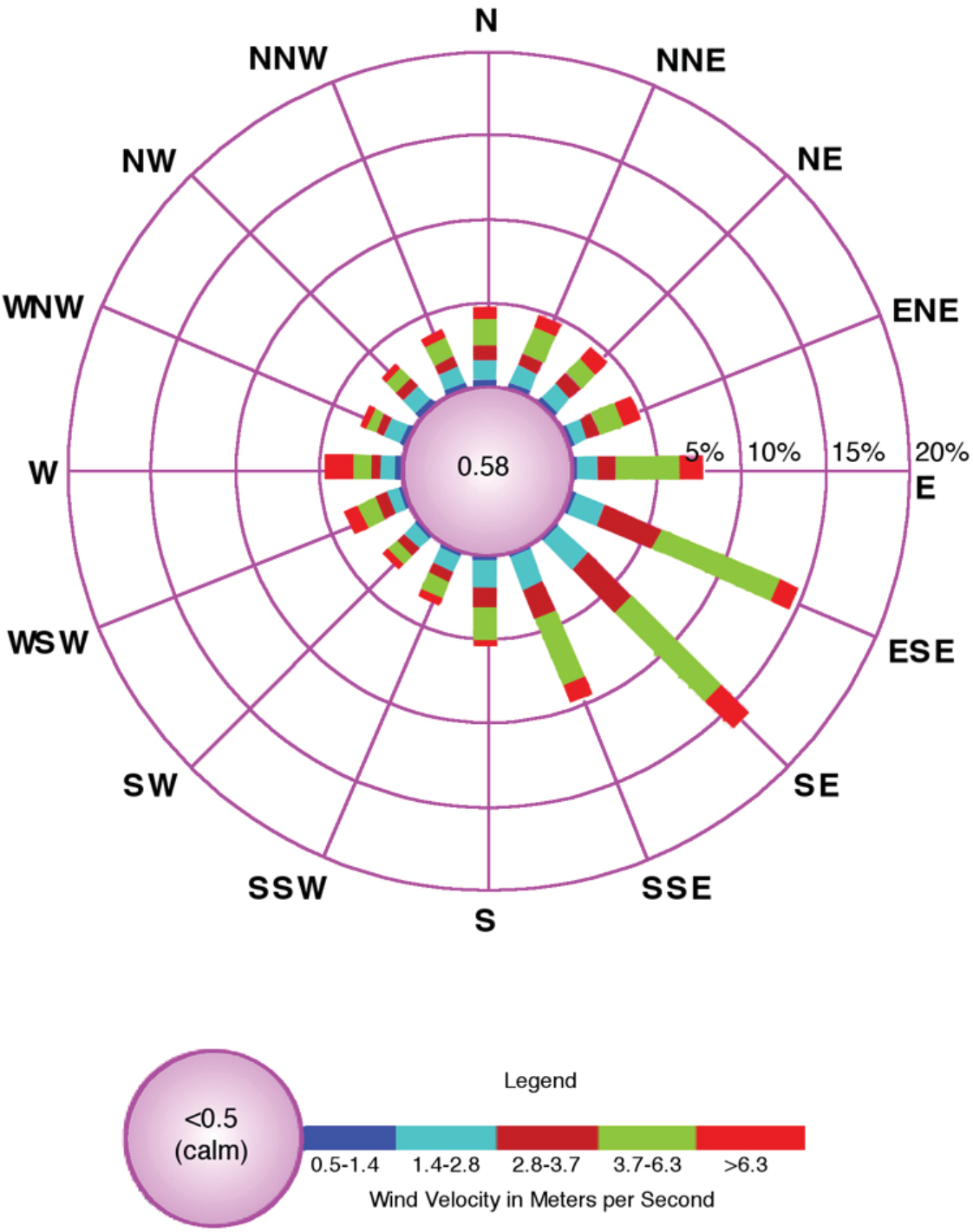

Figure 2-51. 1997 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

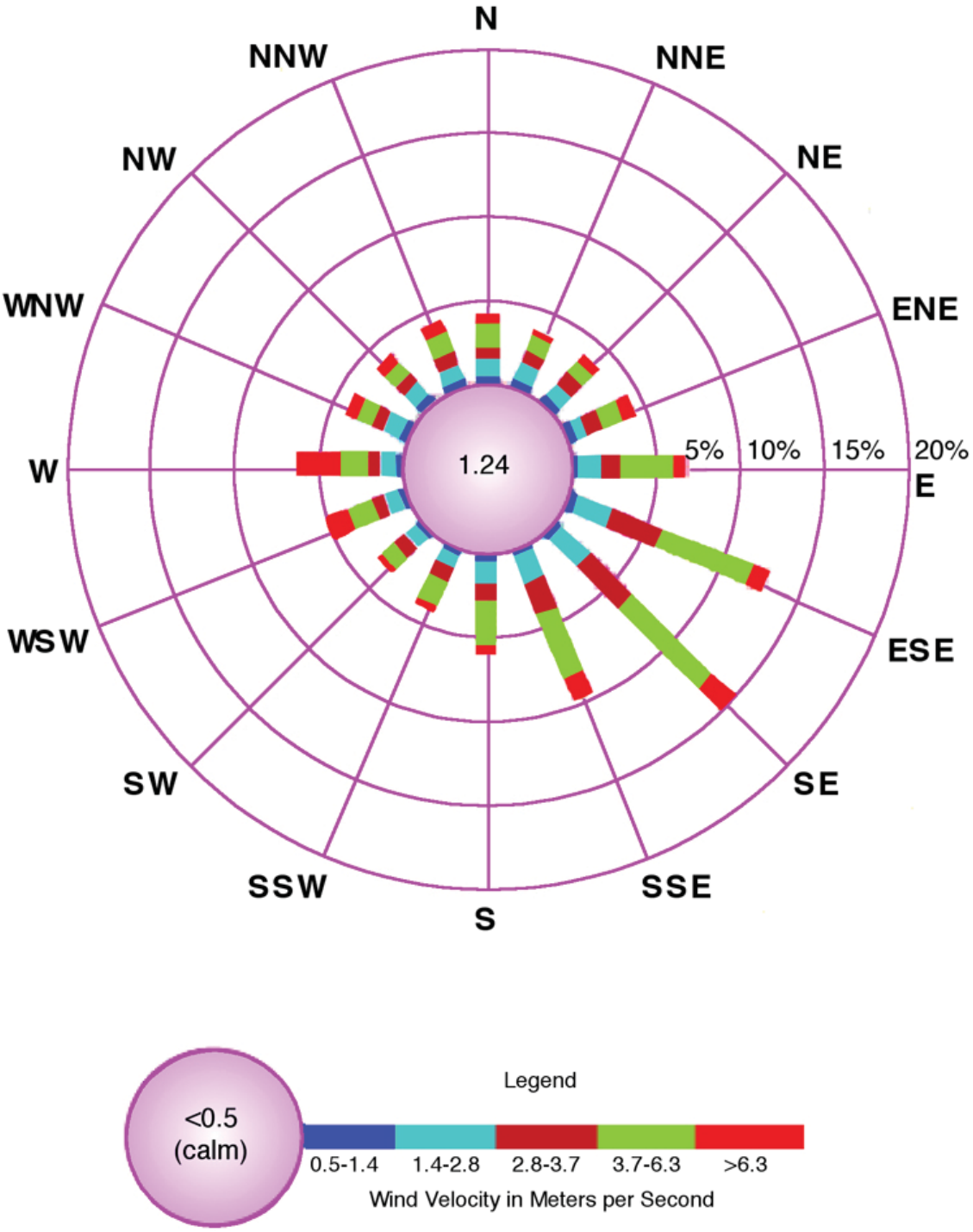

Figure 2-52. 1998 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

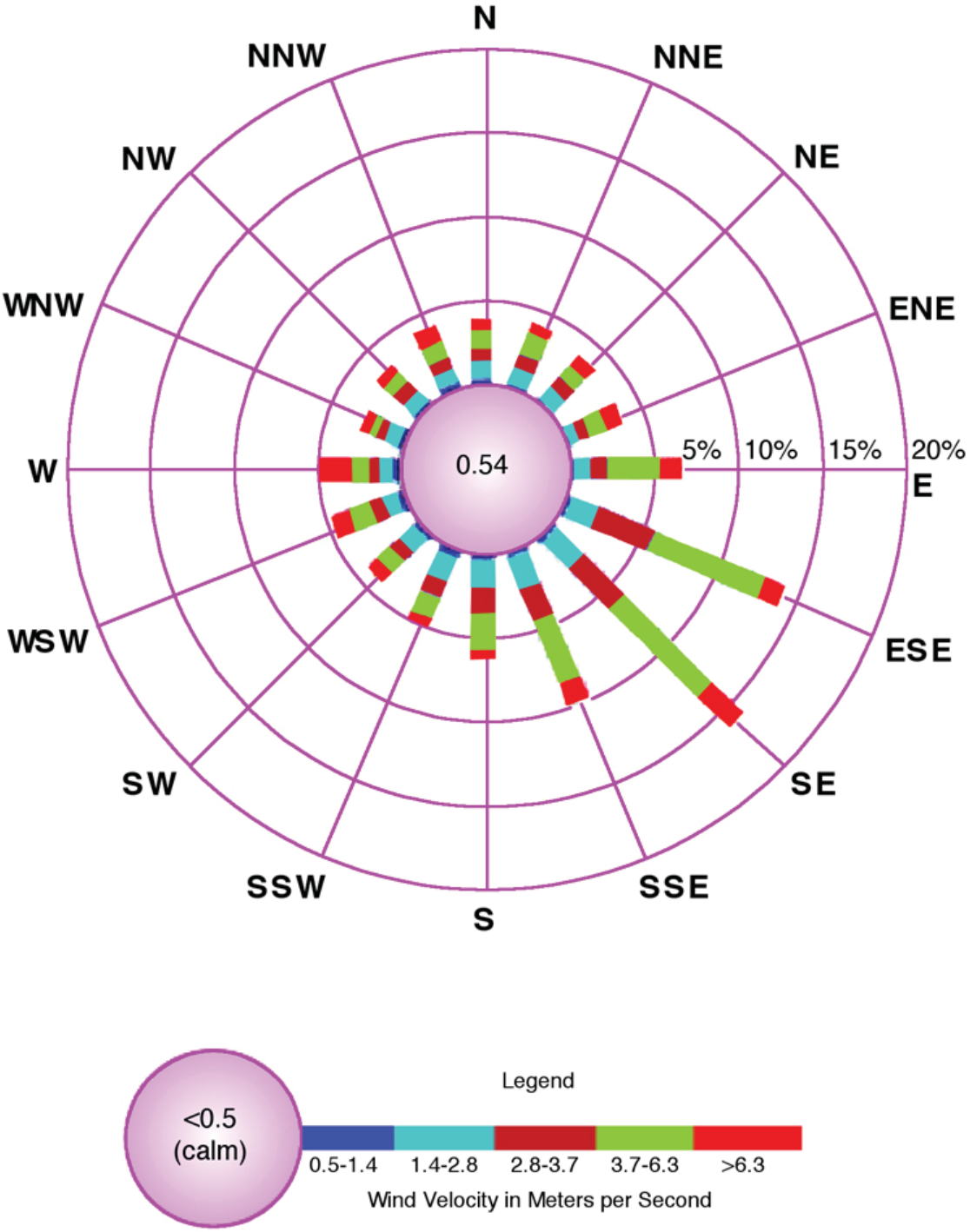

Figure 2-53. 1999 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

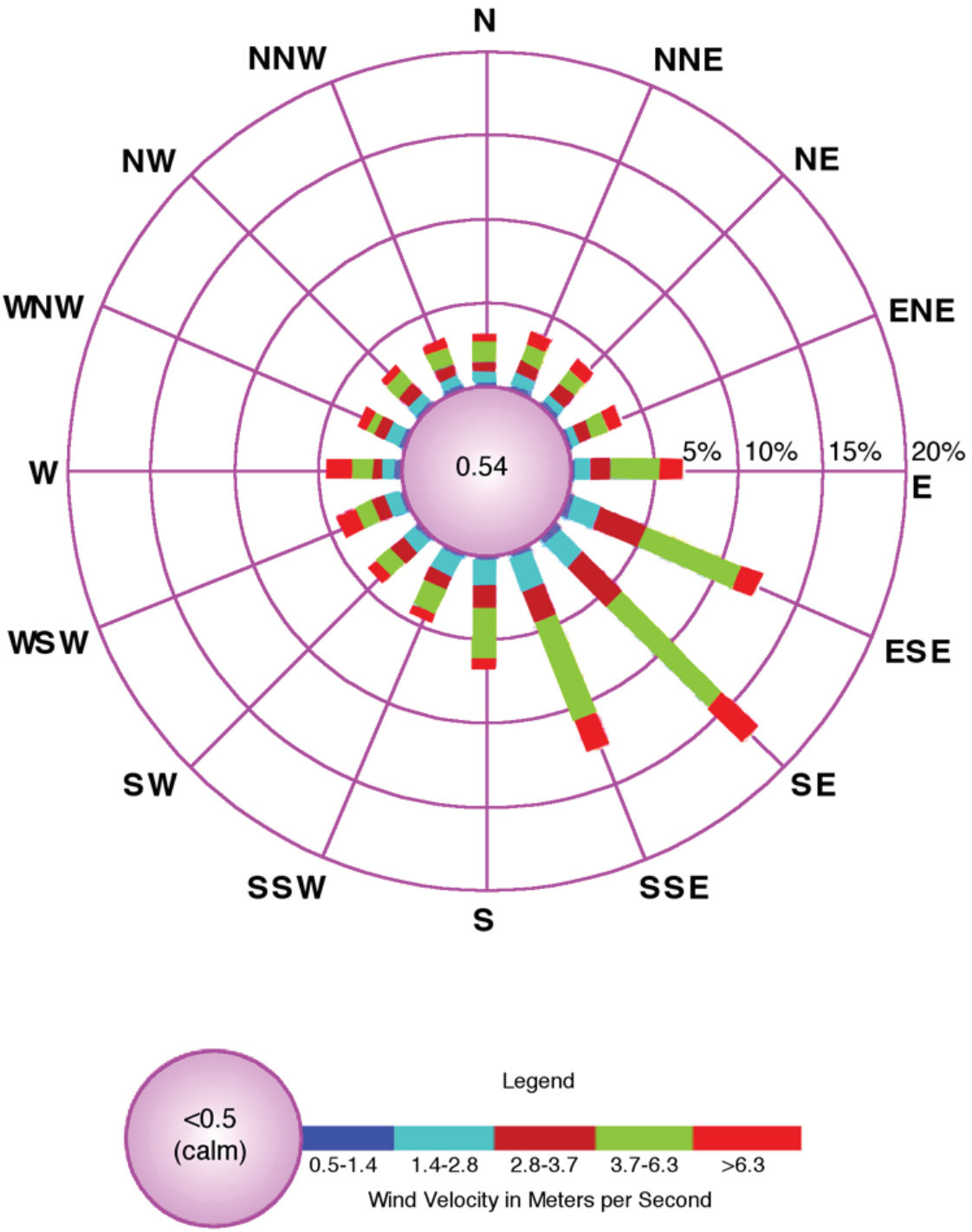

Figure 2-54. 2000 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

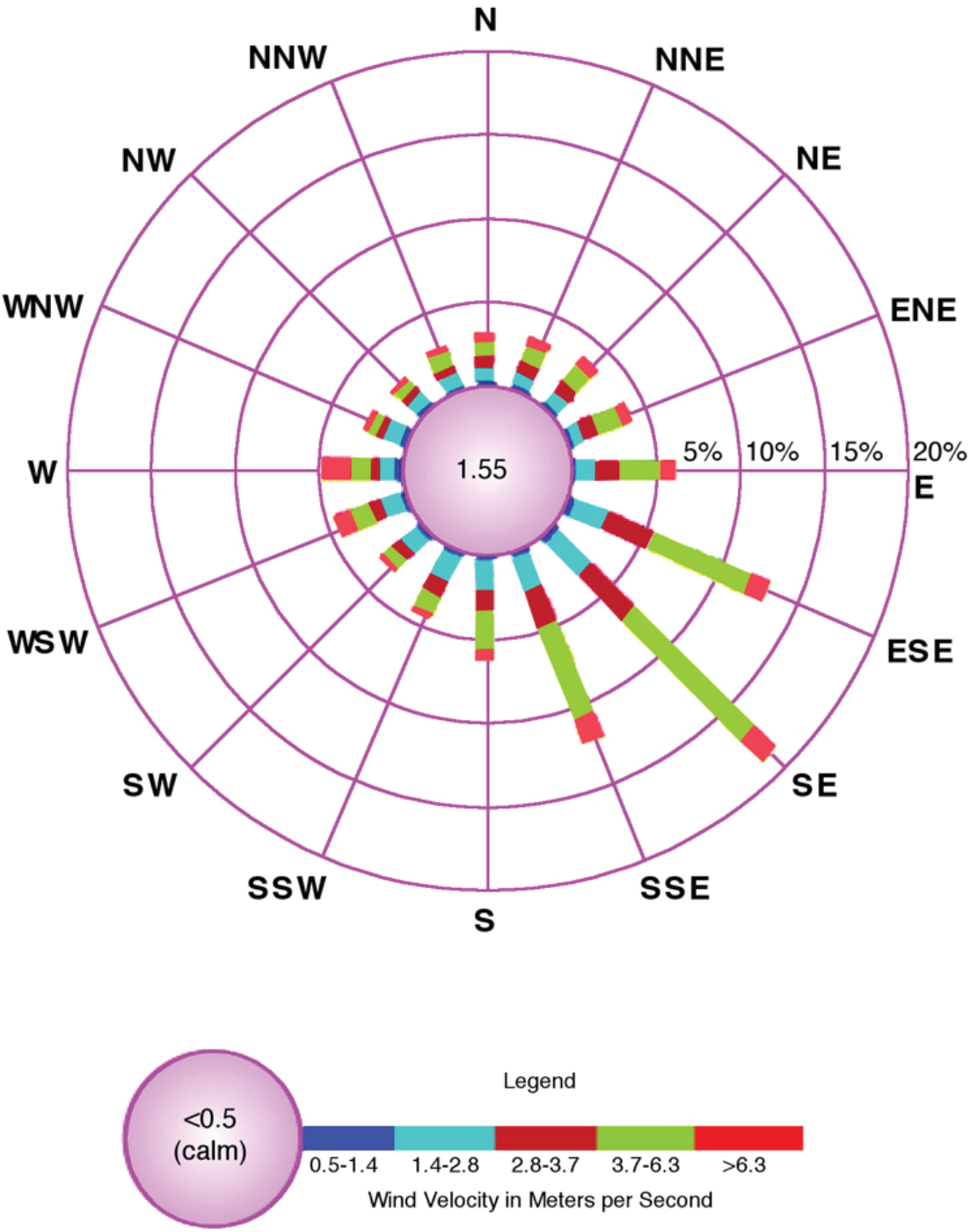

Figure 2-55. 2001 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

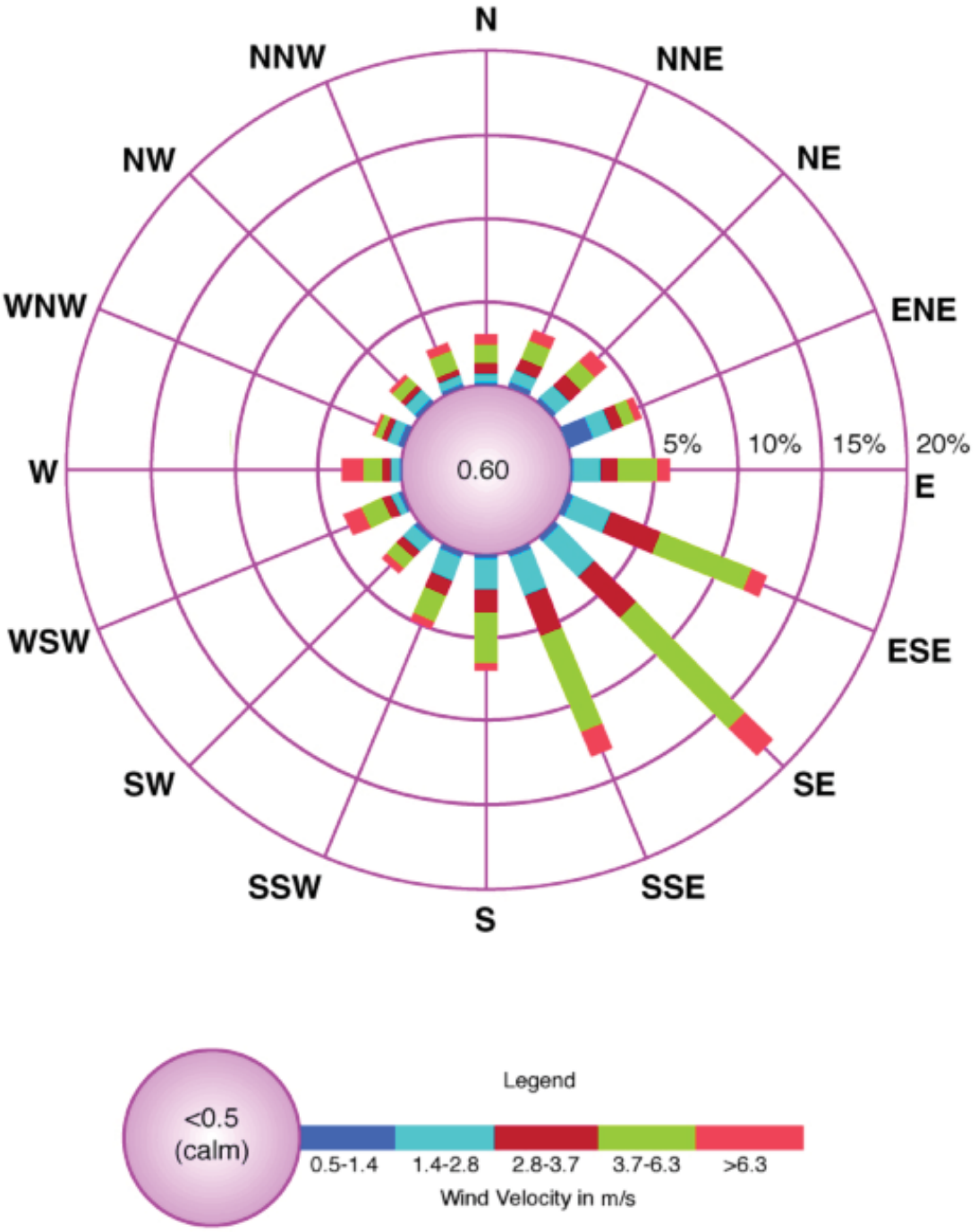

Figure 2-56. 2002 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

modified Mercalli intensity scale. Most of the magnitudes were determined by the New Mexico Institute of Mining and Technology or are described in CCA Appendix GCR and references therein.

2.6.1 Seismic History

Seismic data are presented in two time frames, before and after the time when seismographic data for the region became available. The earthquake record in southern New Mexico dates back only to 1923, and seismic instruments have been in place in the state since 1961. Various records have been examined to determine the seismic history of the area within 180 mi (288 km) of the site. With the exception of a weak shock in 1926 at Hope, New Mexico (approximately 64 km [40 mi] northwest of Carlsbad), and shocks in 1936 and 1949 felt at Carlsbad, all known shocks in the region before 1961 occurred to the west and southwest of the site more than 160 km (100 mi) away.

The strongest earthquake on record occurring within 288 km (180 mi) of the site was the Valentine, Texas earthquake of August 16, 1931. It has been estimated to have been of magnitude 6.4 on the Richter scale (Modified Mercalli Intensity of VIII). The Valentine earthquake was 208 km (130 mi) south-southwest of the site. Its Modified Mercalli Intensity at the site is estimated to have been V; this is believed to be the highest intensity felt at the site in this century.

In 1887, a major earthquake occurred in northeast Sonora, Mexico. Although about 536 km (335 mi) west-southwest of the site, it is indicative of the size of earthquakes possible in the eastern portion of the Basin and Range Province, west of the province containing the site. Its magnitude was estimated to have been 7.8 (VIII to IX in Modified Mercalli Intensity). It was felt over an area of 1.3 million km^2 (0.5 million mi^2) (as far as Santa Fe to the north and Mexico City to the south); fault displacements near the epicenter were as large as 18 m (26 ft).

Since 1961, instrumental coverage has become comprehensive enough to locate most of the moderately strong earthquakes (local magnitude >3.5) in the region. Instrumentally determined shocks that occurred within 288 km (180 mi) of the site between 1961 and 1994 are shown in Figure 2-57. The distribution of these earthquakes may be biased by the fact that seismic stations were more numerous and were in operation for longer periods north and west of the site. Pre-1961 earthquakes can be found in CCA Appendix GCR, Figure 5.2-1.

Except for the activity southeast of the site, the distribution of epicenters since 1961 differs little from that of shocks before that time. There are two clusters, one associated with the Rio Grande Rift on the Texas-Chihuahua border and another associated with the Central Basin Platform in Texas near the southeastern corner of New Mexico. The latter activity was not reported before 1964. It is not clear from the record whether earthquakes were occurring in the Central Basin Platform before 1964, although local historical societies and newspapers tend to confirm their absence before that time.

The April 14, 1995, earthquake near Marathon, Texas, was located 240 km (150 mi) south of the WIPP site. The USGS estimated that moment magnitude for this event was 5.7. At a distance of

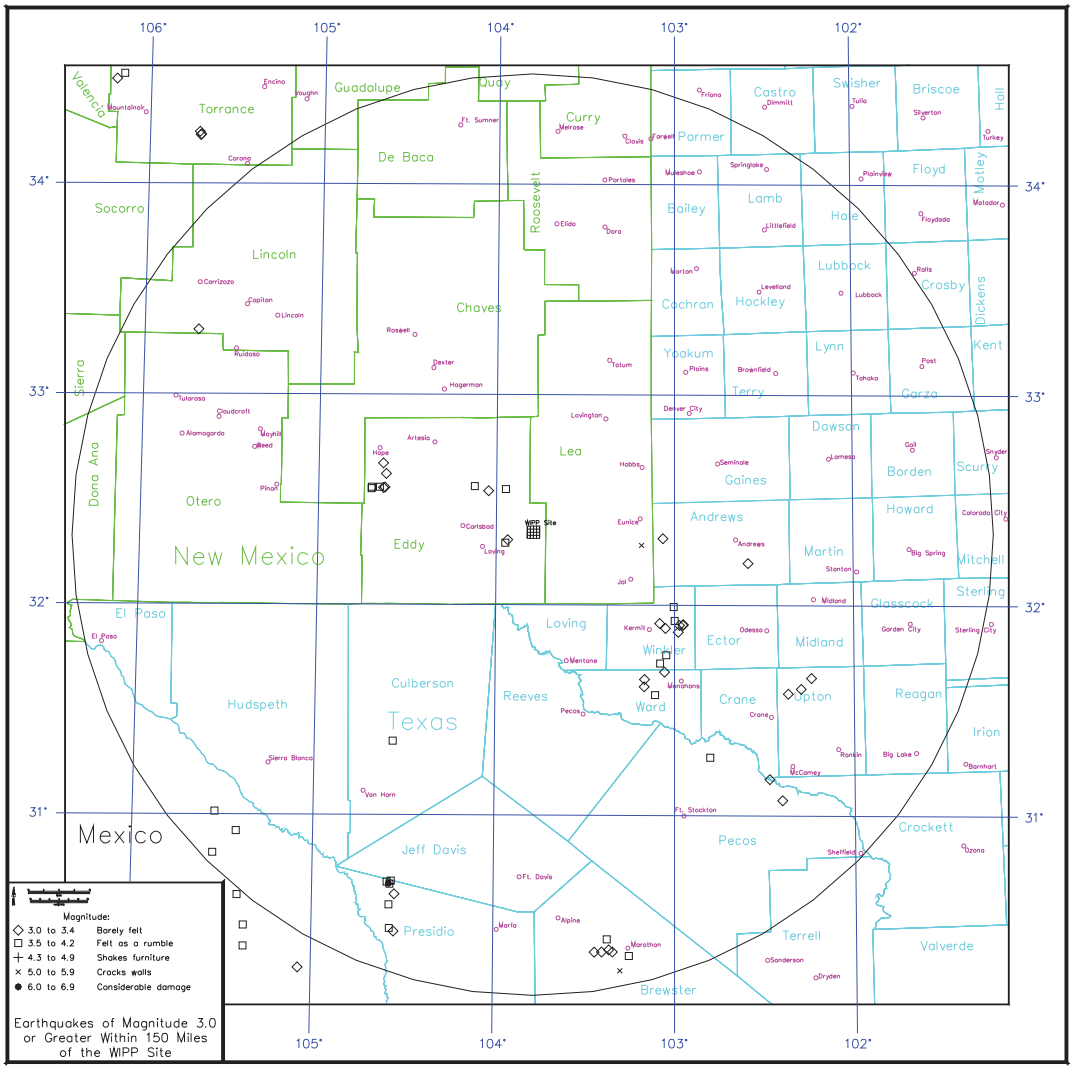

Figure 2-57. Regional Earthquake Epicenters Occurring between 1961 and 2002

240 km (149 mi), an event of magnitude 5.7 would produce a maximum acceleration at the WIPP site of less than 0.01 g (acceleration due to gravity).

The Marathon earthquake should not be considered an unanticipated event. The shock occurred in the Basin and Range Province, a seismotectonic province with evidence for 24 Quarternary faults in West Texas and adjacent parts of Mexico. Two of these faults had recent surface-faulting events in the Holocene. Strong earthquakes have occurred within the West Texas part of the Basin and Range Province, most notably the M_W = 6.4 (Richter) Valentine, Texas earthquake on August 15, 1931.

The WIPP site is located within the Great Plains seismotectonic province, a region that has no evidence of Quarternary faulting, even above major buried structures such as the Central Basin Platform. Because the Great Plains seismotectonic province is geologically distinct from the Basin and Range Province and lacks evidence for recent faulting, the maximum possible or

credible earthquake for this region would be substantially smaller than that for the Basin and Range Province of West Texas.

2.6.2 Seismic Risk

Procedures exist that allow for formal determination of earthquake probabilistic design parameters. In typical seismic risk analyses of this kind, the region of study is divided into seismic source areas within which future events are considered equally likely to occur at any location. For each seismic source area, the rate of occurrence of events above a chosen threshold level is estimated using the observed frequency of historical events. The sizes of successive events in each source are assumed to be independent and exponentially distributed; the slope of the log number versus frequency relationship is estimated from the relative frequency of different sizes of events observed in the historical data. This slope, often termed the b value, is determined either for each seismic source individually or for all sources in the region jointly. Finally, the maximum possible size of events for each source is determined using judgement and the historical record. Thus, all assumptions underlying a measure of earthquake risk derived from this type of analysis are explicit, and a wide range of assumptions may be employed in the analysis procedure.

In this section, the particular earthquake risk parameter calculated is peak acceleration expressed as a function of annual probability of being exceeded at the WIPP site. The particular analysis procedure applied to the calculation of this probabilistic peak acceleration is taken from a computer program written by McGuire (1976). In that program, the seismic source zones are modeled geometrically as quadrilaterals of arbitrary shape. Contributions to site earthquake risk from individual source zones are integrated into the probability distribution of acceleration, and the average annual probability of exceedence then follows directly.

In the analysis, the principal input parameters are as follows: site region acceleration attenuation, source zone geometry, recurrence statistics, and maximum magnitudes. Based on these parameters, several curves showing probabilistic peak acceleration are developed, and the conclusions that may be drawn from these curves are considered. The data treated in this way are used to arrive at a general statement of risk from vibratory ground motion at the site during its active phase of development and use.

2.6.2.1 Acceleration Attenuation

The first input parameters considered have to do with acceleration attenuation in the site region as a function of earthquake magnitude and hypocentral distance. The risk analysis used in this study employs an attenuation law of the form

$$a = b_1 \exp(b_2 M_L) R - b_3 , \qquad (2.3)$$

where a is acceleration in cm/s^2, M_L is Richter local magnitude, and R is the distance in km. The particular formula used in this study is based on a central United States model developed by Nuttli (1973). The formula coefficients $b_1 = 17$, $b_2 = 0.92$, and $b_3 = 1.0$ were selected. A justification for this assumption can be found in CCA Appendix GCR, Section 5.3.2.

2.6.2.2 Seismic Source Zones

Geologic, tectonic, and seismic evidence indicates that three seismic source zones may be used to adequately characterize the region. These are well approximated by the Basin and Range subregion, the Permian Basin subregion exclusive of the Central Basin Platform, and the Central Basin Platform itself. Specific boundaries are taken from a 1976 study by Algermissen and Perkins (1976) of earthquake risks throughout the United States. Additional details on this study are in CCA Appendix GCR, Section 5.3.2.

Site region seismic source zones are shown in Figure 2-58. Superposed on these zones are the earthquake epicenters of Figure 2-57. The zonation presented generally conforms with historical seismicity. The source zonation of Figure 2-58 has no explicit analog to the Permian Basin subregion exclusive of the Central Basin Platform. This is considered part of the broad background region.

For the purposes of this study, some minor modifications of the Algermissen and Perkins (1976) source zones were made. Geologic and tectonic evidence suggests that the physiographic boundary between the Basin and Range and Great Plains provinces provides a good and conservative approximation of the source zones (CCA Appendix GCR). In addition, information from the Kermit seismic array (Appendix to Rogers and Malkiel 1979) indicates that the geometry used to model the limits of the Central Basin Platform source zone may be modified somewhat from the original analogous Algermissen and Perkins (1976) zone. These modifications are shown in Figure 2-59 and constitute the preferred model for the WIPP site region seismic source zones in this study. This model is preferred because it more completely considers geologic and tectonic information, as well as seismic data, and because it results in a more realistic development of risks at the WIPP facility.

With regard to earthquake focal depth, there is little doubt that the focal depths of earthquakes in the WIPP facility region should be considered shallow. Early instrumental locations were achieved using an arc intersection method employing travel-time-distance curves calculated from a given crustal model, and the assumption of focal depths of 5 km (3.1 mi), 10 km (6.2 mi), or, for later calculations, 8 km (5 mi). Good epicentral locations could generally be obtained under these assumptions. For conservatism, a focal depth of 5 km (3.1 mi) is used in all source zones of this study including that of the site. For smaller hypocentral distances, the form of the attenuation law adopted here severely exaggerates the importance of small, close shocks in the estimation of probabilistic acceleration at the WIPP site. Additional discussion is included CCA Appendix GCR, Chapter 5.

2.6.2.3 Source Zone Recurrence Formulas and Maximum Magnitudes

The risk calculation procedure used in this study requires that earthquake recurrence rates for each seismic source zone be specified. This is done formally by computing the constants a and b in the equation

$$\log N = a - bM , \qquad (2.4)$$

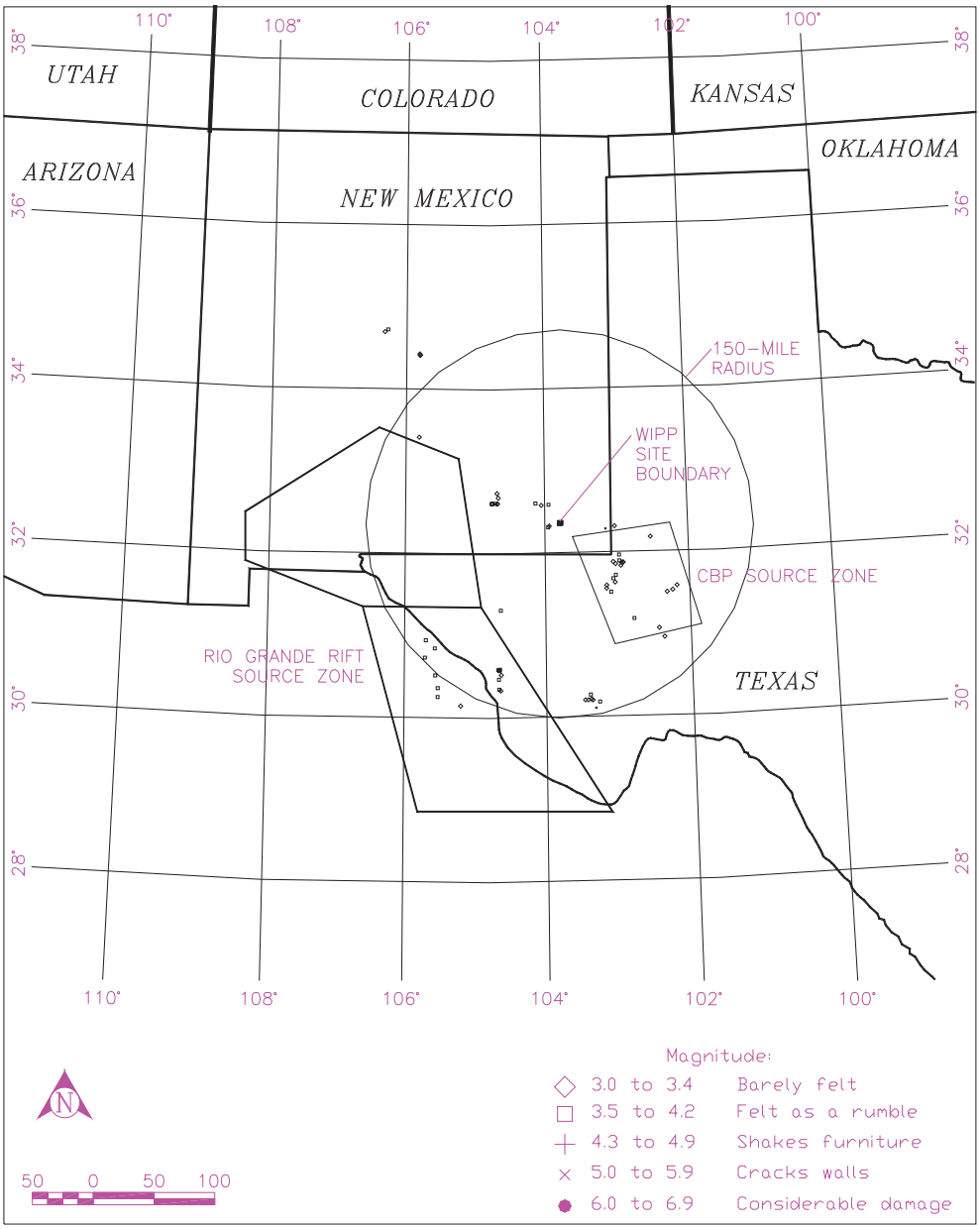

Figure 2-58. Seismic Source Zones

where N is the number of earthquakes of magnitude greater than or equal to M within a specified area occurring during a specified period.

For the WIPP facility region, three formulas of this type are needed: one for the province west and southwest of the site (the Basin and Range subregion or Rio Grande Rift source zone), another for the province of the WIPP facility exclusive of the Central Basin Platform (the Permian Basin subregion or background source zone), and a final one for the Central Basin Platform. In practice, the difficulties in finding meaningful recurrence formulas for such small areas in a region of low historical earthquake activity are formidable.

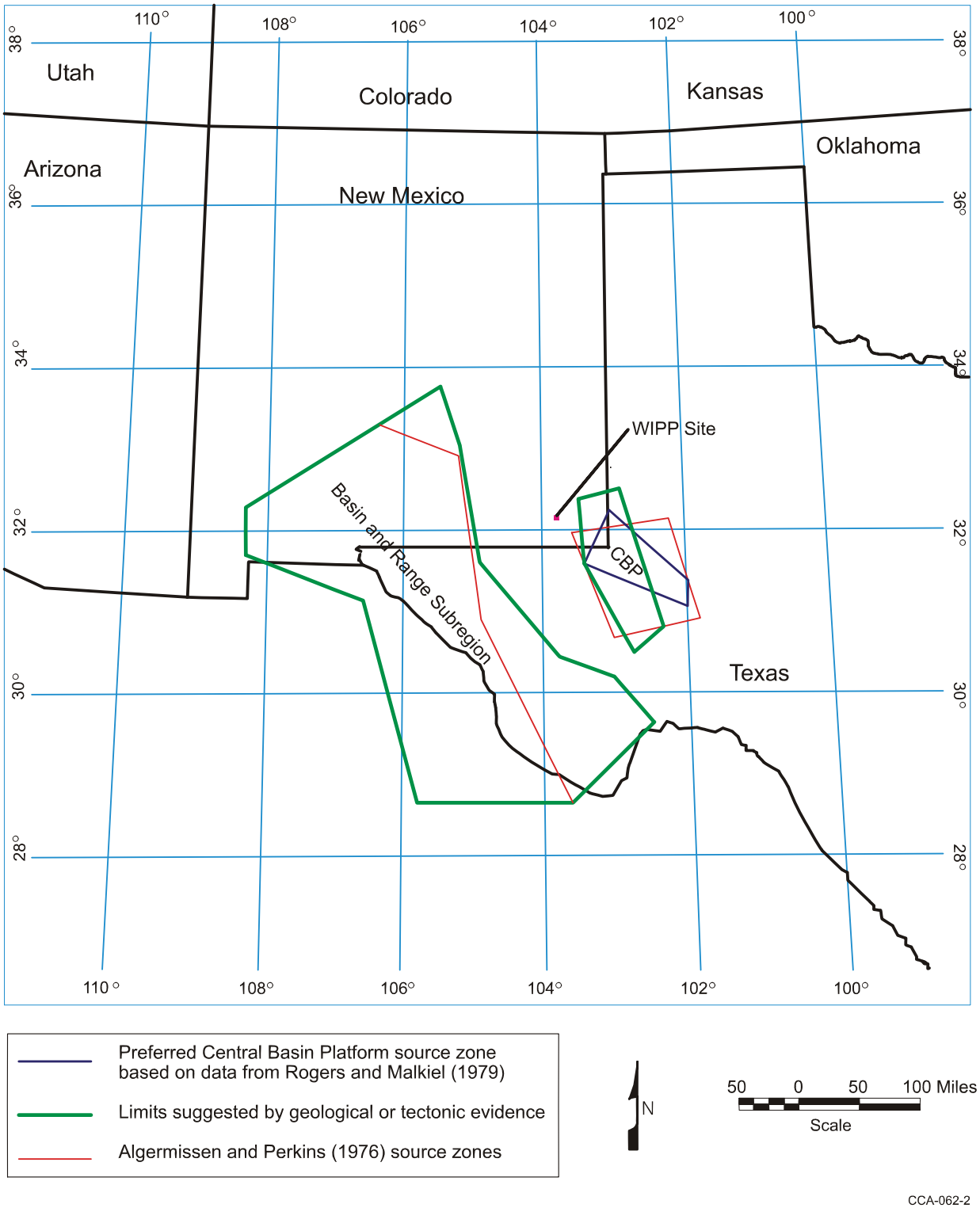

Figure 2-59. Alternate Source Geometries

The formulas have been determined to be

- $\log N = 2.43 - M_{CORR}$ Site source zone (background) (2.5)
- $\log N = 3.25 - M_{CORR}$ Basin and Range subregion (2.6)
- $\log N = 3.19 - 0.9\ M_{CORR}$ Central Basin Platform (2.7)

The rationale for their development and the relationship used to determine M_{CORR} can be found in CCA Appendix GCR, Section 5.3.

2.6.2.4 Design Basis Earthquake

The term Design Basis Earthquake (DBE) is used for the design of surface confinement structures and components at the WIPP facility. As used here, the DBE is equivalent to the design earthquake used in Regulatory Guide 3.24 (Nuclear Regulatory Commission [NRC] 1974). That is, in view of the limited consequences of seismic events in excess of those used as the basis, the DBE is such that it produces ground motion at the WIPP facility with a recurrence interval of 1,000 years. In practice, the DBE is defined in terms of the 1,000-year acceleration and design response spectra.

The generation of curves expressing probability of occurrence or risk as a function of peak WIPP facility ground acceleration is discussed in detail in CCA Appendix GCR, Section 5.3, for a number of possible characterizations of WIPP facility region source zones and source zone earthquake parameters. The most conservative (and the least conservative) risk curves are shown in Figure 2-60.

From this figure, the most conservative calculated estimate of the 1,000-year acceleration at the WIPP facility is approximately 0.075 g. The geologic and seismic assumptions leading to this 1,000-year peak acceleration include the consideration of a Richter magnitude 5.5 earthquake at the site, a 6.0 magnitude earthquake on the Central Basin Platform, and a 7.8 magnitude earthquake in the Basin and Range subregion. These values, especially the first two, are considered quite conservative, as are the other parameters used in the 0.075g derivation. For additional conservatism, a peak design acceleration of 0.1 g is selected for the WIPP facility DBE. The design response spectra for vertical and horizontal motions are taken from Regulatory Guide 1.60 (NRC 1973) with the high-frequency asymptote scaled to this 0.1g peak acceleration value.

This DBE and the risk analysis that serves an important role in its definition are directly applicable to surface confinement structures and components at the WIPP facility. Underground structures and components are not subject to DBE design requirements because according to Pratt et al. (1979), mine experience and studies on earthquake damage to underground facilities show that tunnels are not damaged at sites having peak surface accelerations below 0.2 g.

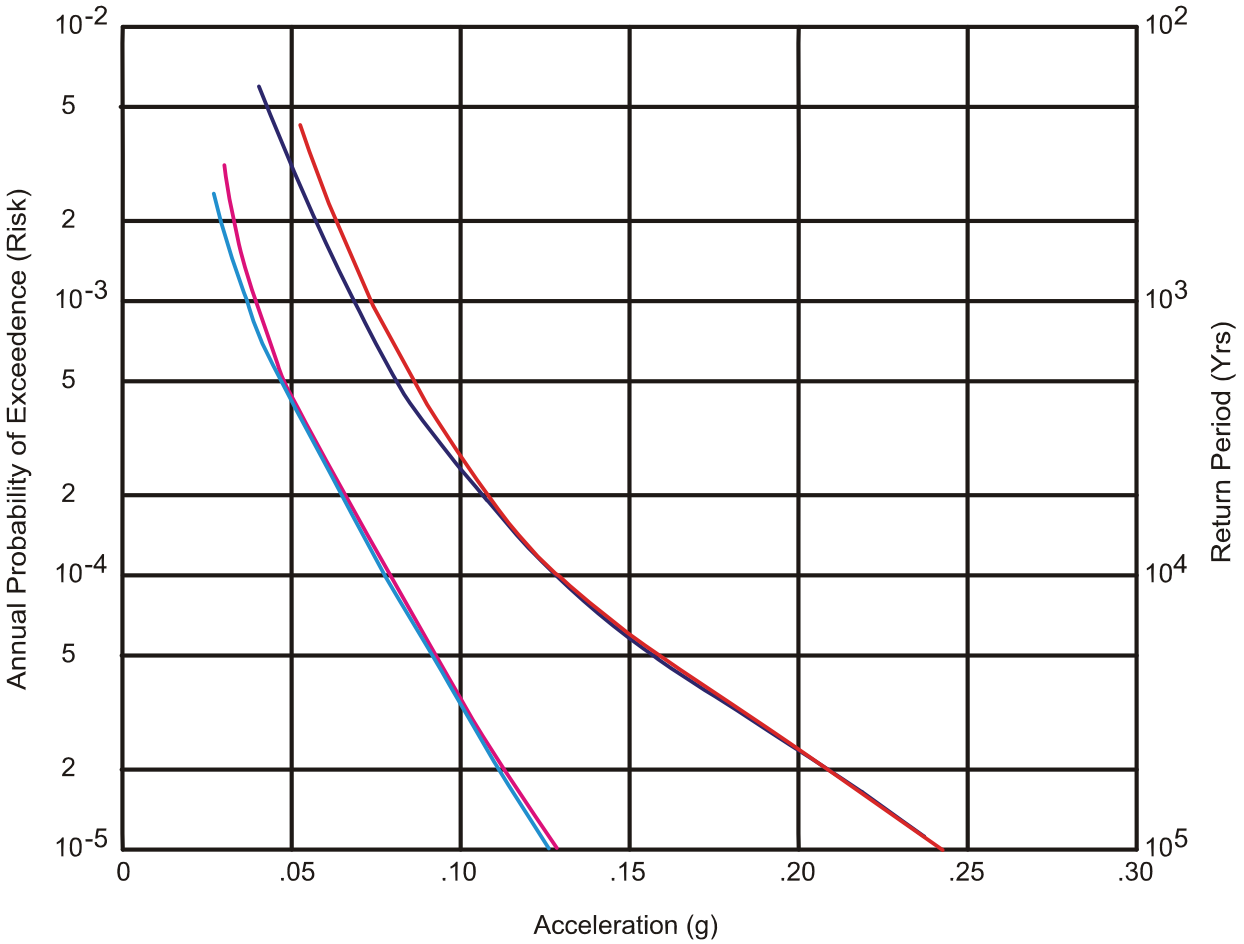

Curve 1	———	Risk from site source zone assuming a maximum magnitude of 4.5.
Curve 2	———	Risk from site and Central Basin Platform source zones assuming maximum magnitudes of 4.5 and 5.0, respectively.
Curve 3	———	Risk from the site source zone assuming a maximum magnitude of 5.0.
Curve 4	———	Risk from the site and Central Basin Platform source zones assuming a maximum magnitude of 5.0 for both.

Note: Risk curves generated by using worst and best case assumption from the parameter variation considered for site region source zones. See Appendix GCR, Figure 5.3-7 for further details.

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Figure 2-60. Total WIPP Facility Risk Curve Extrema

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3.0 FACILITY DESCRIPTION

Chapter 3.0 provides technical information about those engineered systems at the Waste Isolation Pilot Plant (WIPP) disposal system that are important to meeting the disposal standards of Title 40 of the Code of Federal Regulations (CFR) Part 191 Subparts B and C (EPA 1993). The U.S. Department of Energy (DOE) developed a facility design that facilitates the rapid encapsulation of emplaced waste by creep closure of salt, forming a nearly impermeable barrier around the waste. In addition, the DOE has taken a defense in depth approach in the design of engineered shaft sealing systems to ensure the shafts will not become pathways for radionuclide release. Shaft seals incorporate multiple engineered materials and compacted crushed salt which will effectively reduce the permeability of the shaft-seal system to values near those of unexcavated intact salt. The DOE also employs an engineered barrier to chemically condition any brine that may reach the waste in order to reduce radionuclide solubility. Finally, the DOE will close each panel of waste with a panel closure system to provide for operational protection of workers, the public and the environment from emplaced waste.

In this chapter, descriptions are provided for the shafts, the underground waste disposal excavations, and engineered systems that may be significant to long-term performance of the disposal system. Of these engineered systems, the Environmental Protection Agency (EPA) has determined that only magnesium oxide (MgO) meets the regulatory definition of an “engineered barrier” (63 Federal Register [FR] 27397, May 18, 1998). Detailed information on other aspects, such as general facility operations, waste handling, repository mining, ground control, ventilation, transportation, emergency preparedness, training, and maintenance are covered, as appropriate, in other WIPP documents, such as the WIPP Disposal Phase Supplemental Environmental Impact Statement (SEIS-II) (DOE 1997), Contact-Handled Waste Safety Analysis Report (DOE 2003), and other documents available from the DOE.

The facility has been divided into four areas designated for protection of human health and the environment: (1) the property protection area, which is surrounded by a chain-link security fence that encloses approximately 13.7 hectares (34 acres) and provides security and protection for all major surface structures; (2) the exclusive use area, which is approximately 112 hectares (277 acres) restricted exclusively for the use of the DOE, its contractors, and subcontractors in support of the project and posted against trespass and use by the general public; (3) the off limits area, which consists of approximately 5.9 km^2 (1,454 acres) posted and managed as off limits by the DOE; and (4) the WIPP land withdrawal area, the 41.4-km^2 (16 mi^2) federal land area under jurisdiction of the DOE and bounded by the WIPP site boundary (see Figure 3-1). The WIPP land withdrawal area is the controlled area for purposes of demonstrating compliance to 40 CFR Part 191 Subparts B and C. The waste area of the repository lies within the bounds of the off limits area, and within the WIPP land withdrawal area.

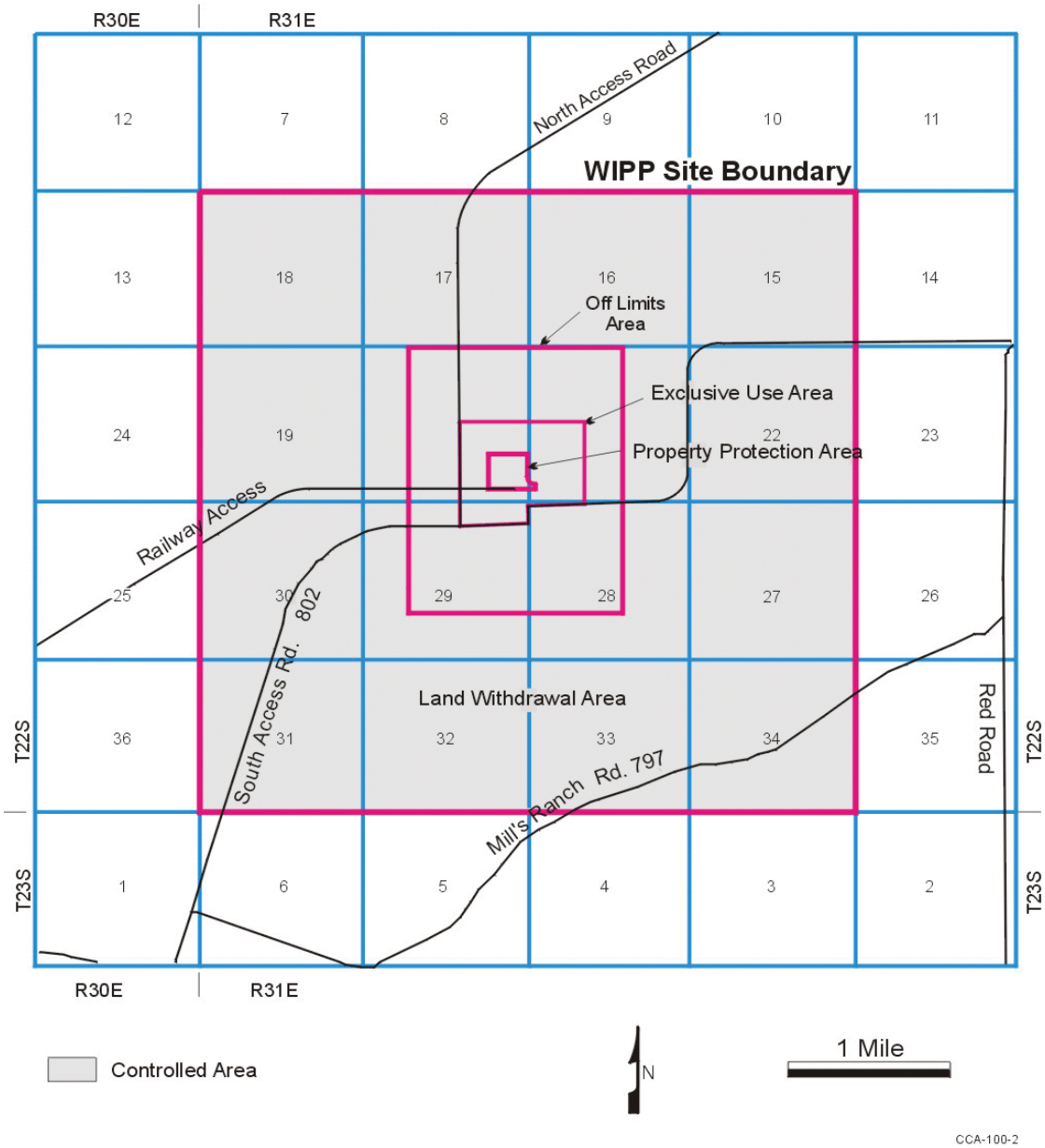

Figure 3-1. WIPP Property Sector Designators

The amount of waste to be received at the WIPP is governed by the WIPP Land Withdrawal Act, Pub. L. No. 104-201, Stat. 2422 (U.S. Congress 1992), which sets the total volume for contact-handled (CH-) and remote-handled (RH-) transuranic (TRU) waste combined at a maximum of 175,600 m^3 (6.2 million ft^3). The 6.2 million ft^3 technically corresponds to 175,564 m^3 but will be routinely represented in this application with four significant digits. The Land Withdrawal Act restricts RH-TRU waste to a maximum activity of 23 curies per liter and not to exceed a total of 5.1 million curies (U.S. Congress 1992) (see Chapter 4 for a description of the waste). There is a volume limit of 0.25 million ft^3 for RH-TRU waste (Agreement for Consultation and Cooperation, DOE 1988). The waste disposal area of the WIPP facility consists of eight panels, each of which contains seven rooms, and the access drifts and crosscuts adjacent to the disposal

panels. This latter region has been labeled Panels 9 and 10 for convenience as shown in Figure 3-2. At the end of the operational period, the DOE will begin the process of sealing the shafts, which is a part of final facility closure.

Disposal operations in Panel 1 are complete and an explosion-isolation wall has been installed. In a typical configuration, waste will be emplaced in all seven rooms of a panel as shown in Figure 3-3 with RH-TRU waste inserted into the walls. Figure 3-4 provides the layout of the waste as it is emplaced in Panel 1. This is not the configuration typically described for WIPP (Compliance Certification Application [CCA]).

In a submittal dated April 26, 2001 [Docket A-98-49, II-B-3, Item 19], the DOE requested that EPA approve a different utilization plan for Panel 1. The flexibility to vary the utilization of Panel 1 was important from both a worker safety and operational efficiency perspective. The rooms of Panel 1 were over 12 years old at the time of the proposed change. The natural processes of room closure had reduced the vertical clearance to the extent that re-mining would be necessary to provide sufficient headroom and acceptable floor conditions for waste to be emplaced as described in the CCA, i.e., three containers high. Based upon the analyses performed by Sandia National Laboratories (SNL), the DOE concluded that this request was not a significant departure from the original design and that aspects of the repository system important to waste containment would not be affected or changed. The EPA agreed with DOE's conclusion in a letter dated August 7, 2001 [Docket A-98-49, II-B-3, Item 19], stating "DOE's proposed alternative use of Panel 1 is compliant with terms and conditions of WIPP's certification." There is no RH-TRU waste disposed in Panel 1.

Table 3-1 delineates pertinent site features of the WIPP facility.

3.1 General Facility Design

The DOE has designed the WIPP facility to accomplish four primary goals:

1. to receive, handle, and dispose of TRU waste and TRU-mixed waste (in this document, the term TRU waste is used to describe both TRU and TRU-mixed waste unless otherwise noted);

2. to protect the health and safety of workers, the public, and the environment;

3. to comply with applicable radiation protection standards; and

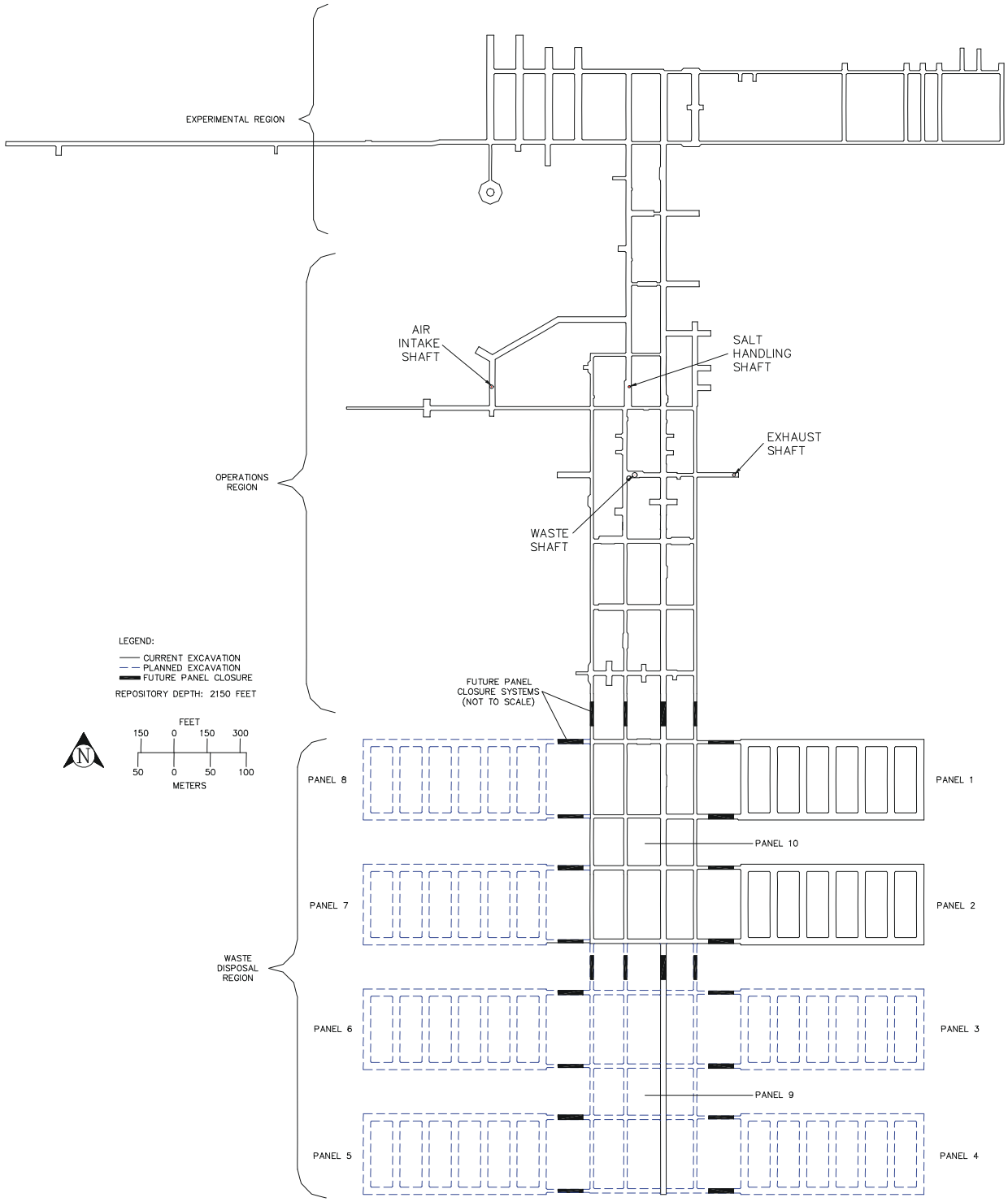

Figure 3-2. Plan View of WIPP Underground Facility and Panel Closure Systems

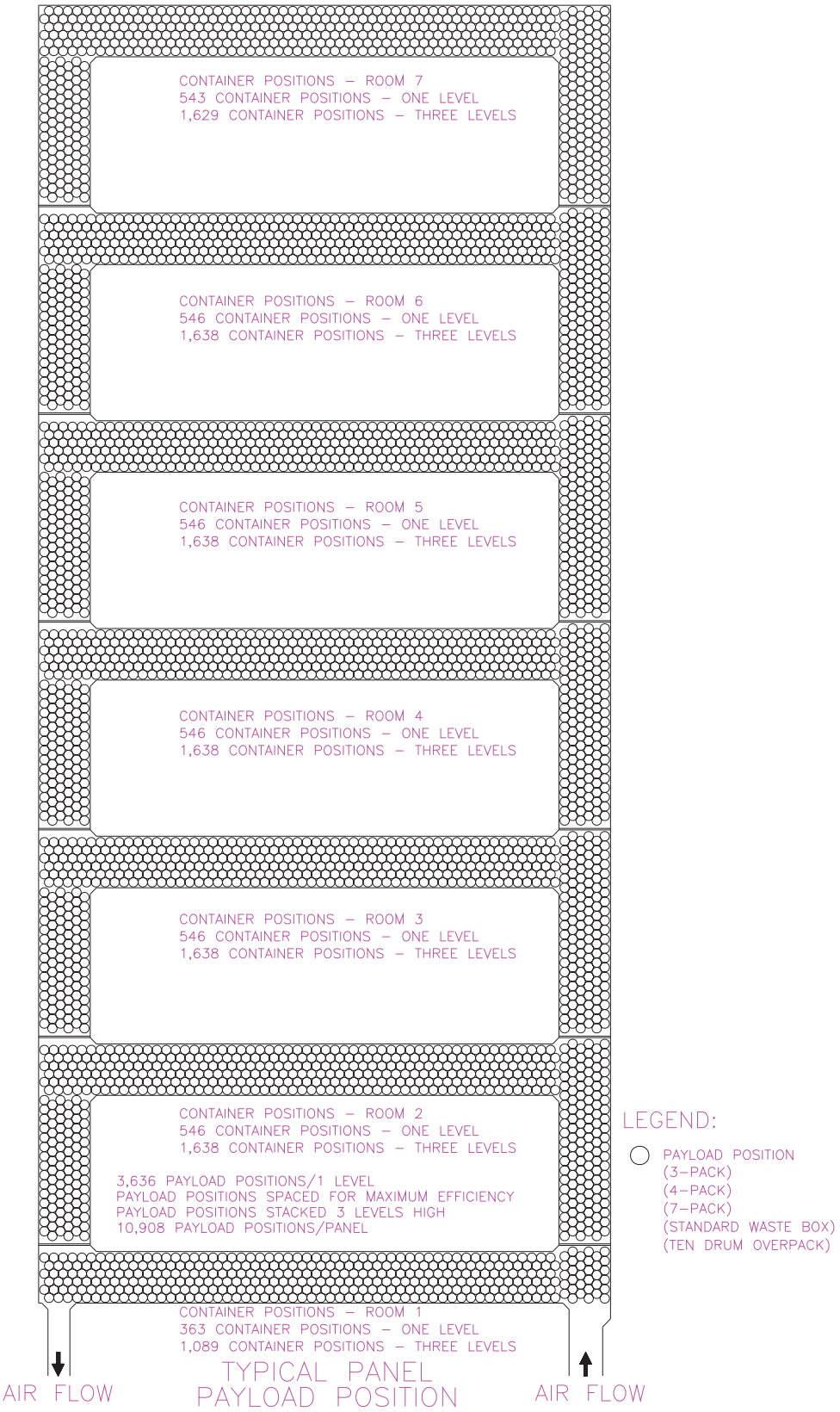

Figure 3-3. Typical Panel Waste Emplacement

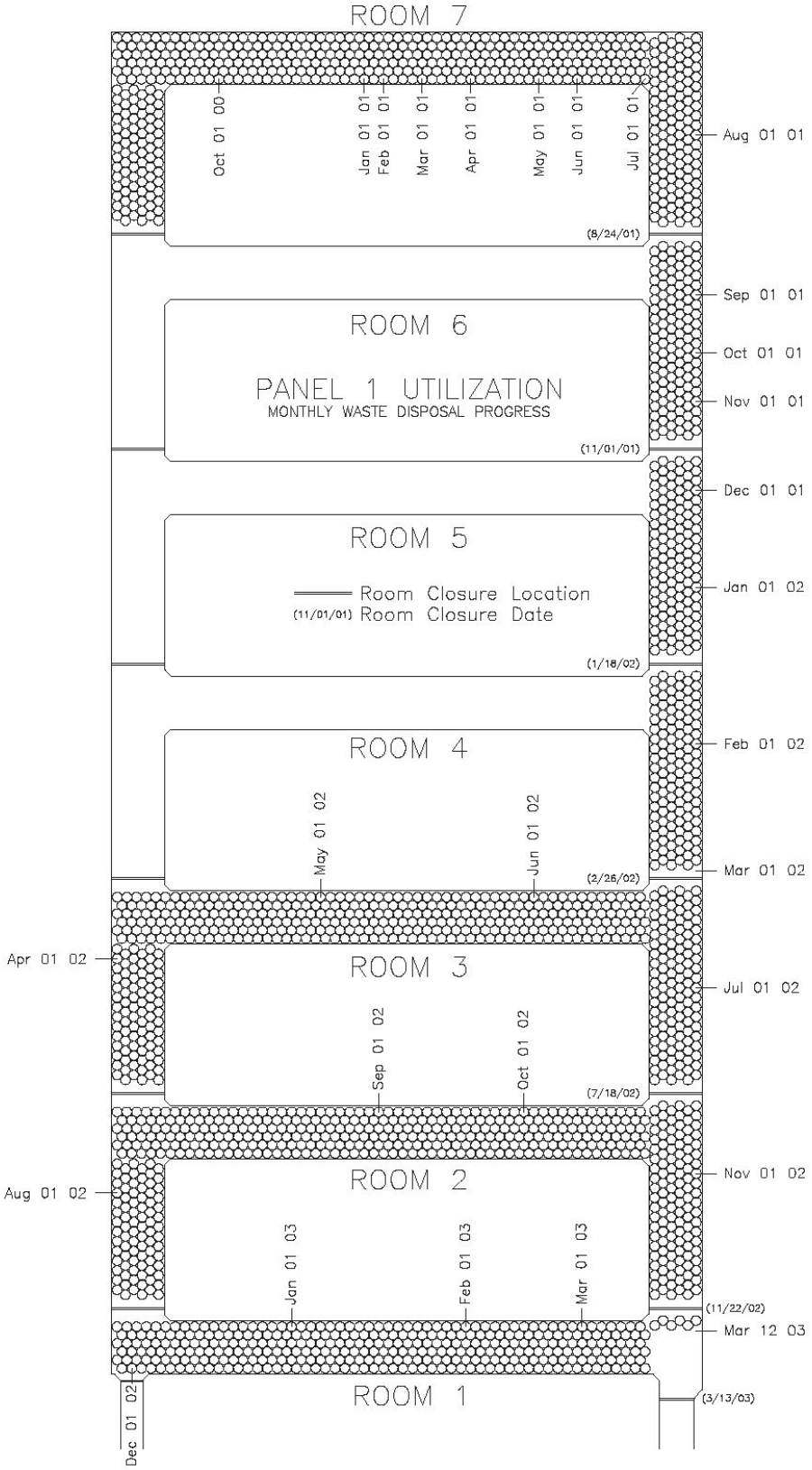

Figure 3-4. Panel 1 Waste Emplacement

Table 3-1. WIPP Site Features

Facility Name	Waste Isolation Pilot Plant (WIPP)
EPA Identification Number	NM 4890139088
Location	41.84 km (26 miles) east of Carlsbad, New Mexico
Latitude	32°22'11"N
Longitude	103°47'30"W
County	Eddy
Section	15-22 and 27-34
Township	22S
Range	31E
Land Withdrawal Area	41.4 km^2 (16 mi^2)
Property Protection Area	13.7 hectares (34 acres)
Depth to repository horizon	655 meters (2,150 feet) below grade level

4. to comply with other environmental statutes and regulations, and requirements of federal, state, and local agencies as discussed in the WIPP Biennial Environmental Compliance Reports (DOE 2002, et seq.).

The surface facilities at the WIPP accommodate the personnel, equipment, and support services required for the safe receipt and transfer of TRU waste from the surface to the underground repository. The surface structures are located within a perimeter security fence. This area is the property protection area on Figure 3-1. Access is controlled by security officers 24 hours a day. Four vertical shafts connect the surface facilities to the underground. The underground facilities include the

- waste disposal area,
- shaft pillar area, and
- associated support facilities.

Figure 3-5 provides a spatial view of the WIPP facility.

The DOE acquisition process that was used for the design and construction of the WIPP determined the steps and processes taken to assure that the WIPP was constructed consistent with applicable codes and standards. This process defined key activities and milestones that were applicable and specified such project management activities as initial and final design, independent review, acceptance testing, start-up, and quality assurance (QA). Additional detail is provided in the following sections.

3.1.1 DOE Facility Acquisition Process

Federal facility acquisition policies were applied to the design and construction of the WIPP facility. WIPP structures are designed to meet the Carlsbad Field Office (CBFO) Functions,

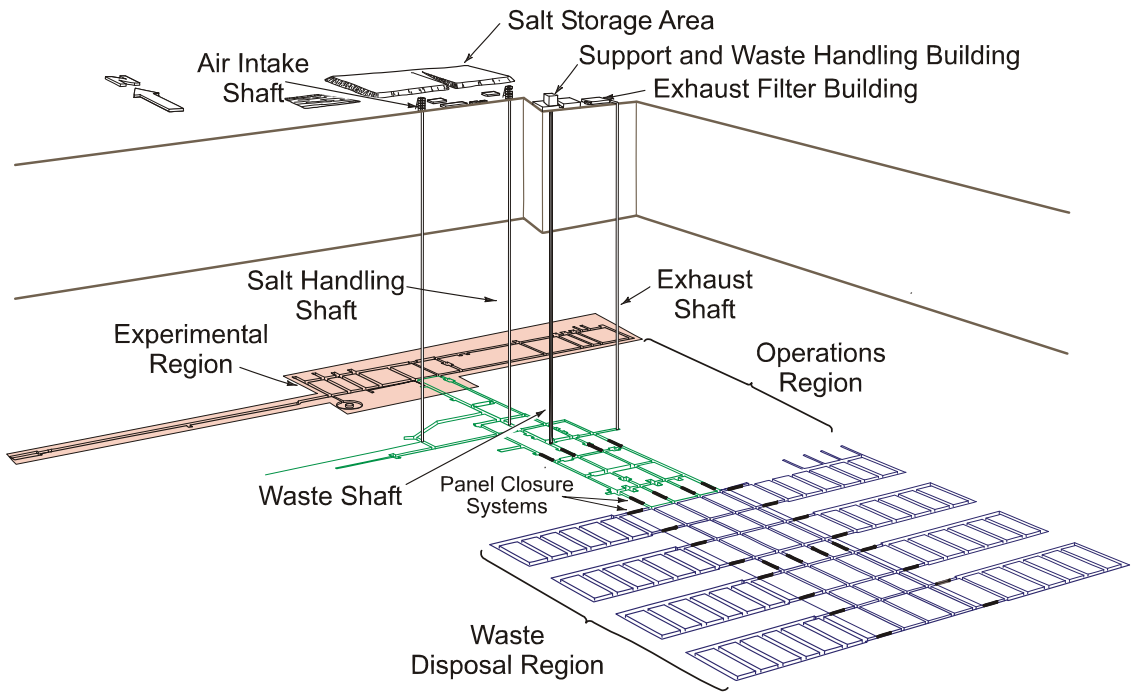

Note: For illustrative purposes only.
Not to scale.

CCA-087-2

Figure 3-5. Spatial View of the WIPP Facility

Responsibilities, and Authorities Manual (DOE/WIPP 98-2287, 2001), 10 CFR Part 830, Subpart B (design qualifications), and the Quality Assurance Program Document (QAPD) (DOE 1996) for general issues of quality. Appropriate structures, systems and components are designed to meet the requirements applicable to Design Class II structures, systems, and components for nonreactor nuclear facilities. The design class designations are categorized in accordance with their importance relative to health and safety of the public and on-site personnel during plant operations.

3.1.2 Configuration Control

The DOE mandates that the configuration control of the WIPP facility be accomplished through written procedures and policies as set forth in DOE Orders and regulations. For example, the WIPP System Design Descriptions provide a framework for the configuration control. Any changes to the facility, and subsequently configuration documentation (design descriptions, as-built drawings, specifications, etc.), must be reviewed and approved by cognizant personnel. These documented reviews determine if the change will affect the ability of the facility to comply with applicable environmental, safety, and health requirements. The DOE must approve proposed changes that impact the safety of the facility and may elect to conduct an independent review of analyses supporting the change.

Quality assurance requirements applicable to the WIPP facility design and configuration control activities are founded on the basic and supplemental requirements of the American Society of Mechanical Engineers' QA program requirements for nuclear facilities (American Society of Mechanical Engineers' NQA-1 1989). As discussed in Section 5.2, the DOE now implements these requirements through the CBFO's QAPD, which is provided in Appendix QAPD. Design QA elements include (1) documentation, review, and approval of design inputs; (2) control of design analyses, design verification, and design changes; and (3) institution of design interface controls and records management practices. These and other applicable configuration management QA requirements are discussed in Section 5.3.3.

3.1.3 Surface Structures

WIPP surface structures accommodate the personnel, equipment, and support services required for the receipt, preparation, and transfer of waste from the surface to the underground areas. These surface structures serve the operational functions of the WIPP and are not intended to serve long-term performance functions. The surface facilities are located in the Property Protection Area within the perimeter fence. The principal surface structure is the Waste Handling Building; other surface structures include the following:

- hoist houses,
- support building,
- guard and security building,
- office trailers,
- exhaust filter building,
- warehouse and shops,
- water pump house,
- training building,
- engineering building,
- materials, tools, and electronics and tool crib building,
- safety and emergency services building.

In addition to these structures, the DOE has employed a system of berms and ditches to divert storm-water runoff away from the surface facilities. The WIPP facility drainage system is designed so that storm runoff caused by the probable maximum precipitation (PMP) event will not flood the WIPP facility (DOE 1995).

The WIPP facility does not lie within a 100-year floodplain. There are no major surface-water bodies within eight km (five mi) of the site, and the nearest river, the Pecos River, is

approximately 19 km (12 mi) away. The general ground elevation in the vicinity of the surface facilities (approximately 1,036 m [3,400 ft] above mean sea level) is about 152 m (500 ft) above the riverbed and 122 m (400 ft) above the 100-year floodplain. (Chapter 2.0 provides more information on surface hydrology and climate.) Protection from flooding or ponding caused by PMPevents is provided by the diversion of water away from the WIPP facility by a system of peripheral interceptor diversions. Additionally, grade elevations of roads and surface facilities are designed so that storm water will not collect on the site under the most severe conditions.

Repository shafts are elevated at least 15.2 cm (6 in.) to prevent surface water from entering the shafts. The floor levels of all surface facilities are above the levels calculated for local flooding due to PMP events.

The mean annual precipitation in the region is about 30 cm (12 in.), and the mean annual runoff is 0.25 to 0.50 cm (0.1 to 0.2 in.). The maximum recorded 24-hour precipitation at Carlsbad was 13 cm (5.12 in.) in August 1916. The six-hour, 100-year precipitation event for the site is 9.1 cm (3.6 in.) and is most likely to occur during the summer. The maximum daily snowfall at Carlsbad was 76 cm (10 in.) in December 1923.

The WIPP facility design includes four shafts: the waste shaft, the salt handling shaft, the exhaust shaft, and the air intake shaft (AIS). Each shaft includes a shaft collar, a shaft lining, and a shaft key section. The shaft and shaft liner design information is discussed in detail in the Site Characterization and Validations studies from 1983 to 1987. The shaft design features have not changed.

The reinforced concrete shaft collars extend from the surface to the top of the underlying consolidated sediments. Each collar serves both to retain adjacent unconsolidated sands and soils and to prevent surface runoff from entering the shaft. The shaft linings extend from the base of the collar to the top of the salt beds approximately 259.1 m (850 ft) below the surface. The shaft lining serves to inhibit water seepage into the shafts from water-bearing formations, such as the Magenta and Culebra members of the Rustler. The liners are also designed to retain loose rock. The shaft liners are concrete except in the salt handling shaft, in which a steel shaft liner has been grouted in place.

The shaft key is a circular reinforced concrete section emplaced in each shaft below the liner at the base of the Rustler Formation and extending about 30.5 m (100 ft) below and into the Salado Formation. The shaft key functions to resist lateral pressures and to contain the water seals.

Two separate water-seal rings are incorporated in each key. Performance of the seals is monitored by inspection of the bottom of the key for seepage. If groundwater is detected flowing past the upper ring, this condition can be corrected by injecting chemical sealants or cementitious grouts to stop the leakage.

On the inside surface of each shaft, excluding the salt handling shaft, there are three water collection rings. The first is located just below the Magenta interval, the second just below the Culebra interval, and the last at the lowermost part of the key section. These collection rings function to collect any groundwater that may seep into the shaft through the liner. Therefore,

flooding of the WIPP repository as a result of PMP events is not a credible event because of the site-runoff design.

Flood-control structures are inspected as part of a general facility inspection at least annually. During this inspection, the structures are checked to assure that there has been no wind or rain erosion or animal-caused damage that would cause the structures to fail. Further, the areas around the structures are inspected to ensure they are free of vegetation, debris, or other items that would impede the diversion of water. Experience with these structures has shown that annual structural inspections are adequate for the climate and soil conditions at the WIPP facility; however, inspections are also conducted after severe natural events, such as severe storms or earthquakes.

3.2 Repository Configuration

A preliminary design of the WIPP repository was presented in the Final EIS (DOE 1980). Validation efforts for the WIPP repository preliminary design began in 1981 with the Site and Preliminary Design Validation (SPDV) program. The SPDV program was implemented to further characterize and validate the WIPP site geology and to provide preliminary validation of the underground excavation. The SPDV program involved the excavation of four full-sized disposal rooms, excavated 4 m (13 ft) high, 10 m (33 ft) wide, and 91 m (300 ft) long, and separated by 31-m (100-ft)-wide pillars. Data obtained from geologic field activities and geomechanical instrumentation were analyzed to determine the suitability of the design criteria and design bases and to provide confirmation of the underground opening reference design. Analyses of these preliminary designs performed by the WIPP architect and engineer can be found in CCA Appendix DVR. These analyses considered expected creep closure rates in determining disposal room sizes. Information in CCA Appendix DVR (Section DVR.6.4.2) meets the criterion specified in 40 CFR § 194.14(b)(2). Figures 12-21 and 12-22 of the Final Design Validation Report in CCA Appendix DVR show the creep closure histories used for designing the disposal rooms. The specified size was selected to ensure no CH-TRU containers would breach due to creep closure while a panel is being filled with waste. A nominal five-year life is used for operational purposes for mining, emplacement, and closure with no risk of CH-TRU waste containers breaching. Remote-handled containers will not breach in this time period due to the canister wall thickness and the 5.08 to 10.16 cm (2 to 4 in.) creep tolerance in each RH-TRU emplacement hole.

The WIPP underground facilities are located on the repository horizon 655 m (2,150 ft) beneath the surface (see Figure 3-2). In Chapter 2.0, Figure 2-12 shows a stratigraphic column which displays the repository and its position relative to mean sea level. These facilities include the waste disposal region, the operations region, an experimental region, and associated support facilities. The underground support facilities service and maintain underground equipment for mining and disposal operations, monitor for radioactive contamination, and allow limited decontamination of personnel and equipment.

Waste panels consist of seven rooms. Each room has nominal dimensions of 91 m (300 ft) long, 10.1 m (33 ft) wide, and 4.0 m (13 ft) high. Pillars between rooms are 30 m (100 ft) thick. Eight waste panels will be separated from each other and the main entries by nominally 61-m (200-ft) pillars. In addition to the eight panels, the main north-south and east-west access drifts in the

waste regions are available for waste disposal. These have been designated Panels 9 and 10 for permitting and modeling purposes (see Figure 3-2). Section 6.4.2.1 describes the treatment of all waste panels in BRAGFLO. Additional information can also be found in Appendix PA, Attachment MASS.5. Rockbolts, or related types of ground support, are used as necessary to maintain safe underground personnel access. In the panels, this will typically consist of localized bolting when needed. All panels will be closed using the panel closure system described in Section 3.3.3.

The underground is connected to the surface by four vertical shafts: the waste shaft, the salt handling shaft, the exhaust shaft, and the AIS. The waste shaft, salt handling shaft, and the air intake shaft have permanently installed hoists capable of moving personnel, equipment, and materials between the surface and the repository. All shafts will eventually be sealed using the seal design described in Section 3.3.2. A summary of information describing existing WIPP shafts is given in Appendix BARRIERS, Section BARRIERS-3.0.

Mining of the shafts and underground passages within the repository gives rise to a disturbed rock zone (DRZ) that is important to repository performance. The DRZ forms as a consequence of unloading the rock in the vicinity of the excavation. Increased permeability is created by microfractures along grain boundaries and by bed separation along lateral seems. The DRZ development begins immediately after excavation and continues as salt creeps into the opening. The DRZ surrounding the shafts is symmetrical and has been characterized and incorporated into the shaft seal design as discussed in Appendix BARRIERS. As shaft seal elements resist inward creep, the stress state becomes compressive and gives rise to fracture healing, and a return of the disturbed salt to its original extremely low permeability. The lateral DRZ along passages in the underground includes fracture in nonhalitic rock, such as anhydrite, and bed separation on clay seams. These zones will not naturally heal in a manner similar to healing of halite. Rigid components of the panel closure system will prevent further development of the DRZ.

In a letter dated June 26, 2000 [Docket A-98-49, II-A-3, Item 24, Attachment 1], the CBFO submitted a planned change to raise the repository horizon in Panels 3, 4, 5, 6, and 9 by approximately 2 m (6.6 ft) so that the back (roof) is at Clay Seam G. Positioning the back at Clay Seam G results in a more stable back configuration and improves repository ground conditions. Raising the horizon also reduces the rate of roof-beam deformation and slows the development of fractures, thus reducing risks during mining and waste handling in the underground repository. This change also results in less maintenance being required to assure acceptable ground conditions. In a letter dated August 11, 2000 [Docket A-98-49, II-A-3, Item 24], the EPA agreed "… that (this change) will enhance operational safety without significantly affecting the long-term performance of the facility." (Chapter 6.0 provides more detail related to Clay Seam G.)

3.3 Disposal-System Barriers

Disposal system barriers are used in the DOE's design of the WIPP to isolate waste and delay the migration of radionuclides to the accessible environment. Disposal-system barriers include the geology and hydrology of the disposal system or natural barriers, engineered systems, and an engineered barrier designed to meet the regulatory requirements of 40 CFR § 194.14(d). In

addition, the incorporation of disposal-system barriers (both engineered and natural barriers) satisfies the criterion stated in 40 CFR § 194.44(a).

> Disposal systems shall incorporate engineered barrier(s) designed to prevent or substantially delay the movement of water or radionuclides toward the accessible environment.

In the CCA, the DOE proposed four elements of the disposal system as engineered barriers:

(1) shaft seals,

(2) panel closures,

(3) MgO around the waste, and

(4) borehole plugs.

In its certification decision, the EPA concluded that only MgO meets the regulatory definition of an engineered barrier. The certification decision includes the following regarding engineered barriers (63 FR 27397, May 18, 1998):

> The EPA finds that DOE complies with Sec. 194.44. The EPA found that DOE conducted the requisite analysis of engineered barriers and selected an engineered barrier designed to prevent or substantially delay the movement of water or radionuclides toward the accessible environment. The DOE provided sufficient documentation to show that MgO can effectively reduce actinide solubility in the disposal system. The DOE proposed to emplace a large amount of MgO around waste drums in order to provide an additional factor of safety and thus account for uncertainties in the geochemical conditions that would affect CO_2 generation and MgO reactions.

Although shaft seals, panel closures, and borehole plugs are not defined by EPA as engineered barriers, these features may affect disposal system performance and thus are included in the performance assessment (PA) (Appendix PA, Section PA-4.2). Shaft seals and borehole plugs will limit migration of liquid and gases in the WIPP shafts and boreholes. Panel closures will limit the communication of brine and gases among waste disposal panels. Designs of shaft seals, borehole plugs, and panel closures use common engineering materials that possess low permeability, appropriate mechanical properties, and durability.

The DOE performed an Engineered Alternatives Cost/Benefit Study (see CCA Appendix EBS) to examine the benefits and detriments associated with an array of engineered barrier alternatives. This study, in combination with past sensitivity and other analyses, was used to make a decision about MgO, which the DOE has chosen to buffer the chemical composition of brine that may enter the repository over the 10,000-year regulatory period. The principal beneficial performance characteristic resulting from MgO is a reduction in actinide solubilities in brine. Specific performance information on MgO is presented in Section 6.4.3 and Appendix BARRIERS.

3.3.1 MgO Engineered Barrier

The DOE has concluded that it is desirable to add MgO to the repository to improve the performance of the disposal system (see Appendix BARRIERS). This additive is being protected in supersacks until the supersacks are broken during creep closure of the room. The

MgO is being packaged in polypropylene supersacks for emplacement in the underground. Emplacement in supersacks (1) facilitates handling and emplacement of MgO; (2) minimizes potential worker exposure to dust; and (3) minimizes the exposure of periclase, the main, reactive constituent of MgO, to atmospheric carbon dioxide (CO_2) and water prior to rupturing of the supersacks. Supersacks, which contain 1900 $\pm$ 23 kg (4200 $\pm$ 50 lbs), are handled and placed using normal waste-handling techniques. Once each row of waste units is in place, a layer of supersacks is placed on top of them as shown in Figure 3-6. The supersacks are constructed of woven polypropylene, which serves as a barrier to CO_2 and moisture. The supersacks are placed on support sheets so that they can be handled and placed in a manner that is identical to how waste units are emplaced. Typically, the space above a stack of containers is 90 to 122 cm (36 to 48 in.), of which about (45 cm (18 in.) will contain MgO .

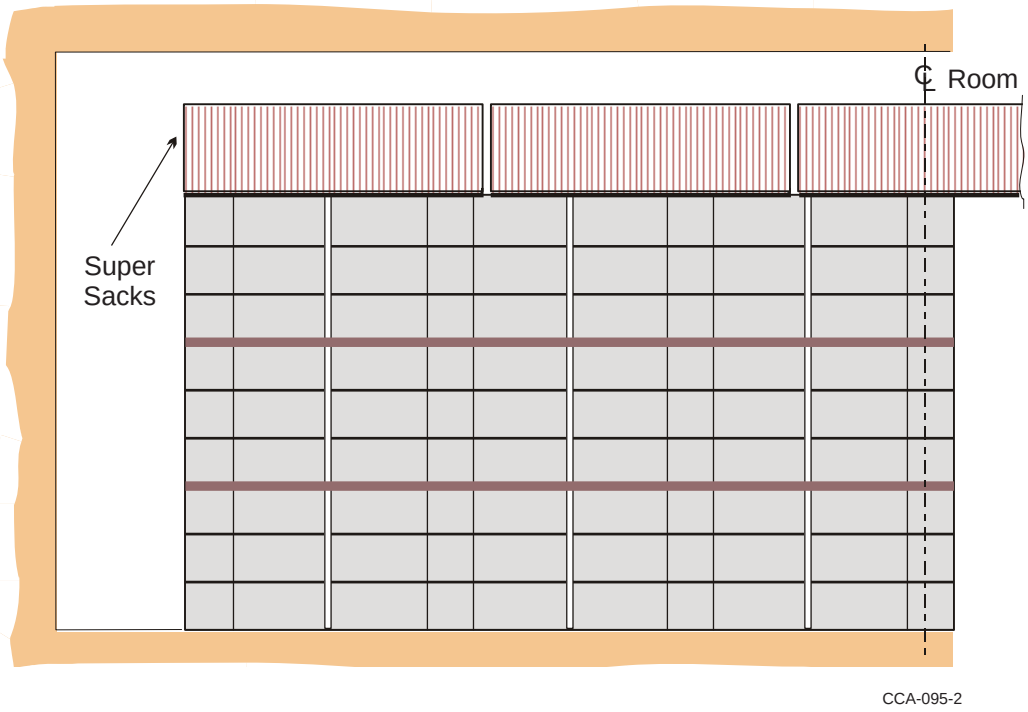

Figure 3-6. Room Cross-Section Showing the Position of Supersacks

The performance of MgO and its impacts on the disposal system are discussed in more detail in Section 6.4.3.4. Appendix BARRIERS provides the rationale for the use of MgO as an engineered barrier and contains information regarding its effects on chemical conditions in the repository. Laboratory experiments and thermodynamic modeling were used to predict the long-term effects of MgO on chemical conditions. Appendix PA, Attachment SOTERM describes how these conditions were used to calculate actinide solubilities.

Initially, MgO was emplaced in both minisacks and supersacks. Minisacks, which contained 11 kg (25 lbs.) of MgO, were placed among the waste containers and on the floor between the waste containers and the ribs. Supersacks, which contain 1900 $\pm$ 23 kg (4200 $\pm$ 50 lb) of MgO, are handled and emplaced using normal waste-handling techniques. Once each stack of waste containers is emplaced, a layer of supersacks is emplaced on top of them. Two changes related

to MgO have occurred since the submittal of the CCA. These changes and their effects are described below.

3.3.1.1 Change of MgO Supplier

After the original supplier stopped producing MgO in 2000, another supplier was selected. The new MgO is slightly less dense than the previous product. To compensate for this, the volume of MgO emplaced in the repository was increased by approximately two percent to ensure the emplacement of the same mass of MgO proposed in the CCA. The product provided by the new supplier meets all of the technical specifications for MgO. The DOE evaluated the properties of the new MgO and concluded that the change has no impact on its expected performance as the engineered barrier (see Appendix BARRIERS).

3.3.1.2 Elimination of MgO Minisacks

In order to enhance worker safety and operational efficiency, DOE requested EPA approval of the elimination of the MgO minisacks. Elimination of the minisacks resulted in a 15 percent reduction in the total mass of MgO to be emplaced in the WIPP. An impact assessment carried out to support the DOE modification request demonstrated that the elimination of minisacks and the associated 15 percent reduction of MgO would not affect its performance as the engineered barrier (consumption of CO_2 from possible microbial activity and concomitant reduction of actinide solubilities). The assessment also demonstrated that the reduction of MgO would not reduce the additional benefits of brine consumption and constant chemical conditions.

In a letter from the EPA dated January 11, 2001 [Docket A-98-49, II-B-3, Item 15], the EPA approved the elimination of the MgO minisacks. Appendix BARRIERS provides additional information on MgO.

3.3.2 Shaft Seals

The purpose of the shaft seal system is to limit fluid flow within four existing shafts after the WIPP is decommissioned. Such a seal system will not be implemented for several decades, but in order to establish performance requirements now that can be achieved at a later date, a shaft seal system has been designed possessing excellent durability, performance, and constructability using existing technology. The design approach is conservative, with redundant functional elements and various common materials. Because this design is not the only possible combination of materials and construction strategies that would adequately limit fluid flow within the shafts, future developments may change the design.

Material specifications and construction techniques for the shaft seal system are given in Appendix BARRIERS; and in CCA Appendix SEAL in SEAL 5.0 and 6.0. Section SEAL 5.0 also provides the rationale and quantification methods used to develop parameter distribution functions. Appendix PA, Section PA-4.2.6 summarizes the representation of the shafts in PA; Appendix PA, Attachment PAR, Table PAR-17 provides parameter values in the modeling. The presently envisaged shaft seal system is described in this section at a summary level with detail provided in Appendix BARRIERS.

The shaft seal design explores function and performance of the WIPP shaft seal system and provides well-documented assurance that such a shaft seal system can be constructed using available materials and methods. Sections of CCA Appendix SEAL provide hydrologic and structural calculations, material specifications and properties, construction methods, and engineering drawings. Documentation of material properties and their satisfactory application in the site-specific environment for regulatory time periods aid in assuring that the WIPP shaft seal system will meet performance expectations. Documentation of the analyses conducted and the results can be referenced in CCA Appendix SEAL (Chapter 2.4 of Appendix A, and Chapter 3.1.2 of Appendix D).

3.3.2.1 Site Setting

The geologic setting and groundwater hydrology in the proximity of the WIPP site are presented in Sections 2.1 and 2.2. These sections describe low brine-flow quantities and low hydrologic gradients, both very positive features with regard to sealing shafts or boreholes. As noted in Section 2.2, one of DOE's site selection criteria was a favorable geologic setting that minimizes fluid flow as a transport mechanism. Although these positive hydrologic attributes are documented, the shaft seal design concentrates on further mitigating fluid transport. For the purposes of the hydrologic sealing evaluation, the lithologies have been divided into the Rustler (and overlying strata) and the Salado. The fluid transport phenomena of seal materials within Salado lithologies are the primary design concerns.

3.3.2.2 Design Objectives

Design objectives for the shaft seal system address the need for the WIPP to comply with system requirements and to follow accepted engineering practices using demonstrated technology. Shaft seal design objectives are summarized as follows:

- limit radionuclides from reaching regulatory boundaries,
- restrict groundwater flow through the sealing system,
- use engineered materials possessing good long-term stability,
- protect against structural failure of system components,
- minimize subsidence and prevent accidental entry, and
- use available construction methods and materials.

Details of the design respond to these qualitative design objectives and present an implementation approach. The shaft seal system design was completed under the QA program described in Chapter 5.0 and includes review by independent, qualified experts. Reviewers examined the complete design including conceptual, mathematical, and numerical models, and computer codes. The design reduces uncertainty associated with any particular element by using multiple sealing system components constructed from different materials.

3.3.2.3 Design Description

A schematic of the shaft seal system as configured for the AIS is shown in Figure 3-7. Slight differences in seal element geometry occur within the four shafts owing to different shaft diameters or stratigraphic variations. The shaft seal system has 13 elements that fill the shaft with engineered materials possessing high density and low permeability. Components of the seal system within the Salado provide the primary barrier by limiting fluid transport along the shaft

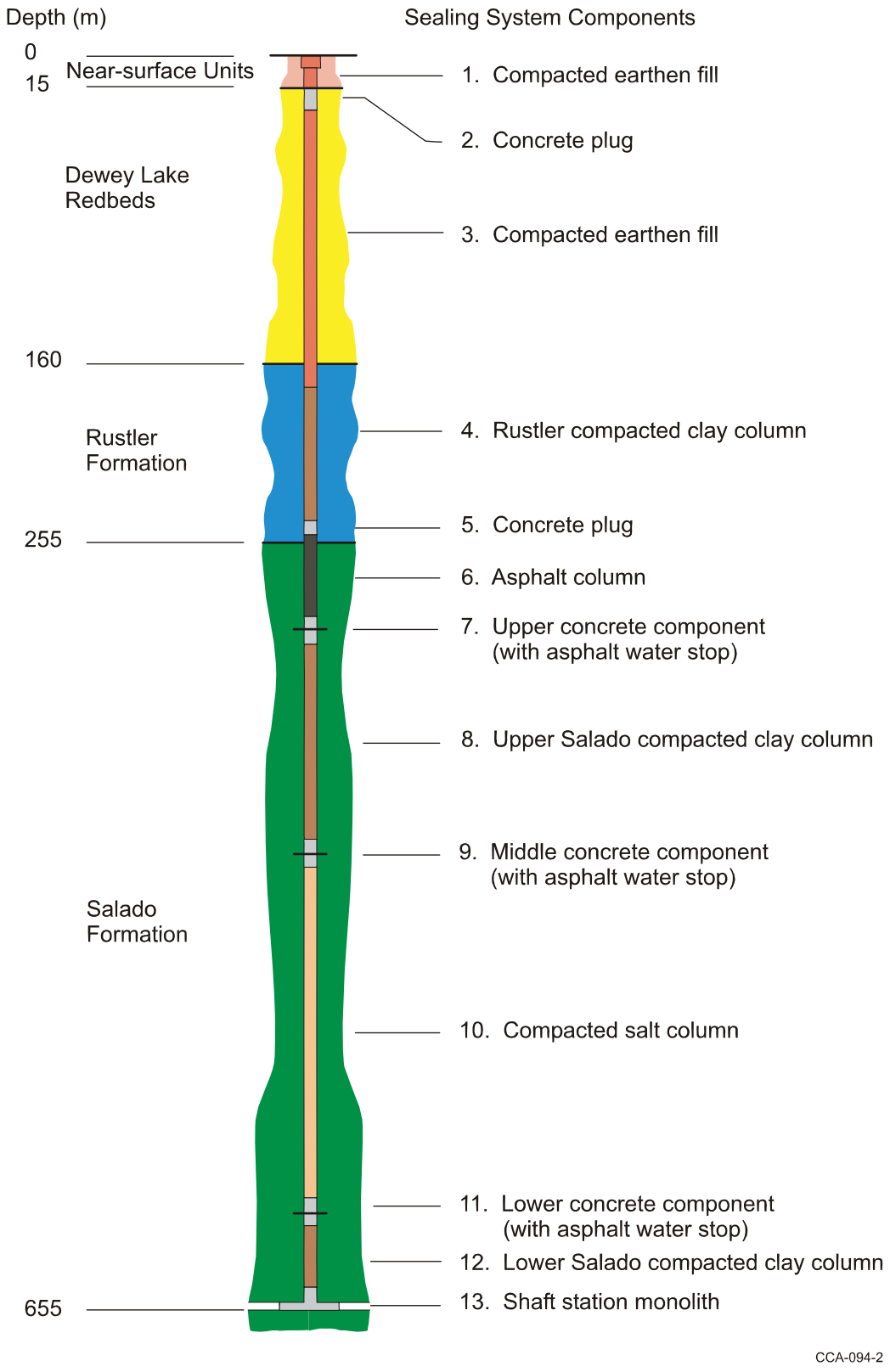

Figure 3-7. Proposed Seal Design for the WIPP AIS

during the 10,000-year regulatory period. Components of the seal system within the Rustler limit commingling of groundwater between water-bearing members. Components of the seal system overlying the Rustler fill the shaft with common materials of high density, consistent with good engineering practices. Appendix BARRIERS provides a detailed description of the shaft seal system and detailed design drawings for each shaft seal.

3.3.3 Panel Closure System

In its final certification decision for WIPP (63 FR 27354), the EPA added a new Appendix A to 40 CFR Part 194. The new appendix specifies four conditions that apply to the certification. Condition 1 pertains to panel closures. It states:

> Condition 1: § 194.14(b), Disposal system design, panel closure system. The Department shall implement the panel seal design designated as Option D in Docket A-93-02, Item II-G-1 (October 29, 1996, Compliance Certification Application submitted to the Agency). The Option D design shall be implemented as described in Appendix PCS of Docket A-93-02, Item II-G-1, with the exception that the Department shall use Salado mass concrete (consistent with that proposed for the shaft seal system, and as described in Appendix SEAL of Docket A-93-02, Item II-G-1) instead of fresh water concrete.

Option D involves installation of a concrete block “explosion-isolation wall,” removal of the DRZ along a section of the panel access drifts, and emplacement of a concrete monolith composed of Salado Mass Concrete in that section of each access drift.

The EPA Preamble to 40 CFR Part 194 Final Rule Section VIII.A.b stated “if a design different from those listed above is identified, the appropriate permit modification will be sought.” Since the certification of WIPP by the EPA, DOE has reevaluated a number of its engineering and construction aspects, including the panel closure systems. Therefore, DOE submitted a proposed change request to EPA on October 7, 2002 (DOE CBFO letter 2002). The EPA responded to DOE with a letter dated November 15, 2002. In this letter, EPA concluded that the panel closure request requires a modification to the rulemaking and “…will likely take a minimum of 12 months to complete from receipt of “complete” information on the requested changes. … Since the rulemaking likely would not be completed before we receive the WIPP compliance recertification application, … we are deferring review of this proposal until after we have issued our recertification decision.” Consistent with this direction from EPA, the PA calculations assume a panel closure with characteristics consistent with Option D (see Figures 3-8 and 3-9). In the same letter, EPA agreed to a delay in completing the panel closure system.

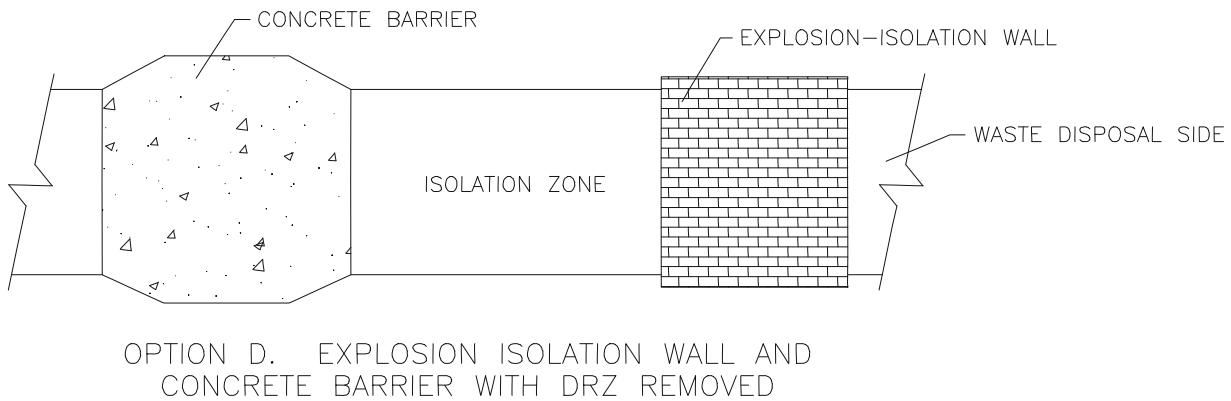

Figure 3-8. Panel Closure

Panel closures have been included for the purpose of Resource Conservation and Recovery Act disposal unit closure and to prevent potentially unacceptable levels of volatile organic compound release during waste management operations. The panel closure system was not designed or intended to support long-term repository performance. The panel closure system has been designed according to a number of operational objectives set out by the DOE, the main elements of which are:

1. the panel closure system shall restrict flow from the panels,

2. the panel closure system should perform its intended functions under loads generated by creep closure, and in general under the most severe ground conditions expected in the waste disposal area during the operational phase,

3. the panel closure system should be capable of containing and continuing to perform its intended function under conditions of a postulated methane explosion,

4. the panel closure system should be constructed of materials that are compatible with its emplacement environment and function,

5. engineering design of the panel closure system should include structural analyses using WIPP specific data, and should address such issues as the thermal cracking of concrete, and

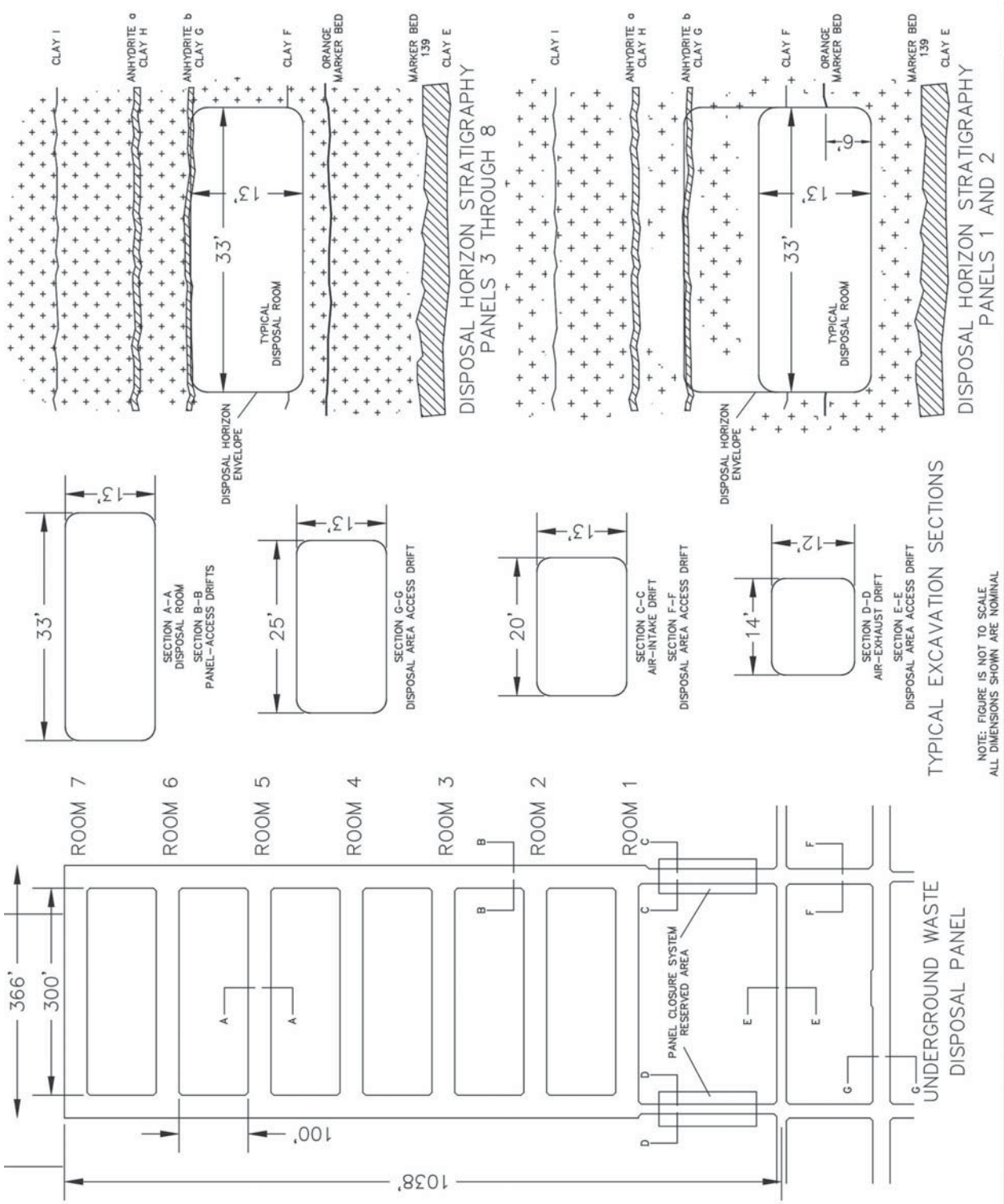

Figure 3-9. Location of Panel Closure System

6. the panel closure system should be designed and constructed using conventional mining practices, with full consideration of shaft and underground access and services. It should be constructed to generally accepted national design and construction standards, with a QA and quality control program used to verify material properties and construction practices.

See Appendix BARRIERS for a detailed discussion of panel closure. Representation of the panel closures in PA is described in Appendix PA, Section PA-4.2.7; parameters relevant to the panel closures are provided in Appendix PA, Attachment PAR, Table PAR-19.

3.3.4 Borehole Plugs

Figure 3-10 identifies existing unplugged boreholes that lie within the controlled area. Of these boreholes, four are deep boreholes that exceed the depth of the repository, and the remainder are shallow boreholes that do not reach the repository horizon.

To mitigate the potential for migration of contaminants toward the accessible environment, the DOE has specified that borehole plugs be designed to limit the volume of water that could be introduced to the repository from the overlying water-bearing zones and to limit the volume of contaminated brine released from the repository to the accessible environment.

Grout-plugging procedures are routinely performed in standard oil-field operations; however, quantitative measurements of plug performance are rarely obtained. The Bell Canyon Test reported by Christensen and Peterson (1981, 25) was a field test demonstration of the use of cementitious plugging materials and modification of existing industrial emplacement techniques to suit repository plugging requirements. The test was performed in an 20 cm (8 in.) well bore near the top of the Bell Canyon. The test bore intercepted an aquifer at a depth of 1,370 m (4,495 ft) with a shut in pressure of 1,800 psi (12.4 megapascals). A 2-m (6-ft) grout plug was emplaced above the aquifer and tested by unloading the hole (that is, removing fluids) above the plug to allow the full pressure in the aquifer to bear on the plug. This plug was observed to reduce the flow by five orders of magnitude, to 0.6 liters per day (0.2 gallons per day).

Cement emplacement technology was found to be generally adequate to satisfy repository plugging requirements. Christensen and Peterson (1981) also report

> that grouts can be effective in sealing boreholes, if proper care is exercised in matching physical properties of the local rock with grout mixtures.

A significant amount of research has been completed by the DOE to optimize concrete mixtures for the conditions expected in the Salado. The results of this research have been used to design the shaft sealing system as discussed in CCA Appendix SEAL. (Concrete is discussed in Appendix A of CCA Appendix SEAL, Section A2.1.) Consequently, the DOE has identified materials that will provide suitable plugs for boreholes. In addition, appropriate national standards such as the American Petroleum Institute Specification 10 and American Society for Testing Materials specification Volume 04.02 are available to assure the quality of borehole plugging material and installation. Section 2.1.4 of the CAO QAPD (see Appendix QAPD) provides the quality assurance requirements for the control of special processes such as plugging.

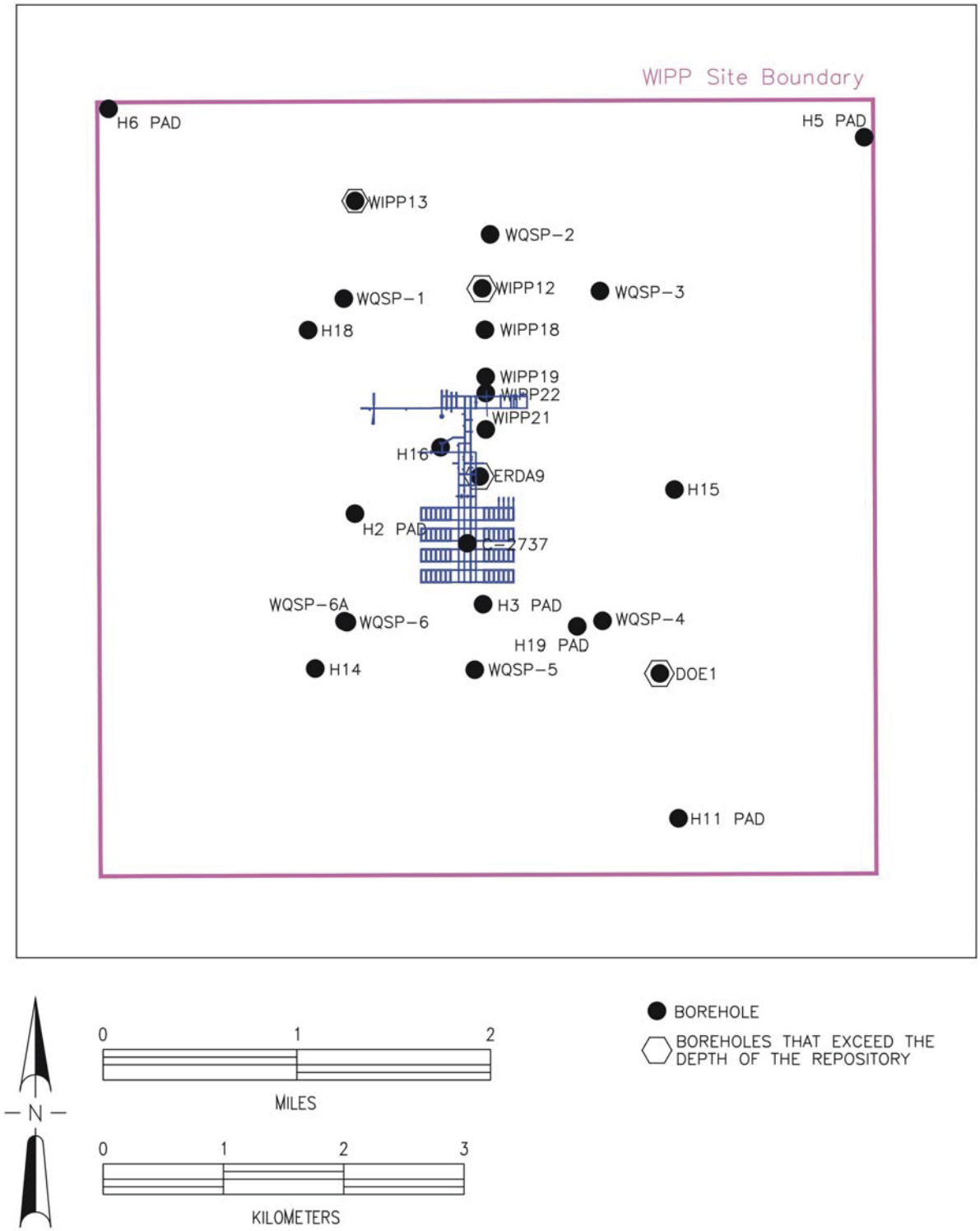

Figure 3-10. Approximate Locations of Unplugged Boreholes

As a result of the Christensen and Peterson (1981) report and subsequent evaluations of plugging materials, the DOE concluded that boreholes within the controlled area, which were previously plugged in accordance with the appropriate state and federal regulations in effect at the time plugging, will mitigate the potential for migration of fluids beyond the repository horizon. Shallow unplugged boreholes within the controlled area will be plugged in accordance with the current state or federal regulations using materials shown to be compatible with the underground environment. Deep unplugged boreholes within the controlled area will be plugged according to the state of New Mexico, Oil Conservation Division (1988), Order R-111-P (see Appendix BARRIERS). The governing regulations for plugging and/or abandonment of boreholes are summarized in Table 3-2. These solid cement plugs will go through the salt section and any water-bearing horizon to prevent liquids or gases from entering the hole above or below the salt section. The boreholes not being used for monitoring will be plugged at decommissioning. Appendix PA, Section PA-4.2.9 summarizes the representation of the borehole plugs in PA; Appendix PA, Attachment PAR, Tables PAR-14, PAR-15, and PAR-16 provide parameter values used in the modeling.

Table 3-2. Governing Regulations for Borehole Abandonment

Federal or State Land	Type of Well or Borehole	Governing Regulation	Summary of Requirements
Both	Groundwater Wells	State of New Mexico (1995), Rules and Regulations Governing Drilling of Wells and Appropriation and Use of Groundwater in New Mexico, Article 4-14	Any specific plugging requirements and provisions made by the state engineer shall be set forth in the permit.
Federal	Oil and Gas Wells	43 CFR Part 3160, 3162.3 4 (DOI 1995a)	The operator shall promptly plug and abandon, in accordance with a plan first approved in writing or prescribed by the authorized officer.
Federal	Potash	43 CFR Part 3590, 3593.1 (DOI 1995b)	(b) Surface boreholes for development or holes for prospecting shall be abandoned to the satisfaction of the authorizing officer by cementing and/or casing or by other methods approved in advance by the authorized officer. The holes shall also be abandoned in a manner to protect the surface and not endanger any present or future underground operation, any deposit of oil, gas, or other mineral substances, or any aquifer.
State	Potash	State of New Mexico (1995), Rules and Regulations Governing Drilling of Wells and Appropriation and Use of Groundwater, Article 4-20.2	In the event that the test or exploratory well is to be abandoned, the state engineer shall be notified. Such well shall be plugged in accordance with Article 4-19.1 so that the fluids will be permanently confined to the specific strata in which they were originally encountered.
State	Oil and Gas Well Outside the Oil-Potash Area	State of New Mexico, Oil Conservation Division (1991), Rule 202 (eff. 3-1-91)	B. Plugging (1) Prior to abandonment, the well shall be plugged in a manner to permanently confine all oil, gas, and water in the separate strata where they were originally found. This can be accomplished by using mud-laden fluid, cement, and plugs singly or in combination as approved by the Division on the notice of intention to plug. (2) The exact location of plugged and abandoned wells shall be marked by the operator with a steel marker not less than 10.16 cm (4 in.) in diameter, set in cement, and extending at least 1.22 m (4 ft) above mean ground level. The metal of the marker shall be permanently engraved, welded, or stamped with the operator name, lease name, and well number and location, including unit letter, section, township, and range.
State	Oil and Gas Wells Inside the Oil-Potash Area	State of New Mexico, Oil Conservation Division (1988), Order No. R-111-P (eff. 4-21-88)	F. Plugging and Abandonment of Wells (1) All existing and future wells that are drilled within the potash area shall be plugged in accordance with the general rules established by the Division. A solid cement plug shall be provided through the salt section and any water-bearing horizon to prevent liquids or gases from entering the hole above or below the salt selection. It shall have suitable proportions—but no greater than three percent of calcium chloride by weight—of cement considered to be the desired mixture when possible.

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4.0 WASTE DESCRIPTION

This chapter describes the type of waste that is emplaced and will be emplaced in the Waste Isolation Pilot Plant (WIPP) and provides an appraisal of the inventory of physical, chemical, and radionuclide components of the waste. This information supports the development of the performance assessment (PA) models that are used in predicting the long-term behavior of the repository. This chapter includes a waste description based on the inventories of existing and projected waste reported for the CCA (1996a) reported in the transuranic (TRU) Waste Baseline Inventory Report (TWBIR) (included in CCA Appendix BIR) and updated for CRA-2004 in Appendix DATA, Attachment F. This chapter also includes a description of the projected waste inventory, waste limits derived from both the PA and operational safety and health considerations, and methods of control to ensure compliance with the identified waste limits. Finally, this chapter provides a discussion of the applicable qualitative and quantitative waste characterization methodologies.

Inventory estimates provided in the CCA (Appendix BIR) represented the information available at that time. It was anticipated that WIPP waste inventory estimates would change as the U.S. Department of Energy (DOE) characterized the contents of waste containers prior to shipment to WIPP and as new TRU wastes were generated. Data on emplaced waste and updated estimates of the entire projected waste inventory are provided in Appendix DATA, Attachments D, E, F and H. The waste-inventory estimates reported in Appendix DATA and in this chapter are based on the available information as of September 30, 2002, unless otherwise noted.

Objectives of this chapter are to:

1. Report quantities and characteristics of the waste emplaced in the repository since certification;

2. Describe the current understanding of the WIPP waste inventory (emplaced, stored, and projected waste) in terms of waste components and characteristics;

3. Update waste inventory information for PA and compliance assessment calculations;

4. Reassess waste components and characteristics and associated waste-emplacement limits that may be important to long-term repository behavior; and

5. Identify changes or new information related to the WIPP waste characterization program that have occurred since certification.

Section 194.24(a) of 40 CFR Part 194 specifies that the DOE shall provide information pertaining to the chemical, radiological, and physical composition of the waste planned to be emplaced in the repository. Specifically, the criterion states

> Any compliance application shall describe the chemical, radiological and physical composition of all existing waste proposed for disposal in the disposal system. To the extent practicable, any compliance application shall also describe the chemical, radiological and physical composition of to-be-generated waste proposed for disposal in the disposal system. These descriptions shall include a list of waste components and their approximate quantities in the waste. The list may be

derived from process knowledge, current non-destructive examination/assay, or other information and methods.

This waste description includes the definition, sources, types, components, and characteristics of the waste planned for emplacement in the WIPP. The description provided in this chapter, along with the waste characterization analysis in Appendix TRU WASTE, Section TRU WASTE-2.0, identifies those physical, chemical, and radiological components of the waste that may singly or in combination affect the ability of the WIPP disposal system to meet the environmental performance standards contained in Part 191. This chapter is supported with several appendices. For example, waste related parameters used in PA are discussed in Appendix PA, Attachment PAR and Appendix TRU WASTE, Section TRU WASTE-2.0. Results of sensitivity analyses with respect to total releases used to generate the mean complementary cumulative distribution function (CCDF) in Section 6.5 are discussed in Appendix PA. The impact of waste components and characteristics on WIPP performance is discussed in Appendix TRU WASTE, Section TRU WASTE-2.0. Limits for waste components are discussed in CCA Appendix WCL; and in Appendix TRU WASTE, Section TRU WASTE-3.0 and summarized in this chapter. This chapter also summarizes methods of control that will be employed by the DOE to ensure that only those wastes that are consistent with those on which the PA is based are actually emplaced in the repository. One such control is the WIPP Waste Information System (WWIS) database for controlling the receipt of and tracking the emplacement of waste (see Section 4.3.2).

Before the final PA for the CCA was designed, DOE performed waste characterization analyses based on iterative preliminary PAs, related sensitivity analyses, and dedicated process studies for specific components and characteristics of the waste. A list of waste components and characteristics that were considered during these analyses, the list of and rationale for the ones retained for inclusion in the final PA, and the ones not included are documented in CCA Appendix WCL. This process has been updated for this recertification application (CRA-2004); waste components and characteristics retained for CRA-2004 PA are documented in Appendix TRU WASTE, Section TRU WASTE-2.0. Retained waste components are assigned fixed values in the final PA (see Appendix PA, Attachment PAR) based on information reported in Appendix DATA, Attachment F. Therefore, during the PA, plausible combinations of fixed values for waste components are included in all PA scenario analyses. Important imprecisely known waste characteristics are assigned ranges and distributions (see Appendix PA) from which values are drawn using a Latin hypercube sampling (LHS) technique that ensures that samples are taken from across the entire range of the distribution (see Section 6.1.5.2).

Since results demonstrate compliance with the quantitative containment requirements in Section 191.13, the individual protection requirements in Section 191.15, and the groundwater protection requirements in Section 191.24, the fixed values used for waste components define a profile of waste suitable for disposal at WIPP. Following the final PA for the CCA, sensitivity analyses determined the contribution of uncertainty in individual input variables to the uncertainty in model predictions (that is, final releases). In that sensitivity analysis, there were no waste characteristics that had a significant impact on the uncertainty about and the location of the mean CCDF reported in CCA Figure 6-39 (see CCA Appendix SA for a discussion of this uncertainty). Therefore, setting waste component limits is not based on PA results but is based on ensuring the validity of repository conditions modeled by PA (see CCA Appendix WCL). The same is true for the CRA-2004. In addition, the limits are repository-scale limits applicable to the inventory

at the time of decommissioning. The process for demonstrating compliance with these limits is to track the waste-component quantity and the uncertainty associated with that quantity as waste is emplaced in the repository. For example, the curie content for plutonium (Pu) and its uncertainty (based on the fact that a large percentage of the waste has yet to be generated) can be accumulated as waste is emplaced throughout the operational phase. Then, at the time of decommissioning, when these repository limits apply, the total curie content for Pu may be provided with a specified level of confidence, such as 95 percent, to demonstrate compliance with the waste component limits.

Figure 4-1 illustrates the information flow pertaining to the waste description and its relationship to other sections of this chapter as well as Chapter 6.0 and appendices to this application.

4.1 Waste Inventory

The waste inventory is defined as the quantity of waste that is anticipated to be emplaced in the WIPP and that waste that is already emplaced. This inventory is generally characterized as the nonradionuclide inventory that consists of both physical and chemical waste constituents, generally expressed in units of density or concentration (kg/m^3); and the radionuclide inventory, which is a tabulation, by specific isotope, of anticipated radionuclides in the waste expressed in units of curies (Ci).

The term TRU waste is defined in the WIPP Land Withdrawal Act (LWA) (Public Law 102-579 as amended by Public Law 104-201) as

> waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for (A) high-level radioactive waste; (B) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations ; or (C) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with part 61 of title 10, Code of Federal Regulations.

TRU waste that was disposed of in on-site, shallow landfill-type configurations prior to the early 1970s is referred to as buried waste. In 1970, the U.S. Atomic Energy Commission concluded that TRU waste should be stored in anticipation of the creation of more confining disposal facilities. TRU waste generated since that date has been segregated from other waste types and placed in retrievable storage. Waste generated after 1970, but before implementation of CBFO certified waste quality assurance (QA) program, is referred to as retrievably stored waste. Waste generated after a site's implementation of CBFO certified QA program is defined as newly generated. These and other relevant terms are defined in Appendix DATA, Attachment F.

Newly generated waste will be characterized in a similar manner to retrievably stored waste, but it will incorporate more real-time, as opposed to historical, acceptable knowledge. As of September 30, 2002, approximately 65 percent of the waste to be disposed of at the WIPP was expected to be newly generated waste, as described in the TWBIR (CCA Appendix BIR). At the time of the data call for CRA-2004 (September 30, 2002), approximately five percent of the waste DOE plans to dispose in the WIPP had been emplaced in the repository. Approximately 73 percent of the waste to be disposed of in the WIPP is classified as retrievably stored waste, approximately 22 percent of the waste identified by the TRU waste sites to be disposed of at the WIPP is expected to be newly generated waste (see Appendix DATA; Attachment F).

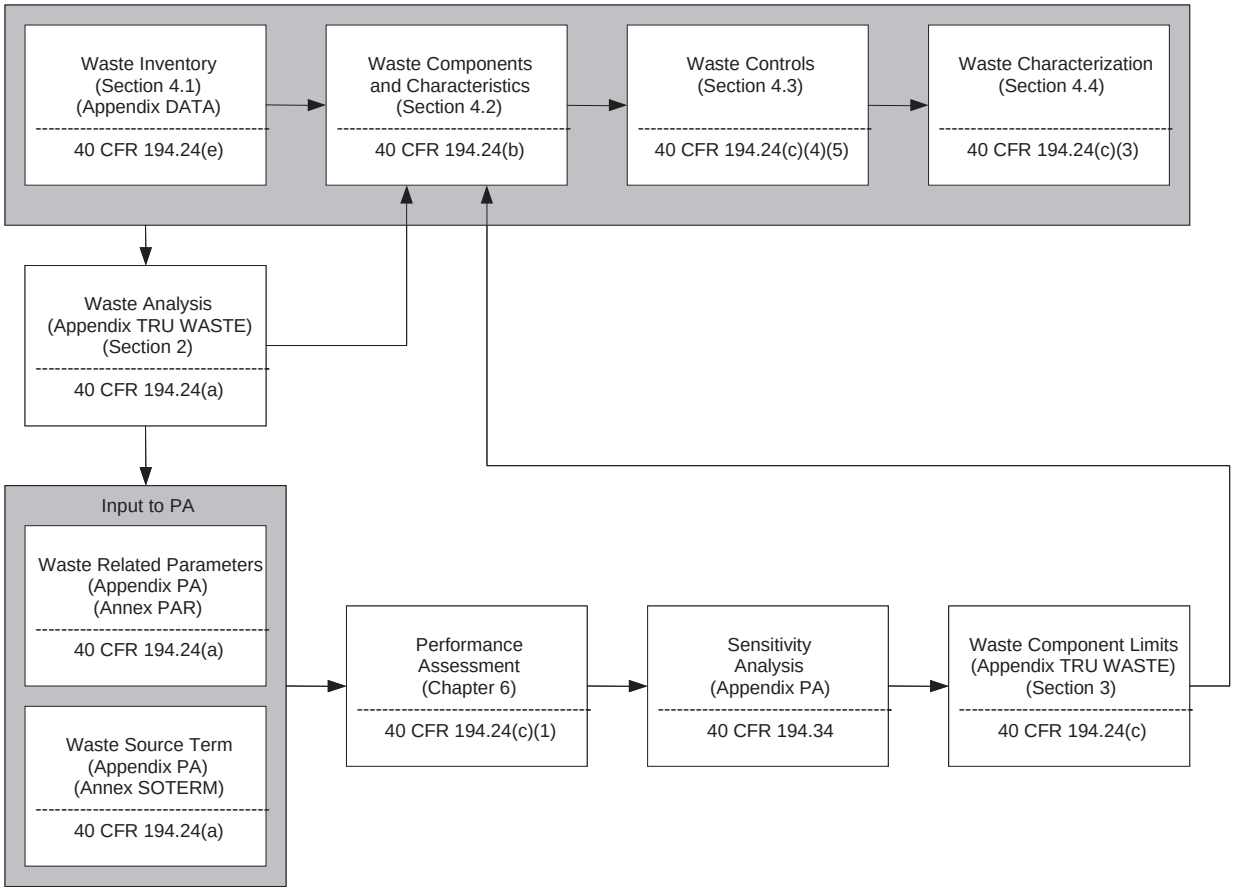

Figure 4-1. Waste Description Information Flow

TRU waste is classified as either contact-handled (CH) or remote-handled (RH) based on the contact dose rate at the surface of the waste container. If the contact dose rate is less than 200 millirem per hour (2 milliSievert per hour), the waste is defined as CH-TRU (DOE 1988). If, on the other hand, the contact dose rate is greater than or equal to 200 millirem per hour (2 milliSievert per hour), the waste and its container are defined as RH-TRU (DOE 1988). Consistent with the LWA, only RH-TRU waste less than or equal to 1000 rem per hour (10 Sievert per hour) is eligible for disposal at the WIPP. Also, to meet the requirements as set forth in the LWA, the total U capacity of WIPP by volume is 6.2 million ft3 (175,564 m3) of TRU waste. Moreover, the LWA also specifies that the emplaced RH-TRU waste is not to exceed a total activity of 5.1 million Ci (~ 18.9×10^{16} Becquerel) and a total activity concentration of 23 Ci per liter maximum activity level (averaged over the volume of the canister). No more than five percent of the emplaced RH-TRU waste may exhibit a dose rate in excess of 100 rem per hour (1 Sievert per hour).

4.1.1 Sources of TRU Waste

The DOE's TRU waste, as described in this chapter, is derived primarily from Pu fabrication and processing, research and development (R&D), decontamination and decommissioning (D&D),

and environmental restoration (ER) programs at DOE sites. Most TRU waste generated at the TRU waste sites results from specific processes and activities that are well defined and well controlled, enabling the sites to characterize the waste on the basis of acceptable knowledge concerning the process, input materials, and finished products. Some examples of these operations include

- Production of nuclear products. Production of nuclear products includes reactor operation, radionuclide separation and finishing, and weapons fabrication and manufacturing. The majority of the TRU waste was generated by weapons fabrication and radionuclide separation and finishing processes. More specifically, wastes typically consist of TRU-contaminated material derived from chemical processes, air and liquid filtration, casting, machining, cleaning, product quality sampling, analytical activities, and maintenance and refurbishment of equipment and facilities.

- Pu recovery. Pu recovery wastes are TRU-contaminated items and materials from the recovery of valuable Pu, including contaminated molds, metals, glass, plastic materials, rags, salts used in electrorefining, precipitates, firebrick, soot, and filters.

- R&D. R&D projects include a variety of hot-cell or glove-box activities that often simulate full-scale operations described above, producing similar TRU wastes. Other types of R&D projects include metallurgical research, actinide separations, process demonstrations, and chemical and physical properties determinations.

- D&D. Facilities and equipment that are no longer needed or usable are decontaminated and decommissioned, resulting in TRU wastes consisting of scrap materials, cleaning agents, tools, piping, filters, Plexiglas, gloveboxes, concrete rubble, asphalt, cinder blocks, and other building materials. This is expected to be the largest category by volume of TRU waste to be generated.

- ER Programs. The implementation of environmental restoration programs at various DOE sites results in the generation of a variety of materials including contaminated soil, building materials and equipment.

Operations carried out in glove boxes and hot cells generate both combustible and noncombustible wastes. Combustible waste contains mixtures of paper, plastic materials, rags, cloth clothing, and wood resulting from Pu operations. Cloth and paper wipes are used to clean parts and glove boxes. Depending on the operations, damp combustibles are usually used and then wrung out, drained, or dried. Noncombustibles consist primarily of glass and metal. Much of this waste is laboratory equipment and glassware from R&D activities.

Filters are sometimes combinations of combustibles and non-combustibles and come from a variety of sources including high-efficiency particulate air (HEPA) filters, filter media, processed filter media, and prefilters. Prefilters and HEPA filters are used on all ventilation intake and exhaust systems associated with Pu operations. Filter frames can be either wood, aluminum, or stainless steel; and the filter media may be paper, Fiberglass, Nomex, or similar material. Filter media are generated from splitting absolute dry box and HEPA filters apart from their frames in the Pu process areas. Loose particulate materials that are dislodged from the filters are stabilized

and packaged separately from the media. Filter media are packaged in plastic bottles or bags. Filter media may also be mixed with portland cement to neutralize any residual nitric acid.

Graphite waste is produced from molds that are broken, cleaned, or scraped in glove boxes to remove excess Pu. Graphite is a uniform, well-defined material.

Benelex™ and Plexiglas™ are well-defined materials that are used as neutron shielding material and in glove-box construction. Benelex™ consists mainly of cellulose with residual amounts of the phenolic resin. Plexiglas™ is a polymethyl methacrylate polymer used for glove-box windows and is generated as waste during the change-out of the glove-box windows.

Inorganic process solids include residues from evaporator and other types of storage tanks, grit, firebrick fines, ash, salts, metal oxides, and filter sludge. This waste is typically solidified in portland- or gypsum-based cements.

Soil, asphalt, and sand contaminated from spills or generated from D&D activities may also be present in the waste.

To isolate the radiological and hazardous contaminants of these wastes from humans and the environment during handling and other life-cycle operations, a primary confinement barrier is used. Both CH-TRU and RH-TRU waste at the WIPP facility will be managed using payload containers that meet the requirements of the U.S. Department of Transportation (DOT) for Type A or equivalent containers (DOE 1995c). The term payload container in this document refers to drum, drum overpack, canister, standard waste box, or ten-drum overpack unit. Internal to these payload containers may be other secondary layers of confinement, including rigid plastic inner liners and multiple layers of plastic bagging. Each container is vented using one or more filters.

4.1.2 TRU Waste Sites

The major TRU waste sites (referred to as large quantity sites [LQSs]) that are in the process of shipping or are planning to ship their TRU waste to the WIPP for disposal include

- Hanford Richland (Hanford-RL); TRU wastes at Hanford under the purview of the DOE Richland Operations Office
- Hanford River Protection (Hanford-RP); TRU wastes at Hanford under the purview of the DOE Office of River Protection
- Idaho National Engineering and Environmental Laboratory (INEEL)
- Los Alamos National Laboratory (LANL)
- Oak Ridge National Laboratory (ORNL)
- Rocky Flats Environmental Technology Site (RFETS)
- Savannah River Site (SRS)

Since certification, Lawrence Livermore National Laboratory (LLNL) and the Nevada Test Site (NTS) have been recategorized as small quantity sites (SQSs). In addition, TRU waste at the Hanford Reservation has been divided into two categories: (1) TRU waste overseen by the DOE Richland Operations Office (Hanford-RL) which corresponds to the TRU waste reported by Hanford for the CCA inventory estimate, and (2) TRU waste overseen by the DOE Office of River Protection (Hanford-RP). The DOE Office of River Protection may send both CH-TRU and RH-TRU waste to the WIPP. The Hanford-RP waste was not included in the Hanford Reservation waste reported for the CCA but is included in the 2004 CRA. The inventories for the SQSs and LQSs are reported in Appendix DATA, Attachment F, Annex J.

At the time of the CCA, INEEL, LANL, and RFETS were expected to be among the first of the major TRU waste sites to begin shipping TRU waste to the WIPP. As of September 30, 2002, the WIPP had received 1,255 shipments totaling 7,716 m^3 (2.7×10^5 ft^3) of CH-TRU waste, primarily from INEEL, LANL, and RFETS. SRS and Hanford-RL have also made shipments. Emplaced, stored, and projected waste volumes, by TRU waste site, are provided in Tables 4-1 and 4-2. No RH-TRU waste has yet been shipped to the WIPP.

Table 4-1. Emplaced, Stored, and Projected CH-TRU Waste Inventory as of September 30, 2002[1]

TRU Waste Site	Emplaced CH-TRU Volume (m^3)	Stored CH-TRU Inventory (m^3)	Projected CH-TRU Inventory (m^3)	Disposal CH-TRU Inventory[3] (m^3)
Hanford-RL	9.8×10^1	1.3×10^4	1.3×10^4	4.1×10^4
Hanford-RP	0.0×10^0	3.9×10^3	0.0×10^0	3.9×10^3
INEEL	2.9×10^3	6.1×10^4	1.2×10^2	6.4×10^4
LANL	2.7×10^2	1.2×10^4	3.3×10^3	1.9×10^4
ORNL	0.0×10^0	0.0×10^0	4.5×10^2	9.5×10^2
RFETS	4.3×10^3	5.4×10^3	2.7×10^3	1.5×10^4
SRS	2.0×10^2	1.3×10^4	2.4×10^3	1.8×10^4
SQS[2]	0.0×10^0	1.2×10^3	2.8×10^3	7.1×10^3
Totals	7.7×10^3	1.1×10^5	2.5×10^4	1.7×10^5

Source: Appendix DATA; Attachment F.

[1] Volume reported by the TRU waste sites as of September 30, 2002. It is not scaled to the disposal volume.

[2] Includes currently identified SQSs; at some TRU waste sites, determinations that waste is generated through defense activities have yet to be made. Inventories for those TRU waste sites are not included in this number.

[3] This is the TRU waste site inventory scaled as follows: emplaced + stored + 2.11 (projected).

As TRU waste sites develop the prerequisite certification programs required for TRU waste disposal at the WIPP, they too will commence shipping waste to the WIPP. Effective implementation by the TRU waste sites of DOE Quality Assurance Program Document (QAPD) (see CCA Appendix QAPD) is a prerequisite for granting TRU waste certification authority to the TRU waste sites. A letter granting such authority will specify the date that the subject TRU waste sites effectively implemented their characterization and certification program. Any limitations imposed on the certification authority will be described in the letter.

As part of the certification for the project (63 FR 27404), the EPA promulgated a new section to the rule, Title 40 CFR 194.8. Section 194.8 establishes the approval process that must be completed before an individual TRU waste site may ship waste to the WIPP. The EPA approval considers the application of QA provisions to the waste-characterization process, including EPA audits or inspections DOE audits of TRU waste site waste-characterization

Table 4-2. Stored and Projected RH-TRU Waste Inventory as of September 30, 2002[1]

TRU Waste Site	Stored RH-TRU Inventory (m^3)	Projected RH-TRU Inventory (m^3)	Disposal RH-TRU Inventory[3] (m^3)
Hanford-RL	3.8×10^2	9.4×10^3	2.0×10^3
Hanford-RP	4.5×10^3	0.0×10^0	4.5×10^3
INEEL	2.2×10^2	0.0×10^0	2.2×10^2
LANL	1.2×10^2	0.0×10^0	1.2×10^2
ORNL	0.0×10^0	6.6×10^2	1.1×10^2
RFETS	0.0×10^0	0.0×10^0	0.0×10^0
SRS	0.0×10^0	2.3×10^1	4.0×10^0
SQS[2]	9.5×10^1	3.3×10^2	1.5×10^2
Totals	5.3×10^3	1.0×10^4	7.1×10^3

Source: Appendix DATA; Attachment F.

[1] Volume reported by the TRU waste sites as of September 30, 2002. It is not scaled to the disposal volume.

[2] Includes currently identified SQSs; at some TRU waste sites, determinations that waste is generated through defense activities have yet to be made. Inventories for those TRU waste sites are not included in this number.

[3] This is the TRU waste site inventory scaled as follows: emplaced + stored + 0.172 (projected)

programs, and provides for public review and comment. Section 194.8 also applies to the application of process knowledge by the TRU waste sites for waste characterization. The DOE must also implement a system of controls at the TRU waste sites to confirm that the total amount of each waste component emplaced in the disposal system will not exceed established limiting values.

Current information on the EPA approval of TRU waste sites to ship waste to WIPP consistent with the requirements of section 194.8 is provided in Table 4-3. In addition to these TRU waste sites, the Central Characterization Project (CCP) has been initiated by DOE and operates using mobile waste characterization equipment. As of September 30, 2003, CCP was operating and approved to ship waste from SRS, Argonne National Laboratory – East (ANL-E), and Nevada Test Site (NTS).

Table 4-3. Approved TRU Waste Site QA and Waste Characterization Programs as of September 30, 2002

TRU Waste Site
Hanford-RL
INEEL
LANL
RFETS
SRS

Source: WWIS

In addition to the major TRU waste sites, there are currently numerous SQSs planning to dispose TRU waste at the WIPP. Options to facilitate disposal of the SQS waste at the WIPP include either direct shipment to the WIPP after on-site characterization and certification or shipment to an interim facility for performing waste consolidation, treatment, and/or characterization and certification in accordance with WIPP requirements. The current list of SQSs that plan to ship directly to WIPP or to a larger site pending shipment to WIPP includes:

- Argonne National Laboratory – East (ANL-E),
- Argonne National Laboratory – West (ANL-W),
- Battelle Columbus Laboratories (BCL),
- Bettis Atomic Power Laboratory (BAPL),
- Knolls Atomic Power Laboratory (KAPL),
- Knolls Atomic Power Laboratory-Nuclear Fuel Services (KAPL-NFS),
- Lawrence Berkeley National Laboratory (LBNL),
- Lawrence Livermore National Laboratory (LLNL),
- Nevada Test Site (NTS),
- Paducah Gaseous Diffusion Plant (PGDP),
- Sandia National Laboratories/NM (SNL), and U.S. Army Material Command (USAMC).

As waste-management plans evolve at these TRU waste sites, the list is expected to change. Some TRU waste sites, for example, may ship waste to alternate facilities for processing pending shipment to WIPP. However, as of September 30, 2002, plans for shipment to alternate facilities had not been finalized. The inventories for these SQSs are reported in Appendix DATA, Attachment F, Annex J.

Six SQSs have shipped their waste to an LQS. These include:

- ARCO Medical Products Company (ARCO) – Shipped to LANL,

- Energy Technology Engineering Center (ETEC) – Shipped to Hanford-RL,
- Mound Plant – Shipped to SRS,
- Missouri University Research Reactor (MURR) – Shipped to ANL-E,[1]
- Pantex Plant - Shipped to LANL, and
- Teledyne Brown Engineering – Shipped to RFETS.

The inventories for these several SQSs are included in the LQS inventories.

Several SQSs plan to ship waste to WIPP, but their waste had not been determined to be defense waste as of September 30, 2002. These include:

- Babcock & Wilcox – Nuclear Engineering Services (B&W-NES),
- Brookhaven National Laboratory (BNL),
- Framatome,
- General Electric Vallecitos Nuclear Center (GE-VNC),
- Separations Process Research Unit (SPRU), and
- West Valley Demonstration Project (WVDP).

The inventories for these SQSs are reported in Appendix DATA, Attachment F, Annex I.

4.1.3 TRU Waste Inventory

A summary of the quantity of stored and projected TRU waste and TRU waste components is contained in Appendix DATA, Attachment F. Appendix DATA, Attachment F documents DOE's current understanding of the total inventory of TRU waste and includes both the TRU waste that is planned to be disposed at the WIPP site and the TRU waste that is not planned to be sent to WIPP as of September 30, 2002. Only the WIPP portion of the TRU waste inventory is used in PA calculations that support the development of CRA-2004.

In preparing CRA-2004, DOE initiated a "data call" to obtain current waste inventory information from its TRU waste sites similar to the data call that was conducted prior to 1995 in preparation for the CCA. Each TRU waste site was asked to review previous data submitted regarding its TRU waste and revise those data based on current knowledge of waste at the TRU waste site.

The results of the "data call" were compiled in a database called the Transuranic Waste Baseline Inventory Database (TWBID) Revision 2.1. Data from the TWBID are reported in detail in

[1] Shipment of MURR waste to ANL-E occurred after September 30, 2002.

Appendix DATA, Attachment F and are summarized here. For the CCA, there were essentially two categories of waste: stored waste and projected waste (see CCA Section 4.1.3.1 for definitions). For CRA-2004, there are three categories of waste: emplaced waste, stored waste, and projected waste (see Section 4.1.3.1 for definitions).

For DOE to consider disposal system performance at full capacity, it is necessary to scale the waste volumes reported by the TRU waste sites. This is because the volume identified by the TRU waste sites is less than the available volume of the repository, 175,564 m^3 (6.2 million ft^3). The projected inventory reported by the TRU waste sites is scaled, to achieve a disposal inventory equal to the repository volume specified by the WIPP LWA. The repository volume remains unchanged.

As of September 30, 2002, the TRU waste sites reported a total CH-TRU waste stored inventory of 1.1×10^5 m^3 (3.9×10^6 ft^3) and a total RH-TRU waste stored inventory of 5.3×10^3 m^3 (1.9×10^5 ft^3) (see Tables 4-1 and 4-2). This is DOE's current estimate of the stored inventory destined for WIPP. In addition to identified stored volumes, the TRU waste sites project that an additional 2.5×10^4 m^3 (8.8×10^5 ft^3) of CH-TRU waste and 1.0×10^4 m^3 (3.5×10^5 ft^3) of RH-TRU waste will be generated in the future.

The stored CH-TRU waste inventory currently reported by the TRU waste sites is larger than the same inventory reported in the CCA. SRS, RFETS, Hanford, and INEEL all reported increased stored CH-TRU volumes based on new information about their waste and increased accessibility to the waste. The Hanford-RP waste was not included in the previous Hanford estimate used in the CCA, although the TWBIR indicated that it might be included in the WIPP inventory at some time in the future. Several SQSs (BCL, BAPL, KAPL, and PGDP) have identified small inventories of CH-TRU stored waste since the CCA was submitted.

While the TRU waste sites are reporting larger quantities of CH-TRU waste in storage, they are reporting smaller quantities of CH-TRU waste in the projected category. The shift from reporting waste as stored rather than projected reflects progress at the TRU waste sites towards cleanup and closure.

Overall, the anticipated CH-TRU waste inventory (stored plus projected) remaining for disposal at WIPP has decreased by an amount that is essentially equivalent to the inventory of CH-TRU waste emplaced in the repository. The total inventory (emplaced plus anticipated) of CH-TRU waste is less than the disposal limit of 168,485 m^3. Therefore, for PA calculations, the CH-TRU waste projected inventory is scaled to produce a disposal inventory equal to the repository limit.

The stored RH-TRU waste inventory currently being reported by the TRU waste sites represents an increase in the stored RH-TRU waste inventory reported in the CCA inventory estimate. Hanford-RP and Hanford-RL both reported more stored RH-TRU waste based on new information about it and increased accessibility to the waste. ANL-E, BAPL, and SNL added small amounts of stored RH-TRU waste to their inventories. ORNL moved all of their RH-TRU waste into the projected waste category because they plan to process the waste using segregation, size reduction, and evaporative drying. As its entire RH-TRU waste inventory will be processed, the ORNL RH-TRU waste is reported only as a projected inventory.

While the stored RH-TRU estimates have increased in the CRA-2004, the projected RH-TRU inventory estimates for CRA-2004 are less than what they were in the CCA inventory estimate. The greatest decrease in projected RH-TRU waste inventory was reported by Hanford-RL. The TRU waste sites report a decrease in the anticipated (stored plus projected) RH-TRU waste inventory for disposal at WIPP, a drop from over 2.6×10^4 m^3 (9.2×10^5 ft^3) reported in the CCA to about 1.0×10^4 m^3 (3.5×10^5 ft^3) as of September 30, 2002.

Nevertheless, the anticipated volume of RH-TRU reported for the CRA-2004 is greater than the repository limit for RH-TRU. Therefore, for PA calculations, the RH-TRU projected inventory is scaled down so the total disposal volume of RH TRU equals the repository limit of 7,079 m^3 (2.5×10^5 ft^3).

In support of the CCA PA, it was necessary for DOE to roll-up waste information on a repository scale. To this end, the TWBIR describes a process for grouping individual waste streams with similar physical and chemical properties into waste profiles, based on the waste matrix code (WMC) assigned by DOE TRU waste sites. The same process was followed for CRA-2004 (see Appendix DATA, Attachment F and Appendix TRU WASTE, Section TRU WASTE-2.0). Waste profiles with similar WMCs are combined across the DOE TRU waste system to provide estimated total volumes and total waste material parameters (WMPs). WMPs and waste components (as used in Section 194.24) are synonymous. Individual waste streams are evaluated to estimate the occurrence and quantities of WMPs (for example, cellulosic materials, iron-base metal and alloys, etc.) and are identified in Appendix TRU WASTE, Section TRU WASTE-2.0 as having either a significant or negligible effect on the performance of the WIPP repository.

4.1.3.1 Inventory Terminology

The following definitions are provided to help clarify the information contained in this chapter. Most of the definitions from the CCA have been included in this section without change. For CRA-2004, some definitions have been refined and others have been added.

Anticipated waste inventory – The sum of the stored and projected TRU waste inventories at DOE TRU waste sites that have not been emplaced at WIPP.

As-Generated Waste – The chemical and physical status of waste when it is generated. The as-generated term applies to both stored and projected waste.

Disposal Inventory – The volume used for CRA-2004 PA calculations. The LWA sets the total amount of TRU waste allowed in the WIPP at 175,564 m^3 (6,200,000 ft^3).

The “Agreement for Consultation and Cooperation” limits the RH-TRU inventory to 7,079 m^3 (250,000 ft^3) (DOE/NM 1981).

Emplaced waste inventory – Waste that has been placed in the repository as of September 30, 2002.

Final Waste Form – The expected physical form of a waste stream. The use of the final waste form helps to group waste streams that are expected to have similar physical and chemical properties at the time of disposal. Waste is assigned to one of 11 final waste forms: solidified inorganics, salt, solidified organics, soils, uncategorized metal, lead/cadmium metal, inorganic non-metal, combustible, graphite, heterogeneous, and filter.

September 30, 2002 (the inventory date) – The date used for determining the emplaced waste inventory included in CRA-2004 and the date TRU waste sites have used as the basis for their revised inventory estimates.

Projected Inventory – The part of the TRU inventory that has not been generated but is estimated to be generated at some time in the future by the TRU waste sites. The projected inventory is the same as the to-be-generated waste referred to in Section 194.24(a).

Stored Inventory – Also referred to as "retrievably stored" inventory. The part of the anticipated waste inventory stored in such a fashion that it can be readily retrieved. Retrievably stored waste includes waste stored at the TRU waste sites since the early 1970s in buildings or berms with earthen cover and does not include waste generated prior to 1970. Retrievably stored waste also includes waste in underground storage tanks, ponds, and as decontamination and decommissioning material identified for disposal that requires retrieval at the TRU waste sites.

Scaling – The process of adjusting, if needed, the projected inventory to the repository limit (disposal inventory) is called scaling. Scaling is needed in *PA* to model the WIPP repository at full capacity (6.2 million ft^3 as set by the LWA). The scaling factor used in the CRA-2004 for CH-TRU waste is 2.11. This is only applied to the projected component of a waste stream. The scaling factor for RH-TRU waste is 0.172, which is also only applied to the projected component of a waste stream.

Scaled Inventory – Synonymous with disposal inventory. The scaled inventory is the volume that fills WIPP capacity and is used for PA calculations. This volume is calculated as the sum of the disposal volumes for all WIPP-eligible waste streams after application of RH-TRU waste and CH-TRU waste scaling computations to each WIPP-eligible projected TRU waste stream.

WIPP Waste Inventory – The sum of the emplaced waste inventory and the anticipated waste inventory.

Waste Characteristic – Section 194.2 defines waste characteristic as a property of the waste that has an impact on the containment of waste in the disposal system.

Waste Component - Section 194.2 defines waste component as an aspect of the total inventory of the waste that influences a waste characteristic.

Waste Matrix Codes (WMCs) – Codes developed by DOE, in response to the Federal Facility Compliance Act (Public Law 102-386), to aid in categorizing mixed waste streams in the DOE system into a series of five-digit alphanumeric codes (for example, S5400; Heterogeneous Debris) that represent different physical and chemical matrices. Using guidance prepared by DOE (DOE 1995e), the WMC is assigned by the TRU waste sites for all mixed waste streams and unmixed waste streams. CRA-2004 has adopted this system to remain consistent with

common terminology used by the DOE TRU waste sites. WMCs are verified with radiographic examination (using either real-time radiography [RTR] or an equivalent methodology) and/or visual examination.

Waste Stream Profile – This is a description of a CH-TRU or RH-TRU waste stream. Waste stream profiles include

- waste stream description;
- waste stream source description, waste stream identification codes, final waste form;
- as-generated waste form volumes and final waste form volumes,
- estimated average values for WMP densities;;
- identification of whether the waste is CH-TRU or RH-TRU;
- final waste form radionuclide inventory (activity in Ci per cubic meter); and
- comments provided by the TRU waste sites to further explain the data provided.

WIPP Waste Profile – The WIPP waste profile represents a summary of TRU wastes at all TRU waste sites that have an identical final waste form. WIPP waste profiles include:

- the final waste form that the profile represents;
- a listing of the TRU waste sites (represented by the same final waste form) that are included in the WIPP waste profile; final waste form volumes of stored and projected waste for each TRU waste site; and
- a summary of the WMP average densities.

Waste Material Parameters (WMP) – This is one or more of the TRU waste stream constituents. The 12 WMPs have been grouped by their chemical and physical properties as shown in the following list.

<u>Inorganics</u>

- Iron-based metals and alloys — includes iron and steel alloys in the waste and does not include the waste container materials.
- Aluminum-based metals and alloys.
- Other metal and alloys — includes all other metals found in the waste materials (for example, copper, lead, zirconium, tantalum, etc.). The lead portion of lead rubber gloves and aprons is also included in this category.
- Other inorganic materials — includes inorganic nonmetal waste materials such as concrete, glass, firebrick, ceramics, sand, and inorganic sorbents.

- Vitrified materials — includes waste that has been melted or fused at high temperatures with glass-forming additives such as soil or silica to form a homogeneous glass-like matrix.

Organics

- Cellulosic Materials — includes those materials generally derived from high-polymer plant carbohydrates. Examples are paper, cardboard, kimwipes, wood, cellophane, cloth, etc.

- Rubber — includes natural or synthetic elastic latex materials. Examples are Hypalon®, neoprene, surgical gloves, leaded-rubber gloves (rubber part only), etc.

- Plastics — includes generally synthetic materials, often derived from petroleum feedstock. Examples are polyethylene, polyvinylchloride, Lucite®, Teflon®, etc.

Solidified Materials

- Inorganic matrix — includes any homogenous materials consisting of sludge or aqueous-based liquids that are solidified with cement, Envirostone™, or other solidification agents. Examples are wastewater treatment sludge, cemented aqueous liquids, inorganic particulates, etc.

- Organic matrix — includes cemented organic resins, solidified organic liquids, and sludges.

- Cement — includes the cement used in solidifying liquids, particulates, and sludges.

Soils

- Soils — generally consists of naturally occurring soils that have been contaminated with inorganic radioactive waste materials.

Although not considered to be a waste component, the associated packaging materials are also listed because they also provide input to the PA calculations.

Packaging Materials

- Steel — weight of the steel component of the standard container. Any necessary overpacking is included in the weight of steel.

- Plastics — weight of any standard plastic secondary confinement within the container.

- Lead — weight of the lead shielding.

The estimated WMP information is expressed in units of kilograms per cubic meter corresponding to the volume the waste package will occupy in the repository. This unit

facilitates scaling the material parameters to address various volumes for PA calculations and sensitivity analysis.

4.1.3.2 Nonradionuclide Inventory Roll-Up

The DOE uses the eleven final waste forms as an intermediate step in determining the inventory of nonradionuclide waste components. These final waste forms are a convenient way for the DOE to categorize waste for the purpose of waste management and waste characterization prior to shipment to the WIPP. Waste streams at each TRU waste site with similar WMCs are grouped together into one of the 11 final waste forms. The grouping of individual waste stream profiles into a WIPP waste profile is based on the similar physical and chemical properties of the waste streams. Current estimates of the final waste form volumes for CH-TRU and RH-TRU waste are provided in Table 4-4. For comparison, estimates of the final waste-form volumes for CH-TRU and RH-TRU waste from the CCA are also provided in Table 4-4. The relative contribution of heterogeneous debris, solidified organics, and filters to the current reported CH-TRU waste volume has increased when compared to the CCA inventory estimate. The most notable increase is in the heterogeneous debris category. SRS, LANL, RFETS, and INEEL all reported larger expected volumes of heterogeneous debris in the CRA-2004 data call than they reported for the CCA inventory estimate. Larger volumes of heterogeneous debris are expected to come from the FB (F-Canyon at SRS) and HB (H-Canyon at SRS) process lines, facility and equipment operations at LANL, decontamination and decommissioning at RFETS, and the start-up of the Advanced Mixed Waste Treatment Facility (AMWTF) at INEEL.

The relative contribution of uncategorized metal, graphite, soil and combustibles to the current reported CH-TRU waste volume has decreased when compared to the CCA inventory estimate. The most notable decrease is in the uncategorized metal category. Hanford-RL, LANL, and INEEL all reported smaller expected volumes of uncategorized metal in the CRA-2004 data call than in the CCA inventory estimate due primarily to reassignment of the waste to other forms based on new characterization information.

The relative contribution of inorganic non-metal, filters, soils, solidified organics, and solidified inorganics to the current reported RH-TRU waste volume has increased when compared to the CCA estimate. The most notable increase is in the solidified inorganic category. Hanford-RP and Hanford-RL reported larger expected volumes of solidified inorganics in the CRA-2004 data call than in the CCA inventory estimate. Larger volumes of solidified inorganics are expected from Hanford-RP due to the waste in underground storage tanks.

The relative contribution of uncategorized metal to the currently reported RH-TRU volume has decreased when compared to the CCA estimate. Hanford-RL reassigned a significant volume of waste that was reported as uncategorized metal in the CCA to other forms based on new characterization information.

To establish the nonradioactive waste component inventory, DOE accumulated WMP information (as WMP average densities in units of kg/m^3) in the CRA-2004 data call by final waste form. This accumulation is shown as a series of tables (Tables DATA-F-10 through DATA-F-30 in Appendix DATA, Attachment F).

These average densities are further summed to determine the total WIPP waste component disposal inventory for CH-TRU and RH-TRU waste and are given in Tables DATA-F-31 and DATA-F-32 of Appendix DATA, Attachment F, and are reproduced here with a comparison to the CCA inventory values in Tables 4-5 (CH-TRU waste) and 4-6 (RH-TRU waste), respectively. It should be noted that MgO is not listed in these tables. Since MgO is not a component of the waste, it is not regarded as a WMP. A discussion of the MgO is contained in Chapter 3.0; CCA Appendix BACK and CCA Appendix SOTERM; Appendix BARRIERS; and Appendix PA, Attachment SOTERM.

Table 4-4. Nonradionuclide TRU Waste Inventory for the WIPP

Final Waste Forms	Current Inventory Volumes (m^3)				Volumes Reported in the CCA (m^3) [1]			
	Emplaced	Stored	Projected	WIPP Disposal	Emplaced	Stored	Projected	WIPP Disposal
	CH-TRU Waste				CH-TRU Waste			
Combustible	6.1×10^2	4.3×10^3	1.9×10^3	8.9×10^3	--	5.8×10^3	4.6×10^3	1.4×10^4
Filter	3.4×10^2	9.9×10^2	5.9×10^2	2.6×10^3	--	2.2×10^2	5.1×10^2	1.2×10^3
Graphite	0.0×10^0	1.2×10^2	1.3×10^0	1.2×10^2	--	5.1×10^2	4.8×10^1	6.0×10^2
Heterogeneous	5.7×10^2	4.9×10^4	9.7×10^3	7.0×10^4	--	2.7×10^4	1.3×10^4	5.1×10^4
Inorganic Nonmetal	9.7×10^2	1.1×10^4	6.8×10^1	1.2×10^4	--	3.1×10^3	9.4×10^2	4.9×10^3
Lead and Cadmium Metal Waste	8.1×10^1	1.4×10^2	3.2×10^1	2.9×10^2	--	3.5×10^1	3.3×10^2	6.6×10^2
Salt Waste	1.5×10^3	1.5×10^2	1.9×10^2	2.1×10^3	--	2.1×10^1	3.3×10^2	6.4×10^2
Soils	0.0×10^0	3.0×10^2	6.0×10^3	1.3×10^4	--	4.1×10^2	6.0×10^3	1.2×10^4
Solidified Inorganics	3.3×10^3	3.5×10^4	7.3×10^2	4.0×10^4	--	9.6×10^3	4.5×10^3	1.8×10^4
Solidified Organics	0.0×10^0	5.2×10^3	3.8×10^2	6.0×10^3	--	9.1×10^2	7.5×10^1	1.1×10^3
Uncategorized Metal	3.6×10^2	2.4×10^3	5.1×10^3	1.4×10^4	--	1.1×10^4	2.3×10^4	5.4×10^4
Total CH-TRU Waste Volumes	7.7×10^3	1.1×10^5	2.5×10^4	1.7×10^5	--	5.8×10^4	5.4×10^4	1.6×10^5

Source: Current inventory volumes - Appendix DATA, Attachment F; Volume reported in the CCA – TWBIR Revision 3

[1] Comparisons between the current inventory values and the values reported in the CCA are made in detail in Appendix DATA, Attachment F, Annex B

[2] The WIPP is limited to 7,079 m^3 of RH-TRU waste by agreement with the State of New Mexico.

Table 4-4. Nonradionuclide TRU Waste Inventory for the WIPP — Continued

Final Waste Forms	Current Inventory Volumes (m^3)				Volumes Reported in the CCA (m^3) [1]			
	Emplaced	Stored	Projected	WIPP Disposal	Emplaced	Stored	Projected	WIPP Disposal
	RH-TRU Waste				RH-TRU Waste			
Combustible	--	1.8×10^1	8.9×10^{-1}	1.8×10^1	--	3.6×10^1	4.9×10^1	--
Filter	--	8.9×10^0	8.9×10^0	1.0×10^1	--	--	--	--
Heterogeneous	--	6.1×10^2	3.8×10^3	1.3×10^3	--	2.3×10^3	5.5×10^3	--
Inorganic Non-Metal	--	4.3×10^1	4.4×10^1	5.1×10^1	--	4.6×10^1	2.1×10^1	--
Lead and Cadmium Metal Waste	--	1.2×10^1	7.1×10^0	1.3×10^1	--	7.1×10^0	6.7×10^1	--
Soils	--	0.0×10^0	2.0×10^2	3.4×10^{-1}	--	--	--	--
Solidified Inorganics	--	4.5×10^3	3.3×10^2	4.6×10^3	--	1.1×10^3	2.3×10^2	--
Solidified Organics	--	9.5×10^0	0.0×10^0	9.5×10^0	--	3.6×10^0	0.0×10^0	--
Uncategorized Metal	--	8.4×10^1	6.1×10^3	1.1×10^3	--	1.2×10^2	1.7×10^4	--
Total RH-TRU Waste Volumes[2]	--	5.3×10^3	1.0×10^4	7.1×10^3	--	3.6×10^3	2.3×10^4	– –
Total TRU Waste Volumes	7.7×10^3	1.1×10^5	3.5×10^4	1.8×10^5	-	6.2×10^4	7.7×10^4	1.7×10^5

Source: Current inventory volumes - Appendix DATA, Attachment F; Volume reported in the CCA – TWBIR Revision 3

[1] Comparisons between the current inventory values and the values reported in the CCA are made in detail in Appendix DATA; Attachment F, Annex B

[2] The WIPP is limited to 7,079 m^3 of RH-TRU waste by agreement with the State of New Mexico.

DOE reports the average density for WMPs because these values are used to generate the waste-related inputs for PA. Section 3.4 of the TWBIR recommends use of the average value, based on the methodology used to obtain and report data. CRA-2004 also uses average values for the WMPs to generate waste-related inputs for PA.

Analysis of the current inventory estimate and the CCA inventory estimate for CH-TRU waste shows that waste materials expected for shipment to WIPP have changed slightly since the CCA. The relative occurrence (expressed as the kg/m^{3}of a given material in the waste) of iron (Fe), aluminum (Al), and other metal alloys is smaller in the current inventory estimate than it was in the CCA inventory estimate. In addition, the relative occurrence of solidified organics, cement, soils, and vitrified material is smaller in the current inventory estimate than it was in the CCA inventory estimate. In contrast, the relative occurrence of cellulosic, plastic, and rubber (CPR) materials and other inorganic materials is larger in the current inventory estimate than it was in the CCA inventory estimate. The current inventory estimate reflects a shift from an expected waste form consisting of 40 percent metals, 15 percent CPR materials and 45 percent other materials reported in the CCA to a waste form that consists of 34 percent metals, 25 percent CPR materials and 41 percent other materials. The current inventory estimate reflects a higher occurrence of CPR materials primarily because of a process change at INEEL. At the time of the CCA, INEEL expected to thermally treat a significant quantity of waste that contained higher than average quantities of CPR materials. Through the process of thermal treatment, the CPR materials in the waste would be destroyed. INEEL currently plans to supercompact the waste that they had originally planned to thermally treat. Supercompaction does not destroy CPR materials in the waste. As a consequence, the waste expected to come to WIPP from INEEL has increased CPR materials relative to those reported for the CCA.

Table 4-5. WIPP CH-TRU Waste and Container Material Disposal Inventory

Waste Materials	Average Density Based on Current Inventory (kg/m^3)	Average Density Reported in the CCA (kg/m^3)
Waste Materials		
Fe-Base Metal/Alloys	1.1×10^2	1.7×10^2
Al-Base Metal/Alloys	1.4×10^1	1.8×10^1
Other Metal/Alloys	3.0×10^1	6.7×10^1
Other Inorganic Materials	4.2×10^1	3.1×10^1
Vitrified Materials	6.2×10^0	5.5×10^1
Cellulosic Material	5.8×10^1	5.4×10^1
Rubber	1.4×10^1	1.0×10^1
Plastic	4.2×10^1	3.4×10^1
Solidified Inorganic Materials	7.7×10^1	5.4×10^1
Solidified Organic Materials	1.6×10^1	5.6×10^0
Cement (Solidified)	2.9×10^1	5.0×10^1
Soil	1.9×10^1	4.4×10^1
Container Materials		

Steel	1.7×10^{2}	1.4×10^{2}
Plastic and Liners	1.6×10^{1}	2.6×10^{1}
Lead	1.4×10^{-2}	0.0×10^{0}

Source: Appendix DATA, Attachment F.

Table 4-6. WIPP RH-TRU Waste and Container Material Disposal Inventory

Waste Materials	Average Density Based on Current Inventory (kg/m^3)	Average Density Reported in the CCA (kg/m^3)
Waste Materials		
Fe-Base Metal/Alloys	1.1×10^{2}	1.0×10^{1}
Al-Base Metal/Alloys	2.5×10^{0}	7.1×10^{0}
Other Metal/Alloys	3.2×10^{1}	2.5×10^{2}
Other Inorganic Materials	3.5×10^{1}	6.4×10^{1}
Vitrified Materials	5.7×10^{-2}	4.7×10^{0}
Cellulosic Material	4.5×10^{0}	1.7×10^{1}
Rubber	3.1×10^{0}	3.3×10^{0}
Plastic	4.9×10^{0}	1.5×10^{1}
Solidified Inorganic Materials	3.9×10^{1}	2.2×10^{1}
Solidified Organic Materials	4.0×10^{0}	9.3×10^{-1}
Cement (Solidified)	8.7×10^{-1}	1.0×10^{0}
Soil	2.6×10^{1}	
Container Materials		
Steel	4.8×10^{2}	4.5×10^{2}
Plastic and Liners	1.4×10^{0}	3.1×10^{0}
Lead	4.4×10^{2}	4.7×10^{2}

Source: Appendix DATA, Attachment F

The container materials for CH-TRU waste are primarily steel, plastic, and lead. The current inventory estimate reflects a higher occurrence of steel, a lower occurrence of plastic, and a higher occurrence of lead in the packages coming to WIPP when compared to the CCA inventory estimate. Additional steel in packages currently planned to come to WIPP results from the planned increased use of overpacks (Type A or equivalent packages, pipe overpacks, ten-drum overpacks, 100-gallon drum overpacks, etc.). The increased use of overpack containers in the current inventory estimate also leads to a reduction in the use of plastic liners in packages coming to WIPP. Thus, the density of plastic packaging material is smaller than it was in the CCA inventory estimate.

The inventory of chemical components of the waste (needed for scoping calculations to determine their importance on performance) was requested in the CRA-2004 data call. The information requested by DOE was specific to solidified waste forms destined for disposal at the WIPP and included complexing agents, nitrates, sulfates, phosphates, and cement. A summary of this information can be found in Appendix DATA, Attachment F. Additional information addressing the impact, limits, and characterization (or noncharacterization) of these chemical

components is provided in Appendix TRU WASTE, Sections TRU WASTE-2.0 and TRU WASTE-3.0. The importance of these chemical components to PA is assessed in Appendix TRU WASTE, Section TRU WASTE-2.0.

4.1.3.3 Radionuclide Inventory Roll-Up

Estimates of the radionuclide inventory are included in Appendix DATA, Attachment F. TRU waste sites derive these estimates based on acceptable knowledge including any quantitative results that may be available. In the data call for CRA-2004, TRU waste sites reported estimated values for radionuclide activities on a waste stream basis including both the stored and projected components. The actual activity of disposed waste is determined quantitatively prior to shipment, as discussed in Section 4.4.2.

The disposal radionuclide inventory for PA is a calculated value based on the radionuclide activities reported for emplaced, stored, and projected waste. The radionuclide activities in the projected component of the waste are scaled using the scaling factor and added to the radionuclide activities for stored and emplaced components of the waste.

This calculation is based on all radionuclide activities decayed to the end of 2001. Radioactive decay and build-up calculations were performed using the commercially available code ORIGEN2 (Croff 1980). The levels of radioactivity reported include contributions from both parent and daughter decay products. For CH-TRU waste, the total Ci for each radionuclide is divided by the CH-TRU disposal volume to obtain a Ci per cubic meter concentration for each radionuclide on a repository level. For RH-TRU waste, the total decayed WIPP Ci for each radionuclide is divided by the RH-TRU disposal volume to obtain a radionuclide concentration in Ci per cubic meter.

The WIPP disposal radionuclide inventory used in PA for both CH-TRU and RH-TRU wastes is shown in Table 4-7. Activities at closure (2033) are used in PA. The table shows individual radionuclide activity in Ci for both CH-TRU and RH-TRU waste. Based on the total Ci shown in Table 4-7 and to the extent to which each radionuclide is regulated by Section 191.13, approximately 98.6 percent of the regulated CH-TRU activity at repository closure is contributed by ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Am.

Table 4-7. Radionuclides Considered in PA

Radionuclide	Current Inventory Values			Values Reported in the CCA			Release Calculations (1)			
	Inventory at Closure (Ci)	EPA Units		Inventory at Closure (Ci)	EPA Units		Cuttings, Cavings, and Spall Release	Direct Brine Release	Salado Release	Culebra Release
		At Closure(4)	At 10,000 years		At Closure	At 10,000 years				
^{238}Pu	1.25×10^{6}	5.04×10^{3}	2.61×10^{-23}	1.94×10^{6}	5.64×10^{3}	1.32×10^{-22}	x	x	(2)	(2)
^{239}Pu	6.65×10^{5}	2.68×10^{3}	2.01×10^{3}	7.95×10^{5}	2.31×10^{3}	1.73×10^{3}	x	x	x	x
^{241}Am	4.58×10^{5}	1.84×10^{3}	2.48×10^{-4}	4.88×10^{5}	1.42×10^{3}	1.78×10^{-4}	x	x	x	x
^{240}Pu	1.08×10^{5}	4.36×10^{2}	1.51×10^{2}	2.14×10^{5}	6.22×10^{2}	2.16×10^{2}	x	x	c	c
^{137}Cs	1.79×10^{5}	7.19×10^{1}	0.00×10^{0}	9.31×10^{4}	2.71×10^{1}	0.00×10^{0}	x	--	--	--
^{90}Sr	1.42×10^{5}	5.71×10^{1}	0.00×10^{0}	8.73×10^{4}	2.54×10^{1}	0.00×10^{0}	x	--	--	--
^{233}U	1.27×10^{3}	5.12×10^{0}	4.91×10^{0}	1.95×10^{3}	5.67×10^{0}	5.44×10^{0}	x	x	c	c
^{229}Th	5.39×10^{0}	2.17×10^{-2}	3.04×10^{0}	9.97×10^{0}	2.90×10^{-2}	3.40×10^{0}	--	x	c	c
^{234}U	3.19×10^{2}	1.28×10^{0}	3.03×10^{0}	7.51×10^{2}	2.18×10^{0}	4.10×10^{0}	x	x	x	x
^{230}Th	1.76×10^{-1}	7.07×10^{-3}	2.64×10^{0}	3.06×10^{-1}	8.90×10^{-3}	3.55×10^{0}	--	x	x	x
^{238}U	1.54×10^{2}	6.21×10^{-1}	6.21×10^{-1}	5.01×10^{1}	1.46×10^{-1}	1.46×10^{-1}	--	x	--	--
^{237}Np	1.01×10^{1}	4.06×10^{-2}	4.27×10^{-1}	6.49×10^{1}	1.89×10^{-1}	4.83×10^{-1}	--	x	--	--
^{232}Th	6.83×10^{0}	2.75×10^{-1}	2.75×10^{-1}	1.01×10^{0}	2.94×10^{-2}	2.94×10^{-2}	--	x	--	--
^{226}Ra	6.28×10^{0}	2.53×10^{-2}	2.07×10^{-1}	1.14×10^{1}	3.31×10^{-2}	2.77×10^{-1}	--	--	--	--
^{210}Pb	4.94×10^{0}	1.99×10^{-2}	2.07×10^{-1}	8.75×10^{0}	2.54×10^{-2}	2.77×10^{-1}	--	x	--	--
^{242}Pu	2.71×10^{1}	1.09×10^{-1}	1.07×10^{-1}	1.17×10^{3}	3.40×10^{0}	3.34×10^{0}	--	x	c	c
^{243}Am	2.17×10^{1}	8.75×10^{-2}	5.74×10^{-2}	3.25×10^{1}	9.45×10^{-2}	3.69×10^{-2}	--	x	--	--
^{236}U	1.65×10^{0}	6.66×10^{-3}	8.62×10^{-2}	6.72×10^{-1}	1.95×10^{-3}	1.16×10^{-1}	--	x	--	--
^{235}U	2.28×10^{0}	9.18×10^{-3}	3.21×10^{-2}	1.75×10^{1}	5.09×10^{-2}	7.06×10^{-2}	--	x	--	--
^{14}C	3.25×10^{0}	1.31×10^{-2}	3.90×10^{-3}	1.28×10^{1}	3.72×10^{-2}	1.11×10^{-2}	--	--		
^{232}U	3.06×10^{0}	1.23×10^{-2}	0.00×10^{0}	1.79×10^{1}	5.20×10^{-2}	0.00×10^{0}	--	--	--	--
^{227}Ac	9.57×10^{-1}	3.85×10^{-3}	8.06×10^{-3}	5.05×10^{-1}	1.47×10^{-3}	1.28×10^{-2}	--	--	--	--
^{231}Pa	1.21×10^{0}	4.88×10^{-3}	8.06×10^{-3}	4.67×10^{-1}	1.36×10^{-3}	1.28×10^{-2}	--	--	--	--
^{243}Cm	4.07×10^{-1}	1.64×10^{-3}	0.00×10^{0}	2.07×10^{1}	6.02×10^{-2}	0.00×10^{0}	--	x	--	--
^{248}Cm	9.32×10^{-2}	3.75×10^{-4}	3.68×10^{-4}	3.72×10^{-2}	1.08×10^{-4}	1.06×10^{-4}	--	x	--	--
^{245}Cm	1.92×10^{-2}	7.72×10^{-5}	3.97×10^{-5}	1.15×10^{-2}	3.40×10^{-5}	$1.85 \times 10\text{-}^{5}$	--	x	--	--

Table 4-7. Radionuclides Considered in PA — Continued

Radionuclide	Current Inventory Values			Values Reported in the CCA			Release Calculations (1)			
	Inventory at Closure (Ci)	EPA Units		Inventory at Closure (Ci)	EPA Units		Cuttings, Cavings, and Spall Release	Direct Brine Release	Salado Release	Culebra Release
		At Closure(4)	At 10,000 years		At Closure	At 10,000 years				
^{244}Pu	1.10×10^{-3}	4.44×10^{-6}	4.47×10^{-6}	1.51×10^{-6}	4.34×10^{-9}	1.26×10^{-8}	--	x	--	--
^{244}Cm	2.51×10^{3}	(3)	(3)	7.44×10^{3}	(3)	(3)	x	x	--	--
^{241}Pu	5.38×10^{5}	(3)	(3)	3.94×10^{5}	(3)	(3)	x	x	--	--
Percent of EPA Units at closure represented by nuclides in source term							99.98%	98.71%	48.95%	48.95%
Percent of EPA Units at 10,000 years represented by nuclides in source term							99.65%	99.99%	99.92%	99.92%

Source: Appendix TRU Waste, Section TRU Waste-2.0

1. See Section 6.3 for a discussion of scenarios analyzed by PA and the release pathways.
2. Pu-238 was included in the Salado transport calculations but the release to the Culebra was too low to merit calculation of its transport within the Culebra. The EPA unit percent total at closure increases to 98.71% with Pu-238 added; the percent at 10,000 years is unaffected.

3. Pu-241 and Cm-244 are not listed by Part 191 of the Code of Federal Regulations but are included because their daughters, ^{241}Am and ^{240}Pu, respectively, are significant to performance
4. At closure is decayed through 2033.

x indicates an isotope included in calculation.
c indicates isotopes that are combined for transport with isotopes having similar characteristics.

Approximately 99.5 percent of the regulated RH-TRU activity at repository closure is contributed by ^{137}Cs, ^{90}Sr, ^{239}Pu, ^{240}Pu, ^{241}Am, and ^{238}Pu (derived from data in TRU WASTE, Section TRU WASTE-2.0, Table TRU WASTE-9). The same radionuclides were identified in the CCA as the largest contributors to the regulated CH-TRU waste and RH-TRU waste activity at repository closure (see CCA Appendix WCA, Section 8.2). Overall, activity for all TRU radionuclides has decreased from 3.44×10^6 Ci (at 2033) reported in the CCA to 2.48×10^6 Ci (at 2033) in the current inventory estimate. The results for RH-TRU waste show variations in individual radionuclide activity and an overall increase in reported activity since the CCA.

The values presented in Table 4-7 are used as input to the PA calculations. A more detailed examination of the programs prepared by DOE to collect supplemental radiological data are provided in Section 4.4.

In addition to the inventory in Table 4-7, DOE has determined the average radionuclide inventory for each of the 779 (693 CH-TRU waste streams and 86 RH-TRU waste streams) CH-TRU and RH-TRU waste streams (see Appendix DATA, Attachment F). In the conceptual model for PA, the distribution of 693 CH-TRU waste streams and one RH-TRU waste stream (representing all of 86 the RH-TRU waste) are randomly sampled in the PA to determine releases due to inadvertent human intrusion. This process is discussed in Section 6.4.12.4 and assumes that each container in the waste stream has the average radionuclide inventory for that stream.

4.2 Waste Components and Characteristics

This section of the application is provided to document compliance with the provisions of Section 194.24(b) and describes, in summary fashion,

- those components or characteristics of the waste that are most important in terms of their impact on the performance of the WIPP disposal system and
- the limits imposed by DOE on the significant components or characteristics of the waste to ensure that emplaced waste will behave in a manner that is consistent with the inventory assumed for the performance calculations.

4.2.1 Identification and Qualification

The waste characteristics and components expected to be most significant to performance are the predominant radionuclides and their associated characteristics and components affecting actinide mobility. These are summarized in Table 4-8; they are unchanged from the CCA.

Table 4-8. Waste Characteristics and Components Expected to be Most Significant to Performance

Component	Characteristic	Reason for Significance
^{239}Pu, ^{240}Pu, ^{241}Am, ^{233}U, and ^{234}U	Activity	99 percent of EPA unit after 2,000 years
^{238}Pu	Activity	Dominates EPA unit at early times
Pu and Am	Solubility	Large EPA unit; mobility depends on solubility
^{238}U	Activity	Very low activity; dilutes higher-activity uranium isotopes for brine-based releases
Iron	Redox Potential	Sustains reducing environment so that lower, less soluble oxidation states of actinides predominate
Cellulosic material, plastic, rubber, nitrate, sulfate	Nutrient for Microbes	Microbial nutrients that are metabolized to methane and several other gases, increasing gas pressure; formation of colloids
Humic materials, cellulose breakdown products	Colloid Formation	Formation of humic colloids that sorb and transport actinides
Nonferrous metals	Organic Complexation	Prevent increase in actinide solubility by binding with ligands
Waste	Shear Strength	Important to spalling and cavings

Source: Appendix TRU Waste, Section 2

The waste unit factor is the number of millions of Ci of alpha-emitting TRU radionuclides with half-lives longer than 20 years (Part 191 of the Code of Federal Regulations, Appendix A). In the WIPP, 2.48[2] million Ci of TRU waste will be in the repository at closure, so the waste unit factor is 2.48. The radionuclides that contribute to the waste unit factor are based on an analysis (see Appendix TRU WASTE, Section TRU WASTE-2.0) of the radionuclide inventory in Appendix DATA, Attachment F and are presented in Table 4-9 (decayed to the end of 2033). The radionuclide contributions to the waste unit factor from the CCA are also presented in Table 4-9. Waste characteristics and components with an insignificant impact on performance are summarized in Table 4-10. This table remains unchanged from CCA Table 4-9.

4.2.2 Repository Limits

The following discussion describes the criteria in Sections 194.24(c)(1) and 194.24(c)(2).

[2] The value for the waste unit factor (WUF) in the CCA was inconsistently described; Chapter 4, Section 4.2.1 correctly listed the WUF that was used in the CCA PA as 3.44. CCA Appendix WCA Sections 1.4.2 and WCA Attachment WCA.8.1 incorrectly stated the 1995 decayed value of 4.07 was used in the CCA PA, however the preface to Attachment WCA.8.2 identified and corrected the error. During the EPA's review of the CCA, EPA required DOE to recalculate a new WUF of 3.59 that was ultimately included in the EPA's PAVT (EPA 1998). After the certification, the DOE incorporated the PAVT WUF value of 3.59 in the compliance baseline through an EPA approved change request (EPA 2002).

Waste components are the controlling factors for the waste characteristics. Therefore, limits imposed on the waste components necessarily serve to limit the waste characteristics. In the case where a characteristic is benign with respect to repository performance, no control of the corresponding component is necessary and no limits need be imposed on that component. Conversely, should repository performance be sensitive to a particular waste characteristic, then control of the corresponding component is mandated and limits are established to restrict the maximum or minimum amounts of that component allowed for disposal.

Based on the PA calculations and the rationale described in Appendix TRU WASTE, Table 4-11 identifies the characteristics of the components for which determination prior to emplacement is required. Table 4-11 also lists any applicable repository-based emplacement limits for the components. Discussions of the rationale for the proposed assaying and emplacement limits for each component are presented in Appendix TRU WASTE. All of the components identified in

Table 4-9. Radionuclides That Contribute to the Waste Unit Factor

Nuclide	Half-Life (years)	Current Inventory Values		Values Reported in the CCA(1)	
		Inventory at Closure (Ci)	Percent of Waste Unit at Closure	Inventory at Closure (Ci)	Percent of Waste Unit at Closure
^{241}Am	4.33×10^{2}	4.58×10^{5}	1.82×10^{1}	4.88×10^{5}	1.42×10^{1}
^{243}Am	7.37×10^{3}	2.17×10^{1}	8.63×10^{-4}	3.25×10^{1}	9.45×10^{-4}
^{249}Cf	3.51×10^{2}	7.24×10^{-2}	2.88×10^{-6}	6.38×10^{-2}	1.85×10^{-6}
^{251}Cf	9.00×10^{2}	5.10×10^{-4}	2.03×10^{-8}	3.67×10^{-3}	1.07×10^{-7}
^{243}Cm	2.91×10^{1}	4.07×10^{-1}	1.62×10^{-5}	2.07×10^{1}	6.02×10^{-4}
^{245}Cm	8.50×10^{3}	1.92×10^{-2}	7.62×10^{-7}	1.15×10^{-2}	3.34×10^{-7}
^{246}Cm	4.76×10^{3}	2.22×10^{0}	8.80×10^{-5}	1.02×10^{-1}	2.97×10^{-6}
^{247}Cm	1.56×10^{7}	9.45×10^{0}	3.75×10^{-4}	9.51×10^{-9}	2.76×10^{-13}
^{248}Cm	3.48×10^{5}	9.32×10^{-2}	3.70×10^{-6}	3.72×10^{-2}	1.08×10^{-6}
^{237}Np	2.14×10^{6}	1.01×10^{1}	4.00×10^{-4}	6.49×10^{1}	1.89×10^{-3}
^{238}Pu	8.77×10^{1}	1.25×10^{6}	4.98×10^{1}	1.94×10^{6}	5.64×10^{1}
^{239}Pu	2.41×10^{4}	6.65×10^{5}	2.64×10^{1}	7.95×10^{5}	2.31×10^{1}
^{240}Pu	6.56×10^{3}	1.08×10^{5}	4.30×10^{0}	2.14×10^{5}	6.22×10^{0}
^{242}Pu	3.75×10^{5}	2.71×10^{1}	1.08×10^{-3}	1.17×10^{3}	3.40×10^{-2}
^{244}Pu	8.00×10^{7}	1.10×10^{-3}	4.38×10^{-8}	1.51×10^{-6}	4.39×10^{-11}
Total	---	2.48×10^{6}	9.86×10^{1}	3.44×10^{6}	9.99×10^{1}

Source: Appendix TRU WASTE, Section TRU WASTE-2.0.
(1) Radionuclide activities and the WUF were reported with conflicting values in several places in the CCA. The values used in this table were the actual values used in the performance assessment for the CCA as recorded in the PAPDB.

Table 4-10. Waste Characteristics and Components Expected to be Insignificant

Characteristics and Component	Reason for insignificant impact
Radionuclides other than those in Table 4-8	EPA unit is negligible fraction of total, even with ingrowth
Substances that may affect pH[1]	pH is buffered by MgO backfill
Substances that produce CO_2 [1]	CO_2 is removed by reaction with MgO backfill
Intrinsic and mineral fragment colloids	Fraction of actinides mobilized by these colloids is insignificant
Organic ligands	Removed by binding with Mg and nonferrous metal
Heat generated by exothermic reactions	Heats of formation are small and thermal mass of repository is large so that temperature rise is negligible
Fluid in the waste	Negligible compared to brine volume

Source: Appendix TRU WASTE [1] These components are significant for gas generation, but not for actinide solubility.

Table 4-11. Repository-Based Emplacement Limits Related to PA

Waste Components	Associated Waste Characteristics	Components Requiring Quantification	Emplacement Limits
radionuclides	radioactivity at closure radioactivity after closure solubility colloid formation reduction-oxidation state	^{241}Am ^{238}Pu ^{239}Pu ^{240}Pu ^{242}Pu ^{233}U ^{234}U ^{238}U ^{90}Sr ^{137}Cs	none[1]
ferrous metals (iron)	reduction-oxidation potential H_2 gas generation complexing with organic ligands	none	minimum = 2×10^7 kilograms (amount from containers)[2]
cellulosic, plastic, rubber materials	gas generation humic colloids (see below) gas generation	sum of emplaced components	maximum = 2.2×10^7 kilograms[3]
sulfates	gas generation	none	none[4]
nitrates	gas generation	none	none[4]
solid components	particle size effective shear resistance to erosion tensile strength	none	none
free liquid emplaced with waste	gas generation	none	maximum = 1684 cubic meters for CH-TRU (limit of 1 percent total waste volume as set by the WAC) [e]
humic substances	radionuclide-bearing humic colloids	none	none
nonferrous metals (metals other than iron)	bind with organic ligands and prevent increased solubility	none	minimum = 2×10^3 kilograms[5]
organic ligands	solubility	none	none[4]

Source: Appendix TRU WASTE, Section TRU WASTE-3.0

1 Inventory curie content will be tracked.

2 Minimum set to ensure sufficient reactants for reducing radionuclides to lower and less soluble oxidation states. .

3 Maximum set to ensure sufficient MgO backfill is available to react with CO_2 produced.

4 For the current waste generation processes that are documented in the Transuranic Waste Inventory Update Report--Supporting Information for the 2004 WIPP Compliance Recertification Application.

5 Minimum quantity for complexing with organic ligands (see Appendix PA, Attachment SOTERM).

CCA Appendix WCA and Appendix TRU WASTE, Section TRU WASTE.2-0 were found to be insignificant to disposal system performance. Therefore, it is not necessary to establish additional container-based emplacement limits for these components.

Table 4-12 is a supplement to Table 4-11; that is, it lists the repository limits imposed by the LWA . Collectively, Tables 4-11 and 4-12 define the WIPP repository-based emplacement limits on the waste.

Since the first waste shipment arrival at the WIPP, DOE has tracked the quantities of materials identified in Tables 4-11 and 4-12 that have been emplaced in the repository. The quantities of these materials emplaced in WIPP since its opening through September 30, 2002, are listed in Tables 4-13 and 4-14.

4.2.3 Waste Container Limits

Waste limits have been established by DOE as part of the WIPP's design development and by the WIPP LWA. Waste container limits relevant to the requirements of the WIPP LWA are identified in Table 4-15. The CH-TRU Waste Acceptance Criteria (WAC) restrict the physical, chemical, and radiological properties of the waste to mitigate conditions that will have adverse impacts on human health and the environment.

DOE requires the TRU waste sites to prepare a waste-certification plan that lists the methods and techniques used to determine compliance with the CH-TRU WAC and the QA program (see Appendix QAPD-2004). This includes QA and quality control criteria that are applied to the generator's waste certification program. Each participating TRU waste site is responsible for developing and implementing specific TRU waste program documents (plans) that address all activities pertaining to TRU waste characterization, certification, packaging, and transportation of TRU waste to the WIPP. These plans include the TRU Waste Certification Plan and associated QA plan, the TRUPACT-II Authorized Methods for Payload Control and associated QA plans, and the TRU waste characterization QAPjP. Methods of compliance with each criterion and requirement are documented or specifically referenced and include procedural and administrative controls.

Table 4-12. Repository-Based Emplacement Limits Imposed by the LWA

Waste Components	Emplacement Limits
Total Capacity (CH- and RH-TRU)	6.2 million ft^3 (175,564 m^3)
RH-TRU waste total Ci	5.1 million Ci (~18.9×10^{16} Becquerels)
RH-TRU waste total dose rate	No more than five percent by volume of RH TRU waste may exceed 100 rems per hour

Table 4-13. Quantities of Radionuclides Emplaced in the Repository as of September 30, 2002[1,2]

NR=Not reported or reported at values less than 10^{-13}

Radionuclide	Quantity (Ci)	Radionuclide	Quantity (Ci)
^{227}Ac	3.64×10^{-4}	^{147}Pm	NR
^{241}Am	1.17×10^{5}	^{238}Pu	5.64×10^{3}
^{243}Am	4.81×10^{-3}	^{239}Pu	1.38×10^{5}
^{14}C	NR	^{240}Pu	3.10×10^{4}
^{249}Cf	NR	^{241}Pu	4.37×10^{5}
^{251}Cf	NR	^{242}Pu	2.96×10^{0}
^{252}Cf	NR	^{244}Pu	NR
^{243}Cm	NR	^{226}Ra	7.88×10^{-6}
^{244}Cm	NR	^{228}Ra	NR
^{245}Cm	NR	^{79}Se	NR
^{246}Cm	NR	^{151}Sm	NR
^{247}Cm	NR	$^{121}Sn^{m}$	NR
^{248}Cm	NR	^{126}Sn	NR
^{60}Co	3.47×10^{-7}	^{90}Sr	NR
^{135}Cs	NR	^{99}Tc	NR
^{137}Cs	3.41×10^{-9}	^{229}Th	NR
^{129}I	NR	^{230}Th	2.41×10^{-5}
^{40}K	2.87×10^{-5}	^{232}Th	2.61×10^{-6}
^{22}Na	5.34×10^{-6}	^{232}U	NR
^{59}Ni	NR	^{233}U	2.73×10^{-1}
^{63}Ni	NR	^{234}U	1.26×10^{0}
^{237}Np	4.00×10^{-1}	^{235}U	1.22×10^{-1}
^{231}Pa	5.04×10^{-4}	^{236}U	NR
^{210}Pb	NR	^{238}U	6.53×10^{0}
^{107}Pd	NR	^{93}Zr	NR

Source: WWIS

[1] These data were taken from the WWIS and differ slightly from the data reported for WIPP in Appendix DATA Attachment F. This is because all data in Appendix DATA Attachment F have been decayed to a single base year 2001 (i.e., decayed through 2001) while the data provided in the WWIS are reported values based on assay and have not been decayed to a single base year.

[2] Isotopes other than the 10 listed in Table 4-11 are not required to be tracked unless required by DOT regulations.

Table 4-14. Quantities of Non-Radionuclide Waste Components Emplaced in the Repository as of September 30, 2002, and Associated Emplacement Limits

Waste Components	Quantity	Emplacement Limit
Ferrous metal (iron)	2,487,261 kilograms	Minimum = 2×10^7 kilograms
Cellulosic, plastic, and rubber materials	700,981 kilograms	Maximum = 2.2×10^7 kilograms
Nonferrous metals (metals other than iron)	31,059 kilograms	Minimum = 2×10^3 kilograms

Source: WWIS

Table 4-15. Container-Based Limits

Waste Component or Characteristic	Limit
CH-TRU and RH-TRU waste activity	> 100 nCi/gram of waste
CH-TRU waste surface dose rate	< 200 mrem/hour (CH)
RH-TRU waste surface dose rate	≤ 1000 rem/hour (RH)
RH-TRU waste Ci per liter	23 Ci/liter averaged over the container

Based on the acceptance of the site-specific waste characterization and QA program, the CBFO Manager is responsible for granting and revoking the program certification that allows the TRU waste site to characterize and to ship waste to WIPP. The CBFO performs certification audits of the TRU waste sites to assess the implementation of and compliance with the approved plans. On the basis of acceptable results of the certification audits, the DOE grants TRU waste certification authority and transportation authority to the TRU waste site. DOE provides continuing oversight of TRU waste sites through periodic audits of TRU waste characterization, certification, and transportation activities.

Consistent with the provisions of section 194.8, the EPA also has a role in the approval process. The EPA determines compliance with requirements for site-specific QA programs.

CH-TRU WAC provides the limits for the physical, radiological, and chemical characteristics of the waste in addition to specifications for the waste packaging. Waste that is characterized according to and approved program and meets the requirements of the CH-TRU WAC can be shipped to the WIPP. Additional information regarding the TRU waste site waste characterization and QA program requirements is provided in Appendix TRU WASTE.

Appropriate changes to the CH-TRU WAC will be published to reflect new restrictions and conditions imposed by permits and certifications. These changes will be communicated to the TRU waste sites as a change to the CH-TRU WAC. Those retrievably stored or newly generated waste streams that do not meet the CH-TRU WAC, however, may require processing (including repackaging and/or treatment) until compliance can be attained. Any such processing is the responsibility of the site proposing to ship the waste to the WIPP. TRU waste that has been characterized in accordance with prior revisions of the CH-TRU WAC may be reconciled with current requirements. This reconciliation is documented and filed at the TRU waste site.

Changes related to waste characterization documents have occurred since the initial certification. Waste characterization elements of the QAPP (TRU Waste Characterization Quality Assurance Program Plan, CAO [CBFO] 94-1010) have been incorporated into recent revisions of the CH-TRU WAC, the WAP, and the QAPD. The QAPP and the TRU Waste Characterization Sampling and Analysis Methods manual (DOE 1995b) have been cancelled.

4.3 Waste Controls

This section describes those processes that ensure compliance with the limits for CH-TRU waste and RH-TRU waste to be emplaced in the WIPP disposal system.

4.3.1 Load Management

The following discusses compliance with Section 194.24(d) and (f).

Load management is the process of controlling the shipment and emplacement of TRU waste in order to achieve a predetermined (that is, nonrandom) distribution of waste within the disposal system. DOE must assess whether the spatial distribution of waste in the repository could have significance for human intrusion on long-term repository performance. As described in Section 6.4.12, drilling events are assumed to be random in time and space. The location of each intrusion borehole within the waste disposal region is sampled randomly. Each intrusion borehole that penetrates waste may encounter CH-TRU waste or RH-TRU waste. For calculating direct releases to the accessible environment, containers are assumed to be placed in the WIPP from the various waste streams which comprise CH-TRU waste in a random manner. In calculating direct releases resulting from a drill bit penetrating containers, each of the three stacked containers can come from different waste streams and have different activity loading. As described in Section 6.5, direct release from cuttings and cavings are the most important releases in assessing compliance with the quantitative containment requirements in Section 191.13(a) for both the CCA and CRA-2004.

The CCDFs presented in Section 6.5 are constructed by estimating cumulative radionuclide releases to the accessible environment for 10,000 different possible futures. The estimated release for each future includes the randomly sampled waste streams for each of the various intruding boreholes that comprise that sampled future. A sampling of 10,000 futures is large enough that the relatively low probability combination of three of the waste streams with higher activity loading occurring in a single drilling event is captured in the CCDFs presented in Section 6.5. As described in Section 6.5, the CCDF is not impacted by sampling uncertainty so the assumption of random emplacement of containers is not important to the location of the CCDF and a load management plan is not necessary to support PA assumptions.

In support of CRA-2004, DOE investigated the impact of non-homogeneous patterns of waste emplacement in the repository. The investigation verified that non-homogeneous emplacement will not have a significant impact on PA. The results of the investigation are reported in Chapter 6.0.

4.3.2 WIPP Waste Information System

The following discusses compliance with the criteria at Sections 194.24(c)(4), (c)(5), and (e).

The WWIS is an electronic data management system used by DOE to gather, store, and process information pertaining to TRU waste destined for or disposed at the WIPP. The system supports those organizations that have responsibility for managing TRU waste by collecting information into one source and providing data in a uniform format that has been verified or certified as being accurate. The WWIS is used to store information pertaining to characterization, certification, and emplacement of waste at the WIPP. Information in this system is supplied by the TRU waste sites and the WIPP facility. Figure 4-2 depicts the process and flow of data from the TRU waste sites to the WWIS.

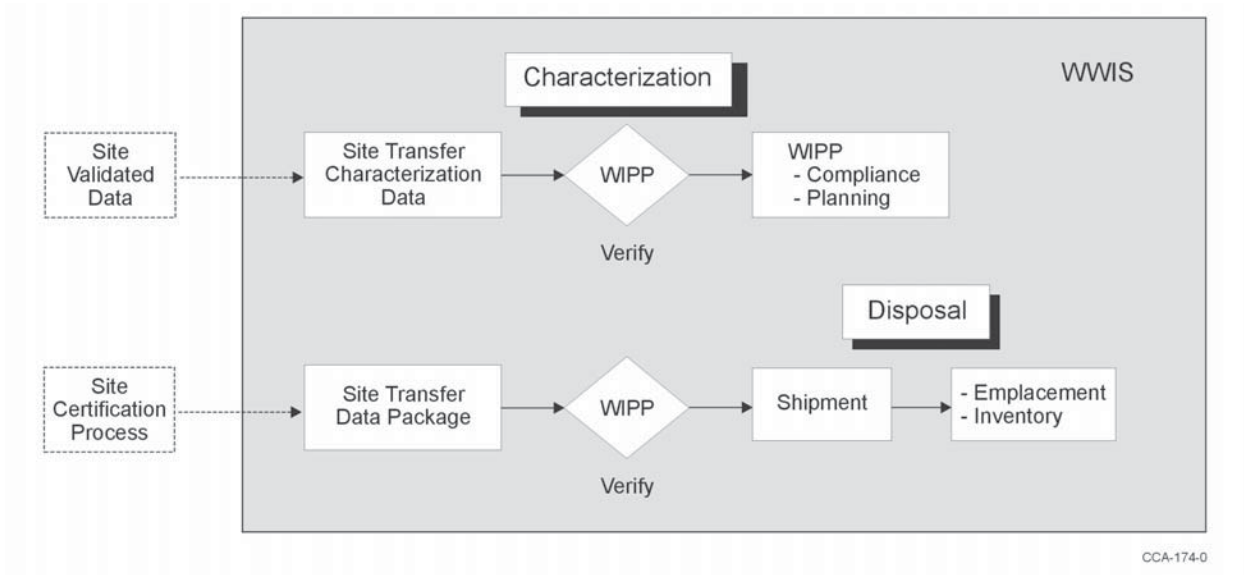

Figure 4-2. WIPP Waste Information System Process and Data Flow

At the time of the CCA, the WWIS used the Oracle (Version 7) database management system that followed American National Standards Institute (ANSI) standard query language. The database management system was resident on a Digital Equipment Corporation hardware platform, compliant with the majority of existing computer hardware throughout the DOE complex. UNIX was the operating system and supported multiuser and multitasking environments. The current computing system remains unchanged except that the software employed now is Oracle Version 9. Additional computing system upgrades may be implemented in the future.

Minor upgrades and improvements have been made to the WWIS since the EPA certification. Minor changes to several documents related to the design and operation of the system have also been made. All changes improved the system or updated information. The WWIS is available seven days a week, 24 hours a day except for periodic maintenance and supports the maximum number of simultaneous users determined by the database management system license agreement and the operating system license agreement. The network communication protocol of the WWIS is Transmission Control Protocol/Internet Protocol (TCP/IP). Other features include automatic

limit, range, and QA checks; automatic report generation; and compliance with QA requirements for computer software for nuclear facility applications (American Society of Mechanical Engineers [ASME], Nuclear Quality Assurance [NQA]-1, NQA-2, Part 2.7, and NQA-3 [ASME 1989a, 1989b, and 1989c]).

The following WWIS documentation has been identified as necessary and sufficient to document the software lifecycle:

- WWIS Evaluation & Recommendation – provides an evaluation of hardware and software configurations for the WWIS and recommends an approach for implementation.

- WWIS Software Quality Assurance Plan – identifies and defines the standards and methodologies required to ensure conformance to accepted quality standards during the development, maintenance, and operation of the WWIS. This plan ensures that products conform to established technical requirements.

- WWIS Software Verification and Validation Plan – describes the criteria for verification and validation activities for the requirements, design, testing, and all necessary documentation.

- WWIS Software Requirements Specification – defines the requirements essential to the WWIS based on the WWIS Functional and Operational Requirements Document. All requirements shall be internally consistent and verifiable through demonstration, analysis, or testing.

- WWIS Software Design Description – defines the major features of the WWIS including the operating environment, databases, tables, external and internal interfaces, overall structure, sizing, modeling, and system throughput.

- WWIS Software Configuration Management Plan – describes the methods used for identifying software configuration items, controlling and implementing changes, and recording and reporting change implementation status.

- WWIS Security Plan – details the information for handling the security needs of the system (data, software, and hardware). This plan also describes password and access control procedures.

- At the time of the CCA, the DOE identified more than 130 data fields for inclusion in the WWIS. An alphabetical listing and description of these data fields is found in the WAP (NMED 2002). The majority of these data fields are considered pertinent to demonstrate compliance with TRU waste transportation and disposal requirements. These listings are now updated and maintained in the WWIS User's Manual (DOE 2001).Radionuclides present in container

- Activity of individual radionuclides

- Uncertainty associated with the activity of individual radionuclides

- Mass of the individual radionuclides
- Uncertainty associated with the mass of individual radionuclides
- Estimated weight of waste material parameters
- Date of assay

To ensure compliance with the data requirements, personnel at the WIPP review the WWIS information on each data package for completeness and adequacy before notifying the shipping site of acceptance. Thus, the WWIS becomes an integral part of the waste information screening process described in the WAP.

4.3.3 Quality Assurance

The implementation of a formal QA program demonstrates the commitment of DOE to perform all work activities and operations to the highest standards of quality. DOE has established an effective QA program that complies with applicable sections of NQA-1, NQA-2 (Part 2.7), and NQA-3. The management controls defined by the various QA plans and procedures ensure that all work is planned, documented, performed under controlled conditions, and periodically assessed to establish work item quality and process effectiveness and to promote improvement. The complexity, inherent risk, and significance of the work to the overall project and to public safety are key factors in determining applicable quality management requirements. Internal and external organizational interfaces and responsibilities are described in detail in Chapter 5.0.

The DOE TRU Waste Characterization QAPP (DOE 1995a) and the TRU Waste Characterization Sampling and Analysis Methods Manual (DOE 1995b) were replaced as of November 26, 1999. Figure 4-3 shows the revised QA document hierarchy for waste characterization.

Additional information regarding the quality assurance and quality controls used in ascertaining the waste description is given in Chapter 5.0.

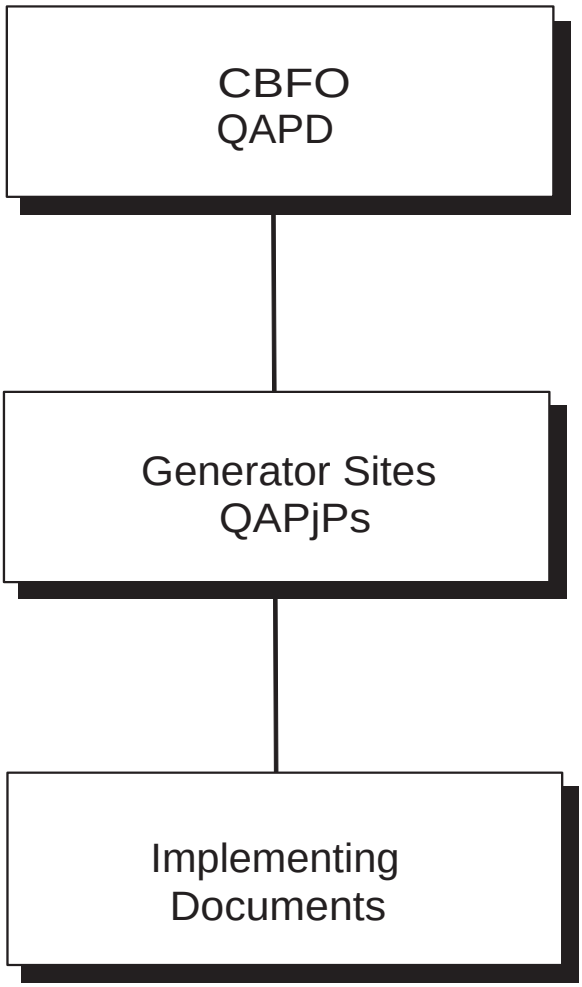

Figure 4-3. QA Documents Hierarchy

4.3.3.1 Performance Demonstration Programs

Another aspect of the waste-characterization QA process that has changed is related to the Performance Demonstration Program (PDP). The program evaluates the capability of sites to perform waste characterization within acceptable limits. Initially, participating laboratories were required to participate in the PDP twice per year. The CBFO has reduced the required frequency from twice per year to once per year. The CBFO described this change to the EPA in correspondence dated November 10, 1998, and April 22, 1999. Based on this information, the EPA determined that the changes reported did not require a modification, suspension, or revocation of the initial certification (EPA June 3, 1999).

The CBFO is the revising and approving authority for the NDA PDP and plans. The CBFO uses the PDP as part of the assessment and approval process for measurement facilities supplying characterization services for the NDA of TRU wastes intended for disposal at WIPP. The NDA PDP is similar to a blind sample program. The NDA PDP plans use 55-gallon drums or SWB's with simulated waste matrix and source standards. The NDA plans identify the elements that comprise the program, the criteria used to evaluate NDA system performance and the

responsibilities of the program participants. The PDP NDA plans are revised as required. NDA analysis of drums or boxes is performed by measurement systems that have demonstrated acceptable PDP performance.

4.4 Waste Characterization

The process of waste characterization identifies the significant physical, chemical, and radiological properties of the waste using a variety of methodologies. The measured waste properties obtained by the TRU waste sites are either on a container or waste stream basis and serve to demonstrate compliance with the limits imposed by transportation requirements (DOT), the Type B package certificate of compliance, the Hazardous Waste Facility Permit (HWFP), and operational safety requirements (DOE). In contrast, the waste component limits described in Appendix WCL are on a repository basis and serve as an upper bound for the accumulative waste inventory. As described in Section 4.3.2, the linkage between the collective waste inventory and the repository limits is provided by the WWIS.

Recognizing that the CH-TRU WAP and the CH-TRU WAC provide the waste characterization requirements for waste destined for the WIPP, it is necessary to understand the complementary role played by the radiological characterization of waste. Figure 4-4 shows the requirements hierarchy governing the characterization of waste for purposes of transportation, disposal, and long-term regulatory compliance. The implementation of waste characterization occurs on a waste-stream basis at the lowest tier of the diagram through the Standard Operating Procedures (SOPs). The next higher tier of Figure 4-4 includes the CH-TRU WAC, followed by progressively higher-tier requirements. The waste characterization requirements for compliance with the EPA's regulations are implemented by the SOPs.

The WAP includes requirements necessary for compliance with the New Mexico Hazardous Waste Act — specifically the identification and quantification of their hazardous components (see Attachment B of the WAP [NMED 2002]). A combination of five waste characterization methodologies is employed by the WAP and includes acceptable knowledge, radiography, visual examination, headspace gas sampling and analysis, and solidified waste sampling and analysis. The capabilities and applicabilities of these five methodologies to TRU mixed waste are discussed in considerable detail in the WAP. Except for a brief overview of acceptable knowledge, radiography, and visual examination, a description of the five waste characterization methodologies presented in the WAP will not be repeated in this document. Radiological characterization of TRU waste is needed for compliance demonstrations to 40 CFR Parts 191 and 194. A quantitative determination of the radionuclides listed in Table 4-11 results from the need to demonstrate compliance with the release limits as specified in Appendix A to Part 191 and the RH-TRU waste curie limit established by the LWA (see Table 4-12).

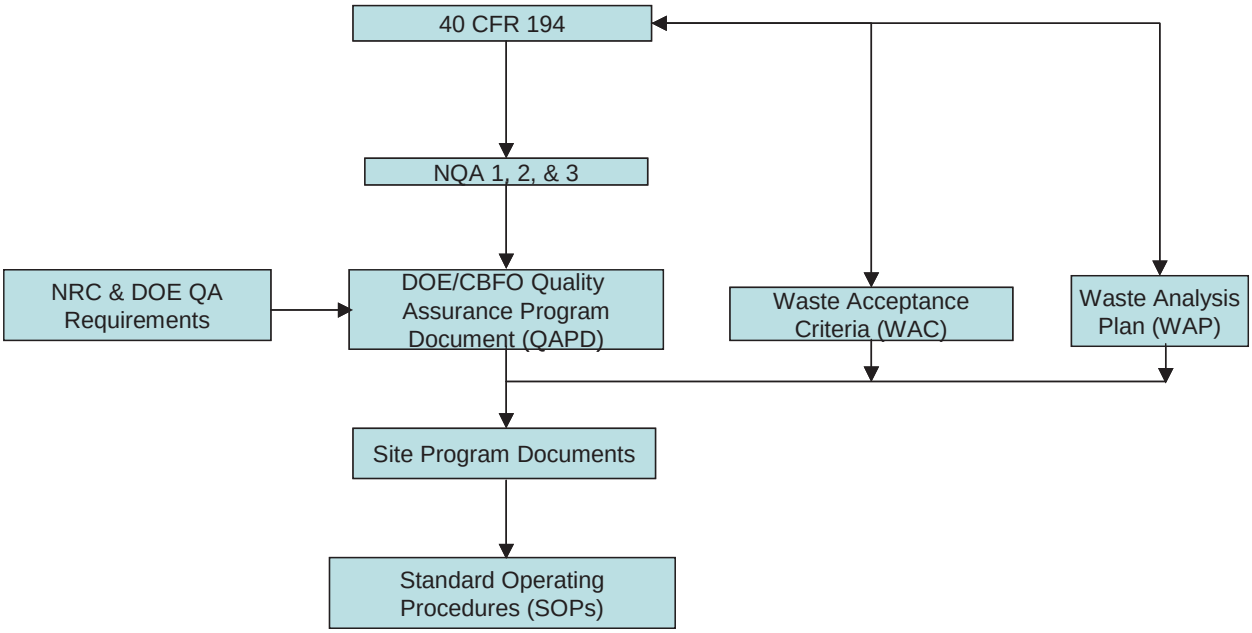

Figure 4-4. Program QA Document Hierarchy

Collectively, those elements of the waste characterization program that support long-term regulatory compliance include the determination of the radionuclide inventory (for purposes of normalizing radionuclide releases as required for comparison with Section191.13(a)), the identification of the physical and chemical waste form inventories (if applicable), and the verification that no wastes are emplaced in the WIPP that exceed the disposal system's safety and/or performance limitations.

In a manner analogous to the WAP, the WIPP waste radioassay characterization program is conducted by TRU waste site personnel and is implemented in accordance with the requirements of the CH-TRU WAC. TRU waste sites may propose alternative characterization methods, either because of the availability of newer technologies offering enhanced performance or the modification of older technologies to facilitate meeting the requirements of Appendix A of the CH-TRU WAC. In these instances, method performance must be demonstrated and approved in accordance with Section 194.8 prior to its use in characterization of TRU waste for disposal at the WIPP.

Implementation of the TRU waste characterization program at DOE TRU waste sites requires that all waste characterization activities be conducted in accordance with approved documentation that describes the management, operations, and QA aspects of the program. Conformance with applicable regulatory, programmatic, and operational requirements is monitored by CBFO audits and surveillances. Refer to Chapter 5 and CCA Appendix QAPD for a more detailed discussion of the CBFO audit and surveillance program. The documentation requirements important to the implementation of the TRU Waste Characterization Program at each TRU waste site are briefly discussed below.

- QA requirements. Implementation of individual site-specific waste certification and characterization programs must meet the QA requirements contained in the CBFO

QAPD, which are traceable to the applicable sections of ASME NQA-1 through NQA-3 (ASME 1989a, 1989b, and 1989c in the References). The WAP and the CH-TRU WAC describe the specific QA objectives (QAOs) for the TRU Waste Characterization Program. The WAP and the CH-TRU WAC, delineate approved analytical methods for meeting regulatory requirements.

- QAPjPs. TRU waste sites prepare site-specific QAPjPs that describe waste characterization activities in support of the TRU waste characterization program. These documents, developed in accordance with the applicable requirements in the CBFO QAPD and the WAP, define QA management and program elements that provide for planning, implementation, and assessment of the TRU waste characterization data-collection activities.

- SOPs. The QAPD requires that each DOE TRU waste site develop, implement, and control written SOPs that provide detailed descriptions of routine, standardized, or critical waste characterization activities. The SOPs serve as the basis for quality assessments of waste characterization activities at the site level because they provide detailed descriptions of required activities.

- PDPs. Analytical facilities characterizing waste for disposal at the WIPP must successfully participate in the applicable portions of the PDP. The PDP supports the determination of a facility's ability to meet the QA requirements identified in the CBFO QAPD. A more detailed description of the PDP can be found in Section 4.3.3.1.

As the TRU waste sites complete the necessary program documentation, they commence waste characterization activities. Information derived from these activities is on a waste-stream basis and is used in preparing the site's waste-stream profile forms required for waste acceptance at the WIPP. The waste characterization data are electronically backed-up in databases at the sites and downloaded into the WWIS database (DOE 1996b). The WWIS is described in Section 4.3.2.

TRU waste sites prepare documented and approved programs controlling their TRU waste characterization, certification (which includes characterization), and transportation processes. Site-specific TRU waste certification plans document how compliance with the CH-WAC is accomplished. Site certification is granted by the CBFO manager upon approval of the following documentation:

1. TRU waste certification plan (including QA),

2. QAPjP(s),

3. NRC Type B packaging methods for payload compliance TRU package transporter, Model 2 (TRUPACT II) Authorized Methods for Payload Compliance,

4. Packaging QA plan, and

5. Performance in applicable PDPs.

In addition to approval of this site-specific documentation, TRU waste sites must pass an initial TRU waste site certification audit where adequate and effective implementation of these programs is assessed (see Sections 5.1 and 5.3.19). Also, as described in Section 4.1.2, EPA approval of QA program documentation and implementation is also required.

Each site that is characterizing TRU waste is recertified by the CBFO annually. A recertification consists of reviewing (if applicable):

1. Site-specific program documents that are written and approved to the latest CH-TRU WAC;

2. Program implementation as determined by a TRU waste site certification audit;

3. Reports from surveillances conducted during the past year;

4. Performance in shipping TRU waste to the WIPP; and

5. Performance in the PDPs.

To ensure that DOE TRU waste sites comply with the WIPP TRU waste certification program, audits are conducted by the CBFO. An initial audit is conducted at each TRU waste site performing waste characterization activities prior to the formal acceptance of the waste-stream profile forms and/or any waste characterization data supplied by TRU waste site personnel. This formal acceptance is referred to as TRU waste site certification. Audits are performed at least annually thereafter, including the possibility of unannounced (not regularly scheduled) audits. These audits verify that the site has implemented a QA program for all certification activities. The accuracy of the physical waste description and the subsequent waste stream assignment are verified by a review of acceptable knowledge documentation, radiography data, and visual examination results (if applicable). Table 4-16 summarizes the characterization requirements and methods detailed in the CH-TRU WAC and the WAP that support this application. The EPA often observes the DOE audits in fulfilling its obligations defined in Section 194.8 (see Section 4.1.2).

Additional information regarding RH-TRU waste characterization has been developed by DOE and has been submitted to the EPA (letter from DOE to EPA December 16, 2002). No RH-TRU waste has been shipped to the WIPP at the time of CRA-2004. EPA approval of DOE's proposed RH-TRU waste characterization procedure is pending.

Table 4-16. Applicable CH- and RH-TRU Waste Component Characterization Methods

Waste Properties	Waste Components	Waste Characterization Methods
Nuclear	Radionuclides	NDA OR previous isotopic distribution from destructive radiochemistry OR previous radioassay data reconciled with CH-TRU WAC requirements
Physical	ferrous metals nonferrous metals cellulosic, plastic, rubber materials solid components free water humic substances	radiography with statistical selection for visual examination OR visual examination and documentation of container content at time of waste packaging for newly generated waste OR documentation and verification (random sampling) for newly generated waste
Chemical	sulfates nitrates organic ligands	No upper or lower limits apply to these chemicals; therefore no waste characterization methods are applied.

4.4.1 Qualitative Methodologies

The criteria at Section 194.24(a) require a description of the physical, chemical, and radiological composition of the TRU waste to be emplaced in the WIPP disposal system. With regard to the waste's nonhazardous physical and chemical components (such as cellulosic materials), there are three qualitative methodologies, used either singularly or in combination, for verifying adherence to the compliance limits. These methodologies include acceptable knowledge, nonintrusive examination using penetrating radiation such as X-ray (referred to as either RTR, radiographic examination, radiometric examination, or nondestructive examination (NDE)), and intrusive visual examination consisting of opening the container and recording the contents. The use of Acceptable Knowledge information is presented in the WAP and the CH-TRU WAC.

4.4.1.1 Acceptable Knowledge

The following discusses compliance with criteria at Section 194.24(c)(3).

Acceptable knowledge is defined in the EPA Guidance Manual (EPA 1994). Acceptable knowledge includes information regarding the physical form of the waste, the base materials composing the waste, and the process that generated the waste. Waste characterization will be used to confirm acceptable knowledge information. The WAP and the CH-WAC provide details regarding the application of acceptable knowledge.

Consistency among DOE TRU waste sites in using acceptable knowledge information to characterize TRU waste involves a three-phase process: (1) compiling the minimum acceptable knowledge documentation in an auditable record, (2) confirming acceptable knowledge information, and (3) auditing acceptable knowledge records.

Acceptable knowledge documentation provides qualitative information that cannot be assessed according to specific data quality objectives that are used for analytical techniques. QAOs for analytical results are described in terms of precision, accuracy, completeness, comparability, and representativeness. Analytical results will be used to confirm the characterization of wastes based on acceptable knowledge.

The acceptable knowledge process and waste stream documentation must be evaluated through internal assessments by QA organizations and assessments by auditors external to the organization (that is, the CBFO).

The CBFO has conducted and will continue to conduct an initial audit of each TRU waste site prior to certifying the TRU waste site for shipment of TRU waste to the WIPP facility (see the Hazardous Waste Facility Permit [NMED 2002] Attachment B through B6, including Figure B4-3). This initial audit will establish an approved baseline that will be reassessed annually.

4.4.1.2 Nondestructive Examination

NDE is a qualitative technique that involves the use of X-rays examination of waste containers to identify and verify the contents. NDE is used to verify the absence of prohibited items and to determine the appropriate methodologies to be used for waste characterization. NDE is not required for newly generated waste because controls exist to verify compatibility of the matrix material(s) and the absence of prohibited items prior to and during waste packaging.

All activities required to achieve the radiography objectives must be described in TRU waste site QAPjPs and SOPs. Retrievably stored containers will have this type of permanent record on file throughout the life of the WIPP project. As a quality control check on NDE, a statistically determined number of retrievably stored containers within the population subjected to NDE will be randomly selected and visually examined.

4.4.1.3 Visual Examination

Visual examination is used by DOE to provide an acceptable level of confidence in NDE. There is no equivalent method in the EPA sampling and analysis guidance documents. TRU waste site personnel develop training programs that are based on waste form and waste management operations. These training programs are used to assess operator performance. The QAPjPs and supporting SOPs specify the training requirements and other activities required to achieve the visual examination objectives. The visual examination expert must be familiar with the waste generating processes that have taken place at that TRU waste site and also with the types of waste being characterized at the site. For an explanation of the hypergeometric approach used in determining the number of containers to be statistically sampled by visual examination, see the WAP.

4.4.2 Quantitative Methodologies

To minimize exposure, the quantitative methodology used to determine the radionuclide inventory of the waste is NDA. The nonintrusive methodology of NDA employs radiation detection techniques for determining the waste's isotopic content and activity. This is the preferred approach because of the safety hazards involved in opening waste containers having radioactive contaminants. Although the data generated by radioassay serve many functions including the calculation of the ^{239}Pu equivalent activity, the ^{239}Pu fissile gram equivalent, and the decay heat of waste containers, the purpose of these data relative to long-term regulatory compliance with 40 CFR Part 191 is to provide corroborative data relating to the radionuclide inventory reported in the CRA-2004 and furnish radionuclide information on a container basis to maintain a running inventory of TRU waste emplaced in the WIPP disposal system.

TRU nuclides emit both ionizing radiation (including alpha particles, beta particles, and gamma rays) and nonionizing radiation (neutrons). Based on detection of these emissions, several technologies have been developed to measure one or more of these radiations as they emerge from the waste container. Although most of the ionizing radiation (alpha and beta particles) are not able to penetrate the walls of the waste container, both gamma rays and neutrons can penetrate the waste matrix as well as the waste container to varying degrees. Combining gamma ray measurements, other advanced particle detection techniques specific to neutrons, and acceptable knowledge provides the precision and accuracy required by the QAOs contained in the CH-TRU WAC Appendix A. Mass spectroscopy and radiochemistry also provide the precision and accuracy to meet the QAO requirements in the CH-TRU WAC Appendix A.

Special techniques, instrumentation, and detectors have been developed to measure the gamma ray energies. Because there are many different gamma rays originating from any one radionuclide with each gamma ray having a unique energy and rate of occurrence characteristic of the radionuclide from which it originated, the resulting distribution or spectrum of gamma ray energies provides a fingerprint or signature of that particular radionuclide. In practice, with the application of appropriate correction factors and the utilization of acceptable knowledge, gamma ray and neutron NDA systems provide radioisotope inventory information about the waste without the need for opening the container.

All radioassay systems must be calibrated using a variety of matrix and source standards to simulate the various waste compositions, source distributions, and interferences common to the waste streams originating from a particular TRU waste site. By applying the resulting correction factors to the measurements, an accurate assessment of the radionuclide inventory within the waste container is feasible. NDA methods appropriate to a particular waste stream profile are used in the radionuclide analysis.

4.4.2.1 Nondestructive Assay

A variety of NDA methodologies are effective in meeting the requirements of the CH-TRU WAC Appendix A. NDA instruments can be classified as belonging to one or more of the four categories listed below:

- gamma ray measurements

- low- and high-resolution spectroscopy using a sodium iodide and intrinsic germanium detector,
- transmission-corrected gamma ray measurement using a segmented gamma ray scanner, and
- transmission-corrected gamma ray measurement using a computed tomographic gamma ray scanner.

- passive neutron measurements
  - passive neutron coincidence counter,
  - advanced matrix-corrected passive neutron counter (add-a-source), and
  - shielded neutron-assay probe totals counter.
- passive and active neutron measurements
  - Am-lithium source-driven coincident counter,
  - californium delayed-neutron counter (shuffler),
  - neutron generator differential die-away counter, and
  - combined thermal and epithermal neutron counter.
- thermal neutron capture
  - californium delayed-neutron counter,
  - neutron generator differential die-away counter, and
  - combined thermal and epithermal neutron counter.

The list is neither complete nor limiting and is meant to illustrate the breadth of choice available. QAOs may be met with the listed systems or by modifications, functionally equivalent alternatives, multiple combinations, or hybrids of the systems.

For each of the radionuclide components identified in Table 4-11 as being significant to PA and requiring assay, any of the above NDA methodologies, either singularly or in combination, may be used in determining the activity and corresponding uncertainty. In the case of 100-percent sampling, these measurements are performed on a container basis. For the case of less than 100-percent sampling, the reported values are on a waste stream basis. Upon receipt of the waste at the WIPP, the measured activity of these significant radionuclide components, plus their associated uncertainty, are accumulated by the WWIS in order to ensure that the volume and activity limits of the repository are not exceeded.

4.4.3 Additional Change to the Waste Characterization Program

Since the certification of the WIPP, an additional change related to the waste characterization program has occurred. In the past, DOE planned to declassify any classified materials in waste before shipment to WIPP. In 2002, the RFETS proposed sending waste containing classified shapes to WIPP, where the associated radiography and VE records would be classified and require a DOE security clearance for review and audit. In 2003, the EPA determined that classified waste may be shipped to WIPP provided DOE meets certain specified requirements (EPA letter of February 11, 2003, to DOE CBFO).

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5.0 QUALITY ASSURANCE

The information in this chapter is a complete revision of the text in the Compliance Certification Application (CCA).

5.1 Introduction

This chapter was revised primarily to incorporate program changes, improve discussion of the characteristics and parameters of the Quality Assurance (QA) program, and clarify implementation of criteria from upper tier requirements documents. The following paragraphs provide an overview of the Carlsbad Field Office (CBFO) Quality Assurance Program Document (QAPD) development since submittal of the CCA.

In November 1999, Revision 3 of the QAPD incorporated transuranic (TRU) waste QA requirements contained in the Carlsbad Area Office (CAO) Quality Assurance Program Plan (QAPP), which was inactivated.

In August 2002, Revision 4 of the QAPD incorporated the Department of Energy (DOE) name change from the CAO to the CBFO, changes to the CBFO organization titles and associated responsibilities, and updated the Quality Improvement Section. It also provided an update of the source requirements documents for the QAPD, added specific QA functional responsibilities of the CBFO management, and eliminated divisions between “general requirements” and “additional requirements.” Editorial, formatting, and paragraph number changes were also incorporated.

The latest revision, Revision 5, of the QAPD was issued in May 2003. This revision was issued to address an Environmental Protection Agency (EPA) finding that the QAPD did not adequately incorporate the Quality Assurance Program Requirements for Nuclear Facilities, ASME NQA-1, 1989 edition criteria regarding assignment of organizational responsibilities for achievement of quality and verification of quality. In addition, Revision 5 deleted the requirement for organizations receiving records to return a receipt acknowledgment to the sender, for TRU waste program participants to maintain a QAPD procedures matrix (neither is required by NQA-1, -2, -3, or other regulatory documents) and deleted references to compliance with the Federal Acquisition Regulations. It also deleted the requirements for maintaining records related to the characterization of mixed TRU waste form as lifetime records, maintaining audit and surveillance checklists as QA records. The revision also changed the requirement for calibration laboratories to comply specifically with ANSI/NCSL Z540-1 to the requirement for compliance to national standards. Finally, Revision 5 added the Safety Analysis Report (SAR) for the HalfPACT shipping package as a source document, deleted Section 5.5 (criteria addressed in Section 5.1G), and corrected typographical errors and section references.

5.1.1 Mission and Policy

In Title 40 of the Code of Federal Regulations (CFR) Part 194, the U.S. EPA establishes the QA requirements criteria for determining compliance with 40 CFR 191 Subparts B and C, which specifies environmental radiation protection standards for disposal of TRU waste. The mission of the U.S. DOE is to protect human health and the environment of the Waste Isolation Pilot Plant (WIPP) for safe disposal of TRU waste, and to manage TRU waste from its acceptance to

its disposal. It is the policy of the DOE to maintain an effective QA program consistent with the criteria in 40 CFR Part 194, and consistent with other applicable federal, state, and local laws and regulations, including applicable DOE Orders. This policy helps to direct the CBFO mission and to ensure that the risks, safety, and environmental impacts are identified and minimized, and that safety, reliability, and performance are optimized.

5.1.2 Quality Assurance Program History

Previous QA program history is given in the CCA. In 1996, the CAO (now CBFO) implemented the QA requirements of 40 CFR § 194.22(a)(1). In addition, both DOE Order 5700.6C, Quality Assurance, and 10 CFR § 830 Subpart A – Quality Assurance Requirements were implemented through the DOE, CBFO QAPD.

In 1999 WIPP began disposal operations by receiving waste. By that time, all applicable regulatory requirements had been incorporated into the QAPD. These include 40 CFR § 194.22(a)(1), 10 CFR Part 830 Subpart A, DOE Order 414.1A, Quality Assurance, and NUREG 1297, Peer Review for High-Level Nuclear Waste Repositories. These requirements continue to be specified and implemented in the QAPD.

5.2 Quality Assurance Program Requirements

5.2.1 Requirements in the Code of Federal Regulations

5.2.1.1 <u>40 CFR Part 194</u>

40 CFR Part 194 sets forth the QA criteria necessary for compliance with 40 CFR 191 Subparts B and C. 40 CFR § 194.8(a), Quality Assurance Programs at Waste Generator Sites, establishes a site-specific QA program plan that addresses the applicable nuclear quality assurance (NQA) criteria of 40 CFR § 194.22(a)(1) for items and activities identified in § 194.22(a)(2), § 194.24(c)(3), and § 194.24(c)(5). The QA Program applied to the National TRU Program was certified in March 1999, and is audited annually by the EPA using the criteria for audits or inspections, including publishing notices in the Federal Register as set forth in § 194.8(a)(2).

5.2.1.2 <u>40 CFR § 194.22, Quality Assurance</u>

The following documents and regulation establish the requirements for the WIPP QA program. Figure 5-1 is a flow-down chart of these requirements documents.

- ASME NQA-1-1989 edition, Quality Assurance Program Requirements for Nuclear Facilities;

- ASME NQA-2-1989 edition, Quality Assurance Requirements for Nuclear Facilities Applications. ASME NQA-2a-1990 addenda, part 2.7, Quality Assurance Requirements of Computer Software for Nuclear Facility Applications;

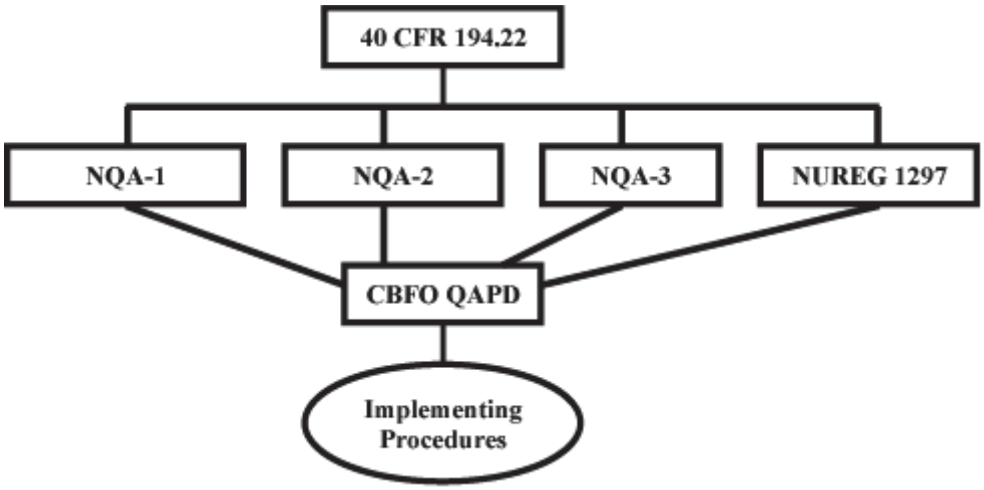

Figure 5-1. Requirements Flow-Down Chart

- ASME NQA-3-1989 edition, Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Nuclear Waste Repositories (excluding Section 2.1 (b) and (c), and Section 17.1); and

- NUREG 1297, Peer Review for High-Level Nuclear Waste Repositories (required by 40 CFR § 194.22(b) for "qualification of data and information," § 194.27 for compliance application documents associated with "conceptual models," § 194.24(b) for "waste characterization analyses," and § 194.44 for "engineered barrier evaluation").

5.2.2 Other Requirements and Standards

The WIPP QA program incorporates QA requirements in 10 CFR Part 71(H), Quality Assurance. The WIPP-related QA program applies to design, purchase, fabrication, handling, shipping, storing, cleaning, assembly, inspection, testing, operation, maintenance, repair, and modifications of components of packaging, transportation, and handling of TRU waste that are important to safety. The WIPP-related QA program also applies to the requirements and standards found in the WIPP Hazardous Waste Facility Permit (HWFP), 10 CFR 830 Subpart A, DOE Orders, and National Consensus Standards. Applicable requirements from these documents are incorporated into the QA program applied to the National TRU Program.

5.3 Incorporation of 40 CFR § 194.22 Criteria in the QAPD

The following section lists 22 criteria incorporated in the CBFO QAPD. These criteria were taken from the requirements documents and regulation described in Section 5.2.1.2. Criteria 1 through 18 were taken from NQA-1-1989; Criterion 19 from NQA-2-1990a, Part 2.7; Criterion 20, 21, and 22 from NQA-3-1989; 40 CFR § 194.22(b) and (c), and NUREG 1297.

5.3.1 Criterion 1 – Organization

The CBFO is structured so that the individual performing the work is responsible for achieving and maintaining quality. Management is responsible for defining quality, developing appropriate

plans to attain quality, supporting the workers in pursuit of quality, and evaluating quality achievement within their area of responsibility. Figure 5-2 illustrates the authority and reporting structures of the CBFO QA and its major program participants.

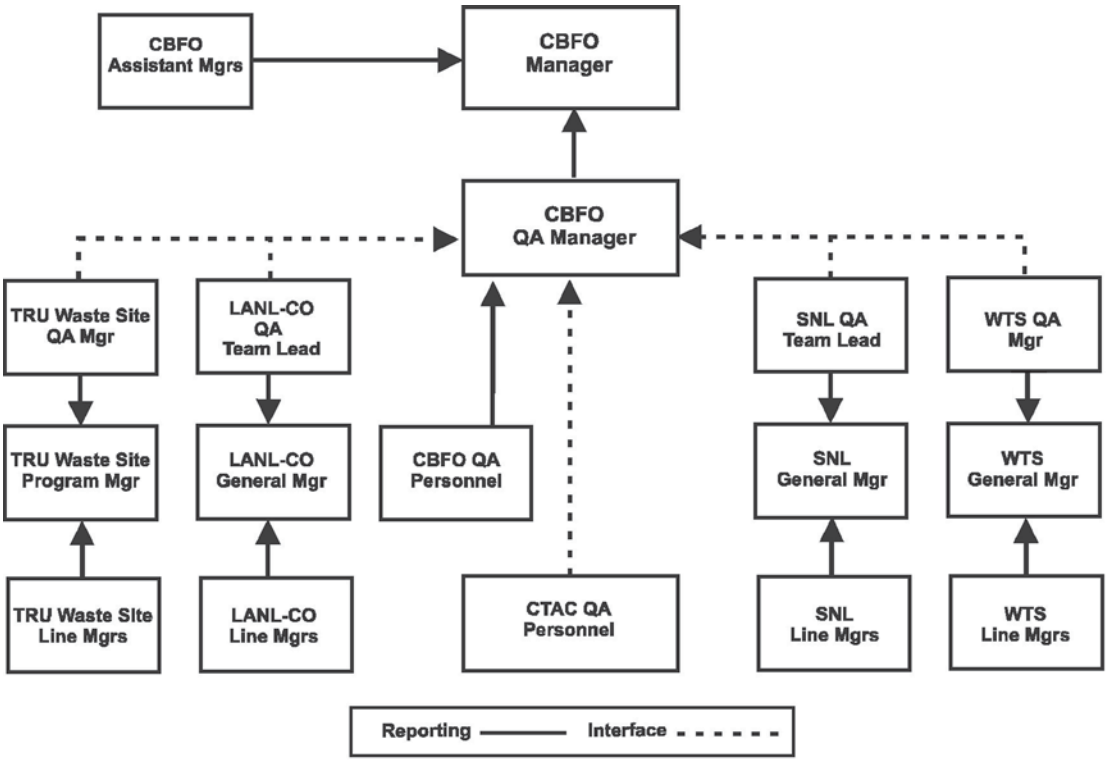

Figure 5-2. Reporting Interface Diagram

All program participants have the authority, organizational freedom, and the overall responsibility to independently assess the effective implementation of the QA program. Reporting is made to a management level so that the required authority and organizational freedom is provided, including sufficient independence from cost and schedule considerations. The QA organizations have sufficient authority, access to work areas, and organizational freedom to:

- verify, through checking, auditing, and inspecting, that quality-affecting activities have been performed correctly;
- identify quality problems;
- initiate, recommend, or provide solutions to quality problems through designated channels;
- verify implementation of solutions; and
- ensure that further processes, delivery, installation, or use is controlled until proper disposition of a nonconformance, deficiency, or condition adverse to quality has occurred.

The CBFO QAPD requires personnel conducting assessments and other quality-affecting activities to be technically qualified and knowledgeable about the item(s) and processes being assessed, and be independent of any direct responsibility for the performance of the activities being assessed. To manage any perceptions of assessment bias, CBFO requires the Carlsbad Field Office Technical Assistance Contractor (CTAC) organization to ensure independence through the implementation of an organizational and individual conflict of interest avoidance and mitigation process.

5.3.2 Criterion 2 – Quality Assurance Program

5.3.2.1 Quality Assurance Program Overview

The CBFO QA program is described in the QAPD and includes QA requirements from multiple sources. The QA organizational structures, primary interfaces, functional responsibilities, and levels of authority for activities affecting quality are described and documented in the QAPD. The major QA organizational interfaces are illustrated in Figure 5-2.

The CBFO Manager directs activities to effectively and efficiently meet DOE and WIPP missions and safety expectations. The Manager reports directly to the DOE Assistant Secretary for Environmental Management for program policy and direction. The Manager is responsible for and maintains a QA program that ensures work activities meet customer requirements, including federal, state, and local laws and regulations, permit requirements, and DOE Orders and requirements. The Manager provides technical direction in interpreting QA requirements and in reviewing and concurring with QA plans and programs.

The CBFO QA Manager has been delegated the authority for executing the QA function by the CBFO Manager and reports directly to the CBFO Manager. The QA Manager has the authority and overall responsibility to independently assess the adequacy, implementation, and effectiveness of the TRU waste QA programs, within both the CBFO organization and program participant organizations. Participant QA managers have the authority and responsibility to independently assess the effective implementation of the applicable QAPD requirements within both their participant organization and any lower-tier organizations.

The following are program participant responsibilities:

- Program participants have the responsibility for TRU waste QA program development, implementation, and assessment within their own and lower-tier organizations. CBFO reviews and accepts the WIPP waste-related QA program documents of Sandia National Laboratories (SNL), Washington TRU Solutions (WTS), the TRU waste generator sites, and other TRU waste program participants, e.g., Los Alamos National Laboratory-Carlsbad (LANL-CO). CBFO performs QA audits and surveillances of these organizations to verify compliance with QA and technical program requirements.

- Washington TRU Solutions has the responsibility for implementing and maintaining the QA program for the operation and maintenance of the WIPP site, monitoring the site environment, and for the receipt of waste. WTS is also responsible for the Central Characterization Project (CCP), which is tasked with characterizing and certifying TRU

waste at specified waste generator sites for disposal at the WIPP. The CBFO Manager and Assistant Manager for the Office of National Transuranic Program provide overall policy direction for the CCP. Specific details of this organization are described in the CCP TRU Waste Certification Plan, CCP-PO-002.

- Sandia National Laboratories has the responsibility for implementing and maintaining a QA program for activities involved in the development, confirmation, and verification of models used to simulate long-term repository performance. SNL's QA program covers research, experiments, and tests performed to collect the data needed for input to the models.

  In January 1999, the SNL QA program converted from a system of QA procedures (QAPs) to an improved system of revised nuclear waste management QA procedures (NPs). The NPs were issued with two objectives. First, the NPs were written to be responsive to requirements contained in the latest CBFO QAPD. These NPs were also verified to be compliant with the CBFO QAPD by completing an extensive matrix to map the upper-tier requirements for each procedure. Second, the NPs were streamlined, and additional information was added to make them easier to use. For example, several QA plans that addressed the same subject area (analyses) have been combined into one NP (NP 9-1).

  These changes implement the same QA program requirements but improve the implementing processes. They do not represent significant changes in activities or conditions pertaining to the disposal system. The SNL QA program is routinely subject to CBFO audits and EPA inspections.

- Los Alamos National Laboratory – Carlsbad has the responsibility for implementing and maintaining a QA program for activities involved in actinide chemistry and for the Transuranic Waste Baseline Inventory Report (TWBIR) (see Appendix BIR). The TWBIR is the inventory source document that provides the waste data used in the performance assessment of the WIPP site.

- Sites intending to send TRU waste to the WIPP are responsible for implementing and maintaining a QA program that meets the applicable requirements of the QAPD, for characterizing TRU waste, for meeting the WAC, and for participating in the waste certification and recertification programs.

5.3.2.2 Grading

Quality assurance grading is used to identify the controls applied to activities that support the TRU waste QA program. Grading is based upon an evaluation of the complexity and importance of the activity to quality, safety, risk, and the environment. Based on the results of the evaluation, appropriate procedural controls are identified. The rigor of QA controls is commensurate with, but not limited to, the following criteria:

- the function or end-use of the item;

- the importance and end-user of the data generated;
- the probability of failure;
- the complexity or uniqueness of the design, fabrication, or implementation;
- the reproducibility of the results;
- the quality history of the item or service;
- the necessity for special controls or processes; and
- the ability to demonstrate functional compliance with applicable regulations.

The CBFO staff and program participants perform management assessments to ensure the QA program meets customer requirements and expectations.

The extent of management and QA controls applied to an item or activity varies as a function of the degree of confidence needed to achieve the desired quality. The grading process provides the flexibility to design and implement controls that best suit the facility or activity but is not intended to reduce or in any way degrade the compliance with applicable requirements.

5.3.2.3 Quality Assurance Program Documents

The CBFO and program participants implement the requirements of the CBFO QAPD in accordance with QA program documents and implementing procedures prepared and maintained by their organizations.

A table of QA program documents that implement the various TRU waste QA programs is presented in Section 5.4 along with a description of the CBFO QAPD and a listing of CBFO procedures.

When the CBFO QAPD is revised, lower-tier documents such as site Quality Assurance Project Plans (QAPjPs), certification documents, QA plans, and program participants implementing procedures are evaluated and appropriately revised to ensure that the QA program of each organization meets all the applicable requirements of the CBFO QAPD.

5.3.2.4 Qualification and Training

Personnel performing work are qualified and capable of performing their assigned tasks. Program participants have established formal methods for the evaluation, selection, indoctrination, training, and qualification of personnel performing work to ensure compliance with the CBFO QAPD requirements.

In the case of Lead Auditors, a comprehensive process, including training and an examination, is required, along with specific experience and education requirements that must be met in order to obtain Lead Auditor certification.

5.3.2.5 Management Assessments

Management assessments are performed by the CBFO and program participants to determine the effectiveness of the QA programs established and implemented to meet customer requirements and expectations.

Key elements of management assessments that help to determine effectiveness include:

- the conduct of regular assessments of the QA program with reports at least annually to senior managers who have sufficient authority to effect corrective measures; and

- the use of management assessment results as a means for determining and taking the necessary actions to correct quality problems, achieve quality, and ensure the proper application of resources to achieve and verify quality.

5.3.3 Criterion 3 – Design Control

Design work, including changes, incorporates appropriate controls and requirements such as general design criteria, design bases, and control of inputs. Design interfaces are identified and controlled. The adequacy of design products is verified by individuals or groups independent from those who performed the work. Verification is completed before approval and implementation of the design. The control of design activities also includes design reviews and qualification testing.

5.3.4 Criterion 4 – Procurement Document Control

Procurement documents address the scope of work, technical requirements, design bases, appropriate codes, standards, regulations, procedures, instructions, tests, inspections, hold points, acceptance criteria, and documentation requirements.

Quality-affecting procurement documents are reviewed to verify that the documents include appropriate provisions for ensuring that items and services meet the prescribed requirements. CBFO requires that these procurement documents be reviewed by technical and QA personnel. The reviewers are required to have access to pertinent information and an adequate understanding of the requirements and scope of the procurement. CBFO conducts audits and surveillances to verify that these requirements are being met.

5.3.5 Criterion 5 – Instructions, Procedures, and Drawings

Activities affecting quality are prescribed by and performed in accordance with the appropriate established, documented, and approved instructions, procedures, or drawings. Instructions, procedures, and drawings are developed, reviewed, and approved by technically competent personnel. The documents contain specific information appropriate to the work to be performed, including the following required elements:

- responsibilities;

- program requirements;

- description of the work;
- acceptance criteria;
- prerequisites, limits, precautions, process parameters, and environmental conditions;
- special qualifications and training requirements;
- verification and hold points;
- methods for demonstrating that the activity was performed as required; and
- identification and classification of QA records to be generated.

The CBFO implementing procedures are listed in Section 5.4.9. Each of the program participants develops implementing documents that address the quality activities applicable to his or her QA program requirements and work scope.

5.3.6 Criterion 6 – Document Control

Documents affecting quality that specify quality requirements, prescribe processes, or establish designs important to compliance with 40 CFR 191 Subparts B and C and 40 CFR Part 194, such as instructions, procedures, drawings, test plans, and management plans, which are controlled to ensure that the correct documents are being employed. Controlled documents are reviewed by competent personnel, using specified criteria for adequacy, correctness, and completeness before approval and issuance. Review comment documentation is maintained by the originating organization. Responsibilities for document preparation are specified and the documents are controlled during the preparation, review, approval, issuance, use, and revision processes.

5.3.7 Criterion 7 – Control of Purchased Items and Services

Controls are established to ensure that procured items and services meet applicable technical and QA requirements and performance specifications. Prospective suppliers are evaluated and selected on the basis of documented criteria. Procurement controls are in place to ensure that approved suppliers continue to provide acceptable items and services. Procurement controls include, as appropriate:

- procurement planning,
- supplier selection and performance evaluation,
- proposal and bid evaluation,
- procurement documents,
- source verification and supplier certification of conformance,
- receipt inspections and post-installation testing,

- control of supplier nonconformances, and
- commercial-grade items.

5.3.8 Criterion 8 – Identification and Control of Items

"Item" is an all-inclusive term used in place of any of the following: appurtenance, assembly, component, equipment, material, module, part, structure, subassembly, subsystem, system, unit, support system, or data.

Items used in support of 40 CFR Part 191 Subparts B and C and 40 CFR Part 194 are identified and controlled. Processes have been established to identify, control, and maintain items from receipt through installation and end-use. Item identification ensures the appropriate traceability as specified in design documents, codes, standards, specifications, and implementing procedures. An identification marking is placed on the item or in documents traceable to the item. Acceptable methods and materials for characteristics and markings are prescribed, and the authority for applying and removing status indicators and markings is also specified.

5.3.9 Criterion 9 – Control of Processes

Work processes that support compliance with 40 CFR Part 191 Subparts B and C and 40 CFR Part 194 are performed in accordance with established, approved, and documented technical standards and administrative controls. Work is planned, authorized, and performed under controlled conditions using approved instructions, procedures, drawings, or other appropriate means. Implementing procedures are developed, reviewed, and approved by qualified and competent personnel. The procedures contain information, including the following elements, appropriate to the work being performed:

- prerequisites, limits, precautions, process parameters, and conditions necessary for performing the process, including calibration requirements;
- special qualifications and training requirements; and
- acceptance criteria, including applicable codes and standards.

Personnel performing work are responsible for complying with appropriate instructions, which include or reference procedure, personnel, and equipment qualification requirements. Handling, storage, cleaning, shipping, and other processes that are implemented to preserve, transport, and package items are conducted in accordance with established work and inspection procedures, shipping instructions, or other specified documents.

Processes that are highly dependent on the control of the process and on the skill of the operator where quality results cannot be readily determined by inspection or test of the product are considered "special processes." Implementing procedures for special processes are required to include the conditions necessary for completion of the special process, including equipment, statistical process control, controlled parameters of the process, and calibration requirements.

5.3.10 Criterion 10 – Inspection

Inspections determine acceptance or rejection of a process, product (item), or service. Inspection documentation required of program participants includes:

- approved implementing procedures;
- identification of the items and processes to be inspected, the parameters or characteristics to be evaluated, the techniques to be used, the acceptance criteria, and any hold points;
- the acceptance of items and processes by qualified and authorized persons; and
- identification of any measuring and test equipment used, including the equipment identification number and the calibration due date.

5.3.11 Criterion 11 – Test Control

Tests determine the capability of an item to meet specified requirements by subjecting the item to a set of defined operating conditions. Tests included as part of scientific investigations are conducted in accordance with the methods described in Section 5.3.20. Test planning is required and includes:

- identification of the procedures and related requirements documents used to control and perform the test (for example, test plans);
- identification of the item to be tested, test requirements, and acceptance criteria;
- identification of the measuring and test equipment (M&TE) including the type, range, accuracy, and tolerance;
- test prerequisites and provisions to ensure that all test requirements and objectives have been met;
- any designated hold points; and
- recording methods used to collect and record the data.

In addition, the documentation of test results identifies (1) the test date, (2) the personnel performing the test, (3) the data collected and the results of the tests, (4) the actual measuring and test equipment used, (5) the actions taken when unexpected results are obtained, and (6) the personnel evaluating the test results. A qualified person evaluates the results to ensure that all test requirements have been met.

5.3.12 Criterion 12 – Control of Measuring, Monitoring, Data Collection and Test Equipment

The M&TE control system is established for monitoring, measuring, testing, and the proper use of data collection equipment to ensure that suspect and out-of-tolerance equipment that could affect quality are not used. If such equipment is inadvertently used, the control system provides

for the segregation of the defective equipment and the evaluation of the data obtained while the out-of-tolerance or defective equipment was used. In addition, the calibration system includes provisions for:

- using documented procedures that describe the calibration system and the detailed calibration methods;
- using qualified calibration services that meet the requirements of the CBFO QAPD;
- developing a schedule for the initial calibration of M&TE and for periodic recalibration to ensure acceptable reliability;
- documenting the results of the calibration;
- labeling and identifying all M&TE to provide the information needed for recalibration and to ensure that adequate standards are traceable to the M&TE;
- identifying any needed precautions for handling, storing, and transporting equipment to prevent damage or out-of-tolerance conditions;
- providing the environment needed to calibrate the M&TE and to take measurements; and
- using calibration standards traceable to nationally recognized standards or physical constants. When such standards do not exist, the bases for calibration are documented.

5.3.13 Criterion 13 – Handling, Storage, and Shipping

Handling, storage, cleaning, packaging, shipping, and preservation of items are controlled to prevent damage or loss and to minimize deterioration. Items supporting compliance with 40 CFR Part 191 Subparts B and C and 40 CFR Part 194 are managed and controlled using approved implementing documents. Precautions taken include the following:

- preparing procedures that describe the methods to be applied, the proper controls, and the records to be generated;
- using and documenting special equipment and environments when required; and
- creating and maintaining markings and labeling that identify the item, any special environments required, and the need for any other special controls as necessary.

5.3.14 Criterion 14 – Inspection, Test, and Operating Status

Authorized persons apply and remove status indicators on items, as appropriate. These status indicators help prevent inadvertent installation, use, or operation of items that have not passed the required inspections or tests. The specific status indicators, their use, and the authority to apply or remove them are delineated in applicable QA plans or implementing procedures. Status indicator processes identify provisions for:

- using and maintaining status indicators to indicate if an item has completed the required inspections or tests and to indicate the operating status of items;
- placing status indicators on the items or in documents traceable to the items;
- using tags, markings, labels, stamps, travelers, inspection and test records, or other appropriate means as status indicators; and
- using and maintaining a lockout/tagout system for setting and maintaining specific conditions.

5.3.15 Criterion 15 – Control of Nonconforming Items

Items that do not conform to specified requirements are controlled to prevent their installation, use, or operation before correction. Nonconforming items may be identified at any time by anyone.

When appropriate, further work on the item is halted until the appropriate actions have been taken and verified. The nonconformance control process is documented in applicable QA plans. The process identifies implementing procedures for identifying nonconforming items, methods that do not adversely affect the end-use of the item, and methods designed to prevent damage or loss and to minimize deterioration. Precautions taken include:

- preparing procedures that describe the methods to be applied, the proper controls, and the records to be generated;
- using and documenting special equipment and environments when necessary;
- creating and maintaining markings and labeling that identify the item, any special environments required, and the need for any other special controls;
- segregating nonconforming items, when practical;
- assigning the responsibility to halt or control further work on the item;
- evaluating and dispositioning nonconforming items by authorized persons; and
- reexamining the item to verify acceptability after rework or repair.

In addition, suppliers are required to identify items that do not meet the requirements of the procurement documents, to document the nonconforming condition and the proposed disposition, and to provide technical justification for the disposition.

5.3.16 Criterion 16 – Corrective Action

“Corrective actions” are measures that are taken to rectify a condition that is adverse to quality and, where necessary, to preclude recurrence.

All personnel are responsible for identifying conditions adverse to quality. Conditions adverse to quality are evaluated, the appropriate corrective actions are defined and implemented, and the completion and effectiveness of the corrective action are verified. If the condition adverse to quality is determined to be significant, corrective action is identified, investigative action is taken, the root cause is determined, and appropriate actions are taken to preclude recurrence. A significant condition adverse to quality is defined as a condition, which, if uncorrected, could have a serious effect on safety, operability, waste confinement, TRU waste site certification, compliance demonstration, or the effective implementation of the QA program.

When appropriate, further work on the item, activity, or process is halted until the appropriate actions have been taken and verified. The corrective action process for conditions adverse to quality is documented in appropriate QA plans and implementing procedures. The process used to identify and control conditions adverse to quality includes provisions for:

- identifying and documenting conditions adverse to quality;
- assigning the responsibility to halt or control further work on the item, activity, or process;
- evaluating and dispositioning conditions adverse to quality by authorized persons;
- notifying management of the results of evaluations of significant conditions adverse to quality;
- preparing corrective action plans that include remedial actions, investigative actions, root cause determinations, expected completion dates, and responsible persons, as appropriate;
- evaluating the corrective action plans and verifying the completion and effectiveness of the corrective actions taken; and
- assigning unique numbers to each corrective action request generated, maintaining a log of the specific status of each request until it is closed, and regularly reporting and reviewing the status of all open corrective action requests.

5.3.17 Criterion 17 – QA Records

Records generated under the QA program are specified, prepared, reviewed, approved, maintained, and disposed of in accordance with the CBFO QAPD. Records provide evidence of work quality and evidence that the QA program has been properly implemented during work performance. The records management system is documented in appropriate QA plans and implementing procedures and includes:

- identifying those documents that will become QA records and identifying the organizations responsible for submitting the QA records to the records system;
- generating records that are legible, accurate, and complete;
- protecting documents that will become QA records during generation and use;

- authenticating the QA record;
- indexing QA records to ensure retrievability and to identify record retention times and the location of the record within the records system;
- classifying QA records as either lifetime, nonpermanent, or postclosure;
- designating the organization that receives and controls QA records;
- storing QA records using methods and facilities that meet the requirements of the CBFO QAPD; and
- correcting, replacing, restoring, and substituting records for any incorrect, lost, or damaged QA records in the QA records system.

The generation, classification, indexing, and retention of QA records are controlled in accordance with appropriate plans and records-related procedures.

5.3.18 Auditor and Technical Specialist Skills and Background

Auditors and Technical Specialists that conduct CBFO audits are qualified and certified in accordance with the CBFO Team Procedure (TP) 10.1, Qualification of Audit Personnel and Certification of Lead Auditors.

The Auditors possess a comprehensive knowledge of ASME NQA-1, DOE Orders, and Codes of Federal Regulations applicable to hazardous waste facilities. These individuals possess knowledge of CBFO program documents including the QAPD, Waste Analysis Plan (WAP), Contact-Handled Transuranic Waste Acceptance Criteria (WAC) For The Waste Isolation Pilot Plant, TRUPAC-II Authorized Methods for Payload Control (TRAMPAC) sufficient to successfully assess assigned activities during an audit. In addition, the audit team possesses experience with and a working knowledge of the corrective action process to properly identify problems, assess corrective action plans, and verify the closure and effectiveness of corrective actions.

Technical Specialists are trained in the audit process. They possess a comprehensive knowledge of the WIPP HWFP and the Program Documents. They have experience in either hazardous or nuclear waste generation or waste management, the Compliance Certification Application, or in a technical discipline associated with the operation of a nuclear facility or laboratory. Technical Specialists have a working knowledge of industry standards, operational methods, and regulations associated with the discipline in which the individual has expertise. In addition, they have a working knowledge of visual examination (VE), nondestructive examination (NDE), acceptable knowledge (AK), data verification and validation (V&V), and nondestructive assay (NDA).

Technical Specialists, Auditors, and Lead Auditors complete training commensurate with the activities they perform during audits. Auditors and Lead Auditors must successfully complete the CBFO Auditor/Lead Auditor Course for qualification. In addition, Lead Auditors must meet educational and experience requirements and pass a comprehensive written examination before

certification. Lead Auditors are required to maintain their proficiency through audit participation, training, or reading assignments. Failure of Lead Auditors to maintain proficiency requires recertification.

Qualification of Technical Specialists and Auditors and the certification of Lead Auditors are documented and maintained as QA records. Lead Auditor maintenance of proficiency is also documented and maintained as a QA record.

With the current audit staff, Lead Auditors, on the average, have over 20 years of experience and expertise in performing audits. Auditors typically average over 15 years of experience in auditing, and Technical Specialists average over 20 years of experience in their technical disciplines

5.3.19 Criterion 18 – Audits and Surveillances

Audits and surveillances verify that the various QA programs properly reflect the requirements of the CBFO QAPD and that they are being effectively implemented.

The CBFO has designated specific meanings that apply to the terms adequacy, implementation, and effectiveness. Adequacy refers to the migration of requirements contained in upper-tier documents into implementing procedures. An adequate procedure is one that contains all appropriate upper-tier requirements. Implementation refers to the performance of the process steps identified in the procedures. An implemented procedure is one for which all steps have been completed as identified within the procedure. Effectiveness refers to a process that produces the desired (specified) end-product or end-service. These terms are used to describe assessment activities throughout this chapter.

The management and control of audits and surveillances are documented in QA plans or implementing procedures. The audit and surveillance processes include provisions for:

- scheduling;
- using qualified, certified, and independent personnel;
- reporting results to the management of the audited or surveilled organization and to other affected organizations;
- requiring a written response to any noted conditions adverse to quality; and
- ensuring that the audited or surveilled organization has taken the appropriate corrective actions and that the corrective actions are effective.

Audits and surveillances conducted since the CCA have been rolled up into summary tables in Appendix AUD 2004. These tables reflect the extensive and comprehensive auditing and surveillance efforts that CBFO has implemented in order to ensure adequacy, implementation, and effectiveness of the TRU waste program.

5.3.20 Criterion 19 – Software Quality Assurance

Software QA controls are in place to ensure that the software meets its intended use and is controlled. These controls apply to software that manipulates or produces data that are, in turn, used to process, gather, or generate information and whose output is relied upon to make design, analytical, operational, or compliance-related decisions affecting the performance of the waste isolation or waste characterization processes. The application of these requirements is prescribed in written plans, policies, procedures, or instructions.

Software controls include inventorying and classifying appropriate software. Plans are prepared at the start of the software life cycle to document the software basis and the objectives of the software to meet its intended use.

The sponsoring organization for software acquisition and related services verifies the capability of the software and the acceptability of the supporting documentation. Any software errors and failures are reported to the sponsoring organization for analysis and then forwarded to the supplier and users, if applicable.

Software not developed under a QA program meeting the requirements of the CBFO QAPD, including preexisting software, is evaluated, uniquely identified, and controlled in accordance with the requirements of the CBFO QAPD, Section 6.0. When accepted, the software is placed under configuration control before use. QA records (for software) are controlled and stored as described in Section 5.3.17.

Software is controlled using an iterative or sequential approach during the various life cycle phases, which include:

- definition of requirements;
- design;
- implementation;
- testing, including verification and validation tests;
- installation and checkout;
- operations and maintenance, including in-use tests; and
- retirement.

Verification and validation of the software, including a review of the completed software activities, documentation, and tests, are performed to ensure that the software adequately and correctly performs all intended functions and does not perform any unintended functions, in accordance with the requirements of the CBFO QAPD. Software verification is performed during the software development phases to verify that the requirements of the previous phase have been fulfilled. Software validation is performed to ensure that the software satisfies all requirements.

Controlled software is placed under configuration management to ensure that changes are controlled and that the appropriate version of the software is used. Configuration management includes the maintenance of unique identification, configuration change control, and configuration status accounting. When appropriate, access is controlled.

Software documentation generated and retained during software development includes:

- procurement documentation for procured software,
- software requirements documentation,
- design and implementation documentation,
- verification and validation documentation,
- any change documentation,
- user documentation, and
- any error and disposition documentation.

For released versions, software problems are documented, evaluated, and if appropriate, corrected. The evaluation of software problems includes the identification of any impact on previous use and any appropriate corrective action. Problems that significantly impact decisions based upon prior use or that require significant modification to the software are identified. Errors that qualify as a condition adverse to quality are controlled as described in Section 5.3.16.

5.3.21 Criterion 20 – Scientific Investigation

Technical investigations and design-development data collection activities are defined, controlled, verified, and documented. Process variables affecting scientific investigations are measured and controlled. Planning for scientific investigations ensures that the appropriate information is collected and that outside factors are eliminated or their effects are minimized. Planning is coordinated with other organizations that provide input or use the results. Planning for scientific investigations includes provisions for:

- identifying and appropriately controlling variables that affect interrelated scientific investigations;
- documenting the intended use of the data before collection;
- verifying the compatibility of data processing with any conceptual or mathematical models used at each applicable stage;
- reviewing and approving the technical acceptability of procedures;
- reviewing and approving the documented development activities used to establish new methods or procedures;

- establishing acceptance criteria for the data quality evaluation;
- identifying known sources of error and uncertainty; and
- identifying input data that are suspect or whose quality is beyond the control of the performing organizations.

Scientific investigations are performed according to requirements and are documented in scientific notebooks or technical implementation documents or both. If no nationally recognized test standard exists, special test procedures are developed and used. Scientific notebooks contain the results of the investigations and are periodically reviewed by a qualified individual for completeness.

Methods used in the investigations are reviewed to ensure that they are technically sound and have been properly selected. Data collection and analyses are controlled by procedures that allow the processes to be replicated. Test media are characterized and controlled in accordance with test procedures.

Data are recorded, identified, and traceable to the scientific investigation from which they are generated. Data collection and analysis are critically reviewed and questions are resolved before the results are used or reported. Uncertainty limits are assigned to the data before their use. Data are controlled to:

- prevent data loss and to permit data retrievability;
- maintain data integrity and security;
- ensure error-free transfer, reduction, and change in the expression or the quality of the data; and
- prevent the use of erroneous, rejected, superseded, or otherwise unsuitable data.

Data used for compliance with 40 CFR Part 191 Subparts B and C and 40 CFR Part 194 that were not collected under a QA program meeting the CBFO QAPD requirements are qualified through one or a combination of five methods detailed in Section 5.3.22. If peer reviews are necessary, the CBFO uses an approved procedure and process that is consistent with NUREG 1297 (1988), Peer Review for High-Level Nuclear Waste Repositories.

5.3.22 Criterion 21 – Data Quality Characteristics

40 CFR § 194.22 (c) stipulates that to the extent practicable, data used to support compliance will be assessed to ensure data accuracy, precision, representativeness, completeness, and comparability. The DOE applies these data characteristics to tasks involving the quantification of specific constituents in an environmental medium through sampling and analysis. The DOE applies these requirements to activities such as the determination of the presence or absence of constituents within TRU waste streams. Waste characterization and environmental monitoring are examples of the types of activities in which data quality characteristics are applied. In these

cases, the performance measurement is the concentration of the constituent of interest. Data quality measures include:

- data accuracy – a measure of the bias in a system, which is the degree of agreement of a measurement with an accepted reference or true value;
- data precision – a measure of mutual agreement among individual measurements of the same property, usually expressed in terms of standard deviation;
- data representativeness – the degree to which data accurately and precisely represent a characteristic of a population, parameter variations at a sampling point, or an environmental condition;
- data completeness – a measure of the amount of valid data obtained from a measurement system compared to the amount that was planned; and
- data comparability – a measure of the confidence with which one data set can be compared to another.

The performance measure that addresses compliance with 40 CFR § 191(B) is the cumulative release of radionuclides to the accessible environment over the next 10,000 years. This measure is estimated using mathematical models. The performance assessment process requires the use of mathematical models for the repository, which, in general, require that parameters be assigned to geologic, hydrologic and waste properties. Since many of these parameters are not amenable to direct measurement, they must be treated as uncertain variables rather than precisely determined quantities, and they are characterized as probability distributions.

Data are used to develop conceptual models and support distributions for parameter values. Between the point of data collection and the final computational model, uncertainty is introduced (for example, experimental design, extrapolation of the experimental results to spatial or temporal scales, etc.). These parameter distributions may span several orders of magnitude, and many parameters derived from data measurements need to be known only within orders of magnitude of their true value.

Uncertainty and sensitivity analyses respectively assess the uncertainty in system performance measures and identify modeling areas and parameters in which reductions in uncertainty can increase confidence. If the uncertainty of a parameter is of importance to the performance of the WIPP, more data may be collected to reduce the uncertainty.

It is often not practicable to document the data quality characteristics for the scientific investigation and characterization of natural systems. As an example, data accuracy would be very difficult, if not impossible, to assess for geologic site characterization activities because reference or true values do not exist.

Instead of quality characteristics, other steps are used to ensure that data are of adequate quality. Upper-tier quality requirement documents specifically define QA requirements for the collection of scientific and technical information. Section 5 of the CBFO QAPD, Scientific Investigation

Requirements, identifies the current requirements and processes used for data collection. For inclusion in compliance calculations, the data must be collected under an approved QA plan or otherwise be qualified as existing data.

In summary, it is not practicable to apply data quality characteristics to most scientific investigations that are used to support a performance assessment in which there is uncertainty in the conceptual models and the resultant ranges of parameters. Instead, controls established by the QA program ensure the necessary quality.

5.3.23 Criterion 22 – Qualification of Data

Data can be qualified by using one or more of the following methods:

- data used in performance assessment have been obtained under an approved QA program that implements the QA requirements referenced in Section 5.2.1.2;
- existing data collected before the implementation of a qualified QA program have been qualified by showing that the data were obtained under a QA program that is equivalent to one satisfying the NQA requirements referenced in Section 5.2;
- existing data have been qualified by peer review conducted in a manner compatible with NUREG 1297, Peer Review for High-Level Nuclear Waste Repositories;
- corroborating data processes may also be used to qualify the data; or
- confirmatory testing may be performed.

For data qualified by the implementation of a QA program meeting the criteria of 40 CFR 194 (first method above), the supporting documents and controls include the QA plan, audits and surveillances of the work that produced the data, and other objective evidence of QA implementation. If the audits show the program to be adequate and effectively implemented, then the data may be qualified. If audits identify significant deficiencies, then data whose quality is affected by those deficiencies are not qualified until impact assessments are completed and corrective actions have been implemented and verified.

Peer reviews are performed when necessary to verify the technical adequacy of work done and to qualify data. The peer review process and peer reviews conducted to support data qualification are described in Chapter 9.0, Peer Review.

Corroborating data are existing data used to support or substantiate other existing data. Existing data may be qualified through the use of corroborating data. Inference drawn to corroborate the existing data needs to be clearly identified, justified, and documented. The level of confidence associated with corroborating data is related to the quality of the program under which it was developed and the number of independent data sets. The amount of corroborating data needed is determined on a case-by-case basis in the documented qualification reviews.

Confirmatory testing is testing conducted under a QA program that investigates the properties of interest (e.g., physical, chemical, geologic, mechanical) of an existing database. Existing data

may be qualified through confirmatory testing. One example of confirmatory testing is testing that is conducted under the same environmental conditions and with the same or similar procedures, test material, and equipment as the original test that generated the existing data. Another type of confirmatory testing is testing conducted by different test methods and equipment but which still investigates the same properties of interest. The amount of confirmatory testing required is determined on a case-by-case basis in the documented qualification reviews.

40 CFR §194.27, Peer Review, requires CBFO to conduct peer reviews on the following:

- conceptual models selected and developed by the Department;
- waste characterization analyses as required in §194.24(b); and
- engineered barrier evaluation as required in §194.44.

5.4 The Carlsbad Field Office Quality Assurance Program Document

5.4.1 Purpose of the Quality Assurance Program Document

The CBFO QAPD describes the QA program requirements that apply to programs and projects managed by the CBFO. This program-wide requirements document describes the TRU waste QA controls applicable to all program participants within the TRU waste management structure.

5.4.2 U.S. Environmental Protection Agency Requirements in the Quality Assurance Program Document

The QAPD meets all EPA criteria for those items important to the containment of TRU waste, including the following items and activities:

- waste characterization activities and assumptions;
- environmental monitoring, monitoring of disposal system performance, and sampling and analysis activities;
- field measurements of geological, groundwater, meteorologic, and topographic characteristics;
- computations, computer codes, models, and methods to demonstrate compliance with 40 CFR Part 194;
- procedures for implementation of expert judgment elicitation to support the applications for certification and recertification of compliance with 40 CFR Part 194;
- design of the disposal system and actions taken to ensure compliance with design specifications;
- collection of data and information to support compliance application(s); and

- other systems, structures, components, and activities important to the containment of waste in the disposal system.

5.4.3 Use of the Graded Approach

The use of a graded approach supports the proper implementation of QA program requirements for items and activities important to compliance with 40 CFR Part 191 Subparts B and C and 40 CFR Part 194. The grading process is described in Section 5.3.2.3.

5.4.4 Quality Assurance Program Document Implementation

Based upon requirements from the QAPD, program participants have developed, implemented, and assessed their management systems and controls to ensure that items, processes, and services meet or exceed applicable requirements.

The adequacy and the effectiveness of implementation of these management systems and controls are verified through audits and surveillances conducted by the DOE and the program participants. The audits and surveillances are used to assess the adequacy, implementation, and effectiveness of the individual QA programs. The adequacy, implementation, and effectiveness of the various TRU waste QA programs are discussed in Section 5.6.

5.4.5 Quality Assurance Program Document Changes

Limited changes to the QAPD have been made since submittal of the CCA. The changes have been made to clarify application of requirements because new source requirement documents have been added to the TRU waste program.

Additional changes incorporated into the QAPD include CBFO organization and responsibility changes. Clarifications have been made in the areas of grading, control of conditions adverse to quality, and the preparation and maintenance of commitment and guidance documents.

5.4.6 Quality Assurance Program Participant Support

The CBFO identifies the QA program requirements applicable to all WIPP participants through the QAPD. The QAPD requirements are further supported and amplified by CBFO and program participant implementing procedures.

In addition to identifying applicable QA requirements through program documents, the participating organizations conduct the following activities in support of the QA program:

- audits and surveillances (external and internal) to evaluate the adequacy, implementation, and effectiveness of the applicable QA programs; and

- development, approval, and issuance of participant implementing documents and the review and approval of lower-tier implementing documents.

5.4.7 Structure of the QAPD

The QA requirements for quality-affecting activities for all program participants (as applicable to the scope of work) are described in the six sections of the QAPD. The QAPD is presented in Appendix QAPD.

5.4.8 Quality Assurance Program Document Crosswalk to NQA-1, -2, and -3 Requirements

Table 5-1 presents a crosswalk of QAPD and NQA requirements.

Table 5-1. QAPD vs. NQA-1, -2, and -3 Requirements

Criteria	Title	QAPD Reference
NQA-1, Criterion 1	Organization	Section 1
NQA-1, Criterion 2	Quality Assurance Program	Section 1
NQA-1, Criterion 3	Design Control	Section 2.2
NQA-1, Criterion 4	Procurement Document Control	Sections 2.3.4 and 2.3.5
NQA-1, Criterion 5	Instructions, Procedures, and Drawings	Sections 1.4 and 2.1.2
NQA-1, Criterion 6	Document Control	Section 1.4
NQA-1, Criterion 7	Control of Purchased Items and Services	Section 2.3
NQA-1, Criterion 8	Identification and Control of Items	Section 2.1.3
NQA-1, Criterion 9	Control of Processes	Section 2.1
NQA-1, Criterion 10	Inspection	Section 2.4
NQA-1, Criterion 11	Test Control	Section 2.4.4
NQA-1, Criterion 12	Control of Measuring and Test Equipment	Section 2.4.6
NQA-1, Criterion 13	Handling, Storage, and Shipping	Section 2.1.5
NQA-1, Criterion 14	Inspection, Test, and Operating Status	Section 2.4
NQA-1, Criterion 15	Control of Nonconforming Items	Section 1.3.2
NQA-1, Criterion 16	Corrective Action	Section 1.3.3
NQA-1, Criterion 17	Quality Assurance Records	Section 1.5
NQA-1, Criterion 18	Audits	Section 3.2.2
NQA-2, Part 2.7, Criterion 19	Software Quality Assurance	Section 6
NQA-3, Criterion 20	Scientific Investigation	Section 5
NQA-3, Criterion 21	Data and Sample Management	Section 4
NQA-3, Criterion 22	Qualification of Data	Section 5

5.4.9 CBFO Implementing Procedures

The CBFO implements Sections 1.4 and 2.1.2 of the QAPD through the use of Management Procedures (MPs) and Team Procedures (TPs):

- MP – An implementing document that specifies the process (methods and controls) for performing activities.
- TP – An implementing document that specifies the process (methods and controls) for performing functional activities within a specific, singular organizational area.

CBFO procedures include:

- MP 1.2, Selection of Quality Levels;
- MP 2.1, Personnel Qualification and Training;
- MP 3.1, Corrective Action Reporting;
- TP 3.2, Trend Identification and Reporting;
- MP 4.1, Preparation and Maintenance of CBFO Procedures;
- MP 4.2, Document Review;
- MP 4.4, Document Preparation and Control;
- MP 4.5, Generating, Receiving, Storing, and Controlling Active CBFO Project Records;
- MP 4.6, Records Filing, Inventorying, Scheduling, and Dispositioning;
- MP 4.7, Disposal of Nonpermanent Records;
- MP 4.8, Records Transfer and Retrieval;
- MP 4.9, Quality Assurance Records;
- MP 4.10, Processing of TRU Waste Site Documents;
- MP 5.2, TRU Waste Site Certification/Recertification;
- MP 5.3, Correspondence Standards;
- MP 7.1, QA Requirements for Procurement of Services;
- MP 9.1, Management Assessment;
- TP 10.1, Qualification of Audit Personnel and Certification of Lead Auditors;
- MP 10.2, Surveillances;
- MP 10.3, Audits;

- MP 10.5, Peer Review; and
- MP 10.7, Operational Assessments.

5.5 Applicability of the QA Program

The CBFO QAPD establishes and describes the QA program requirements. The QA program applies to all CBFO and participant activities affecting quality for the containment of TRU waste in support of the WIPP, including the eight programmatic areas addressed for compliance application (40 CFR § 194.22(a)(2)) demonstration. The QA program has been established as described in this chapter. The following program participants have quality assurance programs approved by the CBFO:

- CBFO Technical Assistance Contractor (CTAC)
- Sandia National Laboratories (SNL) – Carlsbad
- Los Alamos National Laboratory (LANL)
- Los Alamos National Laboratory Carlsbad (LANL-CO)
- Hanford site
- Idaho National Engineering and Environmental Laboratory (INEEL)
- Rocky Flats Environmental Technology Sites (RFETS)
- Savannah River Site (SRS)
- Washington TRU Solutions (WTS)
- Central Characterization Project (CCP)
- Advanced Mixed Waste Treatment Project (AMWTP)
- Argonne National Laboratory – East (ANL-E)

5.5.1 Waste Characterization Activities and Assumptions

The transuranic waste is inventoried and updated to provide an inventory source of waste data used in the performance assessment.

The WAC serves as the primary directive for ensuring that only waste that meets the legal definition of defense TRU waste and can be safety transported, handled, and disposed of is received at the WIPP. The WAC also identifies criteria to ensure generator and storage sites properly certify waste. Revised waste acceptance criteria have been provided to the EPA. In addition, information pertaining to the radiological properties of the waste and other disposal information from the obsolete QAPP has been added to the WAC (See Appendix TRU WASTE).

The Performance Demonstration Program (PDP) is used to evaluate the capability of the generator and storage sites to perform NDA for TRU waste characterization within acceptable limits. Initially, participating laboratories were required to participate in the PDP twice per year. The DOE has reduced the required frequency from twice per year to once per year and described this change to the EPA in correspondence dated November 10, 1998, and April 22, 1999 (Docket A-98-49). Based on this information, the EPA determined that the changes reported did not require modification, suspension, or revocation of the initial certification (refer to Chapter 4, Section 4.3.3.1).

Following is a list of waste generator sites certified to ship waste to the WIPP.

- Nevada Test Site (using CCP) – as of August 2002,
- LANL – as of December 2002,
- Rocky Flats Environmental Technology Site – as of March 2003,
- INEEL – as of May 2003,
- Hanford Site – as of June 2003,
- SRS (using CCP) – as of October 2002,
- Argonne National Lab (East) (using CCP) – as of September 2002, and
- Advanced Mixed Waste Treatment Project – as of August 2003.

5.5.2 Environmental Monitoring, Monitoring of the Performance of the Disposal System, and Sampling and Analysis Activities

All environmental and performance monitoring activities related to compliance with the requirements of 40 CFR Part 191 Subparts B and C and 40 CFR Part 194 are described in Appendix MON 2004.

5.5.3 Design of the Disposal System and Actions Taken to Ensure Compliance with Design Specifications

A change to elevate the horizon at which Panels 3, 4, 5, 6, and 9 are mined was approved by the EPA on August 11, 2000. The change went through the design verification process to ensure compliance with identified requirements. Design controls specified in the WTS QAPD are in place to track and verify the design process. These controls ensure that new designs and design changes are subject to specifications commensurate with the original design and verify that the design analyses remain valid.

5.5.4 Collection of Data and Information to Support Compliance Application(s)

SNL collects information and data from experimental programs that serve multiple purposes in the WIPP project:

- Data relevant to the chemical or physical characteristics of the WIPP site;
- Data that allow estimation of the behavior of the wastes and the system during the 10,000-year regulatory period;
- To develop data to be used in testing alternative conceptual models and selecting the most appropriate model(s) of engineered system behavior for use in the performance assessment modeling process; and
- Scientific data collected in the areas of rock mechanics, actinide source term, chemical transport, disposal room, gas generation, non-Salado flow and transport, Salado Formation hydrology and transport.

5.6 Quality Assurance Program Adequacy, Implementation, and Effectiveness

Audits and other assessments are scheduled and conducted to verify the adequacy, implementation, and effectiveness of the QA program. The DOE, SNL, LANL-CO, and WTS QA programs have been determined to be adequate and effectively implemented in accordance with adequate procedures that meet the CBFO QAPD.

The CBFO maintains and implements an assessment schedule to assess initial and continuing CBFO, SNL, LANL-CO, WTS, and TRU waste generator site QA program adequacy, implementation, and effectiveness. Assessment scheduling is a dynamic process that requires frequent changes to respond to DOE and participant needs. The CBFO assessment schedule is updated monthly and is distributed to WIPP participants and other stakeholders. The assessment schedule accommodates the routine, recurring, and any focused or special purpose assessments that are determined to be appropriate by management.

5.6.1 Adequacy of the Quality Assurance Program

The adequacy of the QA program refers to an approved and documented QA program that meets the applicable requirements addressed in the CBFO QAPD. Adequacy is determined by the review of participant QA programs to ensure that upper-tier requirements have been incorporated into the appropriate documents.

The flow-down of requirements in the established QA program is presented in Figure 5-1. Organizations establishing a QA program or making changes to an established program must evaluate all the requirements addressed in the CBFO QAPD for applicability to their activities and document these criteria in new or revised implementing documents in order to meet the applicable requirements.

The adequacy of the documented QA program and any changes to an established QA program are verified before performing independent reviews for implementation and effectiveness (e.g., determining whether the documentation addresses the proper migration of requirements from the QAPD into the implementing documents).

5.6.2 Implementation of the Quality Assurance Program

Implementation of a QA program is determined by the extent to which the organization complies with its QA and technical procedures. QA program implementation is verified during audits and assessments of the program. Audits are scheduled to begin as early in the life of a project or activity as practicable and continue at intervals consistent with the schedule for accomplishing the work and commensurate with the assigned control levels. Audits, surveillances, management assessments, and other reviews are conducted to determine the acceptability of the procedural implementation.

5.6.3 Effectiveness of the Quality Assurance Program

Effectiveness refers to a process that produces the desired (specified) end-product or end-service. Effectiveness can be determined by:

- Technical Specialists being used to determine the effectiveness of technical processes and documents,
- management assessments being used to determine continued effectiveness, and
- trend analysis data and other information being used to assure process effectiveness.

5.7 The Carlsbad Field Office Audit Process

5.7.1 Overview of the Carlsbad Field Office Assessment Processes

Audits are conducted of CBFO activities (internal audits) and activities performed by organizations outside the CBFO (external audits). External organizations include the WTS, SNL, LANL, TRU waste sites, and other program participants conducting work for the CBFO. The audits are conducted to assess QA and technical activities that relate to regulatory compliance, safety, certification, transportation, and waste isolation.

The CBFO QA Manager coordinates with the CBFO assistant managers to identify appropriate assessments. These assessments are included in the CBFO assessment schedule. The following factors are considered when scheduling audits:

- work activities, level of effort, risk, and importance to regulatory compliance, safety, TRU waste site certification, or waste isolation issues;
- reviews of documentation furnished by, or regarding the work of, the organization or supplier (e.g., certificates of conformance, nonconforming notices, and corrective actions);
- consideration of previous assessment results, trends, corrective actions, effectiveness, and ancillary information (e.g., information from other sources such as industry or other DOE organizations, and regulatory agencies);

- reviews of previous assessments from identical or similar products or services furnished by the same organization or supplier; and
- results of surveillance activities.

Scheduled audits are supplemented, as necessary, to provide continuing coverage of work activities for any of the following reasons:

- to determine the adequacy, implementation, and effectiveness of contractor activities after contract award;
- to assess the impact of any significant changes made to a program or organizational structure;
- to evaluate the cause and impact of any declining trends in quality performance; and
- to verify implementation of extensive, large-scale corrective action activities.

Audit Team Leaders are selected from a list of certified Lead Auditors. The Audit Team Leader selects qualified Auditors and Technical Specialists, as required to meet the scope of the audit. The members of the audit team are selected based on independence from the organization or activities being audited. They have sufficient authority and organizational freedom to objectively conduct the audit.

The Audit Team Leader develops the audit plan and obtains the approval of the CBFO QA Manager. An audit notification letter addressed to the key auditee individual is transmitted to the organization to be audited. The Audit Team Leader provides audit team orientation and notifies any observers. Audit team members prepare the audit checklists, which are approved by the Audit Team Leader. The Audit Team Leader forwards the approved checklists to the audited organization before the audit.

The Audit Team Leader conducts the preaudit meeting and manages the conduct of the audit. The audit team meets daily to discuss audit concerns, status, and exemplary practices. Results are summarized and discussed. A daily meeting is held with the management of the audited organization(s) to inform them of any audit results and the audit status. Deficiencies are documented on Corrective Action Reports (CARs). Isolated deficiencies corrected during the audit are documented as “corrected during the audit” (CDAs). CDAs are documented in the audit report for trending purposes.

The audit report is prepared by the Audit Team Leader and submitted to the CBFO QA Manager for review and approval. The CBFO QA Manager distributes the report to the CBFO Manager, the appropriate management of the audited organization, the responsible CBFO assistant managers, the EPA, the State of New Mexico, and other interested parties in a timely manner.

5.7.2 Auditor and Technical Specialist Independence

Independent assessments of program participants are performed by Lead Auditors, Auditors, and Technical Specialists who are independent of the work and organization being assessed.

Whenever audit team independence may be an issue, a mitigation procedure is utilized to provide alternatives and controls to ensure that audit team independence is achieved and maintained. Examples of mitigation controls include the reassignment of personnel, Audit Team Leader discussions relative to independence with audit team members, and an Audit Team Leader review of the activities and results of those performing the audits. In the event that an audit team member has performed program development activities for a program participant, the individual is not permitted to perform audit activities in those areas until a subsequent independent audit has been performed of those activities (usually one year).

5.7.3 Audit History

The assessment summaries in Tables AUD-1 through AUD-11 of Appendix AUD 2004 reflect assessments that have been performed from 1999 to 2003 of TRU waste generator sites, SNL, LANL-CO, WTS, suppliers performing quality-affecting work, and the CBFO.

REFERENCE

U.S. Department of Energy (DOE). 2003. CBFO Quality Assurance Program Document, DOE/CBFO-94-1012. Carlsbad, NM.

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6.0 CONTAINMENT REQUIREMENTS

6.0.1 Introduction

Because of the amount and complexity of the material presented in Chapter 6.0, an introductory summary is provided below. Detailed discussions of the topics covered in this summary are found in the remainder of the chapter, which is organized as follows.

- Section 6.1 – The overall system performance assessment (PA) methodology used to evaluate compliance with the containment requirements.
- Section 6.2 – A comprehensive list of features, events, and processes (FEPs) that might affect disposal system performance, the screening methodology applied to that list, and the results of the screening process.
- Section 6.3 – Development of the scenarios considered in the system-level consequence analysis.
- Section 6.4 – The conceptual and computational models used to perform the system-level consequence analysis PA, the overall flow of information in the PA, the scenario probabilities, and the construction of a performance measure for comparison with the standard.
- Section 6.5 – The results of the PA.

Additional information supporting this chapter is provided in appendices. See Table 1-1 for a list of these appendices.

The U.S. Department of Energy (DOE) continues to use the same PA methodology for the recertification of WIPP. In general, changes that have been made since the U.S. Environmental Protection Agency (EPA) certified WIPP do not impact PA methodology.

6.0.2 Overview of Chapter 6.0

The EPA determined that the WIPP is in compliance with the Containment Requirements of Title 40 Code of Federal Regulations (CFR) § 191.13 in 1998 (EPA 1998a). The DOE has conducted a new PA for the WIPP. The WIPP Land Withdrawal Act (LWA), Public Law 02-579 as amended by Pubic Law No. 104-201, requires DOE to provide the EPA with documentation of continued compliance with the disposal standards within five years of first waste receipt and every five years thereafter. During review of the initial certification application, EPA required many changes to PA parameters, which have been included in the PA for this recertification application (EPA 1998b). The DOE has also made additional changes to the PA to better represent repository features, such as panel closures, and to account for new information. Table 6-1 summarizes the changes to the PA since the Compliance Certification Application (CCA); additional information is provided in Appendix PA (Attachment MASS, Section 2).

Table 6-1. WIPP Project Changes and Cross References

WIPP Project Change	Cross Reference
Incorporation of 1997 Performance Assessment Verification Test (PAVT) Parameters	
Credit for Passive Institutional Controls	6.4.12.1
K_d (Dissolved-Actinide Matrix Distribution Coefficient)	6.0.2.3.7, 6.4.6.2.2
Probability of Encountering a Brine Reservoir	6.0.2.3.8, 6.4.8, 6.4.12.6
Brine Reservoir Rock Compressibility	6.4.8
Brine Reservoir Porosity	6.4.8
Drill String Angular Velocity	Appendix PA, Attachment MASS (Section16) and Attachment PAR
Waste Permeability	6.4.3.2
Waste Unit Factor	Appendix TRU WASTE
Long-term Borehole Permeability	6.4.7.2
Borehole Plug Permeability	6.4.7.2
Waste Shear Strength and Erodability	Appendix PA, Attachment MASS (Section 16)
DRZ	6.4.5.3, 6.4.10.1
Actinide Solubility	6.4.3.5
Inundated Steel Corrosion Rate	6.4.3.3
Operational Changes	
Option D Panel Closure	6.4.3, 6.4.4
Inventory Update	6.4.3.1, 6.4.3.3
Culebra Water Levels	6.4.6.2, and Appendix PA, Attachment MASS
Spallings Model	6.0.2.3.2; Appendix PA (Section 4.6) and Attachment MASS (Section 16.0)
Drilling Rate	6.0.2.3, 6.2.5.2; Appendix DATA (Section 2 and Attachment A)
Organic Ligands	6.0.2.3.4, 6.4.3.4; Appendix PA, Attachments SOTERM and SCR
FEPs Reassessment	6.2.6; Appendix PA, Attachment SCR
Borehole Plugs Configuration Probability	6.4.7.2
Mining Disposal Horizon to Clay G	Appendix PA, Attachment MASS (Section 20)

From this assessment, the DOE has demonstrated that the WIPP continues to comply with the Containment Requirements of 40 CFR § 191.13. The Containment Requirements are stringent and state that the DOE must demonstrate a reasonable expectation that the probabilities of cumulative radionuclide releases from the disposal system during the 10,000 years following closure will fall below specified limits. The PA analyses supporting this determination must be quantitative and consider uncertainties caused by all significant processes and events that may affect the disposal system, including future inadvertent human intrusion into the repository. A

quantitative PA is conducted using a series of linked computer models in which uncertainties are addressed by a Monte Carlo procedure for sampling selected input parameters.

As required by regulation, results of the PA are displayed as complementary cumulative distribution functions (CCDFs) that display the probability that cumulative radionuclide releases from the disposal system will exceed the values calculated for scenarios considered in the analysis. These CCDFs are calculated using reasonable and, in some cases conservative conceptual models based on the scientific understanding of the disposal system's behavior. Parameters used in these models are derived from experimental data, field observations, and relevant technical literature. Changes to the CCA's parameters and models that have been necessary since the original certification have been incorporated into the PA. Information on the waste already disposed and new estimates of current and projected waste inventories are also incorporated. The overall mean CCDF continues to lie entirely below the specified limits, and the WIPP therefore continues to be in compliance with the containment requirements of 40 CFR Part 191, Subpart B (see Section 6.5.2, Figure 6-1). Sensitivity analysis of results shows that the location of the mean CCDF is dominated by radionuclide releases that could occur on the surface during an inadvertent penetration of the repository by a future drilling operation. Releases of radionuclides to the accessible environment resulting from transport in groundwater through the shaft seal systems and the subsurface geology are resulting negligible, with or without human intrusion, and make no contribution to the location of the mean CCDF. No releases whatsoever are predicted to occur at the ground surface in the absence of human intrusion. The natural and engineered barrier systems of the WIPP provide robust and effective containment of transuranic (TRU) waste even if the repository is penetrated by multiple boreholes.

A list of changes and a citation to where they are discussed is shown in Table 6-1.

6.0.2.1 Conceptual Basis for the Performance Assessment

The foundations of PA are a thorough understanding of the disposal system and the possible future interactions of the repository, waste, and surrounding geology. The recertification application is organized so that site characterization, facility design, and waste characterization are described separately in Chapters 2.0, 3.0, and 4.0, respectively. The DOE's confidence in the results of the recertification PA is based in part on the strength of the original research done during site characterization, experimental results used to develop and confirm parameters and models, the robustness of the facility design, and the knowledge of the updated inventory. Quality assurance (QA) activities, described in Chapter 5.0, demonstrate that the information gathered during these activities is qualified to meet the QA criteria in 40 CFR 194.

Chapters 2.0, 3.0, and 4.0 provide basic descriptions of the disposal system main components. The interactions of the repository and waste with the geologic system, and the response of the disposal system to possible future inadvertent human intrusion, are described in Section 6.4.

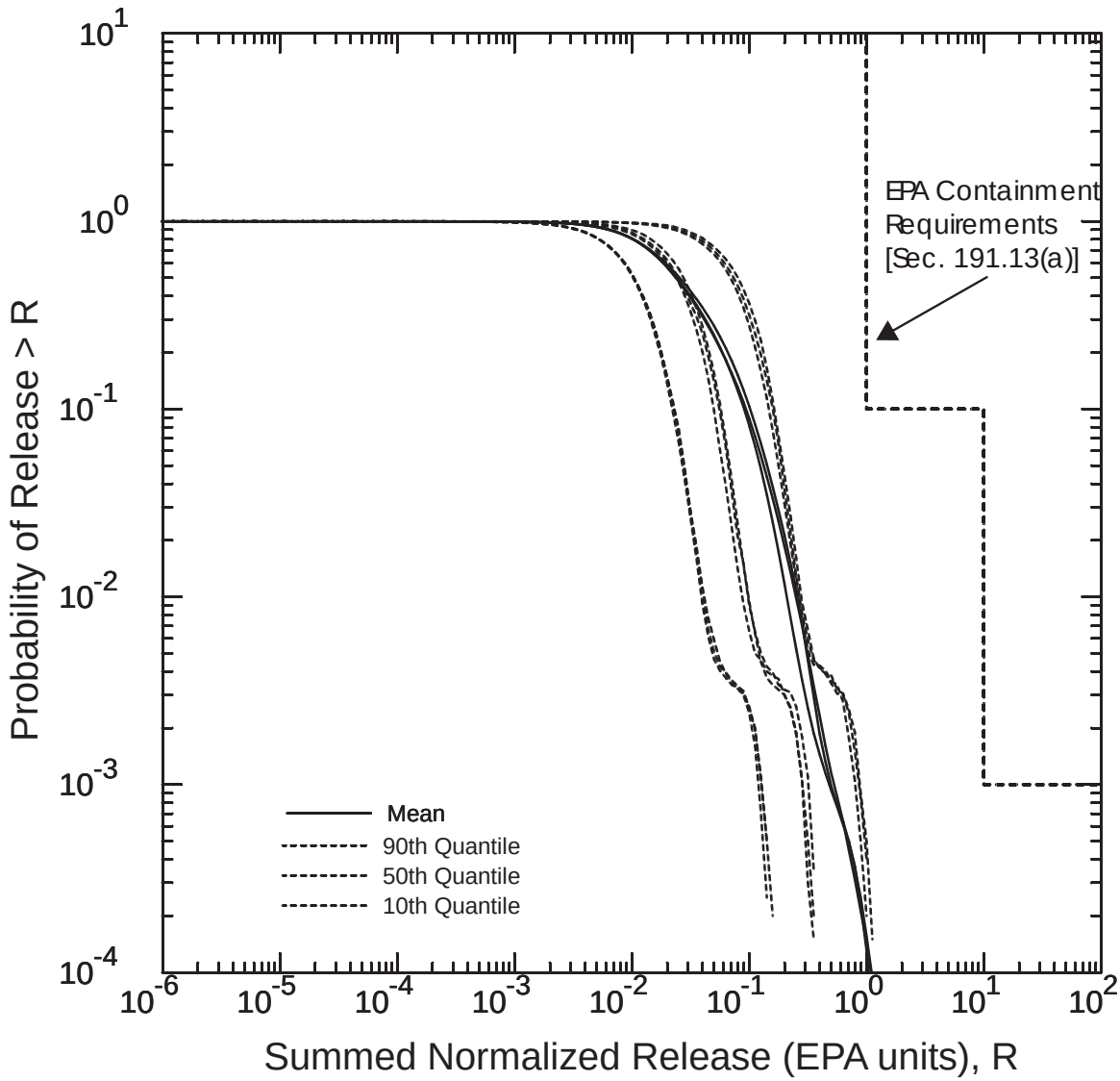

Note: Mean, median, and 10th and 90th percentile CCDFs are shown together with the overall mean. These CCDFs are based on the distributions of CCDFs shown in Figure 6-34, 6-35, and 6-36.

Figure 6-1. Summary CCDFs for Replicates 1, 2, and 3

6.0.2.2 Undisturbed Performance

An evaluation of undisturbed performance, which is defined to exclude human intrusion and unlikely disruptive natural events, is required by regulation (see Sections 191.15 and § 191.24). Evaluation of past and present natural geologic processes in the region indicate that none has the potential to breach the repository within 10,000 years. Disposal system behavior is dominated by the coupled processes of rock deformation surrounding the excavation, fluid flow, and waste degradation. Each of these processes can be described independently, but the extent to which each process occurs is affected by the others.

Deformation of the rock immediately around the repository begins as soon as excavation creates a disturbance in the stress field. Stress relief results in some degree of brittle fracturing and the

formation of a disturbed rock zone (DRZ), which surrounds excavations in all deep mines, including the repository. For the WIPP, the DRZ is characterized by an increase in permeability and a decrease in pore pressure, and may ultimately extend a few meters from the excavated region. Salt will also deform by creep processes, which are a result of deviatoric stress, causing the materials to move inward to fill voids. Salt creep will continue until deviatoric stress is dissipated and the system is once again at stress equilibrium.

The ability of salt to creep, thereby healing fractures and filling porosity, is one of its fundamental advantages as a medium for geologic disposal of radioactive waste and one reason it was recommended by the National Academy of Sciences (NAS). Salt creep provides the mechanism for crushed salt compaction in the shaft seal system, yielding properties approaching those of intact salt within 200 years. Salt creep will also cause the DRZ surrounding the shaft to heal rapidly around the concrete components of the seal system. In the absence of elevated gas pressure in the repository, salt creep would also substantially compact the waste and heal the DRZ around the disposal region. The coupling of salt creep with fluid flow and waste degradation processes results in fluid pressure within the waste disposal region maintaining significant porosity within the disposal region throughout the performance period.

Characterization of the Salado Formation (hereafter referred to as the Salado) indicates that fluid flow does not occur on time scales of interest in the absence of an artificially imposed hydraulic gradient. This lack of fluid flow is the second fundamental reason for the choice of salt as a medium for geologic disposal of radioactive waste. Lack of fluid flow is a result of the extremely low permeability of the evaporite rocks that make up the Salado. Excavation of the repository has disturbed the natural hydraulic gradient and rock properties and has resulted in fluid flow. Small quantities of interstitial brine present in the Salado move toward regions of low hydraulic potential and brine seeps are observed in the underground. The slow flow of brine from halite into more permeable anhydrite marker beds and then through the DRZ into the repository is expected to continue as long as the hydraulic potential within the repository is below that of the far field. The repository environment will also involve gas, and fluid flow that must be modeled as a two-phase process. Initially, the gaseous phase will consist primarily of air trapped at the time of closure, although other gases may form from waste degradation. In the PA, the gaseous phase pressure will rise due to creep closure, gas generation, and brine inflow, creating the potential for flow from the excavated region.

Consideration of waste degradation processes indicates that the gaseous phase in fluid flow and the repository's pressure history will be far more important than if the initial air were the only gas present. Waste degradation can generate significant additional gas by two processes:

1. the generation of hydrogen (H_2) gas by anoxic corrosion of steels, other iron-base (Fe-based) alloys, and aluminum (Al) and Al-based alloys, and

2. the generation of carbon dioxide (CO_2) and methane (CH_4) by anaerobic microbial consumption of waste containing cellulosic, plastic, or rubber materials.

Coupling these gas-generation reactions to fluid flow and salt creep processes is complex. Gas generation will increase fluid pressure in the repository, thereby decreasing the hydraulic gradient and deviatoric stress between the far field and the excavated region and inhibiting the

processes of brine inflow and salt creep. Anoxic corrosion will also consume brine as it breaks down water to oxidize steels and other Fe-based alloys and release H_2. Thus, corrosion has the potential to be a self-limiting process, in that as it consumes all water in contact with steels and other Fe-based alloys, it will cease. Microbial reactions also require water, either in brine or the gaseous phase. It is assumed that microbial reactions will result in neither the consumption nor production of water.

The total volume of gas generated by corrosion and microbial consumption may be sufficient to result in repository pressures that approach lithostatic. Sustained pressures above lithostatic are not physically reasonable within the disposal system, and fracturing of the more brittle anhydrite layers is expected to occur if sufficient gas is present. The conceptual model implemented in the PA causes permeability and porosity of the anhydrite marker beds to increase rapidly as pore pressure approaches and exceeds lithostatic. This conceptual model for pressure-dependent fracturing approximates the hydraulic effect of pressure-induced fracturing and allows gas and brine to move more freely within the marker beds at higher pressures.

Overall, the behavior of the undisturbed disposal system will result in extremely effective isolation of the radioactive waste. Concrete, clay, and asphalt components of the shaft seal system will provide an immediate and effective barrier to fluid flow through the shafts, isolating the repository until salt creep has consolidated the compacted crushed salt components and permanently sealed the shafts. Around the shafts, the DRZ in halite layers will heal rapidly because the presence of the solid material within the shafts will provide rigid resistance to creep. The DRZ around the shaft, therefore, will not provide a continuous pathway for fluid flow. Similarly, the Option D panel closure will provide rigid resistance to creep and rapidly eliminate the DRZ locally by a compressive state of stress. The DRZ is not expected to heal completely around the disposal region, or the operations and experimental regions, and pathways for fluid flow may exist indefinitely to the overlying and underlying anhydrite layers (e.g., Marker Bed (MB)139 and anhydrites a and b). Some quantity of brine will be present in the repository under most conditions and may contain actinides (which dominate the radionuclide inventory and are therefore the elements of primary regulatory interest) mobilized as both dissolved and colloidal species. Gas generation by corrosion and microbial degradation is expected to occur and will result in elevated pressures within the repository. These pressures will not significantly exceed lithostatic, because fracturing within the more brittle anhydrite layers will occur and provide a pathway for gas to leave the repository. Fracturing due to high gas pressures may enhance gas and brine migration from the repository, but gas transport will not contribute to the release of actinides from the disposal system. Brine flowing out of the waste disposal region through anhydrite layers may transport actinides as dissolved and colloidal species, but the quantity of actinides that may reach the accessible environment boundary during undisturbed performance through the interbeds is insignificant and has no effect on the compliance determination. No migration of radionuclides whatsoever is expected to occur vertically through the Salado or through the shaft seal system.

6.0.2.3 Disturbed Performance

Performance assessment is required by regulation to consider scenarios that include intrusions into the repository by inadvertent and intermittent drilling for resources. In the CCA, the probability of these intrusions was based on a future drilling rate of 46.8 boreholes per square

kilometer per 10,000 years. This rate was based on the past record of drilling events in the Delaware Basin, consistent with regulatory criteria. Since the CCA, additional drilling in the Delaware Basin has raised the drilling rate to 52.5 boreholes per square kilometer per 10,000 years (see Appendix DATA, Section DATA-2.0 and Attachment A). Active institutional controls are assumed to be completely effective in preventing intrusion during the first 100 years after closure. Passive institutional controls were originally assumed in the CCA to effectively reduce the drilling rate by two orders of magnitude for the 600 years following the 100 years of active control. However, in certifying the WIPP, EPA denied the application of credit for the effectiveness of passive controls for 600 years. Although the Compliance Recertification Application 2004 PA (2004 PA) does not include a reduced drilling intrusion rate to account for passive institutional controls, future PA may do so. Future drilling practices are assumed to be the same as current practice, also consistent with regulatory criteria. These practices include the type and rate of drilling, emplacement of casing in boreholes, and the procedures implemented when boreholes are plugged and abandoned.

PA results indicate that human intrusion provides the only potential mechanism for significant releases of radionuclides from the disposal system. These releases could occur by five mechanisms:

(1) cuttings, which include material intersected by the rotary drilling bit;

(2) cavings, which include material eroded from the borehole wall during drilling;

(3) spallings, which include solid material carried into the borehole during rapid depressurization of the waste disposal region;

(4) direct brine releases, which include contaminated brine that may flow to the surface during drilling; and

(5) long-term brine releases, which include the contaminated brine that may flow through a borehole after it is abandoned.

The first four mechanisms operate immediately following the intrusion event and are collectively referred to as direct releases. The accessible environment boundary for these releases is the ground surface. The fifth mechanism, actinide transport by long-term groundwater flow, begins when concrete plugs are assumed to degrade in an abandoned borehole and may continue throughout the regulatory period. The accessible environment boundary for these releases may be the ground surface or the lateral subsurface limit of the controlled area.

Repository conditions prior to intrusion will be the same as those for undisturbed performance and all processes active in undisturbed performance will continue to occur following intrusion. Because intrusion provides a pathway for radionuclides to reach the ground surface and to enter the geological units above the Salado, additional processes will occur that are less important in undisturbed performance. These processes include the mobilization of radionuclides as dissolved and colloidal species in repository brine and groundwater flow, and actinide transport in the overlying units. Flow and transport in the Culebra Member of the Rustler Formation (hereafter referred to as the Rustler) are of particular interest because modeling indicates this is the unit to which most flow from a borehole may occur.

6.0.2.3.1 Cuttings and Cavings

In a rotary drilling operation, the volume of material brought to the surface as cuttings is calculated as the cylinder defined by the thickness of the unit and the diameter of the drill bit. The quantity of radionuclides released as cuttings is therefore a function only of the intersected waste activity and the diameter of the intruding drill bit. Like all parameters that describe future drilling activities, the diameter of a drill bit that may intersect waste is speculative. The DOE uses a constant value of 0.311 m (12.25 in.), consistent with bits currently used at the WIPP depth in the Delaware Basin. The intersected waste activity may vary depending on the type of waste intersected, and the DOE considers random penetrations into remote-handled (RH)-TRU waste and each of the 693 different waste streams identified for contact-handled (CH)-TRU waste (569 waste streams were used in the CCA).

The volume of particulate material eroded from the borehole wall by the drilling fluids and brought to the surface as cavings may be affected by the drill bit diameter, the effective shear resistance of the intruded material, the speed of the drill bit, the viscosity of the drilling fluid and the rate at which it is circulated in the borehole, and other properties related to the drilling process. The most important of these parameters, after drill bit diameter, is the effective shear resistance of the intruded material. In the absence of data describing the reasonable and realistic future properties of degraded waste and magnesium oxide (MgO), the DOE used conservative parameter values based on the properties of fine-grained sediment. Other properties are assigned fixed values consistent with current practice. The quantity of radionuclides released as cavings depends on the volume of eroded material and its activity, which is treated in the same manner as the activity of the cuttings.

6.0.2.3.2 Spallings

Unlike releases from cuttings and cavings, which occur with every modeled borehole intrusion, spalling releases will occur only if pressure in the waste-disposal region exceeds the hydrostatic pressure in the borehole. At lower pressures, below about 8 megapascals, fluid in the waste-disposal region will not flow toward the borehole. At higher pressures, gas flow toward the borehole may be sufficiently rapid to cause additional solid material to enter the borehole. If spalling occurs, the volume of spalled material will be affected by the physical properties of the waste, such as its tensile strength and particle diameter. The DOE has based the parameter values used in the PA on reasonable and conservative assumptions. Since the original certification, a revised conceptual model for the spallings phenomena has been developed (see Appendix PA, Section 4.6 and Attachment MASS, Section 16). Model development, execution, and sensitivity studies necessitated implementing parameter values pertaining to waste characteristics, drilling practices and physics of the process. The parameter range for particle size was derived by expert elicitation (EPA 1997, II-G-24).

The quantity of radionuclides released as spalled material depends on the volume of spalled waste and its activity. Because spalling may occur at a greater distance from the borehole than cuttings and cavings, spalled waste is assumed to have the volume-averaged activity of CH-TRU waste rather than the sampled activities of individual waste streams. RH-TRU waste is isolated from the spallings process and does not contribute to the volume or activity of spalled material.

6.0.2.3.3 Direct Brine Flow

Radionuclides may be released to the accessible environment if repository brine enters the borehole during drilling and flows to the ground surface. The quantity of radionuclides released by direct brine flow depends on the volume of brine reaching the ground surface and the concentration of radionuclides contained in the brine. As with spallings, direct releases of brine will not occur if repository pressure is below the hydrostatic pressure in the borehole. At higher repository pressures, mobile brine present in the repository will flow toward the borehole. If the volume of brine flowing from the repository into the borehole is small, it will not affect the drilling operation, and flow may continue until the driller reaches the base of the evaporite section and installs casing in the borehole. This time is estimated to be 72 hours, consistent with current practice. Larger brine flows or large gas flows could cause the driller to lose control of the borehole, and fluid flow, in this case, could continue until repository pressure drops or the hole is contained. The maximum length of time that such flow could continue before the driller controlled the borehole is estimated to be 11 days, consistent with observed drilling events in the Delaware Basin (Appendix PA, Section PA-4.7.8 and Attachment MASS, Section 16.0).

6.0.2.3.4 Mobilization of Actinides in Repository Brine

Actinides may be mobilized in repository brine in two principal ways:

(1) as dissolved species, and

(2) as colloidal species.

The solubilities of actinides depend on their oxidation states, with the more reduced forms (for example, the +III and +IV oxidation states) being less soluble than the oxidized forms (+V and +VI). Conditions within the repository will be strongly reducing because of the large quantity of metallic Fe in the steel containers and the waste, and – in the case of plutonium (Pu) – only the lower-solubility oxidation states (Pu(III) and Pu(IV)) will persist. Microbial activity, if it occurs, will also create reducing conditions. Solubilities also vary with pH. The DOE is therefore emplacing MgO in the waste-disposal region to ensure conditions that favor minimum actinide solubilities. MgO consumes CO_2 and buffers pH, lowering actinide solubilities in WIPP brines. Solubilities in the PA are based on the chemistry of brines that might be present in the waste-disposal region, reactions of these brines with the MgO engineered barrier, and strongly reducing conditions produced by anoxic corrosion of steels and other Fe-based alloys.

The waste contains organic ligands that could increase actinide solubilities by forming complexes with dissolved actinide species. However, these organic ligands also form complexes with other dissolved metals, such as magnesium (Mg), calcium (Ca), Fe, vanadium (V), chromium (Cr), manganese (Mn), and nickel (Ni), that will be present in repository brines due to corrosion of steels and other Fe-based alloys. The CRA-2004 PA speciation and solubility calculations (Attachment SOTERM) confirmed that actinide solubilities are not significantly affected by organic ligands.

Colloidal transport of actinides has been examined and four types have been determined to represent the possible behavior at the WIPP. These include microbial colloids, humic substances, actinide intrinsic colloids, and mineral fragments. Concentrations of actinides

mobilized as these colloidal forms are included in the estimates of total actinide concentrations used in PA.

6.0.2.3.5 Long-Term Brine Flow up an Intrusion Borehole

Long-term releases to the ground surface or groundwater in the Rustler or overlying units may occur after the borehole has been plugged and abandoned. In keeping with regulatory criteria, borehole plugs are assumed to have properties consistent with current practice in the basin. Thus, boreholes are assumed to have concrete plugs emplaced at various locations. Initially, concrete plugs effectively limit fluid flow in the borehole. However, under most circumstances, these plugs cannot be expected to remain fully effective indefinitely. For the purposes of PA, discontinuous borehole plugs above the repository are assumed to degrade 200 years after emplacement. From then on, the borehole is assumed to fill with a silty sand-like material containing degraded concrete, corrosion products from degraded casing, and material that sloughs into the hole from the walls. Of six possible plugged borehole configurations in the Delaware Basin, three are considered either likely or found to adequately represent other possible configurations; one configuration (a two-plug configuration) is explicitly modeled.

If sufficient brine is available in the repository, and if pressure in the repository is higher than in the overlying units, brine may flow up the borehole following degradation of the plugs. In principle, this brine could flow into any permeable unit or to the ground surface if repository pressure were high enough. For modeling purposes, brine is allowed to flow only into the higher permeability units and to the surface. Lower permeability anhydrite and mudstone layers in the Rustler are treated as if they were impermeable, to simplify the analysis while maximizing the amount of flow occurring into units where it could potentially contribute to releases from the disposal system. Model results indicate that essentially all flow occurs into the Culebra, which has been recognized since the early stages of site characterization as the most transmissive unit above the repository and the most likely pathway for subsurface transport.

6.0.2.3.6 Groundwater Flow in the Culebra

Site characterization activities in the units above the Salado have focused on the Culebra. These activities have shown that the direction of groundwater flow in the Culebra varies somewhat regionally, but in the area that lies over the site, flow is southward. Regional variation in groundwater flow direction in the Culebra is influenced by the transmissivity observed and also by the shape of and distribution of rock types in the groundwater basin where the WIPP is located. Site characterization activities have demonstrated that there is no evidence of karst groundwater systems in the controlled area, although groundwater flow in the Culebra is affected by the presence of fractures, fracture fillings, and vuggy pore features. Other laboratory and field activities have focused on the behavior of dissolved and colloidal actinides in the Culebra. These characterization and modeling activities conducted in the units above the Salado confirm that the Culebra is the most transmissive unit above the Salado. The Culebra is the unit into which actinides are likely to be introduced from long-term flow up an abandoned borehole.

Basin-scale regional modeling of three-dimensional groundwater flow in the units above the Salado demonstrates that it is appropriate, for the purposes of estimating radionuclide transport, to conceptualize the Culebra as a two-dimensional confined aquifer. Uncertainty in the flow

field is incorporated in the analysis by using 100 different geostatistically-based transmissivity fields, each of which is consistent with available head and transmissivity data.

Groundwater flow in the Culebra is modeled as a steady-state process, but two mechanisms considered in the PA could affect flow in the future. Potash mining in the McNutt Potash Zone (hereafter referred to as the McNutt) of the Salado, which occurs now in the Delaware Basin outside the controlled area and may continue in the future, could affect flow in the Culebra if subsidence over mined areas causes fracturing or other changes in rock properties. Climatic changes during the next 10,000 years may also affect groundwater flow by altering recharge to the Culebra.

Consistent with regulatory criteria, mining outside the controlled area is assumed to occur in the near future, and mining within the controlled area is assumed to occur with a probability of 1 in 100 per century (adjusted for the effectiveness of active institutional controls during the first 100 years following closure). Consistent with regulatory guidance, the effects of mine subsidence are incorporated in the PA by increasing the transmissivity of the Culebra over the areas identified as mineable by a factor sampled from a uniform distribution between 1 and 1000. Transmissivity fields used in the PA are therefore adjusted and steady-state flow fields calculated accordingly; once for mining that occurs only outside the controlled area, and once for mining that occurs both inside and outside the controlled area. Mining outside the controlled area is considered in both undisturbed and disturbed performance.

The extent to which the climate will change during the next 10,000 years and how such a change will affect groundwater flow in the Culebra are uncertain. Regional three-dimensional modeling of groundwater flow in the units above the Salado indicates that flow velocities in the Culebra may increase by a factor of 1 to 2.25 for reasonably possible future climates. This uncertainty is incorporated in the PA by scaling the calculated steady-state specific discharge within the Culebra by a sampled parameter within this range.

6.0.2.3.7 Actinide Transport in the Culebra

Field tests have shown that the Culebra is best characterized as a double-porosity medium for estimating contaminant transport in groundwater. Groundwater flow and advective transport of dissolved or colloidal species and particles occurs primarily in a small fraction of the rock's total porosity and corresponding to the porosity of open and interconnected fractures and vugs. Diffusion and slower advective flow occur in the remainder of the porosity, which is associated with the low-permeability dolomite matrix. Transported species, including actinides, if present, will diffuse into this porosity.

Diffusion from the advective porosity into the dolomite matrix will retard actinide transport by two mechanisms. Physical retardation occurs simply because actinides that diffuse into the matrix are no longer transported with the flowing groundwater. Transport is interrupted until they diffuse back into the advective porosity. In situ tracer tests have been conducted to demonstrate this phenomenon. Chemical retardation also occurs within the matrix as actinides are sorbed onto dolomite grains. The relationship between sorbed and liquid concentrations is assumed to be linear and reversible. The distribution coefficients (K_ds) that characterize the extent to which actinides will sorb on dolomite were based on experimental data. Based on their

review of the CCA, the EPA required the DOE to use the same ranges but to change the distribution from uniform to log uniform. The DOE continues to use EPA's distributions in CRA-2004 PA. The DOE also corrected a minor error in the calculation of K_ds (see Appendix PA, Attachment PAR).

Modeling indicates that physical and chemical retardation, as supported by field tests and laboratory experiments, will be extremely effective in reducing the transport of dissolved actinides in the Culebra. Experimental work has demonstrated that transport of colloidal actinides is not a significant mechanism in the Culebra. As a result, actinide transport through the Culebra to the subsurface boundary of the controlled area is not a significant pathway for releases from the WIPP. As discussed in Section 6.5.3, the location of the mean CCDF that demonstrates compliance with the containment requirements of 40 CFR § 191.13 is, determined entirely by direct releases at the ground surface during drilling (cuttings, cavings, and spallings).

6.0.2.3.8 Intrusion Scenarios

Human intrusion scenarios evaluated in the PA include both single intrusion events and combinations of multiple boreholes. Two different types of boreholes are considered:

(1) those that penetrate a pressurized brine reservoir in the underlying Castile Formation (hereafter referred to as the Castile), and

(2) those that do not.

The presence of a brine reservoir under the repository is speculative, but cannot be ruled out on the basis of current information. A pressurized brine reservoir was encountered at the WIPP-12 borehole within the controlled area to the northwest of the disposal region and other pressurized brine reservoirs that are associated with regions of deformation in the Castile have been encountered elsewhere in the Delaware Basin. Based on a geostatistical analysis of the distribution of brine encounters in the region, the DOE has estimated that there was a 0.08 probability that a random borehole that penetrates waste in the WIPP will also penetrate an underlying brine reservoir. Upon their review of the CCA, the EPA determined that the DOE should treat this probability as uncertain, ranging from 0.01 to 0.60 in the PAVT. This recertification application uses the EPA's PAVT range (see Appendix PA, Section PA-3.5). The EPA also required the DOE to modify the assumptions concerning Castile properties to increase the brine reservoir volumes (EPA 1998 VII.B.4.d). The EPA determined that changing the rock compressibility of the Castile and the Castile porosity effectively modified the sampled brine reservoir volume to include the possibility of larger brine reservoir volumes like those encountered by the WIPP-12 borehole.

The primary consequence of penetrating a pressurized reservoir is to provide an additional source of brine beyond that which might flow into the repository from the Salado. Direct releases at the ground surface resulting from the first repository intrusion would be unaffected by additional Castile brine even if it flowed to the surface, because brine moving straight up a borehole will not mix significantly with waste. However, the presence of Castile brine could increase radionuclide releases significantly in two ways. First, the volume of contaminated brine that could flow to the surface may be greater for a second or subsequent intrusion into a

repository that has already been connected by a previous borehole to a Castile reservoir. Second, the volume of contaminated brine that may flow up an abandoned borehole after plugs have degraded may be greater for combinations of two or more boreholes that intrude the same panel if one of the boreholes penetrates a pressurized reservoir. Both processes are modeled in the PA.

6.0.2.4 Compliance Demonstration Method

The DOE's approach to demonstrating continued compliance is the PA methodology described in Section 6.1. The PA process comprehensively considers the FEPs relevant to disposal system performance. Those FEPs shown by screening analyses to potentially affect performance are included in quantitative calculations using a system of linked computer models to describe the interaction of the repository with the natural system, both with and without human intrusion. Uncertainty is incorporated in the analysis by a Monte Carlo approach in which multiple simulations (or realizations) are completed using sampled values for 64 imprecisely known or naturally variable input parameters. Distribution functions are constructed that characterize the state of knowledge for these parameters, and each realization of the modeling system uses a different set of sampled input values. A sample size of 100 results in 100 different values of each parameter. Therefore, there are 100 different sets (vectors) of input parameter values. Quality assurance (QA) activities, described in Chapter 5.0, demonstrate that the parameters, software, and analysis used in the PA were the result of a rigorous process conducted under controlled conditions.

Scenario probabilities composed of specific combinations of FEPs are estimated based on regulatory criteria (applied to the probability of future human action) and the understanding of the natural and engineered systems. Cumulative radionuclide releases from the disposal system are calculated for each scenario considered and scenario probabilities are summed for each modeling system realization to construct distributions of CCDFs. Input parameter sampling was performed in three separate replicates, resulting in three independent distributions of CCDFs and allowing the construction of three independent mean CCDFs, each based on 100 individual CCDFs.

6.0.2.5 Results of the Performance Assessment

Section 6.5 addresses the Containment Requirements of 40 CFR Part 191 and the associated criteria of 40 CFR § 194.34. Section 6.5 presents distributions of CCDFs for each replication of the analysis, mean CCDFs, and an overall mean CCDF with the 95 percent confidence interval estimated from the three independent mean distributions.

Families of CCDFs and mean CCDFs for each of the three replicates are also shown in Section 6.5. All 300 individual CCDFs lie below and to the left of the limits specified in 40 CFR § 191.13(a). The overall mean CCDF determined from the three replicates lies entirely below and to the left of the limits specified in 40 CFR § 191.13(a). Thus, the WIPP continues to comply with the containment requirements of 40 CFR Part 191. Comparing the results of the three replicates indicates that the sample size of 100 in each replicate is sufficient to generate a stable distribution of outcomes. Within the region of regulatory interest (that is, at probabilities greater than $10^{-3}/10^{4}$ yr), the mean CCDFs from each replicate are essentially indistinguishable from the overall mean.

As discussed in Section 6.5, examining the normalized releases from cuttings and cavings, spallings, and direct brine release provides insight into the relative importance of each release mode's contribution to the mean CCDF's location and the compliance determination. Releases from cuttings and cavings dominate the mean CCDF. Spallings make a small contribution. Direct brine releases are less important and have very little effect on the location of the mean. Subsurface releases resulting from groundwater transport are less than 10^{-6} EPA units and make no contribution to the mean CCDF's location.

Uncertainties characterized in the natural system and the interaction of waste with the disposal system environment have little effect on the location of the mean CCDF, providing additional confidence in the compliance determination. The natural and engineered barrier systems of the WIPP provide robust and effective containment of TRU waste even if the repository is penetrated by multiple borehole intrusions.

6.1 Performance Assessment Methodology

The EPA, in 40 CFR Part 191, specifies the generally applicable environmental standards for protecting public health and the environment from the disposal of TRU and high-level radioactive wastes. In this section, the DOE addresses compliance with the Containment Requirements of 40 CFR § 191.13 and the associated portions of 40 CFR Part 194 for TRU waste.

Section 191.13 states:

> (a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based on performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:
>
> (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and
>
> (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).
>
> (b) Performance assessments need not provide complete assurance that the requirements of § 191.13(a) will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with § 191.13(a) will be achieved.

The term accessible environment is defined as: "(1) The atmosphere; (2) land surfaces; (3) surface waters; (4) oceans; and (5) all of the lithosphere that is beyond the controlled area" (40 CFR § 191.12). Further, controlled area means: "(1) A surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the

original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location" (40 CFR § 191.12). The controlled area established by the LWA is shown in Figure 3-1. The release limits listed in Appendix A of 40 CFR Part 191 are reproduced as Table 6-2.

For a release to the accessible environment that involves a mix of radionuclides, the limits in Table 6-2 are used to determine a normalized release (nR) of radionuclides for comparison with the release limits

$$nR = \sum_i \left(Q_i / L_i\right)\left(1 \times 10^6\ Ci/C\right), \tag{6.1}$$

where:

Q_i = cumulative release in curies (Ci) of radionuclide i into the accessible environment during the 10,000-year period following repository closure.
L_i = release limit in curies for radionuclide i given in
C = amount of TRU waste curies to be emplaced in the repository (as described in Section 4.1, TRU wastes contain alpha-emitting transuranic radionuclides with half-lives greater than 20 years).

As indicated in Note 1(e) to Table 1 in Appendix A of 40 CFR Part 191, the "other unit of waste" for TRU waste shall be "an amount of transuranic wastes containing 1 million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years."

PAs are the basis for addressing the containment requirements. 40 CFR § 191.12 defines performance as follows:

> "Performance assessment" means an analysis that: (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events.

The DOE's methodology for PA uses information about the disposal system and the waste to evaluate performance in a regulatory context over the 10,000-year regulatory time period.

The general theory for conducting a PA is presented in this section together with details specific to the PA conducted for the WIPP. Figure 6-2 illustrates the general, high-level steps used by the DOE for this final PA of the WIPP. In this figure, the sections of this chapter are indicated that discuss these steps in detail, and several important features of the WIPP PA are shown.

Table 6-2. Release Limits for the Containment Requirements (EPA 1985, Appendix A, Table 1)

Radionuclide	Release Limit L_i per 1,000 MTHM [1] or Other Unit of Waste (curies)
^{241}Am or ^{243}Am	100
^{14}C	100
^{135}Cs or ^{137}Cs	1,000
^{129}I	100
^{237}Np	100
^{238}Pu, ^{239}Pu, ^{240}Pu, or ^{242}Pu	100
^{226}Ra	100
^{90}Sr	1,000
^{99}Te	10,000
^{230}Th or ^{232}Th	10
^{126}Sn	1,000
^{233}U, ^{234}U, ^{235}U, ^{236}U, or ^{238}U	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1,000

[1] Metric tons of heavy metal exposed to a burnup between 25,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM.

Section 6.1 presents the basis for the methodology shown in Figure 6-2. Section 6.1.1 presents the conceptualization of risk, Section 6.1.2 discusses the characterization of uncertainty in risk, Section 6.1.3 discusses regulatory criteria for the quantification of risk, Section 6.1.4 discusses calculation of risk, and Section 6.1.5 discusses techniques for probabilistic analysis.

6.1.1 Conceptualization of Risk

The WIPP PA is fundamentally concerned with evaluating risk, for which comparative measures are defined by regulatory standards. The DOE uses a conceptualization for risk similar to that developed for risk assessments of nuclear power plants. This description provides a structure on which both the representation and calculation of risk can be based.

Kaplan and Garrick (1981, 11-12) have represented risk as a set of ordered triples. The DOE uses this representation and defines risk to be a set R of the form

$$\mathrm{R} = \left[\left(S_i,\ pS,\ \mathbf{cS}_i \right),\ i = 1, \ldots, nS \right], \tag{6.2}$$

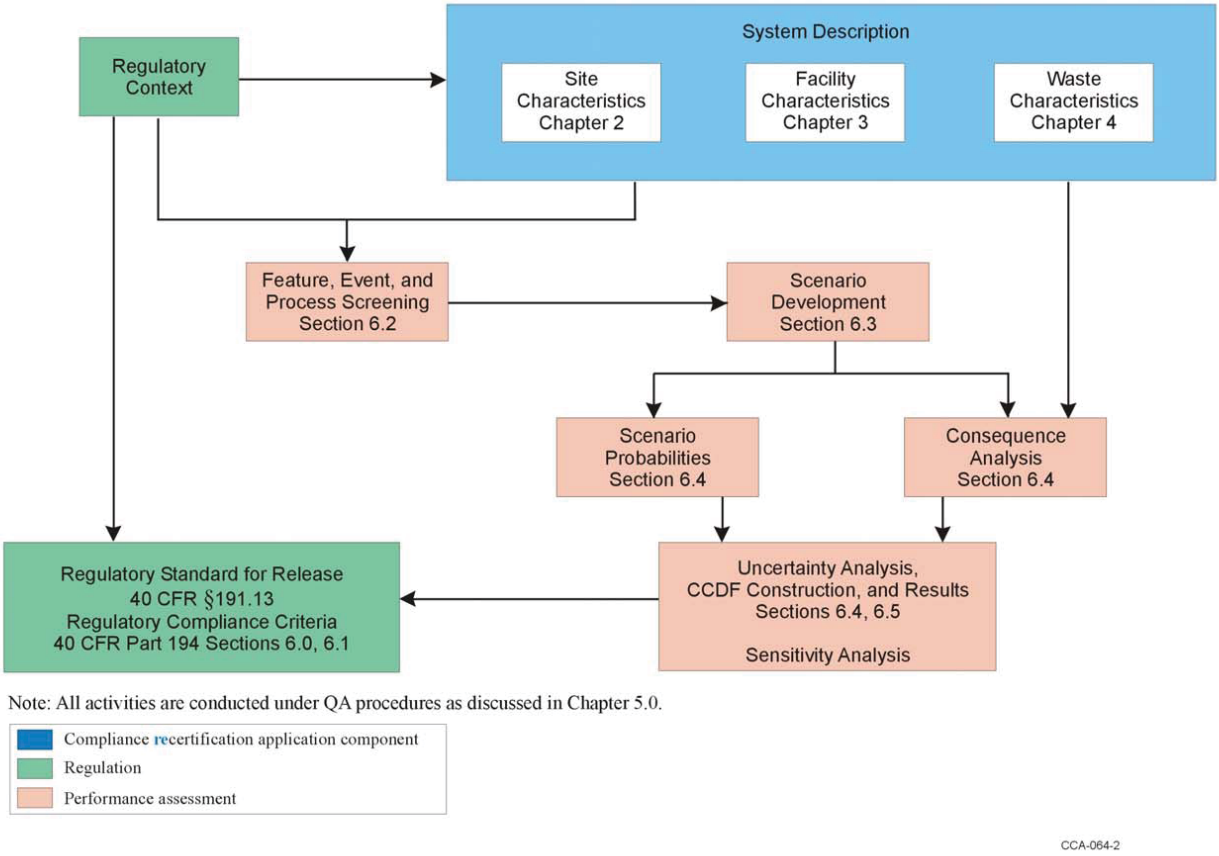

Figure 6-2. Methodology for PA of the WIPP

where

S_i	=	a set of similar occurrences
pS_i	=	probability that an occurrence in set S_i will take place
cS_i	=	a vector of consequences associated with S_i
nS	=	number of sets selected for consideration

and the sets S_i have no occurrences in common (that is, the S_i are disjoint sets). This representation formally decomposes risk into what can happen (the S_i), how likely things are to happen (the pS_i), and the consequences of what can happen (the cS_i). In the WIPP PA, the S_i are scenarios, the pS_i are scenario probabilities, and the vector cS_i contains consequences associated with scenario S_i. Scenario development for the WIPP is discussed in Sections 6.1.2, 6.2, and 6.3. Scenario probabilities and consequence determination are discussed in Section 6.4.

As discussed in the following sections, risk in the set R can be displayed using CCDFs, as required by the EPA. As stated in 40 CFR § 194.34(a),

> The results of performance assessments shall be assembled into "complementary, cumulative distribution functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events.

In the context of Equation (6.2), CCDFs provide information about the consequences cS_i and the probabilities pS_i associated with the scenarios S_i. The probability that cS exceeds a specific consequence value x is determined by the CCDF F defined by

$$F(x) = \sum_{j=i}^{nS} pS_j, \tag{6.3}$$

where the particular consequence result cS under consideration is ordered so that $cS_i \le cS_{i+1}$ for $i = 1, \ldots, nS-1$, and i is the smallest integer such that $cS_i > x$. The function F represents the probabilities that consequence values plotted on the abscissa will be exceeded. An example estimation of F is shown in Figure 6-3. The steps in the CCDF shown in Figure 6-3 result from the evaluation of F with a discrete number of possible occurrences (that is, futures) represented in the sets S_i. Unless the underlying processes are inherently disjoint, using more sets S_i will tend to reduce the size of these steps and, in the limit, result in a smooth curve. To avoid a broken appearance, the DOE plots estimated CCDFs with vertical lines added at the discontinuities.

6.1.2 Characterization of Uncertainty in Risk

Uncertainty in the analysis can be either stochastic or subjective. Stochastic uncertainty derives from lack of knowledge about the future. Subjective uncertainty derives from lack of knowledge about quantities, properties, or attributes believed to have single or certain values. Stochastic uncertainty can be further subdivided into completeness, aggregation, and stochastic variation. Completeness refers to the extent that a PA includes all possible occurrences that could affect performance for the system under consideration. In terms of the risk representation in Equation (6.2), completeness deals with whether all significant occurrences are included in the union of the sets S_i. The DOE addresses completeness in its development of scenarios, discussed here and

in Sections 6.2 and 6.3. Aggregation refers to the division of the possible occurrences into the sets S_i. Resolution is lost if the S_i are defined too coarsely (for example, if nS is too small). Computational efficiency is affected if nS is too large. Aggregation gives rise to the steps in a single CCDF, as shown in Figure 6-3. The DOE addresses aggregation uncertainty in Sections 6.1.4 and 6.4.13. Stochastic variation is represented by the probabilities pS_i, which are functions of the many factors that affect the occurrence of the individual sets S_i. The DOE addresses stochastic variation in Sections 6.1.4 and 6.4.12.

Stochastic uncertainty is taken into account in PA by evaluating the probability of future events (for example, by assuming that the occurrence of certain future events will be random in space and time), and by considering imprecisely known system properties directly associated with the future events. These imprecisely known system properties can be expressed as variables represented by the vector

$$x_{st} = [x_{st,1}, x_{st,2}, \ldots, x_{st,nV(st)}] , \tag{6.4a}$$

where each $x_{st,j}$ [j = 1, 2, …, nV(st)] is an imprecisely known property required in the analysis, nV is the total number of such properties associated with stochastic uncertainty, and the subscript st denotes stochastic uncertainty.

Subjective uncertainty results from incomplete data or measurement uncertainty. These uncertainties are addressed in Section 6.4. Subjective quantities, properties, or attributes may be associated with stochastic uncertainties (events that might occur in the future).

Subjective uncertainty can be characterized in PA by considering system properties that are imprecisely known. These imprecisely known system properties can be expressed as variables represented by vectors

$$x_{su} = [x_{su,1}, x_{su,2}, \ldots, x_{su,nV(su)}] , \tag{6.4b}$$

where each $x_{su,j}$ [j = 1, 2, …, nV(su)] is an imprecisely known property required in the analysis, nV is the total number of such properties associated with subjective uncertainty, and the subscript su denotes subjective uncertainty.

If the analysis has been developed so that each x_j is a quantity for which the overall analysis requires a single value, the representation for risk in Equation 6.2 can be restated as a function of x_{st} and x_{su}:

$$R(x_{su}) = [S_i(x_{su}), pS_i(x_{su}), cS_i(x_{st,i}, x_{su}), i = 1, ..., nS(x_{st} ,x_{su})] , \tag{6.5}$$

where $x_{st,i}$ is included in S_i. Probability distributions are then assigned to the individual variables $x_{su,j}$ and $x_{st,j}$, as defined in Equation 6.4. These probability distributions are of the form

$$D_{st,1}, D_{st,2}, \ldots, D_{st,nV(st)} , \tag{6.6a}$$

$$D_{su,1}, D_{su,2}, \ldots, D_{su,nV(su)} , \tag{6.6b}$$

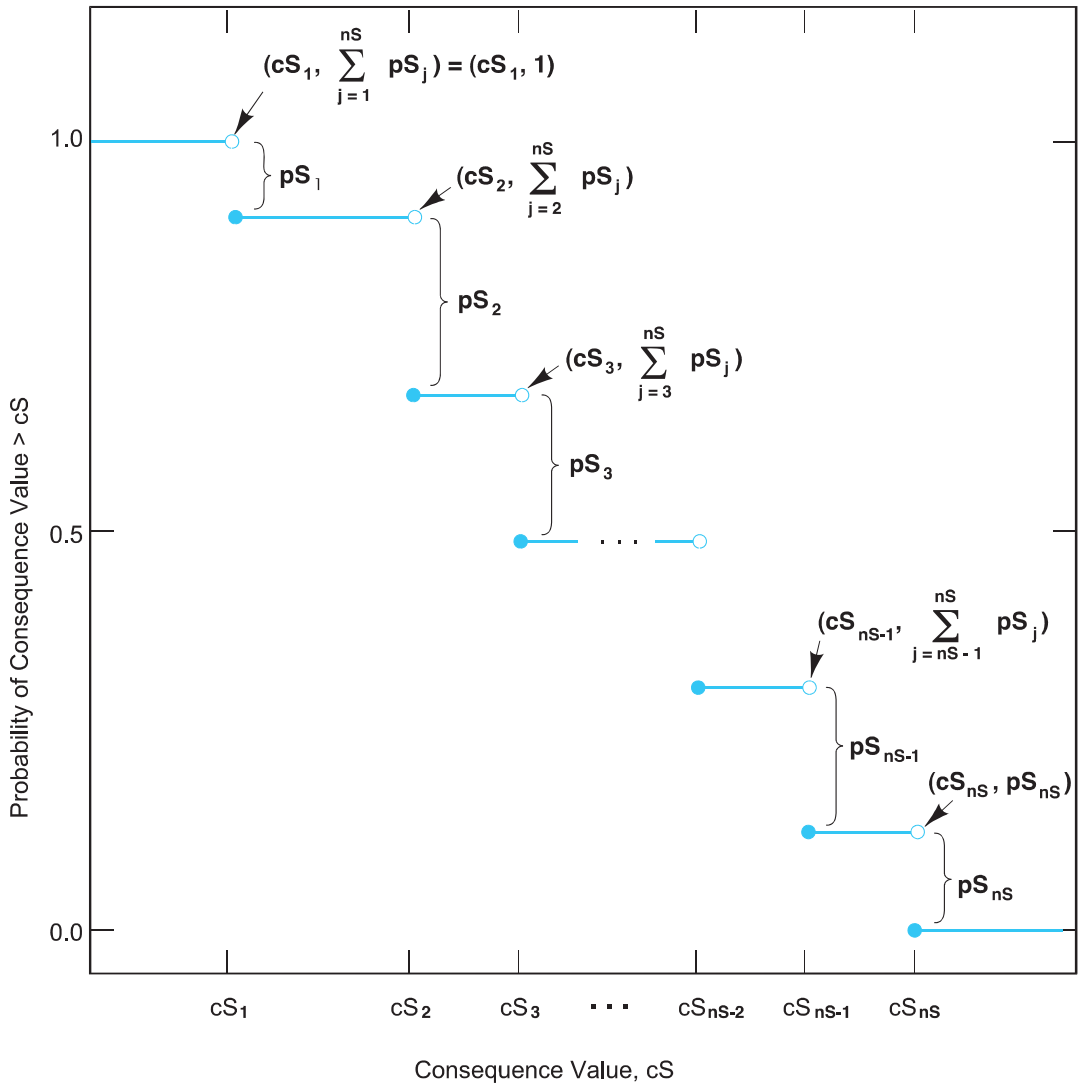

Note: The open and solid circles at the discontinuities indicate the points included on (solid circles) and excluded from (open circles) the CCDF.

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Figure 6-3. Estimated CCDF For Consequence Results

where the D_js are the distributions developed for the variables x_j, $j = 1, 2,...nV$, and the subscripts *st* and *su* denote distributions associated with x_{st} or x_{su}. The definition of these distributions may also be accompanied by the specification of correlations and various restrictions that further define the possible relations among the x_j. These distributions (along with specified correlations or restrictions) probabilistically specify what the appropriate input to use in the PA calculations might be, given that the analysis is structured so that only one value can be used for each variable, x_j, under consideration for a particular calculation.

Monte Carlo techniques can be used to determine the uncertainty in $R(x_{su})$ associated with both x_{st} and x_{su}. The theory of this technique is similar for characterizing both stochastic and

subjective uncertainty. This technique as applied to determining the risk $R(x_{su})$ associated with x_{su} is developed in the following paragraphs.

Once the distributions in Equation 6.6b have been developed, a sample

$$x_k = (x_{k1}, x_{k2}, \ldots, x_{k,nV}),\ k = 1, \ldots, nK \tag{6.7}$$

is generated according to the specified distributions and restrictions where nK is the size of the sample. PA calculations are then performed for each sample element x_k, which yields a sequence of risk results of the form

$$R(x_k) = \{[S_i(x_k), pS_i(x_k), cS_i(x_k)],\ i = 1, \ldots, nS(x_k)\}\ . \tag{6.8}$$

Each set $R(x_k)$ is the result of one complete set of calculations performed with a set of inputs (that is, x_k) obtained from the distributions assigned in Equation 6.6b. Further, associated with each risk result $R(x_k)$ in Equation 6.8 is a weight[1] that can be used in making probabilistic statements about the distribution of R(x).

A single CCDF can be produced for each set $R(x_k)$ of results shown in Equation 6.8, yielding a family of CCDFs of the form shown in Figure 6-4. The distribution of CCDFs in Figure 6-4 can be summarized with the mean and percentile curves shown in Figure 6-5. These curves result from connecting the mean and percentile values corresponding to individual consequence values on the abscissa of Figure 6-4. The percentile curves probabilistically represent the estimated exceedance probability given a fixed consequence value. For example, the probability is 0.8 that the exceedance probability for a particular normalized release is located between the 10 and 90 percentile curves.

To summarize, considering a family of CCDFs allows a distinction between stochastic uncertainty that controls the shape of a single CCDF and subjective uncertainty that results in a distribution of CCDFs. The stepwise shape of a single CCDF reflects aggregation of future events into similar groups. A family of CCDFs arises from imperfect knowledge of quantifiable properties, or, in other words, subjective uncertainty. The distribution arising from subjective uncertainty involves an infinite number of CCDFs; a family of CCDFs is a sample of finite size.

6.1.3 Regulatory Criteria for the Quantification of Risk

The representation for risk in Equation 6.2 provides a conceptual basis for calculating the CCDF of normalized releases specified in 40 CFR § 194.34(a). Further, this representation provides a structure that can be used for both the incorporation of uncertainties and the representation of the effects of uncertainties, as stated in 40 CFR § 194.34.

[1] In random or Latin hypercube sampling (LHS), this weight is the reciprocal of the sample size (that is, $1/nK$) and can be used in estimating means, cumulative distribution functions, and other statistical properties. This weight is often referred to as the probability for each observation (that is, sample x_k). However, this usage is not technically correct. If continuous distributions are involved, the actual probability of each observation is zero.

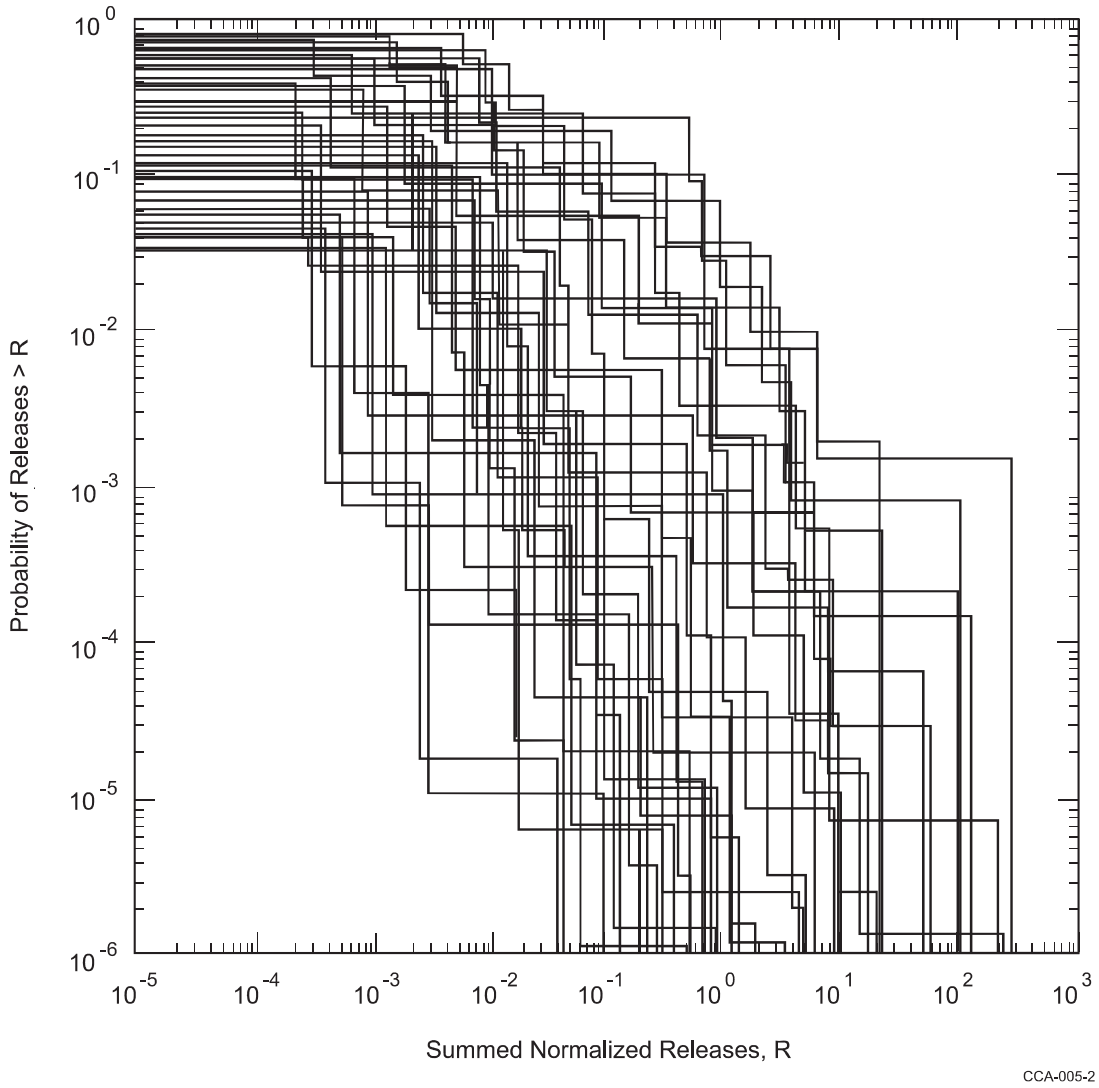

Figure 6-4. Example Distribution of a Family of CCDFs Obtained by Sampling Imprecisely Known Variables

In 40 CFR § 194.34(b), the EPA states that "probability distributions for uncertain disposal system parameter values used in performance assessments shall be developed and documented in any compliance application." The treatment of uncertain parameter values in the performance assessment is discussed in Sections 6.1.4, 6.1.5, and 6.4. Further discussion of distributions assigned to uncertain parameter values is provided in Appendix PA, Attachment PAR.

In 40 CFR § 194.34(c), the EPA states that documentation of the computational techniques used to generate random samples shall be provided. The sampling techniques used are discussed in Section 6.1.5.2. Sampled values are reproduced in tabular form in Appendix PA, Attachment PAR.

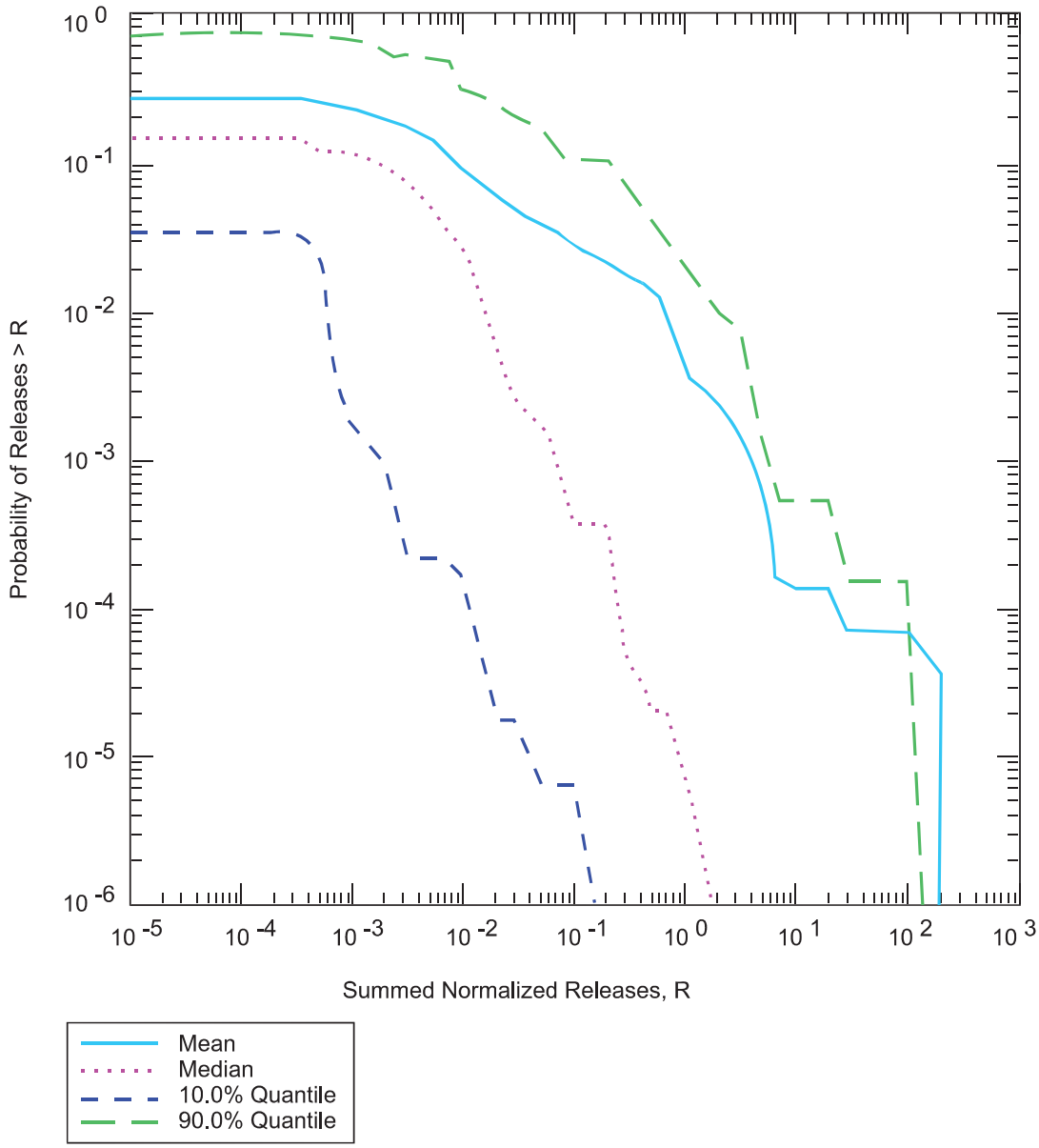

Note: The curves in this figure were obtained by calculating the mean and the indicated percentiles for each consequence value on the abscissa in Figure 6-3. The 90th-percentile curve crosses the mean curve because of highly skewed distributions for exceedance probability. This skew also results in the mean curve being above the median curve.

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Figure 6-5. Example Summary Curves Derived from an Estimated Distribution of CCDFs

In 40 CFR § 194.34(d), the EPA states that "the number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability." The CCDFs resulting from this PA are provided in Section 6.5, with a demonstration that the total number of CCDFs is sufficiently large.

In 40 CFR § 194.34(e), the EPA states that "any compliance application shall display the full range of CCDFs generated." The full range of CCDFs generated is displayed in Section 6.5.

In 40 CFR § 194.34(f), the EPA states that "any compliance application shall provide information which demonstrates that there is at least a 95 percent level of confidence that the mean of the population of CCDFs meets the containment requirements . . . ." Section 6.5 contains a display of the mean CCDF and evidence demonstrating level of confidence.

6.1.4 Calculation of Risk

The methodology presented in Sections 6.1.1and 6.1.2 is based on the work of Kaplan and Garrick (1981) and is one way to estimate the effects of uncertain but characterizable futures. In the Kaplan and Garrick (1981) procedure, the possible futures are defined as literal entities (S_i), and each is associated with a probability of occurrence (pS_i) and a consequence of occurrence (cS_i).

Calculating the probabilities and consequences of future occurrences begins by determining the sets S_i, which are the scenarios to be analyzed. Scenarios are determined through a formal process similar to that proposed by Cranwell et al. (1990, 5-10) and the process used in preliminary PAs for the WIPP. This process has four steps.

1. The FEPs potentially relevant to the WIPP are identified and classified.
2. Certain FEPs are eliminated according to well-defined screening criteria as unimportant or irrelevant to the performance of the WIPP.
3. Scenarios are formed from the remaining FEPs in the context of regulatory performance criteria.
4. Scenarios are specified for consequence analysis.

Through steps 1 and 2 of the scenario development process, the DOE identifies "all significant processes and events that may affect the disposal system" as required by 40 CFR § 191.13(a) and as further addressed in 40 CFR § 194.32. These steps are described in Section 6.2. The grouping of retained FEPs to form scenarios, and the specification of scenarios for consequence analysis, is presented in Section 6.3.

These four steps were used to develop the PA and compliance assessment used in the CCA. This CRA uses the same PA method and basis as that used in the CCA. The steps outlined here were revisited to determine that the basis for the original PA has not been impacted by events, additional information, or regulatory changes that have occurred since the original demonstration of compliance with EPA's disposal standard (as discussed in the following paragraphs).

As discussed in Section 6.2, the DOE eveloped a comprehensive initial list of FEPs for PA. This list assured that the identification of significant processes and events is complete, potential interactions between FEPs are not overlooked, and responses to possible questions are available and well documented. For the CRA-2004, DOE has revisited the initial FEPs list to determine if the screening decisions should be changed as a result of information collected since the EPA certification decision. Specifically, 120 FEPs required updates to their FEP descriptions and/or

screening arguments, and seven of the original baseline FEP screening decisions required a change from their original screening decision. Four of the original baseline FEPs have been deleted or combined with other closely related FEPs. Finally, two new FEPs have been added to the baseline. These two FEPs were previously addressed in an existing FEP; they have been separated for clarity. Table SCR-1 summarizes the changes in the FEP baseline since the CCA. The evaluation of the CCA FEPs list is discussed in Appendix PA, Attachment SCR.

Once scenarios are defined, a calculational methodology for evaluating their consequences must be developed. The calculational methodology must address stochastic uncertainty related to aggregation and stochastic variation, and subjective uncertainty, because of (for example) measurement difficulties or incomplete data. The DOE uses a system of linked computer models to calculate scenario consequences cS_i. As discussed in Section 6.4, these computer models are based on conceptual models that describe the processes relevant to disposal system performance for the defined scenarios. These conceptual models are, in turn, based on site-specific experimental and observational data and the general scientific understanding of natural and engineered systems.

For practical purposes, the DOE separates the calculation of risk because of stochastic uncertainty (represented in an individual CCDF) from risk because of subjective uncertainty (represented by the family of CCDFs). This can be represented mathematically as a double integral of a function with the function representing the probability of exceedance associated with any particular consequence. The inner integral evaluates stochastic uncertainty, or the probability of exceedance associated with any particular consequence. The outer integral evaluates subjective uncertainty and leads to a distribution of exceedance probabilities for any given consequence value. An analytical method for its solution is not available because of the complexity of this double integral for the WIPP. Instead, the DOE approximates the solution of this double integral with a linked system of computer codes. In this computational framework, thePA analysis can be thought of as a double sum, presented here in a stylized form for clarity as

$$\sum_{su}\sum_{st} F(x). \tag{6.9}$$

Here, F(x) is a procedure for estimating the normalized release to the accessible environment associated with each scenario that could occur at the WIPP site. The inner sum denoted with the subscript st is a probabilistic characterization of the uncertainty associated with parameters used to characterize stochastic uncertainty (the x_{st} and D_{st} in Equations 6.4a and 6.6a, respectively). It is the evaluation of F(x) through the inner sum that develops an individual CCDF, as shown in Figure 6-3. The outer sum denoted with the subscript su is a probabilistic characterization of the uncertainty associated with parameters used to characterize subjective uncertainty (the x_{su} and D_{su} in Equations 6.4b and 6.6b, respectively). It is the combined evaluation in the outer sum of the inner sum with F(x) that develops the family of CCDFs, as shown in Figure 6-4.

A separate probabilistic analysis is required to evaluate each sum. Associated with each analysis are parameter distributions representing uncertainty (the D_{st} and D_{su} of Equations 6.6a and 6.6b). For example, uncertainty in the number and time of intrusion boreholes may be associated with the inner sum. The outer sum includes a probabilistic characterization of site properties, such as the permeability of specific rock types.

For the methodology adopted by the DOE to evaluate stochastic uncertainty in the inner sum, consequence calculations are required for model configurations with a set of fixed values for subjective parameters x_{su} taken from their distributions D_{su}, as well as for defined sequences and times of events associated with scenarios. These calculations are referred to in Section 6.4.11 and later sections as deterministic calculations (or deterministic futures). To evaluate stochastic uncertainty and construct a CCDF, the consequences of futures generated probabilistically by random sampling (probabilistic futures) are evaluated in the context of these deterministic futures. This process is discussed in detail in Sections 6.4.12 and 6.4.13.

In certain cases, it may not be obvious whether a particular uncertainty should be classified as subjective or stochastic. For example, whether currently observed geologic properties persist through time could be thought of as either subjective or stochastic uncertainty. For the WIPP, the DOE treats uncertainty associated with significant future human actions as stochastic (for example, drilling for natural resources), and uncertainty in disposal system properties subject to ongoing physical processes as subjective (for example, climate change or gas generation). In particular, DOE's formal separation of evaluating stochastic uncertainty from subjective uncertainty into different probabilistic analyses allows clear understanding of how a particular uncertainty is incorporated.

Once the scenarios are determined and their consequences calculated using the appropriate conceptual and computational models, scenario probabilities must be determined for a CCDF to be constructed. This process is described in Section 6.4.12. CCDF construction is also described in Section 6.4.13.

6.1.5 Techniques for Probabilistic Analysis

Once scenarios are defined, conceptual models are defined, and the computational modeling system developed, DOE uses probabilistic techniques to evaluate the double sum presented above. Monte Carlo analysis is the technique used for probabilistic analysis of the WIPP. Monte Carlo analyses can involve five steps:

1. selecting the variables to be examined and the ranges and distributions for their possible values,
2. generating the samples to be analyzed,
3. propagating the samples through the analysis,
4. performing the uncertainty analysis, and
5. conducting a sensitivity analysis.

These steps are described briefly in the following sections.

Within the general framework of Monte Carlo analysis, PA uses two methods, random sampling and Latin Hypercube Sampling (LHS), to generate the samples propagated through the model system. Random sampling is used to generate samples for stochastic uncertainty, and LHS is used to characterize subjective uncertainty. Each of these methods uses the five steps

summarized in the preceding paragraph, but differs in steps (2) through (5) to account for both subjective and stochastic uncertainty.

6.1.5.1 Selection of Variables and Their Ranges and Distributions

Monte Carlo analyses use a probabilistic procedure for the selection of model input. Therefore, the first step in a Monte Carlo analysis is to select uncertain variables and assign ranges and distributions that characterize them. These variables are typically input parameters to computer models, and the impact of the assigned ranges and distributions can be great; for a given set of conceptual and mathematical models, PA results are largely controlled by the choice of input. Results of uncertainty and sensitivity analyses, in particular, strongly reflect the characterization of uncertainty in the input data.

Information used in the CCA about the ranges and distributions of possible values were drawn from a variety of sources, including field data, laboratory data, and literature. Where sufficient data were not available, the documented solicitation of experts was used. A review process led from the available data to the construction of the distribution functions that characterize uncertainty in input parameters in PA (Appendix PA, Attachment PAR, PAR.2). This addressed the scaling of data collected at experimental scales of observation to the parameter ranges applied to scales of interest in the disposal system. The nature of the available data and the type of analysis unavoidably involved some judgment from investigators and analysts involved. A discussion of parameter ranges developed by this process for the CRA-2004 PA is provided in Appendix PA, Attachment PAR (Section 3). The QA procedures associated with this review process are identified in Section 5.4.2 and Appendix PA, Attachment PAR (Section 2).

The outcome of the review process is a cumulative distribution function (CDF) *D(x)* of the form shown in Figure 6-6 for each independent variable of interest. For a particular variable x_j, the function *D* is defined such that

$$\text{prob}(x < x_j \leq x + \Delta x) = D(x + \Delta x) - D(x) \; . \qquad (6.10)$$

That is, $D(x+\Delta x) - D(x)$ is equal to the probability that the appropriate value for x_j in the particular analysis under consideration falls between x and $x+\Delta x$.

6.1.5.2 Generation of the Sample

Various techniques are available for generating samples from the assigned distribution functions for the variables, including random sampling, stratified sampling, and LHS. The DOE's PA for WIPP uses random sampling and LHS.

Randomly sampling the occurrence of possible future events is used to generate the possible futures (probabilistic futures) that comprise a CCDF. This sampling is used to select values of uncertain parameters associated with future human activities, or in other words, to incorporate stochastic uncertainty into the WIPP PA. This sampling is used for parameters evaluated in the inner sum of the double sum and included in the parameter set x_{st} with associated distributions D_{st}, as shown in Equations 6.4a and 6.6a respectively. Generating futures comprising a CCDF by random sampling, rather than importance or stratified sampling, as used in previous preliminary PAs, largely eliminates errors from aggregation.

LHS, in which the full range of each variable is subdivided into intervals of equal probability and samples are drawn from each interval, is used to select values of uncertain parameters associated with the physical system being simulated. In other words, LHS incorporates subjective uncertainty into the WIPP PA. This sampling is used for parameters that are evaluated in the outer sum of the double sum and are included in the parameter set x_{su} with associated distributions D_{su}, as shown in Equations 6.4b and 6.6b, respectively. The restricted pairing technique of Iman and Conover (1982, 314-319) is used to prevent spurious correlations within the sample.

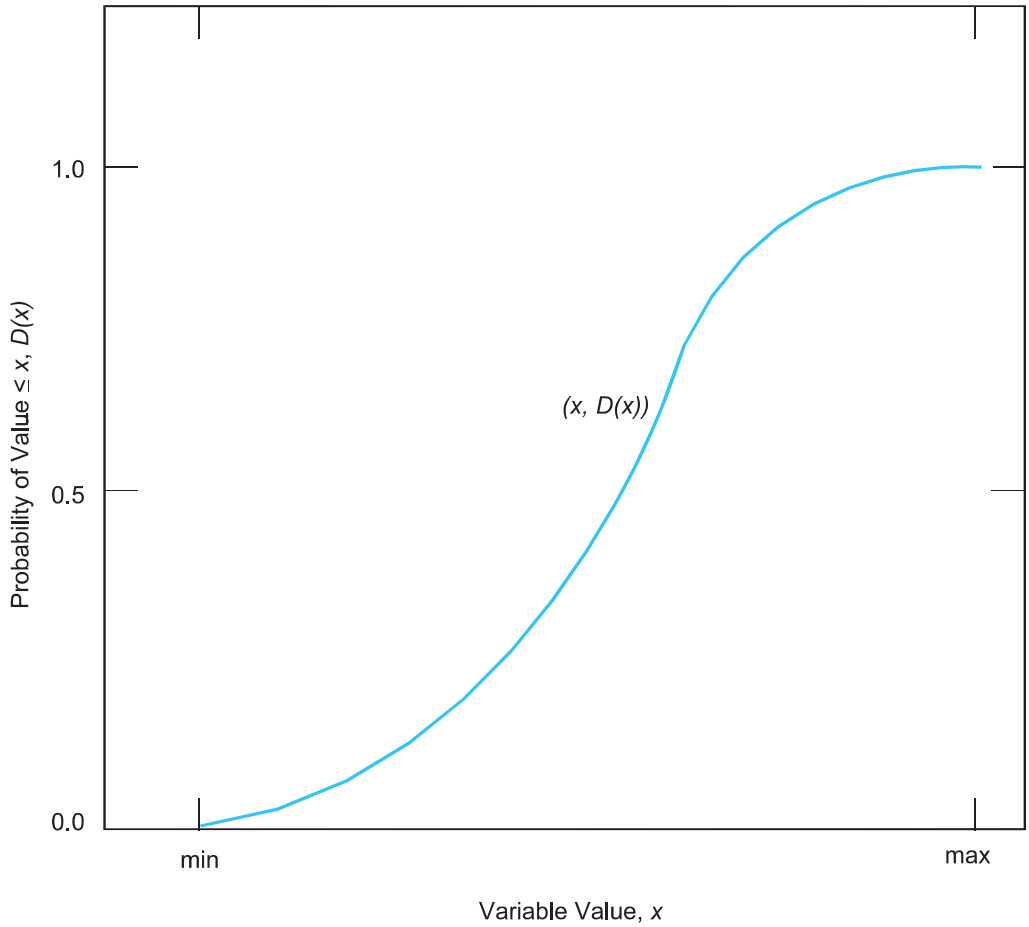

Note: For each value *x* on the abscissa, the corresponding value *D(x)* on the ordinate is the probability that the appropriate value to use in the analysis is less than or equal to *x*.

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Figure 6-6. Distribution Function for an Imprecisely Known Variable

6.1.5.3 Propagation of the Sample through the Analysis

The next step is the propagation of the sample through the analysis. Each element of the sample is supplied to the model system as input, and the corresponding model system predictions are saved for later use in uncertainty and sensitivity studies. The Software Configuration Management System (SCMS) was developed to facilitate the complex calculations performed by the model system and to store the input and output files from each program.

6.1.5.4 Uncertainty Analysis

Uncertainty analyses evaluate uncertainty in performance estimates that results from uncertainty about imprecisely known input parameters. Once a sample has been generated and propagated through the modeling system, uncertainty in the outcome can be interpreted directly from the display of the results. For the WIPP PA, stochastic uncertainty is represented by the shape of the individual CCDFs displayed in Section 6.5. Subjective uncertainty is represented by the family of CCDFs displayed in Section 6.6.

6.1.5.5 Sensitivity Analysis

Sensitivity analyses determine the contribution of individual input variables to the uncertainty in model predictions. This is the final step in a probabilistic study. Sensitivity analyses can identify parameters for which reductions in uncertainty (that is, narrowing the range of values from which the sample used in the Monte Carlo analysis is drawn) have the greatest potential to increase confidence in the estimate of the disposal system's performance. However, because results of these analyses are inherently conditional on the models, data distributions, and techniques used to generate them, the analyses cannot provide insight on the correctness of the conceptual models and data distributions used. Qualitative judgment about the modeling system must be used with sensitivity analyses to set priorities for PA data acquisition and model development. Sensitivity analyses conducted as part of the WIPP PA are described in Appendix PA.

6.2 Identification and Screening of Features, Events, and Processes

The EPA has provided criteria concerning the scope of PAs in 40 CFR § 194.32. In particular, criteria relating to the identification of potential processes and events that may affect the performance disposal system are provided in Section 194.32(e), which states that

> Any compliance application(s) shall include information which:
>
> (1) Identifies all potential processes, events or sequences and combinations of processes and events that may occur during the regulatory time frame and may affect the disposal system;
>
> (2) Identifies the processes, events or sequences and combinations of processes and events included in performance assessments; and
>
> (3) Documents why any processes, events or sequences and combinations of processes and events identified pursuant to paragraph (e)(1) of this section were not included in performance assessment results provided in any compliance application.

This section, CCA Appendix SCR, and Appendix PA, Attachment SCR fulfill these criteria by documenting DOE's identification, screening, and screening results of all potential processes and events consistent with the criteria specified in 40 CFR § 194.32(e).

As discussed in Section 6.1.4, the first two steps in scenario development involve the identification and screening of FEPs potentially relevant to the performance of the disposal system. This section discusses the development of a comprehensive initial set of FEPs used in the CCA, the methodology and criteria used for screening, the method used to reassess the CCA

FEPs for the CRA-2004, and a summary of the FEPs retained for scenario development. Detailed discussion of the basis for eliminating or retaining particular FEPs is provided in Appendix PA, Attachment SCR. The scenarios formed from retained FEPs are discussed in Section 6.3, and the scenarios specified for consequence analysis are addressed in Section 6.4.12.

The original FEPs generation and screening were documented in the CCA and the resulting FEPs list became the FEPs compliance baseline. The baseline contained 237 FEPs and was documented in Appendix SCR of the CCA. The EPA compliance review of FEPs was documented in EPA's Technical Support Document 194.32: Scope of PA (EPA 1998, V-B-21). The EPA numbered each FEP with a different scheme than the DOE used for the CCA. The DOE has since adopted EPA's numbering scheme.

6.2.1 Identification of Features, Events, and Processes

The first step of the scenario development procedure is identifying and classifying FEPs potentially relevant to the disposal system performance. Catalogs of FEPs have been developed in several national radioactive waste disposal programs, as well as internationally. In constructing a comprehensive list of FEPs for the WIPP, the DOE drew on these other radioactive waste disposal programs.

As a starting point, the DOE assembled a list of potentially relevant FEPs from the compilation developed by Stenhouse et al. (1993) for the Swedish Nuclear Power Inspectorate *Statens Kärnkraftinspektion* (SKI). The SKI list was based on a series of FEP lists developed for other disposal programs and is considered the best documented and most comprehensive starting point for the WIPP. For the SKI study, an initial, raw FEP list was compiled from nine different FEP identification studies (Table 6-3). No additional lists of potentially relevant FEPs have been identified since the initial certification.

The compilers of the SKI list eliminated a number of FEPs as irrelevant to the particular disposal concept under consideration in Sweden; these FEPs were reinstated for the WIPP effort, and several FEPs on the SKI list were subdivided to facilitate WIPP screening. Finally, to ensure comprehensiveness, other FEPs specific to the WIPP were added based on a review of key project documents and a broad examination of the preliminary WIPP list by both project participants and stakeholders. The initial, unedited list is contained in CCA Appendix SCR, Attachment 1. The initial, unedited FEP list was restructured and revised to derive the comprehensive WIPP FEP list in the CCA. The number of FEPs was reduced to 237 to avoid the ambiguities caused by using a generic list. Restructuring the list did not remove any substantive issues from the discussion. As discussed in more detail in CCA Appendix SCR, Attachment 1, the following steps were used to create the WIPP FEP list in the CCA.

- References to subsystems were eliminated because the SKI subsystem classification was not appropriate for the WIPP disposal concept. For example, in contrast to the Swedish disposal concept, canister integrity does not have a role in postoperational performance of the WIPP, and the terms near-field, far-field, and biosphere are not unequivocally defined for the WIPP site.

- Duplicate FEPs were eliminated. Duplicate FEPs arose in the SKI list because individual FEPs could act in different subsystems. FEPs have a single entry in this application list whether they are applicable to several parts of the disposal system, or to a single part only. For example, the FEP *Gas Effects: Disruption* appears in the seals, backfill, waste, canister, and near-field subsystems in the initial FEP list. These FEPs are represented by the single FEP *Disruption Due to Gas Effects* for this application.

Table 6-3. FEP Identification Studies Used in the SKI Study

Study	Country	Number of FEPS Identified
Atomic Energy of Canada Limited (AECL) study of disposal of spent fuel in crystalline rock (Goodwin et al. 1994)	Canada	275
SKI & Swedish Nuclear Fuel and Waste Management Company (SKB) study of disposal of spent fuel in crystalline rock (Andersson 1989)	Sweden	157
National Cooperative for the Storage of Radioactive Waste (NAGRA) Project Gewähr study (NAGRA 1985)	Switzerland	44
UK Department of the Environment Dry Run 3 study of deep disposal of low- and intermediate-level waste (L/ILW) (Thorne 1992)	United Kingdom	305
UK Department of Environment assessment of L/ILW disposal in volcanic rock at Sellafield (Miller and Chapman 1992)	United Kingdom	79
UK Nuclear Industry Radioactive Waste Executive (NIREX) study of the deep disposal of L/ILW (Hodgkinson and Sumerling 1989)	United Kingdom	131
Sandia National Laboratories (SNL) study of deep disposal of spent fuel (Cranwell et al. 1990)	United States	29
NEA Working Group on Systematic Approaches to Scenario Development (OECD 1992)	International	122
International Atomic Energy Agency (IAEA) Safety Series (IAEA 1981)	International	56

- FEPs that are not relevant to the WIPP design or inventory were eliminated. Examples include FEPs related to high-level waste, copper canisters, and bentonite backfill.

- FEPs relating to engineering design changes were eliminated because they are not relevant to a compliance application based on the DOE's design for the WIPP. Examples of such FEPs are Design Modifications: Canister and Design Modification: Geometry.

- FEPs relating to constructional, operational, and decommissioning errors were eliminated. The DOE has administrative and quality control procedures to ensure that the facility will be constructed, operated, and decommissioned properly.

- Detailed FEPs relating to processes in the surface environment were aggregated into a small number of generalized FEPs. For example, the SKI list includes the biosphere FEPs *Inhalation of Salt Particles, Smoking, Showers and Humidifiers*, *Inhalation and*

Biotic Material, Household Dust and Fumes, Deposition (wet and dry), Inhalation and Soils and Sediments, Inhalation and Gases and Vapors (indoor and outdoor), and *Suspension in Air*, which are represented by the FEP *Inhalation* in this application.

- FEPs relating to the containment of hazardous metals, volatile organic compounds (VOCs), and other chemicals that are not regulated by 40 CFR Part 191 were not included.

- A few FEPs were renamed to be consistent with terms used to describe specific WIPP processes (for example, *Wicking*, *Brine Inflow*).

6.2.2 Criteria to Screen Features, Events, and Processes and Categorization of Retained Features, Events, and Processes

FEP screening identifies those FEPs that should be accounted for in PA calculations, and those that need not be considered further. The DOE's process of removing FEPs from consideration in PA calculations involved the structured application of explicit screening criteria. The criteria used to screen out FEPs are explicit regulatory exclusions (SO-R), probability (SO-P), or consequence (SO-C). As discussed in Section 6.2.2.1, all three criteria are derived from regulatory requirements. FEPs not screened as SO-R, SO-P, or SO-C have been retained for inclusion in PA calculations and are classified as undisturbed performance (UP) or disturbed performance (DP) FEPs. These screening criteria and FEP classifiers are discussed in this section, and FEP screening is discussed in Sections 6.2.3, 6.2.4, and 6.2.5.

6.2.2.1 Eliminating Features, Events, and Processes Based on Regulation, Probability, or Consequence

Regulation. Specific FEP screening criteria are established by 40 CFR Part 191 and 40 CFR § 194.25, § 194.32 and § 194.54. These criteria relating to the applicability of particular FEPs represent screening decisions made by the EPA. That is, in the process of developing and demonstrating the feasibility of the 40 CFR Part 191 standard and the 40 CFR Part 194 criteria, EPA considered the relevance, consequence, and/or probability of occurrence of particular FEPs and, in so doing, eliminated some FEPs from consideration. For example, 40 CFR § 194.25 outlines consideration of future states. Future human activities are assumed to be as they are today; therefore other regulations that pertain to human activities can be used to screen FEPs (i.e., State and Federal oil well plugging requirements can be used to screen borehole related FEPs). Section 6.2.5 describes the regulatory screening criteria that pertain to limitations on the type of human-initiated events and processes that need be analyzed.

Probability of occurrence of a FEP leading to significant release of radionuclides. Low-probability events can be excluded based on the criterion provided in 40 CFR § 194.32(d), which states that "PAs need not consider processes and events that have less than one chance in 10,000 of occurring over 10,000 years." In practice, for most FEPs screened out on the basis of low probability of occurrence, it has not been possible to estimate a meaningful, quantitative probability. In the absence of quantitative probability estimates, a qualitative argument has been provided.

Potential consequences associated with the occurrence of the FEPs. The DOE identified two applications of this criterion:

1. FEPs can be eliminated from PA calculations on the basis of insignificant consequence. Consequence can refer to effects on the repository or site or to radiological consequence. In particular, 40 CFR § 194.34(a) states that "The results of PAs shall be assembled into "complementary, cumulative distribution functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events" (emphasis added). The DOE has omitted events and processes from PA calculations where there is a reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed by such omissions.

2. FEPs that are potentially beneficial to subsystem performance may be eliminated from PA calculations, if necessary, to simplify the analysis. This argument may be used when there is uncertainty as to exactly how the FEP should be incorporated into assessment calculations or when incorporation would incur unreasonable difficulties.

In some cases, the effects of a particular event or process, although not necessarily insignificant, can be shown to lie within the range of uncertainty of another FEP already accounted for in the PA calculations. In such cases, the event or process may be considered implicitly included in PA calculations, within the range of uncertainty associated with the included FEP.

The distinctions between the screened out-regulation (SO-R), screened out-probability (SO-P), and screened out-consequence (SO-C) classifications are summarized in Figure 6-7. Although some FEPs could be eliminated from PA calculations based on more than one criterion, the most practical screening criterion was used for classification. In particular, a regulatory screening classification was used in preference to a probability or consequence screening classification, as illustrated in Figure 6-7. FEPs that were not screened out based on any one of the three criteria are included in the PA.

6.2.2.2 Undisturbed Performance Features, Events, and Processes

FEPs classified as UP are accounted for in calculations of undisturbed performance of the disposal system. Undisturbed performance is defined in 40 CFR § 191.12 as "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." The UP FEPs are accounted for in the PA calculations to evaluate compliance with the Containment Requirements in 40 CFR § 191.13.

6.2.2.3 Disturbed Performance Features, Events, and Processes

FEPs classified as DP are accounted for only in assessment calculations for DP. The DP FEPs that remain following the screening process relate to the potential disruptive effects of future drilling and mining events in the controlled area. Consideration of both DP and UP FEPs is required to evaluate compliance with 40 CFR § 191.13.

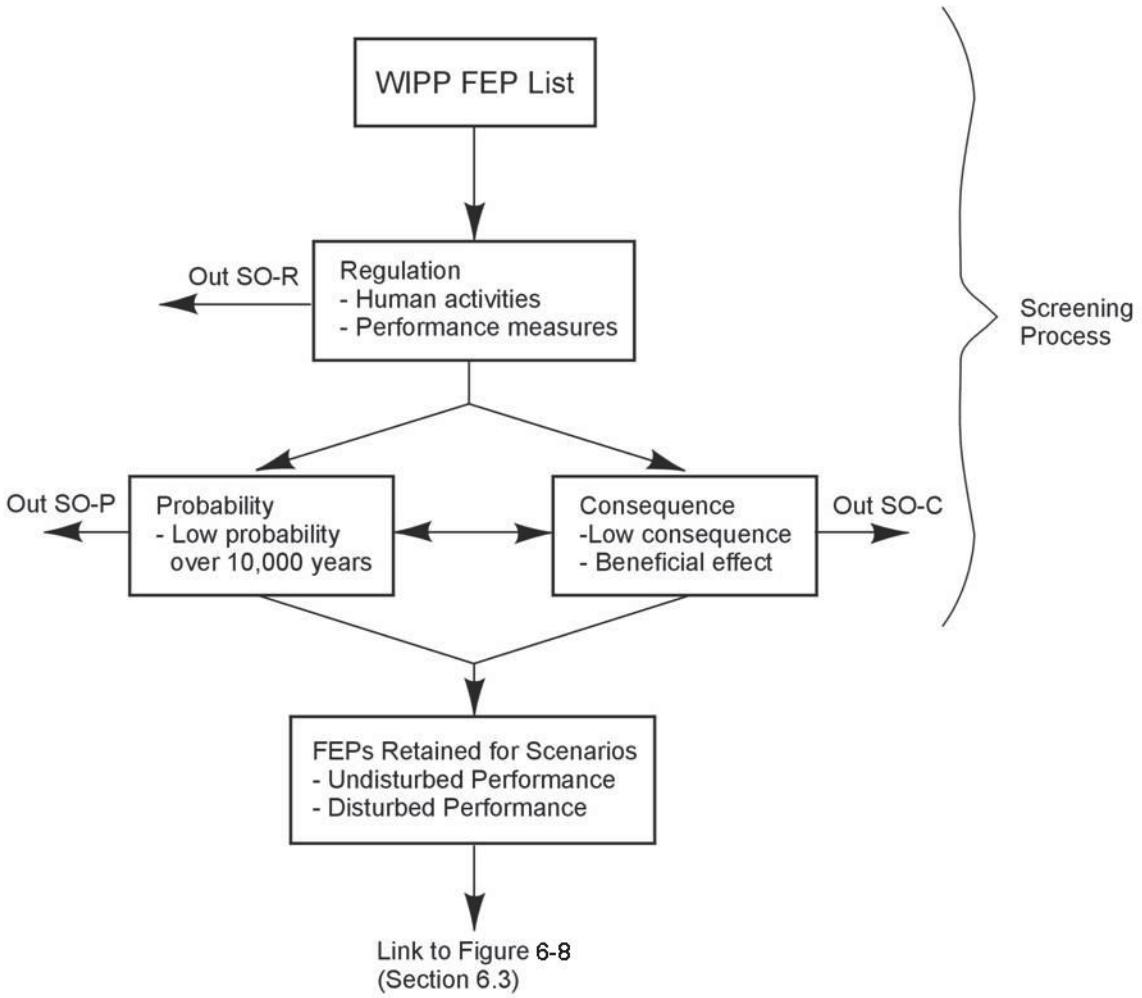

Figure 6-7. Screening Process Based on Screening Classifications

In the following sections, FEPs are discussed under the categories Natural FEPs, Waste- and Repository-Induced FEPs, and Human-Initiated Events and Processes (EPs).

This also allows an evaluation of compliance with the individual dose criterion in 40 CFR § 191.15 and the groundwater protection requirements in 40 CFR § 191.24 (see Chapter 8.0).

6.2.3 Natural Features, Events, and Processes

This subsection briefly discusses natural FEPs with the potential to affect long-term performance of the WIPP disposal system. These FEPs and their screening classifications are listed in Table 6-4; the DOE's detailed screening arguments for natural FEPs are contained in Appendix PA, Attachment SCR. Screening natural FEPs fulfills, in conjunction with the PA calculations, the criterion of the Future States Assumptions in 40 CFR § 194.25(b) that DOE shall "document in any compliance application, to the extent practicable, effects of potential future hydrogeologic, geologic and climatic conditions on the disposal system over the regulatory time frame."

Consistent with Section 194.32(d), the DOE has screened out several natural FEPs from PA calculations based on a low probability of occurrence at or near the WIPP site. In particular, natural events for which there is no evidence indicating that they have occurred within the Delaware Basin were screened on this basis. In this analysis, the probabilities of these events occurring are assumed to be zero. Quantitative, nonzero probabilities for such events, based on numbers of occurrences, cannot be ascribed without considering regions much larger than the Delaware Basin (see for example, FEP N 40, Impact of a Large Meteorite in Appendix PA, Attachment SCR), thus neglecting established geological understanding of the events and processes that occur within particular geographical provinces. No disruptive natural FEPs are likely to occur during the regulatory time frame that could create new pathways or significantly alter existing pathways.

In considering the overall geological setting of the Delaware Basin, the DOE eliminated many FEPs from PA calculations based on low consequence. Events and processes that have had little effect on the characteristics of the region in the past are expected to be of low consequence for the regulatory time period.

6.2.4 Waste- and Repository-Induced Features, Events, and Processes

The waste- and repository-induced FEPs are those that relate specifically to the waste material, waste containers, shaft seals, MgO, panel closures, repository structures, and investigation boreholes. All FEPs related to radionuclide chemistry and radionuclide migration are included in this category. FEPs related to radionuclide transport from future borehole intersections of the WIPP excavation are defined as waste- and repository-induced FEPs. Waste- and repository-induced FEPs and their screening classification are listed in Table 6-5. The DOE's detailed screening discussions for these FEPs are contained in Appendix PA (Attachment SCR).

The DOE has screened out many FEPs in this category on the basis of low consequence to the performance of the disposal system. For example, the DOE has shown that the heat generated by radioactive decay of emplaced RH- and CH-TRU waste will not increase temperature sufficiently to induce significant thermal convection, thermal stresses and strains, or thermally induced chemical perturbations within the disposal system (see Appendix PA, Attachment SCR, FEP W13 and FEP W72). Also, hydration of the emplaced concrete seals and chemical conditioner will be exothermic, but DOE has shown that the heat generated will not significantly affect the disposal system performance (see Appendix PA, Attachment SCR, FEP W72).

Other waste- and repository-induced FEPs were eliminated from PA calculations based on beneficial effect to the performance of the disposal system, if necessary to simplify the analysis.

Waste- and repository-induced FEPs eliminated on the basis of low probability of occurrence over 10,000 years are generally those for which no mechanisms were identified that

Table 6-4. Natural FEPs and Their Screening Classifications

FEPs	Screening Classification	Comments	FEP Number
GEOLOGICAL FEPS			
Stratigraphy			
Stratigraphy	UP		N1
Brine reservoirs	DP		N2
Tectonics			
Changes in regional stress	SO-C		N3
Regional tectonics	SO-C		N4
Regional uplift and subsidence	SO-C		N5
Structural FEPs			
Deformation			
Salt deformation	SO-P	UP near repository.	N6
Diapirism	SO-P		N7
Fracture development			
Formation of fractures	SO-P	UP near repository.	N8
Changes in fracture properties	SO-C	UP near repository.	N9
Fault movement			
Formation of new faults	SO-P		N10
Fault movement	SO-P		N11
Seismic activity			
Seismic activity	UP		N12
Crustal processes			
Igneous activity			
Volcanic activity	SO-P		N13
Magmatic activity	SO-C		N14
Metamorphism			
Metamorphic activity	SO-P		N15
Geochemical FEPs			
Dissolution			
Shallow dissolution	UP		N16
Deep dissolution	SO-P		N18
Breccia pipes	SO-P		N20
Collapse breccias	SO-P		N21
Mineralization			
Fracture infills	SO-C		N22
SUBSURFACE HYDROLOGICAL FEPS			
Groundwater characteristics			
Saturated groundwater flow	UP		N23
Unsaturated groundwater flow	UP	SO-C in Culebra.	N24
Fracture flow	UP		N25

Table 6-4. Natural FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Density effects on groundwater flow	SO-C		N26
Effects of preferential pathways	UP	UP in Salado and Culebra.	N27
Changes in groundwater flow			
Thermal effects on groundwater flow	SO-C		N28
Saline intrusion	SO-P		N29
Freshwater intrusion	SO-P		N30
Hydrological response to earthquakes	SO-C		N31
Natural gas intrusion	SO-P		N32
SUBSURFACE GEOCHEMICAL FEPS			
Groundwater geochemistry			
Groundwater geochemistry	UP		N33
Changes in groundwater chemistry			
Saline intrusion	SO-C		N34
Freshwater intrusion	SO-C		N35
Changes in groundwater Eh	SO-C		N36
Changes in groundwater pH	SO-C		N37
Effects of dissolution	SO-C		N38
GEOMORPHOLOGICAL FEPS			
Physiography			
Physiography	UP		N39
Meteorite impact			
Impact of a large meteorite	SO-P		N40
Denudation			
Weathering			
Mechanical weathering	SO-C		N41
Chemical weathering	SO-C		N42
Erosion			
Aeolian erosion	SO-C		N43
Fluvial erosion	SO-C		N44
Mass wasting	SO-C		N45
Sedimentation			
Aeolian deposition	SO-C		N46
Fluvial deposition	SO-C		N47
Lacustrine deposition	SO-C		N48
Mass wasting	SO-C		N49
Soil development			
Soil development	SO-C		N50
SURFACE HYDROLOGICAL FEPS			
Fluvial			

Table 6-4. Natural FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Stream and river flow	SO-C		N51
Lacustrine			
Surface water bodies	SO-C		N52
Groundwater recharge and discharge			
Groundwater discharge	UP		N53
Groundwater recharge	UP		N54
Infiltration	UP	UP for climate change effects.	N55
Changes in surface hydrology			
Changes in groundwater recharge and discharge	UP		N56
Lake formation	SO-C		N57
River flooding	SO-C		N58
CLIMATIC FEPs			
Climate			
Precipitation (for example, rainfall)	UP		N59
Temperature	UP		N60
Climate change			
Meteorological			
Climate change	UP		N61
Glaciation			
Glaciation	SO-P		N623
Permafrost	SO-P		N63
MARINE FEPs			
Seas			
Seas and oceans	SO-C		N64
Estuaries	SO-C		N65
Marine sedimentology			
Coastal erosion	SO-C		N66
Marine sediment transport and deposition	SO-C		N67
Sea level changes			
Sea level changes	SO-C		N68
ECOLOGICAL FEPs			
Flora & fauna			
Plants	SO-C		N69
Animals	SO-C		N70
Microbes	SO-C	UP for colloidal effects and gas generation	N71
Changes in flora & fauna			

Table 6-4. Natural FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Natural ecological development	SO-C		N72

Legend:

UP FEPs accounted for in the assessment calculations for undisturbed performance for 40 CFR § 191.13 (as well as 40 CFR § 191.15 and Subpart C of 40 CFR Part 191).

DP FEPs accounted for (in addition to all UP FEPs) in the assessment calculations for disturbed performance for 40 CFR § 191.13.

SO-R FEPs eliminated from PA calculations on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR § 194.25, .32 and .54

SO-C FEPs eliminated from PA (and compliance assessment) calculations based on consequence.

SO-P FEPs eliminated from PA (and compliance assessment) calculations based on low probability of occurrence.

Table 6-5. Waste- and Repository-Induced FEPs and Their Screening Classifications

FEPs	Screening Classification	Comments	FEP Number
WASTE AND REPOSITORY CHARACTERISTICS			
Repository characteristics			
Disposal geometry	UP		W1
Waste characteristics			
Waste inventory	UP		W2
Heterogeneity of waste forms	DP		W3
Container characteristics			
Container form	SO-C		W4
Container material inventory	UP		W5
Seal characteristics			
Seal geometry	UP		W6
Seal physical properties	UP		W7
Seal chemical composition	SO-C	Beneficial SO-C	W8
Backfill characteristics			
Backfill physical properties	SO-C		W9
Backfill chemical composition	UP		W10
Postclosure monitoring			
Postclosure monitoring	SO-C		W11
RADIOLOGICAL FEPs			
Radioactive decay			
Radionuclide decay and ingrowth	UP		W12
Heat from radioactive decay			
Heat from radioactive decay	SO-C		W13
Nuclear criticality			
Nuclear criticality: heat	SO-P		W14
Radiological effects on material properties			
Radiological effects on waste	SO-C		W15
Radiological effects on containers	SO-C		W16
Radiological effects on seals	SO-C		W17
GEOLOGICAL AND MECHANICAL FEPs			
Excavation-induced fracturing			
Disturbed rock zone	UP		W18
Excavation-induced changes in stress	UP		W19
Rock creep			
Salt creep	UP		W20
Changes in the stress field	UP		W21
Roof falls			

Table 6-5. Waste- and Repository-Induced FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Roof falls	UP		W22
Subsidence			
Subsidence	SO-C		W23
Large scale rock fracturing	SO-P		W24
Effects of fluid pressure changes			
Disruption due to gas effects	UP		W25
Pressurization	UP		W26
Effects of explosions			
Gas explosions	UP		W27
Nuclear explosions	SO-P		W28
Thermal effects			
Thermal effects on material properties	SO-C		W29
Thermally induced stress changes	SO-C		W30
Differing thermal expansion of repository components	SO-C		W31
Mechanical effects on material properties			
Consolidation of waste	UP		W32
Movement of containers	SO-C		W33
Container integrity	SO-C	Beneficial SO-C	W34
Mechanical effects of backfill	SO-C		W35
Consolidation of seals	UP		W36
Mechanical degradation of seals	UP		W37
Underground boreholes	UP		W39
SUBSURFACE HYDROLOGICAL AND FLUID DYNAMICAL FEPs			
Repository-induced flow			
Brine inflow	UP		W40
Wicking	UP		W41
Effects of gas generation			
Fluid flow due to gas production	UP		W42
Thermal effects			
Convection	SO-C		W43
GEOCHEMICAL AND CHEMICAL FEPs			
Gas generation			
Microbial gas generation			
Degradation of organic material	UP		W44
Effects of temperature on microbial gas generation	UP		W45
Effects of pressure on microbial gas generation	SO-C		W46

Table 6-5. Waste- and Repository-Induced FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Effects of radiation on microbial gas generation	SO-C		W47
Effects of biofilms on microbial gas generation	UP		W48
Corrosion			
Gases from metal corrosion	UP		W49
Galvanic coupling	SO-C		W50
Chemical effects of corrosion	UP		
Radiolytic gas generation			
Radiolysis of brine	SO-C		W52
Radiolysis of cellulose	SO-C		W53
Helium gas production	SO-C		W54
Radioactive gases	SO-C		W55
Chemical speciation			
Speciation	UP	UP in disposal rooms and Culebra. SO-C elsewhere, and beneficial SO-C in cementitious seals.	W56
Kinetics of speciation	SO-C		W57
Precipitation and dissolution			
Dissolution of waste	UP		W58
Precipitation	SO-C	Beneficial SO-C	W59
Kinetics of precipitation and dissolution	SO-C	Kinetics of waste dissolution is a beneficial SO-C	W60
Sorption			
Actinide sorption	UP	UP in the Culebra and Dewey Lake. Beneficial SO-C elsewhere	W61
Kinetics of sorption	UP		W62
Changes in sorptive surfaces	UP		W63
Oxidation-reduction chemistry			
Effect of metal corrosion	UP		W64
Oxidation-reduction fronts	SO-P		W65
Oxidation-reduction kinetics	UP		W66
Localized reducing zones	SO-C		W67
Organic complexation			
Organic complexation	UP		W67
Organic ligands	UP		W69
Humic and fulvic acids	UP		W70
Kinetics of organic complexation	SO-C		W71

Table 6-5. Waste- and Repository-Induced FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Exothermic reactions			
Exothermic reactions	SO-C		W72
Concrete hydration	SO-C		W73
Chemical effects on material properties			
Chemical degradation of seals	UP		W74
Chemical degradation of backfill	SO-C		W75
Microbial growth on concrete	UP		W76
CONTAMINANT TRANSPORT MODE FEPs			
Solute transport			
Solute transport	UP		W77
Colloid transport			
Colloid transport	UP		W78
Colloid formation and stability	UP		W79
Colloid filtration	UP		W80
Colloid sorption	UP		W81
Particulate transport			
Suspensions of particles	DP	SO-C for undisturbed conditions	W82
Rinse	SO-C		W83
Cuttings	DP	Repository intrusion only	W84
Cavings	DP	Repository intrusion only	W85
Spallings	DP	Repository intrusion only	W86
Microbial transport			
Microbial transport	UP		W87
Biofilms	SO-C	Beneficial SO-C	W88
Gas transport			
Transport of radioactive gases	SO-C		W89
CONTAMINANT TRANSPORT PROCESSES			
Advection			
Advection	UP		W90
Diffusion			
Diffusion	UP		W91
Matrix diffusion	UP		W92
Thermochemical transport phenomena			
Soret effect	SO-C		W93
Electrochemical transport phenomena			
Electrochemical effects	SO-C		W94
Galvanic coupling	SO-P		W95

Table 6-5. Waste- and Repository-Induced FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Electrophoresis	SO-C		W96
Physicochemical transport phenomena			
Chemical gradients	SO-C		W97
Osmotic processes	SO-C	Beneficial SO-C	W98
Alpha recoil	SO-C		W99
Enhanced diffusion	SO-C		W100
ECOLOGICAL FEPs			
Plant, animal, and soil uptake			
Plant uptake	SO-R	SO-C for 40 CFR § 191.15	W101
Animal uptake	SO-R		W102
Accumulation in soils	SO-C	Beneficial SO-C	W103
Human uptake			
Ingestion	SO-R	SO-C for 40 CFR § 191.15	W104
Inhalation	SO-R	SO-C for 40 CFR § 191.15	W105
Irradiation	SO-R	SO-C for 40 CFR § 191.15	W106
Dermal sorption	SO-R	SO-C for 40 CFR § 191.15	W107
Injection	SO-R	SO-C for 40 CFR § 191.15	W108

Legend:

UP FEPs accounted for in the assessment calculations for undisturbed performance for 40 CFR § 191.13 (as well as 40 CFR § 191.15 and Subpart C of 40 CFR Part 191).

DP FEPs accounted for (in addition to all UP FEPs) in the assessment calculations for disturbed performance for 40 CFR § 191.13.

SO-R FEPs eliminated from PA calculations on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR § 194. 25, .32 and .54.

SO-C FEPs eliminated from PA (and compliance assessment) calculations based on consequence.

SO-P FEPs eliminated from PA (and compliance assessment) calculations based on low probability of occurrence.

could result in their occurrence within the disposal system. Such FEPs include explosions resulting from nuclear criticality, and the development of large-scale reduction-oxidation fronts.

6.2.5 Human-Initiated Events and Processes

Assessments of compliance with the Containment Requirements in 40 CFR § 191.13 require consideration of "all significant processes and events," including human-initiated EPs. These EPs and their screening classifications are listed in Table 6-6. The DOE's detailed screening arguments for human-initiated EPs are presented in Appendix PA, Attachment SCR.

The scope of PA is clarified with respect to human-initiated events and processes in 40 CFR § 194.32. Section 194.32(a) states that

> Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.

Thus, PA must conside human-initiated EPs relating to mining and drilling activities that might take place during the regulatory time frame. In particular, PAs must consider the potential effects of such activities that might take place within the controlled area at a time when institutional controls cannot be assumed to completely eliminate the possibility of human intrusion.

Further criteria concerning the scope of PAs are provided at 40 CFR § 194.32(c):

> Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

Table 6-6. Human-Initiated EPs and Their Screening Classifications

EPs	Screening Classification		Comments	FEP Number
	Historical/ Ongoing/ Near Future	Future		
GEOLOGICAL EPs				
Drilling			DP for boreholes that penetrate the waste and boreholes that penetrate Castile brine underlying the waste disposal region. SO-C for other future drilling.	
Oil and gas exploration	SO-C	DP		H1
Potash exploration	SO-C	DP		H2
Water resources exploration	SO-C	SO-C		H3
Oil and gas exploitation	SO-C	DP		H4
Groundwater exploitation	SO-C	SO-C		H5
Archeological investigations	SO-R	SO-R		H6
Geothermal	SO-R	SO-R		H7
Other resources	SO-C	DP		H8
Enhanced oil and gas recovery	SO-C	DP		H9
Liquid waste disposal	SO-R	SO-R		H10
Hydrocarbon storage	SO-R	SO-R		H11
Deliberate drilling intrusion	SO-R	SO-R		H12
Excavation activities				
Conventional underground potash mining	UP	DP	UP for mining outside the controlled area. DP for mining inside the controlled area.	H13
Solution mining for potash	SO-R	SO-R	New to FEP Baseline	H58
Solution mining for other resources	SO-R	SO-R	New to FEP Baseline	H59
Other resources	SO-C	SO-R		H14
Tunneling	SO-R	SO-R		H15
Construction of underground facilities (for example storage, disposal, accommodation)	SO-R	SO-R		H16
Archeological excavations	SO-C	SO-R		H17
Deliberate mining intrusion	SO-R	SO-R		H18
Subsurface explosions				
Resource recovery				

Table 6-6. Human-Initiated EPs and Their Screening Classifications — Continued

EPs	Screening Classification		Comments	FEP Number
	Historical/ Ongoing/ Near Future	Future		
Explosions for resource recovery	SO-C	SO-R		H19
Underground nuclear device testing				
Underground nuclear device testing	SO-C	SO-R		H20
SUBSURFACE HYDROLOGICAL AND GEOCHEMICAL EPs				
Borehole fluid flow				
Drilling-induced flow				
Drilling fluid flow	SO-C	DP	DP for boreholes that penetrate the waste. SO-C for other future drilling.	H21
Drilling fluid loss	SO-C	DP	DP for boreholes that penetrate the waste, SO-C for other future drilling	H22
Blowouts	SO-C	DP	DP for boreholes that penetrate the waste and boreholes that penetrate Castile brine underlying the waste disposal region. SO-C for other future drilling.	H23
Drilling-induced geochemical changes	UP	DP	SO-C for units other than the Culebra.	H24
Fluid extraction				
Oil and gas extraction	SO-C	SO-R		H25
Groundwater extraction	SO-C	SO-R		H26
Fluid injection				
Liquid waste disposal	SO-C	SO-C		H27
Enhanced oil and gas production	SO-C	SO-C		H28
Hydrocarbon storage	SO-C	SO-C		H29
Fluid-injection induced geochemical changes	UP	SO-R	SO-C for units other than the Culebra	H30
Flow through abandoned boreholes			Classification distinguishes the time when drilling occurs.	

Table 6-6. Human-Initiated EPs and Their Screening Classifications — Continued

EPs	Screening Classification		Comments	FEP Number
	Historical/ Ongoing/ Near Future	Future		
Natural borehole fluid flow	SO-C	DP	DP for boreholes that penetrate Castile brine underlying the waste disposal region. SO-C for other future boreholes.	H31
Waste-induced borehole flow	SO-R	DP	DP for boreholes that penetrate the waste. SO-C for other future boreholes.	H32
Borehole-induced solution and subsidence	SO-C	SO-C		H34
Borehole-induced mineralization	SO-C	SO-C		H35
Borehole-induced geochemical changes	UP	DP	SO-C for units other than the Culebra	H36
Excavation-induced flow			Classification distinguishes the time when excavation occurs.	
Changes in groundwater flow due to mining	UP	DP	UP for mining outside the controlled area. DP for mining inside the controlled area.	H37
Changes in geochemistry due to mining	SO-C	SO-R		H38
Explosion-induced flow				
Changes in groundwater flow due to explosions	SO-C	SO-R		H39
GEOMORPHOLOGICAL EPs				
Land use and disturbances				
Land use changes	SO-R	SO-R		H40
Surface disruptions	UP	SO-R		H41
SURFACE HYDROLOGICAL EPs				
Water control and use				
Damming of streams or rivers	SO-C	SO-R		H42
Reservoirs	SO-C	SO-R		H43
Irrigation	SO-C	SO-R		H44
Lake usage	SO-R	SO-R		H45
Altered soil or surface water chemistry by human activities	SO-C	SO-R		H46

Table 6-6. Human-Initiated EPs and Their Screening Classifications — Continued

EPs	Screening Classification		Comments	FEP Number
	Historical/ Ongoing/ Near Future	Future		
CLIMATIC EPs				
Anthropogenic climate change				
Greenhouse gas effects	SO-R	SO-R		H47
Acid rain	SO-R	SO-R		H48
Damage to the ozone layer	SO-R	SO-R		H49
MARINE EPs				
Marine activities				
Coastal water use	SO-R	SO-R		H50
Seawater use	SO-R	SO-R		H51
Estuarine water use	SO-R	SO-R		H52
ECOLOGICAL EPs				
Agricultural activities				
Arable farming	SO-C	SO-R		H53
Ranching	SO-C	SO-R		H54
Fish farming	SO-R	SO-R		H55
Social and technological developments				
Demographic change and urban development	SO-R	SO-R		H56
Loss of records	NA	DP		H57

Legend:

UP FEPs accounted for in the assessment calculations for undisturbed performance for 40 CFR § 191.13 (as well as 40 CFR § 191.15 and Subpart C of 40 CFR Part 191).

DP FEPs accounted for (in addition to all UP FEPs) in the assessment calculations for disturbed performance for 40 CFR § 191.13.

SO-R FEPs eliminated from performance assessment calculations on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR § 194. 25, .32 and .54.

SO-C FEPs eliminated from PA (and compliance assessment) calculations based on consequence.

SO-P FEPs eliminated from PA (and compliance assessment) calculations based on low probability of occurrence.

NA FEPs not applicable to the particular category.

PAs must consider all human-initiated EPs relating to activities that have taken place or are reasonably expected to take place outside the controlled area in the near future.

In order to implement the criteria in Section 194.32 relating to the scope of PA, the DOE has divided human activities into three categories: (1) human activities that are currently taking place and those that took place prior to the time of the compliance application, (2) human activities that might be initiated in the near future after submission of the compliance application, and (3) human activities that might be initiated after repository closure. The first two categories

of EPs are considered under undisturbed performance; EPs in the third category lead to disturbed performance conditions.

(1) Historical and current human activities include resource extraction activities that have taken place and are currently taking place outside the controlled area. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. Current human activities taking place within the controlled area are essentially those associated with development of the WIPP repository. Historical activities include existing boreholes.

(2) Near-future human activities include resource extraction activities that may occur outside the controlled area based on existing plans and leases. Thus, the near future includes the expected lives of existing mines and oil and gas fields, and the expected lives of new mines and oil and gas fields that the DOE expects will be developed based on existing plans and leases. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. The only human activities expected to occur within the controlled area in the near future are those associated with WIPP repository development. The DOE assumes that any activity in the near future, based on existing plans and leases, will be initiated prior to repository closure. Activities initiated prior to repository closure are assumed to continue until their completion.

(3) Future human activities include activities that might be initiated within or outside the controlled area after repository closure. This includes drilling and mining for resources within the disposal system when institutional controls cannot be assumed to completely eliminate the possibility of such activities. Future human activities could influence the transport of contaminants within and outside the disposal system by directly removing waste from the disposal system or altering the geological, hydrological, or geochemical characteristics of the disposal system.

To satisfy the criteria in 40 CFR § 194.32, PAs must consider the potential effects of historical, current, near-future, and future human activities on the disposal system performance. The criterion in 40 CFR § 194.25(a) concerned with predicting the future states of society requires that PAs and compliance assessments "shall assume that the characteristics of the future remain what they are at the time the compliance application is prepared." This criterion has been applied to eliminate the following human-initiated EPs from PA calculations:

- drilling associated with geothermal energy production (H7), liquid waste disposal (H10), hydrocarbon storage (H11), and archeological investigations (H6);
- excavation activities associated with tunneling (H15) and construction of underground facilities (H16) (for example, storage, disposal, and accommodation);
- changes in land use (H40);
- anthropogenic climate change (H47, H48 and H49);

- changes in agricultural practices (H53, H54 and H55);
- demographic change, urban developments, and technological developments (H56); and
- solution mining (H58 and H59).

As discussed in Chapter 8.0, compliance assessments (to determine compliance with 40 CFR § 191.15 and Subpart C of 40 CFR Part 191) need to consider the UP of the disposal system.

6.2.5.1 Historical, Current, and Near-Future Human Activities

Historical, current, and near-future human activities could affect WIPP site characteristics after the submission of this application, and could influence the disposal system performance. The hydrogeological impacts of historical, current, and near-future potash mining outside the controlled area are accounted for in calculations of the undisturbed performance of the disposal system. Near-future potash mining is assumed to continue for the expected economic life of each mine. The potential consequences to the disposal system performance from other human-initiated EPs expected to occur in the Delaware Basin in the near future are discussed in Appendix PA, Attachment SCR, which describes how these EPs are eliminated based on low consequence.

6.2.5.2 Future Human Activities

PA (but not compliance assessments, as discussed in Chapter 8.0) must consider the effects of future human activities on the disposal system performance. The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), which limits the scope of consideration of future human actions in PAs to mining and drilling.

6.2.5.2.1 Criteria Concerning Future Mining

The EPA provides additional criteria concerning the type of future mining that should be considered by the DOE in 40 CFR § 194.32(b):

> Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.

Thus, considering future mining may be limited to mining within the controlled area at locations of resources that are similar in quality and type to those currently extracted from the Delaware Basin. Potash is the only resource identified within the controlled area in quality similar to that currently mined from underground deposits elsewhere in the Delaware Basin. Within the controlled area, the McNutt of the Salado provides the only potash of appropriate quality. The hydrogeological impacts of future potash mining within the controlled area are accounted for in DP calculations of the disposal system. Consistent with 40 CFR § 194.32(b), all economically

recoverable resources in the vicinity of the disposal system (outside the controlled area) are assumed to be extracted in the near future.

6.2.5.2.2 Criteria Concerning Future Drilling

With respect to future drilling, in the preamble to 40 CFR Part 194, the EPA "reasoned that while the resources drilled for today may not be the same as those drilled for in the future, the present rates at which these boreholes are drilled can nonetheless provide an estimate of the future rate at which boreholes will be drilled." Criteria concerning the consideration of future deep and shallow drilling[2] in PAs are provided in 40 CFR § 194.33. These criteria require that, to calculate future drilling rates, the DOE should examine the historical rate of drilling for resources in the Delaware Basin. Historical drilling for purposes other than resource exploration and recovery (such as WIPP site investigation) need not be considered in determining future drilling rates.

In particular, when calculating the frequency of future deep drilling, 40 CFR § 194.33(b)(3)(i) states that the DOE should

> Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.

Oil and gas are the only known resources below 655 m (2,150 ft) that have been exploited over the past 100 years in the Delaware Basin. However, some potash and sulfur exploration boreholes have been drilled in the Delaware Basin to depths in excess of 2,150 feet (655 meters) below the surface relative to where the drilling occurred. Thus, consistent with 40 CFR § 194.33(b)(3)(i), the DOE used the historical record of deep drilling associated with oil, gas, potash and sulfur exploration, and oil and gas exploitation in the Delaware Basin to determine the rate of deep drilling within the controlled area and throughout the basin in the future, as discussed in Appendix DATA, Section 2 and Attachment A. Deep drilling may occur within the controlled area after the end of active institutional control (100 years after disposal).

In calculating the frequency of future shallow drilling, 40 CFR § 194.33(b)(4)(i) states that the DOE should

> Identify shallow drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.

An additional criterion with respect to calculating future shallow drilling rates is provided in 40 CFR § 194.33(b)(4)(iii):

> In considering the historical rate of all shallow drilling, the Department may, if justified, consider only the historical rate of shallow drilling for resources of similar type and quality to those in the controlled area.

[2] The EPA has defined two types of drilling in 40 CFR § 194.2: deep drilling, defined as "drilling events in the Delaware Basin that reach or exceed a depth of 2,150 ft below the surface relative to where such drilling occurred"; and shallow drilling, defined as "drilling events in the Delaware Basin that do not reach a depth of 2,150 ft below the surface relative to where such drilling occurred."

As an example, EPA states in the preamble to 40 CFR Part 194 that "if only non-potable water can be found within the controlled area, then the rate of drilling for water may be set equal to the historical rate of drilling for non-potable water in the Delaware Basin over the past 100 years." Thus, the DOE may limit the rate of future shallow drilling based on a determination of the potential resources in the controlled area. Shallow drilling associated with water, potash, sulfur, oil, and gas extraction has taken place in the Delaware Basin over the past 100 years. However, of these resources, only water and potash are present at shallow depths (less than 655 m [2,150 ft] below the surface) within the controlled area. Thus, consistent with 40 CFR § 194.33(b)(4), the DOE used the historical record of shallow drilling associated with water and potash extraction in the Delaware Basin in calculations to determine the rate of shallow drilling within the controlled area, as discussed in Appendix DATA, Section 2 and Attachment A.

The EPA also provides a criterion in 40 CFR § 194.33(d) concerning the use of future boreholes subsequent to drilling:

> With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

Thus, PAs need not consider the effects of techniques used for resource extraction and recovery that would occur after the drilling of a future borehole.

The EPA provides an additional criterion to limit the severity of human intrusion scenarios that must be considered in PAs. In 40 CFR § 194.33(b)(1), EPA states that

> Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario.

Thus, human intrusion scenarios involving deliberate intrusion need not be considered in PAs.

6.2.5.2.3 Screening of Future Human-Initiated EPs

Future human-initiated EPs accounted for in PA calculations for the WIPP are those associated with mining and deep drilling within the controlled area at a time when institutional controls cannot be assumed to completely eliminate the possibility of such activities. All other future human-initiated EPs, if not eliminated from PA calculations based on regulation, have been eliminated based on low consequence or low probability. For example, the effects of future shallow drilling within the controlled area were eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. These screening decisions are listed in Table 6-6 and are discussed in Appendix PA, Attachment SCR.

6.2.6 Reassessment of Features, Events, and Processes for the Compliance Recertification

As part of the recertification effort, the DOE assessed the impacts of new information on the original FEPs baseline to determine if changes to the original decisions are necessary. The FEPs baseline could be affected by new information from literature, experiments, observations from monitoring programs, or changes implemented by the DOE (moving the WIPP horizon to Clay G, for example). The processes and results of the FEPs baseline reassessment are documented in Appendix PA, Attachment SCR.

The FEP assessment resulted in the addition of two new FEPs to better represent solution mining (H57 and H58) and the deletion of four FEPs (by combining the deleted FEPs into other related FEPs). Seven screening decisions were also changed as a result of new information. However, only three FEPs previously screened out were screened into the CRA-2004 PA. The impact of organic ligands (W68 and W69) was screened into the CRA-2004 PA as a result of new information. This FEP screening decision change is the only impact to the PA system. The inclusion of ligands is discussed in Section 6.4.3.4. The FEP Surface Disruptions (H41) was also screened in. This FEP was already implicitly included in PA through past site characterization and current monitoring data (Appendix PA, Attachment SCR). The changes to the FEPs baseline are summarized in Table 6-7.

6.3 Scenario Development and Selection

This section addresses scenarios formed from FEPs that were retained for PA calculations, and introduces the specification of scenarios for consequence analysis. Probabilities associated with scenarios are discussed in Section 6.4.12.

Logic diagrams are used to illustrate the formation of scenarios for consequence analysis from combinations of FEPs that remain after FEP screening (Cranwell et al. 1990) (Figure 6-8). Each scenario shown in Figure 6-8 is defined by a combination of occurrence and

Table 6-7. FEPs Reassessment Summary Results

EPA FEP I.D.	FEP Name	Summary of Change
FEPs Combined with other FEPs		
N17	Lateral Dissolution	Combined with N16, “Shallow Dissolution.” N17 removed from baseline.
N19	Solution Chimneys	Combined with N20, “Breccia Pipes.” N19 removed from Baseline.
H33	Flow Through Undetected Boreholes	Combined with H31, “Natural Borehole Fluid Flow.” H33 removed from baseline.
W38	Investigation Boreholes	Addressed in H31, “Natural Borehole Fluid Flow,” and H33, “Flow Through Undetected Boreholes.” W38 removed from baseline.
FEPs With Changed Screening Decisions		
W50	Galvanic Coupling	SO-P to SO-C
W68	Organic Complexation	SO-C to UP
W69	Organic Ligands	SO-C to UP
H27	Liquid Waste Disposal	SO-R to SO-C
H28	Enhanced Oil and Gas Production	SO-R to SO-C
H29	Hydrocarbon Storage	SO-R to SO-C
H41	Surface Disruptions	SO-C to UP (HCN)
New FEPs for CRA-2004		
H58	Solution Mining for Potash	Separated from H13, “Potash Mining.”
H59	Solution Mining for Other Resources	Separated from H13, “Potash Mining.”

nonoccurrence of all potentially disruptive EPs. Disruptive EPs are defined as those that create new pathways, or significantly alter existing pathways for fluid flow and, potentially, radionuclide transport within the disposal system. Each of these scenarios also contains a set of features and nondisruptive EPs that remain after FEP screening. As shown in Figure 6-8, undisturbed performance (UP) and disturbed performance (DP) scenarios are considered in consequence modeling for the WIPP PA. The (UP) scenario, as discussed in Chapter 8.0, is used for compliance assessments. Important aspects of (UP) and (DP) are summarized in this section.

6.3.1 Undisturbed Performance

Undisturbed performance is defined in 40 CFR § 191.12 to mean "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." Considering only (UP) is required for compliance assessments with respect to the Individual and Groundwater Protection Requirements (40 CFR § 191.15 see Chapter 8.0). Undisturbed performance is also considered with (DP) for PAs with respect to the Containment Requirements (40 CFR § 191.13).

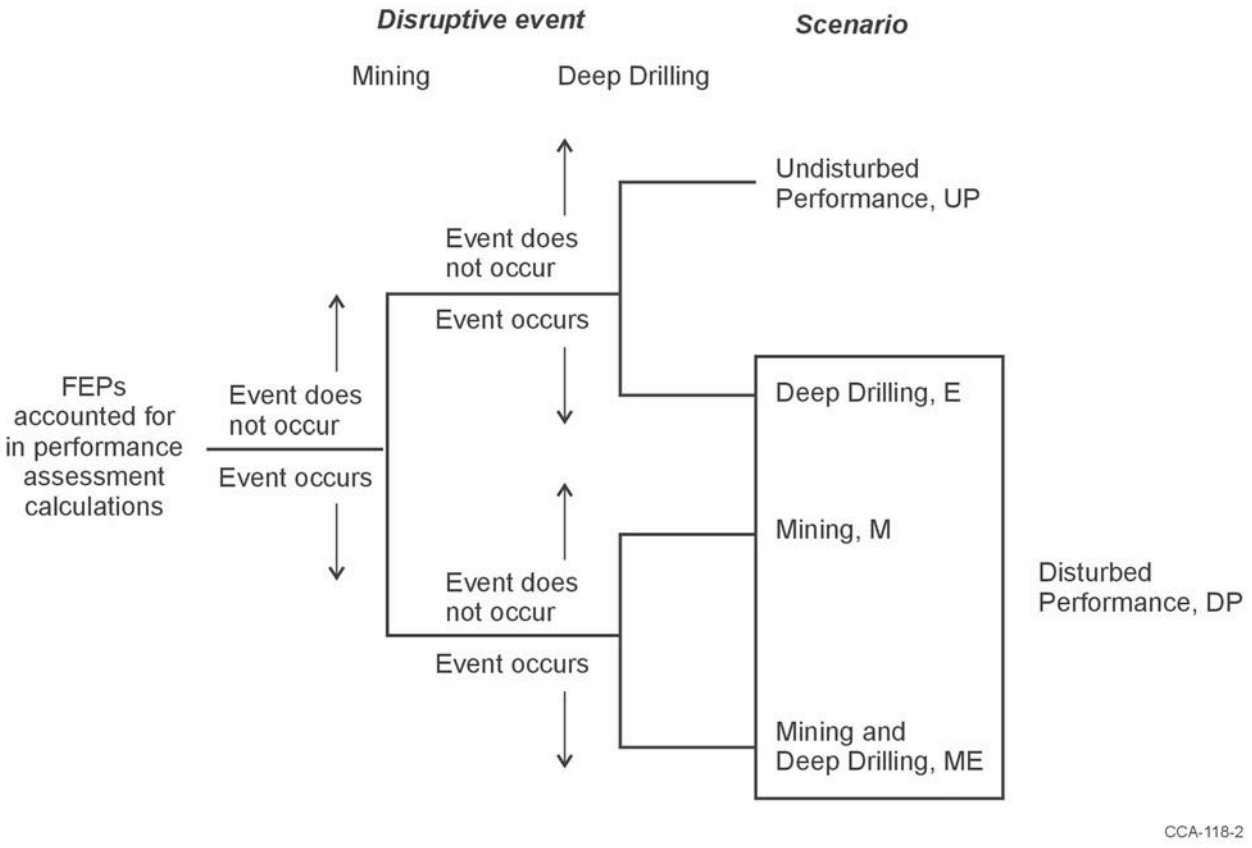

Figure 6-8. Logic Diagram for Scenario Analysis

No potentially disruptive natural EPs are likely to occur during the regulatory time frame (Section 6.2.3 and Appendix PA, Attachment SCR). Therefore, all naturally occurring EPs retained for scenario construction are nondisruptive and are considered as part of (UP). The only natural features and waste- and repository-induced FEPs retained after screening that are not

included in the (UP) scenario but are included in (DP) are those directly associated with the potential effects of future deep drilling within the controlled area. These drilling-related FEPs are discussed in Section 6.3.2. Potash mining outside the controlled area does not constitute a disruption of the disposal system by human intrusion and is included in the (UP) scenario. In total, 70 (UP) FEPs were identified (Section 6.2.3). These FEPs have been assigned a screening designator (UP) in tables in Section 6.2.3 and are listed separately in Table 6-8. Table 6-8 also contains references to text in Section 6.4 that describes the conceptual models, which account for the UP FEPs.

Among the most significant FEPs that will affect the (UP) within the disposal system are excavation-induced fracturing, gas generation, salt creep, and MgO in the disposal rooms.

- The repository excavation and consequent changes in the rock stress field surrounding the excavated opening will create a DRZ immediately adjacent to excavated openings. The DRZ will exhibit mechanical and hydrological properties different than those of the intact rock.

- Organic material in the waste may degrade because of microbial activity, and brine will corrode metals in the waste and waste containers, with concomitant generation of gases. Gas generation may result in pressures sufficient to both maintain or develop fractures and change the fluid flow pattern around the waste disposal region.

- At the repository depth, salt creep will tend to heal fractures and reduce the permeability of the DRZ and the crushed salt component of the long-term shaft seals to near that of the host rock salt.

- The MgO engineered barrier emplaced in the disposal rooms will react with CO_2 and maintain mildly alkaline conditions. Corrosion of metals in the waste and waste containers will maintain reducing conditions. These effects will decrease radionuclide solubility.

Radionuclides can become mobile as a result of waste dissolution and colloid generation following brine flow into the disposal rooms. Colloids may be generated from the waste (humics, mineral fragments, and actinide intrinsic colloids) or from other sources (humics, mineral fragments, and microbes).

Conceptually, there are several pathways for radionuclide transport within the undisturbed disposal system that may result in releases to the accessible environment (Figure 6-9). Contaminated brine may migrate away from the waste-disposal panels if pressure within the panels is elevated by gas generated from corrosion or microbial consumption. Radionuclide transport may occur laterally, through the anhydrite interbeds toward the subsurface boundary of the accessible environment in the Salado, or through access drifts or anhydrite interbeds to the base of the shafts. In the latter case, if the pressure gradient between the panels and overlying strata is sufficient, contaminated brine may migrate up the shafts. As a result, radionuclides may be transported directly to the ground surface, or laterally away from the shafts, through permeable strata such as the Culebra, toward the subsurface boundary of the accessible environment. These conceptual pathways are shown in Figure 6-9.

The modeling system described in Section 6.4 includes potential radionuclide transport along other pathways, such as migration through Salado halite. However, the natural properties of the undisturbed system make radionuclide transport to the accessible environment via these other pathways unlikely.

6.3.2 Disturbed Performance

Assessments for compliance with 40 CFR § 191.13 need to consider the potential effects of future disruptive natural and human-initiated EPs on the performance of the disposal system. As discussed in Section 6.2.3, no potentially disruptive, natural EPs are considered sufficiently likely to require inclusion in analyses of either (UP) or (DP). The only future human-initiated EPs retained after FEP screening are those associated with mining and deep drilling (but not the subsequent use of a borehole) within the controlled area when institutional controls cannot be assumed to eliminate the possibility of such activities (Sections 6.2.5.2 and 6.4.12.1). In total, 21 (DP) FEPs associated with future mining and deep drilling have been identified. These FEPs were assigned a screening designator "DP" in tables in Section 6.2 and are listed separately in Table 6-9. Table 6-9 also contains references to text in Section 6.4 that describes the conceptual models which account for the DP FEPs.

For evaluating the consequences of (DP), the DOE has defined the mining scenario, M, the deep drilling scenario, E, and a mining and drilling scenario, ME. These scenarios are described in the following sections.

6.3.2.1 The Disturbed Performance Mining Scenario

The (DP) mining scenario, M, involves future mining within the controlled area.

Consistent with the criteria stated by the EPA in 40 CFR § 194.32 (b) for PA calculations, the effects of potential future mining within the controlled area are limited to changes in hydraulic conductivity of the Culebra that result from subsidence (as described in Section 6.4.6.2.3.

Radionuclide transport may be affected in the M scenario if a head gradient between the waste-disposal panels and the Culebra causes brine contaminated with radionuclides to move from the waste-disposal panels to the base of the shafts and up to the Culebra. The changes in the Culebra transmissivity field may affect the rate and direction of radionuclide transport within the Culebra. Features of the M scenario are illustrated in Figure 6-10.

The three disturbed performance FEPs labeled "M" in Table 6-9 relate to the occurrence and effects of future mining. The modeling system used for the M scenario is similar to that developed for the UP scenario, but with a modified Culebra transmissivity field in the controlled area to account for the mining effects.

6.3.2.2 The Disturbed Performance Deep Drilling Scenario

The DP deep drilling scenario, E, involves at least one deep drilling event that intersects the waste disposal region. The EPA provides criteria for analyzing the consequences of future drilling events in PAs in 40 CFR § 194.33(c):

Performance assessments shall document that in analyzing the consequences of drilling events, the Department assumed that:

(1) Future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. Such future drilling practices shall include, but shall not be limited to: the types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of such boreholes that are sealed by humans; and

Table 6-8. Undisturbed Performance FEPs

UP FEPs	Section
NATURAL FEPs	
Geological	
Stratigraphy	
Stratigraphy	6.4.2
Structural effects	
Seismic activity	
Seismic activity	6.4.5.3
Geochemical	
Dissolution	
Shallow dissolution	6.4.6.2
Subsurface hydrological	
Groundwater characteristics	
Saturated groundwater flow	6.4.5 6.4.6
Unsaturated groundwater flow	6.4.6
Fracture flow	6.4.6.2
Effects of preferential pathways	6.4.6.2
Subsurface geochemical	
Groundwater geochemistry	
Groundwater geochemistry	6.4.3.4 6.4.6.2
Geomorphological	
Physiography	
Physiography	6.4.2
Surface hydrological	
Groundwater recharge and discharge	
Groundwater discharge	6.4.10.2
Groundwater recharge	6.4.10.2
Infiltration	6.4.10.2
Changes in surface hydrology	
Changes in groundwater recharge and discharge	6.4.9
Climatic	
Climate	
Precipitation (for example, rainfall)	6.4.9
Temperature	6.4.9
Climate change	
Meteorological	
Climate change	6.4.9

Table 6-8. Undisturbed Performance FEPs — Continued

UP FEPs	Section
WASTE- AND REPOSITORY-INDUCED FEPs	
Waste and repository characteristics	
Repository characteristics	
Disposal geometry	6.4.2.1
Waste characteristics	
Waste inventory	6.4.3.3
Container characteristics	
Container material inventory	6.4.3.3
Seal characteristics	
Seal geometry	6.4.3
Seal physical properties	6.4.4
Backfill characteristics	
Backfill chemical composition	6.4.3.4
Radiological	
Radioactive decay	
Radionuclide decay and ingrowth	6.4.5.4.2 6.4.12.4
Geological and Mechanical	
Excavation-induced fracturing	
DRZ	6.4.5.3
Excavation-induced changes in stress	6.4.3.1
Rock creep	
Salt creep	6.4.3.1
Changes in the stress field	6.4.3.1
Roof falls	
Roof falls	6.4.5.3
Effects of fluid pressure changes	
Disruption due to gas effects	6.4.5.2
Pressurization	6.4.5.2
Effects of explosions	
Gas explosions	6.4.5.3
Mechanical effects on material properties	
Consolidation of waste	6.4.3.1
Consolidation of seals	6.4.4
Mechanical degradation of seals	6.4.4
Underground boreholes	6.4.5.3
Subsurface hydrological and fluid dynamics	
Repository-induced flow	

Table 6-8. Undisturbed Performance FEPs — Continued

UP FEPs	Section
Brine inflow	6.4.3.2
Wicking	6.4.3.2
Effects of gas generation	
Fluid flow due to gas production	6.4.3.2
Geochemical and chemical	
Gas generation	
Microbial gas generation	
Consumption of organic materials	6.4.3.3
Effects of temperature on microbial gas generation	6.4.3.3
Effects of biofilms on microbial gas generation	6.4.3.3
Corrosion	
Gases from metal corrosion	6.4.3.3
Chemical effects of corrosion	6.4.3.3
Chemical speciation	
Speciation	6.4.3.4 6.4.3.5
Precipitation and dissolution	
Dissolution of waste	6.4.3.5
Sorption	
Actinide sorption	6.4.3.6 6.4.6.2.1
Kinetics of sorption	6.4.6.2.1
Changes in sorptive surfaces	6.4.6.2.1
Reduction-oxidation chemistry	
Effect of metal corrosion	6.4.3.5
Reduction-oxidation kinetics	6.4.3.5
Organic complexation	
Organic complexation	6.4.3.4
Organic ligands	6.4.3.4
Humic and fulvic acids	6.4.3.6 6.4.6.2.2
Chemical effects on material properties	
Chemical degradation of seals	6.4.4
Microbial growth on concrete	6.4.4
Contaminant transport mode	
Solute transport	

Table 6-8. Undisturbed Performance FEPs — Continued

UP FEPs	Section
Solute transport	6.4.5.4 6.4.6.2.1
Colloid transport	
Colloid transport	6.4.6.2.2
Colloid formation and stability	6.4.3.6
Colloid filtration	6.4.6.2.2
Colloid sorption	6.4.6.2.2
Microbial transport	
Microbial transport	6.4.6.2.2
Contaminant transport processes	
Advection	
Advection	6.4.5.4 6.4.6.2
Diffusion	
Diffusion	6.4.5.4 6.4.6.2
Matrix diffusion	6.4.6.2
HUMAN-INITIATED EPs	
Geomorphological	
Surface disruptions	6.4
Geological	
Excavation activities	
Potash mining outside controlled area	6.4.6.2.3 6.4.12.8 6.4.13.8
Subsurface hydrological and geochemical	
Borehole fluid flow	
Drilling-induced flow	
Drilling induced geochemical changes	6.4.6.2
Fluid injection	
Fluid injection-induced geochemical changes	6.4.6.2
Flow through abandoned boreholes	
Borehole-induced geochemical changes	6.4.6.2
Excavation-induced flow	
Changes in groundwater flow due to mining	6.4.6.2.3 6.4.12.8 6.4.13.8

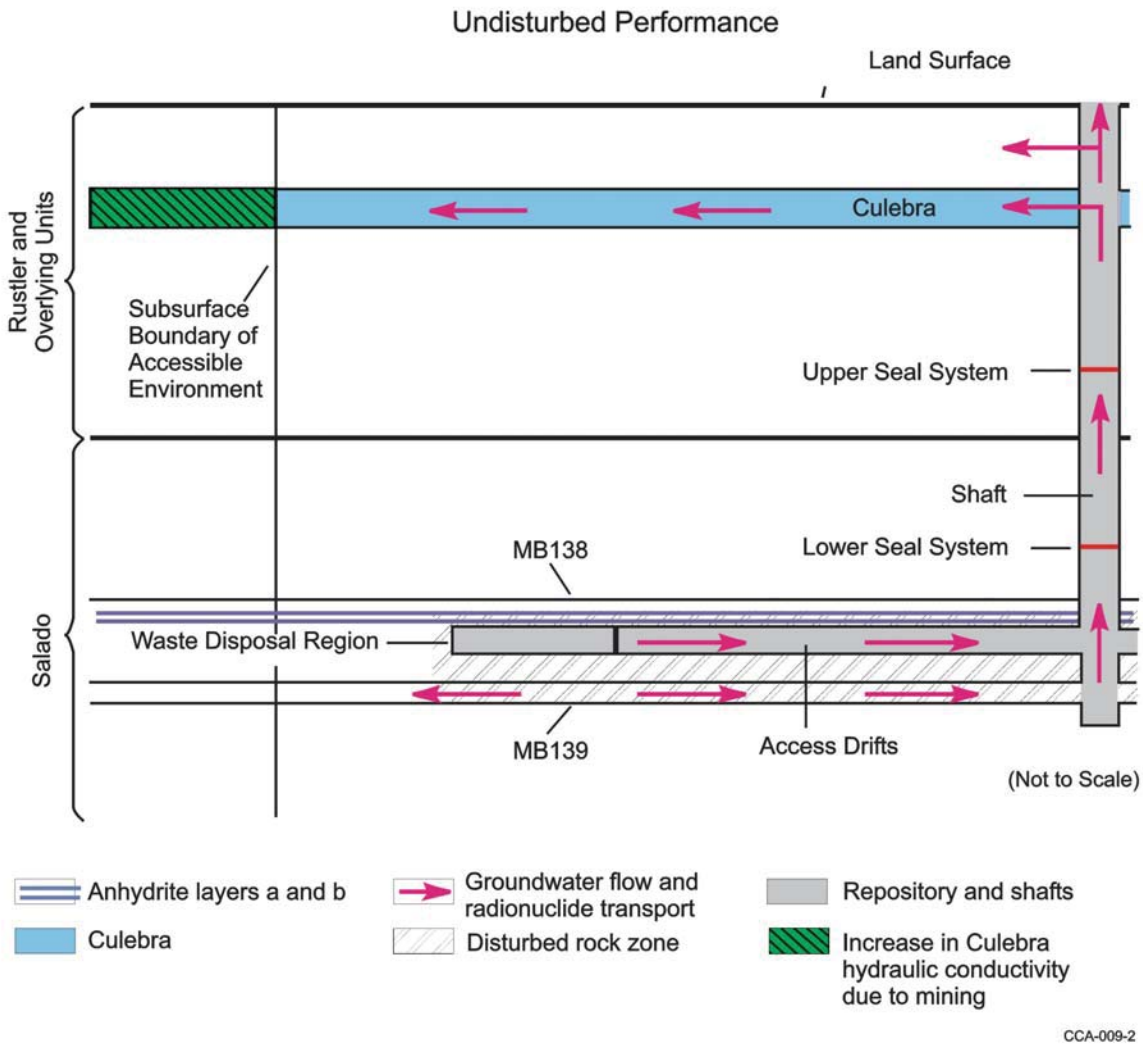

Figure 6-9. Conceptual Release Pathways for the Undisturbed Performance Scenario

(2) Natural processes will degrade or otherwise affect the capability of boreholes to transmit fluids over the regulatory time frame.

Consistent with these criteria, there are several pathways for radionuclides to reach the accessible environment in the E scenario. Before any deep drilling intersects the waste, potential release pathways are identical to those in the UP scenario.

If a borehole intersects the waste in the disposal rooms, releases to the accessible environment may occur as material entrained in the circulating drilling fluid is brought to the surface, as discussed in Section 6.4.7.1. Particulate waste brought to the surface may include cuttings, cavings, and spallings. Cuttings are the materials cut by the drill bit as it passes through waste. Cavings are the materials eroded by the drilling fluid in the annulus around the drill bit. Spallings are the materials forced into the circulating drilling fluid if there is

Table 6-9. Disturbed Performance FEPs

(FEPs)	Scenario	Section
ALL UP FEPs		
NATURAL FEPs		
Geological		
Stratigraphy		
Brine reservoirs	E1	6.4.8 6.4.12.6
WASTE- AND REPOSITORY-INDUCED FEPs		
Waste and repository characteristics		
Waste characteristics		
Heterogeneity of waste forms	E1, E2	6.4.12.4
Contaminant transport mode		
Particulate transport		
Suspensions of particles	E1, E2	6.4.7.1
Cuttings	E1, E2	6.4.7.1
Cavings	E1, E2	6.4.7.1
Spallings	E1, E2	6.4.7.1 6.4.13.7
HUMAN-INITIATED EPs		
Geological		
Drilling		
Oil and gas exploration	E1, E2	6.4.7 6.4.12.2
Potash exploration	E1, E2	6.4.7 6.4.12.2
Oil and gas exploitation	E1, E2	6.4.7 6.4.12.2
Other resources	E1, E2	6.4.7 6.4.12.2
Enhanced oil and gas recovery	E1, E2	6.4.7 6.4.12.2
Excavation activities		
Potash mining	M	6.4.6.2.3 6.4.12.8 6.4.13.8
Subsurface hydrological and geochemical		
Borehole fluid flow		
Drilling-induced flow		
Drilling fluid flow	E1, E2	6.4.7.1
Drilling fluid loss	E2	6.4.7.1.1
Blowouts	E1, E2	6.4.7.1.1

Table 6-9. Disturbed Performance FEPs — Continued

(FEPs)	Scenario	Section
Drilling-induced geochemical changes	E1, E2	6.4.6.2
Flow through abandoned boreholes		
Natural borehole fluid flow	E1, E2	6.4.7.2 6.4.12.7 6.4.13
Waste-induced borehole flow	E1, E2	6.4.7.2 6.4.12.7 6.4.13
Borehole-induced geochemical changes	E1, E2	6.4.6.2
Excavation-induced flow		
Changes to groundwater flow due to mining	M	6.4.6.2.3 6.4.12.8 6.4.13.8
Ecological		
Social and technological developments		
Loss of records	M, E1, E2	6.4.7 6.4.12.1

Legend:
M Mining within the controlled area.
E1 Deep drilling that intersects the waste disposal region and a brine reservoir in the Castile.
E2 Deep drilling that intersects a waste disposal panel.

sufficient pressure in the waste disposal panels. During drilling, contaminated brine may flow up the borehole and reach the surface, depending on fluid pressure within the waste disposal panels.

When abandoned, the borehole is assumed to be plugged in a manner consistent with current practice in the Delaware Basin (see Section 6.4.7.2; and Appendix DEL, Sections DEL.5 and DEL.6; Appendix DATA, Section 2, and CCA Appendix PA, Attachment MASS, Section.16.3). An abandoned intrusion borehole with degraded casing and/or plugs may provide a pathway for fluid flow and contaminant transport from the intersected waste panel to the ground surface if the fluid pressure within the panel is sufficiently greater than hydrostatic. Additionally, if brine flows through the borehole to overlying units, such as the Culebra, it may carry dissolved and colloidal actinides that can be transported laterally to the accessible environment by natural groundwater flow in the overlying units.

Alternatively, the units intersected by an intrusion borehole may provide sources for brine flow to a waste panel during or after drilling. For example, in the northern Delaware Basin, the Castile, which underlies the Salado, contains isolated volumes of brine at fluid pressures greater than hydrostatic (as discussed in Section 2.2.1.2.2). The WIPP-12 penetration of one of these reservoirs provided data on one brine reservoir within the controlled area. The location and properties of brine reservoirs cannot be reliably predicted; thus, the possibility of a deep borehole penetrating both a waste panel and a brine reservoir is accounted for in consequence analysis of the WIPP, as discussed in Section 6.4.8. Such a borehole could provide a connection for brine

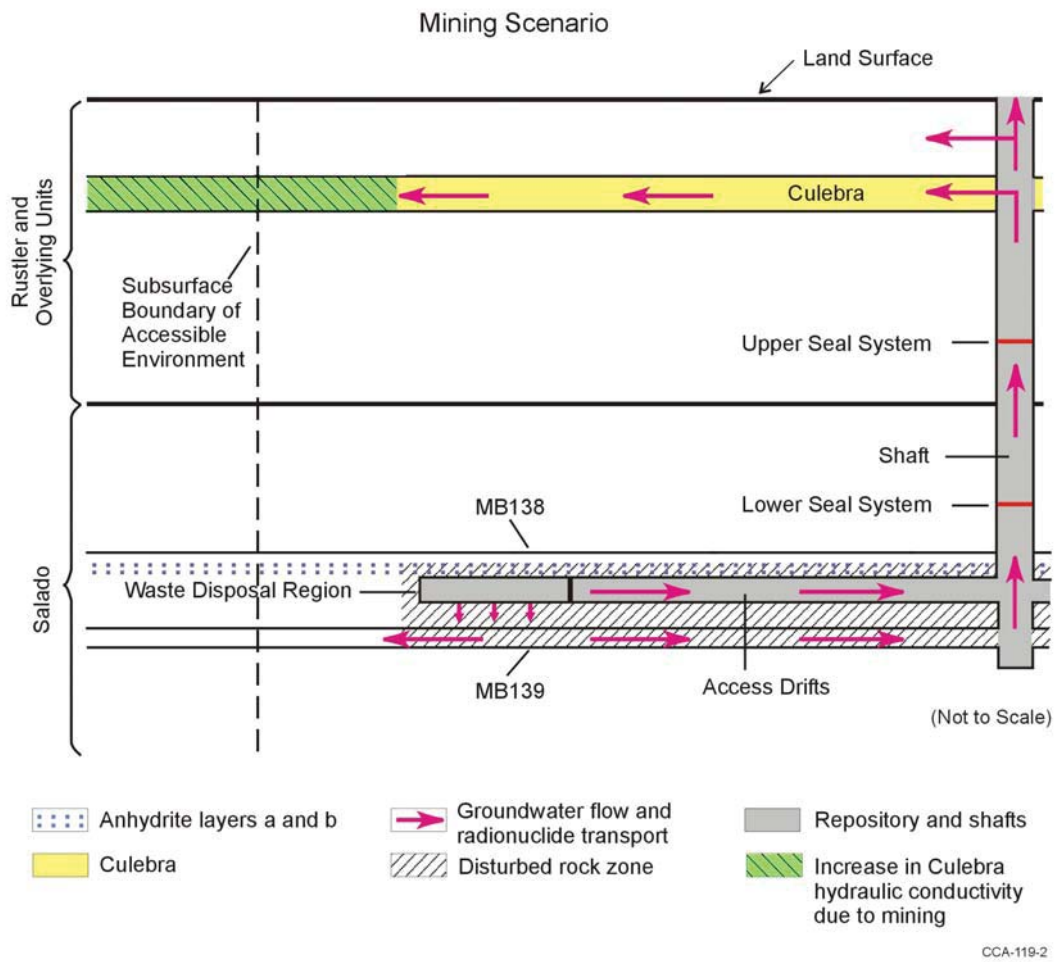

Figure 6-10. Conceptual Release Pathways for the Disturbed Performance Mining Scenario

flow from the Castile to the waste panel, thus increasing fluid pressure and brine volume in the waste panel.

A borehole that is drilled through a disposal room pillar, but does not intersect waste, could also penetrate the brine reservoir underlying the waste disposal region. Such an event would, to some extent, depressurize the brine reservoir, and thus would affect the consequences of any subsequent reservoir intersections. The PA does not take credit for possible brine reservoir depressurization.

The DOE has distinguished two types of deep drilling events by whether or not the borehole intersects a Castile brine reservoir. A borehole that intersects a waste disposal panel and penetrates a Castile brine reservoir is designated an E1 event. The 18 DP FEPs labeled “E1” in Table 6-9 relate to the occurrence and effects of an E1 drilling event. A borehole that intersects a waste panel but does not penetrate a Castile brine reservoir is designated an E2 event. The 18 DP FEPs labeled “E2” in Table 6-9 relate to the occurrence and effects of an “E2” drilling event.

In order to evaluate the consequences of future deep drilling, the DOE has divided the E scenario into three drilling subscenarios; E1, E2, and E1E2, distinguished by the number of E1 and E2 drilling events that are probabilistically assumed to occur in the regulatory time frame. These subscenarios are described in order of increasing complexity in the following sections.

6.3.2.2.1 The E2 Scenario

The E2 scenario is the simplest scenario for inadvertent human intrusion into a waste disposal panel. In this scenario, a panel is penetrated by a drill bit; cuttings, cavings, spallings, and brine flow releases may occur; and brine flow may occur in the borehole after it is plugged and abandoned. Sources for brine that may contribute to long-term flow up the abandoned borehole are the Salado or, under certain conditions, the units above the Salado. An E2 scenario may involve more than one E2 drilling event. Features of the E2 scenario are illustrated in Figure 6-11. A modeling system has been developed to evaluate the consequences of an E2 scenario during which single or multiple E2 events occur.

6.3.2.2.2 The E1 Scenario

Any scenario with one inadvertent penetration of a waste panel that also penetrates a Castile brine reservoir is called E1. Features of this scenario are illustrated in Figure 6-12.

Sources of brine in the E1 scenario are the brine reservoir, the Salado and, under certain conditions, the units above the Salado. However, the brine reservoir is conceptually the dominant source of brine in this scenario. The model configuration developed for the E1 scenario evaluates the consequences of futures that have only one E1 event.

6.3.2.2.3 The E1E2 Scenario

The E1E2 scenario is defined as all futures with multiple penetrations of a waste panel of which at least one intrusion is an E1. One case of this scenario, with a single E1 event and a single E2 event penetrating the same panel, is illustrated in Figure 6-13. However, the E1E2 scenario can include many possible combinations of intrusion times, locations, and types of event (E1 or E2). The sources of brine in this scenario are those listed for the E1 scenario, and multiple E1 sources may be present. The E1E2 scenario has a potential flow path not present in the E1 or E2 scenarios: flow from an E1 borehole through the waste to another borehole. This flow path has the potential to (1) bring large quantities of brine in direct contact with waste and (2) provide a less restrictive path for this brine to flow to the units above the Salado (via multiple boreholes) compared to either the individual E1 or E2 scenarios. It is both the presence of brine reservoirs and the potential for flow through the waste to other boreholes that make this scenario different in terms of potential consequences from combinations of E2 boreholes. The extent to which flow occurs between boreholes, as estimated by modeling, determines whether combinations of E1 and E2 boreholes at specific locations in the repository should be treated as E1E2 scenarios or as independent E1 and E2 scenarios in the consequence analysis.

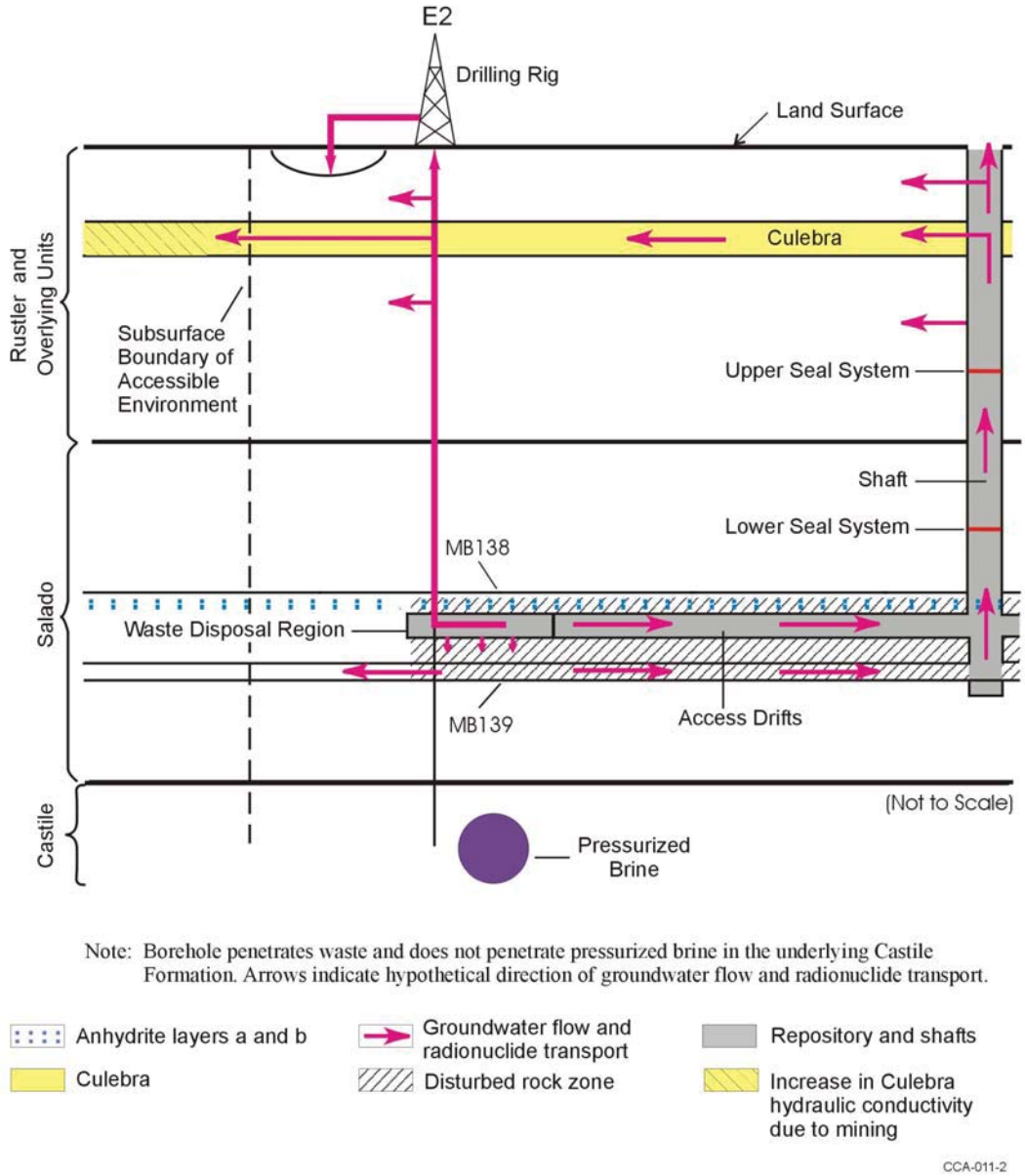

Figure 6-11. Conceptual Release Pathways for the Disturbed Performance Deep Drilling E2 Scenario

The possible combinations of drilling events make the modeling configuration for the E1E2 scenario differ in significant ways from that used to evaluate E1 and E2 scenarios. This configuration is described in Section 6.4.13.5.

6.3.2.3 The Disturbed Performance Mining and Deep Drilling Scenario

Mining in the WIPP site (the M scenario) and deep drilling (the E scenario) may both occur in the future. The DOE calls a future in which both of these events occur the ME scenario. The

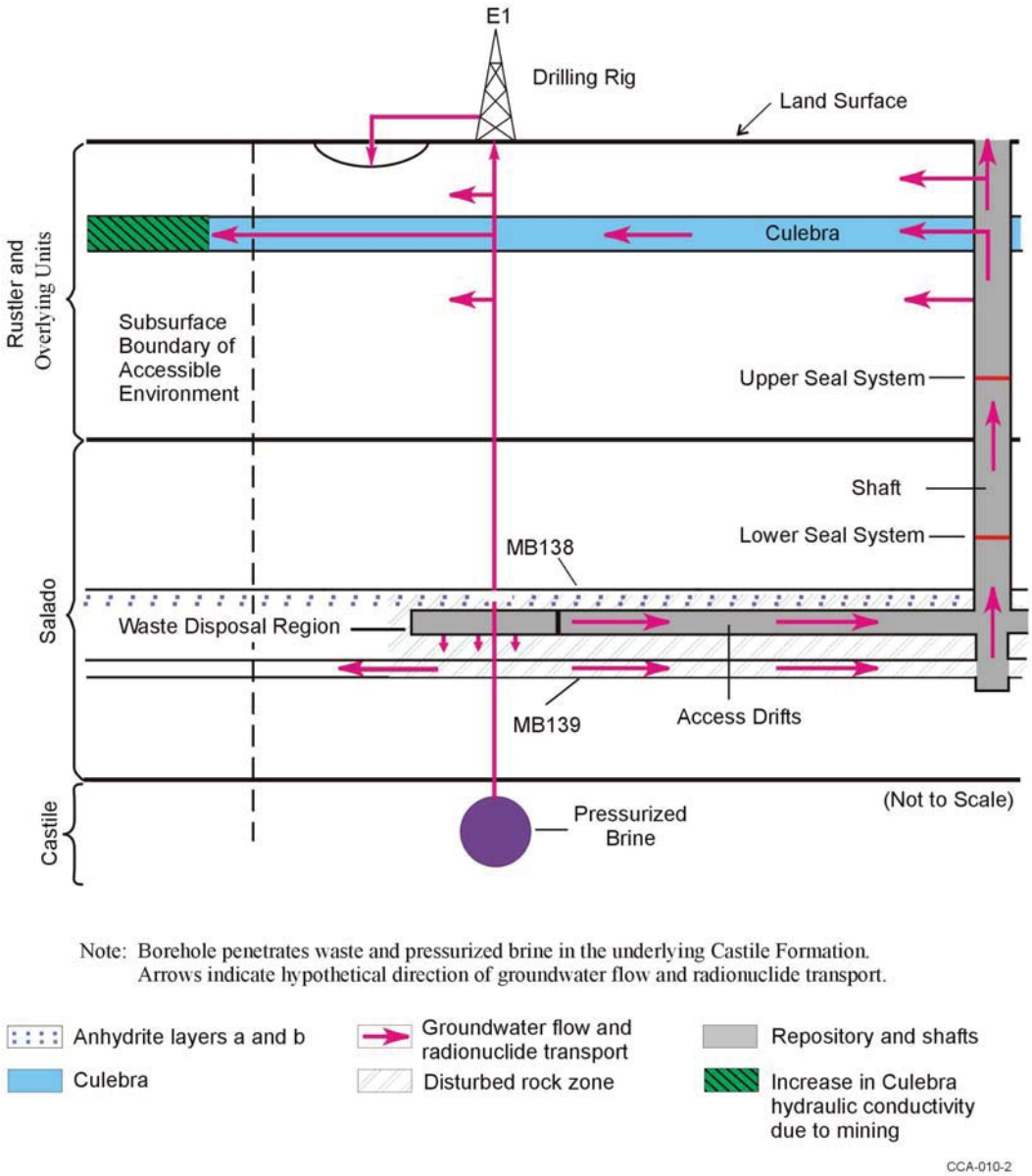

Figure 6-12. Conceptual Release Pathways for the Disturbed Performance Deep Drilling Scenario E1

occurrence of both mining and deep drilling do not create processes beyond those already described separately for the M and E scenarios. For example, the occurrence of mining does not influence any of the interactions between deep boreholes and the repository or brine reservoirs. Nor does the occurrence of drilling impact the effects of mining on Culebra hydrogeology. The difference between the M and E scenarios considered separately and the ME scenario is that the combination of borehole transport to the Culebra (E) and a transmissivity field impacted by mining (M) may result in more rapid transport of actinides to the accessible environment. For example, because the M scenario does not include drilling the only pathway for actinides to reach the Culebra is up the sealed shafts. For clarity in describing

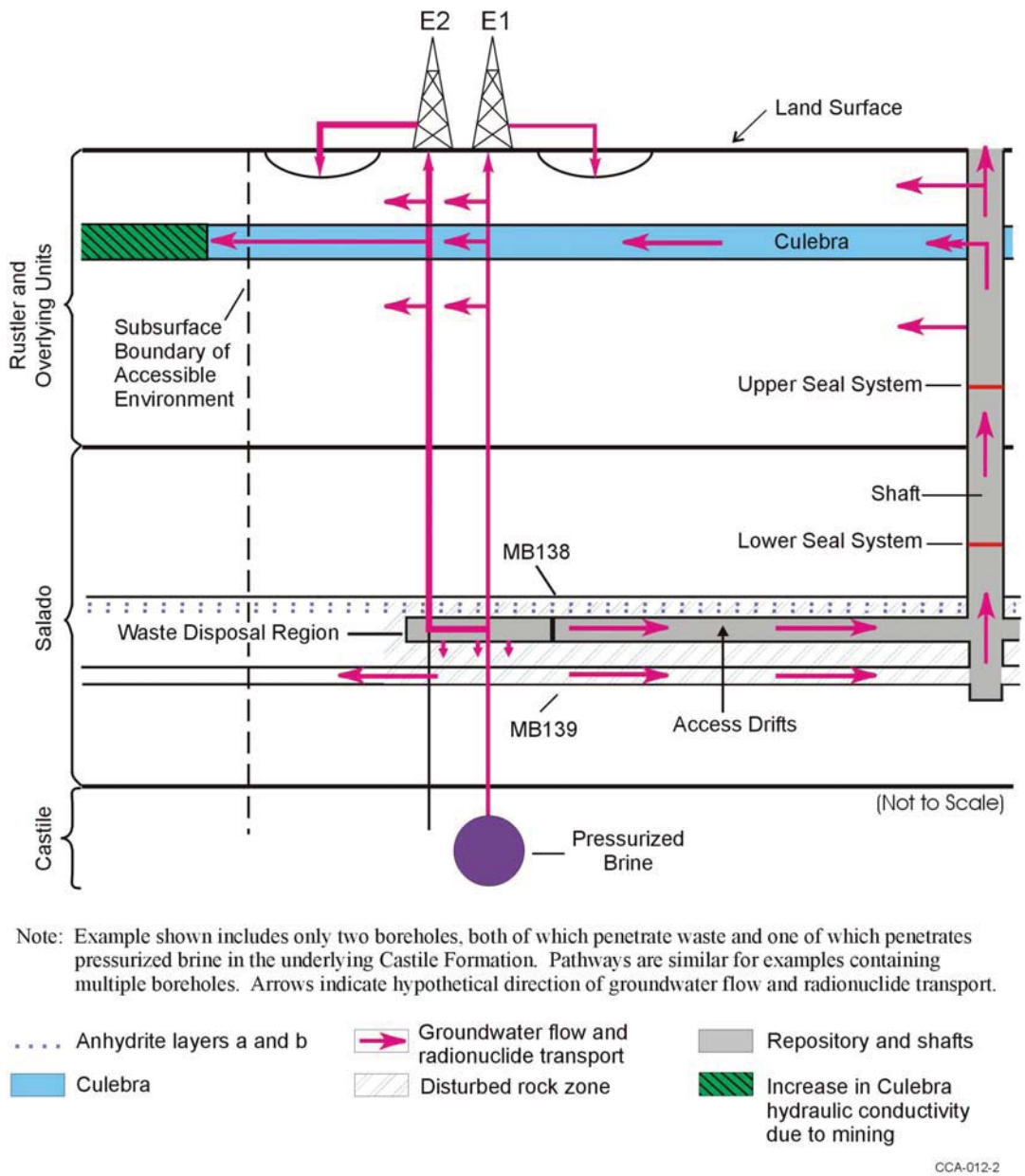

Figure 6-13. Conceptual Release Pathways for the Disturbed Performance Deep Drilling Scenario E1E2

computational results, the ME scenario has been subdivided according to the types of deep drilling subscenarios into the ME1 scenario (M and E1), the ME2 scenario (M and E2), and the ME1E2 scenario (M and E1E2).

The system used to model flow and transport in the Culebra for the ME scenario is similar to that used for the E scenario. However, in the ME scenario, the Culebra transmissivity field is modified to account for mining within the controlled area.

6.3.3 Scenarios Retained for Consequence Analysis

The scenarios described in Sections 6.3.1 and 6.3.2 have been retained for consequence analysis to determine compliance with the Containment Requirements in 40 CFR § 191.13. The modeling systems used to evaluate the consequences of these UP and DP scenarios are discussed in Section 6.4. For consequence analysis, the scenarios and subscenarios are further subdivided into scenarios, S_i. The S_i scenarios are distinguished by, for example, the time of occurrence of disruptive events. The S_i scenarios are generated, and their probabilities determined, by probabilistic sampling of selected processes and events (see Sections 6.1.5.2 and 6.4.12).

6.4 Calculation of Scenario Consequences

Scenario consequence, cS_i, is the third element of the ordered triples shown in Equation (6.2) in Section 6.1.1. Estimating cS_i requires quantitative modeling. PA uses a linked system of individual computer codes. This section discusses the conceptual and computational models and some parameter values used to estimate the consequence of the scenarios described in Section 6.3. Additional discussion of conceptual models and modeling assumptions is provided in Appendix PA, Section PA-2. Additional descriptions of sampled parameter values are included in Appendix PA, Section 5.0 and Attachment PAR.

6.4.1 Types of Models

A single modeling system was used to represent the disposal system and calculate the CCDFs presented in Section 6.5. The modeling system, however, can be conveniently described in terms of various submodels, with each describing a part of the overall system. This section provides, for each submodel defined, an integrated, summary description of the conceptual model, mathematical model, numerical model, computational model, experimental data, and model parameters used. These terms are described below.

The models used in the WIPP PA, as in other complex analyses, exist at four different levels:

(1) **Conceptual models** are a set of qualitative assumptions that describe a system or subsystem for a given purpose. At a minimum, these assumptions concern the geometry and dimensionality of the system, initial and boundary conditions, time dependence, and the nature of the relevant physical and chemical processes. The assumptions should be consistent with one another and with existing information within the context of the given purpose.

(2) **Mathematical models** represent the processes at the site. The conceptual models provide the context within which these mathematical models must operate and define the processes they must characterize. The mathematical models are predictive in the sense that, once provided with the known or assumed properties of the system and possible perturbations to the system, they predict the response of the system. The processes represented by these mathematical models include fluid flow, mechanical deformation, radionuclide transport in groundwater, and removal of waste through intruding boreholes.

(3) **Numerical models** are developed to approximate mathematical model solutions because most mathematical models do not have closed-form solutions.

(4) The complexity of the system requires computer codes to solve the numerical models. The implementation of the numerical model in the computer code with specific initial and boundary conditions and parameter values is generally referred to as the **computational model**.

Data are descriptors of the physical system being considered, normally obtained by experiment or observation. Parameters are values necessary in mathematical, numerical, or computational models. The distinction between data and parameters can be subtle. Parameters are distinct from data, however, for three reasons. First, data may be evaluated, statistically or otherwise, to generate model parameters to account for uncertainty in data. Second, some parameters have no relation to the physical system, such as the parameters in a numerical model to determine when an iterative solution scheme has converged. Third, many model parameters are applied at a different scale than one directly observed or measured in the physical system. The distinction between data and parameter values is described further in Appendix PA, Attachment PAR, where distribution derivations for specific parameters are given. The interpretation and the scaling of experimental and field data are discussed in Appendix PA, Attachment PAR for individual and sampled parameters, as appropriate.

6.4.2 Model Geometries

Although the specific geometries used in PA models are developed after the conceptual and mathematical models are defined, they are introduced here because they provide a useful framework for presenting the full discussion of the modeling system. PA represents the three-dimensional geometry of the disposal system (repository, shafts, and controlled area) using two primary two-dimensional simplifications. In the first geometry, processes that act on the entire disposal system occur within the repository and are simulated in the BRAGFLO (BRine And Gas FLOw) computer code using a geometry that approximates a north-south vertical cross section through the disposal system and some surrounding rock. This geometry simulates processes in the disposal system, such as two-phase flow and movement of actinides, as well as processes acting only within the repository, such as creep closure of disposal rooms and gas generation. In the second geometry, groundwater flow and actinide transport in the Culebra, which provides a potential pathway for lateral transport of actinides to the accessible environment, are simulated in the MODFLOW-2000 and SECOTP2D computer codes using a two-dimensional horizontal geometry that treats the Culebra as a single layer. These two geometries are discussed in the following sections. PA codes and the flow of numerical information through the PA are described in Section 6.4.11 and referenced appendices.

6.4.2.1 Disposal System Geometry

A single disposal system geometry is used in the BRAGFLO computational model (see Appendix PA, Section PA-4.2) with four different maps of material properties: one for undisturbed conditions; one for the E1 intrusion event; one for the E2 intrusion event; and one for the E1E2 intrusion event (see Section 6.4.13.5). The geometry and material maps used in BRAGFLO are similar; each models fluid flow calculations that represent the three-dimensional physical system in a two-dimensional plane cutting vertically through the repository and surrounding strata. Side views of the vertical cross section and two of the material maps are presented in Figures 6-14 and 6-15. In these figures, the boundaries of grid blocks discretized in

the model are shown with dashed lines; each grid block is associated with material properties representing an important feature of the disposal system. These associations between grid blocks and material properties are shown by color and number in the figures. The two figures differ in that the material property map used for E1 intrusion events (Figure 6-15) includes a material region representing the borehole (Column 26) that is not present in the undisturbed case (Figure 6-14). The borehole region vertically transects other material regions and connects the single panel (Rows 10, 11, and 12) with the Castile brine reservoir (Rows 1 and 2), marker beds, overlying units, and the surface. The E2 intrusion event material regions are similar to those of E1, except that the modeled borehole region does not extend below the repository and therefore does not contact a brine reservoir.

Figures 6-14 and 6-15 show the relationship among material regions in the model and how connections are made within the finite-difference scheme. However, by illustrating equidimensional grid blocks, the volumetric relationship between grid blocks is greatly distorted. To show the volumetric relationship among nodal blocks and between the repository and host formations, a scaled side view of the vertical cross section used in BRAGFLO is shown in Figure 6-16. An undistorted 1:1 vertical:horizontal scale side view is in the upper left corner of Figure 6-16; at this scale, important model features are not resolvable. Therefore, two other views are provided in which the vertical scale has been exaggerated to show model features. Notice that the modeling system extends 14 miles (22.4 km) from the edge of the excavated repository in each direction, north and south. The borehole is not centered; rather it is located 24.17 km from the north boundary and 22.46 km from the south boundary. Figure 6-16 colors are consistent with colors for material regions in Figures 6-14 and 6-15.

Effects of flow in the third (out-of-plane) dimension are approximated with a two-dimensional element configuration that simulates convergent or divergent flow to the north and south centered on the repository in intact rocks laterally away from the repository. In this text, the term width corresponds to the x (lateral) dimension of nodes, thickness refers to the y (vertical) dimension, and depth refers to the z (out-of-plane) dimension. The effects of the grid assumptions on fluid flow processes in the Salado are discussed in Appendix PA, Attachment MASS, Section 4.1.

Based on observations in the existing excavations, the DOE approximates the regionally variable dip in the Salado by incorporating a 1-degree dip to the south in the BRAGFLO computational mesh. This dip is not indicated in Figures 6-14, 6-15, and 6-16.

The BRAGFLO definition of hydrostratigraphic units follows formation and member divisions. Inside the Salado, however, further subdivision of hydrostratigraphy has been made based on the observed permeability differences between anhydrite-rich interbeds and halite-rich intervals.

This further subdivision has been made only at elevations near the repository horizon, because only in this region are such distinctions important. The models and assumptions representing the various regions of material properties shown in Figures 6-14 and 6-15 are discussed in Section 6.4.3 and Appendix PA, Section 4.2. The thickness of hydrostatigraphic units used in BRAGFLO are tabulated in Appendix PA, Attachment PAR, Table PAR-49.

6.4.2.2 Culebra Geometry

Although the BRAGFLO model contains a discretization of the Culebra and calculates flow there, the DOE uses a more detailed representation to estimate potential radionuclide releases to the accessible environment resulting from lateral subsurface transport through the Culebra. The conceptual model for flow and transport in this geometry is discussed in Section 6.4.6.2. The boundary and initial conditions applied to this geometry are discussed in Section 6.4.10.2. MODFLOW-2000 and SECOTP2D are used to simulate groundwater flow and radionuclide transport in the Culebra. The SECOFL2D code was used in the CCA to simulate groundwater flow and has been replaced with MODFLOW-2000. The groundwater flow and transport conceptual models have not changed; the implementation of the groundwater model has been updated. The manner in which this geometry is linked to the BRAGFLO geometry described in the preceding section is discussed in Sections 6.4.6.2, 6.4.11, and Appendix PA, Section 4.9. The grids used to model the Culebra are discussed in Section 6.4.6.2 and Appendix PA, Section 4.8 (see also Appendix PA, Attachments MASS and TFIELD).

6.4.3 The Repository

The repository, as shown in Figure 3-2, is represented by areas marked Waste Panel and rest of repository (RoR) north and south in Figures 6-14 and 6-15. These regions include a waste disposal panel, panel closures (DRF_PCS, CONC_PCS, Anhydrite AB, and DRZ_PCS), two areas that represent the other panels and access drifts in the rest of the waste disposal region (RoR north and south), the operations region (Ops), and the experimental region at the north end of the repository (Exp). The shaft (which is further subdivided into two primary regions marked Upper Shaft and Lower Shaft) intersects the repository between the operations region and the experimental region. The shaft is discussed in Section 6.4.4. For human-intrusion events, the borehole intersects the waste disposal region in the Panel. In two-dimensional fluid flow codes, a grid block's length, volume, and cross-sectional area of faces connected to other grid blocks are important model features. For each region of the repository depicted, the BRAGFLO model geometry preserves the excavated volume. Lateral dimensions have been determined to preserve volume and retain important cross-sectional areas and distances between defined regions, as discussed below. These simplifications are conservative with respect to fluid contact with waste, which is a critical factor in determining the quantity of actinides mobilized in the aqueous phase. The simplifications are conservative because (1) all pillars have been removed from the modeled panel, resulting in homogeneous waste regions through which fluid can flow directly; and (2) the panels in the rest of the repository areas do not have pillars, resulting in a large homogeneous region that is assigned an average permeability within the range of those experimentally determined (see Section 6.4.3.2 and Appendix PA, Attachment MASS Section 3.1).

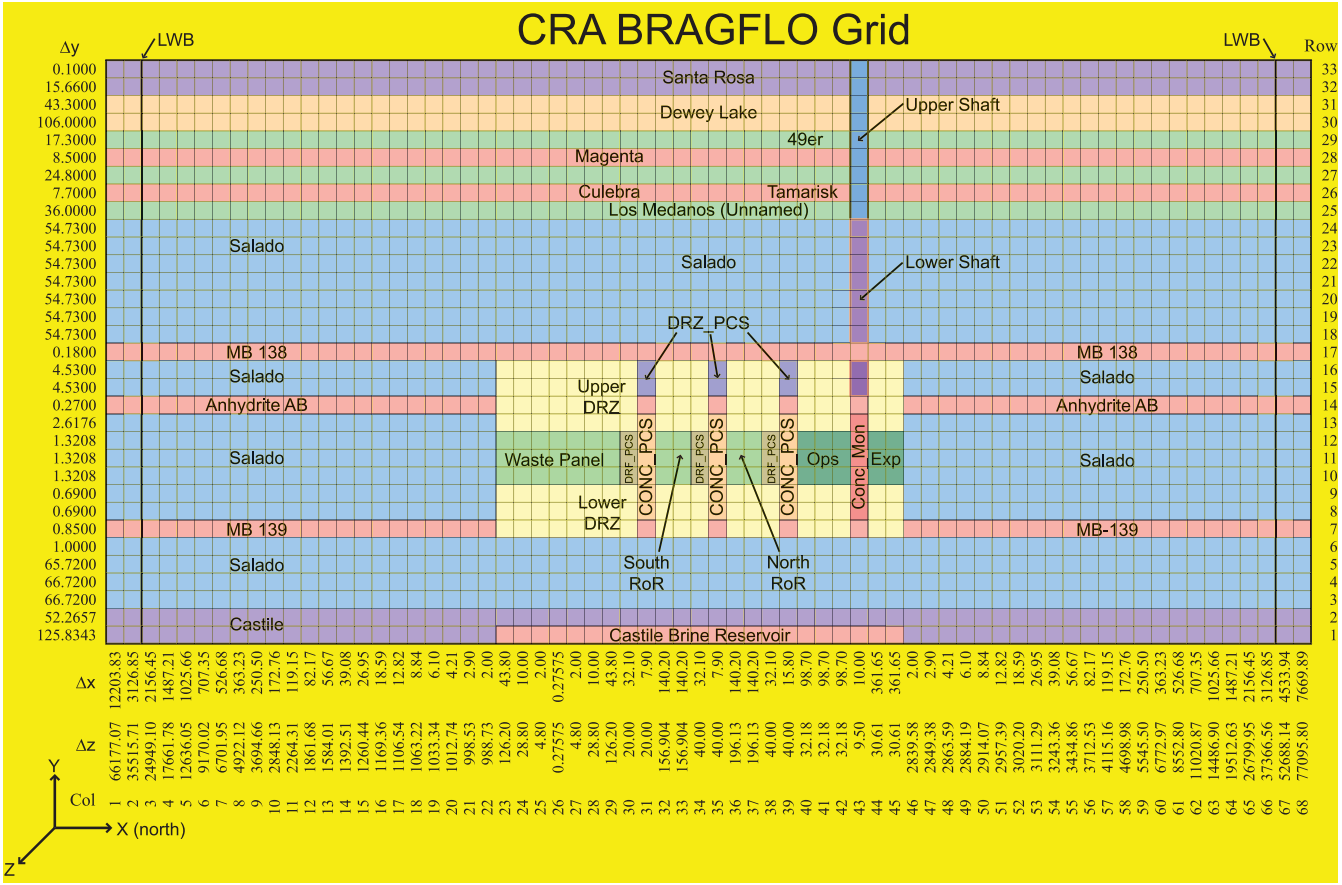

Figure 6-14. A Side View of the BRAGFLO Elements and Material Regions Used for Simulation of Undisturbed Performance

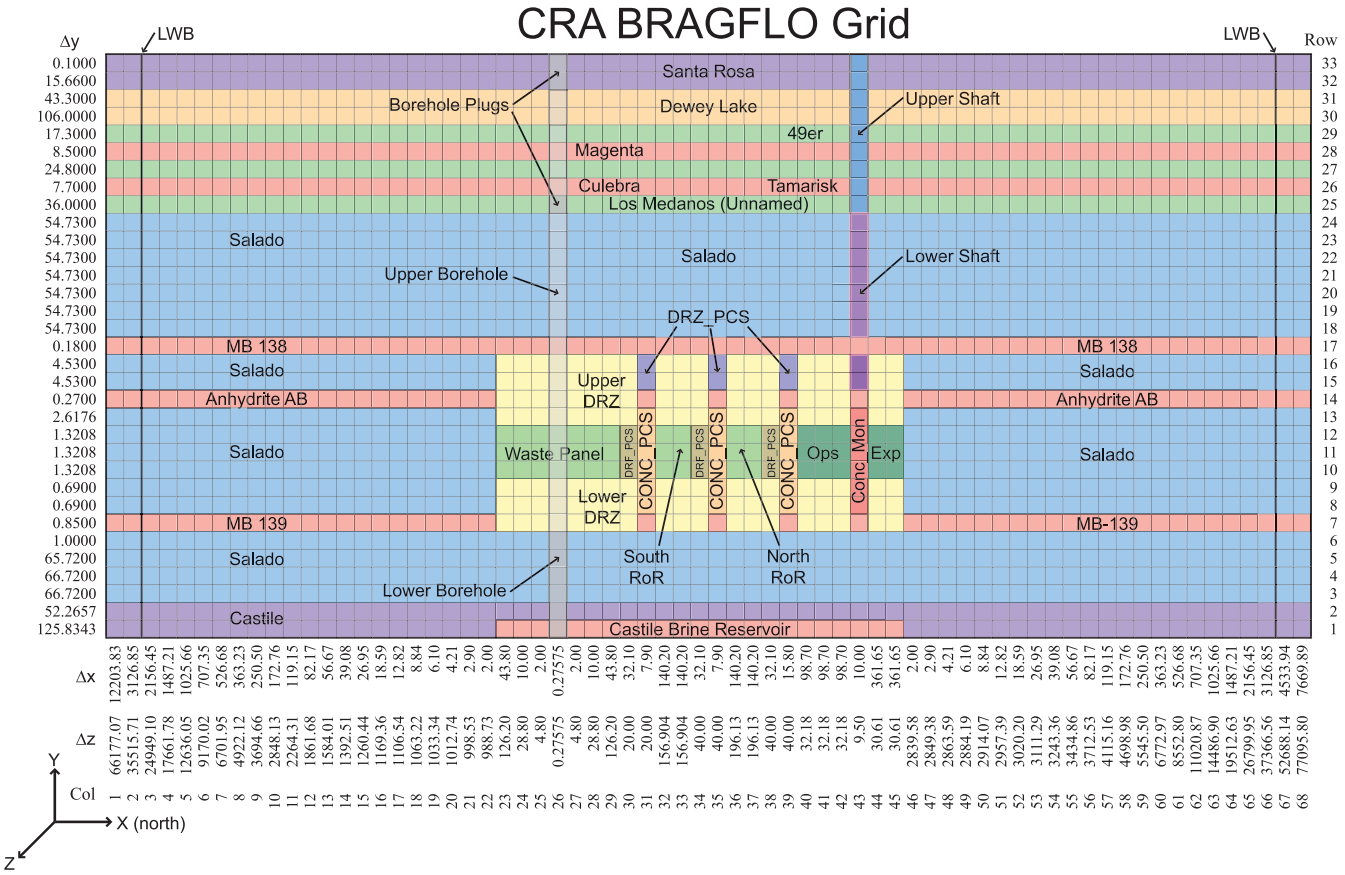

Figure 6-15. A Side View of the BRAGFLO Elements and Material Regions Used to Simulate the E1 Event

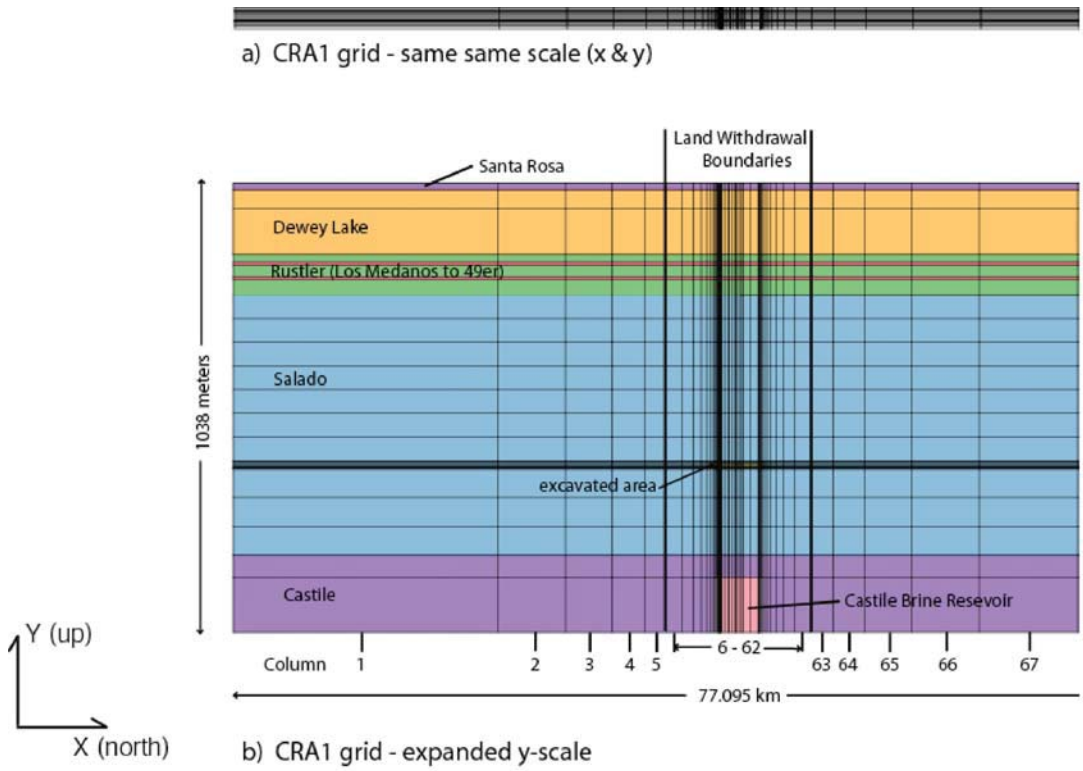

Figure 6-16. A Side View of the BRAGFLO CRA-2004 Geometry Drawn to Scale

The single panel that is represented individually (Panel) is discretized to simulate radial flow to and from the borehole that intersects it. In the CCA grid, the distance from the borehole to the shaft was 1260 m (4133.8 ft), the true distance from the shaft to the south end of the waste disposal region. In the current grid, the distance is 1097 m (3599 ft). The distance was reduced during the re-gridding process that accounted for the Option D panel closures and refinements to represent two RoRs (see Appendix PA, Attachment MASS, Section 4.2.4). In BRAGFLO, the single panel region is the southernmost portion of the repository. It occupies this position because separate modeling activities indicate that slightly larger releases may result from a panel in this position than from alternative placements (see Vaughn et al. 1995).

Panel closures were originally represented generically, since there were four options for the panel closure design. A condition of the original WIPP certification requires the DOE to use the Option D panel closure design constructed with Salado Mass Concrete (SMC). The closure representation for this analysis is modified in the models to better represent the Option D panel closures (see Appendix PA, Section 4.2.8, Attachment MASS, and Chapter 9.0). The panel closure between the panel and the rest of the repository has a cross-sectional area equal to the cross-sectional area of the drifts between panels. The length and total volume of modeled panel closures is consistent with the Option D design. The panel closure between the rest of the repository and the operations regions has a cross-sectional area equal to the cross-sectional area of the drifts between the north end of the waste disposal region and the operations regions. Because there are two closures between the waste disposal region and the shafts in the operations

regions, the modeled panel closures between the rest of the repository and the operations regions have a length and volume consistent with two panel closures.

A number of submodels have been defined within the repository region and are described in this section. The submodels that have been defined for repository processes are Creep Closure (6.4.3.1), Repository Fluid Flow (6.4.3.2), Gas Generation (6.4.3.3), Chemical Conditions in the Repository (6.4.3.4), Dissolved Actinide Source Term (6.4.3.5), and Source Term for Colloidal Actinides (6.4.3.6).

6.4.3.1 Creep Closure

Salt creep occurs naturally in the Salado halite in response to deviatoric stress. Inward creep of rock and the repository response is generally referred to as creep closure. Creep closure of excavated regions begins immediately because of excavation-induced deviatoric stress. If the rooms were empty, closure would proceed to the point where the void volume created by the excavation would be eliminated as the surrounding formation returns to a uniform stress state. In the waste disposal region, waste consolidation continues until loading in the surrounding rock is uniform, at which point salt creep and waste consolidation ceases. The amount of waste consolidation that occurs and the time it takes to consolidate are governed by properties of the waste (waste strength, modulus, etc.), properties of the surrounding rock, the dimensions and location of the room, and the quantities of fluids present.

Fluids that could affect closure are brine that may enter the repository from the Salado or an intrusion borehole, air present in the repository when it is sealed, and gas produced by reactions occurring during waste degradation. Closure and consolidation can be slowed by fluid pressure in the repository. This can be quantified according to the principle of effective stress:

$$\sigma_T = \sigma_e + p \,, \tag{6.11}$$

where σ_T is the stress caused by the weight of the overburden (an essentially constant value), p is the pressure of the repository pore fluid, and σ_e is the stress applied to the waste matrix. In this formulation, the waste is considered a skeleton structure containing pore fluids. As the pore pressure increases, an increasing amount of overburden stress is supported by pore fluid pressure, p, and less overburden stress is supported by the strength of the waste matrix. Waste consolidation will cease when the sum of the stresses felt by the waste matrix and fluid pressure reaches lithostatic pressure. If gas and brine quantities in the repository stabilize, creep closure will act to establish a constant pressure and pore volume.

In summary, creep closure of waste disposal areas will cause their volume to decrease as the Salado deforms to consolidate and encapsulate the waste, changing waste porosity and permeability. Resistance to creep closure will be caused by waste strength and fluid pressure.

Three major material-response models are required for closure analyses. The first model describes how the halite creeps as a function of time and stress. The second model describes the state of waste consolidation as a function of applied stress. A third constitutive model is used to model inelastic behavior of anhydrite marker beds (see Appendix PA, Attachment MASS, Section 13.0).

Halite deformation is predicted using a multimechanism deformation steady-state creep model with work hardening and recovery transient response. For the conditions of the WIPP, creep mechanisms are governed by the temperature and shear stress at a given location in the surroundings at any time. Although WIPP conditions are expected to be nearly isothermal at the ambient natural underground temperature, several mechanisms can be active at the same time because of the large range of stress states that occur around underground rooms and shafts. The focus of the model's mechanistic part is definition of steady-state creep strain, with transient creep strain described through a multiplier on the steady-state rate, thus accommodating both transient changes in stress loading and unloading.

The volumetric plasticity model is the mathematical model for room closure and waste consolidation. The model is discussed further and the experimental data used in this model are summarized and interpreted in Butcher and Mendenhall (1992), Butcher et al. (1991, 65-76) and Luker et al. (1991).

The volumetric plasticity model, multimechanism deformation model, and the inelastic constitutive model for anhydrite were numerically implemented in the SANTOS computer code to calculate the closure of disposal rooms for PA (Appendix PA, Attachment PORSURF).

As a boundary condition, SANTOS requires fluid pressure estimates and hence the quantity of gas present in a disposal room. These estimates are obtained using the average stoichiometry model of gas generation (Section 6.4.3.3) with different rates of gas generation that reflect different assumptions about the quantity of brine available in a waste disposal room. The different rates of gas generation used in SANTOS bound the possible conditions for gas content in the repository. With the volumetric plasticity model and the fluid pressure boundary condition, SANTOS calculates the pore volume of the disposal room through time.

In PA, SANTOS calculates the time-dependent effects on volume as a result of creep closure. These effects are linked to the fluid-flow code BRAGFLO by a porosity surface, which is a look-up table relating porosity (void volume) to (1) time after sealing and (2) gas pressure. At the beginning of a time step, BRAGFLO evaluates the pressure of a cell in the waste disposal regions; the pressure is sensitive to brine and gas flow and the previous pore volume of the cell. The code then consults the porosity surface to find the appropriate void volume of the cell for a given time and pressure. The void volume in the cell is iteratively adjusted during a time step for consistency with gas generation, fluid movement, and repository pressure. Additional details about the porosity surface method are included in Appendix PA, Attachment PORSURF. The porosity surface method of incorporating the creep closure's dynamic effect in PA has been compared to more complex techniques that are computationally impractical in a PA (Freeze et al. 1995). In these comparisons, the porosity surface method was found to reasonably represent behavior observed in more complex models.

The operations area and experimental area (Columns 40 to 45 in Figures 6-14 and 6-15) are modeled as unfilled after closure in this PA. The operations and experimental areas are expected to close in less than 200 years and do not require a porosity surface, in contrast to the region containing waste (Vaughn et al. 1995). These areas are assumed to be "pre-closed" and are assigned a constant low porosity (18 percent) over the entire regulatory time frame.

Additional modeling confirmed that new waste types (compacted waste forms) and waste containers (pipe overpacks) do not impact the adequacy of the original porosity surface modeled in the CCA PA. The porosity surface used in the CCA is used in this analysis.

6.4.3.2 Repository Fluid Flow

Fluid flow modeling within the repository is concerned with (1) fluid flow and distribution in the waste, (2) fluid flow to and from the Salado and shafts, and (3) fluid flow between the repository and intrusion boreholes. These are important in assessing gas generation rates (Section 6.4.3.3), repository pressure, and the mobility of radionuclides in the disposal system. Additional discussion of this topic is provided in Appendix PA, Section PA-4.2.

Disposal region fluid flow is affected by the geometrical association of pillars, rooms, drifts, panel closures, possible borehole locations, time-dependent properties of waste areas resulting from creep closure, flow interactions with other parts of the disposal system, and reactions that generate gas. As described in Section 6.4.3.1, creep closure changes disposal region porosity. Depending on material properties and conditions, brine may flow into the disposal region through the DRZ, or, during disturbed conditions, through a borehole. Brine contained in the Salado may flow to the waste disposal region because of pressure gradients created by the excavation. Brine flow into the repository may be reduced as repository pressure increases, and brine may be expelled from the repository if pressure in the repository exceeds brine pressure in the immediately surrounding rock or borehole. Gas may be generated as waste decomposes, causing a pressure increase. Gas may flow away from the waste area to the anhydrite marker beds by hydrofracturing processes in the DRZ and anhydrite interbeds. Gas flow into intact, halite-rich rock is not expected because of the expected high threshold pressure of halite (see Section 6.4.5.1).

Fluid flow in the disposal system is conceptualized using principles of multiphase flow, except for Culebra flow and transport modeling. In multiphase flow, a residual brine saturation (S_{br}), is defined, which is the minimum saturation at which the brine phase has a nonzero relative permeability; below this saturation, brine is immobile. In accordance with two-phase flow theory, the residual gas saturation (S_{gr}) in the disposal system corresponds to the gas saturation necessary to create an incipient gas-phase relative permeability; below this saturation, waste-generated gas is immobile. The multiphase flow techniques adopted by the DOE are described in Appendix PA, Section 4.2 and Attachment MASS, Section 3.0.

The intrinsic permeability of waste at a given time can influence repository system performance by affecting the flow rate of gas or brine through the waste. Tests reported by Luker et al. (1991, 693-702) on simulated waste have shown material permeabilities of 10^{-12} to 10^{-16} m^2 on waste compacted under a lithostatic load. PA assigns waste permeability as a constant at 2.4×10^{-13} m^2 (Table 6-10). This permeability value was adopted from the value used in the PA verification test (EPA 1998, TSD V-B-14).

Because two-phase relationships have not been measured for waste, PA determines a range of possible two-phase conditions for the repository by applying the LHS technique to parameters within the Brooks-Corey two-phase equations. These and other parameters in the disposal room and repository flow model are shown in Tables 6-10 and 6-11. Details about the two-phase

equations and parameters used in PA are included in Appendix PA, Section 4.2; Attachment MASS, Section 3.0; and Attachment PAR (Parameters 6 and 7).

Material properties in the waste are assumed to be homogeneous and are distributed in the BRAGFLO model to cells whose volumes are much larger than an individual waste container.

Two processes that may occur on scales smaller than the cell volumes in BRAGFLO are wicking (the retention of brine in a capillary fringe) and puddling (the capture of brine in isolated pockets of waste caused by waste heterogeneity). Wicking is accounted for in the gas generation model (Section 6.4.3.3). Vaughn et al. (1995) found that puddling can be neglected.

The experimental and operations regions (Columns 44 and 45 and 40 through 42, respectively, in Figures 6-14 and 6-15) are represented in PA with a porosity of 18 percent and a permeability of 10^{-11} m^2 as a conservative upper bound. For postoperational performance, the panel closures (Columns 31, 35, and 39 in Figures 6-14 and 6-15) are represented with a porosity of 5 percent and a median permeability of 1.78×10^{-19} m^2, as discussed in Appendix PA, Section 4.2, Attachment PAR, Parameter 10, and Attachment MASS, Section 19.0.

6.4.3.3 Gas Generation

Gas will be produced in the repository by a variety of chemical reactions, primarily those occurring among brine, metals, microbes, cellulosic, plastic, and rubber materials, and release of the dissolved gases produced by these reactions to the gaseous phase. The dominant processes are anoxic corrosion of steels and other Fe-based alloys in the waste containers, and the waste and microbial consumption of cellulosic, plastic, and rubber materials. Anoxic corrosion of steels and other Fe-based alloys and Al, and Al-base alloys by water in the brine will occur, producing H_2. Microbial consumption of cellulosic, plastic, and rubber materials could produce a variety of gases; however, for the current waste inventory, CO_2 and CH_4 are expected to dominate (as predicted at the time of the CCA). Radiolysis was demonstrated by laboratory experiment and model calculations to be insignificant (see Appendix PA, Attachment SCR, FEP W15 and W53).

Table 6-10. Repository[1] and Panel Closures Parameter Values

Parameter (units)	Maximum	Minimum	Median or Constant
Permeability, k (square meters) – Waste Region	–	–	2.4×10^{-13}
Permeability, k (square meters) – Operations and Experimental Regions	–	–	10^{-11}
Permeability (square meters) – Panel Closures	1×10^{-17}	2.00×10^{-21}	1.78×10^{-19}
Initial Effective Porosity (percent) – Waste Region	–	–	84.8
Effective Porosity (percent) – Operations and Experimental Regions	–	–	18.0
Effective Porosity (percent) – Panel Closures	–	–	5
Threshold Pressure, P_t (pascals) – Repository [1]	–	–	0
Threshold Pressure, P_t (pascals) – Panel Closures [2]	–	–	1.72×10^{6}
Residual Brine Saturation, S_{br} (unitless) – Repository	0.552	0	0.276
Residual Brine Saturation, S_{br} (unitless) – Operations and Experimental Regions	–	–	0
Residual Brine Saturation, S_{br} (unitless) – Panel Closures	0.60	0	0.20
Residual Gas Saturation, S_{gr} (unitless) – Repository	0.15	0	0.075
Residual Gas Saturation, S_{gr} (unitless) – Operations and Experimental Regions	–	–	0
Residual Gas Saturation, S_{gr} (unitless) – Panel Closures	0.40	0	0.20
Pore Distribution Parameter, λ (unitless) – Repository	5.78	1.44	2.89
Pore Distribution Parameter, λ (unitless) – Operations and Experimental Regions	–	–	0.7
Pore Distribution Parameter, λ (unitless) – Panel Closures	8.10	0.11	0.94
Maximum Capillary Pressure (pascals) – Repository and Panel Closures	–	–	10^{8}
Pore Compressibility (1/pascals) – Repository [3]	–	–	0
Pore Compressibility (1/pascals) – Panel Closures	–	–	6×10^{-11}

[1] Unless specifically listed, Repository refers to operations, experimental, and waste regions.

[2] Threshold pressure (P_t) determined from the relationship: $P_t = PCT_A \cdot k^{PCT_EXP}$ where PCT_A and PCT_EXP are constants and k is the permeability.

[3] Accounted for in porosity surface.

Gas generation will affect repository pressure, which is important in other submodels of the disposal system, such as those calculating creep closure (Section 6.4.3.1), interbed fracturing (Section 6.4.5.2), two-phase flow (Section 6.4.3.2), and the radionuclide releases associated with spallings during an inadvertent drilling intrusion (Section 6.4.7). Thus, gas generation must be estimated in PA.

Table 6-11. BRAGFLO Fluid Properties

Parameter (units)	Value
Reference Temperature (kelvin)[1]	300.15
Liquid Density (kilograms per cubic meter) [1,2] at	
Atmospheric Pressure	1,220.0
8 megapascals	1,223.0
15 megapascals	1,225.7
Liquid Viscosity (pascals * seconds) [2]	2.1×10^{-3}
Liquid Compressibility (1/pascals) [2]	3.1×10^{-10}
Gas Density (kilograms per cubic meter) [1,2] at:	
Atmospheric Pressure	0.0818
8 megapascals	6.17
15 megapascals	11.1
Gas Viscosity (pascals * seconds) [2]	8.93×10^{-6}

[1] These values applied to fluids in all material regions in BRAGFLO.
[2] See Appendix PA (Section 4.2) for equations of state.

PA uses the average-stoichiometry model to estimate gas generation occurring in the waste-disposal region. This model was developed for WIPP PA based on gas-generation experiments performed for the WIPP (see CCA Appendix MASS, Section MASS.8 and MASS Attachment 8-2). The average-stoichiometry model accounts for gas formed by anoxic corrosion of steels and other Fe-based alloys, and microbial consumption of cellulosic, plastic, and rubber materials. For calculating repository pressure and gas flow, the density and viscosity of the generated gas are assumed to be those of H_2. In the average-stoichiometry model, gas is assumed to be generated at a rate dependent on the availability of brine in the computational cell. Gas can be generated by anoxic corrosion in all realizations, and is assumed to be generated by microbial activity in half of the realizations. The average-stoichiometry model is based on experimental data on the rates of gas generation from anoxic corrosion of steels and microbial consumption of papers under inundated and humid conditions. These data were used to develop ranges of possible gas-generation rates, as shown in Table 6-12. In BRAGFLO, a gas-generation rate is determined from the rates listed in Table 6-12 by a linear-interpolation method that combines humid and inundated rates based on the effective liquid saturation (Appendix PA, Section PA-4.2.5).

The effective liquid saturation in a computational cell of BRAGFLO for the purpose of gas generation is the computed liquid saturation in that cell plus an adjustment for uncertainty in the capillary rise (wicking) characteristics of the waste. Refer to Attachment PA, Sections PA-4.2.5 and PA-4.2.6, Attachment PAR (Parameter 8) for details on the treatment of wicking in the gas-generation model.

Anoxic corrosion is represented by a generic equation given in Appendix PA (Section PA-4.2.4). This equation accounts only for corrosion of steels and other Fe-based alloys in the repository by the reaction expected to dominate.

Table 6-12. Average-Stoichiometry Gas Generation Model Parameter Values

Parameter (units)	Maximum	Minimum	Median or Constant
Inundated Corrosion Rate for Steel without CO_2 Present (meters per second)	3.17×10^{-14}	0	1.59
Humid Corrosion Rate for Steel	–	–	0
Probability of Microbial Consumption of Plastic and Rubber Materials in the Waste in the Event of Significant Microbial Gas Generation (see Figure PAR-1) where 0 represents corrosion and no significant microbial gas generation. 1 represents cellulosic degradation only, and 2 represents cellulosic, plastic, and rubber consumption	2	0	2
Rate for Microbial Activity Under Humid Conditions (mole per kilogram ∗ second)	1.27×10^{-9}	0	6.34×10^{-10}
Rate for Microbial Activity under Brine-Inundated Conditions (mole per kilogram ∗ second)	9.51×10^{-9}	3.17×10^{-10}	4.92×10^{-9}
Factor β for Microbial Reaction Rates (unitless)	1.0	0	0.5
Anoxic Corrosion Stoichiometric Factor X (unitless)	–	–	1.0
Average Density of Cellulosic Materials in CH-TRU Waste (kilograms per cubic meter)	–	–	58
Average Density of Cellulosic Materials in RH-TRU Waste (kilograms per cubic meter)	–	–	4.5
Average Density of Steels and Other Fe-Based Alloys in CH-TRU Waste (kilograms per cubic meter)	–	–	110.0
Average Density of Steels and Other Fe-Based Alloys in RH-TRU Waste (kilograms per cubic meter)	–	–	110.0
Average Density of Plastic Materials in CH-TRU Waste (kilograms per cubic meter)	–	–	42.0
Average Density of Plastic Materials in RH-TRU Waste (kilograms per cubic meter)	–	–	4.9
Average Density of Rubber Materials in CH-TRU Waste (kilograms per cubic meter)	–	–	14.0
Average Density of Rubber Materials in RH-TRU Waste (kilograms per cubic meter)	–	–	3.1
Bulk Density of Steel Containers, CH-TRU Waste (kilograms per cubic meter)	–	–	170.0
Bulk Density of Steel Containers, RH-TRU Waste (kilograms per cubic meter)	–	–	480.0
Bulk Density of Plastic Liners, CH-TRU Waste (kilograms per cubic meter)	–	–	16.0
Bulk Density of Plastic Liners, RH-TRU Waste (kilograms per cubic meter)	–	–	1.4
Total Volume of CH-TRU Waste (cubic meters)	–	–	1.69×10^{5}
Total Volume of RH-TRU Waste (cubic meters)	–	–	7.08×10^{3}
Wicking Saturation (unitless)	1.0	0	0.5

Because the total quantity of Al and Al-base alloys is small compared to the quantity of steels and other Fe-based alloys, corrosion of Al is omitted for simplicity. The steels and other Fe-based alloys are depleted separately in each computational cell (that is, a cell-by-cell basis), and gas generation can continue in cells, depending on parameter values, until all the steels and other Fe-based alloys are consumed. Brine in cells is consumed as gas generation proceeds. If a cell has a brine saturation equal to zero, it cannot produce gas by anoxic corrosion.

It is assumed there is no passivation of steels or other Fe-based alloys by CO_2 and H_2S produced by microbial activity because microbial gas generation is too slow and also because CO_2 will be removed from the gaseous phase by reacting with MgO. Details of the equations and parameter values are given in Appendix PA, Attachment PAR (Parameters 1 through 5) and Appendix BARRIERS.

Microbial activity occurs in only half the realizations because of uncertainties associated with this process (Appendix PA, Attachment MASS, Section 8.0). Like anoxic corrosion, microbial gas production is represented by a generic equation, given with other details in Appendix PA (Section 4.2.5). The inventory of cellulosic, plastic, and rubber materials is depleted on a cell-by-cell basis. Depending on parameter values, gas generation by microbial activity can continue until all cellulosic materials in the cell are degraded. Reaction with the MgO engineered barrier consumes CO_2 (see Section 6.4.3.4 and Appendix PA, Attachment SOTERM). Thus, the net quantity of gas developed by microbial consumption of cellulosic, plastic, and rubber materials is correlated with constituents of the waste disposal region. It is assumed that microbial activity neither produces nor consumes water, but its rate is dependent on the amount of liquid present in a computational cell.

Microbes may also consume plastic and rubber materials in the repository. The DOE assumes that in half of the simulations where microbial consumption of cellulosic materials occurs, microbes also consume plastic and rubber materials in the waste-disposal region. As with cellulosic materials, these plastic and rubber materials are depleted on a cell-by-cell basis. Parameter values for the average-stoichiometry model are summarized in Table 6-12 and detailed in Appendix PA, Attachment PAR (Parameters 1 through 5).

6.4.3.4 Chemical Conditions in the Repository

The chemical conditions in the repository determine actinide solubilities, parameters demonstrated in past analyses as important to disposal-system performance. In scenarios with the potential to cause releases to the accessible environment, the DOE has determined that chemical conditions can be modeled in PA as homogeneous throughout the waste-disposal area and constant (with the exception of brine content) throughout the 10,000-year regulatory period. This use of constant, homogeneous conditions is based on the assumption of equilibria (for most processes) among brine (the composition of which is determined by the scenario being considered), minerals that are abundant in the Salado, the MgO engineered barrier, and the actinides in the waste. Some exceptions to this assumption are present in performance-assessment models and are discussed where appropriate. In addition to the following discussion, information supporting this position is presented in Appendix PA, Attachments SOTERM and BARRIERS.

Brine and waste within the WIPP repository are modeled as a homogeneous mixture of dissolved and solid-state species. Thermodynamic equilibrium is assumed for dissolved actinide concentrations, but oxidation-reduction reactions between the actinides and other waste components are not assumed to reach equilibrium. Although materials in the waste will actually dissolve at different rates, the assumption of instantaneous solubility equilibria and, along with assumed disequilibrium oxidation-reduction conditions, yields the largest reasonable concentration of dissolved and colloidal actinides in the repository. No chemical microenvironments that influence the overall chemical environment are expected to persist, nor is supersaturation expected during the 10,000-year regulatory period. The average temperature of the WIPP is expected to increase by less than 10°C from its ambient value of 28°C as a result of radioactive decay and exothermic reactions, such as MgO hydration and carbonization, and the effect of this small increase is assumed negligible (see Appendix PA, Attachment SCR, FEPs W72 and W73).

Brine composition in the repository can vary depending on the sequence of future human events. Calculating brine mixing from different sources is not feasible in PA. The DOE has made the reasonable simplification that in the undisturbed performance and E2 scenarios, which do not include penetration of a Castile brine reservoir, all brine in the repository will have the composition of Salado brine (see Appendix PA, Attachment SOTERM). In these scenarios, there is no process that could introduce Castile brine into the repository. For the E1 and E1E2 scenarios, which include penetration of a brine reservoir in the Castile, brine in the repository is assumed to have the composition of Castile brine at all times. Even though some Salado brine may enter the repository in these scenarios, it is reasonable to assume that Castile brine dominates because the quantity of brine that can flow from a reservoir through a borehole and into the repository is substantial compared to the quantity of brine entering from the Salado.

The chemical environment in the repository after closure is expected to be strongly reducing (that is, lowered oxidation states are expected for elements that can occur in more than one oxidation state). Any gaseous or dissolved oxygen present in the repository will be consumed quickly either by aerobic microbial activity or by oxic corrosion after repository closure. Moreover, the repository will contain large amounts of metallic Fe, and anoxic corrosion has been shown to produce considerable quantities of H_2, Fe(II) oxides and hydroxides, and dissolved Fe(II) species under expected repository conditions (see Appendix MASS, MASS Attachment 8-3 of the CCA). Despite the overall reducing conditions, however, a condition of oxidation-reduction disequilibrium is assumed in that oxidation-reduction reactions between dissolved actinides in possible oxidation states are not assumed to occur.

MgO in polypropylene “supersacks” is emplaced on top of the three-layer waste stacks to create conditions that reduce actinide solubilities in the repository (see Section 3.3.3; Appendix BARRIERS; and Appendix PA, Attachment SOTERM, Section SOTERM-2.0). If brine flows into the repository, MgO will react with water in brine and in the gaseous phase to produce brucite ($Mg[OH]_2$). MgO will react with essentially all of the CO_2 that could be produced by complete microbial consumption of the cellulosic, plastic, and rubber materials in the waste, and will initially create hydromagnesite with the composition $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ and will eventually form magnesite with the composition $MgCO_3$ (Appendix BARRIERS; Appendix PA, Attachment SOTERM, Section 2). The most important MgO hydration and carbonation reactions that will occur in the WIPP are:

$$MgO + H_2O(aq\ or\ g) \rightarrow Mg(OH)_2 \quad (6.12)$$

$$5Mg(OH)_2 + 4CO_2(aq\ or\ g) \rightarrow Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O. \quad (6.13)$$

$$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O + CO_2(aq\ and/or\ g) \rightarrow 5MgCO_3 + 5H_2O \quad (6.14)$$

In these equations, "aq or g" indicates that the H_2O or CO_2 that reacts with MgO or brucite could be present in the aqueous phase (brine) or the gaseous phase. In the CCA, it was assumed that magnesite would be the dominant Mg carbonate in the repository during the 10,000-year regulatory period, and that the brucite-magnesite carbonation reaction (Reaction 6.14) will buffer f_{CO_2} in WIPP whether or not significant microbial CO_2 production occurs. For the PAVT, the EPA specified that the brucite-hydromagnesite carbonation reaction (6.13) will buffer f_{CO_2} in the WIPP whether or not significant microbial CO_2 production occurs (BARIERS-2.4.1). For the CRA-2004 PA, the brucite-hydromagnesite carbonation reaction (6.13) will buffer (control) the fugacity (essentially the partial pressure) of CO_2 at a relatively low value of about $10^{-5.50}$ atm if significant microbial activity occurs. If microbial activity occurs, the predicted value of f_{CO_2} will be identical for both Salado and Castile brine. The brucite-hydromagnesite buffer will control f_{CO_2} effectively because: (1) the DOE is emplacing more than enough MgO to ensure the consumption of essentially all CO_2 that could be produced in the repository, and (2) the reactivity of the MgO being emplaced in the WIPP is such that its carbonation rate exceeds the CO_2 production rate. The brucite dissolution reaction

$$Mg(OH)_2 \rightleftharpoons Mg^{2+} + 2OH^- \quad (6.15)$$

will buffer the pH at about 9 in both Salado and Castile brine if microbial activity occurs (see Appendix PA, Attachment SOTERM, Section 2). For the CRA-2004 PA vectors with microbial activity, the composition of Salado or Castile brine at equilibrium with major Salado minerals such as halite and anhydrite, the f_{CO_2} established by Reaction 13, and the pH established by Reaction 6.15, have been used to calculate actinide solubilities.

The CRA-2004 PA does not assume the same reaction will control f_{CO_2} for vectors without significant microbial CO_2 production. In the absence of microbial activity, the carbonation reaction

$$Mg(OH)_2 + Ca^{2+} + CO_2(aq\ and/or\ g) \rightleftharpoons CaCO_3 + Mg^{2+} + H_2O(aq\ or\ g) \quad (6.16)$$

will buffer f_{CO_2} at $10^{-5.48}$ atm in Salado brine and at $10^{-6.15}$ atm in Castile brine (see BARRIERS-2.4.2.3). Reaction 6.15 will buffer the pH at about 9 in both Salado and Castile brine (see Appendix PA, Attachment SOTERM, Section 2). For the 2004 PA vectors without microbial activity, the composition of Salado or Castile brine at equilibrium with major Salado minerals, the f_{CO_2} established by Reaction 6.16, and the pH established by Reaction 6.15, have been used to calculate actinide solubilities.

There is a relatively small amount of portlandite $Ca(OH)_2$ associated with the Portland cement used to dewater process sludges. The quantity of portlandite is too small, however, to overcome the buffer capacity of the reactions described above.

The DOE will emplace significantly more MgO than is needed to maintain the chemical conditions discussed above. The excess MgO emplaced relative to the amount that is needed has been termed a safety factor. The MgO safety factor is defined as:

$$\text{MgO safety factor} = (\text{MgO}_{\text{emplaced}}) \div (\text{MgO}_{\text{required}}), \tag{6.17}$$

where $\text{MgO}_{\text{emplaced}}$ is the quantity of MgO to be emplaced in the repository and $\text{MgO}_{\text{required}}$ is the quantity of MgO required to consume the maximum amount of CO_2 produced by microbial consumption of all of the emplaced cellulosic, plastic, and rubber materials. This analysis uses: (1) current in the emplaced TRU waste and emplaced materials, and (2) the quantity of MgO emplaced. The EPA has specified a 1.67 safety factor be maintinaed in the repository. Therefore, there will be more than enough MgO to ensure that the conditions described above will be established in the repository (see Appendix BARRIERS, Sections BARRIERS-2.0 and BARRIERS-2.6).

NOTE TO TECH EDITOR: A new equation was added and all subsequent equation numbers and reference to them will need to be revised.

The waste contains organic ligands that could dissolved complexes with actinides and thus increase their solubilities. There are four organic ligands of potential concern in the waste: acetate, citrate, ethylenediaminetetraacetic acid (EDTA), and oxalate. These organic ligands could increase the solubilities of the actinides in the waste because: (1) they are soluble in aqueous solutions such as WIPP brines, and (2) they are known to form complexes with the actinides (see Appendix PA, Attachment SOTERM, Section SOTERM-5.0) Therefore, the effects of acetate, citrate, EDTA, and oxalate have been included in the Fracture-Matrix Transport (FMT) calculations of actinide solubilities for the CRA-2004 PA. These organic ligands will also form complexes with dissolved, cationic species of several metals present in the repository. These metals will thus compete with the actinides for the binding sites on these organic ligands. The effects of two of these metals, Mg^{2+} and Ca^{2+}, have been included in the solubility calculations for the CRA-2004 PA. Including complexation of actinides and of Mg^{2+} and Ca^{2+} by acetate, citrate, EDTA, and oxalate in the solubility calculations for the CRA-2004 PA has confirmed the conclusion in the CCA that organics will not increase the solubilities of the actinides significantly (see CCA Appendix SOTERM, Section SOTERM.5.0).

6.4.3.5 Dissolved Actinide Source Term

The actinide source term used in the CRA-2004 PA calculations represents the aqueous concentrations of thorium (Th), uranium (U), Pu, and americium (Am) in the repository. The source term is the sum of the dissolved species (solubility) and the mobile suspended (colloidal) species of each of these actinides (see Section 6.4.3.6). The source term represents the mobile concentrations of Th, U, Pu, and Am that could be released from the repository in brine.

The actinide source term is limited to those radionuclides that could significantly affect the long-term performance of the WIPP. These radionuclides are all isotopes of Th, U, Pu, and Am. Their potential effects on the long-term performance of the repository can be ordered as Pu ≈ Am >> U > Th (Helton 1998). Other actinides, especially neptunium (Np), were included in the

laboratory and modeling studies used to develop the actinide source term because it was not known which actinides could significantly affect the long-term performance of the repository.

Although commonly referred to as "actinide," these radioelements are almost always present in the waste as solid actinide oxides or solid actinide salts and, if they dissolve in WIPP brines, will form complex species (usually referred to as "complexes") with nonradioactive, inorganic, dissolved species such as carbonate ion (CO_3^{2-}), chloride ion (Cl^-) or hydroxide ion (OH^-), or with nonradioactive, organic, dissolved species such as acetate, citrate, EDTA, or oxalate (see Section 6.4.3.4).

The postclosure chemical environment in the repository will be strongly reducing (see Section 6.4.3.4; Appendix PA, Attachment SOTERM, Section SOTERM-2.0). Previous studies of actinide chemistry imply that, under these conditions, Th will exist as Th(IV) (Appendix PA, Attachment SOTERM, Section 4.1); U will exist as U(IV) or U(VI) (Section 4.2); Np will speciate as Np(IV) or Np(V) (Section 4.3); Pu will exist as Pu(III) and Pu(IV) (Section 4.4); and Am will speciate as Am(III) (Section 4.5). Several actinide oxidation states will be unstable under the strongly reducing conditions expected in the repository. These include Np(VI), Pu(V), Pu(VI), and Am(V). Pu(V) and Pu(VI) could occur in isolated microenvironments in the repository, however, the DOE concludes that would not persist in significant quantities because diffusive transport through any brine present and (especially in the event of human intrusion) advective transport of brine would expose any oxidized Pu to reducing materials like metallic Fe from waste containers and Fe-based materials in the waste, Fe(II)-bearing solids produced by anoxic corrosion of metallic Fe, dissolved Fe(II) species, and metallic Al in the waste (Appendix SOTERM, Sections SOTERM-2 and SOTERM-4; Marcinowski 2001). Microbial activity, if it occurs, would also help create reducing conditions.

The DOE incorporated the uncertainties regarding the oxidation states of U and Pu in PA by assigning a probability of 0.5 that they will exist in the U(IV) and Pu(III) oxidation states, and a probability of 0.5 that these elements will speciate in the U(VI) and the Pu(IV) oxidation states (see also Appendix PA, Section SOTERM-5.2). The oxidation state for both elements is selected by a single variable in the LHS. Therefore, in approximately half of the PA realizations, the oxidation states of the transported actinides are Th(IV), U(IV), Pu(III), and Am(III); and, in the other half of the realizations, the oxidation states are Th(IV), U(VI), Pu(IV), and Am(III).

Laboratory studies with neodymium(III) (Nd(III)), Am(III), and Cm(III) were used to develop a solubility model for the +III actinides, and this model was used to predict the solubilities of Pu(III) and Am(III). Similarly, Th(IV) was used to develop a solubility model for the +IV actinides, which was used for Th(IV), U(IV), Np(IV), and Pu(IV). Literature data for Np(V) were used to develop a solubility model for the +V actinides, which was used only for Np(V). The +V model was not used for other actinides because Pu(V) would not persist in significant quantities in the WIPP. Using the oxidation-state analogy to extend the +III and +IV solubility models to Pu(III) and to U(IV), Np(IV), and Pu(IV), respectively, is valid for these reasons: First, the chemical behavior, especially the speciation and solubilities, of Nd(III), Pu(III), Am(III), and Cm(III) is very similar. Second, the chemical behavior of Th(IV), U(IV), Np(IV), and Pu(IV) is similar, although the solubility of Th(IV) is higher those of U(IV), Np(IV), and especially Pu(IV). Third, Nd, Am, and Cm speciate only in the +III oxidation state, and Th speciates only in the +IV oxidation state under typical laboratory conditions, thus making

experiments with these actinides much easier to carry out and interpret than those with actinides that occur in more than one oxidation state, such as Pu.

The FMT calculations of actinide solubilities for the CRA-2004 PA featured the establishment of equilibrium of Salado brine (GWB) or Castile brine (ERDA-6) with halite and anhydrite, minerals present in large quantities in the Salado at the repository horizon. (These brines are described in Appendix PA, Attachment SOTERM, Section SOTERM-2.2.1). The effects of the MgO included the equilibrium of Salado brine or Castile brine with brucite and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) in the performance-assessment vectors with microbial activity, and with brucite and calcite in the vectors without microbial activity (see Appendix BARRIERS, Section 2; and Appendix PA, Attachment SOTERM). For the 1997 PAVT, it was assumed that Salado brine (Brine A) or Castile brine (ERDA-6) would be in equilibrium with brucite and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) in all of the performance-assessment vectors (both with and without microbial activity) (EPA 1998a, 1998b). For the CCA, equilibria among Salado brine (Brine A) and Castile brine (ERDA-6) and brucite and magnesite were assumed (CCA Appendix BACK).

The FMT calculations for the CRA-2004 PA also included the effects of acetate, citrate, EDTA, and oxalate on the speciation and solubilities of the +III, +IV, and +V actinides (see Appendix PA, Attachment SOTERM). The FMT calculations for the CCA PA and the 1997 PAVT did not include organic ligands.

Table 6-13 provides the solubilities calculated for the +III, +IV, and +V actinides and estimated for the +VI oxidation state for the CRA-2004 PA, and compares them to the solubilities calculated or estimated for the CCA PA and the 1997 PAVT. An uncertainty range of +1.4 orders of magnitude and -2.0 orders of magnitude was applied to the FMT predictions for the CRA-2004 PA (see Appendix PA, Attachment SOTERM, Section SOTERM-3.6). This is the same uncertainty range used for the CCA PA and the 1997 PAVT. LHS was used to sample solubilities from these ranges.

A thermodynamic speciation and solubility model was not developed for U(VI); instead, literature data estimated the solubilities of U(VI) in the repository (Appendix PA, Attachment SOTERM, Section SOTERM-3.0; based on Hobart and Moore [1996]). These estimates have not been used for other actinides in the repository because Np and Pu will not persist in significant quantities in the +VI oxidation state.

The actinide inventory is depleted on a cell-by-cell basis by the computer code NUTS (NUclide Transport Systems) for the undisturbed, E1, and E2 scenarios. The treatment of the E1E2 scenario is described in Section 6.4.13.5. In a computational cell, the processes affecting dissolved actinide concentrations are dissolution of solid actinide compounds, advection of dissolved actinides by brine flow from neighboring cells, and interaction with colloidal particles (see Section 6.4.3.6). NUTS dissolves each actinide until the maximum concentrationdetermined by the actinide-source-term algorithms is obtained or an inventory limit is reached. In the

Table 6-13. Actinide Solubilities (M) Calculated (+III, +IV, and +V) or Estimated (+VI) for the CRA-2004 PA, the 1997 PAVT, and the CCA

Actinide Oxidation State and Brine	CRA-2004 Solubilities, Microbial Vectors[1]	CRA-2004 Solubilities, Nonmicrobial Vectors[1]	1997 PAVT Solubilities[2]	CCA Solubilities[3]
+III, Salado brine	3.07×10^{-7}	3.07×10^{-7}	1.2×10^{-7}	5.82×10^{-7}
+III, Castile brine	1.69×10^{-7}	1.77×10^{-7}	1.3×10^{-8}	1.3×10^{-8}
+IV, Salado brine	1.19×10^{-8}	1.24×10^{-8}	1.3×10^{-8}	4.4×10^{-6}
+IV, Castile brine	2.47×10^{-8}	5.84×10^{-9}	4.1×10^{-8}	6.0×10^{-9}
+V, Salado brine	1.02×10^{-6}	9.72×10^{-7}	2.4×10^{-7}	2.3×10^{-6}
+V, Castile brine	5.08×10^{-6}	2.13×10^{-5}	4.8×10^{-7}	2.2×10^{-6}
+VI, Salado brine[4]	8.7×10^{-6}	8.7×10^{-6}	8.7×10^{-6}	8.7×10^{-6}
+VI, Castile brine[4]	8.8×10^{-6}	8.8×10^{-6}	8.8×10^{-6}	8.8×10^{-6}

[1] Brush and Xiong (2003a) and Downes (2003a,b).

[2] Trovato (1997, Attachment 2), U.S. EPA (1998a, Table 5), U.S. EPA (1998b, Subsection 4.10.4, Tables 4.10-1, 4.10-3 and 4.10-4; and Subsection 12.4, Table 12.4-1), and U.S. EPA (1998c, Subsections 5.26–5.32 and Section 6.0, Table 6.4).

[3] CCA Appendix SOTERM, Table SOTERM-2; based on Novak et al. (1996, Table 1, columns entitled "@Mg"), except that Novak et al. (1996) used molal instead of molar units.

[4] Hobart and Moore (1996).

repository, the transfer of actinides between solid phases and solution is tracked to preserve mass balance of the actinide inventory. Outside the repository, the model does notprecipitate actinides into the solid phase, thereby giving a conservative measure of mobile actinide concentrations (see Appendix PA, Attachment SCR, FEP W59).

See Appendix PA, Attachment SOTERM, Section SOTERM-7.0, for a detailed description of the implementation of the actinide source term in PA.

6.4.3.6 Source Term for Colloidal Actinides

Colloidal actinides are discussed in greater detail in Appendix PA, Attachment SOTERM Section 6. Colloidal particles form in the repository through a variety of processes, including waste degradation, microbial activity, rock decomposition, and chemical condensation. These particles may also be carried into the repository by liquids moving from the Salado or through boreholes. Because of the presence of soils, nutrients, and cellulosic substrates for microbial action in WIPP waste (see Appendix TRU WASTE), humic substances and microbes will be present in disposal room brines, or may form in situ. Actinide-intrinsic colloids may form in the disposal rooms from condensation of dissolved actinides. Mineral fragments, as well as humic substances and microbes, may provide surfaces on which dissolved actinides could sorb.

Four types of colloidal particles are believed to cover the range of possible behavior of all colloid types (see Appendix PA, Attachment SOTERM). The four particle types considered in PA are microbes, humic and fulvic acids (humic substances), actinide-intrinsic (intrinsic), and mineral

fragments. The concentration of actinides carried by each colloidal particle type depends on many of the same chemical conditions that govern the concentration of dissolved actinides.

Actinide concentrations associated with humic substances and microbes are linked to dissolved actinide concentrations through proportionality constants based on experimental results. For humic substances, actinide complexation constants from WIPP-specific experiments or published literature are coupled with experimentally determined site-binding densities and solubilities of different types of humic substances in WIPP brines. For microbes, actinide uptake was experimentally determined through experiments with WIPP-relevant bacteria cultures. Actinide concentrations associated with mineral fragment-type colloidal particles are based on results from experiments designed to determine mobile concentrations in brines, coupled with site-binding densities of mineral substrates. For the plutonium(IV) polymer, actinide concentrations are determined through solubility experiments conducted from over- and undersaturated ranges of pmH values. Intrinsic colloids of other actinides were determined to be negligible and are eliminated from PA calculations. For more discussion on this topic, refer to Appendix PA, Attachment SOTERM.

Actinides associated with microbes and humics are related to the concentration of dissolved actinides in the repository through proportionality constants determined from interpretation of WIPP-relevant experiments and the literature (Appendix PA, Attachment SOTERM). The proportionality-constant relationship is not based on thermodynamic equilibrium but is simply an empirical relationship. The concentration of actinides associated with the plutonium(IV) polymer is a constant value determined from experimental results at the pmH conditions dictated by the presence of the MgO engineered barrier. Likewise, the concentration of actinides associated with mineral colloids is also a constant value, not linked to the concentration of dissolved actinides. Actinides associated with humics and microbes represent most of the colloidal actinide source term. Consequently, the colloidal actinide source term is closely related to the dissolved actinide source term. As discussed in Section 6.4.6.2, however, the source terms are considered separately for transport in the Culebra.

For PA, the concentration of each actinide element on each colloidal particle type during a realization is a fixed value. The concentration parameters are summarized in Table 6-14. Actual values of actinide concentrations on colloidal particles are constrained by inventory limits.

The concentrations of colloidal actinides indicated in this section are assumed to be actinides mobilized on colloidal particles. The indicated concentrations will be entrained in moving brine. For conservatism, it is assumed that no actinides sorb onto colloidal particles that are not mobile in the repository. Thus, all actinides in the repository will be present in the solid phase, dissolved in the aqueous phase, or colloidal actinides suspended in the aqueous phase.

When actinide inventory in a model cell is sufficient, the concentration of colloidal actinides will be at the values indicated in Table 6-14. The total concentration of an actinide in solution and suspension is limited by the amount of solids available from the inventory. This condition is called “inventory-limited.”

Colloid concentrations are calculated by the source-term procedure described in Appendix PA, Section SOTERM-4.3.2. Processes affecting the transport of colloids in the Culebra are addressed in Section 6.4.6.2.2.

6.4.4 Shafts and Shaft Seals

The four shafts connecting the repository to the surface are represented in PA with a single shaft, represented by two primary regions above the repository, and a concrete monolith (Figures 6-14 and 6-15). This single shaft has a cross section and volume equal to the total cross section and volume of the four real shafts it represents and is separated from the waste disposal regions by the true north-south distance from the waste to the nearest shaft (the Waste Shaft). Upon closure of the repository, the shafts will be sealed as described in Section 3.3.1. The seal system was originally represented in the CCA PA by 11 discrete modeled regions in the shaft. The representation was simplified by modeling the behavior of these 11 regions with two primary regions (Upper Shaft and Lower Shaft in Figures 6-14 and 6-15) that have properties simulating the behavior of the original 11 regions (see Appendix PA, Section PA-4.2.7). An analysis of the CCA results concluded that no significant flow of gas or brine would occur within the shaft seal system over the 10,000-year regulatory period. The new shaft model underwent peer review as required by 40 CFR § 194.27 and was incorporated in BRAGFLO (see Appendix PA, Section PA-4.2.7; Section 9.3.1.3.4; and Appendix PEER). The current

Table 6-14. Colloid Concentration Factors

	Concen-tration on Mineral Fragments [1]	Concen-tration as Intrinsic Colloid [1]	Proportion Sorbed on Microbes[-2 5]	Maximum Sorbed on Microbes [3]	Proportion Sorbed on Humics [2]		Maximum Sorbed on Humics [1]
					Salado	Castile	
Th(IV)	2.6×10^{-8}	0.0	3.1	0.0019	6.3	6.3	1.1×10^{-5}
U(IV)	2.6×10^{-8}	0.0	0.0021	0.0021	6.3	6.3	1.1×10^{-5}
U(VI)	2.6×10^{-8}	0.0	0.0021	0.0023	0.12	0.51	1.1×10^{-5}
Np(IV)	2.6×10^{-8}	0.0	12.0	0.0027	6.3	6.3	1.1×10^{-5}
Np(V)	2.6×10^{-8}	0.0	12.0	0.0027	9.1×10^{-4}	7.4×10^{-3}	1.1×10^{-5}
Pu(III)	2.6×10^{-8}	0.0	0.3	6.8×10^{-5}	0.19	1.37d	1.1×10^{-5}
Pu(IV)	2.6×10^{-8}	1.0×10^{-9}	0.3	6.8×10^{-5}	6.3	6.3	1.1×10^{-5}
Am(III)	2.6×10^{-8}	0.0	3.6	NA	0.19	1.37d	1.1×10^{-5}

[1] In units of moles colloidal actinide per liter
[2] In units of moles colloidal actinide per mole dissolved actinide
[3] In units of moles total mobile actinide per liter
[4] A cumulative distribution from 0.065 to 1.60 with a mean value of 1.1 was used.
[5] Microbial colloids are not included in futures without microbial gas generation.

NOTE: The colloidal source term is added to the dissolved source term to arrive at a total source term. Mineral fragments were provided with distributions, but the maximum was used as described in Appendix PA, Attachment SOTERM. Humic proportionality constants for III, IV, and V were provided with distributions, but only the Castile Am(III) and Pu(III) were sampled.

model divides the shaft into an upper region with all elements above the Salado and a lower region with all Salado elements. These regions are assigned material property distributions that

represent the combined properties of all the individual materials in series. Seal material parameter values used in the PA are provided in Table 6-15.

Conceptually, the shafts are assumed to be surrounded by a DRZ in the Salado. Within the bedded halite, the DRZ begins to form immediately after excavation and develops progressively from unloading as the formation creeps toward the excavated area. From a sealing perspective, the most important characteristic of the DRZ is the higher permeability that results from dilatant deformation and increased pore volume.

The properties of the DRZ are known to vary with the type of adjacent material, time, and depth. When the shaft seals are emplaced, back pressures will progressively develop as the surrounding salt creeps inward. The back pressure applied by the seal material will progressively reduce the magnitude of the stress differential, which is the source for the DRZ microfracturing mechanism. The back pressure also results in a higher mean stress, which induces DRZ healing. The shaft DRZ permeability will, over time, approach that of the intact halite. Also, since the creep rate of the salt surrounding the shafts depends on depth, the back pressures supplied by the seal materials will result in DRZ healing at rates that increase with depth. The relative stiffness of the seal material is a factor, as well.

The DRZ surrounding the shaft is not explicitly represented in the BRAGFLO mesh (Figures 6-14 and 6-15). Rather, the mesh was simplified to represent only the cross-sectional area of the four WIPP shafts, and the permeability values of the seal components at different times have been adjusted (in the parameter database) to account for the shaft DRZ. This adjustment, which yields effective permeabilities, can be done because in Darcy flow, the flux through a porous medium is a linear function of the product of the permeability and the cross-sectional area across which flow occurs. Thus, the flux that would occur through a shaft and its surrounding DRZ can be modeled equivalently using the shaft cross-sectional area with a higher seal component permeability. Equations for the derivation of the effective permeabilities are given in Appendix PA, Attachment PAR (Parameters 64 and 65).

6.4.5 The Salado

The Salado is the principal natural barrier to fluid flow between the waste disposal panels and the accessible environment. Fluid flow in the Salado under natural (undisturbed) conditions is discussed in Section 2.2.1.3. Repository excavation has altered natural pressure gradients in the Salado, creating the potential for fluid flow into the excavation. Fluid flow, gas generation, and volume changes from creep closure alter the pressure gradients through time. Salt creep, as well as possible fracturing from high repository pressure, alters the permeability and other flow properties of the rock near the repository. Depending on pressure gradients and altered material properties, gas and brine flow may be enhanced in affected portions of the Salado.

For PA, the DOE conceptualizes the Salado as a porous medium composed of several rock types arranged in layers, through which flow occurs according to Darcy's law. Two rock types, impure halite and anhydrite, are used to represent the intact Salado. Once sampled, model parameters for all layers are uniform and constant, with two exceptions: porosity and permeability. The assumption of constant properties is based on observed compositional and

structural regularity in layers exposed by the repository and on inferred small For several meters above and below the repository, a DRZ has higher permeability than intact rock and offers little

Table 6-15. Shaft Materials Parameter Values

Parameter (units)	Maximum	Minimum	Median or Constant
UPPER SHAFT MATERIAL			
Residual Brine Saturation, S_{br} (unitless)	0.6	0	0.2
Residual Gas Saturation, S_{gr} (unitless)	0.4	0	0.2
Maximum Capillary Pressure (pascals) [1]	–	–	10^8
Permeability (square meters)	3.16×10^{-17}	3.16×10^{-21}	5.01×10^{-19}
Porosity (percent)	–	–	29.1
LOWER SHAFT MATERIAL (0 to 200 years)			
Initial Brine Saturation, (unitless)	–	–	5.34×10^{-1}
Permeability (square meters) [2]	3.16×10^{-17}	1.0×10^{-20}	6.31×10^{-19}
Maximum Capillary Pressure (pascals)[1]	–	–	10^8
Effective Porosity (percent)	–	–	11.3
LOWER SHAFT MATERIAL (200 to 10,000 years)			
Initial Brine Saturation, (unitless)			5.34×10^{-1}
Permeability (square meters)[2]	1×10^{-18}	3.16×10^{-23}	7.94×10^{-21}
Maximum Capillary Pressure (pascals)[a]	–	–	10^8
Effective Porosity (percent)	–	–	11.3

[1] Capillary pressure for all shaft materials is set to 0.
[2] These values represent the permeabilities of the seal material incorporating the surrounding DRZ

resistance to flow between anhydrite interbeds and the repository. Porosity can vary from its initial value due to pressure-dependent compressibility. As discussed in Section 6.4.5.2, a model has been implemented in interbeds to simulate the effects of fracturing caused by high repository pressure as pore pressure approaches or exceeds lithostatic.
Specific information about the three submodels used to represent impure halite, Salado interbeds, and the DRZ is presented in the following sections.

6.4.5.1 Impure Halite

The PA uses a single porous medium with spatially constant rock and hydrologic properties (labeled "Salado" in Figures 6-14 and 6-15) in PA to represent intact, halite-rich layers in the Salado and minor interbeds contained within layers that are not explicitly represented. A comparison was made between the simplified stratigraphy used in the PA model and a model with a more detailed stratigraphy in the vicinity of the repository. This comparison supports use of stratigraphic representation for PA. This model comparison is described in Christian-Frear and Webb (1996).

Gas may not be able to flow through intact, halite-rich strata of the Salado under realistic conditions for the repository. Gas flow in liquid-saturated rock depends on the gas pressure required to overcome capillary resistance to initial gas penetration and interconnected gas

pathways that allow gas flow (threshold pressure). While the permeability of halite is known to be low, its threshold pressure has never been measured. An empirical relationship between threshold pressure and permeability in non-WIPP rocks (Davies 1991, 17-19) suggests that threshold pressure will be high enough that gas will be unable to flow through the halite-rich strata of the Salado under any conditions foreseeable for the WIPP (see Appendix PA, Attachment MASS, Section MASS-13.1). The DOE values for halite threshold pressure are consistent for generic material of low permeability and prevent gas flow into the impure halite regions (Table 6-16). This is a conservative assumption because gas flow in halite would decrease the pressure in the repository and the driving force available for flow elsewhere. Table 6-16 shows various parameter values used in modeling the Salado impure halite. Additional information on parameter values is contained in Appendix PA, Attachment PAR (Parameters 17 through 19 and Table PAR-2).

Table 6-16. Salado Impure Halite Parameter Values

Parameter (units) [1]	Maximum	Minimum	Median or Constant
Permeability (square meters)	10^{-21}	10^{-24}	3.16×10^{-23}
Effective Porosity (percent)	3.0	0.10	1.0
Threshold Pressure, P_t (pascals) [2]	1.13×10^{8}	1.03×10^{7}	3.41×10^{7}
Residual Brine Saturation, S_{br} (unitless)	0.60	0	0.3
Residual Gas Saturation, S_{gr} (unitless)	0.40	0	0.2
Pore Distribution Parameter, λ (unitless)	1.0	0.20	0.7
Maximum Capillary Pressure (pascals)	–	–	10^{8}
Rock Compressibility (1/pascals)[3]	1.92×10^{-10}	2.94×10^{-12}	9.75×10^{-11}

[1] See Table 6-11 for fluid properties.

[2] Threshold pressure (P_t) determined from the relationship: $P_t = PCT_A \cdot k^{PCT_EXP}$ where PCT_A and PCT_EXP are constants and k is the permeability.

[3] Pore compressibility = rock compressibility/effective porosity.

6.4.5.2 Salado Interbeds

Three distinct anhydrite interbeds are modeled in BRAGFLO, representing MB138 (see Figures 6-14 and 6-15), anhydrite layers a and b (Anhydrite AB), and MB139. The three interbeds have the same set of model parameters, and the parameters are initially spatially constant. Porosity and permeability can vary spatially during a simulation, depending on the extent of interbed fracturing. The interbeds differ only in position and thickness.

The three interbeds explicitly represented in the BRAGFLO model are included because they exist in the disturbed region, as modeled around the repository within which fluid is expected to be able to flow with relative ease compared to the surrounding formation. MB139 and anhydrite layers a and b are present within the DRZ that forms around excavations, as shown by Park and Holland (2003) in their analysis of the effects of raising the repository horizon 2.34 meters (7.67 feet). MB138 is included along with a thick DRZ because of uncertainty in the extent and properties of the DRZ and the associated long-term isolation of MB138 from the repository. A more detailed examination of the DRZ was necessary to incorporate the Option D panel closure

into the PA grid. Even though the DRZ would not reach MB 138, PA models the potential for a hydraulic connection between MB 138 and the repository through the DRZ.

In BRAGFLO, brine flows between the Salado and the repository in response to fluid potential gradients that may form over time. Because of the impure halite's low permeability and relatively small surface area, direct brine flow between the impure halite and the repository is relatively small. The interbeds included in the BRAGFLO model of the Salado, however, serve as conduits for brine flow between the impure halite and the repository. Conceptually, brine flows laterally along higher permeability interbeds towards or away from the repository and vertically between the interbeds and the lower permeability halite. Because the interbeds have a very large contact area with adjacent halite-rich rock, even a very small flux from the halite into the interbeds (for brine inflow) or to the halite from the interbeds (for brine outflow) can accumulate significant quantities of brine. In this manner, halite serves as a source or sink for brine in the repository. It is expected that, because of density differences between gas and brine and their stratification within the repository, brine outflow will be predominantly in MB139, and gas outflow will occur in anhydrite a and b or MB138. However, the model does not preclude other flow patterns.

Interbeds contain natural fractures that may be partially healed, but anhydrite lithologies proximal to disposal rooms will be highly distorted as the rooms creep closed. Fractured and distorted anhydrite would not be expected to heal in a manner expected of the DRZ in salt. If high pressure is developed in an interbed, its preexisting fractures may dilate or new fractures may form, altering its porosity and permeability. Pressure-dependent changes in permeability are supported by experiments conducted in the WIPP and in the laboratory (Beauheim et al. 1993). Accordingly, the DOE has implemented in BRAGFLO a porous-media model of interbed dilation and fracturing that causes the porosity and permeability of an interbed's computational cell to increase as its pore pressure rises above a threshold value. Model details are presented in Appendix PA, Section PA-4.2 and Attachment MASS, Section MASS-13.0. To the extent that it occurs, interbed dilation or fracturing is expected to increase the transmissivity of interbed intervals. The threshold pressure of dilated or fractured interbeds is expected to be low because apertures of the fractures increase; thus, fluid is expected to flow outward readily if adequate pressure dilates the interbeds.

The model used to simulate the effects of interbed dilation or fracturing is explained in detail in Appendix PA, Attachment MASS, Section MASS-13.0. In summary, it assigns a fracture initiation pressure above the initial pressure at which local fracturing takes place. Changes in permeability and porosity occur above this pressure. Below this fracture initiation pressure, an interbed has the permeability and compressibility assigned by LHS to represent intact rock. Below the fracture initiation pressure, the initial sampled porosity is modified slightly with pressure caused by compressibility. Above the fracture initiation pressure, the local compressibility of the interbed is assumed to increase linearly with pressure. This greatly increases the rate at which porosity increases with increasing pore pressure. Additionally, permeability increases by a power function of the ratio of altered porosity to initial porosity. For numerical reasons (that is, to prevent unbounded changes in parameter values that would create numerical instabilities in codes), a pressure is specified above which porosity and permeability change no further.

Parameters associated with the interbeds are shown in Table 6-17. Table 6-18 lists parameters used to model interbed dilation and fracture. Additional information about interbed parameters is included in Appendix PA, Attachment PAR, Table 2, and Parameters 20 through 25.

Table 6-17. Parameter Values for Salado Anhydrite Interbeds a and b, and MB138 and MB139

Parameter (units) [1]	Maximum	Minimum	Median or Constant
Permeability (square meters)	7.94×10^{-18}	10^{-21}	1.29×10^{-19}
Effective Porosity (percent)	1.7	0.60	1.1
Threshold Pressure, P_t (pascals) [2]	5.28×10^{6}	2.32×10^{5}	9.74×10^{5}
Residual Brine Saturation, S_{br} (unitless)	0.174	0.00778	0.084
Residual Gas Saturation, S_{gr} (unitless)	0.197	0.014	0.077
Pore Distribution Parameter, λ (unitless)	0.842	0.491	0.644
Maximum Capillary Pressure (pascals)	–	–	10^{8}
Rock Compressibility (1/pascals) [3]	2.75×10^{-10}	1.09×10^{-11}	8.26×10^{-11}

[1] See Table 6-11 for fluid properties.

[2] Threshold pressure (P_t) determined from the relationship: $P_t = PCT_A \cdot k^{PCT_EXP}$ where PCT_A and PCT_EXP are constants and k is the permeability.

[3] Pore compressibility = Rock compressibility/effective porosity.

Table 6-18. Fracture Parameter Values for Salado Anhydrite Interbeds a and b, and MB138 and MB139

Parameter (units)	Constant
Fracture initiation pressure at MB139, base of shaft (pascals)	12.7×10^{6}
Increment to give full fracture porosity (percent), MB139 and MB138 [1]	3.9
Increment to give full fracture porosity (percent), Anhydrite a and b [1]	23.9
Full fracture permeability (square meters)	10^{-9}
Increment above fracture initiation pressure to obtain full fracture pressure (pascals) [1]	3.8×10^{6}

[1] A fitting parameter to yield desired dilation over a variation in pressure.

6.4.5.3 DRZ

In the DRZ (see Figures 6-14 and 6-15) near the repository, permeability and porosity are expected to generally increase in both halite and interbeds. These increases are due to a variety of processes. Creep closure and stress-field alterations as the result of the excavation are the dominant causes, similar to the processes discussed for forming the DRZ around the shaft (see Section 6.4.4). The increases in permeability and porosity in interbeds are not likely to be completely reversible with creep closure of the disposal rooms. The increase in DRZ permeability increases the ability of fluid to flow from interbeds to the waste disposal region. The increase in DRZ porosity provides a volume in which some fluid could be retained so that it does not contact waste or slow actinide movement.

In approximating the effects of the DRZ, PA conservatively overestimates brine flow toward the repository (see Appendix PA, Attachment MASS, Section 13). In the model, the permeability of this region is increased relative to intact Salado rock for the duration of a realization. The porosity of the modeled DRZ is increased by a fixed value of 0.0029 (0.29 percent) above the sampled porosity of the intact Salado impure halite. The modeled DRZ extends above and below the repository from the base of MB138 to MB139, thereby retaining the geometry used in the CCA and 1997 PAVT. The PA treatment of the DRZ creates a region that may allow fluid flow between the repository and affected interbeds. Table 6-19 shows parameter values used in the PA representation of the DRZ.

Table 6-19. DRZ Parameter Values

Parameter (units) [1]	Maximum	Minimum	Median or Constant
Permeability (square meters)	3.16×10^{-13}	3.98×10^{-20}	10^{-16}
Effective porosity (percent) [2]	3.3	0.04	1.29
Threshold pressure, P_t (pascals)	–	–	0
Residual brine saturation, S_{br} (unitless)	–	–	0
Residual gas saturation, S_{gr} (unitless)	–	–	0
Pore distribution parameter, λ (unitless)	–	–	0.7
Maximum capillary pressure (pascals)	–	–	10^8
Rock compressibility (1/pascals) [3]	–	–	7.41×10^{-10}

[1] See Table 6-11 for fluid properties.
[2] The DRZ effective porosity value for each realization is equivalent to the sampled value for the Salado halite plus 0.0029 (0.0029 is the difference between the medians for the DRZ and the halite).
[3] Pore compressibility = rock compressibility/effective porosity.

The DOE originally used a constant permeability for the DRZ over the 10,000-year regulatory time frame. However, the EPA required the DOE to treat the DRZ permeability as uncertain during the PAVT (EPA 1998, TSD V-B-14). The range is sampled to determine a fixed value for each realization over the 10,000-year period. Additionally, in the 1997 PAVT, the anhydrite fracture model was applied to the DRZ to capture the effects of halite fracture under high repository pressures. As was done in the 1997 PAVT, the CRA-2004 PA treats the DRZ permeability as an uncertain parameter, and the anhydrite fracture model is also applied to the DRZ. The parameter values are shown in Table 6-19.

6.4.5.4 Actinide Transport in the Salado

The DOE considers actinide transport in the Salado to be a possible mechanism for release to the accessible environment. As in other areas of the disposal system, actinides in the Salado may be transported as dissolved species or as colloidal particles. Actinide transport is affected by a variety of processes that may occur along the flow path.

The DOE uses the NUTS code (see Appendix PA, Section PA-4.3) to model the migration of radionuclides in the repository and surrounding formations. NUTS models radionuclide transport within all regions for which BRAGFLO computes brine and gas flow, and uses as input

for each realization the corresponding BRAGFLO velocity field, pressures, porosities, saturations, and other model parameters including (for example) the geometrical grid, residual saturation, material map, and compressibility.

The PA uses NUTS in two ways. First, the code is used in a computationally fast tracer mode to identify those BRAGFLO realizations for which it is unnecessary to do full transport calculations because contaminated brine never reaches the top of the salt or the accessible environment within the Salado. Such realizations cannot contribute to the total integrated release of radionuclides from the disposal system. If the tracer calculation indicates a possibility of consequential release, a computationally slow calculation of the full transport of each radionuclide is performed (see Appendix PA, Section 6.7.2).

6.4.5.4.1 NUTS Tracer Calculations

All BRAGFLO realizations are evaluated using NUTS in a tracer mode to identify realizations for which there is no possibility of radionuclides reaching the accessible environment. The tracer simulations consider an infinitely soluble, nondecaying, nondispersive, and nonsorbing species as a tracer element. The tracer is given a unit concentration in all waste disposal areas of 1 kilogram per cubic meter. If this tracer does not reach the selected boundaries (the top of the Salado and the land withdrawal boundary within the Salado) in a cumulative mass greater than or equal to 10^{-7} kilograms within 10,000 years, it is assumed there is no consequential release to these boundaries. If a cumulative mass greater than or equal to 10^{-7} kilograms does reach the selected boundaries within 10,000 years, a complete transport analysis is conducted. The value of 10^{-7} kilograms is selected because, regardless of the isotopic composition of the release, it corresponds to a normalized release less than 10^{-6} EPA units, the smallest release displayed in CCDF construction. The largest normalized release would be 9.98×10^{-7} EPA units, which corresponds to 10^{-7} kilograms of ^{241}Am, if the release was entirely ^{241}Am

6.4.5.4.2 NUTS Transport Calculations

For BRAGFLO realizations with greater than 10^{-7} kilograms reaching the boundaries in the tracer calculations, NUTS models the transport of five different species of radionuclides (^{241}Am, ^{239}Pu, ^{238}Pu, ^{234}U, and ^{230}Th). These radionuclides represent a larger number of radionuclides, as discussed in Appendix TRU WASTE. For decay purposes, radionuclides were grouped together based on similarities such as isotopes of the same element and those with similar half-lives, to simplify the calculations, as discussed in CCA Appendix WCA.3.2.3. For transport purposes, solubilities are lumped to represent both dissolved and colloidal forms. These groupings simplify and expedite calculations.

NUTS models radionuclide transport by advection (see Appendix PA, Attachment MASS). NUTS disregards sorptive and other retarding effects throughout the entire flow region. Physically, some degree of retardation must occur at locations within the repository and the geologic media, and the disregard of retardation processes is therefore conservative. NUTS also disregards reaction-rate aspects of dissolution and colloid formation processes, and mobilization is assumed to occur instantaneously. Neither molecular nor mechanical dispersion is modeled in NUTS. These processes are assumed to be insignificant in comparison to advection, as discussed further in Appendix PA, Attachment MASS.

Colloidal actinides are subject to retardation by chemical interaction between colloids and solid surfaces and by clogging of small pore throats (that is, sieving). There will be some interaction of colloids with solid surfaces in the anhydrite interbeds. The low permeability of intact interbeds is reason to expectpore apertures are small and some sieving will occur. However, colloidal particles, if not retarded, are transported slightly more rapidly than the average velocity of the bulk liquid flow. Because the effects on transport of slightly increased average pore velocity and retarding interactions with solid surfaces and sieving are offsetting, the DOE assumes residual effects of these opposing processes will be either small or beneficial and does not incorporate them in modeling of actinide transport in the Salado interbeds.

If brine that has been in the repository moves into interbeds, it is likely that mineral precipitation reactions will occur. Precipitated minerals may contain actinides as trace constituents. The beneficial effects of the possible mineral co-precipitation process are neglected in PA. Furthermore, colloidal-sized precipitates will behave like mineral-fragment colloids, which are destabilized by brines, quickly agglomerating and settling by gravity. The beneficial consequence of colloid precipitation is also disregarded in PA.

Additional processes that may impact transport in Salado interbeds are related to fractures, channeling, and viscous fingering. Interbeds contain natural fractures. Because of the low permeability of unfractured anhydrite, most fluid flow occurring in interbeds will occur in fractures. Even though some properties of naturally fractured interbeds are characterized by in-situ tests (see Section 2.2.1.3), other uncertainty exists in the characteristics of the fracture network that may be created if gas pressure in the repository becomes high. The PA modeling system accounts for the possible effects on porosity and permeability of fracturing through use of a fracturing model (see Section 6.4.5.2). The processes and effects associated with fracture dilation or fracture propagation that are not already captured by the PA fracture model are negligible (see CCA Appendix MASS, Section MASS.13.3 and MASS Attachment 13.2). Of those processes not already incorporated, channeling is considered to have the greatest potential effect.

Channeling is the movement of fluid through the larger aperture portions of a fracture network (that is, areas of local high permeability). It could locally enhance actinide transport. However, it is assumed that the effects of channeled flow in existing or altered fractures will be negligible on the scale of the disposal system. The DOE believes this assumption is reasonable because processes that act to limit the effectiveness of channels or disperse actinides in them are likely to occur. First, if gas is present in the fracture network, it will be present as the nonwetting phase and will occupy the portions of the fracture network with relatively large apertures, where the highest permeabilities will exist locally. The presence of gas thus removes the most rapid transport pathways from the contaminated brine and decreases the impact of channeling. Second, brine penetrating the Salado from the repository is likely to be completely miscible with in-situ brine. Because of miscibility, diffusion or other local mixing processes will probably broaden fingers (reduce concentration gradients) until the propagating fingers are indistinguishable from the advancing front.

Gas will likely penetrate the liquid-saturated interbeds as a fingered front rather than as a uniform front. Fingers form because of the difference in viscosity between the invading fluid (gas) and the resident fluid (liquid brine), and because of channeling effects. This process does

not affect actinide transport, however, because actinides of interest are transported only in the liquid phase, which will not displace gas in the relatively high-permeability regions because of capillary effects.

6.4.6 Units Above the Salado

The geology and hydrology of units above the Salado are discussed in Sections 2.1.3 and 2.2.1.4, respectively. In this section, the assumptions, simplifications, and models used in PA of these units are described. Because it is unlikely that these units will be impacted by UP, modeling these units is performed mainly because regulations require considering the effects of inadvertent human intrusions. See Appendix PA, Attachment MASS, Section 14 for additional discussion on the units above the Salado.

The principal purpose of BRAGFLO calculations for units above the Salado is to determine the quantity of brine entering each unit from an intrusion borehole or the shaft. It is unrealistic to assume that all flow up an intrusion borehole enters the Culebra. Accordingly, BRAGFLO parameters are specified so that brine flow from the intrusion borehole is possible not only into the Culebra but also into the Magenta, Dewey Lake, and overlying units (as well as to the ground surface), depending on whether liquid rises above the Culebra in the intrusion borehole. Some of the assumptions regarding the properties of units above the Salado are made specifically to allow model simplification and are conservative with respect to actinide transport in the Culebra (that is, overestimate releases).

Consistent with accepted stratigraphic conventions for the area, discussed in Section 2.1.3, the units above the Salado are subdivided into seven layers in PA; these are, in order of lowest to highest, the Los Medaños, the Culebra, the Tamarisk, the Magenta, the Forty-niner, the Dewey Lake, and the units above the Dewey Lake. The conceptual model for each of these layers is described sequentially in the following sections.

A fundamental assumption in the PA conceptual model for modeling actinide transport to the accessible environment in units above the Salado is that lateral actinide transport through rock formations is possible within the next 10,000 years only in the Culebra. This assumption is appropriate for several reasons relating to the properties of other rock units and the groundwater basin conceptual model, discussed in following sections.

Section 2.2.1.4 describes the hydrology of the units above the Salado in terms of the groundwater basin conceptual model. Insight into groundwater basin processes indicates that it is possible to significantly simplify the hydrologic models in the units above the Salado to obtain reasonable estimates of actinide transport (see Corbet and Knupp 1996; Appendix PA, Attachment MASS, Section MASS-14). Therefore, the DOE calculates actinide transport in the units above the Salado with a two-dimensional conceptual and mathematical model. The models used for actinide transport in the units above the Salado are a simplified implementation of the groundwater basin conceptual model. The mathematical model is implemented in the computer codes MODFLOW-2000 and SECOTP2D (see Appendix PA, Section PA-4.8).

6.4.6.1 The Los Medaños

The Los Medaños (formerly the unnamed lower member of the Rustler, Row 25 in Figures 6-14 and 6-15) rests above the Salado. Its transmissivity was measured (see Section 2.2.1.4.1.1) and found to be low, which is consistent with expectations based on its anhydrite, gypsum, halite, clay, and siltstone composition (see Section 2.1.3.5.1). In PA, this member is treated as impermeable, which prevents liquid flow and actinides from entering this unit. The DOE assumes that because of the low permeability of the Los Medaños assumption any brine entering it from an intrusion borehole would be contained well within the site boundary for more than 10,000 years. This treatment is conservative because allowing flow from a borehole or shaft into the Los Medaños would, if anything, decrease flow into the Culebra. This would reduce the release of actinides from the Culebra to the accessible environment. In PA, the thickness of Los Medaños is 36 m (118 ft), and its permeability is zero.

6.4.6.2 The Culebra

The Culebra is represented in BRAGFLO as Row 26 in Figures 6-14 and 6-15. The model geometries for Culebra flow calculations and transport calculations are discussed in this section. Boundary and initial conditions for this geometry are discussed in Section 6.4.10.2. Supplementing the discussion in this section are additional details about the Culebra modeling provided in Section 6.4.13 and Appendix PA, Section PA-4.9.

Conceptually, radionuclides might be introduced into the Culebra through brine flow up the sealed shafts. However, the chief source of actinides in the Culebra is modeled as long-term releases from a borehole that intersects the repository. If radionuclides are introduced into the Culebra, they may be transported from the point of introduction by groundwater flowing naturally through the Culebra.

The Culebra is conceptualized as a confined aquifer. For fluid flow, it is conceptualized as a heterogeneous porous medium represented by variations in transmissivity. A heterogeneous velocity field is used for transport calculations, but all other rock properties (e.g., porosity, K_d) are conceptualized as constant (homogeneous) across the model area. The Culebra is conceptualized as having two types of porosity; a portion associated with high-permeability features where transport occurs by advection, and the rest associated with low-permeability features where flow does not occur and retardation occurs by physical processes (diffusion) and chemical processes (sorption). This type of conceptual model is commonly referred to as "double-porosity." In this conceptual model, transport and retardation of colloidal particles are also considered. This section addresses fluid flow in the Culebra. The transport and retardation of dissolved actinides will be discussed principally in Section 6.4.6.2.1. The transport and retardation of colloidal particles will be discussed principally in Section 6.4.6.2.2.

In the Culebra conceptual model used in PA, the spatial distribution of transmissivity in the Culebra is important. Other potentially important processes acting on Culebra flow and transport are climate change (Section 6.4.9 and CCA Appendix MASS, Section MASS.17) and the effects of subsidence caused by potash mining in the McNutt (Section 6.4.6.2.3 and CCA Appendix MASS, Section MASS.15.4).

The MODFLOW-2000 code uses two-dimensional horizontal grids to simulate groundwater flow. A regional grid approximately 14 miles × 19 miles (22 kilometers × 30 kilometers) (Figure 6-17) with spatially varying transmissivity determines the flow fields in the WIPP region from hydraulic head distributions controlled by distant topographic and hydrologic features (that is, boundary conditions). The grid is made up of 68,768 uniform 100 m × 100 m (328.08 ft) cells. Because this grid is used to define the boundary conditions for the flow and transport calculations, it is discussed in detail in Section 6.4.10.2, along with the specification of boundary conditions. Details about the development and calibration of the flow fields are given in Appendix PA, Attachment TFIELD. For transport in the region of interest, a local grid 7.5 km × 5.4 km (4.5 mi × 3.1 mi) with finer discretization is used in SECOTP2D (Figure 6-18). The grid for the transport domain contains 150 columns and 108 rows of 50 m × 50 m (164 ft) cells, resulting in 16,200 grid blocks.

The local SECOTP2D domain boundaries (Figure 6-18) were chosen to capture all flow paths from the modeled release point above the center of the disposal panels to the accessible environment. Because past analyses indicated that transport in the Culebra occurs within a region that lies from southeast of the repository to west of the repository, the transport domain extends slightly beyond the southern and western boundaries of the controlled area. Because it is not needed, a strip in the northern portion of the controlled area has been omitted from the SECOTP2D domain to ease the computational burden.

Flow directions and transmissivities in the Culebra vary significantly from location to location within and past the site boundary. Consequently, the effects of flow in the region around the WIPP site are important in the conceptual model. The boundaries to the flow model are discussed in Section 6.4.10.2; the domain itself is shown in Figure 6-17.

The conceptual model for the Culebra assumes that fluid fluxes and directions in the future will be the same as at repository closure, unless future mining within the site occurs, in which case changes to fluid flow are calculated. A steady-state flow field is used to represent this assumption. Conditions assumed at site closure are the subsidence effects of mining in the near future outside the site boundary, climate change, and heads similar to those measured in late 2000 (see Appendix PA, Attachment MASS, Sections MASS-15.4 and MASS-14.2, and Attachment TFIELD).

The factors controlling fluid flow in the Culebra are the hydraulic gradient, distribution of transmissivity, and porosity. The hydraulic gradient and transmissivities used in PA are coupled because they are calibrated to observed conditions by a process described in Appendix PA, Attachment TFIELD. Flow fields are calculated with the code MODFLOW-2000 assuming homogeneous porosity in the Culebra. This single value is the total porosity for the Culebra, including both advective and diffusive porosity, as discussed below. Using a single porosity for the flow calculation does not introduce inconsistency with transport calculations because (1) steady-state flow fields are used so flux through the system is not dependent on porosity, and (2) the velocity of liquid for transport is calculated based on a double-porosity model implemented in SECOTP2D. Thus, the important factors for flow calculations are the hydraulic gradient and transmissivity variation.

Because BRAGFLO models a vertical section of the disposal system, the spatial distribution of transmissivity cannot be represented in the BRAGFLO grid. The source term of actinides in the Culebra is calculated in part from BRAGFLO flow fields, so parameters for the Culebra are required in BRAGFLO. Specifically, a single value of Culebra permeability representative for the Culebra in the area immediately over the waste-emplacement panels is input to partition fluid flow among the stratigraphic units along the human-intrusion borehole.

BRAGFLO calculates gas flow and brine flow that may occur up a borehole (see Section 6.4.7). The MODFLOW-2000 code models flow of the liquid phase only. The possible effects of gas on Culebra flow are not modeled. This simplification is reasonable because after gas pressure is relieved by flow to the surface during drilling, little gas will remain in the repository. This gas will move up the borehole at low rates and tend to move directly to the top of the liquid-saturated section of the borehole, bypassing the Culebra. Any gas that does enter the Culebra will tend to displace brine from fractures and reduce the potential for actinide transport. Based on previous modeling (Lappin et al. 1989, Appendix E.1.5.1), the effect of the mass of brine being injected into the Culebra on the natural flow is negligible. Parameter values used in BRAGFLO to describe the Culebra are shown in Table 6-20. Parameter values used in MODFLOW-2000 are shown in Table 6-21. See Appendix PA, Attachment PAR, Table 2 for additional Culebra parameter information.

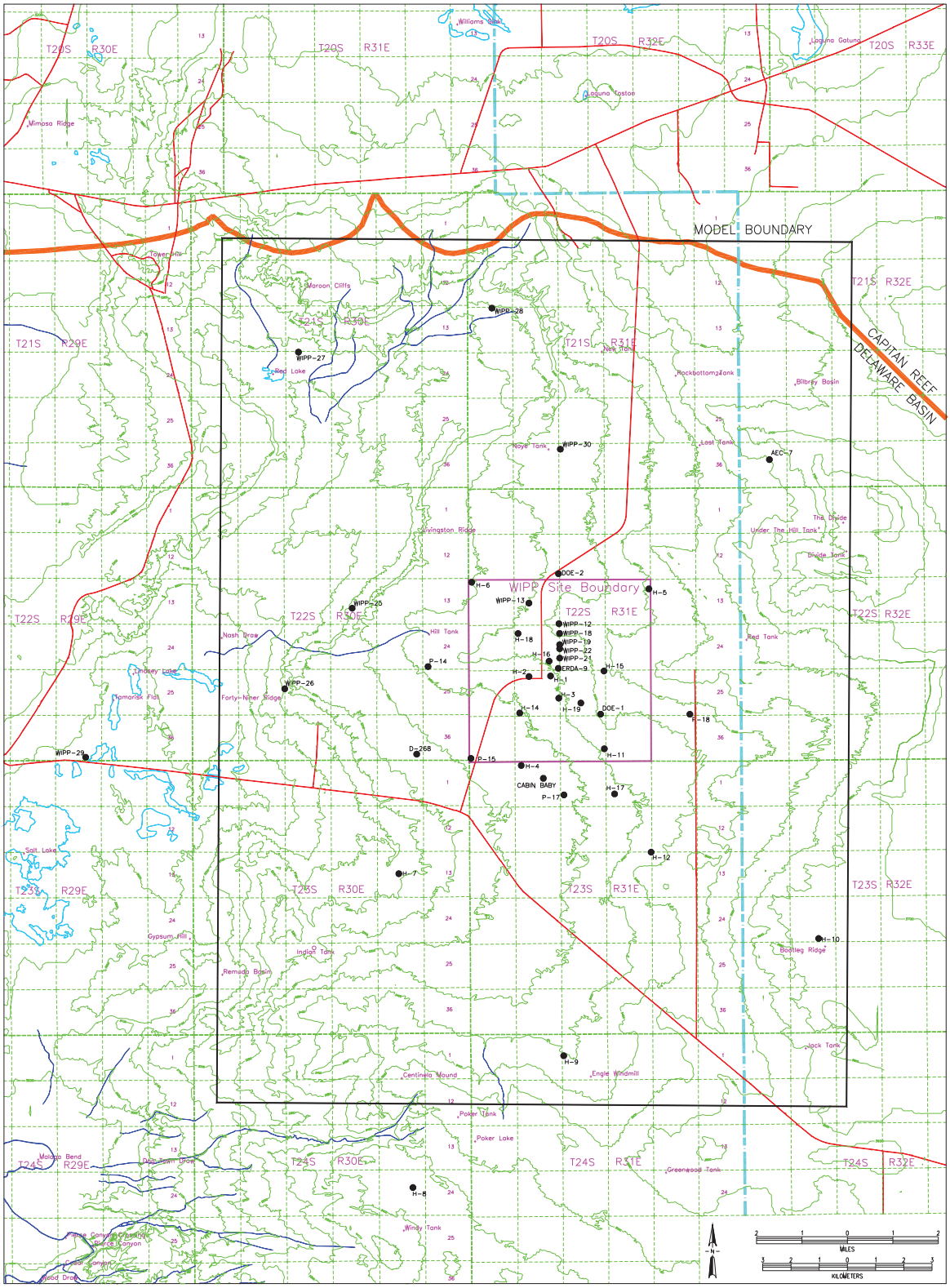

Figure 6-17. The MODFLOW-2000 Domain Used in the Groundwater Model of the Culebra

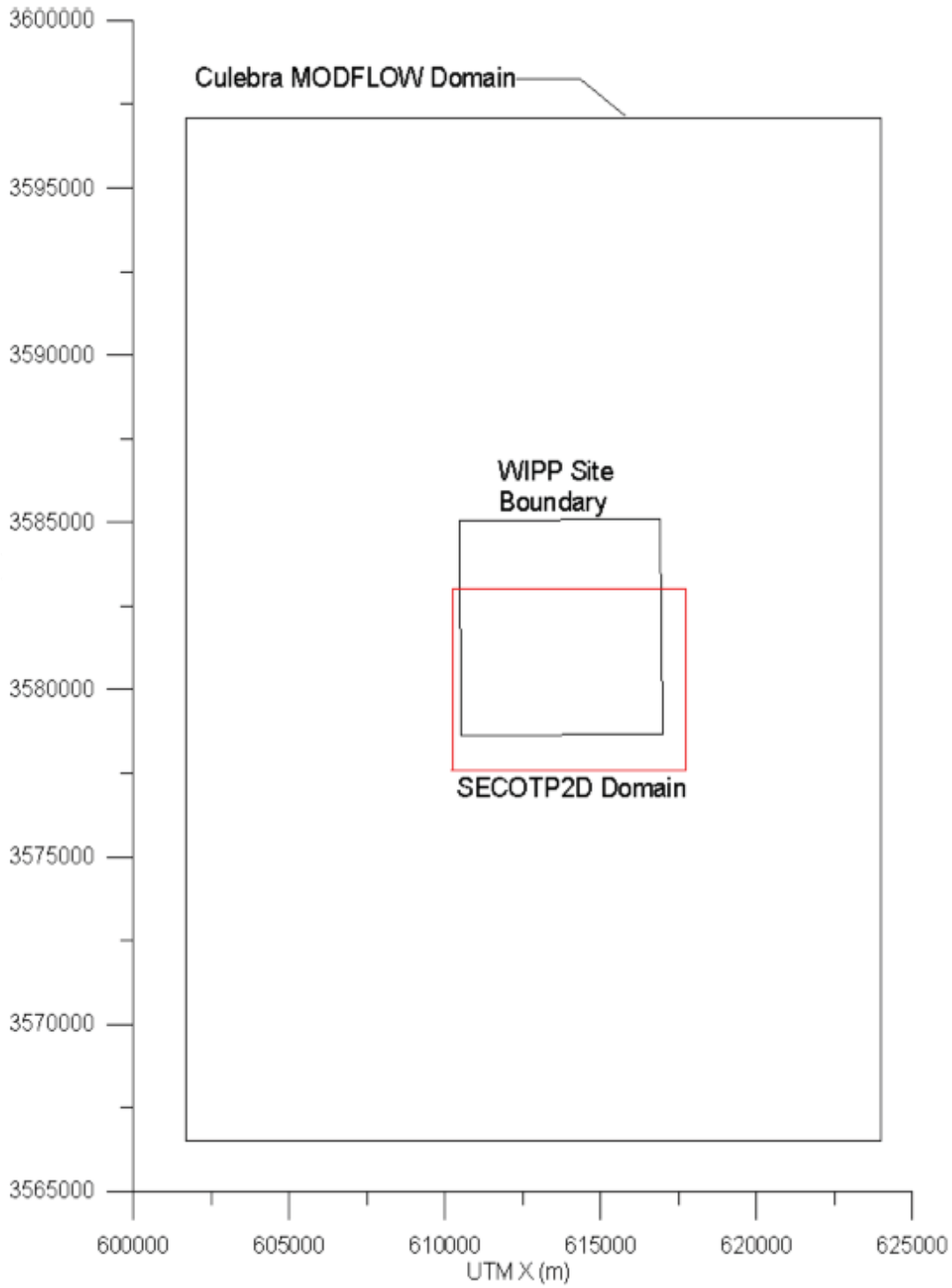

Figure 6-18. Extent of SECOTP2D Domain with Respect to the MODFLOW-2000 Culebra Domain and WIPP Site Boundary

Three different thicknesses of the Culebra were assumed in PA modeling. BRAGFLO uses a thickness of 7.7 m (25.3 ft), representative of the Culebra over the waste disposal panels. For calibrating transmissivity fields (see Appendix PA, Attachment TFIELD) and calculating flow in the Culebra with MODFLOW-2000, a thickness of 7.75 m (25.4 ft) is assumed, consistent with an average thickness over the area modeled. For transport calculations using SECOTP2D, a thickness of 4 m (13 ft) is assumed, consistent with the observed thickness of the Culebra active in transport, which is discussed in Section 6.4.6.2.1. Using different thicknesses does not introduce inconsistencies in the modeling, however, because the transmissivities used in these codes are consistent, and transmissivity governs the total flux of fluid through the Culebra. Furthermore, the fluid flux used in the SECOTP2D model is calculated by MODFLOW-2000, ensuring consistency.

The spatial variation in transmissivity observed in the Culebra is incorporated by assigning different transmissivity values to every computational cell in the model. Because there is uncertainty in the estimated value of Culebra transmissivity where measurements have

Table 6-20. Culebra Parameter Values for the BRAGFLO Model

Parameter (units) [1]	Value
Permeability (square meters)	7.73×10^{-14}
Effective porosity (percent)	15.1
Rock compressibility (1/pascals) [2]	10^{-10}
Threshold pressure, P_t (pascals) [3]	1.5×10^{4}
Residual brine saturation, S_{br} (unitless)	0.084
Residual gas saturation, S_{gr} (unitless)	0.077
Pore distribution parameter, λ (unitless)	0.644
Maximum capillary pressure (pascals)	10^{8}
Thickness (meters)	7.70
Initial Pressure (pascals)	9.14×10^{5}

[1] See Table 6-11 for fluid properties in BRAGFLO.

[2] Pore compressibility = rock compressibility/effective porosity.

[3] Threshold pressure (P_t) determined from relationship: $P_t = PCT_A \cdot k^{PCT_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

Table 6-21. MODFLOW-2000 Fluid Properties

Parameter (units)	Value
Liquid density (kilograms per cubic meter)	1,000
Liquid compressibility (1/pascals)	4.4×10^{-10}

not been made, 100 different transmissivity fields were developed. Each transmissivity field statistically represents the natural variation in transmissivity that honors measured data according to certain criteria. Monte Carlo simulations using a large number of equally-likely transmissivity fields are a statistically sound method of characterizing the uncertainty associated with

transmissivity in the Culebra. For details of the generation and use of transmissivity fields and criteria, refer to Appendix PA, Attachment TFIELD.

Regional flow directions and fluxes are calculated with the regional domain, as described earlier and shown in Figure 6-18. To increase resolution of transport processes a finer grid is used. Within MODFLOW-2000, each 100-m × 100-m cell is divided into four 50-m ×-50 m cells with exactly the same transmissivity as the 100-m × 100-m cell. Darcy velocities are calculated in the 50-m × 50-m cells and then mapped directly into the SECOTP2D grid (Figure 6-18), which also consists of 50-m × 50-m cells. Consistency between the flow calculated in the regional domain and flow in the local domain is important, and is assured by interpolation of the boundary conditions and transmissivity field properties of the regional domain onto the local domain. This process of calculating two flow fields with domains of different extent and resolution is for practical reasons only. It is a method of incorporating regional effects in finely discretized local flow fields that has relatively low computational burden, compared to other possible methods. Additional discussion of this process is provided in Section 6.4.10.2.

In summary, flow in the Culebra is calculated with the code MODFLOW-2000, using a conceptual model of a confined aquifer, regional flow effects, uniform porous medium, steady state, and transmissivity variation. In addition, the effects of subsidence caused by potash mining in the McNutt are incorporated during the flow calculation, as discussed in Section 6.4.6.2.3.

6.4.6.2.1 Transport of Dissolved Actinides in the Culebra

Actinides may be introduced into the Culebra by brine flowing up a borehole or up the shaft. Three principal processes have been demonstrated to occur naturally that affect the transport and retardation of dissolved actinides. Dissolved actinides will be carried by advection in the natural flow of Culebra groundwater. Dissolved actinides will diffuse into the matrix. Dissolved actinides will sorb to varying extents onto the different minerals lining pore walls or fractures. It is possible that dissolved actinides may participate as trace constituents in reactions between water and rock and be bound in newly formed minerals, but this phenomenon is not included in the conceptual model. These processes are complicated to characterize because of known stratigraphic variation in the Culebra and expected heterogeneity in solution chemistry along the possible flow paths from the injection point to the accessible environment.

The basic stratigraphy of the Culebra is continuous across the WIPP site (CCA Appendix FAC, Section FAC.4.1.2), and contains layers with significantly different properties (Holt and Powers 1984, 1986, 1990, and CCA Appendix FAC, Section FAC.5.2). Hydraulically, there are two distinct layers in the Culebra. Mercer and Orr (1979) report the result of a tracer and temperature survey that suggests there is no significant flow in the upper 4.3 m (14 ft) of the Culebra. Culebra hydraulic testing at well H-14 indicates generally low permeabilities but a slightly higher permeability in the upper portion (Beauheim 1987). In descriptions from the air intake shaft, Holt and Powers (1990) noted that most of the fluid produced came from the lower portion of the Culebra. Hydraulic tests at the H-19 hydropad indicate that the permeability of the Culebra's upper portion is significantly lower than the permeability of the lower portion (Beauheim 2000). Consistent with hydraulic indicators, tracer tests conducted at H-19 confirmed that the Culebra's upper portion makes no significant contribution to the transport of dissolved

species, although it may retard solute transport by diffusion into it (Meigs et al. 2000). The Culebra at the WIPP site is conceptualized as having very low permeability in the upper approximately 3 m (9.8 ft), and variable permeability in the lower portion, which can be lower than the upper portion in regions where the Culebra as a whole is relatively impermeable. Thus, the bulk of the data indicates that the majority of the flow and transport takes place in the lower portions of the Culebra. Accordingly, for transport calculations, an effective thickness of 4 m (13.1 ft) is assumed (Meigs and McCord 1996).

There is considerable variability in the structure and size of porous features in the Culebra, including fractures (of a variety of dimensions and interconnectedness), vugs, and interparticle and intercrystalline porosity (Holt 1997). The principal flow occurs in features with the high permeability, and slower flow and diffusion are primary processes in lower permeability features. Tracer test interpretations indicate that at some locations, flow occurs predominantly through fractures (advective porosity is low) and at other locations, slower transport indicates that flow occurs in other permeable features, such as vugs connected by microfractures, and possibly interparticle porosity (higher advective porosity). Tracer test interpretations also indicate that matrix diffusion is an important process in high-permeability regions of the Culebra. In other words, at least two scales of porosity are needed to represent the transport processes in the Culebra (that is, a double-porosity model). At some locations of low permeability, fractures may be absent or filled with gypsum. An alternative conceptual model for transport at these locations is uniform single porosity with a high porosity. To simplify calculations, the uniform single-porosity model was not implemented; the double-porosity model implemented results in faster transport.

In SECOTP2D, advective porosity represents the porous features in which flow occurs. Advective porosity values are low, which is representative of flow in fractures. Diffusive porosity represents those porous features in which no flow occurs and diffusion and sorption occur. Diffusive porosities are large relative to advective porosity, representing the vugs, interparticle, and intercrystalline porosity of the bulk rock.

The processes that occur in the advective porosity portion of the Culebra are advection (flow), dispersion (spreading caused by heterogeneity), diffusion within the advective porosity, and diffusion into the diffusive porosity. Important factors in this conceptual model are the velocities of fluid in the advective porosity, free-water diffusion coefficients, and dispersion coefficients. The most important factor is the fluid velocity. Free-water tracer diffusion coefficients are specified for actinides. Dispersive spreading at the scale of disposal-system modeling is dominated by the effects of heterogeneities explicitly incorporated in the transmissivity fields input to MODFLOW-2000. This eliminates the need to account for larger-scale features by specifying a modeling dispersion coefficient larger than those observed at the hydropad-test scale.

Fluid velocity in SECOTP2D is coupled to the results of the fluid flow modeling conducted with MODFLOW-2000 (see the preceding section). Fluid flow directions and volumetric fluxes in SECOTP2D are calculated in MODFLOW-2000. The flow velocities in the transport calculation are determined using the fluxes from the fluid flow calculation, the Culebra thickness specified for the transport calculation, and the advective porosity specified for the transport calculation.

Because a different transmissivity field is used and the values of several important parameters are sampled, each realization uses a different velocity field.

Retardation is conceptualized as a function of physical effects of diffusion into diffusive porosity and sorption. Diffusion is parameterized by the diffusive porosity (which is essentially a reservoir for diffusion), tortuosity, matrix block length, and free-water diffusion coefficient. Tortuosity represents the tortuous structure of the porosity within the matrix; it slows the diffusion process. The matrix block length is a conceptual construct representing the ratio of the surface area between advective and diffusive porosity to the volume of diffusive porosity features; physical retardation increases as the matrix block length decreases. Physical retardation also increases if tortuosity or the free-water diffusion coefficient of diffusive porosity are larger. See Appendix PA, Sections 4.8 and 4.9 and Attachment MASS, Section 15.2 for more details.

Chemical retardation of dissolved actinides is conceptualized to occur by sorption onto dolomite grains exposed in diffusive porosity because of the large amount of dolomite present in the Culebra. Chemical retardation increases if diffusive porosity is smaller, because there is a larger volume of rock for sorption. Although clay minerals are present and would sorb actinides in the Culebra, their effects are not included in the conceptual model or specified parameter values. Effective properties for the rock matrix, which is assumed to be homogeneous, and solution chemistry are assumed and are incorporated directly in the specified parameters for the retardation model (see Appendix PA, Attachment MASS, Section 15.2, and Attachment PAR, Parameters 49 through 57).

The PA uses a linear isotherm model to represent the retardation that occurs as dissolved actinides are sorbed onto dolomite. This model uses a single parameter K_d to express a linear relationship between sorbed concentration and liquid concentration. The K_ds used in PA were determined from experimental data and are conservatively chosen. Thus, the model predictions of sorption are less than or equal to actual sorption expected along the possible flow paths in the Culebra should a release occur (Appendix PA, Attachment MASS, Section MASS-15.2; and CCA Appendix MASS, Attachment 15-1). Other important parameters in the linear isotherm model are the diffusive porosity and the grain density of the Culebra because these determine the mass of dolomite available on which sorption can occur. Consistent with the assumption of homogeneous rock properties in the conceptual model, K_ds and grain densities are selected, applied to the entire transport domain, and held constant for an entire realization. See CCA Appendix SECOTP2D (Section 7, User Interactions, Input and Output Files) and Appendix PA, Attachment PAR (Parameters 49 through 57) for details of parameter definitions and values.

Selecting the parameter values required by the SECOTP2D model for physical retardation and chemical retardation is performed in LHS according to the CDFs described in Appendix PA, Attachment PAR. Important parameter values are summarized in Table 6-22 and Table 6-23.

Table 6-22. Matrix Distribution Coefficients (K_ds) and Molecular Diffusion Coefficients for Dissolved Actinides in the Culebra

Actinide	K_d (cubic meters per kilogram)			Molecular Diffusion Coefficients (square meters per second) [1] Constant
	Maximum	Minimum	Median	
U(IV)	10.0	0.70	2.6	1.53×10^{-10}
U(VI)	0.020	3.0×10^{-5}	7.7×10^{-4}	4.26×10^{-10}
Th(IV)	10.0	0.70	2.6	1.53×10^{-10}
Pu(III)	0.40	0.02	0.09	3.00×10^{-10}
Pu(IV)	10.0	0.70	2.6	1.53×10^{-10}
Am(III)	0.40	0.02	0.09	3.00×10^{-10}

[1] See Attachment MASS

Table 6-23. Culebra Parameters Required for SECOTP2D

Parameter (units)	Maximum	Minimum	Median or Constant
Advective porosity (percent)	1.0	0.01	0.10
Diffusive porosity (percent)	25.0	10.0	16.0
Half matrix block length (meters)	0.50	0.05	0.275
Longitudinal dispersivity, αL (meters)	–	–	0
Transverse dispersivity, αT (meters)	–	–	0
Grain density (cubic kilograms per cubic meter)	–	–	2.82
Effective thickness (meters)	–	–	4.0
Fracture tortuosity (unitless)	–	–	1.0
Diffusive tortuosity (unitless)	–	–	0.11

In summary, the conceptual model for dissolved actinide transport includes the following: transport in advective porosity, physical retardation (diffusion) into diffusive porosity, chemical retardation (sorption) in diffusive porosity, homogeneous rock properties, and a linear isotherm to describe the sorption process. Some of the more important parameters are advective porosity, diffusive porosity, tortuosity, matrix block length, molecular diffusion coefficients, K_d, and the grain density of dolomite in the Culebra.

6.4.6.2.2 Transport of Colloidal Actinides in the Culebra

Colloidal particles are subject to many of the same processes that affect dissolved actinides, but because of their size, several additional processes affect them. There are three process differences. Colloidal particles in general are preferentially carried in the center of pore throats by faster-moving fluid, which could cause slightly increased rates of transport compared to dissolved species. Colloidal particles can be filtered from flowing groundwater when they encounter small-aperture features in the pore network. Finally, colloidal particles may undergo different sorption processes than dissolved species.

The primary distinction in the transport behavior of the different colloidal particles is whether particles diffuse into the matrix from fractures. This is controlled by the difference between the size of colloidal particles and the mean pore-throat diameters in the diffusive porosity of the Culebra. Colloidal particles that are smaller than the pore throats can diffuse into the diffusive porosity. Actinide intrinsic colloids and humic materials are small enough for this to occur. The conceptual model for these particles includes the processes of advection, diffusion, and dispersion in the advective porosity; diffusion into diffusive porosity; and sorption of actinides in diffusive porosity. This model is analogous to that specified for dissolved actinides, although the parameter values are different. The conceptual model assumes that other retardation processes (for example, filtration) will not occur for actinide-intrinsic colloids and humic materials.

In contrast, colloidal particles larger than pore throats will be excluded from the matrix and will remain in advective porosity. Microbes and mineral fragments are conceptualized as larger than the mean pore-throat diameter in Culebra diffusive porosity. The conceptual model for these particles includes the processes of advection and filtration by small-aperture features that occur within advective porosity. See Appendix PA, Attachment MASS, CCA Section MASS.15.3 for additional discussion.

Experiments demonstrated that mineral fragments and microbes are attenuated so effectively by the advective porosity in the Culebra that it was unnecessary to include those colloids in PA calculations. Under the neutral to slightly basic geochemical conditions expected in the Culebra, humic substances did not influence the sorption behavior of dissolved actinides. Therefore, actinides associated with humic substances were treated as dissolved species in the PA calculations. The only actinide-intrinsic colloid found in significant concentrations was Pu(IV)-polymer. At the WIPP, the total amount of Pu(IV)-polymer introduced to the Culebra was insignificant with respect to the EPA normalized release limit, and so was not included in transport calculations. See Appendix PA, Attachment SOTERM (Section SOTERM-6.0) and Appendix PA, Attachment MASS (Section MASS-15.3.1) for details. See Appendix PA, Attachment MASS (Section MASS-15.3.3) for alternative modeling approaches considered.

Indigenous microbes, humics, and mineral fragment colloids in the Culebra may react with dissolved actinides introduced to the Culebra to create new colloidal actinides. Newly formed actinide-bearing microbial and mineral colloids, however, will be attenuated similarly to colloidal actinides introduced from the repository. Therefore, disregarding the impact of newly formed microbial and mineral fragment colloidal actinides is conservative. Experimental results indicate that humics do not interact with dissolved actinides under Culebra geochemical conditions. Consequently, the quantity of newly formed humic actinides will be insignificant.

6.4.6.2.3 Subsidence Due to Potash Mining

Subsidence effects caused by potash mining are included in this PA because of specific criteria in the EPA's 40 CFR Part 194. To incorporate the effects of subsidence caused by mining, PA uses the conceptual model provided by EPA in 40 CFR Part 194 and supporting documents.

The conceptual model for mining is based on information found in 40 CFR § 194.32 (b) and (c) and clarified in the Preamble and Background Information. These subparts of Section 194.32 (b) and (c) state:

> (b) Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that the mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such minerals resources shall be assumed to occur only once during the regulatory time frame.
>
> (c) Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are reasonably expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

Section 194.32 establishes assumptions as to what gets mined, when it gets mined, and the effects of mining on the disposal system—a conceptual model. Within the disposal system, mineral resources similar in quality and type to those currently mined outside the disposal system may be mined at an uncertain time in the future. Outside the disposal system, mineral resources reasonably expected to be mined in the near future should be assumed to be mined. These effects are included in analyses of both disturbed and undisturbed performance. Inside the disposal system, whether and when a mining event occurs after the active institutional control period is determined by a probabilistic model. Outside the disposal system, what is reasonably expected to be mined is assumed to be mined by the end of WIPP disposal operations. With respect to consequence analysis, mining affects only the hydraulic conductivity of the disposal system units.

The DOE has identified areas assumed to be mined in a manner consistent with the conceptual model and other guidance presented by the EPA in 40 CFR Part 194. The only natural resource currently mined near WIPP is potash in the McNutt, and it is the only mineral considered for future mining. Appendix PA, Attachment TFIELD, Section 9 describes the method used to determine the extent of mining in the McNutt both inside and outside the disposal system. This description also presents additional relevant discussion by the EPA on the extent of mining. The extent of mining outside the disposal system used in this PA is shown in Figure 6-19. It is based on the map of existing leases presented in Chapter 2.0 (Figure 2-44), setbacks from existing boreholes, and the presence of ore in the lease (see Appendix PA, Attachment MASS, Section MASS-15). Inside the disposal system, a region that could be mined in the future is specified based exclusively on the quality and type of ore present. This region was presented in Figure 2-45 (see Chapter 2.0).

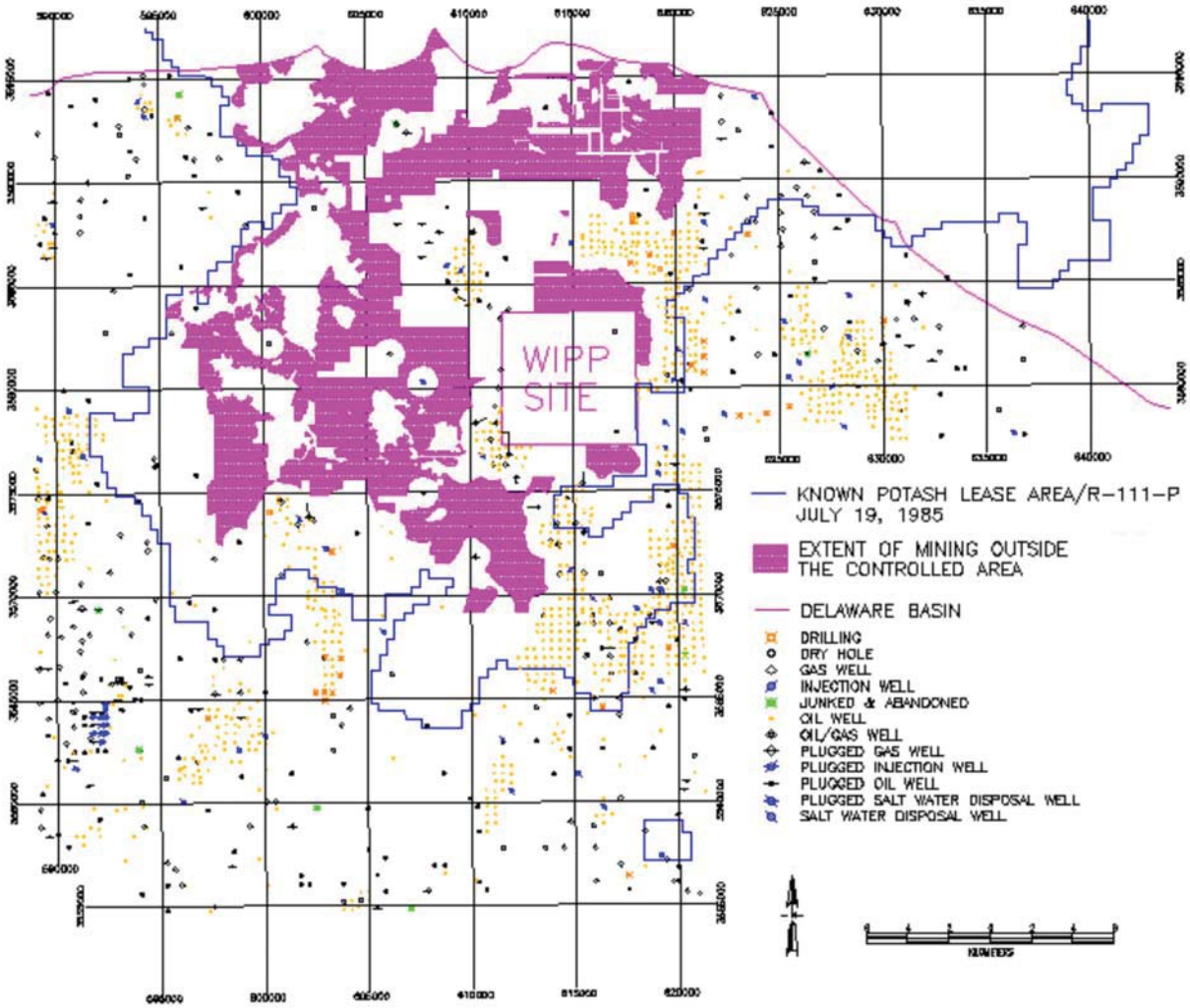

Figure 6-19. Extent of Mining in the McNutt in Undisturbed Performance within MODFLOW-2000 Regional Model Domain

The EPA clarified its conceptual model on the effects of mining on hydraulic conductivity of the disposal system units in the Preamble to 40 CFR Part 194 (EPA 1996a, 61 FR 5229). The EPA states

> Some natural resources in the vicinity of WIPP can be extracted by mining. These natural resources lie within the geologic formations found at shallower depths than the tunnels and shafts of the repository and do not lie vertically above the repository. Were mining of these resources to occur, this could alter the hydrologic properties of overlying formations—including the most transmissive layer in the disposal system, the Culebra dolomite—so as to either increase or decrease groundwater travel times to the accessible environment. For the purposes of modeling these hydrologic properties, this change can be well represented by making corresponding changes in the values for the hydraulic conductivity. The Agency has conducted a review of the data and scientific literature discussing the effects mining can induce in the hydrologic properties of a

> formation. Based on its review of available information, the Agency expects that mining can, in some instances, increase the hydraulic conductivity of overlying formations by as much as a factor of 1,000, although smaller and even negligible changes can also be expected to occur. Thus, the final rule requires DOE to consider the effects of mining in performance assessments. In order to consider the effects of mining in performance assessments, the DOE may use the location-specific values of hydraulic conductivity, established for the different spatial locations within the Culebra dolomite, and treat them as sampled parameters varying between unchanged and increased 1,000-fold relative to the value that would exist in the absence of mining.

This section adds four important clarifying concepts. First, the EPA concluded that there are no minerals vertically above the repository similar in quality and type to those currently extracted elsewhere in the Delaware Basin. Second, the EPA does not draw conclusions about whether mining will increase or decrease groundwater travel times to the accessible environment. Third, it may be assumed that the important effects of change in hydraulic conductivity occur only in the Culebra. Fourth, the spatially variant hydraulic conductivities established in the Culebra by the DOE may be multiplied, where impacted by mining, by a factor from 1 to 1,000. The DOE applied EPA's guidance regarding hydraulic conductivity to the transmissivity at Culebra locations.

In using the EPA's conceptual model for mining, the DOE makes assumptions with respect to two topics in order to formulate the mathematical model. The angle of draw is a parameter necessary to translate the area mined in the McNutt to the area affected in the Culebra. In its Background Information Document for 40 CFR Part 194, the EPA discusses the possible range in the value of angle of draw (EPA 1996b, 9-36). The DOE examined the Background Information for 40 CFR Part 194 (see EPA 1996b, 9-47) and concluded that a 45° angle of draw is the value most consistent with the EPA's discussions and calculations. Second, the Agency does not specify a distribution to the multiplicative factor. As discussed in Appendix PA, Attachment PAR (Parameter 46), the DOE has assigned a uniform distribution to this variable. As discussed in the introduction to Appendix PA, Attachment PAR, a uniform distribution is appropriate when only lower and upper bounds of the range are known.

Applying the angle of draw to the mined areas presented in 6-20 and 6-21 makes the area impacted in the Culebra larger than the area actually mined in the McNutt. The area in the Culebra impacted by mining is shown in Figure 6-20 for outside the controlled area, and in Figure 6-21 for inside and outside the controlled area. These figures are plotted on the regional domain of the MODFLOW-2000 model, which calculated the effects of subsidence caused by mining on flow directions and rates in PA.

The effects of mining outside the disposal system are included in the undisturbed performance scenario, and, therefore, the effects are included in all scenarios. In other words, all calculations of transport in the Culebra include the effects of mining outside the controlled area. This is the undisturbed mining case because mining within the controlled area has not occurred.

These effects are incorporated by multiplying location-specific values in the transmissivity field in the area labeled "Mining Zones " in Figure 6-21 by a factor (mining multiplier) between 1 and 1,000 that is randomly sampled in LHS. The same factor is applied to all affected nodal blocks. In every vector of the LHS, the steady-state flow fields used in the 10,000-year transport simulation incorporate this change to the transmissivity field. These simulations, followed by a

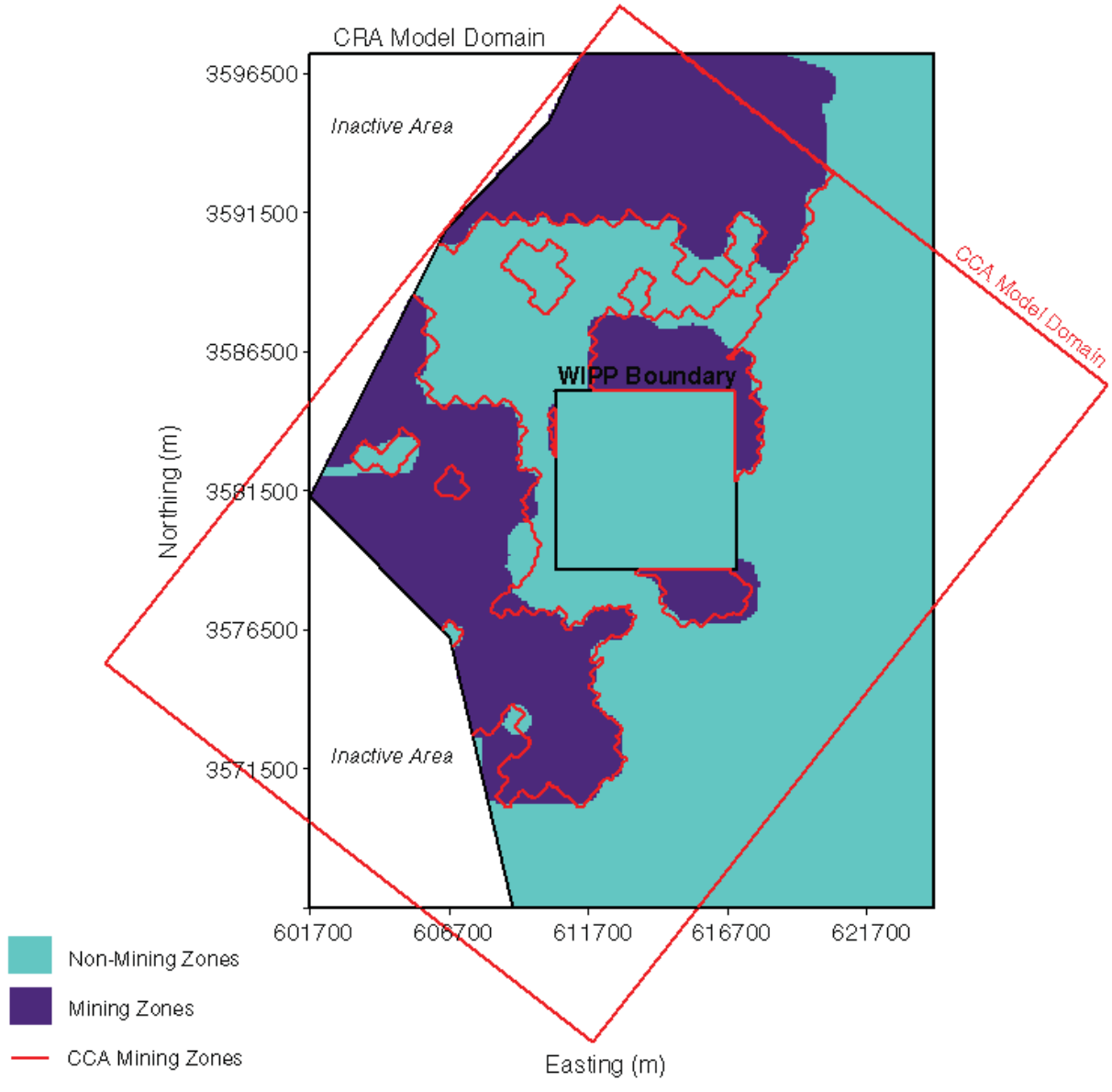

Figure 6-20. Extent of Impacted Area in the Culebra from Mining in the McNutt Potash Zone of the Salado Outside the Controlled Area for Undisturbed Performance

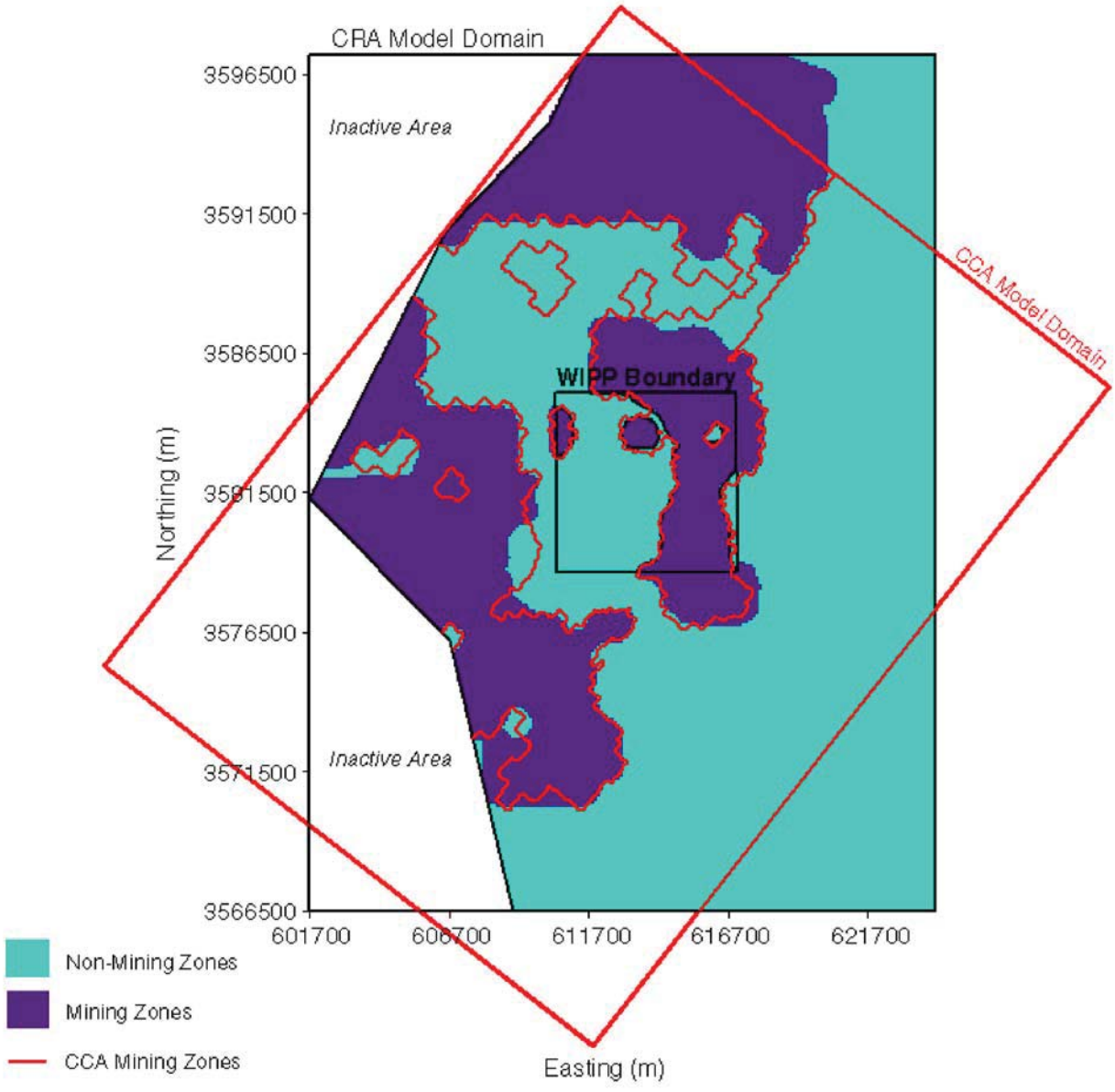

Figure 6-21. Extent of Impacted Area in the Culebra for Disturbed Performance if Mining in the McNutt Potash Zone of the Salado Occurs in the Future Within and Outside of the Controlled Area

transport simulation (as discussed in preceding sections), develop reference conditions for the transport of actinides in the Culebra in the undisturbed mining case.

If mining occurs within the controlled area, an area of the Culebra inside and outside the disposal system is affected. This is the disturbed mining case. To evaluate the impact of disturbed mining, a second simulation of Culebra flow directions and rates is executed. In this second simulation, the affected location-specific values in the transmissivity field within the controlled area are multiplied by the same mining multiplier used for the undisturbed mining case outside the controlled area. These simulations, followed by a transport simulation (as discussed in preceding sections), develop reference conditions (see Section 6.4.11) for transporting actinides following mining inside the controlled area.

The implementation of the EPA's probability model for future mining is presented in Section 6.4.12.8. A discussion of how the reference simulations for the undisturbed and disturbed mining cases are used in CCDF construction is presented in Section 6.4.13.

6.4.6.3 The Tamarisk

The Tamarisk (Row 27 in Figures 6-14 and 6-15) rests between the more transmissive Culebra and Magenta. An in-situ hydraulic test determined that the transmissivity of the Tamarisk is lower than the transmissivity of the Los Medaños (see Section 2.2.1.4.1.3). This low transmissivity is consistent with expectations because of its anhydrite, gypsum, and clay composition (see Section 2.1.3.5.3). In PA, this member is treated as impermeable. This may cause increased flow through the adjacent Culebra and Magenta. This treatment is considered conservative in that allowing flow from the intrusion borehole or shaft into the Tamarisk would, if anything, decrease flow into the Culebra, which would reduce the consequence of radionuclide release to the Rustler. In PA, the thickness of the Tamarisk is assumed to be 24.8 m (81.4 ft) and its permeability is effectively zero (Appendix PA, Attachment PAR).

6.4.6.4 The Magenta

The Magenta is described in Sections 2.1.3.5.4 and 2.2.1.4.1.4 and is shown as Row 28 in Figures 6-14 and 6-15. Transport of actinides through the Magenta to the accessible environment is not modeled. The assumption that no releases will occur from the Magenta is based on the hydraulic test results from wells on the WIPP site (Beauheim 1987, 110-118), which indicate that the Magenta is a porous medium with no hydraulically significant fractures (in contrast to the Culebra), and that its conductivity is lower than that of the Culebra. Early numerical simulations of flow and transport in the Magenta suggested much slower transport than in the Culebra (Barr et al. 1983, 26-27). Therefore, no radionuclides entering the Magenta will reach the accessible environment boundary within the 10,000-year time frame. Accordingly, the BRAGFLO model geometry reasonably approximates the effects of Magenta flow. The Magenta permeability is chosen conservatively as the lowest of measured values near the center of the WIPP site, in order to yield a lower reasonable amount of brine (and radionuclide) storage within the Magenta while continuing to yield an upper bounding flow into the Culebra. The volumes of brine and radionuclides to be stored in the Magenta are tracked and documented, however. Magenta parameter values are summarized in Table 6-24 and are described in more detail in Appendix PA, Attachment PAR.

6.4.6.5 The Forty-niner

In evaluations of radionuclide transport, flow in the Forty-niner is considered insignificant because of its low transmissivity (see Section 2.2.1.4.1.5). As with the Tamarisk and Los Medaños, the Forty-niner is assigned a permeability of effectively zero in PA (Appendix PA, Attachment PAR). This treatment is considered conservative because allowing flow from the intrusion borehole or shaft into the Forty-niner would, if anything, decrease flow into the Culebra, which would reduce the consequence of radionuclide release to the Rustler. Its modeled thickness is 17.3 m (56.8 ft). It is shown as Row 29 in Figures 6-14 and 6-15.

6.4.6.6 Dewey Lake

Release of actinides to the accessible environment from transport in the Dewey Lake is assumed not to occur even if contaminated brine reaches the unit, because the sorptive capacity of this unit appears large. This assumption is based on an analysis (Wallace et al. 1995) that demonstrated that the potential sorption capacity of the Dewey Lake is sufficient to prevent releases for 10,000 years. This analysis consisted of (1) a literature review on the sorptive capacity of redbeds and (2) an estimate of the minimum sorption required to prevent actinide releases that enter the Dewey Lake to the accessible environment in 10,000 years.

Comparison of the sorption values for the Dewey Lake analogues established by literature review with the minimum sorption required to prevent release indicates that the likely sorptive capacity of the Dewey Lake is orders of magnitude greater than required to prevent release. Therefore, the DOE assumes that chemical retardation occurring in the Dewey Lake will prevent release within 10,000 years of any actinides that might enter it. Geological and hydrological information on the Dewey Lake is presented in Sections 2.1.3.6 and 2.2.1.4.2, respectively. Dewey Lake parameter values are summarized in Table 6-25 (see also Appendix PA, Attachment PAR). The Dewey Lake is shown in Figures 6-14 and 6-15.

Table 6-24. Model Parameter Values for the Magenta

Parameter (units)	Minimum	Maximum	Mean or Constant
Permeability (square meters)			6.31×10^{-16}
Effective porosity (percent)	2.7	25.2	13.8
Rock compressibility (1/pascals) [1]	1.16×10^{-10}	4.55×10^{-10}	2.64×10^{-10}
Threshold pressure, P_t (pascals) [2]			5.06×10^{4}
Residual brine saturation, S_{br} (unitless)			0.084
Residual gas saturation, S_{gr} (unitless)			0.077
Pore distribution parameter, λ (unitless)			0.644
Maximum capillary pressure			10^{8}
Thickness (meters)			8.5
Initial pressure (pascals)			9.47×10^{5}

[1] Pore compressibility = rock compressibility/effective porosity.

[2] Threshold Pressure (P_t) determined from the relationship: $PCT_A \cdot k^{PCT_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

Table 6-25. Dewey Lake Parameters for the BRAGFLO Model

Parameter (units)	Minimum	Maximum	Mean or Constant
Permeability (square meters)			5.01×10^{-17}
Effective porosity (percent)	3.5	24.8	14.3
Rock compressibility (1/pascals) [1]			10^{-8}
Threshold pressure, P_t (pascals) [2]			0
Residual brine saturation, S_{br} (unitless)			0.084
Residual gas saturation, S_{gr} (unitless)			0.077
Pore distribution parameter, λ (unitless)			0.644
Maximum capillary pressure (pascals)			10^8
Thickness (meters)			149.3
Initial pressure (below water table at 980 m, 43.3 m below top of formation) (pascals)			hydrostatic
Initial pressure, 20% liquid saturation above water table (atmospheres)			1

[1] Pore compressibility = rock compressibility/effective porosity.

[3] Threshold pressure (P_t) determined from the relationship: $PCT_A \cdot k^{PCT_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

6.4.6.7 Supra-Dewey Lake Units

The units overlying the Dewey Lake are discussed in Sections 2.1.3.7 through 2.1.3.10 and are shown as Rows 32 and 33 in Figures 6-14 and 6-15. Because these units are thin and predominantly unsaturated at the WIPP site, brine that might enter from the borehole (assuming brine can reach this elevation) is assumed to flow downward to the Dewey Lake, where any actinides will be sorbed. These units are included in BRAGFLO, however, and the possibility of actinide transport into them from a borehole is considered in the PA. Actinide transport within the Supra-Dewey Lake units is not modeled, and it is assumed that there can be no actinide release to the accessible environment through these units. For PA, the units overlying the Dewey Lake are represented as a single hydrostratigraphic unit whose parameters are shown in Table 6-26.

6.4.7 The Intrusion Borehole

In accordance with the requirements of 40 CFR § 194.33(b)(1), DOE models consequences of inadvertent and intermittent intrusion into the repository during drilling for natural resources as the most severe human intrusion scenario that could affect long-term performance of the disposal system. This section discusses the conceptual models used for drilling (particulate release during drilling, direct brine release during drilling, and long-term brine flow) and refers to appropriate discussions of numerical modeling codes.

This section does not address the likelihood that inadvertent human intrusion will occur.

Table 6-26. Supra-Dewey Lake Unit Parameters for the BRAGFLO Model

Parameter (units)	Value
Permeability (square meters)	10^{-10}
Effective porosity (percent)	17.5
Rock compressibility (1/pascals) [1]	5.71×10^{-8}
Threshold pressure, P_t (pascals) [2]	0
Residual brine saturation, S_{br} (unitless)	0.084
Residual gas saturation, S_{gr} (unitless)	0.077
Pore distribution parameter, λ (unitless)	0.644
Maximum capillary pressure (pascals)	10^8
Thickness (meters)	15.76
Initial pressure, 8.36% liquid saturation (atmospheres)	1

[1] Pore compressibility = rock compressibility/effective porosity.

[2] Threshold pressure (P_t) determined from the relationship: $PCT_A \cdot k^{PCT_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

The DOE's treatment of the probability of inadvertent human intrusion is discussed in Section 6.4.12.

Human intrusion scenarios require simulating penetration of an intrusion borehole into the waste disposal region. There are two effects associated with drilling: releases from the drilling itself and possible releases from the long-term effects on fluid flow in the disposal system after the borehole casing and plugs have degraded. Both types of releases are estimated for two different types of intrusions: those that intersect pressurized brine in the Castile (E1 events; see Section 6.3.2.2.2), and those that do not (E2 events: see Section 6.3.2.2.1).

6.4.7.1 Releases During Drilling

Consistent with the criterion of 40 CFR § 194.33(c)(1), releases that may occur during and immediately following the drilling event are modeled assuming that future drilling practices will be the same as at present (see CCA Appendix DEL, Sections DEL.5, DEL.6 and Appendix DATA, Section 2.0 and DATA, Attachment A, for a complete description of historical and present drilling practices). Figure 6-22 shows a schematic representation of a standard rotary drilling operation inadvertently penetrating the repository. A drill bit is attached to the bottom of a string of steel pipe, the lowest segments of which are reinforced collars. The drill bit, collars, and pipe are collectively referred to as the drill string. As the drill string rotates, liquid, referred to as drilling mud, is pumped down the interior of the pipe and out through the bit. The drilling fluid cools and lubricates the bit and then returns to the surface outside the pipe in the annulus between the pipe and the borehole wall.

During its return flow, the mud carries the cuttings to the surface where they settle out in a mud pit. The mud is typically a water-based brine that is weighted with additives to maintain a hydrostatic pressure in the borehole equal to or greater than the normally anticipated fluid pressures in the formations being drilled. Salt-saturated brines are generally used in evaporites

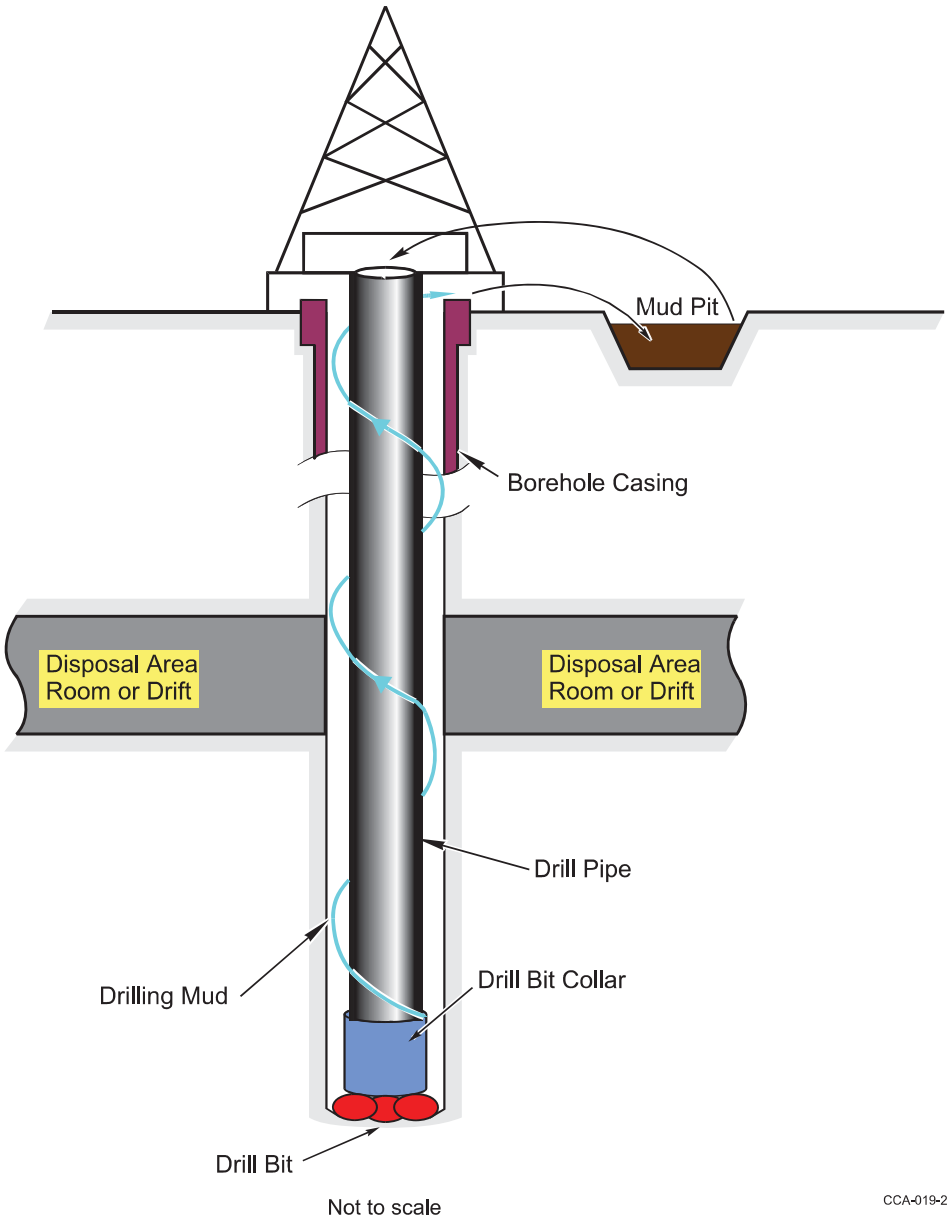

Figure 6-22. Schematic Representation of a Rotary Drilling Operation Penetrating the Repository

to prevent dissolution of the formation. Steel casing is installed in boreholes before entering the salt section to protect the near-surface units from contamination with fluids from deeper units and, after drilling through the salt section, to prevent hole closure on the drill string and subsequent in-hole hardware.

If a rotary drill bit penetrates the waste, radionuclides may be brought to the surface by four means. First, some quantity of cuttings that contain material intersected by the drill bit will be

brought to the surface. Second, cavings, which contain material eroded from the borehole wall by the circulating drill fluid, may also be brought to the surface by the circulating drilling mud. Third, releases of radionuclides may occur if the repository contains fluids at pressures higher than the pressure exerted by the drilling fluid. Spalling of waste material into the borehole may occur if high-pressure gas flows into the borehole. Brine, as well as gas, may enter the borehole from the repository if the driller is unable to control the pressure within the well or chooses not to control the pressure. The brine may flow to the surface, and if it has been in contact with waste, it may contain dissolved or suspended radionuclides.

Releases of particulate waste material (that is, cuttings, cavings, and spallings) are modeled using the CUTTINGS_S and DRSPALL codes, as described in Section 6.4.11 and Appendix PA, Sections PA-4.5 and PA-4.6 Attachment MASS (Section 16.1) discusses the conceptual basis for the model. As discussed in Section 6.4.12.4, cuttings and cavings are calculated separately for CH-TRU and RH-TRU waste, with distinct waste streams considered. Spallings are calculated as homogeneous waste obtained by averaging over all CH-TRU waste. For all releases during drilling, appropriate corrections are made for radioactive decay. Releases of dissolved or suspended radionuclides contained in brine are modeled using the BRAGFLO and PANEL codes, as described in the next section. Casing is assumed to be intact through the Rustler and overlying units during drilling, and there is assumed to be no communication between the borehole and those units. For all direct releases, actinides that enter the borehole are conservatively assumed to reach the surface.

6.4.7.1.1 Direct Brine Release During Drilling

Direct brine release refers to the possibility that brine containing actinides may flow from the waste panels up a borehole to the surface during drilling (Appendix PA, Section PA-4.7 and Attachment MASS, Section 16.2). It is conceptualized that direct brine release to the surface will not occur every time a borehole penetrates the waste panels but rather that it can occur only when two conditions are met. The first condition is the presence of mobile brine in the waste panels. Because of brine consumption by corrosion and low initial saturation, it is possible for liquid saturations below the residual saturation to exist in the repository, in which case direct brine release cannot occur. The second condition is that the pressure in the waste panels must be greater than the pressure at the base of the drilling mud column. Drillers in the Delaware Basin use a salt-saturated mud with a specific gravity of about 1.23 while drilling through the Salado. This corresponds to a pressure of approximately 8 megapascals at the repository horizon (see Appendix PA, Attachment MASS, Section 16.2 and CCA Appendix MASS, Attachment 16-2). If fluid in the waste panels is below this pressure, no direct brine release during drilling can occur because liquid flow in the repository is away from the borehole.

In the conceptual model, resolution of the details of flow near the borehole is considered important, as the changing physical conditions over the short duration of this flow can significantly impact estimates of the total volume released. It is not assumed that a direct brine release would be noticed by the driller (EPA 1996a, 61 FR 5230). Also important to the conceptual model is how long direct brine release occurs. There are several ways in which the direct brine release could be stopped. A driller might detect higher flow rate to the mud pit and take action to mitigate consequences. Alternatively, direct brine release will stop when the driller cases the hole after reaching the base of the salt section. As discussed in Appendix PA,

Section PA-4.7 and CCA Appendix DEL (Section 7.5), the DOE assumes that for low volumes of fluid flow, the borehole will be controlled and cased within 72 hours after penetrating the repository. In all cases, all fluid flow to the surface during drilling is assumed to cease within 11 days after penetrating the repository.

In the conceptual model for direct brine release, several other assumptions are related to other conceptual models. The processes of direct solids release from cuttings, cavings, spall, and direct brine release are treated separately, although the direct brine release model does account for the effects of solids removal (spall) on fluid flow near the well bore. Direct brine release will affect the pressure and saturation in the repository. However, it is assumed that these effects are negligible over the long term because of their transient and local nature; thus, they are not accounted for in long-term (10,000-year) BRAGFLO disposal system calculations. This assumption simplifies modeling because it allows detailed consideration of direct brine release over a short time period, without having to couple the results of these calculations back into the disposal system simulations.

The area over which fluid flow can occur during direct brine release is assumed to be the rooms and drifts of waste panels, the DRZ, room pillars, and panel closures. Because local-scale, short-duration flow is important, the geometry of the waste panels is considered important and is represented in the model. It is assumed that the flow interactions with the Salado other than the DRZ are unimportant during direct brine release. For this model, pillars are arbitrarily assumed to have the properties of the DRZ rather than intact halite, although in reality their properties are probably like a DRZ at their edge and intact halite in their core. Since the DRZ permeability is greater than the permeability of intact halite, this assumption is conservative. A two-dimensional geometry is used parallel to the repository horizon, with a 1 degree dip from north to south. The geometry of the grid used is shown in Figure 6-23.

The BRAGFLO code is used to calculate direct brine release; the mathematical and computational model is called the BRAGFLO direct brine release model (Appendix PA, Section PA-4.7). The initial and boundary conditions for this model are derived from the corresponding BRAGFLO disposal system simulation through several codes, including CUTTINGS_S. Some of the parameters derived from the BRAGFLO disposal system model are permeabilities, porosities, two-phase flow properties, and the height of the waste region. Initial saturations and pressures in the BRAGFLO direct brine release model are mapped from the BRAGFLO disposal system model. Other parameters used in the BRAGFLO direct brine release models are consistent with those used in the BRAGFLO disposal system model (Appendix PA, Section PA-4.7).

It is possible that a direct brine release could occur from a panel connected by a previously-drilled, abandoned borehole to a brine reservoir in the Castile. If this happened, flow directly between the two boreholes, analogous to the E1E2 scenario for long-term performance, might affect the estimate of the total brine released. The direct brine release for this possibility is calculated by BRAGFLO (direct brine release) by placing a

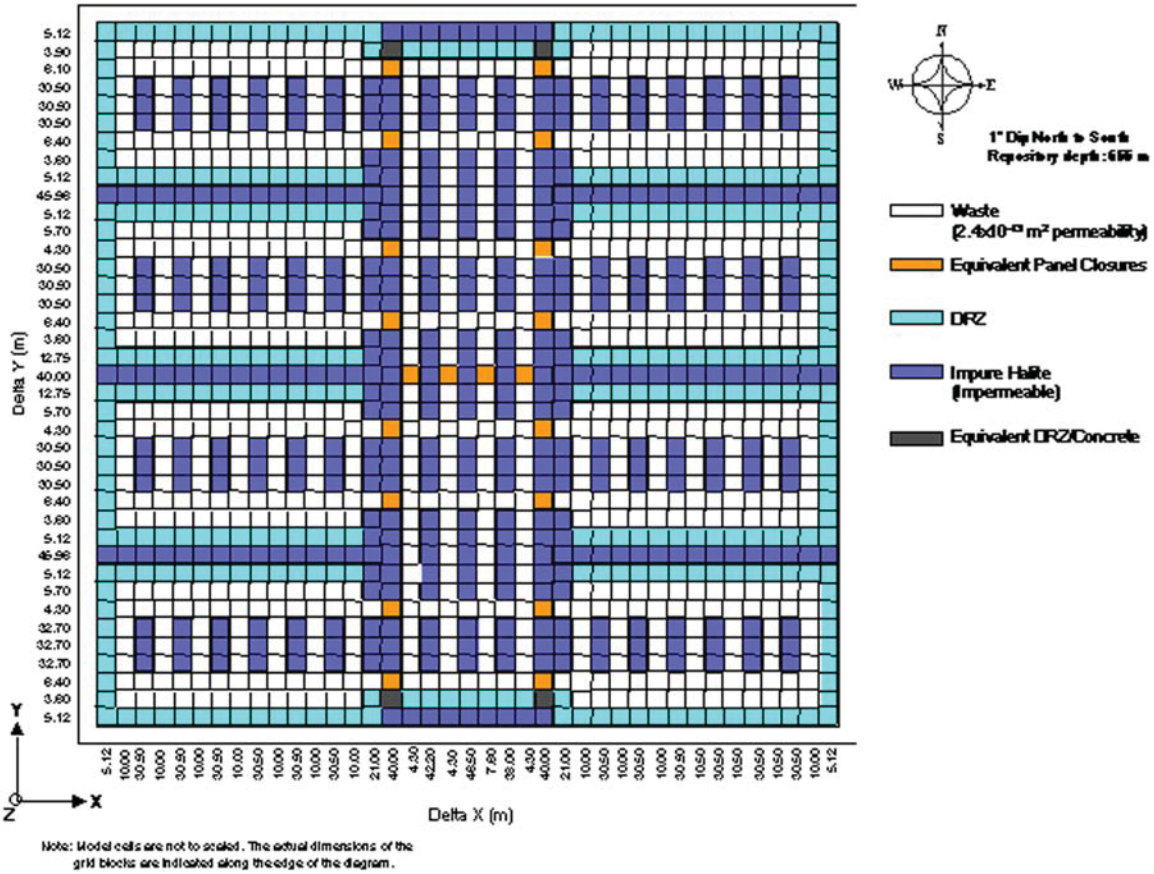

Figure 6-23. Repository-Scale Horizontal BRAGFLO Mesh Used for Direct Brine Release Calculations

constant-pressure, flowing injection well as a boundary condition in the model. The locations of these boreholes are shown in Figure 6-23. It is assumed that a direct brine release from a panel with a previously-drilled, abandoned borehole of the E2 type is unaffected by the presence of the other borehole. Thus, reference direct brine release conditions are calculated for previously unintruded and E2-intruded panels, and for previously-intruded E1 panels. Details about the properties assigned to the flowing-well boundary condition are discussed in Appendix PA, Section PA-4.7. Details about how the consequences of direct brine releases from other possible combinations of boreholes are accounted for in the CCDF are discussed in Section 6.4.13.

A borehole could penetrate the repository anywhere. For simplification, the BRAGFLO direct brine release model assumes that calculating direct brine release from several defined locations provides meaningful reference results for the possible variation in release because of location. The locations of boreholes from which representative results are calculated are indicated in Figure 6-23. In construction of a CCDF (see Section 6.4.13), the direct brine release associated with a borehole whose position is randomly selected is correlated with the reference release most consistent with the geometry near the location of the random borehole.

Accurate representation of the flow into the borehole is important in the BRAGFLO direct brine release model. Accordingly, a number of mathematical methods that are not used to calculate

long-term releases are applied to the conditions in the borehole for calculating direct brine releases. The methods used appear in Appendix PA, Section PA-4.7.

6.4.7.2 Long-Term Releases Following Drilling

Long-term releases to the ground surface or into groundwater in the Rustler or overlying units may occur after the hole has been plugged and abandoned (Appendix PA, Attachment MASS, Section 16.3). As required by regulation, the plugging and abandonment of future boreholes are assumed to be "consistent with practices in the Delaware Basin at the time a compliance application is prepared" [40 CFR § 194.33(c)(1)]. Examining current practices in the Delaware Basin indicates that all boreholes abandoned recently are plugged to meet state and federal regulatory requirements protecting groundwater and natural resources (see Appendix DATA, Section DATA-2.0 and Attachment A; CCA Appendix DEL, Sections DEL.5.5 and DEL.6]; Appendix PA, Attachment MASS, Section MASS-16.3). These plugs will effectively prevent flow in abandoned boreholes for some period of time after emplacement. However, some plugs may fail and radionuclides may be transported in brine flowing up the borehole.

Borehole plug configurations used today in the Delaware Basin vary based on the local stratigraphy encountered in the hole, its total depth, and the types of fluids present. All holes are plugged with some combination of solid concrete plugs isolating different fluid-bearing horizons from each other and from the ground surface. As discussed in detail in Appendix PA, (Attachment MASS (Section 16.3), SNL (2003),) and CCA Appendix DEL (DEL Attachment 7), six different plug configurations are identified that are potentially relevant to future borehole abandonment practice at the WIPP. As discussed in Appendix PA, Attachment MASS (Section 16.3.3) and SNL (2003), these six plug configurations can be approximated for PA by three conceptual plugging patterns. The three plugging configurations addressed in the PA are described in the following section. Probabilities of occurrence for each of these three plugging configurations are discussed in Section 6.4.12.7. Parameters used to describe the borehole and its plugs are summarized in Table 6-27.

6.4.7.2.1 Continuous Concrete Plug through the Salado and Castile

In this configuration, a continuous concrete plug is assumed to exist throughout the Salado and Castile (Appendix PA, Attachment MASS, Section 16.3 and SNL (2003). Such a plug could be installed in keeping with current regulatory requirements of the New Mexico Oil Conservation Division Order R-111-P (State of New Mexico 1988, 10), which is applicable within the potash leasing area that includes the WIPP site. The continuous plug protects potash mining operations from possible hydrocarbon contamination. A continuous concrete plug is also used to approximate flow in boreholes with numerous concrete plugs throughout the salt section.

Examples of such plugging configurations currently used in the Delaware Basin are described in Appendix PA, Attachment MASS, Section 16.3.

Because concrete within a continuous plug will be physically confined and will have very little brine flow through it, degradation will be minimal and limited to the upper and lower ends of the plug (see Appendix PA, Attachment MASS, Section 16.3.3, Appendix C). For the CCA PA the

Table 6-27. Intrusion Borehole Properties for the BRAGFLO and CUTTINGS_S Models

Parameter (units)	Maximum	Minimum	Median or Constant [1]
Permeability of open hole (0 to 200 years) (square meters)	–	–	10^{-9}
Permeability of concrete plugs (0 to 200 years in Rustler and at surface) (square meters) [2]	1×10^{-17}	1×10^{-19}	10^{-18}
Permeability of borehole fill material (>200 years) (square meters) [2]	1×10^{-11}	1×10^{-14}	3.16×10^{-13}
Permeability of lower borehole fill material (>1,200 years) (square meters) [2]	1×10^{-12}	5×10^{-17}	2.24×10^{-14}
Effective porosity (percent)	–	–	0.32
Pore compressibility (1/pascals)	–	–	0
Diameter (meters)	–	–	0.311
Threshold pressure, P_t (pascals)	–	–	0
Pore distribution parameter, λ (unitless)	–	–	0.94
Residual brine saturation, S_{br} (unitless)	–	–	0
Residual gas saturation, S_{gr} (unitless)	–	–	0

[1] Parameters with no maximum and minimum values are treated as constants in the PA.
[2] Borehole permeabilities are for the two-plug case. Continuous three-plug case is treated as undisturbed performance.

permeability of the continuous concrete plug was 5×10^{-17} m^2 for all the plugging configurations. For this application, the DOE adopted EPA's 1997 PAVT range of 10^{-17} to 10^{-19} m^2. Because of the small cross-sectional area and low permeability of the potential pathway, long-term releases through a continuous concrete plug are not calculated explicitly for the PA, and are assumed to be zero.

6.4.7.2.2 The Two-Plug Configuration

In the two-plug configuration, two concrete plugs are assumed to have a significant effect on long-term flow in the borehole (Appendix PA, Attachment MASS, Section16.3 and CCA Appendix MASS Attachment 16-3, Figure 2). The lower plug of interest is assumed to be located somewhere between the hypothetical Castile brine reservoir and underlying formations. A second plug is located within the lower portion of the Rustler, immediately above the Salado. Additional plugs that have little effect on long-term flow are also assumed to be present deeper in the hole and at the land surface.

In E1-type intrusions with two plugs, the brine reservoir and the repository are assumed to be in direct communication through an open cased hole immediately following drilling. The plugs are located in the borehole Column 26 of the BRAGFLO mesh in Figure 6-15 in Rows 32 and 33 (the surface plug) and Row 25 (the Los Medaños). The plugs located below the brine reservoir are not modeled explicitly. Plugs are assigned initial sampled permeabilities of 10^{-17} to 10^{-19} square meters pursuant to EPA's 1997 PAVT parameters. The open segments of borehole between the plugs are assigned an initial permeability of 10^{-9} m^2. Steel casing above the Salado is assumed to begin to degrade within decades after abandonment and is assumed to have failed

completely after 200 years. The concrete plugs above the Salado are also assumed to fail after 200 years, as a result of chemical degradation where they are in contact with brine. The plug below the Castile brine reservoir is in a less aggressive chemical environment, and its properties remain constant in PA.

After the upper plugs and casing have failed, the borehole is assumed to be filled by a silty, sand-like material containing degraded concrete, corrosion products, and material that sloughs into the hole from the walls. Thus, 200 years after the time of intrusion, the entire borehole region in the BRAGFLO model, including the sections previously modeled as concrete plugs, is assigned a permeability corresponding to silty sand. This permeability is sampled from a log-uniform distribution from 10^{-11} square meters to 10^{-14} square meters.

One thousand years after the plug at the base of the Rustler has failed, permeability of the borehole region below the waste-disposal panel in the BRAGFLO model used for E1-type intrusions is decreased from its sampled value by one order of magnitude. For the remainder of the 10,000-year period, the borehole is modeled with its sampled permeability value above the repository and the adjusted value below. Conceptually, the decrease in permeability below the panel corresponds to compaction of the silty, sand-like material by partial creep closure of the borehole's lower portion. As discussed in Appendix PA, Attachment MASS, Section 16, creep closure of boreholes will not be significant above the repository horizon but will be effective at greater depths because of the greater lithostatic stress. Nowhere in the borehole is creep closure assumed to close the hole completely in the regulatory time frame, but closure will be sufficient at depths below the repository to reduce the permeability of the material filling the hole.

6.4.7.2.3 The Three-Plug Configuration

In the three-plug configuration, three concrete plugs are assumed to affect long-term flow in the borehole (Appendix PA, Attachment MASS, Section 16.3). Two of the plugs are identical to those modeled in the two-plug configuration. The third plug is located within the Castile above the brine reservoir and below the waste-disposal panel. This plug is assumed to behave the same as the lower plug in the two-plug configuration: that is, its properties remain unchanged in PA. Otherwise, all portions of the borehole in the three-plug configuration are assumed to have the same material properties as the corresponding regions in the two-plug configuration, with adjustments to borehole-fill permeability occurring 1,000 years after failure of the overlying plug (Appendix PA, Attachment MASS, Section).

Because the three-plug configuration isolates the repository from the brine reservoir for the time period during which the middle plug remains effective, and because the portion of the borehole above the middle plug will already be filled with silty, sand-like material before the middle plug fails, the DOE chose not to model this configuration explicitly in the BRAGFLO calculations. Boreholes in which the three-plug configuration is emplaced are assumed to result in long-term releases comparable to those calculated for E2 intrusions, regardless of whether they penetrate a Castile brine reservoir. Consequences of E1-type intrusions with the three-plug configuration are assumed for the purposes of CCDF construction to be identical to those of E2 intrusions occurring at the same time.

6.4.8 Castile Brine Reservoir

As discussed by Section 2.2.1.2.2, high-pressure Castile brine was encountered in several WIPP area boreholes, including the WIPP-12 borehole within the controlled area and the ERDA-6 borehole northeast of the site. Consequently, the conceptual model for the Castile includes the possibility that brine reservoirs underlie the repository. The E1 and E1E2 scenarios include borehole penetration of both the repository and a brine reservoir in the Castile. The properties of the borehole are discussed in Section 6.4.7.

Unless a borehole penetrates both the repository and a brine reservoir in the Castile, the Castile is conceptually unimportant to PA because of its expected low permeability. Two regions are specified in the Castile horizon in the disposal system geometry: the Castile (Rows 1 and 2 in Figure 6-14) and a reservoir (Row 1, Columns 23 to 45 in Figure 6-15). The Castile region has an extremely low permeability, which prevents it from participating in fluid flow processes.

It is unknown whether a brine reservoir exists below the repository. As a result, the conceptual model for the brine reservoirs is somewhat different from those for known major properties of the natural barrier system, such as stratigraphy. The principal difference is that a reasonable treatment of the uncertainty of the existence of a brine reservoir requires assumptions about the spatial distribution of such reservoir and the probability of intersection (see Appendix MASS, Section MASS.18.1 and CCA MASS Attachment 18-6 for the development of the probability used in the CCA). The EPA required the DOE to use a range of probabilities for a borehole hitting a brine reservoir of 0.01 to 0.60 in the 1997 PAVT (EPA 1998, VII.B.4.d). The DOE added a parameter representing this range of subjective uncertainty for the CRA-2004 PA (Appendix PA, Section PA-3.5).

In addition to the stochastic uncertainty in the location and hence in the probability of intersecting reservoirs, there is also uncertainty in the properties of reservoirs. The manner in which brine reservoirs would behave if penetrated is treated as subjective uncertainty (see Section 6.2.2), and is incorporated in the BRAGFLO calculations of disposal system performance. The conceptual model for the behavior of such brine reservoir is discussed below.

Where they exist, Castile brine reservoirs in the northern Delaware Basin are believed to be fractured systems, with high-angle fractures spaced widely enough that a borehole can penetrate through a volume of rock containing a brine reservoir without intersecting any fractures and therefore not producing brine. They occur in the upper portion of the Castile (Popielak et al. 1983, G-2). Appreciable volumes of brine have been produced from several reservoirs in the Delaware Basin, but there is little direct information on the areal extent of the reservoirs or the existence of the interconnection between them. Data from WIPP-12 and ERDA-6 indicate that fractures have a variety of apertures and permeabilities, and they deplete at different rates. Brine occurrences in the Castile behave as reservoirs—that is, they are bounded systems. The properties specified for brine reservoirs are pressure, permeability, compressibility and porosity. Brine reservoir parameter values used in this PA are shown in Table 6-28.

Brine reservoir pressure in the PA is based on measured pressures in Castile and Salado anhydrites. These values are determined by analyzing brine pressures observed in Salado and Castile anhydrites, corrected for the difference in depth between the observed location and

WIPP-12. The analysis is documented in CCA Appendix MASS (Section 18 and MASS Attachments 18-1 and 18-2) and Appendix PA (Attachment PAR, Parameter 27).

Table 6-28. Parameter Values Used for Brine Reservoirs in the BRAGFLO Calculations

Parameter (units)	Maximum	Minimum	Median or Constant [1]
Permeability (square meters)	1.58×10^{-10}	2.0×10^{-15}	1.58×10^{-12}
Effective porosity (percent)	0.9208	0.1842	0.87
Rock compressibility (1/pascals) [2]	10^{-10}	2.0×10^{-11}	4×10^{-11} (mode)
Initial pressure (pascals)	1.70×10^{7}	1.11×10^{7}	1.27×10^{7}
Threshold pressure, P_t (pascals) [3]	4.59×10^{-6}	2.28×10^{-4}	4.6×10^{-5}
Pore distribution parameter, λ	–	–	0.70
Residual brine saturation, S_{br} (unitless)	–	–	0.20
Residual gas saturation, S_{gr} (unitless)	–	–	0.20

[1] Parameters with no maximum and minimum values are treated as constants in the PA.

[2] Pore compressibility = rock compressibility/effective porosity.

[3] Threshold pressure (P_t) determined from the relationship: $PCT_A \cdot k^{PCT_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

The permeability of brine reservoirs is based on analyzing brine reservoirs tested by DOE in drillholes ERDA-6 and WIPP-12 (Popielak et al. 1983, Sections H-3.4.3 and H-3.4.4). Values used in the PA are shown in Table 6-28. The derivation of these values from the referenced study is documented in Appendix PA, Attachment PAR.

The bulk compressibility range is based on a reanalysis of WIPP-12 data that was requested by the EPA in their 1997 PAVT (EPA 1998). Beauheim (1997) provides a detailed description of this analysis and parameter range.

An effective porosity is defined for the reservoir portion of the Castile in the disposal system geometry (Row 1, Columns 23 to 45 in Figure 6-15). In the EPA's 1997 PAVT (EPA 1998), the EPA specified a range of brine volumes for the reservoir based on an EPA reanalysis of the amount of brine in the reservoir encountered by WIPP-12. The analysis concluded that PA should represent a total volume of brine in the brine reservoir that ranges between 3.40×10^{6} and 1.70×10^{7} m^3. Since the brine reservoir is represented by a region of constant volume, the effective porosity is used to provide the total brine volume in the reservoir rather than representing the actual value, and is not representative of the actual host rock's porosity. This treatment results in an effective porosity range between 0.1842 and 0.9208. The effective porosity is correlated to the values for the bulk compressibility (see Appendix PA, Section 4.2.1 for a detailed discussion of this relationship).

The CRA-2004 PA treatment of brine reservoir volume and porosity is consistent with the 1997 PAVT. In contrast, the CCA PA used a discrete distribution of brine volumes in the reservoir (see CCA Appendix MASS, Section MASS.18 and MASS Attachment 18-3).

The threshold pressure, pore distribution parameter, and residual saturations are parameters describing two-phase flow behavior and are required by BRAGFLO. Because saturations in the brine reservoir remain very near 1.0 in all preliminary and current PAs, the values of these parameters were not important to the model results. The parameter values used in the CRA-2004 PA are the same as those in the 1997 PAVT.

6.4.9 Climate Change

The present climate at the WIPP and the geologic record of past climate change in southeastern New Mexico are discussed in Section 2.5 and Appendix CLI of the CCA. Although meaningful quantitative predictions of future climate for the next 10,000 years are not feasible, effects of reasonably possible climate changes on disposal system performance must be considered. For the WIPP, uncertainty about these effects is incorporated in the PA by considering the effects of various possible future climates on groundwater flow and potential radionuclide transport in groundwater. Direct effects of climate change that do not involve groundwater flow do not affect the long-term performance of the WIPP because of its depth below the land surface. Examples of such direct effects are changes in wind patterns, thermal effects related to changes in surface temperature, and near-future impacts on surface facilities. Long-term effects of climate change on the near-surface portions of the shaft seal system (see Section 6.4.4) are not incorporated in the analysis because BRAGFLO modeling indicates that system performance is unaffected by the behavior of the shaft seal system's upper portion. Additional aspects of climate change screened out from the PA, including glaciation at the site and possible future anthropogenic changes, are discussed in Appendix PA, Attachment SCR (FEPs N62 and H47 through H49).

The effects of postulated climate change on groundwater flow were evaluated outside of the PA calculations using a regional three-dimensional groundwater basin model based on the basin hydrology introduced in Section 2.2.1.1. For the regional analysis, climate-related factors that might affect groundwater flow (such as precipitation, temperature, and evapotranspiration) are treated through a single model parameter, potential recharge, which controls the rate at which water is added to the model at the water table. As described in Appendix PA, Attachment MASS, Section MASS-17.0, changes in this parameter allow simulation of regional groundwater flow under a range of different future states in which the climate may be wetter, the water table may be higher, and groundwater velocity in all units may increase. These and other simulations discussed in CCA Appendix MASS (Section MASS.15 and MASS Attachment 15-7) show that the regional, three-dimensional effects of climate change can be reasonably approximated in PA by directly scaling specific discharge in the two-dimensional, steady-state groundwater velocity field of the Culebra. The velocity field is calculated using MODFLOW-2000, as described in Section 6.4.6.2. Radionuclide transport in the Culebra is then calculated by SECOTP2D using the scaled velocity fields.

Scaling the two-dimensional velocity field is done using the Climate Index (Table 6-29), a dimensionless factor by which the specific discharge in each grid block of the SECOTP2D domain is multiplied. As summarized in Appendix PA, Attachment PAR (Parameter 48), the Climate Index is a sampled parameter in the PA with a bimodal distribution ranging from 1.00 to 1.25 and from 1.50 to 2.25. A single value of the Climate Index is chosen in LHS for each sample element and held constant throughout the 10,000-year SECOTP2D simulation. Each

realization of disposal system performance thus represents a different approximation of future climate. Those

Table 6-29. Climate Change Properties for the SECOTP2D Model

Parameter (units)	Maximum	Minimum	Median
Climate index (dimensionless)	2.25	1.00	1.17

realizations in which the sampled value is close to its maximum of 2.25 represent the most extreme changes in groundwater flow that may result from climatic change.

Sampled values close to the minimum of 1.00 represent climatic changes that have little effect on groundwater-flow velocities. Because all sampled values of the Climate Index are greater than 1.00, climate change as implemented in the PA can only increase the rate of groundwater flow.

The distribution assigned to the Climate Index parameter is based on the results of three-dimensional basin modeling that considers future changes in the temporal pattern of potential recharge (see CCA Appendix MASS, Section MASS.17 and MASS Attachment 17-1, Section F). Potential recharge is defined as the maximum rate at which water can be added at the water table. Recharge itself is a model result and ranges from zero to the potential recharge. For those areas where the water table is at the ground surface and modeling indicates that water is discharging to the land surface through a seepage face, the potential recharge does not enter the model and has no effect on groundwater flow. In areas where the water table is below the land surface, potential recharge becomes actual recharge and tends to cause the water table to rise. If potential recharge is zero, the water table in an idealized basin will tend to fall until it is a horizontal plane with an elevation equal to the lowest topographic point in the basin. Sufficiently large values of potential recharge will cause the water table to rise to the land surface everywhere. Smaller, nonzero values result in solutions with water tables at the land surface at topographic lows (discharge areas) and at some distance below the land surface at topographic highs (recharge areas). Changes in potential recharge cause the elevation of the water table to rise or fall. In the three-dimensional modeling of the WIPP region, potential recharge was assumed to be spatially invariant across the regional model domain and assumed to change through time in response to climate changes.

Both steady-state and transient three-dimensional regional analyses were executed with values of potential recharge varied so that the elevation of the water table ranged from approximately its present position to at or near the land surface. The latter condition provides an upper bound for regional groundwater-flow velocities during future wetter climates. For all simulations examining the effects of climate change, recharge is assumed to be greater at some time in the future than it is at present. Present recharge is assumed to be the same as its minimum value during the Holocene. The dominant effects on climate change during the next 10,000 years are assumed to be natural rather than anthropogenic. This assumption is consistent with regulatory guidance provided by the EPA indicating that considering the effects of climate change should be limited to natural processes (EPA 1996a, 61 FR 5227).

Because of uncertainty about recharge rates during future wet periods and the timing of these periods, transient analyses use two fundamentally different patterns for the change in potential recharge. The first pattern used in the analysis corresponds to a continuation of the inferred climate patterns of the Holocene (see Section 2.5.1 and CCA Appendix CLI, Section 3), with wetter peaks occurring 500, 2,000, 4,000, 6,000, 8,000, and 10,000 years in the future. Potential recharge is assumed to increase and decrease linearly during the wet periods 500 years before and after the peaks, and the wet periods are each separated by 1,000 years of a drier climate, like that of the present. Several different values were examined for the maximum potential recharge imposed at the wet peaks; the largest value was chosen to provide a steady-state solution with the water at, or close to, the land surface throughout the model domain. As discussed in Appendix MASS (CCA Section MASS.17 and MASS Attachment 17-1, Section F), a continuation of the Holocene climatic variability is considered likely during the next 10,000 years, and is assigned a relatively high probability of occurrence (0.75). This recharge function and its probability of occurrence are reflected in the lower portion of the bimodal distribution assigned to the Climate Index parameter.

The second recharge pattern assumes that potential recharge will increase from its present value to a specified larger value 500 years in the future, and that potential recharge will then remain constant throughout the rest of the 10,000-year simulation. As with the Holocene pattern, several different values were examined, the largest resulting in a steady-state solution with the water table at, or close to, the land surface throughout the model domain. Conceptually, this pattern corresponds to a future in which the climate either becomes continuously wetter or the frequency of wetter periods becomes large enough that the hydrologic response is indistinguishable from that of a continuously wetter climate. Step-increase recharge functions were used to simulate the effects of major disruptions of the Holocene climate, analogous to those that might occur during the next 10,000 years in a transition from the present warm interglacial climate to the early stages of a future glacial climate. As discussed in CCA Appendix MASS (Section MASS.17), such disruptions to the Holocene climate are considered unlikely, and the step function is assigned a relatively low probability of occurrence (0.25). This recharge pattern and its probability of occurrence are represented by the upper portion of the bimodal distribution assigned to the Climate Index parameter.

As reported in CCA Appendix MASS (Section MASS.17 and MASS Attachment 17-1, Section E), 17 transient and 54 steady-state, regional, three-dimensional, groundwater-flow simulations were run to examine effects of climate change. Simulations considered both potential recharge functions with varying peak recharge rates and different sets of assumptions about regional rock properties. Total specific discharge into and out of the Culebra within a model region was calculated for each simulation approximately corresponding to the controlled area. Values for the Climate Index parameter were determined by comparing the total lateral specific discharge calculated for each simulation. The largest observed increase in flow for those simulations using realistic values of rock properties was a factor of 2.1. Although some simulations produced a slight reduction in flow, Climate Index parameter values less than 1.0 are not considered in the PA. Changes in flow direction in the Culebra were also noted in some three-dimensional simulations, with a shift in flow toward the west corresponding to a regional increase in the elevation of the water table. These potential changes in flow direction are not incorporated in the two-dimensional flow and transport modeling to simplify the computational process. This treatment is conservative with respect to radionuclide transport because the most

rapid transport possible under any climate conditions will be through the most conductive portion of the Culebra south and east of the repository. Any shift of the flow away from this high conductivity zone would result in slower transport through less permeable rock. Restricting the effects of climate change to a uniform linear scaling of specific discharge in the SECOTP2D model is, therefore, a conservative assumption.

6.4.10 Initial and Boundary Conditions for Disposal System Modeling

The solution of many mathematical models used in PA requires specification of a starting point, called initial conditions, and specification of how the region modeled (that is, volume) interacts with the regions not modeled (boundary conditions). Initial values are required for all of the parameters appearing in a computer code. In practice, however, the term "initial conditions" refers to the values assigned to the primary variables used to describe the system, examples of which may be pressure, composition, and saturation. The term "boundary condition" refers to the specification of primary variables that control the interaction of the modeled region with the regions excluded from the model. In many studies, applied boundary conditions are static in time, although computer codes that implement time-dependent boundary conditions are not uncommon. A common practice in modeling groundwater flow is to place modeled system boundaries somewhat distant from the region in which model results are of interest. This helps ensure that uncertainty in the natural boundaries of the system does not unduly influence model results in the region of interest. The DOE adopts this practice in its application of BRAGFLO and MODFLOW-2000 to the WIPP.

The following sections describe the initial and boundary conditions specified for the major codes used in this PA. Initial values of parameters not discussed in the following sections are set equal to the values assigned from the PA database or LHS sampling discussed elsewhere in Section 6.4.

6.4.10.1 Disposal System Flow and Transport Modeling (BRAGFLO and NUTS)

In BRAGFLO, initial conditions to simulate the regulatory period are consistent with the following:

1. there are no gradients for flow in the far-field Salado;

2. Salado far-field pore pressures are elevated above hydrostatic from the surface but below lithostatic; and

3. near the repository, excavation and waste emplacement results in partial drainage of the DRZ, subsequent evaporation of drained brine into mine air, and removal from the modeled system by air exchanged to the surface.

The term "far-field" refers to the region that is not influenced by the DRZ drainage mentioned in (3). For units above the Salado, initial pressures are consistent with observed pore pressures or normal hydrostatic gradients (Appendix PA, Section 4.2.2).

Estimating the effects of drainage of the DRZ that occurs during the operational period, (3) above, is not simple. For each vector sampled in LHS, the DOE estimates this by using

BRAGFLO to simulate a period of time representing disposal operations. This calculation is called the start-up simulation and covers five years from t = ~5 years to t = 0 years, corresponding to the amount of time a typical panel is expected to be open during disposal operations. Most of the initial parameters used during the regulatory period simulation (t = 0 to t = 10,000 years) are also assigned for the start-up simulations, with some exceptions, described below.

The initial pressures in the Salado for the start-up simulation are based on a sampled pressure at the elevation of MB139 at the shaft and adjusted throughout the Salado and the DRZ to account for changes in hydraulic head due to elevation change. This parameter is discussed in Appendix PA, Attachment PAR (Parameter 26). The adjustment assumes hydrostatic equilibrium. The DRZ permeability is set at 10^{-17} square meters for the start-up simulation. Based on observed changes in the DRZ, the DRZ porosity is adjusted upwards 0.0029 (0.29 percent) from the sampled value for intact, impure halite. Initial pressure for the start-up simulation in the excavated regions is set to atmospheric. The shaft exists and is modeled as unfilled with the same physical properties as the excavation.

For the start-up simulation, an initial water-table surface is specified within the Dewey Lake at an elevation of 980 m (3,215 ft) above mean sea level. This elevation is consistent with observations discussed in Chapter 2, Section 2.2.1.4.2.1. Above the water table, pressure is maintained at one atmosphere, 0.101 megapascals; liquid saturations in these computational cells are held constant at residual liquid saturation (Section 6.4.6.6, Table 6-25). Below the water table, initial liquid saturations in all regions except the repository and shaft are 100 percent. Pressures are set consistent with a hydrostatic gradient below the water table within the Dewey Lake, as well as in the Rustler, except for the Magenta and Culebra. Initial pressures in the Culebra and Magenta are set at 0.9141 and 0.9465 megapascals, respectively. These values are based on fluid level and fluid density data collected from well C-2737, which is located directly over the waste panels (Beauheim 2003). Even though the natural properties of units above the Salado vary considerably over the domain modeled by BRAGFLO, the BRAGFLO initial condition of constant pressure and constant properties for each layer is considered reasonable because BRAGFLO calculates the long-term flux of brine from the borehole or shaft to each unit or to the surface. For this purpose, the pressure and properties at the borehole or shaft are important, but details of regional hydraulic head and unit properties are not.

For the start-up simulation, permeabilities of all units above the Salado are set to zero so that flow cannot occur from these units into the shaft. This modeling assumption is adopted as a simple method of accounting for the effective liners in the shafts during disposal operations.

No-flow boundary conditions are assigned in the BRAGFLO model of the disposal system along all of the exterior boundaries of the computational mesh, except at the far field boundaries of the Culebra and Magenta and the top of the model (that is, the ground surface, Appendix PA, Section PA-4.2.10). The ground surface is maintained at atmospheric pressure. The boundaries of the Culebra and Magenta are maintained at pressures of 0.9141 megapascals and 0.9465 megapascals, respectively, corresponding to the initial pressure conditions used in the Culebra and Magenta. The pressure in the Castile brine reservoir is set at its sampled value for the start-up simulation.

During the start-up simulation, fluid flow calculated by BRAGFLO from the Salado and the DRZ into the excavated region simulates the effect of drainage into the repository during the operational period. Following the start-up simulations, initial conditions are specified for the regulatory period simulation. Boundary conditions for the regulatory period simulation are the same as those for the start-up simulation.

The regulatory period simulation begins with conditions consistent with the sealing of the repository by shaft seals. Certain properties assigned for the start-up simulation are changed to make model conditions consistent with the emplacement of waste and completion of sealing. The liquid saturation in the waste-disposal region of the repository is set at 0.015, which is a conservative value (Butcher 1996), and other areas of the excavation are assigned zero liquid saturation (100 percent gas saturation) regardless of the quantity of brine that may have flowed into the excavation during the start-up simulations. This is consistent with the observed ability of circulating mine air to remove any inflowing brine by evaporation. The entire repository is assigned an initial pressure of one atmosphere. Pressures and saturations in model regions representing rock remain as they were at the end of the start-up simulation. Permeabilities of the units above the Salado are reset to the values specified as discussed in Section 6.4.6. The shaft is assigned properties for shaft seal materials discussed in Section 6.4.4 and Appendix PA, Section PA-4.2.6. Waste is emplaced in the waste-disposal regions at a density of 1.17×10^2 kg/m^3 for ferrous metals and 5.55×10^1 kg/m^3 for biodegradable materials. Other waste properties are assigned as discussed in Section 6.4.3.2. Panel closure properties discussed in Section 6.4.3.2 are assigned to the panel closure regions. Permeability in the DRZ is sampled for each realization and remains constant for the regulatory period (see Appendix PA, Attachment PAR). Corrosion and biodegradation reactions that produce gas are modeled to begin at the start of the regulatory period simulation, and their rates depend on the sampled parameter values for the gas generation model (see Section 6.4.3.3) and the availability of brine. Modeling of creep consolidation through the use of the porosity surface also begins at this time (see Section 6.4.3.1).

6.4.10.2 Culebra Flow and Transport Modeling (MODFLOW-2000, SECOTP2D)

Two principal factors were considered when selecting the boundaries for the MODFLOW-2000 model of the Culebra. First, model boundaries should coincide with natural groundwater divides where feasible, or be far enough from the area of most interest (the SECOTP2D transport domain) to have minimal influence in that area. Second, the model domain should encompass all features with the potential to affect Culebra water levels at the WIPP site (e.g., potash tailings ponds).

The modeling domain is approximately 22.3 km (14 mi) east-west by 30.6 km (19 mi) north-south, aligned with the compass directions (see Figure 6-17 in Section 6.4.6.2). This is the same as the domain used by LaVenue et al. (1990), except that the current domain extends 1 km farther to the west. The modeling domain is discretized into 68,768 uniform 100-m × 100-m cells. The northern model boundary is slightly north of the end of Nash Draw, 12 km (7.5 mi) north of the northern WIPP site boundary. The eastern boundary lies in a low-transmissivity region that contributes little flow to the modeling domain. The southern boundary lies 12.2 km (7.6 mi) south of the southern WIPP site boundary, slightly over 1.7 km (1 mi) south of the southernmost well (H-9) and far enough from the WIPP site to have little effect on transport rates

on the site. These boundaries are all assigned constant-head conditions based on head measurements made in model domain wells. The western model boundary passes through the IMC tailings pond due west of the WIPP site in Nash Draw. However, a no-flow boundary (a flow line) is specified in the model from this tailings pond up the axis of Nash Draw to the northeast, reflecting the concept that groundwater flows down the axis of Nash Draw, forming a groundwater divide. Similarly, another no-flow boundary is specified from the tailings pond down the axis of the southeastern arm of Nash Draw to the southern model boundary, coinciding with a flow line in the regional modeling of Corbet and Knupp (1996). Thus, the northwestern and southwestern corners of the modeling domain are specified as inactive cells in MODFLOW-2000, leaving 53,769 active cells.

Initial conditions are not required for the Culebra flow calculations because these are steady state. Initial actinide concentrations in the transport simulations are assumed to be zero.

6.4.10.3 Initial and Boundary Conditions for Other Computational Models

In addition to BRAGFLO, MODFLOW-2000, and SECOTP2D, several other codes are used in PA that require initial and boundary conditions. In general, these codes are strongly coupled to BRAGFLO, analogous to the manner in which SECOTP2D is coupled to MODFLOW-2000. These additional codes are NUTS, PANEL, the BRAGFLO direct brine release model (BRAGFLO), and CUTTINGS_S.

NUTS transports radionuclides through the BRAGFLO domain based on fluid flow characteristics as calculated by BRAGFLO and, therefore, does not need explicit definition of flow boundary conditions. As actinide transport is not of concern until the repository contains waste and is sealed, a start-up simulation is not executed with NUTS. Boundary conditions for advective transport are consistent with the boundary conditions assumed for fluid flow. Molecular transport boundary conditions for NUTS simulations consist of no diffusion or dispersion in the normal direction across far-field boundaries. Initial actinide concentrations are zero in all regions except the waste. Actinide concentrations in the waste region brine are assigned as discussed in Section 6.4.3.5 (Table 6-13).

PANEL estimates the transport of radionuclides from the repository to the Culebra for the E1E2 scenario (Appendix PA, Section PA-4.4). PANEL assumes homogeneous mixing within a panel of the waste disposal region to determine a source term for radionuclides. PANEL is strongly coupled to BRAGFLO, in that the flux of liquid up the borehole and out the separate panel in BRAGFLO is provided as the flux of liquid leaving the mixing volume in PANEL. Liquid leaving the mixing cell in PANEL is assumed to arrive at the Culebra, thereby maximizing the source of actinides to the Culebra.

Models for direct release to the surface are also strongly coupled to BRAGFLO. CUTTINGS_S (cuttings, cavings, and spall) and BRAGFLO (for direct brine release) acquire fluid pressure, fluid saturation, and other necessary quantities from the appropriate BRAGFLO disposal system model simulation. It is assumed in the direct release models that radionuclides, once entrained in drilling fluid, remain in the drillhole until they reach the surface. In other words, there is no interaction between drilling fluid and the formations between the repository and the surface.

Boundary conditions in the direct brine release model are no-flow except for the sources and sinks of brine through borehole nodes and at the surface.

6.4.11 Numerical Codes Used in Performance Assessment

To evaluate scenario consequences for both undisturbed and disturbed performance, DOE uses many computer codes to simulate relevant features of the disposal system. The flow of information and primary roles of the codes used are discussed in this section; the mathematical models implemented by the codes are discussed in Appendix PA. Parameter values and disposal system conditions must be passed between codes several times in an assessment.

The codes are executed under the requirements of the SCMS), which creates and maintains a complete record of the input data and results of each calculation, along with the exact codes used to create those results. For this application, PA codes used in conjunction with LHS or random sampling were executed under the SCMS.

The major computer codes and the flow of information among them are illustrated in Figure 6-24. As discussed in Section 6.1.4 and indicated in Figure 6-24, some of these codes are used to calculate reference conditions for deterministic futures associated with the parameters in x_{su} (Equation 6.4b [Section 6.1.2]) and their associated uncertainty characterized by distributions D_{su} (Equation 6.6b [Section 6.1.2]). The results of these codes are then used constructing the consequences of probabilistic futures. There are three major steps in evaluating scenario consequences for deterministic futures: (1) preparing input from submodels executed independent of LHS (for example, SANTOS, PEST), (2) LHS of the variables x_{su} in the PA parameter database, and (3) executing the sampling-dependent PA codes (those within the deterministic futures box indicated by dashed lines in Figure 6-24).

Some PA codes are used to calculate probabilistic futures; that is, future events that occur randomly in time and space, and uncertainty of associated parameters in x_{st} (Equation 6.4a [Section 6.1.2]) and characterized by distributions in D_{su} (Equation 6.6a [Section 6.1.2]). There are two major steps in evaluating scenario consequences for probabilistic futures: (1) random sampling of the parameter database, and (2) executing the codes.

Figure 6-24 indicates only those codes that perform the bulk of the computational effort related to simulating the significant physical processes occurring within the disposal system. In addition, a variety of additional codes are used in this PA. These additional codes are transfer data between codes, prepare input files, model output processing, and perform similar tasks. These codes are also executed within the SCMS.

Because these additional codes are not expressly used to simulate physical processes, they have been omitted from discussion here and on Figure 6-24 for clarity. A comprehensive description of the coupling of codes used in this PA is provided in Appendix PA.

Figure 6-25 shows an alternative method of visualizing how the various PA codes relate to each other and to the estimation of scenario consequences. This figure shows a vertical cross section of the disposal system, associating the major codes with the particular components of the system each code simulates. As shown in the figure, BRAGFLO, SANTOS, NUTS, and PANEL address the Salado. PEST, MODFLOW-2000, and SECOTP2D address the Culebra.

CUTTINGS_S, BRAGFLO (direct brine release), DRSPALL, and PANEL address the immediate consequences of inadvertent human intrusion through one or more exploratory boreholes. Combined, Figures 6-24 and 6-25 illustrate the flow of information through major PA codes and the relationship between the codes and the physical system being simulated.

The parameter database is the initial element in the PA process. The database includes the parameters used in PA codes that pertain to the technical aspects of disposal system performance. Parameters pertaining only to the execution of the codes (for example, convergence criteria for Newton-Raphson numerical solvers) are generally not included in the database, but are recorded in input files and traceable through the SCMS. Parameters in the database fall into two categories: those that are assigned fixed values, and those that are uncertain and are therefore assigned a range of values according to a CDF.

Vectors (sets) of parameter values are created from the uncertain variables in the database by LHS of each variable for a set of simulations in the PA. In this PA, 64 parameters are sampled using LHS, and 100 vectors are assembled in each replicate (see Section 6.5). The values assigned to each sampled parameter in each of the vectors in this PA are included in Appendix PA, Attachment PAR. Each of the fixed parameter values from the database and a vector of sampled parameter values are combined to form a realization (a set of input parameters). Each realization is then propagated through the PA codes within the dashed lines shown in Figure 6-24.

Assessing each realization requires that the codes shown in Figure 6-24 for deterministic futures be executed under four code sequence configurations, one each for the undisturbed performance scenario (E0), the E1 scenario, the E2 scenario, and the E1E2 scenario.

Each intrusion scenario may occur with or without mining. The techniques used for each scenario are described in Section 6.4.13.

As shown in Figure 6-25, information for some of the major codes comes from the following additional sources: the SANTOS, PEST, DRSPALL, and FMT codes.

The SANTOS code develops the porosity surface, describing porosity as a function of time and pressure; this information is used in the BRAGFLO code (see Appendix PA, Section PA-4.2 and Attachment PORSURF). PEST is coupled with MODFLO-2000 to calculate numerous possible and equally likely Culebra transmissivity fields; these transmissivity fields are used inthe MODFLOW-2000 code (see Appendix PA, Attachment TFIELD). FMT is used to calculate solubility parameters entered into the parameter database. These parameters, as well as sampled solubility distribution parameters, calculated solubilities for the PA. Actinide solubility in the repository is used by the codes NUTS and PANEL. DRSPALL calculates the volume of solid material that could be removed from the repository by spallings for a set if initial pressure conditions and uncertain parameters. The code CUTTINGS_S uses the DRSPALL results to determine the volume removed by spallings for intrusions at different times and locations.

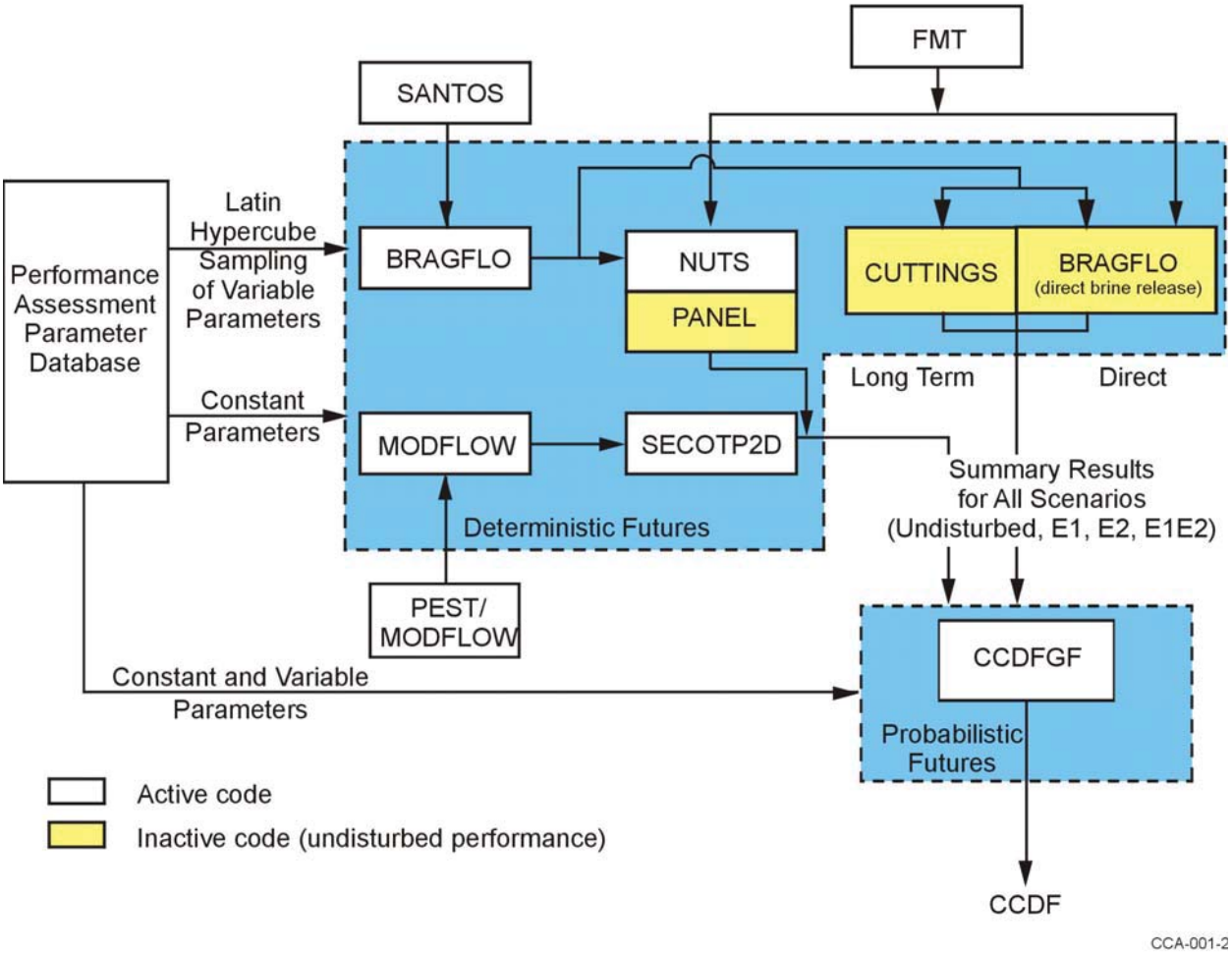

Figure 6-24. Major Codes, Code Linkages, and Flow of Numerical Information in WIPP PA

The PA codes are executed sequentially. Following LHS, BRAGFLO is the first major code executed. Notice that BRAGFLO is listed twice in this sequence. BRAGFLO is used in two applications for PA. In the first application, BRAGFLO calculates the overall movement of gas and brine in the repository and from the Castile to the surface; this movement forms the basis for estimating radionuclide releases to the accessible environment (Appendix PA Sections 4.2 and 6.7). BRAGFLO also contains subsystem models for estimating gas generation in the repository, disposal room closure and consolidation, and interbed fracturing (Appendix PA, Section PA-4.2). BRAGFLO does not calculate the movement of radionuclides. The second application of BRAGFLO is discussed below.

NUTS calculates the overall movement and decay of radionuclides in the repository and disposal system. NUTS uses the same geometry as BRAGFLO, the brine and gas flow fields calculated by BRAGFLO, and the radionuclide source concentrations (solubilities) in the repository defined by the actinide source term models. In simulations of the E1 scenario, NUTS also tracks brine originating in the Castile brine reservoir, including the Castile brine that has flowed out from the borehole and into the waste in the repository. See Appendix PA, Section PA-4.3 for additional

information on the use of NUTS in PA. PANEL calculates actinide source term to the Culebra for the E1E2 scenario, as discussed in Section 6.4.13.5. PANEL is described in detail in Appendix PA, Section PA-4.4.

In all scenarios, the quantity of brine flowing up the shafts or a degraded exploratory borehole to the Culebra is calculated by BRAGFLO, and the concentration of radionuclides in that brine, calculated by NUTS or PANEL, determines the quantity of radionuclides released to the Culebra.

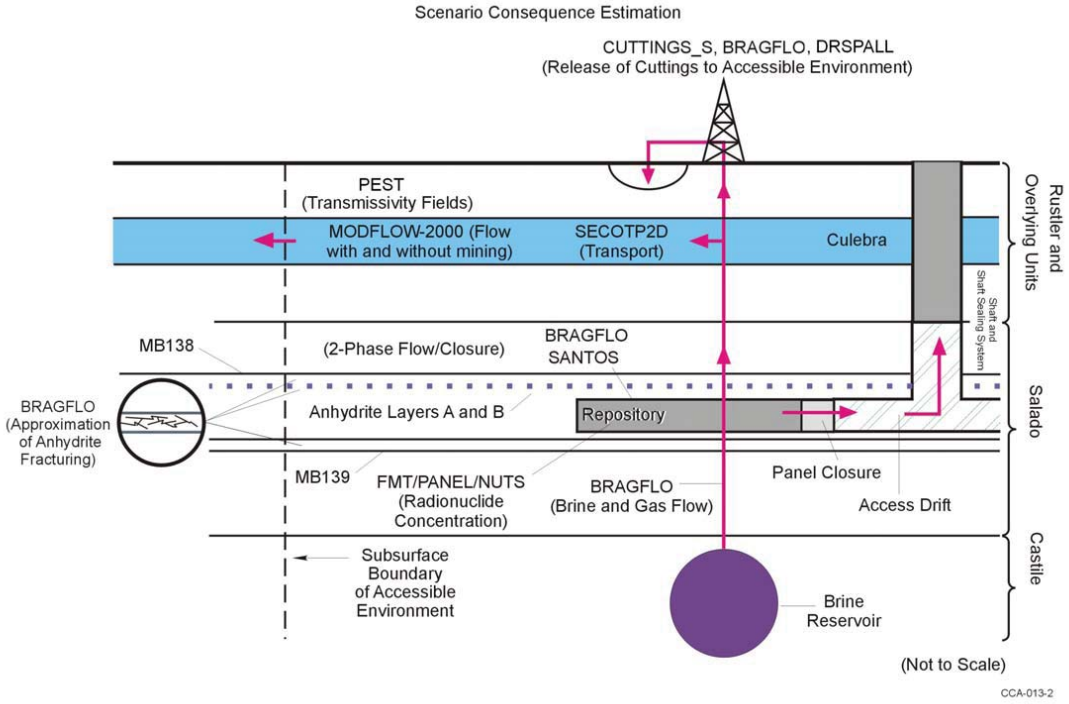

Figure 6-25. Schematic Side View of the Disposal System Associating PA Codes with the Components of the Disposal System Each Code Simulates

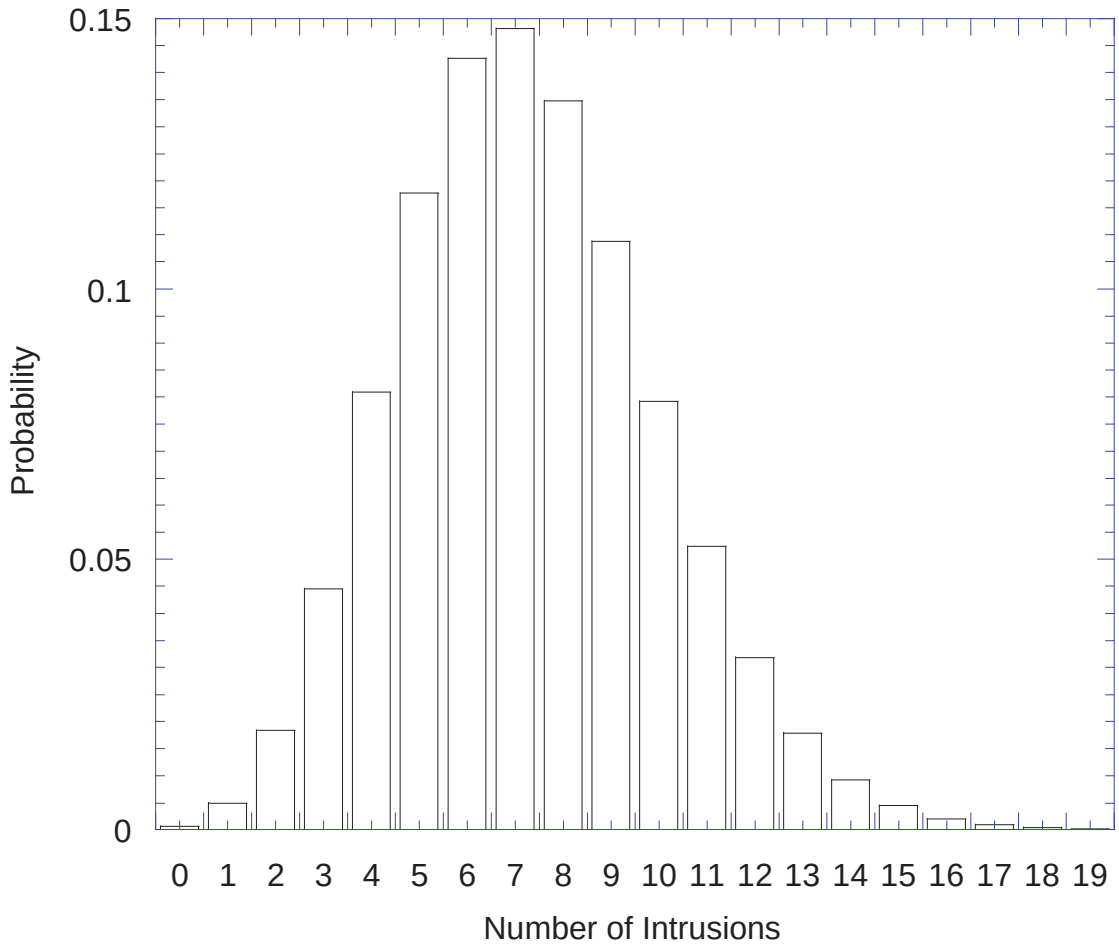

Figure 6-26. Probability of Intrusions in 10,000 Years with Active Institutional Control

CUTTINGS_S and BRAGFLO (direct brine release) evaluate the immediate consequences of inadvertent human intrusion through exploratory drilling. Solid material and brine may be transported to the surface in the drilling fluid. After pressure in the repository is relieved through the first borehole, subsequent boreholes may release less material to the surface. CUTTINGS_S calculates the quantity of solid material transported to the accessible environment at the surface during the drilling activities. This includes material removed directly from the borehole (cuttings), along with cavings and spallings. The code is discussed in Appendix PA, Section PA-4.5. BRAGFLO (direct brine release) calculates the quantity of brine transported up the borehole to the surface.

MODFLOW-2000 and SECOTP2D calculate the detailed movement of radionuclides in the Culebra that occurs if radionuclides flow up the shafts or through a degraded exploratory borehole. MODFLOW-2000 calculates regional Culebra flow fields using an assumption that flow occurs in a single-porosity medium. MODFLOW-2000 uses the transmissivity fields calibrated using PEST (one field in each simulation). SECOTP2D calculates radionuclide transport in a double-porosity medium, accounting for advection in fractures, matrix diffusion, retardation, and decay, as described in Section 6.4.6.2. MODFLOW-2000 and SECOTP2D are

discussed in Appendix PA, Section PA-48 and PA-49, respectively. The NUTS and PANEL codes calculate the actinide source term to the Culebra.

The computer code CCDFGF is used to (1) determine random sequences of future events that may occur over the next 10,000 years at the WIPP site; (2) estimate the radionuclide releases resulting from these random sequences of future events using the results of calculations described thus far; and (3) construct a CCDF for each realization. The manner in which CCDFGF determines random sequences of future events is the subject of Section 6.4.12.

Estimating consequences and constructing a CCDF for these sequences of future events is the subject of Section 6.4.13.

6.4.12 Sequences of Future Events

For this application, sequences of future events that may occur are determined using a random sampling procedure described in Appendix PA, Section PA-3.0. A general description of the technique is presented in this section.

The incorporation of stochastic uncertainty in the PA is based on repeatedly generating independent sequences of events that may occur at the WIPP over the next 10,000 years. Each 10,000-year sequence is generated by randomly sampling six parameters that repeatedly characterize stochastic uncertainty about future events. These parameters include (1) the interval of time between drilling intrusions (which yields both the number and time of intrusions), (2) the location of each drilling intrusion, (3) the activity of the waste penetrated by each drilling intrusion, (4) the plug configuration in the intrusion borehole, (5) the penetration of a Castile brine reservoir, and (6) the occurrence of mining. Probability distribution functions are assigned to each of these six parameters and are discussed in the following sections. Random sampling from these distributions generates 10,000 equally likely, independent futures of the WIPP for each realization executed and CCDF constructed. The computer code CCDFGF (Appendix PA, Sections 3 and PA-6.0) randomly samples sequences of future events, constructs consequences of these sequences, and assembles CCDFs. As described in Section 6.4.13, normalized integrated radionuclide releases to the accessible environment are estimated for each history using the consequence modeling system.

The probability assigned to the occurrence of certain future events at the WIPP site is affected by regulatory guidance and DOE actions taken to deter activities detrimental to WIPP performance. Active and passive institutional controls are discussed extensively in Chapter 7.0. A summary of their use in PA is in this section.

6.4.12.1 Active and Passive Institutional Controls in Performance Assessment

Active institutional controls and passive institutional controls will be implemented at the WIPP site to deter human activity detrimental to repository performance. Active institutional controls and passive institutional controls are described in detail in Chapter 7.0 and in appendices referenced in Chapter 7.0. In this section, the impact of active institutional controls and passive institutional controls on PA is described.

Active institutional controls will be implemented at the WIPP after final facility closure to control site access and ensure that activities detrimental to disposal system performance do not occur within the controlled area. The active institutional controls will preclude human intrusion in the disposal system. A limitation for considering the effectiveness of active institutional controls in PA is established in 40 CFR Part 191. That limitation is 100 years. Because of the nature of the active institutional controls to be implemented and regulatory restrictions, the PA assumes there are no inadvertent human intrusions or mining in the controlled area for 100 years following repository closure.

Passive institutional controls deterr inadvertent human intrusion into the disposal system in PA. Only minimal assumptions were made about future society when designing the passive institutional controls to comply with the assurance requirements. The preamble to 40 CFR Part 194 limits any credit for passive institutional controls in deterring human intrusion to 700 years after disposal (EPA 1996a, 61 FR 5231). Although the DOE originally included credit for passive institutional controls in PA, the CRA-2004 PA does not include such credit. The EPA directed DOE not to take credit for passive institutional controls in the CCA during the certification (EPA 1998, 194.VIII.D.3).

6.4.12.2 Number and Time of Drilling Intrusions

The number of drilling intrusions associated with each 10,000-year history is based on 40 CFR § 194.33(b)(2) and § 194.33(b)(3):

> In performance assessments, drilling shall be assumed to occur in the Delaware Basin at random intervals in time and space during the regulatory time frame. [40 CFR 194.33(b)(2)]
>
> The frequency of deep drilling shall be calculated in the following manner:
>
> (i) Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.
>
> (ii) The total rate of deep drilling shall be the sum of the rates of deep drilling for each resource. [40 CFR 194.33(b)(3)]

The DOE's implementation of these criteria is described in this and the following sections.

Mathematically, events that are random in time can be described as following a Poisson process that can be written as

$$P\left[E_n\left(\Delta t\right)\right] = \frac{\left[\lambda\left(\Delta t\right)\right]^n}{n!} e^{-\lambda \Delta t}, \tag{6.18}$$

where $p[E_n(\Delta t)]$ is the probability (p) that some number (n, an integer) of events (E) will occur in a time interval (Δt) given a rate constant λ with units of events per time.

Inadvertent human intrusions may occur at any time between 100 years and 10,000 years after the decommissioning of the facility. Both the number and time of intrusions are determined sequentially by sampling from a CDF derived from the Poisson model that probabilistically describes the time period elapsing between an intrusion at a fixed time and the next intrusion.

The time interval to the next intrusion following an intrusion may vary from 0 years to greater than 9,900 years, with a probability determined by the rate constant λ. The rate constant is derived from the drilling rate established for the Delaware Basin and the area of the waste disposal region, 0.126 km^2 (0.049 mi^2). The drilling rate used in this analysis was 52.5 boreholes per square kilometer per 10,000 years. As discussed in Appendix DATA, Attachment A, this rate is based on a review of past and present drilling activity in the Delaware Basin. The rate constant λ is assigned different values for two time periods. While active institutional controls are effective, it is equal to zero; after active institutional controls cease, λ is assigned to 52.5 boreholes per square kilometer per 10,000 years.

Intrusion times are determined by random sampling. If the sampled time is greater than 9,900 years (100 + 9,900 = 10,000), no intrusions occur between 100 and 10,000 years. If the sampled time is less than 9,900 years, an intrusion occurs at 100 years plus the sampled time. The post-active institutional controls CDF is sampled iteratively to determine whether intrusions occur in the time interval between the last intrusion and 10,000 years until an intrusion is determined to occur after 10,000 years.

The most likely number of intrusions into the waste disposal region during 10,000 years is seven, with a probability of 0.1482. Zero intrusions occur with a probability of 0.0007. The largest number of intrusions that occur with a probability greater than 10^{-3} per 10,000 years (and which can contribute to releases for comparison with the quantitative release limits) is 16, occurring with a probability of 0.0020. Probabilities for other numbers of intrusions within 10,000 years are given in Table 6-30. These probabilities are shown as a histogram in Figure 6-26.

6.4.12.3 Location of Intrusion Boreholes

Drilling events are assumed to be random in time and space, and the location of each intrusion borehole within the waste disposal region is sampled randomly. This is done in the analysis by discretizing a plan view of the area within the passive institutional control berms (see CCA Appendix PIC, Section VIII) into 144 separate regions and requiring each intruding borehole to penetrate a single region (Figure 6-27). The probability of intersecting each location is equal to 1/144 (about 0.00694), and slight variations in the size of regions are disregarded as unimportant.

Each of the 144 regions contains both excavated and unexcavated areas at the repository horizon. A borehole has an approximately 20 percent chance of intruding excavations and an approximately 80 percent chance of passing through unexcavated Salado (see Appendix PA, Section PA-3.4). The berm area and the proportion of excavated to unexcavated regions at the repository horizon are important in the Castile brine reservoir model, as discussed in Section 6.4.12.6.

Boreholes that penetrate excavations may penetrate either CH-TRU waste or RH-TRU waste For long-term releases and direct brine releases, all penetrations into excavations are treated as if CH-TRU waste is penetrated, and the RH-TRU waste inventory is averaged into the CH-TRU waste inventory for source-term determination. For cuttings and cavings direct releases, there is an approximately 12 percent chance that RH-TRU waste canisters are penetrated and an 88 percent chance that CH-TRU waste is penetrated, corresponding to the relative plan-view areas of each waste type (see Appendix PA, Section PA-3.7).

Table 6-30. Probabilities of Different Numbers of Intrusions into the Waste Disposal Region (for 100 years of active institutional control and 9,900 years of uncontrolled activity)

Number of Intrusions	Probability of Occurrence
0	0.0007
1	0.0050
2	0.0183
3	0.0445
4	0.0809
5	0.1177
6	0.1426
7	0.1482
8	0.1348
9	0.1089
10	0.0792
11	0.0524
12	0.0318
13	0.0178
14	0.0092
15	0.0045
16	0.0020
17	0.0009
18	0.0004
19	0.0001

For cuttings and cavings direct releases, the small area of the panel closures is treated as CH-TRU waste and is included in the CH-TRU waste probability. Because of the low permeability of the region surrounding each RH-TRU waste canister, intrusions into RH-TRU waste are not assumed to produce spallings releases or direct brine releases.

6.4.12.4 Activity of the Intersected Waste

Waste shipped to the WIPP will contain quantities of radionuclides that will vary from container to container. Radioactivity may vary by several orders of magnitude from those waste containers with the largest quantities of radionuclides to those with the smallest.

Information about waste radioactivity has been compiled at several different levels (Figure 6-28). The waste-stream level includes information about waste activities from different processes at generator sites that create TRU waste. At this level, a separate waste stream

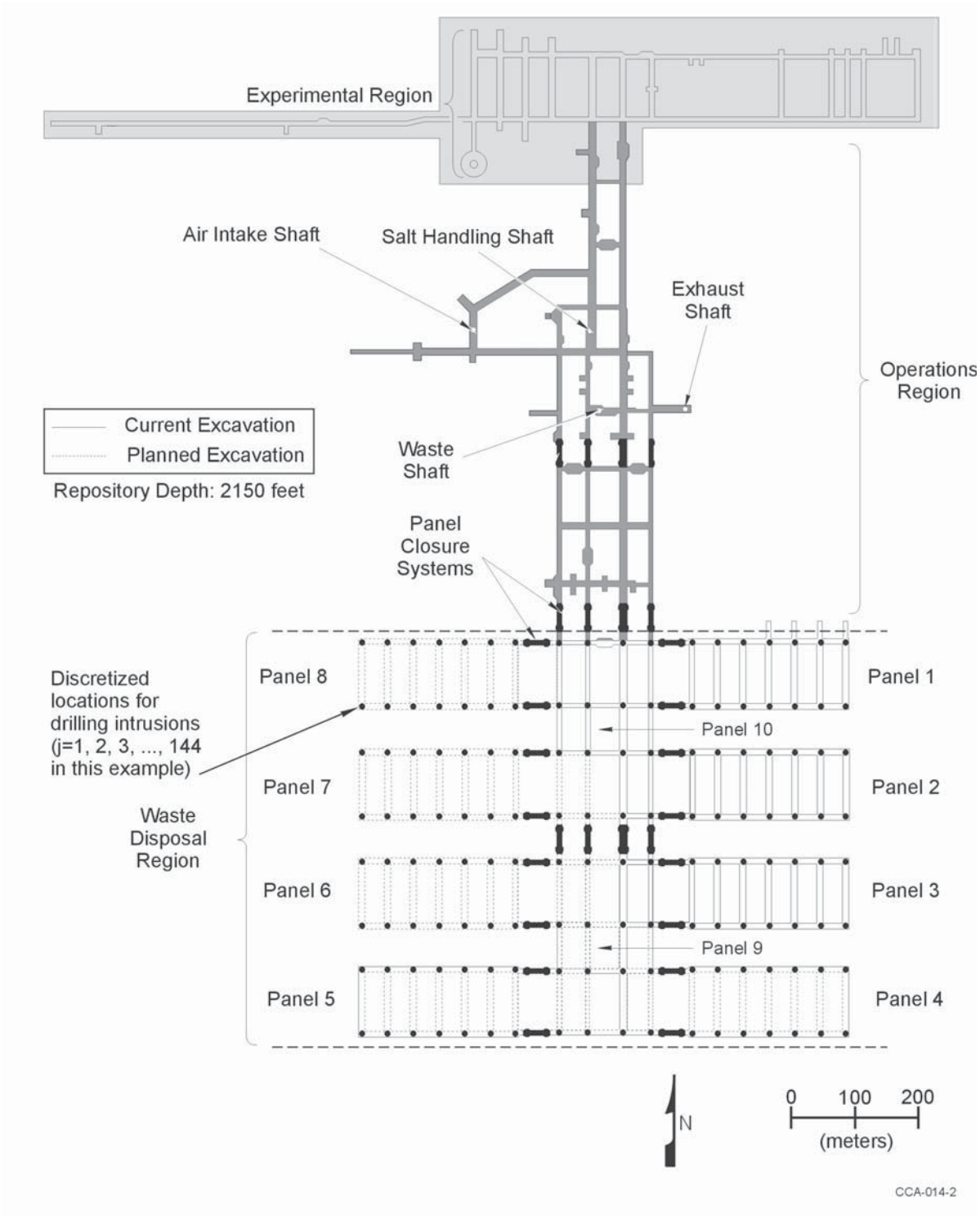

Figure 6-27. Discretized Locations for Random Intrusion by an Exploratory Borehole

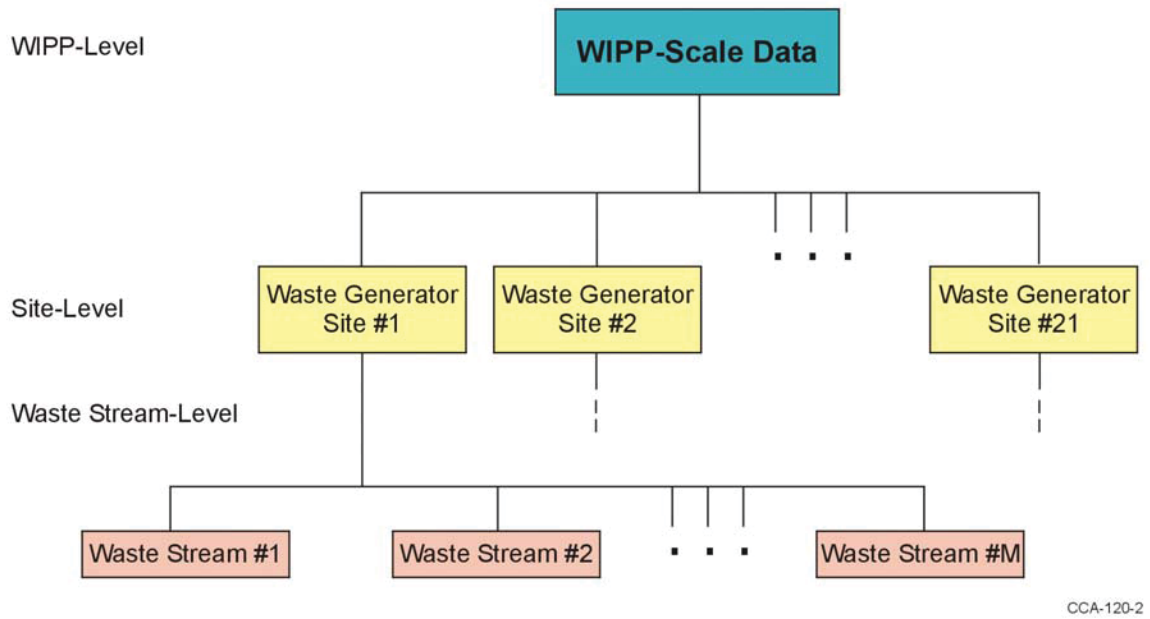

Figure 6-28. Levels of Information Available in the TWBID

characteristic is maintained for RH-TRU. In total, there are approximately 779 CH- and RH-TRU waste streams, of which 693 are CH-TRU. Because the RH-TRU is approximately one percent (actually 1.5 percent) of the total EPA units (not activity) of CH-TRU waste, all the RH-TRU waste was grouped together into one equivalent or average (WIPP-scale) RH-TRU waste stream. Variability in this small fraction is assumed to be negligible. The waste-generator site level includes information integrated over the scale of a generator site. There are 27 generator sites identified for the WIPP (see Section 4.1.2). The WIPP-scale level includes integrated information about all waste destined for the WIPP, including CH- and RH-TRU. Data are present for existing waste and estimates were made for future (to-be-generated) waste. The integration of waste data with the PA is illustrated in Figure 6-29. In the CCA, this information was compiled from the Transuranic Waste Baseline Inventory Database (TWBID), an electronic version of information present in the Transuranic Waste Baseline Inventory Report (TWBIR), Rev. 3, (see CCA Appendix BIR). New information concerning waste inventory has been included in PA for emplaced, stored, and projected waste. The new information is discussed in Chapter 4 and Appendix TRU WASTE (see also Appendix DATA, Section 7.0, Attachment F).

To calculate radionuclide releases from groundwater transport (including direct brine release) and from spallings, spatial variability in the waste activity is assumed to have no significant impact. Concentrations of radionuclides mobilized in repository brine and quantities transported to the ground surface in spallings are assumed to be derived from a sufficiently large volume of waste that container-scale variability can be neglected. Long-term releases and direct brine releases are calculated using WIPP-scale data assuming homogeneous accessibility of RH- and CH-TRU waste activities by liquid in the repository. As discussed previously, spallings releases are not calculated for RH-TRU waste;

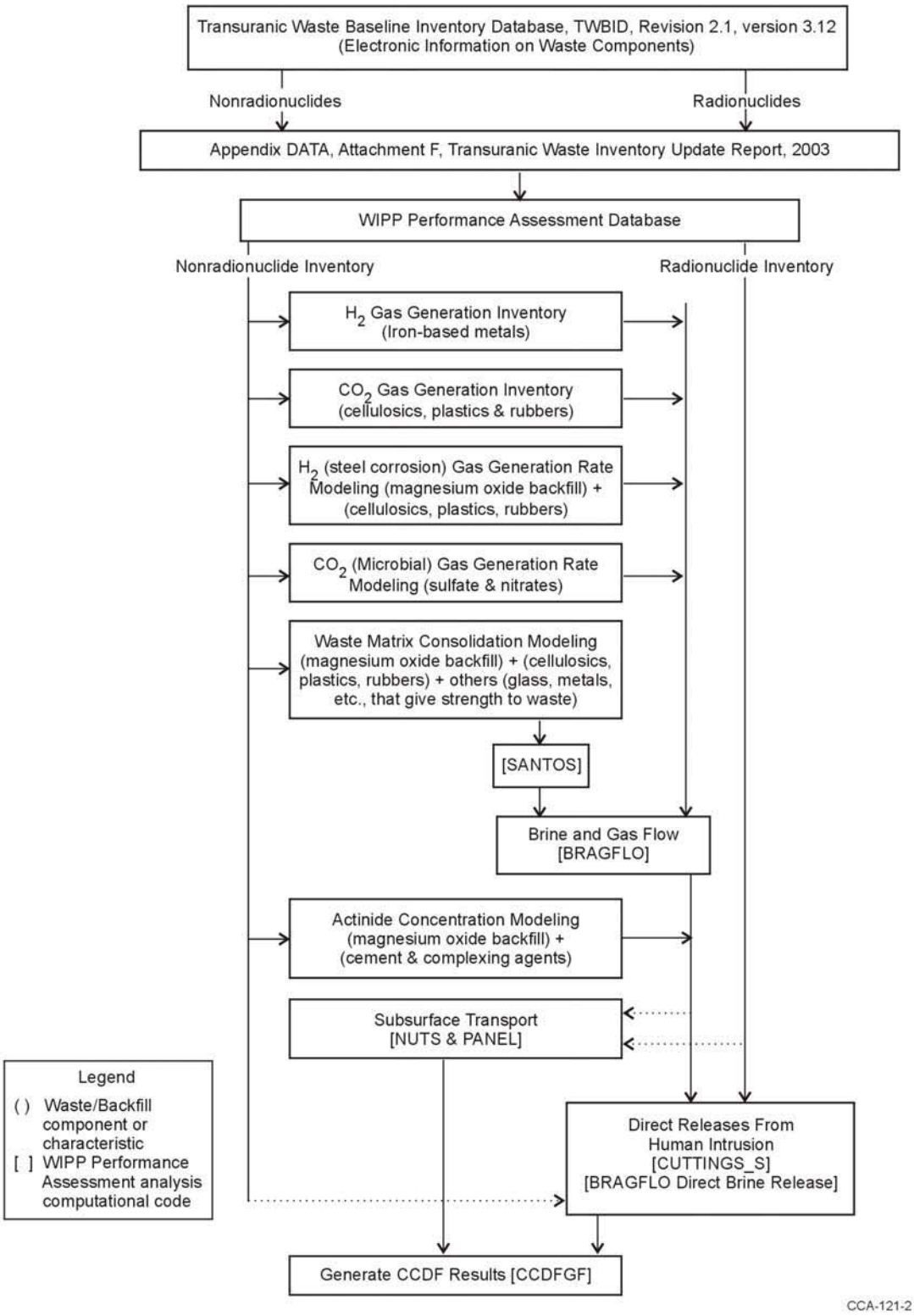

Figure 6-29. Flowchart Showing Integration of TWBID Data in PA Calculations

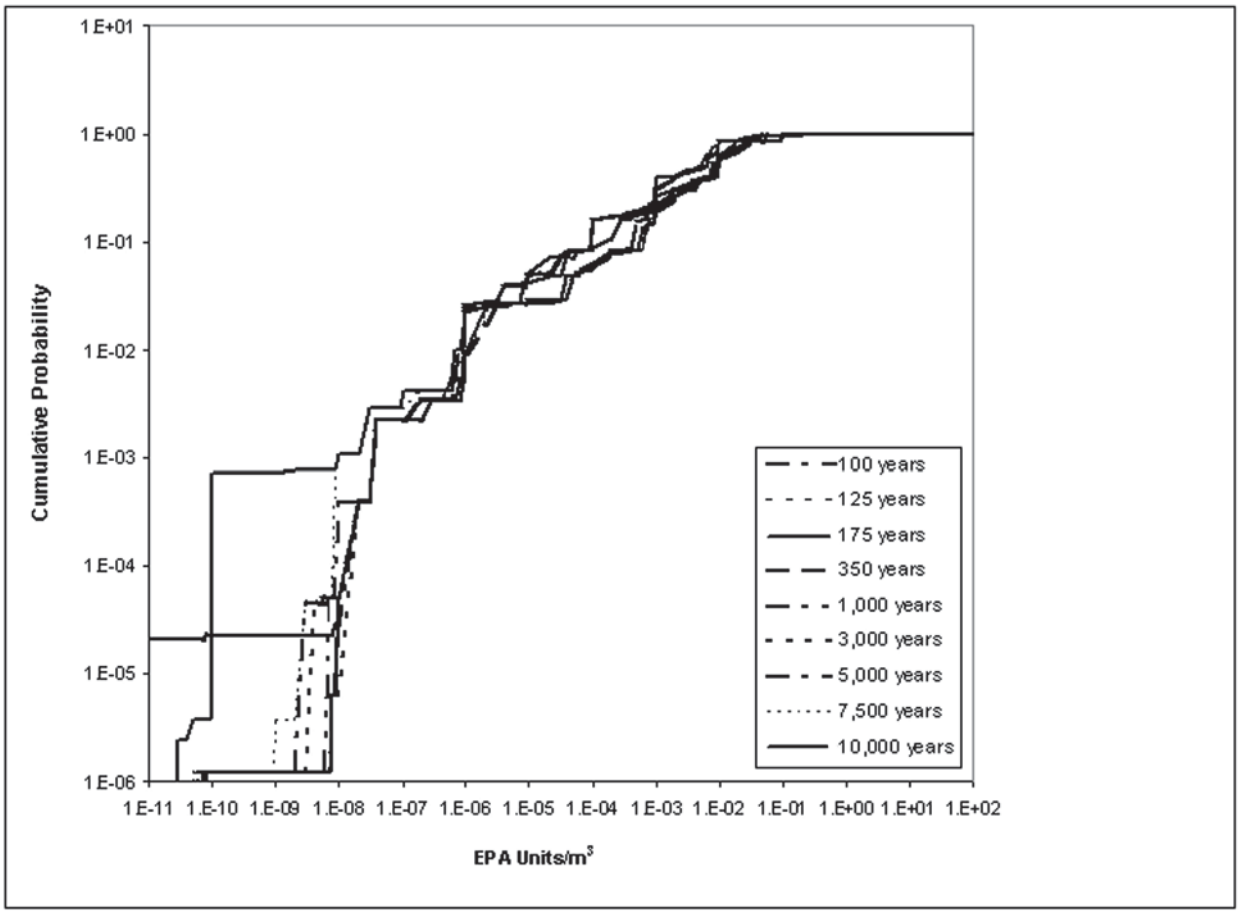

Figure 6-30. Cumulative Distribution Function for Waste Stream EPA Units/Volume

consequently, spallings release activities are determined assuming homogeneous accessibility for only CH-TRU waste.

Direct releases caused by cuttings and cavings access discrete and relatively small portions of the waste, and estimates of the quantity of radioactivity released to the accessible environment may be sensitive to variability in activity loading. The radioactivity of cuttings and cavings releases is calculated using data from the waste-stream level in the following manner.

Containers are assumed to be randomly placed in the WIPP from the various waste streams (see Appendix PA, Attachment MASS, Section 21). Because waste containers are stacked three-high for disposal, a drill bit is assumed to penetrate three containers. The direct-release consequence resulting from a drill bit hitting the edges of containers and generating releases from more than three containers is assumed similar to the consequence of penetrating three containers only (see Appendix PA, Section PA-6.8.3). Each of the three containers penetrated by the drill bit can come from different waste streams and have different associated activities. The waste streams penetrated are randomly sampled according to the relative quantity of waste in each waste stream. Figure 6-30 shows the discretized activities, expressed as the EPA normalized release density, of the 693 CH-TRU waste streams as a CDF and the decay of the waste stream activities through time. Waste stream activities are maintained in PA at 100, 125, 175, 350, 1,000, 3,000,

5,000, 7,500, and 10,000 years. Activities for cuttings and cavings releases at other times are interpolated from these values.

The code CUTTINGS_S calculates the volume of repository material brought to the surface by cuttings and cavings. Of the repository volume removed, approximately 40 percent is waste material; the rest is void space, MgO (backfill), and drum packing material. It is assumed that one-third of the waste material released comes from each of three containers assumed to be intersected. The activity of the release to the surface during drilling by cuttings and cavings is the summed products of one-third the release volume times the three waste stream activities randomly sampled. If random sampling determines that the borehole penetrates RH-TRU waste, 100 percent of the material removed is assumed to be waste and the activity of the release is equal to the volume calculated by CUTTINGS_S times the activity of RH-TRU waste.

6.4.12.5 Diameter of the Intrusion Borehole

Historical Delaware Basin drilling records were reviewed to determine the diameter of a typical intrusion borehole. In PA, the borehole diameter parameter value is held constant for all future drilling and is equal to 0.311 m (12.25 in.). Appendix DATA, Attachment A and CCA Appendix DEL, Attachment 1 discusses current and historical drill stem and drill collar diameters used to drill oil and gas wells in the Delaware Basin. CCA Appendix DEL illustrate a generalized circular cross section of a well plugged according to current practice (see CCA Section DEL.6.1.2.2l and Appendix DATA).

6.4.12.6 Probability of Intersecting a Brine Reservoir

As discussed in Section 6.4.8, there is uncertainty about the existence of brine reservoirs and the probability of intersecting a brine reservoir with a deep borehole. The DOE has examined available data and concluded that there is no reasonable basis to eliminate the possibility of a brine reservoir existing under the site. Therefore, the DOE assumes that a brine reservoir may exist under the waste panels. The DOE determined a reasonable basis for the probability of intersecting a brine reservoir and had pursued three investigations relevant to this issue: geophysical methods, geological structure analysis, and geostatistical correlation (see CCA Section 6.4.8, Appendix MASS Section 18, and MASS Attachments 18-1, 2 and 3 for the investigations that led to the CCA's representation of the brine reservoir). As discussed in Section 6.4.8, the DOE adopted the EPA's representation of the brine reservoir used in the 1997 PAVT (the EPA's basis for this representation is documented in the Technical Support Document for Section 194.23: Parameter Justification Report, A-93-02, V-B-14 and in a technical support document entitled Technical Report Review of TDEM Analysis of WIPP Brine Pockets, A-93-02, V-B-30).

For the CRA-2004 PA, the DOE assumes there is one reservoir under the waste panels and uses probability of a deep borehole hitting the reservoir of between 0.01 to 0.60 (see EPA 1998, VII.B.4.d). The location of boreholes in this area is sampled. They may lie over repository excavations, or over rock in pillar cores, or between panels. The brine reservoir under the waste panels is not assumed to be depleted during the 10,000-year regulatory period by subsequent boreholes drilled anywhere within this area. Boreholes randomly located over rock have the same probability of intersecting the brine reservoir as boreholes located over excavations.

Boreholes located over the excavations are assumed to penetrate waste, and the consequences are modeled as described in Section 6.4.

BRAGFLO calculates the long-term pressure and production of brine from the reservoir for only one two-plug configuration borehole. Subsequent penetrations are assumed to behave identically to the first (see Appendix PA, Section PA-6.8).

6.4.12.7 Plug Configuration in the Abandoned Intrusion Borehole

As stated in Section 6.4.7, three different plug configurations can represent possible future configurations of plugged and abandoned intrusion boreholes. Based on a survey of current practice (see Appendix PA, Attachment MASS, Section 16.0, the two-plug configuration borehole is considered most likely and is assigned a probability of 0.696. The three-plug configuration is considered less likely and is assigned a probability of 0.289. The continuous concrete plug is considered least likely and is assigned a probability of 0.015 (SNL 2003).

6.4.12.8 Probability of Mining Occurring within the Land Withdrawal Area

The EPA has specified the probability of mining in the future. In 40 CFR § 194.32 (b), the EPA states, "Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame."

Also in 40 CFR § 194.32(b), the EPA limits the occurrence of mining to a maximum of once per 10,000 years. The DOE interpreted this probability as a Poisson model with a mining probability of 10^{-4} per year (Appendix PA, Section PA-3.0). The occurrence of mining is sampled from a CDF of the time until mining in a manner similar to the procedure described for the time between drilling intrusions, except that multiple mining events cannot occur.

6.4.13 Construction of a Single CCDF

Construction of a single CCDF requires combining the results of numerical simulations performed using different sets of subjective parameter values (sets selected by LHS) with the probabilistic futures determined by random sampling stochastic parameters (that is, those associated with intermittent drilling) (see Appendix PA, Section PA-3.0). The variety of sequences of events represented in a single CCDF and the impossibility of modeling the details of each future separately requires building a CCDF using methods to construct consequences for any probabilistic future from a limited number of calculations for deterministic, idealized futures. Although this methodology is conceptually straightforward, the details of the process are highly dependent on model and system-specific considerations (see Appendix PA, Section PA-6). Accordingly, insight gained from previous, preliminary PAs as well as analysis of early results for this PA help configure the methodology used for CCDF construction.

Depending on the scenario into which probabilistic futures are classified, different techniques are used for estimating their consequences. The deterministically determined undisturbed performance scenario consequences require no special techniques for application to probabilistic futures. For E1, E2, and E1E2 scenarios, the CCDF construction methodology is primarily based on the principle of scaling, with some simplifying assumptions made for the E2 scenario. Scaling is estimating the consequences of probabilistic futures based on consequence estimates from

deterministic futures. The use of scaling and the building of a CCDF with it is discussed in this section. Note that all of the discussions in Section 6.4.13 are for one vector of parameter values included in the subjective uncertainty analysis. In other words, this section addresses only stochastic variation resulting from uncertainty in the sequence of future events that may occur at the WIPP (see Section 6.1.2).

6.4.13.1 Constructing Consequences of the Undisturbed Performance Scenario

All probabilistic futures in which drilling intrusion and mining within the controlled area do not occur are included in the undisturbed performance scenario. Because there is no stochastic uncertainty for this scenario, all futures within a single LHS vector of undisturbed performance have the same releases to the accessible environment. The following major codes are used to estimate the consequences of undisturbed performance: BRAGFLO, NUTS, and, if actinides reach the Culebra, MODFLOW-2000 and SECOTP2D. To illustrate the flow of information for the undisturbed performance scenario, these codes and the connections between them are highlighted in Figure 6-31. For undisturbed performance, no special techniques are required to modify the results of the deterministic calculation to fit probabilistic futures. Therefore, for a single consequence of undisturbed performance, BRAGFLO is executed once and NUTS is executed once. These calculations determine the release to the accessible environment from transport in the Salado or up the shaft to the surface. If any actinides reach the Culebra following these calculations, MODFLOW-2000 and SECOTP2D determine whether actinides released to the Culebra reach the lateral accessible environment. This information is sufficient to construct consequences for all probabilistic futures that have no intrusion events. This information is also used to evaluate compliance with 40 CFR § 191.15 and 40 CFR § 191.24, described in Chapter 8.0.

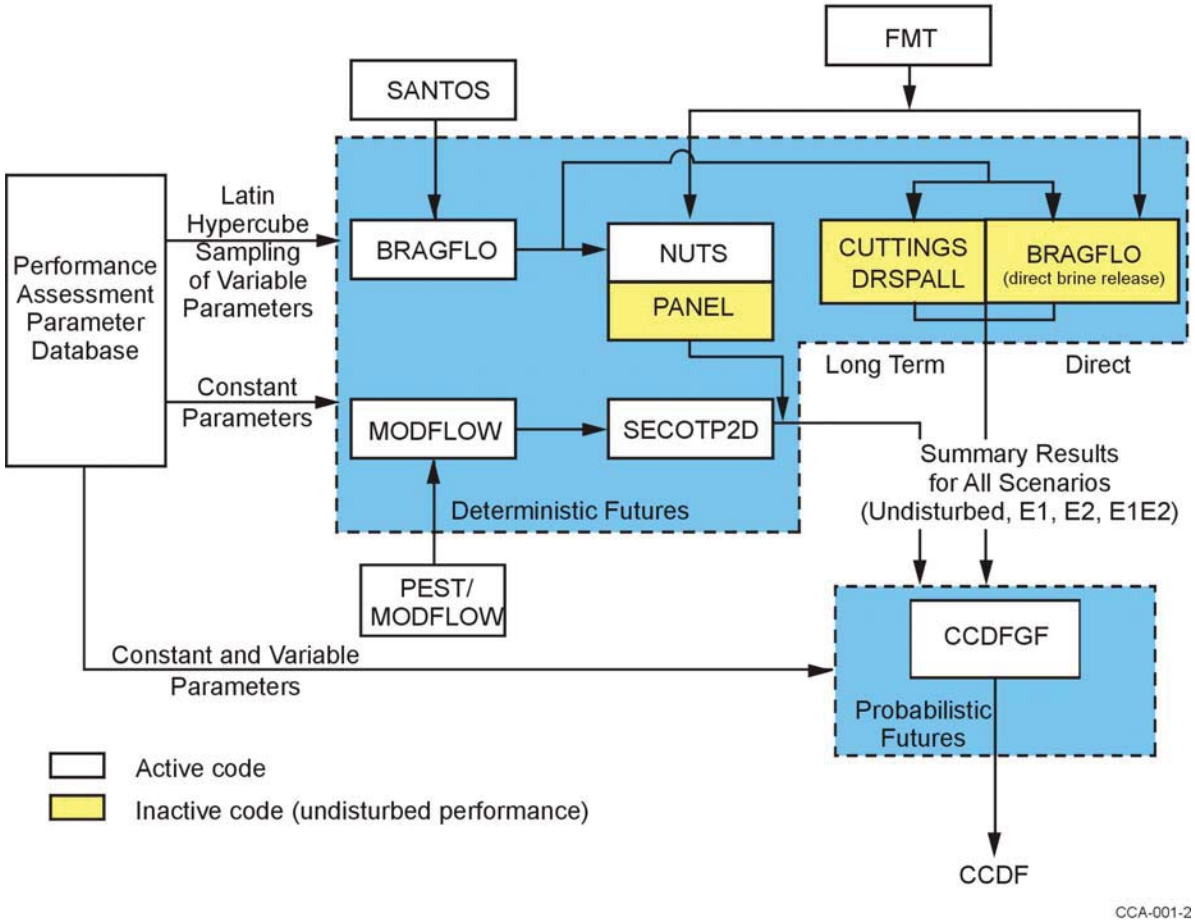

Figure 6-31. Code Configuration for the UP Scenario

6.4.13.2 Scaling Methodology for Disturbed Performance Scenarios

Although 10,000 probabilistic futures are generated to construct a CCDF, the major codes used in PA are executed far fewer times. The results of these calculations are used in part to construct the consequences of all of the probabilistic futures comprising a CCDF in a process called scaling.

The scaling methodology is simple, in concept. First, several simulations are performed with a code to develop a reference behavior for a particular event or process. Each simulation has a defined event occurring at a different time. Then, a large set of futures is developed probabilistically by random sampling. The behavior of the particular event or process in each of the probabilistically sampled futures is estimated by scaling the results of the limited number of deterministic calculations. This scaling is generally simple linear interpolation. For events or processes involving radionuclides, however, scaling becomes more complicated, since it incorporates the effects of radioactive decay and ingrowth. Because scaling is generally less intensive computationally than solving the matrix equations encountered in many PA codes, scaling is an efficient way to develop multiple probabilistic consequence estimates from a

limited number of deterministic calculations. Without scaling, fewer futures would be possible, and resolution in the CCDF would be reduced.

For example, assume that the process of interest is actinides released to the surface during drilling. It is impossible to explicitly model the infinite possibilities present in a probabilistic conceptualization of the future. Thus, scaling is used. To develop a reference behavior for scaling, the CUTTINGS_S code is executed several times with different intrusion times. A probabilistic method is then used to develop a large number of possible, different future intrusion times. To estimate the release to the surface in probabilistic futures, scaling is used in which release at the times in the deterministic calculations closest to the probabilistic time of interest are used as reference points for scaling or interpolation.

Scaling is used for all futures with intrusion boreholes. The times when various codes are executed to develop reference behavior, and how this reference behavior is used by other codes, is the subject of the next two sections. In presenting complete descriptions of the process for each scenario, there will be some duplication of discussion.

6.4.13.3 Estimating Long-Term Releases from the E1 Scenario

The E1 scenario is defined as a single penetration of a panel by a borehole that also intersects a brine reservoir. The code configuration with which the long-term consequences of E1 scenarios are estimated is illustrated in Figure Figure 6-32. For the E1 scenario, BRAGFLO is executed twice more for each CCDF (assuming the undisturbed performance run has already been executed), with the E1-type intrusion occurring at 350 years and 1,000 years. These three BRAGFLO calculations form the foundation for transport modeling that is used for scaling consequences to probabilistic futures.

Consistent with the BRAGFLO intrusion times, NUTS is executed with intrusions occurring at 350 and 1,000 years. These calculations form the basis for (1) estimating releases to the accessible environment via Salado interbeds, or to the surface; and (2) forming the actinide source term to the SECOTP2D code for Culebra transport. For computational efficiency, an intermediate scaling step is conducted prior to calculating the releases associated with probabilistic futures. In this intermediate step, NUTS reference conditions for Culebra releases by an intrusion at 100 years are calculated by using borehole flow from the 350-year intrusion. NUTS reference conditions for intrusions at 3,000, 5,000, 7,000, and 9,000 years are calculated by using borehole flow from the 1,000-year calculation. Thus, to scale consequences of E1 intrusions in probabilistic futures, reference conditions calculated by NUTS are available for 100, 350, 1,000, 3,000, 5,000, 7,000, and 9,000 years postclosure.

Consistent with the BRAGFLO intrusion times, reference behavior for actinide transport in the Culebra is calculated by SECOTP2D for the E1 intrusion occurring at 350 and 1,000 years. Because the equations governing actinide transport and retardation in SECOTP2D are linear, scaling releases to probabilistic E1 penetrations occurring at other times is easily accomplished.

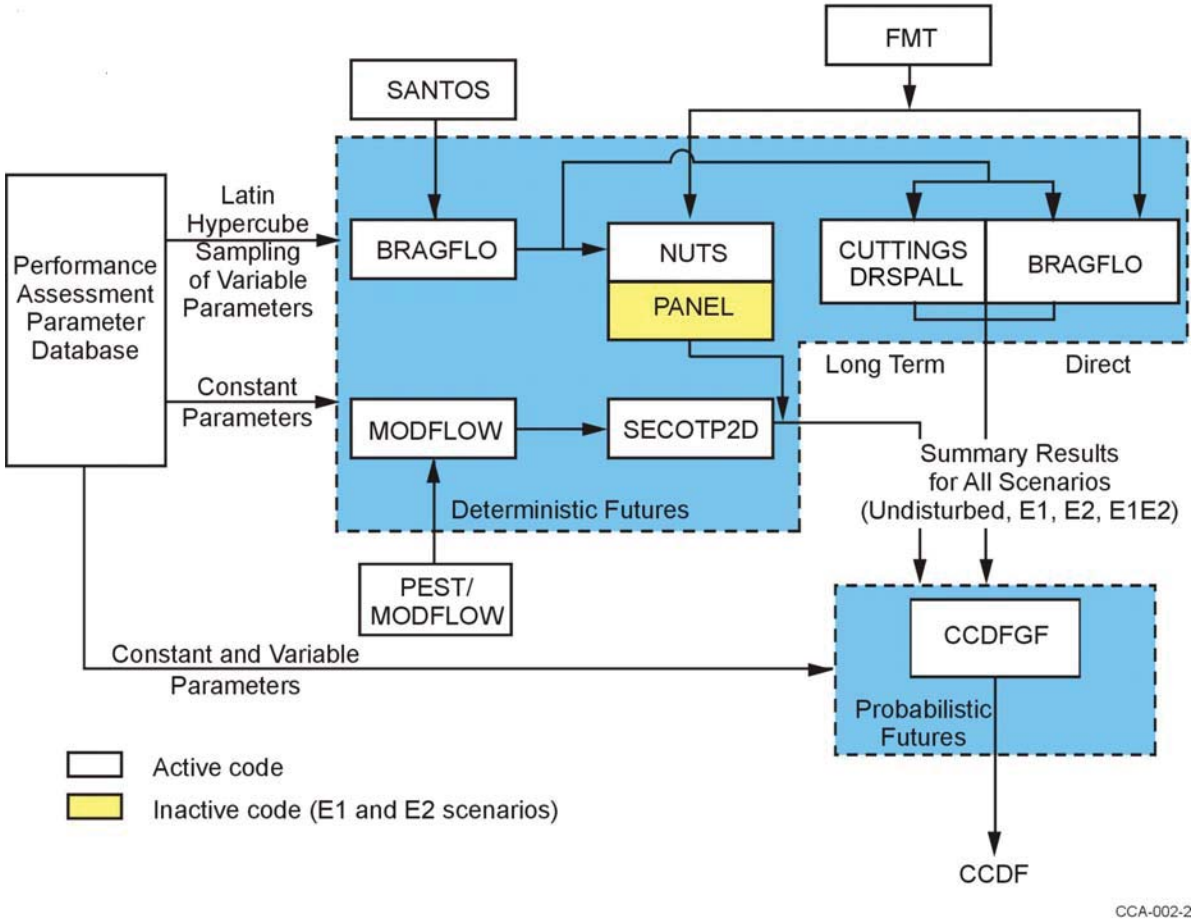

Figure 6-32. Code Configuration for DP Scenarios E1 and E2

6.4.13.4 Estimating Long-Term Releases from the E2 Scenario

The E2 scenario includes all futures with one or more exploratory borehole penetrations of a panel, none of which hits a brine reservoir. Estimating long-term releases from the E2 scenario is slightly more complex than the E1 scenario because the E2 scenario includes the possibility of multiple E2-type intrusions. The same codes used to construct the E1 scenario consequences are used to construct the E2 scenario consequences. These are indicated in Figure 6-33.

As with the E1 scenario, BRAGFLO is executed twice more for each CCDF (assuming the undisturbed performance run has already been executed), with the E2-type intrusion occurring at 350 years and 1,000 years. These three BRAGFLO calculations form the foundation for transport modeling to scale consequences to probabilistic futures.

NUTS is executed with intrusions occurring at 350 and 1,000 years, consistent with the BRAGFLO times of intrusion. These calculations form the basis for (1) estimating releases to the accessible environment via Salado interbeds, or to the surface; and (2) forming the actinide

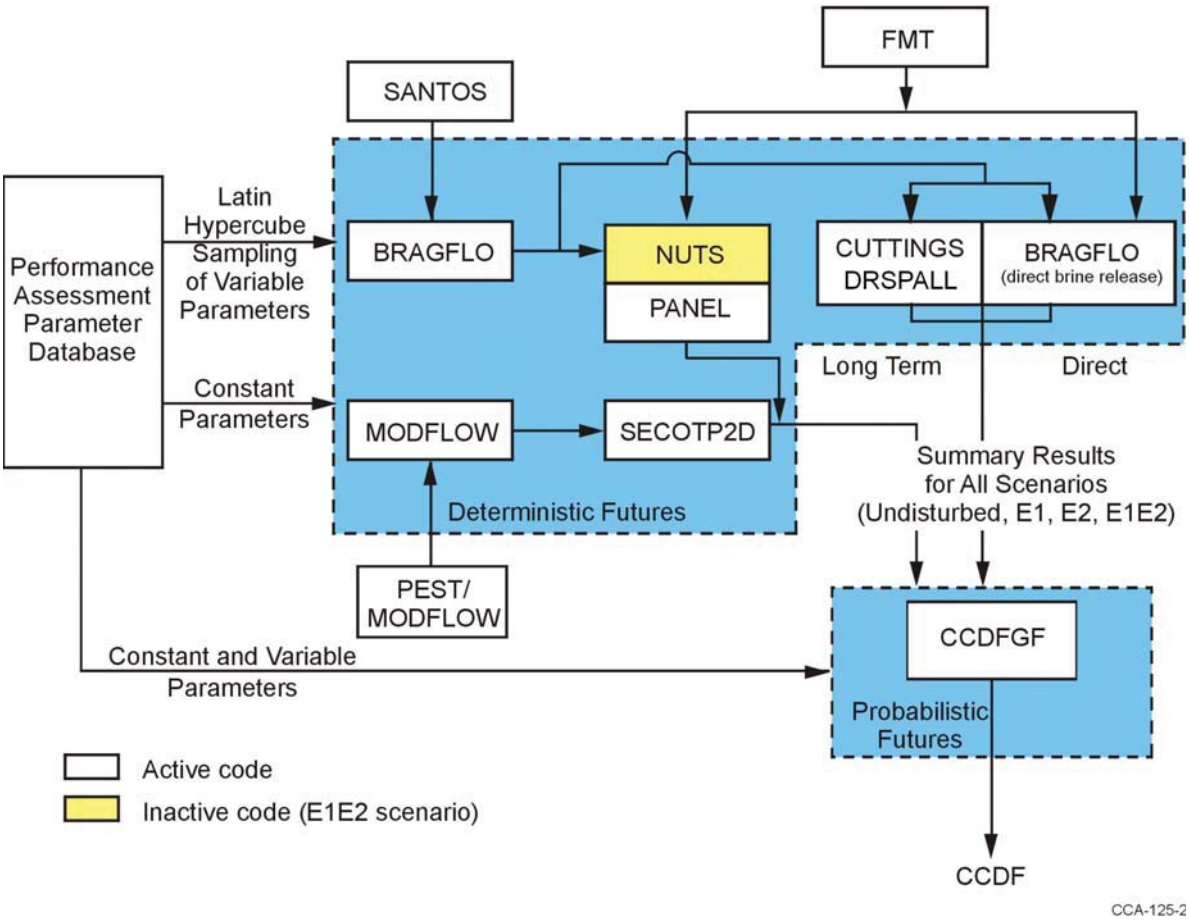

Figure 6-33. Code Configuration for DP Scenario E1E2

source term to the SECOTP2D code for Culebra transport. For computational efficiency, an intermediate scaling step is conducted prior to calculating the releases associated with probabilistic futures. In this intermediate step, NUTS reference conditions for Culebra release by an intrusion at 100 years are estimated by scaling borehole flow from the 350-year intrusion. NUTS reference conditions for intrusions at 3,000, 5,000, 7,000, and 9,000 years are estimated by scaling from the 1,000-year calculation. Thus, to scale consequences of E2 intrusions in probabilistic futures, reference conditions from NUTS calculations are available for 100, 350, 1,000, 3,000, 5,000, 7,000, and 9,000 years.

Consistent with the BRAGFLO intrusion times, reference behavior for actinide transport in the Culebra is calculated by SECOTP2D for the E2 intrusion occurring at 350 and 1,000 years. Because the equations governing actinide transport and retardation in SECOTP2D are linear, scaling releases to probabilistic E2 penetrations occurring at other times is easily accomplished. For futures with two or more E2-type intrusions (and no E1-type intrusions), a simplifying assumption is made. The additional increment to the Culebra's source term for the second and subsequent intrusions is assumed to be zero. This is considered reasonable because in the E2 scenario, the flux of brine to the Culebra is limited by the rate of flow from the Salado to the

waste panels, rather than by borehole properties. For second and subsequent E2 scenarios, only the direct releases to the surface are considered in CCDF construction.

6.4.13.5 Estimating Long-Term Releases from the E1E2 Scenario

The E1E2 scenario is defined as multiple boreholes intersecting a single waste panel, at least one of which is an E1 penetration of a brine reservoir (Section 6.3.2.2.3). The DOE uses both scaling and simplification to develop the consequences of this scenario. Similar to the E1 and E2 scenarios, BRAGFLO and related computer codes are executed with a deterministic sequence of future events to develop reference behavior for the E1E2 consequences (see Figure 6-33). Scaling estimates the consequences for events occurring at different times than those in the BRAGFLO calculations. Simplifying assumptions are used to develop the consequences of E1E2 occurrences in different waste panels, or the consequences of a different sequence of future events leading to the E1E2 scenario, than assumed in the deterministic BRAGFLO calculation.

Reference behavior for brine flow to the Culebra in the E1E2 scenario is predicted by the BRAGFLO disposal system model. This is the same model used to predict brine flow to the Culebra for the E1 and E2 scenarios. The geometry of the grid used is the same as that depicted in Figures 6-14 through 6-16; however, different assumptions are used about the borehole development through time. Even though the E1E2 scenario includes at least two boreholes intersecting the panel, the model used included only one borehole column. As described below, the assumptions used about the way brine mixes in the intruded panel are such that two boreholes are not needed to represent flow through the waste. The assumptions about the development of the borehole are related to the most likely (that is, most probable) sequence of events that gives rise to the E1E2 scenario.

It is most probable that the first borehole into any panel is an E2 borehole (see Section 6.4.12.6). In a BRAGFLO calculation after 1,000 years of undisturbed performance, the properties of the column of elements in BRAGFLO representing the borehole are changed. The changed properties represent the E2 borehole after the Rustler plug has degraded and silty sand fills the borehole. The period during which the plug is effective is not modeled to develop reference behavior for the E1E2 Culebra releases because relatively little happens in the disposal system when the Rustler plug is effective. Reference conditions are developed with the E1 intrusion that follows the initial E2 intrusion occurring after the 200 years it takes Rustler plugs to degrade because it is more probable that a subsequent E1 intrusion occurs after the Rustler plug has degraded. It is assumed that the E1 intrusion occurs 1,000 years after the E2 borehole becomes filled with silty sand, at a simulation time of 2,000 years. At 2,000 years, the properties of the borehole section below the repository horizon are changed to represent an open borehole (the E1 intrusion), allowing flow between the Castile brine reservoir and the repository. After another 200 years, the lower section is assumed to fill with silty sand; after another 1,000 years, the permeability of the lower section is decreased one order of magnitude because of salt creep. These changes are documented in Table 6-31.

Table 6-31. Changes in BRAGFLO Borehole Properties in Developing Reference Behavior for the E1E2 Scenario

Time (years)	Borehole Portion	Properties
0 – 1,000	All	Undisturbed conditions
1,000 – 2,000	Above waste panel Below waste panel	Silty sand Undisturbed conditions
2,000 – 2,200	Above waste panel Below waste panel	Silty sand Open borehole between panel and Castile
2,200 – 3,200	Above waste panel Below waste panel	Silty sand Silty sand
3,200 – 10,000	Above waste panel Below waste panel	Silty sand Silty sand, permeability decreased 1 order of magnitude

Thus, above the waste panel, the E1E2 borehole evolves as an E2 borehole from 1,000 years to 10,000 years. Below the waste panel, the borehole evolves as an E1 borehole from 2,000 to 10,000 years. At 2,200 years, there will be two boreholes above the waste panels with silty-sand properties. The assumption about upper borehole permeability most consistent with that for this scenario of complete mixing in the panel (discussed below) is that the upper portion of the E1 borehole is relatively impermeable and all flow is diverted to the E2 borehole. Therefore, the permeability of the upper borehole remains that of the E2 borehole at 2,200 years.

The concentration of actinides in liquid moving up the borehole assumes homogeneous mixing within the panel and is calculated with the code PANEL. PANEL is a mixing-cell model that sums BRAGFLO fluxes into the waste panel from the boreholes and Salado as inputs to the cell and subtracts the flow up the borehole as a depletion from the model. Brine moving up the borehole is assumed to be at its greatest possible actinide concentration according to the dissolved and colloidal actinide source term models (Sections 6.4.3.5 and 6.4.3.6). In PANEL calculations, all actinides that enter the borehole are conservatively assumed to reach the Culebra.

Random sampling of future events can produce different timing of borehole penetrations. From the time the E2 borehole penetrates until the E1 borehole penetrates, the consequences are determined as they are in the E2 scenario. When the E1 is drilled, completing the E1E2 configuration, the consequences are assumed to be similar to those modeled after the E1 penetration for the reference calculation, accounting for radionuclide decay and ingrowth.

Randomly sampling future events can also produce a different sequence of borehole types. In a randomly sampled future with many E2 intrusions into a waste panel prior to the E1, the consequences are determined as they are for the E2 scenario until the E1 occurs, at which time the E1E2 consequences are used. In a randomly sampled future with the sequence E1 then E2, the consequences are assumed to be similar to an E1 event until the E2 is drilled, whereupon the consequences are assumed to be similar to the E1E2 event following the E1 drilling. In a randomly sampled future with two E1 boreholes, the consequences are assumed to be similar to an E1 borehole until the second E1 is drilled, at which time the consequences are assumed to be similar to the E1E2 behavior.

For computational simplicity, the E1E2 calculations are scaled to E1 intrusions following a prior E2 intrusion occurring at 100, 350, 3,000, 5,000, 7,000, and 9,000 years, similar to the treatment of the E1 and E2 reference conditions.

6.4.13.6 Multiple Scenario Occurrences

For long-term brine flow into the Culebra, scenario occurrences are effectively defined at the panel scale for this PA. It was recognized in preliminary analysis of BRAGFLO results for this analysis that liquid flow between the separate panel and the rest of the repository sections is slow enough that the panel is effectively independent from the rest of the repository. Gas flow does occur, and for this reason, calculations of direct release to the surface are performed at the repository scale. For long-term brine flow to the Culebra, it is considered more reasonable, based on BRAGFLO results, to assume independent panel behavior in developing the CCDF than an interconnected repository.

It is very important to distinguish between model results and model assumptions on this point. For disposal system performance, the DOE is not assuming that panel closures isolate panels from one another. Rather, the DOE has assigned reasonable properties to the panel closures as input to the BRAGFLO calculations and has found that they result in limited liquid flow through the panel closures. Because simplification and scaling must be used to develop CCDFs, the DOE has to assume either that the repository is well interconnected or that the panels behave fairly independently. Based on model results for this analysis, the DOE has established that it is more reasonable in constructing a CCDF to assume that brine does not flow between panels. This simplification of detailed modeling results conducted in BRAGFLO is necessary for CCDF construction. It is not an assumption used in developing conceptual models of disposal system performance. This assumption does affect how scenario consequences are developed.

There are ten panels in the repository and the possibility of many intrusions. If panels behave independently, as they are assumed to in developing consequences of long-term brine flow in the CCDF, it is possible for different configurations of boreholes (scenarios) to occur in different panels. For example, an E1E2 type situation might occur in one panel, an E2 situation in a different panel, and an E1 situation in a third panel. In this example, there are essentially three scenario types occurring. For long-term release, the repository behaves as ten small modules (each comprising one panel), and a different borehole scenario can develop in each of those ten modules. Long-term releases in CCDF construction are based on the premise that releases from each of these modules are independent and that the cumulative release from the repository is equal to the sum of the cumulative releases from the different modules.

6.4.13.7 Estimating Releases During Drilling for All Scenarios

The reference behavior for cuttings and cavings from the first intrusion into a pressurized repository, regardless of whether it is an E1 or E2 intrusion, is established by calculations performed in the CUTTINGS_S code. Cavings releases are also dependent on the effective shear resistance to erosion and the angular velocity of the drill string (Appendix PA, Section PA-4.5). The effects of radioactive decay are captured by calculating reference behavior for cuttings and cavings by the CUTTINGS_S code at 100, 125, 175, 350, 1,000, 3,000, 5,000, 7,500, and 10,000 years.

Spall and direct brine releases during drilling are also dependent on pressure conditions in the repository, and reference releases are calculated by CUTTINGS_S for spall and BRAGFLO (direct brine release) at 100, 350, 1,000, 3000, 5,000, and 10,000 years for intrusions into lower, middle, and upper panels (Appendix PA, Section PA-4.7).

Radionuclide releases from the processes in the CUTTINGS_S code and direct brine release for intrusions occurring at intermediate times are scaled from the closest calculated releases, correcting for radioactive decay (see Section 6.4.12.3 and Figure 6-27). The cuttings and cavings portion of the CUTTINGS_S releases are further adjusted to account for the distribution of CH- and RH-TRU waste streams (see Sections 6.4.12.3 and 6.4.12.4). The processes of spallings and direct brine release are assumed to involve a large enough volume of waste that it is reasonable to use homogeneous waste with average activity to estimate releases.

For multiple-intrusion scenarios, the pressure in the repository at the time of the second and subsequent intrusions may be quite different from that at the time of the first intrusion. This is expected because of the assumptions of relatively permeable boreholes adopted in PA. Therefore, estimates of drilling releases to the accessible environment need to be formed for penetrations of a previously intruded repository. The reference behavior for these subsequent intrusion releases is calculated by the CUTTINGS_S code from BRAGFLO histories with E1- and E2-type intrusions at 350 and 1,000 years. Repository conditions calculated for the effects of a subsequent E1-type penetration are used in consequence analysis for both E1- and E2-type intrusions that follow an E1 intrusion. Conditions from the subsequent E2 calculations are used for intrusions that follow E2 intrusions only. E1 conditions are used for multiple combinations of boreholes that include at least one E1 intrusion, assuming that repository conditions will be dominated by Castile brine if any borehole connects to a brine reservoir. For futures in which more than two E2-type intrusions occur (and no E1-type intrusions occur), third and subsequent spall and direct brine releases are assumed to be the same as for the second release.

For both E1 and E2 conditions following a 350-year intrusion, spall and direct brine release calculations are performed at 550, 750, 2,000, 4,000, and 10,000 years. For the 1,000-year E1 and E2 intrusions, spall and direct brine release calculations are performed at 1,200, 1,400, 3,000, 5,000, and 10,000 years. Because the subsequent intrusion may penetrate either a previously-intruded panel or an unintruded panel, these calculations are done twice, once with initial conditions drawn from the previously-intruded panel in BRAGFLO, and once with conditions drawn from the BRAGFLO subsequent intrusion of the waste-disposal region. As with the first intrusion into a previously undisturbed repository, radionuclide releases from spall and direct brine release for intrusions occurring at intermediate times are scaled from the closest calculated releases, correcting for radioactive decay.

After flow through the repository has occurred for some time, in an E1E2 scenario, portions of the repository may be depleted of actinides. In the estimate of releases during drilling, however, the possibility is not considered that random drilling might penetrate portions of the repository already depleted of actinides from processes initiated by previous drilling. This is conservative because it tends to overestimate releases during drilling.

6.4.13.8 Estimating Releases in the Culebra and the Impact of the Mining Scenario

Ten thousand-year SECOTP2D calculations are performed with Culebra transmissivity fields reflecting undisturbed performance (no future mining within the Land Withdrawal Area) and disturbed performance (see Section 6.4.6.2.3). These calculations are performed with a unit source term of one kilogram of the actinide species of interest at 100 years. Because transport as modeled is a linear process, scaling is used to estimate the consequences of time-variable concentrations and different times of intrusion (see Appendix PA, Section PA-6.8.7). As well, mining may occur at random times in the future. The effect of mining on releases in the Culebra is determined in the following manner.

Boreholes intersecting the repository may provide a source of actinides to the Culebra with concentrations that vary through time. Until mining occurs, the transport behavior of actinides from these borehole sources is estimated by scaling the results of the undisturbed performance Culebra transport calculations. All actinides introduced into the Culebra by the time of mining are transported exclusively in the undisturbed performance flow fields. In other words, actinides in transit in the Culebra when mining occurs are not assumed to be affected and continue to be transported in the undisturbed flow field. Once mining occurs (assumed to be instantaneous), the transport behavior of all actinides subsequently introduced into the Culebra is estimated by scaling the results of the disturbed performance flow fields.

6.4.13.9 Final Construction of a Single CCDF

After consequences for all of the sampled probabilistic futures are estimated by the methodologies presented in the preceding sections, the information necessary to plot the CCDF associated with the probabilistic futures and the particular LHS vector is available.

The sequences of future events used in this PA were generated by random sampling. Thus, each sampled future is assigned an equal weight of occurrence to construct a CCDF. Each sequence of future events is assigned a weight of 1/10,000 of occurrence because 10,000 futures are used for each CCDF. Before plotting, an additional step is performed in which the weights of futures with similar consequences are summed. The first step in the plotting process is to order the grouped futures according to normalized release, as discussed in Section 6.1.1, from lowest normalized release to highest. Following this, the CCDF can be plotted by summing, for a given value of EPA normalized release, the probabilities of all futures whose normalized release exceeds the given value, and where the probabilities are assumed to be equal to the weights. Because the releases cS have been ordered so that $cS_i \leq cS_{i+1}$ for i=1 …, nS-1, the probability that cS exceeds a specific consequence value x is determined by the summation routine (duplicated from Section 6.1.1)

$$F(x) = \sum_{j=i}^{nS} pS_j, \tag{6.19}$$

where i is the smallest integer, that $cS_i > x$. This completes an analysis of stochastic uncertainty for a particular vector of variable values from the LHS sampling.

6.4.14 CCDF Family

The process of CCDF construction described in Section 6.4.13 is repeated once for each vector of subjectively uncertain variable values created by LHS. This process yields a family of CCDFs like those presented in Section 6.5. This family of CCDFs provides a complete display of both stochastic and subjective uncertainty as discussed in Section 6.1.2.

6.5 Performance Assessment Results

This section contains results of the recertification PA and demonstrates that the WIPP continues to comply with the quantitative containment requirements in 40 CFR § 191.13(a). See Section 6.1 for a discussion of the containment requirements. Criteria for presenting the results of PAs are provided by the EPA in 40 CFR § 194.34, and are discussed in Section 6.1.3. These criteria are also summarized here for clarity.

This CRA-2004 PA is different than the original certification PA in the CCA because it includes additional information, changes and new data required by 40 CFR§194.15 recertification application requirements. Section 6.0 details the changes and new information included in this PA. The results of this recertification PA conclude that the repository continues to comply with the disposal standards.

Additional detail about the results of the CRA-2004 PA is contained in Appendix PA, Section PA-9.0, which describes sensitivity analyses conducted as the final step in the Monte Carlo analysis. These sensitivity analyses indicate the relative importance of each of the sampled parameters in terms of their contribution to uncertainty in the estimate of disposal system performance. Analyses also examine the sensitivity of intermediate performance measures to the sampled parameters. Examples of such intermediate performance measures include the quantity of radionuclides released to the accessible environment by any one mechanism (for example, cuttings or direct brine releases), and other model results that describe conditions of interest such as disposal region pressure.

6.5.1 Demonstrating Convergence of the Mean CCDF

As discussed in Sections 6.4.13 and 6.4.14, individual CCDFs for the WIPP are constructed by estimating cumulative radionuclide releases to the accessible environment for 10,000 different possible futures. Each CCDF is calculated for a single LHS vector of input parameters and is conditional on the occurrence of that particular combination of parameter values. Multiple realizations of the PA calculations yield a family of CCDFs in which each individual CCDF is generated from a different LHS vector. Families of CCDFs calculated for the WIPP PA are based on 100 LHS vectors drawn from distributions of values for 64 imprecisely known parameters. As discussed in Section 6.1.2, mean and percentile CCDFs are constructed from families and provide summary measures of disposal system performance.

Criteria provided by the EPA in 40 CFR Part 194.34 address the statistical interpretation of CCDFs:

> The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at

> least a 0.95 probability. Values of cumulative release shall be calculated according to Note 6 of Table 1, Appendix A of Part 191 of this chapter. (40 CFR § 194.34(d))

> Any compliance application shall provide information which demonstrates that there is at least a 95 percent level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 of this chapter. (40 CFR § 194.34(f))

Information provided by the EPA in the Background Information Document for 40 CFR Part 194 clarifies the intent of these criteria.

In 40 CFR Part 194, EPA decided that the statistical portion of the determination of compliance with 40 CFR Part 191 will be based on the sample mean. The LHS sample sizes should be demonstrated operationally (approximately 300 when 50 variables are considered) to improve (reduce the size of) the confidence interval for the estimated mean. The underlying principle is to show convergence of the mean. (EPA 1996b, 8-41)

The DOE has chosen to demonstrate convergence of the mean and to address the associated criteria of 40 CFR Part 194 using an operational approach of multiple replication as proposed by Iman (1982). The complete set of PA calculations was repeated three times with all aspects of the analysis identical except for the random seed used to initiate the LHS procedure. Thus, PA results are available for three replicates, each based on an independent set of 100 LHS vectors drawn from identical CCDFs for imprecisely known parameters and propagated through an identical modeling system. This technique of multiple replication allows evaluation of the adequacy of the sample size chosen in the Monte Carlo analysis and provides a suitable measure of confidence in the estimate of the mean CCDF used to demonstrate compliance with 40 CFR § 191.13(a).

6.5.2 Complementary Cumulative Distribution Functions for the WIPP

Families of CCDFs for each of the three replicates are shown in Figures 6-36, 6-37, and 6-38. Each figure contains 100 CCDFs. These figures address the criterion stated in 40 CFR § 194.34(e):

> Any compliance application shall display the full range of CCDFs generated.

Figures 6-34 through 6-36 show that all 300 CCDFs lie below and to the left of the limits specified in 40 CFR § 191.13(a). They also show qualitatively that the three replicates yield very similar results. Quantitative verification of the similarity of the three replicates is demonstrated in Figure 6-37, which shows the mean CCDFs calculated for each of the three replicates, together with an overall mean CCDF that is the arithmetic mean of the three individual mean CCDFs. Figure 6-37 demonstrates two key points. First, the

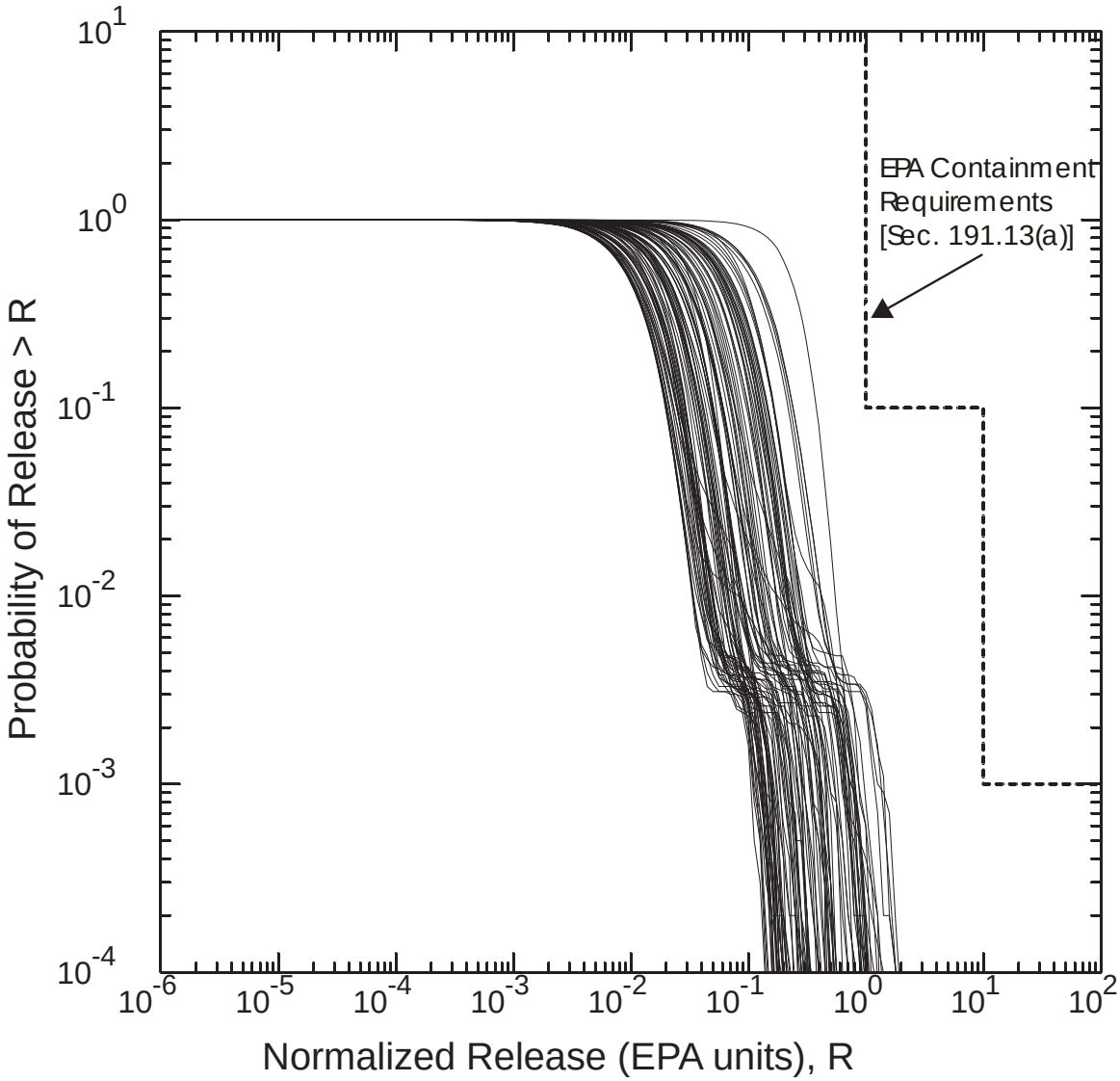

Figure 6-34. Distribution of CCDFs for Normalized Radionuclide Releases to the Accessible Environment from the WIPP, Replicate 1.

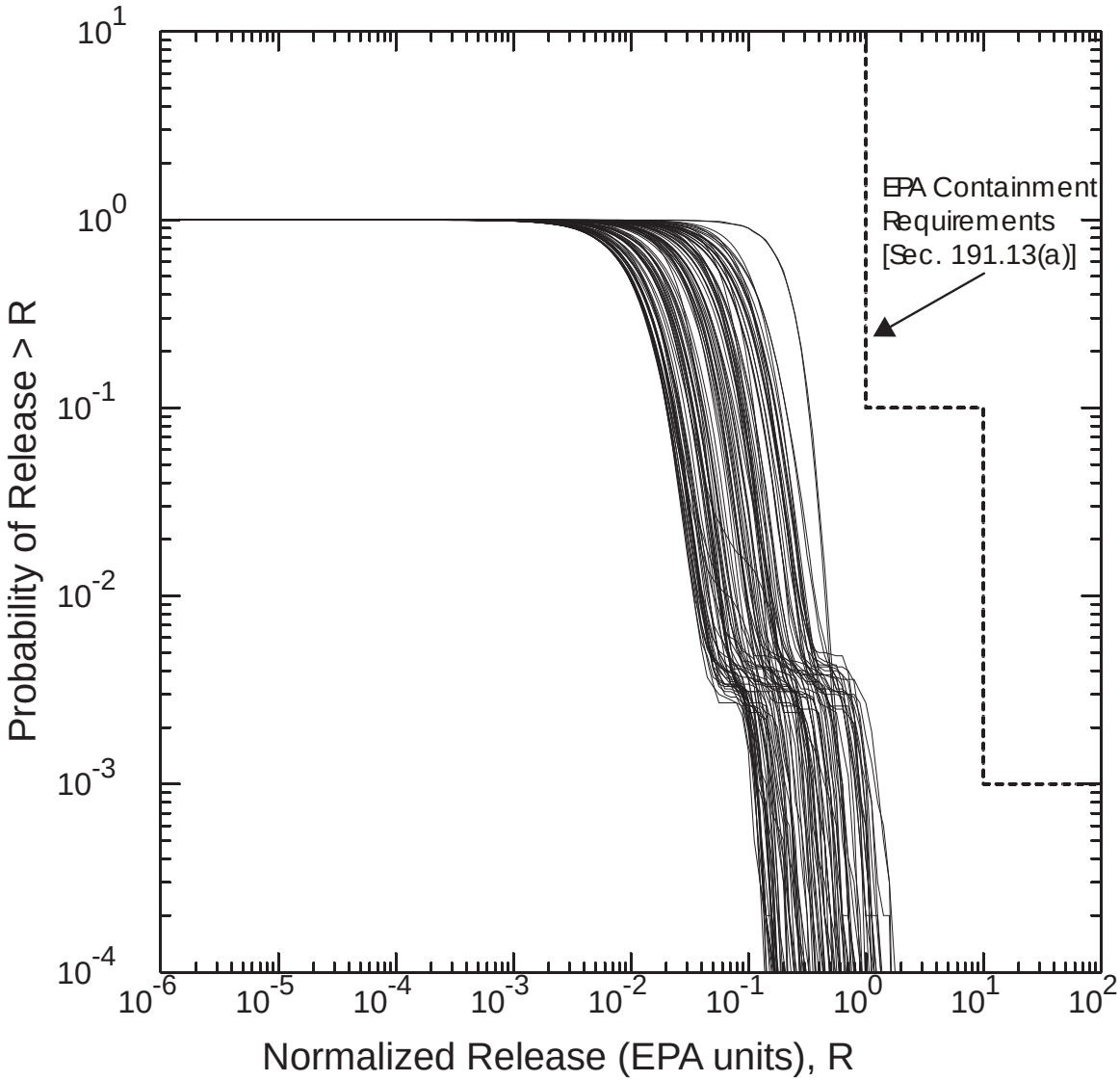

Figure 6-35. Distribution of CCDFs for Normalized Radionuclide Releases to the Accessible Environment from the WIPP, Replicate 2.

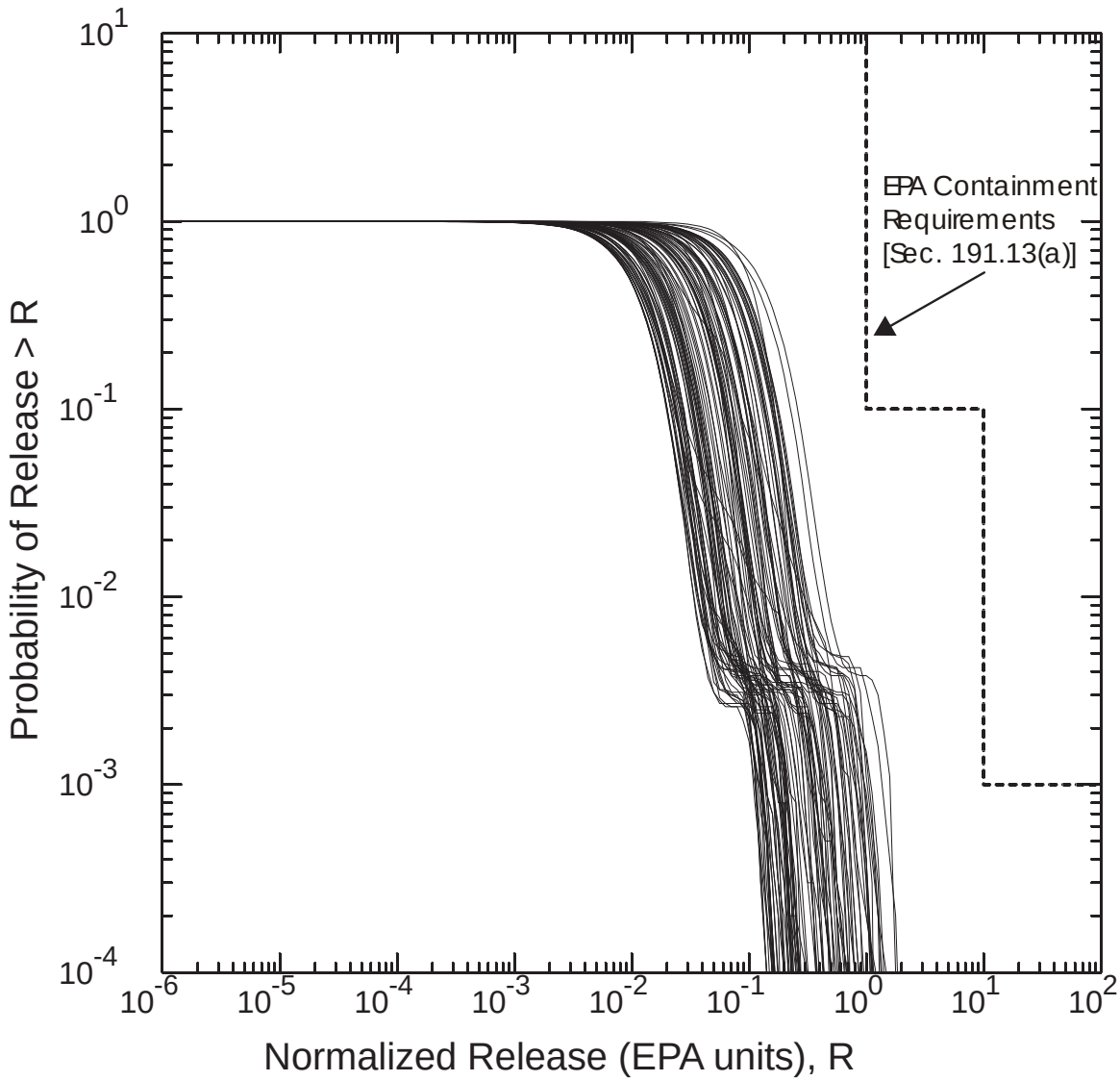

Figure 6-36. Distribution of CCDFs for Normalized Radionuclide Releases to the Accessible Environment from the WIPP, Replicate 3

overall mean CCDF lies entirely below the limits specified in 40 CFR § 191.13(a). Thus, the WIPP is in compliance with the containment requirements of 40 CFR Part 191. Second, the sample size of 100 in each replicate is sufficient to generate a stable distribution of outcomes. Within the region of regulatory interest (that is, at probabilities greater than $10^{-3}/10^{4}$ yr), the mean CCDFs from each replicate are essentially indistinguishable from the overall mean at the resolution of the figure. Figure 6-38 provides quantitative confirmation of the sufficiency of the sample size, by displaying the overall mean together with the 0.95 confidence interval of the Student's t-distribution estimated from the individual means of the three independent replicates (Iman 1982), as shown in Figure 6-37.

Figure 6-1 provides additional summary information about the distributions of CCDFs resulting from the three replicates. This figure shows CCDFs representing the mean,

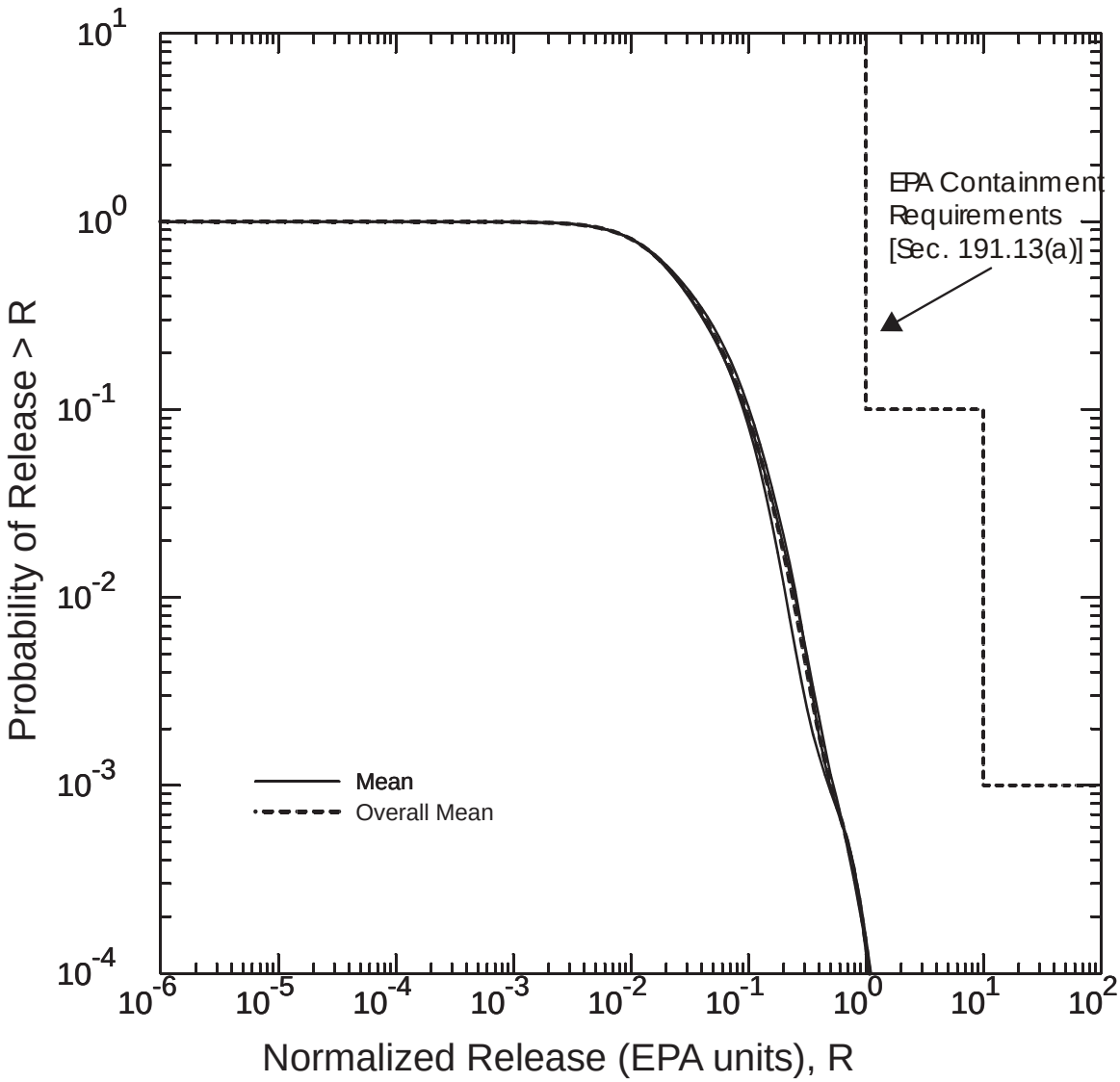

Note: Four CCDFs are shown, including three individual mean CCDFs calculated for each of the three distributions of CCDFs calculated for the three replicates and shown in Figures 6-34, 6-35, 6-36, and an overall mean CCDF that is the arithmetic mean of the three individual mean CCDFs."

Figure 6-37. Mean CCDFs for Normalized Radionuclide Releases to the Accessible Environment

median, and 10th and 90th percentile CCDFs from each replicate, together with the overall mean. Note that for each type of CCDF (for example, the 10th percentile), curves from each replicate overlie closely. This provides quantitative verification of the qualitative observation that distributions from each replicate appear similar.

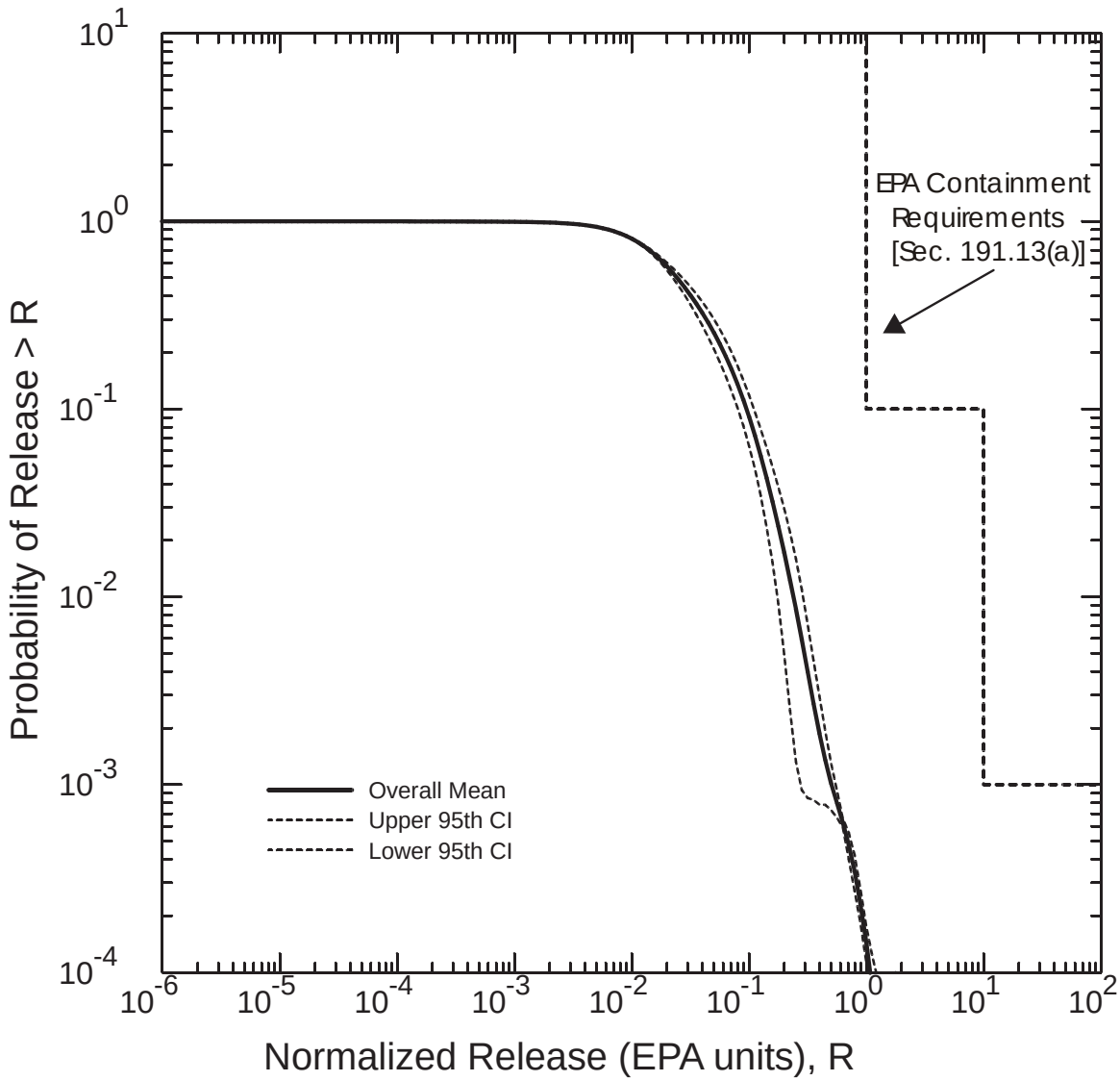

Note: The overall mean CCDF shown in Figure 6-37 is repeated together with the 0.95 confidence interval of the Student-t distribution estimated from the three individual mean CCFDs.

Figure 6-38. Confidence Levels for the Mean CCDF

6.5.3 Release Modes Contributing to the Total Radionuclide Release

Radionuclide releases to the accessible environment can be grouped into four categories according to their mode of release:

(1) cuttings and cavings releases,

(2) spallings releases,

(3) releases resulting from the direct release of brine at the surface during drilling, and

(4) releases in the subsurface following transport in groundwater.

Each of these four modes has the potential to contribute to the total quantity of radionuclides released from the repository, and therefore each has the potential to affect the position of the mean CCDF.

Figure 6-39 provides a display of the relative contribution of each mode to the total release. Releases for each of the three replicates are similar, and results are shown for replicate 1 only for simplicity. Mean CCDFs are shown for the total normalized release (this curve is also shown in Figure 6-1 and is the mean of the family shown in Figure 6-34) and for the normalized releases resulting from cuttings and cavings, spallings, and direct brine release. The mean CCDF for subsurface releases resulting from groundwater transport is not shown because those releases were less than 10^{-6} EPA units and the CCDF cannot be shown at the scale of this figure. Releases from cuttings and cavings are shown to be the most important contributors to the location of mean CCDF, with spallings also making a small contribution. Direct brine releases

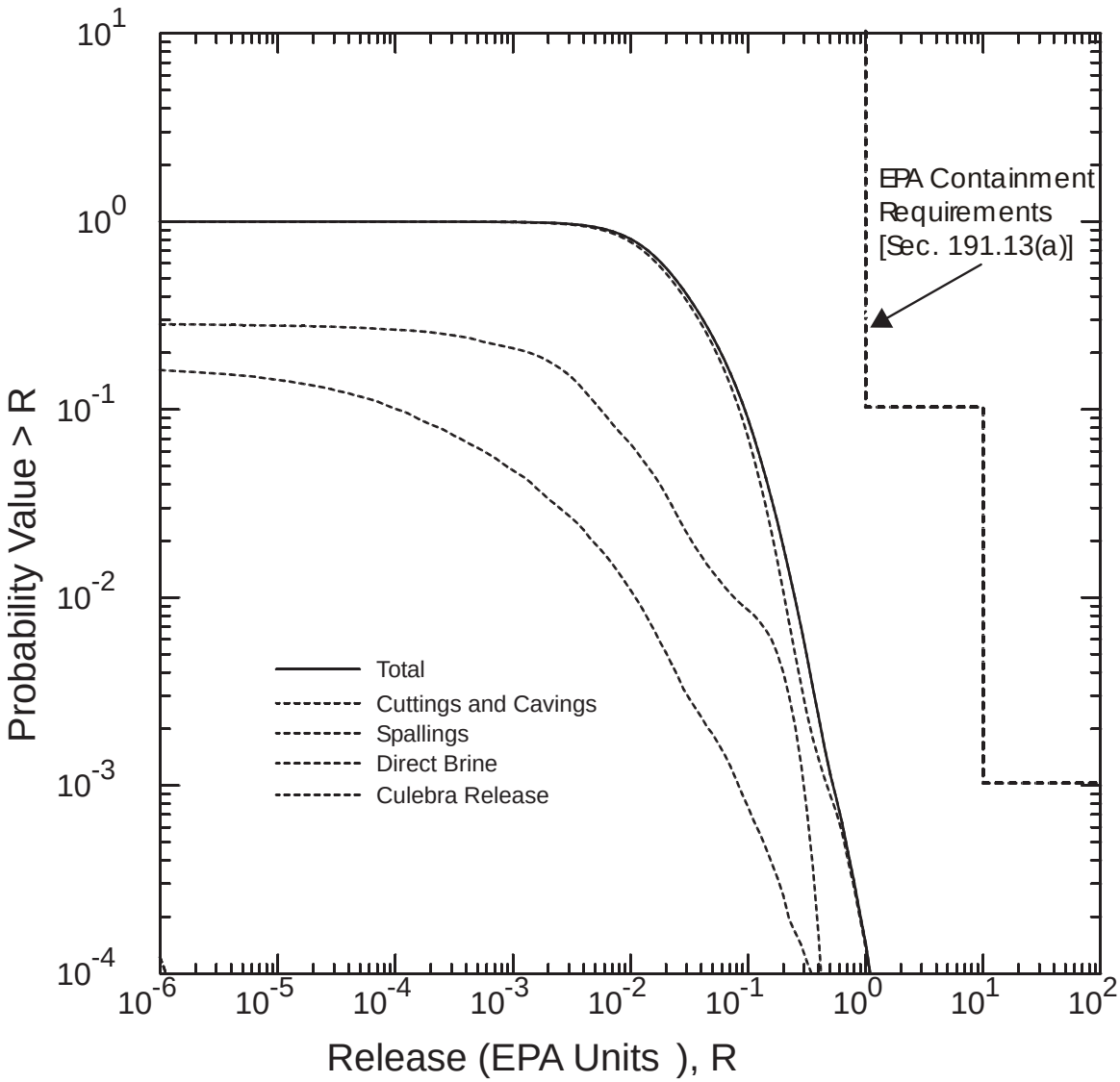

Note: Mean CCDFs are shown for the total normalized release (this curve is also shown in Figure 6-1 and is the mean of the family shown in Figure 6-34) and for the normalized releases resulting from cuttings and cavings, spallings, and direct brine release. The mean CCDF for subsurface releases resulting from groundwater transport is not shown because those releases were less that 10-6 EPA units and the CCDF cannot be shown at the scale of this figure.

Figure 6-39. Mean CCDFs for Specific Release Modes, Replicate 1

are less important, and have very little effect on the location of the mean CCDF. Subsurface groundwater releases are not important, and have essentially no effect on the mean CCDF. See Appendix PA, Section PA-9.0 for additional discussion of the relative importance of the release modes.

6.5.4 Uncertainty and the Role of Conservatism in the Compliance Demonstration

As defined in 40 CFR § 191.12, PAs must "estimate the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant events and processes."

Site characterization, repository design, and waste characterization activities, as described in Chapters 2.0, 3.0, and 4.0, respectively, have removed much uncertainty from the analysis. Uncertainties remain, however, about how best to characterize some aspects of the disposal system and how best to model the complex interactions between the waste and its surrounding environment. These remaining uncertainties have been incorporated in the performance assessment to the extent practicable through the use of reasonable and realistic assumptions about models and parameter values.

In general, the DOE has not attempted to bias the PA toward a conservative outcome, and the mean CCDF represents a reasonable estimate of the expected and, in the case of future human activities including intrusion, prescribed, performance of the disposal system. However, where realistic approaches to incorporating uncertainty are unavailable or impractical and where the impact of the uncertainty on performance is small, the DOE has chosen to simplify the analysis by implementing reasonable and conservative assumptions. These conservative assumptions are reviewed here, not because they bias the location of the mean CCDF, but rather because an understanding of their effects contributes qualitatively to the "reasonable expectation, on the basis of the record before the implementing agency, that compliance with [§] 191.13(a) will be achieved," as required by Section 191.13(b).

As noted in Section 6.2 and Appendix PA, Attachment SCR, in some cases processes have been omitted from the modeling system for simplicity because the only possible effects of including them would be beneficial to system performance. Examples include the decision to model radionuclide dissolution as an equilibrium process (assuming instantaneous leaching and dissolution), and the decision not to model sorption of radionuclides in the Salado or in the seal system.

In other cases, the DOE has made conservative decisions during the design of the conceptual and computational models, as listed in Table 6-32. Some conservative assumptions listed in this table are mentioned below. For example, within the repository portion of the BRAGFLO model, fluid flow in a single panel is treated as if all rooms were a single void (that is, pillars are omitted). This treatment allows brine flow to and from an intrusion borehole to contact more waste than it would if it followed a more realistic flow path between rooms. The effect is conservative with respect to brine flow up a plugged and abandoned borehole. Similarly, the DOE has chosen to model fluid flow through plugged and abandoned boreholes as if all intrusions occurred into a down-dip (that is, southern) panel. As modeled, downdip panels tend to have more brine in them than up-dip panels (see Appendix PA, Section PA-8.0) and this assumption therefore may result in overestimating the amount of brine present in intruded panels.

Radionuclide dissolution to solubility limits is modeled as instantaneous. For E1E2 scenarios, complete mixing is assumed within the intruded panel, and all brine that flows out of the panel and up the borehole is assumed to have been in contact with waste.

Within the shaft seal system, concrete components are modeled as if they degrade after emplacement, underestimating their potential to limit fluid flow over the long-term. For direct releases and E1E2 releases to the Culebra, processes of actinide transport and retardation are not modeled within the intrusion borehole and all actinides that enter the borehole are assumed to be transported to the surface or into an overlying transmissive unit. Within the Culebra (which

modeling indicates will be the only transmissive unit that will receive long-term flow from the borehole), hydraulically significant fractures are assumed for modeling simplicity to be present everywhere, even though test data indicate that the portions of the Culebra above the waste disposal region behave as an unfractured, single porosity matrix.

These conservative assumptions have not significantly affected the location of the mean CCDF, which, as shown in Section 6.5.3, is dominated by cuttings and cavings releases that are, with one exception, independent of the conservative simplifications described here. As discussed in Appendix PA, the parameter making the largest contribution to uncertainty in the location of the mean CCDF is the effective shear resistance of the waste, which affects the quantity of waste eroded from the borehole wall and transported to the surface as cavings. In the absence of data describing the reasonable and realistic future properties of degraded waste and MgO, effective shear resistance of the waste is a parameter for which the DOE has selected a conservative distribution (see Appendix PAR, Parameter 33).

6.5.5 Summary of the Demonstration of Compliance with the Containment Requirements

The WIPP continues to comply with the containment requirements of 40 CFR § 191.13(a), as shown by Figures 6-34 through 6-38. Figures 6-37 and 6-38 demonstrate that the sample size of 100 chosen for this analysis is sufficient to provide the level of statistical confidence specified in 40 CFR § 194.34.

Additional confidence in the compliance determination comes from examination of Figure 6-39, which shows that the location of the mean CCDF depends almost entirely on the relatively simple processes that contribute to cuttings and cavings releases resulting from inadvertent human intrusion by drilling. Uncertainties related to the characterization of the natural system and the interaction of waste with the disposal system environment have little effect on long-term performance. The natural and engineered barrier systems, as described in Chapters 2.0 and 3.0, will provide robust and effective containment of TRU waste even if the repository is penetrated by multiple borehole intrusions.

Table 6-32. Conservative Model and Parameter Assumptions Used in PA (from Appendix PA, Attachment MASS, Table MASS-1)

Conservative Assumption	Code	Cross-Reference
Long-term flow up plugged and abandoned boreholes is modeled as if all intrusions occur into a down-dip (southern) panel.	BRAGFLO	Section 6.4.3
Pillars, individual drifts and rooms are not modeled for long-term performance, and containers provide no barrier to fluid flow.	BRAGFLO	Section 6.4.3, Appendix PA, Attachment MASS, Section 5.0
Brine in the repository will contain a uniform mixture of dissolved and solid-state species. All actinides have instant access to all repository brine.	NUTS PANEL	Section 6.4.3.4 Appendix PA, Attachment SOTERM, Section 2.2
Radionuclide dissolution to solubility limits is instantaneous.	NUTS PANEL	Sections 6.4.3.5 and 6.4.3.4 (Appendix PA, Attachment SOTERM, Section 3.3,)
Radionuclides are not retarded by shaft seals.	NUTS	Section 6.4.4
Shaft concrete components of the lower shaft are modeled as if they degrade after emplacement.	BRAGFLO	Section 6.4.4 Appendix PA, Attachment PAR
The permeability of the DRZ is sampled with the low value similar to intact halite and the higher value representing a fractured material.	BRAGFLO	Section 6.4.5.3 Appendix PA, Attachment MASS, Section 13.4
The Los Medaños member of the Rustler, Tamarisk, and Forty-niner are assumed to be impermeable.	BRAGFLO SECOFL2D	Sections 6.4.6.1, 6.4.6.3, and 6.4.6.5 Appendix PA, Attachment MASS, Section 14.0
Sorption of actinides in the borehole is not modeled.	NUTS	Section 6.4.5.4 Appendix PA, Attachment MASS, Section 13.5
Sorption occurs on dolomite in the matrix. Sorption on clays present in the Culebra is not modeled.	SECOTP2D	Section 6.4.6.2.1 Appendix PA, Attachment MASS, Section 15.2
Particle waste shear is based on properties of marine clays, considered a worst case.	CUTTINGS_S	Section 6.4.7.1 Appendix PA, Attachment PAR
The concentration of actinides in liquid moving up the borehole in the E1E2 scenario assumes homogeneous mixing within the panel.	CCDFGF PANEL	Section 6.4.13.5

Table 6-32. Conservative Model and Parameter Assumptions Used in PA (from Appendix PA, Attachment MASS, Table MASS-1) — Continued

Conservative Assumption	Code	Cross-Reference
For all direct releases to the surface and the E1E2 source term to the Culebra, any actinides that enter the borehole are assumed to reach the surface or Culebra, respectively.	CUTTINGS_S DRSPALL BRAGFLO PANEL CCDFGF	Section 6.4.7.1 Section 6.4.13.5
A hemispherical geometry with one-dimensional spherical symmetry defines the flow field and cavity in the waste	DRSPALL	Section 6.4.7.1 MASS.16.1
Tensile strength, based on completely degraded waste surrogates, is felt to represent extreme, low-end tensile strengths because it does not account for several strengthening mechanisms	DRSPALL	Section 6.4.7.1 MASS.16.1
Shape factor is 0.1, corresponding to particles that are easier to fluidize and entrain in the flow	DRSPALL	Section 6.4.7.1 MASS.16.1
Retardation is assumed to not occur in the Salado.	NUTS CCDFGF	Section 6.4.5.4.2
Depletion of actinides in parts of the repository that have been penetrated by boreholes is not accounted for in calculating the releases from subsequent intrusions at such locations.	CUTTINGS_S	Section 6.4.13.7
Hydraulically-significant fractures are assumed to be present everywhere in the Culebra.	SECOTP2D	Section 6.4.6.2.1

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7.0 ASSURANCE REQUIREMENTS

In the Preamble to Title 40 of the Code of Federal Regulations (CFR) Part 191 (EPA 1985) (50 FR 30879), the U.S. Environmental Protection Agency (EPA) points out that:

> There are too many uncertainties in projecting the behavior of natural and engineered components for many thousands of years—and too many opportunities for mistakes or poor judgments in such calculations—for the numerical requirements on overall system performance in Subpart B to be the sole basis to determine the acceptability of disposal systems for these very hazardous wastes.

In view of this, the EPA developed assurance requirements (40 CFR § 191.14) to ensure that implementing agencies act cautiously and take steps to reduce the impacts of these uncertainties. According to the EPA, these assurance requirements are considered an essential complement to the containment requirements, which, when implemented, should ensure that the level of protection desired by the EPA is achieved. Contained in 40 CFR § 191.14 are these six separate assurance requirements:

- active institutional controls,
- monitoring,
- passive institutional controls,
- use of different types of barriers,
- resource disincentives, and
- waste removal.

Figure 7-1 provides a timeline illustrating the implementation of these assurance requirements. Waste removal is not included in Figure 7-1 because it is not a planned activity. Waste removal is discussed in CCA Appendix WRAC. See Table 1-7 for a list of appendices that provide additional information supporting this chapter.

The provisions of 40 CFR 194 (EPA 1996a) contain detailed criteria that the U.S. Department of Energy (DOE) is to use in implementing the assurance requirements contained in 40 CFR 191. The following sections detail the DOE's compliance with the assurance requirements of 40 CFR 191 and the associated certification criteria in 40 CFR 194. In addition to addressing the six assurance requirements stated above, the DOE used some conservative assumptions in the performance assessment that provide additional assurance. Use of conservative assumptions is discussed in Section 6.5.4.

7.1 Active Institutional Controls

Active institutional controls and passive institutional controls satisfy two roles:

(1) they meet assurance requirements per 40 CFR 191 and 194, and

(2) they contribute to performance assessment per 40 CFR 194.

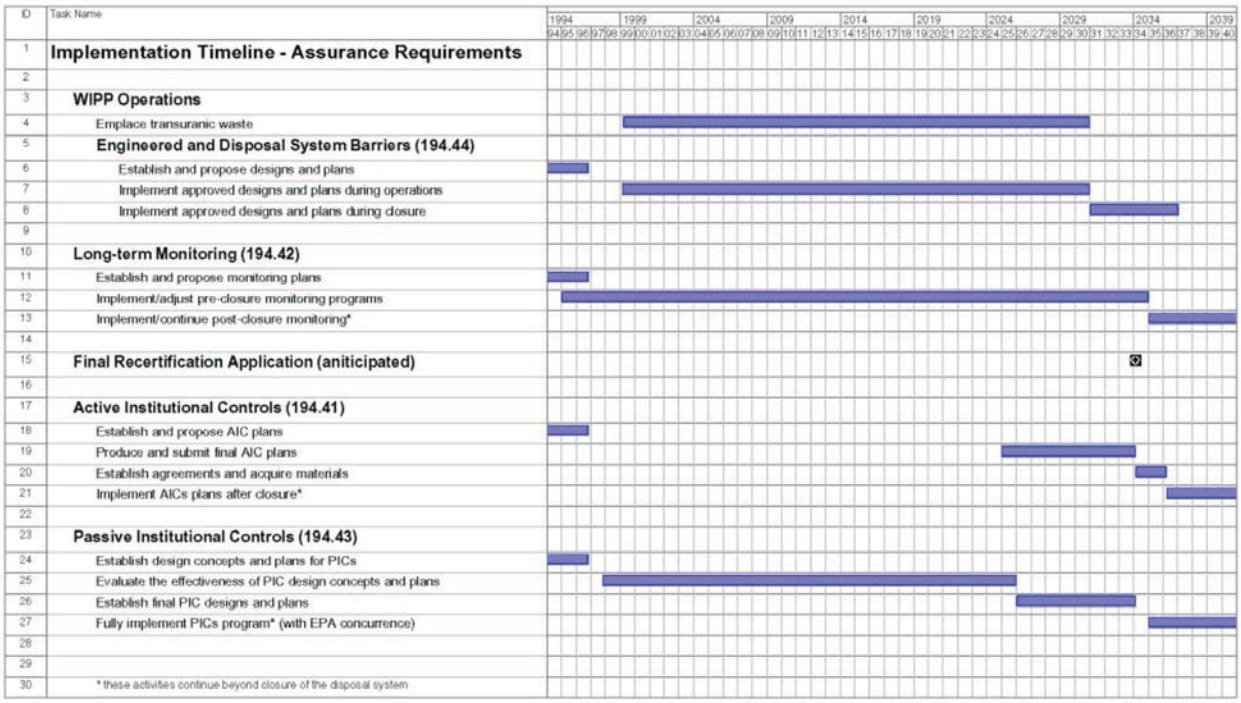

Figure 7-1. Implementation Timeline – Assurance Requirements

Once the facility at the Waste Isolation Pilot Plant (WIPP) is decommissioned and decontaminated (D&D), positive actions (active institutional controls) will be taken to ensure site access control. Active institutional controls begin after final facility closure. The EPA has specified that no more than 100 years of active institutional controls can be assumed in predictions of long-term performance. The DOE interprets this requirement to mean that control programs should be implemented as long as such controls are useful and practical, but credit for active institutional controls cannot be considered in the performance assessment beyond 100 years from the final closure of the repository. Therefore, performance assessment does not consider credit for active institutional controls beyond 100 years.

The EPA defines active institutional controls as "(1) controlling access to a disposal site by any means other than passive institutional controls, (2) performing maintenance operations or remedial actions at the site, (3) controlling or cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance" (40 CFR § 191.12). Active institutional controls to be used by the DOE include facility guarding, evaluation of land use in the area, postoperational monitoring, land reclamation, and maintenance of fences and buildings. In addition, active institutional controls are integrated with the D&D activities described in CCA Appendix D&D. That appendix remains unchanged and, therefore, is not included in this recertification application.

During the rulemaking process for the original WIPP certification, the DOE developed and provided the following to the EPA:

(1) detailed information regarding the schedule for implementing the active institutional controls,

(2) DOE's approach to maintaining and replacing active institutional controls, and

(3) minimum standards that will be applied during construction and maintenance of the active institutional controls.

This information was provided to the EPA via letter dated February 7, 1997 (Docket A-93-02, Item II-I-07, Enclosure 1c).

The DOE also provided sample inspection checklists for site surveillance and maintenance and a discussion of training requirements that will be applied to site patrol personnel. The DOE conducted a "capabilities survey" of regional security firms and concluded that the surveillance requirements for the WIPP site were within the scope of current local capabilities. The EPA contacted the Eddy County Sheriff's Office and confirmed that, while the Sheriff's Office may be able to patrol the site after closure, the services of a private firm would have to be contracted for routine patrols. On the basis of the documentation provided by the DOE, the EPA found the active institutional controls plans to be adequate and that the implementation may be effective for 100 years after disposal (63 FR 27395; see also CARD 41 located in EPA Docket A-93-02, Item V-B-2).

7.1.1 Requirements for Active Institutional Controls

In prescribing active institutional controls, the EPA has specified that "active institutional controls over disposal sites should be maintained for as long a period of time as is practicable after disposal" (40 CFR § 191.14[a]). The EPA addresses the effectiveness of these controls and the length of the time for which such controls should be considered effective for the performance assessment.

Section 194.41(a) specifies that "any compliance application shall include detailed descriptions of proposed active institutional controls, the controls' location, and the period of time the controls are proposed to remain active." Section 194.41(a) also states that any assumptions pertaining to the effectiveness of active controls in preventing inadvertent human intrusion should be supported by such descriptions. This section provides support for the assumptions pertaining to the active institutional controls program for the WIPP facility. Prior to decommissioning of the facility and full implementation of the active controls program, the DOE will reevaluate the proposed active controls program and make any changes necessary as indicated by experience and evaluation of data. The design of the DOE's active controls program is described in CCA Appendix AIC.

For the purposes of this application, the DOE will begin the active controls period within sixty days of completion of final facility closure.

7.1.2 Objectives for Active Institutional Controls

The primary goal of DOE's active institutional controls program is to prevent unauthorized use of the WIPP site. Because of the massive body of rock that separates the waste from the accessible environment, there are not many activities that pose a threat to the WIPP disposal system. The threats that are severe enough or likely enough to consider are addressed in Appendix PA, Attachment SCR and in the conceptual models description located in Section 6.4. The DOE has identified four objectives for the design of the active controls program: (1) eliminating those site features that would cause future populations to develop the WIPP site (see Section 7.1.3.1), (2) identifying allowed and disallowed activities, (3) identifying and minimizing the impacts of the intentional user, and (4) controlling allowed activities and preventing unallowed activities. In addition, the DOE will install and protect monitoring equipment and any test facilities established for evaluating the long-term marker system.

In order to design an active controls program around these four objectives, the DOE has assumed the following:

- site restoration will be to as near the original condition as practicable,
- future authorized site uses will not be significantly different than they are now, as described in CCA Appendix LMP, and
- a threat of future unauthorized use exists.

The WIPP Land Management Plan (LMP) (DOE/WIPP 93-004) provides guidance for managing the land withdrawn for the WIPP through project decommissioning. Active institutional controls

are implemented after decommissioning and, by definition, the LMP is not part of the WIPP active institutional controls program. A planned change pursuant to 40 CFR § 194.4(b)(3) was submitted to the EPA in January 2002 requesting removal of CCA Appendix LMP from the Compliance Baseline. In a letter sent to the DOE dated March 15, 2002 (Marcinowski to Triay; EPA Docket A-98-49, II-B-3, Item 24), the EPA approved the planned change allowing CCA Appendix LMP to be eliminated from future recertification applications.

Restoration of the WIPP site includes any activities associated with demobilization following D&D. In addition, as part of the active institutional controls program, the DOE will implement monitoring systems suitable for assessing disposal system performance. The objectives of the active institutional controls program, the monitoring program, and the decommissioning plan overlap; therefore, the DOE believes it is both prudent and within the EPA's intent to conduct these programs simultaneously. This provides for a more comprehensive understanding of the multitude of activities that will be taking place during the active controls period.

7.1.3 Implementation of the Active Institutional Controls Program

The first step in the process of implementing the active institutional controls program was to identify measures needed to satisfy the active institutional controls requirements. Certain characteristics of active institutional controls measures have been identified, such as minimizing features that would attract future development of the site, warning of potential hazards through signage, implementing the measures for at least 100 years, addressing the standards, and preventing development. These characteristics were used to develop conceptual designs for active institutional controls.

Some active institutional controls were obvious at the outset, including site access control, site remedial actions, site maintenance, and site monitoring. Information and specifications useful in implementing these and possibly other controls have been gathered. A detailed explanation of the resulting active institutional controls is provided in CCA Appendix AIC (Section 2). The plan will be reviewed periodically and updated as appropriate during WIPP's operations phase. Ongoing review and evaluation will ensure that the active institutional controls implemented are appropriate for the conditions that may exist at that time. The DOE will review the design prior to implementation, and should it be determined the design should be modified, the changes shall be reported per the change requirements at 40 CFR § 194.4.

The final operational activity at the repository will be closing the waste disposal area and sealing the shafts. All surface structures, except for the concrete hot cell structure (CCA Appendix AIC), and a sufficient quantity of salt tailings to support construction of the permanent marker berm (CCA Appendix PIC) will be removed and the site regraded and revegetated to as near its original condition as practicable.

In order to determine the active controls that would be beneficial, the DOE analyzed the types of land uses anticipated and, based on that analysis, developed a design plan for active institutional controls. The following two sections summarize the analysis and the design plan.

7.1.3.1 Analysis of Activities

The purpose of the analysis of activities is to determine the types of disturbances that may be associated with each activity, the depth of such disturbances, and the need for any mitigation of these activities. These activities are supported with screening decisions in Appendix PA, Attachment SCR. This section addresses the following activities:

- ranching,
- farming,
- hunting,
- scientific activities,
- utilities and transportation,
- groundwater pumping,
- surface excavation,
- potash exploration,
- hydrocarbon exploration,
- construction, and
- hostile and illegal activities.

Table 7-1 indicates the active institutional controls that will be applied to prevent unauthorized activities.

7.1.3.1.1 Ranching

Description of the Activity: Ranching involves the management of herds of cattle on the public lands surrounding and including the WIPP. These activities are regulated on federal lands such as the WIPP under a permitting process administered by the Bureau of Land Management (BLM). There is little surface-disturbing activity associated with ranching except for the construction of fences, the construction and operation of watering facilities, and the occasional drilling of groundwater wells. Currently, only the 277 acres within the Exclusive Use Area are not used for ranching. In the future, barbed wire enclosures will be constructed to provide security for monitoring facilities, test areas, and construction areas. Eventually, the entire surface is expected to be released for ranching activities. Only those activities associated with groundwater use could have any impact on the disposal system. These are discussed in Section 7.1.3.1.6. Figure 7-2 depicts the current grazing allotments on the WIPP site.

Goal of Active Controls: Active controls will ensure that grazing leases are administered consistently and in compliance with applicable regulations. Fencing will be needed to protect government property. In addition, areas will be fenced as needed to prevent cattle from disturbing reclaimed areas until vegetation has been reestablished.

7.1.3.1.2 Farming

Description of the Activity: Farming includes soil preparation, planting, irrigation, and harvesting. Significant quantities of water are needed to support crops in the Delaware Basin.

Table 7-1. Effectiveness of Active Controls Activities

Active Institutional Controls	*Activities*										
	Ranching	*Farming*	*Hunting*	*Scientific Activities*	*Utilities and Transpor-tation*	*Ground-water Pumping*	*Excavation*	*Potash Explora-tion*	*Hydrocarbon Exploration*	*Con-struction*	*Hostile and Illegal Activities*
Fence	●[1]	●	●				●			●	
Roadway				●	●	●					
Signs		●	●		●		●	●	●	●	●
Contract for Inspection and Maintenance	●	●	●	●	●	●	●	●	●	●	●
Security Surveillance	●	●	●	●	●	●	●	●	●	●	●
Testing				●	●						
Disposal System Monitoring				●		●					
Permanent Marker System Installation				●							
Response	●	●	●	●	●	●	●	●	●	●	●
Reporting	●	●	●	●	●	●	●	●	●	●	●

[1] "●" Indicates component addressed by active institutional controls

Crops grown in the farming area nearest to the WIPP include cotton, alfalfa, peppers, and pecans. Small quantities of other crops are also grown. Farming using irrigation would require access to large amounts of fresh water, either through the diversion of surface water or the construction of groundwater wells. There is currently no known farming near the WIPP because of the lack of good quality water and the poor soil composition. Farming, therefore, is screened out of the performance assessment on the basis that any impacts are of low consequence to the disposal system (see Appendix PA, Attachment SCR, Arable Farming FEP H53).

Goal of Active Controls: While farming is unlikely, the fence, signs, and other measures will prevent farming activities from disturbing test areas or affecting monitoring locations.

7.1.3.1.3 Hunting

Description of the Activity: Currently, hunting occurs outside the WIPP Off Limits Area. The prohibition from hunting is mandated by DOE policy. Unless the restrictions are lifted, hunting will continue to be prohibited in this 1,454-acre (590-hectare) area. The restriction has been placed to provide protection for facilities and personnel working at the WIPP. Game animals in the vicinity include deer, small mammals, and birds. There are no hunting activities that are anticipated to impact the disposal system. Figure 7-3 depicts the area within the WIPP site boundary where hunting is allowed.

Goal of Active Controls: Protection of facilities and personnel engaged in monitoring, reclamation, and testing activities will be needed throughout the active controls period. Local and state hunting laws and restrictions will apply.

7.1.3.1.4 Scientific Activities

Description of the Activity: Scientific activities can include both those conducted by the DOE for the WIPP and those conducted by outside organizations. Types of activities include archeological investigations, wildlife studies, vegetation studies, grazing studies, geomorphic studies, passive marker testing, passive marker construction, hydrologic studies, disposal system monitoring, and others. Prolonged studies of vegetation, geomorphic features, or grazing impacts may require the construction of fenced enclosures. Some may involve the placement of monitoring or other types of equipment or monuments that need to be protected from vandalism.

Goal of Active Controls: In the case of scientific studies, active controls will ensure that scientific activities can proceed undisturbed without impacting the disposal system. Specific needs for protection may be identified with each study proposed for the area.

7.1.3.1.5 Utilities and Transportation

Description of the Activity: Currently, the WIPP site boundary is traversed by several pipelines (natural gas), buried telephone lines, power lines, a highway, and a railroad. Future transportation needs are expected to remain the same. Construction and maintenance of utilities

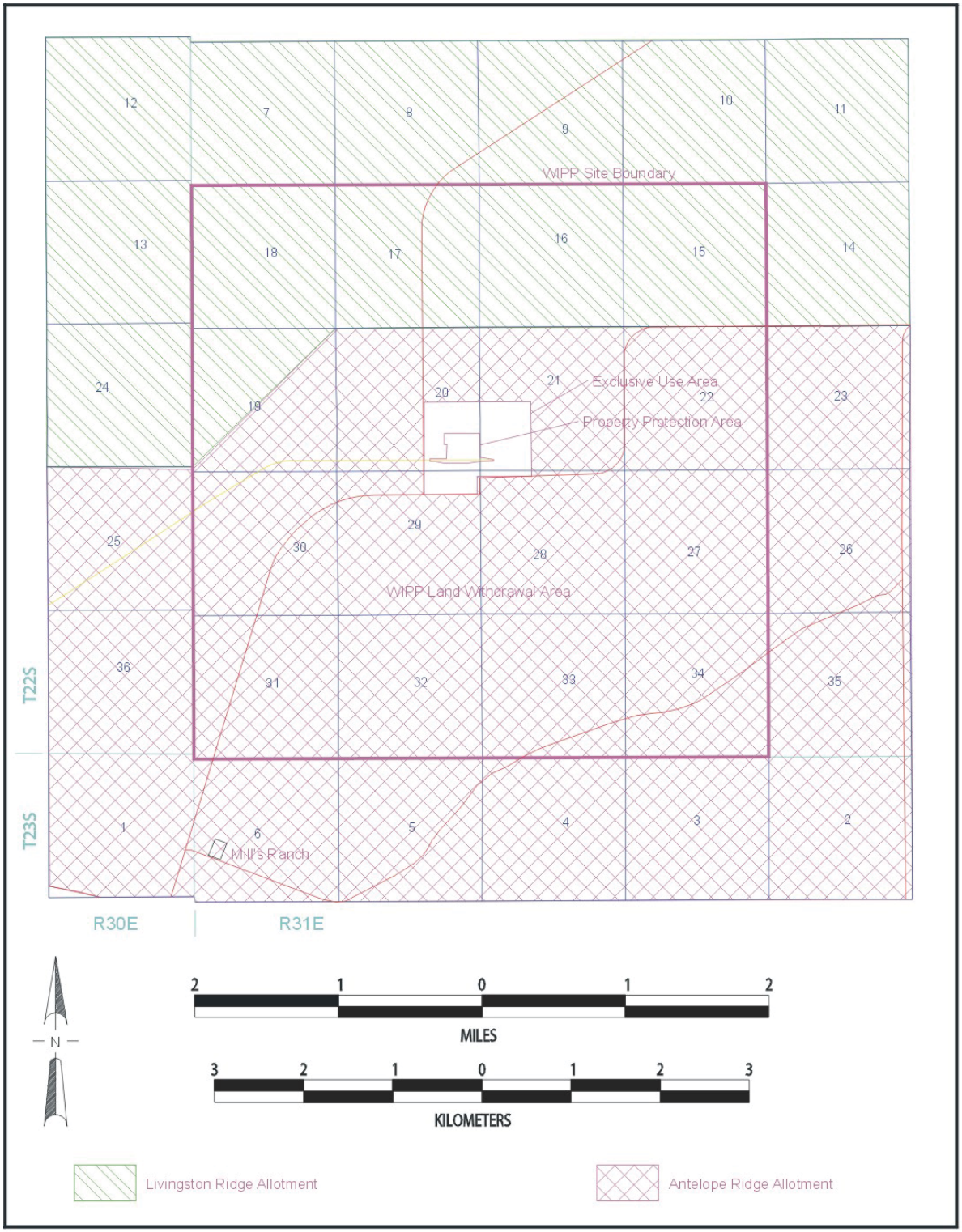

Figure 7-2. Grazing Allotments on the WIPP Site as of September 2002

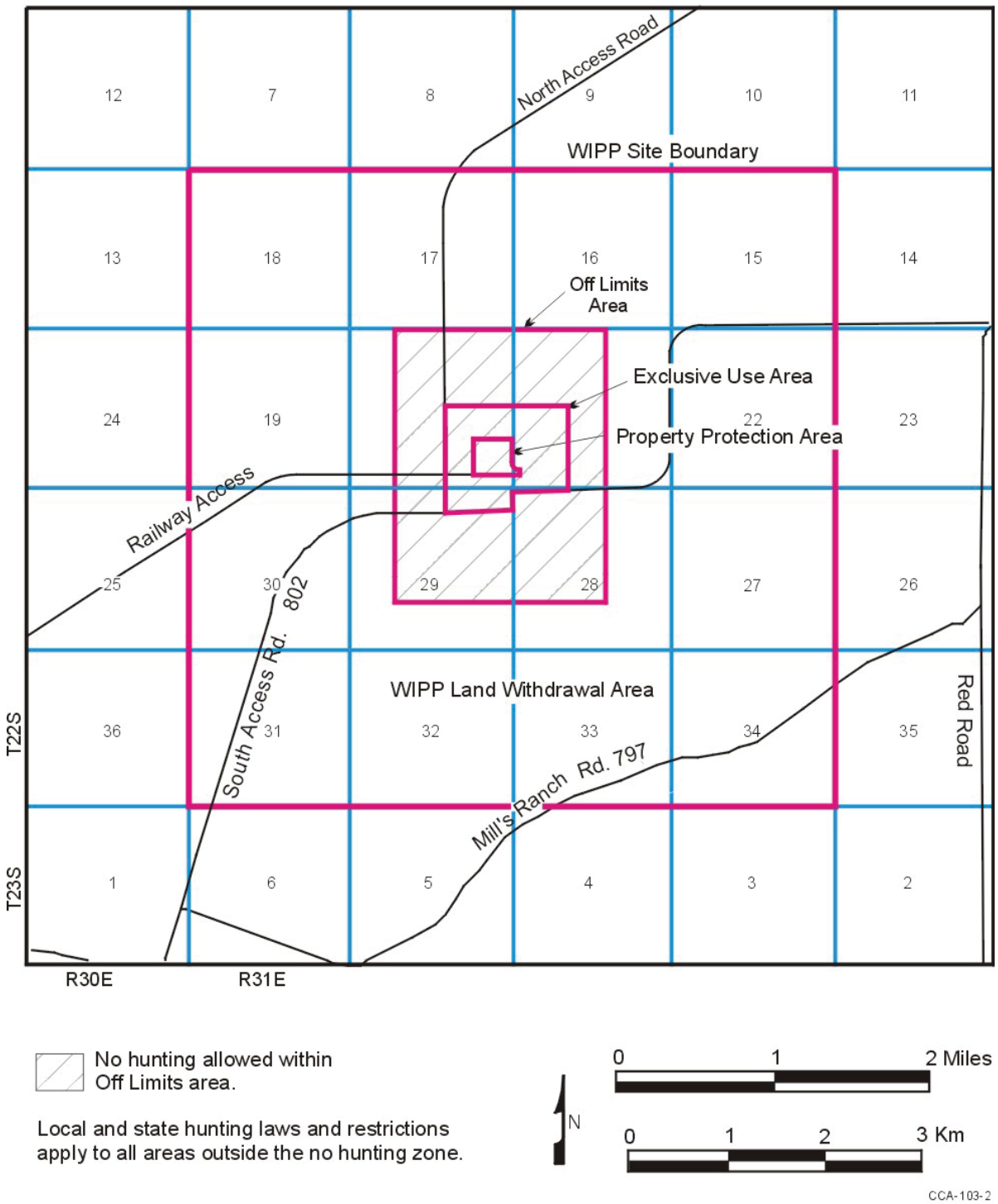

Figure 7-3. Area Where Hunting is Permitted Within the WIPP Site Boundary

and transportation facilities involve significant surface-disturbing activities. However, they are confined to the upper several meters of soil and will not impact the disposal system. Currently, the construction of utilities and transportation facilities are controlled by a permitting process administered by the DOE for the WIPP and the BLM for other federal lands. The BLM ensures that operators remain within designated rights-of-way and that they comply with applicable environmental protection regulations. Figure 7-4 depicts the current rights-of-way that have been granted for utilities or transportation on the WIPP site.

Goal of Active Controls: Active controls will ensure that utility and transportation activities are conducted in a manner that is consistent with permits and that locations are selected to avoid conflicts with permanent markers. Measures, such as fences, may be needed to provide mutual protection for personnel, livestock, and rights-of-way uses.

7.1.3.1.6 Groundwater Pumping

Description of the Activity: Groundwater wells are drilled for several uses near the WIPP. The most common use within the controlled area is in support of the WIPP groundwater monitoring program. These wells generally target water in the Culebra Member of the Rustler Formation. . Before a groundwater well can be drilled, a permit must be obtained and the State Engineer must be notified of the final well configuration and its use. Wells are abandoned in accordance with state regulations that govern the plugging of such wells (see Section 3.3.4). Groundwater well drilling unrelated to the DOE is prohibited by the LWA within the WIPP site boundary. Figure 7-5 shows the location of wells monitored for groundwater composition within the WIPP site boundary.

Goal of Active Controls: The active controls program will ensure that the prohibition on drilling groundwater wells and fluid injection within the WIPP site boundary is enforced and that those wells that currently exist, or that are drilled to support future WIPP activities, are plugged and abandoned in accordance with applicable regulations.

7.1.3.1.7 Surface Excavation

Description of the Activity: Both sand and caliche are mined locally for use in construction. Mining for sand and caliche is always limited to surface quarries. To mine these materials on public lands, a permit must be obtained from the DOE or the BLM. The permit limits the quantity that can be removed and specifies appropriate environmental protections, including reclamation. Sand or caliche removal will have no impact on the disposal system (Appendix PA, Attachment SCR, Other Resources FEP H8).

Many surface quarries within the WIPP site boundary have been remediated, which included recontouring the surface and planting vegetation. Others will be remediated either during the operational phase or as part of postdecommissioning land management. The development of surface quarries unrelated to the DOE is prohibited by the LWA. Figure 7-6 shows the location of surface quarries within the WIPP site boundary.

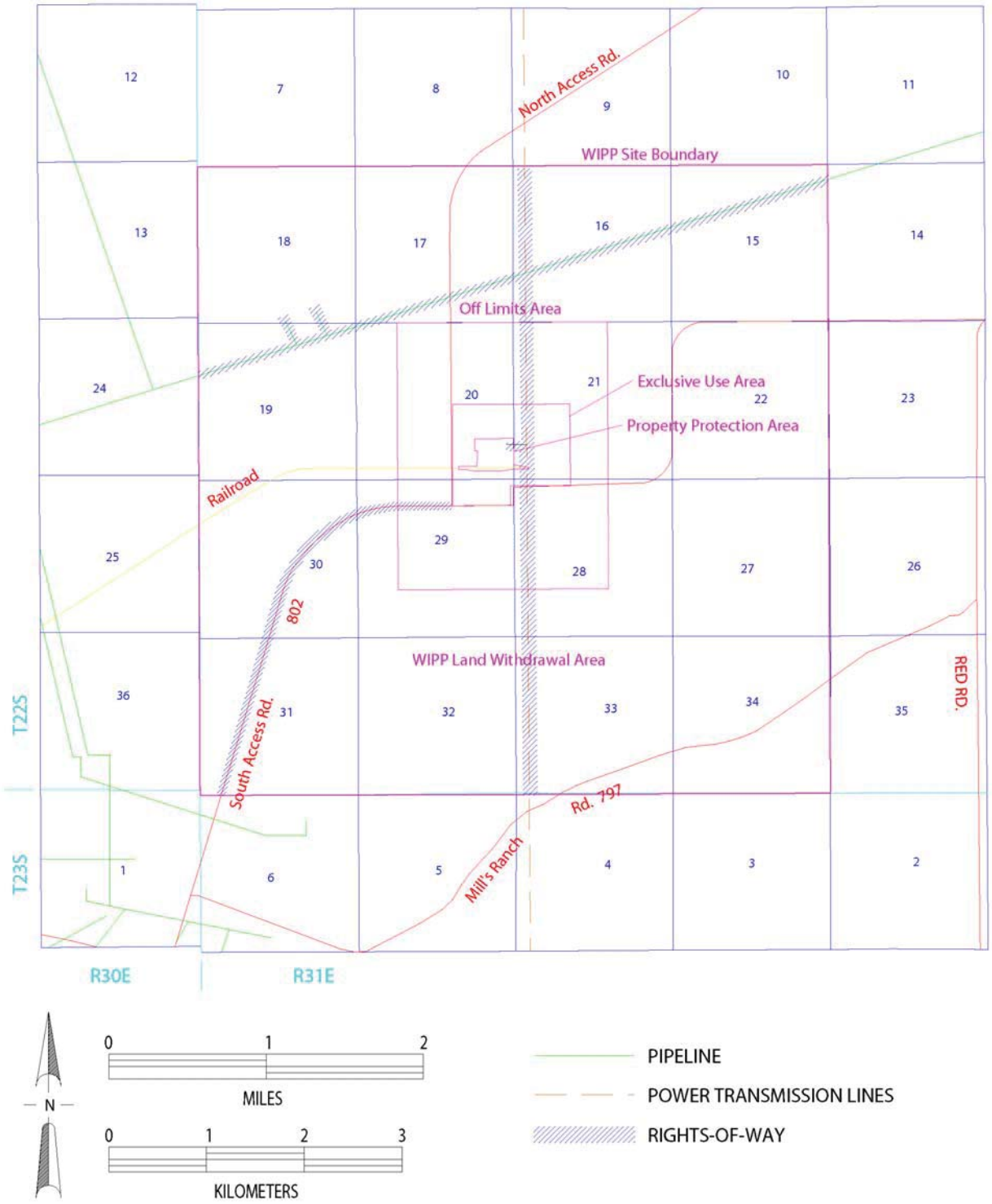

Figure 7-4. Locations of Rights-of-Way Within the WIPP Site Boundary as of September 2002

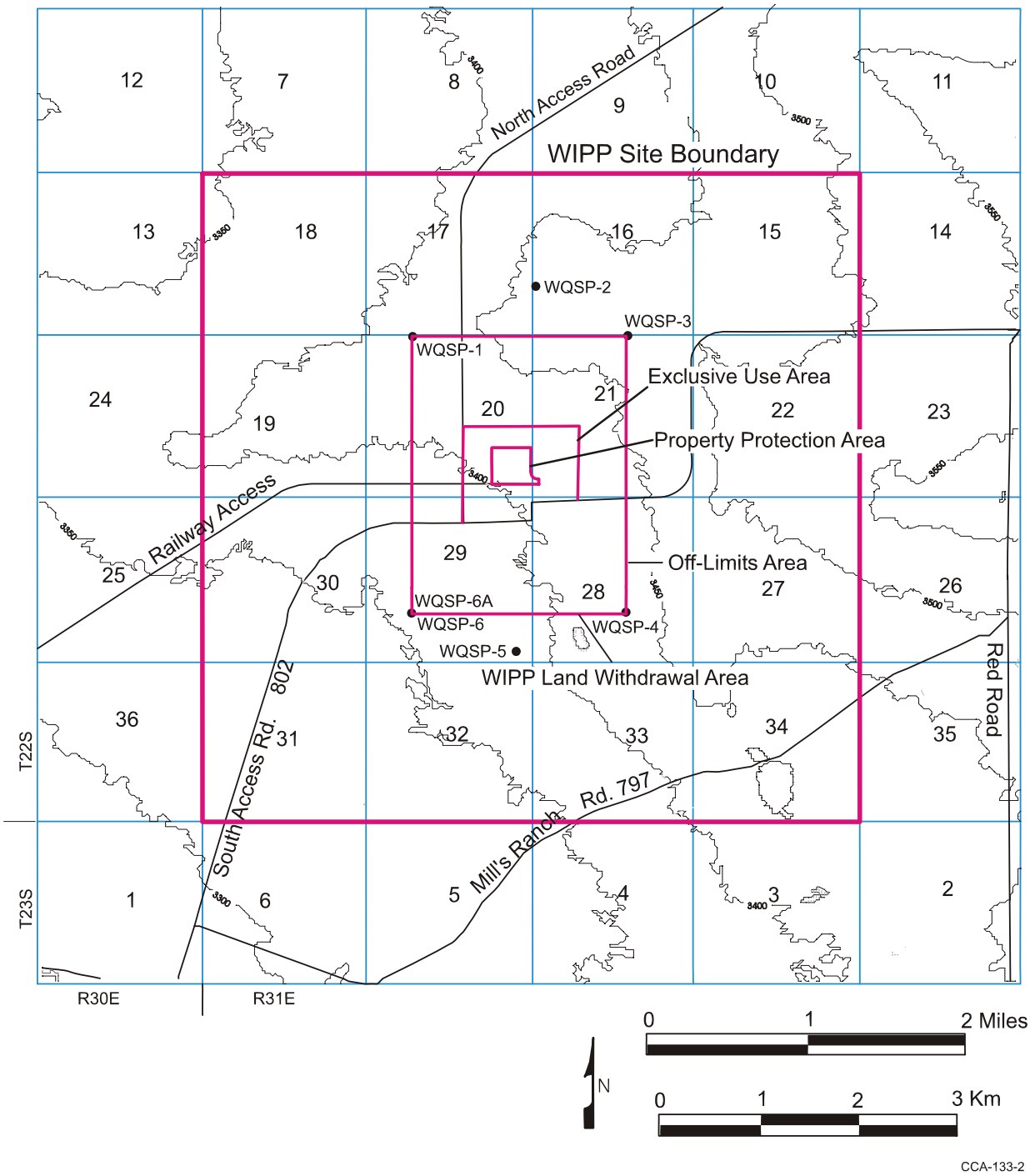

Figure 7-5. Locations of Water Quality Sampling Wells

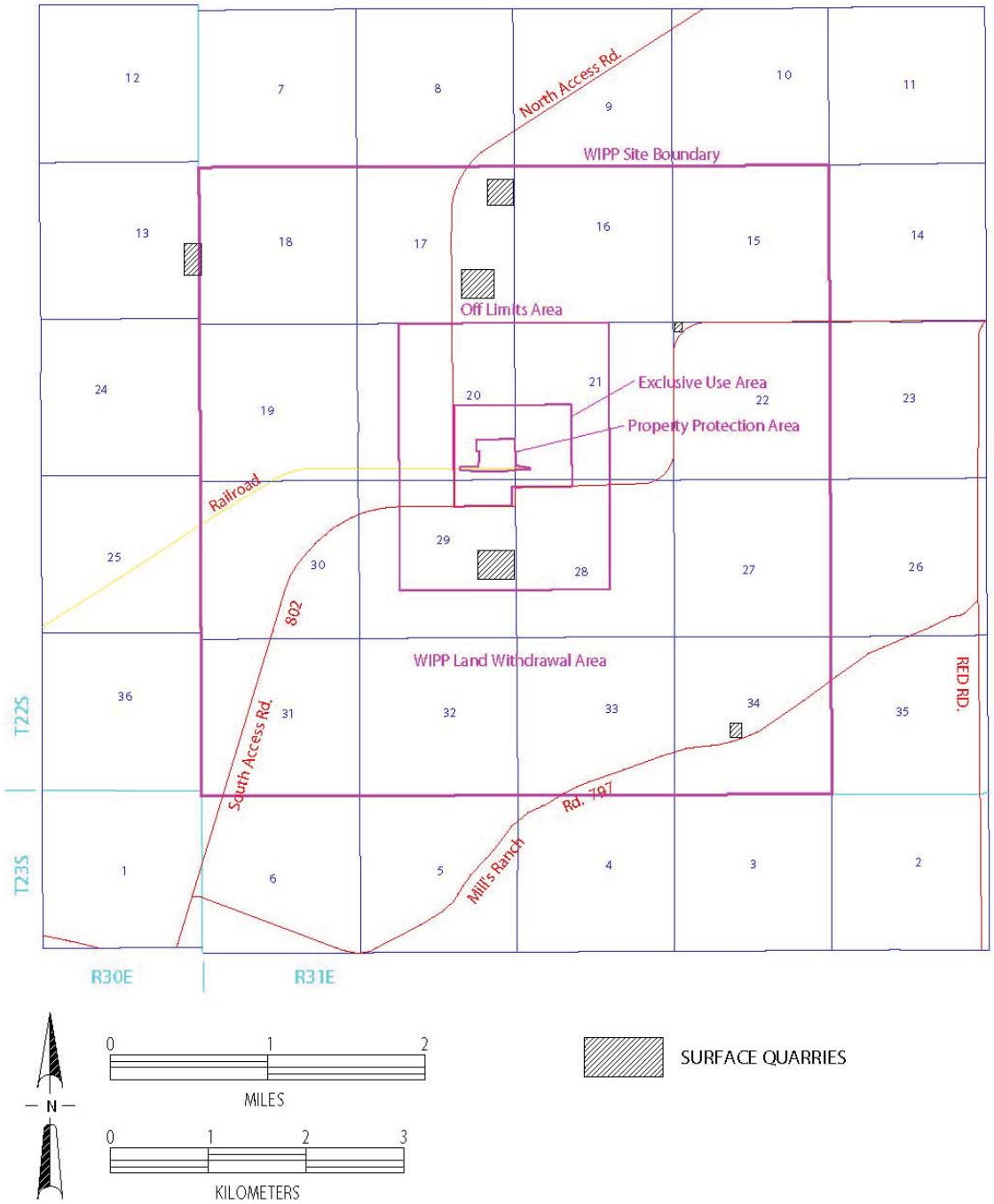

Figure 7-6. Location of Surface Quarries Within the WIPP Site Boundary as of September 2002

Goal of Active Controls: The objective of the DOE with respect to surface excavation is to ensure that the development of mineral leases does not affect the integrity of the disposal system. In accordance with the LWA requirement that no surface or subsurface mining unrelated to the DOE may be conducted within the boundaries of the land withdrawal area, the DOE and the state of New Mexico have entered into a memorandum of understanding (MOU). This MOU dictates that the state will forward any mining and reclamation plans to the DOE for review and comment in determining issuance of such permits within one mile of the withdrawal area boundary. In addition to the commitments in the MOU, the DOE will conduct perimeter surveillance and evaluate potential encroachment of ancillary activities associated with mines.

7.1.3.1.8 Potash Exploration and Extraction

Description of the Activity: Potash mineralization is known to exist beneath the WIPP site (see Section 2.3.1.1). The extent of mineralization is generally determined through the drilling of core holes and the examination and analysis of rock cores. Sufficient core holes have already been drilled within the WIPP site boundary to characterize the resident mineralization. Future drilling, however, is prohibited by the LWA. Holes drilled for the exploration of potash must be closed in accordance with state or federal regulations, depending on the location of the potash lease (see CCA Appendix DEL, Section DEL.5.5). The closure of potash holes within the WIPP site boundary is discussed in Section 3.3.4.

Extraction of potash in the Delaware Basin is accomplished through the use of conventional underground mining technologies. Development of resources within the WIPP site boundary would require that a mine be built in the vicinity or that an existing mine be expanded to include the WIPP. Potash mining is conducted in accordance with the rules and regulations of the BLM on federal lands and the State of New Mexico on state lands. The impacts of mining are evaluated in the performance assessment in accordance with the requirements of 40 CFR § 194.32(b) and are discussed in Section 6.4. Figure 7-7 shows a map of the distribution of potash exploration holes and the extent of currently economically minable reserves.

Goal of Active Controls: The active controls program, especially routine security patrols, will ensure that mineral leasing and development within the WIPP site boundary are prevented and that existing or near future mines do not encroach on the site.

7.1.3.1.9 Hydrocarbon Exploration

Description of the Activity: Hydrocarbon resources are assumed to exist below the WIPP site. The amount of these resources and their locations are projected from information that the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) compiled and interpreted for the DOE in 1995. (See Section 2.3 for a discussion of this report.) Exploration companies use surface-based geophysical techniques to determine likely locations for hydrocarbon accumulations and then investigate the prospect using deep drilling. Both the geophysical and the drilling activities have historically occurred on the WIPP site, but further drilling is prohibited by the LWA. Figure 7-8 shows the location of hydrocarbon wells within the WIPP site boundary.

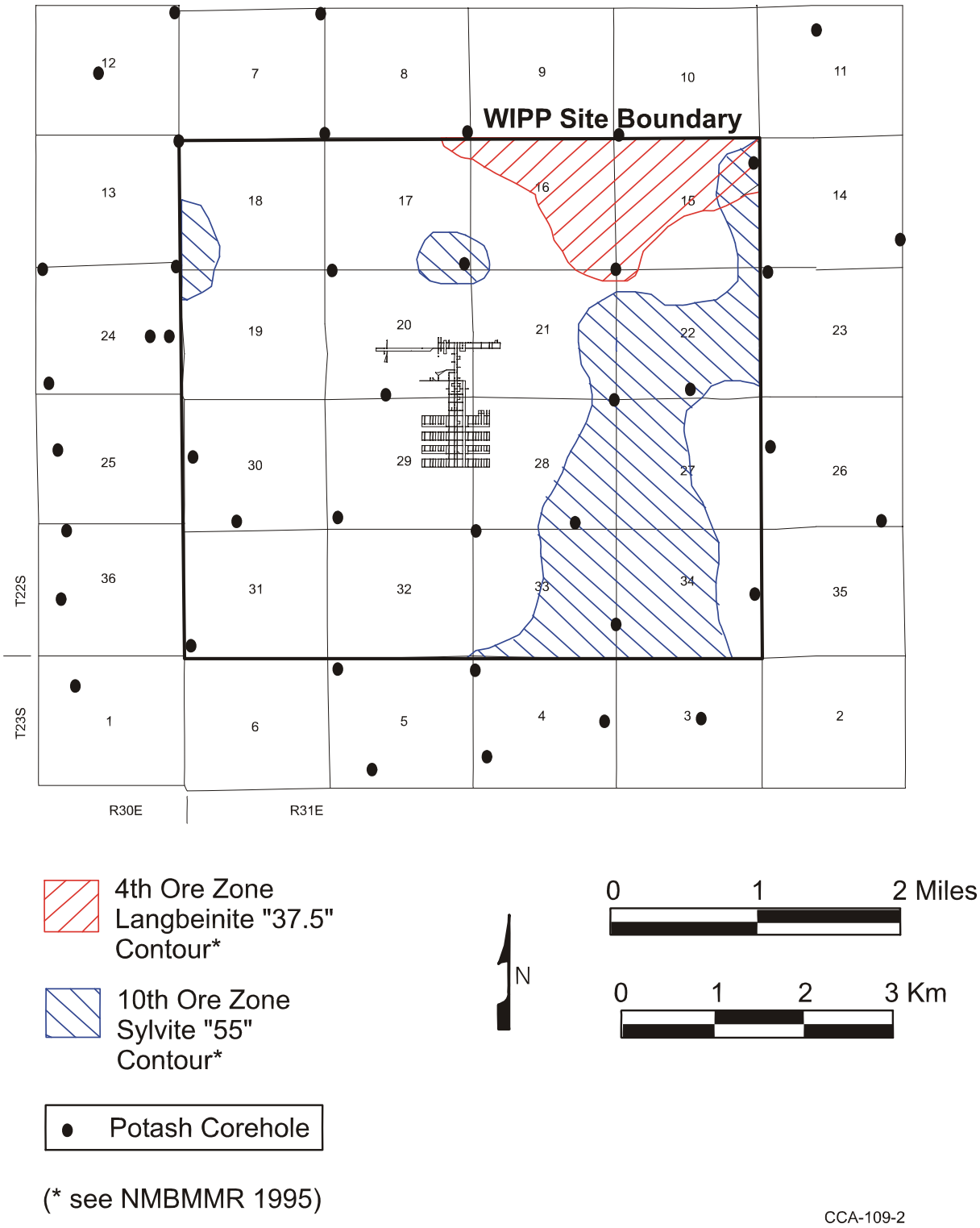

Figure 7-7. Location of Potash Exploration Holes and Economically Minable Potash Within the WIPP Site Boundary as of September 2002

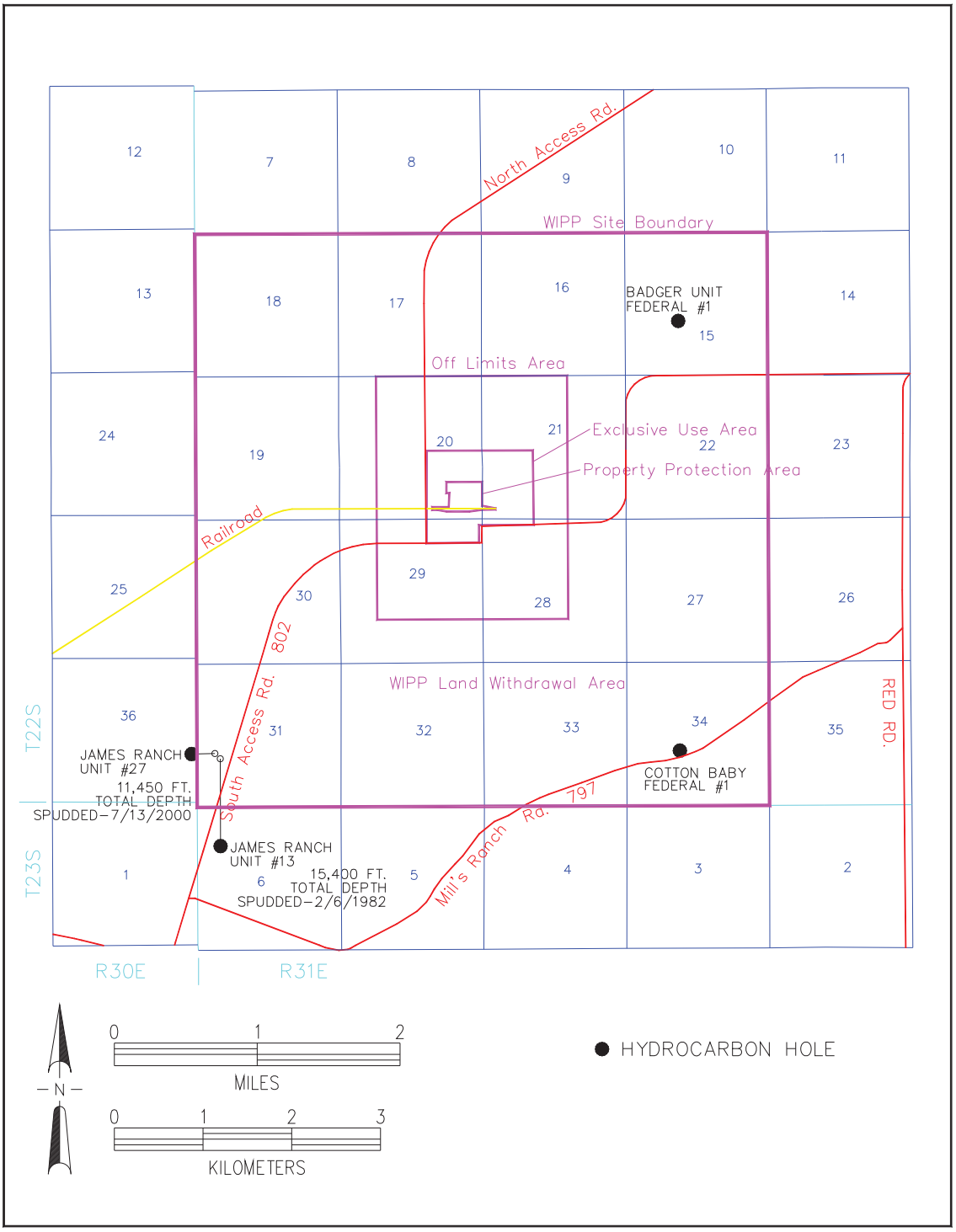

Figure 7-8. Hydrocarbon Holes Located Within the WIPP Site Boundary as of September 2002

Goal of Active Controls: The active controls program will ensure that the prohibition on the drilling of hydrocarbon wells is enforced. In addition, the BLM and the state of New Mexico will administer permits to perform geophysical investigations.

7.1.3.1.10 Construction

Description of Activity: The construction of a permanent building typically involves activities that disturb the surface only to a depth of a few meters, with the exception of the drilling of a groundwater well. Construction is currently prohibited by the DOE for public protection reasons during disposal operations. Because the WIPP site is federally owned, only federal facilities can be built there and any construction will require federal permits. After the conclusion of operations and during the active institutional controls period, construction will not be allowed within the areas reserved for the permanent marker system.

Goal of Active Controls: Controls will ensure that construction does not occur within the WIPP site boundary prior to the end of the active institutional controls period and that no construction will interfere with the goals of the passive controls system.

7.1.3.1.11 Hostile and Illegal Activities

Description of Activity: Activities in this category include vandalism, sabotage, theft, and artifact hunting. All of these activities are prohibited by federal and state law. None is expected to have an impact on the disposal system, although they could impact monitoring efforts, the construction and preservation of permanent markers, the integrity of fences and test areas, and other authorized uses.

Goal of Active Controls: Active controls will prevent the occurrence of hostile and illegal activities to the extent practicable within the WIPP site boundary. Controls may include access control and other security measures.

7.1.3.2 Active Controls Design Features

Based on these possible land uses, the DOE has specified the following design features for the active controls system. Additional detail is presented in CCA Appendix AIC (Section 1).

- Signage will be established to control access to the WIPP site. A fence will be erected along the perimeter of the repository surface footprint. The fence will have gates placed approximately midway along each of the four sides.

- Roadways will be constructed as needed to provide easy visual inspection and ready vehicle access to any point around the fenced perimeter and to facilitate maintenance of the fence line. These roadways will connect to the paved south access road.

- The fence line and the WIPP site perimeter will be posted with signs having as a minimum a legend reading “Danger—Unauthorized Personnel Keep Out” and a warning against entering the area without specific permission of the DOE. Signs prohibiting hunting will also be posted as appropriate. In addition, the DOE will include the area in the local one-call system.

- Upon installation of the permanent marker system, the active institutional controls program will be revised as deemed appropriate.

- Guidelines will be developed for identifying and implementing the appropriate corrective measures to address any abnormal conditions identified during periodic surveillance and inspections.

- Reports of activities associated with the postdisposal active access controls will be prepared in accordance with regulatory requirements for submittal to the appropriate regulatory and legislative authority.

7.1.3.3 Description of Active Institutional Controls Features

Most of the active institutional controls measures, such as long-term site monitoring and site remedial actions, will be implemented simultaneously with facility closure and D&D. It may be possible, however, to implement some measures earlier. For example, salt disposal may begin prior to final facility closure. Reclamation and restoration of unused disturbed surface areas have already begun. Guarding and maintenance activities, which are in place, could evolve into an appropriate type of postclosure activity.

During the disposal phase, the DOE will manage and store waste in a manner that limits the public's exposure to radiation in accordance with the standards of 40 CFR 191, Subpart A. Subsequent to disposal and after shafts are backfilled and sealed, radioactive releases to the accessible environment, exposures to humans, and concentrations in groundwater cannot exceed the standards of 40 CFR Part 191, Subparts B and C. The periods of active institutional controls and passive institutional controls begin when the disposal phase ends, and according to the EPA, run concurrently for at least 100 years. Also per the EPA, after 100 years, credit for active controls must end, but credit for passive controls may continue for up to 700 years after final facility closure (see Section 7.3.4.2).

The active controls program design described above is implemented through the following components. Additional detail is provided in CCA Appendix AIC (Section 2):

- Signage that indicates the areal extent of the WIPP and a fence that restricts access to the repository footprint, respectively, and includes the area in which the passive markers will be constructed. This area (shown in Figure 7-9) is referred to as the repository footprint and represents the surface projection of all areas underground that contain waste. Note that additional fencing may be needed for remote locations that are used for disposal system monitoring. Such fences will meet the same construction specifications as those for the perimeter footprint.

- A 16-foot (4.9 meter) wide roadway around the perimeter of the WIPP site boundary. Roads to remote sites will also be constructed and maintained as needed.

- Surveillance that includes drive-by patrolling two or three times per week. This frequency will be sufficient to detect and remove the most severe threats to the disposal system, such as drilling.

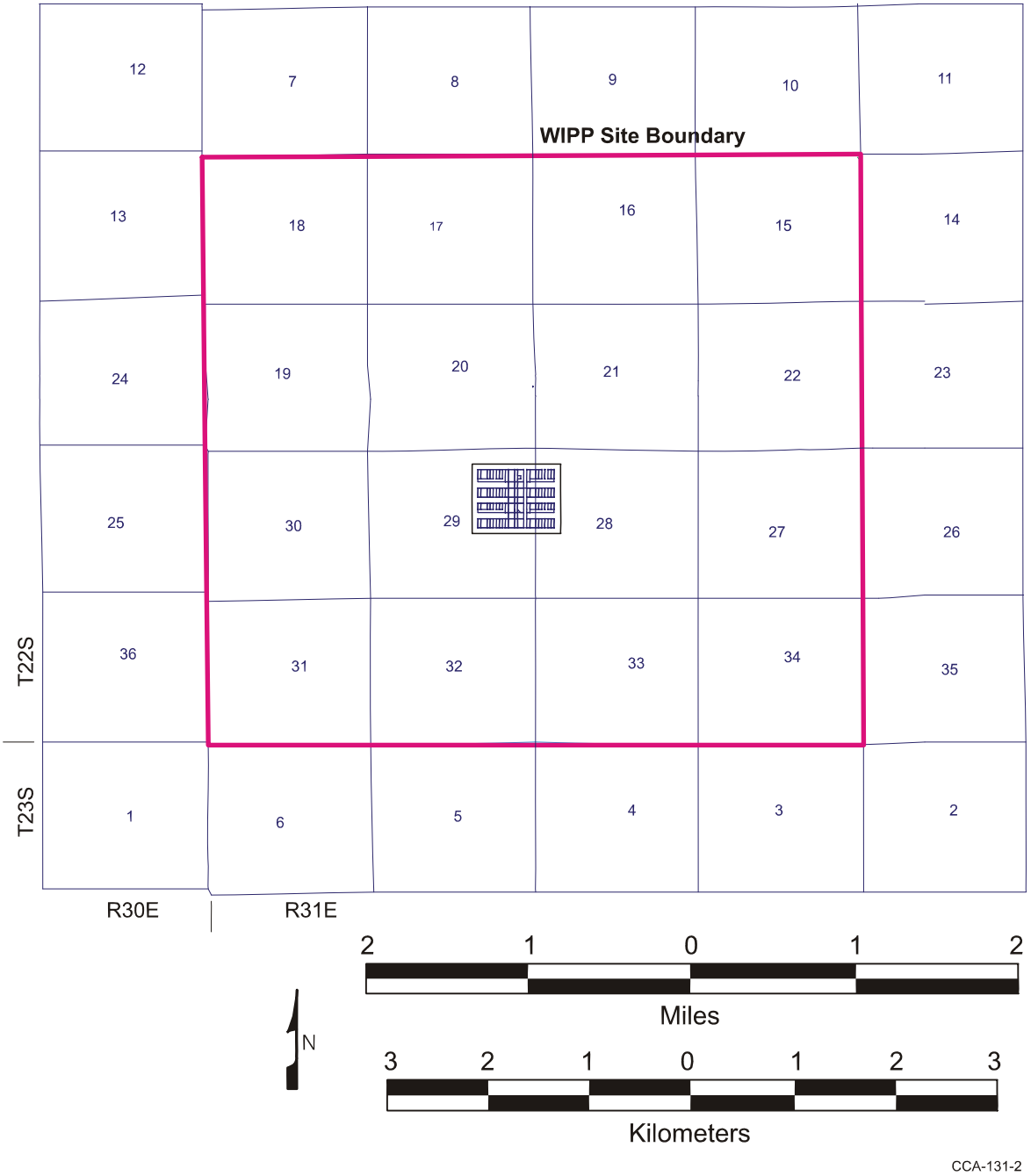

Figure 7-9. Planned Repository Footprint

- Maintenance services for fences, gates, cattle guards, signs, and monitoring equipment.
- Site restoration activities in accordance with the postclosure land management plan.
- Agreements with the BLM to administer grazing and other permitted land uses consistent with the DOE's postclosure land management plan.
- Monitoring of the disposal system.
- Construction of a permanent marker system.

7.1.4 Effectiveness of the Active Institutional Controls Program

Performance assessment for the WIPP assumes that the active institutional controls program will be one hundred percent effective in preventing human intrusion into the repository for the 100 years immediately following disposal. The DOE believes that this assumption is supported by the proposed design features alone (that is, fencing, postings, perimeter inspections, surveillance, and mitigation measures) and the defense-in-depth nature of the features and resulting controls. The DOE believes that taking one hundred percent credit for 100 years of active controls is justified by the repetitive and redundant nature of the active controls that will be implemented at the WIPP site. The DOE is committed to retaining active control over the site for as long as is practicable, but at least for 100 years.

Governments have successfully controlled and protected facilities of national importance for hundreds of years. The U.S. Government has existed and effectively maintained many facilities under its control for over 200 years. The DOE and its predecessor agencies have successfully maintained (preventing intrusion) several major facilities for over 50 years. Therefore, the DOE believes there is a reasonable expectation that active institutional controls will be effective for at least the assumed 100-year institutional control period, and are likely to be effective for substantially longer periods.

In its certification decision (63 FR 27395), EPA ". . . found it reasonable for DOE to assume credit in the PA for 100 years. The EPA found the assumptions regarding longevity and efficacy of the proposed AICs to be acceptable based on the fact that the types of inadvertent intrusion which AICs are designed to obviate are not casual activities, but require extensive resources, lengthy procedures for obtaining legal permission, and substantial time to set up at the site before beginning."

7.2 Monitoring

The requirements for disposal system monitoring are stated in 40 CFR § 191.14(b). In order to certify the DOE's compliance with these requirements, the EPA has established certification criteria that the DOE must satisfy in its application for certification. These criteria are stated in 40 CFR § 194.42. The requirements and the criteria form the basis for the DOE's monitoring program. Appendix MON-2004, Pre-Closure and Post-Closure (Long-Term) Monitoring Plan, describes the details of the DOE's monitoring program.

The criteria provided in 40 CFR § 194.42(a) state

The Department shall conduct an analysis of the effects of disposal system parameters on the containment of waste in the disposal system and shall include the results of such analysis in any compliance application. The results of the analysis shall be used in developing plans for preclosure and postclosure monitoring required pursuant to paragraphs (c) and (d) of this section. The disposal system parameters analyzed shall include, at a minimum:

(1) Properties of backfilled material, including porosity, permeability, and degree of compaction and reconsolidation;

(2) Stresses and extent of deformation of the surrounding roof, walls, and floor of the waste disposal room;

(3) Initiation or displacement of major brittle deformation features in the roof or surrounding rock;

(4) Ground water flow and other effects of human intrusion in the vicinity of the disposal system;

(5) Brine quantity, flux, composition, and spatial distribution;

(6) Gas quantity and composition; and

(7) Temperature distribution.

Attachment 1 (MONPAR) to CCA Appendix MON is an "Analysis of the Effects of Disposal System Parameters on Waste Containment" that the DOE has used to base decisions regarding disposal system monitoring. 40 CFR § 194.42 dictates the manner in which the stated analysis will be used in deriving the monitoring program, including the specification that the program consider preclosure monitoring as an integral component of meeting the monitoring requirements.

CCA Appendix MON, Attachment 1's (MONPAR's) scope of analyzed parameters exceeds the minimum parameters identified in 40 CFR § 194.42(a). The following is a summary of the results of the analysis with respect to those parameters identified in 40 CFR § 194.42(a).

(1) *Properties of backfilled material, including porosity, permeability, and degree of compaction and reconsolidation;*

Backfill Material Properties. The mechanical and hydrologic properties of the backfill are not significant to the performance assessment. Therefore, they will not be monitored during the preclosure or postclosure periods. See CCA Appendix MON (Attachment 1, MONPAR, Section MONPAR.3.5) for additional detail regarding DOE's analysis of backfill.

(2) *Stresses and extent of deformation of the surrounding roof, walls, and floor of the waste disposal system;*

(3) *Initiation or displacement of major brittle deformation features in the roof or surrounding rock;*

Stress and Extent of Deformation. Creep closure of the repository will occur, and is included within compliance assessment and performance assessment models as a control on waste consolidation and other time-dependent disposal room conditions. The

individual creep closure parameters are not significant to performance assessment. Sufficient data have been collected for the purposes of verifying the underlying rock mechanics models. The numerical models of the repository used in performance assessment are based upon assumptions about long-term behavior that are not applicable to behavior during the operational period. Further monitoring of creep closure and stress would not provide information that is useful for calculating disposal system performance, nor would it lead to additional confidence in the performance assessment models.

The initiation or displacement of major brittle deformation features in the roof or surrounding rock, beyond that already accounted for in performance assessment calculations is not significant to the containment of waste. The individual parameters that are used in modeling the mechanical behavior of brittle anhydrite interbeds are not significant to performance assessment. Monitoring mechanical behavior of the interbeds would not provide information that is useful for calculating system performance, nor would it lead to additional confidence in the performance assessment models.

Monitoring of creep closure and mechanical behavior is being conducted during preclosure monitoring to provide information that is relevant to repository operations.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.3.1 and MONPAR.3.2) for additional detail regarding DOE's analysis of creep closure and deformation features.

(4) *Ground water flow and other effects of human intrusion in the vicinity of the disposal system;*

Drilling Intrusions. Intrusion into the repository through drilling may occur during the regulatory time period. In accordance with regulatory requirements, such intrusions are modeled to occur randomly in time and space. Drilling leads to direct releases during the drilling itself and possible long-term releases due to effects on fluid flow in the disposal system. The drilling rate (boreholes per square kilometer per 10,000 years) is significant to repository performance. The DOE uses a drilling rate in performance assessment that is based on historical rates in the Delaware Basin.

The DOE will monitor the drilling activity in the Delaware Basin during the preclosure and postclosure periods and will use the results in performance calculations performed in support of recertification.

Borehole Properties. The properties of a borehole change over time, and are incorporated into performance assessment. The properties are established to be "consistent with practices in the Delaware Basin at the time a compliance application is prepared" (40 CFR § 194.33[c][1]). These parameters are significant to compliance. The current practices will be monitored and changes will be incorporated into the performance assessment models of borehole properties in future calculations in support of recertification.

Groundwater Flow. Historical, current, and near-future human activities in the vicinity of the repository could affect groundwater flow in the Culebra prior to closure of the repository, as well as subsequent to repository closure. The significance of these human activities depends on the extent and magnitude of the induced hydrological, geochemical, and mechanical disturbance. Changes in groundwater in the Culebra are moderately significant to performance. Such changes are incorporated into performance assessment as described in CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.4.4 and MONPAR.4.5). Changes to brine flow in the Salado as a result of any current or near future human activities in the vicinity of the repository are not anticipated, and therefore are not significant to performance assessment.

The DOE will monitor water levels and groundwater flow direction in the Culebra during the operational period. Monitoring of groundwater flow conditions in the Salado could create additional pathways for radionuclide transport, and would potentially jeopardize long-term performance of the disposal system; thus the DOE will not perform such monitoring.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.4.1, MONPAR.4.3, and MONPAR.4.4) for additional detail regarding DOE's analysis of drilling intrusions, borehole properties, and groundwater flow in the vicinity of the repository.

(5) Brine quantity, flux, composition, and spatial distribution;

Salado Hydrology. Hydrologic properties (quantity, flux, and spatial distribution) of the intact Salado Formation are incorporated into performance assessment through parameters that are consistent with extensive experimental observations. Variations in these parameters have a moderate effect on system performance assessment. There is no indication that properties of the intact (far-field) Salado will change during the regulatory period; thus, they will not be monitored during the operational period nor during the postclosure period. Composition of Salado brines has been well established through investigations. Brine composition is significant and is incorporated into performance assessment calculations. Based on the extensive experimental evidence collected, there is no indication that Salado brine composition will change over the regulatory period; thus it will not be routinely monitored during the operational period nor during the postclosure period.

The presence of a disturbed rock zone (DRZ) surrounding the repository has also been incorporated into performance assessment calculations. The properties of the DRZ have been well characterized; they include altered hydrologic properties that are expected to allow enhanced near-field flow both to and from the repository. The initial conditions and enhanced fluid flow are moderately significant to disposal system performance. In an effort to simplify the calculations, the effects are maximized by the conceptual model and altered properties of the DRZ. This treatment is believed to be a conservative choice with respect to the ultimate impact on predicted release.

Mechanical and hydrologic properties of the disposal room are incorporated into performance assessment as they affect gas generation and fluid flow into and out of the repository. These properties and parameters are moderately significant to disposal system performance. Additional properties are significant in the event of intrusion into the repository; these are discussed in CCA Appendix MON (Attachment 1, MONPAR, Section MONPAR.4.2.). The conceptual model of disposal room behavior is based on extensive experimental data that support a number of assumptions about long-term behavior that will not be applicable during the preclosure period. The closed disposal room will not achieve the expected long-term properties predicted in performance assessment during the operational or active control periods. Therefore, monitoring the mechanical and hydrologic properties would not provide relevant information or verify assumptions used in performance assessment. Thus the disposal room properties will not be monitored during the operational period nor during the postclosure period.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.2.1, MONPAR.2.2, MONPAR.3.3, and MONPAR.3.4) for additional detail regarding DOE's analysis of these parameters.

Culebra Hydrology. Hydrologic properties (quantity, flux, and spatial distribution) of the undisturbed Culebra Member of the Rustler Formation exhibit spatial variability and are incorporated into performance assessment through both fixed values and parametric ranges that are consistent with experimental observations to date. Variations in some of the parameters are significant to overall disposal system performance. Culebra groundwater is less saline than Salado and Castile brines. The Culebra groundwater is spatially variable, and its composition has been well established through investigations. Groundwater composition is incorporated into performance assessment calculations; however, it is not significant to performance. Based on extensive experimental evidence, there is no indication that Culebra groundwater composition will change over the regulatory period; however, monitoring will provide information that is relevant to a comprehensive environmental monitoring program.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.2.3 and MONPAR.2.4) for additional details regarding DOE's analysis of these parameters.

Castile Hydrology. The Castile Formation underlying the WIPP may contain reservoirs of pressurized brine. This is incorporated into performance assessment through use of input parameters that address hydrologic properties and the probability that a reservoir will be encountered during an intrusion event. The hydrologic properties are significant to disposal system performance in such an intrusion event. The Castile is not significant to system performance except for the brine reservoirs. There is no indication that the properties of the undisturbed reservoirs will change over the regulatory period. It is not possible to completely define the location and extent of brine reservoirs without jeopardizing the integrity of the disposal system. Composition of brines from two Castile brine reservoirs is moderately significant and is incorporated into performance assessment calculations. There is no evidence to suggest that the brine composition will change over the regulatory period. It is not possible to further investigate composition of any brine that may be present below the repository without jeopardizing the integrity

of the disposal system. Therefore, no further investigations or monitoring will be performed neither during the preclosure period nor during the postclosure period. However, monitoring of drilling activity in the Delaware Basin for instances of encountering pressurized brine reservoirs in the Castile will be a part of the preclosure and postclosure monitoring programs.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.2.5 and MONPAR.2.6) for additional details regarding DOE's analysis of the Castile hydrology parameters.

(6) *Gas quantity and composition;*

Gas Quantity and Composition. Gas generated in the repository may retard creep closure, may fracture the anhydrite interbeds in the DRZ (enhancing fluid flow), and may enhance direct releases (CCA Appendix MON, Attachment 1, MONPAR, Section MONPAR.4.2). These effects are moderately significant and are accounted for in performance assessment. Gas composition (carbon dioxide concentration) and the corrosion rate of metals are controlled chemically by the backfill and are not significant. Gas generation is moderately significant to system performance. The conceptual model of gas generation processes is based on experimental data and incorporates a number of assumptions about long-term behavior that will not be applicable during the operational period (such as anoxic conditions). Monitoring the quantity and composition of gas generated in the closed panels would not provide information that is useful for calculating system performance, nor would it lead to additional confidence in the performance assessment models.

See CCA Appendix MON (Attachment 1, MONPAR, Section MONPAR.3.6) for additional detail regarding DOE's analysis of gas generation.

(7) *Temperature distribution.*

Temperature Distribution. Natural geological thermal gradients have been well characterized and are not significant: they will not affect repository performance, either directly by affecting the containers and repository chemistry, or indirectly by altering fluid flow through the Salado or the Culebra. Similarly waste-induced and repository-induced thermal gradients in the repository are not significant: they will not affect repository performance, either directly by affecting the containers and repository chemistry, or indirectly by altering fluid flow through the Salado or the Culebra. Therefore, natural thermal gradients, waste-induced thermal gradients, and repository-induced thermal gradients will not be monitored during the preclosure period or during the postclosure period.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.2.7 and MONPAR.3.8) for additional detail regarding DOE's analysis of natural temperature distribution.

The criteria state that the DOE is to base decisions regarding disposal system monitoring on "an analysis of the effects of disposal system parameters on the containment of waste in the disposal

system and shall include the results of such analysis in any compliance application." The rule goes on to dictate the manner in which the stated analysis will be used in deriving the monitoring program, including the specification that the program consider preclosure monitoring as an integral component of meeting the monitoring requirements.

The DOE has completed the analysis and has designed a monitoring program (including both preclosure and postclosure monitoring techniques) that meets the requirements of 40 CFR § 191.14(b). The program is documented in a manner that addresses the certification criteria of 40 CFR § 194.42, and is described in this section. More detailed information is provided in CCA Appendix MON.

Additional parametric areas of analysis included in MONPAR (Attachment 1 of CCA Appendix MON) are:

- repository chemical conditions,
- shaft seal system,
- radionuclide transport and retardation,
- direct releases, and
- mining.

Table 7-2 is a list of the specific disposal system parameters discussed in CCA Appendix MON, Attachment 1, MONPAR.

As part of the recertification effort, the analysis documented in CCA Appendix MON, Attachment 1, MONPAR was reviewed to determine if changes to PA methods or results of monitoring programs have impacted the conclusions in CCA Appendix MON, Attachment 1, MONPAR. The PA methodology has not changed since the CCA with the exception of additional refinements in Culebra groundwater modeling.

Results of Culebra monitoring have prompted additional groundwater investigations. These investigations are ongoing and involve additional well drilling and hydrological testing. The

Table 7-2. Potentially Significant Disposal System Parameters

NATURAL PARAMETERS	
Impure halite effective porosity	Culebra diffusional porosity
Impure halite permeability	Culebra longitudinal dispersivity
Impure halite pore compressibility	Climate change index
Impure halite far-field pore pressure	Culebra groundwater quantity
Anhydrite permeability	Culebra groundwater flux
Anhydrite pore compressibility	Culebra groundwater spatial distribution
Anhydrite two-phase flow model choice	Culebra groundwater composition
Salado pore shape	Castile brine volume in reservoir
Salado residual brine saturation	Castile brine reservoir volume selection index
Salado residual gas saturation	Castile brine reservoir pressure
Salado brine quantity	Castile brine reservoir permeability
Salado brine flux	Castile brine reservoir rock compressibility
Salado brine spatial distribution	Castile brine composition
Salado brine composition	Castile brine flux
Culebra transmissivity	Castile brine spatial distribution
Culebra advective porosity	Natural temperature distribution
Culebra fracture spacing	
WASTE AND REPOSITORY PARAMETERS	
Closure rates and stresses	Probability factor for types of microbial degradation
Extent of deformation	Gas quantity
Initiation of brittle deformation	Gas composition
Displacement of major deformation features	Choice of oxidation state distribution
DRZ permeability	Solubility of nine radionuclides in Salado brine
DRZ effective porosity	Solubility of nine radionuclides in Castile brine
DRZ brine flux	Humic colloid concentration in Salado brine
DRZ brine quantity	Humic colloid concentration in Castile brine
Waste area residual gas saturation	Clay shaft seal member permeability
Waste area residual brine saturation	Concrete shaft seal member permeability
Brine wicking	Asphalt shaft seal member permeability
Waste area permeability	Shaft DRZ permeability
Backfill porosity	Crushed salt seal component permeability (permeability selection index)
Backfill permeability	Seal residual gas saturation
Degree of backfill compaction	Seal residual brine saturation
Backfill reconsolidation	Seal pore shape
Inundated steel corrosion rate with CO_2	Waste- and repository-induced temperature distribution
Inundated steel corrosion rate without CO_2	Salado K_ds for dissolved radionuclides
Inundated microbial degradation rate	Culebra K_ds for six dissolved radionuclides
Humid microbial degradation rate	Salado K_ds for colloidal radionuclides
β-factor for microbial degradation process	
Drilling rate	Borehole permeability
Waste particle diameter	Borehole plugging pattern (probability index)
Effective shear resistance to erosion	Change in Salado brine flow

Table 7-2. Potentially Significant Disposal System Parameters— Continued

HUMAN-INITIATED PARAMETERS	
Mud pump rate	Change in Culebra groundwater flow
Drill penetration rate	Probability that mining will occur
Time between intrusions	Mining index for adjusting Culebra transmissivity
Borehole location	Waste activity
Probability of encountering a Castile brine reservoir	Waste tensile strength
Borehole diameter	

information gathered since the CCA as part of the groundwater monitoring program has been addressed in the implementation of the groundwater conceptual model (see Section 2.2.1.4.1.2, Section 6.4.6.2 and Appendix DATA, Section DATA-11). Culebra groundwater monitoring was derived from the CCA Appendix MON, Attachment 1, MONPAR analysis and has proven to be an important element of the WIPP operational monitoring program. The program continues to monitor Culebra groundwater to ensure that changes to important activities and conditions related to WIPP long-term performance are identified and addressed. Future results of the ongoing investigations may necessitate changes to the monitoring program; however, the current monitoring parameters have not changed.

7.2.1 Monitoring Program Requirements

Requirements for monitoring of a disposal system[1] are included in the final disposal regulations as follows:

> Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardize the isolation of the wastes and shall be conducted until there are no significant concerns to be addressed by further monitoring (§ 191.14[b]).

Within this context, monitoring becomes one of several activities to be implemented at the WIPP facility during the active institutional controls period. Monitoring the WIPP disposal system is designed to address significant concerns associated with the performance of the isolation system. The EPA points out that monitoring approaches to address significant concerns should be limited to those that can provide meaningful data in a relatively short period of time (50 FR 38081). In addition, the EPA points out that monitoring must not become a reason to relax the degree of care with which the compliance determination is made. Finally, the EPA specifies that monitoring must not jeopardize the integrity of the disposal system (50 FR 38081).

7.2.2 Monitoring Program Design

The requirements in 40 CFR § 191.14(b) and the criteria in 40 CFR § 194.42 can be translated into five screening criteria for selecting monitoring parameters and for developing monitoring plans. The monitoring plan should

[1] Disposal system means “any combination of engineered and natural barriers that isolate...radioactive waste after disposal” (40 CFR § 191.12).

- address significant disposal system parameters,
- address important disposal system concerns,
- obtain meaningful data in a short time period (50 FR 38081),
- preserve disposal system integrity, and
- be complementary with other regulatory programs.

Each of these screening criteria is discussed below.

7.2.2.1 Significant Disposal System Parameters

In the certification criteria, the EPA states that

> The Department shall conduct an analysis of the effects of disposal system parameters on the containment of waste in the disposal system and shall include the results of such analysis in any compliance application. The results of the analysis shall be used in developing plans for preclosure and postclosure monitoring required pursuant to paragraphs (c) and (d) of this section (40 CFR § 194.42[a]).

The EPA also states that to the extent practicable, preclosure monitoring shall be conducted of significant disposal system parameter(s) as identified by the analysis conducted pursuant to paragraph (a) of this section (40 CFR § 194.42[c]). Though not explicitly stated in the criteria, it is appropriate that the same requirement hold for postclosure monitoring. The EPA defines significant parameters as follows: “A disposal system parameter shall be considered significant if it affects the system’s ability to contain waste or the ability to verify predictions about the future performance of the disposal system” (40 CFR § 194.42[c]).

The terms significant, important, and sensitive have been used in the WIPP program to describe parameters with variability that impact the outcome of performance assessment. While these terms are for the most part interchangeable, the term significant is used in this discussion to maintain consistency with the terminology in the 40 CFR Part 194 criteria.

The DOE has conducted the requisite study of parameters that are inputs to the performance assessment. CCA MONPAR (Attachment 1 of Appendix MON) provides a description of the methodology and results of that study. The DOE has implemented the criteria for significance in CCA Appendix MON.

Verification of parameters used in the system performance analysis may occur in one or both of the following ways:

- measurement of physical or chemical conditions to see if they remain consistent with expected conditions or within the range of conditions incorporated into the assumptions and models, and
- measurement of physical and chemical processes that are currently based on professional judgment or regulatory guidance because data are not available.

The DOE considered the major processes and models described in Section 6.4 and the regulations and developed an initial list of potentially significant parameters as discussed in Attachment 1 to CCA Appendix MON (MONPAR). Parameters were screened for inclusion in the list based on the following criteria:

- the parameter represents one or more important aspects of a chemical or physical process or model,
- the parameter represents subjective uncertainty (such as spatial variability in a physical property or process),
- the parameter represents stochastic uncertainty (such as drilling rate), and
- the parameter proved to be moderately to highly sensitive in terms of modeling results in previous preliminary performance assessments.

The parameters identified through this screening process are summarized in Table 7-2 and discussed in CCA MONPAR (Attachment 1 of Appendix MON).

The parameters identified in Table 7-2 are assigned high, medium, and low significance values (EPA 1996c). Those parameters that would significantly affect a release are assigned a HIGH level. Parameters that influence a release are assigned a MEDIUM value. Parameters that are not significant (represent spatial variability or an uncertainty in a given value) are assigned a LOW value. Those that were determined as having a high significance are shown in Table 7-3.

Table 7-3. Disposal System Parameters Determined to be of Highest Significance to Disposal System Performance

Parameter	Significance to Containment	Significance to Verification
NATURAL PARAMETERS		
Salado anhydrite permeability	HIGH	HIGH
Salado brine composition	HIGH	HIGH
Culebra fracture spacing	HIGH	HIGH
Castile brine reservoir volume selection index	HIGH	HIGH
Castile brine reservoir pressure	HIGH	HIGH
Castile brine reservoir permeability	HIGH	HIGH
Castile brine reservoir rock compressibility	HIGH	HIGH
Castile brine reservoir volume selection index	HIGH	HIGH
Castile brine flux	HIGH	HIGH
Castile brine spatial distribution	HIGH	HIGH
Castile brine composition	HIGH	HIGH
WASTE AND REPOSITORY PARAMETERS		
Inundated steel corrosion rate without CO_2	HIGH	HIGH
Choice of oxidation state distribution	HIGH	HIGH
Solubility of nine radionuclides in Salado brine	HIGH	HIGH
Solubility of nine radionuclides in Castile brine	HIGH	HIGH
Humic colloid concentration in Salado brine	HIGH	HIGH
Humic colloid concentration in Castile brine	HIGH	HIGH
Culebra K_ds for dissolved radionuclides	HIGH	HIGH
Crushed salt seal component permeability (permeability selection index)	HIGH	HIGH
HUMAN INITIATED PARAMETERS		
Drilling rate	HIGH	HIGH
Waste particle diameter	HIGH	HIGH
Borehole permeability	HIGH	HIGH
Borehole plugging pattern (probability index)	HIGH	HIGH
Time between intrusions	HIGH	HIGH
Borehole location	HIGH	HIGH
Probability of encountering Castile brine reservoir	HIGH	HIGH
Waste activity	HIGH	HIGH
Effective shear resistance to erosion	HIGH	HIGH

7.2.2.2 Important Disposal System Concern

This criterion is closely tied with the first in that, in the final analysis, the most significant parameters are related to important disposal system concerns. However, the DOE has included this category as a separate criterion to identify any other parameters that, while they are not

significant in performance assessment, do describe important disposal system features. For example, the creep properties of the Salado can be considered an important feature of the disposal system, although the parameter analysis identified them as having a minor effect on the outcome of the analysis. Creep properties are identified in CCA Appendix MON (Attachment 1, MONPAR) because they can provide a body of information that allows the DOE to evaluate its conceptual model of Salado creep closure.

In order to select these parameters for further evaluation, the DOE divided the disposal system into five major components: Salado and repository physical properties, Salado and repository hydrological properties, non-Salado hydrological properties, waste properties, and engineered barrier properties. Based on this division, the DOE revisited the list of potentially significant parameters and determined those parameters that were related to a measurable property of the disposal system. Those parameters are shown in Table 7-4.

7.2.2.3 Meaningful Data in a Relatively Short Time

The amount of time available for the DOE to obtain data regarding important disposal system parameters is limited. This period consists of a preclosure period and 100 years of active institutional controls. However, the DOE will continue monitoring programs for as long as needed if meaningful data are collected or are expected.

In screening parameters using this criterion, the DOE applied two qualifications. First, parameters had to be amenable to measurement within the disposal system and, second, parameter changes expected to occur within the first 127 years and affecting long-term disposal system performance had to be predictable. For example, parameters such as the shape of pore spaces cannot be reasonably measured and, therefore, would not become candidates for a monitoring program. Likewise, changes in parameters such as the actual brine concentration within the Salado are likely to be rapid initially and not necessarily diagnostic of the steady state that will exist over most of the regulatory time period.

The results of the screenings of the parameters in Tables 7-3 and 7-4 are given in Table 7-5.

In some cases, the parameter is indicated as a measurable parameter, meaning that it can either be directly monitored or be deduced from a monitoring program. Other parameters are indicated as observed. This means that the parameter represents an event that occurs at unspecified intervals or changes too slowly or too intermittently to be a viable monitoring candidate. For example, displacements of deformation features occur intermittently and can be observed only when they occur, even though other processes leading up to displacement (such as creep) can be monitored.

7.2.2.4 Preservation of Disposal System Integrity

Disposal system integrity could be compromised by drill holes, conduits, or other entries that are left in place to allow access to monitoring equipment. The requirement to avoid such conditions leads to the conclusion that the only viable monitoring systems are those that can be operated directly during operations, those that can transmit information without cabling (telemetry), and

Table 7-4. Parameters Related to Measurable Disposal System Properties

Parameter	Significance to Containment	Significance to Verification
SALADO PHYSICAL PARAMETERS		
Creep closure and stresses	LOW	LOW
Extent of deformation	LOW	LOW
Initiation of brittle deformation	LOW	LOW
Displacement of major deformation features	LOW	LOW
Natural temperature distribution	LOW	LOW
SALADO HYDROLOGICAL PARAMETERS		
Impure halite pore compressibility	LOW	LOW
Impure halite far-field pore pressure	MEDIUM	MEDIUM
Salado pore shape	MEDIUM	MEDIUM
Impure halite effective porosity	MEDIUM	MEDIUM
Impure halite permeability	MEDIUM	MEDIUM
Anhydrite permeability	HIGH	HIGH
Anhydrite pore compressibility	MEDIUM	MEDIUM
Salado residual brine saturation	MEDIUM	MEDIUM
Salado residual gas saturation	MEDIUM	MEDIUM
Salado brine quantity	LOW	LOW
Salado brine flux	MEDIUM	MEDIUM
Salado brine spatial distribution	LOW	LOW
Salado brine composition	HIGH	HIGH
Salado K_ds for dissolved radionuclides	LOW	LOW
Salado K_ds for colloidal radionuclides	LOW	LOW
Salado change in groundwater brine	LOW	LOW
Natural temperature distribution	LOW	LOW
DRZ permeability	MEDIUM	MEDIUM
DRZ effective porosity	MEDIUM	MEDIUM
DRZ brine flux	MEDIUM	MEDIUM
DRZ brine quantity and spatial distribution	LOW	LOW
NON-SALADO HYDROLOGICAL PROPERTIES		
Culebra transmissivity	MEDIUM	MEDIUM
Culebra advective porosity	MEDIUM	MEDIUM
Culebra fracture spacing	HIGH	HIGH
Culebra diffusional porosity	MEDIUM	MEDIUM
Culebra longitudinal dispersivity	LOW	LOW
Culebra groundwater quantity	LOW	LOW
Culebra groundwater flux	MEDIUM	MEDIUM
Culebra groundwater spatial distribution	LOW	LOW
Culebra groundwater composition	LOW	LOW

Table 7-4. Parameters Related to Measurable Disposal System Properties — Continued

Parameter	Significance to Containment	Significance to Verification
Castile brine reservoir pressure	HIGH	HIGH
Castile brine reservoir permeability	HIGH	HIGH
Castile brine reservoir rock compressibility	HIGH	HIGH
Castile brine reservoir brine volume	HIGH	HIGH
Castile brine flux	HIGH	HIGH
Castile brine spatial distribution	HIGH	HIGH
Castile brine composition	MEDIUM	MEDIUM
Natural temperature distribution	LOW	LOW
Culebra K_ds for six dissolved radionuclides	HIGH	HIGH
Culebra K_ds for humic and actinide-intrinsic colloidal radionuclides	MEDIUM	MEDIUM
Drilling rate	HIGH	HIGH
Effective decay constant for microbes	MEDIUM	MEDIUM
Culebra change in groundwater flow	MEDIUM	MEDIUM
WASTE RELATED PARAMETERS		
Waste area residual gas saturation	MEDIUM	MEDIUM
Waste area residual brine saturation	MEDIUM	MEDIUM
Waste area permeability	MEDIUM	MEDIUM
Brine wicking	MEDIUM	MEDIUM
Inundated steel corrosion rate with CO_2	LOW	LOW
Inundated steel corrosion rate without CO_2	MEDIUM	MEDIUM
Inundated microbial degradation rate	LOW	LOW
Humid microbial degradation rate	LOW	LOW
Gas quantity	MEDIUM	MEDIUM
Gas composition	LOW	LOW
Choice of oxidation state distribution	HIGH	HIGH
Solubility of nine radionuclides in Salado brine	HIGH	HIGH
Solubility of nine radionuclides in Castile brine	HIGH	HIGH
Humic colloid concentrations in Salado brine	HIGH	HIGH
Humic colloid concentrations in Castile brine	HIGH	HIGH
Waste particle diameter	HIGH	HIGH
Effective shear resistance to erosion	MEDIUM	MEDIUM
Waste activity	HIGH	HIGH
Waste tensile strength	HIGH	HIGH
Mud pump rate	LOW	LOW
Drill penetration rate	LOW	LOW

Table 7-4. Parameters Related to Measurable Disposal System Properties — Continued

Parameter	Significance to Containment	Significance to Verification
ENGINEERED BARRIER PROPERTIES		
Shaft DRZ permeability	MEDIUM	MEDIUM
Backfill porosity	LOW	LOW
Backfill permeability	LOW	LOW
Degree of backfill compaction	LOW	LOW
Backfill reconsolidation	LOW	LOW
Clay seal member permeability	MEDIUM	MEDIUM
Concrete seal member permeability	MEDIUM	MEDIUM
Asphalt seal member permeability	MEDIUM	MEDIUM
Seal residual gas saturation	LOW	LOW
Seal residual brine saturation	LOW	LOW
Seal pore shape	LOW	LOW
Long-term borehole permeability	HIGH	HIGH

Table 7-5. Parameters That Can Produce Meaningful Data During Monitoring Period

Parameter	Comment
SALADO PHYSICAL PARAMETERS	
Creep closure and stresses	Can be measured during operations
Extent of deformation	Can be measured during operations
Initiation of brittle deformation	Can be measured during operations
Displacement of deformation features	Can be observed during operations
SALADO HYDROLOGICAL PARAMETERS	
Salado brine composition	Can be measured during operations
NON-SALADO HYDROLOGICAL PROPERTIES	
Culebra groundwater composition	Can be measured for entire period
Castile brine reservoir location	Can be observed for entire period
Drilling rate	Can be observed for entire period
Culebra change in groundwater flow	Can be observed for entire period
WASTE RELATED PARAMETERS	
Waste activity	Can be calculated using measurements made during waste characterization

those that can be used to evaluate parameters using remote sensing techniques. Each is discussed briefly below. Table 7-6 shows the final screening of parameters in order to determine those that are candidates for a monitoring program. Table 7-7 identifies those parameters included in the preclosure and postclosure monitoring programs. The presence of a DRZ surrounding the repository has been

Table 7-6. Parameters That Can Be Measured Without Violating Repository Integrity

Parameter	Comment
SALADO PHYSICAL PARAMETERS	
Creep closure	Direct measurement in open areas of the repository
Extent of deformation	Direct measurement in open areas of the repository
Initiation of brittle deformation	Direct measurement in open areas of the repository
Displacement of deformation features	Directly observed from other open areas of the repository
NON-SALADO HYDROLOGICAL PROPERTIES	
Culebra groundwater composition	Can be measured using existing or additional groundwater surveillance wells
Probability of encountering a Castile brine reservoir	Can be developed based on observations of drilling activity in Delaware Basin
Drilling rate	Can be developed based on observations of drilling activity in Delaware Basin
Culebra change in groundwater flow	Can be determined using existing or additional groundwater surveillance wells
WASTE RELATED PARAMETERS	
Waste activity	Limited to observations during waste characterization activities

Table 7-7. Preclosure and Postclosure Monitored Parameters

Monitored Parameter	Preclosure	Postclosure
Culebra groundwater composition	X	X
Culebra change in groundwater flow	X	X
Probability of encountering a Castile brine reservoir	X	X
Drilling rate	X	X
Subsidence measurements	X	X
Waste activity	X	
Creep closure and stresses	X	
Extent of deformation	X	
Initiation of brittle deformation	X	
Displacement of deformation features	X	

incorporated into performance assessment calculations. The properties of the DRZ have been characterized; they include altered hydrologic properties that are expected to enhance near-field fluid flow both to and from the repository. The initial conditions and enhanced fluid flow are considered moderately significant to disposal system performance. Monitoring the DRZ hydrologic properties would not provide relevant information or verify assumptions used in performance assessment; therefore they will not be monitored during the operational period or during the postclosure period. For more detail regarding DRZ-related parameters, see CCA Appendix MON (Attachment 1, MONPAR, Section MONPAR.3.3).

Composition of Salado brines has been established through investigations. Brine composition is significant and is incorporated into performance assessment calculations. Based on the extensive experimental evidence collected, there is no indication that Salado brine composition will change over the regulatory period; thus it will not be routinely monitored during the operational period or during the postclosure period. For more detail regarding Salado brine composition, see CCA Appendix MON (Attachment 1, Section MONPAR.2.2).

7.2.2.4.1 Evaluation of Monitored Parameters

The preclosure and postclosure parameters identified in Table 7-7 have been evaluated for this CRA (see Appendix DATA) as a part of the plan described in Appendix MON-2004. Significant deviations in expected values of any of these parameters from those ranges of values in the performance assessment models have been and will continue to be evaluated. Where applicable, any new information will be incorporated into the performance assessment conducted for recertification. Parameter values outside of expected ranges will also prompt the evaluation of models and their modification, where appropriate, for use in recertification performance assessment activity.

Culebra groundwater composition, Culebra changes in groundwater flow, Castile brine reservoir encounters, Castile brine reservoir pressure, and drilling rate parameters are evaluated to substantiate that they remain within the range of values assumed in model development and performance assessment. Should there be a significant change outside the assumed range of values used in the 2004 PA models, the DOE will evaluate and, where appropriate, modify models for incorporation into the next performance assessment recertification.

In the unlikely event that subsidence values fall significantly outside the range of values predicted and experienced elsewhere in the Delaware Basin, additional evaluation of the potential effects of such deviations will be conducted. If the evaluation requires changes to models used in the performance assessment, these changes will be made and the revised models incorporated into a future recertification performance assessment.

The waste activity (see Appendix TRU WASTE for a detailed discussion) is monitored to ensure compliance with the requirements of the LWA and that the values are within the range of values used in PA models. New inventory data, including waste activity information, have been incorporated into the 2004 PA; these values are tracked in the preclosure monitoring program. Any significant deviation from the values used in the PA baseline will be addressed by the DOE in a timely fashion to avoid any violation of the compliance certification.

Creep closure and stresses, extent of deformation, initiation of brittle deformation, and displacement of deformation features are all parameters that reflect on the geomechanical nature of the repository. Evaluation of these parameters influence the operational aspects of safe operation of the repository. However, should any of these parameters exhibit properties that are significantly outside the experience and expectations of the information baselines developed to date, the DOE will evaluate the impact on the design of the repository and the design of the shaft seal system.

The EPA will be notified of any deviation that the DOE evaluates as significant with respect to complying with the regulations or the certification of the WIPP as a safe repository.

7.2.2.4.2 Direct Measurement

Direct measurement includes current programs such as the underground geomechanical monitoring program and the groundwater surveillance program. In such cases, the monitoring equipment can be inspected, calibrated, and used with high reliability. Malfunctioning equipment can be easily repaired or replaced. Power requirements are met with portable power units such as rechargeable batteries or generators. In some cases, analog measurements can be made mechanically and recorded in notebooks. In other cases, digital logging equipment is available to record large quantities of data and information. Direct measurement allows for changing the measurement parameters as environmental conditions change. Replicate samples can be taken easily if needed. Unusual conditions can be investigated to provide unambiguous interpretation of data.

7.2.2.4.3 Telemetry Systems

In the early 1970s to the mid 1980s, the U.S. Bureau of Mines and the Mine Safety and Health Administration demonstrated that reliable communications can be established between underground mines and the surface for the purpose of locating and rescuing trapped miners (see Powell 1976; Murphy and Parkinson 1978, p. 42). Low-frequency radio equipment was demonstrated in numerous mine environments and at many depths. The systems evaluated used low-duty cycle transmitters connected to loop antennae powered by miners' cap lamp batteries. Although through-the-earth transmission of signals is feasible, any system that uses this type of telemetry must deal with the following design problems.

First, because the purpose of the telemetry is to obviate the need for cabling to the surface, all power must be self-contained. For the WIPP, this will require extending battery or portable generators beyond the tens of years that can now be achieved for low-duty cycle systems. Second, issues regarding durability must be addressed since the environmental conditions will be severe. Components will have to withstand the brine and gas environments that are predicted, as well as the effects of creep closure and repressurization. Third, reliability will have to be addressed since failed sensors cannot be replaced nor can calibrations be performed or adjustments made. Finally, in addition to the equipment issues, there are concerns about interpreting results in an environment where interference, such as background electromagnetic noise, can only be, at best, poorly characterized. While these issues and concerns can be addressed with technology development programs, it is doubtful that the high cost is justifiable for the limited amount of data that may be obtained from such systems.

7.2.2.4.4 Remote Sensing Systems

The use of remote techniques to determine the characteristics of the earth have been well established. Generally classified as geophysical measurements, these systems look for variations in a parameter within the earth in order to determine geological relationships. Typical parameters that are measured remotely are resistivity, acoustic velocity, magnetism, density, temperature, moisture content, radioactivity, and radiometry (infrared). The general conclusion

is that the changes in the repository are too small (in scale), too far from the surface, and too slow to be detectable using remote techniques.

7.2.2.5 Complementary With Other Regulatory Programs Monitoring is performed by the DOE at and near the WIPP site to comply with the requirements of other regulatory programs. This includes groundwater monitoring in support of the Resource Conservation and Recovery Act (RCRA) program for the project. None of the monitoring activities implemented by the DOE in support of 40 CFR Part 191 and Part 194 compliance demonstrations interfere with or contradict monitoring performed for other regulatory programs.

Based on the approach the DOE has taken to monitoring program implementation, the criterion of compatibility with other regulatory programs is met.

7.2.3 Monitoring Program Description

Based on the parameter screening described above and the analysis in CCA Appendix MON, the DOE has selected a monitoring program with the following components:

- preclosure monitoring

  - Geomechanical monitoring parameters until closure:
    Creep closure and stresses,
    Extent of deformation,
    Initiation of brittle deformation, and
    Displacement of deformation features.

  - Waste Characterization monitoring parameters until last waste shipment :

Waste activity

- preclosure and postclosure monitoring parameters (100 years after closure or until DOE can demonstrate that there are no significant concerns to be addressed by further monitoring)

  - groundwater surveillance:

    Culebra groundwater composition,

    Change in Culebra groundwater flow

  - observation of drilling activities (100 years after closure):[2]

    Probability of encountering a Castile brine reservoir, and
    drilling rate.

- postclosure monitoring parameter (100 years after closure or until DOE can demonstrate that there are no significant concerns to be addressed by further monitoring)

- subsidence monitoring.

The rationale for eliminating the volatile organic compound (VOC) monitoring component of the program is described in Section 7.2.3.2. Other changes to this list have been made to more clearly indicate DOE's intent.

Each of these programs is described in the following sections. Individual program plans are included in CCA Appendices GWMP, SMP, and DMP. Relevant information from these CCA appendices has been consolidated into Appendix MON-2004. Consistent with EPA concurrence (EPA letter of March 15, 2002 to DOE; EPA Docket A-98-49, II-B-3, Item 24), CCA Appendices GWMP, SMP, and DMP are not repeated in this recertification application.

Waste monitoring is not discussed in the following sections because it is tracked in the WIPP Waste Information System (WWIS), as described in Chapter 4.0.

7.2.3.1 Geomechanical Monitoring Program

The geomechanical monitoring program at the WIPP facility is an integral part of the DOE's ground control program. Disposal rooms, drifts, and operational area excavations will be monitored to provide confirmation of structural integrity. Geomechanical data on the performance of the repository shafts and excavated areas are currently collected as part of the geotechnical field monitoring program. The results of the geotechnical investigations are reported annually. The report describes monitoring programs and geomechanical data collected during the previous year.

The instrumentation in Table 7-8 is available for use in support of the geomechanical program. The minimum instrumentation for Panels 2 through 8 is one borehole extensometer installed in the roof at the center of each disposal room. The roof extensometers will monitor the dilation of the immediate salt roof beam and possible bed separations along clay seams. Additional instrumentation may be installed as conditions warrant. Panel 1 is more extensively instrumented than subsequent panels because it was the first panel excavated and because it remained open for a relatively long period of time. After the last emplacement of waste in Panel 1, the communication cables from the instrumentation were cut and geomechanical monitoring ceased in the panel. In a similar manner, other waste panels will be monitored until each is full and panel seals are emplaced.

Polling of the geomechanical instrumentation will be performed at least once every month. This frequency may be increased to accommodate any changes that may develop. The results from the remotely read instrumentation will be evaluated after each scheduled polling. Documentation of the results are provided annually in the Geotechnical Analysis Report.

The instrumentation system provides for data maintenance, retrieval, and presentation. The instrumentation system cognizant engineer first retrieves the data from the instrumentation system and verifies their accuracy by assuring the measurements were taken in accordance with applicable instructions and procedures. Next, the cognizant engineer reviews the data after each polling to assess the performance of the instrument and the excavation. Data that look anomalous are detected during this polling and are investigated to determine the cause (for

Table 7-8. Instrumentation Used in Support of the Geomechanical Monitoring System

Instrument Type	Features	Parameter Measured	Range
Borehole extensometer	The extensometer provides for monitoring the deformation parallel to the borehole axis. Units suitable for up to five measurement anchors in addition to the reference head.	Cumulative deformation	0-2 inches
Borehole television camera	Closed circuit television may be used for monitoring areas otherwise inaccessible, such as boreholes or shafts.	Video image	N/A
Convergence points and tape extensometers	Mechanically anchored eyebolts to which a portable tape extensometer is attached.	Cumulative deformation	2-50 feet
Convergence meters	Includes wire and sonic meters. Mounted on rigid plates anchored to the rock surface.	Cumulative deformation	2-50 feet
Inclinometers	Both vertical and horizontal inclinometers are used. Traversing type of system in which a probe is moved periodically through casing located in the borehole whose inclination is being measured.	Cumulative deformation	0-30 degrees
Rock bolt load cells	Spool type units suitable for use with rock bolts. Tensile stress is inferred from strain gauges mounted on the surface of the spool.	Load	0-300 kips
Earth pressure cells	Installed between concrete keys and rock. Preferred type is a hydraulic pressure plate connected to a vibrating wire transmitter.	Lithostatic pressure	0-1,000 pounds per square inch
Piezometer pressure transducers	Located in shafts and of robust design and construction. Periodic checks on operability required.	Fluid pressure	0-500 pounds per square inch
Strain gauges	Installed within the concrete shaft key. Suitably sealed for the environment. Two types used—surface mounted and embedded.	Cumulative deformation	0-3,000 microinches per inch (embedded) 0-2,500 microinches per inch (surface)

example, instrumentation problem, error in recording, or changing rock conditions). The data are then processed to calculate various parameters such as the change between successive readings and deformation rates. The results of this assessment are reported to the ground control cognizant engineer and operations personnel. The stability of an open panel excavation is generally determined by the rock deformation rate. Unexpected deformation rates are investigated by Geotechnical Engineering to determine if remediation is needed.

The evaluation of the performance of the excavation is also performed by Geotechnical Engineering. These evaluations will provide an estimate of the stand-up time of the excavation. If the trend is toward adverse (unstable) conditions, then the results of these assessments are reported to the operations manager to determine appropriate operational responses.

Roof conditions are assessed from observation boreholes and extensometer measurements. Measurements of room closure, rock displacements, and observations of fracture development i the immediate roof beam are used to evaluate the performance of a panel. A summary of the Panel 1 monitoring program was presented to the members of the Geotechnical Experts Panel ir 1991, who concurred that the monitoring was adequate to determine deterioration within the rooms and could provide early warning of deteriorating conditions.

The assessment and evaluation of the condition of WIPP excavations is an iterative, continuous process using the data from the monitoring programs. Criteria for corrective action are continually reevaluated and reassessed based on total performance to date. Actions taken are based on these analyses and on planned utilization of the excavation. Because WIPP excavatior are in a natural geologic medium, there is inherent variability from point to point. The principle adopted is to anticipate potential ground control requirements and implement them in a timely manner rather than to wait until a need arises.

Both creep closure of the excavation and the development of the DRZ are included in the conceptual model of disposal system performance. Creep closure is discussed in Section 6.4.3.1 and Appendix PA, Attachment PORSURF. The numerical model for predicting creep closure has been developed based on both theoretical considerations and observations. The goal of monitoring is to detect any substantial and detrimental deviations from the expected behavior of Salado halite and to determine the significance of such deviations. Data are analyzed after each round of measurements and results are distributed for use in making ground control decisions. A compilation of data (current and previous) is published annually in the Geotechnical Analysis Report. This compilation is useful determining long-term trends in the behavior of undergrounc openings and can be a diagnostic tool for determining substantial and detrimental deviations from expected performance.

The DRZ is modeled as discussed in Section 6.4.5.3. It is assumed that the DRZ maintains its permeability throughout the model period as shown in Table 6-19. Marker bed (MB) 138 and 139 are modeled to be separate geological units with permeabilities lower than those in the DRZ as shown in Table 6-18. Substantial and detrimental deviations from these expectations may impact repository performance. Consequently, as discussed in Section 4.3 of CCA Appendix GTMP, observations of excavation effects, along with the other geotechnical measurements wil be useful to detect deviations in expectations for near-term DRZ development.

7.2.3.2 VOC Confirmatory Monitoring Program

In Docket A-93-02, Compliance Application Review Document No. 42, Section 42.C.5, the EP concludes:

> The VOC monitoring acts only as a secondary indicator of creep closure because there is not a direct relationship between VOC levels and creep closure rates. While VOC levels might indicate changes in creep closure rates, such changes would be observed earlier and would be better defined by direct geomechanical monitoring, which will be conducted throughout the operation of the WIPP. DOE stated that VOC monitoring will also provide data on gas producing processes (p. 7-58). The DOE did not include gas producing processes as one of the parameters to be monitored, however, because the modeling of gas-producing processes is based on data and assumptions about long-term behavior that will not be applicable during the operational period (p. 7-36).

The EPA indicated that VOC monitoring is not necessary as a secondary indicator of creep closure or to fulfill the requirements of Section 194.42. A planned change per 40 CFR § 194.4(b)(3) was submitted to the EPA in January 2002 requesting removal of CCA Appendix VCMP from the compliance baseline. In March 2002, the EPA approved the request to eliminate CCA Appendix VCMP from the WIPP certification basis. Based on the approval letter, this section and all references to CCA Appendix VCMP are eliminated from future recertification applications.

7.2.3.3 Groundwater Surveillance Program

In the development of the WIPP monitoring programs, potential pathways for release of hazardous constituents to the environment were evaluated. This evaluation indicated no credible release pathway via surface water. Comparisons between data sets are performed using standard statistical tests. The selection of the specific test is dependent upon the relative power of the test and the degree to which the underlying requirements of the test are met. In addition to tests comparing data from distinct locations and times, trend analyses are performed on time series where sufficient data exist.

Citation of the source of the test method or the software used to perform the tests will be made when results are reported. Data and subsequent calculated values are reported in the annual site environmental report.

The two parameters of interest from the groundwater surveillance program are the composition of the Culebra groundwater and water levels. Significant and persistent changes in the composition of the Culebra groundwater are investigated and impacts to the modeling assumptions for long-term performance in Section 6.4.6.2 are evaluated. Large and rapid water-level fluctuations may be diagnostic of nearby human activity such as potash mining and fluid injection and withdrawal. Water-level changes within the groundwater modeling domain in Section 6.4.6.2 that cannot be explained either based on observed trends or on past experience are being investigated and assessed relative to the assumptions made in the regional groundwater flow model (see Appendix DATA, Section DATA-11).

7.2.3.4 Observation of Drilling Activities

As part of the ongoing compliance activities, the DOE has continued to populate and maintain the database of drilling activity within the Delaware Basin. In addition, the DOE has an ongoing program of field checking each well that is drilled within one mile of the WIPP site boundary. Field checking includes verifying the location as listed on the Application for Permission to Drill (APD), monitoring drilling and completion activities, and noting abandonment and plugging. Both the maintenance of the database and the field observation program will be continued throughout the operational period to develop additional statistics on the following parameters:

- drilling rates,
- drilling practices,
- Castile brine reservoirs encountered,

- Castile brine characteristics (where available), and
- plugging practices.

Data collected are addressed as appropriate in the recertification process. Any analyses that indicate parameter values are changing are studied to evaluate the impact of the changes.

Significant changes in drilling practices, such as borehole diameters, plug and abandonment practices, mining techniques, Castile brine occurrence, and injection well use are evaluated for potential impacts on disposal system performance. Any significant deviations are reported to the EPA.

Annual reports of the Delaware Basin Monitoring Program provide the total number of deep boreholes drilled within the Delaware Basin. This information is reported in compliance with 40 CFR § 194.33(b)(3), which specifies the manner in which the frequency of deep drilling events assumed in performance assessments shall be determined. The rule specifies that the DOE shall:

> (i) Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.

In addition, the rule specifies that:

> (ii) The total rate of deep drilling shall be the sum of the rates of deep drilling for each resource.

The specification of a 100-year period "prior to the time at which a compliance application is prepared" has had the effect of increasing the deep drilling frequency that must be assumed in performance assessment calculations. This is because significant deep drilling activity did not exist within the Basin in the early part of the 20th century, while the last 10 years has been a period of significant oil drilling activity in the basin. Consistent with this, it is anticipated that the intrusion rate assumed in performance assessments will continue to increase throughout the operational period of the WIPP, as long as drilling continues to occur. The intrusion rate calculated in this manner for the CCA in 1996 is 46.8 deep holes per square kilometer over 10,000 years. Based on current information, this rate is 52.2 deep intrusions per square kilometer over 10,000 years (supporting data are provided in Appendix DATA). The implications of this increased rate of deep drilling are addressed in Chapter 6.0.

7.2.3.5 Subsidence Monitoring

Subsidence monitoring is accomplished with leveling surveys having maximum errors not greater than Second Order, Class II specifications. The relevant subsidence monitoring information presented in CCA Appendix SMP is incorporated into Appendix MON-2004.

Although the CCA indicates that surveys will be performed every 10 years, the surveys are currently performed annually. These surveys will be performed during the operational phase and thereafter in accordance with Appendix MON-2004.

The leveling survey procedures ensure that the data are documented and validated. The data are included in the baseline.

The monitoring program includes the following:

- management of the disposal phase monitoring program,
- maintenance of monitoring procedures and quality assurance/quality control documents,
- performance of all necessary field work,
- maintenance of the subsidence network,
- maintenance (and revision as necessary) of the monitoring schedule,
- maintenance and storage of baseline database,
- review of data and evaluation of performance,
- eventual decommissioning of the disposal system monitoring program, and
- archiving of monitoring data.

Subsidence predictions exist for the WIPP. These will be reevaluated at the time of closure. Subsidence measurements will be used to compare actual subsidence with predictions. Significant deviations between expected subsidence and actual subsidence will be investigated to determine if a substantial and detrimental deviation in the expected performance of the repository is indicated.

7.2.4 Reporting

The results of the DOE's monitoring program are submitted annually. The report includes the results from the previous year, plus any cumulative information that is useful in interpreting the data. The annual report contains a summary assessment of results to ensure that the performance of the repository can be evaluated on a continuous and consistent basis. Other reports, such as those stipulated in 40 CFR § 194.4 (b)(3), are issued when necessary.

Since the submittal of the CCA, the DOE has prepared over 20 annual reports pertaining to geomechanical monitoring, groundwater surveillance, subsidence monitoring, Delaware Basin monitoring, and waste characteristics monitoring. Data resulting from the various monitoring programs are reported in Appendix DATA. These reports are submitted to the EPA with the Annual 194.4(b)(4) Change Report.

7.2.5 Compliance Monitoring Parameter Data Results

In the EPA certification of compliance (63 FR 27354, May 18, 1998), the EPA concurred on the list of 10 compliance monitoring parameters (compliance parameters) that DOE proposed to monitor during the operational period of the project. The 10 compliance parameters are:

- Culebra groundwater composition,
- change in Culebra groundwater flow,
- probability of encountering a Castile brine reservoir,
- drilling rate,
- subsidence measurement,
- waste activity,
- creep closure and stresses,
- extent of brittle deformation,
- initiation of brittle deformation, and
- displacement of deformation features.

These parameters have been continually monitored over a period of several years, most of them before the initial receipt of waste. Existing WIPP monitoring programs gather data and information to develop the compliance parameter values. These programs are described in Appendix MON-2004; data resulting from these monitoring programs are provided in Appendix DATA.

The EPA also requires the DOE to report any negative condition that may indicate the repository will not function as predicted or a condition that is substantially different from the information contained in the most recent compliance application. Annual assessments of compliance parameters allow the DOE to monitor the predicted performance of the repository and report any condition adverse to waste containment.

All monitoring activities performed as part of the compliance parameters program have generated data within expected ranges, except for the changes in Culebra groundwater flow compliance parameter (the drilling rate was changed for PA; however, this parameter is monitored as a regulatory requirement and not to ensure it is within an expected range). For this compliance parameter, data related to water levels in monitoring wells have been recorded that are outside expected ranges. The implications of these unexpected monitoring parameter values are described in Chapters 2.0 and 6.0 of this recertification application.

7.3 Passive Institutional Controls

Passive institutional controls, as opposed to active institutional controls, are controls that once established, can be expected to remain effective with no on-site human support. The DOE will implement passive institutional controls that involve multiple types and multiple levels of passive controls to make human intrusion into the disposal site unlikely. To accomplish this, the DOE intends to use several types of monuments and markers, land ownership, and written notations in land records in numerous locations (see Section XVI of CCA Appendix PIC).

Written documentation will include information on the location, design, and disposal contents and hazards, as well as stipulations on allowable land uses. Components of the passive controls system will be instituted at the site and at remote locations (see CCA Appendix PIC).

As technology advances, this design concept will be revisited over the operational lifetime of the WIPP. If the DOE believes the design can be enhanced, changes will be proposed during the recertification process for EPA approval. The program described in CCA Appendix PIC will fulfill the requirements of 40 CFR Part 191 and satisfy the certification criteria of 40 CFR Part 194.

7.3.1 Requirements for Passive Institutional Controls

The EPA has specified that "[d]isposal sites shall be designated by the most permanent markers, records, and other passive institutional controls practicable" (40 CFR § 191.14[c]). The EPA then goes on to define passive institutional controls to mean "(1) permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system" (40 CFR § 191.12[e]). The DOE has interpreted this regulatory language to mandate the development and implementation of a system of passive institutional controls consistent with those components listed in the EPA's definition in order to protect the integrity of the disposal system for as long as practicable after disposal.

Guidance is provided by the EPA in 40 CFR § 194.43 on what subject areas must be addressed in order to demonstrate compliance with the regulation. Three subject areas must be addressed: (a) detailed descriptions of the passive institutional controls must be provided, (b) the period of time that the passive institutional controls are expected to endure and be understood must be estimated, and (c) credit for the passive institutional controls in reducing the likelihood of inadvertent human intrusion in performance assessments must be justified for the proposed time period. Additional guidance is provided in EPA (1996b) indicating what documentation is required in the compliance application to address 40 CFR § 194.43(a), the need for rationales to explain the estimates of how long the passive institutional controls are expected to endure and be understood in 40 CFR § 194.43(b), and the limitations of effectiveness and duration of the effectiveness of the passive institutional controls in performance assessment to address 40 CFR § 194.43(c).

In addition, as part of the initial EPA certification decision, the EPA added Condition 4. This condition is applicable to the implementation of the passive institutional controls, and has been included in 40 CFR Part 194 as Appendix A. The appendix provides that not later than the final recertification application submitted before closure of the disposal system, the DOE will provide the following to the EPA:

1. A schedule for implementing passive institutional controls that demonstrates markers will be fabricated and emplaced and other measures will be implemented as soon as possible following closure of the WIPP. The schedule will also describe how testing of any aspect of the conceptual design will be completed before or soon after closure and what changes to the design of passive institutional controls may be expected to result from such testing.

2. Documentation showing that the granite pieces for the proposed monuments and information rooms described in Docket A-93-02, Item II-G-1, may be quarried (cut and removed from the ground) without cracking due to tensile stresses from handling or isostatic rebound; engraved on the scale required by the design; transported to the site, given the weight and dimensions of the granite pieces and the capacity of existing rail cars and rail lines; loaded, unloaded, and erected without cracking based on the capacity of available equipment; and successfully joined.

3. Documentation showing that archives and record centers will accept the documents identified and maintain them in the manner identified in Docket A-93-02, Item II-G-1.

4. Documentation showing that proposed recipients of WIPP information other than archives and record centers will accept the information and make use of it in the manner indicated by the DOE in Docket A-93-02, Item II-G-1, and supplementary information.

7.3.2 Objectives for Passive Institutional Controls

As prescribed by the standards, the objectives of DOE's passive institutional controls for the WIPP are to convey the following:

- location,
- facility design,
- content, and
- hazard.

The passive institutional controls program described within this application will be effective in accomplishing these objectives.

7.3.3 Implementation of the Passive Institutional Controls Program

The DOE began addressing the issue of passive institutional controls in the context of the assurance requirements by convening two panels of experts to identify what future societies might be like (Hora et al. 1991). The panels were convened so that the appropriate types of messages, the contents of the messages, and the types of media for transmitting the messages can be selected and to identify design concepts for the system of markers at the repository footprint (Trauth et al. 1993), which is one of the passive institutional controls. The work of the two panels was completed prior to promulgation of 40 CFR Part 194. To address the issues of the passive institutional controls in addition to the markers at the repository footprint and to incorporate the concept of practicability into the design, the DOE developed a conceptual design, which is included in CCA Appendix PIC. With the promulgation of 40 CFR Part 194, the EPA provided guidance on how credit for the passive institutional controls deterring inadvertent human intrusion can be obtained for use in performance assessment. To address the issue of credit for passive institutional controls, the DOE produced CCA Appendix EPIC.

In addition, the DOE has developed new information pertaining to the permanent markers portion of the passive institutional controls program and furthered the planning process since the development and submittal of the CCA. This material is documented in the following reports:

1. Permanent Markers Testing Program Plan, Waste Isolation Pilot Plant (DOE 2000) – This document presents DOE plans for the program to test reference designs and alternative permanent markers materials, physical configurations, and locations. The markers testing program will develop information useful in materials selection and in the development of final designs. Testing will help to determine the effectiveness and durability of selected and alternative materials and design configurations. The testing plan provides the following information:

   Program Overview – Implementing the testing program will require performing a series of general activities, such as literature reviews and a survey and assessment of existing markers, the development of some testing methods, and the performance of both laboratory and field-scale tests. The coordination and integration of these activities is described.

   Testing Rationale – The rationale for the testing process is described. The testing rationale links individual marker systems, applicable design criteria, and testing objectives and issues. The testing objectives and issues are, in turn, addressed by the performance of specific tests and analyses.

   Tests Specification – Specific tests appropriate to address individual testing objectives and issues are identified for those cases where an appropriate method currently exists. Cases are identified where no method currently exists.

   Detailed Test Plans – Information that must be addressed in detailed test and analysis plans is identified in the plan. These plans must be developed before testing begins and will address topics such as test objectives, management of the testing activity, specific test methods, data quality objectives, data management, reporting, quality assurance (QA) provisions, and others.

   Evaluation of Results – The general manner in which testing and analyses results will be evaluated in the markers systems design process is described.

   Program Organization – The organization of the testing and analysis program in a sequential progression of activities and the general schedule of testing activities are described in the plan.

   QA – QA provisions applicable to the implementation of the testing program are described.

2. Contractor Report, Permanent Markers Monument Survey, Waste Isolation Pilot Plant (John Hart and Associates, P.A. 2000a) – The DOE is currently investigating alternative materials for the construction of permanent markers. One of the important considerations is the ability of the marker material to be inscribed with warning messages and the durability of these messages over very long time frames. In the CCA,

the DOE provides details regarding the implementation of the permanent markers program. An important objective of the program is to optimize the design of the marker systems by evaluating alternative configurations and materials and aiding in the development of final designs. A related activity identified in the CCA is the survey of monuments within 150 miles of the WIPP site to obtain any information useful in the selection of marker materials and the development of marker designs. This report documents the results of a survey performed in the summer of 2000. The objective of this survey was to collect and compile information relevant to the assessment of the durability of ancient inscriptions made on various rock types. Conclusions are provided related to the durability of various rock types, the effects of aspect, the rates of erosion of inscriptions, the effects of inscription form, and the importance of contrast in color and texture in regard to inscription legibility. Recommendations based on study observations and related to the longevity of inscriptions on various rock types are provided. These include:

Rock Types – Rocks of hardness and durability suitable for use as WIPP permanent markers are available within a few hundred miles of the WIPP site. Basalt and sandstone are the most abundant, so one or both of these should be selected for further evaluation. Intrusive igneous rocks that are susceptible to exfoliation should not be used.

Form of Inscriptions – To the extent consistent with the necessary written and symbolic warnings and messages, inscriptions should be as large as possible, with groove widths several times the largest mineral particle size. Unless the rock is very fine-grained, like basalt, it probably will not be practical to inscribe letters smaller than about 25mm minimum plan dimension or less than 5mm deep.

Additional Studies – Given the consistent findings over the 16 sites included in this survey, it is anticipated that additional monument (petroglyph) surveys would not be useful. However, studies on material properties of rock and man-made materials would be useful, with emphasis on surface hardness, methods to create and preserve color contrast, and the effects of rock texture on inscribability and inscription durability.

3. Contractor Report, Permanent Markers Materials Analysis, Waste Isolation Pilot Plant (John Hart and Associates P.A., 2000b) – This report documents assessments of marker materials included in the reference design as well as potential alternative materials. The permanent markers will be constructed of materials that will be selected through an evaluation process. Candidate materials identified in the CCA reference designs will be evaluated against performance criteria. The evaluations are being performed using methods identified in the Permanent Markers Testing Program Plan. Information obtained from literature reviews is provided in this report and has been used to refine the evolving candidate materials lists. The literature review also provides information supporting preliminary evaluations of the candidate materials. This information is also of value in planning laboratory and field tests that will provide additional information necessary to make final marker material selections.

4. Contractor Report, Ancient Cementitious Materials (John Hart and Associates, P.A. 2000c) – The current reference design for WIPP permanent markers calls for granite as the primary construction material for the large surface markers, small surface markers, buried storage rooms, and the information center. Although the reference design specifies granite, the DOE has committed to evaluate alternative materials in an effort to optimize final designs. One potential alternative material is concrete. Accordingly, a literature review was performed to investigate instances in which man-made cementitious materials have survived for very long time periods. The intent of this effort was to determine and document, when possible, the attributes of cementitious materials that contribute to their survival for long periods.

   This literature review showed that cementitious materials used nearly 9,000 years ago have survived intact to the present day. Concretes that have survived over such long periods have been some form of pozzolanic concrete. Results suggest that the blending of ancient and modern concrete technologies may provide a durable, long-lasting concrete meeting the DOE goal to mark the WIPP site for a very long time.

7.3.3.1 Definition of Passive Institutional Design Appropriate for the WIPP

In deciding which passive institutional controls are appropriate for the WIPP, the DOE was guided by the regulatory language in 40 CFR § 191.14(c) that states that the controls should be practicable. The DOE is expected to address the components of the passive institutional controls listed in the definition of 40 CFR § 191.12(e). The components of the passive institutional controls for the WIPP consist of (1) monuments that define the boundary of the withdrawal area, (2) markers at the footprint of the repository that consist of monuments that identify the outer boundary of the subsurface facility, a berm surrounding the repository footprint, an information center on the surface at the center of the repository footprint, a buried room halfway between the information center and the berm, a buried room halfway between the berm and the hot cell, and randomly spaced buried markers distributed across the repository footprint, (3) sets of records distributed to national and international archives, (4) sets of records distributed to records centers locally, nationally, and internationally (both those of a general nature and those specializing in land and resource use), (5) government control and land-use restrictions, and (6) other means of communication, such as encyclopedias, dictionaries, textbooks, and various maps and road atlases. CCA Appendix PIC contains a detailed description of the designs of each of these components.

Trauth et al. (1993) examined a variety of configurations and materials in concluding that a system comprised of natural materials incorporating massive structures with messages provided in an enduring configuration offered the best system for permanently marking the site. The permanent marker system incorporates these concepts and thus is the best system of passive institutional controls for permanently marking the repository. The use of archives and national publications as described in CCA Appendix PIC is the most extensive means of widespread distribution of the WIPP information. Use of radio or television is transient and will not provide the long-term societal memory.

7.3.3.1.1 Markers

Two groups of experts, the Futures Panel and the Markers Panel, were established to examine the issues involved with designing an effective system of permanent markers. Hora et al. (1991) incorporates judgments of the Futures Panel and discusses the underlying physical and societal factors that would influence society and the likely modes of human intrusion at the WIPP site.

The Hora et al. report was an important reference and source of information for the preparation of Trauth et al. (1993). Trauth et al. (1993) reports the results of the Markers Panel, which considered various concepts of marking the site and conveying to future generations information regarding the presence of dangerous waste material and the potential consequence of intrusion into the waste repository. CCA Appendix PIC (Section I) is a modification of the ideas developed by this panel.

CCA Appendix PIC sets forth the permanent markers system for the WIPP facility. This system involves the use of surface monuments, small subsurface warning markers, buried rooms, and large earthen structures marking the WIPP repository footprint on the surface. CCA Appendix EPIC (Section EPIC.6) indicates the period of time during which passive institutional controls will be effective.

The surface monuments are large monuments erected on the surface at both the repository footprint and the controlled area boundaries. To facilitate fabrication and shipping of the monuments, each monument will consist of two separate stones connected by a tendon joint. The large monuments will be engraved with Level II and III messages and Level IV pictographs, as described in CCA Appendix PIC (Section IV).[3] Figures 7-10 and 7-11 provide the

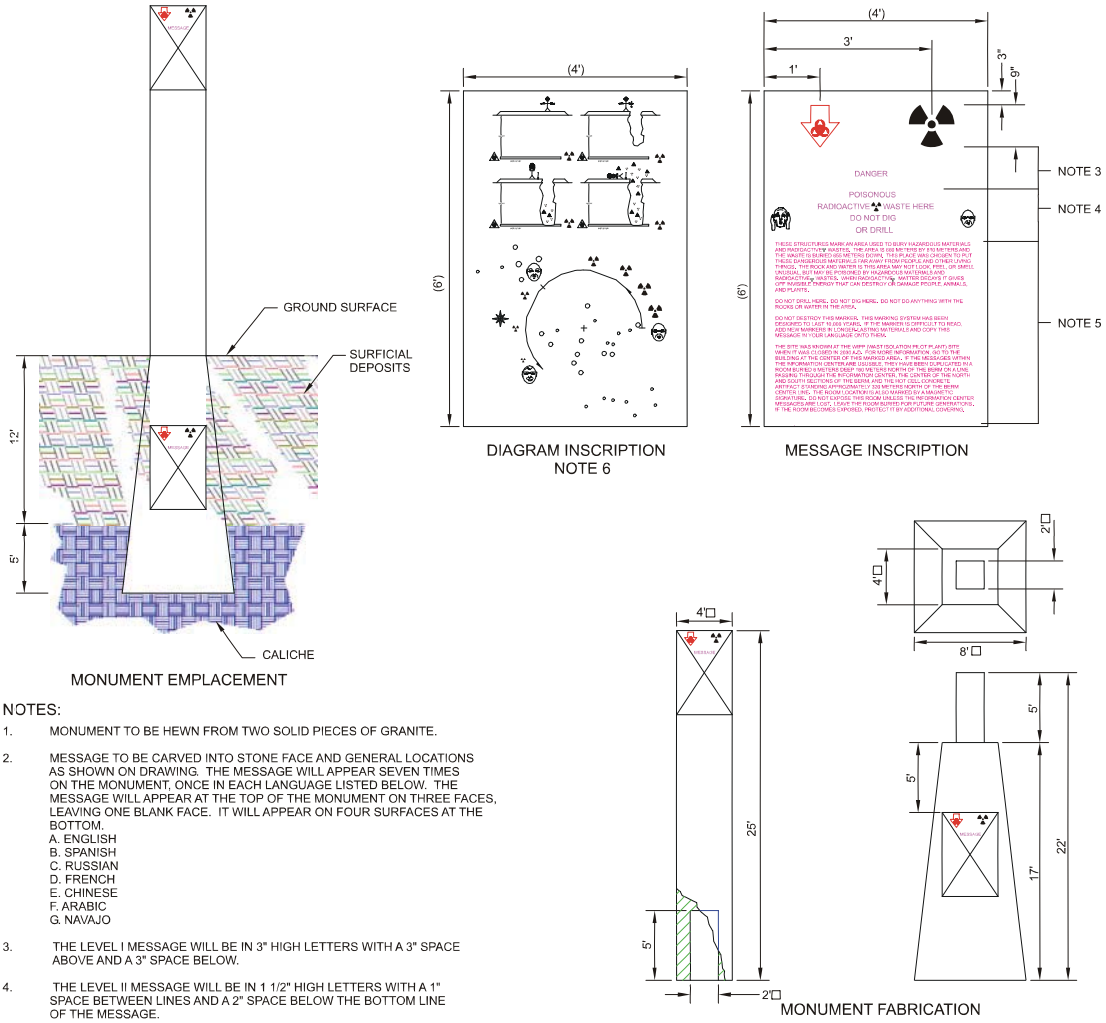

NOTES:

1. MONUMENT TO BE HEWN FROM TWO SOLID PIECES OF GRANITE.
2. MESSAGE TO BE CARVED INTO STONE FACE AND GENERAL LOCATIONS AS SHOWN ON DRAWING. THE MESSAGE WILL APPEAR SEVEN TIMES ON THE MONUMENT, ONCE IN EACH LANGUAGE LISTED BELOW. THE MESSAGE WILL APPEAR AT THE TOP OF THE MONUMENT ON THREE FACES, LEAVING ONE BLANK FACE. IT WILL APPEAR ON FOUR SURFACES AT THE BOTTOM.
   A. ENGLISH
   B. SPANISH
   C. RUSSIAN
   D. FRENCH
   E. CHINESE
   F. ARABIC
   G. NAVAJO
3. THE LEVEL I MESSAGE WILL BE IN 3" HIGH LETTERS WITH A 3" SPACE ABOVE AND A 3" SPACE BELOW.
4. THE LEVEL II MESSAGE WILL BE IN 1 1/2" HIGH LETTERS WITH A 1" SPACE BETWEEN LINES AND A 2" SPACE BELOW THE BOTTOM LINE OF THE MESSAGE.
5. THE LEVEL III MESSAGE WILL BE IN 1" HIGH LETTERS WITH A 5/8" SPACE BETWEEN THE LINES. THERE WILL BE A 1 1/2" SPACE BETWEEN THE PARAGRAPHS OF THE MESSAGE.
6. THE DIAGRAM INSCRIPTION WILL APPEAR ON THE BLANK FACE ON THE TOP OF THE MONUMENT. THE DIAGRAM DESCRIBES THE HAZARDS OF DIGGING HERE AND HOW LONG THAT HAZARD WILL EXIST.

Figure 7-10. Repository Footprint Perimeter Monument Configuration

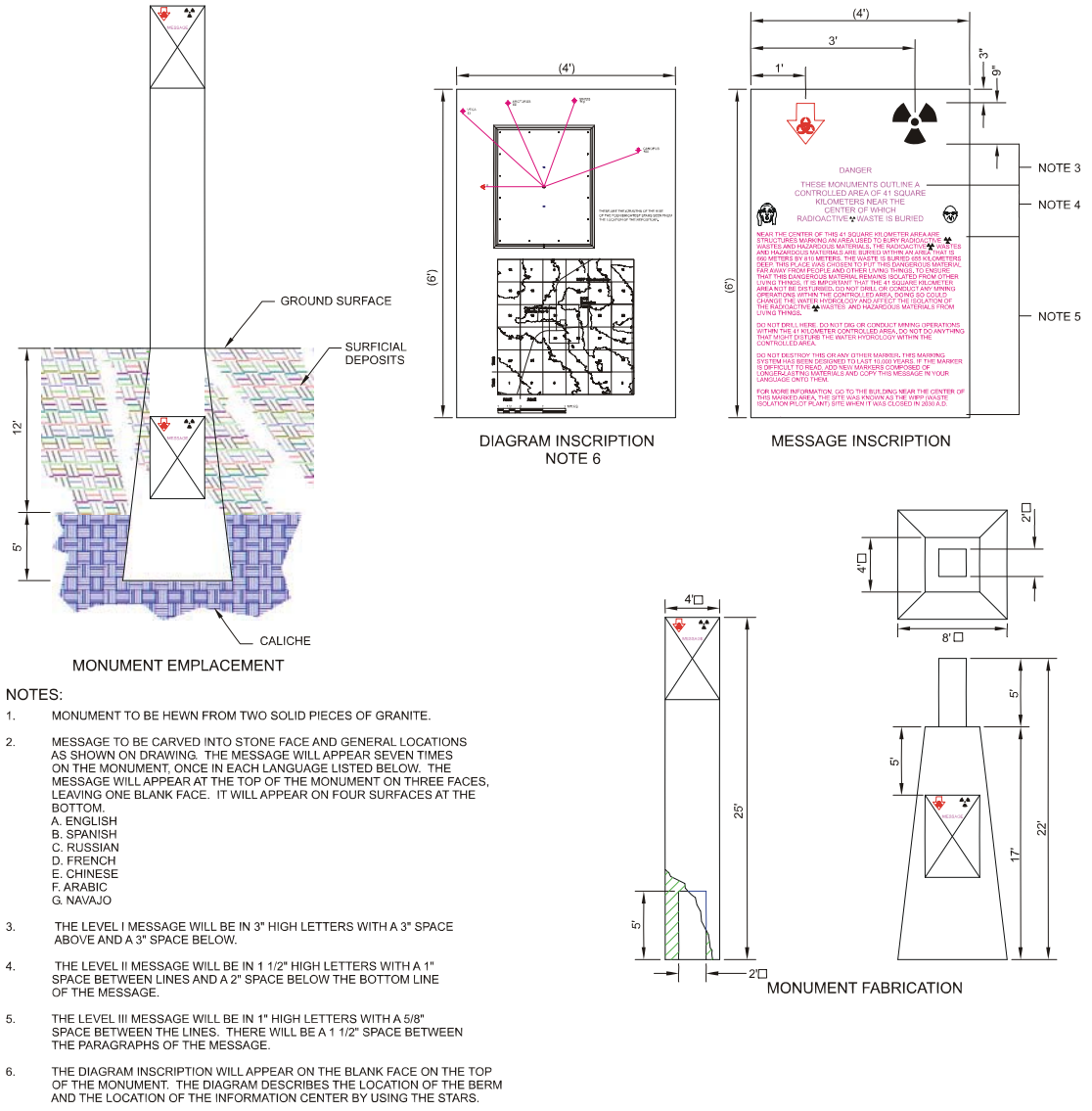

NOTES:

1. MONUMENT TO BE HEWN FROM TWO SOLID PIECES OF GRANITE.
2. MESSAGE TO BE CARVED INTO STONE FACE AND GENERAL LOCATIONS AS SHOWN ON DRAWING. THE MESSAGE WILL APPEAR SEVEN TIMES ON THE MONUMENT, ONCE IN EACH LANGUAGE LISTED BELOW. THE MESSAGE WILL APPEAR AT THE TOP OF THE MONUMENT ON THREE FACES, LEAVING ONE BLANK FACE. IT WILL APPEAR ON FOUR SURFACES AT THE BOTTOM.
   A. ENGLISH
   B. SPANISH
   C. RUSSIAN
   D. FRENCH
   E. CHINESE
   F. ARABIC
   G. NAVAJO
3. THE LEVEL I MESSAGE WILL BE IN 3" HIGH LETTERS WITH A 3" SPACE ABOVE AND A 3" SPACE BELOW.
4. THE LEVEL II MESSAGE WILL BE IN 1 1/2" HIGH LETTERS WITH A 1" SPACE BETWEEN LINES AND A 2" SPACE BELOW THE BOTTOM LINE OF THE MESSAGE.
5. THE LEVEL III MESSAGE WILL BE IN 1" HIGH LETTERS WITH A 5/8" SPACE BETWEEN THE LINES. THERE WILL BE A 1 1/2" SPACE BETWEEN THE PARAGRAPHS OF THE MESSAGE.
6. THE DIAGRAM INSCRIPTION WILL APPEAR ON THE BLANK FACE ON THE TOP OF THE MONUMENT. THE DIAGRAM DESCRIBES THE LOCATION OF THE BERM AND THE LOCATION OF THE INFORMATION CENTER BY USING THE STARS.

Figure 7-11. Controlled Area Perimeter Monument Configuration

dimensional characteristics of the large monuments. The monuments intended for marking the controlled area boundaries will differ from the monuments marking the repository footprint. Each footprint monument will be inscribed with the Level II and III messages in seven languages, the six official United Nations languages (English, French, Spanish, Chinese, Russian, and Arabic), and Navajo. The controlled area boundary monuments will be inscribed with warning messages. Trauth et al. (1993, Appendix F) discusses in some detail the selection of these languages by the Markers Panel.

The monuments will be quarried from granite and shipped by rail to the WIPP site. Each monument base will be soundly founded by excavating into the near-surface caliche. After

emplacing the base monument, the excavation will be backfilled and the upper monument will be placed over the base tendon.

The small warning marker is shown in Figure 7-12. The Level II messages placed on the small subsurface warning markers will be in the seven languages previously listed. However, each marker will have the message in only one of the seven languages. Warning markers will be placed throughout the repository footprint and within the berm. The warning markers will be made of a diversity of durable materials, such as granite, aluminum oxide, and fired clay, thus improving the likelihood that at least some of the markers will endure for thousands of years.

Diameter of Disk is 23 cm. (9 in.)
Not to Scale

CCA-114-2

Figure 7-12. Small Buried Warning Marker

The small buried warning markers will be randomly spaced in locations and at depths to provide a reasonable expectation of discovery by any organized exploration effort, but to discourage organized efforts at collecting the markers. The current petroleum industry practice in the Delaware Basin is to remove surface soil down to the caliche layer over an area sufficiently large to set up a drilling rig and dig a mud pit. Nominally, this area is 50,000 ft^2 (4,648 m^2). By placing the small warning markers above the caliche at intervals of a few feet, several of the warning markers should be unearthed during any soil clearing operation.

The inclusion of a berm in Figure 7-13 in the permanent marker design is based upon the following criteria (see CCA Appendix PIC, Section VII, for more detail).

- The surface footprint of the repository should be essentially outlined by some enduring structure.
- The structure should be sufficiently massive to provide reasonable expectation that it will endure for thousands of years.
- The structure's profile should minimize the likelihood that it can become buried by shifting sands or that characteristics of the profile may lead to fabrication stresses affecting the ability of the structure to retain its configuration.
- The structure should be constructable without the need for sophisticated equipment or processes.

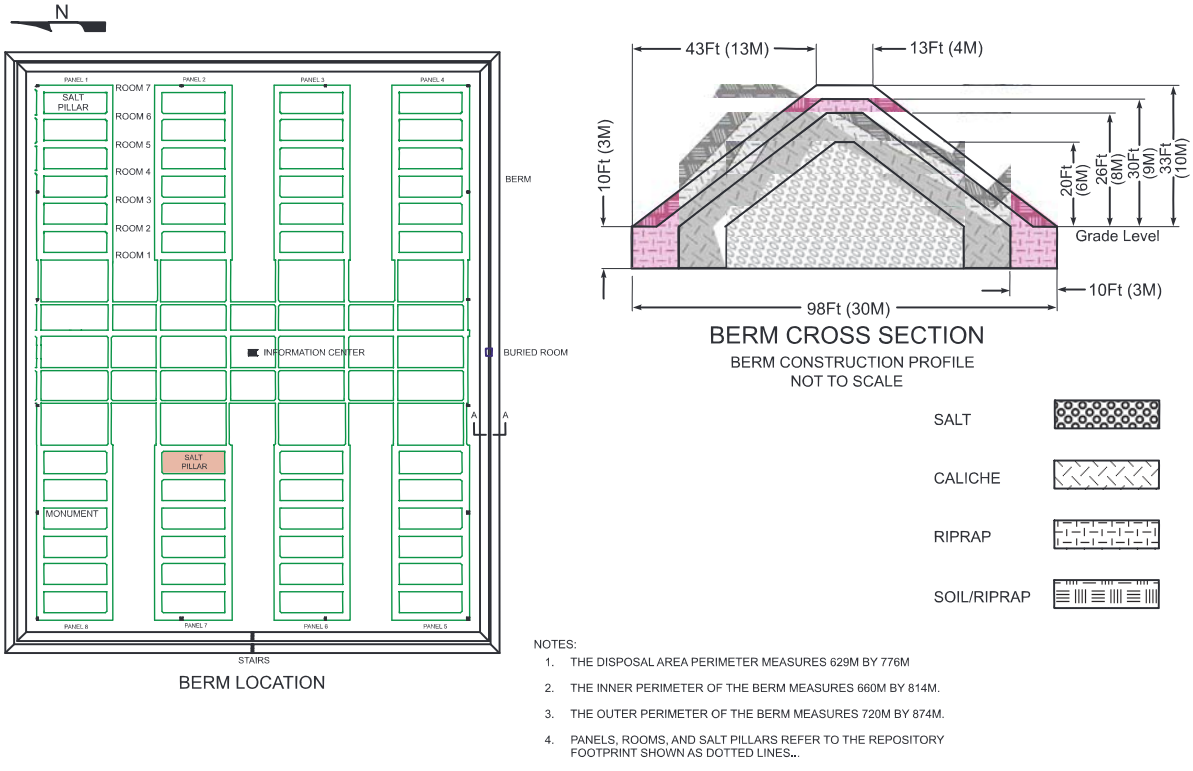

Figure 7-13. Berm Construction

- The construction materials should be reasonably available to the WIPP site and have little intrinsic value.

- The cost should not be disproportionately high for the advantages that the alternative provides.

- To the extent practicable, the nature of the structure should lend itself to testing over a period of two to five decades.

The berm is proposed to encompass the repository footprint. Figure 7-13 also depicts the reference design berm cross section.

As reported in John Hart and Associates, P.A. (2000b), the permanent markers will be constructed of materials selected through an evaluation process. Candidate materials identified in the CCA reference designs will be evaluated against performance criteria. The evaluations will be performed using methods identified in the Permanent Markers Testing Program Plan (DOE 2000).

A variety of earth materials that occur on or close to the WIPP site are available for use in the construction of the berm including native soils and caliche. Salt, excavated from the WIPP underground and stockpiled on site, may not be a good material for use in the berm. Its solubility and low strength make it an unreliable material to form the core of the berm, and use at shallower locations in the berm, while structurally of less consequence, nevertheless may not be feasible because of the closer proximity to infiltrating groundwater and the resulting increased risk of dissolution.

The berm design shown in Figure 7-13, including materials of construction, will be refined through the ongoing design-development process and finalized prior to its construction. Final design specifications will be provided to the EPA for approval prior to construction.

To provide a distinctive magnetic signature for the berm, large permanent magnets or other magnetically distinct materials buried at intervals in the berm will be used. These materials are intended to produce a detectable signature with current airborne detection equipment. The magnetic signal's geometric form will provide strong indication that it could only have been humanly engineered. This magnetic signature should motivate any organization capable of magnetic surveying to further investigate this anomaly prior to initiating drilling activities.

Similarly, to provide a distinctive radar-reflective signature unique from the surrounding terrain, DOE will consider the use of radar-reflective trihedrals for placement within the top layer of the berm.

Another aspect of the marker system includes on-site buried storage rooms containing the Level IV message and associated diagrams. These rooms will be designed to endure for a similar time period as the permanent marker system and will be buried (see CCA Appendix PIC). The design characteristics contributing to this longevity will be the material and environmental conditions associated with construction and location. The rooms will be made of granite with a minimum number of joints. Individual walls, the floors, and the roofs will comprise single granite slabs

joined only at the edges. The configuration minimizes the risk of failure caused by chemical interactions between the construction material and the environment. The message texts contained within the buried storage rooms will be engraved on the walls. To provide redundancy, additional granite slabs engraved with the message text and the diagrams will be held in place against the interior walls. Although some damage could be inflicted by vandals, the granite composition of the message-carrying materials will provide the greatest opportunity for preventing complete destruction of the information contained within the buried rooms.

In addition to the buried storage rooms, an information center, as described in CCA Appendix PIC (Section VII), will be located on the surface, providing access to the same information that is contained in the buried rooms. Details regarding the location of one of the buried storage rooms and identical information will be contained in the information center.

7.3.3.1.2 Records

A significant part of the overall system will be the archiving of important information at sites remote to the repository. The archived material will include information that defines the location, design, content, and hazards associated with the WIPP. The amount of information will be more extensive than that available within the permanent marker system at the repository location. Information will be preserved using practicable materials and techniques at record centers and archives throughout the world. CCA Appendix EPIC (Section EPIC.6) provides justification for a period of time that materials placed in archives and records centers are expected to endure and be understood.

Although DOE has not yet established the specific archival files, examples of the types of documents that will be archived include the following. The specific requirements of 40 CFR § 194.43 (a)(2) are listed and responsive documents are indicated in parentheses.

- (i) The location of the controlled area and the disposal system (detailed maps describing the exact location of the repository, Safety Analysis Report, the Final Environmental Impact Statement (FEIS) for WIPP and the supplement(s) to the FEIS, the RCRA Permit, the last compliance recertification application (CRA))

- (ii) The design of the disposal system (Safety Analysis Report, the FEIS for WIPP and the supplement(s) to the FEIS, the RCRA Permit, the last CRA, drawings defining the construction and configuration of the repository and shafts, design information for the passive institutional controls)

- (iii) The nature and hazard of the waste (Safety Analysis Report, the FEIS for WIPP and the supplement(s) to the FEIS, the RCRA Permit, the last CRA, records of the waste container contents and disposal locations within the WIPP repository)

- (iv) Geologic, geochemical, hydrologic, and other site data pertinent to the containment of waste in the disposal system, or the location of such information (Safety Analysis Report, the FEIS for WIPP and the supplement(s) to the FEIS, the RCRA Permit, the last CRA, environmental and ecological background data collected during the preoperational

phase of WIPP and summaries of data collected during the disposal and decommissioning phases of WIPP)

- (v) The results of tests, experiments, and other analyses relating to backfill of excavated areas, shaft sealing, waste interaction with the disposal system, and other tests, experiments, or analyses pertinent to the containment of waste in the disposal system, or the location of such information. (Safety Analysis Report, the FEIS for WIPP and the supplement(s) to the FEIS, the RCRA Permit, the last CRA, drawings, procedures, and design reports describing how the waste was emplaced, and how the repository was decommissioned, closed and sealed)

The National Archives will be one organization responsible for the permanent storage of this information. As discussed in CCA Appendix PIC, the information will also be distributed to appropriate organizations such as the following for long-term safekeeping:

- federal and state government agencies,
- federal, state, tribal, and local archives and libraries,
- local and state and record repositories (for example, the Eddy County Clerk New Mexico)
- national archives and libraries of nations that possess nuclear weapons and nuclear energy or produce natural gas and oil resources, and
- professional and technical societies.

The archival and record centers identified in CCA Appendix PIC as planned recipients of information were selected based upon one or more of the following criteria:

- representing an international location in a nation which had citizens engaged in the oil and gas exploration and exploitation industry,
- representing an international location in a nation which had the potential to generate radioactive waste,
- representing a local governmental organization frequented by individuals engaged in the oil and gas exploration and exploitation industry,
- representing a National Archival location,
- representing a Regional Library, or
- is a public funded location.

The DOE intends to submit WIPP records to over 100 archives nationally and internationally as identified in CCA Appendix PIC. The final number of archive recipients will depend upon the agreements reached between DOE and the facilities. The initial submittal of these records will

occur after closure and decommissioning of the WIPP. Since this time frame is decades into the future and thus significant changes will occur to some or all of the archives as well as some of the governments, the DOE has not attempted to identify the practices employed by each archive and repository for maintaining records and making them accessible to the public. However, the National Archive-Rocky Mountain Region practices are described and are representative of the National Archives and its regional facilities. The state of New Mexico Archive and the Canadian National Archive were also contacted and their practices are similar to those employed by the U.S. National Archives. There are also international standards for the organization and operation of archives that enable the world's archives to function similarly in many aspects of the practices governing maintenance of records and access to the records by members of the public.

To ensure the proper storage and retrievability of archived material, the DOE archivist will develop a filing code system specifically for the WIPP material. This system will be a part of the overall document submittal the DOE will provide to the various archival locations. In the development of the filing code system and communications with worldwide archives, it is expected that differing cultural issues will be addressed in order that the DOE gain acceptance of the information from as many archives as possible.

To reduce the possibility that future archivists may destroy the provided documents, each volume containing documents will be labeled with a warning that the intent of providing the archived material is to ensure its preservation for the 10,000-year regulatory time frame stipulated in the U.S. Government's regulations controlling the disposal of transuranic waste. It is recognized that the federal government may incur some long-term financial obligations to the archival locations to ensure retention. Within two years following the distribution of archival material and at least every 15 years thereafter during the active institutional controls period, the DOE will conduct audits of selected archival locations to verify retention and retrievability of the historical documents.

As an example of how an archive will handle archived information, the National Archive will use the indexing system provided by the DOE in organizing the WIPP material submitted for archiving and public use. Upon receipt of the material in boxes, the archive staff will examine the documents; remove staples, paper clips, rubber bands, and other miscellaneous materials that may damage or are otherwise incompatible with the records over an extended period of time; enclose any damaged material in individual protective covers; place the records in acid-free boxes; and store those boxes in an environmentally controlled vault. The individual boxes are labeled with coded alpha-numeric designations that tie the contents back to the agency submitting the documents, the year in which the documents were received, and the general content of the documents. Finding aids, content indices, or significant word lists are developed to aid researchers in identifying the material desired. The coded number will also provide information relative to whether or not the documents may be destroyed after a given amount of time. Many government documents are scheduled to be destroyed after 30 years. Other documents are preserved indefinitely.

Title 36 CFR Part 1254, Availability of Records and Donated Historical Materials, regulates the manner in which archival material within the National Archive system is made available to members of the public. In general, researchers must register each day that they enter a research facility and may be required to provide identification. The researcher must sign for the

documents received and again may be required to show identification. The researcher is not permitted to leave the room without notifying the room attendant and placing all documents in their proper containers. Documents must be returned to the research room attendant prior to the room closing. Documents may not be used where there is food, drink, or the presence of ink. Only pencils may be used in the room containing original documents. If the researcher requires copies of documents, the appropriate document must be marked with a paper tab provided by the archive. No paper clips or rubber bands may be used on the documents. The room attendant will provide the copying services for the researcher. Documents must be maintained in order by the researcher; however if the documents become disordered, the room attendant must perform the re-ordering function and not the researcher. Upon exiting a research room, the researcher must present for examination any article that could contain documents.

In addition to the national and state archives, Indian tribes and pueblos (for example, Navajo, Mescalero Apache, and Zuni) were contacted to determine the extent of any archival activity. Only the Zuni were establishing a limited internal archive. Other groups forward archive worthy materials to federal storage facilities. The DOE will continue to work with key nations, tribes, and pueblos to establish pertinent agreements and to ensure that appropriate WIPP records are distributed for archiving and reference purposes.

Finally, the International Atomic Energy Agency (IAEA), with the DOE as a current participatory through the agency of its Scientific Advisor, is developing a procedure for the archiving of records pertinent to the disposal of radioactive waste in deep geological repositories. The procedure, published in July 1999, is titled Maintenance of Records for Radioactive Waste Disposal (IAEA 1999). The DOE embraces this effort.

7.3.3.2 Implementation of Programs to Collect Information

Prior to implementing the passive institutional controls, a testing program will determine whether the specific messages proposed can be expected to convey the intended warnings and information across cultures and whether the proposed media for transmitting the messages will endure to the degree anticipated in the development of the conceptual model. The testing to be conducted will address the refinement of the messages, diagrams, and the method of presentation. As recommended in Trauth et al. (1993), the translated versions of the message text should be evaluated by presentations to groups indigenous to the countries whose language is represented in the message. This process should provide input into how comprehensible the messages are and provide information regarding any idiom changes that may be necessary in the translated versions. When considering that the messages were developed by educated individuals residing in the U.S., it is prudent that the effectiveness of the messages to convey their intended content to a broader cross-section of individuals be thoroughly tested. The testing therefore should include cross-cultural groups in evaluating the effectiveness of conveying the intended messages through diagrams and pictures as well as script. The DOE will continue to develop and review the details of a testing program to ensure that a comprehensive effort is made to test the final written and pictograph message comprehensibility. For those components that include either large volumes of various materials (for example, the berm) or the movement of heavy objects (for example, the sections of granite in the monuments), procedures will be tested for transporting the material and constructing the specified designs. The testing programs are

described in CCA Appendix PIC. See CCA Appendix EPIC for a discussion of the durability of materials to be used to construct passive institutional controls.

7.3.3.3 Passive Institutional Controls Timelines

The DOE has prepared a tentative schedule of the implementation of the passive controls program. The schedule is shown in Figure 7-14. The following is provided as a brief expansion of the timelines provided in Figure 7-14.

- 1996 – 2083 Design and Test Permanent Marker Concepts and Materials. During this period the testing and monitoring described in CCA Appendix PIC related to the permanent marker components, materials, and communication concepts are conducted.
    - 2004-2009 Construct Test Markers. During this period, the DOE will install prototype markers for testing. The types of prototype markers and their materials of construction will be based on results of screening tests.

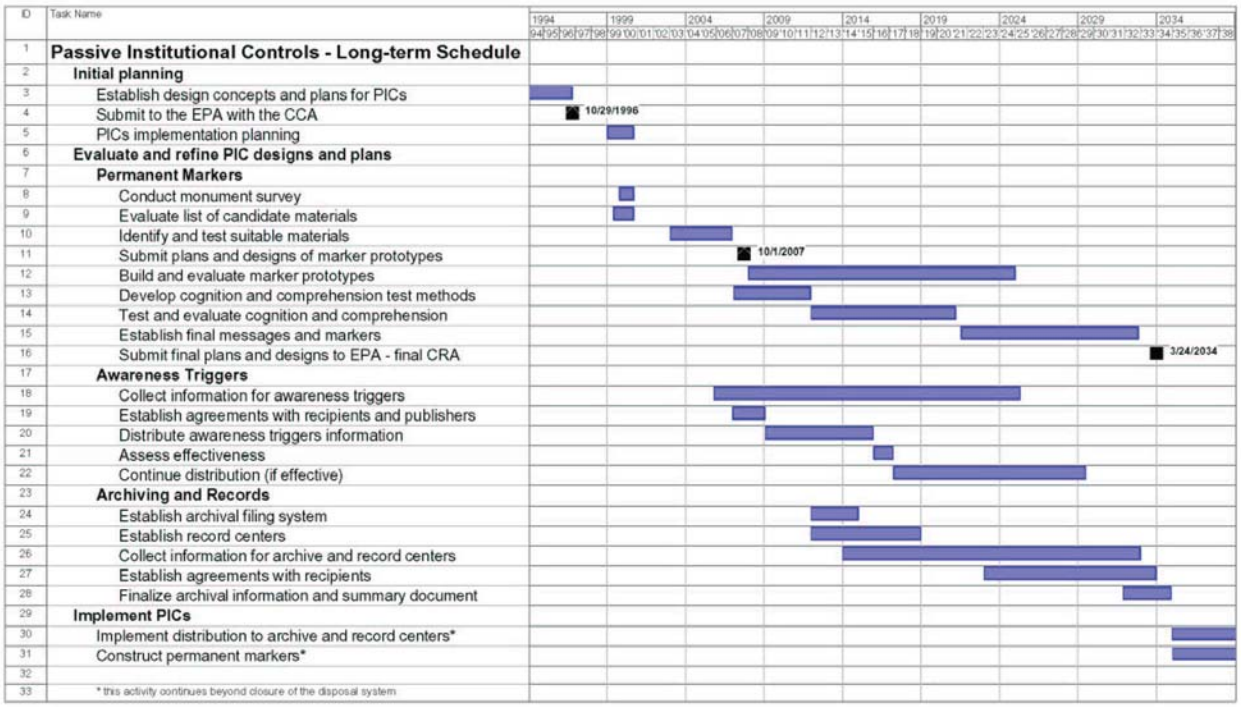

Figure 7-14. Passive Institutional Controls - Long Term Schedule 2007-2083

Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2004

- Monitor Performance of Prototype Markers. During this period, the DOE will monitor the performance of the test structures to develop information for use in the final design.

- 2018 – 2023 Test Message Comprehension. The DOE will gain operational experience for any information that may affect the composition of the intended messages, both narrative and pictogram, and then conduct testing for comprehension by populations indigenous to the countries represented by the languages used in the messages.

- 2083 – 2090 Final Design. During this period, the DOE will complete the final design of the permanent marker system.

- 2090 – 2093 Construct Permanent Marker System. During the period, the permanent marker system will be constructed including installation of messages.

- 1999 – 2093 Implement Information Collection and Establish Archival and Record Center Agreements. During this period the actions required to implement record keeping and record storage aspects of PICs are conducted. Individual actions and associated timelines are:

• 2004 Establish Filing System. The DOE will establish the filing system under which the record center and archival information will be assembled. Completion of the system by 2004 will support the information collection program.

- 2003 – 2033 Collect Operational Information. Collect the information relative to WIPP operation, including decommissioning, which will be included in the promulgated documentation.

- 2033 – 2090 Collect Active Control Period Information and Marker Configuration. Collect the information relative to WIPP active controls and the results of testing of the permanent marker system components and communication concepts.

- 2023 – 2034 Establish Agreements with Recipients. During this period the DOE will communicate with the planned document recipients to develop general agreements with respect to language translation, scope of translated material, format in which the material will be provided, and any financial support required to achieve acceptance by each recipient. Beginning about 2023 when most of the documentation should have been developed, this effort should start. The DOE expects two to three years to establish the agreements and another five to eight years for translation, with completion about the time that decommissioning and decontamination are finished. This provides for the incorporation of information related to decommissioning and decontamination.

- 2033 – 2034 Develop Summary Document. The DOE will develop the WIPP summary document to be provided for ease of public access and understanding of the WIPP.

- 2035 Promulgate Information Accumulated Through WIPP Closure and Decommissioning. The DOE will make a distribution of documents accumulated through the final closure, decontamination, and decommissioning of the WIPP.

- 2023 – 2033 Establish Agreements and Submit Information to Publishers. During this period, the DOE will establish agreements with map makers and text publishers including financial support and provide hazard, history, and location information to be included on maps and various text materials.

- 2083 – 2093 Finalize Archival Information. During this period, the DOE will develop the final additions to the planned submittal, which include information describing the WIPP history during the first 50 to 60 years following closure and the final configuration of the permanent marker system.

- 2093 Promulgate Archival & Records Center Information. The DOE will make the distribution of the final portion of the archived information nationally and internationally.

In a letter dated May 16, 2002 from Dr. Ines Triay to Mr. Frank Marcinowski, the DOE proposed to the EPA changes regarding the submittal of detailed plans and drawings depicting the permanent marker prototypes. The request includes a proposed revised schedule, as detailed in Table 7-9.

The EPA responded to the DOE request in a letter dated November 7, 2002, from Mr. Marcinowski to Dr. Triay (EPA Docket A-98-49, Category IIB-3, Item 41). The EPA response states that the schedule changes proposed by the DOE are insignificant with respect to the Certification Decision (63 FR 27396, May 18, 1998). The EPA also concluded that the DOE plans for testing provide significant details to support the need for additional testing time. As such, the EPA determined that the DOE may proceed with the proposed changes. In addition, the EPA provided the following comments related to the implementation of the passive institutional controls program. These comments serve as guidance to the DOE.

1. The Permanent Markers Testing Program Plan is a welcome development. The EPA appreciates the thoroughness of DOE's approach to this topic, especially the inclusion of references to the Quality Assurance Program Document. The use of reference standards and established quality processes, as well as a methodical approach to testing, will be important factors in demonstrating to the EPA that any future changes to the conceptual design have an adequate technical basis.

2. The DOE is obligated to execute site markers as described in the CCA and subsequent DOE correspondence (February 7, 1997, letter from G. Dials to R. Trovato; Air Docket A-93-02, Item II-I-07). If the DOE determines that the original marker design (including location, number, materials, and configuration) should be altered or

Table 7-9. Activities Related to the Implementation of the Permanent Markers Program

Activity	Reference Event	Original Timeframe	Current Status	Proposed Timeframe
Stone Monument Survey	First five years of operations	1999-2004	Completed	N/A
Identification of suitable source material	First five years of operations	1999-2004	Pending decisions on changes to design and material selection	2007
Submit plans for the test marker system	1st CRA submittal	2003	Proposed change to submit prior to second CRA	2007
Construct and test berm and test markers	Second five years of operations	2004-2009	Pending proposed change and testing program	2008
Monitor performance of test berm and test markers	After construction	2007-2083	Pending proposed change and testing program	2009 - until closure
Testing comprehension of marker messages submittal of testing plans to EPA	Fourth CRA submittal	2018	No change	N/A
Develop final design of markers	Upon termination of testing program	2083-2090	Final design to be submitted with the final CRA	2033 (anticipated)
Finalized Translated Messages	Prior to building of final permanent markers	N/A	Finalized messages will be submitted with the final CRA	2033 (anticipated)

improved, the Department must notify the EPA and receive the Agency's approval before proceeding.

Certain changes (such as different component materials or dimensions) may be possible without modifying the certification, as long as the design itself remains essentially the same. However, the introductory section of the proposal (page 2) states, "DOE plans to re-examine whether…all of the components of the permanent marker system proposed in the CCA are needed." Elimination of one or more components may require modification.

3. Condition 4 of the Certification Decision requires the DOE to show that PICs will be implemented "as soon as possible following closure of the WIPP." DOE's change notice states that all measures in their final form will be presented in the last recertification application before site closure (approximately 2033). Throughout the operational phase of the WIPP, the DOE should present information in each recertification application showing progress with regard to testing and implementation of all PICs (markers, archived records, etc.).

4. Based on conclusions reached by John Hart and Associates, the DOE suggests that "portions of the permanent marker system originally conceptualized…are impractical" (page 1 of the introductory section). Concerns about the specific design of the surface granite monoliths led us to require further information about the monoliths in Section(a)(2) of Condition 4 of the WIPP Certification. Nevertheless, the EPA explicitly concluded in the Certification Decision that the proposed marker system – including the salt-core based berm – was practicable. To justify a departure from the markers that were proposed, the DOE would be expected to provide an adequate technical basis showing that an alternative is likely to be more durable and effective as a marker. EPA believes that further testing and analysis of materials (e.g., basalt), processes (e.g., granite exfoliation), and configurations (e.g., salt core of the berm) should be done before DOE concludes that certain features of the marker system are impractical.

7.3.4 Effectiveness of Passive Controls in Reducing the Rate of Human Intrusion

The EPA raises the issue of the expected ability of the passive institutional controls to convey information to future societies in two areas. In the context of the assurance requirement in which no assumptions can be made to limit the uncertainty of the future states of societies, the EPA states

> Any compliance application shall include the period of time passive institutional controls are expected to endure and be understood. (40 CFR § 194.43[b])

In the context of credit for passive institutional controls in deterring inadvertent human intrusion for use in performance assessments, the EPA goes on to state that

> The Administrator may allow the Department to assume passive institutional controls credit, in the form of reduced likelihood of human intrusion, if the Department demonstrates in the compliance application that such credit is justified because the passive institutional controls are expected to endure and be understood by potential intruders for the time period approved by the Administrator. Such credit, or a smaller credit as determined by the Administrator, cannot be used for more than several hundred years and may decrease over time. In no case, however, shall passive institutional controls be assumed to eliminate the likelihood of human intrusion entirely (40 CFR § 194.43[c]).

To limit the speculation about the state of future society, the EPA has provided additional guidance by stating that "EPA expects that the DOE will establish a framework of assumptions for passive institutional controls that is a prudent extrapolation of the future state assumptions established in 194.25" (EPA 1996b, p. 61) and by providing for the existence of certain societal "common denominators" based on "patterns of human behavior that may be detected throughout history and around the world" (EPA 1996b, p. 61).

Section 7.3.4.1 addresses the issue of how long the passive institutional controls are expected to endure and be understood in the context of the Assurance Requirement (40 CFR § 194.43[b]) and Section 7.3.4.2 addresses the issues of how long these controls are expected to endure and be understood and the resulting credit in deterring inadvertent human intrusion in performance assessment calculations (40 CFR § 194.43[c]).

7.3.4.1 Expected Effectiveness

The passive institutional controls in the Conceptual Design Report (DOE 1994) were developed from the recommendations of the Markers Panel convened in 1991, modifying them for reasons such as constructability or resource requirements. The Markers Panel developed fundamental principles of long-term communication making only the most minimal assumptions about what future societies would be like (for example, they will be human beings similar to what we are today). No assumptions were made about what languages they might be speaking or how technologically sophisticated they might be. Because no assumptions were made about language or technology, the Markers Panel developed strategies that attempt strategies to communicate with individuals in a variety of means and in a systems approach whereby the various components reinforce and supplement the other messages.

Without assumptions about technological sophistication, messages will be provided in various levels of complexity, ranging from the most basic marker of human construction rather than a natural phenomenon, to the entire written record of information about the repository and its certification. Because it is not known what languages will be spoken in the future, the markers will include non-linguistic means of communication, such as pictures of humans, star charts, and the periodic table of the elements. In this way, the design of the markers responds to the EPA's requirement for the "most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location" (40 CFR § 191.14[c]). While the Markers Panel focused its efforts on the repository footprint, based on the 40 CFR 191 definition of human intrusion, the entire withdrawal area will be identified by on-site passive institutional controls to satisfy criteria in 40 CFR § 194.43. Because of the requirement for records and archives, plans have been made to place materials within the existing governmental and scientific systems of recordkeeping.

In addressing the issue of credit for passive institutional controls in performance assessment calculations, the DOE examined historical analogues for the controls components (see CCA Appendix EPIC, Chapter 5). Certain design characteristics of these historical analogues have survived destruction from both societal turmoil and natural processes. By designing the PICs to mimic and enhance these design characteristics, the DOE believes that the passive institutional controls for the WIPP will be capable of surviving at least as long as the historical analogues. Based on the characteristics of the markers, these components have the capability of lasting in excess of several thousand years. This conclusion is consistent with the conclusions of both teams of the Markers Panel whose estimates were based on basically the same design characteristics for the markers and on a wide variety of future states of society. The multiple copies of the records in the records centers and archives, the selection of highly durable materials (that is, archival paper and carbon-black ink), and the fact that the records will have value in the economic and health areas suggest that at least some copies of the records have a high probability of surviving for many hundreds to thousands of years.

The Markers Panel concluded that the messages proposed have a high probability (greater than 0.70) of being understood by all potential levels of technology for at least 2,000 years (Team A estimated at least 5,000 years). Although the Markers Panel considered only the messages on the markers, the same information, both text and pictographs, will be included in the records in

records centers and archives. As a result, the DOE concludes that these records will be interpretable for as long as the documents survive.

7.3.4.2 Credit Taken in Performance Assessment Calculations

In addition to their use for compliance with the assurance requirements, credit for passive institutional controls may be used in PA calculations. In 40 CFR § 194.43(c), EPA allows credit in the form of reduced likelihood of human intrusion. The Preamble to 40 CFR 194 limits any credit for passive institutional controls in deterring inadvertent human intrusion to 700 years after disposal**.** During the certification process, the DOE sought passive institutional controls credit in the CCA based on the conclusions of a designated task force. CCA Appendix EPIC documents the basis for this credit. For the performance assessment calculations in the CCA, the passive institutional controls were considered to be 0.99 effective in deterring inadvertent human intrusion over the entire withdrawal area for 700 years.

However, the EPA performance assessment verification test (PAVT) calculations did not include credit for passive institutional controls (63 FR 27396). In the certification decision (EPA 1998), the EPA concluded its discussion on this matter as follows:

> However, EPA's final decision today applies only to the credit proposal in the CCA and should not be interpreted as a judgement on the use of PICs credit in PAs generally. In the future, DOE may present to EPA additional information derived from an expert elicitation of PICs credit. Any future PICs credit proposals will be considered in the context of a modification rulemaking, and will be subject to public examination (63 FR 27396).

In this recertification application, the DOE claims no credit for the effectiveness of passive institutional controls. As indicated by the EPA, the DOE may claim such credit in future recertification applications.

7.4 Multiple Barriers

The WIPP facility has incorporated multiple natural and engineered barriers, including plugs, seals, and backfill into its design. As a part of the DOE's program to evaluate multiple barriers, an Engineered Alternatives Task Force (EATF) evaluated optional additional engineering measures for the WIPP facility. The findings of the task force are summarized in the *Evaluation of the Effectiveness and Feasibility of the Waste Isolation Pilot Plant Engineered Alternatives* (DOE 1991). A more recent study, the Engineered Alternatives Cost/Benefit Study, updated the 1991 EATF activity and augmented it with more in-depth and comprehensive analyses of the relative benefits and detriments of the alternatives. Benefits and detriments at the waste generation and storage sites were evaluated in this study as well as those at the WIPP. (This study is included in CCA Appendix EBS.)

Beyond the requirements contained in 40 CFR § 191.14(d) relating to multiple barriers, 40 CFR § 194.44 has imposed certification criteria upon the DOE with regard to engineered barriers. The following sections provide a discussion of the manner in which the DOE has complied with the multiple barrier requirement of 40 CFR § 191.14(d) and an overview of the manner in which the engineered barrier criteria of 40 CFR § 194.44 have been met. A detailed discussion of the cost and benefit analysis dictated in 40 CFR § 194.44 is provided in CCA Appendix EBS.

7.4.1 Requirements for Multiple Barriers

By requiring the use of both natural and engineered barrier types as the assurance requirement, the EPA intends to ensure that the impacts of the failure of any single barrier type will be minimized.

In the LWA, Congress mandated that the Secretary will use both natural and engineered barriers. Waste form modifications may be used at the WIPP to isolate waste after disposal to the extent necessary to comply with the final disposal regulations. Therefore, the disposal system design involving the Salado as a natural barrier and the shaft seals as engineered barriers complies with this assurance requirement as indicated by the compliant complementary cumulative distribution functions (CCDFs) shown in Section 6.5.

7.4.2 Objectives for Multiple Barriers

The primary objective for the implementation and the use of multiple barriers at the WIPP facility is to help guard against unexpectedly poor performance from one type of barrier. This is accomplished by a design that includes multiple types of barriers.

7.4.3 Implementation of Multiple Barriers

The baseline design for the WIPP facility includes the concept of multiple barriers for isolation and containment of waste. Barriers that are part of the design include natural barriers (for example, hydrological, geological, and geochemical conditions) and engineered barriers (for example, borehole plugs, shaft seals, panel closures, and backfill). The effectiveness of these barriers is modeled in the performance assessment to demonstrate the ability of the disposal system to meet EPA standards.

Although the DOE plans to apply multiple engineered systems to aid in waste isolation, the EPA specified in the WIPP certification that only MgO backfill meets the regulatory definition of an engineered barrier.

Section 194.44(a) provides a criterion for certification for the analysis of the cost and benefits of various engineered barrier options. The text in the following subsections describes the DOE program that meets the engineered barrier requirements.

7.4.3.1 Engineered Alternatives Cost and Benefit Study

To fulfill the benefit and detriment evaluation criterion contained in 40 CFR § 194.44(b), the DOE published *Engineered Alternatives Cost/Benefit Study; Final Report* (DOE 1995) (see CCA Appendix EBS). The EPA's criterion for this cost and benefit study is as follows:

> In selecting any engineered barrier(s) for the disposal system, the Department shall evaluate the benefit and detriment of engineered barrier alternatives, including but not limited to: cementation, shredding, supercompaction, incineration, vitrification, improved waste canisters, grout and bentonite backfill, melting of metals, alternative configurations of waste placements in the disposal system, and alternative disposal system dimensions. The results of this evaluation shall be included in any compliance application and shall be used to justify the selection and rejection of each engineered barrier evaluated. (40 CFR § 194.44[b])

The primary purpose of this cost and benefit study was to provide the DOE with information for use in selection or rejection of additional engineered barriers that provide assurance in the performance calculations. The current facility baseline, as represented in performance assessment, provides sufficient multiple barriers to obtain compliance with the requirements of 40 CFR § 191.14(d) as described in Sections 6.4.4 (Shaft Seal Engineered Barriers), 6.4.5 (The Salado Formation Natural Barrier), and 6.5 (Performance Assessment Results).

The approach used in the study was to screen potential engineered alternatives compiled from previous studies, the ten technologies specified in 40 CFR § 194.44(b), and input elicited from stakeholders. The screening process used a working group composed of technical professionals from various related fields to compare the proposed engineered alternatives to the established definition of an engineered alternative and then to determine if those alternatives that meet the definition also meet regulatory and technological feasibility criteria. The outputs of the screening process were

- a list of engineered alternatives that did not meet the definition or screening criteria, along with the justification for their rejection, and
- a list of engineered alternatives retained for further consideration.

The screening process evaluated 111 proposed engineered alternatives and screened out all but 54 (see CCA Appendix EBS, Section 2.2.2). The 54 alternatives retained were then subjected to a DOE management-level assessment to determine the set of alternatives that would be retained for full analysis through the study. The basis for this assessment was to:

- develop a set of alternatives that address important WIPP performance issues, such as reducing the solubility of actinides in brine and improving the strength of the waste,
- analyze those alternatives that have high technical feasibility (that is, those alternatives that have been subjected to bench-scale testing at the least), and
- assess those alternatives that have a high likelihood of being permitted in a reasonable amount of time.

This assessment resulted in the selection of 18 alternatives for full analysis through the study. The screening process, including this DOE management-level assessment, was included in the scope of an independent peer review done on the study to address the requirements of 40 CFR § 194.27(a)(3). The peer review panel concluded that the entire screening process was reasonable and acceptable. Details of the peer review are found in CCA Appendix PEER (Section 3.2).

The 18 alternatives finally selected for further study consisted of nine basic alternatives and nine variations. The 18 alternatives were compared to the criteria in 40 CFR § 194.44(c):

> (i) The ability of the engineered barrier to prevent or substantially delay the movement of water or waste toward the accessible environment;

(ii) The impact on worker exposure to radiation both during and after incorporation of engineered barriers;

(iii) The increased ease or difficulty of removing the waste from the disposal system;

(iv) The increased or reduced risk of transporting the waste to the disposal system;

(v) The increased or reduced uncertainty in compliance assessment;

(vi) Public comments requesting specific engineered barriers;

(vii) The increased or reduced total system costs;

(viii) The impact, if any, on other waste disposal programs from the incorporation of engineered barriers (for example, the extent to which the incorporation of engineered barriers affects the volume of waste);

(ix) The effects on mitigating the consequences of human intrusion. (40 CFR § 194.44[c][1])

In addition to the criteria listed above, CCA Appendix EBS includes analyses that evaluated

- existing waste that is already packaged,
- existing waste that is not yet packaged,
- existing waste that is in need of repackaging, and
- to-be-generated waste.

All 18 alternatives met the intent of these criteria. This process is further described in Section 2 and Appendix O of CCA Appendix EBS. The variations originated in the screening process, details of which can be found in Sections 2.2 and 2.3.1 of CCA Appendix EBS.

For comparison, the baseline was considered to be the WIPP facility with no additional engineered barriers beyond shaft seals and panel closures. The 18 final engineered alternatives, along with a brief description of each, are listed below.

- **Supercompact Organics and Inorganics.** Solid organic and inorganic wastes are sorted to remove items that cannot be compacted. Sorted waste is precompacted in 35-gallon (132.6-liter) drums and then supercompacted. Usually, the contents of four supercompacted drums are placed in a 55-gallon (208-liter) drum. Sludges are not processed.

- **Shred and Compact Organics and Inorganics.** Solid organics and inorganics are shredded and compacted in 55-gallon (208-liter) drums using a mechanical shredder and a low-pressure compactor. Sludges are not processed.

- **Plasma Processing of All Wastes.** All wastes are processed through a mechanical shredder and the input waste stream is controlled to ensure a suitable metal to nonmetal

ratio. The waste is processed through a plasma arc centrifugal treatment system and placed into 55-gallon (208-liter) drums.

- **Sand Plus Clay Backfill.** A mixture of medium-grained sand and granulated clay is used as backfill. The mixture is placed around the waste stack and between the drums, filling the void space between drums and unmined host salt in waste emplacement panels. A fifty percent void space is assumed.

- **Salt-Aggregate (Grout) Backfill.** A salt-aggregate grout mixture is used as backfill to fill the void spaces between drums and unmined host salt in waste emplacement panels. This backfill consists of a cementitious-based, salt-aggregate grout with crushed salt aggregate and is pumped around the waste stack and between the drums filling the void spaces. A twenty percent void space is assumed.

- **Cementitious Grout Backfill.** A cementitious grout backfill consisting of ordinary Portland cement, sand, and fresh water is pumped around the waste stack and between the drums filling the void space. A twenty percent void space is assumed.

- **Supercompact Organics and Inorganics, Salt-Aggregate and Grout Backfill.** Monolayer of 2,000 drums in a room that is 6 feet (1.83 meters) high, 33 feet (10.1 meters) wide, and 300 feet (91.4 meters) long.

- **Supercompact Organics and Inorganics, Clay-Based Backfill.** Monolayer of 2,000 drums in a room that is 6 feet (1.83 meter) high, 33 feet (10.1 meter) wide, and 300 feet (91.4 meter) long.

- **Supercompact Organics and Inorganics, Sand and Clay Backfill.** Monolayer of 2,000 drums in a room that is 6 feet (1.83 meter) high, 33 feet (10.1 meter) wide, and 300 feet (91.4 meter) long.

- **Supercompact Organics and Inorganics, CaO Backfill.** Monolayer of 2,000 drums in a room that is 6 feet (1.83 meter) high, 33 feet (10.1 meter) wide, and 300 feet (91.4 meter) long.

- **Salt Backfill with CaO.** A backfill of commercially available granulated lime and crushed salt is placed around the waste stacks and between the drums filling the void space. A fifty percent void space is assumed.

- **Enhanced Cement Sludges, Shred and Add Clay-Based Materials to Organics and Inorganics, No Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly-generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums.

- **Enhanced Cement Sludges, Shred, and Add Clay-Based Materials to Organics and Inorganics, Sand and Clay Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly-generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums. A mixture of medium-grained sand and granulated clay is used as backfill. The mixture is placed around the waste stack and between the drums filling the void space between drums and unmined host salt in waste emplacement panels. A fifty percent void space is assumed.

- **Enhanced Cement Sludges, Shred, and Add Clay-Based Materials to Organics and Inorganics, Cementitious Grout Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly-generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums. A cementitious grout backfill consisting of ordinary Portland cement, sand, and fresh water is pumped around the waste stack and between the drums filling the void space. A twenty percent void space is assumed.

- **Enhanced Cement Sludges, Shred, and Add Clay-Based Materials to Organics and Inorganics, Salt Aggregate Grout Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly-generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums. A salt-aggregate grout mixture is used as backfill to fill the void spaces between drums and unmined host salt in waste emplacement panels. This backfill consists of a cementitious-based, salt-aggregate grout with crushed salt aggregate and is pumped around the waste stack and between the drums filling the void spaces. A twenty percent void space is assumed.

- **Enhanced Cement Sludges, Shred, and Add Clay-Based Materials to Organics and Inorganics, Clay-Based Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly-generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums. A

backfill consisting of commercially available pelletized clay is placed around the waste stack and between the drums, filling the void space. A fifty percent void space is assumed.

- **Enhanced Cement Sludges, Shred, and Add Clay-Based Materials to Organics and Inorganics, CaO and Salt Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums. A backfill of commercially available granulated lime and crushed salt is placed around the waste stacks and between the drums filling the void space. A fifty percent void space is assumed.

- **Clay-Based Backfill.** A backfill consisting of commercially available pelletized clay is placed around the waste stack and between the drums, filling the void space. A fifty percent void space is assumed.

The product from the evaluation of each factor evaluated was integrated into a quantifiable result called a performance vector. This vector expresses the performance of each engineered alternative relative to the baseline. The results of the factor analyses are presented in detail in CCA Appendix EBS (Section 5.4).

The Engineered Alternatives Cost/Benefit Study (CCA Appendix EBS) was useful to the DOE, as it identified engineered barriers that could be used to improve long-term repository performance. Specifically, the advantages of a backfill that chemically altered the pH of brine in the disposal room were identified in CCA Appendix EBS (Section 3.1) as providing significant benefit in reducing the quantity of mobile actinides. Alkaline earth oxides (such as calcium oxide [CaO]) are known to readily react with water to form hydroxides. These hydroxides are free to react with carbonic acid that may form in the disposal room. The reaction buffers the brines to a pH that reduces the amount of actinide in solution. After further analysis, which is documented in CCA Appendix BACK and discussed in CCA Appendix SOTERM, the DOE selected magnesium oxide (MgO) as the backfill material that provided the desired long-term benefit while minimizing the operational impacts associated with the more caustic CaO. The beneficial effects of MgO backfill are now included in the WIPP performance assessment calculation. Relevant discussions can be found in Sections 3.3.3 and 6.4.3.4. Additional related information developed since the preparation of the CCA is provided in Appendix BARRIERS.

7.4.3.2 Incorporation into Repository Design

In its guidance to implementation of the certification criteria in 40 CFR § 194.44(d), the EPA requested that the DOE describe how engineered barriers are incorporated into the repository. The purpose of this section is to identify the location of these descriptions and the location of the analysis that evaluates the performance of the engineered barriers.

Shaft seals delay the movements of radionuclides toward the accessible environment through the shafts. These shaft seals are described in detail in CCA Appendix SEAL and are summarized in Section 3.3.2. Analysis of the effectiveness of shaft seals is included in CCA Appendix SEAL (Section 8) and Section 6.4.4. Panel closures prevent the movement of radionuclides toward the accessible environment by limiting the magnitude of releases that can occur during certain human intrusion events. The design of panel closures is described in CCA Appendix PCS, summarized in Section 3.3.2, and their role in the repository model is discussed in Section 6.4.3. More recent related information is provided in Appendix BARRIERS**.** Backfill substantially delays the movement of radionuclides toward the accessible environment by limiting, through chemical means, the amount of actinides that can be dissolved in brines that enter the repository. The placement of backfill is described in Section 3.3.1, and its design and functions are described in CCA Appendix SOTERM and Appendix PA, Attachment SOTERM. Actinide mobility is discussed in Section 6.4.3. Borehole plugs are used to limit the volume of water that could be introduced to the repository from overlying water-bearing zones and to limit the volume of contaminated brine that could be released to the accessible environment. Borehole plug design is addressed in Section 3.3.4. In addition, parameter values selected to implement the various engineered components into the PA model are described in Appendix PA, Attachment PAR. Borehole plugs, as described in Section 3.3.4, are also included to mitigate the potential for contaminant migration.

The EPA concluded in its certification that the use of MgO backfill meets the regulatory intent of the engineered barriers portion of the regulation. The certification decision (EPA 1998) includes the following regarding engineered barriers:

> The EPA finds that DOE complies with Section 194.44. The EPA found that DOE conducted the requisite analysis of engineered barriers and selected an engineered barrier designed to prevent or substantially delay the movement of water or radionuclides toward the accessible environment. The DOE provided sufficient documentation to show that MgO can effectively reduce actinide solubility in the disposal system. The DOE proposed to emplace a large amount of MgO around waste drums in order to provide an additional factor of safety and thus account for uncertainties in the geochemical conditions that would affect CO_2 generation and MgO reactions (63 FR 27397).

Since the certification, the DOE has performed additional MgO-related analyses. These analyses are reported in Appendix BARRIERS.

7.5 Resource Considerations

The EPA discourages the location of repositories in areas in which valuable natural resources are present, through the assurance requirements in 40 CFR § 191.14(e). This assurance requirement states that

> Places where there has been mining for resources, or where there is a reasonable expectation of exploration for scarce or easily accessible resources, or where there is a significant concentration of any material that is not widely available from other sources, should be avoided in selecting disposal sites. Resources to be considered shall include minerals, petroleum or natural gas, valuable geologic formations, and ground waters that are either irreplaceable because there is no reasonable alternative source of drinking water available for substantial populations or that are vital to the preservation of unique and sensitive ecosystems. Such places shall not be used for disposal of the wastes covered by this part unless the favorable characteristics of such places compensate for their greater likelihood of being disturbed in the future (40 CFR § 191.14[e]).

The purpose of the requirement is to provide assurance that site selection actions further reduce the likelihood of future intrusion into the repository by giving preference to those sites without currently recognized resources.

In promulgating 40 CFR 194, the EPA provided for a clear manner in which to assess compliance with this requirement, stating that

> If performance assessments predict that the disposal system meets the containment requirements of § 191.13 of this chapter, then the Agency will assume that the requirements of this section and § 191.14(e) of this chapter have been fulfilled (40 CFR § 194.45).

Section 6.5 demonstrates compliance with 40 CFR § 191.13, including resource considerations, and hence compliance with 40 CFR § 194.14(e). The EPA further provides, in its guidance to 40 CFR Part 194, that the DOE

- document that the effects of mining and drilling over the regulatory time frame have been incorporated into performance assessments according to the requirements of § 194.32, § 194.33, and § 194.43;
- document that performance assessments incorporate the effects on the disposal system of any activities that occur in the vicinity of the disposal system or are expected to occur in the vicinity of the disposal system soon after disposal, according to the requirements of § 194.32; and
- document whether the results of performance assessments demonstrate compliance with the containment requirements of § 191.13.

The DOE has satisfied the EPA criteria concerning resource evaluation. This information is documented in Section 6.5.2. The mean CCDFs in Figure 6-36 incorporate both the effects of mining inside the controlled area (see Section 6.4.6.2.3 for a description of the mining conceptual model) and the effects of intermittent and inadvertent drilling (see Section 6.4.7 for a discussion of the drilling conceptual model). In addition, the impacts of resource development outside the controlled area were considered in the development of disposal system conceptual models.

7.5.1 Resource Considerations Prior to 40 CFR Parts 191 and 194

The WIPP site selection occurred prior to promulgation of 40 CFR Parts 191 and 194. Resource considerations were included in the site selection process for the WIPP and are documented in the WIPP FEIS (DOE 1980) and CCA Appendices GCR and IRD. The objective of the program for demonstrating compliance with the resource considerations requirement is to document the rationale used in the decision-making process.

7.5.2 Implementation of Resource Considerations

Resource considerations were included in the site selection process for the WIPP and are documented in the WIPP FEIS (DOE 1980, Section 7.3.7). The FEIS describes a four-step decision-making process that was applied to siting the repository. This process is summarized below:

- Step 1 – Bedded salt was selected as the most promising geologic medium, and geographic regions that contain extensive bedded salt formations were identified. This was accomplished by gathering and evaluating existing information concerning rock types and their geographic distribution. Desirable criteria were identified and the most favorable regions were identified.

- Step 2 – A literature review was performed to narrow the number of regions identified in Step 1. Once a region was selected, candidate sites within the region were chosen. Selection criteria were used to compare the sites. Those sites that satisfied the most criteria were selected for further evaluation. Resource-conflict considerations were applied on a broad scale at this stage of the process.

- Step 3 – The candidate sites identified in Step 2 were subjected to further investigations covering geology, hydrology, archaeology, demography, and biological resources. The results of all the site evaluations were compared, and the site that best met the selection criteria was selected for additional site characterization. At this stage, the types and quantities of natural resources present at the site were considered in detail.

- Step 4 – In this final step, a detailed system analysis was performed. This analysis addressed the specific geologic environment, the waste forms, the disposal facility design, and the potential failure modes with respect to radiation safety and environmental impact.

Based upon the above process, the DOE concluded that the favorable characteristics of the WIPP site (good hydrological characteristics, salt medium, moderate depth, salt thickness, low population density, lack of significant economic conflicts, and others) uniquely qualified it for a repository for defense waste. These characteristics also compensate for any increased likelihood of future disturbance. CCA Appendix IRD provides further analysis of compliance with the resource disincentive requirement. Section 2.3.1 provides a summary of known and inferred resources in the vicinity of the WIPP. CCA Appendix DEL contains resource-development-related information used in the conceptual model of disposal system performance.

7.6 Waste Removal

Removal of the waste any time after emplacement is possible. Because the repository was initially mined to provide access to the repository rooms, access to the waste can be accomplished using similar mining technologies. Location and removal are also possible using similar equipment modified to operate remotely. A remote retrieval demonstration was conducted at the WIPP in April 1992.

7.6.1 Requirements for Waste Removal

With the promulgation of 40 CFR Part 194, and in particular 40 CFR § 194.46, the EPA specifies the criteria for demonstrating compliance with this requirement. Specifically, the EPA mandates that “any compliance application shall include documentation which demonstrates that removal of waste is feasible for a reasonable period of time after disposal.” The EPA states that this

documentation should "include an analysis of the technological feasibility of mining the sealed disposal system, given technology levels at the time a compliance application is prepared."

In promulgating its disposal regulations, the EPA stated that "any current concept for a mined geologic repository meets this requirement without any additional procedures or design features" (EPA 1985, 50 FR 38082).

Because the WIPP facility is a mined repository, no additional actions other than documentation to meet this assurance requirement are necessary. The rationale for this assurance requirement is to preclude use of some disposal technologies that would not allow future generations to recover the wastes, should they decide to do so. According to the EPA, recovery need not be easy or inexpensive but only possible (EPA 1985). CCA Appendix WRAC describes a feasible system for waste removal using available mining technologies.

7.6.2 Implementation of Waste Removal

After determining the existing repository condition, the mining and waste removal operations will be designed to minimize the amount of contamination and exposure to allow limited human access for assessments, equipment retrieval, and repairs. Any radiological work will be performed using standard industry practices and approved procedures.

Radiological sampling activities will be planned and implemented so that recovered wastes can be handled. Packaging the removed waste and any decontamination of containers can be accomplished with standard automation techniques. Plans and procedures will ensure that the amount of additional contaminated material produced during the actual waste removal is minimized.

The removal concept is composed of the following five phases.

Phase 1 – Planning and permitting.

Phase 2 – Initial above ground setup and shaft sinking.

Phase 3 – Underground excavation and facility setup of underground ventilation, radiation control, packaging areas, decontamination areas, maintenance, remote control center, and personnel support rooms.

Phase 4 – Waste location and removal operations, including mining waste removal, packaging, package surveying and decontamination, transportation to surface, staging for off-site transportation, and off-site transportation.

Phase 5 – Closure and D&D of the facility.

Each of the five phases is summarized below and described in detail in CCA Appendix WRAC (Section 5).

7.6.2.1 Planning and Permitting

A decision to remove waste will initiate the planning and permitting phase. Permitting requirements will be based on governing regulations at the time removal is authorized. The planning and permitting program will identify all permits and research the available technologies at that time to determine available removal techniques and the condition of the repository. After initial research is completed, a plan will be drafted to itemize and schedule all removal activities.

7.6.2.2 Initial Above Ground Setup and Shaft Sinking

Above ground support buildings will house the exhaust fans and filters, administration, operations and maintenance facilities, control center waste staging and decontamination areas, the warehouse (containers), and others, as deemed necessary.

7.6.2.3 Underground Excavation and Facility Setup

After the shafts are completed, drifts will be run and ventilation paths will be established using air control regulators. Support rooms will be excavated for maintenance, control rooms, and packaging areas. Air locks will be constructed to provide the necessary level of control and separation. All equipment required for removal, packaging, and related support equipment will be installed.

Excavation will be in two stages. Initial excavation will not contact waste, but will mine support rooms and haulage drifts that provide ventilation and access to the waste. The second stage will remove the waste.

7.6.2.4 Waste Location and Removal Operations

The waste removal will be performed in separate operations. The waste will be removed by mining the area where the waste was emplaced. The mined waste will be transported to the packaging areas. The waste can be removed many ways using standard equipment. CCA Appendix WRAC (Sections 6 and 7) contains a brief description and feasibility of using various mining techniques for waste removal. An appropriate level of radiological controls will be used, depending upon the radioactivity of the mined waste.

7.6.2.5 Closure and D&D of the Facility

After waste is removed from the repository, the facility will be decommissioned according to the current regulations at that time.

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8.0 INDIVIDUAL AND GROUNDWATER PROTECTION REQUIREMENTS

The quantitative release limits set forth in the Containment Requirements provisions of Title 40 of the Code of Federal Regulations (CFR) § 191.13 are one of three long-term numerical performance requirements contained in 40 CFR Part 191 Subparts B and C. The Waste Isolation Pilot Plant (WIPP) must also comply with two other numerical performance standards that are contained in the individual (40 CFR § 191.15) and groundwater (40 CFR Part 191, Subpart C) protection requirements. This section describes the U.S. Department of Energy's (DOE's) demonstration of compliance for the WIPP with both the individual and groundwater protection requirements.

In performing the compliance assessment for the CCA, the DOE applied a bounding-analysis approach using unrealistic assumptions that resulted in an overestimation of potential doses and contaminant concentrations. To provide added assurance, the DOE assumed the presence of an underground source of drinking water (USDW) in close proximity to the WIPP Land Withdrawal Area boundary, even though available data indicate that none exists near the boundary. Using this very conservative approach, the calculated maximum potential dose to an individual was found for the CCA evaluation to be about one-sixteenth of the individual protection standard. Concentrations of contamination in the hypothetical USDW would be less than half of the U.S. Environmental Protection Agency (EPA) groundwater protection limits and potential doses to a receptor who drinks from the hypothetical USDW would be an order of magnitude less.

This conservative approach also assumes that all contaminants reaching the accessible environment are directly available to a receptor. The analysis bounds any potential impacts of underground interconnections among bodies of surface water, groundwater, and any USDW.

In support of its recertification effort, the DOE has reexamined concentrations of radionuclides that could potentially reach the accessible environment under undisturbed conditions. This evaluation shows that the maximum concentration of radionuclides reaching the boundary is now projected to be six orders of magnitude less than the maximum concentration projected in the CCA. Based on this and additional updated information presented in the remainder of this chapter, the DOE concludes that the project continues to comply with the individual and groundwater protection provisions of Part 191, Subparts B and C. (See Table 1-1 in Chapter 1.0 for a list of appendices that provide additional information supporting this chapter.)

8.1 Individual Protection Requirements

The individual protection requirements are contained in 40 CFR § 191.15 of the long-term disposal regulations. 40 CFR § 191.15(a) requires that

> Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual committed effective dose, received through all potential pathways from the disposal system to any member of the public in the accessible environment, to exceed 15 millirems (150 microsieverts).

Undisturbed performance (UP) is defined in Subpart B of 40 CFR Part 191 to mean "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted

behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events" (40 CFR § 191.12). Section 6.3.1 provides a description of UP, the conceptual models associated with UP, and the screening of features, events, and processes (FEPs) that are important to UP.

The method used to evaluate compliance with the individual protection requirements is related to that developed for assessing compliance with the containment requirements. If the evaluation of the UP scenario considered for the containment requirements shows contaminants will reach the accessible environment, the resulting dose to exposed individuals must be calculated and compared to the 15-millirem annual committed effective dose specified in 40 CFR § 191.15.

Further guidance on the implementation of the individual protection requirements is found in 40 CFR Part 194. 40 CFR § 194.51 states that

> Compliance assessments that analyze compliance with § 191.15 of this chapter shall assume that an individual resides at the single geographic point on the surface of the accessible environment where that individual would be expected to receive the highest dose from radionuclide releases from the disposal system.

40 CFR § 194.52 states that

> In compliance assessment that analyze compliance with § 191.15 of this chapter, all potential exposure pathways from the disposal system to individuals shall be considered. Compliance assessments with part 191, subpart C and § 191.15 of this chapter shall assume that individuals consume 2 liters per day of drinking water from any underground sources of drinking water in the accessible environment.

In addition, 40 CFR § 194.25(a) provides criteria related to the assumptions that should be made when undertaking dose calculations:

> Unless otherwise specified in this part or in the disposal regulations, performance assessments and compliance assessments conducted pursuant to the provisions of this part to demonstrate compliance with § 191.13, § 191.15 and part 191, subpart C shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions.

8.1.1 Compliance Assessment of Undisturbed Performance

40 CFR § 194.52 specifies that compliance assessments consider "all potential pathways from the disposal system to individuals." The DOE has considered the following potential pathways for groundwater flow and radionuclide transport:

- existing boreholes, as required by 40 CFR § 194.55(b)(1); and
- potential boreholes, including those that may be used for fluid injection as required, by 40 CFR § 194.32(c) and 40 CFR § 194.54(b)(2).

After considering all of these *pathways***,** the DOE found that contaminated brine may migrate away from the waste-disposal panels if pressure within the panels is elevated by gas generated from corrosion or microbial degradation. Two credible pathways by which radionuclides could reach the accessible environment have been identified.

1. Radionuclide transport may occur laterally, through the anhydrite interbeds toward the subsurface boundary of the accessible environment in the Salado Formation.

2. Transport may occur through access drifts or anhydrite interbeds (primarily Marker Bed [MB] 139) to the base of the shafts. In this case, if the pressure gradient between the panels and overlying strata is sufficient, contaminated brine may migrate up the shafts. As a result, radionuclides may be transported directly to the ground surface, or laterally away from the shafts, through permeable strata such as the Culebra, toward the subsurface boundary of the accessible environment.

These conceptual release pathways for UP are illustrated in Figure 6-9. The modeling system described in Section 6.4 does not preclude potential radionuclide transport along other pathways, such as migration through Salado halite. However, the natural properties of the undisturbed system make radionuclide transport to the accessible environment via these other pathways unlikely.

Although both pathways are possible, the performance assessment (PA) modeling indicates that under undisturbed conditions, only the first is a potential pathway during the 10,000-year period of interest specified in the regulation (see Appendix PA, Section PA-7.2).

The DOE has used the modeling system applied to the PA, as described in Chapter 6.0, to make this determination. Scenario screening for the UP is described in Appendix PA, Attachment SCR. As specified by 40 CFR § 194.54(b)(2), Appendix PA, Attachment SCR identifies activities that may occur in the vicinity of the disposal system prior to or soon after disposal and documents which of these are included in the compliance assessment calculations. Table 6-8 in Section 6.2 identifies FEPs included in the UP modeling. Appendix PA, Attachment SCR also identifies FEPs that were considered, but are not included, in the modeling evaluation and the reasons for their elimination.

As specified by 40 CFR § 194.55(a), uncertainty in the performance of the compliance assessment is documented in Section 6.1.2. Probability distributions for uncertain disposal system parameter values used in the compliance assessment were developed and are documented in Appendix PA, Attachment PAR. Section 8.1.5 identifies sampled parameters used in the compliance assessment.

For both the CCA compliance assessment and the CRA compliance assessment, 300 realizations of the modeling system were generated to evaluate UP. These 300 realizations are composed of three sets of 100 realizations each generated using the Latin hypercube sampling (LHS) method. In both the CCA and CRA evaluations, none of the 300 realizations show any radionuclides reaching the top of the Salado through the sealed shafts.

In the CCA evaluation, nine of the 300 realizations show concentrations of radionuclides greater than zero reaching the accessible environment through the anhydrite interbeds. None of the remaining 291 realizations show radionuclides reaching the accessible environment through the anhydrite interbeds during 10,000 years. Table 8-1 shows the maximum concentrations of radionuclides calculated by the modeling evaluation as reaching the accessible environment in the nine nonzero CCA realizations. The full range of estimated values for radionuclide

concentrations for the CCA evaluation is from zero to the values shown in Table 8-1. The maximum concentration values shown in Table 8-1 occur 10,000 years after the time of decommissioning.

Table 8-1. Maximum Concentrations of Radionuclides Within the Salado Interbeds at the Disposal System Boundary for the CCA Analysis

CCA Realization No.	Maximum Concentrations (curies/liter)					
	Vector No.[1]	^{241}Am	^{239}Pu	^{238}Pu	^{234}U	^{230}Th
1	Replicate 1 Vector 46	1.36×10^{-17}	4.33×10^{-12}	Negligible[2]	5.82×10^{-13}	2.10×10^{-14}
2	Replicate 2 Vector 16	Negligible	5.13×10^{-14}	Negligible	6.77×10^{-15}	1.89×10^{-17}
3	Replicate 2 Vector 25	Negligible	1.35×10^{-15}	Negligible	1.65×10^{-16}	7.00×10^{-18}
4	Replicate 2 Vector 33	1.32×10^{-17}	7.18×10^{-14}	Negligible	9.76×10^{-15}	9.36×10^{-16}
5	Replicate 2 Vector 81	Negligible	6.23×10^{-18}	Negligible	Negligible	Negligible
6	Replicate 2 Vector 90	Negligible	5.20×10^{-16}	Negligible	7.40×10^{-17}	Negligible
7	Replicate 3 Vector 3	3.50×10^{-18}	3.08×10^{-13}	Negligible	4.32×10^{-14}	1.07×10^{-16}
8	Replicate 3 Vector 60	5.98×10^{-17}	7.41×10^{-14}	Negligible	9.09×10^{-15}	2.30×10^{-15}
9	Replicate 3 Vector 64	5.42×10^{-17}	5.85×10^{-12}	Negligible	7.61×10^{-13}	4.68×10^{-15}
10-300		Negligible	Negligible	Negligible	Negligible	Negligible

[1] Parameter values applied to each vector may be found in CCA (Appendix IRES, Tables IRES-2, IRES-3, and IRES-4).
[2] Values less than 10^{-18} curies per liter are considered negligible relative to the other values and are not reported.

The maximum concentrations of radionuclides calculated by the CRA evaluation to reach the accessible environment are shown in Table 8-2. In the CRA evaluation, only one of the 300 realizations shows concentrations of radionuclides greater than zero reaching the accessible environment through the anhydrite interbeds (see Appendix PA, Section PA-7.2). The remaining 299 realizations show no radionuclides reaching the accessible environment during the 10,000-year period. The reduction in the number of realizations showing radionuclides reaching the accessible environment is due to changes in the BRAGFLO grid and enhancements to the PA modeling system that have increased model accuracy and decreased numerical dispersion.

Table 8-2. Maximum Concentrations of Radionuclides Within the Salado Interbeds at the Disposal System Boundary for the CRA Analysis

CRA Realization No.	Vector No.[1]	Maximum Concentrations (curies/liter)				
		^{241}Am	^{239}Pu	^{238}Pu	^{234}U	^{230}Th
1	Replicate 1 Vector 82	Negligible	2.53×10^{-18}	Negligible	Negligible	Negligible
2-300	—	Negligible	Negligible	Negligible	Negligible	Negligible

[1] Parameter values applied to each vector may be found in Appendix PA, Attachment PAR.
[2] Values less than 10^{-18} curies per liter are considered negligible relative to the other values and are not reported.

In this single CRA realization, only one radionuclide has a non-zero concentration reaching the accessible environment. The radionuclide plutonium-239 (^{239}Pu) has a concentration of 2.53×10^{-18} curies per liter (Garner 2003). This compares with the maximum concentration of ^{239}Pu calculated for the CCA evaluation of 5.85×10^{-12} curies per liter. The concentration of ^{239}Pu in the CRA evaluation is six orders of magnitude lower than that shown for the CCA evaluation. In the CRA evaluation, no other radionuclides are calculated in concentrations greater than the 10^{-18} cut-off, where americium-241 (^{241}Am), uranium-234 (^{234}U), and thorium-230 (^{230}Th) all had concentrations exceeding the cut-off in the CCA. Since the CRA evaluation shows only one radionuclide contributing to a potential dose, and the concentration is six orders of magnitude lower than that shown for the CCA evaluation, the CCA dose estimates are bounding. No new dose calculations are necessary.

8.1.2 Dose Calculation

As quoted earlier, 40 CFR Part 194 states that doses must be estimated for an individual who resides at the location in the accessible environment where that individual would be expected to receive the highest exposure to radionuclide releases from the disposal system (40 CFR § 194.51). All potential pathways for exposure associated with the UP of the repository must be assessed (40 CFR § 194.52).

8.1.2.1 Transport Pathway

To perform the required dose calculation, it is necessary to specify possible pathways for the transport of the contaminants from the anhydrite interbeds to a receptor. The specified pathway is an abandoned, deep borehole that intersects the contaminant plume in the accessible environment. Consistent with assumptions described in Section 6.4.7.2 and the information provided in CCA Appendix DEL, the hole is assumed to have the permeability of an uncased hole filled with silty sand after the degradation of a borehole plug in the Rustler Formation. A pressure gradient is assumed to exist because of the pressures in the anhydrite resulting from gas generation in the repository. The pressures are assumed to be sufficient to force contaminants up the abandoned hole to the Culebra Formation or the Dewey Lake Formation. The contaminants would then be available to a receptor through a well used to supply drinking water. This conceptual transport pathway is shown in Figure 8-1. This is the only credible pathway that the DOE has been able to identify. As such, no inhalation or direct radiation exposures are anticipated.

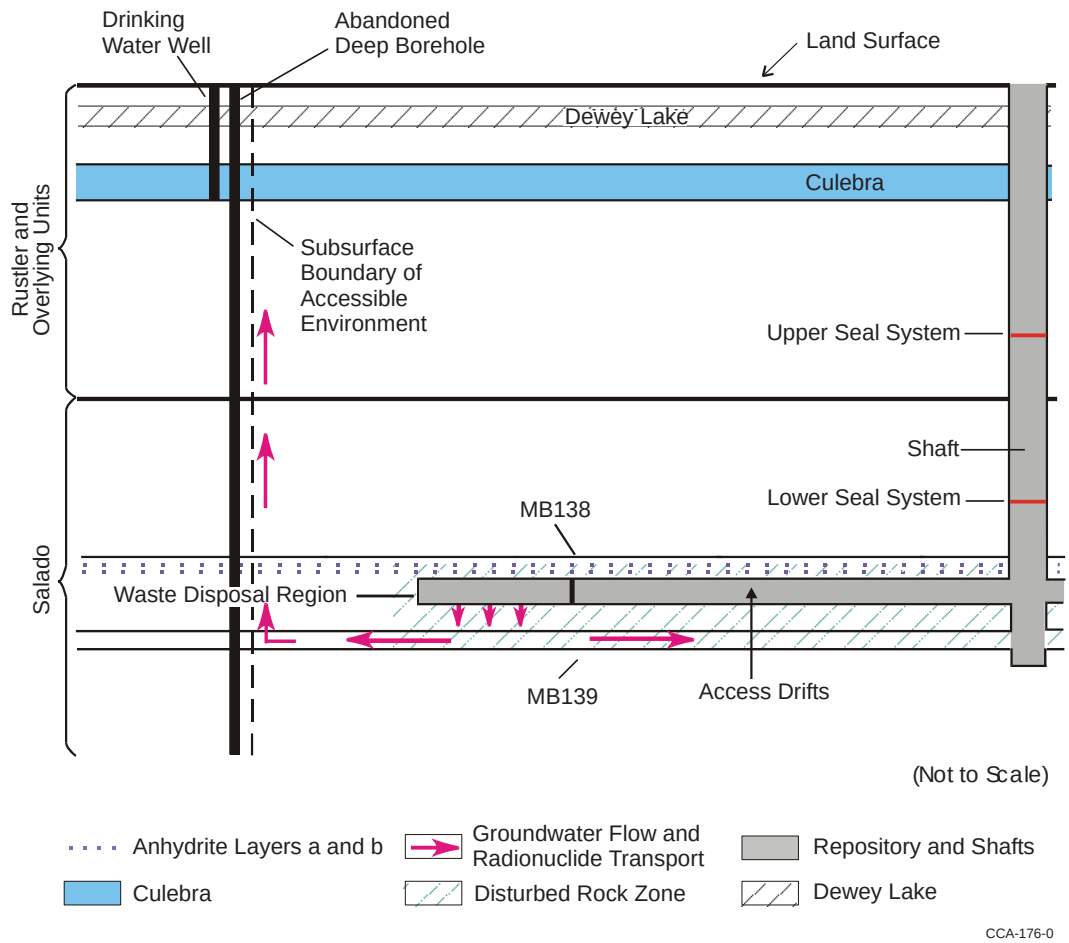

Figure 8-1. Conceptual Transport Pathway

As specified in 40 CFR § 194.54(b), this pathway considers the presence of an existing borehole. As discussed in Section 6.2.5, the influence of other existing boreholes has been evaluated in the FEPs screening for UP.

8.1.2.2 Bounding Analysis

Uncertainty in the calculation of radionuclide concentrations in the anhydrite interbeds is described in Section 6.1.2. Additional uncertainty is involved in the calculation of doses resulting from the specified exposure pathway. Given this uncertainty, the DOE elected for the CCA evaluation to perform a bounding analysis using assumptions that do not represent reality, but that would result instead in a bounding estimate much greater than any reasonably expected dose to a receptor. If this unrealistic, yet bounding, analysis results in calculated doses to the receptor that are below the regulatory limit, compliance with the standard is demonstrated. If subsequent analyses, such as those performed to support this application, have lower initial concentrations than the bounding CCA analysis, recalculation of the doses is unnecessary because the original bounding analysis is conservative and shows results below regulatory limits.

The bounding analysis used for the CCA assessment was based on the following factors and assumptions.

1. No specific transport mechanism was postulated. Instead, all of the contaminants reaching the accessible environment within the anhydrite interbeds during the year of maximum releases (that is, year 10,000) were assumed to be available to a receptor.

2. Brine derived from the anhydrite interbeds had total dissolved solids (TDS) concentrations of about 324,000 parts per million; this represents a concentration that could not be consumed by humans. For the bounding analysis, the calculation includes the dilution of this brine by a factor of 32.4 to a TDS concentration of 10,000 parts per million, which is the upper limit for potable water.

3. The resulting annual committed effective dose was calculated based on a 50-year dose commitment. A 50-year dose commitment was selected because this period is specified in Appendix B of 40 CFR Part 191 and because it is the duration for which published external dose-rate conversion factors are readily available in the literature (DOE 1988).

4. The individual receptor was assumed to drink two liters of water each day (as specified in 40 CFR § 194.52) for one year (in accordance with the specification of an annual committed effective dose in Appendix B of 40 CFR Part 191).

40 CFR § 194.51 states that DOE shall assume an individual resides at the single geographic point where that individual would receive the highest dose. With the bounding analysis, the DOE complies with the intent of this criterion but the specific location of the receptor is not identified, because all of the contaminants reaching the accessible environment within the anhydrite interbeds during the year of maximum releases are assumed to be directly available to the receptor, regardless of the receptor's location. The well from which the receptor drinks is assumed to be located where the contaminants reaching the anhydrite interbeds are delivered directly to the well.

The bounding analysis dose calculation was performed using the GENII-A code. CCA Appendix GENII describes the modeling method. GENII-A incorporates dose-calculation guidance provided in Appendix B of 40 CFR Part 191.

8.1.3 Dose Calculation Results

The maximum doses calculated from the releases listed in Table 8-1, after applying the factors and assumptions listed above, are shown in Table 8-3. These doses are greater than any realistic doses that could be delivered to a receptor. The calculated doses are well below the regulatory standard, which is an annual committed effective dose of 15 millirems.

Table 8-3. Calculated Maximum Annual Committed Effective Doses for the CCA Evaluation

Realization No.	Vector No.[1]	Maximum Annual Committed Effective Dose (millirems)
1	Replicate 1 Vector 46	3.4×10^{-1}
2	Replicate 2 Vector 16	4.3×10^{-3}
3	Replicate 2 Vector 25	1.1×10^{-4}
4	Replicate 2 Vector 33	5.8×10^{-3}
5	Replicate 2 Vector 81	5.1×10^{-7}
6	Replicate 2 Vector 90	4.3×10^{-5}
7	Replicate 3 Vector 3	2.5×10^{-2}
8	Replicate 3 Vector 60	6.2×10^{-3}
9	Replicate 3 Vector 64	4.7×10^{-1}
10-300	—	Negligible[2]

[1] Parameter values applied to each vector may be found in CCA Appendix IRES, Tables IRES-2, IRES-3, and IRES-4.
[2] Doses derived from Table 8-1 concentration values of less than 10^{-18} curies per liter are considered negligible and are not reported.

On February 26, 1997, DOE submitted supplementary information to EPA in response to an EPA request for additional information (Docket A-93-02, Item II-I-10, Enclosure 2h). The supplementary information describes how DOE extended its initial bounding analysis to account for exposure pathways besides direct ingestion of contaminated water by humans. Specifically, the analysis was expanded to include consumption of contaminated water by cattle (leading to the receptor's consumption of contaminated milk and beef), consumption of crops irrigated with contaminated water, and inhalation of airborne dust from soil contaminated by irrigation. DOE found that the contribution of these pathways added 0.46 millirem per year to the calculated dose associated with the realization showing the highest concentration of radionuclides reaching the boundary of the accessible environment under undisturbed conditions. The maximum total dose calculated from all pathways was 0.93 millirem per year, well below the 15-millirem-per-year regulatory standard.

Given that the maximum concentration of radionuclides shown to reach the accessible environment for the CRA analysis is six orders of magnitude less than the maximum value calculated for the CCA evaluation, resulting potential doses to the receptor would also be well below the 15-millirem standard. As such, the CCA dose calculation bounds any possible dose to a receptor for the CRA evaluation and new dose calculations are not needed to demonstrate

compliance. The CCA results are bounding, and continued compliance with the individual protection standard is demonstrated.

8.1.4 Statistical Assessment

EPA criterion 40 CFR § 194.55(d) specifies that the "number of estimates generated pursuant to paragraph (c) of this section shall be large enough such that the maximum estimates of doses and concentrations generated exceed the 99th percentile of the population of estimates with at least a 0.95 probability." The probability that an individual estimate is below the 99th percentile is, by definition, 0.99. This means that only 1 in 100 estimates would have a value exceeding the 99th percentile, or conversely, 99 times out of 100, the estimate would have a value below the 99th percentile. It follows that for two independent events, the probability of both estimates having a value below the 99th percentile is equal to the product (0.99)(0.99), or $(0.99)^2$, and that for n events, the probability that all estimates have a value below the 99th percentile is equal to $(0.99)^n$. To ensure a value exceeds the 99th percentile with a specified probability, the complement $(1 – 0.99^n)$ is used to calculate the number of estimates required.

The probability specified by 40 CFR § 194.55(d) is 0.95, or 95-percent confidence, that the maximum estimates of doses and concentrations generated exceed the 99th percentile of the population of estimates. Therefore, the following equation can be solved for n, and the number of estimates required is

$$1 – 0.99^n = 0.95 \text{ or } n\log(0.99) = \log(0.05), \qquad (8.1)$$

which implies $n > 298$.

The solution requires n to be greater than 298 and was used to determine that 300 realizations of the modeling system is a sufficient number to meet the confidence level specified in 40 CFR § 194.55(d).

The 300 realizations of the modeling system (as described in Section 8.1.1) report concentrations of radionuclides reaching the accessible environment within the Salado anhydrite interbeds and not doses to a receptor, as specified by 40 CFR § 194.55(d). Nevertheless, the maximum possible resulting dose to an individual is 0.93 millirems, the sum of 0.47 millirems, as reported in Table 8-3, plus the additional value of 0.46 millirems, determined to be contributed through additional dose pathways. All other potential doses resulting from the 300 realizations of the modeling system for both the CCA and CRA evaluations are below this value.

EPA criterion 40 CFR § 194.55(f) specifies that DOE shall

> document that there is at least a 95 percent level of statistical confidence that the mean and the median of the range of estimated radiation doses and the range of estimated radionuclide concentrations meet the requirements of § 191.15 and part 191, subpart C of this chapter, respectively.

Because the DOE has developed a bounding analysis, it is not meaningful to calculate and present mean and median dose values. Instead, the bounding analysis provides 100 percent confidence that all potential doses will be below the 0.93 millirem value.

8.1.5 Parameter Values

Parameter values applied to the CCA modeling assessment for UP are described in CCA Appendix PAR and Section 8.1.5. Parameters used in the PA and compliance assessment modeling program for the CRA are described in Appendix PA, Attachment PAR. As provided by 40 CFR § 194.55(b), Appendix PA, Attachment PAR also identifies the probability distributions for these parameters, their units, the models and codes in which the parameters are used, the functional form of the probability distributions used for the sampled parameters, and associated input data.

8.1.6 Summary of Compliance with the Individual Protection Standard

In performing the compliance assessment, DOE applied a bounding-analysis approach using unrealistic assumptions that over-estimate potential doses and contaminant concentrations. This conservative approach assumes that all contaminants reaching the accessible environment are directly available to a receptor. Using this very conservative approach, the calculated maximum potential dose to an individual from the CCA evaluation would be about one-sixteenth of the individual protection standard. Given that modeled maximum radionuclide concentrations in the accessible environment for the CRA evaluation are well below those of the CCA evaluation, the CCA results are bounding and continued compliance with the individual protection standard is demonstrated.

8.2 Groundwater Protection Requirements

The groundwater protection requirements are contained in Subpart C of 40 CFR Part 191. In particular, 40 CFR § 191.24(a)(1) requires that

> *General*. Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that 10,000 years of undisturbed performance after disposal shall not cause the levels of radioactivity in any underground source of drinking water, in the accessible environment, to exceed the limits specified in 40 CFR Part 141 as they exist on January 19, 1994.

EPA rule 40 CFR Part 141 specifies the National Primary Drinking Water Standards. The levels of radioactivity (and dose equivalent in the case of 40 CFR § 141.16[a]) specified in 40 CFR Part 141, as of January 19, 1994 were:

1. Combined ^{226}Ra and ^{228}Ra(40 CFR § 141.15[a]): 5 picocuries per liter;

2. Gross alpha particle activity, including ^{226}Ra but excluding radon and uranium (40 CFR § 141.15[b]): 15 picocuries per liter;

3. Annual dose equivalent to the total body or any internal organ from the average annual concentration of beta particle and photon radioactivity from man-made radionuclides (40 CFR § 141.16[a]): 4 millirem per year.

In addition, Section 194.53 applies to DOE's consideration of USDWs. The criterion specifies that

> In compliance assessments that analyze compliance with part 191, subpart C of this chapter, all underground sources of drinking water in the accessible environment that are expected to be affected by the disposal system over the regulatory time frame shall be considered. In determining whether underground sources of drinking water are expected to be affected by the disposal system, underground interconnections among bodies of surface water, groundwater, and underground sources of drinking water shall be considered.

To assess compliance with these provisions of the regulations, it is first necessary to identify any USDW that may be located near the WIPP. DOE's evaluation of whether any USDW is located near the WIPP is provided as CCA Appendix USDW and is summarized in Section 8.2.2. In developing the CRA, DOE reevaluated the presence of USDWs near the WIPP and supplemented the information presented in CCA Appendix USDW. The supplemental information is also provided in Section 8.2.2. Based on this review, DOE believes that no deviation from the findings and conclusions of the 1996 evaluation is warranted.

8.2.1 Criteria for USDW Determination

In evaluating the presence of any USDW, it is necessary to establish criteria to apply to water quality and quantity data from wells in the vicinity of the WIPP. The criteria must be based on the regulatory definition of a USDW, as provided in 40 CFR § 191.22. A USDW is defined in 40 CFR § 191.22 to mean an aquifer or its portion that

> (1) Supplies any public water system; or
>
> (2) Contains a sufficient quantity of groundwater to supply a public water system; and
>
> (I) Currently supplies drinking water for human consumption; or
>
> (ii) Contains fewer than 10,000 milligrams of total dissolved solids per liter.
>
> "Public water system" means a system for the provision to the public of piped water for human consumption, if such system has at least fifteen service connections or regularly serves at least twenty-five individuals. Such term includes:
>
> (1) Any collection, treatment, storage, and distribution facilities under control of the operator of such system and used primarily in connection with such system; and
>
> (2) Any collection or pretreatment storage facilities not under such control which are used primarily in connection with such system.
>
> "Total dissolved solids" means the total dissolved (filterable) solids in water as determined by use of the method specified in 40 CFR Part 136.

Criteria based on these definitions were developed by the DOE and are used to assess the presence of any USDW near the WIPP. These criteria are defined in the following subsections.

8.2.1.1 Groundwater Quantity

Two subcriteria have been identified by the DOE and applied to the groundwater quantity definition:

1. An aquifer or its portion must be capable of producing water at an adequate rate, and

2. An aquifer or its portion must be capable of producing water for a sufficient duration.

Water-consumption information was evaluated by the DOE to define the first subcriterion (the ability to produce at an adequate rate). The value to be applied is determined by obtaining the following information.

1. The rate, over a 24-hour period, at which water is consumed by 15 service connections.

2. The rate, over a 24-hour period, at which water is consumed by 25 individuals.

To conservatively define a USDW, the lower of these two values is assigned by the DOE to the first subcriterion. Based on calculations presented in CCA Appendix USDW and updated in support of the CRA, a quantity of five gallons per minute is assigned as the first subcriterion. Details on the derivation of the five-gallon-per-minute value are provided below.

For the CCA evaluation, the rate of consumption by 15 service connections was calculated using the data provided in Table 8-4. These are 1990 U.S. Bureau of the Census data for the number of persons per household in southeastern New Mexico communities and water-consumption data for the same communities. The water-consumption data were obtained from the New Mexico State Engineer's Office (Wilson 1992).

Table 8-4. Persons Per Household and Water Consumption Values Used in the CCA

Community	Persons Per Household, 1990	Gallons Per Capita Per Day
Artesia	2.69	285
Carlsbad	2.63	307
Hobbs	2.81	267
Lovington	2.96	264
Roswell	2.66	285
Average	2.75	282

Sources: U.S. Bureau of the Census (1990); Wilson (1992).

As reported in Wilson (1992), the average water usage in these communities was 282 gallons per person per day. The 1990 census statistics for these communities show an average of 2.75 people per household. One household equals one service connection.

Therefore:

2.75 people × 282 gallons per person per day = 775.5 gallons per service connection per day,

775.5 gallons per day per service connection × 15 connections = 11,633 gallons per day, and

11,633 gallons per day/1,440 minutes per day = 8.08 gallons per minute.

The rate of consumption by 15 service connections, based on the 1990 and 1992 statistics, is calculated to be 8.08 gallons per minute.

The rate over a 24-hour period at which water would be consumed by 25 individuals may be calculated using these same data. The average water usage was 282 gallons per person per day in area communities. The consumption of water by 25 people equals:

282 gallons per person per day × 25 people = 7050 gallons per day, and

7050 gallons per day/1,440 minutes per day = 4.89 gallons per minute.

Based on these two calculations, the quantity consumed by 25 individuals (4.89 gallons per minute; nominally 5 gallons per minute) is smaller than the quantity consumed by 15 service connections (8.08 gallons per minute). To conservatively determine the quantity derived from a well that meets this DOE quantity criterion, the five-gallons-per-minute value was applied to the CCA evaluations.

In updating this calculation for the CRA, more current census data and water consumption data were obtained. These more current data are provided in Table 8-5. The updated calculations are provided below.

Table 8-5. Persons Per Household and Water Consumption Values Used in the CRA

Community	Persons Per Household, 2000[1]	Gallons Per Capita Per Day, 2000[2]
Artesia	2.61	390
Carlsbad	2.51	277
Hobbs	2.72	284
Lovington	2.80	289
Roswell	2.58	283
Average	2.64	305

Sources: 1. U.S. Bureau of the Census (2000); 2. New Mexico Office of the State Engineer (2002).

The average water usage in these communities is 305 gallons per person per day. The 2000 census statistics for these communities show an average of 2.64 people per household. One household equals one service connection.

Therefore:

2.64 people × 305 gallons per person per day = 805.2 gallons per service connection per day,

805.2 gallons per day per service connection × 15 connections = 12,078 gallons per day, and

12,078 gallons per day/1,440 minutes per day = 8.39 gallons per minute.

Using updated data, the rate of consumption by 15 service connections is calculated to be 8.39 gallons per minute.

The rate over a 24-hour period at which water would be consumed by 25 individuals may be calculated using these same data. The current average water usage is 305 gallons per person per day in area communities. The consumption of water by 25 people equals:

305 gallons per person per day × 25 people = 7625 gallons per day, and

7625 gallons per day/1,440 minutes per day = 5.30 gallons per minute.

Based on these two calculations, the quantity consumed by 25 individuals (5.30 gallons per minute; nominally 5 gallons per minute) is smaller than the quantity consumed by 15 service connections (8.39 gallons per minute). To conservatively determine the quantity derived from a well that meets the quantity subcriterion, the five-gallons-per-minute value is applied. No change in this subcriterion is warranted as a result of applying current census and water consumption data to the calculation.

The definition of the second quantity subcriterion (the acceptable production duration from a well) is more subjective. Because the creation of a public water supply system involves considerable capital expense, it is reasonable to assume that such a water system would not be constructed unless the water source would continue to be available for some time, at least long enough to recover the capital expense. The Rural Utility Service of the U.S. Department of Agriculture provides loans for funding new rural water supply systems. The loan periods are generally 40 years in duration. Based on this, a duration of 40 years is applied by the DOE to the second quantity subcriterion.

8.2.1.2 Groundwater Quality

A criterion of 10,000 mg/L of TDS is specified in 40 CFR § 191.22. Any aquifer or its portion producing water having TDS concentrations below this level is determined to produce water that meets the quality criterion for a USDW. Any aquifer or its portion producing water TDS concentrations at or above this level is determined to produce water that does not meet the quality criterion and the regulatory definition of a USDW.

8.2.2 Comparison with Underground Source of Drinking Water Determination Criteria

For the CCA evaluation, current conditions and available hydrogeologic data were reviewed by the DOE to assess the presence of USDWs near the WIPP. This assessment compares current conditions and available data to the groundwater quantity and quality criteria described above. The results of this comparison are summarized below and provided in detail in CCA Appendix USDW. In addition, relevant updated information is provided here to support the CRA.

Five geologic units within the vicinity of the WIPP could potentially meet the definition of a USDW under Subpart C of 40 CFR Part 191. These include:

1. the Capitan Aquifer of the Guadalupian reef complex,
2. the Culebra,
3. the Magenta Dolomite Member of the Rustler Formation,

4. the Dewey Lake, and

5. the Santa Rosa Sandstone of the Dockum Group.

Investigations conducted in the vicinity of the WIPP to characterize the hydrology of these formations are described in CCA Appendix USDW. Important sources of relevant information are identified and findings or conclusions related to the presence of USDWs are provided. Based on this work and the recent update performed to support the CRA, the DOE has concluded that USDWs are present in the Culebra, and, because of inconclusive groundwater production data, possible USDWs are present in the Dewey Lake and the Santa Rosa. USDWs in the Culebra are located at WIPP water quality sampling program (WQSP) wells H-07b1, H-08b, and H-09b about 4.8, 14.5, and 10.5 km (3, 9, and 6.5 mi) to the south/southwest of the controlled area boundary, respectively. Possible USDWs may occur in the Dewey Lake, about 1.6 km (1 mi) south of the controlled area boundary, and the Santa Rosa, 12.4 to 14.5 km (7.7 to 9 mi) to the east of the controlled area boundary, where private wells (used predominantly for supplying water to livestock) have not generated available groundwater production data to assess their potential to yield a sufficient quantity to meet 40 CFR § 191.22 requirements. In the absence of such data, and to be conservative, these wells are designated as being located in possible USDWs.

In reevaluating the conclusions presented in CCA Appendix USDW, DOE reviewed available groundwater quality and quantity data for the wells identified in the appendix to determine if any data collected since 1996 are available. No new TDS or groundwater quantity data were obtained by WIPP WQSP personnel after 1996. The WQSP is a detection monitoring program operated under the provisions of the WIPP Hazardous Waste Facility Permit. Data for a variety of parameters are collected through the WIPP WQSP, but not TDS concentrations or water quantity data.

In addition, a review was performed to determine if any wells not reported in CCA Appendix USDW were drilled that may provide groundwater quality (i.e., TDS concentrations) and groundwater quantity data. One new well, identified as well C-2737, was developed at the WIPP site. This well was drilled during February and March of 2001 to replace well H-1, which was plugged and abandoned. In February of 2001, a water sample from the upper Dewey Lake Formation was obtained from this well. Laboratory analysis of this sample showed a TDS concentration of 2,590 ppm (Powers 2002).

Additional wells were installed across the WIPP site to investigate the extent of groundwater at the contact of the Santa Rosa and Dewey Lake Formations. Four monitoring wells and 12 piezometer wells were emplaced. The results of multiple rounds of sampling and analyses from these holes are reported in DES (1997). Samples from several of these holes show TDS concentrations both below and above 10,000 ppm, although it was not possible to pump water from any of these holes at rates of five gallons per minute or more.

In addition, State of New Mexico records indicate that several new wells were drilled in the southwestern portion of the study area evaluated in CCA Appendix USDW. These records, however, include no TDS or production data.

Based on this review, no modification of the USDW determinations reported in CCA Appendix USDW is warranted. The DOE continues to conclude that USDWs are present in the Culebra, and, because of inconclusive groundwater production data, possible USDWs are present in the Dewey Lake and the Santa Rosa Formations.

During its review of the CCA, EPA requested that DOE provide a map or maps showing the location of USDWs. The DOE responded to this request with supplementary information dated February 26, 1997 (Air Docket A-93-02, Item II-I-10, Enclosure 1j). The supplementary information includes a map showing the boundaries of potential USDWs nearest the WIPP in the Culebra, Santa Rosa, and Dewey Lake Formations. The EPA found the map to be sufficient for purposes of compliance assessment because it identifies potential USDWs near the WIPP. No change to this map is deemed appropriate at this time.

8.2.3 Comparison with the National Primary Drinking Water Standards

To provide additional assurance of the safety of the WIPP, the DOE prepared a bounding assessment of the concentrations of contaminants that could occur in a nearby USDW. Bounding doses that could be received by drinking from the USDW are also calculated. As was done to assess compliance with the individual protection standard, the analysis is bounding; the results do not represent reality, but rather illustrate the maximum yet unrealistic concentrations of contaminants in a hypothetical USDW and the maximum yet unrealistic resulting doses. As with the dose calculations, maximum concentrations were summed to develop concentrations for comparison with the National Primary Drinking Water Standards. The conclusions of this work, provided in the following subsections, illustrate that the consequences of the undisturbed repository are negligible, even when unrealistic assumptions are applied to the performance evaluation. The results of the bounding analysis support the position that additional characterization of groundwater near the WIPP to make a more definitive USDW determination is not warranted.

8.2.3.1 Transport Pathway

Section 8.1.2.1 describes the transport pathway assumed for the bounding analysis performed to evaluate compliance with the individual protection standard. This same transport pathway is assessed for the evaluation of compliance with the groundwater protection standard.

This pathway assumes that a USDW is located where the maximum possible concentration of radionuclides could be realized in the USDW and the maximum possible dose to an individual who drinks from the USDW could be delivered to the individual. As such, the analysis bounds the 40 CFR § 194.53 criterion specifying that DOE must consider underground interconnections among bodies of surface water, groundwater, and USDWs.

8.2.3.2 Combined ^{226}Ra and ^{228}Ra

The modeling system employed to simulate the performance of the undisturbed repository tracks the transport of the radionuclides of greatest importance to releases to the accessible environment (see Appendix TRU WASTE). These radionuclides of interest, listed in Table 8-1, are ^{241}Am, ^{239}Pu, ^{238}Pu, ^{234}U, and ^{230}Th. They do not include ^{226}Ra or ^{228}Ra because these radionuclides are

not a prevalent component of the projected inventory of the repository. However, an analysis of ^{226}Ra and ^{228}Ra is required to evaluate compliance with the groundwater protection standard.

To perform the bounding analysis, the results of a NUTS code tracer exercise were used to scale the anticipated releases of ^{226}Ra and ^{228}Ra. The tracer exercise shows that an initial concentration of radionuclides in the repository of 1 kg/m^3 results in a concentration at the accessible environment boundary of 1.025×10^{-7} kg/m^3. By applying this scaling factor to the quantity of ^{226}Ra and ^{228}Ra projected to be emplaced in the repository, it is determined that the maximum concentration of these radionuclides in the accessible environment is 0.07 picocuries per liter (Wagner 2003), which is below the 40 CFR § 141.15(a) standard of 5 picocuries per liter.

This concentration is calculated by transporting the passive tracer in the flow field generated using the BRAGFLO code for Realization 1 (Replicate 1, Vector 82), shown in Table 8-2. The calculation uses the mass and activity loads for ^{226}Ra and ^{228}Ra in the radionuclide inventory at closure and at 10,000 years. These values are provided in Table 8-6. The ORIGEN 2.2 code is used to calculate the activity loads at 10,000 years; these loads are 51.43 curies of ^{226}Ra in contact-handled (CH-) and remote-handled (RH-) transuranic (TRU) waste and 7.95 curies of ^{228}Ra in CH- and RH-TRU waste. The calculated concentration is

Table 8-6. Total Inventory and Mass Loading of ^{226}Ra and ^{228}Ra

Radionuclide	Waste Type	Total Inventory at Closure (Ci)	Total Inventory at 10,000 Years (Ci)	Mass Loading (kilograms)
^{226}Ra	CH	6.28×10^{0}	4.98×10^{1}	6.35×10^{-3}
^{226}Ra	RH	4.99×10^{-5}	1.63×10^{0}	5.05×10^{-8}
^{228}Ra	CH	7.63×10^{0}	7.70×10^{0}	2.81×10^{-5}
^{228}Ra	RH	2.51×10^{-1}	2.54×10^{-1}	9.23×10^{-7}

Source: Leigh (2003)

based on the volume of brine, 5577 m^3 (169,924 ft^3), in the repository at time zero in the BRAGFLO calculation.

The total concentration (CH- and RH-TRU) of either ^{226}Ra or ^{228}Ra 10,000 years at the accessible environment boundary is calculated accordingly.

1. Calculate the total mass load at 10,000 years by multiplying the total mass load at decommissioning by the ratio of activity loadings at 10,000 years and decommissioning, respectively.

2. Calculate the total mass concentration at the accessible environment boundary by dividing by the value of brine from the BRAGFLO simulation and multiplying by the scaling factor.

3. Convert to total concentration of activity at the accessible environment boundary by multiplying by the ratio of activity loading to mass loading at decommissioning.

4. Divide the concentration by the dilution factor 32.4 (See Section 8.1.2.2).

The 0.07 picocurie per liter maximum concentration occurs in the anhydrite interbeds within the Salado and not in a zone that could realistically be a source of drinking water.

In the CCA, this value is reported as 2 picocuries per liter. During the performance of the Performance Assessment Verification Test (PAVT) (SNL 1997), it was determined that the CCA calculation used an inappropriate brine volume value and failed to account for the dilution factor. Accordingly, the PAVT analysis shows that the correct value that should have been reported in the CCA is 0.14 picocuries per liter.

8.2.3.3 Gross Alpha Particle Activity Including ^{226}Ra But Excluding Radon and Uranium

For the CCA evaluation, compliance with the 40 CFR § 141.15(b) standard was assessed by summing the maximum concentration values provided in Table 8-1 for ^{241}Am, ^{239}Pu, ^{238}Pu, and ^{230}Th and adding the value for ^{226}Ra obtained to perform the 40 CFR § 141.15(a) assessment. The value obtained by this method is 7.81 picocuries per liter, which is below the 40 CFR § 141.15(b) standard of 15 picocuries per liter. This concentration occurs in the anhydrite interbeds within the Salado and not in a zone that could realistically be a source of drinking water.

For the CRA evaluation, the only contributing radionuclide is ^{239}Pu with a concentration of 2.53 $\times 10^{-18}$ picocuries per liter (Table 8-2). This value, summed with the 0.07-picocurie-per-liter value derived for the 40 CFR § 141.15(a) assessment, is essentially 0.07 picocuries per liter, well below the 15-picocuries-per-liter standard.

8.2.3.4 Annual Dose Equivalent to the Total Body or Any Internal Organ from the Average Annual Concentration of Beta Particle and Photon Radioactivity from Man-Made Radionuclides

To assess compliance with the 40 CFR § 141.16(a) standard, an annual dose equivalent of 4 millirem per year, the transport of the following radionuclides was evaluated: ^{239}Pu, ^{238}Pu, ^{234}U, and ^{230}Th. The maximum annual committed effective dose calculated for the CCA evaluation from any of these radionuclides is 0.93 millirems, which is the value reported for transport through MB139 and is well below the regulatory standard. The 0.93 millirem value includes alpha particle radioactivity, as well as beta particle and photon radioactivity. Thus, the value is very conservative in that the 4 millirem annual dose equivalent limit is only for beta particle and photon radioactivity.

By comparison, the maximum radionuclide concentration in the accessible environment calculated for the CRA evaluation is six orders of magnitude less than the maximum bounding value calculated for the CCA (see Section 8.1.1). Resulting doses for the CRA case would be correspondingly lower, as well.

8.3 Compliance Summary

In performing the compliance assessment, the DOE applied a bounding-analysis approach using unrealistic assumptions that overestimate potential doses and contaminant concentrations. To provide added assurance, the DOE assumed the presence of a USDW in close proximity to the WIPP Land Withdrawal Area boundary, even though available data indicate that none currently exists near the boundary. Using this very conservative approach, the calculated maximum potential dose to an individual determined for the CCA evaluation would be about one-sixteenth of the individual protection standard.

For the CRA evaluation, this concentration is well below the CCA value. In addition, the maximum concentrations of contamination in the hypothetical USDW would be much less than half of the EPA groundwater protection limits and the maximum potential dose to a receptor who drinks from the hypothetical USDW would be well below one-quarter of the standard.

This conservative approach also assumes that all contaminants reaching the accessible environment are directly available to a receptor. The analysis bounds any potential impacts of underground interconnections among bodies of surface water, groundwater, and underground sources of drinking water.

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9.0. PEER-2004 REVIEW

This chapter describes the regulatory basis for the conduct of peer reviews and summarizes relevant peer reviews performed at the Waste Isolation Pilot Plant (WIPP). Key elements of the U.S. Department of Energy (DOE) Carlsbad Field Office's (CBFO's) peer review program (for example, the review process, reports, selection criteria, and training for review panel members) are discussed. Two categories of peer reviews are reported in this chapter: (1) those conducted after the promulgation of Title 40 of the Code of Federal Regulations (CFR) Part 194 (U.S. Environmental Protection Agency [EPA] 1996a); and (2) those conducted earlier.

Seven peer reviews were initiated subsequent to the promulgation of 40 CFR Part 194 and prior to submission of the Compliance Certification Application (CCA) in 1996. Per the criteria of 40 CFR § 194.27, they were conducted in a manner compatible with NUREG-1297 (Altman, et al. 1988). The subjects of these reviews included: conceptual models; waste characterization analysis; engineered alternatives cost/benefit study (EACBS) ; engineered systems data qualification; waste form and disposal room data qualification; natural barriers data qualification; and passive institutional controls. The conceptual model peer review group published three supplementary reports in 1996 and 1997 after the submission of the CCA. Two additional peer reviews related to conceptual models were completed in 2003 prior to submission of the first Compliance Recertification Application (CRA-2004), and are described in Section 9.3.1. These reviews are summarized in the following sections:

- 9.3.1 – Conceptual Models Peer Review
- 9.3.2 – Waste Characterization Analysis Peer Review
- 9.3.3 – Engineered Alternatives Cost/Benefit Study Peer Review
- 9.3.4 – Engineered Systems Data Qualification Peer Review
- 9.3.5 – Natural Barriers Data Qualification Peer Review
- 9.3.6 – Waste Form and Disposal Room Data Qualification Peer Review
- 9.3.7 – Passive Institutional Controls Peer Review

The applicable peer review plans, complete peer review reports, and selected supporting documentation for peer reviews completed before submission of the CCA in 1996 were provided in CCA Appendix PEER. The plans, reports, and supporting documentation for the peer reviews performed after the submission of the)CCA are provided in Appendix PEER-2004. This chapter also presents the DOE responses to the findings and recommendations of the peer reviews. Additional documentation is available in project record packages in the CBFO Records Holding Facility located in Carlsbad, New Mexico.

Peer reviews that occurred prior to the promulgation of 40 CFR Part 194 were not necessarily conducted in accordance with NUREG-1297 guidelines. Therefore, candidate reviews were evaluated against specific criteria to determine whether they were appropriate for inclusion in

this application. The selected historical reviews were summarized in the following sections of the CCA Chapter 9:

- 9.4.1 – National Academy of Sciences WIPP Panel Reviews (12 reports)
- 9.4.2 – Performance Assessment Peer Review Panel
- 9.4.3 – Shaft Seal Design Independent Review
- 9.4.4 – Engineered Alternatives Task Force Report Peer Review
- 9.4.5 – Blue Ribbon Panel Peer Review
- 9.4.6 – Advisory Committee on Nuclear Facility Safety Review (two reports)
- 9.4.7 – Performance Assessment Review Team (PART)
- 9.4.8 – INTRAVAL
- 9.4.9 – WIPP Conceptual Model Uncertainty Group Review
- 9.4.10 – Environmental Evaluation Group Reviews (15 reports)
- 9.4.11 – Fracture Expert Group Review
- 9.4.12 – Fanghänel Review
- 9.4.13 – Independent Technical Review of the Bin and Alcove Test Programs
- 9.4.14 – Performance Assessment (PA) Reviews
- 9.4.15 – Technical Support Group Reviews (two reports)
- 9.4.16 – National Environmental Policy Act Reviews

The full reports from these reviews and selected supporting material were provided in CCA Appendix PEER.

Summaries of additional reviews performed by oversight organizations since the submission of CCA are included in the following sections:

- 9.4.1.13 to 9.4.1.15 – National Academy of Sciences WIPP Panel Reviews (three reports),
- 9.4.10.16 to 9.4.10.26 – Environmental Evaluation Group (EEG) Reviews (11 reports),

- 9.4.17 – International Atomic Energy Agency (IAEA) and Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) Joint Report (one report),

- 9.4.18 – GEOTRAP (An NEA/OECD project), and

- 9.4.19 – Institute for Regulatory Science (RSI) of the American Society of Mechanical Engineers (ASME) (two reports).

These reviews are in addition to those required by 40 CFR Part 194.27(a), do not meet the requirements of NUREG-1297, and are not used directly by the DOE for the analyses in the CRA. The full reports from these reviews and selected supporting materials are provided in Appendix PEER-2004.

9.1 Regulatory Requirements

The certification criteria in 40 CFR Part 194 prescribes the use of peer reviews to support certain areas of the compliance evaluation. Compliance criteria in 40 CFR § 194.27 state that peer review at the WIPP be performed for several specific aspects of the program and that they be performed in a manner compatible with NUREG-1297. NUREG-1297 provides guidance on the definition of peer reviews, the areas for which a peer review is appropriate, the acceptability of peers, and the conduct and documentation of peer reviews. 40 CFR Part 194 states that "The specific requirements in NUREG-1297 that discuss for which activities peer review should be conducted do not apply, nor do they supersede the requirements of the final rule." (61 Federal Register [FR] 5228) Specific sections of 40 CFR Part 194 and NUREG-1297 provide the regulatory basis for this chapter.

The certification criteria state that any application for certification shall include documentation for the following peer reviews that are to be conducted: conceptual models used in the PA; waste characterization analysis; and engineered barrier evaluation (40 CFR § 194.27[a]). Section 194.27(b) states that these peer reviews, if conducted subsequent to the promulgation of 40 CFR Part 194, should be conducted in a manner that is compatible with NUREG-1297. Section 194.27(c)(2) also requires this application to include documentation of any peer review processes conducted in addition to those of 40 CFR § 194.27(a).

NUREG-1297 defines peer review as "a documented, critical review performed by peers who are independent of the work being reviewed." NUREG-1297 also states that a "peer review is an in-depth critique of the assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn from the original work."

The 40 CFR Part 194 Background Information Document (EPA 1996b) states that peer reviews can be used as part of "a comprehensive quality assurance program" to give "confidence that work completed, underway, or planned was, is, or will be properly performed." The Background Information Document also notes that "additional peer review is also necessary to establish the validity of procedures, methods, or interpretations which may not be addressed by a quality assurance (QA) program . . . ASME-NQA-3-1989 . . . includes peer review among those

activities affecting quality associated with the collection of scientific and technical information, when other established methods cannot be used to establish the adequacy of information."

NUREG-1297 states that for a repository,

> peer reviews should be used as a management tool to achieve confidence in the validity of certain technical and programmatic judgments. The intent of a peer review is to pass judgment on the technical adequacy of the work or data submitted for review, to identify aspects of the work on which technical consensus exists, to identify aspects on which technical consensus does not exist, and to identify aspects of the reviewed work which the reviewers believe to be incorrect or which need amplification. A peer review provides assurance in cases where scientific uncertainties and ambiguities exist but in which technical and programmatic judgments and decisions still must be made.

9.2 Peer Review Process

NUREG-1297 suggests that procedures be developed to "implement the NUREG-1297 guidance" and to "provide methods for initiating a peer review." These procedures, for any given peer review, "should require a planning document that describes the work to be reviewed, the size and spectrum of the peer review group, and the suggested method and schedule to arrive at a peer review report."

WIPP-specific plans and procedures ensure that peer reviews performed subsequent to promulgation of 40 CFR Part 194 were conducted in accordance with the criteria of 40 CFR Part 194 and compatible with NUREG-1297. The most pertinent of the plans and procedures are discussed briefly below.

A Peer Review Management Plan (PRMP) (DOE 1996b) was developed and approved by the CAO to describe the management processes used to control the planning, implementation, and documentation of these reviews. The PRMP defines the management approach, resources, schedule, and technical requirements for using peer reviews to confirm and/or verify the adequacy of data and/or information utilized to support the WIPP application.

CAO Team Procedure (TP) 10.5, Peer Review (DOE 1996c) has been replaced by CBFO Management Procedure (MP) 10.5 (DOE/CBFO 2003). TP 10.5 was used to guide the peer reviews performed prior to submission of the CCA and the three supplementary conceptual model peer reviews performed after CCA in October 1996 to April 1997. MP 10.5 guided the peer reviews performed in 2002-2003. Both procedures define the responsibilities, requirements, and methodologies incorporated in the performance of peer reviews conducted by the CAO (for CCA) and the CBFO (for CRA-2004) pursuant to the criteria of 40 CFR § 194.27. The procedures provided the criteria for determining the size and composition of the review panel and for selecting individual peer review panel members, and outline the orientation and training to be provided for the panelists. The procedures also describe the actual peer review process, provide criteria for development of peer review plans and report preparation, and define the responsibilities of individuals involved in the process. Both TP 10.5 and MP 10.5 were developed in accordance with, and to implement, the guidance in NUREG-1297, "Peer Review for High-Level Nuclear Waste Repositories."

Specific peer review plans were developed for each peer review at the WIPP. These plans documented the planning process for the peer reviews and were prepared and approved prior to performing the particular review (see Section 9.2.1).

As discussed more completely in Chapter 5.0, the Quality Assurance Program Document, Rev.5 (QAPD) (DOE 2003) establishes the minimum requirements for the WIPP QA program. It provides guidance for development and implementation of QA programs for all aspects of the WIPP project. In particular, the QAPD provides general requirements for training, document control, and QA records management.

9.2.1 Peer Review Plan

MP 10.5 requires that the Peer Review Manager ensure that a peer review plan is prepared and approved prior to the performance of each peer review. Specific plans are approved by the CBFO.

The plan documents the planning of the peer review. It provides the scope of the peer review, a description of the work to be reviewed, the intended use of the work, and methods for conducting peer reviews.

40 CFR § 194.27(b) specifies that peer reviews performed subsequent to the promulgation of 40 CFR Part 194 be conducted in a manner compatible with NUREG-1297. NUREG-1297 states that

> The peer review process may vary from case to case, and should be determined by the chairperson of the peer review group, consistent with the guidance provided in this GTP (Generic Technical Position). In meetings and/or correspondence, the peer review group should evaluate and report on: (a) validity of assumptions; (b) alternate interpretations; (c) uncertainty of results and consequences if wrong; (d) appropriateness and limitations of methodology and procedures; (e) adequacy of application; (f) accuracy of calculations; (g) validity of conclusions; (h) adequacy of requirements and criteria. Furthermore, full and frank discussions between the peer reviewers and the performers of the work are encouraged.

The WIPP peer review process consists of an in-depth analysis and evaluation of documented assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn in the original work. MP 10.5 specifically incorporates the above NUREG-1297 requirements into the WIPP peer review process.

9.2.2 Size and Composition of Peer Review Panels

NUREG-1297 states that

> The number of peers comprising a peer group should vary with the complexity of the work to be reviewed, its importance to establishing that safety or waste isolation performance goals are met, the number of technical disciplines involved, the degree to which uncertainties in the data or technical approach exist, and the extent to which differing viewpoints are strongly held within the applicable technical and scientific community concerning the issues under review. The collective technical expertise and qualifications of peer group members should span the technical issues and areas involved in the work to be reviewed, including any differing bodies of scientific thought. Technical areas more central to the work to be reviewed should receive proportionally more representation on the peer review group.

The NUREG-1297 guidance also states that

> The peer review group should represent major schools of scientific thought. The potential for technical or organizational partiality should be minimized by selecting peers to provide a balanced review group.

The size and composition of peer review panels established after the promulgation 40 CFR Part 194 were determined by a selection committee consisting of the Peer Review Manager and two members selected by the Peer Review Manager.

Technical requirements for each peer review panel were established by the Peer Review Manager and provided to the selection committee, which then developed a list of potentially qualified personnel. Once a panel member was officially selected and had agreed to serve, the selection committee members documented the rationale for the selection of that peer review panel member on a "Peer Review Panel Selection, Size and Composition Justification/Decision Form," which is maintained as a QA record.

The number of members selected for a particular panel depended on the amount and complexity of the work to be reviewed, its importance for establishing that safety or waste isolation performance goals are met, the number of technical disciplines involved, the degree to which uncertainties in the data or technical approach exist, and the extent to which differing viewpoints were strongly held within the applicable technical and scientific community concerning the issues under review. The panel members were selected based on their collective technical expertise and qualifications so that they spanned the technical issues and areas involved in the work to be reviewed, including differing bodies of scientific thought. The technical areas more central to the work under review received proportionally more representation on the peer review panel. To the extent practical, the panels represented the major schools of scientific thought pertinent to the subject being reviewed. The selection committee strived to eliminate the potential for technical or organizational partiality by selecting peer reviewers that provided a balanced panel.

9.2.3 Technical Qualifications of Panel Members

NUREG-1297 states that

> The technical qualifications of the peer reviewers, in their review areas, should be at least equivalent to that needed for the original work under review and should be the primary consideration in the selection of peer reviewers. Each peer reviewer should have recognized and verifiable technical credentials in the technical area he or she has been selected to cover. The technical qualifications of each peer, and hence of the peer review group as a whole, should relate to the importance of the subject matter to be reviewed.

MP 10.5 specifies that the acceptability of any peer review panel member be based on the above NUREG-1297 requirements. The Peer Review Manager is required to ensure that education and pertinent experience information is verified and documented prior to the start of the peer review process. This documentation is also maintained as QA records.

9.2.4 Independence of Panel Members

NUREG-1297 states that

> Members of the peer review group should be independent of the original work to be reviewed. Independence in this case means that the peer, a) was not involved as a participant, supervisor, technical reviewer or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to assure the work is impartially reviewed.
>
> Because of DOE's pervasive effort in the waste management area, the lack or unavailability of other technical expertise in certain areas, and the possibility of reducing the technical qualifications of the reviewers in order that total independence is maintained, it may not be possible to exclude all DOE or DOE contractor personnel from participating in a peer review. In those cases where total independence cannot be met, a documented rationale as to why someone of equivalent technical qualifications and greater independence was not selected should be placed in the peer review report.

NUREG-1297 allows both the work under review and the peer review of that work to be funded by DOE. It also provides the caveat that the

> …independence criteria is not meant to exclude eminent scientists or engineers upon whose earlier work certain of the work under review is based so long as a general scientific consensus has been reached regarding the validity of their earlier work.

MP 10.5 provides that the above NUREG-1297 requirements be used in selecting panel members. Each peer review panel member is required to document his or her independence. These documents are reviewed and approved by the Peer Review Manager and maintained as QA records.

9.2.5 Training of Peer Review Panel Members

MP 10.5 requires that the Peer Review Manager ensure all peer review panel members receive adequate training prior to beginning a peer review. Training consists of reading assignments and, if deemed necessary by the Peer Review Manager or the Peer Review Panel Coordinator, briefings and classroom training. Assigned reading includes 40 CFR Parts 191 (EPA 1993) and 194, NUREG-1297, the CBFO QAPD, MP 10.5, and the applicable Peer Review Plans.

MP 10.5 further requires that all panel members receive an orientation prior to the start of the peer review process. The orientation includes information on the peer review process, administrative requirements, the applicable Peer Review Plan, a summary of the technical subject matter, and an overview of MP 10.5. Panel member training and orientation are documented and this documentation is maintained as a QA record.

9.2.6 Peer Review Panel Report

NUREG-1297 states that

> A written report documenting the results of the peer review should be issued. It is usually prepared under the direction of the chairperson of the peer review group, and is signed by each member individually. It should clearly state the work or issue that was peer reviewed and the conclusions reached by the peer review process . . . The report should include individual

> statements by peer review group members reflecting dissenting views or additional comments, as appropriate. The peer review report should contain a listing of the reviewers and any acceptability information (i.e., technical qualifications and independence) for each member of the peer group, including potential technical and/or organizational partiality.

MP 10.5 requires that a peer review report be prepared for each peer review. Each panel member is required to sign and date the report. The report describes the work or issue that was reviewed as well as the conclusions reached by the panel, and provides individual statements by the members reflecting dissenting views or additional comments, as appropriate. Finally, the report lists the peer review panel members and provides technical qualifications and independence information for each member.

9.2.7 Quality Assurance Records Management

NUREG-1297 specifies that written "…minutes should be prepared of meetings, deliberations, and activities of the peer review process."

MP 10.5 requires that written minutes, including graphic or calculated materials used in panel meetings, be prepared for meetings, deliberations, daily caucuses, and other activities. These written minutes are maintained as QA records. MP 10.5 also requires that a QA records management system be developed and implemented to ensure that peer review documents are identified, assembled, and transferred on a timely basis and in an orderly manner to the appropriate records center.

9.2.8 Quality Assurance Oversight

Section V of NUREG-1297 states that "As a minimum, the QA organization should provide surveillance of the peer review process to ensure that the procedures conform to the guidance of this GTP and that they are followed by the peer review group."

The QAPD establishes requirements for implementing the QA program for the WIPP peer review process. The QAPD requires that assessments be conducted to ensure that all aspects of the peer review conform to the guidance of NUREG-1297. Additional details regarding the WIPP QA program are provided in Chapter 5.0.

9.3 Peer Reviews Conducted After Promulgation of 40 CFR Part 194

Seven peer reviews were performed by the WIPP project prior to submitting the CCA in 1996 to address issues deemed necessary by the DOE. These peer reviews included reviews of conceptual models, waste characterization analysis, and an evaluation of the benefits and detriments of potential engineered barriers and alternatives as stated in 40 CFR § 194.27(a); data reviews of engineered systems, waste form and disposal room, and natural barriers as stated in 40 CFR § 194.22(b); and a passive institutional controls review. These peer reviews were conducted subsequent to the promulgation of 40 CFR Part 194 and were conducted in a manner consistent with the NUREG-1297 guidance, as implemented by TP 10.5 and the QAPD.

Specifically, the following peer reviews have been conducted:

- evaluation of the adequacy and reasonableness of the WIPP conceptual models;
- a review of the adequacy and completeness of the waste characterization analysis;
- an assessment of the validity of the assumptions and approach used to select or reject engineered alternatives, as delineated in the EACBS (DOE 1995b) for the WIPP;
- a data qualification review of parameters used to describe engineered systems;
- a data qualification of parameters used to describe natural barriers;
- a data qualification of parameters used to describe the waste form and disposal room; and
- a determination of whether the passive institutional controls have a reasonable expectation of meeting their intended purpose.

The conceptual model peer review group published three supplementary reports in 1996 and 1997 after the DOE submitted the CCA. These were also conducted in a manner consistent with the NUREG-1297 guidance, as implemented by TP 10.5 and the QAPD.

Two additional peer reviews related to conceptual models were completed in 2003. These were conducted in a manner consistent with the NUREG-1297 guidance, as implemented by CBFO's MP 10.5 and the QAPD. These five post-CCA peer review reports are summarized in Section 9.3.1 and the full reports are included in Appendix PEER-2004.

These reviews are discussed, and the WIPP project response to the peer review panel's comments is provided in the following sections. The general process used by the DOE to plan and conduct the seven peer reviews is described in Section 9.2. The complete reports of peer reviews performed before submitting the CCA were included in CCA Appendix PEER, and those performed after submitting the CCA are provided in Appendix PEER-2004. The reports were all consensus documents signed by all members of the specific panel involved: that is, there were no dissenting views on any of the final reports for the seven subject reviews.

9.3.1 Conceptual Models Peer Review

40 CFR § 194.23(a)(3)(v) specifies that this application include documentation that the conceptual models have undergone peer review consistent with 40 CFR § 194.27. A Conceptual Model Peer Review (CMPR) Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of CAO's TP 10.5 (Replaced by MP 10.5 for CRA-2004). The CMPR Plan describes the peer review process used to ensure that the conceptual models used in the WIPP PA reasonably represent possible future states of the disposal system.

In accordance with the provisions of TP 10.5, a peer review panel was selected and organized in April 1996. The six-member panel was composed of the following individuals:

- Charles R. Wilson (Chairman), Private Consultant;

- Florie A. Caporuscio, Informatics Corporation;
- John F. Gibbons II, Private Consultant;
- Eric B. Oswald, Private Consultant;
- Darrell D. Porter, Science Applications International Corporation; and
- Glen L. Sjoblom, Private Consultant.

Florie A. Caporuscio has a Ph.D. in Geology and more than 10 years of applied pertinent experience, including having served as the Acting Section Chief, WIPP Technical Review, at EPA Headquarters' Office of Radiation and Indoor Air and as a Staff Geologist at EPA Region II. In addition to Dr. Caporuscio's highly relevant regulatory expertise, his pertinent technical qualifications include extensive expertise in site characterization, geochemistry, radionuclide transport in geological media, and related conceptual models.

John F. Gibbons II has a Ph.D. in Geomechanics and more than 20 years of relevant experience, including having served as the Technical Director of Applied Research Associates for site characterization technology research and development activities augmented by involvement in numerous site characterizations. Dr. Gibbons' site characterization and technology research and development (R&D) experience is particularly pertinent for peer reviews involving geology, tectonics, hydrology, and related conceptual models.

Eric B. Oswald has a Ph.D. in Hydrology and Water Resources Administration and more than 25 years of applied pertinent technical and regulatory experience. Dr. Oswald's technical qualifications include extensive surface and groundwater flow system analyses and control, contaminant transport, and related conceptual models.

Darrell D. Porter has a Ph.D. in Mineral Engineering and more than 34 years of experience in earth sciences programs with emphasis on rock mechanics. Dr. Porter's pertinent technical qualifications include extensive involvement in site characterization, regulatory compliance, QA, and technical review activities in support of deep geologic repository development.

Glen L. Sjoblom has a M.Sc. in Chemical Engineering and more than 26 years of experience in environmental radiation protection, including having served as the Director of Radiation Programs at the EPA during the development and promulgation of 40 CFR Part 191. Mr. Sjoblom's extensive environmental radiation protection experience also includes serving as Special Assistant to the Director of the Office of Inspection and Enforcement and Deputy Director of the Division of Industrial and Regulatory Medical Nuclear Safety at the NRC. Mr. Sjoblom's pertinent technical qualifications include chemistry, waste characterization, deterministic and stochastic risk and safety analysis, and environmental protection activities in support of deep geologic repository development.

Charles R. Wilson has a Ph.D. in Civil Engineering–Groundwater and more than 26 years of relevant experience in earth sciences programs. Dr. Wilson's pertinent technical qualifications include lead roles in the geology, hydrology, geochemistry, and geotechnical engineering disciplines on teams involved in site characterization, model development, and modeling of

landfills; water resources; groundwater flow systems; contaminant and radionuclide transport; and nuclear waste repositories in the United States and abroad.

Additional details regarding the technical qualifications and independence of the panel members are provided in Appendix A of the July 1996 peer review report (see CCA Appendix PEER). Each panel member's background was carefully reviewed to ensure his strong qualifications, verify his independence from other WIPP work, and confirm the absence of conflicts of interest.

The initial peer review, described in detail in the CCA and summarized in this chapter, was conducted from April through August 1996. After orientation and training, the panel was provided draft conceptual model descriptions and other relevant information and was briefed by WIPP project staff. Panel members also had access to the Sandia National Laboratories (SNL) Nuclear Waste Management Program Library and to reports of prior peer reviews.

The objective of the review was to determine the adequacy and reasonableness of 24 conceptual models representing features, events, and processes (FEPs) involved in assessing the long-term performance of WIPP. As stated in the CMPR report:

> A conceptual model is a statement of how important features, events, and processes) such as fluid flow, chemical processes, or intrusion scenarios are to be represented in performance assessment. To be used in performance assessment, the conceptual model must be successfully translated into analytical statements and mathematical analogs. The Panel reviewed in detail the twenty four conceptual models against criteria of the EPA....The Panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall performance assessment model.

Per the criteria of 40 CFR Part 194, the peer review was conducted in a manner compatible with the provisions of NUREG-1297. The 8 adequacy criteria from NUREG-1297 were used as a basis for review of each model (see Section 9.2.1).

The first CMPR Report was issued in July 1996 (a copy of the CMPR Report is provided in CCA Appendix PEER). The panel initially concluded that 13 of the models were adequate for implementation and that the remaining 11 models were not adequate for use in PA. The DOE provided additional information in response to the panel's concerns, and the panel subsequently determined that the responses for 6 of those 11 models reasonably addressed their concerns. In addition, the panel concluded that some of the responses (multiple concerns were identified for some models) relating to three additional models also reasonably addressed its concerns. Finally, the panel concluded that responses regarding three models did not reasonably address its concerns; however, one of these models was determined to have no consequence to PA. The DOE's justification for using these unresolved models is discussed in Section 9.3.1.2 of the CCA and is briefly described in the same section of this chapter.

The 24 models reviewed by the panel are listed in Table 9-1. Also provided are the panel's conclusions about the adequacy of the models and whether the panel believed that the DOE's responses reasonably addressed its concerns about those models it determined to be inadequate.

Table 9-1. Adequacy of WIPP Conceptual Models

Model	Report Findings	DOE Response Reasonable?
Disposal System Geometry	Adequate	Not Applicable
Culebra Hydrogeology	Not Adequate [1]	Yes
Repository Fluid Flow	Not Adequate	Yes
Salado	Adequate	Not Applicable
Impure Halite	Adequate	Not Applicable
Salado Interbeds	Not Adequate	Yes
DRZ	Adequate	Not Applicable
Actinide Transport in the Salado	Adequate	Not Applicable
Units Above the Salado	Not Adequate [1]	No[1]
Transport of Dissolved Actinides in the Culebra	Adequate	Not Applicable
Transport of Colloidal Actinides in the Culebra	Not Adequate	No
Exploration Boreholes	Not Adequate	Partially[2]
Cuttings and Cavings	Adequate	Not Applicable
Spallings	Not Adequate	Yes
Direct Brine Release (DBR)	Not Adequate	No
Castile and Brine Reservoir	Not Adequate	Partially[3]
Multiple Intrusions	Adequate	Not Applicable
Climate Change	Adequate	Not Applicable
Creep Closure	Adequate	Not Applicable
Shafts and Shaft Seals	Adequate	Not Applicable
Gas Generation	Not Adequate	Yes
Chemical Conditions	Not Adequate	Partially[4]
Dissolved Actinide Source Term	Adequate	Not Applicable
Colloidal Actinide Source Term	Adequate	Not Applicable

[1] Although the model was found to be inadequate, it was determined to have no consequence to PA.
[2] The panel concluded that responses to three of their four concerns were reasonable.
[3] The panel concluded that responses to two of their three concerns were reasonable.
[4] The panel concluded that responses to two of their three concerns were reasonable.

Section 9.3.1.1 provides a brief description of the panel's discussion on the models it deemed adequate. Section 9.3.1.2 of the CCA provided a description of the panel's discussion on the models deemed inadequate; the DOE's responses to the panel's concerns; the panel's comments on those responses; and the DOE's technical position on those concerns wherein the panel concluded that the responses did not reasonably address its concerns. Section 9.3.1.2 of this chapter summarizes that discussion.

The same panel continued additional reviews after the submission of CCA, with supplementary reports published in December 1996, January 1997, and April 1997. These supplementary peer reviews are described in Section 9.3.1.3.

9.3.1.1 Adequate Models

The following excerpts are from the CMPR Report. They address those 13 models the panel determined to be adequate.

9.3.1.1.1 Disposal System Geometry

> The conceptual model for the disposal system geometry provides a suitable framework for modeling the important processes and their interactions in the disposal system. . .The concept that the spatial effects of processes and interactions can be represented in two dimensions is defensible. The simplification in the system representation and computational method to simulate the two dimensions are defensible and adequate for implementation. The basic grid framework for representing the material properties of the disposal system, adjacent DRZ [disturbed rock zone], geologic formations, and intrusion scenarios is adequate and the proposed use of a finite difference method to connect the nodes and generate flow fields is also defensible and adequate for implementation.

9.3.1.1.2 Salado

> Given that the conceptual model predicts that there will be enough brine to corrode the waste and that other assumptions appear conservative, making other impacts unlikely, the model is adequate for its intended use. . .The conclusions appear to be valid. Estimates of inflow volumes from the mechanisms proposed in the model appear to be reasonable. . .The model is adequate for implementation.

9.3.1.1.3 Impure Halite

> Although differences in the behavior of pure and impure halite, variable degrees of impurity, and complexities of stratigraphic distribution of zones of impurity exist, the modeling of all halite rocks in the Salado as impure halite is an acceptable model simplification. . .The model appears to be adequate for the same reasons that the overall Salado model is adequate. Brine inflow sufficient to corrode the waste and to drive biogenic degradation is assumed. For error to be significant, brine inflow would have to be very large, which is unlikely. . .The conclusions drawn on the basis of the impure halite model are valid for PA purposes.

9.3.1.1.4 Disturbed Rock Zone

> All observed considerations of analysis, study, and proposed engineered applications regarding the DRZ and its impacts on effective shaft sealing appear to be valid. The understandings developed of DRZ phenomena and data reveal it is critical to engineering waste containment overall because of its potential for negative impact on shaft seals permeability and integrity and fluid flow in the rooms and their seals. It appears that all considerations of this impact and the conclusions discussed here are sound and

valid. . .The panel concludes that the present DRZ model is adequate to be implemented in performance calculations.

9.3.1.1.5 Actinide Transport in the Salado

It seems DOE has provided a very rational way to “lump” all the various solubilities of dissolved actinides and to describe how the four main types of colloids will be “lumped” for transport. Both of these source terms have complex properties that could have been negated by the “lumping” factor. . .These two philosophies of solubility “lumping” have been clearly explained for dissolved and colloidal actinide transport. . .by the principal investigator and by this means the implementation was determined to be adequate. . .this model is wholly adequate and reasonable for implementation.

9.3.1.1.6 Transport of Dissolved Actinides in the Culebra

It is concluded that a dual porosity model is adequate for dissolved actinide transport analyses if ranges of model parameters are chosen properly in light of uncertainties. . .The conclusion that the actinide transport in the Culebra can be adequately modeled in a dual porosity model, with advective transport in the main flow porosity, diffusion into and physical and chemical retardation in the rock matrix porosity, is valid. . .The conceptual model appears compatible with other models it intersects with directly.

9.3.1.1.7 Cuttings/Cavings

This model is fundamentally appropriate. It is based on straightforward analysis, concepts, and technology that is well developed and believed to be adequate for depicting that part of the consequences of a waste room penetration by a borehole drill that is covered by this model....The CUTTINGS_S model contains well thought out and evaluated mathematics based on researched and established fluid flow technology and science. . .This model is sufficiently developed and uncomplicated that no serious concerns were found. It appears to be capable of accurately representing the waste that might be removed during a drilling intrusion and is fully adequate for implementation in support of the WIPP performance assessment.

9.3.1.1.8 Multiple Intrusions

The conceptual model for multiple intrusions is fundamentally sound and appropriately conservative, given the simplifications that are required to model a complex set of conditions in an efficient manner. . .The application of the conceptual model to the numerical model is adequate, again given the simplifications that are required to model a complex set of conditions in an efficient manner. . .The Multiple Intrusion conceptual model is adequate for implementation in performance assessment.

9.3.1.1.9 Climate Change

The climate change conceptual model represents a reasonable and defensible range of potential future climate extremes for incorporation into the performance assessment. The

conceptual model includes a range of conditions, bounded by reasonably foreseeable future climates and their effects that are adequate to represent impacts to groundwater flows in the Culebra Dolomite Member of the Rustler Formation. In addition to providing adequate representation of conditions for implementation, the background research and analysis supporting the formulation of the conceptual model for climate change provides adequate information for satisfying EPA guidance.

9.3.1.1.10 Creep Closure

The adequacy of the Creep Closure conceptual model is demonstrated by its predictiveness of room closure in existing WIPP excavations. The uncertainties inherent in the model must be assessed through the sensitivity of the porosity surface calculation. The model appears to be adequately predictive. . .The porosity surface calculation appears to address the complex issues of timing among processes and provides a means of choosing representative parameters for individual process with respect to uncertainty about process results and timing during dynamic process evolution.

9.3.1.1.11 Shaft and Shaft Seals

Comments concerning two issues from the preceding section are also applicable to the model's adequacy for implementation: 1) further analysis of the salt compaction data base, firmed up with additional data, is important to support parameter permeability values, and 2) an analysis has not been found to assure the shaft monolith does not create a shear zone at the shaft perimeter interface. Aside from these, the foregoing discussions outline an insightful piece of scientific and engineering work. The shafts and seals program is well thought through and the areas of perceived concern have been addressed to various degrees of detail, each believed sufficiently adequate to support qualifying this model as adequate to proceed in supporting performance assessment.

9.3.1.1.12 Dissolved Actinide Source Term

The true unknowns are to be found in the assumptions that the chemistry rapidly approaches equilibrium and that the waste has uniform characteristics and inventory. These fundamental assumptions are a basis of the conceptual model and are most probably adequate and reasonable. . .This model has turned out to be a very strong representation of how actinides would dissolve in the two major brines (Salado and Castile) of the repository and is adequate to support performance assessment.

9.3.1.1.13 Colloidal Actinide Source Term

Since this model is inexorably linked to the solubility concentrations of the dissolved actinide source term, one may conclude that this model is valid contingent on the validity of the other model (which was determined to be valid, with minor caveats)... The Colloidal Actinide Source Term model is a reasonable, if somewhat overly conservative representation of how actinides would sorb onto colloids in the two major brines (Salado and Castile) available for the repository. This conceptual model is adequate to support performance assessment.

9.3.1.2 Inadequate Models

As indicated above, the CMPR panel initially determined that 11 of the models they reviewed were inadequate. The CMPR panel concerns, the DOE's interpretation of the panel's concerns (Statement of Issue), the DOE response to the panel's concerns (Response to Issue), and the panel's reaction to the interpretation and responses (Peer Reviewer Consideration of Response) are provided in CCA Section 9.3.1.2. In those instances in which the panel determined the response did not reasonably address its concerns, the DOE developed additional information regarding its position (DOE Technical Position versus Panel Issue). These are also provided in CCA Section 9.3.1.2. For pre-CCA peer reviews, the issues raised by the panel and the panel's responses after considering the DOE responses are mentioned in this chapter, but the detailed exchanges between the DOE and the panel are not repeated.

9.3.1.2.1 Peer Review Panel Concerns – Culebra Hydrogeology

> No conceptual model which explains the variability of hydrologic properties and processes in the Culebra at a scale which is useful in correlating those properties in the numerical hydrologic flow model was developed.
>
> An extensive hydrologic testing database and an apparently adequate numerical flow model were developed as a substitute for performance assessment purposes.
>
> Although the Culebra conceptual model was found to be inadequate to support numerical modeling, this inadequacy was inconsequential for performance assessment because an extensive hydrologic database was developed and serves as an adequate substitute to support numerical modeling.

After consideration of the DOE response, the panel concluded that the DOE understood the issues and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.2 Peer Review Panel Concerns – Repository Fluid Flow; First Concern

> The conceptual model and its two-dimensional (2D) numerical implementation may unrealistically restrict brine movement within the repository to the anhydrite interbeds because of the shallow depths of the borehole and shaft model cells. These restrictions could result in underestimating brine migration in the interbeds toward the accessible environment.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and the response reasonably addressed the panel's concern. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.3 Peer Review Panel Concern – Repository Fluid Flow; Second Concern

> The conceptual model and its two-dimensional numerical implementation do not include the presence of the unplugged ERDA-9 borehole within the walls of the operations area. This borehole could provide a pathway for gas and possibly brine to the ground surface,

> and no description of the plugging plan for this hole was seen in the documentation provided by the Panel.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.4 Peer Review Panel Concern – Repository Fluid Flow; Third Concern

> The sensitivity of model results to the selection of constant permeability values for the waste, panel seals, and repository DRZ has not been evaluated for the current PA. Early time permeabilities may be significantly greater than the model parameter for each of these media, and could lead to underestimation of radionuclide releases.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.5 Peer Review Panel Concern – Repository Fluid Flow; Fourth Concern

> The long-term performance of the panel closure seals has not been subjected to a detailed engineering evaluation of the type performed for the shaft seal. The role of the panel seals in restricting brine flow among the waste panels and into other parts of the repository is an important element of the conceptual model and its implementation in PA.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.6 Peer Review Panel Concern – Salado Interbeds

> The conceptual model does not consider how the physical properties of the bounding clay seams affect model fracture propagation and permeability. Ignoring the characteristics of the clay seams may significantly overestimate the threshold pressure at which repository gases may be released.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.7 Peer Review Panel Concern – Units Above the Salado

> The conceptual models and the testing database are inadequate to exclude the Dewey Lake Redbeds and the Magenta Dolomites as potential transport pathways for radionuclides in the event of an intrusion.

After consideration of the DOE response, the panel concluded that the DOE understood the issues; however, the panel concluded that the response did not reasonably address its concerns. The panel noted, however, that the inadequacy of the model is of no consequence to the PA. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.8 Peer Review Panel Concerns – Transport of Colloidal Actinides in the Culebra; First Concern

> The conceptual model does not adequately support the assumption that dissolved actinides will not interact with Culebra colloids. Ignoring this phenomenon could overestimate the travel time calculated for radionuclides to reach the accessible environment.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address its concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.9 Peer Review Panel Concern – Transport of Colloidal Actinides in the Culebra; Second Concern

> The experimental K_ds determined for this model are not fully defensible. Such values may overestimate the retardation of actinides in the Culebra.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address their concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.10 Peer Review Panel Concerns – Transport of Colloidal Actinides in the Culebra; Third Concern

> Recent experimental work to support assumptions and data for this model has not yet been published and were not available for panel review.

After consideration of the DOE response, the panel concluded that insofar as this issue was not based on a technical issue, the panel was not requested to review the response.

9.3.1.2.11 Peer Review Panel Concerns – Exploration Boreholes; First Concern

> The potential for releases or changes in repository conditions from borehole penetrations in the operations and experimental areas of the repository does not appear to have been evaluated. Radionuclides that may have migrated into those areas through the panel closures by diffusion or other transport mechanisms could be released to the ground surface, and gas pressures could be relieved by such boreholes. Also, brine could migrate into those areas from a borehole and then into the waste panels.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.12 Peer Review Panel Concerns – Exploration Boreholes; Second Concern

> The assumption that shorter (40 m) (131.2 ft) borehole plugs beneath the repository horizon will not significantly degrade during the 10,000-year regulatory time frame has not been adequately supported. For the two- and three-plug configurations, degradation of these plugs could result in creation of a low permeability pathway for fluid migration between the Bell Canyon and the repository. For the three-plug configuration, degradation could result in increased fluid migration from a Castile brine reservoir to the repository.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.13 Peer Review Panel Concern – Exploration Boreholes; Third Concern

> The possibility that an effect on the repository could result from Castile brine encountered in an E1 borehole that is assigned a three-plug configuration does not appear to have been considered in the conceptual model. Castile brine could enter the repository during drilling before the borehole is cased and result in increased rates of corrosion, waste degradation, and gas production

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address its concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.14 Peer Review Panel Concerns – Exploration Boreholes; Fourth Concern

> The sensitivity of the performance assessment to the simplified approach taken to determine reference conditions for BRAGFLO output does not appear to have been evaluated for the current model configuration. If reference conditions are not provided at sufficiently frequent time intervals, the modeling results may be erroneous.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.15 Peer Review Panel Concerns – Spallings; First Concern

> The conceptual model for channel flow of gases toward an exploratory borehole appears to be valid but has not been adequately evaluated. Spallings is a potentially important mechanism for direct waste release to the ground surface.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.16 Peer Review Panel Concern – Spallings; Second Concern

> The conceptual model for waste erosion by flowing gases has not been adequately defined. The model describing the source(s) of waste erosion resistance and the parameter(s) characterizing that resistance have not been adequately evaluated. Errors in this conceptual model could lead to over estimating or under estimating the volume of waste released in the spallings process.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.17 Peer Review Panel Concern – Spallings; Third Concern

> The waste has not been adequately characterized and the understanding of its physical properties in its decayed state has not been adequately developed to support the Spallings model. An adequate understanding of waste erosion processes requires an adequate understanding of the properties of the waste.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.18 Peer Panel Concern – Direct Brine Release; First Concern

> The basis for the assumption that radionuclides do not accompany the direct discharge of Castile brine has not been adequately supported. This assumption could lead to underestimating radionuclide releases.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel determined that the response did not reasonably address their concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.19 Review Panel Concern – Direct Brine Release; Second Concern

> Radionuclide transport through entrainment of brine and waste solids in rapid, two-phase liquid/gas releases during inadvertent borehole intrusions does not appear to have been evaluated. This transport mechanism may be an important component of the conceptual model.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address their concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue." The CMPR panel further addressed several issues related to the spallings conceptual model in 1996-97 after submission of the CCA. In addition, a new peer review panel addressed the spallings issues in 2003. Results of these additional peer reviews are discussed in Section 9.3.1.3 and the reports are included in Appendix PEER-2004.

9.3.1.2.20 Peer Review Panel Concern – Direct Brine Release; Third Concern

Releases resulting from flow into an exploration borehole intersecting a disturbed rock zone in the wall of a waste panel do not appear to have been evaluated. Large, open fractures in the walls could significantly increase the local halite permeability, allowing gas and brine to migrate through the borehole to the ground surface.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address their concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.21 Peer Review Panel Concerns – Castile Formation Brine Reservoirs; First and Second Concerns

The basis for excluding larger, potentially depressurized brine reservoirs from performance assessment has not been adequately supported. Larger reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

The basis for the concept of reservoir depletion through previous borehole penetrations has not been adequately supported. Non-depleted reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

After consideration of the DOE response, the panel concluded that the DOE understood the issues and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.22 Peer Review Panel Concern – Castile Formation Brine Reservoirs; Third Concern

The expected probability of encountering pressurized brine beneath the waste panels has not been adequately supported, nor has the basis for apparently ignoring the quantitative value of site-specific geophysical data been presented. Unrealistically low probabilities of encountering brine may result in underestimating radionuclide releases.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address its concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.23 Peer Review Panel Concern – Gas Generation; First Concern

The conceptual model does not consider aluminum in the waste, steel in the rock bolts and netting, radiolysis of water by undissolved alpha emitters, and radiolysis of plastics and cellulosics as sources of additional hydrogen (H), oxygen (O_2), and other gases. Ignoring gases generated by these effects could result in underestimating the gas pressure in the repository.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.24 Peer Review Panel Concern – Gas Generation; Second Concern

> An adequate basis has not been presented for the assumption of complete and rapid carbon dioxide removal by magnesium oxide (MgO) in the waste panels. The chemical conditions in the repository would significantly change if the MgO did not function as planned, and could result in higher radionuclide releases than the model would estimate.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and the response reasonably addressed this gas generation concern. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.25 Peer Review Panel Concern – Gas Generation; Third Concern

> An adequate basis has not been presented for ignoring the effects of heat generation from corrosion and microbial actions. Higher ambient repository temperatures could increase the rates of chemical reactions, fluid flow, and halite creep.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.26 Peer Review Panel Concern – Chemical Conditions; First Concern

> The combined temperature increase (due to radioactive decay and exothermic reactions) and its effect on repository conditions has not been adequately addressed. Significantly higher repository temperatures could accelerate chemical reactions, fluid flow, and halite creep rates.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.27 Peer Review Panel Concerns – Chemical Conditions; Second and Third Concerns

> Phase equilibria have not been critically assessed within the chemical parameters of the conceptual model. A major element stable phase that was overlooked could significantly alter the chemical conditions of the repository and vary the actinide source terms.
>
> The MgO backfill has not been demonstrated to be able to react completely with carbon dioxide (CO_2) generated by microbial action. If the MgO backfill did not react as planned, the pH buffering capability of the repository would be significantly compromised, and could result in underestimating the actinide source terms.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel determined that the DOE response did not reasonably address their phase-equilibria concern. The panel did conclude that the response reasonably addressed their

concern regarding the MgO backfill/CO_2 concern. See CCA Section 9.3.1.2 for details of the DOE response, including "DOE Technical Position versus Panel Issues."

9.3.1.3 Post-CCA Conceptual Models Peer Review

The CMPR panel (CMPRP) started its work in April 1996 and submitted its first report in July 1996. The July 1996 report is discussed in Sections 9.3.1.1 and 9.3.1.2, and was included in CCA Appendix PEER. DOE retained this panel after submitting the CCA to continue addressing the issues that were not completely resolved, although acceptable from a PA point of view. The panel issued three supplementary reports between December 1996 and April 1997. The results of these additional reviews are described in Sections 9.3.1.3.1 through 9.3.1.3.3, below, and the three supplementary reports are included in Appendix PEER-2004.

Two additional conceptual models peer reviews on Salado flow and spallings were conducted in 2003. These are described in Sections 9.3.1.3.4 and 9.3.1.3.5 below, and the two reports are included in Appendix PEER-2004.

9.3.1.3.1 Conceptual Models Supplementary Peer Review – October to December 1996

In its July 1996 report (see Section 9.3.1.2), the CMPRP concluded that of the 24 conceptual models, 13 were adequate for implementation and 11 were not, based on the panel review of the available information and the stated EPA criteria. The DOE reconvened the panel in October 1996 to review changes to the conceptual models, the DOE responses to the findings in the July 1996 panel report, and information available in the CCA (DOE 1996a). In December 1996, the panel issued a report (Docket II-G-12) supplementing the July 1996 report that assessed the changes to the models and DOE responses. For the December 1996 supplementary report, the panel evaluated DOE responses to the panel's findings in the July 1996 report, additional information available since the earlier report, changes that were made to 11 of the models, and the results obtained from implementing the models in PA. Based on this evaluation, the panel's concerns were resolved for all but two of the 11 models previously identified as inadequate. In addition, the new information obtained during this supplemental evaluation did not change the panel's previous conclusions of the 13 models that were found to be adequate.

The two models that remained inadequate in the panel's evaluation were the Chemical Conditions and the Spallings.

For the Chemical Conditions model, the panel's concern related to the ability of the MgO backfill to perform as assumed in PA. The panel stated:

> The ability of the MgO backfill to react completely and rapidly with CO_2 to buffer the chemical system and limit actinide solubilities has not been adequately substantiated by experimental physical results that correctly simulate conditions in the repository. Although the pH buffering assumptions are of considerable importance to many other conceptual models, the conclusion that the MgO will in fact perform as assumed has not been adequately supported.

A full discussion of the panel's position on the Spallings model is contained in Section 3.14 of the panel's report (See Appendix PEER-2004, Section PEER-2004-1.1.3). In summary, the panel stated in Section 5.0 of its report:

> An adequate basis for the parameters used in the mathematical expression of the model has not been developed. In particular, ignoring capillary forces and correlating tensile strength with surface erosion have not been adequately supported by either first principles or experiment.
>
> The principal assumptions upon which the mathematical model is based appear to be incomplete. Waste removal by entrainment in gas flow is expected to occur in a highly dynamic sequence principally involving a spalling process driven by gas flow out of the porous waste normal to the eroded surface. Subsequent erosion by gas flow parallel to the eroded surface in pathways that are not expected to be the primary effect controlling the volume of spall, particularly in early times. In addition, the DOE has not adequately shown that the steady-state assumptions of the model conservatively approximate releases associated with the dynamic process of spall, and the possibility of transonic velocities has apparently not been considered.
>
> The experiments conducted in support of this model appear to have been designed to reproduce the assumptions upon which the model is based, rather than to simulate the dynamic repository system. Although the experiments may support adoption of specific model parameters, they do not demonstrate that the model adequately represents future states of the repository.

9.3.1.3.2 Conceptual Models Second Supplementary Peer Review – January 1997

DOE reconvened the Conceptual Models panel in January 1997 to review additional information developed in response to the remaining issues of the two models, Spallings and Chemical Conditions, found inadequate in December 1996. The panel issued a second supplementary report in January 1997 to supplement the panel's July 1996 and December 1996 reports. In summary, the panel concluded that the Spallings model and the Chemical Conditions model remained inadequate to represent the future states of the repository. An account of the DOE's new presentations to the panel and the panel's responses are given below.

9.3.1.3.2.1 *The Spallings Model in the Conceptual Model Second Supplementary Peer Review*

The DOE responded to the panel's continued concerns through the SNL Spallings Release Position Paper (Hansen et al. 1997a), oral presentations, subsequent discussions, and presentations of additional information. The position paper and initial oral presentations addressed the panel's concerns by grouping them into categories of waste characterization, analog comparisons, and conceptual model issues.

The waste characterization information discussed the physical condition of the waste capable of release by a spallings process, the waste strength, and the expected significance of these results relative to spallings releases. Key points made were that any waste capable of spallings release would be at least partially degraded and have some moisture content, because without the presence of brine, the elevated gas pressure that drives the spallings process could not exist. The model assumption that the degraded waste would have the average characteristics of fine sand were considered by DOE to be highly conservative, because not all of the waste would have degraded to that end state during the 10,000-year regulatory period. The 1 psi (6,895 pascals) cementation strength assumed in the model was also considered conservative, and experimental results were presented showing that dried samples of sand saturated with WIPP brine had indirectly determined tensile strengths that averaged 49 psi. Higher average tensile strengths ranging up to 114 psi were found when NaCl and MgO were added to the brine. The DOE concluded that waste strength dominates spallings releases, the assumed waste strength of 1 psi

(6,895 pascals) was conservatively low, and degraded waste will be heterogeneous and cemented, significantly impeding erosion.

Analog comparisons were presented for spallings-type releases induced by pressure surging to stimulate methane (CH_4) production from coal beds, industrial techniques to remove cuttings by air injection during borehole drilling, the downhole pressure gradient requirements for removal of hydrofracture proppants, wellbore stability and sand production as a function of fluid velocities, and the limitations of the borehole as a transport pathway.

A DOE team made preliminary scoping calculations using an elastic, Mohr-Coulomb model of waste that would be released by tensile failure using the pressure-transient data described above and ranges of values for the key waste strength properties. Several cases were run in which assumed waste compressive strength and internal friction were varied. The details of these analyses are presented in Hansen et al. (1997b). The results indicated that the volume released from a 1-m (3.28-ft) thick waste horizon (representing the fully compacted state of the waste) ranged from 0.37 to 0.59 m^3 (13.06 to 20.8 ft^3), and approached approximately 0.6 m^3 (21.1 ft^3) as the waste tensile strength approached zero.

In response to the DOE's presentations, the panel stated that the additional analog, waste strength, model descriptions, and calculational information provided were either not adequately correlated with WIPP repository conditions or not sufficiently complete or supported to determine that either the spallings model or the results obtained from that model were conservative. Details of the panel's response can be found in Appendix PEER-2004, Section PEER-2004-1.1.4.

9.3.1.3.2.2 *Chemical Conditions Model in the Conceptual Model Second Supplementary Peer Review*

The DOE summarized a calculation of complementary cumulative distribution functions (CCDFs) intended to show the importance of MgO on repository system performance. The CCDFs without MgO present showed increased releases compared to those with MgO present. Releases with MgO present predominantly result from cuttings/cavings and spallings, but without MgO present, the contribution from direct brine release (DBR) significantly increases. DOE emphasized that the mean CCDF without MgO present still remained lower than the EPA limit. DOE also provided additional results of experiments with MgO from the ongoing test program.

The panel examined the various assumptions and parameters used to compute the CCDFs without MgO present and felt that the differences in CCDFs with and without MgO represented the degree of the chemical getter's importance to repository performance. The panel stated its belief that adding the MgO would positively benefit and not detract from the repository performance. However, the panel identified a few additional factors to include for such a CCDF calculation to be definitive, including the effect on corrosion rates, gas generation rates, and pressures over time. However, inasmuch as calculations without MgO showed that DBR would become an important contributor to overall releases, the Chemical Conditions model was a significant contributor to the future states of the repository. Furthermore, according to the panel,

the additional results from the ongoing test program, while interesting, were not sufficient to resolve the panel's concerns about MgO effectiveness.

The results presented to the panel concerned the effect of CO_2 diffusion into the MgO pellets. Test runs of four days following dye infusion indicated that in 24 hours, the dye would travel through the reaction rims to the center of the pellet. However, the panel stated that the test runs were short, the reaction rims were thin and may not have been fully formed, and there were no transient information or bounding calculations to support a conclusion regarding the role of the reaction rims in impeding CO_2 diffusion. According to the panel, information was not available on the diffusion rate of CO_2 into the MgO pellets, especially as a function of reaction rim thickening. The panel believed that the aforementioned test program had not sufficiently progressed to provide a definitive verification that the MgO would perform as planned under repository conditions. Therefore, the panel concluded that the Chemical Conditions model was not sufficiently developed to adequately support PA. For the DOE response to this conclusion from the panel and the panel's final conclusion, see Section 9.3.1.3.3.1.

9.3.1.3.3 Conceptual Model Third Supplementary Peer Review – April 1997

In its January 1997 second supplementary report, the panel continued to find two of the models inadequate to represent the future states of the repository. For the two models found inadequate, Spallings and Chemical Conditions, the panel identified the remaining issues. In the third supplementary report (Docket II-G-22), the panel considered the DOE's April 1997 responses to these remaining issues. The DOE's responses as well as the panel's evaluation of these responses, are presented in Section 3 of the third supplementary report (see Appendix PEER-2004, Section PEER-2004-1.1.5).

For the Spallings model, the panel concluded that the predicted volumes of spalled materials presented in the WIPP CCA are reasonable based on additional consideration of processes that could lead to spalled releases. The panel also concluded that the MgO backfill component of the Chemical Conditions model will function as assumed in the CCA and that this model adequately represents the future states of the repository. Details of the DOE submission to the panel in April 1997 (in response to the panel's findings in the first and second supplementary reports) are provided in the panel's third supplementary report (Appendix PEER-2004, Section PEER-2004-1.1.5) and are summarized below.

9.3.1.3.3.1 *The Spallings Model in the Conceptual Model Third Supplementary Peer Review*

In response to the panel's finding that the existing model used to estimate spalling inadequately represented critical components of the spalling process, DOE initiated a new, mechanistically based computational approach. This approach was composed of three new computational methods to develop additional information on the spalling process. These are called the cavity growth, the quasi-static, and the numerical computation methods. This approach represented the first time that borehole hydrodynamics and cavity growth were linked. The cavity growth method was presented as the primary method for estimating spall volumes. The method simulated the entire response period of the system to an intrusion event, not just the end point. Assuming initial gas pressures and waste strength, the method accounted for the progressive mechanical response of the waste to a transient solution of gas flow in the waste and included the

hydrodynamics of mud and waste ejection through the borehole. The cavity growth method predicted small spalling volumes for assumed initial gas pressures below lithostatic (14.8 MPa) (2147 psi) and a maximum spalling volume of 0.25 m^3 (8.8 ft^3).

The quasi-static method also estimated spall volumes using the same mechanisms and approach as the cavity growth method, but not in a fully coupled manner. This method predicted pore pressure gradients from a consideration of borehole and porous media flow, and used these gradients to compute stresses, failure, and spall volumes. The method was applied to estimate gas volumes, gas pressure distributions, and flow rates for comparison to those predicted by the cavity growth. Graphic comparisons of gas flows and pressures predicted by the cavity growth and quasi-static methods illustrated close agreement.

The numerical method was presented as a tool for evaluating complexities not clearly represented by the other methods. The numerical method couples fluid pressure to the stress response in the waste following a drilling intrusion. Numerical calculations implemented through various computer codes were used to investigate solids mass transport, sensitivity of waste panel geometry, and effects of waste heterogeneity, in addition to predictions of gas pressures and flow rates. Numerical calculations were applied to predict gas pressures and flow rates for comparison to semi-analytic results. The numerical calculations consistently predicted lower pressure gradients and gas flow rates than the other methods. The gradients and rates predicted by the numerical method were significantly lower than those of the other methods at early time steps. Investigations of layered and random configurations of heterogeneous waste using numerical calculations resulted in reduced key parameters that determine spalling volume. Solids mass transport was investigated and determined to be limited prior to mud ejection. Tensile strength was determined to govern the system response, thereby minimizing the overall effects of waste panel geometry and flow properties.

In response to the panel's concern about the properties of the waste that would influence the spalling process, the DOE developed analogs for waste based on ranges of waste contents, corrosion, and biodegradation that could be present following extended exposure to WIPP conditions. The surrogate samples contained varying amounts of corroded and uncorroded iron metal, including addition of goethite, crushed glass and soil, salt and concrete, and MgO, in some cases. Physically degraded paper, plastic, and peat were added to represent chemically degraded organics in the waste. These surrogate waste materials were mixed with brine and consolidated to either 5 or 15 MPa (725 to 2176 psi) to simulate repository conditions. Some of the samples were subsequently dried. Standard testing procedures were used, including Brazilian and hollow cylinder tensile tests, unconfined and triaxial compression tests, and permeability tests. Various parameters, including permeability, porosity, cohesion, tensile strength, compressive strength, Young's modulus, and Poisson's ratio were determined from the test results. These parameters were then used in the various analytical calculations. DOE asserted that these parameters adequately represented the degraded waste expected in WIPP.

The panel was also presented with documentation of analogs to the spalling process at WIPP, mostly rooted in petroleum production technology. The dynamic cavitation of wellbores, specifically those through coal beds, was found to have notable attributes analogous to the spalling process at WIPP. Dynamic cavitation has many similarities to the spalling process at WIPP, such as a pressure pulse phenomenon, gas-driven particulate removal, and a highly

similar physical configuration. The ability to apply established computational codes and the available database of results from this analog helped to corroborate testing and/or computational results.

For the spallings model, DOE did not request the panel to reconsider its conclusion that the original model did not adequately represent the future states of the repository, and did not ask the panel to review a new model against the criteria of 40 CFR 194. The panel was instead requested to determine if the predicted volumes of spalled materials presented in the CCA were reasonable, based on additional consideration of processes that could lead to spalled releases.

In its conclusion on this issue, the panel stated:

> Upon reviewing the DOE's written materials, oral presentations, and responses to specific issues raised by the Panel, the Panel concluded that no significant issues remained regarding the reasonableness of the spallings volumes used by DOE in its CCA for the WIPP. Although the additional waste strength, analog information, and calculational results that were presented to the Panel could be further refined, the Panel determined that this information was sufficiently accurate and complete to support a conclusion that the spallings volumes used in the CCA are reasonable, and in fact appear to overestimate the actual waste volumes that would be expected to be released by the spallings process.

Detailed arguments for reaching this conclusion are provided in the panel's report (see Appendix PEER-2004, Section PEER-2004-1.1.5).

9.3.1.3.3.2 *The Chemical Conditions Model in the Conceptual Model Third Supplementary Peer Review*

The panel concluded in the second supplementary report that the ongoing test program did not sufficiently provide a definitive verification that the MgO would perform as planned under repository conditions. The panel was particularly concerned about whether the results of early tests indicated that reaction rims would inhibit the ability of the MgO to react completely and rapidly with CO_2 to buffer the chemical system and limit actinide solubility.

The DOE provided a draft report to the panel, "Chemical Conditions Model: Results of the MgO Backfill Efficacy Investigation," dated April 23, 1997, along with oral briefings on this report. This report summarized the then-available data and analyses developed from SNL Test Plan TP-97-01. DOE indicated that of the various phases formed from brine contact with MgO pellets, the initial phase, and brucite, will crystallize to nesquehonite and hydromagnesite during short to intermediate times and, over long periods, will dehydrate to magnesite. DOE stated that the brine pH and CO_2 fugacity are controlled at levels throughout the process that effectively lead to low actinide solubilities. Earlier short-term experiments at high CO_2 contact rates indicated the formation of reaction rims. The results for longer periods with high CO_2 contact rates indicated the growth of brucite films, followed by increasing density of nesquehonite needles projecting from the pellets. Shortly thereafter, hydromagnesite forms among the nesquehonite needles, as well as farther from the pellets.

DOE concluded that while there was considerable retardation of CO_2 access to the pellets, accessibility for transfer was maintained. DOE further indicated that the predominant chemical

diffusing species were MgOH+ diffusing from the pellets and HCO_3 diffusing toward the pellets. This gave rise to the precipitation of hydrous magnesium carbonates outside the pellets.

DOE further indicated that, in contrast to the experiments where relatively high CO_2 fluxes occur, the brine at WIPP would become saturated with magnesium compounds before significant introduction of CO_2 species occurs. The reactions would occur at nucleation sites still farther from the pellets, further improving the contact between the reacting species and reducing the formation of reaction rims. This supported the conceptual model assumption that the CO_2 would rapidly and completely react with the MgO. The DOE also reiterated that four times the amount of MgO needed to react with the total quantity of CO_2 generated will be emplaced in the repository.

DOE reviewed the effect of MgO control of pH and CO_2 fugacity in actinide solubility, with hydromagnesite being the predominant intermediate carbonate phase. DOE concluded that most solubilities would be lower with hydromagnesite than if the transition to magnesite occurred, as assumed earlier. DOE also concluded that the results of the test program and analyses demonstrated that MgO will function in the WIPP according to the Chemical Conditions model in the CCA.

In response to the DOE's presentation described above, the panel concluded:

> Based on the information presented to the Panel in the written material and in oral discussion, the Panel concludes that the results available provide an adequate basis to determine that the MgO backfill will function according to the Chemical Conditions Conceptual Model, as used in the CCA, with respect to reaction with generated CO2 gas.

Detailed arguments for reaching this conclusion are provided in the panel's report (see Appendix PEER-2004, Section PEER-2004-1.1.5).

9.3.1.3.4 Salado Flow Conceptual Models Peer Review – March 2003

9.3.1.3.4.1 *Introduction*

Three conceptual models (viz., Disposal System Geometry, Repository Fluid Flow, and DRZ) related to the flow in the Salado used in the CCA were revised due to changes invoked by EPA or knowledge gained since the original conceptual models were developed for the CCA. The Salado Flow Conceptual Models Peer Review panel performed a peer review of the three revised conceptual models between April 2002 and March 2003 and published a report, "Salado Flow Conceptual Models Final Peer Review Report" in March 2003. This report is reproduced in Appendix PEER-2004.

This peer review was performed to fulfill the provisions of 40 CFR 194.27 that require peer reviews of all conceptual models used in any compliance application, and was conducted according to the guidance in NUREG-1297.

9.3.1.3.4.2 *Members of the Peer Review Panel*

Dr. Florie Caporuscio, Dr. John Gibbons, Dr. E. B. Oswald, and Dr. Chunhong Li performed this peer review. Their complete biography data are included in the panel's report (Appendix PEER-2004). The following is a summary of their technical qualifications and experience.

Florie A. Caporuscio has a Ph.D. in Geology and more than 10 years of applied pertinent experience, including having served as the Acting Section Chief, WIPP Technical Review, at EPA Headquarters' Office of Radiation and Indoor Air and as a Staff Geologist at EPA Region II. In addition to Dr. Caporuscio's highly relevant regulatory expertise, his pertinent technical qualifications include extensive expertise in site characterization, geochemistry, radionuclide transport in geological media, and related conceptual models.

John F. Gibbons II has a Ph.D. in Geomechanics and more than 20 years of relevant experience, including having served as the Technical Director of Applied Research Associates for site characterization technology research and development activities augmented by involvement in numerous site characterizations. Dr. Gibbons' site characterization and technology R&D experience is particularly pertinent for peer reviews involving geology, tectonics, hydrology, and related conceptual models.

Eric B. Oswald has a Ph.D. in Hydrology and Water Resources Administration and more than 25 years of applied pertinent technical and regulatory experience. Dr. Oswald's technical qualifications include extensive surface and groundwater flow system analyses and control, contaminant transport, and related conceptual models.

Chunhong Li, Ph.D., is a groundwater modeler with experience in numerical modeling for groundwater flow and transport, numerical simulations to study the influence of matrix diffusion on radionuclide transport in fractured media, and solving scaling-related problems in groundwater modeling.

9.3.1.3.4.3 *Results of the Peer Review*

The panel reviewed the three conceptual models of interest in detail, including the assumptions and scientific information used to develop the model, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The panel also assessed the information used and whether the conceptual model was adequate for implementation in an overall WIPP PA. The review process and review criteria are discussed in Section 2 of the panel's report (see Appendix PEER-2004, Section PEER-2004-2.1.3).

The changed models were reviewed in the context of the WIPP PA. The review included an assessment of the reasonableness of changes in performance estimates resulting from changes in parameter ranges and in changes to, or resulting from, single values. The review evaluated changes in the conceptual structure of the models and changes in component process models and compared the performance results of the changed models with the results of the earlier models to confirm that the changes in performance estimates were reasonable in sense and magnitude. Changes in computations or in fundamental model aspects, such as gridding, were also considered. The review considered the impacts of the changed models on the other WIPP conceptual models and related issues, such as the Option D panel closures.

The panel applied the stringent assessment criteria provided in NUREG-1297, Peer Review of High-Level Nuclear Waste Repositories. The panel member qualifications, independence, and lack of organizational conflict of interest are documented in Appendices A, B, and C of the panel's report (see Appendix PEER-2004, Section PEER-2004-2.1.3).

The following is a summary of the panel's evaluation for each of the three revised conceptual models, as contained in the panel's report.

Disposal System Geometry: The changes in the Disposal System Geometry conceptual model retain the necessary features of the original conceptual model, and the grid changes appear reasonable and sound. The Disposal System Geometry conceptual model continues to be adequate. The results of a PA for the Technical Baseline Migration (TBM) illustrated that the effects of changes in the conceptual model are minimal. The Disposal System Geometry conceptual model continues to represent repository performance with no significant change from its representation in the baseline.

Repository Fluid Flow: The Repository Fluid Flow conceptual model was determined to be both reasonable and adequate for its intended purpose. The identified changes (shaft simplification, EPA mandated parameters, cellulosic molecular structure, and fluid flow paths) appear reasonable and are expected to have minimal impact. The interaction of this conceptual model with the Option D Panel closure (with revised anhydrite fracturing and "flow around" features at high pressure), and subsequent gas pressure realizations in waste panels have been illustrated by a series of TBM CCDFs that show very little resultant change. The influence of the model when coupled with the other conceptual models appears appropriate and adequate.

Disturbed Rock Zone: Four changes to the DRZ conceptual model have the potential to impact PA. These are adopting a range of limiting porosity values to replace the CCA single value for the halite and anhydrite layers in which the DRZ is developed; defining a flow path through the floor of the repository openings into Interbed #139; flow paths around the tops and bottoms of panel seals at high pressure; and an elevation change of the waste panels in the southern end of the repository. Based upon data and analyses presented by SNL, these changes appear reasonable. The change of waste panel elevation aids repository operations and is not considered a significant change. The impact of these changes on PA calculations and CCDF plots appears negligible. The impact on releases sensitive to repository pressures, saturation, and brine volume show that changes in the DRZ model do not significantly impact the predicted compliance of the repository.

9.3.1.3.5 Spallings Model Peer Review – September 2003

9.3.1.3.5.1 *Introduction*

In accordance with the requirement of 40 CFR Part 194.27, the CBFO of the DOE has conducted a peer review of the new spallings conceptual model developed for CRA-2004.

The spallings conceptual model is one of 24 conceptual models used in the WIPP PA. This conceptual model describes a potential release of degraded solid waste materials when repository gas pressure exceeds the hydrostatic pressure in the drilling fluid at the bottom of an intrusion borehole. The CMPRP found in 1997 (see Section 9.3.1.3.3.1) that the Spallings conceptual

model implemented in the CCA was inadequate to describe the detailed spallings process. However, the CMPRP also concluded that "the spallings volumes used in the CCA are reasonable, and may actually overestimate the actual waste volumes that could potentially be expected to be released by the spallings process at the WIPP" (Wilson et al. 1997, Section 4). The EPA agreed with the CMPRP that the spallings conceptual model was inadequate but the results were acceptable for use in PA (EPA 1998a, Section viii; 1998b, Section 7).

After the CCA and PAVT were completed, work continued on the development of a new Spallings conceptual model that would be more technically defensible than the original model.

This independent peer review was conducted in July to October 2003 by a three-member interdisciplinary team having the requisite broad experience and expertise to address the range of issues associated with the spallings scenario and the new numerical model developed by DOE to carry out the predictive PA calculations. The peer review was conducted primarily in Albuquerque, New Mexico, at the DOE Energy Training Center (ETC). The peer review panel was given access to the conceptual model descriptions, scientific reports, briefings, and SNL staff. The panel also had access to reports of prior peer reviews and was given the full cooperation of the DOE and SNL throughout the review. Representatives of the EPA, DOE, and the New Mexico Environmental Evaluation Group (EEG) observed the SNL technical presentations and the panel's questions and deliberations.

This peer review met the regulatory requirements of 40 CFR Part 191 and the implementation of those requirements by 40 CFR Part 194. The peer review was conducted in accordance with the NRC's NUREG-1297, Peer Review of High-Level Nuclear Waste Repositories. The adequacy criteria set forth in NUREG-1297 were those used by the peer review panel for reviewing the new Spallings conceptual model. The peer review panel followed the DOE CBFO MP-10.5, Peer Review, to perform the peer review.

9.3.1.3.5.2 *Members of the Peer Review Panel*

Dr. Ching Yew, Dr. Jonathan Hanson, and Dr. Lawrence Teufel served as members of this panel and authored the panel's report. The panel members' qualifications are briefly described below. Their detailed biographies can be found in the report of the panel (Yew et al. 2003), included in Appendix PEER-2004.

Ching Yew, Ph.D., Chairman: Dr. Yew is currently a Consulting Engineer with over 40 years experience in mechanical engineering. He has a Ph.D. in Mechanical Engineering from the University of California at Berkeley. He worked for the University of Texas at Austin providing research and teaching for 32 years. He is now a Professor Emeritus in the Department of Aerospace Engineering and Engineering Mechanics at the University of Texas at Austin. Dr. Yew is a fellow of the American Society of Mechanical Engineers (ASME) and a member of the Society of Petroleum Engineers (SPE).

Jonathan Hanson, Ph.D.: Dr. Hanson has over 18 years experience as a Consulting Geophysicist. His primary focus as consultant is the development, and subsequent software implementation, of research and analysis tools used in the earth sciences, engineering, and technology. Areas within which this work has been carried out include oil field drilling dynamics and drill bit design and

performance optimization, CH_4 desorption in coal, tailored pulse loading for well stimulation, Vertical Seismic Profiling (VSP) acoustic data analysis, and Coordinate Measurement Machine (CMM) analysis software for manufacturing QA.

Dr. Hanson has a Ph.D. in Geophysics from Oregon State University. He was employed by the University of California Lawrence Livermore National Laboratory from 1978 to 1985, where he worked in the Earth Sciences Division. He has published over 50 related articles and reports. He is a member of the Society of Petroleum Engineers.

Lawrence Teufel, Ph.D.: Dr. Teufel is currently a Langdon Taylor Professor in the Petroleum Engineering Department at the New Mexico Institute of Mining and Technology in Socorro, New Mexico. Dr. Teufel has over 24 years experience in petroleum and natural gas industry. He was chairman of the Petroleum Engineering Department at the New Mexico Institute of Mining and Technology Department from 1997 to 2000. He has a Ph.D. in Geology from Texas A&M University.

Dr. Teufel was employed by SNL as a member of the Technical Staff, Geomechanics Department, from 1979 to 1986, Senior Member from 1986 to 1993, and Distinguished Member from 1993 to 1999.

9.3.1.3.5.3 *The New Spallings Model*

As stated above, DOE developed and presented a new spallings model for this peer review. DR_SPALL (from Direct Release Spall) is a new numerical code written to calculate the volume of WIPP solid waste subject to material failure and transport to the surface as a result of an inadvertent drilling intrusion. The code calculates coupled repository and wellbore transient compressible fluid flow before, during, and after the drilling intrusion process. Mathematical models are included for bit penetration, multiphase (mud, salt, waste, and gas) fluid flow in the well, fluid expulsion at the surface, coupling of the well and the drilled repository, repository spalling (tensile) failure, fluidized bed transport of failed waste, and repository internal gas flow. The wellbore model is one-dimensional with linear flow, while the repository model is one-dimensional with either spherical or cylindrical flow.

Previous work (Hansen et al. 1997b) has shown that the parameter extremes most likely to be of importance to spalling releases are high repository gas pressure, low waste mechanical strength, small waste particle size (after failure), and low waste permeability. DR_SPALL was used to confirm these observations and to better establish the ranges of these parameter values that are important. Since conventional drilling practices are assumed, allowances are made for the continuous pumping of mud during drilling, the possible stoppage of the mud pump, continuous drilling after repository penetration, and the possible stoppage of drilling, based on observations made at the surface by the driller. Of course, one possibility is the continuance of pumping and drilling despite the intrusion into a high-pressure subsurface region.

DR_SPALL is based on the theory of one-dimensional, time-dependent compressible isothermal fluid flow. Somewhat different forms of that theory are used, depending on whether the flow is in the wellbore or in the repository, and whether or not the wellbore currently penetrates the repository. The wellbore and repository flows are coupled at a specified boundary by a set of

conditions. Throughout the process, the drillbit can move downward as a function of time, removing salt or waste material. Flow in the well is treated as a compressible, viscous, multiphase mixture of mud, gas, salt, and possibly waste solids. Flow in the repository is treated as viscous, compressible single-phase gas flow in a porous solid. At the cavity forming the repository-wellbore boundary (following penetration), waste solids freed by drilling, tensile failure, and associated fluidization may enter the wellbore flow stream. Between the well and the repository, flow is treated according to the state of penetration.

Thus, the major elements of the new spallings model include:

- Consideration of multiphase flow processes in the intrusion borehole,
- Consideration of fluidization and transport of waste particulates from the intact waste mass to the borehole, and
- A numerical solution for the coupled mechanical/hydrological response of the waste as a porous medium.

9.3.1.3.5.4 *Criteria for the New Spallings Conceptual Model Review*

The nine criteria used by the peer review members are based on the criteria in EPA regulation 40 CFR Part 194.27, NUREG-1297, the EPA Compliance Application Guidance, and peer panel discussions.

9.3.1.3.5.4.1 Information Used to Review the Conceptual Model

This criterion is an evaluation of data and information used to review the conceptual model. It includes attributes of the disposal system learned by SNL during site characterization activities, exercising the model, and a review of the science and concepts the model is based upon. It also includes pertinent information gained during repository operation.

9.3.1.3.5.4.2 Validity of Assumptions

The validity of key assumptions in the model and its application are assessed in terms of how they might affect the validity of the conceptual model. The review addresses the comprehensive inclusion of important FEPs, and other key assumptions. Examples are the assumption of Darcy flow, use of the ideal gas law at high pressures, and the mathematical method chosen to develop the model grid.

9.3.1.3.5.4.3 Alternative Interpretations

This criterion identifies and assesses plausible alternative conceptual models considered, but not used, by DOE and the rationale for why such alternative models were not used.

9.3.1.3.5.4.4 Uncertainty of Results and Consequences if Wrong

This criterion includes an evaluation of the key uncertainties in the selected conceptual model and a discussion of the consequences if aspects of the conceptual model chosen were

inappropriate or incompletely constrained for the site or subject process. This is not an exhaustive evaluation, but it does ask, “What if the model is wrong?”

9.3.1.3.5.4.5 Appropriateness and Limitations of Method and Procedures

Based primarily on the previous four criteria, this criterion assesses whether the individual conceptual model represents a reasonable approximation of the WIPP disposal system performance.

9.3.1.3.5.4.6 Adequacy of Application

This criterion assesses whether the conceptual model is adequately applied into an acceptable overall PA system. This particular assessment does not cover the relationships among conceptual models, but rather whether the significant components of the conceptual model are appropriately implemented in support of PA. For example, are the various geometrical systems and representations of the conceptual model adequately applied within the performance modeling system, or are there discontinuities between the conceptual model and its application? Also, are there alterations of important key assumptions between the conceptual model and its implementation in performance modeling?

9.3.1.3.5.4.7 Accuracy of Calculations

This criterion assesses whether the results of performance modeling using the conceptual model within the performance system are reliable and accurate to adequately simulate the physical and chemical processes represented.

9.3.1.3.5.4.8 Validity of Conclusions

This criterion judges the validity of the key conclusions based on results of the implementation of the conceptual model in the modeling framework. The key question is whether or not conclusions from model implementation appropriately relate to the expected goal of assessing the long-term performance of the WIPP disposal system. This judgment requires an evaluation of output information from the total system PA.

9.3.1.3.5.4.9 Adequacy for Implementation

This is an overall assessment of whether the conceptual model as implemented in the PA represents a reasonable approximation of the actual disposal system.

9.3.1.3.5.5 *Summary Findings of the Spallings Peer Review Panel*

This section describes the findings of the peer review panel as related to the review criteria discussed in Section 9.3.1.3.5.4. The panel reviewed the spallings conceptual model in detail, including the assumptions and scientific information used to develop the model, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall WIPP PA. The Spallings model was reviewed in the context of the overall approach to the WIPP PA. The review evaluated the structure of the conceptual

model and the mathematics used to embody the model in code. The review also included an assessment of the reasonableness of outputs based on sensitivity to parameter inputs.

The panel refers to presentations by SNL. SNL developed the Spallings model and presented it to the panel on behalf of the DOE.

The complete report of the panel (Yew et al. 2003) is included in Appendix PEER-2004, Section PEER-2004-3.1.2. The following are the findings of the panel as stated in the panel's report.

9.3.1.3.5.5.1 Information Used to Review the Conceptual Model

The data and information available was sufficient to allow a thorough technical review. Necessary attributes of the disposal system are well characterized and understood. The science and concepts upon which the model is based are sound. The model has been benchmarked against other quantified experience in coal fields, and sensitivity analyses indicate the model is valid within the range of its intended use.

9.3.1.3.5.5.2 Validity of Assumptions

The validity of key assumptions in the model and its applications has been assessed in terms of how they might affect the validity of the conceptual model. The review addressed the comprehensive inclusion of important FEPs and other key assumptions. Examples are the assumption of Darcy flow, use of the ideal gas law at high pressures, and the mathematical method chosen to develop the model grid. The essential assumptions used by SNL to develop and exercise the Spallings model were found to be appropriate and valid.

Two assumptions of the model were imposed by the requirements of successful numerical implementation. These were: (1) the existence of the Drilling Damage Zone (DDZ) and (2) a characteristic averaging length required for tensile failure. The former was required for numerical stability of the code as the bit approaches and intersects the repository, and the latter is required for spalling to occur at the face of the cavity. Both of these assumptions are reasonable and have been shown, based on a limited sensitivity analysis, likely to have little effect upon model predictions. It must be emphasized, however, that the inclusion of these mechanisms was motivated primarily by numerical purposes and have not been substantiated by laboratory measurement.

9.3.1.3.5.5.3 Alternative Interpretations

During the spallings peer review, information presented and considered by the panel did not include alternatives or options for the Spallings conceptual model. The original Spallings conceptual model can be considered an alternative. In the present model development, it appears that SNL has employed the simplest and the most straightforward approach in modeling this complex and highly coupled problem. Each individual scenario is described by applying the basic physical equations. The panel concluded that this approach would provide a conservative estimation of spalling release.

9.3.1.3.5.5.4 Uncertainty of Results and Consequences if Wrong

The panel concluded that the conceptual model contains all of the necessary components to adequately represent the physics of the spalling problem. This is a highly coupled and nonlinear problem that involves a fluid-filled wellbore, pre-penetration leak-off from the repository, post-penetration depressurization of the repository, and resulting tensile failure of waste and transport of that waste to the surface.

Obviously, there will be uncertainty in the predictions. This uncertainty can be categorized as follows:

1. Uncertainty in the physical model,
2. Uncertainty associated with numerical implementation of the model, and
3. Uncertainty associated with the input parameters to the model.

The panel judged the physical model used to represent the process to be adequate. The uncertainty associated with the numerical implementation of the model falls within the category of features invoked for numerical stability or other reasons that have little justification in terms expected physical processes or actual laboratory measurement. These principally include the existence and characteristics of the DDZ and the requirement of a characteristic averaging length near the cavity wall necessary for tensile failure to occur. Probably the largest effect on prediction error will be the uncertainty associated with the input parameters to the model, most notably the waste properties.

All of these uncertainties will affect the predicted spallings volume. Some limited sensitivity analyses have been carried out at the panel's request to look at the effect of DDZ parameters and tensile stress averaging length on predicted spall volumes. These analyses suggest that, even though these parameters do affect the volumes, the effect is probably small.

The largest uncertainty will be associated with assumed material parameters of the waste that serve as input to the model. These include tensile strength, porosity, permeability, particle size, and so on. Extensive laboratory measurements of these parameters were carried out on simulated waste material under predicted in situ conditions. The uncertainty in these parameters is associated with the uncertainty in how they may be modified by degradation over time in the in situ environment. This cannot be predicted with any degree of certainty. Therefore, one must make a reasonable estimate of the possible range of these parameters and look at the variability of the model output due to this range of input.

The panel concluded that the range of waste material properties used is reasonable based on the current understanding of these parameters and how they may change in time under in situ conditions.

Based on these arguments, the panel concluded that the combined uncertainty in the model, implementation, and input will necessarily lead to some level of model prediction error. This error, however, is expected to be small and acceptable within the context of best practices.

9.3.1.3.5.5.5 Appropriateness and Limitations of Method and Procedures

Based primarily on the previous four criteria, the panel concluded that the methods and procedures used by SNL to develop and present the spallings model are acceptable and reasonably represent future repository performance.

9.3.1.3.5.5.6 Adequacy of Application

The peer review panel found the new spallings conceptual model to be adequate. The model structure is technically sound in mathematical formulation and numerical implementation. The panel also found that the model reasonably approximates the expected WIPP disposal system performance. The panel's assessment did not address the relationships among conceptual models in detail, but rather whether the significant components of the spallings conceptual model are appropriately implemented in support of PA. For example, the various geometrical systems and representations of the conceptual model appear to be adequately applied within the performance modeling system, with no significant inconsistencies in the application of the conceptual model to model the WIPP waste disposal system.

9.3.1.3.5.5.7 Accuracy of Calculations

The results yielded using the Spallings conceptual model appear reliable and reasonably accurate to adequately simulate the physical processes of the WIPP waste disposal system.

9.3.1.3.5.5.8 Validity of Conclusions

There are no specific conclusions drawn, with respect to the Spallings conceptual model, other than its ability to characterize appropriate properties, processes, and features of the repository during a potential spallings event. The panel concludes that the Spallings conceptual model reasonably represents future repository performance.

9.3.1.3.5.5.9 Adequacy for Implementation

The WIPP conceptual models, as interpreted through the various codes, are ultimately integrated at the CCDFGF where results are prepared. The integration of the conceptual models, therefore, identifies the overall WIPP PA model as a complex structure that represents 24 conceptual models through preparatory, process, flow and transport, presentation, and enabling codes.

Applying evaluation criteria to the integration of a given conceptual model, as a step in the assessment of model adequacy, results in most of the discussion focusing on the review criteria discussed in Section 9.3.1.3.5.4. For example, evaluation of information used in the integration, assumptions, uncertainties, adequacies, accuracy, and validity are all based on the conceptual model, or the implementing mathematical representation or code, being evaluated.

Because a total and complete system PA was not available for the panel to review, the overall adequacy for implementation of the spallings model integrated with the other conceptual models can only be judged at this time relative to the criteria discussed earlier in this section. Based on the review of the Spallings conceptual model, the supporting assumptions, and mathematical

implementation, integration of this conceptual model with the other conceptual models is expected to be adequate.

Thus, the panel applied the stringent assessment criteria provided in NUREG-1297, Peer Review of High-Level Nuclear Waste Repositories, and concluded:

- The new Spallings conceptual model appears generally sound in its structure and reasonableness.
- The proposed implementation of the new Spallings model appears reasonable.

9.3.2 Waste Characterization Analysis Peer Review

40 CFR § 194.27(a)(2) states that a compliance application shall include documentation of peer review conducted for "waste characterization analyses as required in § 194.24(b)." 40 CFR § 194.24 (b) states:

> The Department shall submit in the compliance certification application the results of an analysis which substantiates:
>
> (1) That all waste characteristics influencing containment of waste in the disposal system have been identified and assessed for their impact on disposal system performance. The characteristics to be analyzed shall include, but shall not be limited to: solubility; formation of colloidal suspensions containing radionuclides; production of gas from the waste; shear strength; compactability; and other waste-related inputs into the computer models that are used in the performance assessment.
>
> (2) That all waste components influencing the waste characteristics identified in paragraph (b)(1) of this section have been identified and assessed for their impact on disposal system performance. The components to be analyzed shall include, but shall not be limited to: metals; cellulosics; chelating agents; water and other liquids; and activity in curies of each isotope of the radionuclides present.
>
> (3) Any decision to exclude consideration of any waste characteristic or waste component because such characteristic or component is not expected to significantly influence the containment of the waste in the disposal system.

A Waste Characterization Peer Review (WCPR) Plan (see CCA Appendix PEER) was prepared and approved in accordance with the requirements of TP 10.5. The DOE convened a four-member peer review panel, in accordance with the guidance of NUREG-1297, to perform the review. The panel members were:

- Duane C. Hrncir (Panel Chairman), University of Texas, Dallas;
- Evaristo J. Bonano, Beta Corporation International;
- James F. Bresson, Informatics Corporation; and
- Patricia J. Robinson, Energy, Inc.

See CCA Appendix PEER for the qualifications of the panel.

9.3.2.1 General Results

The following excerpts are from the WCPR report (CCA Appendix PEER). They address areas that the panel considered adequate.

- Radionuclide Inventory and Release Limits. The analysis performed in estimating the parameters needed to establish the radionuclide inventory and release limits for estimating the CCDF was very thorough and systematic. This is a solid piece of work.
- Solubility. The median values for actinide solubility are reasonable.
- Colloids. The experiments dealing with colloids in the repository were well done.
- Production of Gas. (Appendix WCA) adequately identifies the major issues of gas generation in the waste.
- Permeability. There are experimental data to support the conclusions about permeability discussed in (Appendix WCA). The panel concurs with the conclusions.
- Heat Generation. The analyses presented in (Appendix WCA) concerning heat generation are well done. The conclusion that this characteristic will have a negligible effect on performance is justified.
- Metals. The assumption that low valent metals in the repository will maintain a reducing atmosphere in the repository is substantiated by experimental data.
- Cellulosics. Cellulosics will be microbially degraded to carbon dioxide and CH_4. They also may provide a source of humic colloids. Treatment of these issues by (Appendix WCA) has been discussed in the appropriate sections above.
- Water and Other Liquids. The panel agrees with the findings in (Appendix WCA). Water in the waste is not an issue in repository performance.
- Exclusion of Waste. (1) The analysis performed to support the exclusion of radionuclides is methodical, complete and well done. (2) The exclusion of hazardous wastes is justified.

9.3.2.2 Waste Characterization Peer Review Panel Concerns

The WCPR panel concluded that several areas they examined were inadequate. The WCPR panel's concerns, the DOE's response to the panel's concerns, and the panel's responses are briefly described below. For details of the DOE and the panel's interactions, see CCA Appendix PEER.

9.3.2.2.1 Peer Review Panel Concern – Radionuclide Inventory and Release Limits

> The analysis used to determine the heterogeneous source term for the intrusion scenario was not clearly presented in CCA Appendix WCA, resulting in an inability to judge its validity and degree of conservation.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.2 Peer Review Panel Concern – Solubility; First Concern

> The median values for actinide solubility are reasonable, but the uncertainty ranges about the median are too low and inconsistent with earlier results from the expert judgment panel study.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.3 Peer Review Panel Concern – Solubility; Second Concern

> The issue of actinide solubility is not adequately addressed in CCA Appendix WCA because the controlling assumption concerning MgO chemistry in the repository has no experimental data to support it.

After consideration of the DOE response, the panel concluded that the DOE understood the issues; however, the panel determined that the response did not reasonably address their concern. See CCA Section 9.3.2.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.2.2.4 Peer Review Panel Concern – Colloids

> The uncertainty given for the colloid actinide source term is not adequate for purposes of PA calculations because the number of experiments performed does not generate meaningful statistical samples from which an uncertainty could be adequately calculated.

After consideration of the DOE response, the panel concluded that the DOE understood the issues and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.5 Peer Review Panel Concern – Production of Gas; First Concern

> The issue of the reaction of carbon dioxide with the MgO backfill is not adequately resolved in CCA Appendix WCA, because of a lack of experimental data which demonstrated that this chemistry occurs under conditions anticipated in the repository.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address their concern. See CCA Section 9.3.2.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.2.2.6 Peer Review Panel Concerns – Production of Gas; Second and Third Concerns

> CCA Appendix WCA does not adequately address the fate of microbially generated CH_4.

> The treatment of gas generation in CCA Appendix WCA is generally well done. However, the Appendix does not deal with the disposition of the generated CH_4. The gas

> will be produced on a mole per mole basis with carbon dioxide and yet there is no mention of its fate in the repository.

After consideration of the DOE response, the panel concluded that the DOE understood the issues and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.7 Peer Review Panel Concern – Compressibility

> Appendix WCA references studies describing the analysis of waste compressibility; however, it fails to provide any discussion of the results of these studies.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.8 Peer Review Panel Concern – Strength

> CCA Appendix WCA references a study on waste strength, but fails to discuss the results of this study in the context of its impact on disposal system performance.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.9 Peer Review Panel Concern – Porosity

> There are conflicting statements in CCA Appendix WCA concerning the importance of porosity to the performance of the repository. As a result, the panel was unable to evaluate the treatment of this parameter.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.10 Peer Review Panel Concern – Metals

> The position taken in CCA Appendix WCA concerning the uptake of organic ligands by the transition metals is not defensible due to lack of experimental data. It is not correct to apply results from experiments performed in low ionic strength solutions to WIPP brines.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.11 Peer Review Panel Concern – Chelating Agents

> The position that transition metals will react with the organic ligands in the waste to render them unavailable for reaction with actinides should be justified with experiments done in high ionic strength brines.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.3 Engineered Alternatives Cost/Benefit Study Peer Review

Per the criteria of 40 CFR § 194.27(a)(3), a compliance application shall include documentation of a peer review that was conducted for "(e)ngineered barrier evaluation as required in §194.44." 40 CFR § 194.44(b) states

> In selecting any engineered barrier (s) for the disposal system, the Department shall evaluate the benefit and detriment of engineered barrier alternatives, including but not limited to: Cementation, shredding, supercompaction, incineration, vitrification, improved waste canisters, grout and bentonite backfill, melting of metals, alternative configurations of waste placement in the disposal system, and alternative disposal system dimensions. The results of this evaluation shall be included in any compliance application and shall be used to justify the selection and rejection of each engineered barrier evaluated.

In September 1989, DOE established the Engineered Alternatives Task Force (EATF) to identify and screen potential engineered alternatives (EAs) with respect to both effectiveness and feasibility of implementation in addressing concerns about gas generation and human intrusion. EAs are engineered barriers, waste modifications, facility modifications, process changes, or any other approach that enhances disposal system performance or reduces uncertainty in the predictions of disposal system performance.

The EATF, in turn, chartered an Engineered Alternatives Multidisciplinary Panel that qualitatively screened an initial 64 alternatives to 36. The EATF then combined these candidates into 14 logically consistent and potentially actionable EAs. These 14 candidates, plus a base case, were evaluated with respect to relative effectiveness and feasibility in addressing gas generation and inadvertent human intrusion impacts. The EATF issued its final report in July 1991 (DOE 1991). A subsequent peer review of the EATF Report is documented below (Section 9.4.4).

The DOE prepared the Engineered Alternatives Cost/Benefit Study (EACBS) Final Report (DOE 1995b and CCA Appendix BARRIERS, Attachment EBS) in 1995. The EACBS Report includes a qualitative assessment of estimated costs, potential risks and benefits, and relative repository performance impacts resulting from the implementation of EAs .

The EACBS differs from the 1991 EATF in two fundamental ways. First, in the EACBS, EAs are assessed against 8 factors specified in 40 CFR § 194.44(c)(1) that provide the data and information for use in selecting or rejecting an EA. The eight factors are:

1. Long-term repository performance,
2. Uncertainty in compliance assessment,
3. Impact on public and worker exposure,
4. Impact on waste removal,
5. Transportation risk,
6. Public confidence,

7. Impact on system cost and schedule, and

8. Impact on other disposal systems.

Second, the 1991 EATF study was aimed at identifying alternatives which, if needed, would improve disposal system performance to the point where compliance with quantifiable standards was achieved. The EACBS begins with the assumption that compliance is achieved and the comparison of alternatives is to assist future decision making should a need for additional EAs be identified.

An EACBS Peer Review Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of TP 10.5. The plan describes the peer review process used to ensure a sound technical basis for the selection or rejection of EAs should it be determined that additional engineered barriers are needed to satisfy the requirements of 40 CFR Part 191 Subparts B and C.

An independent peer review committee was assembled by the Waste-Management Education and Research Consortium (WERC) to provide the DOE with a review of the EACBS Final Report. The peer review was conducted in 1996, in a manner consistent with NUREG-1297 (NRC 1988) guidance and the requirements of TP 10.5 (DOE 1996c).

The purpose of the EACBS peer review was to assess the validity of the assumptions and the technical approach used in the EACBS and evaluate the adequacy of the work. The peer panel review focused on determining the reasonableness of the report's conclusions.

In accordance with the provisions of TP 10.5, a panel was selected. The nine-member panel was composed of the following individuals:

- Rohinton K. Bhada (Chairman), New Mexico State University;
- Catherine T. Aimone-Martin, New Mexico Institute of Mining and Technology;
- Arturo Duran, Environmental Consulting and Engineering;
- Douglass J. Kuhns, Lockheed-Martin Idaho Technologies Corporation;
- Cindy R. Lewis, Parsons Engineering Science, Inc.;
- James D. Navratil, Rust Federal Services;
- Jamal Rostami, Earth Mechanics Institute;
- Dennis M. Smith, Technical & Management Systems and Services, Inc.; and
- Krishan K. Wahi, Geological Repository Assessment Methodologies, Inc.

See CCA Chapter 9, Section 9.3.3, for the panel members' qualifications and other details regarding the EACB peer review.

Panel members have established academic qualifications, as well as substantial relevant experience, and are independent of the WIPP project. Additional information regarding the technical qualifications of the panel members is provided in the final peer review report (see CCA Appendix PEER). A letter from the Peer Review Manager regarding the verification of independence for panel members is also presented in CCA Appendix PEER (additional information regarding the independence of the panelists is available in the CBFO Record Center.) All technical disciplines needed to perform the review were represented.

After orientation and training, as required by TP 10.5, the panel was briefed by the EACBS report authors and DOE staff. To review the large amount of information provided in the EACBS and supporting documentation, the peer panel divided itself into three subcommittees to address specific factors of the study. The subcommittees were formed on the basis of the expertise that was most appropriate for each set of factors. Eventually, all subcommittee findings were reviewed by the entire panel.

9.3.3.1 General Results

Following its review, the panel prepared a final report on July 10, 1996. The results of the EACBS peer review evaluation are summarized in Table 9-2 and a copy of the complete report is provided in CCA Appendix PEER. The following conclusions are presented in the final report:

- the information presented within the EACBS is of high quality,
- the approach taken is valid,
- the conclusions drawn are reasonable, and
- the analysis was conducted in accordance with 40 CFR § 194.44 criteria.

The EACBS panel report also identifies several findings/concerns/issues. The DOE developed a response to the issues identified in the panel report. The panel's concerns and the DOE responses are discussed in the following sections.

9.3.3.2 Engineered Alternatives Cost/Benefit Study Peer Review Panel Concerns

The DOE conducted an evaluation to assess the relative benefit and associated cost of various EAs for the disposal system. The analytical methodology and final results of the EACBS were critically reviewed for technical merit, adequacy, and accuracy of results by a team of outside experts.

Table 9-2. Summary of the Peer Review of the EACBS Evaluation Factors and Criteria

Engineered Alternatives Evaluation Factors	A. Adequacy of Requirements and Criteria	B. Validity of Assumptions	C. Alternative Interpretations	D. Uncertainty of Results and Consequences if Wrong	E. Appropriateness and Limitations of Methodology and Procedures	F. Adequacy of Application	G. Accuracy of Calculations	H. Validity of Conclusions
Evaluation of the EA Screening Process	Generally considered to be adequate, although some other potential EAs could have been added.	Evaluation was qualitative and was to assess assurance, not compliance. This assumption was prescribed by law and was therefore considered valid.	None.	The screening process was conservative in nature and was thus more inclusive than exclusive.	The screening process was considered to be appropriate. A better description of the process would have enhanced the report.	The sequence of comparing, scoring, prioritizing, etc. was adequate to achieve the results.	The use of algorithms and professional judgement were deemed appropriate.	The final list of EAs selected for further analysis was reasonable.
1. Long Term Repository Performance	Adequate	Broad Level: Appropriate. Detailed Level: Intrusion scenarios assumed to occur at 5,000 years; and actinide solubility assumptions were conservative. Broad Level: Appropriate; Detailed Level: Uncertainty in creep parameters was not considered. Differences in creep closure estimates could affect the quantity and rates of release; early intrusion could result in significantly different releases; and EAs with plasma processing or clay backfill were not credited with enhanced Pu immobilization.	Different creep closure models or model coefficients may affect the relative benefits of EAs; and the effects of future mining nearby could have been considered as an additional human intrusion scenario.	Uncertainty will result due to the uncertainty of input parameters; however, no severe consequences if wrong; conservative parameter estimates were used.	Use of the Design Analysis Model (DAM) model to predict performance was appropriate; however, important advances in creep modeling were not used. Model did not (and cannot) consider stratigraphy (e.g., anhydrite layers) in the mechanical response calculations.	Compressive strengths of waste/backfill EAs is misleading; and intrusion before creep closure not adequately analyzed.	Creep rate calculations checked and qualitatively agree.	Effectiveness of some EAs may have been under-estimated due to simultaneous consideration of pre-closure and post-closure risks.

Table 9-2. Summary of the Peer Review of the EACBS Evaluation Factors and Criteria — Continued

Engineered Alternatives Evaluation Factors	A. Adequacy of Requirements and Criteria	B. Validity of Assumptions	C. Alternative Interpretations	D. Uncertainty of Results and Consequences if Wrong	E. Appropriateness and Limitations of Methodology and Procedures	F. Adequacy of Application	G. Accuracy of Calculations	H. Validity of Conclusions
2. Uncertainty in Compliance Assessment				Relative nature of analysis allows meaningful conclusions to be drawn. Discussion of uncertainty in the results does not fully reflect the uncertainty analysis that was in fact carried out.		Methods used are completely applicable for comparative screening process		
3. Worker and Public Risk	Adequate	Risk assumptions are conservative, conventional, and adequate for the work performed.	None.	Uncertainties err on the side of safety and risks are likely overstated.	Methodology did not account for risks inherent in current waste handling methods. For example, relative risks could have been different for these EAs having long development/ processing time.	Methods are applicable for the comparative screening process.	Calculations are reasonable and consistent.	Risk conclusions for CH-TRU waste appear valid. Risk conclusions for RH-TRU waste are absent.
4. Impact on Waste Removal	200-year period for waste removal requires justification; different time frames have a major impact on the methods used for retrieval.	Assumed excavation technology is appropriate, but the data used in the calculations is not state of the art. For long term retrieval, assumptions and methodology used for mining rate and time estimates are correct; quantitative studies are needed. Short-term retrieval method, rate, and schedule not	Alternative methods for recovery based on different time frames could have been performed.	Uncertainty associated with the compressive strength of the EAs is not critical to the relative comparison of EAs. The waste is removable with today's technology and the decisions made based on the EACBS are not irreversible.	Methodology was appropriate to estimate time required for long-term removal; however, some of the assumptions, data, and terminology were not suitable for the application.	Time of waste removal was not adequately addressed.	Overall, calculations could not be checked for accuracy; there is no reference to machine type, specifications, and utilization.	Although the quantitative results of the analysis can not be directly used for assessment of the EAs, the general conclusions based on a qualitative comparison with the baseline are valid and

Table 9-2. Summary of the Peer Review of the EACBS Evaluation Factors and Criteria — Continued

Engineered Alternatives Evaluation Factors	A. Adequacy of Requirements and Criteria	B. Validity of Assumptions	C. Alternative Interpretations	D. Uncertainty of Results and Consequences if Wrong	E. Appropriateness and Limitations of Methodology and Procedures	F. Adequacy of Application	G. Accuracy of Calculations	H. Validity of Conclusions
		addressed.						acceptable for long-term removal. Consideration of short-term removal could change the results.
5. Transportation Risk	Adequate	Risk analysis assumes 20 year active life, yet the WIPP operational window is for 33 to 35 years. Transportation is by truck only; no explanation why rail is not evaluated. Overall, however, risk assumptions are conservative, reasonable and well within contemporary transportation risk analysis.	There is no reasonable alternative interpretation.	Population densities will be different if the period of transportation and disposal is greater than 20 years. An added risk could occur for those EAs that have a longer time frame.	The methodologies were considered to be generally appropriate. Limitations include addressing only CH-TRU waste, a "bounding" accident not being evaluated, and lack of justification for selected values. The limitations should not compromise the EA evaluation so long as the 20 versus 35 year issue is recognized.	Methods used are applicable for comparative screening process.	Calculations appear to be reasonable and consistent with the methodology.	The conclusions drawn for purposes of a qualitative comparison of the transportation risks of the various EAs appears valid.
6. Public Confidence in the Performance of the Disposal System	Adequate	Assumptions regarding the public's concerns as to content, categorization, timeliness, and affected in-state population are	Slightly different interpretations are possible, but would not affect the	Uncertainty is low regarding the public's position on the EAs and slight misinterpretations are not considered	The methodology used to assess public confidence was appropriate. A limitation is the lack of	Application of the methodology was considered proper.	Categorization of public comments was checked and determined to be relatively	The conclusions appear appropriate.

Table 9-2. Summary of the Peer Review of the EACBS Evaluation Factors and Criteria — Continued

Engineered Alternatives Evaluation Factors	A. Adequacy of Requirements and Criteria	B. Validity of Assumptions	C. Alternative Interpretations	D. Uncertainty of Results and Consequences if Wrong	E. Appropriateness and Limitations of Methodology and Procedures	F. Adequacy of Application	G. Accuracy of Calculations	H. Validity of Conclusions
		reasonable. Although out-of-state populations were not addressed, this is not considered to be a major deficiency.	conclusions of the study.	serious.	opportunity for out of state public comment.		accurate with only minor discrepancies.	
7. System Cost and Schedule	Adequate	Cost and schedule assumptions are considered to be valid with uncertainty of approximately 30 percent associated with the uncertainty of the waste inventories.	A few alternate interpretations may originate from the guidance documents. However, they would have little effect on the study's results.	The estimated costs and schedules were reasonable.	The methodology for cost and schedule evaluation is considered appropriate.	Methodologies were appropriately applied.	Spot checks determined that calculations were performed according to accepted methods and procedures.	In general, the conclusions are valid.
8. Impact on Other Disposal Systems	Adequate	The assumptions of waste type and volume have uncertainties associated with them that may impact other disposal systems. The assumptions used appear reasonable.	The uncertainties associated with waste volume can be interpreted in different ways. Some interpretations will result in higher volumes while others will result in lower volumes.	Uncertainty of results are +10 percent to 25 percent based on waste volume uncertainty. No serious negative consequences should occur because of this uncertainty.	Procedures used are technically defensible. A limitation of the methodology is the reliance on the accuracy of waste volume.	The techniques used were adequate to meet the intended goal.	The basis of calculations was not provided in the EACBS; however, using reasonable assumptions, data spot checks were found to be accurate.	The conclusions reached are valid and support the end use of the report.

The EACBS panel expressed several concerns regarding the EACBS. Details of the EACBS panel's concerns and the DOE's response to the panel's concerns (Response to Issue) are presented in CCA Appendix PEER and CCA Section 9.3.3.2. The panel was asked to review the DOE responses and determine whether they agreed with the responses. The panel's reaction to the responses are also provided in CCA Appendix PEER (Peer Reviewer Consideration of Response). In those instances where panel members disagreed, from a technical-based perspective, with the DOE response, the DOE developed additional information that describes the justification for its final technical position on the concern (DOE Technical Position versus Panel Issue). A summary of the panel's concerns and the panel's reaction to the DOE responses are provided below. For details, see CCA Appendix PEER.

9.3.3.2.1 First Peer Review Panel Concern – Results of the Engineered Alternatives Identification/Screening Process

> Clarification is needed in the text of the report on the steps involved in the identification/screening process, including steps that occurred after the Engineered Alternatives Task Force performed their initial evaluation. Better define what is meant by "screening," "optimization," and "prioritization." Clearly state the criteria used for each stage of the process.

The DOE stated that it understood the confusion surrounding these terms, particularly in light of the multiplicity of the agencies and organizations that have expressed interest in how EAs should be applied to the WIPP. In this application, DOE had attempted to use these terms in a fashion consistent with the EPA's usage in 40 CFR Part 194 and the Compliance Application Guidance (CAG) (EPA 1996c). The three processes are documented in the EACBS. The specifics of the screening process and original prioritization are found in Appendix D. The optimization process is briefly described in Appendix D; this process included management decisions not defined in the report.

Four panel members commented on the DOE response to this concern. Two members agreed with the response and one disagreed. The fourth panelist, although agreeing that the information in the response was adequate, believed this information should be provided in the main part of the EACBS.

The DOE has clarified the process in Section 7.4.3.1 of the CCA, which includes a description of the DOE Management Assessment used to determine the final 18 EA used in the analysis.

9.3.3.2.2 Second Peer Review Panel Concern – Results of the Engineered Alternatives Identification/Screening Process

> Some concern was expressed that the screening process was conducted independent of a consideration of the eight factors used in evaluating the EAs. If the screening process and evaluation of EAs according to the eight factors had been iterative, the list of EAs analyzed as well as the results of both the screening process and the evaluation of the EAs may have been different. However, this would probably be an endless process of iterations and not justified because of cost and time involved.

In response, the DOE stated that to ensure a reasonable menu of alternatives for potential selection of engineered barriers, the DOE elected to separate the screening process from the actual factor analyses. The key screening criteria to select EAs for detailed factor analysis was therefore the impact on improving long-term performance, with additional concern given to technological and regulatory feasibility of implementation. The selected alternatives were then evaluated with respect to the eight factors. Factors such as waste retrieval or public perception were not considered in the selection criteria because these factors are not related to compliance with 40 CFR Part 191 Subparts B and C.

Three panel members commented on the response. One panelist agreed with the response as written and one other disagreed. The third commenter agreed with the response but believed that the DOE should make a stronger case that the EACBS considered the breadth of plausible alternatives.

The DOE's technical position is that the DOE developed a screening process that used a qualitative assessment of the potential benefits on the WIPP disposal system. Good engineering practices were used in this assessment. A pure quantitative rating could not be justified because it would require a complete analysis of each EA by all eight factors. The intent of the screening process was to identify EAs with the highest potential to benefit the disposal system and further analyze their impacts within the multifactor analysis.

9.3.3.2.3 Third Peer Review Panel Concern – Results of the Engineered Alternatives Identification/Screening Process

> Remote-handled waste was not considered. This issue may have implications to the compliance application.

In response, the DOE stated that RH-TRU waste constitutes a maximum of five percent of the inventory by volume. This material is practically identical to CH-TRU waste except that it is contaminated with short-lived beta-gamma emitters, as well as the long-lived actinides present in CH-TRU waste. There is therefore no need to consider RH-TRU waste separately from a long-term performance standpoint. There may have been some differences in the treatment costs for the RH-TRU fraction because of the possible need for a greater degree of shielding, and there may have been additional worker risks involved because of the penetrating radiation. The Engineered Alternatives Screening Working Group concluded, therefore, that the limited volume of RH-TRU waste did not justify separate consideration of this small fraction of the inventory.

The only panel member who commented on the response agreed, in part, with the response; however, the panelist suggested that, for completeness, a factor approach be used that could weigh the risk and cost of handling RH-TRU waste into each EA under evaluation.

The DOE's position is that because the RH-TRU waste is a small percentage of the total WIPP waste inventory, is limited by the Land Withdrawal Area, and will decay to CH-TRU waste levels in a relatively short time, the DOE believes that RH-TRU wastes need not be considered separately in the EACBS.

9.3.3.2.4 Peer Review Concern – Evaluation of Factors 1 and 2: Impacts on Long-Term Repository Performance and Uncertainty in Compliance Assessment

These factors focused primarily on the analyses performed with the DAM computer simulation program. This program was used to predict the future performance of the repository with different EAs given three different human intrusion scenarios. Values for several parameters are required as input to the model. Many input parameters were treated as being uncertain; that is, ranges and distributions were assigned to such parameters. Other parameters were given constant (single point) values. The panel members checked many of these parameters, as well as QA documentation for the computer simulation itself. No major discrepancies or errors were noted. It was noted by the panel members that much of the information used in the model was selected to be consistent with the PA conducted by SNL. The DAM was chosen to determine relative repository performance because it parallels SNL's PA work in a less complex manner, allowing various changes to the inputs to be run quickly on a PC format. For details on a number of subissues under this category, see CCA Chapter 9.0 and CCA Appendix PEER.

9.3.3.2.5 First Peer Review Panel Concern – Evaluation of Factor 3: Impact of Engineered Alternatives on Worker and Public Risk

> An evaluation of the risks associated with the processing of remote-handled (RH) waste is absent. It would be helpful to include a discussion of the possible relative comparison between the risk associated with CH and RH wastes. For example, one can draw conclusions based on radionuclide difference, radionuclide mobility, potential for release, transport mechanisms, and exposure scenarios associated with both waste processing and long-term performance.

The DOE responded that the inventory of RH-TRU waste was combined with the CH-TRU waste and was not considered separately in the EACBS. RH-TRU waste is limited by statute to comprise no more than five percent by volume of the total WIPP waste inventory. This material is practically identical to CH-TRU waste, except that it is contaminated with short-lived beta-gamma emitters as well as the long-lived actinides present in CH-TRU waste. These beta-gamma emitters will rapidly decay in the 100-year postclosure period during active institutional control. Therefore, there is no need to consider RH-TRU waste separately from a long-term performance standpoint.

The only panel member who commented on this response partially agreed with the DOE response. That panelist made the same comment as for the RH-TRU waste concern discussed in Section 9.3.3.2.3.

The DOE's position is that because the inventory of RH-TRU wastes is a small percentage of the total WIPP waste inventory, is limited by the Land Withdrawal Area, and will decay to CH-TRU waste levels in a relatively short time period, the DOE believes that RH-TRU wastes need not be considered separately in the EACBS.

9.3.3.2.6 Second Peer Review Panel Concern – Evaluation of Factor 3: Impact of Engineered Alternatives on Worker and Public Risk

> Many of the assumptions used in assessing worker and public risk appear to be borrowed from the Environmental Management Programmatic Environmental Impact Statement (EMPEIS). While these assumptions may be valid, additional discussion of them in the text of the EACBS would provide further clarification.

The DOE responded that many of the assumptions and initial analysis parameter values were, as the panel has noted, taken from the EMPEIS. This consistency was important to keep the EACBS risk analysis consistent with important aspects of other related DOE risk evaluations nationwide. The entire suite of WIPP National Environmental Policy Act (NEPA) documents is available for review in several locations. The DOE did not see the need to discuss these assumptions in any greater detail within the EACBS.

The only panel member who commented on this response agreed with the DOE response.

9.3.3.2.7 Third Peer Review Panel Concern – Evaluation of Factor 3: Impact of Engineered Alternatives on Worker and Public Risk

> Additional risks posed by allowing the waste to remain above ground for longer time periods necessitated by some of the EAs were not evaluated. This could underestimate risks associated with those EAs.

The DOE responded that the purpose of the EACBS study was to determine relative risks from various TRU waste processing and disposal alternatives, and did not directly include waste storage impacts, as noted. It is true that in some cases waste would be stored aboveground for a longer time for some of the EAs, particularly when a given treatment process has not yet been fully developed for TRU waste. However, ultimately, a long-term disposal decision would be needed. The scope of the EACBS was to look at alternatives to support the disposal decision. It is assumed that the waste containers would be stored for an additional time period within the expected lifetime of the container, and therefore no repackaging related risks would be included. It is further assumed that workers will continue to limit their exposure to stored waste containers in accordance with the as low as reasonably achievable (ALARA) policy. Therefore, the loss of resolution did not affect the DOE decisions in important ways.

The only panel member who commented on this response agreed with the DOE response.

9.3.3.2.8 Peer Review Panel Concern – Evaluation of Factor 4: Waste Removal Impact

The evaluation of Factor 4 was conducted in the context of 40 CFR § 194.44, assuming that the removal of the emplaced waste and backfill (after the regulatory closure) is possible. The factor considers the impact of EAs on waste removal after 200 years with no justification. The methodology used and the conclusions made based on a qualitative comparison using the volume and the time required for removal were acceptable to the panel. However, the panel made some comments with respect to this factor. See CCA Appendix PEER for the details of these comments and their resolution.

9.3.3.2.9 Peer Review Panel Concern – Evaluation of Factor 5: Impact of Engineered Alternatives on Transportation Risk

A number of procedural-type questions were raised by the panel related to the impact of EAs on transportation risk. DOE provided satisfactory explanations for these questions and no outstanding issues remained. See CCA Chapter 9 and CCA Appendix PEER for details.

9.3.3.2.10 Evaluation of Factor 6: Impact of Engineered Alternatives on Public Confidence

The peer review panel did not find any particular areas of concern with the public confidence evaluation, and felt that the methods used and conclusions reached were appropriate and reasonable. There are no specific comments or areas of concern in need of response.

9.3.3.2.11 Evaluation of Factor 7: Total System Cost and Schedule Estimates

The peer review panel found no significant flaws in the cost and schedule analysis. The panel agreed that the development of cost and schedule estimates was reasonable, appropriate, and defensible. There were no specific comments or areas of concern in need of response for this factor.

9.3.3.2.12 Peer Review Panel Concern – Evaluation of Factor 8: Impact on Other Waste Disposal Programs

The peer review panel concluded that the analysis for impacts to other waste disposal programs was conducted using the best available information. However, they felt that the evaluation should be updated as more recent and accurate data become available to ensure adequate facilities and resources are available for disposal. DOE provided additional details that satisfied the panel. See CCA Chapter 9 and CCA Appendix PEER.

9.3.4 Engineered Systems Data Qualification Peer Review

An Engineered Systems Peer Review (ESPR) Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of TP 10.5. The plan describes the peer review process used to ensure that the data used in the models describing engineered systems for rock mechanics and shaft/borehole seals in the PA are qualified to demonstrate compliance.

The DOE used an Independent Review Team (IRT) to carefully review the existing data that was necessary to support the PA. Much of the existing data were qualified because the IRT determined that the QA program in place at the time of its collection was equivalent to American Society of Mechanical Engineers (ASME) nuclear quality assurance (NQA) requirements. It was determined, however, that some data used to describe engineered systems could not be qualified in that manner.

40 CFR § 194.22(b) states that:

> Any compliance application shall include information which demonstrates that data and information collected prior to the implementation of the quality assurance program required pursuant to paragraph (a)(1) of this section have been qualified in accordance with an alternate methodology, approved by the administrator or the administrator's authorized representative, that

> employs one or more of the following methods: peer review, conducted in a manner that is compatible with NUREG-1297....

The purpose of the ESPR was to seek qualification of scientific data by systematically reviewing parameters and subsystems used in the models describing engineered systems. The conceptual models used in the PA of the engineered systems include components of

- disposal room geometry,
- creep closure,
- repository fluid flow,
- shafts and shaft seals, and
- DRZ.

The review was conducted by four panel members. The panel members and their affiliation were

- Dermot Ross-Brown (Chairman), Independent Consultant;
- John Gibbons, Independent Consultant;
- Darrell Porter, Science Applications International Corporation; and
- John Schatz, Independent Consultant.

See CCA Chapter 9 and CCA Appendix PEER for details of the qualifications of the panel members.

The panel performed an in-depth critique of assumptions, alternate interpretations, methodology and acceptance criteria employed, and of conclusions in the original work. According to the "Description of Work Performed" in their final report, the panel members considered:

- sources of the parameters and data: for example, professional judgment, published source material, field tests, laboratory experiments, etc.;
- appropriateness of the parameters and data for their intended use; and
- assumptions, calculations, extrapolations interpretations, methods, appropriateness, validity, sensitivities, and conclusions pertinent to the parameters and data used as input to the WIPP PA.

The data considered by the panel supported the models describing engineered systems and were used to derive parameter values that are incorporated into the models. In some instances, parameters were consolidated into parameter groups.

Fourteen parameters (several of which were actually groups of closely related parameters) were evaluated by the panel. The panel qualified seven of the parameters and two of the parameter groups (properties of halite and anhydrite, and data on final porosity surface). In the panel's opinion, minor changes needed to be made to two of the parameters (pore volume compressibility of Salado Mass Concrete (SMC) and permeability of consolidated waste), and further analysis by SNL was needed on two other of the parameter groups (permeability of crushed salt and the strength of the waste for spalling (blowout) releases. The panel concurred with SNL's general treatment of the remaining parameter (general treatment of the DRZ). Table 9-3 lists the parameters reviewed by the panel and summarizes the panel's conclusions regarding their adequacy.

Table 9-3. Summary of Qualification Status of Parameters, as a Result of the Engineered Systems Peer Review

Subsystem	Parameter Name	Qualification Status of Parameters
Shaft/shaft Seal	Porosity of SMC	Qualified
	Pore Volume Compressibility of SMC	Minor change to value suggested [1]
	Bulk Modulus of Crushed Salt	Qualified
	Permeability of Crushed Salt	Requires further analysis by SNL[1]
	Permeability of SMC	Qualified
	Permeability of Compacted Clay	Qualified
Disposal Room/Rock Mechanics	Initial Density of Waste	Qualified
	Mechanical Properties of Waste	Qualified
	Initial Water Content of Waste	Qualified
	Permeability of Consolidated Waste	Minor change to value suggested [1]
	Strength of Waste for "Blowout"	Insufficient data to qualify [1]
	Properties of Halite and Anhydrite	Qualified, based on limited review[2]
	Data on Final Porosity Surface	Qualified, based on limited review[2]
DRZ	Characterization of DRZ	Concepts qualified

[1] The panel subsequently determined, on the basis of additional input from DOE, that DOE responses had reasonably addressed their concerns.
[2] The panel chose to consider these parameters from an overview approach; however, the panel was able to qualify these parameters.

Initially, the ESPR panel failed to qualify four of the parameters (or parameter groups) they reviewed. Where appropriate, the DOE interpreted the ESPR panel's concern and in all four cases developed a WIPP project response. The ESPR panel's concerns (in italics), the DOE's interpretations of the panel's concerns (Statement of Issue), where appropriate, and their responses (Response to Issue) are provided below. The panel then reviewed the response to determine whether the DOE understood the issue and provided a reasonable response (Peer Reviewer Consideration of Response).

The DOE responses were provided to the panel as individual memoranda. For incorporation into this application, the responses were edited to remove the memorandum format, consolidate references, replace first-person text, insert cross-references where appropriate, and correct typographical errors. Substantive technical content of the responses was not changed.

Based on the additional information the DOE provided in response to the panel's concerns, the panel subsequently concluded that the DOE had reasonably addressed their concerns for all the parameters and parameter groups. The data used to derive the parameters and parameter groups that were reviewed by the ESPR panel were therefore qualified per 40 CFR § 194.22(b).

At the completion of the review, the panel prepared a documented summary of its work and an evaluation of the selected parameters reviewed by the panel. A copy of the Engineered Systems Data Qualification Peer Review Report, dated July 1996, is provided in CCA Appendix PEER. For detailed discussion of the panel's work and the interaction between the panel and the DOE technical staff, see CCA Chapter 9. Since the panel concluded that the DOE had reasonably addressed their concerns for all the parameters and parameter groups, the work of the panel is not further discussed here.

9.3.5 Natural Barriers Data Qualification Peer Review

The DOE used an IRT to carefully review the existing data that was necessary to support the PA. Much of the existing data was qualified because the IRT determined that the QA program in place at the time of its collection was equivalent to ASME NQA requirements. It was determined, however, that some data used to describe natural barrier subsystems could not be qualified in that manner.

A Natural Barriers Peer Review (NBPR) Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of TP 10.5. The purpose of the plan was to describe the NBPR process. The NBPR panel evaluated existing data and information that form the basis of the parameter values used in the mathematical expression of conceptual models for the natural barriers subsystems in the WIPP. The parameters selected for evaluation were those that had not previously been fully qualified for use in PA.

The conceptual models used in the PA of the natural barriers subsystem include components of: (1) disposal system geometry; (2) Culebra model geometry; (3) repository fluid flow; (4) Salado; (5) impure halite; (6) Salado interbeds; (7) DRZ; (8) actinide transport (Salado); (9) units above the Salado; (10) dissolved Actinides (Culebra); (11) colloidal actinides (Culebra); (12) exploration boreholes; (13) cuttings and cavings; (14) spallings; (15) DBR; (16) Castile and brine reservoir; (17) multiple intrusions; and (18) climate changes.

A peer review panel, consisting of the following six members, was convened to undertake the work:

- Darrel E. Dunn (Chairman), Independent Consultant;
- Florie Caporuscio, LANL;
- Paul L. Cloke, Independent Consultant;
- David A. Sommers, Independent Consultant;
- Charles Wilson, Independent Consultant; and

- Chuan-Mian Zhang, Woodward-Clyde Federal Services.

See CCA Chapter 9 and CCA Appendix PEER for details of the panel members' qualifications.

Upon completion of the orientation and training required by TP 10.5, the panel was provided 32 parameter packages for their review. In addition, technical reports and documents were obtained by the panel from the SNL waste management library and records center to supplement the information in the parameter packages. Both formal and informal technical discussions were held with SNL principal investigators to assist the panel members to more fully understand the concepts and parameter derivation and application in the PA.

The NBPR panel evaluated 142 parameters against the eight review criteria cited in NUREG-1297 (NRC 1988). The parameters were organized into 32 parameter packages, some of which contained more than one parameter. The parameter packages were grouped into three subsystems; Salado, Castile, and units above the Salado, to facilitate the review process.

In some subsystems, individual parameter values were evaluated and a determination made of their adequacy as used in the WIPP PA program. In others, sets of parameters were evaluated to determine their collective contribution to a combined parameter value. The panel performed an in-depth critique of assumptions, alternate interpretations, methodology and acceptance criteria employed, and the conclusions drawn in the original work. In evaluating the existing unqualified data, the peer review panel members considered the following:

- The source of the parameters and data (for example, professional judgment, published source material, field tests, laboratory experiments, etc.);
- The appropriateness of the parameters and data for their intended use; and
- The assumptions, calculations, extrapolations, interpretations, methods, appropriateness, validity, sensitivities, and conclusions pertinent to the parameters and data used as input to the WIPP PA.

At the conclusion of its review, the panel developed a final report (August 1996). A copy of the NBPR Report is provided in CCA Appendix PEER.

Table 9-4 provides a listing of the 32 parameter packages, the appropriate subsystem, the number of parameters in the specific packages, and the qualification status of each as determined by the peer review panel. The panel concluded that 31 of the parameter packages were fully qualified. Therefore, the data supporting those parameters are qualified per 40 CFR § 194.22(b). The panel had a concern about one of the 21 data packages for the Culebra transmissivity parameter at well P-18.

Table 9-4. Summary of Parameters Reviewed and Qualification Status

Parameter Package	Subsystem	Number of Parameters	Qualification of Parameter
DRZ Compressibility	Salado	2	Adequate
Undisturbed Halite Pore Pressure		1	Adequate
Undisturbed Halite Compressibility		1	Adequate
Effective Halite Porosity		1	Adequate
Undisturbed Halite Permeability		3	Adequate
Undisturbed Anhydrite Pressure		2	Adequate
Undisturbed Anhydrite Rock Compressibility		3	Adequate
Brine Salt Mass Fraction		1	Adequate
Brine Viscosity		1	Adequate
Brine Density		1	Adequate
Brine Compressibility		1	Adequate
Castile Brine Reservoir Rock Compressibility	Castile	1	Adequate
Castile Brine Reservoir Porosity		1	Adequate
Castile Brine Reservoir Pressure		1	Adequate
Castile Brine Reservoir Permeability		3	Adequate
Castile Brine Reservoir Volume		1	Adequate
Non-Salado Effective Porosity	Units Above the Salado	6	Adequate
Non-Salado Pressure		4	Adequate
Non-Salado Permeability		6	Adequate
Culebra Permeability		3	Adequate
Climate Index		1	Adequate
Culebra Transmissivity Data		100 Values	Adequate[1]
Culebra Thickness		1	Adequate
Culebra Storativity		1	Adequate
Culebra Fluid Density		32 Values	Adequate
Culebra Steady-State Freshwater Heads		31 Values	Adequate
Culebra Dolomite Grain Density		1	Adequate
Effective Culebra Thickness		1	Adequate
Advective Porosity		1	Adequate
Half Matrix Block Length		1	Adequate
Diffusive (Matrix) Porosity		1	Adequate
Diffusive (Matrix) Tortuosity		1	Adequate

[1] One of the 21 data packages for the Culebra Transmissivity parameter was deemed inadequate.

The NBPR panel's concern (in italics), the DOE's interpretation of the panel's concern (Statement of Issue), and the DOE response (Response to Issue) are provided in CCA Appendix PEER. The panel then reviewed the response to determine whether the DOE understood the issue and provided a reasonable response (Peer Reviewer Consideration of Response). The justification for the DOE's continued use of the Well P-18 transmissivity value is also provided (DOE Technical Position versus Panel Issue) in CCA Appendix PEER and is reproduced below.

Regarding the transmissivity value selected for the well P-18, the DOE's technical position is that the appropriate transmissivity value was selected; however, whichever transmissivity value

is used (4.6×10^{-9} m^2 /s or 7.5×10^{-11} m^2 /s) (4.3×10^{-3} ft^2/day or 7×10^{-5} ft^2/day), the well P-18 data point does not substantially influence the critical migration pathways through the Culebra. This interpretation is supported by the panel in Table 1.1 of its report (CCA Appendix PEER), where the Culebra Transmissivity Data was determined to be adequate.

9.3.6 Waste Form and Disposal Room Data Qualification Peer Review

A Waste Form and Disposal Room (WFDR) Peer Review Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of TP 10.5. The plan describes the process used to plan and perform the review. The purpose of the peer review was ensure that the scientific data used in the models describing the waste form and the disposal room closure and chemistry are qualified for use in the WIPP PA.

The DOE used IRTs to carefully review the existing data necessary to support the PA. Many of the existing data were qualified because the QA program in place at the time of its collection was equivalent in effect to ASME NQA requirements. However, some of the data needed to support the waste form and disposal room models were not qualified by the IRTs.

In accordance with 40 CFR § 194.22 (b), a panel consisting of the following two members was selected to review data that had not been qualified by the IRTs:

- Duane C. Hrncir (Chairman), University of Texas at Dallas; and
- Robert D. Knecht, Colorado School of Mines.

Dr. Hrncir is an associate professor of chemistry and former head of the chemistry programs at the University of Texas at Dallas. He has 24 years of experience in research involving the interactions of metals with organic molecules.

Dr. Knecht is a research professor at the Colorado School of Mines and holds a Ph.D. in Chemical-Petroleum Refining Engineering and a Ph.D. in Metallurgical Engineering. He has provided management and technical assistance to a variety of energy, minerals, and waste industries and to government.

The panel members were both highly qualified to conduct this review and were independent of the WIPP PA program. Additional information concerning the qualifications of the panel members is provided in the peer review panel report (see CCA Appendix PEER). Documentation regarding the independence of the panel members is also provided in CCA Appendix PEER.

The panel received administrative orientation and training on the peer review plan, 40 CFR Parts 191 and 194, NUREG-1297, the QAPD, and TP 10.5. During the course of its work, the panel reviewed information packages provided by SNL for each parameter. In addition, technical reports, published literature, and internal documents supplemented information in the parameter packages. Discussions were held with SNL staff to more fully understand the concepts and parameter derivation.

The panel members evaluated existing data and information that form the basis of the parameter values used to mathematically express conceptual models for the waste form and disposal room subsystem. As discussed above, the parameters evaluated had not previously been fully qualified for use in PA. The conceptual models used in the PA of the waste form and disposal room subsystem include components of:

- Gas generation;
- Chemical conditions;
- Dissolved actinide source term; and
- Colloidal actinide source term.

The WFDR peer review panel evaluated 26 parameters against the eight NUREG-1297 review criteria. The parameters were solubilities of the actinides from the repository wastes in brines from the Salado and Castile.

The panel compared each calculated solubility parameter to those published in the peer-reviewed literature, when such data were available. To make this comparison, the panel considered compatibility of solvents, solution pH, and the absence of potentially ligating carbonate. The latter criterion is an imposed condition controlling the disposal room chemistry. When literature values were unavailable, the panel considered experimental data obtained from several different laboratories. In using these data, the panel evaluated the experimental approach to ascertain that the methods used for data acquisition and interpretation were consistent with recognized standards.

When experimental data were not available for particular parameters, the panel examined the method of calculation used to derive the value. The experimental data used as input to the calculation were evaluated and the validity of the calculation result was critiqued relative to similar calculated values where experimental data were available.

The panel members carefully reviewed each of the 26 parameters submitted for peer review. Based on their review, the panel prepared a final report in July 1996. A copy of the final report is provided in CCA Appendix PEER.

Table 9-5 provides a listing and status of the reviewed parameters. As shown in Table 9-5, the panel concluded that all 26 values were qualified for use in the WIPP PA of actinide solubility under repository conditions. Therefore, the data supporting these parameters are qualified per 40 CFR § 194.22(b).

9.3.7 Passive Institutional Controls Peer Review

40 CFR § 194.43 states that

> Any compliance application shall include detailed descriptions of the measure that will be employed to preserve knowledge about the location, design, and contents of the disposal system.

Table 9-5. Listing and Status of Reviewed Parameters

ID number	Species	Brine	Status
A. Inorganic Chemistry Controlled by $Mg(OH)_2/MgCO_3$			
WP037105	Am(III)	Salado	Qualified
WP037106	Am(III)	Castile	Qualified
WP037109	Pu(III)	Salado	Qualified
WP037108	Pu(III)	Castile	Qualified
WP037129	General An(III)	Salado	Qualified
WP037125	General An(III)	Castile	Qualified
WP037110	Pu(IV)	Salado	Qualified
WP037111	Pu(IV)	Castile	Qualified
WP037115	Th(IV)	Salado	Qualified
WP037112	U(IV)	Salado	Qualified
WP037130	General An(IV)	Salado	Qualified
WP037126	General An(IV)	Castile	Qualified
WP037131	General An(V)	Salado	Qualified
WP037127	General An(V)	Castile	Qualified
WP037113	U(VI)	Salado	Qualified
WP037114	U(VI)	Castile	Qualified
WP037132	General An(VI)	Salado	Qualified
WP037128	General An(VI)	Castile	Qualified
B. Organic Chemistry Controlled by $Mg(OH)_2/MgCO_3$			
WP037116	General An(III)	Salado	Qualified
WP037121	General An(III)	Castile	Qualified
WP037117	General An(IV)	Salado	Qualified
WP037122	General An(IV)	Castile	Qualified
WP037118	General An(V)	Salado	Qualified
WP037123	General An(V)	Castile	Qualified
WP037120	General An(VI)	Salado	Qualified
WP037124	General An(VI)	Castile	Qualified

A Passive Institutional Controls Peer Review Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of TP 10.5. The plan describes the peer review process used to ensure that the passive institutional controls proposed by the DOE will reasonably preserve knowledge about the location, design, and contents of the WIPP disposal system and reduce the likelihood of inadvertent intrusion.

A three-member panel of experts was convened in May 1996 to conduct an independent peer review of the system of passive institutional controls designed by the DOE. The panel reviewed the findings of the Passive Institutional Controls Task Force (PTF), evaluating detailed

descriptions of the measures intended to preserve knowledge about the location, design, and contents of the WIPP disposal system. The evaluation determined whether the passive institutional controls are adequate and have a reasonable expectation of reducing the likelihood of inadvertent intrusion.

The panel members were:

- Jessica Glicken (Chairman), Ecological Planning and Toxicology, Inc.;
- Elizabeth K. Hocking, Argonne National Laboratory; and
- Paul R. La Pointe, Golder Associates.

The panel members were well-qualified for this review and independent of the WIPP PA program. Additional information concerning the qualifications of the panel members is presented in the panel report (see CCA Appendix PEER). Documentation of the panel member's independence from the WIPP project is also provided in CCA Appendix PEER.

After administrative orientation and training, the panel members familiarized themselves with regulations impacting radioactive waste disposal at the WIPP (40 CFR Parts 191 and 194) and requirements for the conduct of peer reviews (NUREG-1297 and TP 10.5). Following briefings by members of the PTF and other WIPP project staff, panel members were provided two documents that formed the basis of their peer review:

> Effectiveness of Passive Institutional Controls in Reducing Inadvertent Human Intrusion into the Waste Isolation Pilot Plant for Use in Performance Assessments (referred to as the Passive Institutional Controls Efficacy Report; see DOE (1996a, Appendix EPIC); and,
>
> Passive Institutional Controls Conceptual Design Report (referred to as the Conceptual Design Report (CDR); see DOE 1996a, Appendix PIC).

Supplemental information requested by the panel was also used in the evaluation.

The peer review panel evaluated the assumptions and results presented in the Passive Institutional Controls Efficacy Report. The panel's findings, as presented in their final report, dated July 1996, are provided below. A complete copy of the panel's report is provided in CCA Appendix PEER.

The panel identified several concerns during their review. The panel's concerns, the DOE's interpretation of the panel's concerns (Statement of Issue), the DOE's response to the panel's concerns ("Response to Issue"), and the panel's reaction to the interpretation and responses ("Peer Reviewer Consideration of Response") are provided in CCA Chapter 9. When the panel determined the response did not reasonably address their concerns, the DOE's justification for its position (DOE Technical Position versus Panel Issue) was provided (see CCA Chapter 9).

9.4 Peer Reviews Conducted in Addition to Those Required by 40 CFR Part 194.27(a)

40 CFR Part 194 states that

> Additionally, this section requires compliance applications to include documentation of any peer review activities that DOE may have conducted apart from those required by this rule, including those activities which are similar to peer review, such as the reviews conducted by the WIPP Panel of the National Academy of Sciences. (61 FR 5228)

and that

> Peer review which has been conducted prior to today's action must be documented in compliance applications.

Over the course of the WIPP endeavor, the project has undergone extensive review. The reviews included in this section of the CCA were conducted prior to implementing 40 CFR Part 194 and are briefly mentioned in this section. Additional reviews not specifically required by 40 CFR Part 194.27(a) and conducted after submitting the CCA are described in more detail in this section. They provide additional information to the peer reviews specifically stated in 40 CFR § 194.27(a). These reviews were evaluated against criteria developed from 40 CFR Parts 191 and 194 and NUREG-1297 to determine which ones were appropriate for incorporation in this application. The following criteria were used to screen the historical reviews:

1. Was the peer review relevant to this application?

   The purpose of this application is to demonstrate the WIPP's continued compliance with the disposal regulations found in 40 CFR Part 191. 40 CFR Part 194 provides significant detail concerning the necessary contents of the application. Reviews that cover subject matter pertinent to those contents are considered relevant to this application.

2. Was there a formal report by the reviewer?

   NUREG-1297 requires a peer review to be documented.

3. Was the review a peer review, rather than a technical review?

   NUREG-1297 states that

   > A peer review is an in-depth critique of the assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn from the original work. Peer reviews confirm the <u>adequacy</u> of work. In contrast to peer review, the term "technical review," as used in this GTP, refers to a review to verify compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.

4. Was the review a peer review, rather than an expert judgment?

   As discussed above, a peer review confirms the adequacy of the work being reviewed. 40 CFR Part 194 states that

   > Typically, expert judgment is used to elicit two types of information: (1) Numerical values for parameters (variables) which are measurable only by experiments that cannot be conducted due to limitations of time, money and physical situation; and (2) essentially unknowable information, such as which features should be incorporated into passive institutional controls that will deter human intrusion into the repository. (61 FR 5228)

5. Was the technical expertise of the reviewer at least that needed to perform the original work?

   NUREG-1297 states that

   > The technical qualifications of the peer reviewers, in their review area should be at least equivalent to that needed for the original work under review and should be the primary consideration in the selection of peer reviewers. Each peer reviewer should have recognized and verifiable technical credentials in the technical area he or she has been selected to cover. The technical qualifications of each peer, and hence of the peer review group as a whole, should relate to the importance of the subject matter to be reviewed.

6. Were the reviewers independent?

   A. Were they involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed?

   B. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?

   Regarding the reviewers' independence, NUREG-1297 states:

   > Members of the peer review group should be independent of the original work to be reviewed. Independence in this case means that the peer, a) was not involved as a participant, supervisor, technical reviewer or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to assure the work is impartially reviewed.
>
> Because of DOE's pervasive effort in the waste management area, the lack or unavailability of other technical expertise in certain areas, and the possibility of reducing the technical qualifications of the reviewers in order that total independence is maintained, it may not be possible to exclude all DOE or DOE contractor personnel from participating in a peer review. In those cases where total independence cannot be met, a documented rationale as to why someone of equivalent technical qualifications and greater independence was not selected should be placed in the peer review report.
>
> The pervasive nature of DOE's effort in the waste management area also makes it necessary that both the work under review as well as the peer review of this work be allowed to be funded by DOE.
>
> The independence criteria is not meant to exclude eminent scientists or engineer upon whose earlier work certain of the work under review is based so long as a general scientific consensus has been reached regarding the validity of their earlier work.

7. If the answer to any of the above questions is no, is there an overriding consideration that would still serve to qualify the review as an appropriate and acceptable peer review for incorporation into the historical review section of this application?

Interviews with former and current WIPP project personnel were conducted to identify past reviews that should be considered for inclusion in this application. Records of the historical reviews were obtained and evaluated against the above screening criteria to select the specific reviews to document in the application. The selected reviews are discussed below. Copies of the

reports that were published prior to the submission of the CCA were provided in CCA Appendix PEER; those published after the CCA are provided in Appendix PEER-2004.

A historical review may provide an evaluation of completed work by the WIPP project; for example, the Engineered Alternatives Task Force Report (DOE 1991) review. In most cases, however, the reviews were sought by the project to seek guidance and an outside perspective as to appropriate "next steps." It should be remembered that most of these reviews were actually evaluating work in progress. They focus on the status of ongoing work at a specific point in time to guide future emphasis and direction of the work and, by their very nature, tend to accentuate aspects of the work that need improvement. They have been very important to the WIPP project because they have consistently provided an understanding of deficiencies and contributed heavily in guiding the project's future direction and needs. The historical peer reviews provide an overall perspective of the evolution and growth of the project.

9.4.1 NAS WIPP Panel Reviews

The National Research Council was established by the National Academy of Sciences (NAS) in 1916. The Council operates in accordance with Academy general policies under the authority of the NAS congressional charter of 1863. The National Research Council has become a principal NAS operating agency for providing services to the government, the public, and the scientific and engineering communities.

In March 1978, the DOE requested the National Research Council:

> review the scientific and technical criteria and guidelines for designing, constructing and operating a Waste Isolation Pilot Plant for isolating radioactive wastes from the biosphere.

The National Research Council assigned the study to the Committee on Radioactive Waste Management under the Commission on Natural Resources. The Committee organized the panel on the WIPP to:

> …review the scientific and technical adequacy of the site-suitability criteria; the guidelines for the site confirmation studies; the design criteria for the repository, including the waste acceptance criteria, the design philosophy, and the operational philosophy; the criteria for determining the environmental safety of future planned operations, viewed from the perspective of the environmental conditions of the repository site; and the design criteria for the experimental testing program of the behavior of the waste-geologic medium interaction.

Panel members were independent of the WIPP project and were nationally recognized experts in their respective disciplines. The panel was selected to provide an appropriate balance of relevant technical disciplines. The scope of the panel's expertise was very broad and included environmental engineering, geology, geochemistry, nuclear science and technology, nuclear engineering, materials science, and mining engineering. The panel regularly made use of other members of the National Research Council Board of Radioactive Waste Management and/or consultants, as necessary, to provide additional expertise.

The panel remained active from 1979 to 1996, during which time its membership changed due to retirement of some members and induction of new members to fill vacancies or to provide coverage in newly identified subject specialties. However, a continuity of knowledge about the

WIPP project was maintained because of a significant overlap of members. Names and backgrounds of members who served on the initial NAS WIPP panel were provided in CCA Chapter 9 and CCA Appendix PEER. Two additional panels have been constituted since 1997 to address specific issues requested by DOE. The membership of those panels and their work is described later in this section.

Between 1979 and 1996, the first WIPP panel produced several reports reflecting their review efforts. An evaluation of the NAS reviews against the previously described screening criteria is provided in Table 9-6. Summaries of the review reports are provided in the following sections. This chapter includes only the titles of the old reports discussed at length in CCA Chapter 9. The reports published by the new NAS panels after the submission of the CCA are described in this chapter.

9.4.1.1 Letter Report of May 1, 1979

See CCA Section 9.4.1.1 for details.

9.4.1.2 Letter Report of September 10, 1979

See CCA Section 9.4.1.2 for details.

9.4.1.3 Continuing Evaluation of the Carlsbad Site

This July 28, 1980 report (see CCA Appendix PEER) reviewed the Carlsbad site in light of the President's decision to cancel the WIPP project. See CCA Section 9.4.1.3 for details.

9.4.1.4 Review of the Criteria for the Site Suitability, Design, Construction, and Operation of the Proposed Waste Isolation Pilot Plant (WIPP); Progress Report: July 1, 1978, to December 31, 1979

This September 1981 report (see CCA Appendix PEER) recounts the panel's findings through the end of 1979. See CCA Section 9.4.1.4 for details.

9.4.1.5 Review of the Criteria for the Site Suitability, Design, Construction, and Operation of the Proposed Waste Isolation Pilot Plant (WIPP); Interim Report: July 1, 1978, to July 31, 1982

This 1983 report (see Appendix PEER) updates the panel's review of WIPP and recounts the panel's findings through the end of July 1982. See CCA Section 9.4.1.5 for details.

Table 9-6. NAS WIPP Panel Reviews

1. Is the peer review relevant to the CCA?	Yes – The panel has dealt with many WIPP issues and most are directly relevant to the CCA.
2. Was there a formal report prepared by the reviewer?	Yes – There have been a series of formal reports.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – Most of the reviews have addressed the adequacy of PA, site selection, etc., activities at WIPP.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – The reviews have all evaluated the adequacy of work prepared by the WIPP project or others.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – Panel members are nationally recognized experts in their respective fields.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – The panel was established by the National Research Council in the 1970s.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A – However, 40 CFR 194 (Supplementary Information re: §194.27) specifically indicates the NAS Panel reviews are appropriate for the CCA.

9.4.1.6 Review of the Scientific and Technical Criteria for the Waste Isolation Pilot Plant (WIPP)

This 1984 report (see CCA Appendix PEER, Section PEER 9.6) updates the panel's review of the WIPP and recounts the panel's findings through December 31, 1983. See CCA Section 9.4.1.6 for details.

9.4.1.7 Letter Report of April 1987 on Planned Sorbing-Tracer Field Tests

The WIPP panel considered the sorbing-tracer field test planned at WIPP and provided their comments in April 1987 (see CCA Appendix PEER). See CCA Section 9.4.1.7 for details.

9.4.1.8 Report of March 3, 1988 on Brine Accumulation in the WIPP Facility

See CCA Section 9.4.1.8 for details.

9.4.1.9 Letter Report of December 1988 on Experiments of Room Closure Rates

See CCA Section 9.4.1.9 for details.

9.4.1.10 Review Comments on DOE Document DOE/WIPP 89-011: Draft Plan for the Waste Isolation Pilot Plant Test Phase: Performance Assessment and Operations Demonstration

This July 19, 1989 report (see Appendix PEER) documents the WIPP panel's review of the subject document. See CCA Section 9.4.1.10 for details.

9.4.1.11 Letter Report of April 1991, Summary of Recommendations

This April 1991 report (see CCA Appendix PEER) summarizes the views of the WIPP panel on the status of the DOE program to assess the WIPP's ability to isolate TRU waste and to demonstrate compliance with relevant regulations. See CCA Section 9.4.1.11 for details.

9.4.1.12 Letter Report of June 1992

This June 1992 report (see CCA Appendix PEER) addressed the experimental plan for the WIPP and was based principally on a review of various documents submitted to the panel and presentations by the DOE and its contractors before the panel over the preceding three years. See CCA Section 9.4.1.12 for details.

9.4.1.13 The Waste Isolation Pilot Plant: A Potential Solution for the Disposal of Transuranic Waste (NAS 1996)

The final report of the NAS Committee set up in 1978 was published in October 1996. Since this report was published after the submission of the CCA, it was not included in the CCA. The full report is reproduced in Appendix PEER-2004.

The members of the committee, who also authored the report, were:

- Charles A. Fairhurst;
- Howard I. Adler;
- John O. Blomeke;
- Sue B. Clark;
- Fred M. Ernsberger;
- Rodney C. Ewing;
- John B. Garrick;
- Leonard F. Konikow;

- Konrad B. Krauskopf;
- Della M. Roy;
- David A. White;
- Chris G. Whipple; and
- Thomas A Zordan.

Biographies of the members are included in Appendix PEER-2004.

The National Research Council Committee on the WIPP was formed in 1978 at the request of DOE to provide scientific and technical evaluations of DOE investigations at WIPP. The committee's statement of task charged it to report on the current state and progress of the scientific and technical issues that form the core of a submission by DOE to EPA for certification of the WIPP facility. The committee reported the following findings, conclusions, and recommendations. The text in the rest of this section represents the views of the NAS committee and not necessarily those of DOE.

9.4.1.13.1 Findings

With regard to the results of committee evaluations and their implications for the overall suitability of WIPP as a repository for TRU waste, this report presented the following findings:

- Although TRU waste contains long-lived radionuclides that require geologic isolation, the overall level of radioactivity is much lower than that of high-level radioactive waste.
- The early recognition of salt as an attractive medium for geological isolation (e.g., National Research Council/National Academy of Sciences 1957) of radioactive waste has been confirmed by subsequent studies.
- Provided it is sealed effectively and remains undisturbed by human activity, the committee finds that the WIPP repository has the ability to isolate TRU waste for more than 10,000 years. The geologic stability and isolation capability of the Salado, which consists of bedded salt, are the primary factors leading to this finding.
- The only known possibilities for serious release of radionuclides appear to be from poor seals or some form of future human activity that results in repository intrusion. The committee anticipates that the consequences of such human intrusion can be reduced based on available engineering design options and on improved understanding obtained from ongoing scientific studies.
- EPA's regulations (i.e., 40 CFR 191, as specified for WIPP in 40 CFR 194) relating to human intrusion do not take into account that if radionuclide releases to the environment via groundwater pathways at WIPP occur, they will be predominantly in non-potable water. This greatly reduces the risk of human exposure compared to a similar release in potable water.

9.4.1.13.2 General Conclusions and Recommendations

The combination of general considerations, such as those outlined above, and detailed studies described later in this report, led the committee to the following conclusions and recommendations.

Based on available scientific evidence, the only probable threat to satisfactory isolation performance of the repository is the possibility of disturbance by human activity, deliberate or unintentional, that could compromise the repository's integrity. Engineering methods are available, if needed, to reduce the consequences of human intrusion to acceptable levels.

Conclusion: Human exposure to radionuclide releases from TRU waste disposed in WIPP is likely to be low compared to U.S. and international standards.

Considering the consequences of future activities that could violate the natural or undisturbed integrity of the repository is valuable for assessing the relative vulnerability of the repository to such activities and in identifying ways to reduce this vulnerability, but assessing human technologies thousands of years hence is highly conjectural and lacks a sound scientific foundation.

Recommendation: Speculative scenarios of human intrusion should not be used as the sole or primary basis to judge the acceptability of WIPP (and, by extension, any geological repository).

9.4.1.13.3 Findings, Conclusions, and Recommendations on Department of Energy Studies

The following comments of the committee related specifically to the DOE compliance (with 40 CFR Parts 191 and 194) activities. According to the committee, most of the issues discussed below are significant only in the event of human intrusion.

9.4.1.13.3.1 *The Role of Performance Assessment*

PA examines the combined effect of each component of the total system to assess the overall ability of the repository to isolate radionuclides from the biosphere. As used by DOE, PA responds to the question, "Is WIPP in compliance with federal regulations?"

Although PA has made important contributions to the WIPP project, in retrospect, it is clear that the potential of PA is greater, and important opportunities to put PA to good use have been missed. PA is valuable at all stages of the repository evaluation process. It can identify the most critical components of the system, assess the significance of engineered supplements to the natural geological barriers, and aid planning and management decisions on the most effective allocation of staff and project resources.

9.4.1.13.3.2 *Conservatism of Performance Assessment Models*

The PA models currently used by DOE are too conservative in some respects. Such conservatism masks the potential for identifying and assessing the benefits of relatively simple engineering design procedures in reducing the consequences of human intrusion.

The assumption that the DRZ bordering the room excavations remains a relatively high-permeability region throughout the first 10,000 years of the repository appears overly conservative. This is in marked contrast to the assumption (see Chapter 4.0) that the DRZ around the shaft will heal, achieving a permeability of between 10^{-16} m^2 (10^{-15} ft^2) and 10^{-18} m^2 (10^{-17} ft^2) within 50 to 100 years and approaching the essentially impermeable condition of intact salt within a small fraction of 10,000 years. Such a conservative assumption with respect to the DRZ in the PA models may prevent a realistic evaluation of the major benefits of waste compartmentation by room and panel seals in reducing the consequences of repository disturbance by intrusion.

9.4.1.13.3.3 *Complexity of Performance Assessment Models*

DOE's PA modeling of radionuclide releases from WIPP involves such complex combinations of many variables that, to the non-specialist, it is not clear how the predicted releases depend on the component FEPs in the geological isolation system.

The committee recommends that DOE develop, in parallel with the complex PA models, simpler versions that provide a more transparent, traceable path from the model inputs to the predicted releases. The insights gained from the simpler model as to which components of the isolation system are most critical to improved repository performance would serve a very useful role in decision-making and in resource allocation for WIPP. It is essential, of course, that the simpler PA models still identify correctly the key FEPs upon which repository performance depends.

To illustrate this recommendation: because plutonium (Pu) is the dominant radioactive element of concern in the WIPP inventory, a simpler model could focus on Pu in the source term to the exclusion of other radioactive elements. However, understanding and predicting the behavior of Pu in the WIPP system is challenging, and experimental work with other actinides is necessary to develop the parameters for Pu required for the PA models, for both the full model and any simpler version. While studies of other actinides are necessary to support the chemical model developed for Pu, a simpler PA of the kind proposed here would consider only Pu isotopes as a source term, and only the dominant pathway(s) for environmental releases, with no more complexity than needed for an adequate representation.

9.4.1.13.3.4 *Waste Characterization*

The waste characterization program considered by DOE does not appear to be based on the needs for information important to an assessment of the long-term facility performance. Ideally, the PA should be used to determine what characterization is required.

9.4.1.13.3.5 *Nonradioactive Constituents of Transuranic Waste*

Nonradioactive hazardous constituents of TRU waste are considered to pose negligible long-term hazards compared to the radioactive constituents of WIPP waste.

9.4.1.13.3.6 *Behavior of Salt at the Waste Isolation Pilot Plant Site*

Time-dependent deformation of the salt and associated stratigraphic layers at WIPP is now understood well enough to allow reliable long-term calculations of salt deformation behavior as it relates to repository performance.

9.4.1.13.3.7 *Salado Brine*

Small quantities of brine seep from the DRZ in the immediate vicinity of any excavation in the Salado. The amount of brine accumulation is not sufficient to be a credible cause for significant escape of radionuclides from the sealed repository.

9.4.1.13.3.8 *Non-Salado Brine*

Apart from possible effects of deep-well fluid injection in adjacent areas, brine flooding is only likely if, after loss of administrative controls, an intrusion borehole connects the repository with a deeper source of pressurized brine, as has been encountered by some deep boreholes in the vicinity of the repository.

9.4.1.13.3.9 *Gas Generation in the Repository*

Gas generation will be minimal in a dry or nearly dry repository like WIPP because both chemical and biological gas-generating processes (e.g., metal corrosion and bacterial action on organic matter) require a liquid phase for mass transport of the reactants and products that are involved in gas formation.

9.4.1.13.3.10 *Treatment of Waste*

Sophisticated treatment (e.g., incineration) of the TRU waste in a well-engineered WIPP repository is unwarranted to further improve repository performance, because gas generation is not a serious concern (see Chapter 3.0).

9.4.1.13.3.11 *Backfilling and Compartmentation*

Simple repository engineering measures, such as backfilling the rooms and tunnels in which the waste is emplaced, can be valuable and cost-effective methods of reducing the consequences of human intrusion and any associated brine flooding. Room and panel seals via backfill are relatively well-defined engineering procedures for improving the isolation process. In this regard, compartmentation is recommended by the committee to provide effective seals that eliminate hydrological communication between the waste-filled rooms.

9.4.1.13.3.12 *Non-Salado Hydrology*

A more comprehensive understanding of the non-Salado hydrology is needed before a reasonable judgment can be made as to the role of the Rustler and adjacent formations in delaying radionuclide releases in the event of human intrusion. To date, studies have been overly focused on a two-dimensional (2-D) analysis of the Culebra Dolomite. They have not sufficiently considered other possible hydrogeologic release pathways for radionuclides or interconnections

between the Culebra and other formations. Potential releases to the Dewey Lake Red Beds, which are less conductive than the Culebra, but contain some potable water, are recommended for further study.

9.4.1.13.3.13 *Potash Mining*

The consequences to the non-Salado hydrology of subsidence damage due to possible future mining of potash resources above the repository have not yet been evaluated by DOE. If the potential consequences are found to be seriously adverse, it is technically feasible to extract these resources preemptively, in a way that avoids subsidence and associated effects and that reduces the potential for human intrusion by drilling.

9.4.1.13.3.14 *Deep Well Fluid Injection*

The requirement to consider the effects on the repository of fluid injection activities was a relatively new addition to the final version of EPA criteria for certification (40 CFR part 194.32(c)). Neither the probability nor the effects on the repository from nearby injection of water or brine have been evaluated in detail by the committee, nor has DOE published an analysis of this issue. A comprehensive analysis of the risks and consequences of this scenario should be completed and documented.

9.4.1.13.3.15 *Waste Solubility and Transport*

The PA completed by DOE in 1992, and all subsequent analyses, have consistently identified a set of issues with the greatest impact on the compliance of WIPP in the event of human intrusion and associated brine flooding of the repository. Prominent among these issues are:

- actinide solubilities in brine,
- formation and transport of colloids containing radionuclides, and
- retardation of radionuclides during transport through the Culebra.

The EPA has also identified these issues as critical to its evaluation of the CCA.

At the time of this report, the data and models to represent these three issues in the next version of the PA (to support the CCA) were not available for review.

9.4.1.13.3.16 *Continuation of Experiments and Analyses*

Continuation of analyses and experiments initiated in the WIPP program to address concerns related to Non-Salado Hydrology, Deep Well Fluid Injection, and Waste Solubility and Transport is recommended by the committee, even though the results may not be available in time for the compliance submission. Results of such testing could reduce uncertainties in the long-term performance of WIPP, eliminate concern over other issues, and be useful in judging the cost-effectiveness of various waste isolation procedures at WIPP and other repositories.

In summary, the committee offered the following opinions:

- Provided the WIPP repository is sealed effectively and undisturbed by human activity, the committee knows of no credible or probable scenario for release of radionuclides.

- For the WIPP repository disturbed by future human activity, the committee has noted three ways in which confidence in the performance of the repository could be increased:

1. Re-evaluation of the probability and/or consequences assigned to highly speculative scenarios of future human activities may reduce the estimated risk of radionuclide release.

2. Experimental and field programs in progress or planned may show that key parameters (e.g., actinide transport) are well within the range required to reduce the impacts of human activities on radionuclide releases substantially.

3. The implementation of available engineering options (e.g., compartmentation, treated backfill), which have not been considered in published DOE analyses, could reduce the consequences of human intrusion. The cost effectiveness of these options will depend on the outcome of (1) and (2) above.

The committee believes that some combination of the above three considerations will very probably be sufficient to allow DOE to demonstrate that a WIPP repository will keep radionuclide release within acceptable levels for the disturbed case.

9.4.1.14 Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant – Final Report (April 2001)

Following the publication of the NAS WIPP committee's 1996 report described in Section 9.4.1.13, a new NAS WIPP committee was created to carry out the tasks described below. The committee produced an interim report in April 2000 that was included as Appendix A1 of this final report (National Research Council/National Academy of Sciences 2001). The full report is included in Appendix PEER-2004. Since the main findings and recommendations from the interim report have been incorporated into the body of this report, the interim report is not discussed separately in this chapter.

The committee's task was twofold: (1) to identify technical issues that could be addressed to enhance confidence in the safe and long-term performance of the repository, and (2) to identify opportunities for improving the National TRU Program for waste management, especially with regard to the safety of workers and the public.

The following members served on this committee:

- B. John Garrick, Chair, Garrick Consulting, Laguna Beach, California;
- Mark D. Abkowitz, Vanderbilt University, Nashville, Tennessee;
- Alfred W. Grella, Grella Consulting, Locust Grove, Virginia;
- Michael P. Hardy, Agapito Associates, Inc., Grand Junction, Colorado;
- Stanley Kaplan, Bayesian Systems Inc., Rockville, Maryland;
- Howard M. Kingston, Duquesne University, Pittsburgh, Pennsylvania;

- W. John Lee, Texas A&M University, College Station;
- Milton Levenson, Bechtel International, Inc. (retired), Menlo Park, California;
- Werner F. Lutze, University of New Mexico, Albuquerque;
- Kimberly Ogden, University of Arizona, Tucson;
- Martha R. Scott, Texas A&M University, College Station;
- John M. Sharp, Jr., The University of Texas, Austin;
- Paul G. Shewmon, Ohio State University (retired), Columbus;
- James E. Watson, Jr., University of North Carolina, Chapel Hill; and
- Ching H. Yew, The University of Texas (retired), Austin.

In addition, Dalene C. Hoffman and James O. Leckie served as liaisons and Lynda L. Brothers and John T. Smith served as consultants. National Research Council/National Academy of Sciences staff members Barbara Pastina and Thomas E. Kiess served as Study Directors and Angela R. Taylor as Senior Project Assistant. Biographies of the committee members are provided in the report (National Research Council/National Academy of Sciences 2001) (see Appendix PEER-2004).

The text in the rest of this section represents the views of the NAS committee and not necessarily those of DOE.

9.4.1.14.1 Findings and Recommendations

The overarching finding and recommendation of this report is that the activity that would best enhance confidence in the safe and long-term performance of the repository is to monitor critical performance parameters during the long preclosure phase of repository operations (35 to possibly 100 years). Indeed, in the first 50 to 100 years, the rates of important processes such as salt creep, brine inflow (if any), and microbial activity are predicted to be the highest and will be less significant later. The committee recommends that the results of the on-site monitoring program be used to improve the PA for recertification purposes. These results will determine whether the need for a new PA is warranted. For the National TRU Program, the committee finds that the DOE is implementing many of the recommendations of its interim report. It is important that the DOE continue its efforts to improve the packaging, characterization, and transportation of the TRU waste.

The committee's specific findings and recommendations have been grouped into three categories: (1) site performance, (2) site characterization, and (3) the National TRU Program, as described below.

9.4.1.14.1.1 *Site Performance*

- The committee recommends preclosure monitoring to gain information on brine migration and moisture access to the repository. Observation should continue at least until the repository shafts are sealed and longer, if possible. The committee recommends that the results of the on-site monitoring program be used to improve the PA for recertification purposes.

- The committee recommends preclosure monitoring of gas generation rates, as well as of the volume of H, carbon dioxide (CO_2), and CH_4 produced. Such monitoring could enhance confidence in the performance of the repository, especially if no gas generation is observed. Observation should continue at least until the repository shafts are sealed and longer, if possible. The results of the gas generation monitoring program should be used to improve the PA for recertification purposes.

- MgO is used as backfill in WIPP to provide some control of the chemical environment of the waste and, to a lesser extent, to fill voids in the disposal locations, thus enhancing the healing process. The chemical performance of MgO depends on gas generation and brine inflow, as well as other chemical processes taking place in the repository. The committee finds that there is uncertainty about the effectiveness of MgO in controlling the chemical environment of the waste. Therefore, the committee recommends that the net benefit of MgO used as backfill be reevaluated. The option to discontinue emplacement of MgO should be considered.

- The committee recommends preclosure monitoring of the status of room deformation and of the DRZ healing. Seal performance should also be assessed. Observation should continue at least until the repository shafts are sealed and longer, if possible. The results of the monitoring of room deformation and DRZ healing should be included in the PA and used for recertification purposes.

9.4.1.14.1.2 *Site Characterization*

- The committee recommends a monitoring program to characterize the geohydrology of the Culebra Dolomite. Tests and measurements that should be considered include angled boreholes, natural gradient tracer tests, and additional pump or injection tests. These new data should be used to confirm or modify the conceptual and numerical models now proposed as a reasonable simulation of the actual system.

- The committee recommends the use of seismic survey techniques for detecting large brine reservoirs below the repository. In case a brine reservoir was found beneath the WIPP and its size was larger than what is already taken into account in the PA, the DOE should conduct an extensive review of the impact of such a reservoir on the repository performance. A basis would then exist to take appropriate action to ensure repository safety.

- The committee recommends developing a database to collect information on drilling, production enhancement, mining operations, well abandonments, and unusual events (accidents and natural events) in the vicinity of the WIPP site.

- The committee recommends that the DOE continue implementing its plan to sample oil-field brines, petroleum, and solids associated with current and future hydrocarbon production, as necessary, to assess the magnitude and variability of naturally occurring radioactive material (NORM) in the vicinity of the WIPP site for baselining purposes.

9.4.1.14.1.3 *The National Transuranic Program*

9.4.1.14.1.3.1 Waste Characterization and Packaging

The committee recommends that the DOE's efforts to review waste characterization and packaging requirements continue and those changes be implemented over the entire National TRU Program. The committee recommends that the resources required to complete these improvements be made available by the DOE.

9.4.1.14.1.3.2 Total Inventory of Organic Materials Allowed in the Repository

The committee recommends a risk-based analysis of the total organic material regulatory limits in WIPP. If accounting for the organic material is important to the safety of the repository, an inventory record system should be implemented as soon as possible to provide a basis for meaningful safety analysis.

9.4.1.14.1.4 *Waste Transportation*

9.4.1.14.1.4.1 Department of Energy's Communication and Notification Program

The DOE appears to be moving systematically toward the implementation of an efficient, comprehensive, and state-of-the-art communication and notification system called TRANSCOM 2000. The committee recommends that the DOE implement as soon as possible the new TRANSCOM 2000 communication and notification system. Moreover, because the human factor is an important element of transportation system quality, TRANSCOM 2000 should include methods to minimize the occurrence and impact of human errors.

9.4.1.14.1.4.2 Department of Energy's Emergency Response Training

The committee recommends that the DOE facilitate the involvement of states in developing and maintaining an up-to-date, practical, and cost-effective spatial information database system to coordinate emergency responses. The DOE should also develop an ongoing assessment program for states' emergency response capabilities and allocate training resources to address deficiencies in coverage along WIPP routes.

9.4.1.14.1.4.3 Rail as a Transportation Option for Certain Transuranic Waste

The committee recommends that all reasonable transportation options, including reduction in the number of shipments, such as rail and road transportation with better-adapted containers, should

be part of the decision-making process of transporting TRU waste from generator and storage sites to the WIPP. Future transportation studies should consider railway shipments and their impact on both the safety and the cost of the program. The DOE should also continue to pursue the development of packaging alternatives for materials not suitable for TRUPACT-ll containers.

9.4.1.14.1.4.4 Gas Generation Safety Analysis for TRUPACT-II Containers

The committee recommends a risk-informed analysis of WIPP specific shipment issues to identify core problems related to hydrogen generation and, perhaps, provide a basis for alternative cost-effective criteria while reducing risk. The committee recommends the use of such risk-informed analysis in the application for revision of the NRC certificate of compliance concerning hydrogen generation limits for transportation purposes.

9.4.14.1.4.5 *The Department of Energy's Response*

The DOE provided detailed responses to most of these recommendations, which are included in Appendix A2 of National Research Council/National Academy of Sciences (2001) (Appendix PEER-2004). In brief, the DOE agreed with the committee's findings and observations and has implemented most of the recommendations.

9.4.1.15 Characterization of Remote-Handled Transuranic Waste for the Waste Isolation Pilot Plant – Final Report (2002)

In 2001, a new NAS WIPP committee (Committee on the Characterization of Remote-Handled Transuranic Waste for the Waste Isolation Pilot Plant) was established to review a proposed characterization plan for RH-TRU waste and to provide recommendations for improving the plan's technical soundness, protection of worker safety and health, and compliance with regulatory requirements. The committee published its final report in 2002 (National Research Council/National Academy of Sciences 2002).

The following members served on the committee and authored the report:

- Eula Bingham, Chair, University of Cincinnati, Ohio;
- Sanford Cohen, SC&A, Inc., McLean, Virginia;
- Milton Levenson, Independent Consultant, Menlo Park, California;
- Kenneth Mossman, Arizona State University, Tempe;
- Ernest Nieschmidt, Idaho State University, Idaho Falls;
- John Plodinec, Mississippi State University, Starkville; and
- Anne E. Smith, Charles River Associates, Washington, D.C.

Heino Nitsche served as a consultant and Alexander Maclachlan served as liaison to the National Research Council/NAS Board on Radioactive Waste Management. The National Research

Council/NAS staff members were Study Director Barbara Pastina, Senior Project Assistant Angela Taylor, and Research Assistant Darla Thompson.

The text in the rest of this section represents the views of the NAS committee and not necessarily those of DOE.

9.4.1.15.1 Committee's Assessment of Department of Energy's Proposed Characterization Plan

The committee used the criteria listed in the statement of task to assess DOE's proposed characterization plan to address: (1) the context of RH-TRU waste characterization, (2) the characterization plan's technical soundness, (3) protection of worker safety and health, and (4) compliance with regulatory requirements.

9.4.1.15.1.1 *Context of Remote-Handled Transuranic Waste Characterization*

DOE should emphasize the argument that the characterization information collected for most of RH-TRU waste does not need confirmatory measurements because the repackaging or generation of waste will be carried out under a certified QA program. If the volume of RH-TRU waste represents between 2 and 4 percent of the volume of TRU waste, and the information collected for over 95 percent of RH-TRU waste does not need confirmation, then only the remaining 5 percent of the RH-TRU waste inventory (between 0.1 and 0.2 percent of the total inventory) needs confirmation activities.

DOE uses the term Acceptable Knowledge (AK) to indicate both the historical information and the newly generated characterization information collected at the time of waste generation, packaging, or repackaging. However, for 95 percent of the RH-TRU waste inventory, AK refers mostly to the latter. The committee recommended that DOE use a different term than AK for this newly generated information. Using AK for both historical and newly generated information is potentially confusing because AK is generally associated with historical information, which requires some type of confirmation.

9.4.1.15.1.2 *Characterization Plan's Technical Soundness*

The committee found that DOE's proposed characterization plan is not completely performance-based, and that several characterization activities are based on nontechnical considerations. The committee questioned the technical bases of some of these characterization activities. The committee acknowledged that nontechnical considerations may be important for maintaining effective working relationships among DOE, EPA, and NMED; however, DOE should propose only characterization activities that have a technical, health and safety, or regulatory basis.

DOE's proposed characterization plan should address tolerable decision error rates associated with characterization information. These errors should not be overly stringent so as to negatively impact the sites' ability to implement ALARA.

The characterization plan should clarify under which conditions confirmation of historical AK is warranted and the most effective methods proposed. DOE should provide justification for the technologies proposed to obtain confirmatory data and provide evidence of their effectiveness across the entire spectrum of dose rates for RH-TRU waste.

9.4.1.15.1.3 *Protection of Worker Safety and Health*

DOE could strengthen the rationale of its characterization plan for RH-TRU waste by discussing estimates of worker doses and characterization costs in the three site-specific plans accompanying the submittal documents. DOE should continue its effort to ensure sufficient flexibility for generator sites in the implementation of the characterization plan. However, characterization activities that share common elements across sites should be standardized.

9.4.1.15.1.4 *Compliance with Regulatory Requirements*

The committee recommends that DOE evaluate whether existing characterization practices for CH-TRU waste, when applied to the characterization of RH-TRU waste, have an impact on the protection of the environment, health and safety of public and workers, and cost-effectiveness of the characterization program.

The committee recommends that submittal documents focus on regulatory requirements under the relevant agency's purview and distinguish between these requirements and ancillary information describing the context of RH-TRU waste characterization.

9.4.1.15.2 Department of Energy's Response

The DOE has taken into account the committee's recommendations in developing the RH-TRU waste characterization plan.

9.4.2 Performance Assessment Peer Review Panel

The Performance Assessment Peer Review Panel (PAPRP) was established in 1987 as a standing group under contract to the WIPP PA Department at SNL. The PAPRP charter states that the purpose for establishment of the panel was as follows:

> An external Peer Review Panel has been established for significant PA documentation so that the DOE can be assured that the performance evaluation is well-conceived and being carried out with professional competence, and so that scientists and state officials can be assured that the DOE's conclusions as to the suitability of the WIPP as a repository are credible.

An evaluation of the PAPRP reviews against the screening criteria is provided in Table 9-7. Panel members were selected on the basis of their professional stature within the university, scientific and/or engineering communities. The PAPRP membership provides expertise in environmental research, geology, nuclear engineering, hydrogeology, and public policy development. Members were chosen explicitly for their independence from PA work undertaken by SNL. Panel members were:

- G. Ross Heath (Chairman), University of Washington;

Table 9-7. Performance Assessment Peer Review Panel

1. Is the peer review relevant to the CCA?	Yes – the PAPRP evaluates SNL PA efforts.
2. Was there a formal report prepared by the reviewer?	Yes – formal reports are developed.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the PAPRP reviews the adequacy of the SNL PA activities.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the PAPRP performs documented, in-depth, critical evaluations of PA reports and other documentation, addressing validity of basic assumptions, alternative approaches, methodology, uncertainty, supportability of conclusions, and consequences of incorrect assumptions or conclusions.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – all members of the PAPRP are recognized experts in their fields.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the PAPRP operates as a independent group under contract to the SNL PA Department. Uncensored comments by the panel are maintained in the SWCF.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

- Robert J. Budnitz, Future Resources Associates, Inc., Berkeley, California;
- Thomas A. Cotton, JK Research Associates, Inc., Washington, D.C.;
- Peter A. Domenico, Texas A&M University (Until 1990);
- C. John Mann, University of Illinois, Urbana;
- Thomas H. Pigford, University of California, Berkeley; and
- Frank W. Schwartz, Ohio State University (since 1990).

The panel finished its work with the preparation of the CCA. The PAPRP chairman was responsible for ensuring that members did not have a conflict of interest.

Panel members were requested to address the following areas, as applicable, for each review:

1. Validity of basic assumptions and extrapolations;
2. Alternative interpretations or approaches;
3. Appropriateness, logic, and limitations of methodology;
4. Uncertainty of results;
5. Supportability of the conclusions drawn;
6. Consequences of incorrect assumptions or conclusions; and
7. Other issues appropriate to the review subject.

The major issues (and their resolutions) raised by the PAPRP during its review of PA documentation from 1987 to 1995 are provided in CCA Chapter 9 and CCA Appendix PEER, Section PEER.11.

9.4.3 Shaft Seal Design Independent Review

A review plan, titled Shaft Seal System Design for the Waste Isolation Pilot Plant (WIPP), was developed and approved on January 12, 1996 (Hansen 1996). The review plan governed the preliminary and final reviews of the WIPP shaft seal system.

Members of the review panel were selected based on their respective knowledge, experience, and independence from the WIPP shaft seal design effort. The group had expertise in computational geomechanics, rock mechanics, mining engineering, civil engineering, and the design and construction of underground seals and bulkheads. The panel for both the preliminary and final reviews consisted of a review team chairman and three reviewers:

- R.E. Stinebaugh (Chairman), SNL;
- Dr. Malcolm Gray, Atomic Energy of Canada Limited Whiteshell Laboratories;
- Stephen Phillips, Phillips Mining; and
- Dr. John Tinucci, Itasca Consulting Group.

A evaluation of the shaft seal design reviews against the screening criteria used to determine whether this review should be addressed in this application is presented in Table 9-8.

Shaft seal design activities were conducted under an approved QA program. The review was conducted in accordance with the requirements of SNL QAP 3-2, entitled Verification of Design Adequacy, approved 7/31/95 (QA Department 1995), and the provisions of the review

Table 9-8. Shaft Seal System Design Review

1. Is the peer review relevant to the CCA?	Yes – the seal system is directly relevant to PA.
2. Was there a formal report prepared by the reviewer?	Yes – the title of the report is "Final WIPP Shaft Seal System Design Review."
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the review focused on the adequacy of the shaft seal system that was developed by SNL
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the review evaluated the adequacy of the work of others (the design of the shaft seal system).
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the reviewers were specifically chosen because of their expertise in seal design and related disciplines.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – it may appear that the independence could be questioned because of the chairman's affiliation with SNL. However, his organizational independence from the WIPP project and his actual role in the review process (see Section 9.4.3 for additional discussion) preserved the independence of the review.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

plan. Panel members were trained in accordance with the provisions of QAP 3-2 prior to beginning the design review. A member of the SNL QA staff (Organization 6860) briefed the panel at the onset of the review, monitored the review as it progressed, and inspected record-keeping activities. Records of panel training and other QA records concerning this review were maintained in accordance with SNL QA program requirements.

In both reviews, the panel was asked to address the following questions:

1. Will the shaft seal system satisfy design guidance?

2. Are there elements of the design that will prevent the sealing system from meeting design requirements?

3. Can the design be successfully implemented?

A short summary of each review is provided below.

Review of the Preliminary Shaft Seal Design

The preliminary design review considered the adequacy of design concepts summarized in DOE (1995c). The report includes descriptions of the WIPP setting, design guidance derived from the regulations, a description of the design, materials comprising the seal components, and preliminary evaluations of the shaft seal system.

The review of the Sealing System Design Report was initiated in January 1996 and completed in March 1996. Following their review of the Sealing System Design Report, Dr. Gray, Dr. Tinucci, and Mr. Phillips prepared detailed comments. These comments were forwarded to the appropriate design staff and formal responses were prepared. The reviewers evaluated the responses and determined their responsiveness to the concern.

Subsequent to resolution of outstanding issues, the updated information was used to amend the documentation provided to the review panel for its final review (discussed below). At the conclusion of the final review, all of the reviewers, without exception, stated that the actions promised in the responses to the preliminary review comments had been completed.

Review of the Final Shaft Seal System Design

During April 1996, the panel was convened to review the Compliance Submittal Design package for the WIPP shaft sealing system (Hansen 1996). Panel input was subsequently incorporated into the final Compliance Submittal Design report (Repository Isolation Systems Department 1996). The review was based on documentation provided by SNL and briefings by the WIPP technical staff. The documentation included an enhanced, annotated outline for the compliance shaft seal design report, detailed drawings, a material specifications framework, and topical summaries of structural and fluid flow calculations. Briefings provided the panel with additional information covering the design, laboratory and in-situ experimentation results, and analyses that were completed.

Following completion of the review, each panel member prepared specific comments regarding the design (see CCA Appendix PEER). The WIPP staff prepared specific responses to the comments and met with the reviewers to resolve them. In some instances, the WIPP staff, in response to the reviewer comments, promised to make certain changes or additions to the design drawings, the documentation of the analyses, or the report test. In some of these cases, a reviewer conditionally accepted those responses but required a copy of the marked up document to remove the condition for full acceptance. The comments were formally tracked with comment resolution forms. In addition, conditionally accepted comments were formally closed by sending the text changes to the reviewer as evidence of the direct incorporation of his or her comments. Final comment closure was documented in the form of a letter from the reviewer stating full acceptance of the changes.

Each reviewer also prepared a summary statement (see CCA Appendix PEER). The summary statements provided recognition or explanation of specific technical concerns in the final documentation, identified the need for future work prior to emplacement of the seals, provided suggestions for design and analysis enhancements or simplifications, and encouraged more

detailed quantification of design guidance. Each of the reviewers provided "bottom-line" assessments. Excerpts from the summary statements are provided below:

> In summary and conclusion, I consider that when completed as stated immediately above, it is likely that the documents being developed will present a design that will meet the general requirement of shaft sealing systems that will mitigate against water and gas flows from the repository to the biosphere and that can be built using existing technologies or reasonable extrapolation therefrom. (Dr. Malcom Gray)

> It is considered improbable that the seal design, as presented including the revisions recently discussed, can be significantly and practically improved within the limits of existing construction materials and technologies, except in some areas where optimization of materials and methods of emplacement can be achieved. (Mr. Stephen Phillips)

> The design that has been put forth presents one way of efficiently sealing shafts. Recognizing that other ways could also be made to work, the design presented here is similar to others suggested by the scientific community for sealing deep geologic nuclear waste repositories. The concepts presented have been developed from sound engineering judgment and sound analyses techniques. The anticipated performance of individual sealing components are within reasonable expectations based on currently available field and laboratory data, albeit limited. To address the wide scale of uncertainties, the design has been conservatively laid-out with redundant multiple-barrier components so that the overall seal system performance is not dependent on the functionality of an individual component. The design as it exists today is a conceptual design since it describes basic concepts and provides sufficient backup analyses to demonstrate that those concepts will reasonably satisfy the qualitative design guidelines. (Dr. John Tinucci)

9.4.4 Engineered Alternatives Task Force Report Peer Review

The EATF was established by the DOE in 1989. The EATF was tasked to evaluate the effectiveness, feasibility, and risk of implementing alternative facility designs, backfills, and/or waste forms in improving the long-term performance of the WIPP disposal system. The purpose, methodology, assumptions, and conclusions of the EATF are documented in DOE 1991. The author of the report, IT Corporation, convened a peer review panel to review a final draft version of the report during 1991. An evaluation of the EATF review against the screening criteria is provided in Table 9-9. The panel consisted of experts in chemical and nuclear engineering and geology. The members of the panel and their affiliations were as follows:

- Dr. H. Eric Nutall, University of New Mexico and Nutall & Associates, Inc.;
- Dr. Douglas Brookings, University of New Mexico;
- Dr. Robert J. Budnitz, Future Resources Associates, Inc.; and
- Donald E. Shaw, P.E., Engineering and Management Consultant.

A formal comment resolution process was employed to ensure that the reviewers' comments were incorporated into the final version of the report. The comments of the panel can be grouped into three general topics: (1) quality of technical work, (2) utility of a single figure-of-merit, and (3) use of relative versus absolute risk.

Table 9-9. Engineered Alternatives Task Force Report Review

1. Is the peer review relevant to the CCA?	Yes – the review was conducted on the 1991 EATF report which formed the basis for the subsequent EACBS.
2. Was there a formal report prepared by the reviewer?	Yes – the report consists of review comment record forms that were used to formally document the comments, responses, and their dispositions.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the purpose of the review was to determine the adequacy of the EATF report.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the review evaluated the adequacy of the EATF report.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the reviewers were nationally recognized experts in their respective fields.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the reviewers were not involved in the preparation of the work and were free from funding considerations.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

The comments made by the peer review panel (see CCA Appendix PEER) and the WIPP project responses are discussed below.

9.4.4.1 Quality of Technical Work

One reviewer commented that:

> "The complex technical risk analysis work aimed at determining risk-reduction factors of the many different risk endpoints and for 16 different alternative scenarios, is of high quality and deserves commendation. The technical information buried in the back of the Attachments to this report can provide an excellent basis for decision-makers to understand the various risk issues, and make decisions about them. The choice of alternative scenarios, the assumptions made to limit the scope of the analysis, the risk endpoints identified, and the analysis methods used are all fully

> acceptable to me. I am particularly pleased with how the analysis of specific risk endpoints was accomplished in a way that focused on the key issues relevant to the alternative scenarios. This part of the report can be a gold mine for further study by experts, as well as of use to decision-makers if presented properly."

The future value of the work predicted by the reviewers was an accurate prediction because the methodology and models developed for the EATF formed the basis for the subsequent EACBS (DOE 1995b) performed in 1995. The EACBS was recently the subject for another peer review panel (see Section 9.3.3).

9.4.4.2 Utility of a Single Figure-of-Merit

The reviewers questioned the utility of a single figure-of-merit to express the aggregated risk elements. The EATF used a Multi-Attribute Utility Theory approach to combine the risk components for each alternative into a single value for alternative ranking purposes. These risk components included the routine and accidental risks from waste transportation and handling, exposure to radiation and hazardous constituents in the waste during treatment, and cost, schedule, and benefits to future generations from a safer disposal system. One reviewer commented that:

> Although I admire the attempt to come up with a single figure-of-merit useful to decision-makers by which to judge the overall benefit/disbenefit of each of the various scenarios being studied, in my view the effort has not succeeded. The methodology did use established decision-theory methods to identify and calculate such a single figure-of-merit, and seems to break some new ground, but in my opinion, the single figure-of-merit identified is not sufficiently useful to decision-makers to justify the continuation of work along those lines. In fact, I believe that the use of a single figure-of-merit obscures rather than illuminates the situation. Decision-makers are in my opinion fully capable of dealing with multiple attributes presented separately and of weighing them in their own ways for decision-making purposes--this goes on every day in the upper-management board rooms of large enterprises and agencies. But to make these judgements, decision-makers need the best available disaggregated information about the issues at hand, in this case, the best absolute numbers and uncertainties about the specific risk endpoints. I don't believe that high-level decision-makers generally use aggregated information very much or very well, and I don't believe that the aggregated information based on the single figure-of-merit developed in this report will be of much use.

The WIPP project believed that, although dissaggregated information may be used by many decisionmakers in finance and industry, it was not sufficient for the EATF. A compromise was reached in final version of the EATF report. That compromise consisted of providing both the aggregate and individual risk components. This allows a decisionmaker the option to develop an independent figure-of-merit based on personal weighting factors and preferences.

9.4.4.3 Use of Relative versus Absolute Risk

The EATF methodology involved the calculation of relative risk reduction factors rather than absolute risks for each alternative. These relative risk reduction factors were based on a risk of unity for the baseline case (defined as: no waste treatment; a crushed salt backfill; and the current repository design). Risks for each EA were ratioed against the risk for the baseline case, yielding the risk reduction factor. The main advantage of this relative risk approach is that many parameters that affect absolute risk will cancel when calculating relative risk. Uncertainties in those parameter values do not translate into uncertainties in the relative factors. Some reviewers

felt that the calculation of absolute rather than relative risks would have been more useful to decisionmakers. For instance, one reviewer commented that:

> In my view, the approach of identifying and working with risk-reduction factors (RRFs) is a very useful intermediate step toward what is actually needed. Indeed, calculating RRFs is often simpler than calculating absolute magnitudes of risks for reasons cited well in the report. However, I believe that for decision-makers these RRFs cannot adequately substitute for knowing the actual magnitudes of the risks involved, except in special cases, such as when almost no changes occur (RRF near unity) or when absolute risk magnitudes and minuscule small for both the base-case scenario and the alternative scenarios.

The WIPP project concluded that although absolute risks convey a greater amount of information for decisionmakers than relative risks, the calculation of absolute risks were outside the scope of the EATF study and would have entailed a considerably greater effort than was warranted. For instance, calculating absolute long-term risks to future generations for each alternative would require performing a complete PA for each alternative.

9.4.5 Blue Ribbon Panel Peer Review

The Secretary of Energy established the WIPP Blue Ribbon Panel (BRP) in August 1989. The panel was composed of the following five members:

- Dr. Thomas Bahr;
- Robert W. Bishop, esq.;
- Dr. Arthur S. Kubo;
- Leonard C. Slosky; and
- Newal Squyres.

Dr. Bahr, a water quality management expert and the Director of the New Mexico Water Resource Research Institute, was nominated to the BRP by the Governor of New Mexico. Mr. Bishop, General Counsel and Corporate Secretary for the Nuclear Management Resources Council, and Dr. Kubo, a nuclear and civil engineer and a vice president of the BDM Corporation, were appointed to the BRP by the Secretary of Energy. Mr. Slosky, an environmental consultant, and Mr. Squyres, an attorney, were nominated by the Governors of Colorado and Idaho, respectively.

The panel members were each requested to provide an independent technical review of WIPP issues and individually report on the following:

- The concept and timing of DOE's proposed WIPP Operations Demonstration,
- Whether or not the operations demonstrations should be conducted in parallel with the PA, and

- An evaluation of DOE's validation plan for certification of TRU waste to meet the WIPP WAC.

The panel conducted site visits at the WIPP facility and portions of INEL and the Rocky Flats Plant. The panel met with and/or was briefed by staff from the DOE and its contractors, the NAS Board of Radioactive Waste Management WIPP Panel, the EEG, and the EPA. The panel members were provided an extensive amount of documentation and were encouraged to address questions to the above groups. An evaluation of the BRP review against the screening criteria is provided in Table 9-10.

Table 9-10. Blue Ribbon Panel Review

1. Is the peer review relevant to the CCA?	Yes – the reviews addressed waste certification and PA aspects.
2. Was there a formal report prepared by the reviewer?	Yes – each panel member prepared an individual report.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the panel reviewed the adequacy of work being done primarily at WIPP, Rocky Flats Plant, and INEL.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the panel reviewed DOE plans and processes.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – panel members were specifically chosen by the governors and the Secretary of Energy because of their qualifications.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the panel members were not otherwise associated with the WIPP project.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

Following submission of its reports, the BRP was asked to continue its service by providing their observations and recommendations to the DOE in three areas: (1) continued review of DOE plans to characterize Rocky Flats Plant TRU and mixed waste; (2) assist DOE in developing a strategy for achieving compliance with Resource Conservation and Recovery Act (RCRA) and other environmental regulations at WIPP; and (3) evaluate the Final Test Plan and ancillary documents. Subsequently, DOE expanded the BRP charge to include a management review of the WIPP project, review of the rationale and plans to characterize waste for the test phase, and a review of plans for EAs relating to the waste form.

The BRP was also asked in late November 1989 to comment on questions submitted by members of the New Mexico Congressional Delegation. The questions were: (1) what is the rationale for conducting in-situ experiments at the WIPP rather than at existing waste generation and storage sites; (2) how much waste would need to be emplaced at the WIPP for the experiments; and (3) what are the BRP's recommendations regarding DOE's proposed Operational Demonstration experiments?

The BRP provided individual responses to the congressional delegation and provided testimony to the Senate Committee on Energy and Natural Resources on April 26, 1990. The general observations of the panel were provided to the Senate by Dr. Bahr who stated the following:

> At this point Mr. Chairman, rather than going into my specific observations and recommendations and then having each of the panel members do the same, we decided in order to save time that I would very briefly summarize the general observations of the panel to date. The first and most significant observation in my opinion is that each member of the Blue Ribbon Panel has independently arrived at similar conclusions on each of the issues we were asked to evaluate. Also noteworthy is the high level of congruence of our findings with those of the Advisory Committee on Nuclear Facility Safety (Ahearne Committee). We have also participated in meeting with the WIPP Panel of the National Academy of Sciences and I can report that we also generally share the same views on those issues we have both looked into. Let me now highlight those items upon which members of the Blue Ribbon Panel seem to agree.
>
> 1. The deep bedded salt repository at the WIPP appears to be a safe site for long term isolation of transuranic waste; certainly safer than where this waste is presently stored. Radioactive releases over the long term for an <u>undisturbed</u> WIPP site will probably meet EPA standards (40 CFR 191 Subpart B). Meeting this standard having to consider human intrusion scenarios will be more difficult. Treating the waste so as to change the waste form and thereby force the repository environment to known conditions will significantly reduce present uncertainties. The most controllable variable in the design of the repository environment is the waste form.
>
> 2. <u>In situ</u> testing is important and necessary and should begin as soon as possible. Results of bin and alcove testing should significantly increase the confidence of long range predictions undertaken in the performance assessment. Individual members of the Blue Ribbon Panel agree that the quantity of waste emplaced for experimental purposes should not be limited such as to preclude justifiable experiments. A limit of approximately 1% of the WIPP waste capacity is reasonable. A limit of 0.5% may be too restrictive by precluding the opportunity to undertake important Phase III bin testing of different waste forms resulting from different engineered modifications.
>
> 3. Members of the Blue Ribbon Panel agree conceptually that the EPA suggestion of adding two filled rooms for monitoring purposes is worthy of further consideration by DOE. This approach, however, should be evaluated in the context of verifying facility performance and not considered as part of the test phase itself. We have not, however, been asked to evaluate EPA's suggestion.

> 4. On the subject of Operations Demonstration, our panel agrees that such an undertaking will provide valuable information because of the practical experience gained in system-wide operations. We are in general agreement, however, that a full "ramping up" of an Operations Demonstration should be postponed until such time as the final waste form and repository configuration are determined and that there is a high level of certainty that the Subpart B standard can be met.
>
> 5. We also have general agreement that DOE had underestimated the complexity and level of effort required to comply with RCRA in managing its transuranic-mixed wastes.
>
> Mr. Chairman, I have touched the high points and obviously skipped over many details. Other panel members may wish to elaborate on these and other items. In closing, there is one last item of strong agreement expressed by all panel members. We are very impressed by the responsiveness of DOE to our suggestions. Some examples include 1) The significant improvements that have been made in the DOE organization toward overall systems integration, both vertically and horizontally among the varied elements of transuranic and mixed-transuranic waste management; 2) The significant increase in effort being placed on evaluation of engineered alternatives and waste treatment; 3) The accelerated activity and seriousness with which DOE is now placing on dealing with RCRA and in particular on waste characterization issues; and finally 4) The decision by the Secretary to postpone the start up of the Operations Demonstration program.

The full text of the panel's testimony to the Senate and of the independent reports prepared by the individual panel members are provided in Appendix PEER-2004. There have been significant changes as a result of the recommendations of the BRP and other reviews of the project. These changes are especially dramatic with regard to the PA activities and review. All of the findings and recommendations from the BRP were resolved by the WIPP project to the extent that they were formally closed by the individual BRP members.

9.4.6 Advisory Committee on Nuclear Facility Safety Review

The Advisory Committee on Nuclear Facility Safety (ACNFS) was established by DOE on November 13, 1987, on the recommendation of the NAS. The ACNFS was appointed by the Secretary of Energy to provide advice and recommendations on the safety of DOE's nuclear production and utilization facilities. The facilities reviewed by the ACNFS included the WIPP site and the waste generator sites. An evaluation of the ACNFS review with the screening criteria is provided in Table 9-11.

The ACNFS was composed largely of recognized experts (from outside the DOE) in the field of nuclear energy. Specific expertise of the committee members included environmental chemistry, risk assessment, radioactive waste management, medicine, geology, geochemistry, biophysics, health physics, and environmental regulatory compliance. The ACNFS panel was composed of the following members:

- John Ahearne (Chairman), Sigma Xi;
- Jess Cleveland, U.S. Geological Survey;
- Floyd Culler, EPRI;
- Jacob Fabrikant, University of California, Berkeley;

Table 9-11. Advisory Committee on Nuclear Facility Safety

1. Is the peer review relevant to the CCA?	Yes – The review addressed long term performance, gas generation, and EA issues.
2. Was there a formal report prepared by the reviewer?	Yes – There was a formal report.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes –Although much of the ACNFS's scope could be characterized as technical review, there were other issues, such as the adequacy of the WIPP programs to address gas generation, long term performance, and waste characterization that would be better characterized as peer review.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes –ACNFS reviewed DOE operations, processes and documentation.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes –ACNFS members were recognized experts in the field of nuclear energy.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes –ACNFS members were from outside the DOE and were appointed by the Secretary of Energy under the Federal Advisory Committee Act.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

- William Kastenberg, University of California, Los Angeles;
- Terry Lash, Consultant;
- Harold Lewis, University of California, Santa Barbara;
- James Martin, University of Michigan;
- Dana Powers, SNL;
- William Schull, University of Texas;
- Robert Seale, University of Arizona;

- C. Frederick Sears, Northeast Utilities;
- Gerald Tape, Associated Universities; and
- Victoria Tschinkel, Landers and Parsons.

The ACNFS visited WIPP in June 1989, at which time a subcommittee was formed to review safety issues in further detail. The WIPP subcommittee was chaired by Dr. Tape (Paul D. Rice, a consultant, chaired the subcommittee until October 1990). Members included Drs. Kastenberg, Lash, Martin, and Seale. Special consultants to the subcommittee included

- Konrad Krauskopf, Stanford University (until October 1990);
- James Ling, Consultant (until October 1990);
- Thomas Pestorius, Consultant;
- Thomas Pigford, University of California, Berkeley (until October 1990);
- Bernard T. Resnick, Consultant; and
- Frank Rowsome, Consultant (until October 1990).

The subcommittee subsequently revisited WIPP and other related facilities: SNL, INEL, and the Rocky Flats Plant. Areas of review included unresolved short-term technical and operational issues and long-term environmental performance. A report to the Secretary was issued by the ACNFS on December 11, 1989 (see CCA Appendix PEER, Section PEER.15) and a final report was issued in November 1991 (see CCA Appendix PEER) for the WIPP chapter of the final report.

The 1989 report identified several recommendations to resolve issues related to both short-term operations and long-term performance of the repository. The final report, titled “Final Report on Department of Energy Nuclear Facilities” (Document PB92-119809), contained a section that dealt with its review of WIPP. This final report contained the following recommendations to “increase the probability of successful compliance with EPA’s proposed standards in a shorter period of time . . .”

> Prepare a concise report in a timely manner comparing the expected performance of WIPP with the requirements in EPA’s proposed standard (40 CFR 191). This report should specifically focus on those parameters that are currently significantly uncertain and set forth the actions including alternatives, necessary to reduce the uncertainties to acceptable levels for demonstrating regulatory compliance.
>
> Change current project priorities by putting more emphasis on the use of experts. At this time, panels of experts will provide more significant input to the demonstration of compliance with EPA standards than will the results of the Dry Bin Tests. The Bin Test Program should continue to be focused on reducing uncertainties in those parameters that are most important in determining compliance with EPA’s proposed standards.

> Initially dispose only the contact handled TRU waste that will not pose a gas generation problem. Other TRU wastes can be safely stored above ground until it is determined whether they can be buried at WIPP in compliance with regulatory requirements or have to be treated so that disposal at WIPP is acceptable.

> Immediately begin development and implementation of engineered alternative, especially for newly generated waste. DOE should be a technological leader in waste management and this initiative should go forward even if it were not specifically required to demonstrate compliance with EPA's proposed standards.

The WIPP project initiated and continued several activities to resolve the ACNFS concerns. Specific action plans were developed and implemented. In June 1990, the DOE prepared a concise report summarizing the current understanding of expected performance and the potential for demonstrating compliance with 40 CFR Part 191, Subpart B (Bertram-Howery and Swift 1990). Preliminary PAs in 1990, 1991, and 1992 identified significant uncertainties and provided guidance to the project. The experimental program was refocused to meet the needs of the compliance evaluation, and the underground bin and alcove tests were canceled. Chapter 4.0, and CCA Appendices WCA and WCL address which wastes will be emplaced at WIPP. The subject of EAs was reviewed by two recent peer review panels (see Sections 9.3.3 and 9.4.4). The ACNFS recommendations were formally closed by the Advisory Committee.

9.4.7 Performance Assessment Review Team

The Performance Assessment Review Team (PART) was organized in 1992 by the DOE's Director of Environmental Restoration and Waste Management WIPP Project Management Division (EM-342). The purpose of the PART review was "to assess the adequacy of the WIPP PA program for meeting relevant regulatory standards for the disposal of radioactive and hazardous wastes, to identify any deficiencies in the program, and to make recommendations for improvements." The team members were as follows:

- Bryan Bower (Chairman), DOE/EM-342;
- Charles Voss (Deputy Chairman), Golder Associates, Inc.;
- James Russell, Texas A&M University;
- Neville Carter, Texas A&M University;
- Pamela Doctor, Pacific Northwest Laboratory; and
- Charles Cole, Pacific Northwest Laboratory.

The group was very knowledgeable of geologic repositories and included specific expertise in PA methodology, brine migration, flow and transport modeling, creep and room closure, and site operations. The review team was not completely independent because the chairman of the review team was a staff member of DOE/EM-342, which had oversight responsibility for WIPP. Section 1.4.1 of the PART report (the complete report is provided in Appendix PEER) states that

> The Director of EM-342 and the PART chairperson selected the PART members on the basis of their knowledge of components and processes associated with salt repository and their independence from the WIPP Project. More specific criteria included (1) familiarity with geologic repositories; (2) PA expertise or knowledge of risk assessment techniques; (3) knowledge of RCRA and/or 40 CFR 191 requirements; and (4) no direct association with any of the PA activities for the WIPP.

Note that the report findings "reflect the consensus of team members" and that the final report was signed by all team members. It was included in this application because of its insight into the PA effort at a pivotal time in the direction of PA for the WIPP project. An evaluation of the PART review against the screening criteria is provided in Table 9-12.

The review was primarily conducted during the first half of 1993 and a final report was issued in February 1994. All PART activities were conducted and documented in accordance with EM-342's NQA-1 based QA program. The PART reviewed the pertinent PA documents and activities, toured the WIPP site, and interviewed members of the project staff. The team concluded that

> The review team finds that the work on the WIPP has generally been perceptive, incisive and fundamentally sound. However, for compliance with current standards and regulations, substantial progress and improvements will be necessary in certain areas where additional investigations and documentation may be required; the PA department is fully aware of most of them. These areas include PA documentation, parameter evaluation, conceptual model justification, time-dependent behavior of natural and engineered barriers to fluid migration from the coupled disposal system, and a total system model.

Considerable effort was made to resolve the concerns identified in this review. The PA process has changed significantly since the PART report to address issues identified in this report, as well as to document the conformance with the requirements of 40 CFR Part 191 and criteria of 40 CFR Part 194. Finally, note that the PART final report was provided to the recent conceptual models peer review panel (see Section 9.3.1) for its consideration. The issue of EAs, as they relate to PA, was specifically reviewed by recent peer review panels (see Section 9.3.3).

9.4.8 INTRAVAL

The INTRAVAL project was initiated in 1987 in Stockholm as an international effort to validate geosphere models for transport of radionuclides. The project was initiated by the Swedish Nuclear Power Inspectorate and was first formed as an ad-hoc group with representatives from eight organizations. By the 1990s, INTRAVAL grew to include 24 "parties" from 14 countries and was coordinated by the Nuclear Energy Authority (NEA) of the Organization for Economic Cooperation and Development (OECD). The INTRAVAL philosophy was to use results from laboratory and field experiments as well as natural analog studies in a systematic study of the model validation process. The goal was to evaluate conceptual and mathematical models for groundwater flow and radionuclide transport in the context of PA of repositories for radioactive waste, with particular focus on the validity of model concepts. The project ended in 1997.

Table 9-12. PART Independent Review of WIPP PA

1. Is the peer review relevant to the CCA?	Yes – the review dealt directly with the PA.
2. Was there a formal report prepared by the reviewer?	Yes – the report is titled "Performance Assessment Team's Independent Review of WIPP Performance Assessment Activities (40 CFR 191 and 40 CFR 268.6) for EM-342." The report is dated February 1994.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the review focused on the adequacy of then current PA and RCRA activities at WIPP.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the review evaluated the adequacy of the work of others.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – Section 1.4.1 states "The Director of EM-342 and the PART Chairperson selected the PART members on the basis of their knowledge of components and processes associated with salt repository and their independence from the WIPP Project. More specific criteria included (1) familiarity with geologic repositories, especially salt; (2) PA expertise or knowledge of risk assessment techniques; (3) knowledge of RCRA and/or 40 CFR 191 requirements; and (4) no direct association with any of the PA activities for the WIPP."
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	No – the team chairman was a DOE EM-342 employee. EM-342 has oversight responsibility for WIPP. The remaining members were university staff and a professional consultant.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Yes – report findings reflect the consensus of team members and the final report was signed by all team members.

A number of test cases were studied at various locations around the world. These test cases included field tests, mining operations, natural analogs, and laboratory experiments. In 1990, two test cases from the WIPP site were included as part of the INTRAVAL investigations, and were designated as WIPP1 and WIPP2. An evaluation of the INTRAVAL project reviews against the screening criteria is provided in Table 9-13. These two test cases are discussed in INTRAVAL Progress Reports (numbers 5 through 10) (see CCA Appendix PEER).

Table 9-13. INTRAVAL

1. Is the peer review relevant to the CCA?	Yes – although not a review of the WIPP project specifically, INTRAVAL used WIPP site characterization data to validate models of groundwater flow.
2. Was there a formal report prepared by the reviewer?	Yes – annual INTRAVAL reports and journal articles provide summaries of the findings.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the two cases discussed provide independent evaluation of the validity of the conceptual models used for Salado brine inflow and Culebra groundwater flow at WIPP.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the two cases evaluated the validity of conceptual models for the WIPP site.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – reviewers were internationally recognized experts in their respective fields. Many had extensive experience in radioactive waste disposal projects in other countries.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – reviewers were not involved in the WIPP project, were impartial, and were free from funding considerations.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

9.4.9 Waste Isolation Pilot Plant Conceptual Model Uncertainty Group Review

The WIPP Conceptual Model Uncertainty Group (CMUG) was an advisory group formed and operated in 1993 to provide guidance to SNL's WIPP PA effort. An evaluation of the CMUG activities against the screening criteria is provided in Table 9-14. A report of their evaluation of the WIPP PA was prepared September 27, 1993 (see CCA Appendix PEER) and is summarized below.

Table 9-14. Conceptual Model Uncertainty Group

1. Is the peer review relevant to the CCA?	Yes – the CMUG reviewed the 1992 conceptual models used for PA.
2. Was there a formal report prepared by the reviewer?	Yes – meeting summaries were prepared.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – it was a review of the adequacy of the WIPP conceptual models.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Partially – although the CMUG reviewed the existing PA models, its primary thrust was to recommend improvements in the models.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – group members are internationally recognized experts in their respective fields.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the recommendations were provided from an independent and impartial perspective.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Yes – the review conducted a detailed review of the WIPP conceptual models and provided extensive comment on those models.

The CMUG included expertise in hydrology, geology, geochemistry, risk assessment, and environmental modeling. All committee members were consultants who, at that time, worked outside the SNL community. The panel members were as follows:

- Craig Bethke, University of Illinois;
- Rafael Bras, Massachusetts Institute of Technology;
- Jesus Carrera, Universidad Politechnica de Catluta;
- Neil Chapman, Intera Information Technologies Ltd.;

- Ghislain de Marsily, University Pierre et Marie Curie;
- Daniel Galson, Galson Sciences Ltd.;
- Steven Gorelick, Stanford University;
- Jane Long, Lawrence Berkeley Laboratory; and
- Dennis McLaughlin (Chairman), Massachusetts Institute of Technology.

The charter of the CMUG states

> The conceptual model uncertainty ... group is being formed to provide guidance to the WIPP PA program on how to account for uncertainty associated with conceptual models for the groundwater flow and radionuclide transport systems in the Rustler and other non-Salado formations.

The group was also asked to "... help ... on the development of alternative conceptual models and treatment of conceptual model uncertainty ..."

During its first two meetings in March and October of 1993, the CMUG focused on gaps, ambiguities, questionable assumptions, and simplifications that should be resolved before a final PA is submitted. The CMUG's initial reaction was that the WIPP PA has concentrated too much on simulation exercises and too little on identifying potential pathways and processes. They recommended that the PA should devote more effort to understanding the origins and evolution of the non-Salado environment, particularly its geology, geochemistry, and hydrology. Specific concerns were provided in four areas: (1) regional hydrology, recharge, and the effects of climate change; (2) geologic history, evolution, and structure over a range of scales; (3) geochemical evolution and composition of groundwater; and (4) alternative transport pathways. These concerns are documented in the CMUG report, which is provided in CCA Appendix PEER.

Most of the recommendations provided by the CMUG were implemented. In direct response to the CMUG recommendations, an in-house working group was formed in the spring of 1993 to reevaluate conceptual models for use in PA. That group contained representatives of both PA and experimental activities, and made significant progress during the remainder of 1993 in redefining PA conceptual models. The DOE performed a complete rescreening of all FEPs as part of the preparation of this application. CMUG concerns were addressed as part of this activity. Also, the CMUG reports were provided to the CMPR panel (see CCA Section 9.3.1) for consideration in its assessment of the WIPP PA conceptual models.

9.4.10 Environmental Evaluation Group Reviews

The EEG was established in 1978 as an independent technical advisory group to assist in the State review of the WIPP project. The EEG continues to be funded by the DOE through the New Mexico Institute of Mining and Technology.

The following is a list of the EEG staff members and their technical disciplines in October 2003:

- Matthew Silva (Director), Chemical Engineer;

- James Channell (Deputy Director), Environmental Engineer;
- Larry Allen, Geologic Engineer;
- George Anastas, Health Physicist /Nuclear Engineer;
- Sally C. Ballard, Radiochemical Analyst;
- Radene Bradley, Secretary;
- Patricia Fairchild, Secretary;
- Don H. Gray, Laboratory Manager;
- John Haschets, Assistant Environmental Technician;
- Linda Kennedy, Librarian;
- Lanny King, Environmental Technician;
- Tom Klein, Environmental Scientist;
- Jill Shortencarier, Executive Assistant;
- Susan Stokum, Administrative Secretary;
- Ben A. Walker, QA Specialist;
- Scott Webb, Health Physicist II; and
- Judith F. Youngman, Administrative Officer.

The EEG conducts independent technical analyses of numerous aspects of the WIPP project. These analyses include assessments of reports issued by the DOE and its contractors as they relate to the potential health, safety, and environmental impacts from the WIPP. The EEG also performs independent environmental monitoring of background radioactivity in air, water, and soil, both on- and off-site.

The EEG has published 86 reports relating to numerous aspects of the WIPP project since 1978. An evaluation of the EEG reviews against the screening criteria is provided in Table 9-15. When evaluated against the screening criteria, it was determined that most of the reports (and associated work) involved issues outside the scope of this application and/or appear to represent expert judgment or technical review. However, 15 of the reports published

Table 9-15. EEG Reports

1. Is the peer review relevant to the CCA?	Some of the reports address site characterization and other CCA issues.
2. Was there a formal report prepared by the reviewer?	Yes – EEG prepares and publishes formal reports.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Some of the reports fit the NUREG-1297 definition of peer review.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Some of the reports review the adequacy of the work of others.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the EEG is recognized as an expert group.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – EEG was created to provide an independent technical review of WIPP.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Only those reports which pass the above criteria will be incorporated into the CCA.

before the submission of the CCA appeared to qualify as peer reviews, per NUREG-1297, and address issues relevant to the compliance certification application. Those 15 reports were discussed in CCA Chapter 9 and are mentioned by titles and authors only in this chapter. The EEG has published 25 additional reports since August 1996, EEG-62 to EEG-86. Out of these, 11 reports (EEG-62, 64, 66, 68, 69, 75, 77, 82, 83, 85, and 86) appear to qualify as peer reviews, per NUREG-1297, and address issues relevant to the CRA-2004. Each of these 11 reports is discussed below.

The issues and concerns raised by EEG have been continually evaluated by the WIPP project. A considerable amount of additional testing and analysis have been undertaken because of EEG's involvement, and substantial changes have occurred in the WIPP project as a result.

9.4.10.1 EEG-2 (1978): Review Comments on the GCR, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico, SAND78-1596, Volumes I and II

See CCA Chapter 9 for a summary of this report.

9.4.10.2 EEG-3 (1979): Radiological Health Review of the Draft Environmental Impact Statement (DOE/EIS-0026-D) Waste Isolation Pilot Plant, U.S. Department of Energy

See CCA Chapter 9 for a summary of this report.

9.4.10.3 EEG-8 (1980): The Significance of Certain Rustler Aquifer Parameters for Predicting Long-Term Radiation Doses from WIPP

See CCA Chapter 9 for a summary of this report.

9.4.10.4 EEG-9 (1981): An Approach to Calculating Upper Bounds on Maximum Individual Doses from the Use of Contaminated Well Water Following a WIPP Repository Breach

See CCA Chapter 9 for a summary of this report.

9.4.10.5 EEG-10 (1981): Radiological Health Review of the Final Environmental Impact Statement, (DOE/EIS-0026), Waste Isolation Pilot Plant, U.S. Department of Energy

See CCA Chapter 9 for a summary of this report.

9.4.10.6 EEG-11 (1982): Calculated Radiation Doses from Radionuclides Brought to the Surface If Future Drilling Intercepts the WIPP Repository and Pressurized Brine

See CCA Chapter 9 for a summary of this report.

9.4.10.7 EEG-12 (1982): Potential Release Scenario and Radiological Consequence Evaluation of Mineral Resources at WIPP

See CCA Chapter 9 for a summary of this report.

9.4.10.8 EEG-22 (1983): EEG Review Comments on the Geotechnical Reports Provided by DOE to EEG Under the Stipulated Agreement Through March 1, 1983; and EEG-23 (1983): Evaluation of the Suitability of the WIPP Site

See CCA Chapter 9 for summaries of these reports.

9.4.10.9 EEG-29 (1985): Evaluation of the Safety Analysis Report for the Waste Isolation Pilot Plant Project

See CCA Chapter 9 for a summary of this report.

9.4.10.10 EEG-40 (1989): Review of the Final Safety Analysis Report (Draft), DOE Waste Isolation Pilot Plant

See CCA Chapter 9 for a summary of this report.

9.4.10.11 EEG-41 (1989): Review of the Draft SEIS, DOE Waste Isolation Pilot Plant, April 1989

See CCA Chapter 9 for a summary of this report.

9.4.10.12 EEG-50 (1992): Implications of Oil and Gas Leases at the WIPP on Compliance with EPA TRU Waste Disposal Standards

See CCA Chapter 9 for a summary of this report.

9.4.10.13 EEG-57 (1994): An Appraisal of the 1992 Preliminary Performance Assessment for the Waste Isolation Pilot Plant

See CCA Chapter 9 for a summary of this report.

9.4.10.14 EEG-61 (1996): Review of the WIPP Draft Application to Show Compliance with EPA TRU Waste Disposal Standards

See CCA Chapter 9 for a summary of this report.

9.4.10.15 EEG-62 (1996): Fluid Injection for Salt Water Disposal and Enhanced Oil Recovery as a Potential Problem for the WIPP: Proceedings of a June 1995 Workshop and Analysis, by Matthew K. Silva (Silva 1996)

The following is a summary of the EEG report (EEG-62) and therefore represents the views of the EEG and not necessarily those of DOE.

The potential impact of brine injection on the long-term performance of the WIPP prompted the EEG to organize a June 13, 1995 workshop on the issue. This report publishes the workshop presentations and presents the author's analysis of the workshop issues based on information from the scientific literature, public records, the draft compliance application submitted by the DOE to the U.S. EPA, and the WIPP-specific compliance criteria promulgated by the EPA. The workshop included presentations describing the extent of oil and gas resources, the anomalous water level rises in the Culebra Aquifer, the documented effects of water flooding on the Salado, the geology of waterflooded areas in southeast New Mexico, the current petroleum production practices, the treatment of water injection by the PA effort, and the need for a water flooding scenario in the WIPP PA calculations.

The issues identified include questions about (1) the productive life of an oil field in the Delaware Basin, (2) the extent of oil and gas reserves in unexplored areas, (3) the potential for waterflooding and other secondary recovery methods, (4) the volumes of water to be injected, (5) the availability of water for waterflooding, (6) delays in oil and gas drilling due to the presence of potash, (7) the true extent of potash reserves, (8) evidence of communication between

formations above and below the WIPP through vertical pathways possibly created by the improper abandonment of wells, poorly cemented and cased wells, degraded well casings and cement in saline environments, and (9) violation of existing regulations.

In response to the recommendations in this report, the DOE considered fluid injection as a scenario in the PA included in the CCA. The EPA accepted the DOE arguments and analysis (See EPA Docket A-93-02, Item II-I-1, Attachment 2 and Items II-1-9, II-1-7, II-1-25, II-1-27, II-1-32, and II-1-37).

9.4.10.16 EEG-64 (1997): Review of the Draft Supplement to the WIPP Environmental Impact Statement DOE/EIS-0026-S-2, by Robert H. Neill, James K. Channell, Peter Spiegler, and Lokesh Chaturvedi (Neill et al. 1997)

The following is a summary of the EEG report (EEG-64) and therefore represents the views of the EEG and not necessarily those of DOE.

EEG's review of the WIPP Disposal Phase Draft Supplemental Environmental Impact Statement (SEIS-ll) concentrated on the radiological aspects of the proposed action, including transportation. The alternatives were reviewed in less detail. Some calculations were checked, mostly for the proposed action. Because of time constraints, there was little review of hazardous chemicals, economics, or other environmental assessments.

EEG stated that compared to the proposed action, the proposed alternatives dealt with larger volumes of TRU waste continued over a much longer period of time, and were evaluated in a less rigorous manner. According to EEG, there was a need for real options to dispose of TRU wastes not included in the WIPP statutory limits.

EEG checked the transportation calculations in Appendix E of SEIS-II and compared these results to those contained in EEG-46. EEG concluded that the assessment of transportation risks in SEIS-II is reasonable and adequately conservative.

Analyses in SEIS-II indicated potential advantages to using rail rather than truck transportation for wastes. The rail analyses were not as rigorous as those for truck transportation. However, the findings were consistent with analyses in the FEIS, SEIS-I, and other documents. EEG recommended that DOE should take this opportunity to seriously reevaluate the merits of a "truck/rail mix" or a "maximum rail" policy for WIPP wastes.

9.4.10.17 EEG-66 (1998): Individual Radiation Doses from Transuranic Waste Brought to the Surface by Human Intrusion at the WIPP by James K. Channell and Robert H. Neill (Channell and Neill 1998)

The following is a summary of the EEG report (EEG-66) and therefore represents the views of the EEG and not necessarily those of DOE.

The EPA standards 40 CFR Part 191 require the DOE to evaluate the effects of releases from the repository for both undisturbed and disturbed conditions. Releases from undisturbed events must be evaluated for the radiation dose to individuals (§191.15) and the effect on groundwater quality (§191.24), as well as for the cumulative release of TRU to the accessible environment. Most

other countries with nuclear waste require that radiological risk to an individual be assessed for both undisturbed and disturbed scenarios.

The specific purpose of this report was to:

1. Calculate likely individual doses that would result from the same releases predicted by the CCA,

2. Determine whether these calculated doses exceed limits for radiation exposure from other activities,

3. Compare the stringency of an individual dose standard at WIPP with the release limits in 40 CFR Part 191, and

4. Discuss the appropriateness and feasibility of reducing potential doses to an individual from human intrusion at WIPP.

The deterministic calculations in this report rely primarily on drilling-related analyses in the CCA to determine the source term. Details of the scenarios for workers, individual members of the public, and the population within 80 kilometers (50 miles) of the site are adapted from scenarios in prior WIPP reports. Pathway analyses and dose conversion factors primarily use current methodology from EPA and NRC reports.

There are inherent uncertainties in estimating repository conditions, human actions, and individual doses at WIPP over a 10,000-year period. With this caveat, the report reached the following conclusions.

- Calculated doses to drillers and the resident farmer exceeded annual dose limits for occupational radiation workers only for the low-probability scenarios at the 100-year intrusion time.

- Calculated doses to drilling crew members and the resident farmer exceeded 100 mrem (1 mSv) y^{-1} at the 95 percent probability level. This is greater than the limits allowed in other standards regulating radioactive material, waste disposal, and contaminated site cleanup.

- Calculated doses to the resident non-farmer and the non-resident farmer (for the 95 percent probability release) are greater than the 500-mrem (5 mSv) y^{-1} value NRC used for similar scenarios in establishing low-level radioactive waste concentration limits in 10 CFR Part 61.

- Health effects predicted from a very preliminary integrated collective dose calculation are less than, but within an order of magnitude of, the health effects implied from 40 CFR Part 191 for the amounts released in the CCA.

- An individual dose limit of 100 mrem (1 mSv) y^{-1} (at 95 percent probability level) to the resident farmer at WIPP would be an order-of-magnitude more restrictive than the cumulative release limit in 40 CFR 191. Releases predicted in the CCA would be less

than the 100 mrem (1 mSv) y^{-1}limit but releases predicted in the PAVT would be > 100 mrem (1 mSv) y^{-1}.

- Since individual doses can be substantial, DOE should use ALARA designs (such as treating the waste) to limit these doses.

9.4.10.18 EEG-68 (1998): Evaluation of the WIPP Project's Compliance with the EPA Radiation Protection Standards for Disposal of Transuranic Waste by Robert H. Neill, Lokesh Chaturvedi, Dale F. Rucker, Matthew K. Silva, Ben A. Walker, James K. Channell, and Thomas M. Clemo (Neill et al. 1998)

This report provided the EEG's technical evaluation of the CCA and the EPA's proposed rule to certify WIPP (EPA 1997). The full report is included in Appendix PEER-2004.

The rest of the text in this section contains a summary of the EEG report (EEG-68) and therefore represents the views of the EEG and not necessarily those of DOE.

9.4.10.18.1 Solubility

The solubility of actinides is very important to calculating the releases from the repository. The CCA uses a model known as Fracture-Matrix Transport (FMT) to calculate these solubilities. EEG found that the model predicts differences for actinide sulfate solubilities that cannot be explained by chemistry, thus raising questions about the reliability of this model.

Rather than using an extensive plutonium database, the FMT predictions relied on thermodynamic data for other elements and an oxidation state analog argument. EEG recommended that the calculations be performed using data for plutonium and the values for solubility and complex ion formation contained in the peer-reviewed data compilation by the NEA/OECD.

EEG agreed with EPA's documentation of the shortcomings of the solubility uncertainty ranges advanced by DOE. However, EEG questioned EPA's argument that the ranges are adequate. As noted by EPA, there is a lack of data to determine the uncertainty ranges for oxidation states IV and VI. EEG recommended that the uncertainty range needed to be determined with the appropriate plutonium data.

According to EEG, in the solubility calculations, the CCA inappropriately discounted the role of organic ligands on plutonium solubility by arguing that EDTA is the strongest complexing agent and there is not enough present in the inventory to make a difference. But, EEG argued, citrate forms very strong complexes with actinides in the +4 oxidation state and very weak complexes with other cations. Thus, the solubility of a stable plutonium-citrate complex in individual waste containers needed to be calculated.

EEG claimed that there are serious unanswered questions about the impact of MgO backfill on the solubility of the actinides. It is proposed that MgO will reduce the solubility of the actinides by controlling the pH. However, it is not known how long the early reaction product, nesquehonite, would persist. The FMT model calculates that the presence of nesquehonite drives

the solubility of the +4 actinides, such as Pu, higher than in the no-backfill case. EEG suggested that this required further investigation.

9.4.10.18.2 Spallings

The EEG stated that the CCA spallings model was rejected by the DOE's peer review after submission of the CCA, but a new coherent model and a computer code that calculates the projected releases had not been developed. The EEG found the basis of accepting the predicted release volumes due to spallings as determined by the CCA to be both unnecessarily convoluted and faulty. EEG argued that since this is a mechanism for the largest projected releases from the repository, it is essential that it be treated through defensible conceptual and numerical models.

9.4.10.18.3 Air Drilling

The EEG stated that the air drilling scenario proposed by Dr. John Bredehoeft was rejected on the basis of regulation, despite records of such drilling in the Delaware Basin. Low probability and low consequence are also discussed in EPA's Air Drilling Analysis (EPA 1998c), and the scenario was ruled out again. However, the EEG did not believe that the issue had been resolved. Neither EPA nor DOE examined drilling records in the Texas portion of the Delaware Basin. New developments in underbalanced drilling also inhibit a full understanding of the capabilities of this expanding technology. According to EEG, the EPA's analysis of low consequence, in which a spreadsheet model was used, had serious shortcomings.

9.4.10.18.4 Fluid Injection

According to EEG, for fluid injection activities adjacent to the site, the EPA had accepted a "low consequence" argument based on a model that had not been verified with oil field water flood data, despite the availability of such data. According to EEG, EPA offered a low probability argument based on its expectations of fluid injection practices, although DOE maintained that the probability of future fluid injection practices would be difficult to define. The low probability argument had not been reconciled with the common observation of water flowing through the Salado in water flood operations throughout southeast New Mexico. Further, according to EEG, neither the DOE nor the EPA had adequately addressed concerns about future CO_2 flooding in the vicinity of WIPP. The basis for dismissing the Rhodes-Yates incident did not reflect a review of the technical information presented in that case. DOE had not explained the anomalous water level rises observed for the last 10 years in the Culebra aquifer despite the documented concerns of EEG, EPA, and the NAS WIPP Committee. EEG recommended additional effort to explain the Rhodes-Yates water flooding incident. The EEG maintained that the fluid injection scenario could not be dismissed either on the basis of low consequence or low probability.

9.4.10.18.5 Anhydrite Fracturing

The EEG had a number of questions about the validity of the anhydrite fracture model used in the BRAGFLO code. The EEG stated that the model was unusual in that the effect of fracturing was treated using an equivalent porous medium. All the relevant literature examined by EEG treated fractures as distinct porosity. Use of an equivalent porous medium is not in itself unreasonable; however, the DOE had not referenced a description of similar treatment of the dependence of porosity and permeability on pressure as a result of fracturing. The lack of a clear

development of the BRAGFLO model from established models made its review difficult. The EPA should request that the anhydrite fracture model of BRAGFLO be compared to the treatment of fracture development in hydrofracing codes commonly used in the industry. According to EEG, until the model and its assumptions were properly justified, the EEG found it difficult to accept the results derived from this model.

9.4.10.18.6 Solution Mining

EEG stated that the EPA's conclusion that potash solution mining was not likely at WIPP relied on solicited comments that were factually incorrect and inconsistent with the published scientific literature. DOE and EPA maintain that excavation mining captures the effects of solution mining on the hydraulic conductivity of the overlying aquifers. However, according to EEG, the prediction of subsidence above solution mines can be much more complex than the prediction of subsidence due to excavation mining. According to EEG, it appeared incorrect to calculate mining probability based on past potash production, which was inherently dependent on past mineral economics and the availability of high-grade ore. EEG argued that potash is used by the fertilizer industry and is ultimately used for the production of food. It seemed reasonable to EEG to assume that the demand for food would continue and low-grade potash ores would eventually be mined to meet this demand.

9.4.10.18.7 Groundwater Flow and Radionuclide Transport through the Culebra

EEG stated that a number of questions related to the flow and transport through the Culebra had been identified by the EEG that were not addressed by the EPA. These questions relate to the conceptual models of the origin and flow of water in the Culebra aquifer, transport modeling through the Culebra, and justifying the assumed values of the chemical retardation parameter (K_d) in the CCA calculations.

9.4.10.18.8 BRAGFLO 2D/3D Modeling

According to EEG, the results of the DOE's screening analysis for repository processes (FEP S-1) suggest that the 2D BRAGFLO model used in the CCA calculations may misrepresent repository performance at pressures above the anhydrite fracture pressure. There is the potential of substantially greater brine saturation in the repository at higher pressures than calculated for the CCA. The discrepancy between the 2D and 3D versions of BRAGFLO may have underestimated radionuclide releases to the surface. To resolve this issue, the EEG recommended that several three-dimensional (3D) BRAGFLO simulations of the repository should be performed using the parameter values of vectors used in the CCA PA. The 3D BRAGFLO simulations should be used to provide repository conditions for the normal suite of DBR calculations. The calculations should also be assessed in terms of impact on spallings calculations.

The DOE and EEG held a meeting on February 17, 1998 to try and resolve this issue. It was agreed at that meeting that there was sufficient reason to further investigate the potential for greater brine inflow to the repository using 3D modeling compared to the calculated value using the 2D model of the CCA. It was agreed that a simulation corresponding to a parameter vector

that led to high pressure and anhydrite fracturing in the CCA calculations would be sufficient to demonstrate the potentially increased brine inflow compared to the CCA calculation.

9.4.10.18.9 Brine Reservoirs

The EEG raised a number of issues related to the Castile Formation brine reservoirs in commenting on the CCA. The EPA accepted all the EEG suggestions except one related to the assumption of the probability of encountering brine reservoirs. EEG disagreed with the EPA on this issue. The CCA assumed an eight percent probability on the basis of faulty assumptions. The EEG recommended a 100 percent probability on the basis that the WIPP-12 brine reservoir was large enough to most likely extend under the repository. The EPA sampled on a range of 1 to 60 percent, but, according to EEG, provided no basis for assuming less than 60 percent. Based on the arguments that the geophysical (time-domain electro-magnetic survey) data may be interpreted to indicate the brine to be under 60 percent of the repository, and that some boreholes adjacent to the brine-producing boreholes are known to be dry, the EEG was willing to accept the assumption of a fixed 60 percent probability of encounter, and recommended that a new PA calculation be run with that fixed value.

9.4.10.18.10 Waste Issues

DOE calculations showed that nonrandom emplacement of radionuclides in the repository led to significantly higher releases from cuttings and cavings and spallings. EEG recommended that revised calculations should be incorporated into the CCDF even though partial sensitivity analyses indicate that nonrandom emplacement would not, in itself, result in noncompliance.

EEG also stated that the expected quantity of cellulosics, rubber, and plastic (CRP) materials in the repository was slightly greater than the waste repository limit and that the ability to characterize CRP waste with sufficient accuracy had not been shown. EEG recommended that the limit should be controlled on a per-panel basis rather than for the entire repository.

9.4.10.18.11 Assurance Requirements

There are six assurance requirements in the EPA standards (40 CFR 191) that were incorporated to provide additional confidence in the repository because of the inherent uncertainty in projecting the future behavior of natural systems and inadvertent human action. The EEG agreed with the EPA determination of two of these six requirements, the active and the passive institutional controls, but had questions about the other four. According to EEG:

1. The monitoring plan did not appear to meet the intent of the standards.

2. DOE's retrieval plan and the EPA's determination of its compliance with the requirement appeared to give a false sense of security regarding the retrievability of waste.

3. WIPP did not appear to meet the intent of the resource disincentive requirement. EEG argued that this is another reason for additional engineered barriers to be incorporated in the WIPP design for making the waste less respirable and soluble through treatment and repackaging. Since DOE had plans to treat or repackage 85 percent of the existing CH-TRU waste anyway, EEG argued, this recommendation should be easy to implement.

9.4.10.18.12 Individual Protection Requirements

Although EEG had minor disagreements about several DOE assumptions in evaluating the Individual Dose Requirements, they agreed that compliance with these requirements had been demonstrated.

9.4.10.18.13 Environmental Standards for Ground water Protection

EEG believed there was a very low probability of significant Underground Source of Drinking Water (USDW) contamination by an undisturbed release. However, EEG stated that 40 CFR 191.24 specifies that no contamination is permitted if the USDW is initially at or above the radionuclide limits of 40 CFR 141. Therefore, EEG recommended submitting data showing the USDWs were below allowed limits or that there was a zero probability of any contamination reaching the USDW.

The EPA gave serious consideration to all the comments in this report. Their responses were provided in the EPA's Response to Comments (EPA 1998b).

9.4.10.19 EEG-69 (1998): Sensitivity Analysis of Performance Parameters Used in Modeling the WIPP by Dale F. Rucker (Rucker 1998)

The following is a summary of the EEG report (EEG-69) and therefore represents the views of the EEG and not necessarily those of DOE.

This report contains the results of sensitivity analysis on the WIPP PA performed by EEG by changing selected values or the range of selected values that were used in the CCA. This type of sensitivity analysis would distinguish the important parameters of repository performance, while testing the robustness of the codes involved. The analysis also allowed for the testing of the limit to which the disposal system would fail under extreme conditions. This is also useful in characterizing the important parameters. The results are briefly described below. The full report is included in Appendix PEER-2004.

9.4.10.19.1 Borehole Intrusion Rate

The consequence of future human intrusion scenarios into the WIPP was investigated in the CCA, as required by EPA in 40 CFR Part 194 (EPA 1996b), and included the possibility of mining and deep and shallow drilling for resources.

The 40 CFR Part 194.33 criteria state that the likelihood of a drilling intrusion into the Delaware Basin be calculated by considering the frequency of drilling over the past 100 years for all resources and using that rate for the 10,000-year future of the WIPP. A total of 46.8 boreholes per km^2 per 10,000 years were estimated based on past drilling of resources at depths greater than 655 m (2150 ft), which equal 10,804 boreholes per century in 23,102.1 km^2 (14,439 mi^2) (area of Delaware Basin).

The above drill intrusion rate for the 10,000-year future of the WIPP was used by DOE in the CCDFGF model. Due to the uncertainty in predicting future human activities, the effect of altering this rate on the CCA calculations has been assessed in this report.

The modeling associated with an increased borehole rate shows that a factor of approximately 23 is needed to reach the EPA release limit at a probability of 10^{-1} from values used in the CCA. The overall mean for the highest release tested at 0.468 boreholes/km^2/yr (1.2 boreholes/mi^2/yr) exceeds 10 EPA unit limit at the 10^{-3} probability on the CCDF curve. This high rate of borehole intrusion, however, does not seem likely, as the number of boreholes drilled in the Delaware Basin in 10,000 years would have to exceed 1,000,000 per century, or 4,680 boreholes per km^2 (11,981 boreholes per mi^2) per 104 years.

9.4.10.19.2 Probability of Brine Encounter at WIPP

The probability of encountering brine at the WIPP from an intrusion into a Castile brine reservoir is uncertain. The parameter describing the probability was set to eight percent in the CCA, and changed to a range of probabilities from 1 percent to 60 percent in the EPA's PAVT. Since the extent of the reservoir beneath the WIPP is unknown, the influence of this parameter was tested at higher values at 50 percent and 100 percent. These values were based on the potential that the Castile brine reservoir encountered by WIPP-12 extends below the waste area.

The modeling presented in this report only compared CCA release values to the proposed higher probability of encounter, and found the parameter to be unimportant in the CCA. The increase in releases from the 8 percent to 100 percent was only 0.1 EPA units (35 Ci).

9.4.10.19.3 Castile Brine Reservoir Parameters

The reservoir parameters used in the CCA were derived from borehole information that is mainly outside the domain of the WIPP repository. The borehole distances ranged from 6 km (3.75 mi) to over 17.7 km (11 mi) from the repository center. New values were assigned to several parameters that describe a Castile brine reservoir based on WIPP-12 data more closely identified to the conditions at the repository.

The parameters associated with describing a Castile brine reservoir include reservoir volume, rock compressibility, reservoir pressure, and permeability. Assuming an inadvertent human intrusion, modeling of these parameters began with the two-phase flow code, BRAGFLO, and ended with calculations of solid and liquid waste released to the accessible environment. The outcome showed that there is no significant change in releases for the CCDF due to small changes in the reservoir parameters.

9.4.10.19.4 Solubility Modeling of Actinides

The results of the EEG analysis showed that increases in solubility using CCA brine release volumes had limited effect on compliance, with an overall increase on the mean CCDFs by 0.09 EPA units. Even when the solubility was increased to absurdly high values, the maximum release was limited by the availability of the actinide source. At a solubility of 8×10^{-3} M (compared to the CCA's 4.4×10^{-6} M for Pu+4 in Salado brine), the overall mean for DBR was increased from 0.04 to 1.3 EPA units.

Bounding calculations were performed on conditions resulting in the highest solubilities in the repository. These included nesquehonite and no backfill. For the nesquehonite simulations, it was assumed that the mineral would persist for the entire proposed history of the repository.

Only median solubility values were used, as opposed to the CCA, which generated a set of expected values from a range of -2 to +1.4 orders of magnitude from the median to capture the uncertainty. The assumption of the intermediate species being long-lived overestimates the expected conditions, and the EEG does not suggest that MgO should not be used as a backfill material. The models were established to better understand the performance of the repository.

The consequences of higher solubilities were quite high. The overall mean release for the CCA and PAVT were 0.2 and 0.4 EPA units at 10^{-3} probability, respectively. The overall mean for the increased solubilities of nesquehonite and no backfill are 6.0 and 8.0 EPA units at the 10^{-3} probability, respectively. The limit for compliance, according to 40 CFR Part 194, is 10 EPA units. While these calculations, based on DOE's own solubility values, do not violate the containment requirements, they show that there is little margin for error.

9.4.10.19.5 Flow and Transport Modeling within the Culebra

The EEG's concern in the Culebra modeling related to actinide sorption (K_d values), limitations in assumed future mining, and actinide solubility values assumed. The effects of extended mining, low K_ds, and high solubilities were combined in an effort to test the synergistic effect of all the previous results. The overall mean for the release through the Culebra was as high as one EPA unit (or 344 Ci) at a 10^{-3} probability of release. The addition of the Culebra releases to the overall mean of all combined releases moved the CCDF closer to the EPA compliance limit by 12 percent, but did not show noncompliance.

The EPA gave serious consideration to all the comments in this report. The responses were provided in the EPA's Response to Comments (EPA 1998b).

9.4.10.20 <u>EEG-75 (1999): Evaluation of Risk and Waste Characterization Requirements for the Transuranic Waste Emplaced in WIPP during 1999 by James C. Channell and Ben A. Walker (Channell and Walker 2000)</u>

The following is a summary of the EEG report (EEG-75) and therefore represents the views of the EEG and not necessarily those of DOE.

Section IV.B.2.b of the RCRA permit from the NMED contained language that appeared to prohibit placement of non-mixed wastes that were not characterized in accordance with the requirements of the permit's Waste Analysis Plan (WAP). The justification for adding Section IV.B.2.b was that mixing WAP-certified wastes with pre-permit wastes created unknown risks that should not be a part of permit performance standards. Statements were made during permit public hearings and in written testimony that the risks might be substantial, but there was no indication of the nature of these risks or their magnitude.

This report provides a technical evaluation, conclusions, and recommendations of the following Section IV.B.2.b issues:

- A comparison of pertinent WAP requirements with pre-permit waste characterization;
- A risk analysis of the pre-permit waste emplaced in Room 7. Expected and bounding risks from routine operations and possible accidents are evaluated.

9.4.10.20.1 Conclusions

1. The NMED-approved WAP has made explicit many of the undocumented assumptions and implied good practices from the DOE's pre-permit waste characterization program. Although there are differences between the pre-permit and WAP characterization programs, the pre-permit program appears to substantially meet the technical requirements in the WAP.

2. Deviations granted by DOE during pre-permit waste characterization and premature closures of some corrective actions generated during independent audits may be the most significant differences from the permit waste characterization requirements.

3. Estimated carcinogenic risks to an underground worker, a surface worker, and a member of the public due to routine operations from all the TRU wastes emplaced in Room 7 in 1999 are 6 to 8 orders of magnitude less than risk levels allowed by the permit. Noncarcinogenic risks are 7 to 10 orders of magnitude below allowed risks.

4. Even if volatile organic compound (VOC) emissions are much higher than risk calculations estimate, the Confirmatory VOC Monitoring Plan in use at WIPP would detect concentrations that are three orders of magnitude below allowable permit limits.

5. Risks to the surface worker and member of the public from low-probability accidents are essentially all from radionuclide releases and are lower than the allowable permit risks from routine VOC releases. Risk to the underground worker is significant (1.7×10^{-3} if the accident occurs).

9.4.10.20.2 Recommendations

Questionable data for the individual container lots of pre-permit waste could be reviewed by NMED for conformance with the WAP requirements, if necessary. This determination should consider all deviations and include input from the DOE.

The calculated nonaccidental risks from the pre-permit waste in Room 7 are too low to justify any remedial or other actions involving these wastes.

Radionuclide risks to underground workers from low-probability spontaneous fire and roof-fall accidents should be considered when setting restrictions on worker access to the south 1600 and east 300 drifts.

DOE and NMED have successfully resolved these issues.

9.4.10.21 EEG-77 (2000): Plutonium Chemistry Under Conditions Relevant for WIPP Performance Assessment: Review of Experimental Results and Recommendations for Future Work by Virginia Oversby (Oversby 2000)

The following is a summary of the EEG report (EEG-77) and therefore represents the views of the EEG and not necessarily those of DOE.

This report reviewed the issues related to the chemistry of Pu as it may affect the potential for release of radioactivity from the WIPP repository after closure. Emphasis was placed on conditions appropriate for the human intrusion scenario(s), since human intrusion has the largest potential for releasing radioactivity to the environment under WIPP conditions. According to the author, the most significant issues that need to be addressed in relation to Pu chemistry under WIPP conditions are (1) the effects of heterogeneity in the repository on Pu concentrations in brines introduced under the human intrusion scenario, (2) the redox state of Pu in solution and potential for Pu in solid phases to have a different redox state from that in the solution phase, (3) the effect of organic ligands on the solubility of Pu in WIPP-relevant brines, and (4) the effects of TRU-waste characteristics in determining the solubility of Pu. These issues are reviewed with respect to the treatment they received in the CCA (DOE 1996a), DOE's response to EEG's comments on the CCA, and EPA's response to those comments as reflected in the final EPA rule that led to the opening of the WIPP (EPA 1998a). Experimental results obtained in DOE's Actinide Source-Term Test Program (STTP) during the last two years are reviewed and interpreted in the light of other developments in the field of Pu solution chemistry. This analysis is used as the basis for a conceptual model for Pu behavior under WIPP conditions.

This report identifies three issues that, according to the author, can be addressed as part of the five-year recertification cycles. First, the impact of organic ligands on the complexation of a system with multiple cations could be delineated by some simple experiments with thorium (Th) (IV), citrate, EDTA, Ca^{2+}, and one or more transition metals. An experiment with Pu (IV) could be designed to determine the liability of Pu oxidation states in the presence of organic ligands. Second, the issue of using analogs for Pu could be addressed with appropriate experiments using uranium (U) and Pu at redox conditions in the range anticipated at the WIPP. Attention to the published experimental results of U and Pu could make a considerable contribution to this effort. Third, the issue of uncertainty in calculated actinide solubility can be resolved with experimental data for Pu (IV) compounds of appropriate compositions. The report also recommends starting by constructing a database for U and Pu using the published, peer-reviewed NEA/OECD U and Pu databases.

These issues are addressed in CRA-2004 and will continue to be addressed in future recertifications.

9.4.10.22 EEG-82 (2001): Evaluation of Proposed Panel Closure Modifications at WIPP by Lawrence E. Allen, Matthew K. Silva, James K. Channell, John F. Abel, and Dudley R. Morgan (Allen et al. 2001)

The following is a summary of the EEG report (EEG-82) and therefore represents the views of the EEG and not necessarily those of DOE.

A key component in the design of the WIPP repository is the installation of concrete structures as panel seals in the intake and exhaust drifts after a panel has been filled with waste containers. As noted in the EPA final rule, the panel seal closure system is intended to block brine flow between the waste panels at the WIPP. On April 17, 2001, the DOE proposed seven modifications to the EPA concerning the design of the panel closure system.

EPA approval of these modifications is necessary since the details of the panel design are specified in EPA's final rule as a condition for WIPP certification. However, the EPA has not determined whether a rulemaking would be required for these proposed design modifications. On September 4, 2001, the DOE withdrew the request, noting that it would be resubmitted on a future date.

The EEG contracted with two engineers, Dr. John Abel and Dr. Rusty Morgan, to evaluate the proposed modifications. The EEG has accepted the conclusions and recommendations from these two experts:

1. replacement of SMC with a generic salt-based concrete,
2. replacement of the explosion wall with a construction wall,
3. replacement of freshwater grouting with salt-based grouting,
4. allowing surface or underground mixing, and
5. allowing up to one year for completion of closure.

The proposed modification to allow local carbonate river rock as aggregate is acceptable pending demonstration that no problems will exist in the resulting concrete. The proposed modification to give the contractor discretion in removal of steel forms is not supported. Instead, several recommendations are made to specifically reduce the number of forms left, thereby reducing potential migration pathways.

EEG's recommendations have been considered in the DOE's decision-making process.

9.4.10.23 EEG-83 (2002): Identification of Issues Relevant to the First Recertification of WIPP by Lawrence E. Allen, Matthew K. Silva, James K. Channell (Allen et al. 2002)

The following is a summary of the EEG report (EEG-83) and therefore represents the views of the EEG and not necessarily those of DOE.

This report updates issues that the EEG considers important for the first recertification of WIPP. These issues encompass a variety of technical areas, including actinide solubility, fluid injection scenarios, solution mining, Culebra flow and transport, spallings modeling, and nonrandom waste emplacement. The report made the following recommendations.

Some uncertainty remains in understanding the persistence of higher Pu oxidation states because of reliance on modeling (with its associated assumptions) and limited experimental results. The EEG recommends additional experimental work towards parameters for a proposed conceptual kinetic model of Pu solubility. In addition, the EEG recommends an intrusion scenario in PA that would account for a heterogeneous, noninundated repository that may include persisting higher oxidation states of Pu.

Intrusion scenarios including the consequences of fluid injection were rejected at the time of the CCA. With increasing drilling activity in the vicinity of the WIPP, fluid injection scenarios

should be reexamined for recertification PA. These scenarios should consider potential consequences from oil field secondary recovery techniques, such as waterflooding, in addition to ancillary injection operations, such as brine disposal and pressure maintenance wells. The WIPP resides in a resource rich locale, and PA should consider all reasonable activities associated with such a location.

Likewise, solution mining scenarios should also be reconsidered during recertification. Solution mining should be anticipated for extraction of potash reserves as well as for the excavation of salt caverns for storage of natural gas, oil field wastes, and chemical feedstocks. Consideration of solution mining for potash extraction is a natural alternative for a maturing mineral district as ore grades decrease below the economic cutoff necessary for traditional mining methods. Dissolution of halite to create underground storage caverns is a practice already used in the Delaware Basin for oil field waste and natural gas. Research suggests that it may also be a viable method for storage of other items, such as chemical feedstocks.

The Culebra dolomite unit of the Rustler Formation is acknowledged as a likely pathway for breach of the WIPP repository. Hence, long-term PA requires an accurate understanding and modeling of flow and potential actinide transport.

Most of the issues concerning the Culebra raised at the time of the CCA resulted from poor discretization of the modeling grid and the inherent heterogeneity of the aquifer. The DOE had originally planned to replace the previous flow code with MODFLOW and implement a finer grid. This, coupled with a new transport code, STAMMT-L, would have addressed problems with numerical dispersion and spatial truncation errors. In addition, STAMMT-L incorporates a dual-porosity, multirate approach, which the DOE demonstrated to be a superior representation of transport within the heterogeneous character of the Culebra.

The EEG remains concerned over the continuing water level increases in the Culebra aquifer. The DOE is currently engaged in an effort to determine the source, or sources, of the rising water elevations, which have continued to increase for the last 14 years. Until a cause is determined, the validity of the Culebra conceptual for PA is in question. The EEG recommends that the DOE reconsider its decision not to change the Culebra modeling codes and grid discretization. In addition, the EEG urges the DOE to conclusively determine the source of the water level increases and adjust the conceptual model accordingly.

The CCA demonstrated the importance of spallings as a potential release mechanism. The spallings model used in the CCA did not adequately characterize the physical processes of spall. Work was in progress by the DOE on a new spallings model intended for use during recertification. This model was to improve predictions of long-term performance, reduce uncertainty, and enhance public confidence. However, the DOE recently announced that the new model would only be used for impact analysis and not for recertification PA. The EEG urges the DOE to reconsider and to use the new model for PA.

Random emplacement of waste in the repository was assumed in the CCA. However, waste emplacement practice since the 1999 opening has demonstrated that random emplacement is not likely. Specific waste-streams shipments to WIPP depend on the DOE's agreements with the host states, and on the readiness of particular waste streams for shipment. It has been previously

demonstrated by the DOE that nonrandom emplacement could increase the mean release values. The EEG recommends that DOE develop a waste-loading plan based on their shipment schedule. All intrusion scenarios could then consider nonrandom emplacement, providing better estimates of releases.

The DOE has considered all these recommendations in the preparation of CRA-2004.

9.4.10.24 EEG-85 (2003): Analysis of Emplaced Waste Data and Implications of Non-Random Emplacement for Performance Assessment for the WIPP by Lawrence E. Allen and James K. Channell (Allen and Channell 2003)

The following is a summary of the EEG report (EEG-85) and therefore represents the views of the EEG and not necessarily those of DOE.

The WIPP Land Withdrawal Act (LWA) recognized that after the initial certification of the WIPP and start of disposal operations, operating experience and ongoing research would result in new technical and scientific information. The EEG has previously reported on issues that it considers important as the DOE works towards the first recertification. One of these issues involves the assumption of random emplacement of waste used in the PA calculations in support of the initial certification application. As actual waste emplacement data are now available from four years of disposal, the EEG performed an analysis to evaluate the validity of that initial assumption and determine implications for PA.

Panel 1 was closed in March 2003. The degree of deviation between actual emplaced waste in Panel 1 and an assumption of random emplacement is apparent with concentrations of ^{239}Pu being 3.20 times, ^{240}Pu being 2.67 times, and ^{241}Am (americium) being 4.13 times the projected repository average for the space occupied by the waste.

A spatial statistical analysis was performed using available Panel 1 data retrieved from the WWIS and assigned room coordinates by SNL. A comparison was made between the waste as emplaced and a randomization of the same waste. Conversely, the distribution of waste as emplaced is similar to the distribution of waste in the individual containers and can be characterized as bimodal and skewed with a long high-concentration tail. The distribution of randomized waste is fairly symmetrical, as would be expected from classical statistical theory. In the event of a future drilling intrusion, comparison of these two distributions shows a higher probability of intersecting a high-concentration stack of the actual emplaced waste over that of the same waste emplaced in a randomized manner, as was assumed in the certified PA calculations. This suggests that the methodology used during the certification PA calculations underestimated potential releases by cuttings and cavings. That methodology sampled each layer in a stack separately and used the mean concentration for each waste stream.

The DOE performed a spallings release bounding analysis at the time of the initial certification. However, the selection of the statistical sample size of the bounding analysis assumed independence of samples, which is not characteristic of nonrandom waste emplacement. Instead, it is demonstrated that the emplaced waste is spatially dependent. Therefore, the bounding analysis may not be adequate in the event of continued nonrandom emplacement. As for cuttings and cavings releases, the probability of a high-concentration intersection during an intrusion is

increased because of nonrandom emplacement. PA calculations should either incorporate this increased probability or an adequate bounding calculation should be performed using spatial statistical methodology.

The use of Pipe Overpack Containers for isolation of the high ^{239}Pu waste may reduce the amount of material brought to the surface as a result of an intrusion. However, the integrity of these containers over the regulatory period has not yet been demonstrated. If the DOE wishes to take credit for the container, the DOE needs to provide an analysis of structural integrity and the potential effects resulting from the use of Pipe Overpack Containers.

The DOE has addressed the issues raised in this report in the preparation of CRA-2004.

9.4.10.25 EEG-86 (2003): Contact Handled Transuranic Waste Characterization Requirements at the Waste Isolation Pilot Plant by Matthew K. Silva, James C. Channell, Ben A. Walker, and George Anastas (Silva et al. 2003)

The following is a summary of the EEG report (EEG-86) and therefore represents the views of the EEG and not necessarily those of DOE.

The EEG has been evaluating the development of WAC since 1979. This report consolidates the findings and recommendations of the EEG's technical reviews and current positions with respect to waste characterization requirements. Through this report, the EEG has offered the following observations and recommendations for waste characterization requirements

9.4.10.25.1 Acceptable Knowledge

AK is the principle waste characterization technique for all of the regulatory agencies. AK is necessary and should be retained. At this time, EEG supports the use of the Hazardous Waste Facility Permit (HWFP) AK requirements, since they are the most explicit.

9.4.10.25.2 Headspace Gas Sampling and Analysis

It is desirable to maintain a comprehensive Headspace Gas (HSG) program for WIPP CH-TRU waste. However, it should be possible to require less than 100 percent headspace gas sampling in some cases. The primary concern is with organic sludges and older waste containers where knowledge of the waste is of lesser quality.

9.4.10.25.3 Drum Age Criteria

Drum Age Criteria (DAC) is necessary to ensure that HSG sampling of waste containers will measure gas concentrations at least 90 percent of equilibrium. DAC values are required in both the HWFP and the TRAMPAC. The EEG supports this requirement.

9.4.10.25.4 Real Time Radiography

All WIPP waste containers are required to undergo either radiography or visual examination (VE) by the HWFP. Usually retrieved wastes undergo Real Time Radiography (RTR) and newly generated wastes are examined by VE. RTR has been a very effective means of verifying AK

and discovering prohibited items in waste containers. It is also used to show compliance with several EPA and TRAMPAC requirements. The overall radiography program is an important part of the WIPP waste characterization program and should be retained. It may be possible to reduce some of the detailed procedural requirements in the HWFP.

9.4.10.25.5 Visual Examination for Retrievably Stored Waste

A small percentage (currently less than two percent) of retrievably stored waste is required by the HWFP to undergo VE for confirmation of RTR. The VE process has the potential for slightly greater radiation exposure than the other waste characterization requirements, although the EEG has seen no data to indicate that exposures are significant enough to justify reducing the requirement. The DOE has been successful in modifying the HWFP on retrievably stored VE, and this would be the preferred process for seeking further reductions.

9.4.10.25.6 Visual Examination for Newly Generated Waste

VE is the method DOE usually prefers for newly generated waste because it can be done at the time the waste container is filled. The EEG has not objected to any part of this requirement except to state that the requirement for two trained VE operators to perform the visual process "may be overkill" and that a single verification should be adequate.

9.4.10.25.7 Coring Sampling and Analysis

Currently the EEG continues to believe that the homogeneous sampling and analysis are unnecessary characterization requirements in the HWFP. EEG's principal reason for this position is that the data are not used for any additional regulatory control (metals releases from accidents or long-term processes would be controlled by radionuclide control requirements and VOCs and semi-volatile organic compound (SVOC) by HSG or the Confirmatory VOC Monitoring Plan).

9.4.10.25.8 Level II Management and Waste Certification HWFP Requirements

The DOE has listed these management and certification requirements as characterization activities in a recent cost analysis. EEG has not previously commented on these requirements. However, EEG indicated that their current evaluation stated that the required procedures are very detailed and somewhat redundant. This may be one of the areas to which the general EEG comment, "We believe waste characterization requirements are excessive," applies.

9.4.10.25.9 Characterization Support HWFP Requirements

EEG remains supportive of the WIPP audit and surveillance program. EEG has also stated that it does not believe the relaxation of audit requirements and QA/QC is an appropriate way to reduce the regulatory burden.

9.4.10.25.10 EPA Non-Radiological Requirements

EPA's residual liquids, nonferrous metal, and CPR materials requirements should remain and can continue to be determined as they are now, by the RTR and VE requirements of the HWFP.

The ferrous metal requirement can continue to be met by counting waste containers emplaced in the repository.

9.4.10.25.11 EPA Radiological Requirements

The EEG agrees with the radioassay requirements for CH-TRU waste specified in Appendix A of the report and the current procedures for modifying the document.

Current requirements for reporting the 10 required radionuclides should remain. ^{241}Pu should also be reported. The current requirement that all radioassay should be performed by WIPP-certified assay systems should be maintained. Justification for less than 100 percent quantification and determination of isotopic ratios may be possible for some, but certainly not all, waste streams.

9.4.10.25.12 NRC Container Properties

The TRAMPAC requirements for residual liquids, filter vents, and the sealed container prohibition should be retained. These are all verified by requirements in the current HWFP.

9.4.10.25.13 NRC Nuclear Properties

All nuclear property requirements should be retained and Appendix A of the CH-TRU WAC methodology should be used.

9.4.10.25.14 NRC Gas Generation Requirements

Requirements for measuring the chemical, payload classification, and radionuclide concentrations necessary to ensure H gas concentration criteria are met must be retained. There have been many changes, via the Certificate of Compliance (C of C) revision process, which have allowed additional containers to be shipped without changing the H gas criteria and additional changes may be justifiable in the future.

The flammable gas concentration limit of ≤ 500 ppm should be retained as described in the current revision of the TRAMPAC. Alternate methods (with appropriate QA) will be necessary if future changes to the HWFP affects the use of HSG sampling as the method for meeting this criteria.

9.4.10.25.15 Waste Isolation Pilot Plant Waste Acceptance Criteria

The WAC has served a useful historic purpose in developing initial criteria that have been adopted by the other three regulatory agencies. Currently it is a useful document for listing most of the requirements from all four sets of criteria. It would be more useful if the technical justification for each criteria or requirement were restored.

The unique role of the WAC in including any necessary operational safety and health requirements not included elsewhere is very important and must be constantly evaluated via the technical safety requirements (TSR) portion of the CH-TRU Safety Analysis Report, and any necessary changes incorporated into the CH-TRU WAC.

This report was published in late September 2003, during the final preparation phase of CRA-2004. It has been included here for completeness. The DOE will consider these recommendations in dealing with the waste characterization issues in the future.

9.4.11 Fracture Expert Group Review

SNL convened the Fracture Expert Group (FxG) during the spring of 1993. A summary report of the FxG meeting (see CCA Appendix PEER) was prepared in March 1993.

As discussed in the meeting report, the charter of the group was to:

1. Review the current (as of 1993) BRAGFLO model assumptions for permeability and porosity as a function of pressure for their adequacy as first-order representations of the changes in the anhydrite beds adjacent to the waste disposal horizons due to pressurization of the formation.

2. Recommend improvements in the characterization of changes in permeability and porosity in the anhydrite beds adjacent to the waste disposal horizons due to pressurization of the formation.

An evaluation of the FxG review against the screening criteria is provided in Table 9-16. Since the 19-member FxG contained SNL staff, SNL contractors, and external experts, it was not a truly independent review group. However, the group, and especially the 11 external experts, provided a valuable review of the issues and made several valuable recommendations which were, to a large extent, independent. The group included nationally and internationally recognized expertise in experimental mechanics, materials science, fracture and fluid mechanics, and computational fluid dynamics. The group members were as follows:

- Pierre Bérest, Ecole Polytechnique, Palaiseau, France;
- Barry Butcher, SNL;
- Peter Davies, SNL;

Table 9-16. Fracture Expert Group

1. Is the peer review relevant to the CCA?	Partially – although the FxG reviewed the BRAGFLO conceptual model, its focus was primarily related to compliance with Part 268, rather than Part 191, requirements.
2. Was there a formal report prepared by the reviewer?	Yes – meeting summaries were prepared.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the FxG reviewed the adequacy of 1993 BRAGFLO model assumptions as they relate to repository pressurization.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Partially – the FxG's purpose was as much to recommend improvements in BRAGFLO as to evaluate its adequacy.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – group members are recognized experts in their respective fields.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Partially – the 19-member FxG contained SNL staff, SNL contractors, and external experts so it was not a truly independent review group. However, the 11 external experts provided valuable review and recommendations from an independent and impartial perspective.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Yes – the FxG provided valuable review of one of the conceptual models used in PA.

- Chandrakant Desai, University of Arizona;
- Dick Ewing, Texas A&M University;
- Mert Fewell, SNL;
- Mel Friedman, Texas A&M University;
- Bezalel Haimson, University of Wisconsin;
- Samuel W. Key, RE/SPEC Inc.;

- Jane Long, Lawrence Berkeley Laboratory;
- Darrell Munson, SNL;
- Sia Nemat-Nasser, University of California-San Diego;
- Karsten Pruess, Lawrence Berkeley Laboratory;
- Thomas Russel, University of Colorado at Denver;
- Chin-Fu Tsang, Lawrence Berkeley Laboratory;
- Palmer Vaughn, Applied Physics Inc.;
- Wolfgang Wawersik, SNL;
- Stephen Webb, SNL; and
- Teng-Fong Wong, State University of New York-Stonybrook.

The meeting summary report concluded that "The proposed first-order model in BRAGFLO for representing changes in permeability and porosity due to pressure-induced changes in the anhydrite is an acceptable first approximation." The FxG report also made recommendations for additional studies to support an extended and improved second-order model in BRAGFLO for simulating the two-phase flow occurring in the altered anhydrite marker beds (MB 138 and MB 139). These recommendations are summarized in the FxG report (CCA Appendix PEER).

Recommendations by the FxG for additional studies of fracturing were driven by concerns regarding the gas-phase transport of VOCs away from the repository via pressure-induced fractures. Gas-phase transport is not a mechanism that could contribute to actinide releases from the disposal system. The DOE therefore concludes that the current PA model used to approximate the effects of pressure-induced fracturing, which is a refinement of the model presented to the FxG, is adequate for estimating actinide releases from liquid-phase transport. The FxG meeting summaries were provided to the recent conceptual models peer review panel for consideration during its evaluation of the WIPP conceptual models.

9.4.12 Fanghänel Review – WIPP Thermodynamic Model for Trivalent Actinides

Dr. Thomas Fanghänel of the Institut für Nukleare Entsorgungstechnik, Forschungszentrum Karlsruhe, Germany, was contracted to perform an independent review of the thermodynamic models WIPP developed to predict potential dissolved concentrations of actinides in WIPP brines. An evaluation of his review against the screening criteria is provided in Table 9-17.

He was tasked to provide an independent assessment of the methods used to estimate the dissolved concentrations of III, IV, and VI actinides. For the V actinides, he performed an independent assessment of the WIPP augmentation of his neptunium (Np)(V) thermodynamic

Table 9-17. Fanghänel Review of the WIPP Thermodynamic Model for Trivalent Actinides

1. Is the peer review relevant to the CCA?	Yes – the reviewer evaluated one of the models used in the WIPP PA.
2. Was there a formal report prepared by the reviewer?	Yes – a report was prepared.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the work was a review of the WIPP thermodynamic model for predicting dissolved concentrations of trivalent actinides in WIPP brines.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the review evaluated the adequacy of the WIPP thermodynamic model for trivalent actinides.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – Dr. Fanghänel is an internationally recognized expert.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the reviewer is independent of the WIPP project.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

model, as well as its use for estimating dissolved concentrations of V actinides in WIPP brines. He performed the review and submitted his final report, dated May 7, 1996. A copy of the full report is provided in CCA Appendix PEER.

Dr. Fanghänel is an internationally recognized expert regarding the thermodynamic modeling of actinides and is completely independent of the WIPP project. His qualifications include extensive experience with the development and evaluation of thermodynamic models for actinides. He is first author of a journal publication documenting the Np(V) dissolved concentration model that serves as the basis for the WIPP +V actinide dissolved concentration model.

The following paragraphs are quoted from Dr. Fanghänel's report:

> For the WIPP thermodynamic model the ion interaction approach (Pitzer equations) was chosen for modeling the excess properties of the aqueous solution (activity coefficient model). At present, the Pitzer approach is the most sophisticated semiempirical approach for the Gibbs excess energy of a concentrated electrolyte solution. It is widely used and a database with ion interaction parameters covering a large variety of different solution species is available.....
>
> The WIPP model treats the interaction of AN(III) with Cl^- and SO_4^- as strong ion-ion interaction without invoking the formation of complex species. Within the composition range of the WIPP brines, this is a reasonable approach, which was demonstrated in several comparisons between model calculations and data...
>
> The applied assumptions for the development of the WIPP thermodynamic model are conservative and simplify the overall model. This is a prerequisite for calculating dissolved actinide concentrations in the very complex repository system.
>
> In general, the model represents the present state of the knowledge of aqueous solution thermodynamics. The chosen activity coefficient model and the applied data base are, with a few exceptions, suitable for calculating maximum trivalent actinide concentrations in WIPP brines.
>
> The model needs to be improved in some parts. This concerns in particular the hydrolysis equilibria of trivalent actinides which have to be introduced into the model. Moreover, the reviewer recommends that the model regarding the interaction of carbonate complexes in concentrated electrolyte solutions be refined.

In accordance with Dr. Fanghänel's suggested improvement in the model concerning the hydrolysis equilibria of trivalent actinides, the recommended data were incorporated into the CHEMDAT database. Regarding the second suggestion, carbonates are no longer considered to be significant to repository performance due to the implementation of MgO backfill.

9.4.13 Independent Technical Review of the Bin and Alcove Test Programs

The objective of this ITR team assessment of proposed TRU waste experiments at WIPP, as specified in the charter, was to: "Review the need for, and technical validity of, the Bin and Alcove test programs, as defined in the Test Phase Plan, the Technical Needs Assessment Document, and individual test plans."

The team consisted of nine technical personnel from the DOE, LANL, Lawrence Livermore National Laboratory (LLNL), and private consultants. The team members had a large amount of expertise and experience in mechanical, chemical and civil engineering, earth and environmental science, and geology. The team was composed of the following members:

- Stephan Brocoum (Team Leader), DOE, Office of Geologic Disposal;
- Philip Thullen (ITR Team Leader), LANL;
- Deborah Bennett (ITR Team Leader), LANL;
- Richard Beddoes, Golder Associates;
- Corale Brierley, Private Consultant;
- Jan Docka, Roy F. Weston, Inc.;

- Joseph Farmer, LLNL;
- Ron Guimond, Ogden Environmental and Energy Services;
- Stan Kosiewicz, LANL;
- Abraham Lerman, Northwestern University;
- John Shaler, Private Consultant;
- Terry Steinborn, Applied Research Associates, Inc.; and
- Dave Swale, British Nuclear Fuels Limited.

Although the independence of the ITR could be questioned because it had a DOE staff member as Team Leader, Dr. Brocoum, as a Director in the Office of Geologic Disposal, had no responsibility or authority as regards the WIPP project. Further assurance of the independence of the team was provided by the credentials and professional stature of the team members and the direct oversight of the ITR review by the Technical Oversight Board (TOB). The independence and technical qualifications of the ITR members were verified by several parties prior to commencement of work. A summary evaluation of the ITR team against the screening criteria for peer reviews is shown in Table 9-18.

The team began its review in July 1993, and completed a final report (see CCA Appendix PEER) in December of that year. The review process consisted of document review, formal presentations by the DOE and its contractors and other groups, and interviews with personnel. The team met several times to develop consensus on issues and recommendations and to prepare its report.

A TOB was chartered to review all aspects of the ITR team's activities. The TOB was composed of senior level individuals with extensive experience in the development, execution, management, and evaluation of large and technically involved projects. The TOB members included

- Dr. Colin Heath (Chairman), GC Management Associates;
- Mr. Richard Baxter, Independent Consultant;
- Mr. William Hamilton, Independent Consultant;
- Dr. Mujid Kazimi, Massachusetts Institute of Technology;
- Mr. Dennis Lachel, Lachel and Associates, Inc.;
- Mr. John Maddox, Independent Consultant; and
- Ms. Debra Marsh, Marsh Consulting Group, Ltd.

Table 9-18. Independent Technical Review of the Bin and Alcove Test Programs at the WIPP

1. Is the peer review relevant to the CCA?	Yes – this review addresses waste characterization and gas generation issues.
2. Was there a formal report prepared by the reviewer?	Yes – there was a formal report.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – this review addressed the adequacy of plans for testing to be done for waste characterization and PA.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – this review addressed the adequacy of the work and made recommendations for changes.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the team members are recognized as experts in their respective disciplines.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – although the Team Leader was a DOE staff member, he had no organizational responsibility for the WIPP project. Also, the professional stature of the ITR members and the oversight of the TOB ensured the independence of the ITR team review.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

They provided a solid reference point of experience and ideas against which the ITR team tested its ideas regarding lines of inquiry and the logic and validity of findings and conclusions. The results of the review were discussed with the TOB, and their guidance was used in preparation of the ITR report.

The following statements are excerpted from the "Executive Summary" of the ITR report.

> Principal Assessment
>
> The review team concluded that: there is no scientific, regulatory, or operational imperative to perform the Bin or Alcove tests at WIPP with radioactive waste. Other tests can and should be performed at WIPP and elsewhere to confirm information used for regulatory compliance

> demonstration and certification. This is an assessment of the technical justification for the tests, not of the ability of site personnel to perform the tests or of the repository to accept TRU waste.
>
> Path Forward Recommendation
>
> Preparation and submission of compliance and permitting packages at the earliest possible date are the foundation of the recommended path forward. All other near term work elements should support these activities. All regulatory permits, approvals, and certification should be acquired before any in situ confirmatory or operational tests are performed in WIPP with radioactive waste.
>
> A lack of clear guidance from cognizant regulators on specific requirements for regulatory compliance should be the only source of future delay in operating WIPP as a TRU waste repository. While most, although not all, of the relevant regulations exist, no clear statement of what constitutes acceptable submissions has been produced by the regulatory bodies....The ITR team believes that delay will be minimized by making the regulators part of the process through early submission of the regulatory packages.
>
> Although all regulations do not exist and existing regulations may change, the ITR team believes that sufficient gas generation information is available to complete the performance assessments and other elements required to prepare and submit compliance and permitting packages within 18 months. The recommended conceptual compliance and permitting process will allow the TRU waste disposal phase to begin in three years if specified milestones are met...
>
> Bench-scale laboratory tests using simulated and/or actual waste should be continued or completed, and additional tests initiated if required. Results of bench-scale tests will not only explain individual gas generation mechanisms but also the synergistic effects of combined mechanisms....
>
> ..... These tests can be performed above ground, at WIPP or elsewhere, unencumbered by mine safety regulations.

As recommended by the ITR team, the bin and alcove tests were subsequently abandoned and the WIPP program was redirected to completing the regulatory compliance documentation on an accelerated schedule. Bench-scale laboratory tests using actual TRU wastes were conducted at LANL and the INEL.

9.4.14 Performance Assessment Reviews

In 1989, SNL prepared a PA methodology report (Marietta et al. 1989) which provided information on the PA process developed to demonstrate compliance with criteria under development for 40 CFR Part 191, Subpart B. Formal comments on the methodology report were provided to the DOE by the EPA and the NMED. The DOE responses to the comments were subsequently provided in the 1990 PA report.

The DOE, through SNL, published iterative PA reports describing the WIPP disposal system beginning with the first PA report in 1990 (Bertram-Howery et al. 1990), followed by subsequent iterations in 1991 and 1992. Each updated report constituted a substantial revision of the previous document based on new information, experiments, and comments from interested individuals. With regard to comments from interested parties, a number of these reviews could be classified as peer reviews for the purposes of this application. An evaluation of these reviews against the screening criteria for peer reviews is provided in Table 9-19.

Table 9-19. External Review of the WIPP PA Reports

1. Is the peer review relevant to the CCA?	Yes – the reviews specifically focused on the PA reports.
2. Was there a formal report prepared by the reviewer?	Yes – the reviews evaluated the adequacy of the WIPP PA reports.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the reviews addressed the adequacy of the PA reports.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the reviews were based on evaluations of the PA.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the reviewing organizations are recognized as experts in their respective disciplines.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the reviewers were independent of the WIPP project.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

9.4.14.1 1990 Performance Assessment Report

The first PA report (Bertram-Howery et al. 1990) was issued in December 1990. As noted above, the 1990 report provided responses to the EPA and NMED comments that had been received on the 1989 methodology document.

Several groups reviewed and commented on the 1990 report. In particular, several requests were made from the NMED and others for additional clarification of several aspects of the report. Specific responses to the comments provided by the various reviews were developed and subsequently documented in the 1991 PA report.

9.4.14.2 1991 Performance Assessment Report

The second PA report (WIPP Performance Assessment Division 1991) was issued in December 1991. The 1991 report included responses to comments that had been received from the reviews of the 1990 report.

Intera, Inc. was requested by the SNL WIPP Performance Assessment Division to review Volumes 1-4 of the 1991 WIPP PA report (WIPP Performance Assessment Division 1991).

Although the independence of the review could be questioned because it was contracted directly by the WIPP PA Division, it is provided here for completeness; the results of the review were important in establishing the direction of PA. The review's purpose, as stated in the Intera report (see Appendix PEER-2004), was to consider "technical questions pertaining to the performance assessment methodology and its application and results, as well as issues of organization, presentation and flow of information between the various sections, chapters and volumes."

The review is contained in a March 1992 report (see CCA Appendix PEER). The report summary states the following:

> Our major technical concerns are in the general area of treatment of uncertainty in the assessment, including in particular treatment of scenario uncertainty, data and parameter uncertainty, and model uncertainty....
>
> We have also suggested a possible modification to the methodology for generating CCDFs for human intrusion events, and have noted that the treatment of human intrusion, as a particular class of scenarios, is imbalanced in places...
>
> With regard to presentation and organization of the report, there is substantial room for improvement.... In particular, the report is excessively long, and very much in need of a good summary of the order of 100 pages (or less). More attention needs to be paid to the relevance of the information presented to the final assessment results, and to the potential audience for the report. Excessive use of mathematics is made throughout the report, and figures are too few in number, are poorly explained or are too complex. In addition, relatively minor errors are rife, particularly in Volume 3.

The Intera comments were carefully considered by SNL while preparing the succeeding report. Accordingly, appropriate modifications were incorporated in the 1992 PA report. Specific responses to the various third-party reviews were documented in the 1992 PA report.

9.4.14.3 1992 Performance Assessment Report

The third PA report (WIPP Performance Assessment Department 1992) was published in December of 1992. This report provided responses to comments that had been received on the 1991 PA report. As with the earlier PA reports, several groups reviewed and provided comments on the 1992 report. In particular, EPA, NMED, EEG, and the Attorney General (AG) provided comments to DOE. Comments received from the EPA, NMED, and the AG are discussed below. Comments from the EEG are discussed in Section 9.4.10.13.

9.4.14.3.1 Environmental Protection Agency Review of the 1992 Performance Assessment Report

The EPA's review of the 1992 iteration of PA was provided in two separate transmittals. The first group of review comments addressed only Volumes 1 through 3. The second set of comments primarily addressed Volumes 4 and 5.

Review of Volumes 1 through 3

In January 1994, the EPA provided extensive comments on Volumes 1 through 3 of the 1992 iteration of the PA. The EPA grouped its discussion of the issues into six primary categories: (1) format and content, (2) access to information, (3) regulatory issues, (4) use of expert panel elicitation and investigator judgement, (5) models, and (6) QA. The EPA comments and the DOE responses for each comment are provided in Appendix PEER-2004.

Volumes 4 and 5

In October of 1994, the EPA provided final comments to the DOE on the 1992 iteration of PA. Although the comments addressed the entire PA, the primary focus was Volumes 4 and 5. The EPA grouped its comments into five primary categories: (1) scenarios, (2) BRAGFLO and SANCHO computer code relationships, (3) Culebra groundwater modeling, (4) inventory, and (5) institutional controls. The EPA comments and the DOE responses for each comment are provided in Appendix PEER-2004.

9.4.14.3.2 New Mexico Attorney General Review of the 1992 Performance Assessment Report

The New Mexico AG also provided comments on the 1992 PA report. These comments are provided in CCA Appendix PEER, along with the DOE responses.

As part of his review, the Attorney General contracted with Dr. Elisabeth Paté-Cornell. Dr. Paté-Cornell is a Professor of Industrial Engineering and Engineering Management at Stanford University and is currently president of the Society for Risk Analysis. She has written and lectured extensively on probabilistic risk assessment and has testified in Congress on proposed legislation on the subject. Dr. Paté-Cornell prepared a report for the AG entitled Conservatism of the Performance Assessment and Decision Criteria for WIPP. The comments are provided in CCA Appendix PEER with a cover letter documenting its transmittal from the AG to DOE.

9.4.14.3.3 NMED Review of the 1992 Performance Assessment Report

The NMED also provided comments on the 1992 PA report. The comments are provided in Appendix PEER together with DOE responses. The NMED's comments were detailed but focused upon several issues relevant to screening scenarios and events for PA. Within this context, NMED provided detailed comments on three primary issues:

1. additional groundwater migration pathways (the Dewey Lake (Redbeds) Formations and Magenta Member of the Rustler),

2. subsidence potential related to dissolution of evaporite units caused by downward percolation of meteoric or groundwater through inner or outer zones of boreholes, and

3. subsidence potential related to extraction of oil and gas adjacent to the facility boundary.

9.4.14.4 Department of Energy Response to Comments on the 1990, 1991, and 1992 Performance Assessment Reports

In summary, DOE responded to comments from interested groups and individuals by revision of subsequent PA reports and by providing specific responses to those comments in the subsequent reports. Chapter 6.0 is the result of many years of work on PA activities by the DOE. PA has undergone extensive revision as a result of input from groups such as EPA, NMED, EEG, and the AG.

9.4.15 Technical Support Group Reviews

During 1993, the Technical Support Group (TSG) was tasked by the DOE to provide recommendations on the following topics:

- Experimental Plan for Tracer Testing in the Culebra Dolomite,
- PA Parameters, and
- Large-Scale Seals Test Program.

Evaluating the resulting reviews against the screening criteria developed for this application indicated that the first two qualify as peer reviews (see Table 9-20). As regards the large-scale seals test program, the review team was mostly comprised of subcontractors with a long working relationship with the WIPP project. The reviewers' independence could also be questioned for the other two reviews; however, the case for the review's independence was stronger. These reviews are included in this application for the sake of completeness and because they were significant in terms of the PA program. The reports were provided to the appropriate recent peer review panels for consideration. A brief discussion of the selected reviews is presented below.

The members of the review teams included expertise in geochemistry, geomechanics, hydrology, physical chemistry, NEPA compliance, PA, and waste management. The members involved in the reviews included the following:

- Paul Drez (TSG Core Member), Independent Consultant;
- Paul Cloke, Science Applications International Corporation – Nevada;
- David Dennison, Advanced Sciences, Inc. – Denver;

Table 9-20. Technical Support Group Reviews

1. Is the peer review relevant to the CCA?	Yes – the reviews involved aspects of site characterization and PA.
2. Was there a formal report prepared by the reviewer?	Yes – reports were prepared.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the reviews addressed the adequacy of WIPP plans and programs.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the reports addressed the adequacy of work prepared by the WIPP project.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the reviewers are recognized experts in their respective disciplines.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Partially – although several of the reviewers were independent, some of the TSG members involved in the reports discussed in this section routinely participated in the WIPP project over a period of several years as subcontractors to DOE.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Yes – the reports were significant in terms of their impact on the WIPP PA program. The reports were also provided to the recent peer review panels.

- Darrel Dunn, Advanced Sciences, Inc. – Denver;
- John Kircher, Battelle;
- David Lechel, Independent Consultant;
- John Schatz, Independent Consultant;
- Jim Tollison, Independent Consultant; and
- Rose Zeiler, Advanced Sciences, Inc. – Denver.

9.4.15.1 Review of Experimental Plan for Tracer Testing in the Culebra Dolomite

The review team was asked to address whether additional experiments for fluid flow and transport characterization of the Culebra are necessary. Additionally, if these experiments were determined to be necessary, the team was asked to evaluate whether the planned Culebra Tracer Tests, as described in the proposed Test Plan, would provide the data necessary to establish whether the Culebra retards radionuclide transport sufficiently to demonstrate that the Culebra is an effective geologic barrier.

The formal report prepared by the team as a result of the review is provided in CCA Appendix PEER, along with the transmittal letter to the DOE.

The recommendations from the TSG report on tracer testing in the Culebra dolomite were considered in the planning of ongoing hydrological studies and testing performed at the WIPP site. In addition, the review resulted in enhanced communication between the principal investigators generating data and the PA staff. The TSG report was provided to the recent conceptual models peer review panel for its consideration.

9.4.15.2 Performance Assessment Parameters

A copy of the report that resulted from the TSG review of the PA parameters is provided in CCA Appendix PEER. The purpose of the TSG review, as stated in the transmittal letter to the DOE, was to

> conduct a detailed review of many of the parameters that form the basis for the PA calculations for the WIPP Project. This effort emphasized the key 49 PA parameters that were sampled in the 1992 PA calculations, and, as time permitted, included a preliminary review of an additional 80 parameters. Data type, data quality, data interpretation, and source documentation were evaluated and each reviewer categorized the data based on their professional judgment. A database called PERFORM was developed to help in the management of the reviews.

From the report's "Summary of Findings," the team concluded that "Results of the TSG review of PA parameters indicate that improvement is needed in areas of Data Quality, Data Interpretation, and Source Documentation. It is the opinion of the TSG that this needs to be accomplished to ensure regulatory compliance."

IRTs were subsequently formed to specifically review and qualify, where appropriate, existing data. As discussed in Chapter 5.0, the IRTs were successful in qualifying a large amount of the data that had been collected prior to establishment of a qualified QA program. Data that were not qualified by the IRTs were qualified by three of the recent peer review panels, as discussed in Sections 9.3.4, 9.3.5, and 9.3.6.

PA parameter values were developed and controlled in accordance with the SNL QAPD and QAPs. QAP 9-2 was developed and used to document the selection, development, and entry of parameter values used in the PA. The PA database is controlled and maintained using SNL QAP 9-4. This QAP establishes the process for ensuring that parameter values and their associated documentation are maintained in a traceable, retrievable, and controlled environment and allow for the reproducibility of results.

Once the requirements controlling the development of parameter values (QAP 9-1 or QAP 9-5) are fulfilled, the parameter/distribution development is documented or referenced on the applicable WIPP Parameter Entry Form (Form 464). Form 464 provides a traceable link to the qualification of those portions of the data packages that support the parameter development.

9.4.16 NEPA Reviews

The NEPA requires formal analysis, documentation, and an appropriate level of review for proposed major federal actions involving potentially significant environmental impacts. NEPA documentation and the associated public review and comment periods provided environmental input and opposing viewpoints from a variety of sources for the DOE decisions regarding development of the WIPP. An evaluation of the external NEPA reviews against the screening criteria is provided in Table 9-21.

NEPA documentation of the WIPP includes the 1980 Final Environmental Impact Statement (FEIS) (DOE 1980) and the 1990 Final Supplement Environmental Impact Statement (FSEIS) (DOE 1990a). Another environmental impact statement, the SEIS-II (DOE 1997), was completed in 1997.

A Draft Environmental Impact Statement (DEIS) (DOE 1979) was prepared by the DOE and provided to the public for review in April 1979. The significance of impacts associated with the various alternatives were assessed. Comments on the DEIS were obtained during seven days of public hearings and a 141-day written-comment period. A total of 167 persons presented oral statements on the WIPP during the public hearings that were held in Santa Fe, Carlsbad, and Hobbs, New Mexico; Idaho Falls, Idaho; and, Odessa, Texas. Ninety-three letters, several longer than 50 pages, were received during the written-comments period. Commenters included: federal agencies such as EPA, NRC, the Department of the Interior, and the Department of Health, Education and Welfare; agencies from at least 26 states, including several New Mexico agencies; and groups like the EEG.

In response to the comments, the DEIS was extensively revised to prepare the FEIS, which was published in October 1980. Comments were grouped into 30 major issues, which were then discussed in Chapter 15 of the FEIS. Appendix P of the FEIS reproduced in full the comments received from various federal agencies and the cover letters from all official responses from the various states. Copies of all comments received, including transcripts of the public hearings, were placed in the DOE public reading rooms for WIPP. The DOE Record of Decision, published January 28, 1981, announced the DOE decision to proceed with the construction of surface and subsurface facilities in southeastern New Mexico.

A draft SEIS (DOE 1989) was published and provided to the public in April 1989. During the 90-day comment period, the DOE held nine public hearings at locations in Colorado, Georgia, Idaho, New Mexico, Oregon, Texas, and Utah. In addition to the testimony of nearly 1,000 individuals who spoke at the hearings, the DOE received 1,275 written documents and two petitions with a combined total of approximately 2,200 signatures.

Table 9-21. NEPA Documentation Reviews

1. Is the peer review relevant to the CCA?	Yes – NEPA documentation addresses long-term performance, siting issues, mitigation, etc. which are directly relevant.
2. Was there a formal report prepared by the reviewer?	Yes – the results of the public reviews were submitted to the DOE. The DOE formally compiled comments and responses.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the reviews focused on the adequacy of NEPA documentation prepared for the DOE.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the review evaluated the adequacy of environmental documentation produced for the DOE.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Mixed – the technical expertise of the reviewers varied widely, but included several public agencies and oversight groups (e.g., NRC, EEG).
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Mostly – very few of the reviewers had any affiliation with the WIPP or DOE.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Yes – the public comments on the WIPP NEPA documents have, in aggregate, provided an extensive and thorough review of many issues, several of which are relevant to the CCA.

The DOE reviewed the comments, categorized them by issue, revised the draft SEIS as appropriate, and prepared a comment-response document (Volume 3 of the FSEIS) that presents synopses of the comments and the DOE's responses. Indices to the comments were provided in Volumes 4 and 5 of the FSEIS and served to help locate specific questions or statements and the DOE response. Volumes 6 through 13 of the FSEIS reproduce the public comments received on the draft SEIS and transcripts of oral testimony provided during the public hearings. The draft SEIS was extensively revised, as a result of the comments, in development of the FSEIS, which was published in January 1990. The Record of Decision, dated June 22, 1990, documented the DOE determination to proceed with the phased development of the WIPP. The Record of

Decision included a commitment to prepare SEIS-II before deciding whether to proceed with the WIPP disposal phase.

Public scoping activities prior to the publication of SEIS-II included:

- publishing a Notice of Intent in the Federal Register on August 23, 1995 and a notice reopening the comment period, published on October 13, 1995;
- a public comment period from August 23, 1995 to October 16, 1995; and
- public scoping meetings held in Carlsbad, Albuquerque, and Santa Fe, New Mexico; in Boise, Idaho; and two meetings in Denver, Colorado.

The Implementation Plan (DOE 1996d), published in May 1996, documents the results of the scoping process and provides guidance for preparing SEIS-II.

SEIS-II (DOE 1997) was published in September 1997. The purpose of this document was to provide information on environmental impacts of the DOE's TRU waste disposal operations at WIPP. SEIS-II evaluated a Proposed Action, three Action Alternatives based on the waste management options presented in the Final Waste Management Programmatic Environmental Impact Statement, and two No Action Alternatives. The Proposed Action described the treatment and disposal of the basic inventory of TRU waste over a 35-year period. The basic inventory is that waste currently permitted in WIPP based on current laws and agreements. The Action Alternatives propose the treatment of the basic inventory and an additional inventory as well as the transportation of the treated waste to WIPP for disposal over a 150- to 190-year period. The three Action Alternatives included the treatment of TRU waste at consolidation sites to meet WIPP planning-basis WAC, the thermal treatment of TRU waste to meet Land Disposal Restrictions, and the treatment of TRU waste by a shred and grout process. The No Action Alternatives proposed the dismantling and closure of WIPP and storage of the waste. One No Action Alternative proposed treating the waste thermally before placing it in retrievable storage.

SEIS-II evaluated environmental impacts resulting from the various treatment options; the transportation of TRU waste to WIPP using truck, a combination of truck and regular rail service, a combination of truck and dedicated rail service, and the disposal of this waste in the repository. Evaluated impacts included those to the general environment and to human health. Additional issues associated with the implementation of the alternatives were discussed to provide further understanding of the decisions to be reached and to provide the opportunity for public input on improving DOE's Environmental Management Program.

9.4.17 International Peer Review by the Nuclear Energy Authority/ International Atomic Energy Agency International Review Group, 1996-97 (NEA/IAEA 1997)

Agreement was reached on June 7, 1996 between the DOE, the NEA OECD, and the International Atomic Energy Agency (IAEA) to organize an international peer review of the long-term safety analysis of the WIPP. The objective of the joint NEA/IAEA peer review was to examine whether the postclosure assessment of the WIPP described in this application is appropriate, technically sound, and in conformity with international standards and practices.

The peer review was organized jointly by the NEA and the IAEA. The agencies appointed an International Review Group (IRG) of seven international experts actively involved in national radioactive waste management programs - from waste management organizations, national regulatory bodies, universities, and scientific consultancies. Two representatives each from the NEA and the IAEA provided a joint secretariat and contributed technically to the review.

None of the members of the IRG had ever worked directly on the WIPP project (or worked as a contractor or subcontractor to the DOE). All, however, had participated in international meetings, projects, and comparison exercises in which the WIPP project had been represented, and had some prior knowledge of the project and of PA as practiced by the DOE. In some cases, this knowledge was extensive and detailed, and gained over many years in bilateral or multilateral exchanges.

The following members served on the IRG:

- Ken Bragg, AECB, Canada, Chairman;
- Jordi Bruno, QuantiSci, Spain;
- Klaus Kühn, Technical University of Clausthal, Germany;
- Sören Norby, SKI, Sweden;
- Richard Storck, GRS, Germany;
- Trevor Summerling, Safety Assessment Management Ltd., U.K.;
- Hiroyuki Umeki, PNC, Japan;
- Arnold Bonne, IAEA, Secretariat;
- Gordon Linsley, IAEA, Secretariat;
- Phillipe Lalieux, NEA/OECD, Secretariat; and
- Claudio Pescatore, NEA/OECD, Secretariat.

The review began in October 1996 and was conducted over a six-month period. The review was based on detailed documentation provided by the DOE, a site visit to the WIPP, and discussions with the specialists in the WIPP project. A report titled “International Peer Review of the 1996 Performance Assessment of the US Waste Isolation Pilot Plant (WIPP)”containing the group’s findings were published in April 1997. The full report is included in Appendix PEER-2004.

The rest of the text in this section is a summary of the IRG report and therefore represents the views of the IRG and not necessarily those of DOE.

9.4.17.1 Objective of the Review

The terms of reference for the review were negotiated between the DOE, the NEA, and the IAEA based on a first proposal by the DOE. The significant parts of the Terms of Reference are reproduced in Appendix 2 of the URG report (NEA/IAEA 1997). Therein, it is stated that:

> The objective of the international review is to examine whether the post-closure performance assessment of the WIPP in the CCA is appropriate, technically sound and in conformity with international standards and practices.

The interpretation of this objective was discussed at length within the IRG, especially the phrase "in conformity with international standards and practices."

The IRG decided to conduct its examination to answer the following broad questions stemming from the above statement.

1. Is the WIPP 1996 post-closure PA appropriate?

   The IRG agreed that this should be interpreted as meaning appropriate in the context of the objective of the CCA, which is to satisfy the EPA regulations. The IRG also agreed that it should not undertake a formal comparison with the EPA regulations since this is the responsibility of the EPA. In this respect, it is emphasized that this review was organized to provide the DOE an independent, international perspective on the 1996 post-closure PA of the WIPP.

2. Is the WIPP 1996 post-closure PA technically sound?

   The IRG agreed that this item should be the primary focus of the review. For example: Have adequate data and process information been used? Are the conceptual models and their underlying assumptions scientifically based or reasonable? Have adequately tested mathematical and computer tools been applied?

3. Is the WIPP 1996 post-closure PA in conformity with international practices? That is, is the scope of the assessment, methods of analysis, and quality of application consistent with good practice in other countries?

4. Is the WIPP 1996 post-closure PA in conformity with international guidance and standards? That is, are the calculated end-points consistent with international guidance and standards in the manner these are formulated in other countries?

9.4.17.2 Scope

The terms of reference identify the CCA (Volume I) as the primary material to be reviewed. After individual examination of this document and joint discussions, the IRG made the following initial observations and decisions:

- The CCA was prepared by the DOE to comply with the EPA regulations. These regulations provide detailed guidance on how to demonstrate compliance and are focused on the evaluation of specific performance indicators.

- The CCA, Volume I does not constitute a self-contained or sufficient description of the 1996 PA. Rather, it is necessary to examine many of the CCA appendices in order to find technical information at the level required by the IRG.

- The iterative program of PA of the WIPP has been the subject of a number of previous independent reviews, notably by the NAS (1996). These other reviews, several of which are summarized in Chapter 9 of the CCA, Volume I, would not be examined as part of this review.

- Preparing a view on the four broad questions identified in Section 9.4.17.1, the IRG considered that it would also be able to examine and comment on other issues indicated by the terms of reference, such as the clarity and transparency of the documentation.

9.4.17.3 Conclusions

9.4.17.3.1 Observations on the Specificity of the Waste Isolation Pilot Plant Case

- The WIPP project and the CCA are different in several respects from geological disposal projects and assessment documentation in other countries.

- The WIPP facility is sited in an area in which mineral resources are being actively and extensively exploited.

- The regulator has provided detailed guidance on the assessment approach, documentation and, for the assessment of future human actions, model assumptions.

- The CCA is tightly focused on compliance with the EPA regulations, and does not represent a full safety case as understood in most other countries.

These observations are statements of fact, not criticisms. Such differences, however, have had a strong influence on the PA carried out by the DOE, and have been taken into account by the IRG in formulating its conclusions.

9.4.17.3.2 Evaluation with Respect to the Terms of Reference

9.4.17.3.2.1 *Appropriateness*

The CCA was specifically designed by the DOE to meet the requirements of the EPA regulations. The IRG has not found any indication that the information presented is not appropriate in the context of the EPA requirement. This, however, is a matter for the EPA to judge.

9.4.17.3.2.2 *Technical Soundness*

The analyses contained in the CCA are based on an extensive geological data set resulting from high quality acquisition programs and compilation of regional data. This has been supplemented by a focused geotechnical and experimental program that has provided a world-leading understanding of processes relevant to rock-salt behaviour. The uncertainty associated with

characterization of the wastes, processes related to waste and backfill evolution in the repository, and chemical speciation of radionuclides in the repository environment are less well understood. In particular:

1. The CCA does not sufficiently explore the possible physical implications of the chemical reactions that the MgO backfill may undergo. These implications may be both favourable and unfavourable to the performance of the facility; and

2. The CCA does not support the assumption, applied in the performance calculations, that the physically and chemically heterogeneous array of waste, packaging, backfill, reaction products, and void space will quickly reach well-mixed homogeneous conditions within the disposal rooms. The basis for this assumption and implications of heterogeneities need to be analysed further.

The CCA indicates good code configuration and management of data flows. The IRG has confidence that the procedures applied in these areas are consistent with best practice for computer simulation internationally. The IRG is also aware of the long involvement of the WIPP project in international comparison exercises, which gives added confidence in the performance of several of the detailed models.

Thus, the IRG has overall confidence in the majority of judgments and assumptions made in developing calculational models of the disposal system and concludes that, in the main, the analyses presented in the CCA are based on appropriate studies and are technically sound.

9.4.17.3.2.3 *Conformity with International Practices*

The methods used to assess the performance of the WIPP facility are generally in conformity with practices used in other countries. These include:

- the selection of FEPs,
- development of scenarios and models representing the evolution of conditions in the repository and the release of radionuclides,
- quantitative analysis of selected scenarios by means of a linked set of models and comparison of the results to regulatory limits.

The probabilistic analysis methods used by the DOE are comparable to those employed in a number of other countries, and the DOE contractors contributed substantially to the development of probabilistic methods in the field of repository postclosure assessment.

Specific aspects of the assessment carried out by the DOE are not in accordance with assessment practices in other countries, and this can be partly traced to the influence of the EPA regulations and the strong focus of the CCA on compliance. For example:

- The probabilistic approach applied by the DOE deals only with parameter-based uncertainty. Conceptual model and scenario uncertainty are not discussed in the CCA. These are considered to be important internationally;

- Results in the CCA focus on the CCDFs of cumulative radionuclide release. Information on the behaviour of intermediate parameters and results of representative deterministic calculations, especially as a function of time, are lacking. Without this, it may not be possible to develop a good understanding of the disposal system's behavior; and

- The EPA has ruled that the DOE only needs to consider a limited set of future human actions and has specified the assumptions to make in assessing these actions. Thus, some scenarios that might affect safety have not been evaluated. The lack of a logically argued explanation for the choice of scenarios analysed, or evaluation of these other scenarios, leads to the impression that the assessment is arbitrary.

9.4.17.3.2.4 *Conformity with International Guidance and Standards*

The CCA focuses on a demonstration of compliance with the EPA containment requirement. The latter is based on collective dose considerations, refers to the total activity in the repository, and cannot be related to the standards based on individual dose and risk adopted in most other countries. Moreover, the EPA regulations do not require the applicant to present descriptions or arguments concerning the performance of the disposal system beyond the 10,000-year regulatory period. Thus, for the general case, the CCA does not present calculated end-points that can be compared with international guidance and standards as implemented in other countries.

The CCA does present dose estimates for the undisturbed performance within the 10,000-year regulatory period based on a conservative hypothetical dose pathway. In this case, the results indicate that the WIPP can easily meet typical performance criteria based on dose to the individual. It is likely that, if undisturbed, the facility could meet individual dose criteria over much longer times, due to the long-term stability of the site and the absence of local, viable fresh water resources.

The IRG asked for information, not included in the CCA, on doses that might be received in the disturbed case from drilling of a borehole into the repository. The results provided by the DOE indicated that, for this scenario, the WIPP facility would meet an individual risk-based standard typical of those used in other countries. The CCA does not demonstrate, however, that no other scenarios could contribute significantly to risk.

9.4.17.3.3 Overall Judgement

The WIPP project and the CCA are markedly different from geological disposal projects and assessment documentation in other countries. In particular, important decisions relating to what is a sufficient method and scope of assessment have already been taken, and the CCA is not required to present a complete PA as understood internationally.

The CCA documentation is not transparent and is difficult to follow even from the point of view of experienced PA practitioners. Technical issues are often difficult to trace and some of the choices made and modeling assumptions are not well supported. This, combined with the specificity of the EPA regulations, made it challenging to distinguish between decisions determined by the regulator and those made by the DOE.

Focusing on the decisions for which the DOE must take technical responsibility, the IRG finds that the PA methodology implemented in the CCA is generally acceptable and conforms to practices in other countries. The IRG also has overall confidence in the majority of judgements and assumptions made in developing calculational models, and believes that the quality of assessment codes and data handling is generally good. Thus, in the main, the analyses contained in the CCA are technically sound.

On specific points, the IRG considers that the DOE should give further attention to:

1. the implications - favourable and unfavourable - that the behaviour of the MgO backfill may have on the performance of the facility, and

2. the basis for assuming that homogeneous conditions will be rapidly reached in the disposal rooms, and the potential consequences of heterogeneities in the source term.

The IRG is of the view that, in the case of undisturbed performance, the WIPP facility would meet radiological performance standards typical of those used in other countries. This judgement is based on the analysis presented in the CCA in respect of the 10,000-year regulatory period and, for times beyond 10,000 years, on the geological stability of the site and the absence of viable fresh water resources. The case of disturbed performance is less clear: supplementary analyses by the DOE indicate that a risk target would be met in respect of an exploratory borehole drilling scenario. The CCA does not (and need not) make the case that this is the most important scenario to consider and, therefore, the IRG cannot reach a definite judgment.

Finally, from the experience of the review, the IRG observes that, by commissioning this international peer review, the DOE has demonstrated a commendable openness and commitment to improving confidence in the PA of the WIPP facility. The DOE and their contractors were very open in their discussions with the IRG, and were able to provide useful responses, often at short notice, on most issues raised. This was very useful and helpful to the review.

9.4.18 GEOTRAP

GEOTRAP is the NEA/OECD Project on Radionuclide Migration in Geologic, Heterogeneous Media. GEOTRAP is devoted to the exchange of information and in-depth discussions on present approaches to acquiring field data and testing and modeling flow and transport of radionuclides in geologic formations for site evaluation and safety assessment of deep repository systems. This information is important for both national waste management programs and the wider scientific community. The WIPP project has actively participated in this project since its inception in 1996.

The project is structured as a series of forum-like workshops at which implementers, regulators, and scientists interact.

The first GEOTRAP workshop, “Field Tracer Experiments: Role in the Prediction of Radionuclide Migration,” was coorganized with the European Commission. It provided an overview of ongoing and planned work in the study of radionuclide transport phenomena and the characterization of relevant geologic media properties.

Variability (heterogeneity) in the properties of the rocks over a wide range of spatial scales is a common feature of most geologic media. Broad agreement exists that its characterization and the corresponding analysis of the consequences for groundwater flow and radionuclide transport form an important part of the safety of deep geologic repositories assessment. The second GEOTRAP workshop, "Modelling the Effects of Spatial Variability on Radionuclide Migration," explored these issues and provided an overview of current developments in the field.

The subject of the third GEOTRAP workshop was "Characterisation of Water-Conducting Features and their Representation in Models of Radionuclide Migration." It investigated how water-conducting features can determine the rate of radionuclide release from the near-field to the far-field, the rate at which radionuclides can migrate with flowing groundwater, and the degree of retention in the geosphere. A key finding of the workshop was that the characterization of the structure and properties of water-conducting features is an important requirement for any PA of deep repository systems.

The fourth GEOTRAP workshop, "Confidence in Models of Radionuclide Transport for Site-specific Performance Assessments," was held in June 1999. The workshop examined the issue of technical confidence building and provided an overview of current developments in this field.

The fifth workshop addressed "Geological Evidence and Theoretical Bases for Radionuclide-Retention Processes in Heterogeneous Media." The Swedish Nuclear Fuel and Waste Management Company (SKB) hosted this workshop in May 2001. The following proceedings of these workshops are available from the OECD Bookshop at www.oecd.org/bookshop.

- Radionuclide Retention in Geologic Media
  Workshop Proceedings, Oskarshamn, Sweden, 7-9 May 2001

- GEOTRAP: Radionuclide Migration in Geologic, Heterogeneous Media
  Summary of Accomplishments (pdf format, 216 kb)

- Confidence in Models of Radionuclide Transport for Site-specific Assessments
  Synthesis and Proceedings of the fourth GEOTRAP Workshop, Carlsbad, New Mexico, United States, 14-17 June 1999

- Water-Conducting Features and their Representation in Models of Radionuclide Migration
  Synthesis and Proceedings from the third GEOTRAP Workshop, Barcelona, Spain, 10-12 June 1998

- Modelling the Effects of Spatial Variability on Radionuclide Migration
  Synthesis and Proceedings from the second GEOTRAP Workshop, Paris, France, 9-11 June 1997

- Field Tracer Experiments: Role in the Prediction of Radionuclide Migration
  Synthesis and Proceedings of an NEA/EC GEOTRAP Workshop, Cologne, Germany, 28-30 August 1996 - Coedition with the European Communities Series Disposal of Radioactive Waste

9.4.19 Institute for Regulatory Science Reviews

RSI is a non-profit scientific and educational organization. It provides independent scientific peer reviews and technical assessments. These reviews and assessments are generally performed in association with professional societies. RSI has performed two peer reviews for the WIPP project. These are briefly described below. Full reports of these reviews are provided in Appendix PEER-2004.

9.4.19.1 Requirements for Disposal of Remote-Handled Transuranic Waste at the Waste Isolation Pilot Plant (2002) (RSI 2002)

This peer review examined methods and techniques DOE proposes to use for characterization of TRU waste and various QA processes. The peer review focused on the DOE's draft Permit Modification Request (Draft Request) to NMED for RH-TRU waste characterization and the corresponding Notification of Proposed Change to EPA.

The RSI review panel (RP) findings are summarized in the following discussion:

Reliance on AK as the analysis tool to meet the waste characterization requirements as listed in the Draft Request can be consistent with the relevant regulations in some instances. In other instances, additional confirmation methodologies in a hierarchy of methods proposed by DOE will be needed to characterize wastes accepted at the WIPP to meet the Data Quality Objectives (DQO). Whether AK alone is sufficient will be dependent upon the nature of the waste and the source and completeness of the data that constitute the AK. The application of the Performance-Based Measurement System approach meets the EPA's guidance on performance-based measurement systems. The Draft Request presents an RH-TRU waste characterization program that is not consistent in all cases with the recommendations of the National Research Council. The Draft Request still includes characterization requirements which the National Research Council criticized as being self-imposed and overly conservative and which have no legal or safety basis.

The Notification of Proposed Change to the EPA 40 CFR Part 194 Certification of the Waste Isolation Pilot Plant describes the nature and scope of the proposed RH-TRU Waste Characterization Program. Consistency with EPA disposal regulations is fully demonstrated and documented in resource documents. The significance of the change is clearly and adequately addressed. The consequences for compliance determinations are clearly stated and technically justified.

The RH-TRU Waste Characterization Program Implementation Plan presented meets the performance factors of the waste characterization program. The waste components have been identified and justified in a general sense, but a detailed description of waste streams from the waste-generating sites is lacking. The programmatic AK steps are somewhat conservative but are sufficient to accomplish the DQOs adopted by DOE- CBFO, and can be reasonably relied upon to meet the DQOs for materials received at WIPP. The distinction between the characterization activities, AK, supplementary, confirmatory, or verification is inadequate in the RH-TRU Waste Characterization Program Implementation Plan, and is made particularly confusing by the definitions.

The Notification of Proposed Change adequately explains and justifies how AK and the WWIS are used to satisfy the quantification and control requirements. The WWIS tracking and control system is currently in use in the CH-TRU waste program, and it is operating satisfactorily. To meet additional tracking and control requirements imposed on RH-TRU waste by the LWA, WWIS will be modified by the addition of data fields.

The RH-TRU Waste Characterization Program Implementation Plan describes a QA program that addresses the appropriate requirements but lacks sufficient detail. Use of the 40 CFR § 194.22 provisions in waste characterization is sufficiently explained. The RH-TRU waste characterization program is reasonably consistent with the report, Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant (National Research Council/National Academy of Sciences 2001), including its finding of self-imposed requirements that have no legal or safety basis. The Draft Request and RH-TRU Waste Characterization Program Implementation Plan are consistent with the ALARA concept.

Based on a careful assessment of the information presented to the RP and the findings developed in response to the review criteria, the RP provides the following recommendations.

1. A detailed procedure for determining whether there is sufficient AK available on a waste should be developed as part of the permit application.

2. In the final request for RCRA Class 3 Permit Modification, a detailed procedure should be provided to go to other characterization methods if AK is found to be insufficient.

3. DOE should implement the National Research Council recommendation that review of characterization and packaging requirements continue, especially implementation "... over the entire National TRU Program."

4. DOE should provide to the EPA a complete inventory of radionuclides and waste forms so that the EPA may verify the repository performance using its own methods for certification.

5. Appropriate interaction with the EPA and the NMED is recommended.

6. Prior to submission, all permit related documents should be reviewed in detail for completeness, specificity, and clarity by a team experienced in the permitting process.

7. The request for RCRA Class 3 Permit Modification must be expanded to include more specifics and examples for clarity and completeness.

8. The discussion for Table 1 of the draft request for RCRA Class 3 Permit Modification should be expanded to justify why sections of the documents require "no action" or "no changes."

9. Supplemental information should be supplied detailing the waste characterization plans for each waste generating site and DOE's procedures for determining that these plans meet the WIPP WAC.

10. Detailed audit procedures for WIPP and the waste-generating sites should be provided.

11. More detail and specificity on WAC using AK, VE, and radiography should be provided in the permit application.

12. DOE should evaluate the necessity of identifying waste streams by EPA hazardous waste numbers or characteristics.

13. A complete review should be made of what is gained from the remote swiping procedure for "clean" RH-TRU containers and how the information will be used.

The DOE accepted many of the recommendations of the RSI's review panel in revising the documents reviewed by the panel.

9.4.19.2 Desirability of Performing Certain Transuranic Waste Characterization Tests (RSI 2003)

The following is a summary of the RSI report, "Desirabilty of Performing Certain Transuranic Waste Characterization Tests":

This report contains the results of an independent peer review performed by the RSI responding to a request from Bob Forrest, Mayor of Carlsbad, New Mexico, to critically review a claim included in a Senate Committee report. The Senate language indicated that the NAS and the EEG had endorsed the elimination of certain tests currently performed to characterize hazardous waste constituents of TRU waste for disposal at the WIPP.

The RP reviewed two relevant reports of the National Research Council (National Research Council 2001, 2002)—the research arm of the NAS, National Academy of Engineering, and the Institute of Medicine. In addition, the RP reviewed a number of documents published by the EEG, an independent group associated with New Mexico Institute of Mining and Technology.

As the principal facility for disposal of the nation's TRU waste generated as a result of nuclear weapons research, development, and production, WIPP must comply with relevant requirements of the EPA and NMED. Where the EPA regulates certain aspects of the radioactivity content of TRU waste, the NMED regulates the hazardous waste constituents of TRU waste. In addition, WIPP must comply with relevant transportation regulations. Waste must be properly characterized to demonstrate that it meets the requirements for transportation to and disposal at WIPP. Waste characterization activities required at the time of the review included the following, although not all of these techniques were used on each container:

1. Radiography, which is an x-ray technique to determine physical contents of containers;

2. VE of opened containers as an alternative way to determine their physical contents or to verify radiography results;

3. HSG sampling to determine VOC contents of gases in the void volume of the containers;

4. Sampling and analysis of waste forms that are homogeneous and can be representatively sampled to determine concentrations of hazardous waste constituents and toxicity-characteristic contaminants of waste in containers;

5. Compilation of AK documentation into an auditable record, including process knowledge and prior sampling and analysis data; and

6. Non-destructive assay, typically segmented gamma scans and passive/active neutron interrogation, to quantify radionuclides.

Confirmation that the waste complies with the requirement of being not ignitable, corrosive, or reactive is accomplished by AK or appropriate tests.

The U.S. Senate Bill S.1424 states that waste confirmation for all waste received for storage and disposal be limited to:

1. Confirmation that the waste contains no ignitable, corrosive, or reactive waste through the use of either radiography or VE of a statistically representative subpopulation of the waste; and

2. Review of the Waste Stream Profile Form to verify that the waste contains no ignitable, corrosive, or reactive waste and that assigned EPA hazardous waste numbers are allowed for storage and disposal by the WIPP HWFP.

Furthermore, the U.S. Senate Bill S.1424 states that compliance with the disposal room performance standards of the WAP shall be demonstrated exclusively by monitoring airborne VOCs in underground disposal rooms in which waste has been emplaced until panel closure.

The RP was asked to respond to three review criteria identified by the Mayor of Carlsbad, New Mexico. After careful review of documents provided to the RP and appropriate deliberations, the RP provided the following principal conclusions.

1. Based on careful evaluation of the two relevant NRC reports, the RP concludes that the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S.1424 is supported by the NRC.

2. It appears that EEG agrees that the current characterization requirements are excessive. It appears that EEG also agrees that monitoring VOCs in underground disposal rooms is sufficient.

3. Based on the information presented to the RP, the permit modification listed under Section 310 of U.S. Senate Bill 1424 is technically defensible. There is no reason to perform waste confirmation tests that (1) provide insignificant health and safety benefits to the U.S. population, and (2) pose serious radiological and occupational health and safety risks to the workers performing these tests.

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1.0 INTRODUCTION

Tables AUD-1 through AUD-11 of this Appendix summarize assessments performed between November 2, 1998, and May 31, 2003, of transuranic (TRU) waste sites, Sandia National Laboratories (SNL), Washington TRU Solutions (WTS), LLC, suppliers performing quality-affecting work, and the Carlsbad Field Office (CBFO), and supplement the information contained in the Compliance Certification Application (CCA). The summaries are grouped in chronological order by audited agency. Each assessment entry outlines the assessment scope and results. Results of the assessment normally determine the adequacy, implementation, and effectiveness of the auditee's quality assurance program. Adequacy addresses the migration of requirements from upper-tier program documents into implementing procedures. Implementation addresses the extent of compliance with procedures. Effectiveness addresses whether the controls established in the implementing procedures produce the desired results or end product. For ease of reference, CBFO is used throughout this appendix to mean CAO (Carlsbad Area Office) or CBFO, as appropriate. Below is a list of sites audited and the table that contains the summaries:

Table 1. Los Alamos National Laboratory (LANL) Audits – Page 2
Table 2. Los Alamos National Laboratory - Carlsbad Operations (LANL-CO) Audits – Page 4
Table 3. Nevada Test Site (NTS) Audits – Page 5
Table 4. Hanford Site Audits – Page 6
Table 5. Rocky Flats Environmental Technology Site (RFETS) Audits – Page 8
Table 6. Idaho National Engineering and Environmental Laboratory (INEEL) Audits – Page 12
Table 7. Washington TRU Solutions (WTS) Audits – Page 16
Table 8. Sandia National Laboratories (SNL) Audits – Page 20
Table 9. Savannah River Site (SRS) Audits – Page 22
Table 10. Carlsbad Field Office (CBFO) Audits – Page 23
Table 11. Carlsbad Field Office (CBFO) Supplier Audits – Page 24

The summary tables include the organization that was assessed, the assessment number, the scope of the assessment, and the results of the assessment expressed as "satisfactory" (S), "marginal" (M), "unsatisfactory" (U), "not applicable" (N/A), or "indeterminate" (I) for the three factors considered during an assessment (i.e., "adequacy," "implementation," and "effectiveness"). Indications of M, U, and I are addressed through the corrective action program to bring them up to S (satisfactory). They have been corrected or satisfactorily addressed and verified through subsequent audits, surveillances, corrective action reports, or other means prior to initial certification or continued certification for shipping to WIPP.

Only those CBFO assessment activities directly related to 40 CFR 191 and 194 are included in this appendix. Additional CBFO assessments are performed in other critical areas. In addition, each participant performs internal assessments of their own activities.

AUDIT SUMMARY TABLES

Table AUD-1. Los Alamos National Laboratory (LANL) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
Los Alamos National Laboratory (LANL)	A-99-04	6/14-17/99 and 6/28-7/1/99	Technical and quality assurance (QA) activities related to LANL TRU waste characterization-certification activities added since the last CBFO recertification audit.	S	S	S
				The QA program was satisfactory in meeting requirements and implementation. Minor concerns were noted in the area of software QA. In the area of acceptable knowledge (AK), the technical processes were determined adequate and implemented. All corrective actions were completed and verified.		
LANL	A-00-03	11/9-10/00	Annual recertification audit of TRU Waste Characterization and Certification QA program.	S	S	S
				The QA program was adequate, satisfactorily implemented and effective.		
LANL	A-00-13	8/21-25/00 and 8/28-31/00	Remainder of the LANL TRU waste characterization activities for waste characterization and transportation activities for debris waste.	S	S	S
				The technical and QA programs were adequate in accordance with the Hazardous Waste Facility Permit (HWFP) requirements, satisfactorily implemented, and effective.		
LANL	A-00-16	9/25-29/00	Technical activities and associated QA program requirements related to the LANL TRU waste characterization and certification programs for debris waste.	S	S	S
				The QA programs and technical programs were adequate, effective, and satisfactorily implemented.		
LANL	A-01-11 (two visits)	5/8-9/01 and 5/14-17/01	Technical activities and associated QA program requirements related to the LANL TRU waste characterization and certification programs for debris wastes. Specifically, the visual examination (VE) technique associated with packaging operations conducted in TA-55, repackaging of containers exceeding the wattage limits in the Waste Characterization, Reduction, and Repository (WCRR) Facility, and packaging source materials for the Off-Site Source Recovery (OSR) Program.	S	S	S
				The LANL program for performing the VE technique for TA-55 and the OSR program was adequate, satisfactorily implemented, and effective.		

Table AUD-1. Los Alamos National Laboratory (LANL) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
LANL	S-01-31	7/16-17/01	The LANL TRU Waste Characterization Project (TWCP) QA and technical program as related to the Document Control program and TRU waste characterization activities.	S	S	S
				QA program requirements related to the activities evaluated during the surveillance were adequate, satisfactorily implemented, and effective.		
LANL	A-02-04	10/22-26/01	The LANL TWCP, including QA, nondestructive assay (NDA), transportation, and WIPP Waste Analysis Plan (WAP) activities.	S	S	S
				The QA programs and technical programs were adequate, satisfactorily implemented, and effective.		
LANL	A-02-16	2/25-28/02	Selected technical activities related to the LANL TRU waste characterization and certification programs for debris wastes. Audit included the evaluation of two new NDA systems: the Combined Thermal-Epithermal Neutron (CTEN) system and a portable tomographic gamma scanner (P-TGS).	S	S	S
				The LANL technical processes for the CTEN system were adequate, satisfactorily implemented, and effective. The technical activities related to the P-TGS were judged to be indeterminate. The QA program continues to be adequate, satisfactorily implemented, and effective.		
LANL	A-02-30	8/26-30/02	LANL TWCP, including QA and WIPP HWFP activities. Audit conducted to evaluate Summary Category Group S5000, contact-handled and newly generated heterogeneous debris waste.	S	S	S
				The LANL technical and QA procedures continue to be adequate. The LANL technical processes were satisfactorily implemented and effective. The LANL process for manual headspace gas sampling of S5000 waste was concluded to be indeterminate, due to a limited operational time and lack of analytical batch data reports.		
LANL	A-03-07	10/29-31/02	Obtaining manual samples of headspace gas (HSG) in Summa® canisters and utilizing the Idaho National Engineering and Environmental Laboratory (INEEL) for analytical services.	S	S	S
				The LANL process for obtaining manual HSG samples was adequate. The LANL technical processes were satisfactorily implemented and effective.		
LANL	S-03-07	12/17-20/02	Loading of high-wattage waste at LANL and shipment of the waste to WIPP. Receipt and venting of the inner containment vessel (ICV) at WIPP.	S	S	S
				The LANL team displayed excellent job control and conduct of operations techniques during TRUPACT-II operations. LANL management, the Transportation Certification Official, QA personnel, Radiological Control personnel, and the DOE-National Nuclear Security Administration-Los Alamos Site Office Program Management and Facility Representatives were supportive and actively involved in all phases of TRUPACT-II operations.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-2. Los Alamos National Laboratory – Carlsbad Operations Office (LANL-CO) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
LANL-CO	A-03-12	12/17-19/02	LANL-CO QA program in accordance with CBFO Quality Assurance Program Description (QAPD) for performing quality-affecting work including the Actinide Chemistry program for the WIPP. LANL-CO implementation of the Sandia National Laboratories (SNL) QA program as detailed in the SNL and LANL Memorandum of Agreement (MOA) dated 8/2/02 and revised MOA dated 12/06/02 for performing work on the Transuranic Waste Baseline Inventory Report (TWBIR) in supporting the Performance Assessment (PA) for SNL and the WIPP.	S	I	I
				The status of LANL-CO QA program is adequate with one exception concerning nonconformances. The TWBIR program implementation performed by LANL-CO in accordance with SNL procedures was considered indeterminate. See S-03-11 for follow-up.		
LANL-CO	S-03-11	1/23/03	Implementation of the LANL-CO corrective action for Corrective Action Report (CAR) W-03-02 issued for conditions adverse to quality identified in conducting TWBIR activities.	S	S	S
				The corrective actions identified in CAR W-03-02, issued during audit A-03-01, were completed with the exception of the agreed upon LANL-CO surveillance of the TWBIR program activities, which was scheduled for the last week in February. The actions implemented for CAR W-03-02 are considered satisfactory.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-3. Nevada Test Site (NTS) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
Nevada Test Site (NTS)	A-99-01	11/2-6/98	The NTS TRU waste characterization and certification activities.	S	S	S
				Overall the adequacy, implementation, and effectiveness were satisfactory; however, two areas (integration process with mobile service contractor and data reconciliation) were concluded to be indeterminate.		
Audit of TRUtech, Inc. at NTS	A-99-02	12/7-11/98	The technical and QA programs related to TRUtech TRU waste characterization and certification activities.	S	S	S
				The adequacy, implementation, and effectiveness of the TRUtech QA program were satisfactory.		
Audit of Mobile Characterization Systems (MCS) at NTS	A-99-03	11/2-6/98	The technical and QA programs related to MCS TRU waste characterization and certification activities.	S	S	S
				MCS's technical and QA programs were adequate, satisfactorily implemented, and effective; however, improvements were needed in the areas of drum filter procurements, software configuration management, and the collection of field duplicates for HSG analysis.		
NTS	A-99-20	6/7-11/99	The NTS TRU waste characterization and certification activities including the AK process and the mobile services contractor interface.	S	S/M	S/M
				The adequacy of QA programs was satisfactory. However, the technical program was only marginally implemented and marginally effective. Corrective actions in the marginal areas were implemented and verified.		
NTS using the Central Characterization Project (CCP)	A-02-15	9/23-27/02	The CCP TRU waste characterization and certification activities related to Summary Category Group S5000 (debris waste) contracted to Bechtel-Nevada.	S	S	S
				The CCP technical and QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD, the WAP of the WIPP HWFP, and the WIPP Waste Acceptance Criteria (WAC). The assessed activities were being satisfactorily implemented and the QA program was determined to be effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) – Indeterminate

Table AUD-4. Hanford Site Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
Hanford	A-99-05	7/12-17/99	The TRU waste characterization, certification, and transportation programs.	S	S/M	S/M
				The QA program's adequacy, implementation, and effectiveness were satisfactory. Technical processes were marginally implemented and marginally effective.		
Hanford	S-00-04	3/28-30/00	Technical processes related to NDA systems. Also, the verification of corrective actions implemented for issues identified in Carlsbad Field Office (CBFO) Audits A-99-05 and A-00-05.	S	S	S
				Overall, the Hanford Site technical and QA programs were determined to be adequate in accordance with the CBFO QAPD. The audit team also concluded that Hanford procedures were being satisfactorily implemented and that the evaluated processes were effective.		
Hanford	A-00-05	1/24-28/00	The technical and QA processes related to Hanford TRU waste characterization and transportation activities.	S	S	S
				The QA program was satisfactory and implemented as required. Technical processes evaluated were determined to also be adequate, effective and satisfactorily implemented.		
Hanford	A-01-03	6/11-15/01	The Hanford TRU waste characterization activities for contact-handled debris waste.	S	S	S
				Hanford technical and QA programs continue to meet requirements. The audit team concluded that the defined QA and technical processes for the audited activities continue to be implemented in accordance with the Hanford Quality requirements and implementing procedures and that the processes were effective.		
Hanford	S-01-04	1/16/01	The Hanford Site QA program as it relates to the Hanford organization.	S	S	S
				The Hanford activities evaluated relating to QA were adequate, satisfactorily implemented, and effective.		
Hanford	A-01-16	6/11-15/01	The applicable technical and QA activities related to the TRU waste characterization activities performed at the Plutonium Finishing Plant (PFP). Hanford procedures and processes for assay, visual examination, and repackaging of waste at the PFP as applied to retrievably stored debris were examined during this audit.	S	S	S
				The Hanford technical and QA procedures for the PFP were adequate relative to the migration of requirements from the CBFO QAPD, the WAP, and the WAC. The Hanford procedures were being satisfactorily implemented and the evaluated processes were effective.		

Table AUD-4. Hanford Site Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
Hanford	S-01-33	8/8-9/01	The Hanford Site TWCP QA and technical program, as related to the Document Control program and TRU waste characterization activities.	S	S	S
				The QA program requirements related to the activities evaluated during the surveillance were adequate, satisfactorily implemented, and effective.		
Hanford	S-02-04	12/18-19/01	The technical activities related to the Hanford Site TRU waste characterization activities performed at the PFP. Hanford procedures and processes for assay, visual examination, and repackaging of waste at the PFP as applied to retrievably stored debris (S5000) and homogenous solid (S3000) waste were examined during this surveillance.	S	S	S
				The Hanford technical procedures are adequate relative to the flow down of requirements from the CBFO QAPD, and the WAC. The Hanford QA program satisfactorily met the requirements of the QAPD and WAC and is being satisfactorily implemented. The Hanford QA program was verified and documented during recertification Audit A-01-03. The Hanford technical processes evaluated for PFP are satisfactorily implemented, and effective.		
Hanford	A-02-23	6/24-28/02	Re-evaluation of the Hanford Site TRU waste characterization, transportation, and certification activities.	S	S	S
				The Hanford QA program continues to satisfactorily meet the requirements of the QAPD, WAP, contact-handled (CH) WAC, and TRUPACT-II Authorized Methods for Payload Control (TRAMPAC). The QA program is satisfactorily implemented and effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) – Indeterminate

Table AUD-5. Rocky Flats Environmental Technology Site (RFETS) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RFETS	A-99-07	2/23-25/99	The technical and QA processes related to the RFETS TRU waste characterization, certification, and transportation activities.	S	S/M	S
				The RFETS QA program was adequate, satisfactorily implemented, and effective. Document control was found to be marginally implemented, but effective.		
RFETS	A-99-09	3/8-12/99	The RFETS TRU waste characterization activities associated with Salt Stabilization and LECO® Crucible Repackaging.	S	S/M	S/M
				The QA program was adequate, effective, and satisfactorily implemented. The implementation and effectiveness of the technical processes were marginal.		
RFETS	A-99-13	3/24-25/99	The software QA program as evaluated by RFETS and implemented by Canberra, relative to the TRU waste characterization program.	S	S	S
				The software QA program was adequate, effective, and satisfactorily implemented for the QA program and technical processes.		
RFETS	A-99-16	4/27-29/99	The technical and QA processes related to RFETS TRU waste characterization and certification activities associated with Salt Residue Stabilization and LECO® Crucible Repackaging processes.	S	S	S
				The QA and technical processes evaluated were adequate, satisfactorily implemented, and effective.		
RFETS	A-99-17	9/13-17/99	The technical and QA processes related to RFETS TRU waste characterization and certification activities associated with Salt Residue Repack, Dry Residue Repack, Ash Repack, and Combustible Residue Repack.	S	S	S
				The audit team concluded that the adequacy, implementation, and effectiveness of the technical and QA programs were satisfactory in meeting requirements.		
RFETS	A-00-02	11/16-17/00	The technical and QA processes related to the RFETS TRU waste characterization and certification activities associated with Segmented Gamma Scanner (SGS) Drum Counter, SGS Can Counters, and mobile TGS, AK, and Field Sample QC Data Collections.	S	S	S
				All activities assessed were adequate, satisfactorily implemented, and effective.		

Table AUD-5. Rocky Flats Environmental Technology Site (RFETS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RFETS	A-00-07	1/29-2/1/00	The TRU waste characterization activities relative to the requirements detailed in the WIPP HWFP and the CBFO QAPD.	S	S	S
				The RFETS technical and QA programs were adequate. The defined QA and technical programs for these activities were being satisfactorily implemented in accordance with the RFETS QA documents and the processes were effective.		
RFETS	A-00-08	12/13-17/99 and 1/18-20/00	The RFETS TRU waste characterization activities for debris waste.	S	S	S
				The RFETS technical and QA programs were adequate. The defined QA and technical programs for these activities were being implemented in accordance with the RFETS Quality Assurance Project Plan (QAPP) and the implementing procedures and processes were effective.		
RFETS	A-00-10	3/6-8/00	Proper maintenance of the RFETS QA program since the last certification audit in March 1999. Recertification audit.	S	S	S
				All activities assessed were adequate, satisfactorily implemented, and effective.		
RFETS	A-00-12	9/18-22/00 and 11/1-2/00	The RFETS TRU waste activities as they relate to the HWFP for homogenous solid waste.	S	S	S
				All activities assessed were adequate, satisfactorily implemented, and effective.		
RFETS	A-01-05	3/26-28/01	Evaluate two additional waste streams and the indeterminate actions of CBFO audit A-00-12, with the exception of the on-line HSG unit that the RFETS no longer intends to use.	S	S	S
				The adequacy of the RFETS technical and Quality Assurance (QA) programs was satisfactory. All activities assessed were satisfactorily implemented and effective.		
RFETS	A-01-07	1/29-2/1/01	The RFETS TRU waste activities related to HWFP and QA elements.	S	S	S
				All activities assessed were adequate, satisfactorily implemented, and effective.		
RFETS	A-01-12	5/14-18/01	The RFETS TRU waste activities as they related to three new NDA systems, radiography, visual examination, and the Waste and Environmental Management System (WEMS)- WIPP Waste Information System (WWIS) interface.	S	S	S
				The RFETS technical and QA programs were determined to be adequate, satisfactorily implemented, and effective.		

Table AUD-5. Rocky Flats Environmental Technology Site (RFETS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RFETS	S-01-30	7/11-12/01	Evaluate the RFETS QA and technical program, as related to the document control program and TRU waste characterization activities.	S	S	S
				The QA program was adequate, satisfactorily implemented, and effective.		
RFETS	S-01-39	9/25-27/01	The RFETS automated procurement system.	S	S	S
				The automated procurement system was adequate, satisfactorily implemented, and effective.		
RFETS	A-02-05	11/27-30/01	The RFETS TRU waste characterization activities for debris waste, particularly newly generated debris waste.	S	S	S
				The overall adequacy of the RFETS technical and QA programs was satisfactory in meeting requirements. The defined QA and technical programs for these activities were being satisfactorily implemented and the processes were effective.		
RFETS	A-02-07	2/4-8/02	The RFETS TRU waste characterization activities for debris and solid waste.	S	S	S
				The adequacy of the RFETS technical and QA programs was satisfactory and the defined QA and technical processes were being satisfactorily implemented and were effective.		
RFETS	A-02-19	6/4-6/02	The RFETS TRU waste characterization activities for debris waste. A new mobile real-time radiography (RTR) unit and a new multipurpose crate counter (MPCC) were also evaluated.	S	S	S
				The overall adequacy of the RFETS technical and QA programs was satisfactory and the defined QA and technical programs for these activities were being satisfactorily implemented and are effective.		
RFETS	A-03-02	11/19-20/02	The audit scope included Summary Category Groups S5000 debris and S3000 solid wastes. The audit evaluated a new VE facility (in Building 371) to confirm RTR, and polychlorinated biphenyl (PCB) analysis. In addition, the Building 440 gas generation testing program (GGTP) was evaluated.	S	S	S
				The overall adequacy of the RFETS technical and QA programs was satisfactory in meeting requirements. The audit team also concluded that the defined QA and technical programs for these activities (except PCB analysis and GGTP) were being implemented in accordance with the RFETS QAPP and the applicable implementing procedures and processes were effective. The audit team found that the adequacy, implementation, and effectiveness of the PCB analysis and GGTP activities were indeterminate.		

Table AUD-5. Rocky Flats Environmental Technology Site (RFETS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RFETS	A-03-03	3/4-7/03	The RFETS TRU waste characterization activities relative to the requirements detailed in the WIPP HWFP and the CBFO QAPD. Three new activities were evaluated during the audit: the Building 440 GGTP, Building 371 HSG Sampling Using an Automated Manifold, and Building 664 Mobile RTR (for lead-lined drums).	S	S	S
				Overall, the RFETS technical and QA programs were satisfactory in meeting requirements. The defined QA and technical programs for these activities were being implemented in accordance with the RFETS QAPP and its implementing procedures, and the processes were effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) – Indeterminate

Table AUD-6. Idaho National Engineering and Environmental Laboratory (INEEL) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
Idaho National Engineering and Environmental Laboratory (INEEL)	A-99-08	5/17-20/99	The INEEL TRU waste characterization, transportation, and certification activities.	M	M	M
				The QA program was marginally adequate. Technical areas were also marginally implemented and marginally effective.		
INEEL	S-99-10	5/3-4/99	The INEEL software QA program as it relates to the Transuranic Reporting, Inventory and Processing System (TRIPS).	S	M	S
				The activities evaluated relating to QA were adequate and marginally implemented. The technical activities were determined to be effective.		
INEEL	A-00-06	4/24-28/00	The INEEL TRU waste characterization, transportation, and certification activities.	S	S	S
				The defined QA program was adequate and effectively implemented in accordance with the INEEL quality and implementing procedures. Also, except for the visual examination process, the INEEL technical areas were satisfactorily implemented and effective.		
INEEL	A-00-07	4/24-28/00	The INEEL TRU waste characterization, transportation, and certification activities for retrievably stored debris waste.	S	S	S
				The technical and QA procedures were adequate and the QA and technical programs were effectively implemented except for visual examination, which was marginally acceptable.		

Table AUD-6. Idaho National Engineering and Environmental Laboratory (INEEL) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
INEEL	A-01-02	12/5-8/01 and 1/18/01	The INEEL TRU waste characterization, transportation, and certification activities associated with solid wastes.	S	S	S
				All activities assessed were adequate, satisfactorily implemented, and effective.		
INEEL	S-01-06	5/1/01	The INEEL QA program as it relates to the organization. Also evaluation of the trailer mounted RTR unit, analysis of gas samples for hydrogen and methane, new gas chromatography/flame ionization detector equipment, and the TRUPACT loading and unloading operations.	S	S	S
				The QA activities were adequate, satisfactorily implemented, and effective. The audit team also concluded that the RTR and TRUPACT operations procedures were adequate, implemented, and effective.		
INEEL	A-01-14	7/30-8/3/01	The INEEL TRU waste characterization, transportation, and certification activities for retrievably stored debris waste.	S	S	S
				The INEEL technical and QA procedures continue to be adequate relative to the CBFO QAPD, WAP, WAC, and TRAMPAC. Also, the procedures were adequate, satisfactorily implemented, and effective.		
INEEL	S-01-29	7/2-3/01 and 7/25-26/01	The INEEL process for use of the Waste Assay Gamma Ray Spectrometer (WAGS).	S	S	S
				The WAGS procedure was adequate. The surveillance team determined that the activities evaluated relating to WAGS process were adequate, satisfactorily implemented, and effective.		
INEEL	S-02-03	10/30/01	Evaluate new analytical equipment and the process of reducing data from composited HSG analysis results at the INEEL.	S	S	S
				The new equipment was identical to existing equipment and the process for data reduction is acceptable.		

Table AUD-6. Idaho National Engineering and Environmental Laboratory (INEEL) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
INEEL	A-02-21	4/9-11/02	Evaluate the NDA of summary category groups S3000 solid waste and S5000 heterogeneous debris waste using the WAGS and the Stored Waste Examination Pilot Plant (SWEPP) Gamma Ray Spectrometer (SGRS) Systems in absolute mode. The audit also evaluated the NDA assay of category groups S3000 homogeneous solidified organic waste streams using the Passive-Active Neutron (PAN) system in combination with the WAGS system and in combination with the SGRS system. Concurrent with the evaluation of the new NDA systems, an evaluation was conducted of the Data Review Expert System (DRXS) for NDA validation and INEEL's software QA program as they are implemented for the NDA platforms in use at INEEL.	S	S	S
				Overall, the INEEL technical and QA procedures were adequate relative to the requirements of the CBFO QAPD and WAC. The defined software QA program implemented for the NDA platforms, the SGRS and WAGS Absolute Systems, the PAN/WAGS and PAN/SGRS systems, and the DRXS were satisfactorily implemented and effective.		
INEEL	S-02-17	5/21-22/02	The INEEL recovery option of standard waste box (SWB) blending activities as applied to the payload assembly, certification, and loading process, and the TRIPS and WIPP Waste Information System (WWIS) Interface for this option.	S	S	S
				The blending methods and payload assembly, certification, and loading processes utilized were adequate, satisfactory implemented, and effective.		
INEEL	A-02-27	8/5-9/02	The INEEL Transuranic Waste Characterization, Certification, and Transportation Programs, including the following activities: Transportation, HSG sampling and analysis, VE, RTR, NDA of CH-TRU debris and organic and inorganic homogeneous solid waste, and overpacking activities associated with the SWBs.	S	S	S
				The INEEL technical and QA procedures continue to be adequate relative to the flow down of requirements from the CBFO QAPD, WIPP WAP, WAC, and TRAMPAC. The defined QA Program continued to be satisfactorily implemented in accordance with the INEEL QAPP and implementing procedures. The INEEL technical areas evaluated continue to be satisfactorily implemented and remain effective.		

Table AUD-6. Idaho National Engineering and Environmental Laboratory (INEEL) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
INEEL	S-03-01	1/28-29/03	The INEEL characterization and certification activities for the period between audit A-02-27 (August 5-9, 2002) and the last shipment of TRU waste to WIPP (October 21, 2002), 3100 m^3 project closeout activities including records disposition and turnover activities, preparation and turnover of applicable software programs for continued access and use, and the disposition and turnover of acceptable knowledge records for waste that is to be transferred to the Advanced Mixed Waste Treatment Project (AMWTP).	S	S	S
				All activities evaluated are adequate, satisfactorily implemented, and effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-7. Washington TRU Solutions (WTS) Audits

NOTE: The M&OC had three different names during this time period. Up to January 2001, the M&OC was Westinghouse Waste Isolation Division (WID). From January 2001 through January 2003, the M&OC was Westinghouse TRU Solutions (WTS). From January 2003 to present, the M&OC has been Washington TRU Solutions (WTS). These names are reflected, as appropriate, in this table.

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
Westinghouse Waste Isolation Division (WID)	A-99-14	6/28-7/2/99	Evaluate the WID QA and technical programs.	S	S	S
				The audit team concluded that the technical and QA processes were adequate, satisfactorily implemented, and effective.		
WID	A-99-11	2/15-19/99	Evaluate the WID Self-Assessment Program.	S	S	S
				The WTS Self-Assessment Program was adequate, satisfactorily implemented, and effective.		
WID	S-00-03	3/13-15/00	The WID procedures and work processes related to the WWIS and WID compliance with the recently issued HWFP.	S	S	M
				The WID procedures related to the WWIS were adequate and implemented. The effectiveness of the WID QA program elements associated with the WWIS were rated as marginal due to inconsistencies identified during the surveillance.		
WID	A-00-14	8/7-8/00	The WTS QA program activities.	S	S	S
				The QA programs were adequate, satisfactorily implemented, and effective.		
Westinghouse TRU Solutions (WTS)	S-01-07	2/12-13/01	The WTS WIPP Coring Operations procedure.	S	S	S
				Current programmatic and procedural requirements relative to core storage, handling, and distribution processes were adequate, satisfactorily implemented, and effective.		
WTS	S-01-08	3/5/01	The WTS WIPP groundwater level measurement program.	S	S	S
				The procedures were adequate, satisfactorily implemented, and effective.		
WTS	S-01-12	3/19-21/01	Software used for Intranet security purposes and the process used for posting CBFO controlled documents on the Intranet and Internet.	S	S	S
				With one exception, the purchase and control of software was adequate, satisfactorily implemented, and effective.		

Table AUD-7. Washington TRU Solutions (WTS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
WTS	A-01-13	5/7-11/01	Verify continued implementation of the QA requirements in CBFO and WTS QAPDs – Sections 1 and 2, and applicable NQA-1 elements and implementing procedures.	M	M	M
				The WTS QA procedures were marginally adequate relative to the flow down of requirements from the CBFO QAPD. The audit team also concluded that the CBFO quality requirements contained within the CBFO QAPD Sections 1 and 2 were being marginally implemented through the WTS QAPD and WTS implementing procedures and the processes were marginally effective.		
WTS	S-01-14	8/13-16/01	The WIPP site's compliance with the requirements of the National Pollutant Discharge Elimination System (NPDES) Multi-Sector General Permit (MSGP).	S	S	S
				The design, operation, and maintenance of the WIPP storm water management system at the facility was outstanding and the Best Management Practices (BMPs) were satisfactorily implemented and effective.		
WTS	A-01-18	7/30-8/2/01	The QA requirements in the CBFO and WTS QAPDs – Sections 3 and 4, applicable NQA-1 elements and implementing procedures.	M	M	M
				The WTS QA procedures were marginally adequate relative to the CBFO QAPD. The CBFO quality requirements contained within the CBFO QAPD Sections 3 and 4 were being marginally implemented through the WTS QAPD and the WTS implementing procedures. The processes were marginally effective.		
WTS	A-02-08	10/1-10/01	The WTS conduct of operations program.	S	S	S
				Overall, the conduct of operations program was adequate in accordance with the applicable WTS implementing procedures. The WTS conduct of operations were satisfactorily implemented and effective.		
WTS	A-02-02	11/27-30/01	Continued implementation of the software QA requirements defined in the CBFO and WTS QAPDs, Section 6, and the applicable WTS implementing procedures.	M	S	S
				The WTS software QA procedures are marginally adequate relative to the flow-down of requirements from the CBFO QAPD. The CBFO quality requirements contained within the CBFO QAPD Section 6 are being satisfactorily implemented through the WTS QAPD and WTS implementing procedures. The processes are effective.		

Table AUD-7. Washington TRU Solutions (WTS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation		Effectiveness
S (Centralized Procurement Program)	A-02-10	11/6-8/01	The WTS QAPD pertaining to the Centralized Procurement Program. (Joint audit by INEEL and Hanford site auditors.)	Supplier Evaluation	S	S	I
				CBFO Supplemental Audit	M	M	I
				Verification of CAR 01-028	S	S	S
				See specific area above (Supplier Evaluation, CBFO Supplemental Audit, and Verification of CAR 01-028).			
WTS	S-02-19	3/26/02	Verify corrective actions and assess the adequacy of the WTS implementing procedures and updated WTS QA Procedures Matrix for compliance with the applicable portions of the CBFO QAPD. (Closeout of open items from Audits A-01-13, A-01-18, and A-02-02.)	S	N/A		N/A
				The procedures currently implemented by WTS and the updated WTS Matrix adequately address and meet applicable elements of the CBFO QAPD.			
WTS	A-02-24	5/20-21/02	The WTS QAPD requirements in accordance with the CBFO QAPD and ASME/NQA-1, 1989, Criteria 1, 2 and 3. (Included Sections 1.1, 1.2, 1.3, 2.2, 3.1 and 3.2 and the associated implementing procedures.)	S	S		S
				Overall, the WTS QA program is adequate relative to the flow-down of requirements from the CBFO QAPD and ASME/NQA-1 Criteria 1, 2, and 3. Implementation is satisfactory and the program is effective. Corrective action continues to be effective for CARs previously identified.			
WTS	A-02-25	7/9-12/02	The WTS QAPD requirements in accordance with the CBFO QAPD and ASME NQA-1, Criteria 4, 5, 7, 8, 9, and 13. Sections 2.1 and 2.3 of the WTS QAPD were also evaluated.	S	S		S
				Overall, the WTS QA program is adequate relative to the flow-down of requirements from the CBFO QAPD and NQA-1 Criteria. The implementing procedures are satisfactorily implemented and are effective. The corrective actions continue to be effective for CARs previously generated.			
WTS	S-02-23	7/23-24/02	The WTS software configuration management, software change control, software life cycle documentation, and data entry for container overpacking activities for the WWIS.	S	S		S
				All audited processes are adequate, satisfactorily implemented, and effective.			

Table AUD-7. Washington TRU Solutions (WTS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
WTS	A-03-06	11/12-15/02	The WTS QAPD requirements in accordance with the CBFO QAPD and NQA-1, Criteria 10, 11, 12, 14, and QAPD Section 4. Sections 2.4.1, 2.4.2, 2.4.3, and 2.1.3.B.5 were also evaluated.	S	S	S
				Overall, the WTS QA program is adequate relative to the flow-down of requirements from the CBFO QAPD. The implementing procedures are satisfactorily implemented and are effective. The corrective actions continue to be effective for CARs previously generated.		
Washington TRU Solutions (WTS)	A-03-10	1/13-16/03	The WTS QAPD requirements in accordance with NQA-1, Criteria 6, 15, 16, 17, and 18, the CBFO QAPD, and TRAMPAC (WTS QAPD Sections 1.3, 1.4, 1.5, 3, and 6).	S	S	S
				Overall, the WTS QA program is adequate relative to the flow-down of requirements from the CBFO QAPD to the WTS QAPD and implementing procedures. The implementing procedures are satisfactorily implemented and are effective. Corrective actions continue to be effective for previously generated CARs, except in the area of nonconforming items.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-8. Sandia National Laboratories (SNL) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
Sandia National Laboratories (SNL)	S-99-07	2/23-25/99	The SNL document control program.	S	S	S
				The document control program was adequate, satisfactorily implemented, and effective.		
SNL	A-00-01	11/8-11/00	The SNL QA program requirements implementation.	S	S	S
				The SNL QA program was adequate, satisfactorily implemented, and effective.		
SNL	A-01-04	11/27-12/1/00	The SNL technical and QA activities.	S	M	M
				The QA program was adequate; however, implementation and effectiveness were marginal. The areas of performance assessment, parameters, and sensitivity analysis were determined to be marginal. Software QA was inadequate and the implementation and effectiveness unsatisfactory.		
SNL	A-02-01	10/29-11/2/01	The SNL QA program for WIPP activities in accordance with the CBFO QAPD, Revision 3. Scope included a technical review of performance assessment (PA), sensitivity analysis, parameters, software QA activities, and an evaluation of the effectiveness of corrective actions implemented for conditions adverse to quality identified during the previous audit (A-00-01).	S	M	S
				The SNL QA program for WIPP remains adequate and effective; however, implementation was considered to be marginal.		
SNL-C	S-02-11	3/19-20/02	The SNL-WIPP Geologic Core management activities, including evaluation of controls for the SNL-WIPP Geologic Core stored in the WIPP underground located in Q Room Access Drift (W700), and geologic cores transferred and maintained at SNL's analytical laboratories in Carlsbad.	S	S	S
				Current procedures relative to core identification, storage, handling, custody, distribution, and records controls are adequately defined, satisfactorily implemented, and effective.		
SNL-C	A-03-11	11/4-7/02	The SNL Nuclear Waste Management Program (NWMP) QA Program for the WIPP. Evaluation included a technical review of PA, sensitivity analysis, parameters, and software QA activities.	S	S	S
				The SNL QA program for the WIPP remains adequate, satisfactorily implemented, and effective.		

Table AUD-8. Sandia National Laboratories (SNL) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
SNL-C	S-03-09	2/4-5/03	The Compliance Recertification Application (CRA) activities of SNL, Carlsbad, New Mexico.	S	S	S
				SNL's activities pertaining to the CRA activities are adequate, satisfactorily implemented, and effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-9. Savannah River Site (SRS) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
Savannah River Site (SRS)	S-01-32	7/19-20/01	The SRS QA and technical program related to the Document Control program and TRU waste characterization activities.	S	S	S
				The QA program requirements related to the activities evaluated were adequate, satisfactorily implemented, and effective.		
SRS	A-02-06	12/10-14/01	The SRS TRU waste characterization activities relative to the requirements detailed in the WIPP HWFP and the CBFO QAPD.	S	S	S
				The overall adequacy of the SRS technical and QA programs, as applicable to audited activities, was satisfactory in meeting requirements, and the procedures and processes were satisfactorily implemented and effective.		
SRS	A-02-20	3/13-14/02	The TRU waste characterization activities for new HSG sampling and analysis systems and processes.	S	S	S
				The overall SRS technical and QA programs, as applicable to compositing with the currently certified HSG analysis equipment and the new canister cleaning station, were adequate and satisfactory in meeting requirements, and the procedures and processes were satisfactorily implemented and effective.		
SRS	S-02-20	7/1/02	The Acceptable Knowledge (AK) process at the SRS. Examined the characterization of contact-handled debris waste (Summary Category Group S5000) training, AK reporting, control of discrepancies and confirmation.	S	S	S
				SRS AK process is adequate and satisfactorily implementing procedural requirements and the AK process continues to be satisfactorily implemented and effective.		
SRS (CCP)	A-02-09	10/15-19/01	The Central Characterization Program (CCP) characterization and certification activities; technical and QA related to Summary Category Group S5000 (debris waste).	S	S	S
				The CCP technical and QA procedures were adequate relative to the CBFO QAPD, the WAP of the WIPP HWFP, and the WAC of the WIPP. Assessed activities were being implemented in accordance with the CCP QAPP and implementing procedures. The established technical processes and the QA program were effective.		
SRS (CCP)	A-03-01	10/22-25/02	The TRU waste characterization activities performed by the CCP.	S	S	S
				The evaluation procedures and programs were adequate and met requirements. The defined QA and technical programs for these activities were being satisfactorily implemented, and the implementing procedures and processes were effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) – Indeterminate

Table AUD-10. Carlsbad Field Office (CBFO) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
DOE Carlsbad Field Office (CBFO)	A-00-04	4/24-28/00	Internal QA audit by DOE/Headquarters of CBFO.	S	S	S
				The QA program was adequate, satisfactorily implemented, and effective.		
CBFO	A-01-15	4/30-5/4/01	Internal QA audit of CBFO by DOE/Headquarters.	S	S	S
				The CBFO implementation of DOE 414.1A into the QA program was adequate, satisfactorily implemented, and effective.		
CBFO	S-01-20	7/24-25/01	The CBFO observation process.	M	M	S
				The observation process was effective, but marginally implemented and marginally adequate. Corrective action reports have all been completed and closed.		
CBFO	S-03-08	2/10-13/03	Activities within the Office of Program Support.	S	U	U
				The QA program was adequate but it was not being satisfactorily implemented and was not effective. Corrective action is being taken through the CAR system.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-11. Carlsbad Field Office (CBFO) Supplier Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
Carlsbad Field Office Technical Assistance Contractor (CTAC) (Portage Environmental)	A-02-11	1/21-24/02 and 1/29-31/02	The WIPP Performance Demonstration Program (PDP) activities. Verify compliance to the requirements detailed in the WIPP HWFP and the QAPD.	S	S	S
				The QA and technical activities of the PDP were adequate, satisfactorily implemented, and effective. Programmatic direction and oversight activities by the DOE/CBFO and CTAC, as specified in the PDP plans and implementing procedures, were adequate, satisfactorily implemented, and effective.		
Carlsbad Field Office Technical Assistance Contractor (CTAC) (Portage Environmental)	A-02-22	4/16, 17/02 and 4/29/02	The WIPP Performance Demonstration Program (PDP) for Nondestructive Assay. Verify compliance to the requirements detailed in the WIPP HWFP and the QAPD for drummed and boxed waste.	S	S	S
				The PDP NDA activities evaluated from PDP NDA Cycles 6 through 8 were adequate, satisfactorily implemented, and effective.		
Argonne National Laboratory East (ANL-E)	S-01-15	7/10-11/01	The Argonne National Laboratory (ANL-E) technical support activities for the preparation of samples needed to support the WIPP HSG PDP.	S	S	S
				The HSG PDP activities were adequate, satisfactorily implemented, and effective. The implementing procedures and activities for sample preparation, verification, and distribution were also adequate, satisfactorily implemented, and effective.		
ANL-E/CCP	A-02-03 and A-03-13	9/9-13/02 and 2/10-13/03	The ANL-E/CCP TRU waste characterization and certification activities related to Summary Category Groups S5000 (debris waste) and S3000 (homogeneous solid waste). Previous audit assessed the technical and QA activities and the characterization of homogeneous solid waste activities.	S	S	S
				The ANL-E/CCP technical and QA programs met the requirements contained in the HWFP. The deficiencies identified in previous CARs have been corrected. The QA and technical processes are adequate and are being implemented in accordance with the CCP Transuranic Waste QAPP and the associated implementing procedures. The processes were also found to be effective.		
Battelle Columbus Lab (BCL)	A-99-15	5/6-7/99	The BCL Decommissioning Project (BCLDP) TRU Waste AK activities.	N/A	U	U
				The procedures related to AK were not implemented and the evaluated processes were ineffective.		
BCL	S-01-37	7/28-30/01	Assess the implementation of the BCLDP AK program as it applies to selected waste attributes.	S	S	S
				Battelle has established a program that can quantify these waste attributes.		

Table AUD-11. Carlsbad Field Office (CBFO) Supplier Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
Mobile Characterization Services, LLC (MCS)	A-99-18	6/7-11/99	The QA processes related to the MCS TRU waste characterization and certification activities.	S	S	S
				The QA and technical programs were adequate, satisfactorily implemented, and effective.		
Carlsbad Environmental Monitoring and Research Center (CEMRC)	A-03-09	12/10-13/02	Audit A-03-09 was conducted to qualify the Carlsbad Environmental Monitoring and Research Center (CEMRC) QA program for quality-affecting activities for the WIPP. CEMRC may provide actinide chemistry support in the future.	M	M	M
				The CEMRC QA program for quality-affecting activities for the WIPP was marginally inadequate, implemented, and effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix BARRIERS

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix BARRIERS

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ACRONYMS AND ABBREVIATIONS

AISC	American Institute of Steel Construction
AISinR	a synthetic brine representative of fluids sampled from the Culebra Member of the Rustler Formation in the WIPP Air Intake Shaft
alumina	Al_2O_3
aq	aqueous
ASTM	American Society for Testing Materials
atm	atmosphere(s)
BLM	Bureau of Land Management
BRAGFLO	Brine and Gas Flow
brucite	$Mg(OH_2)$
ºC	degrees Celsius
calcite	$CaCO_3$
CCA	(WIPP) Compliance Certification Application
CPR	cellulosic, plastic, and rubber (materials)
CRA	(WIPP) Compliance Recertification Application
DI	deionized (water)
DOE	(U.S.) Department of Energy
DRZ	Disturbed Rock Zone
EPA	(U.S.) Environmental Protection Agency
EQ3/6	a geochemical software package for speciation and solubility calculations (EQ3NR) and reaction-path calculations (EQ6)
ERDA-6	Energy Research and Development Administration (WIPP Well) 6, a synthetic brine representative of fluids in Castile-Formation brine reservoirs
f_{CO_2}	fugacity (similar to the partial pressure) of CO_2
FMT	Fracture-Matrix Transport, a geochemical speciation and solubility code
forsterite	Mg_2SiO_4
ft	foot (feet)
g	gaseous or gram(s)
G Seep	a naturally occurring brine collected from G Drift in the WIPP underground
gal	gallon(s)
GWB	Generic Weep Brine, a synthetic brine representative of intergranular Salado-Formation brines
H-17	a synthetic brine representative of brine from the Culebra at the WIPP H-17 Hydropad
halite	NaCl
hydromagnesite	$Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O$ or $Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$
in.	inch(es)
K_d	distribution coefficient
kg	kilogram(s)
km	kilometer(s)
L	liter(s)
lb	pound(s)
lime	CaO
m	meter(s)

M	molar
magnesite	$MgCO_3$
mL	milliliters
mm	millimeter
µm	micrometer(s)
mol	mole(s)
monticellite	$CaMgSiO_4$
MSHA	Mine Safety and Health Administration
nesquehonite	$MgCO_3 \cdot 3H_2O$
nm	nanometer(s)
PA	performance assessment
PAVT	(WIPP) Performance Assessment Verification Test
periclase	pure, crystalline magnesium oxide, the primary constituent of the WIPP engineered barrier
pH	the negative, common logarithm of the activity of hydrogen ion
portlandite	$Ca(OH)_2$
RCRA	Resource Conservation and Recovery Act
RH	relative humidity or remote-handled (TRU waste)
s	second(s)
silica	SiO_2
SMC	Salado Mass Concrete
SPC	Salado Primary Constituents, a synthetic brine similar to Brine A
spinel	$MgAl_2O_4$
SWB	standard waste box
TDOP	ten-drum overpack
TRU	transuranic (waste)
ulvöspinel	$Ti(Fe,Mg)_2O_4$
WIPP	(U.S. DOE) Waste Isolation Pilot Plant
wt	weight
WTS	Westinghouse TRU Solutions
VOC	volatile organic compound
XRD	X-ray diffraction

BARRIERS-1.0 INTRODUCTION

BARRIERS-1.1 Purpose and Objectives

Appendix BARRIERS to the Waste Isolation Pilot Plant (WIPP) Compliance Recertification Application (2004) consolidates the information pertaining to engineered and disposal system barriers related to the WIPP repository. In the initial Compliance Certification Application (CCA) (DOE 1996a), this information was contained in Appendices BACK, EBS, PCS, and SEAL.

This appendix documents how the WIPP satisfies the Environmental Protection Agency (EPA) assurance requirement to provide different types of barriers to isolate the waste from the accessible environment as required by Title 40 Code of Federal Regulations (CFR) § 191.14(d) (EPA 1993). The EPA's Certification Criteria also required the Department of Energy (DOE) to conduct a benefit and detriment study (40 CFR § 194.44) when considering engineered barrier alternatives. The CCA documented this study in Appendix EBS and is included by reference.

BARRIERS-1.2 Background

To address the requirements of 40 CFR 194.44, the DOE performed an Engineered Alternatives Cost/Benefit Study (see CCA Appendix EBS) to examine the benefits and detriments associated with an array of engineered barrier alternatives. Based on the results of these studies and the existing repository design, the DOE proposed four engineered barriers in the CCA: shaft seals, panel closures, magnesium oxide (MgO), and borehole plugs.

In Docket A-93-02 Item V-B-2, Compliance Application Review Document No. 44, the EPA states:

> "EPA reviewed the information contained in the CCA and agreed that the emplacement of MgO in waste panels of the WIPP may be expected to substantially delay the movement of water or radionuclides…For compliance with this requirement, EPA did not evaluate panel seals, shaft seals or borehole plugs. EPA considered these items to be features of the disposal system design and evaluated them in that context."

In the final certification decision for WIPP (63 FR 27397) (EPA 1998a) the EPA concluded:

> "The EPA finds that DOE complies with § 194.44. The EPA found that DOE conducted the requisite analysis of engineered barriers and selected an engineered barrier designed to prevent or substantially delay the movement of water or radionuclides toward the accessible environment. The DOE provided sufficient documentation to show that MgO can effectively reduce actinide solubility in the disposal system. The DOE proposed to emplace a large amount of MgO around waste drums in order to provide additional factor of safety and thus account for uncertainties in the geochemical conditions that would affect CO_2 generation and MgO reactions."

The EPA determined that MgO met the regulatory definition of an engineered barrier. The other three systems proposed as engineered barriers by the DOE were viewed by the EPA as part of the disposal system design. For completeness, this appendix describes both the MgO engineered barrier and the other barriers used by the DOE in the repository design which are not considered to meet the regulatory assurance requirement.

BARRIERS-2.0 ENGINEERED BARRIER

BARRIERS-2.1 Introduction

The DOE is emplacing MgO in the disposal system. The effect of MgO in the disposal system will be to decrease the solubilities of the actinide elements in transuranic (TRU) waste in any brine present in the repository after closure. MgO will decrease actinide solubilities by consuming essentially all carbon dioxide (CO_2) that would be produced by microbial activity-should all cellulosic, plastic, and rubber (CPR) materials in TRU waste and the waste containers be consumed. Although MgO will consume essentially all CO_2, minute quantities (relative to the quantity that would be produced by microbial consumption of all CPR materials) will persist in the aqueous and gaseous phases. The residual quantity will be so small relative to the initial quantity that the adverb "essentially" is omitted hereafter in this appendix. Consumption of CO_2 will prevent the acidification of brine or the production of significant quantities of carbonate ion (CO_3^{2-}), which could increase actinide solubilities.

The effects of MgO carbonation (consumption of CO_2) were included in the CCA performance assessment (PA) and the recertification PA by assuming there is no CO_2 in the disposal system. This assumption is included in PA by (1) removing CO_2 from the gaseous phase in Brine and Gas Flow (BRAGFLO) calculations, thereby reducing somewhat the predicted pressurization of the repository (see Appendix PA, Section PA-4.2); and (2) using the values of f_{CO_2} and pH established by reactions among MgO, brine, and aqueous or gaseous CO_2 to calculate actinide solubilities (see Appendix PA, Attachment SOTERM).

Although the hydration of MgO will remove water (H_2O) from the repository, MgO hydration is not included in PA. Not including MgO hydration in PA is considered a conservative assumption.

In this appendix, "MgO" refers to the bulk, granular material being emplaced in the WIPP to serve as the engineered barrier. MgO comprises periclase (pure, crystalline MgO - the main, reactive constituent of the WIPP engineered barrier) and various impurities (see Section 2.5.1 of this appendix). Pure, crystalline MgO is always referred to as periclase in this appendix. The term "periclase" and other mineral names used herein are, strictly speaking, restricted to naturally occurring forms of the materials that meet all other requirements of the definition of a mineral (see, for example, Bates and Jackson 1984). However, mineral names are used for convenience in this appendix.

BARRIERS-2.2 Description of the Waste Isolation Pilot Plant Engineered-Barrier System

The DOE is emplacing MgO in polypropylene "supersacks" on top of the stacks of three seven-packs of 55-gal (208-L) drums, three standard waste boxes (SWBs), or various combinations of these and other waste containers. Other such containers include ten-drum overpacks (TDOPs), four-packs of 85-gal (321-L) drums, and three-packs of 100-gal (379-L) drums (see Appendix DATA, Attachment H). Each supersack contains 4200 ± 50 lb (1905 ± 23 kg) of MgO (WTS 2003).

Emplacement of MgO in supersacks: (1) facilitates handling and emplacement of MgO; (2) minimizes potential worker exposure to dust; and (3) minimizes the exposure of periclase, the main, reactive constituent of MgO, to atmospheric CO_2 and H_2O during handling and emplacement, and prior to panel closure. WTS (2003) provides detailed specifications for the supersacks. In particular, WTS (2003) specifies that the supersacks "shall provide a barrier to atmospheric moisture and carbon dioxide (CO_2) … equivalent to or better than that provided by a standard commercial cement bag" and "must be able to retain [their] contents for a period of two years after emplacement without rupturing from [their] own weight." The specifications also require a certificate of compliance with all requirements of WTS (2003) for every shipment of MgO (see next paragraph), and a certified chemical analysis of each new lot of MgO. The supersacks are subject to random receipt inspection at the WIPP to ensure compliance with the dimensions and labeling specified by WTS (2003), and to identify any shipping damage.

The supersacks contain dry, granular MgO, of which less than 0.5 percent can exceed 3/8 in. (9.5 mm) in diameter (WTS 2003). Emplacement of granular MgO instead of powder (1) results in a bulk density high enough that sufficient MgO can be emplaced without causing major operational difficulties, (2) reduces the likelihood of formation and release of dust in the event of premature rupture of a supersack, and (3) ensures that the permeability of the material is high enough to promote complete reaction with aqueous or gaseous CO_2.

Creep closure of WIPP disposal rooms will rupture the supersacks and disperse the MgO among and within the ruptured waste containers. This will in turn expose the MgO to the room atmosphere, to any CO_2 produced by microbial consumption of CPR materials, and to H_2O vapor and any brine present.

BARRIERS-2.2.1 Changes in MgO Emplacement since the CCA

Two changes have occurred in MgO emplacement since the CCA, a new supplier was needed for the bulk MgO and operational concerns necessitated the elimination of the minisacks.

National Magnesia Chemicals provided the MgO emplaced in the WIPP from 1999 through 2000. After National Magnesia Chemicals stopped producing MgO, Premier Chemicals in Gabbs, Nevada, was selected as the supplier. Premier MgO was selected based on cost and a technical evaluation verifying its suitability as the engineered barrier (Papenguth 1999). The technical evaluation included a reactivity test developed by Krumhansl et al. (1997). Premier Chemicals has supplied MgO since 2000.

Initially, MgO was emplaced in both supersacks and minisacks. The 25-pound minisacks were emplaced among the waste containers and between the waste containers and the ribs (sides) of the disposal rooms (see CCA Chapter 3). In 2000, however, the DOE requested EPA approval of the elimination of the minisacks (see Triay 2000); the EPA approved this request in 2001 (EPA 2001a).

BARRIERS-2.3 Backfill Conceptual Model

The function of backfill is included in the chemical conditions conceptual model. MgO will create conditions in the repository that decrease actinide solubilities. These lower solubilities are

a result of the consumption of CO_2 produced by microbial consumption of CPR materials and by buffering $f_{CO_2}$and pH in the disposal system. In the model, MgO will initially hydrate by reacting with any brine present in the repository to form brucite:

$$MgO + H_2O(aq \text{ or } g) \rightleftharpoons Mg(OH)_2. \quad (1)$$

Brucite dissolution is expected to buffer brine by:

$$Mg(OH)_2 \rightleftharpoons Mg^{2+} + 2OH^-, \quad (2)$$

CO_2 in the system will initially react with brucite to form metastable phases including hydrogagnesite:

$$5Mg(OH)_2 + 4CO_2(aq \text{ or } g) \rightleftharpoons Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O, \quad (3)$$

or:

$$4Mg(OH)_2 + 3CO_2(aq \text{ or } g) \rightleftharpoons Mg_4(CO_3)_3(OH)_2{\cdot}3H_2O, \quad (4)$$

and nesquehonite:

$$Mg(OH) + 2H_2O + CO_2(aq \text{ or } g) \rightleftharpoons MgCO_3\ 3H_2O, \quad (5)$$

The DOE believes that hydromagnesite, the most likely metastable phase, and nesquehonite, another possible metastable phase, will dehydrate to form magnesite (MgCO3), the stable carbonate, in the event of microbial activity:

$$Mg_5(CO_3)_4(OH)_2\ 4H_2O + CO_2(aq \text{ or } g) \rightleftharpoons 5MgCO_3 + 5H_2O, \quad (6)$$

EPA summarized the chemical conditions conceptual model in their TSD for 194.24 (Docket A-93-02, V-B-17; EPA 1998d):

> "Based on the above discussion, the sequence of events resulting from brine infiltration and reaction with the MgO backfill in the repository may be conceptualized by the following reactions, in order:
>
> 1. Rapid reaction (hours to days) between the brine and MgO to produce brucite.
> 2. Rapid carbonation (hours to days) of the brucite to produce nesquehonite and possibly hydromagnesite.
> 3. Rapid conversion (days to weeks) of the nesquehonite to hydromagnesite.
> 4. Slow conversion (hundreds to thousands of years) of the hydromagnesite to magnesite.

> The available rate data indicate that some portion, perhaps all, of the hydromagnesite will be converted to magnesite over the 10,000-year period for repository performance. The exact time required for complete conversion has not been established for all chemical conditions. However, the available laboratory and field data clearly indicate that magnesite formation takes from few hundred to, perhaps, a few thousand years. Thus, the early repository conditions can be best represented by the equilibrium between brucite and hydromagnesite. These conditions will eventually evolve to equilibrium between brucite and magnesite."

For the 2004 Compliance Recertification Application (CRA-2004), DOE has adopted the approach EPA used in the 1997 Performance Assessment Verification Test (PAVT). The DOE assumes for its actinide-solubility calculations that the metastable brucite-hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) carbonation reaction will buffer f_{CO_2}. However, in the long-term, the brucite-magnesite carbonation reaction will buffer f_{CO_2}.

BARRIERS-2.4 Predictions of the Effects of Magnesium Oxide

The following sections discuss the effects of MgO on the disposal system. The predicted effects used in the CCA and the effects now included in the CRA are discussed.

BARRIERS-2.4.1 Previous Predictions of the Effects of Magnesium Oxide

Novak et al. (1996) and CCA Appendix BACK concluded that magnesite will be the dominant Mg carbonate in the repository during the 10,000-year regulatory period, and that the brucite-magnesite carbonation reaction,

$$Mg(OH)_2 + CO_2(\text{aq or g}) \rightleftharpoons MgCO_3 + H_2O(\text{aq or g}), \qquad (7)$$

will buffer f_{CO_2} in the WIPP whether or not significant microbial CO_2 production occurs. Novak et al. (1996) calculated actinide solubilities for the CCA PA. They did not report f_{CO_2}, but the EPA (1998d, Tables 4-6 and 4-7) reported a value of $10^{-6.89}$ atm for both Salado Primary Constituents (SPC[1]) and Energy Research and Development Administration (WIPP Well) 6 (ERDA-6[2]) brines in equilibrium with brucite and magnesite. This value of f_{CO_2} was used for the actinide-speciation and -solubility calculations for all CCA PA vectors (both with and without microbial activity). (Other minerals, such as halite and anhydrite, were also present.) Novak et al. (1996) used the brucite dissolution reaction (see Reaction (2), above) to buffer the pH in their actinide-solubility calculations, but did not report their results. The EPA (EPA 1998d, Tables 4-6 and 4-7) reported pH values of 8.69 and 9.24 for SPC and ERDA-6, respectively, in equilibrium with the mineral assemblages provided above. These values of pH were used for the solubility calculations for all CCA PA vectors.

1 SPC is similar to Brine A, another synthetic fluid that has been used to represent intergranular Salado brines (molecke 1983).
2 ERDA-6 is a synthetic brine representative of fluids in brine reservoirs in the Castile Formation (Popielak et al. 1983)

For the 1997 PAVT, the EPA specified that the brucite-hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) carbonation reaction (see Reaction (3), above) will buffer f_{CO_2} in the WIPP whether or not significant microbial CO_2 production occurs. The EPA (1998b, Tables 4.10-3 and 4.10-4; 1998d, Tables 4-8 and 4-9) reported a value of $10^{-5.50}$ atm for both SPC and ERDA-6 in equilibrium with brucite and hydromagnesite. This value of f_{CO_2} was used for the actinide-solubility calculations for all 1997 PAVT vectors (both with and without microbial activity; other minerals, such as halite and anhydrite, were also present). The EPA (1998b, Tables 4.10-3 and 4.10-4; 1998d, Tables 4-8 and 4-9) reported pH values of 8.69 and 9.24 for SPC and ERDA-6, respectively, in equilibrium with the mineral assemblages provided above. These pH values were used for the solubility calculations for all 1997 PAVT vectors.

*BARRIERS-2.4.2 Current Predictions of the Effects of Magnesium Oxid*e

The following sections describe the implementation of the chemical conditions conceptual model in the CRA-2004 PA. Specifically, the effects of MgO hydration and carbonation are discussed along with discussions of MgO's buffering ability and potential impacts on other significant chemical processes included in the CRA-2004 PA.

BARRIERS-2.4.2.1 Effects of Magnesium Oxide Hydration and Carbonation

The most important effect of MgO modeled in PA is its ability to sequester CO_2 and buffer f_{CO_2}. The PA includes the impacts of MgO on two elements relating to gas generation and actinide solubilities. With respect to gas generation, PA assumes there is no CO_2 in the disposal system for vectors with microbial activity. For MgO's effect on actinide solubilities, the CRA-2004 PA, Brush and Xiong (2003b) determined the log f_{CO_2} and pH for use in PA solubility calculations. Table BARRIERS-2 compares the values of log f_{CO_2} and pH calculated for the CRA-2004 PA solubility calculations by Brush and Xiong (2003b) with those calculated for the CCA PA and the 1997 PAVT. Table BARRIERS-2 shows that, despite modest differences in the predicted values of log f_{CO_2} and pH, reactions among brine, CO_2, and MgO will consume essentially all CO_2 that could be produced in the repository, buffer f_{CO_2} within a range of about 10^{-5} to 10^{-6} atm (or about 10^{-7} atm if significant quantities of magnesite form), and buffer the pH at about 9.

Table BARRIERS-1. Comparison of Log f_{CO_2} and pH Calculated for the CRA-2004 PA, the 1997 PAVT, and the CCA PA[1,2,3]

Property and Brine	CRA,[1] Microbial Vectors	CRA,[1] Nonmicrobial Vectors	1997 PAVT,[3] All Vectors	CCA,[2] All Vectors
Log f_{CO_2}, Salado Brine	-5.50	-5.48	-5.50	-6.9
Log f_{CO_2}, Castile Brine	-5.50	-6.15	-5.50	-6.9
pH, Salado Brine	8.69	8.69	8.69	8.69
pH, Castile Brine	9.02	8.99	9.24	9.24

[1] From Brush and Xiong (2003b). See text for details.
[2] From Novak et al. (1996) and EPA (1998c). See text for details.
[3] From EPA (1998b, 1998c). See text for details.

These values of f_{CO_2} are significantly lower than those anticipated in the absence of MgO (see CCA Appendix SOTERM, Figures SOTERM-1 and SOTERM-2).

BARRIERS-2.4.2.2 Effects of Magnesium Oxide in the Event of Significant Microbial Activity

The DOE is emplacing significantly more MgO than would be required to sequester the CO_2 that could be produced by microbial consumption of all CPR materials in the WIPP (see Section 2.6 of this appendix). Therefore, both brucite and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$), or brucite, a Mg-Cl-OH-H_2O phase, and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$), will be present in the repository even if all CPR materials are consumed; and these solids will buffer f_{CO_2} (see Reaction (2), above). In this and other reactions used for thermodynamic calculations, it has been assumed that the effects of possible substitution of Fe(II) for Mg in Mg-bearing solids such as brucite and hydromagnesite are insignificant. Brush and Xiong (2003a, 2003b) used equilibria among Generic Weep Brine (GWB[3]), brucite, $Mg_2Cl(OH)_3{\cdot}4H_2O$, and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$), or among ERDA-6, brucite, and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$), to buffer f_{CO_2} for the actinide-speciation and -solubility calculations for the CRA-2004 PA vectors with microbial activity. Brush and Xiong (2003b, Table 6) reported a value of $10^{-5.50}$ atm for f_{CO_2} for both GWB and ERDA-6 and the mineral assemblages provided above. Other minerals, such as halite (NaCl) and anhydrite ($CaSO_4$), were also present in these mineral assemblages, but are not reactants or products of the carbonation reaction(s) that buffer f_{CO_2}.

The brucite dissolution reaction (see Reaction (2) above), will buffer pH in the WIPP in the event of significant microbial activity. Brush and Xiong (2003b, Table 6) reported a pH value of 8.69 for GWB and 9.02 for ERDA-6.

These values of f_{CO_2} and pH were used for the actinide-speciation and -solubility calculations for the CRA-2004 PA vectors with significant microbial activity (see Appendix PA, Attachment SOTERM, Section SOTERM-3.0).

BARRIERS-2.4.2.3 Effects of Magnesium Oxide in the Absence of Significant Microbial Activity

Brush and Xiong (2003a) redefined the reaction that will buffer f_{CO_2} for those PA vectors without microbial activity. Brush and Xiong (2003b) evaluated the effects of this change on f_{CO_2} and pH, and on the speciation and solubilities of thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), and americium (Am). Brush and Xiong (2003b) demonstrated that redefining the reaction that will buffer f_{CO_2} does not change f_{CO_2}, pH, or actinide solubilities significantly. However,

3 GWB is a synthetic brine typical of intergranular (grain-boundary) fluids from the Salado Formation at or near the stratigraphic horizon of the repository (Snider 2003b)

implementation of this change in the CRA-2004 PA has made the actinide solubilities used in these calculations consistent with the conceptual model for microbial activity in the WIPP (see above).

Calcite ($CaCO_3$) is more stable under expected WIPP conditions than magnesite, hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$ or $Mg_4(CO_3)_3(OH)_2 \cdot 4H_2O$) or nesquehonite. Furthermore, calcite precipitates readily under the low-temperature conditions expected in the WIPP. Formation of calcite from the carbonation of lime (CaO) and/or portlandite ($Ca(OH)_2$)(has been observed in as little as 16 days in GWB, and by 50 days in ERDA-6, in the carbonation experiments described above. Therefore, Brush and Xiong (2003a, 2003b) suppressed (prevented the formation of) calcite (and magnesite) by "disabling" it in their input files, thereby allowing the formation of hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$), the third-most-stable carbonate mineral under expected WIPP conditions. This was appropriate for the vectors with microbial activity because the large quantities of CO_2 produced in these vectors would overwhelm the capacity of dissolved calcium (Ca^{2+}) to precipitate CO_2 as calcite, thus leaving most of the microbial CO_2 to react with periclase, brucite, or $Mg_2Cl(OH)_3 \cdot 4H_2O$ and produce hydromagnesite or (initially) nesquehonite. However, in the absence of microbial CO_2 production, the quantity of Ca^{2+} present would be sufficient to precipitate any CO_2 present as calcite without formation of metastable Mg carbonates. Therefore, for the vectors without microbial activity, Brush and Xiong (2003a, 2003b) allowed calcite to precipitate. The reaction that will buffer f_{CO_2} in the absence of microbial activity is:

$$Mg(OH)_2 + Ca^{2+} + CO_2(\text{aq or g}) \rightleftharpoons CaCO_3 + Mg^{2+} + H_2O(\text{aq or g}). \qquad (8)$$

Unlike the brucite-hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) carbonation reaction (see Reaction (2), above), which buffers f_{CO_2} at a unique value of $10^{-5.50}$ atm, the value of f_{CO_2} maintained by the brucite-calcite carbonation reaction (Reaction (4)) depends on the ratio of the activities of Mg^{2+} and Ca^{2+}, which in turn depends on the composition of the brine after equilibration with MgO. Brush and Xiong (2003b, Table 6) reported a value of $10^{-5.48}$ atm for GWB, brucite, and calcite, and $10^{-6.15}$ atm for ERDA-6, brucite, and calcite. (Other minerals, such as halite and anhydrite, were also present.)

The brucite dissolution reaction (see Reaction (3), above) would also buffer pH in the WIPP in the absence of significant microbial activity. Brush and Xiong (2003b, Table 6) reported pH values of 8.69 for GWB and 8.99 for ERDA-6.

These values of f_{CO_2} and pH were used for the actinide-speciation and -solubility calculations for the CRA-2004 PA vectors without microbial activity (see Appendix PA, Attachment SOTERM, Section SOTERM-3.0).

BARRIERS-2.4.2.4 <u>Effects of Magnesium Oxide on Colloidal Actinide Concentrations</u>

Colloids could affect the long-term performance of the WIPP because of their potential ability to bind cationic metals such as the actinide elements in TRU waste and because of their potential mobility under expected repository conditions (Choppin 1988). Colloids are typically defined as phases intermediate in size between dissolved ionic or molecular species and suspended particles

large enough to settle by gravity. The size range of colloids is typically on the order of 1 nm to 1 μm.

Humic substances, microbes, and mineral fragments could bind actinides in the WIPP. Under some conditions, actinides could also form intrinsic colloids without binding to humics, microbes, or minerals. Even if one or more of these four types of colloids form(s) in the WIPP, they would not transport actinides out of the repository unless they remain suspended in brine. If coagulation occurs, any actinides bound to these colloids would be immobile, at least with respect to direct brine releases or injection of brine into the Culebra Member of the Rustler Formation.

Chemical conditions in the repository will affect the colloidal actinide source term. For example, the pH of any brine present will affect the concentration(s) of intrinsic colloids. Studies carried out to quantify the colloidal source term included experiments under conditions that will be established by MgO (see Appendix PA, Attachment SOTERM, Section SOTERM-6.0).

BARRIERS 2.5 Experimental Activities and Modeling Investigations Since the CCA

The Scientific Advisor (SA) has investigated MgO efficacy through various experiments to test key functions. Specifically the SA has characterized MgO samples from suppliers and performed hydration and carbonation experiments. The following sections discuss the experiments and implications on the chemical conditions conceptual models.

BARRIERS-2.5.1 Characterization of Premier Magnesium Oxide

As stated in Section 2.2.1, Premier Chemicals manufactures the MgO currently being emplaced in the WIPP by mining ore from a sedimentary magnesite deposit and calcining it to expel all CO_2 from magnesite, thereby producing periclase. Calcination of accessory calcite produces small quantities of lime. Calcination of other accessory minerals in the ore creates minor quantities of oxide and silicate minerals such as spinel ($MgAl_2O_4$), ulvöspinel ($Ti(Fe,Mg)_2O_4$), forsterite (Mg_2SiO_4), and monticellite ($CaMgSiO_4$). Calcination also drives off all H_2O in the ore.

Bryan and Snider (2001a) reported that a typical chemical analysis of Premier MgO yields about 91 wt percent MgO, 1 wt percent alumina (Al_2O_3), 3 wt percent silica (SiO_2), 4 wt percent calcium oxide (CaO), and 1 wt percent iron(III) (Fe(III)) oxide (Fe_2O_3). Most of the MgO and some of the CaO occur as periclase and lime, respectively, in Premier MgO. However, some of the MgO and CaO, and most – if not all – Al_2O_3, SiO_2, and Fe(III) oxide are present in the accessory oxide and silicate minerals described above.

Snider (2003a) used inductively coupled plasma-optical emission spectroscopy, gravimetric analysis, and XRD analysis to quantify the mineralogical composition of one of the lots of Premier MgO used for the experiments described below. Based on the assumption that the silicate in this MgO is forsterite, this lot of MgO contains 86.86 wt percent periclase, 2.386 wt percent lime, 2.071 wt percent spinel, and 5.02 wt percent forsterite. If the silicate is monticellite, this lot contains 88.73 wt percent periclase, 1.273 wt percent lime, 2.071 wt percent spinel, and 5.756 wt percent monticellite. Given the

uncertainties inherent in quantifying the mineralogical composition of materials such as Premier MgO, it is reasonable to conclude that this material contains about 90 wt percent reactive phases (periclase + lime) and 10 wt percent nonreactive phases (oxides and silicates).

After the WIPP is filled and sealed, periclase will react with H_2O in the gaseous phase to form brucite ($Mg(OH_2)$), or with H_2O in brine to form brucite or amorphous or crystalline Mg-Cl-OH-H_2O-bearing solids such as $Mg_3Cl(OH)_5{\cdot}4H_2O$ or $Mg_2Cl(OH)_3{\cdot}4H_2O$. Periclase, brucite, and the Mg-Cl-OH-H_2O phases will react with aqueous or gaseous CO_2 to form solids such as hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ or perhaps $Mg_4(CO_3)_3(OH)_2{\cdot}3H_2O$), nesquehonite ($MgCO_3{\cdot}3H_2O$), and perhaps magnesite. Lime will react with aqueous or gaseous H_2O to form portlandite, and lime and portlandite will react with aqueous or gaseous CO_2 to form calcite. Oxides other than periclase and lime, and silicates will not react with H_2O and CO_2 to a significant extent during the 10,000-year regulatory period. Therefore, oxides other than periclase and lime, and silicates are not included in the calculation of the CO_2 consumption capacity used to calculate the MgO safety factor (see Section 2.6 of this appendix). Furthermore, these oxides and silicates will not affect chemical conditions in the repository significantly.

Bryan and Snider (2001a) carried out particle-size analysis of two of the batches of MgO used for their experiments. Table BARRIERS-1 provides the results of this analysis.

Table BARRIERS-2. Particle-Size Distribution of Two Batches of Premier MgO

(Bryan and Snider 2001a)

Size Range (mm)	Batch 1	Batch 2
< 0.15	30.95%	9.89%
0.15 to 0.30	8.36%	29.37%
0.30 to 0.50	4.59%	29.72%
0.50 to 0.71	3.50%	14.98%
0.71 to 2.00	14.16%	14.51%
> 2.00	37.41%	1.53%

BARRIERS-2.5.2 Hydration of Magnesium Oxide

The SA investigated MgO hydration, including experiments under conditions similar to those expected in the repository. Bryan and Snider (2001a, 2001b) and Snider (2002, 2003a) studied the hydration of Premier MgO, the material currently being emplaced in the WIPP, under humid and inundated conditions. Humid experiments have been carried out with 3 g of uncrushed Premier MgO at a relative humidity (RH) of 35, 50, 75, or 95 percent and temperatures of 25, 40,

60, or 80 ºC for up to 460 days (Snider 2003a); inundated experiments have been conducted with 5 g of uncrushed Premier MgO in 100 mL of deionized (DI) H_2O, 4.00-M sodium chloride (NaCl), ERDA-6, or GWB at temperatures of 25, 50, 70, and 90 °C for up to 360 days (Snider 2003a).

Reaction (1)(see above) is the only hydration reaction observed to date in the humid experiments. Reaction (1) is also the only hydration reaction observed so far in the inundated runs with ERDA-6 (Snider 2003a). In inundated experiments with GWB, hydration has produced both brucite and an amorphous or crystalline Mg-Cl-OH-H_2O phase (Snider 2003a). In most of the runs with GWB, the Mg-Cl-OH-H_2O phase is amorphous and its exact composition has not been determined. In a few experiments at 25 ºC, however, a crystalline phase with the composition $Mg_3Cl(OH)_5{\cdot}4H_2O$ has been identified by X-ray diffraction (XRD) analysis. The thermodynamic speciation and solubility code Fracture-Matrix Transport (FMT) (Babb and Novak 1997 and addenda, Wang 1998) also predicts that both brucite and $Mg_2Cl(OH)_3{\cdot}4H_2O$ are stable in GWB. However, long-term experiments with GWB suggest that brucite may be replacing the amorphous Mg-Cl-OH-H_2O phase.

BARRIERS-2.5.3 Carbonation of Magnesium Oxide

The SA investigated MgO carbonation and intermediate hydrous phases. Bryan and Snider (2001a, 2001b), Snider (2002), Snider and Xiong (2002), and Xiong and Snider (2003) have studied the carbonation of Premier MgO, the material currently being emplaced in the WIPP, and reagent-grade materials under inundated conditions. Inundated experiments have been carried out with 5 g of uncrushed Premier MgO in 100 mL of DI H_2O, 4.00-M NaCl, ERDA-6, or GWB under an atmosphere consisting of compressed, ambient, laboratory air at room temperature for up to 327 days (Snider and Xiong 2002); inundated experiments have also been conducted with uncrushed Premier MgO; crushed, prehydrated Premier MgO; Fisher reagent-grade periclase; or prehydrated Fisher periclase in 100 mL of ERDA-6 or GWB under an atmosphere containing 5 percent CO_2 for periods up to 91 days (Snider and Xiong, 2002). Humid experiments have been performed with 2.5 g of prehydrated Fisher periclase in an atmosphere consisting of compressed, ambient, laboratory air at an RH of 33, 58, 75, or 95 percent at room temperature and 40 ºC.

In experiments with ERDA-6 and atmospheric CO_2, Snider and Xiong (2002) have detected hydromagnesite with the composition $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ by XRD analysis. No other Mg carbonates have been detected in runs with ERDA-6 and atmospheric CO_2. Snider and Xiong (2002) have detected both hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) and nesquehonite by XRD analysis in the experiments with ERDA-6 and 5 percent CO_2, but hydromagnesite is clearly replacing nesquehonite as these experiments proceed. In experiments with GWB, hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) is the only Mg carbonate that has been detected by XRD analysis (Snider and Xiong 2002). Therefore, consistent with the chemical conditions conceptual model, there is strong evidence that hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) will be the dominant Mg carbonate for at least part of the 10,000-year regulatory period. The duration of these experiments supports the conclusion that an intermediate phase will occur early in the disposal system where magnesite formation is not expected for hundreds of years.

Additionally, thermodynamic calculations with EQ3/6 (Daveler and Wolery 1992, Wolery 1992a, 1992b, Wolery and Daveler 1992) and FMT imply the magnesite is stable with respect to

both hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$ or $Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O$) and nesquehonite under expected WIPP conditions (see Brush and Xiong 2003a). Furthermore, magnesite is commonly observed in the Salado (Lang 1939; Adams 1944; Lowenstein 1983, 1988; Stein 1985) and in other formations in the Delaware Basin (Garber et al. 1990). Lowenstein (1988, p. 598) describes the siliciclastic-carbonate mudstone, in which magnesite is most abundant, as a "non-evaporitic sediment" and attributes its origin to subaqueous "settling of fine-grained, suspended material in the center of the Salado basin where the energy of inflow waters had largely dissipated." Therefore, the magnesite observed in the Salado did not necessarily form in situ. However, Garber et al. (1990), who reported that magnesite "occurs pervasively" throughout an 82-m (270-ft) interval of core recovered from a stratigraphic test well located along the subsurface trend of the Capitan Reef 27 km (17 miles) northeast of Carlsbad, concluded that "the most likely origin for the magnesite in the core is the downward movement of dense fluids from the Ochoan Series, Salado Formation into the underlying, and [at the time] shallowly buried Tansil and Yates formations." Clearly, magnesite either formed or persisted for long periods in the Delaware Basin. Therefore, consistent with the chemical conditions conceptual model, the possibility that significant quantities of magnesite could form from carbonation of MgO during the 10,000-year regulatory period cannot be ruled out.

BARRIERS-2.5.4 Effects of Magnesium Oxide on Gas Generation

The two gas-producing processes included in PA are anoxic corrosion of steels and other Fe-base alloys, which produces H_2, and microbial consumption of CPR materials, which produces mainly CO_2 and methane (CH_4).

BARRIERS-2.5.4.1 Potential MgO Impacts on Gas Generation from Anoxic Corrosion of Steels and Other Iron-Base Alloys

Telander and Westerman (1993, 1997) studied anoxic corrosion of various metals and concomitant H_2 production under expected WIPP conditions. Wang and Brush (1996a, 1996c) used results from three types of experiments carried out by Telander and Westerman (1993, 1997) to establish ranges and probability distributions of H_2-production rates for the CCA PA: (1) experiments with low-carbon (C) steels in or above Brine A under atmospheres consisting of initially pure CO_2, nitrogen (N_2), or hydrogen sulfide (H_2S) in inert (noncorroding), metallic containers at low-to-intermediate pressures (about 1 to 20 atm); (2) experiments with low-C steels in Brine A under H_2, CO_2, or N_2 in autoclaves at high pressures (35 to 127 atm); and (3) runs with low-C steels in ERDA-6 at pH values of 2.8 to 10.6 under N_2. All these experiments were conducted at 30 ± 5 ºC. Brine A and ERDA-6 are described above (see Section 2.4.1 of this appendix).

Anoxic corrosion of low-C steels in Brine A under initially pure N_2 resulted in a pH of 8.3, 8.3, and 8.4 after 6, 12, and 24 months, respectively (see Telander and Westerman 1993, Table 6-3, Test Containers 10, 17, and 25). Wang and Brush (1996a, 1996c) used the 12-to-24-month data from these experiments to establish a range and probability distribution of inundated, anoxic-corrosion rates of steels and other Fe-base alloys of 0 to 0.5 μm/year for the CCA PA. This is equivalent to a range of 0 to 1.59×10^{-14} m/s. Data on the effects of pH on corrosion rates (Telander and Westerman 1997, Table 6-5) have demonstrated that rates obtained at a pH of 8.3 or 8.4 are somewhat higher than those at a pH of 8.69, 8.99, or 9.02, the values expected for the

brucite dissolution reaction (see Reaction (3), above). Therefore, the anoxic-corrosion rates established by Brush and Wang (1996a, 1996c) for the CCA incorporated the effects of MgO on pH.

For the 1997 PAVT, the EPA specified that the upper limit of the range of the inundated anoxic-corrosion rate be increased from 1.59×10^{-14} m/s to 3.17×10^{-14} m/s (Trovato 1997a, Enclosure 2; EPA 1998c, Table ES-4, Section 5.15, and Tables 6.3 and 6.4; Hansen and Leigh 2003). A range of 0 to 3.17×10^{-14} m/s was also used for the CRA-2004 PA (see Appendix PA, Section PA-5.2).

BARRIERS-2.5.4.2 <u>Microbial Gas Generation</u>

Francis and Gillow (1994, 2000), Francis et al. (1997), and Gillow and Francis (2001a, 2001b, 2002a, 2002b) did not include MgO or the effects of pH in their study of microbial gas generation under expected WIPP conditions. Instead, they included bentonite in about half of their experiments because a backfill consisting of 70 wt percent crushed salt and 30 wt percent bentonite had been proposed as an alternative to a backfill consisting entirely of crushed salt, the design-basis backfill in January 1992 when these microbial gas-generation experiments were started. No microbial experiments have been carried out with MgO since the use of this material was proposed in 1996 to consume CO_2 and control f_{CO_2} and pH in the WIPP.

The brucite dissolution reaction (see Reaction (3), above) will buffer the pH of any brines present at about 9 whether or not significant microbial activity occurs in the WIPP. This mildly basic value is somewhat higher than the mildly acidic values of pH produced by dissolution of microbial CO_2 in the experiments described by Francis and Gillow (1994, 2000), Francis et al. (1997), and Gillow and Francis (2001a, 2001b, 2002a, 2002b). However, emplacement of MgO in the WIPP and a consequent, mildly basic pH of 9 will not in and of itself preclude significant microbial activity in the repository. This conclusion is based on the common observation of viable alkalohalophilic microbes in alkaline lakes with pH values of 9 to 10. Such alkaline lakes occur frequently in arid and semiarid environments, such as southeastern New Mexico and adjacent areas of west Texas, and could be one of the sources of the halophilic microbes observed in the WIPP.

However, several investigators have reported that MgO and compounds derived from MgO possess inhibitory or even biocidal properties (Asghari and Farrah 1993, Chapman et al. 1995; Koper et al. 2002; Sawai 2003; Sawai et al. 1995a, 1995b, 1996, 2000a, 2000b; Stoimenov et al. 2002; Yamamoto et al. 1998). Some of the results of these studies may be applicable to the WIPP.

First, the inhibitory or biocidal effects of MgO probably result from the presence of brucite, not periclase (Sawai et al. 1995a), because most of the experiments cited above were conducted in aqueous solutions or in growth media that contained H_2O, and most of these experiments were long enough for significant nucleation and growth of brucite on periclase surfaces exposed to these solutions or media.

Second, the inhibitory or biocidal effects of MgO do not seem to be caused by the mildly basic pH that results from the presence of brucite in aqueous solutions or growth media. Sawai et al.

(1997) reported that the survival of Escherichia coli (E. coli) was unaffected by a MgO-free, alkaline growth medium at pH values of 10, 10.25, and 10.5, but that E. coli survival decreased significantly in the same medium at pH values of 10.75 and 11. This result agrees with the conclusion that a mildly basic pH of about 9 caused by the brucite dissolution reaction (see Reaction (3), above) will not by itself preclude microbial activity in the WIPP.

Third, the presence of solid Mg peroxide (MgO_2) (Asghari and Farrah 1993) and/or the anionic dioxygenyl radical ($O_2^{\bullet-}$) (Sawai et al. 1995b) along with periclase may be largely responsible for the inhibitory or biocidal effects of MgO. MgO_2 could be produced by reactions between dissolved hydrogen peroxide (H_2O_2), which will be produced by α radiolysis of H_2O in WIPP brines, and periclase, brucite, or perhaps other Mg-bearing solids. Radiolysis will also produce anionic $O_2^{\bullet-}$.

Fourth, inhibition of microbial activity seems to require contact between MgO particles and microbes (Sawai et al. 2000a). This conclusion is based on the observation that increased shaking speed of an MgO-bearing slurry increased the mortality of E. coli in the slurry.

Fifth, the inhibitory effect is inversely proportional to the size of the MgO particles (Sawai et al. 1996; Koper et al. 2002; Stoimenov et al. 2002) and the temperature at which the MgO was prepared (Sawai et al. 1996).

Application of these results to microbial activity in the WIPP is difficult in the absence of long-term experiments under expected repository conditions. Biocides are often used for sterilization of solid materials, but become ineffective as the volume of the material(s) to be sterilized increases. This is because it becomes progressively more difficult to ensure uniform distribution of the biocide throughout these materials, and hence to ensure contact between the biocide and the microbes, as the volume increases. Therefore, sterilization methods such as autoclaving and radiation are used for materials with large volumes. In the case of MgO, Sawai et al. (2000a) reported that inhibition of microbial activity seems to require contact between MgO particles and microbes. Although room closure will rupture the supersacks and disperse the MgO into the interstices among and within the ruptured waste containers, this will not ensure contact between MgO particles and microbes. Furthermore, survival of microbes in samples subjected to treatment with an inhibitory or biocidal agent such as MgO, especially those that have had some contact with particulate MgO, would probably result in the development of increased resistance to MgO.

Nevertheless, the results described above suggest that MgO might reduce the rate of microbial gas generation in the WIPP. In the absence of repository-specific experiments, however, it is not possible to reduce the microbial gas-production rates used in PA. Therefore, the rates and probability distributions used for the CRA-2004 PA are identical to those used for the CCA PA and the 1997 PAVT.

BARRIERS-2.5.5 Effects of Magnesium Oxide on Room Closure

In the CCA PA, the 1997 PAVT, and the CRA-2004 PA calculations, room closure initially proceeded as if the rooms were open. The free air space was eliminated early in the calculations by unmitigated creep closure. Eventually, the salt contacted the waste and deformed it according

to the waste response model. At the same time, corrosion and gas production pressurized the rooms. The coupled processes involved compression owing to the superincumbent rock counterbalanced by gas production, which was obtained from sampled parameters. Thus, room closure was due to salt creep modified by the structural response of the waste and by gas production. MgO had no effect on room closure.

BARRIERS-2.5.6 Effects of Magnesium Oxide on Far-Field Actinide Transport

MgO could affect the matrix distribution coefficients (K_ds) used to predict transport of dissolved Th, U, Pu, and Am through the Culebra (see Brush 1996 or Brush and Storz 1996 for a definition of matrix K_ds). For the CCA PA, data from an empirical sorption study, a mechanistic sorption study, and a column-transport study were used to establish ranges and probability distributions of K_ds for Th, U, Pu, and Am.

Most of these K_ds were obtained from six-week, empirical sorption experiments carried out with 1 g of dolomite-rich rock crushed to a size range of 75 to 500 μm; 20 mL of Brine A, ERDA-6, AISinR, or H-17 with dissolved Th(IV), U(VI), Np(V), Pu(V), or Am(III); and a controlled atmosphere containing 0.24, 1.4, or 4.1 percent CO_2 to simulate the expected range of f_{CO_2} in the Culebra, about $10^{-3.5}$ to $10^{-1.50}$ atm (see Brush 1996; Brush and Storz 1996). Brine A and ERDA-6 are described above (see Section 2.4.1 of this appendix); AISinR is a synthetic brine representative of fluids sampled from the Culebra in the WIPP Air Intake Shaft; and H-17 simulates Culebra brine from the H-17 Hydropad.

Brush (1996) and Brush and Storz (1996) extended the empirical K_ds obtained with Brine A and ERDA-6 to a pH of about 9 or 10 with data from a mechanistic sorption study that quantified the effects of f_{CO_2}, pH and ionic strength on the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by well-characterized, pure dolomite. Therefore, the K_ds for Brine A and ERDA-6 used for the CCA PA included the effects of MgO on pH. The K_ds for the Culebra brines, however, did not include the effects of MgO on pH because it was assumed that, if mixing is sufficient to produce fluids with compositions similar to those of Culebra brines, the pH of these mixtures will also be similar to those of Culebra brines (Brush 1996; Brush and Storz 1996).

For the 1997 PAVT, the EPA specified that the probability distributions for the K_ds be changed from uniform to log uniform (Trovato 1997b, Enclosure 2; EPA 1998c, Tables ES-3 and ES-4, Sections 5.34 to 5.38 and Tables 6.3 and 6.4; Hansen and Leigh 2003). However, the EPA did not change any of the K_ds.

Brush and Storz (1996) corrected some of the ranges of K_ds established by Brush (1996) for the CCA PA. These corrections were too late for the far-field transport calculations for the CCA PA, and were not included in the far-field transport calculations for the 1997 PAVT. Hansen and Leigh (2003), however, incorporated them in the PA database, and the CRA-2004 PA used the corrected K_ds along with the log-uniform probability distributions specified by the EPA (see Appendix PA, Section PA-5.2). The K_ds for Brine A and ERDA-6 used for the CRA-2004 PA included the effects of MgO on pH (Reaction (8) in Section 2.4.2.3 of this appendix), but the K_ds for the Culebra brines do not (see above).

BARRIERS-2.6 Magnesium Oxide Safety Factor

The MgO safety factor was first established in a request for additional information during the first WIPP certification (DOE 1997, see also Section 2.3). EPA requested information that demonstrated that the excess MgO volume proposed could actually be emplaced in the space above the waste. Documentation developed during the minisack-elimination proposal (Triay 2000 and EPA 2001a) detail the method used to determine the amount needed to ensure the chemical conditions assumptions used in PA. Actual waste emplacement information is used to determine emplaced and projected amounts of MgO that will be emplaced. The excess MgO above that needed was termed the safety factor. More specifically, the MgO safety factor is defined as the quantity of MgO to be emplaced in the WIPP divided by the quantity required to consume all CO_2 that would be produced by microbial consumption of all CPR materials in the repository. The amount of CO_2 was conservatively determined by assuming a one-to-one mole conversion of organic C in the waste to CO_2, the highest amount that could possibly be produced. The safety factor was determined to be 1.95 (DOE 1997). However, this value was later reduced to 1.67 as specified by EPA during their acceptance of DOE's request to eliminate the MgO minisacks (EPA 2001a). Therefore, the DOE MgO emplacement scheme maintains the specified 1.67 safety factor in each panel.

BARRIERS-2.6.1 Calculation of Magnesium Oxide Safety Factor

As stated above, the MgO safety factor must be maintained at or above 1.67 times the amount necessary to ensure the related assumptions in PA are maintained. The amount needed is that which will sequester the maximum amount of CO_2 that could be produced in the repository. This method conservatively assumes no other reactions that will sequester CO_2 such as reactions with the waste (i.e., reactions with cementitious materials and iron) or the natural environment (i.e., precipitation of calcite by Ca^{2+} from dissolution of SO42—bearing minerals such as anhydrite) occur. The amount of CO_2 produced by microbial consumption of CPR materials assumes a 1:1 molar ratio for the conversion of organic C in the waste to CO_2. Emplaced-waste information and projected waste information are used to determine the amounts of CPR materials in the disposal system. The amount of CPR materials stated in the CCA did not account for CPR materials contained in remote handled (RH) waste or the emplacement materials used to aid the disposal process. The current process includes these materials and therefore is more representative of actual materials in the repository.

The amount of MgO that would be emplaced in the repository was originally determined in the CCA to be 85,600 tons (later reduced to account for minisack elimination). This was the amount believed to fit in the space above the waste stacks. Current waste-emplacement data are available to better quantify the amount of MgO that has been and will be emplaced. The current safety-factor calculations use the emplacement information and not the amount assumed in the CCA.

As stated above, the 1.67 safety factor will be maintained by adding additional MgO if necessary to account for locally higher concentrations of CPR materials in the repository. The default MgO emplacement configuration of one supersack per stack of waste will continue to be maintained throughout the disposal rooms. The safety factor calculation used in EPA's approval of the elimination of minisacks (EPA 2001a) in CRA-2004 can be expressed as:

$$S_F^{MgO} = \frac{\left(M_{emp}^{MgO}\right)}{M_{req}^{MgO}} \tag{9}$$

where

M_{emp}^{MgO} = moles MgO emplaced

M_{req}^{MgO} = moles MgO required to consume CO_2 produced

Each of these terms is discussed below.

MOLES MgO EMPLACED

The mass of MgO emplaced will be tracked by the DOE as each room is filled. The conversion from mass to moles is as follows:

$$M_{emp}^{MgO} = m_{emp}^{MgO}\left(\frac{\text{kg}}{2.2046\ \text{lbs}}\right)\left(\frac{1000\text{g}}{\text{kg}}\right)\left(\frac{\text{mole}}{40.3\text{g}}\right) \tag{10}$$

Where

M_{emp}^{MgO} **= moles MgO emplaced**

m_{emp}^{MgO} **= mass of MgO emplaced in pounds**

MOLES MgO REQUIRED TO CONSUME CO_2 PRODUCED

Calculation of the moles of MgO required to consume CO_2 is based on the assumption that one mole of MgO is required to sequester one mole of CO_2 as was done for the safety factor calculation used in the EPA's approval of the elimination of minisacks (EPA 2001a). CO_2 will be produced through the metabolic utilization of CPR materials by microbes in the repository.

The moles of organic C in the repository are derived from the mass of CPR materials. The total moles of organic C can be expressed as:

$$M_T^{OC} = \gamma_{CH}^{OC} \bullet M_{CH} \tag{11}$$

Where

M_T^{OC} = total moles of organic carbon

γ_{CE}^{OC} = moles of organic carbon per mole of cellulose

M_{CE} = moles of cellulose equivalent

Wang and Brush (1996a) concluded that $\gamma_{CE}^{OC} = 6$

The moles of cellulose equivalent are given in Equation 12 (Wang and Brush 1996a). An adjustment is made to account for higher densities of C in plastic materials.

$$M_{CE} = \frac{m_C + m_R + 1.7 \bullet m_P}{MW_{CE}} \tag{12}$$

where

M_{CE} = moles of cellulose equivalent

MW_{CE} = molecular weight of cellulose = 162 g/mole

m_C = mass of cellulose

m_R = mass of rubber

m_P = mass of plastic

Equation (9) determines the safety factor. Operational controls track CPR materials emplaced in the repository and the amount of MgO emplaced. As waste is emplaced, the safety factor will be periodically calculated to determine if additional MgO is necessary to maintain the safety factor.

BARRIERS.2.6.2 Microbial Investigations since the CCA

The SA has continued to investigate microbial gas generation and its impact on long-term repository performance. The MgO engineered barrier will consume CO_2 produced by microbial consumption of CPR materials in the repository. Gas generation from anoxic corrosion of steel and microbial consumption of CPR materials is modeled in PA as described in CRA Chapter 6, Section 6.4.3.3. Microbial consumption of CPR materials is expected to progress via a sequence of processes based on the availability of electron acceptors in the disposal system. The conceptual model of sequential use of electron acceptors is based on the well-known observations that: (1) microbes use the electron acceptor (oxidant) that yields the most free energy per mole of organic C consumed; (2) after depletion of the best available electron acceptor, these microbes – or other microbes – begin to consume the next best electron acceptor; and (3) this process continues until all substrate (CPR materials in the case of the WIPP) is consumed, an essential nutrient is consumed, or some other limiting condition is attained. Sequential use of electron acceptors has been observed in a diverse array of natural environments, such as lacustrine, riverine, estuarine, and oceanic sediments; soils; and in anthropogenic environments, such as landfills. In these environments, the order of use observed is oxygen (O_2) (referred to as aerobic respiration), NO_3^- (denitrification), manganese(IV) (Mn(IV)) oxides and hydroxides (Mn reduction), Fe(III) oxides and hydroxides (Fe reduction), SO_4^{2-} (SO_4^{2--} reduction), and CO_2 (fermentation and methanogenesis) (Froelich et al. 1979;

Berner 1980; Criddle et al. 1991; Chapelle 1993; Wang and Van Cappellen 1996; Schlesinger 1997; Hunter et al. 1998; Fenchel et al. 2000). (In the following discussion, fermentation and methanogenesis are usually referred to as "methanogenesis" for simplicity.) The sequential reactions used to represent possible denitrification, sulfate (SO_4^{2--}) reduction, and methanogenesis in the WIPP (Wang and Brush 1996a) are:

$$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow 7.4H_2O + 6CO_2 + 2.4N_2; \quad (13)$$

$$C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S; \quad (14)$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2. \quad (15)$$

For these reactions, the CO_2 yields are 1 mole of CO_2 per mole of organic C consumed from denitrification and SO_4^{2--} reduction, and 0.5 moles of CO_2 per mole of C from methanogenesis**.**

Results of the long-term study of microbial gas generation now confirm that methanogenesis is a likely respiratory pathway in the repository if significant microbial activity occurs. By the time that Wang and Brush (1996a, 1996b) established the model and parameters for microbial gas generation for the CCA PA, Francis and Gillow (1994) and Francis et al. (1997) had observed aerobic respiration and denitrification - but not methanogenesis - in their experiments, which had been carried out for up to 1,228 days (3.36 years). Therefore, there was no experimental evidence at the time of the CCA that methanogenesis would actually occur in the WIPP, that the quantity of CPR materials consumed by methanogenesis in the WIPP would greatly exceed those consumed by denitrification and SO_4^{2--} reduction, or that the overall CO_2 yield in the repository would be close to 0.50 mol per mol of organic C consumed. At the time of the CCA, a possible explanation for the absence of methanogenesis was that no viable fermentative and/or methanogenic microbes were present in these experiments. There were two reasons why viable fermenters and/or methanogens might not have been present: (1) none were present in the materials used to inoculate these experiments (laboratory dust, brine, and mud from the salt lakes in Nash Draw, and G Seep brine collected from G Drift - a drift located in the northern end of the WIPP underground workings and used previously for in-situ experiments); and (2) communities of halophilic, fermentative, and methanogenic microbes capable of metabolizing complex, organic substrates, such as cellulosic materials under expected WIPP conditions, do not exist.

Since the CCA PA, however, methanogenesis has been observed in numerous experiments carried out under several combinations of conditions (Francis and Gillow 2000, pp. 2, 3, and 10; Gillow and Francis 2001, pp. 3-4 and 3-5; Gillow and Francis 2002a, pp. 2.1 - 12 to 2.1 – 14; and Gillow and Francis 2002b, pp. 3.1 - 5 to 3.1 - 6). Several definitive conclusions can be drawn from these results.

It is now clear that the absence of experimental evidence for methanogenesis at the time of CCA PA was because microbial activity in the initially aerobic experiments had not progressed through aerobic resp/iration, denitrification, and SO_4^{2--} reduction to methanogenesis; and that microbial activity in the initially anaerobic experiments had not progressed through denitrification and SO_4^{2--} reduction to methanogenesis. The requirement that these steps be completed prior to the onset of methanogenesis is a consequence of the conceptual model of

sequential use of electron acceptors (see above), according to which methanogenesis does not start until any and all NO_3^- and SO_4^{2--} are depleted, or until some other process renders the environment unsuitable for denitrification and SO_4^{2--} reduction. Although methanogenesis had not been observed by the time of the CCA PA in experiments carried out for up to 1,228 days (3.36 years), it was later observed in inundated experiments after 2,718 days (7.44 years) and in humid experiments after 2,653 days (7.26 years).

Therefore, it is also clear now that: (1) there exist communities of halophilic, fermentative, and methanogenic microbes capable of metabolizing complex organic substrates, such as cellulosic materials, under expected WIPP conditions; (2) such microbes are present – and viable – in one or more of the materials used to inoculate these experiments; and (3) these microbes are capable of surviving exposure to O_2. Methanogens are obligate anaerobes and, as such, are extremely sensitive to exposure to O_2. The fact that they produced CH_4 after exposure to O_2 implies that they are capable of producing resistant forms that can survive initially oxic conditions in these experiments.

Furthermore, results from the microbial gas-generation study have confirmed that viable halophilic fermenters and methanogens capable of metabolizing cellulosic materials under expected near-field conditions are present in the WIPP underground workings. Francis and Gillow (2000, pp. 2 and 10) detected CH_4 in initially oxic, unamended, and uninoculated experiments, and in initially anoxic, unamended, and uninoculated experiments. The most likely explanation for microbial gas production in these uninoculated experiments is that G Seep, the brine used for these inundated experiments, was collected from the WIPP underground workings. This brine contained a small but viable microflora, including methanogens, and was not sterilized prior to use. The fact that these microbes produced CH_4 after exposure to O_2 in the air used to ventilate G Drift and in initially oxic experiments implies that they are capable of producing resistant forms that can withstand initially oxic conditions in the repository.

However, the presence of viable halophilic fermenters and methanogens in the WIPP does not preclude the possibility that similar communities of microbes are also present in the other materials used to inoculate these experiments, especially brine and mud from the salt lakes in Nash Draw. It is quite possible that methanogens in these lakes are also capable of producing resistant forms that can survive the oxic conditions encountered during eolian transport from Nash Draw to the WIPP Air Intake Shaft, and initially oxic conditions in the repository. Therefore, the presence of viable methanogens in the WIPP does not depend on the claim that microbes have survived in the Salado since the Permian Period (Vreeland et al. 2000), a claim that is controversial (see, for example, Hazen and Roedder 2001; Powers et al. 2001).

Finally, exclusive use of Reaction (16) (gas-producing methanogenesis) to represent methanogenesis in PA (the current implementation of this respiratory pathway) is probably conservative because Reaction (16) produces an equimolar mixture of CH_4 and CO_2. However, another methanogenic reaction,

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O, \qquad (17)$$

which actually consumes CO_2 and H_2, is likely in the WIPP because it is energetically favored with respect to Reaction (16) (see, for example, Madigan et al. 2003, pp. 454-455). Reaction

(17) has been simplified somewhat inasmuch as microbes that use this respiratory pathway typically use acetate ($CH_3CO_2^+$) or other organic acids along with H_2 to reduce CO_2 to CH_4. (Reactions (14), (15), and (16) have also been simplified somewhat, as is typically the case when used for geochemical applications such as predicting the CO_2 yield from microbial consumption of CPR materials in the WIPP.) Nevertheless, if CO_2 and H_2 (and acetate) are present, Reaction (17) (gas-consuming methanogenesis, or – strictly speaking – gas-consuming acetotrophic methanogenesis) will probably proceed instead of Reaction (16). Alternatively, Reaction (17) could probably proceed along with Reaction (16). In either case, Reaction (17) could consume significant quantities of CO_2.

In the event of significant microbial activity in the WIPP, CO_2 and H_2 (and acetate) will be present because: (1) consumption of CPR via Reaction (14), (15), or (16) will produce CO_2, (2) anoxic corrosion of steels and other Fe-base alloys in waste containers and in the waste will produce H_2 (if brine is present), and (3) acetic acid and sodium acetate are present in the TRU waste to be emplaced in the WIPP (see Appendix DATA, Attachment F) and will dissolve in any brines that enter the repository, possibly reaching a concentration of 3.57×10^{-3} M (Brush and Xiong 2003c).

BARRIERS-3.0 DISPOSAL SYSTEM BARRIERS

BARRIERS-3.1 Definition of a Disposal System Barrier

Disposal system barriers are included as an integral part of the disposal system design. These disposal system barriers are designed to delay the migration of radionuclides to the accessible environment. Frequently, these disposal system barriers are designed to mitigate impacts to the natural strata and block pathways created in the construction and operational phases of the WIPP facility. As such, they are a necessary part of the overall disposal system design.

BARRIERS-3.2 Description of Waste Isolation Pilot Plant Disposal System Barriers

The DOE incorporated three types of disposal system barriers into the design of the disposal system: panel closures, shaft seals, and borehole plugs.

BARRIERS-3.2.1 Panel Closures

In the CCA, the DOE described four possible panel closure designs to be used depending upon ground conditions and potential for gas generation. CCA Appendix PCS was a design report prepared and signed by a professional engineer certified by the state of New Mexico.

In the final certification decision for WIPP (63 FR 27405) (EPA 1998a), EPA specified four conditions that apply to the certification. Condition 1 details the panel closure system to be used as Option D with Salado Mass Concrete (SMC)**:**

> Condition 1: § 194.14(b), Disposal system design, panel closure system. The Department shall implement the panel seal design designated as Option D in Docket A-93-02, Item II-G-1 (October 29, 1996, Compliance Certification Application submitted to the Agency). The Option D design shall be implemented as described in [CCA] Appendix PCS of Docket A-93-02, Item II-G-1, with the exception that the Department shall use Salado mass concrete (consistent with that proposed

for the shaft seal system, and as described in CCA Appendix SEAL of Docket A-93-02, Item II-g-1) instead of fresh water concrete.

Panel closures are included for Resource Conservation and Recovery Act (RCRA) disposal unit closure to prevent potentially unacceptable levels of volatile organic compound (VOC) release during waste management operations, and to protect against the effects of a postulated deflagration in a closed panel. While the panel closures provide a solid structure within the drifts, they were not intended to support long-term repository performance. Of the four options proposed in the CCA, the EPA specified that one of these, Option D, should be used. This Option consists of a concrete barrier emplaced after removing the disturbed rock zone (DRZ), and an explosion wall. EPA also specified that SMC be used for the barrier (EPA 1998a), which was a potential alternative to ordinary portland cement noted in the CCA.

Characteristics of the Option D design are incorporated into the PA grid and computational methodologies for the recertification calculations (Appendix PA, Section PA-4.2.8). However, the DOE believes that a redesign of the panel closure system is warranted. In a letter to the EPA dated October 7, 2002 (DOE 2002-0205715), the DOE requested approval of a proposed change to the EPA 40 CFR Part 194 Certification of the Waste Isolation Pilot Plant with regard to the design of the panel closure system. The DOE believes that the redesigned panel closure is a simpler design concept that provides equivalent or improved performance.

The EPA responded in a letter dated November 15, 2002 that concluded that the panel closure system design change request would require a rulemaking. Because the rulemaking likely would not be completed before this application would be submitted, the EPA deferred review of the proposal until after the recertification decision. The EPA did agree to construction of the explosion wall and a delay in construction of the Option D concrete monolith after completion of waste emplacement in Panel 1 until a regulatory decision was made on the proposed new panel closure design (Docket A-98-49, II-B-3, Item 44). Until a design change is approved by the EPA and the State of New Mexico, the regulatory baseline includes the modified Option D Panel Closure System.

A description of the Option D Panel Closure System, initially provided in CCA Appendix PCS, is discussed in Sections 3.2.1.1 through 3.2.1.5 of this appendix.

BARRIERS-3.2.1.1 <u>Overview</u>

The panel closure system provides assurance that the RCRA limit for the migration of potential VOCs will be met at the point of compliance, the WIPP site boundary. The panel closure system will be located in the air-intake and air-exhaust drifts to each panel, as shown in Figure BARRIERS-1. The design process commenced with the evaluation of the performance requirements of the panel closure; and the system components have been designed to maintain their intended functional requirements under loads generated from salt creep, internal pressure, and a postulated methane explosion.

BARRIERS-3.2.1.2 Design

The mandated panel closure system is an enlarged tapered concrete barrier that will be grouted along the interface and an explosion-isolation wall. Figure BARRIERS-2 illustrates this design. The design concept for the enlarged concrete barrier incorporates:

- A concrete barrier that is tapered to promote the rapid stress buildup on the host rock. The stiffness was selected to provide rapid buildup of compressive stress and reduction in shear stress in the host rock.

- The enlarged barrier requires DRZ removal to keep the tapered shape approximately spherical. DRZ removal limits potential VOC flow through the panel closure system.

- The design of the panel closure system includes an explosion-isolation wall designed to provide strength and deformational serviceability during the operational period. The length was selected to assure that uniform compression develops over a substantial portion of the structure and that end-shear loading that might result in fracturing of salt into the back is reduced. While no requirements for barricading waste areas exist under the MSHA, the intent of the regulations is to safely isolate abandoned areas from active workings using barricades of "substantial construction." The CCA examined the potential issue of methane gas generation from TRU waste in closed areas. The principal concern is the postulated occurrence of an explosive mixture of methane and an ignition source, which would result in deflagration. An explosion-isolation wall has been designed of sufficient thickness to resist dynamic loads from such a deflagration and creep loads from closure of the salt around the wall.

The CRA-2004 PA calculations implement a conceptual design consistent with Option D, as described above. As noted above, the DOE has reevaluated this panel closure design and believes that a modification is warranted.

BARRIERS-3.2.1.3 Design Components

The following subsections present system and components design features.

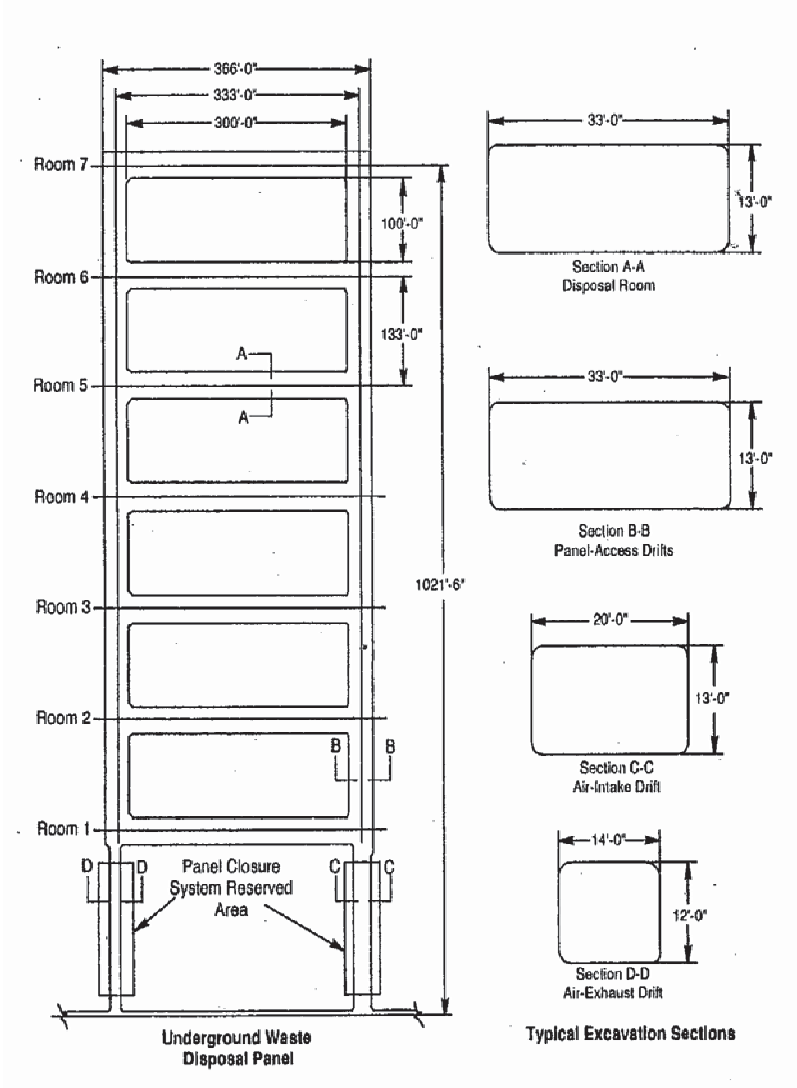

Figure BARRIERS-1. Typical Facilities--Typical Disposal Panel After Westinghouse (1996c)
(Note: Figure is not to Scale. All Dimensions Shown are Nominal)

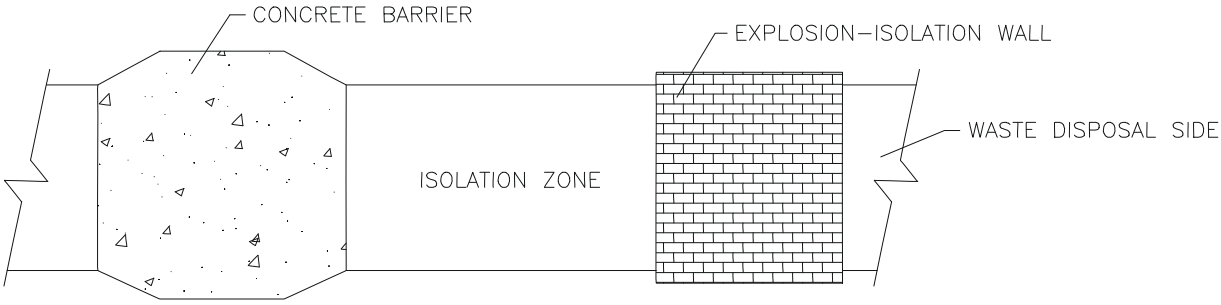

Figure BARRIERS-2. Option D. Explosion-Isolation Wall and Concrete Barrier with DRZ Removed

BARRIERS-3.2.1.3.1 Concrete Barrier

The enlarged concrete barrier consists of SMC, with sufficient unconfined compressive strength and with an approximately circular cross-section excavated into the salt over the central portion of the barrier. The enlarged concrete barrier will be located at the optimum locations in the air-intake and air-exhaust drifts, with the central portion extending just beyond Clay G and MB 139.

The enlarged concrete barrier will be placed in four cells, with construction joints perpendicular to the direction of potential air flow. The concrete strength will be selected according to the standards specified by the latest edition of the ACI code for plain concrete. The concrete will be placed through 6-in- (15-cm)-diameter steel pipes and vibrated from outside the formwork. The formwork is designed to withstand the hydrostatic loads during construction, with minimal bracing onto exposed salt surfaces. This will be accomplished by placing a series of steel plates that are stiffened by angle iron, with load reactions carried by spacer rods. The spacer rods will be staggered to reduce potential flow along the rod surfaces through the barrier. Some exterior bracing will be required when the first cell is poured. All structural steel will be American Society for Testing Materials (ASTM) A36, with detailing, fabrication, and erection of structural steel in conformance with the latest edition of the AISC steel manual (AISC 1989). After concrete placement, the formwork will be left in place.

BARRIERS-3.2.1.3.2 Explosion Wall

An explosion-isolation wall, consisting of concrete blocks, will mitigate the effects of a postulated methane explosion. The concrete block wall design complies with MSHA requirements (MSHA 1987) because it uses incombustible materials of substantial construction.

The explosion-isolation wall in the Panel 1 access drift consists of a structure constructed across the entire cross-section of each drift. Each wall is 12 ft (3.65 m) long and is created from solid concrete blocks mortared together and set in a 0.5-ft (0.15-m) deep keyway cut around the full perimeter of the drifts (Figure BARRIERS-3). The explosion-isolation walls were constructed to the specifications the CCA Appendix PCS, except as noted below.

The revised design, in which the walls are 30 ft (9.1 m) long, uses identical construction techniques, but specifies materials of higher strengths. In summary, the following changes were specified:

- The mortar shall conform to ASTM C 270 type M, using the property specification 3000 psi (20.88 MPa) at 28 days, as a minimum requirement. (The wording of the specification was changed slightly, but the compressive strength requirement is unchanged.)

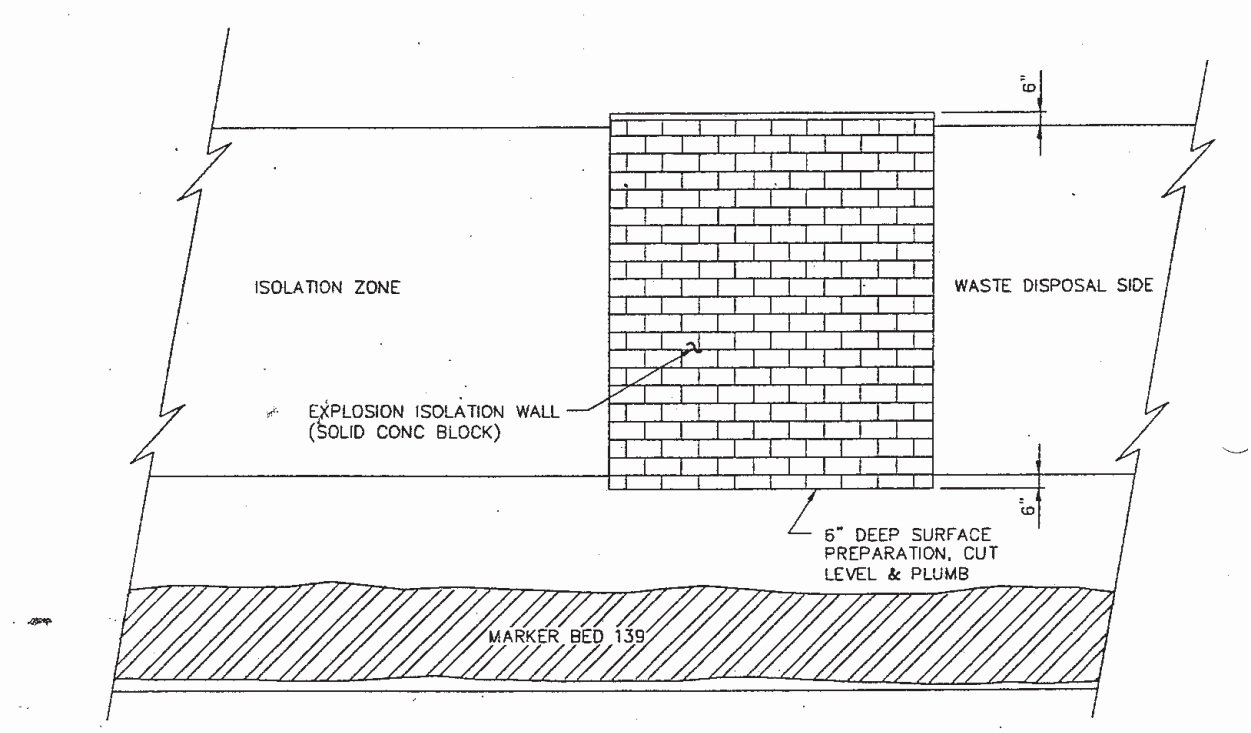

Figure BARRIERS-3. Explosion-Isolation Wall (not to scale)

- The concrete masonry units shall be solid (no cavities or cores), load-bearing, high-strength individual units, having a minimum compressive strength of 5500 psi (37.92 MPa) (average of three units) or 5000 psi (34.47 MPa) for individual unit. (Compressive strength increased from 3500 psi (average of three units) and 3000 psi for individual units.)

- The compressive strength of masonry in each masonry unit shall exceed 5000 psi. (The HWFP specifications do not include this test, which must be performed for each 2000 ft^3 (56.63 m^3) of masonry structure.)

The result of these changes is that materials meeting the specifications of the revised design are consistent with the specification outlined in CCA Appendix PCS. The explosion-isolation wall in Panel 1 was constructed soon after waste emplacement was completed.

BARRIERS-3.2.1.3.3 Interface Grouting

After construction of the main concrete barrier, the interface between the main concrete barrier and the salt will be grouted through a series of grout-supply and air-return lines that will terminate in grout distribution collection boxes. The openings in these boxes will be protected during concrete placement (Figure BARRIERS-4). The grout boxes will be mounted near the top of the barrier. The grout will be injected through one distribution system, with air and return grout flowing through a second distribution system.

BARRIERS-3.2.1.4 Panel-Closure System Construction

The design uses common construction practices according to existing standards. The proposed construction sequence follows completion of the waste-emplacement activities in each panel: (1) perform subsurface exploration to determine the optimum location for the panel closure system, (2) prepare surfaces for the explosion-isolation walls, (3) install these walls, (4) excavate for the enlarged concrete barrier, (5) install concrete formwork, (6) emplace concrete for the first cell, (7) grout the completed cell, and (8) install subsequent formwork, concrete, and grout until completion of the enlarged concrete barrier.

The explosion-isolation walls will be located at some distance from the main concrete barrier. The host rock will be excavated 6 in (15 cm) around the entire perimeter prior to installing the explosion-isolation wall. The surface preparation will produce a level surface for placing the first layer of concrete blocks. Excavation may be performed by either mechanical or manual means.

Excavation for the enlarged concrete barrier will be performed using mechanical means, such as a cutting head on a suitable boom. The existing roadheader at the main barrier location in each drift is capable of excavating the back and the portions of the ribs above the floor level. Some manual excavation may be required in this situation as well. If mechanical means are not available, drilling boreholes and an expansive agent can be used to fragment the rock (Fernandez et al. 1989). Excavation will follow the lines and grades established for the design. The tolerances for the enlarged concrete-barrier excavation are +6 to 0 inches (+15 to 0 cm). In addition, loose or spalling rock from the excavation surface will be removed to provide an appropriate surface abutting the enlarged concrete barrier. The excavations will be performed according to approved ground control plans.

Following completion of the roof excavation for the enlarged barrier, the floor will be excavated. If mechanical means are not available, drilling boreholes and using an expansive agent to fragment the rock (Fernandez et al. 1989) is a method that can be used. Expansive agents would load the rock salt and anhydrite, producing localized tensile fracturing in a controlled manner to produce a sound surface.

A batch plant at the surface or underground will be utilized for batching, mixing, and delivering the concrete to the underground in sufficient quantity to complete placement of the concrete within one form cell.

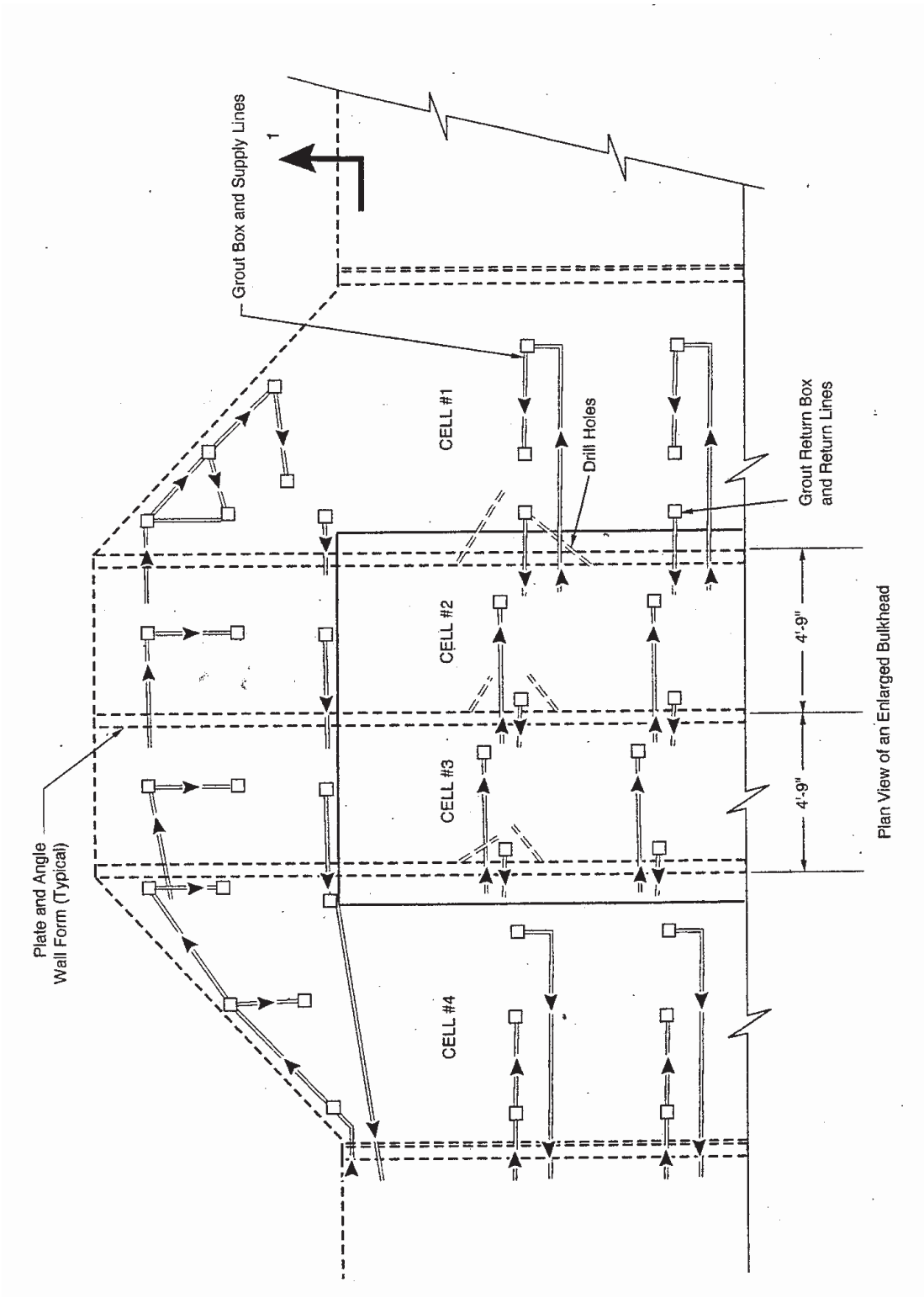

Figure BARRIERS-4. Grouting Details

Pumping equipment suitable for placing the concrete into the forms will be provided at the main concrete barrier location. After transporting, and prior to pumping, the concrete will be remixed to compensate for segregation of aggregate during transport. Batch concrete will be checked at the surface at the time of mixing and again at the point of transfer to the pump for slump and temperature. Admixtures may be added at the remix stage in accordance with the batch design.

BARRIERS-3.2.1.5 Conclusion

A design basis, including the operational requirements, structural and material requirements, and construction requirements, was developed that addresses the governing regulations for the panel closure system. The panel closure system design incorporates mitigative measures to address the treatment in the rock around the openings after fracture and therefore counter the potential migration of VOCs. Several alternatives were evaluated for the treatment of fractures. These included excavation and emplacement of a fully enlarged barrier with removal of the DRZ, excavation of the roof and emplacement of a partially enlarged barrier, and emplacement of a standard barrier with formation grouting. In its final ruling on the CCA, the EPA required, in condition 1, that the Option D design be implemented. This design requires the excavation and emplacement of a fully enlarged barrier. Until resolution is reached on the DOE's proposed design change, the design remains as required by EPA.

To investigate several key design issues and to implement the design, design evaluations were performed. These design evaluations can be divided into evaluations satisfying the operational requirements of the system and evaluations satisfying the structural and materials requirements of the system. The conclusions reached from the evaluations addressing the operational requirements are as follows:

- Based on an air-flow model used to predict the mass flow rate of carbon tetrachloride through the panel-closure system for the alternatives, the air-flow analysis suggests that the fully enlarged barrier is protective for restricting potential VOCs during the operational period of 35 years.

- Interface grouting would be performed at the upper boundary of the concrete barrier.

- The results of the transverse plane-strain models show that high stresses could form in nearby brittle marker beds following excavation, but that after installation of the panel closure system, an increase in barrier-confining stress and a reduction in shear stress would result. The concrete barrier would provide substantial uniform confining stresses as the barrier is subjected to secondary salt creep.

- The removal of the fractured salt prior to installation of the main concrete barrier would reduce the potential for flexure.

The conclusions reached from the design evaluations addressing the structural and material requirements of the panel closure system are as follows:

- Existing information on the heat of hydration of the concrete supports placing concrete with a low cement content to reduce the temperature rise associated with hydration.

Plasticizers might be used to achieve the required slump at the required strength. A thermal analysis, coupled with a salt creep analysis, suggests installation of the enlarged barrier at or below ambient temperatures to adequately control hydration temperatures.

- The trace amounts of brine from the salt at the repository horizon will not degrade the main concrete barrier for at least 35 years.

- In 20 years, the open passage above the waste stack in the rooms would be reduced in size. Furthermore, rooms with bulkheads at each end would be isolated in the panel. It is unlikely that a long passage with an open geometry would exist; therefore, the dynamic analysis considered a deflagration with a peak explosive pressure of 240 psi (1.7 MPa).

- The heat-transfer analysis shows that elevated temperatures would occur within the salt and the explosion-isolation wall; however, the elevated temperatures will be isolated by the panel closure system. Temperature gradients will not significantly affect the stability of the wall.

- The fractures in the roof and floor could be affected by expanding gas products reaching pressures on the order of 240 psi (1.7 MPa). Because the peak internal pressure from the deflagration is only one fifth of the pressure, fractures could not propagate beyond the barrier.

BARRIERS-3.2.2 Shaft Seals

There have been no changes to the shaft seals since the CCA. A description of the shaft seals, initially provided in CCA Appendix SEAL, is discussed in Sections 3.2.2.1 through 3.2.2.4 of this appendix. The representation of the shaft seals in PA has been simplified; see Appendix PA, Section PA-4.2.7 for details.

BARRIERS-3.2.2.1 Overview

The WIPP underground facilities are accessed by four shafts commonly referred to as the waste, air intake, exhaust, and salt handling shafts. These shafts were constructed between 1981 and 1988. Each of the four shafts from the surface to the underground repository must be sealed to limit hazardous material release to the accessible environment and to limit groundwater flow into the repository. Although the seals will be permanent, the regulatory period applicable to the repository system analyses is 10,000 years.

BARRIERS-3.2.2.2 Seal Components

The shaft sealing system comprises 13 elements that completely fill the shaft with engineered materials possessing high density and low permeability (Figure BARRIERS-5). Salado components provide the primary regulatory barrier by limiting fluid transport along the shaft

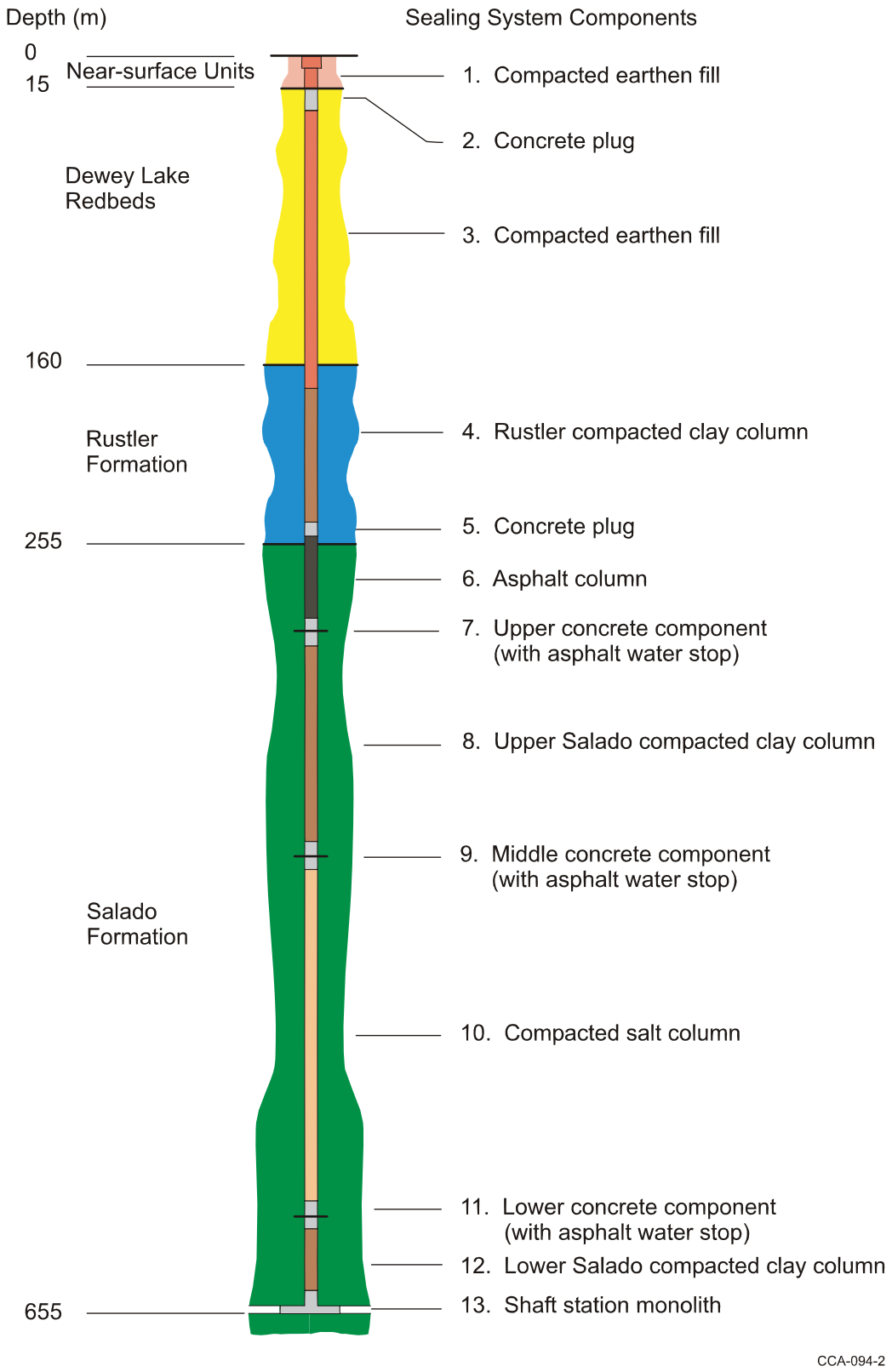

Figure BARRIERS-5. Shaft Sealing System Components

during and beyond the 10,000-year regulatory period. Components within the Rustler Formation limit commingling between brine-bearing members, as required by state regulations. Components from the Rustler Formation to the surface fill the shaft with common materials of high density, consistent with good engineering practice. A synopsis of each component is given below.

BARRIERS-3.2.2.2.1 Shaft Station Monolith

At the bottom of each shaft a salt-saturated concrete monolith supports the local roof. A salt-saturated concrete, called SMC, is specific and is placed using a conventional slickline construction procedure where the concrete is batched at the surface.

SMC has been tailored to match site conditions. The salt-handling shaft and the waste-handling shaft have sumps which will also be filled with salt-saturated concrete as part of the monolith. The monoliths function to support the shaft wall and adjacent drift roof, thus preventing damage to the seal system as the access drift closes from natural processes.

BARRIERS-3.2.2.2.2 Clay Columns

A sodium bentonite is used for three compacted clay components in the Salado and Rustler Formations. Although alternative construction specifications are viable, labor-intensive placement of compressed blocks is specified because of proven performance. Clay columns effectively limit brine movement from the time they are placed to beyond the 10,000-year regulatory period. The upper clay column ranges in length from 102 to 107 m (335 to 351 ft), and the lower clay column ranges in length from 29 to 33 m (94 to 107 ft) in the four shafts. The locations for the upper and lower clay columns were selected based on the need to limit fluid migration into the compacting salt column. The lower clay column stiffness is sufficient to promote healing of fractures in the surrounding rock salt near the bottom of the shafts, thus removing the proximal DRZ as a potential pathway (CCA Appendix SEAL, Appendix D, Section 5.2.1). The Rustler clay column limits brine communication between the Magenta and Culebra Members of the Rustler Formation.

A commercial well-sealing-grade sodium bentonite will be used to construct the Rustler compacted clay column, which will effectively limit fluid movement from the time of placement and provide an effective barrier to fluid migration throughout the 10,000-year regulatory period and thereafter. Design length of the Rustler clay column is about 71 m (234 to 235 ft) in the four shafts.

BARRIERS-3.2.2.2.3 Concrete-Asphalt Waterstop Components

The upper, middle, and lower concrete-asphalt waterstops are identical and are composed of three elements: an upper concrete plug, a central asphalt waterstop, and a lower concrete plug. The concrete specified is SMC. In all cases, the component's overall design length is 15 m (50 ft).

The upper and lower concrete plugs of the concrete-asphalt waterstop are identical. They fill the shaft cross-section and have design length of 7 m (23 ft). The plugs are keyed into the shaft wall to provide positive support for the plug and overlying sealing materials. The interface between

the concrete plugs and the surrounding formation will be pressure grouted. The upper plug in each component will support dynamic compaction of the overlying sealing material if compaction is specified. Dynamic compaction of the salt column is discussed in CCA Appendix SEAL (Section 6).

The asphalt waterstop is located between the upper and lower concrete plugs. In all cases, a kerf extending one shaft radius beyond the shaft wall is cut in the surrounding salt to contain the waterstop. The kerf is 0.3 m (1 ft) high at its edge and 0.6 m (2 ft) high at the shaft wall. The kerf, which cuts through the existing shaft DRZ, will result in the formation of a new DRZ along its perimeter. This new DRZ will heal shortly after construction of the waterstop, and thereafter the waterstop will provide a very low permeability barrier to fluid migration through the DRZ. The formation and healing of the DRZ around the waterstop is discussed in CCA Appendix SEAL (Section 7.6.1). The asphalt fill for the waterstop extends two feet above the top of the kerf to assure complete filling of the kerf. The construction procedure used assures that shrinkage of the asphalt from cooling will not result in the creation of voids within the kerf and will minimize the size of any void below the upper plug.

Concrete-asphalt waterstops are placed at the top of the upper clay column, the top of the compacted salt column, and the top of the lower clay column. The concrete-asphalt waterstops provide independent seals of the shaft cross-section and the DRZ. The SMC plugs (and grout) will fill irregularities in the shaft wall, bond to the shaft wall, and seal the interface. Salt creep against the rigid concrete components will place a compressive load on the salt and promote early healing of the salt DRZ surrounding the SMC plugs. The asphalt waterstop will seal the shaft cross-section and the DRZ.

The position of the concrete components was first determined by the location of the salt and clay columns. The components were then moved upward or downward from their initial design location to assure the components were located in regions where halite was predominant. This positioning, coupled with variations in stratigraphy, is responsible for the variations in the lengths of the salt and clay columns.

BARRIERS-3.2.2.2.4 Compacted Salt Column

Each shaft seal includes a column of compacted WIPP salt with 1.5 percent weight water added to the natural material. The compacted salt column will be constructed of crushed salt taken from the Salado. The length of the salt column varies from 170 to 172 m (556 to 567 ft) in the four shafts. The compacted salt column is sized to allow the column and concrete-asphalt waterstops at either end to be placed between the Vaca Triste Unit and MB 136. The salt will be placed and compacted to a density approaching 90 percent of the average density of intact Salado salt. The effects of creep closure will cause this density to increase with time, further reducing permeability. The salt column will offer limited resistance to fluid migration immediately after emplacement, but it will become less permeable as creep closure further compacts the salt. Salt creep increases rapidly with depth; therefore, at any time, creep closure of the shaft will be greater at greater depth. The location and initial compaction density of the compacted salt column were chosen to assure consolidation of the compacted slat column in the 100 years following repository closure. The state of salt consolidation, results of analyses predicting the creep closure of the shaft, consolidation and healing of the compacted salt, and healing of the

DRZ surrounding the compacted salt columns can be found in CCA Appendix SEAL (Sections 7.5 and 8.4). The location of the compacted salt column near the bottom of the shaft assures the fastest achievable consolidation of the compacted salt column after closure of the repository. Analyses indicate that the salt column becomes an effective long-term barrier in under 100 years.

BARRIERS-3.2.2.2.5 Asphalt Column

An asphalt-aggregate mixture is specified for the asphalt column. This column is 42 to 44 m (138 to 143 ft) in length in the four shafts. The asphalt column is located above the upper concrete-asphalt waterstop; it extends approximately 5 m (16 ft) above the Rustler/Salado interface. A 6-m (20-ft) long concrete plug (part of the Rustler seals) is located just above the asphalt column.

The existing shaft linings will be removed from a point well above the top of the asphalt column to the top of the shaft keys. The concrete shaft keys will be removed to a point just below the lowest chemical seal ring in each key. The asphalt column is located at the top of the Salado and provides an essentially impermeable seal for the shaft cross section and along the shaft wall interface. The length of the asphalt column will decrease slightly as the column cools. The procedure for placing the flowable asphalt-aggregate mixture is described in CCA Appendix SEAL (Section 6).

BARRIERS-3.2.2.2.6 Concrete Plugs

The Rustler concrete plug is constructed of SMC. The plug is 6 m (20 ft) long and will fill the shaft cross-section. The plug is placed directly on top of the asphalt column of the Salado seals. The plug will be keyed into the surrounding rock and grouted. The plug permits work to begin on the overlying clay column before the asphalt has completely cooled. The option of constructing the overlying clay columns using dynamic compaction (present planning calls for construction using compressed clay blocks) is also maintained by keying the plug into the surrounding rock. Current plans call for an SMC near-surface concrete plug (Component 2, Figure BARRIERS-5). However, freshwater concrete may be used if found to be desirable at a future time. The plug extends 12 m (40 ft) downward from the top of the Dewey Lake Redbeds. It is placed inside the existing shaft lining, and the interface is grouted.

BARRIERS-3.2.2.2.7 Earthen Fill

The upper shaft is filled with locally available earthen fill. The near-surface upper compacted earthen fill (Component 1 in Figure BARRIERS-5) will be compacted to a density near that of the surrounding material to inhibit the migration of surface waters into the shaft cross-section. The length of this column varies from 17 to 28 m (56 to 92 ft) in the four shafts. In all cases, this portion of the WIPP sealing system may be modified as required to facilitate decommissioning of the WIPP surface facilities. The near-surface lower compacted earthen fill (Component 3 in Figure BARRIERS-5) will be constructed using locally available fill, which will be placed using dynamic compaction (the same method used to construct the salt column). The fill will be compacted to a density equal to or greater than the surrounding materials to inhibit the migration of surface waters into the shaft cross-section. The length of this column varies from 136 to 148 m (447 to 486 ft) in the four shafts.

BARRIERS-3.2.2.3 Material

The four shafts will be entirely filled with dense materials possessing low permeability and other desirable engineering and economic attributes. Seal materials include concrete, clay, asphalt, and compacted salt. Other construction and fill materials include cementitious grout and earthen fill. Concrete, clay, and asphalt are common construction materials used extensively in sealing applications. Their descriptions, drawn from literature and site-specific references, are given in CCA Appendix SEAL (Appendix A). Compaction and natural reconsolidation of crushed salt are uniquely applied here. Therefore, crushed salt specification includes discussion of constitutive behavior and sealing performance, specific to WIPP applications. Cementitious grout is also specified in some detail.

Seal system components are materials possessing high durability and compatibility with the host rock. The system contains functional redundancy and uses differing materials to reduce uncertainty in performance. All materials used in the shaft seal system are expected to maintain their integrity for very long periods. Some sealing components reduce fluid flow soon after placement, while other components are designed to function well beyond the regulatory period.

A major environmental advantage of the WIPP locale is an overall lack of groundwater to seal against. Even though very little regional water is present in the geologic setting, the seal system reflects great concern for groundwater's potential influence on the shaft seal system. If the hydrologic system sustained considerable fluid flow, brine geochemistry could impact engineered materials. Brine would not chemically change the compacted salt column, but mechanical effects of pore pressure are of concern to reconsolidation. The geochemical setting will have little influence on concrete, asphalt, and clay shaft seal materials. Each material is durable because the potential for degradation or alteration is very low.

Materials used to form the shaft seals are the same as those identified in the scientific and engineering literature as appropriate for sealing deep geologic repositories for radioactive wastes. Durability or longevity of seal components is a primary concern for any long-term isolation system. Issues of possible degradation have been studied throughout the international community and within waste isolation programs in the USA. Specific degradation studies are not detailed in this document because longevity is one of the over-riding attributes of the materials selected and degradation is not perceived to be likely. However, it is acknowledged here that microbial degradation, seal material interaction, mineral transformation, such as silicification of bentonite, and effects of a thermal pulse from asphalt or hydrating concrete are areas of continuing investigation.

Among longevity concerns, degradation of concrete is the most recognized. At this stage of the design, it is established that only small volumes of brine ever reach the concrete elements (CCA Appendix SEAL, Appendix C, Section C4). Further analysis concerned with borehole plugging using cementitious materials shows that at least 100 pore volumes of brine in an open system would be needed to begin degradation processes. In a closed system, such as the hydrologic setting in the WIPP shafts, phase transformations create a degradation product of increased volume. Net volume increase owing to phase transformation in the absence of mass transport would decrease rather than increase permeability of concrete seal elements.

Asphalt has existed for thousands of years as natural seeps. Longevity studies specific to DOE's Hanford site have utilized asphalt artifacts buried in ancient ceremonies to assess long-term stability (Wing and Gee 1994). Asphalt used as a seal component deep in the shaft will inhabit a benign environment, devoid of ultraviolet light or an oxidizing atmosphere. Additional assurance against possible microbial degradation in asphalt elements is provided with addition of characteristics well beyond the regulatory period.

Natural bentonite is a stable material that generally will not change significantly over a period of 10,000 years. Bentonitic clays have been widely used in field and laboratory experiments concerned with radioactive waste disposal. As noted by Gray (1993), three internal mechanisms, illitization, silicification, and charge change, could affect sealing properties of bentonite. Illitization and silicification are thermally driven processes and, following discussion by Gray (1993), are not possible in the environment or time frame of concern at the WIPP. The naturally occurring Wyoming bentonite, which is the specified material for the WIPP shaft seal, is well over a million years old. It is, therefore, highly unlikely that the metamorphism of bentonite enters as a design concern.

BARRIERS-3.2.2.4 Conclusion

The principal conclusion is that an effective, implementable shaft seal system has been designed for the WIPP. Design guidance is addressed by limiting any transport of fluids within the shaft, thereby limiting transport of hazardous material to regulatory boundaries. The application or adaptation of existing technologies for placement of seal components combined with the use of available, common materials provide confidence that the design can be constructed. The structural setting for seal elements is compressive, with shear stresses well below the strength of seal materials. Because of the favorable hydrologic regime coupled with the low intrinsic permeability of seal materials, long-term stability of the shaft seal system is expected. Credibility of these conclusions is bolstered by the basic design approach of using multiple components to perform each sealing function and by using extensive lengths within the shafts to effect a sealing system. The shaft seal system adequately meets design requirements and can be constructed.

BARRIERS-3.2.3 Borehole Plugs

BARRIERS-3.2.3.1 Overview

Exploration drilling has been in progress in the vicinity of the WIPP since 1928 (nine township area). This drilling is done primarily for oil, gas, and potash exploration, although several water wells have been drilled. The drilling and abandonment practices for oil and gas wells or potash exploration holes are regulated by either the Bureau of Land Management (BLM) for federal land or the State of New Mexico for State and private land. The WIPP site has no control over the plugging and abandonment (P&A) of oil and gas wells in the vicinity of the site. See Section 3.2.3.3 of this appendix for a description of the regulations that apply to these oil and gas wells.

The New Mexico State Engineers Office has regulatory authority over the P&A of groundwater production and monitoring wells in the state. The State of New Mexico has several groundwater basins, with each basin having its own district office providing oversight of groundwater issues.

The WIPP area is under the jurisdiction of the Roswell, New Mexico branch of the State Engineers Office. The Roswell office will be the principal regulatory body to approve the WIPP plans for well P&A. In all cases, the permit process will be carried out through the appropriate regulatory agency. This will be the State of New Mexico, State Engineers Office for P&A of all water wells (DOE 1999).

Sealing and plugging of boreholes and monitoring wells associated with underground waste repositories has been an important issue for many years. To develop the most effective methods to limit the potential for fluids to migrate between formations within a sealed borehole, the DOE has conducted extensive research on plugging and sealing materials and emplacement technologies. In some cases, previous P&A research and regulatory compliance documents have recommended or committed to plugging test wells and boreholes following specific guidelines and techniques. In the CCA, the DOE committed to plugging WIPP's shallow boreholes within the controlled area in accordance with applicable state or federal regulations. The WIPP's deep boreholes within the controlled area will be plugged in accordance with OCD, Order R-111P (NM 1988). The WIPP Final Environmental Impact Statement (DOE 1980) states that all boreholes will be plugged with materials that are physically and chemically compatible with the surrounding rock, resistant to groundwater attack, and will securely bond to surrounding geologic materials.

BARRIERS-3.2.3.2 Monitoring Wells

As of the date of this compliance application, the DOE has 92 operational monitoring wells within the vicinity of WIPP. Of these, 17 have been drilled and put into use since submittal of the CCA (see Appendix DATA, Attachment G for a description of the groundwater monitoring wells applicable to this compliance application). Also since the CCA, 10 monitoring wells have been plugged to the surface with cement. Two new shallow wells (54 ft. and 19 ft.) were drilled and plugged with drill cuttings and bentonite gel (Appendix DATA, Attachment G).

Existing boreholes within the controlled area are identified in Figure BARRIERS-6. Of these boreholes, four exceed the depth of the repository and the rest are shallow boreholes that do not reach the repository horizon.

When no longer needed, the four deep wells, DOE 1, ERDA 9, WIPP 12, and WIPP 13 will be plugged according to the State of New Mexico, Oil and Conservation Division, Order R-111-P. See Figures BARRIERS-6 and BARRIERS-7.

The key provisions of Order No. R-111-P are as follows:

- A salt protection string of casing must be installed at least 100 feet (30 meters) below and not more than 600 ft (183 m) below the base of the salt section. Cementing requirements for both shallow wells (above 5,000 ft [1,524 m]) and deep wells (below 5,000 ft [1,524 m]) above or below the Delaware Mountain Group are specified.

- All oil and gas wells drilled within the potash area must provide a solid cement plug through the salt section and any water bearing horizon and prevent liquids or gases from entering the hole above or below the salt section.

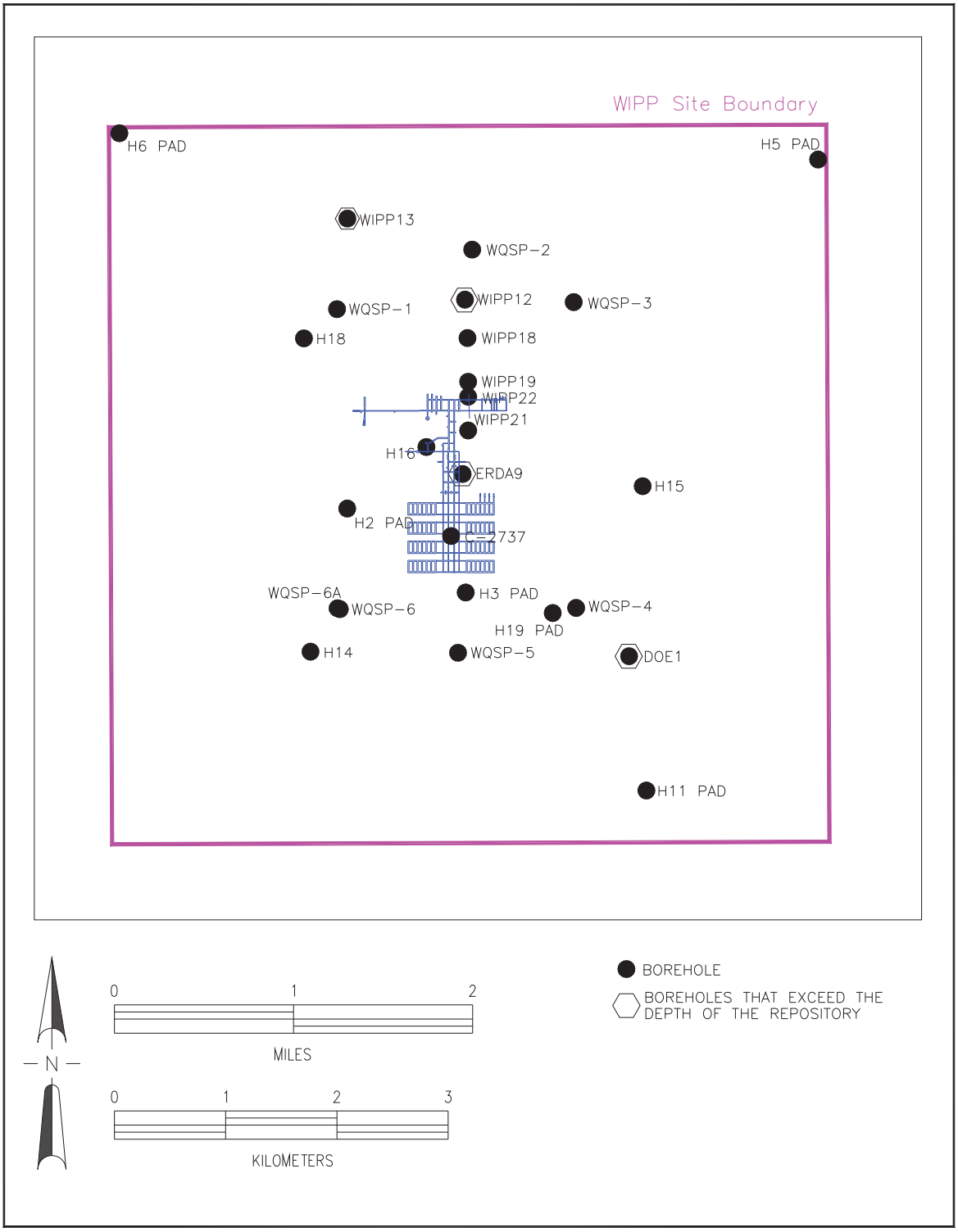

Figure BARRIERS-6. Approximate Locations of Unplugged Boreholes

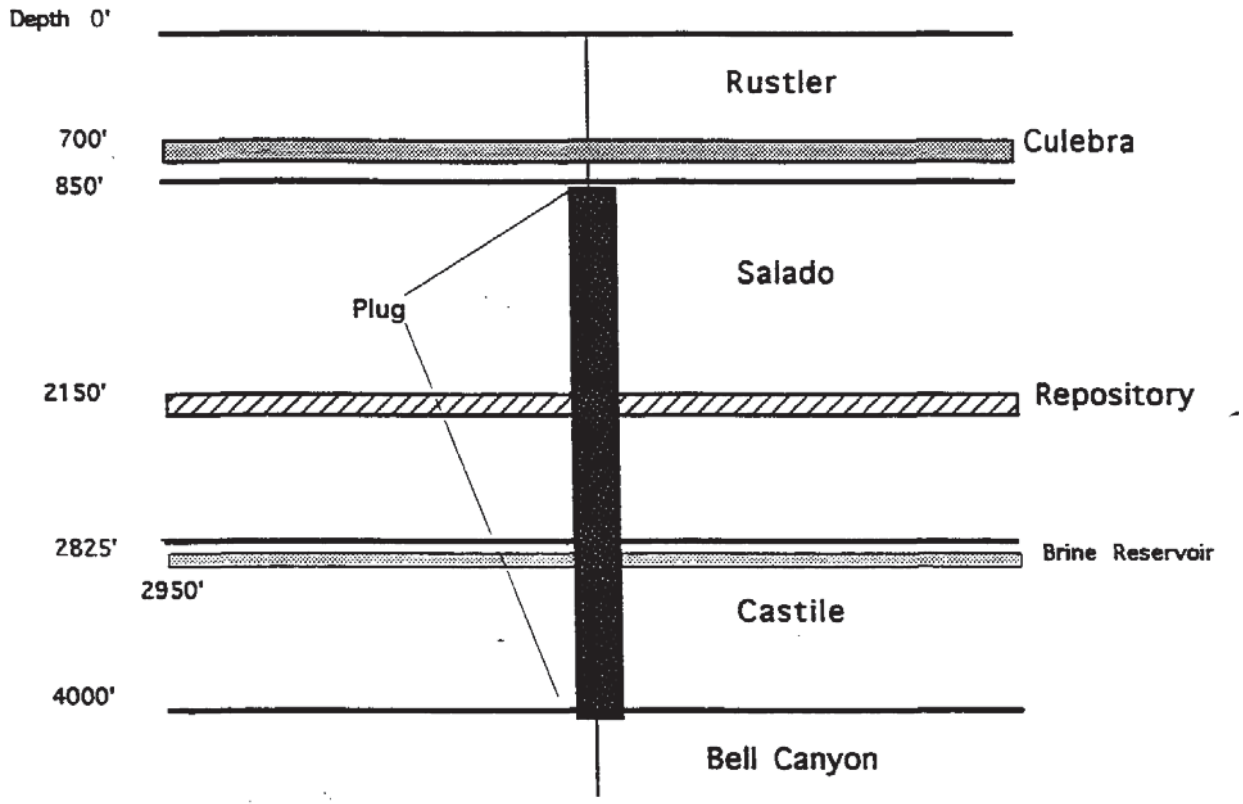

Figure BARRIERS-7. Schematic Diagram for a Continuous Plug

- The fluid used to mix the (plugging) cement must be saturated with salts common to the salt section penetrated but not more than three percent of calcium chloride by weight of cement wherever possible.

As mentioned above, WIPP has been plugging monitoring wells with cement plugs from the bottom to the top of the borehole.

The boreholes not being used for monitoring will be plugged at decommissioning. These boreholes will be plugged to limit the volume of water that could be introduced to the repository from the overlying water-bearing zones and the volume of contaminated brine that could be released from the repository to the accessible environment.

BARRIERS-3.2.3.3 <u>Well Plugging and Abandonment Practices</u>

A description of the plugging and abandonment practices in the area around the WIPP, initially provided in CCA Appendix DEL, is discussed in Sections 3.2.3.3.5 through 3.2.3.4 of this appendix. The representation of borehole plugs in PA is presented in Chapter 6.0, Section 6.4.7.2.

BARRIERS-3.2.3.3.1 BLM Oil and Gas Plugging and Abandonment

The BLM regulations on oil and gas plugging and abandonment in 43 CFR § 3162.3-4 and Oil and Gas Order No. 2 are discussed in detail in CCA Appendix DEL, Section DEL.4.1.2.2. This section serves as a summary of that discussion.

BARRIERS-3.2.3.3.1.1 Oil and Gas Well Plugging Sequence

The first step in plugging and abandoning a well is the submission of the Sundry Notice (Form 3160-5, Attachment 2) that informs the BLM of the operator's intent to abandon the well. This form must include a plan by the operator detailing how the well will be plugged. BLM inspectors will review and approve the plan as presented or make modifications that the operator must follow.

The operator must provide a 24-hour notice to the BLM before beginning abandonment operations in order to allow BLM personnel an opportunity to witness the operation. BLM does not consider the plugging and abandonment procedure completed until a surface cap has been welded on the opening to the casing, a 4-in (10 cm)-diameter pipe, 10 ft (3 m) long, has been embedded in cement and extended 4 feet (1 m) above ground level, and the cellars have been filled to the surface. When all phases of the abandonment are complete and have been inspected, the well plugging bond may be released (see CCA Appendix DEL, Section DEL.6.1.5).

Plugging operations are typically carried out using a pulling unit (a truck with a large mounted derrick). The pulling unit sets up over the wellbore and is used to complete the plug and abandonment operation. The first step in the plugging process is to set the required cast iron bridge plug at the depth shown in the plugging plan approved by the BLM. The point of placement for the bridge plug is just above the uppermost production perforations in the casing. Once the bridge plug is in place, the pulling unit operator will tag the bridge plug (touch the top of the plug with the tubing) to make certain that it is set at the correct depth as specified on the plugging plan contained in Form 3160-5 (Attachment 2).

When the proper depth is confirmed, a minimum of 25 ft (8 m) of cement is placed on top of the bridge plug. The operator will then fill the borehole with at least nine-lb mud or brine water, filling the borehole to the site of the next plug location. The viscosity of the mud allows the operator to then pump a type C or H cement through the tubing to its correct depth on top of the mud. The mud column will support the weight of the cement until it sets up. The operator, if required by the BLM, will again tag the top of the cement to verify both the position and length of the plug.

While the NMOCD has inspection personnel on site in every instance to verify this process, the BLM elects to witness only selected plugging operations. The process of setting plugs will continue in the same manner until each of the plugs identified on the plugging plan has been properly placed. At this point, plugging operations are complete. The only remaining requirement to complete the plug and abandonment operation is that of returning the drill pad to a near-original state. This process may be completed in only a few days or possibly up to several months after plugging has been completed.

BARRIERS-3.2.3.3.1.2 Plugging of Temporarily Abandoned Wells

Wells may be temporarily abandoned for up to five one-year periods with BLM approval (see CCA Appendix DEL, Section DEL.6.1.2.3). A Sundry Notice must be submitted requesting temporary abandonment (Form 3160-5, Attachment 2). The notice must include a description of the abandonment procedure, a complete wellbore diagram, and the anticipated date the operations will occur. As with plugging and abandonment, this plan must be reviewed and approved by BLM inspectors. Once approved, a 48-hour notice must be given to BLM to allow an opportunity for the plugging inspection. Operators must install a bridge plug or a cement plug 50 to 100 ft (15 to 30 m) above the perforations. If a cement plug is chosen, it must be tagged to make certain it is at the proper depth. Bridge plugs are set using a wireline with the proper depth being verified before the plug is set.

The integrity of the casing must be also be verified. If testing indicates problems with the casing, repairs must be made before the well may be temporarily abandoned.

BARRIERS-3.2.3.3.1.3 Plugging in the Potash Resource Area

BLM requirements for plugging and abandonment in the potash areas are the same as in non-potash areas. Although the BLM has not overseen the plugging of any oil or gas wells in the potash area in a number of years, the requirements of the New Mexico Oil Conservation Commission (NMOCC) Order R-111-P (see CCA Appendix DEL, Section DEL.6.2.4) will be considered at the appropriate time (Personal Communication 1996a). According to the Secretary of the Interior Order of October 28, 1986 (51 FR 39425) on oil, gas, and potash leasing, the BLM will cooperate with the NMOCD in implementing state rules and regulations although the BLM will make the final decision.

BARRIERS-3.2.3.3.1.4 Most Common Technical Violations for Oil and Gas Well Plugging

Large national oil companies and large independent companies normally comply strictly with the oil and gas well plugging requirements. Large businesses, which have the necessary resources to properly plug and abandon their wells, typically contract with other large businesses to perform their plugging operations. It has been BLM's experience that these companies follow sound business practices and wish to remain in good standing with the BLM. Smaller, independent operators are more likely to lack resources to respond as quickly to the BLM and may not plug a well with the same expertise that a larger established company might have. The BLM is aware of situations that pose a potential for improper plugging. If the agency has a concern regarding a contractor's methods, BLM personnel are present during the entire plugging operation (Personal Communication 1996b).

Plugging bonds are required to ensure that wells are plugged and abandoned properly and within a reasonable time frame (see CCA Appendix DEL, Sections DEL.6.1.5 and DEL.6.2.1). Both NMOCD and BLM have experienced higher rates recently of what they refer to as "orphan wells." These are wells that should be plugged and abandoned, but the owners of these wells cannot be located. When this occurs, plugging of these wells becomes the responsibility of the agency upon whose land they are located. Both agencies have orphan-well-plugging funds that are funded partially through plugging bonds that have not been returned and money from their

operating budgets. These orphan wells are a matter of concern to both agencies, and they are working to conserve financial resources for plugging.

BARRIERS-3.2.3.3.2 State of New Mexico Oil and Gas Plugging and Abandonment

The NMOCD regulations on well plugging and abandonment are discussed in CCA Appendix DEL, Sections DEL.6.2.2 and DEL.6.2.3. They are similar in many respects to the BLM requirements.

BARRIERS-3.2.3.3.2.1 Plugging Outside the Potash Resource Area

The major distinction between NMOCD and BLM practices is that NMOCD witnesses every well plugging and abandonment operation on state and private land, whereas the BLM is only able to witness approximately 50 percent of the plugging operations on federal leases. Both agencies require sundry notices to be filed with an abandonment plan and both agencies review and approve or modify those plans.

BARRIERS-3.2.3.3.2.2 Plugging Within the Potash Resource Area (R-111-P)

Operators must follow the same procedures within the potash enclave as they do in other areas, with the exception that the NMOCD requires the operator to run a solid cement plug through the entire salt section and water bearing zones in addition to installing a bridge plug above the perforations. Installing a solid cement plug through the salt provides additional assurance that no fluids or gases escape through the casing into potash mining areas or fresh water formations (see CCA Appendix DEL, Section DEL.6.2.3 on NMOCC Order R-111-P).

BARRIERS-3.2.3.3.2.3 Most Common Technical Violations for State of New Mexico Oil and Gas Well Plugging

Because NMOCD inspectors are able to witness 100 percent of the plugging and abandonment operations, technical violations are very rare. NMOCD inspectors are present for each step in the plugging operation. Operators are informed that plugging operations are not to begin before NMOCD inspectors are on site. If NMOCD inspectors are not present when plugging operations begin, the operator may be required to remove everything from the well and start over. The NMOCD also requires plugging bonds to be secured by the operator before plugging and abandonment are carried out (see CCA Appendix DEL, Section DEL.6.2.1). The bond is not released until all requirements for plug and abandonment have been properly completed (Personal Communication 1996c).

BARRIERS-3.2.3.3.3 Plugging of Oil and Gas Service Wells

Oil and gas operators are required to follow NMOCD Rule 705 on commencement, discontinuance, and abandonment of injection operations when plugging an injection well. This rule requires operators to file a Notice of Discontinuance when a decision has been made to cease injection operations. The rule forbids temporary abandonment of service wells. Plugging requirements are the same as when plugging oil and gas wells or dry holes.

BARRIERS-3.2.3.3.4 Plugging of Potash Coreholes

In June 1975, the land that is now the WIPP land withdrawal area became part of the Carlsbad Underground Water Basin. This placed potash coreholes under the jurisdiction of the State Engineer. A review of the records maintained by BLM on commercial potash coreholes indicates that, since 1975, 155 coreholes have been drilled and plugged in the New Mexico portion of the Delaware Basin. Of the 155 coreholes, 151 were plugged from bottom to top with solid cement while four were plugged with a mixture of mud and cement. As indicated by this review, the current plugging practice is to fill potash coreholes with a cement slurry from the bottom of the hole to the surface.

BARRIERS-3.2.3.3.5 Plugging of Water Wells

The State Engineer has authority for all water wells. The State Engineer must be notified when a well is to be plugged and then designates how it is to be plugged. The method typically used in the Carlsbad Underground Water Basin is to remove all casing from the hole, clean the hole to the bottom using a sand pump or a cable tool drilling rig with a bailer, and fill the hole with red clay. The red clay is compacted as the hole is filled. Another method of filling the hole is to circulate the hole full of cement. This method is more expensive and is not typically used.

BARRIERS-3.2.3.4 Conclusion

The WIPP is surrounded by land where oil and gas drilling is taking place. Plugging and abandonment of these oil and gas wells is regulated by either the BLM or the State of New Mexico, depending on the ownership of the land. Water wells also exist in the vicinity of WIPP and are regulated by the State of New Mexico. WIPP has no control over the plugging and abandonment of these wells.

WIPP has drilled monitoring wells to sample for constituents. These wells are regulated by the State of Mexico and will be plugged and abandoned according to the regulations when they are no longer needed for monitoring.

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Xiong, Y.-L., and A.C. Snider. 2003. "Carbonation Rates of the Magnesium Oxide Hydration Product Brucite in Various Solutions," *Sandia National Laboratories Technical Baseline Reports*, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI 03-210, January 31, 2003. Sandia National Laboratories. Carlsbad, NM. ERMS 526049. 4.3-1 to 4.3-11.

Yamamoto, O. Sawai, J., Hotta, M., Kojima, H., and T. Sasamoto. 1998. "Growth Inhibition of Bacteria by MgO-ZnO Solid-Solution Powders," *Journal of the Ceramic Society of Japan*. Vol. 106, no. 12, 1252-1254.

Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix DATA

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix DATA

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DATA 1.0 INTRODUCTION

Appendix DATA provides the data used to develop the 2004 Compliance Recertification Application (CRA). Interpretation and analysis of that data is provided in the appropriate sections of CRA-2004.

Title 40 of the Code of Federal Regulations (CFR) paragraph 194.15, Content of Recertification Applications (Sections 194.15 (a) (1), (2), (3), and (5)), requires that the U.S. Department of Energy (DOE) provide information gained since the Compliance Certification Application (CCA) related to site geology, hydrology, meteorology, and emplaced waste. Additional monitoring results and the results of laboratory investigations completed after the CCA must also be provided, as well as information regarding the waste emplaced in the disposal system.

In the initial U.S. Environmental Protection Agency (EPA) certification of compliance for the WIPP (63 FR 27354), the EPA agreed that 10 compliance monitoring parameters (COMPs) would be monitored during the operational period of the project. Of the 10, subsidence does not have to be monitored during the operational period, but is done to gage the behavior of the disposal system. This document provides monitoring data related to these COMPs. The locations, in this appendix, of the data for the COMPS are listed below:

COMP	Location of Relevant Data
Culebra groundwater composition	Sections 5, 10, 11, and Attachment C
Change in Culebra groundwater flow	Sections 5, 10, 11, and Attachment B
Probability of encountering a Castile brine reservoir	Sections 2, 10, and Attachment A
Drilling rate	Sections 2, 10, and Attachment A
Subsidence measurement	Sections 3 and 10
Waste activity	Sections 7, 10, and Attachments D-F
Creep closure and stresses	Sections 4 and 10
Extent of brittle deformation	Sections 4, 9, and 10
Initiation of brittle deformation	Sections 4 and 10
Displacement of deformation features	Sections 4 and 10

Monitoring is performed to detect substantial deviations from the assumptions used in the CCA. The above COMPs are being monitored during the pre-closure period.

DATA 2.0 DELAWARE BASIN DRILLING SURVEILLANCE PROGRAM (DBDSP)

The Delaware Basin Drilling Surveillance Program monitors drilling activities in the vicinity of WIPP. This section provides a brief discussion of that program and identifies the relevant data reports.

DATA 2.1 Program Overview

The EPA requires the DOE to demonstrate the expected containment performance of the disposal system using a performance assessment (PA). The PA documented in the CCA demonstrated that the WIPP complies with the EPA's containment standards for undisturbed and human intrusion scenarios.

The EPA required the use of historic drilling information to derive the drilling rate for PA intrusion scenarios. The DBDSP monitoring data is used to determine the drilling rate and continues to monitor drilling related activities to ensure the assumptions and scenarios used in PA remain valid. These monitoring activities will continue until the DOE and EPA agree that no benefit can be gained by further monitoring.

DATA 2.2 Reported Data

Relevant data generated through the Delaware Basin Monitoring Program are provided in Attachment A, as well as the following reports.

- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 0, September 1999.
- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 1, September 2000.
- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 2, September 2001.
- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 3, September 2002.

DATA 3.0 SUBSIDENCE MONITORING PROGRAM (SMP)

Subsidence monitoring is the measurement of vertical movement of the land surface relative to a reference location, using state-of-the-art leveling equipment. This section provides a brief discussion of this program and identifies the relevant data reports.

DATA 3.1 Program Overview

The subsidence monitoring program uses a leveling survey to measure the relative vertical height differences between benchmarks placed a known distance apart. Usually, one reference benchmark is the standard and the relative movement of the other benchmarks is measured to detect vertical height differences. Land surface movement is determined by comparing more recent survey data with survey results from earlier surveys. Subsidence measurements would detect substantial deviations from expected subsidence.

DATA 3.2 Reported Data

Data generated through the Subsidence Monitoring Program are provided in the following reports. Each report is inclusive of previous data collection activities.

- WIPP Subsidence Monument Leveling Surveys 1986, 1997, DOE/WIPP 98-2293, June 1998.
- WIPP Subsidence Monument Leveling Surveys 1998, DOE/WIPP 99-2293, October 1998.
- WIPP Subsidence Monument Leveling Surveys 1999, DOE/WIPP 00-2293, October 1999.
- WIPP Subsidence Monument Leveling Surveys 2000, DOE/WIPP 01-2293, October 2000.
- WIPP Subsidence Monument Leveling Surveys 2001, DOE/WIPP 02-2293, October 2001.
- WIPP Subsidence Monument Leveling Surveys 2002, DOE/WIPP 03-2293, October 2002.

DATA 4.0 GEOTECHNICAL MONITORING PROGRAM (GMP)

The geotechnical monitoring program measures in-situ geotechnical data in the WIPP repository. This section provides a brief discussion of the geotechnical monitoring program and identifies the relevant data reports.

DATA 4.1 Program Overview

The geotechnical monitoring program obtains in-situ data to support the continuous assessment of underground facilities. A detailed description of the geotechnical programs and procedures is presented in WP07-1, Geotechnical Engineering Program Plan. Specifically, the program provides for:

- early detection of conditions that could affect operational safety;
- guidance for design modifications and remedial actions; and
- data for interpreting the behavior of underground openings in comparison with established design criteria.

The geotechnical programs generate instrumentation data and observations, confirm the understanding of site characteristics, and aid in the assessment of the stability and performance of the underground facility. Associated programs include the Geosciences Program, the Geomechanics Program, and the Rock Mechanics Program. They are described in the following paragraphs.

The Geosciences Program serves to confirm site suitability through surface and underground field investigations. These activities generate data used in monitoring the repository and in rock mechanics studies. Information from the Geosciences Program is used to document the existing geologic conditions and characteristics and to monitor excavation response. Activities associated with this program include geologic and fracture mapping of the excavation surface, core logging, and borehole observations.

The Geomechanics Program monitors the geomechancial response of the underground openings after mining using instrumentation installed in the shafts and drifts of the facility. Geotechnical instrumentation installed underground in the shafts and drifts include tape extensometer points, convergence meters, borehole extensometers, piezometers, strain gages, load cells, and crack meters. The instrumentation is sensitive enough to detect small changes in rock displacements and stresses.

In order to determine significant deviations from expected conditions, the Rock Mechanics Program assesses the performance of the WIPP for long-term safety and excavation stability of the underground openings during the operational phase. The results from these assessments allow the identification of areas of potential instability and the application of remedial actions, if necessary. Field data are used to compare the actual mechanical performance of the excavations to expected results. Analytical methods, such as numerical modeling, are used to determine the potential effects of mining new excavations, excavation sequence, and long-term behavior of the

repository. The time-dependent properties of the salt are of significance. Extensive experimental work and observations have established an appropriate, constitutive relationship for salt that is used to predict its in-situ mechanical performance. These assessments rely heavily on the in-situ instrumentation data and field observations from the geosciences and geomechanics programs.

DATA 4.2 Reported Data

Data generated through the geotechnical monitoring program are reported annually in the Geotechnical Analysis Report. References for these reports prepared since the development of the CCA are provided below. Each report is inclusive of previous data collection activities.

- Westinghouse Electric Corporation, 1997, Geotechnical Analysis Report for July 1995 – June 1996, Carlsbad, NM.
- Westinghouse Electric Corporation, 1998, Geotechnical Analysis Report for July 1996 – June 1997, DOE/WIPP 98-3118, Carlsbad, NM.
- Westinghouse Electric Corporation, 1999, Geotechnical Analysis Report for July 1997 – June 1998, DOE/WIPP 99-2300, Carlsbad, NM.
- Westinghouse TRU Solutions, LLC, 2000, Geotechnical Analysis Report for July 1998 – June 1999, DOE/WIPP 00-3177, Carlsbad, NM.
- Westinghouse TRU Solutions, LLC, 2001, Geotechnical Analysis Report for July1999 – June 2000, DOE/WIPP 01-3177, Carlsbad, NM.
- Westinghouse TRU Solutions, LLC, 2002, Geotechnical Analysis Report for July2000 – June 2001, DOE/WIPP 02-3177, Carlsbad, NM.
- Washington TRU Solutions, LLC, 2003, Geotechnical Analysis Report for July 2001 – June 2002, DOE/WIPP 03-3177, Carlsbad, NM.

DATA 5.0 GROUNDWATER MONITORING PROGRAM (GWMP)

The Groundwater Monitoring Program collects and analyzes groundwater from various wells at or near the WIPP Site. This section briefly describes the GWMP and identifies relevant reports.

DATA 5.1 Program Overview

The GWMP is designed to ensure compliance with the WIPP Compliance Certification mandated by 40 CFR 191 Subparts B and C. One function of the GWMP most relevant to compliance with 40 CFR 191 Subparts B and C and 40 CFR 194 is the collection of Culebra groundwater data such as water levels and water quality from numerous wells located at and near the facility. The Culebra was selected as the focus of the GWMP. It has been extensively studied during past hydrologic characterization programs and was found to be the most likely hydrologic pathway to the accessible environment for any potential human-intrusion-caused release scenario. Data obtained through this program are used to generate the Culebra groundwater composition and the Culebra groundwater flow COMP parameters. Details on how the program is implemented are provided in Appendix MON-2004.

DATA 5.2 Reported Data

Attachment B provides a summary of water levels during the recertification time frame. Attachment C shows the water quality data for the Water Quality Sampling Program (WQSP) wells. The annual Site Environmental Reports listed below provide data relevant to the GWMP.

- Westinghouse Electric Corporation, 1996, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1995, DOE/WIPP 96-2182, Carlsbad, NM.
- Westinghouse Electric Corporation, 1997, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1996, DOE/WIPP 97-2225, Carlsbad, NM.
- Westinghouse Electric Corporation, 1998, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1997, DOE/WIPP 98-2225, Carlsbad, NM.
- Westinghouse Electric Corporation, 1999, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1998, DOE/WIPP 99-2225, Carlsbad, NM.
- Environmental Science & Research Foundation, 2000, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1999, DOE/WIPP 00-2225, Carlsbad, NM.
- Environmental Science & Research Foundation, 2001, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 2000, DOE/WIPP 01-2225, Carlsbad, NM.
- Westinghouse TRU Solutions, 2002, Waste Isolation Pilot Plant 2001 Site Environmental Report, DOE/WIPP 02-2225, Carlsbad, NM.
- Washington Regulatory & Environmental Services, 2003, Waste Isolation Pilot Plant Site Environmental Report Calendar Year 2002, DOE/WIPP 03-2225, Carlsbad, NM.

DATA 6.0 METEOROLOGICAL MONITORING PROGRAM

The meteorological monitoring program measures atmospheric data for the WIPP Site. This section provides a brief description of the program and a list of relevant reports.

DATA 6.1 Program Description

The primary WIPP meteorological station is located 600.5 m (1,970 ft) northeast of the Waste Handling Building. The main function of the station is to provide data for atmospheric modeling. The station measures and records wind speed, wind direction, and temperature at elevations of 2, 10, and 50 m (6.5, 33, and 165 ft). The station records ground-level measurements of barometric pressure, relative humidity, precipitation, and solar radiation.

DATA 6.2 Reported Data

The annual Site Environmental Reports listed in Section 5.2 provide data relevant to the Meteorological Monitoring Program. CCA Appendix CLI provides information on past (long-term) climatic conditions and possible future expectations at the WIPP site.

DATA 7.0 WASTE INFORMATION

Two types of information related to waste characteristics are collected: (1) information regarding the waste that has been emplaced in the WIPP underground repository; and (2) information regarding the future inventory that will be emplaced in the WIPP underground repository during the entire lifetime of the project. This section provides a brief description of the programs and a list of relevant reports.

DATA 7.1 Program Overview

Information concerning waste that has been emplaced in the repository is tracked and recorded using the WIPP Waste Information System (WWIS), as described in Chapter 4 of this document. Information concerning future wastes is developed through periodic updates of the Transuranic Waste Baseline Inventory Report (BIR) of DOE (1996). To capture changes in the TRU waste inventory since the CCA, each TRU waste site reviewed data submitted to the 1996 CCA and made revisions as appropriate. The TRU Waste Inventory Update Report (2003) information is based on estimations of existing waste volumes, as well as estimations of waste volumes to be generated by future activities.

DATA 7.2 Reported Data

Attachment D provides summary information based on the emplaced waste data in the WWIS as of 9/30/2002. Attachment E is the WWIS summary data for radionuclides as of 9/30/2002.

The TRU Waste Inventory Update Report, 2003, Attachment F, provides information regarding future inventories planned for emplacement in the WIPP.

DATA 8.0 WIPP BOREHOLES

Information regarding WIPP monitoring wells is identified in this section and relevant data are provided.

DATA 8.1 Program Overview

Information provided in this section was reported in DOE/WIPP 95-2092, Rev. 1, Waste Isolation Pilot Plant Borehole Data Report (CCA Appendix BH). The purpose of CCA Appendix BH was to serve as a central document providing data on boreholes. The report contained a comprehensive database on wells drilled in support of the WIPP and boreholes that were located within the 16-section Land Withdrawal Area.

DATA 8.2 Reported Data

Attachment G provides updates on all of the monitoring wells used in Appendix BH and the new monitoring wells drilled since the initial certification. The attachment also adds the wells that were in use but inadvertently omitted from CCA Appendix BH.

DATA 9.0 REPOSITORY INVESTIGATIONS

The WIPP repository investigations program conducts research activities to confirm assumptions, reduce uncertainty and resolve issues regarding the conceptual models and parameters used in performance assessment. The program is briefly described in this section and references to relevant reports are provided.

DATA 9.1 Program Overview

The DOE has implemented and/or continued several experimental activities that were designed to address specific issues/needs of the WIPP repository. In addition, other investigations have been initiated to examine impacts of planned changes. The general areas covered under these investigations include:

- geochemistry,
- engineered barriers, and
- rock mechanics.

DATA 9.2 Reported Data

Data acquired by the DOE from the repository investigations are available in the following reports published since the initial certification:

- Los Alamos National Laboratory, The Actinide Source-Term Waste Test Program (STTP) Final Report, Volume I, LA-UR-01-6822, Summer 2001.
- Sandia National Laboratories, 2001a, “Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.4, Repository Investigations, Milestone RI010, January 31, 2001,” ERMS 516749, Sandia WIPP Records Center, Carlsbad, NM.
- Sandia National Laboratories, 2001b, “Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.4, Repository Investigations, Milestone RI020, July 31, 2001,” ERMS 518970, Sandia WIPP Records Center, Carlsbad, NM.
- Sandia National Laboratories, 2002a, “Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI110, January 31, 2002,” ERMS 520467, Sandia WIPP Records Center, Carlsbad, NM.
- Sandia National Laboratories, 2002b, “Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI130, July 31, 2002,” ERMS 523189, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2003, “Sandia National Laboratories Technical Baseline Report, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI 03-210, January 31, 2003,” ERMS 526049, Sandia WIPP Records Center, Carlsbad, NM

DATA 10.0 COMPLIANCE MONITORING PROGRAM (CMP)

Annually, the CMP extracts data from the repository investigations and five of the monitoring programs described above (DBDSP, SMP, GMP, GWMP, and WWIS) to derive values for the ten COMPs described in Section DATA 1.0 and to evaluate if significant changes in the parameters have occurred. The CMP activities are briefly described in this section. Data generated under the CMP are also identified.

DATA 10.1 Program Overview

The objective of the CMP is to provide assurance that any deviations from the expected long-term performance of the repository are identified at the earliest possible time. The CMP is implemented in accordance with DOE/WIPP-99-3119, 40 CFR Parts 191 and 194 Compliance Monitoring Implementation Plan. Annual evaluations of the compliance parameters follow the requirements found in Sandia Analysis Plan AP-069, An Analysis Plan for Annually Deriving Compliance Monitoring Parameters and their Assessment Against Performance Expectations to Meet the Requirements of 40 CFR § 194.42.

DATA 10.2 Reported Data

The data and the results of the annual COMPs assessments performed in accordance with the requirements of the CMP are provided in the four reports cited below.

- Sandia National Laboratories, 2000a, “Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment (for Year 1998), WBS 1.2.10.09.01.02, Pkg. No. 510062, July,” Carlsbad, NM.

- Sandia National Laboratories, 2000b, “Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment (for Year 1999), WBS 1.2.10.09.01.02, Pkg. No. 510062, October,” Carlsbad, NM.

- Sandia National Laboratories, 2001, “Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment Report (for Year 2001), WBS 1.3.5.3.1, Pkg. No. 510062, October,” Carlsbad, NM.

- Sandia National Laboratories, 2002, “Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment (for Year 2002), WBS 1.3.5.3.1, 191/194 Compliance Monitoring, November,” Carlsbad, NM.

DATA 11.0 HYDROLOGIC INVESTIGATIONS

The Exhaust Shaft Hydraulic Assessment was initiated in September 1996 to investigate the source and extent of water seepage into the exhaust shaft at the WIPP, and an investigation of rising water levels in the Culebra member was initiated in 1999. These hydrologic investigations are briefly described in this section. Sources of data generated from the investigations are also identified.

DATA 11.1 Program Overview

DATA 11.1.1 Exhaust Shaft Hydraulic Assessment

Investigations led to the observation of a shallow perched groundwater horizon in a saturated layer within the lower Santa Rosa Formation and the upper Dewey Lake Formation, about 15 m (49 ft) below ground surface. During the original drilling of the shaft, no water was encountered at that horizon, indicating that the presence of water may be related to site activities subsequent to shaft drilling. Three wells and 12 piezometers were installed over an 80-acre area between September 1996 and July 1997. Water level and water quality parameters have been monitored and reported on a regular basis since installation.

DATA 11.1.2 Culebra Water-Level Rise Investigation

During the 1999 annual COMPs assessment, Culebra water levels in many of the WIPP monitoring wells exceeded the ranges of uncertainty established for equilibrium freshwater heads used in the CCA to calibrate transmissivity fields needed for Culebra flow and transport calculations. Culebra water-level rises had also been observed at the time of the CCA submittal in 1996, but were attributed to natural recovery of water levels following years of hydraulic well testing at the WIPP site and grouting of the WIPP shafts to prevent observed leakage. Subsequent to the 1999 COMPs assessment, Culebra water levels showed a continued rise even though water levels at the WIPP site were thought to have fully recovered from hydraulic testing and shaft grouting. In response to this observation, the DOE initiated an investigation into the cause of the water-level rise and the impact of the rise on the long-term performance of the WIPP.

DATA 11.2 Reported Data

Data acquired from the two hydrologic investigations are provided in the reports cited below under separate headings for the exhaust shaft hydraulic assessment and the Culebra water-level rise investigation.

DATA 11.2.1 Exhaust Shaft Hydraulic Assessment

The Geotechnical Analysis Reports listed in Section 4.2 provide data relevant to the exhaust shaft hydraulic assessment.

- INTERA, 1997, “Exhaust Shaft Hydraulic Assessment Data Report,” DOE-WIPP 97-2219, Carlsbad, NM, Waste Isolation Pilot Plant.

- U.S. Department of Energy, 1997, "Exhaust Shaft: Phase 2 Hydraulic Assessment Data Report Involving Drilling, Installation, Water-Quality Sampling and Testing of Piezometers 1 – 12," DOE-WIPP 97-2278, Carlsbad, NM, Waste Isolation Pilot Plant.

- U.S. Department of Energy, 2000, "Exhaust Shaft: Phase III Hydraulic Assessment Data Report, October 1997 – October 1998," DOE-WIPP 99-2302, Carlsbad, NM, Waste Isolation Pilot Plant.

DATA 11.2.2 Culebra Water-Level Rise Investigation

- Beauheim, R.L, 2002, "Analysis Plan for Evaluation of the Effects of Head Changes on Calibration of Culebra Transmissivity Fields, AP-088, Rev. 1," ERMS 524785, Carlsbad, NM, Sandia National Laboratories.

- Chace, D.A., 2003a, "Testing of Wells at the WIPP Site, Test Plan TP 03-01, Rev. 0," ERMS 525667, Carlsbad, NM, Sandia National Laboratories.

- Chace, D.A., 2003b, "Compliance Monitoring Program: Recompletion and Testing of Wells for Evaluation of Monitoring Data from the Magenta Member of the Rustler Formation at the WIPP Site, Test Plan TP 00-03, Rev. 1," ERMS 525860, Carlsbad, NM, Sandia National Laboratories.

- Holt, R.M., 2002, "Analysis Report Task 2 of AP-088 Estimating Base Transmissivity Fields," ERMS 523889, Carlsbad, NM, Sandia National Laboratories.

- Holt, R.M., 2003a, "Addendum to Analysis Report Task 2 of AP-088 Estimating Base Transmissivity Fields," ERMS 527601, Carlsbad, NM, Sandia National Laboratories.

- Holt, R.M., 2003b, "Addendum 2 to Analysis Report Task 2 of AP-088 Estimating Base Transmissivity Fields," ERMS 529416, Carlsbad, NM, Sandia National Laboratories.

- Jepsen, R.A., 2000, "Test Plan, TP 99-10 Groundwater Monitoring Activities: Troll Measurements, Bell Canyon Injection Well Monitoring Near H-9, and Meteorological Monitoring at H-9, Rev. 0," ERMS 509869, Carlsbad, NM, Sandia National Laboratories.

- Lowry, T.S., 2003. "Analysis Report Task 5 of AP-088 Evaluation of Mining Scenarios," ERMS 531138, Carlsbad, NM, Sandia National Laboratories.

- McKenna, S.A., and D. Hart, 2003a, "Analysis Report Task 3 of AP-088 Conditioning of Base T Fields to Steady-State Heads," ERMS 529633, Carlsbad, NM, Sandia National Laboratories.

- McKenna, S.A., and D. Hart, 2003b, "Analysis Report Task 4 of AP-088 Conditioning of Base T Fields to Transient Heads," ERMS 531124, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., 2001, "Examining Culebra Water Levels, TP 01-01, Rev. 0," ERMS 518995, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., 2002a, "Analysis Report Task 1 of AP-088 Construction of Geologic Contour Maps," ERMS 522086, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., 2002b, "Addendum to Analysis Report Task 1 of AP-088 Construction of Geologic Contour Maps," ERMS 523886, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., 2003a, "Addendum 2 to Analysis Report Task 1 of AP-088 Construction of Geologic Contour Maps," ERMS 525199, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., 2003b, "Test Plan for Geohydrological Conceptual Model for the Dewey Lake Formation in the Vicinity of the Waste Isolation Pilot Plant (WIPP), TP 02-05, Rev. 0," ERMS 526493, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., Holt, R.M., Beauheim, R.L., and McKenna, S.A. (2003 in press). "Geological factors related to the transmissivity of the Culebra Dolomite Member, Permian Rustler Formation, Delaware Basin, southeastern New Mexico," in Johnson, K.S., and Neal, J.T., eds., Evaporite Karst and Engineering/Environmental Problems in the United States: Oklahoma Geological Survey Circular 109.

- Sandia National Laboratories, 2001a, "Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.4, Repository Investigations, Milestone RI010, January 31, 2001," ERMS 516749, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2001b, "Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.4, Repository Investigations, Milestone RI020, July 31, 2001," ERMS 518970, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2002a, "Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI110, January 31, 2002," ERMS 520467, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2002b, "Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI130, July 31, 2002," ERMS 523189, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2003a, "Sandia National Laboratories Technical Baseline Report, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI 03-210, January 31, 2003," ERMS 526049, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2003b. "Program Plan WIPP Integrated Groundwater Hydrology Program, FY03-FY09, Revision 0, March 14, 2003." ERMS 526671, Sandia WIPP Records Center, Carlsbad, NM.

- U.S. Department of Energy, 2003, Strategic Plan for Groundwater Monitoring at the Waste Isolation Pilot Plant. DOE/WIPP-03-3220, February 2003, Carlsbad, NM.

DATA 12.0 WASTE CONTAINERS AND EMPLACEMENT

Information regarding WIPP waste emplacement containers and underground waste emplacement layouts are provided in this section. Approved containers that are inside other containers, such as pipe overpacks, will not be discussed.

DATA 12.1 Program Overview

Information provided in this section was compiled from several sources to serve as a central document describing both waste emplacement containers and waste emplacement layouts. Both Contact Handled- (CH-) and Remote Handled- (RH-) waste containers are described along with CH- and RH-waste emplacement layouts in a typical panel in the underground repository. Only containers approved for storage in the repository will be discussed.

DATA 12.2 Reported Data

Attachment H provides the detailed information on the various waste containers and their emplacement in the underground repository.

APPENDIX DATA

ATTACHMENT A: DELAWARE BASIN DRILLING SURVEILLANCE DATA

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DATA-A-1.0 DELAWARE BASIN DRILLING SURVEILLANCE PROGRAM

The Delaware Basin Drilling Surveillance Program (DBDSP) is designed to monitor drilling activities in the vicinity of the Waste Isolation Pilot Plant (WIPP). The Environmental Protection Agency (EPA) requires the Department of Energy (DOE) to demonstrate the expected performance of the disposal system using a probabilistic risk assessment or performance assessment (PA). The PA must show that the expected repository performance will not release radioactive material above limits set by the EPA's standard and must consider inadvertent drilling into the repository horizon at some future time. The EPA regulations also state that current drilling practice, which is monitored by the DBDSP, should be assumed for future inadvertent intrusions.

The DOE continues to provide surveillance of the drilling activity in the Delaware Basin in accordance with the criteria established in 40 CFR § 194.33. This activity will continue until the DOE and the EPA mutually agree that no benefit can be gained from continued surveillance. The results of the ongoing surveillance activity will be used to determine if a significant change has occurred which would be detrimental to the performance of the disposal system.

DATA-A-2.0 QUALITY ASSURANCE

Because the DBDSP collects information only, the program's Quality Assurance (QA) process is not required to comply with Nuclear Quality Assurance (NQA) standards. Information collected from the various agencies and commercial sources is on an "as is" basis. However, QA is maintained by ensuring that the information collected is verified between the various sources for accuracy, to the extent possible. Also, any discrepancies noted are verified against the extant records at the state offices. As each well is completed, a copy of the drilling report is made from the records submitted to state offices in New Mexico and kept on file by the DBDSP. Before changes are made to any of the records in the databases, a paper copy is used to verify the change being made.

DATA-A-3.0 COLLECTION TIME PERIOD

The DBDSP collects the drilling-related information to be used for future PA calculations. The information collected during the first recertification monitoring period (July 1995 through September 2002) was added to the existing information maintained by the DBDSP. The information is collected weekly from Internet sites provided by the New Mexico Oil Conservation Division (OCD) for the entire state and from a commercial source for Southeastern New Mexico and Texas Railroad Commission, Oil and Gas Division, District 8. This information is then reviewed to determine which wells are within the Delaware Basin and need to be added to the databases. Other sources of information include the Bureau of Land Management (BLM) and the New Mexico Institute of Mining and Technology. The drilling-related activities monitored during the first recertification period by the DBDSP include:

- Drilling-related parameters/data, such as drilling rate, drill bit diameter, drill collar diameter and length, surface casing diameter, drill pipe diameter, speed of drill string rotation, penetration rate through the Salado Formation, type and characteristics (e.g.,

density, viscosity, etc.) of drilling mud, quantity of drilling fluid used, and occurrences of air drilling;

- Castile brine-related parameters/data, such as number of encounters of pressurized brine within the Castile Formation, Castile brine reservoir pressure and volume, and shortest and longest time until well shut-in occurs after a pressure encounter;

- Borehole plug-related parameters/data, such as pattern of plugs, plug materials and lengths; total number, location, and depth of abandoned boreholes; and type of steel alloy in the well casing;

- Enhanced recovery data, including occurrences of fluid injection (water flood) within the nine-township area, carbon dioxide (CO_2) miscible flooding, salt water disposal within the nine-township area, and volume (barrels) of fluid injected near WIPP within the nine-township area;

- Gas storage data, including occurrences of gas storage (cavern and/or reservoir) near WIPP;

- Solution mining data, including occurrences of solution mining within the Delaware Basin;

- Potash mining data, including changes in existing leases within the nine-township area; and

- Seismic data including history of relevant events, e.g., earthquake (natural or human induced) activity, relation of epicenters with geologic structures, geologic setting, etc.

DATA-A-4.0 COMPLIANCE MONITORING PARAMETERS

Two of the ten parameters monitored by the DBDSP are the drilling rate and the probability of encountering a Castile brine reservoir. Both parameters will continue to be monitored during postclosure.

Performance assessment is required by regulation to consider disturbed case scenarios that include intrusions into the repository by inadvertent and intermittent drilling for resources. The probability of these intrusions was based on a future drilling rate of 46.8 boreholes as used in the Compliance Certification Application (CCA) per square kilometer per 10,000 years. This rate is based on consideration of the past record of drilling events in the Delaware Basin.

Two different types of boreholes are considered: those that penetrate a pressurized brine reservoir in the underlying the Castile Formation and those that do not. While the presence of pressurized brine under the repository is speculative, it cannot be completely ruled out based on available information. The primary consequence of contacting pressurized brine is the introduction of an additional source of brine beyond that which is assumed to be released into the repository from the Salado. The human intrusion scenario models are based on extensive field data sets collected by the DOE.

The basis for the drilling rate to be used in PA for this Compliance Recertification Application (CRA) is shown in Table DATA-A-1. The drilling rate is calculated using wells that are deeper than 655 m (2,150 ft) below the surface since a well drilled to that depth would breach the repository horizon.

Table DATA-A-1. Wells in the Delaware Basin Deeper Than 655 m (2,150 ft)

Data collected from 1903 through September 2002

Well Type	Texas	New Mexico	Totals
Core Hole	5	0	5
Dry Hole	2,173	841	3,014
Gas Well	832	611	1,443
Injection Well	248	71	319
Junked and Abandoned Well	56	15	71
Oil Well	3,821	1,805	5,626
Oil and Gas Well	92	5	97
Plugged Gas Well	176	127	303
Plugged Injection Well	0	20	20
Plugged Oil Well	508	278	786
Plugged Oil and Gas Well	36	0	36
Plugged Brine Well	0	1	1
Plugged Salt Water Disposal Well	0	7	7
Drilling or Waiting on Paperwork	20	8	28
Brine Well	5	0	5
Salt Water Disposal Well	5	103	108
Service Well	101	3	104
Stratigraphic Test Hole	43	2	45
Sulfur Core Hole	85	0	85
Potash Core Hole	0	19	19
WIPP Core Hole	0	11	11
Other (Mine Shafts, Gnome Project Wells)	0	6	6
Totals	8,206	3,933	12,139

The drilling rate is calculated as follows: number of deep holes (12,139) × 10,000 years/ Delaware Basin surface area (23,102.1 km^2 [8921.7 mi^2])/100 years. The drilling rate is 52.5 boreholes per square kilometer over 10,000 years. This is an increase from the 46.8 boreholes per square kilometer reported in the CCA. This number is anticipated to rise for quite a few years before it begins to drop. This is because of the 100-year time frame used for drilling results. As new wells are added to the count, wells older than 100 years are dropped. It will be 2011 before any wells are dropped from the count while a number of new wells are expected to be added due to increased oil and gas activity, thus driving up the count.

Castile brine encounters are shown in Table DATA-A-2. The table shows the original encounters used in the CCA and the new brine encounters that occurred from July 1995 through September 2002.

Table DATA-A-2. Castile Brine Encounters

#	Location	Well Name	Spud Date	Status	Well Information
Original CCA-related Castile Brine Encounters – 1896 Through June 1995					
1	21S-31E-26	Federal #1	10/31/1979	P&A	Identified as encountering Castile Brine.
2	21S-31E-35	ERDA-6	06/13/1975	P&A	Identified as encountering Castile Brine.
3	21S-31E-35	Federal “FI” #1	09/25/1981	P&A	Identified as encountering Castile Brine.
4	21S-31E-36	Lost Tank “AIS” State #1	12/07/1991	Oil Well	Identified as encountering Castile Brine.
5	21S-31E-36	Lost Tank “AIS” State #4	11/19/1991	Oil Well	Identified as encountering Castile Brine.
6	21S-32E-31	Lost Tank SWD #1	11/12/1991	SWD	Identified as encountering Castile Brine.
7	22S-29E-09	Danford Permit #1	05/18/1937	P&A	Identified as encountering Castile Brine.
8	22S-31E-01	Unocal “AHU” Federal #1	04/02/1991	Oil Well	Identified as encountering Castile Brine.
9	22S-31E-01	Molly State #1	09/25/1991	Oil Well	Identified as encountering Castile Brine.
10	22S-31E-01	Molly State #3	10/20/1991	Oil Well	Identified as encountering Castile Brine.
11	22S-31E-02	State “2” #3	11/28/1991	Oil Well	Identified as encountering Castile Brine.
12	22S-31E-11	Martha “AIK” Federal #3	05/06/1991	Oil Well	Identified as encountering Castile Brine.
13	22S-31E-11	Martha “AIK” Federal #4	09/02/1991	Oil Well	Identified as encountering Castile Brine.
14	22S-31E-12	Federal “12” #8	03/28/1992	Oil Well	Identified as encountering Castile Brine.
15	22S-31E-13	Neff “13” Federal #5	02/04/1991	Oil Well	Identified as encountering Castile Brine.
16	22S-31E-17	WIPP-12	11/17/1978	Monitoring	Identified as encountering Castile Brine.
17	22S-32E-05	Bilbrey “5” Federal #1	11/26/1981	Oil Well	Identified as encountering Castile Brine.
18	22S-32E-15	Lechuza Federal #4	12/29/1992	Oil Well	Identified as encountering Castile Brine.
19	22S-32E-16	Kiwi “AKX” State #1	04/28/1992	Oil Well	Identified as encountering Castile Brine.
20	22S-32E-25	Covington “A” Federal #1	02/07/1975	Oil Well	Identified as encountering Castile Brine.
21	22S-32E-26	Culberson #1	12/15/1944	P&A	Identified as encountering Castile Brine.
22	22S-32E-34	Red Tank “34” Federal #1	09/23/1992	Oil Well	Identified as encountering Castile Brine.
23	22S-32E-36	Richardson State #1	07/20/1962	P&A	Identified as encountering Castile Brine.
24	22S-32E-36	Shell State #1	02/22/1964	Oil Well	Identified as encountering Castile Brine.
25	22S-33E-20	Cloyd Permit #1	09/07/1937	P&A	Identified as encountering Castile Brine.
26	22S-33E-20	Cloyd Permit #2	06/22/1938	P&A	Identified as encountering Castile Brine.
27	23S-30E-01	Hudson Federal #1	02/25/1974	SWD	Identified as encountering Castile Brine.
New CRA-related Castile Brine Encounters – July 1995 Through September 2002					
1	21S-31E-35	Lost Tank “35” State #4	09/11/2000	Oil Well	Estimated several hundred barrels per hour. Continued drilling.
2	21S-31E-35	Lost Tank “35” State #16	02/06/2002	Oil Well	At 2,705 ft, encountered 1,000 B/H. Shut-in to get room in reserve pit with pressure of 180 psi. Shut in next day with pressure at 100 psi and waterflow of 450 B/H. Two days later no water flow and full returns.
3	22S-31E-02	Graham “AKB” State #8	04/12/2002	Oil Well	Estimated 105 barrels per hour. Continued drilling.
4	23S-30E-01	James Ranch Unit #63	12/23/1999	Oil Well	Sulfur water encountered at 2,900 ft. 35 PPM was reported but quickly dissipated to 3 PPM in a matter of minutes. Continued drilling.
5	23S-30E-01	Hudson “1” Federal #7	01/06/2001	Oil Well	Estimated initial flow at 400 to 500 barrels per hour with a total volume of 600-800 barrels. Continued drilling.

No official documentation of New Mexico state records exists for the five new Castile brine encounters. Four were reported by WIPP site personnel during discussions with area drillers,

while the fifth was reported by one of the operators on the Annual Survey performed by the DBDSP. The Annual Survey is sent to regional area operators requesting information that is not available through other means.

All five wells were drilled in areas where Castile brine was previously encountered during the drilling process. Three wells were drilled in the vicinity of Well #ERDA-6 and the other two were southwest of the WIPP site. All were located in the nine-township area. During this time period, 345 wells were drilled in the nine-township area.

DATA-A-5.0 SUMMARY OF INFORMATION

DATA-A-5.1 Drilling-Related Parameters/Data

Tables DATA-A-3 through DATA-A-6 provide these drilling-related parameters/data: drill bit diameter, drill collar diameter and length, surface casing diameter, drill pipe diameter, speed of drill string rotation, penetration rate through the Salado, type and characteristics (density, viscosity, etc.) of drilling mud, quantity of drilling fluid used, and occurrences of air drilling.

Table DATA-A-3 lists drill bit sizes for the various wells drilled in the nine-township area during the recertification monitoring period. Currently, an 11” bit would be used to drill the same depth as the repository but in the CCA a 12 ¼” bit was modeled.

Table DATA-A-3. Nine-Township Area Bit Sizes

Three-String Hole

Bit Size	Surface Hole	Intermediate Hole	Production Hole	Totals
17 ½"	79	0	0	79
14 ¾"	25	0	0	25
14"	1	0	0	1
12 ¼"	0	16	0	16
11"	0	77	0	77
9 ⅞"	0	12	0	12
8 ⅞"	0	0	1	1
8 ¾"	0	0	3	3
7 ⅞"	0	0	89	89
6 ¾"	0	0	12	12
Totals	105	105	105	315

Note: Bit size information was available on 114 holes out of 345 that were spudded in the nine-township area from July 1995 through September 2002. Of the 114 holes completed, 105 were drilled using a three-string setup.

Two-String Hole

Bit Size	Surface Hole	Production Hole	Totals
12 ¼"	4	0	4
11"	5	0	5
7 ⅞"	0	9	9
Totals	9	9	18

Note: Of the 114 holes with available bit size information, nine holes were completed using a two-string setup.

Table DATA-A-4 lists the different casing sizes for wells drilled in the nine-township area during the recertification monitoring period. Information for casing sizes is acquired from

commercial sources and thus is readily available while drill bit size is acquired from state records which are not available until several months after a well has been completed.

Table DATA-A-4. Nine-Township Area Casing Sizes

Three-String Hole

Casing Size	Surface Casing	Intermediate Casing	Production Casing	Totals
20"	1	0	0	1
13 ⅜"	203	1	0	204
11 ¾"	44	0	0	44
10 ¾"	54	0	0	54
9 ⅞"	0	1	0	1
9 ⅝"	3	12	1	16
8 ⅝"	0	236	0	236
7 ⅞"	0	2	0	2
7 ⅝"	0	50	1	51
7"	0	3	6	9
5 ½"	0	0	235	235
4 ½"	0	0	62	62
Totals	305	305	305	915

Note: There were 345 wells drilled in the nine-township area from July 1995 through September 2002. Casing size information was available on 305 wells which used a three-string casing assembly to complete the well.

Two-String Hole

Casing Size	Surface Casing	Production Casing	Totals
10 ¾"	1	0	1
9 ⅝"	1	0	1
8 ⅝"	17	0	17
7"	0	1	1
5 ½"	0	18	18
Totals	19	19	38

Note: There were 19 wells completed as a two-string assembly out of the 345 wells drilled in the nine-township area during the recertification monitoring period.

Table DATA-A-5 lists these drilling related parameters: drill collar diameter and length, drill pipe diameter, speed of drill string rotation, penetration rate through the Salado, type and characteristics (density, viscosity, etc.) of drilling mud, and quantity of drilling fluid. This information was acquired from the annual surveys of area well operators performed each year during the recertification monitoring period.

Table DATA-A-5. Nine-Township Drilling Survey Information

#	Well Name and No.	Drill Pipe	Rotation Speed	Penetration Rate	Mud Density	Mud Viscosity	Mud Yield	Collar Diameter	Collar Length	Number of Collars
1	Lucy “ALC” State #3	4 ½"	75-85 RPM	35.4 ft/HR	10 PPG	28 SEC/QT	No Report	S=8 1/16 I=7 ½ P=6 ½	No Report	S=25 I=27 P=27
2	Jacque “AQJ” State #5	4 ½"	75-90 RPM	60 ft/HR	10 PPG	28 SEC/QT	No Report	S=7 15/16 I=7 ½ P=6 ⅝	No Report	S=16 I=27 P=27
3	Graham “AKB” State #5	4 ½"	40-90 RPM	68.7 ft/HR	10 PPG	28 SEC/QT	No Report	S=7 11/16 I=8 P=6	No Report	S=18 I=33 P=33
4	Graham “AKB” State #8	4 ½"	50-80 RPM	68 ft/HR	9.9-10.2 PPG	28 SEC/QT	No Report	S=8 I=8 P=6	No Report	S=18 I=33 P=33
5	Flora “AKF” State #3	4 ½"	60-105 RPM	65 ft/HR	10 PPG	28 SEC/QT	No Report	S=7 ⅞ I=7 ⅞ P=6	No Report	S=18 I=33 P=33
6	Remuda Basin State #9	4 ½"	No Report	91.6 ft/HR	8.3 PPG	38 SEC/QT	No Report	S=8	S=30 ft	No Report
7	Remuda Basin State #10	4 ½"	No Report	105 ft/HR	8.7 PPG	29 SEC/QT	No Report	S=8	S=30 ft	No Report
8	Remuda Basin State #11A	4 ½"	No Report	37.9 ft/HR	8.3 PPG	38 SEC/QT	No Report	S=8	S=30 ft	No Report
9	Barclay Federal #15	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=14 I=14 P=26
10	Barclay Federal #10	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=14 I=14 P=26
11	Barclay Federal #21	4 ½"	115 RPM	28 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=813 ft I=781 ft P=782 ft	No Report
12	Barclay Federal #18	4 ½"	120 RPM	28 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=812 ft I=780 ft P=783 ft	No Report

Table DATA-A-5. CRA Nine-Township Drilling Survey Information — Continued

#	Well Name and No.	Drill Pipe	Rotation Speed	Penetration Rate	Mud Density	Mud Viscosity	Mud Yield	Collar Diameter	Collar Length	Number of Collars
13	Barclay Federal #20	4 ½"	115 RPM	28 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=813 ft I=780 ft P=782 ft	No Report
14	Barclay Federal #27		120 RPM	20 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=810 ft I=785 ft P=780 ft	No Report
15	Barclay Federal #28	4 ½"	115 RPM	28 ft/HR	No Report	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=812 ft I=784 ft P=782 ft	No Report
16	Barclay State #7	4 ½"	120 RPM	28 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=810 ft I=781 ft P=780 ft	No Report
17	Barclay State #9	4 ½"	115 RPM		8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=815 ft I=785 ft P=786 ft	No Report
18	Barclay Federal #8	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=13 I=27 P=26
19	Barclay Federal #11	4 ½"	115 RPM	28 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=810 ft I=780 ft P=784 ft	No Report
20	Barclay Federal #13	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=13 I=27 P=26
21	Barclay Federal #17	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=13 I=27 P=26
22	Barclay Federal #19	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=13 I=27 P=26
23	Barclay Federal #25	4 ½"	118 RPM	29 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=815 ft I=784 ft P=782 ft	No Report

Note: Under the columns for Collars, the "S" indicates surface string, the "I" indicates intermediate string, and the "P" indicates production string. Also, under the Collar Diameter the production string on some wells indicates 8- and 6-in. collars. This is obviously an error since the hole diameter for that portion of the well is 7 ⅞ inches.

Table DATA-A-6 lists the known instances of air drilling that have occurred in the New Mexico portion of the Delaware Basin since hydrocarbon drilling has been performed. During the 100 years of drilling used for the CCA, there were 15 suspected cases where air may have been used to drill some portion of a well. During the recertification monitoring period, there was one proven incidence of air drilling, although not through the salt section, which occurred near the airport in Carlsbad 40.23 km (25 mi) west of the WIPP site.

Table DATA-A-6. Air-Drilled Wells

#	Location	Well Name and No.	Spud Date	Status	Well Information
Wells Drilled Prior to Submittal of the CCA With Some Portion Drilled by Air					
1	21S-28E-33	Richardson & Bass #1	07/27/1961	P&A	Air drilled through the salt. Between 2,545 and 2,685 encountered water and changed from air to mud based drilling.
2	21S-32E-26	Lincoln Federal Unit #1	04/01/1991	P&A	Lost circulation at 1290. Hole was dry drilled to 1,792. Supposedly air drilled from 2,984 to 4,725.
3	23S-26E-17	Exxon “17” Federal #1	08/01/1989	Gas Well	Air drilled through the salt from 575 to 2,707.
4	23S-28E-11	CP Pardue #1	10/28/1958	P&A	Air drilled through the salt from 390 to 2,620.
5	23S-28E-11	Amoco Federal #1	08/04/1979	Oil Well	Air drilled from 475 to 9,700.
6	23S-28E-11	Amoco Federal #3	02/28/1980	Oil Well	Air drilled from 6271 to 9,692.
7	23S-28E-23	South Culebra Bluff Unit #3	01/21/1979	Oil Well	Air drilled from 6345 to 8,000.
8	23S-28E-23	South Culebra Bluff Unit #4	08/09/1979	Oil Well	Air drilled from 450 to 9,802.
9	24S-31E-03	Lilly “ALY” Federal #2	05/01/1994	Oil Well	Air drilled conductor hole to 40.
10	24S-31E-03	Lilly “ALY” Federal #4	05/16/1994	Oil Well	Air drilled conductor hole to 40.
11	24S-34E-04	Antelope Ridge Unit #2	09/13/1962	Gas Well	Attempted to drill with gas. Had to convert to water at 1,035. Tried again several times at different depths.
12	24S-34E-09	Federal “9” Com #1	12/3/1963	Gas Well	Hit water while gas drilling at 4,865.
13	24S-34E-13	Federal Johnson #1	06/23/1958	P&A	Proposed to drill with air but no information in the records indicate air drilling.
14	26S-32E-20	Russell Federal #1	03/16/1966	Oil Well	Drilled with air to 1,330.
15	26S-32E-36	North El Mar Unit #44	02/19/1959	Oil Well	Proposed to drill with air but no information in the records indicate air drilling.
Wells Drilled After Supplemental Information Provided to the Docket					
1	22S-26E-28	Sheep Draw “28” Federal #13	07/01/1997	Oil Well	Air drilled the first 358 ft.

Note: The research on “air drilling” is a continuous effort since every new well drilled is checked to determine if any portion of the well was drilled by air. A copy of all completion reports are on file for all wells completed within the New Mexico portion of the Delaware Basin.

DATA-A-5.2 Borehole Plug-Related Parameters/Data

Borehole plug-related parameters/data including pattern of plugs; plug materials and lengths; total number, location, and depth of abandoned boreholes; and type of well casing steel alloy are shown in Table DATA-A-7.

Table DATA-A-7. Plugged Wells in the Nine-Township Area of the Delaware Basin – July 1995 Through September 2002

#	Location	Well Name and No.	Plug Date	R-111-P	Depth	No. Plugs	Plug Length	No. Sacks	Cement	Steel Alloy
1	21S-30E-33	Kaleidoscope "AKO" #1	03/13/1996	Yes	7,340	5	35 ft 50ft 100 ft 227 ft 264 ft	35 ft 10 Sacks 25 Sacks 25 Sacks 80 Sacks	Class C	S=J-55 I=J-55 P=J-55
2	21S-30E-34	Julia "AJL" Federal #4	03/19/1996	Yes	7,455	6	35 ft 100 ft 100 ft 185 ft No Report 50 ft	35 ft 25 Sacks 25 Sacks 25 Sacks 65 Sacks 5 Sacks	Class C	S=J-55 I=J-55 P=J-55
3	21S-32E-22	Bilbrey North "22" Federal #1	07/29/1998	Yes	15,020	5	330 ft 180 ft 150 ft 2,150 ft 50 ft	35 Sacks 180 ft 150 ft 750 Sacks 5 Sacks	No Report	S=J-55 I=N-80 P=P-110
4	21S-32E-31	Luke Federal #2	04/26/1998	Yes	8,585	4	No Report 100 ft 424 ft 50 ft	6 Sacks 11 Sacks 362 Sacks 50 Sacks	Class C	S=H-40 I=K-55 P=K-55
5	21S-32E-35	Anderson #1	07/27/1995	No	8,763	5	40 ft No Report 297 ft 197 ft 50 ft	40 ft 15 Sacks 70 Sacks 50 Sacks 10 Sacks	Class C	S=K-55 I=J-55 P=J-55
6	22S-32E-14	Prohibition Federal #5	05/24/1996	No	8,914	6	No Report 192 ft 336 ft 154 ft 125 ft 60 ft	25 Sacks 20 Sacks 50 Sacks 40 Sacks 65 Sacks 40 Sacks	Unknown Unknown Unknown Class C Class C Class C	S=J-55 I=J-55 P=J-55/N-80
7	22S-32E-22	Cercion Federal #8	03/25/1998	No	8,900	6	200 ft 100 ft 100 ft 100 ft 100 ft 20 ft	70 Sacks 50 Sacks 100 Sacks 35 Sacks 35 Sacks 20 Sacks	Class H Class H Class C Class C Class C Class C	No Report

Table DATA-A-7. Plugged Wells in the Nine-Township Area of the Delaware Basin – July 1995 Through September 2002 — Continued

#	Location	Well Name and No.	Plug Date	R-111-P	Depth	No. Plugs	Plug Length	No. Sacks	Cement	Steel Alloy
8	23S-32E-09	Aracanga Federal #2	02/04/1998	No	8,985	4	No Report 100 ft 100 ft 430 ft	35 Sacks 25 Sacks 25 Sacks 112 Sacks	No Report	S=H-40 I=J-55 P=J-55
9	23S-32E-12	Pronghorn Federal “12” #1	02/18/1999	No	9,200	7	50 ft 100 ft 100 ft 150 ft 100 ft 100 ft 50 ft	50 ft 50 Sacks 40 Sacks 60 Sacks 35 Sacks 35 Sacks 15 Sacks	Class H Class C Class C Class C Class C Class C Class C	No Report
10	23S-32E-15	Codorniz Federal #2	12/31/1996	No	9,039	5	100 ft 100 ft 100 ft 100 ft 60 ft	50 Sacks 50 Sacks 50 Sacks 50 Sacks 20 Sacks	Class H	S=H-40 I=J-55/S-80 P=K-55
11	23S-32E-18	Sand “18” Federal #2	05/24/1996	No	8,800	4	200 ft 265 ft 141 ft 75 ft	55 Sacks 180 Sacks 45 Sacks 57 Sacks	Class H	S=WC-40 I=WC-50 P=K-55/L-80
12	23S-32E-24	Red Deer “24” Federal #1	05/27/1997	No	9,101	4	216 ft 115 ft 180 ft 730 ft	50 Sacks 25 Sacks 35 Sacks 140 Sacks	Class C	S=K-55 I=K-55
13	23S-32E-35	Red Ruby “35” Federal #1	08/17/1997	No	9,100	6	202 ft 101 ft 125 ft 110 ft 110 ft 15 ft	60 Sacks 45 Sacks 70 Sacks 30 Sacks 30 Sacks 15 Sacks	No Report	S=J-55 I=NS-80

Note: Under the column for Steel Alloy the “S” indicates surface casing, the “I” indicates intermediate casing, and the “P” indicates production casing. The plugging regulations in New Mexico have not changed since the 1996 CCA.

DATA-A-5.3 Enhanced Recovery Data

Enhanced recovery data, including occurrences of fluid injection (water flood) within the nine-township area; CO_2 miscible flooding; salt water disposal within the nine-township area; and volume (barrels) of fluid injected near WIPP within the nine-township area are shown in the following Figure DATA-A-1 and Table DATA-A-8.

DATA-A-5.3.1 CO_2 Flooding

There are no secondary or tertiary recovery projects in the vicinity of the WIPP site utilizing carbon dioxide flooding as a means to recover oil. The nearest operation of this type is located 40.23 km (25 mi) to the south in Loving County, Texas.

There are no CO_2 pipelines to any of the oil fields in the New Mexico portion of the Delaware Basin where secondary recovery is ongoing. The one field near the WIPP site (El Mar) where secondary recovery is ongoing is located approximately 40.23 km (25 mi) from the CO_2 flooding operation in Loving County, Texas.

DATA-A-5.4 Gas Storage Data

Gas storage data including occurrences of gas storage (cavern and/or reservoir) near WIPP are shown in Table DATA-A-9.

A common underground gas storage facility is a cavern solution mined from the salt formations underlying the surface. They are made by dissolving the salt with fresh water and then pumping the brine to the surface, leaving a cavity that can be used for storage of hydrocarbons while a depleted reservoir storage system utilizes a reservoir from which most or all economically recoverable hydrocarbons have been produced.

In 1992, there were six gas storage facilities permitted in the state of New Mexico. Five were located in Southeast New Mexico, with one being inside the boundaries of the Delaware Basin and of interest to the WIPP site. The Washington Ranch Storage Project, located in the Delaware Basin about 79.03 km (46 mi) to the southwest of the WIPP site, is a multiwell system in a depleted gas reservoir, storing produced natural gas at a depth of approximately 1981.2 to 2133.6 m (6,500 to 7,000 ft). It is still in operation at this time, although at a much reduced level than in 1992.

Of the five facilities located in southeast New Mexico, only three are cavern-type facilities solution mined from the salt. All three store liquefied petroleum gas and are between 53.1 and 56.33 km (33 and 35 mi) from the WIPP site. The two that store produced natural gas do so in a depleted gas reservoir with the nearest facility located 32.19 km (20 mi) from the WIPP site, leaving the Washington Ranch Storage Project the furthest from the site at 79.03 km (46 mi).

At this time, there are no known underground gas storage facilities in the Texas portion of the Delaware Basin.

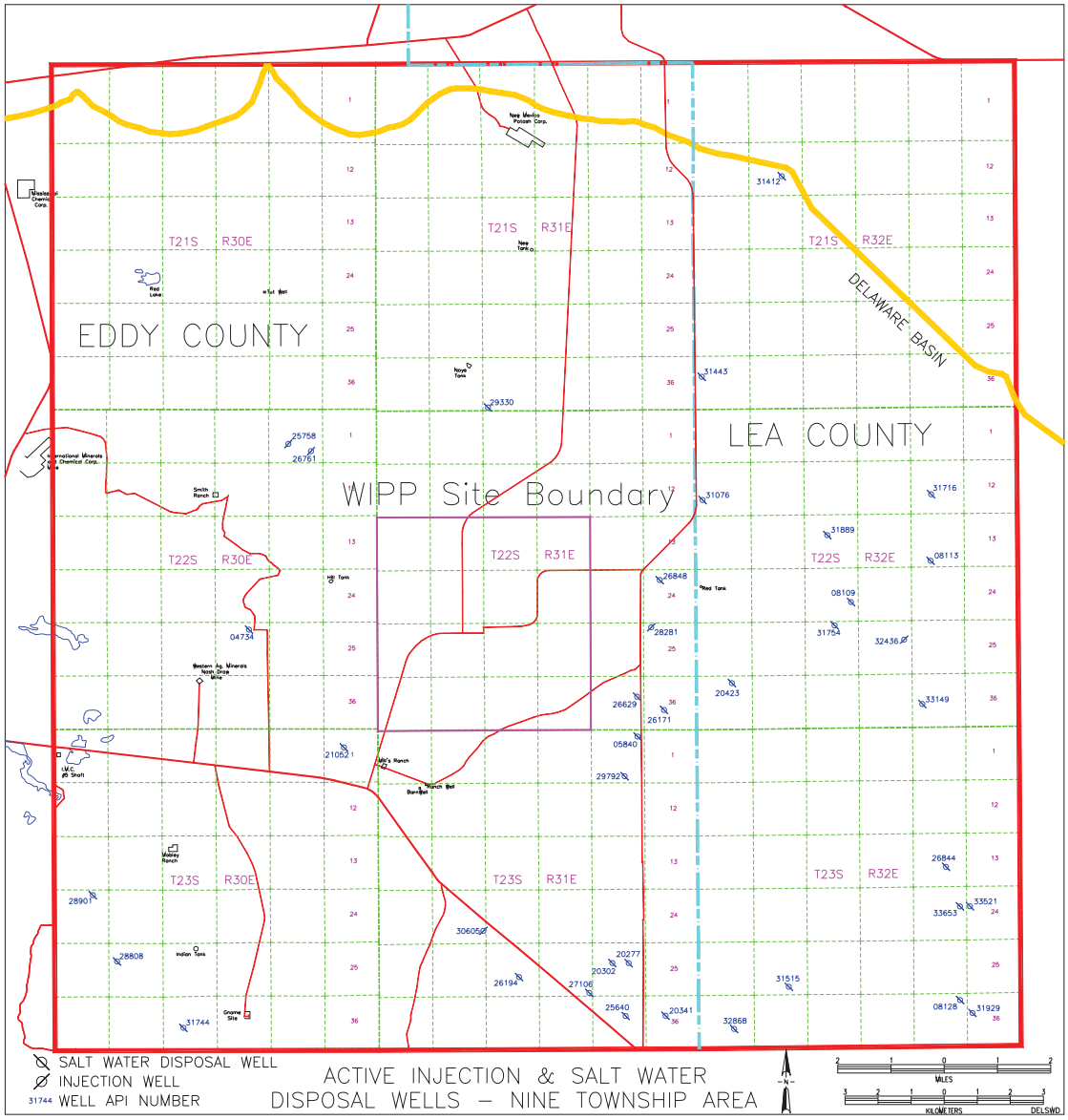

Figure DATA-A-1. Active Injection and Salt Water Disposal Wells

Table DATA-A-8. Nine-Township Injection and Salt Water Disposal (SWD) Well Information

No.	Location	Well Name and No.	Well Status	Injection Zone	1st Inj	Latest Inj	Inj Press	Cumulative Barrels
Wells Completed Prior to the Initial Certification								
1	21S-32E-08	Union “AJS” Federal #1	Salt Water Disposal	4826-5978	1991	June-2002	700 psi	4,784,288 Barrels
2	21S-32E-31	Lost Tank SWD #1	Salt Water Disposal	4618-6012	1992	June-2002	20 psi	157,463 Barrels
3	22S-30E-02	James “A” #3	Injection	7200-7264	1993	June-2002	855 psi	6,376,961 Barrels
4	22S-30E-02	James “A” #12	Injection	5600-7400	1991	June-2002	776 psi	6,758,551 Barrels
5	22S-30E-27	RH Legg Federal #1	Salt Water Disposal	3820-3915	1981	June-2002	760 psi	1,947,467 Barrels
6	22S-31E-24	Getty “24” Federal #5	Salt Water Disposal	4519-5110	1991	June-2002	No Report	4,694,840 Barrels
7	22S-31E-25	Neff Federal #3	Injection	7050-7068	1995	June-2002	600 psi	3,069,445 Barrels
8	22S-31E-35	David Ross “AIT” Federal #1	Salt Water Disposal	4500-5670	1991	June-2002	700 psi	7,791,690 Barrels
9	22S-32E-07	Flamenco Federal #1	Salt Water Disposal	4676-5814	1991	June-2002	300 psi	5,014,465 Barrels
10	22S-32E-11	Prohibition Federal #2	Salt Water Disposal	5200-8706	1994	June-2002	450 psi	915,747 Barrels
11	22S-32E-14	Red Tank “BT” Federal #2	Salt Water Disposal	4900-6080	1994	May-2002	No Report	2,564,127 Barrels
12	22S-32E-16	Kiwi “AKX” State #8	Salt Water Disposal	5240-8710	1995	June-2002	700 psi	4,750,431 Barrels
13	22S-32E-21	Gilmore Federal #1	Salt Water Disposal	4755-5110	1992	June-2002	550 psi	1,847,930 Barrels
14	22S-32E-28	Red Tank “28” Federal #3	Salt Water Disposal	4690-5800	1993	June-2002	300 psi	397,081 Barrels
15	22S-32E-31	Proximity “31” Federal #4	Salt Water Disposal	4662-5915	1993	June-2002	550 psi	2,976,033 Barrels
16	22S-32E-35	Red Tank “35” Federal #3	Salt Water Disposal	4950-6252	1995	June-2002	400 psi	2,025,597 Barrels
17	23S-30E-29	Charger “29” Federal #1	Salt Water Disposal	5479-7220	1996	June-2002	375 psi	1,587,535 Barrels
18	23S-31E-26	Todd Federal “26” #2	Salt Water Disposal	4460-5134	1992	June-2002	900 psi	3,231,147 Barrels
19	23S-31E-26	Todd Federal “26” #3	Salt Water Disposal	4390-6048	1971	June-2002	900 psi	4,460,450 Barrels
20	23S-31E-28	Sand Dunes “28” Federal #1	Salt Water Disposal	4295-5570	1993	June-2002	440 psi	2,944,921 Barrels
21	23S-31E-35	Cal-Mon #5	Salt Water Disposal	4484-5780	1993	June-2002	732 psi	2,347,175 Barrels
22	23S-31E-36	Todd “36” State #1	Salt Water Disposal	5980-6560	1994	June-2002	700 psi	6,836,860 Barrels
23	23S-32E-14	Cuervo Federal #1	Salt Water Disposal	5496-6014	1991	June-2002	550 psi	1,071,613 Barrels
24	23S-32E-29	James Federal #1	Salt Water Disposal	4844-4944	1992	June-2002	650 psi	2,882,040 Barrels
25	23S-32E-31	SDE “31” Federal #9	Salt Water Disposal	5150-5700	1996	June-2002	No Report	629,554 Barrels
26	23S-32E-35	James Federal #1A	Salt Water Disposal	5062-5100	1969	March-2002	850 psi	142,681 Barrels
27	23S-32E-36	Triste Draw “36” State #1	Salt Water Disposal	5364-6138	1995	May-2002	No Report	1,035,920 Barrels

Table DATA-A-8. Nine-Township Injection and Salt Water Disposal (SWD) Well Information — Continued

No.	Location	Well Name and No.	Well Status	Injection Zone	1st Inj	Latest Inj	Inj Press	Cumulative Barrels
Wells Completed Since the Initial Certification								
28	21S-31E-33	Lost Tank “33” Federal #2	Salt Water Disposal	4166-5160	1998	June-2002	360 psi	1,383,513 Barrels
29	22S-31E-36	Medano State Commercial #1	Salt Water Disposal	4500-5700	1998	Sept-2001	950 psi	2,500,628 Barrels
30	22S-32E-27	Prize Federal #4	Injection	6831-8388	1998	April-1999	No Report	No Report
31	23S-30E-01	Hudson Federal #1	Salt Water Disposal	4040-4825	2001	June-2002	800 psi	561,873 Barrels
32	23S-30E-19	Remuda Basin “19” Federal #2	Salt Water Disposal	3402-4609	1997	No Report	No Report	No Report
33	23S-30E-33	Poker Lake Unit #170	Salt Water Disposal	4546-6760	2002	No Report	No Report	No Report
34	23S-31E-02	Conoco State AA-2 #1	Salt Water Disposal	4489-5670	1997	Sept-2001	1010 psi	3,726,488 Barrels
35	23S-31E-02	Barclay State #4	Salt Water Disposal	4500-5850	1998	Sept-2001	1030 psi	2,908,070 Barrels
36	23S-31E-20	Pure Gold “B” Federal #20	Injection	7740-7774	2001	Dec-2001	No Report	244,642 Barrels
37	23S-31E-27	Todd “27” Federal	Salt Water Disposal	4694-5284	1998	No Report	No Report	No Report
38	23S-32E-23	Diamondtail “23” Federal #2	Salt Water Disposal	5954-6064	?	May-2001	420 psi	911,167 Barrels
39	23S-32E-24	Diamondtail “24” Federal #1	Salt Water Disposal	5925-6042	?	June-2002	No Report	732,490 Barrels

Note: Information collected from OCD offices in Artesia and Hobbs. Also, Cumulative Barrels information is collected from the New Mexico Oil & Gas Engineering Committee, Inc. and is valid through June 2002.

Table DATA-A-9. Underground Gas Storage Facilities in the Vicinity of the WIPP Site

Facility/Operator	Type of Facility	Location	Delaware Basin	Capacity	Material Stored
Washington Ranch Storage Project El Paso Natural Gas Company	Multiwell system utilizing a depleted gas reservoir found at a depth of 6,500 to 7,000 ft.	25S-24E 26S-24E Eddy County	Yes	67,253 MMCF	Produced Natural Gas
Loco Hills Arrow Gas Company	Three-well system interconnected by a cavity in the salt section at a depth of 500 to 600 ft.	17S-29E-22 Eddy County	No	235,000 to 238,000 barrels	Liquified Petroleum Gas
LPG Storage Well No. 1 Warren Petroleum Company	One-well storage facility in the salt section at a depth of 1,892 ft.	20S-36E-01 Lea County	No	168,000 barrels	Liquified Petroleum Gas
LPG Storage Well No. 2 Warren Petroleum Company	One-well storage facility in the salt section at a depth of 1,469 ft.	19S-36E-36 Lea County	No	245,000 barrels	Liquified Petroleum Gas
Grama Ridge Morrow Unit Llano, Inc.	Four-well storage facility (two injectors, two withdrawal wells) in a portion of the Grama Ridge Gas Pool at a depth of 12,700 to 13,200 ft.	21S-34E-34 22S-34E-03 Lea County	No	13,000 MMCF	Produced Natural Gas

DATA-A-5.5 Solution Mining

This section discusses occurrences of solution mining within the Delaware Basin. The discussion addresses the following four categories:

- Potash solution mining,
- Sulfur solution mining,
- Brine wells, and
- Naturally occurring radioactive materials (NORM) facilities.

DATA-A-5.5.1 Potash Solution Mining

No solution mining for potash has occurred at any of the mines located within the Delaware Basin in the vicinity of the WIPP site. The DOE is not aware of any plans being considered by any mining companies to use potash solution mining in the Delaware Basin. However, this process has occurred outside the Delaware Basin in the Carlsbad Mining District, which comprises all of the potash mines in the area. Potash can be found in the Mcnutt

The first solution mining attempt was in the late 1960s. Conoco Minerals installed a pilot scale in-situ solution mine on the AMAX lease in 19S-30E-12. This solution cavity was mapped in 1974 from the surface using radar. The cavern created was 213.36 m (700 ft) in diameter and approximately 3.04 m (10 ft) high. There were four boreholes drilled to create this cavity — one injection well and three withdrawal wells. This project was designed to test solution mining of potassium minerals, but the potash ore zone was deemed too thin to make this method economically viable. This occurred approximately 22 miles north of the WIPP Site.

The second potash solution mining endeavor is still in the initial phases and solution mining activities have not yet commenced. In May 1997, Mississippi Chemical filed a notice of intent to proceed with solution mining of potash in the Clayton Basin just to the north of the Delaware Basin. The next step in the process is for a detailed plan to be submitted to the Bureau of Land Management (BLM) for further evaluation. This plan was not submitted until March 2002. BLM approved the test plan in May 2002 for the pilot project. After the pilot phase is completed, an Environmental Impact Statement will be required before work can proceed. Currently, Mississippi Chemical has put the plan on hold due to a lack of funding. Talks with the BLM have indicated that the plan is still of a proprietary nature and the BLM will not allow anyone to review the plan without approval from Mississippi Chemical. However, BLM personnel did indicate that the facility would be located at the old Eddy Potash mine, which is located outside of the Delaware Basin and north-northwest of the WIPP site approximately 30.68 km (19 mi). The proposed plan is to pump water down the shaft into a section of the mine that has been previously mined out, circulating the water around pillars until it becomes saturated with potash, and then pumping the saturated fluid to the surface where it would be dumped into a two- to three-acre evaporation pond. The residue would then be refined. This information was acquired in a phone conversation with BLM personnel on 3/13/02.

DATA-A-5.5.2 Sulfur Solution Mining

Solution mining for sulfur has occurred in the Delaware Basin. Currently, there are no active sulfur solution mining projects within the Delaware Basin. Past activity was at the sulfur mine located west of Orla, Texas, in Culberson County. This facility utilized a number of Class III injection wells to remove sulfur from underground mineral deposits. This mine was closed in June 1999.

DATA-A-5.5.3 Brine Wells

Brine wells are classified as Class II injection wells. In the Delaware Basin, the process involves injecting fresh water through the wells into a salt formation to create a saturated brine solution, which is then extracted and utilized as a drilling agent when drilling a new well. These wells are tracked by the DBDSP on a continuing basis. Supplemental information provided to the EPA in 1997 showed 11 brine wells in the Delaware Basin. Further research showed there to be 15 brine wells. Four of these are plugged and abandoned with 11 being active (see Table DATA-A-10). One new well has been permitted in the Delaware Basin since submittal of the initial certification application (Quito West Unit #207). One well has yet to be verified and is not listed in the table below. Records indicate it has been permitted, but there are no records to indicate whether it was drilled. If records are found to verify when the well was drilled, it will be added to the databases maintained by the DBDSP and classified as a brine well.

Table DATA-A-10. Delaware Basin Brine Well Status

County	Location	API No.	Well Name and No.	Operator	Status
Eddy	22S-26E-36	3001521842	City of Carlsbad #WS-1	Key Energy Services	Brine Well
Eddy	22S-27E-03	3001520331	Tracy #3	Ray Westall	Plugged Brine Well
Eddy	22S-27E-17	3001522574	Eugenie #WS-1	I & W Inc	Brine Well
Eddy	22S-27E-17	3001523031	Eugenie #WS-2	I & W Inc	Plugged Brine Well
Loving	Blk 29-03	4230110142	Lineberry Brine Station #1	Chance Properties	Brine Well
Loving	Blk 01-82	4230130680	Chapman Ford #BR1	Herricks & Son Co.	Plugged Brine Well
Loving	Blk 33-80	4230180318	Mentone Brine Station #1D	Basic Energy Services	Brine Well
Loving	Blk 29-28	4230180319	East Mentone Brine Station #1	Permian Brine Sales, Inc.	Plugged Brine Well
Loving	Blk 01-83	4230180320	North Mentone #1	Chance Properties	Brine Well
Reeves	Blk 56-30	4238900408	Orla Brine Station #1D	Mesquite SWD Inc.	Brine Well
Reeves	Blk 04-08	4238920100	North Pecos Brine Station #WD-1	Chance Properties	Brine Well
Reeves	Blk 07-21	4238980476	Coyanosa Brine Station #1	Chance Properties	Brine Well
Ward	Blk 17-20	4247531742	Pyote Brine Station #WD-1	Chance Properties	Brine Well
Ward	Blk 01-13	4247534514	Quito West Unit #207	Seaboard Oil Co.	Brine Well
Ward	Blk 34-174	4247582265	Barstow Brine Station #1	Chance Properties	Brine Well

DATA-A-5.5.4 Naturally Occurring Radioactive Materials Facilities

NORM facilities are considered because they may be created in salt formations by solution mining to dispose of NORM wastes. According to conversations with the NORM Director for the Texas Railroad Commission, there are four permitted NORM sites in the state of Texas. Three are located in the Permian Basin but well outside of the Delaware Basin. The Andrews facility, approximately 96.56 km (60 mi) east of the WIPP Site, is operated by Lotus LLC and will eventually have a capacity of 570,000 barrels. Another facility is located near Fort Stockton by NES Permian and will have a capacity of 1,000,000 barrels. The third facility is also operated by NES Permian near Big Spring and is considerably smaller. All of these facilities are located in salt formations and were solution mined to facilitate the reinjection of NORM wastes by the oil companies. This information is tracked by the DBDSP. There is no requirement to track NORM facilities outside of the Delaware Basin, but the DBDSP does so for possible future impacts to activities within the Delaware Basin.

DATA-A-5.6 Potash Mining Data

Potash mining data include a map of current potash leases (Figure DATA-A-2) and changes in existing leases within the nine-township area (see Table DATA-A-11). A full-sized copy of Figure DATA-A-2 can be found in a pocket at the end of this volume.

DATA-A-5.7 Seismic Data

Seismic data include a history of relevant events, e.g., earthquake (natural or human induced) activity, relation of epicenters with geologic structures, geologic setting, etc. This information is provided in Figure DATA-A-3 and Table DATA-A-12. A full-sized copy of Figure DATA-A-3 can be found in a pocket at the end of this volume.

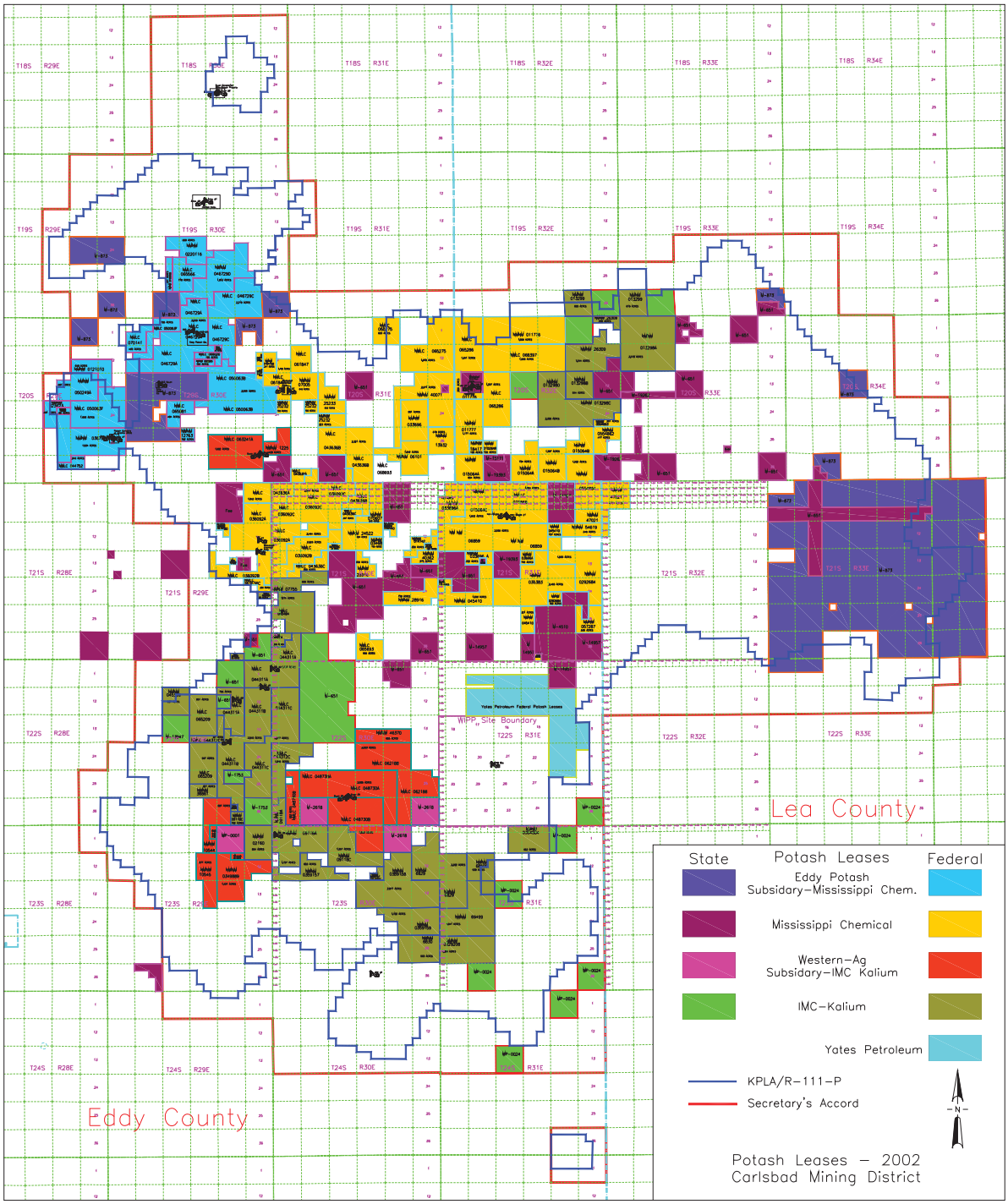

Figure DATA-A-2. Current Potash Leases

Table DATA-A-11. Potash Leases in the Vicinity of the WIPP Site

Company	1995	2002	Federal Leases	Acreage	Lease Eff. Date	State Leases	Acreage	Lease Eff. Date
Horizon Corp	Yes	No	Cancelled			Cancelled		
Eddy Potash (Subsidiary of Mississippi Chemical)	Yes	Yes	NMLC-044752 NMLC-046729A NMLC-046729C NMLC-046729D NMLC-050063B NMLC-050063F NMLC-065081-01 NMLC-065566-01 NMLC-066026-01 NMLC-070141-01 NMNM-023623-01 NMNM-036791 NMNM-050249A NMNM-088285 NMNM-0121810-01 NMNM-0135065 NMNM-0220116 NMNM-13933 NMNM-12763	240.00 2,558.76 2,279.95 1,840.00 2,560.00 2,358.36 480.00 720.00 200.00 438.91 400.00 1,840.00 880.00 120.00 640.00 200.00 800.00 80.00 160.00	09/01/1956 01/18/1933 01/18/1933 01/18/1933 040/1/1939 04/01/1939 12/06/1950 09/28/1951 09/01/1955 01/01/1959 02/01/1962 10/01/1957 09/01/1963 080/1/1960 01/01/1965 06/01/1961 12/01/1961 10/01/1971 06/01/1971	M-873	37,850.28	Unknown
Western-Ag Minerals (Subsidiary of IMC Kalium)	Yes	Yes	NMLC-048730A NMLC-048730B NMLC-062188 NMLC-063241A NMNM-0349889-01 NMNM-1225 NMNM-10544 NMNM-10545 NMNM-46370 NMNM-84935 NMNM-86720	2,560.00 2,556.40 2,520.00 1,600.00 1,400.00 480.00 240.09 800.00 640.00 160.03 640.00	08/21/1952 08/21/1952 12/01/1959 11/30/1949 11/01/1967 06/20/1932 11/01/1969 11/01/1969 02/01/1982 04/01/1991 03/01/1993	MP-001 M-2618	642.97 1,951.18	Unknown Unknown
Harroun	Yes	No	Cancelled			None		
National Potash Company	Yes	No	Owned by Mississippi			None		
New Mexico Potash	Yes	No	Owned by Mississippi			Mississippi		
IMC Global/Noranda	Yes	No	Owned by IMC Kalium			IMC Kalium		

Table DATA-A-11. Potash Leases in the Vicinity of the WIPP Site — Continued

Company	1995	2002	Federal Leases	Acreage	Lease Eff. Date	State Leases	Acreage	Lease Eff. Date
Yates Petroleum/Pogo Producing Co	Yes	Yes		5,184.72	1992	None		
IMC Kalium	Yes	Yes	NMLC-044311A	2,550.33	10/26/1938	M-13947	637.05	Unknown
			NMLC-044311B	2,560.00	10/26/1938	M-1753	921.33	Unknown
			NMLC-044311C	2,563.28	10/26/1938	M-651	5,734.52	Unknown
			NMLC-044312A	302.37	11/15/1946	MP-0024	4,472.90	Unknown
			NMLC-044312B	40.00	11/15/1946	Unknown	2,517.63	Unknown
			NMLC-044312C	1,400.29	11/15/1946			
			NMLC-065209	1,920.00	11/01/1949			
			NMLC-065484-01	1,331.76	01/5/1953			
			NMNM-02160-01	798.78	11/01/1956			
			NMNM-07755-01	665.65	060/1/1957			
			NMNM-09118A	1,766.71	07/02/1951			
			NMNM-09118C	1,400.60	07/02/1951			
			NMNM-045326-01	640.00	05/01/1958			
			NMNM-0329208-01	1,287.00	03/01/1967			
			NMNM-0359157-01	960.20	11/01/1967			
			NMNM-0359158-01	2,520.00	11/01/1967			
			NMNM-0359159-01	1,160.00	02/01/1968			
			NMNM-0384584-01	957.69	11/01/1967			
			NMNM-6829	2,211.12	11/01/1967			
			NMNM-6830	960.00	11/01/1967			
			NMNM-36861	320.00	01/01/1981			
			NMNM-69499	1,926.40	03/01/1967			
			NMNM-68500	640.00	03/01/1967			
			NMNM-013298A	2,564.33	02/24/1953			
			NMNM-013298B	640.00	02/24/1953			
			NMNM-013298C	2,360.00	02/24/1953			
			NMNM-013299	1,277.80	02/24/1953			
			NMNM-26309	1,438.80	02/24/1953			

Table DATA-A-11. Potash Leases in the Vicinity of the WIPP Site — Continued

Company	1995	2002	Federal Leases	Acreage	Lease Eff. Date	State Leases	Acreage	Lease Eff. Date
Mississippi Potash	Yes	Yes	NMLC-036092A	2,436.85	11/21/1929	M-651	19,973.52	Unknown
			NMLC-036092B	2,025.59	11/21/1929	M-19262	1,512.52	Unknown
			NMLC-036092C	2,559.15	11/21/1929	M-14957	2,632.51	Unknown
			NMLC-043636A	1,044.03	06/20/1932	M-15171	121.13	Unknown
			NMLC-043636B	2,311.66	06/20/1932	M-19393	1,084.16	Unknown
			NMLC-043636C	920.00	06/20/1932	M-4510	2,270.97	Unknown
			NMLC-061847-01	1,115.24	07/01/1951			
			NMLC-065693-01	560.00	02/01/1958			
			NMLC-065275-01	2,550.56	01/09/1952			
			NMLC-068397	1,920.00	01/09/1952			
			NMLC-065286-01	2,553.87	01/09/1952			
			NMLC-071868-01	1,938.24	09/01/1955			
			NMNM-06101-01	1,040.00	02/01/1958			
			NMNM-03468	160.00	07/01/1958			
			NMNM-07005	636.28	01/02/1952			
			NMNM-016540-01	120.00	04/04/1960			
			NMNM-033696	960.00	03/01/1958			
			NMNM-063880	120.00	07/01/1959			
			NMNM-070607	551.70	02/01/1960			
			NMNM-0184149	80.00	01/01/1955			
			NMNM-0184150	240.00	11/30/1949			
			NMNM-13932	640.00	11/01/1974			
			NMNM-24522	800.00	03/01/1982			
			NMNM-25232	640.00	07/06/1951			
			NMNM-25233	640.00	01/02/1952			
			NMNM-25234	80.00	11/30/1949			
			NMNM-28916	880.00	08/01/1963			
			NMNM-011776	2,559.06	01/09/1952			
			NMNM-011777	1,117.64	01/09/1952			
			NMNM-40071	2,080.00	05/01/1980			
			NMNM-06859-01	2,554.24	10/26/1953			
			NMNM-014742-01	640.00	08/01/1963			
			NMNM-033696A	1,240.62	03/01/1958			
			NMNM-035383	2,400.00	01/01/1958			
			NMNM-045410	2,438.30	06/01/1958			
			NMNM-057287-01	560.00	01/01/1964			

Table DATA-A-11. Potash Leases in the Vicinity of the WIPP Site — Concluded

Company	1995	2002	Federal Leases	Acreage	Lease Eff. Date	State Leases	Acreage	Lease Eff. Date
Mississippi Potash (continued)	Yes	Yes	NMNM-015064A	1,599.76	10/26/1953			
			NMNM-015064B	1,280.00	10/26/1953			
			NMNM-015064C	1,049.40	10/25/1953			
			NMNM-0292684-01	1,720.00	12/01/1966			
			NMNM-0554862	480.00	02/24/1953			
			NMNM-0554863	200.00	02/24/1953			
			NMNM-0554864	1,250.04	02/24/1953			
			NMNM-18417	160.00	01/09/1952			
			NMNM-28915	117.94	06/01/1958			
			NMNM-40362	280.00	12/01/1980			
			NMNM-41639	120.00	07/01/1981			
			NMNM-47021	1,104.26	07/01/1982			
			NMNM-54619	565.88	03/01/1983			
			NMNM-80707	2,520.00	08/01/1963			

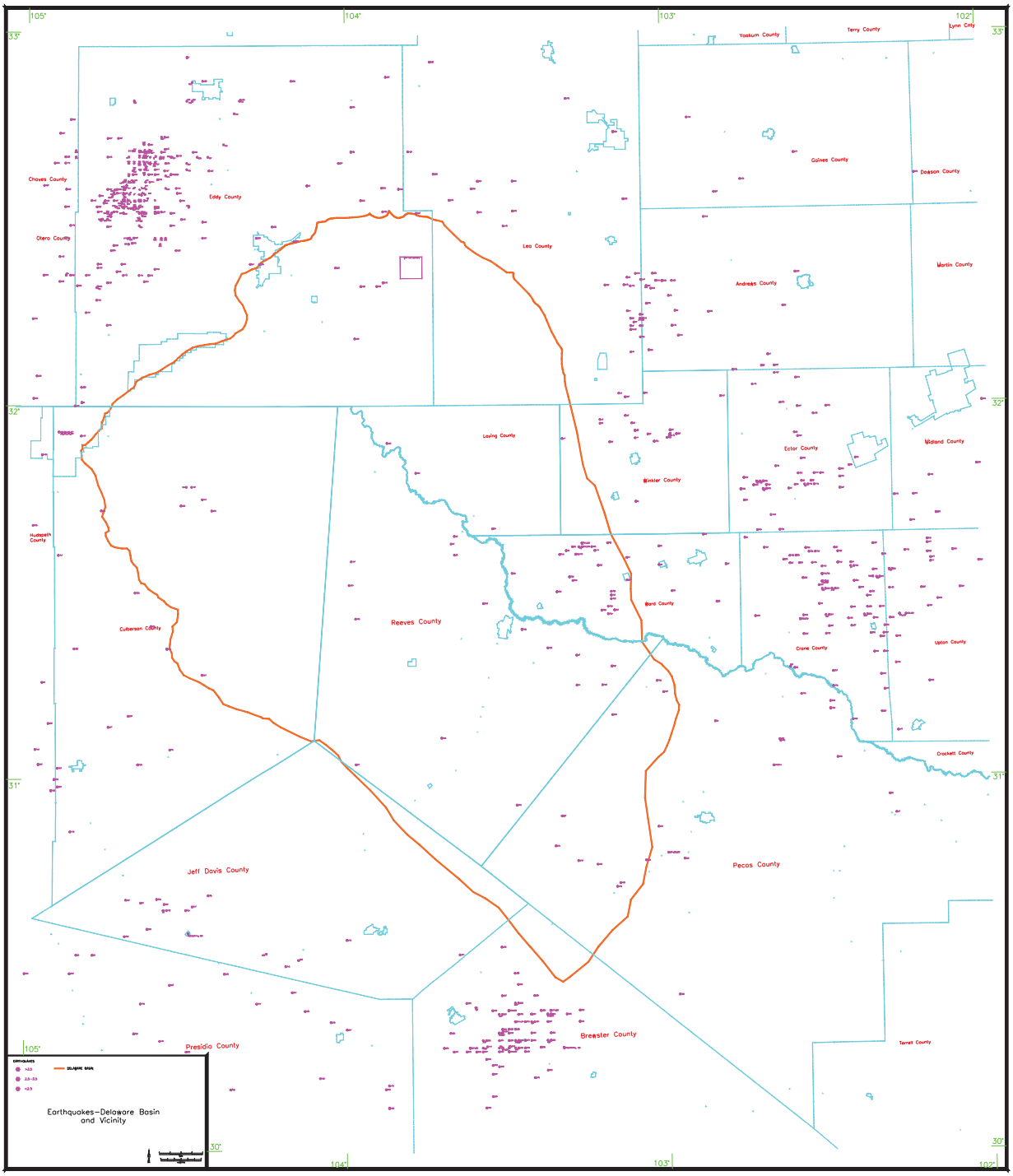

Figure DATA-A-3. Seismic Activity in the Delaware Basin

Table DATA-A-12. Earthquake Events in the Delaware Basin

County	No. of Events	Earliest Event	Latest Event	Smallest Magnitude	Largest Magnitude
Culberson	6	12/30/1997	08/04/2002	1	1.9
Eddy	5	04/24/1983	12/03/1998	1.1	3.5
Loving	3	02/04/1976	04/28/1997	1.1	1.3
Pecos	10	04/03/1977	12/22/1998	1	2.2
Reeves	16	08/03/1975	05/25/2002	1	2.5
Ward	26	09/24/1971	08/18/1984	0.8	3
Winkler	1	04/30/1976	04/30/1976	1.5	1.5
Totals	67	09/24/1971	08/04/2002	0.8	3.5

Key:

Magnitude	
Less than 2	Very seldom ever felt
2.0 to 3.4	Barely felt
3.5 to 4.2	Felt as a rumble
4.3 to 4.9	Shakes furniture; can break dishes
5.0 to 5.9	Dislodges heavy objects; cracks walls
6.0 to 6.9	Considerable damage to buildings
7.0 to 7.3	Major damage to buildings; breaks underground pipe
7.4 to 7.9	Great damage; destroys masonry and frame buildings
Above 8.0	Complete destruction; ground moves in waves

Note: Three of the five earthquake events in Eddy County can be directly attributed to mining activities. The other two remain unexplained. Most of the seismic events recorded in the vicinity of the Delaware Basin can be attributed to oil and gas activities—such as the number of events that continue to occur in the Dagger Draw or Cass Ranch area of Central Eddy County—where a large number of oil and gas activities are being conducted.

The table includes only reported data.

APPENDIX DATA

ATTACHMENT B: HISTORICAL WATER LEVEL DATA

Historical Water Level Data

Groundwater monitoring activities during the 2004 Compliance Recertification Application monitoring period (mid 1995 through September 30, 2002) included groundwater level measurements to support performance assessment. An array of 75 wells are used to acquire data on water levels in seven different water-bearing zones. The two zones of primary interest are the Culebra and Magenta members of the Rustler Formation.

The Groundwater Monitoring Program (GWMP) measures water levels on a monthly basis in at least one accessible well bore at each well site for each available formation. Redundant well bores at each well site are measured on a quarterly basis. Some of the wells were completed at multiple depths and by using packers, these well bores may be monitored in more than one formation.

Water levels are reported in elevation (feet above mean sea level). This is accomplished by measuring from the top of the well casing (a surveyed elevation point) to the top of the water level and subtracting the measured number from the known elevation. Due to the high concentration of total dissolved solids (TDS) in WIPP groundwater, density must be taken into account to accurately determine relative water levels between wells. Measured water levels are adjusted to equivalent fresh-water head values, considering fluid density differences between measuring points.

An activity that affects the ability to take water level measurements is well maintenance. Maintenance is performed to prepare wells for future experiments, repair nonfunctioning wells, recomplete wells to monitor additional zones of interest, and plugging and abandonment of wells that are no longer useful. Well maintenance is an ongoing process and as the following tables and charts show, not all wells have reported water levels at regular intervals. Wells with missing data may have been taken out of service for any of the above reasons.

Historical Water Level Data

Groundwater monitoring activities during the 2004 Compliance Recertification Application monitoring period (mid 1995 through September 30, 2002) included groundwater level measurements to support performance assessment. An array of 75 wells are used to acquire data on water levels in seven different water-bearing zones. The two zones of primary interest are the Culebra and Magenta members of the Rustler Formation.

The Groundwater Monitoring Program (GWMP) measures water levels on a monthly basis in at least one accessible well bore at each well site for each available formation. Redundant well bores at each well site are measured on a quarterly basis. Some of the wells were completed at multiple depths and by using packers, these well bores may be monitored in more than one formation.

Water levels are reported in elevation (feet above mean sea level). This is accomplished by measuring from the top of the well casing (a surveyed elevation point) to the top of the water level and subtracting the measured number from the known elevation. Due to the high concentration of total dissolved solids (TDS) in WIPP groundwater, density must be taken into account to accurately determine relative water levels between wells. Measured water levels are adjusted to equivalent fresh-water head values, considering fluid density differences between measuring points.

An activity that affects the ability to take water level measurements is well maintenance. Maintenance is performed to prepare wells for future experiments, repair nonfunctioning wells, recomplete wells to monitor additional zones of interest, and plugging and abandonment of wells that are no longer useful. Well maintenance is an ongoing process and as the following tables and charts show, not all wells have reported water levels at regular intervals. Wells with missing data may have been taken out of service for any of the above reasons.

Table 1 - Well No. AEC-7 Culebra

January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3036.43	3059.22
02/14/95	3036.45	3059.24
03/13/95	3036.35	3059.13
04/12/95	3036.09	3058.85
05/08/95	3036.54	3059.34
06/05/95	3036.54	3059.34
07/19/95	3036.44	3059.23
08/16/95	3036.60	3059.41
09/08/95	3036.36	3059.14
10/18/95	3036.45	3059.24
11/08/95	3036.35	3059.13
12/06/95	3036.40	3059.19
01/10/96	3036.43	3059.22
02/07/96	3036.43	3059.22
03/13/96	3036.53	3059.33
04/17/96	3036.52	3059.32
05/15/96	3036.48	3059.27
06/12/96	3036.72	3059.54
07/17/96	3036.69	3059.50
08/14/96	3036.91	3059.74
09/05/96	3038.25	3061.20
10/16/96	3037.43	3060.31
11/13/96	3036.95	3059.79
12/11/96	3037.08	3059.93
01/14/97	3036.98	3059.82
02/12/97	3036.87	3059.70
03/12/97	3036.83	3059.66
04/16/97	3036.91	3059.74
05/14/97	3037.16	3060.02
06/12/97	3037.04	3059.88
07/16/97	3037.15	3060.00
08/13/97	3036.95	3059.79
09/17/97	3037.51	3060.40
10/16/97	3037.68	3060.58
11/12/97	3038.42	3061.39
12/10/97	3037.62	3060.52

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3037.81	3060.72
02/11/98	3037.83	3060.75
03/11/98	3038.40	3061.37
04/15/98	3039.19	3062.23
05/13/98	3039.34	3062.39
06/11/98	3039.29	3062.34
07/15/98	3039.22	3062.26
08/12/98	3039.01	3062.03
09/10/98	3038.99	3062.01
10/14/98	3039.10	3062.13
11/11/98	3038.69	3061.68
12/07/98	3038.91	3061.92
01/13/99	3038.71	3061.71
02/08/99	3038.74	3061.74
03/10/99	3038.79	3061.79
04/14/99	3038.74	3061.74
05/12/99	3038.60	3061.59
06/10/99	3038.67	3061.66
07/21/99	3038.46	3061.43
08/11/99	3038.66	3061.65
09/09/99	3038.55	3061.53
10/06/99	3038.50	3061.48
11/10/99	3038.58	3061.56
12/08/99	3038.70	3061.69
01/19/00	3038.44	3061.41
02/16/00	3038.44	3061.41
03/08/00	3038.62	3061.61
04/19/00	3038.63	3061.62
05/15/00	3038.52	3061.50
06/05/00	3038.47	3061.44
07/11/00	3038.62	3061.61
08/16/00	3038.37	3061.33
09/13/00	3038.35	3061.31
10/11/00	3038.30	3061.26
11/06/00	3038.61	3061.60
12/07/00	3038.22	3061.17

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3038.29	3061.25
02/06/01	3038.22	3061.17
03/06/01	3038.33	3061.29
04/04/01	3038.48	3061.45
05/08/01	3038.22	3061.17
06/07/01	3038.36	3061.32
07/10/01	3038.26	3061.21
08/08/01	3038.12	3061.06
09/07/01	3038.50	3061.48
10/08/01	3038.23	3061.18
11/13/01	3038.29	3061.25
12/04/01	3038.29	3061.25
01/15/02	3038.09	3061.03
02/06/02	3038.11	3061.05
03/12/02	3038.17	3061.12
04/09/02	3038.10	3061.04
05/08/02	3038.30	3061.26
06/12/02	3038.24	3061.19
07/15/02	3038.09	3061.03
08/13/02	3038.33	3061.29
09/09/02	3038.21	3061.16

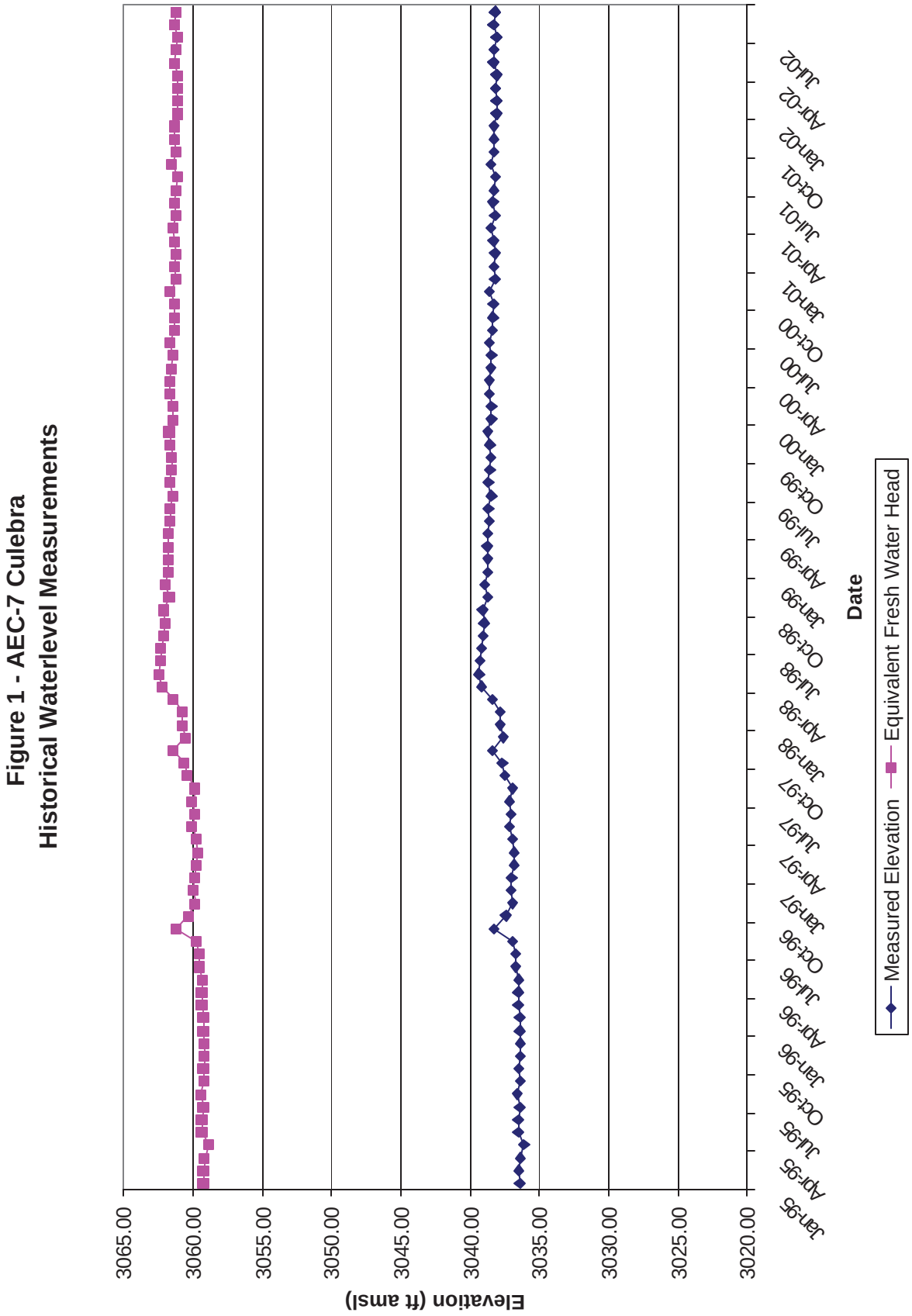
Figure 1 - AEC-7 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3065.00
3060.00
3055.00
3050.00
3045.00
3040.00
3035.00
3030.00
3025.00
3020.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 2 - Well No. AEC-8 Bell Canyon
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	2959.19	N/A
02/14/95	2959.51	N/A
03/13/95	2959.86	N/A
04/12/95	2959.99	N/A
05/08/95	2960.75	N/A
06/05/95	2961.31	N/A
07/19/95	2961.99	N/A
08/16/95	2962.49	N/A
09/08/95	2962.67	N/A
10/18/95	2963.59	N/A
11/08/95	2963.78	N/A
12/06/95	2964.37	N/A
01/10/96	2964.62	N/A
02/07/96	2965.62	N/A
03/13/96	2965.69	N/A
04/17/96	2966.32	N/A
05/15/96	2966.87	N/A
06/12/96	2967.67	N/A
07/17/96	2968.42	N/A
08/14/96	2968.99	N/A
09/05/96	2969.59	N/A
10/16/96	2970.54	N/A
11/13/96	2971.15	N/A
12/11/96	2971.82	N/A
01/14/97	2972.68	N/A
02/12/97	2973.30	N/A
03/13/97	2974.13	N/A
04/16/97	2975.24	N/A
05/14/97	2976.10	N/A
06/12/97	2976.96	N/A
07/16/97	2977.96	N/A
08/13/97	2978.80	N/A
09/17/97	2979.86	N/A
10/16/97	2980.90	N/A
11/12/97	2981.69	N/A
12/10/97	2982.53	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2983.80	N/A
02/11/98	2984.90	N/A
03/11/98	2985.89	N/A
04/15/98	2987.16	N/A
05/13/98	2988.15	N/A
06/11/98	2989.19	N/A
07/15/98	2990.44	N/A
08/12/98	2991.48	N/A
09/10/98	2992.56	N/A
10/14/98	2993.83	N/A
11/09/98	2994.82	N/A
12/07/98	2996.36	N/A
01/13/99	2997.40	N/A
02/08/99	2998.49	N/A
03/08/99	2999.52	N/A
04/14/99	3000.99	N/A
05/10/99	3002.04	N/A
06/04/99	3001.69	N/A
07/21/99	3004.83	N/A
08/11/99	3005.52	N/A
09/09/99	3006.67	N/A
10/06/99	3007.79	N/A
11/10/99	3009.20	N/A
12/08/99	3010.37	N/A
01/19/00	3012.08	N/A
02/16/00	3013.35	N/A
03/08/00	3014.26	N/A
04/19/00	3016.07	N/A
05/15/00	3017.21	N/A
06/05/00	3018.12	N/A
07/11/00	3019.73	N/A
08/16/00	3021.24	N/A
09/13/00	3022.43	N/A
10/11/00	3023.79	N/A
11/06/00	3024.75	N/A
12/07/00	3026.09	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3026.52	N/A
02/06/01	3028.72	N/A
03/06/01	3030.18	N/A
04/04/01	3031.04	N/A
05/08/01	3032.97	N/A
06/07/01	3034.57	N/A
07/10/01	3036.28	N/A
08/08/01	3037.79	N/A
09/07/01	3039.41	N/A
10/08/01	3040.95	N/A
11/12/01	3042.66	N/A
12/03/01	3043.70	N/A
01/15/02	3045.58	N/A
02/06/02	3046.71	N/A
03/12/02	3048.16	N/A
04/09/02	3049.45	N/A
05/08/02	3050.74	N/A
06/13/02	3052.26	N/A
07/15/02	3054.57	N/A
08/13/02	3056.90	N/A
09/10/02	3058.88	N/A

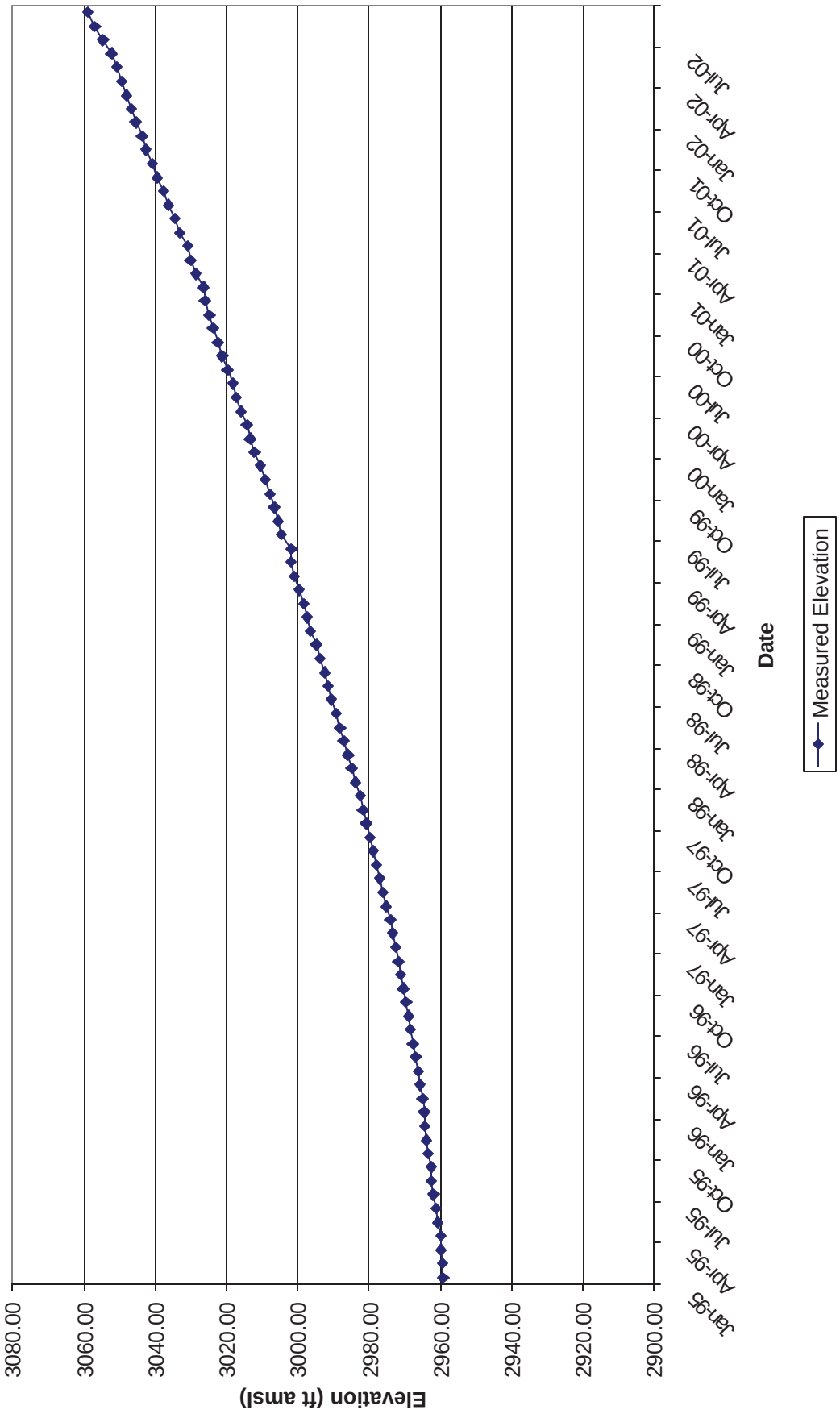
Figure 2 - AEC-8 Bell Canyon
Historical Waterlevel Measurments
Elevation (ft amsl)
3080.00
3060.00
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation

Table 3 - Well No. C-2737 (PIP) Culebra
April 2001 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
04/05/01	3013.98	N/A
05/08/01	3024.01	N/A
06/06/01	3014.11	N/A
07/09/01	3014.23	N/A
08/07/01	3014.30	N/A
09/06/01	3014.63	N/A
10/10/01	3014.62	N/A
11/14/01	3014.50	N/A
12/05/01	3014.27	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/02	3014.44	N/A
02/05/02	3014.55	N/A
03/12/02	3016.05	N/A
04/08/02	3016.32	N/A
05/07/02	3016.37	N/A
06/10/02	3016.72	N/A
07/15/02	3016.70	N/A
08/13/02	3017.01	N/A
09/12/02	3017.04	N/A

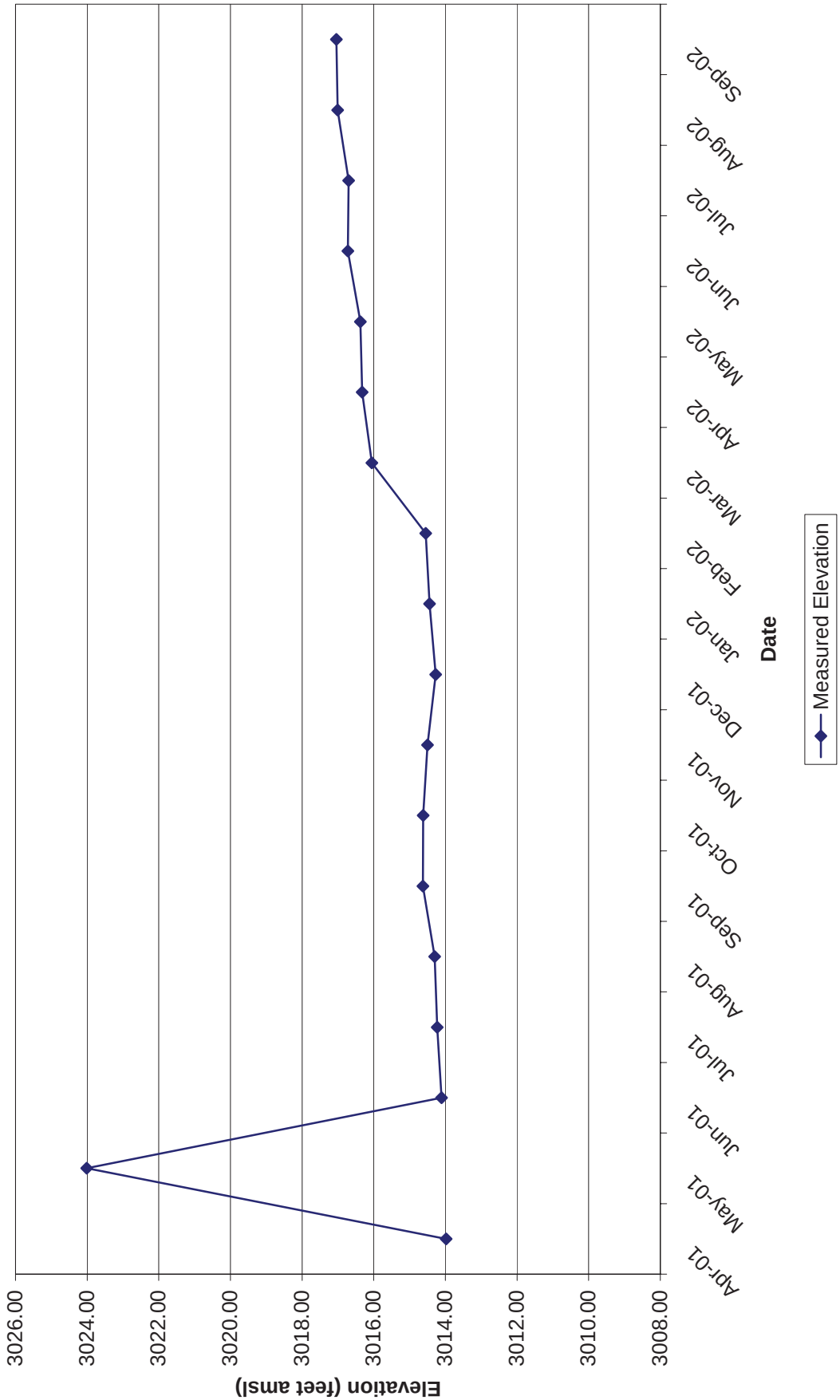
Figure 3 - C-2737 Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3026.00
3024.00
3022.00
3020.00
3018.00
3016.00
3014.00
3012.00
3010.00
3008.00
Apr-01
May-01
Jun-01
Jul-01
Aug-01
Sep-01
Oct-01
Nov-01
Dec-01
Jan-02
Feb-02
Mar-02
Apr-02
May-02
Jun-02
Jul-02
Aug-02
Sep-02
Date
Measured Elevation

Table 4 - Well No. C-2737 (ANNULUS) Magenta
April 2001 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
04/05/01	3141.47	N/A
05/08/01	3145.34	N/A
06/06/01	3145.86	N/A
07/09/01	3145.72	N/A
08/07/01	3145.53	N/A
09/06/01	3145.51	N/A
10/10/01	3145.30	N/A
11/14/01	3144.40	N/A
12/05/01	3144.96	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/02	3144.81	N/A
02/05/02	3144.67	N/A
03/12/02	3144.04	N/A
04/08/02	3143.83	N/A
05/07/02	3143.24	N/A
06/10/02	3142.97	N/A
07/16/02	3142.43	N/A
08/13/02	3142.35	N/A
09/12/02	3142.07	N/A

Figure 4 - C-2737 Magenta
Historical Water level Measurements

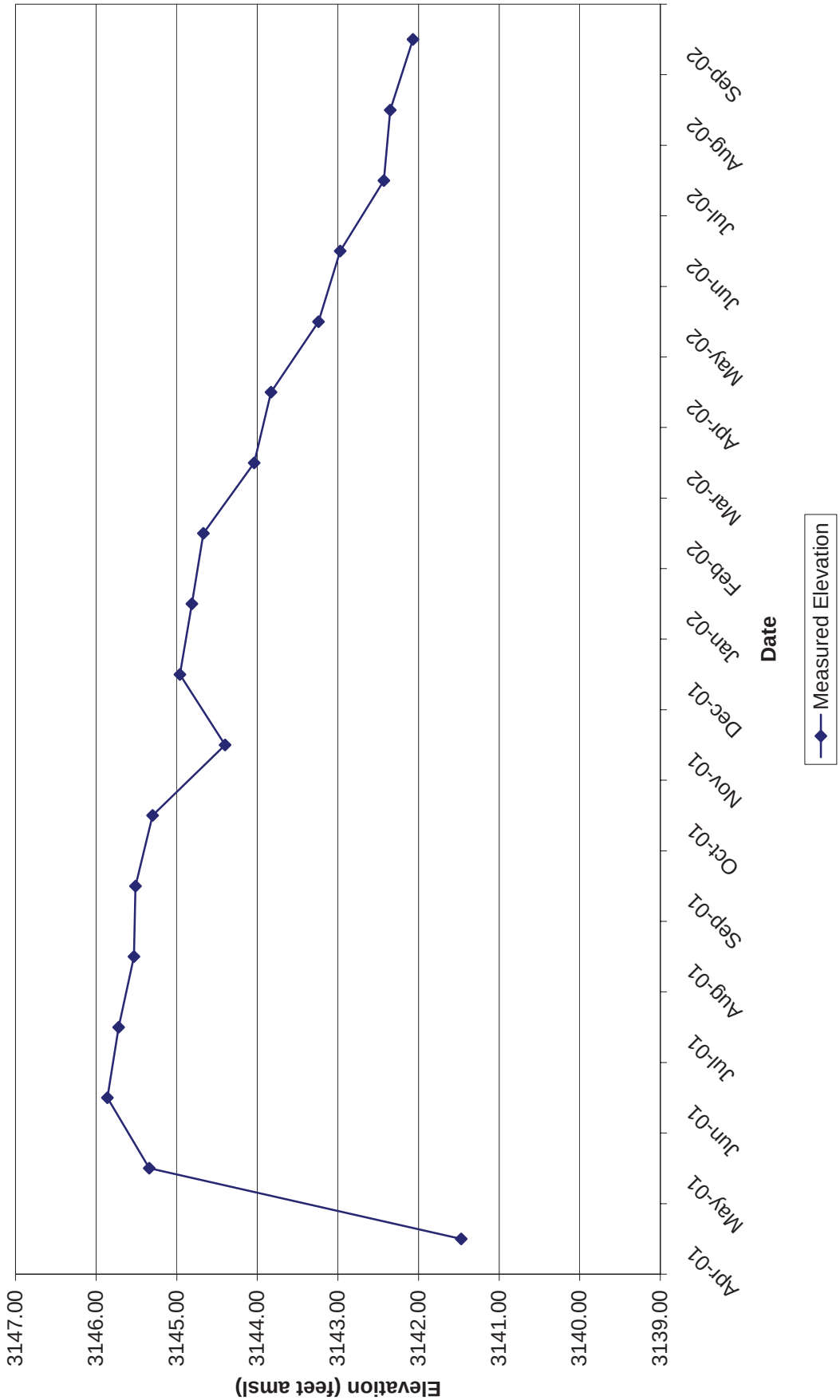

Table 5 - Well No. Cabin Baby-1 Culebra
April 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
04/15/97	2964.46	2967.78
05/14/97	2964.38	2967.70
06/11/97	2964.22	2967.54
07/15/97	2964.11	2967.42
08/12/97	2964.08	2967.39
09/16/97	2964.28	2967.60
10/15/97	2964.38	2967.70
11/11/97	2964.69	2968.02
12/09/97	2964.90	2968.24
01/13/98	2965.31	2968.66
02/10/98	2965.65	2969.01
03/10/98	2965.73	2969.09
04/14/98	2966.21	2969.59
05/12/98	2966.35	2969.73
06/10/98	2966.38	2969.76
07/14/98	2966.41	2969.79
08/11/98	2966.49	2969.88
09/09/98	2966.69	2970.08
10/13/98	2966.83	2970.23
11/10/98	2967.09	2970.4
12/08/98	2967.25	2970.66

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/99	2967.55	2970.97
02/09/99	2967.83	2971.26
03/09/99	2968.11	2971.55
04/13/99	2968.43	2971.88
05/11/99	2968.75	2972.21
06/08/99	2968.93	2972.39
07/20/99	2969.15	2972.62
08/10/99	2969.44	2972.92
09/08/99	3234.71	3246.41
10/05/99	3239.43	3251.28
11/09/99	3241.22	3253.12
12/08/99	3242.45	3254.39
01/08/00	3244.39	3256.39
02/15/00	3237.18	3248.96
03/07/00	3225.76	3237.18
04/18/00	3228.59	3240.10
05/16/00	3233.90	3245.58
06/06/00	3239.19	3251.03
07/11/00	3248.52	3260.65
08/15/00	3250.00	3262.17
09/11/00	3229.12	3240.65
10/11/00	3230.78	3242.36
11/09/00	3244.04	3256.03
12/05/00	3245.85	3257.90

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3244.31	3256.31
02/05/01	3245.41	3257.44
03/07/01	3247.19	3259.28
04/05/01	3251.09	3263.30
05/09/01	3255.92	3268.28
06/06/01	3253.44	3265.72
07/11/01	3252.86	3265.12
08/07/01	3256.52	3268.90
09/05/01	3260.96	3273.47
10/09/01	3266.23	3278.91
11/12/01	3271.28	3284.11
12/03/01	3274.28	3287.21
01/15/02	3280.35	3293.47
02/05/02	3283.14	3296.34
03/13/03	3288.01	3301.36
04/10/02	3291.66	3305.13
06/11/02	2864.73	2864.96
07/16/02	2888.16	2889.12
08/14/02	2905.50	2907.00
09/12/02	2921.53	2923.52

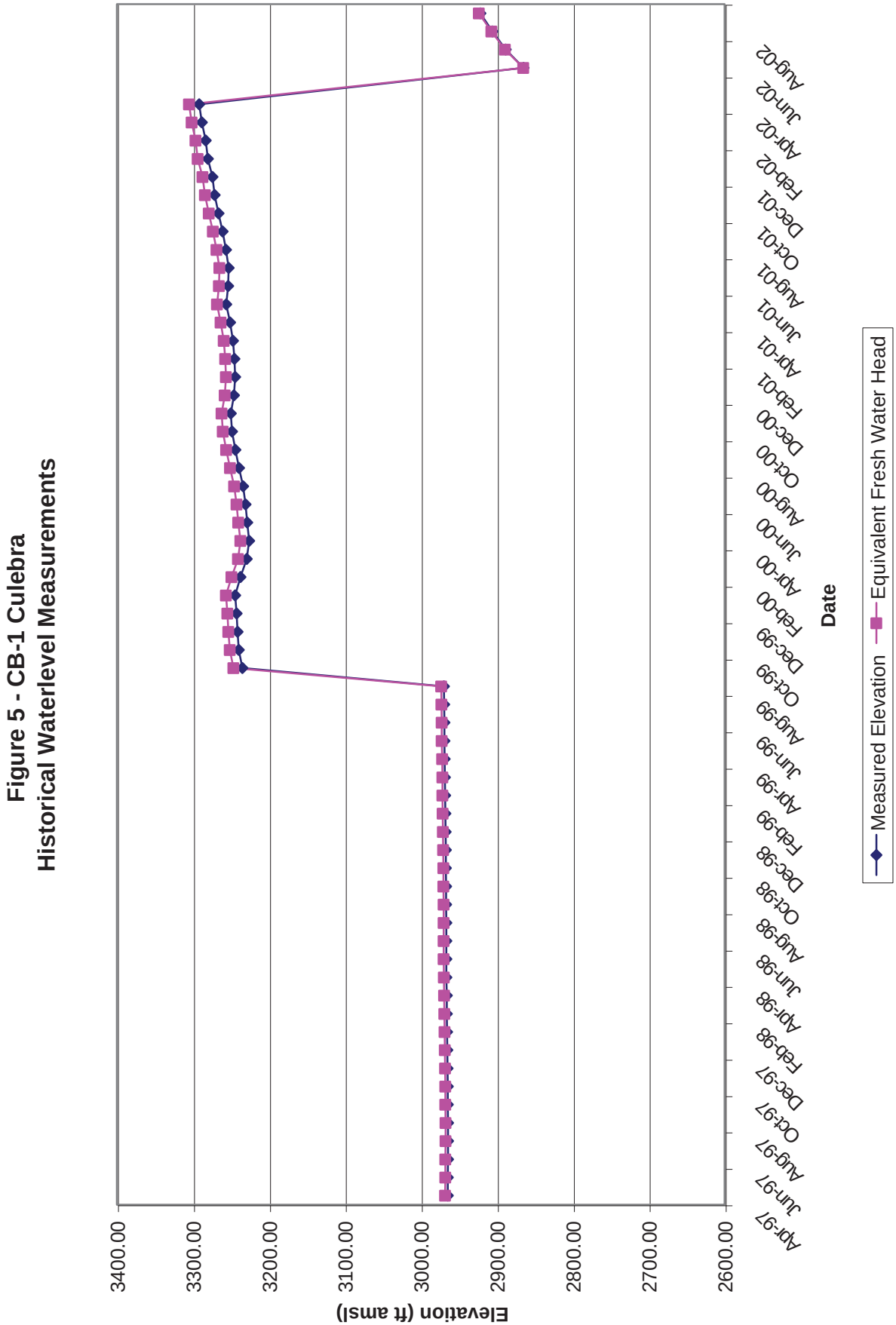
Figure 5 - CB-1 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3400.00
3300.00
3200.00
3100.00
3000.00
2900.00
2800.00
2700.00
2600.00
Date
Apr-97
Jun-97
Aug-97
Oct-97
Dec-97
Feb-98
Apr-98
Jun-98
Aug-98
Oct-98
Dec-98
Feb-99
Apr-99
Jun-99
Aug-99
Oct-99
Dec-99
Feb-00
Apr-00
Jun-00
Aug-00
Oct-00
Dec-00
Feb-01
Apr-01
Jun-01
Aug-01
Oct-01
Dec-01
Feb-02
Apr-02
Jun-02
Aug-02
Measured Elevation
Equivalent Fresh Water Head

Table 6 - Well No. Cabin Baby-1 (PIP) B ell Canyon
September 1999 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
09/08/99	2999.35	N/A
10/05/99	3010.43	N/A
11/09/99	3013.43	N/A
12/08/99	3014.30	N/A
01/18/00	3014.50	N/A
02/15/00	3014.73	N/A
03/07/00	3014.81	N/A
04/18/00	3014.84	N/A
05/16/00	3014.88	N/A
06/06/00	3014.73	N/A
07/11/00	3014.82	N/A
08/15/00	3014.71	N/A
09/11/00	3014.80	N/A
10/11/00	3014.65	N/A
11/09/00	3014.84	N/A
12/05/00	3014.65	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3014.78	N/A
02/05/01	3014.68	N/A
03/07/01	3014.72	N/A
04/05/01	3014.85	N/A
05/09/01	3014.71	N/A
06/06/01	3014.77	N/A
07/11/01	3015.14	N/A
08/07/01	3014.64	N/A
09/05/01	3014.66	N/A
10/09/01	3014.74	N/A
11/12/01	3014.56	N/A
12/03/01	3014.66	N/A
01/15/02	3014.65	N/A
02/05/02	3014.65	N/A
03/13/02	3014.80	N/A
04/10/02	3014.62	N/A
06/11/02	3014.74	N/A
07/16/02	3014.55	N/A
08/14/02	3014.60	N/A
09/12/02	3014.55	N/A

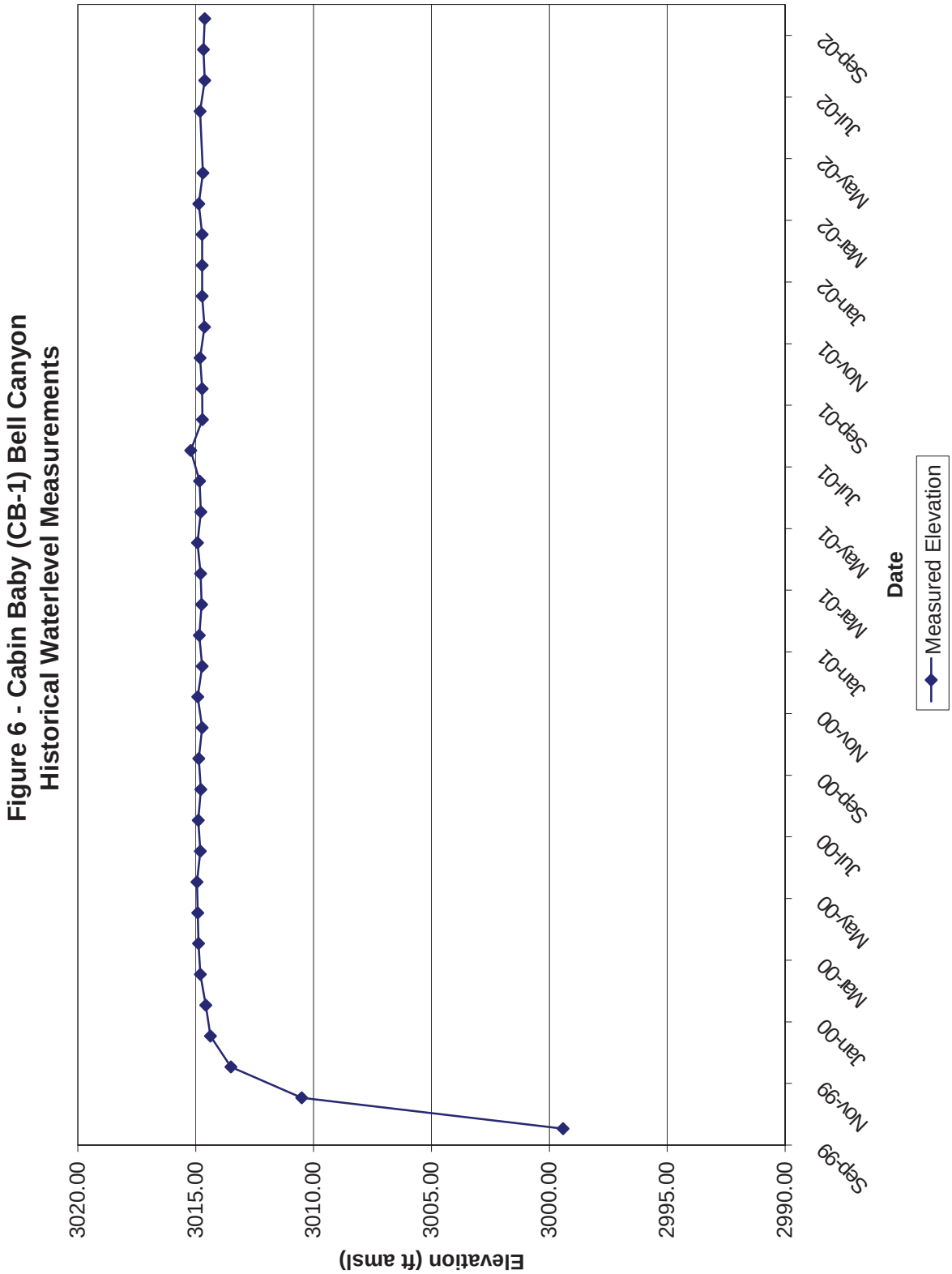
Figure 6 - Cabin Baby (CB-1) Bell Canyon
Historical Waterlevel Measurements
Elevation (ft amsl)
3020.00
3015.00
3010.00
3005.00
3000.00
2995.00
2990.00
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Date
Measured Elevation

Table 7 - Well No. D-268 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3005.89	N/A
02/14/95	3005.35	N/A
03/15/95	3004.94	N/A
04/12/95	3004.85	N/A
05/10/95	3004.90	N/A
06/07/95	3005.14	N/A
07/18/95	3005.35	N/A
08/17/95	3005.42	N/A
09/07/95	3005.25	N/A
10/19/95	3005.37	N/A
11/08/95	3005.28	N/A
12/06/95	3005.38	N/A
01/10/96	3005.41	N/A
02/07/96	3005.44	N/A
03/14/96	3005.47	N/A
04/17/96	3005.44	N/A
05/14/96	3005.40	N/A
06/13/96	3005.35	N/A
07/16/96	3005.36	N/A
08/14/96	3005.31	N/A
09/05/96	3005.61	N/A
10/15/96	3005.81	N/A
11/12/96	3005.46	N/A
12/11/96	3005.70	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/15/97	3005.62	N/A
02/12/97	3005.73	N/A
03/12/97	3005.99	N/A
04/16/97	3005.95	N/A
05/15/97	3006.24	N/A
06/11/97	3006.43	N/A
07/16/97	3006.07	N/A
08/12/97	3006.22	N/A
09/16/97	3006.31	N/A
10/15/97	3006.01	N/A
11/12/97	3006.31	N/A
12/10/97	3006.12	N/A
01/14/98	3006.13	N/A
02/11/98	3006.19	N/A
03/11/98	3005.88	N/A
04/15/98	3006.33	N/A
05/12/98	3006.18	N/A
06/11/98	3005.96	N/A
07/15/98	3005.76	N/A
08/10/98	3005.74	N/A
09/11/98	3005.76	N/A
10/13/98	3005.74	N/A
11/11/98	3005.72	N/A
12/08/98	3005.63	N/A

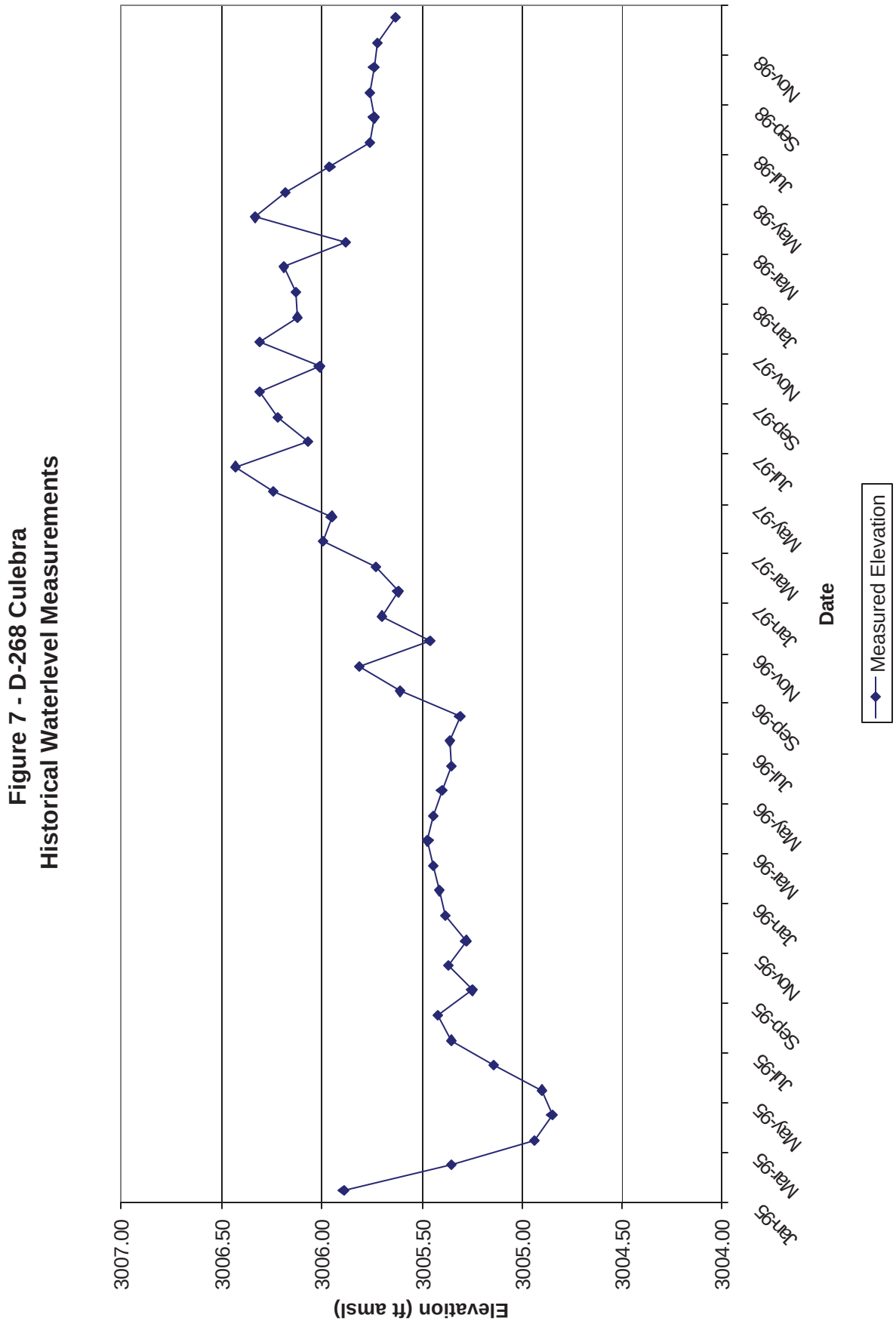
Figure 7 - D-268 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3007.00
3006.50
3006.00
3005.50
3005.00
3004.50
3004.00
Jan-95
Mar-95
May-95
Jul-95
Sep-95
Nov-95
Jan-96
Mar-96
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Date
Measured Elevation

Table 8 - Well No. DOE-1 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2963.19	2991.43
02/14/95	2964.26	2992.59
03/13/95	2965.55	2993.10
04/12/95	2968.49	2996.29
05/09/95	2970.30	2998.25
06/06/95	2969.51	2997.39
07/19/95	2960.60	2987.74
08/14/95	2953.20	2979.73
09/07/95	2958.54	2985.51
10/18/95	2965.68	2993.24
11/07/95	2966.08	2993.68
12/05/95	2967.48	2995.19
01/09/96	2958.88	2985.88
02/06/96	2954.52	2981.16
03/12/96	2937.75	2963.00
04/17/96	2947.70	2973.77
05/14/96	2957.57	2984.46
06/12/96	2961.27	2988.47
07/16/96	2965.73	2993.30
08/13/96	2967.87	2995.62
09/05/96	2968.99	2996.83
10/15/96	2970.02	2997.94
11/12/96	2970.79	2998.78
12/10/96	2971.50	2999.55
01/13/97	2972.13	3000.23
02/11/97	2972.41	3000.53
03/10/97	2972.58	3000.72
04/15/97	2972.44	3000.56
05/14/97	2972.45	3000.58
06/11/97	2972.37	3000.49
07/16/97	2972.15	3000.25
08/12/97	2972.03	3000.12
09/16/97	2972.28	3000.39
10/15/97	2972.67	3000.81
11/11/97	2972.96	3001.13
12/09/97	2973.25	3001.44

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2973.48	3001.69
02/11/98	2974.03	3002.29
03/11/98	2974.05	3002.31
04/15/98	2973.98	3002.23
05/12/98	2973.92	3002.17
06/10/98	2973.72	3001.95
07/15/98	2973.58	3001.80
08/12/98	2973.56	3001.78
09/10/98	2973.32	3001.52
10/13/98	2973.33	3001.53
11/11/98	2973.37	3001.57
12/08/98	2973.65	3001.87
01/12/99	2973.88	3002.12
02/09/99	2974.13	3002.39
03/10/99	2974.41	3002.70
04/12/99	2974.60	3002.90
05/10/99	2974.69	3003.00
06/08/99	2974.78	3003.10
07/20/99	2974.83	3003.15
08/09/99	2974.93	3003.26
09/07/99	2974.96	3003.29
10/05/99	2974.86	3003.19
11/08/99	2974.56	3002.86
12/08/99	2974.68	3002.99
01/18/00	2974.68	3002.99
02/15/00	2974.78	3003.10
03/08/00	2974.84	3003.16
04/18/00	2974.91	3003.24
05/17/00	2975.03	3003.37
06/06/00	2975.05	3003.39
07/10/00	2975.16	3003.51
08/14/00	2974.97	3003.30
09/11/00	2975.17	3003.52
10/11/00	2975.05	3003.39
11/09/00	2975.14	3003.49
12/05/00	2975.04	3003.38

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2975.19	3003.54
02/05/01	2975.25	3003.61
03/08/01	2975.62	3004.01
04/05/01	2975.92	3004.33
05/09/01	2976.09	3004.52
06/06/01	2976.25	3004.69
07/10/01	2976.40	3004.85
08/07/01	2976.64	3005.11
09/07/01	2976.61	3005.08
10/09/01	2976.69	3005.17
11/13/01	2976.65	3005.12
12/05/01	2976.71	3005.19
01/16/02	2976.88	3005.37
02/05/02	2977.09	3005.60
03/13/02	2977.24	3005.76
04/10/02	2976.74	3005.22
05/07/02	2977.22	3005.74
06/11/02	2977.56	3006.11
07/15/02	2977.86	3006.43
08/14/02	2977.98	3006.56
09/11/02	2978.09	3006.68

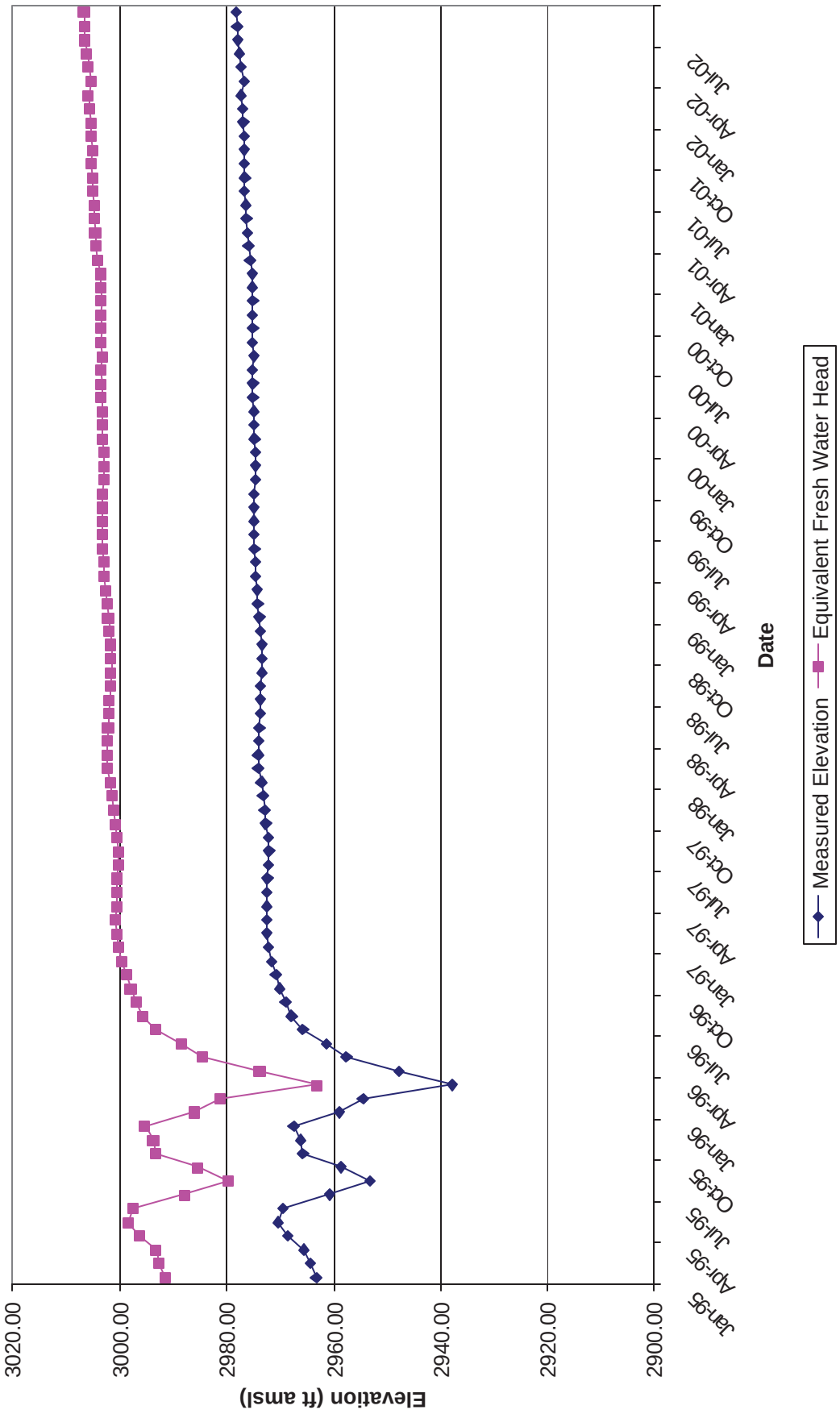
Figure 8 - DOE-1 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 9 - Well No. DOE-2 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3053.92	3067.07
02/13/95	3053.28	3066.41
03/13/95	3053.36	3066.49
04/12/95	3052.88	3066.00
05/08/95	3053.21	3066.34
06/05/95	3053.31	3066.44
07/17/95	3053.22	3066.35
08/14/95	3053.53	3066.67
09/05/95	3052.48	3065.59
10/18/95	3052.94	3066.06
11/08/95	3052.92	3066.04
12/04/95	3053.05	3066.17
01/11/96	3052.90	3066.02
02/07/96	3052.19	3065.29
03/11/96	3052.08	3065.18
04/15/96	3052.21	3065.31
05/13/96	3052.35	3065.45
06/12/96	3052.72	3065.83
07/16/96	3052.89	3066.01
08/14/96	3052.52	3065.63
09/05/96	3052.93	3066.05
10/16/96	3052.97	3066.09
11/13/96	3052.64	3065.75
12/11/96	3052.87	3065.99
01/13/97	3053.11	3066.24
02/10/97	3053.01	3066.13
03/10/97	3053.24	3066.37
04/14/97	3053.56	3066.70
05/14/97	3053.45	3066.58
06/11/97	3053.84	3066.99
07/16/97	3054.33	3067.49
08/12/97	3053.83	3066.98
09/15/97	3053.92	3067.07
10/15/97	3053.64	3066.78
11/12/97	3053.50	3066.64
12/08/97	3052.64	3065.75

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3052.76	3065.88
02/09/98	3055.40	3068.59
03/11/98	3056.54	3069.76
04/15/98	3056.19	3069.40
05/11/98	3055.66	3068.86
06/11/98	3055.21	3068.39
07/15/98	3055.03	3068.21
08/12/98	3055.12	3068.30
09/10/98	3060.89	3074.23
10/14/98	3056.72	3069.95
11/11/98	3055.02	3068.20
12/08/98	3059.31	3072.61
01/11/99	3058.78	3072.06
02/08/99	3058.61	3071.89
03/10/99	3058.42	3071.69
04/12/99	3058.17	3071.44
05/10/99	3058.16	3071.43
06/07/99	3058.05	3071.31
07/20/99	3057.79	3071.05
08/09/99	3057.66	3070.91
09/07/99	3057.47	3070.72
10/04/99	3057.38	3070.62
11/08/99	3057.43	3070.68
12/06/99	3057.50	3070.75
01/17/00	3057.60	3070.85
02/14/00	3057.72	3070.97
03/06/00	3057.76	3071.02
04/17/00	3057.81	3071.07
05/15/00	3057.27	3070.51
06/05/00	3041.95	3054.76
07/10/00	3041.14	3053.93
08/14/00	3040.94	3053.72
09/12/00	3040.98	3053.77
10/09/00	3040.79	3053.57
11/06/00	3041.01	3053.80
12/07/00	3040.80	3053.58

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3040.85	3053.63
02/06/01	3040.74	3053.52
03/06/01	3040.78	3053.56

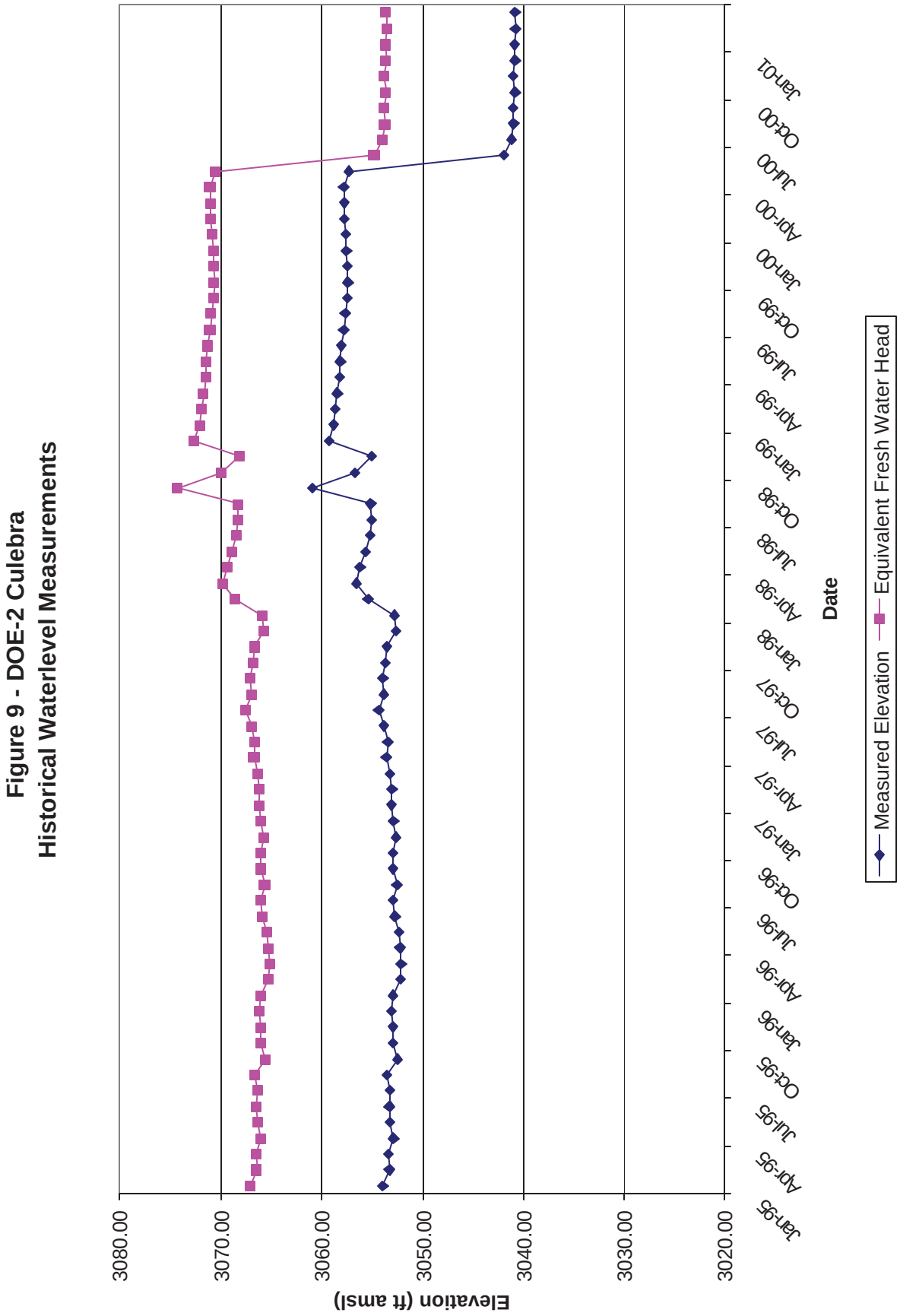
Figure 9 - DOE-2 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3080.00
3070.00
3060.00
3050.00
3040.00
3030.00
3020.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Date
Measured Elevation
Equivalent Fresh Water Head

Table 10 - Well No. DOE-2 Magenta
April 2001 through January 2002

Date	Measured Elevation	Equivalent Fresh Water Head
04/04/01	2942.34	N/A
05/08/01	3047.58	N/A
06/05/01	3048.44	N/A
07/09/01	3049.24	N/A
09/12/01	3053.11	N/A
10/23/01	3056.55	N/A
11/12/01	3057.19	N/A
12/03/01	3058.12	N/A
01/09/02	3059.80	N/A

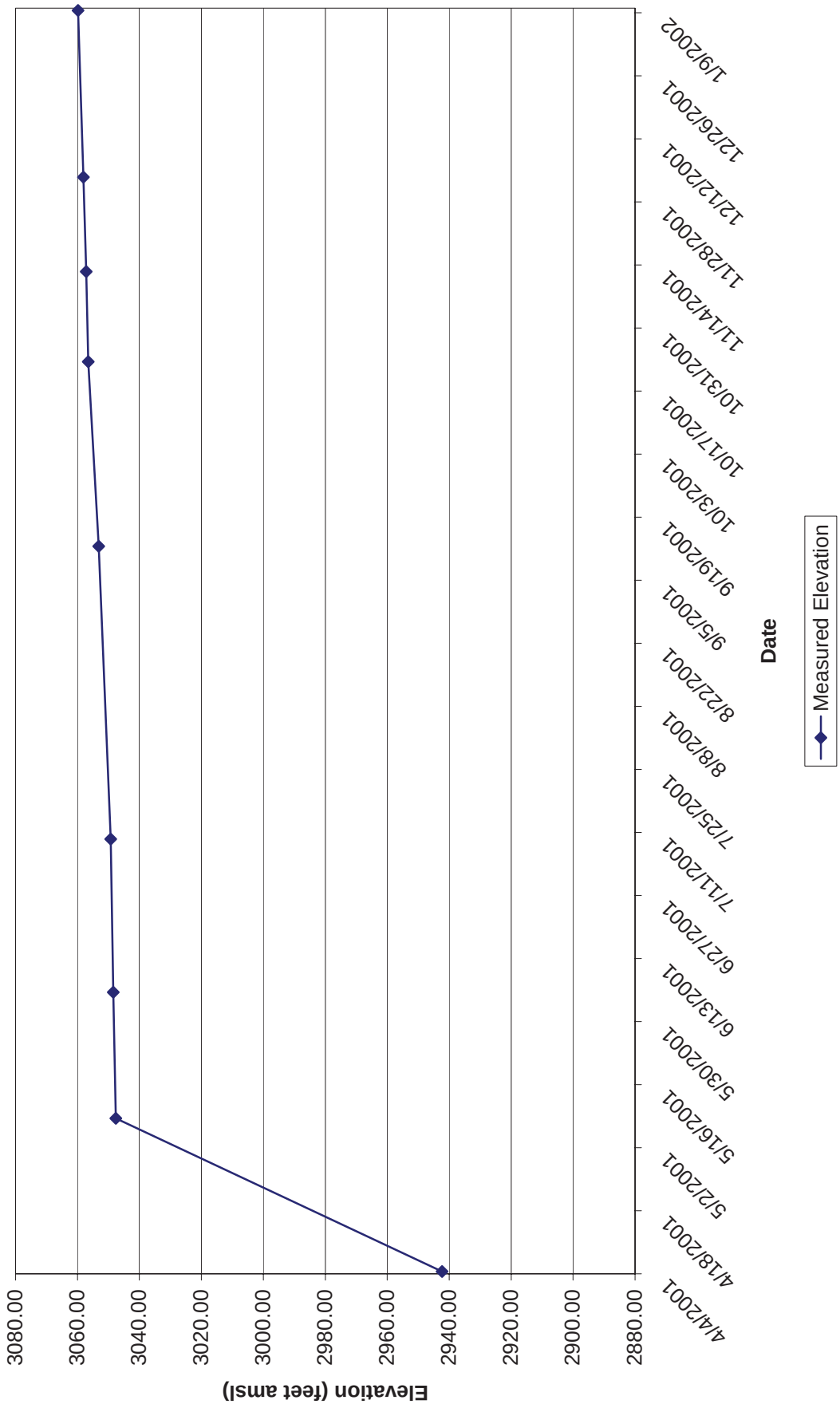
Figure 10 - DOE-2 Magenta
Historical Waterlevel Measurements
Elevation (feet amsl)
3080.00
3060.00
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
2880.00
4/4/2001
4/18/2001
5/2/2001
5/16/2001
5/30/2001
6/13/2001
6/27/2001
7/11/2001
7/25/2001
8/8/2001
8/22/2001
9/5/2001
9/19/2001
10/3/2001
10/17/2001
10/31/2001
11/14/2001
11/28/2001
12/12/2001
12/26/2001
1/9/2002
Date
Measured Elevation

Table 11 - Well No. ERDA-9 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3002.33	3017.47
02/15/95	3002.77	3017.93
03/15/95	3001.36	3016.45
04/12/95	3002.00	3017.12
05/10/95	3002.11	3017.24
06/07/95	3000.26	3015.30
07/19/95	2989.37	3003.87
08/17/95	2984.28	2998.54
09/07/95	2986.21	3000.56
10/18/95	2987.55	3001.97
11/09/95	2989.58	3004.09
12/04/95	2991.66	3006.28
01/11/96	2984.07	2998.31
02/07/96	2974.68	2988.46
03/14/96	2968.17	2981.64
04/17/96	2965.89	2979.24
05/15/96	2972.85	2986.55
06/12/96	2979.06	2993.06
07/17/96	2984.98	2999.27
08/13/96	2988.42	3002.88
09/05/96	2990.82	3005.40
10/16/96	2993.41	3008.11
11/13/96	2994.88	3009.65
12/10/96	2996.40	3011.25
01/16/97	2997.53	3012.43
02/11/97	2998.25	3013.19
03/12/97	2999.37	3014.36
04/16/97	3000.44	3015.49
05/14/97	3001.17	3016.25
06/11/97	3001.47	3016.57
07/16/97	3001.75	3016.86
08/13/97	3002.13	3017.26
09/17/97	3002.51	3017.66
10/15/97	3001.64	3016.75
11/12/97	3002.94	3018.11
12/10/97	3003.17	3018.35

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3003.17	3018.35
02/11/98	3003.59	3018.79
03/11/98	3003.94	3019.16
04/15/98	3004.67	3019.92
05/13/98	3004.86	3020.12
06/10/98	3005.05	3020.32
07/15/98	3005.32	3020.61
08/12/98	3005.42	3020.71
09/10/98	3005.64	3020.94
10/14/98	3005.61	3020.91
11/11/98	3005.62	3020.92
12/09/98	3005.74	3021.05
01/13/99	3005.71	3021.02
02/10/99	3006.03	3021.35
03/10/99	3006.26	3021.60
04/12/99	3006.37	3021.71
05/10/99	3006.61	3021.96
06/09/99	3006.82	3022.18
07/20/99	3006.95	3022.32
08/09/99	3007.18	3022.56
09/07/99	3007.35	3022.74
10/05/99	3007.24	3022.62
11/08/99	3006.94	3022.31
12/08/99	3007.08	3022.45
01/19/00	3006.83	3022.19
02/15/00	3006.75	3022.11
03/08/00	3007.09	3022.47
04/18/00	3007.35	3022.74
05/17/00	3007.60	3023.00
06/07/00	3007.56	3022.96
07/10/00	3007.95	3023.37
08/14/00	3008.03	3023.45
09/11/00	3008.17	3023.60
10/11/00	3007.90	3023.31
11/08/00	3007.98	3023.40
12/06/00	3007.53	3022.93

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3007.29	3022.68
02/05/01	3006.65	3022.00
03/07/01	3007.28	3022.66
04/05/01	3007.75	3023.16
05/08/01	3007.89	3023.30
06/06/01	3008.28	3023.71
07/11/01	3008.45	3023.89
08/07/01	3008.59	3024.04
09/06/01	3008.79	3024.25
10/10/01	3008.84	3024.30
11/14/01	3008.70	3024.15
12/05/01	3008.60	3024.05
01/16/02	3008.40	3023.84
02/05/02	3008.46	3023.90
03/12/02	3008.53	3023.98
04/08/02	3008.87	3024.33
05/07/02	3009.13	3024.61
06/10/02	3009.48	3024.97
07/15/02	3009.66	3025.16
08/14/02	3009.87	3025.38
09/10/02	3009.95	3025.47

Figure 11 - ERDA-9 Culebra
Historical Waterlevel Measurements

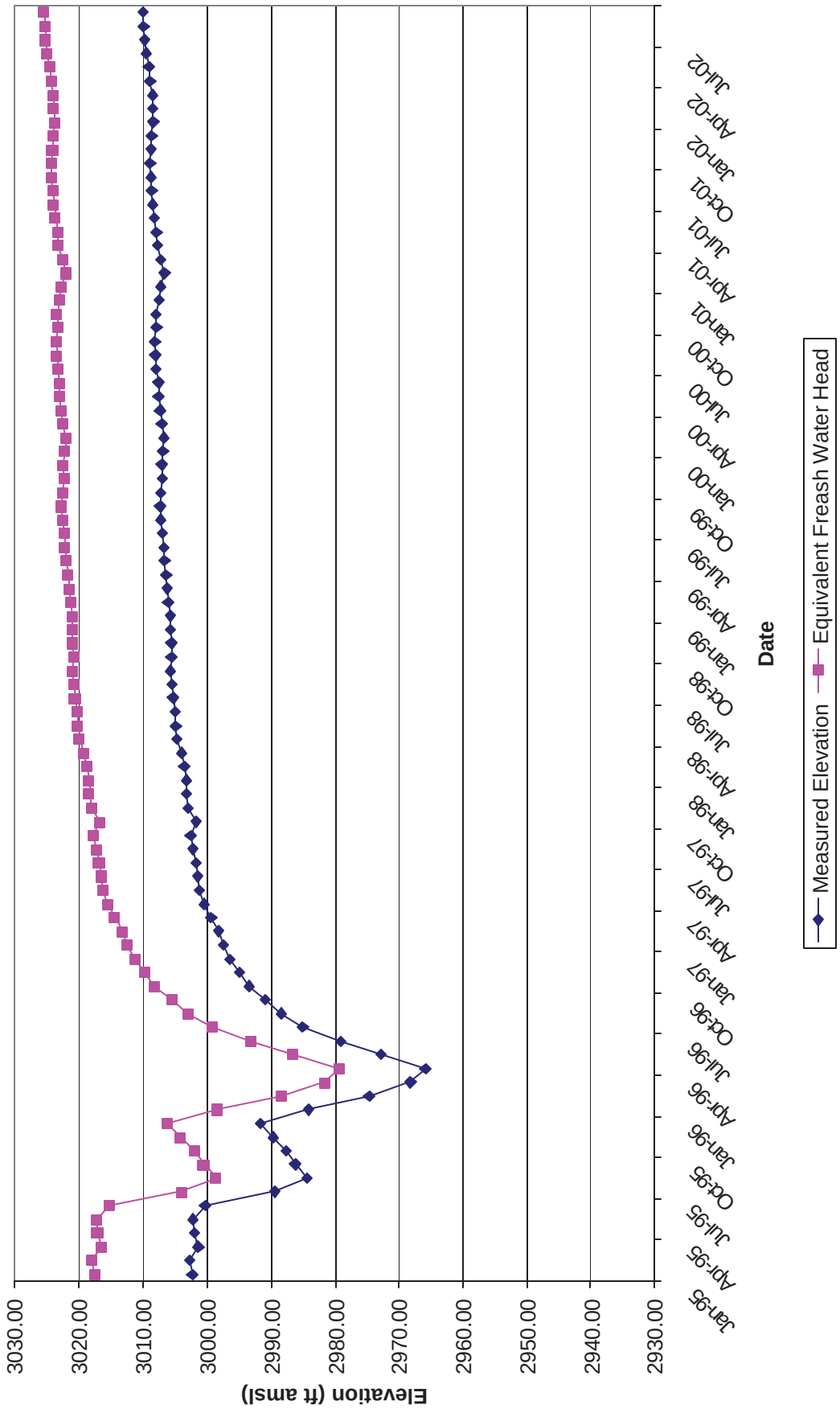

Table 12 - Well No. H-01 (ANNULUS) Magenta
January 1995 through February 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3134.92	N/A
02/14/95	3135.20	N/A
03/15/95	3135.34	N/A
04/12/95	3135.56	N/A
05/10/95	3135.91	N/A
06/07/95	3136.25	N/A
07/19/95	3136.47	N/A
08/17/95	3136.85	N/A
09/07/95	3136.97	N/A
10/18/95	3137.40	N/A
11/09/95	3137.64	N/A
12/06/95	3137.93	N/A
01/11/96	3138.23	N/A
02/07/96	3138.46	N/A
03/14/96	3138.66	N/A
04/17/96	3137.73	N/A
05/15/96	3138.77	N/A
06/12/96	3138.90	N/A
07/17/96	3138.99	N/A
08/13/96	3138.95	N/A
09/05/96	3139.30	N/A
10/16/96	3139.55	N/A
11/13/96	3139.75	N/A
12/10/96	3140.21	N/A
01/16/97	3140.54	N/A
02/11/97	3141.14	N/A
03/12/97	3141.22	N/A
04/16/97	3141.54	N/A
05/14/97	3141.82	N/A
06/11/97	3141.62	N/A
07/16/97	3141.73	N/A
08/13/97	3145.56	N/A
09/17/97	3156.88	N/A
10/15/97	3163.91	N/A
11/12/97	3176.57	N/A
12/10/97	3189.28	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3192.84	N/A
02/11/98	3208.35	N/A
03/11/98	3211.58	N/A
04/15/98	3226.84	N/A
05/13/98	3225.20	N/A
06/10/98	3220.90	N/A
07/15/98	3219.41	N/A
08/12/98	3220.06	N/A
09/10/98	3218.03	N/A
10/12/98	3217.62	N/A
11/09/98	3230.91	N/A
12/09/98	3230.12	N/A
01/13/99	3230.55	N/A
02/08/99	3231.89	N/A
03/10/99	3230.07	N/A
04/13/99	3228.51	N/A
05/10/99	3231.18	N/A
06/09/99	3183.95	N/A
07/21/99	3197.92	N/A
09/09/99	3212.90	N/A
10/05/99	3206.63	N/A
11/10/99	3199.56	N/A
12/08/95	3216.46	N/A
01/19/00	3224.86	N/A
02/16/00	3229.00	N/A
03/08/00	3229.46	N/A
04/18/00	3227.02	N/A
05/17/00	3213.25	N/A
06/07/00	3189.09	N/A
07/10/00	3217.01	N/A
08/14/00	3227.24	N/A
09/11/00	3229.57	N/A
10/11/00	3222.34	N/A
11/08/00	3230.08	N/A
12/06/00	3229.17	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3231.57	N/A
02/05/01	3229.89	N/A

Figure 12 - H-1 Magenta
Historical Waterlevel Measurements

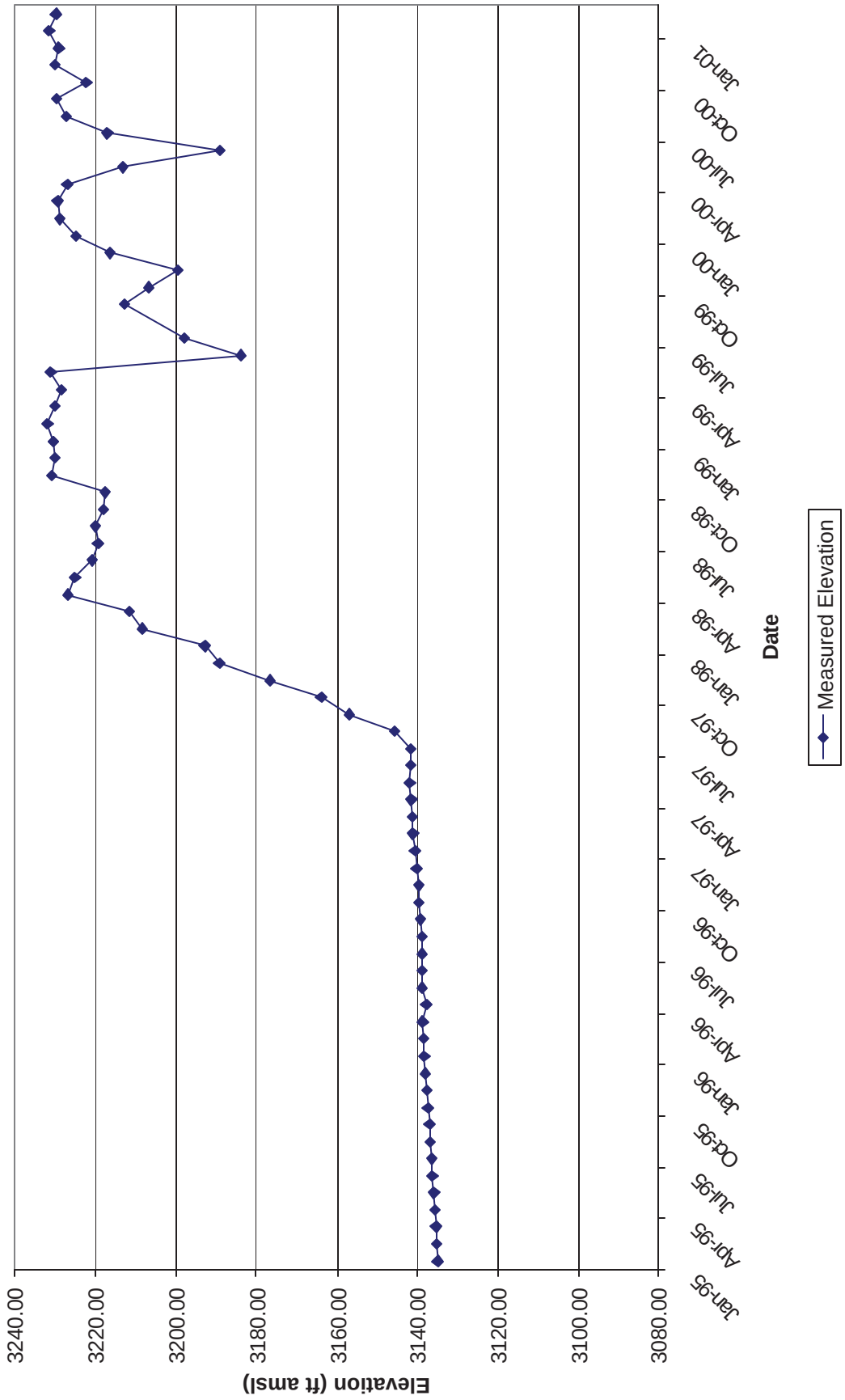

Table 13 - Well No. H-01 (PIP) Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3020.49	3021.11
02/14/95	3021.07	3021.69
03/15/95	3019.85	3020.47
04/12/95	3020.17	3020.79
05/10/95	3020.55	3021.17
06/07/95	3019.48	3020.10
07/19/95	3010.66	3011.26
08/17/95	2998.85	2999.43
09/07/95	3004.54	3005.13
10/18/95	3004.48	3005.07
11/09/95	3006.62	3007.21
12/06/95	3008.26	3008.86
01/11/96	3004.17	3004.76
02/07/96	2994.94	2995.51
03/14/96	2988.37	2988.93
04/17/96	2985.21	2985.76
05/15/96	2989.52	2990.08
06/12/96	2995.30	2995.87
07/17/96	3001.21	3001.79
08/13/96	3004.68	3005.27
09/05/96	3007.34	3007.93
10/16/96	3010.37	3010.97
11/13/96	3011.87	3012.47
12/10/96	3013.70	3014.31

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3021.39	3022.01
02/11/98	3021.67	3022.29
03/11/98	3021.85	3022.47
04/15/98	3022.76	3023.39
05/13/98	3022.98	3023.61
06/10/98	3022.88	3023.51
07/15/98	3023.11	3023.74
08/12/98	3023.26	3023.89
09/10/98	3023.46	3024.09
10/12/98	3023.35	3023.98
11/09/98	3023.47	3024.10
12/09/98	3021.46	3022.08
01/13/99	3021.63	3022.25
02/08/99	3024.29	3024.92
03/10/99	3024.34	3024.97
04/13/99	3024.45	3025.08
05/10/99	3025.17	3025.80
06/09/99	3027.11	3027.74
07/21/99	3027.40	3028.03
08/11/99	3148.39	3148.97
09/09/99	3034.91	3035.26
10/05/99	3037.82	3038.48
11/10/99	3035.58	3036.23
12/08/99	3035.95	3036.60

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3035.50	3036.15
02/05/01	3035.33	3035.98

01/16/97	3014.99	3015.60
02/11/97	3016.16	3016.77
03/12/97	3017.21	3017.82
04/16/97	3018.21	3018.83
05/14/97	3019.03	3019.65
06/11/97	3019.43	3020.05
07/16/97	3019.49	3020.11
08/13/97	3019.77	3020.39
09/17/97	3020.41	3021.03
10/15/97	3020.34	3020.96
11/12/97	3020.95	3021.57
12/10/97	3021.10	3021.72

01/19/00	3034.94	3035.59
02/16/00	3034.93	3035.58
03/08/00	3034.91	3035.56
04/18/00	3036.27	3036.92
05/17/00	3036.26	3036.91
06/07/00	3035.45	3036.10
07/10/00	3035.27	3035.92
08/14/00	3036.16	3036.81
09/11/00	3035.95	3036.60
10/11/00	3035.81	3036.46
11/08/00	3035.78	3036.43
12/06/00	3035.57	3036.22

Figure 13 - H-1 Culebra
Historical Waterlevel Measurements

Table 14 - Well No. H-02a Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/15/95	3028.57	3031.99
06/07/95	3030.22	3033.66
09/07/95	3030.86	3034.30
12/06/95	3030.56	3034.00
03/14/96	3030.06	3033.50
06/12/96	3028.73	3032.15
09/05/96	3027.87	3031.28
12/10/96	3027.85	3031.26
03/12/97	3028.32	3031.73
06/12/97	3029.22	3032.65
09/17/97	3030.27	3033.71
12/10/97	3030.98	3034.43

Date	Measured Elevation	Equivalent Fresh Water Head
03/11/98	3031.68	3035.13
06/10/98	3032.50	3035.96
09/10/98	3033.06	3036.53
12/09/98	3033.56	3037.04
03/10/99	3034.09	3037.57
06/09/99	3034.57	3038.06
09/09/99	3035.04	3038.54
12/09/99	3035.40	3038.90
03/08/00	3035.69	3039.19
06/07/00	3036.10	3039.61
09/11/00	3036.50	3040.01
12/06/00	3036.78	3040.30

Date	Measured Elevation	Equivalent Fresh Water Head
03/08/01	3037.06	3040.58
06/06/01	3037.34	3040.86
09/06/01	3037.59	3041.12
12/05/01	3037.77	3041.30
03/13/02	3038.08	3041.61
06/11/02	3038.30	3041.83
09/10/02	3038.52	3042.06

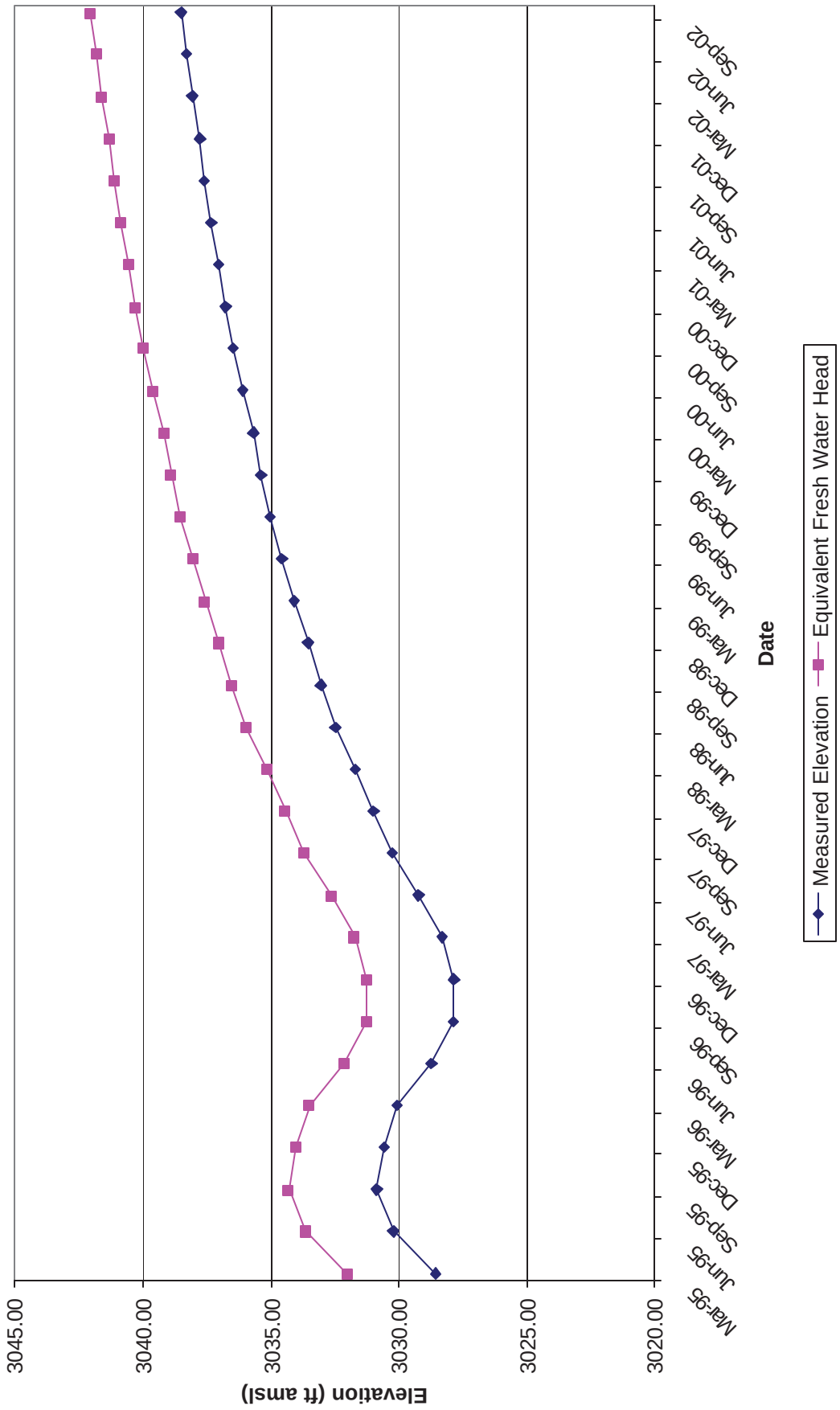
Figure 14 - H-2a Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3045.00
3040.00
3035.00
3030.00
3025.00
3020.00
Mar-95
Jun-95
Sep-95
Dec-95
Mar-96
Jun-96
Sep-96
Dec-96
Mar-97
Jun-97
Sep-97
Dec-97
Mar-98
Jun-98
Sep-98
Dec-98
Mar-99
Jun-99
Sep-99
Dec-99
Mar-00
Jun-00
Sep-00
Dec-00
Mar-01
Jun-01
Sep-01
Dec-01
Mar-02
Jun-02
Sep-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 15 - Well No. H2b1 Magenta

January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3128.91	N/A
02/15/95	3129.30	N/A
03/15/95	3129.62	N/A
04/12/95	3129.84	N/A
05/10/95	3130.25	N/A
06/07/95	3130.61	N/A
07/19/95	3131.01	N/A
08/17/95	3131.26	N/A
09/07/95	3131.42	N/A
10/19/95	3131.76	N/A
11/08/95	3131.88	N/A
12/06/95	3132.13	N/A
01/10/96	3132.38	N/A
02/07/96	3132.61	N/A
03/14/96	3132.88	N/A
04/17/96	3133.15	N/A
05/15/96	3133.37	N/A
06/12/96	3133.62	N/A
07/17/96	3133.85	N/A
08/13/96	3134.00	N/A
09/05/96	3134.15	N/A
10/15/96	3134.42	N/A
11/13/96	3134.59	N/A
12/10/96	3134.71	N/A
01/16/97	3134.87	N/A
02/12/97	3134.96	N/A
03/12/97	3135.14	N/A
04/16/97	3135.30	N/A
05/14/97	3135.47	N/A
06/12/97	3135.58	N/A
07/16/97	3135.68	N/A
08/13/97	3135.73	N/A
09/17/97	3135.78	N/A
10/15/97	3135.85	N/A
11/12/97	3135.91	N/A
12/10/97	3135.99	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3136.10	N/A
02/11/98	3136.20	N/A
03/11/98	3136.34	N/A
04/15/98	3136.58	N/A
05/13/98	3136.82	N/A
06/10/98	3137.09	N/A
07/15/98	3137.46	N/A
08/12/98	3137.84	N/A
09/10/98	3138.24	N/A
10/14/98	3138.73	N/A
11/11/98	3139.14	N/A
12/09/98	3139.57	N/A
01/13/99	3140.12	N/A
02/10/99	3140.65	N/A
03/10/99	3141.13	N/A
04/13/99	3141.71	N/A
05/11/99	3142.02	N/A
06/09/99	3142.37	N/A
07/21/99	3142.85	N/A
08/11/99	3143.15	N/A
09/09/99	3143.49	N/A
10/06/99	3143.79	N/A
11/10/99	3144.16	N/A
12/09/99	3144.47	N/A
01/20/00	3144.76	N/A
02/16/00	3144.93	N/A
03/08/00	3145.07	N/A
04/19/00	3145.35	N/A
05/17/00	3145.52	N/A
06/07/00	3145.66	N/A
07/10/00	3145.88	N/A
08/15/00	3146.09	N/A
09/11/00	3146.22	N/A
10/11/00	3146.31	N/A
11/06/00	3146.43	N/A
12/06/00	3146.54	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3146.56	N/A
02/06/01	3146.48	N/A
03/08/01	3146.58	N/A
04/05/01	3146.72	N/A
05/08/01	3146.85	N/A
06/06/01	3146.95	N/A
07/11/01	3147.04	N/A
08/07/01	3147.12	N/A
09/06/01	3147.23	N/A
10/10/01	3147.23	N/A
11/14/01	3147.20	N/A
12/05/01	3147.19	N/A
01/16/02	3147.15	N/A
02/05/02	3147.17	N/A
03/13/02	3147.15	N/A
04/08/02	3147.21	N/A
05/08/02	3147.17	N/A
06/11/02	3147.14	N/A
07/16/02	3147.09	N/A
08/13/02	3147.01	N/A
09/10/02	3146.96	N/A

Figure 15 - H-2b1 Magenta
Historical Waterlevel Measurements

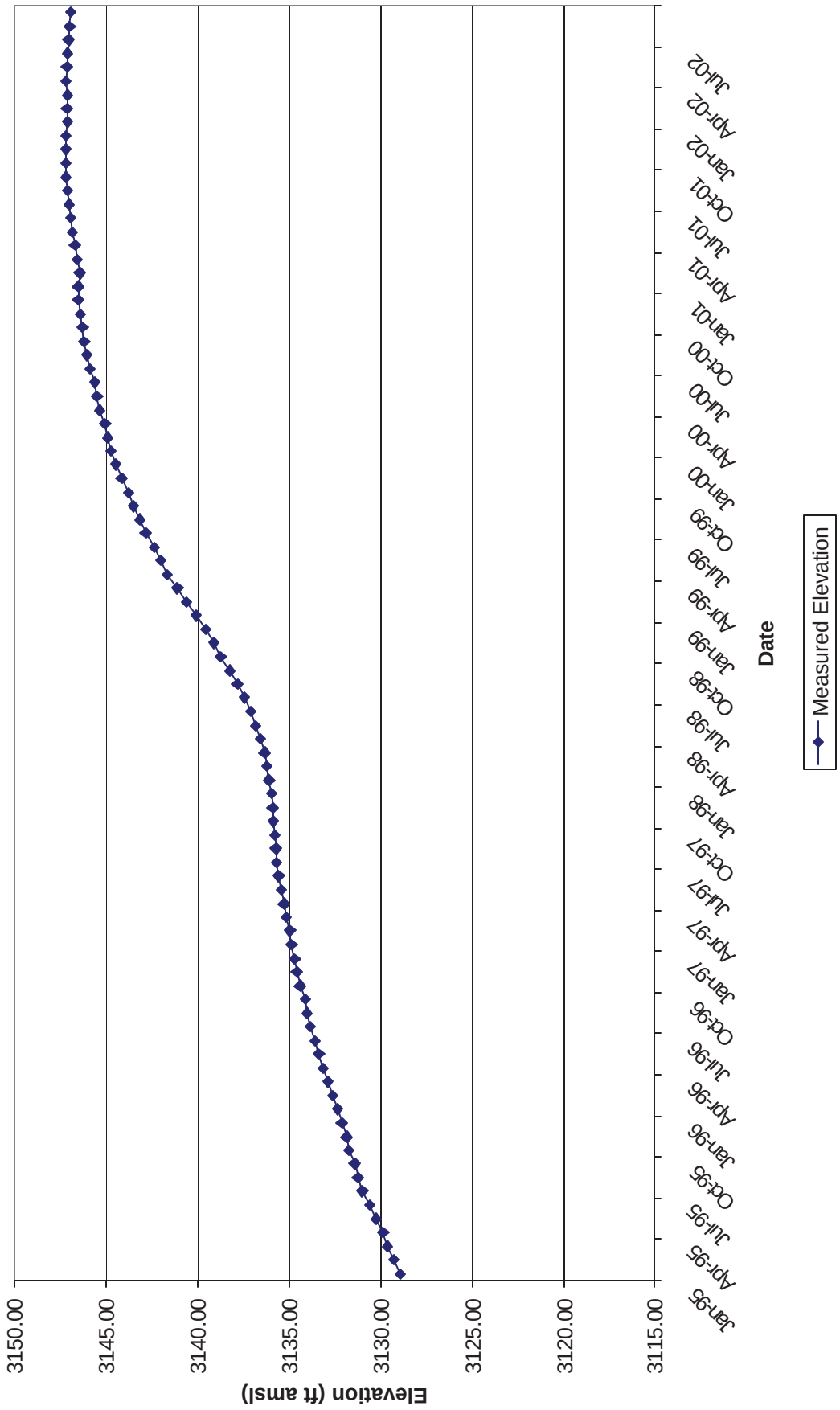

Table 16 - Well No. H2b2 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3031.50	3033.80
02/15/95	3031.92	3034.23
03/15/95	3031.91	3034.22
04/12/95	3031.92	3034.23
05/10/95	3032.26	3034.57
06/07/95	3032.62	3034.93
07/19/95	3031.68	3033.98
08/17/95	3029.83	3032.12
09/07/95	3028.71	3030.99
10/19/95	3027.83	3030.10
11/08/95	3027.53	3029.80
12/06/95	3027.88	3030.15
01/10/96	3028.17	3030.45
02/07/96	3026.97	3029.24
03/14/96	3024.10	3026.34
04/17/96	3021.62	3023.84
05/15/96	3020.57	3022.79
06/12/96	3020.98	3023.20
07/17/96	3022.24	3024.47
08/13/96	3023.34	3025.58
09/05/96	3024.58	3026.83
10/15/96	3026.23	3028.49
11/13/96	3027.01	3029.28
12/10/96	3028.04	3030.32
01/16/97	3028.76	3031.04
02/12/97	3029.59	3031.88
03/12/97	3030.31	3032.60
04/16/97	3030.87	3033.17
05/14/97	3031.52	3033.82
06/12/97	3031.91	3034.22
07/16/97	3032.01	3034.32
08/13/97	3032.29	3034.60
09/17/97	3032.80	3035.11
10/15/97	3032.78	3035.09
11/12/97	3033.25	3035.57
12/10/97	3033.36	3035.68

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3033.54	3035.86
02/11/98	3033.66	3035.98
03/11/98	3033.70	3036.02
04/15/98	3034.52	3036.85
05/13/98	3034.71	3037.04
06/10/98	3034.70	3037.03
07/15/98	3034.67	3037.00
08/12/98	3034.75	3037.08
09/10/98	3034.98	3037.31
10/14/98	3035.21	3037.54
11/11/98	3035.01	3037.34
12/09/98	3035.35	3037.38
01/13/99	3035.26	3037.59
02/10/99	3035.50	3037.84
03/10/99	3035.61	3037.95
04/13/99	3035.81	3038.15
05/11/99	3036.06	3038.40
06/09/99	3035.88	3038.22
07/21/99	3035.93	3038.27
08/11/99	3036.11	3038.45
09/09/99	3036.08	3038.42
10/06/99	3036.18	3038.52
11/10/99	3036.20	3038.54
12/09/99	3036.12	3038.46
01/20/00	3034.12	3036.44
02/16/00	3036.06	3038.40
03/08/00	3036.27	3038.61
04/19/00	3036.55	3038.89
05/17/00	3036.66	3039.00
06/07/00	3036.40	3038.74
07/10/00	3036.69	3039.03
08/15/00	3036.61	3038.95
09/11/00	3036.83	3039.18
10/11/00	3036.73	3039.08
11/06/00	3037.10	3039.45
12/06/00	3036.63	3038.97

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3036.85	3039.20
02/06/01	3036.91	3039.26
03/08/01	3037.12	3039.47
04/05/01	3037.16	3039.51
05/08/01	3036.99	3039.34
06/06/01	3037.28	3039.63
07/11/01	3037.27	3039.62
08/07/01	3037.30	3039.65
09/06/01	3037.61	3039.96
10/10/01	3037.62	3039.97
11/14/01	3037.79	3040.14
12/05/01	3037.60	3039.95
01/16/02	3037.74	3040.09
02/05/02	3037.85	3040.20
03/13/02	3038.18	3040.54
04/08/02	3038.31	3040.67
05/08/02	3038.42	3040.78
06/11/02	3038.45	3040.81
07/16/02	3038.41	3040.77
08/13/02	3038.66	3041.02
09/10/02	3038.65	3041.01

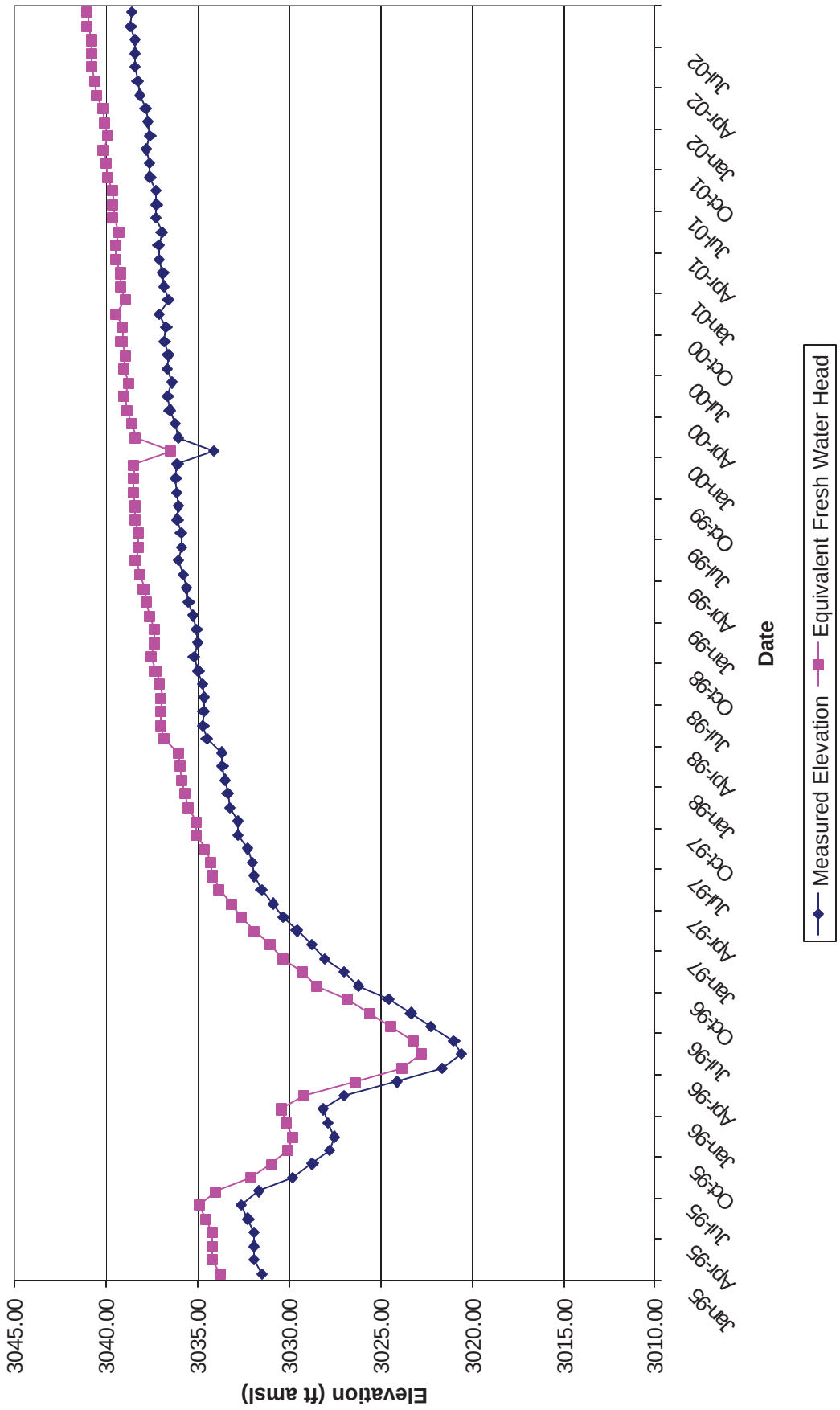
Figure 16 - H-2b2 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3045.00
3040.00
3035.00
3030.00
3025.00
3020.00
3015.00
3010.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 17 - Well No. H-02c Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/15/95	3031.83	3044.51
06/07/95	3032.45	3045.16
09/07/95	3028.67	3041.21
12/06/95	3027.81	3040.31
03/14/96	3024.21	3036.55
06/12/96	3021.05	3033.25
09/05/96	3024.52	3036.88
12/10/96	3027.82	3040.32
03/12/97	3030.13	3042.73
06/12/97	3031.77	3044.45
09/17/97	3032.61	3045.32
12/10/97	3033.27	3046.01
03/11/98	3033.59	3046.35
06/10/98	3034.59	3047.39
09/10/98	3034.81	3047.62
12/09/98	3034.87	3047.68
03/10/99	3035.43	3048.27
06/09/99	3035.78	3048.63
09/09/99	3035.92	3048.78
12/09/99	3036.07	3048.89
03/08/00	3036.47	3049.31
06/07/00	3036.52	3049.36
09/11/00	3036.98	3049.84
12/06/00	3036.78	3049.63
03/08/01	3037.02	3049.88
06/06/01	3037.41	3050.29
09/06/01	3037.64	3050.53
12/05/01	3038.71	3051.65
03/13/02	3038.02	3050.93
06/11/02	3038.41	3051.33
09/10/02	3038.68	3051.62

Figure 17 - H-2c Culebra
Historical Waterlevel Measurements

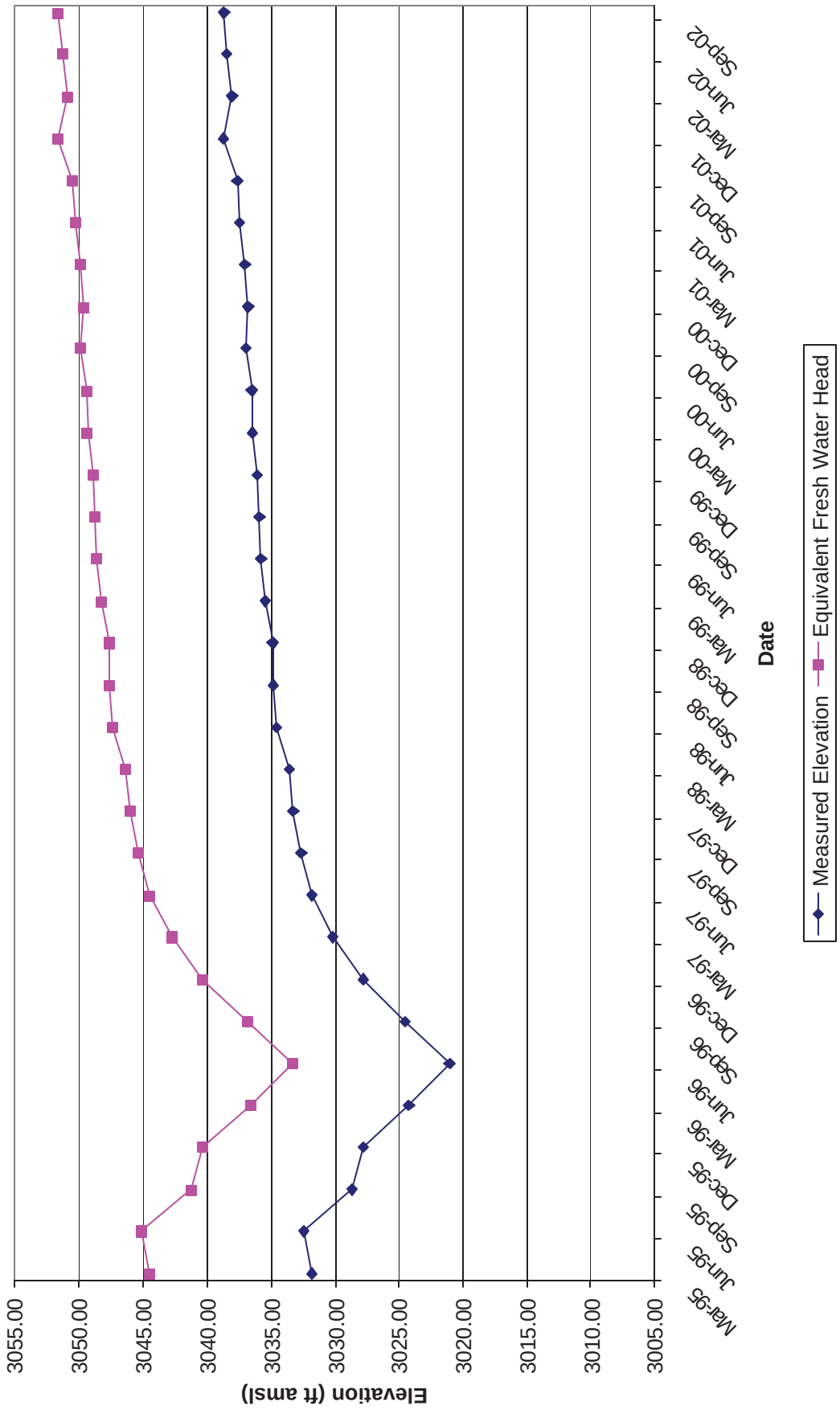

Table 18 - Well No. H-03b1 Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3140.74	N/A
02/15/95	3140.94	N/A
03/14/95	3140.90	N/A
04/12/95	3141.06	N/A
05/10/95	3141.43	N/A
06/07/95	3141.79	N/A
07/20/95	3142.07	N/A
08/17/95	3142.27	N/A
09/07/95	3142.37	N/A
10/18/95	3142.59	N/A
11/08/95	3142.61	N/A
12/06/95	3142.67	N/A
01/10/96	3142.76	N/A
02/07/96	3142.89	N/A
03/13/96	3143.10	N/A
04/17/96	3143.18	N/A
05/15/96	3143.27	N/A
06/12/96	3143.37	N/A
07/17/96	3143.44	N/A
08/13/96	3143.43	N/A
09/05/96	3143.58	N/A
10/17/96	3143.65	N/A
11/13/96	3143.52	N/A
12/10/96	3143.74	N/A
01/16/97	3143.73	N/A
02/12/97	3143.87	N/A
03/12/97	3143.99	N/A
04/16/97	3144.10	N/A
05/14/97	3144.34	N/A
06/12/97	3144.39	N/A
07/16/97	3144.42	N/A
08/13/97	3144.45	N/A
09/17/97	3144.61	N/A
10/15/97	3144.62	N/A
11/12/97	3144.98	N/A
12/10/97	3145.30	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3145.73	N/A
02/11/98	3146.15	N/A
03/11/98	3146.40	N/A
04/15/98	3147.28	N/A
05/13/98	3147.70	N/A
06/10/98	3148.02	N/A
07/15/98	3148.44	N/A
08/12/98	3148.69	N/A
09/10/98	3146.00	N/A
10/14/98	3149.28	N/A
11/11/98	3149.55	N/A
12/09/98	3149.70	N/A
01/13/99	3150.08	N/A
02/10/99	3150.31	N/A
03/16/99	3150.52	N/A
04/13/99	3150.66	N/A
05/11/99	3150.89	N/A
06/09/99	3150.97	N/A
07/21/99	3150.88	N/A
08/11/99	3151.01	N/A
09/09/99	3150.98	N/A
10/05/99	3150.93	N/A
11/10/99	3151.00	N/A
12/08/99	3151.14	N/A
01/19/00	3151.15	N/A
02/15/00	3151.39	N/A
03/08/00	3151.50	N/A
04/18/00	3151.61	N/A
05/17/00	3151.75	N/A
06/07/00	3151.63	N/A
07/10/00	3151.83	N/A
08/14/00	3151.74	N/A
09/11/00	3151.83	N/A
10/11/00	3151.62	N/A
11/08/00	3151.92	N/A
12/06/00	3151.71	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3151.88	N/A
02/06/01	3151.95	N/A
03/08/01	3152.19	N/A
04/05/01	3151.26	N/A
05/09/01	3150.98	N/A
06/06/01	3151.17	N/A
07/10/01	3151.01	N/A
08/07/01	3150.88	N/A
09/06/01	3150.91	N/A
10/10/01	3150.77	N/A
11/14/01	3150.63	N/A
12/05/01	3150.55	N/A
01/16/02	3150.44	N/A
02/05/02	3150.30	N/A
03/18/02	3127.49	N/A
04/09/02	3124.24	N/A
05/08/02	3130.63	N/A
06/10/02	3131.46	N/A
07/17/02	3133.11	N/A
08/14/02	3133.23	N/A
09/10/02	3132.85	N/A

Figure 18 - H-3b1 Magenta
Historical Waterlevel Measurements

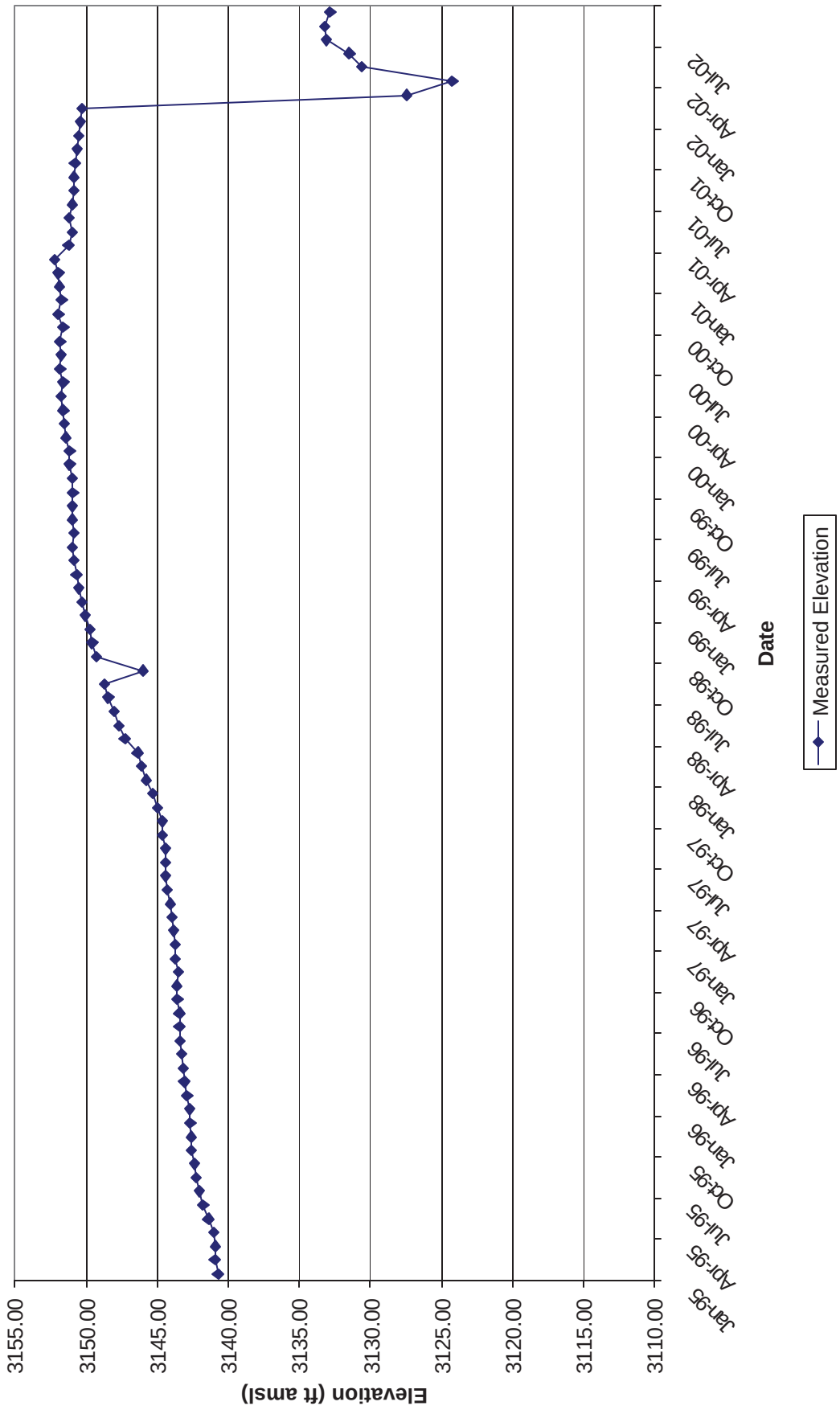

Table 19 - Well No. H-03b2 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2994.87	3006.06
02/15/95	2995.16	3006.36
03/14/95	2992.23	3003.32
04/12/95	2993.53	3004.67
05/10/95	2993.02	3004.14
06/07/95	2982.13	2992.84
07/20/95	2950.69	2960.20
08/17/95	2965.44	2975.51
09/07/95	2961.96	2971.90
10/18/95	2973.67	2984.06
11/08/95	2975.13	2985.57
12/06/95	2977.36	2987.89
01/10/96	2943.94	2953.20
02/07/96	2929.10	2937.79
03/13/96	2927.07	2935.69
04/17/96	2932.67	2941.50
05/15/96	2953.96	2963.60
06/12/96	2962.55	2972.51
07/17/96	2972.18	2982.51
08/13/96	2976.67	2987.17
09/05/96	2979.83	2990.45
10/17/96	2982.34	2993.06
11/13/96	2984.58	2995.38
12/10/96	2986.74	2997.62
01/16/97	2988.17	2999.11
02/12/97	2989.50	3000.49
03/12/97	2990.44	3001.46
04/16/97	2991.07	3002.12
05/14/97	2991.72	3002.79
06/12/97	2991.14	3002.19
07/16/97	2990.87	3001.91
08/13/97	2991.67	3002.74
09/17/97	2991.88	3002.96
10/15/97	2992.00	3003.08
11/12/97	2992.98	3004.10
12/10/97	2993.35	3004.48

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2993.92	3005.08
02/11/98	2994.33	3005.50
03/11/98	2994.38	3005.55
04/15/98	2995.22	3006.43
05/13/98	2994.66	3005.84
06/10/98	2994.73	3005.92
07/15/98	2995.16	3006.36
08/12/98	2995.33	3006.54
09/10/98	2995.65	3006.87
10/14/98	2995.14	3006.34
11/11/98	2995.67	3006.89
12/09/98	2995.93	3007.16
01/13/99	2996.14	3007.38
02/10/99	2996.56	3007.82
03/16/99	2996.83	3008.10
04/13/99	2997.07	3008.35
05/11/99	2996.33	3007.58
06/09/99	2997.02	3008.29
07/21/99	2997.11	3008.39
08/11/99	2997.40	3008.69
09/09/99	2997.53	3008.82
10/05/99	2997.62	3008.92
11/10/99	2996.90	3008.17
12/08/99	2997.61	3008.91
01/19/00	2997.65	3008.95
02/15/00	2997.84	3009.15
03/08/00	2997.82	3009.12
04/18/00	2997.42	3008.71
05/17/00	2997.68	3008.98
06/07/00	2997.75	3009.05
07/10/00	2998.05	3009.36
08/14/00	2998.14	3009.46
09/11/00	2998.26	3009.58
10/11/00	2998.13	3009.45
11/08/00	2997.67	3008.97
12/06/00	2997.81	3009.11

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	2998.23	3009.55
02/06/01	2998.35	3009.67
03/08/01	2998.58	3009.91
04/05/01	2998.67	3010.01
05/09/01	2997.89	3009.20
06/06/01	2998.63	3009.97
07/10/01	2998.88	3010.22
08/07/01	2998.88	3010.22
09/06/01	2999.29	3010.65
10/10/01	2999.24	3010.60
11/14/01	2998.85	3010.19
12/05/01	2998.94	3010.29
01/16/02	2999.35	3010.71
02/05/02	2999.43	3010.80
03/18/02	2999.15	3010.50
04/09/02	2999.15	3010.50
05/07/02	2999.07	3010.42
06/10/02	2999.74	3011.12
07/17/02	2999.72	3011.10
08/14/02	3000.02	3011.41
09/10/02	3000.05	3011.44

Figure 19 - H-3b2 Culebra
Historical Waterlevel Measurements

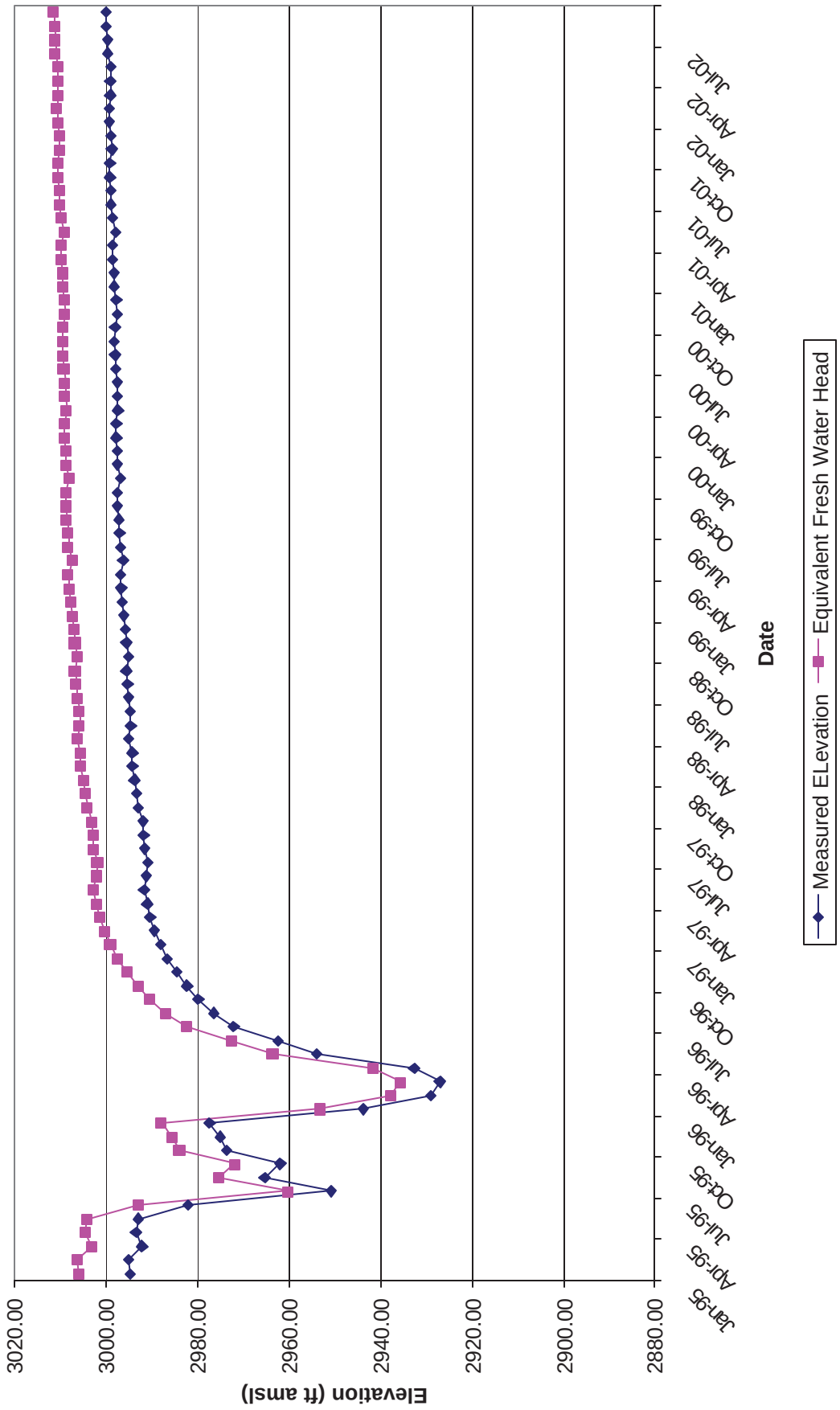

Table 20 - Well No. H-03b3 Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2992.38	3001.87
06/07/95	2982.25	2991.40
09/07/95	2961.99	2970.47
12/06/95	2977.81	2986.82
03/13/96	2927.18	2934.51
06/12/96	2962.77	2971.28
09/05/96	2979.85	2988.92
12/10/96	2986.98	2996.29
03/12/97	2990.67	3000.10
06/12/97	2991.24	3000.69
09/17/97	2992.16	3001.64
12/10/97	2993.55	3003.07

Date	Measured Elevation	Equivalent Fresh Water Head
03/11/98	2994.55	3004.11
06/10/98	2994.78	3004.35
09/10/98	2995.70	3005.30
12/09/98	2996.09	3005.70
03/16/99	2997.05	3006.69
06/09/99	2997.02	3006.66
09/09/99	2997.74	3007.40
12/08/99	2997.79	3007.45
03/08/00	2997.91	3007.58
06/07/00	2997.93	3007.60
09/11/00	2998.43	3008.12
12/06/00	2997.98	3007.65

Date	Measured Elevation	Equivalent Fresh Water Head
03/08/01	2998.33	3008.01
06/06/01	2998.82	3008.52
09/06/01	2999.47	3009.19
12/05/01	2999.00	3008.70
03/18/02	3003.45	3013.30
06/10/02	3004.04	3013.91
09/10/02	3004.41	3014.29

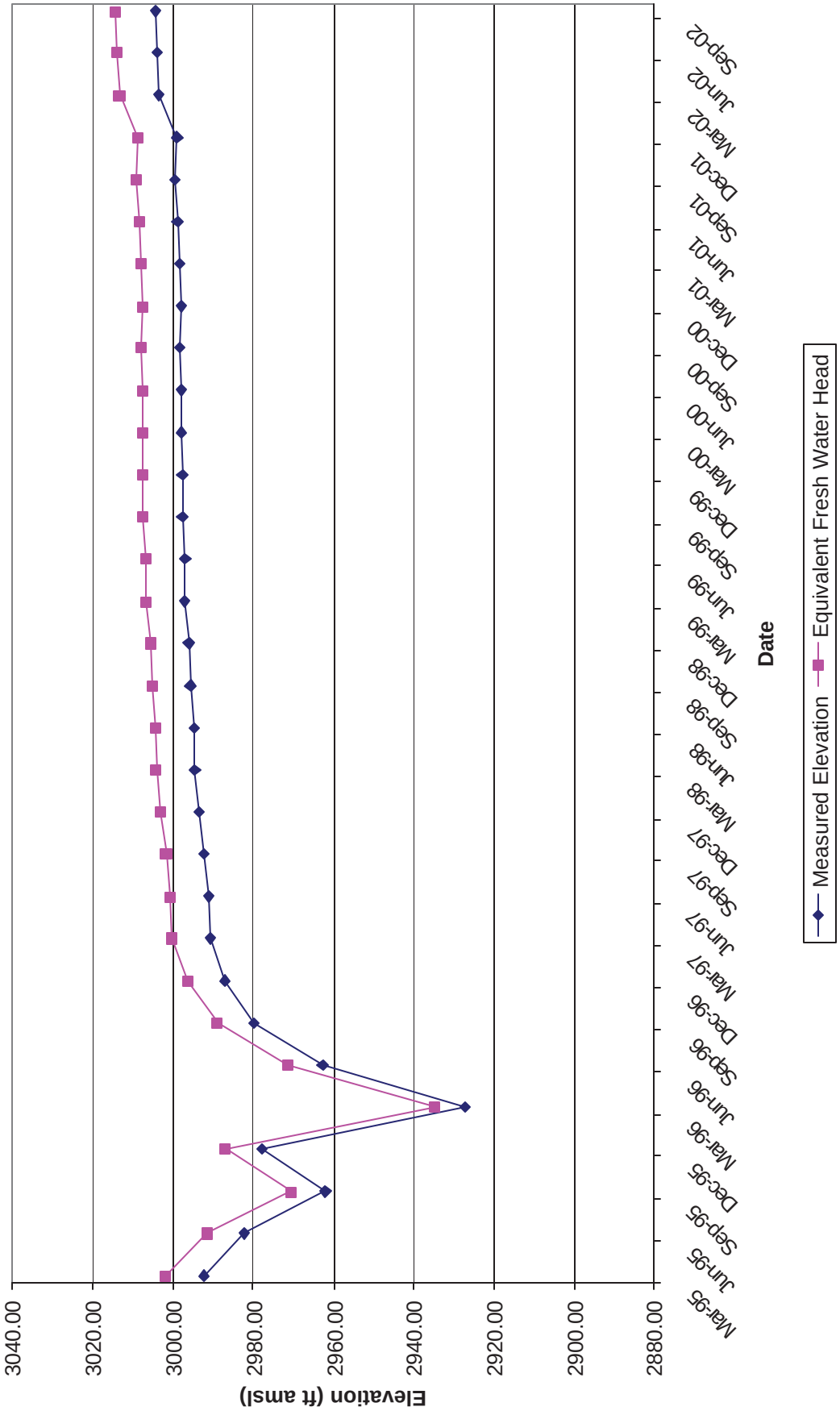
Figure 20 - H-3b3 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
2880.00
Mar-95
Jun-95
Sep-95
Dec-95
Mar-96
Jun-96
Sep-96
Dec-96
Mar-97
Jun-97
Sep-97
Dec-97
Mar-98
Jun-98
Sep-98
Dec-98
Mar-99
Jun-99
Sep-99
Dec-99
Mar-00
Jun-00
Sep-00
Dec-00
Mar-01
Jun-01
Sep-01
Dec-01
Mar-02
Jun-02
Sep-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 21 - Well No. H-03d/49 (PIP) 49er
January 1995 through February 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3081.68	N/A
02/15/95	3081.74	N/A
03/14/95	3081.83	N/A
04/12/95	3081.84	N/A
05/10/95	3082.02	N/A
06/07/95	3082.17	N/A
07/20/95	3082.38	N/A
08/17/95	3082.47	N/A
09/07/95	3082.42	N/A
10/18/95	3082.77	N/A
11/08/95	3082.81	N/A
12/06/95	3082.79	N/A
01/10/96	3082.91	N/A
02/07/96	3082.98	N/A
03/13/96	3083.38	N/A
04/17/96	3083.26	N/A
05/15/96	3083.34	N/A
06/12/96	3083.43	N/A
07/17/96	3083.46	N/A
08/13/96	3083.52	N/A
09/05/96	3083.63	N/A
10/17/96	3083.71	N/A
11/13/96	3083.70	N/A
12/10/96	3083.79	N/A
01/16/97	3083.84	N/A
02/12/97	3083.93	N/A
03/12/97	3084.07	N/A
04/16/97	3084.26	N/A
05/14/97	3084.44	N/A
06/12/97	3084.49	N/A
07/16/97	3084.52	N/A
08/13/97	3084.61	N/A
09/17/97	3084.56	N/A
10/15/97	3084.73	N/A
11/12/97	3084.82	N/A
12/10/97	3084.89	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3085.10	N/A
02/11/98	3085.26	N/A
03/11/98	3085.39	N/A
04/15/98	3085.54	N/A
05/13/98	3085.56	N/A
06/10/98	3085.52	N/A
07/15/98	3085.46	N/A
08/12/98	3085.59	N/A
09/10/98	3085.63	N/A
10/14/98	3085.65	N/A
11/11/98	3085.85	N/A
12/09/98	3085.95	N/A
01/13/99	3086.08	N/A
02/10/99	3086.20	N/A
03/16/99	3086.37	N/A
04/13/99	3086.48	N/A
05/11/99	3086.68	N/A
06/09/99	3086.69	N/A
07/21/99	3086.84	N/A
08/11/99	3086.79	N/A
09/09/99	3086.79	N/A
10/05/99	3086.94	N/A
11/10/99	3087.03	N/A
12/08/99	3087.12	N/A
01/19/00	3087.31	N/A
02/15/00	3087.48	N/A
03/08/00	3087.62	N/A
04/18/00	3087.91	N/A
05/17/00	3088.12	N/A
06/07/00	3088.22	N/A
07/10/00	3088.70	N/A
08/14/00	3088.84	N/A
09/11/00	3088.97	N/A
10/11/00	3089.04	N/A
11/08/00	3089.38	N/A
12/06/00	3089.45	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3089.71	N/A
02/06/01	3089.86	N/A
03/08/01	3090.18	N/A
04/05/01	3090.42	N/A
05/09/01	3090.73	N/A
06/06/01	3090.89	N/A
07/10/01	3091.00	N/A
08/07/01	3090.97	N/A
09/06/01	3091.23	N/A
10/10/01	3091.39	N/A
11/14/01	3091.61	N/A
12/05/01	3091.64	N/A
01/16/02	3091.95	N/A
02/05/02	3092.15	N/A

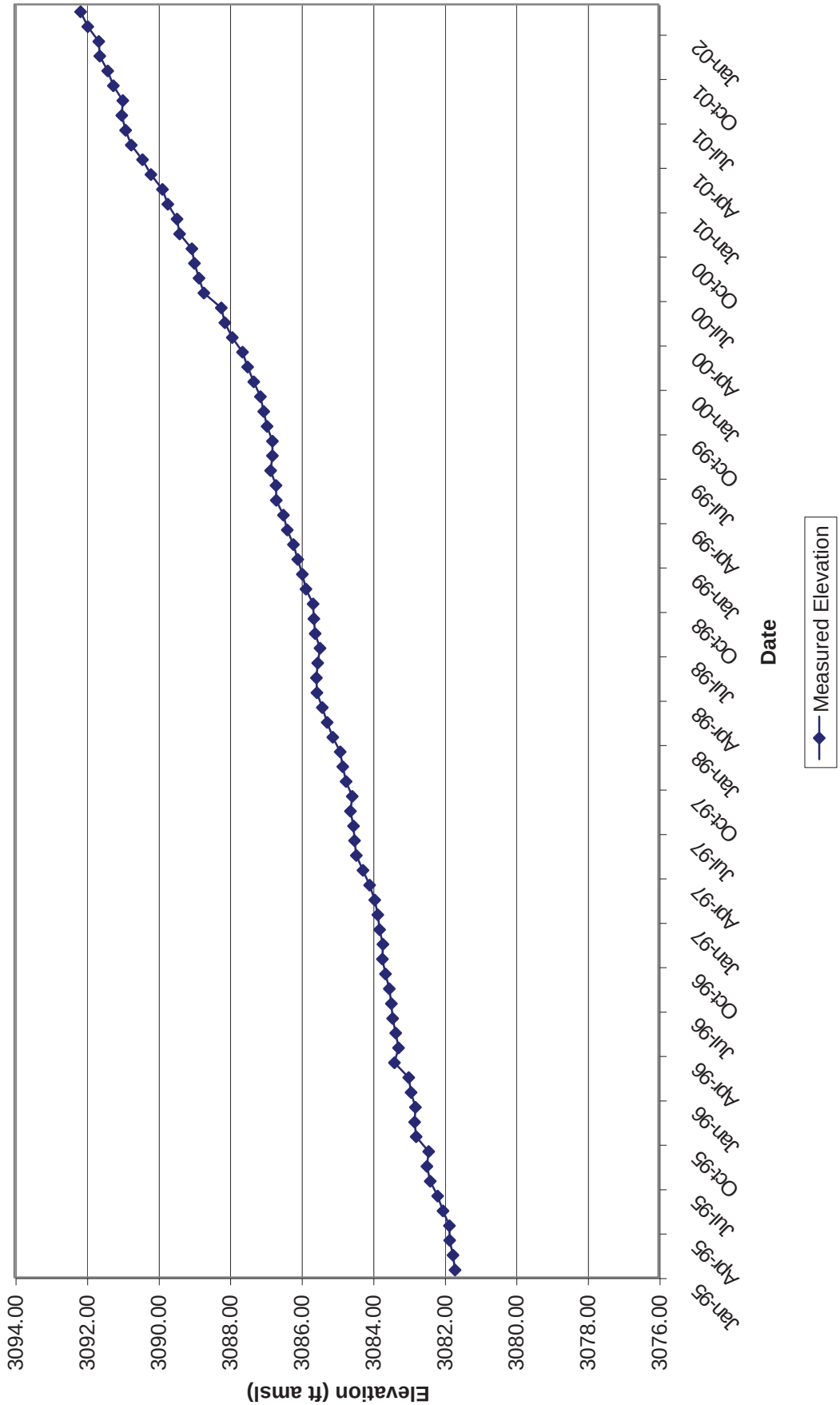
Figure 21 - H-3d 49er
Historical Waterlevel Measurements
Elevation (ft amsl)
3094.00
3092.00
3090.00
3088.00
3086.00
3084.00
3082.00
3080.00
3078.00
3076.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Date
Measured Elevation

Table 22 - Well No. H-03d (PVC) Dewey Lake
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3074.91	N/A
02/15/95	3074.79	N/A
03/14/95	3074.67	N/A
04/12/95	3074.43	N/A
05/10/95	3074.44	N/A
06/07/95	3074.41	N/A
07/20/95	3074.23	N/A
08/17/95	3074.16	N/A
09/07/95	3074.00	N/A
10/18/95	3073.86	N/A
11/08/95	3073.78	N/A
12/06/95	3073.78	N/A
01/10/96	3073.65	N/A
02/07/96	3073.44	N/A
03/13/96	3073.38	N/A
04/17/96	3073.29	N/A
05/15/96	3073.23	N/A
06/12/96	3073.25	N/A
07/17/96	3073.13	N/A
08/13/96	3073.07	N/A
09/05/96	3073.00	N/A
10/17/96	3072.92	N/A
11/13/96	3072.87	N/A
12/10/96	3072.82	N/A
01/16/97	3072.73	N/A
02/12/97	3072.65	N/A
03/12/97	3072.63	N/A
04/16/97	3072.63	N/A
05/14/97	3072.62	N/A
06/12/97	3072.60	N/A
07/16/97	3072.35	N/A
08/13/97	3072.54	N/A
09/17/97	3072.51	N/A
10/15/97	3072.49	N/A
11/12/97	3072.44	N/A
12/10/97	3072.43	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3072.41	N/A
02/11/98	3072.45	N/A
03/11/98	3072.45	N/A
04/15/98	3072.44	N/A
05/13/98	3072.45	N/A
06/10/98	3072.45	N/A
07/15/98	3072.35	N/A
08/12/98	3072.43	N/A
09/10/98	3072.43	N/A
10/14/98	3072.35	N/A
11/11/98	3072.39	N/A
12/09/98	3072.32	N/A
01/13/99	3072.31	N/A
02/10/99	3072.32	N/A
03/16/99	3072.39	N/A
04/13/99	3072.41	N/A
05/11/99	3072.43	N/A
06/09/99	3072.45	N/A
07/21/99	3072.45	N/A
08/11/99	3072.50	N/A
09/09/99	3072.51	N/A
10/05/99	3072.52	N/A
11/10/99	3072.52	N/A
12/08/99	3072.52	N/A
01/19/00	3072.49	N/A
02/15/00	3072.51	N/A
03/08/00	3072.52	N/A
04/18/00	3072.58	N/A
05/17/00	3072.61	N/A
06/07/00	3072.64	N/A
07/10/00	3072.71	N/A
08/14/00	3072.78	N/A
09/11/00	3072.82	N/A
10/11/00	3072.88	N/A
11/08/00	3072.94	N/A
12/06/00	3073.01	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3073.10	N/A
02/06/01	3073.09	N/A
03/08/01	3073.25	N/A
04/05/01	3073.32	N/A
05/09/01	3073.46	N/A
06/06/01	3073.53	N/A
07/10/01	3073.65	N/A
08/07/01	3073.70	N/A
09/04/01	3073.79	N/A
10/10/01	3073.86	N/A
11/14/01	3073.94	N/A
12/05/01	3073.96	N/A
01/16/02	3074.10	N/A
02/05/02	3074.21	N/A
03/18/02	3074.14	N/A
04/09/02	3074.21	N/A
05/07/02	3074.33	N/A
06/10/02	3074.44	N/A
07/17/02	3074.51	N/A
08/14/02	3074.60	N/A
09/10/02	3074.68	N/A

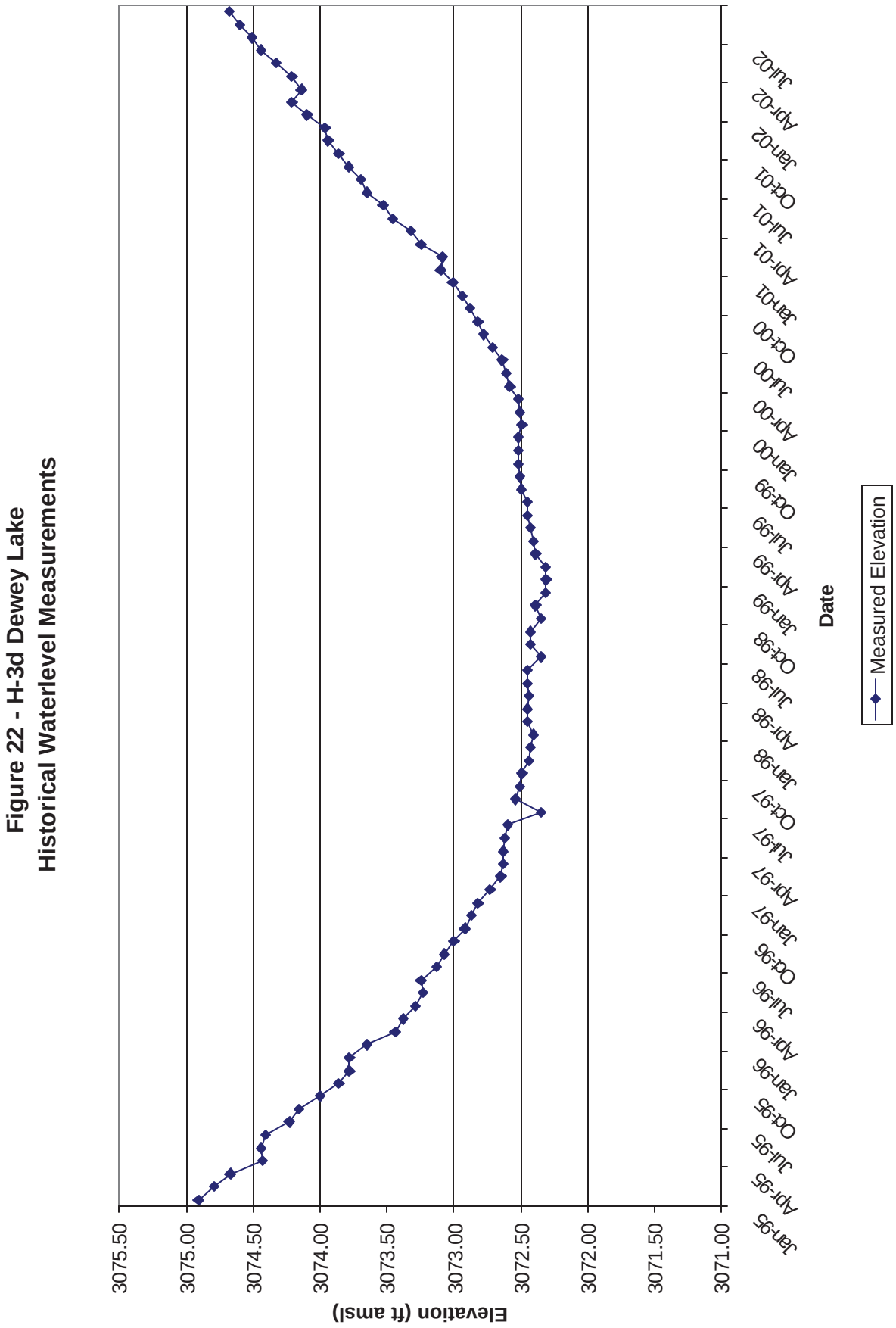
Figure 22 - H-3d Dewey Lake
Historical Waterlevel Measurements
Elevation (ft amsl)
3075.50
3075.00
3074.50
3074.00
3073.50
3073.00
3072.50
3072.00
3071.50
3071.00
Date
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Measured Elevation

Table 23 - Well No. H-04b Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	2999.48	3003.03
02/15/95	2999.76	3003.32
03/14/95	2999.67	3003.23
04/12/95	2999.73	3003.29
05/10/95	3000.01	3003.57
06/07/95	3000.30	3003.87
07/19/95	3000.15	3003.72
08/17/95	3000.12	3003.69
09/07/95	2999.66	3003.22
10/18/95	2999.56	3003.11
11/08/95	2999.35	3002.90
12/06/95	2999.47	3003.02
01/10/96	2999.50	3003.05
02/07/96	2999.48	3003.03
03/14/96	2999.01	3002.55
04/17/96	2998.44	3001.97
05/15/96	2998.70	3002.24
06/12/96	2999.05	3002.59
07/17/96	2999.32	3002.87
08/13/96	2999.75	3003.31
09/05/96	2999.93	3003.49
10/16/96	3000.09	3003.65
11/13/96	2999.93	3003.49
12/11/96	3000.24	3003.81
01/14/97	3000.21	3003.78
02/12/97	3000.14	3003.71
03/12/97	2999.57	3003.12
04/16/97	2998.79	3002.33
05/14/97	2998.70	3002.24
06/12/97	2998.47	3002.00
07/16/97	2998.05	3001.57
08/13/97	2998.00	3001.52
09/16/97	2998.44	3001.97
10/15/97	2998.36	3001.89
11/12/97	2998.77	3002.31
12/10/97	2998.89	3002.43

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2999.14	3002.68
02/11/98	2999.29	3002.84
03/11/98	2999.21	3002.76
04/15/98	2999.73	3003.29
05/12/98	2999.56	3003.11
06/10/98	2999.28	3002.83
07/15/98	2999.20	3002.75
08/12/98	2999.15	3002.69
09/10/98	2999.27	3002.82
10/14/98	2999.33	3002.88
11/11/98	2999.36	3002.91
12/09/98	2999.36	3002.91
01/12/99	2999.73	3003.29
02/10/99	2999.78	3003.34
03/10/99	3000.02	3003.58
04/13/99	3000.17	3003.74
05/11/99	3000.27	3003.84
06/09/99	3000.45	3004.02
07/21/99	3000.27	3003.84
08/11/99	3000.42	3003.99
09/09/99	3000.39	3003.96
10/05/99	3000.19	3003.76
11/10/99	3000.13	3003.70
12/08/99	3000.27	3003.84
01/19/00	3000.13	3003.70
02/15/00	3000.19	3003.76
03/08/00	3002.66	3006.28
04/17/00	3000.34	3003.91
05/17/00	3000.61	3004.19
06/07/00	3000.36	3003.93
07/12/00	3000.45	3004.02
08/14/00	3001.30	3004.89
09/11/00	3000.49	3004.06
10/10/00	3000.26	3003.83
11/09/00	3000.55	3004.12
12/06/00	3000.30	3003.87

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3000.50	3004.07
02/07/01	3000.75	3004.33
03/08/01	3000.95	3004.53
04/05/01	3001.06	3004.64
05/09/01	3001.10	3004.69
06/06/01	3001.38	3004.97
07/11/01	3001.16	3004.75
08/07/01	3000.99	3004.57
09/06/01	3001.11	3004.70
10/10/01	3001.04	3004.62
11/14/01	3001.17	3004.76
12/05/01	3001.07	3004.66
01/16/02	3001.24	3004.83
02/05/02	3001.31	3004.90
03/13/02	3001.66	3005.26
04/09/02	3001.52	3005.11
05/08/02	3001.86	3005.46
06/10/02	3002.01	3005.61
07/16/02	3001.81	3005.41
08/12/02	3001.92	3005.52
09/11/02	3001.73	3005.33

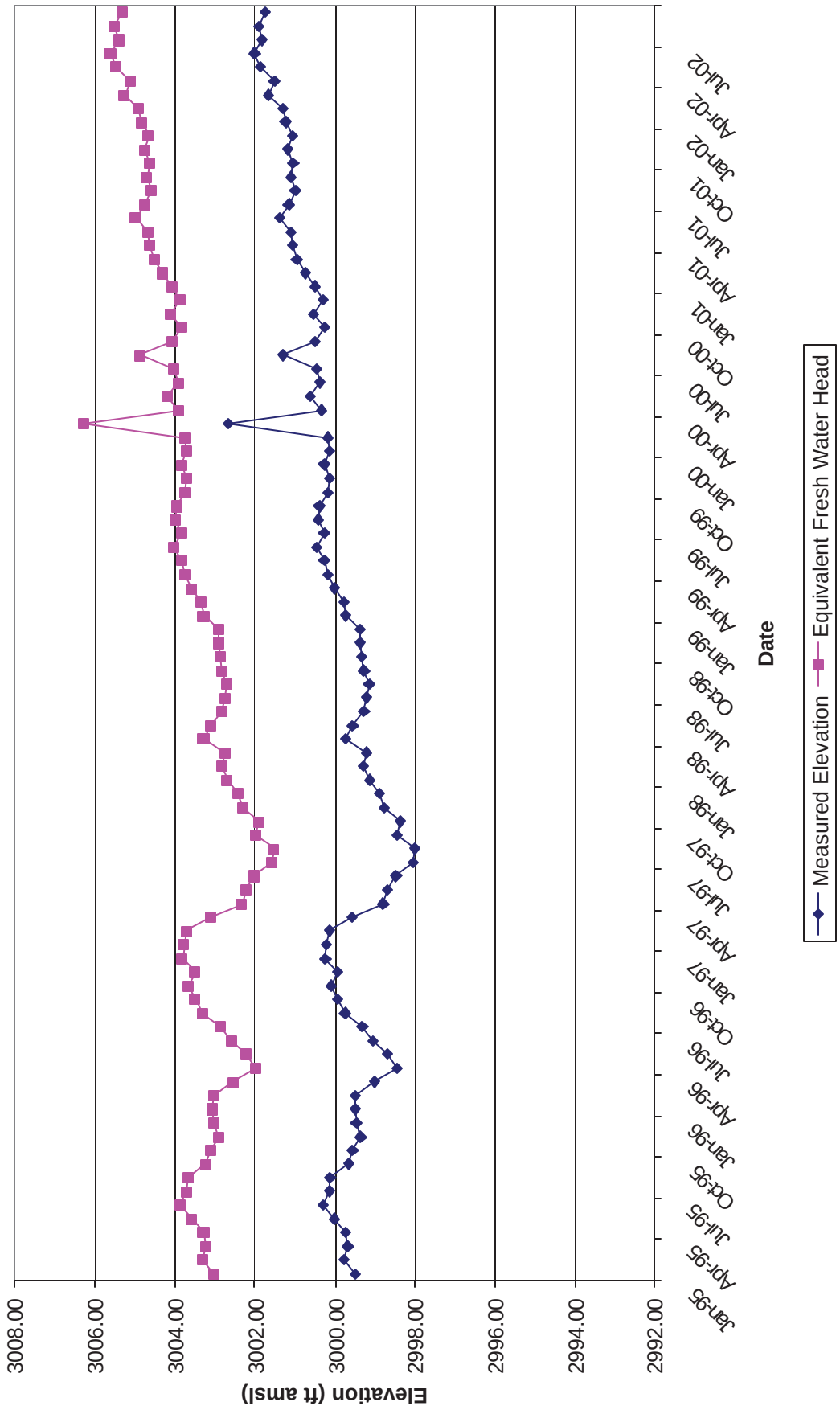
Figure 23 - H-4b Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3008.00
3006.00
3004.00
3002.00
3000.00
2998.00
2996.00
2994.00
2992.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 24 - Well No. H-04c Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3141.97	N/A
02/15/95	3142.01	N/A
03/14/95	3141.92	N/A
04/12/95	3141.94	N/A
05/10/95	3142.04	N/A
06/07/95	3142.16	N/A
07/19/95	3142.19	N/A
08/17/95	3142.13	N/A
09/07/95	3142.02	N/A
10/18/95	3142.18	N/A
11/08/95	3142.09	N/A
12/06/95	3142.10	N/A
01/10/96	3142.08	N/A
02/07/96	3142.12	N/A
03/14/96	3142.26	N/A
04/17/96	3142.35	N/A
05/15/96	3142.35	N/A
06/12/96	3142.36	N/A
07/17/96	3142.50	N/A
08/13/96	3142.38	N/A
09/05/96	3142.57	N/A
10/16/96	3142.45	N/A
11/13/96	3142.34	N/A
12/11/96	3142.48	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3142.84	N/A
02/11/98	3142.89	N/A
03/11/98	3142.93	N/A
04/15/98	3143.00	N/A
05/12/98	3143.01	N/A
06/10/98	3142.91	N/A
07/15/98	3142.89	N/A
08/12/98	3142.96	N/A
09/10/98	3142.93	N/A
10/14/98	3142.96	N/A
11/11/98	3143.11	N/A
12/09/98	3143.02	N/A
01/12/99	3143.05	N/A
02/10/99	3143.16	N/A
03/10/99	3143.22	N/A
04/13/99	3143.22	N/A
05/11/99	3143.33	N/A
06/09/99	3143.40	N/A
07/21/99	3143.15	N/A
08/11/99	3143.27	N/A
09/09/99	3143.25	N/A
10/05/99	3143.19	N/A
11/10/99	3143.19	N/A
12/08/99	3143.28	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3143.98	N/A
02/07/01	3144.04	N/A
03/08/01	3144.16	N/A
04/05/01	3144.30	N/A
05/09/01	3144.18	N/A
06/06/01	3144.32	N/A
07/11/01	3144.19	N/A
08/07/01	3144.19	N/A
09/06/01	3144.33	N/A
10/10/01	3144.28	N/A
11/14/01	3144.22	N/A
12/05/01	3144.33	N/A
01/16/02	3144.31	N/A
02/05/02	3144.31	N/A
03/13/02	3144.44	N/A
04/08/02	3144.58	N/A
05/08/02	3144.60	N/A
06/10/02	3144.57	N/A
07/16/02	3144.53	N/A
08/12/02	3144.52	N/A
09/11/02	3144.39	N/A

01/14/97	3142.41	N/A
02/12/97	3142.44	N/A
03/12/97	3142.56	N/A
04/16/97	3142.57	N/A
05/14/97	3142.70	N/A
06/12/97	3142.69	N/A
07/16/97	3142.75	N/A
08/13/97	3142.69	N/A
09/16/97	3142.69	N/A
10/15/97	3142.67	N/A
11/12/97	3142.73	N/A
12/10/97	3142.79	N/A

01/19/00	3143.20	N/A
02/15/00	3143.32	N/A
03/08/00	3152.87	N/A
04/17/00	3144.60	N/A
05/17/00	3144.19	N/A
06/07/00	3144.01	N/A
07/12/00	3144.19	N/A
08/14/00	3145.24	N/A
09/11/00	3144.28	N/A
10/10/00	3143.90	N/A
11/09/00	3144.13	N/A
12/06/00	3143.93	N/A

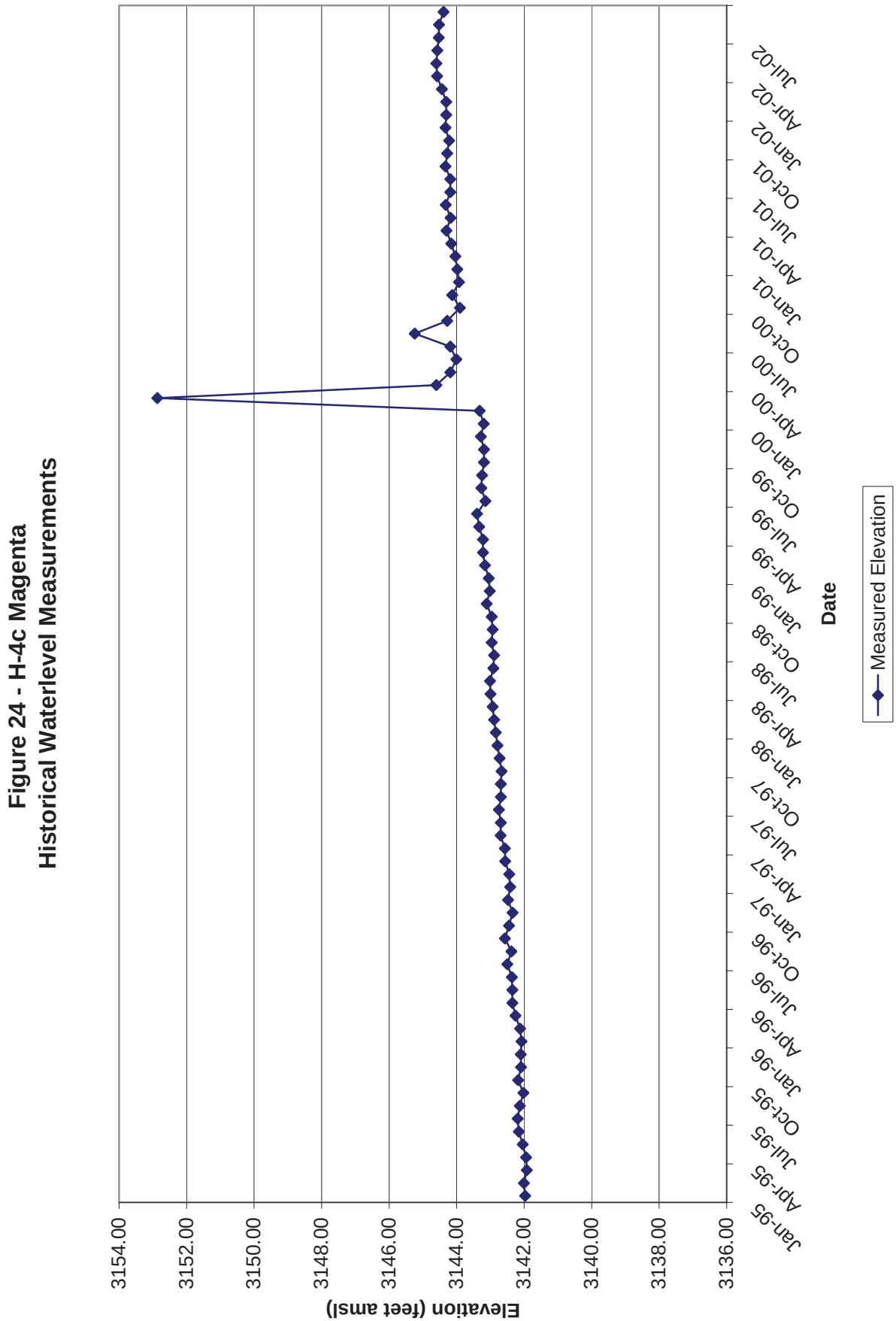
Figure 24 - H-4c Magenta
Historical Waterlevel Measurements
Elevation (feet amsl)
3154.00
3152.00
3150.00
3148.00
3146.00
3144.00
3142.00
3140.00
3138.00
3136.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation

Table 25 - Well No. H-05a Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/15/95	3028.81	3068.53
06/07/95	3029.12	3068.87
09/07/95	3029.14	3068.89
12/06/95	3028.93	3068.66
03/13/96	3029.63	3069.43
06/12/96	3029.72	3069.52
09/05/96	3029.30	3069.07
12/11/96	3029.83	3069.64
03/12/97	3029.29	3069.06
06/12/97	3029.93	3069.75
09/17/97	3029.88	3069.70
12/10/97	3030.06	3069.90

Date	Measured Elevation	Equivalent Fresh Water Head
03/11/98	3030.01	3069.84
06/10/98	3030.28	3070.14
09/10/98	3030.37	3070.23
12/07/98	3030.48	3070.35
03/10/99	3030.64	3070.53
06/09/99	3030.73	3070.63
09/09/99	3030.70	3070.60
12/08/99	3030.89	3070.80
03/08/00	3030.88	3070.79
06/05/00	3030.86	3070.77
09/12/00	3031.04	3070.97
12/07/00	3031.05	3070.98

Date	Measured Elevation	Equivalent Fresh Water Head
03/07/01	3031.15	3071.09
06/07/01	3031.19	3071.13
09/10/01	3031.01	3070.93
12/04/01	3031.30	3071.25
03/12/02	3031.34	3071.29
06/12/02	3031.50	3071.47
09/10/02	3031.41	3071.37

Figure 25 - H-5a Culebra
Historical Waterlevel Measrurements

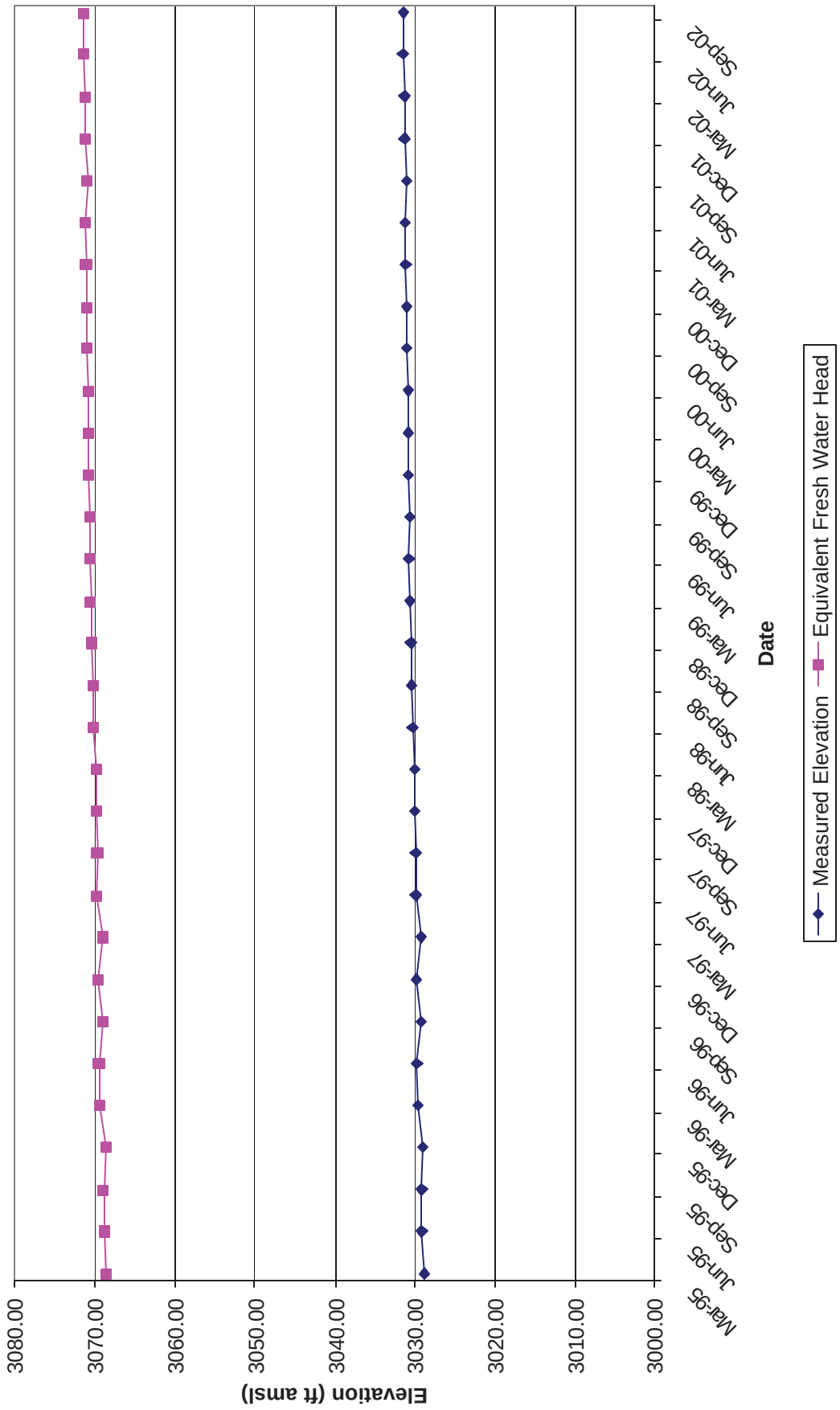

Table 26 - Well No. H-05b Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3026.03	3070.66
02/14/95	3026.08	3070.72
03/13/95	3026.11	3070.75
04/12/95	3025.92	3070.54
05/08/95	3026.35	3071.01
06/05/95	3026.37	3071.04
07/19/95	3026.46	3071.14
08/16/95	3026.56	3071.25
09/08/95	3026.39	3071.06
10/18/95	3026.59	3071.28
11/08/95	3026.50	3071.18
12/06/95	3026.61	3071.30
01/10/96	3026.64	3071.34
02/07/96	3026.68	3071.38
03/13/96	3026.90	3071.62
04/17/96	3026.89	3071.61
05/15/96	3026.90	3071.62
06/12/96	3027.04	3071.78
07/17/96	3026.46	3071.14
08/14/96	3026.93	3071.66
09/05/96	3027.04	3071.78
10/16/96	3027.04	3071.78
11/13/96	3026.83	3071.54
12/11/96	3027.06	3071.80
01/14/97	3026.93	3071.66
02/12/97	3026.96	3071.69
03/12/97	3027.00	3071.73
04/16/97	3027.09	3071.83
05/14/97	3027.51	3072.30
06/12/97	3027.22	3071.98
07/16/97	3027.08	3071.82
08/13/97	3027.08	3071.82
09/17/97	3027.18	3071.93
10/16/97	3027.12	3071.86
11/12/97	3027.35	3072.12
12/10/97	3027.36	3072.13

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3027.38	3072.15
02/11/98	3027.49	3072.27
03/11/98	3027.32	3072.09
04/15/98	3027.69	3072.49
05/13/98	3027.70	3072.51
06/10/98	3027.62	3072.42
07/15/98	3027.65	3072.45
08/12/98	3027.62	3072.42
09/10/98	3027.70	3072.51
10/14/98	3027.70	3072.51
11/11/98	3027.66	3072.46
12/07/98	3027.80	3072.62
01/13/99	3027.80	3072.62
02/08/99	3027.83	3072.65
03/10/99	3027.93	3072.76
04/13/99	3027.95	3072.78
05/12/99	3027.96	3072.79
06/09/99	3028.06	3072.90
07/21/99	3027.92	3072.75
08/11/99	3028.09	3072.94
09/09/99	3028.03	3072.87
10/06/99	3027.99	3072.83
11/10/99	3028.02	3072.86
12/08/99	3028.14	3072.99
01/19/00	3028.07	3072.91
02/16/00	3028.11	3072.96
03/08/00	3028.21	3073.07
04/19/00	3028.30	3073.17
05/15/00	3028.20	3073.06
06/05/00	3028.20	3073.06
07/11/00	3028.47	3073.36
08/15/00	3028.34	3073.21
09/12/00	3028.43	3073.31
10/11/00	3028.23	3073.09
11/06/00	3028.57	3073.47
12/07/00	3028.30	3073.17

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3028.37	3073.24
02/06/01	3028.33	3073.20
03/07/01	3028.45	3073.33
04/04/01	3028.64	3073.54
05/08/01	3028.42	3073.30
06/07/01	3028.54	3073.43
07/10/01	3028.48	3073.37
08/08/01	3028.44	3073.32
09/10/01	3028.42	3073.30
10/10/01	3028.55	3073.44
11/13/01	3028.49	3073.38
12/04/01	3028.57	3073.47
01/16/02	3028.53	3073.42
02/06/02	3028.58	3073.48
03/12/02	3028.65	3073.55
04/09/02	3028.74	3073.65
05/08/02	3028.85	3073.77
06/12/02	3028.84	3073.76
07/15/02	3028.79	3073.71
08/13/02	3028.86	3073.79
09/10/02	3028.77	3073.69

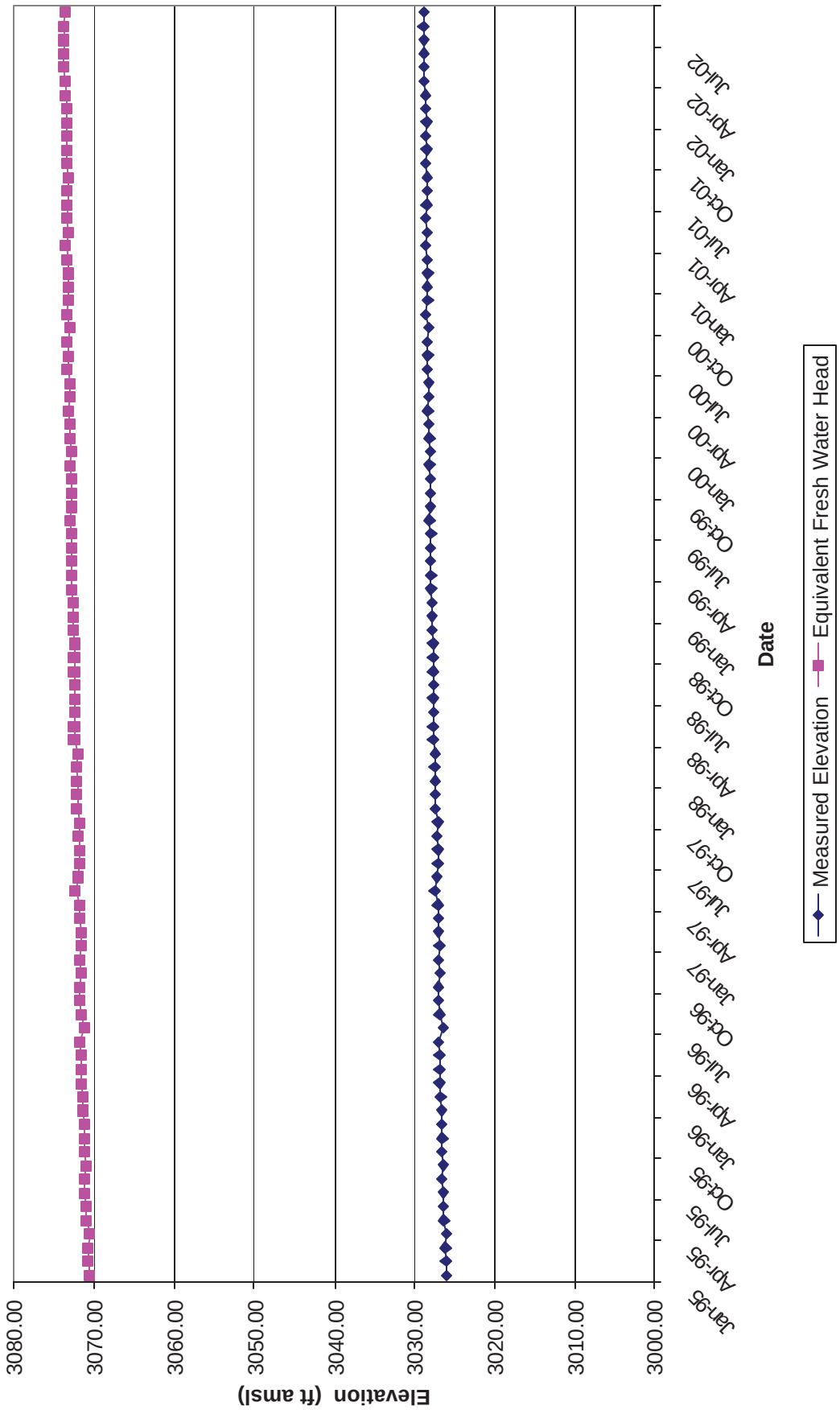
Figure 26 - H-5b Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3080.00
3070.00
3060.00
3050.00
3040.00
3030.00
3020.00
3010.00
3000.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 27 - Well No. H-05c Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3156.04	N/A
02/14/95	3155.96	N/A
03/13/95	3155.93	N/A
04/12/95	3155.76	N/A
05/08/95	3156.03	N/A
06/05/95	3156.01	N/A
07/19/95	3155.92	N/A
08/16/95	3156.00	N/A
09/08/95	3155.86	N/A
10/18/95	3155.93	N/A
11/08/95	3155.86	N/A
12/06/95	3155.92	N/A
01/10/96	3155.98	N/A
02/07/96	3155.91	N/A
03/13/96	3156.10	N/A
04/17/96	3156.08	N/A
05/15/96	3156.08	N/A
06/12/96	3156.13	N/A
07/17/96	3156.08	N/A
08/14/96	3156.02	N/A
09/05/96	3156.21	N/A
10/16/96	3156.14	N/A
11/13/96	3155.93	N/A
12/11/96	3156.13	N/A
01/14/97	3156.01	N/A
02/12/97	3156.00	N/A
03/12/97	3156.06	N/A
04/16/97	3156.08	N/A
05/14/97	3156.26	N/A
06/12/97	3156.29	N/A
07/16/97	3156.06	N/A
08/13/97	3156.03	N/A
09/17/97	3156.12	N/A
10/16/97	3156.13	N/A
11/12/97	3156.25	N/A
12/10/97	3156.25	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3156.23	N/A
02/11/98	3156.29	N/A
03/11/98	3156.13	N/A
04/15/98	3156.52	N/A
05/13/98	3156.41	N/A
06/10/98	3156.28	N/A
07/15/98	3156.23	N/A
08/12/98	3156.15	N/A
09/10/98	3156.22	N/A
10/14/98	3156.19	N/A
11/11/98	3156.18	N/A
12/07/98	3156.29	N/A
01/13/99	3156.29	N/A
02/08/99	3156.34	N/A
03/10/99	3156.59	N/A
04/13/99	3156.42	N/A
05/12/99	3156.48	N/A
06/09/99	3156.52	N/A
07/21/99	3156.38	N/A
08/11/99	3156.70	N/A
09/09/99	3156.49	N/A
10/06/99	3156.45	N/A
11/10/99	3156.50	N/A
12/08/99	3156.62	N/A
01/19/00	3156.59	N/A
02/16/00	3156.63	N/A
03/08/00	3156.72	N/A
04/19/00	3156.79	N/A
05/15/00	3156.74	N/A
06/05/00	3156.74	N/A
07/11/00	3156.95	N/A
08/15/00	3156.89	N/A
09/12/00	3156.92	N/A
10/11/00	3156.80	N/A
11/06/00	3157.19	N/A
12/07/00	3156.91	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3156.96	N/A
02/06/01	3157.04	N/A
03/07/01	3157.09	N/A
04/04/01	3157.33	N/A
05/08/01	3157.12	N/A
06/07/01	3157.39	N/A
07/10/01	3157.21	N/A
08/08/01	3157.20	N/A
09/10/01	3157.15	N/A
10/10/01	3157.29	N/A
11/13/01	3157.19	N/A
12/04/01	3157.29	N/A
01/16/02	3157.18	N/A
02/06/02	3157.24	N/A
03/12/02	3157.25	N/A
04/09/02	3157.27	N/A
05/08/02	3157.37	N/A
06/12/02	3157.30	N/A
07/15/02	3157.19	N/A
08/13/02	3157.22	N/A
09/10/02	3157.05	N/A

Figure 27 - H-5c Magenta
Historical Waterlevel Measurements

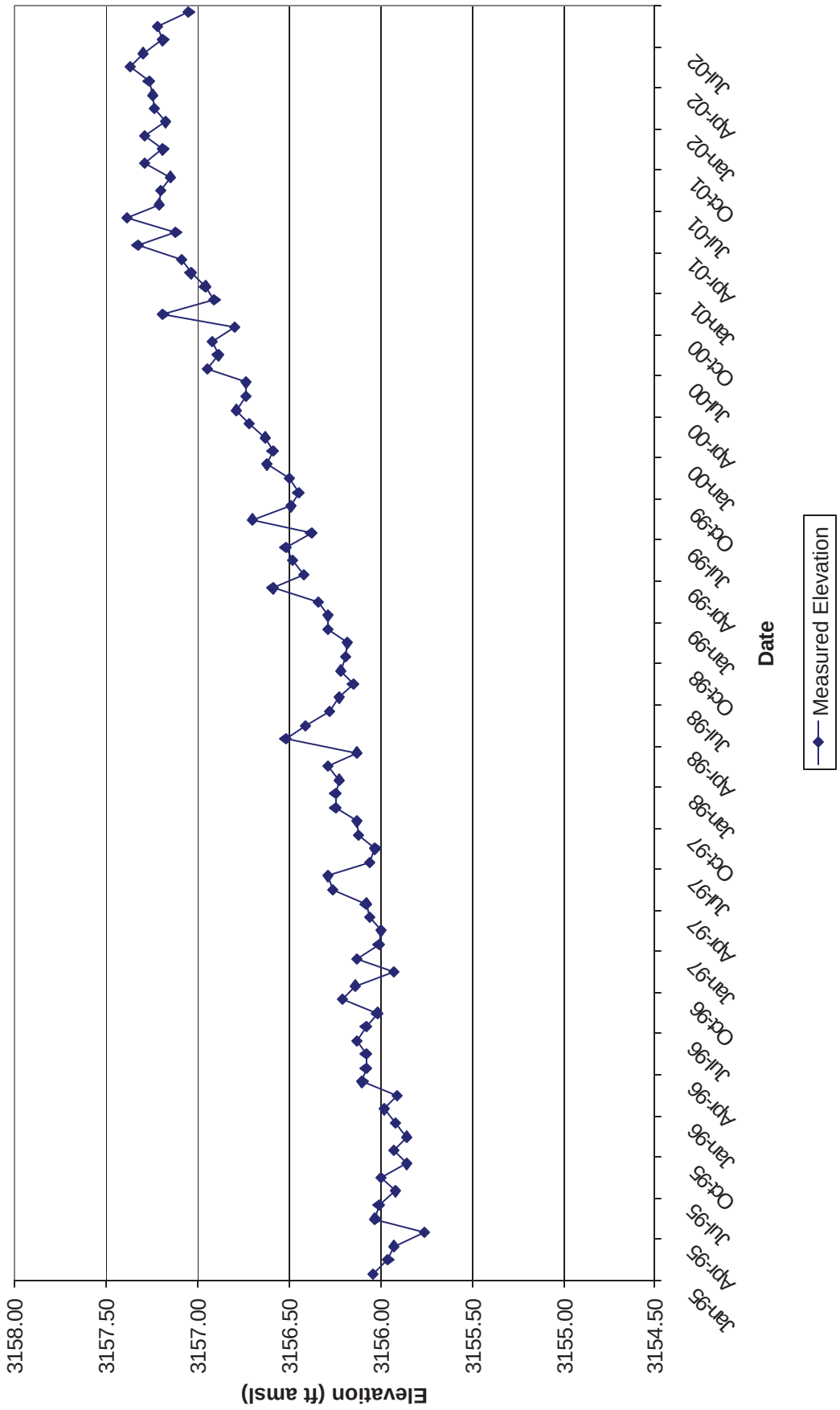

Table 28 - Well No. H-06a Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/13/95	3049.75	3061.83
06/05/95	3050.06	3062.16
09/05/95	3049.95	3062.04
12/04/95	3050.52	3062.63
03/11/96	3050.10	3062.20
06/10/96	3050.68	3062.80
09/03/96	3051.06	3063.19
12/09/96	3050.78	3062.90
03/10/97	3051.00	3063.13
06/09/97	3051.32	3063.46
09/15/97	3051.16	3063.30
12/08/97	3050.43	3062.54

Date	Measured Elevation	Equivalent Fresh Water Head
03/11/98	3051.63	3063.79
06/11/98	3051.01	3063.14
09/10/98	3050.82	3062.94
12/07/98	3050.63	3062.75
03/10/99	3051.17	3063.31
06/07/99	3051.23	3063.37
09/08/99	3050.98	3063.11
12/09/99	3051.86	3064.02
03/06/00	3052.41	3064.59
06/05/00	3052.00	3064.17
09/12/00	3052.17	3064.35
12/07/00	3052.32	3064.50

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/01	3052.57	3064.76
06/05/01	3052.95	3065.16
09/04/01	3053.01	3065.22
12/04/01	3053.14	3065.35
03/11/02	3053.99	3066.23
06/10/02	3054.46	3066.72
09/09/02	3054.72	3066.99

Figure 28 - H-6a Culebra
Historical Waterlevel Measurements

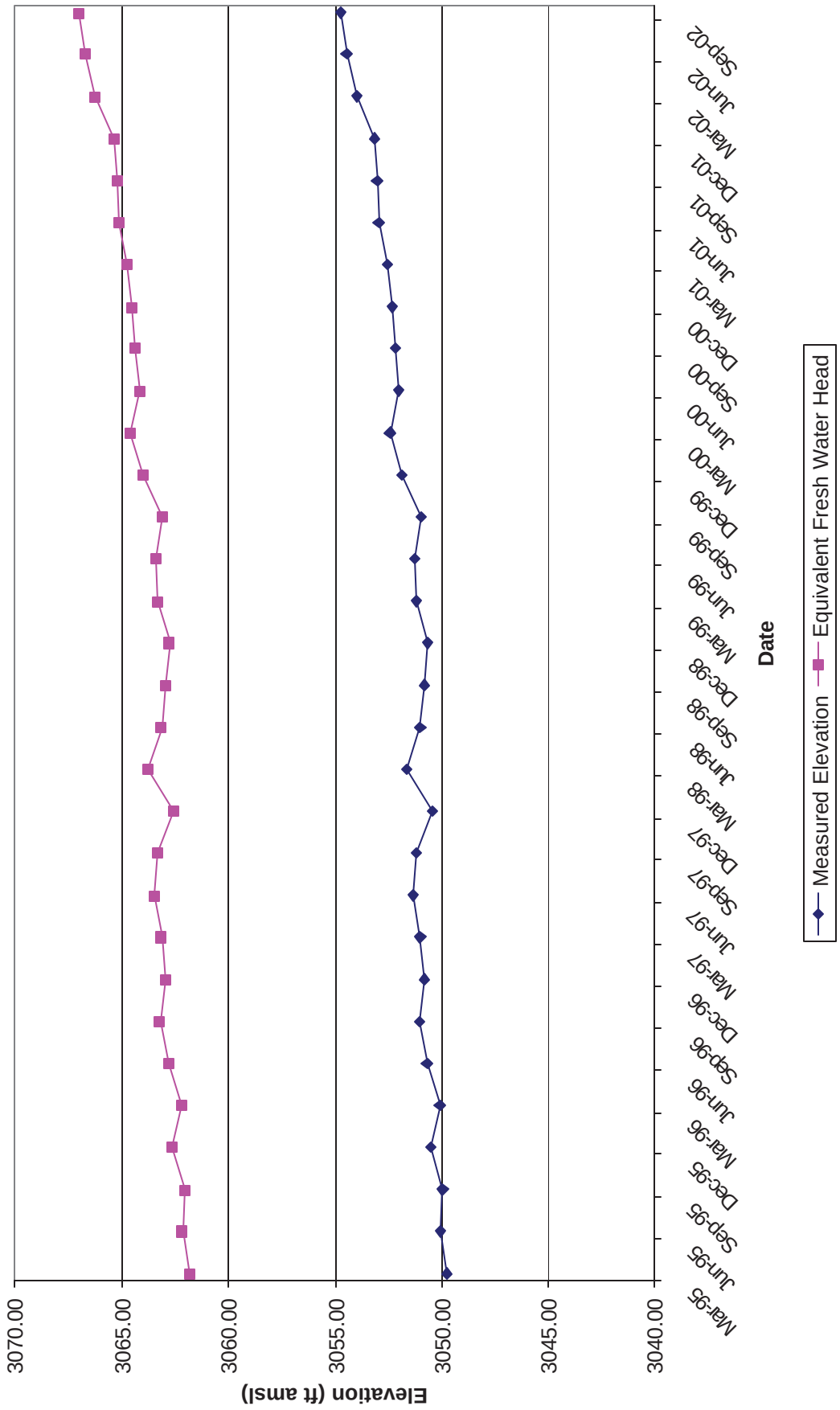

Table 29 - Well No. H-06b Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3049.30	3061.35
02/13/95	3049.23	3061.28
03/13/95	3049.20	3061.25
04/10/95	3049.20	3061.25
05/08/95	3049.40	3061.46
06/05/95	3049.48	3061.54
07/17/95	3049.68	3061.75
08/14/95	3049.89	3061.97
09/05/95	3049.38	3061.44
10/16/95	3049.81	3061.88
11/06/95	3049.97	3062.05
12/04/95	3049.82	3061.89
01/08/96	3049.80	3061.87
02/05/96	3049.34	3061.40
03/11/96	3049.62	3061.69
04/15/96	3049.40	3061.46
05/13/96	3049.75	3061.82
06/10/96	3049.98	3062.06
07/15/96	3050.00	3062.08
08/12/96	3049.88	3061.96
09/03/96	3050.34	3062.43
10/14/96	3050.24	3062.33
11/11/96	3049.98	3062.06
12/09/96	3050.07	3062.15
01/13/97	3050.06	3062.14
02/10/97	3050.12	3062.21
03/10/97	3050.27	3062.36
04/14/97	3050.45	3062.55
05/13/97	3050.59	3062.69
06/09/97	3050.62	3062.72
07/16/97	3050.74	3062.85
08/11/97	3050.64	3062.75
09/15/97	3050.48	3062.58
10/13/97	3050.12	3062.21
11/10/97	3050.03	3062.11
12/08/97	3049.76	3061.83

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3049.73	3061.80
02/09/98	3051.05	3063.17
03/11/98	3051.13	3063.25
04/15/98	3051.33	3063.46
05/11/98	3051.00	3063.12
06/11/98	3050.73	3062.84
07/15/98	3050.69	3062.80
08/12/98	3050.67	3062.78
09/10/98	3050.64	3062.75
10/14/98	3050.63	3062.74
11/11/98	3050.41	3062.51
12/07/98	3050.46	3062.56
01/11/99	3050.67	3062.78
02/09/99	3050.95	3063.07
03/10/99	3051.01	3063.13
04/12/99	3050.83	3062.94
05/10/99	3051.22	3063.35
06/07/99	3051.05	3063.17
07/19/99	3050.76	3062.87
08/09/99	3050.68	3062.79
09/08/99	3050.75	3062.86
10/04/99	3050.65	3062.76
11/08/99	3051.14	3063.26
12/09/99	3051.30	3063.43
01/19/00	3051.86	3064.01
02/14/00	3051.74	3063.89
03/06/00	3051.89	3064.04
04/17/00	3051.73	3063.88
05/15/00	3051.74	3063.89
06/05/00	3051.46	3063.60
07/11/00	3051.74	3063.89
08/15/00	3051.45	3063.59
09/12/00	3051.59	3063.73
10/09/00	3051.29	3063.42
11/06/00	3051.90	3064.05
12/07/00	3051.70	3063.85

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3051.80	3063.95
02/06/01	3051.93	3064.08
03/06/01	3051.92	3064.07
04/04/01	3052.21	3064.38
05/08/01	3052.00	3064.16
06/05/01	3052.28	3064.45
07/09/01	3052.31	3064.48
08/07/01	3052.26	3064.43
09/04/01	3052.37	3064.54
10/10/01	3052.42	3064.59
11/14/01	3052.63	3064.81
12/05/01	3052.50	3064.68
01/16/02	3052.86	3065.05
02/05/02	3052.99	3065.18
03/11/02	3053.26	3065.47
04/08/02	3053.49	3065.70
05/06/02	3053.55	3065.77
06/10/02	3053.71	3065.93
07/15/02	3053.88	3066.11
08/12/02	3054.00	3066.23
09/09/02	3053.94	3066.17

Figure 29 - H-6b Culebra
Historical Waterlevel Measurements

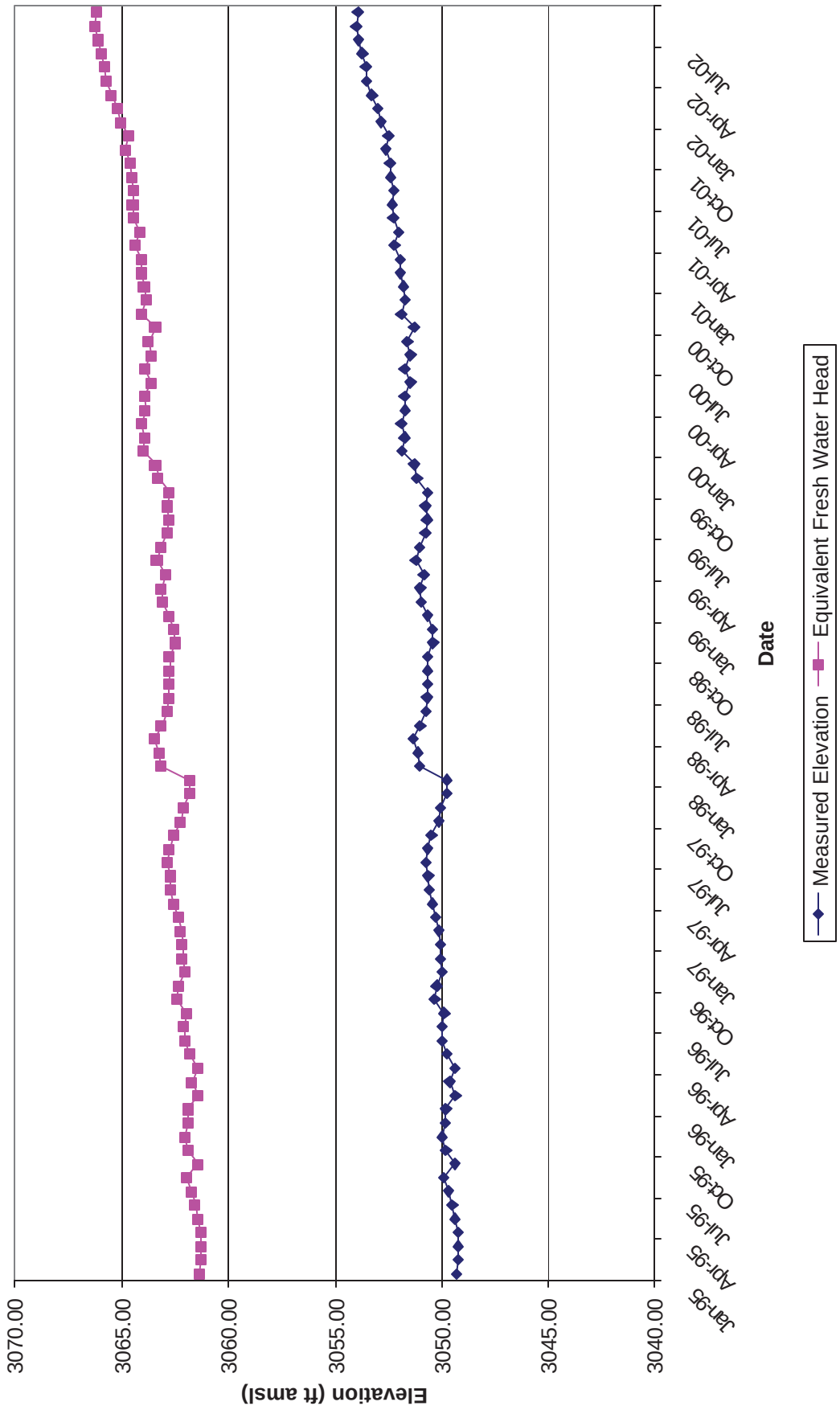

Table 30 - Well No. H-06c Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3061.65	N/A
02/13/95	3061.50	N/A
03/13/95	3061.50	N/A
04/10/95	3061.61	N/A
05/08/95	3061.71	N/A
06/05/95	3061.71	N/A
07/17/95	3061.65	N/A
08/14/95	3061.79	N/A
09/05/95	3061.58	N/A
10/16/95	3061.77	N/A
11/06/95	3061.90	N/A
12/04/95	3061.81	N/A
01/08/96	3061.80	N/A
02/05/96	3061.83	N/A
03/11/96	3061.94	N/A
04/15/96	3061.94	N/A
05/13/96	3062.16	N/A
06/10/96	3062.28	N/A
07/15/96	3062.22	N/A
08/12/96	3062.29	N/A
09/03/96	3062.46	N/A
10/14/96	3062.46	N/A
11/11/96	3062.43	N/A
12/09/96	3062.48	N/A
01/13/97	3062.31	N/A
02/10/97	3062.42	N/A
03/10/97	3062.59	N/A
04/14/97	3062.72	N/A
05/13/97	3062.96	N/A
06/09/97	3062.92	N/A
07/16/97	3062.89	N/A
08/11/97	3062.93	N/A
09/15/97	3062.99	N/A
10/13/97	3062.99	N/A
11/10/97	3062.99	N/A
12/08/97	3063.26	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3063.31	N/A
02/09/98	3063.42	N/A
03/11/98	3063.15	N/A
04/15/98	3063.54	N/A
05/11/98	3063.48	N/A
06/11/98	3063.45	N/A
07/15/98	363.35	N/A
08/12/98	3063.30	N/A
09/10/98	3063.38	N/A
10/14/98	3063.46	N/A
11/11/98	3063.37	N/A
12/07/98	3063.49	N/A
01/11/99	3063.42	N/A
02/09/99	3063.59	N/A
03/10/99	3063.71	N/A
04/12/99	3063.60	N/A
05/10/99	3063.83	N/A
06/07/99	3063.73	N/A
07/19/99	3063.70	N/A
08/09/99	3063.82	N/A
09/08/99	3063.82	N/A
10/04/99	3063.69	N/A
11/08/99	3063.79	N/A
12/09/99	3063.82	N/A
01/19/00	3062.63	N/A
02/14/00	3063.94	N/A
03/06/00	3064.04	N/A
04/17/00	3064.03	N/A
05/15/00	3064.08	N/A
06/05/00	3063.95	N/A
07/11/00	3064.35	N/A
08/15/00	3064.15	N/A
09/12/00	3064.33	N/A
10/09/00	3063.94	N/A
11/06/00	3064.60	N/A
12/07/00	3064.40	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3064.43	N/A
02/06/01	3064.54	N/A
03/06/01	3064.54	N/A
04/04/01	3064.75	N/A
05/08/01	3064.50	N/A
06/05/01	3064.81	N/A
07/09/01	3064.69	N/A
08/07/01	3064.67	N/A
09/04/01	3064.76	N/A
10/10/01	3064.83	N/A
11/14/01	3064.92	N/A
12/05/01	3064.84	N/A
01/16/02	3064.95	N/A
02/05/02	3065.02	N/A
03/11/02	3065.20	N/A
04/08/02	3065.43	N/A
05/06/02	3065.32	N/A
06/10/02	3065.42	N/A
07/15/02	3065.32	N/A
08/12/02	3065.39	N/A
09/09/02	3065.29	N/A

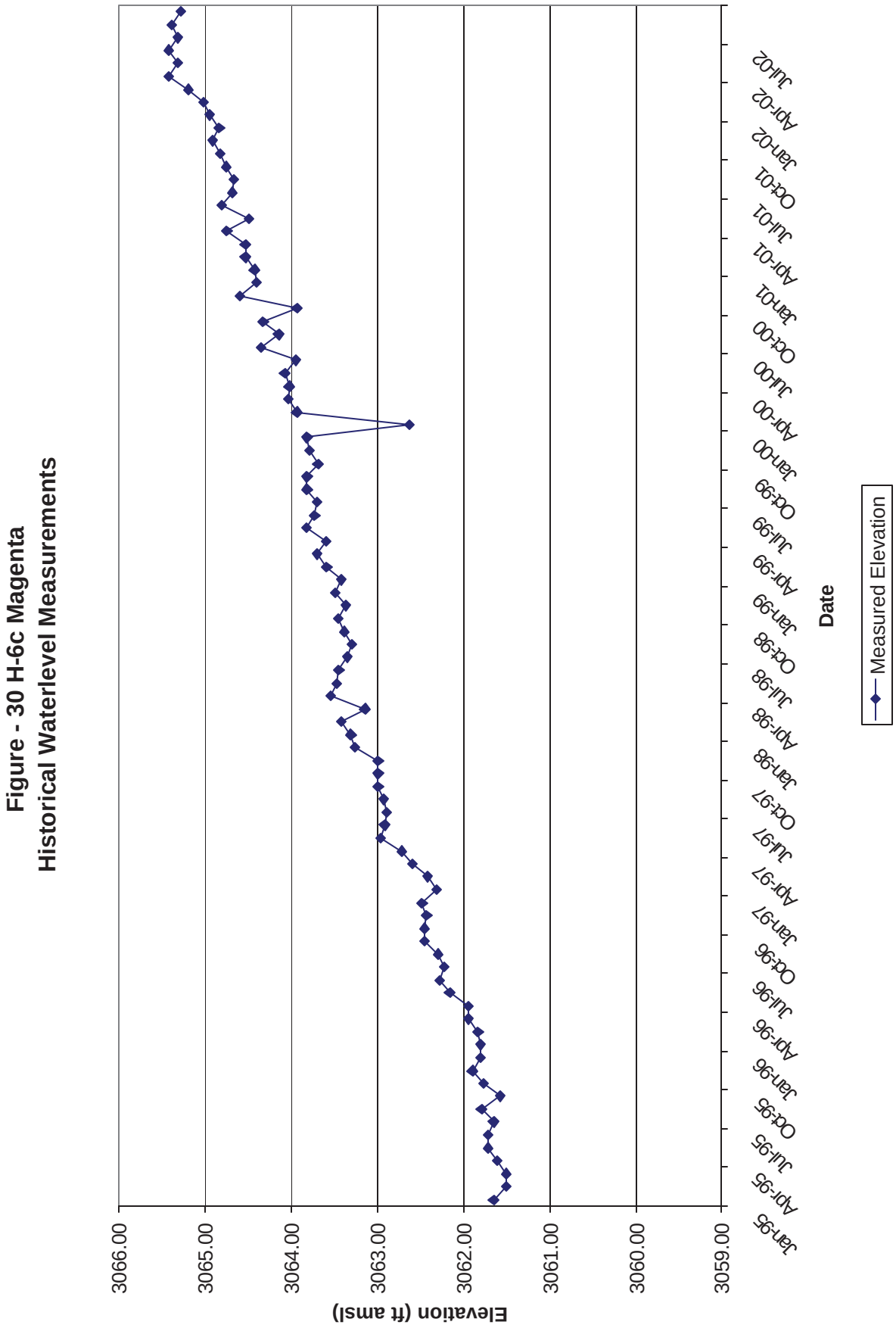
Figure - 30 H-6c Magenta
Historical Waterlevel Measurements
Elevation (ft amsl)
3066.00
3065.00
3064.00
3063.00
3062.00
3061.00
3060.00
3059.00
Date
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Measured Elevation

Table 31 - Well No. H-07b1 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head	Date	Measured Elevation	Equivalent Fresh Water Head	Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2995.90	2996.34	01/13/98	2996.89	2997.33	03/05/01	2997.87	2998.32
02/14/95	2995.97	2996.41	02/10/98	2997.05	2997.49	06/04/01	2998.18	2998.63
03/14/95	2995.78	2996.22	03/10/98	2996.59	2997.03	09/05/01	2997.73	2998.18
04/11/95	2995.76	2996.20	04/14/98	2997.11	2997.56	12/03/01	2997.69	2998.14
05/09/95	2995.92	2996.36	05/12/98	2997.13	2997.58			
06/06/95	2996.13	2996.57	06/09/98	2996.94	2997.38			
07/18/95	2995.99	2996.43	07/14/98	2996.82	2997.26			
08/15/95	2996.17	2996.61	09/09/98	2996.79	2997.23			
09/06/95	2996.12	2996.56	12/08/98	2996.47	2996.91			
10/17/95	2996.34	2996.78						
11/07/95	2996.23	2996.67						
12/05/95	2996.44	2996.88						
01/09/96	2996.40	2996.84	03/09/99	2996.85	2997.29	03/11/02	2997.97	2998.42
02/06/96	2996.36	2996.80	06/08/99	2996.90	2997.34	06/12/02	2997.88	2998.33
03/12/96	2996.60	2997.04	09/08/99	2997.13	2997.58	09/11/02	2997.60	2998.05
04/16/96	2996.43	2996.87	12/07/99	2997.28	2997.73			
05/14/96	2996.60	2997.04						
06/11/96	2996.52	2996.96						
07/16/96	2996.51	2996.95						
08/13/96	2996.45	2996.89						
09/04/96	2996.62	2997.06						
10/15/96	2996.76	2997.20						
11/12/96	2996.47	2996.91						
12/10/96	2996.75	2997.19						
01/15/97	2996.65	2997.09	03/07/00	2997.47	2997.92			
02/11/97	2996.70	2997.14	06/06/00	2997.01	2997.45			
03/11/97	2996.65	2997.09	09/13/00	2997.84	2998.29			
04/15/97	2996.28	2996.72	12/05/00	2997.78	2998.23			
05/13/97	2996.69	2997.13						
06/10/97	2996.56	2997.00						
07/15/97	2996.44	2996.88						
08/12/97	2996.58	2997.02						
09/16/97	2996.83	2997.27						
10/14/97	2996.46	2996.90						
11/11/97	2996.90	2997.34						
12/11/97	2996.62	2997.06						

Figure 31 - H-7b1 Culebra
Historical Waterlevel Measurements

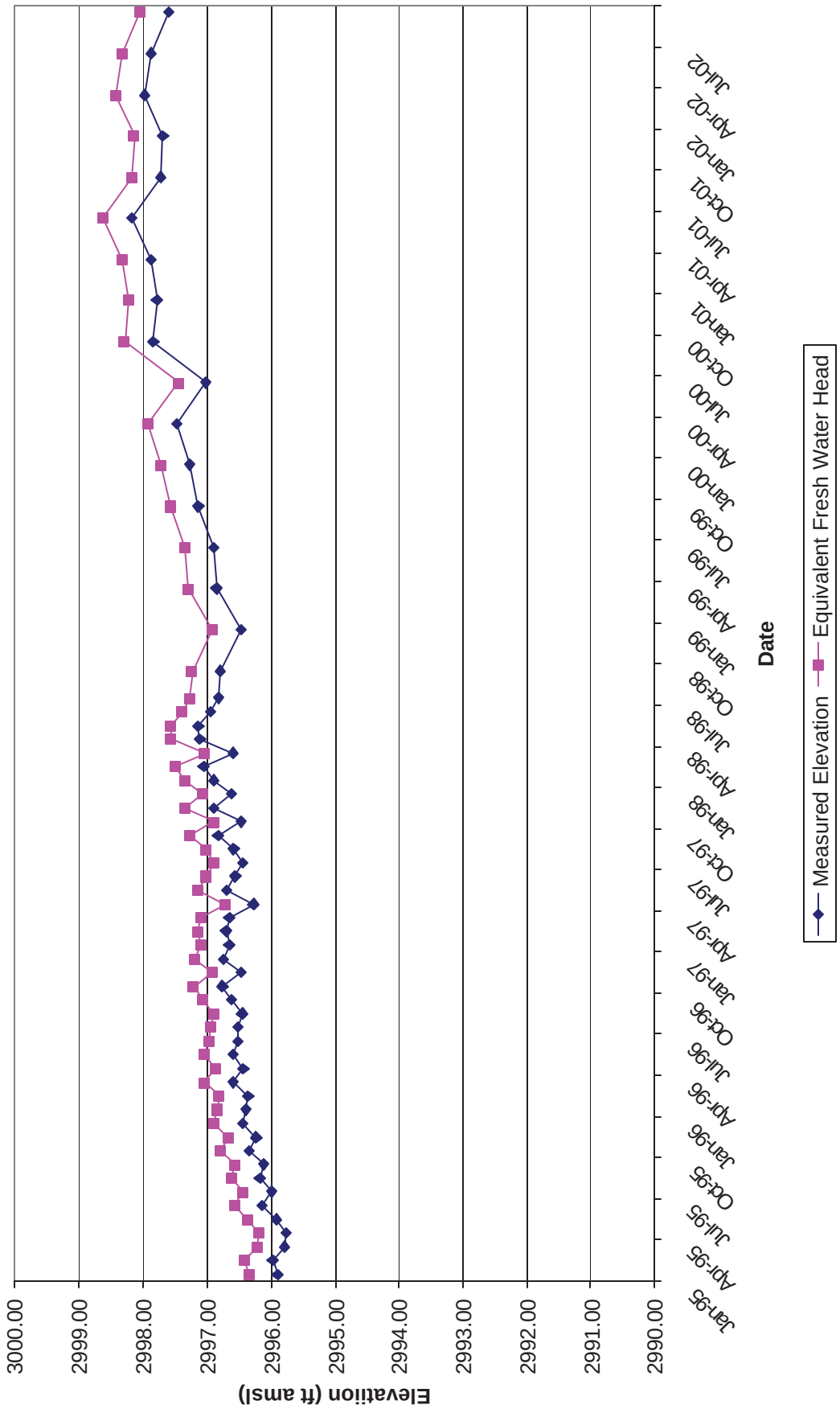

Table 32 - Well No. H-07b2 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2995.60	2995.51
06/06/95	2995.66	2995.57
09/06/95	2995.95	2995.86
12/05/95	2996.25	2996.16
03/12/96	2996.40	2996.31
06/11/96	2996.35	2996.26
09/04/96	2996.45	2996.36
12/10/96	2996.57	2996.48
03/11/97	2996.46	2996.37
06/10/97	2996.37	2996.28
09/16/97	2996.63	2996.54
12/11/97	2996.42	2996.33

Date	Measured Elevation	Equivalent Fresh Water Head
03/10/98	2996.39	2996.30
06/09/98	2996.73	2996.64
08/11/98	2996.55	2996.46
09/09/98	2996.58	2996.49
10/13/98	2996.40	2996.31
11/10/98	2996.41	2996.32
12/08/98	2996.25	2996.16
01/12/99	2996.77	2996.68
02/09/99	2996.57	2996.48
03/09/99	2996.64	2996.55
04/13/99	2996.78	2996.69
05/11/99	2996.78	2996.69
06/08/99	2996.68	2996.59
07/20/99	2996.77	2996.68
08/10/99	2996.93	2996.84
09/08/99	2996.91	2996.82
10/05/99	2996.80	2996.71
11/09/99	2997.01	2996.92
12/07/99	2997.08	2996.99
01/18/00	2996.94	2996.85
02/14/00	2997.11	2997.02
03/07/00	2997.24	2997.15
04/18/00	2997.06	2996.97
05/16/00	2997.09	2997.00
06/06/00	2996.79	2996.70
07/11/00	2997.45	2997.36
08/15/00	2997.56	2997.47
09/13/00	2997.65	2997.56
10/10/00	2997.58	2997.49
11/07/00	2997.91	2997.82
12/05/00	2997.56	2997.47

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2997.92	2997.83
02/07/01	2998.02	2997.93
03/05/01	2997.61	2997.52
04/03/01	2998.00	2997.91
05/07/01	2997.74	2997.65
06/04/01	2998.04	2997.95
07/09/01	2997.72	2997.63
08/06/01	2997.56	2997.47
09/05/01	2997.60	2997.51
10/08/01	2997.60	2997.51
11/12/01	2997.60	2997.51
12/03/01	2997.54	2997.45
01/14/02	2997.48	2997.39
02/06/02	2997.55	2997.46
03/11/02	2997.81	2997.72
04/10/02	2997.52	2997.43
06/12/02	2997.63	2997.54
07/16/02	2996.77	2996.68
08/12/02	2997.50	2997.41
09/11/02	2997.34	2997.25

Figure 32 - H-7b2 Culebra
Historical Waterlevel Measurements

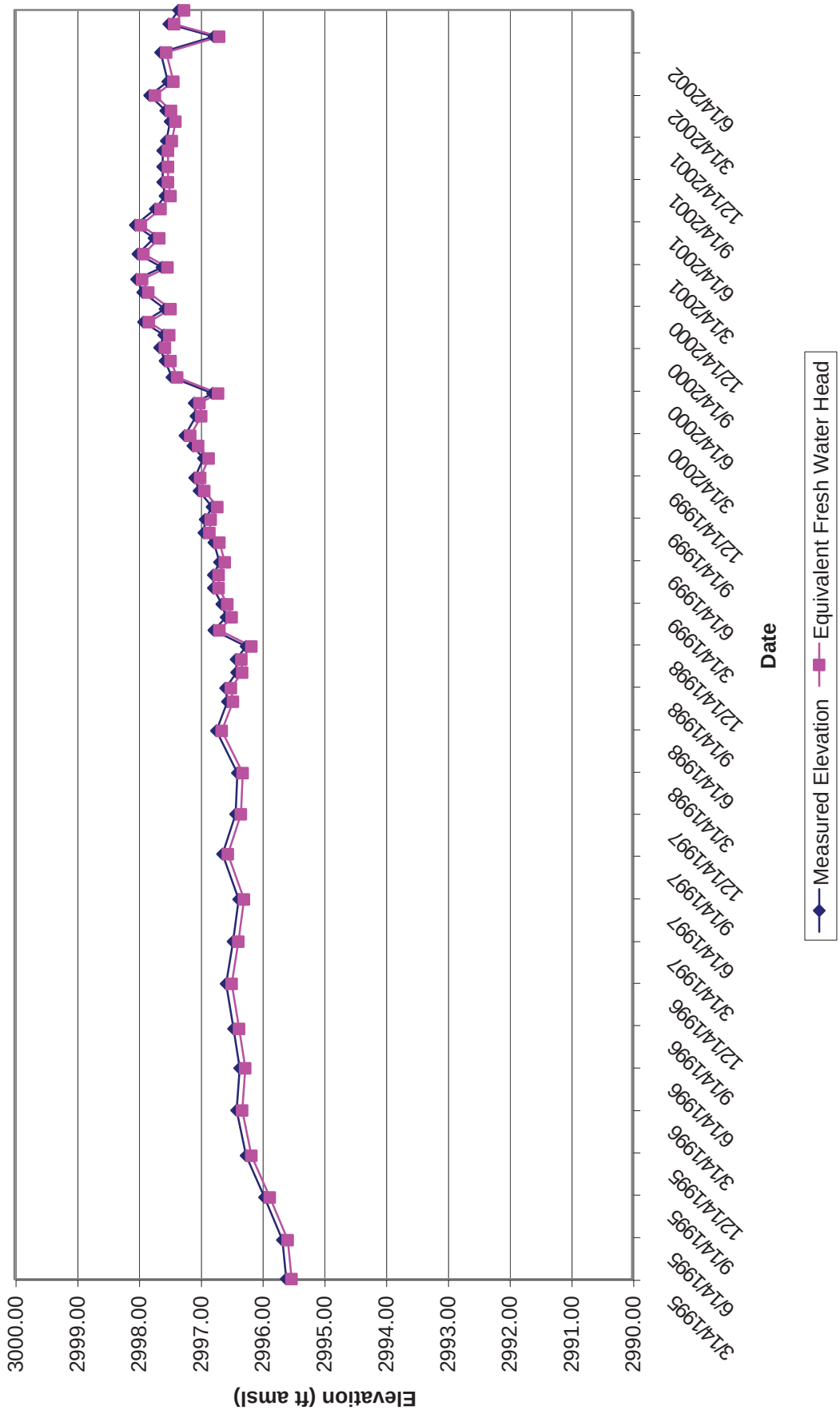

Table 33 - Well No. H-08a Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3027.56	N/A
02/14/95	3027.57	N/A
03/14/95	3027.56	N/A
04/11/95	3027.36	N/A
05/09/95	3027.60	N/A
06/06/95	3027.68	N/A
07/18/95	3027.66	N/A
08/15/95	3027.72	N/A
09/06/95	3027.64	N/A
10/17/95	3027.67	N/A
11/07/95	3027.67	N/A
12/05/95	3027.64	N/A
01/09/96	3027.63	N/A
02/06/96	3027.63	N/A
03/12/96	3027.68	N/A
04/16/96	3027.73	N/A
05/14/96	3027.77	N/A
06/11/96	3027.92	N/A
07/16/96	3027.84	N/A
08/14/96	3027.78	N/A
09/04/96	3027.79	N/A
10/15/96	3027.78	N/A
11/12/96	3027.75	N/A
12/10/96	3027.74	N/A
01/15/97	3027.70	N/A
02/11/97	3027.61	N/A
03/11/97	3027.65	N/A
04/15/97	3027.72	N/A
05/13/97	3027.74	N/A
06/10/97	3027.81	N/A
07/15/97	3027.72	N/A
08/12/97	3027.67	N/A
09/16/97	3027.63	N/A
10/14/97	3027.65	N/A
11/11/97	3027.62	N/A
12/09/97	3027.56	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	3027.59	N/A
02/10/98	3027.67	N/A
03/10/98	3027.68	N/A
04/14/98	3027.70	N/A
05/12/98	3027.67	N/A
06/09/98	3027.62	N/A
07/14/98	3027.53	N/A
08/11/98	3027.49	N/A
09/09/98	3027.42	N/A
10/13/98	3027.40	N/A
11/10/98	3027.37	N/A
12/08/98	3027.35	N/A
01/12/99	3027.32	N/A
02/09/99	3027.33	N/A
03/09/99	3027.40	N/A
04/13/99	3027.42	N/A
05/11/99	3027.48	N/A
06/08/99	3027.46	N/A
07/20/99	3027.39	N/A
08/10/99	3027.43	N/A
09/08/99	3027.36	N/A
10/05/99	3027.28	N/A
11/09/99	3027.21	N/A
12/07/99	3027.20	N/A
01/18/00	3027.15	N/A
02/15/00	3027.13	N/A
03/07/00	3027.14	N/A
04/18/00	3027.17	N/A
05/16/00	3027.19	N/A
06/06/00	3027.19	N/A
07/11/00	3027.24	N/A
08/15/00	3027.21	N/A
09/13/00	3027.19	N/A
10/10/00	3027.08	N/A
11/08/00	3027.10	N/A
12/05/00	3027.07	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3027.04	N/A
02/07/01	3026.94	N/A
03/05/01	3027.09	N/A
04/03/01	3027.11	N/A
05/07/01	3027.11	N/A
06/07/01	3027.10	N/A
07/10/01	3027.03	N/A
08/06/01	3027.00	N/A
09/05/01	3026.95	N/A
10/09/01	3026.88	N/A
11/13/01	3026.84	N/A
12/04/01	3026.83	N/A
01/15/02	3026.76	N/A
02/06/02	3026.87	N/A
03/13/02	3026.90	N/A
04/10/02	3026.96	N/A
05/06/02	3027.01	N/A
06/11/02	3027.03	N/A
07/16/02	3026.89	N/A
08/13/02	3026.98	N/A
09/11/02	3026.97	N/A

Figure 33 - H-8a Magenta
Historical Waterlevel Measurements

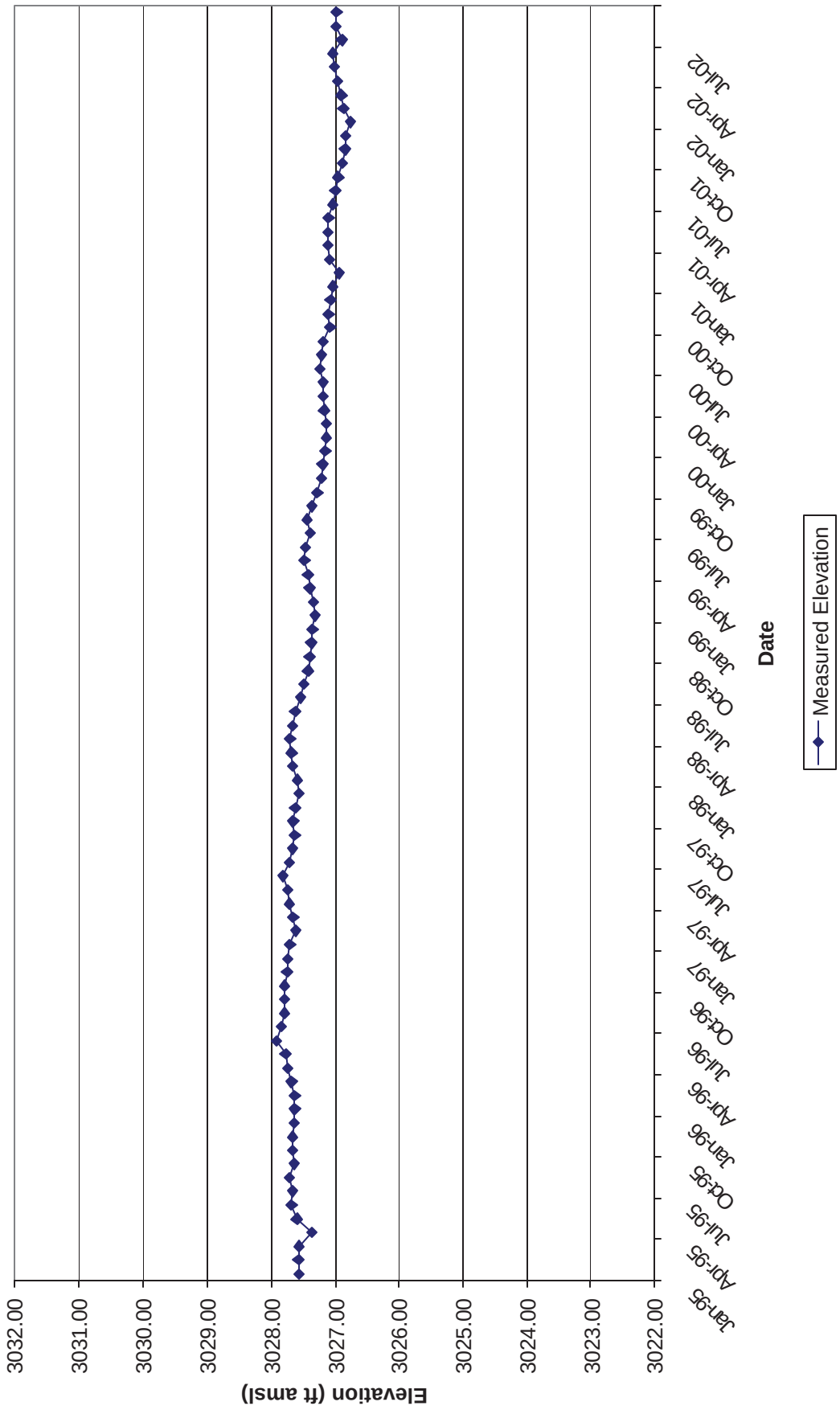

Table 34 - Well No. H-08c Rustler/Salado
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2979.34	N/A
02/14/95	2979.39	N/A
03/14/95	2979.37	N/A
04/11/95	2979.08	N/A
05/09/95	2979.35	N/A
06/06/95	2979.37	N/A
07/18/95	2979.39	N/A
08/15/95	2979.46	N/A
09/06/95	2979.37	N/A
10/17/95	2979.52	N/A
11/07/95	2979.37	N/A
12/05/95	2979.37	N/A
01/09/96	2979.38	N/A
02/06/96	2979.35	N/A
03/12/96	2979.39	N/A
04/16/96	2979.39	N/A
05/14/96	2979.43	N/A
06/11/96	2979.62	N/A
07/16/96	2979.58	N/A
08/14/96	2979.55	N/A
09/04/96	2979.58	N/A
10/15/96	2979.56	N/A
11/12/96	2979.55	N/A
12/10/96	2979.56	N/A
01/15/97	2979.33	N/A
02/11/97	2979.43	N/A
03/11/97	2979.46	N/A
04/15/97	2979.56	N/A
05/13/97	2979.57	N/A
06/10/97	2979.62	N/A
07/15/97	2979.58	N/A
08/12/97	2979.62	N/A
09/16/97	2979.60	N/A
10/14/97	2979.61	N/A
11/11/97	2979.57	N/A
12/09/97	2979.50	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2979.51	N/A
02/10/98	2979.58	N/A
03/10/98	2979.57	N/A
04/14/98	2979.56	N/A
05/12/98	2979.55	N/A
06/09/98	2979.61	N/A
07/14/98	2979.57	N/A
08/11/98	2979.34	N/A
09/09/98	2979.50	N/A
10/13/98	2979.46	N/A
11/10/98	2979.37	N/A
12/08/98	2979.35	N/A
01/12/99	2979.29	N/A
02/09/99	2979.25	N/A
03/09/99	2979.36	N/A
04/13/99	2979.38	N/A
05/11/99	2979.41	N/A
06/08/99	2979.42	N/A
07/20/99	2979.38	N/A
08/10/99	2979.42	N/A
09/08/99	2979.39	N/A
10/05/99	2979.31	N/A
11/09/99	2979.24	N/A
12/07/99	2979.20	N/A
01/18/00	2979.12	N/A
02/15/00	2979.10	N/A
03/07/00	2979.09	N/A
04/18/00	2979.11	N/A
05/16/00	2979.15	N/A
06/06/00	2979.14	N/A
07/11/00	2979.19	N/A
08/15/00	2979.18	N/A
09/13/00	2979.18	N/A
10/10/00	2979.11	N/A
11/07/00	2979.10	N/A
12/05/00	2979.12	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2979.11	N/A
02/07/01	2979.02	N/A
03/05/01	2979.17	N/A
04/03/01	2979.11	N/A
05/07/01	2979.25	N/A
06/07/01	2979.28	N/A
07/10/01	2979.30	N/A
08/06/01	2979.29	N/A
09/05/01	2979.25	N/A
10/09/01	2979.35	N/A
11/13/01	2979.23	N/A
12/04/01	2979.22	N/A
01/15/02	2979.18	N/A
02/06/02	2979.34	N/A
03/13/02	2979.38	N/A
04/10/02	2979.45	N/A
05/06/02	2979.53	N/A
06/11/02	2979.60	N/A
07/16/02	2979.66	N/A
08/13/02	2979.67	N/A
09/11/02	2979.71	N/A

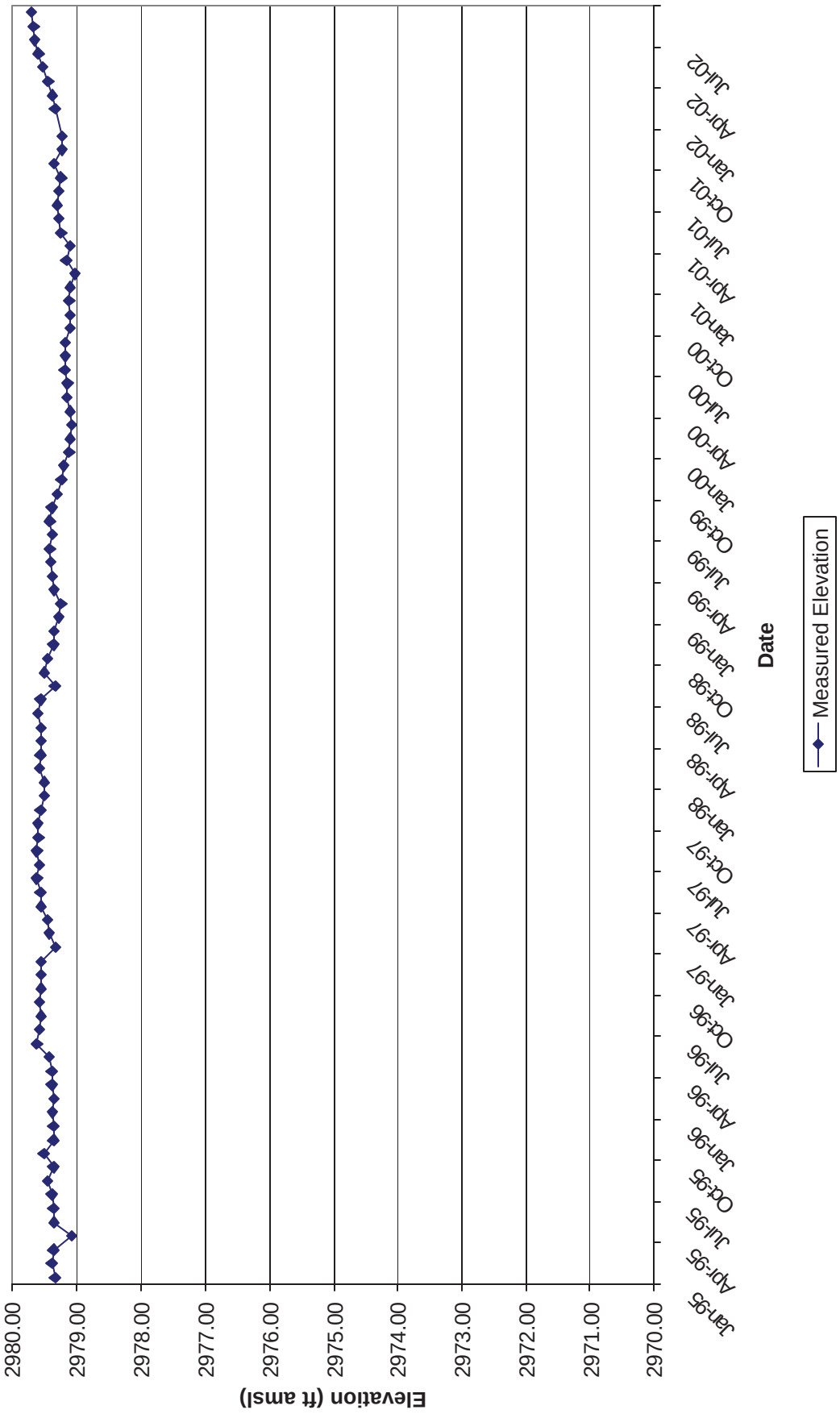
Figure 34 - H-8c Magenta
Historical Waterlevel Measurements
Elevation (ft amsl)
2980.00
2979.00
2978.00
2977.00
2976.00
2975.00
2974.00
2973.00
2972.00
2971.00
2970.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation

Table 35 - Well No. H-09a Culebra
March 1995 through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2990.97	2991.22
06/06/95	2993.10	2993.35
09/06/95	2992.10	2992.35
12/05/95	2992.48	2992.73
03/12/96	2993.10	2993.35
06/11/96	2993.91	2994.16
09/04/96	2993.97	2994.22
12/10/96	2993.53	2993.78
03/11/97	2985.81	2986.05
06/10/97	2984.92	2985.16
09/16/97	2987.80	2988.04
12/09/97	2988.86	2989.10

Date	Measured Elevation	Equivalent Fresh Water Head
03/10/98	2989.46	2989.71
06/09/98	2987.59	2987.83
09/09/98	2988.78	2989.02
12/08/98	2989.19	2989.44
03/09/99	2991.18	2991.43
06/08/99	2991.84	2992.09
09/08/99	2990.64	2990.35
12/07/99	2990.42	2990.67
03/07/00	2991.02	2991.27
06/06/00	2990.74	2990.99
09/13/00	2989.27	2989.52
12/05/00	2989.91	2990.16

Date	Measured Elevation	Equivalent Fresh Water Head
03/05/01	2991.87	2992.12
06/06/01	2992.49	2992.74
09/05/01	2991.14	2991.39
12/04/01	2992.45	2992.70

Figure 35 - H-9a Culebra Historical Waterlevel Measurements

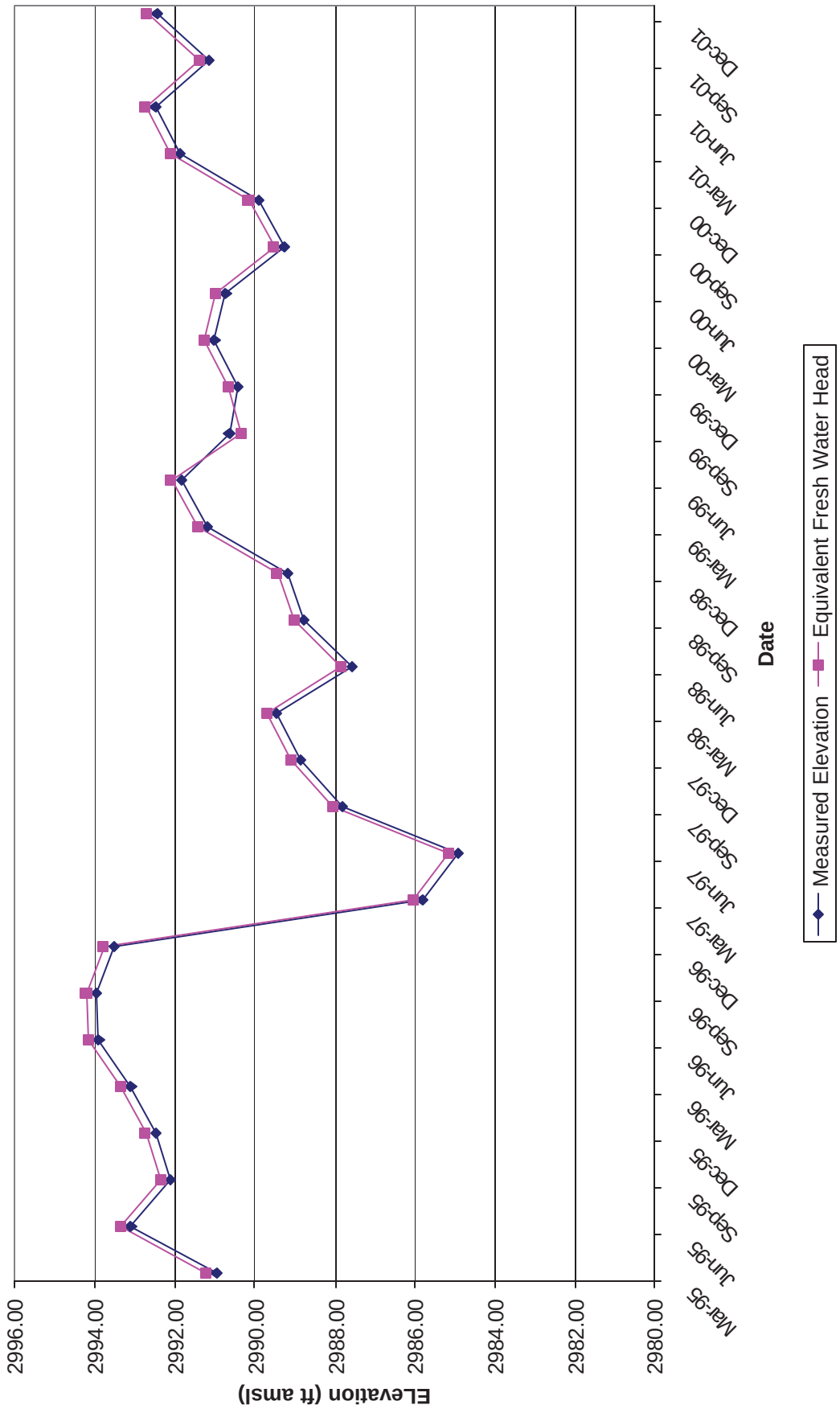

Table 36 - Well No. H-09b Culebra
January 1995 through April 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2990.48	2990.73
02/14/95	2991.16	2991.41
03/14/95	2991.09	2991.34
04/11/95	2991.89	2992.14
05/09/95	2992.69	2992.94
06/06/95	2993.25	2993.50
07/18/95	2993.15	2993.40
08/15/95	2993.09	2993.34
09/06/95	2992.21	2992.46
10/17/95	2991.82	2992.07
11/07/95	2992.42	2992.67
12/05/95	2992.62	2992.87
01/09/96	2992.96	2993.21
02/06/96	2992.93	2993.18
03/12/96	2993.24	2993.49
04/16/96	2993.06	2993.31
05/14/96	2993.94	2994.19
06/11/96	2994.05	2994.30
07/16/96	2994.04	2994.29
08/14/96	2994.13	2994.38
09/04/96	2994.11	2994.36
10/15/96	2994.22	2994.47
11/12/96	2993.58	2993.83
12/10/96	2993.65	2993.90
01/15/97	2993.44	2993.69
02/11/97	2989.97	2990.22
03/11/97	2985.92	2986.16
04/15/97	2985.79	2986.03
05/13/97	2985.46	2985.70
06/10/97	2985.02	2985.26
07/15/97	2984.84	2985.08
08/12/97	2986.42	2986.66
09/16/97	2987.91	2988.15
10/14/97	2987.21	2987.45
11/11/97	2988.40	2988.64
12/09/97	2988.92	2989.17

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2989.48	2989.73
02/10/98	2989.92	2990.17
03/10/98	2989.54	2989.79
04/14/98	2989.51	2989.76
05/12/98	2988.08	2988.32
06/09/98	2987.66	2987.90
07/14/98	2988.46	2988.70
08/11/98	2988.66	2988.91
09/09/98	2988.90	2989.15
10/13/98	2989.39	2989.64
11/10/98	2989.66	2989.91
12/08/98	2989.28	2989.53
01/12/99	2990.50	2990.75
02/09/99	2990.71	2990.96
03/09/99	2991.25	2991.50
04/13/99	2991.84	2992.09
05/11/99	2992.04	2992.29
06/08/99	2991.90	2992.15
07/20/99	2991.80	2992.05
08/10/99	2991.71	2991.96
09/08/99	2990.94	2991.73
10/05/99	2990.68	2990.93
11/09/99	2990.68	2990.93
12/07/99	2990.71	2990.96
01/18/00	2990.44	2990.69
02/15/00	2990.85	2991.10
03/07/00	2991.33	2991.58
04/18/00	2991.77	2992.02
05/16/00	2991.69	2991.94
06/06/00	2991.06	2991.31
07/11/00	2990.78	2991.03
08/15/00	2989.45	2989.70
09/13/00	2989.56	2989.81
10/10/00	2989.93	2990.18
11/08/00	2990.23	2990.48
12/05/00	2990.20	2990.45

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2990.90	2991.15
02/07/01	2991.81	2992.06
03/05/01	2992.19	2992.44
04/03/01	2992.95	2993.20
05/07/01	2992.99	2993.24
06/06/01	2992.82	2993.07
07/10/01	2991.39	2991.64
08/06/01	2991.11	2991.36
09/05/01	2991.47	2991.72
10/09/01	2992.03	2992.28
11/13/01	2990.59	2990.84
12/04/01	2991.31	2991.56
01/15/02	2991.84	2992.09
02/06/02	2992.67	2992.92
03/13/02	3140.35	3140.75
04/10/02	2864.06	2864.18

Figure 36 - H-9b Culebra
Historical Waterlevel Measurements

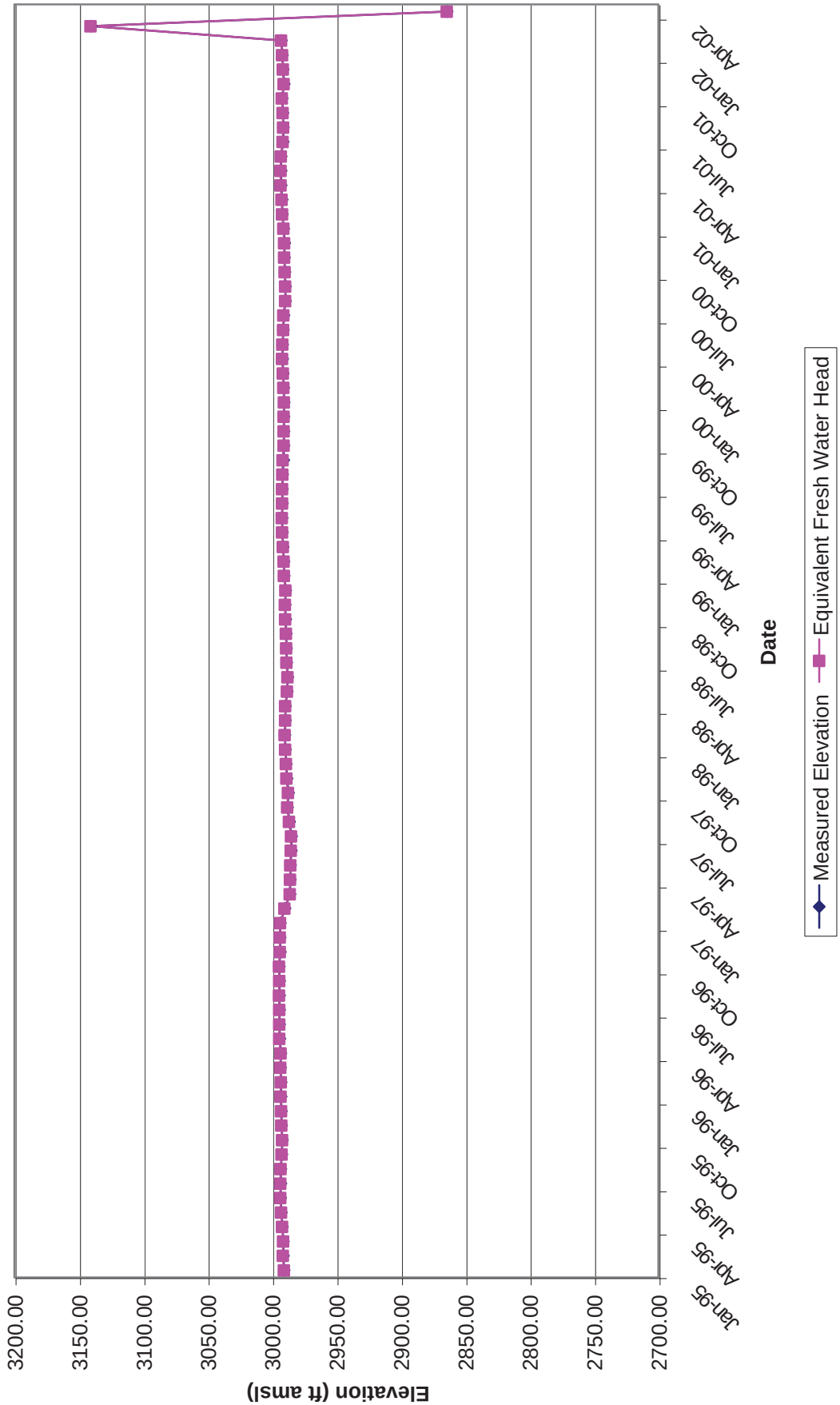

Table 37 - Well No. H-09c Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2991.02	2991.27
06/06/95	2993.18	2993.43
09/06/95	2992.16	2992.41
12/05/95	2992.56	2992.81
03/12/96	2993.21	2993.46
06/11/96	2994.00	2994.25
09/04/96	2994.05	2994.30
12/10/96	2993.60	2993.85
03/11/97	2985.86	2986.10
06/10/97	2984.92	2985.16
09/16/97	2987.88	2988.12
12/09/97	2987.85	2988.09

Date	Measured Elevation	Equivalent Fresh Water Head
03/10/98	2989.46	2989.70
06/09/98	2987.59	2987.83
09/09/98	2988.82	2989.06
12/08/98	2989.18	2989.42
03/09/99	2991.20	2991.45
06/08/99	2991.82	2992.07
09/08/99	2991.47	2991.72
12/07/99	2990.24	2990.49
03/07/00	2990.87	2991.12
06/06/00	2990.59	2990.84
09/13/00	2989.09	2989.33
12/05/00	2989.75	2990.00

Date	Measured Elevation	Equivalent Fresh Water Head
03/05/01	2991.73	2991.98
06/06/01	2992.34	2992.59
09/05/01	2991.00	2991.25
12/04/01	2992.38	2992.63

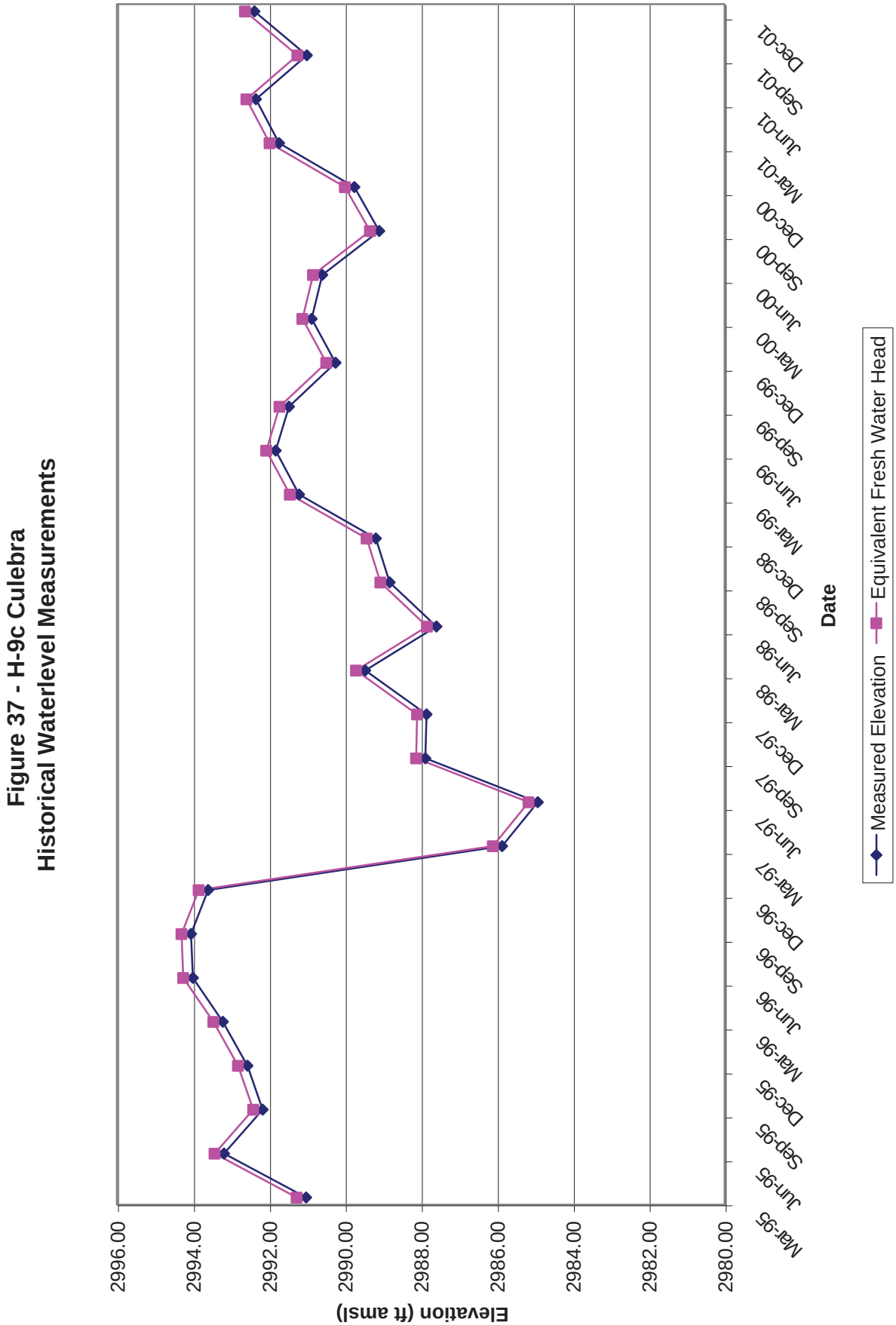
Figure 37 - H-9c Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
2996.00
2994.00
2992.00
2990.00
2988.00
2986.00
2984.00
2982.00
2980.00
Mar-95
Jun-95
Sep-95
Dec-95
Mar-96
Jun-96
Sep-96
Dec-96
Mar-97
Jun-97
Sep-97
Dec-97
Mar-98
Jun-98
Sep-98
Dec-98
Mar-99
Jun-99
Sep-99
Dec-99
Mar-00
Jun-00
Sep-00
Dec-00
Mar-01
Jun-01
Sep-01
Dec-01
Date
Measured Elevation
Equivalent Fresh Water Head

Table 38 - Well No. H-10a Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3159.77	N/A
02/14/95	3159.73	N/A
03/14/95	3159.70	N/A
04/11/95	3159.44	N/A
05/09/95	3159.73	N/A
06/06/95	3159.69	N/A
07/18/95	3159.59	N/A
08/15/95	3159.60	N/A
09/06/95	3159.43	N/A
10/17/95	3159.42	N/A
11/07/95	3159.37	N/A
12/05/95	3159.32	N/A
01/09/96	3159.25	N/A
02/06/96	3159.26	N/A
03/12/96	3159.29	N/A
04/16/96	3159.34	N/A
05/14/96	3159.31	N/A
06/11/96	3159.40	N/A
07/16/96	3159.28	N/A
08/14/96	3159.23	N/A
09/04/96	3159.35	N/A
10/15/96	3159.41	N/A
11/12/96	3159.31	N/A
12/10/96	3159.36	N/A
01/15/97	3159.36	N/A
02/11/97	3159.26	N/A
03/11/97	3159.35	N/A
04/15/97	3159.63	N/A
05/13/97	3159.63	N/A
06/11/97	3159.59	N/A
07/15/97	3159.56	N/A
08/12/97	3159.48	N/A
09/16/97	3159.50	N/A
10/14/97	3159.57	N/A
11/11/97	3159.61	N/A
12/09/97	3159.62	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	3159.65	N/A
02/10/98	3159.82	N/A
03/10/98	3159.82	N/A
04/14/98	3159.84	N/A
05/12/98	3159.82	N/A
06/09/98	3159.77	N/A
07/14/98	3159.70	N/A
08/11/98	3159.65	N/A
09/09/98	3159.65	N/A
10/13/98	3159.64	N/A
11/10/98	3159.60	N/A
12/08/98	3159.64	N/A
01/12/99	3159.66	N/A
02/09/99	3159.71	N/A
03/09/99	3159.86	N/A
04/13/99	3159.91	N/A
05/11/99	3159.97	N/A
06/08/99	3159.96	N/A
07/20/99	3159.89	N/A
08/10/99	3159.95	N/A
09/08/99	3159.98	N/A
10/05/99	3159.96	N/A
11/09/99	3159.92	N/A
12/07/99	3159.97	N/A
01/18/00	3159.97	N/A
02/15/00	3160.04	N/A
03/07/00	3160.08	N/A
04/18/00	3160.15	N/A
05/16/00	3160.18	N/A
06/06/00	3160.16	N/A
07/11/00	3160.29	N/A
08/15/00	3160.20	N/A
09/13/00	3160.20	N/A
10/10/00	3160.07	N/A
11/08/00	3160.24	N/A
12/05/00	3160.18	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3160.28	N/A
02/07/01	3160.26	N/A
03/07/01	3160.59	N/A
04/04/01	3160.75	N/A
05/07/01	3160.82	N/A
06/06/01	3161.18	N/A
07/11/01	3161.76	N/A
08/06/01	3162.04	N/A
09/05/01	3162.13	N/A
10/09/01	3162.16	N/A
11/13/01	3162.08	N/A
12/04/01	3162.18	N/A
01/15/02	3162.08	N/A
02/06/02	3204.00	N/A
03/13/02	3219.79	N/A
04/10/02	3220.33	N/A
05/06/02	3220.32	N/A
06/11/02	3220.20	N/A
07/16/02	3219.99	N/A
08/13/02	3219.97	N/A
09/11/02	3219.92	N/A

Figure 38 - H-10a Magenta
Historical Waterlevel Measurements

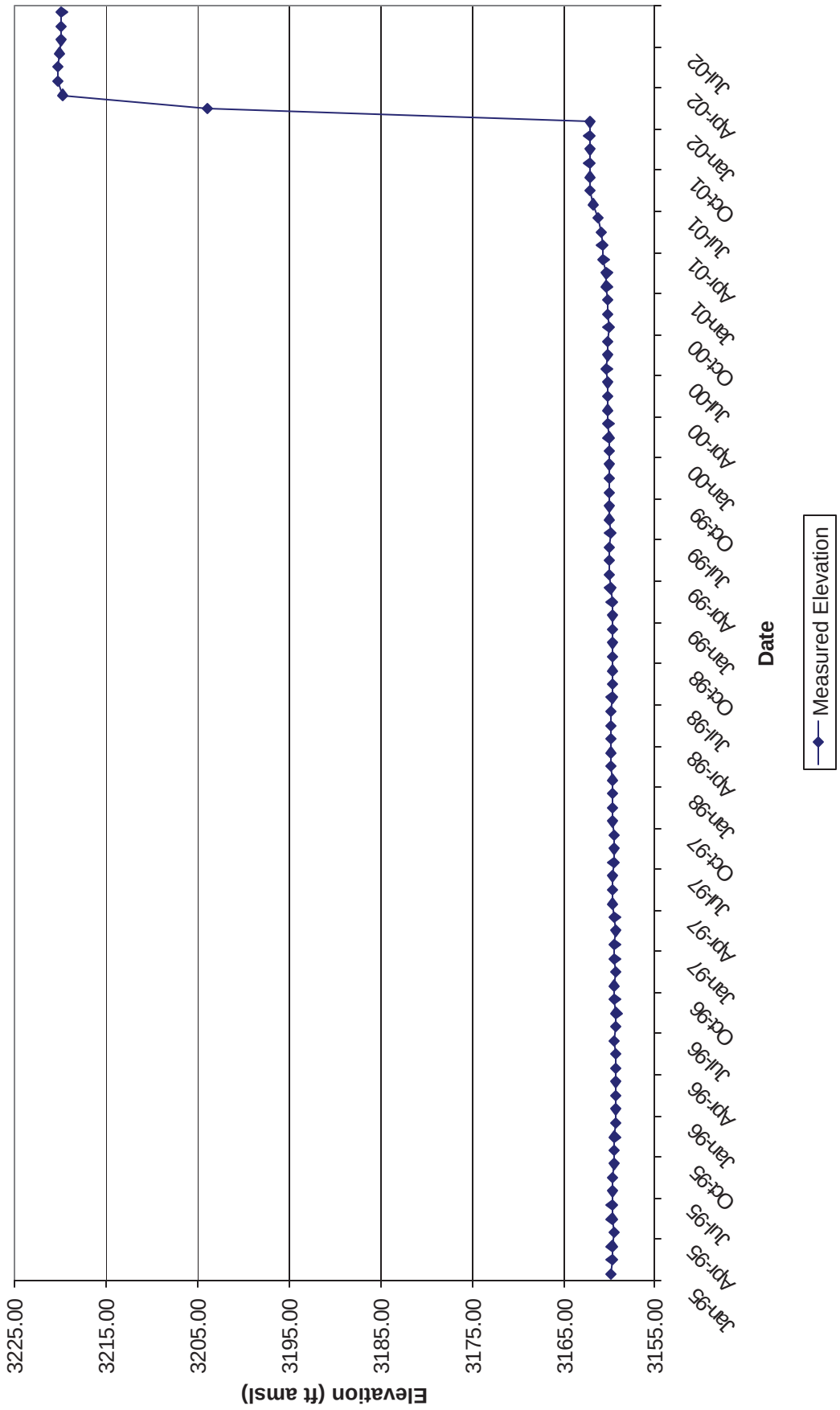

Table 39 - Well No. H-10b Culebra
January 1995 through January 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2992.12	3024.11
02/14/95	2992.15	3024.14
03/14/95	2992.08	3024.07
04/11/95	2992.01	3023.99
05/09/95	2992.39	3024.39
06/06/95	2992.45	3024.45
07/18/95	2992.42	3024.42
08/15/95	2992.67	3024.68
09/06/95	2992.48	3024.49
10/17/95	2992.74	3024.76
11/07/95	2992.75	3024.77
12/05/95	2992.83	3024.85
01/09/96	2992.79	3024.81
02/06/96	2992.76	3024.78
03/12/96	2992.96	3024.99
04/16/96	2992.96	3024.99
05/14/96	2993.15	3025.19
06/11/96	2993.47	3025.52
07/16/96	2993.57	3025.63
08/14/96	2993.53	3025.58
09/04/96	2993.74	3025.80
10/15/96	2993.81	3025.88
11/12/96	2993.73	3025.79
12/10/96	2993.88	3025.95
01/15/97	2993.91	3025.98
02/11/97	2993.77	3025.84
03/11/97	2993.87	3025.94
04/15/97	2994.12	3026.20
05/13/97	2994.25	3026.34
06/11/97	2994.28	3026.37
07/15/97	2994.31	3026.40
08/12/97	2994.40	3026.50
09/16/97	2994.61	3026.72
10/14/97	2994.60	3026.71
11/11/97	2994.78	3026.89
12/09/97	2994.94	3027.06

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2994.86	3026.98
02/10/98	2994.98	3027.10
03/10/98	2994.61	3026.72
04/14/98	2994.80	3026.91
05/12/98	2994.76	3026.87
06/09/98	2994.58	3026.68
07/14/98	2994.38	3026.47
08/11/98	2994.26	3026.35
09/09/98	2994.30	3026.39
10/13/98	2994.18	3026.27
11/10/98	2994.27	3026.36
12/08/98	2994.19	3026.28
01/12/99	2994.26	3026.35
02/09/99	2994.15	3026.23
03/09/99	2994.22	3026.31
04/13/99	2994.12	3026.20
05/11/99	2994.18	3026.27
06/08/99	2994.04	3026.12
07/20/99	2993.81	3025.88
08/10/99	2993.93	3026.00
09/08/99	2993.87	3025.94
10/05/99	2993.66	3025.72
11/09/99	2993.76	3025.83
12/07/99	2993.79	3025.86
01/18/00	2993.62	3025.68
02/15/00	2993.68	3025.74
03/07/00	2993.76	3025.83
04/18/00	2993.74	3025.80
05/16/00	2993.76	3025.83
06/06/00	2993.63	3025.69
07/11/00	2993.98	3026.06
08/15/00	2994.18	3026.27
09/13/00	2994.30	3026.39
10/10/00	2994.05	3026.13
11/08/00	2994.50	3026.60
12/05/00	2994.49	3026.59

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2994.87	3026.99
02/07/01	2994.90	3027.02
03/07/01	2994.83	3026.95
04/04/01	2994.98	3027.10
05/07/01	2995.03	3027.16
06/06/01	2995.40	3027.54
07/11/01	2995.25	3027.39
08/06/01	2995.17	3027.30
09/05/01	2995.01	3027.13
10/09/01	2994.87	3026.99
11/13/01	2994.67	3026.78
12/04/01	2994.70	3026.81
01/15/02	2994.44	3026.54

Figure 39 - H-10b Culebra
Historical Waterlevel Meausrements

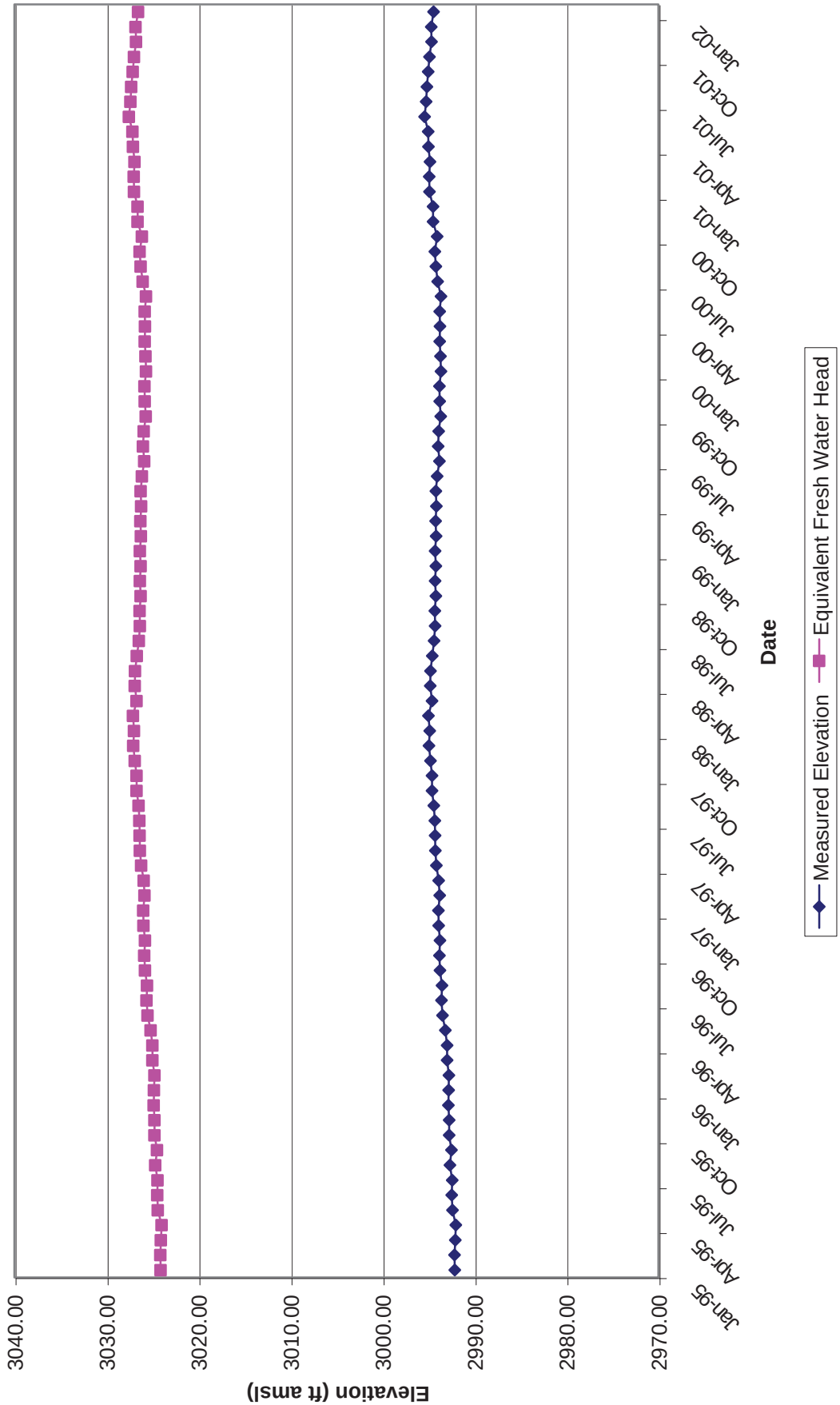

Table 40 - Well No. H-10c Culebra
June 2002 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/02	3026.95	N/A
07/16/02	3026.34	N/A
08/13/02	3026.08	N/A
09/11/02	3026.32	N/A

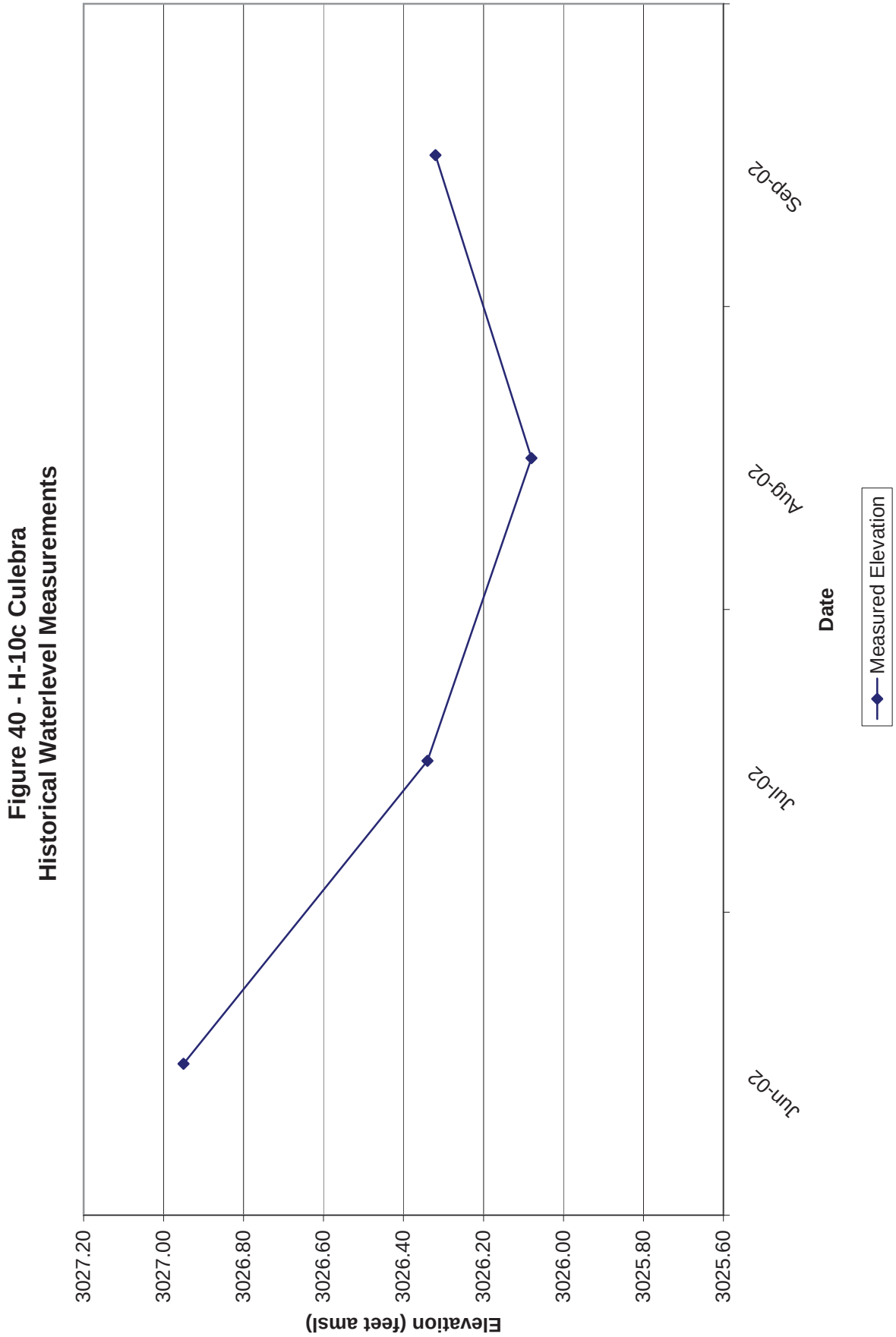
Figure 40 - H-10c Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3027.20
3027.00
3026.80
3026.60
3026.40
3026.20
3026.00
3025.80
3025.60
Jun-02
Jul-02
Aug-02
Sep-02
Date
Measured Elevation

Table 41 - Well No. H-11b1 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2978.88	3001.89
06/06/95	2978.88	3001.89
12/05/95	2975.87	2998.65
03/12/96	2901.78	2919.08
06/11/96	2970.45	2992.83
09/04/96	2975.77	2998.54
12/10/96	2977.74	3000.66
03/11/97	2977.86	3000.79
06/11/97	2976.78	2999.63
09/16/97	2977.01	2999.88
12/09/97	2977.94	3000.88

Date	Measured Elevation	Equivalent Fresh Water Head
03/10/98	2978.55	3001.53
06/09/98	2978.50	3001.48
09/09/98	2978.69	3001.68
12/08/98	2978.77	3001.77
03/09/99	2979.43	3002.48
06/08/99	2979.45	3002.50
09/08/99	2979.37	3002.41
12/07/99	2979.74	3002.81
03/07/00	2979.64	3002.70
06/06/00	2980.13	3003.23
09/13/00	2980.05	3003.14
12/05/00	2980.08	3003.17

Date	Measured Elevation	Equivalent Fresh Water Head
03/07/01	2980.57	3003.70
06/06/01	2981.20	3004.38
09/05/01	2981.32	3004.50
12/03/01	2981.23	3004.41
06/11/02	2992.41	3016.42
09/12/02	2992.59	3016.61

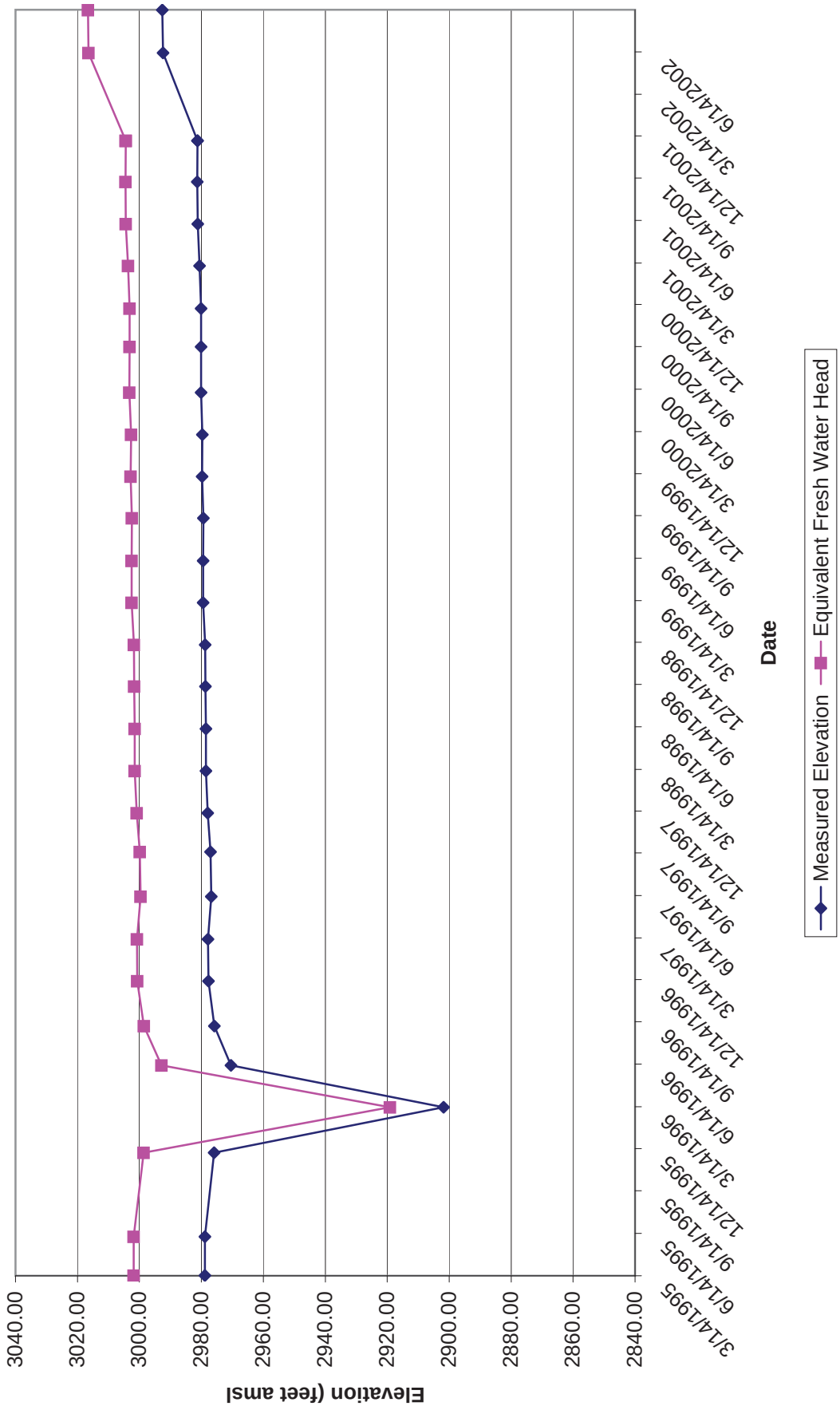
Figure 41 - H-11b1 Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
2880.00
2860.00
2840.00
3/14/1995
6/14/1995
9/14/1995
12/14/1995
3/14/1996
6/14/1996
9/14/1996
12/14/1996
3/14/1997
6/14/1997
9/14/1997
12/14/1997
3/14/1998
6/14/1998
9/14/1998
12/14/1998
3/14/1999
6/14/1999
9/14/1999
12/14/1999
3/14/2000
6/14/2000
9/14/2000
12/14/2000
3/14/2001
6/14/2001
9/14/2001
12/14/2001
3/14/2002
6/14/2002
Date
Measured Elevation
Equivalent Fresh Water Head

Table 42 - Well No. H-11b2 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2978.83	3002.59
02/14/95	2979.16	3002.94
03/14/95	2978.43	3002.16
04/11/95	2978.79	3002.55
05/09/95	2978.95	3002.72
06/06/95	2977.76	3001.44
07/19/95	2971.80	2995.03
08/16/95	2955.96	2977.98
09/07/95	2968.80	2991.80
10/18/95	2973.64	2997.01
11/07/95	2974.26	2997.67
12/05/95	2975.26	2998.75
01/08/96	2965.94	2988.72
02/01/96	2966.66	2989.49
03/12/96	2941.58	2962.51
04/16/96	2959.87	2982.19
05/14/96	2967.55	2990.45
06/11/96	2971.03	2994.20
07/16/96	2973.56	2996.92
08/13/96	2975.27	2998.76
09/04/96	2976.07	2999.62
10/16/96	2976.91	3000.52
11/12/96	2977.21	3000.85
12/10/96	2977.91	3001.60
01/15/97	2978.34	3002.06
02/11/97	2978.46	3002.19
03/11/97	2977.96	3001.65
04/15/97	2977.40	3001.05
05/14/97	2977.27	3000.91
06/11/97	2976.97	3000.59
07/15/97	2976.43	3000.01
08/12/97	2976.65	3000.24
09/16/97	2977.03	3000.65
10/15/97	2977.06	3000.69
11/11/97	2977.69	3001.36
12/09/97	2978.01	3001.71

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2978.16	3001.87
02/10/98	2978.57	3002.31
03/10/98	2978.47	3002.20
04/14/98	2979.42	3003.22
05/12/98	2978.74	3002.49
06/09/98	2978.44	3002.17
07/14/98	2978.48	3002.21
08/11/98	2978.57	3002.31
09/09/98	2978.68	3002.43
10/13/98	2978.62	3002.36
11/10/98	2978.82	3002.58
12/08/98	2978.81	3002.57
03/09/99	2979.41	3003.21
06/08/99	2979.93	3003.77
09/08/99	2980.14	3004.00
12/07/99	2980.13	3003.99
03/07/00	2980.02	3003.87
06/06/00	2979.93	3003.77
09/13/00	2980.02	3003.87
12/05/00	2980.09	3003.94
03/05/01	2980.05	3003.90

Figure 42 - H-11b2 Culebra
Historical Waterlevel Measurements

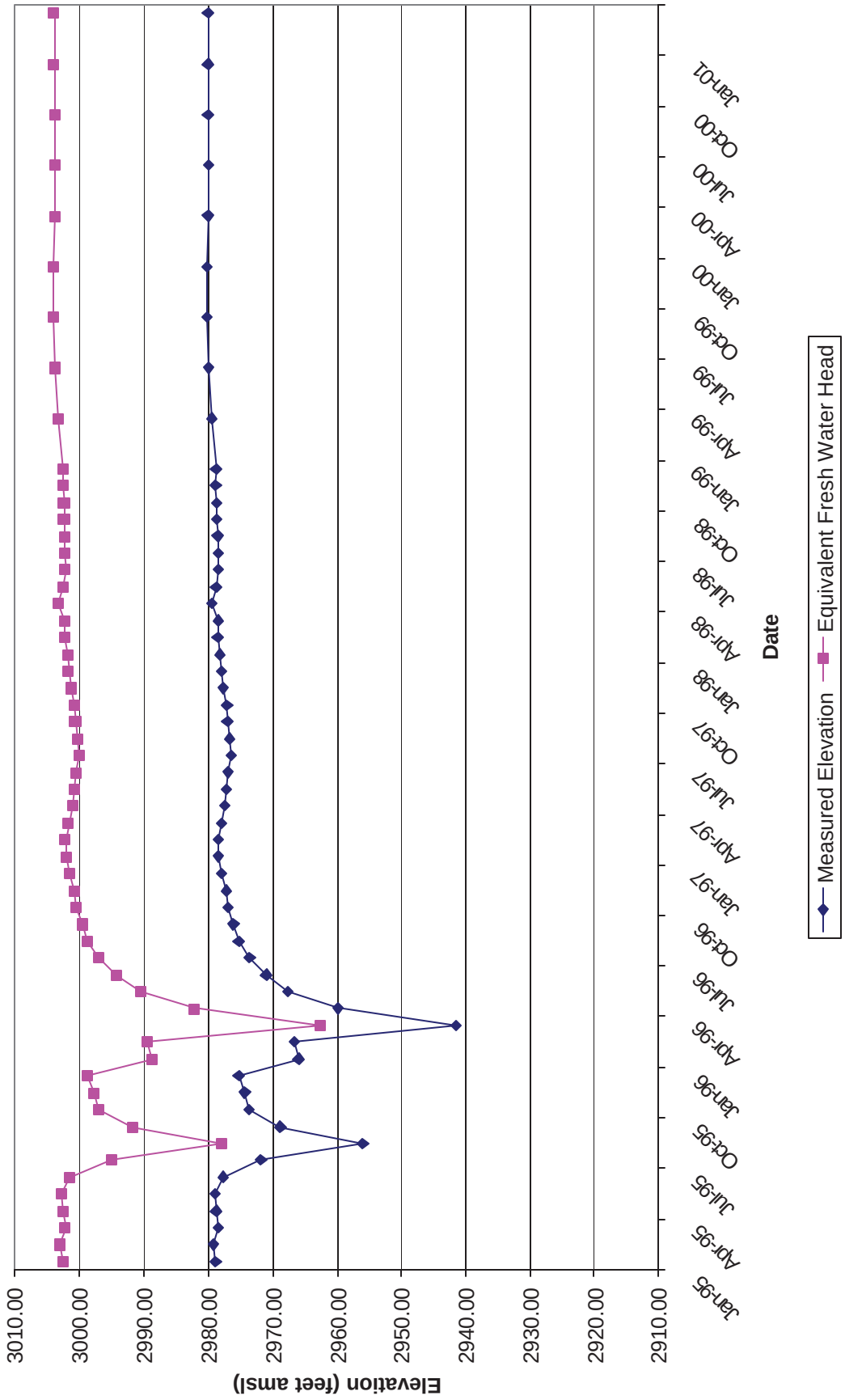

Table 43 - Well No. H-11b2 Magenta
June 2001 through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
06/06/01	3127.40	N/A
07/10/01	3127.48	N/A
09/11/01	3127.34	N/A
10/03/01	3127.52	N/A
11/12/01	3127.48	N/A
12/03/01	3127.59	N/A

Figure 43 - H-11b2 Magenta
Historical Waterlevel Measurements

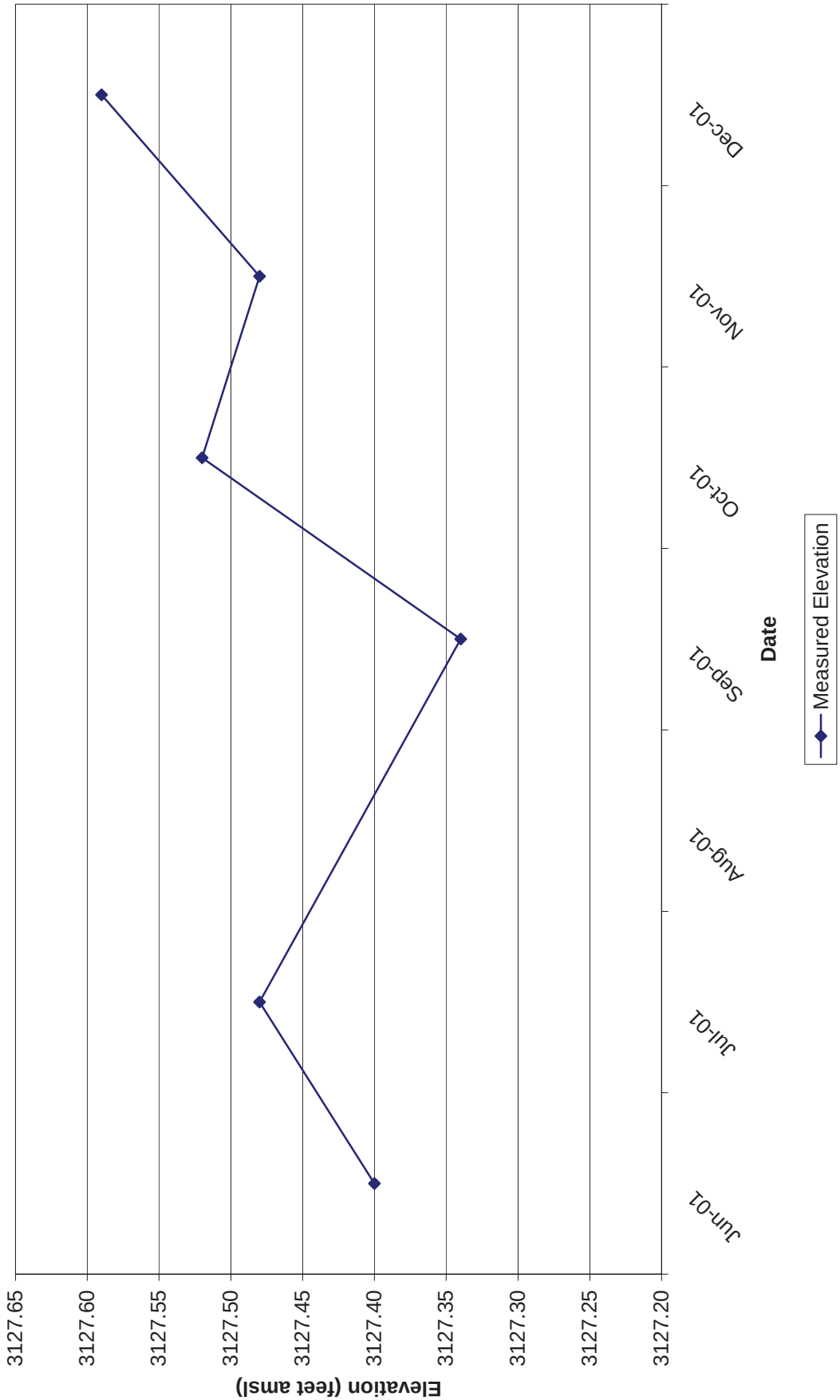

Table 44 - Well No. H-11b3 Culebra
March 1995 through March 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2978.76	3003.51
06/06/95	2978.11	3002.81
09/07/95	2968.58	2992.52
12/05/95	2975.46	2999.95
03/12/96	2941.43	2963.23
06/11/96	2970.61	2994.71
09/04/96	2975.71	3000.22
12/10/96	2977.60	3002.26
03/11/97	2977.66	3002.32
06/11/97	2976.54	3001.11
09/16/97	2976.67	3001.25
12/09/97	2977.77	3002.44

Date	Measured Elevation	Equivalent Fresh Water Head
03/10/98	2978.24	3002.95
06/09/98	2978.21	3002.91
09/09/98	2978.42	3003.14
12/08/98	2978.58	3003.31
03/09/99	2979.37	3004.16
06/08/99	2979.86	3004.69
09/08/99	2979.83	3004.66
12/07/99	2979.86	3004.69
03/07/00	2979.81	3004.64
06/06/00	2979.90	3004.73
09/13/00	2979.80	3004.63
12/05/00	2979.88	3004.71

Date	Measured Elevation	Equivalent Fresh Water Head
03/07/01	2980.21	3005.07
06/06/01	2980.86	3005.77
09/05/01	2980.69	3005.59
12/03/01	2980.87	3005.78
03/13/02	2980.52	3005.40

Figure 44 - H-11b3 Culebra
Historical Waterlevel Measurements

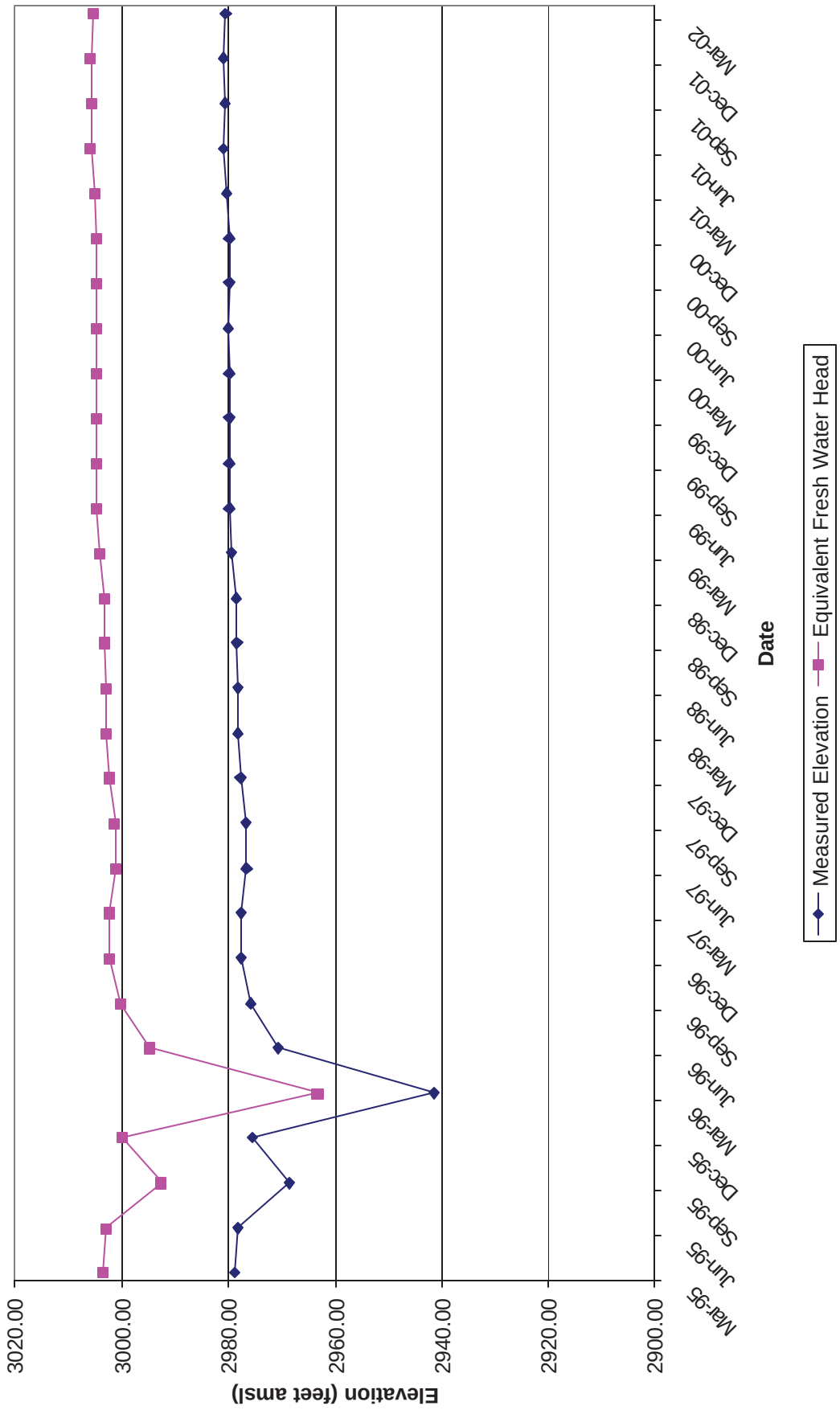

Table 45 - Well No. H-11b4 Culebra
August 1998 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
08/11/98	2981.88	3001.80
09/09/98	2982.06	3002.00
10/13/98	2982.04	3001.97
11/10/98	2982.23	3002.18
12/08/98	2982.23	3002.18
01/11/99	2982.74	3002.72
02/09/99	2982.70	3002.68
03/09/99	2983.01	3003.01
04/13/99	2983.30	3003.32
05/11/99	2983.28	3003.30
06/08/99	2983.53	3003.56
07/20/99	2983.49	3003.52
08/10/99	2983.66	3003.70
09/08/99	2983.58	3003.61
10/05/99	2983.42	3003.44
11/09/99	2983.42	3003.44
12/07/99	2983.57	3003.60
01/18/00	2983.22	3003.23
02/15/00	2983.40	3003.42
03/07/00	2983.50	3003.53
04/18/00	2983.53	3003.56
05/16/00	2983.72	3003.76
06/06/00	2983.51	3003.54
07/11/00	2983.77	3003.82
08/15/00	2983.59	3003.63
09/13/00	2983.53	3003.56
10/11/00	2982.99	3002.99
11/09/00	2983.61	3003.65
12/05/00	2983.61	3003.65

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2983.77	3003.82
02/05/01	2983.82	3003.87
03/07/01	2983.98	3004.04
04/05/01	2984.33	3004.41
05/09/01	2984.43	3004.52
06/06/01	2984.64	3004.74
07/10/01	2984.67	3004.78
08/07/01	2984.39	3004.48
09/05/01	2984.47	3004.56
10/09/01	2984.64	3004.74
11/12/01	2984.48	3004.57
12/03/01	2984.65	3004.75
01/15/02	2984.54	3004.64
02/05/02	2984.70	3004.81
03/13/02	2976.57	2996.15
04/10/02	2982.96	3002.95
05/06/02	2983.46	3003.49
06/11/02	2983.84	3003.89
07/16/02	2983.91	3003.97
08/14/02	2984.05	3004.12
09/12/02	2984.09	3004.16

Figure 45 - H-11b4 Culebra
Historical Waterlevel Measurements

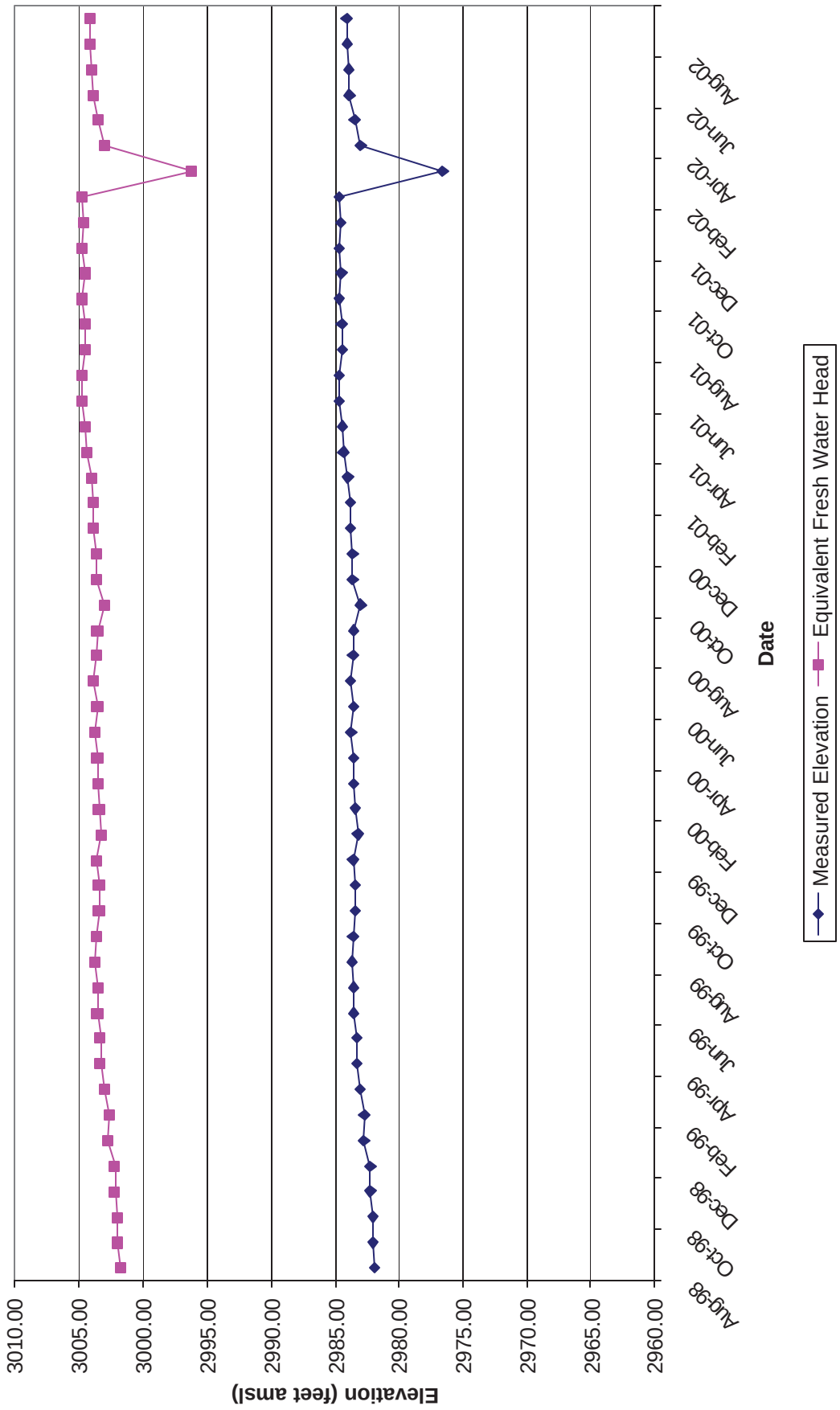

Table 46 - Well No. H-12 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2969.58	3006.83
02/14/95	2969.54	3006.79
03/14/95	2969.64	3006.90
04/11/95	2969.34	3006.57
05/09/95	2969.70	3006.96
06/06/95	2969.83	3007.10
07/18/95	2969.70	3006.96
08/16/95	2969.84	3007.12
09/06/95	2969.62	3006.87
10/17/95	2969.58	3006.83
11/07/95	2969.86	3007.14
12/05/95	2969.54	3006.79
01/09/96	2969.41	3006.64
02/06/96	2969.37	3006.60
03/11/96	2969.40	3006.63
04/16/96	2969.07	3006.27
05/14/96	2969.08	3006.28
06/11/96	2969.41	3006.64
07/16/96	2969.29	3006.51
08/14/96	2969.44	3006.68
09/04/96	2969.60	3006.85
10/15/96	2969.70	3006.96
11/12/96	2969.76	3007.03
12/10/96	2969.85	3007.13
01/15/97	2969.86	3007.14
02/11/97	2969.82	3007.09
03/11/97	2969.84	3007.12
04/15/97	2969.73	3006.99
05/13/97	2969.64	3006.90
06/11/97	2969.57	3006.82
07/15/97	2969.01	3006.20
08/12/97	2968.99	3006.18
09/16/97	2968.85	3006.03
10/14/97	2968.70	3005.86
11/11/97	2968.87	3006.05
12/09/97	2969.05	3006.25

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2969.00	3006.19
02/10/98	2969.30	3006.52
03/10/98	2969.05	3006.25
04/14/98	2969.48	3006.72
05/12/98	2969.54	3006.79
06/09/98	2969.47	3006.71
07/14/98	2969.36	3006.59
08/11/98	2969.30	3006.52
09/09/98	2969.40	3006.63
10/13/98	2969.32	3006.54
11/10/98	2969.44	3006.68
12/08/98	2969.37	3006.60
01/12/99	2969.60	3006.85
02/09/99	2969.67	3006.93
03/09/99	2969.80	3007.07
04/13/99	2969.86	3007.14
05/11/99	2969.99	3007.28
06/08/99	2969.90	3007.18
07/20/99	2969.82	3007.09
08/10/99	2970.08	3007.38
09/08/99	2969.86	3007.14
10/05/99	2969.66	3006.92
11/09/99	2969.60	3006.85
12/07/99	2969.58	3006.83
01/18/00	2969.44	3006.68
02/15/00	2969.48	3006.72
03/07/00	2969.53	3006.77
04/18/00	2969.42	3006.65
05/16/00	2969.45	3006.69
06/06/00	2969.35	3006.58
07/11/00	2969.44	3006.68
08/15/00	2969.31	3006.53
09/13/00	2969.31	3006.53
10/10/00	2969.00	3006.19
11/08/00	2969.24	3006.46
12/05/00	2968.94	3006.13

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2969.14	3006.35
02/07/01	2969.16	3006.37
03/07/01	2969.17	3006.38
04/04/01	2969.39	3006.62
05/07/01	2969.38	3006.61
06/06/01	2969.63	3006.88
07/10/01	2969.56	3006.81
08/07/01	2969.49	3006.73
09/05/01	2970.55	3007.89
10/09/01	2969.58	3006.83
11/13/01	2969.55	3006.80
12/04/01	2969.63	3006.88
01/15/02	2969.62	3006.87
02/06/02	2969.69	3006.95
03/13/02	2970.07	3007.37
04/10/02	2969.93	3007.21
05/06/02	2970.19	3007.50
06/11/02	2970.38	3007.71
07/16/02	2970.29	3007.61
08/13/02	2970.78	3008.15
09/11/02	2970.50	3007.84

Figure 46 - H-12 Culebra
Historical Waterlevel Measurements

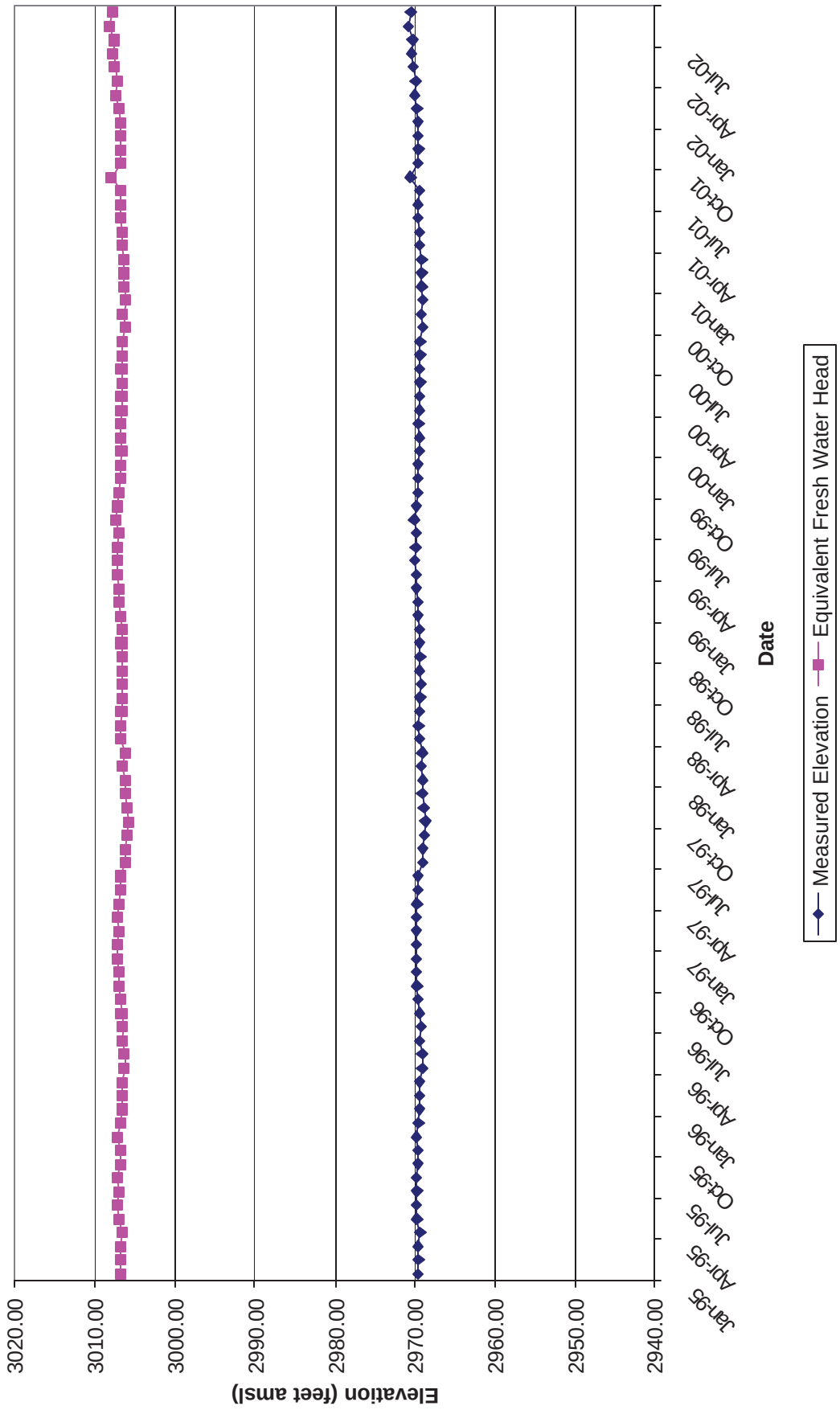

Table 47 - Well No. H14 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3009.19	3012.07
02/15/95	3009.51	3012.39
03/14/95	3009.42	3012.30
04/11/95	3009.36	3012.24
05/09/95	3009.63	3012.51
06/07/95	3009.71	3012.59
07/19/95	3008.44	3011.31
08/17/95	3007.78	3010.64
09/07/95	3006.89	3009.74
10/19/95	2999.41	3002.16
11/08/95	3004.20	3007.01
12/06/95	3004.78	3007.60
01/10/96	3004.46	3007.27
02/07/96	3003.99	3006.80
03/14/96	3000.27	3003.03
04/17/96	2998.79	3001.53
05/14/96	2998.05	3000.78
06/12/96	2998.13	3000.86
07/16/96	2997.21	2999.93
08/14/96	2998.83	3001.57
09/04/96	2999.93	3002.69
10/15/96	3000.31	3003.07
11/13/96	3001.37	3004.14
12/10/96	3002.69	3005.48
01/15/97	3003.69	3006.49
02/11/97	3004.31	3007.12
03/12/97	3004.95	3007.77
04/14/97	3004.33	3007.14
05/14/97	3005.50	3008.33
06/11/97	3005.84	3008.67
07/16/97	3005.00	3007.82
08/12/97	3005.66	3008.49
09/16/97	3006.14	3008.98
10/15/97	3006.14	3008.98
11/12/97	3006.61	3009.45
12/10/97	3006.75	3009.59

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3007.03	3009.88
02/11/98	3007.28	3010.13
03/12/98	3007.15	3010.00
04/16/98	3007.75	3010.61
05/12/98	3007.91	3010.77
06/11/98	3006.90	3009.75
07/14/98	3006.44	3009.28
08/12/98	3007.66	3010.52
09/10/98	3007.83	3010.69
10/13/98	3007.91	3010.77
11/13/98	3007.31	3010.16
12/09/98	3007.68	3010.54
01/12/99	3008.20	3011.06
02/10/99	3008.31	3011.17
03/10/99	3008.55	3011.42
04/13/99	3008.73	3011.60
05/10/99	3008.91	3011.78
06/09/99	3008.37	3011.23
07/21/99	3008.63	3011.50
08/11/99	3008.93	3011.80
09/08/99	3009.01	3011.88
10/04/99	3008.99	3011.86
11/10/99	3008.45	3011.32
12/08/99	3008.98	3011.85
01/19/00	3009.20	3012.08
02/15/00	3009.31	3012.19
03/06/00	3009.42	3012.30
04/17/00	3009.44	3012.32
05/17/00	3008.93	3011.80
06/07/00	3008.96	3011.83
07/12/00	3009.48	3012.36
08/14/00	3009.52	3012.40
09/11/00	3009.68	3012.56
10/10/00	3009.48	3012.36
11/08/00	3009.79	3012.67
12/06/00	3008.98	3011.85

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3009.53	3012.41
02/05/01	3009.40	3012.28
03/08/01	3009.63	3012.51

Figure 47 - H-14 Culebra
Historical Waterlevel Measurements

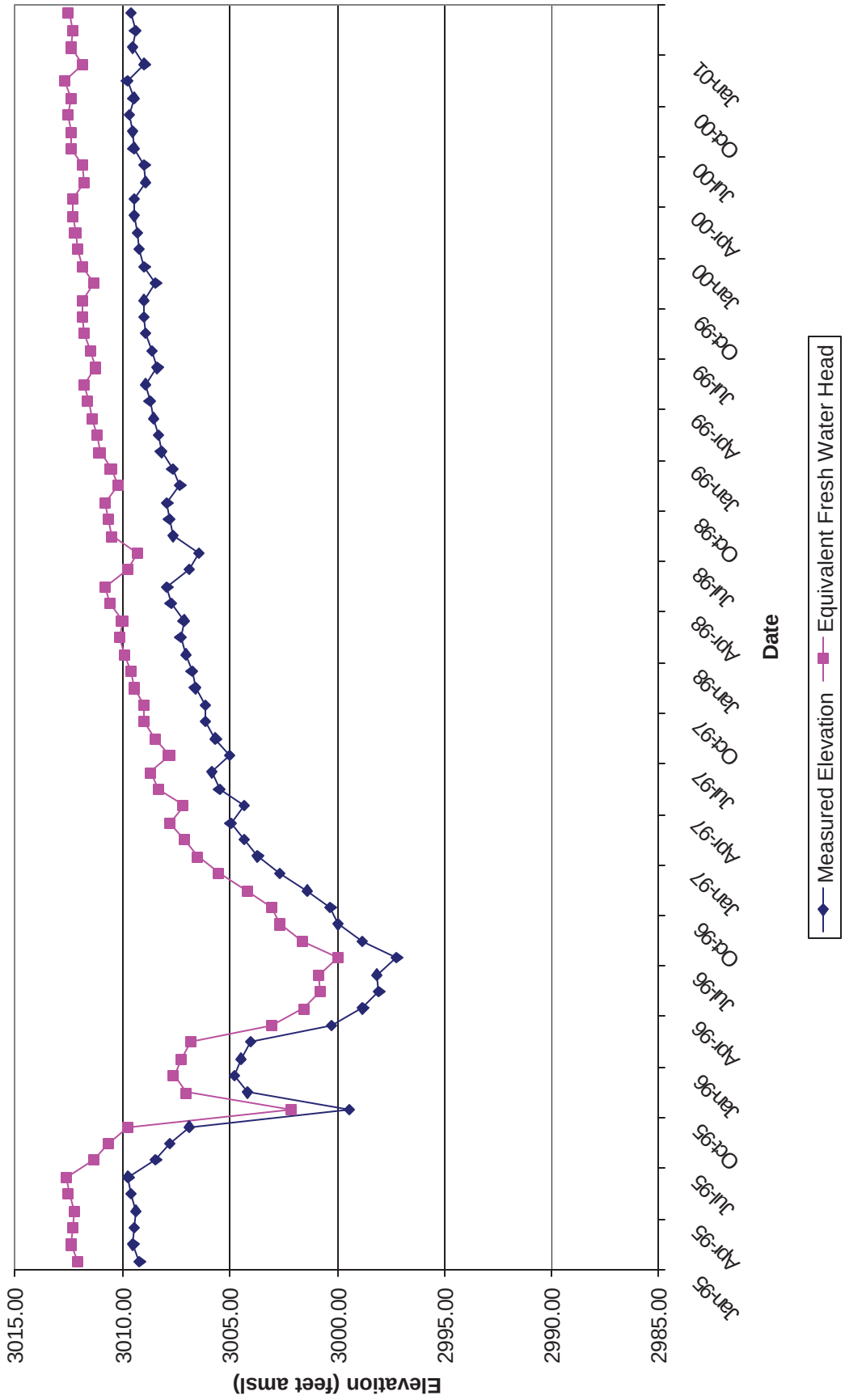

Table 48 - Well No. H-14 Magenta
April 2001through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
04/05/01	3106.99	N/A
05/09/01	3035.07	N/A
06/06/01	3049.31	N/A
07/11/01	3065.32	N/A
09/12/01	3090.39	N/A
10/03/01	3096.00	N/A
11/12/01	3101.86	N/A
12/03/01	3102.47	N/A

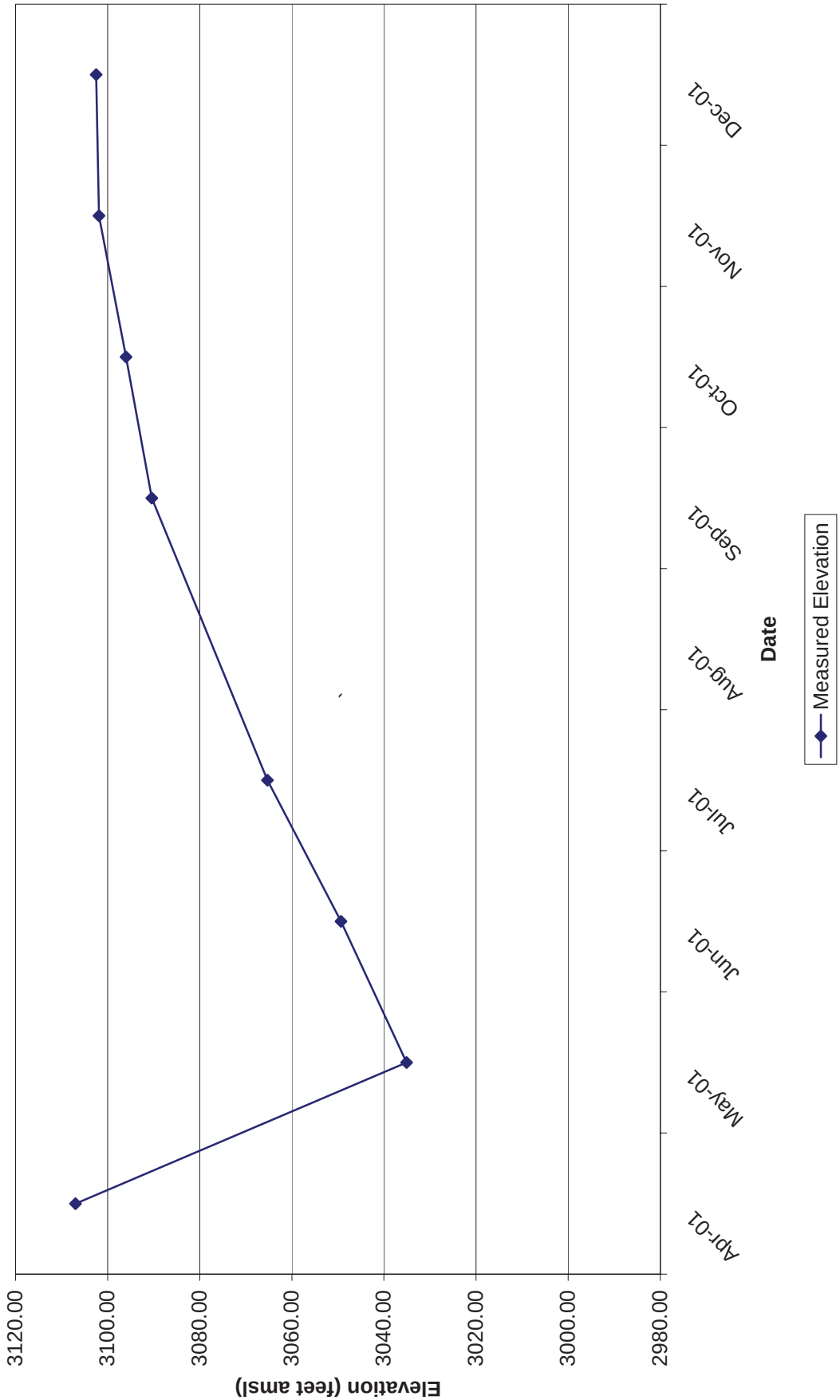
Figure 48 - H-14 Magenta
Historical Waterlevel Measurements
Elevation (feet amsl)
3120.00
3100.00
3080.00
3060.00
3040.00
3020.00
3000.00
2980.00
Apr-01
May-01
Jun-01
Jul-01
Aug-01
Sep-01
Oct-01
Nov-01
Dec-01
Date
Measured Elevation

Table 49 - Well No. H-15 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	2959.70	3012.57
02/15/95	2959.92	3012.82
03/13/95	2959.26	3012.06
04/11/95	2959.18	3011.97
05/09/95	2959.73	3012.60
06/07/95	2959.29	3012.09
07/19/95	2953.98	3005.98
08/17/95	2949.50	3000.82
09/05/95	2945.94	2996.73
10/18/95	2947.36	2998.36
11/08/95	2949.85	3001.23
12/04/95	2951.30	3002.90
01/09/96	2949.09	3000.35
02/05/96	2943.71	2994.16
03/11/96	2932.70	2981.49
04/15/96	2928.45	2976.60
05/15/96	2934.49	2983.55
06/10/96	2939.32	2989.11
07/16/96	2944.10	2994.61
08/12/96	2946.92	2997.86
09/04/96	2948.96	3000.20
10/16/96	2951.26	3002.85
11/13/96	2952.42	3004.19
12/10/96	2953.72	3005.68
01/13/97	2954.75	3006.87
02/12/97	2955.62	3007.87
03/12/97	2956.23	3008.57
04/16/97	2956.70	3009.11
05/14/97	2957.01	3009.47
06/12/97	2957.10	3009.57
07/16/97	2957.03	3009.49
08/13/97	2957.11	3009.58
09/16/97	2957.50	3010.03
10/15/97	2957.60	3010.15
11/12/97	2957.95	3010.55
12/10/97	2958.25	3010.90

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2958.63	3011.33
02/12/98	2959.02	3011.78
03/12/98	2959.06	3011.83
04/16/98	2959.65	3012.51
05/13/98	2959.74	3012.61
06/11/98	2959.64	3012.50
07/15/98	2959.67	3012.53
08/12/98	2959.72	3012.59
09/10/98	2959.92	3012.82
10/14/98	2959.97	3012.88
11/13/98	2960.01	3012.92
12/09/98	2960.15	3013.08
01/13/99	2960.44	3013.42
02/10/99	2960.58	3013.58
03/10/99	2960.88	3013.92
04/13/99	2961.03	3014.10
05/11/99	2961.20	3014.29
06/09/99	2961.26	3014.36
07/21/99	2961.31	3014.42
08/11/99	2961.55	3014.69
09/08/99	2961.60	3014.75
10/04/99	2961.59	3014.74
11/10/99	2961.51	3014.65
12/08/99	2961.62	3014.78
01/19/00	2961.59	3014.74
02/15/00	2961.70	3014.87
03/08/00	2961.77	3014.95
04/18/00	2961.83	3015.02
05/17/00	2961.90	3015.10
06/07/00	2961.79	3014.97
07/10/00	2962.00	3015.21
08/14/00	2961.98	3015.19
09/11/00	2962.10	3015.33
10/11/00	2961.88	3015.07
11/08/00	2962.05	3015.27
12/06/00	2961.86	3015.05

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	2962.01	3015.22
02/05/01	2961.90	3015.10
03/05/01	2962.22	3015.47

Figure 49 - H-15 Culebra
Historical Waterlevel Measurements

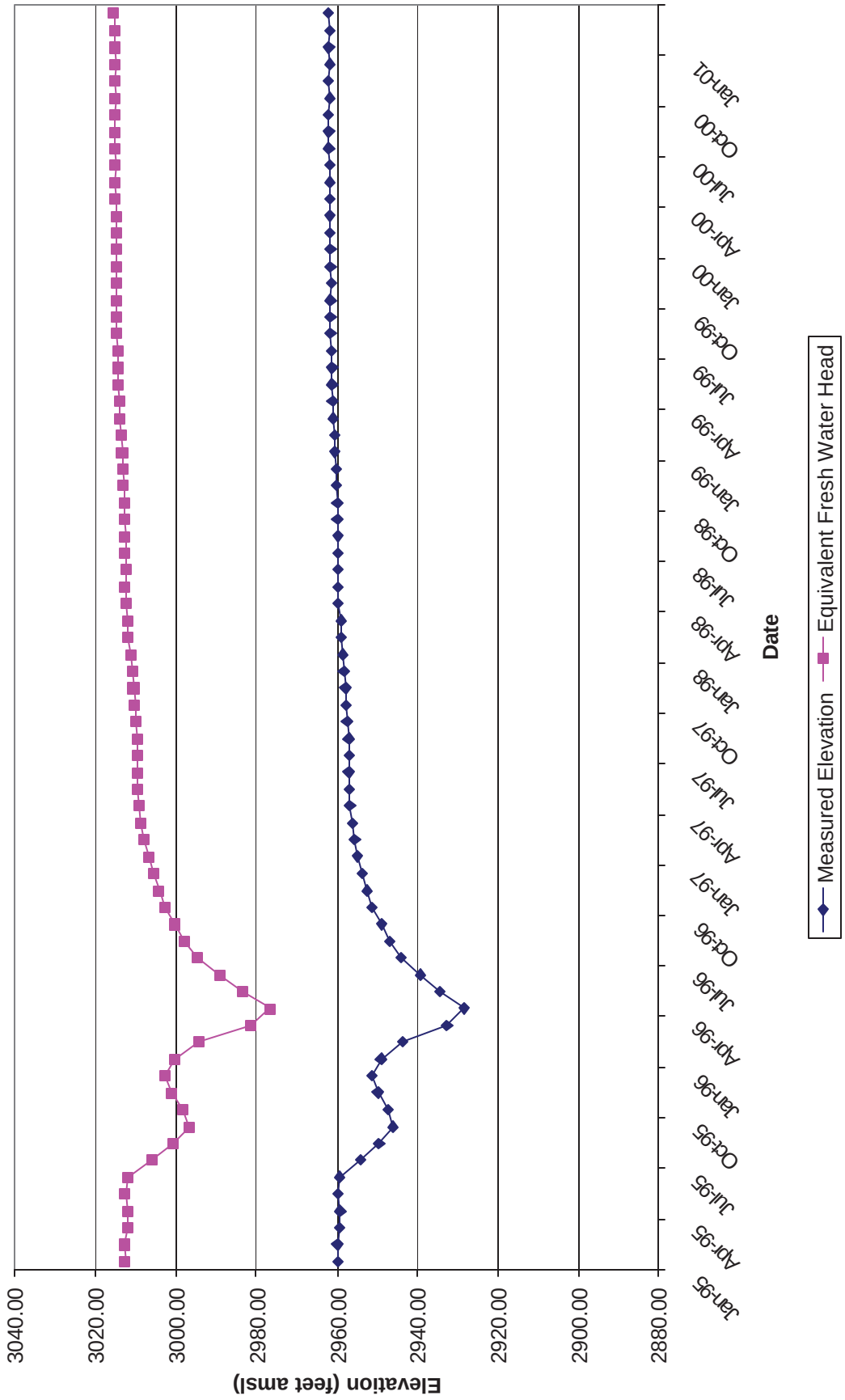

Table 50 - Well No. H-15 Magenta
April 2001through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
04/06/01	3098.69	N/A
05/08/01	3112.21	N/A
06/07/01	3112.59	N/A
07/11/01	3113.04	N/A
09/12/01	3112.86	N/A
10/03/01	3113.53	N/A
11/12/01	3112.95	N/A
12/03/01	3113.00	N/A

Figure 50 - H-15 Magenta
Historical Waterlevel Measurements

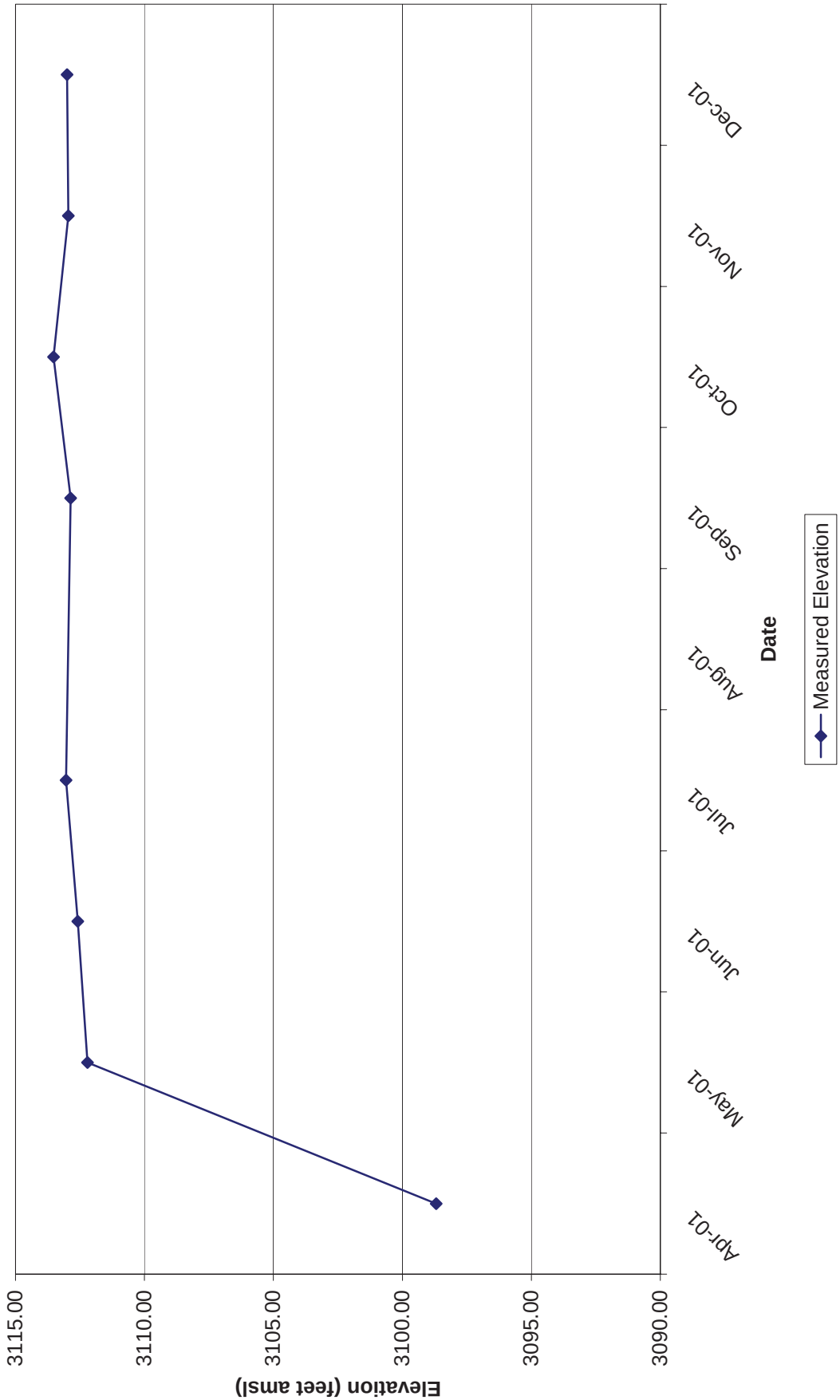

Table 51 - Well No. H-16 (PVC) Los Medanos Member
January 1995 through July 2000

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3050.51	N/A
02/15/95	3050.42	N/A
03/15/95	3050.04	N/A
04/12/95	3049.42	N/A
05/10/95	3049.06	N/A
06/07/95	3048.61	N/A
07/20/95	3048.12	N/A
08/17/95	3047.98	N/A
09/08/95	3047.93	N/A
10/19/95	3048.47	N/A
11/09/95	3048.56	N/A
12/06/95	3048.57	N/A
01/11/96	3048.07	N/A
02/07/96	3047.46	N/A
03/14/96	3046.26	N/A
04/18/96	3044.88	N/A
05/15/96	3044.09	N/A
06/13/96	3043.66	N/A
07/17/96	3043.21	N/A
08/15/96	3043.15	N/A
09/06/96	3043.26	N/A
10/17/96	3045.16	N/A
11/13/96	3046.57	N/A
12/11/96	3047.67	N/A
01/16/97	3048.25	N/A
02/12/97	3048.15	N/A
03/13/97	3047.76	N/A
04/16/97	3047.05	N/A
05/15/97	3046.35	N/A
06/12/97	3045.78	N/A
07/16/97	3045.35	N/A
08/14/97	3045.25	N/A
09/17/97	3045.47	N/A
10/16/97	3046.01	N/A
11/13/97	3046.43	N/A
12/11/97	3046.63	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/15/98	3046.57	N/A
02/12/98	3046.29	N/A
03/12/98	3045.64	N/A
04/16/98	3044.59	N/A
05/13/98	3043.77	N/A
06/11/98	3042.97	N/A
07/15/98	3042.49	N/A
08/12/98	3042.31	N/A
09/11/98	3042.01	N/A
10/15/98	3043.03	N/A
11/13/98	3043.60	N/A
12/09/98	3043.98	N/A
01/13/99	3004.10	N/A
02/10/99	3044.06	N/A
03/10/99	3043.72	N/A
04/14/99	3042.85	N/A
05/12/99	3042.14	N/A
06/10/99	3041.43	N/A
07/21/99	3041.59	N/A
08/11/99	3041.71	N/A
09/09/99	3042.63	N/A
10/06/99	3043.49	N/A
11/10/99	3044.21	N/A
12/09/99	3045.14	N/A
01/20/00	3045.50	N/A
02/16/00	3045.42	N/A
03/08/00	3045.23	N/A
04/19/00	3043.82	N/A
05/17/00	3043.38	N/A
06/08/00	3043.23	N/A
07/12/00	3044.71	N/A

Figure 51 - H-16 Los Medanos Member Historical Waterlevel Measurements

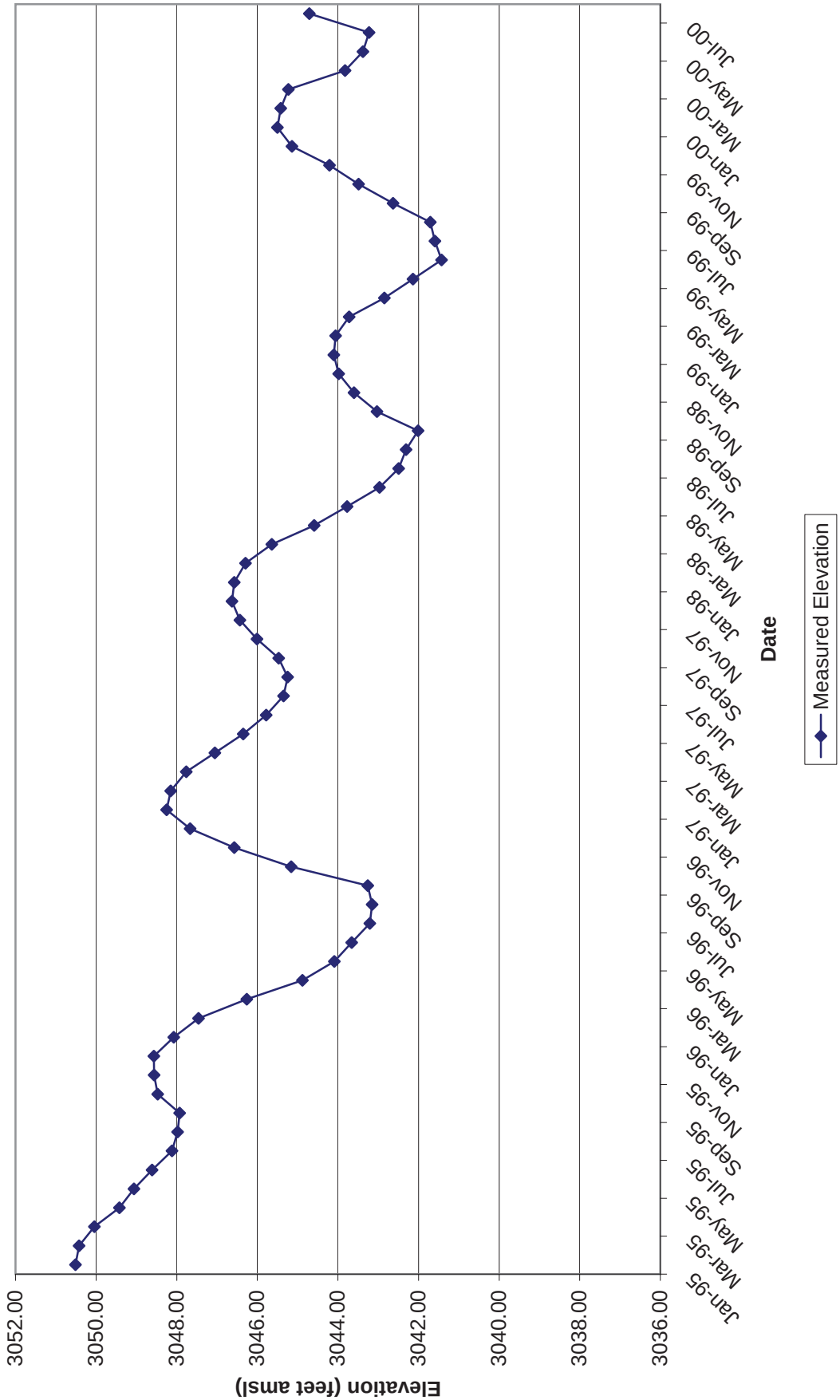

Table 52 - Well No. H-16 (PVC) Dewey Lake
January 1995 through July 2000

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3352.32	N/A
02/15/95	3351.33	N/A
03/15/95	3350.28	N/A
04/12/95	3349.27	N/A
05/10/95	3348.34	N/A
06/07/95	3347.37	N/A
07/20/95	3345.76	N/A
08/17/95	3344.77	N/A
09/08/95	3343.98	N/A
10/19/95	3342.52	N/A
11/09/95	3341.77	N/A
12/06/95	3340.69	N/A
01/11/96	3339.45	N/A
02/07/96	3338.52	N/A
03/14/96	3337.20	N/A
04/18/96	3336.00	N/A
05/15/96	3335.11	N/A
06/13/96	3334.05	N/A
07/17/96	3332.62	N/A
08/15/96	3331.78	N/A
09/06/96	3331.14	N/A
10/17/96	3329.61	N/A
11/13/96	3328.77	N/A
12/11/96	3327.91	N/A
01/16/97	3326.66	N/A
02/12/97	3325.76	N/A
03/13/97	3324.76	N/A
04/16/97	3323.65	N/A
05/15/97	3322.74	N/A
06/12/97	3321.86	N/A
07/16/97	3320.73	N/A
08/14/97	3320.06	N/A
09/17/97	3318.67	N/A
10/16/97	3317.74	N/A
11/13/97	3316.62	N/A
12/11/97	3315.94	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/15/98	3314.85	N/A
02/12/98	3313.95	N/A
03/12/98	3313.05	N/A
04/16/98	3311.94	N/A
05/13/98	3311.10	N/A
06/11/98	3310.18	N/A
07/15/98	3309.07	N/A
08/12/98	3308.07	N/A
09/11/98	3307.14	N/A
10/15/98	3306.13	N/A
11/13/98	3305.22	N/A
12/09/98	3304.45	N/A
01/13/99	3303.43	N/A
02/10/99	3302.61	N/A
03/10/99	3301.84	N/A
04/14/99	3300.91	N/A
05/12/99	3300.11	N/A
06/10/99	3299.58	N/A
07/21/99	3332.85	N/A
08/11/99	3332.33	N/A
09/09/99	3331.42	N/A
10/06/99	3330.59	N/A
11/10/99	3329.50	N/A
12/09/99	3328.61	N/A
01/20/00	3327.31	N/A
02/16/00	3326.49	N/A
03/08/00	3325.84	N/A
04/19/00	3324.55	N/A
05/17/00	3322.77	N/A
06/08/00	3323.03	N/A
07/12/00	3405.95	N/A

Figure 52 - H-16 Dewey Lake Historical Waterlevel Measurements

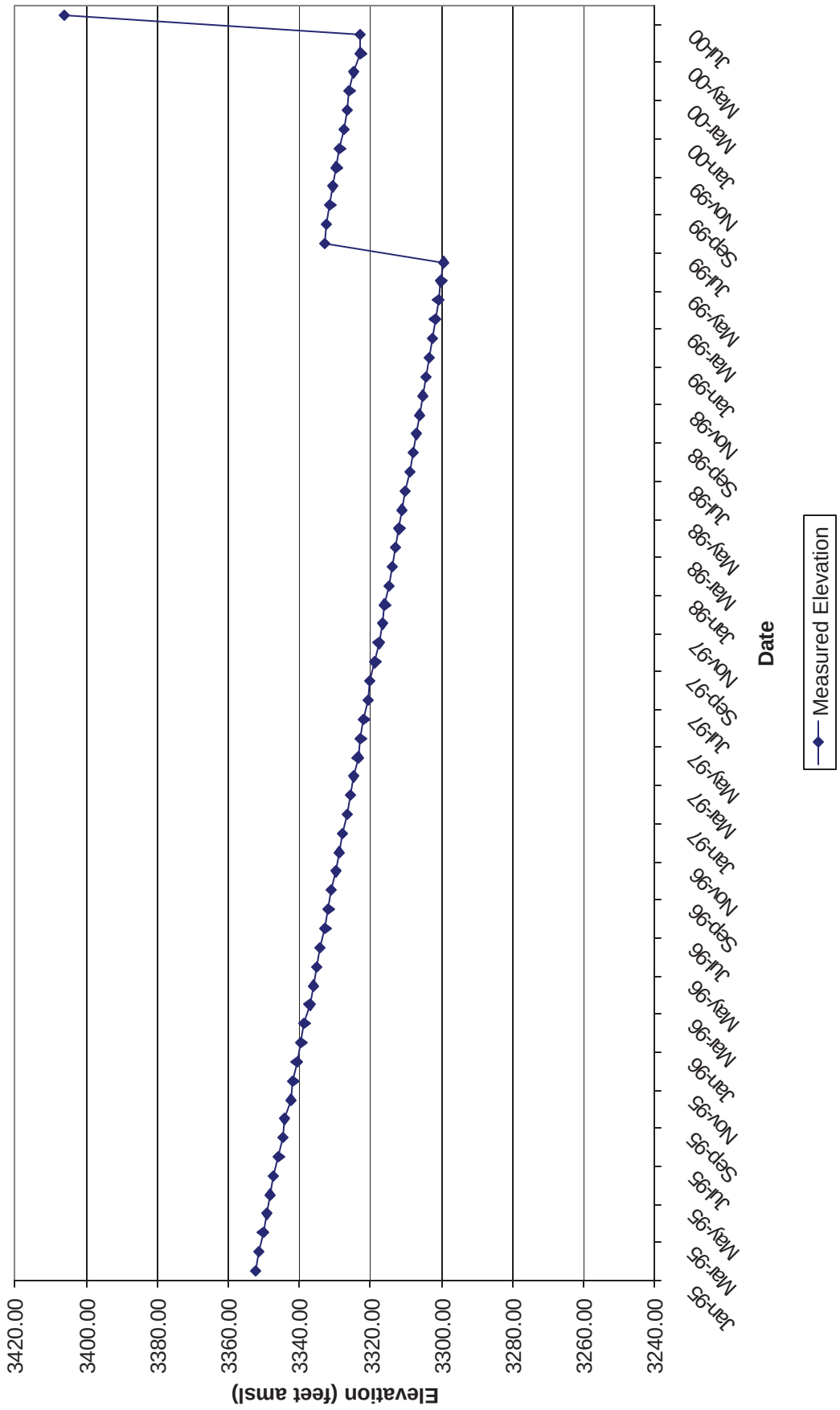

Table 53 - Well No. H-17 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2956.74	3005.00
02/14/95	2956.96	3005.26
03/14/95	2956.90	3005.19
04/11/95	2957.00	3005.30
05/09/95	2957.48	3005.86
06/06/95	2957.61	3006.02
07/19/95	2956.58	3004.81
08/16/95	2955.80	3003.91
09/07/95	2953.77	3001.54
10/18/95	2955.41	3003.45
11/07/95	2955.69	3003.78
12/05/95	2956.08	3004.23
01/09/96	2955.47	3003.52
02/06/96	2954.60	3002.51
03/12/96	2950.18	2997.35
04/16/96	2949.30	2996.33
05/14/96	2952.14	2999.64
06/11/96	2954.02	3001.83
07/16/96	2955.41	3003.45
08/13/96	2956.38	3004.58
09/04/96	2956.84	3005.12
10/16/96	2957.36	3005.72
11/12/96	2957.58	3005.98
12/10/96	2957.98	3006.45
01/15/97	2958.24	3006.75
02/11/97	2958.27	3006.79
03/11/97	2958.08	3006.56
04/15/97	2957.58	3005.98
05/14/97	2957.40	3005.77
06/11/97	2957.14	3005.47
07/15/97	2956.84	3005.12
08/12/97	2956.82	3005.09
09/16/97	2957.10	3005.42
10/15/97	2957.20	3005.54
11/11/97	2957.53	3005.92
12/09/97	2957.88	3006.33

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2958.10	3006.59
02/10/98	2958.47	3007.02
03/10/98	2958.45	3007.00
04/14/98	2958.91	3007.53
05/12/98	2958.97	3007.60
06/10/98	2958.74	3007.33
07/14/98	2958.68	3007.26
08/11/98	2958.71	3007.30
09/09/98	2958.86	3007.47
10/13/98	2958.89	3007.51
11/10/98	2959.08	3007.73
12/08/98	2959.08	3007.73
01/12/99	2959.34	3008.13
02/09/99	2959.48	3008.29
03/09/99	2959.76	3008.62
04/13/99	2959.93	3008.82
05/11/99	2960.17	3009.10
06/08/99	2960.26	3009.20
07/20/99	2960.28	3009.23
08/10/99	2960.45	3009.42
09/08/99	2960.50	3009.48
10/05/99	2960.33	3009.29
11/09/99	2960.31	3009.26
12/07/99	2960.39	3009.36
01/18/00	2960.24	3009.18
02/15/00	2960.41	3009.38
03/07/00	2960.52	3009.51
04/18/00	2960.58	3009.58
05/16/00	2960.71	3009.73
06/06/00	2960.66	3009.67
07/11/00	2960.82	3009.86
08/15/00	2960.72	3009.74
09/13/00	2960.71	3009.73
10/11/00	2960.53	3009.52
11/09/00	2960.82	3009.86
12/05/00	2960.56	3009.55

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2960.85	3009.89
02/05/01	2960.79	3009.82
03/07/01	2961.12	3010.21
04/05/01	2961.46	3010.60
05/09/01	2961.52	3010.67
06/06/01	2961.90	3011.12
07/11/01	2961.90	3011.12
08/07/01	2961.74	3010.93
09/05/01	2961.77	3010.96
10/09/01	2961.72	3010.91
11/13/01	2961.87	3011.08
12/04/01	2961.97	3011.20
01/15/02	2962.03	3011.27
02/05/02	2962.11	3011.36
03/13/02	2962.62	3011.96
04/10/02	2962.36	3011.65
05/07/02	2962.71	3012.06
06/11/02	2962.99	3012.39
07/16/02	2962.95	3012.34
08/14/02	2963.12	3012.54
09/12/02	2963.07	3012.48

Figure 53 - H-17 Culebra
Historical Waterlevel Measurements

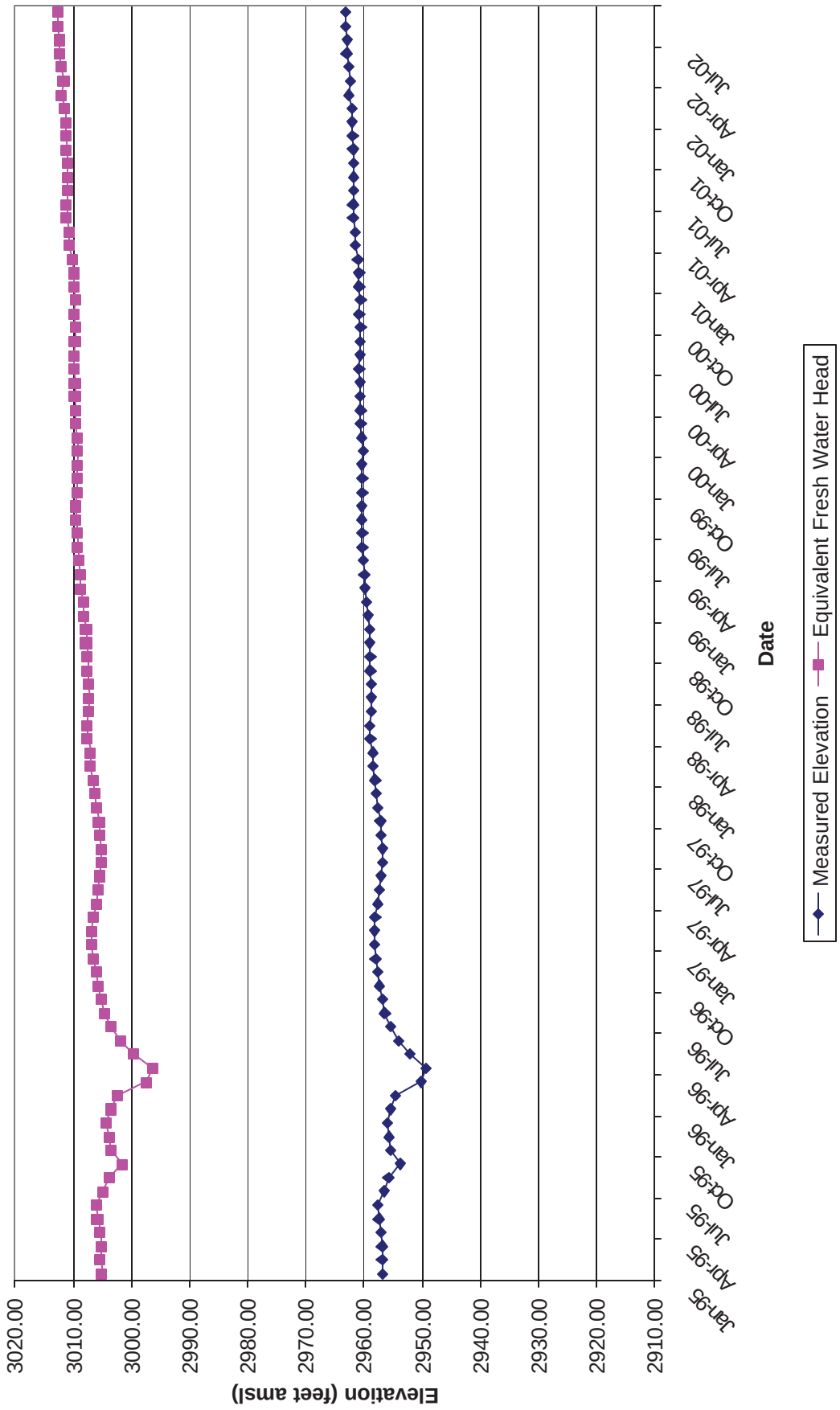

Table 54 - Well No. H18 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3055.91	3071.07
02/13/95	3055.85	3071.01
03/13/95	3055.86	3071.02
04/10/95	3053.81	3068.88
05/08/95	3056.41	3071.59
06/05/95	3056.66	3071.85
07/17/95	3056.80	3072.00
08/14/95	3056.99	3072.20
09/05/95	3056.22	3071.39
10/16/95	3056.83	3072.03
11/06/95	3057.26	3072.48
12/04/95	3057.16	3072.38
01/08/96	3057.11	3072.32
02/05/96	3055.86	3071.02
03/11/96	3056.23	3071.40
04/15/96	3056.11	3071.28
05/13/96	3056.70	3071.89
06/10/96	3057.00	3072.21
07/15/96	3057.16	3072.38
08/12/96	3056.91	3072.11
09/03/96	3057.38	3072.60
10/14/96	3057.52	3072.75
11/11/96	3057.18	3072.40
12/09/96	3057.47	3072.70
01/13/97	3057.53	3072.76
02/10/97	3057.63	3072.87
03/10/97	3057.85	3073.10
04/14/97	3058.12	3073.38
05/13/97	3058.14	3073.40
06/09/97	3058.44	3073.71
07/16/97	3058.68	3073.96
08/11/97	3058.58	3073.86
09/15/97	3058.59	3073.87
10/13/97	3058.27	3073.53
11/10/97	3058.18	3073.44
12/08/97	3057.74	3072.98

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3057.70	3072.94
02/09/98	3059.82	3075.15
03/09/98	3060.43	3075.79
04/15/98	3060.59	3075.96
05/11/98	3060.11	3075.46
06/10/98	3059.64	3074.96
07/15/98	3059.13	3074.43
08/11/98	3059.41	3074.72
09/10/98	3059.25	3074.56
10/14/98	3059.06	3074.36
11/11/98	3058.88	3074.17
12/07/98	3058.81	3074.10
01/11/99	3058.90	3074.13
02/09/99	3059.24	3074.49
03/09/99	3059.25	3074.50
04/12/99	3059.19	3074.44
05/10/99	3058.53	3073.79
06/07/99	3059.42	3074.68
07/19/99	3059.23	3074.48
08/09/99	3059.27	3074.52
09/08/99	3059.11	3074.35
10/04/99	3059.12	3074.36
11/08/99	3059.44	3074.70
12/09/99	3059.51	3074.77
01/19/00	3059.90	3075.18
02/14/00	3059.93	3075.21
03/06/00	3060.00	3075.28
04/17/00	3059.91	3075.19
05/15/00	3059.89	3075.17
06/05/00	3059.65	3074.92
07/10/00	3059.81	3075.08
08/14/00	3059.74	3075.01
09/12/00	3059.61	3074.88
10/09/00	3059.25	3074.50
11/06/00	3059.92	3075.20
12/07/00	3059.60	3074.87

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3059.66	3074.93
02/05/01	3059.70	3074.97
03/06/01	3059.61	3074.88

Figure 54 - H-18 Culebra
Historical Waterlevel Measurements

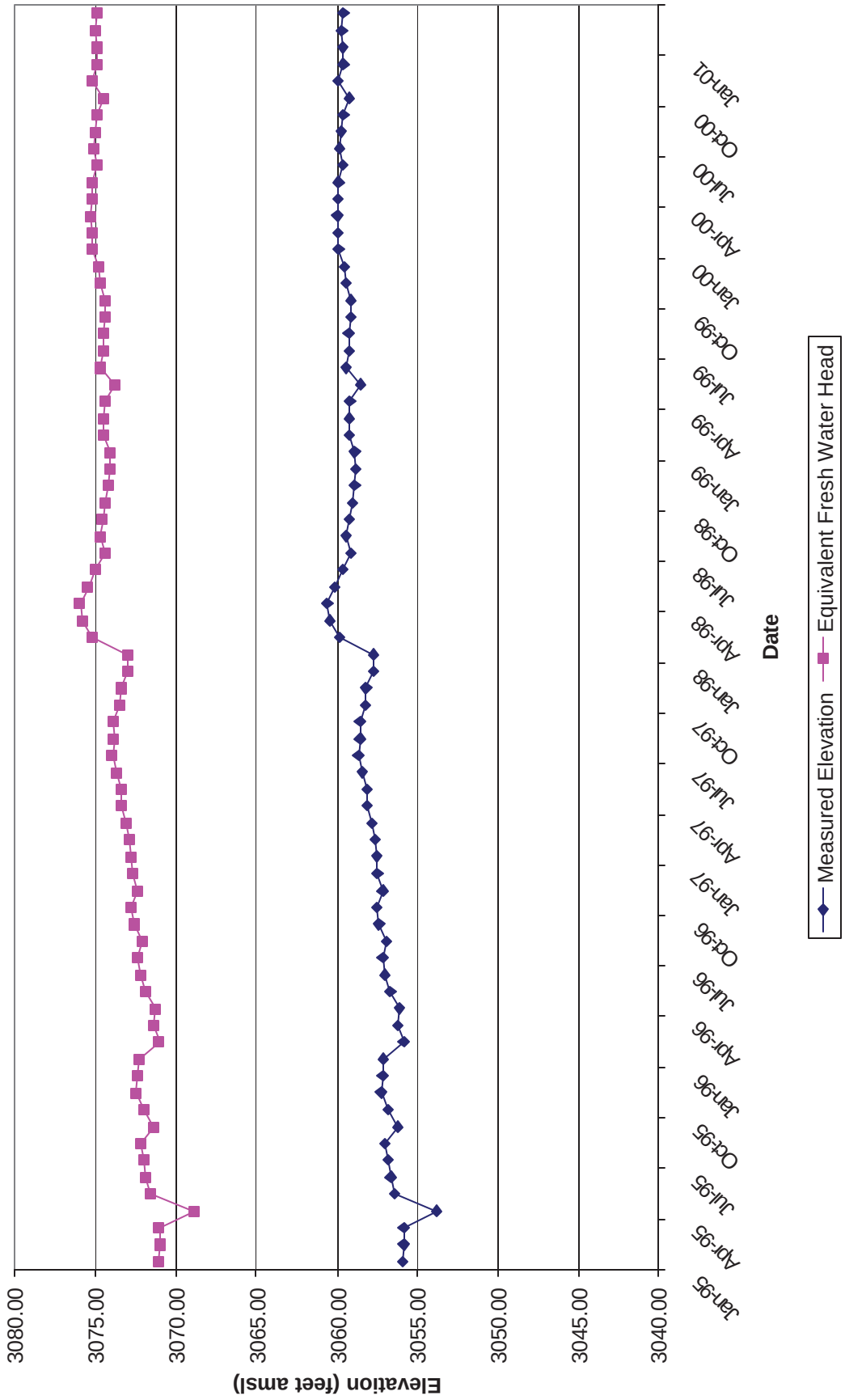

Table 55 - Well No. H-18 Magenta
April 2001through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
04/04/01	2939.73	N/A
05/08/01	3078.59	N/A
06/05/01	3078.42	N/A
07/09/01	3078.12	N/A
09/12/01	3077.34	N/A
10/03/01	3077.36	N/A
11/12/01	3077.17	N/A
12/03/01	3077.25	N/A

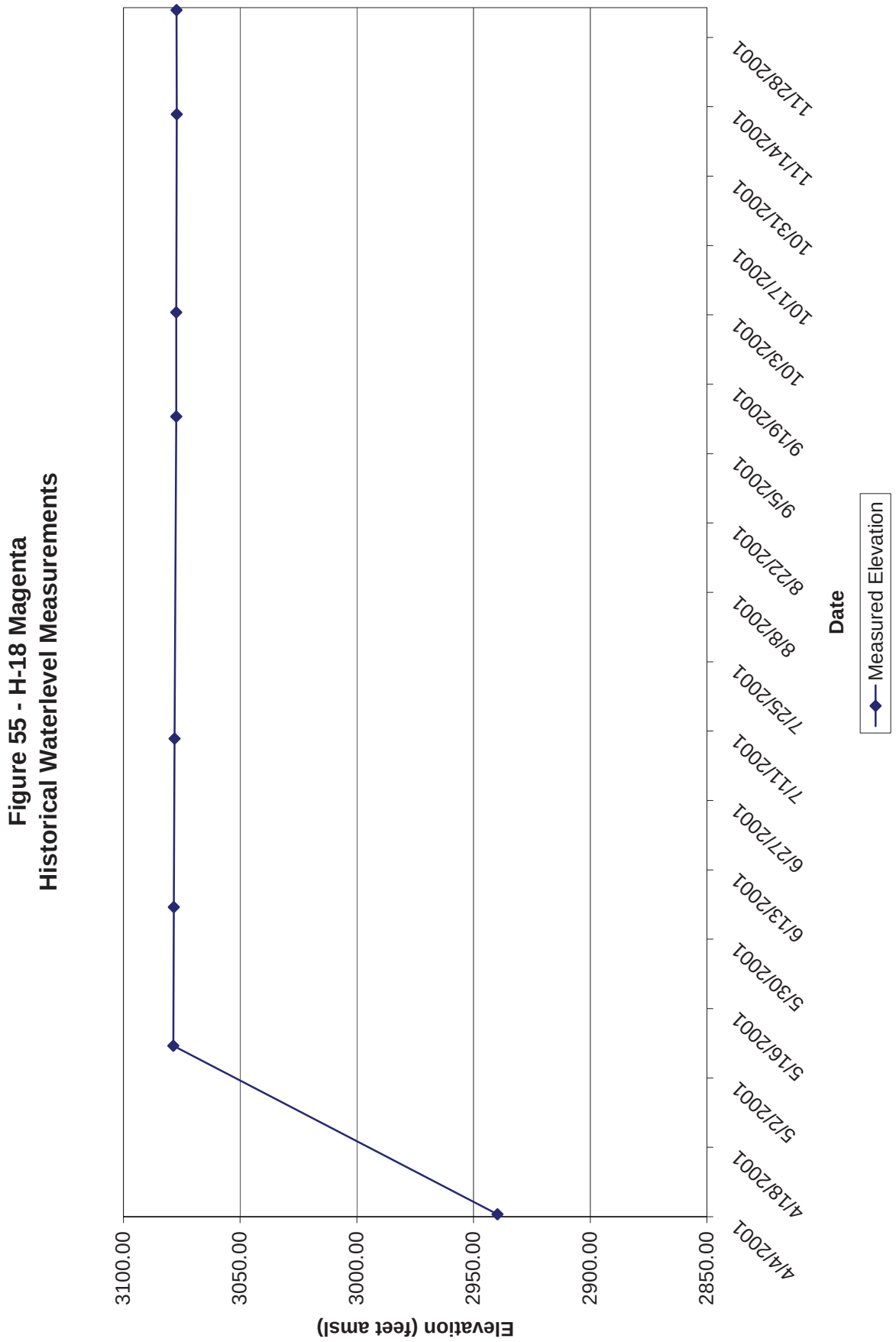
Figure 55 - H-18 Magenta
Historical Waterlevel Measurements
Elevation (feet amsl)
3100.00
3050.00
3000.00
2950.00
2900.00
2850.00
4/4/2001
4/18/2001
5/2/2001
5/16/2001
5/30/2001
6/13/2001
6/27/2001
7/11/2001
7/25/2001
8/8/2001
8/22/2001
9/5/2001
9/19/2001
10/3/2001
10/17/2001
10/31/2001
11/14/2001
11/28/2001
Date
Measured Elevation

Table 56 - Well No. H-19b0 Culebra
April 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
04/15/97	2982.92	3004.23
05/14/97	2983.32	3004.66
06/11/97	2982.22	3003.48
07/15/97	2982.58	3003.87
08/13/97	2983.11	3004.43
09/17/97	2983.20	3004.53
10/16/97	2983.57	3004.92
11/12/97	2984.33	3005.74
12/10/97	2984.61	3006.03
01/13/98	2985.16	3006.62
02/11/98	2985.54	3007.03
03/12/98	2985.67	3007.16
04/15/98	2986.38	3007.92
05/12/98	2985.58	3007.07
06/10/98	2985.91	3007.42
07/14/98	2986.26	3007.79
08/11/98	2986.43	3007.98
09/10/98	2985.31	3006.78
10/14/98	2986.33	3007.87
11/11/98	2986.62	3008.18
12/09/98	2986.85	3008.42
01/12/99	2987.31	3008.91
02/09/99	2987.32	3008.93
03/09/99	2987.66	3009.29
04/12/99	2987.68	3009.31
05/11/99	2987.49	3009.11
06/08/99	2987.93	3009.58
07/19/99	2988.10	3009.76
08/09/99	2988.27	3009.94
09/08/99	2988.40	3010.08
10/04/99	2988.29	3009.96
11/08/99	2987.89	3009.53
12/08/99	2988.42	3010.10

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/00	2988.42	3010.10
02/14/00	2988.57	3010.26
03/06/00	2988.67	3010.37
04/17/00	2987.94	3009.59
05/17/00	2988.62	3010.31
06/07/00	2988.58	3010.27
07/10/00	2988.88	3010.59
08/14/00	2988.91	3010.62
09/11/00	2989.01	3010.73
10/11/00	2988.88	3010.59
11/09/00	2988.66	3010.36
12/06/00	2988.52	3010.21
01/10/01	2989.00	3010.72
02/06/01	2989.03	3010.75
03/08/01	2989.34	3011.08
04/05/01	2989.40	3011.14
05/09/01	2988.98	3010.70
06/06/01	2989.48	3011.23
07/11/01	2989.71	3011.48
08/07/01	2989.74	3011.51
09/07/01	2990.05	3011.84
10/09/01	2990.08	3011.87
11/13/01	2989.72	3011.49
12/05/01	2989.73	3011.50
01/16/02	2990.08	3011.87
02/05/02	2990.19	3011.99
03/13/02	2990.36	3012.17
04/09/02	2990.08	3011.87
05/07/02	2990.32	3012.13
06/11/02	2990.78	3012.62
07/15/02	2990.84	3012.68
08/14/02	2990.98	3012.83
09/10/02	2990.99	3012.84

Figure 56 - H-19b0 Culebra
Historical Waterlevel Measurements

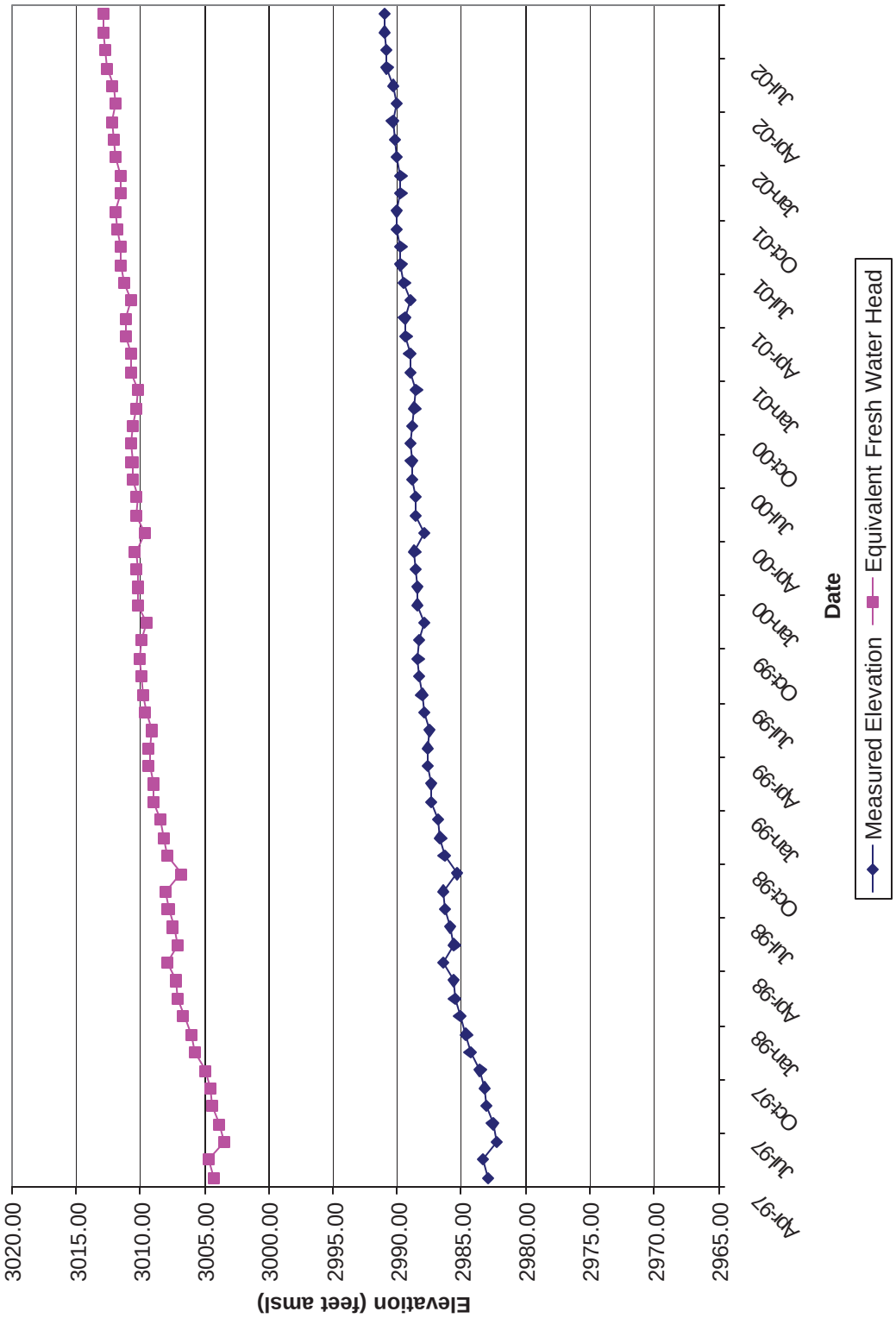

Table 57 - Well No. H-19b2 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2981.60	3002.93
09/17/97	2982.54	3003.93
12/10/97	2984.01	3005.50
03/12/98	2984.98	3006.53
06/10/98	2985.27	3006.84
09/10/98	2987.21	3008.91
12/09/98	2986.21	3007.84
03/09/99	2987.01	3008.70
06/08/99	2987.29	3009.00
09/08/99	2987.76	3009.50
12/08/99	2987.75	3009.49

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2988.02	3009.78
06/07/00	2987.92	3009.67
09/11/00	2988.33	3010.11
12/06/00	2987.86	3009.61
03/08/01	2988.68	3010.48
06/06/01	2988.78	3010.59
09/07/01	2989.38	3011.23
12/05/01	2989.08	3010.91
03/13/02	2989.68	3011.55
06/11/02	2990.09	3011.98
09/10/02	2990.30	3012.21

Figure 57 - H-19b2 Culebra
Historical Waterlevel Measurements

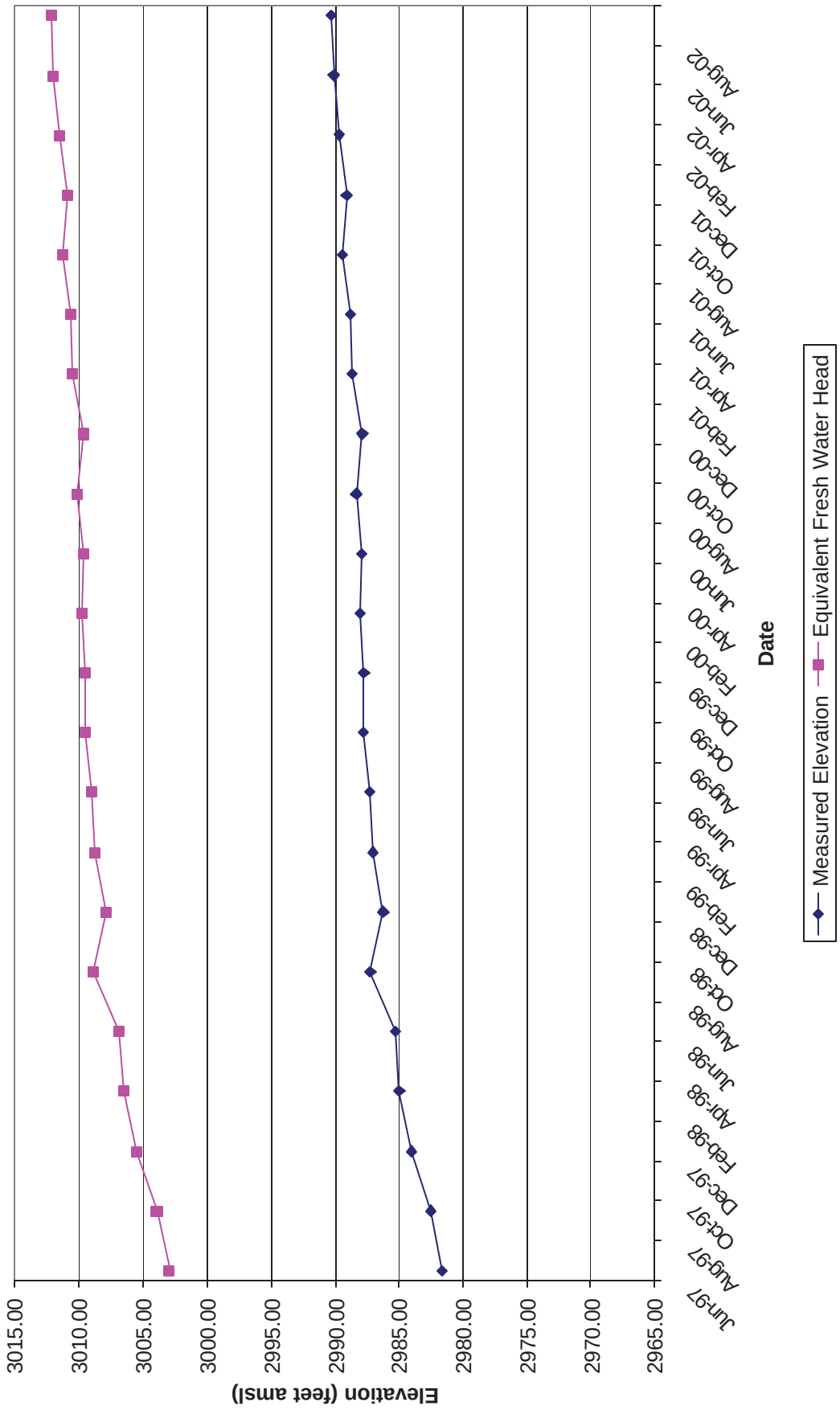

Table 58 - Well No. H-19b3 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2981.45	3002.67
09/17/97	2982.39	3003.67
12/10/97	2983.85	3005.23
03/12/98	2984.84	3006.28
06/10/98	2985.12	3006.58
09/10/98	2985.79	3007.30
12/09/98	2986.05	3007.57
03/09/99	2986.85	3008.43
06/08/99	2987.16	3008.76
09/08/99	2987.60	3009.23
12/08/99	2987.60	3009.23

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2987.87	3009.52
06/07/00	2987.79	3009.43
09/11/00	2988.19	3009.86
12/06/00	2987.73	3009.37
03/08/01	2988.54	3010.23
06/06/01	2988.71	3010.41
09/07/01	2989.26	3011.00
12/05/01	2988.95	3010.67
03/13/02	2989.54	3011.30
06/11/02	2989.95	3011.74
09/10/02	2990.18	3011.98

Figure 58 - H-19b3 Culebra
Historical Waterlevel Measurements

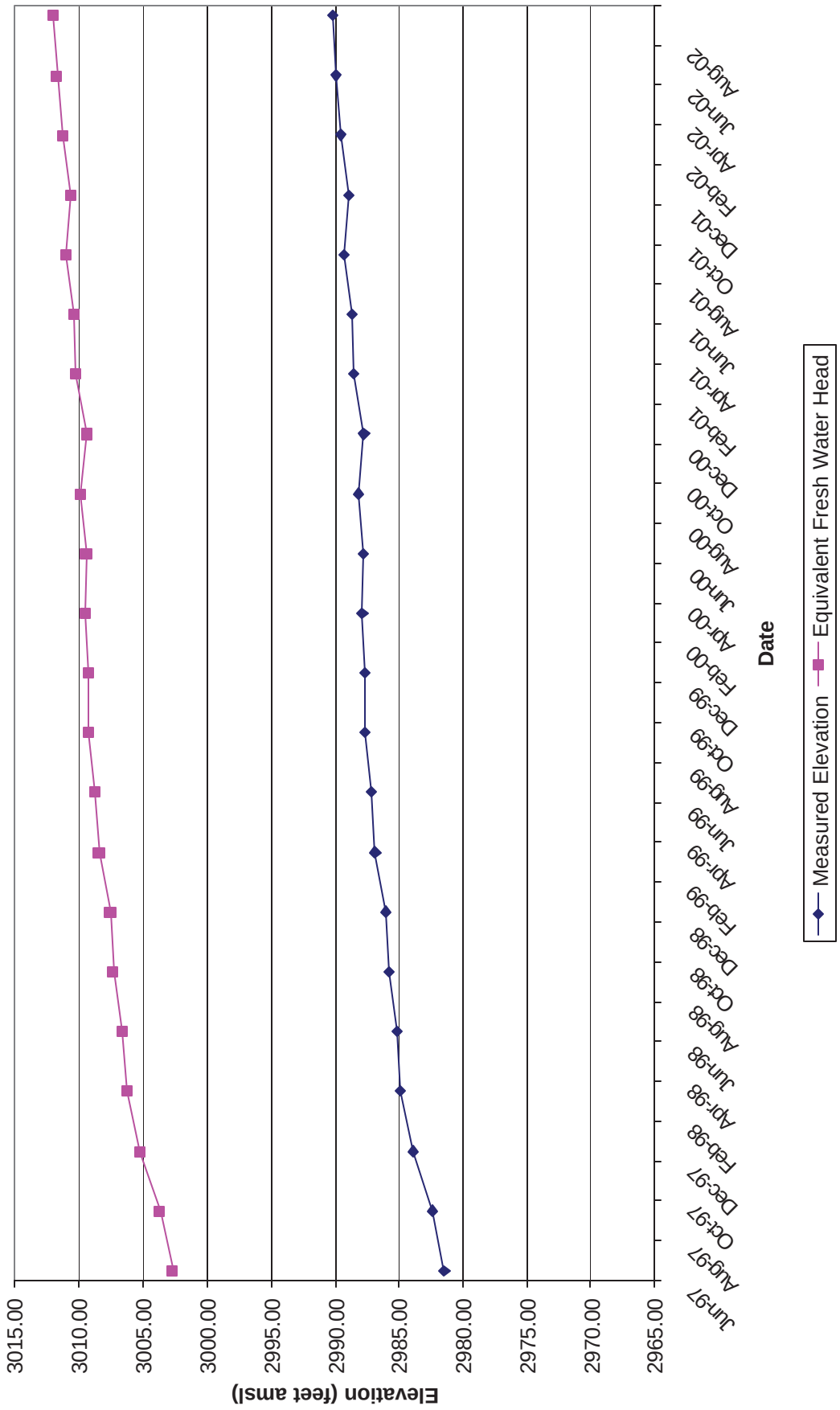

Table 59 - Well No. H-19b4 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2982.12	3003.23
09/17/97	2983.05	3004.22
12/10/97	2984.54	3005.81
03/12/98	2985.53	3006.87
06/10/98	2985.80	3007.16
09/10/98	2986.48	3007.88
12/09/98	2986.75	3009.16
03/09/99	2987.54	3009.01
06/08/99	2987.87	3009.36
09/08/99	2989.28	3010.87
12/08/99	2988.29	3009.81

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2988.58	3010.12
06/07/00	2988.49	3010.03
09/11/00	2988.87	3010.43
12/06/00	2988.41	3009.94
03/08/01	2989.25	3010.84
06/06/01	2989.63	3011.24
09/07/01	2989.95	3011.58
12/05/01	2989.54	3011.15
03/13/02	2990.24	3011.89
06/11/02	2990.65	3012.33
09/10/02	2990.89	3012.59

Figure 59 - H-19b4 Culebra Historical Waterlevel Measurements

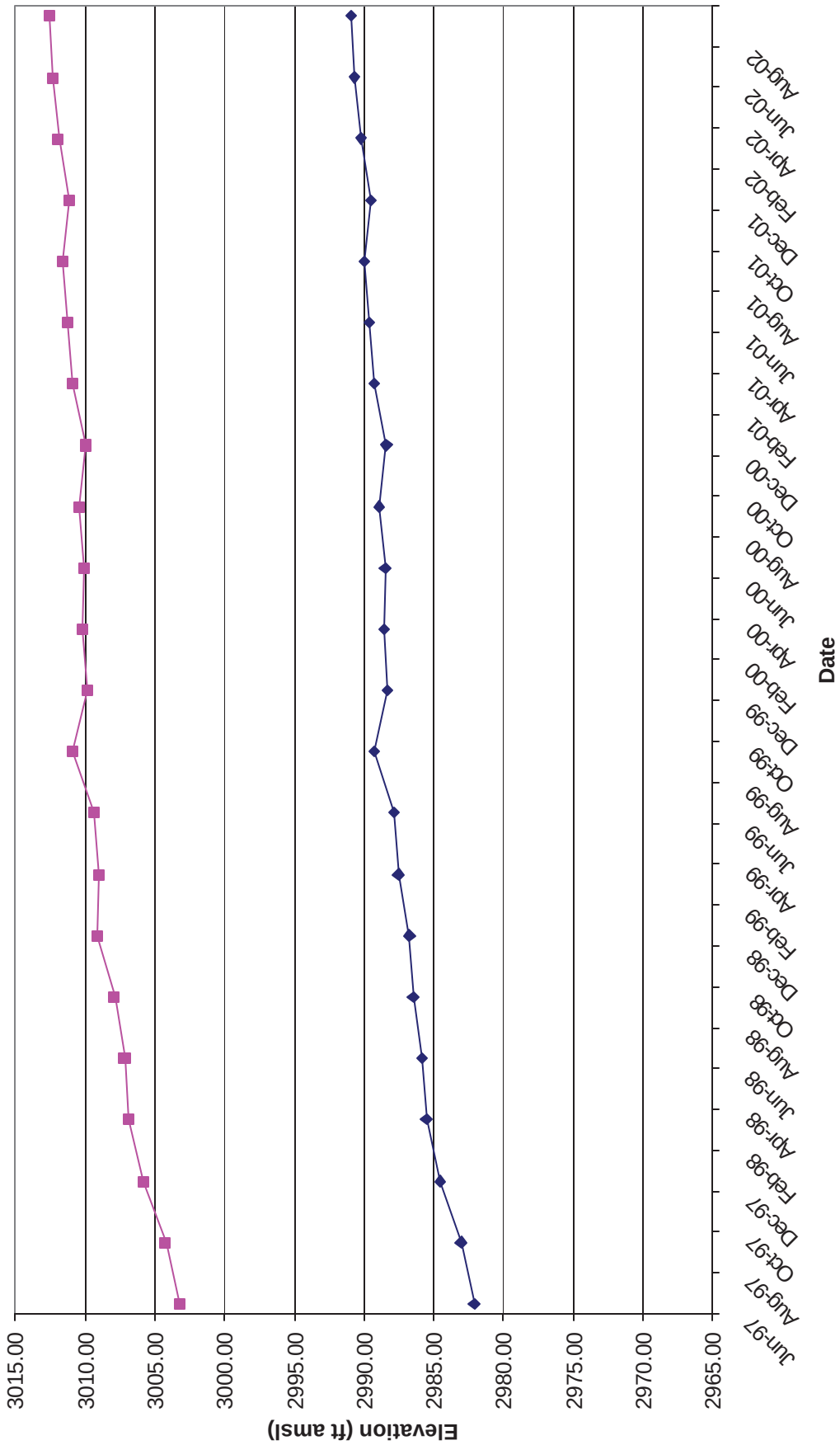

Table 60 - Well No. H-19b5 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2981.03	3002.01
09/17/97	2982.45	3003.52
12/10/97	2983.90	3005.07
03/12/98	2984.92	3006.16
06/10/98	2985.20	3006.46
09/10/98	2985.87	3007.17
12/09/98	2986.19	3007.51
03/09/99	2986.95	3008.32
06/08/99	2987.25	3008.64
09/08/99	2988.73	3010.22
12/08/99	2987.73	3009.16

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2988.02	3009.46
07/07/00	2987.02	3009.36
09/11/00	2988.36	3009.83
12/06/00	2987.88	3009.32
03/08/01	2988.69	3010.18
06/06/01	2988.88	3010.38
09/07/01	2989.39	3010.93
12/05/01	2989.12	3010.64
03/13/02	2989.73	3011.29
06/11/02	2990.14	3011.73
09/10/02	2990.36	3011.96

Figure 60 - H-19b5 Culebra
Historical Waterlevel Measurements

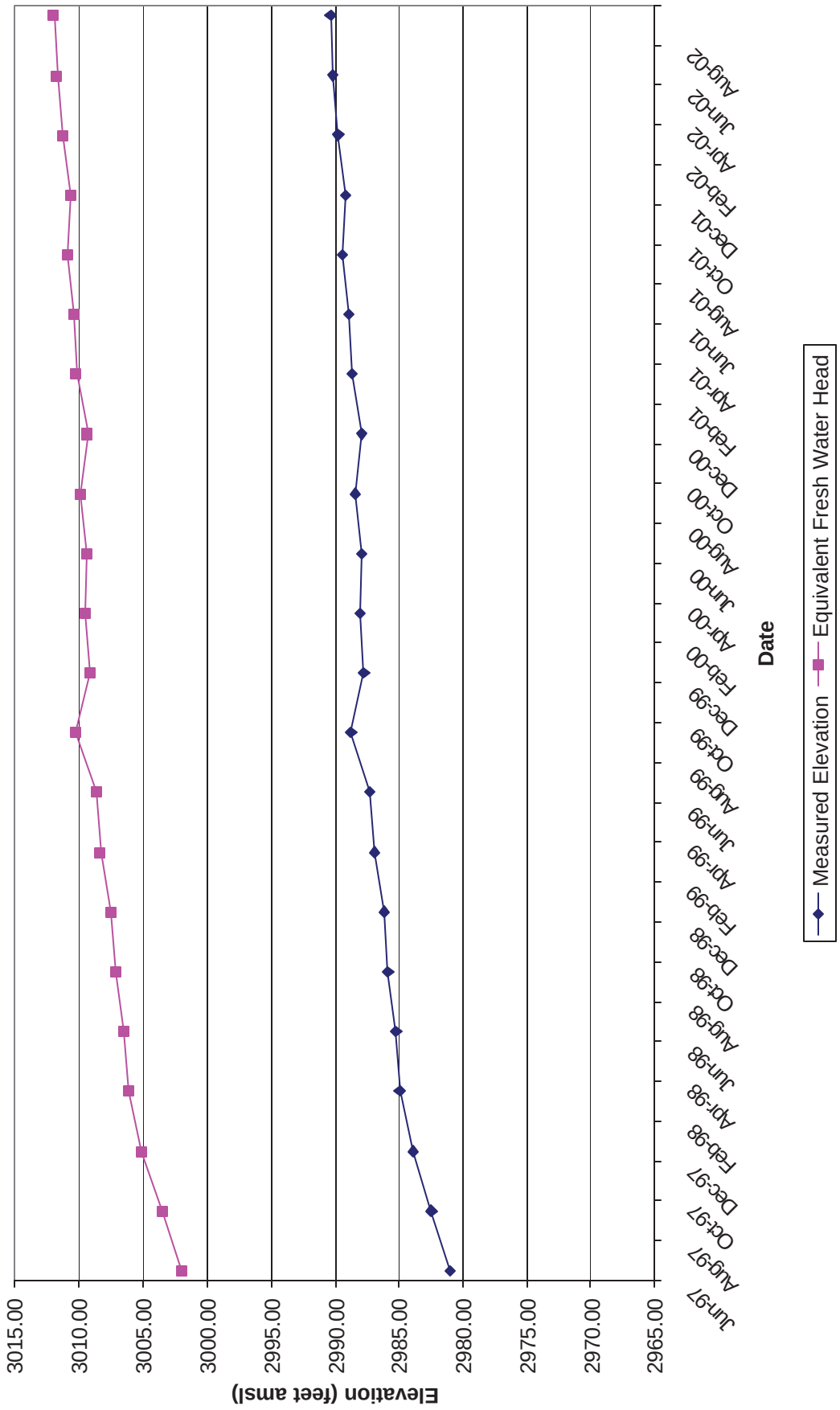

Table 61 - Well No. H-19b6 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2981.62	3002.78
09/17/97	2982.57	3003.79
12/10/97	2984.02	3005.34
03/12/98	2985.01	3006.40
06/10/98	2985.27	3006.67
09/10/98	2985.94	3007.39
12/09/98	2986.19	3007.66
03/09/99	2986.99	3008.51
06/08/99	2987.29	3008.83
09/08/99	2987.68	3009.25
12/08/99	2987.68	3009.25

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2987.97	3009.56
06/07/00	2987.87	3009.45
09/11/00	2988.27	3009.88
12/06/00	2987.81	3009.38
03/08/01	2988.64	3010.27
06/06/01	2988.78	3010.42
09/07/01	2989.36	3011.04
12/05/01	2989.03	3010.69
03/13/02	2989.62	3011.32
06/11/02	2990.03	3011.75
09/10/02	2990.26	3012.00

Figure 61 - H-19b6 Culebra
Historical Waterlevel Measurements

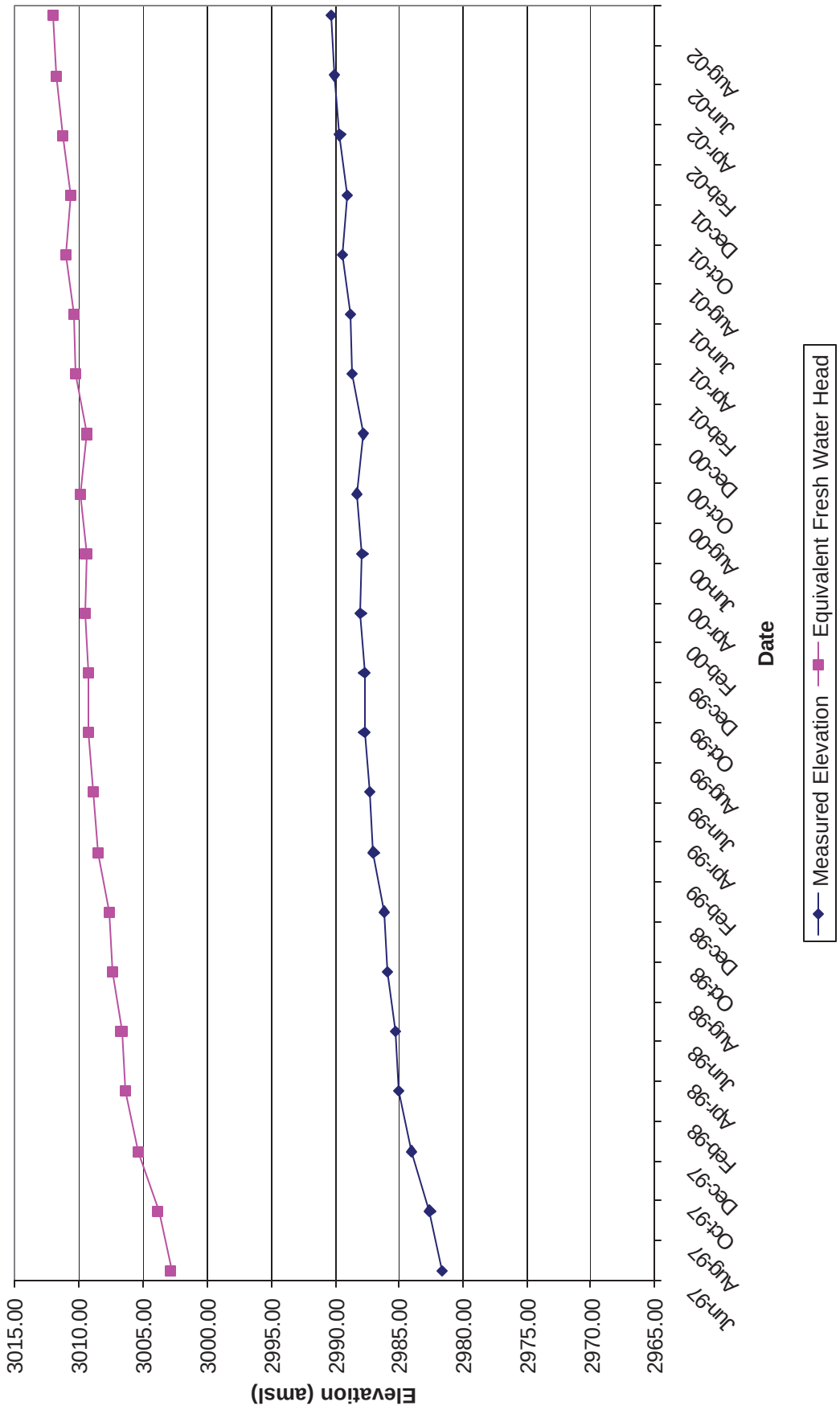

Table 62 - Well No. H-19b7 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2981.27	3002.45
09/17/97	2982.22	3003.46
12/10/97	2983.69	3005.03
03/12/98	2984.68	3006.09
06/10/98	2984.97	3006.40
09/10/98	2985.63	3007.10
12/09/98	2985.90	3007.39
03/09/99	2986.71	3008.25
06/08/99	2987.01	3008.57
09/08/99	2987.45	3009.04
12/08/99	2987.46	3009.05

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2987.73	3009.34
06/07/00	2987.65	3009.26
09/11/00	2988.05	3009.68
12/06/00	2988.59	3010.26
03/08/01	2988.42	3010.08
06/06/01	2988.57	3010.24
09/07/01	2989.10	3010.80
12/05/01	2988.81	3010.50
03/13/02	2989.40	3011.12
06/11/02	2989.83	3011.58
09/10/02	2990.04	3011.81

Figure 62 - H-19b7 Culebra
Historical Waterlevel Measurements

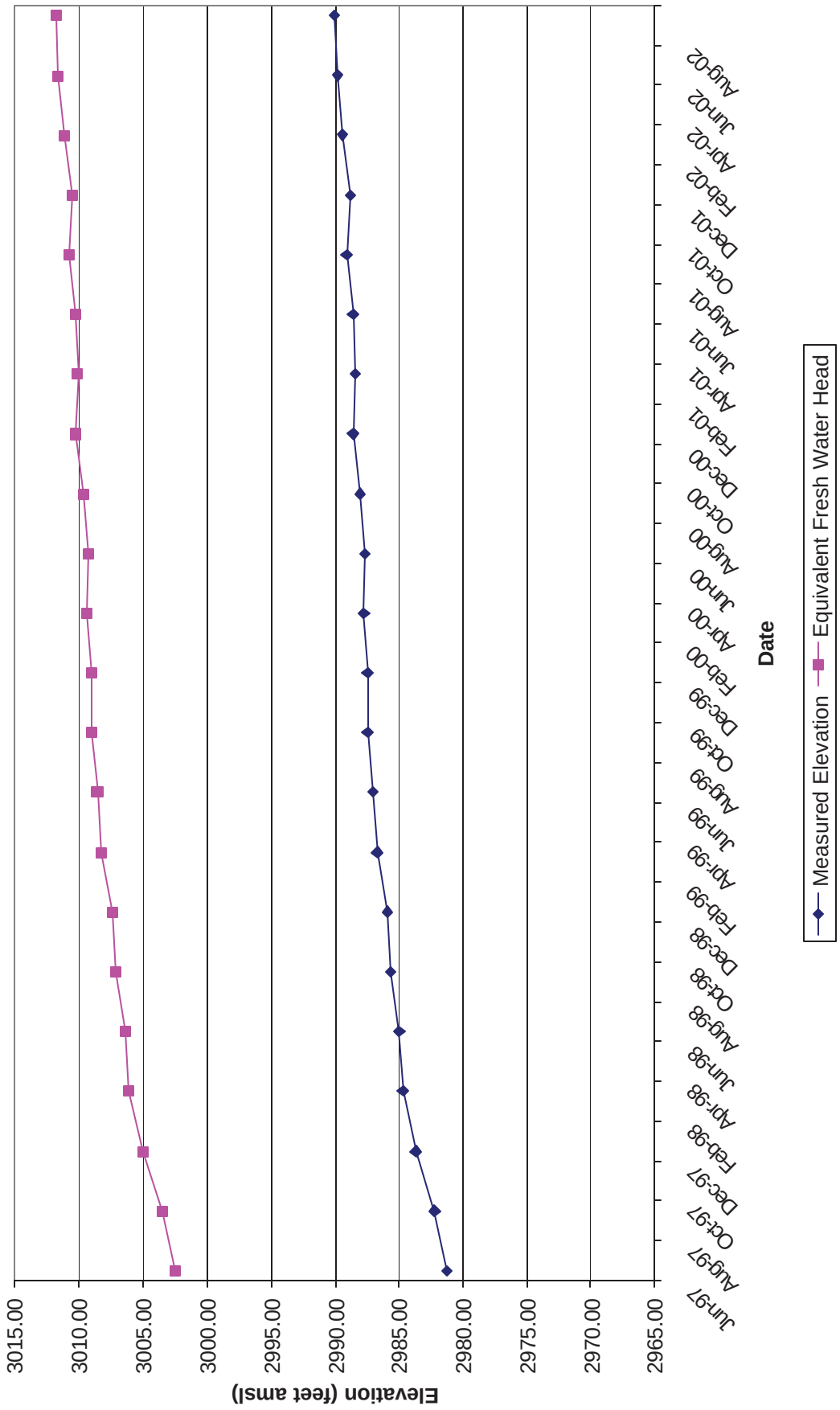

Table 63 - Well No. P-15 Culebra
January 1995 through January 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3012.35	3013.11
02/15/95	3012.41	3013.17
03/15/95	3012.13	3012.89
04/10/95	3012.40	3013.16
05/10/95	3012.39	3013.15
06/07/95	3012.58	3013.34
07/19/95	3012.47	3013.23
08/17/95	3012.49	3013.25
09/07/95	3012.44	3013.20
10/19/95	3012.42	3013.18
11/08/95	3012.28	3013.04
12/06/95	3012.33	3013.09
01/10/96	3012.30	3013.06
02/06/96	3012.26	3013.02
03/14/96	3012.47	3013.23
04/16/96	3012.26	3013.02
05/14/96	3012.15	3012.91
06/12/96	3012.22	3012.98
07/16/96	3012.21	3012.97
08/14/96	3012.33	3013.09
09/04/96	3012.55	3013.31
10/15/96	3012.70	3013.46
11/12/96	3012.75	3013.51
12/11/96	3012.24	3013.00
01/15/97	3013.32	3014.09
02/12/97	3013.38	3014.15
03/12/97	3013.42	3014.19
04/16/97	3013.16	3013.92
05/14/97	3013.20	3013.96
06/11/97	3012.91	3013.67
07/16/97	3012.68	3013.44
08/12/97	3012.55	3013.31
09/16/97	3012.51	3013.27
10/15/97	3012.23	3012.99
11/12/97	3012.54	3013.30
12/10/97	3012.48	3013.24

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3012.52	3013.28
02/11/98	3012.55	3013.31
03/11/98	3012.37	3013.13
04/14/98	3012.85	3013.61
05/12/98	3012.87	3013.63
06/09/98	3012.76	3013.52
07/15/98	3012.73	3013.49
08/10/98	3012.65	3013.41
09/08/98	3012.68	3013.44
10/13/98	3012.58	3013.34
11/11/98	3012.59	3013.35
12/08/98	3012.52	3013.28
01/11/99	3012.61	3013.37
02/09/99	3012.80	3013.56
03/09/99	3012.89	3013.65
04/12/99	3012.86	3013.62
05/10/99	3013.16	3013.92
06/08/99	3013.18	3013.94
07/20/99	3013.14	3013.90
08/10/99	3013.26	3014.02
09/08/99	3013.34	3014.11
10/05/99	3013.16	3013.92
11/10/99	3013.18	3013.94
12/08/99	3013.39	3014.16
01/19/00	3013.31	3014.08
02/14/00	3013.80	3014.57
03/08/00	3013.98	3014.75
04/18/00	3014.18	3014.95
05/17/00	3014.54	3015.31
06/07/00	3014.32	3015.09
07/12/00	3015.17	3015.95
08/15/00	3015.31	3016.09
09/11/00	3016.08	3016.86
10/10/00	3016.10	3016.88
11/09/00	3016.26	3017.04
12/04/00	3015.89	3016.67

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3015.83	3016.61
02/05/01	3015.58	3016.36
03/08/01	3016.03	3016.81
04/05/01	3015.82	3016.60
05/08/01	3015.59	3016.37
06/04/01	3015.93	3016.71
07/11/01	3015.69	3016.47
08/07/01	3015.61	3016.39
09/05/01	3015.60	3016.38
10/08/01	3015.60	3016.38
11/12/01	3015.48	3016.26
12/05/01	3015.60	3016.38
01/16/02	3015.07	3015.85

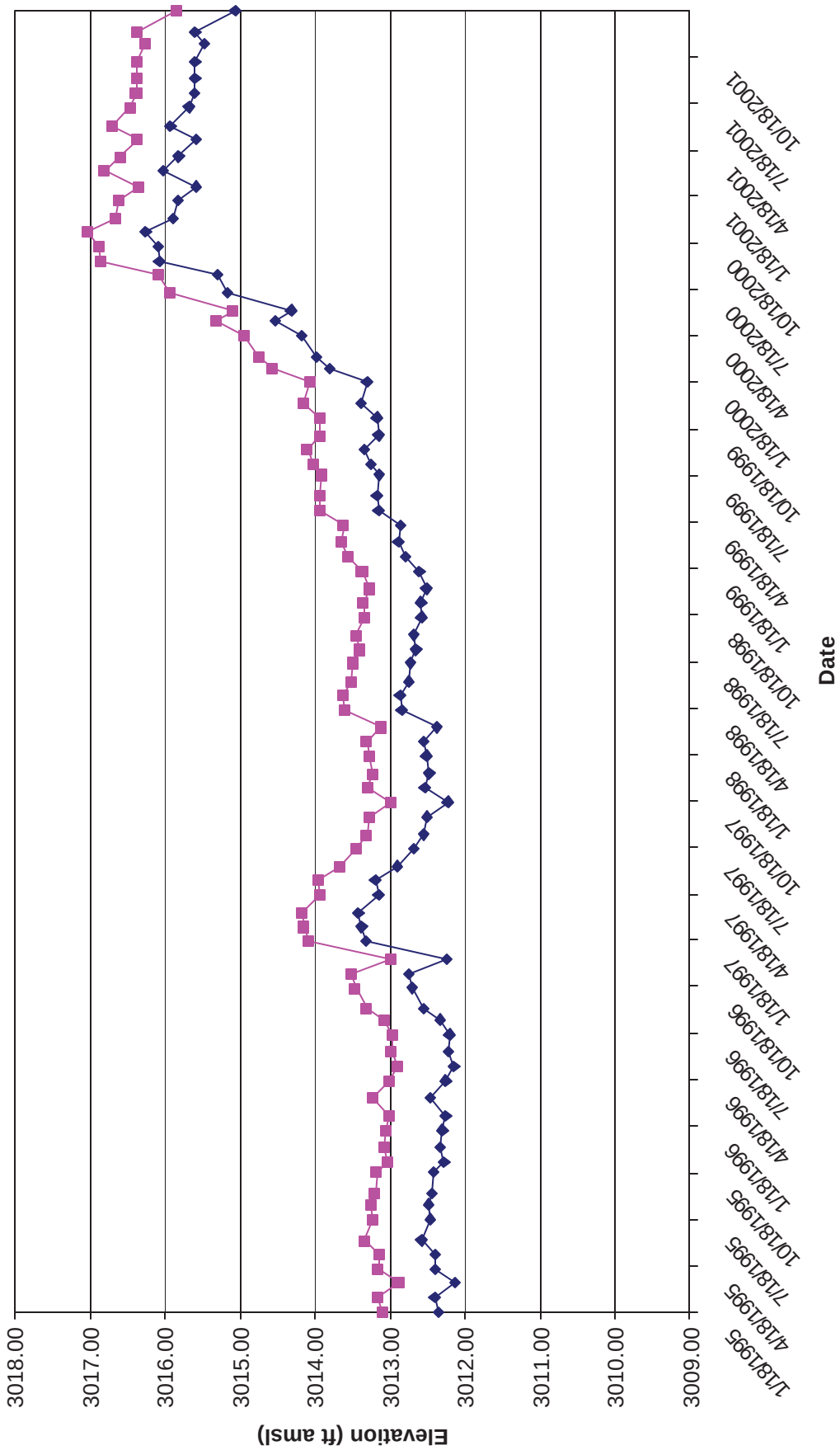

Figure 63 - P-15 Culebra
Historical Waterlevel Measurements

Table 64 - Well No. P-17 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2983.75	2997.95
02/14/95	2983.88	2998.09
03/14/95	2983.76	2997.96
04/11/95	2983.77	2997.97
05/09/95	2984.13	2998.36
06/06/95	2984.40	2998.64
07/19/95	2984.02	2998.24
08/16/95	2983.68	2997.88
09/07/95	2982.83	2996.97
10/18/95	2982.58	2996.71
11/07/95	2982.54	2996.66
12/05/95	2982.72	2996.85
01/09/96	2982.63	2996.76
02/06/96	2982.32	2996.43
03/12/96	2981.06	2995.09
04/16/96	2979.30	2993.21
05/14/96	2979.80	2993.74
06/11/96	2980.60	2994.60
07/16/96	2981.31	2995.35
08/13/96	2982.03	2996.12
09/04/96	2982.42	2996.53
10/16/96	2982.83	2996.97
11/12/96	2982.82	2996.96
12/10/96	2983.22	2997.39
01/15/97	2983.35	2997.53
02/11/97	2983.38	2997.56
03/11/97	2983.11	2997.27
04/15/97	2982.48	2996.60
05/14/97	2982.21	2996.31
06/11/97	2981.81	2995.89
07/15/97	2981.38	2995.43
08/12/97	2981.20	2995.24
09/16/97	2981.39	2995.44
10/15/97	2981.29	2995.33
11/11/97	2981.64	2995.70
12/09/97	2981.85	2995.93

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2981.92	2996.00
02/10/98	2982.18	2996.28
03/10/98	2982.00	2996.09
04/14/98	2982.50	2996.62
05/12/98	2982.47	2996.59
06/09/98	2982.19	2996.29
07/14/98	2982.06	2996.15
08/11/98	2981.97	2996.06
09/09/98	2982.02	2996.11
10/13/98	2981.92	2996.00
11/10/98	2982.00	2996.09
12/08/98	2981.90	2995.98
01/12/99	2982.27	2996.38
02/09/99	2982.25	2996.35
03/09/99	2982.43	2996.55
04/13/99	2982.65	2996.78
05/11/99	2982.72	2996.85
06/08/99	2982.83	2996.97
07/20/99	2982.83	2996.97
08/10/99	2982.98	2997.13
09/08/99	2983.15	2997.31
10/05/99	2982.88	2997.02
11/09/99	2982.85	2996.99
12/08/99	2982.82	2996.96
01/18/00	2982.55	2996.67
02/15/00	2982.61	2996.74
03/07/00	2982.67	2996.80
04/18/00	2982.72	2996.85
05/16/00	2982.84	2996.98
06/06/00	2982.71	2996.84
07/11/00	2982.83	2996.97
08/15/00	2982.69	2996.82
09/11/00	2982.78	2996.92
10/11/00	2982.18	2996.28
11/09/00	2982.76	2996.90
12/05/00	2983.47	2997.65

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2982.72	2996.85
02/05/01	2982.60	2996.73
03/07/01	2982.84	2996.98
04/05/01	2983.10	2997.26
05/09/01	2983.17	2997.33
06/06/01	2983.46	2997.64
07/11/01	2983.47	2997.65
08/07/01	2983.30	2997.47
09/05/01	2983.24	2997.41
10/09/01	2983.31	2997.48
11/12/01	2983.25	2997.42
12/03/01	2983.35	2997.53
01/15/02	2983.47	2997.65
02/05/02	2983.53	2997.72
03/13/02	2983.94	2998.15
04/10/02	2983.79	2997.99
05/07/02	2984.09	2998.31
06/11/02	2984.32	2998.56
07/16/02	2984.24	2998.47
08/14/02	2984.37	2998.61
09/12/02	2984.34	2998.58

Figure 64 - P-17 Culebra
Historical Waterlevel Measurements

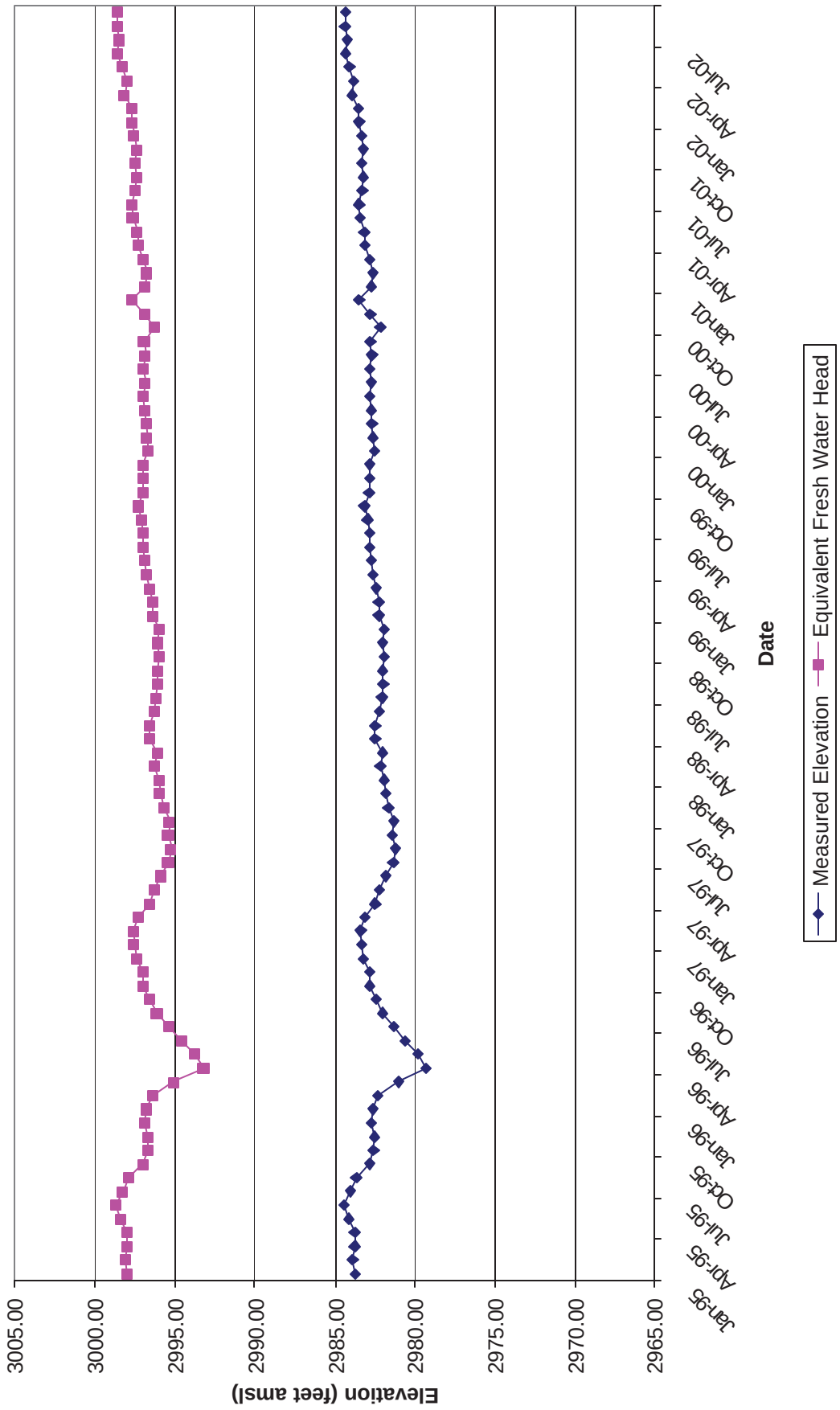

Table 65 - Well No. P-18 Culebra
January 1995 through February 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3122.04	3188.82
02/14/95	3122.92	3189.80
03/14/95	3123.92	3190.92
04/11/95	3124.66	3191.74
05/09/95	3125.64	3192.84
06/06/95	3126.52	3193.82
07/18/95	3127.78	3195.23
08/16/95	3128.88	3196.46
09/06/95	3129.89	3197.59
10/17/95	3131.57	3199.46
11/07/95	3132.34	3200.32
12/05/95	3133.34	3201.44
01/09/96	3134.51	3202.75
02/06/96	3135.51	3203.86
03/12/96	3136.63	3205.11
04/16/96	3137.72	3206.33
05/14/96	3138.63	3207.35
06/11/96	3139.54	3208.36
07/16/96	3140.63	3209.58
08/14/96	3141.31	3210.34
09/04/96	3141.83	3210.92
10/15/96	3142.77	3211.97
11/12/96	3143.37	3212.64
12/10/96	3144.06	3213.41
01/15/97	3144.90	3214.35
02/11/97	3145.48	3215.00
03/11/97	3146.08	3215.67
04/15/97	3146.86	3216.54
05/13/97	3147.40	3217.14
06/11/97	3147.97	3217.78
07/15/97	3148.60	3218.48
08/12/97	3149.04	3218.98
09/16/97	3149.72	3219.74
10/14/97	3150.67	3220.24
11/11/97	3150.67	3220.80
12/09/97	3151.07	3221.24

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	3151.53	3221.76
02/10/98	3152.06	3222.35
03/10/98	3152.48	3222.82
04/14/98	3153.04	3223.44
05/12/98	3153.49	3223.95
06/09/98	3153.87	3224.37
07/14/98	3154.37	3224.93
08/11/98	3154.73	3225.33
09/09/98	3155.15	3225.80
10/13/98	3155.64	3226.35
11/10/98	3156.01	3226.76
12/08/98	3156.37	3227.16
01/12/99	3156.84	3227.69
02/09/99	3157.21	3228.10
03/09/99	3157.61	3228.55
04/13/99	3158.05	3229.04
05/11/99	3158.37	3229.40
06/08/99	3158.71	3229.78
07/20/99	3159.16	3230.28
08/10/99	3159.43	3230.58
09/08/99	3159.75	3230.94
10/05/99	3160.00	3231.22
11/09/99	3160.34	3231.60
12/07/99	3160.60	3231.89
01/18/00	3160.98	3232.31
02/15/00	3161.26	3232.63
03/07/00	3161.45	3232.84
04/18/00	3161.82	3233.25
05/16/00	3162.06	3233.52
06/06/00	3162.13	3233.60
07/11/00	3162.13	3233.60
08/15/00	3162.16	3233.63
09/13/00	3162.25	3233.73
10/10/00	3162.28	3233.76
11/09/00	3162.35	3233.84
12/05/00	3162.44	3233.94

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3162.62	3234.14
02/07/01	3162.73	3234.27
03/07/01	3162.93	3234.49
04/04/01	3163.08	3234.66
05/07/01	3163.24	3234.84
06/06/01	3163.38	3234.99
07/10/01	3163.50	3235.13
08/07/01	3163.58	3235.22
09/05/01	3163.72	3235.37
10/09/01	3163.82	3235.48
11/13/01	3163.95	3235.63
12/04/01	3164.05	3235.74
01/15/02	3164.17	3235.88
02/06/02	3163.79	3235.45

Figure 65 - P-18 Culebra
Historical Waterlevel Measurements

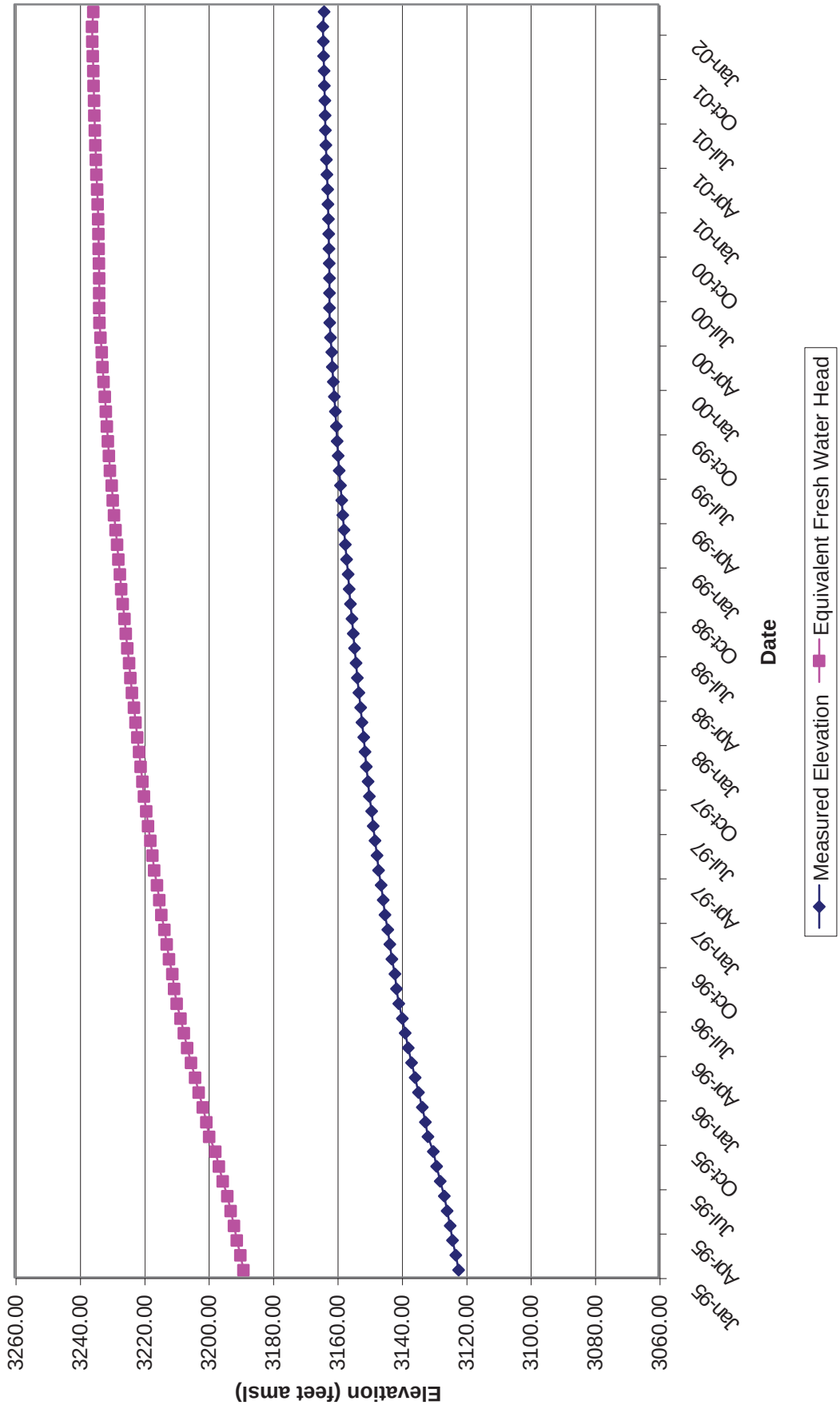

Table 66 - Well No. WIPP-12 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3030.02	3066.62
02/15/95	3030.20	3066.81
03/13/95	3030.24	3066.86
04/10/95	3030.06	3066.66
05/09/95	3030.28	3066.90
06/05/95	3030.08	3066.68
07/17/95	3030.34	3066.97
08/14/95	3030.56	3067.21
09/05/95	3030.02	3066.62
10/16/95	3029.93	3066.52
11/07/95	3029.98	3066.57
12/04/95	3030.12	3066.73
01/08/96	3030.21	3066.83
02/05/96	3029.91	3066.50
03/14/96	3028.43	3064.87
04/15/96	3029.37	3065.90
05/13/96	3029.13	3065.64
06/10/96	3029.31	3065.84
07/15/96	3029.54	3066.09
08/12/96	3029.38	3065.92
09/03/96	3029.61	3066.17
10/14/96	3029.96	3066.55
11/11/96	3030.02	3066.62
12/09/96	3030.10	3066.70
01/13/97	3030.40	3067.03
02/10/97	3030.40	3067.03
03/10/97	3030.61	3067.26
04/14/97	3030.85	3067.53
05/12/97	3030.73	3067.40
06/09/97	3030.98	3067.67
07/14/97	3031.26	3067.98
08/11/97	3031.26	3067.98
09/15/97	3031.25	3067.97
10/13/97	3031.25	3067.97
11/10/97	3031.10	3067.80
12/08/97	3030.75	3067.42

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3030.49	3067.13
02/09/98	3031.25	3067.97
03/12/98	3032.76	3069.62
04/13/98	3033.09	3069.98
05/11/98	3032.83	3069.70
06/08/98	3032.45	3069.28
07/13/98	3031.96	3068.74
08/10/98	3031.76	3068.52
09/08/98	3031.81	3068.58
10/12/98	3031.63	3068.38
11/09/98	3031.45	3068.18
12/07/98	3031.43	3068.16
01/11/99	3031.34	3068.06
02/08/99	3031.54	3068.28
03/08/99	3031.74	3068.50
04/12/99	3031.65	3068.40
05/10/99	3031.77	3068.54
06/07/99	3031.75	3068.51
07/19/99	3031.67	3068.43
08/09/99	3031.71	3068.47
09/07/99	3031.61	3068.36
10/04/99	3031.59	3068.34
11/08/99	3031.60	3068.35
12/06/99	3031.76	3068.52
01/19/00	3031.90	3068.68
02/14/00	3032.08	3068.87
03/06/00	3032.15	3068.95
04/17/00	3032.06	3068.85
05/15/00	3032.06	3068.85
06/05/00	3031.93	3068.71
07/10/00	3031.98	3068.77
08/14/00	3031.76	3068.52
09/11/00	3031.79	3068.56
10/09/00	3031.53	3068.27
11/08/00	3031.63	3068.38
12/06/00	3031.51	3068.25

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3031.59	3068.34
02/05/01	3031.53	3068.27
03/07/01	3031.69	3068.45
04/05/01	3031.84	3068.61
05/08/01	3031.76	3068.52
06/05/01	3032.09	3068.89
07/11/01	3032.01	3068.80
08/08/01	3031.98	3068.77
09/06/01	3031.93	3068.71
10/10/01	3031.97	3068.75
11/14/01	3031.93	3068.71
12/05/01	3032.15	3068.95
01/16/02	3032.24	3069.05
02/05/02	3032.38	3069.20
03/12/02	3032.59	3069.43
04/08/02	3032.83	3069.70
05/07/02	3032.96	3069.84
06/10/02	3033.11	3070.00
07/15/02	3033.16	3070.06
08/13/02	3033.22	3070.12
09/10/02	3033.21	3070.11

Figure 66 - WIPP-12 Culebra
Historical Waterlevel Measurements

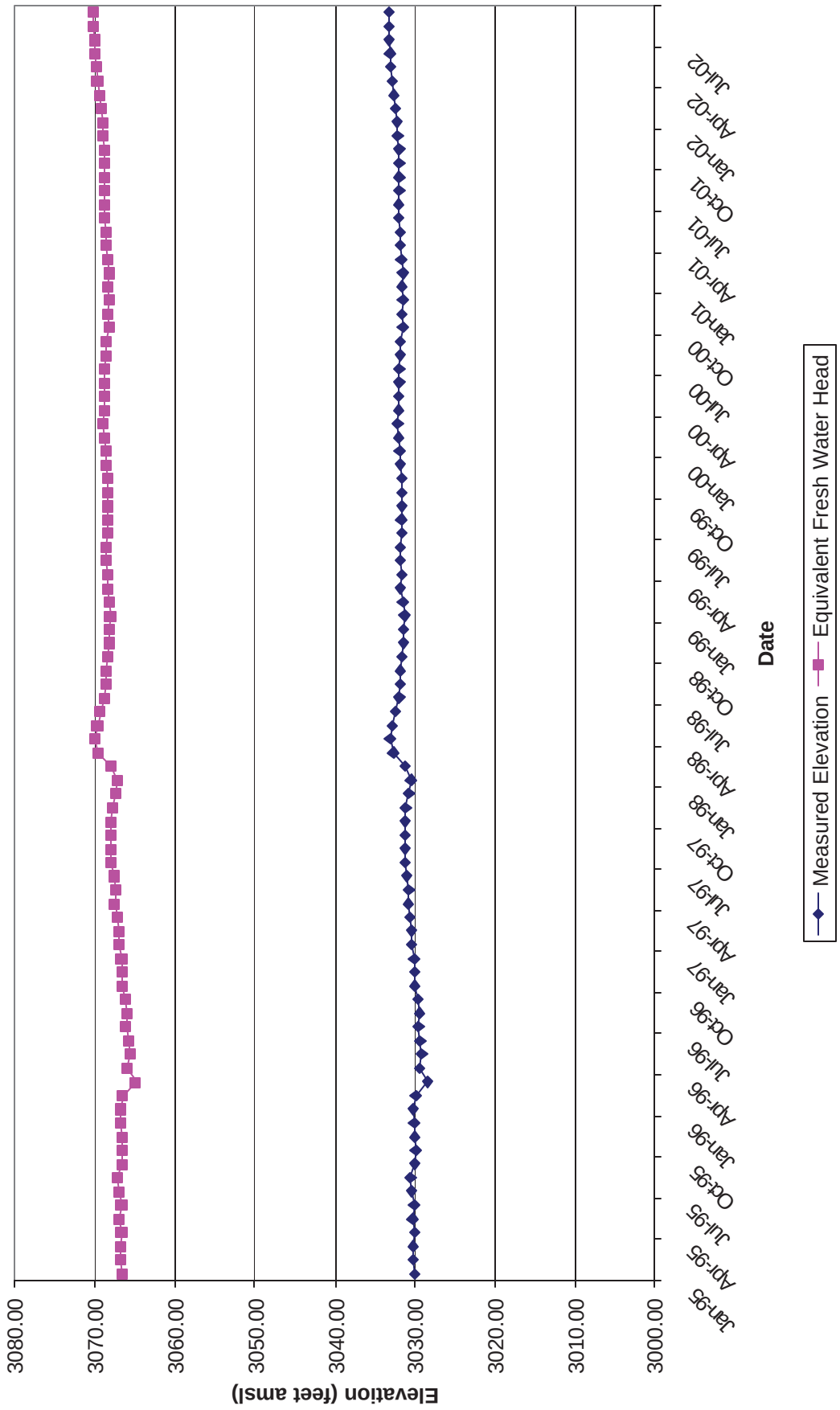

Table 67 - Well No. WIPP-13 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3057.33	3067.90
02/13/95	3057.24	3067.81
03/13/95	3057.13	3067.69
04/10/95	3056.50	3067.05
05/08/95	3057.35	3067.92
06/05/95	3057.52	3068.10
07/17/95	3057.56	3068.14
08/14/95	3057.64	3068.22
09/05/95	3056.95	3067.51
10/16/95	3057.66	3068.24
11/07/95	3057.64	3068.22
12/04/95	3057.73	3068.31
01/08/96	3057.70	3068.28
02/05/96	3056.76	3067.31
03/11/96	3057.06	3067.62
04/15/96	3056.80	3067.35
05/13/96	3057.26	3067.83
06/10/96	3057.57	3068.15
07/15/96	3057.71	3068.29
08/14/96	3057.48	3068.05
09/03/96	3057.94	3068.53
10/14/96	3057.93	3068.52
11/11/96	3057.65	3068.23
12/09/96	3057.78	3068.36
01/13/97	3057.88	3068.47
02/10/97	3057.81	3068.39
03/10/97	3058.01	3068.60
04/14/97	3058.36	3068.96
05/12/97	3058.13	3068.72
06/09/97	3058.53	3069.13
07/14/97	3058.84	3069.45
08/11/97	3058.58	3069.19
09/15/97	3058.44	3069.04
10/13/97	3058.08	3068.67
11/10/97	3058.06	3068.65
12/08/97	3057.40	3067.97

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3057.48	3068.05
02/09/98	3060.42	3071.08
03/09/98	3060.82	3071.49
04/13/98	3060.12	3070.77
05/11/98	3059.73	3070.37
06/08/98	3059.30	3069.93
07/13/98	3058.60	3069.21
08/10/98	3058.86	3069.47
09/08/98	3058.80	3069.41
10/12/98	3058.23	3068.83
11/09/98	3058.80	3069.41
12/07/98	3058.14	3068.73
01/11/99	3058.40	3069.00
02/08/99	3058.75	3069.36
03/08/99	3058.62	3069.23
04/12/99	3058.47	3069.07
05/10/99	3058.79	3069.40
06/07/99	3058.62	3069.23
07/19/99	3058.37	3068.97
08/09/99	3058.21	3068.81
09/07/99	3058.19	3068.78
10/04/99	3058.04	3068.63
11/08/99	3058.38	3068.98
12/06/99	3058.43	3069.03
01/17/00	3058.45	3069.05
02/14/00	3058.57	3069.18
03/06/00	3058.89	3069.50
04/17/00	3058.38	3068.98
05/15/00	3058.24	3068.84
06/05/00	3058.01	3068.60
07/10/00	3058.02	3068.61
08/14/00	3057.91	3068.50
09/12/00	3057.72	3068.30
10/09/00	3057.36	3067.93
11/06/00	3057.88	3068.47
12/07/00	3057.57	3068.15

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3057.50	3068.07
02/05/01	3057.54	3068.12
03/06/01	3057.46	3068.03
04/04/01	3057.33	3067.90
05/07/01	3057.43	3068.00
06/05/01	3057.62	3068.20
07/09/01	3057.48	3068.05
08/08/01	3057.31	3067.88
09/04/01	3057.04	3067.60
10/10/01	3057.19	3067.76
11/14/01	3057.26	3067.83
12/05/01	3057.08	3067.64
01/15/02	3057.26	3067.83
02/05/02	3057.25	3067.82
03/11/02	3057.49	3068.06
04/08/02	3057.64	3068.22
05/06/02	3057.67	3068.25
06/11/02	3057.91	3068.50
07/15/02	3057.84	3068.42
08/13/02	3057.90	3068.49
09/09/02	3057.79	3068.37

Figure 67 - WIPP-13 Culebra
Historical Waterlevel Measurements

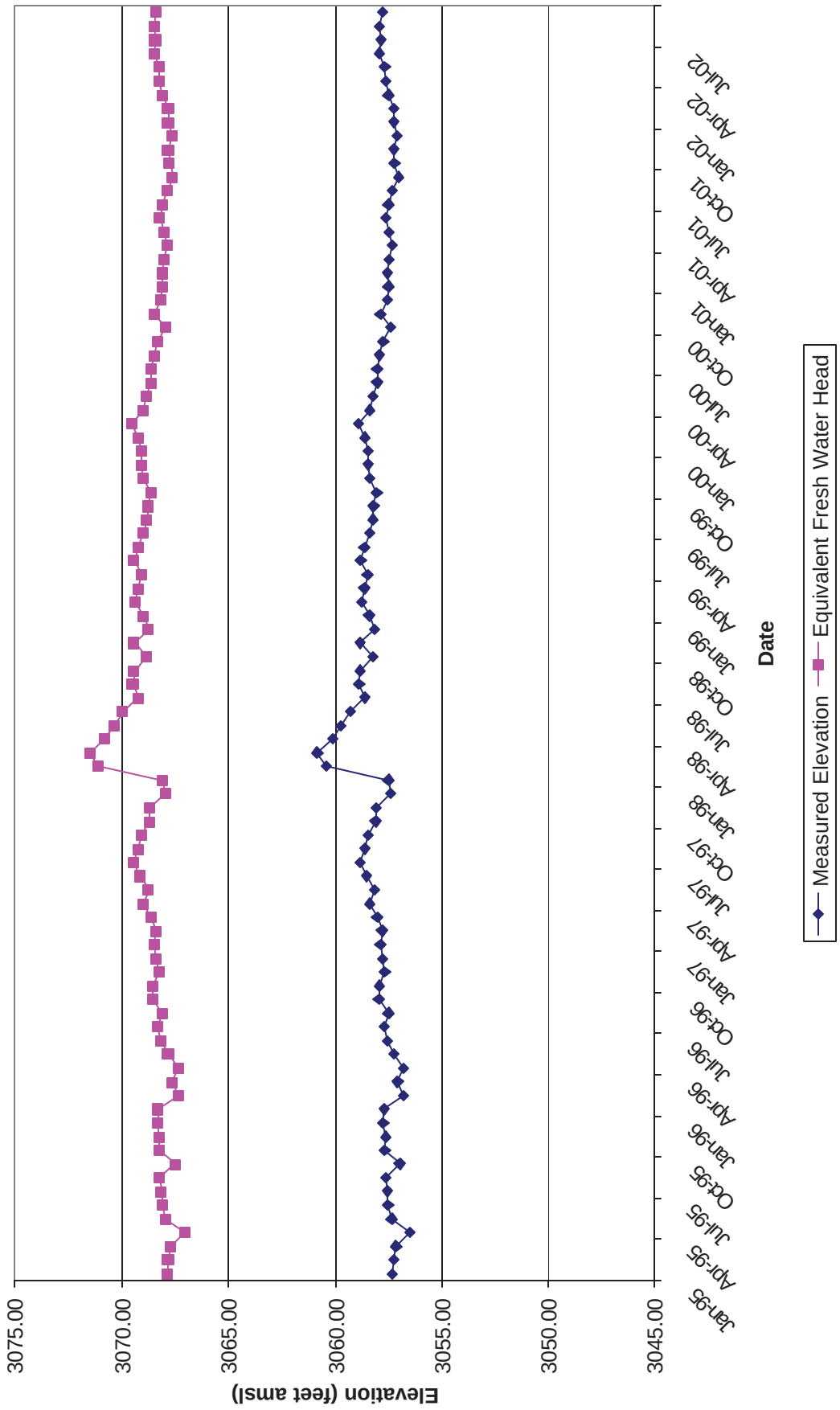

Table 68 - Well No. WIPP-18 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3027.92	3064.82
02/15/95	3028.27	3065.21
03/13/95	3028.32	3065.26
04/10/95	3028.34	3065.28
05/09/95	3025.95	3062.65
06/05/95	3027.94	3064.84
07/17/95	3028.47	3065.43
08/14/95	3028.50	3065.46
09/05/95	3027.85	3064.74
10/16/95	3027.34	3064.18
11/07/95	3027.48	3064.34
12/04/95	3027.76	3064.64
01/08/96	3027.99	3064.90
02/05/96	3027.28	3064.12
03/14/96	3026.67	3063.45
04/15/96	3026.22	3062.95
05/13/96	3026.16	3062.88
06/10/96	3026.18	3062.91
07/15/96	3026.66	3063.43
08/12/96	3026.95	3063.75
09/03/96	3027.39	3064.24
10/14/96	3027.91	3064.81
11/11/96	3028.13	3065.05
12/09/96	3028.53	3065.49
01/13/97	3028.85	3064.90
02/10/97	3029.09	3064.12
03/10/97	3029.42	3063.45
04/14/97	3029.87	3062.95
05/12/97	3030.00	3062.88
06/09/97	3030.25	3062.91
07/14/97	3030.68	3063.43
08/11/97	3030.78	3063.75
09/15/97	3030.75	3064.24
10/13/97	3030.82	3064.81
11/10/97	3030.86	3065.05
12/08/97	3030.80	3065.49

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3031.67	3068.95
02/09/98	3031.57	3068.84
03/09/98	3032.41	3069.76
04/13/98	3033.06	3070.47
05/11/98	3032.80	3070.19
06/08/98	3032.64	3070.01
07/13/98	3032.49	3069.85
08/10/98	3032.50	3069.86
09/08/98	3032.43	3069.78
10/12/98	3032.12	3069.44
11/09/98	3032.35	3069.69
12/07/98	3032.27	3069.61
01/11/99	3032.20	3069.53
02/08/99	3032.56	3069.92
03/08/99	3032.75	3070.13
04/12/99	3032.46	3069.81
05/10/99	3032.81	3070.20
06/07/99	3032.82	3070.21
07/19/99	3032.83	3070.22
08/09/99	3032.87	3070.27
09/07/99	3032.94	3070.34
10/04/99	3032.87	3070.27
11/08/99	3033.00	3070.41
12/06/99	3033.16	3070.58
01/19/00	3033.45	3070.90
02/14/00	3033.61	3071.08
03/06/00	3033.68	3071.16
04/17/00	3033.60	3071.07
05/15/00	3033.62	3071.09
06/05/00	3033.60	3071.07
07/10/00	3033.79	3071.28
08/14/00	3033.74	3071.22
09/11/00	3033.79	3071.28
10/09/00	3033.37	3070.82
11/08/00	3033.67	3071.15
12/06/00	3033.55	3071.01

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3033.65	3071.12
02/05/01	3033.53	3070.99
03/05/01	3033.69	3071.17

Figure 68 - WIPP-18 Culebra Historical Waterlevel Measurements

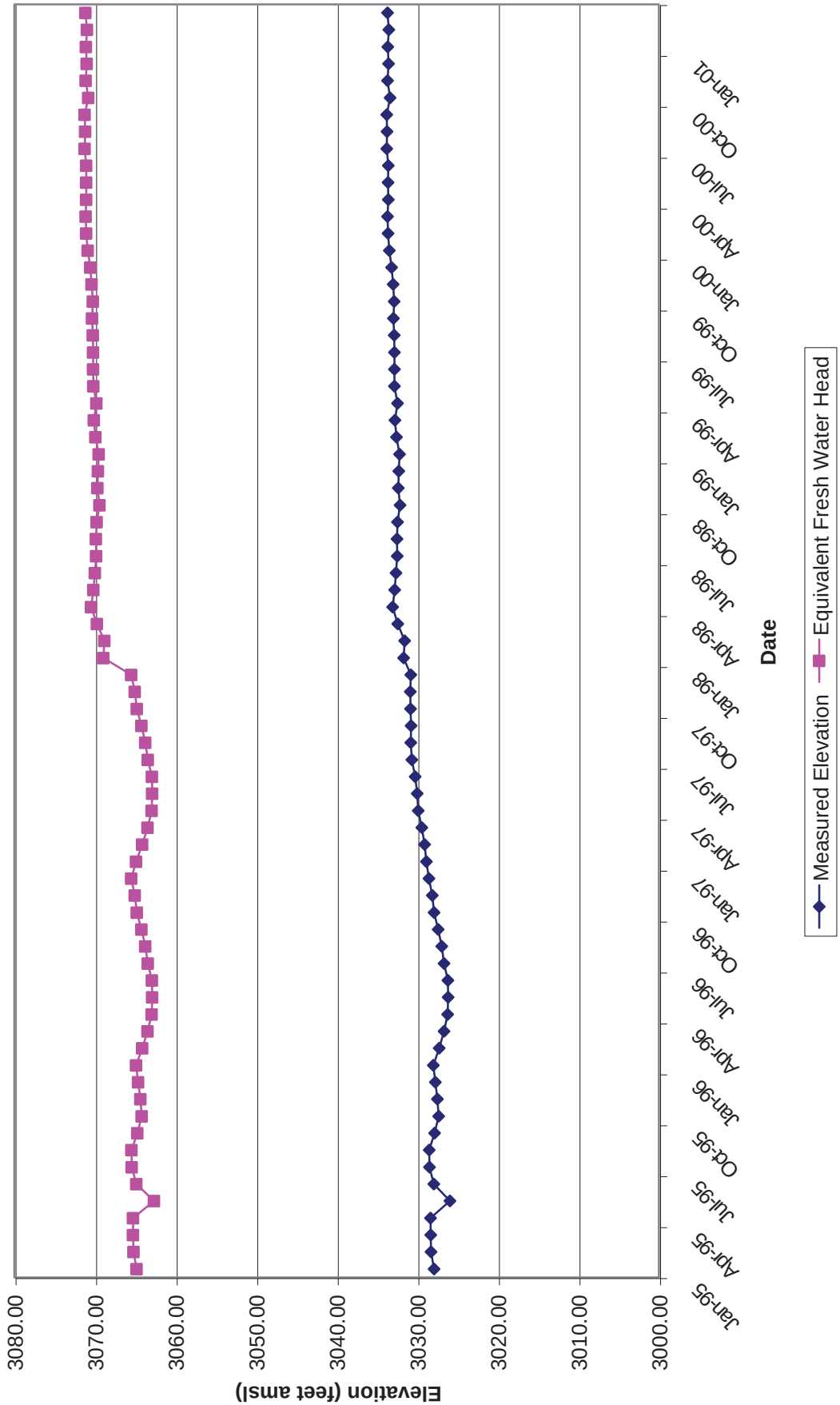

Table 69 - Well No. WIPP-18 Magenta
April 2001 through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
04/05/01	2936.11	N/A
05/08/01	3139.57	N/A
06/05/01	3140.68	N/A
07/11/01	3140.15	N/A
09/12/01	3132.14	N/A
10/03/01	3125.88	N/A
11/12/01	3116.43	N/A
12/03/01	3112.86	N/A

Figure 69 - WIPP-18 Magenta
Historical Waterlevel Measurements

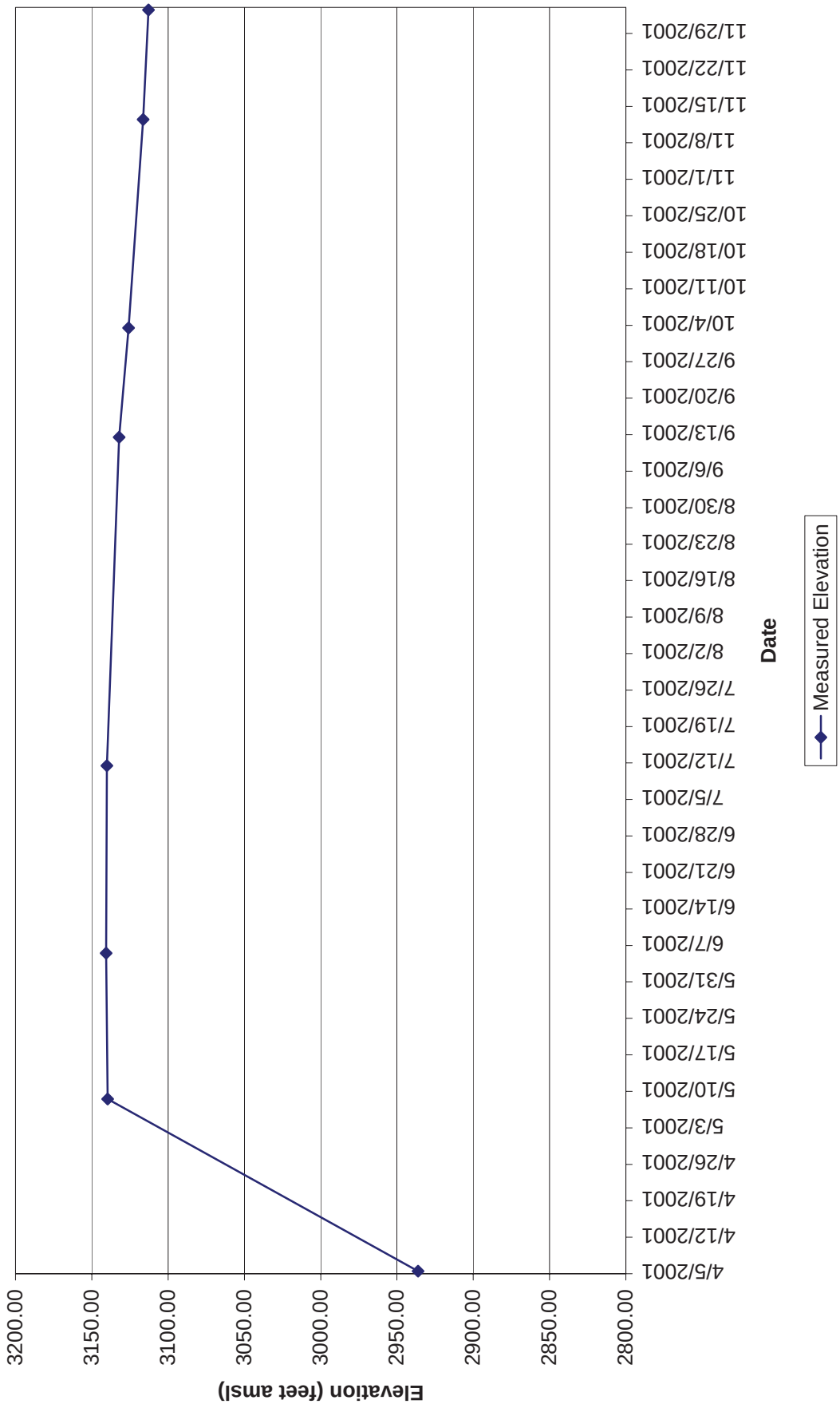

Table 70 - Well No. WIPP-19 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3035.22	3072.55
02/15/95	3035.61	3072.98
03/13/95	3035.52	3072.88
04/10/95	3035.58	3072.94
05/09/95	3027.91	3064.50
06/05/95	3034.60	3071.87
07/17/95	3034.65	3071.92
08/14/95	3033.63	3070.80
09/05/95	3032.89	3069.98
10/16/95	3032.54	3069.60
11/07/95	3032.67	3069.74
12/04/95	3033.11	3070.23
01/08/96	3033.23	3070.36
02/05/96	3031.47	3068.42
03/11/96	3029.42	3066.16
04/15/96	3028.14	3064.75
05/13/96	3028.46	3065.11
06/10/96	3029.07	3065.78
07/15/96	3030.19	3067.01
08/12/96	3031.10	3068.01
09/03/96	3031.89	3068.88
10/14/96	3032.88	3069.97
11/11/96	3033.27	3070.40
12/09/96	3033.88	3071.07
01/13/97	3034.25	3071.48
02/10/97	3034.69	3071.97
03/10/97	3035.03	3072.34
04/14/97	3035.55	3072.91
05/12/97	3035.84	3073.23
06/09/97	3036.28	3073.72
07/14/97	3036.46	3073.91
08/11/97	3036.71	3074.19
09/15/97	3036.77	3074.26
10/13/97	3036.72	3074.20
11/10/97	3036.79	3074.28
12/08/97	3036.90	3074.40

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3036.68	3074.16
02/09/98	3037.31	3074.85
03/09/98	3037.94	3075.54
04/13/98	3038.63	3076.30
05/11/98	3038.65	3076.33
06/08/98	3038.50	3076.16
07/13/98	3038.39	3076.04
08/10/98	3038.40	3076.05
09/08/98	3038.46	3076.12
10/12/98	3038.10	3075.72
11/09/98	3038.43	3076.08
12/07/98	3038.16	3075.79
01/11/99	3038.07	3075.69
02/08/99	3038.33	3075.97
03/08/99	3038.52	3076.18
04/12/99	3038.35	3075.99
05/10/99	3038.68	3076.36
06/07/99	3038.61	3076.28
07/19/99	3038.63	3076.30
08/09/99	3038.72	3076.40
09/07/99	3038.75	3076.44
10/04/99	3038.55	3076.21
11/08/99	3038.78	3076.47
12/06/99	3038.85	3076.55
01/19/00	3039.04	3076.75
02/14/00	3039.07	3076.79
03/06/00	3039.16	3076.89
04/17/00	3039.15	3076.88
05/15/00	3039.13	3076.85
06/05/00	3039.08	3076.80
07/10/00	3039.30	3077.04
08/14/00	3039.27	3077.01
09/11/00	3039.32	3077.06
10/09/00	3038.86	3076.56
11/08/00	3039.15	3076.88
12/06/00	3038.93	3076.63

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3038.99	3076.70
02/05/01	3038.82	3076.51
03/07/01	3038.98	3076.69
04/05/01	3039.13	3076.85
05/08/01	3039.04	3076.75
06/05/01	3039.45	3077.21
07/11/01	3039.56	3077.33
08/08/01	3039.63	3077.40
09/06/01	3039.74	3077.53
10/10/01	3039.84	3077.64
11/14/01	3039.96	3077.77
12/05/01	3039.83	3077.62
01/16/02	3040.01	3077.82
02/05/02	3040.13	3077.95
03/12/02	3040.24	3078.08
04/08/02	3040.52	3078.38
05/07/02	3040.64	3078.52
06/10/02	3040.90	3078.80
07/15/02	3040.88	3078.78
08/13/02	3041.09	3079.01
09/10/02	3041.06	3078.98

Figure 70 -WIPP-19 Culebra
Historical Waterlevel Measurements

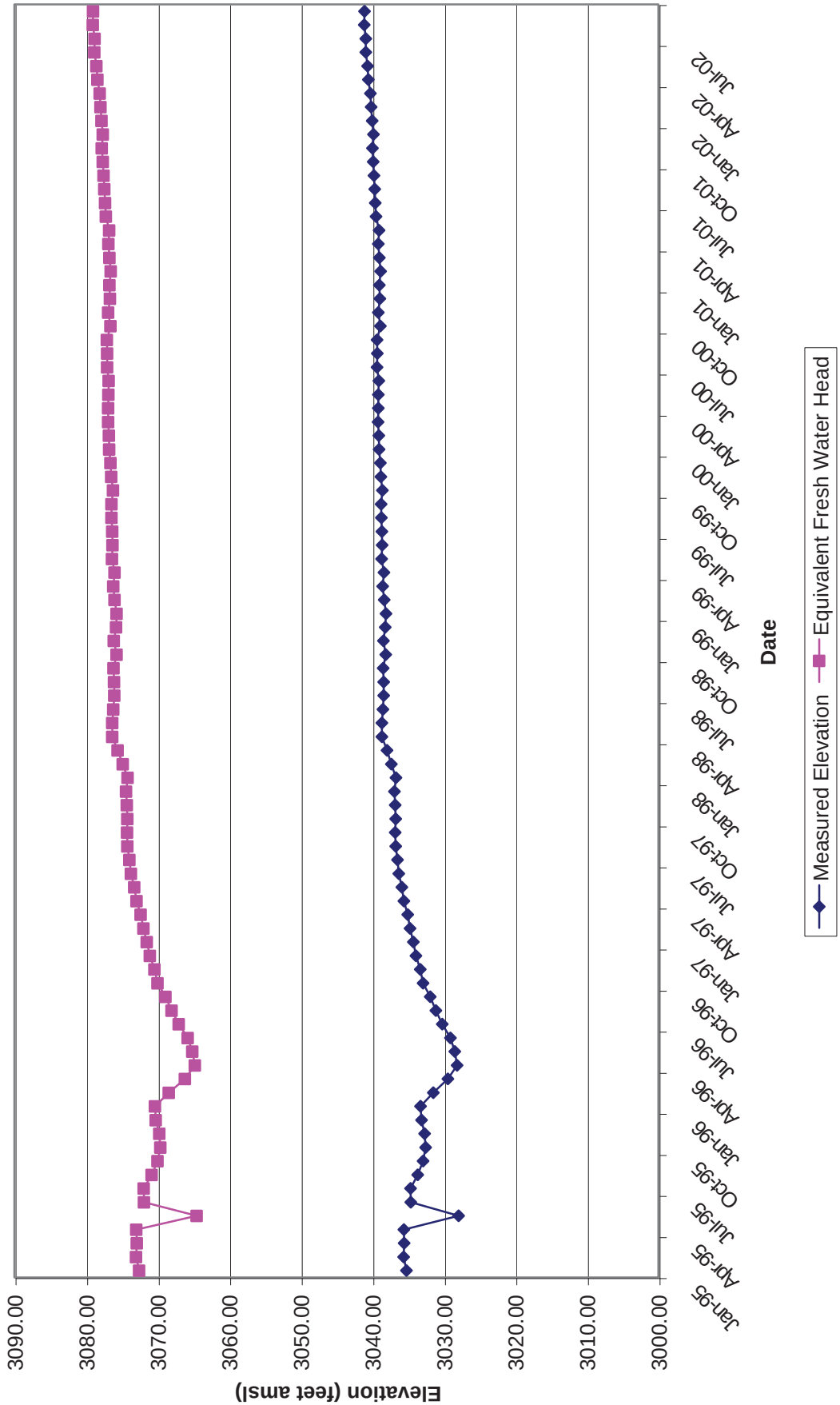

Table 71 - Well No. WIPP-21 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3010.06	3033.78
02/15/95	3010.54	3034.29
03/13/95	3009.78	3033.48
04/10/95	3010.26	3033.99
05/09/95	3008.75	3032.38
06/05/95	3008.98	3032.62
07/17/95	3003.47	3026.72
08/14/95	3000.19	3023.21
09/05/95	3000.55	3023.59
10/16/95	3000.99	3024.06
11/07/95	3002.25	3025.41
12/04/95	3003.19	3026.42
01/08/96	3000.23	3023.25
02/05/96	2993.77	3016.33
03/11/96	2988.73	3010.93
04/15/96	2990.24	3012.55
05/13/96	2990.03	3012.33
06/10/96	2993.96	3016.54
07/15/96	2997.86	3020.71
08/12/96	3000.37	3023.40
09/03/96	3002.09	3025.24
10/14/96	3004.03	3027.32
11/11/96	3005.16	3028.53
12/09/96	3005.99	3029.42
01/13/97	3006.76	3030.24
02/10/97	3007.32	3030.84
03/10/97	3008.27	3031.86
04/14/97	3009.29	3032.95
05/12/97	3009.90	3033.61
06/09/97	3010.37	3034.11
07/14/97	3010.70	3034.46
08/11/97	3011.05	3034.84
09/15/97	3011.29	3035.10
10/13/97	3011.47	3035.29
11/10/97	3011.47	3035.29
12/08/97	3011.68	3035.51

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3011.47	3035.29
02/09/98	3011.91	3035.76
03/09/98	3012.36	3036.24
04/13/98	3013.14	3037.08
05/11/98	3013.35	3037.30
06/08/98	3013.52	3037.48
07/13/98	3013.63	3037.60
08/10/98	3013.67	3037.64
09/08/98	3013.83	3037.82
10/12/98	3013.68	3037.66
11/09/98	3013.82	3037.81
12/07/98	3013.82	3037.81
01/11/99	3013.53	3037.49
02/08/99	3013.90	3037.89
03/08/99	3014.18	3038.19
04/12/99	3014.18	3038.19
05/10/99	3014.47	3038.50
06/07/99	3014.60	3038.64
07/19/99	3014.71	3038.76
08/09/99	3014.90	3038.96
09/07/99	3015.04	3039.11
10/04/99	3014.86	3038.92
11/08/99	3014.74	3038.79
12/06/99	3014.94	3039.00
01/19/00	3014.71	3038.76
02/14/00	3014.76	3038.81
03/06/00	3014.98	3039.05
04/17/00	3015.15	3039.23
05/15/00	3015.32	3039.41
06/05/00	3015.40	3039.50
07/10/00	3015.38	3039.48
08/14/00	3015.71	3039.83
09/11/00	3015.82	3039.95
10/09/00	3015.33	3039.42
11/08/00	3015.58	3039.69
12/06/00	3015.17	3039.25

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3014.93	3038.99
02/05/01	3014.43	3038.46
03/07/01	3014.88	3038.94
04/05/01	3015.32	3039.41
05/08/01	3015.42	3039.52
06/05/01	3015.93	3040.07
07/11/01	3016.05	3040.19
08/08/01	3016.16	3040.31
09/06/01	3016.27	3040.43
10/10/01	3016.36	3040.53
11/14/01	3016.31	3040.47
12/05/01	3016.10	3040.25
01/16/02	3015.97	3040.11
02/05/02	3016.08	3040.23
03/12/02	3016.16	3040.31
04/08/02	3016.57	3040.75
05/07/02	3016.80	3041.00
06/10/02	3017.13	3041.35
07/15/02	3017.25	3041.48
08/13/02	3017.46	3041.70
09/10/02	3017.76	3042.02

Figure 71 - WIPP-21 Culebra
Historical Waterlevel Measurements

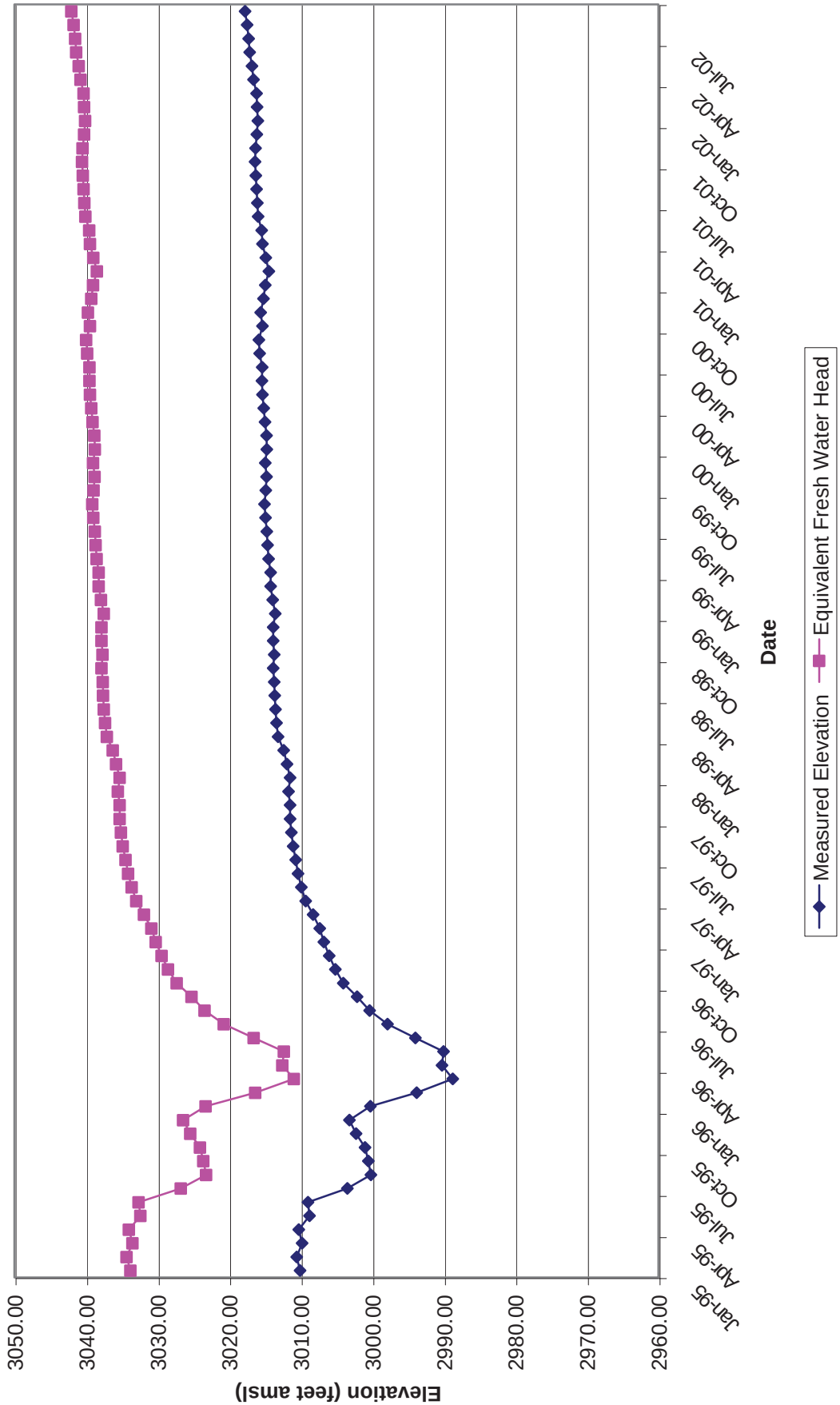

Table 72 - Well No. WIPP-22 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3023.56	3054.06
02/15/95	3023.98	3054.52
03/13/95	3023.86	3054.38
04/10/95	3023.97	3054.50
05/09/95	3017.44	3047.41
06/05/95	3022.90	3053.34
07/17/95	3021.87	3052.22
08/14/95	3019.93	3050.11
09/05/95	3019.48	3049.62
10/16/95	3019.18	3049.30
11/07/95	3019.71	3049.87
12/04/95	3020.25	3050.46
01/08/96	3020.00	3050.19
02/05/96	3017.12	3047.06
03/11/96	3013.94	3043.60
04/15/96	3012.67	3042.22
05/13/96	3012.91	3042.48
06/10/96	3014.66	3044.38
07/15/96	3016.64	3046.54
08/12/96	3018.07	3048.09
09/03/96	3019.20	3049.32
10/14/96	3020.50	3050.73
11/11/96	3021.24	3051.54
12/09/96	3021.96	3052.32
01/13/97	3022.51	3052.92
02/10/97	3022.84	3053.28
03/10/97	3023.48	3053.97
04/14/97	3024.24	3054.80
05/12/97	3024.67	3055.27
06/09/97	3025.10	3055.73
07/14/97	3025.45	3056.11
08/11/97	3025.67	3056.35
09/15/97	3025.89	3056.59
10/13/97	3025.98	3056.69
11/10/97	3026.01	3056.72
12/08/97	3026.14	3056.86

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3025.98	3056.69
02/09/98	3026.44	3057.19
03/09/98	3027.05	3057.85
04/13/98	3027.83	3058.70
05/11/98	3027.96	3058.84
06/08/98	3027.93	3058.81
07/13/98	3027.90	3058.78
08/10/98	3027.90	3058.78
09/08/98	3028.01	3058.90
10/12/98	3027.80	3058.67
11/09/98	3027.96	3058.84
12/07/98	3027.88	3058.75
01/11/99	3027.71	3058.57
02/08/99	3028.02	3058.91
03/08/99	3028.26	3059.17
04/12/99	3028.16	3059.06
05/10/99	3028.47	3059.40
06/07/99	3028.47	3059.40
07/19/99	3028.53	3059.46
08/09/99	3028.71	3059.66
09/07/99	3028.79	3059.74
10/04/99	3028.64	3059.58
11/08/99	3028.70	3059.65
12/06/99	3028.76	3059.71
01/19/00	3028.87	3059.83
02/14/00	3029.00	3059.97
03/06/00	3029.10	3060.08
04/17/00	3029.17	3060.16
05/15/00	3029.19	3060.18
06/05/00	3029.20	3060.19
07/10/00	3029.44	3060.45
08/14/00	3029.43	3060.44
09/11/00	3029.51	3060.53
10/09/00	3029.10	3060.08
11/08/00	3029.41	3060.42
12/06/00	3029.15	3060.14

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3029.13	3060.11
02/05/01	3028.84	3059.80
03/07/01	3029.08	3060.06
04/05/01	3029.32	3060.32
05/08/01	3029.32	3060.32
06/05/01	3029.77	3060.81
07/11/01	3029.85	3060.90
08/08/01	3029.92	3060.97
09/06/01	3030.05	3061.11
10/10/01	3030.16	3061.23
11/14/01	3030.22	3061.30
12/05/01	3030.12	3061.19
01/16/02	3030.17	3061.24
02/05/02	3030.26	3061.34
03/12/02	3030.39	3061.48
04/08/02	3030.73	3061.85
05/07/02	3030.84	3061.97
06/10/02	3031.13	3062.29
07/15/02	3031.89	3063.11
08/13/02	3031.37	3062.55
09/10/02	3031.37	3062.55

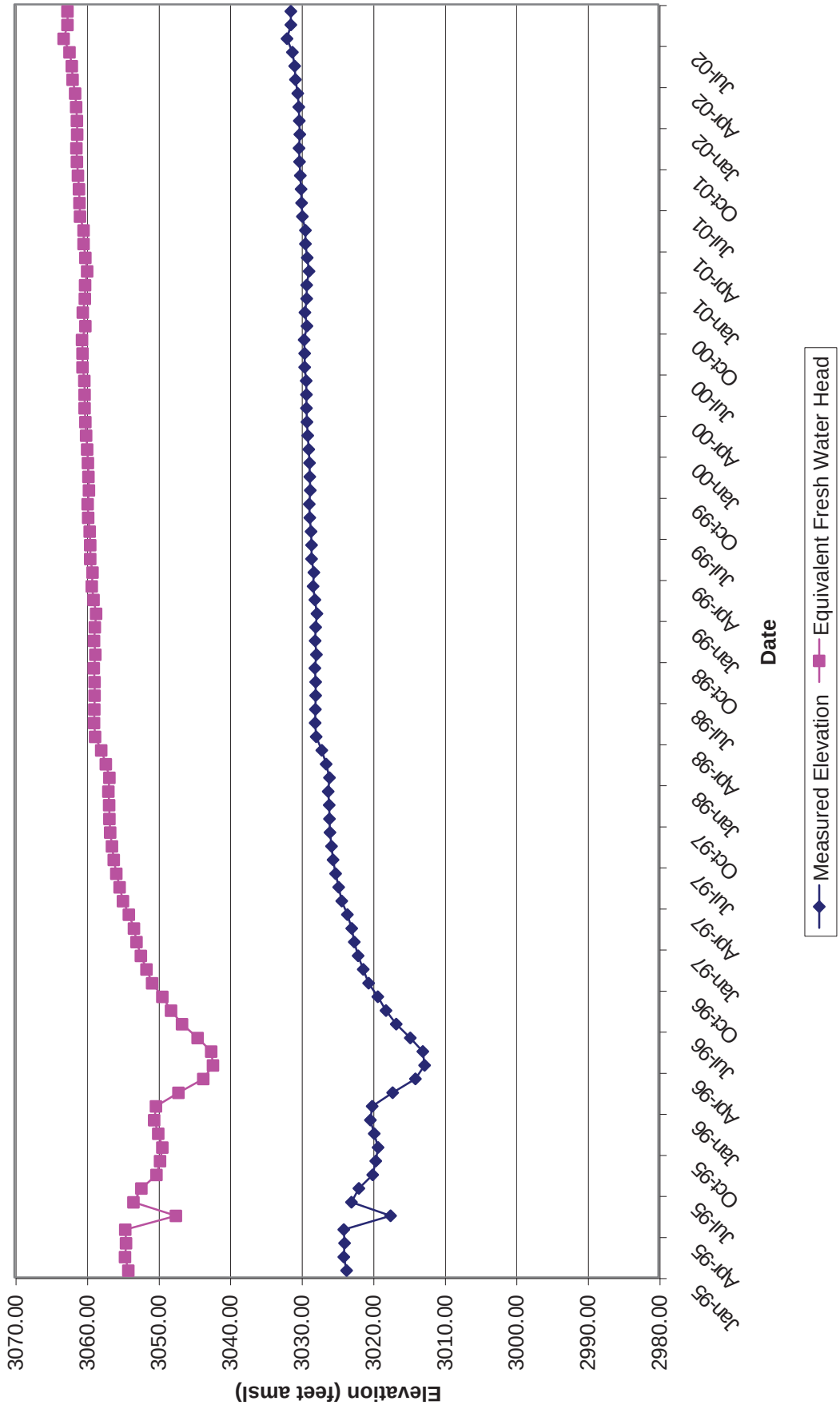

Figure 72 - WIPP-22 Culebra Historical Waterlevel Measurements

Table 73 - Well No. WIPP-25 (ANNULUS) Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3056.23	N/A
02/13/95	3056.45	N/A
03/13/95	3056.59	N/A
04/10/95	3056.61	N/A
05/08/95	3056.79	N/A
06/05/95	3056.90	N/A
07/17/95	3057.03	N/A
08/14/95	3056.82	N/A
09/05/95	3057.24	N/A
10/16/95	3057.43	N/A
11/06/95	3057.47	N/A
12/04/95	3057.52	N/A
01/08/96	3057.58	N/A
02/05/96	3057.61	N/A
03/11/96	3057.67	N/A
04/15/96	3057.72	N/A
05/13/96	3057.76	N/A
06/10/96	3057.84	N/A
07/15/96	3057.88	N/A
08/12/96	3057.92	N/A
09/03/96	3057.55	N/A
10/14/96	3058.09	N/A
11/11/96	3058.08	N/A
12/09/96	3058.01	N/A
01/13/97	3057.99	N/A
02/10/97	3057.97	N/A
03/10/97	3057.99	N/A
04/14/97	3057.99	N/A
05/13/97	3058.04	N/A
06/09/97	3058.05	N/A
07/14/97	3058.05	N/A
08/11/97	3058.06	N/A
09/15/97	3057.66	N/A
10/13/97	3058.02	N/A
11/10/97	3057.98	N/A
12/08/97	3057.89	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3057.78	N/A
02/09/98	3057.68	N/A
03/09/98	3057.64	N/A
04/13/98	3057.58	N/A
05/11/98	3057.55	N/A
06/08/98	3057.51	N/A
07/13/98	3057.46	N/A
08/10/98	3057.49	N/A
09/08/98	3057.49	N/A
10/12/98	3057.49	N/A
11/09/98	3057.49	N/A
12/07/98	3057.46	N/A
01/11/99	3057.50	N/A
02/08/99	3057.61	N/A
03/08/99	3057.51	N/A
04/12/99	3057.81	N/A
05/10/99	3057.86	N/A
06/07/99	3057.83	N/A
07/19/99	3058.03	N/A
08/09/99	3058.08	N/A
09/07/99	3058.06	N/A
10/04/99	3058.08	N/A
11/08/99	3058.17	N/A
12/06/99	3058.29	N/A
01/17/00	3058.13	N/A
09/12/00	3046.23	N/A
10/10/00	3047.01	N/A
11/06/00	3047.63	N/A
12/07/00	3048.23	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3048.77	N/A
02/05/01	3048.70	N/A
03/06/01	3049.60	N/A
04/03/01	3050.02	N/A
05/07/01	3050.28	N/A
06/05/01	3050.52	N/A
07/09/01	3050.69	N/A
08/08/01	3050.79	N/A
09/04/01	3050.85	N/A
10/08/01	3050.77	N/A
11/13/01	3050.55	N/A
12/04/01	3050.54	N/A
01/14/02	3050.61	N/A
02/06/02	3050.80	N/A
03/11/02	3050.55	N/A
04/09/02	3051.22	N/A
05/06/02	3051.35	N/A
06/10/02	3051.42	N/A
07/16/02	3051.67	N/A
08/12/02	3051.77	N/A
09/11/02	3051.83	N/A

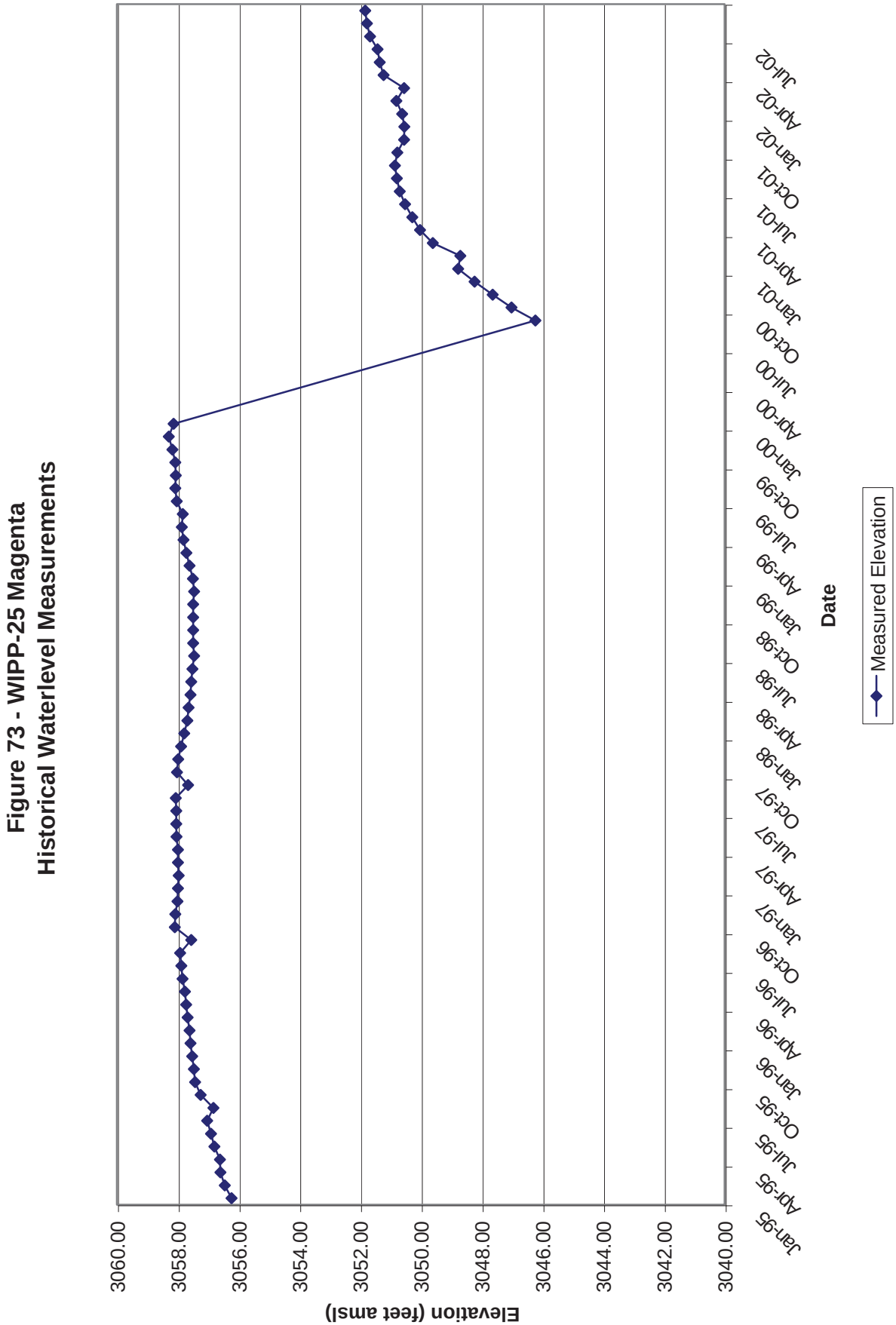
Figure 73 - WIPP-25 Magenta
Historical Waterlevel Measurements
Elevation (feet amsl)
3060.00
3058.00
3056.00
3054.00
3052.00
3050.00
3048.00
3046.00
3044.00
3042.00
3040.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation

Table 74 - Well No. WIPP-25 (PIP) Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3056.31	3053.28
02/13/95	3056.72	3053.68
03/13/95	3057.79	3054.74
04/10/95	3056.83	3053.79
05/08/95	3056.71	3053.67
06/05/95	3056.84	3053.80
07/17/95	3057.37	3054.33
08/14/95	3057.53	3054.48
09/05/95	3057.45	3054.41
10/16/95	3057.38	3054.34
11/06/95	3057.36	3054.32
12/04/95	3057.26	3054.22
01/08/96	3057.30	3054.26
02/05/96	3057.43	3054.39
03/11/96	3057.66	3054.61
04/15/96	3057.59	3054.44
05/13/96	3057.71	3054.66
06/10/96	3057.77	3054.72
07/15/96	3057.83	3054.78
08/12/96	3057.93	3054.88
09/03/96	3058.81	3055.45
10/14/96	3057.92	3054.87
11/11/96	3057.69	3054.64
12/09/96	3057.76	3054.71
01/13/97	3057.75	3054.70
02/10/97	3057.93	3054.88
03/10/97	3058.09	3055.04
04/14/97	3058.13	3055.08
05/13/97	3058.25	3055.20
06/09/97	3058.08	3055.03
07/14/97	3058.40	3055.35
08/11/97	3058.13	3055.08
09/15/97	3057.92	3054.87
10/13/97	3057.62	3054.57
11/10/97	3057.11	3054.07
12/08/97	3056.82	3053.78

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3056.91	3053.87
02/09/98	3057.18	3054.14
03/09/98	3057.09	3054.05
04/13/98	3056.74	3053.70
05/11/98	3057.47	3054.42
06/08/98	3057.43	3054.39
07/13/98	3057.46	3054.42
08/10/98	3057.68	3054.63
09/08/98	3057.75	3054.70
10/12/98	3057.40	3054.36
11/09/98	3057.94	3054.89
12/07/98	3057.81	3054.76
01/11/99	3058.37	3055.32
02/08/99	3058.40	3055.35
03/08/99	3058.47	3055.41
04/12/99	3058.32	3055.27
05/10/99	3058.46	3055.41
06/07/99	3058.61	3055.55
07/19/99	3058.14	3055.09
08/09/99	3057.71	3054.66
09/07/99	3058.02	3054.97
10/04/99	3058.10	3055.05
11/08/99	3058.47	3055.41
12/06/99	3059.02	3055.96
01/17/00	3059.59	3056.52
02/14/00	3059.61	3056.54
03/06/00	3059.72	3056.65
04/17/00	3059.70	3056.63
05/15/00	3059.66	3056.59
06/06/00	3059.53	3056.46
07/11/00	3060.05	3056.98
08/14/00	3059.65	3056.58
09/12/00	3053.17	3050.17
10/10/00	3055.38	3052.36
11/06/00	3056.67	3053.63
12/07/00	3057.46	3054.42

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3058.06	3055.01
02/05/01	3058.63	3055.57
03/06/01	3058.96	3055.90
04/03/01	3059.37	3056.31
05/07/01	3059.46	3056.40
06/05/01	3059.60	3056.53
07/09/01	3059.85	3056.78
08/08/01	3059.91	3056.84
09/04/01	3059.86	3056.79
10/08/01	3060.02	3056.95
11/13/01	3060.11	3057.04
12/04/01	3060.43	3057.36
01/14/02	3060.61	3057.53
02/06/02	3060.90	3057.82
03/11/02	3061.19	3058.11
04/09/02	3061.25	3058.17
05/06/02	3061.55	3058.46
06/10/02	3061.64	3058.55
07/16/02	3061.97	3058.88
08/12/02	3062.16	3059.07
09/11/02	3062.10	3059.01

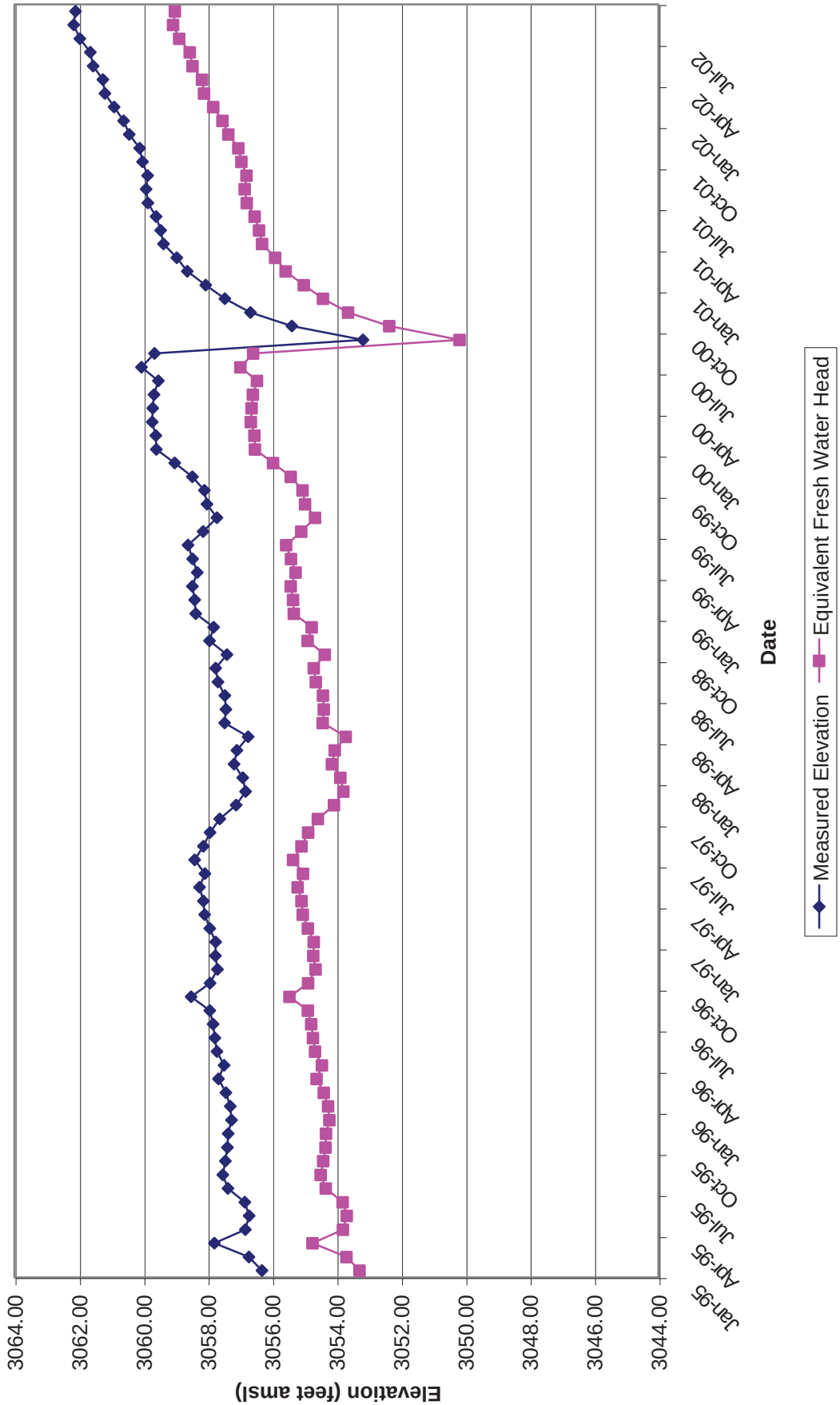

Figure 74 - WIPP-25 Culebra Historical Waterlevel Measurements

Table 75 - Well No. WIPP-26 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3018.25	3018.38
02/13/95	3018.27	3018.40
03/13/95	3018.31	3018.44
04/10/95	3018.26	3018.39
05/08/95	3018.29	3018.42
06/05/95	3018.53	3018.66
07/18/95	3019.14	3019.27
08/14/95	3019.02	3019.15
09/05/95	3018.91	3019.04
10/17/95	3019.12	3019.25
11/07/95	3019.08	3019.21
12/04/95	3019.25	3019.38
01/08/96	3019.25	3019.38
02/05/96	3019.25	3019.38
03/11/96	3019.48	3019.61
04/15/96	3019.23	3019.36
05/13/96	3019.26	3019.39
06/11/96	3019.17	3019.30
07/15/96	3019.40	3019.53
08/13/96	3019.50	3019.63
09/03/96	3020.12	3020.25
10/14/96	3020.44	3020.57
11/11/96	3020.28	3020.41
12/09/96	3020.25	3020.38
01/13/97	3019.96	3020.09
02/10/97	3020.02	3020.15
03/10/97	3020.15	3020.28
04/14/97	3020.06	3020.19
05/12/97	3020.15	3020.28
06/09/97	3019.63	3019.76
07/14/97	3020.14	3020.27
08/11/97	3020.25	3020.38
09/15/97	3020.25	3020.38
10/15/97	3020.25	3020.38
11/13/97	3020.24	3020.37
12/08/97	3020.19	3020.32

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3020.30	3020.43
02/09/98	3020.41	3020.54
03/10/98	3020.05	3020.18
04/13/98	3020.23	3020.36
05/11/98	3020.15	3020.28
06/08/98	3019.98	3020.11
07/13/98	3019.57	3019.70
08/10/98	3019.88	3020.01
09/08/98	3020.00	3020.13
10/12/98	3019.66	3019.79
11/09/98	3020.10	3020.23
12/07/98	3019.78	3019.91
01/11/99	3019.96	3020.09
02/08/99	3020.14	3020.27
03/08/99	3020.11	3020.24
04/12/99	3019.94	3020.07
05/10/99	3020.03	3020.16
06/07/99	3020.07	3020.20
07/19/99	3020.10	3020.23
08/09/99	3020.22	3020.35
09/07/99	3020.07	3020.20
10/04/99	3020.12	3020.25
11/08/99	3020.35	3020.48
12/06/99	3020.41	3020.54
01/19/00	3020.67	3020.80
02/14/00	3020.71	3020.84
03/06/00	3020.87	3021.00
04/17/00	3020.89	3021.02
05/15/00	3020.87	3021.00
06/07/00	3020.71	3020.84
07/11/00	3022.42	3022.56
08/14/00	3021.92	3022.06
09/12/00	3021.64	3021.77
10/10/00	3021.40	3021.53
11/06/00	3021.65	3021.78
12/04/00	3021.71	3021.84

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3021.75	3021.89
02/07/01	3021.83	3021.97
03/06/01	3021.64	3021.77
04/03/01	3022.05	3022.19
05/07/01	3021.95	3022.09
06/04/01	3021.20	3021.33
07/09/01	3021.79	3021.93
08/06/01	3021.40	3021.53
09/05/01	3020.57	3020.70
10/08/01	3021.41	3021.54
11/13/01	3022.14	3022.28
12/05/01	3021.40	3021.53
01/15/02	3021.72	3021.85
02/06/02	3021.82	3021.96
03/11/02	3021.84	3021.98
04/09/02	3021.95	3022.09
05/06/02	3022.14	3022.28
06/12/02	3021.93	3022.07
07/16/02	3022.43	3022.57
08/12/02	3022.39	3022.53
09/11/02	3021.86	3022.00

Figure 75 - WIPP-26 Culebra Historical Waterlevel Measruements

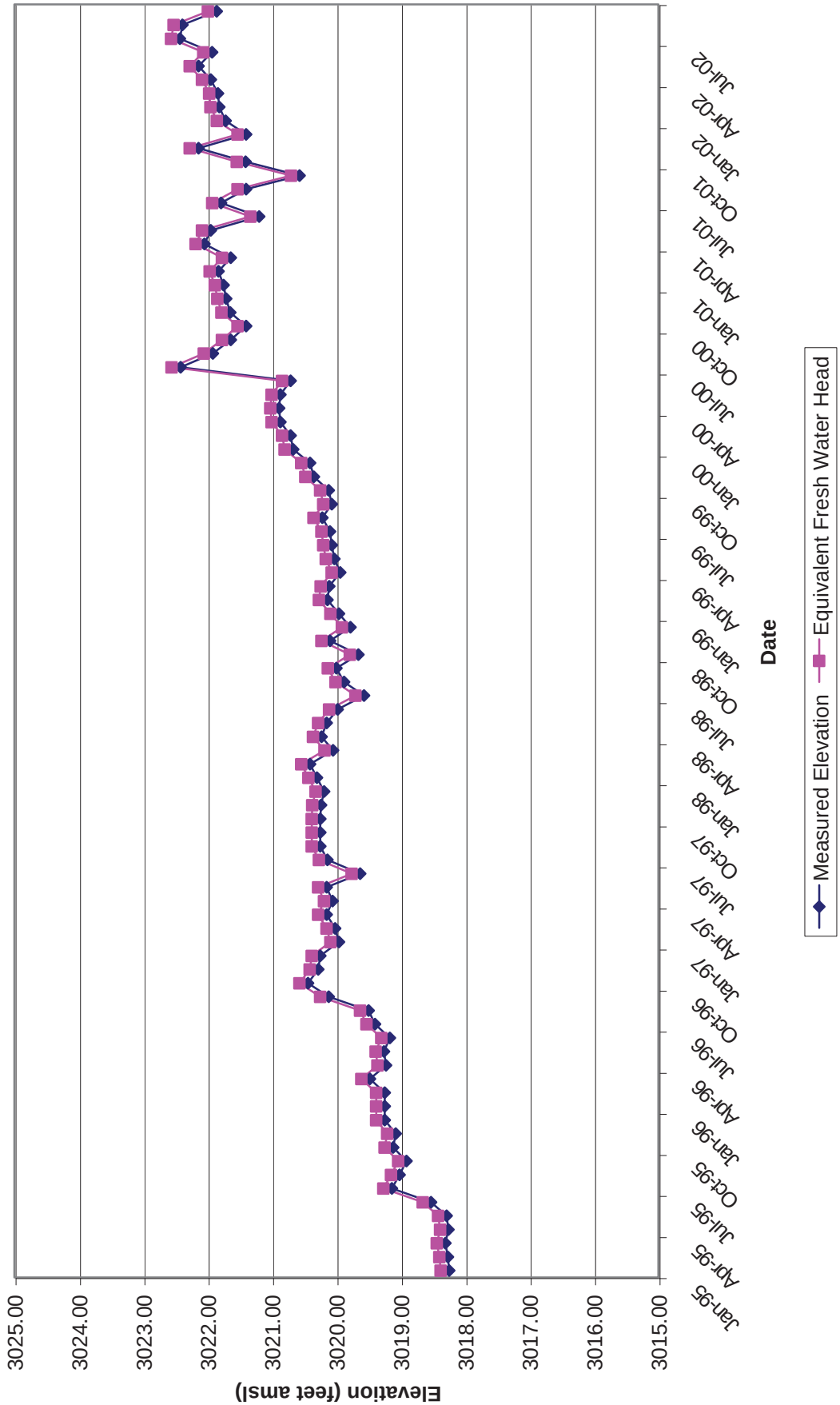

Table 76 - Well No. WIPP-27 (ANNULUS) Magenta
January 1995 through September 1997

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3073.33	N/A
02/13/95	3072.85	N/A
03/13/95	3072.24	N/A
04/10/95	3072.00	N/A
05/08/95	3072.54	N/A
06/05/95	3072.78	N/A
07/17/95	3073.08	N/A
08/14/95	3072.89	N/A
09/05/95	3072.76	N/A
10/16/95	3072.95	N/A
11/06/95	3072.99	N/A
12/04/95	3073.11	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/96	3073.27	N/A
02/05/96	3073.16	N/A
03/11/96	3073.06	N/A
04/15/96	3072.98	N/A
05/13/96	3072.91	N/A
06/10/96	3072.85	N/A
07/15/96	3072.47	N/A
08/12/96	3072.07	N/A
09/03/96	3071.61	N/A
10/14/96	3072.10	N/A
11/11/96	3072.63	N/A
12/09/96	3072.79	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/97	3072.62	N/A
02/10/97	3072.77	N/A
03/10/97	3072.73	N/A
04/14/97	3072.72	N/A
05/12/97	3072.57	N/A
06/09/97	3072.24	N/A
07/14/97	3071.94	N/A
08/11/97	3071.81	N/A
09/15/97	3071.40	N/A

Figure 76 - WIPP-27 Magenta Historical Waterlevel Measurements

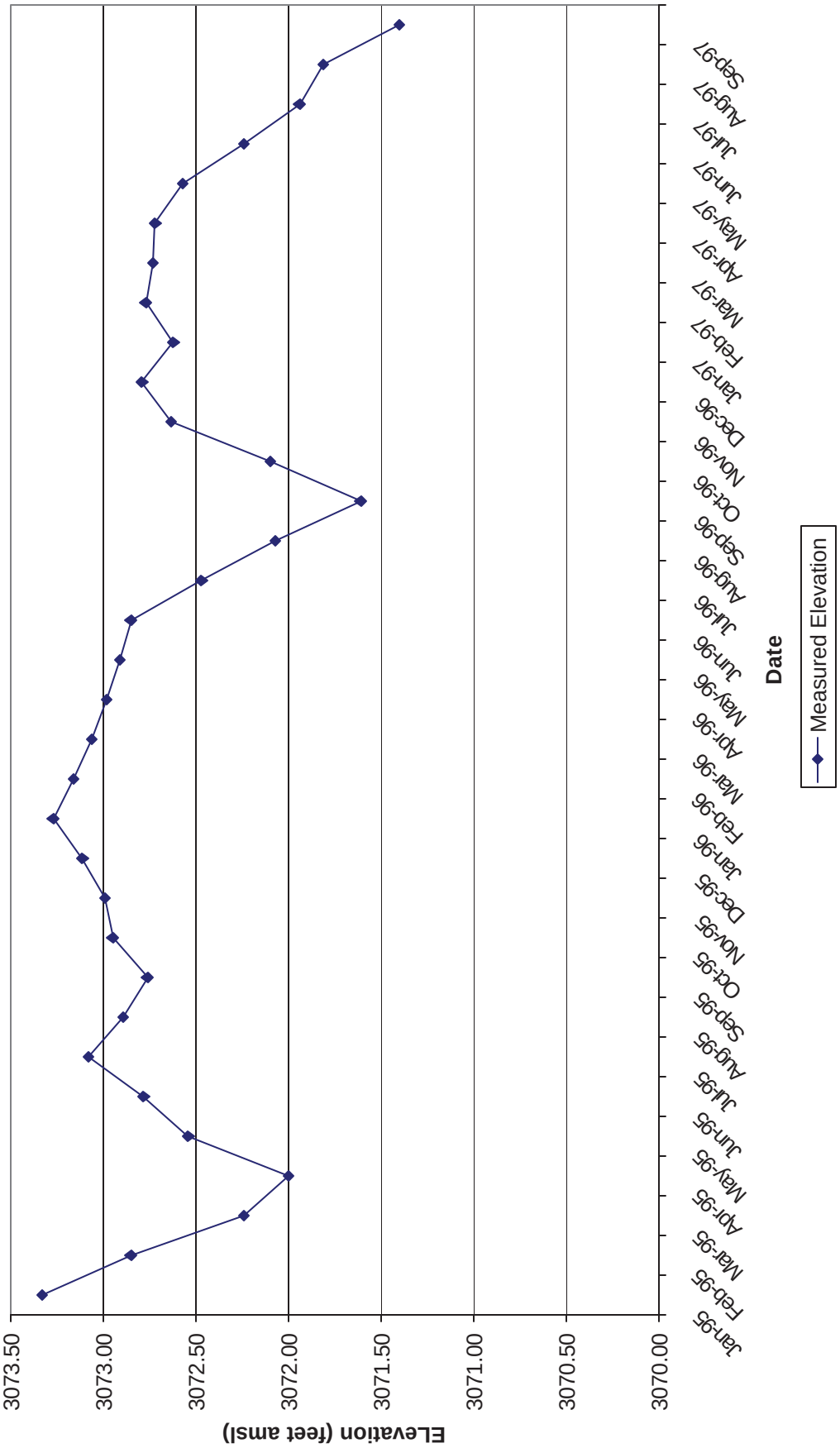

Table 77 - Well No. WIPP-27 (PIP)Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3080.85	3086.90
02/13/95	3079.84	3085.86
03/13/95	3078.96	3084.96
04/10/95	3078.67	3084.66
05/08/95	3079.28	3085.29
06/05/95	3079.46	3085.47
07/17/95	3080.23	3086.26
08/14/95	3080.01	3086.04
09/05/95	3079.71	3085.73
10/16/95	3079.95	3085.98
11/06/95	3080.02	3086.05
12/04/95	3080.24	3086.27
01/08/96	3080.50	3086.54
02/05/96	3080.40	3086.44
03/11/96	3080.27	3086.31
04/15/96	3080.15	3086.18
05/13/96	3080.16	3086.19
06/10/96	3080.15	3086.18
07/15/96	3079.80	3085.82
08/12/96	3079.33	3085.34
09/03/96	3079.22	3085.22
10/14/96	3079.41	3085.42
11/11/96	3079.90	3085.92
12/09/96	3080.29	3086.33
01/13/97	3080.12	3086.15
02/10/97	3080.26	3086.29
03/10/97	3080.18	3086.21
04/14/97	3080.22	3086.25
05/12/97	3080.04	3086.07
06/09/97	3079.68	3085.70
07/14/97	3079.29	3085.30
08/11/97	3079.19	3085.19
09/15/97	3079.22	3085.22
10/13/97	3079.11	3085.11
11/10/97	3079.15	3085.15
12/08/97	3079.18	3085.18

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3079.17	3085.17
02/09/98	3079.31	3085.32
03/09/98	3079.41	3085.42
04/13/98	3078.50	3084.48
05/11/98	3079.25	3085.26
06/08/98	3079.17	3085.17
07/13/98	3079.19	3085.19
08/10/98	3079.49	3085.50
09/08/98	3079.79	3085.81
10/12/98	3079.79	3085.81
11/09/98	3080.09	3086.12
12/07/98	3081.37	3087.44
01/11/99	3080.84	3086.89
02/08/99	3080.81	3086.86
03/08/99	3080.40	3086.44
04/12/99	3080.30	3086.34
05/10/99	3080.32	3086.36
06/07/99	3080.54	3086.58
07/19/99	3080.75	3086.80
08/09/99	3080.71	3086.76
09/07/99	3080.70	3086.75
10/04/99	3080.59	3086.63
11/08/99	3080.69	3086.74
12/06/99	3080.73	3086.78
01/17/00	3080.91	3086.96
02/14/00	3081.07	3087.13
03/06/00	3081.20	3087.26
04/17/00	3081.07	3087.13
05/15/00	3080.87	3086.92
06/05/00	3080.77	3086.82
07/10/00	3081.22	3087.28
09/12/00	3080.98	3087.04
10/09/00	3080.93	3086.98
11/06/00	3081.09	3087.15
12/04/00	3081.22	3087.28

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3081.14	3087.20
02/06/01	3081.02	3087.08
03/06/01	3080.87	3086.92
04/03/01	3080.83	3086.88
05/07/01	3080.65	3086.70
06/04/01	3080.80	3086.85
07/09/01	3080.44	3086.48
08/06/01	3080.13	3086.16
09/04/01	3080.17	3086.20
10/08/01	3080.81	3086.86
11/13/01	3081.45	3087.52
12/04/01	3082.10	3088.19
01/14/02	3082.55	3088.65
02/06/02	3082.65	3088.75
03/11/02	3082.79	3088.90
04/09/02	3082.60	3088.70
05/06/02	3082.62	3088.72
06/10/02	3082.30	3088.39
07/16/02	3081.96	3088.04
08/12/02	3081.86	3087.94
09/10/02	3081.68	3087.76

Figure 77 - WIPP-27 Culebra Historical Waterlevel Measurements

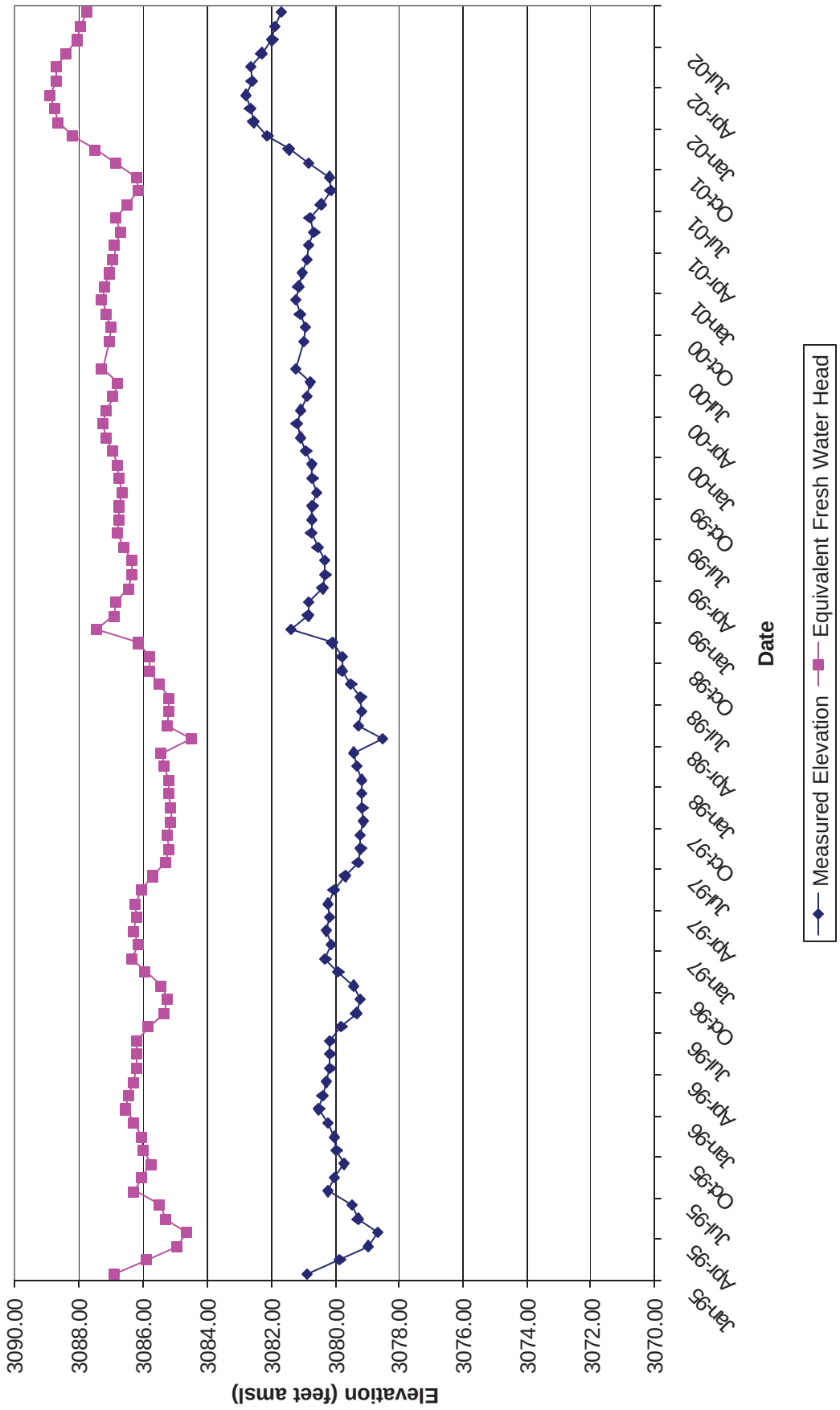

Table 78 - Well No. WIPP-28 (PIP) Rustler/Salado
January 1995 through December 1998

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3052.97	N/A
02/13/95	3052.63	N/A
03/13/95	3052.43	N/A
04/10/95	3052.50	N/A
05/08/95	3052.39	N/A
06/05/95	3052.11	N/A
07/17/95	3051.63	N/A
08/14/95	3051.75	N/A
09/05/95	3051.47	N/A
10/16/95	3051.34	N/A
11/06/95	3051.47	N/A
12/04/95	3051.11	N/A
01/08/96	3050.82	N/A
02/05/96	3050.82	N/A
03/11/96	3051.17	N/A
04/15/96	3050.68	N/A
05/13/96	3050.98	N/A
06/10/96	3050.53	N/A
07/15/96	3050.59	N/A
08/12/96	3050.45	N/A
09/03/96	3050.53	N/A
10/14/96	3050.43	N/A
11/11/96	3050.26	N/A
12/09/96	3050.21	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/97	3049.76	N/A
02/10/97	3049.78	N/A
03/10/97	3049.83	N/A
04/14/97	3050.02	N/A
05/13/97	3050.20	N/A
06/09/97	3050.27	N/A
07/14/97	3050.25	N/A
08/11/97	3050.21	N/A
09/15/97	3050.05	N/A
10/13/97	3049.87	N/A
11/10/97	3049.77	N/A
12/08/97	3050.15	N/A
01/12/98	3050.09	N/A
02/09/98	3050.19	N/A
03/09/98	3049.77	N/A
04/13/98	3049.35	N/A
05/11/98	3050.02	N/A
06/08/98	3049.99	N/A
07/13/98	3049.81	N/A
08/10/98	3049.66	N/A
09/08/98	3049.80	N/A
10/12/98	3049.59	N/A
11/09/98	3049.92	N/A
12/07/98	3049.65	N/A

Figure 78 - WIPP-28 Rustler/Salado Historical Waterlevel Measurements

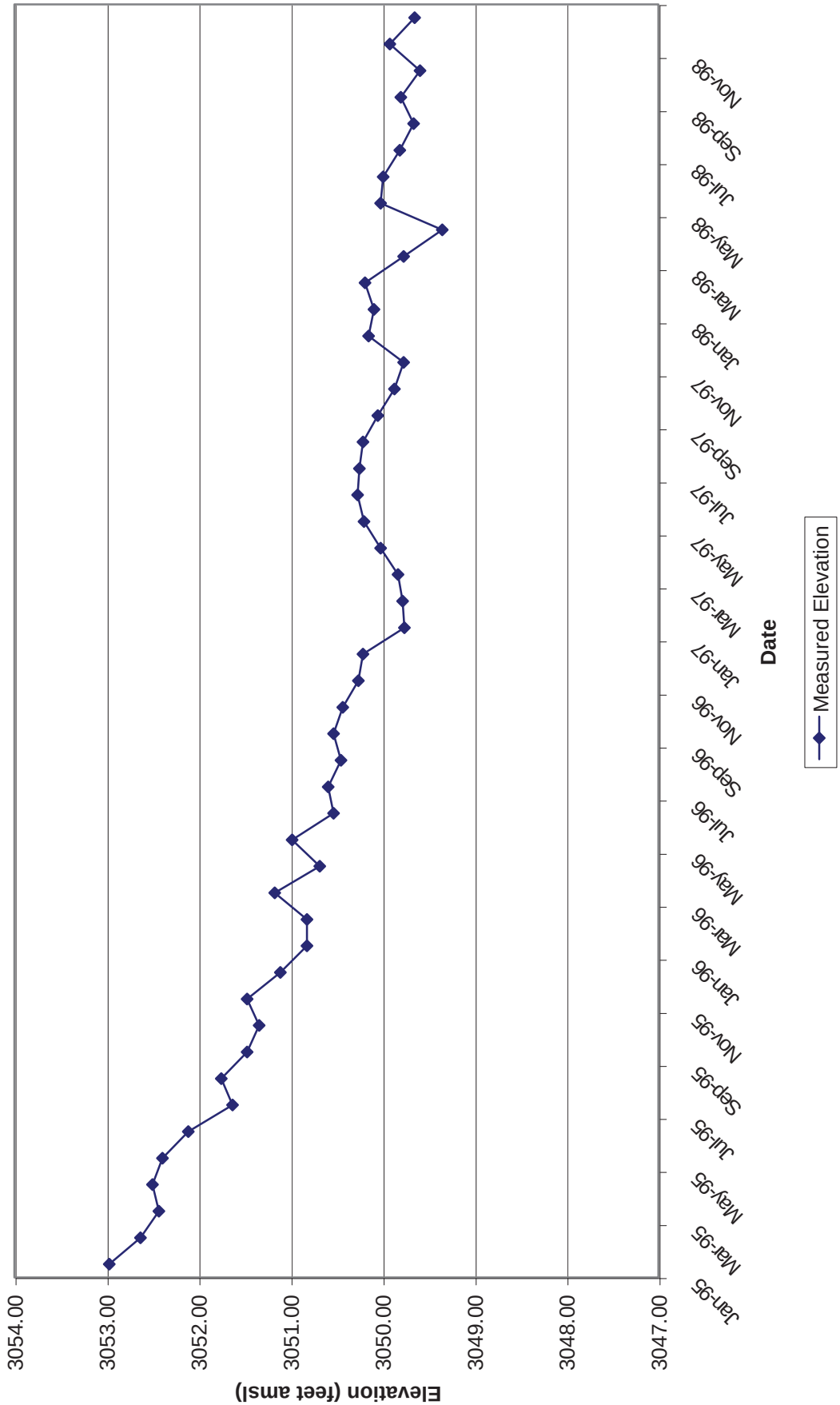

Table 79 - Well No. WIPP-29 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	2966.84	2969.96
02/14/95	2966.90	2970.04
03/14/95	2966.91	2970.05
04/10/95	2966.93	2970.07
05/09/95	2966.87	2970.00
06/05/95	2966.85	2969.98
07/18/95	2966.95	2970.10
08/14/95	2966.64	2969.73
09/05/95	2966.81	2969.93
10/17/95	2966.89	2970.02
11/07/95	2966.75	2969.86
12/04/95	2966.60	2969.68
01/08/96	2966.66	2969.75
02/05/96	2966.55	2969.62
03/11/96	2966.34	2969.37
04/15/96	2966.70	2969.80
05/14/96	2966.67	2969.76
06/11/96	2966.50	2969.56
07/15/96	2966.66	2969.75
08/13/96	2966.61	2969.69
09/03/96	2967.16	2970.34
10/14/96	2966.64	2969.73
11/11/96	2966.48	2969.54
12/09/96	2966.53	2969.60
01/13/97	2966.51	2969.57
02/10/97	2966.52	2969.59
03/10/97	2966.98	2970.13
04/14/97	2966.95	2970.10
05/12/97	2967.02	2970.18
06/09/97	2967.24	2970.44
07/14/97	2967.36	2970.58
08/11/97	2966.99	2970.14
09/15/97	2966.97	2970.12
10/15/97	2967.39	2970.62
11/10/97	2967.00	2970.15
12/08/97	2967.10	2970.27

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	2967.42	2970.65
02/09/98	2967.33	2970.55
03/10/98	2967.14	2970.32
04/13/98	2967.24	2970.44
05/11/98	2967.14	2970.32
06/08/98	2966.94	2970.08
07/13/98	2967.06	2970.23
08/10/98	2966.98	2970.13
09/08/98	2966.77	2969.88
10/12/98	2967.01	2970.17
11/09/98	2967.22	2970.41
12/07/98	2966.73	2969.83
01/11/99	2966.78	2969.89
02/08/99	2966.93	2970.07
03/08/99	2966.84	2969.96
04/12/99	2966.76	2969.87
05/10/99	2966.85	2969.98
06/07/99	2966.99	2970.14
07/19/99	2967.04	2970.20
08/09/99	2966.94	2970.08
09/07/99	2967.03	2970.19
10/04/99	2966.87	2970.00
11/08/99	2966.68	2969.78
12/06/99	2966.62	2969.70
01/18/00	2966.76	2969.87
02/14/00	2966.82	2969.94
03/06/00	2966.83	2969.95
04/17/00	2966.92	2970.06
05/15/00	2966.77	2969.88
06/07/00	2967.11	2970.28
07/11/00	2967.74	2971.03
08/14/00	2967.17	2970.36
09/12/00	2967.24	2970.44
10/10/00	2967.16	2970.34
11/06/00	2967.66	2970.94
12/04/00	2967.37	2970.59

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	2967.17	2970.36
02/07/01	2967.26	2970.46
03/06/01	2967.23	2970.43
04/04/01	2967.11	2970.28
05/07/01	2967.06	2970.23
06/04/01	2966.91	2970.05
07/09/01	2966.60	2969.68
08/06/01	2967.01	2970.17
09/04/01	2966.86	2969.99
10/08/01	2966.93	2970.07
11/13/01	2966.75	2969.86
12/04/01	2967.06	2970.23
01/14/02	2966.84	2969.96
02/06/02	2967.15	2970.33
03/11/02	2967.00	2970.15
04/09/02	2967.25	2970.45
05/06/02	2967.29	2970.50
06/12/02	2967.07	2970.24
07/16/02	2967.10	2970.27
08/12/02	2967.16	2970.34
09/11/02	2967.07	2970.24

Figure 79 - WIPP-29 Culebra Historical Waterlevel Measurements

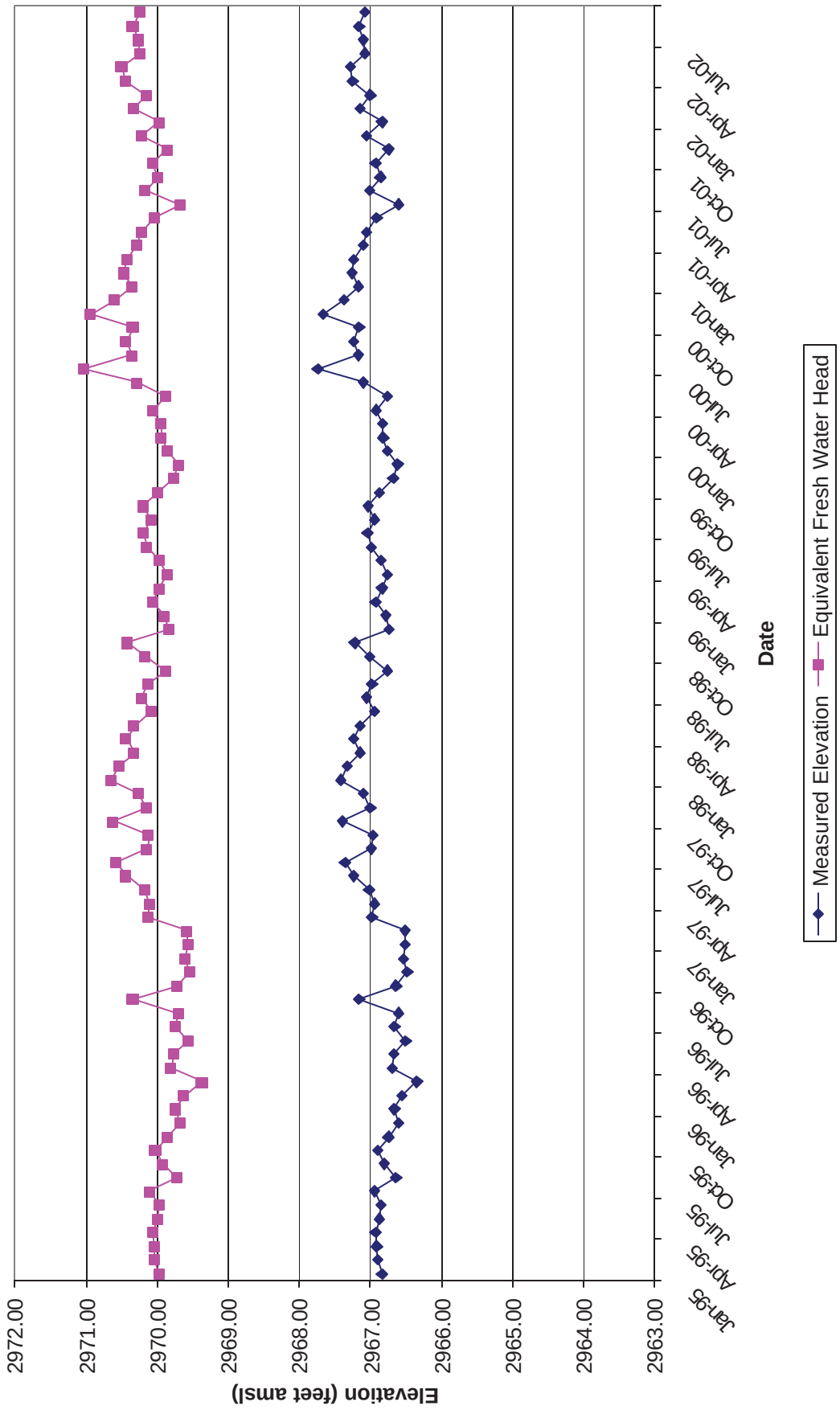

Table 80 - Well No. WIPP-30 (ANNULUS) Magenta
August 2000 through March 2002

Date	Measured Elevation	Equivalent Fresh Water Head
09/12/00	3128.43	N/A
10/09/00	3093.56	N/A
11/06/00	3091.75	N/A
12/07/00	3092.94	N/A
01/08/01	3095.29	N/A
02/06/01	3097.69	N/A
03/06/01	3099.43	N/A
04/04/01	3100.33	N/A
05/08/01	3102.10	N/A
06/05/01	3104.27	N/A
07/10/01	3106.28	N/A
08/08/01	3107.15	N/A
09/04/01	3107.50	N/A
10/10/01	3108.40	N/A
11/12/01	3109.14	N/A
12/03/01	3110.68	N/A
01/15/02	3111.36	N/A
02/06/02	3111.47	N/A
02/06/02	3111.47	N/A
02/06/02	3111.47	N/A
03/11/02	3110.55	N/A

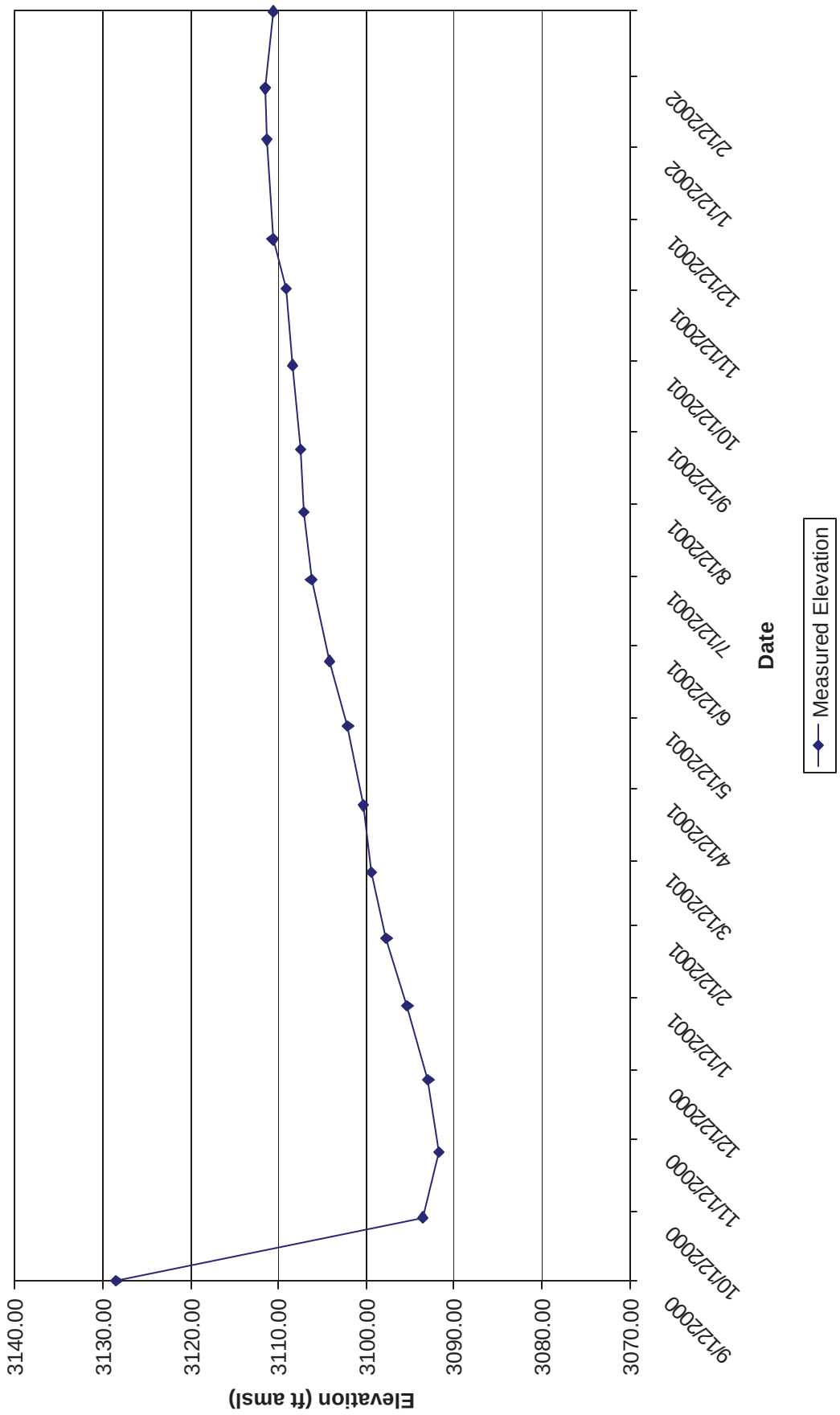
Figure 80 - WIPP-30 Magenta
Historical Waterlevel Measurements
Elevation (ft amsl)
3140.00
3130.00
3120.00
3110.00
3100.00
3090.00
3080.00
3070.00
9/12/2000
10/12/2000
11/12/2000
12/12/2000
1/12/2001
2/12/2001
3/12/2001
4/12/2001
5/12/2001
6/12/2001
7/12/2001
8/12/2001
9/12/2001
10/12/2001
11/12/2001
12/12/2001
1/12/2002
2/12/2002
Date
Measured Elevation

Table 81 - Well No. WIPP-30 (PIP) Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3064.64	3071.62
02/13/95	3064.50	3071.48
03/13/95	3064.45	3071.42
04/10/95	3064.50	3071.48
05/08/95	3064.64	3071.62
06/05/95	3064.74	3071.72
07/17/95	3064.69	3071.67
08/14/95	3064.97	3071.96
09/05/95	3064.67	3071.65
10/16/95	3064.72	3071.70
11/06/95	3065.01	3072.00
12/04/95	3062.52	3069.45
01/08/96	3064.83	3071.81
02/05/96	3064.58	3071.56
03/11/96	3064.62	3071.60
04/15/96	3064.61	3071.59
05/13/96	3064.64	3071.62
06/10/96	3064.90	3071.89
07/15/96	3065.16	3072.15
08/12/96	3065.08	3072.07
09/03/96	3065.18	3072.17
10/14/96	3065.14	3072.13
11/11/96	3065.09	3072.08
12/09/96	3065.09	3072.08
01/13/97	3065.11	3072.10
02/10/97	3065.15	3072.14
03/10/97	3065.32	3072.32
04/14/97	3065.53	3072.53
05/12/97	3065.59	3072.59
06/09/97	3065.93	3072.94
07/14/97	3066.21	3073.23
08/11/97	3066.14	3073.16
09/15/97	3065.99	3073.00
10/13/97	3065.65	3072.65
11/10/97	3065.48	3072.48
12/08/97	3064.95	3071.94

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3065.05	3072.04
02/09/98	3068.89	3075.98
03/09/98	3069.76	3076.87
04/13/98	3068.72	3075.80
05/11/98	3068.27	3075.34
06/08/98	3067.70	3074.76
07/13/98	3067.40	3074.45
08/10/98	3069.46	3076.56
09/08/98	3067.05	3074.09
10/12/98	3066.34	3073.36
11/09/98	3066.55	3073.58
12/07/98	3066.11	3073.13
01/11/99	3066.23	3073.25
02/08/99	3066.71	3073.74
03/08/99	3066.72	3073.75
04/12/99	3066.55	3073.58
05/10/99	3066.92	3073.96
06/07/99	3066.71	3073.74
07/19/99	3066.51	3073.54
08/09/99	3066.43	3073.45
09/07/99	3066.49	3073.52
10/04/99	3066.46	3073.48
11/08/99	3066.64	3073.67
12/06/99	3066.73	3073.76
01/17/00	3066.72	3073.75
02/16/00	3066.86	3073.89
03/06/00	3067.00	3074.04
04/17/00	3066.79	3073.82
05/15/00	3066.73	3073.76
06/05/00	3066.50	3073.53
07/10/00	3066.54	3073.57
08/14/00	3066.41	3073.43
09/12/00	3064.56	3071.54
10/09/00	3060.69	3067.57
11/06/00	3060.98	3067.87
12/07/00	3061.22	3068.11

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3061.98	3068.89
02/06/01	3062.98	3069.92
03/06/01	3063.93	3070.89
04/04/01	3064.94	3071.93
05/08/01	3065.72	3072.73
06/05/01	3066.59	3073.62
07/10/01	3066.76	3073.79
08/08/01	3066.62	3073.65
09/04/01	3067.12	3074.16
10/10/01	3067.41	3074.46
11/12/01	3067.57	3074.62
12/03/01	3067.85	3074.91
01/15/02	3068.26	3075.33
02/06/02	3068.41	3075.48
03/11/02	3069.00	3076.09
04/09/02	3069.16	3076.25
05/08/02	3069.70	3076.81
06/12/02	3069.94	3077.05
07/15/02	3070.02	3077.13
08/13/02	3070.23	3077.35
09/09/02	3070.19	3077.31

Figure 81 - WIPP-30 Culebra Historical Waterlevel Measurements

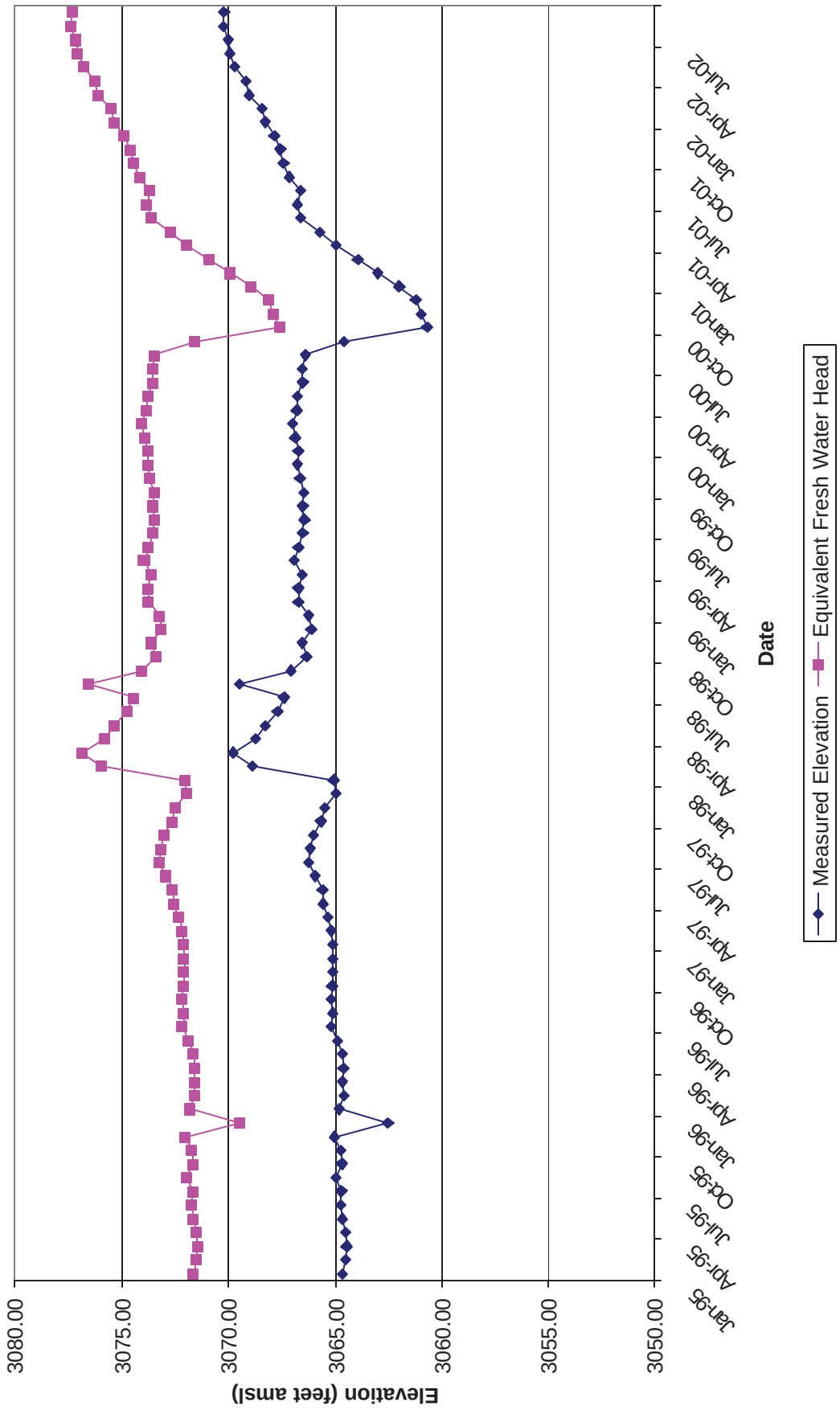

Table 82 - Well No. WQSP-1 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/05/95	3051.58	3068.16
07/17/95	3051.61	3068.19
08/07/95	3051.63	3068.22
09/05/95	3050.68	3067.22
10/16/95	3051.40	3067.97
11/06/95	3051.81	3068.40
12/04/95	3051.68	3068.27
01/10/96	3051.85	3067.59
02/08/96	3051.03	3067.59
03/11/96	3051.00	3067.56
04/15/96	3050.79	3067.34
05/13/96	3051.24	3067.81
06/10/96	3051.68	3068.27
07/15/96	3051.75	3068.34
08/12/96	3051.39	3067.96
09/03/96	3051.95	3068.55
10/14/96	3051.97	3068.57
11/11/96	3051.63	3068.22
12/09/96	3051.87	3068.47
01/13/97	3051.99	3068.59
02/10/97	3051.87	3068.47
03/10/97	3052.12	3068.73
04/14/97	3052.49	3069.12
05/13/97	3052.51	3069.14
06/09/97	3052.76	3069.40
07/15/97	3053.13	3069.79
08/11/97	3052.79	3069.43
09/15/97	3052.67	3069.31
10/13/97	3052.30	3068.92
11/10/97	3052.30	3068.92
12/08/97	3051.65	3068.24

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3051.75	3068.34
02/09/98	3054.69	3071.42
03/09/98	3055.03	3071.78
04/13/98	3054.51	3071.23
05/11/98	3054.09	3070.79
06/08/98	3053.65	3070.33
07/13/98	3053.32	3069.99
08/10/98	3053.31	3069.98
09/08/98	3053.22	3069.88
10/12/98	3052.68	3069.32
11/13/98	3052.75	3069.39
12/07/98	3052.60	3069.23
01/11/99	3052.86	3069.50
02/08/99	3053.24	3069.90
03/08/99	3053.15	3069.81
04/12/99	3053.03	3069.68
05/10/99	3053.35	3070.02
06/07/99	3053.21	3069.87
07/19/99	3052.95	3069.60
08/09/99	3052.84	3069.48
09/07/99	3052.88	3069.53
10/04/99	3052.72	3069.36
11/08/99	3053.10	3069.76
12/06/99	3053.31	3069.98
01/18/00	3053.49	3070.16
02/14/00	3053.45	3070.12
03/06/00	3053.82	3070.51
04/17/00	3053.38	3070.05
05/15/00	3053.36	3070.03
06/05/00	3053.06	3069.71
07/10/00	3053.20	3069.86
08/14/00	3053.16	3069.82
09/12/00	3052.95	3069.60
10/09/00	3052.71	3069.35
11/06/00	3053.31	3069.98
12/07/00	3053.00	3069.65

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3053.00	3069.65
02/06/01	3053.09	3069.75
03/06/01	3053.10	3069.76
04/05/01	3053.09	3069.75
05/08/01	3053.41	3070.08
06/05/01	3053.68	3070.36
07/09/01	3053.65	3070.33
08/07/01	3053.48	3070.15
09/04/01	3053.54	3070.22
10/10/01	3053.58	3070.26
11/14/01	3053.81	3070.50
12/05/01	3053.61	3070.29
01/16/02	3053.89	3070.58
02/05/02	3054.02	3070.72
03/11/02	3054.37	3071.09
04/08/02	3054.62	3071.35
05/06/02	3054.74	3071.47
06/10/02	3054.96	3071.71
07/15/02	3054.97	3071.72
08/12/02	3055.13	3071.88
09/09/02	3055.02	3071.77

Figure 82 - WQSP-1 Culebra
Historical Waterlevel Measurements

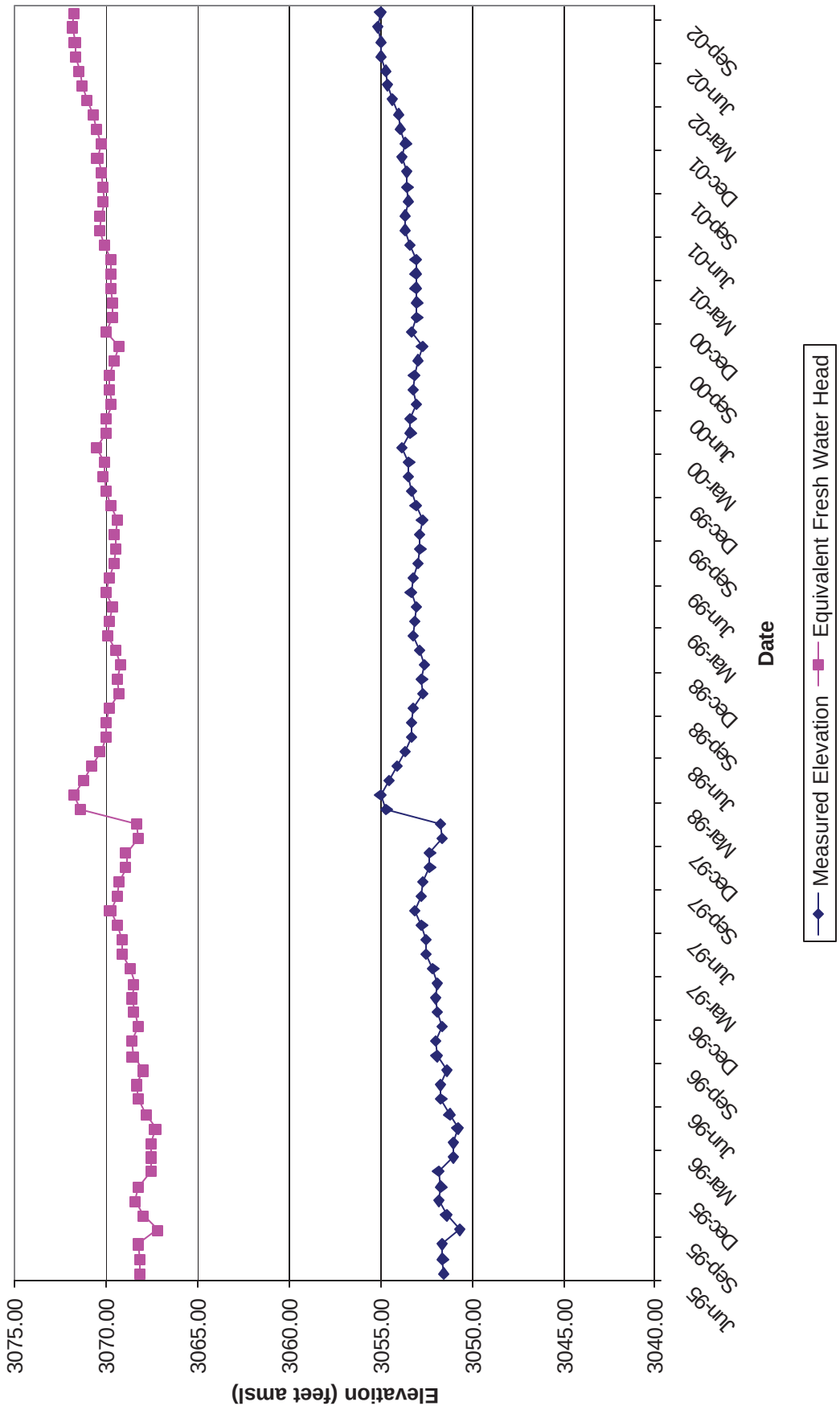

Table 83 - Well No. WQSP-2 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/05/95	3057.26	3076.90
07/19/95	3058.39	3078.08
08/16/95	3055.89	3075.47
09/08/95	3054.09	3073.58
10/18/95	3055.80	3075.37
11/08/95	3056.51	3076.11
12/06/95	3057.65	3077.31
01/10/96	3058.86	3078.46
02/08/96	3058.75	3078.46
03/11/96	3057.16	3076.79
04/15/96	3058.23	3077.92
05/13/96	3056.37	3075.97
06/10/96	3057.90	3077.57
07/15/96	3058.99	3078.71
08/12/96	3056.48	3076.08
09/03/96	3057.97	3077.64
10/14/96	3059.18	3078.91
11/11/96	3059.18	3078.91
12/09/96	3060.12	3079.89
01/14/97	3060.77	3080.57
02/10/97	3060.82	3080.63
03/10/97	3061.46	3081.30
04/14/97	3062.30	3082.18
05/14/97	3058.98	3078.70
06/11/97	3060.29	3080.07
07/15/97	3061.59	3081.43
08/13/97	3059.34	3079.08
09/17/97	3060.59	3080.39
10/16/97	3060.86	3080.67
11/10/97	3061.34	3081.17
12/08/97	3060.88	3080.69

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3061.28	3081.11
02/09/98	3064.57	3084.55
03/09/98	3065.11	3085.12
04/13/98	3061.66	3081.51
05/11/98	3060.91	3080.72
06/08/98	3061.08	3080.90
07/13/98	3061.48	3081.32
08/10/98	3062.00	3081.86
09/08/98	3060.01	3079.78
10/12/98	3060.16	3079.94
11/13/98	3060.80	3080.61
12/07/98	3060.96	3080.77
01/11/99	3061.72	3081.57
02/08/99	3062.24	3082.11
03/08/99	3059.93	3079.69
04/12/99	3059.93	3079.69
05/10/99	3060.76	3080.56
06/07/99	3061.16	3080.98
07/19/99	3061.41	3081.24
08/09/99	3061.52	3081.36
09/07/99	3061.73	3081.58
10/04/99	3058.05	3077.73
11/08/99	3058.96	3078.68
12/06/99	3059.44	3079.18
01/17/00	3059.95	3079.72
02/14/00	3060.42	3080.21
03/06/00	3061.02	3080.84
04/17/00	3059.16	3078.89
05/15/00	3059.41	3079.15
06/05/00	3059.43	3079.17
07/10/00	3059.85	3079.61
08/14/00	3060.08	3079.85
09/12/00	3060.25	3080.03
10/09/00	3058.22	3077.90
11/06/00	3059.13	3078.86
12/07/00	3059.11	3078.84

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3059.47	3079.21
02/06/01	3059.73	3079.49
03/07/01	3059.97	3079.74
04/04/01	3058.68	3078.39
05/08/01	3058.92	3078.64
06/05/01	3059.69	3079.44
07/09/01	3059.90	3079.66
08/08/01	3060.00	3079.77
09/06/01	3060.16	3079.94
10/10/01	3059.01	3078.73
11/14/01	3059.42	3079.16
12/05/01	3059.45	3079.19
01/16/02	3060.01	3079.78
02/05/02	3060.23	3080.01
03/12/02	3060.75	3080.55
04/08/02	3060.01	3079.78
05/06/02	3060.28	3080.06
06/10/02	3060.71	3080.51
07/15/02	3060.83	3080.64
08/12/02	3061.17	3080.99
09/09/02	3061.22	3081.05

Figure 83 - WQSP-2 Culebra
Historical Waterlevel Measurements

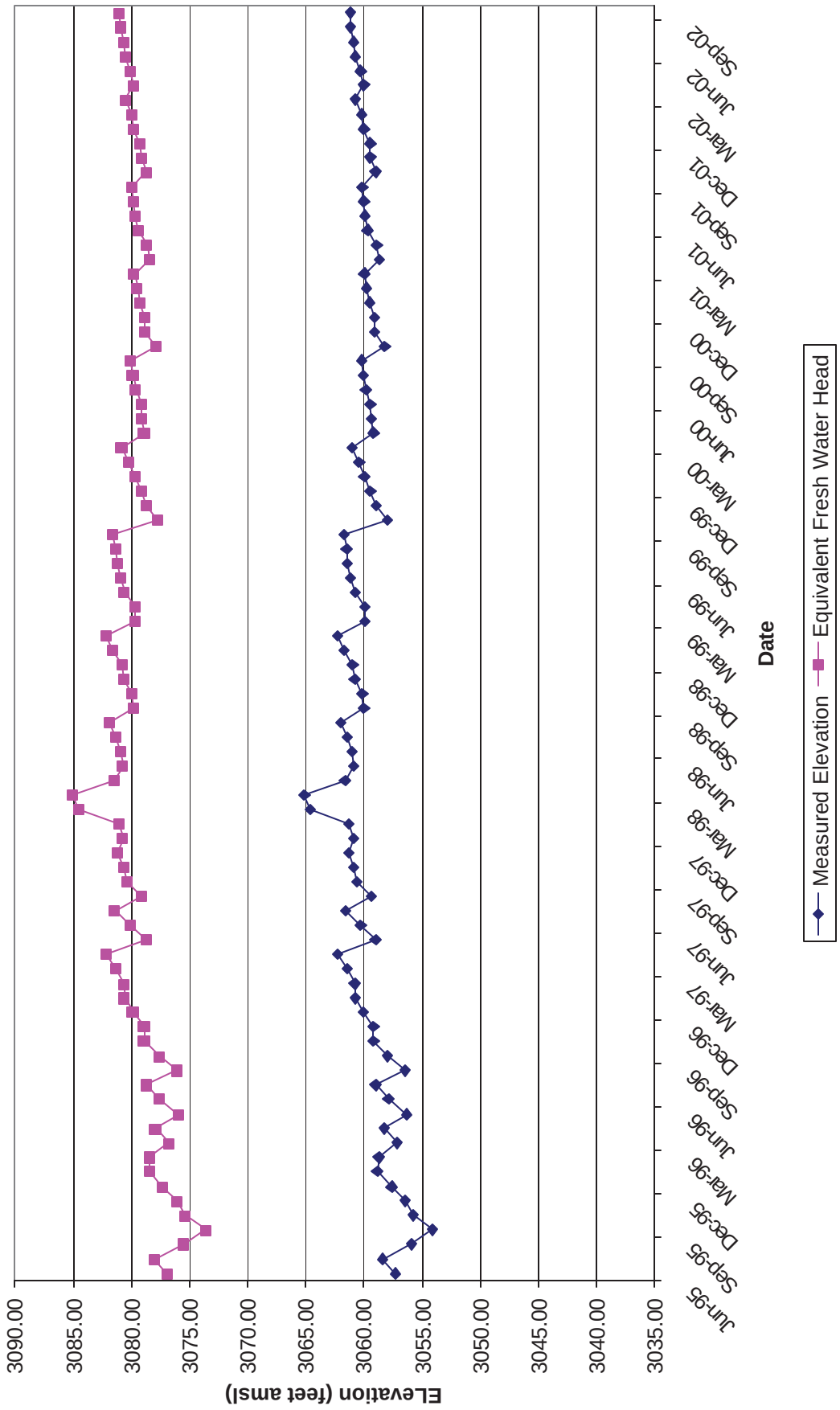

Table 84 - Well No. WQSP-3 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/05/95	3037.27	3098.12
07/19/95	3039.43	3100.59
08/17/95	3038.24	3099.23
09/05/95	3038.58	3099.62
10/16/95	3007.56	3064.07
11/08/95	3010.90	3067.90
12/04/95	3013.43	3070.80
01/10/96	3016.19	3076.00
02/05/96	3017.97	3076.00
03/11/96	3019.42	3077.66
04/15/96	3021.27	3079.78
05/15/96	2999.80	3055.18
06/10/96	3008.24	3064.85
07/17/96	3010.77	3067.75
08/12/96	3012.49	3069.72
09/05/96	3005.51	3061.72
10/14/96	3009.38	3066.16
11/11/96	3011.29	3068.35
12/09/96	3013.00	3070.31
01/13/97	3014.85	3072.43
02/10/97	3016.25	3074.03
03/10/97	3017.73	3075.73
04/14/97	3019.40	3077.64
05/12/97	3020.51	3078.91
06/09/97	3009.34	3066.11
07/15/97	3011.91	3069.06
08/13/97	3008.92	3065.63
09/15/97	3009.04	3065.77
10/16/97	3010.63	3067.59
11/10/97	3011.48	3068.56
12/08/97	3012.24	3069.43

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3012.92	3070.21
02/09/98	3014.13	3071.60
03/12/98	3015.68	3073.38
04/13/98	3016.98	3074.87
05/11/98	3010.44	3067.37
06/11/98	3011.96	3069.11
07/15/98	3012.73	3070.00
08/10/98	3013.30	3070.65
09/08/98	3008.94	3065.65
10/12/98	3010.82	3067.81
11/13/98	3011.60	3068.70
12/07/98	3012.19	3069.38
01/11/99	3012.62	3069.87
02/08/99	3013.28	3070.63
03/08/99	3013.81	3071.23
04/12/99	3003.45	3059.36
05/10/99	3010.33	3067.25
06/07/99	3011.12	3068.15
07/19/99	3011.76	3068.88
08/09/99	3012.10	3069.27
09/07/99	3012.41	3069.63
10/20/99	3009.96	3066.82
11/08/99	3012.13	3069.31
12/06/99	3011.75	3068.87
01/17/00	3012.42	3069.64
02/14/00	3012.89	3070.18
03/06/00	3013.14	3070.47
04/17/00	3010.87	3067.86
05/15/00	3011.66	3068.77
06/05/00	3011.89	3069.03
07/10/00	3012.44	3069.66
08/14/00	3012.60	3069.85
09/11/00	3012.82	3070.10
10/09/00	3004.86	3060.98
11/08/00	3010.83	3067.82
12/06/00	3011.21	3068.25

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3010.35	3067.27
02/05/01	3010.78	3067.76
03/07/01	3011.38	3068.45
04/05/01	3007.35	3063.83
05/08/01	3010.52	3067.46
06/05/01	3011.30	3068.36
07/11/01	3011.58	3068.68
08/08/01	3011.83	3068.96
09/06/01	3012.06	3069.23
10/10/01	3007.59	3064.11
11/14/01	3011.18	3068.22
12/05/01	3011.42	3068.49
01/16/02	3011.98	3069.14
02/05/02	3012.22	3069.41
03/12/02	3012.62	3069.87
04/08/02	3008.24	3064.85
05/07/02	3012.05	3069.22
06/10/02	3012.70	3069.96
07/15/02	3012.90	3070.19
08/12/02	3013.13	3070.45
09/09/02	3013.24	3070.58

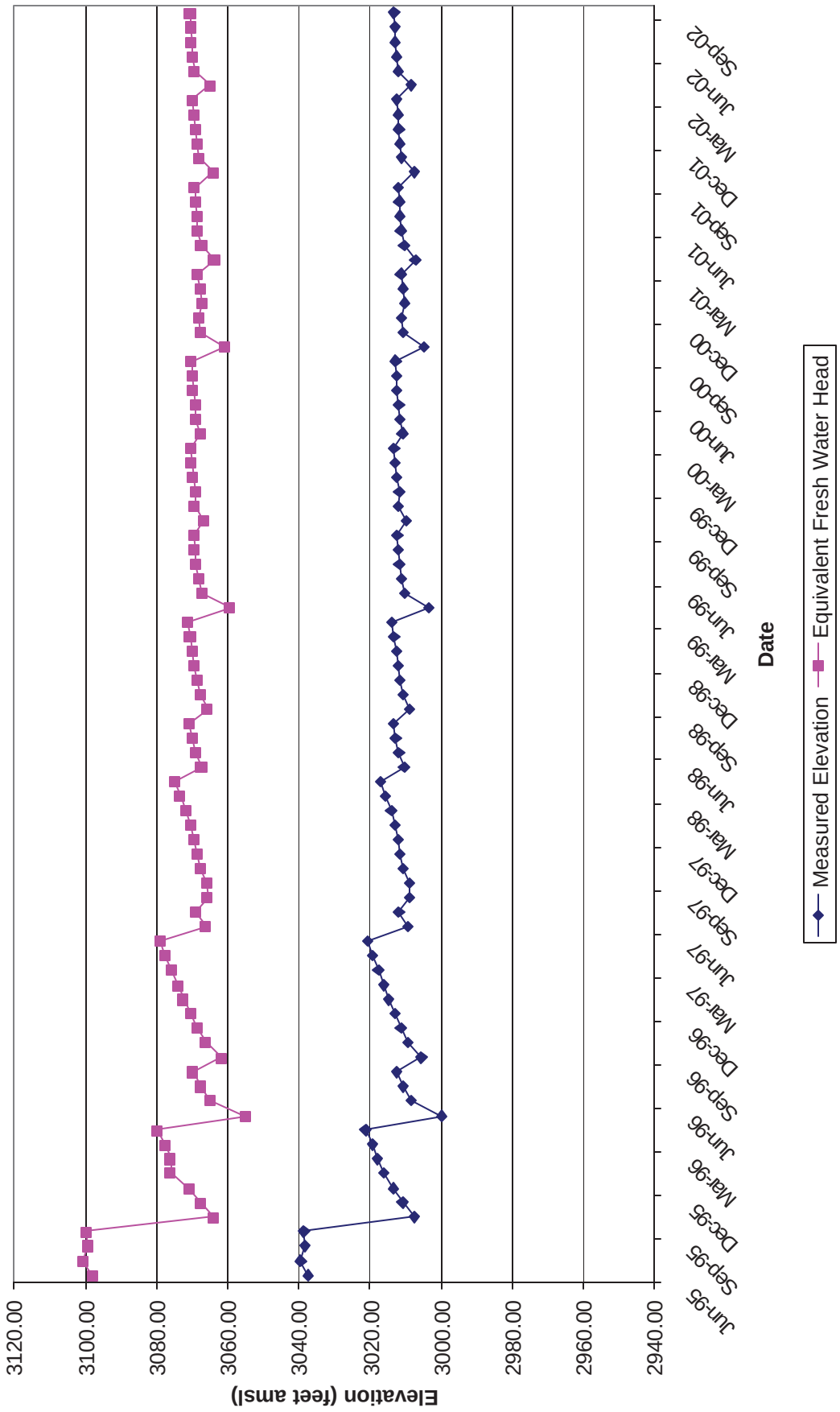
Figure 84 - WQSP-3 Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3120.00
3100.00
3080.00
3060.00
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
Jun-95
Sep-95
Dec-95
Mar-96
Jun-96
Sep-96
Dec-96
Mar-97
Jun-97
Sep-97
Dec-97
Mar-98
Jun-98
Sep-98
Dec-98
Mar-99
Jun-99
Sep-99
Dec-99
Mar-00
Jun-00
Sep-00
Dec-00
Mar-01
Jun-01
Sep-01
Dec-01
Mar-02
Jun-02
Sep-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 85 - Well No. WQSP-4 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/07/95	2962.46	2985.74
07/19/95	2927.58	2948.14
08/17/95	2956.06	2978.86
09/08/95	2951.31	2973.76
11/07/95	2965.45	2988.96
12/04/95	2969.09	2992.87
01/10/96	2918.78	2926.01
02/07/96	2906.89	2926.01
03/12/96	2909.46	2928.77
04/17/96	2926.78	2947.39
05/15/96	2948.24	2970.46
06/12/96	2956.52	2979.36
07/17/96	2964.61	2988.06
08/13/96	2968.62	2992.37
09/05/96	2970.92	2994.84
10/16/96	2973.40	2997.51
11/13/96	2975.24	2999.48
12/10/96	2976.99	3001.36
01/13/97	2978.17	3002.63
02/10/97	2979.06	3003.59
03/10/97	2979.91	3004.50
04/15/97	2980.56	3005.20
05/14/97	2980.92	3005.59
06/11/97	2979.81	3004.40
07/15/97	2980.21	3004.83
08/13/97	2980.66	3005.31
09/16/97	2980.64	3005.29
10/16/97	2981.14	3005.83
11/12/97	2981.86	3006.60
12/10/97	2982.17	3006.93

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2982.70	3007.50
02/11/98	2983.10	3007.93
03/12/98	2983.22	3008.06
04/16/98	2983.84	3008.73
05/12/98	2983.12	3007.95
06/11/98	2983.38	3008.23
07/15/98	2983.72	3008.60
08/12/98	2983.87	3008.76
09/10/98	2984.10	3009.01
10/14/98	2983.85	3008.74
11/13/98	2984.05	3008.95
12/09/98	2984.34	3009.27
01/12/99	2984.79	3009.73
02/10/99	2984.93	3009.88
03/10/99	2985.22	3010.19
04/12/99	2985.17	3010.14
05/11/99	2984.96	3009.91
06/09/99	2985.47	3010.46
07/19/99	2985.62	3010.62
08/09/99	2985.78	3010.79
09/07/99	2985.92	3010.94
10/04/99	2985.74	3010.75
11/08/99	2985.38	3010.36
12/08/99	2985.83	3010.84
01/18/00	2985.91	3010.93
02/14/00	2986.01	3011.04
03/06/00	2986.10	3011.14
04/17/00	2985.38	3010.36
05/17/00	2986.05	3011.08
06/07/00	2986.01	3011.04
07/10/00	2986.28	3011.33
08/14/00	2986.29	3011.34
09/11/00	2986.34	3011.39
10/11/00	2986.48	3011.54
11/09/00	2986.06	3011.09
12/05/00	2986.23	3011.27

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2986.43	3011.49
02/06/01	2985.50	3010.49
03/08/01	2986.74	3011.82
04/05/01	2986.73	3011.81
05/09/01	2986.45	3011.51
06/06/01	2986.92	3011.83
07/11/01	2987.13	3012.05
08/07/01	2987.16	3012.09
09/07/01	2987.45	3012.40
10/09/01	2987.48	3012.43
11/13/01	2987.21	3012.14
12/05/01	2987.17	3012.10
01/16/02	2987.46	3012.41
02/05/02	2987.58	3012.54
03/13/02	2987.74	3012.71
04/09/02	2987.46	3012.41
05/07/02	2987.69	3012.66
06/10/02	2988.11	3013.11
07/15/02	2988.22	3013.23
08/12/02	2988.47	3013.50
09/09/02	2988.45	3013.47

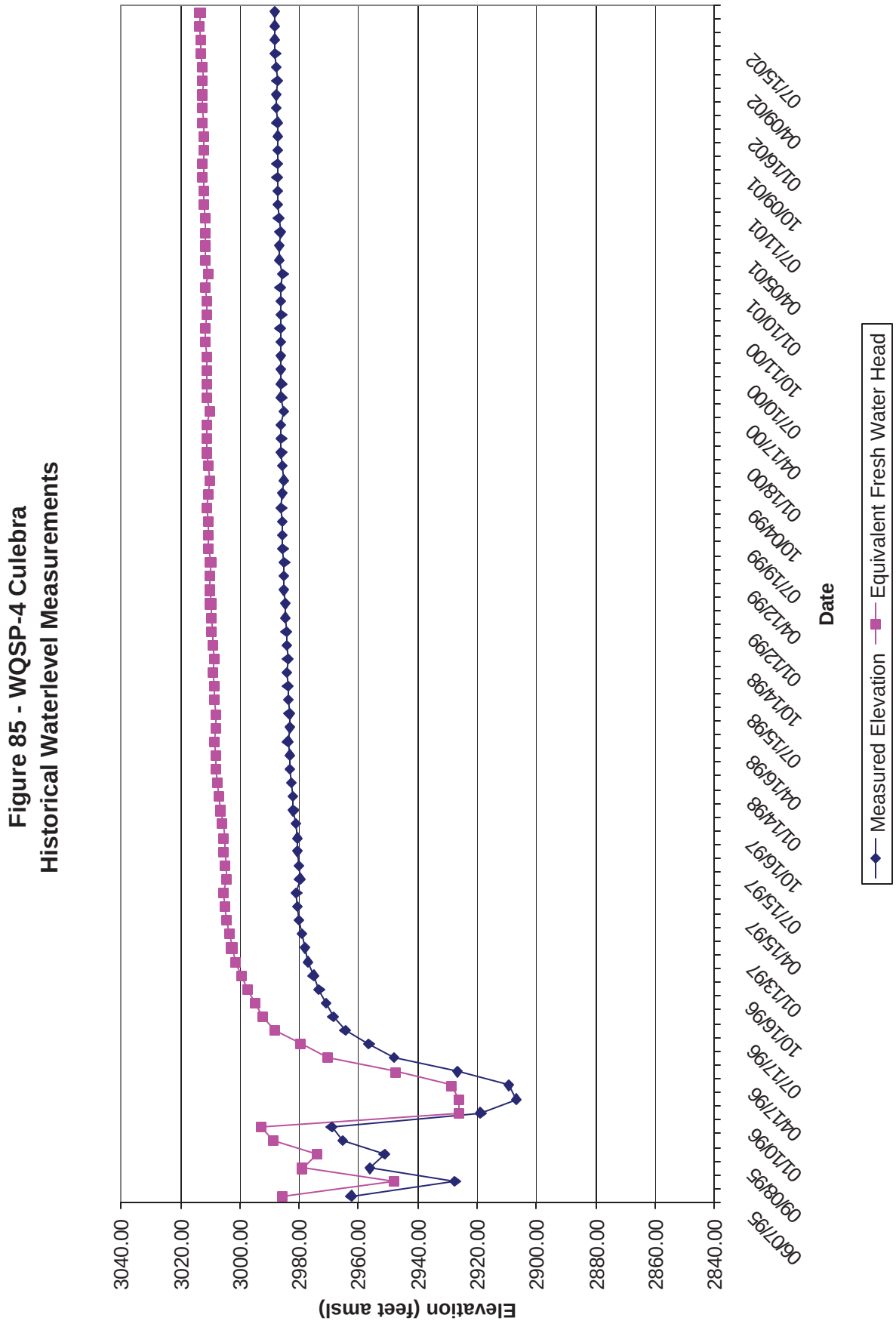
Figure 85 - WQSP-4 Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
2880.00
2860.00
2840.00
06/07/95
09/08/95
01/10/96
04/17/96
07/17/96
10/16/96
01/13/97
04/15/97
07/15/97
10/16/97
01/14/98
04/16/98
07/15/98
10/14/98
01/12/99
04/12/99
07/19/99
10/04/99
01/18/00
04/17/00
07/10/00
10/13/00
01/10/01
04/05/01
07/11/01
10/09/01
01/16/02
04/09/02
07/15/02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 86 - Well No. WQSP-5 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/07/95	2994.44	3001.29
07/19/95	2970.42	2976.67
08/17/95	2974.85	2981.21
09/07/95	2974.25	2980.59
10/18/95	2981.93	2988.46
11/03/95	2982.65	2989.20
12/06/95	2978.95	2985.41
01/10/96	2961.71	2953.07
02/07/96	2947.40	2953.07
03/12/96	2942.21	2947.75
04/17/96	2942.93	2948.49
05/15/96	2960.20	2966.19
06/12/96	2964.35	2970.44
07/17/96	2975.64	2982.02
08/13/96	2980.85	2987.36
09/05/96	2984.33	2990.92
10/16/96	2985.50	2992.12
11/13/96	2988.43	2995.13
12/10/96	2991.08	2997.84
01/14/97	2993.36	3000.18
02/10/97	2994.50	3001.35
03/12/97	2996.02	3002.91
04/15/97	2997.10	3004.01
05/14/97	2997.81	3004.74
06/09/97	2997.50	3004.42
07/15/97	2995.01	3001.87
08/13/97	2996.11	3003.00
09/16/97	2996.65	3003.55
10/16/97	2996.15	3003.04
11/12/97	2997.20	3004.12
12/10/97	2997.67	3004.60

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2998.30	3005.24
02/11/98	2998.73	3005.68
03/12/98	2998.91	3005.87
04/16/98	2999.68	3006.66
05/12/98	2999.43	3006.40
06/11/98	2998.59	3005.54
07/15/98	2999.13	3006.09
08/12/98	2999.37	3006.34
09/10/98	2999.64	3006.62
10/14/98	2998.70	3005.65
11/13/98	2999.41	3006.38
12/09/98	2999.76	3006.74
01/12/99	3000.36	3007.35
02/10/99	3000.57	3007.57
03/10/99	3000.86	3007.87
04/12/99	3000.84	3007.85
05/11/99	2999.72	3006.70
06/09/99	3000.85	3007.86
07/19/99	3001.10	3008.11
08/09/99	3001.28	3008.30
09/07/99	3001.54	3008.56
10/04/99	3001.13	3008.14
11/08/99	3000.44	3007.44
12/08/99	3001.23	3008.25
01/18/00	3001.34	3008.36
02/14/00	3001.54	3008.56
03/06/00	3001.64	3008.67
04/17/00	3001.31	3008.33
05/17/00	3001.42	3008.44
06/07/00	3001.41	3008.43
07/10/00	3001.76	3008.79
08/14/00	3001.87	3008.90
09/11/00	3001.98	3009.01
10/11/00	3001.94	3008.97
11/09/00	3001.15	3008.16
12/05/00	3001.69	3008.72

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3001.97	3009.00
02/07/01	3002.09	3009.13
03/08/01	3002.36	3009.40
04/05/01	3002.37	3009.41
05/09/01	3001.19	3008.20
06/06/01	3001.25	3008.27
07/11/01	3002.52	3009.57
08/07/01	3002.61	3009.66
09/07/01	3003.02	3010.08
10/09/01	3003.04	3010.10
11/14/01	3002.40	3009.45
12/05/01	3002.59	3009.64
01/16/02	3002.97	3010.03
02/05/02	3003.11	3010.17
03/13/02	3003.10	3010.16
04/09/02	3003.12	3010.18
05/08/02	3002.94	3010.00
06/10/02	3003.63	3010.71
07/15/02	3003.72	3010.80
08/12/02	3004.00	3011.09
09/09/02	3004.04	3011.13

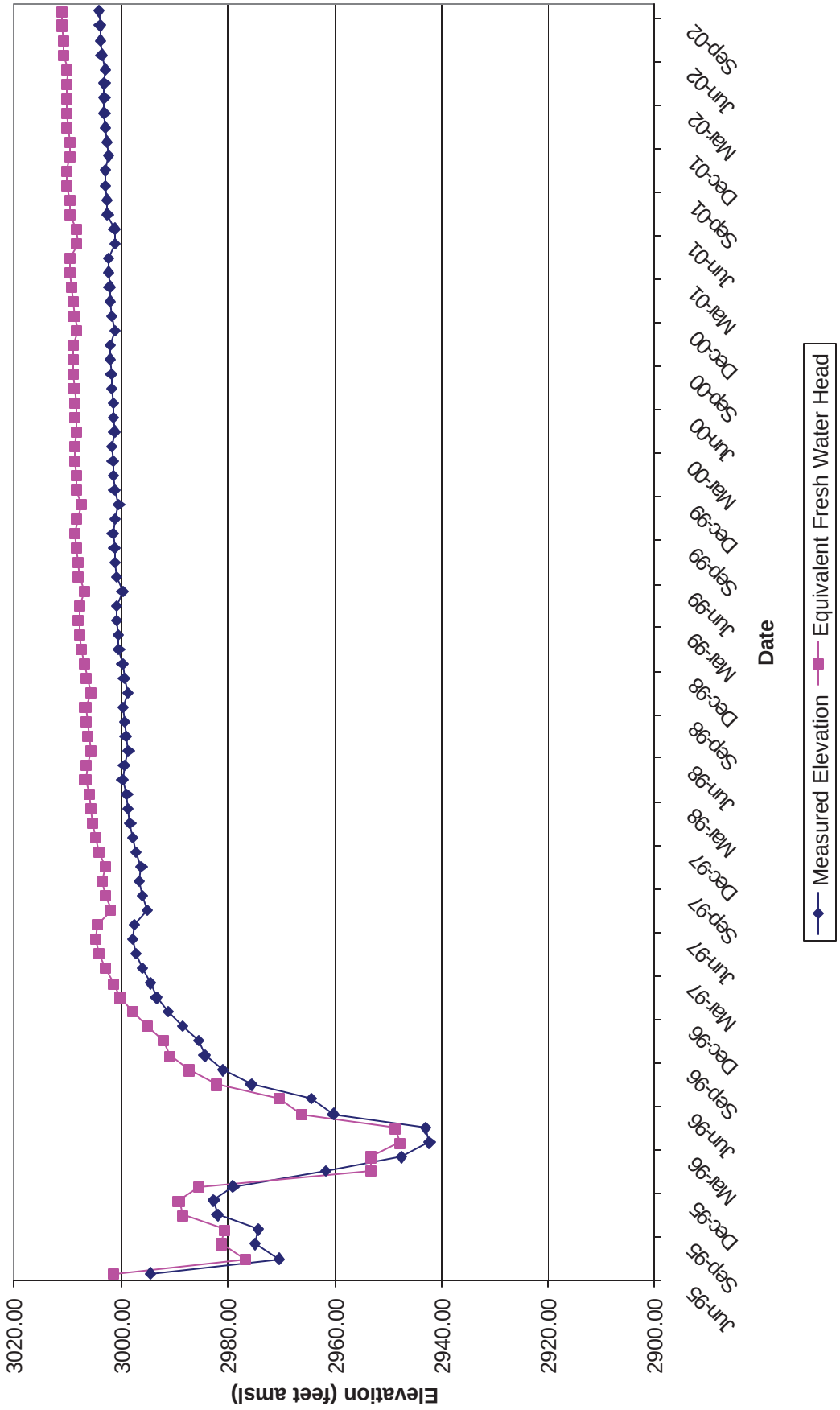
Figure 86 - WQSP-5 Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
Jun-95
Sep-95
Dec-95
Mar-96
Jun-96
Sep-96
Dec-96
Mar-97
Jun-97
Sep-97
Dec-97
Mar-98
Jun-98
Sep-98
Dec-98
Mar-99
Jun-99
Sep-99
Dec-99
Mar-00
Jun-00
Sep-00
Dec-00
Mar-01
Jun-01
Sep-01
Dec-01
Mar-02
Jun-02
Sep-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 87 - Well No. WQSP-6 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/07/95	3005.12	3008.69
07/19/95	3002.11	3005.63
08/17/95	2999.17	3002.65
09/07/95	2998.24	3001.70
10/18/95	2983.78	2987.03
11/08/95	3000.45	3003.95
12/06/95	3002.09	3005.61
01/10/96	3002.06	3003.34
02/07/96	2999.85	3003.34
03/14/96	2974.25	2977.35
04/17/96	2991.96	2995.33
05/15/96	2991.97	2995.34
06/12/96	2993.39	2996.78
07/17/96	2993.39	2996.78
08/13/96	2996.65	3000.09
09/05/96	2998.66	3002.13
10/16/96	2995.43	2998.85
11/13/96	3001.37	3004.88
12/10/96	3003.33	3006.87
01/14/97	3004.76	3008.32
02/10/97	3005.58	3009.15
03/12/97	3006.68	3010.27
04/15/97	3005.17	3008.74
05/14/97	3007.94	3011.55
06/11/97	3008.61	3012.23
07/15/97	3007.24	3010.84
08/13/97	3008.65	3012.27
09/16/97	3009.50	3013.13
10/16/97	3009.57	3013.20
11/12/97	3010.18	3013.82
12/10/97	3010.37	3014.02

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3010.84	3014.49
02/11/98	3011.10	3014.76
03/12/98	3011.15	3014.81
04/16/98	3011.82	3015.49
05/12/98	3012.04	3015.71
06/11/98	3008.56	3012.18
07/15/98	3011.62	3015.28
08/12/98	3011.99	3015.66
09/10/98	3012.28	3015.95
10/14/98	3012.55	3016.23
11/13/98	3011.62	3015.28
12/09/98	3012.45	3016.13
01/12/99	3013.07	3016.76
02/10/99	3013.29	3016.98
03/10/99	3013.51	3017.20
04/12/99	3013.55	3017.24
05/11/99	3013.84	3017.54
06/09/99	3012.81	3016.49
07/19/99	3013.68	3017.38
08/09/99	3013.98	3017.68
09/07/99	3014.21	3017.91
10/04/99	3013.93	3017.63
11/08/99	3010.96	3013.80
12/08/99	3014.19	3017.89
01/18/00	3014.39	3018.10
02/14/00	3014.65	3018.36
03/06/00	3014.81	3018.52
04/17/00	3014.85	3018.56
05/17/00	3012.02	3015.69
06/07/00	3014.23	3017.93
07/10/00	3014.99	3018.71
08/14/00	3015.15	3018.87
09/11/00	3015.36	3019.08
10/11/00	3015.27	3018.99
11/09/00	3015.54	3019.26
12/06/00	3014.19	3017.89

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3015.26	3018.98
02/07/01	3015.51	3019.23
03/08/01	3015.74	3019.47
04/05/01	3015.82	3019.55
05/09/01	3015.73	3019.46
06/06/01	3014.80	3018.51
07/11/01	3015.60	3019.32
08/07/01	3015.76	3019.49
09/07/01	3016.22	3019.95
10/10/01	3016.22	3019.95
11/14/01	3013.34	3017.03
12/05/01	3015.51	3019.23
01/16/02	3016.19	3019.92
02/05/02	3016.33	3020.07
03/13/02	3016.73	3020.47
04/09/02	3016.60	3020.34
05/08/02	3016.97	3020.72
06/10/02	3016.37	3020.11
07/15/02	3016.74	3020.48
08/12/02	3017.01	3020.76
09/09/02	3017.09	3020.84

Figure 87 - WQSP-6 Culebra
Historical Waterlevel Measurements

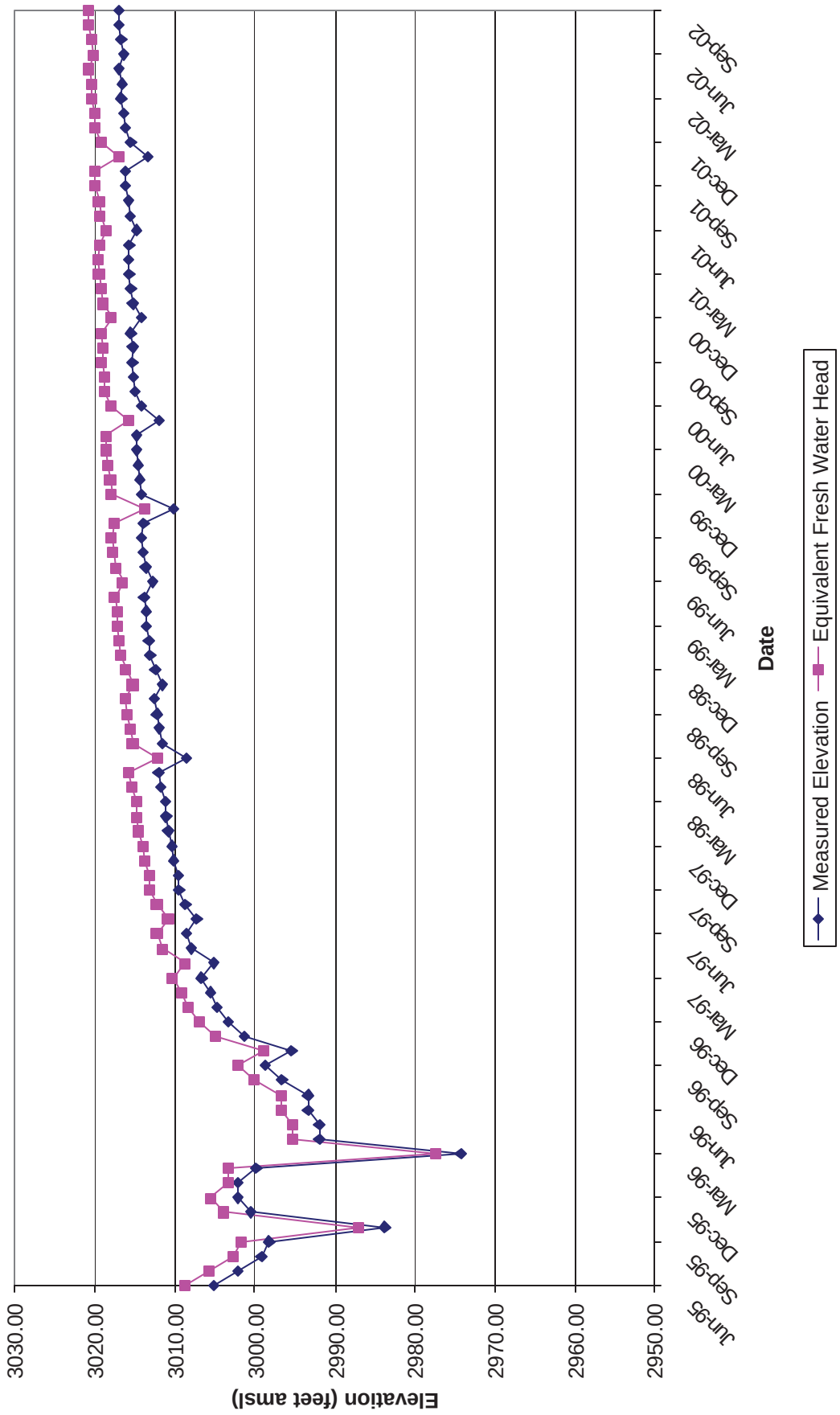

Table 88 - Well No. WQSP-6a Dewey Lake
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/07/95	3199.29	N/A
07/19/95	3199.14	N/A
08/17/95	3199.16	N/A
09/07/95	3199.10	N/A
10/18/95	3198.95	N/A
11/08/95	3198.99	N/A
12/06/95	3199.17	N/A
01/04/96	3196.64	N/A
02/07/96	3199.24	N/A
03/14/96	3199.36	N/A
04/17/96	3199.25	N/A
05/15/96	3199.23	N/A
06/12/96	3199.17	N/A
07/17/96	3199.11	N/A
08/13/96	3199.05	N/A
09/05/96	3199.18	N/A
10/16/96	3199.29	N/A
11/13/96	3198.91	N/A
12/10/96	3199.24	N/A
01/14/97	3199.11	N/A
02/10/97	3198.94	N/A
03/12/97	3199.10	N/A
04/15/97	3199.03	N/A
05/14/97	3199.25	N/A
06/11/97	3199.13	N/A
07/15/97	3198.95	N/A
08/13/97	3198.93	N/A
09/16/97	3199.11	N/A
10/16/97	3198.72	N/A
11/12/97	3199.16	N/A
12/10/97	3198.89	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3198.88	N/A
02/11/98	3198.89	N/A
03/12/98	3199.62	N/A
04/16/98	3198.98	N/A
05/12/98	3199.03	N/A
06/11/98	3198.80	N/A
07/15/98	3198.86	N/A
08/12/98	3198.79	N/A
09/10/98	3198.87	N/A
10/14/98	3198.96	N/A
11/13/98	3198.72	N/A
12/09/98	3198.78	N/A
01/12/99	3199.16	N/A
02/10/99	3199.07	N/A
03/10/99	3199.02	N/A
04/12/99	3198.74	N/A
05/11/99	3198.84	N/A
06/09/99	3198.93	N/A
07/19/99	3198.77	N/A
08/09/99	3198.91	N/A
09/07/99	3198.97	N/A
10/04/99	3198.66	N/A
11/08/99	3198.80	N/A
12/08/99	3199.06	N/A
01/18/00	3198.83	N/A
02/14/00	3198.82	N/A
03/06/00	3198.86	N/A
04/17/00	3198.63	N/A
05/17/00	3198.87	N/A
06/07/00	3198.50	N/A
07/10/00	3198.56	N/A
08/14/00	3198.51	N/A
09/11/00	3198.54	N/A
10/11/00	3198.51	N/A
11/09/00	3198.57	N/A
12/06/00	3198.25	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3198.60	N/A
02/07/01	3198.63	N/A
03/08/01	3198.57	N/A
04/05/01	3198.34	N/A
05/09/01	3198.24	N/A
06/04/01	3198.51	N/A
07/11/01	3198.33	N/A
08/07/01	3198.16	N/A
09/07/01	3198.45	N/A
10/10/01	3198.31	N/A
11/12/01	3198.26	N/A
12/05/01	3198.11	N/A
01/16/02	3198.26	N/A
02/05/02	3198.24	N/A
03/13/02	3198.48	N/A
04/09/02	3198.03	N/A
05/08/02	3198.39	N/A
06/10/02	3198.37	N/A
07/15/02	3198.21	N/A
08/12/02	3198.27	N/A
09/09/02	3198.10	N/A

Figure 88 - WQSP-6a Dewey Lake Historical Waterlevel Measurements

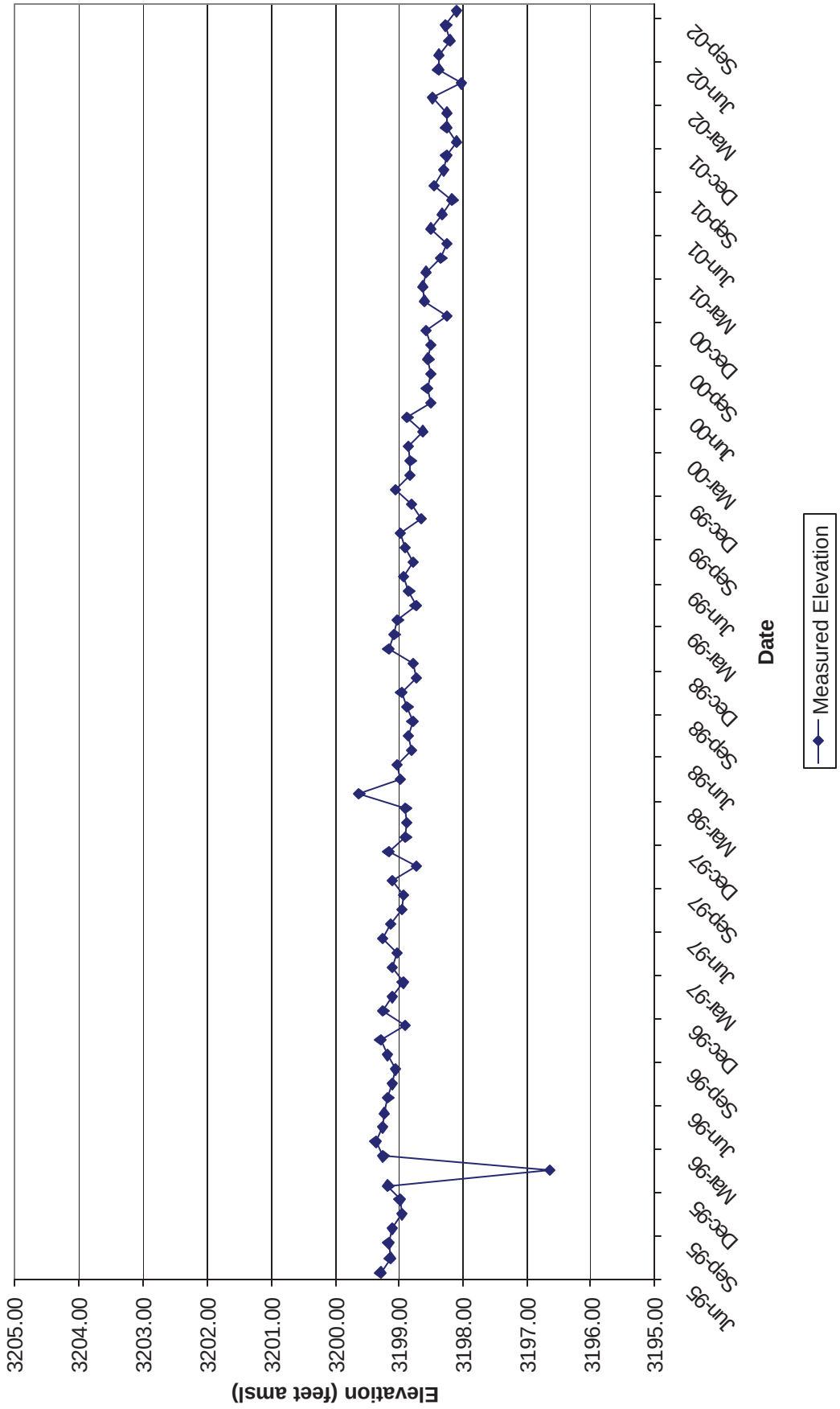

APPENDIX DATA

ATTACHMENT C: WATER QUALITY SAMPLING DATA

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Groundwater Quality Data

Groundwater monitoring activities during the 2004 Compliance Recertification Application monitoring period (mid 1995 through September 30, 2002) included groundwater quality sampling to support performance assessment. Groundwater quality data were gathered from six wells (WQSP-1 through WQSP-6) in the Culebra member of the Rustler Formation and one well (WQSP-6A) in the Dewey Lake Formation.

The Groundwater Monitoring Program (GWMP) is required to sample for groundwater quality twice a year, from March through May and, again, from September through November. Each sampling period is called a round.

There are seven constituents sampled and analyzed by the GWMP for performance assessment. Of the seven, five have a Chemical Abstract Service (CAS) registry number applied to them. CAS number refers to a unique, identifying number applied to each distinct chemical substance in the CAS Chemical Registry System. Governmental agencies (EPA being one) have found CAS numbers ideal for keeping track of substances because the numbers are unique, can be validated quickly and reliably, and are internationally recognized. Of the monitored substances, Alkalinity and Sulfate do not have CAS numbers associated with them since they are not distinct substances.

In the following tables and charts, either the 95th upper tolerance limit value (UTLV) or the 95th percentile value is presented, depending on the type of distribution exhibited by the parameter. Both values represent the value beneath which 95 percent of the values in a population are expected to occur.

WQSP-1 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		1700.0		1670.0	mg/L	2.0	2087.0			<	0.2	1	08/28/95	08/17/95
7440-70-2	CALCIUM		1710.0		1690.0	mg/L	2.0	2087.0	<	0.2	<	0.2	2	05/07/96	04/11/96
7440-70-2	CALCIUM		1740.0		1670.0	mg/L	2.0	2087.0	<	0.2	<	0.2	3	07/30/96	07/25/96
7440-70-2	CALCIUM		1410.0		1510.0	mg/L	2.0	2087.0	<	0.2	<	0.2	4	05/02/97	04/24/97
7440-70-2	CALCIUM		1720.0		1700.0	mg/L	2.0	2087.0	<	0.2	<	0.2	5	08/15/97	07/24/97
7440-70-2	CALCIUM		1610.0		1660.0	mg/L	2.0	2087.0			<	0.2	6	03/19/98	03/05/98
7440-70-2	CALCIUM		1710.0		1570.0	mg/L	0.5	2087.0			<	0.5	7	08/17/98	07/15/98
7440-70-2	CALCIUM		1770.0	<	0.5	mg/L	0.5	2087.0			<	0.5	8	03/15/99	03/03/99
7440-70-2	CALCIUM		1710.0		1726.0	mg/L	0.5	2087.0			<	0.5	9	09/16/99	09/01/99
7440-70-2	CALCIUM		1800.0		1780.0	mg/L	5.0	2087.0				0.1	10	03/06/00	03/02/00
7440-70-2	CALCIUM		2030.0		2160.0	mg/L	5.0	2087.0					10	06/19/00	06/19/00
7440-70-2	CALCIUM		1760.0		1680.0	mg/L	2.0	2087.0			<	1.0	11	10/11/00	09/07/00
7440-70-2	CALCIUM		1854.0		1794.0	mg/L	0.5	2087.0			<	0.5	12	05/10/01	03/01/01
7440-70-2	CALCIUM		1828.0		1795.0	mg/L	0.2	2087.0			<	0.2	13	10/02/01	09/06/01
7440-70-2	CALCIUM		1630.0		1580.0	mg/L	0.2	2087.0			<	0.6	14	03/18/02	03/06/02

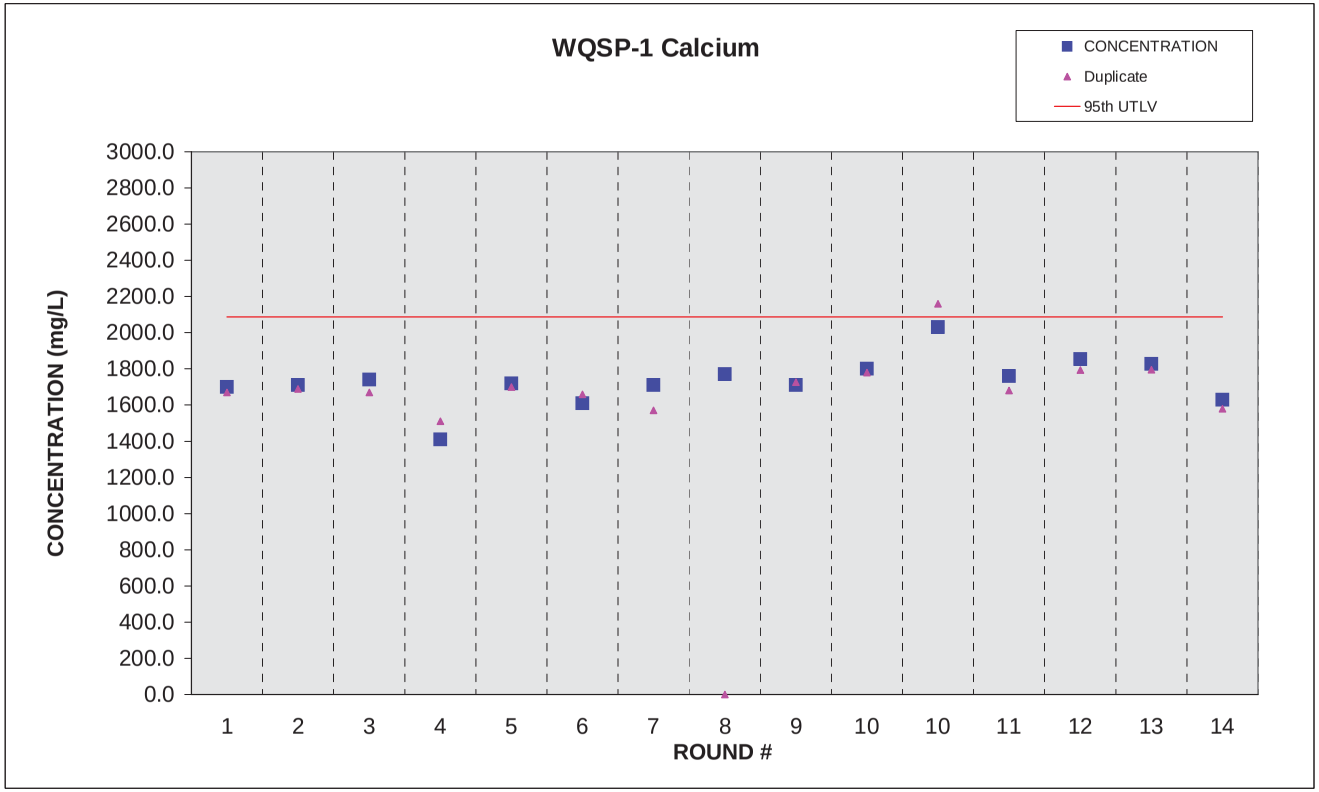

WQSP-1 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		497.0		474.0	mg/L	0.2	799.0			<	0.2	1	08/28/95	08/17/95
7440-09-7	POTASSIUM		476.0		465.0	mg/L	10.0	799.0	<	0.2	<	0.2	2	04/25/96	04/11/96
7440-09-7	POTASSIUM		471.0		451.0	mg/L	2.0	799.0	<	0.2	<	0.2	3	07/30/96	07/25/96
7440-09-7	POTASSIUM		443.0		468.0	mg/L	2.0	799.0	<	0.2	<	0.2	4	05/01/97	04/24/97
7440-09-7	POTASSIUM		499.0		476.0	mg/L	2.0	799.0	<	0.2	<	0.2	5	07/29/97	07/24/97
7440-09-7	POTASSIUM		467.0		487.0	mg/L	2.0	799.0			<	0.2	6	03/19/98	03/05/98
7440-09-7	POTASSIUM		710.0		640.0	mg/L	0.5	799.0			<	0.5	7	08/17/98	07/15/98
7440-09-7	POTASSIUM		661.0	<	1.0	mg/L	1.0	799.0			<	1.0	8	03/15/99	03/03/99
7440-09-7	POTASSIUM		700.0		728.0	mg/L	0.5	799.0			<	0.5	9	09/16/99	09/01/99
7440-09-7	POTASSIUM		442.0		441.0	mg/L	5.0	799.0				0.0	10	03/06/00	03/02/00
7440-09-7	POTASSIUM		717.0		687.0	mg/L	2.0	799.0				0.3	11	10/11/00	09/07/00
7440-09-7	POTASSIUM		767.0		745.0	mg/L	0.5	799.0				0.5	12	05/10/01	03/01/01
7440-09-7	POTASSIUM		896.0		871.0	mg/L	0.2	799.0			<	0.3	13	10/02/01	09/06/01
7440-09-7	POTASSIUM		695.0		721.0	mg/L	0.2	799.0			<	0.6	14	04/24/02	03/06/02

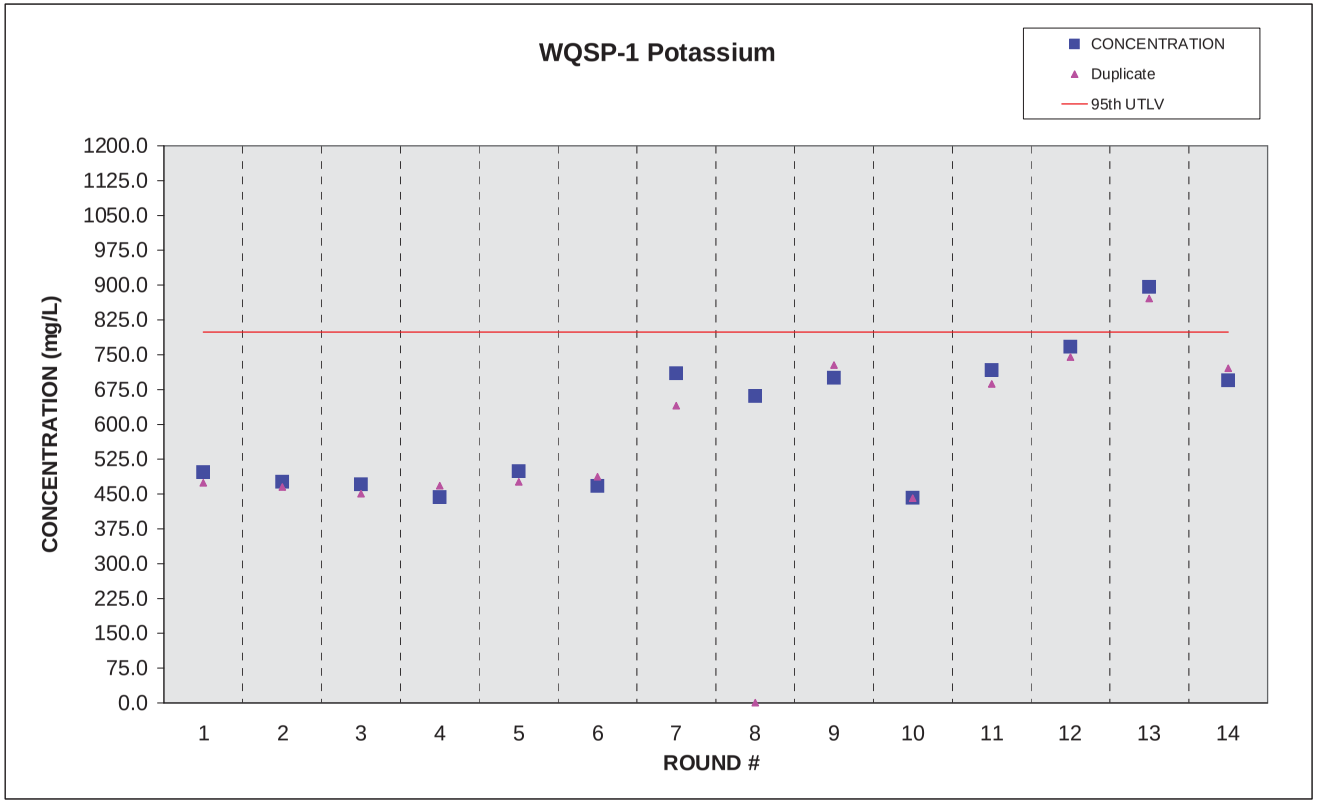

WQSP-1 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		1110.0		1080.0	mg/L	1.0	1247.0			<	0.1	1	08/28/95	08/17/95
7439-95-4	MAGNESIUM		1050.0		1040.0	mg/L	0.5	1247.0	<	0.1	<	0.1	2	05/07/96	04/11/96
7439-95-4	MAGNESIUM		1020.0		982.0	mg/L	0.5	1247.0	<	0.1	<	0.1	3	07/30/96	07/25/96
7439-95-4	MAGNESIUM		928.0		1000.0	mg/L	1.0	1247.0	<	0.1	<	0.1	4	05/02/97	04/24/97
7439-95-4	MAGNESIUM		1180.0		1170.0	mg/L	0.5	1247.0	<	0.1	<	0.1	5	08/15/97	07/24/97
7439-95-4	MAGNESIUM		1160.0		1130.0	mg/L	0.5	1247.0			<	0.1	6	03/19/98	03/05/98
7439-95-4	MAGNESIUM		1140.0		1060.0	mg/L	0.5	1247.0			<	0.5	7	08/17/98	07/15/98
7439-95-4	MAGNESIUM		993.0	<	1.0	mg/L	0.5	1247.0			<	0.5	8	03/15/99	03/03/99
7439-95-4	MAGNESIUM		1100.0		1120.0	mg/L	0.5	1247.0			<	0.5	9	09/16/99	09/01/99
7439-95-4	MAGNESIUM		1112.0		1100.0	mg/L	5.0	1247.0			<	5.0	10	03/06/00	03/02/00
7439-95-4	MAGNESIUM		1200.0		1120.0	mg/L	2.0	1247.0				0.0	11	10/11/00	09/07/00
7439-95-4	MAGNESIUM		1255.0		1180.0	mg/L	0.5	1247.0			<	0.5	12	05/10/01	03/01/01
7439-95-4	MAGNESIUM		1262.0		1270.0	mg/L	0.2	1247.0			<	0.2	13	10/02/01	09/06/01
7439-95-4	MAGNESIUM		1240.0		1220.0	mg/L	0.2	1247.0			<	0.6	14	03/18/02	03/06/02

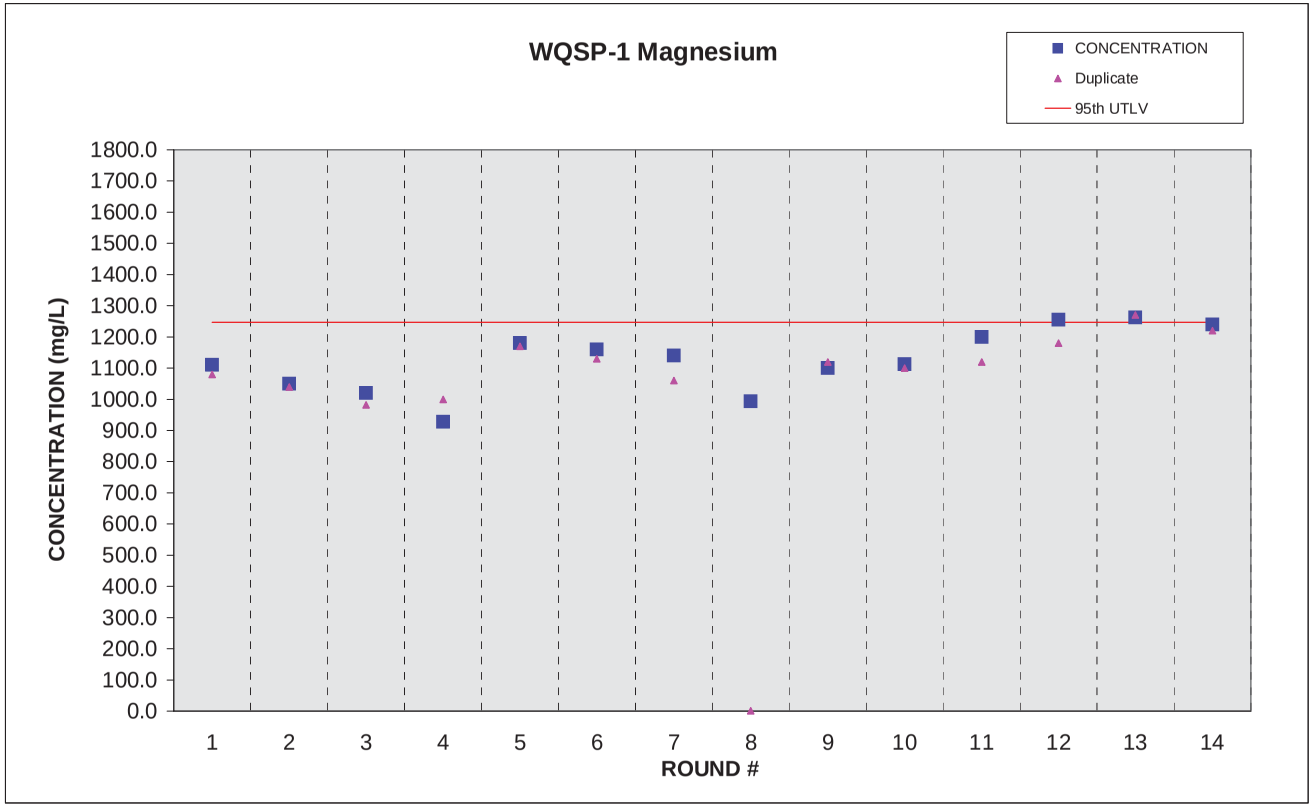

WQSP-1 Sodium

CAS #	PARAMETER		Concentration		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		20100.0		19800.0	mg/L	5.0	22090.0			<	0.5	1	08/28/95	08/17/95
7440-23-5	SODIUM		18500.0		18200.0	mg/L	25.0	22090.0	<	0.5	<	0.5	2	04/25/96	04/11/96
7440-23-5	SODIUM		18900.0		18400.0	mg/L	25.0	22090.0	<	0.5	<	0.5	3	07/30/96	07/25/96
7440-23-5	SODIUM		17700.0		19600.0	mg/L	10.0	22090.0	<	0.5	<	0.2	4	05/01/97	04/24/97
7440-23-5	SODIUM		19400.0		17500.0	mg/L	10.0	22090.0	<	0.2	<	0.2	5	07/29/97	07/24/97
7440-23-5	SODIUM		19800.0		20000.0	mg/L	4.0	22090.0			<	0.2	6	03/19/98	03/05/98
7440-23-5	SODIUM		17550.0		16500.0	mg/L	0.5	22090.0			<	0.5	7	08/17/98	07/15/98
7440-23-5	SODIUM		19700.0	<	1.0	mg/L	1.0	22090.0			<	1.0	8	03/15/99	03/03/99
7440-23-5	SODIUM		16446.0		16234.0	mg/L	5.0	22090.0			<	5.0	10	03/06/00	03/02/00
7440-23-5	SODIUM		19000.0		18600.0	mg/L	2.0	22090.0				0.5	11	10/11/00	09/07/00
7440-23-5	SODIUM		19170.0		17460.0	mg/L	0.5	22090.0				0.7	12	05/10/01	03/01/01
7440-23-5	SODIUM		18450.0		17430.0	mg/L	0.2	22090.0				0.4	13	10/03/01	09/06/01
7440-23-5	SODIUM		18400.0		19600.0	mg/L	0.2	22090.0			<	0.6	14	03/18/02	03/06/02

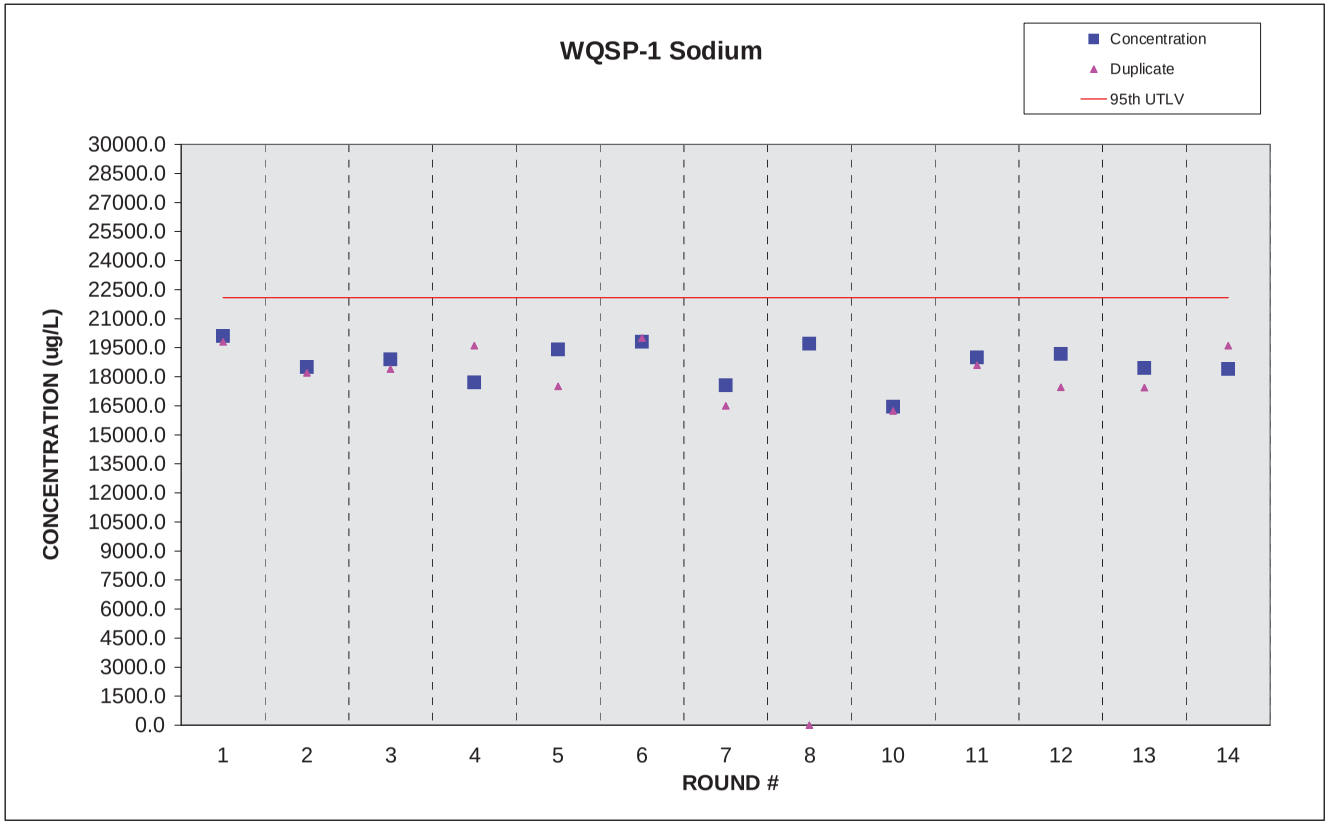

WQSP-1 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
==========	==========	===	==========	==	==========	======	==========	==========	===	==========	===	==========	=======	==========	==========
	ALKALINITY		46.5		47.5	mg/L	5.0	55.7			<	5.0	1	08/29/95	08/17/95
	ALKALINITY		53.0		52.0	mg/L	5.0	55.7			<	5.0	2	04/25/96	04/11/96
	ALKALINITY		50.1		50.1	mg/L	5.0	55.7			<	5.0	3	08/06/96	07/25/96
	ALKALINITY		51.2		50.8	mg/L	5.0	55.7			<	5.0	4	04/30/97	04/24/97
	ALKALINITY		50.0		50.0	mg/L	5.0	55.7			<	5.0	5	08/26/97	07/24/97
	ALKALINITY		50.0		50.0	mg/L	1.0	55.7			<	1.0	7	07/29/98	07/15/98
	ALKALINITY		55.0		50.0	mg/L	4.0	55.7			<	4.0	8	03/05/99	03/03/99
	ALKALINITY		46.0		46.0	mg/L	4.0	55.7			<	4.0	9	09/08/99	09/01/99
	ALKALINITY		49.0		49.0	mg/L	4.0	55.7			<	4.0	10	03/15/00	03/02/00
	ALKALINITY		50.0		52.0	mg/L	6.0	55.7			<	6.0	11	09/07/00	09/07/00
	ALKALINITY		51.0		52.0	mg/L	4.0	55.7			<	4.0	12	03/01/01	03/01/01
	ALKALINITY		50.0		52.0	mg/L	4.0	55.7					13	09/12/01	09/06/01
	ALKALINITY		50.0		48.0	mg/L	4.0	55.7					14	03/12/02	03/06/02

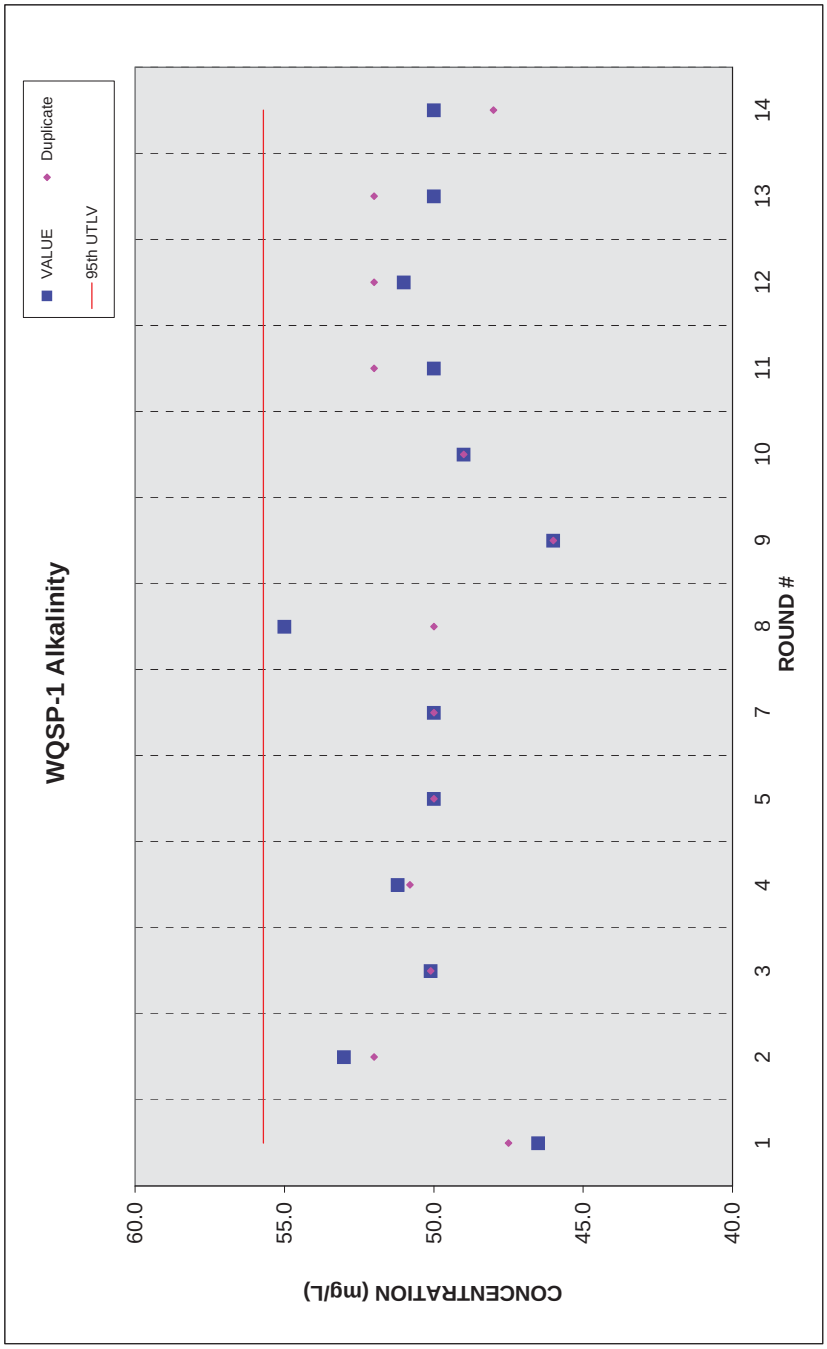

WQSP-1 Chloride

CAS #	PARAMETER		VALUE		VALUE DUPLICATE	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		34500.0		35000.0	mg/L	5.0	40472.0			<	5.0	1	08/23/95	08/17/95
7782-50-5	CHLORIDE		33000.0		33500.0	mg/L	5000.0	40472.0			<	5.0	2	04/22/96	04/11/96
7782-50-5	CHLORIDE		37200.0		37000.0	mg/L	5.0	40472.0			<	5.0	3	08/06/96	07/25/96
7782-50-5	CHLORIDE		34200.0		34200.0	mg/L	250.0	40472.0			<	5.0	4	05/01/97	04/24/97
7782-50-5	CHLORIDE		35700.0		35500.0	mg/L	2500.0	40472.0			<	5.0	5	08/29/97	07/24/97
7782-50-5	CHLORIDE		37600.0		34500.0	mg/L	2500.0	40472.0					6	03/19/98	03/05/98
7782-50-5	CHLORIDE		34000.0		33000.0	mg/L	0.5	40472.0				1.0	7	07/26/98	07/15/98
7782-50-5	CHLORIDE		33000.0		33000.0	mg/L	0.5	40472.0			<	0.5	8	03/03/99	03/03/99
7782-50-5	CHLORIDE		40000.0		40000.0	mg/L	0.5	40472.0			<	0.5	9	09/07/99	09/01/99
7782-50-5	CHLORIDE		36000.0		36000.0	mg/L	0.5	40472.0			<	0.5	10	03/06/00	03/02/00
7782-50-5	CHLORIDE		36000.0		34000.0	mg/L	2.0	40472.0			<	2.0	11	09/21/00	09/07/00
7782-50-5	CHLORIDE		37000.0		36000.0	mg/L	0.5	40472.0			<	0.5	12	03/01/01	03/01/01
7782-50-5	CHLORIDE		35900.0		36100.0	mg/L	0.5	40472.0					13	10/19/01	09/06/01
7782-50-5	CHLORIDE		36600.0		32300.0	mg/L	0.5	40472.0					14	03/08/02	03/06/02

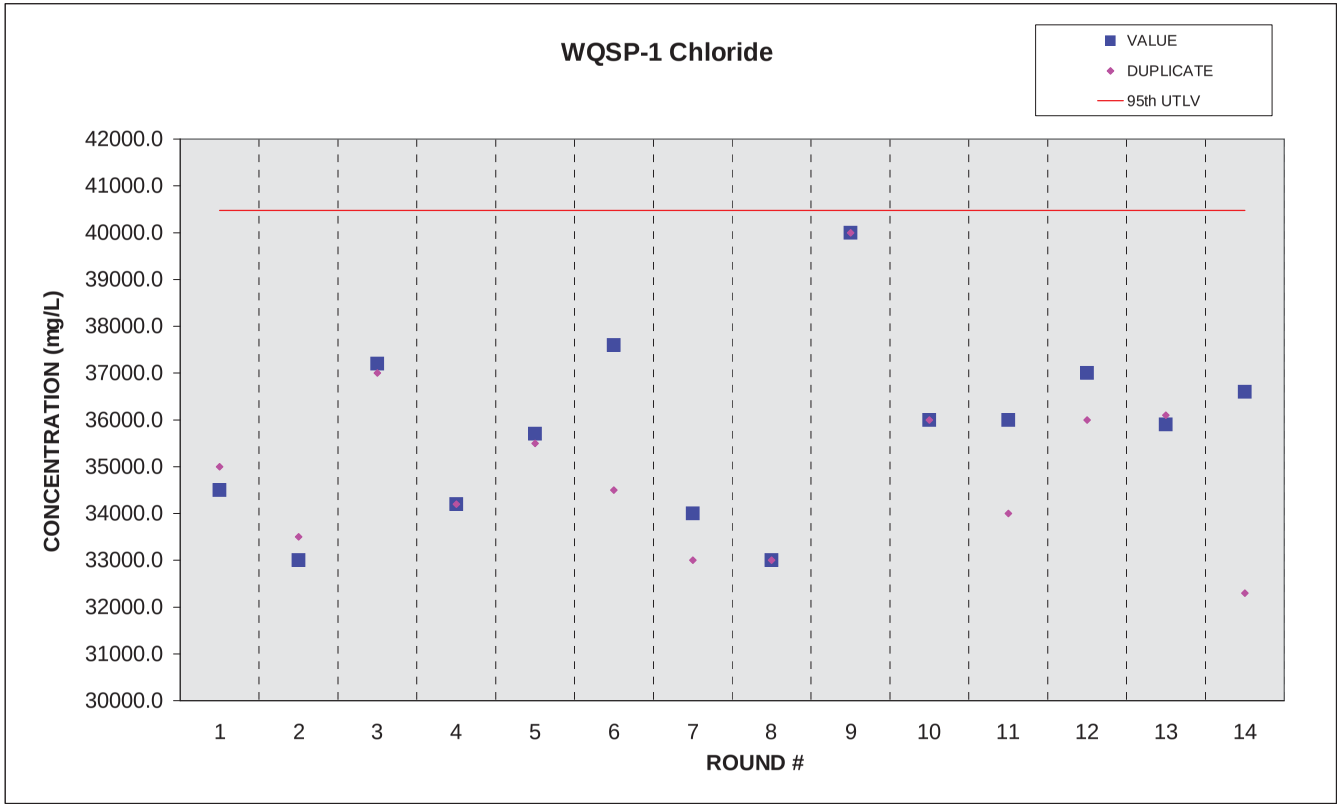

WQSP-1 Sulfate

CASE #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		5230.0		5490.0	mg/L	10.0	5757.0			<	10.0	1	08/29/95	08/17/95
	SULFATE		5480.0		5600.0	mg/L	2500.0	5757.0			<	10.0	2	04/25/96	04/11/96
	SULFATE		4920.0		4950.0	mg/L	1000.0	5757.0			<	10.0	3	08/21/96	07/25/96
	SULFATE		4760.0		4700.0	mg/L	10.0	5757.0			<	10.0	4	05/01/97	04/24/97
	SULFATE		4260.0		4460.0	mg/L	2500.0	5757.0			<	10.0	5	09/03/97	07/24/97
	SULFATE		4400.0		4350.0	mg/L	1000.0	5757.0			<	10.0	6	03/11/98	03/05/98
	SULFATE		4900.0		4400.0	mg/L	0.5	5757.0			<	0.5	7	07/26/98	07/15/98
	SULFATE		4600.0		4900.0	mg/L	0.5	5757.0			<	0.5	8	03/03/99	03/03/99
	SULFATE		5000.0		4700.0	mg/L	0.5	5757.0			<	0.5	9	09/07/99	09/01/99
	SULFATE		4800.0		4700.0	mg/L	0.5	5757.0			<	0.5	10	03/06/00	03/02/00
	SULFATE		4800.0		4700.0	mg/L	0.5	5757.0			<	0.5	11	09/07/00	09/07/00
	SULFATE		4900.0		4800.0	mg/L	0.5	5757.0			<	0.5	12	03/01/01	03/01/01
	SULFATE		4730.0		4720.0	mg/L	0.5	5757.0					13	09/27/01	09/06/01
	SULFATE		4270.0		4010.0	mg/L	0.5	5757.0					14	03/18/02	03/06/02

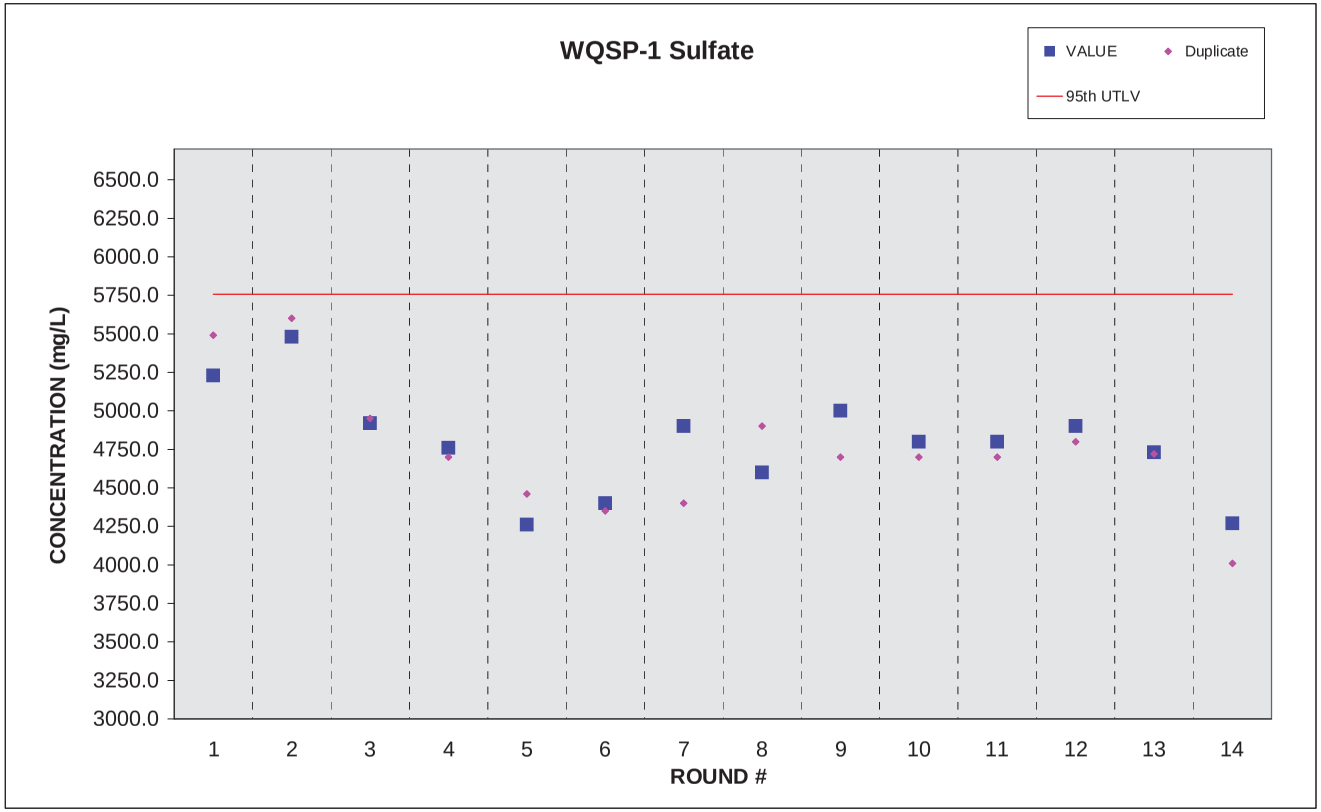

WQSP-2 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		1460.0		1450.0	mg/L	2.0	1827.0			<	0.2	1	09/12/95	08/31/95
7440-70-2	CALCIUM		1480.0		1410.0	mg/L	2.0	1827.0	<	0.2	<	0.2	2	05/10/96	04/25/96
7440-70-2	CALCIUM		1440.0		1400.0	mg/L	2.0	1827.0	<	0.2	<	0.2	3	08/21/96	08/08/96
7440-70-2	CALCIUM		1320.0		1290.0	mg/L	2.0	1827.0	<	0.2	<	0.2	4	05/21/97	05/08/97
7440-70-2	CALCIUM		1540.0		1460.0	mg/L	2.0	1827.0	<	0.2	<	0.2	5	08/15/97	08/07/97
7440-70-2	CALCIUM		1540.0		1505.0	mg/L	12.0	1827.0			<	12.0	6	05/05/98	04/15/98
7440-70-2	CALCIUM		1380.0		1460.0	mg/L	2.0	1827.0	<	0.2	<	5.0	7	09/16/98	08/12/98
7440-70-2	CALCIUM		1510.0		1470.0	mg/L	0.5	1827.0			<	0.5	8	03/19/99	03/17/99
7440-70-2	CALCIUM		1509.0		1428.0	mg/L	0.5	1827.0			<	0.5	9	09/16/99	09/15/99
7440-70-2	CALCIUM		1619.0		1742.0	mg/L	5.0	1827.0					10	03/16/00	03/15/00
7440-70-2	CALCIUM		1840.0		1730.0	mg/L	5.0	1827.0					10	06/19/00	06/19/00
7440-70-2	CALCIUM		1460.0		1530.0	mg/L	1.0	1827.0			<	1.0	11	10/26/00	09/20/00
7440-70-2	CALCIUM		1651.0		1715.0	mg/L	0.5	1827.0			<	0.5	12	05/10/01	03/14/01
7440-70-2	CALCIUM		1689.0		1676.0	mg/L	0.2	1827.0					13	11/09/01	09/19/01
7440-70-2	CALCIUM		1662.0		1624.0	mg/L	0.5	1827.0			<	0.5	14	03/25/02	03/20/02

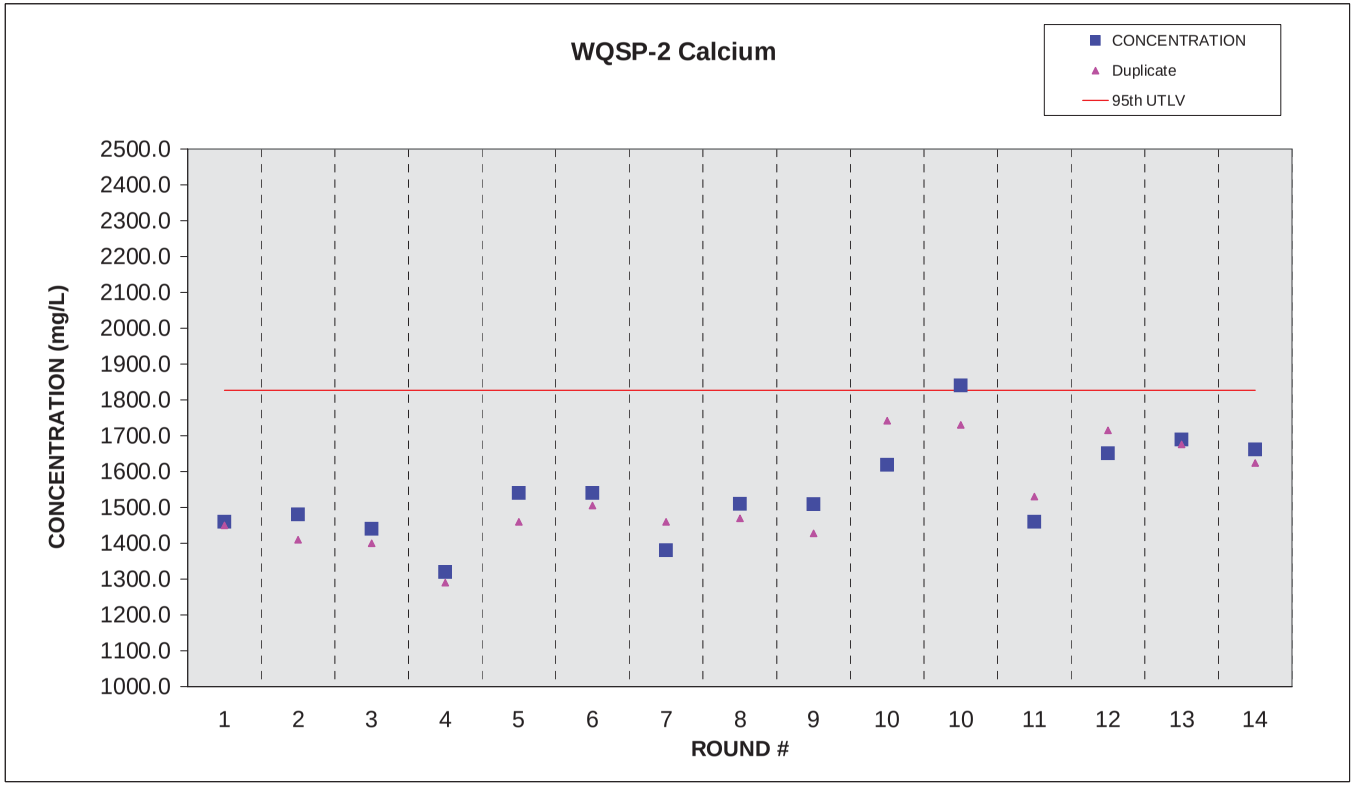

WQSP-2 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		1110.0		1080.0	mg/L	1.0	1244.0			<	0.1	1	08/28/95	08/17/95
7439-95-4	MAGNESIUM		1050.0		1040.0	mg/L	0.5	1244.0	<	0.1	<	0.1	2	05/07/96	04/11/96
7439-95-4	MAGNESIUM		1020.0		982.0	mg/L	0.5	1244.0	<	0.1	<	0.1	3	07/30/96	07/25/96
7439-95-4	MAGNESIUM		928.0		1000.0	mg/L	1.0	1244.0	<	0.1	<	0.1	4	05/02/97	04/24/97
7439-95-4	MAGNESIUM		1180.0		1170.0	mg/L	0.5	1244.0	<	0.1	<	0.1	5	08/15/97	07/24/97
7439-95-4	MAGNESIUM		1160.0		1130.0	mg/L	0.5	1244.0			<	0.1	6	03/19/98	03/05/98
7439-95-4	MAGNESIUM		1140.0		1060.0	mg/L	0.5	1244.0			<	0.5	7	08/17/98	07/15/98
7439-95-4	MAGNESIUM		993.0	<	1.0	mg/L	0.5	1244.0			<	0.5	8	03/15/99	03/03/99
7439-95-4	MAGNESIUM		1100.0		1120.0	mg/L	0.5	1244.0			<	0.5	9	09/16/99	09/01/99
7439-95-4	MAGNESIUM		1033.0		1107.0	mg/L	5.0	1244.0					10	03/16/00	03/15/00
7439-95-4	MAGNESIUM		982.0		1040.0	mg/L	1.0	1244.0			<	1.0	11	10/26/00	09/20/00
7439-95-4	MAGNESIUM		1199.0		1188.0	mg/L	0.5	1244.0			<	0.5	12	05/10/01	03/14/01
7439-95-4	MAGNESIUM		1175.0		1193.0	mg/L	0.2	1244.0					13	11/09/01	09/19/01
7439-95-4	MAGNESIUM		1093.0		1074.0	mg/L	0.5	1244.0			<	0.5	14	03/25/02	03/20/02

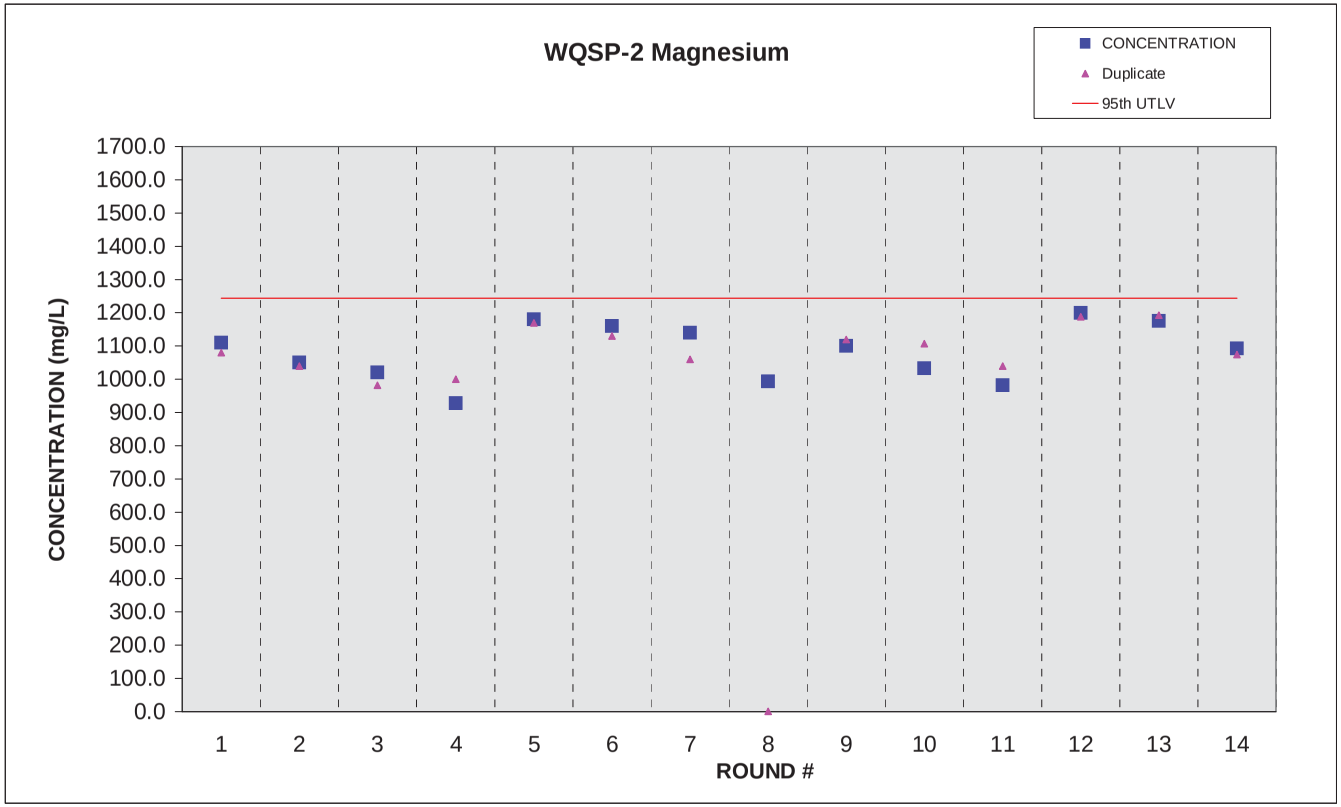

WQSP-2 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		497.0		474.0	mg/L	0.2	845.0			<	0.2	1	08/28/95	08/17/95
7440-09-7	POTASSIUM		476.0		465.0	mg/L	10.0	845.0	<	0.2	<	0.2	2	04/25/96	04/11/96
7440-09-7	POTASSIUM		471.0		451.0	mg/L	2.0	845.0	<	0.2	<	0.2	3	07/30/96	07/25/96
7440-09-7	POTASSIUM		443.0		468.0	mg/L	2.0	845.0	<	0.2	<	0.2	4	05/01/97	04/24/97
7440-09-7	POTASSIUM		499.0		476.0	mg/L	2.0	845.0	<	0.2	<	0.2	5	07/29/97	07/24/97
7440-09-7	POTASSIUM		467.0		487.0	mg/L	2.0	845.0			<	0.2	6	03/19/98	03/05/98
7440-09-7	POTASSIUM		710.0		640.0	mg/L	0.5	845.0			<	0.5	7	08/17/98	07/15/98
7440-09-7	POTASSIUM		661.0	<	1.0	mg/L	0.5	845.0			<	0.5	8	03/15/99	03/03/99
7440-09-7	POTASSIUM		700.0		728.0	mg/L	0.5	845.0			<	0.5	9	09/16/99	09/01/99
7440-09-7	POTASSIUM		333.0		380.0	mg/L	0.0	845.0					10	03/16/00	03/15/00
7440-09-7	POTASSIUM		815.0		823.0	mg/L	1.0	845.0				10.1	11	10/26/00	09/20/00
7440-09-7	POTASSIUM		706.0		768.0	mg/L	0.5	845.0			<	0.5	12	05/10/01	03/14/01
7440-09-7	POTASSIUM		841.0		856.0	mg/L	0.2	845.0					13	11/09/01	09/19/01
7440-09-7	POTASSIUM		759.0		797.0	mg/L	0.5	845.0			<	0.5	14	03/25/02	03/20/02

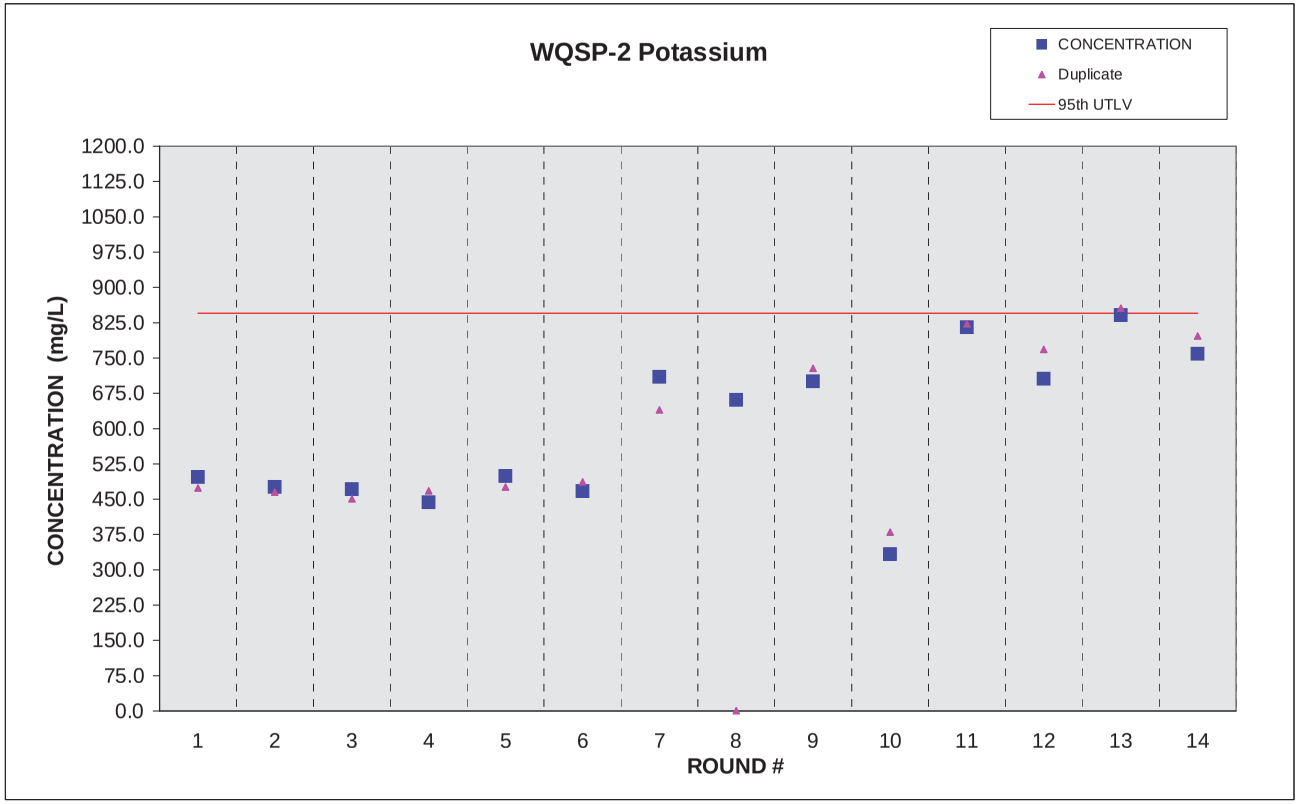

WQSP-2 Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		20100.0		19800.0	mg/L	5.0	21900.0			<	0.5	1	08/28/95	08/17/95
7440-23-5	SODIUM		18500.0		18200.0	mg/L	25.0	21900.0	<	0.5	<	0.5	2	04/25/96	04/11/96
7440-23-5	SODIUM		18900.0		18400.0	mg/L	25.0	21900.0	<	0.5	<	0.5	3	07/30/96	07/25/96
7440-23-5	SODIUM		17700.0		19600.0	mg/L	10.0	21900.0	<	0.5	<	0.2	4	05/01/97	04/24/97
7440-23-5	SODIUM		19400.0		17500.0	mg/L	10.0	21900.0	<	0.2	<	0.2	5	07/29/97	07/24/97
7440-23-5	SODIUM		19800.0		20000.0	mg/L	4.0	21900.0			<	0.2	6	03/19/98	03/05/98
7440-23-5	SODIUM		17550.0		16500.0	mg/L	0.5	21900.0			<	0.5	7	08/17/98	07/15/98
7440-23-5	SODIUM		19700.0	<	1.0	mg/L	1.0	21900.0			<	1.0	8	03/15/99	03/03/99
7440-23-5	SODIUM		15374.0		16396.0	mg/L	5.0	21900.0					10	03/16/00	03/15/00
7440-23-5	SODIUM		19800.0		20300.0	mg/L	1.0	21900.0				22.0	11	10/26/00	09/20/00
7440-23-5	SODIUM		19790.0		21340.0	mg/L	0.5	21900.0			<	0.5	12	05/10/01	03/14/01
7440-23-5	SODIUM		20910.0		21060.0	mg/L	0.2	21900.0					13	11/09/01	09/19/01
7440-23-5	SODIUM		20240.0		20490.0	mg/L	0.5	21900.0			<	0.5	14	03/25/02	03/20/02

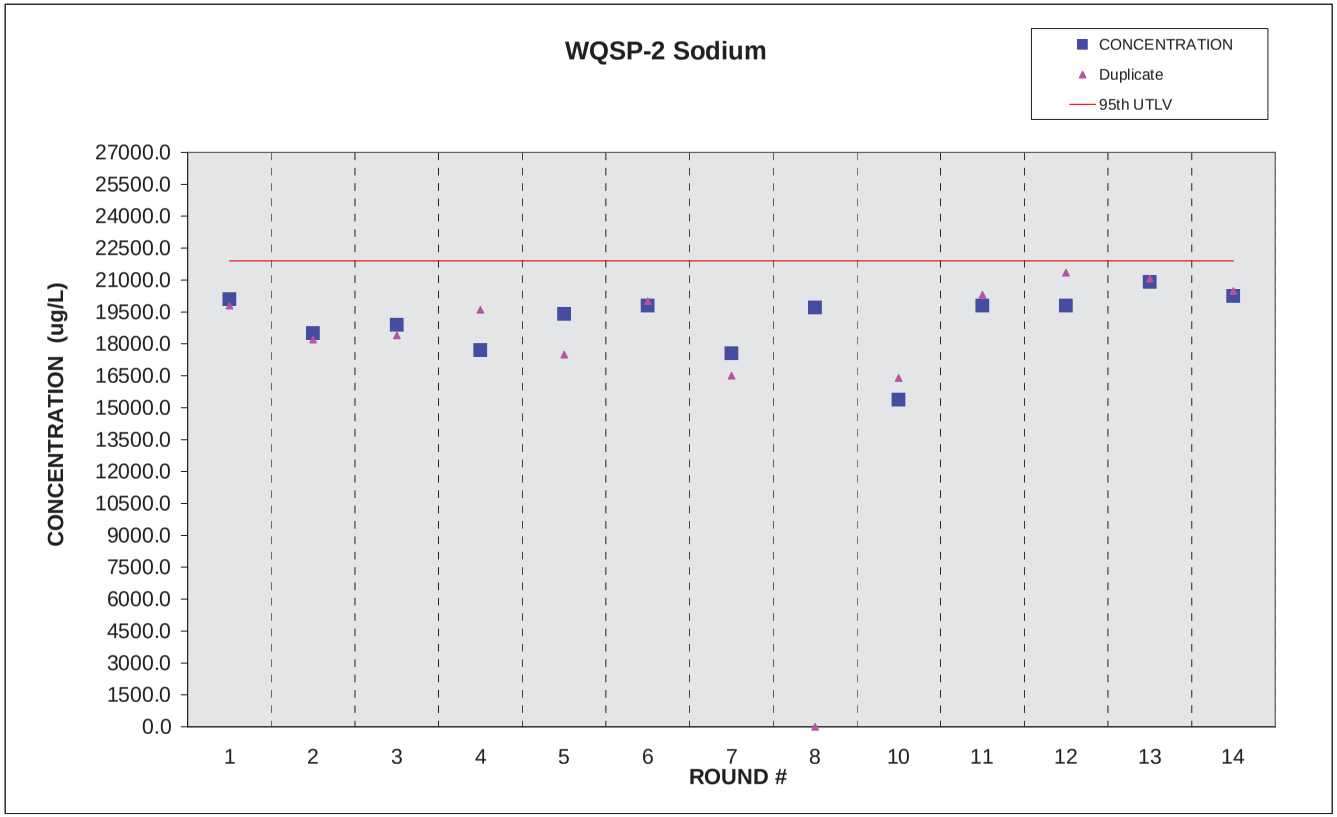

WQSP-2 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		52.5		5.3	mg/L	5.0	70.3			<	5.0	1	09/07/95	08/31/95
	ALKALINITY		48.1		48.1	mg/L	5.0	70.3		0.0	<	5.0	2	05/08/96	04/25/96
	ALKALINITY		48.1		48.1	mg/L	5.0	70.3		0.0	<	5.0	3	08/15/96	08/08/96
	ALKALINITY		50.1		50.1	mg/L	5.0	70.3			<	5.0	4	05/14/97	05/08/97
	ALKALINITY		46.0		47.0	mg/L	5.0	70.3			<	5.0	5	08/26/97	08/07/97
	ALKALINITY		43.0		48.0	mg/L	5.0	70.3					6	04/16/98	04/15/98
	ALKALINITY		46.0		48.0	mg/L	5.0	70.3			<	1.0	7	08/18/98	08/12/98
	ALKALINITY		47.0		49.0	mg/L	5.0	70.3					8	03/18/99	03/17/99
	ALKALINITY		44.0		46.0	mg/L	5.0	70.3					10	03/17/00	03/15/00
	ALKALINITY		51.0		48.0	mg/L	6.0	70.3			<	6.0	11	09/22/00	09/20/00
	ALKALINITY		48.0		50.0	mg/L	4.0	70.3					12	03/20/01	03/14/01
	ALKALINITY		46.0		48.0	mg/L	4.0	70.3					13	09/25/01	09/19/01
	ALKALINITY		48.0		46.0	mg/L	4.0	70.3					14	03/26/02	03/20/02

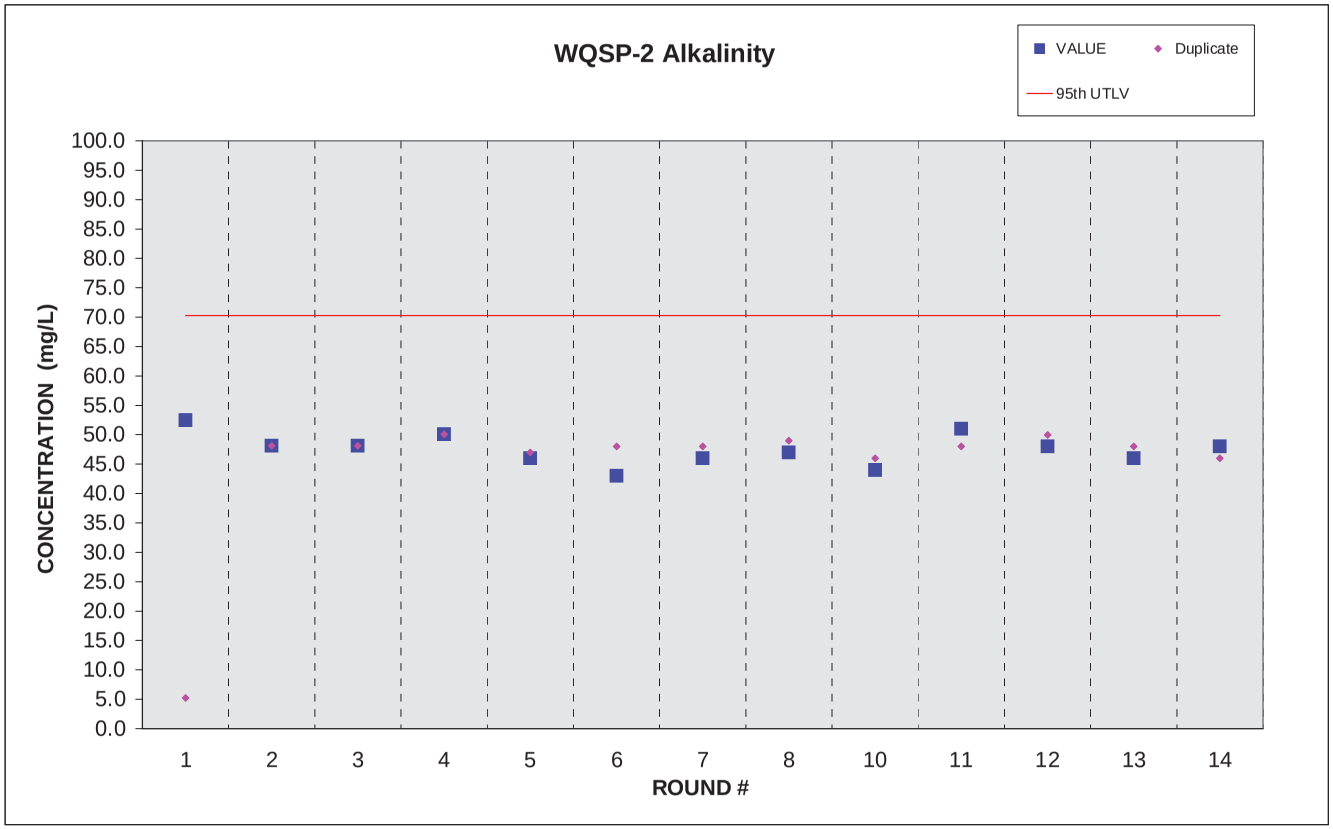

WQSP-2 Chloride

CAS #	PARAMETER		VALUE		VALUE DUPLICATE	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		38500.0		38500.0	mg/L	5.0	39670.0			<	5.0	1	09/08/95	08/31/95
7782-50-5	CHLORIDE		34200.0		36000.0	mg/L	2500.0	39670.0		0.0	<	5.0	2	05/01/96	04/25/96
7782-50-5	CHLORIDE		36000.0		36000.0	mg/L	2500.0	39670.0		0.0	<	5.0	3	08/20/96	08/08/96
7782-50-5	CHLORIDE		33000.0		32700.0	mg/L	2500.0	39670.0			<	5.0	4	05/17/97	05/08/97
7782-50-5	CHLORIDE		32500.0		33000.0	mg/L	2500.0	39670.0			<	5.0	5	08/29/97	08/07/97
7782-50-5	CHLORIDE		35500.0		35300.0	mg/L	0.2	39670.0				0.0	6	04/16/98	04/15/98
7782-50-5	CHLORIDE		37000.0		35000.0	mg/L	2500.0	39670.0				1.7	7	08/17/98	08/12/98
7782-50-5	CHLORIDE		34000.0		34000.0	mg/L	0.5	39670.0			<	0.5	8	03/19/99	03/17/99
7782-50-5	CHLORIDE		36000.0		36000.0	mg/L	0.5	39670.0			<	0.5	9	09/15/99	09/15/99
7782-50-5	CHLORIDE		37000.0		37000.0	mg/L	0.5	39670.0			<	0.5	10	03/21/00	03/15/00
7782-50-5	CHLORIDE		37000.0		36000.0	mg/L	2.0	39670.0			<	0.5	11	09/21/00	09/20/00
7782-50-5	CHLORIDE		35000.0		36000.0	mg/L	0.5	39670.0					12	03/19/01	03/14/01
7782-50-5	CHLORIDE		34900.0		34800.0	mg/L	2.0	39670.0					13	10/08/01	09/19/01
7782-50-5	CHLORIDE		34500.0		33900.0	mg/L	2.0	39670.0					14	03/26/02	03/20/02

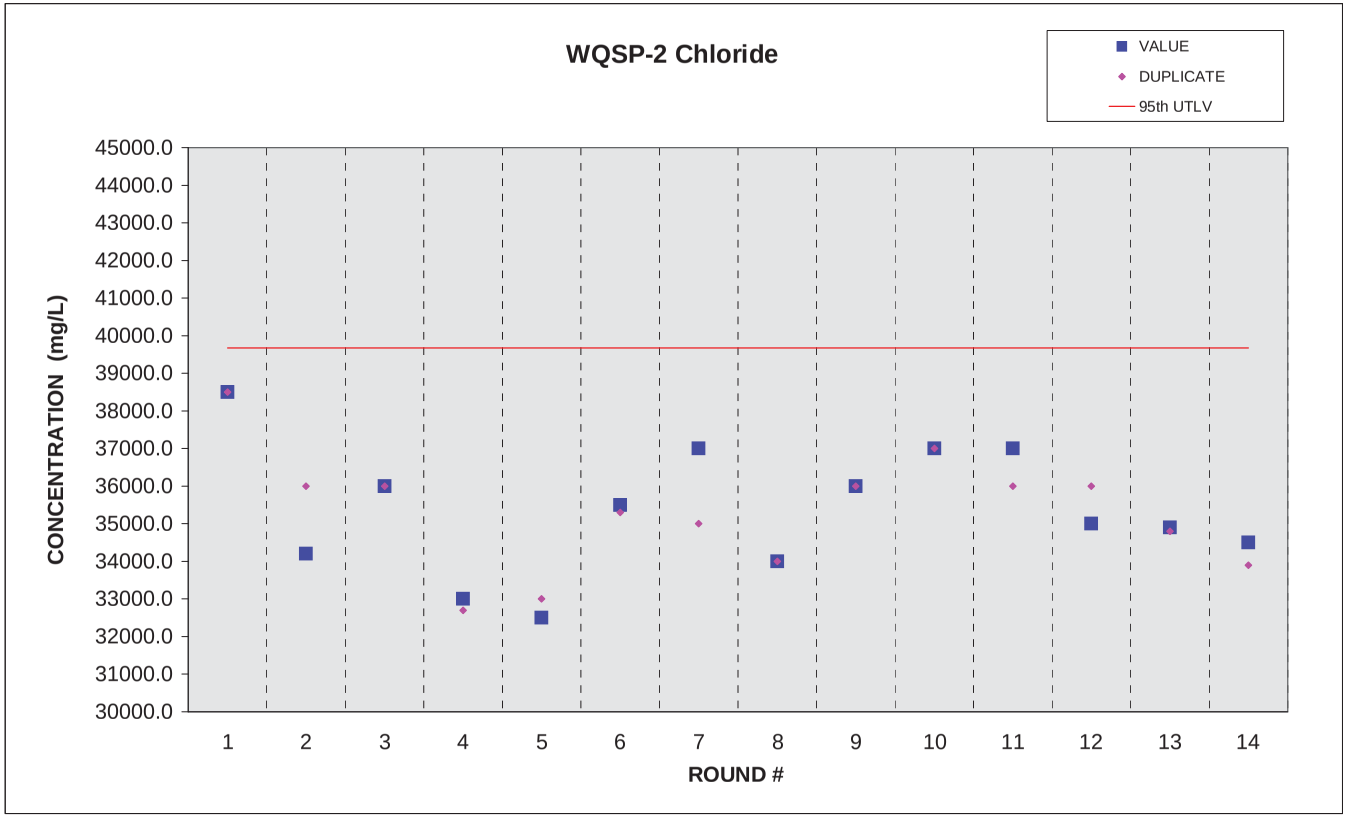

WQSP-2 Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		5540.0		5470.0	mg/L	10.0	6590.0			<	10.0	1	09/06/95	08/31/95
	SULFATE		5610.0		5640.0	mg/L	2500.0	6590.0			<	10.0	2	05/08/96	04/25/96
	SULFATE		5700.0		5710.0	mg/L	1000.0	6590.0			<	10.0	3	08/21/96	08/08/96
	SULFATE		6360.0		6020.0	mg/L	2500.0	6590.0			<	10.0	4	05/19/97	05/08/97
	SULFATE		4990.0		4900.0	mg/L	2500.0	6590.0			<	10.0	5	09/03/97	08/07/97
	SULFATE		5280.0		5260.0	mg/L	0.2	6590.0			<	0.2	6	04/16/98	04/15/98
	SULFATE		5400.0		5000.0	mg/L	2500.0	6590.0			<	0.5	7	08/18/98	08/12/98
	SULFATE		5000.0		4600.0	mg/L	0.5	6590.0			<	0.5	8	03/22/99	03/17/99
	SULFATE		5900.0		6000.0	mg/L	0.5	6590.0			<	0.5	10	03/15/00	03/15/00
	SULFATE		5800.0		5600.0	mg/L	0.5	6590.0			<	0.5	11	09/21/00	09/20/00
	SULFATE		5200.0		5600.0	mg/L	0.5	6590.0					12	03/19/01	03/14/01
	SULFATE		5160.0		5060.0	mg/L	2.0	6590.0					13	10/08/01	09/19/01
	SULFATE		5570.0		5650.0	mg/L	2.0	6590.0					14	03/26/02	03/20/02

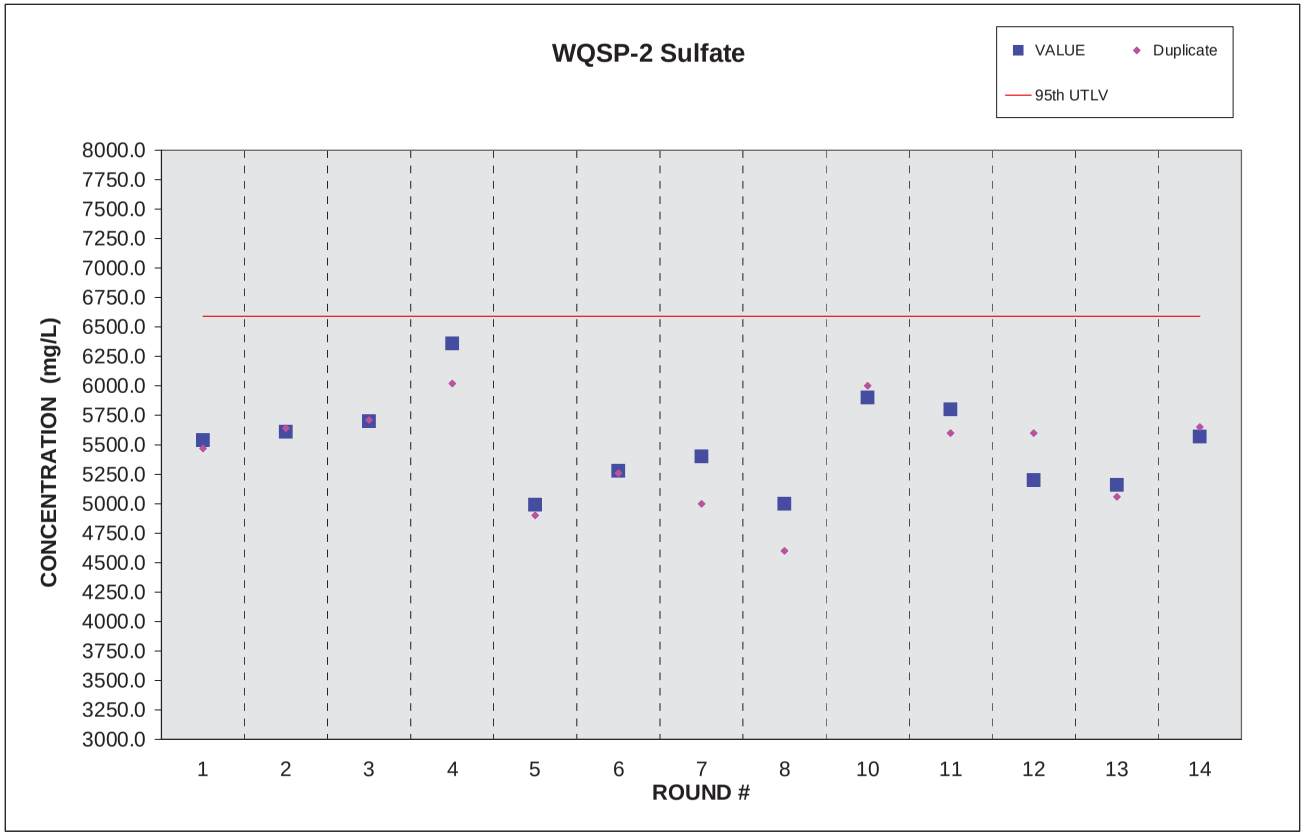

WQSP-3 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		1420.0		1350.0	mg/L	8.0	1680.0			<	0.2	1	10/20/95	09/19/95
7440-70-2	CALCIUM		1480.0		1450.0	mg/L	2.0	1680.0	<	0.2	<	0.2	2	06/03/96	05/09/96
7440-70-2	CALCIUM		1300.0		1260.0	mg/L	2.0	1680.0	<	0.2	<	0.2	3	08/29/96	08/22/96
7440-70-2	CALCIUM		1100.0		1200.0	mg/L	2.0	1680.0	<	0.2	<	0.2	4	06/13/97	05/22/97
7440-70-2	CALCIUM		1210.0		1120.0	mg/L	2.0	1680.0	<	0.2	<	0.2	5	09/05/97	08/21/97
7440-70-2	CALCIUM		1380.0		1409.4	mg/L	0.0	1680.0			<	0.0	6	04/24/98	04/22/98
7440-70-2	CALCIUM		1200.0		1500.0	mg/L	0.1	1680.0			<	0.1	7	09/29/98	08/26/98
7440-70-2	CALCIUM		1400.0		1530.0	mg/L	1.0	1680.0			<	1.0	8	04/15/99	04/08/99
7440-70-2	CALCIUM		1500.0		1500.0	mg/L	1.0	1680.0			<	1.0	9	11/25/99	10/06/99
7440-70-2	CALCIUM		1390.0		1440.0	mg/L	5.0	1680.0				0.1	10	04/06/00	03/23/00
7440-70-2	CALCIUM		1410.0		1420.0	mg/L	1.0	1680.0			<	1.0	11	10/24/00	10/05/00
7440-70-2	CALCIUM		1310.0		1300.0	mg/L	0.5	1680.0			<	0.5	12	06/25/01	03/29/01
7440-70-2	CALCIUM		1537.0		1430.0	mg/L	0.2	1680.0					13	10/17/01	10/04/01
7440-70-2	CALCIUM		1500.0		1560.0	mg/L	0.5	1680.0					14	04/15/02	04/04/02

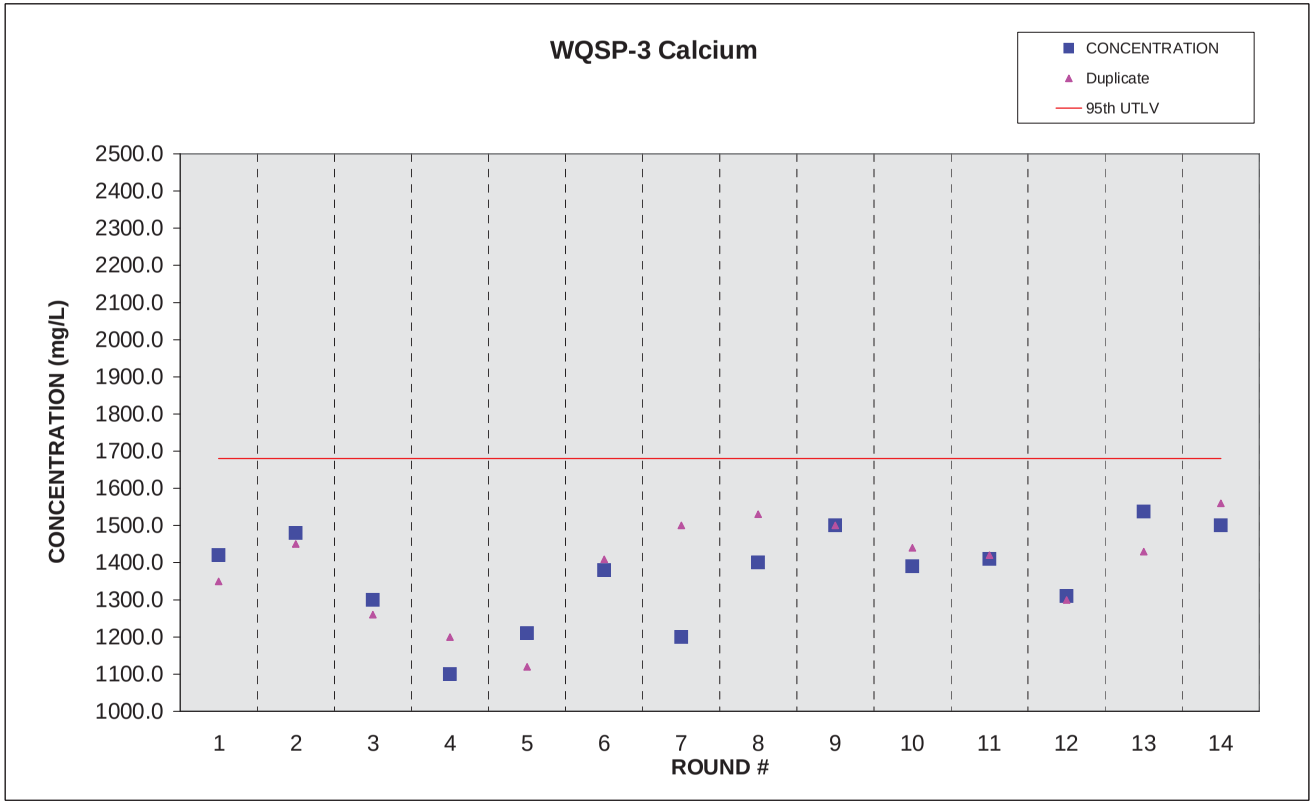

WQSP-3 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		2210.0		2110.0	mg/L	4.0	2625.0			<	0.1	1	10/20/95	09/19/95
7439-95-4	MAGNESIUM		2000.0		1970.0	mg/L	0.5	2625.0	<	0.1	<	0.1	2	06/03/96	05/09/96
7439-95-4	MAGNESIUM		1960.0		1890.0	mg/L	0.5	2625.0	<	0.1	<	0.1	3	08/29/96	08/22/96
7439-95-4	MAGNESIUM		1890.0		2050.0	mg/L	1.0	2625.0	<	0.1	<	0.1	4	06/13/97	05/22/97
7439-95-4	MAGNESIUM		1910.0		1770.0	mg/L	1.0	2625.0	<	0.1	<	0.1	5	09/05/97	08/21/97
7439-95-4	MAGNESIUM		2340.0		2404.0	mg/L	0.1	2625.0			<	0.1	6	04/24/98	04/22/98
7439-95-4	MAGNESIUM		2100.0		2500.0	mg/L	0.1	2625.0			<	0.0	7	09/29/98	08/26/98
7439-95-4	MAGNESIUM		2070.0		2290.0	mg/L	1.0	2625.0			<	1.0	8	04/15/99	04/08/99
7439-95-4	MAGNESIUM		2290.0		2310.0	mg/L	0.5	2625.0			<	0.5	9	11/25/99	10/06/99
7439-95-4	MAGNESIUM		2110.0		2140.0	mg/L	5.0	2625.0				0.1	10	04/06/00	03/23/00
7439-95-4	MAGNESIUM		2120.0		2140.0	mg/L	1.0	2625.0			<	1.0	11	10/24/00	10/05/00
7439-95-4	MAGNESIUM		2120.0		2040.0	mg/L	0.5	2625.0			<	0.5	12	06/25/01	03/29/01
7439-95-4	MAGNESIUM		2455.0		2312.0	mg/L	0.2	2625.0					13	10/17/01	10/04/01
7439-95-4	MAGNESIUM		2270.0		2400.0	mg/L	0.5	2625.0					14	04/15/02	04/04/02

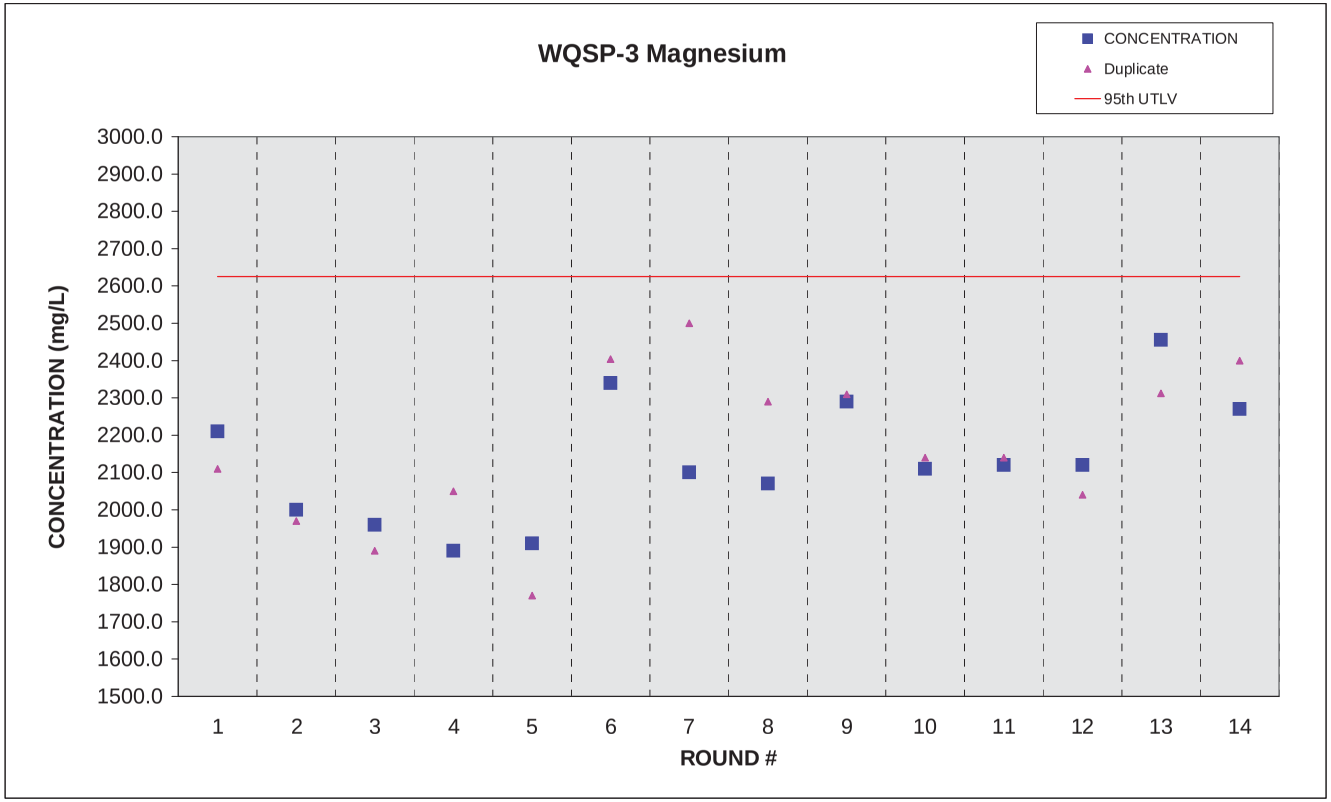

WQSP-3 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		1380.0		1310.0	mg/L	8.0	3438.0			<	0.2	1	10/20/95	09/19/95
7440-09-7	POTASSIUM		1710.0		1710.0	mg/L	0.2	3438.0	<	0.2	<	0.2	2	05/29/96	05/09/96
7440-09-7	POTASSIUM		1360.0		1450.0	mg/L	2.0	3438.0	<	0.2	<	0.2	3	08/29/96	08/22/96
7440-09-7	POTASSIUM		1370.0		1480.0	mg/L	2.0	3438.0	<	0.2	<	0.2	4	05/29/97	05/22/97
7440-09-7	POTASSIUM		1530.0		1400.0	mg/L	2.0	3438.0	<	0.2	<	0.2	5	08/28/97	08/21/97
7440-09-7	POTASSIUM		1460.0		1502.0	mg/L	0.1	3438.0			<	0.1	6	04/24/98	04/22/98
7440-09-7	POTASSIUM		1300.0		1600.0	mg/L	0.1	3438.0			<	0.1	7	09/29/98	08/26/98
7440-09-7	POTASSIUM		2140.0		2440.0	mg/L	1.0	3438.0			<	1.0	8	04/15/99	04/08/99
7440-09-7	POTASSIUM		2870.0		2800.0	mg/L	0.5	3438.0			<	0.5	9	11/25/99	10/07/99
7440-09-7	POTASSIUM		2700.0		2700.0	mg/L	5.0	3438.0				0.1	10	04/06/00	03/23/00
7440-09-7	POTASSIUM		2880.0		3030.0	mg/L	1.0	3438.0				0.2	11	10/24/00	10/05/00
7440-09-7	POTASSIUM		2180.0		2190.0	mg/L	0.5	3438.0			<	0.5	12	06/25/01	03/29/01
7440-09-7	POTASSIUM		3035.0		2862.0	mg/L	0.2	3438.0					13	10/17/01	10/04/01
7440-09-7	POTASSIUM		1960.0		1950.0	mg/L	0.5	3438.0					14	05/06/02	04/04/02

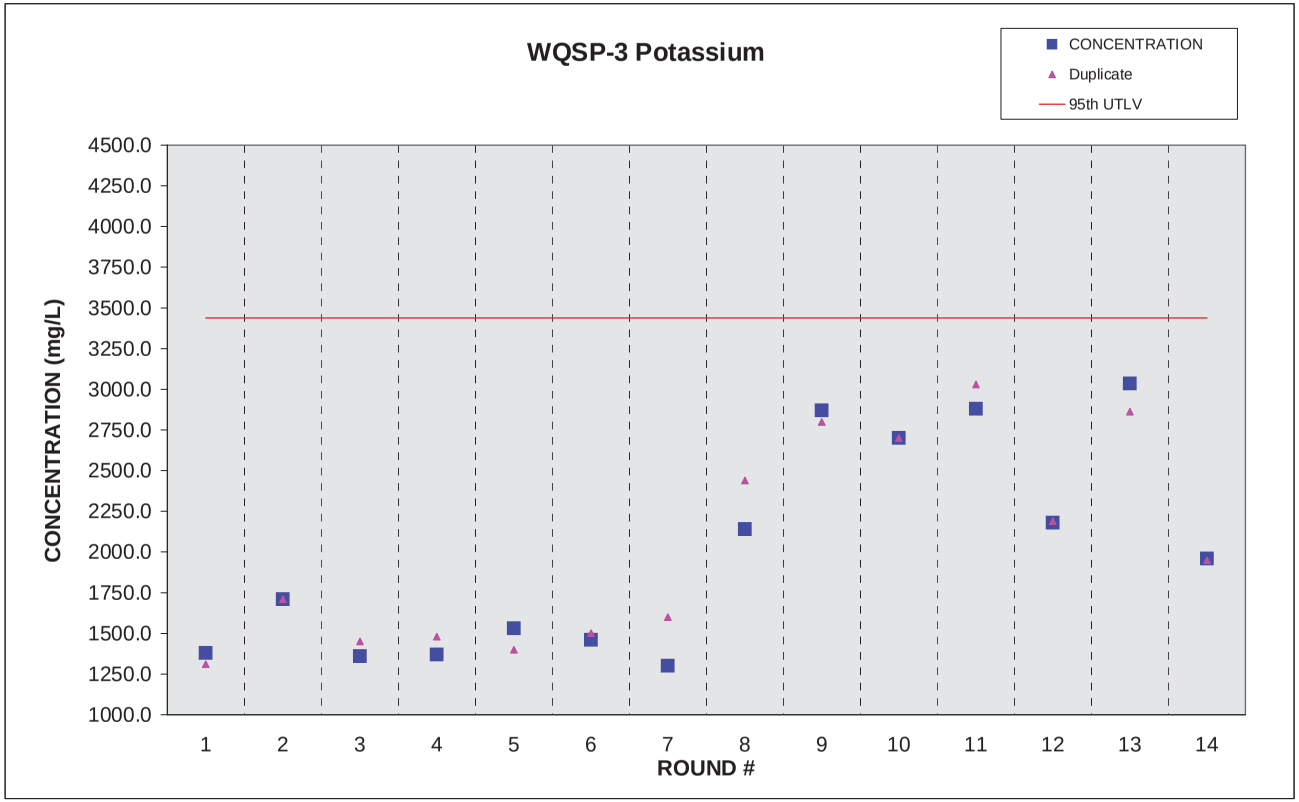

WQSP-3 Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		79100.0		76700.0	mg/L	100.0	140400.0			<	0.5	1	10/20/95	09/19/95
7440-23-5	SODIUM		74200.0		73700.0	mg/L	50.0	140400.0	<	0.5	<	0.5	2	05/29/96	05/09/96
7440-23-5	SODIUM		76700.0		68200.0	mg/L	50.0	140400.0	<	0.5	<	0.5	3	08/29/96	08/22/96
7440-23-5	SODIUM		71200.0		71800.0	mg/L	25.0	140400.0	<	0.5	<	0.5	4	05/29/97	05/22/97
7440-23-5	SODIUM		75700.0		74200.0	mg/L	25.0	140400.0	<	0.5	<	0.5	5	08/28/97	08/21/97
7440-23-5	SODIUM		74900.0		77660.0	mg/L	0.0	140400.0			<	0.0	6	04/24/98	04/22/98
7440-23-5	SODIUM		58000.0		71000.0	mg/L	0.1	140400.0			<	0.1	7	09/29/98	08/26/98
7440-23-5	SODIUM		146800.0		134000.0	mg/L	1.0	140400.0			<	1.0	8	04/15/99	04/08/99
7440-23-5	SODIUM		66600.0		68300.0	mg/L	1.0	140400.0			<	1.0	9	11/25/99	10/06/99
7440-23-5	SODIUM		75200.0		75200.0	mg/L	5.0	140400.0				0.2	10	04/06/00	03/23/00
7440-23-5	SODIUM		77900.0		77800.0	mg/L	5.0	140400.0				0.4	11	12/22/00	10/05/00
7440-23-5	SODIUM		68300.0		71100.0	mg/L	0.5	140400.0			<	0.5	12	06/25/01	03/29/01
7440-23-5	SODIUM		81600.0		74400.0	mg/L	0.2	140400.0					13	10/16/01	10/04/01
7440-23-5	SODIUM		73200.0		75100.0	mg/L	0.5	140400.0					14	04/15/02	04/04/02

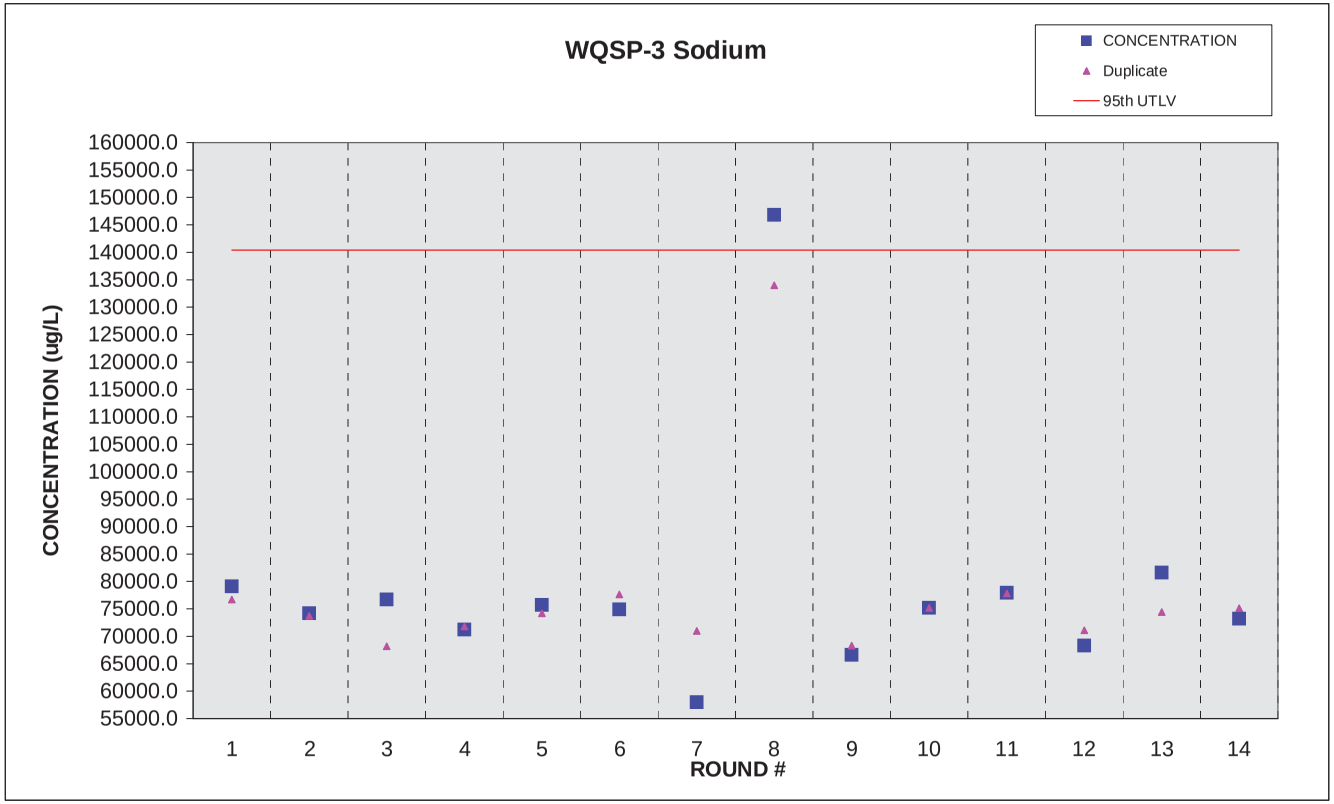

WQSP-3 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		44.0		44.0	mg/L	5.0	54.5			<	5.0	1	10/02/95	09/19/95
	ALKALINITY		35.0		35.0	mg/L	5.0	54.5			<	5.0	2	05/15/96	05/09/96
	ALKALINITY		36.1		35.1	mg/L	5.0	54.5			<	5.0	3	09/12/96	08/22/96
	ALKALINITY		33.0		33.0	mg/L	5.0	54.5			<	5.0	4	06/09/97	05/22/97
	ALKALINITY		32.0		33.0	mg/L	5.0	54.5			<	5.0	5	08/26/97	08/21/97
	ALKALINITY		33.0		33.0	mg/L	5.0	54.5					6	04/24/98	4/22/98
	ALKALINITY		31.0		31.0	mg/L	1.0	54.5			<	1.0	7	09/09/98	08/26/98
	ALKALINITY		31.0		33.0	mg/L	3.0	54.5			<	3.0	8	04/11/99	04/08/99
	ALKALINITY		36.0		37.0	mg/L	3.0	54.5					9	10/12/99	10/06/99
	ALKALINITY		55.0		54.0	mg/L	3.0	54.5					10	03/30/00	03/23/00
	ALKALINITY		35.0		36.0	mg/L	6.0	54.5			<	4.0	11	10/11/00	10/05/00
	ALKALINITY		34.0		32.0	mg/L	4.0	54.5					12	04/04/01	03/29/01
	ALKALINITY		32.0		34.0	mg/L	4.0	54.5					13	10/11/01	10/04/01
	ALKALINITY		36.0		38.0	mg/L	4.0	54.5					14	04/04/02	04/04/02

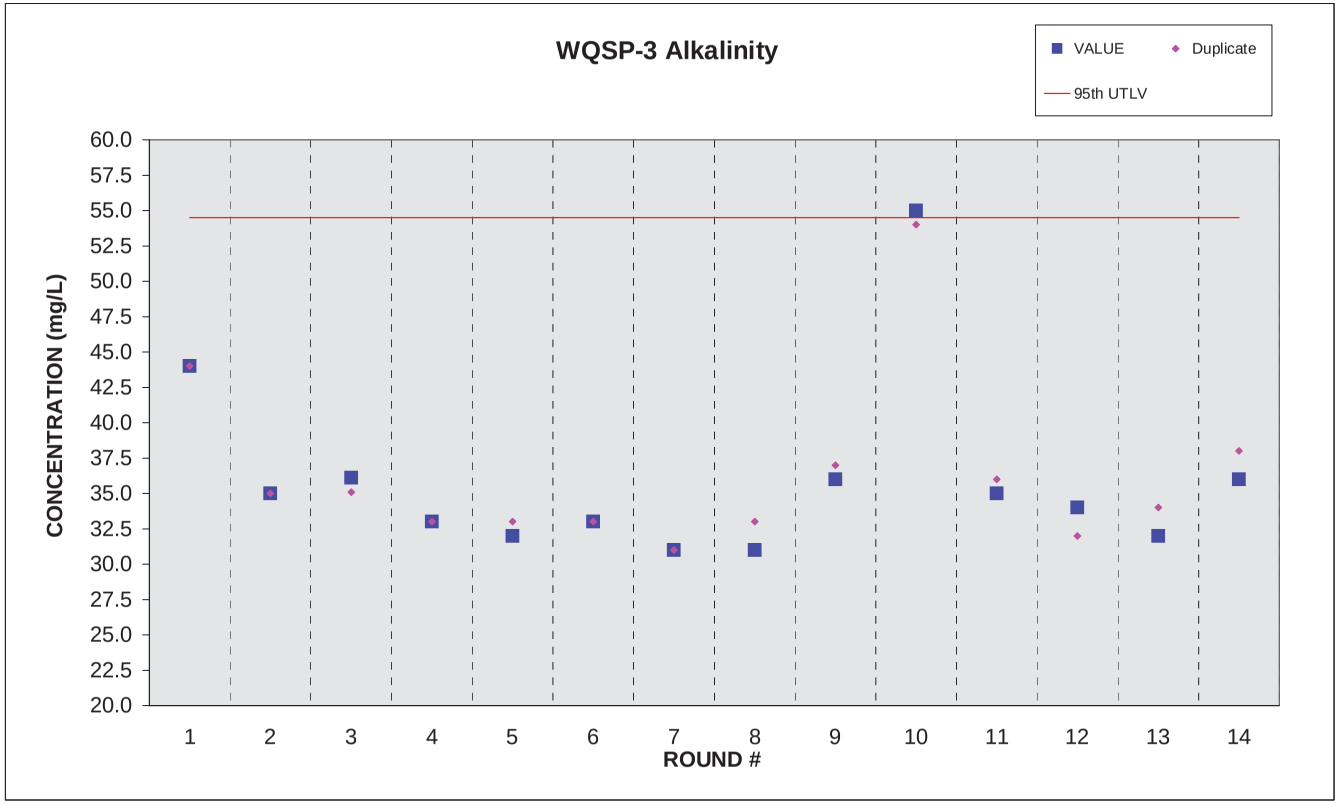

WQSP-3 Chloride

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
7782-50-5	CHLORIDE		130000.0		138000.0	mg/L	5.0	149100.0			<	5.0	1	09/22/95	09/19/95
7782-50-5	CHLORIDE		144000.0		145000.0	mg/L	5000.0	149100.0		0.0	<	5.0	2	05/16/96	05/09/96
7782-50-5	CHLORIDE		129000.0		128000.0	mg/L	5000.0	149100.0		0.0	<	5.0	3	09/18/96	08/22/96
7782-50-5	CHLORIDE		128000.0		129000.0	mg/L	5000.0	149100.0			<	5.0	4	06/04/97	05/22/97
7782-50-5	CHLORIDE		121000.0		123000.0	mg/L	5000.0	149100.0			<	5.0	5	08/29/97	08/21/97
7782-50-5	CHLORIDE		125000.0		125000.0	mg/L	0.0	149100.0				0.0	6	04/24/98	04/22/98
7782-50-5	CHLORIDE		120000.0		130000.0	mg/L	0.5	149100.0				1.7	7	09/03/98	08/26/98
7782-50-5	CHLORIDE		120000.0		130000.0	mg/L	0.5	149100.0			<	0.5	8	04/09/99	04/08/99
7782-50-5	CHLORIDE		140000.0		140000.0	mg/L	0.5	149100.0			<	0.5	9	10/06/99	10/06/99
7782-50-5	CHLORIDE		123000.0		123000.0	mg/L	0.5	149100.0			<	0.5	10	03/24/00	03/23/00
7782-50-5	CHLORIDE		130000.0		130000.0	mg/L	0.5	149100.0			<	0.5	11	10/11/00	10/05/00
7782-50-5	CHLORIDE		130000.0		130000.0	mg/L	0.5	149100.0					12	04/04/01	03/29/01
7782-50-5	CHLORIDE		131000.0		129000.0	mg/L	2.0	149100.0					13	10/12/01	10/04/01
7782-50-5	CHLORIDE		125000.0		126000.0	mg/L	2.0	149100.0					14	04/04/02	04/04/02

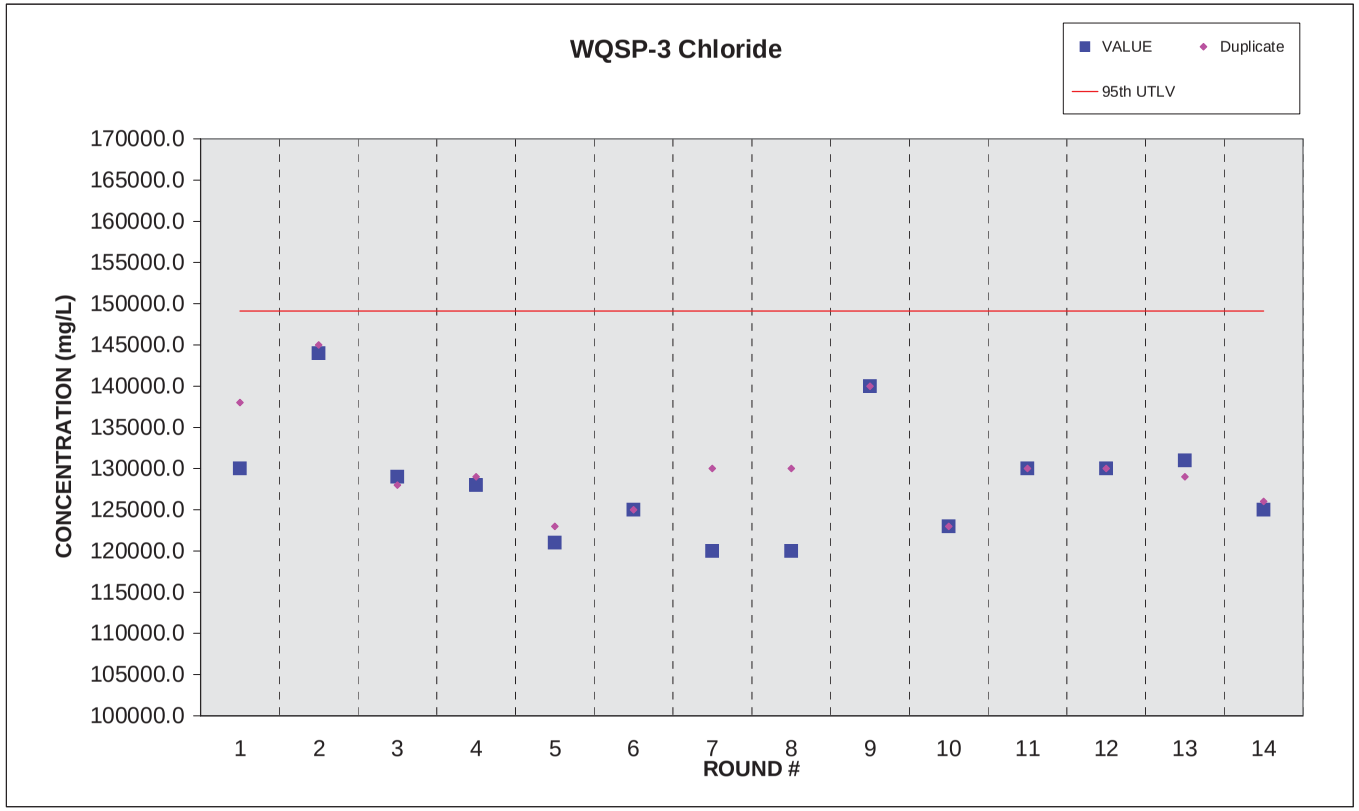

WQSP-3 Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		6710.0		6700.0	mg/L	10.0	8015.0			<	10.0	1	08/29/95	08/17/95
	SULFATE		6760.0		6840.0	mg/L	2.5	8015.0			<	10.0	2	04/25/96	04/11/96
	SULFATE		7650.0		7650.0	mg/L	2.5	8015.0			<	10.0	3	08/21/96	07/25/96
	SULFATE		7230.0		7260.0	mg/L	2.5	8015.0			<	10.0	4	05/01/97	04/24/97
	SULFATE		7400.0		6400.0	mg/L	2.5	8015.0			<	10.0	5	09/03/97	07/24/97
	SULFATE		6770.0		6769.4	mg/L	0.0	8015.0			<	0.0	6	03/11/98	03/05/98
	SULFATE		7400.0		7200.0	mg/L	0.5	8015.0					7	07/26/98	07/15/98
	SULFATE		7300.0		7300.0	mg/L	0.5	8015.0			<	0.5	8	03/03/99	03/03/99
	SULFATE		7500.0		7400.0	mg/L	0.5	8015.0			<	0.5	9	09/07/99	09/01/99
	SULFATE		7500.0		7200.0	mg/L	0.5	8015.0			<	0.5	10	03/24/00	03/23/00
	SULFATE		7000.0		6800.0	mg/L	0.5	8015.0			<	0.5	11	10/09/00	10/05/00
	SULFATE		7200.0		7200.0	mg/L	0.5	8015.0					12	04/04/01	03/29/01
	SULFATE		7460.0		7190.0	mg/L	2.0	8015.0					13	10/12/01	10/04/01
	SULFATE		7540.0		7150.0	mg/L	2.0	8015.0					14	04/04/02	04/04/02

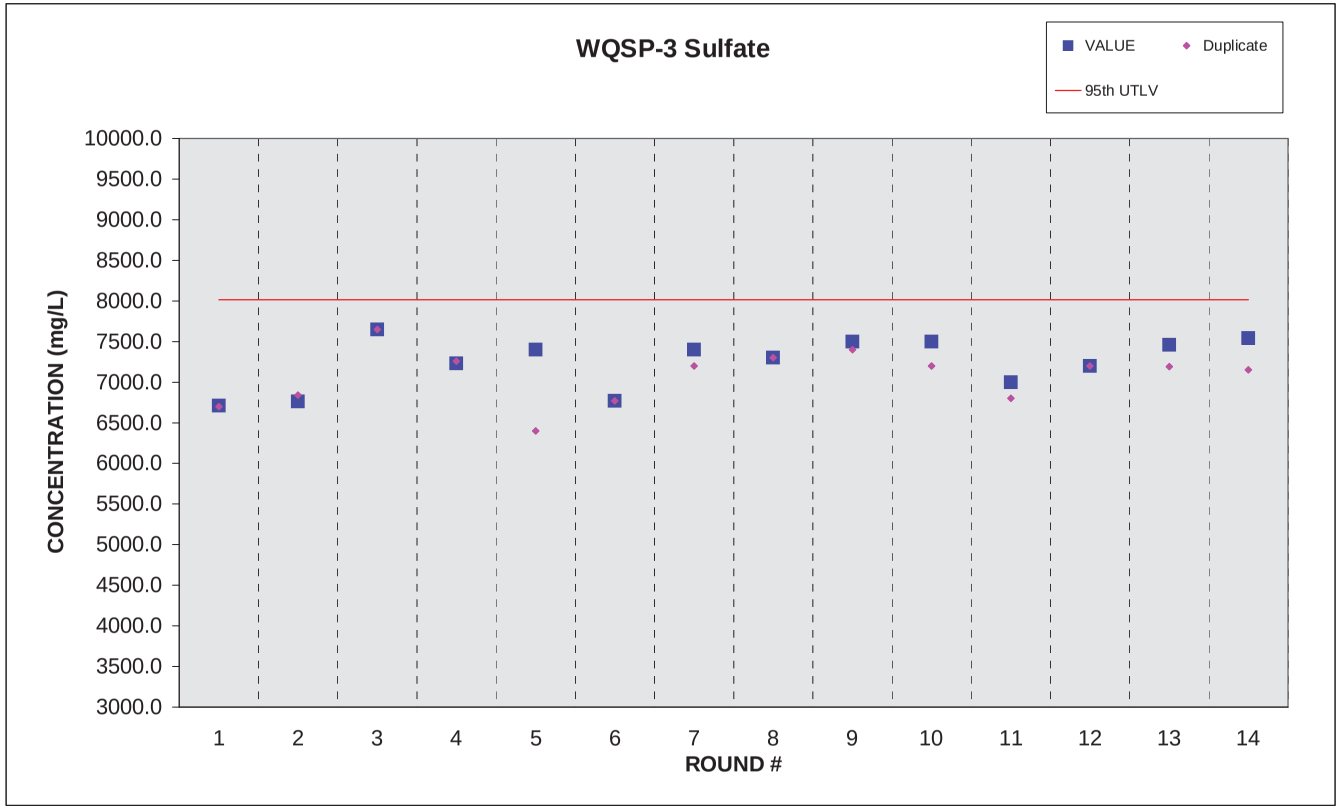

WQSP-4 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		1710.0		1650.0	mg/L	40.0	1834.0			<	0.2	1	10/20/95	09/28/95
7440-70-2	CALCIUM		1570.0		1550.0	mg/L	2.0	1834.0	<	0.2	<	0.2	2	06/18/96	05/23/96
7440-70-2	CALCIUM		1590.0		1600.0	mg/L	2.0	1834.0	<	0.2	<	0.2	3	09/18/96	09/12/96
7440-70-2	CALCIUM		1490.0		1470.0	mg/L	2.0	1834.0	<	0.2	<	0.2	4	06/17/97	06/05/97
7440-70-2	CALCIUM		1480.0		1550.0	mg/L	2.0	1834.0	<	0.2	<	0.2	5	09/30/97	09/11/97
7440-70-2	CALCIUM		1600.0		1600.0	mg/L	0.0	1834.0				0.0	6	05/12/98	05/06/98
7440-70-2	CALCIUM		1560.0		1740.0	mg/L	0.5	1834.0			<	0.5	7	09/28/98	09/23/98
7440-70-2	CALCIUM		1480.0		1670.0	mg/L	1.0	1834.0			<	1.0	8	04/27/99	04/21/99
7440-70-2	CALCIUM		1640.0		1824.0	mg/L	0.1	1834.0			<	0.1	9	12/01/99	11/25/99
7440-70-2	CALCIUM		1610.0		1670.0	mg/L	0.1	1834.0			<	0.1	10	04/24/00	04/12/00
7440-70-2	CALCIUM		1560.0		1550.0	mg/L	5.0	1834.0			<	5.0	11	10/26/00	10/26/00
7440-70-2	CALCIUM		1520.0		1650.0	mg/L	0.5	1834.0			<	0.5	12	06/25/01	04/18/01
7440-70-2	CALCIUM		1470.0		1505.0	mg/L	0.2	1834.0					13	10/29/01	10/17/01
7440-70-2	CALCIUM		1610.0		1590.0	mg/L	0.5	1834.0					14	04/24/02	04/17/02

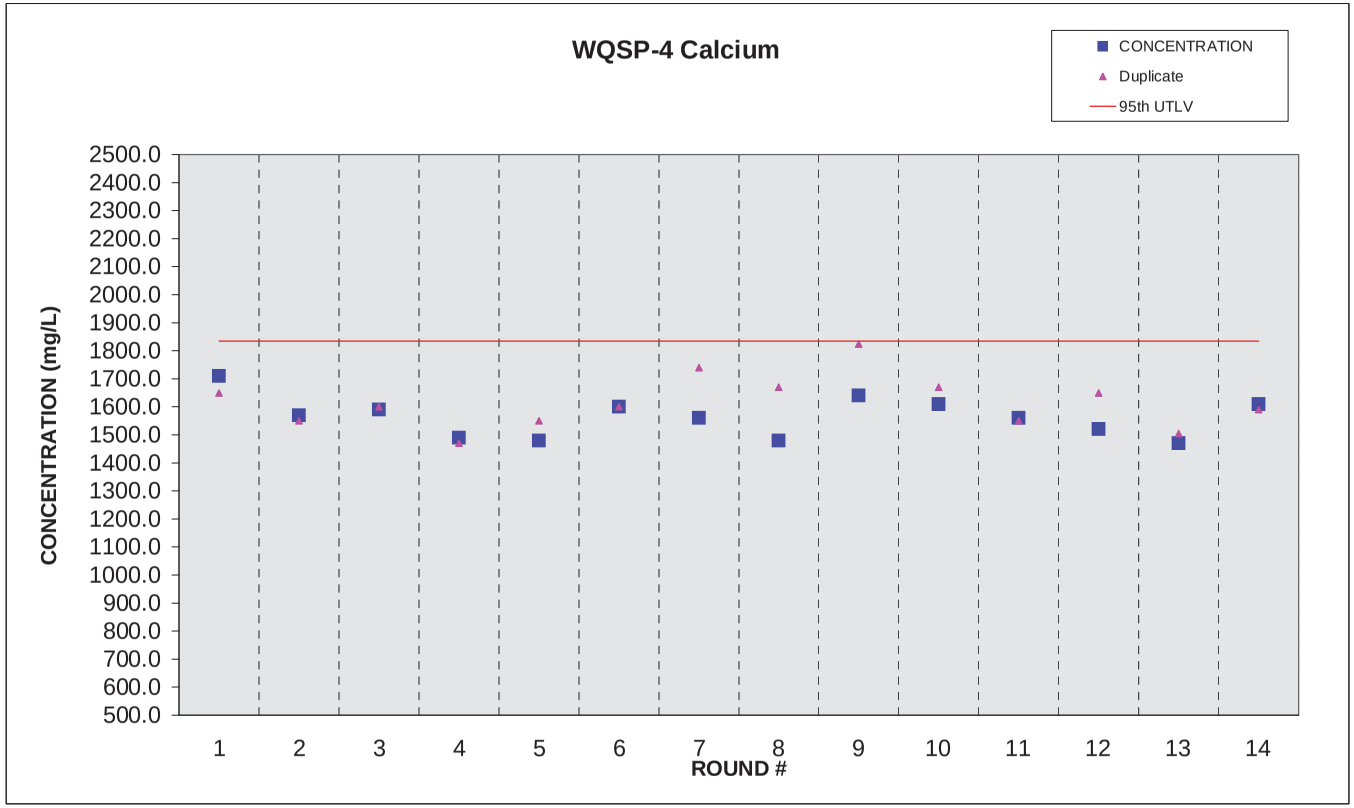

WQSP-4 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		1270.0		1230.0	mg/L	4.0	1472.0			<	0.1	1	10/20/95	09/28/95
7439-95-4	MAGNESIUM		1100.0		1070.0	mg/L	0.5	1472.0	<	0.1	<	0.1	2	06/18/96	05/23/96
7439-95-4	MAGNESIUM		1140.0		1150.0	mg/L	0.5	1472.0	<	0.1	<	0.1	3	09/18/96	09/12/96
7439-95-4	MAGNESIUM		1040.0		1040.0	mg/L	1.0	1472.0	<	0.1	<	0.1	4	06/17/97	06/05/97
7439-95-4	MAGNESIUM		1130.0		1180.0	mg/L	1.0	1472.0	<	0.1	<	0.1	5	09/30/97	09/11/97
7439-95-4	MAGNESIUM		1280.0		1280.0	mg/L	0.1	1472.0				0.1	6	05/12/98	05/06/98
7439-95-4	MAGNESIUM		1230.0		1420.0	mg/L	0.5	1472.0			<	0.5	7	09/28/98	09/23/98
7439-95-4	MAGNESIUM		1040.0		1180.0	mg/L	1.0	1472.0			<	1.0	8	04/27/99	04/21/99
7439-95-4	MAGNESIUM		1249.0		1397.0	mg/L	0.5	1472.0			<	0.5	9	12/01/99	10/13/99
7439-95-4	MAGNESIUM		1180.0		1210.0	mg/L	0.1	1472.0			<	0.5	10	04/24/00	04/12/00
7439-95-4	MAGNESIUM		1190.0		1180.0	mg/L	5.0	1472.0			<	5.0	11	10/26/00	10/18/00
7439-95-4	MAGNESIUM		1050.0		1060.0	mg/L	0.5	1472.0			<	0.5	12	06/25/01	04/18/01
7439-95-4	MAGNESIUM		1093.0		1134.0	mg/L	0.2	1472.0					13	10/29/01	10/17/01
7439-95-4	MAGNESIUM		1260.0		1200.0	mg/L	0.5	1472.0					14	04/24/02	04/17/02

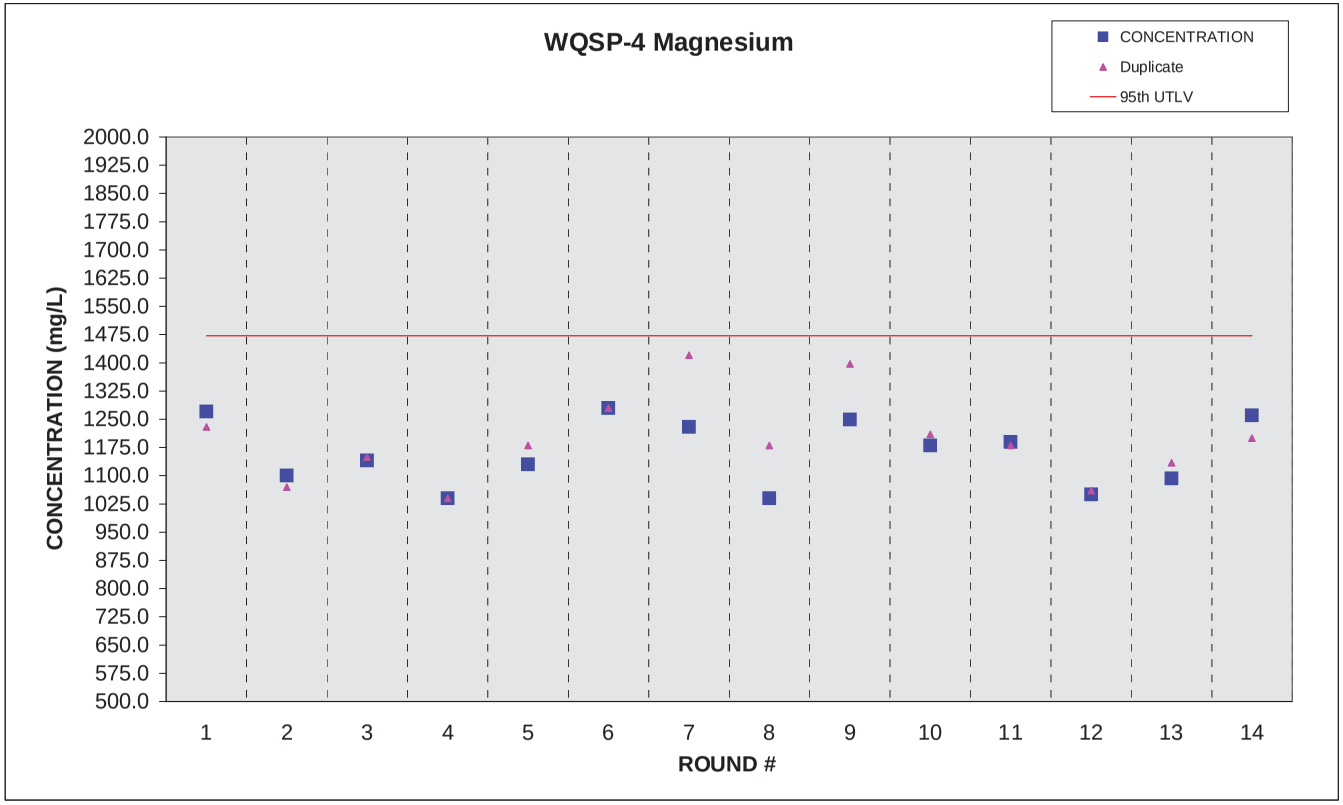

WQSP-4 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		764.0		732.0	mg/L	40.0	1648.0			<	0.2	1	10/20/95	09/28/95
7440-09-7	POTASSIUM		700.0		691.0	mg/L	2.0	1648.0	<	0.2	<	0.2	2	05/29/96	05/23/96
7440-09-7	POTASSIUM		733.0		782.0	mg/L	2.0	1648.0	<	0.2	<	0.2	3	09/20/96	09/12/96
7440-09-7	POTASSIUM		672.0		654.0	mg/L	2.0	1648.0	<	0.2	<	0.2	4	06/13/97	06/05/97
7440-09-7	POTASSIUM		681.0		664.0	mg/L	2.0	1648.0	<	0.2	<	0.2	5	09/19/97	09/11/97
7440-09-7	POTASSIUM		760.0		760.0	mg/L	0.1	1648.0			<	0.1	6	05/12/98	05/06/98
7440-09-7	POTASSIUM		1370.0		1440.0	mg/L	0.5	1648.0			<	0.5	7	09/28/98	09/23/98
7440-09-7	POTASSIUM		935.0		1060.0	mg/L	1.0	1648.0			<	1.0	8	04/27/99	04/21/99
7440-09-7	POTASSIUM		980.0		1049.0	mg/L	0.5	1648.0			<	0.5	9	12/01/99	10/13/99
7440-09-7	POTASSIUM		1180.0		1217.0	mg/L	0.1	1648.0			<	0.5	10	04/24/00	04/12/00
7440-09-7	POTASSIUM		1350.0		1350.0	mg/L	1.0	1648.0					10	06/19/00	same
7440-09-7	POTASSIUM		1320.0		1320.0	mg/L	5.0	1648.0			<	0.2	11	10/26/00	10/18/00
7440-09-7	POTASSIUM		1020.0		1090.0	mg/L	0.5	1648.0			<	0.5	12	06/25/01	04/18/01
7440-09-7	POTASSIUM		1221.0		1245.0	mg/L	0.2	1648.0					13	10/29/01	10/17/01
7440-09-7	POTASSIUM		1220.0		1230.0	mg/L	0.5	1648.0					14	04/24/02	04/17/02

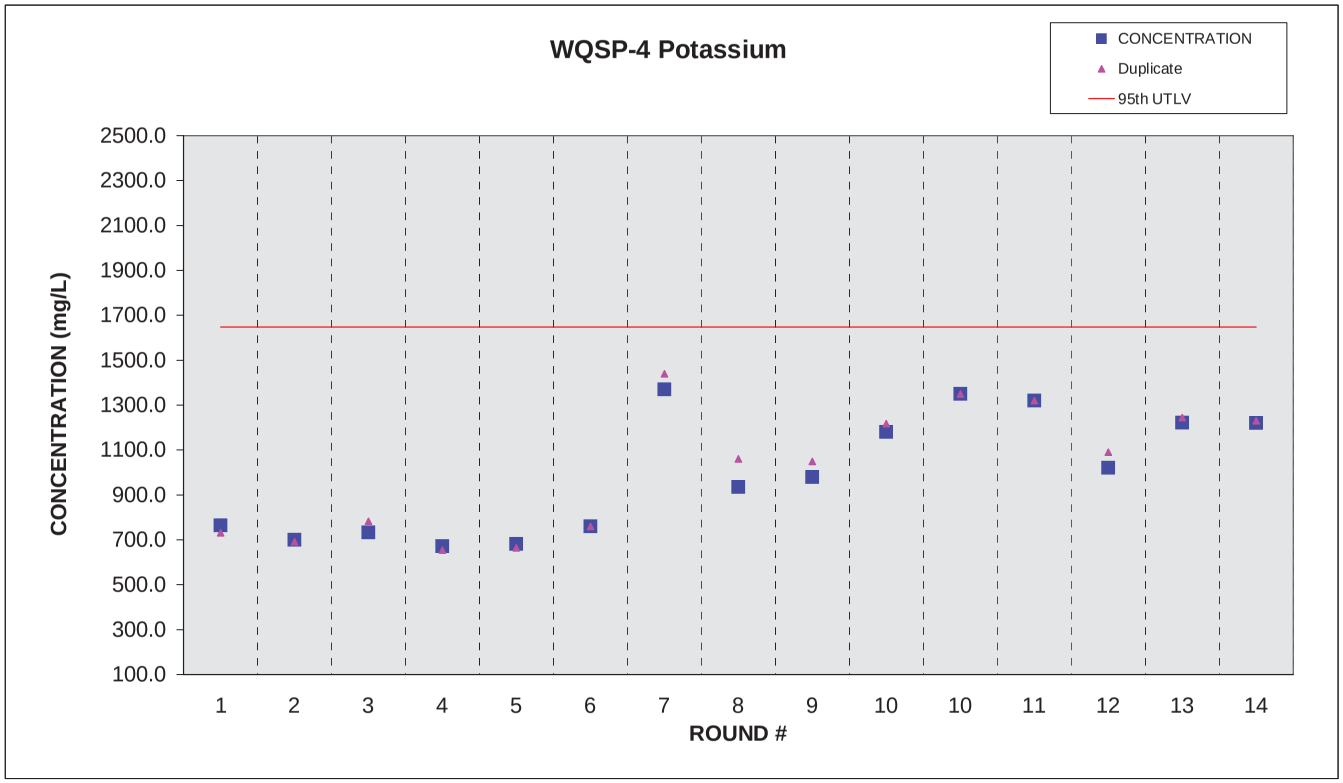

WQSP-4 Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		35900.0		34400.0	mg/L	100.0	38790.0			<	0.5	1	10/20/95	09/28/95
7440-23-5	SODIUM		33600.0		32400.0	mg/L	25.0	38790.0	<	0.5	<	0.5	2	05/29/96	05/23/96
7440-23-5	SODIUM		33300.0		32900.0	mg/L	5.0	38790.0	<	0.5	<	0.5	3	09/20/96	09/12/96
7440-23-5	SODIUM		30800.0		31300.0	mg/L	25.0	38790.0	<	0.5	<	0.5	4	06/13/97	06/05/97
7440-23-5	SODIUM		32600.0		31200.0	mg/L	25.0	38790.0	<	0.5	<	0.5	5	09/19/97	09/11/97
7440-23-5	SODIUM		37300.0		37300.0	mg/L	0.0	38790.0				0.1	6	05/12/98	05/06/98
7440-23-5	SODIUM		31700.0		26900.0	mg/L	0.5	38790.0			<	0.5	7	09/28/98	09/23/98
7440-23-5	SODIUM		32900.0		32500.0	mg/L	1.0	38790.0			<	1.0	8	04/27/99	04/21/99
7440-23-5	SODIUM		30310.0		33250.0	mg/L	0.5	38790.0			<	0.5	9	12/01/99	10/13/99
7440-23-5	SODIUM		34000.0		35200.0	mg/L	0.1	38790.0			<	0.5	10	04/24/00	04/12/00
7440-23-5	SODIUM		30700.0		26100.0	mg/L	5.0	38790.0				0.4	11	10/28/00	10/18/00
7440-23-5	SODIUM		35000.0		34200.0	mg/L	0.5	38790.0			<	0.5	12	06/25/01	04/18/01
7440-23-5	SODIUM		34100.0		33170.0	mg/L	0.2	38790.0					13	10/29/01	10/17/01
7440-23-5	SODIUM		27200.0		31600.0	mg/L	0.5	38790.0					14	04/24/02	04/17/02

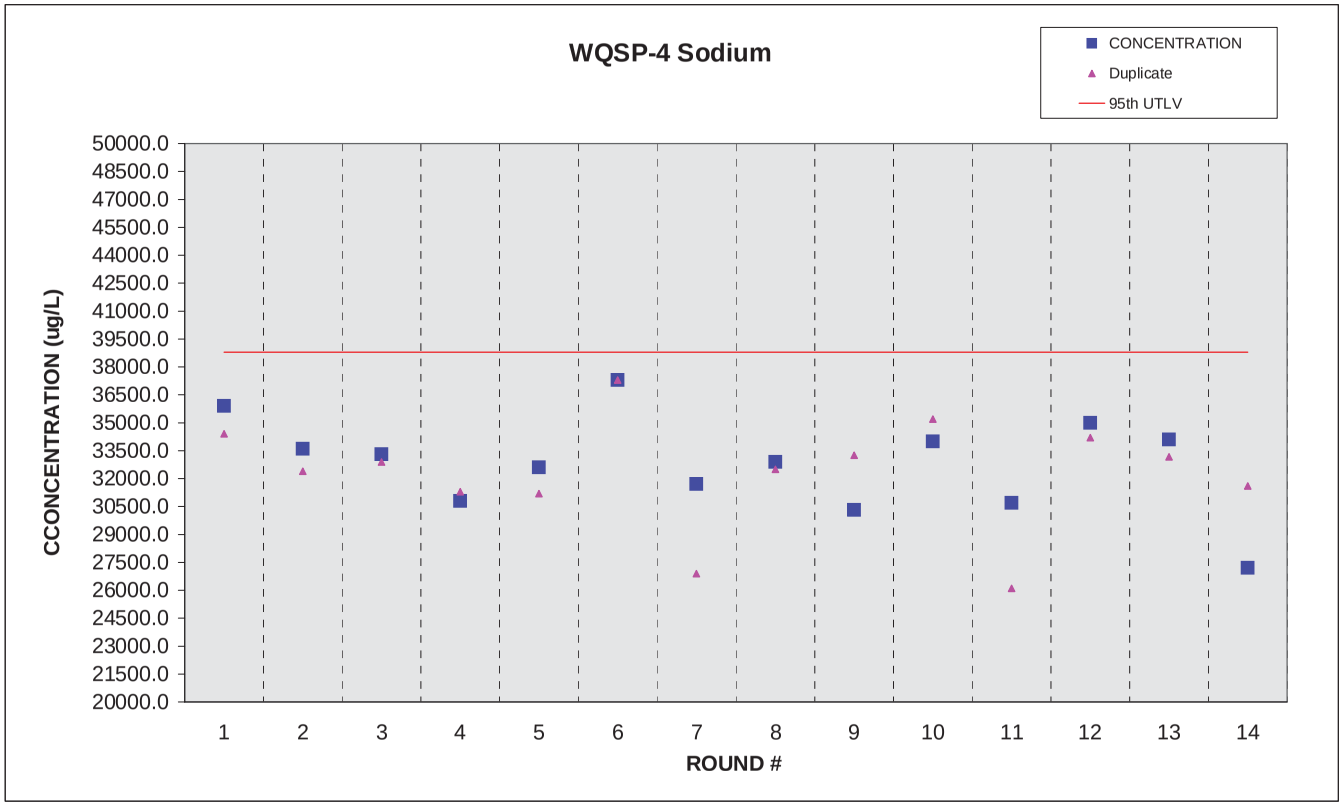

WQSP-4 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		40.0		42.0	mg/L	5.0	47.1			<	5.0	1	10/02/95	09/28/95
	ALKALINITY		29.0		30.0	mg/L	5.0	47.1		0.0	<	5.0	2	05/31/96	05/23/96
	ALKALINITY		39.0		40.1	mg/L	5.0	47.1		0.0	<	5.0	3	09/26/96	09/12/96
	ALKALINITY		38.0		36.0	mg/L	5.0	47.1			<	5.0	4	06/09/97	06/05/97
	ALKALINITY		41.0		40.0	mg/L	5.0	47.1		0.0	<	5.0	5	09/26/97	09/11/97
	ALKALINITY		38.0		38.0	mg/L	5.0	47.1					6	05/12/98	05/06/98
	ALKALINITY		44.0		42.0	mg/L	1.0	47.1			<	1.0	7	09/30/98	09/23/98
	ALKALINITY		39.0		39.0	mg/L	4.0	47.1			<	4.0	8	04/22/99	04/21/99
	ALKALINITY		38.0		36.0	mg/L	4.0	47.1					9	10/22/99	10/13/99
	ALKALINITY		41.0		39.0	mg/L	4.0	47.1					10	04/17/00	04/12/00
	ALKALINITY		36.0		40.0	mg/L	4.0	47.1			<	4.0	11	10/31/00	10/18/00
	ALKALINITY		40.0		38.0	mg/L	4.0	47.1					12	04/25/01	04/18/01
	ALKALINITY		36.0		34.0	mg/L	4.0	47.1					13	10/23/01	10/17/01
	ALKALINITY		42.0		40.0	mg/L	4.0	47.1					14	04/18/02	04/17/02

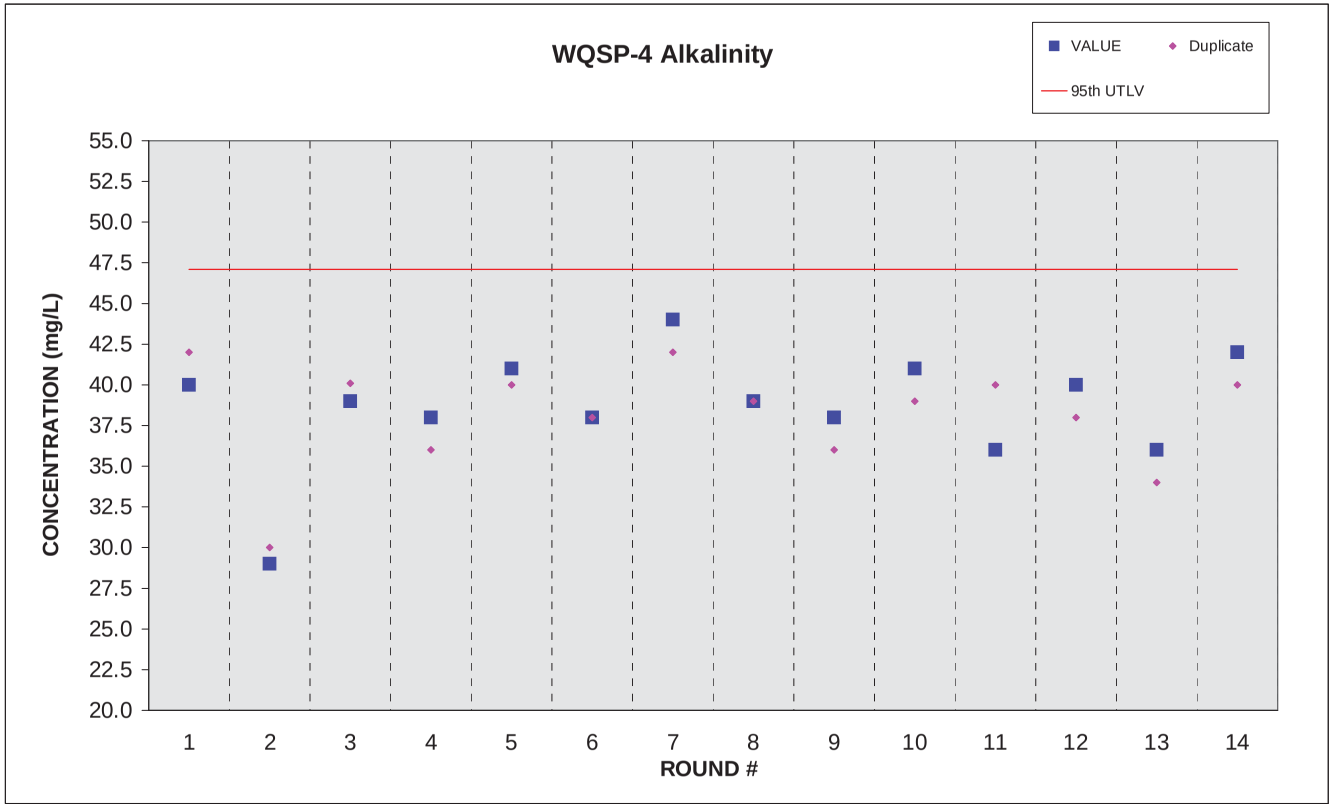

WQSP-4 Chloride

CAS #	PARAMETER		VALUE		VALUE DUPLICATE	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		61200.0		60700.0	mg/L	5.0	63960.0			<	5.0	1	10/13/95	09/28/95
7782-50-5	CHLORIDE		61500.0		61200.0	mg/L	2500.0	63960.0			<	5.0	2	05/29/96	05/23/96
7782-50-5	CHLORIDE		59700.0		57000.0	mg/L	2500.0	63960.0			<	5.0	3	09/18/96	09/12/96
7782-50-5	CHLORIDE		59500.0		59500.0	mg/L	5000.0	63960.0			<	5.0	4	06/18/97	06/05/97
7782-50-5	CHLORIDE		58700.0		58200.0	mg/L	5000.0	63960.0			<	5.0	5	09/26/97	09/11/97
7782-50-5	CHLORIDE		57100.0		55800.0	mg/L	0.0	63960.0				0.0	6	05/12/98	05/06/98
7782-50-5	CHLORIDE		53000.0		55000.0	mg/L	0.5	63960.0				2.0	7	09/28/98	09/23/98
7782-50-5	CHLORIDE		57000.0		57000.0	mg/L	0.5	63960.0			<	0.5	8	04/22/99	04/21/99
7782-50-5	CHLORIDE		57000.0		55000.0	mg/L	0.5	63960.0			<	0.5	9	10/13/99	10/13/99
7782-50-5	CHLORIDE		59000.0		61000.0	mg/L	0.5	63960.0			<	0.5	10	04/18/00	04/12/00
7782-50-5	CHLORIDE		60000.0		54000.0	mg/L	0.5	63960.0			<	0.5	11	11/15/00	10/18/00
7782-50-5	CHLORIDE		54900.0		52100.0	mg/L	0.5	63960.0					12	04/19/01	04/18/01
7782-50-5	CHLORIDE		55300.0		55000.0	mg/L	2.0	63960.0					13	10/23/01	10/17/01
7782-50-5	CHLORIDE		49700.0		50500.0	mg/L	2.0	63960.0					14	04/22/02	04/17/02

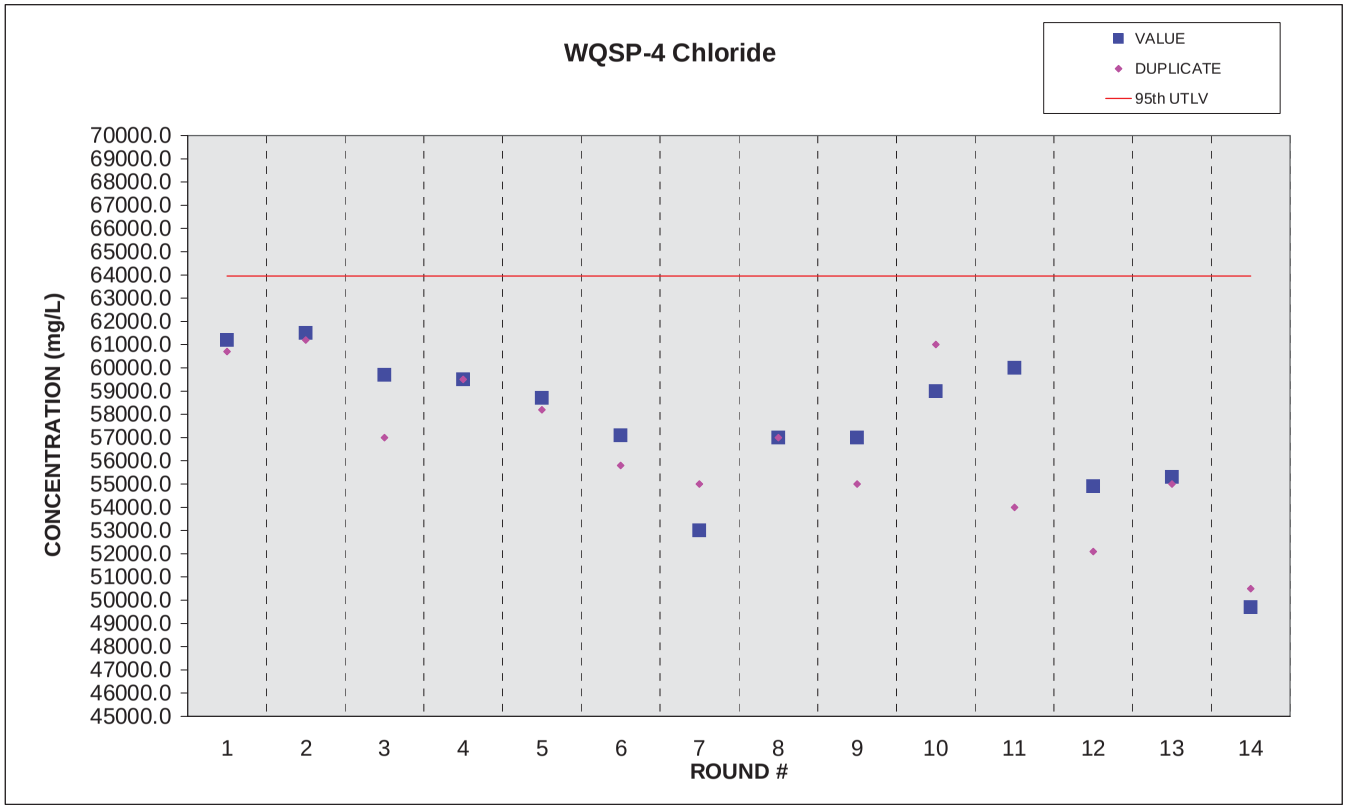

WQSP-4 Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		7100.0		7050.0	mg/L	10.0	7927.0			<	10.0	1	10/13/95	09/28/95
	SULFATE		6520.0		5960.0	mg/L	2500.0	7927.0			<	10.0	2	05/29/96	05/23/96
	SULFATE		6860.0		7660.0	mg/L	2500.0	7927.0			<	10.0	3	09/18/96	09/12/96
	SULFATE		7040.0		7380.0	mg/L	2500.0	7927.0			<	10.0	4	06/18/97	06/05/97
	SULFATE		6940.0		6880.0	mg/L	2500.0	7927.0			<	10.0	5	09/30/97	09/11/97
	SULFATE		6020.0		5820.0	mg/L	0.0	7927.0				0.1	6	05/12/98	05/06/98
	SULFATE		6000.0		6100.0	mg/L	0.5	7927.0					7	10/01/98	09/23/98
	SULFATE		6800.0		6600.0	mg/L	0.5	7927.0			<	0.5	8	04/22/99	04/21/99
	SULFATE		6500.0		6200.0	mg/L	0.5	7927.0			<	0.5	9	10/13/99	10/13/99
	SULFATE		6700.0		7300.0	mg/L	0.5	7927.0			<	0.5	10	04/18/00	04/12/00
	SULFATE		6700.0		6300.0	mg/L	0.5	7927.0			<	0.5	11	11/15/00	10/18/00
	SULFATE		6470.0		6380.0	mg/L	0.5	7927.0					12	04/19/01	04/18/01
	SULFATE		6300.0		6130.0	mg/L	2.0	7927.0					13	10/22/01	10/17/01
	SULFATE		6560.0		6400.0	mg/L	2.0	7927.0					14	04/22/02	04/17/02

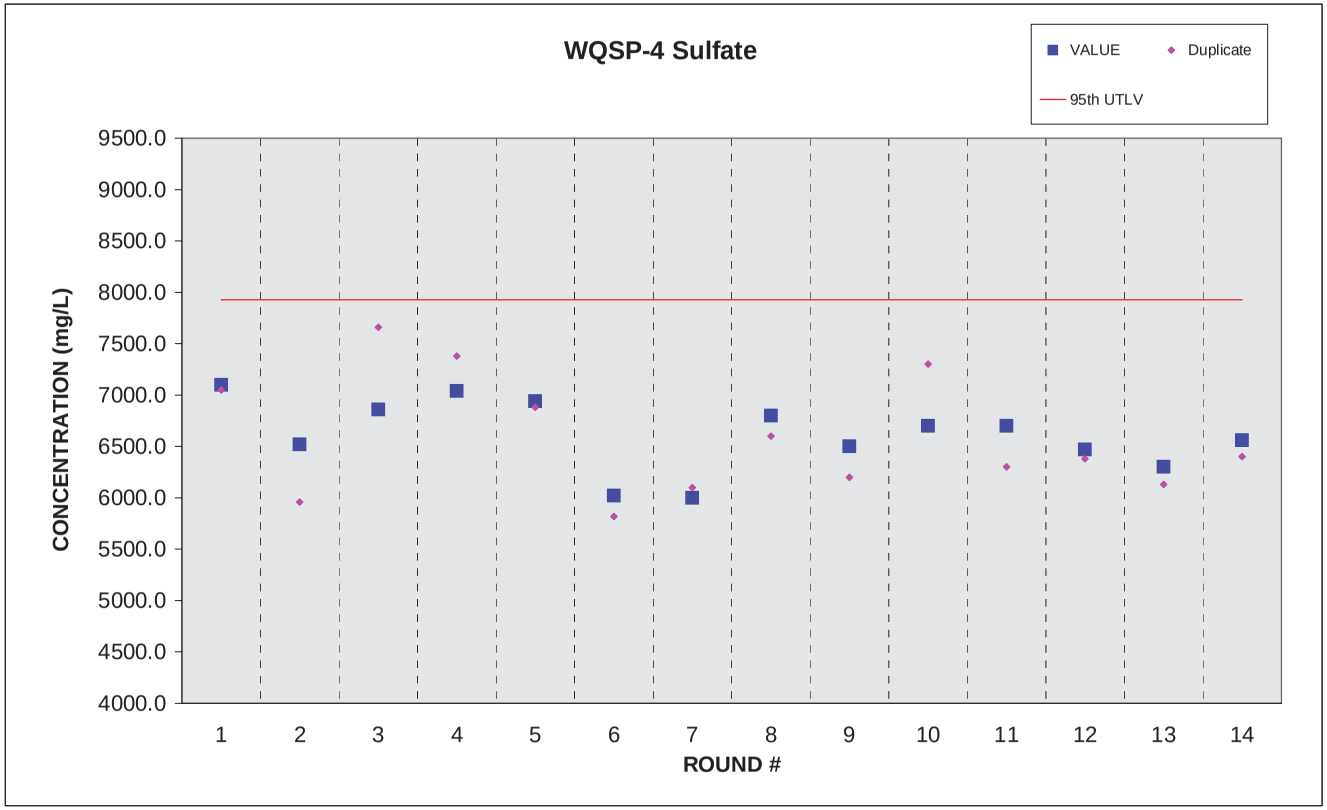

WQSP-5 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		987.0		982.0	mg/L	2.0	1303.0	<	0.2	<	0.2	1	12/15/95	11/20/95
7440-70-2	CALCIUM		1020.0		1020.0	mg/L	2.0	1303.0	<	0.2	<	0.2	2	06/18/96	06/06/96
7440-70-2	CALCIUM		1010.0		1030.0	mg/L	2.0	1303.0	<	0.2	<	0.2	3	10/01/96	09/26/96
7440-70-2	CALCIUM		980.0		982.0	mg/L	2.0	1303.0	<	0.2	<	0.2	4	06/26/97	06/19/97
7440-70-2	CALCIUM		986.0		945.0	mg/L	2.0	1303.0	<	0.2	<	0.2	5	10/27/97	09/25/97
7440-70-2	CALCIUM		1040.0		992.2	mg/L	0.0	1303.0			<	0.0	6	05/22/98	05/20/98
7440-70-2	CALCIUM		1100.0		1030.0	mg/L	0.5	1303.0				0.1	7	11/27/98	10/07/98
7440-70-2	CALCIUM		1090.0		1220.0	mg/L	1.0	1303.0			<	1.0	8	05/12/99	05/05/99
7440-70-2	CALCIUM		1071.0		1126.0	mg/L	0.1	1303.0			<	0.1	9	12/01/99	10/27/99
7440-70-2	CALCIUM		1410.0		991.0	mg/L	5.0	1303.0				0.3	10	05/24/00	04/26/00
7440-70-2	CALCIUM		1170.0		1070.0	mg/L	5.0	1303.0					10	06/19/00	06/19/00
7440-70-2	CALCIUM		1020.0		1010.0	mg/L	5.0	1303.0				0.0	11	11/24/00	11/01/00
7440-70-2	CALCIUM		1011.0		1029.0	mg/L	5.0	1303.0					12	06/25/01	05/02/01
7440-70-2	CALCIUM		1090.0		1080.0	mg/L	0.2	1303.0					13	11/05/01	10/31/01
7440-70-2	CALCIUM		1010.0		1080.0	mg/L	0.5	1303.0					14	05/06/02	05/01/02

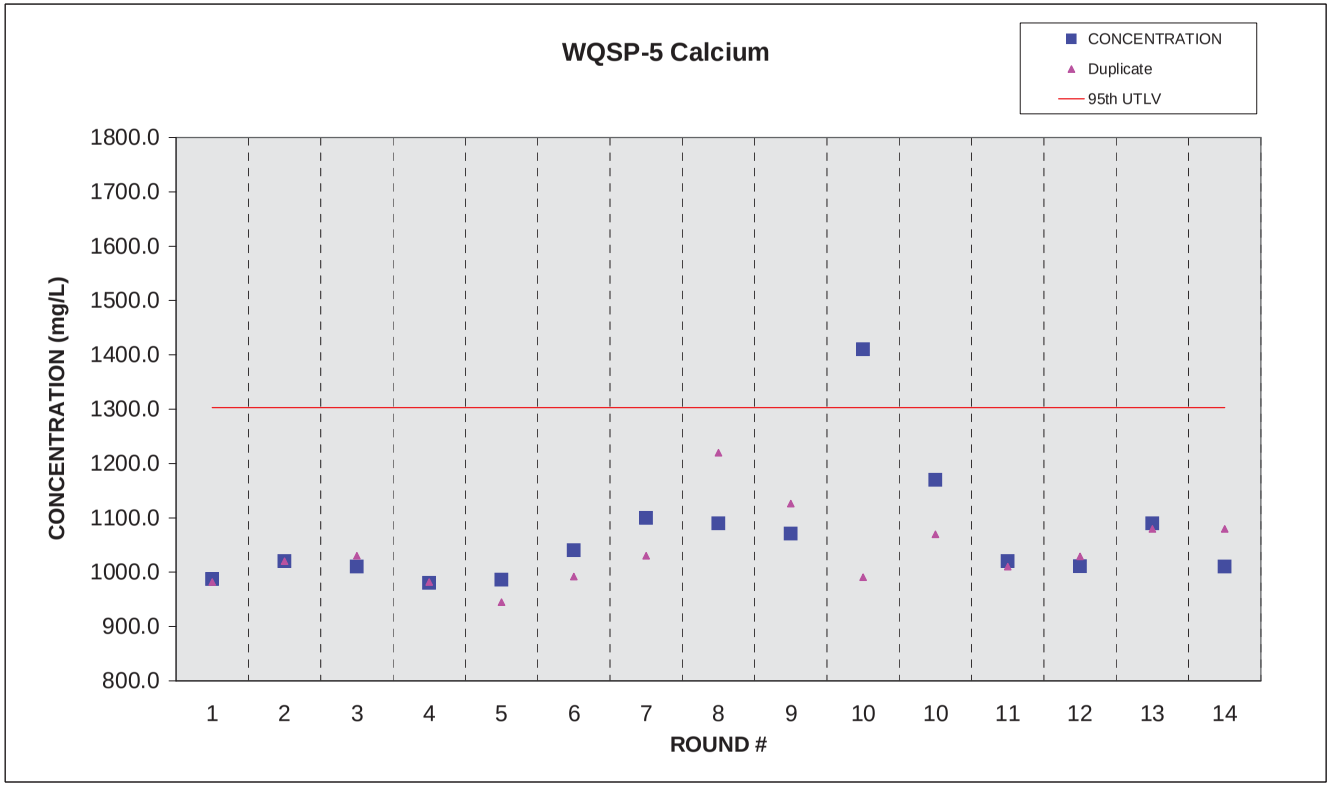

WQSP-5 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		434.0		432.0	mg/L	1.0	547.0	<	0.1	<	0.1	1	12/15/95	11/20/95
7439-95-4	MAGNESIUM		427.0		417.0	mg/L	0.5	547.0	<	0.1	<	0.1	2	06/18/96	06/06/96
7439-95-4	MAGNESIUM		421.0		427.0	mg/L	0.5	547.0	<	0.1	<	0.1	3	10/01/96	09/26/96
7439-95-4	MAGNESIUM		452.0		454.0	mg/L	1.0	547.0	<	0.1	<	0.1	4	06/26/97	06/19/97
7439-95-4	MAGNESIUM		441.0		425.0	mg/L	0.5	547.0	<	0.1	<	0.1	5	10/27/97	09/25/97
7439-95-4	MAGNESIUM		485.0		468.4	mg/L	0.1	547.0			<	0.1	6	05/22/98	05/20/98
7439-95-4	MAGNESIUM		508.0		484.0	mg/L	0.5	547.0			<	0.1	7	11/27/98	10/07/98
7439-95-4	MAGNESIUM		474.0		547.0	mg/L	1.0	547.0			<	1.0	8	05/12/99	05/05/99
7439-95-4	MAGNESIUM		484.0		515.0	mg/L	0.5	547.0			<	0.5	9	12/01/99	10/27/99
7439-95-4	MAGNESIUM		850.0		431.0	mg/L	5.0	547.0				0.2	10	05/24/00	04/26/00
7439-95-4	MAGNESIUM		500.0		450.0	mg/L	5.0	547.0					10	06/19/00	same
7439-95-4	MAGNESIUM		454.0		462.0	mg/L	5.0	547.0				0.1	11	11/24/00	11/01/00
7439-95-4	MAGNESIUM		425.0		437.0	mg/L	5.0	547.0					12	06/25/01	05/02/01
7439-95-4	MAGNESIUM		545.0		545.0	mg/L	0.2	547.0					13	11/05/01	10/31/01
7439-95-4	MAGNESIUM		451.0		457.0	mg/L	0.5	547.0					14	05/06/02	05/01/02

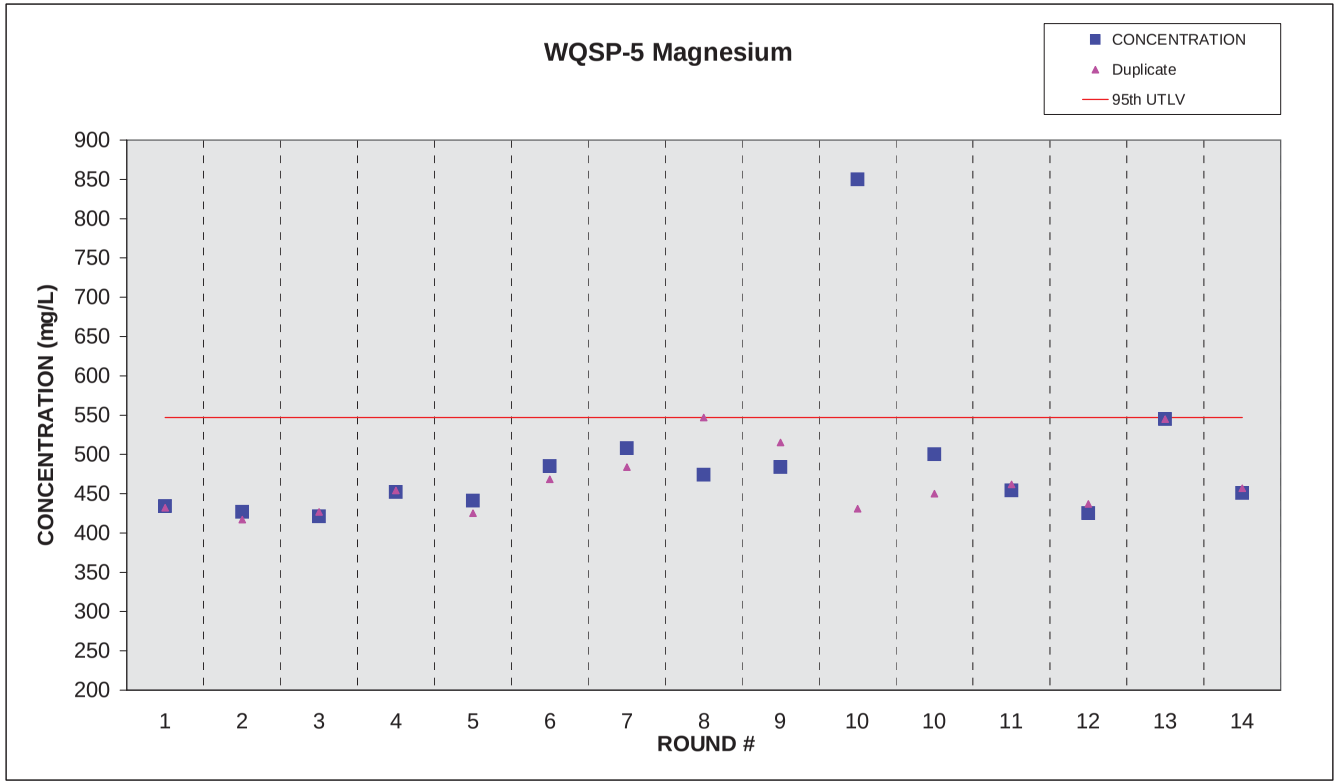

WQSP-5 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		286.0		286.0	mg/L	2.0	622.0	<	0.2	<	0.2	1	12/15/95	11/20/95
7440-09-7	POTASSIUM		290.0		288.0	mg/L	2.0	622.0	<	0.2	<	0.2	2	06/13/96	06/06/96
7440-09-7	POTASSIUM		292.0		291.0	mg/L	2.0	622.0	<	0.2	<	0.2	3	10/02/96	09/26/96
7440-09-7	POTASSIUM		284.0		281.0	mg/L	2.0	622.0	<	0.2	<	0.2	4	06/25/97	06/19/97
7440-09-7	POTASSIUM		282.0		290.0	mg/L	2.0	622.0	<	0.2	<	0.2	5	10/21/97	09/25/97
7440-09-7	POTASSIUM		304.0		301.3	mg/L	0.1	622.0			<	0.1	6	05/22/98	05/20/98
7440-09-7	POTASSIUM		360.0		340.0	mg/L	0.5	622.0			<	0.1	7	11/27/98	10/07/98
7440-09-7	POTASSIUM		527.0		582.0	mg/L	1.0	622.0			<	1.0	8	05/12/99	05/05/99
7440-09-7	POTASSIUM		385.0		416.0	mg/L	0.5	622.0			<	0.5	9	12/01/99	10/27/99
7440-09-7	POTASSIUM		594.0		254.0	mg/L	5.0	622.0				0.2	10	05/24/00	04/23/00
7440-09-7	POTASSIUM		450.0		400.0	mg/L	5.0	622.0					10	06/19/00	06/19/00
7440-09-7	POTASSIUM		395.0		410.0	mg/L	5.0	622.0					11	11/24/00	11/01/00
7440-09-7	POTASSIUM		474.0		505.0	mg/L	5.0	622.0					12	06/25/01	05/02/01
7440-09-7	POTASSIUM		452.0		454.0	mg/L	0.2	622.0					13	11/05/01	10/31/01
7440-09-7	POTASSIUM		398.0		422.0	mg/L	0.5	622.0					14	05/06/02	05/01/02

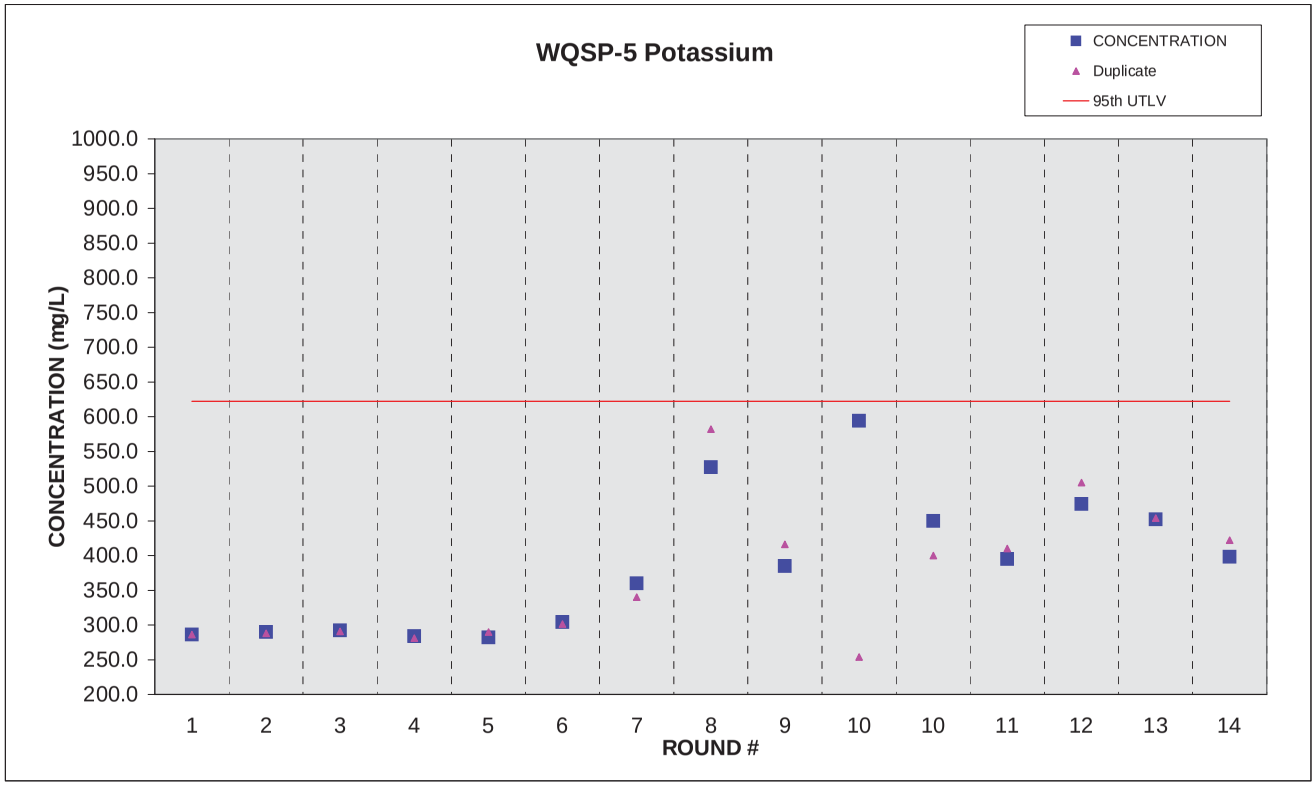

WQSP-5 Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		8880.0		8900.0	mg/L	5.0	11190.0	<	0.5	<	0.5	1	12/15/95	11/20/95
7440-23-5	SODIUM		9580.0		9420.0	mg/L	25.0	11190.0	<	0.5	<	0.5	2	06/13/96	06/06/96
7440-23-5	SODIUM		9400.0		8870.0	mg/L	25.0	11190.0	<	0.5	<	0.5	3	10/02/96	09/26/96
7440-23-5	SODIUM		9220.0		6230.0	mg/L	25.0	11190.0	<	0.5	<	0.5	4	06/25/97	06/19/97
7440-23-5	SODIUM		9160.0		9390.0	mg/L	10.0	11190.0	<	0.2	<	0.2	5	10/21/97	09/25/97
7440-23-5	SODIUM		10500.0		10078.4	mg/L	0.0	11190.0				0.0	6	05/22/98	05/20/98
7440-23-5	SODIUM		9560.0		9140.0	mg/L	0.5	11190.0			<	0.1	7	11/27/98	10/07/98
7440-23-5	SODIUM		9675.0		9545.0	mg/L	1.0	11190.0			<	1.0	8	05/12/99	05/05/99
7440-23-5	SODIUM		8380.0		8739.0	mg/L	0.5	11190.0			<	0.5	9	12/01/99	10/27/99
7440-23-5	SODIUM		8470.0		7860.0	mg/L	0.0	11190.0				0.2	10	05/24/00	04/26/00
7440-23-5	SODIUM		9040.0		8750.0	mg/L	5.0	11190.0				0.2	11	12/22/00	11/01/00
7440-23-5	SODIUM		9756.0		9712.0	mg/L	5.0	11190.0					12	06/25/01	05/02/01
7440-23-5	SODIUM		10600.0		10200.0	mg/L	0.2	11190.0					13	11/05/02	10/31/01
7440-23-5	SODIUM		8740.0		7750.0	mg/L	0.5	11190.0					14	05/06/02	05/01/02

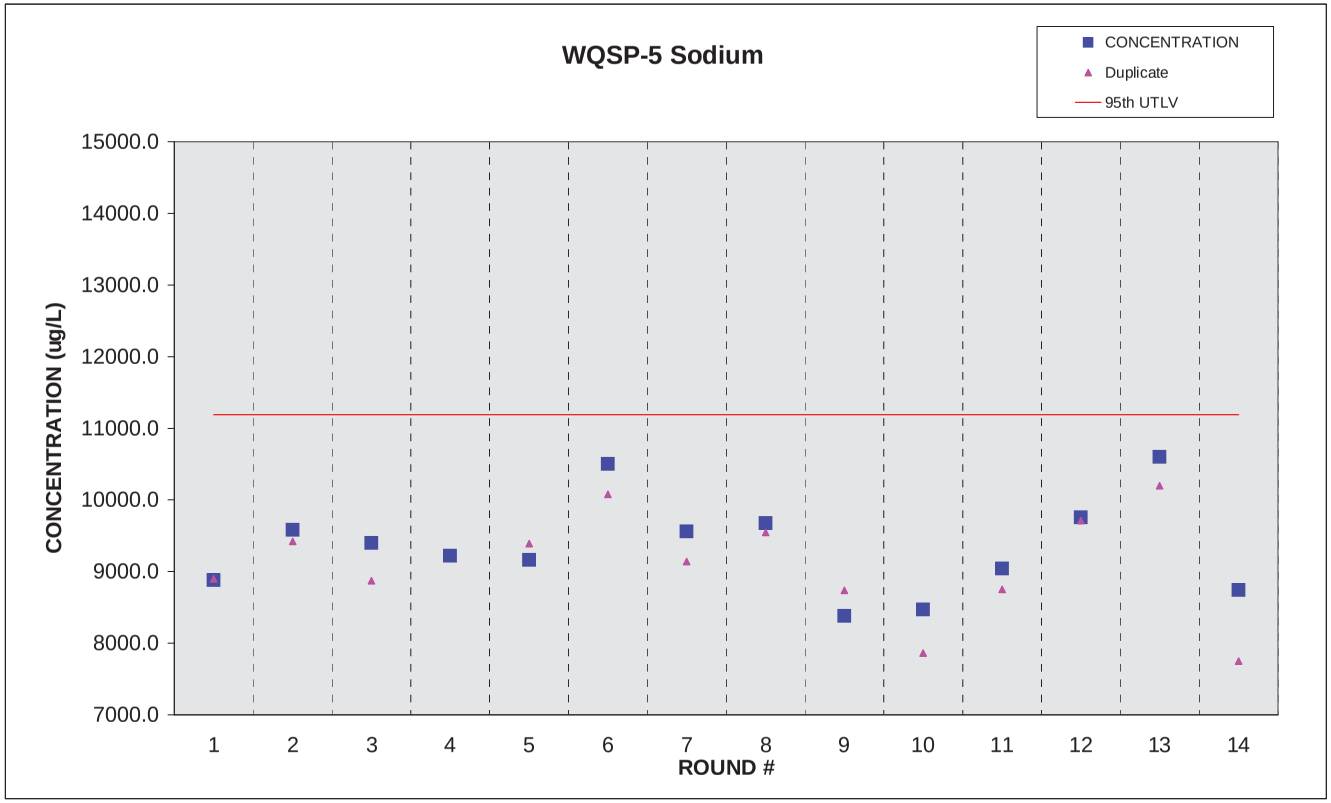

WQSP-5 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		52.0		50.0	mg/L	5.0	56.0			<	5.0	1	11/27/95	11/20/95
	ALKALINITY		41.1		42.1	mg/L	5.0	56.0			<	5.0	2	06/11/96	06/06/96
	ALKALINITY		49.1		51.1	mg/L	5.0	56.0			<	5.0	3	10/03/96	09/26/96
	ALKALINITY		52.0		51.0	mg/L	5.0	56.0			<	5.0	4	06/27/97	06/19/97
	ALKALINITY		49.0		49.0	mg/L	5.0	56.0			<	5.0	5	09/26/97	09/25/97
	ALKALINITY		48.0		48.0	mg/L		56.0					6	05/22/98	05/20/98
	ALKALINITY		48.0		50.0	mg/L	1.0	56.0			<	1.0	7	10/09/98	10/07/98
	ALKALINITY		50.0		46.0	mg/L	1.0	56.0			<	1.0	8	05/11/99	05/05/99
	ALKALINITY		44.0		46.0	mg/L		56.0			<	1.0	9	11/02/99	10/27/99
	ALKALINITY		48.0		46.0	mg/L		56.0			<	1.0	10	05/02/00	04/26/00
	ALKALINITY		46.0		48.0	mg/L	4.0	56.0			<	4.0	11	11/17/00	11/01/00
	ALKALINITY		46.0		46.0	mg/L	4.0	56.0					12	05/08/01	05/02/01
	ALKALINITY		46.0		44.0	mg/L	4.0	56.0					13	11/13/01	10/31/01
	ALKALINITY		46.0		48.0	mg/L	4.0	56.0					14	05/03/02	05/01/02

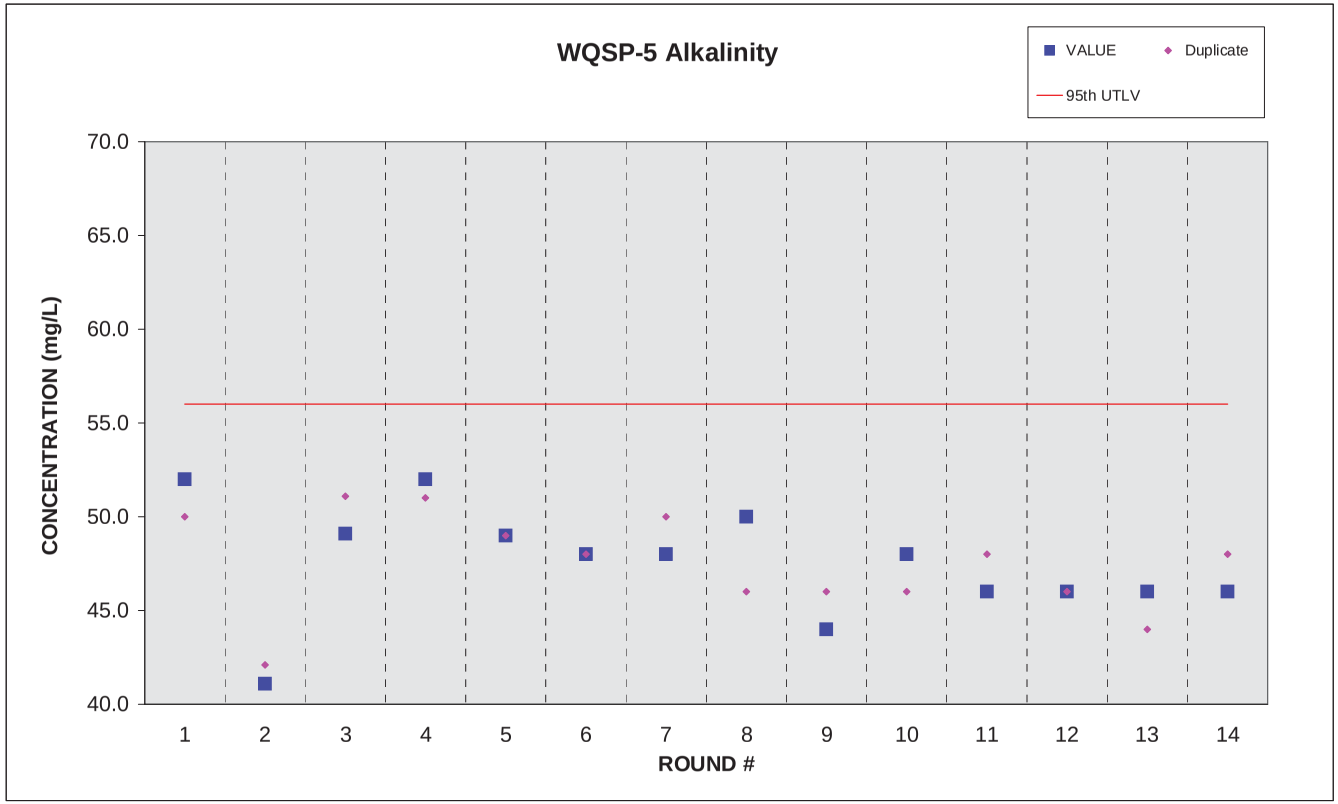

WQSP-5 Chloride

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		15000.0		14800.0	mg/L	5.0	18100.0			<	5.0	1	11/27/95	11/20/95
7782-50-5	CHLORIDE		15700.0		16000.0	mg/L	2500.0	18100.0			<	5.0	2	06/28/96	06/06/96
7782-50-5	CHLORIDE		15700.0		16200.0	mg/L	2500.0	18100.0			<	5.0	3	10/15/96	09/26/96
7782-50-5	CHLORIDE		14500.0		14500.0	mg/L	5000.0	18100.0			<	5.0	4	07/07/97	06/19/97
7782-50-5	CHLORIDE		15300.0		15100.0	mg/L	1000.0	18100.0			<	5.0	5	10/13/97	09/25/97
7782-50-5	CHLORIDE		15300.0		13591.0	mg/L	0.0	18100.0				0.0	6	05/22/98	05/20/98
7782-50-5	CHLORIDE		19000.0		16000.0	mg/L	0.5	18100.0			<	0.5	7	10/13/98	10/07/98
7782-50-5	CHLORIDE		15000.0		16000.0	mg/L	0.5	18100.0			<	0.5	8	05/05/99	05/05/99
7782-50-5	CHLORIDE		15000.0		15000.0	mg/L	0.5	18100.0			<	0.5	9	10/28/99	10/27/99
7782-50-5	CHLORIDE		16000.0		16000.0	mg/L	0.5	18100.0			<	0.5	10	05/04/00	04/26/00
7782-50-5	CHLORIDE		16000.0		16000.0	mg/L	0.5	18100.0			<	0.5	11	11/02/00	11/01/00
7782-50-5	CHLORIDE		16100.0		15700.0	mg/L	0.5	18100.0					12	05/03/01	05/02/01
7782-50-5	CHLORIDE		15600.0		14800.0	mg/L	2.0	18100.0					13	11/15/01	10/31/01
7782-50-5	CHLORIDE		15900.0		15200.0	mg/L	2.0	18100.0					14	05/07/02	05/01/02

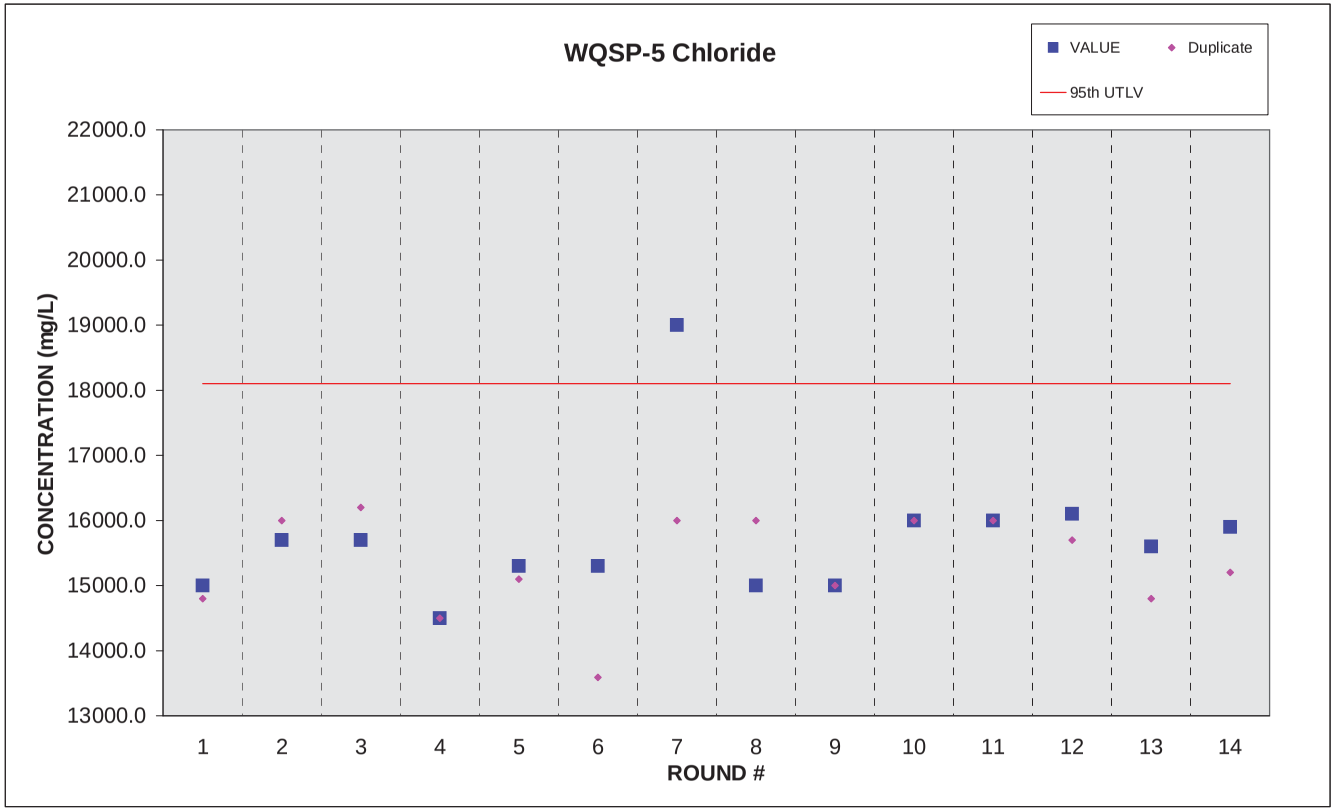

WQSP-5 Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		5370.0		5380.0	mg/L	10.0	6129.0			<	10.0	1	11/27/95	11/20/95
	SULFATE		5730.0		5900.0	mg/L	2500.0	6129.0			<	10.0	2	06/10/96	06/06/96
	SULFATE		5240.0		4940.0	mg/L	2500.0	6129.0			<	10.0	3	10/01/96	09/26/96
	SULFATE		4460.0		4460.0	mg/L	2500.0	6129.0			<	10.0	4	07/07/97	06/19/97
	SULFATE		4900.0		4640.0	mg/L	2500.0	6129.0			<	10.0	5	09/30/97	09/25/97
	SULFATE		4970.0		4370.6	mg/L	0.0	6129.0			<	0.1	6	05/22/98	05/20/98
	SULFATE		5400.0		5000.0	mg/L	0.5	6129.0			<	0.5	7	10/13/98	10/07/98
	SULFATE		4900.0		5200.0	mg/L	0.5	6129.0			<	0.5	8	05/05/99	05/05/99
	SULFATE		4300.0		4300.0	mg/L	0.5	6129.0			<	0.5	9	10/28/99	10/27/99
	SULFATE		5400.0		5200.0	mg/L	0.5	6129.0			<	0.5	10	05/02/00	04/26/00
	SULFATE		5200.0		4800.0	mg/L	0.5	6129.0			<	0.5	11	11/15/00	11/01/00
	SULFATE		4890.0		4800.0	mg/L	0.5	6129.0					12	05/03/01	05/02/01
	SULFATE		4690.0		4470.0	mg/L	2.0	6129.0					13	11/15/01	10/31/01
	SULFATE		5230.0		5250.0	mg/L	2.0	6129.0					14	05/07/02	05/01/02

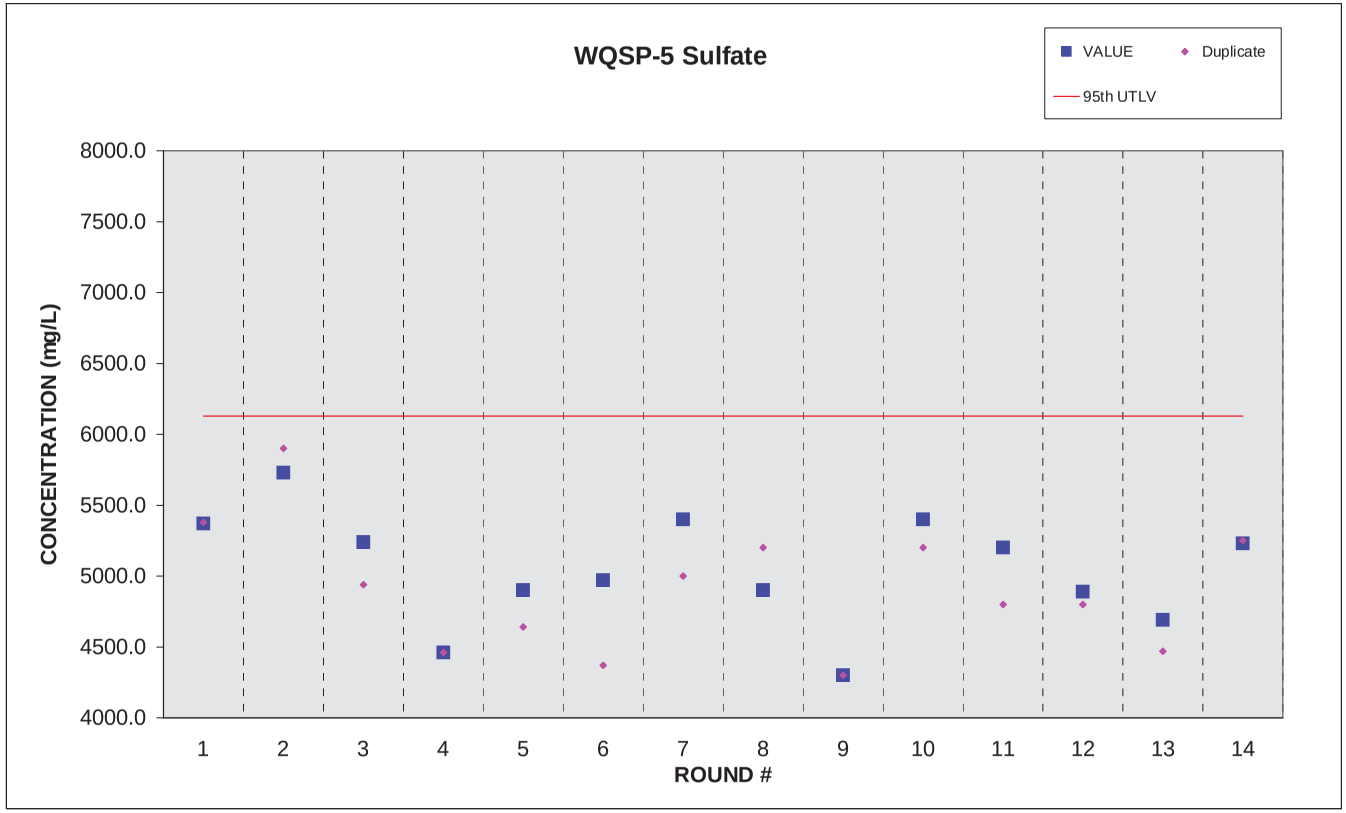

WQSP-6 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		719.0		731.0	mg/L	2.0	796.0			<	0.2	1	10/25/95	10/16/95
7440-70-2	CALCIUM		663.0		659.0	mg/L	0.5	796.0	<	0.2	<	0.2	2	03/27/96	03/12/96
7440-70-2	CALCIUM		696.0		709.0	mg/L	2.0	796.0	<	0.2	<	0.2	3	07/26/96	06/27/96
7440-70-2	CALCIUM		662.0		657.0	mg/L	2.0	796.0	<	0.2	<	0.2	4	04/11/97	04/03/97
7440-70-2	CALCIUM		572.0		584.0	mg/L	2.0	796.0	<	0.2	<	0.2	5	07/11/97	06/25/97
7440-70-2	CALCIUM		714.0		703.6	mg/L	0.0	796.0				0.0	6	06/05/98	06/03/98
7440-70-2	CALCIUM		680.0		633.0	mg/L	0.5	796.0			<	0.5	7	11/27/98	10/21/98
7440-70-2	CALCIUM		675.0		728.0	mg/L	1.0	796.0			<	1.0	8	05/29/99	05/19/99
7440-70-2	CALCIUM		677.0		690.0	mg/L	1.0	796.0			<	1.0	9	12/09/99	11/03/99
7440-70-2	CALCIUM		707.0		774.0	mg/L	50.0	796.0			<	0.0	10	06/20/00	05/10/00
7440-70-2	CALCIUM		747.0		766.0	mg/L	5.0	796.0			<	5.0	11	11/24/00	11/15/00
7440-70-2	CALCIUM		663.0		667.0	mg/L	0.5	796.0					12	06/15/01	05/16/01
7440-70-2	CALCIUM		672.0		688.0	mg/L	0.2	796.0					13	11/20/01	11/07/01
7440-70-2	CALCIUM		738.0		735.0	mg/L	0.5	796.0					14	05/31/02	05/15/02

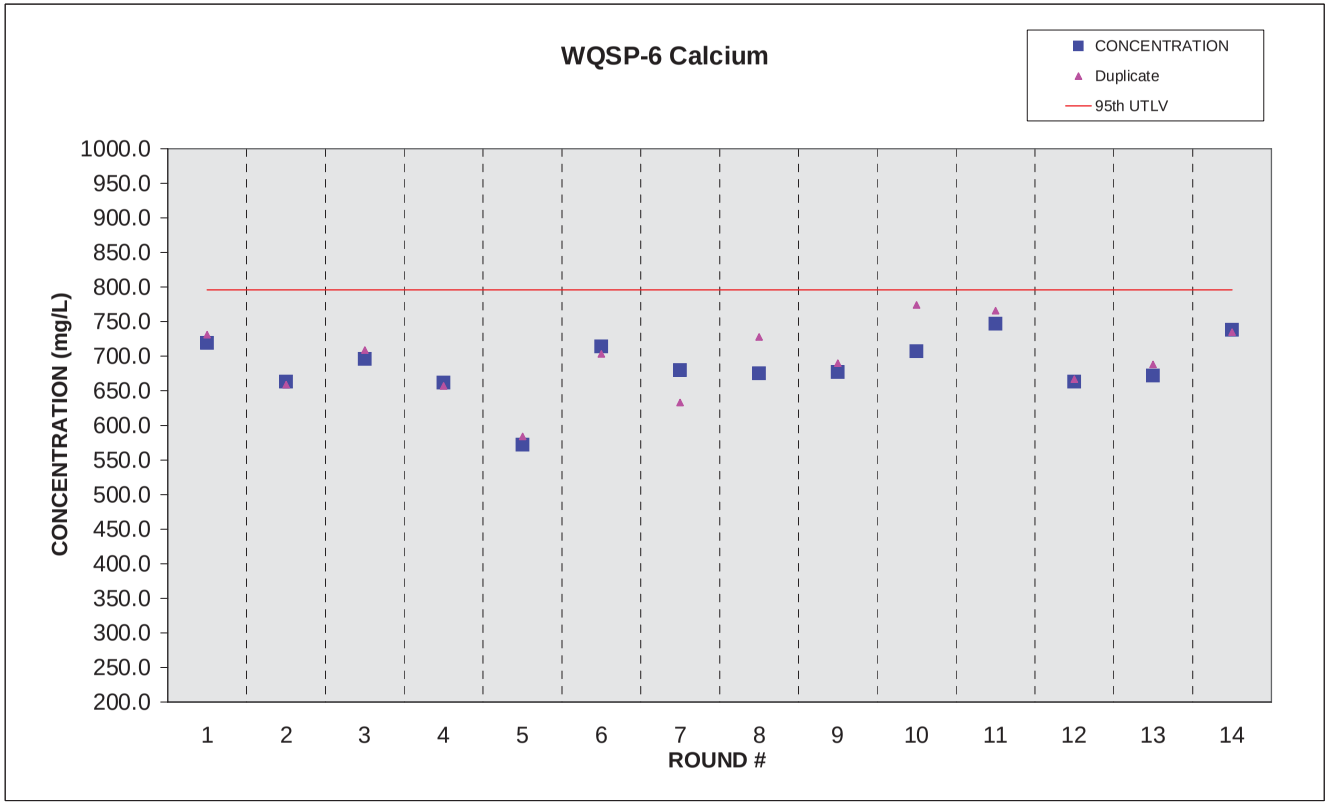

WQSP-6 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		250.0		253.0	mg/L	1.0	255.0			<	0.1	1	10/25/95	10/16/95
7439-95-4	MAGNESIUM		214.0		213.0	mg/L	0.1	255.0	<	0.1	<	0.1	2	03/27/96	03/12/96
7439-95-4	MAGNESIUM		199.0		202.0	mg/L	0.5	255.0	<	0.1	<	0.1	3	07/26/96	06/27/96
7439-95-4	MAGNESIUM		203.0		201.0	mg/L	1.0	255.0	<	0.1	<	0.1	4	04/11/97	04/03/97
7439-95-4	MAGNESIUM		210.0		212.0	mg/L	1.0	255.0	<	0.1	<	0.1	5	07/11/97	06/25/97
7439-95-4	MAGNESIUM		219.0		219.0	mg/L	0.1	255.0				0.1	6	06/05/98	06/03/98
7439-95-4	MAGNESIUM		200.0		194.0	mg/L	0.5	255.0			<	0.5	7	11/27/98	10/21/98
7439-95-4	MAGNESIUM		201.0		210.0	mg/L	1.0	255.0			<	1.0	8	05/29/99	05/19/99
7439-95-4	MAGNESIUM		214.0		218.0	mg/L	1.0	255.0			<	1.0	9	12/09/99	11/03/99
7439-95-4	MAGNESIUM		222.0		240.0	mg/L	0.5	255.0			<	0.5	10	06/20/00	05/10/00
7439-95-4	MAGNESIUM		226.0		236.0	mg/L	5.0	255.0			<	5.0	11	11/24/00	11/15/00
7439-95-4	MAGNESIUM		212.0		231.0	mg/L	0.5	255.0					12	06/15/01	05/16/01
7439-95-4	MAGNESIUM		234.0		236.0	mg/L	0.2	255.0					13	11/20/01	11/07/01
7439-95-4	MAGNESIUM		238.0		238.0	mg/L	0.5	255.0					14	05/31/02	05/15/02

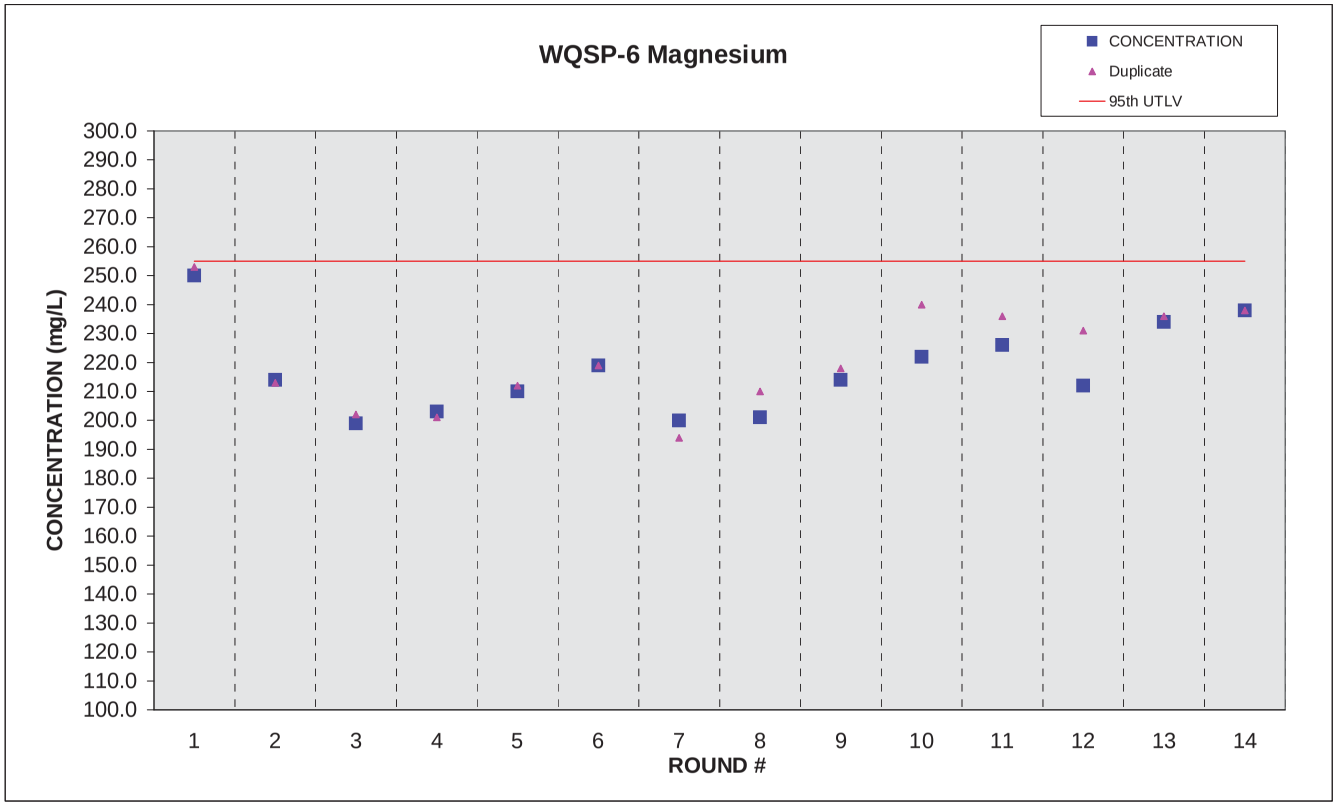

WQSP-6 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		182.0		184.0	mg/L	0.2	270.0			<	0.2	1	10/25/95	10/16/95
7440-09-7	POTASSIUM		199.0		190.0	mg/L	5.0	270.0	<	0.2	<	0.2	2	03/27/96	03/12/96
7440-09-7	POTASSIUM		152.0		151.0	mg/L	2.0	270.0		0.2	<	0.2	3	07/29/96	06/27/96
7440-09-7	POTASSIUM		150.0		148.0	mg/L	2.0	270.0	<	0.2	<	0.2	4	04/11/97	04/03/97
7440-09-7	POTASSIUM		148.0		157.0	mg/L	2.0	270.0	<	0.2	<	0.2	5	07/10/97	06/25/97
7440-09-7	POTASSIUM		161.0		169.8	mg/L	0.1	270.0				0.1	6	06/05/98	06/03/98
7440-09-7	POTASSIUM		144.0		137.0	mg/L	0.5	270.0			<	0.5	7	11/27/98	10/21/98
7440-09-7	POTASSIUM		215.0		226.0	mg/L	1.0	270.0			<	1.0	8	05/29/99	05/19/99
7440-09-7	POTASSIUM		239.0		244.0	mg/L	1.0	270.0			<	1.0	9	12/09/99	11/25/99
7440-09-7	POTASSIUM		184.0		200.0	mg/L	0.5	270.0			<	0.5	10	06/20/00	05/10/00
7440-09-7	POTASSIUM		224.0		227.0	mg/L	5.0	270.0				0.0	11	11/24/00	11/15/00
7440-09-7	POTASSIUM		208.0		204.0	mg/L	0.5	270.0					12	06/15/01	05/16/01
7440-09-7	POTASSIUM		278.0		282.0	mg/L	0.2	270.0					13	11/20/01	11/07/01
7440-09-7	POTASSIUM		221.0		223.0	mg/L	0.5	270.0					14	05/31/02	05/15/02

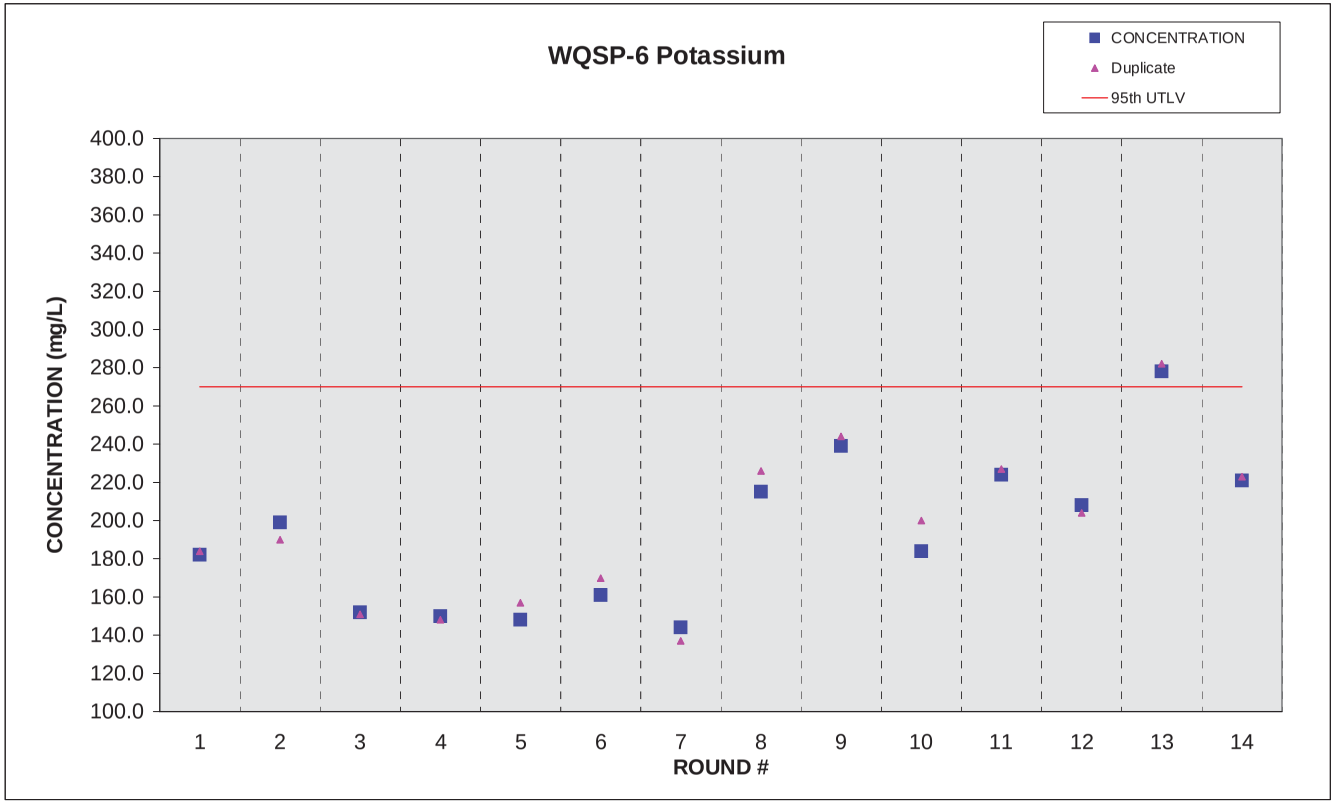

WQSP-6 Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		6070.0		6050.0	mg/L	5.0	6290.0			<	0.5	1	10/25/95	10/16/95
7440-23-5	SODIUM		5540.0		5370.0	mg/L	13.0	6290.0	<	0.5	<	0.5	2	03/27/96	03/12/96
7440-23-5	SODIUM		4470.0		4450.0	mg/L	5.0	6290.0	<	0.5	<	0.5	3	07/29/96	06/27/96
7440-23-5	SODIUM		4280.0		4230.0	mg/L	5.0	6290.0	<	0.5	<	0.5	4	04/11/97	04/03/97
7440-23-5	SODIUM		4210.0		4430.0	mg/L	2.0	6290.0	<	0.5	<	0.5	5	07/10/97	06/25/97
7440-23-5	SODIUM		4890.0		4834.7	mg/L	0.0	6290.0				0.0	6	06/05/98	06/03/98
7440-23-5	SODIUM		4460.0		4090.0	mg/L	1.0	6290.0			<	1.0	8	06/11/99	05/19/99
7440-23-5	SODIUM		4350.0		4470.0	mg/L	1.0	6290.0			<	1.0	9	12/09/99	11/03/99
7440-23-5	SODIUM		4280.0		4740.0	mg/L	0.5	6290.0			<	0.5	10	06/20/00	05/10/00
7440-22-5	SODIUM		4120.0		4280.0	mg/L	5.0	6290.0				0.0	11	11/24/00	11/15/00
7440-22-5	SODIUM		4320.0		4330.0	mg/L	0.5	6290.0					12	06/15/01	05/16/01
7440-22-5	SODIUM		4090.0		4230.0	mg/L	0.2	6290.0					13	11/20/01	11/07/01
7440-22-5	SODIUM		3870.0		3860.0	mg/L	0.5	6290.0					14	05/31/02	05/15/02

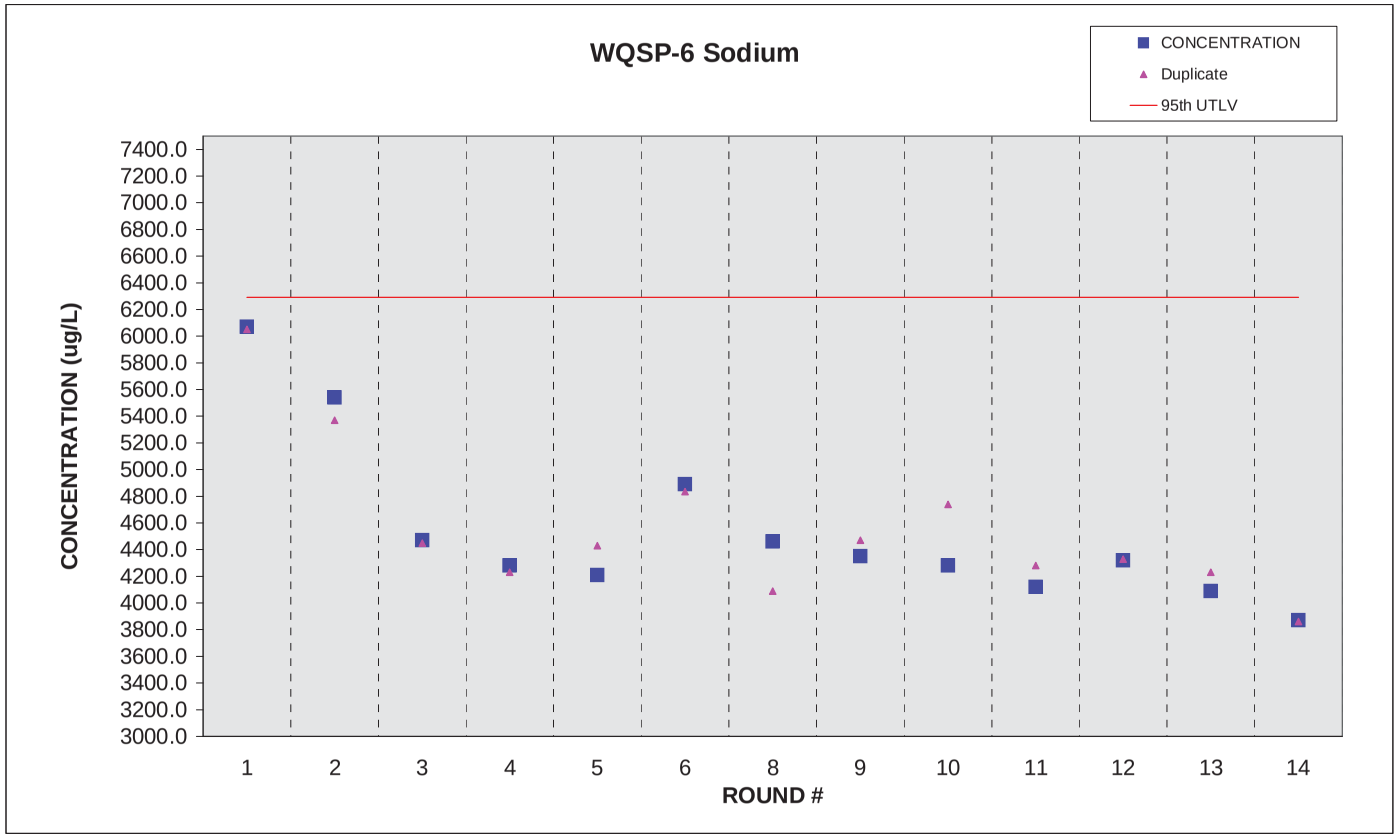

WQSP-6 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		52.5		52.5	mg/L	5.0	55.8			<	5.0	1	10/18/95	10/16/95
	ALKALINITY		54.0		49.0	mg/L	5.0	55.8			<	5.0	2	03/22/96	03/12/96
	ALKALINITY		48.1		47.1	mg/L	5.0	55.8					3	07/10/96	06/27/96
	ALKALINITY		53.2		51.1	mg/L	5.0	55.8			<	5.0	4	04/16/97	04/03/97
	ALKALINITY		47.0		48.0	mg/L	5.0	55.8			<	5.0	5	06/27/97	06/25/97
	ALKALINITY		43.0		43.0	mg/L	1.0	55.8					6	06/05/98	06/03/98
	ALKALINITY		46.0		48.0	mg/L	1.0	55.8			<	4.0	7	11/02/98	10/21/98
	ALKALINITY		46.0		47.0	mg/L	0.1	55.8			<	4.0	8	05/21/99	05/19/99
	ALKALINITY		44.0		46.0	mg/L	1.0	55.8					9	11/12/99	11/03/99
	ALKALINITY		45.0		45.0	mg/L	4.0	55.8					10	05/19/00	05/10/00
	ALKALINITY		48.0		50.0	mg/L	4.0	55.8			<	4.0	11	11/21/00	11/15/00
	ALKALINITY		42.0		42.0	mg/L	4.0	55.8					12	05/24/01	05/16/01
	ALKALINITY		46.0		44.0	mg/L	4.0	55.8					13	11/19/01	11/07/01
	ALKALINITY		46.0		46.0	mg/L	4.0	55.8					14	05/21/02	05/15/02

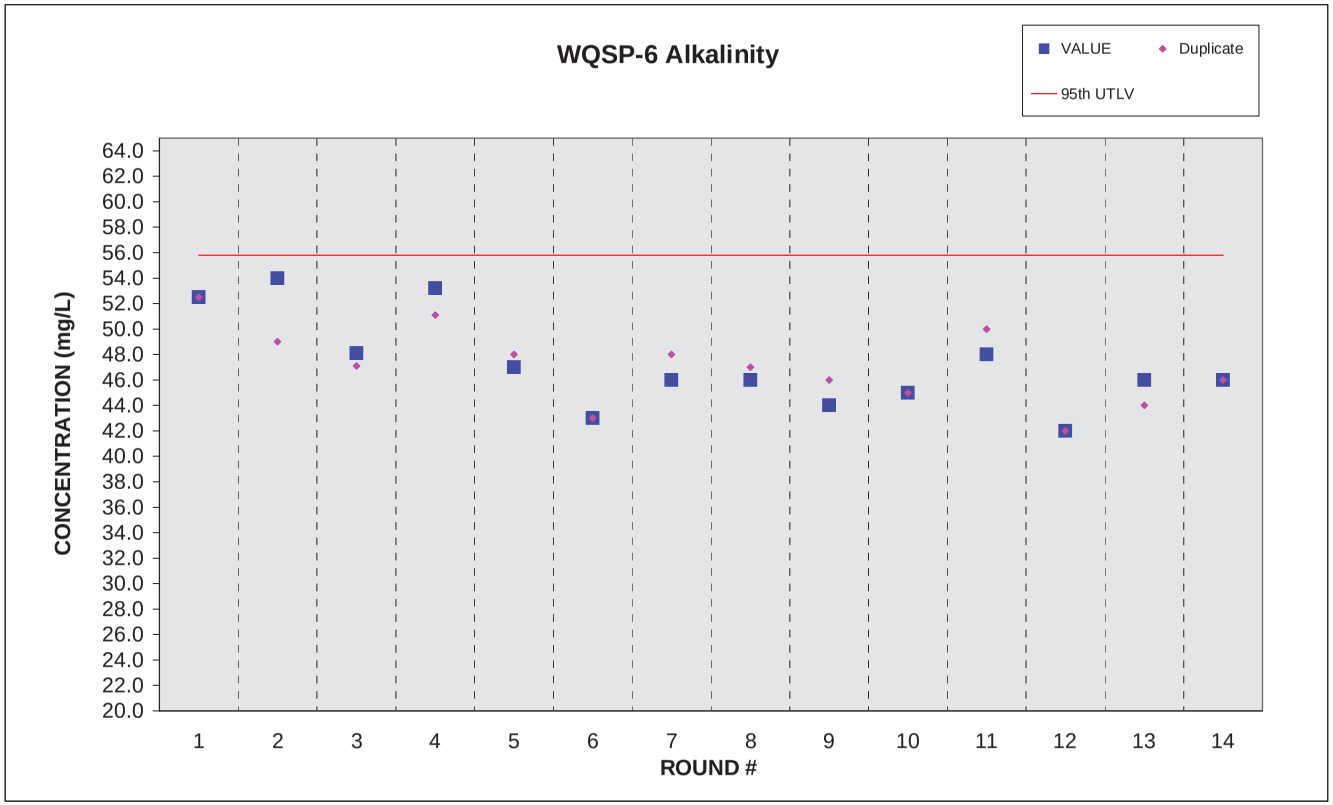

WQSP-6 Chloride

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		15800.0		15800.0	mg/L	5.0	6200.0			<	5.0	1	10/19/95	10/16/95
7782-50-5	CHLORIDE		6200.0		6200.0	mg/L	1000.0	6200.0			<	5.0	2	03/21/96	03/12/96
7782-50-5	CHLORIDE		6198.0		6098.0	mg/L	500.0	6200.0			<	5.0	3	07/10/96	06/27/96
7782-50-5	CHLORIDE		5973.0		5923.0	mg/L	250.0	6200.0			<	5.0	4	04/14/97	04/03/97
7782-50-5	CHLORIDE		5500.0		5750.0	mg/L	5000.0	6200.0			<	5.0	5	07/07/97	06/25/97
7782-50-5	CHLORIDE		6070.0		6053.3	mg/L	0.0	6200.0				0.1	6	06/05/98	06/03/98
7782-50-5	CHLORIDE		6000.0		6000.0	mg/L	0.5	6200.0				1.7	7	10/22/98	10/21/98
7782-50-5	CHLORIDE		5900.0		6000.0	mg/L	0.5	6200.0			<	0.5	8	05/20/99	05/19/99
7782-50-5	CHLORIDE		6000.0		5700.0	mg/L	0.5	6200.0			<	0.5	9	11/03/99	11/03/99
7782-50-5	CHLORIDE		5600.0		5500.0	mg/L	0.5	6200.0			<	0.5	10	05/19/00	05/10/00
7782-50-5	CHLORIDE		5500.0		5500.0	mg/L	2.0	6200.0			<	0.5	11	11/16/00	11/15/00
7782-50-5	CHLORIDE		5140.0		5170.0	mg/L	0.5	6200.0					12	05/23/01	05/16/01
7782-50-5	CHLORIDE		4970.0		4820.0	mg/L	2.0	6200.0					13	11/27/01	11/07/01
7782-50-5	CHLORIDE		4990.0		4950.0	mg/L	2.0	6200.0					14	05/23/02	05/15/02

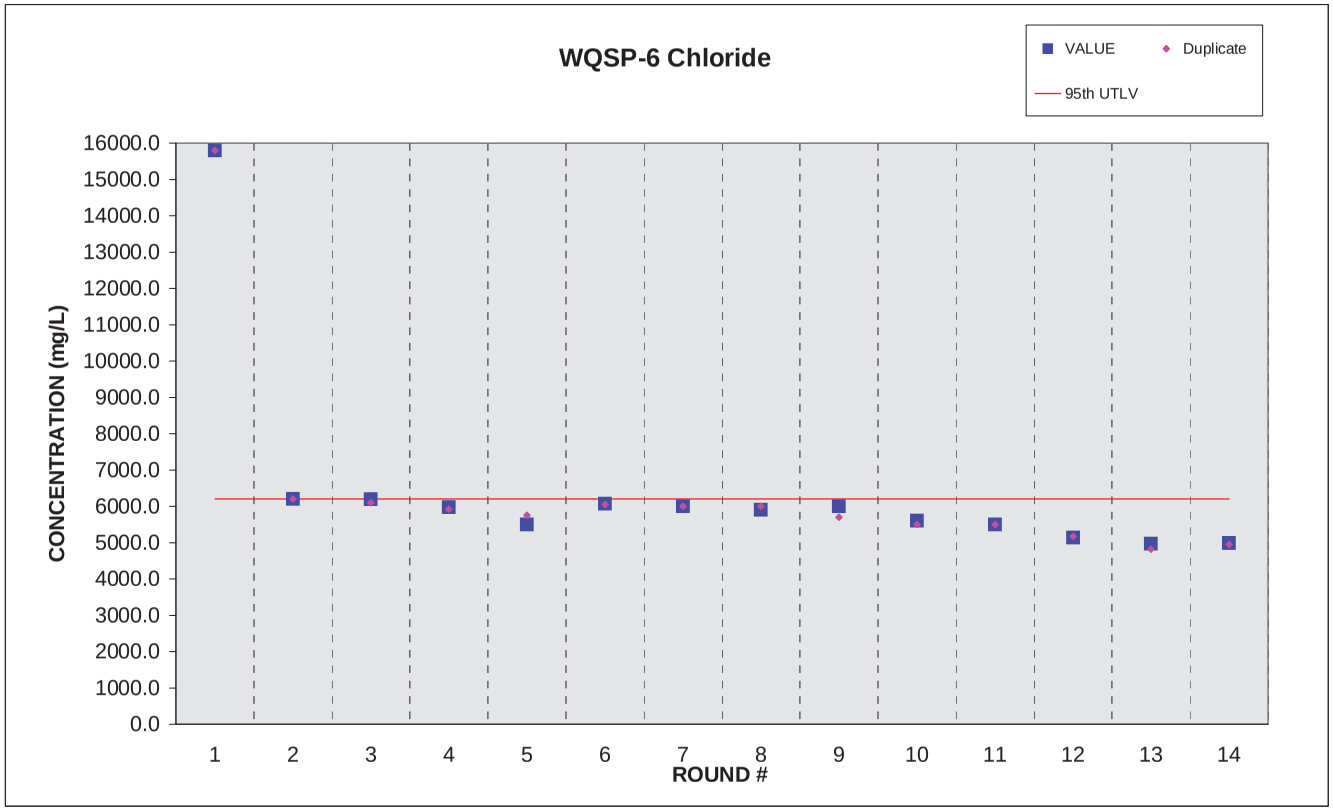

WQSP-6 Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		5590.0		5340.0	mg/L	10.0	5557.0			<	10.0	1	10/19/95	10/16/95
	SULFATE		4730.0		4670.0	mg/L	1000.0	5557.0			<	10.0	2	03/21/96	03/12/96
	SULFATE		4523.0		4337.0	mg/L	1000.0	5557.0			<	10.0	3	07/10/96	06/27/96
	SULFATE		4670.0		4650.0	mg/L	10.0	5557.0			<	10.0	4	04/15/97	04/03/97
	SULFATE		5100.0		4670.0	mg/L	2500.0	5557.0			<	10.0	5	07/07/97	06/25/97
	SULFATE		4660.0		4613.8	mg/L	0.0	5557.0				0.0	6	06/05/98	06/03/98
	SULFATE		4800.0		4900.0	mg/L	0.5	5557.0			<	0.5	7	10/22/98	10/21/98
	SULFATE		4400.0		4200.0	mg/L	0.5	5557.0			<	0.5	8	05/20/99	05/19/99
	SULFATE		5000.0		4800.0	mg/L	0.5	5557.0			<	0.5	9	11/03/99	11/03/99
	SULFATE		4700.0		4600.0	mg/L	0.5	5557.0			<	0.5	10	05/18/00	05/10/00
	SULFATE		4800.0		4700.0	mg/L	0.5	5557.0			<	0.5	11	11/16/00	11/15/00
	SULFATE		4600.0		4720.0	mg/L	0.5	5557.0					12	05/23/01	05/16/01
	SULFATE		4500.0		4510.0	mg/L	2.0	5557.0					13	11/27/01	11/07/01
	SULFATE		4640.0		4600.0	mg/L	2.0	5557.0					14	05/21/02	05/15/02

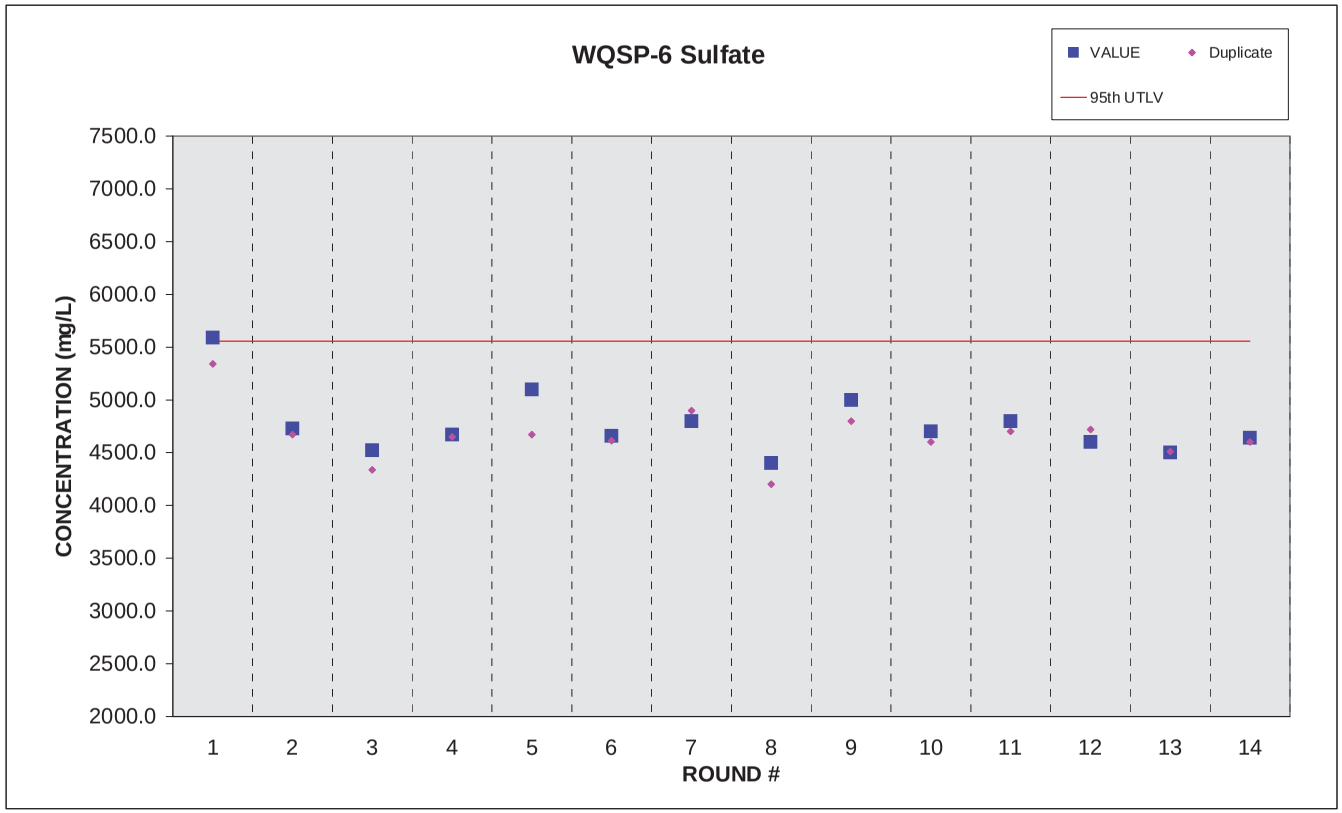

WQSP-6A Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		681.0		681.0	mg/L	0.8	733.0	<	0.2	<	0.2	1	07/18/95	07/13/95
7440-70-2	CALCIUM		564.0		568.0	mg/L	0.5	733.0	<	0.2	<	0.2	2	04/05/96	03/28/96
7440-70-2	CALCIUM		645.0		648.0	mg/L	2.0	733.0	<	0.2	<	0.2	3	07/30/96	07/11/96
7440-70-2	CALCIUM		563.0		573.0	mg/L	0.5	733.0	<	0.2	<	0.2	4	04/17/97	04/10/97
7440-70-2	CALCIUM		675.0		631.0	mg/L	2.0	733.0	<	0.2	<	0.2	5	07/17/97	07/10/97
7440-70-2	CALCIUM		649.0		661.0	mg/L	0.0	733.0				0.0	6	06/15/98	06/10/98
7440-70-2	CALCIUM		646.0		674.0	mg/L	0.5	733.0			<	0.5	7	12/15/98	11/03/98
7440-70-2	CALCIUM		654.0		637.0	mg/L	1.0	733.0			<	1.0	8	05/29/99	05/26/99
7440-70-2	CALCIUM		613.0		606.0	mg/L	0.5	733.0			<	0.5	9	12/10/99	11/10/99
7440-70-2	CALCIUM		681.0		664.0	mg/L	0.5	733.0			<	0.5	10	06/20/00	05/24/00
7440-70-2	CALCIUM		655.0		658.0	mg/L	5.0	733.0				1.6	11	12/11/00	11/30/00
7440-70-2	CALCIUM		570.0		540.0	mg/L	0.5	733.0			<	0.5	12	06/25/01	06/06/01
7440-70-2	CALCIUM		622.0		620.0	mg/L	0.5	733.0			<	0.5	13	02/13/02	11/14/01
7440-70-2	CALCIUM		573.0		552.0	mg/L	0.5	733.0			<	0.5	14	06/05/02	05/22/02

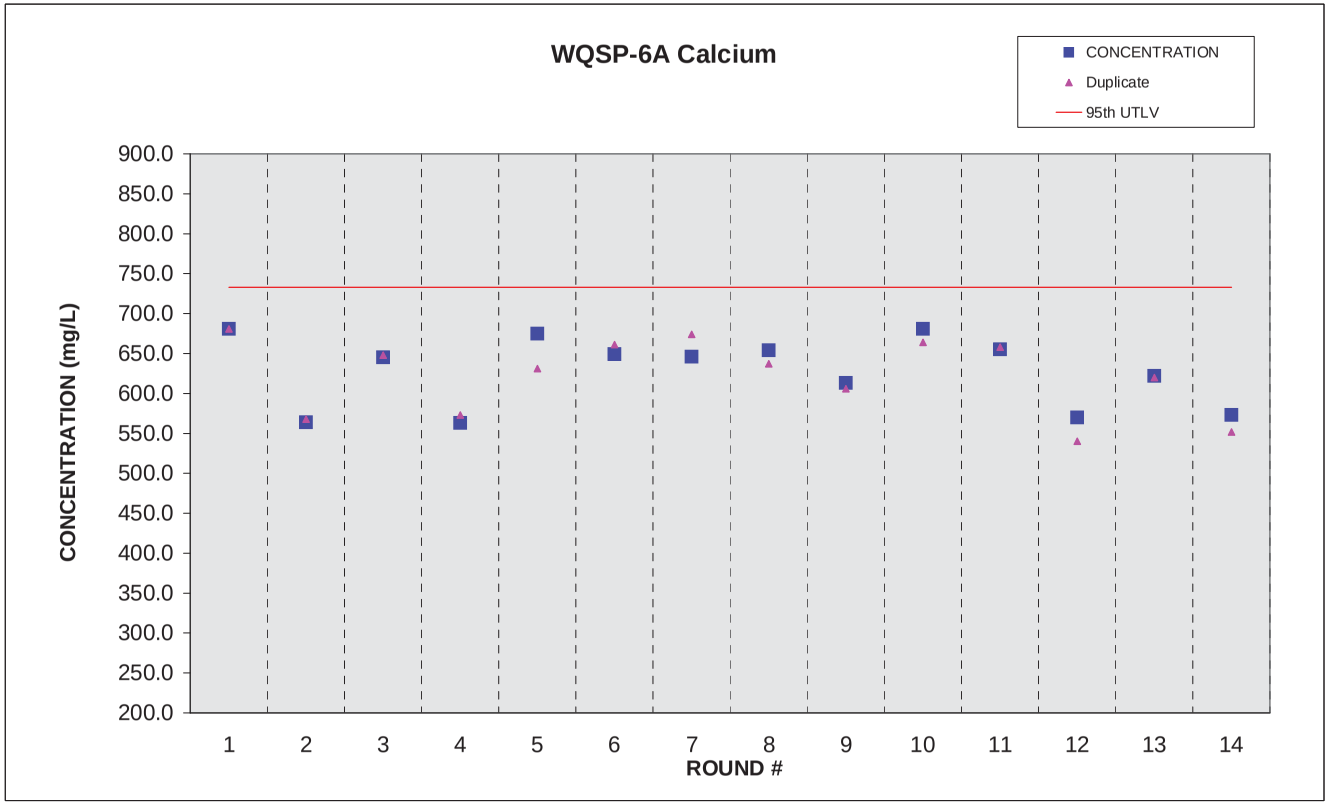

WQSP-6A Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		181.0		181.0	mg/L	0.4	188.0	<	0.1	<	0.1	1	07/18/95	07/13/95
7439-95-4	MAGNESIUM		155.0		156.0	mg/L	0.1	188.0	<	0.1	<	0.1	2	04/05/96	03/28/96
7439-95-4	MAGNESIUM		155.0		156.0	mg/L	0.5	188.0	<	0.1	<	0.1	3	07/30/96	07/11/96
7439-95-4	MAGNESIUM		150.0		147.0	mg/L	0.1	188.0	<	0.1	<	0.1	4	04/17/97	04/10/97
7439-95-4	MAGNESIUM		173.0		161.0	mg/L	1.0	188.0	<	0.1	<	0.1	5	07/17/97	07/10/97
7439-95-4	MAGNESIUM		173.0		174.0	mg/L	0.1	188.0				0.2	6	06/15/98	06/10/98
7439-95-4	MAGNESIUM		166.0		173.0	mg/L	0.5	188.0			<	0.5	7	12/15/98	11/03/98
7439-95-4	MAGNESIUM		172.0		168.0	mg/L	1.0	188.0			<	1.0	8	05/29/99	05/26/99
7439-95-4	MAGNESIUM		167.0		166.0	mg/L	0.5	188.0			<	0.5	9	12/09/99	11/10/99
7439-95-4	MAGNESIUM		167.0		162.0	mg/L	0.5	188.0			<	0.5	10	06/20/00	05/24/00
7439-95-4	MAGNESIUM		187.0		179.0	mg/L	5.0	188.0				3.7	11	12/11/00	11/30/00
7439-95-4	MAGNESIUM		150.0		146.0	mg/L	0.5	188.0			<	0.5	12	06/25/01	06/06/01
7439-95-4	MAGNESIUM		186.0		169.0	mg/L	0.5	188.0			<	0.5	13	02/13/02	11/14/01
7439-95-4	MAGNESIUM		151.0		154.0	mg/L	0.5	188.0			<	0.5	14	06/05/02	05/22/02

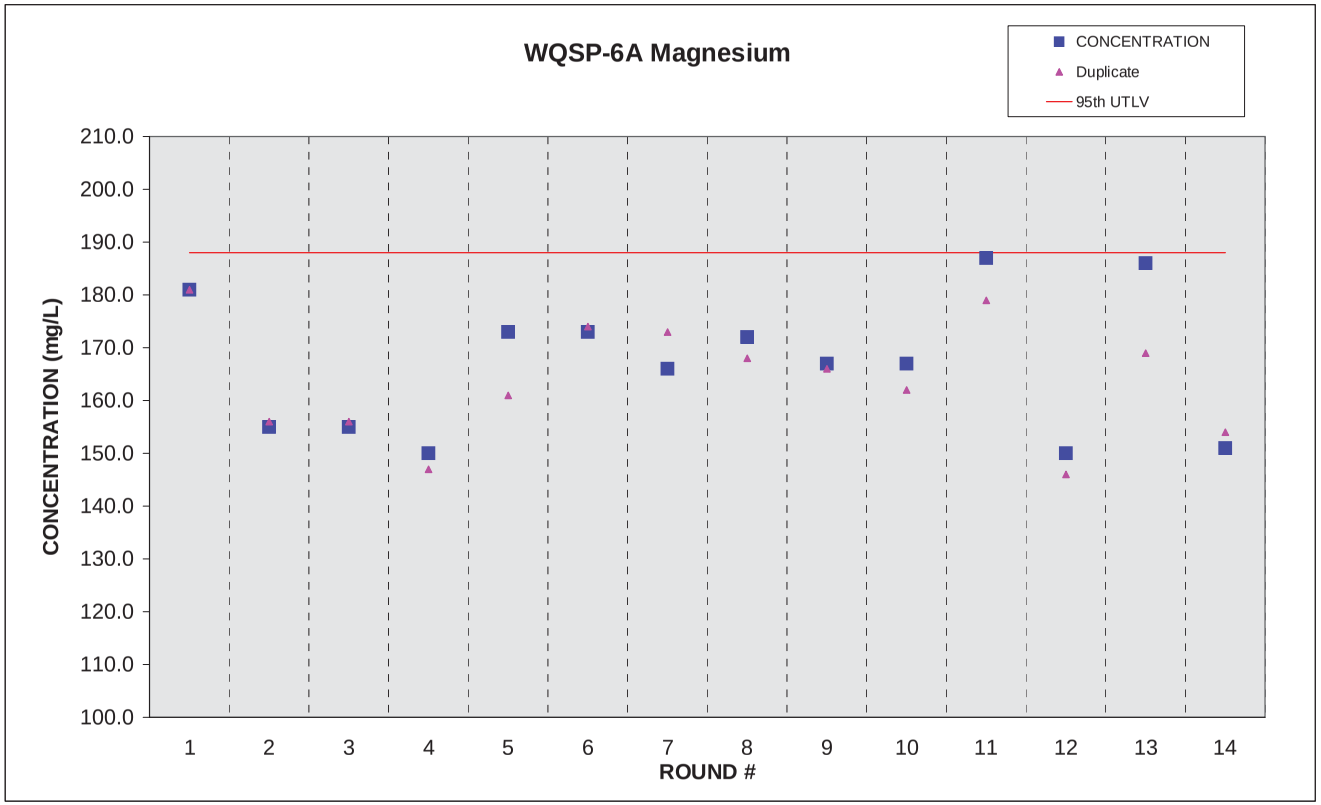

WQSP-6A Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		4.8		4.8	mg/L	0.8	10.1	<	0.2	<	0.2	1	07/18/95	07/13/95
7440-09-7	POTASSIUM		3.9		3.8	mg/L	0.5	10.1	<	0.2	<	0.2	2	04/05/96	03/28/96
7440-09-7	POTASSIUM		5.0		5.1	mg/L	2.0	10.1	<	0.2	<	0.2	3	07/30/96	07/11/96
7440-09-7	POTASSIUM		4.2		4.1	mg/L	0.5	10.1	<	0.2	<	0.2	4	04/17/97	04/10/97
7440-09-7	POTASSIUM		4.5		4.2	mg/L	2.0	10.1	<	0.2	<	0.2	5	07/18/97	07/10/97
7440-09-7	POTASSIUM		4.5		4.4	mg/L	0.0	10.1				0.0	6	06/15/98	06/10/98
7440-09-7	POTASSIUM		7.5		7.5	mg/L	0.5	10.1			<	0.5	7	12/15/98	11/03/98
7440-09-7	POTASSIUM		10.0		9.4	mg/L	1.0	10.1			<	1.0	8	05/29/99	05/26/99
7440-09-7	POTASSIUM	<	10.0	<	10.0	mg/L	1.0	10.1			<	1.0	9	12/09/99	11/10/99
7440-09-7	POTASSIUM		5.2		5.4	mg/L	1.0	10.1			<	1.0	10	06/20/00	05/24/00
7440-09-7	POTASSIUM		3.3		3.0	mg/L	5.0	10.1				0.5	11	12/11/00	11/30/00
7440-09-7	POTASSIUM		7.2		7.5	mg/L	0.5	10.1			<	0.5	12	06/25/01	06/06/01
7440-09-7	POTASSIUM		7.6		7.6	mg/L	0.5	10.1			<	0.5	13	02/13/02	11/14/01
7440-09-7	POTASSIUM		7.3		7.5	mg/L	0.5	10.1			<	0.5	14	06/05/02	05/22/02

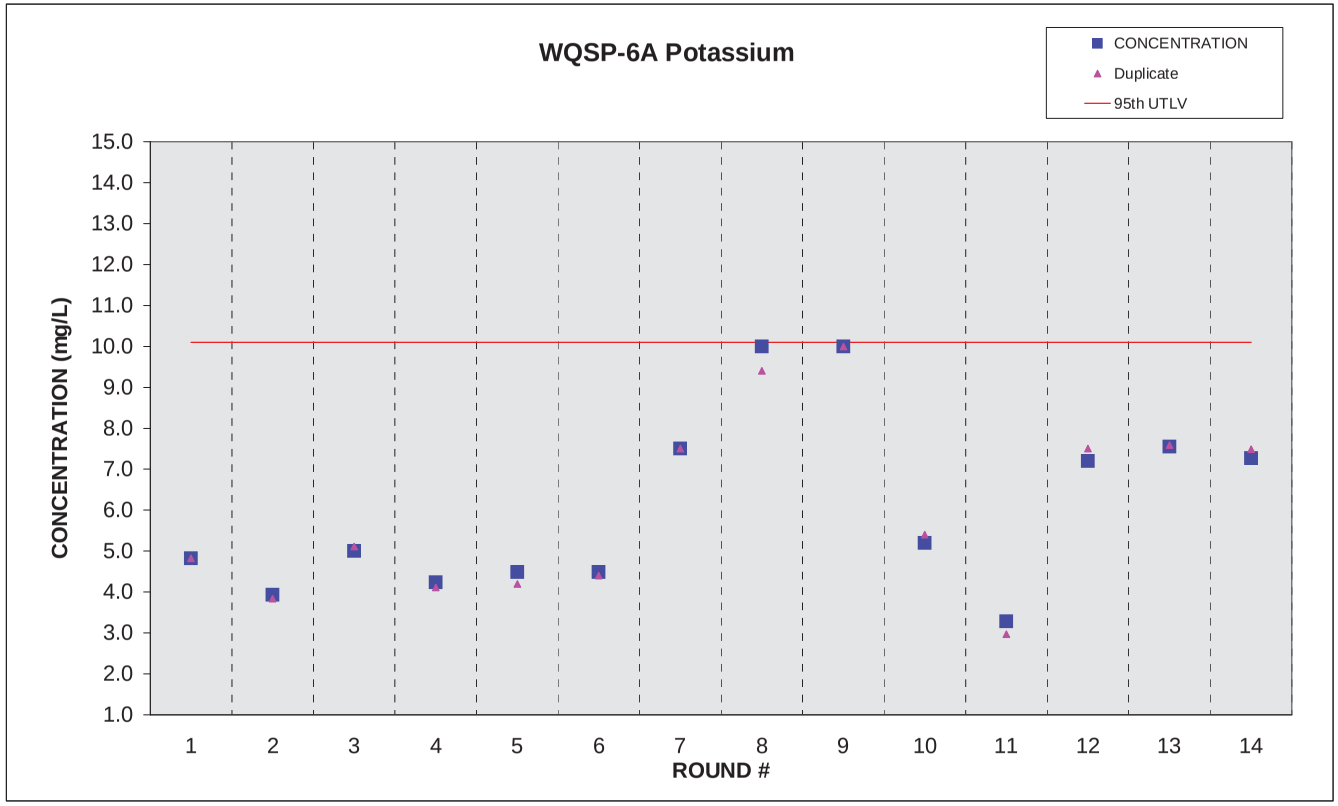

WQSP-6A Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		347.0		347.0	mg/L	2.0	369.0		0.5		0.5	1	07/18/95	07/13/95
7440-23-5	SODIUM		282.0		282.0	mg/L	1.3	369.0	<	0.5	<	0.5	2	04/05/96	03/28/96
7440-23-5	SODIUM		314.0		314.0	mg/L	5.0	369.0	<	0.5	<	0.5	3	07/30/96	07/11/96
7440-23-5	SODIUM		292.0		284.0	mg/L	1.3	369.0	<	0.5	<	0.5	4	04/17/97	04/10/97
7440-23-5	SODIUM		311.0		290.0	mg/L	5.0	369.0	<	0.5	<	0.5	5	07/18/97	07/10/97
7440-23-5	SODIUM		335.0		334.0	mg/L	0.1	369.0				0.1	6	06/15/98	06/10/98
7440-23-5	SODIUM		313.0		334.0	mg/L	0.5	369.0			<	0.5	7	12/15/98	11/03/98
7440-23-5	SODIUM		291.0		299.0	mg/L	1.0	369.0			<	1.0	8	06/11/99	05/26/99
7440-23-5	SODIUM		269.0		267.0	mg/L	0.5	369.0			<	0.5	9	12/10/99	11/10/99
7440-23-5	SODIUM		279.0		291.0	mg/L	0.5	369.0			<	0.5	10	06/20/00	05/24/00
7440-23-5	SODIUM		258.0		250.0	mg/L	5.0	369.0				0.8	11	12/11/00	11/30/00
7440-25-5	SODIUM		260.0		255.0	mg/L	0.5	369.0			<	0.5	12	06/25/01	06/06/01
7440-25-5	SODIUM		302.0		267.0	mg/L	0.5	369.0			<	0.5	13	02/13/02	11/14/01
7440-25-5	SODIUM		253.0		254.0	mg/L	0.5	369.0			<	0.5	14	06/05/02	05/22/02

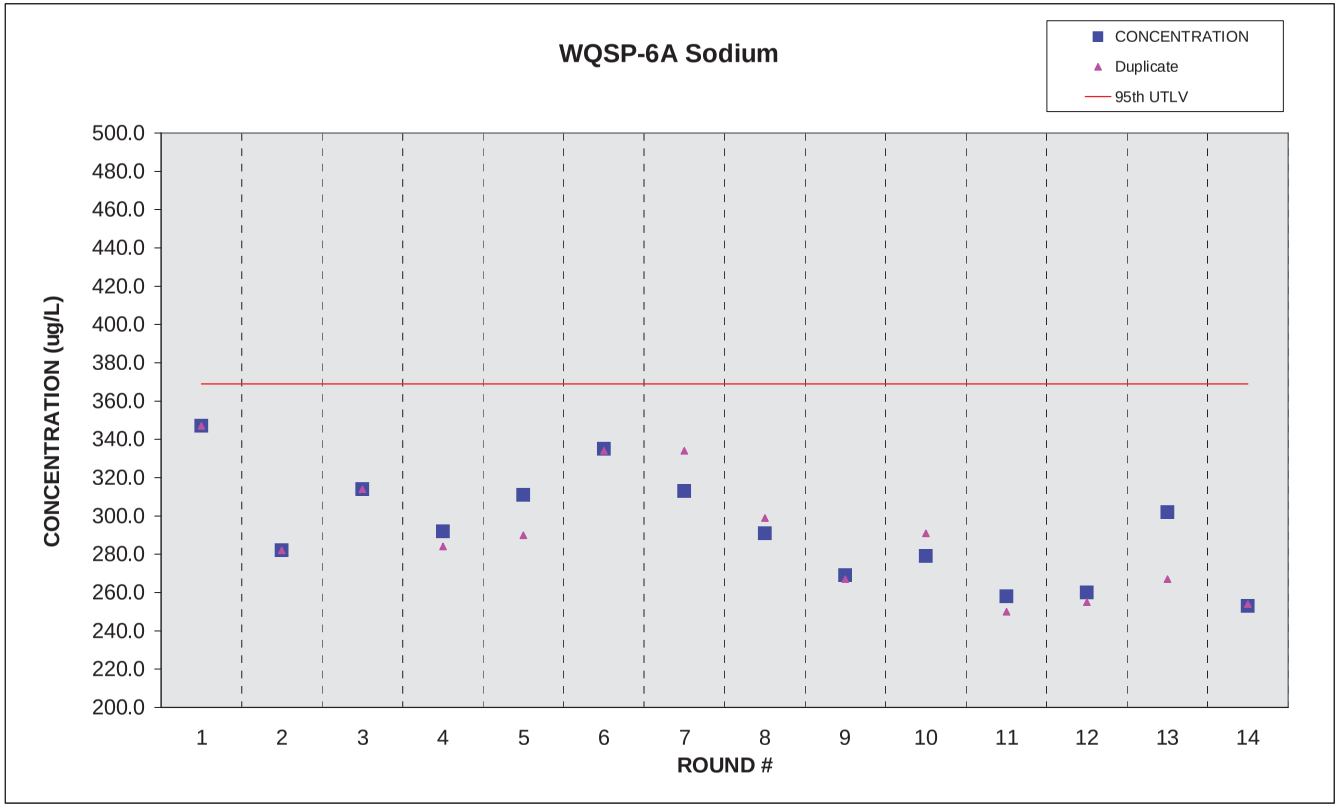

WQSP-6A Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		111.0		111.0	mg/L	5.0	113.0			<	5.0	1	07/25/95	07/13/95
	ALKALINITY		101.0		102.0	mg/L	5.0	113.0			<	5.0	2	04/09/96	03/28/96
	ALKALINITY		104.2		105.2	mg/L	5.0	113.0			<	5.0	3	07/25/96	07/11/96
	ALKALINITY		106.0		109.0	mg/L	5.0	113.0			<	5.0	4	04/16/97	04/10/97
	ALKALINITY		102.0		102.0	mg/L	5.0	113.0			<	5.0	5	07/24/97	07/10/97
	ALKALINITY		103.0		103.0	mg/L	5.0	113.0					6	06/13/98	06/10/98
	ALKALINITY		100.0		100.0	mg/L	5.0	113.0			<	5.0	7	11/17/98	11/03/98
	ALKALINITY		102.0		106.0	mg/L	4.0	113.0				4.0	8	05/27/99	05/26/99
	ALKALINITY		100.0		102.0	mg/L	4.0	113.0					9	11/12/99	11/10/99
	ALKALINITY		108.0		103.0	mg/L	6.0	113.0			<	6.0	10	05/30/00	05/24/00
	ALKALINITY		108.0		102.0	mg/L	4.0	113.0					11	11/30/00	12/05/00
	ALKALINITY		104.0		106.0	mg/L	4.0	113.0					12	06/12/01	06/06/01
	ALKALINITY		102.0		102.0	mg/L	4.0	113.0					13	11/27/01	11/14/01
	ALKALINITY		106.0		104.0	mg/L	4.0	113.0					14	05/30/02	05/22/02

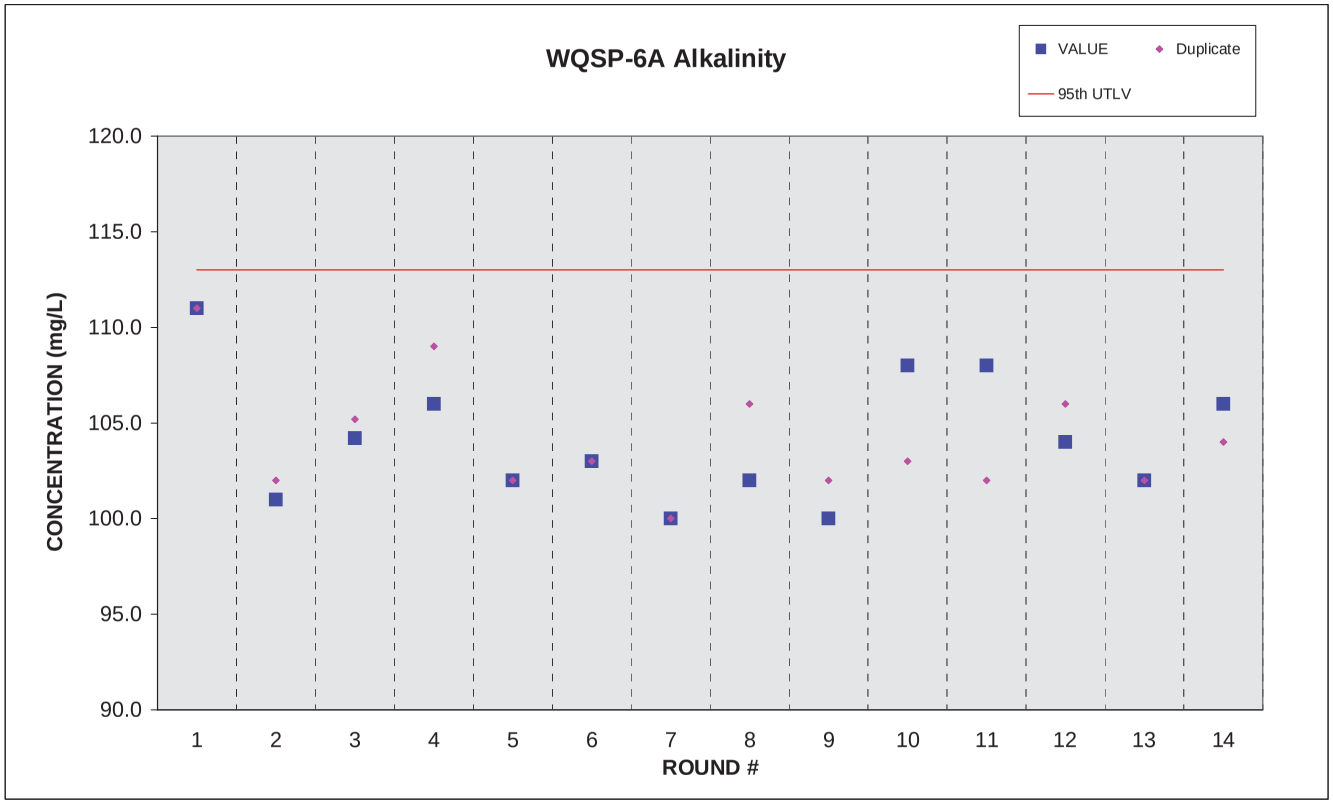

WQSP-6A Chloride

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		1040.0		1040.0	mg/L	5.0	1040.0			<	5.0	1	07/25/95	07/13/95
7782-50-5	CHLORIDE		507.0		515.0	mg/L	50.0	1040.0			<	5.0	2	04/10/96	03/28/96
7782-50-5	CHLORIDE		6748.0		6698.0	mg/L	5.0	1040.0			<	5.0	3	07/17/96	07/11/96
7782-50-5	CHLORIDE		675.0		665.0	mg/L	250.0	1040.0			<	5.0	4	04/14/97	04/10/97
7782-50-5	CHLORIDE		660.0		665.0	mg/L	50.0	1040.0			<	5.0	5	08/29/97	07/10/97
7782-50-5	CHLORIDE		644.0		624.0	mg/L	0.0	1040.0					6	06/13/98	06/10/98
7782-50-5	CHLORIDE		770.0		680.0	mg/L	0.5	1040.0				1.1	7	11/05/98	11/03/98
7782-50-5	CHLORIDE		540.0		510.0	mg/L	0.5	1040.0			<	0.5	8	05/28/99	05/26/99
7782-50-5	CHLORIDE		540.0		540.0	mg/L	0.5	1040.0			<	0.5	9	11/11/99	11/10/99
7782-50-5	CHLORIDE		530.0		510.0	mg/L	0.5	1040.0			<	0.5	10	05/24/00	05/24/00
7782-50-5	CHLORIDE		480.0		480.0	mg/L	0.5	1040.0					11	11/30/00	11/30/00
7782-50-5	CHLORIDE		536.0		505.0	mg/L	0.5	1040.0					12	06/07/01	06/06/01
7782-50-5	CHLORIDE		414.0		411.0	mg/L	2.0	1040.0					13	11/27/01	11/14/01
7782-50-5	CHLORIDE		487.0		400.0	mg/L	2.0	1040.0					14	05/23/02	05/22/02

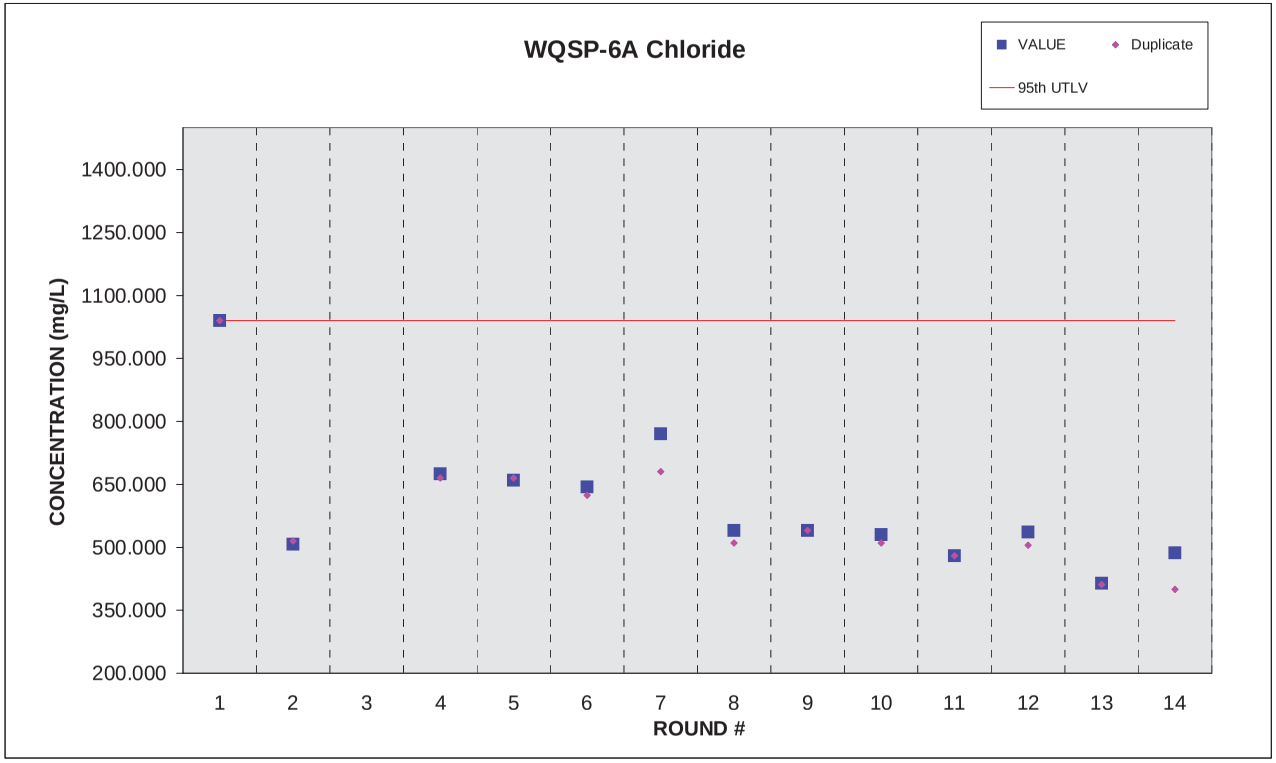

WQSP-6A Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		1905.0		1905.0	mg/L	10.0	2543.0			<	10.0	1	07/22/95	07/13/95
	SULFATE		1810.0		1790.0	mg/L	10.0	2543.0			<	10.0	2	04/15/96	03/28/96
	SULFATE		1970.5		1989.5	mg/L	10.0	2543.0			<	10.0	3	07/22/96	07/11/96
	SULFATE		2240.0		2240.0	mg/L	10.0	2543.0			<	10.0	4	04/15/97	04/10/97
	SULFATE		2560.0		2480.0	mg/L	10.0	2543.0			<	10.0	5	09/03/97	07/10/97
	SULFATE		1950.0		1890.0	mg/L	0.0	2543.0					6	06/13/98	06/10/98
	SULFATE		2100.0		1900.0	mg/L	0.5	2543.0			<	5.0	7	11/05/98	11/03/98
	SULFATE		1900.0		1900.0	mg/L	0.5	2543.0			<	0.5	8	05/28/99	05/26/99
	SULFATE		1900.0		2000.0	mg/L	0.5	2543.0			<	0.5	9	11/11/99	11/10/99
	SULFATE		2100.0		2000.0	mg/L	0.5	2543.0			<	0.5	10	05/24/00	05/24/00
	SULFATE		1900.0		1900.0	mg/L	0.5	2543.0					11	11/30/00	11/30/00
	SULFATE		1900.0		1830.0	mg/L	0.5	2543.0					12	06/07/01	06/06/01
	SULFATE		1900.0		1870.0	mg/L	2.0	2543.0					13	11/27/01	11/14/01
	SULFATE		1930.0		1940.0	mg/L	2.0	2543.0					14	05/23/02	05/22/02

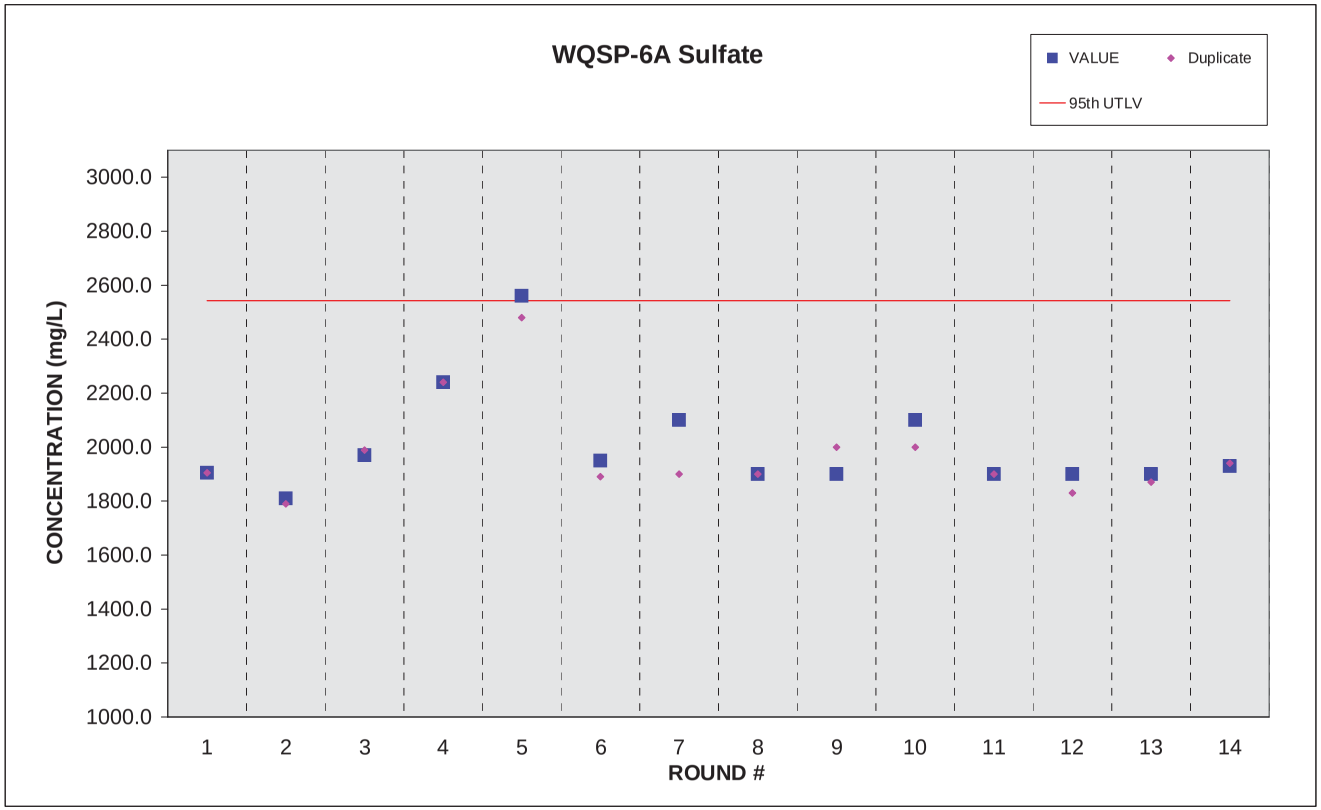

APPENDIX DATA

ATTACHMENT D: INVENTORY AND EMPLACED WASTE DATA

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Waste Inventory as of September 2002

This attachment identifies the total amounts of certain categories of materials used in performance assessment (PA) activities that are emplaced in the repository as of September 30, 2002. The information is derived from reports generated by the WIPP Waste Information System (WWIS). The WWIS database is a computerized data management system used by the WIPP to gather, store, and process information pertaining to contact-handled (CH) transuranic (TRU) waste destined for or disposed of at the WIPP.

Table DATA-D1. Nuclide Inventory (Totals)

Nuclide	Curies	Kilograms
^{227}Ac	3.6430E-04	5.0000E-09
^{241}Am	1.1743E+05	3.3843E+01
^{243}Am	4.8047E-03	2.3856E-05
^{60}Co	3.4700E-07	0.0000E+00
^{137}Cs	3.4124E-04	5.0000E-09
^{40}K	2.8697E-05	5.0809E-03
^{22}Na	5.3430E-06	0.0000E+00
^{237}Np	4.0009E-01	5.6115E-01
^{231}Pa	5.0402E-04	1.0432E-05
^{238}Pu	5.6437E+03	3.2628E-01
^{239}Pu	1.3760E+05	2.1876E+03
^{240}Pu	3.0994E+04	1.3476E+02
^{241}Pu	4.3677E+05	4.2006E+00
^{242}Pu	2.9546E+00	7.4437E-01
^{226}Ra	7.8780E-06	8.0000E-09
^{90}Sr	0.0000E+00	0.0000E+00
^{230}Th	2.4100E-05	1.1800E-06
^{232}Th	2.6070E-06	2.3646E-02
^{233}U	2.7269E-01	2.7939E-02
^{234}U	1.2636E+00	1.9993E-01
^{235}U	1.2202E-01	5.5718E+01
^{238}U	6.5298E+00	1.9204E+04
Total:	7.2845E+05	2.1622E+04

Table DATA-D2. Materials Inventory – CPR

Waste Material	Kilograms
Cellulose	618,821.60
Plastic	306,345.40
Rubber	2,450.31
Total:	927,617.31

Table DATA-D3. Materials Inventory – Metals

Metal	Kilograms
Ferrous	2,487,932.00
Non-Ferrous	31,059.28
Total:	2,518,991.28

Table DATA-D4. Compliance Certification Application Relevant Parameters (March 1, 1999 to September 30, 2002)[1]

Site	Shipments	Container Type	Containers	Weight (kg)	Volume (m3)
EMPLACED WASTE CONTAINERS:					
Savannah River	16	55-Gallon Drum	672	39142.40	141.12
Idaho	509	55-Gallon Drum	13661	2388941.34	2868.81
Idaho	3	Standard Waste Box - Used to overpack four, 55-gallon drums in good condition	8	9106.78	15.04
Los Alamos	1	55-Gallon Drum	28	1535.00	5.88
Los Alamos	25	Standard Waste Box	141	57194.00	265.08
Rocky Flats	101	55-Gallon Drum	3072	202452.34	645.12
Rocky Flats	569	55-Gallon Pipe Overpack - 12 Inch Pipe Overpack	15680	2482536.14	3292.80
Rocky Flats	30	Standard Waste Box	172	135262.98	323.36
Rocky Flats	12	55-Gallon Drum	467	32289.60	98.07
Savannah River	7	55-Gallon Drum	294	17412.40	61.74
		Totals:	34195	5365872.98	7717.02
EMPLACED DUNNAGE[2] CONTAINERS:					
Idaho	226	55-Gallon Drum	516	14964.00	108.36
Rocky Flats	15	55-Gallon Drum	36	1044.00	7.56
Richland	1	55-Gallon Drum	2	58.00	0.42
		Totals:	554	16066.00	116.34

[1] Total Inventory as of 9/30/2002 Containers, Volumes, and Weights by Generator Site and Container type for emplaced waste only.
[2] Dunnage containers are empty containers used to complete a shipping configuration, such as the seven-pack, if too few containers are available that meet transportation requirements. Dunnage containers must clearly be marked “Empty.”

APPENDIX DATA

ATTACHMENT E: WWIS NUCLIDE REPORT

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Panel One Nuclide Inventory by Room

This attachment identifies the total amounts of radionuclides by nuclide emplaced in each room of Panel 1 as of September 30, 2002. The information is derived from reports generated by the WIPP Waste Information System (WWIS). The WWIS database is a computerized data management system used by the WIPP to gather, store, and process information pertaining to contact-handled (CH) transuranic (TRU) waste destined for or disposed of at the WIPP.

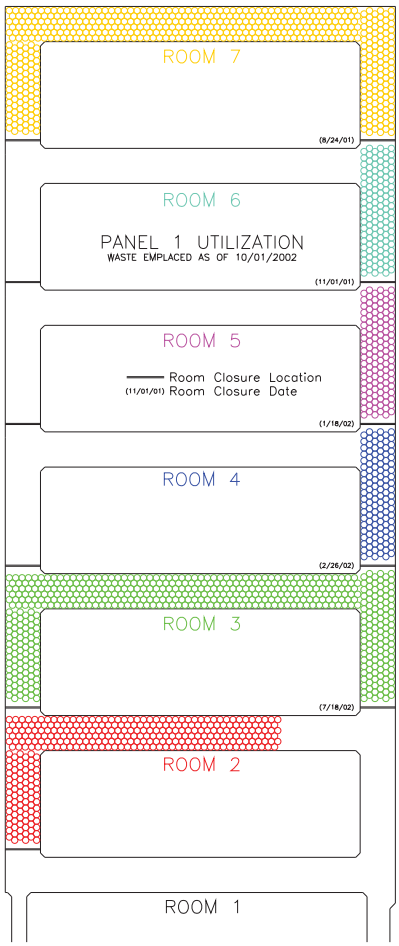

Figure DATA-E1. Panel 1 Waste Emplacement

Table DATA-E1. Panel 1 – Room 2

Radionuclide	Activity (Curies)	Mass (Grams)
^{241}Am – Americium 241	9.2850E+03	2.6758E+03
^{243}Am – Americium 243	9.9560E-04	4.9289E-03
^{137}Cs – Cesium 137	8.0278E-05	9.1225E-07
^{40}K – Potassium 40	8.4940E-06	1.5047E+00
^{237}Np – Neptunium 237	1.4797E-02	2.0754E+01
^{238}Pu – Plutonium 238	5.0904E+02	2.9424E+01
^{239}Pu – Plutonium 239	1.4237E+04	2.2634E+05
^{240}Pu – Plutonium 240	3.2407E+03	1.4090E+04
^{241}Pu – Plutonium 241	5.0010E+04	4.8087E+02
^{242}Pu – Plutonium 242	3.1581E-01	7.9550E+01
^{90}Sr – Strontium 90	0.0000E+00	0.0000E+00
^{233}U – Uranium 233	1.0058E-01	1.0305E+01
^{234}U – Uranium 234	4.7176E-01	7.4619E+01
^{235}U – Uranium 235	4.0517E-02	1.8501E+04
^{238}U – Uranium 238	2.8812E+00	8.4742E+06
Totals	7.7285E+04	8.7365E+06

Table DATA-E2. Panel 1 – Room 3

Radionuclide	Activity (Curies)	Mass (Grams)
^{241}Am – Americium 241	4.8984E+04	1.4116E+04
^{137}Cs – Cesium 137	1.2539E-05	1.4248E-07
^{237}Np – Neptunium 237	1.5878E-01	2.2269E+02
^{238}Pu – Plutonium 238	2.1564E+03	1.2465E+02
^{239}Pu – Plutonium 239	5.5875E+04	8.8832E+05
^{240}Pu – Plutonium 240	1.2569E+04	5.4648E+04
^{241}Pu – Plutonium 241	1.7815E+05	1.7129E+03
^{242}Pu – Plutonium 242	1.1899E+00	2.9973E+02
^{226}Ra – Radium 226	7.8785E-06	7.8785E-06
^{90}Sr – Strontium 90	0.0000E+00	0.0000E+00
^{233}U – Uranium 233	2.8513E-02	2.9214E+00
^{234}U – Uranium 234	4.3515E-01	6.8854E+01
^{235}U – Uranium 235	4.7486E-02	2.1683E+04
^{238}U – Uranium 238	2.3434E+00	6.8923E+06
Totals	2.9774E+05	7.8735E+06

Table DATA-E3. Panel 1 – Room 4

Radionuclide	Activity (Curies)	Mass (Grams)
^{241}Am – Americium 241	5.6147E+03	1.6181E+03
^{237}Np – Neptunium 237	1.6499E-02	2.3141E+01
^{238}Pu – Plutonium 238	7.1070E+02	4.1081E+01
^{239}Pu – Plutonium 239	1.5038E+04	2.3908E+05
^{240}Pu – Plutonium 240	3.3797E+03	1.4694E+04
^{241}Pu – Plutonium 241	5.7280E+04	5.5077E+02
^{242}Pu – Plutonium 242	3.2172E-01	8.1037E+01
^{234}U – Uranium 234	1.0038E-01	1.5883E+01
^{235}U – Uranium 235	9.3989E-03	4.2917E+03
^{238}U – Uranium 238	4.3477E-01	1.2787E+06
Totals	8.2025E+04	1.5391E+06

Table DATA-E4. Panel 1 – Room 5

Radionuclide	Activity (Curies)	Mass (Grams)
^{241}Am – Americium 241	1.1232E+04	3.2369E+03
^{237}Np – Neptunium 237	4.1192E-02	5.7773E+01
^{238}Pu – Plutonium 238	4.9307E+02	2.8501E+01
^{239}Pu – Plutonium 239	1.2341E+04	1.9620E+05
^{240}Pu – Plutonium 240	2.7427E+03	1.1925E+04
^{241}Pu – Plutonium 241	3.8036E+04	3.6573E+02
^{242}Pu – Plutonium 242	2.3423E-01	5.9000E+01
^{233}U – Uranium 233	5.2969E-03	5.4272E-01
^{234}U – Uranium 234	6.4339E-02	1.0180E+01
^{235}U – Uranium 235	8.3825E-03	3.8276E+03
^{238}U – Uranium 238	2.6287E-01	7.7313E+05
Totals	6.4845E+04	9.8885E+05

Table DATA-E5. Panel 1 – Room 6

Radionuclide	Activity (Curies)	Mass (Grams)
^{227}Ac – Actinium	3.6430E-04	4.9741E-06
^{241}Am – Americium 241	1.4472E+04	4.1705E+03
^{243}Am – Americium 243	1.5729E-03	7.7878E-03
^{137}Cs – Cesium 137	7.2349E-06	7.6137E-07
^{40}K – Potassium 40	1.6160E-06	2.8610E-01
^{237}Np – Neptunium 237	7.5073E-02	1.0530E+02

Table DATA-E5. Panel 1 – Room 6 — Continued

Radionuclide	Activity (Curies)	Mass (Grams)
^{231}Pa – Protactinium 231	4.9790E-04	1.0419E-02
^{238}Pu – Plutonium 238	3.3829E+02	1.9554E+01
^{239}Pu – Plutonium 239	1.2851E+04	2.0432E+05
^{240}Pu – Plutonium 240	2.8699E+03	1.2478E+04
^{241}Pu – Plutonium 241	2.6727E+04	2.5699E+02
^{242}Pu – Plutonium 242	2.1064E-01	5.3054E+01
^{230}Th – Thorium	2.4100E-05	1.1800E-03
^{233}U – Uranium 233	4.3707E-03	4.4782E-01
^{234}U – Uranium 234	2.8120E-02	4.4512E+00
^{235}U – Uranium 235	2.5512E-03	1.1650E+03
^{238}U – Uranium 238	1.2067E-01	3.5492E+05
Totals	5.7259E+04	5.7749E+05

Table DATA-E6. Panel 1 – Room 7

Radionuclide	Activity (Curies)	Mass (Grams)
^{241}Am – Americium 241	2.7844E+04	8.0252E+03
^{243}Am – Americium 243	2.2362E-03	1.1140E-02
^{60}Co – Cobalt 60	3.4696E-07	3.0400E-10
^{137}Cs – Cesium 137	2.4119E-04	2.7401E-06
^{40}K – Potassium 40	1.8587E-05	3.2901E+00
^{22}Na – Sodium 22 (NA-22)	5.3435E-06	8.4500E-10
^{237}Np – Neptunium 237	9.3755E-02	1.3149E+02
^{231}Pa – Protactinium 231	6.1146E-06	1.3003E-05
^{238}Pu – Plutonium 238	1.4362E+03	8.3073E+01
^{239}Pu – Plutonium 239	2.7257E+04	4.3332E+05
^{240}Pu – Plutonium 240	6.1924E+03	2.6925E+04
^{241}Pu – Plutonium 241	8.6568E+04	8.3333E+02
^{242}Pu – Plutonium 242	6.8228E-01	1.7200E+02
^{230}Th – Thorium	2.6073E-06	2.3646E+01
^{233}U – Uranium 233	1.3393E-01	1.3722E+01
^{234}U – Uranium 234	1.6387E-01	2.5948E+01
^{235}U – Uranium 235	1.3687E-02	6.2499E+03
^{238}U – Uranium 238	4.8689E-01	1.4312E+06
Totals	1.4930E+05	1.9070E+06

Panel 1 – Room Totals	7.2845E+05	2.1622E+07

ATTACHMENT F: TRANSURANIC WASTE INVENTORY UPDATE REPORT, 2003
TO
APPENDIX DATA

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ACRONYMS AND ABBREVIATIONS

AE	Argonne National Laboratory – East site identifier
ANL-E	Argonne National Laboratory East
ANL-W	Argonne National Laboratory West
AL	Ames Laboratory site identifier
AM	ARCO Medical Products Company site identifier
AW	Argonne National Laboratory - West Side identifier
BC	Battelle Columbus Laboratory site identifier
BAPL	Bettis Atomic Power Laboratory
BCL	Battelle Columbus Laboratory
BL	Babcock and Wilcox Lynchberg site identifier
BLIP	Brookhaven Linear Isotope Production
BT	Bettis Atomic Power Laboratory site identifier
C&C Agreement	Agreement for Consultation and Cooperation between the Department of Energy and the State of New Mexico on the Waste Isolation Pilot Plant
Ca	Calcium
CAO	Carlsbad Area Office
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CFR	Code of Federal Regulations
CH	Contact-handled
CPR	Cellulosic, Plastic, and Rubber Materials
CRA-2004	Compliance Recertification Application
CY	Calendar Year
D&D	Decontamination and Decommissioning
DOE	U.S. Department of Energy
DOR	Direct Oxide Reduction
EDTA	ethylenediaminetetraacetic acid
EPA	U.S. Environmental Protection Agency
ER	Environmental restoration or electro-refining (salts)
ERMS	Electronic Records Management System
ET	Energy Technology Engineering Center site identifier
FFCAct	Federal Facilities Compliance Act
ft^3	Cubic feet
FR	Framatome (Richland) site identifier
GE	General Electric Vallecitos Nuclear Center site identifier
HEPA	High Efficiency Particulate Air
IDB	Integrated Database
IDC	Item Description Code
IN	Idaho National Engineering and Environmental Laboratory site identifier
INEEL	Idaho National Engineering and Environmental Laboratory
IT	Inhalation Toxicology Research Institute (now known as Lovelace Respiratory Research Institute, LRRI) site identifier
JASPER	Joint Actinide Shock Physics Experimental Research
K	Potassium
KA	Knolls Atomic Power Laboratory-Schenectady site identifier

KAPL	Knolls Atomic Power Laboratory
kg	Kilograms
KN	Knolls Atomic Power Laboratory – Nuclear Fuels Service site identifier
LA	Los Alamos National Laboratory site identifier
LANL	Los Alamos National Laboratory
LANL-CO	Los Alamos National Laboratory – Carlsbad Operations
LB	Lawrence Berkeley National Laboratory site identifier
LBNL	Lawrence Berkeley National Laboratory
LECO	Trade name for manufacture of crucibles, furnaces and analytical instrumentation
LL	Lawrence Livermore National Laboratory site identifier
LLNL	Lawrence Livermore National Laboratory
LRRI	Lovelace Respiratory Research Institute
LWA	Land Withdrawal Act
m^3	cubic meters
MC	U.S. Army Material Command site identifier
MgO	Magnesium Oxide
mrem	Millirem
MSE	Molten Salt Extraction
MU	University of Missouri Research Reactor site identifier
MURR	University of Missouri Research Reactor
NT	Nevada Test Site site identifier
NTS	Nevada Test Site
NWMP	Nuclear Waste Management Program
OP	Overpack
OR	Oak Ridge National Laboratory site identifier
ORIGEN2	Oak Ridge Isotope Generation and Depletion Code
ORNL	Oak Ridge National Laboratory
OSR	Offsite Source Recovery
ORP	Office of River Protection
PA	Performance Assessment
PA	Paducah Gaseous Diffusion Plant site identifier (in waste profiles only)
PCB	Polychlorinated Biphenyls
PE	Polyethylene
PGDP	Paducah Gaseous Diffusion Plant
POC	Pipe Overpack Component
Pu	Plutonium
PX	Pantex Plant site identifier
QA	Quality Assurance
RCRA	Resource Conservation and Recovery Act
RF	Rocky Flats Environmental Technology site identifier
RFETS	Rocky Flats Environmental Technology Site
RH	Remote-handled
RL	Hanford (Richland Operations Office) site identifier
RP	Hanford (Office of River Protection) site identifier
SA	Sandia National Laboratories site identifier

SBW	Sodium-bearing waste
SNL	Sandia National Laboratories
SP	Separations Process Research Unit site identifier
SPRU	Separations Process Research Unit
SQAP	Software Quality Assurance Plan
SR	Savannah River Site site identifier
SRS	Savannah River Site
STTP	Source Term Test Program
SWB	Standard Waste Box
TDOP	Ten Drum Overpack
TOC	Total Organic Carbon
TRU	Transuranic
TRUPACT II	Transuranic Package Transporter – II
TWBID	Transuranic Waste Baseline Inventory Database, Rev. 2.1
TWBIR	Transuranic Waste Baseline Inventory Report
TWIUR	Transuranic Waste Inventory Update Report
USAMC	U.S. Army Material Command
WAC	Waste Acceptance Criteria
WHO	Waste Handling Operations
WIPP	Waste Isolation Pilot Plant
WIR	Waste Incidental to Reprocessing
WM	Waste Material
WMC	Waste Matrix Code
WMP	Waste Material Parameter
WP	WIPP repository site identifier
WTWBIR	WIPP Transuranic Waste Baseline Inventory Report
WV	West Valley Demonstration Project site identifier
WWIS	WIPP Waste Information System
Zn	Zinc
Zn-Mg	Zinc-Magnesium (metal alloy)

ABBREVIATED NAMES

TWBIR Revision 3	Transuranic Waste Baseline Inventory Report, Revision 3 (DOE 1996a)
TWBIR Revision 2	Transuranic Waste Baseline Inventory Report, Revision 2 (DOE 1995b)
TWBID Revision 2.1	Transuranic Waste Baseline Inventory Database (LANL 2003a)
2003 Update Report	Transuranic Waste Inventory Update Report – 2003 (this document)
Computational Methodology	Transuranic Waste Inventory Update Report – 2003 Computational methodology (LANL 2003b)

PREFACE

The information in this report summarizes the U.S. Department of Energy's (DOE's) transuranic (TRU) waste inventory, projections, and characteristics, and reports emplaced waste. Revision 0 of the Waste Isolation Pilot Plant (WIPP) Transuranic Waste Baseline Inventory Report (WTWBIR) published in June 1994 (DOE 1994), was the first attempt ever made by the DOE complex to report all of its TRU waste at the waste stream level. The waste data reported in Revision 0 were considered preliminary until the DOE TRU waste generator/storage sites completed quality checks of the data. Data changes resulting from the site reviews were contained in Revision 1 of the WTWBIR (DOE 1995a). Subsequently, two additional baseline reports, Transuranic Waste Baseline Inventory Report (TWBIR) Revisions 2 and 3 (DOE 1995b and DOE 1996a), were published in 1995 and 1996 to include WIPP and non-WIPP wastes and other additional characteristic information.

This document, the Transuranic Waste Inventory Update Report, 2003, is the first update report to these baselines primarily focused on support of performance assessment (PA) in support of the Compliance Recertification Application (CRA-2004) and U.S. Environmental Protection Agency (EPA) concerns related to repository operation. The primary differences between previous data submittals and this update are:

- This report accounts for the Idaho National Engineering and Environmental Laboratory (INEEL) Advanced Mixed Waste Treatment Facility process by which 55-gallon drums are compacted and put into 100-gallon drums and disregards those calculations related to future waste incineration described in the TWBIR Revision 3 (DOE 1996a) that never went into operation.

- This report includes 7,095 m^3 (250,595 ft^3) of stored Hanford tank waste that was added to the inventory in December 2002.

- This report also addresses the waste that has been emplaced since the WIPP opened in 1999.

Finally, this report includes updates to all site Waste Stream Profiles that were reported in TWBIR Revision 2 (DOE 1995b). The TRU waste sites provided updated Waste Stream Profiles which contain parameters that are important to the PA. The updated Waste Stream Profiles for non-WIPP, WIPP, and emplaced waste streams are given in Annexes I, J, and K, respectively. The information contained in these profiles is considered the best estimate as of the inventory date, September 30, 2002, because more TRU waste characterization data are now available. However, a caveat to the profile information is warranted because the profiles contain the TRU waste site's best estimates of their TRU waste inventory. Due to the nature of the information, some inconsistencies remain in the profiles. A thorough review of the profiles was conducted during the CRA-2004 review, resulting in identification of specific inconsistencies in the waste stream information. All inconsistencies that were identified by the CRA-2004 reviewers are anticipated to have no significant impact on the PA calculations. The TRU Waste Baseline Inventory Waste Profile forms only reflect the data as reported by the TRU Waste Sites. During the process of generating the TRU Waste Baseline Inventory Report for the CRA, priority was given to developing data on those parameters considered important to performance

assessment (PA). Work is now in progress to correct noted inconsistencies in the forms. SNL will evaluate whether any of the individual or cumulative corrections of the reported inconsistencies have an impact on PA.

DATA-F-1.0 INTRODUCTION

DATA-F-1.1 Background

The U.S. Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) opened on March 26, 1999, becoming the nation's first deep geologic repository for the permanent disposal of defense-generated TRU waste. This waste is currently retrievably stored at 27 sites across the country (see Figure DATA-F-1). From the WIPP's opening through the inventory date (September 30, 2002), 1255 shipments of TRU waste were safely characterized, transported, and disposed in the WIPP.

TRU waste is defined as "…waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years…" (U.S. Congress 1996). TRU wastes are classified as either contact-handled- (CH-) waste or remote-handled- (RH-) waste, depending on the dose rate at the surface of the waste container. CH-TRU wastes are packaged TRU wastes with an external surface dose rate less than 200 millirem (mrem) per hour, while RH-TRU wastes are packaged TRU wastes with an external surface dose rate of 200 mrem or greater per hour (Pub. L. No. 102-579, 110 Stat. 2422 (1992), as amended by 104-201 (1996)). Unless otherwise indicated, for the purpose of this attachment, all references to TRU waste include TRU waste and mixed TRU waste (waste that contains both radioactive and hazardous components, as defined by the Atomic Energy Act [U.S. Congress 1954] and the Resource Conservation and Recovery Act [RCRA] as codified in Title 40 Code of Federal Regulations [CFR] Part 261.3 [EPA 1980]).

The DOE is committed to demonstrating compliance with all applicable regulations for the permanent disposal of TRU defense wastes in the WIPP repository. These regulations are the environmental standards for management and disposal of TRU defense wastes as mandated in 40 CFR Part 191 (EPA 1993) and Part 194 (EPA 1996), and the RCRA regulations. Compliance demonstration through PA calculations for CRA-2004 will be based on the inventory of existing and currently projected waste streams compiled in this document.

The purpose of the WIPP TRU Waste Baseline Inventory Report (WTWBIR) Revision 0 (DOE 1994) and Revision 1 (DOE 1995a) was to provide data to be included in the PA processes for the WIPP. The Transuranic Waste Baseline Inventory Report, Revision 2 (hereafter referred to as TWBIR Revision 2) (DOE 1995b) expanded the original purpose of Revisions 0 and 1 to include support for the WIPP Land Withdrawal Act (LWA) (Pub. L. No. 102-579, 110 Stat. 2422 (1992), as amended by 104-201 (1996)) by providing the total DOE TRU waste inventory. The TWBIR Revision 2 included a chapter and an appendix that discussed the total DOE TRU waste inventory, including nondefense, commercial, polychlorinated biphenyl (PCB)-contaminated, and buried (predominately pre-1970) TRU wastes that were not planned at the time for disposal in WIPP.

The Transuranic Waste Baseline Inventory Report, Revision 3 (hereafter referred to as TWBIR Revision 3) (DOE 1996a) was based on the TWBIR Revision 2 data, which were supplemented by data in several memoranda issued during early calendar year (CY) 1996. These memoranda summarize additional data requested by the DOE to support PA modeling.

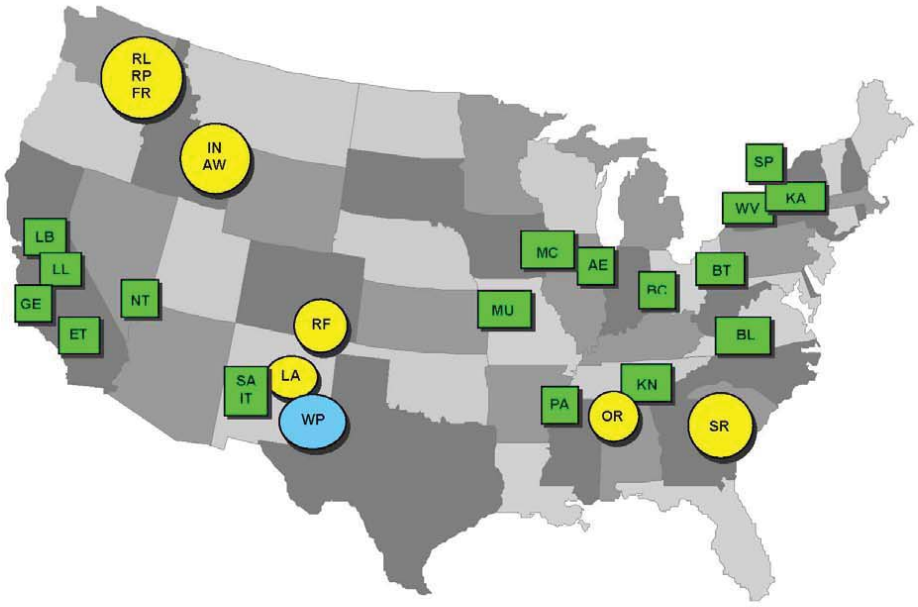

AE	Argonne National Laboratory-East
AW	Argonne National Laboratory-West
BC	Battelle Columbus Laboratories
BT	Bettis Atomic Power Laboratory
BL	Babcock & Wilcox-Lynchburg
ET	Energy Technology Engineering Center
FR	Framatome
GE	General Electric Vallecitos Nuclear Center
IN	Idaho National Engineering and Environmental Laboratory
IT	Inhalation Toxicology Research Institute (known as Lovelace Respiratory Research Institute)
KA	Knolls Atomic Power Laboratory
KN	Knolls Atomic Power Laboratory-Nuclear Fuels Services
LA	Los Alamos National Laboratory
LB	Lawrence Berkeley Laboratory
LL	Lawrence Livermore National Laboratory
MC	U.S. Army Material Command
MU	University of Missouri Research Reactor
NT	Nevada Test Site
OR	Oak Ridge National Laboratory
PA	Paducah Gaseous Diffusion Plant
RF	Rocky Flats Environmental Technology Site
RL	Hanford Site (Richland Operations Office)
RP	Hanford Site (Office of River Protection)
SA	Sandia National Laboratories
SP	Separations Process Research Unit
SR	Savannah River Site
WV	West Valley Demonstration Project
WP	Waste Isolation Pilot Plant

Figure DATA-F-1. U.S. Department of Energy TRU Waste Sites.

The primary purpose of TWBIR Revision 3 was to provide the summary data from TWBIR Revision 2) and the supplemental information used in the PA for the development of the Compliance Certification Application (CCA) (DOE 1996b) that was delivered to the Environmental Protection Agency (EPA), and to support the LWA. The supplemental information was generated from specific data requests to the TRU waste sites since the publication of the TWBIR Revision 2. These supplemental data included: radionuclides, data estimates for complexing agents, oxyanions, and cement content in solidified waste.

DATA-F-1.2 Purpose and Objectives

The purpose of this Transuranic Waste Inventory Update Report – 2003 (hereafter referred to as the 2003 Update Report) is to document the total inventory of DOE TRU waste as defined by the DOE TRU waste sites. The primary purpose of this document is to provide the summary data and the supplemental information required for the PA in support of the CRA-2004 which is to be delivered to the EPA for the five-year recertification as required by the LWA (Pub. L. No. 102-579, 110 Stat. 2422 (1992), as amended by 104-201 (1996)). Knowing that the WIPP waste inventory numbers have changed as a result of characterization activities and improved estimation processes, the EPA has requested that an update to the CCA inventory be included in the CRA-2004. In a letter from the EPA dated August 6, 2002 (EPA 2002), one of the items requested was "Waste inventory (actual inventory to date plus revisions to the estimated inventory as expressed in the Baseline Inventory Report)." This inventory update provides these changes.

The TWBIR Revision 2 (DOE 1995b) contained the waste profiles for all waste streams reported by the generator sites at that time, including some TRU waste streams that are unacceptable for disposal at WIPP. The waste stream profiles resided in two appendices in TWBIR Revision 2: Appendix O reported the "Non-WIPP" waste streams and Appendix P reported the "WIPP" waste streams. For the 2003 Update Report, Annex I reports the Non-WIPP waste streams and Annex J reports the WIPP waste streams, and Annex K reports the "emplaced waste." Although all TRU waste streams currently reported by the sites are accounted for in the current database and are reported in the 2003 Update Report, the non-WIPP waste streams do not contribute to the volume and scaling calculations. Hence, the non-WIPP waste streams will not contribute to inventory for the CRA-2004 PA calculations.

The objectives of the 2003 Update Report are to:

1. Define the DOE TRU waste inventory;

2. Provide the required information and data for use in the calculations for the CRA-2004; and

3. Maintain a consistent DOE complex-wide methodology for tracking TRU waste. A consistent methodology in support of the CRA-2004 provides a common frame of reference for discussion of TRU waste issues with regulatory organizations.

DATA-F-1.3 Sources of Transuranic Waste Information

The TRU waste inventory is taken from existing information about the waste, which has been provided by the TRU waste sites. In addition, information obtained from site Acceptable Knowledge Summary Reports has been incorporated to provide the most up to date data on waste streams that are currently being shipped to WIPP. Particular focus on data collection involved discussion with TRU waste sites about changes to the inventory since the certification of WIPP. Sites visits and onsite interviews facilitated data collection and ensured data were accurately represented. At the conclusion of data collection, each site was asked to provide information concerning what had changed since the baseline data collection and why the changes took place.

The information found in the TWBIR Revision 2 (DOE 1995b) has not been updated since the publication of that document. The TWBIR Revision 3 (DOE 1996a) used the same data plus other supplemental data that were needed for PA calculations. In addition, the WIPP has been open and receiving waste since March 1999. Therefore, data from the emplaced waste through September 30, 2002, are included in this report as obtained from the WIPP Waste Information System (WWIS).

The changes to the inventory since 1996 were requested from and provided by the TRU waste sites. Each site has verified the data that were entered into the database and has been asked to explain what the changes are in their current inventory when compared to TWBIR Revision 2 and 3 and why the inventory changed.

DATA-F-1.4 Document Organization

The 2003 Update Report (Appendix DATA, Attachment F) is organized into sections of text, figures, tables, and supporting annexes that are consistent with the TWBIR Revision 3 (DOE 1996a). The contents of remaining sections in this document are summarized below:

- Section DATA-F-2.0 presents the approach and methods used for gathering and compiling the WIPP waste disposal inventory information including the quality assurance program applied to the inventory project activities. A description of the TWBID Revision 2.1 database, analysis methods, and records used to document data and analysis results are also included in this chapter.

- Section DATA-F-3.0 presents summaries of inventory information including the waste volumes, waste material parameters (WMPs), packaging materials, chemical components, radiological components, discussion regarding the non-WIPP and future potential TRU waste, and discussion regarding the materials used to emplace the waste in the WIPP.

- Section DATA-F-4.0 provides the references used in the preparation of this document.

DATA-F-2.0 METHODS AND APPROACH

This 2003 Update Report provides the information needed for the PA calculations to be generated as part of the completion of the WIPP CRA-2004. The work was performed by Los Alamos National Laboratory—Carlsbad Operations (LANL-CO) and Sandia National

Laboratories (SNL). The role of SNL was to perform the PA calculations and provide documented results for the CRA-2004. The role of LANL-CO was to provide the updated inventory in support of the CRA-2004 PA. The technical work performed and documentation produced was under the controls provided by the SNL Quality Assurance (QA) Program developed for the SNL Nuclear Waste Management Program (NWMP). Inventory personnel:

1. collected TRU waste stream information from the TRU waste sites via site visits and additional communication, as needed;

2. compiled the data into a qualified electronic database;

3. performed analyses of the data in support of the CRA-2004 PA; and

4. published the results as official NWMP records acceptable for use in WIPP PA calculations.

The process is illustrated in Figure DATA-F-2 along with the controlling aspects of the SNL QA program. Figure DATA-F-2 also illustrates the governing SNL QA program procedures implemented in each step of the process.

The sections below describe the four basic process steps leading to the issuance of this report. Section DATA-F-2.1 discusses data collection, compilation and verification. Section DATA-F-2.2 discusses the development of the qualified electronic database, the Transuranic Waste Baseline Inventory Database Revision 2.1 [hereafter referred to as TWBID Revision 2.1] (LANL 2003a), that contains the TRU waste inventory data as of September 30, 2002. Section DATA-F-2.3 discusses the analyses performed in support of the CRA-2004 PA, and Section DATA-F-2.4 discusses the process of documentation in the SNL WIPP Records Center.

DATA-F-2.1 Data Collection, Compilation and Verification

The sections that follow describe the process of data collection, entry, and verification used to ensure data quality was maintained throughout the TRU waste inventory process. The data requirements found in Section DATA-F-2.1.1 were specifically called out by SNL to address the PA data needs. The data were then collected from the TRU waste sites, entered into the TWBID Revision 2.1 (LANL 2003a), and independently reviewed and verified by data entry personnel and the sites themselves. The process by which data were gathered, entered, reviewed, and verified is described in Sections DATA-F-2.2.2 through DATA-F-2.2.4.

All of the activities described in this section were governed by SNL procedure SP 9-6 Baseline Inventory Report (BIR) Change Report Data Collection and Entry (SNL 2003b). A collection of the documents compiled for each site is provided in Table DATA-F-1 including their respective Electronic Records Management System number (ERMS #).

DATA-F-2.1.1 Data Requirements

The data requirements for the 2003 Update Report were called out in a series of communications shown in Annexes G and H.

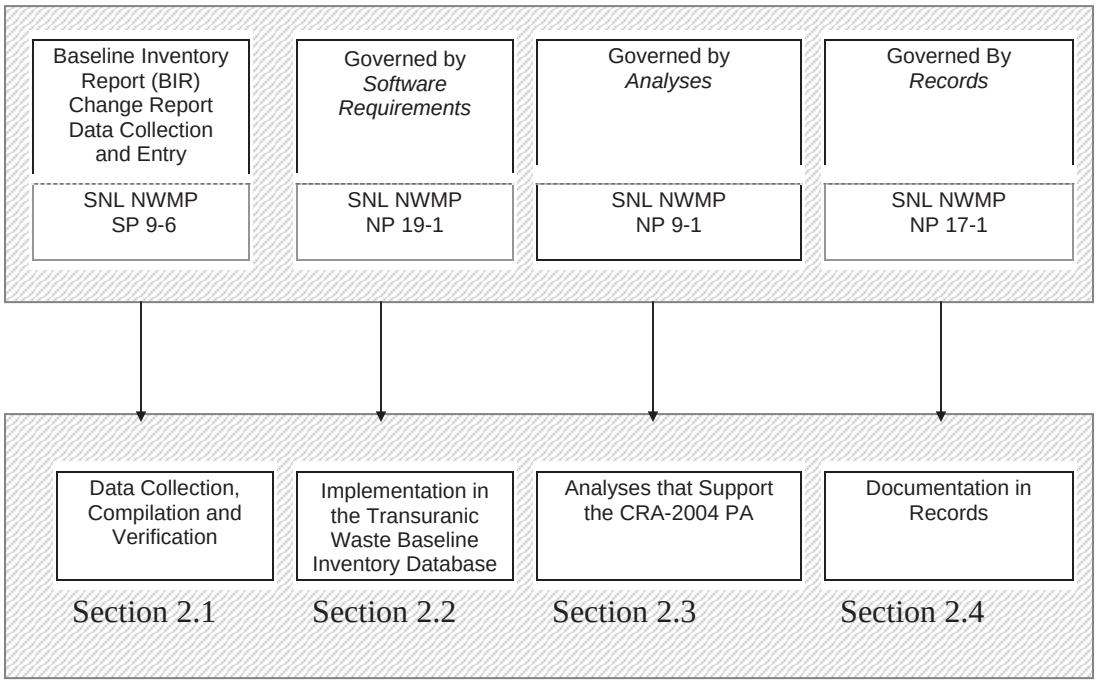

Figure DATA-F-2. Quality Methods for Generating the Transuranic Waste Inventory Update Report – 2003

Specifically, the data requirements for PA were given in Giambalvo (2002) and include the following:

- Waste stream volumes;
- Inventory of radionuclides on a waste stream basis for both CH- and RH-TRU waste and that the radionuclides reported be decayed to a common base year;
- Inventory of all non-radioactive waste material parameters that were previously tracked in the TWBIR Revision 3 (DOE 1996a). In addition, identify whether waste streams contain pyrochemical salts;
- Inventory of any other non-radioactive waste materials that are discovered to account for a significant portion of a waste stream as a result of changes to the inventory;
- Inventory of cellulosic, plastic, and rubber (CPR) materials, and other biodegradable materials used to facilitate emplacement of waste and MgO in the WIPP;
- Inventory of organic complexing agents and oxyanions (sulfate, nitrate, and phosphate; and
- Waste stream level inventories of radionuclides and non-radioactive waste material parameters for waste currently emplaced in the WIPP.

In addition to the seven data requirements listed above, the following was requested:

- A breakdown of the volume of the waste in the inventory into categories of stored, projected, and anticipated.

DATA-F-2.1.2 Collection Method

The EPA is mainly concerned with what has changed in the TRU waste inventory since the CCA (DOE 1996b) that resulted in the certification of the WIPP. To appropriately capture these changes, each TRU waste site was sent a copy of their data (in the form of waste profiles from the TWBIR Revision 2 (DOE 1995b) that they had submitted in 1995 for the CCA (DOE 1996b). With this transmittal to the site, guidance was provided delineating what the sites needed to address. The sites were requested to mark the changes on these profiles. The data were provided, followed by discussions focused on clarifying questions to ensure the data were correct. The data were entered into the electronic database, the TWBID Revision 2.1 (LANL 2003a), and qualified under SNL NP 19-1, Software Requirements (SNL 2002a). Upon completion of data entry, each site was provided with a signature sheet requesting that the DOE site representative responsible for TRU waste verify the data.

The methodology used to collect data and enter data into the TWBID Revision 2.1 (LANL 2003a) from DOE TRU waste sites is captured in procedure SP-9-6, Baseline Inventory Report (BIR) Change Report Data Collection and Entry (SNL 2003b). The process described in this procedure was initiated by a data call based on a request for modification of waste profile information that was included in the TWBIR Revision 2 (DOE 1995b). This data call was followed by a second data call specifically requesting data required by SNL (Giambalvo 2002). During the time these data calls were issued, LANL-CO visited sites to facilitate data collection and worked with the sites to assist with questions and issues as they came up.

DATA-F-2.1.3 Implementation in the Transuranic Waste Baseline Inventory Database, Revision 2.1

Preliminary data collected from the sites included database disks, notes from discussions with waste management personnel, email correspondence, site literature, and data spreadsheets. After data were gathered, they were submitted to the SNL WIPP Records Center.

These data were used to update the TWBID Revision 2.1 (LANL 2003a) by deletion of waste streams that were no longer maintained, modification of waste streams, and addition of new waste streams. Waste stream profile information was modified for sites that either had additional information or had modified TWBIR Revision 2 (DOE 1995b) waste streams. When data discrepancies were found or sites requested changes to data after preliminary data were entered into the database, change information was collected on forms found in procedure SP-9-6, Baseline Inventory Report (BIR) Change Report Data Collection and Entry (SNL 2003b). The database was changed to reflect this new information, accordingly.

DATA-F-2.1.4 Validation and Verification of Data

Upon completion of data entry, an independent review of all changes that were made to the database was conducted. This review was documented in the database. When all changes were completed, the database record was sent back to the sites for final verification and authentication

by the site DOE representative. The verified results were entered into the SNL WIPP Records Center, as were the signed forms from each of the DOE TRU waste sites.

Additional records were collected from the DOE TRU waste sites after the inventory was verified and authenticated by DOE site representatives. Records were received from each site explaining changes that had occurred with their inventory since the baseline data collection was performed in 1995. These records were also entered into the SNL WIPP Records Center.

DATA-F-2.2 Transuranic Waste Baseline Inventory Database

Data tables included in this report were generated by a Microsoft Access 2000 database application known as the TWBID Revision 2.1 (LANL 2003a). TWBID Revision 2.1 was used to manage, maintain, and perform calculations on inventory data.

The sections that follow describe the database and its development. Section DATA-F-2.2.1 describes the origins of the database. Section DATA-F-2.2.2 describes the database in general terms. Section DATA-F-2.2.3 describes configuration control.

All of the activities described in this section were governed by the SNL QA procedure, NP 19-1 Software Requirements (SNL 2002a).

DATA-F-2.2.1 Origins of the Transuranic Waste Baseline Inventory Database

The database used to generate TWBIR Revision 3 (DOE 1996a) (TWBIR.mdb, dated 1/29/1996) was used as a baseline for TWBID Revision 2.1 (LANL 2003a). The database was originally provided in Microsoft® Access 2.0 format, and was subsequently converted to Microsoft® Access 2000 format. Structural changes were then made to the new version to accommodate new requirements. These changes were captured in Microsoft® Visual Source Safe (see Section DATA-F-2.2.3, below).

Development of the TWBID Revision 2.1 (LANL 2003a) was governed by the SNL QA procedure, NP 19-1 Software Requirements (SNL 2002a). NP 19-1 outlines a process whereby a software QA plan (the SQAP) is written for the software product. Following the SQAP, the requirements for the product are defined and documented, the design of the product is created and documented, the product is implemented and its implementation is documented, a plan for testing the product is written, the product is tested and its verification and validation is documented, and the installation of the product is documented. The product and its documentation are reviewed at each step in this process by a technical, QA, and management reviewer.

Each of these steps was completed for the TWBID Revision 2.1 (LANL 2003a). Table DATA-F-3 provides references and ERMS identifiers for the QA documents for the TWBID Revision 2.1 (LANL 2003a).

DATA-F-2.2.2 Database Description

The TWBID Revision 2.1 (LANL 2003a) consists of two main interface database files that link to a third, common data file. The first interface file, TWBID.mdb, contains the interface forms

that data entry personnel use to browse, add, modify, or delete waste streams and related information. Users must log in to this interface in order to gain access to modify the data. A central file, TWBID.mdw, which contains username, password, and permission information, manages authentication. The second interface file, REPORTS.mdb, contains the database objects (tables, queries, reports, macros, and modules) required to generate the tables and reports used within the 2003 Update Report. The third file, TWBID_Data.mdb, contains the raw data used by both the TWBID.mdb and REPORTS.mdb databases. This data file is "linked" to the other two by using the table-linking feature intrinsic to Microsoft® Access 2000. By utilizing linked tables, a multiple-user, client-server environment was established for the TWBID Revision 2.1.

The Microsoft® Access Database files are hosted on a Windows NT 4.0 Server, and are protected by a Windows NT File System permission structure, allowing only approved database users to have access to the files. In addition, there are database-level access controls established using the Workgroup security function inherent in Microsoft® Access.

The tables in the database have no predefined relationships using primary and foreign key values to automatically associate data existing in separate tables. All functionality that relates and manipulates data across tables is established through table joins specified within the database queries themselves.

DATA-F-2.2.3 Configuration Management

The TWBID Revision 2.1 (LANL 2003a) software was placed under configuration control on November 17, 2002 as version 3.01. TWBID Revision 2.1 has undergone several iterative revisions and has been under strict configuration control since that date. The current version of the TWBID Revision 2.1 software is 3.12 (at the point of the publication of this document).

In addition, the data used by the TWBID is also under strict configuration control. Versions of the data were captured at designated points throughout the data entry process. At the point of publication of this document, the current data version was D.4.09.

The tool used to maintain configuration control of the TWBID Revision 2.1 is Microsoft® Visual SourceSafe Version 6.0. The Visual SourceSafe database maintains an archive of all revisions to the TWBID Revision 2.1 software, and allows for easy retrieval of any revision throughout the development and data entry processes. All changes to the TWBID Revision 2.1 database software (not the source code) were approved per procedure NP 19-1, Software Requirements (SNL 2002a). A hardcopy printout of the data from the database was generated for each version update and entered in the SNL WIPP Records Center.

DATA-F-2.3 Analysis Methods

In addition to collecting and processing data from the TRU waste sites and securing the site data in a qualified database for future use, analyses were performed on the data to support the CRA-2004 PA. For example, in preparation of this report, volume data from waste streams was rolled up into stored, projected, and anticipated categories; WMPs were rolled up to provide average

waste material densities in the repository; radionuclides were decay-corrected to the end of calendar year 2001; and radionuclide activities were scaled for the full repository.

All of the analyses performed in support of the CRA-2004 PA were governed by SNL procedure NP 9-1 Analyses (SNL 2001). NP 9-1 requires that an analysis plan governing the work is written. The analysis plan governing the analysis in support of the CRA-2004 PA is AP-092, Analysis Plan for Transuranic Waste Inventory Update Report, 2003 (SNL 2002b). AP-092 specifies that the first step in the analyses in support of the CRA-2004 PA is documentation of the computational methods that will be used to perform the required analyses. Those methods were documented in Transuranic Waste Inventory Update Report, 2003 Computational Methodology [hereafter referred to as the Computational Methodology] (LANL 2003b).

The sections that follow describe the radionuclide decay calculations (Section DATA-F-2.3.1), the roll-up and scaling calculations (Section DATA-F-2.3.2), and calculations of chemical components in the repository (Section DATA-F-2.3.3).

DATA-F-2.3.1 Radionuclide Decay Calculations

One of the data requirements for the radionuclide inventory (see Section DATA-F-2.1.1) for the PA is that all radionuclides reported by waste stream in TWBID Revision 2.1 (LANL 2003a) will be decayed to a common base year. However, the site-provided data consisted of radionuclide activity concentrations at the date of assay for the waste stream (if the waste stream was assayed) or at the date that the site calculated the activity concentrations. Therefore, the radionuclide activity concentration data reported by the sites was exported from the TWBID Revision 2.1 into an external application that performed the radionuclide decay calculations and then imported back into the TWBID Revision 2.1 for storage.

The process of exporting the data from TWBID Revision 2.1 so that it can be decayed and importing the decayed data back into TWBID Revision 2.2 was governed by SNL procedure NP 9-1 Analyses: Appendix C, Routine Calculations (SNL 2001). Documentation of that calculation is provided in Unit Conversion and Data Transfer Between the TWBID Revision 2.1 Version 3.12 and ORIGEN2, Version 2.2 for the Transuranic Waste Inventory Update Report, 2003 (LANL 2003c).

The external application used for the radionuclide decay calculations was ORIGEN 2.2. The software code, ORIGEN 2.2 (Croff 1983; Croff 1980) is an isotope generation and depletion code that uses the matrix exponential solution method. The software was developed and is distributed by the Radiation Safety Information Computational Center at the Oak Ridge National Laboratory (ORNL).

The software was acquired to calculate the inventory of radionuclides decayed to the common base year, December 31, 2001. Qualification of ORIGEN 2.2 in support of these analyses was performed under SNL procedure, NP 19-1 Software Requirements (SNL 2002a). The steps involved in qualification of software under NP 19-1 were described in Section DATA-F-2.2.1. Each of the steps was completed for ORIGEN 2.2. Table DATA-F-4 gives the reader references and ERMS identifiers for the QA documents for ORIGEN 2.2. While the ORIGEN 2.2 software

has many capabilities, the qualification of ORIGEN 2.2 (Croff 1983; Croff 1980) under the SNL QA program is limited to radionuclide buildup and decay calculations.

DATA-F-2.3.2 Roll-up and Scaling Calculations

The roll-up and scaling calculations performed in support of this report were performed within the TWBID Revision 2.1 (LANL 2003a). As discussed in Section DATA-F-2.2.2, TWBID Revision 2.1 was qualified as software under SNL procedure NP 19-1, Software Requirements. That qualification included the qualification of the queries and reports designed to produce the roll-up and scaled information specified in Giambalvo (2002).

The computational methods that apply to the roll-up and scaling calculations were defined in the Computational Methodology (LANL 2003b). This document was used as the basis for drafting the design documentation required for software qualification of TWBID Revision 2.1. The queries that have been qualified for use in TWBID Revision 2.1 produce the data that are tabulated throughout this report and documented in records submitted to the SNL WIPP Records Center.

DATA-F-2.3.3 Chemical Component Calculations

A final requirement set forth in Giambalvo (2002) is that this report supply information about the chemical components of the waste like that supplied in support of the CCA PA in the TWBIR Revision 3 (DOE 1996a). This includes a calculation of the mass of organic ligands (complexing agents), the mass of oxyanions (nitrate, sulfate, and phosphate), and the mass of cement expected in the disposal volume for WIPP.

The calculation of the mass of organic ligands, oxyanions, and cement in the disposal volume for WIPP was governed by SNL procedure NP 9-1, Analyses. Each of these masses was calculated by hand following the processes outlined in NP 9-1 and each is documented in reports that were reviewed by three reviewers (technical, management, and QA), and then submitted to the SNL WIPP Records Center. The reports are discussed briefly in Sections DATA-F-3.2.3.1, DATA-F-3.2.3.2, and DATA-F-3.2.3.3. Appendix DATA, Attachment F, Annex A contains the results of an analysis of the inventory for pyrochemical salts.

Table DATA-F-5 gives the reader ERMS identifiers for the reports on organic ligands, oxyanions, and cement.

DATA-F-2.4 Records

The entire process of data collection, database development, and analysis leading up to the publication of this report has been documented in the SNL WIPP Records Center. The following sections give the reader a roadmap for the official records that support this body of work. All records have been submitted to the SNL WIPP Records Center in accordance with SNL procedure NP 17-1, Records (SNL 2003a).

DATA-F-2.4.1 Records Related to Data

The most extensive set of records pertaining to this body of work are the records related to the data collected from the sites. These data were collected as described in Section DATA-F-2.1, with the initial data call being issued to the sites by CBFO (Gist 2002). This initial data call is stored in the SNL WIPP Records Center under identifiers listed in Table DATA-F-1. The site responses were collected and reviewed to ensure the data were authenticated by signature and date prior to submittal to the SNL WIPP Records Center with the ERMS numbers shown in Table DATA-F--1.

A technical review of these records and a subsequent accuracy check to make sure that the data had been entered correctly into the TWBID Revision 2.1 (LANL 2003a) were then performed. Any modifications made at the time of this review were documented in the site data records listed in Table DATA-F-1.

Upon completion of the technical review that determined that site data had been entered correctly in the TWBID Revision 2.1, a final series of checks was performed to ascertain the completeness and consistency of the data. The methods applied for the completeness and consistency checks were based on a number of database queries documented in the corrections packages listed in Table DATA-F-2. The corrections for completeness and consistency were made incrementally in a series of three steps. Before each step, the proposed changes were reviewed. Then they were implemented. Verification of the changes was printed and submitted as authenticated records to the SNL WIPP Records Center as shown in Table DATA-F-1.

Finally when the accuracy and completeness checks on the database were complete, an electronic file of the data from the TWBID Revision 2.1 was sent to the sites for final verification and authentication. Their concurrence with the data in the TWBID Revision 2.1 was also submitted to records.

DATA-F-2.4.2 Records Related to Software Qualification

The records related to the qualification of the TWBID Revision 2.1 (LANL 2003a) are listed in Table DATA-F-3. The records related to qualification of ORIGEN 2.2 are listed in Table DATA-F-4.

DATA-F-2.4.3 Records Related to Analyses

The records related to analyses have been discussed individually in Section 2.3 of this attachment and are listed for the reader’s convenience in Table DATA-F-5.

DATA-F-3.0 TRANSURANIC WASTE INVENTORY

This section presents the TRU waste inventory that was collected on behalf of the DOE in support of CRA-2004. The data are stored in an electronic database, the TWBID Revision 2.1 Version 3.12 (LANL 2003a), which has been qualified for use in PA calculations as discussed in Section 2 of this attachment.

Table DATA-F-1. Records Related to Data Collection and Processing for the Transuranic Waste Inventory Update Report 2003

Document	ERMS#
Initial Memorandum for Data Call-Gist 2002	525955, 525962, 526065, 526077, 526094, 526113, 526167, 526410, 526598, 526526, 526540, 526558, 526568, 526592, 526609, 526679, 526698, 526739, 526768, 526782, 526428, 526447, 525956, 526054
Data Package For Ames	525948
Data Package For ARCO	526059
Data Package For Mound	525953 and 525958
Data Package For Pantex	525937
Data Package For Teledyne Brown	525934
Data Package For MURR	526555
Data Package For AW	526407 and 528082
Data Package For BC	526424
Data Package For BT	526164 and 528084
Data Package For BL	526051
Data Package For ET	526444 and 528054
Data Package For FR	525983
Data Package For IN	526765 (CH), 526179 (RH) and 528085
Data Package For KA	526087
Data Package For KN	525960 and 526104
Data Package For LA	526504 and 528065
Data Package For LB	526523
Data Package For LL	526536
Data Package For MC	525940
Data Package For NT (Jasper)	526576
Data Package For NT	526565
Data Package For OR	526589 and 528046
Data Package For PA	526074
Data Package For RF	526779 and 528074
Data Package For RL	526736
Data Package For RP	526473
Data Package For SA/IT	526606 and 526799
Data Package For SP	526063
Data Package For SR	526680
Data Package For GE	526463
Data Package For WV	526695
Data Package For WP	528118

Table DATA-F-2. Records Related to Computational Methods

Document Type	ERMS #
Transuranic Waste Inventory Update Report, 2003 Computational Methodology Revision 2	527821
Data Corrections in the TWBID Revision 2.1 Database – Data Screening Package	528538
Data Corrections in the TWBID Revision 2.1 Databases – Volume Package	528542
Data Corrections in the TWBID Revision 2.1 Databases – Waste Material Parameter Package	529603 and 529596
Data Corrections in the TWBID Revision 2.1 Databases – Radionuclide Package	528543

Table DATA-F-3. QA Documents for the TWBID Revision 2.1 (Records Package 526290)

Document Type	ERMS #
Software QA Plan	526292
Requirements Document	526293
Design Document	530621
Implementation Document	530621
Verification and Validation Plan	530623
Validation Document	530623
User's Manual	530622

Table DATA-F-4. QA Documents for ORIGEN2 Version 2.2 (Records Package 525783)

Document Type	ERMS #
Access Control Memorandum	528200
Requirements Document	525785
Code Classification of ORIGEN2, Version 2.2	525790
Implementation Document	525788
Verification and Validation Plan	525786
Validation Document	525786

Table DATA-F-5. Records Related to Inventory Analyses in Support of the CRA-2004 PA (Records Package 525272)

Document Type	ERMS #
Analysis Plan Governing Work	525797
Documentation of Waste Material Parameter Roll-up	530767
Documentation of Radionuclide Inventory Roll-up	530992
Calculation of Organic Ligand Masses	531319
Calculation of Oxyanion Masses	530984
Calculation of Cement Masses	531562

This presentation of the TRU waste inventory for CRA-2004 consists of summaries of the inventory information collected from the generator sites and the information calculated from the data submitted by the sites in support of the PA calculations for CRA-2004. Section DATA-F-3.1 presents the volume information provided by the sites for CH- and RH-TRU waste and the volume roll-ups to the WIPP repository capacity needed for PA. Section DATA-F-3.2 presents the non-radiological waste inventory as reported by the sites and as needed for PA. This includes roll-ups of the waste materials (Section DATA-F-3.2.1), roll-ups of the packaging materials (Section DATA-F-3.2.2), and information about the chemical components of the waste (Section DATA-F-3.2.3). Section DATA-F-3.3 presents the radionuclide inventory reported by the sites and WIPP-level roll-ups of the radionuclide data needed for PA.

Section DATA-F-3.4 presents a discussion of the non-WIPP and future potential waste, and provides the total volumes of the non-WIPP wastes, with the exception of the pre-1970 buried waste. Waste profiles are provided for these waste streams in Appendix DATA, Attachment F, Annex I. Appendix DATA, Attachment F, Section DATA-F-3.5 provides data for the materials used to facilitate waste emplacement at the WIPP. The material in Appendix DATA, Attachment F, Sections DATA-F-3.4 and DATA-F-3.5 is provided for completeness but is not used to support the WIPP PA.

In addition to the summary information presented in this section, a complete TRU waste inventory for all waste streams at all of the sites has been prepared in support of the CRA. That inventory is presented in Appendix DATA, Attachment F, Annexes I, J, and K. Appendix DATA, Attachment F, Annex I presents individual waste stream profiles for all of the waste streams that have been designated as Non-WIPP waste streams, as discussed in Appendix DATA, Attachment F, Section DATA-F-3.4. Annex J presents individual waste stream profiles for all WIPP waste streams planned for emplacement in the WIPP. Appendix DATA, Attachment F, Annex K presents individual waste stream profiles for all WIPP waste streams that were emplaced in the WIPP as of September 30, 2002.

Annex B presents the comparisons of 2003 volume, WMP, and radionuclide data to TWBIR Revision 3 data. Appendix DATA, Attachment F, Annex C presents the crosswalk of waste streams between TWBIR Revision 2 and the 2003 Update Report, and explanations for these changes. Appendix DATA, Attachment F, Annex D presents the packaging materials.

DATA-F-3.1 Transuranic Waste Volume Inventory

The volume information requested from the sites was broken down as follows:

- stored waste – waste that currently exists at the site, regardless of whether it is in its final form, and
- projected waste – waste that will be generated in the future.

Data for emplaced wastes were obtained from the WWIS. The total waste stream volume collected from the sites included stored (v_s) and projected (v_p) components as applicable for each TRU waste stream. The sites also reported both "As Generated" and "Final Form" waste volumes for their waste streams (see Glossary for definitions). This "Final Form" volume accounts for the entire waste container (the volume the waste container occupies in the repository). Since PA only considers the waste volume that will be disposed in the WIPP, only the "Final Form" volumes were used in the calculation of actual (reported by the site) and scaled (used in PA) waste volumes.

Table DATA-F-6 presents the CH-TRU waste anticipated inventory volumes reported by the sites. Table DATA-F-7 presents the RH-TRU waste anticipated inventory volume reported by the sites. The data presented in Tables DATA-F-6 and DATA-F-7 were derived by summing the waste-stream-level data into a site-level roll-up. For each site, all stored waste stream volumes (v_s) were summed to arrive at the total stored volume for the site, V_s. All projected waste stream volumes (v_p) were summed to arrive at the total projected volume for the site, V_p. The sum of the total stored volume and the total projected volume is the anticipated volume, V_a.

$$V_s + V_p = V_a, \qquad (1)$$

where

V_a is the total anticipated volume at the site
V_s is the total stored volume at the site
V_p is the total projected volume at the site.

DATA-F-3.1.1 Waste Isolation Pilot Plant-Level Roll-Up of Waste Inventory for Performance Assessment

Performance assessments conducted in support of the WIPP have been predicated on the assumption that the WIPP repository will be filled to its design capacity at the time of closure. The design capacity for WIPP is 175,564 m^3 (6,200,000 ft^3) (U.S. Congress 1996) with a limit of 7079 m^3 (250,000 ft^3) for RH-TRU waste as imposed by the Consultation and Cooperation Agreement (DOE and State of New Mexico 1981). The volume of anticipated plus emplaced (CH-TRU and RH-TRU) waste reported by the sites in support of the CRA-2004 is less than and more than, respectively, the design capacity for WIPP. Therefore, scaling the CH- and RH-TRU waste volumes (up and down, respectively) to the design capacity for each in the WIPP is necessary for PA. The scaled inventory for PA is referred to as the disposal volume

Table DATA-F-6. WIPP CH-TRU Waste Anticipated Inventory By Site

TRU Waste Site	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
Argonne National Laboratory - East	1.1×10^2	7.9×10^1	1.9×10^2
Argonne National Laboratory - West	6.0×10^0	3.8×10^1	4.4×10^1
Battelle Columbus Laboratories	5.2×10^0	0.0×10^0	5.2×10^0
Bettis Atomic Power Laboratory	1.9×10^1	0.0×10^0	1.9×10^1
Energy Technology Engineering Center	2.3×10^0	0.0×10^0	2.3×10^0
Hanford (Richland-RL)	1.3×10^4	1.3×10^4	2.5×10^4
Hanford (River Protection-RP)	3.9×10^3	0.0×10^0	3.9×10^3
Idaho National Engineering & Environmental Laboratory	6.1×10^4	1.2×10^2	6.1×10^4
Knolls Atomic Power Laboratory - Nuclear Fuel Services	5.5×10^1	1.7×10^2	2.3×10^2
Lawrence Livermore National Laboratory	3.5×10^2	2.1×10^3	2.4×10^3
Los Alamos National Laboratory	1.2×10^4	3.3×10^3	1.5×10^4
Nevada Test Site	6.2×10^2	4.6×10^2	1.1×10^3
Oak Ridge National Laboratory	0.0×10^0	4.5×10^2	4.5×10^2
Paducah Gaseous Diffusion Plant	5.7×10^0	5.7×10^0	1.1×10^1
Rocky Flats Environmental Technology Site	5.4×10^3	2.7×10^3	8.1×10^3
Sandia National Laboratories - Albuquerque	2.4×10^1	0.0×10^0	2.4×10^1
Savannah River Site (SRS)	1.3×10^4	2.4×10^3	1.5×10^4
U.S. Army Material Command	2.5×10^0	0.0×10^0	2.5×10^0
University of Missouri Research Reactor	1.5×10^0	0.0×10^0	1.5×10^0
Totals	1.1×10^5	2.5×10^4	1.3×10^5
Emplaced Volume			
Waste Isolation Pilot Plant	7.7×10^3	0.0×10^0	7.7×10^3
Grand Totals	1.2×10^5	2.5×10^4	1.4×10^5

as described in the Glossary. The CH-TRU waste was scaled up since the anticipated volume is less than the allowable capacity. The RH-TRU waste was scaled down because the anticipated volume of RH-TRU waste exceeded the allowable limit. Scaling is performed only on projected waste.

Table DATA-F-8 presents the volume scaling factors. The following sections discuss the calculation of the WIPP-level roll-up for CH- and RH-TRU waste.

DATA-F-3.1.1.1 Calculation of Waste Isolation Pilot Plant-Level Roll-Up for Contact-Handled- Transuranic Waste

The WIPP disposal limit for CH-TRU waste is 168,485 m^3 (5,950,000 ft^3). Since the total reported volume of CH-TRU waste is less than the WIPP limit, the projected volume was scaled so the total volume equaled the CH-TRU waste disposal limit for WIPP. The scaling

Table DATA-F-7. WIPP RH-TRU Waste Anticipated Inventory By Site

TRU Waste Site	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
Argonne National Laboratory – East	1.5×10^1	1.0×10^2	1.2×10^2
Argonne National Laboratory - West	2.4×10^1	6.9×10^1	9.3×10^1
Battelle Columbus Laboratories	4.4×10^1	1.8×10^0	4.6×10^1
Bettis Atomic Power Laboratory	2.0×10^0	0.0×10^0	2.0×10^0
Energy Technology Engineering Center	5.0×10^0	0.0×10^0	5.0×10^0
Hanford (Richland-RL)	3.8×10^2	9.4×10^3	9.8×10^3
Hanford (River Protection-RP)	4.5×10^3	0.0×10^0	4.5×10^3
Idaho National Engineering & Environmental Laboratory	2.2×10^2	0.0×10^0	2.2×10^2
Knolls Atomic Power Laboratory - Schenectady	0.0×10^0	1.4×10^2	1.4×10^2
Los Alamos National Laboratory	1.2×10^2	0.0×10^0	1.2×10^2
Oak Ridge National Laboratory	0.0×10^0	6.6×10^2	6.6×10^2
Sandia National Laboratories - Albuquerque	4.6×10^0	0.0×10^0	4.6×10^0
Savannah River Site	0.0×10^0	2.3×10^1	2.3×10^1
Totals	5.3×10^3	1.0×10^4	1.6×10^4

factor for CH-TRU waste was calculated using the following equation applied to WIPP waste streams .

The CH-TRU waste volume scaling factor was calculated as follows:

$$SF_{CH} = (\text{CH-TRU Design Capacity in } m^3 - V_s - V_e)/ V_p, \quad (2)$$

where

SF_{CH} is the scaling factor for the CH-TRU waste volume
V_s is the total stored volume over all waste streams and all sites for CH-TRU waste
V_p is the total projected volume over all waste streams and all sites for CH-TRU waste
V_e is the total emplaced volume for CH-TRU waste over all waste streams and all sites as of September 30, 2002.

The disposal inventory for a single CH-TRU waste stream was obtained by multiplying the CH-TRU waste projected volume by the appropriate scaling factor and adding that value to the stored and emplaced volumes for each waste stream.

$$v_{CH\text{-}Disposal} = SF_{CH}\,(v_p) + v_s + v_e, \quad (3)$$

where

$v_{CH\text{-}Disposal}$ is the disposal volume for CH-TRU waste for a single waste stream
SF_{CH} is the scaling factor for the CH-TRU waste volume
v_p is the projected inventory volume for a single CH-TRU waste stream before scaling
v_s is the stored inventory volume for a single CH-TRU waste stream before scaling
v_e is the emplaced inventory volume for a CH-TRU single waste stream before scaling.

Table DATA-F-8 shows the calculation for the CH-TRU waste scaling factor and the CH-TRU waste volumes. The total CH-TRU waste disposal inventory, $V_{CH\text{-}Disposal}$, is the sum of the scaled CH-TRU waste stream volumes. The scaled waste stream volumes for the CH-TRU waste streams included in the estimate of volume for PA are given in Appendix DATA, Attachment F, Annex E, Table DATA-F-E-1. All volume and scaling calculated results were derived from the data and information that were reported in the updated TWBID Revision 2.1 (LANL 2003a) for each CH-TRU waste stream. The volume rollups and scaling calculations were performed under the SNL QA program as described in the Computational Methodology (LANL 2003b).

DATA-F-3.1.1.2 <u>Calculation of Waste Isolation Pilot Plant-level Roll-up for Remote-Handled Transuranic Waste</u>

The WIPP disposal limit for RH-TRU waste is 7,079 m^3 (250,000 ft^3) (U.S. DOE and State of New Mexico 1981). The reported volume of stored RH-TRU waste is less than the disposal limit but the sum of the stored and projected volumes is greater than the disposal limit. Since the total reported volume of RH-TRU waste is greater than the WIPP limit, the projected volume was scaled down so the total volume for PA equaled the RH-TRU waste disposal limit for WIPP. The scaling factor for RH-TRU waste was obtained after RH-TRU waste streams designated as Non-WIPP waste streams were removed for WIPP waste streams.

The scaling factor for RH-TRU waste was calculated using the following equation:

$$SF_{RH} = (\text{RH-TRU Design Capacity in } m^3 - V_s - V_e)/ V_p, \qquad (4)$$

where

SF_{RH} is the scaling factor for the RH-TRU waste volume
V_s is the total stored volume over all waste streams and all sites for RH-TRU waste
V_e is the total emplaced volume over all waste streams and all sites for RH-TRU waste
V_p is the total projected volume over all waste streams and all sites for RH waste.

There is currently no RH-TRU waste emplaced in the WIPP, so the total RH-TRU waste emplaced volume, V_e, is zero.

The disposal inventory for a single RH-TRU waste stream was then obtained by multiplying the RH-TRU waste projected volume by the appropriate scaling factor and adding that value to the stored and emplaced volumes for each waste stream.

$$v_{RH\text{-}Disposal} = SF_{RH}\,(v_p) + v_s + v_e, \qquad (5)$$

where

$v_{RH\text{-}Disposal}$	is the disposal volume for RH-TRU waste for a single waste stream
SF_{RH}	is the scaling factor for the RH-TRU waste volume
v_s	is the stored inventory volume for a single RH-TRU waste stream before scaling
v_e	is the emplaced inventory volume for a single RH-TRU waste stream before scaling
v_p	is the projected inventory volume for a single RH-TRU waste stream before scaling

Table DATA-F-8 shows the calculation for the RH-TRU waste scaling factor and the RH-TRU waste volumes. The total RH-TRU waste disposal inventory, $V_{RH\text{-}Disposal}$, is the sum of the scaled RH-TRU waste stream inventories. The scaled waste stream volumes for the RH-TRU waste streams included in the estimate of volume for PA is given in Appendix DATA, Attachment F, Annex E, Table DATA-F-E-2. All volume and scaling calculated results were derived from the data and information that were reported in the updated TWBID Revision 2.1 (LANL 2003a) for each RH-TRU waste stream. The volume rollups and scaling calculations were performed under the SNL QA program as described in the Computational Methodology (LANL 2003b).

The total disposal inventory for the WIPP repository is the sum of the disposal volumes for CH- and RH-TRU wastes for all waste streams after scaling ($V_{CH\text{-}Disposal}$ and $V_{RH\text{-}Disposal}$).

DATA-F-3.2 Non-Radiological Transuranic Waste Inventory

This section presents the non-radiological TRU waste inventory that was collected on behalf of the DOE in support of the CRA. Section DATA-F-3.2.1 presents the inventory of waste materials. Section DATA-F-3.2.2 presents the inventory of packaging materials, and DATA-F-3.2.3 presents the inventory of chemical components.

The DOE has many reasons for obtaining and tracking non-radiological information about the TRU waste inventory destined for WIPP. For example, the DOE tracks the waste materials that go into the repository (i.e., CPR materials) because they may affect gas generation in the repository. As another example, the DOE tracks the chemical components of the waste going into the repository because they affect the solubility of actinides in the waste. The DOE needs to know the non-radiological properties of the waste not only for PA but also to support safe and economical transportation of the waste and operation of the facility.

Table DATA-F-8. Volume Scaling Factors

CH-WASTE	
WIPP capacity for waste	1.68×10^5 m^3
Total stored volume	1.09×10^5 m^3
Total projected volume	2.48×10^4 m^3
Total emplaced volume	7.72×10^3 m^3
Volume scaling factor (SF_{CH})	2.11×10^0
Note: $\frac{(1.68\times10^5)-((1.09\times10^5)+(7.72\times10^3))}{(2.48\times10^4)} = 2.11\times10^0$	
RH-WASTE	
WIPP capacity for waste	7.08×10^3 m^3
Total stored volume	5.29×10^3 m^3
Total projected volume	1.04×10^4 m^3
Total emplaced volume	0.00×10^0 m^3
Volume scaling factor (SF_{RH})	1.72×10^{-1}
Note: $\frac{(7.08\times10^3)-((5.29\times10^3)+(0.00\times10^0))}{(1.04\times10^4)} = 1.72\times10^{-1}$	

The DOE has established a system of tracking the non-radiological waste inventory destined for WIPP. It involves a description of the waste streams in terms of their waste matrix codes (WMCs), their WMPs, and their final waste forms.

The WMPs, final waste forms, and WMCs are defined in the Glossary, and were previously described in the TWBIR Revision 2 (DOE 1995b). The final waste forms and WMCs are also described in detail in the DOE Waste Treatability Group Guidance (DOE 1995c).

The following WMP descriptions were excerpted from the TWBIR Revision 2 and are operative in this document:

- Iron-base metal/alloys – This designation is meant to include iron and steel alloys in the waste and does not include the waste container materials. This also includes an iron-base metallic phase associated with any vitrification process, if applicable;

- Aluminum-base metal/alloys – Aluminum or aluminum-base alloys in the waste materials;

- Other metal/alloys – All other metals found in the waste materials (e.g., copper, lead, zirconium, tantalum, etc.). The lead portion of lead rubber gloves/aprons is also included in this category;

- Other inorganic material – Includes inorganic non-metal waste materials such as concrete, glass, firebrick, ceramics, graphite, sand, and inorganic sorbents;

- Vitrified material – This refers to waste that has been melted or fused at high temperatures with glass forming additives such as soil or silica in appropriate proportions to result in a homogeneous glass-like matrix. (Note that any unoxidized metallic phases, if present, are included in the iron-base metal/alloys waste material parameter.);

- Cellulosic material – Includes those materials generally derived from high polymer plant carbohydrates. Examples are paper, cardboard, kimwipes, wood, cellophane, cloth, etc;

- Rubber material – Includes natural or manmade elastic latex materials. Examples are Hypalon®, neoprene, surgeons' gloves, leaded-rubber gloves (rubber part only), etc;

- Plastic material – Includes generally manmade materials, often derived from petroleum feedstock. Examples are polyethylene, polyvinylchloride, Lucite®, Teflon®, etc;

- Solidified inorganic material – Includes any homogeneous materials consisting of sludge or aqueous-base liquids that are solidified with cement, Envirostone®, or other solidification agents. Examples are wastewater treatment sludge, cemented aqueous liquids, and inorganic particulates, etc. If a TRU waste site has not reported cement used as part of the solidification process in the cement (solidified) waste material parameter, the density of the cement is included in this field;

- Solidified organic material – Includes cemented organic resins, solidified organic liquids, and sludges;

- Cement (solidified) – Includes the cement used in solidifying liquids, particulates, and sludges. If for a solidified final waste form this field is left blank, it means that either cement is not the solidifying agent or that the cement is included in the solidified inorganic material waste material parameter, and

- Soil – Generally consists of naturally occurring soils that have been contaminated with inorganic radioactive waste materials.

Packaging material parameters are described in further detail in Section DATA-F-3.2.2 and in Annex D. Packaging material parameters were reported from the material parameter descriptions described in the TWBIR Revision 2. These parameters were determined by weights defined as follows:

- Steel – The weight of the steel part of the packaging from container information provided by the TRU waste generator/storage sites. Any necessary overpacking is included in the weight;

- Plastic – The weight of any plastic packaging submitted by the TRU waste sites. When weight of a rigid liner is not given, a 90-mil high density polyethylene (HDPE) liner is assumed; and

- Lead – The weight of the lead shielding in a RH-TRU canister is assumed if not provided by the TRU waste generator/storage sites.

Final waste form refers to the expected physical and chemical form of that waste stream after it is ready for disposal (i.e., once the waste has been processed, treated, or repackaged as necessary). Each final waste form consists of one or more WMCs that are grouped together. The WMCs associated with each of the final waste forms listed below are included in the TWBIR Revision 3 (DOE 1996a, Table 1-2). The purpose of the final waste form is to group waste streams that are expected to have similar physical and chemical properties at the time of disposal. A final waste form was assigned to all reported WIPP waste streams by each of the sites. The final waste forms are:

- Solidified inorganic material,
- Salt,
- Solidified organic material,
- Soil,
- Uncategorized metal (metal waste other than lead and/or cadmium) ,
- Lead/cadmium metal,
- Inorganic non-metal,
- Combustible material,
- Graphite,
- Heterogeneous debris,
- Filter material,
- Excluded waste streams (excluded from disposal at WIPP), and
- Unknown (excluded from disposal at WIPP).

The purpose of the WMCs is to aid in categorizing mixed waste streams into groups based on their different physical and chemical characteristics. The sites assign the WMCs for all of their mixed waste streams and generally assign them for their non-mixed waste streams, as well. The WMC system description and terminology used by the sites and the DOE is detailed in the DOE Waste Treatability Group Guidance. The WMCs are numerous, and are therefore not all listed here. However, the summary category groups (referred to as matrix parameter categories in the DOE Waste Treatability Group Guidance) are debris (S5000), homogeneous solids (S3000), and soil/gravel (S4000).

There are several WMCs in each of these summary category groups. For example, within the debris (S5000) summary category group, there are inorganic debris (S5100), organic debris (S5300), heterogeneous debris (S5400), and unknown/other debris (S5900). Within the inorganic debris group (S5100), there are metal debris (S5110), inorganic nonmetal debris

(S5120), and unknown/other inorganic debris (S5190). Within the metal debris (S5110) group, there are metal debris without lead or cadmium (S5111) and so on. These are detailed in the DOE Waste Treatability Group Guidance document.

DATA-F-3.2.1 Waste Materials

As part of the data call for this 2003 Update Report, the sites were asked to provide information about the materials contained in the waste. For each waste stream they were asked to designate a final waste form and to provide the density of each of the WMPs in the waste stream. The sites were asked to provide minimum, maximum, and average values for the WMPs in each waste stream. In some cases the sites provided all of the information required; in other cases, they did not.

For those waste streams where the site did not provide information regarding WMPs, the WMPs were estimated using the methods described in the Computational Methodology (LANL 2003b) and in the WMP corrections packages as identified in Table DATA-F-2. In summary, when partial information was provided (i.e., the minimum value or maximum value but not the average), it was used to calculate the average WMPs density (which was needed for PA). When no WMPs density information was given for a waste stream, the average density was inferred by identifying an analogous waste stream, and mapping the WMP from that waste stream into the waste stream that lacked WMPs.

For example, when information for a waste stream at a site was missing, the other waste streams from that site were reviewed to identify waste streams with similar final waste forms, WMCs, and waste stream descriptions. If a similar waste stream was identified, the WMPs from that waste stream (source) were attributed to the waste stream that lacked WMPs (destination waste stream). If there were no similar waste streams reported by that site, the other sites were examined to identify an appropriate similar waste regardless of its site of origin. Then the WMPs from the similar waste stream were copied (source to destination waste stream). In both cases, the packaging material parameters were edited using the waste packaging densities discussed in Section DATA-F-3.2.2 as appropriate for the type of container(s) in the destination waste stream.

In some cases, more than one similar waste stream was identified. In these instances, an average of the WMPs from similar streams was calculated and used. It was not necessary to calculate an average set of WMPs based on final waste form, as discussed in the Computational Methodology (LANL 2003b).

Waste streams were sometimes comprised of more than one container type (for example, 55-gallon drums and standard waste boxes (SWBs)). In these instances, when the site provided only one set of WMPs, those WMPs were used for both container types; except for the packaging material parameters which were corrected for the container type using the waste packaging densities given in Section DATA-F-3.2.2. The TWBID Revision 2.1 contains the WMPs list for every container type in a waste stream. However, the waste profiles in Annexes I and J (non-WIPP and WIPP waste streams, respectively) have a weighted average of the WMPs for all container types used in a waste stream. If the site provided a WMPs list for each container type,

those lists were maintained in the TWBID Revision 2.1 and a weighted average of the WMPs for all container types was used in the waste profiles.

In some cases, the sites provided incomplete WMP data from which the needed data could be inferred. Specifically, the WMP average densities were inferred from minimum and maximum WMP data. However, the minimum and maximum values will not be used for CRA PA and therefore were not reported. There are three cases in which WMP data were inferred. If maximum and minimum WMP values were reported, but no average density was reported, the average density was calculated as one half the sum of the maximum and minimum WMPs. If only a minimum WMP was reported, the minimum was assigned as the average density. If only a maximum WMP was reported, the average was calculated as one half the maximum WMP value, and assumed that the minimum was zero.

DATA-F-3.2.1.1 Roll-Up of Final Waste Form Volumes

Table DATA-F-9 presents a roll-up of the final waste form volumes for CH- and RH-TRU waste. Every WIPP waste stream in the TWBID Revision 2.1 (LANL 2003a) has been assigned a final waste form. The total volume for each of the final waste form categories is calculated by summing the actual (not scaled) waste stream volume components (emplaced, stored, and projected) with the same final waste form designation for all waste streams destined for WIPP.

DATA-F-3.2.1.2 Waste Material Parameter average Densities for Each Final Waste Form

Tables DATA-F-10 through DATA-F-29 present the WMP average densities for each final waste form in CH- and RH-TRU waste. Tables DATA-F-10 through DATA-F-20 are for CH-TRU waste. Tables DATA-F-21 through DATA-F-29 are for RH-TRU waste. These tables include the rolled up WMP average densities for each final waste form and the rolled up waste volumes by site that contributed to the total final waste form volume. These volumes are broken out into stored and projected volumes, and the total volume of waste by site for each final waste form. The emplaced volume is given by site, with the WIPP being the only applicable site. The final waste forms that have an emplaced waste CH-TRU waste volume are combustible, filter, heterogeneous, inorganic non-metal, lead/cadmium metal, salt, solidified inorganics, and uncategorized metal. There is no RH-TRU waste emplaced at this time.

For example, Table DATA-F-10 presents the WMP average densities for all CH-TRU waste streams with the combustible final waste form designation. The table shows roll-ups for stored, projected, and emplaced CH-TRU waste with the combustible final waste form designation for each site. This information is derived by summing the component volumes for each CH-TRU waste stream in the combustible category at each site.

Calculation of the WMP average densities in a final waste form requires combining data from the individual waste streams with the same final waste form designation as follows:

$$
\begin{aligned}
{}^{WM}m_i^j &= {}^{WM}p_i^j \times v_i^j \\
{}^{WM}M^j &= \sum {}^{WM}m_i^j \qquad (6) \\
{}^{WM}P^j &= {}^{WM}M^j \,/\, V^j,
\end{aligned}
$$

where

${}^{WM}m_i^j$	is the mass of the waste material (WM) in waste stream i with a final waste form designation j
${}^{WM}p_i^j$	is the average density of the WM in waste stream i with a final form designation j
v_i^j	is the volume of waste stream i (stored + projected + emplaced) with a final form designation of j
${}^{WM}M^j$	is the total mass of WM in all waste streams with a final form designation of j
V^j	is the total volume of all waste streams with a final form designation of j
${}^{WM}P^j$	is the average density of the WM in all waste streams the final form designation j.

Portions of some waste streams have been shipped to the WIPP and emplaced and others have yet to be characterized and shipped. If there was no emplaced waste for a waste stream as of the inventory date, then the emplaced volume in the equation above for that waste stream was zero. If there was no emplaced waste for any of the waste streams within the final waste forms considered, the total emplaced volume for the final waste form was also zero.

There are several notable differences in the WMP average densities for the roll-ups by final waste form when compared to the TWBIR Revision 3 (DOE 1996a). These changes are tabulated and discussed in Appendix DATA, Attachment F, and Annex B.2.

DATA-F-3.2.1.3 Waste Isolation Pilot Plant-Scale Waste Material Parameter Densities

Performance assessments conducted in support of the WIPP have been predicated on the assumption that waste materials are distributed homogeneously throughout the repository. As a result, a WIPP-scale average value for waste material densities is needed for PA. The WIPP-scale WMP average densities for CH- and RH-TRU wastes in support of the CRA are presented in Tables DATA-A-30 and DATA-F-31, respectively. These are equivalent to TWBIR Revision 3 (DOE 1996a) Tables 2-2 and 2-3, respectively. Note also that the TWBIR Revision 3 Tables 2-2 and 2-3 are the same as TWBIR Revision 2 (DOE 1995b, Tables 3-2 and 3-3, respectively). Although these tables in TWBIR Revisions 2 and 3 contain the minimum, maximum, and average densities for the WMP, this report contains only the average densities of the waste because only average values are used in PA.

WMPs were combined, or “rolled up,” for the whole repository according to the Computational Methodology (LANL 2003b). Specifically, the roll-up of WMP average densities required combining data from all of the WIPP waste streams reported by the sites. A weighted average value for the WMP based on the individual waste stream volumes in the total inventory was calculated from the WMP average densities provided by the sites as shown below:

$$
\begin{aligned}
{}^{WM}m_i &= {}^{WM}p_i \times v_i \\
{}^{WM}M &= \sum {}^{WM}m_i \qquad (7) \\
{}^{WM}P &= {}^{WM}M \,/\, V,
\end{aligned}
$$

where

${}^{WM}m_i$	is the mass of the WM in waste stream i
${}^{WM}p_i$	is the average density of the WM in waste stream i
v_i	is the actual (not-scaled) volume of waste stream i (stored + projected + emplaced)
${}^{WM}M$	is the total mass of WM in all waste streams
V	is the actual (not-scaled) volume of all waste streams
${}^{WM}P$	is the average density of the WM in all waste streams.

DATA-F-3.2.1.4 Additional Information Received After Transuranic Waste Baseline Inventory Database, Revision 2.1, Version 3.12, Data Version 4.09

After the TWBID, Revision 2.1 was configured for PA calculations, a typographical error was discovered in six of LANL's waste streams. The final form of these waste streams was listed as "solidified organic material" but should have been "solidified inorganic material" to match the waste matrix code. Therefore, the solidified organic material reported in Table DATA-F-9 and the volume identified for LANL in Table DATA-F-19 would decrease by 3,827 m^3. The solidified inorganic material reported in Table DATA-F-9 and the volume identified for LANL in Table DATA-F-18 would increase by 3,827 m^3. Volumes will also be affected in Tables DATA-F-B-12 and DATA-F-B-13 as well as the analyses for solidified inorganic material and solidified organic material in Appendix DATA, Attachment F, Annex B, Section DATA-F-B-1.4.

Table DATA-F-9. Transuranic Waste Inventory By Final Waste Form For WIPP

Final Waste Forms	Stored Waste	Projected Waste	Emplaced Waste	Total Waste
Contact Handled Waste Volumes (m^3)				
Combustible Material	4.3×10^3	1.9×10^3	6.1×10^2	6.8×10^3
Filter Material	9.9×10^2	5.9×10^2	3.4×10^2	1.9×10^3
Graphite	1.2×10^2	1.3×10^0	0.0×10^0	1.3×10^2
Heterogeneous Debris	4.9×10^4	9.7×10^3	5.7×10^2	5.9×10^4
Inorganic Non-Metal	1.1×10^4	6.8×10^1	9.7×10^2	1.2×10^4
Lead/Cadmium Metal	1.4×10^2	3.2×10^1	8.1×10^1	2.6×10^2
Salt	1.5×10^2	1.9×10^2	1.5×10^3	1.8×10^3
Soil	3.0×10^2	6.0×10^3	0.0×10^0	6.3×10^3
Solidified Inorganic Material [1]	3.5×10^4	7.3×10^2	3.3×10^3	3.9×10^4
Solidified Organic Material [1]	5.2×10^3	3.8×10^2	0.0×10^0	5.5×10^3
Uncategorized Metal	2.4×10^3	5.1×10^3	3.6×10^2	7.9×10^3
Total CH-TRU Waste Volumes	1.1×10^5	2.5×10^4	7.7×10^3	1.4×10^5
Remote-Handled Waste Volumes (m^3)				
Combustible Material	1.8×10^1	8.9×10^{-1}	0.0×10^0	1.9×10^1
Filter Material	8.9×10^0	8.9×10^0	0.0×10^0	1.8×10^1
Heterogeneous Debris	6.1×10^2	3.8×10^3	0.0×10^0	4.4×10^3
Inorganic Non-Metal	4.3×10^1	4.4×10^1	0.0×10^0	8.6×10^1
Lead/Cadmium Metal	1.2×10^1	7.1×10^0	0.0×10^0	1.9×10^1
Soil	0.0×10^0	2.0×10^2	0.0×10^0	2.0×10^2
Solidified Inorganic Material	4.5×10^3	3.3×10^2	0.0×10^0	4.8×10^3
Solidified Organic Material	9.5×10^0	0.0×10^0	0.0×10^0	9.5×10^0
Uncategorized Metal	8.4×10^1	6.1×10^3	0.0×10^0	6.1×10^3
Total RH-TRU Waste Volumes	5.3×10^3	1.0×10^4	0.0×10^0	1.6×10^4
Total TRU Waste Volumes (m^3)	1.1×10^5	3.5×10^4	7.7×10^3	1.6×10^5

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09
[1]See Section DATA-F-3.2.1.4 for additional information.

Table DATA-F-10. WIPP CH-TRU Waste Profiles – Combustible Material

Final Waste Form: **Combustible Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory – East	9.0×10^1	6.6×10^1	1.6×10^2
Argonne National Laboratory - West	5.4×10^0	4.4×10^0	9.8×10^0
Battelle Columbus Laboratories	5.2×10^0	0.0×10^0	5.2×10^0
Hanford (Richland-RL)	9.8×10^1	0.0×10^0	9.8×10^1
Los Alamos National Laboratory	2.9×10^3	1.4×10^3	4.3×10^3
Rocky Flats Environmental Technology Site	1.2×10^3	4.5×10^2	1.6×10^3
TRU Waste Site Total	4.3×10^3	1.9×10^3	6.2×10^3
Emplaced Waste Volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	6.1×10^2	0.0×10^0	6.1×10^2
Emplaced Waste Total	6.1×10^2	0.0×10^0	6.1×10^2
Total Waste Volume (m^3)	4.9×10^3	1.9×10^3	6.8×10^3
Waste Material Parameters	Average Density (kg/m^3)		
Iron-Base Metal/Alloys	1.5×10^1		
Aluminum-Base Metal/Alloys	8.4×10^{-1}		
Other Metal/Alloys	7.9×10^0		
Other Inorganic Material	1.0×10^1		
Cellulosic Material	2.0×10^1		
Rubber Material	1.3×10^1		
Plastic Material	4.9×10^1		
Solidified Inorganic Material	9.4×10^{-1}		
Cement (Solidified)	4.8×10^{-2}		
Vitrified Material	0.0×10^0		
Solidified Organic Material	1.2×10^1		
Soil	8.8×10^{-1}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-11. WIPP Contact-Handled Waste Profiles – Filter Material

Final Waste Form: **Filter Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	2.2×10^1	0.0×10^0	2.2×10^1
Lawrence Livermore National Laboratory	1.9×10^2	4.5×10^2	6.4×10^2
Los Alamos National Laboratory	3.3×10^2	0.0×10^0	3.3×10^2
Rocky Flats Environmental Technology Site	4.5×10^2	1.4×10^2	5.8×10^2
TRU Waste Site Total	9.9×10^2	5.9×10^2	1.6×10^3
Emplaced Waste volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	3.4×10^2	0.0×10^0	3.4×10^2
Emplaced Waste Total	3.4×10^2	0.0×10^0	3.4×10^2
Total Waste Volume (m^3)	1.3×10^3	5.9×10^2	1.9×10^3
Waste Material Parameters	Average Density (kg/m^3)		
Iron-Base Metal/Alloys	4.5×10^1		
Aluminum-Base Metal/Alloys	1.8×10^1		
Other Metal/Alloys	5.7×10^0		
Other Inorganic Material	1.6×10^1		
Cellulosic Material	4.6×10^1		
Rubber Material	6.2×10^0		
Plastic Material	1.6×10^1		
Solidified Inorganic Material	6.0×10^{-1}		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	3.5×10^{-1}		
Soil	4.8×10^0		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-12. WIPP CH-TRU Waste Profiles – Graphite

Final Waste Form: **Graphite**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Rocky Flats Environmental Technology Site	1.2×10^2	1.3×10^0	1.3×10^2
TRU Waste Site Total	1.2×10^2	1.3×10^0	1.3×10^2
Total Waste Volume (m^3)	1.2×10^2	1.3×10^0	1.3×10^2

Waste Material Parameters	**Average Density (kg/m^3)**
Iron-Base Metal/Alloys	1.9×10^1
Aluminum-Base Metal/Alloys	0.0×10^0
Other Metal/Alloys	0.0×10^0
Other Inorganic Material	1.7×10^2
Cellulosic Material	8.6×10^1
Rubber Material	0.0×10^0
Plastic Material	2.3×10^1
Solidified Inorganic Material	7.1×10^0
Cement (Solidified)	0.0×10^0
Vitrified Material	0.0×10^0
Solidified Organic Material	0.0×10^0
Soil	0.0×10^0

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-13. WIPP CH-TRU Waste Profiles – Heterogeneous Debris

Final Waste Form: **Heterogeneous Debris**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory - West	6.2×10^{-1}	3.4×10^{1}	3.4×10^{1}
Bettis Atomic Power Laboratory	1.9×10^{1}	0.0×10^{0}	1.9×10^{1}
Energy Technology Engineering Center	1.5×10^{0}	0.0×10^{0}	1.5×10^{0}
Hanford (Richland-RL)	1.2×10^{4}	2.1×10^{3}	1.4×10^{4}
Idaho National Engineering & Environmental Laboratory	2.0×10^{4}	2.3×10^{1}	2.0×10^{4}
Knolls Atomic Power Laboratory - Nuclear Fuel Services	5.5×10^{1}	1.7×10^{2}	2.3×10^{2}
Lawrence Livermore National Laboratory	1.3×10^{2}	1.4×10^{3}	1.6×10^{3}
Los Alamos National Laboratory	2.1×10^{3}	1.4×10^{3}	3.5×10^{3}
Nevada Test Site	6.1×10^{2}	4.6×10^{2}	1.1×10^{3}
Oak Ridge National Laboratory	0.0×10^{0}	4.5×10^{2}	4.5×10^{2}
Rocky Flats Environmental Technology Site	1.0×10^{3}	1.2×10^{3}	2.2×10^{3}
Sandia National Laboratories - Albuquerque	2.4×10^{1}	0.0×10^{0}	2.4×10^{1}
Savannah River Site	1.3×10^{4}	2.4×10^{3}	1.5×10^{4}
U.S. Army Material Command	2.5×10^{0}	0.0×10^{0}	2.5×10^{0}
University of Missouri Research Reactor	1.5×10^{0}	0.0×10^{0}	1.5×10^{0}
TRU Waste Site Total	4.9×10^{4}	9.7×10^{3}	5.9×10^{4}
Emplaced Waste Volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	5.7×10^{2}	0.0×10^{0}	5.7×10^{2}
Emplaced Waste Total	5.7×10^{2}	0.0×10^{0}	5.7×10^{2}
Total Waste Volume (m^3)	4.9×10^{4}	9.7×10^{3}	5.9×10^{4}
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	2.4×10^{2}		
Aluminum-Base Metal/Alloys	3.3×10^{1}		
Other Metal/Alloys	5.7×10^{1}		
Other Inorganic Material	5.6×10^{1}		
Cellulosic Material	1.2×10^{2}		
Rubber Material	3.2×10^{1}		
Plastic Material	9.0×10^{1}		
Solidified Inorganic Material	3.6×10^{0}		
Cement (Solidified)	0.0×10^{0}		
Vitrified Material	0.0×10^{0}		
Solidified Organic Material	1.8×10^{0}		
Soil	4.2×10^{0}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-14. WIPP CH-TRU Waste Profiles – Inorganic Non-Metal

Final Waste Form: **Inorganic Non-Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	1.1×10^1	3.0×10^1	4.2×10^1
Idaho National Engineering & Environmental Laboratory	1.1×10^4	0.0×10^0	1.1×10^4
Paducah Gaseous Diffusion Plant	5.7×10^0	5.7×10^0	1.1×10^1
Rocky Flats Environmental Technology Site	6.5×10^2	3.2×10^1	6.8×10^2
TRU Waste Site Total	1.1×10^4	6.8×10^1	1.1×10^4
Emplaced Waste Volumes (m^3)			
Site	Stored (m^3)	Projected (m^3)	Total (m^3)
Waste Isolation Pilot Plant	9.7×10^2	0.0×10^0	9.7×10^2
Emplaced Waste Total	9.7×10^2	0.0×10^0	9.7×10^2
Total Waste Volume (m^3)	1.2×10^4	6.8×10^1	1.2×10^4
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	4.2×10^0		
Aluminum-Base Metal/Alloys	1.2×10^{-2}		
Other Metal/Alloys	5.0×10^0		
Other Inorganic Material	5.5×10^1		
Cellulosic Material	1.9×10^1		
Rubber Material	1.1×10^{-1}		
Plastic Material	2.7×10^0		
Solidified Inorganic Material	9.0×10^{-1}		
Cement (Solidified)	0.0×10^0		
Vitrified Material	7.1×10^1		
Solidified Organic Material	2.7×10^{-5}		
Soil	1.8×10^{-3}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-15. WIPP CH-TRU Waste Profiles – Lead/Cadmium Metal

Final Waste Form: **Lead/Cadmium Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	1.7×10^1	1.4×10^1	3.1×10^1
Los Alamos National Laboratory	3.7×10^0	0.0×10^0	3.7×10^0
Rocky Flats Environmental Technology Site	1.2×10^2	1.8×10^1	1.4×10^2
TRU Waste Site Total	1.4×10^2	3.2×10^1	1.8×10^2
Emplaced Waste Volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	8.1×10^1	0.0×10^0	8.1×10^1
Emplaced Waste Total	8.1×10^1	0.0×10^0	8.1×10^1
Total Waste Volume (m^3)	2.2×10^2	3.2×10^1	2.6×10^2
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	9.2×10^2		
Aluminum-Base Metal/Alloys	1.8×10^1		
Other Metal/Alloys	1.5×10^2		
Other Inorganic Material	1.8×10^1		
Cellulosic Material	5.0×10^0		
Rubber Material	3.3×10^0		
Plastic Material	9.3×10^0		
Solidified Inorganic Material	8.2×10^{-1}		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	1.1×10^{-2}		
Soil	1.6×10^{-1}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-16. WIPP CH-TRU Waste Profiles – Salt

Final Waste Form: **Salt**

TRU Waste Site Volumes (m3)			
Site	Stored	Projected	Total
Lawrence Livermore National Laboratory	1.2×10^{0}	1.5×10^{1}	1.6×10^{1}
Los Alamos National Laboratory	1.3×10^{2}	1.7×10^{2}	3.0×10^{2}
Rocky Flats Environmental Technology Site	2.5×10^{1}	0.0×10^{0}	2.5×10^{1}
TRU Waste Site Total	1.5×10^{2}	1.9×10^{2}	3.4×10^{2}
Emplaced Waste Volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	1.5×10^{3}	0.0×10^{0}	1.5×10^{3}
Emplaced Waste Total	1.5×10^{3}	0.0×10^{0}	1.5×10^{3}
Total Waste Volume (m^3)	1.6×10^{3}	1.9×10^{2}	1.8×10^{3}
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	9.3×10^{0}		
Aluminum-Base Metal/Alloys	5.7×10^{-2}		
Other Metal/Alloys	3.1×10^{0}		
Other Inorganic Material	2.1×10^{2}		
Cellulosic Material	1.4×10^{2}		
Rubber Material	4.1×10^{-2}		
Plastic Material	8.9×10^{-1}		
Solidified Inorganic Material	1.3×10^{1}		
Cement (Solidified)	0.0×10^{0}		
Vitrified Material	0.0×10^{0}		
Solidified Organic Material	1.2×10^{1}		
Soil	1.5×10^{0}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-17. WIPP CH-TRU Waste Profiles – Soil

Final Waste Form: **Soil**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	1.1×10^2	5.9×10^3	6.0×10^3
Idaho National Engineering & Environmental Laboratory	0.0×10^0	9.7×10^1	9.7×10^1
Los Alamos National Laboratory	1.9×10^2	0.0×10^0	1.9×10^2
TRU Waste Site Total	3.0×10^2	6.0×10^3	6.3×10^3
Total Waste Volume (m^3)	3.0×10^2	6.0×10^3	6.3×10^3

Waste Material Parameters	**Average Density (kg/m^3)**
Iron-Base Metal/Alloys	2.4×10^{-2}
Aluminum-Base Metal/Alloys	9.1×10^{-3}
Other Metal/Alloys	6.4×10^{-2}
Other Inorganic Material	9.1×10^{-1}
Cellulosic Material	1.5×10^{-1}
Rubber Material	2.7×10^{-2}
Plastic Material	1.4×10^{-1}
Solidified Inorganic Material	1.8×10^0
Cement (Solidified)	1.8×10^0
Vitrified Material	0.0×10^0
Solidified Organic Material	5.0×10^0
Soil	3.2×10^2

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-18. WIPP CH-TRU Waste Profiles – Solidified Inorganic Material[1]

Final Waste Form: **Solidified Inorganic Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory - East	2.4×10^1	1.3×10^1	3.7×10^1
Hanford (Richland-RL)	1.9×10^2	3.0×10^1	2.2×10^2
Hanford (River Protection-RP)	3.9×10^3	0.0×10^0	3.9×10^3
Idaho National Engineering & Environmental Laboratory	2.9×10^4	0.0×10^0	2.9×10^4
Lawrence Livermore National Laboratory	1.4×10^1	1.8×10^2	1.9×10^2
Los Alamos National Laboratory	6.5×10^2	2.4×10^2	8.9×10^2
Nevada Test Site	5.7×10^0	0.0×10^0	5.7×10^0
Rocky Flats Environmental Technology Site	8.1×10^2	2.7×10^2	1.1×10^3
Savannah River Site	2.4×10^1	0.0×10^0	2.4×10^1
TRU Waste Site Total	3.5×10^4	7.3×10^2	3.6×10^4
Emplaced Waste Volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	3.3×10^3	0.0×10^0	3.3×10^3
Emplaced Waste Total	3.3×10^3	0.0×10^0	3.3×10^3
Total Waste Volume (m^3)	3.8×10^4	7.3×10^2	3.9×10^4
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	9.5×10^{-1}		
Aluminum-Base Metal/Alloys	2.9×10^{-2}		
Other Metal/Alloys	1.4×10^0		
Other Inorganic Material	3.3×10^1		
Cellulosic Material	7.6×10^0		
Rubber Material	1.3×10^{-2}		
Plastic Material	3.8×10^0		
Solidified Inorganic Material	2.5×10^2		
Cement (Solidified)	9.8×10^1		
Vitrified Material	4.6×10^{-2}		
Solidified Organic Material	2.7×10^0		
Soil	4.2×10^0		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09
[1]See Section DATA-F-3.2.1.4 for additional information.

Table DATA-F-19. WIPP CH-TRU Waste Profiles – Solidified Organic Material[1]

Final Waste Form: **Solidified Organic Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Energy Technology Engineering Center	8.4×10^{-1}	0.0×10^{0}	8.4×10^{-1}
Hanford (Richland-RL)	2.3×10^{0}	3.4×10^{2}	3.4×10^{2}
Idaho National Engineering & Environmental Laboratory	1.1×10^{3}	0.0×10^{0}	1.1×10^{3}
Lawrence Livermore National Laboratory	8.1×10^{0}	4.8×10^{0}	1.3×10^{1}
Los Alamos National Laboratory	3.9×10^{3}	2.7×10^{1}	3.9×10^{3}
Rocky Flats Environmental Technology Site	1.4×10^{2}	4.4×10^{0}	1.4×10^{2}
TRU Waste Site Total	5.2×10^{3}	3.8×10^{2}	5.5×10^{3}
Total Waste Volume (m^3)	5.2×10^{3}	3.8×10^{2}	5.5×10^{3}
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	3.9×10^{-1}		
Aluminum-Base Metal/Alloys	1.9×10^{-1}		
Other Metal/Alloys	2.8×10^{-1}		
Other Inorganic Material	2.7×10^{1}		
Cellulosic Material	3.7×10^{-1}		
Rubber Material	2.5×10^{-1}		
Plastic Material	7.1×10^{0}		
Solidified Inorganic Material	1.4×10^{2}		
Cement (Solidified)	3.8×10^{1}		
Vitrified Material	0.0×10^{0}		
Solidified Organic Material	3.3×10^{2}		
Soil	3.6×10^{1}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09
[1]See Section DATA-F-3.2.1.4 for additional information.

Table DATA-F-20. WIPP CH-TRU Waste Profiles – Uncategorized Metal

Final Waste Form: **Uncategorized Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	1.1×10^2	4.4×10^3	4.5×10^3
Idaho National Engineering & Environmental Laboratory	9.4×10^0	0.0×10^0	9.4×10^0
Los Alamos National Laboratory	1.5×10^3	3.2×10^1	1.5×10^3
Rocky Flats Environmental Technology Site	7.9×10^2	6.7×10^2	1.5×10^3
TRU Waste Site Total	2.4×10^3	5.1×10^3	7.5×10^3
Emplaced Waste Volume (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	3.6×10^2	0.0×10^0	3.6×10^2
Emplaced Waste Total	3.6×10^2	0.0×10^0	3.6×10^2
Total Waste Volume (m^3)	2.8×10^3	5.1×10^3	7.9×10^3
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	8.8×10^1		
Aluminum-Base Metal/Alloys	5.3×10^0		
Other Metal/Alloys	8.5×10^1		
Other Inorganic Material	1.2×10^0		
Cellulosic Material	2.3×10^0		
Rubber Material	1.5×10^0		
Plastic Material	7.5×10^0		
Solidified Inorganic Material	7.7×10^0		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	6.7×10^{-1}		
Soil	6.1×10^{-2}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-21. WIPP RH-TRU Waste Profiles – Combustible Material

Final Waste Form: **Combustible Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Battelle Columbus Laboratories	1.7×10^{1}	8.9×10^{-1}	1.8×10^{1}
Hanford (Richland-RL)	8.9×10^{-1}	0.0×10^{0}	8.9×10^{-1}
TRU Waste Site Total	1.8×10^{1}	8.9×10^{-1}	1.9×10^{1}
Total Waste Volume (m^3)	1.8×10^{1}	8.9×10^{-1}	1.9×10^{1}
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	8.7×10^{0}		
Aluminum-Base Metal/Alloys	7.6×10^{0}		
Other Metal/Alloys	6.3×10^{0}		
Other Inorganic Material	9.2×10^{0}		
Cellulosic Material	3.9×10^{1}		
Rubber Material	2.3×10^{1}		
Plastic Material	9.2×10^{1}		
Solidified Inorganic Material	0.0×10^{0}		
Cement (Solidified)	1.7×10^{1}		
Vitrified Material	0.0×10^{0}		
Solidified Organic Material	1.5×1^{0}		
Soil	1.4×10^{0}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-22. WIPP RH-TRU Waste Profiles – Filter Material

Final Waste Form: **Filter Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory - West	1.8×10^0	8.9×10^0	1.1×10^1
Battelle Columbus Laboratories	5.3×10^0	0.0×10^0	5.3×10^0
Hanford (Richland-RL)	1.8×10^0	0.0×10^0	1.8×10^0
TRU Waste Site Total	8.9×10^0	8.9×10^0	1.8×10^1
Total Waste Volume (m^3)	8.9×10^0	8.9×10^0	1.8×10^1

Waste Material Parameters	**Average Density (kg/m^3)**
Iron-Base Metal/Alloys	3.3×10^1
Aluminum-Base Metal/Alloys	1.7×10^1
Other Metal/Alloys	4.3×10^1
Other Inorganic Material	1.1×10^2
Cellulosic Material	7.3×10^1
Rubber Material	1.9×10^1
Plastic Material	6.3×10^0
Solidified Inorganic Material	0.0×10^0
Cement (Solidified)	7.7×10^0
Vitrified Material	0.0×10^0
Solidified Organic Material	1.2×10^1
Soil	0.0×10^0

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-23. WIPP RH-TRU Waste Profiles – Heterogeneous Debris

Final Waste Form: **Heterogeneous Debris**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory - East	1.5×10^1	1.0×10^2	1.2×10^2
Argonne National Laboratory - West	6.2×10^0	3.6×10^1	4.3×10^1
Bettis Atomic Power Laboratory	2.0×10^0	0.0×10^0	2.0×10^0
Energy Technology Engineering Center	8.9×10^{-1}	0.0×10^0	8.9×10^{-1}
Hanford (Richland-RL)	2.6×10^2	3.2×10^3	3.5×10^3
Idaho National Engineering & Environmental Laboratory	2.0×10^2	0.0×10^0	2.0×10^2
Knolls Atomic Power Laboratory - Schenectady	0.0×10^0	1.4×10^2	1.4×10^2
Los Alamos National Laboratory	1.2×10^2	0.0×10^0	1.2×10^2
Oak Ridge National Laboratory	0.0×10^0	2.7×10^2	2.7×10^2
Sandia National Laboratories - Albuquerque	4.6×10^0	0.0×10^0	4.6×10^0
Savannah River Site	0.0×10^0	2.3×10^1	2.3×10^1
TRU Waste Site Total	6.1×10^2	3.8×10^3	4.4×10^3
Total Waste Volume (m^3)	6.1×10^2	3.8×10^3	4.4×10^3
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	1.2×10^2		
Aluminum-Base Metal/Alloys	8.0×10^0		
Other Metal/Alloys	3.5×10^1		
Other Inorganic Material	4.7×10^1		
Cellulosic Material	1.6×10^1		
Rubber Material	1.1×10^1		
Plastic Material	1.6×10^1		
Solidified Inorganic Material	3.6×10^1		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	1.4×10^1		
Soil	3.5×10^1		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-24. WIPP RH-TRU Waste Profiles – Inorganic Non-Metal

Final Waste Form: **Inorganic Non-Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Battelle Columbus Laboratories	1.4×10^1	8.9×10^{-1}	1.5×10^1
Hanford (Richland-RL)	2.8×10^1	4.3×10^1	7.1×10^1
TRU Waste Site Total	4.3×10^1	4.4×10^1	8.6×10^1
Total Waste Volume (m^3)	4.3×10^1	4.4×10^1	8.6×10^1
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	1.6×10^2		
Aluminum-Base Metal/Alloys	2.1×10^1		
Other Metal/Alloys	4.8×10^1		
Other Inorganic Material	9.9×10^2		
Cellulosic Material	3.9×10^0		
Rubber Material	1.8×10^0		
Plastic Material	2.4×10^1		
Solidified Inorganic Material	1.5×10^1		
Cement (Solidified)	3.1×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	2.8×10^{-1}		
Soil	7.1×10^0		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-25. WIPP RH-TRU Waste Profiles – Lead/Cadmium Metal

Final Waste Form: **Lead/Cadmium Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	1.2×10^1	7.1×10^0	1.9×10^1
TRU Waste Site Total	1.2×10^1	7.1×10^0	1.9×10^1
Total Waste Volume (m^3)	1.2×10^1	7.1×10^0	1.9×10^1
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	5.4×10^3		
Aluminum-Base Metal/Alloys	0.0×10^0		
Other Metal/Alloys	7.4×10^1		
Other Inorganic Material	0.0×10^0		
Cellulosic Material	0.0×10^0		
Rubber Material	0.0×10^0		
Plastic Material	0.0×10^0		
Solidified Inorganic Material	0.0×10^0		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	0.0×10^0		
Soil	0.0×10^0		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-26. WIPP RH-TRU Waste Profiles – Soil

Final Waste Form: **Soil**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Oak Ridge National Laboratory	0.0×10^0	2.0×10^2	2.0×10^2
TRU Waste Site Total	0.0×10^0	2.0×10^2	2.0×10^2
Total Waste Volume (m^3)	0.0×10^0	2.0×10^2	2.0×10^2
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	0.0×10^0		
Aluminum-Base Metal/Alloys	0.0×10^0		
Other Metal/Alloys	0.0×10^0		
Other Inorganic Material	0.0×10^0		
Cellulosic Material	0.0×10^0		
Rubber Material	0.0×10^0		
Plastic Material	0.0×10^0		
Solidified Inorganic Material	0.0×10^0		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	0.0×10^0		
Soil	1.3×10^3		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-27. WIPP RH-TRU Waste Profiles – Solidified Inorganic Material

Final Waste Form: **Solidified Inorganic Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory - West	1.6×10^1	2.3×10^1	3.9×10^1
Battelle Columbus Laboratories	1.8×10^0	0.0×10^0	1.8×10^0
Hanford (Richland-RL)	1.5×10^1	1.2×10^2	1.3×10^2
Hanford (River Protection-RP)	4.5×10^3	0.0×10^0	4.5×10^3
Idaho National Engineering & Environmental Laboratory	8.9×10^{-1}	0.0×10^0	8.9×10^{-1}
Oak Ridge National Laboratory	0.0×10^0	1.9×10^2	1.9×10^2
TRU Waste Site Total	4.5×10^3	3.3×10^2	4.8×10^3
Total Waste Volume (m^3)	4.5×10^3	3.3×10^2	4.8×10^3

Waste Material Parameters	**Average Density (kg/m^3)**
Iron-Base Metal/Alloys	6.8×10^0
Aluminum-Base Metal/Alloys	0.0×10^0
Other Metal/Alloys	3.4×10^{-2}
Other Inorganic Material	6.9×10^{-1}
Cellulosic Material	3.5×10^{-3}
Rubber Material	0.0×10^0
Plastic Material	1.6×10^{-2}
Solidified Inorganic Material	9.2×10^1
Cement (Solidified)	2.4×10^0
Vitrified Material	1.8×10^{-1}
Solidified Organic Material	3.1×10^{-2}
Soil	4.1×10^{-3}

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-28. WIPP RH-TRU Waste Profiles – Solidified Organic Material

Final Waste Form: **Solidified Organic Material**

TRU Waste Site Volumes ($m^{3)}$			
Site	Stored	Projected	Total
Battelle Columbus Laboratories	5.3×10^0	0.0×10^0	5.3×10^0
Energy Technology Engineering Center	4.1×10^0	0.0×10^0	4.1×10^0
TRU Waste Site Total	9.5×10^0	0.0×10^0	9.5×10^0
Total Waste Volume (m^3)	9.5×10^0	0.0×10^0	9.5×10^0
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	4.9×10^1		
Aluminum-Base Metal/Alloys	0.0×10^0		
Other Metal/Alloys	0.0×10^0		
Other Inorganic Material	1.2×10^1		
Cellulosic Material	2.0×10^1		
Rubber Material	4.2×10^0		
Plastic Material	2.0×10^1		
Solidified Inorganic Material	0.0×10^0		
Cement (Solidified)	1.4×10^2		
Vitrified Material	0.0×10^0		
Solidified Organic Material	1.7×10^2		
Soil	0.0×10^0		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-29. WIPP RH-TRU Waste Profiles – Uncategorized Metal

Final Waste Form: **Uncategorized Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Battelle Columbus Laboratories	8.9×10^{-1}	0.0×10^{0}	8.9×10^{-1}
Hanford (Richland-RL)	6.1×10^{1}	6.1×10^{3}	6.1×10^{3}
Idaho National Engineering & Environmental Laboratory	2.2×10^{1}	0.0×10^{0}	2.2×10^{1}
TRU Waste Site Total	8.4×10^{1}	6.1×10^{3}	6.1×10^{3}
Total Waste Volume (m^3)	8.4×10^{1}	6.1×10^{3}	6.1×10^{3}

Waste Material Parameters	**Average Density (kg/m^3)**
Iron-Base Metal/Alloys	1.8×10^{2}
Aluminum-Base Metal/Alloys	4.5×10^{-1}
Other Metal/Alloys	5.6×10^{1}
Other Inorganic Material	4.0×10^{1}
Cellulosic Material	7.5×10^{-2}
Rubber Material	5.2×10^{-2}
Plastic Material	7.8×10^{-2}
Solidified Inorganic Material	3.1×10^{-3}
Cement (Solidified)	0.0×10^{0}
Vitrified Material	0.0×10^{0}
Solidified Organic Material	0.0×10^{0}
Soil	6.2×10^{-2}

Table DATA-F-30. WIPP CH-TRU Waste Material Parameter Disposal Inventory

Waste Material Parameters	Average Density (kg/m^3)
Iron-Base Metal/Alloys	1.1×10^2
Aluminum-Base Metal/Alloys	1.4×10^1
Other Metal/Alloys	3.0×10^1
Other Inorganic Material	4.2×10^1
Cellulosic Material	5.8×10^1
Rubber Material	1.4×10^1
Plastic Material	4.2×10^1
Solidified Inorganic Material	7.7×10^1
Cement (Solidified)	2.9×10^1
Vitrified Material	6.2×10^0
Solidified Organic Material	1.6×10^1
Soil	1.9×10^1
Container Materials	
Steel	1.7×10^2
Plastic	1.6×10^1
Lead	1.4×10^{-2}

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-31. WIPP RH-TRU Waste Material Parameter Disposal Inventory

Waste Material Parameters	Average Density (kg/m^3)
Iron-Base Metal/Alloys	1.1×10^2
Aluminum-Base Metal/Alloys	2.5×10^0
Other Metal/Alloys	3.2×10^1
Other Inorganic Material	3.5×10^1
Cellulosic Material	4.5×10^0
Rubber Material	3.1×10^0
Plastic Material	4.9×10^0
Solidified Inorganic Material	3.9×10^1
Cement (Solidified)	8.7×10^{-1}
Vitrified Material	5.7×10^{-2}
Solidified Organic Material	4.0×10^0
Soil	2.6×10^1
Container Materials	
Steel	4.8×10^2
Plastic	1.4×10^0
Lead	4.4×10^2

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

DATA-F-3.2.2 Packaging Materials

The PA assumption that materials are distributed homogeneously throughout the repository also applies to packaging materials. As a result, a WIPP-scale average value for packaging material densities is needed for PA. The WIPP-scale packaging (container) material average densities for CH- and RH-TRU wastes in support of the CRA are presented in Tables DATA-F-30 and DATA-F-31, respectively. These are equivalent to the TWBIR Revision 3 (DOE 1996a), Tables 2-2 and 2-3, respectively. Note also that the TWBIR Revision 3 Tables 2-2 and 2-3 are the same as TWBIR Revision 2 (DOE 1995b), Tables 3-2 and 3-3, respectively.

Analysis of the packaging material data submitted by the sites identified inconsistencies in reporting among the sites. Therefore, adjustments were made at the waste stream level to achieve consistency among the waste streams. In particular, a consistent set of densities for packaging materials for different types of containers was used unless otherwise noted by the site. Table 1-3 of the TWBIR Revision 2 identified the packaging materials and packaging material densities for the waste containers that were being used at that time. These values were used in this 2003 Update Report as well. Since the time of the TWBIR Revision 2, the sites have begun using ten-drum overpacks (TDOPs) for packaging waste. The calculated packaging material densities for TDOPs are presented in Appendix DATA, Attachment F, Annex D, Packaging Materials.

In addition, sites are also reporting that they use 85 and 100-gallon drums. This is possible because Section 2.1 in the pending update to the TRAMPAC document (DOE 2002b) has been revised to add the 85-gallon drum as an authorized payload container for shipment in the TRUPACT II (the 85-gallon drum is currently authorized for shipment in the Half PACT), and to add the 100-gallon drum as an authorized payload container in the Half PACT (the 100-gallon drum is currently authorized for shipment in the TRUPACT II). This section of the TRAMPAC document has also been revised to specify a range of sizes (75 to 88 gallons) for a container identified as an “85-gallon drum.”

Table DATA-F-32 is a summary of the assumed waste packaging material densities for some common final form container types reported by the sites. The packaging material densities in Table DATA-F-32 for 55-, 85-, and 100-gallon drums, SWBs, RH-TRU canisters, and TDOPs are calculated as shown in Appendix DATA, Attachment F, Annex D.

DATA-F-3.2.3 Chemical Components in Solidified Transuranic Waste

As part of the data call for this 2003 Update Report, the sites were asked to provide information about the chemical components of the waste. The sites were asked about complexing agents (acetate, citrate, oxylate, EDTA), oxyanions (nitrate, sulfate, and phosphate), cement, and pyrochemical salts.

Table DATA-F-32. Assumed Packaging Material Densities[1]

Container Configuration	Steel (kg/m^3)	Plastic (kg/m^3)	Lead (kg/m^3)	Volume (m^3)[2]
55-gallon drum	131	37	0	0.208
SWB (direct load)	154	1.2	0	1.89
SWB (overpack 4 55-gal. drums)	211	16	0	1.89
RH-TRU Waste Canister (direct load)	434	0	464	0.89
RH-TRU Waste Canister (overpack 3 55-gal. drums)	526	26	464	0.89
85-gallon drum	114	0	0	0.322
100-gallon drum	114	81	0	0.379
Ten-Drum Overpacks	218	16	0	4.79

[1] This table was used when sites did not report container volumes.
[2] Container volumes differ from WWIS container volumes.

This section presents the summary of the chemical components that are present in the solidified TRU waste inventory in support of the CRA. Specifically, complexing agents, oxyanions, and cement are calculated as the sum of the constituents found in anticipated waste scheduled for delivery to WIPP and any waste that has already been placed in the repository. The information provided is based on input from the TWBIR Revision 3 (DOE 1996a) and updates received from Rocky Flats Environmental Technology Site (RFETS), Los Alamos National Laboratory (LANL), Idaho National Engineering and Environmental Laboratory (INEEL), Hanford-Richland Operations (Hanford RL) and Hanford-Office of River Protection (Hanford RP). The methods used to estimate the masses of cement, complexing agents, and oxyanions are discussed in Leigh and Lott (2003), Crawford and Leigh (2003), and Leigh and Sparks-Roybal (2003), respectively. A brief discussion of pyrochemical salts is presented in Appendix DATA, Attachment F, Annex A.

DATA-F-3.2.3.1 Cement Content in Solidified Transuranic Waste

The PA for the CRA requires an estimate of the mass of cement in waste expected for disposal in the repository. An estimate of the cement mass for the CCA was given in Appendix B-7 of the TWBIR Revision 3 (DOE 1996a). While the waste stream volumes reported by the generator sites in the 2003 Update Report have changed when compared to the TWBIR Revision 3 volumes, the waste streams identified by the sites at the time of the TWBIR Revision 3 as containing cement have not changed. On the whole, the TRU waste generator sites did not report any new information about cement in this 2003 Update Report. As a result, the mass of cement in the repository was calculated for the PA in support of the CRA as the sum of the mass of cement reported in the TWBIR Revision 3 adjusting for the new waste stream volumes from this update.

The total estimated mass of cement in the scaled solidified waste streams for this 2003 Update Report is 1.20×10^7 kg (2.65×10^7 lb). This estimate of cement mass in the WIPP repository is larger than the estimate made for the CCA (8.54×10^6 kg [1.88×10^7 lb]). The increase in

cement mass is primarily because of larger volumes projected for existing waste streams. The calculations for cement masses are given in Leigh and Lott (2003).

DATA-F-3.2.3.2 Complexing Agents in Solidified Transuranic Waste

The DOE tracks the mass of complexing agents going into the repository because of their impact on solubility of actinides in the waste. In the latest request by DOE for data from the sites, none of the sites updated or modified their estimates of complexing agents in the waste streams that had been reported previously in the TWBIR Revision 3 (DOE 1996a). When applicable, the sites did report the expected masses of complexing agents in waste streams added to their inventory since publication of the TWBIR Revision 3. As a result, the mass of complexing agents in the repository was calculated for the PA in support of the CRA as the sum of the mass of complexing agents reported in the TWBIR Revision 3 plus the mass of complexing agents reported by the sites for their new waste streams.

The TWBIR Revision 3 contained information on complexing agents that was used in the PA in support of the CCA. TWBIR Revision 3 presented two estimates for complexing agents in the WIPP repository; one assuming reduction of complexing agents due to thermal treatment and one without the thermal treatment assumption. Since publication of the TWBIR Revision 3, the DOE's strategy for wastes at the INEEL has changed, and incineration operations for INEEL TRU waste did not occur as planned. Therefore, the data reported in Appendix B-4 of the TWBIR Revision 3 without the thermal treatment assumption is used in the current calculation of mass of complexing agents.

Only two sites reported complexing agents in new waste streams; RFETS and Hanford RP. For their new waste streams, RFETS reported that ethylenediaminetetraacetic acid (EDTA) might be present at trace levels (< 1 wt%) in their waste. Hanford RP identified sodium acetate and sodium oxalate in their new waste streams. The total mass of acetic acid, sodium acetate, citric acid, sodium citrate, oxalic acid, sodium oxalate, and sodium EDTA estimated for the WIPP repository are reported in Table DATA-F-33.

Table DATA-F-33. Mass of Potential Complexing Agents in the WIPP Repository

Compound	RFETS (kg)	LANL(kg)	Hanford RP (kg)	Total (kg)
Acetic Acid	132	10	---	142
Sodium Acetate	1,110	---	7,400	8,510
Citric Acid	90	1,100.5	---	1,190.5
Sodium Citrate	400	---	---	400
Oxalic Acid	90	13,706	---	13,796
Sodium Oxalate	---	---	33,940	33,940
EDTA	25.6	---	---	25.6

Source: Crawford and Leigh (2003)

Only a slight increase in EDTA was reported with this updated information over that reported in 1996 (DOE 1996a). The increase comes from one waste stream at RFETS that reported trace amounts of EDTA present in the waste and is reported as the upper limit of expected

concentration. Waste from Hanford RP waste tanks is included in Table DATA-F-33 as well, and represents a significant increase in sodium acetate and sodium oxalate that had not been reported for the TRU inventory in 1996 (DOE 1996a).

DATA-F-3.2.3.3 Mass of Oxyanions in Solidified Transuranic Waste

The PA for the CRA requires an estimate of the mass of nitrate, sulfate, and phosphate in waste expected for disposal in the repository. An estimate of the oxyanion masses for the CCA was given in Appendix B-6 of the TWBIR Revision 3 (DOE 1996a). The TRU waste sites did not report any new information about oxyanions for this 2003 Update Report with the exception of new waste streams reported by Hanford RP and LANL and revised values for a waste stream at RFETS. Therefore, the mass of nitrate, sulfate, and phosphate in the repository was calculated for the PA in support of the CRA as the sum of the mass of nitrate, sulfate, and phosphate in the TWBIR Revision 3 adjusting for the new waste stream volumes from this update plus the mass of nitrate, sulfate, and phosphate reported by the sites for their new waste streams. Table DATA-F-34 presents the mass of nitrate, sulfate, and phosphate in the WIPP repository for the CRA. The calculations for oxyanion masses are given in Leigh and Sparks-Roybal (2003).

The estimate of nitrate mass in the WIPP repository (2.51×10^6 kg [5.53×10^6 lb]) is larger than the estimate made for the CCA which was 1.62×10^6 kg (3.57×10^6 lb). The increase in nitrate mass is due primarily to larger volumes projected for existing waste streams and the added waste streams from Hanford RP. The estimate of sulfate mass in the WIPP repository (4.21×10^5 kg [9.28×10^5 lb]) is less than the estimate made for the CCA which was 6.33×10^5 kg (1.39×10^6 lb).

The estimate of phosphate mass in the WIPP repository (1.05×10^5 kg [2.31×105 lb]) is significant when compared to the CCA. There was no phosphate of reportable quantity given by the generator sites in the TWBIR Revision 3. The primary source of phosphate in the current estimate is the tank waste from Hanford RP which is now a waste stream to be disposed at WIPP.

Table DATA-F-34. Mass of Oxyanions and Cement In the WIPP Disposal Inventory

Chemical Component	Mass Contained in the Disposal Inventory (kg)
Nitrate	2.51×10^6
Sulfate	4.21×10^5
Phosphate	1.05×10^5
Cement	1.20×10^7

Sources: Leigh and Lott (2003); Leigh and Sparks-Roybal (2003)

DATA-F-3.2.3.4 Pyrochemical Salts in Waste Isolation Pilot Plant Transuranic Waste

Five waste streams at LANL, one waste stream at Lawrence Livermore National Laboratory (LLNL), and seven waste streams at RFETS have been identified as containing pyrochemical salts. Direct oxide reduction (DOR) salts have been identified in two waste streams at LANL (LA-TA-55-39 and LA-TA-55-53), the LLNL waste stream (LL-T004) and in two RFETS waste

streams (RF-TT454X and RF-TT433X). The pyrochemical salt waste streams are given in Appendix DATA, Attachment F, Annex A.

DATA-F-3.3 Transuranic Waste Radionuclide Inventory

As part of the data call for this 2003 Update Report, the sites were asked to provide information about the radiological components in the waste they intend to ship to WIPP. For each waste stream they were asked to specify the radionuclide activity concentrations (in Ci/m^3), to provide the generation or last assay date for each waste stream. In some cases, the sites provided all of the information required; in other cases, they did not.

For those waste streams where the site did not provide adequate information regarding the radiological components of the waste, radionuclide activities were estimated using the methods described in the Computational Methodology (LANL 2003b) and in the radionuclide correction package as identified in Table DATA-F-2. Radionuclide data for comparable waste streams at the same site were mapped into waste streams with missing data. For 73 waste streams without data, this mapping was accomplished by first matching to the site, the handling (RH or CH), and the WMC. Then, if there were no matches, the waste description was used to find a comparable waste stream. In this way, a waste stream requiring radionuclide data was matched to a waste stream that was generated by the same or very similar process. Seven waste streams without data were matched to waste streams with WMCs that were identical through the first two digits. Three waste streams without data were soil waste at Hanford and were matched to another Hanford soil waste stream. Two waste streams, from LANL, were found to have no similar waste stream in the present inventory but were reported in the TWBIR Revision 2 (DOE 1995b) inventory. Data from the TWBIR Revision 2 were used to fill out the radionuclide data for these two waste streams.

All of the radionuclide data were decayed to a common base year of CY 2001 (December 31, 2001) using Oak Ridge National Laboratory Isotope Generation and Depletion Code, Version 2.2 (hereafter referred to as ORIGEN 2.2) (Croff 1983; Croff 1980). ORIGEN 2.2 is a computer code that calculates the buildup and decay of radionuclides. ORIGEN 2.2 was qualified according to SNL procedure, NP 19-1, Software Requirements (SNL 2002a) for the decay calculations that were done for the TRU waste radionuclide inventory. ORIGEN 2.2 uses a matrix exponential method to solve a large system of coupled, linear, first-order ordinary differential equations with constant coefficients.

The ORIGEN 2.2 half-life data are contained within libraries that remain unchanged since their use (via ORIGEN 2.1; ORNL 2002) for the TWBIR Revision 3 (DOE 1996a) in 1996. The results obtained for data in 1996 using ORIGEN 2.1 and those that would be obtained using the current version of ORIGEN 2.2 for 1996 data would be identical. Therefore, the only differences expected between the data obtained in 1996 using ORIGEN 2.1 and those reported for the 2003 Update Report using ORIGEN 2.2 are those related to time.

Updated waste stream volumes were used to calculate waste stream radionuclide activity from the decayed ORIGEN 2.2 radionuclide activity concentrations as shown in the following equation:

$$a(RN)_{Disposal} = \alpha(RN) \cdot v_{Disposal}, \quad (8)$$

where

$a(RN)_{Disposal}$	is the activity of the radionuclide RN in the scaled waste stream volume,
$\alpha(RN)$	is the decayed radionuclide activity in Ci/m^3 from ORIGEN 2.2 for radionuclide RN, and
$v_{Disposal}$	is the waste stream disposal volume for CH-TRU or RH-TRU waste.

More information on how $v_{Disposal}$ was calculated can be found in Section DATA-F-3.1.

The WIPP-scale radionuclide activities were calculated as shown in the following equations for both CH- and RH-TRU wastes. In the first step, the activities of each radionuclide in the scaled waste stream volumes ($a(RN)_{Disposal}$) are summed for all waste streams to give the total activity for each radionuclide in CH-TRU and RH-TRU waste in the repository. In the second step, the total activity for each radionuclide in CH-TRU and RH-TRU waste in the repository is divided by the volume limit (168,485 m^3 [5,950,000 ft^3]for CH-TRU waste and 7,079 m^3 [250,000 ft^3] for RH-TRU waste) to give the activity concentration for a radionuclide in CH-TRU or RH-TRU waste in the repository.

$$A(RN) = \Sigma\, a(RN)_{Disposal}$$

$$\hat{A}(RN) = A(RN)/Limit, \quad (9)$$

where

$A(RN)$	is the total activity (Ci) for a radionuclide in CH-TRU or RH-TRU waste in the repository (after scaling)
$\hat{A}(RN)$	is the activity concentration for a radionuclide in CH-TRU or RH-TRU waste in the repository (Ci/m^3)
$a(RN)_{Disposal}$	is the activity (Ci) of the radionuclide RN in the scaled waste stream volume,
Limit	is 168,485 m^3 (5,950,000 ft^3) for CH-waste and 7,079 m^3 (250,000 ft^3) for RH-TRU waste.

DATA-F-3.3.1 Site-Level Roll-up of Radionuclide Activities

Tables DATA-F-35 and DATA-F-36 provide the site-specific radionuclide inventory estimates in total curies decayed through 2001 for CH-TRU and RH-TRU waste, respectively. The data shown in Tables DATA-F-35 and DATA-F-36 are the radionuclide inventories as the sum of the actual stored and projected volumes (not scaled) reported by the site.

DATA-F-3.3.2 Waste-Stream-Level Radionuclide Activities

The radionuclide activities in the scaled waste stream volumes for the CH-TRU waste streams included in the estimate of volume for PA are given in Appendix DATA, Attachment F, Annex E, Table DATA-F-E-1. The radionuclide activities in the scaled waste stream volumes for the

RH-TRU waste streams included in the estimate of volume for PA are given in Appendix DATA, Attachment F, Annex E, Table DATA-F-E-2.

DATA-F-3.3.3 Waste Isolation Pilot Plant-Level Roll-up of Radionuclide Activities

Table DATA-F-37 presents the WIPP-level roll-up of radionuclide activities for the disposal inventory (scaled for a full WIPP repository) in Ci/$m^3$and total Ci decayed through 2001 for both CH-TRU and RH-TRU waste. Table DATA-F-37 corresponds to Table 3-1, TWBIR Revision 3 (DOE 1996a). The waste-stream-level radionuclide activities provide the decayed (through December 31, 2001) radionuclide inventory by waste stream for all the waste streams included in Appendix DATA, Attachment F, Annex J.

A comparison of TWBIR Revision 3, Table 3-1 data to the data reported in Table DATA-F-37 can be found in Appendix DATA, Attachment F, Annex B Table DATA-F-B-27 for CH-TRU waste and Table DATA-F-B-28 for RH-TRU waste. A review of the results for CH-TRU waste indicates that although there is a substantial change in some radionuclides from 1995 to 2001, with the exception of ^{239}Pu and ^{240}Pu the activities for the dominant five radionuclides (^{241}Am, ^{238}Pu,^{239}Pu, ^{240}Pu, and ^{241}Pu) have decreased. The overall activity for all radionuclides has decreased by 17 percent. The results for RH-TRU waste show substantial variations in individual radionuclide activity. An overall increase in activity of 30 percent was observed with this update. Five radionuclides made up 99.0 percent of the CH-TRU waste curies in the TWBIR Revision 3 and the same five make up 97.2 percent of the total CH-TRU waste curies in this report. The five most abundant RH-TRU waste isotopes in the TWBIR Revision 3 (^{137m}Ba, ^{137}Cs, ^{241}Pu, ^{90}Sr, and ^{90}Y) are still the most abundant in the 2003 Update Report. These five radionuclides made up 96.1 percent of the RH-TRU waste curies in the TWBIR Revision 3 and make up 97.6 percent of the total RH-TRU waste curies in the 2003 Update Report.

DATA-F-3.4 Non-Waste Isolation Pilot Plant and Future Potential Waste

This section identifies waste streams not included in the WIPP inventory used for PA. The waste permitted to come to WIPP is restricted by radionuclide activity limits, volume, and waste generated only from defense activities. Non-WIPP waste streams in Appendix DATA, Attachment F, Annex I are summarized in Section DATA-F-3.4.1.

Other restrictions to the waste result from how the waste has been managed at the TRU waste sites. There are some materials that have not been declared TRU waste by the DOE TRU waste sites at this time that may become TRU waste in the future. Some waste has been identified in the TRU inventory but the option for processing has not been determined at this time. These possible future waste streams may ultimately become eligible for shipment to WIPP and are discussed in Section DATA-F-3.4.2.

Table DATA-F-35. CH-TRU Waste Curies on a Site-by-Site Basis [1]

Radionuclide	AE	AW	MC	BC	BT	ET	IN	KN	LA	LL	MU	NT	OR	PA	RF	RL	RP	SA	SR	WP	Total Of Curies
^{225}Ac	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.8×10^{-5}	1.3×10^{0}
^{227}Ac	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.1×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.9×10^{-6}	---	---	8.3×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{228}Ac	4.9×10^{-5}	---	---	---	---	3.8×10^{-18}	4.8×10^{0}	---	9.4×10^{-7}	---	---	1.9×10^{-15}	1.1×10^{-3}	---	5.4×10^{-13}	---	---	3.7×10^{-3}	9.1×10^{-13}	8.8×10^{-7}	4.8×10^{0}
^{109m}Ag	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.3×10^{-4}	---	---	1.3×10^{-4}
^{110}Ag	---	---	---	---	---	---	---	---	---	---	---	---	2.1×10^{-11}	---	---	---	---	---	---	---	2.1×10^{-11}
^{110m}Ag	---	---	---	---	---	---	---	---	---	---	---	---	1.6×10^{-9}	---	---	---	---	---	---	---	1.6×10^{-9}
^{241}Am	6.1×10^{1}	1.0×10^{-1}	1.6×10^{-1}	6.5×10^{0}	8.4×10^{-3}	2.3×10^{-1}	1.6×10^{5}	7.8×10^{1}	6.8×10^{3}	2.5×10^{3}	2.2×10^{0}	3.7×10^{2}	2.5×10^{3}	---	2.6×10^{4}	3.3×10^{4}	5.2×10^{2}	9.0×10^{0}	8.7×10^{3}	1.2×10^{5}	3.6×10^{5}
^{242}Am	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	4.7×10^{-2}	---	---	4.7×10^{-2}
^{242m}Am	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	4.8×10^{-2}	---	---	4.8×10^{-2}
^{243}Am	---	---	---	---	4.0×10^{-5}	---	6.4×10^{-3}	---	3.8×10^{-3}	---	---	1.2×10^{0}	9.4×10^{0}	---	---	---	---	1.4×10^{-2}	---	4.8×10^{-3}	1.1×10^{1}
^{245}Am	---	---	---	---	---	---	---	---	2.0×10^{-13}	---	---	---	6.2×10^{-11}	---	---	---	---	---	---	---	6.2×10^{-11}
^{217}At	1.6×10^{4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.9×10^{-5}	1.3×10^{0}
^{137m}Ba	3.4×10^{0}	2.8×10^{-1}	---	---	2.0×10^{1}	1.5×10^{-2}	---	---	1.1×10^{-2}	---	---	2.6×10^{-2}	3.4×10^{3}	---	1.5×10^{-2}	3.4×10^{2}	1.3×10^{3}	7.3×10^{1}	---	3.6×10^{-4}	5.2×10^{3}
^{210}Bi	6.2×10^{-10}	1.7×10^{-14}	---	---	---	9.3×10^{-12}	2.7×10^{-8}	---	1.0×10^{-6}	---	---	9.8×10^{-2}	1.2×10^{0}	5.5×10^{-5}	2.6×10^{-8}	---	---	1.1×10^{-2}	5.2×10^{-6}	2.4×10^{-7}	1.3×10^{0}
^{211}Bi	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.0×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.8×10^{-6}	---	---	8.2×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{212}Bi	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.2×10^{0}	---	1.7×10^{-6}	---	---	1.6×10^{-2}	5.0×10^{-1}	---	3.1×10^{-13}	---	---	8.5×10^{-3}	8.7×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{213}Bi	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.8×10^{-5}	1.3×10^{0}
^{214}Bi	4.3×10^{-9}	1.8×10^{-12}	---	---	---	7.6×10^{-11}	2.9×10^{-7}	---	2.3×10^{-6}	---	2.7×10^{-20}	2.5×10^{-1}	2.8×10^{0}	3.1×10^{-4}	2.3×10^{-7}	---	---	5.0×10^{-2}	2.8×10^{-5}	7.8×10^{-6}	3.1×10^{0}
^{249}Bk	---	---	---	---	---	---	---	---	1.4×10^{-8}	---	---	---	4.3×10^{-6}	---	---	---	---	---	---	---	4.3×10^{-6}
^{250}Bk	---	---	---	---	---	---	---	---	---	---	---	---	1.7×10^{-12}	---	---	---	---	---	---	---	1.7×10^{-12}
^{14}C	---	---	---	---	5.3×10^{-4}	---	---	---	---	---	---	2.5×10^{-4}	2.1×10^{-4}	---	---	1.1×10^{0}	9.9×10^{-2}	---	---	---	1.2×10^{0}
^{109}Cd	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.3×10^{-4}	---	---	1.3×10^{-4}
^{144}Ce	---	---	---	---	---	---	---	---	---	---	---	---	1.2×10^{-7}	---	---	---	---	3.6×10^{-4}	---	---	3.6×10^{-4}
^{249}Cf	---	---	---	---	7.6×10^{-13}	---	---	---	1.2×10^{-4}	---	---	1.1×10^{-2}	3.1×10^{-2}	---	---	---	---	---	---	---	4.2×10^{-2}
^{250}Cf	---	---	---	---	---	---	---	---	---	---	---	1.4×10^{-1}	1.9×10^{-2}	---	---	---	---	---	---	---	1.6×10^{-1}
^{251}Cf	---	---	---	---	3.6×10^{-14}	---	---	---	---	---	---	---	1.7×10^{-4}	---	---	---	---	---	---	---	1.7×10^{-4}
^{252}Cf	---	---	---	---	---	---	3.0×10^{-3}	---	---	---	---	8.3×10^{-2}	5.7×10^{-2}	---	---	---	---	---	---	---	1.4×10^{-1}
^{242}Cm	---	---	---	---	---	---	---	---	---	---	---	---	4.3×10^{-10}	---	---	---	---	3.9×10^{-2}	---	---	3.9×10^{-2}
^{243}Cm	---	---	---	---	4.5×10^{-5}	---	---	---	---	---	---	4.6×10^{-4}	---	---	---	---	---	4.0×10^{-1}	---	---	4.0×10^{-1}
^{244}Cm	---	---	---	---	2.5×10^{-3}	---	---	---	3.3×10^{3}	2.6×10^{3}	---	2.3×10^{0}	1.7×10^{3}	---	---	---	---	4.8×10^{0}	---	---	7.6×10^{3}
^{245}Cm	---	---	---	---	2.7×10^{-7}	---	---	---	2.5×10^{-7}	---	---	1.5×10^{-5}	4.0×10^{-3}	---	---	---	---	---	---	---	4.0×10^{-3}

Table DATA-F-35. CH-TRU Waste Curies on a Site-by-Site Basis [1] — Continued

Radionuclide	AE	AW	MC	BC	BT	ET	IN	KN	LA	LL	MU	NT	OR	PA	RF	RL	RP	SA	SR	WP	Total Of Curies
^{246}Cm	---	---	---	---	4.6×10^{-8}	---	---	---	---	---	---	5.2×10^{-4}	7.4×10^{-1}	---	---	---	---	---	---	---	7.4×10^{-1}
^{247}Cm	---	---	---	---	1.1×10^{-13}	---	---	---	---	---	---	---	1.3×10^{-10}	---	---	---	---	---	---	---	1.3×10^{-10}
^{248}Cm	---	---	---	---	1.9×10^{-13}	---	6.8×10^{-7}	---	---	---	---	4.1×10^{-5}	4.3×10^{-2}	---	---	---	---	---	---	---	4.3×10^{-2}
^{250}Cm	---	---	---	---	---	---	---	---	---	---	---	---	3.2×10^{-11}	---	---	---	---	---	---	---	3.2×10^{-11}
^{60}Co	---	---	---	---	9.3×10^{-1}	---	---	---	8.1×10^{-8}	---	---	---	3.5×10^{-3}	---	---	---	---	4.8×10^{-2}	---	1.5×10^{-7}	9.8×10^{-1}
^{134}Cs	---	---	---	---	---	---	---	---	2.2×10^{-10}	---	---	---	8.1×10^{-4}	---	---	---	---	1.9×10^{-2}	---	---	2.0×10^{-2}
^{137}Cs	3.6×10^{0}	3.0×10^{-1}	---	---	2.1×10^{1}	1.6×10^{-2}	---	---	1.1×10^{-2}	---	---	2.8×10^{-2}	3.7×10^{3}	---	1.6×10^{-2}	3.5×10^{2}	1.4×10^{3}	7.8×10^{1}	---	3.9×10^{-4}	5.5×10^{3}
^{152}Eu	---	---	---	---	9.3×10^{-1}	---	---	---	6.8×10^{-8}	---	---	9.2×10^{-1}	4.1×10^{-2}	---	---	---	---	---	---	---	1.9×10^{0}
^{154}Eu	---	---	---	---	9.3×10^{-1}	---	---	---	3.0×10^{-7}	---	---	3.4×10^{-1}	1.2×10^{-1}	---	---	---	---	1.3×10^{-1}	---	---	1.5×10^{0}
^{155}Eu	---	---	---	---	---	---	---	---	2.7×10^{-5}	---	---	---	3.1×10^{-2}	---	---	---	---	1.8×10^{-3}	---	---	3.3×10^{-2}
^{221}Fr	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.8×10^{-5}	1.3×10^{0}
^{223}Fr	2.9×10^{-9}	3.3×10^{-13}	4.4×10^{-17}	---	---	7.3×10^{-16}	5.6×10^{-8}	---	1.7×10^{-5}	---	4.9×10^{-18}	2.8×10^{-6}	3.3×10^{-3}	8.2×10^{-16}	5.3×10^{-8}	---	---	1.1×10^{-5}	3.3×10^{-9}	5.1×10^{-6}	3.3×10^{-3}
^{152}Gd	---	---	---	---	---	---	---	---	4.1×10^{-21}	---	---	3.9×10^{-14}	1.9×10^{-15}	---	---	---	---	---	---	---	4.1×10^{-14}
^{3}H	---	---	---	---	---	---	---	---	2.1×10^{2}	---	---	5.2×10^{-2}	---	---	---	3.4×10^{0}	---	1.8×10^{-2}	---	---	2.2×10^{2}
^{129}I	---	---	---	---	7.0×10^{-6}	---	---	---	---	---	---	---	---	---	---	---	5.0×10^{-4}	---	---	---	5.1×10^{-4}
^{85}Kr	---	---	---	---	---	---	---	---	---	---	---	1.4×10^{-1}	---	---	---	---	---	3.2×10^{-1}	---	---	4.6×10^{-1}
^{22}Na	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	3.9×10^{-7}	3.9×10^{-7}
^{59}Ni	---	---	---	---	7.6×10^{-2}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	7.6×10^{-2}
^{63}Ni	---	---	---	---	3.7×10^{0}	---	---	---	---	---	---	---	1.2×10^{-4}	---	---	---	---	---	---	---	3.7×10^{0}
^{237}Np	6.9×10^{-1}	3.3×10^{-8}	4.0×10^{-7}	---	5.6×10^{-5}	9.9×10^{-7}	8.8×10^{-1}	---	4.0×10^{-2}	---	4.7×10^{-4}	6.5×10^{-3}	8.0×10^{-1}	4.1×10^{-2}	2.5×10^{-1}	---	3.2×10^{-3}	1.4×10^{-1}	4.8×10^{-2}	5.4×10^{-1}	3.4×10^{0}
^{238}Np	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	2.4×10^{-4}	---	---	2.4×10^{-4}
^{239}Np	---	---	---	---	---	---	6.3×10^{-3}	---	3.7×10^{-3}	---	---	1.2×10^{0}	9.2×10^{0}	---	---	---	---	1.4×10^{-2}	---	4.8×10^{-3}	1.0×10^{1}
^{240m}Np	---	---	---	---	---	---	5.1×10^{-14}	---	1.8×10^{-7}	---	---	1.0×10^{-6}	5.7×10^{-9}	---	---	---	---	---	---	---	1.2×10^{-6}
^{231}Pa	9.9×10^{-7}	1.6×10^{-9}	4.0×10^{-14}	---	---	4.1×10^{-13}	2.2×10^{-5}	---	2.9×10^{-6}	---	8.8×10^{-15}	5.1×10^{-4}	5.7×10^{-1}	4.8×10^{-13}	2.3×10^{-5}	---	---	5.6×10^{-3}	1.0×10^{-6}	5.0×10^{-4}	5.8×10^{-1}
^{233}Pa	6.9×10^{-1}	3.3×10^{-8}	4.0×10^{-7}	---	---	9.8×10^{-7}	8.7×10^{-1}	---	4.0×10^{-2}	---	4.7×10^{-4}	6.4×10^{-3}	7.9×10^{-1}	4.1×10^{-2}	2.5×10^{-1}	---	---	1.4×10^{-1}	4.8×10^{-2}	5.3×10^{-1}	3.4×10^{0}

Table DATA-F-35. CH-TRU Waste Curies on a Site-by-Site Basis [1] — Continued

Radionuclide	AE	AW	MC	BC	BT	ET	IN	KN	LA	LL	MU	NT	OR	PA	RF	RL	RP	SA	SR	WP	Total Of Curies
^{234}Pa	6.7×10^{-5}	3.5×10^{-10}	---	---	---	5.4×10^{-18}	3.0×10^{-5}	---	2.7×10^{-4}	---	3.1×10^{-10}	2.0×10^{-7}	8.7×10^{-5}	---	2.3×10^{-4}	---	---	1.2×10^{-5}	---	8.4×10^{-3}	9.1×10^{-3}
^{234m}Pa	5.2×10^{-2}	2.7×10^{-7}	---	---	---	4.1×10^{-15}	2.3×10^{-2}	---	2.0×10^{-1}	---	2.4×10^{-7}	1.5×10^{-4}	6.7×10^{-2}	---	1.8×10^{-1}	---	---	8.9×10^{-3}	---	6.5×10^{0}	7.0×10^{0}
^{209}Pb	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.8×10^{-5}	1.3×10^{0}
^{210}Pb	6.3×10^{-10}	1.7×10^{-14}	---	---	---	9.4×10^{-12}	2.7×10^{-8}	---	1.0×10^{-6}	---	---	9.9×10^{-2}	1.2×10^{0}	5.5×10^{-5}	2.6×10^{-8}	---	---	1.1×10^{-2}	5.3×10^{-6}	2.4×10^{-7}	1.3×10^{0}
^{211}Pb	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.0×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.8×10^{-6}	---	---	8.2×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{212}Pb	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.1×10^{0}	---	1.7×10^{-6}	---	---	1.6×10^{-2}	4.9×10^{-1}	---	3.1×10^{-13}	---	---	8.5×10^{-3}	8.7×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{214}Pb	4.3×10^{-9}	1.8×10^{-12}	---	---	---	7.7×10^{-11}	2.9×10^{-7}	---	2.3×10^{-6}	---	2.7×10^{-20}	2.5×10^{-1}	2.8×10^{0}	3.1×10^{-4}	2.3×10^{-7}	---	---	5.0×10^{-2}	2.8×10^{-5}	7.8×10^{-6}	3.1×10^{0}
^{147}Pm	---	---	---	---	9.3×10^{-1}	---	---	---	---	---	---	---	9.5×10^{-2}	---	---	---	---	6.9×10^{-1}	---	---	1.7×10^{0}
^{210}Po	6.3×10^{-10}	5.5×10^{-15}	---	---	---	9.4×10^{-12}	2.7×10^{-8}	---	1.0×10^{-6}	---	---	9.9×10^{-2}	1.2×10^{0}	5.5×10^{-5}	2.6×10^{-8}	---	---	1.1×10^{-2}	5.3×10^{-6}	1.3×10^{-7}	1.3×10^{0}
^{211}Po	6.4×10^{-10}	7.4×10^{-14}	9.7×10^{-18}	---	---	1.6×10^{-16}	1.2×10^{-8}	---	3.8×10^{-6}	---	1.1×10^{-18}	6.1×10^{-7}	7.2×10^{-4}	1.8×10^{-16}	1.2×10^{-8}	---	---	2.5×10^{-6}	7.2×10^{-10}	1.1×10^{-6}	7.3×10^{-4}
^{212}Po	2.7×10^{-1}	---	---	---	---	1.5×10^{-18}	2.6×10^{0}	---	1.1×10^{-6}	---	---	1.0×10^{-2}	3.2×10^{-1}	---	2.0×10^{-13}	---	---	5.4×10^{-3}	5.6×10^{-13}	2.8×10^{-7}	3.2×10^{0}
^{213}Po	1.6×10^{-4}	9.8×10^{-10}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.3×10^{-9}	---	---	1.1×10^{-6}	1.8×10^{-9}	9.6×10^{-5}	1.3×10^{0}
^{214}Po	4.3×10^{-9}	1.8×10^{-12}	---	---	---	7.7×10^{-11}	2.9×10^{-7}	---	2.3×10^{-6}	---	2.7×10^{-20}	2.5×10^{-1}	2.8×10^{0}	3.1×10^{-4}	2.3×10^{-7}	---	---	5.0×10^{-2}	2.8×10^{-5}	7.8×10^{-6}	3.1×10^{0}
^{215}Po	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.0×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.8×10^{-6}	---	---	8.2×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{216}Po	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.1×10^{0}	---	1.7×10^{-6}	---	---	1.6×10^{-2}	4.9×10^{-1}	---	3.1×10^{-13}	---	---	8.5×10^{-3}	8.7×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{218}Po	4.2×10^{-9}	1.7×10^{-12}	---	---	---	7.5×10^{-11}	2.8×10^{-7}	---	2.3×10^{-6}	---	2.7×10^{-20}	2.5×10^{-1}	2.8×10^{0}	3.0×10^{-4}	2.3×10^{-7}	---	---	4.9×10^{-2}	2.7×10^{-5}	7.7×10^{-6}	3.1×10^{0}
^{144}Pr	---	---	---	---	---	---	---	---	---	---	---	---	1.1×10^{-7}	---	---	---	---	3.5×10^{-4}	---	---	3.5×10^{-4}
^{236}Pu	2.1×10^{-7}	---	---	---	---	---	4.4×10^{-4}	---	---	---	---	---	---	---	---	---	---	---	---	---	4.4×10^{-4}
^{238}Pu	1.4×10^{1}	1.5×10^{2}	---	1.8×10^{3}	9.3×10^{-1}	1.2×10^{-2}	6.9×10^{4}	1.3×10^{1}	9.9×10^{4}	5.5×10^{2}	---	1.6×10^{2}	5.3×10^{3}	---	2.7×10^{3}	1.1×10^{5}	2.2×10^{1}	1.7×10^{0}	1.0×10^{6}	5.4×10^{3}	1.3×10^{6}
^{239}Pu	1.9×10^{2}	1.2×10^{2}	6.1×10^{-2}	2.9×10^{1}	7.3×10^{-4}	2.1×10^{-1}	5.7×10^{4}	1.6×10^{2}	1.1×10^{4}	3.1×10^{3}	5.3×10^{-2}	2.9×10^{3}	1.3×10^{3}	2.7×10^{-1}	7.4×10^{4}	7.2×10^{4}	3.2×10^{3}	4.6×10^{0}	2.0×10^{5}	1.4×10^{5}	5.6×10^{5}
^{240}Pu	1.0×10^{2}	7.0×10^{-1}	---	7.5×10^{0}	1.5×10^{-3}	8.1×10^{-2}	7.6×10^{3}	5.3×10^{1}	3.7×10^{3}	1.4×10^{3}	---	6.3×10^{1}	1.3×10^{3}	---	1.7×10^{4}	1.9×10^{4}	2.7×10^{2}	5.0×10^{-1}	4.9×10^{3}	3.1×10^{4}	8.6×10^{4}
^{241}Pu	2.6×10^{2}	6.2×10^{-1}	1.9×10^{-1}	3.6×10^{2}	1.6×10^{-1}	8.9×10^{-1}	5.1×10^{4}	2.8×10^{2}	3.1×10^{4}	4.3×10^{4}	---	1.4×10^{3}	4.3×10^{4}	---	1.8×10^{5}	1.1×10^{6}	5.4×10^{2}	6.7×10^{0}	9.7×10^{4}	3.4×10^{5}	1.9×10^{6}
^{242}Pu	6.9×10^{-2}	8.8×10^{-6}	---	1.2×10^{-3}	1.2×10^{-5}	2.0×10^{-6}	1.2×10^{1}	4.1×10^{-4}	8.2×10^{-1}	---	---	8.9×10^{-2}	3.8×10^{-1}	---	1.7×10^{0}	4.0×10^{0}	7.7×10^{-3}	7.7×10^{-8}	---	3.0×10^{0}	2.2×10^{1}
^{243}Pu	---	---	---	---	--	---	---	---	---	---	---	---	1.3×10^{-10}	---	---	---	---	---	---	---	1.3×10^{-10}
^{244}Pu	---	---	---	---	6.6×10^{-13}	---	5.0×10^{-14}	---	1.8×10^{-7}	---	---	1.0×10^{-6}	5.7×10^{-9}	---	---	---	---	---	---	---	1.2×10^{-6}

Table DATA-F-35. CH-TRU Waste Curies on a Site-by-Site Basis [1] — Continued

Radionuclide	AE	AW	MC	BC	BT	ET	IN	KN	LA	LL	MU	NT	OR	PA	RF	RL	RP	SA	SR	WP	Total Of Curies
^{223}Ra	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.1×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.9×10^{-6}	---	---	8.3×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{224}Ra	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.1×10	---	1.7×10^{-6}	---	---	1.6×10^{-2}	4.9×10^{-1}	---	3.1×10^{-13}	---	---	8.5×10^{-3}	8.7×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{225}Ra	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.9×10^{-5}	1.3×10^{0}
^{226}Ra	4.3×10^{-9}	1.8×10^{-12}	---	---	---	7.7×10^{-11}	2.9×10^{-7}	---	2.3×10^{-6}	---	2.8×10^{-20}	2.5×10^{-1}	2.9×10^{0}	3.1×10^{-4}	2.3×10^{-7}	---	---	5.1×10^{-2}	2.8×10^{-5}	7.9×10^{-6}	3.2×10^{0}
^{228}Ra	5.8×10^{-5}	---	---	---	---	4.4×10^{-18}	5.7×10^{0}	---	1.1×10^{-6}	---	---	2.2×10^{-15}	1.3×10^{-3}	---	6.4×10^{-13}	---	---	4.3×10^{-3}	1.1×10^{-12}	1.0×10^{-6}	5.7×10^{0}
^{106}Rh	---	---	---	---	---	---	---	---	8.5×10^{-11}	---	---	---	2.4×10^{-5}	---	---	---	---	1.1×10^{-4}	---	---	1.3×10^{-4}
^{219}Rn	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.0×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.8×10^{-6}	---	---	8.2×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{220}Rn	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.1×10^{0}	---	1.7×10^{-6}	---	---	1.6×10^{-2}	4.9×10^{-1}	---	3.1×10^{-13}	---	---	8.5×10^{-3}	8.7×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{222}Rn	4.3×10^{-9}	1.8×10^{-12}	---	---	---	7.7×10^{-11}	2.9×10^{-7}	---	2.3×10^{-6}	---	2.7×10^{-20}	2.5×10^{-1}	2.8×10^{0}	3.1×10^{-4}	2.3×10^{-7}	---	---	5.0×10^{-2}	2.8×10^{-5}	7.8×10^{-6}	3.1×10^{0}
^{106}Ru	---	---	---	---	---	---	---	---	8.6×10^{-11}	---	---	---	2.4×10^{-5}	---	---	---	---	1.1×10^{-4}	---	---	1.3×10^{-4}
^{125}Sb	---	---	---	---	---	---	---	---	2.9×10^{-6}	---	---	---	2.4×10^{-3}	---	---	---	---	---	---	---	2.4×10^{-3}
^{79}Se	---	---	---	---	1.3×10^{-4}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.3×10^{-4}
^{147}Sm	---	---	---	---	---	---	---	---	---	---	---	---	2.0×10^{-10}	---	---	---	---	4.6×10^{-11}	---	---	2.5×10^{-10}
^{151}Sm	---	---	---	---	1.0×10^{-1}	---	---	---	---	---	---	---	---	---	---	---	5.6×10^{1}	2.7×10^{-1}	---	---	5.7×10^{1}
^{90}Sr	2.6×10^{0}	1.5×10^{0}	---	---	2.1×10^{1}	1.2×10^{-2}	---	---	---	---	---	9.5×10^{-5}	2.2×10^{3}	---	---	1.4×10^{2}	5.3×10^{4}	7.4×10^{1}	---	---	5.5×10^{4}
^{99}Tc	5.8×10^{0}	---	---	---	4.7×10^{-3}	---	---	2.5×10^{-2}	---	---	---	---	3.1×10^{1}	2.9×10^{0}	---	4.1×10^{-3}	8.9×10^{1}	1.6×10^{-3}	---	---	1.3×10^{2}
^{123}Te	---	---	---	---	---	---	---	---	---	---	---	---	3.2×10^{-5}	---	---	---	---	---	---	---	3.2×10^{-5}
^{123m}Te	---	---	---	---	---	---	---	---	---	---	---	---	2.4×10^{-19}	---	---	---	---	---	---	---	2.4×10^{-19}
^{125m}Te	---	---	---	---	---	---	---	---	7.1×10^{-7}	---	---	---	5.8×10^{-4}	---	---	---	---	---	---	---	5.8×10^{-4}
^{227}Th	2.1×10^{-7}	2.4×10^{-11}	3.1×10^{-15}	---	---	5.2×10^{-14}	4.0×10^{-6}	---	1.2×10^{-3}	---	3.5×10^{-16}	2.0×10^{-4}	2.3×10^{-1}	5.9×10^{-14}	3.8×10^{-6}	---	---	8.1×10^{-4}	2.3×10^{-7}	3.6×10^{-4}	2.4×10^{-1}
^{228}Th	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.2×10^{0}	1.7×10^{-4}	1.7×10^{-6}	---	---	1.6×10^{-2}	5.0×10^{-1}	---	3.2×10^{-13}	---	---	8.5×10^{-3}	8.8×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{229}Th	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.3×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.9×10^{-5}	1.3×10^{0}
^{230}Th	1.3×10^{-6}	8.9×10^{-9}	---	---	---	2.8×10^{-8}	1.6×10^{-4}	---	5.6×10^{-5}	---	4.8×10^{-17}	1.2×10^{-6}	3.2×10^{-3}	5.6×10^{-2}	9.1×10^{-5}	---	---	8.5×10^{-6}	7.0×10^{-3}	4.9×10^{-5}	6.6×10^{-2}
^{231}Th	2.9×10^{-3}	7.3×10^{-5}	4.7×10^{-10}	---	---	2.8×10^{-9}	8.1×10^{-2}	---	5.8×10^{-3}	---	2.1×10^{-10}	1.5×10^{-4}	1.0×10^{-2}	3.5×10^{-9}	9.0×10^{-2}	---	---	1.2×10^{-2}	3.9×10^{-3}	1.2×10^{-1}	3.3×10^{-1}
^{232}Th	6.2×10^{-5}	5.1×10^{-19}	---	---	5.6×10^{-14}	1.1×10^{-17}	6.6×10^{0}	2.9×10^{-5}	1.1×10^{-6}	---	---	4.9×10^{-15}	1.3×10^{-3}	---	1.8×10^{-12}	4.4×10^{-2}	---	3.9×10^{-3}	1.8×10^{-12}	2.6×10^{-6}	6.6×10^{0}

Table DATA-F-35. CH-TRU Waste Curies on a Site-by-Site Basis [1] — Continued

Radionuclide	AE	AW	MC	BC	BT	ET	IN	KN	LA	LL	MU	NT	OR	PA	RF	RL	RP	SA	SR	WP	Total Of Curies
^{234}Th	5.2×10^{-2}	2.7×10^{-7}	---	---	---	4.1×10^{-15}	2.3×10^{-2}	---	2.1×10^{-1}	---	2.4×10^{-7}	1.5×10^{-4}	6.7×10^{-2}	---	1.8×10^{-1}	---	---	8.9×10^{-3}	---	6.5×10^{0}	7.0×10^{0}
^{207}Tl	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.0×10^{-6}	---	1.3×10^{-3}	---	3.5×10^{-16}	2.0×10^{-4}	2.3×10^{-1}	5.9×10^{-14}	3.8×10^{-6}	---	---	8.1×10^{-4}	2.3×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{208}Tl	1.5×10^{-1}	---	---	---	---	8.2×10^{-19}	1.5×10^{0}	---	6.1×10^{-7}	---	---	5.7×10^{-3}	1.8×10^{-1}	---	1.1×10^{-13}	---	---	3.1×10^{-3}	3.1×10^{-13}	1.6×10^{-7}	1.8×10^{0}
^{209}Tl	3.5×10^{-6}	2.2×10^{-11}	3.8×10^{-17}	---	---	2.7×10^{-16}	2.4×10^{-2}	---	3.1×10^{-5}	---	3.3×10^{-14}	6.0×10^{-5}	4.9×10^{-3}	3.1×10^{-11}	1.2×10^{-10}	---	---	2.4×10^{-8}	4.1×10^{-11}	2.2×10^{-6}	2.9×10^{-2}
^{232}U	4.1×10^{-1}	---	---	---	1.3×10^{-5}	---	3.6×10^{-4}	1.7×10^{-4}	7.3×10^{-7}	---	---	1.6×10^{-2}	4.9×10^{-1}	---	---	---	---	---	---	---	9.1×10^{-1}
^{233}U	1.1×10^{-1}	1.1×10^{-5}	6.9×10^{-12}	---	---	2.9×10^{-11}	8.8×10^{2}	1.5×10^{-2}	5.7×10^{-1}	---	8.0×10^{-9}	1.8×10^{0}	1.4×10^{2}	2.3×10^{-6}	1.0×10^{-5}	5.3×10^{1}	1.1×10^{-5}	2.4×10^{-3}	2.3×10^{-6}	2.7×10^{-1}	1.1×10^{3}
^{234}U	9.1×10^{-3}	1.2×10^{-3}	---	---	2.0×10^{-3}	2.4×10^{-4}	2.6×10^{0}	1.1×10^{-3}	7.6×10^{-1}	---	2.7×10^{-12}	1.2×10^{-2}	2.1×10^{1}	---	8.9×10^{-1}	3.3×10^{1}	1.3×10^{1}	1.9×10^{-1}	6.3×10^{1}	1.3×10^{0}	1.3×10^{2}
^{235}U	2.9×10^{-3}	7.4×10^{-5}	4.8×10^{-10}	---	2.6×10^{-5}	2.8×10^{-9}	8.2×10^{-2}	5.1×10^{-5}	5.8×10^{-3}	---	2.1×10^{-10}	1.5×10^{-4}	1.0×10^{-2}	3.5×10^{-9}	9.1×10^{-2}	3.9×10^{-1}	5.8×10^{-1}	1.2×10^{-2}	4.0×10^{-3}	1.2×10^{-1}	1.3×10^{0}
^{236}U	6.7×10^{-5}	2.1×10^{-8}	---	---	3.0×10^{-4}	3.3×10^{-8}	2.9×10^{-3}	---	2.6×10^{-3}	---	---	1.2×10^{-5}	8.1×10^{-4}	---	6.0×10^{-3}	1.6×10^{-5}	1.0×10^{-1}	7.4×10^{-8}	3.0×10^{-3}	4.5×10^{-3}	1.3×10^{-1}
^{237}U	6.3×10^{-3}	1.5×10^{-5}	4.6×10^{-6}	---	---	2.2×10^{-5}	1.3×10^{0}	---	7.5×10^{-1}	---	---	6.0×10^{-3}	1.1×10^{0}	---	4.3×10^{0}	---	---	1.6×10^{-4}	2.4×10^{0}	8.5×10^{0}	1.8×10^{1}
^{238}U	5.2×10^{-2}	2.7×10^{-7}	---	---	1.2×10^{-7}	4.2×10^{-15}	2.3×10^{-2}	4.0×10^{-3}	2.1×10^{-1}	---	2.4×10^{-7}	1.6×10^{-4}	6.8×10^{-2}	---	1.8×10^{-1}	4.0×10^{0}	1.3×10^{1}	9.0×10^{-3}	---	6.5×10^{0}	2.4×10^{1}
^{240}U	---	---	---	---	---	---	5.0×10^{-14}	---	1.8×10^{-7}	---	---	1.0×10^{-6}	5.6×10^{-9}	---	---	---	---	---	---	---	1.2×10^{-6}
^{90}Y	2.6×10^{0}	1.5×10^{0}	---	---	2.1×10^{1}	1.1×10^{-2}	---	---	---	---	---	9.4×10^{-5}	2.2×10^{3}	---	---	1.4×10^{2}	5.3×10^{4}	7.3×10^{1}	---	---	5.5×10^{4}
^{65}Zn	---	---	---	---	---	---	---	---	---	---	---	---	1.1×10^{-10}	---	---	---	---	---	---	---	1.1×10^{-10}
^{93}Zr	---	---	---	---	1.1×10^{-3}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.1×10^{-3}
Total:	6.5×10^{2}	2.7×10^{2}	4.0×10^{-1}	2.2×10^{3}	9.3×10^{1}	1.5×10	3.5×10^{5}	5.8×10^{2}	1.6×10^{5}	5.3×10^{4}	2.22×10^{0}	4.86×10^{3}	6.68×10^{4}	3.36×10^{0}	2.96×10^{5}	1.33×10^{6}	1.13×10^{5}	3.27×10^{2}	1.33×10^{6}	6.38×10^{5}	4.34×10^{6}

[1] Decayed through December 31, 2001

Table DATA-F-36. RH-TRU Waste Curies on a Site-by-Site Basis [1]

Radionuclide	AE	AW	BC	BT	ET	IN	KA	LA	OR	RL	RP	SA	SR	Total Of Curies
^{225}Ac	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{227}Ac	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.9×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.3 \text{ X } 10^{-5}$	---	---	$4.4 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{228}Ac	1.1×10^{-15}	1.2×10^{-14}	---	---	9.2×10^{-18}	2.4×10^{-16}	3.5×10^{-11}	$1.0 \text{ X } 10^{-16}$	$8.3 \text{ X } 10^{-1}$	---	---	$1.2 \text{ X } 10^{-18}$	---	$8.3 \text{ X } 10^{-1}$
^{110}Ag	---	---	---	---	---	---	---	---	$1.1 \text{ X } 10^{-10}$	---	---	---	---	$1.1 \text{ X } 10^{-10}$
^{110m}Ag	---	---	---	---	---	---	---	---	$8.5 \text{ X } 10^{-9}$	---	---	---	---	$8.5 \text{ X } 10^{-9}$
^{241}Am	1.0×10^{1}	1.2×10^{1}	8.6×10^{1}	2.5×10^{0}	6.5×10^{-1}	3.0×10^{1}	3.0×10^{-2}	$2.5 \text{ X } 10^{-2}$	$3.2 \text{ X } 10^{2}$	$4.5 \text{ X } 10^{3}$	$1.1 \text{ X } 10^{4}$	$2.1 \text{ X } 10^{1}$	---	$1.6 \text{ X } 10^{4}$
^{242}Am	---	5.0×10^{-3}	---	---	---	---	---	---	---	---	---	---	---	$5.0 \text{ X } 10^{-3}$
^{242m}Am	---	5.0×10^{-3}	2.0×10^{-1}	---	---	---	---	---	---	---	---	---	---	$2.1 \text{ X } 10^{-1}$
^{243}Am	3.2×10^{-5}	5.4×10^{-4}	6.7×10^{-1}	1.2×10^{-2}	---	---	5.3×10^{-5}	---	$3.3 \text{ X } 10^{-1}$	---	---	---	$4.1 \text{ X } 10^{-2}$	$1.0 \text{ X } 10^{0}$
^{217}At	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{137m}Ba	4.3×10^{1}	1.6×10^{3}	---	6.2×10^{3}	9.2×10^{0}	1.9×10^{2}	7.2×10^{1}	$1.5 \text{ X } 10^{1}$	$1.5 \text{ X } 10^{4}$	$2.6 \text{ X } 10^{5}$	$1.2 \text{ X } 10^{5}$	$4.6 \text{ X } 10^{2}$	$5.8 \text{ X } 10^{1}$	$4.0 \text{ X } 10^{5}$
^{210}Bi	7.0×10^{-11}	4.3×10^{-11}	---	---	9.8×10^{-16}	9.2×10^{-11}	2.5×10^{-9}	$9.1 \text{ X } 10^{-12}$	$1.2 \text{ X } 10^{-6}$	---	---	$1.8 \text{ X } 10^{-11}$	$2.1 \text{ X } 10^{-13}$	$1.2 \text{ X } 10^{-6}$
^{211}Bi	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.8×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{212}Bi	1.1×10^{-15}	5.6×10^{-15}	---	---	5.4×10^{-18}	9.8×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{213}Bi	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{214}Bi	3.8×10^{-10}	7.2×10^{-10}	---	---	1.7×10^{-14}	1.8×10^{-9}	9.5×10^{-9}	$3.6 \text{ X } 10^{-11}$	$7.9 \text{ X } 10^{-6}$	---	---	$3.5 \text{ X } 10^{-10}$	$3.5 \text{ X } 10^{-12}$	$7.9 \text{ X } 10^{-6}$
^{14}C	---	---	---	1.6×10^{-1}	---	---	1.9×10^{-3}	---	$4.8 \text{ X } 10^{-4}$	$4.9 \text{ X } 10^{0}$	$1.0 \text{ X } 10^{0}$	---	---	$6.1 \text{ X } 10^{0}$
^{113m}Cd	5.9×10^{-1}	---	---	---	---	---	---	---	---	---	---	---	---	$5.9 \text{ X } 10^{-1}$
^{141}Ce	---	4.3×10^{-19}	---	---	---	---	---	---	---	---	---	---	---	$4.3 \text{ X } 10^{-19}$
^{144}Ce	2.0×10^{-9}	7.3×10^{0}	---	---	---	---	---	---	$6.2 \text{ X } 10^{-7}$	---	---	---	---	$7.3 \text{ X } 10^{0}$
^{249}Cf	---	---	---	2.3×10^{-10}	---	---	4.0×10^{-12}	---	$4.9 \text{ X } 10^{-3}$	---	---	---	---	$4.9 \text{ X } 10^{-3}$
^{250}Cf	---	---	---	---	---	---	---	---	$8.7 \text{ X } 10^{-2}$	---	---	---	---	$8.7 \text{ X } 10^{-2}$
^{251}Cf	---	---	---	1.1×10^{-11}	---	---	5.0×10^{-14}	---	$9.3 \text{ X } 10^{-4}$	---	---	---	---	$9.3 \text{ X } 10^{-4}$
^{252}Cf	---	---	---	---	---	---	1.9×10^{-15}	---	$1.0 \text{ X } 10^{-1}$	---	---	---	---	$1.0 \text{ X } 10^{-1}$
^{242}Cm	1.5×10^{-21}	4.2×10^{-3}	---	---	---	---	---	---	$8.9 \text{ X } 10^{-12}$	---	---	---	---	$4.2 \text{ X } 10^{-3}$
^{243}Cm	---	1.4×10^{-4}	4.6×10^{-1}	1.3×10^{-2}	---	---	1.5×10^{-5}	---	$3.1 \text{ X } 10^{-7}$	---	---	$3.8 \text{ X } 10^{-2}$	---	$5.1 \text{ X } 10^{-1}$

Table DATA-F-36. RH-TRU Waste Curies on a Site-by-Site Basis [1]— Continued

Radionuclide	AE	AW	BC	BT	ET	IN	KA	LA	OR	RL	RP	SA	SR	Total Of Curies
^{244}Cm	1.9×10^{-1}	4.4×10^{-3}	6.8×10^{1}	7.6×10^{-1}	---	---	1.5×10^{-3}	---	$1.2 \text{ X } 10^{3}$	---	---	$4.2 \text{ X } 10^{-1}$	---	$1.3 \text{ X } 10^{3}$
^{245}Cm	---	---	1.1×10^{-2}	8.1×10^{-5}	---	---	4.9×10^{-7}	---	$6.9 \text{ X } 10^{-6}$	---	---	---	---	$1.1 \text{ X } 10^{-2}$
^{246}Cm	---	---	1.6×10^{-4}	1.4×10^{-5}	---	---	6.3×10^{-8}	---	$3.9 \text{ X } 10^{0}$	---	---	---	---	$3.9 \text{ X } 10^{0}$
^{247}Cm	---	---	---	3.2×10^{-11}	---	---	1.5×10^{-13}	---	$7.1 \text{ X } 10^{-10}$	---	---	---	$5.5 \text{ X } 10^{1}$	$5.5 \text{ X } 10^{1}$
^{248}Cm	---	---	---	5.8×10^{-11}	---	---	3.0×10^{-13}	---	$1.1 \text{ X } 10^{-2}$	---	---	---	---	$1.1 \text{ X } 10^{-2}$
^{60}Co	2.2×10^{-1}	1.7×10^{1}	5.0×10^{2}	2.8×10^{2}	---	---	---	---	$1.7 \text{ X } 10^{2}$	$8.8 \text{ X } 10^{2}$	---	$3.3 \text{ X } 10^{-2}$	---	$1.8 \text{ X } 10^{3}$
^{134}Cs	8.8×10^{-5}	2.5×10^{1}	2.7×10^{-4}	---	---	---	---	---	$4.5 \text{ X } 10^{-3}$	---	---	$1.6 \text{ X } 10^{1}$	---	$4.2 \text{ X } 10^{1}$
^{135}Cs	---	---	---	---	---	---	4.0×10^{-4}	---	---	---	---	---	---	$4.0 \text{ X } 10^{-4}$
^{137}Cs	4.5×10^{1}	1.7×10^{3}	2.3×10^{3}	6.4×10^{3}	9.8×10^{0}	2.0×10^{2}	7.7×10^{1}	$1.6 \text{ X } 10^{1}$	$1.6 \text{ X } 10^{4}$	$2.8 \text{ X } 10^{5}$	$1.2 \text{ X } 10^{5}$	$4.9 \text{ X } 10^{2}$	$6.2 \text{ X } 10^{1}$	$4.3 \text{ X } 10^{5}$
^{152}Eu	1.7×10^{-4}	---	1.4×10^{-2}	2.8×10^{2}	---	---	---	---	$2.4 \text{ X } 10^{3}$	---	---	---	---	$2.7 \text{ X } 10^{3}$
^{154}Eu	8.2×10^{-3}	3.6×10^{0}	3.8×10^{-1}	2.8×10^{2}	---	---	---	---	$8.2 \text{ X } 10^{2}$	---	---	$1.3 \text{ X } 10^{0}$	---	$1.1 \text{ X } 10^{3}$
^{155}Eu	1.0×10^{-2}	2.2×10^{1}	---	---	---	---	---	$7.9 \text{ X } 10^{-3}$	$8.2 \text{ X } 10^{1}$	---	---	---	---	$1.0 \text{ X } 10^{2}$
^{55}Fe	1.5×10^{-1}	---	---	---	---	---	---	---	---	---	---	---	---	$1.5 \text{ X } 10^{-1}$
^{221}Fr	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{223}Fr	4.0×10^{-10}	4.5×10^{-10}	---	---	2.4×10^{-10}	2.9×10^{-10}	6.6×10^{-10}	$3.3 \text{ X } 10^{-10}$	$3.1 \text{ X } 10^{-7}$	---	---	$6.0 \text{ X } 10^{-11}$	---	$3.1 \text{ X } 10^{-7}$
^{152}Gd	1.7×10^{-17}	---	---	---	---	---	---	---	$1.1 \text{ X } 10^{-10}$	---	---	---	---	$1.1 \text{ X } 10^{-10}$
^{3}H	---	6.8×10^{-4}	---	---	---	---	---	---	$2.6 \text{ X } 10^{-1}$	$6.4 \text{ X } 10^{0}$	---	---	---	$6.7 \text{ X } 10^{0}$
^{129}I	---	---	---	2.1×10^{-3}	---	---	3.7×10^{-5}	---	---	$1.9 \text{ X } 10^{-3}$	$8.0 \text{ X } 10^{-2}$	---	---	$8.4 \text{ X } 10^{-2}$
^{85}Kr	4.1×10^{-1}	---	---	---	---	---	---	---	---	---	---	---	---	$4.1 \text{ X } 10^{-1}$
^{54}Mn	2.5×10^{-9}	2.1×10^{0}	---	---	---	---	---	---	---	---	---	---	---	$2.1 \text{ X } 10^{0}$
^{22}Na	---	3.3×10^{-1}	---	---	---	---	---	---	---	---	---	---	---	$3.3 \text{ X } 10^{-1}$
^{93m}Nb	9.2×10^{-4}	---	---	---	---	---	1.2×10^{-4}	---	---	---	---	---	---	$1.0 \text{ X } 10^{-3}$
^{95}Nb	---	2.4×10^{-13}	---	---	---	---	---	---	---	---	---	---	---	$2.4 \text{ X } 10^{-13}$
^{95m}Nb	---	8.1×10^{-16}	---	---	---	---	---	---	---	---	---	---	---	$8.1 \text{ X } 10^{-16}$
^{59}Ni	---	---	---	2.3×10^{1}	---	---	1.7×10^{-4}	---	---	---	---	---	---	$2.3 \text{ X } 10^{1}$
^{63}Ni	---	---	---	1.1×10^{3}	---	---	1.9×10^{-2}	---	---	---	---	---	---	$1.1 \text{ X } 10^{3}$
^{237}Np	1.7×10^{-3}	1.9×10^{-3}	1.2×10^{-2}	1.7×10^{-2}	2.6×10^{-6}	6.8×10^{-5}	8.5×10^{-4}	$1.6 \text{ X } 10^{-7}$	$1.8 \text{ X } 10^{-3}$	$2.6 \text{ X } 10^{-6}$	$6.4 \text{ X } 10^{-1}$	$9.0 \text{ X } 10^{-4}$	---	$6.7 \text{ X } 10^{-1}$

Table DATA-F-36. RH-TRU Waste Curies on a Site-by-Site Basis [1]— Continued

Radionuclide	AE	AW	BC	BT	ET	IN	KA	LA	OR	RL	RP	SA	SR	Total Of Curies
^{238}Np	---	2.5×10^{-5}	---	---	---	---	---	---	---	---	---	---	---	$2.5 \text{ X } 10^{-5}$
^{239}Np	3.1×10^{-5}	5.3×10^{-4}	---	---	---	---	5.2×10^{-5}	---	$3.2 \text{ X } 10^{-1}$	---	---	---	$4.1 \text{ X } 10^{-2}$	$3.7 \text{ X } 10^{-1}$
^{240m}Np	---	---	---	---	---	---	1.7×10^{-12}	---	$6.5 \text{ X } 10^{-3}$	---	---	---	---	$6.5 \text{ X } 10^{-3}$
^{231}Pa	8.9×10^{-8}	3.7×10^{-7}	---	---	1.5×10^{-7}	2.0×10^{-7}	9.7×10^{-8}	$6.6 \text{ X } 10^{-8}$	$9.9 \text{ X } 10^{-5}$	---	---	$5.8 \text{ X } 10^{-8}$	$5.3 \text{ X } 10^{-19}$	$1.0 \text{ X } 10^{-4}$
^{233}Pa	1.6×10^{-3}	1.9×10^{-3}	---	---	2.6×10^{-6}	6.7×10^{-5}	8.4×10^{-4}	$1.6 \text{ X } 10^{-7}$	$1.8 \text{ X } 10^{-3}$	---	---	$9.0 \text{ X } 10^{-4}$	---	$7.1 \text{ X } 10^{-3}$
^{234}Pa	7.8×10^{-8}	5.9×10^{-7}	---	---	2.9×10^{-6}	1.4×10^{-15}	4.1×10^{-10}	$5.7 \text{ X } 10^{-10}$	$1.6 \text{ X } 10^{-2}$	---	---	$2.4 \text{ X } 10^{-7}$	---	$1.6 \text{ X } 10^{-2}$
^{234m}Pa	6.0×10^{-5}	4.6×10^{-4}	---	---	2.2×10^{-3}	1.1×10^{-12}	3.1×10^{-7}	$4.3 \text{ X } 10^{-7}$	$1.3 \text{ X } 10^{1}$	---	---	$1.8 \text{ X } 10^{-4}$	---	$1.3 \text{ X } 10^{1}$
^{209}Pb	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{210}Pb	7.0×10^{-11}	4.3×10^{-11}	---	---	9.9×10^{-16}	9.3×10^{-11}	2.5×10^{-9}	$9.2 \text{ X } 10^{-12}$	$1.2 \text{ X } 10^{-6}$	---	---	$1.8 \text{ X } 10^{-11}$	$2.1 \text{ X } 10^{-13}$	$1.2 \text{ X } 10^{-6}$
^{211}Pb	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.8×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{212}Pb	1.1×10^{-15}	5.6×10^{-15}	---	---	5.4×10^{-18}	9.8×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{214}Pb	3.9×10^{-10}	7.2×10^{-10}	---	---	1.7×10^{-14}	1.8×10^{-9}	9.5×10^{-9}	$3.6 \text{ X } 10^{-11}$	$7.9 \text{ X } 10^{-6}$	---	---	$3.5 \text{ X } 10^{-10}$	$3.5 \text{ X } 10^{-12}$	$7.9 \text{ X } 10^{-6}$
^{107}Pd	---	---	---	---	---	---	1.7×10^{-5}	---	---	---	---	---	---	$1.7 \text{ X } 10^{-5}$
^{147}Pm	3.0×10^{-2}	3.7×10^{2}	---	2.8×10^{2}	---	---	5.9×10^{-2}	---	---	---	---	$7.0 \text{ X } 10^{0}$	$2.2 \text{ X } 10^{0}$	$6.6 \text{ X } 10^{2}$
^{210}Po	7.0×10^{-11}	4.3×10^{-11}	---	---	9.9×10^{-16}	9.3×10^{-11}	2.0×10^{-9}	$9.2 \text{ X } 10^{-12}$	$1.2 \text{ X } 10^{-6}$	---	---	$1.8 \text{ X } 10^{-11}$	$2.1 \text{ X } 10^{-13}$	$1.2 \text{ X } 10^{-6}$
^{211}Po	8.8×10^{-11}	1.0×10^{-10}	---	---	5.4×10^{-11}	6.3×10^{-11}	1.5×10^{-10}	$7.2 \text{ X } 10^{-11}$	$6.8 \text{ X } 10^{-8}$	---	---	$1.3 \text{ X } 10^{-11}$	---	$6.9 \text{ X } 10^{-8}$
^{212}Po	6.8×10^{-16}	3.5×10^{-15}	---	---	3.5×10^{-18}	6.3×10^{-17}	6.6×10^{-6}	$6.6 \text{ X } 10^{-17}$	$1.0 \text{ X } 10^{1}$	---	---	$2.1 \text{ X } 10^{-19}$	---	$1.0 \text{ X } 10^{1}$
^{213}Po	4.5×10^{-7}	1.1×10^{-4}	---	---	3.1×10^{-14}	2.2×10^{-13}	9.4×10^{-10}	$6.0 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.5 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{214}Po	3.9×10^{-10}	7.2×10^{-10}	---	---	1.7×10^{-14}	1.8×10^{-9}	9.5×10^{-9}	$3.6 \text{ X } 10^{-11}$	$7.9 \text{ X } 10^{-6}$	---	---	$3.5 \text{ X } 10^{-10}$	$3.5 \text{ X } 10^{-12}$	$7.9 \text{ X } 10^{-6}$
^{215}Po	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.8×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{216}Po	1.1×10^{-15}	5.5×10^{-15}	---	---	5.4×10^{-18}	9.8×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{218}Po	3.8×10^{-10}	7.1×10^{-10}	---	---	1.6×10^{-14}	1.7×10^{-9}	9.3×10^{-9}	$3.5 \text{ X } 10^{-11}$	$7.8 \text{ X } 10^{-6}$	---	---	$3.5 \text{ X } 10^{-10}$	$3.5 \text{ X } 10^{-12}$	$7.8 \text{ X } 10^{-6}$
^{144}Pr	2.0×10^{-9}	7.1×10^{0}	---	---	---	---	---	---	$6.1 \text{ X } 10^{-7}$	---	---	---	---	$7.1 \text{ X } 10^{0}$
^{238}Pu	9.2×10^{0}	1.2×10^{0}	7.8×10^{1}	2.8×10^{2}	1.5×10^{-2}	2.7×10^{3}	2.8×10^{0}	$1.3 \text{ X } 10^{-2}$	$2.5 \text{ X } 10^{2}$	$1.1 \text{ X } 10^{3}$	$1.0 \text{ X } 10^{1}$	$4.2 \text{ X } 10^{0}$	$3.6 \text{ X } 10^{0}$	$4.5 \text{ X } 10^{3}$
^{239}Pu	1.8×10^{1}	4.2×10^{1}	1.0×10^{1}	2.2×10^{-1}	1.1×10^{0}	3.5×10^{1}	7.6×10^{-3}	$2.5 \text{ X } 10^{0}$	$1.4 \text{ X } 10^{2}$	$2.3 \text{ X } 10^{3}$	$4.2 \text{ X } 10^{3}$	$2.8 \text{ X } 10^{0}$	$4.8 \text{ X } 10^{-6}$	$6.8 \text{ X } 10^{3}$
^{240}Pu	3.8×10^{0}	2.3×10^{1}	1.6×10^{1}	4.5×10^{-1}	2.7×10^{-1}	3.3×10^{1}	1.9×10^{-3}	$2.7 \text{ X } 10^{-2}$	$3.4 \text{ X } 10^{1}$	$1.3 \text{ X } 10^{3}$	$1.0 \text{ X } 10^{3}$	$4.3 \text{ X } 10^{-1}$	---	$2.4 \text{ X } 10^{3}$
^{241}Pu	3.0×10^{1}	7.2×10^{2}	1.3×10^{3}	4.8×10^{1}	2.2×10^{0}	6.6×10^{1}	2.7×10^{-1}	$2.2 \text{ X } 10^{-1}$	$1.5 \text{ X } 10^{2}$	$1.4 \text{ X } 10^{5}$	$1.8 \text{ X } 10^{4}$	$2.5 \text{ X } 10^{-2}$	---	$1.6 \text{ X } 10^{5}$

Table DATA-F-36. RH-TRU Waste Curies on a Site-by-Site Basis [1]— Continued

Radionuclide	AE	AW	BC	BT	ET	IN	KA	LA	OR	RL	RP	SA	SR	Total Of Curies
^{242}Pu	---	5.5×10^{-4}	4.8×10^{-2}	3.5×10^{-3}	---	1.0×10^{-3}	7.2×10^{-6}	$1.6 \text{ X } 10^{-5}$	$7.1 \text{ X } 10^{-2}$	$4.4 \text{ X } 10^{-1}$	$2.2 \text{ X } 10^{-1}$	---	---	$7.8 \text{ X } 10^{-1}$
^{243}Pu	---	---	---	---	---	---	1.5×10^{-13}	---	$7.0 \text{ X } 10^{-10}$	---	---	---	$5.4 \text{ X } 10^{1}$	$5.4 \text{ X } 10^{1}$
^{244}Pu	---	---	---	2.0×10^{-10}	---	---	1.7×10^{-12}	---	$6.4 \text{ X } 10^{-3}$	---	---	---	---	$6.4 \text{ X } 10^{-3}$
^{223}Ra	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.9×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.3 \text{ X } 10^{-5}$	---	---	$4.4 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{224}Ra	1.1×10^{-15}	5.5×10^{-15}	---	---	5.4×10^{-18}	9.8×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{225}Ra	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{226}Ra	3.9×10^{-10}	7.3×10^{-10}	---	---	1.7×10^{-14}	1.8×10^{-9}	9.6×10^{-9}	$3.6 \text{ X } 10^{-11}$	$8.0 \text{ X } 10^{-6}$	---	---	$3.6 \text{ X } 10^{-10}$	$3.6 \text{ X } 10^{-12}$	$8.0 \text{ X } 10^{-6}$
^{228}Ra	1.3×10^{-15}	1.4×10^{-14}	---	---	1.1×10^{-17}	2.8×10^{-16}	4.1×10^{-11}	$1.2 \text{ X } 10^{-16}$	$9.8 \text{ X } 10^{-1}$	---	---	$1.4 \text{ X } 10^{-18}$	---	$9.8 \text{ X } 10^{-1}$
^{106}Rh	3.6×10^{-7}	---	---	---	---	---	---	$1.3 \text{ X } 10^{-10}$	$2.2 \text{ X } 10^{-3}$	$3.9 \text{ X } 10^{-1}$	---	---	---	$4.0 \text{ X } 10^{-1}$
^{219}Rn	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.8×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{220}Rn	1.1×10^{-15}	5.6×10^{-15}	---	---	5.4×10^{-18}	9.8×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{222}Rn	3.9×10^{-10}	7.2×10^{-10}	---	---	1.7×10^{-14}	1.8×10^{-9}	9.5×10^{-9}	$3.6 \text{ X } 10^{-11}$	$7.9 \text{ X } 10^{-6}$	---	---	$3.5 \text{ X } 10^{-10}$	$3.5 \text{ X } 10^{-12}$	$7.9 \text{ X } 10^{-6}$
^{106}Ru	3.6×10^{-7}	---	---	---	---	---	---	$1.3 \text{ X } 10^{-10}$	$2.3 \text{ X } 10^{-3}$	$3.9 \text{ X } 10^{-1}$	---	---	---	$4.0 \text{ X } 10^{-1}$
^{125}Sb	3.7×10^{-3}	5.0×10^{0}	2.8×10^{-3}	---	---	---	---	$5.5 \text{ X } 10^{-4}$	$1.3 \text{ X } 10^{-2}$	---	---	---	---	$5.0 \text{ X } 10^{0}$
^{126}Sb	1.2×10^{-4}	---	---	---	---	---	4.7×10^{-5}	---	---	---	---	---	---	$1.7 \text{ X } 10^{-4}$
^{126m}Sb	8.7×10^{-4}	---	---	---	---	---	3.4×10^{-4}	---	---	---	---	---	---	$1.2 \text{ X } 10^{-3}$
^{79}Se	---	---	---	4.0×10^{-2}	---	---	1.0×10^{-4}	---	---	$2.8 \text{ X } 10^{-2}$	---	---	---	$6.7 \text{ X } 10^{-2}$
^{147}Sm	9.3×10^{-10}	3.5×10^{-8}	---	---	---	---	4.4×10^{-13}	---	---	---	---	$4.7 \text{ X } 10^{-10}$	$4.0 \text{ X } 10^{-10}$	$3.7 \text{ X } 10^{-8}$
^{151}Sm	2.0×10^{0}	3.5×10^{1}	---	3.1×10^{1}	---	---	1.2×10^{0}	---	---	$3.5 \text{ X } 10^{2}$	$2.4 \text{ X } 10^{2}$	---	---	$6.6 \text{ X } 10^{2}$
^{121m}Sn	---	---	---	---	---	---	3.0×10^{-3}	---	---	---	---	---	---	$3.0 \text{ X } 10^{-3}$
^{126}Sn	8.7×10^{-4}	---	---	---	---	---	3.4×10^{-4}	---	---	---	---	---	---	$1.2 \text{ X } 10^{-3}$
^{90}Sr	2.6×10^{1}	1.3×10^{3}	1.5×10^{3}	6.4×10^{3}	9.5×10^{0}	---	7.3×10^{1}	---	$5.6 \text{ X } 10^{4}$	$1.9 \text{ X } 10^{5}$	$7.5 \text{ X } 10^{4}$	$4.9 \text{ X } 10^{2}$	$5.8 \text{ X } 10^{1}$	$3.3 \text{ X } 10^{5}$
^{99}Tc	1.1×10^{-2}	---	4.4×10^{-1}	1.4×10^{0}	---	---	2.1×10^{-2}	---	$6.5 \text{ X } 10^{-9}$	$6.6 \text{ X } 10^{-3}$	$1.6 \text{ X } 10^{2}$	---	---	$1.6 \text{ X } 10^{2}$
^{125m}Te	8.9×10^{-4}	1.2×10^{0}	---	---	---	---	---	$1.3 \text{ X } 10^{-4}$	$3.1 \text{ X } 10^{-3}$	---	---	---	---	$1.2 \text{ X } 10^{0}$
^{227}Th	2.8×10^{-8}	3.2×10^{-8}	---	---	1.7×10^{-8}	2.0×10^{-8}	4.7×10^{-8}	$2.3 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.2 \text{ X } 10^{-5}$
^{228}Th	1.1×10^{-15}	5.6×10^{-15}	---	---	5.5×10^{-18}	9.9×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{229}Th	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$

Table DATA-F-36. RH-TRU Waste Curies on a Site-by-Site Basis [1]— Continued

Radionuclide	AE	AW	BC	BT	ET	IN	KA	LA	OR	RL	RP	SA	SR	Total Of Curies
^{230}Th	9.8×10^{-8}	5.6×10^{-7}	---	---	1.4×10^{-11}	1.8×10^{-6}	1.4×10^{-6}	$5.5 \text{ X } 10^{-9}$	$2.2 \text{ X } 10^{-3}$	---	---	$3.3 \text{ X } 10^{-7}$	$3.1 \text{ X } 10^{-9}$	$2.2 \text{ X } 10^{-3}$
^{231}Th	1.5×10^{-4}	2.9×10^{-3}	---	---	8.9×10^{-4}	1.3×10^{-3}	7.1×10^{-5}	$9.9 \text{ X } 10^{-5}$	$2.7 \text{ X } 10^{-1}$	---	---	$5.4 \text{ X } 10^{-4}$	$1.2 \text{ X } 10^{-14}$	$2.8 \text{ X } 10^{-1}$
^{232}Th	2.0×10^{-15}	4.7×10^{-14}	---	1.7×10^{-11}	2.9×10^{-17}	1.2×10^{-15}	4.1×10^{-11}	$1.5 \text{ X } 10^{-16}$	$1.0 \text{ X } 10^{0}$	$4.3 \text{ X } 10^{-2}$	---	$7.8 \text{ X } 10^{-18}$	---	$1.1 \text{ X } 10^{0}$
^{234}Th	6.0×10^{-5}	4.6×10^{-4}	---	---	2.2×10^{-3}	1.1×10^{-12}	3.1×10^{-7}	$4.4 \text{ X } 10^{-7}$	$1.3 \text{ X } 10^{1}$	---	---	$1.8 \text{ X } 10^{-4}$	---	$1.3 \text{ X } 10^{1}$
^{207}Tl	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.8×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.2 \text{ X } 10^{-5}$
^{208}Tl	3.8×10^{-16}	2.0×10^{-15}	2.3×10^{-3}	---	2.0×10^{-18}	3.5×10^{-17}	3.7×10^{-6}	$3.7 \text{ X } 10^{-17}$	$5.6 \text{ X } 10^{0}$	---	---	$1.2 \text{ X } 10^{-19}$	---	$5.6 \text{ X } 10^{0}$
^{209}Tl	1.0×10^{-8}	2.6×10^{-6}	---	---	7.1×10^{-16}	4.9×10^{-15}	2.1×10^{-11}	$1.3 \text{ X } 10^{-16}$	$4.7 \text{ X } 10^{-3}$	---	---	$1.0 \text{ X } 10^{-13}$	---	$4.7 \text{ X } 10^{-3}$
^{232}U	---	---	7.3×10^{-4}	4.0×10^{-3}	---	---	3.4×10^{-5}	---	$1.5 \text{ X } 10^{1}$	---	---	---	---	$1.5 \text{ X } 10^{1}$
^{233}U	1.8×10^{-4}	2.1×10^{-1}	1.3×10^{-6}	---	7.6×10^{-11}	1.0×10^{-9}	3.9×10^{-7}	$7.9 \text{ X } 10^{-12}$	$1.3 \text{ X } 10^{2}$	$8.5 \text{ X } 10^{0}$	$2.3 \text{ X } 10^{0}$	$1.9 \text{ X } 10^{-8}$	---	$1.5 \text{ X } 10^{2}$
^{234}U	7.8×10^{-4}	1.0×10^{-2}	2.8×10^{-2}	6.0×10^{-1}	4.0×10^{-7}	5.5×10^{-2}	4.8×10^{-3}	$2.0 \text{ X } 10^{-5}$	$1.4 \text{ X } 10^{1}$	$9.2 \text{ X } 10^{0}$	$1.5 \text{ X } 10^{1}$	$7.4 \text{ X } 10^{-3}$	$8.4 \text{ X } 10^{-5}$	$3.9 \text{ X } 10^{1}$
^{235}U	1.6×10^{-4}	2.9×10^{-3}	4.1×10^{-4}	7.8×10^{-3}	9.0×10^{-4}	1.4×10^{-3}	7.2×10^{-5}	$1.0 \text{ X } 10^{-4}$	$2.8 \text{ X } 10^{-1}$	$5.3 \text{ X } 10^{-1}$	$5.6 \text{ X } 10^{-1}$	$5.5 \text{ X } 10^{-4}$	$1.3 \text{ X } 10^{-14}$	$1.4 \text{ X } 10^{0}$
^{236}U	3.1×10^{-6}	1.6×10^{-4}	5.4×10^{-3}	8.9×10^{-2}	9.4×10^{-8}	6.8×10^{-6}	6.8×10^{-4}	$1.1 \text{ X } 10^{-7}$	$4.9 \text{ X } 10^{-2}$	$8.3 \text{ X } 10^{-1}$	$1.2 \text{ X } 10^{0}$	$6.3 \text{ X } 10^{-8}$	---	$2.2 \text{ X } 10^{0}$
^{237}U	7.3×10^{-4}	1.8×10^{-2}	---	---	5.4×10^{-5}	1.6×10^{-3}	6.6×10^{-6}	$5.5 \text{ X } 10^{-6}$	$3.7 \text{ X } 10^{-3}$	---	---	$6.1 \text{ X } 10^{-7}$	---	$2.4 \text{ X } 10^{-2}$
^{238}U	6.1×10^{-5}	4.6×10^{-4}	8.0×10^{-3}	3.6×10^{-5}	2.2×10^{-3}	1.1×10^{-12}	3.2×10^{-7}	$4.4 \text{ X } 10^{-7}$	$1.3 \text{ X } 10^{1}$	$4.5 \text{ X } 10^{0}$	$1.3 \text{ X } 10^{2}$	$1.8 \text{ X } 10^{-4}$	---	$1.4 \text{ X } 10^{2}$
^{240}U	---	---	---	---	---	---	1.7×10^{-12}	---	$6.4 \text{ X } 10^{-3}$	---	---	---	---	$6.4 \text{ X } 10^{-3}$
^{90}Y	2.5×10^{1}	1.3×10^{3}	---	6.4×10^{3}	9.4×10^{0}	---	7.2×10^{1}	---	$5.5 \text{ X } 10^{4}$	$1.8 \text{ X } 10^{5}$	$7.5 \text{ X } 10^{4}$	$4.8 \text{ X } 10^{2}$	$5.7 \text{ X } 10^{1}$	$3.2 \text{ X } 10^{5}$
^{91}Y	---	4.7×10^{-12}	---	---	---	---	---	---	---	---	---	---	---	$4.7 \text{ X } 10^{-12}$
^{93}Zr	1.3×10^{-3}	---	---	3.4×10^{-1}	---	---	2.6×10^{-3}	---	---	---	---	---	---	$3.4 \text{ X } 10^{-1}$
^{95}Zr	---	1.1×10^{-13}	---	---	---	---	---	---	---	---	---	---	---	$1.1 \text{ X } 10^{-13}$
Total:	2.1×10^{2}	7.2×10^{3}	5.8×10^{3}	2.8×10^{4}	4.2×10^{1}	3.3×10^{3}	3.0×10^{2}	$3.3 \text{ X } 10^{1}$	$1.5 \text{ X } 10^{5}$	$1.1 \text{ X } 10^{6}$	$4.3 \text{ X } 10^{5}$	$2.0 \text{ X } 10^{3}$	$3.5 \text{ X } 10^{2}$	$1.7 \text{ X } 10^{6}$

[1] Decayed through December 31, 2001

Table DATA-F-37. WIPP Disposal Radionuclide Inventory for the CRA[1, 2]

Radionuclide	CH Concentration (Ci/m^3)	RH Concentration (Ci/m^3)	CH-TRU Curies	RH-TRU Curies
^{225}Ac	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{227}Ac	3.0×10^{-6}	5.7×10^{-10}	5.1×10^{-1}	4.0×10^{-6}
^{228}Ac	2.8×10^{-5}	2.0×10^{-5}	4.8×10^{0}	1.4×10^{-1}
^{109m}Ag	7.5×10^{-10}	NR	1.3×10^{-4}	NR
^{110}Ag	2.6×10^{-16}	2.7×10^{-15}	4.4×10^{-11}	1.9×10^{-11}
^{110m}Ag	2.0×10^{-14}	2.1×10^{-13}	3.3×10^{-9}	1.5×10^{-9}
^{241}Am	2.4×10^{0}	1.9×10^{0}	4.0×10^{5}	1.4×10^{4}
^{242}Am	2.8×10^{-7}	1.2×10^{-7}	4.7×10^{-2}	8.5×10^{-4}
^{242m}Am	2.8×10^{-7}	2.8×10^{-5}	4.8×10^{-2}	2.0×10^{-1}
^{243}Am	1.3×10^{-4}	1.0×10^{-4}	2.1×10^{1}	7.2×10^{-1}
^{245}Am	7.8×10^{-16}	NR	1.3×10^{-10}	NR
^{217}At	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{137m}Ba	5.4×10^{-2}	4.7×10^{1}	9.1×10^{3}	3.4×10^{5}
^{210}Bi	1.5×10^{-5}	3.0×10^{-11}	2.6×10^{0}	2.1×10^{-7}
^{211}Bi	3.0×10^{-6}	5.6×10^{-10}	5.0×10^{-1}	4.0×10^{-6}
^{212}Bi	3.5×10^{-5}	3.8×10^{-4}	5.8×10^{0}	2.7×10^{0}
^{213}Bi	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{214}Bi	3.7×10^{-5}	1.9×10^{-10}	6.3×10^{0}	1.4×10^{-6}
^{249}Bk	5.4×10^{-11}	NR	9.1×10^{-6}	NR
^{250}Bk	2.2×10^{-17}	NR	3.7×10^{-12}	NR
^{14}C	7.2×10^{-6}	2.9×10^{-4}	1.2×10^{0}	2.1×10^{0}
^{109}Cd	7.6×10^{-10}	NR	1.3×10^{-4}	NR
^{113m}Cd	NR	2.3×10^{-5}	NR	1.6×10^{-1}
^{141}Ce	NR	5.3×10^{-23}	NR	3.8×10^{-19}
^{144}Ce	2.1×10^{-9}	2.6×10^{-4}	3.6×10^{-4}	1.8×10^{0}
^{249}Cf	4.5×10^{-7}	1.2×10^{-7}	7.6×10^{-2}	8.4×10^{-4}
^{250}Cf	1.1×10^{-6}	2.1×10^{-6}	1.8×10^{-1}	1.5×10^{-2}
^{251}Cf	2.2×10^{-9}	2.3×10^{-8}	3.6×10^{-4}	1.6×10^{-4}
^{252}Cf	1.2×10^{-6}	2.5×10^{-6}	2.1×10^{-1}	1.8×10^{-2}
^{242}Cm	2.3×10^{-7}	1.0×10^{-7}	3.9×10^{-2}	7.2×10^{-4}
^{243}Cm	2.4×10^{-6}	6.9×10^{-5}	4.0×10^{-1}	4.9×10^{-1}
^{244}Cm	6.9×10^{-2}	3.8×10^{-2}	1.2×10^{4}	2.7×10^{2}
^{245}Cm	5.0×10^{-8}	1.5×10^{-6}	8.4×10^{-3}	1.1×10^{-2}
^{246}Cm	9.2×10^{-6}	9.5×10^{-5}	1.6×10^{0}	6.7×10^{-1}
^{247}Cm	1.7×10^{-15}	1.3×10^{-3}	2.8×10^{-10}	9.4×10^{0}
^{248}Cm	5.4×10^{-7}	2.6×10^{-7}	9.1×10^{-2}	1.8×10^{-3}

Table DATA-F-37. WIPP Disposal Radionuclide Inventory for the CRA[1, 2]—Continued

Radionuclide	CH Concentration (Ci/m^3)	RH Concentration (Ci/m^3)	CH-TRU Curies	RH-TRU Curies
^{250}Cm	3.9×10^{-16}	NR	6.6×10^{-11}	NR
^{60}Co	5.9×10^{-6}	2.4×10^{-1}	9.9×10^{-1}	1.7×10^{3}
^{134}Cs	1.2×10^{-7}	4.8×10^{-3}	2.1×10^{-2}	3.4×10^{1}
^{135}Cs	NR	9.8×10^{-9}	NR	6.9×10^{-5}
^{137}Cs	5.7×10^{-2}	5.2×10^{1}	9.7×10^{3}	3.7×10^{5}
^{152}Eu	1.2×10^{-5}	9.8×10^{-2}	2.0×10^{0}	7.0×10^{2}
^{154}Eu	9.8×10^{-6}	6.0×10^{-2}	1.7×10^{0}	4.2×10^{2}
^{155}Eu	4.0×10^{-7}	2.6×10^{-3}	6.7×10^{-2}	1.9×10^{1}
^{55}Fe	NR	5.9×10^{-6}	NR	4.2×10^{-2}
^{221}Fr	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{223}Fr	4.1×10^{-8}	7.7×10^{-12}	6.9×10^{-3}	5.5×10^{-8}
^{152}Gd	2.6×10^{-19}	2.8×10^{-15}	4.4×10^{-14}	2.0×10^{-11}
^{3}H	1.3×10^{-3}	1.6×10^{-4}	2.2×10^{2}	1.2×10^{0}
^{129}I	3.0×10^{-9}	1.2×10^{-5}	5.1×10^{-4}	8.2×10^{-2}
^{85}Kr	2.7×10^{-6}	1.6×10^{-5}	4.6×10^{-1}	1.1×10^{-1}
^{54}Mn	NR	2.6×10^{-4}	NR	1.8×10^{0}
^{22}Na	2.3×10^{-12}	4.2×10^{-5}	3.9×10^{-7}	3.0×10^{-1}
^{93m}Nb	NR	3.9×10^{-8}	NR	2.8×10^{-4}
^{95}Nb	NR	1.1×10^{-17}	NR	7.5×10^{-14}
^{95m}Nb	NR	3.6×10^{-20}	NR	2.5×10^{-16}
^{59}Ni	4.5×10^{-7}	3.3×10^{-3}	7.6×10^{-2}	2.3×10^{1}
^{63}Ni	2.2×10^{-5}	1.6×10^{-1}	3.7×10^{0}	1.1×10^{3}
^{237}Np	2.8×10^{-5}	9.4×10^{-5}	4.8×10^{0}	6.7×10^{-1}
^{238}Np	1.4×10^{-9}	6.1×10^{-10}	2.4×10^{-4}	4.3×10^{-6}
^{239}Np	1.2×10^{-4}	8.9×10^{-6}	2.1×10^{1}	6.3×10^{-2}
^{240m}Np	7.8×10^{-12}	1.6×10^{-7}	1.3×10^{-6}	1.1×10^{-3}
^{231}Pa	7.2×10^{-6}	2.5×10^{-9}	1.2×10^{0}	1.8×10^{-5}
^{233}Pa	2.8×10^{-5}	3.3×10^{-7}	4.8×10^{0}	2.3×10^{-3}
^{234}Pa	5.5×10^{-8}	4.0×10^{-7}	9.3×10^{-3}	2.8×10^{-3}
^{234m}Pa	4.2×10^{-5}	3.1×10^{-4}	7.1×10^{0}	2.2×10^{0}
^{209}Pb	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{210}Pb	1.6×10^{-5}	3.0×10^{-11}	2.6×10^{0}	2.1×10^{-7}
^{211}Pb	3.0×10^{-6}	5.6×10^{-10}	5.0×10^{-1}	4.0×10^{-6}
^{212}Pb	3.5×10^{-5}	3.8×10^{-4}	5.8×10^{0}	2.7×10^{0}
^{214}Pb	3.7×10^{-5}	1.9×10^{-10}	6.3×10^{0}	1.4×10^{-6}
^{107}Pd	NR	4.1×10^{-10}	NR	2.9×10^{-6}
^{147}Pm	1.1×10^{-5}	5.0×10^{-2}	1.8×10^{0}	3.5×10^{2}

Table DATA-F-37. WIPP Disposal Radionuclide Inventory for the CRA[1, 2]—Continued

Radionuclide	CH Concentration (Ci/m^3)	RH Concentration (Ci/m^3)	CH-TRU Curies	RH-TRU Curies
^{210}Po	1.6×10^{-5}	3.0×10^{-11}	2.6×10^{0}	2.1×10^{-7}
^{211}Po	9.1×10^{-9}	1.7×10^{-12}	1.5×10^{-3}	1.2×10^{-8}
^{212}Po	2.2×10^{-5}	2.4×10^{-4}	3.7×10^{0}	1.7×10^{0}
^{213}Po	9.0×10^{-6}	5.1×10^{-6}	1.5×10^{0}	3.6×10^{-2}
^{214}Po	3.7×10^{-5}	1.9×10^{-10}	6.3×10^{0}	1.4×10^{-6}
^{215}Po	3.0×10^{-6}	5.6×10^{-10}	5.0×10^{-1}	4.0×10^{-6}
^{216}Po	3.5×10^{-5}	3.8×10^{-4}	5.8×10^{0}	2.7×10^{0}
^{218}Po	3.7×10^{-5}	1.9×10^{-10}	6.2×10^{0}	1.3×10^{-6}
^{144}Pr	2.1×10^{-9}	2.5×10^{-4}	3.5×10^{-4}	1.8×10^{0}
^{236}Pu	2.6×10^{-9}	NR	4.4×10^{-4}	NR
^{238}Pu	9.6×10^{0}	5.1×10^{-1}	1.6×10^{6}	3.6×10^{3}
^{239}Pu	3.9×10^{0}	7.6×10^{-1}	6.6×10^{5}	5.4×10^{3}
^{240}Pu	6.4×10^{-1}	2.4×10^{-1}	1.1×10^{5}	1.7×10^{3}
^{241}Pu	1.4×10^{1}	1.6×10^{1}	2.4×10^{6}	1.1×10^{5}
^{242}Pu	1.6×10^{-4}	6.7×10^{-5}	2.7×10^{1}	4.7×10^{-1}
^{243}Pu	1.6×10^{-15}	1.3×10^{-3}	2.7×10^{-10}	9.3×10^{0}
^{244}Pu	7.7×10^{-12}	1.6×10^{-7}	1.3×10^{-6}	1.1×10^{-3}
^{223}Ra	3.0×10^{-6}	5.6×10^{-10}	5.1×10^{-1}	4.0×10^{-6}
^{224}Ra	3.5×10^{-5}	3.8×10^{-4}	5.8×10^{0}	2.7×10^{0}
^{225}Ra	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{226}Ra	3.8×10^{-5}	2.0×10^{-10}	6.4×10^{0}	1.4×10^{-6}
^{228}Ra	3.4×10^{-5}	2.4×10^{-5}	5.7×10^{0}	1.7×10^{-1}
^{106}Rh	9.4×10^{-10}	9.6×10^{-6}	1.6×10^{-4}	6.8×10^{-2}
^{219}Rn	3.0×10^{-6}	5.6×10^{-10}	5.0×10^{-1}	4.0×10^{-6}
^{220}Rn	3.5×10^{-5}	3.8×10^{-4}	5.8×10^{0}	2.7×10^{0}
^{222}Rn	3.7×10^{-5}	1.9×10^{-10}	6.3×10^{0}	1.4×10^{-6}
^{106}Ru	9.5×10^{-10}	9.6×10^{-6}	1.6×10^{-4}	6.8×10^{-2}
^{125}Sb	3.0×10^{-8}	6.2×10^{-4}	5.0×10^{-3}	4.4×10^{0}
^{126}Sb	NR	5.9×10^{-9}	NR	4.2×10^{-5}
^{126m}Sb	NR	4.2×10^{-8}	NR	3.0×10^{-4}
^{79}Se	7.8×10^{-10}	6.3×10^{-6}	1.3×10^{-4}	4.5×10^{-2}
^{147}Sm	2.8×10^{-15}	9.7×10^{-13}	4.8×10^{-10}	6.9×10^{-9}
^{151}Sm	3.4×10^{-4}	8.2×10^{-2}	5.7×10^{1}	5.8×10^{2}
^{121m}Sn	NR	7.3×10^{-8}	NR	5.2×10^{-4}
^{126}Sn	NR	4.2×10^{-8}	NR	3.0×10^{-4}
^{90}Sr	3.4×10^{-1}	3.5×10^{1}	5.8×10^{4}	2.5×10^{5}
^{99}Tc	9.9×10^{-4}	2.3×10^{-2}	1.7×10^{2}	1.6×10^{2}

Table DATA-F-37. WIPP Disposal Radionuclide Inventory for the CRA[1, 2]—Continued

Radionuclide	CH Concentration (Ci/m^3)	RH Concentration (Ci/m^3)	CH-TRU Curies	RH-TRU Curies
^{123}Te	4.0×10^{-10}	NR	6.8×10^{-5}	NR
^{123m}Te	3.0×10^{-24}	NR	5.0×10^{-19}	NR
^{125m}Te	7.2×10^{-9}	1.5×10^{-4}	1.2×10^{-3}	1.1×10^{0}
^{227}Th	2.9×10^{-6}	5.5×10^{-10}	4.9×10^{-1}	3.9×10^{-6}
^{228}Th	3.5×10^{-5}	3.9×10^{-4}	5.9×10^{0}	2.7×10^{0}
^{229}Th	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{230}Th	6.0×10^{-7}	5.3×10^{-8}	1.0×10^{-1}	3.8×10^{-4}
^{231}Th	2.1×10^{-6}	7.4×10^{-6}	3.5×10^{-1}	5.2×10^{-2}
^{232}Th	3.9×10^{-5}	3.1×10^{-5}	6.6×10^{0}	2.2×10^{-1}
^{234}Th	4.2×10^{-5}	3.1×10^{-4}	7.1×10^{0}	2.2×10^{0}
^{207}Tl	3.0×10^{-6}	5.6×10^{-10}	5.0×10^{-1}	3.9×10^{-6}
^{208}Tl	1.2×10^{-5}	1.4×10^{-4}	2.1×10^{0}	9.7×10^{-1}
^{209}Tl	2.0×10^{-7}	1.1×10^{-7}	3.4×10^{-2}	8.1×10^{-4}
^{232}U	9.8×10^{-6}	3.6×10^{-4}	1.6×10^{0}	2.5×10^{0}
^{233}U	7.3×10^{-3}	4.8×10^{-3}	1.2×10^{3}	3.4×10^{1}
^{234}U	1.0×10^{-3}	3.1×10^{-3}	1.7×10^{2}	2.2×10^{1}
^{235}U	7.8×10^{-6}	1.3×10^{-4}	1.3×10^{0}	9.4×10^{-1}
^{236}U	7.7×10^{-7}	2.0×10^{-4}	1.3×10^{-1}	1.4×10^{0}
^{237}U	1.3×10^{-4}	2.5×10^{-6}	2.2×10^{1}	1.8×10^{-2}
^{238}U	1.5×10^{-4}	1.8×10^{-2}	2.4×10^{1}	1.3×10^{2}
^{240}U	7.6×10^{-12}	1.5×10^{-7}	1.3×10^{-6}	1.1×10^{-3}
^{90}Y	3.4×10^{-1}	3.4×10^{1}	5.7×10^{4}	2.4×10^{5}
^{91}Y	NR	1.2×10^{-16}	NR	8.1×10^{-13}
^{65}Zn	1.4×10^{-15}	NR	2.3×10^{-10}	NR
^{93}Zr	6.7×10^{-9}	4.8×10^{-5}	1.1×10^{-3}	3.4×10^{-1}
^{95}Zr	NR	4.8×10^{-18}	NR	3.4×10^{-14}
Total:	3.2×10^{1}	1.9×10^{2}	5.3×10^{6}	1.3×10^{6}

NR=Not Reported

[1] Decayed through 2001

[2] Total curies estimated by assuming 168,485 m^3 for CH-TRU Waste and 7,079 m^3 for RH-TRU Waste

DATA-F-3.4.1 Non-Defense TRU Waste-Waste Isolation Pilot Plant Future Potential Waste

The DOE has several categories of waste that are currently not acceptable for disposal in WIPP. These are summarized below:

- Non-Defense Waste—The National Security Programs (Public Law 96-164, 1980, National Security and Military Applications of Nuclear Energy Authorization Act of

1980, 93 Stat. 1259), which authorized the construction of the WIPP, states that the WIPP is to be a defense waste repository. Therefore, those wastes that are identified as non-defense are not currently allowed to be disposed in the WIPP. Waste streams from sites for which a defense determination has not been made are identified in Table DATA-F-38 and in Table DATA-F-39.

Table DATA-F-38. Non-Defense TRU Waste (Final Waste Form)

Waste Stream ID	Waste Stream Name	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
Non-defense TRU Waste				
FM-MOX-MT0	Framatome MOX Fuel Plant D&D Mixed TRU Waste	4.2×10^{-1}	0.0×10^{0}	4.2×10^{-1}
FM-MOX-T01	Framatome MOX Fuel Plant D&D TRU Waste	6.9×10^{0}	0.0×10^{0}	6.9×10^{0}
LA-OS-00-02	Isotopic sources waiting determination of eligibility for WIPP disposal	0.0×10^{0}	1.6×10^{2}	1.6×10^{2}
LA-TA-00-06	Containers waiting assignment to waste streams	4.5×10^{1}	0.0×10^{0}	4.5×10^{1}
LB-T001	LBL -Waste	6.2×10^{-1}	1.0×10^{0}	1.7×10^{0}
RL-W684	327 TRU RH heterogeneous S5420 Non-mixed	8.9×10^{-1}	0.0×10^{0}	8.9×10^{-1}
VN-CHT001		0.0×10^{0}	2.0×10^{1}	2.0×10^{1}
VN-RHT001		0.0×10^{0}	1.2×10^{1}	1.2×10^{1}
	Totals	5.3×10^{1}	1.9×10^{2}	2.4×10^{2}

Table DATA-F-39. Possible Future Waste for WIPP

Waste Stream ID	Waste Stream Name	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
BL-001	Reactor Fuel Test Specimens	4.5×10^{1}	0.0×10^{0}	4.5×10^{1}
LA-TA-00-01	Containers waiting assignment to waste streams	7.7×10^{1}	0.0×10^{0}	7.7×10^{1}
LA-TA-00-02	Containers waiting assignment to waste streams	1.1×10^{2}	0.0×10^{0}	1.1×10^{2}
LA-TA-00-03	Containers waiting assignment to waste streams	7.7×10^{0}	0.0×10^{0}	7.7×10^{0}
LA-TA-00-04	Containers waiting assignment to waste streams	2.1×10^{2}	0.0×10^{0}	2.1×10^{2}
LA-TA-00-05	Containers waiting assignment to waste streams	4.2×10^{2}	0.0×10^{0}	4.2×10^{2}
LA-TA-00-06	Containers waiting assignment to waste streams	4.5×10^{1}	0.0×10^{0}	4.5×10^{1}
LA-TA-00-07	Containers waiting assignment to waste streams	1.8×10^{1}	0.0×10^{0}	1.8×10^{1}
PA-B015	Transuranic and Technetium Wastes - Liquid	2.5×10^{0}	0.0×10^{0}	2.5×10^{0}
PA-W014	Transuranic Waste Liquid	4.2×10^{-1}	0.0×10^{0}	4.2×10^{-1}
RF-MT0503		1.7×10^{0}	0.0×10^{0}	1.7×10^{0}
RF-MT0505		2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RF-MT0529		2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RF-MT0533		3.1×10^{0}	0.0×10^{0}	3.1×10^{0}
RF-MT0535		6.3×10^{-1}	0.0×10^{0}	6.3×10^{-1}
RF-TT0533		8.3×10^{-1}	0.0×10^{0}	8.3×10^{-1}
RL-W284	201C Unknown form CH RCRA MTRU w/ met	4.2×10^{-1}	0.0×10^{0}	4.2×10^{-1}
RL-W332	2345Z Unknown form CH St MTRU	1.9×10^{0}	0.0×10^{0}	1.9×10^{0}

Table DATA-F-39. Possible Future Waste for WIPP — Continued

Waste Stream ID	Waste Stream Name	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
RL-W357	KAPL Unknown form CH/r TRU	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W366	202A Unknown form CH TRU	1.5×10^{0}	8.3×10^{-1}	2.3×10^{0}
RL-W382	2345Z Unknown form CH TRU	1.9×10^{1}	6.1×10^{1}	8.0×10^{1}
RL-W391	308 Combustible unknown form CH TRU	4.2×10^{-1}	0.0×10^{0}	4.2×10^{-1}
RL-W471	202A MTRU CH unknown forms S9000 Mixed RCRA w/ org, met, Hg	1.9×10^{0}	0.0×10^{0}	1.9×10^{0}
RL-W472	202A MTRU CH unknown forms S9000 Mixed RCRA w/ met	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W556	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ org, met, Hg	4.2×10^{-1}	0.0×10^{0}	4.2×10^{-1}
RL-W557	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ org, ign	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W558	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ org	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W559	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ met, ign	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W560	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ met	4.0×10^{0}	0.0×10^{0}	4.0×10^{0}
RL-W561	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ met, Hg, cor	2.1×10^{-1}	$0.0 \text{ x } 10^{0}$	2.1×10^{-1}
RL-W562	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ met, Hg	1.0×10^{0}	0.0×10^{0}	1.0×10^{0}
RL-W577	2345Z TRU RH unknown forms S9000 Non-mixed	2.7×10^{0}	0.0×10^{0}	2.7×10^{0}
RL-W578	2345Z TRU RH unknown forms U9999 Non-mixed	5.3×10^{0}	0.0×10^{0}	5.3×10^{0}
RL-W609	324 MTRU CH unknown forms S9000 Mixed RCRA w/org, met, Hg	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W650	325 TRU CH unknown forms S9000 Non-mixed	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W651	325 MTRU CH unknown forms S9000 Mixed RCRA w/org, met	1.0×10^{0}	0.0×10^{0}	1.0×10^{0}
RL-W652	325 MTRU CH unknown forms S9000 Mixed RCRA w/org	3.8×10^{0}	0.0×10^{0}	3.8×10^{0}
RL-W667	325 TRU RH unknown forms S9000 Non-mixed	8.9×10^{-1}	0.0×10^{0}	8.9×10^{-1}
RL-W722	MCGEE TRU CH unknown forms S9000 Non-mixed	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
SR-T001-WSB-3	Unknown	0.0×10^{0}	1.4×10^{2}	1.4×10^{2}
VN-CHT001		0.0×10^{0}	2.0×10^{1}	2.0×10^{1}
VN-RHT001		0.0×10^{0}	1.2×10^{1}	1.2×10^{1}

Table DATA-F-39. Possible Future Waste for WIPP — Continued

Waste Stream ID	Waste Stream Name	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
WV-M007	TRU General Waste	1.1×10^1	0.0×10^0	1.1×10^1
WV-T004	Fissile Material - Other	6.2×10^{-1}	0.0×10^0	6.2×10^{-1}
WV-T020	PPC/XC2 PPE and DAW	0.0×10^0	2.3×10^2	2.3×10^2
	Totals	1.2×10^3	6.7×10^2	1.9×10^3
WV-M005	TRU Filters	6.0×10^1	4.6×10^1	1.1×10^2
WV-M008	TRU Concrete	2.1×10^{-1}	0.0×10^0	2.1×10^{-1}
WV-M010	TRU Spent Absorbents	8.3×10^{-1}	0.0×10^0	8.3×10^{-1}
WV-M013	Sweeping Compound	1.9×10^0	0.0×10^0	1.9×10^0
WV-M015	Chemical Process Cell General Waste	6.0×10^0	0.0×10^0	6.0×10^0
WV-T001	Fissile Material -Solids	3.7×10^1	0.0×10^0	3.7×10^1
WV-T006	TRU General Waste	1.0×10^1	1.0×10^1	2.1×10^1
WV-T009	TRU General Laboratory Waste	1.0×10^1	2.1×10^1	3.1×10^1
WV-T011	TRU Glove Boxes	1.0×10^1	0.0×10^0	1.0×10^1
WV-T014	Chemical Process Cell Vessels	1.1×10^1	0.0×10^0	1.1×10^1
WV-T016	Chemical Process Cell Miscellaneous Equipment	8.5×10^0	0.0×10^0	8.5×10^0
WV-T017	Spent Filter Media	2.5×10^0	0.0×10^0	2.5×10^0
WV-T018	Head End Cell Debris	5.4×10^1	2.6×10^1	8.0×10^1
WV-T019	FRS Pool Filters	0.0×10^0	2.1×10^1	2.1×10^1
WV-T021	RHWF Process	0.0×10^0	8.1×10^1	8.1×10^1
WV-W024	TRU Lead	1.9×10^1	0.0×10^0	1.9×10^1
	Totals	1.2×10^3	6.7×10^2	1.9×10^3

- Pre-1970 buried TRU Waste—Several sites (i.e., LANL, SRS, SNL, Hanford Site, INEEL, Oak Ridge National Laboratory, and West Valley Demonstration Project) have TRU wastes that were buried prior to 1970. The final disposition of the buried pre-1970 TRU waste at DOE sites is still undecided.

- Classified Waste—Some classified TRU waste is now acceptable to be disposed of at WIPP. TRU-contaminated classified materials are materials used in weapons production. These materials are classified for security and national defense purposes due to their physical shape or form. TRU-contaminated classified materials include graphite shapes, metal shapes, tooling, and plastic shapes. The same characterization and associated QA activities, as currently required under the WIPP program, will be implemented for the characterization of classified materials in waste. The primary change associated with the proposed acceptance at WIPP of classified materials in waste is the security qualifications of the responsible parties implementing the waste characterization requirements and the associated QA requirements. Due to national security requirements, responsible parties

for waste characterization and related QA activities will possess a DOE "Q" clearance. Site and CBFO personnel will accomplish waste characterization and related QA activities in accordance with currently approved requirements.

- Polychlorinated Biphenyls (PCBs) —The U.S. Environmental Protection Agency, Region 6, Dallas, Texas office approved the disposal of non-liquid polychlorinated biphenyl-contaminated TRU waste (PCB/TRU waste) and PCB/TRU waste mixed with hazardous waste (PCB/TRU mixed waste) at the WIPP in May 2003. However, at the time the inventory data was prepared for the PA, this approval had not been received, therefore PCB-contaminated TRU waste > 50ppm was not included in this updated inventory data.

- RH-TRU waste that exceeds 23,000 Curies/m3 (650 Curies/ft3)—This limit is from the LWA (Pub. L. No. 102-579, 110 Stat. 2422 (1992), as amended by 104-201 (1996)).

- Waste streams that have unknown waste matrices —There are waste streams at the TRU waste sites that have not been characterized and therefore the determination cannot be made regarding the make up of the waste stream. These wastes are assigned unknown WMCs or final forms and have no known WMPs or radionuclide content.

DATA-F-3.4.2 Other Possible Future Waste Isolation Pilot Plant Waste

There are several other categories of material that eventually may become waste acceptable at WIPP. These include the following wastes.

- One category of potential future waste may come from waste streams that have been currently declared "unknown." These waste streams are summarized in Table DATA-F-39. These wastes have not been characterized adequately to determine the final waste form and/or other significant parameters. If these wastes are characterized, and if they meet the WAC (DOE 2002a), they will be included in the WIPP inventory in the future.

- Babcock and Wilcox in Lynchburg, Virginia, currently has approximately 45 m^3 (1,590 ft^3) of TRU waste that requires a defense determination, in on-site storage silos of which a portion may be possible future TRU waste. Virtually all of the material was generated from the Light Water Reactor Extended Burn-up Program. That program was responsible for sending test elements of reactor fuel to various hot cells, including the one at Lynchburg. The waste consists mostly of cellulosic material, rubber material, and lead-lined gloves.

- Another potential TRU waste site is the Brookhaven National Laboratory (BNL). BNL has identified an existing legacy 17,500-lb concrete vault stored at the Hazardous Waste Management Facility as TRU waste based on recalculation of ^{239}Pu curie content. The vault holds five plutonium foils (TRU waste) and other non-TRU waste constituents including Brookhaven Linear Isotope Production (BLIP) waste and cesium and cobalt sources embedded in concrete. The vault must now be managed as TRU waste.

- There are four waste streams at the SRS that were not listed in Table DATA-F-39. These waste streams will account for nearly 9.6×10^3 m^3 (3.3×10^5 ft^3) of possible future TRU

waste for WIPP. These waste streams will come from proposed facilities at SRS. Those waste streams are SR-T001-WSB-1, SR-T001-WSB-2, SR-W026-PDCF-1, and SR-W026-MFFF-1.

- Sodium-Bearing Waste (SBW) at INEEL requires a declaration that it is waste incidental to reprocessing (WIR). Several treatment options are being considered with the final treatment option to be selected in the near future. For this update, the SBW is included in the Non-WIPP TRU waste and has been entered using the bounding case for RH-TRU waste. That is, the case in which RH-TRU waste is generated from the calcine process.

- Beryllium Block Waste from the INEEL is a waste stream that includes beryllium blocks and outer shim control cylinders from the Advanced Test Reactor. The radionuclide concentrations are too great to be considered in this update but may considered in the future.

DATA-F-3.5 Emplacement Materials

The inventory of CPR materials used by WIPP Waste Handling Operations (WHO) to facilitate waste emplacement was estimated to support the CRA-2004 PA. Other materials that were not accounted for by the sites in their waste/ packaging material parameter data submissions were also estimated. Finally, the mass of magnesium oxide (MgO) used as backfill was estimated for the full repository. The results of these estimations were summarized in a letter to SNL (Crawford 2003a).

The estimates for CPR materials, other emplacement materials, and MgO are based on the number and type of waste containers emplaced in the WIPP as of the inventory date, September 30, 2002.

The TRUPACT-II Authorized Methods for Payload Control (TRAMPAC), Revision 19c (NMED 2002) allows certain container types to be transported in the Transuranic Package Transporter-II (TRUPACT-II). These are 55-gallon drums, 100-gallon drums, SWB, and ten-drum overpacks (TDOP).

The WIPP was designed to receive both CH- and RH-TRU waste. CH-TRU waste that has been emplaced in the WIPP since the repository opened is in seven-packs of 55-gallon drums and/or pipe overpack components (POCs), SWBs, and TDOPs. RH-TRU waste has not been shipped to the WIPP to date.

WIPP WHO uses several materials to facilitate the emplacement of TRU waste, and MgO is used as barrier. Plastic and cellulosic materials are used to emplace CH-TRU waste. The MgO is placed on top of the containers and comes in a woven plastic bag called a “supersack.” RH-TRU waste will be emplaced in boreholes in the salt and then a shield plug, which consists of concrete (cement), steel, and plastic, will be installed to seal the canister into the borehole and provide shielding. There are no rubber materials used for waste emplacement.

The materials used to emplace CH-TRU waste are:

- Polyethylene (PE) slip-sheets for the seven-packs of 55-gallon drums and/or POCs and the MgO supersacks (plastics);
- Fiberboard slip-sheet for the SWB and TDOP (cellulosic material);
- Woven polypropylene supersacks containing MgO (plastic material/MgO);
- Cardboard stabilizers for the supersacks (cellulosic material); and
- Stretch wrap for the seven-packs (plastic material).

The materials that will be used to emplace RH-TRU waste are:

- Shield plug (cement components);
- Shield plug (steel components); and
- Shield plug (plastic components).

Data on the MgO and other emplacement materials were obtained from WIPP WHO drawings and procedures, from WWIS personnel, from the WIPP CH-TRU Waste Safety Analysis Report, and from the internet. These sources are referenced in a letter to SNL (Crawford 2003a).

For CH-TRU waste, the total mass of each of the emplacement materials (plastic, cellulosic, and MgO) as of the inventory date was calculated. These total masses were then divided by the total volume of the emplaced waste (as of the inventory date September 30, 2002) to obtain the density of these materials in the WIPP as of the inventory date. These densities were then scaled to a full repository based on the volume limit for CH-TRU waste of 168,485 m^3 (5,950,000 ft^3).

The total masses of the emplacement materials (cement, steel, and plastic) that will be used for RH-TRU waste emplaced in the WIPP in the future were calculated. This was done by first determining the total number of RH-TRU waste shield plugs that will be used in the repository. The total mass of each shield plug component for the repository was then calculated by determining the mass of each component for each shield plug and multiplying that mass by the number of plugs to be used.

The estimates for CPR and MgO, as well as for the steel and cement used in the RH-TRU waste shield plug, are provided in Table DATA-F-40.

Table DATA-F-40. Estimates of Materials Used to Facilitate Emplacement of Waste in the WIPP

Material Parameter	Mass used for CH Waste (kg) [1]	Density used for CH Waste (kg/m^3) [1]	CH Mass-Scaled to CH Limit[2] (kg)	RH Mass-for the WIPP (kg)	Total (CH+RH) WIPP Mass (kg)
Cellulosic Material (fibreboard slip-sheets)	2.03×10^3	2.63×10^{-1}	4.44×10^4	N/A	4.44×10^4
Cellulosic Material (cardboard stabilizers)	7.02×10^3	9.09×10^{-1}	1.53×10^5	N/A	1.53×10^5
Total Cellulosic Material	9.06×10^3	1.17×10^0	1.98×10^5	N/A	1.98×10^5
Plastic (slip-sheets)	1.02×10^5	1.33×10^1	2.23×10^6	N/A	2.23×10^6
Plastic (poly bag)	6.24×10^3	8.08×10^{-1}	1.36×10^5	N/A	1.36×10^5
Plastic (shrink wrap)	3.56×10^3	4.62×10^{-1}	7.78×10^4	N/A	7.78×10^4
Plastic (RH shield plug)				1.73×10^5	1.73×10^5
Total Plastic Material	1.12×10^5	1.45×10^1	2.45×10^6	1.73×10^5	2.62×10^6
Rubber Material	N/A	N/A	N/A	N/A	N/A
Cement (RH-TRU Waste shield plug)	N/A	N/A	N/A	6.33×10^6	6.33×10^6
Steel (RH-TRU Waste shield plug)	N/A	N/A	N/A	7.95×10^4	7.95×10^4
Magnesium Oxide	3.20×10^6	4.14×10^2	6.98×10^7	N/A	6.98×10^7

[1] These are the masses and densities of the materials that were used to facilitate emplacement of waste in the WIPP as of September 30, 2002. There was no RH-TRU waste emplaced as of that date.

[2] The CH-TRU waste limit is 1.68×10^5 m^3.

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APPENDIX DATA

ATTACHMENT G: WIPP BOREHOLE UPDATE

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WIPP BOREHOLES

The Department of Energy (DOE) prepared DOE/WIPP 95-2092, Rev. 1, Waste Isolation Pilot Plant Borehole Data Report (CCA Appendix BH) to serve as a central document providing data on boreholes used in characterizing the site. The report contained a comprehensive database on wells drilled in support of the WIPP and boreholes that were located within the 16-section Land Withdrawal Area.

This report was categorized into seven groups of boreholes: commercially drilled boreholes, DOE wells, geologic exploration boreholes, hydrologic test boreholes, potash boreholes, subsurface exploration boreholes, and Water Quality Sampling Program boreholes. There were 179 boreholes in the report. At the time of the CCA, 80 of those boreholes were being used as monitoring wells. The rest of the boreholes were plugged and abandoned after being drilled for their specific purpose, i.e., potash information, hydrocarbon information, or WIPP site characterization information.

This report updates all of the monitoring wells identified in CCA Appendix BH and adds the new monitoring wells drilled since the initial certification. This report also adds the wells that were in use but inadvertently omitted from CCA Appendix BH.

Table DATA-G-1. Monitoring Well Status

Well Name	CCA Monitoring Status	CRA Monitoring Status	Depth	Year Drilled	Year Plugged
AEC-7	Culebra	Culebra	4734 ft	1974	N/A
AEC-8	Bell Canyon	Bell Canyon	4922 ft	1974	N/A
B-1	Observation	Observation	58 ft	1978	N/A
B-1A	Observation	Observation	13 ft	1978	N/A
B-4	Observation	Observation	39 ft	1978	N/A
B-4A	Observation	Observation	14 ft	1978	N/A
B-13	Observation	Observation	28 ft	1978	N/A
B-16	Observation	Observation	31 ft	1978	N/A
B-18	Observation	Observation	33 ft	1978	N/A
B-20	Observation	Observation	14 ft	1978	N/A
B-20A	Observation	Observation	34 ft	1978	N/A
B-38	Observation	Observation	50 ft	1979	N/A
B-54	Observation	Observation	210 ft	1979	N/A
D-268	Culebra	Rancher’s Water Well	1411 ft	1984	1999
DOE-1	Culebra	Culebra	4057 ft	1982	N/A
DOE-2	Culebra	Magenta	4325 ft	1984	N/A
ERDA-9	Culebra	Culebra	2886 ft	1976	N/A
H-1	Culebra/Magenta	Plugged	856 ft	1976	2001
H-2A	Culebra	Culebra	672 ft	1977	N/A
H-2B1	Magenta	Magenta	661 ft	1977	N/A

1

Table DATA-G-1. Monitoring Well Status — Continued

Well Name	CCA Monitoring Status	CRA Monitoring Status	Depth	Year Drilled	Year Plugged
H-2B2	Culebra	Culebra	660 ft	1984	N/A
H-2C	Magenta	Culebra	795 ft	1977	N/A
H-3B1	Magenta	Magenta	902 ft	1976	N/A
H-3B2	Culebra	Culebra	725 ft	1983	N/A
H-3B3	Magenta	Culebra	730 ft	1983	N/A
H-3D	Dewey Lake	Dewey Lake	554 ft	1987	N/A
H-4A	not in use	Plugged	532 ft	1978	2000
H-4B	Culebra	Culebra	529 ft	1978	N/A
H-4C	Magenta	Magenta	661 ft	1978	N/A
H-5A	Culebra	Culebra	930 ft	1978	N/A
H-5B	Culebra	Culebra	925 ft	1978	N/A
H-5C	Magenta	Magenta	1076 ft	1978	N/A
H-6A	Culebra	Culebra	637 ft	1978	N/A
H-6B	Culebra	Culebra	640 ft	1978	N/A
H-6C	Culebra	Culebra	741 ft	1978	N/A
H-7A	not in use	Plugged	154 ft	1979	2000
H-7B1	Culebra	Culebra	286 ft	1979	N/A
H-7B2	Culebra	Culebra	295 ft	1983	N/A
H-7C	not in use	not in use	420 ft	1979	N/A
H-8A	Magenta	Magenta	505 ft	1979	N/A
H-8B	not in use	Rancher’s Water Well	624 ft	1979	1987
H-8C	Rustler	Rustler	808 ft	1979	N/A
H-9A	Culebra	Plugged	692 ft	1979	2002
H-9B	Culebra	Culebra	708 ft	1979	N/A
H-9C	Culebra	Magenta	816 ft	1979	N/A
H-10A	Magenta	Magenta	1318 ft	1979	N/A
H-10B	Magenta	Plugged	1398 ft	1979	2002
H-10C	not in use	Culebra	1550 ft	1979	N/A
H-11B1	Culebra	Culebra	785 ft	1983	N/A
H-11B2	Culebra	Magenta	776 ft	1983	N/A
H-11B3	Culebra	Plugged	789 ft	1983	2002
H-11B4	not in use	Culebra	765 ft	1988	N/A
H-12	Culebra	Culebra	1001 ft	1983	N/A
H-14	Culebra	Magenta	589 ft	1986	N/A
H-15	Culebra	Magenta	900 ft	1986	N/A
H-16	Dewey Lake	not in use	851 ft	1987	N/A

Table DATA-G-1. Monitoring Well Status — Continued

Well Name	CCA Monitoring Status	CRA Monitoring Status	Depth	Year Drilled	Year Plugged
H-17	Culebra	Culebra	880 ft	1987	N/A
H-18	Culebra	Magenta	840 ft	1987	N/A
H-19B0	not in use	Culebra	779 ft	1995	N/A
H-19B2	not in use	Culebra	785 ft	1995	N/A
H-19B3	not in use	Culebra	785 ft	1995	N/A
H-19B4	not in use	Culebra	782 ft	1995	N/A
H-19B5	not in use	Culebra	786 ft	1995	N/A
H-19B6	not in use	Culebra	788 ft	1995	N/A
H-19B7	not in use	Culebra	785 ft	1995	N/A
P-14	Culebra	Plugged	1545 ft	1976	1999
P-15	Culebra	Plugged	1465 ft	1976	2002
P-17	Culebra	Culebra	1660 ft	1976	N/A
P-18	Culebra	Plugged	1998 ft	1976	2002
WIPP-12	Culebra	Culebra	3928 ft	1978	N/A
WIPP-13	Culebra	Culebra	3856 ft	1978	N/A
WIPP -18	Culebra	Magenta	1060 ft	1978	N/A
WIPP-19	Culebra	Culebra	1038 ft	1978	N/A
WIPP-21	Culebra	Culebra	1045 ft	1978	N/A
WIPP-22	Culebra	Culebra	1450 ft	1978	N/A
WIPP-25	Culebra/Magenta	Culebra/Magenta	650 ft	1978	N/A
WIPP-26	Culebra	Culebra	503 ft	1978	N/A
WIPP-27	Culebra/Magenta	Culebra	592 ft	1978	N/A
WIPP-28	Rustler	Plugged	801 ft	1978	1999
WIPP-29	Culebra	Culebra	377 ft	1978	N/A
WIPP-30	Culebra/Magenta	Culebra/Magenta	913 ft	1978	N/A
WQSP-1	Culebra	Culebra	737 ft	1994	N/A
WQSP-2	Culebra	Culebra	846 ft	1994	N/A
WQSP-3	Culebra	Culebra	879 ft	1994	N/A
WQSP-4	Culebra	Culebra	800 ft	1994	N/A
WQSP-5	Culebra	Culebra	681 ft	1994	N/A
WQSP-6	Culebra	Culebra	617 ft	1994	N/A
WQSP-6A	Dewey Lake	Dewey Lake	225 ft	1994	N/A
Wells Inadvertently Omitted From Appendix BH of the CCA					
CB-1	Culebra	Culebra/Bell Canyon	4291 ft	1974	N/A
D-207	Potash/plugged	Plugged	1613 ft	1958	1958
H-19B	Not in Use/Capped	not in use/capped	40 ft	1995	N/A
H-19B1	plugged	Plugged	733 ft	1995	1995

Table DATA-G-1. Monitoring Well Status — Continued

Well Name	CCA Monitoring Status	CRA Monitoring Status	Depth	Year Drilled	Year Plugged
I-457	Potash/plugged	Plugged	1885 ft	1976	1976
New Monitoring Wells Drilled During the First CRA Time Period					
C-2505	N/A	Santa Rosa/Dewey Lake	97 ft	1996	N/A
C-2506	N/A	Santa Rosa/Dewey Lake	69 ft	1996	N/A
C-2507	N/A	Santa Rosa/Dewey Lake	73 ft	1996	N/A
C-2737	N/A	Culebra/Magenta	710 ft	2001	N/A
C-2811	N/A	Santa Rosa/Dewey Lake	80 ft	2001	N/A
ES-001	N/A	Plugged	54 ft	1996	1996
ES-002	N/A	Plugged	19 ft	1996	1996
PZ-1	N/A	Santa Rosa	68 ft	1997	N/A
PZ-2	N/A	Santa Rosa	65 ft	1997	N/A
PZ-3	N/A	Santa Rosa	71 ft	1997	N/A
PZ-4	N/A	Santa Rosa	65 ft	1997	N/A
PZ-5	N/A	Santa Rosa	72 ft	1997	N/A
PZ-6	N/A	Santa Rosa	66 ft	1997	N/A
PZ-7	N/A	Santa Rosa	72 ft	1997	N/A
PZ-8	N/A	Santa Rosa	68 ft	1997	N/A
PZ-9	N/A	Santa Rosa	82 ft	1997	N/A
PZ-10	N/A	Santa Rosa	57 ft	1997	N/A
PZ-11	N/A	Santa Rosa	82 ft	1997	N/A
PZ-12	N/A	Santa Rosa	72 ft	1997	N/A

Individual Well Reports

This section provides data on the plugged wells and the new wells drilled during the CRA monitoring period (July 1995 through September 2002).

C-2505

Location: T22S-R31E-20 Spud Date: 09/23/1996 Total Depth: 97 ft
Status: Monitoring Well Completed: 09/24/1996 Elevation: 3413 ft
Hole Size: 0-97 ft = 7 7/8" Stratigraphy: 0-9 = Holocene Deposits
Casing Size: 0-65 ft = 4 ½" PVC 9-12 = Mescalero Caliche Formation
12-49 = Gatuña Formation
49-54 = Santa Rosa Formation Sandstone
54-65 = Dewey Lake Formation Redbeds

C-2506

Location: T22S-R31E-20 Spud Date: 09/25/1996 Total Depth: 69 ft
Status: Monitoring Well Completed: 09/25/1996 Elevation: 3413 ft
Hole Size: 0-69 ft = 7 7/8" Stratigraphy: 0-10 = Holocene Deposits
Casing Size: 0-65 ft = 4 ½" PVC 10-48 = Gatuña Formation
48-54 = Santa Rosa Formation Sandstone
54-65 = Dewey Lake Formation Redbeds

C-2507

Location: T22S-R31E-20 Spud Date: 10/01/1996 Total Depth: 73 ft
Status: Monitoring Well Completed: 10/02/1996 Elevation: 3410 ft
Hole Size: 0-73 ft = 7 7/8" Stratigraphy: 0-10 = Holocene Deposits
Casing Size: 0-69 ft = 4 ½" PVC 10-40 = Gatuña Formation
40-54 = Santa Rosa Formation Sandstone
54-69 = Dewey Lake Formation Redbeds

C-2737

Location: T22S-R31E-29 Spud Date: 02/14/2001 Total Depth: 710 ft
Status: Monitoring Well Completed: 03/09/2001 Elevation: 3397 ft
Hole Size: 0-710 ft = 12 ¼" Stratigraphy: 35-40 = Santa Rosa Formation Sandstone
Casing Size: 0-700 ft = 7" Fiberglass 40-505 = Dewey Lake Formation Redbeds
505-561 = Forty-niner Member
561-584 = Magenta Dolomite Member
584-675 = Tamarisk Member
675-698 = Culebra Dolomite Member
698-710 = Los Medaños Member

C-2811

Location: T22S-R31E-29 Spud Date: 03/12/2001 Total Depth: 80 ft
Status: Monitoring Well Completed: 03/12/2001 Elevation: 3399 ft
Hole Size: No Report Stratigraphy: 0-10 = Holocene Deposits
Casing Size: 0-80 ft = 2" PVC 10-48 = Gatuña Formation
48-54 = Santa Rosa Formation Sandstone
54-65 = Dewey Lake Formation Redbeds

CB-1

Location: T23S-R31E-05 Spud Date: 05/31/1974 Total Depth: 4299 ft
Status: Monitoring Well Completed: 02/08/1975 Elevation: 3320 ft
Casing Size: 0-650 ft = 13 3/8"
Notes: Originally drilled as a hydrocarbon exploration well. Before the operator plugged and abandoned the well, it was turned over to DOE to be utilized as a monitoring well. Currently used to monitor the Culebra Dolomite Member and Bell Canyon Formation.

D-207
Location: T22S-R31E-19 Spud Date: 06/15/1958 Total Depth: 1613 ft
Status: Plugged Completed: 07/03/1958 Elevation: No Report
Plug Date: 07/03/1958
Notes: Potash core hole located on the Land Withdrawal Area. Hole was filled with cement and brine water from total depth to 560 ft. From that depth to the surface, it was filled with cuttings and soil.

D-268
Location: T22S-R30E-35 Spud Date: 07/10/1984 Total Depth: 1411 ft
Status: Rancher's Water Well Completed: 07/26/1984 Elevation: No Report
Hole Size: No Report Stratigraphy: No Report
Casing Size: 0-528 ft = 8 5/8"
Notes: Originally drilled as a potash core test, it was converted to a monitoring well in 1988. Plugged back to 493 ft and converted to a water well for livestock use in 1999. Ownership transferred.

ES-001
Location: T22S-R31E-20 Spud Date: 10/02/1996 Total Depth: 54 ft
Status: Plugged Completed: 10/02/1996 Elevation: 3413 ft
Plug Date: 10/02/1996
Notes: Backfilled to land surface. Drill cuttings and bentonite gel used to plug well.

ES-002
Location: T22S-R31E-20 Spud Date: 10/03/1996 Total Depth: 19 ft
Status: Plugged Completed: 10/03/1996 Elevation: 3413 ft
Plug Date: 10/03/1996
Notes: Backfilled to land surface with drill cuttings and bentonite gel used to plug well.

H-1
Location: T22S-R31E-29 Spud Date: 05/20/1976 Total Depth: 856 ft
Status: Plugged Completed: 06/10/1976 Elevation: 3400 ft
Plug Date: 02/19/2001
Casing Size: 0-848 ft = 7"
Notes: Plugged to surface with cement.

H-4A
Location: T22S-R31E-05 Spud Date: 04/30/1978 Total Depth: 532 ft
Status: Plugged Completed: 05/23/1978 Elevation: 3333 ft
Plug Date: 10/25/2000
Casing Size: 0-364 ft = 5 1/2"
Notes: Plugged to surface with cement.

H-7A
Location: T23S-R30E-14 Spud Date: 09/18/1979 Total Depth: 154 ft
Status: Plugged Completed: 10/18/1979 Elevation: 3164 ft
Plug Date: 06/23/2000
Casing Size: 0-109 ft = 7"
Notes: Plugged to surface with cement.

H-8B
Location: T24S-R30E-23 Spud Date: 08/06/1979 Total Depth: 624 ft
Status: Rancher's Water Well Completed: 08/12/1979 Elevation: 3434 ft
Casing Size: 0-574 ft = 7"
Notes: Turned over to rancher for livestock use in 1987.

H-9A
Location: T24S-R31E-04 Spud Date: 07/09/1979 Total Depth: 692 ft
Status: Plugged Completed: 09/05/1979 Elevation: 3407 ft
Plug Date: 02/11/2002
Casing Size: 0-570 ft = 7"
Notes: Plugged to surface with cement.

H-10B
Location: T23S-R32E-20 Spud Date: 10/07/1979 Total Depth: 1398 ft
Status: Plugged Completed: 10/13/1979 Elevation: 3689 ft
Plug Date: 01/31/2002
Casing Size: 0-1346 ft = 7"
Notes: Well bore was plugged with cement from the bottom to the surface.

H-11B3
Location: T22S-R31E-33 Spud Date: 12/01/1983 Total Depth: 789 ft
Status: Plugged Completed: 01/04/1984 Elevation: 3412 ft
Plug Date: 08/28/2002
Casing Size: 0-733 ft = 5 1/2"
Notes: Well was plugged with cement from the bottom to the surface.

H-19B
Location: T22S-R31E-28 Spud Date: xx/xx/1995 Total Depth: 40 ft
Status: Capped Completed: xx/xx/1995 Elevation: 3417 ft
Casing Size: 0-38 ft = 20"
Notes: Cap welded on surface casing.

H-19B1
Location: T22S-R31E-28 Spud Date: 02/14/1995 Total Depth: 733 ft
Status: Plugged Completed: 03/19/1995 Elevation: 3417 ft
Plug Date: 03/19/1995
Notes: Well was plugged and abandoned because drilling tools stuck in the hole were not retrievable.

I-457
Location: T22S-R31E-27 Spud Date: 07/08/1976 Total Depth: 1885 ft
Status: Plugged Completed: 07/22/1976 Elevation: 3460 ft
Plug Date: 07/22/1976
Notes: Potash core hole, plugged with cement and all casings recovered.

P-14
Location: T22S-R30E-24 Spud Date: 09/24/1976 Total Depth: 1545 ft
Status: Plugged Completed: 10/04/1976 Elevation: 3358 ft
Plug Date: 08/26/1999
Casing Size: 0-775 ft = 4 1/2"
Notes: Hole was plugged back from 1545 ft to 775 ft with cement and converted to monitoring well in 1979. Plugged in 1999 with 200 ft^3 of cement from 775 ft to the surface.

P-15
Location: T22S-R31E-31 Spud Date: 10/04/1976 Total Depth: 1465 ft
Status: Plugged Completed: 10/15/1976 Elevation: 3310 ft
Plug Date: 02/11/2002
Casing Size: 0-635 ft = 4 1/2"
Notes: In 1977, well was plugged back to 620 ft. and converted to monitoring well. Plugged in 2002 with cement from the bottom to the surface, leaving 210 ft of casing in hole.

P-18
Location: T22S-R31E-26 Spud Date: 10/19/1976 Total Depth: 1998 ft
Status: Plugged Completed: 11/06/1976 Elevation: 3479 ft
Plug Date: 02/28/2002
Casing Size: 0-1138 ft = 4 1/2"
Notes: Converted to monitoring well in 1977 by plugging back well to 1125 ft. Abandoned and plugged in 2002 with cement from the well bottom to the surface.

PZ-1
Location: T22S-R31E-20 Spud Date: 06/23/1997 Total Depth: 68 ft
Status: Monitoring Well Completed: 07/10/1997 Elevation: 3413 ft
Hole Size: 0-68 ft = 6 5/8" Stratigraphy: 40-56 = Santa Rosa Sandstone
Casing Size: 0-62 ft = 2" PVC 56-68 = Dewey Lake Redbeds

PZ-2

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 65 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3413 ft
Hole Size: 0-65 ft = 6 5/8" | Stratigraphy: 0-9 = Holocene Deposits
Casing Size: 0-62 ft = 2" PVC | 9-12 = Mescalero Caliche Formation
12-39 = Gatuña Formation
39-57 = Santa Rosa Formation Sandstone
57-65 = Dewey Lake Formation Redbeds

PZ-3

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 71 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3416 ft
Hole Size: 0-71 ft = 6 5/8" | Stratigraphy: 0-8 = Holocene Deposits
Casing Size: 0-65 ft = 2" PVC | 8-10 = Mescalero Caliche Formation
10-38 = Gatuña Formation
38-63 = Santa Rosa Formation Sandstone
63-71 = Dewey Lake Formation Redbeds

PZ-4

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 65 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3412 ft
Hole Size: 0-65 ft = 6 5/8" | Stratigraphy: 0-9 = Holocene Deposits
Casing Size: 0-60 ft = 2" PVC | 9-12 = Mescalero Caliche Formation
12-31 = Gatuña Formation
31-57 = Santa Rosa Formation Sandstone
57-65 = Dewey Lake Formation Redbeds

PZ-5

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 72 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3415 ft
Hole Size: 0-72 ft = 6 5/8" | Stratigraphy: 0-7 = Holocene Deposits
Casing Size: 0-65 ft = 2" PVC | 7-9 = Mescalero Caliche Formation
9-36 = Gatuña Formation
36-63 = Santa Rosa Formation Sandstone
63-72 = Dewey Lake Formation Redbeds

PZ-6

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 66 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3413 ft
Hole Size: 0-66 ft = 6 5/8" | Stratigraphy: 0-7 = Holocene Deposits
Casing Size: 0-62 ft = 2" PVC | 7-9 = Mescalero Caliche Formation
9-32 = Gatuña Formation
32-55 = Santa Rosa Formation Sandstone
55-66 = Dewey Lake Formation Redbeds

PZ-7

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 72 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3414 ft
Hole Size: 0-72 ft = 6 5/8" | Stratigraphy: 0-8 = Holocene Deposits
Casing Size: 0-71 ft = 2" PVC | 8-10 = Mescalero Caliche Formation
10-30 = Gatuña Formation
30-69 = Santa Rosa Formation Sandstone
69-72 = Dewey Lake Formation Redbeds

PZ-8

Location: T22S-R31E-21 | Spud Date: 06/23/1997 | Total Depth: 68 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3418 ft
Hole Size: 0-68 ft = 6 5/8" | Stratigraphy: 0-7 = Holocene Deposits
Casing Size: 0-68 ft = 2" PVC | 7-9 = Mescalero Caliche Formation
9-31 = Gatuña Formation
31-60 = Santa Rosa Formation Sandstone
60-68 = Dewey Lake Formation Redbeds

PZ-9

Location: T22S-R31E-21 | Spud Date: 06/23/1997 | Total Depth: 82 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3421 ft
Hole Size: 0-82 ft = 6 5/8" | Stratigraphy: 0-8 = Holocene Deposits
Casing Size: 0-75 ft = 2" PVC | 8-11 = Mescalero Caliche Formation
11-36 = Gatuña Formation
36-75 = Santa Rosa Formation Sandstone
75-82 = Dewey Lake Formation Redbeds

PZ-10

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 57 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3406 ft
Hole Size: 0-57 ft = 6 5/8" | Stratigraphy: 0-6 = Holocene Deposits
Casing Size: 0-54 ft = 2" PVC | 6-9 = Mescalero Caliche Formation
9-28 = Gatuña Formation
28-46 = Santa Rosa Formation Sandstone
46-57 = Dewey Lake Formation Redbeds

PZ-11

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 82 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3419 ft
Hole Size: 0-82 ft = 6 5/8" | Stratigraphy: 0-10 = Holocene Deposits
Casing Size: 0-71 ft = 2" PVC | 10-13 = Mescalero Caliche Formation
13-34 = Gatuña Formation
34-71 = Santa Rosa Formation Sandstone
71-82 = Dewey Lake Formation Redbeds

PZ-12

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 72 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3409 ft
Hole Size: 0-72 ft = 6 5/8" | Stratigraphy: 0-6 = Holocene Deposits
Casing Size: 0-64 ft = 2" PVC | 6-8 = Mescalero Caliche Formation
8-39 = Gatuña Formation
39-62 = Santa Rosa Formation Sandstone
62-72 = Dewey Lake Formation Redbeds

WIPP-28

Location: T21S-R31E-18 | Spud Date: 08/07/1978 | Total Depth: 801 ft
Status: Plugged | Completed: 08/28/1978 | Elevation: 3349 ft
Plug Date: 11/29/1999
Notes: All casing was removed and hole was plugged with cement.

APPENDIX DATA

ATTACHMENT H: WIPP WASTE CONTAINERS AND EMPLACEMENT

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DATA-H-1.0 AUTHORIZED WASTE EMPLACEMENT CONTAINERS

DATA-H-1.1 Container Descriptions

The Compliance Certification Application (CCA) to the Environmental Protection Agency (EPA) identified the following containers as outer containment vessels for waste emplacement in the repository:

- 208-L (55-g) Drum
- 322-L (85-g) Drum (Short)
- 322-L (85-g) Drum (Tall)
- 379-L (100-g) Drum
- Standard Waste Box (SWB)
- 10-Drum Overpack (TDOP)
- RH-TRU Waste Canister

DATA-H-1.2 Dunnage Containers

Dunnage containers are empty containers used to complete a shipping configuration, such as the seven-pack, if too few containers are available that meet transportation requirements. Dunnage containers must clearly be marked “Empty.” The TDOP and the RH-TRU Waste Canister are not used as dunnage containers for shipping purposes. For emplacement purposes in the repository, the 208-, 322-, and 379-L (55-, 85-, and 100-g) drums can be used as dunnage containers and only if they arrive in a shrink-wrapped package assembly such as the seven-pack, four-pack, or three-pack. To date, only 208-L (55-g) drums have been emplaced in the repository as dunnage containers.

The 208-L (55-g) drum is shipped in a seven-pack configuration and is normally emplaced in the repository in the same configuration, but can be emplaced as an individual unit should the need arise. A single drum can be used for collecting and storing site-derived waste. An illustration of the 55-gallon drum components and emplacement configuration are provided in Figure DATA-H-1. The drum's specifications are provided in Table DATA-H-1.

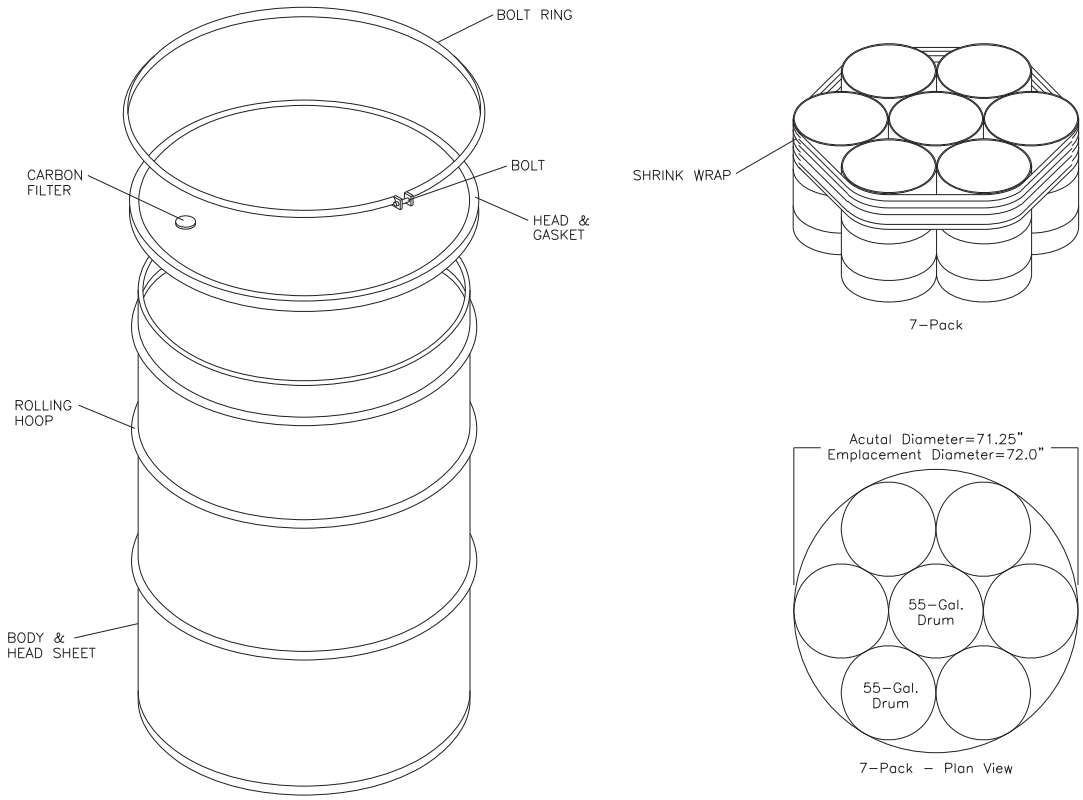

Figure DATA-H-1. 55-Gallon Drum Components and Emplacement Configuration.

Table DATA-H-1. 55-Gallon Drum Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	32 ⅝	34 ¼	830	870	Gallons	55
Diameter	22 ½	23 ¾	572	603	Liters	208
					Cubic Feet	7.35
					Cubic Meters	0.208

The 322-L (85-g) drum is shipped in a four-pack configuration and will be emplaced in the repository in the same configuration but can be emplaced as an individual unit should the need arise. A single drum can be used for collecting and storing site-derived waste. An illustration of the 85-gallon drum (short) components and emplacement configuration are provided in Figure DATA-H-2. The drum's specifications are provided in Table DATA-H-2.

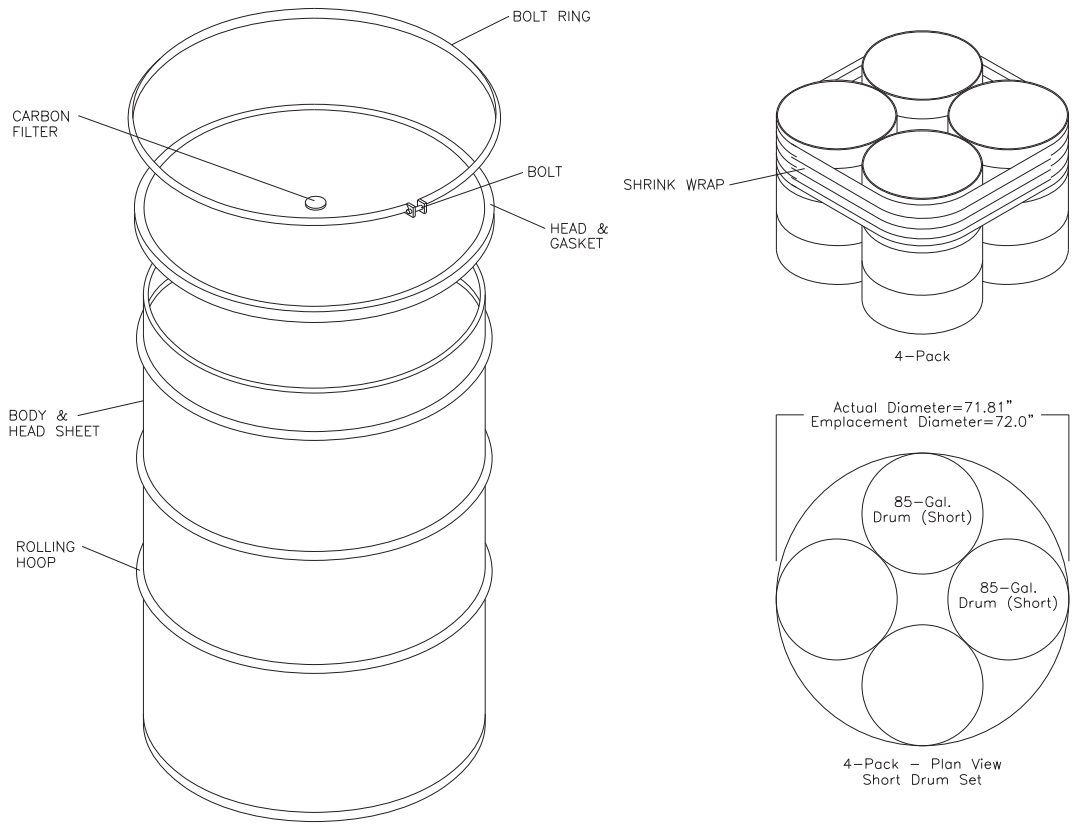

Figure DATA-H-2. 85-Gallon Drum (Short) Components and Emplacement Configuration.

Table DATA-H-2. 85-Gallon Drum (Short) Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	33 ¼	35	845	889	Gallons	85
Diameter	27 ⅛	29 ¾	689	756	Liters	322
					Cubic Feet	11.3
					Cubic Meters	0.32

The 322-L (85-g) drum is shipped in a four-pack configuration and will be emplaced in the repository in the same configuration. It is also used for overpacking 208-L (55-g) drums that are individually emplaced in the repository. A single drum can be used for collecting and storing site-derived waste. An illustration of the 85-gallon drum (tall) components and emplacement configuration are provided in Figure DATA-H-3. The drum's specifications are provided in Table DATA-H-3.

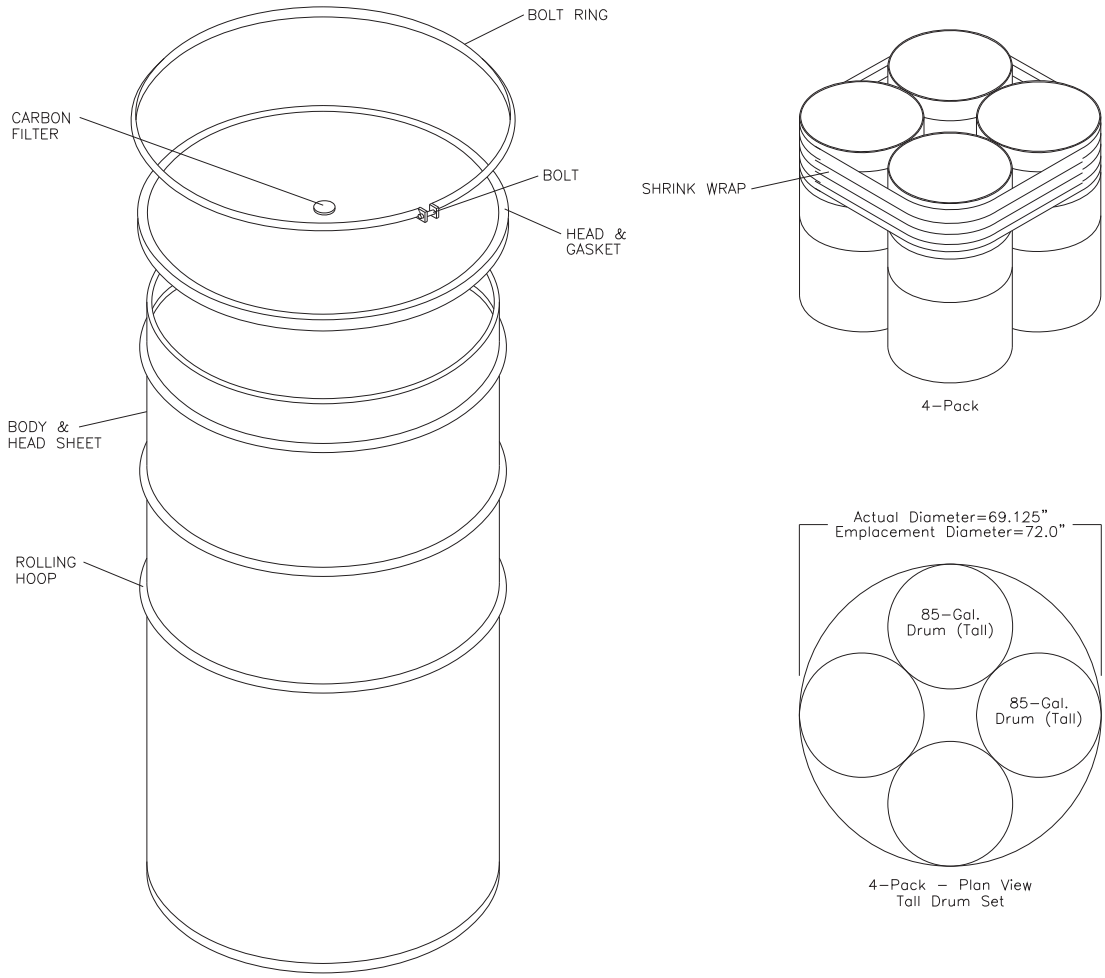

Figure DATA-H-3. 85-Gallon Drum (Tall) Components and Emplacement Configuration.

Table DATA-H-3. 85-Gallon Drum (Tall) Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	38 ¼	40 ¼	972	1,022	Gallons	85
Diameter	26	28 ⅝	660	728	Liters	322
					Cubic Feet	11.3
					Cubic Meters	0.32

The 379-L (100-g) drum is shipped in a three-pack configuration and will be emplaced in the repository in the same configuration. The 379-L (100-g) drum can be emplaced as an individual unit should the need arise. An illustration of the 100-gallon drum components and emplacement configuration are provided in Figure DATA-H-4. The drum's specifications are provided in Table DATA-H-4.

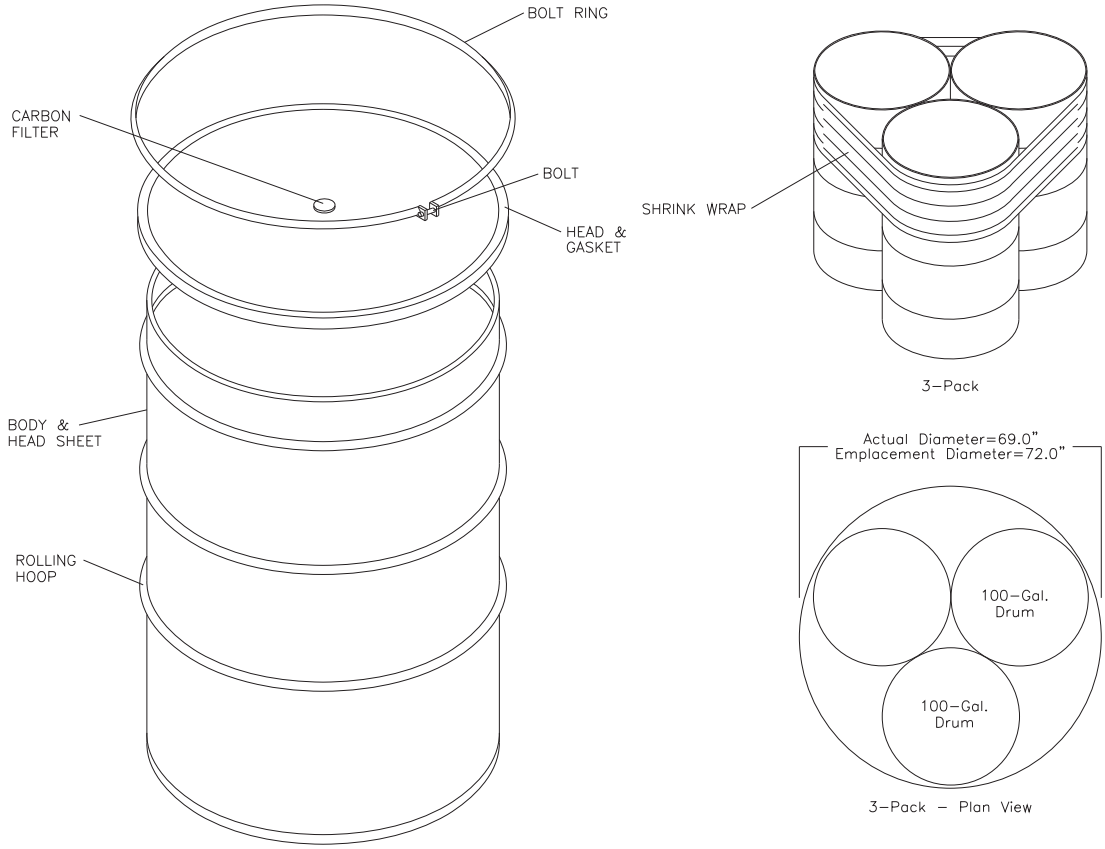

Figure DATA-H-4. 100-Gallon Drum Components and Emplacement Configuration.

Table DATA-H-4. 100-Gallon Drum Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	33	35	838	889	Gallons	100
Diameter	30	32	762	813	Liters	379
					Cubic Feet	13.4
					Cubic Meters	0.38

The SWB is shipped and emplaced as an individual unit. Normally, two SWBs are shipped in a TRUPACT-II shipping container. An illustration of the SWB is provided in Figure DATA-H-5. The box's specifications are provided in Table DATA-H-5.

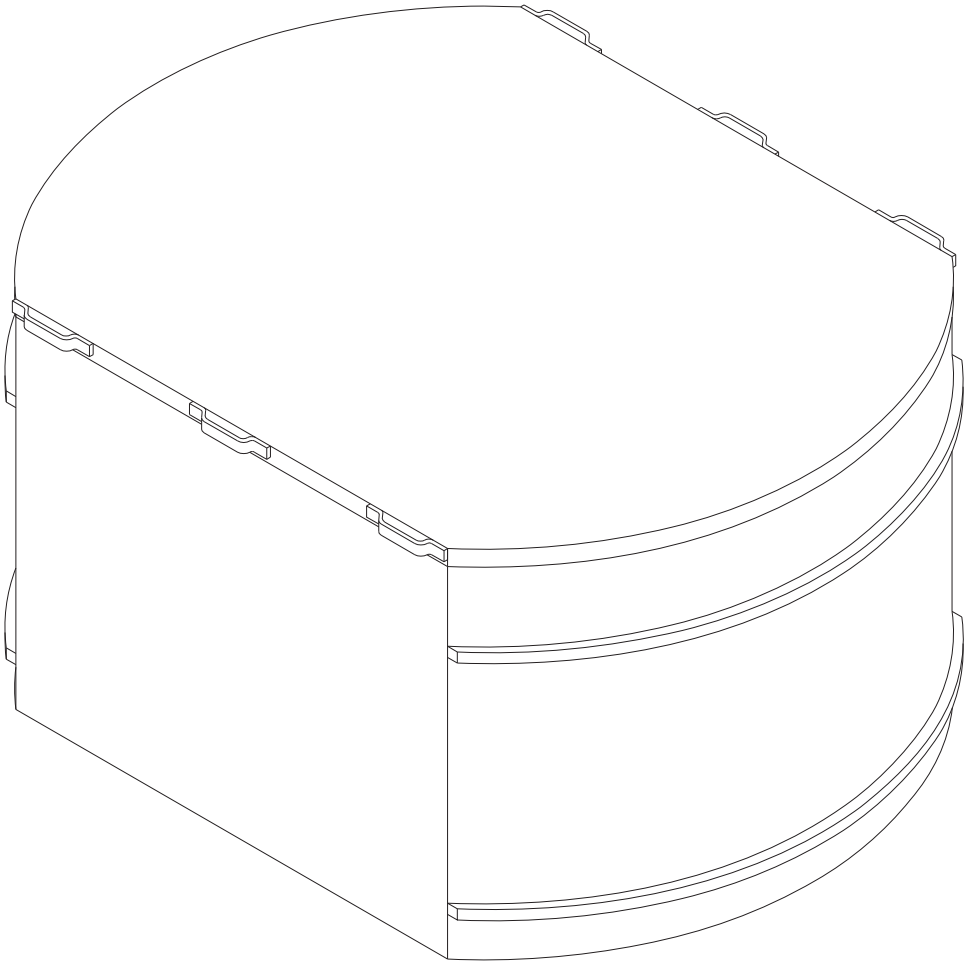

Figure DATA-H-5. Illustration of a Standard Waste Box.

Table DATA-H-5. SWB Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	36 ¾	37	933	940	Gallons	496
Length	68 ¾	71	1,746	1,803	Liters	1,877
Width	51 ⅞	54	1,318	1,372	Cubic Feet	66.3
					Cubic Meters	1.88

The TDOP is shipped as an individual unit and emplaced as an individual unit. An illustration of the TDOP's components is provided in Figure DATA-H-6. The overpack's specifications are provided in Table DATA-H-6.

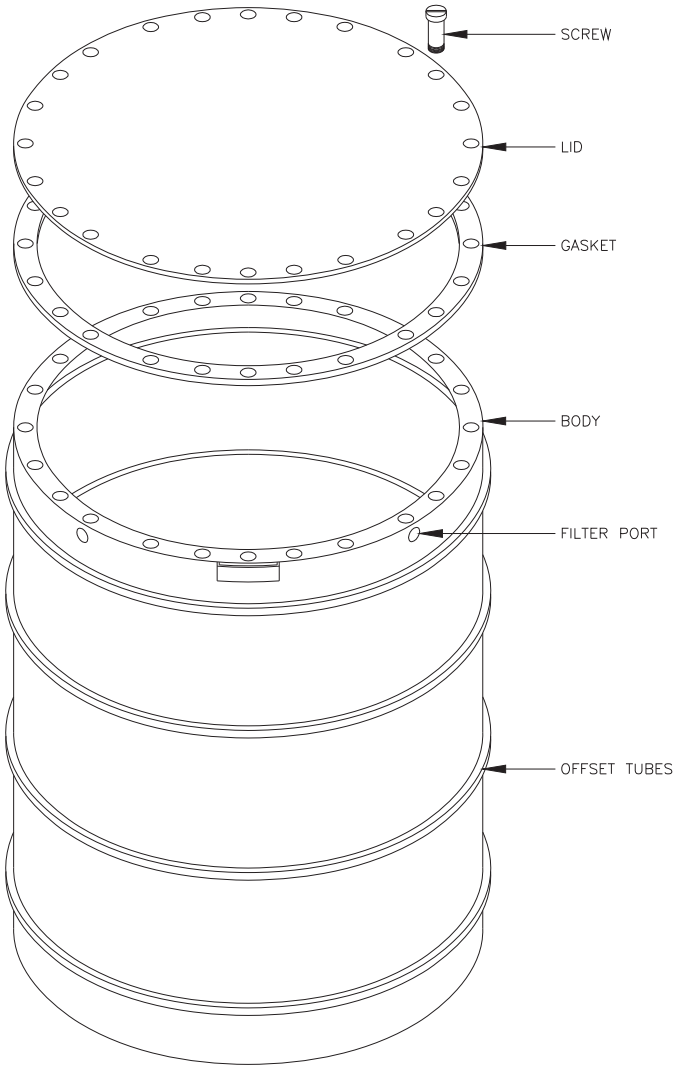

Figure DATA-H-6. TDOP Components.

Table DATA-H-6. TDOP Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	70 ½	73	1791	1,854	Gallons	1,197
Diameter	71 ½	72	1,816	1,829	Liters	4,531
					Cubic Feet	160
					Cubic Meters	4.5

The RH-TRU Waste Canister is shipped as a single unit and emplaced as a single unit. Illustrations of the canister's components are provided in Figure DATA-H-7. The canister's specifications are provided in Table DATA-H-7.

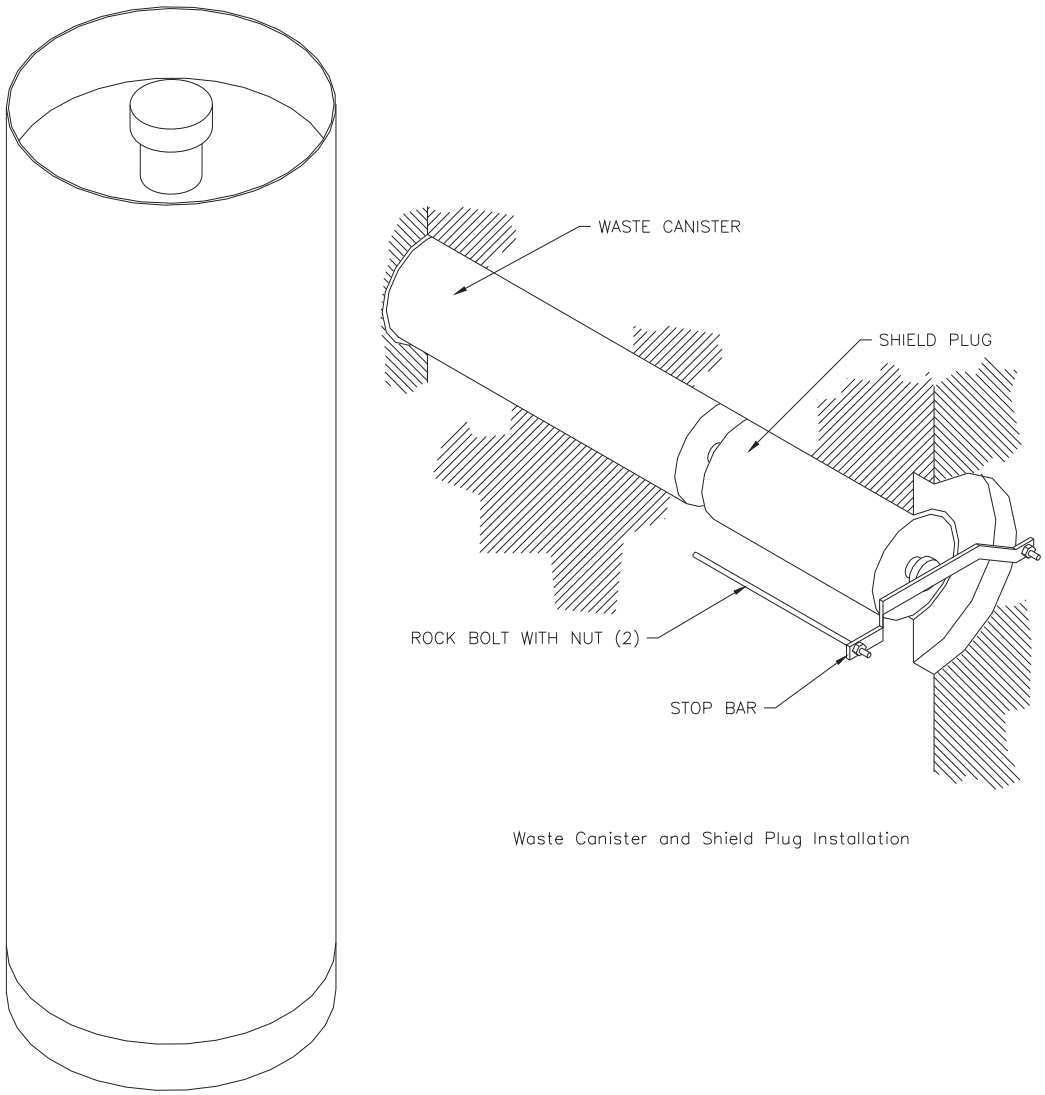

Figure DATA-H-7. RH-TRU Waste Canister Components.

Table DATA-H-7. RH-TRU Waste Canister Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	108	121	2,743	3,073	Gallons	235
Diameter	25 ½	26	648	660	Liters	890
					Cubic Feet	31.44
					Cubic Meters	0.89

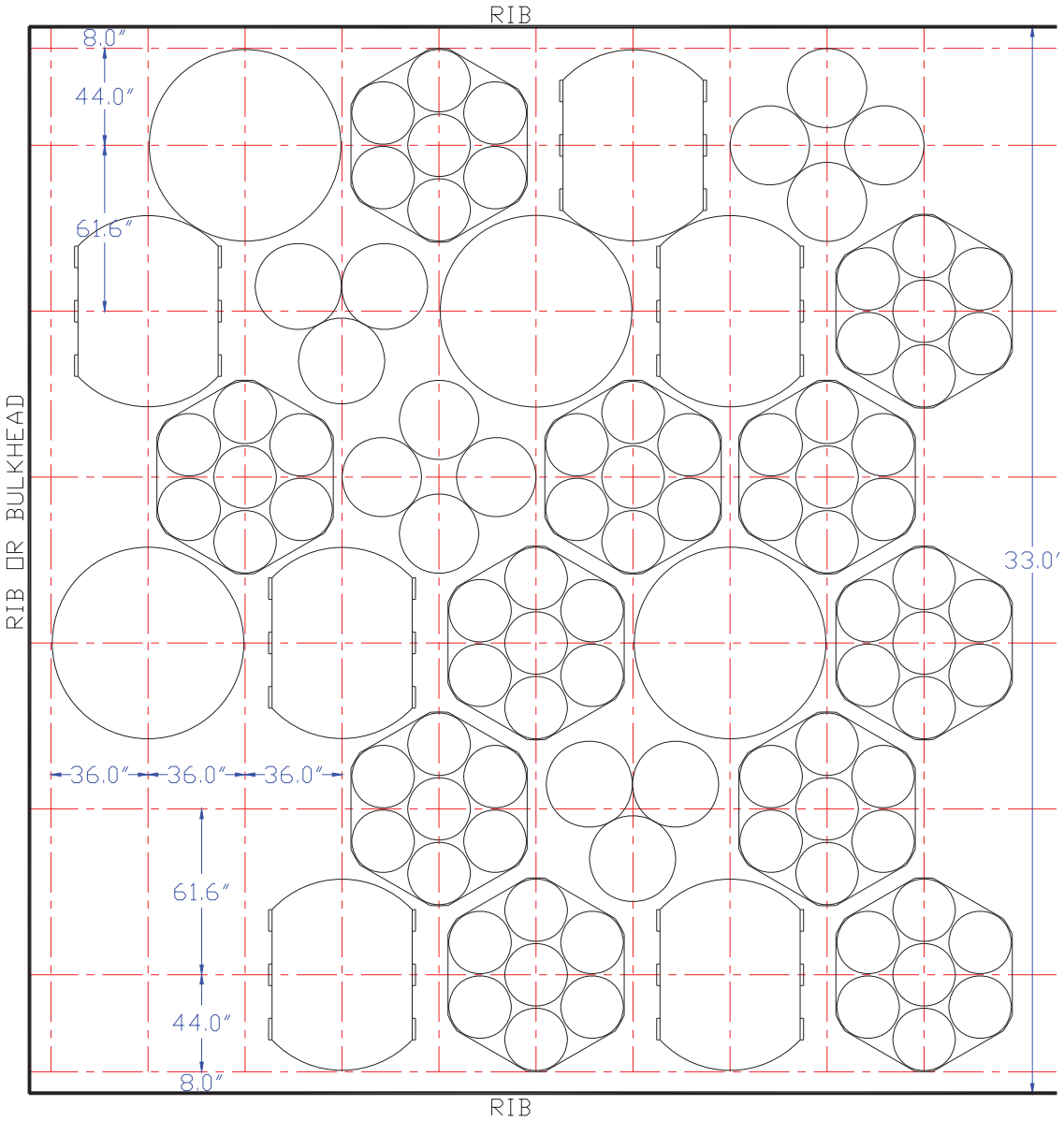

Figure DATA-H-8. CH-TRU Waste Emplacement Layout.

Shown above in Figure DATA-H-8 is the typical position for waste emplacement containers in a room of a panel. TDOPs are only emplaced on the bottom position with another assembly stacked on top. All of the other assemblies can be stacked three high before the MgO supersack is emplaced on the top of the stack. CH-TRU waste emplacement within the repository panels is shown in Figure DATA-H-9. The planned RH-TRU waste emplacement is shown in Figure DATA-H-10.

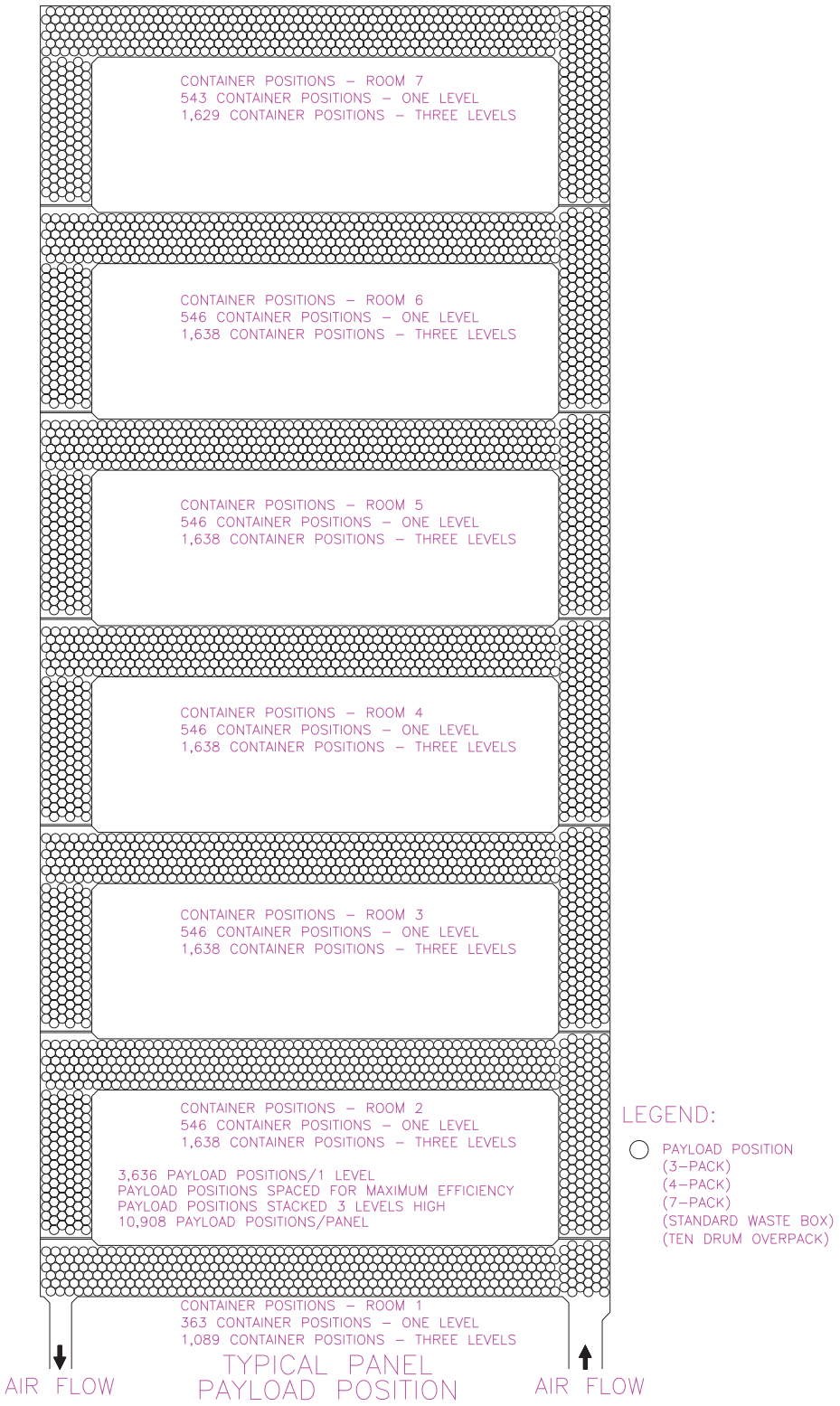

Figure DATA-H-9. CH-TRU Waste Emplacement.

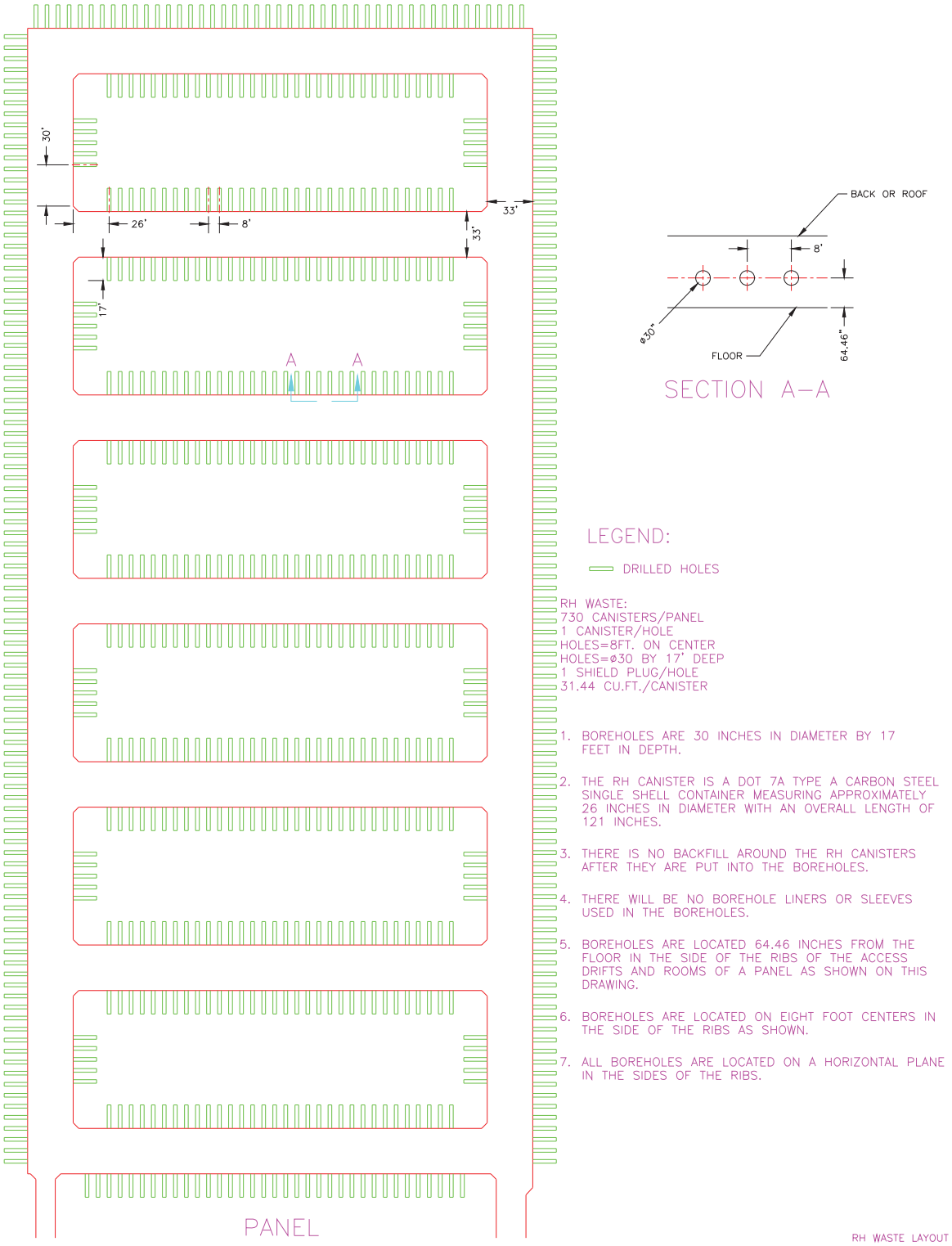

Figure DATA-H-10. Planned RH-TRU Waste Emplacement.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix MON 2004

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Preclosure and Postclosure Compliance Monitoring

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ACRONYMS AND ABBREVIATIONS

ACR	Annual Charge Report
ASER	Annual Site Environmental Report
CARD	Compliance Application Review Document
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CMP	Compliance Monitoring Program
COMPs	Compliance Monitoring Parameters
CRA	Compliance Recertification Application
DBDSP	Delaware Basin Drilling Surveillance Program
DOE	Department of Energy
DRZ	disturbed rock zone
EPA	Environmental Protection Agency
FEP	feature, event, or process
GWMP	Groundwater Monitoring Program
M&OC	Management and Operating Contractor
M&TE	measuring and test equipment
PA	performance assessment
QA	Quality Assurance
QAPD	Quality Assurance Program Document
SA	Scientific Advisor
SMP	Subsidence Monitoring Program
SNL	Sandia National Laboratory
WIPP	Waste Isolation Pilot Plant
WQSP	Water Quality Sampling Program
WWIS	WIPP Waste Information System

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MON-1.0 INTRODUCTION

This Appendix to the Compliance Recertification Application (CRA) is a new document and it replaces the October 1996, version submitted with the Compliance Certification Application (CCA) (DOE 1996). This appendix describes a specific monitoring program that was developed to meet commitments contained in the DOE's application to the Environmental Protection Agency (EPA) which demonstrated compliance with radioactive waste disposal regulations 40 CFR 191 Subparts B and C and 40 CFR Part 194. This appendix does not address monitoring activities intended to demonstrate compliance with 40 CFR Part 191 Subpart A. The monitoring activities described are performed as assurance measures to ensure that deviations from the expected long-term radioactive containment performance of the repository are identified at the earliest possible time. The EPA requires a monitoring program to detect substantial deviations from expected performance. This program is to consist of a preclosure and postclosure monitoring program that uses monitoring techniques that do not jeopardize the isolation of the waste and must be conducted until there are no significant concerns to be addressed by further monitoring. The long-term performance expectations for the disposal system are to be derived from conceptual models, scenarios, and assumptions developed for the Waste Isolation Pilot Plant (WIPP) performance assessment (PA).

On January 3, 2002, the DOE Carlsbad Field Office (CBFO) submitted a letter to the EPA. This letter requested EPA approval to delete CCA Appendices BECR, LMP, and VCMP from the compliance certification because they are not needed to demonstrate compliance with 40 CFR § 191.14(b). The letter also requested CCA Appendices SER and DEL be changed to references, Appendices EMP, GWMP, GTMP, SMP, and DMP be deleted, and that Appendix MON be rewritten to incorporate the portions of those plans required to demonstrate compliance with 40 CFR § 191.14(b) in accordance with the criteria established by 40 CFR § 194.42. The EPA approved these requests in a letter to CBFO on March 15, 2002.

The activities performed for the overall monitoring programs at WIPP comprehensively address the range of regulatory requirements at departmental, state, and federal levels. This appendix addresses those activities relevant to long-term monitoring of the disposal system. This document provides an overview of the Compliance Monitoring Program (CMP) and specifically describes how information and data are extracted from the various WIPP monitoring and sampling programs, how the compliance monitoring parameters are derived from the data, how the assessments are made against repository performance expectations, and how the results are reported to the EPA. The descriptions provided in this appendix are specific to the CMP and thus the requirements of 191.14(b) and 194.42.

MON-1.1 Compliance Monitoring Program

This appendix describes the compliance monitoring program for the WIPP. Compliance monitoring concentrates on the following areas:

- Geotechnical Engineering Program Plan,
- Groundwater Monitoring Program (GWMP),

- Delaware Basin Drilling Surveillance Program (DBDSP),
- Subsidence Monitoring Program (SMP), and
- WIPP Waste Tracking and Control.

The data and information collected since the issuance of the CCA for the above listed programs are recorded or referenced in Appendix DATA.

MON-1.2 Preclosure and Postclosure Monitoring

The requirements of 40 CFR § 191.14, 40 CFR § 194.42, and the initial EPA certification serve as the regulatory basis for compliance monitoring. These requirements specify that disposal systems be monitored after waste disposal to detect substantial deviation from expected disposal system performance.

MON-1.3 Monitoring Assessment

The DOE was required by 40 CFR § 194.42(a) to perform an analysis to determine effects of parameters on the performance of the disposal system and to use the results in preclosure and postclosure monitoring plans. The results identified 10 monitoring parameters, listed in Section 2.1 of this appendix, to be monitored and assessed within the CMP. The discussion of preclosure monitoring activities for these 10 parameters in this appendix includes the following:

- identifying activities required to comply with the monitoring requirements of the EPA's certification of compliance with 40 CFR Part 191 Subparts B and C during the preclosure phase of the project (more commonly referred to as the "operational" or "disposal" phase);
- identifying the organizations that generate the monitoring data, the organizations that convert the data to monitoring parameters and assess the results against expected results, and the organization that reports the results of the assessments to the EPA;
- identifying the compliance monitoring schedule; and
- providing an overview of quality assurance (QA) requirements applicable to the compliance monitoring program.

MON-1.4 Appendix Summary

Section 2.0 of this Appendix identifies the monitoring requirements of 40 CFR 191 Subparts B and C and 40 CFR 194. Section 3.0 describes the preclosure monitoring program associated with each monitoring parameter, the monitoring schedules, and program outputs. Section 4.0 describes the planned postclosure monitoring. Section 5.0 describes the QA requirements applicable to the Compliance Monitoring Program.

MON-2.0 COMPLIANCE MONITORING PROGRAM REQUIREMENTS

The DOE's preclosure CMP assesses the performance of specific aspects of the disposal system. The relevant monitoring requirements are identified in:

- 40 CFR § 191.14(b),
- 40 CFR § 194.42, and
- the EPA's initial certification of the WIPP (EPA 1998).

MON-2.1 Compliance Certification

The original approach used to develop the CMP was based on the results of the parameter analysis documented in CCA Chapter 7, and Appendix MON, Attachment MONPAR. The EPA documented its approval of the DOE monitoring approach in the compliance certification (EPA 1998) and Certification Application Review Document (CARD) Number 42 (EPA 1998a). The current CMP description is contained in Chapter 7, and this Appendix. Sandia National Laboratory (SNL) conducted an assessment of the CCA Attachment MONPAR and determined the original conclusions and monitoring parameters identified in MONPAR remain valid and unchanged (Wagner and Kirkes 2003). The EPA-approved monitoring approach recognizes that DOE will monitor 10 parameters. These parameters are:

1. creep closure and stresses,
2. extent of brittle deformation,
3. initiation of brittle deformation,
4. displacement of deformation features,
5. Culebra groundwater composition,
6. change in Culebra groundwater flow,
7. drilling rate,
8. probability of encountering a Castile brine reservoir,
9. subsidence, and
10. waste activity.

All of the above parameters are being monitored during the preclosure period.

The CCA describes DOE's plans for postclosure monitoring and this description has been brought forward as Attachment A. DOE will revisit this plan for postclosure monitoring before the end of facility operations, expected some 35 years in the future.

The 10 parameters listed are called "compliance monitoring parameters (COMPs)." As discussed previously, the DOE determined that during the WIPP certification activities, these parameters met regulatory requirements.

The data used to generate the 10 separate monitoring parameters of the CMP are generated by five separate monitoring programs (described in Sections 3.1 through 3.5). Each of the monitoring programs focuses on the collection of direct field measurements related to CCA requirements and other information relating to the site. Each program that generates or evaluates the data is described in Section 6.0. Results from each monitoring program are documented individually in annual reports (see Appendix DATA) while the results of the assessment of the 10 parameters are documented and reported annually in a compliance monitoring parameter assessment report which is provided annually to the EPA in the Annual Change Report (ACR). The monitoring parameters which have related PA parameters include:

- drilling rate,
- probability of encountering Castile brine,
- Culebra water-level,
- Culebra groundwater composition, and
- waste activity.

The other monitoring parameters are related to screening decisions for repository features, events or processes (FEPs). Table MON-1 provides a description of the related PA parameters and the major FEP screening decisions. The 10 monitoring parameters will be evaluated to determine if there is an impact on the PA-related parameters, conceptual models, or FEP screening decisions. All Scientific Advisor (SA) processes and procedures used in the parameter analysis and reporting are governed by their QA and document control procedures.

As stated earlier, if any of the data, parameters, or observations are not consistent with the CCA PA expectations, the SA again will report its evaluations and recommendations to the DOE. If needed, the CMP process will be modified to address concerns or recommendations identified by unexpected results.

Results from monitoring programs will be generated on an ongoing basis throughout the operational period of the repository. Compliance monitoring data are provided to the cognizant individuals and organizations within the project, evaluated for their significance, and evaluation results and data summaries are reported to the EPA on an annual basis. Section 6.0 describes the process of communicating and reporting CMP results and evaluations.

Table MON-1. Monitoring Parameters

Monitoring Parameter	Monitoring Program	Frequency of Data Collection and Reporting	Related Performance Assessment Parameter	Related FEPs Evaluation Cycle	Evaluation of Data
Creep Closure and Stresses	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data are reported annually.	Not directly related to a PA parameter. May provide a short-term (operational) observation of the geomechanical response of repository excavation. Can provide confidence in the creep closure model.	Salt creep, excavation-induced stress changes, changes in stress field, pressurization. Consolidation of waste/backfill.	Data from this monitoring program are evaluated annually and during recertification.
Extent of Brittle Deformation	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data reported annually.	Not directly related to a PA parameter. Can provide confidence in the long-term behavior of the disturbed rock zone (DRZ) as modeled. Intrinsic shaft DRZ permeability and effective shaft seal permeabilities calculated from this parameter.	DRZ, roof falls, consolidation of seals.	Data are evaluated annually and during recertification.
Initiation of Brittle Deformation	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data reported annually.	Not directly related to a PA parameter. Can provide confidence in the anhydrite fracture model implemented in the BRAGFLO code. May provide related repository observation data on initiation or displacement of major brittle deformation features in the roof or surrounding rock.	Disruption due to gas effects.	Data are evaluated annually and during recertification.
Displacement of Deformation Features	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data reported annually.	Not directly related to a PA parameter. Provides related repository operational data on initiation or displacement of major brittle deformation features in the roof or surrounding rock.	Stability of open panel.	Data are evaluated annually and during recertification.
Culebra Groundwater Composition	Groundwater Monitoring Program	Data are collected semiannually and reported annually.	Average Culebra brines composition and matrix distribution coefficient for U(IV, VI), Pu(III, IV), Th(IV), Am(III). Matrix distribution coefficient is not a sensitive PA parameter.	Groundwater geochemistry, actinide sorption.	Data are evaluated annually and during recertification.

Table MON-1. Monitoring Parameters — Continued

Monitoring Parameter	Monitoring Program	Frequency of Data Collection and Reporting	Related Performance Assessment Parameter	Related FEPs Evaluation Cycle	Evaluation of Data
Change in Culebra Groundwater Flow (Water Level)	Groundwater Monitoring Program	Data collected monthly and reported annually.	Culebra transmissivity, fracture and matrix porosity, fracture spacing, dispersivity, and climate index. Changes in Culebra groundwater flow are moderately significant to performance and incorporated into the PA.	Groundwater flow and recharge/discharge. Infiltration. Precipitation.	Data are evaluated annually and during recertification.
Drilling Rate	Delaware Basin Drilling Surveillance Program	As well records are received (weekly and monthly basis). Data are reported annually.	Drilling rate per unit area. The number of holes is used to calculate a frequency of potential future intrusions into the repository.	Drilling.	Data are evaluated annually and during recertification.
Probability of Encountering a Castile Brine Reservoir	Delaware Basin Drilling Surveillance Program	As drilling records are received. Data are reported annually.	Probability of encountering a Castile brine reservoir, reservoir pressure, and volume. The probability of encountering a brine reservoir is significant to long-term repository performance.	Drilling fluid flow, drilling fluid loss, blowouts, brine reservoirs.	Data are evaluated annually and during recertification.
Subsidence	Subsidence Monitoring Program	Annually or as determined necessary by the DOE. Data are reported annually or as determined necessary by the DOE.	Not directly related to a PA parameter. Can provide spatial information on surface subsidence (if any) over the influence area of the underground openings during operations.	Changes to groundwater flow due to mining effects; subsidence baseline.	Data are evaluated annually or as determined necessary by the DOE.
Waste Activity	WIPP Waste Tracking and Control	Continually updated as waste is approved for shipment to WIPP. Data are reported annually.	Radionuclide inventory. Material parameter weights.	Waste radiological characteristics.	Data are evaluated annually and during recertification.

MON-3.0 PRECLOSURE COMPLIANCE MONITORING

This section provides a general description of the preclosure CMP and the resulting data. The 10 parameters, associated monitoring program for each, frequency of data collection and reporting, related PA parameters, and related screening decisions used to support the PA are listed in Table MON-1. WIPP Waste Tracking and Control is listed as a monitoring program because waste-related data are extracted from reports it generates.

MON-3.1 Geotechnical Engineering Program Plan

The WIPP Geotechnical Engineering Program Plan (WIPP 2002) defines the field programs and investigations carried out by the Geotechnical Engineering group within the M&OC (Management and Operating Contractor). The geotechnical engineering activities are designed to provide geologic information related to geotechnical characteristics and to assess the stability and performance of the underground facility. The activities within this plan that collect data related to PA parameters are Geomechanical Monitoring and Geosciences.

MON-3.1.1 Geomechanical Monitoring Activities

The purpose of the geomechanical monitoring activities is to determine the geomechanical performance of the underground by monitoring the geomechanical response of the underground openings after excavation. It also monitors geotechnical instruments installed in the shafts and drifts of the WIPP facility. This activity generates data related to the four following parameters:

1. creep closure and stresses,
2. extent of brittle deformation,
3. initiation of brittle deformation, and
4. displacement of deformation features.

MON-3.1.1.1 Scope

The instrumentation system for geomechanical monitoring activities provides data on the WIPP design for routine evaluation of safety and stability of excavations, and for collecting data on the behavior of underground openings. From an operational point of view, data related to identifying areas of potential instability allow corrective action to be taken in a timely manner. For underground opening behavior, in-situ data are used to model long-term disposal system performance.

MON-3.1.1.2 Instrumentation

Geomechanical instruments installed in the shafts and along drifts within the WIPP facility monitor the geotechnical parameters. Instrumentation in the shafts and the underground repository presently include tape extensometer stations, convergence meters, borehole extensometers, piezometers, embedment strain gauges, stress gauges, inclinometers, load cells, and crack meters.

Geomechanical instruments installation and monitoring are governed by approved procedures. Instruments in the underground are either monitored remotely by a surface data logger or read manually.

MON-3.1.1.3 Data Acquisition

Geomechanical data are acquired either remotely by the geomechanical data logging system or manually by geotechnical engineering technicians. Manually acquired data are collected on a quarterly basis and remotely acquired data are collected on a monthly basis, as a minimum.

MON-3.1.1.4 Data Analysis and Dissemination

The frequency of data analysis on geomechanical data is based upon the requirements established in the WIPP Safety Analysis Report (DOE 1995). Data analysis is performed on an annual basis and published. The results of the analyses are published annually in the Geotechnical Analysis Report (DOE 2002).

An assessment of convergence measurements and geotechnical observations is made after each round of data collection. The results of each assessment are distributed to affected underground operations, engineering, and safety managers.

MON-3.1.2 Geosciences Activities

The purpose of the Geosciences activities is to document existing geologic conditions and characteristics and to monitor for changes resulting from the excavations. This activity generates data related to the following four parameters:

- creep closure and stresses,
- extent of brittle deformation,
- initiation of brittle deformation, and
- displacement of deformation features.

MON-3.1.2.1 Scope

Changes resulting from excavations are monitored by routine inspections of selected borehole arrays to detect and quantify the occurrences of discontinuities such as fractures and bed separations. The data collected from these inspections further the understanding of fracture development within the Salado Formation that occurs around the excavations. Geosciences activities also provide geologic and fracture mapping, geologic sampling, and seismic monitoring.

MON-3.1.3 Schedule

The following activities are performed on the indicated schedule:

- Geomechanical Monitoring – This program consists of monitoring using instrumentation located in the shafts and drifts, including tape extensometer stations, convergence meters, borehole extensometers, piezometers, embedment strain gauges, stress gauges, inclinometers, load cells, and crack meters. Instruments are read monthly (remotely read instruments) or quarterly (manually read instruments) as a minimum;

- Seismic Monitoring – Regional seismic monitoring and evaluation are conducted by the New Mexico Institute of Mining and Technology. The network is operated continuously and monitoring results are reported quarterly; and

- Geologic Mapping – Geologic mapping is conducted in newly excavated areas and in other areas when deemed necessary by the cognizant engineer or Geotechnical Engineering Manager.

At a minimum, a complete analysis of geotechnical data is performed annually. The geotechnical activities will be ongoing throughout the operations period.

MON-3.2 Groundwater Monitoring Program

The purpose of the Groundwater Monitoring Program (GWMP) is to collect groundwater data from numerous wells located near the facility. Groundwater monitoring at the WIPP is carried out under the WIPP GWMP (WIPP 2003).

The Culebra Dolomite Member remains the focus of the GWMP. It has been extensively studied during past hydrologic characterization programs and was found to be the most likely hydrologic pathway to the accessible environment or compliance point for any potential human-intrusion-caused release scenario.

Data obtained through this program are used to generate the Culebra groundwater composition and the Culebra groundwater flow parameters. Details on how the program is implemented are provided in the GWMP (WIPP 2003) and Strategic Plan for Groundwater Monitoring at the Waste Isolation Pilot Plant (DOE 2003).

MON-3.2.1 Scope

The GWMP addresses requirements for sample collection, groundwater surface elevation monitoring, groundwater flow direction, data management, and reporting of groundwater monitoring data. It also identifies analytical parameters selected to assess groundwater quality.

Seven wells were drilled as part of the WIPP GWMP (see Figure 2-2 in Chapter 2). They are as follows: six wells, WQSP-1 through WQSP-6, completed to the Culebra Member of the Rustler Formation, and one other well, WQSP-6a, completed to the Dewey Lake Formation. Water samples are collected from these wells and analyzed for certain chemical and physical parameters. This activity generates data in support of the Culebra Groundwater Composition Parameter. This parameter calls for the analysis of the following:

- Ca^{2+},

- Cl^-,
- HCO_3^{2-},
- K^+,
- Mg^{2+},
- Na^+, and
- SO_4^{2-}.

Water level data are collected to assess changes in Culebra groundwater flow. Water level measurements are tracked over time using Water Quality Sampling Program (WQSP) wells and other wells that are widely distributed across the WIPP area to monitor the area's potentiometric surface and groundwater flow directions. If changes in water level or water levels occur, the cause is investigated and any potential impact on the long-term performance of the repository is assessed.

MON-3.2.1.1 Sampling and Reporting for Water Quality

Sampling for water quality is performed at seven groundwater monitoring wells. The Culebra is monitored using wells WQSP-1 through WQSP-6 and the Dewey Lake is monitored using well WQSP-6a. Two types of water samples are collected in accordance with approved procedures maintained by M&OC: serial samples and final samples.

Serial samples are taken at regular intervals and analyzed for various physical and chemical parameters (called field indicator parameters) in a mobile field laboratory positioned at the wellhead. The serial sample data are used to determine when the borehole effects are minimized so a representative sample of the formation water can be taken. The field indicator parameters are chloride, divalent cations, alkalinity, total iron, pH, Eh, temperature, specific conductance, and specific gravity. Interpretation of the serial sampling data determines when conditions representative of undisturbed groundwater are attained in the pumped groundwater.

When the field indicator parameters have stabilized, indicating that the sample is representative of formation groundwater, final samples are collected in the appropriate type of container for the specific analysis to be performed to meet state and federal requirements. The final samples are submitted to laboratories for chemical analysis. Section 3.2.1 lists the analytes needed to support the PA parameter.

The sample tracking system at WIPP uses uniquely numbered Chain of Custody Forms and Request for Analysis Forms. The primary consideration for storage or transportation is that samples must be analyzed within the prescribed holding times for the parameters of interest. Procedures for sample tracking and preservation are generated, approved, and maintained by the M&OC.

MON-3.2.1.2 Sampling and Reporting for Water Level Fluctuations

Water level measurements are taken in the seven groundwater monitoring wells (WQSP-1 through WQSP-6a) and other available WIPP wells in the monitoring network (see Figure 2-2 in Chapter 2). The objective of water level monitoring is to identify water level fluctuations.

In addition to the water level measurements, pressure density surveys are conducted to determine the specific gravity of the water in the wells. These surveys allow the water level measurements to be converted to equivalent freshwater heads that can be used to develop potentiometric surface maps. Specific procedures regarding water level monitoring activities are generated, approved, and maintained by the M&OC.

MON-3.2.2 Schedule

Background water quality in both the upgradient and downgradient monitoring wells has been established for the WIPP. Therefore, the seven WQSP monitoring wells constructed for the GWMP are sampled on a semiannual basis to confirm the existing baseline water quality.

The groundwater level is measured by monitoring the wells on a monthly basis. Groundwater level measurements are monitored and collected for other WIPP wells, as well as for the WQSP wells. The water levels are determined in at least one accessible completed interval at each available well pad and quarterly in redundant wells at well pads with two or more wells completed in the same interval. Groundwater level measurements are made primarily to examine changes in groundwater flow rate and direction to identify any changes pertinent to compliance. These groundwater data supplement the area water level database.

The characteristics of the GWMP, such as the frequency of sampling and the location of the sampled wells, will be reevaluated if significant changes are observed in the groundwater flow direction or gradient. Monitoring frequencies are listed in Table MON-2.

Table MON-2. WIPP Groundwater Monitoring Program Sample Collection and Water Level Measurement Frequency

Type of Well	Frequency
Water Quality Sampling	
WQSP wells (7)	Semiannually
Other WIPP wells	On special request only
Water Level Monitoring	
WQSP wells (7)	Monthly and before sampling events
Other WIPP wells	Monthly

Note: These frequencies are subject to change as WIPP permits are modified and updated.

MON-3.2.3 Program Outputs

The groundwater samples are analyzed to quantify the following Culebra Groundwater Composition parameters and water quality parameters such as pH and density:

- Ca^{2+},
- Cl^{-},
- HCO_3^{2-},
- K^{+},
- Mg^{2+},
- Na^{+}, and
- SO_4^{2-}.

The GWMP also generates Culebra water level data. The data and results of the GWMP are summarized and published on an annual basis in the WIPP Annual Site Environmental Report (ASER) (DOE 2002a).

MON-3.3 Delaware Basin Drilling Surveillance Program

The Delaware Basin Drilling Surveillance Program (DBDSP) is described in the Delaware Basin Drilling Surveillance Plan (WIPP 1997). This plan provides for the surveillance of drilling activities within the Delaware Basin, with specific emphasis on the nine-township area surrounding the WIPP site. The DBDSP collects information related to the following two parameters:

1. probability of encountering a Castile brine reservoir, and
2. drilling rate.

In addition to the parameters listed above, the DBDSP collects information on the following activities:

- borehole plugging,
- enhanced recovery,
- gas storage,
- solution mining,
- potash mining, and
- seismic events.

The WIPP PA includes the impacts of drilling on the performance of the repository. The number of deep boreholes drilled per square kilometer is a parameter used in PA calculations for WIPP

inadvertent intrusion scenarios. They are based on actual drilling rates within the Delaware Basin over the last 100 years as required by 40 CFR § 194.33.

The results of the DBDSP continue to build on the existing database. The purpose of this program is to update these data to detect any substantial deviations from the assumptions used in the previous PA (see Table MON-3 below). The collection of additional information about resource exploration and exploitation activities and practices in the Delaware Basin provides information to determine whether the drilling scenarios, assumptions, and probabilities used in the PA continue to be valid for each five-year recertification of the WIPP.

Drilling information for the study area is obtained through commercially available electronic databases and from the records of government agencies. The electronic database is updated and reviewed weekly to reflect drilling activities in the Delaware Basin.

MON-3.3.1 Schedule

Table MON-3. DBDSP Data Collection Schedule

Information Collected	Frequency
Borehole plugging	Weekly
Enhanced recovery	Monthly
Gas storage	Annually
Solution mining	Annually
Potash mining	Annually
Seismic events	Quarterly
Drilling-related	Weekly
Probability of encountering a Castile brine reservoir	Weekly
Drilling rate calculations	Quarterly

MON-3.3.2 Program Outputs

The DBDSP updates and maintains a database of drilling activities and related practices in the Delaware Basin. Maps of the Delaware Basin are published on request. For the nine-township area surrounding the WIPP, the DBDSP updates and maintains a database containing the following information:

- plugging and abandonment activities including descriptions of plugging configurations;
- determination of the fraction of plugged and abandoned boreholes that are sealed;
- well conversion activities (injection, disposal, water);
- injection well operation (disposal and secondary recovery);

- drilling activities including borehole depths, diameters, and type and amount of drilling fluid;
- identification of ownership of all state and federal minerals and hydrocarbon leases within the area; and
- occurrences of pressurized brine within the Castile.

Data collected and recorded by the DBDSP are reported annually in the Delaware Basin Monitoring Annual Program Report (DOE 2002b).

MON-3.4 Subsidence Monitoring Program

The Subsidence Monitoring Program (SMP) is described in detail in the WIPP Underground and Surface Surveying Program (WIPP 2003a). Subsidence monitoring is the measurement of vertical movement of the land surface relative to a reference location, using state-of-the-art leveling equipment. The technique used to monitor subsidence measures the vertical height difference between two or more markers placed on a surface a known distance away from each other using a leveling survey. A reference benchmark is used as the standard and the relative movement of the other benchmark(s) is measured to detect vertical movement over time. Subsidence measurements are relative because the reference is fixed only with respect to the subsidence markers.

The activities associated with the SMP are designed to:

- provide time-related spatial information on surface subsidence within 152.4 m (500 ft) surrounding the waste shaft during the operational phase of the repository;
- provide time-related spatial information on surface subsidence over the influence area of the underground openings for comparison with subsidence predictions; and
- maintain a database of subsidence data.

With current technology, vertical elevation can be measured at a precision of 0.0305 cm (0.001 ft). Subsidence monitoring was chosen by the DOE as a long-term monitoring tool because it effectively meets the requirements in 40 CFR § 191.14(b) for long-term monitoring. Subsidence monitoring is conducted to detect substantial deviations from expected repository performance by allowing a comparison of actual subsidence to that calculated previously.

Subsidence data are currently being compiled and will be compared to subsidence predictions. In addition, monitoring subsidence during the operational phase generates data to establish a baseline against which long-term subsidence data and information may be evaluated.

MON-3.4.1 Schedule

Subsidence surveys are performed throughout the operations period as deemed necessary. After closure of the repository, subsidence surveys will be performed at 10-year intervals for at least 100 years or until no further useful information may be obtained through continued monitoring.

MON-3.4.2 Program Outputs

The SMP generates annual surface subsidence data for 32.19 km (20 mi) of leveling loops through approximately 50 monuments. Results are reported annually in the WIPP Subsidence Monument Leveling Survey (DOE 2002c).

MON-3.5 WIPP Waste Information System

Information on the waste activity parameter is measured or estimated by generator sites through waste characterization activities. Sites are required to report certain information in the WIPP Waste Information System (WWIS). Reports are generated by Waste Tracking and Control to provide tabulations of key waste parameters. The waste activity parameter includes tracking the total material parameter weights and curie content of 10 radionuclides, listed in Section 3.5.2.

MON-3.5.1 Schedule

Radionuclide inventory data and material parameter weights for every container of waste placed in the WIPP underground are submitted to the WWIS database. A current collection of radionuclide inventory data and material parameter weights for the WIPP is maintained within the WWIS.

MON-3.5.2 Program Outputs

The curie content of the radionuclides americium-241, plutonium-238, plutonium-239, plutonium-240, plutonium-242, uranium-233, uranium-234, uranium-238, strontium-90, and cesium-137 and the material parameter weights (cellulose, plastics and rubber (CPR) materials, free liquids, and metals) for the waste emplaced in the WIPP underground are reported in November of each year to the EPA in the annual 40 CFR § 194.4(b)(4) report (DOE 2002d).

MON-4.0 POSTCLOSURE (LONG-TERM) MONITORING

The final Postclosure Monitoring Plan will be developed prior to final facility closure (sealing of the shafts), but will not be implemented until after facility closure. This plan will include a review of CCA Appendix MON, sections MON.6 through MON.7, which are brought forward as Attachment A of this Appendix. Attachment A is as written in the CCA and any references in Attachment A are to the CCA. When the final Postclosure Monitoring Plan is written, any proposed changes to the commitments made in Attachment A will only be made after review and approval by the appropriate regulatory authorities.

MON-5.0 MONITORING PROGRAMS QUALITY ASSURANCE REQUIREMENTS

The quality of the work performed under the DOE CMP is controlled by the application of the CBFO Quality Assurance Program Document (QAPD) (DOE 2003a) and existing QA procedures employed by the CBFO. Waste information is controlled by implementation of the QAPD at generator sites.

In addition to the management requirements, such as document and record control established in the QAPD, requirements related to sampling and monitoring activities are specified. In particular, the following two sections of the QAPD are directly related to the performance of monitoring work and the control of samples:

- **Section 2.4 – Inspection and Testing**
  - qualification of personnel,
  - inspection,
  - test requirements,
  - monitoring, measuring, testing, and data collection,
  - use and control of measuring and test equipment (M&TE), and
  - calibration.
- **Section 4.0 – Sample Control Requirements**
  - sample control,
  - sample identification,
  - handling, storing, and shipping samples, and
  - disposition of nonconforming samples.

Sampling and monitoring activities follow properly documented and implemented quality assurance/quality control procedures. WIPP monitoring programs are subject to EPA inspections in accordance with 40 CFR § 194.21.

The CMP relies on the individual monitoring plans' QA programs to ensure compliance with DOE WIPP requirements for data quality assessments, objectives, and analyses. Each sampling and monitoring program is implemented through individual implementation plans, which include the QA descriptions, objectives, and references to the applicable governing QA documents.

MON-6.0 REPORTING AND ASSESSMENT

Information flow is controlled to ensure important monitoring results are communicated to the appropriate individuals and groups.

MON-6.1 Monitoring Data Reporting

The monitoring programs that generate the data used in the CMP are implemented by the M&OC. The reporting of the data for the 10 compliance monitoring parameters is coordinated through the M&OC.

It is the responsibility of the M&OC to ensure that the DOE is fully informed regarding any occurrence of anomalous CMP results and evaluations. The M&OC communicates important monitoring results to the SA. The SA communicate to the M&OC, via the DOE, any information generated that may impact the M&OC monitoring activities during their assessment.

MON-6.1.1 Assessing Compliance Monitoring Parameters

The SA is responsible for assessing compliance monitoring parameters against PA expectations and will report results through an annual compliance assessment report to the DOE.

It is the responsibility of the SA to ensure that the DOE is fully informed in the event that the SA's activities generate information that changes current understanding of data, parameter values, or conceptual models that are important to the assessment of the performance of the repository. In this role, the SA integrates the information generated through the various SA activities and presents a single position to the DOE. When unexpected or anomalous results are generated, the SA recommends to the DOE actions appropriate to mitigate or respond to the unexpected result. The SA also serves the information-exchange function described above by communicating to the M&OC any results that may impact the M&OC monitoring activities. The SA develops the compliance monitoring parameter assessment annually. This report is sent to the EPA as part of the annual reporting requirement of 40 CFR § 194.4(b)(4).

MON-6.1.2 Reporting and Assessment Point of Contact

In its role as the centralized point of contact for monitoring activities, the DOE is responsible for the following activities:

- Review monitoring results – CMP results may indicate two general cases:

  (1) normal or expected conditions in which results are generally consistent with existing data, parameter values, and conceptual models; or

  (2) anomalous conditions that are inconsistent with existing data, parameter values, or conceptual models. It is the responsibility of the DOE to review recommendations provided by the M&OC and the SA generated through the monitoring programs to determine whether these results are consistent or inconsistent with expected

conditions modeled in PA or screening decisions used to support the compliance determination.

- Definition of responsive actions or changes – Anomalous results may warrant changes in the monitoring programs, research activities, PA assumptions, or some other aspect of the overall compliance program. In addition, occasions may arise when it is appropriate to modify existing monitoring programs for modifications that may be required by regulators or are initiated from within the project.

MON-6.1.3 External Reporting

The DOE will review the recommendations of the M&OC and the SA to evaluate their significance. Significance will be determined based on consideration of the following criteria:

- containment requirements established pursuant to 40 CFR § 191.13 are, or are expected to be, exceeded;

- releases from waste already emplaced lead to committed effective doses that are, or are expected to be, in excess of those established pursuant to 40 CFR § 191.15 (not including emissions from operations covered pursuant to Subpart A of 40 CFR Part 191); or

- releases have caused, or are expected to cause, concentrations of radionuclides (or estimated doses due to radionuclides in underground sources of drinking water in the accessible environment) to exceed the limits established pursuant to 40 CFR 191, Subpart C.

If monitoring results meet any of these criteria, the results will be considered to be significant. Monitoring results determined by the CBFO to be significant will be promptly reported to the EPA. The report will be accompanied by a recommended course of action, including the appropriate external reporting. If the monitoring results indicate an exceedance or possible exceedance of containment requirements or release as specified in 40 CFR § 194.4(b)(3)(ii), the CBFO will immediately cease emplacement of waste in the WIPP and notify the EPA within 24 hours.

If monitoring results are significant but do not indicate an immediate or imminent exceedance or release as described in 40 CFR § 194.4(b)(3)(ii), the CBFO will prepare a written report of its findings. The CBFO Manager provides this report to the EPA within 10 days.

For normal conditions where monitoring results are within expectations, the compliance monitoring parameter assessment will document this condition annually. As stated previously, this report is sent to the EPA as part of the annual reporting requirement of 40 CFR § 194.4(b)(4).

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ATTACHMENT A
TO
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ACRONYMS

BEAR	Backfill Engineering Analysis Report
DOE	Department of Energy
DOI	Department of Interior
FEIS	Final Environmental Impact Statement
FSAR	Final Safety Analysis Report
NGS	National Geodetic Survey
QAPD	Quality Assurance Program Description
SNL	Sandia National Laboratories
S-Caps	Subsidence Monuments
WEC	Westinghouse Electric Corporation
WIPP	Waste Isolation Pilot Plant

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POSTCLOSURE MONITORING

MON-A-6. REVIEW OF POSTCLOSURE MONITORING TECHNOLOGIES

Each of the technologies listed below are discussed, defining the monitoring technology and describing the past, current, and future work using this technology as related to performance monitoring. Also defined are the advantages, disadvantages, and proposed uses of the technologies in postclosure monitoring of the repository.

- Subsidence
- Seismic reflection and refraction
- Gravitational
- Electromagnetic
- Resistivity
- Direct repository monitoring

MON-A-6.1 Subsidence

Subsidence is defined as vertical movement of the land surface anywhere in the subsidence basin. Subsidence monitoring is defined as the measurement of *relative vertical movement* of the land surface. This movement can be up (uplift) or down (subsidence) and is relative to a fixed reference. This reference is assumed fixed, even though it is subjected to the same factors that cause the surface movement and is moving also. Subsidence monitoring is used to determine the measurable vertical movement of a land mass. The techniques used to monitor subsidence measure the vertical height difference between two or more markers placed on the surface a known distance away from each other and is done with a leveling survey. Usually, one reference benchmark is used as the standard and the relative movement of other stations or benchmarks is measured to detect vertical movement over time. All subsidence measurements are relative because the reference is not fixed.

The error of the survey is determined by the equipment and distances between the stations. A first order survey has an error of one part in 100,000 and a second order survey has an error of one part in 20,000. With current technology, several thousandths of an inch vertical movement can be measured to the stated accuracy.

Subsidence can be caused by a variety of factors. Mining, hydrocarbon extraction, water injection and extraction, geological tilt, and dissolutioning are major subsidence causing factors all of which may be applicable to the WIPP over the long term.

MON-A-6.1.1 Advantages of Subsidence Monitoring

Subsidence monitoring is advantageous because it is a passive monitoring technique that is relatively simple to perform and uses well established technologies. The cost of the survey is

low compared to other technologies. This technique requires little system maintenance or monitoring and has no power requirement. The benchmarks are not affected by weather and can last for hundreds of years. Benchmarks can be replaced if required and the data can be offset to account for the change without affecting data quality.

MON-A-6.1.2 Disadvantages of Subsidence Monitoring

The disadvantages associated with subsidence monitoring are in the benchmark placement. The benchmark should be left undisturbed. Existing benchmarks may be destroyed or moved if new construction occurs over the benchmarks. The permanent markers design calls for large earthen berms around the facility after closure. The placement of the berm may cover some of the existing benchmarks and may preclude the necessary line-of-sight measurements between existing benchmarks. The benchmarks are also not currently protected, and could be destroyed during land use by ranchers, drillers, or developers. This necessitates replacing markers and incorporating new markers on the berm to maintain a line-of-sight reference with the benchmarks. Future advancements in global positioning systems may eliminate the need for line-of-sight placement of the benchmarks.

MON-A-6.1.3 Past Subsidence Work

During the initial site selection process, 195 miles (314 kilometers) of first order, Class 1 leveling survey was performed in 1977 by the National Geodetic Survey (NGS). Later, new survey lines were established that connected the previous first order benchmarks through Carlsbad to second order survey lines through Eunice and Hobbs. Benchmarks were placed over the Nash Draw from the north end to the Remuda Basin, over potash mines, the WIPP site, and the San Simon Sink (Powers 1993). Independent of the NGS benchmarks, an additional 52 benchmarks were installed over the WIPP site and surrounding area.

The NGS network was resurveyed in 1981 and the relative movement between Carlsbad and the WIPP site was measured to be about 0.8 inches (2 centimeters). The relationships between subsidence and potash mining in the WIPP vicinity are discussed in Powers (1993). From data in this report, potash mining was shown to have caused significant subsidence at mines close to the WIPP. Two benchmarks over the Mississippi Chemical Corporation mine measured relative to Carlsbad show 10- and 40-inch (25.4- and 102.7-centimeter) movement downward from 1977 to 1981. Powers (1993) also discusses mining effects on surface subsidence at other mines and correlated a relationship between mining and the surface area effects. This effect is of importance to WIPP monitoring in that estimations of area mining and WIPP mining can be calculated into the subsidence predictions. From Powers (1993), "In May, 1982, the NGS placed and leveled 15 additional high-quality benchmarks along a north-south line across the position of WIPP 12 (1 mile [1.6 kilometers] north of WIPP surface facilities) and the underlying brine reservoirs in the Castile Formation." After testing and fluid production of approximately 27,058 barrels of brine from the brine reservoir, the NGS resurveyed these benchmarks in January, 1983. According to Powers (1993), "The major difference in elevation across these 15 benchmarks from May, 1982 to January, 1983, is about 6 to 7 millimeters between the north end of the line and the approximate position of the WIPP."

MON-A-6.1.4 Subsidence Predictions

Subsidence predictions as a result of mining can also be calculated empirically. Techniques such as mass conservation, National Coal Board, and profile and influence functions can be used to calculate subsidence caused by mining. The influence function technique can estimate subsidence from room and pillar type mining, which is the type of mining used at the WIPP (Sutherland and Munson 1983). Four studies have been performed that have calculated subsidence predictions, the results are found in the *Final Environmental Impact Statement* (FEIS) (DOE 1980), the *Final Safety Analysis Report (FSAR)* (DOE 1990), Sandia National Laboratories' (SNL's) 1991 comparison with 40 CFR Part 191 (WIPP Performance Assessment Division 1991), and the *Backfill Engineering Analysis Report (BEAR)* (WEC 1994b). The following details each report's maximum subsidence predictions:

MAXIMUM SUBSIDENCE PREDICTIONS

FEIS

70-percent backfill density	1-foot (0.3-meter) subsidence
50-percent backfill density	1.6-foot (0.5-meter) subsidence
No backfill	3.28-foot (1.0-meter) subsidence

FSAR

Shaft pillar area	1- to 1.2-foot (0.3- to 0.38-meter) subsidence

(backfill type and amount not specified)

SNL

35E angle	0.3-foot (0.09-meter) subsidence
25E angle	0.4-foot (0.13-meter) subsidence

BEAR

No backfill	1.3- to 2-foot (0.40- to 0.60-meter) subsidence
Highly compacted backfill	1- to 1.7-foot (0.30- to 0.52-meter) subsidence

MON-A.6.1.5 Current Work in Subsidence Monitoring

Current subsidence work includes annual monitoring, a proposed NGS, and a satellite positioning survey. The WIPP Subsidence Monitoring Program is performed annually allowing for a comparison of the data, development of a database, and analysis of subsidence characteristics at the WIPP site. The program includes surface subsidence monitoring involving twenty miles of leveling loops through approximately fifty monuments (S-Caps). Subsidence monitoring surveys include Global Positioning Satellite and surveys of the S-Caps. Figure SMP-1 (see Appendix SMP) identifies approximately 50 benchmarks (those designated "S" and "PT") distributed throughout the area of influence of the repository and excavated support regions. The annual survey is completed so as to achieve closures that exceed a minimum standard of Second Order Class II for vertical control surveys. State of the art digital leveling technology is employed for all subsidence surveys. From 1996 onward, the survey is being performed to yet higher standards to allow for upgrading the precision of measurements.

Maintenance and calibration of equipment used for monitoring is addressed in Section 2.4.4 of the Westinghouse Waste Isolation Division Quality Assurance Program Description, (see Appendix QAPD). For subsidence measurements, maintenance and calibration are performed by the equipment vendor in accordance with national standards. Equipment is only procured from, maintained, and calibrated by vendors on the WIPP approved Qualified Supplier's List.

Data, plots, graphics, and reports generated as a result of the subsidence surveys are reviewed by cognizant technical engineering personnel to ensure their adequacy and accuracy in accordance with DOE and DOE/WIPP Quality Assurance Review procedures.

The WIPP currently monitors the existing benchmarks as indicated in Figure SMP-1 (see Appendix SMP) on an annual basis (drawing by John West Engineering Co., 1-11-93).

MON-A-6.1.6 Future Work on Subsidence Monitoring

A NGS survey was performed in 1996 however the final report has not yet been published. The current plan is to resurvey about every 10 years. The last NGS survey was performed in 1982.

MON-A-6.1.7 Define Use of Subsidence Surveys for Postclosure Monitoring

This report assumes that substantial work will be performed during the operational phase to gather subsidence information and data. This data will be used to relate expected subsidence over time for various scenarios of repository performance. The effects of petroleum production, mining, and geological subsidence must be accounted for in these scenarios. These estimates would be compared to actual measurements.

During the operational phase, the current benchmarks and new benchmark network will be used to gather baseline data. After the operational phase, however, decommissioning of the surface facilities and erection of active and passive controls will eliminate some of this network. For this reason, during the decommissioning, damaged or lost stations should be replaced. Additional stations may be necessary to compensate for line-of-sight losses incurred as a result of the proposed passive permanent markers. It is expected that analysis may have determined subsidence estimates at specific locations; these locations should be included in the benchmark network.

After decommissioning and adjustment of the benchmark network, a Class 1 leveling survey will be performed to determine baseline data. The network will be monitored after closure and until monitoring is determined to be no longer necessary. The monitoring frequency is to be every third year for the first 15 years. During this time, the data will be compared to the previous trends and if no important anomalies are found, the monitoring frequencies will be adjusted to 10-year intervals.

MON-A-6.2 Seismic Reflection and Refraction Surveys

Seismic reflection and refraction surveys are used to determine the depth, thickness, composition, and physical properties of geologic layers. Data from the survey can locate specific horizons such as water tables, clay layers, and bedrock. This technology can be used to map the

geological structures of large areas at great depths. Survey results are often used by geologists to locate specific geologies that may contain hydrocarbon reserves.

This method uses seismic wave transmissions to determine geologic structure depth and composition. Seismic waves travel at different velocities depending on the soil and rock type. Hard and dense rock has higher wave velocities than soft and less dense rock. Seismic waves can travel through, reflect, or refract off of geological structures. Some of the wave energy will travel along the layers. This phenomenon is used to determine depth and composition of the strata by measuring the return time of an induced wave generated at the surface and reflected and refracted back from the underlying strata.

This technique measures wave travel times through a sensor array called geophones placed over the area of interest. A seismic wave is generated by dropping a weight (anything from a hand sledge to truck-mounted ram), or by using high explosives. A seismograph is used to amplify and record the data. By using various seismic wave input energies, sensor array spacings and numbers, specific depths can be mapped. The map corresponds to a geological profile along the line surveyed. Figure MON-A.6 details the basic seismic surveying technique.

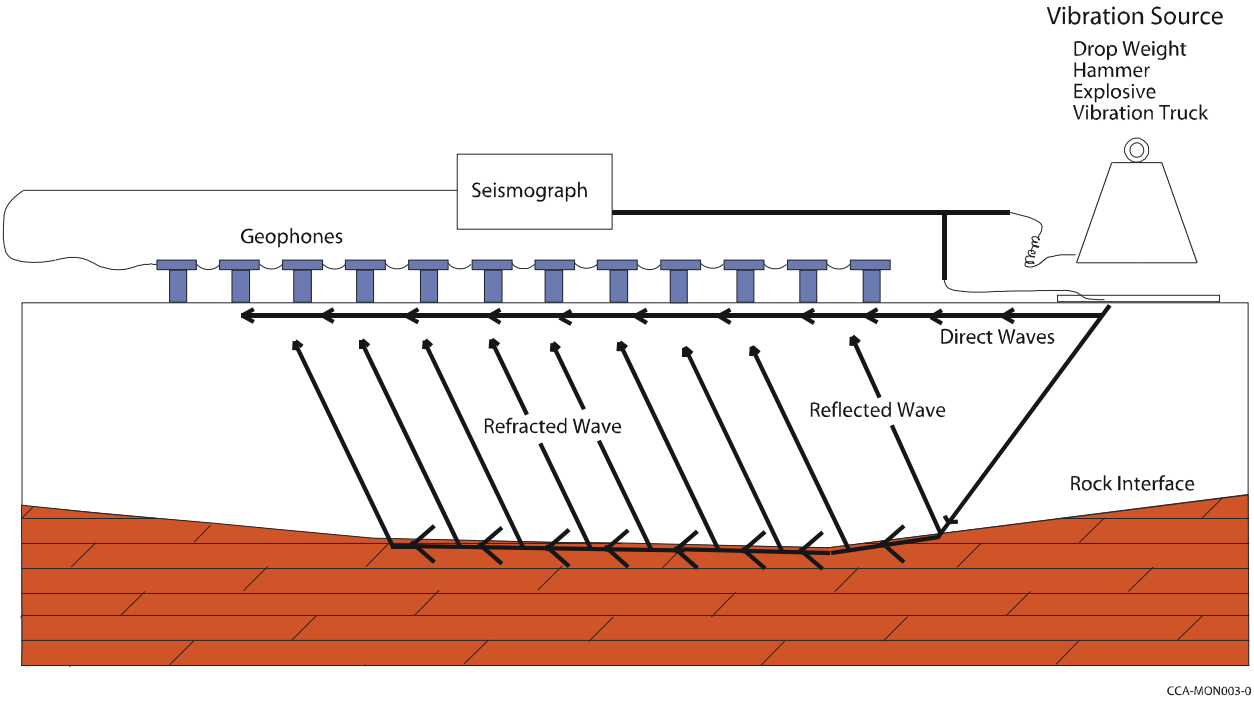

Figure MON-A.6. Seismic Reflection and Refraction Survey Concept

MON-A-6.2.1 Advantages of Seismic Reflection and Refraction Surveys

One advantage of this technique is the abundance of existing data. Numerous petroleum companies have performed seismic surveys in the WIPP area and several other surveys were performed during site selection (Powers et al. 1978; included in this compliance application as Appendix GCR). This data can be used as a reference to detect changes by comparison with new

data. The quality of the data is good for lower structures but is not as useful above the 3,000-foot (914-meter) level (Appendix GCR).

Seismic surveys are nonintrusive and require no permanent devices to be installed at the site. Seismic surveys are relatively inexpensive.

MON-A-6.2.2 Disadvantages of Seismic Reflection and Refraction Surveys

Basic disadvantages of this technique include data quality and interpretation. This technique is sensitive to noise and equipment set-up. The data must be electronically processed, conditioned, and interpreted by an experienced geologist. Interpretation is an art form and no two interpretations are the same (Griswold 1977). This can create repeatability errors if the surveys are repeated on the same geology. The results are usually compared to core samples to verify the interpretation and validate the results.

Seismic surveys use equipment that allows for many variations in how data are collected. For comparison reasons, surveys must be performed using similar equipment set-ups, that is, array spacings, line locations, and data conditioning. Any variations in the technique and equipment must be accounted for in the interpretation of the data to ensure that changes caused when different equipment is used for repeated surveys are not interpreted as geological changes. Relatively thin strata and layers of similar densities cannot be distinguished. Because the technique is based on wave velocities, layers of material that may have different chemical and geological characteristics, but similar velocity components, cannot be differentiated.

MON-A-6.2.3 Past Seismic Reflection and Refraction Survey Work

During the siting process for the WIPP, several geophysical techniques were used to gather geological data that would identify a suitable site location.

From 1976 to 1978, SNL conducted three surveys totaling 79 line miles (127 kilometers) of data, of which 72 line miles (116 kilometers) were over or near the WIPP site (Hern et al. 1978). The first survey consisted of three lines totaling 24.98 line miles (40.47 kilometers) of conventional petroleum style data and was collected from petroleum companies. The other two surveys were conducted using short geophone spacing and high signal frequency for better shallow field resolution above 4,000 feet (1,220 meters) (Appendix GCR). One of these surveys totaled 47.04 line miles (67.65 kilometers) involving 13 lines. The third survey included 7.5 line miles (12 kilometers) of profiling run along crossing lines through the site (Griswold 1977; Hern et al. 1978).

Approximately 189 line miles (304 kilometers) of older (1950s to 1960s) seismic surveys performed by Shell Oil Co. were purchased from a brokerage firm (G.J. Long Associates 1976). Exxon allowed 196 line miles (315 kilometers) of their data to be viewed at their office, Amoco allowed 513 line miles (825 kilometers) of data to be viewed (G.J. Long Associates 1976). This data were considered proprietary and could not be distributed to other sources. All of the listed data were gathered and interpreted during 1976 (Griswold 1977). Results of the data were used to map the geological layers around the WIPP site. These maps are found in WP 02-9, FSAR Section 2.7 (DOE 1990).

In 1976, attempts were made to perform a high-resolution shallow survey using weight drop techniques. This survey produced data that was not interpretable when compared to known geological information (Hern et al. 1978).

In 1979, an extensive seismic survey was performed that profiled lines directly over the WIPP site boundaries in north-south and east-west patterns. The north-south lines were spaced at 0.25-mile (0.4-kilometer) intervals and the east-west lines were spaced 0.5-mile (0.8-kilometer) apart in Zone 2. In the areas between Zones 2 and 3, the lines were spaced farther apart. The north-south lines were separated by 0.5-miles (0.8-kilometers) and the east-west lines were spaced at one mile (1.62 kilometers). This survey used the same basic parameters as the original Sandia National Laboratories (SNL) survey with closer line spacing. The intent was to improve the accuracy of the data above the Salado.

MON-A-6.2.4 Current Seismic Reflection and Refraction Work

No seismic surveys are being performed.

MON-A-6.2.5 Define Uses for Seismic Reflection and Refraction Surveys in Postclosure Monitoring

The seismic method determines the difference in geology by measuring the velocity of a wave through the rock. Any physical change in the rock is accompanied by a corresponding change in its velocity. Seismic surveys can be used to map the repository at various times. The specific depths and densities of various formations can be mapped and compared to data generated in the future to evaluate the repository performance. Changes in the strata, such as changes in aquifer depth and strata density changes, can be determined.

After the repository is sealed and the facility is decommissioned, a seismic survey could be performed over the repository and surrounding area. This survey could be performed to provide good resolution above and below the repository. The survey results and raw data could be documented and all interpretations of the data could be documented. The results and data could be archived so baseline data can be used for comparison to future seismic data if the need arises. The baseline data will help identify changes in the geology surrounding the facility that could help determine if the repository performance is acceptable. The survey could be performed after closure and will not be resurveyed unless new data are required.

The following are requirements for seismic monitoring uses in postclosure monitoring.

- Archive data in at least two permanent formats,
- Line surveys will be referenced to benchmarks in the subsidence network,
- All data reduction programs will be included in the archive data,
- The exact location for the survey will be in accordance with the recommendation of an experienced geologist, and

- Research will be conducted to identify methods to improve repeatability in geophone placement.

MON-A-6.3 Gravitational Surveys

The gravity survey method maps small variations in the earth's gravitational field. These variations result from mass and density difference in the subsurface lithography of the earth's crust. Interpretation of the data from a gravity survey can detect structural displacement in the strata (Barrows et al. 1983). The survey is performed by using a gravimeter. The instrument measures the gravity intensity at a point. The data is expressed in milligal, where a gal is an acceleration of 1 centimeter per square second. Standard equipment is accurate to within a tenth of a milligal.

MON-A-6.3.1 Advantages of Gravitational Surveys

This technology is helpful in determining the depth and area of various geological anomalies. In itself, gravity surveys are not concise, but aid the researcher in determining areas (anomalies) that should be explored using other geophysical techniques to determine the specifics of the anomaly. The gravity survey is nonintrusive and relatively inexpensive when compared to other geophysical monitoring techniques.

MON-A-6.3.2 Disadvantages of Gravitational Surveys

Gravity surveys do not provide the type of information that allows a geologist to determine the exact geological description and location of the strata surveyed.

This technique is very dependent on placement of the gravimeter. Placement errors can cause variability in results if the survey is repeated. For repeatability, exact placement of the gravimeter must be recorded and verified. This variation is not as pronounced when the results are mapped over a large area.

The data from the gravimeter is sensitive to surface structure, elevation, geographic latitude, and solar and lunar tides (Barrows et al. 1983). Corrections must be made for the terrain and usually cause an error of ± 0.3 milligal (DOE U.S. Department of the Interior [DOI] 1981). Surveying data point position and altitude is half the effort of the gravity survey. This method is prone to human error because manual recording is used. The data is often edited by reviewing the data and deleting any suspected transcription errors.

MON-A-6.3.3 Past Gravitational Survey Work

During the siting phase a regional gravity control was purchased in 1976, from a geophysical company (Griswold 1977, DOE 1983). Over 3,000 miles (4,800 kilometers) of gravity data were collected in the area as part of various hydrocarbon exploration surveys (Westinghouse Electric Corporation [WEC] 1990, *Final Safety Analysis Report [FSAR]* 2.7-27). Also, two gravity surveys, the main site and the reconnaissance profiles, were conducted by SNL. Three smaller areas within the main site survey were resurveyed in greater detail to provide information on suspected anomalies.

The main site survey covered approximately 8.5 square miles (13.7 square kilometers). The lines were spaced 0.6 miles (0.27 kilometers) apart and ran north-south with the stations spaced at 0.18-mile (0.09-kilometer) intervals (Barrows et al. 1983). During this survey, an anomaly was discovered and a borehole was drilled in that area. This area was surveyed in greater detail and covered an area 1,164 feet by 679 feet (355 meters by 207 meters). The stations were spaced in a grid 97 feet (30 meters) apart. Two other smaller areas were resurveyed to provide enhanced detail.

These data were used to detect anomalies in the strata and develop an interpretation of the disturbed zone. However, the disturbed zone data was inconclusive (Barrows et al. 1983). Areas surveyed detected some karst development. A gravity contour map of the WIPP site areas surveyed is found in Barrows et al. (1983).

MON-A-6.3.4 Current Gravitational Survey Work

No gravitational survey work is currently being performed by the DOE.

MON-A-6.3.5 Define Uses of Gravitational Surveys for Postclosure Monitoring

Gravity survey data could be included in the baseline database. All past surveys could be included along with extensive documentation defining the equipment, procedures, and data collection and processing techniques used. Surveys could be performed over the repository after closure and decommissioning, to provide baseline data for the repository. The original gravity survey data will not include the influence of over 6 million cubic feet (170 thousand cubic meters) of waste, so a new survey would be needed to provide a baseline after closure.

MON-A-6.4 Electromagnetic Conductivity Surveys

The term electromagnetic conductivity is used by many geological companies to describe various geophysical equipment. For this report, the term is defined as a method that measures subsurface conductivity by low-frequency electromagnetic induction. This method uses a coil placed on the surface that transmits electromagnetic pulses that induce eddy current loops in the layered strata below the transmitting loop. The induced loop currents are in theory directly proportional to the resistance of the strata. The induced current produces a secondary field current that can be sensed by a receiving coil placed a fixed distance from the transmitting coil. The reading is a bulk measurement of conductivity of the strata directly below the transmitting loop to the effective depth of the instrument. The instruments effective depth is related to the distance between the transmitting and receiving coils. The electromagnetic system usually measures conductivity of the materials in millimhos per meter and is easily converted to resistivity. Conductivity is the reciprocal of resistivity.

The electromagnetic system determines the conductivity of the strata that is related to the soil and rock geophysical and geochemical properties. Properties such as porosity, permeability, concentrations of colloids and dissolved electrolytes in the pores, and conductive minerals all influence conductivity, but the most influential factor is water content. Because water is the main factor, aquifers and brine pockets can be detected. Pipes, waste containers, metallic debris, and wire lines can also be detected.

Electromagnetic systems can be used to profile and map strata. Both stationary and mobile systems are available. Mobile systems are capable of taking continuous readings. A diagram of the basic system configuration is shown in Figure MON-A.7.

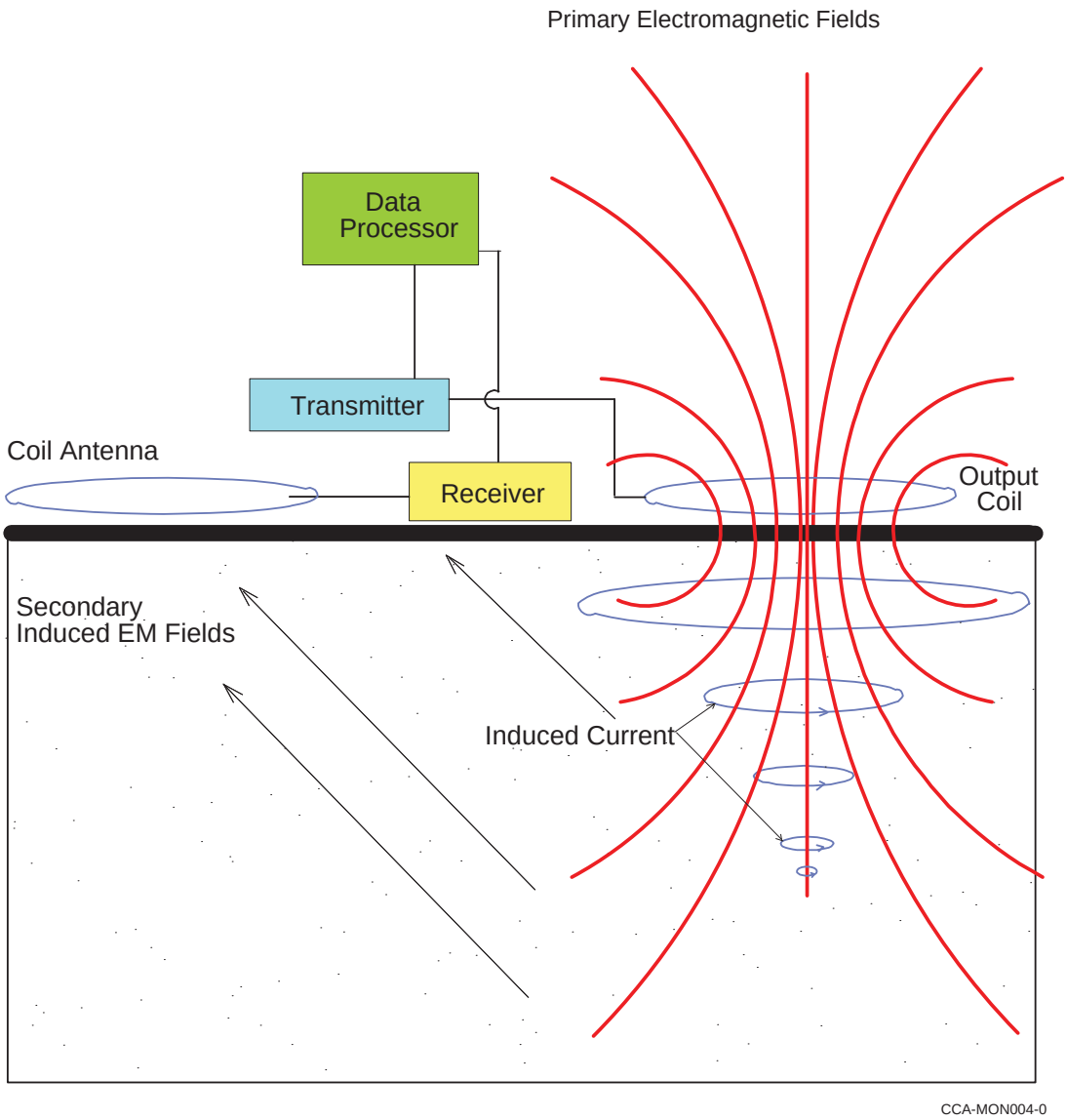

Figure MON-A.7. Electromagnetic Survey Technique

MON-A-6.4.1 Advantages of Electromagnetic Conductivity Surveys

The electromagnetic method is nonintrusive and can detect brine occurrences, strata layers with differing physical properties, and aquifers. Mapping of an area can be compared to subsequently acquired data to determine changes such as brine movements. The depth and area of brine pockets can be determined which can then be used to estimate the volumes of the pockets. Electromagnetic surveys may be used to locate waste after placement.

The electromagnetic method does not require ground contact and the measurements can be taken continuously. Methods of this nature have good repeatability. Measurements can be made at ground level or from aerial surveys.

MON-A-6.4.2 Disadvantages of Electromagnetic Conductivity Surveys

Electromagnetic technology falls short in data interpretation when a highly resistive layer is sandwiched between two highly conductive layers. Strata can have the same relative conductivity but be entirely different geologically. This method is not concise enough to be a stand-alone method, but can be used along with other geophysical techniques to interpret the strata.

The results can vary with ground moisture content. Results after substantial rains are significantly different than those performed after prolonged droughts. Interpretation of the data must account for these variations.

MON-A-6.4.3 Past Electromagnetic Conductivity Survey Work

Several electromagnetic type surveys were performed by SNL. One survey was initiated to map brine occurrences in the strata above and below the repository. The survey measured 36 locations in a 0.9- by 0.6-mile (1.5- by 1.0-kilometer) grid directly over the repository. Two other measurements were made, one at the WIPP-12 borehole and the other at the DOE-1 borehole. A calibration measurement was made at ERDA-9. The final interpretation of the survey data details brine occurrences. These results correlated well with the depths of the brine occurrences found at WIPP-12 and ERDA-9 (Earth Technology Corporation 1988).

When comparing the results of electromagnetic survey data with borehole logs, the accuracy of determining the depth to brine is better than 246 feet (75 meters) at depths between 3,280 to 4,920 feet (1,000 to 1,500 meters).

Aeromagnetic survey maps are available from the U.S. Geological Survey (Map GP-861, Carlsbad/West Texas) and Aero Service Library (No. 43-6, Carlsbad/West Texas) (Elliot Geophysical Co. 1976).

MON-A-6.4.4 Current Electromagnetic Conductivity Survey Work

No electromagnetic work is currently being performed.

MON-A-6.4.5 Define Uses of Electromagnetic Conductivity Surveys for Postclosure Monitoring

Electromagnetic surveying is capable of detecting water or brine occurrences, and can differentiate layers with varying physical properties. This technique could be used to monitor the facility after closure to determine if brine has migrated into the shafts, boreholes and/or repository.

The performance of the shaft, borehole seals, and boreholes could be monitored to determine if they are maintaining the isolation between the aquifers in the Rustler Formation. The repository

could be mapped directly after the repository is sealed and included in the baseline data to be used for comparison at a later date.

MON-A-6.5 Resistivity Surveys

The resistivity method is similar in nature to the electromagnetic method. Resistivity measures the resistance of the rock and electromagnetic measures the conductance. Resistance is the reciprocal of conductance. The resistivity of the rock and soil is influenced by the same factors listed in the previous section for conductivity. By varying the electrode spacing geometries and currents, different parameters can be measured. Two specific methods used during WIPP siting are called Schlumberger sounding and gradient array profiling.

The resistivity method uses four sets of electrodes on the surface, spaced in a specific geometry. Two electrodes are energized to create a current through the strata between the electrodes. The second pair of electrodes measures the potential produced from the first pair. The strata's resistivity can be calculated from the potential and electrode geometry and spacing.

As with the other types of geophysical monitoring methods, resistivity measurements can be used to perform sounding and profiling. Profiling maps the changes in the subsurface resistivity horizontally. Sounding can detect vertical changes in subsurface resistivity. The interpretation of the results can be used to determine the depth and thickness of geologic layers of different resistivity. This method can detect soil thickness and depth to aquifers or brine layers. A diagram describing the basic system configuration is shown in Figure MON-A.8.

MON-A-6.5.1 Advantages of Resistivity Surveys

The gradient array method is a relatively simple method. The electrodes are separated at large distances which enables economical mapping of large areas. The advantages of this method are identical to the electromagnetic method.

MON-A-6.5.2 Disadvantages of Resistivity Surveys

Variations in placement will give differing results if the survey is repeated in the same area. The resistivity surveys require direct ground contact and cannot be performed continuously. The condition of the surface layer can affect the results because variation in the soils moisture content can be detected. Measurements performed shortly after rains will be significantly different than measurements taken after prolonged droughts. However, this can be accounted for in the interpretation of the results. Resistivity also has the same disadvantages as the electromagnetic method.

MON-A-6.5.3 Past Resistivity Survey Work

Extensive resistivity surveys were conducted during the siting of the WIPP from 1976 to 1978. Areas around suspected breccia pipes and sinks (off-site) were surveyed to determine if resistivity surveys could be used to detect these structures within the WIPP site. All zones of the WIPP site were surveyed. Mining Geophysical Surveys, Inc. performed 53 Schlumberger array soundings and approximately 391 line miles (629 kilometers) of gradient array profiling (9,880 measurements) (Elliot Geophysical Co. 1977).

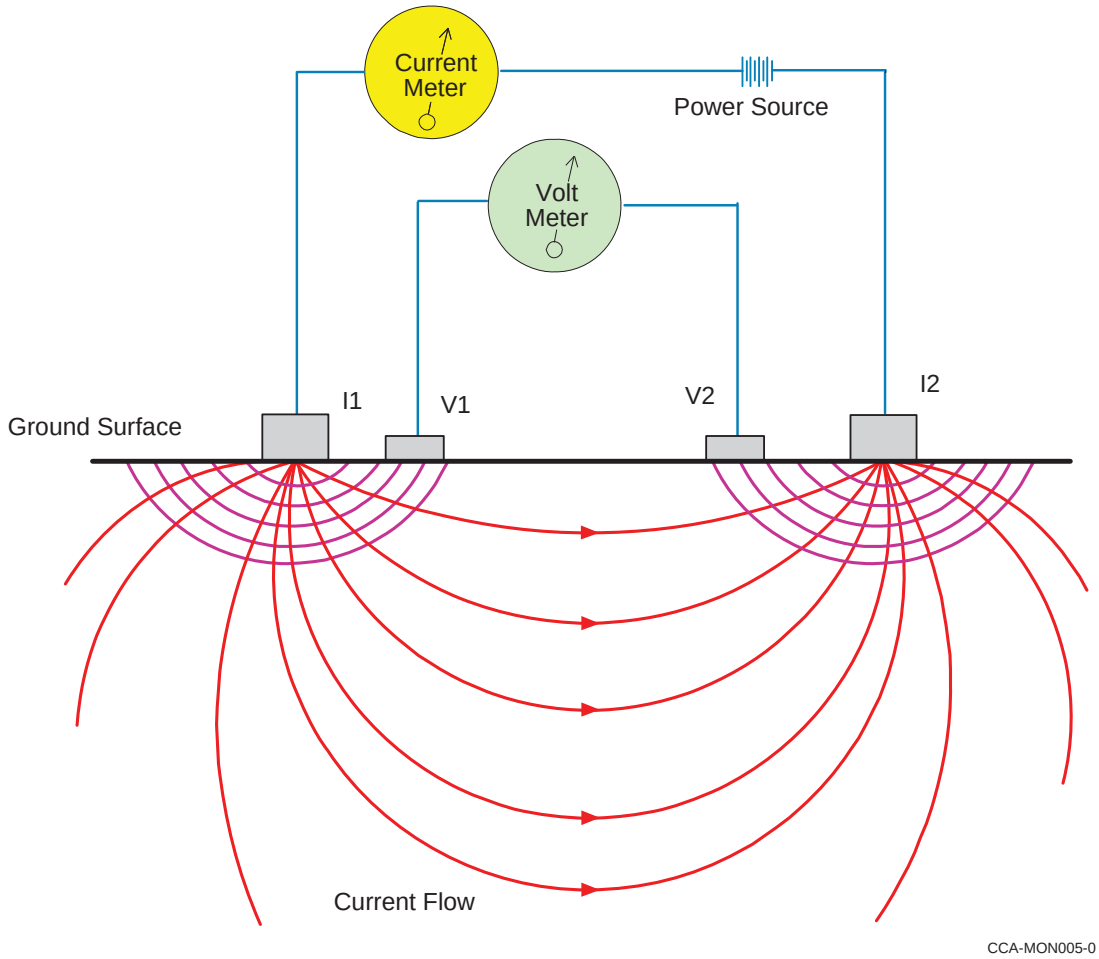

Figure MON-A.8. Resistivity Survey Content

MON-A-6.5.4 Current Resistivity Survey Work

No resistivity work is currently being performed.

MON-A-6.5.5 Define Uses of Resistivity Surveys for Postclosure Monitoring

This technology can be used along with electromagnetic techniques to gather data immediately after the repository is sealed. Both profiling and sounding would be performed to produce geological maps of the strata's resistivity. When the surveys are made, the exact locations and methods used could be carefully documented. If possible, research could be required to develop a system for electrode placement to ensure good repeatability in the surveys. This data would be documented in the baseline database for future comparison.

MON-A-6.6 Environmental Monitoring

Environmental monitoring of the WIPP repository will be performed during the operational and decontamination-and-decommissioning periods. The C&C between the state of New Mexico and the DOE requires radiological environmental monitoring for at least five years after final facility closure. This agreement specifies that the environmental monitoring program in place

during the operational phase must be continued after closure and decommissioning for at least two years, and that an abbreviated program with a limited number of radiological air, soil, water, and background samples be continued for the following three years.

The postclosure environmental monitoring program is required to include the following (DOE 1994a):

- Radiological Environmental Monitoring (first two years after decontamination and decommissioning)

  - Airborne particulate
    lo-vol sampling, eight stations

  - Vegetation
    four sites

  - Beef
    annual muscle samples if available

  - Game animals
    annual muscle samples of rabbits and quail.

  - Soil samples
    annual, multiple samples at multiple depths at six locations.

  - Surface and drinking water
    annual surface water samples from 12 major bodies of surface water in the vicinity of the site (drinking water will not exist after decontamination and decommissioning)

  - Groundwater
    annually, one sample from eight of the wells within the 16 sections boundary taken from the Culebra Dolomite.

  - Aquatic foodstuffs
    samples of catfish taken from the Pecos River and Brantley Lake and analysis annually.

  - Sediment sampling
    annual samples taken from the Hill and Indian tank and the Pecos River near Artesia and Malaga, New Mexico.

- Abbreviated radiological environmental monitoring (three, four, and five years after decontamination and decommissioning).

  - Airborne particulate
    intermittent operation of the state-operated high-volume air sampling stations.

- Soil
  four annual soil surface samples.

- Water
  four annual well water samples.

Only the radiological environmental monitoring techniques that apply after final closure are included. Items such as effluent monitoring at the exhaust shaft were not included because they do not apply after final facility closure.

Environmental monitoring has been an ongoing program since the WIPP's inception. Baseline environmental data were gathered and reported in annual reports and an environmental monitoring plan was created. The current operational environmental monitoring plan is detailed in the *Waste Isolation Pilot Plant Environmental Monitoring Plan*, WIPP/DOE 94-024 (DOE 1994a) and the *Waste Isolation Pilot Plant Site Environmental Report for the Calendar Year 1993*, DOE/WIPP 94-2033 (DOE 1994b).

MON-A-6.7 Direct Repository Monitoring

From earlier discussions, no proposed postclosure monitoring techniques include technologies to directly monitor the repository. This is due to the inherent difficulties imposed by the noninvasive requirement. No wiring or boreholes will be used to connect monitoring equipment in the repository to the surface.

The U.S. Bureau of Mines and commercial companies throughout the world are currently researching techniques to communicate through the strata to mine working areas using very-low frequency and ultra-low frequency electromagnetic radiation. Several companies have developed mine paging systems that use very-low frequency to warn workers within the mine using a system placed on the surface. One system can transmit messages with up to 32 characters to mobile mine pagers. This technology shows promise in remote instrumentation communication that could directly monitor the repository. It has been demonstrated in other salt mines that communication from the surface to the depth of the WIPP repository is possible.

Recently, researchers have started to investigate methods to remotely monitor the sealed rooms and panels. This work uses very-low frequency technology to link sensors and equipment in sealed rooms to the data recorder without a hardwired link. Current work is focused on communication from where the link between the transmitter and receiver is only 10 to 33 feet (3 to 10 meters).

Very-low frequency could be used to transmit data from the surface to equipment located in the repository but the problem lies in communicating the sensor data to the surface. The power required to transmit between the surface and the underground using the current technology is related to the strata conductivity, the output power at the transmitter, and the antenna design. Tests performed in actual mines used large loop antennas on the surface to transmit the signal. Tests have shown that loop diameter is more important in transmission efficiency than output power. Antennas ranging from 98 feet to over 328 feet (30 meters to over 100 meters) in diameter have been used (DOI 1991).

There are many problems that must be overcome to directly monitor the repository after closure. Some of these problems are listed below.

- Future sensor and transducer calibration would not be possible,
- Sensor longevity in the repository environment is not likely,
- Data collection and transmission power requirements could be problematic, and
- Antenna locations and sizes could pose issues with regard to other surface structures and activities.

MON-A-6.7.1 Sensor Calibration

Over time, most sensors, such as pressure, gas analyzer, and extensometer sensor and transducer, experience some change in resolution or drift. Any type of sensor and transducer used would need to operate for 100 years without recalibration. To overcome this problem, redundant sensors, sensor drift calculations, and accessible sensors as standards could be used to limit the induced errors. However, this would not ensure accuracy over the required time frame.

MON-A-6.7.2 Sensor Longevity

The sensors used for postclosure monitoring would be required to operate in a salt/brine environment for over 100 years. This imposes the biggest obstacle in direct repository monitoring. Corrosion, oxidation, and various chemical reactions would easily limit the life span to less than 50 years.

MON-A-6.7.3 Data Collection and Transmission Power Requirements

A power source that could operate for the time required is not currently available. Battery systems have limited shelf lives and capacities. Lithium-type batteries have the longest shelf life of the common battery types. Standard shelf lives of five to 10 years at their rated capacity is standard with some manufacturer's claiming 80-percent capacity after 15 years. Because the capacity requirements are dependent on the equipment load, the highest current requirement would occur during data transmittal. From experimental work, an estimate of at least 350 watts may be required to transmit to the surface. This can be accomplished with standard power sources for the short-term, but other currently unavailable methods of power generation would be required for the long-term.

One potential method is power transmission and retention. Power could be transmitted from the surface using ultra-low frequency energy and an antenna would intercept this energy and store it in capacitors or a special battery. Because the system could be charged for long periods of time between data transmissions, only a small amount of surface transmitted power is required. The problem with this approach is power storage.

The chemical nature of rechargeable batteries limits their life span. The effects of oxidation, outgasing, and heat damage will cause a battery to fail. The life span of most common rechargeable (lead acid, gel, and nickel cadmium) batteries is dependent on the number of

recharge cycles, the rate of discharge, and charge rates. Under favorable conditions, most rechargeable batteries can last up to 10 years.

The capacitor is a device that stores energy on two plates separated by an insulator. Capacitors can be designed for this application that would last the required time frame. The problem associated with capacitors is related to power storage capability and size. In comparison, a capacitor and a battery with the same approximate volume do not have the same energy storage capacity. For example, a one-microfarad capacitor charged to 1,000 volts has 0.5 Joules of energy storage, a 500-mAh nickel cadmium (1.2 volts) of similar volume has 2,160 Joules of energy storage. A capacitor that has this energy storage potential would be extremely large (4,320 times larger).

Satellite power sources use nuclear energy to generate power. The systems are not considered off-the-shelf technology. However, work is progressing on a nuclear heat power source using (almost) off-the-shelf technology. One experimental study calls this type of power source a Powerstick (Chmielewski and Ewell 1994). This theoretical device would use a nuclear heat source and a thermopile to generate an electrical potential. The heat source is a common satellite product used to heat instrumentation. The power source is capable of producing 42 milliwatts at 15 volts initially and would degrade to 37 milliwatts at 14 volts in 10 years. These power sources could be used to slowly charge batteries and/or capacitors that would then be used for a short duration, high-demand data transmission cycle or in parallel for a higher current source.

The regulatory issues associated with nuclear power sources have not been researched. If the remotely-handled waste could supply an adequate heat source and WIPP receives remotely-handled waste, the regulatory issues may be overcome.

The nuclear and thermopile power source technology has not been proven and there is no prototype as yet. Advances in battery design and the development of this nuclear power source could eventually allow this technology to power a direct repository monitor.

MON-A-6.7.4 Antenna Location and Size

The size of the antenna may pose a problem in the mine setting. If the antenna is placed inside a room, diameters are limited to a maximum of approximately 328 feet (100 meters). If the antenna can be wrapped around a pillar, the antenna would have a radius of approximately 164 feet (50 meters) but diameters between 32.8 feet and 328 feet (10 meters and 100 meters) would require special provisions. Also, the effects of the metal in the room will increase the power requirement. These problems can be overcome and experimentation would be needed to verify the effectiveness of the antenna design.

From current technology, no known system is currently available that could be used to directly transmit data to the surface without a hardwired link. Extensive research and development is needed to develop such a system; however, the systems longevity will be suspect, since actual long-term testing could not be accomplished and new technologies are rarely foolproof. For this reason, direct repository monitoring is not recommended at this time for postclosure monitoring.

MON-A-6.8 Conclusion

There is no single geophysical technical exploratory technique that can determine the condition of the surveyed strata. Several techniques are used to gather data to assess the geological structure that is being examined because interpretation of one technique often uses data from another. For this reason, no single technique could be used to fully assess the repository's condition. One technique can be used as an identifier to alert that a condition may exist and other techniques can be used in unison to assess and validate the condition.

From the review of geophysical survey techniques, the best current monitoring technology that can be used for a postclosure monitoring identifier is subsidence. This method is the most practical because it is a simple, repeatable, low-cost, low-maintenance, low-technology approach to monitoring the repository. This method should be used as a primary monitor technique for determining that a possible repository performance problem exists. Other techniques can then be utilized to determine the cause of the problem.

A combination of seismic, electromagnetic, resistivity, and gravitational surveys can be used to assess repository performance. However, it is not practical to perform these on a regular basis. These techniques are also not needed if there is good confidence that a performance-related event will not occur. For this reason, an initial collection of surveys could be compiled and used as a standard to assess future data and perform subsidence monitoring to forewarn of changing conditions that may significantly affect repository performance.

MON-A-7. POSTCLOSURE MONITORING PROGRAM SUMMARY

Physical, chemical, economical, and technical factors have been included in the conceptual approach to designing a practical, yet effective, postclosure monitoring system. The needed information can be obtained from a monitoring system composed of a subsidence network, a monitoring program, a baseline database, a closure review study, and a subsidence data study.

The following summarizes the postclosure monitoring program.

- The DOE will create a baseline database that includes data from developmental and operational phase activities.
- The DOE will perform a subsidence data study.
- The DOE will compile subsidence predictions and include any performance assessment-developed scenarios of repository performance which fall outside the baseline subsidence predictions. The DOE will develop proper benchmark locations over the repository. The subsidence predictions will be developed from the information available in the *Backfill Engineering Analysis Report (BEAR)* (WEC 1994b) and from any additional information provided by the performance assessment.
- The DOE will create a subsidence network over and around the facility.
- The DOE will perform a closure review study.

- The DOE will perform the following surveys to establish baseline data for the baseline database.
  - Seismic survey over the waste panels after final facility closure (one time).
  - Resistivity survey over the waste panels after final facility closure (one time).
  - Electromagnetic survey over the waste panels after closure (one time).
  - Gravitational survey after final facility closure (one time).
  - Subsidence survey (throughout the program lifetime).
  - Obtain and archive core samples from previous core work (one time).
- The DOE will initiate the monitoring program after closure. The DOE will perform periodic leveling surveys of the subsidence network and develop a schedule for future surveys. The DOE will perform the radiological environmental monitoring program for two years and the abbreviated program for an additional three years.
- The DOE will compare leveling survey data to expected results.
- The DOE will perform periodic reviews at least every two years during the monitoring program to evaluate the monitoring schedule.
- The DOE will perform maintenance on RCRA wells, replacing casings as required or every 25 years until monitoring ceases. The DOE will monitor in accordance with the postclosure monitoring schedule and postclosure monitoring plan requirements.
- The DOE will perform maintenance on subsidence network as required (determined during the leveling surveys).

This monitoring concept is based on current technologies and data for monitoring repository performance. Future monitoring during the repository development and operational phases may provide data that lead to the conclusion that postclosure monitoring will not be relevant or may identify new parameters that must be monitored.

The monitoring techniques specified in this report can be used to meet the requirements in the current regulations governing the facility and to monitor performance of the facility. This concept provides for a reliable database against which future monitoring results can be compared.

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Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix PA

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix PA

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ACRONYMS AND ABBREVIATIONS

AMG	algebraic multi-grid solver
CDF	cumulative distribution function
CCDF	complementary cumulative distribution function
CFR	Code of Federal Regulations
CH-TRU	contact-handled transuranic (waste)
DBR	direct brine release
DOE	United States Department of Energy
DDZ	drilling damaged zone
DRZ	disturbed rock zone
EPA	United States Environmental Protection Agency
FEP	feature, event, or process
LHS	Latin Hypercube Sample
LMG	Link- algebraic multi-grid solver
LWB	Land Withdrawal Boundary
MB	Marker Bed
PA	performance assessment
PAVT	Performance Assessment Verification Test
PCS	panel closure system
PDF	probability density function
PDE	partial differential equations
PRCC	partial rank correlation coefficient
RH-TRU	remote-handled transuranic (waste)
SMC	Salado Mass Concrete
SOR	successive over-relaxation
TRU	transuranic (waste)
TVD	Total Variation Diminishing
WIPP	Waste Isolation Pilot Plan

PA-1.0 INTRODUCTION

This appendix presents the mathematical models used to evaluate performance of the Waste Isolation Pilot Plant (WIPP) and the results of these models for the CRA-2004 Performance Assessment (PA). This appendix supplements information presented in Chapter 6 of this application.

This appendix is organized as follows. Section PA-2.0 describes the overall conceptual structure of the CRA-2004 PA. As described in Section 6.1, the WIPP PA is designed to answer the requirements of Title 40 Code of Federal Regulations (CFR) Part 191, and thus involves three basic entities: (1) A probabilistic characterization of different futures that could occur at the WIPP site over the next 10,000 years, (2) Models for the physical processes that take place at the WIPP site and for the estimation of potential radionuclide releases that may be associated with these processes, and (3) A probabilistic characterization of the uncertainty in the models and parameters that underlie the WIPP PA. Section PA-2.0 is supplemented by Attachment SCR, which documents the results of the screening process for features, events, and processes (FEPs) that are retained in the conceptual models of repository performance.

Section PA-3.0 describes the probabilistic characterization of different futures. This characterization plays an important role in the construction of the complementary cumulative distribution function (CCDF) specified in 40 CFR § 191.13. Regulatory guidance and extensive review of the WIPP site resulted in identification of exploratory drilling for natural resources and the mining of potash as the only significant disruptions at the WIPP site with the potential to affect radionuclide releases to the accessible environment (Section 6.2.5). Section PA-3.0 summarizes the stochastic variables that represent future drilling and mining events in the PA.

Section PA-4.0 presents the mathematical models for the physical processes that take place at the WIPP and for the estimation of potential radionuclide releases. The mathematical models implement the conceptual models described in Section 6.4, and permit the construction of the CCDF specified in 40 CFR § 191.13. Models presented in Section PA-4.0 include: two-phase (i.e., gas and brine) flow in the vicinity of the repository; radionuclide transport in the Salado; releases to the surface at the time of a drilling intrusion due to cuttings, cavings, spallings, and direct releases of brine; brine flow in the Culebra Dolomite Formation; and radionuclide transport in the Culebra Dolomite. Section PA-4.0 is supplemented by Attachments MASS, TFIELD, and PORSURF. Attachment MASS discusses the modeling assumptions used in the WIPP PA. Attachment TFIELD discusses the generation of the transmissivity fields used to model fluid flow in the Culebra. Attachment PORSURF presents results of modeling the effects of excavated region closure, waste consolidation, and gas generation in the repository.

Section PA-5.0 discusses the probabilistic characterization of parameter uncertainty, and summarizes the uncertain variables incorporated into the 2004 PA, the distributions assigned to these variables, and the correlations between variables. Section PA-5.0 is supplemented by Attachments PAR and SOTERM. Attachment PAR catalogs the full set of parameters used in the CRA-2004 PA. Attachment SOTERM describes the actinide source term for the WIPP performance calculations, including calculation of the mobile concentrations of actinides that may be released from the repository in brine.

Section PA-6.0 summarizes the computational procedures used in the CRA-2004 PA, including: sampling techniques (i.e., random and Latin hypercube sampling); sample size; statistical confidence for mean CCDF; generation of Latin hypercube samples (LHSs); generation of individual futures; construction of CCDFs; calculations performed with the models discussed in Section PA-4.0; construction of releases for each future; and the sensitivity analysis techniques in use.

Section PA-7.0 presents the results of the PA for an undisturbed repository. Releases from the undisturbed repository are determined by radionuclide transport in brine flowing from the repository to the land withdrawal boundary (LWB) through the marker beds (MBs) or shafts (Section 6.3.1. Releases in the undisturbed scenario are used to demonstrate compliance with the individual and groundwater protection requirements in 40 CFR Part 191 (Chapter 8).

Section PA-8.0 presents PA results for a disturbed repository. As discussed in Section 6.2.3, the only future events and processes in the analysis of disturbed performance are those associated with mining and deep drilling. Release mechanisms include direct releases at the time of the intrusion via cuttings, cavings, spallings, and direct release of brine; and radionuclide transport up abandoned boreholes to the Culebra and thence to the land withdrawal boundary. Section PA-8.0 presents results for the most significant output variables from the PA models, accompanied by sensitivity analyses to determine which subjectively uncertain parameters are most influential in the uncertainty of PA results.

Section PA-9.0 presents the set of CCDFs resulting from the CRA-2004 PA. This material supplements Section 6.5, which demonstrates compliance with the containment requirements of 40 CFR § 191.13. Section PA.9.0 includes sensitivity analyses that identify which uncertain parameters are most significant in the calculation of releases.

This appendix follows the approach used by Helton et al. (1998) to document the mathematical models used in the CCA PA and the results of that analysis. Much of the content of this appendix derives from Helton et al. (1998); these authors' contributions are gratefully acknowledged.

PA-2.0 CONCEPTUAL STRUCTURE OF THE PERFORMANCE ASSESSMENT

The conceptual structure of the CRA-2004 PA is unchanged from the CCA PA. Section 6.1 provides a general, less technical overview of the PA conceptual structure. This section of Appendix PA presents the conceptual basis for the CRA-2004 PA in a more formal manner. A corresponding presentation for the CCA PA is provided in Helton et al. (1998).

PA-2.1 Regulatory Requirements

The conceptual structure of the CRA-2004 PA derives from the regulatory requirements imposed on this facility. The primary regulation determining this structure is the Environmental Protection Agency's (EPA's) standard for the geologic disposal of radioactive waste, Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR Part 191) (EPA 1985, 1993), which is divided into three subparts. Subpart A applies to a disposal facility prior to decommissioning and limits the annual radiation doses members of the public can be exposed to from waste management and storage operations. Subpart B applies after decommissioning and sets probabilistic limits on cumulative releases of radionuclides to the accessible environment for 10,000 years (40 CFR § 191.13) and assurance requirements to provide confidence that 40 CFR Section 191.13 will be met (40 CFR Section 191.14). Subpart B also sets limits on radiation doses to members of the public in the accessible environment for 10,000 years of undisturbed performance (40 CFR § 191.15). Subpart C limits radioactive contamination of groundwater for 10,000 years after disposal (40 CFR § 191.24). The Department of Energy (DOE) must demonstrate a reasonable expectation that the WIPP will continue to comply with the requirements of Subparts B and C of 40 CFR Part 191.

The following is the central requirement in 40 CFR Part 191, Subpart B, and the primary determinant of the conceptual structure of the CRA-2004 PA (p. 38086, EPA 1985):

> § 191.13 Containment requirements:
>
> (a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:
>
> (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and
>
> (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).
>
> (b) Performance assessments need not provide complete assurance that the requirements of 191.13(a) will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with 191.13(a) will be achieved.

Section 191.13(a) refers to "quantities calculated according to Table 1 (Appendix A)," which means a normalized radionuclide release to the accessible environment based on the type of waste being disposed of, the initial waste inventory, and the size of release that may occur (EPA 1985, Appendix A). Table 1 of Appendix A specifies allowable releases (i.e., release limits) for individual radionuclides and is reproduced as Table PA-1 of this appendix. The WIPP is a repository to transuranic (TRU) waste, which is defined as "waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years, per gram of waste" (p. 38084, EPA 1985). The normalized release R for transuranic waste is defined by

$$R = \sum_i \left(\frac{Q_i}{L_i}\right)\left(1 \times 10^6\ Ci/C\right) \tag{1}$$

where Q_i is the cumulative release of radionuclide i to the accessible environment during the 10,000-year period following closure of the repository (curies), L_i is the release limit for radionuclide i given in Table PA-1 (curies), and C is the amount of TRU waste emplaced in the repository (curies). In the CRA-2004 PA, $C = 2.48 \times 10^6$ curies (Appendix TRU WASTE, Section TRU WASTE-2.3.1). Further, accessible environment means (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all of the lithosphere that is beyond the controlled area; and controlled area means (1) a surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system and (2) the subsurface underlying such a surface location (40 CFR § 191.13).

To help clarify the intent of 40 CFR Part 191, the EPA promulgated 40 CFR Part 194, Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance With the 40 CFR Part 191 Disposal Regulations. There, the following elaboration on the intent of 40 CFR § 191.13 set out.

> § 194.34 Results of performance assessments.
>
> (a) The results of performance assessments shall be assembled into "complementary, cumulative distributions functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events.
>
> (b) Probability distributions for uncertain disposal system parameter values used in performance assessments shall be developed and documented in any compliance application.
>
> (c) Computational techniques, which draw random samples from across the entire range of the probability distributions developed pursuant to paragraph (b) of this section, shall be used in generating CCDFs and shall be documented in any compliance application.
>
> (d) The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability.

Table PA-1. Release Limits for the Containment Requirements (EPA 1985, Appendix A, Table 1)

Radionuclide	Release Limit L_i per 1000 MTHM[1] or other unit of waste[2]
Americium (Am)-241 or –243	100
Carbon 14	100
Cesium-135 or -137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium (Pu)-238, -239, -240, or -242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium (Th)-230 or -232	10
Tin-126	1,000
Uranium (U)-233, -234, -235, -236, or -238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1,000

[1] Metric tons of heavy metal exposed to a burnup between 25,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM

[2] An amount of transuranic wastes containing one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years

(e) Any compliance application shall display the full range of CCDFs generated.

(f) Any compliance application shall provide information which demonstrates that there is at least a 95 percent level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 of this chapter.

Three basic entities (EN1, EN2, EN3) underlie the results required by Sections 191.13 and § 194.34 and ultimately determine the conceptual and computational structure of the CRA-2004 PA:

EN1 - a probabilistic characterization of the likelihood of different futures occurring at the WIPP site over the next 10,000 years,

EN2 - a procedure for estimating the radionuclide releases to the accessible environment associated with each of the possible futures that could occur at the WIPP site over the next 10,000 years,

EN3 - a probabilistic characterization of the uncertainty in the parameters used in the definition of EN1 and EN2.

The preceding entities arise from an attempt to answer three questions about the WIPP:

Q1 - What events could occur at the WIPP site over the next 10,000 years?

Q2 - How likely are the different futures that could take place at the WIPP site over the next 10,000 years?

Q3 - What are the consequences of the different occurrences that could take place at the WIPP site over the next 10,000 years?

and one question about the PA:

Q4 - How much confidence can be placed in answers to these questions?

In the WIPP PA, EN1 provides answers to Q1 and Q2, EN2 provides an answer to Q3, and EN3 provides an answer to Q4. Together, EN1 and EN2 give rise to the CCDF specified in Section 191.13(a), and EN3 corresponds to the distributions specified by Section 194.34(b). The nature of EN1, EN2 and EN3, the role that they play in the CRA-2004 PA, and the method for constructing CCDFs are elaborated on in the next three sections.

PA-2.2 EN1: Probabilistic Characterization of Different Futures

The entity EN1 results from the scenario development process for the WIPP outlined in Section 6.3. The EN1 entity provides a probabilistic characterization of the likelihood of different futures that could occur at the WIPP site over the 10,000-year period specified in 40 CFR Part 191. Formally, EN1 is defined by a probability space $\left(\boldsymbol{X_{st}, S_{st}, p_{st}}\right)$, with the sample space X_{st} given by Equation (2).

$$\boldsymbol{X_{st}} = \left\{\boldsymbol{x_{st}} : \boldsymbol{x_{st}} \textit{ is a possible 10,000-year sequence of occurrences at the WIPP}\right\} \qquad (2)$$

The subscript st refers to stochastic (i.e., aleatory) uncertainty and is used because $\left(\boldsymbol{X_{st}, S_{st}, p_{st}}\right)$ is providing a probabilistic characterization of occurrences that may take place in the future (Helton 1997). Incorporation of stochastic uncertainty is fundamental to the DOE's methodology for performance assessment Section 6.1.2. It is this stochastic uncertainty that gives rise to the distribution of releases evident in a CCDF.

A probability space $\left(\boldsymbol{X, S, p}\right)$ consists of three components: a set X that contains everything that could occur for the particular "universe" under consideration, a suitably restricted set S of subsets of X and a function p defined for elements of S that actually defines probability (Feller 1971). In the terminology of probability theory, X is the sample space, the elements of X are elementary events, the subsets of X contained in S are events, and p is a probability measure. In most applied problems, the function p defined on S is replaced by a probability density function (PDF) d (e.g., d_{st} in Figure PA-1).

In the CCA PA, the scenario development process for the WIPP identified exploratory drilling for natural resources as the only disruption with sufficient likelihood and consequence for

inclusion in the definition of EN1 (CCA Appendix SCR [DOE 1996]). Reexamination of the FEPs and the scenario development process for the CRA-2004 PA did not change this conclusion (Section 6.2.6). In addition, 40 CFR Part 194 specifies that the occurrence of mining within the land withdrawal boundary must be included in the PA. As a result, the elements $\boldsymbol{x}_{st}$ of X_{st} are vectors of the form

$$\boldsymbol{x}_{st} = [\underbrace{t_1, e_1, l_1, b_1, p_1, \mathbf{a}_1}_{1^{st}\ intrusion}, \underbrace{t_2, e_2, l_2, b_2, p_2, \mathbf{a}_2}_{2^{nd}\ intrusion}, \ldots, \underbrace{t_n, e_n, l_n, b_n, p_n, \mathbf{a}_n}_{n^{th}\ intrusion}, t_{min}] , \qquad (3)$$

where n is the number of drilling intrusions, t_i is the time (year) of the ith $_{intrusion}$, l_i designates the location of the ith intrusion, e_i designates the penetration of an excavated or nonexcavated area by the ith intrusion, b_i designates whether or not the ith intrusion penetrates pressurized brine in the Castile Formation, p_i designates the plugging procedure used with the ith intrusion (i.e., continuous plug, two discrete plugs, three discrete plugs), $\mathbf{a}_i$ designates the type of waste penetrated by the ith intrusion (i.e., no waste, contact-handled (CH-TRU) waste, remote-handled (RH-TRU) waste), and t_{min} is the time at which potash mining occurs within the land withdrawal boundary.

In the development of $(\boldsymbol{X}_{st}, \boldsymbol{S}_{st}, \boldsymbol{p}_{st})$, the probabilistic characterization of n, t_i, l_i and e_i is based on the assumption that drilling intrusions will occur randomly in time and space (i.e., follow a Poisson process), the probabilistic characterization of b_i derives from assessed properties of brine pockets, the probabilistic characterization of $\mathbf{a}_i$ derives from the properties of the waste emplaced in the WIPP, and the probabilistic characterization of p_i derives from current drilling practices in the sedimentary basin (i.e., the Delaware Basin) in which the WIPP is located. A vector notation is used for $\mathbf{a}_i$ because it is possible for a given drilling intrusion to penetrate several different types of waste. Further, the probabilistic characterization for t_{min} follows from the guidance in 40 CFR Part 194 that the occurrence of potash mining within the land withdrawal boundary should be assumed to occur randomly in time (i.e., follow a Poisson process with a rate constant of $\lambda_m = 10^{-4}$ yr^{-1}), with all commercially viable potash reserves within the land withdrawal boundary being extracted at time t_{min}.

With respect to the three fundamental questions discussed about, X_{st} provides an answer to Q1, while S_{st} and p_{st} provide an answer to Q2. In practice, Q2 will be answered by specifying distributions for n , t_i , e_i , l_i , b_i , p_i , $\mathbf{a}_i$, and t_{min} , which in turn lead to definitions for S_{st} and p_{st} . The CCDF in 40 CFR Part 191 will be obtained by evaluating an integral involving $(\boldsymbol{X}_{st}, \boldsymbol{S}_{st}, \boldsymbol{p}_{st})$ (Figure PA-1). The definition of $(\boldsymbol{X}_{st}, \boldsymbol{S}_{st}, \boldsymbol{p}_{st})$ is discussed in more detail in Section PA-3.0.

PA-2.3 EN2: Estimation of Releases

The entity EN2 is the outcome of the model development process for the WIPP and provides a way to estimate radionuclide releases to the accessible environment for the different futures (i.e.,

elements $\mathbf{x}_{st}$ of X_{st}) that could occur at the WIPP. Estimation of environmental releases corresponds to evaluation of the function f in Figure PA-1. Release mechanisms associated with f include direct transport of material to the surface at the time of a drilling intrusion (i.e., cuttings, spallings, brine flow) and release subsequent to a drilling intrusion due to brine flow up a borehole with a degraded plug (i.e., groundwater transport).

The function f in Figure PA-1 is evaluated by a series of computational models shown in Figure PA-2. These computational models implement the conceptual models representing the repository system as described in Section 6.4, and the mathematical models for physical processes that are presented in Section PA-4.0. Most of the computational models involve the numerical solution of partial differential equations used to represent processes such as material deformation, fluid flow and radionuclide transport.

The models in Figure PA-2 are too complex to permit a closed form evaluation of the integral in Figure PA-1 that defines the CCDF specified in 40 CFR Part 191. Rather, a Monte Carlo procedure is used in the CRA-2004 PA. Specifically, elements $\mathbf{x}_{st,i}$, i = 1, 2, …, nS are randomly sampled from X_{st} in consistency with the definition of $\left(X_{st}, S_{st}, p_{st}\right)$. Then, the integral in Figure PA-1, and hence the associated CCDF, is approximated by

$$prob\left(Rel > R\right) = \int_{S_{st}} \delta_R\left[f\left(\mathbf{x}_{st}\right)\right] d_{st}\left(\mathbf{x}_{st}\right) dV_{st} = \sum_{i=1}^{nS} \delta_R\left[f\left(\mathbf{x}_{st,i}\right)\right] / nS\,, \qquad (4)$$

where $\delta_R\left[f\left(\mathbf{x}_{st}\right)\right] = 1$ if $f\left(\mathbf{x}_{st}\right) > R$ and $\delta_R\left[f\left(\mathbf{x}_{st}\right)\right] = 0$ if $f\left(\mathbf{x}_{st}\right) \le R$ (Helton and Shiver 1996). However, the models in Figure PA-2 are also too computationally intensive to permit their evaluation for every element $\mathbf{x}_{st,i}$ of X_{st} in Equation (4). Due to this constraint, the models in Figure PA-2 are evaluated for representative elements of X_{st} and the results of these evaluations are used to construct values of f for the large number of $\mathbf{x}_{st,i}$ (e.g., nS = 10,000) in Equation (4). The representative elements are the scenarios E0, E1, E2, and E1E2 defined in Section PA-3.9; the procedure for constructing a CCDF from these scenarios is described in Section PA-6.0.

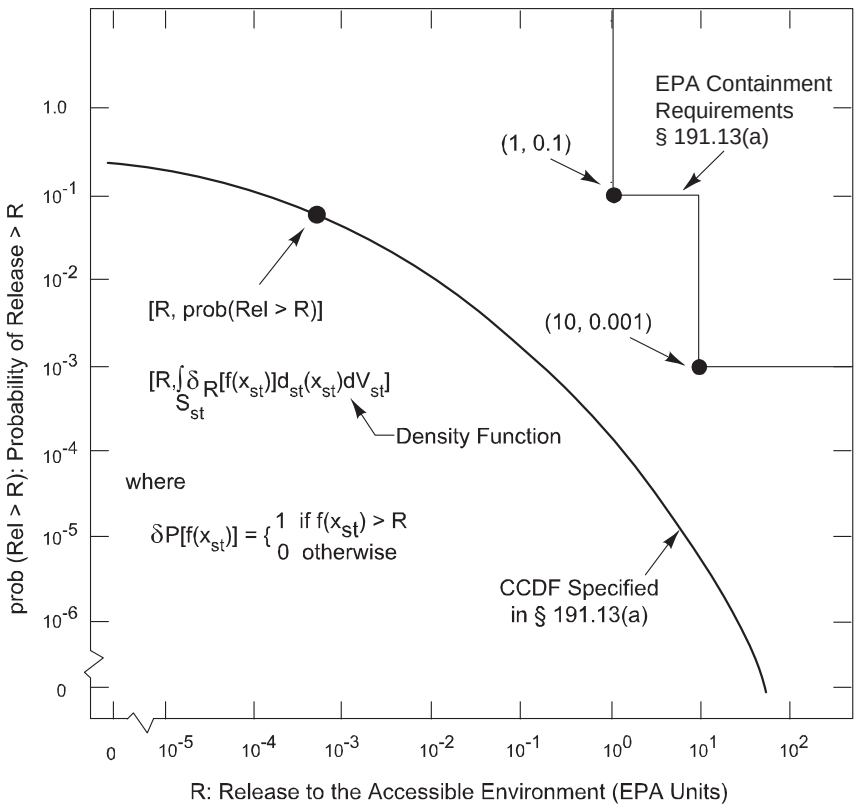

Figure PA-1. Construction of the CCDF Specified in 40 CFR Part 191, Subpart B.

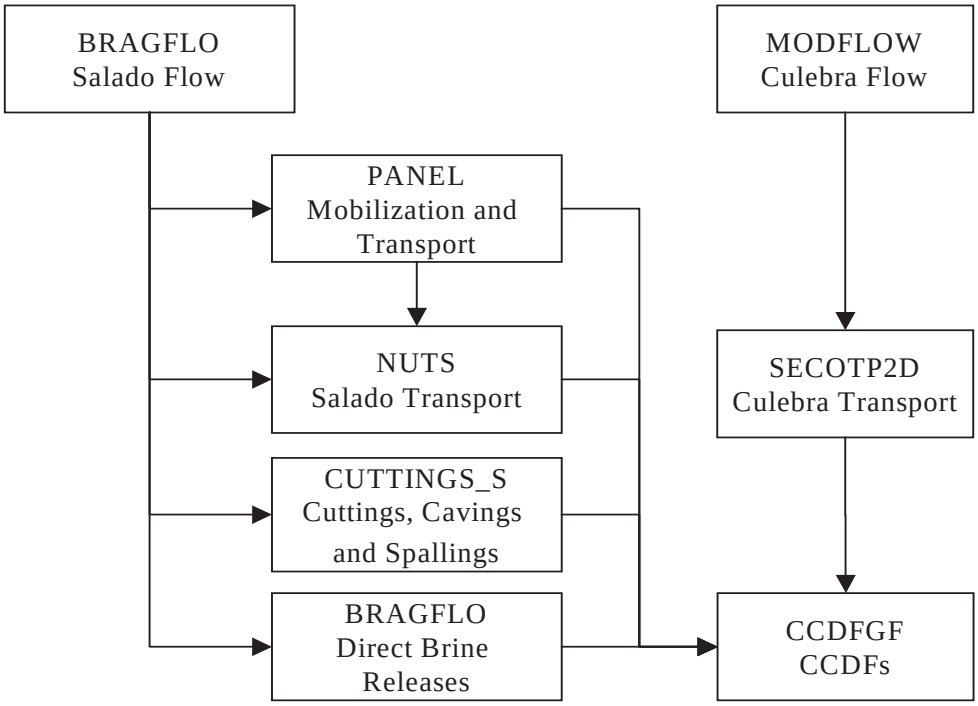

Figure PA-2. Computational Models Used in the CRA-2004 PA.

PA-2.4 EN3: Probabilistic Characterization of Parameter Uncertainty

The entity EN3 is the outcome of the data development effort for the WIPP (summarized in Chapter 2) and provides a probabilistic characterization of the uncertainty in the parameters that underlie the CRA-2004 PA. When viewed formally, EN3 is defined by a probability space $\left(X_{su}, S_{su}, p_{su}\right)$, with the sample space X_{su} given by Equation (5).

$$X_{su} = \left\{ \mathbf{x}_{su} : \mathbf{x}_{su} \textit{ is a possible vector of parameter values for the WIPP PA models} \right\} \tag{5}$$

The subscript su refers to subjective (i.e., epistemic) uncertainty and is used because $\left(X_{su}, S_{su}, p_{su}\right)$ is providing a probabilistic characterization of the possible inputs to the WIPP PA (Helton 1997). In practice, some elements of $\mathbf{x}_{su}$ could affect the definition of $\left(X_{st}, S_{st}, p_{st}\right)$ (e.g., the rate constant λ used to define the Poisson process for drilling intrusions) and other elements could relate to the models in Figure PA-2 that determine the function f in Figure PA-1 (e.g., radionuclide solubilities in Castile brine). Incorporation of subjective uncertainty is fundamental to the DOE's methodology for PA (Section 6.1.2).

If the value for $\mathbf{x}_{su}$ was precisely known, the CCDF in Figure PA-1 could be determined with certainty and compared with the boundary line specified in 40 CFR Part 191. However, given the complexity of the WIPP site and the 10,000-year time period under consideration, $\mathbf{x}_{su}$ can never be known with certainty. Rather, uncertainty in $\mathbf{x}_{su}$ as characterized by $\left(X_{su}, S_{su}, p_{su}\right)$ will lead to a distribution of CCDFs (Figure PA-3), with a different CCDF resulting for each possible value that $\mathbf{x}_{su}$ can take on. The proximity of this distribution to the boundary line in Figure PA-1 provides an indication of the confidence with which 40 CFR Part 191 will be met.

The distribution of CCDFs in Figure PA-3 can be summarized by distributions of exceedance probabilities conditional on individual release values (Figure PA-4). For a given release value R, this distribution is defined by a double integral over X_{su} and X_{st} (Helton 1996, 1997). In practice, this integral is too complex to permit a closed-form evaluation. Instead, the WIPP PA uses Latin hypercube sampling (McKay et al. 1979) to evaluate the integral over S_{su} and, as indicated in Equation (4), simple random sampling to evaluate the integral over X_{st}.

Specifically, a LHS $\mathbf{x}_{su,k}$, k = 1, 2, …, nLHS, is generated from S_{su} in consistency with the definition of $\left(X_{su}, S_{su}, p_{su}\right)$ and a random sample $\mathbf{x}_{st,i}$, i = 1, 2, …, nS, is generated from X_{st} in consistency with the definition of $\left(X_{st}, S_{st}, p_{st}\right)$. The probability $prob\left(p \le P \middle| R\right)$ is approximated by

$$prob\left(p \le P \mid R\right) \cong 1 - \sum_{k=1}^{nLHS} \delta_P \left[\sum_{i=1}^{nS} \delta_R \left[f\left(\mathbf{x}_{st,i}, \mathbf{x}_{su,k}\right)\right] / nS \right] / nLHS \tag{6}$$

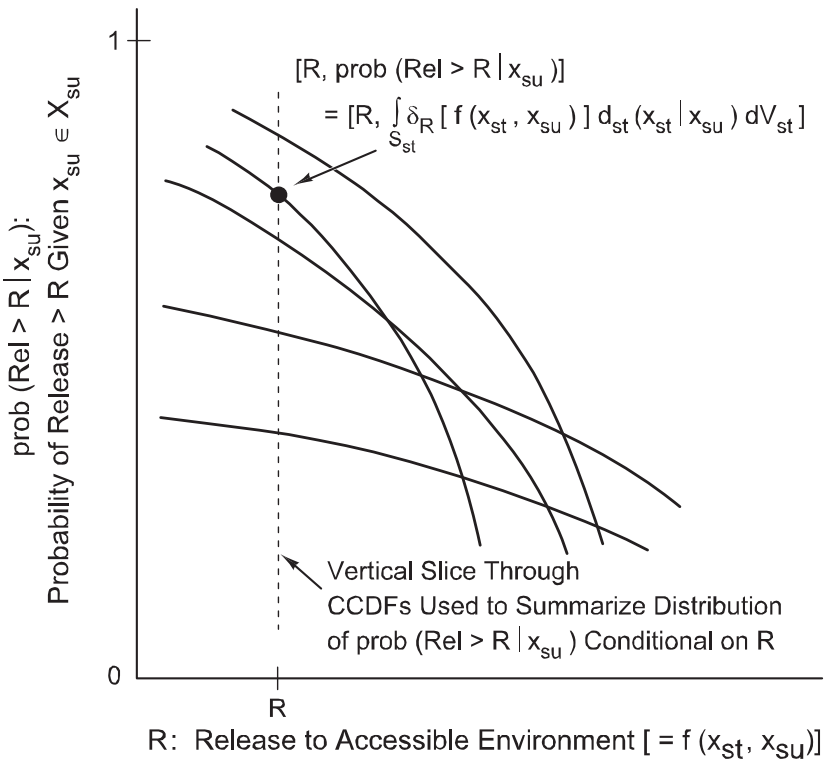

Figure PA-3. Distribution of CCDFs Resulting from Possible Values for $x_{su} \in X_{su}$.

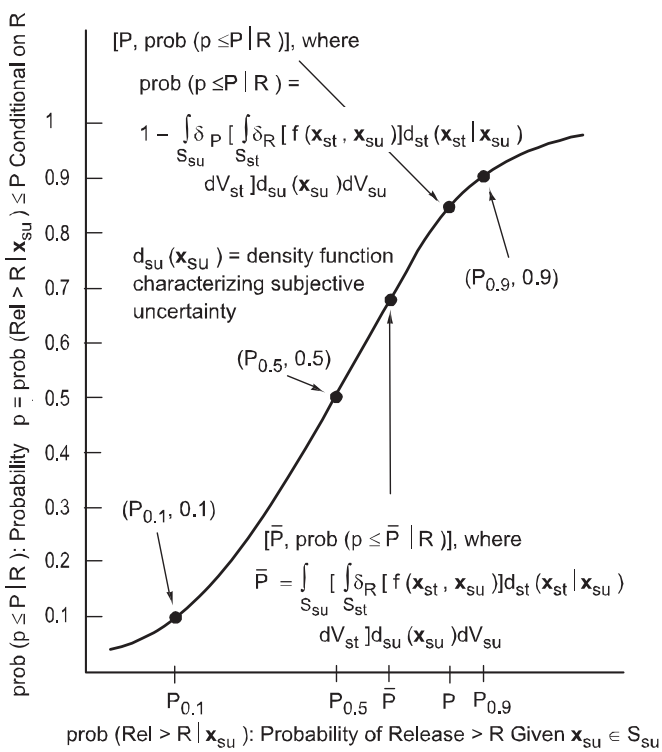

Figure PA-4. Distribution of Exceedance Probabilities Due to Subjective Uncertainty.

The result of the preceding calculation is typically displayed by plotting percentile values (e.g., $P_{0.1}$, $P_{0.5}$, $P_{0.9}$ in Figure PA-4) and also mean values for exceedance probabilities above the corresponding release values (i.e., R) and then connecting these points to form continuous curves (Figure PA-5). The proximity of these curves to the indicated boundary line provides an indication of the confidence with which 40 CFR Part 191 will be met.

With respect to the previously indicated questions, $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$ and results derived from $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$ (e.g., the distributions in Figure PA-3 and Figure PA-5) provide an answer to Q4. The definition of $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$ is discussed in more detail in Section PA-5.0.

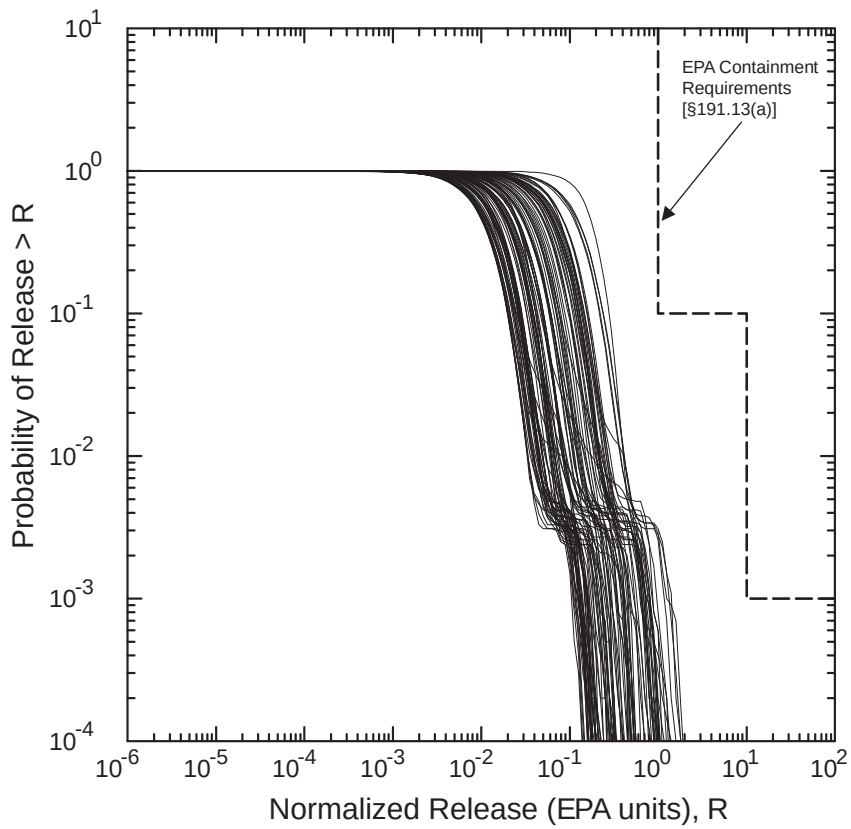

Figure PA-5. Example CCDF Distribution From CRA-2004 PA.

PA-3.0 PROBABILISTIC CHARACTERIZATION OF FUTURES

This section describes how stochastic uncertainty is implemented in PA. Screening analyses of possible future events concluded that the only significant events with potential to affect radionuclide releases to the accessible environment are drilling and mining within the land withdrawal boundary (Section 6.2.6). Consequently, modeling the future states of the repository focuses on representing the occurrences and effects of these two events.

PA-3.1 Probability Space

The first entity that underlies the CRA-2004 PA is a probabilistic characterization of the likelihood of different futures occurring at the WIPP site over the next 10,000 years. As discussed in Section PA-2.2, this entity is defined by a probability space $\left(X_{st}, S_{st}, p_{st}\right)$ that characterizes stochastic uncertainty. The individual elements x_{st} of X_{st} are vectors of the form shown in Equation (3). Sections PA-3.2 through PA-3.8 describe the individual components t_i, e_i, l_i, b_i, p_i, a_i, and t_{min} of x_{st}, and their associated probability distributions. These components and their associated distributions give rise to the probability space $\left(X_{st}, S_{st}, p_{st}\right)$ for stochastic uncertainty. The concept of a scenario as a subset of the sample space X_{st} for stochastic uncertainty is discussed in Section PA-3.9. Further, the procedure used to sample the individual elements $x_{st,i}$ of X_{st} indicated in Equation (4) is described in Section PA-6.5.

PA-3.2 Drilling Intrusion

As described in Section 6.3.2, drilling intrusions in the CRA-2004 PA are assumed to occur randomly in time and space (i.e., follow a Poisson process). Specifically, the drilling rate considered within the area marked by a berm as part of the system for passive institutional controls (Figure PA-6) is 5.25×10^{-3} intrusions per km $^{-2}$ yr $^{-1}$ (Section 6.4.12.2). Active institutional controls are assumed to prevent any drilling intrusions for the first 100 years after the decommissioning of the WIPP (Section 7.1). Unlike in the CCA PA, passive institutional controls are not assumed to reduce the drilling rate after decommissioning (Section 7.3).

For the computational implementation of the CRA-2004 PA, it is convenient to represent the Poisson process for drilling intrusions by its corresponding rate term $\lambda_d\left(t\right)$ for intrusions into the area marked by the berm. Specifically,

$$\lambda_d\left(t\right) = \begin{cases} 0 & 0 \le t \le 100\,yr \\ (0.6285\ km^2)(52.5\ km^{-2}\,10^{-4}\,yr) = 3.3 \times 10^{-3}\ yr^{-1} & 100 \le t \le 10{,}000\,yr \end{cases} \tag{7}$$

where 0.6285 km^2 is the area of the berm Attachment PAR, Table PAR-45 and t is elapsed time since decommissioning of the WIPP.

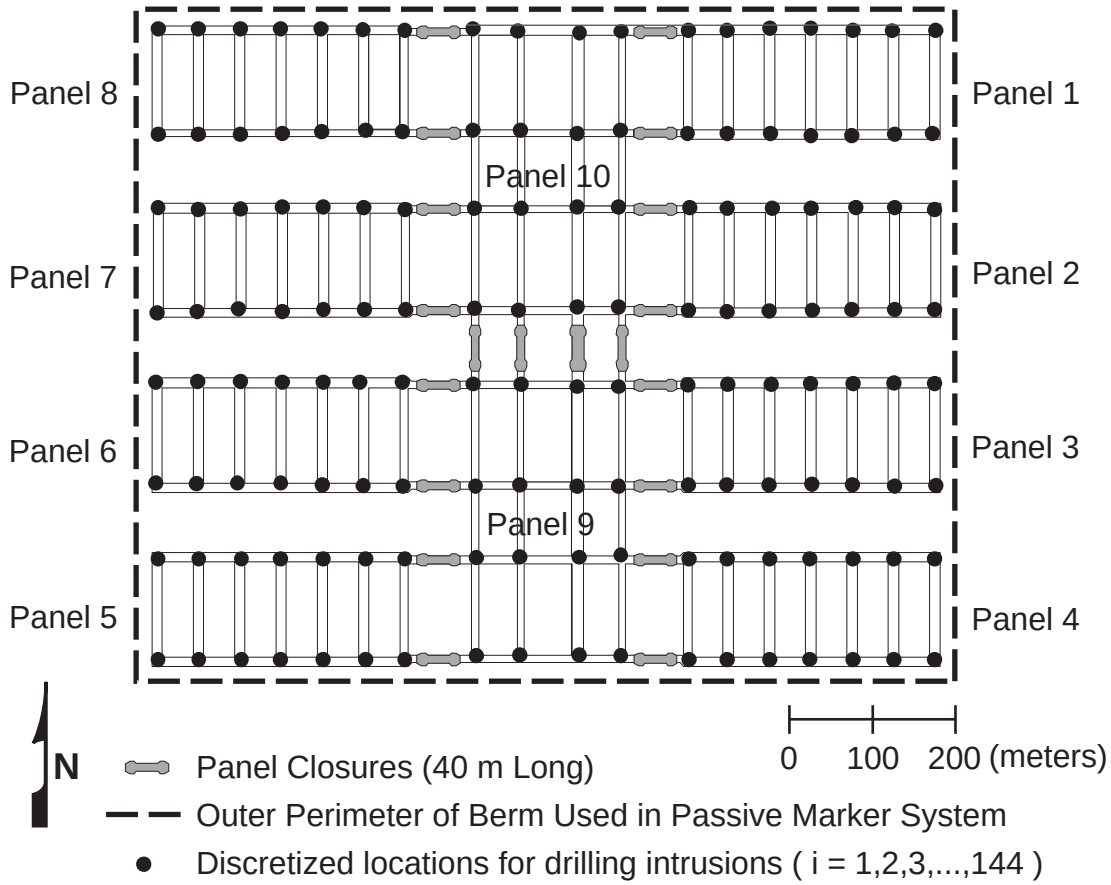

Figure PA-6. Location of Berm Used in Passive Marker System.

The function $\lambda_d(t)$ defines the part of the probability space (X_{st}, S_{st}, p_{st}) in Section PA-2.2 that corresponds to t_i . In the computational implementation of the analysis, $\lambda_d(t)$ is used to define the distribution of time between drilling intrusions (Figure PA-7). As a reminder, the occurrence of one event in a Poisson process has no effect on the occurrence of the next event. Thus, the cumulative distributions in Figure PA-7 can be used to define the time from one drilling event to the next (Section PA-6.5). Due to the 10,000-year regulatory period specified in 40 CFR § 191.13, t_i is assumed to be bounded above by 10,000 years in the definition of X_{st}. Further, t_i is bounded below by 100 years as defined in Equation (7).

The function $\lambda_d(t)$ also determines the probability $prob(nBH = n \| [a,b])$ that a future will have exactly n drilling intrusions in the time interval [a, b] (Helton 1993), where

$$prob(nBH = n \,|\, [a,b]) = \left[\left(\int_a^b \lambda_d(t)dt \right)^n / n! \right] \exp\left(-\int_a^b \lambda_d(t)dt \right). \tag{8}$$

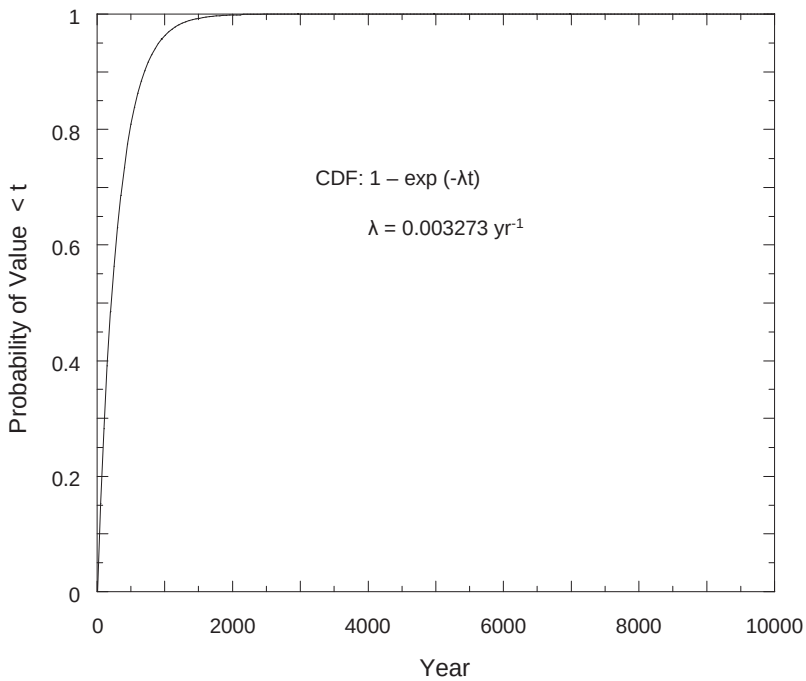

Figure PA-7. Cumulative Distribution Function (CDF) for Time Between Drilling Intrusions.

Further, the probability $prob\left(nBH \geq n \middle| [a,b]\right)$ that a future will have greater than or equal to n drilling intrusions in the time interval [a, b] is given by

$$prob(nBH \geq n \,|\, [a,b]) = \begin{cases} 1 & n = 0 \\ 1 - \sum_{m=0}^{n-1} prob(nBH = m \,|\, [a,b]) & n > 0 \end{cases} \tag{9}$$

PA-3.3 Penetration of Excavated/Nonexcavated Area

The variable e_i is a designator for whether or not the ith drilling intrusion penetrates an excavated, waste-filled area of the repository (i.e., e_i = 0, 1 implies penetration of nonexcavated, excavated area, respectively). The corresponding probabilities pE_0 and pE_1 for e_i = 0 and e_i = 1 are

$$pE_1 = 0.1273\ km^2 / 0.6285\ km^2 = 0.203 \tag{10}$$

$$pE_0 = 1 - pE_1 = 0.797\ , \tag{11}$$

where 0.1273 km^2 and 0.6285 km^2 are the excavated area of the repository filled with waste and the area of the berm, respectively (Attachment PAR, Table PAR-45). The probabilities pE_0 and pE_1 define the part of $\left(X_{st}, S_{st}, p_{st}\right)$ in Section PA.2.2 associated with e_i.

PA-3.4 Drilling Location

Locations of drilling intrusions through the excavated, waste-filled area of the repository are discretized to the 144 locations in Figure PA-6. Assuming that a drilling intrusion occurs within the excavated area, it is assumed to be equally likely to occur at each of these 144 locations. Thus, the (conditional) probability pL_j that drilling intrusion i will occur at location L_j, j = 1, 2, …, 144, in Figure PA-6 is

$$pL_j = 1/144 = 6.94 \times 10^{-3}. \tag{12}$$

The probabilities pL_j define the part of $\left(X_{st}, S_{st}, p_{st}\right)$ in Section PA.2.2 associated with l_i.

PA-3.5 Penetration of Pressurized Brine

The conceptual models for the Castile Formation include the possibility that pressurized brine reservoirs underlie the repository (Section 6.4.8). The variable b_i is a designator for whether or not the ith drilling intrusion penetrates pressurized brine, where $b_i = 0$ signifies nonpenetration and $b_i = 1$ signifies penetration of pressurized brine. In the CCA PA, the probabilities pB_0 and pB_1 for $b_i = 0$ and $b_i = 1$ were 0.92 and 0.08, respectively (see CCA Section 6.4.12.6). In the CRA-2004 PA, the probability pB_1 is sampled from a uniform distribution ranging from 0.01 to 0.60 (Section 6.4.12.6; see also PBRINE in Table PA-17). The probabilities pB_0 and pB_1 define the part of $\left(X_{st}, S_{st}, p_{st}\right)$ in Section PA-2.2 that corresponds to b_i.

PA-3.6 Plugging Pattern

As presented in Section 6.4.7.2, three borehole plugging patterns are considered in the 2004 PA: (1) p_1, a full concrete plug through Salado Formation to the Bell Canyon Formation, (2) p_2, a two plug configuration with concrete plugs at Rustler/Salado interface and Castile/Bell Canyon interface, and (3) p_3, a three plug configuration with concrete plugs at the Rustler/Salado, Salado/Castile and Castile/Bell Canyon interfaces. The probability that a given drilling intrusion will be sealed with plugging pattern p_j, j = 1, 2, 3, is given by pPL_j, where $pPL_1 = 0.015$, $pPL_2 = 0.696$ and $pPL_3 = 0.289$ (Section 6.4.12.7). The probabilities pPL_j define the part of $\left(X_{st}, S_{st}, p_{st}\right)$ in Section PA-2.2 that corresponds to p_i.

PA-3.7 Activity Level

The waste intended for disposal at the WIPP is represented by 779 distinct waste streams with 693 of these waste streams designated as CH-TRU waste and 86 designated as RH-TRU waste. For the CRA-2004 PA, the 86 separate RH-TRU waste streams are represented by a single, combined RH-TRU waste stream. The activity levels for the waste streams are given in Attachment PAR, Table PAR-50. Each waste container emplaced in the repository contains waste from a single CH-TRU waste stream. Waste packaged in 55-gallon drums is stacked three drums high within the repository. Although waste in other packages (e.g., standard waste boxes, 10 drum overpacks, etc.) may not be stacked three high, the CRA-2004 PA assumes that each

drilling intrusion into CH-TRU waste might intersect three different waste streams. In contrast, all RH-TRU waste is represented by a single waste stream, and so each drilling intrusion through RH-TRU waste is assumed to intersect this single waste stream. Attachment MASS (Section MASS.21) examines the sensitivity of PA results to the assumption that three waste streams are intersected by each drilling intrusion into CH-TRU waste.

The vector $\boldsymbol{a_i}$ characterizes the type of waste penetrated by the ith drilling intrusion. Specifically,

$$\boldsymbol{a_i} = 0 \text{ if } e_i = 0 \tag{13}$$

(i.e., if the ith drilling intrusion does not penetrate an excavated area of the repository);

$$\boldsymbol{a_i} = 1 \text{ if } e_i = 1 \text{ and RH-TRU is penetrated;} \tag{14}$$

and

$$\boldsymbol{a_i} = [iCH_{i1}, CH_{i2}, iCH_{i3}] \text{ if } e_i = 1 \text{ and CH-TRU is penetrated ,} \tag{15}$$

where iCH_{i1}, iCH_{i2} and iCH_{i3} are integer designators for the CH-TRU waste streams intersected by the ith drilling intrusion (i.e., each of iCH_{i1}, iCH_{i2} and iCH_{i3} is an integer between 1 and 693).

Whether the ith intrusion penetrates a nonexcavated or excavated area is determined by the probabilities pE_0 and pE_1 discussed in Section PA-3.4. The type of waste penetrated is determined by the probabilities pCH and pRH. The excavated area used for disposal of CH-TRU waste is 1.115×105 m^2 and the area used for disposal of RH-TRU waste is 1.576×10^4 m^2 (Attachment PAR, Table PAR-43), for a total disposal area of aEX = aCH + aRH = 1.273×10^5 m^2. Given that the ith intrusion penetrates an excavated area, the probabilities pCH and pRH of penetrating CH- and RH-TRU waste are given by

$$\boldsymbol{pCH = aCH / aEX = \left(1.115 \times 10^5\ m^2\right) / \left(1.273 \times 10^5\ m^2\right) = 0.876} \tag{16}$$

$$\boldsymbol{pCH = aCH / aEX = \left(1.576 \times 10^4\ m^2\right) / \left(1.273 \times 10^5\ m^2\right) = 0.124\ .} \tag{17}$$

As indicated in this section, the probabilistic characterization of $\boldsymbol{a_i}$ in $\left(\boldsymbol{X_{st}, S_{st}, p_{st}}\right)$ depends on a number of individual probabilities. Specifically, pE_0 and pE_1 determine whether a nonexcavated or excavated area is penetrated (Section PA-3.4); pCH and pRH determine whether CH- or RH-TRU waste is encountered given penetration of an excavated area; and the individual waste stream probabilities in Attachment PAR, Table PAR-50 determine the specific waste streams iCH_{i1} , iCH_{i2} , and iCH_{i3} encountered given a penetration of CH-TRU waste.

PA-3.8 Mining Time

As presented in Section 6.2.5.2, full mining of known potash reserves within the land withdrawal boundary is assumed to occur at time t_{min}. The occurrence of mining within the land withdrawal boundary in the absence of institutional controls is specified as following a Poisson process with a rate of $\lambda_m = 1 \times 10^{-4}$ yr^{-1}. However, this rate can be reduced by active and passive institutional controls. Specifically, active institutional controls are assumed to result in no possibility of mining for the first 100 years after decommissioning of the WIPP (Section 7.1.4). In the CCA PA, passive institutional controls were assumed to reduce the base mining rate by two orders of magnitude between 100 and 700 years after decommissioning (CCA Section 7.3.4). In the CRA-2004 PA, passive institutional controls do not affect the mining rate (Section 7.3.4). Thus, the mining rate $\lambda_m(t)$ is:

$$\lambda_m(t) = 0 \ yr^{-1} \quad for\ 0 \le t \le 100\ yrs \tag{18}$$

$$\lambda_m(t) = 1 \times 10^{-4}\ yr^{-1} \quad for\ 100 \le t \le 10{,}000\ yrs\ , \tag{19}$$

where t is elapsed time since decommissioning of the WIPP. The function $\lambda_m(t)$ defines the part of (X_{st}, S_{st}, p_{st}) that corresponds to t_{min}.

In the computational implementation of the analysis, $\lambda_m(t)$ is used to define the distribution of time to mining. The use of $\lambda_m(t)$ to characterize t_{min} is analogous to the use of λ_d to characterize the t_i except that only one mining event is assumed to occur (i.e., x_{st} contains only one value for t_{min}) in consistency with guidance given in 40 CFR Part 194 that mining within the land withdrawal boundary should be assumed to remove all economically viable potash reserves. Due to the 10,000-year regulatory period specified in 40 CFR § 191.13, t_{min} is assumed to be bounded above by 10,000 years in the definition of X_{st}.

PA-3.9 Scenarios and Scenario Probabilities

A scenario is a subset $\mathcal{S}$ of the sample space X_{st} for stochastic uncertainty. More specifically, a scenario is an element $\mathcal{S}$ of the set S_{st} in the probability space (X_{st}, S_{st}, p_{st}) for stochastic uncertainty, and the probability of $\mathcal{S}$ is given by $p_{st}(\mathcal{S})$. Thus, a scenario is what is called an event in the usual terminology of probability theory.

Given the complexity of the elements x_{st} of X_{st} (see Equation (3)), many different scenarios can be defined. The computational complexity of the function f in Figure PA-1 limits evaluation to only a few scenarios. As presented in Section 6.3, the CRA-2004 PA considers four fundamental scenarios:

E0 = { x_{st} : x_{st} involves no drilling intrusion through an excavated area of the repository (i.e., n = 0 or e_i = 0 in Equation (3) for i = 1, 2, …, n > 0)};

E1 = { $\boldsymbol{x}_{st} : \boldsymbol{x}_{st}$ involves one drilling intrusion through an excavated area of the repository with this intrusion penetrating pressurized brine in the Castile Formation (i.e., n > 0 in Equation (3) and there exists exactly one integer i such that $1 \le i \le n$, $e_i = 1$, $b_i = 1$, and $e_j = 0$ for $j \ne i$ and $1 \le j \le n$)};

E2 = { $\boldsymbol{x}_{st} : \boldsymbol{x}_{st}$ involves one drilling intrusion through an excavated area of the repository, with this intrusion not penetrating pressurized brine in the Castile Formation (i.e., n > 0 in Equation (3) and there exists exactly one integer i such that $1 \le i \le n$, $e_i = 1$, $b_i = 0$, and $e_j = 0$ for $j \ne i$ and $1 \le j \le n$)};

E1E2 = { $\boldsymbol{x}_{st} : \boldsymbol{x}_{st}$ involves two drilling intrusions through excavated areas of the repository, with the first intrusion not penetrating pressurized brine and the second intrusion penetrating pressurized brine (i.e., $n \ge 2$ in Equation (3) and there exist two integers i, j such that $1 \le i < j \le n$, $e_i = 1$, $b_i = 0$, $e_j = 1$, $b_j = 1$, and $e_k = 0$ for $k \ne i, j$ and $1 \le k \le n$)}.

The definitions of the preceding four scenarios are quite simple. In general, scenarios can be defined on the basis of any possible characterization of the properties of the individual elements of $\boldsymbol{x}_{st}$, which can lead to very complex scenario definitions.

The scenarios E0, E1, E2, and E1E2 are elements of S_{st}, and their probabilities are formally represented by $p_{st}(E0)$, $p_{st}(E1)$, $p_{st}(E2)$, and $p_{st}(E1E2)$, with these probabilities deriving from the probability distributions assigned to the individual elements of $\boldsymbol{x}_{st}$. For example, assume that pB_1 takes on its mean value of 0.305 (see Section PA-3.5), the probabilities of the first three scenarios can be calculated exactly:

$$p_{st}(E0) = \exp\left(-\int_a^b pE_1 \lambda_d(t)\,dt\right) = 1.3 \times 10^{-3} \tag{20}$$

$$p_{st}(E1) = \left[\left(\int_a^b pE_1 \lambda_d(t)\,dt\right)^1 \Big/ 1!\right]\left[\exp\left(-\int_a^b pE_1 \lambda_d(t)\,dt\right)\right]\left[pB_1\right] = 2.6 \times 10^{-3} \tag{21}$$

$$p_{st}(E2) = \left[\left(\int_a^b pE_1 \lambda_d(t)\,dt\right)^1 \Big/ 1!\right]\left[\exp\left(-\int_a^b pE_1 \lambda_d(t)\,dt\right)\right]\left[pB_0\right] = 6.0 \times 10^{-3}, \tag{22}$$

where $[a,b] = [100,\ 10{,}000\ yrs]$, $pE_1 = 0.203$ (see Section PA-3.4), $\lambda_d(t)$ is defined in Equation (7), and the probabilities in Equation (21) and Equation (22) are based on the relationship in Equation (8).

The expressions defining $p_{st}(E0)$, $p_{st}(E1)$, and $p_{st}(E2)$ are relatively simple because the scenarios E0, E1, and E2 are relatively simple. The scenario E1E2 is more complex and, as a

result, $p_{st}(E1E2)$ is also more complex. Closed-form formulas for the probabilities of quite complex scenarios can be derived but they are very complicated and involve large numbers of iterated integrals (Helton 1993). Thus, p_{st} can be defined in concept but does not have a simple form that can be easily displayed.

The fundamental scenarios E0, E1, E2, and E1E2 have infinitely many elements because the drilling intrusions and mining events can occur throughout the regulatory period. However, scenarios involving drilling intrusions that occur at specific times will have a probability of zero. For example, the scenario

$$\mathcal{S} = \left\{ x_{st} : x_{st} = \left[t_1 = 350\,yr,\ e_1 = 1,\ l_1,\ b_1 = 1,\ p_1 = 2,\ a_1,\ t_{min} \right] \right\}, \tag{23}$$

where e_1, a_1 and t_{min} are arbitrary, contains infinitely many futures (i.e., infinitely many x_{st} meet the criteria to belong to $\mathcal{S}$ due to the infinite number of values that l_1, a_1, and t_{min} can assume) and also has a probability of zero (i.e., $p_{st}(\mathcal{S}) = 0$) because t_1 is restricted to a single value. Sets that contain single elements of X_{st} are also scenarios, but such scenarios will typically have a probability of zero; the only single element scenario that has a nonzero probability contains the future that has no drilling intrusions and no mining.

Releases from the repository are calculated (i.e. the function f in Figure PA-1 is evaluated) for a small number of elements belonging to each of the four fundamental scenarios (Sections PA-6.7 and PA-6.8). Releases for an arbitrary element x_{st} of X_{st} are estimated from the results of the fundamental scenarios (Section PA-6.8); these releases are used to construct CCDFs by Equation (4).

PA-3.10 Historical Review of CCDF Construction

The 1991 and 1992 WIPP PAs used an approach to the construction of the CCDF specified in 40 CFR § 191.13 based on the exhaustive division of X_{st} into a collection of mutually exclusive scenarios $S_{st,i}$, i = 1, 2, …, nS (Helton and Iuzzolino 1993). A probability $p_{st}(S_{st,i})$ and a normalized release R_i were then calculated for each scenario $S_{st,i}$ and used to construct the CCDF specified in 40 CFR § 191.13. Due to the complexity of the elements x_{st} of X_{st} (see Equation (3)), this approach was not used in the CCA PA. In particular, the decomposition of X_{st} into a suitable and defensible collection of scenarios $S_{st,i}$, i = 1, 2, …, nS, is quite difficult. Further, once these scenarios are defined, it is necessary to calculate their probabilities $p_{st}(S_{st,i})$, which is also not easy. Although the calculation of the probabilities $p_{st}(S_{st,i})$ is difficult, the development of an appropriate and acceptable decomposition of X_{st} into the scenarios $S_{st,i}$ posed a great challenge. Accordingly, the CCA PA used the Monte Carlo approach to CCDF construction indicated in Equation (4), thus avoiding the difficulties associated with decomposing X_{st} into a collection of mutually exclusive scenarios and then

calculating the probabilities of these scenarios. The CRA-2004 PA uses the same approach as used in the CCA PA.

PA-4.0 ESTIMATION OF RELEASES

This section describes how releases to the accessible environment are estimated for a particular future in the CRA-2004 PA.

PA-4.1 Results for Specific Futures

The function $f\left(x_{st}\right)$ (Figure PA-1) estimates the radionuclide releases to the accessible environment associated with each of the possible futures x_{st} that could occur at the WIPP site over the next 10,000 years. In practice, f is quite complex and is constructed by the models implemented in computer programs used to simulate important processes and releases at the WIPP. In the context of these models, f has the form

$$\begin{aligned} f\left(x_{st}\right) = {} & f_C\left(x_{st}\right) + f_{SP}\left[x_{st}, f_B\left(x_{st}\right)\right] + f_{DBR}\left[x_{st}, f_B\left(x_{st}\right)\right] \\ & + f_{MB}\left[x_{st}, f_B\left(x_{st}\right)\right] + f_{DL}\left[x_{st}, f_B\left(x_{st}\right)\right] + f_S\left[x_{st}, f_B\left(x_{st}\right)\right], \\ & + f_{ST}\left[x_{st,0}, f_{MF}\left(x_{st}\right), f_{NP}\left[x_{st}, f_B\left(x_{st}\right)\right]\right] \end{aligned} \tag{24}$$

where

x_{st} ~ particular future under consideration,

$x_{st,0}$ ~ future involving no drilling intrusions but a mining event at the same time t_{min} as in x_{st},

$f_C\left(x_{st}\right)$ ~ cuttings and cavings release to accessible environment for x_{st} calculated with CUTTINGS_S,

$f_B\left(x_{st}\right)$ ~ two-phase flow in and around the repository calculated for x_{st} with BRAGFLO; in practice, $f_B\left(x_{st}\right)$ is a vector containing a large amount of information, including pressure and brine saturation in various geologic members,

$f_{SP}\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ spallings release to accessible environment for x_{st} calculated with the spallings model contained in CUTTINGS_S; this calculation requires repository conditions calculated by $f_B\left(x_{st}\right)$ as input,

$f_{DBR}\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ direct brine release to accessible environment for x_{st} also calculated with BRAGFLO; this calculation requires repository conditions calculated by $f_B\left(x_{st}\right)$ as input,

$f_{MB}\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ release through anhydrite marker beds to accessible environment for x_{st} calculated with NUTS; this calculation requires flows in and around the repository calculated by $f_B\left(x_{st}\right)$ as input,

$f_{DL}\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ release through Dewey Lake Red Beds to accessible environment for x_{st} calculated with NUTS; this calculation requires flows in and around the repository calculated by $f_B\left(x_{st}\right)$ as input,

$f_S\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ release to land surface due to brine flow up a plugged borehole for x_{st} calculated with NUTS or PANEL; this calculation requires flows in and around the repository calculated by $f_B\left(x_{st}\right)$ as input,

$f_{MF}\left(x_{st,0}\right)$ ~ flow field in the Culebra calculated for $x_{st,0}$ with MODFLOW,

$f_{NP}\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ release to Culebra for x_{st} calculated with NUTS or PANEL as appropriate; this calculation requires flows in and around the repository calculated by $f_B\left(x_{st}\right)$ as input, and

$f_{ST}\left[x_{st,0}, f_{MF}\left(x_{st,0}\right), f_{NP}\left[x_{st}, f_B\left(x_{st}\right)\right]\right]$ ~ groundwater transport release through Culebra to accessible environment calculated with SECOTP2D.This calculation requires MODFLOW results (i.e., $f_{MF}\left(x_{st,0}\right)$) and NUTS or PANEL results (i.e., $f_{NP}\left[x_{st}, f_B\left(x_{st}\right)\right]$ as input; $x_{st,0}$ is used as an argument to f_{ST} because drilling intrusions are assumed to cause no perturbations to the flow field in the Culebra.

The remainder of this section describes the mathematical structure of the mechanistic models that underlie the component functions of f in Equation (24).

The Monte Carlo CCDF construction procedure, implemented in the code CCDFGF (WIPP PA 2003a), uses a sample of size nS = 10,000 in the CRA-2004 PA. The individual programs that estimate releases do not run fast enough to allow this number of evaluations of f. As a result, a two-step procedure is being used to evaluate f in the calculation of the integral in Equation (4). First, f and its component functions are evaluated with the procedures (i.e., models) described in this section for a group of preselected futures. Second, values of $f\left(x_{st,i}\right)$ for the randomly

selected futures $\mathbf{x}_{st,i}$ used in the numerical evaluation of the integral in Equation (4) are then constructed from results obtained in the first step. These constructions are described in Sections PA-6.7 and PA-6.8, and produce the evaluations of f that are actually used in Equation (4).

For notational simplicity, the functions on the right hand side of Equation (24) will typically be written with only $\mathbf{x}_{st}$ as an argument (e.g., $f_{SP}\left(\mathbf{x}_{st}\right)$ will be used instead of $f_{SP}\left[\mathbf{x}_{st}, f_B\left(\mathbf{x}_{st}\right)\right]$). However, the underlying dependency on the other arguments will still be present.

The major topics considered in this chapter are two-phase flow in the vicinity of the repository as modeled by BRAGFLO (i.e., f_B) (Section PA-4.2), radionuclide transport in the vicinity of the repository as modeled by NUTS (i.e., f_{MB}, f_{DL}, f_S, f_{NP}) (Section PA-4.3), radionuclide transport in the vicinity of the repository as modeled by PANEL (i.e., f_S, f_{NP}) (Section PA-4.4), cuttings and cavings releases to the surface as modeled by CUTTINGS_S (i.e., f_C) (Section PA-4.5), spallings releases to the surface as modeled by DRSPALL and CUTTINGS_S (i.e., f_{SP}) (Section PA-4.6), direct brine releases to the surface as modeled by BRAGFLO (i.e., f_{DBR}) (Section PA-4.7), brine flow in the Culebra as modeled by MODFLOW (i.e., f_{MF}) (Section PA-4.8), and radionuclide transport in the Culebra as modeled by SECOTP2D (i.e., f_{ST}) (Section PA-4.9).

PA-4.2 Two-Phase Flow: BRAGFLO

Quantification of the effects of gas and brine flow on radionuclide transport from the repository requires use of a two-phase (brine and gas) flow code. For the CRA-2004 PA, the DOE uses the two-phase flow code BRAGFLO to simulate gas and brine flow in and around the repository (WIPP PA 2003b). Additionally, the BRAGFLO code incorporates the effects of disposal room consolidation and closure, gas generation, and rock fracturing in response to gas pressure. This section describes the mathematical models on which BRAGFLO is based, the representation of the repository in the model, and the numerical techniques employed in the solution.

PA-4.2.1 Mathematical Description

Two-phase flow in the vicinity of the repository is represented by the following system of two conservation equations, two constraint equations, and three equations of state:

Gas Conservation

$$\nabla \bullet \left[\frac{\alpha \rho_g \mathbf{K}_g k_{rg}}{\mu_g} \left(\nabla p_g + \rho_g g \nabla h \right) \right] + \alpha q_{wg} + \alpha q_{rg} = \alpha \frac{\partial \left(\phi \rho_g S_g \right)}{\partial t}, \tag{25a}$$

Brine Conservation

$$\nabla \bullet \left[\frac{\alpha \rho_b \mathbf{K}_b k_{rb}}{\mu_b} \left(\nabla p_b + \rho_b g \nabla h \right) \right] + \alpha q_{wb} + \alpha q_{rb} = \alpha \frac{\partial \left(\phi \rho_b S_b \right)}{\partial t}, \tag{25b}$$

Saturation Constraint

$$S_g + S_b = 1, \tag{25c}$$

Capillary Pressure Constraint

$$p_C = p_g - p_b = f\left(S_b\right), \tag{25d}$$

Gas Density

ρ_g (determined by Redlich-Kwong-Soave equation of state; see Equation (46)), (25e)

Brine Density

$$\rho_b = \rho_0 \exp\left[\beta_b\left(\rho_b - \rho_{b0}\right)\right], \text{ and} \tag{25f}$$

Formation Porosity

$$\phi_b = \phi_0 \exp\left[\beta_f\left(\rho_b - \rho_{b0}\right)\right], \tag{25g}$$

where

g = acceleration due to gravity (m/s^2)

h = vertical distance from a reference location (m)

K_l = permeability tensor (m^2) for fluid l (l = g ~ gas, l = b ~ brine)

k_{rl} = relative permeability (dimensionless) to fluid l

p_C = capillary pressure (Pa)

p_l = pressure of fluid l (Pa)

q_{rl} = rate of production (or consumption, if negative) of fluid l due to chemical reaction (kg/m^3 s)

q_{wl} = rate of injection (or removal, if negative) of fluid l (kg/m^3 s)

S_l = saturation of fluid l (dimensionless)

t = time (s)

α = geometry factor (m)

ρ_l = density of fluid l (kg/m^3)

μ_l = viscosity of fluid l (Pa s)

ϕ = porosity (dimensionless)

ϕ_0 = reference (i.e., initial) porosity (dimensionless)

p_{b0} = reference (i.e., initial) brine pressure (Pa), constant in Equation (25f) and spatially variable in Equation (25g)

ρ_0 = reference (i.e., initial) brine density (kg/m^3)

β_f = pore compressibility (Pa^{-1})

β_b = brine compressibility (Pa^{-1}).

The conservation equations are valid in one (i.e., $\nabla = [\partial/\partial \boldsymbol{x}]$), two (i.e., $\nabla = [\partial/\partial \boldsymbol{x}, \partial/\partial \boldsymbol{y}]$) and three (i.e., $\nabla = [\partial/\partial \boldsymbol{x}, \partial/\partial \boldsymbol{y}, \partial/\partial \boldsymbol{z}]$) dimensions. In the CRA-2004 PA, the preceding system of equations is used to model two-phase fluid flow within the two-dimensional region shown in Figure PA-8. The details of this system are now discussed.

The α term in Equation (25a) and Equation (25b) is a dimension-dependent geometry factor and is specified by

α = area normal to flow direction in one-dimensional flow (i.e., $\Delta y \Delta z$; units = m^2),

= thickness normal to flow plane in two-dimensional flow (i.e., Δz; units = m),

= 1 in three-dimensional flow (dimensionless). (26)

The CRA-2004 PA uses a two-dimensional geometry for computation of two-phase flow in the vicinity of the repository, and as a result, α is the thickness of the modeled region (i.e., Δz) normal to the flow plane (Figure PA-8). Due to the use of the two-dimensional grid in Figure PA-8, α is spatially dependent, with the values used for α defined in the column labeled "Δz ." Specifically, α increases with distance away from the repository edge in both directions to incorporate the increasing pore volume through which fluid flow occurs. The method used in the CRA-2004 PA, called rectangular flaring, is illustrated in Figure PA-9 and ensures that the total volume surrounding the repository is conserved in the numerical grid. The equations and

method used to determine α for the grid shown in Figure PA-8 are described in detail by Stein (2002a).

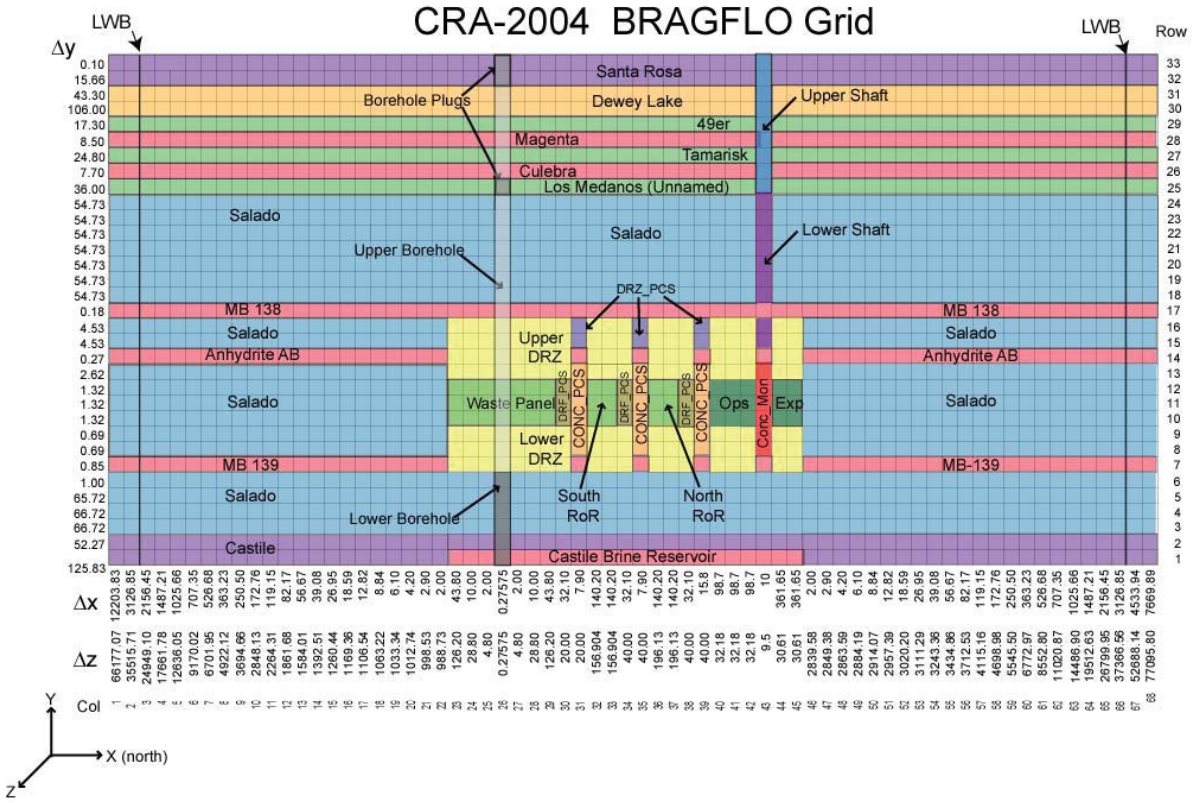

Figure PA-8. Computational Grid Used in BRAGFLO in the CRA-2004 PA.

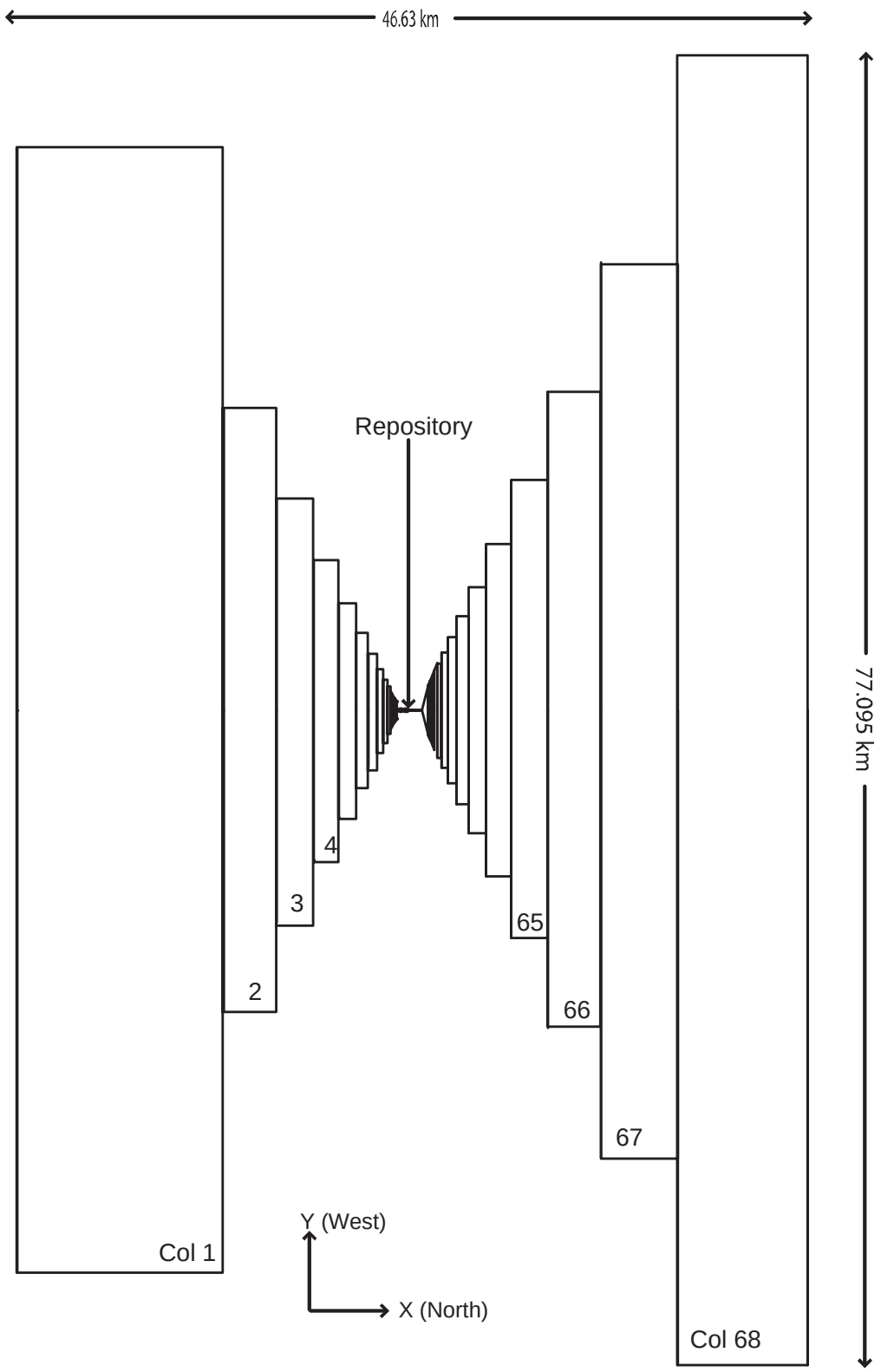

Figure PA-9. Definition of Element Depth in BRAGFLO Grid in the CRA-2004 PA.

The h term in Equation (25a) and Equation (25b) defines vertical distance from a reference point. In the CRA-2004 PA, this reference point is taken to be the center of MB 139 at the location of the shaft (i.e., $\left(x_{ref}, y_{ref}\right) = \left(23664.9\ m,\ 378.685\ m\right)$, which is the center of cell 1266 in Figure PA-10). Specifically, h is defined by

$$h\left(x, y\right) = \left(x - x_{ref}\right)\sin\theta + \left(y - y_{ref}\right)\cos\theta, \tag{27}$$

where θ is the inclination of the formation in which the point $\left(x, y\right)$ is located. In the CRA-2004 PA, the Salado Formation is modeled as having an inclination of 1° from north to south, and all other formations are modeled as being horizontal. Thus, θ = 1° for points within the Salado, and θ = 0° otherwise. Treating the Salado as an inclined formation and treating the Castile Formation, Castile brine reservoir, Rustler Formation, and overlying units as horizontal creates discontinuities in the grid at the lower and upper boundaries of the Salado. However, this treatment does not create a computational problem, since the Salado is isolated from vertical flow; its upper boundary adjoins the impermeable Los Medaños Member (formerly referred to as the Unnamed Member) at the base of the Rustler Formation, and its lower boundary adjoins the impermeable Castile Formation.

In the solution of Equation (25), S_b and S_g are functions of location and time. Thus, p_C, k_{rb} and k_{rg} are functions of the form $p_C\left(x, y, t\right)$, $k_{rb}\left(x, y, t\right)$, and $k_{rg}\left(x, y, t\right)$. In the computational implementation of the solution of the preceding equations, flow of phase l out of a computational cell (Figure PA-10) cannot occur when $S_l\left(x, y, t\right) \le S_{lr}\left(x, y, t\right)$, where S_{lr} denotes the residual saturation for phase l. The values used for S_{lr}, l = b, g are summarized in Table PA-2.

Values for ϕ_0 and β_f (Equation (25g)) are also given in Table PA-2. Initial porosity ϕ_0 for the DRZ is a function of the uncertain parameter for initial halite porosity ϕ_{0H} (HALPOR; see Table PA-17) and is given by Martell (1996a, Chapter 4; Bean et al. 1996)

$$\phi_0 = \phi_{0H} + 0.0029\ . \tag{28}$$

This representation is used because the DRZ and halite porosities are correlated, with the high, low, and median porosity values for the DRZ being 0.0029 higher than the corresponding undisturbed halite values. Initial porosity ϕ_0 of the Castile brine reservoir is correlated to the uncertain sampled parameter for bulk compressibility (BPCOMP; see Table PA-17), according to the following relationship:

$$\phi_0 = \frac{BPCOMP}{1.0823 \times 10^{-10}}, \tag{29}$$

where 1.0860×10^{-10} is a scaling constant that ensures that the productivity ratio, PR, remains constant at 2.0×10^{-3} m^3/Pa. The productivity ratio PR is computed by

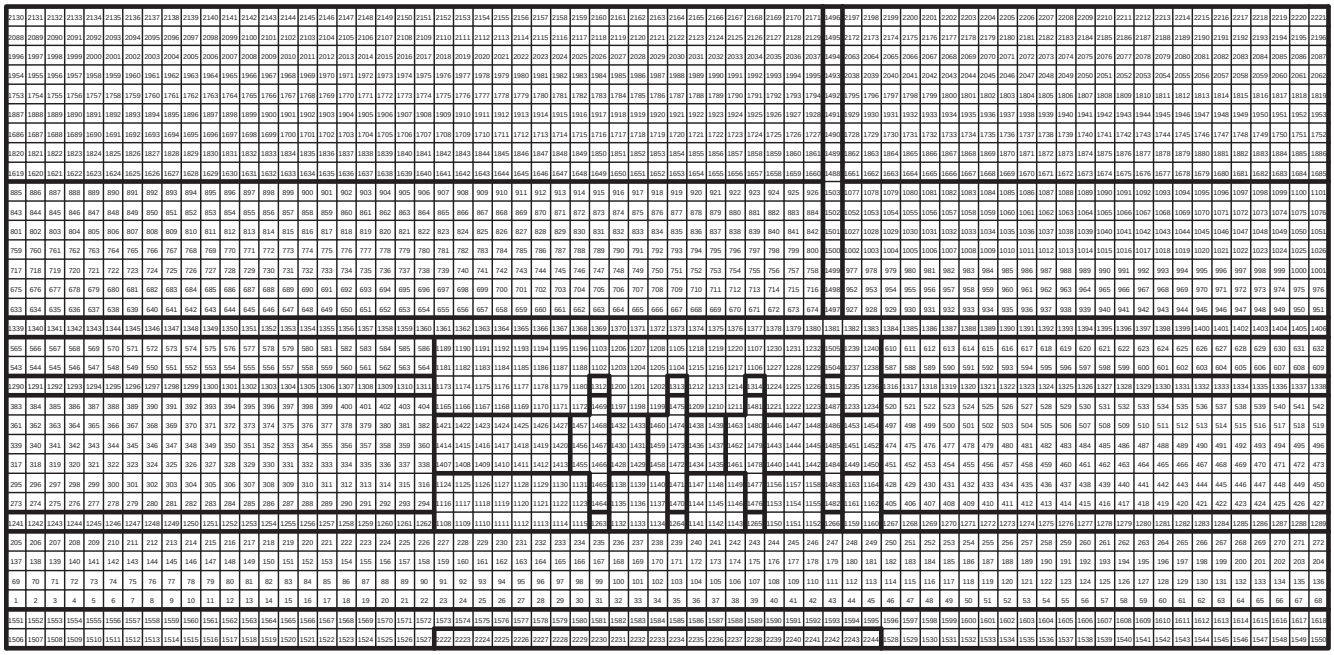

Figure PA-10. Identification of Individual Cells in BRAGFLO Grid in the CRA-2004 PA.

Table PA-2. Parameter Values Used in Representation of Two Phase Flow

Region	Material	Material Description	Brooks-Corey Pore Distribution λ	Threshold Pressure Linear Parameter a	Threshold Pressure Exponential Parameter η	Residual Brine Saturation S_{br}	Residual Gas Saturation S_{gr}	Porosity ϕ_0	Pore Compressibility β_f	Intrinsic Permeability k, m2
Salado	S_HALITE	Undisturbed halite	0.7	0.56	–0.346	0.3	0.2	HALPOR1	f(HALCOMP1)3	10x, x = HALPRM1
Upper DRZ	DRZ_0	Disturbed rock zone, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMP1)3	9.999999 × 10–18
	DRZ_1	Disturbed rock zone, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMP1)3	10x, x = DRZPRM1
Lower DRZ	DRZ_0	Disturbed rock zone, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMP1)3	9.999999 × 10–18
	DRZ_1	Disturbed rock zone, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMP1)3	10x, x = DRZPRM1
MB 138	S_MB138	Anhydrite marker bed in Salado Formation	ANHBCEXP1	0.26	–0.348	ANRBSAT1	ANRGSSAT1	0.011	f(ANHCOMP1)3	10x, x = ANHPRM1
Anhydrite AB	S_ANH_AB	Anhydrite layers a and b in Salado Formation	ANHBCEXP1	0.26	–0.348	ANRBSAT1	ANRGSSAT1	0.011	f(ANHCOMP1)3	10x, x = ANHPRM1
MB 139	S_MB139	Anhydrite marker bed in Salado Formation	ANHBCEXP1	0.26	–0.348	ANRBSAT1	ANRGSSAT1	0.011	f(ANHCOMP1)3	10x, x = ANHPRM1
Waste Panel	CAVITY_1	Single waste panel, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	WAS_AREA	Single waste panel, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT1	WRGSSAT1	0.8485	0.0	2.4 × 10–13
South RoR	CAVITY_2	Rest of repository, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	REPOSIT	Rest of repository, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT1	WRGSSAT1	0.848 5	0.0	2.4 × 10–13
North RoR	CAVITY_2	Rest of repository, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	REPOSIT	Rest of repository, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT1	WRGSSAT1	0.848 5	0.0	2.4 × 10–13
Ops	CAVITY_3	Operations area, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	OPS_AREA	Operations area, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	0.18	0.0	1.0 × 10–11

Table PA-2. Parameter Values Used in Representation of Two Phase Flow — Continued

Region	Material	Material Description	Brooks-Corey Pore Distribution λ	Threshold Pressure Linear Parameter a	Threshold Pressure Exponential Parameter η	Residual Brine Saturation S_{br}	Residual Gas Saturation S_{gr}	Porosity ϕ_0	Pore Compressibility β_f	Intrinsic Permeability k, m2
Exp	CAVITY_3	Experimental area, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	EXP_AREA	Experimental area, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	0.18	0.0	1.0 × 10–11
Castile	IMPERM_Z	Castile Formation	0.7	0.0	0.0	0.0	0.0	0.005	0.0	9.999999 × 10–36
Castile Brine Reservoir	CASTILER	Brine Reservoir in Castile Formation	0.7	0.56	–0.346	0.2	0.2	f(BPCOMP 1)4	f(BPCOMP 1)3	10x, x = BPPRM1
Culebra	CULEBRA	Culebra Member of Rustler Formation	0.6436	0.26	–0.348	0.08363	0.07711	0.151	6.622517 × 10–10	2.098938 × 10–14
Magenta	MAGENTA	Magenta Member of Rustler Formation	0.6436	0.26	–0.348	0.08363	0.07711	0.138	1.915942 × 10–9	6.309576 × 10–16
Dewey Lake	DEWYLAKE	Dewey Lake Redbeds	0.6436	0.0	0.0	0.08363	0.07711	0.143	6.993007 × 10–8	5.011881 × 10–17
Santa Rosa	SANTAROS	Santa Rosa Formation	0.6436	0.0	0.0	0.08363	0.07711	0.175	5.714286 × 10–8	1.0 × 10–10
Los Medanos	UNNAMED	Los Medaños Member of Rustler Formation	0.7	0.0	0.0	0.2	0.2	0.181	0.0	9.999999 × 10–36
Tamarisk	TAMARISK	Tamarisk Member of Rustler Formation	0.7	0.0	0.0	0.2	0.2	0.064	0.0	9.999999 × 10–36
49er	FORTYNIN	Fortyniner Member of Rustler Formation	0.7	0.0	0.0	0.2	0.2	0.082	0.0	9.999999 × 10–36
DRZ_PCS	DRZ_0	Disturbed rock zone, -5 to 0 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMP1)3	9.999999 × 10–18
DRZ_PCS	DRZ_PCS	DRZ above the panel closures, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMPa)c	10x, x = DRZPCPRM1
CONC_PCS	CAVITY_4	Concrete portion of panel closures, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	CONC_PCS	Concrete portion of panel closures, 0 to 10,000 years	0.9193	0.0	0.0	CONBRSAT1	CONGSSAT1	0.005	1.2 × 10–9	10x, x = CONPRM1
DRF_PCS	CAVITY_4	Drift adjacent to panel closures, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10

Table PA-2. Parameter Values Used in Representation of Two Phase Flow — Continued

Region	Material	Material Description	Brooks-Corey Pore Distribution λ	Threshold Pressure Linear Parameter a	Threshold Pressure Exponential Parameter η	Residual Brine Saturation S_{br}	Residual Gas Saturation S_{gr}	Porosity ϕ_0	Pore Compressibility β_f	Intrinsic Permeability k, m2
	DRF_PCS	Drift adjacent to panel closures, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT1	WRGSSAT1	0.848	0.0	2.4×10^{-13}
CONC_MON	CAVITY_4	Concrete monolith portion of shaft seals, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0×10^{-10}
	CONC_MON	Concrete monolith portion of shaft seals, 0 to 10,000 years	0.94	0.0	0.0	SHURBRN1	SHURGAS1	0.05	1.2×10^{-9}	1.0×10^{-14}
Upper Shaft	CAVITY_4	Upper portion of shaft seals, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0×10^{-10}
	SHFTU	Upper portion of shaft seals, 0 to 10,000 years	0.9193	0.0	0.0	SHURBRN1	SHURGAS1	0.005	2.05×10^{-8}	10x, x = SHUPRM 1
Lower Shaft	CAVITY_4	Lower portion of shaft seals, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0×10^{-10}
	SHFTL_T1	Lower portion of shaft seals, 0 - 200 years	0.9193	0.0	0.0	SHURBRN1	SHURGAS1	0.005	4.28×10^{-9}	10x, x = SHLPRM11
	SHFTL_T2	Lower portion of shaft seals, 200 - 10,000 years	0.9193	0.0	0.0	SHURBRN1	SHURGAS1	0.005	4.28×10^{-9}	10x, x = SHLPRM21
Borehole plugs	CONC_PLG	Concrete borehole plug, before plug degradation	0.94	0.0	0.0	0.0	0.0	0.32	0.0	10x, x = PLGPRM1
	BH_SAND	Borehole after plug degradation, 200 years after intrusion	0.94	0.0	0.0	0.0	0.0	0.32	0.0	10x, x = BHPRM1
Upper Borehole	BH_OPEN	Borehole above repository before plug degradation	0.7	0.0	0.0	0.0	0.0	0.32	0.0	1.0×10^{-9}
	BH_SAND	Borehole after plug degradation, 200 years after intrusion	0.94	0.0	0.0	0.0	0.0	0.32	0.0	10x, x = BHPRM1
Lower Borehole	BH_OPEN	Borehole below repository before creep closure	0.7	0.0	0.0	0.0	0.0	0.32	0.0	1.0×10^{-9}

Table PA-2. Parameter Values Used in Representation of Two Phase Flow — Continued

Region	Material	Material Description	Brooks-Corey Pore Distribution λ	Threshold Pressure Linear Parameter a	Threshold Pressure Exponential Parameter η	Residual Brine Saturation S_{br}	Residual Gas Saturation S_{gr}	Porosity ϕ_0	Pore Compressibility β_f	Intrinsic Permeability k, m2
	BH_CREEP	Borehole below repository after creep closure, 1,000 years after intrusion	0.94	0.0	0.0	0.0	0.0	0.32	0.0	10x/10, x = BHPRM1

[1] Uncertain variable, see Table PA-17.
[2] See Equation (28).
[3] See Equation (31); ϕ_0 can also be defined by an uncertain variable.
[4] See Equation (29).
[5] Initial value of porosity ϕ_0; porosity changes dynamically to account for creep closure (see Section PA-4.2.3).

$$PR = V \frac{BPCOMP}{\phi_0}, \tag{30}$$

where V is the volume of the grid block representing the Castile brine reservoir in Figure PA-8. The effect of this relationship is that the initial porosity of the brine reservoir ranges from 0.1842 to 0.9208. This range of porosity is not meant to represent an actual reservoir, but rather allows a reservoir to supply a volume of brine to the repository in the event of an E1 intrusion consistent with observed brine flows in the Delaware Basin.

The compressibility β_f in Equation (25f) and Table PA-2 is pore compressibility. Compressibility is treated as uncertain for Salado anhydrite, Salado halite, and regions of pressurized brine in the Castile Formation. However, the sampled value for each of these variables corresponds to bulk compressibility rather than to the pore compressibility actually used in the calculation. The conversion from bulk compressibility β_{fB} to pore compressibility β_f is approximated by

$$\beta_f = \beta_{fB} / \phi_0 , \tag{31}$$

where ϕ_0 is the initial porosity in the region under consideration.

The primary model used in the CRA-2004 PA for capillary pressure p_C and relative permeability k_{rl} is a modification of the Brooks-Corey model (Brooks and Corey 1964). In this model, p_C, k_{rb} and k_{rg} are defined by

$$p_C = p_t(k) / S_{e2}^{1/\lambda} \tag{32a}$$

$$k_{rb} = S_{e1}^{(2+3\lambda)/\lambda} \tag{32b}$$

$$k_{rg} = \left(1 - S_{e2}\right)^2 \left(1 - S_{e2}^{(2+\lambda)/\lambda}\right), \tag{32c}$$

where

λ = pore distribution parameter (dimensionless)

$p_t(k)$ = capillary threshold pressure (Pa) as a function of intrinsic permeability k (Webb 1992)

$$= ak^{\eta} \tag{33}$$

S_{e1} = effective brine saturation (dimensionless) without correction for residual gas saturation

$$= \left(S_b - S_{br}\right) / \left(1 - S_{br}\right) \tag{34}$$

S_{e2} = effective brine saturation (dimensionless) with correction for

residual gas saturation

$$= \left(S_b - S_{br}\right) \Big/ \left(1 - S_{gr} - S_{br}\right) \ . \tag{35}$$

The values used for λ, a, η, S_{br}, S_{gr}, and k are summarized in Table PA-2. The statement that the Brooks-Corey model is in use means that p_C , k_{rb}, and k_{rg} are defined by Equation (32). The Brooks-Corey model is used for all materials with the two exceptions, as identified in Table PA-3. In the anhydrite MBs, either the Brooks-Corey model or the van Genuchten-Parker model is used as determined by the subjectively uncertain parameter ANHBCVGP (see Table PA-17). A linear model is used in the representation of two-phase flow in an open borehole (i.e., for the first 200 years after a drilling intrusion for boreholes with two-plug or three-plug configurations (Section 6.4.7.2)). Each of these alternatives to the Brooks-Corey model is now discussed.

Table PA-3. Models for Relative Permeability and Capillary Pressure for Two-Phase Flow

Material	Relative Permeability[1]	Capillary Pressure[2]	Material	Relative Permeability[1]	Capillary Pressure[2]
S_HALITE	4	2	WAS_AREA	4	1
DRZ_0	4	1	DRZ_1	4	1
S_MB139	ANHBCVGP[3]	2	DRZ_PCS	4	1
S_ANH_AB	ANHBCVGP[3]	2	CONC_PCS	4	1
S_MB138	ANHBCVGP[3]	2	UNNAMED	4	1
CAVITY_1	4	1	TAMARISK	4	1
CAVITY_2	4	1	FORTYNIN	4	1
CAVITY_3	4	1	DRF_PCS	4	1
CAVITY_4	4	1	REPOSIT	4	1
IMPERM_Z	4	1	CONC_MON	4	1
CASTILER	4	2	SHFTU	4	1
OPS_AREA	4	1	SHFTL_T1	4	1
EXP_AREA	4	1	SHFTL_T2	4	1
CULEBRA	4	2	CONC_PLG	4	1
MAGENTA	4	2	BH_OPEN	5	1
DEWYLAKE	4	1	BH_SAND	4	1
SANTAROS	4	1	BH_CREEP	4	1

[1] Relative permeability model, where 4 ~ Brooks-Corey model (Equation (32)), 5 ~ linear model (Equation (37)), and ANHBCVGP ~ use of Brooks-Corey or van Genuchten-Parker model treated as a subjective uncertainty.

[2] Capillary pressure model, where 1 ~ p_C = 0 Pa, 2 ~ p_C bounded above by 1×10^8 Pa as S_b approaches S_{br}.

[3] See ANHBCVGP in Table PA-17.

In the van Genuchten-Parker model, p_C, k_{rb}, and k_{rg} are defined by (van Genuchten 1978):

$$p_C = p_{VGP}\left(S_{e2}^{-1/m} - 1\right)^{1-m} \tag{36a}$$

$$k_{rb} = S_{e1}^{1/2}\left[1-\left(1-S_{e1}^{1/m}\right)^{m}\right]^{2} \tag{36b}$$

$$k_{rg} = \left(1-S_{e2}\right)^{1/2}\left(1-S_{e2}^{1/m}\right)^{2m}, \tag{36c}$$

where $m = \lambda/(1+\lambda)$ and the capillary pressure parameter p_{VGP} is determined by requiring that the capillary pressures defined in Equation (32a) and Equation (36a) are equal at an effective brine saturation of $S_{e2} = 0.5$ (Webb 1992). The van Genuchten-Parker model is only used for the anhydrite MBs in the Salado and uses the same values for λ , S_{br}, and S_{gr} as the Brooks-Corey model (Table PA-2).

In the linear model, p_C , k_{rb}, and k_{rg} are defined by:

$$p_C = 0,\ k_{rb} = S_{e1},\ k_{rg} = 1 - S_{e1}. \tag{37}$$

Capillary pressure p_C for both the van Genuchten-Parker and Brooks-Corey models becomes unbounded as brine saturation S_b approaches the residual brine saturation, S_{br} . To avoid unbounded values, p_C is capped at 1×10^8 Pa in selected regions (Table PA-3).

The saturation and capillary pressure constraints (i.e., Equation (25c) and Equation (25d)) permit a reduction of the number of equations to be solved from four to two. In particular, the constraint equations are used to reformulate Equation (25a) and Equation (25b) so that the unknown functions are gas saturation S_g and brine pressure p_b . Specifically, the saturation constraint in Equation (25c) allows S_b to be expressed as

$$S_b = 1 - S_g, \tag{38}$$

and thus allows S_{e1} and S_{e2} in Equation (34) and Equation (35) to be reformulated as

$$S_{e1} = \left(1 - S_g - S_{br}\right)/\left(1 - S_{br}\right) \tag{39}$$

$$S_{e1} = \left(1 - S_g - S_{br}\right)/\left(1 - S_{gr} - S_{br}\right). \tag{40}$$

Further, the capillary pressure constraint in Equation (25d) allows p_g to be expressed as

$$p_g = p_b + p_C$$

$$= p_b + p_t(k)/S_{e2}^{1/2} \quad \text{for Brooks-Corey model, Equation (32a)} \tag{41a}$$

$$= p_b + p_{VGP}\left(S_{e2}^{-1/m} - 1\right)^{1-m} \tag{41b}$$

for van Genuchten-Parker model, Equation (36a)

$= p_b$ for linear model, Equation (37). (41c)

The equalities in Equation (39), Equation (40), and Equation (41) allow the transformation of Equation (25a) and Equation (25b) into two equations whose unknown functions are S_g and p_b, which are the equations that are actually solved in BRAGFLO:

$$\nabla \bullet \left[\frac{\alpha \rho_g K_g k_{rg}}{\mu_g} \left(\nabla p_g + \rho_g g \nabla h \right) \right] + \alpha q_{wg} + \alpha q_{rg} = \alpha \frac{\partial \left(\phi \rho_g S_g \right)}{\partial t} \tag{42a}$$

$$\nabla \bullet \left[\frac{\alpha \rho_b K_b k_{rb}}{\mu_b} \left(\nabla p_b + \rho_b g \nabla h \right) \right] + \alpha q_{wb} + \alpha q_{rb} = \alpha \frac{\partial \left(\phi \rho_b S_b \right)}{\partial t}. \tag{42b}$$

Once S_g and p_b are known, S_b and p_g can be obtained from Equation (38) and from Equation (41), respectively.

All materials are assumed to be isotropic (Howarth and Christian-Frear 1997). Thus, the tensor K_l in Equation (25) has the form

$$\mathbf{K}_l = \begin{bmatrix} k_l & 0 \\ 0 & k_l \end{bmatrix}, \tag{43}$$

where k_l is the permeability to fluid l for the particular material under consideration. For brine (i.e., fluid l = b), the permeability k_b is the same as the intrinsic permeability k in Table PA-2. For gas (i.e., fluid l = g), the permeability k_g is obtained by modifying the intrinsic permeability k to account for the Klinkenberg effect (Klinkenberg 1941). Specifically,

$$k_g = k \left(\frac{1 + b k^a}{p_g} \right), \tag{44}$$

where $a = a_{klink}$ and $b = b_{klink}$ are gas- and formation-dependent constants. Values of $a_{klink} = -0.3410$ and $b_{klink} = 0.2710$ were determined from data obtained for MB 139 (Christian-Frear 1996), with these values used for all regions in Figure PA-8. A pressure-dependent modification of k is used in the anhydrite MBs and in the DRZ in the presence of pressure-induced fracturing (see Section PA-4.2.4).

Gas density is computed using the Redlich-Kwong-Soave (RKS) equation of state, with the gas assumed to be pure hydrogen. For a pure gas, the RKS equation of state has the form (pp. 43-54, Walas 1985)

$$p_g = \frac{RT}{V - b} - \frac{a\alpha}{V(V + b)}, \tag{45}$$

where

R = gas constant = 8.31451 J mol^{-1} K^{-1},

T = temperature (K) = 300.15 K (= 30° C),

V = molar volume (m^3 mol^{-1}),

a = $0.42747\ R^2 T_c^2 / P_c$,

b = $0.08664\ RT_c / P_c$,

α = $\left[1+\left(0.48508+1.55171\omega-0.15613\omega^2\right)\left(1-T_r^{0.5}\right)\right]^2$

≈ $1.202\exp\left(-0.30288T_r\right)$ for hydrogen (Graboski and Daubert 1979),

T_c = critical temperature (K),

P_c = critical pressure (Pa),

T_r = T / T_c = reduced temperature,

ω = acentric factor
= 0 for hydrogen (Graboski and Daubert 1979).

For hydrogen, pseudo-critical temperature and pressure values of T_c = 43.6 °K and $P_c = 2.047 \times 10^6$ Pa are used instead of the true values of these properties (Prausnitz 1969). Equation (45) is solved for molar volume V. The gas density ρ_g then is given by

$$\rho_g = \frac{M_{w,H_2}}{V}, \tag{46}$$

where M_{w,H_2} is the molecular weight of hydrogen (i.e., 2.01588×10^{-3} kg/mol; see p. B-26, Weast 1969).

Brine density ρ_b is defined by Equation (25f), with ρ_0 = 1230.0 kg/m^3 at a pressure of p_{b0} = 1.0132×10^5 Pa and $\beta_b = 2.5 \times 10^{-10}$ Pa^{-1} (Roberts 1996). Porosity, ϕ, is used as defined by Equation (25g) with two exceptions: in the repository (see Section PA-4.2.3) and in the MBs subsequent to fracturing (see Section PA-4.2.4). The values of ϕ_0 and β_f used in conjunction with Equation (25g) are listed in Table PA-2. The reference pressure p_{b0} in Equation (25g) is spatially-variable and corresponds to the initial pressures $p_b\left(x, y, -5\right)$ (see Section PA-4.2.2).

The gas and brine viscosities μ_l, l = g, b in Equation (25a) and Equation (25b) were assumed to have values of $\mu_g = 8.92 \times 10^{-6}$ Pa s (Vargaftik 1975) and $\mu_b = 2.1 \times 10^{-3}$ Pa s (McTigue 1993).

The terms q_{wg}, q_{rg}, q_{wb}, and q_{rb} in Equation (25a) and Equation (25b) relate to well injection or removal (i.e., q_{wg} , q_{wb}) and reaction production or consumption (i.e., q_{rg} , q_{rb}) of gas and brine, with positive signs corresponding to injection or production and negative signs corresponding to removal or consumption. No injection or removal of gas or brine is assumed to take place within the region in Figure PA-8. Thus, q_{wg} and q_{wb} are equal to zero. Further, no gas consumption occurs (see below), and gas production has the potential to occur (due to corrosion of steel or microbial degradation of cellulosic, plastic, or rubber (CPR) materials) only in the waste disposal regions of the repository (i.e., Waste Panel, South RoR, and North RoR in Figure PA-8). Thus,

$$\begin{aligned} q_{rg} &\geq 0 \quad \text{in waste disposal regions of Figure PA-8} \\ &= 0 \quad \text{elsewhere.} \end{aligned} \tag{47}$$

In actuality, some gas consumption does occur due to the reaction of CO_2 with the MgO in the waste panels. This gas consumption is not modeled explicitly and is accounted for by reducing the gas generation rate q_{rg}, as discussed in Section PA-4.2.5. Finally, no brine production occurs, and brine consumption has the potential to occur (due to the consumption of brine during the corrosion of steel) only in the waste disposal regions of the repository. Thus,

$$\begin{aligned} q_{rb} &\leq 0 \quad \text{in waste disposal regions of Figure PA-8} \\ &= 0 \quad \text{elsewhere.} \end{aligned} \tag{48}$$

More detail on the definition of q_{rg} and q_{rb} is provided in Section PA-4.2.5.

PA-4.2.2 Initial Conditions

In each two-phase flow simulation, a short period of time representing disposal operations is simulated. This period of time is called the start-up period and covers five years from t = –5 years to 0 years, corresponding to the amount of time a typical panel is expected to be open during disposal operations. All grid locations require initial brine pressure and gas saturation at the beginning of the simulation (t = –5 years).

The Rustler Formation and overlying units (except in the shaft) are modeled as horizontal with spatially constant initial pressure in each layer (see Figure PA-8). Table PA-4 lists the initial brine pressure p_b and gas saturation S_g for the Rustler Formation.

Table PA-4. Initial Conditions in the Rustler Formation

Name	Mesh Row (Figure PA-8)	$p_b(x, y, -5)$, Pa	$S_g(x, y, -5)$
Santa Rosa Formation	33	1.013250×10^5	1 – Sbr = 0.916

Santa Rosa Formation	32	1.013250×10^5	1 – Sbr = 0.916
Dewey Lake	31	1.013250×10^5	1 – Sbr = 0.916
Dewey Lake	30	7.355092×10^5	1 – Sbr = 0.916
49er	29	1.473284×10^6	0
Magenta	28	9.170000×10^5	0
Tamarisk	27	1.827087×10^6	0
Culebra	26	8.220000×10^5	0
Los Medaños Unnamed	25	2.274809×10^6	0

The Salado Formation (mesh rows 3 – 24 in Figure PA-8) is assumed to dip uniformly θ = 1° downward from north to south (right to left in Figure PA-8). Except in the repository excavations and in the shaft, brine is assumed initially (i.e., at –5 years) to be in hydrostatic equilibrium relative to an uncertain initial pressure $p_{b,ref}$ (SALPRES, see Table PA-17) at a reference point located at center of shaft at the elevation of the midpoint of MB139, which is the center of cell 1266 in Figure PA-10). This gives rise to the condition

$$p_b\left(x, y, -5\right) = p_{b0} + \left(\frac{1}{\beta_b}\right) \ln\left[\frac{\rho_b\left(x, y, -5\right)}{\rho_{b0}}\right], \tag{49}$$

where

$$\rho_b\left(x, y, -5\right) = \frac{1}{g\,\beta_b\left[y_e - \Phi\left(x_{ref}, y_{ref}, -5\right) + \dfrac{1}{g\,\beta_b\,\rho_{b0}}\right]}$$

$$\Phi\left(x_{ref}, y_{ref}, -5\right) = y_{ref} + \frac{1}{g\,\beta_b}\left[\frac{1}{\rho_{b0}} - \frac{1}{\rho_b\left(x_{ref}, y_{ref}, -5\right)}\right]$$

$$\rho_b\left(x_{ref}, y_{ref}, -5\right) = \rho_{b0} \exp\left[-\beta_b\left(p_{b,ref} - p_{b0}\right)\right]$$

$$y_e = y_{ref} + h(x, y) = y_{ref} + \left(x - x_{ref}\right)\sin\theta + \left(y - y_{ref}\right)\cos\theta \quad \text{(see Equation (27))}$$

and ρ_{b0} = 1220 kg/m^3, $\beta_b = 3.1 \times 10^{-10}$ Pa^{-1}, g = 9.80665 m/s^2, and $p_{b0} = 1.01325 \times 10^5$ Pa. In the Salado Formation, initial gas saturation $S_g\left(x, y, -5\right) = 0$.

The Castile Formation (mesh rows 1 and 2) is modeled as horizontal, and initial brine pressure is spatially constant within each layer, except that the brine reservoir is treated as a different

material from rest of Castile and has a different initial pressure. Specifically, outside the brine reservoir,

$$p_b(x, y, -5) = \begin{cases} 1.54445 \times 10^7 \ Pa & \text{in mesh row 2} \\ 1.65151 \times 10^7 \ Pa & \text{in mesh row 1} \end{cases}. \tag{50}$$

Within the reservoir, $p_b(x, y, -5) = BPINTPRS$, the uncertain initial pressure in the reservoir (see Table PA-17). Initial gas saturation $S_g(x, y, -5) = 0$.

Within the shaft (areas Upper Shaft, Lower Shaft, and CONC_MON) and panel closures (areas CONC_PCS and DRF_PCS), $p_b(x, y, -5) = 1.01325 \times 10^5$ Pa and $S_g(x, y, -5) = 1 \times 10^{-7}$. Within the excavated areas (Waste Panel, South RoR, and North RoR, Ops and Exp), $p_b(x, y, -5) = 1.01325 \times 10^5$ Pa and $S_g(x, y, -5) = 0$.

At the end of the initial five-year start-up period and the beginning of the regulatory period (t = 0 years), brine pressure and gas saturation are reset in the shaft, panel closures, and excavated areas. In the shaft (areas Upper Shaft, Lower Shaft, and CONC_MON) and panel closures (areas CONC_PCS and DRF_PCS), $p_b(x, y, 0) = 1.01325 \times 10^5$ Pa and $S_g(x, y, 0) = 1 \times 10^{-7}$. In the waste disposal regions (areas Waste Panel, South RoR, and North RoR), $p_b(x, y, 0) = 1.01325 \times 10^5$ Pa and $S_g(x, y, 0) = 0.985$. In the other excavated areas, $p_b(x, y, 0) = 1.01325 \times 10^5$ Pa and $S_g(x, y, 0) = 1.0$.

PA-4.2.3 Creep Closure of Repository

The porosity of the waste disposal regions and neighboring access drifts (i.e., Waste Panel, South RoR, North RoR, and DRF_PCS in Figure PA-8) is assumed to change through time due to creep closure of the halite surrounding the excavations. The equations on which BRAGFLO is based do not incorporate this type of deformation. Therefore, the changes in repository porosity due to halite deformation are modeled in a separate analysis with the geomechanical program SANTOS, which implements a quasi-static, large-deformation, finite-element procedure (Stone 1997). Interpolation procedures are then used with the SANTOS results to define ϕ within the repository as a function of time, pressure, and gas generation rate.

For more information on the generation of the porosity surface for BRAGFLO for the CRA-2004 PA, see Appendix PA, Attachment PORSURF.

PA-4.2.4 Fracturing of Marker Beds and Disturbed Rock Zone

Fracturing within the anhydrite MBs (i.e., regions MB 138, Anhydrite AB, and MB 139 in Figure PA-8) and in the DRZ (region DRZ in Figure PA-8) is assumed to occur at pressures slightly below lithostatic pressure and is implemented through a pressure-dependent

compressibility $\beta_f\left(p_b\right)$ (Mendenhall and Gerstle 1995). Specifically, fracturing of the MBs begins at a brine pressure of

$$p_{bi} = p_{b0} + \Delta p_i \ , \tag{51}$$

where p_{bi} and p_{b0} are spatially dependent (i.e., $p_{b0} = p_b\left(x, y, 0\right)$ as in Section PA-4.2.2) and $\Delta p_i = 2 \times 10^5$ Pa.

Fracturing ceases at a pressure of

$$p_{ba} = p_{b0} + \Delta p_a \tag{52}$$

and a fully-fractured porosity of

$$\phi\left(p_{ba}\right) = \phi_a = \phi_0 + \Delta\phi_a \ , \tag{53}$$

where $\Delta p_a = 3.8 \times 10^6$ Pa, ϕ_0 is spatially dependent (Table PA-2), and $\Delta\phi_a$ = 0.04, 0.24, and 0.04 for anhydrite materials S_MB138, S_ANH_AB and S_MB139, respectively.

Compressibility β_f is a linear function

$$\beta_f\left(p_b\right) = \beta_f + \left(\frac{p_b - p_{bi}}{p_{ba} - p_{bi}}\right)\left(\beta_{fa} - \beta_f\right) \tag{54}$$

of brine pressure for $p_{bi} \le p_b \le p_{ba}$, with β_{fa} defined so that the solution ϕ of

$$\frac{d\phi}{dp_b} = \beta_{fa}(p_b)\phi, \quad where \ \ \phi(p_{bi}) = \phi_0 \exp\left[\beta_f(p_{bi} - p_{b0})\right] \tag{55}$$

satisfies $\phi\left(p_{ba}\right) = \phi_a$; specifically, β_{fa} is given by

$$\beta_{fa} = \beta_f\left[1 - \frac{2\left(p_{ba} - p_{b0}\right)}{p_{ba} - p_{bi}}\right] + \left[\frac{2}{p_{ba} - p_{bi}}\right]\ln\left(\frac{\phi_a}{\phi_0}\right) \ . \tag{56}$$

The permeability $k_f\left(p_b\right)$ of fractured material at brine pressure p_b is related to the permeability of unfractured material at brine pressure p_{bi} by

$$k_f(p_b) = \left[\frac{\phi(p_b)}{\phi(p_{bi})}\right]^n k \ , \tag{57}$$

where k is the permeability of unfractured material (i.e., at p_{bi}) and n is defined so that $k_f(p_b) = 1 \times 10^{-9}\ m^2$ (i.e., n is a function of k, which is an uncertain input to the analysis; see ANHPRM in Table PA-17). When fracturing occurs, $k_f(p_b)$ is used instead of k in the definition of the permeability tensor K_l in Equation (43) for the fractured areas of the anhydrite MBs.

Fracturing is also modeled in the DRZ. The implementation of the fracture model is the same as for the anhydrite materials. In this case, fracturing would be in halite rather than anhydrite, but because of the limited extent of the DRZ and the proximity of the nearby interbeds, this representation was deemed acceptable by the Salado Flow Peer Review panel (Caporuscio et al. 2003).

PA-4.2.5 Gas Generation

Gas production is assumed to result from anoxic corrosion of steel and microbial degradation of CPR materials. Thus, the gas generation rate q_{rg} in Equation (25a) is of the form

$$q_{rg} = q_{rgc} + q_{rgm}\,, \tag{58}$$

where q_{rgc} is the rate of gas production per unit volume of waste (kg/m^3/s) due to anoxic corrosion of Fe-base metals and q_{rgm} is the rate of gas production per unit volume of waste (kg/m^3/s) due to microbial degradation of CPR materials. Furthermore, q_{rb} in Equation (25b) is used to describe the consumption of brine during the corrosion process.

Gas generation takes place only within the waste disposal regions (i.e., Waste Panel, South RoR, and North RoR in Figure PA-8) and all the generated gas is assumed to have the same properties as H_2 (see discussion in Attachment MASS, Section MASS-3.2). In the CCA PA and the CRA-2004 PA, the consumable materials are assumed to be homogeneously distributed throughout the waste disposal regions (i.e., the concentration of Fe-base metals and of CPR materials in the waste is a constant; see Appendix TRU WASTE, Table TRU WASTE-1). A separate analysis examined the potential effects on PA results of spatially-varying concentrations of Fe-base metals and CPR materials, and concluded that PA results are not affected by representing these materials with spatially-varying concentrations (see Attachment MASS, Section MASS.21).

The rates q_{rgc}, q_{rb} and q_{rgm} are defined by

$$q_{rgc} = \left(R_{ci}S_{b,eff} + R_{ch}S_g^*\right)D_s\rho_{Fe}X_c\left(H_2|Fe\right)M_{H_2} \tag{59}$$

$$q_{rb} = \left(q_{rgc}/M_{H_2}\right)X_c\left(H_2O|H_2\right)M_{H_2O} \tag{60}$$

$$q_{rgm} = \left(R_{mi}S_{b,eff} + R_{mh}S_g^*\right)D_c y\left(H_2|C\right)M_{H_2}\,, \tag{61}$$

where

D_s = surface area concentration of steel in the repository ((m^2 surface area steel)/(m^3 disposal volume)),

D_c = mass concentration of cellulosics in the repository ((kg biodegradable material)/(m^3 of disposal volume)),

M_{H_2} = molecular weight of H_2 (kg H_2/mol H_2),

M_{H_2O} = molecular weight of H_2O (kg H_2O/mol H_2O),

R_{ci} = corrosion rate under inundated conditions (m/s),

R_{ch} = corrosion rate under humid conditions (m/s),

R_{mi} = rate of cellulose biodegradation under inundated conditions (mol $C_6H_{10}O_5$/kg $C_6H_{10}O_5$/s),

R_{mh} = rate of cellulose biodegradation under humid conditions (mol $C_6H_{10}O_5$/kg $C_6H_{10}O_5$/s),

$S_{b,eff}$ = effective brine saturation due to capillary action in the waste materials (see Equation (78) in Section PA-4.2.6),

$$S_g^* = \begin{cases} 1 - S_{b,eff} & \text{if } S_{b,eff} > 0 \\ 0 & \text{if } S_{b,eff} = 0 \end{cases},$$

$X_c(H_2|Fe)$ = stoichiometric coefficient for gas generation due to corrosion of steel, i.e., moles of H_2 produced by the corrosion of 1 mole of Fe (mol H_2 / mol Fe),

$X_c(H_2O|H_2)$ = stoichiometric coefficient for brine consumption due to corrosion of steel, i.e., moles of H_2O consumed per mole of H_2 generated by corrosion (mol H_2O / mol H_2),

$y(H_2|C)$ = average stoichiometric factor for microbial degradation of cellulose, i.e., the moles of H_2 generated per mole of carbon consumed by microbial action (mol H_2 / mol $C_6H_{10}O_5$), and

ρ_{Fe} = molar density of steel (mol/m^3).

The products $R_{ci}\ D_s\ \rho_{Fe}\ X_c$, $R_{ch}\ D_s\ \rho_{Fe}\ X_c$, $R_{mi}\ D_c\ y$, and $R_{mh}\ D_c\ y$ in Equation (59) and Equation (61) define constant rates of gas generation (mol/m^3/s) that continue until the associated substrate (i.e. steel or cellulose) is exhausted (i.e., zero order kinetics). The terms $S_{b,eff}$ and S_g^* in Equation (59) and Equation (61), which are functions of location and time, correct for the amount of substrate that is exposed to inundated and humid conditions, respectively. All the corrosion and microbial action is assumed to cease when no brine is present, which is the reason that 0 replaces $S_g = 1$ in the definition of S_g^*. In the CRA-2004 PA, $R_{ch} = 0$ and R_{ci}, R_{mh}, and R_{mi} are defined by uncertain variables (see WGRCOR, WGRMICH, WGRMICI in Table PA-17). Further, $M_{H_2} = 2.02 \times 10^{-3}$ kg/mol (pp. 1-7, 1-8, Lide 1991), $M_{H_2O} = 1.80 \times 10^{-2}$ kg/mol (pp. 1-7, 1-8, Lide 1991), $\rho_{Fe} = 1.41 \times 10^5$ mol/m^3 (Telander and Westerman 1993), and D_s , D_c , $X_c\left(H_2O \middle| H_2\right)$, $X_c\left(H_2 \middle| Fe\right)$ and $y\left(H_2 \middle| C\right)$ are discussed below.

The concentration D_s in Equation (59) is defined by

$$D_s = A_d n_d / V_R , \tag{62}$$

where

A_d = surface area of steel associated with a waste disposal drum (m^2/drum),

V_R = initial volume of the repository (m^3), and

n_d = number of waste drums required to hold all the waste emplaced in the repository (drums).

In the CRA-2004 PA, $A_d = 6$ m^2/drum (Vol. 3, WIPP PA 1991-1992), $V_R = 438{,}406$ m^3 (Stein 2002b), and $n_d = 818{,}498$ drums ($n_d = V_R \times$ DROOM / VROOM, where DROOM is the number of drums per room {6804 drums} and VROOM is the volume of each room {3644 m^3}).

The biodegradable materials to be disposed of at the WIPP consist of cellulosic materials, rubbers, and both waste plastics and container plastics. Cellulosics have been demonstrated experimentally to be the most biodegradable among these materials (Francis et al. 1997). The occurrence of significant microbial gas generation in the repository will depend on: (1) whether microbes capable of consuming the emplaced organic materials will be present and active; (2) whether sufficient electron acceptors will be present and available; and (3) whether enough nutrients will be present and available. Given the uncertainties in these factors, a probability of 0.5 is assigned to the occurrence of microbial gas generation (see WMICDFLG in Table PA-17). Furthermore, two factors may increase the biodegradability of plastics and rubbers: long time scale and cometabolism. Over a time scale of 10,000 years, the chemical properties of plastics and rubbers may change, increasing their biodegradability. Cometabolism means that microbes

may degrade organic compounds, but do not use them as a source of energy, which is derived from other substrates. Both of these factors are highly uncertain and therefore a probability of 0.5 is assigned to biodegradation of plastics and rubbers conditional on the occurrence of biodegradation of cellulosic materials(see WMICDFLG in Table PA-17). In cases where biodegradation of rubbers and plastics occur, rubbers and plastics are converted to an equivalent quantity of cellulosics based on their carbon equivalence (Wang and Brush 1996a). This produces the density calculation

$$D_c = \begin{cases} m_{cel} / V_R & \text{for biodegradation of cellulosics only} \\ \left(m_{cel} + m_r + 1.7 m_p\right) / V_R & \text{for biodegradation of CPR materials,} \end{cases} \tag{63}$$

where m_{cel} is mass of cellulosics (kg), m_r is the mass of rubbers (kg), and m_p is the mass of plastics (kg). The factor of 1.7 converts all plastics to an equivalent quantity of cellulosics based on carbon equivalence. In the CRA-2004 PA,

$$m_{cel} = [(58.0 \text{ kg/ m}^3 \times 168{,}485 \text{ m}^3) + (4.5 \text{ kg/ m}^3 \times 7{,}079 \text{ m}^3)] = 9.8 \times 10^6 \text{ kg},$$

$$m_r = [(14.0 \text{ kg/ m}^3 \times 168{,}485 \text{ m}^3) + (3.1 \text{ kg/m3} \times 7{,}079 \text{ m}^3)] = 2.4 \times 10^6 \text{ kg}$$

$$m_p = [(58.0 \text{ kg/m3} \times 168{,}485 \text{ m}^3) + (6.3 \text{ kg/m3} \times 7{,}079 \text{ m}^3)] = 9.8 \times 10^6 \text{ kg}.$$

Values for the density for CPR materials can be found in Appendix DATA, Attachment F.

The most plausible corrosion reactions after closure of the WIPP are believed to be (Wang and Brush 1996a)

$$Fe + 2H_2O = Fe(OH)_2 + H_2 \tag{64}$$

and

$$3Fe + 4H_2O = Fe_3O_4 + 4H_2. \tag{65}$$

When linearly weighted by the factors x and $1 - x$ $\left(0 \le x \le 1\right)$, the two preceding reactions become

$$Fe + \left(\frac{4 + 2x}{3}\right) H_2O = \left(\frac{4 - x}{3}\right) H_2 + xFe(OH)_2 + \left(\frac{1 - x}{3}\right) Fe_3O_4 , \tag{66}$$

where x and $1 - x$ are the fractions of iron consumed in the reactions in Reaction (64) and Reaction (65), respectively. Although magnetite (Fe_3O_4) has been observed to form on iron as a corrosion product in low-Mg anoxic brines at elevated temperatures (Telander and Westerman 1997) and in oxic brine (Haberman and Frydrych 1988), there is no evidence that it will form at WIPP repository temperatures. If Fe_3O_4 were to form, H_2 would be produced (on a molar basis)

in excess of the amount of Fe consumed. However, anoxic corrosion experiments (Telander and Westerman 1993) did not indicate the production of H_2 in excess of the amount of Fe consumed. Therefore, the stoichiometric factor x in Reaction (66) is set to 1.0 (i.e., x = 1), which implies that Reaction (64) represents corrosion. Thus, the stoichiometric factor for corrosion is

$$X_c\left(H_2 \middle| Fe\right) = \left(4 - x\right)/3 = 1\ mol/mol\ , \tag{67}$$

which implies that one mole of H_2 is produced for each mole of iron consumed, and the stoichiometric factor for brine consumption is

$$X_c\left(H_2O \middle| H_2\right) = \left(4 + 2x\right)/3 = 2\ mol/mol\ , \tag{68}$$

which implies that two moles of H_2O are consumed for each mole of H_2 produced. The most plausible biodegradation reactions after closure of the WIPP are believed to be (Wang and Brush 1996a)

Denitrification: $$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- = 7.4H_2O + 6CO_2 + 2.4N_2\ , \tag{69a}$$

Sulfate reduction: $$C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} = 5H_2O + 6CO_2 + 3H_2S\ , \tag{69b}$$

Methanogenesis: $$C_6H_{10}O_5 + H_2O = 3CH_4 + 3CO_2\ . \tag{69c}$$

Accumulation of CO_2 produced by the above reactions could decrease pH and thus increase actinide solubility in the repository (Wang and Brush 1996b). To improve WIPP performance, a sufficient amount of MgO will be added to the repository to remove CO_2 (Bynum et al. 1997). The consumption of CO_2 by MgO in the repository takes place by the reactions outlined in Section 6.4.3.4. The removal of CO_2 by MgO is not explicitly represented in the BRAGFLO code. Rather, the effect of CO_2 consumption is accounted for by modifying the stoichiometry of Reaction (69) to remove the CO_2 from the mass of gas produced by microbial action.

The average stoichiometry of Reaction (69), is

$$C_6H_{10}O_5 + unknowns = 6\,y\ (mol)\ gas + \ unknowns\ , \tag{70}$$

where the average stoichiometric factor y in Reaction (70) represents the number of moles of gas produced and retained in the repository from each mole of carbon consumed. This factor y depends on the extent of the individual biodegradation pathways in Reaction (69), and the consumption of CO_2 by MgO. An range of values for y is estimated by considering the maximum mass of gas that can be produced from consumption of cellulosics (M_{cel}) and Fe-base metals (M_{Fe}), and is derived as follows (Wang and Brush 1996b).

Estimates of the maximum quantities M_{cel} and M_{Fe} (mol) of cellulosics (i.e., $C_6H_{10}O_5$) and steels that can be potentially consumed in 10,000 years are given by

$$M_{cel} = \min\left\{\frac{6000 m_{cel}}{162},\ 3.2 \times 10^{11} R_m m_{cel}\right\} \tag{71}$$

$$M_{Fe} = \min\left\{\frac{1000 m_{Fe}}{56},\ 4.4 \times 10^{16} R_{ci} A_d n_d\right\}, \tag{72}$$

where m_{cel} and m_{Fe} are the masses (kg) of cellulosics (see Equation (63) for definition) and steels initially present in the repository. The mass of cellulosics that can be consumed is determined by the uncertain parameter WMICDFLG (see Table PA-17). The mass of steels, $m_{Fe} = 5.15 \times 10^7$ kg; this value is calculated as:

$$V_{CH}\left(\rho_{WCH} + \rho_{CCH}\right) + V_{RH}\left(\rho_{WRH} + \rho_{CRH}\right), \tag{73}$$

where V_{CH} and V_{RH} are the volumes of CH- and RH-TRU waste, ρ_{WCH} and ρ_{WRH} are the iron densities in CH- and RH-TRU waste, and ρ_{CCH} and ρ_{CRH} are the iron densities of the containers of CH- and RH-TRU waste (Appendix DATA, Attachment F). The terms 6000 m_{cel}/162 and 1000 m_{Fe}/56 in Equation (71) and Equation (72) equal the inventories in moles of cellulosics and steel, respectively. The terms 3.2×10^{11} $R_m m_{cel}$ and 4.4×10^{16} $R_{ci} A_d n_d$ equal the maximum amounts of cellulosics and steel that could be consumed over 10,000 years. In Equation (71), $R_m = \max\left\{R_{mh}, R_{mi}\right\}$, where R_{mh} and R_{mi} are defined by uncertain variables (see WGRMICH and WGRMICI in Table PA-17, respectively), and $3.2 \times 10^{11} = (3.15569 \times 10^7$ s/yr) (10^4 yr). In Equation (72), $A_d n_d$ is the total surface area of all drums (m^2) and the factor $4.4 \times 10^{16} = (3.15569 \times 10^7$ s/yr) (10^4 yr) (1.41×10^5 mol/ m^3), where $\rho_{Fe} = 1.41 \times 10^5$ mol/m^3 (see Equation (59)) (Telander and Westerman 1993), converts the corrosion rate from m/s to mol/m^2/s.

A range of possible values for the average stoichiometric factor y in Reaction (70) can be obtained by considering individual biodegradation pathways involving M_{cel} and accounting for the removal of CO_2 by the MgO. Two extreme cases corresponding to the maximum and minimum values of y exist: (1) there is no reaction of microbially produced H_2S with ferrous metals and metal corrosion products, and (2) there is a complete reaction of microbially produced H_2S with ferrous metals and metal corrosion products. If no H_2S is consumed by reactions with Fe and Fe-corrosion products, the maximum quantity of microbial gas will be retained in the repository and therefore the maximum value for y results. Thus, the maximum value of y can be estimated by averaging the gas yields for all reaction pathways to produce

$$y_{max} = \frac{\dfrac{2.4 M_{NO_3}}{4.8} + \dfrac{3 M_{SO_4}}{3} + 0.5\left(M_{cel} - \dfrac{6 M_{NO_3}}{4.8} - \dfrac{6 M_{SO_4}}{3}\right)}{M_{cel}}, \tag{74}$$

where M_{NO_3} and M_{SO_4} are the quantities of NO_3^- and SO_4^{2-} (in moles) initially present in the repository. Specifically, M_{NO_3} = 2.51 × 10^7 mol and M_{SO_4} = 4.21 × 10^5 mol (Appendix DATA, Attachment F, Table DATA-F-35).

If H_2S reacts with Fe and Fe- corrosion products, a significant quantity or perhaps all of the microbially produced H_2S would be consumed to produce FeS, which would result in the minimum value of y. Specifically,

$$y_{min} = \frac{\frac{2.4 M_{NO_3}}{4.8} + \frac{3 M_{SO_4}}{3} + 0.5\left(M_{cel} - \frac{6 M_{NO_3}}{4.8} - \frac{6 M_{SO_4}}{3} \right) - G}{M_{cel}} = y_{max} - \frac{G}{M_{cel}}, \quad (75)$$

where

$$G = \min\left\{ \frac{3 M_{SO_4}}{3}, M_{Fe} \right\}. \quad (76)$$

The stoichiometric factor y value is believed to be located within the interval $\left[y_{min}, y_{max} \right]$. That is,

$$y = y_{min} + \beta\left(y_{max} - y_{min} \right), \quad 0 \le \beta \le 1. \quad (77)$$

The variable β in the preceding equation is treated as an uncertain quantity in the CRA-2004 PA (see WFBETCEL in Table PA-17).

PA-4.2.6 Capillary Action in the Waste

Capillary action (wicking) refers to the ability of a material to carry a fluid by capillary forces above the level it would normally seek in response to gravity. In the current analysis, this phenomena is accounted for by defining an effective saturation given by

$$S_{b,eff} = \begin{cases} S_b + S_{wick} & \text{if } 0 < S_b < 1 - S_{wick} \\ 0 & \text{if } S_b = 0 \\ 1 & \text{if } S_b > 1 - S_{wick} \end{cases}, \quad (78)$$

where

$S_{b,eff}$ = effective brine saturation,

S_b = brine saturation,

S_{wick} = wicking saturation.

The effective saturation is used on a grid block basis within all waste regions (Waste Panel, South RoR, and North RoR in Figure PA-8). The wicking saturation, S_{wick}, is treated as an uncertain variable (see WASTWICK in Table PA-17). The effective brine saturation $S_{b,eff}$ is only used in the calculation of the corrosion of steel (Equation (59)) and the microbial degradation of cellulose (Equation (61)) and does not directly affect the two-phase flow calculations indicated.

PA-4.2.7 Shaft Treatment

The WIPP excavation includes four shafts that connect the repository region to the surface: the air intake shaft, salt handing shaft, waste handling shaft, and exhaust shaft. In both the CCA PA and the CRA-2004 PA, these four shafts are modeled as a single shaft. The rationale for this modeling treatment is set forth in WIPP PA 1992-1993 (Section 2.3, Vol. 5).

A shaft seal model is included in the CRA-2004 grid (column 43 in Figure PA-8), but it is implemented in a simpler fashion than for the CCA PA. A detailed description of the new implementation and its parameters are discussed in AP-094 (James and Stein 2002) and the resulting analysis report (James and Stein 2003). The final version of the shaft seal model used in the CRA-2004 PA is described by Stein and Zelinski (2003a); this model was approved by the Salado Flow Peer Review panel (Caporuscio et al. 2003).

The planned design of the shaft seals involves numerous materials including earth, crushed salt, clay, asphalt, and Salado Mass Concrete (SMC) (CCA Appendix SEAL). The design is intended to control both short-term and long-term fluid flow through the Salado portion of the shafts. For the CCA PA, each material in the shaft seal was represented in the BRAGFLO grid. Analysis of the flow results from the CCA PA and subsequent 1997 Performance Assessment Verification Test (PAVT) (SNL 1997) indicated that no significant flows of brine or gas occurred in the shaft during the 10,000-year regulatory period. As a result of these analyses, a simplified shaft seal model was developed for the CRA-2004 PA.

A conceptual representation of the simplified shaft seal system used in CRA-2004 PA is shown in Figure PA-11. The simplified model divides the shaft into three sections: an upper section (shaft seal above the Salado), a lower section (within the Salado), and a concrete monolith section within the repository horizon. A detailed discussion on how the material properties were assigned for the simplified shaft seal model is included in James and Stein (2003). The permeability value used to represent the upper and lower sections is defined as the harmonic mean of the permeability of the component materials in the detailed shaft seal model (including permeability adjustments made for the DRZ assumed to surround the lower shaft seal section within the Salado). Porosity is defined as the thickness-weighted mean porosity of the component materials. Other material properties are described in James and Stein (2003).

The lower section of the shaft experiences a change in material properties at 200 years. This change simulates the consolidation of the seal materials within the Salado and results in a significant decrease in permeability. This time was chosen as a conservative overestimate of the amount of time expected for this section of the shaft to become consolidated. The concrete monolith section of the shaft is unchanged from the CCA PA and is represented as being highly permeable for 10,000 years to ensure that fluids can access the north end (operations and

experimental areas) in the model. In three thin regions at the stratigraphic position of the anhydrite MBs, the shaft seal is modeled as MB material (Figure PA-11). This model feature is included so that fluids flowing in the DRZ and MB fractures can access the interbeds to the north of the repository "around" the shaft seals. Because these layers are so thin, they have virtually no effect on the effective permeability of the shaft seal itself.

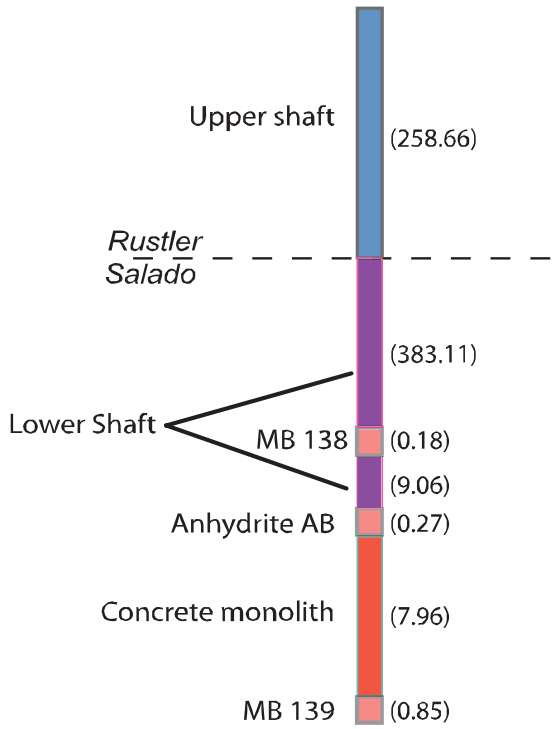

Figure PA-11. Schematic View of the Simplified Shaft Model.

The simplified shaft model was tested in the AP-106 analysis (Stein and Zelinski 2003a), which supported the Salado Flow Peer Review. The results of the AP-106 analysis demonstrated that vertical brine flow through the simplified shaft model was comparable to brine flows seen through the detailed shaft model used in the CCA PA and subsequent PAVT calculations.

PA-4.2.8 Option D Panel Closures

The CRA-2004 PA includes panel closures models that represent the Option D panel closure design (Section 6.4.3). Option D closures (Figure PA-12) are designed to allow minimal fluid flow between panels. The CRA-2004 PA explicitly represents selected Option D panel closures in the computational grid using a model that was approved by the Salado Flow Peer Review Panel (Caporuscio et al. 2003). The Option D panel closure design has several components: an SMC monolith, which extends into the DRZ in all directions, an empty drift section, and a block and mortar explosion wall (Figure PA-13). Each set of panel closures are represented in the BRAGFLO grid by four materials in 13 grid cells:

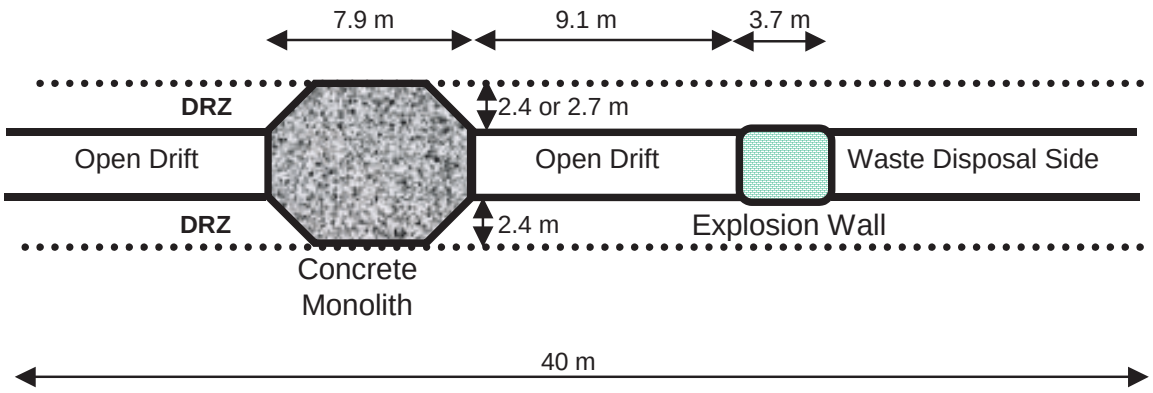

Figure PA-12. Schematic Side View of Option D Panel Closure.

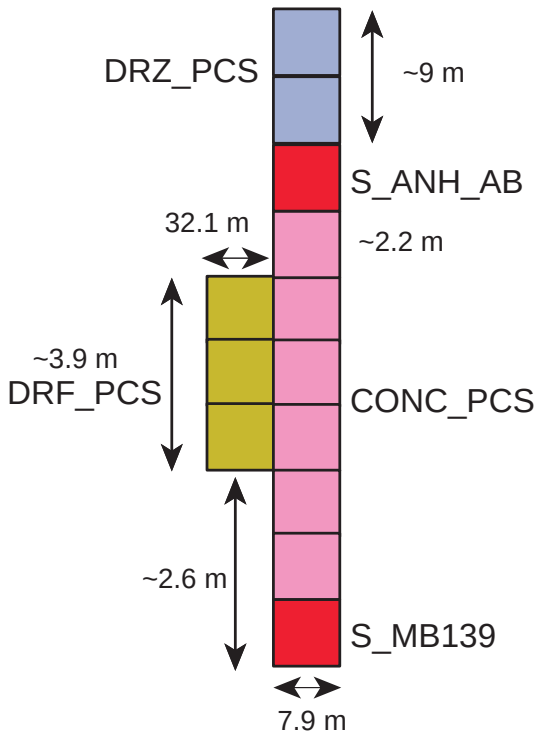

Figure PA-13. Representation of Option D Panel Closures in the BRAGFLO Grid.

- Six cells of panel closure concrete (area CONC_PCS, material CONC_PCS),
- One cell above and one cell below the concrete material consisting of MB anhydrite (areas MB 139 and Anhydrite AB, materials S_MB139 and S_ANH_AB, respectively),
- Two cells of healed DRZ above Anhydrite AB above the panel closure system (PCS) (area DRZ_PCS, material DRZ_PCS), and
- Three cells of empty drift and explosion wall (area DRF_PCS, material DRF_PCS).

Properties for the materials comprising the panel closure system are listed in Table PA-2.

PA-4.2.8.1 Panel Closure Concrete

The Option D panel closure design requires the use of a salt-saturated concrete, identified as SMC, as specified for the shaft seal system. The design of the shaft seal system and the properties of SMC are described in Hurtado et al. (1997). The BRAGFLO grid incorporates the material, CONC_PCS, which is assigned the material properties of undegraded SMC and is used to represent the concrete portion of the Option D panel closure system (Figure PA-8). A double-thick concrete segment is used to represent the northernmost set of panel closures (between the north rest of repository and the operations area). This feature is meant to represent the two sets of panel closures in series that will be emplaced between the waste filled repository and the shaft.

PA-4.2.8.2 Panel Closure Abutment with Marker Beds

In the BRAGFLO grid, regions where the Option D panel closures intersect the MBs are represented as blocks of MB material (Figure PA-8). This representation is warranted for two reasons:

1. The MB material has a very similar permeability distribution (10^{-21} to $10^{-17.1}$ m^2) as the concrete portion of the Option D panel closures ($10^{-20.699}$ to 10^{-17} m^2), and thus, assigning this material as anhydrite MB in the model has essentially the same effect as calling it concrete, as long as pressures are below the fracture initiation pressure.

2. In the case of high pressures, it is expected that fracturing may occur in the anhydrite MBs and flow could go “around” the panel closures out of the two-dimensional plane considered in the model grid. In this case, the flow would be through the MB material, which incorporates a fracture model, as described above.

PA-4.2.8.3 Disturbed Rock Zone Above the Panel Closure

After construction of the concrete portion of the panel closure, the salt surrounding the monolith will be subjected to compressive stresses, which will facilitate the rapid healing of disturbed halite. The rounded configuration of the monolith creates a situation very favorable for concrete durability: high compressive stresses and low stress differences. In turn, the compressive stresses developed within the salt will quickly heal any damage caused by construction excavation, thereby eliminating the DRZ along the length of this portion of the panel closure. The permeability of the salt immediately above and below the rigid concrete monolith component of Option D will approach the intrinsic permeability of the undisturbed Salado halite.

To represent the DRZ above the monoliths, the CRA-2004 PA uses the material, DRZ_PCS, in the BRAGFLO grid (Figure PA-8). The values assigned to DRZ_PCS are the same as those values used for the DRZ above the excavated areas (material DRZ_1, see Table PA-2), except for the properties PRMX_LOG, PRMY_LOG, and PRMZ_LOG, the logarithm of permeability in the x, y, and z directions, respectively. These permeability values are assigned the same distributions used for the material CONC_PCS. In this instance, the values are based on the

nature of the model set-up, and not directly on experimental data (although the general range of the distribution agrees with experimental observations of healed salt). The use of these permeabilities ensures that any fluid flow is equally probable through or around the Option D panel closures and represents the range of uncertainty that exists in the performance of the panel closure system.

PA-4.2.8.4 Empty Drift and Explosion Wall Materials

The DRF_PCS is the material representing the empty drift and explosion wall. For simplicity, this material is assumed to have hydrologic properties equivalent to the material representing the waste panel and is used for the three sets of panel closures represented in the grid (Figure PA-8). The creep closure model is applied to this material to be consistent with the neighboring materials. The assignment of a high permeability to this region containing the explosion wall is justified because the explosion wall is not designed to withstand the stresses imposed by creep closure and will be highly permeable following rapid room closure.

PA-4.2.9 Borehole Model

The major disruptive event in the CRA-2004 PA is the penetration of the repository by a drilling intrusion. In the undisturbed scenario (scenario S1; see Section PA-6.7.1), these blocks have the material properties of the neighboring stratigraphic or excavated modeling unit, and there is no designation in the grid of a borehole except for the reduced lateral dimensions of this particular column of grid blocks.

In the scenarios simulating drilling disturbance, these cells start out with the same material properties as in the undisturbed scenario, but at the time of intrusion the borehole grid blocks are reassigned to borehole material properties. The drilling intrusion is modeled by modifying the permeability of the grid blocks in column 26 of Figure PA-8 (values listed in Table PA-5). Further, the drilling intrusion is assumed to produce a borehole with a diameter of 12.25 in. (0.31 m) (Vaughn 1996; Howard 1996); borehole fill is assumed to be incompressible; capillary effects are ignored; residual gas and brine saturations are set to zero; and porosity is set to 0.32 (see materials CONC_PLG, BH_OPEN, BH_SAND and BH_CREEP in Table PA-2). When a borehole that penetrates pressurized brine in the Castile Formation is simulated (i.e., an E1 intrusion), the permeability modifications indicated in Table PA-5 extend from the land surface (i.e., grid cell 2155 in Figure PA-10) to the base of the pressurized brine (i.e., grid cell 2225 in Figure PA-10). When a borehole that does not penetrate pressurized brine in the Castile Formation is under consideration (i.e., an E2 intrusion), the permeability modifications indicated in Table PA-5 stop at the bottom of the lower DRZ (i.e., grid cell 1111 in Figure PA-10).

Table PA-5. Permeabilities for Drilling Intrusions Through the Repository

Time After Intrusion	Assigned Permeabilities
0 - 200 years	Concrete plugs are assumed to be emplaced at the Santa Rosa Formation (i.e., a surface plug with a length of 15.76 m; corresponds to grid cells 2113, 2155 in Figure PA-10) and the Los Medanõs Member of the Rustler Formation (i.e., a plug at top of Salado with a length of 36 m; corresponds to grid cell 1644 in Figure PA-10). Concrete plugs are assumed to have a permeability of $k = 5 \times 10^{-17}$ m^2; open potions of the borehole are assumed to have a permeability of 1×10^{-9} m^2. See material CONC_PLG in Table PA-3.
200 - 1200 years	Concrete plugs are assumed to fail after 200 years (DOE 1995) an entire borehole is assigned a permeability typical of silty sand, i.e., $k = 10^x$ m^2, x = BHPRM, where BHPRM is an uncertain input to the analysis (see Table PA-17). See material BH_SAND in Table PA-3.
> 1200 years	Permeability reduced by one order of magnitude in Salado Formation beneath repository due to creep closure of borehole (Thompson et al. 1996) (i.e., $k = 10^x/10$, x = BHPRM, in grid cells 2225, 1576, 26, 94, 162, 230, 1111, 1119, 1127 of Figure PA-10). No changes are made within and above the lower DRZ. See material BH_CREEP in Table PA-3.

PA-4.2.10 Numerical Solution

Determination of gas and brine flow in the vicinity of the repository requires the numerical solution of the two nonlinear partial differential equations in Equation (42) on the computational domain in Figure PA-8 together with evaluation of appropriate auxiliary conditions (Equation (25f), Equation (25g), and Equation (41)). The actual unknown functions in this solution are p_b and S_g, although the constraint conditions also give rise to values for p_g and S_b. As two dimensions in space and one dimension in time are in use, p_b, p_g, S_b and S_g are functions of the form $p_b(x,y,t)$, $p_g(x,y,t)$, $S_b(x,y,t)$ and $S_g(x,y,t)$.

The solution of Equation (42) requires both initial value and boundary value conditions for p_b and S_g . The initial value conditions for p_b and S_g are given in Section PA.4.2.2. As indicated there, the calculation starts at time t = –5 years, with a possible resetting of values at t = 0 years, which corresponds to final waste emplacement and sealing of the repository. The boundary conditions are such that no brine or gas moves across the exterior grid boundary (Table PA-6). This Neumann-type boundary condition is maintained for all time. Further, BRAGFLO allows the user to specify pressure and/or saturation at any grid block. This feature is used to specify Dirichlet-type conditions at the surface grid blocks (i = 1, 2, …, 68, j = 33, Figure PA-8) and at the far field locations in the Culebra and Magenta Formations (i = 1, 68, j = 26 and i = 1, 68, j = 28, Figure PA-8). These auxiliary conditions are summarized in Table PA-7).

Table PA-6. Boundary Value Conditions for p_g and p_b

Boundaries below (y = 0 m) and above (y = 1039 m) system for 0 ≤ x ≤ 46630 m and –5 yr ≤ t	
$\left(\nabla p_g + \rho_g g \nabla h\right)\Big\|_{(x,y,t)} \cdot j = 0 \ Pa/m$	no gas flow condition
$\left(\nabla p_b + \rho_b g \nabla h\right)\Big\|_{(x,y,t)} \cdot j = 0 \ Pa/m$	no brine flow condition
Boundaries at left (x = 0 m) and right (x = 46630 m) of system for 0 ≤ y ≤ 1039 m and –5 yr ≤ t	
$\left(\nabla p_g + \rho_g g \nabla h\right)\Big\|_{(x,y,t)} \cdot i = 0 \ Pa/m$	no gas flow condition
$\left(\nabla p_b + \rho_b g \nabla h\right)\Big\|_{(x,y,t)} \cdot i = 0 \ Pa/m$	no brine flow condition

Table PA-7. Auxiliary Dirichlet Conditions for p_b and S_g

Surface Grid Blocks	
$S_g(i,j,t)$ = 0.08363	i = 1, 2, …, 68, j = 33, –5 yr ≤ t
$p_b(i,j,t)$ = 1.01×10^5 Pa	i = 1, 2, …, 68, j = 33, –5 yr ≤ t
Culebra and Magenta Far Field	
$p_b(i,26,t)$ = 8.22×10^5 Pa	i = 1 and 68, j = 26, –5 yr ≤ t (Culebra)
$p_b(i,28,t)$ = 9.17×10^5 Pa	i = 1 and 68, j = 28, –5 yr ≤ t (Magenta)

A fully implicit finite difference procedure is used to solve Equation (42). The associated discretization of the gas mass balance equation is given by

$$\frac{1}{\Delta x_i}\left\{\frac{1}{x_{i+1}-x_i}\left[\frac{\alpha\rho_g k_x k_{rg}}{\mu_g}\right]^{n+1}_{i+1/2,j}\left(\Phi^{x-}_{g_{i+1,j}}-\Phi^{x+}_{g_{i,j}}\right)^{n+1}\right.$$

$$\left.-\frac{1}{x_i-x_{i-1}}\left[\frac{\alpha\rho_g k_x k_{rg}}{\mu_g}\right]^{n+1}_{i-1/2,j}\left(\Phi^{x-}_{g_{i,j}}-\Phi^{x+}_{g_{i-1,j}}\right)^{n+1}\right\}$$

$$+\frac{1}{\Delta y_j}\left\{\frac{1}{y_{j+1}-y_j}\left[\frac{\alpha\rho_g k_y k_{rg}}{\mu_g}\right]^{n+1}_{i,j+1/2}\left(\Phi^{y-}_{g_{i,j+1}}-\Phi^{y+}_{g_{i,j}}\right)^{n+1}\right.$$

$$-\frac{1}{y_j - y_{j-1}}\left[\frac{\alpha\rho_g k_y k_{rg}}{\mu_g}\right]_{i,j-1/2}^{n+1}\left(\Phi_{g_{i,j}}^{y-} - \Phi_{g_{i,j-1}}^{y+}\right)^{n+1}\Bigg\}$$

$$+\alpha_{i,j}q_{wg_{i,j}}^{n+1} + \alpha_{i,j}q_{rg_{i,j}}^{n+1} - \frac{\left(\alpha\phi\rho_g S_g\right)_{i,j}^{n+1} - \left(\alpha\phi\rho_g S_g\right)_{i,j}^{n}}{\Delta t} = 0\,, \tag{79}$$

where Φ represents the phase potentials given by

$$\Phi_{gi,j}^{x+} = p_{gi,j} + \rho_{gi+1/2,j}gh_{i,j}, \quad \Phi_{gi,j}^{x-} = p_{gi,j} + \rho_{gi-1/2\,j}gh_{i,j}$$

and

$$\Phi_{gi,j}^{y+} = p_{gi,j} + \rho_{gi,j+1/2}gh_{i,j}, \quad \Phi_{gi,j}^{y-} = p_{gi,j} + \rho_{gi,j-1/2}gh_{i,j}\,,$$

and the subscripts are defined by

i = x-direction grid index

j = y-direction grid index

$i \pm 1/2$ = x-direction grid block interface

$j \pm 1/2$ = y-direction grid block interface

x_i = grid block center in the x-coordinate direction (m)

y_j = grid block center in the y-coordinate direction (m)

Δx_i = grid block length in the x-coordinate direction (m)

Δy_j = grid block length in the y-coordinate direction (m),

the superscripts are defined by

n= index in the time discretization, known solution time level

n+1= index in the time discretization, unknown solution time level,

and the interblock densities are defined by

$$\rho_{gi+1/2,j} = \frac{\Delta x_{i+1,j}}{\Delta x_{i,j} + \Delta x_{i+1,j}}\rho_{gi,j} + \frac{\Delta x_{i,j}}{\Delta x_{i,j} + \Delta x_{i+1,j}}\rho_{gi+1,j}\,,$$

$$\rho_{gi-1/2,j} = \frac{\Delta x_{i,j}}{\Delta x_{i-1,j} + \Delta x_{i,j}} \rho_{g,i-1,j} + \frac{\Delta x_{i-1,j}}{\Delta x_{i-1,j} + \Delta x_{i,j}} \rho_{gi,j} ,$$

$$\rho_{gi,j+1/2} = \frac{\Delta y_{i,j+1}}{\Delta y_{i,j} + \Delta y_{i,j+1}} \rho_{gi,j} + \frac{\Delta y_{i,j}}{\Delta y_{i,j} + \Delta y_{i,j+1}} \rho_{gi,j+1} ,$$

$$\rho_{gi,j-1/2} = \frac{\Delta y_{i,j}}{\Delta y_{i,j-1} + \Delta y_{i,j}} \rho_{gi,j-1} + \frac{\Delta y_{i,j-1}}{\Delta y_{i,j-1} + \Delta y_{i,j}} \rho_{gi,j} .$$

The interface values of k_{rg} in Equation (79) are evaluated using upstream weighted values (i.e., the relative permeabilities at each grid block interface are defined to be the relative permeabilities at the center of the adjacent grid block that has the highest potential). Further, interface values for $\alpha \rho_g k_x / \mu_g$ and $\alpha \rho_g k_y / \mu_g$ are obtained by harmonic averaging of adjacent grid block values for these expressions.

The discretization of the brine mass balance equation is obtained by replacing the subscript for gas, g, by the subscript for brine, b. As a reminder, p_g and S_b are replaced in the numerical implementation with the substitutions indicated by Equation (25d) and Equation (25c), respectively. For the CRA-2004 PA, wells are not used in the conceptual model. Thus, the terms q_{wg} and q_{wb} are zero. For this analysis, the wellbore is not treated by a well model, but rather is explicitly modeled within the grid as a distinct material region (i.e., Upper Borehole and Lower Borehole in Figure PA-8).

The resultant coupled system of nonlinear brine and gas mass balance equations is integrated in time using the Newton-Raphson method with upstream weighting of the relative permeabilities as previously indicated. The primary unknowns at each computational cell center are brine pressure and gas saturation.

PA-4.2.11 Gas and Brine Flow across Specified Boundaries

The Darcy velocity vectors $\mathbf{v}_g(x, y, t)$ and $\mathbf{v}_b(x, y, t)$ for gas and brine flow ($(m^3/m^2)/s = m/s$) are defined by the expressions

$$\mathbf{v}_g(x,y,t) = \mathbf{K}_g k_{rg} \left(\nabla p_g + \rho_g g \nabla h \right) / \mu_g \tag{80}$$

and

$$\mathbf{v}_b(x,y,t) = \mathbf{K}_b k_{rb} \left(\nabla p_b + \rho_b g \nabla h \right) / \mu_b . \tag{81}$$

Values for $\mathbf{v}_g$ and $\mathbf{v}_b$ are obtained and saved as the numerical solution of Equation (42) is carried out. Cumulative flows of gas, $C_g(t,\mathcal{B})$, and brine, $C_b(t,\mathcal{B})$, from time 0 to time t across an arbitrary boundary $\mathcal{B}$ in the domain of (Figure PA-8) is then given by

$$C_l(t,\mathcal{B}) = \int_0^t \left[\int_{\mathcal{B}} \alpha(x,y)\, \mathbf{v}_l(x,y,t) \cdot \mathbf{n}(x,y)\, ds \right] dt \tag{82}$$

for l = g, b, where $\alpha(x,y)$ is the geometry factor defined in Figure PA-9, $\mathbf{n}(x,y)$ is an outward pointing unit normal vector, and $\int_{\mathcal{B}} ds$ denotes a line integral. As an example, $\mathcal{B}$ could correspond to the boundary of the waste disposal regions in Figure PA-8. The integrals defining $C_g(t,\mathcal{B})$ and $C_b(t,\mathcal{B})$ are evaluated using the Darcy velocities defined by Equation (80) and Equation (81). Due to the dependence of gas volume on pressure, $C_g(t,\mathcal{B})$ is typically calculated in moles or in m^3 at standard temperature and pressure, which requires an appropriate change of units for $\mathbf{v}_g$ in Equation (82).

PA-4.2.12 Additional Information

Additional information on BRAGFLO and its use in the CRA-2004 PA can be found in the BRAGFLO User's Manual (WIPP PA 2003c) and in the analysis package for the Salado flow calculations for the CRA-2004 PA (Stein and Zelinski 2003b).

PA-4.3 Radionuclide Transport in the Salado: NUTS

This section describes the model used to compute transport of radionuclides in the Salado for E0, E1 and E2 scenarios (defined in Section 6.3). The model for transport in the E1E2 scenario is described in Section PA-4.4.

PA-4.3.1 Mathematical Description

The following system of partial differential equations is used to model radionuclide transport in the Salado:

$$-\nabla \cdot \alpha \mathbf{v}_b C_{bl} + \alpha S_l = \alpha \frac{\partial}{\partial t}\left(\phi S_b C_{bl}\right) + \left(\alpha \phi S_b C_{bl}\right)\lambda_l - \alpha \phi S_b \sum_{p \in P(l)} C_{bp}\lambda_p \tag{83a}$$

$$-S_l = \frac{\partial}{\partial t}\left(C_{sl}\right) + C_{sl}\lambda_l - \sum_{p \in P(l)} C_{sp}\lambda_p \tag{83b}$$

for l = 1, 2, …, nR, where

$\mathbf{v}_b$ = Darcy velocity vector ((m^3/m^2)/s = m/s) for brine (supplied by BRAGFLO from solution of Equation (81)),

C_{bl} = concentration (kg/m^3) of radionuclide l in brine,

C_{sl} = concentration (kg/m^3) of radionuclide l in solid phase (i.e., not in brine), with concentration defined with respect to total (i.e., bulk) formation volume (only used in repository; see Figure PA-8),

S_l = linkage term ((kg/m^3)/s) due to dissolution/precipitation between radionuclide l in brine and in solid phase (see Equation (84)),

ϕ = porosity (supplied by BRAGFLO from solution of Equation (25)),

S_b = brine saturation (supplied by BRAGFLO from solution of Equations (25)),

λ_l = decay constant (s^{-1}) for radionuclide l,

$P(l)$ = {p: radionuclide p is a parent of radionuclide l},

nR = number of radionuclides,

and α is the dimension dependent geometry factor in Equation (26). The CRA-2004 PA uses a two-dimensional representation for fluid flow and radionuclide transport in the vicinity of the repository with α defined by the element depths in Figure PA-8 . Although omitted from the notation for brevity, the terms α, $\boldsymbol{v_b}$, C_{bl}, C_{sl}, S_l, ϕ and S_b are functions $\boldsymbol{\alpha(x,y)}$, $\boldsymbol{v_b(x,y,t)}$, $\boldsymbol{C_{bl}(x,y,t)}$, $\boldsymbol{C_{sl}(x,y,t)}$, $\boldsymbol{S_l(x,y,t)}$, $\boldsymbol{\phi(x,y,t)}$, and $\boldsymbol{S_b(x,y,t)}$ of time t and the spatial variables x, y. Equation (83) is defined and solved on the same computational grid used with BRAGFLO for the solution of Equation (25) (Figure PA-8).

Radionuclides are assumed to be present in both brine (Equation (83a)) and in an immobile solid phase (Equation (83b)). Radionuclide transport takes place only by brine flow (Equation (83a)). A maximum radionuclide concentration in brine is assumed for each element (Section PA-4.3.2). Then, each individual radionuclide equilibrates between the brine and solid phases on the basis of the maximum concentration of its associated element and the mole fractions of other isotopes of this element that are included in the calculation. The linkage between the brine and solid phases in Equation (83) accomplished by the term S_l, where

$$\boldsymbol{S_l} = \begin{cases} \boldsymbol{\delta(\tau - t)\, Dif\left(S_T, C_{b,El(l)}\right) MF_{sl}} & \boldsymbol{if\ \ 0 \le Dif\left(S_T, C_{b,El(l)}\right) \le C_{s,El(l)} / (\phi S_b),\ 0 < S_b} \\ \boldsymbol{\delta(\tau - t)\left[C_{s,El(l)} / (\phi S_b)\right] MF_{sl}} & \boldsymbol{if\ \ 0 \le C_{s,El(l)} / (\phi S_b) < Dif\left(S_T, C_{b,El(l)}\right),\ 0 < S_b} \\ \boldsymbol{\delta(\tau - t)\, Dif\left(S_T, C_{b,El(l)}\right) MF_{bl}} & \boldsymbol{if\ \ Dif\left(S_T, C_{b,El(l)}\right) < 0,\ 0 < S_b} \\ \boldsymbol{0} & \boldsymbol{otherwise} \end{cases} \quad (84)$$

with

$S_T\left[Br(t), Ox(l), Mi, El(l)\right]$ = maximum concentration (kg/m^3) of element $El(l)$ in oxidation state $Ox(l)$ in brine type $Br(t)$, where $El(l)$ denotes the element of which radionuclide l is an isotope, $Ox(l)$ denotes the oxidation state in which element $El(l)$ is present, Mi indicates whether microbial activity is present, and $Br(t)$ denotes the type of brine present in the repository at time t (see Section PA-4.3.2 for definition of $S_T\left(Br, Ox, Mi, El\right)$.

$C_{p,El(l)}$ = concentration (kg/m^3) of element $El(l)$ in brine (p = b) or solid (p = s) (i.e., sum of concentrations of radionuclides that are isotopes of same element as radionuclide l, where $k \in El(l)$ only if k is an isotope of element $El(l)$)

$$= \sum_{k \in El(l)} C_{pk} \tag{85}$$

$Dif\left(S_T, C_{b,El(l)}\right)$ = difference (kg/m^3) between maximum concentration of element $El(l)$ in brine and existing concentration of element $El(l)$ in brine

$$= S_T\left[Br(t), Ox(l), Mi, El(l)\right] - C_{b,El(l)} \tag{86}$$

MF_{pl} = mole fraction of radionuclide l in phase p, where p = b ~ brine and p = s ~ solids

$$= C_{pl}CM_l \Big/ \sum_{k \in El(l)} C_{pk}CM_k \tag{87}$$

CM_l = conversion factor (mole/kg) from kilograms to moles for radionuclide l

$\delta(\tau - t)$ = Dirac delta function (s^{-1})(i.e., $\delta(\tau - t) = 0 \;\; if \;\; \tau \neq t \;\; and \;\; \int_{-\infty}^{\infty} \delta(\tau - t)\, d\tau = 1$).

Although omitted for brevity, the terms S_l, $C_{p,El(l)}$, MF_{pl}, ϕ and S_b are functions of time t and spatial variables x, y. The Dirac delta function, $\delta(t - \tau)$, appears in Equation (84) to indicate that the adjustments to concentration are implemented instantaneously within the numerical solution of Equation (83) whenever a concentration imbalance is observed.

The velocity vector v_b in Equation (83) is defined in Equation (81) and is obtained from the numerical solution of Equation (25). If $\mathcal{B}$ denotes an arbitrary boundary (e.g., the land withdrawal boundary) in the domain of Equation (83) (i.e., Figure PA-8), then the cumulative transport of $C_l(t, \mathcal{B})$ of radionuclide l from time 0 to time t across $\mathcal{B}$ is given by

$$C_l(t,\mathcal{B}) = \int_0^t \left[\int_{\mathcal{B}} \mathbf{v}_b(x,y,t) C_l(x,y,t) \alpha(x,y) \cdot \mathbf{n}(x,y) ds \right] dt \ , \tag{88}$$

where $\mathbf{n}(x,y)$ is an outward pointing unit normal vector and $\int_{\mathcal{B}} ds$ denotes a line integral over $\mathcal{B}$.

Equation (83) models advective radionuclide transport due to the velocity vector $\mathbf{v}_b$. Although the effects of solubility limits are considered, no chemical or physical retardation is included in the model. Also, molecular diffusion is not included in the model, with this omission having little effect as the radionuclides under consideration have molecular diffusion coefficients on the order of 10^{-10} m^2/s and thus can be expected to move approximately 10 m over 10,000 years due to molecular diffusion. Mechanical dispersion is also not included, with this omission having little effect on the final results due to the uniform initial radionuclide concentrations assumed within the repository and the use of time-integrated releases in assessing compliance with 40 CFR § 191.13.

PA-4.3.2 Calculation of Maximum Concentration $S_T(Br,Ox,Mi,El)$

A maximum concentration $S_T(Br,Ox,Mi,El)$ S_T(Br, Ox, Mi, El) (mol/l) is calculated for each brine type (Br ~ Salado, Castile), oxidation state (Ox ~ +3, +4, +5, +6), presence of microbial action (present or not) and element (El ~ Am, Pu, U, and Th). The maximum concentration is given by

$$S_T(Br,Ox,Mi,El) = S_D(Br,Ox,Mi,El) + S_C(Br,Ox,Mi,El), \tag{89}$$

where $S_D(Br,Ox,Mi,El)$ is the dissolved solubility (mol/l) and $S_C(Br,Ox,Mi,El)$ is the concentration (mol/l) of the element sorbed to colloids.

The dissolved solubility $S_D(Br,Ox,Mi,El)$ is given by

$$S_D(Br,Ox,Mi,El) = S_{FMT}(Br,Ox,Mi) \times 10^{UF(Br,Ox,El)} \tag{90}$$

where

$S_{FMT}(Br,Ox,Mi)$ = dissolved solubility (mol/l) calculated by FMT model (WIPP PA 1998a) for brine type Br, oxidation state Ox, and presence of microbial action Mi,

$UF(Br,Ox,El)$ = logarithm (base 10) of uncertainty factor for solubilities calculated by FMT expressed as a function of brine type Br, oxidation state Ox and element El.

Table PA-8 lists the calculated values of $S_{FMT}(Br,Ox,Mi)$; details of the calculation are provided in Attachment SOTERM. The values of Mi are determined by the uncertain parameter

WMICDFLG; see Table PA-17. The uncertainty factors $UF(Br, Ox, El)$ are determined by the uncertain parameters listed in Table PA-9; definition of each uncertain parameter is provided in Table PA-17.

Table PA-8. Calculated Values for Dissolved Solubility

Brine/Microbial action	Oxidation State			
	+3	+4	+5	+6
Salado/No microbial gas generation	3.07×10^{-7}	1.24×10^{-8}	9.72×10^{-7}	8.7×10^{-6}
Castile/No microbial gas generation	1.77×10^{-7}	5.84×10^{-9}	2.13×10^{-5}	8.8×10^{-6}
Salado/With microbial gas generation	3.07×10^{-7}	1.19×10^{-8}	1.02×10^{-6}	8.7×10^{-6}
Castile/With microbial gas generation	1.69×10^{-7}	2.47×10^{-8}	5.08×10^{-6}	8.8×10^{-6}

Table PA-9. Uncertainty Factors for Dissolved Solubility

Brine	Oxidation State, Element					
	+3, Am	+3, Pu	+4, Pu	+4, U	+6, U	+4, Th
Salado	WSOLAM3S	WSOLPU3S	WSOLPU4S	WSOLU4S	WSOLU6S	WSOLTH4S
Castile	WSOLAM3C	WSOLPU3C	WSOLPU4C	WSOLU4C	WSOLU6C	WSOLTH4C

The concentration (mol/l) of the element sorbed to colloids $S_C(Br, Ox, Mi, El)$ is given by

$$S_C(Br, Ox, Mi, El) = S_{Hum}(Br, Ox, Mi, El) + S_{Mic}(Br, Ox, Mi, El) + S_{Act}(El) + S_{Mn}, \quad (91)$$

where

$S_{Hum}(Br, Ox, Mi, El)$ = solubility (i.e., concentration expressed in mol/l) in brine type Br of element El in oxidation state Ox with or without microbial action (Mi) resulting from formation of humic colloids

$$= \min\left\{SF_{Hum}(Br, Ox, El) \times S_D(Br, Ox, Mi, El), UB_{Hum}\right\}$$

$SF_{Hum}(Br, Ox, El)$ = scale factor used as a multiplier on $S_D(Br, Ox, Mi, El)$ in definition of $S_{Hum}(Br, Ox, Mi, El)$ (see Table PA-10),

Table PA-10. Scale Factor $SF_{Hum}(Br, Ox, El)$ Used in Definition of $S_{Hum}(Br, Ox, Mi, El)$

Brine	Oxidation state, Element					
	+3, Am	+3, Pu	+4, Pu	+4, U	+6, U	+4, Th
Salado	0.19	0.19	6.3	6.3	0.12	6.3
Castile	WPHUMOX3[1]	WPHUMOX3[1]	6.3	6.3	0.51	6.3

[1] See Table PA-17.

UB_{Hum} = upper bound on solubility (i.e., concentration expressed in mol/l) of individual actinide elements resulting from formation of humic colloids

= 1.1×10^{-5} mol/l,

$S_{Mic}(Br, Ox, Mi, El)$ = solubility (i.e., concentration expressed in mol/l) in brine type Br of element El in oxidation state Ox with or without microbial action (Mi) resulting from formation of microbial colloids

$$= \min\left\{SF_{Mic}(Ox, Mi, El) \times S_D(Br, Ox, Mi, El), UB_{Mic}(Ox, El)\right\},$$

$SF_{Mic}(Ox, Mi, El)$ = scale factor used as multiplier on $S_D(Br, Ox, Mi, El)$ in definition of $S_{Mic}(Br, Ox, Mi, El)$ (see Table PA-11),

$UB_{Mic}(Ox, El)$ = upper bound on solubility (i.e., concentration expressed in mol/l) of element El in oxidation state Ox resulting from formation of microbial colloids (see Table PA-11),

Table PA-11. Scale Factor $SF_{Mic}(Ox, Mi, El)$ and Upper Bound $UB_{Mic}(Ox, Mi, El)$ (mol/l) Used in Definition of $S_{Mic}(Br, Ox, Mi, El)$

	Oxidation state, Element					
	+3, Am	+3, Pu	+4, Pu	+4, U	+6, U	+4, Th
No Microbial Action						
$SF_{Mic}(Ox, Mi, El)$	0.0	0.0	0.0	0.0	0.0	0.0
$UB_{Mic}(Ox, Mi, El)$	0.0	0.0	0.0	0.0	0.0	0.0
Microbial Action						
$SF_{Mic}(Ox, Mi, El)$	3.6	0.3	0.3	2.1×10^{-3}	2.1×10^{-3}	3.1
$UB_{Mic}(Ox, Mi, El)$	1	6.8×10^{-5}	6.8×10^{-5}	2.1×10^{-3}	2.1×10^{-3}	1.9×10^{-3}

$S_{Act}(El)$ = solubility (i.e., concentration expressed in mol/l) of element El resulting from formation of actinide intrinsic colloids

$$= \begin{cases} 1 \times 10^{-9} \text{ mol/l} & \text{if } El = \text{plutonium} \\ 0 \text{ mol/l} & \text{otherwise} \end{cases},$$

S_{Mn} = solubility (i.e., concentration expressed in mol/l) of individual actinide element resulting from formation of mineral fragment colloids

= 2.6 × 10–8 mol/l.

PA-4.3.3 Radionuclides Transported

Appendix TRU WASTE (Table TRU WASTE-9) lists the radionuclides included in the transport calculations. With the exceptions of ^{137}Cs, ^{147}Pm, and ^{90}Sr, the radionuclides in Table TRU WASTE-9 belong to the following decay chains:

$$^{242}U \rightarrow \begin{matrix} ^{238}Pu \\ \Downarrow \\ ^{238}U \end{matrix} \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \tag{92a}$$

$$\begin{matrix} ^{243}Cm \\ \Downarrow \\ ^{243}Am \end{matrix} \rightarrow {}^{239}Pu \rightarrow {}^{235}U \rightarrow {}^{231}Pa \tag{92b}$$

$$^{252}Cf \rightarrow {}^{248}Cm \rightarrow {}^{244}Pu \rightarrow {}^{240}Pu \rightarrow {}^{236}U \rightarrow {}^{232}Th \rightarrow {}^{228}Ra \tag{92c}$$

$$^{245}Cm \rightarrow {}^{241}Pu \rightarrow {}^{241}Am \rightarrow {}^{237}Np \rightarrow {}^{233}U \rightarrow {}^{229}Th\,. \tag{92d}$$

Since the solution of Equation (83) for this many radionuclides and decay chains would be very time-consuming, the number of radionuclides for direct inclusion in the analysis was reduced using the algorithm shown in Appendix TRU WASTE (Figure TRU WASTE-5); the rationale for each radionuclide excluded from transport is presented in Table TRU WASTE-10. The CRA-2004 PA uses the same reduction algorithm as was used in the CCA PA (see CCA Appendix WCA); the algorithm was found to be acceptable in the review of the CCA (EPA 1998, Section 4.6.1.1).

After the reduction of radionuclides summarized in Table TRU WASTE-10, the following 10 radionuclides remained from the decay chains shown above:

$$^{242}Pu \text{ and } {}^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \tag{93a}$$

$$^{239}Pu \tag{93b}$$

$$^{240}Pu \tag{93b}$$

$$^{241}Pu \rightarrow {}^{241}Am \rightarrow {}^{233}U \rightarrow {}^{229}Th\,. \tag{93d}$$

Next, ^{238}Pu was eliminated from transport calculations due to its short half-life (87.8 years). The remaining nine radionuclides were then further reduced by combining radionuclides that have similar decay and transport properties. In particular, ^{234}U, ^{230}Th, and ^{239}Pu were used as surrogates for the groups {^{234}U, ^{233}U}, {^{230}Th, ^{229}Th}, and {^{242}Pu, ^{239}Pu, ^{240}Pu}, with the initial inventories of ^{234}U, ^{230}Th and ^{239}Pu being redefined to account for the additional radionuclide(s) in each group. In redefining the initial inventories, the individual radionuclides were combined on either a mole or curie basis (i.e., moles added and then converted back to curies or curies added directly). In each case, the method that maximized the combined inventory was used, i.e.: ^{233}U was added to ^{234}U by curies; ^{240}Pu was added to ^{239}Pu by curies; ^{242}Pu was added to ^{239}Pu by moles; and ^{229}Th was added to ^{230}Th by curies. In addition, ^{241}Pu was added to ^{241}Am by moles because ^{241}Pu has a half life of 14 years and will quickly decay to ^{241}Am, and neglect of this ingrowth would underestimate the ^{241}Am inventory by about four percent (Table PA-12). The outcome of this process was the following five radionuclides and three simplified decay chains:

$$^{241}Am, \quad ^{238}Pu \rightarrow {}^{234}U \rightarrow {}^{230}Th, \quad ^{239}Pu, \tag{94}$$

which were then used with Equation (83) for transport in the vicinity of the repository and also for transport in the Culebra Dolomite (Section PA-4.9). These radionuclides account for 99 percent of the EPA units in the waste after 2,000 years (Appendix TRU WASTE, Table TRU WASTE-9), and hence will dominate any releases by transport.

Table PA-12. Combination of Radionuclides for Transport

Combination	Isotope Initial Values	Combination Procedure	Combined Inventory
$^{233}U \rightarrow {}^{234}U$	1.27×10^3 Ci ^{233}U 3.19×10^2 Ci ^{234}U	1.27×10^3 Ci ^{233}U $\rightarrow 1.27 \times 10^3$ Ci ^{234}U	1.59×10^3 Ci ^{234}U
$^{242}Pu \rightarrow {}^{239}Pu$ $^{240}Pu \rightarrow {}^{239}Pu$	2.71×10^1 Ci ^{242}Pu 1.08×10^5 Ci ^{240}Pu 6.65×10^5 Ci ^{239}Pu	2.71×10^1 Ci ^{242}Pu $= 2.82 \times 10^1$ moles ^{242}Pu $\rightarrow 2.82 \times 10^1$ moles ^{239}Pu $= 4.24 \times 10^2$ Ci ^{239}Pu 1.08×10^5 Ci ^{240}Pu $\rightarrow 1.08 \times 10^5$ Ci ^{239}Pu	7.73×10^5 Ci ^{239}Pu
$^{229}Th \rightarrow {}^{230}Th$	5.39×10^0 Ci ^{229}Th 1.76×10^{-1} Ci ^{230}Th	5.39×10^0 Ci ^{229}Th $\rightarrow 5.39 \times 10^0$ Ci ^{230}Th	5.57×10^0 Ci ^{230}Th
$^{241}Pu \rightarrow {}^{241}Am$	5.38×10^5 Ci ^{241}Pu 4.58×10^5 Ci ^{241}Am	5.38×10^5 Ci ^{241}Pu $= 2.15 \times 10^1$ moles ^{241}Pu $\rightarrow 2.15 \times 10^1$ moles ^{241}Am $= 1.80 \times 10^4$ Ci ^{241}Am	4.60×10^5 Ci ^{241}Am

PA-4.3.4 Numerical Solution

Equation (83) is numerically solved by the NUTS program (WIPP PA 1997a) on the same computational grid (Figure PA-8) used by BRAGFLO in the solution of Equation (25). In the solution procedure, Equation (83a) is numerically solved with $S_l = 0$ for each time step, with the instantaneous updating of concentrations indicated in Equation (84) and the appropriate modification to C_{sl} in Equation (83b) taking place after the time step. The solution is carried out for the five radionuclides indicated in Equation (94).

The initial value and boundary value conditions used with Equation (83) are given in Table PA-13. At time t = 0 (i.e., year 2033), the total inventory of each radionuclide is assumed to be in brine; the solubility constraints associated with Equation (84) then immediately adjust the values for $C_{bl}(x, y, t)$ and $C_{sl}(x, y, t)$ for consistency with the constraints imposed by $S_T\,[Br(t), Ox(l), Mi, El(l)]$ and available radionuclide inventory.

Table PA-13. Initial and Boundary Conditions for $C_{bl}(x, y, t)$ and $C_{sl}(x, y, t)$

Initial Conditions for $C_{bl}(x, y, t)$ and $C_{sl}(x, y, t)$	
$C_{bl}(x, y, t)$	= $A_l(0)/V_b(0)$ if x, y is a point in the repository (i.e., areas Waste Panel, South RoR and North RoR, in Figure PA-8), where $A_l(0)$ is the amount (kg) of radionuclide l present at time t = 0 (Table PA-12) and $V_b(0)$ is the amount (m^3) of brine in repository at time t = 0 (from solution of Equation (25) with BRAGFLO) for all x, y.
	= 0 otherwise.
$C_{sl}(x, y, t)$	= 0 if x, y is a point in the repository.
Boundary Conditions for $C_{bl}(x, y, t)$	
$f_l(\mathcal{B}, t)$	= $\int_{\mathcal{B}} v_b(x, y, t)\, C_{bl}(x, y, t)\, \alpha(x, y)\, n(x, y)\, ds$, where $\mathcal{B}$ is any subset of the outer boundary of the computational grid in Figure PA-8, $f_l(\mathcal{B}, t)$ is the flux (kg/s) at time t of radionuclide l across $\mathcal{B}$, $v_b(x, y, t)$ is the Darcy velocity ((m^3/m^2)/s) of brine at (x, y) on $\mathcal{B}$ and is obtained from the solution of Equation (25) by BRAGFLO, $n(x, y)$ denotes an outward-pointing unit normal vector, and $\int_{\mathcal{B}} ds$ denotes a line integral along $\mathcal{B}$.

The nR partial differential equations in Equation (83a) are discretized in two dimensions and then developed into a linear system of algebraic equations for numerical implementation. The following conventions are used in the representation of each discretized equation:

- the subscript b is dropped from C_{bl}, with the result that the unknown function is represented by C_l,

- a superscript n denotes time (t_n), with the assumption that the solution C_l is known at time t_n and is to be advanced (i.e., computed) at time t_{n+1},

- the grid indices are i in the x-direction, j in the y-direction, and are identical with the BRAGFLO grid indices; fractional indices refer to quantities evaluated at grid block interfaces, and

- each time step by NUTS is equal to 20 BRAGFLO time steps, which results because BRAGFLO reported (i.e., stored) results (i.e., $\boldsymbol{v}_b$, ϕ, S_b) every 20 time steps.

The following finite difference discretization is used for the lth equation in each grid block i, j:

$$q_{b,i+1/2,j}^{n+1} C_{l,i+1/2,j}^{n+1} - q_{b,i-1/2,j}^{n+1} C_{l,i-1/2,j}^{n+1} + q_{b,i,j+1/2}^{n+1} C_{l,i,j+1/2}^{n+1} - q_{b,i,j-1/2}^{n+1} C_{l,i,j-1/2}^{n+1} =$$

$$\frac{V_{R,i,j}}{\Delta t}\left[\left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n+1} - \left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n}\right] \qquad (95)$$

$$+ V_{R,i,j}\left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n+1} \lambda_l - V_{R,i,j}\left(\phi_{i,j} S_{b_{i,j}}\right)^{n+1} \sum_{p \in P(l)} C_{p,i,j}^{n+1} \lambda_p$$

where q_b is the grid block interfacial brine flow rate (m^3/s) and V_R is the grid block volume (m^3). The quantity q_b is based on $\boldsymbol{v}_b$ and α in Equation (83a), and the quantity V_R is based on grid block dimensions (Figure PA-8) and α .

The interfacial values of concentration in Equation (95) are discretized using the one-point upstream weighting method (Aziz and Settari 1979), which results in

$$q_{b,i+1/2,j}^{n+1}\left(\omega_{i+1} C_{l,i,j}^{n+1} + \left(1-\omega_{i+1}\right) C_{l,i+1,j}^{n+1}\right) - q_{b,i-1/2,j}^{n+1}\left(\omega_i C_{l,i-1,j}^{n+1} + \left(1-\omega_i\right) C_{l,i,j}^{n+1}\right)$$
$$+ q_{b,i,j+1/2}^{n+1}\left(\omega_{j+1} C_{l,i,j}^{n+1} + \left(1-\omega_{j+1}\right) C_{l,i,j+1}^{n+1}\right) - q_{b,i,j-1/2}^{n+1}\left(\omega_j C_{b,i,j-1}^{n+1} + \left(1-\omega_j\right) C_{l,i,j}^{n+1}\right) =$$

$$\frac{V_{R,i,j}}{\Delta t}\left[\left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n+1} - \left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n}\right] + V_{R,i,j}\left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n+1} \lambda_l \qquad (96)$$

$$- V_{R,i,j}\left(\phi_{i,j} S_{b_{i,j}}\right)^{n+1} \sum_{p \in P(l)} C_{p,i,j}^{n+1} \lambda_p$$

where ω derives from the upstream weighting for flow between adjacent grid blocks and is defined by

$$\omega_i = \begin{cases} 1 & \textit{if flow is from grid block } i-1, j \textit{ to grid block } i, j \\ 0 & \textit{otherwise} \end{cases}$$

$$\omega_j = \begin{cases} 1 & \textit{if flow is from grid block } i, j-1 \textit{ to grid block } i, j \\ 0 & \textit{otherwise.} \end{cases}$$

By collecting similar terms, Equation (96) can be represented by the linear equation

$$AC_{l,i,j-1}^{n+1} + BC_{l,i-1,j}^{n+1} - j + DC_{l,i,j}^{n+1} + EC_{l,i+1,j}^{n+1} + FC_{l,i,j+1}^{n+1} = R_{l,i,j}, \tag{97}$$

where

$$A = -\omega_j q_{b,i,j-1/2}^{n+1} \qquad B = -\omega_j q_{b,i-1/2,j}^{n+1}$$
$$E = \left(1-\omega_{i+1}\right) q_{b,i+1/2,j}^{n+1} \qquad F = \left(1-\omega_{j+1}\right) q_{b,i,j+1/2}^{n+1}$$

$$D = -\left(1-\omega_j\right) q_{b,i,j-1/2}^{n+1} - \left(1-\omega_i\right) q_{b,i-1/2,j}^{n+1} + \omega_{j+1} q_{b,i,j+1/2}^{n+1} + \omega_{i+1} q_{b,i+1/2,j}^{n+1}$$
$$-\left(\frac{V_{R,i,j}}{\Delta t} - V_{R,i,j}\lambda_l\right)\left\{\phi_{i,j} S_{b_{i,j}}\right\}^{n+1}$$

$$R_{l,i,j} = -\frac{V_{R,i,j}}{\Delta t}\left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n} - V_{R,i,j}\left(\phi_{i,j} S_{b_{i,j}}\right)^{n+1} \sum_{p \in P(l)} C_{p,i,j}^{n+1} \lambda_p \, .$$

Given the form of Equation (97), the solution of Equation (83a) has now been reduced to the solution of nR × nG linear algebraic equations in nR × nG unknowns, where nR is the number of equations for each grid block (i.e., the number of radionuclides) and nG is the number of grid blocks into which the spatial domain is discretized (Figure PA-8).

The system of partial differential equations in Equation (83a) is strongly coupled because of the contribution from parental decay to the equation governing the immediate daughter. Consequently, a sequential method is used to solve the system in which radionuclide concentrations are solved for by starting at the top of a decay chain and working down from parent to daughter. This implies that when solving Equation (97) for the lth isotope concentration, all parent concentrations occurring in the right hand side term R are known. The resulting system of equations is then linear in the concentrations of the lth isotope. As a result, solution of Equation (83a) is reduced from the solution of one algebraic equation at each time step with nR × nG unknowns to the solution of nR algebraic equations each with nG unknowns at each time step, which can result in a significant computational savings.

The matrix resulting from one-point upstream weighting has the following structural form for a 3 × 3 system of grid blocks and a similar structure for a larger number of grid blocks:

	1	2	3	4	5	6	7	8	9
1	X	X	0	X					
2	X	X	X	0	X				
3	0	X	X	0	0	X			
4	X	0	0	X	X	0	X		
5		X	0	X	X	X	0	X	
6			X	0	X	X	0	0	X
7				X	0	0	X	X	0
8					X	0	X	X	X
9						X	0	X	X

,

where X designates possible nonzero matrix entries, and 0 designates zero entries. Entries outside of the banded structure are zero. Because of this structure, a banded direct elimination solver (Aziz and Settari 1979, Section 8.2.1) is used to solve the linear system for each radionuclide. The bandwidth is minimized by indexing equations first in the coordinate direction having the minimum number of grid blocks. The coefficient matrix is stored in this banded structure and all infill coefficients calculated during the elimination procedure are contained within the band structure. Therefore, for the matrix system in two dimensions, a pentadiagonal matrix of dimension IBW × nG is inverted instead of a full nG × nG matrix, where IBW is the band width.

The numerical implementation of Equation (83b) enters the solution process through an updating of the radionuclide concentrations in Equation (96) between each time step as indicated in Equation (84). The numerical solution of Equation (83) also generates the concentrations required for the numerical evaluation of the integral that defines $C_l(t,B)$ in Equation (88).

PA-4.3.5 Additional Information

Additional information on NUTS and its use in WIPP PA can be found in the NUTS users manual (WIPP PA 1997a) and in the analysis package for Salado transport calculations for the CRA-2004 PA (Lowry 2003). Furthermore, additional information on dissolved and colloidal actinides is given in Attachment SOTERM.

PA-4.4 Radionuclide Transport in the Salado: PANEL

This section describes the model used to compute transport of radionuclides in the Salado for E1E2 scenario. The model for transport in E0, E1, and E2 scenarios is described in Section PA-4.3.

PA-4.4.1 Mathematical Description

A relatively simple mixed-cell model is used for radionuclide transport in the vicinity of the repository when connecting flow between two drilling intrusions into the same waste panel is assumed to take place (i.e., an E1E2 intrusion). With this model, the amount of radionuclide l contained in a waste panel is represented by

$$\frac{dA_l}{dt} = -r_b C_{bl} - \lambda_l A_l + \sum_{p \in P(l)} \lambda_p A_p \,, \tag{98}$$

where

$A_l(t)$ = amount (mol) of radionuclide l in waste panel at time t,

$C_{bl}(t)$ = concentration (mol/m^3) of radionuclide l in brine in waste panel at time t (Equation (99)),

$r_b(t)$ = rate (m^3/s) at which brine flows out of the repository at time t (supplied by BRAGFLO from solution of Equation (81), and λ_l and $P(l)$ are defined in conjunction with Equation (84).

The brine concentration C_{bl} in Equation (98) is defined by

$$C_{bl}(t) = S_T\left[Br(t), Ox(l), Mi, El(l)\right] MF_l(t) \quad \text{if} \quad S_T\left[Br(t), Ox(l), Mi, El(l)\right] \le \sum_{k \in El(l)} A_k(t)/V_b(t) \tag{99a}$$

$$= A_l(t)/V_b(t) \quad \text{if} \quad \sum_{k \in El(l)} A_k(t)/V_b(t) < S_T\left[Br(l), Ox(l), Mi, El(l)\right], \tag{99b}$$

where

$MF_l(t)$ = mole fraction of radionuclide l in waste panel at time t

$$= \frac{A_l(t)}{\sum_{k \in El(l)} A_k(t)} \tag{100}$$

$V_b(t)$ = volume (m^3) of brine in waste panel at time t (supplied by BRAGFLO from solution of Equation (25)), and $S_T\left[Br(l), Ox(l), Mi, El(l)\right]$ and $E(l)$ are by Equation (89).

For use in Equation (99), $S_T\left[Br(l), Ox(l), Mi, El(l)\right]$ must be expressed in units of mol/l. In words, $C_{bl}(t)$ is defined to be the maximum concentration (S_T in Equation (89)) if there is sufficient radionuclide inventory in the waste panel to generate this concentration (Equation (99a)); otherwise, $C_{bl}(t)$ is defined by the concentration that results when all the relevant element in the waste panel is placed in solution (Equation (99b)).

Given r_b and C_{bl}, evaluation of the integral

$$v_i(x,y) = \left[u_i(x,y), v_i(x,y)\right] = SFC\left[K_i(x,y)\nabla h_i(x,y)\right]^T \tag{101}$$

provides the cumulative release $R_l(t)$ of radionuclide l from the waste panel through time t.

PA-4.4.2 Numerical Solution

Equation (98) is numerically evaluated by the PANEL model (WIPP PA 1998b).

A discretization based on 50-year or smaller time steps is used by PANEL. Specifically, Equation (98) is evaluated with the approximation

$$A_l(t_{n+1}) = A_l(t_n) - \left[\int_{t_n}^{t_{n+1}} r_b(\tau)\,d\tau\right] C_{bl}(t_n) - A_l(t_n)\exp(-\lambda_l \Delta t) + G_l(t_n, t_{n+1}), \tag{102}$$

where

$G_l(t_n, t_{n+1})$ = gain in radionuclide l due to the decay of precursor radionuclides between t_n and t_{n+1} (see Equation (103)),

$\Delta t = t_{n+1} - t_n = 50\ yr$.

As the solution progresses, values for $C_{bl}(t_n)$ are updated in consistency with Equation (99) and the products $r_b(t_n)C_{bl}(t_n)$ are accumulated to provide an approximation to R_l in Equation (101).

The term $G_l(t_n, t_{n+1})$ in Equation (102) is evaluated with the Bateman equations (Bateman 1910), with PANEL programmed to handle up to four succeeding generations of a given radionuclide (i.e., decay chains of length 5). As a single example, if radionuclide l is the third radionuclide in a decay chain (i.e., l = 3) and the two preceding radionuclides in the decay chain are designated by l = 1 and l = 2, then

$$
\begin{aligned}
G_3(t_n, t_{n+1}) = {} & \lambda_2 A_2(t_n)\left[\exp(-\lambda_2 \Delta t) - \exp(-\lambda_3 \Delta t)\right] / (\lambda_3 - \lambda_2) \\
& + \lambda_1 \lambda_2 A_2(t_n)\Big\{\left[\exp(-\lambda_1 \Delta t)\right] / \left[(\lambda_2 \lambda_1)(\lambda_3 \lambda_1)\right] \\
& \quad + \left[\exp(-\lambda_2 \Delta t)\right] / \left[(\lambda_3 - \lambda_2)(\lambda_1 - \lambda_2)\right] \\
& \quad + \left[\exp(-\lambda_3 \Delta t)\right] / \left[(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)\right]\Big\}
\end{aligned}
\tag{103}
$$

in Equation (102).

PA-4.4.3 Implementation in Performance Assessment

The preceding model was used in two ways in the CRA-2004 PA. First, Equation (101) was used to estimate releases to the Culebra associated with E1E2 intrusions (scenario S6; see Section PA-6.7). Second, with r_b set to a very small number and V_b set to a fixed value, Equation (98) and Equation (99) were used to estimate radionuclide concentrations in brine for use in the estimation of direct brine releases (see Section PA-6.8.5).

For E1E2 intrusions, the initial amount A_l of radionuclide l is the inventory of the isotope decayed to at the time of the E1 intrusion. Isotopes considered in the PANEL calculations for release to the Culebra are listed in Appendix TRU WASTE (Table TRU WASTE-9). PANEL calculates the inventory of each radionuclide throughout the regulatory period. The initial concentration C_{bl} of radionuclide l is computed by Equation (98) and Equation (99). For use as part of the direct brine release calculations, the initial amount Al of radionuclide l is the inventory of the isotope at the time of repository closure; isotopes considered in the PANEL calculations for direct brine releases are listed in Appendix TRU WASTE (Table TRU WASTE-9).

PA-4.4.4 Additional Information

Additional information on PANEL and its use in the CRA-2004 PA calculations can be found in the PANEL user's manual (WIPP PA 2003d) and the analysis package for PANEL calculations (Garner 2003).

PA-4.5 Cuttings and Cavings to Surface: CUTTINGS_S

Cuttings are waste solids contained in the cylindrical volume created by the cutting action of the drill bit passing through the waste. Cavings are additional waste solids eroded from the borehole by the upward-flowing drilling fluid within the borehole. The releases associated with these processes are computed within the CUTTINGS_S code (WIPP PA 2003e). The mathematical representations used for the first two processes, cuttings and cavings, are described in this section.

PA-4.5.1 Cuttings

The uncompacted volume of cuttings removed and transported to the surface in the drilling mud, V_{cut}, is given by

$$V_{cut} = AH_i = \pi D^2 H_i / 4 , \tag{104}$$

where H_i is the initial (i.e., uncompacted) repository height (m), A is the drill bit area (m^2), and D is the drill-bit diameter (m). In the CRA-2004 PA, D = 12.25 in. = 0.31115 m and H_i = 3.96 m (Attachment PAR, Table PAR-13). For drilling intrusions through RH-TRU waste, H_i = 0.509 m is used (Attachment PAR, Table PAR-45).

PA-4.5.2 Cavings

The cavings component of the direct surface release is caused by the shearing action of the drilling fluid (mud) on the waste as the mud flows up the borehole annulus. As for the cuttings release, the cavings release is assumed to be independent of the conditions that exist in the repository at the time of a drilling intrusion.

The final diameter of the borehole will depend on the diameter of the drillbit and on the extent to which the actual borehole diameter exceeds the drill-bit diameter. Although a number of factors affect erosion within a borehole (Broc 1982), the most important factor is believed to be the fluid shear stress on the borehole wall (i.e., the shearing force per unit area, (kg m/s^2/m^2)) resulting from circulating drilling fluids (Darley 1969; Walker and Holman 1971). As a result, the CRA-2004 PA estimates cavings removal with a model based on the effect of shear stress on the borehole diameter. In particular, the borehole diameter is assumed to grow until the shear stress on the borehole wall is equal to the shear strength of the waste (i.e., the limiting shear stress below which the erosion of the waste ceases).

The final eroded diameter D_f (m) of the borehole through the waste determines the volume V (m^3) of uncompacted waste that will be removed to the surface by circulating drilling fluid. Specifically,

$$V = V_{cut} + V_{cav} = \pi D_f^2 H_i / 4 , \tag{105}$$

where V_{cav} is the volume (m^3) of waste removed as cavings.

Most borehole erosion is believed to occur in the vicinity of the drill collar (Figure PA-14) because of decreased flow area and consequent increased mud velocity (Rechard et al. 1990, Letters 1a and 1b, App. A). An important determinant of the extent of this erosion is whether the flow of the drilling fluid in the vicinity of the collar is laminar or turbulent. The CRA-2004 PA uses Reynolds numbers to distinguish between the occurrence of laminar flow and turbulent flow. The Reynolds number is the ratio between inertial and viscous (i.e., shear) forces in a fluid and can be expressed as (Fox and McDonald 1985):

$$R_e = \frac{\rho_f \|\mathbf{v}\| D_e}{\eta} , \tag{106}$$

where R_e is the Reynolds number (dimensionless), ρ_f is the fluid density (kg m^{-3}), D_e is the equivalent diameter (m), v is the fluid velocity (m s^{-1}), and η is the fluid viscosity (kg m^{-1} s^{-1}).

Typically, ρ, v and η are averages over a control volume with an equivalent diameter of D_e. In the CRA-2004 PA, $\rho f = 1.21 \times 10^3$ kg m^{-3} (Attachment PAR, Table PAR-13), $\|\boldsymbol{v}\| = 0.7089$ m s^{-1} (based on 40 gallons/min per inch of drill diameter) (Berglund 1992), and $D_e = 2\,(R - R_i)$, as shown in Figure PA-14. The diameter of the drill collar (i.e., $2R_i$ in Figure PA-14) is 8.0 in = 0.2032 m (Dunagan 2003b). The determination of η is discussed below. Reynolds numbers less than 2100 are assumed to be associated with laminar flow, while Reynolds numbers greater than 2100 are assumed to be associated with turbulent flow (Walker 1976).

Drilling fluids are modeled as non-Newtonian, which means that the viscosity η is a function of the shear rate within the fluid (i.e., the rate at which the fluid velocity changes normal to the flow direction, ((m/s)/m). The CRA-2004 PA uses a model proposed by Oldroyd (1958) to estimate the viscosity of drilling fluids. As discussed by Broc (1982), the Oldroyd model leads to the following expression for the Reynolds number associated with the helical flow of a drilling fluid within an annulus:

$$R_e = \frac{0.8165\,\rho_f\,\|\boldsymbol{v}\|\,D_e}{\eta_\infty}, \tag{107}$$

where ρ_f, $\|\boldsymbol{v}\|$ and D_e are defined as in Equation (106), and η_∞ is the asymptotic value for the derivative of the shear stress (τ, kg m^{-1} s^{-2}) with respect to the shear rate (Γ, s^{-1}) obtained as the shear rate increases (i.e., $\eta_\infty = d\tau/d\Gamma \;\; as\; \Gamma \to \infty$). The CRA-2004 PA uses Equation (107) to obtain the Reynolds numbers that are used to determine whether drilling fluids in the area of the drill collar are undergoing laminar or turbulent flow.

The Oldroyd model assumes that the shear stress τ is related to the shear rate Γ by the relationship

$$\tau = \eta_0 \left(\frac{1 + \sigma_2 \Gamma^2}{1 + \sigma_1 \Gamma^2} \right) \Gamma, \tag{108}$$

where η_0 is the asymptotic value of the viscosity (kg m^{-1} s^{-1}) that results as the shear rate Γ approaches zero, and σ_1, σ_2 are constants (s^2). The expression leads to

$$\eta_\infty = \eta_0 \left(\frac{\sigma_2}{\sigma_1} \right). \tag{109}$$

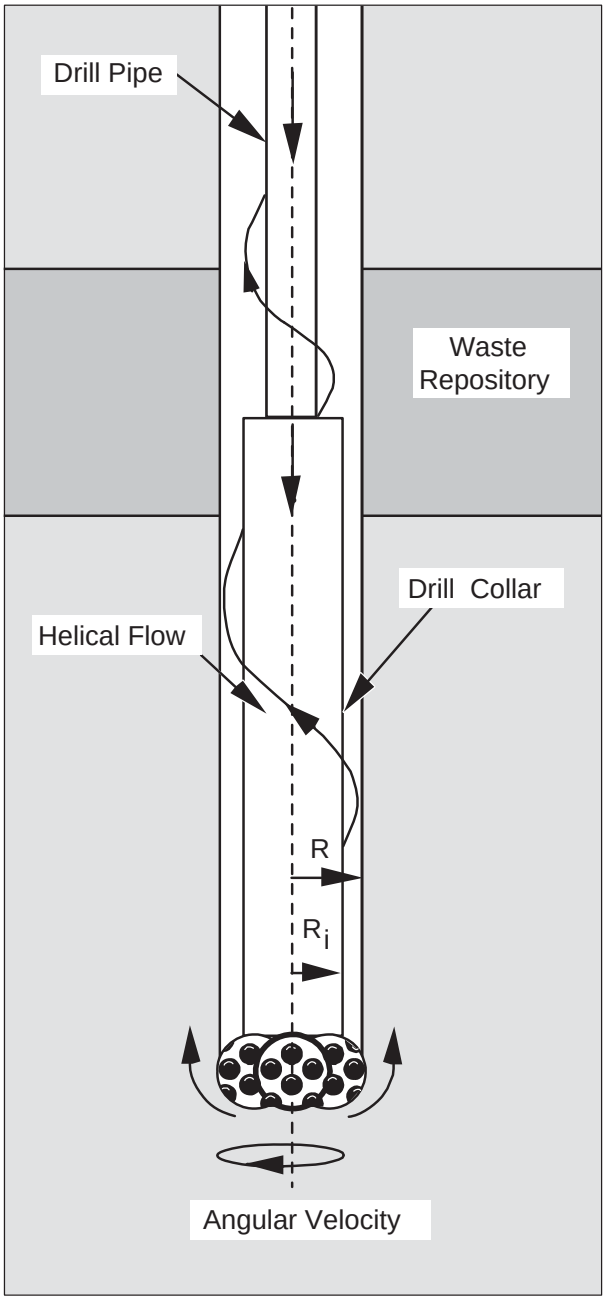

Figure PA-14. Detail of Rotary Drill String Adjacent to Drill Bit.

The CRA-2004 PA uses values of $\eta_0 = 1.834 \times 10^{-2}$ kg m^{-1} s^{-1}, $\sigma_1 = 1.082 \times 10^{-6}$ s^2 and $\sigma_2 = 5.410 \times 10^{-7}$ s^2 (Berglund 1996), and a resultant value of $\eta_\infty = 9.17 \times 10^{-3}$ kg m^{-1} s^{-1}. The quantity η_∞ is comparable to the plastic viscosity of the fluid (Broc 1982).

As previously indicated, different models are used to determine the eroded diameter D_f of a borehole depending on whether flow in the vicinity of the drill collar is laminar or turbulent. The model for borehole erosion in the presence of laminar flow is described next, and is then followed by a description of the model for borehole erosion in the presence of turbulent flow.

PA-4.5.2.1 Laminar Flow Model

As shown by Savins and Wallick (1966), the shear stresses associated with the laminar helical flow of a non-Newtonian fluid can be expressed as

$$\tau(R,r) = \left\{ \left[\frac{C}{r^2} \right]^2 + \left[\frac{RJ}{2} \left(\frac{r^2 - \lambda^2}{r} \right) \right]^2 \right\}^{1/2} \tag{110}$$

for $R_i / R \le r \le 1$, where R_i and R are the inner and outer radii within which the flow occurs as indicated in Figure PA-14; $\tau(R,\rho)$ is the shear stress (kg m^{-1} s^{-2}) at a radial distance ΔR beyond the inner boundary (i.e., at $r = (R_i + \Delta R)/R$); and the quantities C, J, and λ are functions of R that satisfy conditions indicated below. The shear stress at the outer boundary (i.e., R) is given by

$$\tau(R,1) = \left\{ C^2 + \left[\frac{RJ}{2} \left(1 - \lambda^2 \right) \right]^2 \right\}^{1/2} . \tag{111}$$

As previously indicated, the borehole radius R is assumed to increase as a result of erosional processes until a value of R is reached at which $\tau(R,1)$ is equal to the shear strength of the waste. In the CRA-2004 PA, the shear strength of the waste is treated as an uncertain parameter (see WTAUFAIL in Table PA-17). Computationally, determination of the eroded borehole diameter R associated with a particular value for waste shear strength requires repeated evaluation of $\tau(R,1)$, as indicated in Equation (111), until a value of R is determined for which $\tau(R,1)$ equals that shear strength.

The quantities C, J, and λ must satisfy the following three conditions (Savins and Wallick 1966) for the expression in Equation (111) to be valid:

$$0 = \int_{R_i/R}^{1} \left(\frac{\rho^2 - \lambda^2}{\rho \eta} \right) d\rho \tag{112a}$$

$$0 = C \int_{R_i / R}^{1} \left(\frac{1}{\rho^3 \eta} \right) d\rho - \Delta\Omega \tag{112b}$$

and

$$0 = \frac{4Q}{\pi R^3} + 2RJ \int_{R_i / R}^{1} \left(\frac{\left(R_i / R\right)^2 - \rho^2}{\rho\eta} \right) \left(\frac{\rho^2 - \lambda^2}{\rho\eta} \right) d\rho , \tag{112c}$$

where η is the drilling fluid viscosity (kg m^{-1} s^{-1}) and is a function of R and ρ, $\Delta\Omega$ is the drill string angular velocity (rad s^{-1}), and Q is the drilling fluid flow rate (m^3 s^{-1}).

The viscosity η in Equation (112) is introduced into the analysis through the assumption that the drilling fluid follows the Oldroyd model for shear stress in Equation (108). In particular, because

$$\tau = \eta\Gamma \tag{113}$$

as a result of the definition of the viscosity η and

$$\Gamma^2 = \frac{\left(\eta - \eta_0\right)}{\left(\eta_0\sigma_2 - \eta\sigma_1\right)} \tag{114}$$

from Equation (108), the expression in Equation (110) can be reformulated as

$$\frac{\eta^2 \left(\eta - \eta_0\right)^2}{\left(\eta_0\sigma_2 - \eta\sigma_1\right)^2} = \left[\frac{C}{\rho^2} \right]^2 + \left[\frac{RJ}{2} \left(\frac{\rho^2 - \lambda^2}{\rho} \right) \right]^2 . \tag{115}$$

As discussed by Savins and Wallick (1966) and also by Berglund (1992), the expressions in Equation (112) and Equation (114) can be numerically evaluated to obtain C, J, and λ for use in Equation (110) and Equation (111). In the CRA-2004 PA, the drill string angular velocity $\Delta\Omega$ is treated as an uncertain parameter (see DOMEGA in Table PA-17), and

$$Q = \|\mathbf{v}\| \left(\pi R^2 - \pi R_i^2 \right), \tag{116}$$

where $\|\mathbf{v}\|$ = 0.7089 m s^{-1} as used in Equation (106), and η_0, σ_1, and σ_2 are defined by Equation (109).

PA-4.5.2.2 <u>Turbulent Flow Model</u>

The model for borehole erosion in the presence of turbulent flow is now described. Unlike the theoretically derived relationship for erosion in the presence of laminar flow, the model for borehole erosion in the presence of turbulent flow is empirically based. In particular, pressure

loss for axial flow in an annulus under turbulent flow conditions can be approximated by (Broc 1982)

$$\Delta P = \frac{2 f L \rho_f \|\mathbf{v}\|^2}{0.8165 D_e} \tag{117}$$

where ΔP is the pressure change (Pa), L is distance (m) over which pressure change ΔP occurs, f is the Fanning friction factor (dimensionless), and ρ_f, $\|\mathbf{v}\|$ and D_e are defined in Equation (106).

For pipe flow, f is empirically related to the Reynolds number R_e and a roughness term ε by (Whittaker 1985)

$$\frac{1}{\sqrt{f}} = -4 \log_{10}\left(\frac{\varepsilon}{3.72 D} + \frac{1.255}{R_e \sqrt{f}}\right), \tag{118}$$

where D is the inside diameter (m) of the pipe and ε is the average depth (m) of pipe wall irregularities. In the absence of a similar equation for flow in an annulus, Equation (118) is used in the CRA-2004 PA to define f for use in Equation (117), with D replaced by the effective diameter $D_e = 2\left(R - R_i\right)$ and ε equal to the average depth of irregularities in the waste-borehole interface. In the present analysis, ε = 0.025 m (Attachment PAR, Table PAR-34), which exceeds the value often chosen for use in calculations involving very rough concrete or riveted steel piping (Streeter 1958). Further, the Reynolds number R_e is defined in Equation (107).

The pressure change ΔP in Equation (117) and the corresponding shear stress τ at the walls of the annulus are approximately related by

$$\Delta P\left[\pi\left(R^2 - R_i^2\right)\right] = \tau\left[2\pi L\left(R + R_i\right)\right] \tag{119}$$

where $\pi\left(R^2 - R_i^2\right)$ is the cross-sectional area of the annulus (see Figure PA-14) and $2\pi L\left(R + R_i\right)$ is the total (i.e., interior and exterior) surface area of the annulus. Rearrangement of Equation (117) and use of the relationship in Equation (113) yields

$$\tau = \frac{f \rho_f \|\mathbf{v}\|^2}{2(0.8165)}, \tag{120}$$

which was used in the 1991 and 1992 WIPP PAs to define the shear stress at the surface of a borehole of radius R. As a reminder, R enters into Equation (112a) through the use of $D = 2\left(R - R_i\right)$ in the definition of f in Equation (118). As in the case for laminar flow, the borehole radius R is assumed to increase until a value of τ (actually, $\tau\left(R\right)$) is reached that equals

the sample value for the shear strength of the waste (i.e., the uncertain parameter WTAUFAIL in Table PA-17). Computationally, the eroded borehole diameter is determined by solving Equation (120) for R under the assumption that τ equals the assumed shear strength of the waste.

In the CRA-2004 PA, a slight modification to the definition of τ in Equation (120) was made to account for drill string rotation when fluid flow in the vicinity of the drill collars is turbulent (Abdul Khader and Rao 1974; Bilgen et al. 1973). Specifically, an axial flow velocity correction factor (i.e., a rotation factor), F_r, was introduced into the definition of τ. The correction factor F_r is defined by

$$F_r = \|\mathbf{v}_{2100}\| / \|\mathbf{v}\|, \tag{121}$$

where $\|\mathbf{v}_{2100}\|$ is the norm of the flow velocity required for the eroded diameters to be the same for turbulent and laminar flow at a Reynolds number of $R_e = 2100$ and is obtained by solving

$$\tau_{fail} = \frac{f \rho_f \|\mathbf{v}_{2100}\|^2}{2(0.8165)} \tag{122}$$

for $\|\mathbf{v}_{2100}\|$ with D in the definition of f in Equation (118) assigned the final diameter value that results for laminar flow at a Reynolds number of $R_e = 2100$ (i.e., the D in $D_e = 2(R - R_i) = D - 2R_i$ obtained from Equation (107) with $R_e = 2100$). The modified definition of τ is

$$\tau = \frac{f \rho_f \left(F_r \|\mathbf{v}\|\right)^2}{2(0.8165)}, \tag{123}$$

and results in turbulent and laminar flow having the same eroded diameter at a Reynolds number of 2100, which is the Reynolds number at which a transition between turbulent and laminar flow is assumed to take place.

PA-4.5.2.3 <u>Calculation of R_f</u>

The following algorithm was used to determine the final eroded radius R_f of a borehole and incorporates the possible occurrence of a transition from turbulent to laminar fluid flow within a borehole.

Step 1. Use Equation (107) to determine an initial Reynolds number R_e, with R set to the drill-bit radius, $R_0 = 12.25$ in (Attachment PAR, Table PAR-13).

Step 2. If $R_e < 2100$, the flow is laminar and the procedure in Section PA-4.5.2.1 is used to determine R_f. Because any increase in the borehole diameter will cause the Reynolds number to decrease, the flow will remain laminar and there is no need to consider the

possibility of turbulent flow as the borehole diameter increases, with the result that R_f determined in this step is the final eroded radius of the borehole.

Step 3. If $R_e \geq 2100$, then the flow is turbulent and the procedure discussed in Section PA-4.5.2.2 is used to determine R_f. Once R_f is determined, the associated Reynolds number R_e is calculated with Equation (107) and $R = R_f$. If $R_e > 2100$, then a transition from turbulent to laminar flow cannot take place, and the final eroded radius is R_f determined in this step.

Step 4. If the Reynolds number R_e determined in Step 3 satisfies the inequality $R_e \leq 2100$, then a transition from turbulent to laminar flow is assumed to have taken place. In this case, the calculation of R_f is redone for laminar flow, with the outer borehole radius R initially defined to be the radius at which the transition from turbulent to laminar flow occurs (i.e., the radius associated with $R_e = 2100$). In particular, the initial value for R is given by

$$R = R_i + \frac{2100\eta_\infty}{2(0.8165)\|v\|\rho}, \tag{124}$$

which is obtained from Equation (107) by solving for R with $R_e = 2100$. A new value for R_f is then calculated with the procedure discussed in Section PA-4.5.2.1 for laminar flow, with this value of R_f replacing the value from Step 3 as the final eroded diameter of the borehole.

Step 5. Once R_f is known, the amount of waste removed to the surface is determined by Equation (105) with $D_f = 2R_f$.

PA-4.5.3 Additional Information

Additional information on CUTTINGS_S and its use in the CRA-2004 PA to determine cuttings and cavings releases can be found in the CUTTINGS_S user's manual (WIPP PA 2003e) and in the analysis package for cuttings and cavings releases (Dunagan 2003a).

PA-4.6 Spallings to Surface: DRSPALL and CUTTINGS_S

Spallings are waste solids introduced into a borehole by the movement of waste-generated gas towards the lower-pressure borehole. In engineering literature, the term "spalling" is used to describe the phenomenon of dynamic fracture of a solid material such as rock or metal (Antoun et al. 2003). In WIPP PA, the model for spallings describes a series of processes including tensile failure of solid waste, fluidization of failed material, entrainment into the wellbore flow, and transport up the wellbore to the land surface. Spallings releases could occur when pressure differences between the repository and the wellbore are sufficient to cause solid stresses in the waste exceeding the waste material strength and gas velocities sufficient to mobilize failed waste material.

The spallings model is described in the following sections. Presented first are the primary modeling assumptions used to build the conceptual model. Next, the mathematical model and its numerical implementation in the FORTRAN code DRSPALL (for Direct Release Spall) are described. Finally, implementation of the spallings model in WIPP PA by means of the code CUTTINGS_S.

PA-4.6.1 Summary of Assumptions

Assumptions underlying the spallings model include the future state of the waste, specifications of drilling equipment, and the driller's actions at the time of intrusion. Consistent with the other PA models, the spallings model assumes massive degradation of the emplaced waste through mechanical compaction, corrosion, and biodegradation. Waste is modeled as a homogeneous, isotropic, weakly-consolidated material with uniform particle size and shape. The rationale for selection of the spallings model material properties is addressed in detail in reports by Hansen et al. (1997, 2003).

Drilling equipment specifications, such as bit diameter and drilling mud density, are based on surveys of drillers in the Delaware Basin (Hansen et al. 2003). Assumptions about the driller's actions during the intrusion are conservative. Typically, the drilling mud density is controlled to maintain a slightly "overbalanced" condition so that the mud pressure is always slightly higher that the fluid pressures in the formation. If the borehole suddenly passes through a high-pressure zone, the well can quickly become "underbalanced," with a resulting fluid pressure gradient driving formation fluids into the wellbore. This situation is known as a "kick," and is of great concern to drillers because a violent kick can lead to a blowout of mud, gas, and oil from the wellbore, leading to equipment damage and worker injury. Standard drilling practice is to watch diligently for kicks. The first indicator of a kick is typically an increase in mud return rate leading to an increase in mud pit volume (Frigaard and Humphries 1997). Down-hole monitors detect whether the kick is air, H_2S, or brine. If the kick fluid is air, the standard procedure is to stop drilling and continue pumping mud in order to circulate the air pocket out. If the mud return rate continues to grow after drilling has stopped and the driller believes that the kick is sufficiently large to cause damage, the well may be shut in by closing the blowout preventer. Once shut in, the well pressure may be bled off slowly and mud weight eventually increased and circulated to offset the higher formation pressure before drilling continues. The spallings model simulates an underbalanced system in which a gas kick is assured, and the kick proceeds with no intervention from the drill operation. Therefore, drilling and pumping continue during the entire blowout event.

PA-4.6.2 Conceptual Model

The spallings model calculates transient repository and wellbore fluid flow before, during, and after the drilling intrusion. To simplify the calculations, both the wellbore and the repository are modeled by one-dimensional geometries. The wellbore assumes a compressible Newtonian fluid consisting of a mixture of mud, gas, salt and waste solids; viscosity of the mixture varies with the fraction of waste solids in the flow. In the repository, flow is viscous, isothermal, compressible single-phase (gas) flow in a porous medium.

The wellbore and repository flows are coupled by a cylinder of porous media before penetration, and by a cavity representing the bottom of the borehole after penetration. Schematic diagrams of the flow geometry prior to and after penetration are shown in Figure PA-15 and Figure PA-16, respectively. The drill bit moves downward as a function of time, removing salt or waste material. After penetration, waste solids freed by drilling, tensile failure, and associated fluidization may enter the wellbore flow stream at the cavity forming the repository-wellbore boundary.

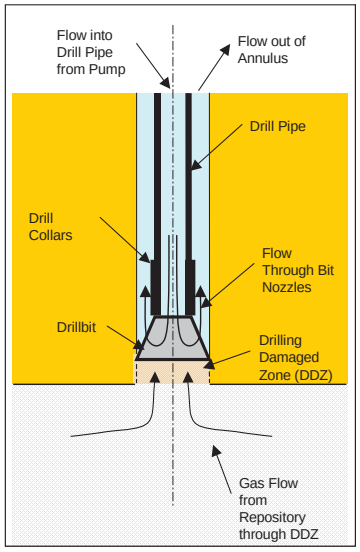

Figure PA-15. Schematic Diagram of the Flow Geometry Prior to Repository Penetration.

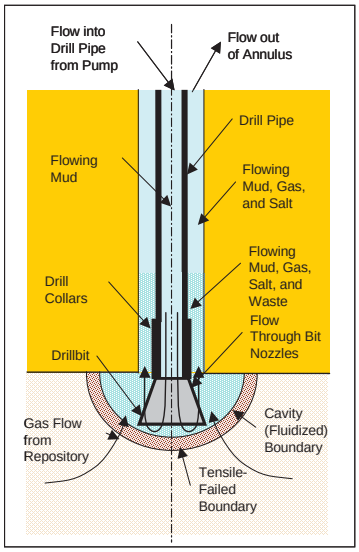

Figure PA-16. Schematic Diagram of the Flow Geometry After Repository Penetration.

PA-4.6.2.1 Wellbore Flow Model

Flow in the well is modeled as one-dimensional pipe flow with cross-sectional areas corresponding to the appropriate flow area at a given position in the well, as shown in Figure PA-17 and Figure PA-18. In concept, this model is similar to that proposed by Podio and Yang (1986) and now in use in the oil and gas industry. Drilling mud is added at the wellbore entrance by the pump. Flow through the drill bit is treated as a choke with cross-sectional area appropriate for the bit nozzle area. At the annulus output to the surface, mixture ejection is to a constant atmospheric pressure. The gravitational body force acts in its appropriate direction based on position before or after the bit.

Prior to drill bit penetration into the repository, gas from the repository can flow through drilling-damaged salt into the well. After penetration, the cavity at the bottom of the wellbore couples the wellbore flow and the repository flow models; gas and waste material can exit the repository domain into the cavity. The cavity radius increases as waste materials are moved into the wellbore.

The system of equations representing flow in the wellbore includes: four equations for mass conservation, one for each phase (salt, waste, mud and gas); one equation for conservation of total momentum; two equations relating gas and mud density to pressure; the definition of density for the fluid mixture; and one constraint imposed by the fixed volume of the wellbore. The conservation of mass and momentum are described by:

$$\frac{\partial}{\partial t}\left(\rho_q V_q\right) + \frac{\partial}{\partial z}\left(\rho_q V_q u\right) = S_q \tag{125a}$$

$$\frac{\partial}{\partial t}\left(\rho V u\right) + \frac{\partial}{\partial z}\left(\rho V u^2\right) = -V\left(\frac{\partial P}{\partial z} - \rho g + F\right) + S_{mom}\,, \tag{125b}$$

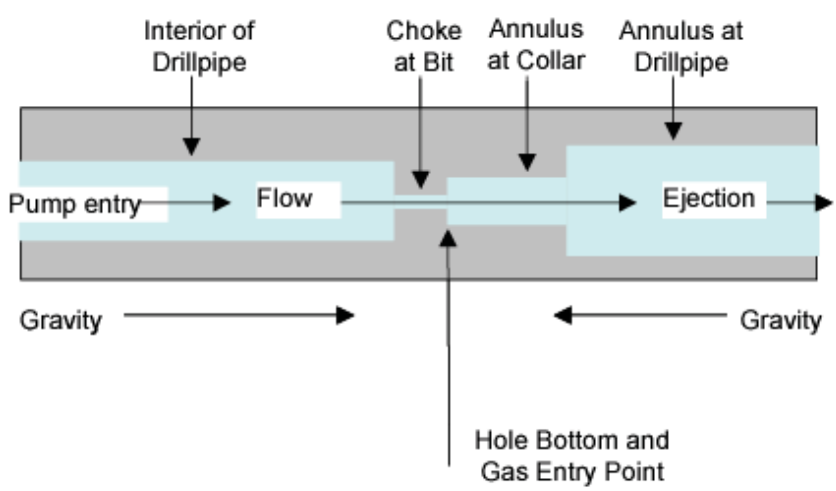

Figure PA-17. Effective Wellbore Flow Geometry Before Bit Penetration.

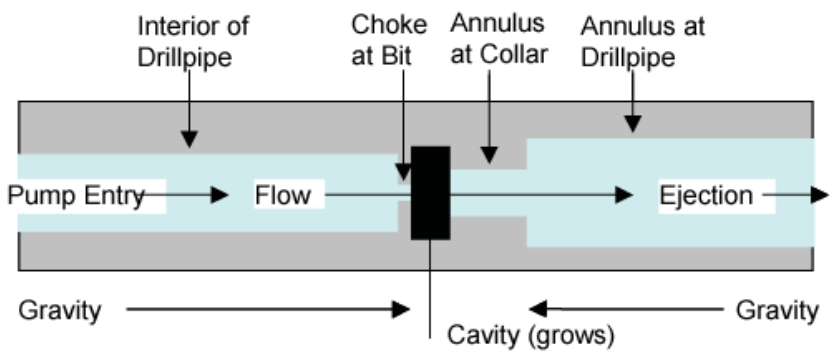

Figure PA-18. Effective Wellbore Flow Geometry After Bit Penetration.

where

q = phase (w for waste, s for salt, m for mud, and g for gas),

V_q = volume (m^3) of phase q,

V = total volume (m^3) ,

ρ_q = density (kg/m^3) of phase q, constant for salt and waste (2180 and 2650 kg/m^3, respectively) and pressure-dependent for gas and mud (see Equation (126) and Equation (127)),

ρ = density of fluid mixture (kg/m^3) determined by Equation (128),

u = velocity (m/s) of fluid mixture in wellbore ,

t = time (s),

z = distance (m) from inlet at top of well ,

S_q = rate of mass (kg/s) of phase q entering and exiting wellbore domain at position z (Equation (138)),

S_{mom} = rate of momentum (kg m / s^2) entering and exiting wellbore domain at position z (Equation (141)),

P = pressure (Pa) at position z ,

g = gravity constant (9.8067 kg/m s^2),

F = friction loss using pipe flow model ($kg/m^2\ s^2$) determined by Equation (130).

Gas is treated as isothermal and ideal, so

$$\frac{\rho}{\rho_{g,0}} = \frac{P}{P_{atm}}, \tag{126}$$

where $\rho_{g,0}$ is the density of the gas at atmospheric pressure (8.24182×10^{-2} kg/m^3 in the CRA-2004 PA).

The mud is assumed to be a compressible liquid, so

$$\rho_m = \rho_{m,0}\left[1 + c_m\left(P - P_{atm}\right)\right], \tag{127}$$

where $\rho_{m,0}$ is the density of the mud at atmospheric pressure (1210 kg/m^3 in the CRA-2004 PA) and c_m is the compressibility of the mud (3.1×10^{-10} Pa^{-1} in the CRA-2004 PA).

The density of the fluid mixture is determined from the densities and volumes occupied by the phases:

$$\rho = \frac{\rho_g V_g + \rho_m V_m + \rho_s V_s + \rho_w V_w}{V}. \tag{128}$$

The volume of each phase is constrained by the fixed volume of the wellbore:

$$V = V_g + V_m + V_s + V_w. \tag{129}$$

The friction loss is a standard formulation for pipe flow (Fox and McDonald 1985), where the head loss per unit length is given as:

$$F = f\frac{\rho}{d_h}\frac{u^2}{2}. \tag{130}$$

The hydraulic diameter d_h is given by

$$d_h = \frac{4A}{\pi\left(D_i + D_o\right)}. \tag{131}$$

In the CRA-2004 PA, D_o = 0.31115 m throughout the domain. From the bit to the top of the collar, D_i = 0.2032 m; above the collar, D_i = 0.1143 m. The area A is calculated as the area of the annulus between the outer and inner radii. Thus, d_h = 0.108 m from the bit to the top of the collar, and d_h = 0.197 m above the collar.

The friction factor f is determined by method of Colebrook (Fox and MacDonald 1985). In the laminar regime (Re < 2100)

$$f = \frac{64}{\mathbf{Re}}, \tag{132}$$

and in the turbulent regime (Re > 2100)

$$\frac{1}{\sqrt{f}} = 1.0 \log\left(\frac{\varepsilon/d_h}{3.7} + \frac{2.51}{\mathbf{Re}\sqrt{f}}\right), \tag{133}$$

where $\mathbf{Re} = \frac{u\rho d_h}{\eta}$ is the Reynolds number of the mixture, and η is the viscosity calculated by Equation (134). As the wellbore mixture becomes particle-laden, the viscosity of the mixture is determined from an empirical relationship developed for proppant slurry flows in channels for the oil and gas industry (Barree and Conway 1995). Viscosity is computed by an approximate slurry formula based on the volume fraction of waste solids:

$$\eta = \eta_0 \left(1 - \frac{w}{w_{max}}\right)^s, \tag{134}$$

where η_0 is a base mixture viscosity (9.17×10^{-3} Pa sec in the CRA-2004 PA), $w = V_w / V$ is the current volume fraction of waste solids, w_{max} is an empirically determined maximal volume fraction above which flow is choked (0.615 in the CRA-2004 PA), and s is an empirically determined constant (–1.5 in the CRA-2004 PA) (Hansen et al. 2003).

PA.-4.6.2.1.1 Wellbore initial conditions

Initial conditions in the wellbore approximate mixture flow conditions just prior to penetration into the waste. The wellbore is assumed to contain only mud and salt. Initial conditions for the pressure, fluid density, volume fractions of mud and salt, and the mixture velocity are set by the following algorithm.

Step 1. Set pressure in the wellbore to hydrostatic: $P(z) = P_{atm} + \rho_{m,0} g z$.

Step 2. Set mud density using Equation (127).

Step 3. Set mixture velocity: $u(z) = \frac{R_m}{A(z)}$, where R_m is the volume flow rate of the pump (0.0202 m^3/s in the CRA-2004 PA), and $A(z)$ is the cross-sectional area of the wellbore.

Step 4. Set volume of salt in each cell: $V_{s,i} = R_{drill} A_{bit} \frac{\Delta z_i}{u_i}$, where R_{drill} is the rate of drilling (0.004445 m/s in the CRA-2004 PA), $A_{bit} = \frac{\pi d_{bit}^2}{4}$ is the area of the bottom of the wellbore and d_{bit} is the diameter of the bit (0.31115 m in the CRA-2004 PA).

Step 5. Set volume fraction of mud in each cell: $V_{m,i} = V_i - V_{s,i}$.

Step 6. Recalculate mixture density using Equation (128), assuming no waste or gas in the wellbore.

The initial conditions set by this algorithm approximate a solution to the wellbore flow (Equation (125)) for constant flow of mud and salt in the well. The approximation rapidly converges to a solution for wellbore flow if steady-state conditions are maintained (WIPP PA 2003f).

PA-4.6.2.1.2 Wellbore boundary conditions

For simplicity, the CRA-2004 PA does not model flow of mud down the pipe to the bit. Mass can enter the wellbore below the drill bit, and can exit at the wellbore outlet. Below the bit, mud, salt, gas, and waste can enter the wellbore. The CRA-2004 PA assumes a constant volume of mud flow down the drilling pipe; therefore, the source term for mud, $S_{m,\,in}$, is set by the volume flow rate of the pump R_m (0.0202 m^3/s in the CRA-2004 PA) and the density of the mud at the bottom of the wellbore:

$$S_{m,in} = \rho_m R_m \,. \tag{135}$$

Until the drill bit penetrates the repository, salt enters the wellbore at a constant rate:

$$S_{s,in} = \rho_s R_{drill} A_{bit} \,. \tag{136}$$

Additional mass enters the wellbore by gas flow from the repository ($S_{gas,in}$) or by drilling or spalling of waste material ($S_{w,in}$); these mass sources are discussed in Section PA-4.6.2.3. The outlet of the wellbore is set to atmospheric pressure. Mass exiting the wellbore is determined from the mixture velocity, the area of the outlet A_{out} (0.066 m^2 in the CRA-2004 PA), and the density and volume fraction of each phase at the outlet of the wellbore:

$$S_{q,out} = \rho u_{out} A_{out} \frac{V_q}{V} \,. \tag{137}$$

Finally, the net change in mass for phase q is

$$S_q = S_{q,in} - S_{q,out} \,. \tag{138}$$

$$S_{mom,in} = \frac{\rho_{0,m}}{A_p} R_{mudpump} \cdot \tag{139}$$

The outlet of the wellbore is set to atmospheric pressure. Momentum exiting the wellbore is determined from the fluid velocity and the area of the outlet A_{out} (0.066 m^2 in the CRA-2004 PA):

$$S_{mom,out} = -\rho A_{out} u_{out}^2 \cdot \tag{140}$$

No momentum is added by mass flow into the wellbore from the repository, thus:

$$S_{mom} = S_{mom,in} - S_{mom,out} \cdot \tag{141}$$

PA-4.6.2.2 Repository Flow Model

The repository is modeled as a radially-symmetric domain. A spherical coordinate system is used for this presentation and for most DRSPALL calculations in the CRA-2004 PA. In a few circumstances, cylindrical coordinates are used in CRA-2004 PA calculations, where spall volumes are large enough that spherical coordinates are not representative of the physical process (Lord et al. 2003). Cylindrical coordinates are also available; the Design Document for DRSPALL (WIPP PA 2003g) provides details on the implementation of the repository flow model in cylindrical coordinates.

Flow in the repository is transient, compressible, viscous, and single phase (gas) flow in a porous medium. Gas is treated as isothermal and ideal. The equations governing flow in the repository are the equation of state for gas, conservation of mass, and Darcy's law with the Forchheimer correction (Aronson 1986; Whitaker 1996):

$$\frac{\rho_g}{\rho_{g,0}} = \frac{P}{P_{atm}}, \tag{142a}$$

$$\phi \frac{\partial \rho_g}{\partial t} + \nabla \cdot \left(\rho_g u \right) = 0, \tag{142b}$$

$$\nabla P = -\frac{\eta_g}{k} \left(1 + F \right) u, \tag{142c}$$

where

P = pressure in pore space (Pa),

ρ_g = density of gas (kg/m^3),

u = velocity of gas in pore space (m/s),

ϕ = porosity of the solid (unitless),

η_g = gas viscosity (8.934×10^{-6} Pa s),

k = permeability of waste solid (m^2),

F = Forchheimer coefficient (unitless).

The Forchheimer correction is included to account for inertia in the flowing gas, which becomes important at high gas velocities (Ruth and Ma 1992). When the Forchheimer coefficient is zero, Equation (142c) reduces to Darcy's Law. A derivation of Equation (142c) from the Navier-Stokes equations is given by Whitaker (1996); the derivation suggests that F is a linear function of gas velocity for a wide range of Reynolds numbers.

In the CRA-2004 PA, the Forchheimer coefficient takes the form

$$F = \beta_{nd} \rho u \,, \tag{143}$$

where β_{nd} is the non-Darcy coefficient, which depends on material properties such as the tortuosity and area of internal flow channels, and is empirically determined (Belhaj et al. 2003). The CRA-2004 PA uses a value from a study by Li et al. (2001) that measured high-velocity nitrogen flow through porous sandstone wafers, giving the result

$$\beta_{nd} = \frac{1.15 \times 10^{-6}}{k\phi} \,. \tag{144}$$

Equation (142) combines into a single equation for pressure in the porous solid:

$$\frac{\partial P}{\partial t} = \frac{k'}{2\phi\eta_g} \nabla^2 P^2 + \frac{1}{2\phi\eta_g} \nabla P^2 \cdot \nabla k' \,, \tag{145}$$

where

$$k' = \frac{k}{1+F} = \frac{k}{1+\beta_{nd}\rho u} \,, \tag{146}$$

and the operator in a radially-symmetric coordinate system is given by

$$\nabla^2 = \frac{1}{r^{n-1}} \frac{\partial}{\partial r}\left(r^{n-1} \frac{\partial}{\partial r} \right) \,, \tag{147}$$

where n = 2 and n = 3 for cylindrical and spherical coordinates, respectively.

In the CRA-2004 PA, the permeability of the waste solid is a subjectively uncertain parameter that is constant for waste material that has not failed and fluidized. In a region of waste that has

failed, the permeability increases as the waste fluidizes by a factor of $1 + F_f$, where F_f is the fraction of failed material that has fluidized and is based on the fluidization relaxation time. This approximately accounts for the bulking of material as it fluidizes.

Initial pressure in the repository is set to a constant value P_{ff}. A no-flow boundary condition is imposed at the outer boundary (r = R):

$$\nabla \boldsymbol{P}(\boldsymbol{R}) = \boldsymbol{0}\,. \tag{148}$$

At the inner boundary ($r = r_{cav}$), the pressure is specified as $\boldsymbol{P}(\boldsymbol{r_{cav}}, \boldsymbol{t}) = \boldsymbol{P_{cav}}(\boldsymbol{t})$, where $\boldsymbol{P_{cav}}(\boldsymbol{t})$ is defined in the next section. The cavity radius r_{cav} increases as drilling progresses and as waste material fails and moves into the wellbore; calculation of r_{cav} is described in Section PA-4.6.2.3.3.

PA-4.6.2.3 <u>Wellbore to Repository Coupling</u>

Prior to penetration, a cylinder of altered-permeability salt material with diameter equal to the drill bit is assumed to connect the bottom of the wellbore to the repository. At the junction of the repository and this cylinder of salt, a small, artificial cavity is used to determine the boundary pressure for repository flow. After penetration, the cavity merges with the bottom of the wellbore to connect the wellbore to the repository.

PA-4.6.2.3.1 Flow Prior to Penetration

The cylinder of salt connecting the wellbore to the repository is referred to as the Drilling Damaged Zone (DDZ) in Figure PA-15. The permeability of the DDZ, k_{DDZ}, is 1×10^{-14} (m^2) in the CRA-2004 PA. The spall model starts with the bit 0.15 m above the repository; the bit advances at a rate of $R_{drill} = 0.004445$ (m/s).

To couple the repository to the DDZ, the model uses an artificial pseudo-cavity in the small hemispherical region of the repository below the wellbore, with the same surface area as the bottom of the wellbore (Figure PA-18). The pseudo-cavity is a numerical device that smoothes the discontinuities in pressure and flow that would otherwise occur upon bit penetration of the repository. The pseudo-cavity contains only gas and is initially at repository pressure. The mass of gas in the cavity m_{cav} is given by:

$$\frac{d\boldsymbol{m_{cav}}}{d\boldsymbol{t}} = \boldsymbol{S_{rep}} - \boldsymbol{S_{g,in}}\,, \tag{149}$$

where

S_{rep} = gas flow from repository into pseudo-cavity (kg/s); see Equation (150),

$S_{g,\,in}$ = gas flow from pseudo-cavity through DDZ into wellbore (kg/s); see Equation (151).

Flow from the repository into the pseudo-cavity is given by

$$S_{rep} = \rho_{g,rep} u_{rep} \phi A_{cav}, \tag{150}$$

where

$\rho_{g,rep}$ = gas density in repository at cavity surface (kg/m^3) = $\rho_g\left(r_{cav}\right)$,

u_{rep} = gas velocity (m/s) in repository at cavity surface = $u\left(r_{cav}\right)$,

ϕ = porosity of waste (unitless),

A_{cav} = surface area of hemispherical part of the cavity (m^2),

= $\frac{\pi}{4} d_{bit}^2$, where d_{bit} is the diameter of the bit (m).

Flow out of the pseudo-cavity through the DDZ and into the wellbore is modeled as steady-state using Darcy's Law:

$$S_{g,in} = \frac{k_{DDZ}\pi\left(\frac{d_{bit}}{2}\right)^2}{2\eta_g R_0 T L}\left(P_{cav}^2 - P_{BH}^2\right), \tag{151}$$

where

η_g = gas viscosity (8.934×10^{-6} Pa s),

R_0 = ideal gas constant for hydrogen (4116 J / kg °K),

T = repository temperature (constant at 300 °K),

L = length (m) of DDZ (from bottom of borehole to top of repository)

P_{cav} = pressure in pseudo-cavity (Pa),

P_{BH} = pressure at bottom of wellbore (Pa).

A justification for the use of this steady-state equation is provided in the Design Document for DRSPALL (WIPP PA 2003g). The pseudo-cavity is initially filled with gas at a pressure of P_{ff}. The boundary pressure on the well side (P_{BH}) is the pressure immediately below the bit, determined by Equation (125). The pressure in the pseudo-cavity (P_{cav}) is determined by the ideal gas law:

$$P_{cav} = \frac{m_{cav} R_0 T}{V_{cav}}, \tag{152}$$

where the volume of the cavity V_{cav} is given by

$$V_{cav} = \left(\frac{\pi}{24\sqrt{2}} \right) d_{bit}^3 . \tag{153}$$

In the CRA-2004 PA the drilling rate is constant at 0.004445 (m/s) thus $L = L_i - 0.004445t$ until $L = 0$, at which time the bit penetrates the waste. The term L_i is the distance from the bit to the waste at the start of calculation (0.15 m in the CRA-2004 PA).

PA-4.6.2.3.2 Flow After Penetration

After penetration of the waste, the bottom of the wellbore is modeled as a hemispherical cavity in the repository, the radius of which grows as drilling progresses and as material fails and moves into the cavity. Gas, drilling mud, and waste are assumed to thoroughly mix in this cavity; the resulting mixture flows around the drill collars and then up the annulus between the wellbore and the drill string. Gas flow from the repository into the cavity is given by Equation (150); however, A_{cav} is now dependent on the increasing radius of the cavity (see Section PA-4.6.2.3.3). Mudflow into the cavity from the wellbore is given by Equation (135). Waste flow into the cavity is possible if the waste fails and fluidizes; these mechanisms are discussed in Sections PA-4.6.2.3.4 and PA-4.6.2.3.5. Pressure in the cavity is equal to the pressure at the bottom of the wellbore and is computed by Equation (152).

PA-4.6.2.3.3 Cavity Volume After Penetration

The cylindrical cavity of increasing depth created by drilling is mapped to a hemispherical volume at the bottom of the wellbore to form the cavity. This mapping maintains equal surface areas in order to preserve the gas flux from the repository to the wellbore. The cavity radius from drilling is thus

$$r_{drill} = \sqrt{\frac{d_{bit}^2 + 4 d_{bit} \Delta H}{8}}, \tag{154}$$

where ΔH is the depth of the drilled cylinder. In the CRA-2004 PA, the drilling rate is constant at 0.004445 (m/s) thus $\Delta H = 0.004445t$ until $\Delta H = H$, the height of compacted waste (m). Since the initial height of the repository is 3.96 m, H is computed from the porosity ϕ by $H = 3.96 \times \frac{1-\phi_0}{1-\phi}$, where ϕ is the initial porosity of a waste-filled room.

The cavity radius r_{cav} is increased by the radius of failed and fluidized material r_{fluid}, which is the depth to which fluidization has occurred beyond the drilled radius. That is,

$$r_{cav} = r_{drill} + r_{fluid} \cdot \tag{155}$$

PA-4.6.2.3.4 Waste Failure

Gas flow from the waste creates a pressure gradient within the waste, which induces elastic stresses in addition to the far-field confining stress. These stresses may lead to tensile failure of the waste material, assumed to be prerequisite to spallings releases. While the fluid calculations using Equation (142) are fully transient, the elastic stress calculations are assumed to be quasi-static (i.e., sound-speed phenomena in the solid are ignored). Elastic effective stresses are (Timoshenko and Goodier 1970):

$$\sigma_r(r) = \sigma_{sr}(r) + \sigma_{ff}\left(1 - \left(\frac{r_{cav}}{r}\right)^3\right) + P(r_{cav})\left(\frac{r_{cav}}{r}\right)^3 - \beta P(r), \tag{156}$$

$$\sigma_\theta(r) = \sigma_{s\theta}(r) + \sigma_{ff}\left[1 + \frac{1}{2}\left(\frac{r_{cav}}{r}\right)^2\right] - \frac{P(r_{cav})}{2}\left(\frac{r_{cav}}{r}\right)^3 - \beta P(r), \tag{157}$$

where β is Biot's constant (1.0 in the CRA-2004 PA) and σ_{ff} is the confining far-field stress (assumed constant at 14.9 MPa in the CRA-2004 PA).

The flow-related radial and tangential stresses (σ_{sr} and $\sigma_{s\theta}$, respectively) are computed by equations analogous to differential thermal expansion (Timoshenko and Goodier 1970):

$$\sigma_{sr}(r) = 2\beta\left(\frac{1-2\upsilon}{1-\upsilon}\right)\frac{1}{r^3}\int_{r_{cav}}^{r}\left(P(s) - P_{ff}\right)s^2 ds, \tag{158}$$

$$\sigma_{s\theta}(r) = -\beta\left(\frac{1-2\upsilon}{1-\upsilon}\right)\left(\frac{1}{r^3}\int_{r_{cav}}^{r}\left(P(s) - P_{ff}\right)s^2 ds - \left(P(r) - P_{ff}\right)\right), \tag{159}$$

where P_{ff} is the initial repository pressure and υ is Poisson's ratio (0.38 in the CRA-2004 PA).

Since stresses are calculated as quasi-static, an initial stress reduction caused by an instantaneous pressure drop at the cavity face propagates instantaneously through the waste. The result of calculating Equation (156) can be an instantaneous early-time tensile failure of the entire repository if the boundary pressure is allowed to change suddenly. This is non-physical and merely a result of the quasi-static stress assumption combined with the true transient pore pressure and flow-related stress equations. To prevent this non-physical behavior, tensile failure propagation is limited by a tensile failure velocity (1000 m/s in the CRA-2004 PA; see Hansen et al. 1997). This limit has no quantitative effect on results other than to prevent non-physical tensile failure.

At the cavity face, Equation (156) and Equation (158) evaluate to zero, consistent with the quasi-static stress assumption. This implies that the waste immediately at the cavity face cannot experience tensile failure; however, tensile failure may occur at some distance into the waste material. Consequently, the radial effective stress σ_r is averaged from the cavity boundary into the waste over a characteristic length L_t (0.02 m in the CRA-2004 PA). If this average radial stress $\bar{\sigma}_r$ is tensile and its magnitude exceeds the material tensile strength ($|\bar{\sigma}_r| > \boldsymbol{TENSLSTR}$), the waste is no longer capable of supporting radial stress and fails, permitting fluidization. The waste tensile strength is an uncertain parameter in the analysis (see TENSLSTR in Table PA-14).

Equation (157) and (159) evaluate shear stresses in the waste. The CRA-2004 PA does not use the shear stresses in the waste in the calculation of waste failure for spall releases. These stresses are included in this discussion for completeness.

PA-4.6.2.3.5 Waste Fluidization

Failed waste material is assumed to be disaggregated, but not in motion; it remains as a porous, bedded material lining the cavity face, and is treated as a continuous part of the repository from the perspective of the porous flow calculations. The bedded material may be mobilized and may enter the wellbore if the gas velocity in the failed material (see Equation (142c)) exceeds a minimum fluidization velocity, U_f. The minimum fluidization velocity is determined by solving the following quadratic equation (Cherimisinoff and Cherimisinoff 1984; Ergun 1952):

$$\frac{1.75}{a\phi^3}\left(\frac{d_p U_f \rho_g}{\eta_g}\right)^2 + 150\left(\frac{1-\phi}{a^2\phi^3}\right)\left(\frac{d_p U_f \rho_g}{\eta_g}\right) = \frac{d_p^3 \rho_g \left(\rho_w - \rho_g\right) g}{\eta_g^2}, \qquad (160)$$

where

a = particle shape factor (unitless),

d_p = particle diameter (m).

Fluidization occurs in the failed material to the depth at which gas velocity does not exceed the fluidization velocity; this depth is denoted by r_{fluid} and is used to determine cavity radius (Section PA-4.6.2.3.3). If fluidization occurs, the gas and waste particles mix into the cavity at the bottom of the wellbore. To account for the fact that this mixing cannot be instantaneous, which would be non-physical (much as allowing instantaneous tensile failure propagation would be non-physical), a small artificial relaxation time, equal to the cavity radius r_{cav} divided by the superficial gas velocity $u\left(r_{cav}\right)$, is imposed upon the mixing phenomenon. The fluidized material is released into the cavity uniformly over the relaxation time.

PA-4.6.3 Numerical Model

The numerical model implements the conceptual and mathematical models described above. Both the wellbore and the repository domain calculations use time-marching finite differences.

These are part of a single computational loop and therefore use the same time step. The differencing schemes for the wellbore and repository calculations are similar, but not identical.

PA-4.6.3.1 Numerical Method – Wellbore

The wellbore is zoned for finite differencing as shown in Figure PA-19. This shows zones, zone indices, grid boundaries, volumes, and interface areas. The method is Eulerian; i.e., zone boundaries are fixed, and fluid flows across the interfaces by advection. Quantities are zone-centered and integration is explicit in time.

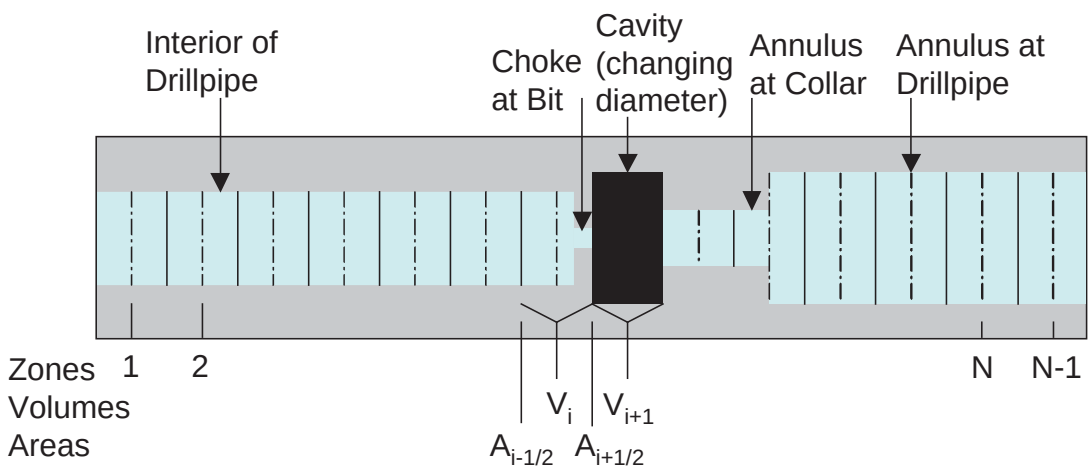

Figure PA-19. Finite Difference Zoning for Wellbore.

To reduce computation time, an iterative scheme is employed to update the wellbore flow solution. The finite difference scheme first solves Equation (125) for the mass of each phase in each grid cell and the momentum in each grid cell.

The updated solution to Equation (125) is then used to compute the volume of each phase, the pressure, and the mixture velocity in each grid cell.

All of the materials (mud, salt, gas, and waste) are assumed to move together as a mixture. Since fluid moves through the cell boundaries, the calculation requires values for the flow through cell boundaries during a timestep. These values are obtained by averaging the fluid velocities at the zone centers, given by:

$$u_{i+1/2} = \frac{1}{2}\left(u_{i+1}^{n-1} + u_i^{n-1}\right). \tag{161}$$

The mass transport equation, prior to any volume change, becomes

$$V_i\ \rho_i^* = V_i\ \rho_i^{n-1} - \Delta t\left(A_{i+1/2}\rho_{i+1/2}^{n-1}u_{i+1/2} - A_{i-1/2}\rho_{i-1/2}^{n-1}u_{i-1/2}\right) + \Delta t S_{m,i}\,. \tag{162}$$

Here, the source terms $\left(S_{m,i}\right)$ are set to correspond to material entering or exiting at the pump, cavity, and surface. The "upwind" zone centered densities are used for the interfaces values, $\rho_{i+1/2}^{n-1}$ and $\rho_{i-1/2}^{n-1}$.

Finally any changed volumes are incorporated and numerical mass diffusion is added for stability:

$$V_i \rho_i^n = V_i \rho_i^* + \Delta z_i \sum_{q=w,m,s,g} \zeta_q D_{i,q}, \tag{163}$$

where

$$D_{i,q} = \left[A_{i+1/2}\left(\left(\rho f_q\right)_{i+1}^{n-1} - \left(\rho f_q\right)_i^{n-1}\right) - A_{i-1/2}\left(\left(\rho f_q\right)_i^{n-1} - \left(\rho f_q\right)_{i-1}^{n-1}\right)\right]$$

and ζ_q is the diffusion coefficient for phase q. The density ρf_q for the phase q being diffused is calculated from the mixture density, ρ, and the mass fraction, f_q, of the phase q in the referenced cell ($f_q = \rho V_{q,i} / \rho V_i$). The numerical diffusion coefficient ζ_q is chosen empirically for stability. Separate diffusion coefficients could be used for the different materials (mud, gas, etc.). However, sufficient stability is obtained by only diffusing mud and salt using the same coefficient ($\zeta_m = \zeta_s = 0.0001$ and $\zeta_w = \zeta_g = 0$ in the CRA-2004 PA).

Momentum is differenced as:

$$\begin{aligned} V_i \ (\rho u)_i^* = V_i \ (\rho u)_i^{n-1} - \Delta t\left(A_{i+1/2}(\rho u)_{i+1/2}^{n-1} u_{i+1/2} - A_{i-1/2}(\rho u)_{i-1/2}^{n-1} u_{i-1/2}\right) \\ - V_i \ \Delta t\left(\frac{P_{i+1}^{n-1} - P_{i-1}^{n-1}}{2\Delta z} - \rho_i^{n-1} g + F_i^{n-1}\right) + \Delta t S_{mom,i}, \end{aligned} \tag{164}$$

where the dissipation term F_i^{n-1} is obtained from Equation (130) and is constrained by:

$$\left|F_i^{n-1}\right| \le \left|\frac{P_{i+1}^{n-1} - P_{i-1}^{n-1}}{2\Delta z} - \rho_i^{n-1} g\right|, \qquad 165)$$

and the sign of F_i^{n-1} is chosen to oppose flow. Finally, numerical momentum diffusion is added without distinguishing between phases in the mixture (ρ is the mixture density).

$$V_i \ (\rho u)_i^n = V_i \ (\rho u)_i^* - \zeta_p \Delta x_i \left[A_{i+1/2}\left((\rho u)_{i+1}^{n-1} - (\rho u)_i^{n-1}\right) - A_{i-1/2}\left((\rho u)_i^{n-1} - (\rho u)_{i-1}^{n-1}\right)\right]. \tag{166}$$

In the CRA-2004 PA, $\zeta_p = 0.01$.

Equation (127), Equation (128), and Equation (129) comprise a simultaneous system of equations for the volumes of gas and mud, and the pressure in the wellbore. The volumes of salt and waste will be known, since they are considered incompressible. Equation (127) and Equation (128) combine into a quadratic equation for gas volume

$$aV_g^2 + bV_g - c = 0\,, \tag{167}$$

where

$$\begin{aligned} a &= 1 - c_m P_{atm}\,, \\ b &= c_m P_{atm} V_{g,0} - aV^* + V_{m,0}\,, \\ c &= V^* c_m P_{atm} V_{g,0}\,, \\ V_{g,0} &= m_g / \rho_{g,0}\,, \\ V_{m,0} &= m_m / \rho_{m,0}\,, \end{aligned}$$

and

$$V^* = V_m + V_g = V - V_s - V_w$$

The volume of the mud phase follows from Equation (127) and the pressure from Equation (126). Once mixture density in each cell (ρ_i) is updated by Equation (128), mixture velocity in each cell (u_i) is computed by

$$u_i = \frac{(\rho u)_i}{\rho_i}\,,$$

where the quantity ρ u is determined by Equation (166).

PA-4.6.3.2 <u>Numerical Method – Repository</u>

The time integration method for the repository flow is implicit, with spatial derivatives determined after the time increment. This method requires the inversion of a matrix for the entire repository, which is usually straightforward. The implicit scheme is unconditionally stable. However, it is still necessary to use small time steps to ensure gradient accuracy.

The numerical method follows Press et al. (1989). For simplicity, the equations are presented for constant zone size, although DRSPALL implements difference equations that allow for a variable zone size. Near the cavity, a small, constant zone size is used, and then zones are allowed to grow geometrically as the outer boundary is approached. This procedure greatly increases computational efficiency without sacrificing accuracy in the region of interest.

For an isothermal ideal gas, the pseudopressure is defined as

$$\psi = \frac{P^2}{\eta} \quad \text{or} \quad P = \sqrt{\eta\psi}\,. \tag{168}$$

Using Equation (168), Equation (145) is expanded to

$$\frac{\partial\psi}{\partial t} = D(\psi)\left[\frac{\partial^2\psi}{\partial r^2} + \frac{(m-1)}{r}\frac{\partial\psi}{\partial r} + \frac{1}{k'}\frac{\partial k'}{\partial r}\frac{\partial\psi}{\partial r}\right], \tag{169}$$

where $D(\psi) = \frac{k'}{\phi}\sqrt{\frac{\psi}{\eta}} = \frac{k'P}{\phi\eta}$; Equation (169) is then converted to a difference equation by treating $D(\psi)$ as constant over a zone, using its zone-centered value at the current time D_j^n:

$$\frac{\psi_j^{n+1} - \psi_j^n}{\Delta t} = \frac{D_j^n}{\Delta r}\left[\frac{\psi_{j+1}^{n+1} - 2\psi_j^{n+1} + \psi_{j-1}^{n+1}}{\Delta r} + \frac{(m-1)\left(\psi_{j+1}^{n+1} - \psi_{j-1}^{n+1}\right)}{2r_j} + \frac{\left(k'^{\,n+1}_{j+1} - k'^{\,n+1}_{j-1}\right)\left(\psi_{j+1}^{n+1} - \psi_{j-1}^{n+1}\right)}{4k'\Delta r}\right]. \tag{170}$$

Collecting similar terms in ψ leads to a tridiagonal system:

$$-\alpha 1\psi_{j-1}^{n+1} + (1 + 2\alpha\alpha)_j^{n+1} - \alpha 2\psi_{j+1}^{n+1} = \psi_j^n - \alpha_1\Psi_{j-1}^{n+1} + (1 + 2\alpha \quad j = 1,2\ldots, \tag{171}$$

where

$$\alpha = \frac{D_j^n \Delta t}{(\Delta r)^2},$$

$$\alpha_1 = \left(\frac{D_j^n}{\Delta r}\right)\left(\frac{1}{\Delta r} - \frac{(m-1)}{2r_j} - \frac{k'^{\,n+1}_{i+1} - k'^{\,n+1}_{i-1}}{4k'\Delta r}\right)\Delta t\,,$$

$$\alpha_2 = \left(\frac{D_j^n}{\Delta r}\right)\left(\frac{1}{\Delta r} + \frac{(m-1)}{2r_j} + \frac{k'^{\,n+1}_{i+1} - k'^{\,n+1}_{i-1}}{4k'\Delta r}\right)\Delta t\,.$$

Equation (171) may be solved by simplified LU decomposition as presented in Press et al. (1989).

The boundary condition at the inner radius is implemented by noting that for i = 1 (the first intact or non-fluidized cell), ψ_{i-1} is the cavity pseudopressure, which is known, and therefore can be moved to the right hand side of Equation (171):

$$\left(1+2\alpha\right)\psi_1^{n+1} - \alpha_2\psi_2^{n+1} = \psi_1^n + \alpha_1\psi_{cav}^{n+1}. \tag{172}$$

The far field boundary condition is a zero gradient, which is implemented by setting $\psi_{j+1}^{n+1} = \psi_j^{n+1}$ in Equation (172), recognizing that $1+2\alpha = 1+\alpha_1+\alpha_2$ and rearranging, which gives

$$-\alpha_1\psi_{j-1}^{n+1} + \left(1+\alpha_1\right)\psi_j^{n+1} = \psi_j^n, \tag{173}$$

where j is the index of the last computational cell.

PA-4.6.3.3 Numerical Method – Wellbore to Repository Coupling

The term u_{rep}, appearing in Equation (150), is the gas velocity in the repository at the waste-cavity interface and is determined from the pressure gradient inside the waste. The CRA-2004 PA uses the pressure (P_1) at the center of the first numerical zone in the waste to determine u_{rep} :

$$u_{rep} = \frac{k\left(P_1 - P_{cav}\right)}{\Delta r\,\eta_g\phi}. \tag{174}$$

PA-4.6.4 Implementation

During development of the spallings model, a total of five parameters were determined to be both uncertain and potentially significant to model results (Hansen et al. 2003; Lord and Rudeen 2003). All five parameters relate to the repository conditions or the state of the waste at the time of intrusion. Table PA-14 lists the uncertain parameters in the DRSPALL calculations.

The computational requirements of DRSPALL prohibit calculation of spall volumes for all possible combinations of initial conditions and parameter values. Since repository pressure is a time-dependent value computed by the BRAGFLO model (see Section PA-4.2), DRSPALL calculations were performed for a small number of pressures. Sensitivity studies showed that spall does not occur at pressures below 10 MPa; this value was used as the lower bound on

Table PA-14. Uncertain Parameters in the DRSPALL Calculations

Parameter	Variable	Implementation
Repository Pressure	REPIPRES	Initial repository pressure (Pa); spall calculated for values of 10, 12, 14, and 14.8 MPa. Defines initial repository pressure in Equation (145) (see Section PA-4.6.2.2) and Pff in Equation (158).
Repository Permeability	REPIPERM	Permeability (m^2) of waste, implemented by parameter SPALLMOD/REPIPERM. Loguniform distribution from 2.4×10^{-14} to 2.4×10^{-12}. Defines k in Equation (142c).
Repository Porosity	REPIPOR	Porosity (dimensionless) of waste, implemented by parameter SPALLMOD/REPIPOR. Uniform distribution from 0.35 to 0.66. Defines ϕ in Equation (142b).
Particle Diameter	PARTDIAM	Particle diameter of waste (m) after tensile failure, implemented by parameter SPALLMOD/PARTDIAM. Loguniform distribution from 0.001 to 0.1 (m). Defines d_p in Equation (160).
Tensile Strength	TENSLSTR	Tensile strength of waste (Pa), implemented by parameter SPALLMOD/TENSLSTR. Uniform distribution from 0.12 MPa to 0.17 MPa. Defines $\overline{\sigma}_r$ in Section PA-4.6.2.3.5.

pressure. In DRSPALL, the repository pressure cannot exceed the far-field confining stress (14.9 MPa in the CRA-2004 PA); consequently, 14.8 MPa was used as the upper bound on pressure. Computations were also performed for intermediate pressures of 12 and 14 MPa.

The remaining four parameters listed in Table PA-14 were treated as subjectively uncertain. The uncertainty represented by these parameters pertains to the future state of the waste, which is modeled in PA as a homogeneous material with uncertain properties. In order to ensure that sampled values are independent and that the extremes of each parameter's range are represented in the results, the CRA-2004 PA uses Latin hypercube sampling to generate a sample of 50 elements. The LHS generated for DRSPALL calculations is independent of the LHS generated for the general PA calculations. Spall volumes are computed for each combination of initial pressure and sample element, for a total of $4 \times 50 = 200$ model runs. Although repository porosity could be treated as an initial condition (using the time-dependent value computed by BRAGFLO), to reduce the number of computational cases, and to ensure that extreme porosity values were represented, repository porosity was included as a sampled parameter. The LHS for DRSPALL and the results of the DRSPALL calculations are presented in Lord et al. (2003).

The spallings submodel of the code CUTTINGS_S uses the DRSPALL results to compute the spall volume for a given initial pressure P. An uncertain parameter SPALLMOD/RNDSPALL is included in the LHS for performance assessment (see Section PA-5.2) and is sampled from a uniform distribution on $[0,1]$. This parameter selects a sample element from the LHS for DRSPALL. The DRSPALL results for the selected sample element are used to construct the spall volume. If $P < 10$ MPa or $P > 14.8$ MPa, the spall volume is the value computed for REPIPRESS = 10 MPa or REPIPRESS = 14.8 MPa, respectively. If P falls between 10 and 14.8 MPa, the spall volume is constructed by linear interpolation between the DRSPALL results for pressures which bracket P.

PA-4.6.5 Additional Information

Additional information on DRSPALL and its use in the CRA-2004 PA to determine spallings releases can be found in the User's Manual for DRSPALL (WIPP PA 2003h) and in the analysis package for spallings releases (Lord et al. 2003). Additional information on the construction of spall volumes by the code CUTTINGS_S can be found in the CUTTINGS_S Design Document (WIPP PA 2003i).

PA-4.7 Direct Brine Release to Surface: BRAGFLO

This section describes the model for direct brine release (DBR) volumes, which are volumes of brine released to the surface at the time of a drilling intrusion. DBR volumes are calculated by the code BRAGFLO, the same code used to compute two-phase flow in and around the repository (see Section PA-4.2).

PA-4.7.1 Overview of Conceptual Model

DBRs could occur if the pressure in the repository at the time of a drilling intrusion exceeds 8 MPa, which is the pressure exerted by a column of brine-saturated drilling fluid at the depth of the repository (Stoelzel and O'Brien 1996). For repository pressures less than 8 MPa, no DBRs are assumed to occur. However, even if the repository pressure exceeds 8 MPa at the time of a drilling intrusion, a DBR is not assured, as there might not be sufficient mobile brine in the repository to result in movement towards the borehole.

DBRs are estimated for the following cases: (1) an initial intrusion into the repository into either a lower (down-dip), middle, or upper (up-dip) panel, (2) an intrusion into a waste panel that has been preceded by an E1 intrusion into either the same waste panel, an adjacent panel, or a non-adjacent panel, and (3) an intrusion into a waste panel that has been preceded by an E2 intrusion into either the same waste panel, an adjacent panel, or a non-adjacent panel (see Section PA-6.7). To determine releases for the above cases, the DBR calculations use a computational grid that explicitly includes all 10 waste panels (Figure PA-20).

The DBRs are assumed to take place over a relatively short period of time (i.e., 3 to 11 days) following the drilling intrusion. The initial value conditions for determining DBR volumes are obtained by mapping solutions of Equation (25) obtained from BRAGFLO with the computational grid in Figure PA-8 onto the grid in Figure PA-20.

In concept, the DBR for a drilling intrusion has the form

$$\boldsymbol{DBR} = \int_0^{t_e} \boldsymbol{rDBR}(t)\,dt\,, \tag{175}$$

where

DBR = direct brine release volume (m^3) for drilling intrusion,

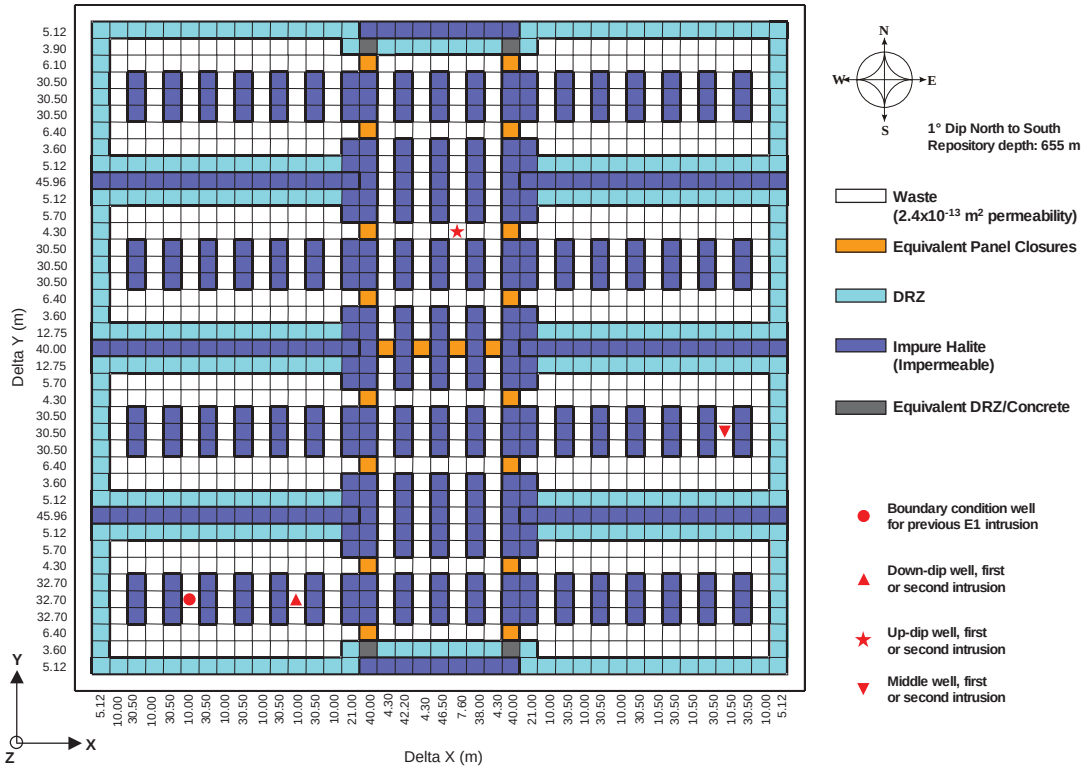

Note: Model cells are not to scale. The actual dimensions of the grid blocks are indicated along the edge of the diagram.

Figure PA-20. DBR Logical Mesh.

$rDBR(t)$ = rate (m^3) at time t at which brine flows up intruding borehole,

t = elapsed time (s) since drilling intrusion,

t_e = time (s) at which direct brine release ends.

The definition of $rDBR(t)$ is discussed in the following sections and is based on the two-phase flow relationships in Equation (25) and use of the Poettmann-Carpenter correlation (Poettmann and Carpenter 1952) to determine a boundary pressure at the connection between the intruding borehole and the repository. The time t_e is based on current drilling practices in the Delaware Basin (Section PA-4.7.8).

PA-4.7.2 Linkage to Two-Phase Flow Calculation

The mesh in Figure PA-20 was linked to the mesh in Figure PA-8 by subdividing the waste disposal area in the mesh in Figure PA-8 into three regions (Figure PA-21). Region 1 represents the northern rest of repository North RoR area in Figure PA-8. Region 2 represents the southern rest of repository South RoR area in Figure PA-8. Region 3 represents the farthest down-dip repository area Waste Panel in Figure PA-8 that contained waste and thus corresponds to the single down-dip waste panel. The linkage between the solutions to

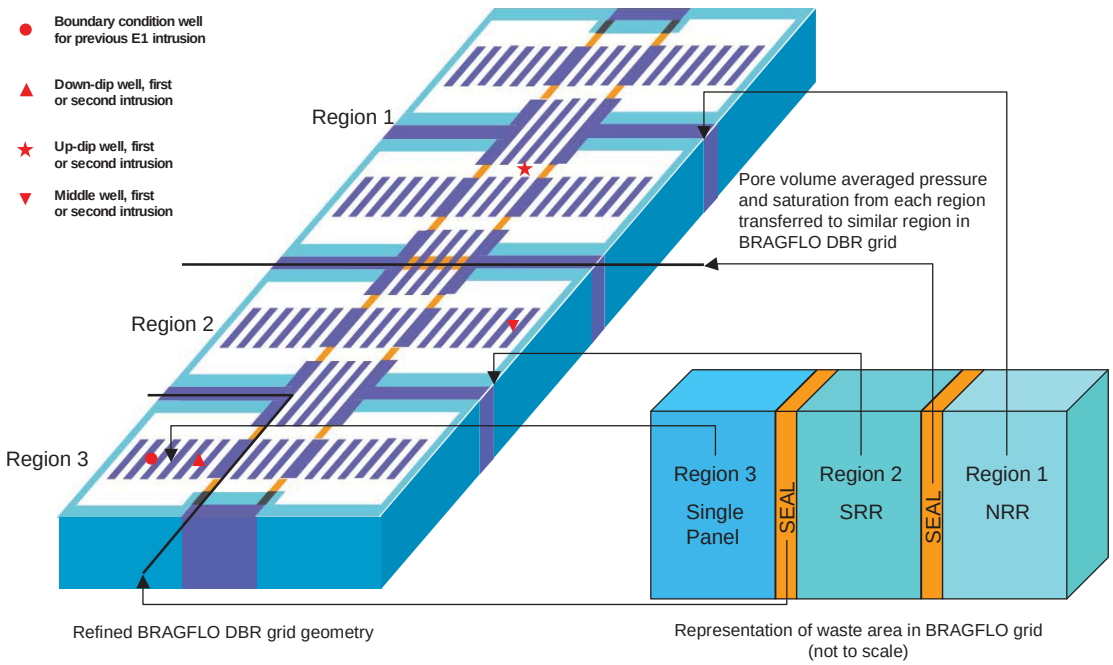

Figure PA-21. Assignment of Initial Conditions for DBR Calculation at Each Intrusion Time.

Equation (25) and the DBR calculations was made by assigning quantities calculated by BRAGFLO for each region in Figure PA-8 to the corresponding waste region in Figure PA-20.

The height of the grid in Figure PA-20 was assigned a value that corresponded to the crushed height h (m) of the waste as predicted by the solution of Equation (25). Specifically,

$$h = h_i \frac{1-\phi_i}{1-\phi}, \tag{176}$$

where h_i and ϕ_i are the initial height (m) and porosity of the waste and ϕ is the volume-averaged porosity of the waste at the particular time under consideration (Section PA-4.2.3). The areas designated equivalent panel closures, DRZ, and impure halite in Figure PA-20 were assigned the same pressures and saturations as the corresponding grid blocks in the 10,000 year BRAGFLO calculations. The area designated equivalent DRZ/concrete (Figure PA-20) was assigned the same pressures and saturations as the DRZ. These areas were assigned porosities that resulted in a conservation of the initial pore volumes used for these areas in the solution of Equation (25) on the grid in Figure PA-8. Specifically, the pore volumes associated with the panel closures, DRZ, and impure halite do not change with time, with this constancy implemented by the definitions of $\varphi(x,y,0)$ in Table PA-15.

The initial brine pressure $p_b(x,y,0)$ and gas saturation $S_g(x,y,0)$ in the grid in Figure PA-20 are assigned by:

$$p_b(x,y,0) = \int_R \tilde{p}_b(\tilde{x},\tilde{y},t_{int})dV / \int_R dV \,, \tag{177}$$

$$S_g(x,y,0) = \int_R \tilde{S}_g(\tilde{x},\tilde{y},t_{int})dV / \int_R dV \,, \tag{178}$$

where (x,y) designates a point in the grid in Figure PA-20, $\tilde{p}_b$ and $\tilde{S}_g$ denote solutions to Equation (25), $\tilde{x}$ and $\tilde{y}$ denote the variables of integration, tint is the time at which the drilling intrusion occurs, and R corresponds to the region in the computational grid for BRAGFLO (Figure PA-8) that is mapped into the region in the computational grid for BRAGFLO for DBR (Figure PA-20) that contains the point (x,y) (Figure PA-21). Note that t_{int} defines a time in the solution of Equation (25); t = 0 defines the start time for the DBR calculation and corresponds to t_{int} in the solution of Equation (25).

The initial porosity $\phi(x,y,0)$ in the grid in Figure PA-20 is set by the equations listed in Table PA-15. In Table PA-15, hi is initial height of waste panels (3.96 m), $\phi_{WP,i}$ is initial porosity of waste panels (0.848), $h(t_{int})$ is height of repository at time of intrusion (typically 1 to 1.5 m; corresponds to h in Equation (25)), $h_{DRZ,i}$ is initial height for DRZ (43.60 m) that results in DRZ in Figure PA-20 having the same pore volume as the initial pore volume of the DRZ in Figure PA-8, A_{DRZ} is area associated with DRZ in Figure PA-20, and $\phi_{DRZ,i}$ is initial porosity of DRZ (see Table PA-2). The quantity $h_{DRZ,i} \times A_{DRZ} \times \phi_{DRZ,i}$ is equal to pore volume of DRZ above and below the waste filled regions in Figure PA-8. In Table PA-15, the term ϕ_C is the porosity of the panel closure concrete material (CONC_PCS; see Table PA-2), d_1 is the length of the drift/explosion wall portion of the panel closure (32.1 m; see Figure PA-13), and d_2 is the length of the concrete portion of the panel closure (7.9 m; see Figure PA-13). The porosity of the panel closure and the equivalent DRZ/concrete materials are defined as the volume-weighted mean porosity of the component materials; this definition results in the same brine volume within the pore space in each set of panel closures in Figure PA-8 and Figure PA-20. In Table PA-15, $h_{H,i}$ is initial height of undisturbed halite in Figure PA-20, which is arbitrarily taken to be 8.98 m. However, this value is unimportant because of the extremely low permeability of the undisturbed halite (~3.16×10^{-23} m^2); any brine in the halite could not flow into the waste over the short time period of the DBR calculation, so no effort was made to preserve halite pore volume when mapping from the computational grid in Figure PA-8 to the computational grid in Figure PA-20. The quantity $\phi_{H,i}$ is initial porosity of halite (HALPOR, see Table PA-17).

PA-4.7.3 Conceptual Representation for Flow Rate rDBR(t)

The driving force that would give rise to the DBR is a difference between waste panel pressure, p_w (Pa), and the flowing bottomhole pressure in the borehole, p_{wf} (Pa) at the time of the intrusion. The flowing bottomhole pressure p_{wf}, defined as the dynamic pressure at the

Table PA-15. Initial Porosity in the DBR Calculation

Grid region	Initial Porosity $\varphi(x, y, 0)$
Waste	$1 - h_i \dfrac{1 - \phi_{WP,i}}{h(t_{\mathrm{int}})}$
Panel Closures	$\dfrac{\phi_C d_2 + d_1 \left[1 - h_i \left(1 - \phi_{WP,i} \right) / h(t_{int}) \right]}{d_1 + d_2}$
DRZ	$\dfrac{h_{DRZ,i} \phi_{DRZ,i}}{h(t_{int})}$
Impure Halite	$\dfrac{h_{H,i} \phi_{H,i}}{h(t_{int})}$
Equivalent DRZ/Concrete	$\dfrac{\phi_C d_1 + \phi_{DRZ,i} d_2}{d_1 + d_2}$

inlet of the intruding borehole to the waste panel, is less than the static pressure p_w due to elevation, friction and acceleration effects. The rate at which brine and gas are transported up the intruding borehole is determined by the difference $p_w - p_{wf}$ and a productivity index J_p for the intruded waste panel (Mattax and Dalton 1990, p. 79):

$$q_p(t) = J_p \left[p_w(t) - p_{wf} \right], \tag{179}$$

where

$q_p(t)$ = flow rate (m^3/s) at time t for phase p (p = b ~ brine, p = g ~ gas),

J_p = productivity index ($m^3/Pa \cdot s$) for phase p

and p_w and p_{wf} are defined above. As indicated by the inclusion/exclusion of a dependence on t, the terms J_p and p_{wf} are constant during the determination of $q_p(t)$ for a particular drilling intrusion in the present analysis, and $p_w(t)$ changes as a function of time. In concept, the DBR is given by

$$DBR = \int_0^{t_e} rDBR(t)\,dt = \int_0^{t_e} J_b \left[p_w(t) - p_{wf} \right] dt, \tag{180}$$

once J_p, p_w and p_{wf} are determined. Section PA-4.7.4 discusses the determination of J_p; Section PA-4.7.5 presents the numerical determination of p_w and DBR; and the determination of

p_{wf} is discussed in Section PA-4.7.6. The associated gas release is given by the corresponding integral with J_g rather than J_b. In the computational implementation of the analysis, DBR is determined as part of the numerical solution of the system of partial differential equations that defines p_w (Section PA-4.7.5).

PA-4.7.4 Determination of Productivity Index J_p

In a radial drainage area with uniform saturation, which is assumed to be valid throughout the DBR, the following representation for J_p can be determined from Darcy's law (Mattax and Dalton 1990, p. 79; Williamson and Chappelear 1981; Chappelear and Williamson 1981):

$$J_p = \frac{2\pi\pi k_{rp} h}{\mu_p \left[\ln(r_e / r_w) + s + c \right]}, \tag{181}$$

where

k = absolute permeability (assumed to be constant through time at 2.4×10^{-13} m^2),

k_{rp} = relative permeability to phase p (calculated with modified Brooks-Corey model in Equation (32) and brine and gas saturations, S_b and S_g, obtained by mapping solutions of Equation (25) obtained with grid in Figure PA-8 onto grid in Figure PA-20),

h = crushed panel height (Equation (176)),

μ_p = viscosity of fluid phase (assumed to be constant through time with $\mu_b = 1.8 \times 10^{-3}$ Pa·s, and $\mu_g = 8.92 \times 10^{-6}$ Pa·s (Kaufmann 1960)),

r_e = external drainage radius (for use with the rectangular grid-blocks in Figure PA-20, r_e is taken to be the equivalent areal radius; see Equation (182)),

r_w = wellbore radius (assumed to be constant through time at 0.1556 m (Table 14.7, Gatlin 1960)),

c = –0.50 for pseudo steady-state flow,

s = skin factor, which is used to incorporate flow stimulation caused by spallings release (see Equation (183)).

In the present analysis,

$$r_e = \sqrt{(\Delta\Delta x)(\Delta y)/}, \tag{182}$$

where Δx is the x-dimension (m) and Δy is the y-dimension (m) of the grid block containing the down-dip well in Figure PA-20 (Δx = 10 m and Δy = 32.7 m).

The skin factor s is derived from the spallings release through the following petroleum engineering well testing relationship (pp. 5-7, Lee 1982):

$$s = \left(\frac{k}{k_s} - 1\right) \ln\left(\frac{r_s}{r_w}\right), \tag{183}$$

where

k_s = permeability (m^2) of an open channel as a result of spallings releases (assumed to be infinite),

r_s = effective radius (m) of the wellbore with the spalled volume removed.

In the CCA PA, the effective radius r_s was obtained by converting the spalled volume release V_i into a cylinder of equal volume, then computing the radius of the cylinder. The area of the cylinder A_i is

$$A_i = \frac{V_i}{h_i}. \tag{184}$$

Then,

$$r_s = \sqrt{A_i / \pi} \tag{185}$$

and substitution of r_s into Equation (183) with $k_s = \infty$ yields

$$s = -\ln\left[\frac{\sqrt{A_i / \pi}}{r_w}\right]. \tag{186}$$

For the CRA-2004 PA, calculation of the skin factor was simplified by assuming that the spalled volume, V_i, would be equal to 4 m^3 for all intrusions. This assumption was made only for the calculation of the skin factor to determine DBRs. This assumption is conservative since it will overestimate the well productivity index and consequently overestimate DBRs for all intrusions where the spalled volume is less than 4 m^3.

PA-4.7.5 Determination of Waste Panel Pressure $p_w(t)$ and Direct Brine Release

The repository pressure $p_w(t)$ in Equation (180) after a drilling intrusion is determined with the same system of nonlinear partial differential equations discussed in Section PA-4.2. These equations are solved numerically by the code BRAGFLO used with the computational grid in

Figure PA-20 and assumptions (i.e., parameter values, initial value conditions, and boundary value conditions) that are appropriate for representing brine flow to an intruding borehole over a relatively short time period immediately after the intrusion (i.e., 3 – 11 days). Due to the short time periods under consideration, the model for DBR does not include gas generation due to either corrosion or microbial action and also does not include changes in repository height due to creep closure. Furthermore, to stabilize the calculation and thus allow longer time steps in the numerical solution, the capillary pressure was assigned a value of 0 Pa in all modeled regions (Figure PA-20); in the analysis of the full system in Section PA-4.2, capillary pressure had a value of 0 Pa in the waste regions and the DRZ but a nonzero value in the panel closures (Table PA-3). Use of a capillary pressure of 0 Pa results in the brine pressure $p_b(x,y,t)$ and the gas pressure $p_g(x,y,t)$ being equal, with the pressure $p_w(t)$ in Equation (180) given by

$$p_w(t) = p_b(x,y,t). \tag{187}$$

Although the determination of DBR can be conceptually represented by the integral in Equation (175), in the numerical implementation of the analysis, DBR is determined within the numerical solution of the system of partial differential equations that defines $p_b(x,y,t)$.

With the specific assumptions for DBR, Equation (25) becomes:

Gas Conservation
$$\nabla \bullet \left[\frac{\alpha \rho_g K_g k_{rg}}{\mu_g} \left(\nabla p_g + \rho_g g \nabla h \right) \right] = \alpha \frac{\partial \left(\phi \rho_g S_g \right)}{\partial t}, \tag{188a}$$

Brine Conservation
$$\nabla \bullet \left[\frac{\alpha \rho_b K_b k_{rb}}{\mu_b} \left(\nabla p_b + \rho_b g \nabla h \right) \right] = \alpha \frac{\partial \left(\phi \rho_b S_b \right)}{\partial t}, \tag{188b}$$

Saturation Constraint
$$S_g + S_b = 1, \tag{188c}$$

Capillary Pressure Constraint
$$p_g - p_b = 0, \tag{188d}$$

Gas Density ρ_g determined by Redlich-Kwong-Soave equation of state (Equation (45)) (188e)

Brine Density
$$\rho_b = \rho_0 \exp\left[\beta_b \left(p_b - p_{b0} \right) \right], \tag{188f}$$

Formation Porosity
$$\phi = \phi_0 \exp\left[\beta_f \left(p_b - p_{b0} \right) \right], \tag{188g}$$

with all symbols having the same definitions as in Equation (25).

The primary differences between the BRAGFLO calculations described in Section PA-4.2 and the BRAGFLO calculations described in this section are in the computational meshes used (Figure PA-20 and Figure PA-8), the initial values used (Table PA-2 and Section PA-4.7.2), and the boundary conditions used (Table PA-16). In particular, brine and gas flow associated with

intruding boreholes in the DBR calculations are incorporated by the appropriate assignment of boundary conditions. Specifically, brine flow up an intruding borehole is incorporated into Equation (188) by using the Poettmann-Carpenter wellbore model to determine the pressure at the outflow point in a waste panel (Figure PA-20), with this pressure entering the calculation as a boundary value condition (Table PA-16). The details of this determination are discussed in Section PA-4.7.6. Further, for calculations that assume a prior E1 intrusion, the effects of this intrusion are also incorporated into the analysis by specifying a pressure specified as a boundary condition (Table PA-16). The determination of this pressure is discussed in Section PA-4.7.6.

Table PA-16. Boundary Conditions for p_b and S_g in DBR Calculations

(x, y) on Upper (Northern) or Lower (Southern) Boundary in Figure PA-20, $0 \le t$	
$\left(\nabla p_g + \rho_g g \nabla h\right)\Big\vert_{(x,y,t)} \cdot j = 0 \;\; Pa/m$	no gas flow condition
$\left(\nabla p_b + \rho_b g \nabla h\right)\Big\vert_{(x,y,t)} \cdot j = 0 \;\; Pa/m$	no brine flow condition
(x, y) on Right (Eastern) or Left (Western) Boundary in Figure PA-20, $0 \le t$	
$\left(\nabla p_g + \rho_g g \nabla h\right)\Big\vert_{(x,y,t)} \cdot i = 0 \;\; Pa/m$	no gas flow condition
$\left(\nabla p_b + \rho_b g \nabla h\right)\Big\vert_{(x,y,t)} \cdot i = 0 \;\; Pa/m$	no brine flow condition
(x, y) at Location of Drilling Intrusion under Consideration (see indicated points in Figure PA-20), $0 \le t$	
$P_b(x, y, t) = P_{wf}$ (see Section PA.4.7.6)	constant pressure condition
(x, y) at Location of Prior Drilling Intrusion into Pressurized Brine (see indicated point in Figure PA-20), $0 \le t$	
$P_b(x, y, t) = P_{wE1}$ (see Section PA.4.7.7)	constant pressure condition

For perspective, the following provides a quick comparison of the assumptions that underlie the solution of Equation (25) on the mesh in Figure PA-8 (i.e., the BRAGFLO mesh) and the solution of Equation (188) on the mesh in Figure PA-20 (i.e., the BRAGFLO mesh for DBR):

1. The BRAGFLO mesh for DBR is defined in the areal plane with the z-dimension (height) one element thick; the BRAGFLO mesh is defined as a cross-section, with multiple layers in height and the thickness (y-dimension) one element thick.

2. The BRAGFLO mesh for DBR uses constant thickness, while BRAGFLO uses rectangular flaring to account for three-dimensional volumes in a two-dimensional grid (Figure PA-9).

3. The BRAGFLO mesh for DBR represents flow only in the waste area. The BRAGFLO model includes the surrounding geology as well as the entire WIPP excavation (including operations, experimental, and shaft regions).

4. Local scale heterogeneities are included in the BRAGFLO mesh for DBR, including the salt pillars, rooms, panel closures, and passageways that contain waste. These are not fully represented in the BRAGFLO mesh.

5. The DRZ is included in both models, but exists above and below the excavated regions in the BRAGFLO model, whereas the DRZ surrounds the waste rooms on the sides of the BRAGFLO mesh for DBR.

6. Both models include a one-degree formation dip through the excavated regions (Equation (27)).

PA-4.7.6 Boundary Value Pressure p_{wf}

The boundary value pressure p_{wf} at the inlet of the intruding borehole is defined by a system of equations of the following form:

$$\frac{dp}{dh} = G\left(q_b\left[p(0)\right], q_g\left[p(0)\right], p(h), h\right), \quad 0 \le h \le 655m\,, \tag{189a}$$

$$p(655) = 1.013 \times 10^5 \ Pa\,, \tag{189b}$$

$$q_b\left[p(0)\right] = J_b\left[p_w - p(0)\right], \tag{189c}$$

$$q_g\left[p(0)\right] = J_g\left[p_w - p(0)\right], \tag{189d}$$

where $p(h)$ is pressure (Pa) at elevation h (m) in the borehole with h = 0 m corresponding to the entry point of the borehole into the waste panel and h = 655 m corresponding to the land surface (Figure PA-22), G is a function (Pa/m) characterizing the change of pressure with elevation in the borehole, $p(655)$ is an initial value condition requiring that pressure at the land surface (i.e., the outlet point of the borehole) be equal to atmospheric pressure, $q_b\left[p(0)\right]$ and $q_b\left[p(0)\right]$ define brine and gas flow rates (m^3/s) into the borehole, J_b and J_g are productivity indexes (m^3/Pa s) (see Equation (181)), and p_w is the pressure (Pa) in the repository at the time of the drilling intrusion.

The boundary value pressure p_{wf} is defined by

$$p_{wf} = p(0)\,. \tag{190}$$

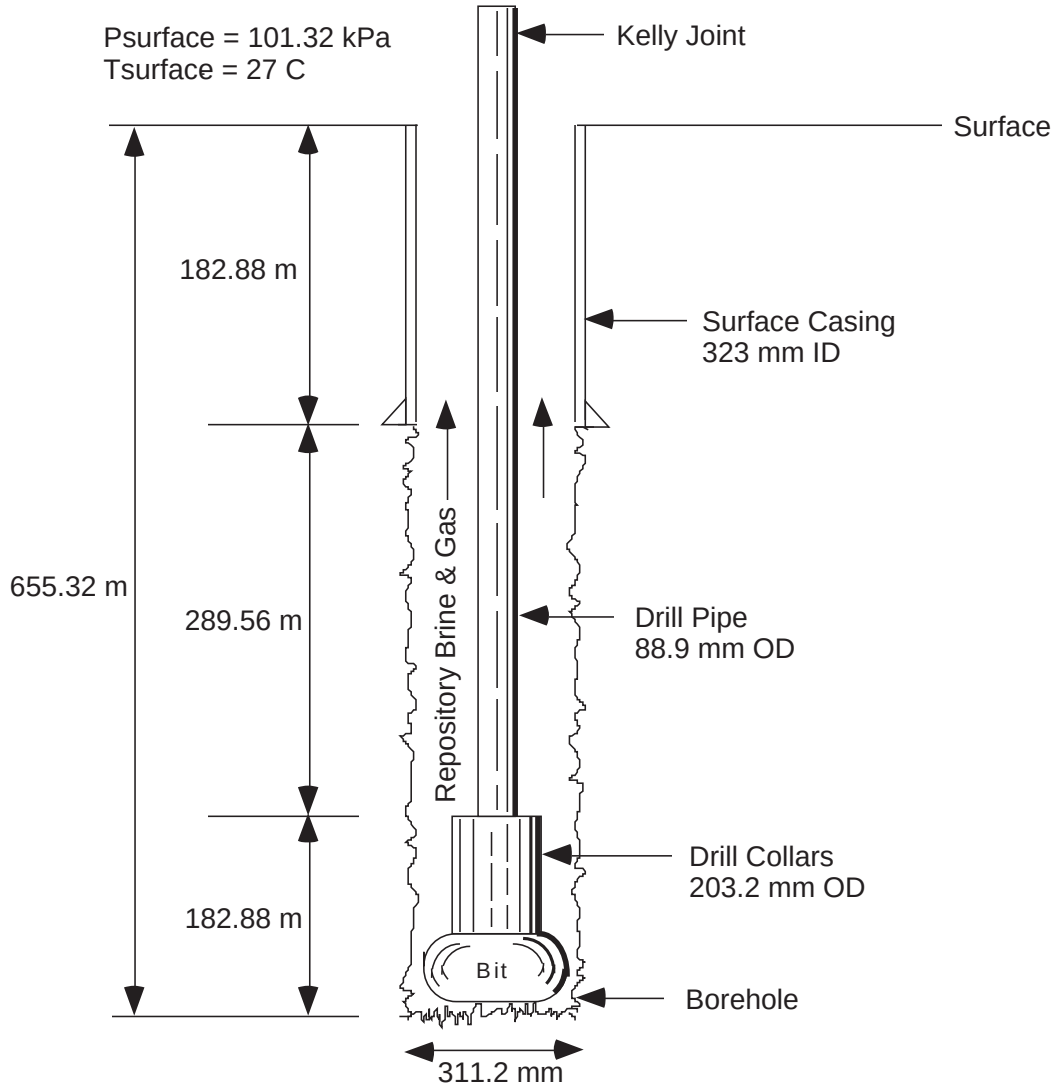

Figure PA-22. Borehole Representation Used for Poettmann-Carpenter Correlation.

Thus, p_{wf} is determined by the numerical solution of Equation (189a) for $\boldsymbol{p}(\boldsymbol{0})$ subject to the constraints in Equation (189b), Equation (189c) and Equation (189d).

The pressure p_w corresponds to the pressure $\boldsymbol{p_w}(\boldsymbol{0})$ in Equation (187) and is obtained from the solution of Equation (25) with the computational grid in Figure PA-8 (see Section PA-4.7.2). The production indexes J_b and J_g are defined in Equation (181). Thus, the only quantity remaining to be specified in Equation (189) is the function G.

Brine and gas flow up a borehole is governed by complex physics dependent on frictional effects and two-phase fluid properties. This phenomenon has been widely studied in the petroleum industry and many modeling procedures have been developed to predict flow rates and pressures in vertical two-phase pipe flow (i.e., to define G in Equation (189a)) (Brill and Beggs 1986). For this analysis, the Poettmann-Carpenter model (Poettmann and Carpenter 1952, Welchon et al.

1962) was used to define G because it accounts for multiphase frictional effects based on empirical (i.e., field) data from flowing wells, is one of the few modeling approaches that included annular flow data in its development, and is relatively easy to implement. Specifically, the Poettmann-Carpenter model defines G by:

$$G\left(q_b\left[p(0)\right], q_g\left[p(0)\right], p(h), h\right) = gm(h) + f'\left(m(h), D(h), q_b\left[p(0)\right]\right) gm(h) F^2(h) / D^5(h), \quad (191)$$

where

g = acceleration due to gravity (9.8 m/s^2),

m(h) = density (kg/m^3) of fluids (i.e., gas and brine) in wellbore at elevation h (Note: ***m(h)*** is a function of $q_b\left[p(0)\right]$ and $q_g\left[p(0)\right]$; see Equation (192), below),

$f'\left\{m(h), D(h) q_b\left[p(0)\right]\right\}$ = empirically defined scale factor (m/s^2) (Note: f' is the scale factor in the Poettmann-Carpenter model for fluid flow in a wellbore [Poettmann and Carpenter 1952]; see discussion below),

$F(h)$ = flow rate (m^3/s) of fluids (i.e., gas and brine) in wellbore at elevation h (Note: $F(h)$ is a function of $q_b\left[p(0)\right]$ and $q_g\left[p(0)\right]$; see Equation (193), below),

$D(h)$ = effective diameter (m) of wellbore (see Equation (196), below).

The first term, $gm(h)$, in Equation (191) results from the contribution of elevation to pressure; the second term results from frictional effects (Poettmann and Carpenter 1952). The fluid density $m(h)$ at elevation h is given by

$$m(h) = \frac{q_b\left[p(0)\right]\rho_b\left[p(0)\right] + q_g\left[p(0)\right]\rho_g\left[p(0)\right]}{F(h)}, \quad (192)$$

where

$$F(h) = q_b\left[p(0)\right] + \frac{z(h)\,p(h)}{p(0)} q_g\left[p(0)\right], \quad (193)$$

and

$\rho_b\left[p(0)\right]$ = density (kg/m^3) of brine at pressure $p(0)$ and temperature 300.1°K, which is fixed at 1230 kg/m^3,

$\rho_g\,[p(0)]$ = density (kg/m^3) of H_2 at pressure $p(0)$ and temperature 300.1°K (see Equation (194), below),

$z(h)$ = z-factor for compressibility of H_2 at elevation h (Note: $z(h)$ is a function of $p(h)$; see Equation (195), below), and $q_g\,[p(0)]$ and $q_g\,[p(0)]$ are defined in Equation (189).

The gas density in Equation (192) is obtained from the universal gas law, PV = nRT, by

$$\rho_g\,[p(0)] = C_{m,\,kg}\,\frac{n}{V} = C_{m,\,kg}\,\frac{P}{RT}, \tag{194}$$

where n is the amount of gas (mol) in a volume V, $C_{m,kg}$ is the conversion factor from moles to kilograms for H_2 (i.e., 2.02×10^{-3} kg/mol), $P = p(0)$, R = 8.3145 kg m^2/mol°K s^2, and T = 300.1°K. The z-factor is given by

$$z(h) = 1 + (8.54 \times 10^{-8}\ Pa^{-1})\,p(h), \tag{195}$$

and was obtained from calculations performed with the SUPERTRAPP program (Ely and Huber 1992) for pure H_2 and a temperature of 300.1°K (Stoelzel and O'Brien 1996, Figure 4.7.4). The preceding approximation to $z(h)$ was obtained by fitting a straight line between the results for pressures of 0 psi and 3000 psi and a hydrogen mole fraction of 1 in Stoelzel and O'Brien (1996, Figure 4.7.4); the actual calculations used the more complex, but numerically similar, regression model given in Stoelzel and O'Brien (1996, Figure 4.7.4). The numerator and denominator in Equation (192) involve rates, with the time units canceling to give $m(h)$ in units of kg/m^3.

The effective diameter $D(h)$ in Equation (191) is defined with the hydraulic radius concept. Specifically,

$$D^5(h) = [D_0(h) + D_i(h)]^2\,[D_0(h) - Di/(h)]^3, \tag{196}$$

where $D_i(h)$ and $D_0(h)$ are the inner and outer diameters (m) of the wellbore at elevation $h(m)$ (see Figure PA-22). The factor f' in Equation (191) is a function of $m(h)$, $D(h)$ and $q_g\,[p(0)]$.

In the original development by Poettmann and Carpenter (1952, Figure 4), f' is defined in terms of quantities commonly used to measure production from oil and gas wells. The result is that f' is expressed in quantities that are unfamiliar outside of the oil and gas industry. For clarity, Equation (191) and the quantities contained in it are expressed in SI units. However, to allow use of the original correlations developed by Poettmann and Carpenter to define f', the calculations within the CCA PA (Stoelzel and O'Brien 1996) were performed in the same oilfield units originally used by Poettmann and Carpenter (1952).

Subsequent to submittal of the CCA PA, it was discovered that the factor of 2π was omitted from Equation (181). This error was determined to be of no consequence to the conclusions of the CCA PA (Hadgu et al. 1999) and has been corrected in the CRA-2004 PA. As a consequence of the error correction, the regression models used to determine the boundary pressure p_{wf} were recalculated (Hadgu et al. 1999). The corrected regression models are reported in this appendix.

The following iterative procedure based on bisection method was used to approximate solutions to Equation (189).

Step 1. Estimate $p(0)$ using a bisection algorithm. (Initial guess for $p(0)$ is the midpoint $\frac{1}{2}p_w$ of interval $[0, p_w]$, where p_w is the pressure in the repository at the time of the drilling intrusion used in Equation (189)). Next guess for $p(0)$ is at the midpoint of either $\left[0, \frac{1}{2}p_w\right]$ or $\left[\frac{1}{2}p_w, p_w\right]$ depending on whether resultant approximation to $p(655)$ is above or below atmospheric pressure. Subsequent guesses for $p(0)$ are made in a similar manner.

Step 2. Use $p(0)$, known values for J_b, J_g and p_w, and Equation (189) to determine $q_b[p(0)]$ and $q_g[p(0)]$.

Step 3. Use the bisection method with Δh = 25 ft = 7.62 m and appropriate changes in annular diameter (Figure PA-22) to determine $p(655)$ (i.e., $p(h+\Delta h) = p(h) + G\left(q_b[p(0)], q_g[p(0)], p(h), h\right)\Delta h$).

Step 4. Stop if $p(655)$ is within 0.07% of atmospheric pressure (i.e., if $\left|1.013\times 10^5\ Pa - p(655)\right| \le 70\ Pa$). Otherwise, return to Step 1 and repeat process.

The preceding procedure is continued until the specified error tolerance (i.e., 0.07percent) has been met. The computational design of the PA has the potential to require more than 23,000 separate DBR calculations (3 replicates × 5 scenarios × 3 drilling locations × 100 vectors × 5 to 6 intrusion times per scenario). In concept, each of these cases requires the solution of Equation (189) with the iterative procedure just presented to obtain the boundary value condition $p_{wf} = p(0)$ (Table PA-16). To help hold computational costs down, $p(0)$ was calculated for approximately 2000 randomly generated vectors of the form

$$v = \left[p_w, h, S_{br}, S_{gr}, S_b, A_i\right], \tag{197}$$

where p_w is the repository pressure (used in definition of $q_b\left[p(0)\right]$ and $q_g\left[p(0)\right]$ in Equation (189)), h is the crushed height of the repository (used in definition of J_p in Equation (181)), S_{br} and S_{gr} are the residual saturations for gas and brine in the repository (used in definition of k_{rp} in Equation (181)), S_b is the saturation of brine in the repository (used in definition of k_{rp} in Equation (181)), and A_i is the equivalent area of material removed by spallings (used in definition of skin factor s in Equation (186)). The outcomes of these calculations were divided into three cases:

1. mobile brine only (i.e., $k_{rg} = 0$ in Equation (188a))
2. brine-dominated flow (i.e., $k_{rb} > k_{rg}$), and
3. gas-dominated flow (i.e., $k_{rg} > k_{rb}$).

Then, regression procedures were used to fit algebraic models that can be used to estimate $p(0)$. These regression models were then used to determine $p(0)$, and hence p_{wf}. The resulting three regression models (or curve fit equations) for flowing bottomhole pressure (p_{wf}) are as follows.

1. For a system with only mobile brine (i.e., $k_{rg} = 0$)

$$p_{wf} = a + bx + cy + dx^2 + ey^2 + fxy + gx^3 + hy^3 + ixy^2 + jx^2y\,, \qquad (198a)$$

where $x = \mathbf{log}\left(J_b\right)$ and $y = p_w$ (= repository pressure). The coefficients in Equation (198a) were determined to be:

$$\begin{aligned}
a &= 3.2279346 \times 10^{11},\\
b &= 9.4816648 \times 10^{10},\\
c &= -6.2002715 \times 10^{3},\\
d &= 9.2450601 \times 10^{9},\\
e &= 4.1464475 \times 10^{-6},\\
f &= -1.2886068 \times 10^{3},\\
g &= 2.9905582 \times 10^{8},\\
h &= 1.0857041 \times 10^{-14},\\
i &= 4.7119798 \times 10^{-7},\\
j &= -6.690712 \times 10^{-1},
\end{aligned}$$

with resulting coefficient of determination $R^2 = 0.974$.

2. For brine dominated flow ($k_{rb} > k_{rg}$):

$$Pwf = \frac{a + bx + cx^2 + dy}{1 + ex + fx^2 + gx^3 + hy}, \tag{198b}$$

where $x = \log\left(\frac{k_{rg}}{k_{rb}}\right)$ and $y = p_w$ (= repository pressure). The coefficients in Equation (198b) were determined to be:

a = 1.6065077×10^{6},
b = 2.6243397×10^{6},
c = 2.4768899×10^{6},
d = $-5.3635476 \times 10^{-2}$,
e = 7.0815693×10^{-1},
f = 3.8012696×10^{-1},
g = 4.1916956×10^{-3},
h = $-2.4887085 \times 10^{-8}$,

with resulting coefficient of determination $R^2 = 0.997$.

3. For gas dominated flow ($k_{rg} > k_{rb}$):

$$p_{wf} = a + b\frac{1}{x} + cy + d\frac{1}{x^2} + ey^2 + f\frac{x}{y} + g\frac{1}{x^3} + hy^3 + i\frac{y^2}{x} + j\frac{y}{x^2}, \tag{198c}$$

where $x = \log\left(J_g\right)$ and $y = p_w$ (= repository pressure). The coefficients in Equation (198c) were determined to be:

a = -1.0098405×10^{9},
b = $-2.3044622 \times 10^{10}$,
c = 9.8039146,
d = $-1.7426466 \times 10^{11}$,
e = 1.8309137×10^{-7},
f = 1.7497064×10^{2},
g = $-4.3698224 \times 10^{11}$,
h = $-1.4891198 \times 10^{-16}$,
i = 1.3006196×10^{-6},
j = 7.5744833×10^{2},

with resulting coefficient of determination $R^2 = 0.949$.

PA-4.7.7 Boundary Value Pressure p_{wE1}

Some of the calculations for DBR are for a drilling intrusion that has been preceded by an E1 intrusion in either the same waste panel, an adjacent waste panel, or a nonadjacent waste panel (Section PA-6.7.5). The effects of these prior E1 intrusions are incorporated into the solution of Equation (188), and hence into the DBR, by the specification of a boundary pressure p_{wE1} at the location of the E1 intrusion into the repository (Table PA-16).

Two cases are considered for the definition of p_{wE1}: (1) an open borehole between the brine pocket and the repository, and (2) a borehole between the brine pocket and the repository filled with material with properties similar to silty sand. The first case corresponds to the situation in which the drilling intrusion under consideration has occurred within 200 years of a prior drilling intrusion that penetrated the pressurized brine pocket, and the second case corresponds to the situation in which the drilling intrusion under consideration has occurred more than 200 years after a prior drilling intrusion that penetrated the pressurized brine pocket.

PA-4.7.7.1 Solution for Open Borehole

In this case, p_{wE1} is set equal to the flowing well pressure p_{wfBP} of an open borehole between the brine pocket and the repository and is given by:

$$Q = f_1\left(p_{BP}, p_{wfBP}\right), \tag{199a}$$

$$Q = f_2\left(p_{wfBP}, p_{wfBI}\right), \tag{199b}$$

$$Q = f_3\left(p_{wfBI}, p_{wfBO}\right), \tag{199c}$$

where

pB = pressure (Pa) in brine pocket,

p_{wfBP} = flowing well pressure (Pa) at outlet from brine pocket,

p_{wfBI} = flowing well pressure (Pa) at inlet to repository from brine pocket,

p_{wfBO} = flowing well pressure (Pa) at outlet from repository due to intruding borehole (Note: The boreholes associated with p_{wfBI} and p_{wfBO} arise from different drilling intrusions and hence are at different locations; see Figure PA-20),

Q = brine flow rate (m^3/s) from brine pocket to repository, through repository, and then to surface,

and f_1, f_2 and f_3 are linear functions of their arguments. In the development, p_{BP} and p_{wfBO} are assumed to be known, with the result that Equation (199) constitutes a system of three linear

equations in three unknowns (i.e., p_{wfBP}, p_{wfBI}, Q) that can be solved to obtain p_{wfBI}. In the determination of $p_{wfBI} = p_{wE1}$ for use in a particular solution of Equation (188), p_{BP} is the pressure in the brine pocket at the time of the intrusion obtained from the solution of Equation (25) with BRAGFLO, and p_{wfBO} is the flowing well pressure obtained from conditions at the time of the intrusion (from the solution of Equation (25)) and the solutions of the Poettmann-Carpenter model embodied in Equation (198) (i.e., given pressure, k_{rg} and k_{rb} at the time of the intrusion from the solution of Equation (25) with BRAGFLO and J_b from both the solution of Equation (25) with BRAGFLO and the evaluation of the spallings release (assumed to be a constant of 4 m^3), p_{wfBO} is determined from the regression models indicated in Equation (198).

The definition of Equation (199) is now discussed. Equation (199a) characterizes flow out of the brine pocket into an open borehole and has the form (Williamson and Chappelear 1981, Chappelear and Williamson 1981):

$$Q = \left(\frac{2\pi k_{BP} h_{BP}}{\mu \left[\ln\left(r_{eBP} / r_w \right) - 0.5 \right]} \right) \left(p_{BP} - p_{wfBP} \right), \tag{200}$$

where

k_{BP} = brine pocket permeability (m^2),

h_{BP} = effective brine pocket height (m),

r_{eBP} = effective brine pocket radius (m),

r_w = wellbore radius (m),

μ = brine viscosity (Pa s).

In the present analysis, k_{BP} is an uncertain analysis input (see BHPRM in Table PA-17), h_{BP} = 125.83 m, r_{eBP} = 114 m (Stoelzel and O'Brien 1996), which corresponds to the size of the largest brine pocket that could fit under one waste panel, r_w = (8.921 in.) / 2 = 0.1133 m, which is the inside radius of a 9 5/8 in. outside diameter casing (Gatlin 1960, Table 14.7), $\mu = 1.8 \times 10^{-3}$ Pa s, and p_{BP} is determined from the solution of Equation (25) as previously indicated.

Equation (199b) characterizes flow up an open borehole from the brine pocket to the repository and is based on Poiseuille's Law (Prasuhn 1980, Eqs. 7-21, 7-22). Specifically, Equation (199b) has the form

$$Q = \left[\frac{\pi D^4}{128\mu \left(y_{BP} - y_{rep} \right)} \right] \left[\left(p_{wfBP} - p_{wfBI} \right) + g\rho \left(y_{rep} - y_{BP} \right) \right], \tag{201}$$

where

D = wellbore diameter (m),

y_{rep} = elevation of repository (m) measured from surface,

y_{BP} = elevation of brine pocket (m) measured from surface,

g = acceleration due to gravity (9.8 m/s^2),

ρ = density of brine (kg/m^3),

and the remaining symbols have already been defined.

In the present analysis, $D = 2r_w = 0.2266$ m, $\rho = 1230$ kg/m^3, and $y_{rep} - y_{BP} = 247$ m. With the preceding values,

$$128\mu\left(y_{BP} - y_{rep}\right)\Big/\pi D^4 = 6.87 \times 10^3 \ \ Pa\ s/m^3 \ , \tag{202}$$

$$g\rho\left(y_{rep} - y_{BP}\right) == 2.98 \times 10^6 \ \ Pa \ . \tag{203}$$

Thus,

$$p_{wfBI} = p_{wfBP} - 2.98 \times 10^6 \ \ Pa \ . \tag{204}$$

when Q is small (≤ 0.1 m^3/s). When appropriate, this approximation can be used to simplify the construction of solutions to Equation (199).

Equation (199c) characterizes flow through the repository from the lower borehole to the bottom of the borehole associated with the drilling intrusion under consideration and has the same form as Equation (200). Specifically,

$$Q = \left(\frac{2\pi k_{rep} h_{rep}}{\mu\left[\ln\left(r_{e,rep}/r_w\right) - 0.5\right]}\right)\left(p_{wfBI} - p_{wfBO}\right), \tag{205}$$

where

k_{rep} = repository permeability (m^2),

h_{rep} = repository height (m),

$r_{e,rep}$ = effective repository radius (m),

and the remaining symbols have already been defined. In the present analysis, $k_{rep} = 2.4 \times 10^{-13}\, m^2$; h_{rep} at the time of the drilling intrusion under consideration is obtained from the solution of Equation (25) (see Equation (176)); and $r_{e,rep}$ is the same as the radius r_e defined in Equation (182). As previously indicated, p_{wfBO} is obtained from the solutions to the Poettmann-Carpenter model summarized in Equation (198).

Three equations (i.e., Equation (200), Equation (201) and Equation (205)) in three unknowns (i.e., p_{wfBP}, p_{wfBI} and Q) have now been developed. The solution for p_{wfBI} defines the initial value p_{wE1} in Table PA-16. When the simplification in Equation (204) is used, the resultant solution for p_{wfBI} is

$$p_{wfBI} = \frac{p_{wfBO} + \left(p_{BP} - 2.98 \times 10^6\right) K_1}{1 + K_1}, \tag{206}$$

where

$$K_1 = \frac{k_{BP} h_{BP} \left[\ln\left(\frac{r_{e,rep}}{r_w} \right) - \frac{1}{2} \right]}{k_{rep} h_{rep} \left[\ln\left(\frac{r_{eBP}}{r_w} \right) - \frac{1}{2} \right]}, \tag{207}$$

and -2.98×10^6 comes from Equation (203). The expression in Equation (207) was used to define p_{wE1} in the CCA PA in the determination of DBRs for a drilling intrusion that occurred within 200 years of a preceding E1 intrusion (see Table PA-5). The same approach was used for the CRA-2004 PA.

PA-4.7.7.2 Solution for Sand-Filled Borehole

The determination of the pressure p_{wfBI} with the assumption that a borehole filled with material with properties similar to silty sand connects the brine pocket and the repository is now considered. The approach is similar to that used for the open borehole except that Equation (199a) and Equation (199b) are replaced by a single equation based on Darcy's Law. Specifically, flow from the brine pocket to the repository is represented by

$$Q = \frac{k_{BH} A_{BH} \left[\left(p_{wfBP} - p_{wfBI} \right) + g\rho \right]}{\mu \left(y_{BP} - y_{rep} \right)}, \tag{208}$$

where

k_{BH} = borehole permeability (m^2),

A_{BH} = borehole cross-sectional area (m^2),

and the remaining symbols have been defined previously. In the present analysis, k_{BH} is an uncertain input (see BHPRM in Table PA-17) and A_{BH} is defined by the assumption that the borehole diameter is the same as the drill bit diameter (i.e., 12.25 in. = 0.311 m).

The representation for flow from the brine pocket inlet point to the repository to the outlet point associated with the drilling intrusion under consideration remains as defined in Equation (205). Thus, two equations (i.e., Equation (208) and Equation (205)) and two unknowns (i.e., p_{wfBI} and Q) are under consideration. Solution for p_{wfBI} and yields

$$p_{wfBI} = \frac{p_{wfBO} + K_2 p_{BP} - 2.98 \times 10^6 K_2}{1 + K_2} \tag{209}$$

where

$$K_2 = \frac{\pi k_{BH} r_w^2 \left[\ln\left(\frac{r_{eBP}}{r_w} \right) - \frac{1}{2} \right]}{2\pi h_{rep} k_{rep} \left(y_{BP} - y_{rep} \right)} \tag{210}$$

and -2.98×10^6 comes from Equation (203). The expression in Equation (209) was used to define p_{wE1} in the determination of DBRs for a drilling intrusion that occurred more than 200 years after a preceding E1 intrusion (see Table PA-5).

PA-4.7.8 End of Direct Brine Release

The CRA-2004 PA has 23,400 cases that potentially required solution of Equation (188) to obtain the DBR volume (See Section PA-6.7.5). However, the DBR was set to zero without solution of Equation (188) when there was no possibility of a release (i.e., the intruded waste panel at the time of the intrusion had either a pressure less than 8 MPa or a brine saturation below the residual brine saturation S_{br}).

For the remaining cases, Equation (188) was solved for a time period of 50 days, although the value used for t_e was always less than 50 days. The minimum value used for t_e was three days, which is an estimate of the time required to drill from the repository through the Castile Formation and then cement the intermediate casing. If there is little or no gas flow associated with brine inflow into the borehole during drilling in the Salado Formation, current industry practice is to allow the brine to “seep” into the drilling mud and be discharged to the mud pits until the salt section is cased.

If there is a significant amount of gas flow, then it is possible that the driller will lose control of the well. In such cases, DBRs will take place until the gas flow is brought under control. Two possibilities exist: (1) the driller will regain control of the well when the gas flow drops to a manageable level, and (2) aggressive measures will be taken to shut off the gas flow before it

drops to a manageable level. In the CCA PA, the driller was assumed to be able to regain control of the well when the gas flow dropped to a "cut-off" rate of 1×10^5 standard cubic feet per day (SCF/d in commonly used oil field units). Experience at the South Culebra Bluff Unit #1, which blew out in January 1978, suggests that approximately 11 days may be needed to bring a well under control before the gas flow drops to a manageable level (i.e., 1×10^5 SCF/d) (DOE 1996, Appendix MASS Attachment MASS 16-2). In particular, it took 11 days to assemble the equipment and personnel needed to bring that well under control.

Given the preceding, t_e is defined by

$$t_e = \begin{cases} \max\left\{3\ d, t_f\right\} & \text{if } t_f \le 11\ d \\ 11\ d & \text{if } t_f > 11\ d \end{cases} \tag{211}$$

in the CRA-2004 PA, where t_f is the time at which the gas flow out of the well drops below 1×10^5 SCF/d. As a reminder, gas flow out of the repository in the intruding borehole, and hence t_e, is determined as part of the solution to Equation (188).

PA.-4.7.9 Numerical Solution

As previously indicated, the BRAGFLO program is used to solve Equation (188) with the computational grid in Figure PA-20, the initial value conditions in Section PA-4.7.2, the boundary value conditions in Table PA-16, and parameter values appropriate for modeling DBRs. Thus, the numerical procedures in use for Equation (188) are the same as those described in Section PA-4.2.10 for the solution of Equation (25).

In this solution, the boundary value conditions associated with drilling intrusions (i.e., p_{wf} and pwE1 in Table PA-16) are implemented through the specification of fluid withdrawal terms (i.e., q_{wg} and q_{wb} in Equation (25)) rather than as defined boundary value conditions. With this implementation, the representations in Equation (188a) and Equation (188b) for gas and brine conservation become

$$\nabla \cdot \left[\frac{\alpha \rho_g K_g k_{rg}}{\mu_g} \left(\nabla p_g + \rho_g g \nabla h \right) \right] + \alpha q_{wg} = \alpha \frac{\partial \left(\phi \rho_g S_g \right)}{\partial t} \tag{212a}$$

$$\nabla \cdot \left[\frac{\alpha \rho_b K_b k_{rb}}{\mu_b} \left(\nabla p_b + \rho_b g \nabla h \right) \right] + \alpha q_{wb} = \alpha \frac{\partial \left(\phi \rho_b S_b \right)}{\partial t}, \tag{212b}$$

and the constraints in Equation (188) remain unchanged. As used in Equation (212), q_{wg} and q_{wb} are independent of the computational grid in use (Figure PA-20). In practice, q_{wg} and q_{wb} are defined with a productivity index (see Equation (181)) that is a function of the specific computational grid in use, with the result that these definitions are only meaningful in the context of the computational grid that they are intended to be used with. This specificity results because

q_{wg} and q_{wb} as used in Equation (212) are defined on a much smaller scale than can typically be implemented with a reasonable-sized computational grid. As a result, the values used for q_{wg} and q_{wb} in the numerical solution of Equation (212) must incorporate the actual size of the grid in use.

In the solution of Equation (212) with the computational grid in Figure PA-20, q_{wg} is used to incorporate gas flow out of the repository and q_{wb} is used to incorporate both brine inflow to the repository from a pressurized brine pocket and brine flow out of the repository. For gas flow out of the repository,

$$q_{wg}(x,y,t) = \frac{kk_{rg}(x,y,t)[p_g(x,y,t) - p_{wf}]}{\mu_g[\ln(r_e/r_w) + s + c]}, \tag{213}$$

if (x,y) is at the center of the grid cell containing the drilling intrusion (Figure PA-20) and $q_{wg}(x,y,t)$ = 0 (kg/m^3)/s otherwise, where k, k_{rg}, μ_g, r_e, r_w, s and c are defined in conjunction with Equation (181), p_g is gas pressure, and p_{wf} is the flowing well pressure at the outlet borehole (i.e., the boundary value condition in Table PA-16). The factor h in Equation (181) is the crushed height of the repository as indicated in Equation (176) and defines the factor α in Equation (212). In the numerical solution, $q_{wg}(x,y,t)$ defines $q^{n+1}_{wgi,j}$ in Equation (79), with $q^{n+1}_{wgi,j}$ having a nonzero value only when i, j correspond to the grid cell containing the borehole through which gas outflow is taking place (i.e., the grid cells containing the down-dip and up-dip wells in Figure PA-20).

For brine flow,

$$q_{wb}(x,y,t) = \frac{kk_{rb}(x,y,t)[p_b(x,y,t) - p_{wf}]}{\mu_b[\ln(r_e/r_w) + s + c]}, \tag{214}$$

if (x,y) is at the center of the grid cell containing the drilling intrusion through which brine outflow from the repository is taking place (Figure PA-20);

$$q_{wb}(x,y,t) = \frac{kk_{rb}(x,y,t)[p_{wE1} - p_b(x,y,t)]}{\mu_b[\ln(r_e/r_w) + c]}, \tag{215}$$

if (x,y) is at the center of the grid cell containing a prior drilling intrusion into a pressurized brine pocket (Figure PA-20), where p_{wE1} is the boundary value condition defined in Table PA-16; and $q_{wb}(x,y,t)$ = 0 otherwise. In the numerical solution of Equation (212a), $q_{wb}(x,y,t)$ defines $q^{n+1}_{wbi,j}$ in a discretization for Equation (212b) that is equivalent to the discretization for Equation (212a) shown in Equation (79), with $q^{n+1}_{wbi,j}$ having a nonzero value only when i, j

correspond to the grid cell containing the borehole through which brine outflow is taking place (i.e., the grid cells containing the down-dip and up-dip wells in Figure PA-20, in which case, Equation (214) defines $q_{wbi,j}^{n+1}$ or to the grid cell containing the borehole through which brine inflow to the repository from a pressurized brine pocket is taking place (i.e., the grid cell containing the E1 intrusion in Figure PA-20; in which case, Equation (215) defines $q_{wbi,j}^{n+1}$.

PA-4.7.10 Additional Information

Additional information on BRAGFLO and its use in the CRA-2004 PA to determine DBRs can be found in the analysis package for DBR (Stein 2003) and in the BRAGFLO User's Manual (WIPP PA 2003c).

PA-4.8 Brine Flow in Culebra: MODFLOW

This section describes the model for the calculation of brine flow in the Culebra.

PA-4.8.1 Mathematical Description

Groundwater flow in the Culebra Dolomite is represented by the partial differential equation

$$S\left(\frac{\partial h}{\partial t}\right) = \nabla\cdot\left(bK\nabla h\right) - Q\,, \tag{216}$$

where

S = medium storativity (dimensionless),

h = hydraulic head (m),

t = time (s),

b = aquifer thickness (m),

K = hydraulic conductivity tensor (m/s),

Q = source/sink term expressed as the volumetric flux per unit area ($(m^3/m^2)/s = m/s$).

Further, the Culebra is assumed to be isotropic, and as a result, K is defined by

$$K(x,y) = k(x,y)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \tag{217}$$

where $k(x,y)$ is the hydraulic conductivity (m/s) at the point (x,y). The following simplifying assumptions are also made: fluid flow in the Culebra is at steady state (i.e., $\partial h/\partial t = 0$), and

source and sink effects arising from borehole intrusions and infiltration are negligible (i.e., Q = 0). Given these assumptions, Equation (216) simplifies to

$$\nabla \cdot \left(\boldsymbol{bK} \nabla \boldsymbol{h} \right) = \boldsymbol{0} \,, \tag{218}$$

which is the equation actually solved to obtain fluid flow (i.e., $\boldsymbol{K} \nabla \boldsymbol{h}$) in the Culebra. In the CRA-2004 PA, b = 7.75 m, and $\boldsymbol{k}\left(\boldsymbol{x}, \boldsymbol{y}\right)$ in Equation (217) is a function of an imprecisely known transmissivity field, as discussed in Section PA-4.8.2.

PA-4.8.2 Implementation

The first step in the analysis of fluid flow in the Culebra is to generate transmissivity fields ***t(x, y)*** (m^2/s) for the Culebra and to characterize the uncertainty in these fields. This was accomplished by generating a large number of plausible transmissivity fields. A description of the method used to construct these transmissivity fields is included in Attachment TFIELD. Below, a brief outline of the method is presented.

The transmissivity fields used for the CRA-2004 PA are based on several types of information, including a regression model developed on WIPP-site geologic data, measured head levels in the Culebra for the year 2000, and well drawdown test results. The following steps led to the final transmissivity fields used in this analysis:

Geologic data including: (1) depth to the top of the Culebra, (2) reduction in thickness of the upper Salado Formation by dissolution, and (3) the spatial distribution of halite in the Rustler Formation below and above the Culebra were used to define a geologic regression model that relates transmissivity at any location to a set of geologically defined parameters.

Base transmissivity fields are defined for a modeling domain measuring 22.4 km east-west by 30.7 km north-south using a method of stochastic simulation. The base transmissivity fields were constructed from information on the depth to the Culebra, indicator functions defining the location of Salado dissolution, halite occurrence, and high transmissivity zones.

Seed transmissivity fields are defined by conditioning base transmissivity fields to measured values of transmissivity. This conditioning is performed with a Gaussian geostatistical simulation algorithm.

The seed transmissivity fields are calibrated to transient water level data from the year 2000 in 37 wells across the region using parameter estimation program PEST (Doherty 2002). The PEST program iteratively changes the seed transmissivity field values to minimize an objective function, using MODFLOW to rerun the flow solution between each iteration. The objective function minimized by PEST is a combination of the weighted sum of the squared residuals between the measured and modeled head data and a second weighted sum of the squared differences in the estimated transmissivity between pairs of pilot points. The second weighted sum is designed to keep the transmissivity field as homogeneous as possible and to provide numerical stability when estimating more parameters than there are data.

The calibrated transmissivity fields produced by PEST and MODFLOW are screened according to specific acceptance criteria. Calibrated transmissivity fields that meet the acceptance criteria are modified for the partial and full mining scenarios. This modification increases transmissivity by a random factor between 1 and 1000 in areas identified as containing potash reserves, as described below. Steady-state flow simulations are then run using the mining-modified transmissivity fields.

The transport code SECOTP2D uses a grid with uniform cells of 50 × 50 m. Thus as a final step, MODFLOW runs with a 50 × 50 m grid to calculate the flow fields required for the transport code. The hydraulic conductivities for the finer grid are obtained by dividing each 100 × 100 m cell into four 50 × 50 m cells. The conductivity assigned to each of the four cells is equal to the conductivity of the larger cell (Leigh et al. 2003).

The hydraulic conductivity $\boldsymbol{k}(\boldsymbol{x},\boldsymbol{y})$ in Equation (217) is defined in terms of the transmissivity fields $\boldsymbol{t}(\boldsymbol{x},\boldsymbol{y})$ by

$$\boldsymbol{k}(\boldsymbol{x},\boldsymbol{y}) = \boldsymbol{t}(\boldsymbol{x},\boldsymbol{y})/\boldsymbol{b}\,. \tag{219}$$

Fluid flow (i.e., $\boldsymbol{K}\nabla\boldsymbol{h}$) is determined by solving Equation (218) for two different cases: (1) a partial mining case (mining of potash deposits outside the land withdrawal boundary), and (2) a full mining case (mining of potash deposits inside and outside the land withdrawal boundary) (Figure PA-23). As specified by guidance in 40 CFR Part 194 (p. 5229, EPA 1996), potash mining increases the hydraulic conductivity in the Culebra in the vicinity of such mining by an uncertain factor with a value between 1 and 1000. As specified in 40 CFR § 194.32 and described in Section PA-3.8, economic potash reserves outside the land withdrawal boundary are assumed to have been fully mined by the end of the 100 year-period of active institutional controls, after which the occurrence of potash mining within the land withdrawal boundary follows a Poisson process with a rate constant of $\lambda_m = 1 \times 10^{-4}$ yr^{-1}.

In the partial mining case, the hydraulic conductivity $\boldsymbol{k_{PM}}(\boldsymbol{x},\boldsymbol{y})$ is defined by Equation (219) inside the WIPP boundary and by $\boldsymbol{k_{PM}}(\boldsymbol{x},\boldsymbol{y}) = \boldsymbol{k}(\boldsymbol{x},\boldsymbol{y}) \times \boldsymbol{MF}$ outside the WIPP boundary, where MF is determined by the uncertain parameter CTRANSFM (see Table PA-17). In the full mining case, the hydraulic conductivity $\boldsymbol{k_{FM}}(\boldsymbol{x},\boldsymbol{y}) = \boldsymbol{k}(\boldsymbol{x},\boldsymbol{y}) \times \boldsymbol{MF}$ in all areas of the modeling domain.

In turn, $\boldsymbol{k_{PM}}(\boldsymbol{x},\boldsymbol{y})$ and $\boldsymbol{k_{FM}}(\boldsymbol{x},\boldsymbol{y})$ result in the following definition for the hydraulic conductivity tensor K:

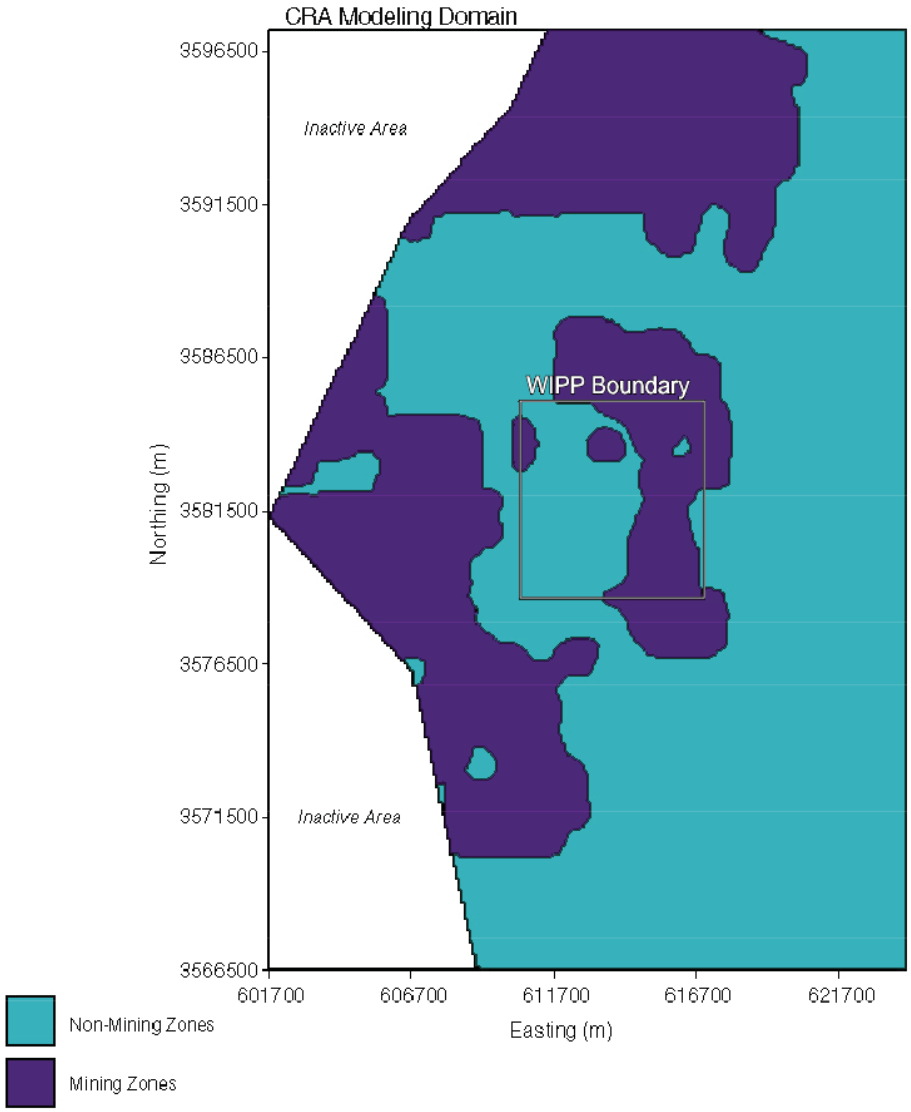

Figure PA-23. Areas of Potash Mining in the McNutt Potash Zone.

$$K_i(x,y) = k_i(x,y)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad i = PM, FM \ . \tag{220}$$

In the analysis, Equation (218) is solved with each of the preceding definitions of K_i to obtain characterizations of fluid flow in the Culebra for partially-mined conditions (i.e., $K_{PM}\nabla h$) and fully-mined conditions (i.e., $K_{FM}\nabla h$).

The determination of fluid flow in the Culebra through the solution of Equation (218) does not incorporate the potential effects of climate change on fluid flow. Such effects are incorporated into the analysis by an uncertain scale factor to introduce the potential effects of climate change

into the analysis (Corbet and Swift 1996a, 1996b). Specifically, the Darcy fluid velocity $\boldsymbol{v_i}(x,y)$ actually used in the radionuclide transport calculations is given by

$$\boldsymbol{v_i}(x,y) = \left[u_i(x,y), v_i(x,y)\right] = SFC\left[\boldsymbol{K_i}(x,y)\nabla h_i(x,y)\right]^T, \tag{221}$$

where $u_i(x,y)$ and $v_i(x,y)$ represent Darcy fluid velocities (m/s) at the point (x,y) in the x and y directions, respectively, $\nabla h_i(x,y)$ is obtained from Equation (218) with $\boldsymbol{K} = \boldsymbol{K_i}$, and SFC is a scale factor used to incorporate the uncertainty that results from possible climate changes. The scale factor SFC is determined by the uncertain parameter CCLIMSF (see Table PA-17).

PA-4.8.3 Computational Grids and Boundary Value Conditions

The representation for fluid flow in the Culebra in Equation (218) is evaluated on a numerical grid 22.4 km east-west by 30.7 km north-south, aligned with the compass directions (Figure PA-24). The modeling domain is discretized into 68,768 uniform 100-m × 100-m cells. The northern model boundary is slightly north of the northern end of Nash Draw, 12 km north of the northern WIPP site boundary, and about 1 km north of Mississippi Potash Incorporated's east tailings pile. The eastern boundary lies in a low-T region that contributes little flow to the modeling domain. The southern boundary lies 12.2 km south of the southern WIPP site boundary, 1.7 km south of WIPP's southernmost well (H-9), and far enough from the WIPP site to have little effect on transport rates on the site. The western model boundary passes through the IMC tailings pond (Laguna Uno; see Hunter (1985)) due west of the WIPP site in Nash Draw.

Two types of boundary conditions are specified: constant-head and no-flow (Figure PA-25). Constant-head conditions are assigned along the eastern boundary of the model domain, and along the central and eastern portions of the northern and southern boundaries. Values of these heads are obtained from the kriged initial head field. The western model boundary passes through the IMC tailings pond (Laguna Uno) due west of the WIPP site in Nash Draw. A no-flow boundary (a flow line) is specified in the model from this tailings pond up the axis of Nash Draw to the northeast, reflecting the concept that groundwater flows down the axis of Nash Draw, forming a groundwater divide. Similarly, another no-flow boundary is specified from the tailings pond down the axis of the southeastern arm of Nash Draw to the southern model boundary, coinciding with a flow line in the regional modeling of Corbet and Knupp (1996). Thus, the northwestern and southwestern corners of the modeling domain are specified as inactive cells in MODFLOW.

PA-4.8.4 Numerical Solution

The flow model in Equation (218) is evaluated with a second-order difference procedure (McDonald and Harbaugh 1988, p. 126) on the computational grid described in Section PA.4.8.3. Specifically, the discretized form of Equation (218) is

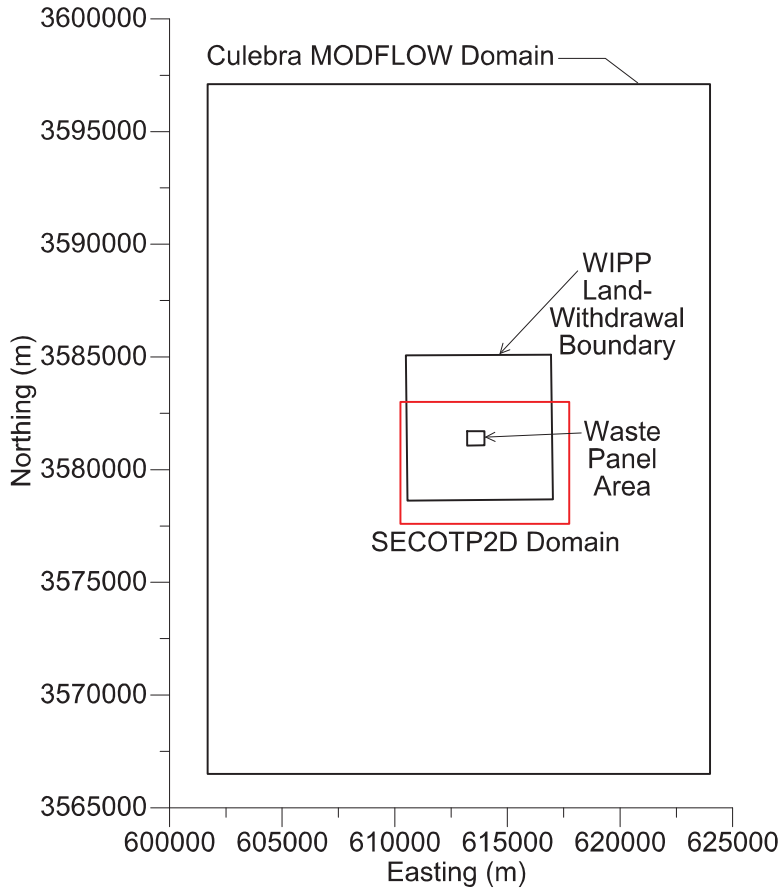

Figure PA-24. Modeling Domain for Groundwater Flow (MODFLOW) and Transport (SECOTP2D) in the Culebra.

$$0 = CR_{i,j-1/2}\left(h_{i,j-1} - h_{i,j}\right) + CR_{i,j+1/2}\left(h_{i,j+1} - h_{i,j}\right)$$

$$+ CC_{i-1/2,j}\left(h_{i-1,j} - h_{i,j}\right) + CC_{i+1/2,j}\left(h_{i+1,j} - h_{i,j}\right) , \qquad (222)$$

where CR and CC are the row and column hydraulic conductances at the cell interface between node i, j and a neighboring node (m^2/s). Since the grid is uniform, the hydraulic conductance is simply the harmonic mean of the hydraulic conductivity in the two neighboring cells multiplied by the aquifer thickness. For example, the hydraulic conductance between cells (i, j) and $(i, j-1)$ is given by $CR_{i,j-1/2}$ and the hydraulic conductance between cells (i, j) and $(i+1, j)$ is given by $CC_{i+1/2,j}$:

$$CR_{i,j-1/2} = \frac{2k_{i,j}k_{i,j-1}}{k_{i,j} + k_{i,j-1}} \times b \quad \text{and} \quad CC_{i+1/2,j} = \frac{2k_{i,j}k_{i+1,j}}{k_{i,j} + k_{i+1,j}} \times b ,$$

where $k_{i,j}$ is the hydraulic conductivity in cell i, j (m/s) and b is the aquifer thickness (m).

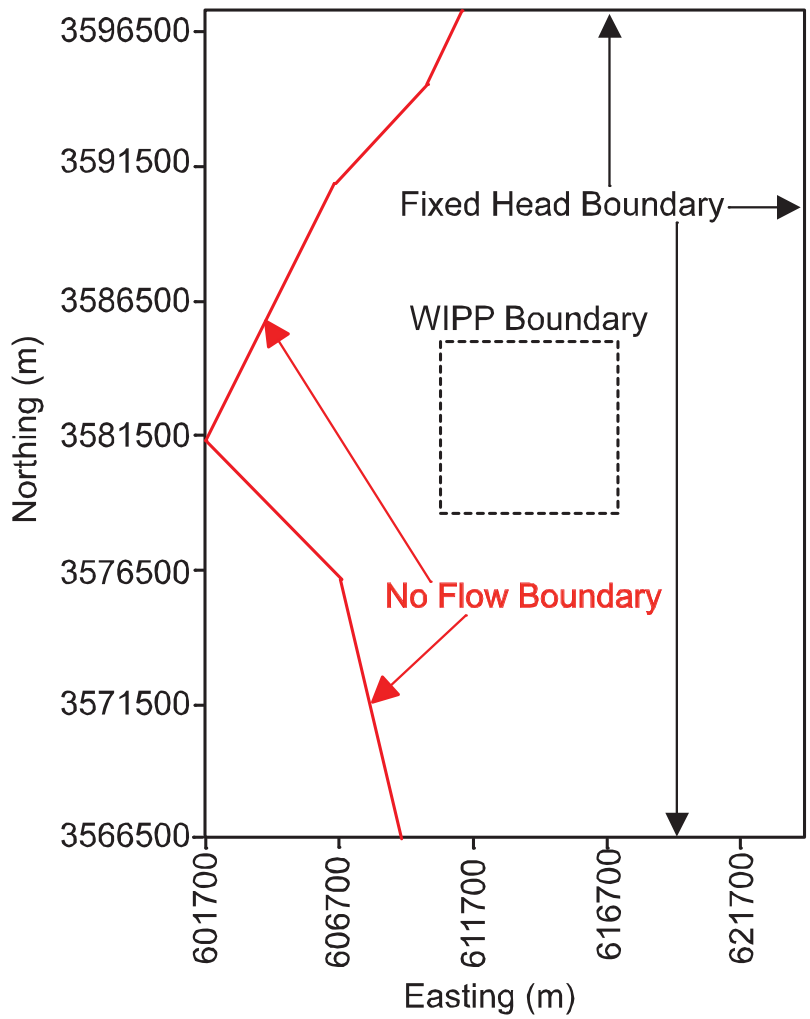

Figure PA-25. Boundary Conditions Used for Simulations of Brine Flow in the Culebra.

Figure PA-26 illustrates the cell numbering convention used in the finite difference grid for MODFLOW. The determination of h is then completed by the solution of the linear system of equations in Equation (222) for the unknown heads $h_{i,j}$. The solution is accomplished using the algebraic multigrid solver (AMG) (Ruge and Stuben 1987) that is part of the Link-AMG (LMG) package within MODFLOW (Mehl and Hill 2001). The AMG method solves Equation (222) with the successive over-relaxation (SOR) iterative method (Roache 1972) on different grids that are coarser than the original grid. The coarser grid solutions provide the initial condition to the next finer solution until a solution based on the original grid size is obtained. The advantage of the AMG method is that the larger grid solutions reduce the large frequency oscillations in the numerical solution much faster than if solved on a finer grid. The finer grid solutions are then able to remove the small frequency oscillations to obtain the final solution. While memory intensive, the AMG method produces solutions faster than ordinary iterative methods (Mehl and Hill 2001). Brine fluxes at cell interfaces are calculated from the values for $h_{i,j}$ internally in MODFLOW.

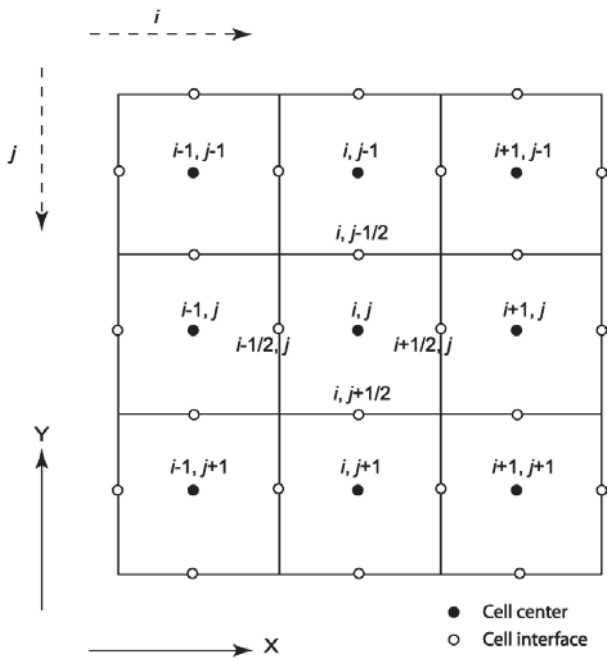

Figure PA-26. Finite Difference Grid Showing Cell Index Numbering Convention Used by MODFLOW.

PA-4.8.5 Additional Information

Additional information on MODFLOW and its use in the CRA-2004 PA to determine fluid flow in the Culebra can be found in the MODFLOW-2000 User's Manual (Harbaugh et al. 2000) and in McKenna and Hart (2003) and Lowry (2003). The flow fields computed for the CRA-2004 PA are presented in Attachment TFIELD.

PA-4.9 Radionuclide Transport in Culebra: SECOTP2D

Radionuclide transport in the Culebra formation is computed using the SECOTP2D computer code. The mathematical equations solved by the code SECOTP2D and the numerical methods used are described in the following sections.

PA-4.9.1 Mathematical Description

Radionuclide transport in the Culebra Dolomite is described by a parallel plate dual porosity model (Meigs and McCord 1996). The parallel plate dual porosity conceptualization assumes that the numerous fractures within the formation are aligned in a parallel fashion and treats the fractured porous media as two overlapping continua: one representing the fractures and the other representing the surrounding porous rock matrix (See Figure PA-27). In this model, one system of partial differential equations (PDEs) is used to represent advective transport in fractures within the Culebra Dolomite and another PDE system is used to represent diffusive transport and sorption in the matrix that surrounds the fractures.

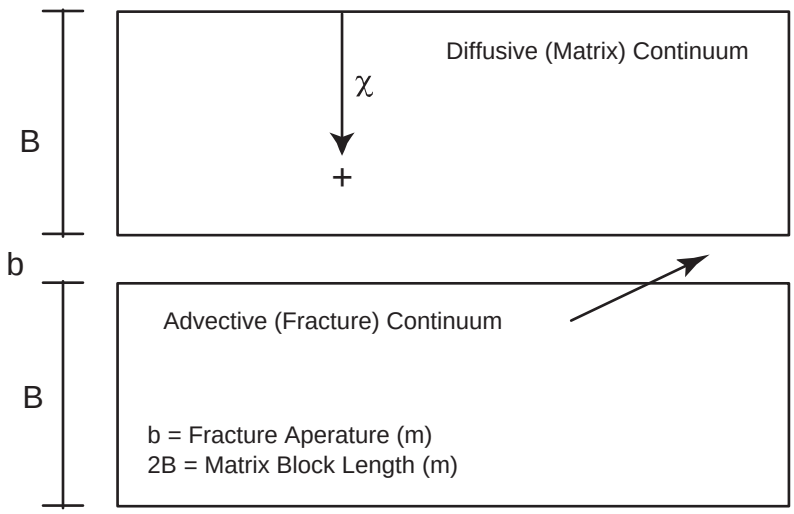

Figure PA-27. Parallel Plate Dual Porosity Conceptualization.

PA-4.9.1.1 Advective Transport in Fractures

The PDE system used to represent advective transport in fractures is given by (WIPP PA 1997b)

$$\nabla \bullet \left[\phi D_k \nabla C_k - v C_k \right] = \phi R_k \left(\frac{\partial C_k}{\partial t} \right) + \phi R_k \lambda_k C_k - \phi R_{k-1} \lambda_{k-1} C_{k-1} - Q_k - \Gamma_k , \qquad (223)$$

for $k = 1, 2, \ldots, nR$, where

nR = number of radionuclides under consideration,

C_k = concentration of radionuclide k in brine (kg/m^3),

D_k = hydrodynamic dispersion tensor (m^2/s),

v = Darcy velocity (i.e., specific discharge) of brine ($m/s = (m^3/m^2)/s$),

ϕ = advective (i.e., fracture) porosity (dimensionless),

R_k = advective retardation coefficient (dimensionless),

λ_k = decay constant for radionuclide k (s^{-1}),

Q_k = injection rate of radionuclide k per unit bulk volume of formation ($(kg/s)/m^3$) (Note: $Q_k > 0$ corresponds to injection into the fractures),

$\boldsymbol{\Gamma_k}$ = mass transfer rate of radionuclide k per unit bulk volume of formation due to diffusion between fractures and surrounding matrix ((kg/s)/m^3) (Note: $\boldsymbol{\Gamma_k} > 0$ corresponds to diffusion into fractures).

The Darcy velocity $\boldsymbol{v}$ is obtained from the solution of Equation (218); specifically, $\boldsymbol{v}$ is defined by the relationship in Equation (221). The advective porosity ϕ, defined as the ratio of the interconnected fracture pore volume to the total volume, is determined by an uncertain parameter (see CFRCPOR in Table PA-17).

The hydrodynamic dispersion tensor is defined by (WIPP PA 1997b; Bear 1972)

$$\boldsymbol{D_k} = \frac{1}{\|\boldsymbol{v}\|\phi}\begin{bmatrix} u & -v \\ v & u \end{bmatrix}\begin{bmatrix} \alpha_L & 0 \\ 0 & \alpha_T \end{bmatrix}\begin{bmatrix} u & v \\ -v & u \end{bmatrix} + \tau D_k^* \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \tag{224}$$

where α_L and α_T are the longitudinal and transverse dispersivities (m); u and v are the x and y components of $\boldsymbol{v}$ (i.e., $\boldsymbol{v} = [u, v]$); D_k^* is the free water molecular diffusion coefficient (m^2 s^{-1}) for radionuclide k; and τ is the advective tortuosity, defined as the ratio of the true length of the flow path of a fluid particle to the straight-line distance between the starting and finishing points of the particle's motion. As in the CCA PA (Helton et al. 1998), the CRA-2004 PA uses $\alpha_L = \alpha_T = 0$ m and $\tau = 1$. Thus, the definition of $\boldsymbol{D_k}$ used in the CRA-2004 PA reduces to

$$\boldsymbol{D_k} = D_k^* \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{225}$$

The diffusion coefficient D_k^* equals 3×10^{-10} m^2/s for radionuclides in the +3 oxidation state (i.e., Am(III), Pu(III)), 1.53×10^{-10} m^2/s for radionuclides in the +4 oxidation state (i.e., Pu(IV), Th(IV), U(IV)), and 4.26×10^{-10} m^2/s for radionuclides in the +6 oxidation state (i.e., U(VI)) (Attachment PAR, Table PAR-35). The existence of Pu in the +3 or +4 oxidation state (i.e., as Pu(III) or Pu(IV)) and the existence of U in the +4 or +6 oxidation state (i.e., as U(IV) or U(VI)) is determined by an uncertain parameter (see WOXSTAT in Table PA-17).

The advective retardation coefficient R_k is defined by

$$\boldsymbol{R_k} = 1 + (1 - \phi)\rho_A K_{Ak} / \phi, \tag{226}$$

where

ρ_A = surface area density of fractures in Culebra (m^2/m^3 = 1/m) (i.e., surface area of fractures (m^2) divided by volume of fractures (m^3)),

K_{Ak} = surface area distribution coefficient ((kg/m^2)/(kg/m^3) = m) (i.e., concentration of radionuclide k sorbed on fracture surfaces (kg/m^2) divided by concentration of radionuclide k dissolved in brine within fractures (kg/m^3)).

Following the logic of the CCA PA (Helton et al. 1998), $K_{Ak} = 0$ and thus $R_k = 1$ in the 2004 PA.

In concept, the term Q_k in Equation (223) provides the link between the releases to the Culebra calculated with NUTS and PANEL (Section PA-6.7) and transport within the Culebra. In the computational implementation of the CRA-2004 PA, radionuclide transport calculations in the Culebra were performed for unit radionuclide releases to the Culebra and then the outcomes of these calculations were used to construct the release to the accessible environment associated with time-dependent releases into the Culebra derived from NUTS and PANEL calculations (Section PA-6.8.7). The definition of Q_k is discussed in more detail in Section PA-4.9.1.4.

The initial condition for Equation (223) is

$$C_k(x, y, 0) = 0 \text{ kg / m}^3. \tag{227}$$

Furthermore, the boundary value conditions for Equation (223) are defined at individual points on the boundary of the grid in Figure (PA-24) on the basis of whether the flow vector $\mathbf{V} = [u, v]$ defines a flow entering the grid or leaving the grid. The following Neumann boundary value condition is imposed at points (x, y) where flow leaves the grid:

$$\nabla C_k(x, y, t) \cdot n(x, y) = 0 \text{ (kg/m}^3\text{)/m}, \tag{228}$$

where $n(x, y)$ is an outward-pointing unit normal vector defined at (x, y). The following Dirichlet boundary value condition is imposed at points (x, y) where flow enters the grid:

$$C_k(x, y, t) = 0 \text{ kg/m}^3. \tag{229}$$

PA-4.9.1.2 <u>Diffusive Transport in the Matrix</u>

The system of PDEs used to represent diffusive transport in the matrix surrounding the fractures is given by (WIPP PA 1997b)

$$\frac{\partial}{\partial \chi}\left(\phi'_k D'_k \frac{\partial C'_k}{\partial \chi}\right) = \phi' R'_k \left(\frac{\partial C'_k}{\partial t}\right) + \phi' R'_k \lambda_k C'_k - \phi' R'_{k-1} \lambda_{k-1} C'_{k-1} \ , \tag{230}$$

where χ is the spatial coordinate in Figure PA-27, D'_k is the matrix diffusion coefficient (m^2/s) for radionuclide k defined by $D'_k = D^*_k \tau'$, and τ' is the matrix tortuosity. The remaining terms have the same meaning as those in Equation (223) except that the prime denotes properties of the matrix surrounding the fractures. A constant value ($\tau' = 0.11$) for the matrix (i.e., diffusive)

tortuosity is used in the CRA-2004 PA (Meigs 1996). The matrix (i.e., diffusive) porosity φ' is an uncertain input to the analysis (see CMTRXPOR in Table PA-17). The matrix retardation R'_k is defined by

$$R'_k = 1 + \left(1 - \phi'\right)\rho_s K_{dk} / \phi' , \tag{231}$$

where ρ_s is the particle density (kg/m^3) of the matrix and K_{dk} is the distribution coefficient ((Ci/kg)/(Ci/m^3) = m^3/kg) for radionuclide k in the matrix. The density ρ_s is assigned a value of 2.82×10^3 kg/m^3 (Martell 1996b). The distribution coefficients K_{dk} are uncertain inputs to the analysis and dependent on the uncertain oxidation state of the relevant element (see CMKDAM3, CMKDPU3, CMKDPU4, CMKDTH4, CMKDU4, CMKDU6, and WOXSTAT in Table PA-17).

The initial and boundary value conditions used in the formulation of Equation (230) are

$$C'_k\left(x, y, \chi, 0\right) = 0 \ kg / m^3 , \tag{232}$$

$$\partial C'_k\left(x, y, 0, t\right) / \partial z = 0 \ \ kg / m^2 , \tag{233}$$

$$C'_k\left(x, y, B, t\right) = C_k(x, y, t), \tag{234}$$

where $\left(x, y\right)$ corresponds to a point in the domain on which Equation (223) is solved and B is the matrix half block length (m) in Figure PA-27 (i.e., 2B is the thickness of the matrix between two fractures). The initial condition in Equation (232) means that no radionuclide is present in the matrix at the beginning of the calculation. The boundary value condition in Equation (233) implies that no radionuclide movement can take place across the centerline of a matrix block separating two fractures. The boundary value condition in Equation (234) ensures that the dissolved radionuclide concentration in the matrix at the boundary with the fracture is the same as the dissolved radionuclide concentration within the fracture. The matrix half block length B is an uncertain input to the analysis (see CFRCSP in Table PA-17).

PA-4.9.1.3 Coupling Between Fracture and Matrix Equations

The linkage between Equation (223) and Equation (230) is accomplished through the term Γ_k, defining the rate at which radionuclide k diffuses across the boundary between a fracture and the adjacent matrix (see Figure PA-27). Specifically,

$$\Gamma_k = -\frac{2\phi}{b}\left(\phi' D'_k \left.\frac{\partial C'_k}{\partial \chi}\right|_{z=\chi}\right), \tag{235}$$

where b is the fracture aperture (m) defined by

$$b = \phi B\left(1 - \phi\right). \tag{236}$$

PA-4.9.1.4 Source Term

As already indicated, Equation (223) and Equation (230) are solved for unit radionuclide releases to the Culebra. Specifically, a release of 1 kg of each radionuclide under consideration was assumed to take place over a time interval from 0 to 50 years, with this release taking place into the computational cell WPAc , located at the center of the Waste Panel Area in Figure PA-24, that has dimensions of 50 m × 50 m. The volume of this cell is given by

$$V = (50m)(50m)(4m) = 1 \times 10^4 \ m^3 , \tag{237}$$

where 4 m is the assumed thickness of the Culebra Dolomite (Meigs and McCord 1996). As a result, $Q_k(x, y, t)$ has the form

$$Q_k(x, y, t) = \frac{1 \ kg}{(1 \times 10^4 \ m^3)(50 \ yr)(3.16 \times 10^7 \ s / yr)} = 6.33 \times 10^{-14} \ kg / m^3 / s \tag{238}$$

for $0 \le t \le 50$ yr and (x, y) is in cell WPAC and $Q_k(x, y, t) = 0$ (kg/m^3/s) otherwise.

PA-4.9.1.5 Cumulative Releases

If $\mathcal{B}$ denotes an arbitrary boundary (e.g., the land withdrawal boundary) in the domain of Equation (223) (i.e., Figure PA-24), then the cumulative transport of $C_k(t, \mathcal{B})$ of radionuclide k from time 0 to time t across $\mathcal{B}$ is given by

$$C_k(t, \mathcal{B}) = \int_0^t \left[\int_{\mathcal{B}} \left\{ \mathbf{v}(x, y) C_k(x, y, \tau) - \phi \mathbf{D}_k(x, y, t) \nabla C_k(x, y, \tau) \right\} \mathbf{b} \bullet \mathbf{n}(x, y) ds \right] d\tau , \tag{239}$$

where h is the thickness of the Culebra (4 m), ϕ is the advective porosity in Equation (223), $\mathbf{n}(x, y)$ is an outward pointing unit normal vector, and $\int_{\mathcal{B}} ds$ denotes a line integral over $\mathcal{B}$.

PA-4.9.2 Numerical Solution

The numerical solution to the coupled PDE system represented by Equation (223), and Equation (230) is computed using SECOTP2D, an implicit finite volume code for the simulation of multispecies reactive transport. A high-level description of the numerical procedures implemented in SECOTP2D follows, with more detail available in WIPP PA (1997b).

PA-4.9.2.1 Discretization of Fracture Domain

The fracture domain is discretized in space using the block centered finite difference method indicated in Figure PA-28. In this formulation, cell concentrations are defined at grid block centers while the velocity components $[u, v]$ are defined on grid cell faces. A uniform mesh with 50 m × 50 m cells is used for the spatial discretization. Ghost cells are placed outside the

problem domain for the purpose of implementing boundary conditions. The temporal discretization is accomplished using variable time step sizes.

The dispersive term, $\nabla\cdot\left(\phi D_k \nabla C_k\right)$, in Equation (223) is approximated using a second-order central difference formula (Fletcher 1988).

The advective term, $\nabla\cdot v C_k$, is approximated using the Total Variation Diminishing (TVD) method (Sweby 1984). The TVD method provides a way of accurately resolving advection dominated transport problems without the occurrence of nonphysical oscillations commonly present in second-order solutions. This method invokes a weighted upstream differencing scheme that locally adjusts the weighting to prevent oscillatory behavior and maximize solution accuracy. The weighting parameters are known as the TVD flux limiters $\Phi\left(x, y, r\right)$, where r is a function of the concentration gradient and direction of flow. PA uses the van Leer TVD limiter (Sweby 1984, p. 1005), which is defined as

$$\Phi\left(x, y, r\right) = \max\left\{0, \min\left\{2r, \frac{r+|r|}{1+|r|}\right\}\right\}. \tag{240}$$

At locations where u (i.e., the Darcy velocity in the x direction) is positive, r is defined at the j–1/2, k interface by

$$r_{j-1/2,k} = \frac{\partial C/\partial x\big|_{j-3/2,k}}{\partial C/\partial x\big|_{j-1/2,k}}, \tag{241}$$

and at locations where u is negative, r is defined by

$$r_{j-1/2,k} = \frac{\partial C/\partial x\big|_{j+1/2,k}}{\partial C/\partial x\big|_{j-1/2,k}}. \tag{242}$$

Similar definitions are made for r at the j, k–1/2 interface in the y-direction with v (i.e., the Darcy velocity in the y direction) used instead of u.

Because Φ_k is a function of C_k, the discretized set of equations is nonlinear. This nonlinearity is addressed by treating the flux limiters explicitly (i.e., time lagged). Explicit treatment of the limiter functions, however, can lead to oscillatory and sometimes unstable solutions when the Courant number exceeds unity (Cr > 1), where Cr is defined by

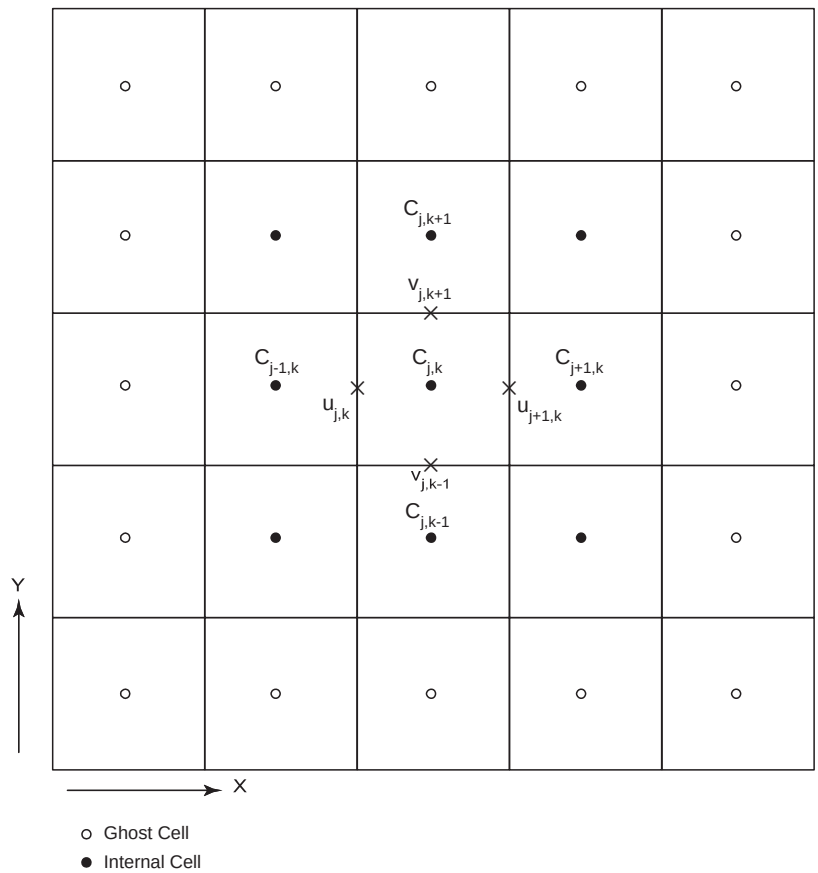

Figure PA-28. Schematic of Finite Volume Staggered Mesh Showing Internal and Ghost Cells.

$$Cr = \max\left\{Cr_x, Cr_y\right\}, \ \textit{where } Cr_x = |u|\Delta t/\phi\Delta x \ \textit{ and } \ Cr_y = |v|\Delta t/\phi\Delta y. \tag{243}$$

To avoid this behavior, the application of the TVD method is restricted to regions in which the Courant numbers are less than one. In regions where Cr > 1, a first order full upwinding scheme is invoked, which is unconditionally stable and nonoscillatory.

The discretized form of Equation (223) can be expressed in a delta formulation as

$$\left(\boldsymbol{I} + \boldsymbol{L_{xx}} + \boldsymbol{L_{yy}} + \boldsymbol{S}\right)\Delta \boldsymbol{C^{n+1}} = \boldsymbol{RHS^n}, \tag{244}$$

where $\boldsymbol{I}$ is the identity matrix, $\boldsymbol{L_{xx}}$ and $\boldsymbol{L_{yy}}$ are finite difference operators in the x and y directions, $\boldsymbol{S}$ is an implicit source term that accounts for decay and mass transfer between the matrix and the fracture, $\boldsymbol{RHS}$ consists of the right hand side known values at time level n, and $\Delta \boldsymbol{C_{n+1}} = \boldsymbol{C_{n+1}} - \boldsymbol{C_n}$. Direct inversion of Equation (244) for a typical Culebra transport problem is very computationally intensive, requiring large amounts of memory and time. To reduce these requirements, the operator in Equation (244) is factored as follows:

$$\left(\boldsymbol{I}+\boldsymbol{L}_{xx}+\alpha_x\boldsymbol{S}\right)\left(\boldsymbol{I}+\boldsymbol{L}_{yy}+\alpha_y\boldsymbol{S}\right)\Delta\boldsymbol{C}^{n+1}=\boldsymbol{RHS}^n, \tag{245}$$

where α_x and α_y are constants that must sum to one (i.e., $\alpha_x + \alpha_y = 1$). The left hand sides in Equation (244) and Equation (245) are not equivalent, with the result that the factorization of Equation (244) in Equation (245) is referred to as an approximate factorization (Fletcher 1988). The advantage of approximately factoring Equation (244) is that the resulting equation consists of the product of two finite difference operators that are easily inverted independently using a tridiagonal solver. Hence, the solution to the original problem is obtained by solving a sequence of problems in the following order:

$$\left(\boldsymbol{I}+\boldsymbol{L}_{xx}+\alpha_x\boldsymbol{S}\right)\Delta\overline{\boldsymbol{C}}=\boldsymbol{RHS}^n, \tag{246}$$

$$\left(\boldsymbol{I}+\boldsymbol{L}_{yy}+\alpha_y\boldsymbol{S}\right)\Delta\boldsymbol{C}^{n+1}=\Delta\overline{\boldsymbol{C}}, \tag{247}$$

$$\boldsymbol{C}^{n+1}=\boldsymbol{C}^n+\Delta\boldsymbol{C}^{n+1}. \tag{248}$$

PA-4.9.2.2 Discretization of Matrix Equation

The nonuniform mesh used to discretize the matrix equation is shown in Figure PA-29. Straightforward application of standard finite difference or finite volume discretizations on nonuniform meshes results in truncation error terms which are proportional to the mesh spacing variation (Hirsch 1988). For nonuniform meshes, the discretization can be performed after a transformation from the Cartesian physical space (χ) to a stretched Cartesian computational space (ξ). The transformation is chosen so that the nonuniform grid spacing in physical space is transformed to a uniform spacing of unit length in computational space (the computational space is thus a one-dimensional domain with a uniform mesh). The transformed equations contain metric coefficients that must be discretized, introducing the mesh size influence into the difference formulas. Then standard unweighted differencing schemes can then be applied to the governing equations in the computational space.

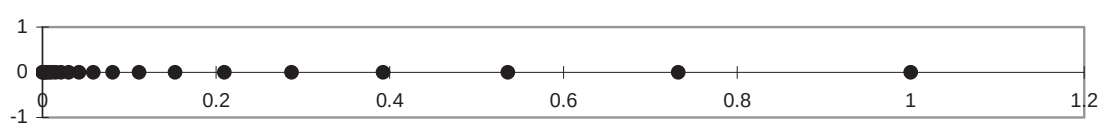

Figure PA-29. Illustration of Stretched Grid Used for Discretization of Matrix Domain.

The SECOTP2D code applies such a coordinate transformation to the nonuniform diffusion domain mesh, solving the transformed system of equations in the uniform computational space. The transformed matrix equation is written as:

$$\phi' R'_k \frac{\partial \hat{C}'_k}{\partial t} - \frac{\partial \hat{F}'_v}{\partial \xi'} = -\phi' R'_k \lambda_k \hat{C}'_k + \phi' R'_{k-1} \lambda_{k-1} \hat{C}'_{k-1}, \tag{249}$$

where

$$\hat{C}'_k = \frac{C'_k}{J}, \tag{250}$$

$$\hat{F}'_v = D' \xi'_x \frac{\partial C'_k}{\partial \xi'}. \tag{251}$$

In the uniform computational space, a first-order backwards difference formula is used to approximate the temporal derivative while a second-order accurate central difference is used to approximate spatial derivatives.

PA-4.9.2.3 Fracture-Matrix Coupling

The equations for the fracture and the matrix are coupled through the mass transfer term Γ_k. In the numerical solution, these equations are coupled in a fully implicit manner and solved simultaneously. A procedure outlined in (Huyakorn et al. 1983) was adapted and redeveloped for an approximate factorization algorithm with the delta formulation and a finite volume grid. The coupling procedure consists of three steps.

Step 1. Write the mass transfer term Γ_k in a delta (Δ) form.

Step 2. Evaluate Δ terms that are added to the implicit part of the fracture equation. This is accomplished using the inversion process (LU factorization) in the solution of the matrix equation. After the construction of the lower tridiagonal matrix L and the intermediate solution, there is enough information to evaluate the Δ terms. This new information is fed into the fracture equation that subsequently is solved for concentrations in the fracture at the new time level (n+1).

Step 3. Construct the boundary condition for the matrix equation at the fracture-matrix interface using fracture concentrations at the (n+1) time level. Matrix concentrations are then obtained using the upper tridiagonal matrix U by back substitution. A detailed description of this technique and its implementation is given in the SECOTP2D User's Manual (WIPP PA 1997b).

PA-4.9.2.4 Cumulative Releases

The cumulative transport $C_k(t, \mathcal{B})$ of individual radionuclides across specified boundaries indicated in Equation (239) is also accumulated during the numerical solution of Equation (223) and Equation (230).

PA-4.9.3 Additional Information

Additional information on SECOTP2D and its use in the CRA-2004 PA to determine radionuclide transport in the Culebra Dolomite can be found in the SECOTP2D User's Manual (WIPP PA 1997b) and in the analysis package for radionuclide transport in the Culebra Dolomite (Kanney 2003).

PA-5.0 PROBABILISTIC CHARACTERIZATION OF SUBJECTIVE UNCERTAINTY

This section summarizes the uncertain parameters in the CRA-2004 PA that constitute the space for subjective uncertainty defined in Section PA-2.4.

PA-5.1 Probability Space

As discussed in Section PA-2.4, the third entity (EN3) that underlies the CRA-2004 PA is a probabilistic characterization of the uncertainty in important variables used as input to the analysis. This entity is defined by a probability space $\left(X_{su}, S_{su}, p_{su}\right)$ that characterizes subjective uncertainty. The individual elements of S_{su} are vectors x_{su} of the form

$$x_{su} = \left[x_1, x_2, \ldots x_{nV}\right], \tag{252}$$

where each x_j is an imprecisely-known input to the analysis and nV is the number of such inputs.

The uncertainty in the x_j, and hence in x_{su}, is characterized by developing a distribution

$$D_j, \;\; j = 1, 2, \ldots, nV \;, \tag{253}$$

for each x_j. Each distribution is based on all available knowledge about the corresponding variable and describes a degree of belief as to where the appropriate value to use for this variable is located. This degree of belief is conditional on the numerical, spatial, and temporal resolution of the models selected for use in the CRA-2004 PA (Chapter PA-4.0). When appropriate, correlations between imprecisely-known variables are also possible, with such correlations indicating a dependency in the knowledge about the correlated variables. It is the distributions in Equation (253) and any associated correlations between the x_j that define $\left(X_{su}, S_{su}, p_{su}\right)$.

The uncertain variables (i.e., x_j) incorporated into the CRA-2004 PA are discussed in Section PA-5.2. Then, the distributions and correlations assigned to these variables are described in Section PA-5.3 and Section PA-5.4. Finally, a discussion of the concept of a scenario is given in Section PA-5.5.

PA-5.2 Variables Included For Subjective Uncertainty

The CRA-2004 PA selected nV = 64 imprecisely-known variables for inclusion in the analysis (Table PA-17). The individual variables in Table PA-17 correspond to the elements x_j of the vector x_{su} in Equation (252). Most variables listed in Table PA-17 were also treated as uncertain in the CCA PA (CCA Appendix PAR). Table PA-18 lists the differences between the set of subjectively uncertain variables in the CCA PA and the CRA-2004 PA. Most differences result from the inclusion of additional uncertain variables from the 1997 PAVT. All subjectively uncertain variables incorporated into the CRA-2004 PA are used as input to the models discussed in Section PA-2.3 and Chapter 4.0.

PA-5.3 Variable Distributions

Each uncertain variable is assigned a distribution that characterizes the subjective uncertainty in that variable. Distributions for each parameter are described in Attachment PAR. Attachment PAR contains documentation for each of the 64 parameters that were sampled by the LHS code during the PA.

PA-5.4 Correlations

Most of the variables in Table PA-17 are assumed to be uncorrelated. However, the pairs (ANHCOMP, ANHPRM), (HALCOMP, HALPRM), and (BPCOMP, BPPRM) are assumed to have rank correlations of –0.99, –0.99, and –0.75, respectively (Figure PA-30, Figure PA-31, and Figure PA-32). These correlations result form a belief that the underlying physics implies that a large value for one variable in a pair should be associated with a small value for the other variable in the pair. The scatterplots in Figure PA-29, Figure PA-30, and Figure PA-31 result from the LHSs described in Section PA-6.4, with the rank correlations within the pairs (ANHCOMP, ANHPRM), (HALCOMP, HALPRM), and (BPCOMP, BPPRM) induced with the Iman and Conover (1982) restricted pairing technique.

The distributions and associated correlations indicated in Table PA-17 and Figure PA-29, Figure PA-30, and Figure PA-31 define the probability space $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$ for subjective uncertainty in Section PA.2.4. The vector $\boldsymbol{x_{su}}$ in Equation (252) has the form

$$\boldsymbol{x_{su}} = \left[\boldsymbol{ANHBCEXP, ANHBCVGP, ..., WTAUFAIL}\right], \tag{254}$$

where the individual elements of $\boldsymbol{x_{su}}$ are the subjectively uncertain variables described in Table PA-17.

PA-5.5 Separation of Stochastic and Subjective Uncertainty

The CRA-2004 PA uses the term “scenario” to refer to subsets E_{st} of the sample space, S_{st} for stochastic uncertainty, with scenario probabilities $\boldsymbol{p_{st}}\left(\boldsymbol{E_{st}}\right)$ being defined by the function p_{st} associated with the probability space $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$ (Section PA-3.9). This definition is consistent with the concept that a scenario is something that could happen in the future. Subsets E_{su} of the sample space for subjective uncertainty S_{su} are not referred to as scenarios to maintain the important distinction between the two sample spaces. In particular, a scenario E_{st} contains vectors $\boldsymbol{x_{st}}$ of the form defined in Equation (3), and the probability $\boldsymbol{p_{st}}\left(\boldsymbol{E_{st}}\right)$ for E_{st} characterizes the likelihood that a vector $\boldsymbol{x_{st}}$ in E_{st} will match the occurrences that will take place at the WIPP over the next 10,000 years. In contrast, a subset E_{su} from the space of subjective uncertainty X_{su} contains vectors $\boldsymbol{x_{su}}$ of the form defined in Equation (252) and the probability $\boldsymbol{p_{su}}\left(\boldsymbol{E_{su}}\right)$ characterizes a degree of belief that a vector $\boldsymbol{x_{su}}$ in E_{su} contains the appropriate values for the 64 uncertain variables in Table PA-17.

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA

Sample Position	Variable Name	Material Name	Property Name	Description
1	WGRCOR	STEEL	CORRMCO2	Rate of anoxic steel corrosion (m/s) under brine inundated conditions and with no CO_2 present. Defines R_{ci} in Equation (59) for areas Waste Panel, South RoR, and North RoR in Figure PA-8.
2	WMICDFLG	WAS_AREA	PROBDEG	Index for model of microbial degradation of CPR materials (dimensionless). Used in areas Waste Panel, South RoR, and North RoR in Figure PA-8.
3	WGRMICI	WAS_AREA	GRATMICI	Rate of CPR biodegradation (mol $C_6H_{10}O_5$ / kg $C_6H_{10}O_5$ / s) under anaerobic, brine-inundated conditions. Defines R_{mi} in Equation (61) for areas Waste Panel, South RoR, and North RoR, in Figure PA-8.
4	WGRMICH	WAS_AREA	GRATMICH	Rate of CPR biodegradation (mol $C_6H_{10}O_5$ / kg $C_6H_{10}O_5$ / s) under anaerobic, humid conditions. Defines R_{mh} in Equation (61) for areas Waste Panel, South RoR, and North RoR, in Figure PA-8.
5	WFBETCEL	CELLULS	FBETA	Scale factor used in definition of stoichiometric coefficient for microbial gas generation (dimensionless). Defines β in Equation (77) for areas Waste Panel, South RoR, and North RoR, in Figure PA-8.
6	WRGSSAT	WAS_AREA	SAT_RGAS	Residual gas saturation in waste (dimensionless). Defines S_{gr} in Equation (35) for areas Waste Panel, South RoR, and North RoR in Figure PA-8; also used in waste material in Figure PA-20 for calculation of DBR; see Section PA-4.7.
7	WRBRNSAT	WAS_AREA	SAT_RBRN	Residual brine saturation in waste (dimensionless). Defines S_{br} in Equation (34) for areas Waste Panel, South RoR, and North RoR, in Figure PA-8; also used in waste material in Figure PA-20 for calculation of DBR; see Section PA-4.7.
8	WASTWICK	WAS_AREA	SAT_WICK	Increase in brine saturation of waste due to capillary forces (dimensionless). Defines S_{wick} in Equation (78) for areas Waste Panel, South RoR, and North RoR, in Figure PA-8.

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA — Continued

Sample Position	Variable Name	Material Name	Property Name	Description
9	DRZPCPRM	DRZ_PCS	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the DRZ immediately above the panel closure concrete (Section PA-4.2.8.3). Used in region DRZ_PCS in Figure PA-8.
10	CONPRM	CONC_PCS	PRMX_LOG	Logarithm of intrinsic permeability (m^2) for the concrete portion of the panel closure. (Section PA-4.2.8.1). Used in region CONC_PCS in Figure PA-8.
11	WSOLU4C	SOLU4	SOLCIM	Uncertainty factor (dimensionless) for solubility of U in the +IV oxidation state in Castile brine. Defines UF(Castile, +4, U) in Equation (90).
12	WSOLTH4C	SOLTH4	SOLCIM	Uncertainty factor (dimensionless) for solubility of Th in the +IV oxidation state in Castile brine. Defines UF(Castile, +4, Th) in Equation (90).
14	CONGSSAT	CONC_PCS	SAT_RGAS	Residual gas saturation (dimensionless) in panel closure concrete (Section PA-4.2.8.1). Defines S_{gr} in Equation (35) for area CONC_PCS in Figure PA-8.
15	CONBRSAT	CONC_PCS	SAT_RBRN	Residual brine saturation (dimensionless) in panel closure concrete (Section PA-4.2.8.1). Defines S_{br} in Equation (35) for use in region CONC_PCS in Figure PA-8.
16	CONBCEXP	CONC_PCS	PORE_DIS	Brooks-Corey pore distribution parameter (dimensionless) for panel closure concrete (Section PA-4.2.8.1). Defines λ in Equation (32) for region CONC_PCS of Figure PA-8 for use with Brooks-Corey model; defines λ in $m = \lambda/(1 + \lambda)$ in Equation (36) for use with van Genuchten-Parker model in region CONC_PCS.
17	HALPOR	S_HALITE	POROSITY	Halite porosity (dimensionless). Defines ϕ_0 in Equation (25g) for region Salado in Figure PA-8.
18	HALPRM	S_HALITE	PRMX_LOG	Logarithm of intrinsic halite permeability (m^2). Used in region Salado in Figure PA-8.
19	HALCOMP	S_HALITE	COMP_RCK	Bulk compressibility of halite (Pa^{-1}). Defines β_{fB} in Equation (31) for region Salado of Figure PA-8.
20	ANHPRM	S_MB139	PRMX_LOG	Logarithm of intrinsic anhydrite permeability (m^2). Used in regions MB 138, Anhydrite AB, and MB 139 in Figure PA-8.
21	ANHCOMP	S_MB139	COMP_RCK	Bulk compressibility of anhydrite (Pa^{-1}). Defines β_{fB} in Equation (31) for regions MB 138, Anhydrite AB and MB 139 in Figure PA-8.

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA — Continued

Sample Position	Variable Name	Material Name	Property Name	Description
22	ANHBCVGP	S_MB139	RELP_MOD	Indicator for relative permeability model (dimensionless) for regions MB 138, Anhydrite AB and MB 139 in Figure PA-8. See Table PA-3.
23	ANRBRSAT	S_MB139	SAT_RBRN	Residual brine saturation in anhydrite (dimensionless). Defines S_{br} in Equation (35) for regions MB 138, Anhydrite AB, and MB 139 in Figure PA-8.
24	ANRGSSAT	S_MB139	SAT_RGAS	Residual gas saturation in anhydrite (dimensionless). Defines S_{gr} in Equation (34) for regions MB 138, Anhydrite AB, and MB 139 in Figure PA-8.
25	ANHBCEXP	S_MB139	PORE_DIS	Brooks-Corey pore distribution parameter for anhydrite (dimensionless). Defines λ in Equation (32) for regions MB 138, Anhydrite AB, and MB 139 of Figure PA-8 for use with Brooks-Corey model; defines λ in $m = \lambda/(1 + \lambda)$ in Equations (36) for use with van Genuchten-Parker model in the same regions.
26	SALPRES	S_HALITE	PRESSURE	Initial brine pore pressure (Pa) in the Salado halite, applied at an elevation consistent with the intersection of MB 139. Defines $p_{b,ref}$ for Equation (49) for region Salado in Figure PA-8.
27	BPINTPRS	CASTILER	PRESSURE	Initial brine pore pressure in the Castile brine reservoir. Defines $Pb(x, y, -5)$ in Equation (50) for region CASTILER in Figure PA-8.
28	BPPRM	CASTILER	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the Castile brine reservoir. Used in region CASTILER in Figure PA-8.
29	BPCOMP	CASTILER	COMP_RCK	Bulk compressibility (Pa^{-1}) of Castile brine reservoir. Defines β_{fB} in Equation (29) for region CASTILER of Figure PA-8
30	BHPERM	BH_SAND	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the silty sand-filled borehole (Table PA-5). Used in regions Upper Borehole and Lower Borehole in Figure PA-8.
31	DRZPRM	DRZ_1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the DRZ. Used in regions Upper DRZ and Lower DRZ in Figure PA-8.
32	PLGPRM	CONC_PLG	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the concrete borehole plugs (Table PA-5). Used in region Borehole Plugs in Figure PA-8.
34	WSOLAM3S	SOLAM3	SOLSIM	Uncertainty factor (dimensionless) for solubility of Am in the +III oxidation state in Salado brine. Defines UF(Salado, +3, Am) in Equation (90).

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA — Continued

Sample Position	Variable Name	Material Name	Property Name	Description
35	WSOLAM3C	SOLAM3	SOLCIM	Uncertainty factor (dimensionless) for solubility of Am in the +III oxidation state in Castile brine. Defines UF(Castile, +3, Am) in Equation (90).
36	WSOLPU3S	SOLPU3	SOLSIM	Uncertainty factor (dimensionless) for solubility of Pu in the +III oxidation state in Salado brine. Defines UF(Salado, +3, Pu) in Equation (90).
37	WSOLPU3C	SOLPU3	SOLCIM	Uncertainty factor (dimensionless) for solubility of Pu in the +III oxidation state in Castile brine. Defines UF(Castile, +3, Pu) in Equation (90).
38	WSOLPU4S	SOLPU4	SOLSIM	Uncertainty factor (dimensionless) for solubility of Pu in the +IV oxidation state in Salado brine. Defines UF(Salado, +4, Pu) in Equation (90).
39	WSOLPU4C	SOLPU4	SOLCIM	Uncertainty factor (dimensionless) for solubility of Pu in the +IV oxidation state in Castile brine. Defines UF(Castile, +4, Pu) in Equation (90).
40	WSOLU4S	SOLU4	SOLSIM	Uncertainty factor (dimensionless) for solubility of U in the +IV oxidation state in Salado brine. Defines UF(Salado, +4, U) in Equation (90).
41	WSOLU6S	SOLU6	SOLSIM	Uncertainty factor (dimensionless) for solubility of U in the +VI oxidation state in Salado brine. Defines UF(Salado, +6, U) in Equation (90).
42	WSOLU6C	SOLU6	SOLCIM	Uncertainty factor (dimensionless) for solubility of U in the +VI oxidation state in Castile brine. Defines UF(Castile, +6, U) in Equation (90).
43	WSOLTH4S	SOLTH4	SOLSIM	Uncertainty factor (dimensionless) for solubility of Th in the +IV oxidation state in Salado brine. Defines UF(Salado, +4, Th) in Equation (90).
44	WPHUMOX3	PHUMOX3	PHUMCIM	Ratio (dimensionless) of concentration of actinides attached to humic colloids to dissolved concentration of actinides for oxidation state +III in Castile brine. Defines SF_{Hum}(Castile, +3, Am) and SF_{Hum}(Castile, +3, Pu) for Equation (90).
45	WOXSTAT	GLOBAL	OXSTAT	Indicator variable for elemental oxidation states (dimensionless). WOXSTAT = 0 indicates use of CMKDPU3, CMKDU4, WSOLPU3C, WSOLPUS, , WSOLU4C, and WSOLU4S. WOXSTAT = 1 implies use of CMKDPU4, CMKDU6, WSOLPU4C, WSOLPU4S, WSOLU6C, and WSOLU6S.

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA — Continued

Sample Position	Variable Name	Material Name	Property Name	Description
46	CTRANSFM	CULEBRA	MINP_FAC	Multiplier (dimensionless) applied to transmissivity of the Culebra within the land withdrawal boundary after mining of potash reserves. Defines MF in Equation (216) (See section PA-4.8.2).
47	CTRAN	GLOBAL	TRANSIDX	Indicator variable for selecting transmissivity field. See Section PA-4.8.2.
48	CCLIMSF	GLOBAL	CLIMTIDX	Climate scale factor (dimensionless) for Culebra flow field. Defines SFC in Equation (221).
49	CFRACSP	CULEBRA	HMBLKLT	Culebra fracture spacing (m). Equal to half the distance between fractures (i.e., the Culebra half matrix block length). Defines B in Equation (236) and Figure PA-26.
50	CFRACPOR	CULEBRA	APOROS	Culebra fracture (i.e., advective) porosity (dimensionless). Defines ϕ in Equation (223).
51	CMTRXPOR	CULEBRA	DPOROS	Culebra matrix (i.e., diffusive) porosity (dimensionless). Defines ϕ' in Equation (230).
52	CMKDU6	U+6	MKD_U	Matrix distribution coefficient (m^3/kg) for U in +6 oxidation state. Defines K_{dk} in Equation (231).
53	CMKDU4	U+4	MKD_U	Matrix distribution coefficient (m^3/kg) for U in +4 oxidation state. Defines K_{dk} in Equation (231).
54	CMKDPU3	PU+3	MKD_PU	Matrix distribution coefficient (m^3/kg) for Pu in +3 oxidation state. Defines K_{dk} in Equation (231).
55	CMKDPU4	PU+4	MKD_PU	Matrix distribution coefficient (m^3/kg) for Pu in +4 oxidation state. Defines K_{dk} in Equation (231).
56	CMKDTH4	TH+4	MKD_TH	Matrix distribution coefficient (m^3/kg) for Th in +4 oxidation state. Defines K_{dk} in Equation (231).
57	CMKDAM3	AM+3	MKD_AM	Matrix distribution coefficient (m^3/kg) for Am in +3 oxidation state. Defines K_{dk} in Equation (231).
58	WTAUFAIL	BOREHOLE	TAUFAIL	Shear strength of waste (Pa). Defines $r(R,1)$ in Equation (111).
60	PBRINE	GLOBAL	PBRINE	Probability that a drilling intrusion penetrates pressurized brine in the Castile Formation. Defines p_{B1}; see Section PA-3.5.

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA — Continued

Sample Position	Variable Name	Material Name	Property Name	Description
61	DOMEGA	BOREHOLE	DOMEGA	Drill string angular velocity (rad/s). Defines $\Delta\Omega$ in Equation (112b).
62	SHURBRN	SHFTU	SAT_RBRN	Residual brine saturation in upper shaft seal materials (dimensionless). Defines S_{br} in Equation (35) for region Upper Shaft in Figure PA-8.
63	SHURGAS	SHFTU	SAT_RGAS	Residual gas saturation in upper shaft seal materials (dimensionless). Defines S_{gr} in Equation (34) for region Upper Shaft in Figure PA-8.
64	SHUPRM	SHFTU	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of upper shaft seal materials. Used in region Upper Shaft in Figure PA-8.
65	SHLPRM1	SHFTL_T1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of lower shaft seal materials for the first 200 years after closure. Used in region Lower Shaft in Figure PA-8.
66	SHLPRM2	SHFTL_T2	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of lower shaft seal materials from 200 years to 10,000 years after closure. Used in region Lower Shaft in Figure PA-8.
75	RNDSPALL	SPALLMOD	RNDSPALL	Indicator variable for selecting element from the LHS for DRSPALL. See Section PA-4.6.4.

Table PA-18. Differences in Uncertain Parameters in the CCA PA and CRA-2004 PA

Material Name	Property Name	Description	When Used	Reason for Removal or Addition
DRZ_PCS	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the DRZ immediately above the panel closure concrete.	2003	Added due to the addition of the Option D panel closures.
CONC_PCS	PRMX_LOG	Logarithm of intrinsic permeability (m^2) for the concrete portion of the panel closure.	2003	Added due to the addition of the Option D panel closures.
SOLU4	SOLCIM	Uncertainty factor (dimensionless) for solubility of U in the +IV oxidation state in Castile brine.	2003	Added for completeness.
SOLTH4	SOLCIM	Uncertainty factor (dimensionless) for solubility of Th in the +IV oxidation state in Castile brine.	2003	Added for completeness.
DRZ_1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the DRZ.	2003	Added from 1997 PAVT (Hansen and Leigh 2003).
CONC_PLG	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the concrete borehole plugs.	2003	Added from 1997 PAVT (Hansen and Leigh 2003).
GLOBAL	PBRINE	Probability that a drilling intrusion penetrates pressurized brine in the Castile Formation.	2003	Added due to change in Castile Brine pocket modeling (Section 6.12.4.6).
BOREHOLE	DOMEGA	Drill string angular velocity (rad/s).	2003	Added from 1997 PAVT (Hansen and Leigh 2003).
SHFTU	SAT_RBRN	Residual brine saturation in upper shaft seal materials (dimensionless).	2003	Added due to the simplified shaft model.
SHFTU	SAT_RGAS	Residual gas saturation in upper shaft seal materials (dimensionless).	2003	Added due to the simplified shaft model.
SHFTU	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of upper shaft seal materials.	2003	Added due to the simplified shaft model.
SHFTL_T1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of lower shaft seal materials for the first 200 years after closure.	2003	Added due to the simplified shaft model.
SHFTL_T2	PRMX_LOG	Logarithm of permeability of lower shaft seal materials (m^2) from 200 years to 10,000 years after closure.	2003	Added due to the simplified shaft model.
SPALLMOD	RNDSPALL	Indicator variable for selecting element from the LHS for DRSPALL.	2003	Use of DRSPALL to calculate spall volumes.

Table PA-18. Differences in Uncertain Parameters in the CCA PA and CRA-2004 PA — Continued

Material Name	Property Name	Description	When Used	Reason for Removal or Addition
CL_L_T1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) for clay components of shaft.	1996	Removed due to the simplified shaft model.
CONC_T1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) for concrete component of shaft seal for 0 to 400 years.	1996	Removed due to the simplified shaft model.
ASPHALT	PRMX_LOG	Logarithm of intrinsic permeability (m^2) for clay components of shaft seal (m^2).	1996	Removed due to the simplified shaft model.
SHFT_DRZ	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of DRZ surrounding shaft.	1996	Removed due to the simplified shaft model.
SALT_T1	CUMPROB	Pointer variable used to select intrinsic permeability in crushed salt component of shaft seal at different times.	1996	Removed due to the simplified shaft model.
CASTILER	GRIDFLO	Pointer variable for selection of brine pocket volume.	1996	Removed due to changes in Castile Brine pocket modeling (Section 6.12.4.6).
BLOWOUT	PARTDIA	Waste particle diameter (m).	1996	Removed due to replacement of spall model.

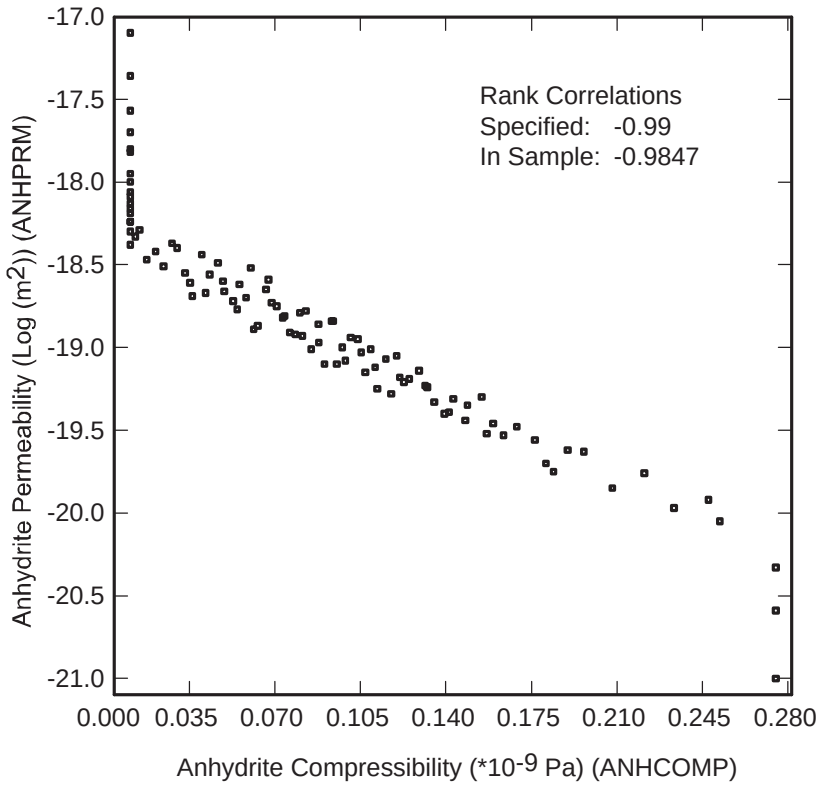

Figure PA-30. Correlation Between ANHCOMP and ANHPRM.

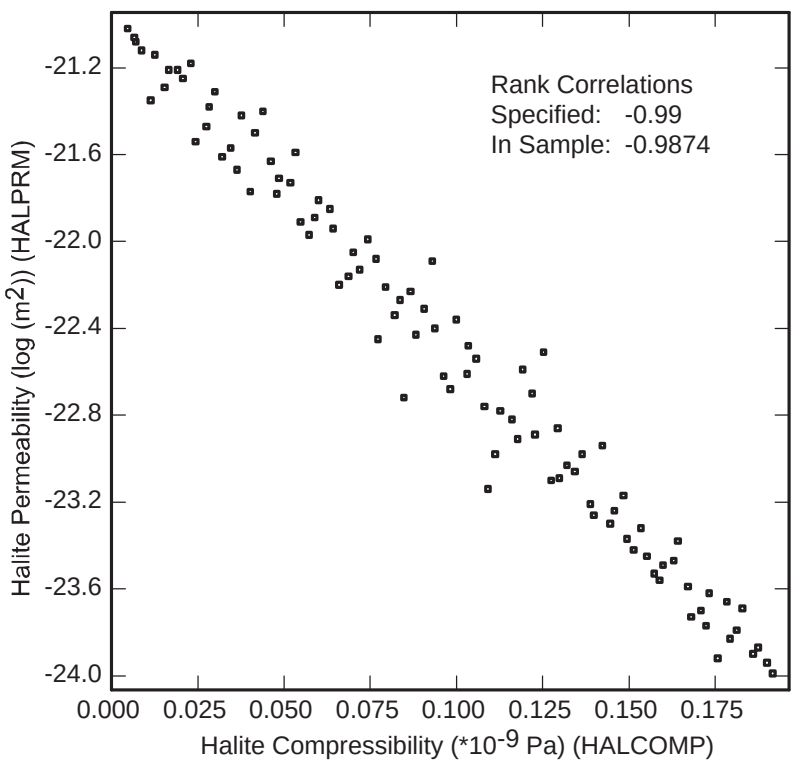

Figure PA-31. Correlation Between HALCOMP and HALPRM.

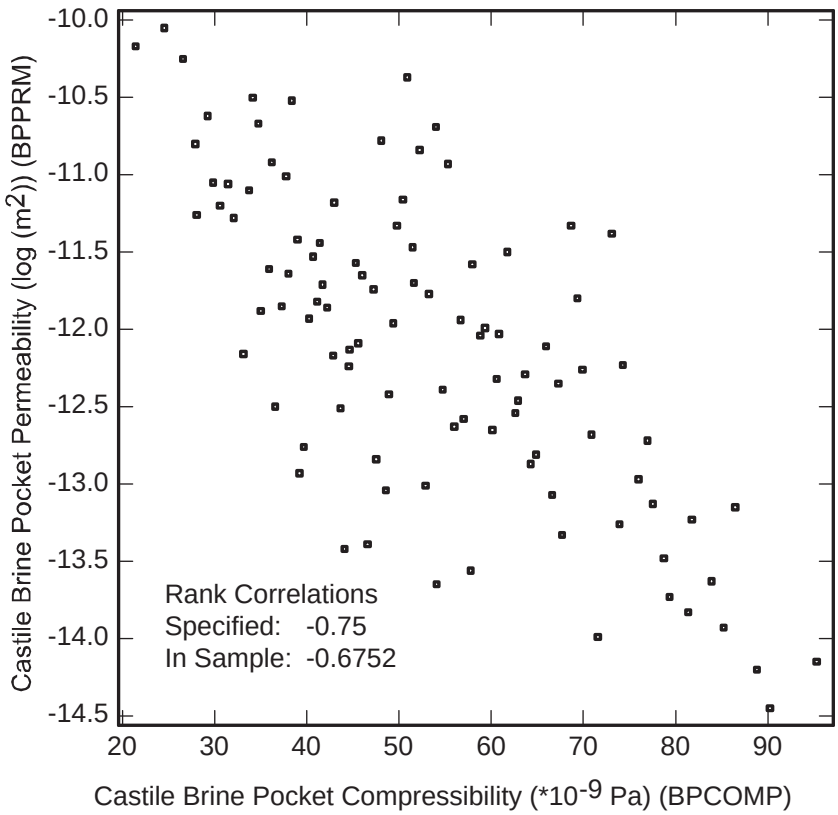

Figure PA-32. Correlation between BPCOMP and BPPRM.

PA-6.0 COMPUTATIONAL PROCEDURES

This section outlines the computational procedures used to execute the CRA-2004 PA. First, this section outlines the sampling procedures applied to evaluate performance accounting for subjective and stochastic uncertainty. The mechanistic calculations used to evaluate the function f in Equation (24) are tabulated, followed by a description of the algorithms used to compute releases. This section concludes with a discussion of sensitivity analysis techniques used to identify which uncertain parameters are primary contributors to the uncertainty in the PA results.

PA-6.1 Sampling Procedures

Extensive use is made of sampling procedures in the CRA-2004 PA. In particular, random sampling is used in the generation of individual CCDFs (i.e., for integration over the probability space $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$ for stochastic uncertainty; see Section PA-2.3) and Latin hypercube sampling is used for the assessment of the effects of imprecisely known analysis inputs (i.e., for integration over the probability space $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$ for subjective uncertainty; see Section PA-2.4).

In random sampling, sometimes also called simple random sampling, the observations

$$\boldsymbol{x_k} = \left[\boldsymbol{x_{k1}}, \boldsymbol{x_{k2}}, \ldots, \boldsymbol{x_{knV}}\right], \text{ k = 1, 2, ..., nR,} \tag{255}$$

where nR is the sample size, are selected according to the joint probability distribution for the elements of x as defined by $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$. In practice, $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$ is defined by specifying a distribution D_j for each element x_j of $\boldsymbol{x}$. Points from different regions of the sample space S_{st}, occur in direct relationship to the probability of occurrence of these regions. Furthermore, each sample element is selected independently of all other sample elements. The random sampling provides unbiased estimates for means, variances, and distributions of the elements x that comprise $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$.

The random sampling to integrate over the probability space for $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$ for stochastic uncertainty is implemented in the WIPP PA code CCDFGF. The code CCDFGF is capable of generating and evaluating thousands of possible futures; the CRA-2004 PA uses a sample size nS = 10,000 from the space $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$ to estimate repository releases. This sample size is sufficient to estimate the 0.999 quantile of the distribution of releases to the accessible environment.

Latin hypercube sampling is used to integrate over the space for subjective uncertainty $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$. This technique was first introduced by McKay et al (1979). In Latin hypercube sampling, the range of each variable (i.e., the x_j) is divided into nLHS intervals of equal probability and one value is selected at random from each interval. The nLHS values thus obtained for x_1 are paired at random without replacement with the nLHS values obtained for x_2. These nLHS pairs are combined in a random manner without replacement with the nLHS values

of x_3 to form nLHS triples. This process is continued until a set of nLHS nV-tuples is formed. These nV-tuples are of the form

$$\boldsymbol{x_k} = \left[x_{k1}, x_{k2}, \ldots, x_{knV} \right], \text{ k = 1, ..., nLHS,} \tag{256}$$

and constitute the Latin hypercube sample. The individual x_j must be independent for the preceding construction procedure to work; a method for generating Latin hypercube and random samples from correlated variables was developed by Iman and Conover (1982) and is used in WIPP PA. For more information about Latin hypercube sampling and a comparison with other sampling techniques, see Helton and Davis (2003).

Latin hypercube sampling provides unbiased estimates for means and distribution functions and dense stratification across the range of each sampled variable (McKay et al. 1979), ensuring that the sampled values cover the full range of each uncertain element x_j of $\boldsymbol{x}$. In particular, uncertainty and sensitivity analysis results obtained with Latin hypercube sampling are robust even when relatively small samples (i.e., nLHS = 50 to 200) are used (Iman and Helton 1988, 1991; Helton et al. 1995).

PA-6.2 Sample Size for Incorporation of Subjective Uncertainty

Section 194.34(d) states that "The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability." For an LHS of size nLHS, the preceding guidance is equivalent to the inequality

$$1 - 0.99^{nLHS} > 0.95, \tag{257}$$

which results in a minimum value of 298 for nLHS. The CRA-2004 PA uses a total sample size of 300 to integrate over the probability space $\left(X_{su}, S_{su}, p_{su} \right)$ for subjective uncertainty. As discussed in the next section, however, in order to demonstrate convergence of the mean for the population of CCDFs, the total sample of 300 is created by means of three replicated samples of size 100 each.

PA-6.3 Statistical Confidence on Mean CCDF

Section 194.34(f) states that "Any compliance assessment shall provide information which demonstrates that there is at least a 95 percent level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 of this chapter." Given that Latin hypercube sampling is used, the confidence intervals required by Section 194.34(f) are obtained with a replicated sampling technique proposed by Iman (1982). In this technique, the sampling in Equation (256) is repeated nR times with different random seeds. These samples lead to a sequence $\bar{P}_r(R),\ r = 1, 2, \ldots, nR,$ of estimated mean exceedance probabilities, where $\bar{P}_r(R)$ defines the mean CCDF obtained for sample r (i.e., $\bar{P}_r(R)$ is the mean probability that a normalized release of size R will be exceeded; see Section PA-2.4) and nR is the number of independent samples generated with different random seeds. Then,

$$\bar{P}(R) = \sum_{r=1}^{nR} \bar{P}_r(R) / nR \tag{258}$$

and

$$SE(R) = \left\{ \sum_{r=1}^{nR} \left[\bar{P}_r(R) - \bar{P}(R) \right]^2 / nR(nR-1) \right\}^{1/2} \tag{259}$$

provide an additional estimate of the mean CCDF and an estimate of the standard error associated with the mean exceedance probabilities. The t-distribution with nR–1 degrees of freedom can be used to place confidence intervals around the mean exceedance probabilities for individual R values (i.e., around $\bar{P}(R)$). Specifically, the 1–α confidence interval is given by $\bar{P}_r(R) \pm t_{1-\alpha/2} SE(R)$, where $t_{1-\alpha/2}$ is the $1-\alpha/2$ quantile of the t-distribution with nR–1 degrees of freedom (e.g., $t_1 - \alpha/2 = 4.303$ for α = 0.05 and nR = 3). The same procedure can also be used to place pointwise confidence intervals around percentile curves.

PA-6.4 Generation of LHSs

The LHS program (WIPP PA 1996) is used to produce three independently generated LHSs of size nLHS = 100 each, for a total of 300 sample elements. Each individual replicate is an LHS of the form

$$x_{su,k} = \left[x_{k1}, x_{k2}, \ldots, x_{knV} \right], \text{ k = 1, 2, …, nLHS = 100.} \tag{260}$$

In the context of the replicated sampling procedure described in Section PA-6.2, nR = 3 replicates of 100 are used. For notational convenience, the replicates are designated by R1, R2, and R3.

The restricted pairing technique described in Section PA-6.2 is used to induce requested correlations and also to assure that uncorrelated variables have correlations close to zero. The variable pairs (ANHCOMP, ANHPRM), (HALCOMP, HALPRM), and (BPCOMP, BPPRM) are assigned rank correlations of –0.99, –0.99, and –0.75, respectively (Section PA-5.4). All other variable pairs are assigned rank correlations of zero. The restricted pairing technique is very successful in producing these correlations (Table PA-19). Specifically, the correlated variables have correlations that are close to their specified values and uncorrelated variables have correlations that are close to zero.

Table PA-19. Example Correlations in Replicate R1

	WGRCOR	WMICDFLG	WGRMICI	WGRMICH	WFBETCEL	WRGSSAT	WRBRNSAT	WASTWICK
WGRCOR	1.0000							
WMICDFLG	-0.0993	1.0000						
WGRMICI	0.0152	0.0495	1.0000					
WGRMICH	0.0191	-0.0098	0.0150	1.0000				
WFBETCEL	0.0113	-0.0139	-0.0273	0.0033	1.0000			
WRGSSAT	0.0004	0.0712	-0.0451	-0.0058	-0.0517	1.0000		
WRBRNSAT	0.0192	0.0244	-0.0558	0.0321	-0.0128	-0.0260	1.0000	
WASTWICK	-0.0096	0.0955	-0.0099	0.0043	0.0057	-0.0147	0.0076	1.0000

PA-6.5 Generation of Individual Futures

Random sampling (Section PA-6.1) is used to generate elements $\boldsymbol{x_{st}}$ of S_{st} for CCDF construction. Table PA-20 outlines the algorithm used to generate a single future $\boldsymbol{x_{st}}$ in the CRA-2004 PA. For each LHS element $\boldsymbol{x_{su,k}}$, k = 1, 2, …, 300, a total of nS = 10,000 individual futures of the form

$$\boldsymbol{x_{st,i}} = \left[t_{i1}, e_{i1}, l_{i1}, b_{i1}, p_{i1}, a_{i1}, t_{i2}, e_{i2}, l_{i2}, b_{i2}, p_{i2}, a_{i2}, \ldots, t_{in}, e_{in}, l_{in}, b_{in}, p_{in}, a_{in}, t_{i,min} \right], \quad i = 1, 2, \ldots, nS = 10{,}000 \tag{261}$$

are generated in the construction of all CCDFs for that LHS element. A different random seed is used to initiate the sampling of $\boldsymbol{x_{st}}$ for each LHS element, with the result that each LHS element uses different values for $\boldsymbol{x_{st}}$ in CCDF construction. As 300 LHS elements are used in the analysis and 10,000 futures are sampled for each LHS element, the total number of futures $\boldsymbol{x_{st}}$ used in the analysis in CCDF construction is 3×10^6.

The drilling rate λ_d is used to generate the times at which drilling intrusions occur. For a Poisson process with a constant λ_d (i.e., a stationary process), the CDF for the time Δt between the successive events is given by (Ross 1987, p. 113)

$$prob\left(t \le \Delta t\right) = 1 - \exp\left(-\lambda_d \Delta t\right). \tag{262}$$

A uniformly distributed random number is selected from [0, 1]. Then, solution of

$$r_1 = 1 - \exp\left(-\lambda_d\, t_1\right) \tag{263}$$

Table PA-20. Algorithm to Generate a Single Future x_{st} from S_{st}

1. Sample t_1 with a time dependent λ_d given by $\lambda_d(t) = \begin{cases} 0 & \text{if } 0 \le t \le tA \\ \lambda_d & \text{if } t > tA \end{cases}$, where tA = 100 yr (i.e., time at which administrative control ends) and $\lambda_d = 3.30 \times 10^{-3}\ \text{yr}^{-1}$ (see Section PA-3.2).
2. Sample e_1 with a probability of $pE_0 = 0.797$ that the intrusion will be in an unexcavated area and a probability of $pE_1 = 0.203$ that the intrusion will be in an excavated area (see Section PA-3.3).
3. Sample l_1 with a probability of $pL_j = 6.74 \times 10^{-3}$ for each of the j = 1, 2, …, 144 nodes in Figure PA-6 (see Section PA-3.4).
4. Sample b_1 with a probability of $pB_1 = p(x_{su})$ that the intrusion will penetrate pressurized brine (see Section PA-3.5).
5. Sample p_1 with probabilities of $pPL_1 = 0.015$, $pPL_2 = 0.696$, and $pPL_3 = 0.289$ that plugging pattern 1, 2, or 3, respectively, will be used (see Section PA-3.6).
6. Sample a_1 (see Section PA-3.7). 6.1 Penetration of nonexcavated area (i.e., $e_1 = 0$): $a_i = a_1 = 0$. 6.2 Penetration of excavated area (i.e., $e_1 = 1$): Sample to determine if intrusion penetrates RH-TRU or CH-TRU waste with probabilities of pRH = 0.124 and pCH = 0.876 of penetrating RH-TRU and CH-TRU waste, respectively. 6.3 Penetration of RH-TRU waste: $a_i = a_1 = 1$. 6.4 Penetration of CH-TRU waste: Use probabilities pCH_j of intersecting waste stream j, j = 1, 2, …, 693, (see Attachment PAR, Table PAR-50) to independently sample three intersected waste streams iCH_{11}, iCH_{12}, iCH_{13} (i.e., each of iCH_{11}, iCH_{12}, iCH_{13} is an integer between 1 and 693). Then, a_1 = [2, iCH_{11}, iCH_{12}, iCH_{13}].
7. Repeat steps 1 - 6 to determine properties (i.e., t_i, e_i, l_i, b_i, p_i, a_i) of the ith drilling intrusion.
8. Continue until $t_{n+1} > 10{,}000$ yr; the n intrusions thusly generated define the drilling intrusions associated with x_{st}.
9. Sample t_{min} with a time dependent λ_m given by $\lambda_m(t) = \begin{cases} 0 & \text{if } 0 \le t \le tA \\ \lambda_m & \text{if } t > tA \end{cases}$ where tA = 100 yr and $\lambda_m = 1 \times 10^{-4}\ \text{yr}^{-1}$ (see Section PA-3.8).

for t_1 gives the time of the first drilling intrusion. An initial period of 100 years of administrative control is assumed, thus 100 years is added to the t_1 obtained in Equation (263) to obtain the time of the first drilling intrusion. Selection of a second random number r_2 and solution of

$$r_2 = 1 - \exp\left(-\lambda_d \, \Delta t_1\right) \tag{264}$$

for Δt_1 gives the time interval between the first and second drilling intrusions, with the outcome that $t_2 = t_1 + \Delta t_1$. This process is continued until t_{n+1} exceeds 10,000 yr. The times $t_1, t_2, \ldots, t_n$ then constitute the drilling times in x_{st} in Equation (261).

The mining time t_{min} is sampled in a manner similar to sampling the drilling times. Additional uniformly distributed random numbers from $[0,1]$ are used to generate the elements e_i, l_i, b_i, p_i, a_i of x_{st} from their assigned distributions (see Section PA-3.0).

PA-6.6 Construction of CCDFs

In the CRA-2004 PA, the sampling of individual futures (Section PA-6.5) and associated CCDF construction is carried out by the CCDFGF program (WIPP PA 2003d). The sampled futures $x_{st,i}$ in Equation (261) are used to construct CCDFs for many different quantities (e.g., cuttings and cavings releases, spallings releases, direct brine releases, etc.). The construction process is the same for each quantity. For notational convenience, assume that the particular quantity under consideration can be represented by a function $f\left(x_{st,i}\right)$, with the result that 10,000 values

$$f\left(x_{st,i}\right),\ i = 1, 2, \ldots, 10{,}000 \tag{265}$$

are available for use in CCDF construction. Formally, the resultant CCDF is defined by the expression in Equation (4). In practice, the indicator function δ_R is not directly used and the desired CCDF is obtained after an appropriate ordering of the $f\left(x_{st,i}\right)$ (i.e., from smallest to largest or largest to smallest) as described below.

The CRA-2004 PA uses a binning procedure in CCDF construction to simplify sorting the individual $f\left(x_{st,i}\right)$ and to reduce the number of plot points. Specifically, the range of f is divided into intervals (i.e., bins) by the specified points

$$f_{min} = b_0 < b_1 < b_2 < \ldots < b_n = f_{max}, \tag{266}$$

where f_{min} is the minimum value of f to be plotted (typically 10^{-6} or 10^{-5} when an EPA normalized release is under consideration), f_{max} is the maximum value of f to be plotted (typically 100 when an EPA normalized release is under consideration), n is the number of bins in use, and the b_i are typically loguniformly placed with 20 values per order of magnitude. A counter nB_j is used for each interval $\left[b_{j-1}, b_j\right]$. All counters are initially set to zero. Then, as individual values $f\left(x_{st,i}\right)$ are generated, the counter nB_j is incremented by 1 when the inequality

$$b_{j-1} < f\left(x_{st,i}\right) \le b_j \tag{267}$$

is satisfied. When necessary, f_{max} is increased in value so that the inequality $f\left(x_{st,i}\right) < f_{max}$ will always be satisfied. Once the 10,000 values for $f\left(x_{st,i}\right)$ have been generated, a value of nB_j exists for each interval $\left[b_{j-1}, b_j\right]$. The quotient

$$pB_j = nB_j / 10{,}000 \tag{268}$$

provides an approximation to the probability that $f\left(x_{st}\right)$ will have a value that falls in the interval $\left[b_{j-1}, b_j\right]$. The resultant CCDF is then defined by the points

$$\left(b_j,\ prob\left(value > b_j\right)\right) = \left(b_j,\ \sum_{k=j+1}^{n} pB_k\right) \tag{269}$$

for j = 0, 1, 2, …, n–1, where $prob\left(value > b_j\right)$ is the probability that a value greater than b_j will occur.

The binning technique produces histograms that are difficult to read when multiple CCDFs appear in a single plot. As the number of futures is increased and the bins are refined, the histogram CCDF should converge to a continuous CCDF as additional points (i.e., elements x_{st} of S_{st}) are used in its construction. The continuous CCDF is approximated by drawing diagonal lines from the left end of one bin to the left end of the next bin.

When multiple CCDFs appear in a single plot, the bottom of the plot becomes very congested as the individual CCDFs drop to zero on the abscissa. For this reason, each CCDF stops at the largest observed consequence value among the 10,000 values calculated for that CCDF. Stopping at the largest consequence value rather than the left bin boundary of the bin that contains this value permits the CCDF to explicitly show the largest observed consequence. Due to the use of a sample size of 10,000 in the generation of CCDFs for comparison with the EPA release limits, the last nonzero exceedance probability in the resultant CCDFs is typically 10^{-4}; Figure PA-5 shows an example of CCDFs from the 2004 PA.

PA-6.7 Mechanistic Calculations

For the CRA-2004 PA, calculations were performed with the models described in Chapter PA-4.0 for selected elements of S_{st} (see Section PA-3.9) and the results were used to determine the releases to the accessible environment for the large number (i.e., 10,000) of randomly sampled futures used in the estimation of individual CCDFs. The same set of mechanistic calculations was performed for each LHS element. This section summarizes the calculations performed with each of the models described in Chapter PA-4.0; Section PA-6.8 outlines the algorithms used to construct releases for the randomly sampled elements $x_{st,i}$ of S_{st} from the results of the

mechanistic calculations. Long (2003) documents execution of the calculations and archiving of calculation results.

PA-6.7.1 BRAGFLO Calculations

The BRAGFLO code (Section PA-4.2) computes two-phase (brine and gas) flow in and around the repository. BRAGFLO results are used as initial conditions in the models for Salado Transport (implemented in NUTS and PANEL), spallings (implemented in CUTTINGS_S) and DBR (also calculated by BRAGFLO). Thus, the BRAGFLO scenarios are used to define scenarios for other codes.

The four fundamental scenarios for the CRA-2004 PA (Section PA-3.9) define four categories of calculations to be performed with BRAGFLO (i.e., E0, E1, E2, and E1E2). These four fundamental scenarios were expanded into six general scenarios by specifying the time of drilling intrusions. Table PA-21 summarizes the specific scenarios used in the CRA-2004 PA. A total of 6 scenarios × nR × nLHS = 6 × 3 × 100 = 1800 BRAGFLO calculations were conducted for the CRA-2004 PA.

Table PA-21. BRAGFLO Scenarios in the CRA-2004 PA

Fundamental Scenario (Section PA-3.9)	*Specific Scenario*	*Time of drilling intrusion(s)*
E0: no drilling intrusions	S1	N/A
E1: single intrusion into excavated area (e_1 = 1), pressurized brine is penetrated (b_1 = 1), and plugging pattern 2 is used (p_1 = 2).	S2	350 years
	S3	1,000 years
E2: single intrusion into excavated area (e_1 = 1), pressurized brine is penetrated (b_1 = 1) and plugging pattern 3 is used (p_1 = 3), or pressurized brine is not penetrated (b_1 = 0).	S4	350 years
	S5	1,000 years
E1E2: two intrusions into the same waste panel (e_1 = e_2 = 1), the first being an E2 intrusion and the second being an E1 intrusion.	S6	800 years for E2 intrusion 2,000 years for E1 intrusion

Values for the activity level a_1 and for mining time t_{min} are not needed for the mechanistic calculations; these values are used in the construction of the releases from the results of the mechanistic calculations (Section PA-6.8). Although a value for drilling location l_1 is not specified, a drilling location is required for the BRAGFLO calculations. If equivalent grids were used in the definition of x_{st} (Figure PA-6) and in the numerical solution of the partial differential equations on which BRAGFLO is based (Figure PA-8), the location of the drilling intrusion used in the BRAGFLO calculations could be specified as a specific value for l_1, which in turn would correspond to one of the 144 locations in Figure PA-6 that are designated by l in the definition of x_{st}. However, as these grids are not the same, a unique pairing between a value for l_1 and the location of the drilling intrusion used in the computational grid employed with BRAGFLO is not possible. The BRAGFLO computational grid divides the repository into

a lower waste panel (area Waste Panel), a middle group of four waste panels (area South RoR), and an upper group of five waste panels (area North RoR), with the drilling intrusion taking place through the center of the lower panel (Figure PA-8). Thus, in the context of the locations in Figure PA-6 potentially indexed by l_1, the drilling intrusions in Scenario S2, Scenario S3, Scenario S4 and Scenario S5 occur at a location in Panel 5. In Scenario S6, both intrusions occur at a location in Panel 5, with the effects of flow between the two boreholes implemented through assumptions involving the time-dependent behavior of borehole permeability (Table PA-5).

PA-6.7.2 NUTS Calculations

Transport through the Salado is computed by the code NUTS (Section PA-4.3) using the flow fields computed by BRAGFLO. Two types of calculations are performed with NUTS. First, a set of screening calculations identifies elements of the sample from S_{su} for which radionuclide transport is possible through the Salado to the LWB or to the Culebra. The screening calculations identify a subset of the sample from S_{st} for which transport is possible and for which releases calculations are performed. Screening calculations are performed for all BRAGFLO cases, for a total of 1500 screening calculations with NUTS (Table PA-21). Table PA-22 summarizes the NUTS release calculations for the CRA-2004 PA. Based on the screening calculations, a total of 1402 release calculations are performed for the CRA-2004 PA. For each vector that is retained (based on the screening calculations), release calculations are performed for a set of intrusion times.

Table PA-22. NUTS Release Calculations in the CRA-2004 PA

NUTS Scenario	Number of vectors (all replicates)	Flow field	Intrusion time (t_1)
S1	1 + 0 + 0 = 1	BRAGFLO S1 scenario	N/A
S2	60 + 64 + 61 = 185	BRAGFLO S2 scenario	E1 intrusion at 100 and 350 years
S3	49 + 55 + 51 = 155	BRAGFLO S3 scenario	E1 intrusion at 1,000, 3,000, 5,000, 7,000 and 9,000 years
S4	13 + 14 + 11 = 38	BRAGFLO S4 scenario	E2 intrusion at 100, 350 years
S5	12 + 13 + 11 = 36	BRAGFLO S5 scenario	E2 intrusion at 1,000, 3,000, 5,000, 7,000 and 9,000 years

Table PA-22 lists five scenarios for release calculations corresponding to the five BRAGFLO scenarios. Each NUTS scenario uses the flow field computed for the corresponding BRAGFLO scenario. The intrusion times for the NUTS scenarios are accommodated by shifting the BRAGFLO flow fields in time so that the NUTS and BRAGFLO intrusions coincide. For example, the NUTS S3 scenario with an intrusion at 3,000 years requires a flow field for the time interval between (3,000 yr, 10,000 yr); this scenario uses the BRAGFLO S3 flow field for the time interval between (1,000 yr, 8,000 yr).

Values for the variables indicating intrusion into excavated area (e_1), penetration of pressurized brine (b_1), plugging pattern (p_1) and drilling location (l_1) are the same as in the corresponding

BRAGFLO scenario. Values for the activity level a_i and for mining time t_{min} are not specified for the NUTS scenarios.

PA-6.7.3 PANEL Calculations

As outlined in Section PA-4.4, the code PANEL is used to estimate releases to the Culebra associated with E1E2 scenarios and to estimate radionuclide concentrations in brine for use in the estimation of direct brine releases. An E1E2 scenario assumes two drilling intrusions into the same waste panel: the first intrusion being an E2 intrusion (Table PA-22) occurring at time t1 and the second intrusion being an E1 intrusion (Table PA-22) occurring at time t_2. PANEL calculations are performed for t_2 = 100, 350, 1,000, 2,000, 4,000, 6,000 and 9,000 years using the flow field produced by the single BRAGFLO calculation for Scenario S6, for a total of 7 × nR × nLHS = 7 × 3 × 100 = 2100 PANEL calculations. The BRAGFLO flow field is shifted forward or backward in time as appropriate so that the time of the second intrusion (t_2) coincides. The shifting of the BRAGFLO flow field results in values for the time (t_1) of the first intrusion (E2) for the PANEL calculations given by

$$t_1 = \max\left\{100\,yr,\ t_2 - 1200\,yr\right\}, \tag{270}$$

where the restriction that t_1 cannot be less than 100 years results from the definition of x_{st}, which does not allow negative intrusion times, and from the assumption of 100 years of administrative control during which there is no drilling (i.e., $\lambda_d(t)$ = 0 yr^{-1} for $0 \le t \le 100$ yr; see Equation (7)). Under this convention, what is specified in concept by the definition of Scenario S6 for the BRAGFLO calculations differs from what is actually done computationally because t_1 does not always precede t_2 by 1200 yr in the PANEL calculation. Values for the other variables defining the element x_{st} of S_{st} for the PANEL E1E2 scenarios are the same as in the BRAGFLO S6 scenario.

Calculation of radionuclide concentration are not specific to any BRAGFLO scenario. The concentration calculations compute the mobilized activity in two different brines (Castile and Salado) and are performed at 100, 125, 175, 350, 1,000, 3,000, 5,000, 7,500 and 10,000 years for a total of 2 × 9 × nR = 54 calculations.

PA-6.7.4 CUTTINGS_S Calculations

The code CUTTINGS_S computes the volumes of solids removed from the repository by cuttings and cavings (see Section PA-4.5) and spallings (see Section PA-4.6). Table PA-23 lists the CUTTINGS_S calculations performed for the CRA-2004 PA, totaling 78 × nR × nLHS = 78 × 3 × 100 = 23,400 CUTTINGS_S calculations.

Table PA-23. CUTTINGS_S Scenarios in the CRA-2004 PA

Scenario	Description
S1	Intrusion into lower, middle, and upper waste panel in undisturbed (i.e., E0 conditions) repository at 100, 350, 1,000, 3,000, 5,000, and 10,000 years = 18 combinations.
S2	Initial E1 intrusion at 350 years followed by a second intrusion into the same, adjacent, and nonadjacent waste panel at 550, 750, 2,000, 4,000 or 10,000 years = 15 combinations.
S3	Initial E1 intrusion at 1000 years followed by a second intrusion into the same, adjacent, and nonadjacent waste panel at 1200, 1,400, 3,000, 5,000 or 10,000 years = 15 combinations.
S4	Initial E2 intrusion at 350 years followed by a second intrusion into the same, adjacent, and nonadjacent waste panel at 550, 750, 2,000, 4,000 or 10,000 years = 15 combinations.
S5	Initial E2 intrusion at 1000 years followed by a second intrusion into the same, adjacent, and nonadjacent waste panel at 1,200, 1,400, 3,000, 5,000 or 10,000 years = 15 combinations.

The CUTTINGS_S S1 scenario computes volumes of solid material released from the initial intrusion in the repository. Initial conditions for the CUTTINGS_S S1 scenario are taken from the results of the BRAGFLO S1 scenario at the time of the intrusion for areas Waste Panel, South RoR, and North RoR in Figure PA-8, corresponding to the lower, middle, and upper waste panels. In this scenario, the excavated area is penetrated ($e_1 = 1$) and the drilling location (l_1) is defined as one of the nodes (Figure PA-6) in the appropriate panel of Figure PA-20. The actual locations at which the intrusions are assumed to occur correspond to the points in Figure PA-20 designated “Down-dip well,” “Middle well,” and “Up-Dip Well” for the lower, middle, and upper waste panel, respectively. Values for the variables indicating penetration of pressurized brine (b_1), plugging pattern (p_1), activity level ($\boldsymbol{a_1}$), and for mining time (t_{min}) are not specified for the CUTTINGS_S S1 scenario.

The other CUTTINGS_S scenarios (Scenario S2, Scenario S3, Scenario S4, and Scenario S5) compute volumes of solids released by a second or subsequent intrusion. Initial conditions are taken from the results of the corresponding BRAGFLO scenario at the time of the second intrusion. As in the BRAGFLO scenarios, the first intrusion occurs in the lower waste panel (area Waste Panel in Figure PA-8) so the drilling location (l_1) is defined as one of the nodes in Panel 5 (Figure PA-6). The second intrusion occurs in the same waste panel as the first intrusion (area Waste Panel in Figure PA-8), an adjacent waste panel (area South RoR in Figure PA-8), or a nonadjacent waste panel (area North RoR in Figure PA-8). Hence the drilling location (l_2) is defined as one of the nodes (Figure PA-6) in the appropriate panel of Figure PA-20.

The activity level for the first intrusion $\boldsymbol{a_1}$ takes a value that indicates penetration of CH-TRU waste (i.e., $\boldsymbol{a_1}$ = [2, CH_{11}, CH_{12}, CH_{13}]) but the specific waste streams penetrated (i.e. CH_{11}, CH_{12}, CH_{13}) are not specified. For the second intrusion, the excavated area is penetrated

(e_2 = 1) and the drilling location (l_2) is defined as one of the nodes (Figure PA-6) in the appropriate panel, as described above. The actual locations at which the intrusions are assumed to occur correspond to the point in Figure PA-20 designated "Down-dip well" for the first intrusion for Category (1) intrusions and "Up-dip well, first or second intrusion" for Category (2) intrusions. As for the first intrusion, the activity level a_2 only indicates penetration of CH-TRU waste. Values for the other variables defining the first intrusion (e_1, b_1, and p_1) are the same as in the corresponding BRAGFLO scenario. Values for the other variables defining the second intrusion (b_2 and p_2) and the mining time t_{min} are not specified for the CUTTINGS_S scenarios.

PA-6.7.5 BRAGFLO Calculations for Direct Brine Release Volumes

Volumes of brine released to the surface at the time of an intrusion are calculated using BRAGFLO as described in Section PA-4.7. Calculations of DBR volumes were conducted for the same scenarios as for CUTTINGS_S (Table PA-23). Thus, the elements of S_{st} described in Section PA-6.7.4 also characterize the elements of S_{st} for which DBR volumes are computed; a total of 23,400 BRAGFLO calculations were performed.

PA-6.7.6 MODFLOW Calculations

As described in Section PA-4.8, the MODFLOW calculations produce flow fields in the Culebra for two categories of conditions: partially-mined conditions in the vicinity of the repository and fully-mined conditions in the vicinity of the repository (Figure PA-23). As specified in 40 CFR § 194.32(b), partially-mined conditions are assumed to exist by the end of the period of administrative control (i.e., at 100 years after closure). After the time that mining occurs within the LWB (t_{min}; see Section PA-3.8), fully-mined conditions are assumed for the remainder of the 10,000 regulatory period. The flow fields for partially-mined conditions are calculated by MODFLOW using the t-fields for partially-mined conditions (see Section PA-4.8.2). Additional MODFLOW calculations determine the flow fields for fully-mined conditions and are performed using the t-fields for fully-mined conditions. Thus a total of 2 × nR × nLHS = 2 × 3 × 100 = 600 MODFLOW calculations were performed. The element CTRAN of x_{su} (see Table PA-17) specifies the association between the uncertain transmissivity fields and the calculation of flow fields by MODFLOW.

Table PA-24. MODFLOW Scenarios in the CRA-2004 PA

MODFLOW: 600 Flow-Field Calculations
PM: Partially mined conditions in vicinity of repository
FM: Fully mined conditions in vicinity of repository
Total calculations = 2 nR nLHS = 2 × 3 × 100 = 600
Note: Only 100 unique transmissivity fields were constructed with MODFLOW for use in the analysis. The transmissivity fields are an input to the calculation of flow-fields. In each replicate, the transmissivity field used for a particular flow field was assigned using an index value (CTRAN, see Table PA-17) included in the LHS.

PA-6.7.7 SECOTP2D Calculations

The SECOTP2D calculations are performed for the same elements $x_{st,0}$ and $x_{st,m}$ of S_{st} defined in Section PA-6.7.6 for the MODFLOW calculations for a total of $2 \times nR \times nLHS = 2 \times 3 \times 100 = 600$ SECOTP2D calculations.

Table PA-25. SECOTP2D Scenarios in the CRA-2004 PA

SECOTP2D: 600 Calculations
PM: Partially mined conditions in vicinity of repository
FM: Fully mined conditions in vicinity of repository
Total calculations = 2 nR nLHS = $2 \times 3 \times 100 = 600$
Note: Each calculation includes a unit release of each of four radionuclides: ^{241}Am, ^{239}Pu, ^{230}Th, ^{234}U.

PA-6.8 Computation of Releases

The mechanistic computations outlined in Section PA-6.7 are used to compute releases for each sampled element x_{st} of S_{st}. Releases from the repository can be partitioned into three categories: undisturbed releases, which may occur in futures without drilling intrusions; direct releases, which occur at the time of a drilling event; and long-term releases, which occur as a consequence of a history of drilling intrusions. For a given future (x_{st} of S_{st} in Equation (261)) other than undisturbed conditions ($x_{st,0}$) the direct and long-term releases are computed by the code CCDFGF (WIPP PA 2003a) from the results of the mechanistic calculations summarized in Section PA-6.7, performed with the models presented in Chapter PA-4.0. Releases from an undisturbed repository are computed from the results of the NUTS S1 scenario (Section PA-6.7.2).

PA-6.8.1 Undisturbed Releases

Releases from the repository for the futures ($x_{st,0}$) in which no drilling intrusions occur are computed by the NUTS release calculations for E0 conditions (Table PA-22). The NUTS model computes the activity of each radionuclide that reaches the accessible environment during the regulatory period via transport through the MBs and through the Dewey Lake Red Beds. These releases are represented as $f_{MB}\left[x_{st,0}, f_B\left(x_{st,0}\right)\right]$ and $f_{DL}\left[x_{st,0}, f_B\left(x_{st,0}\right)\right]$ in Equation (24).

PA-6.8.2 Direct Releases

Direct releases include cuttings, cavings, spallings, and DBRs. The model for each component of direct releases computes a volume (solids or liquid) released to directly to the surface for each drilling intrusion. These volumes are combined with an appropriate concentration of activity in the released waste.

PA-6.8.3 Construction of Cuttings and Cavings Releases

Each drilling intrusion encountering waste is assumed to release a volume of solid material as cuttings as described in Section PA-4.5.2. The uncompacted volume of waste removed by cuttings (V_{cut}) is computed by Equation (104). In addition, drilling intrusions that encounter CH-TRU waste may release additional solid material as cavings, as described in Section PA-4.5.2. The uncompacted volume of material removed by cuttings and cavings combined ($\boldsymbol{V} = \boldsymbol{V_{cut}} + \boldsymbol{V_{cav}}$) is computed by Equation (105). For a drilling intrusion that encounter RH-TRU waste, the final eroded diameter D_f in Equation (105) is equal to the bit diameter in Equation (104). In the CRA-2004 PA, all drilling intrusions assume a drill bit diameter of 12.25 in (Attachment PAR, Table PAR-13).

The uncompacted volume of material removed is not composed entirely of waste material; rather, the uncompacted volume includes MgO and any void space initially present around the waste containers. The volume of waste removed (V_w) is determined by multiplying the uncompacted volume by the fraction of excavated volume (FVW) of the repository that is occupied by waste. In the CRA-2004 PA, FVW = 0.386 for CH-TRU waste and FVW = 1.0 for RH-TRU waste (Attachment PAR, Table PAR-45), thus

$$\boldsymbol{V_w} = \boldsymbol{V} \times \boldsymbol{FVW} \ . \tag{271}$$

The activity in the material released by cuttings and cavings is determined by stochastically selecting a subset of the set of all waste streams. The vector ($\boldsymbol{a_i}$) described in Section PA-3.7 determines which type of waste (CH-TRU or RH-TRU) and which waste streams are selected. The activity per m^3 of waste stream volume is computed for each waste stream at a discrete set of times by the code EPAUNI (Fox 2003), the results of the EPAUNI calculations are presented in Attachment PAR, Tables PAR-50 through PAR-61. Activities at other times are determined by linear interpolation. The cuttings and cavings release $\boldsymbol{f_C}\left(\boldsymbol{x_{st}}\right)$ is the product of the average activity per m^3 (C_r, computed as the average activity over the waste streams comprising the selected subset with the assumption that each waste stream contributes an equal volume to the release) and the volume of waste released (Equation (272)).

$$\boldsymbol{f_C}\left(\boldsymbol{x_{st}}\right) = \boldsymbol{V_w} \times \boldsymbol{C_r} \ . \tag{272}$$

PA-6.8.4 Determining Initial Conditions for Direct and Transport Releases

A sequence of intrusions into the repository can change the conditions in and around the repository and hence affect releases from subsequent intrusions. This section describes how panel and repository conditions are determined for a given intrusion.

PA-6.8.4.1 Determining Repository and Panel Conditions

Direct releases by DBR and spallings, and subsequent releases by radionuclide transport require a determination of the conditions in the intruded panel and in the repository at the time of the intrusion. One of three conditions is assigned to the repository:

E0 the repository is undisturbed by drilling,

E1 the repository has at least one E1 intrusion, or

E2 the repository has one or more E2 intrusions but no E1 intrusions.

In addition, each panel is assigned one of four conditions:

E0 the excavated regions of the panel have not been intruded by drilling,

E1 the panel has one previous E1 intrusions (intersects a brine reservoir in the Castile),

E2 the panel has one or more previous E2 intrusions (none intersect brine reservoirs), or

E1E2 the panel has at least two previous intrusions, at least one of which is an E1 intrusion.

Repository conditions are used to determine direct releases for each intrusion by DBRs and spallings. Panel conditions are used to determine releases by transport through the Culebra.

When an intrusion into CH-TRU waste occurs, the stochastic variables in Table PA-20 are used in the algorithm shown in Figure PA-33 to determine the type of the intrusion (E1 or E2). The type of the intrusion is used to update the conditions for the intruded panel and the repository before stepping forward in time to the next intrusion.

PA-6.8.4.2 Determining Distance from Previous Intrusions

Direct releases by DBR and spallings require a determination of the distance between the panel hit by the current intrusion and the panels hit by previous intrusions. In the CRA-2004 PA, the 10 panels are divided into three groups: lower, consisting of only panel 5; middle, including of panels 3, 4, 6, and 9; and upper, including of panels 1, 2, 7, 8, and 10, as shown in Figure PA-21. These divisions are consistent with the representation of the repository in the BRAGFLO model for Salado flow (Section PA-4.2) and for DBRs (Section PA-4.7).

Although the initial intrusion can occur in any of the 10 actual waste panels, direct releases for the initial intrusion are modeled as if the initial intrusion occurred in a lower waste panel (panel 4 or 5; see Figure PA-6), by using initial conditions for direct releases from the waste panel in the BRAGFLO grid (Figure PA-8), which are mapped to the lower panel in Figure PA-21. This treatment is the same as in the CCA PA and is conservative, since the waste panel typically has higher brine saturation than do the panels in the rest of repository areas (see Sections PA-7.1.2 and PA-8.3.2). Initial conditions for direct releases from subsequent intrusions are modeled by one of three cases: lower, middle, and upper, corresponding to the three panel groups shown in Figure PA-21 and listed in Table PA-24. The lower case represents a second intrusion into a previously intruded panel. The middle case represents an intrusion into an undisturbed

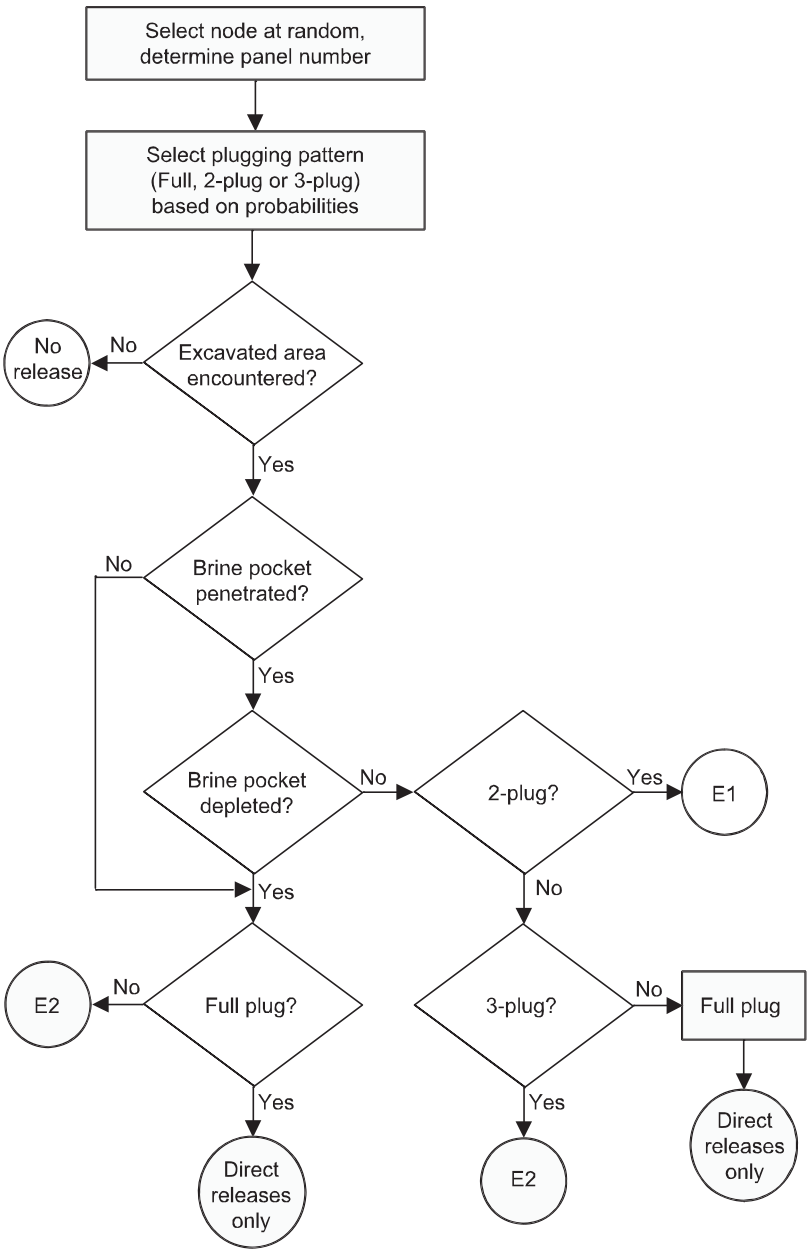

Figure PA-33. The Determination of the Type of Intrusion.

panel that is adjacent to a previously disturbed panel. The upper case represents an intrusion into an undisturbed panel that is not adjacent to a previously disturbed panel. Adjacent panels share one side in common and nonadjacent panels share no sides in common.

Selection of the time and location of the previous intrusion used to determine distance from the current intrusion depends on the repository condition. The repository condition is determined by the intrusion of greatest consequence across all panels prior to the current intrusion. E1 intrusions are assumed to be of the greater consequence than E2 intrusions. The previous intrusion is selected by finding the closest panel (same, adjacent, nonadjacent) whose intrusion condition, excluding the current intrusion, is equal to the repository condition. The time of the

previous intrusion is the time of the most recent intrusion having the greatest consequence and closest distance. Likewise, the condition of each panel is equal to the intrusion of greatest consequence into the panel prior to the current intrusion.

PA-6.8.5 Construction of Direct Brine Releases

DBRs (also termed blowout releases) are calculated for all intrusions that encounter CH-TRU waste. DBRs $f_{DBR}(x_{st})$ are constructed from volume of brine released (V_{DBR}) to the surface (Equation (175)) and radionuclide concentrations in brine (C_{bl}, see Equation (85)). Brine volume released to the surface is computed by BRAGFLO (Section PA-4.7.3) for the times listed in Table PA-23; brine volumes released for intrusions at other times are computed by linear interpolation (WIPP PA 2003d).

Calculation of DBR volumes distinguishes between the first intrusion and subsequent intrusions. The release volumes for the initial intrusion (E0 repository conditions) are further distinguished by the panel group (upper, middle, and lower). As shown in Table PA-23, BRAGFLO computes release volumes for the initial intrusion at each of a series of intrusion times; the release volume for the initial intrusion at other times is computed by linear interpolation (WIPP PA 2003a). Release volumes for subsequent intrusions are distinguished by the current state of the repository (E1 or E2) and the relative distance between the panel intruded by the current borehole and the panel of the initial intrusion (same, adjacent, non-adjacent). The algorithms for determining repository conditions and distance between intrusions are described in Section PA-6.8.4.

As indicated in Table PA-23, DBR volumes for a second intrusion are computed by BRAGFLO for a set of combinations of repository condition, distance between intrusions, and time between intrusions. Brine release volumes for other combinations of condition, distance, and time are computed by linear interpolation (WIPP PA 2003a). Brine releases from third and subsequent intrusions are computed as if the current intrusion was the second intrusion into the repository.

Radionuclide concentrations in brine (C_{bl}) are calculated by PANEL (Section PA-6.7.3) for the times listed in Table PA-22; concentrations at other times are computed by linear interpolation (WIPP PA 2003a). The type of intrusion (E1 or E2) determines the brine (Salado or Castile brine) selected for the concentration calculation; for E1 intrusions, Castile brine is used, and Salado brine is used for E2 intrusions.

The direct brine release is computed as the product of the release concentration and the volume, V_{DBR}, i.e.

$$f_{DBR}(x_{st}) = V_{DBR} \times C_{bl} \tag{273}$$

PA-6.8.6 Construction of Spallings Releases

Spallings releases are calculated for all intrusions that encounter CH-TRU waste. The construction of the spallings release $f_{SP}(x_{st})$ is nearly identical to that described in Section PA-6.8.5 for the calculation of DBRs except that volumes of solid material released will be used rather than volumes of brine. These solid releases are calculated with the spallings submodel of

the CUTTINGS_S program for the combinations of repository condition, distance from previous intrusions, and time between intrusions listed in Table PA-23. Linear interpolation determines the releases for other combinations of repository condition, distance, and time between intrusions (WIPP PA 2003a).

The concentration of radionuclides in the spallings release volume is computed as the average activity per m^3 in the CH-TRU waste at the time of intrusion. Activities in each waste stream are computed at a discrete set of times by the code EPAUNI (Fox 2003); activities at other times are determined by linear interpolation.

PA-6.8.7 Radionuclide Transport Through the Culebra

One potential path for radionuclide transport from the repository is up through boreholes to the Culebra, then through the Culebra to the LWB (Section 6.4.6). As indicated in Table PA-22, the NUTS and PANEL models are used to estimate radionuclide transport through boreholes to the Culebra $f_{NP}(x_{st})$ for a fixed set of intrusion times; releases to the Culebra for intrusions at other times are determined by linear interpolation (WIPP PA 2003a). NUTS computes the release to the Culebra over time for E1 and E2 boreholes; PANEL computes the release to the Culebra for an E1E2 borehole.

Each borehole may create a pathway for releases to the Culebra. The first E1 or E2 borehole in each panel creates a release path, with the radionuclide release taken from the appropriate NUTS data. Subsequent E2 boreholes into a panel with only E2 boreholes do not cause additional releases; WIPP PA assumes that a subsequent E2 borehole into a panel having only earlier E2 intrusions does not provide a significant source of additional brine, and thus does not release additional radionuclides to the Culebra.

An E1E2 borehole results from the combination of two or more intrusions into the same panel, at least one of which is an E1 intrusion. A subsequent E1 borehole changes the panel's condition to E1E2, as does an E2 borehole into a panel that has an earlier E1 intrusion. Once E1E2 conditions exist in a panel, they persist throughout the regulatory period. However, releases from a panel with E1E2 conditions are restarted for each subsequent E1 intrusion into that panel, since additional E1 intrusions may introduce new volumes of brine to the panel.

Releases to the Culebra are summed across all release pathways to the Culebra to obtain total releases to the Culebra $r_k(t)$ for the kth radionuclide at each time t. Releases to the Culebra include both dissolved radionuclides and radionuclides sorbed to colloids. The WIPP PA assumes that radionuclides sorbed to humic colloids disassociate and transport as do dissolved radionuclides; other colloid species do not transport in the Culebra (see Attachment SOTERM). The release to the Culebra is partitioned into dissolved and colloid species by multiplying $r_k(t)$ by radionuclide-specific factors for the fraction dissolved and the fraction on colloids (see Table 4.3.1). Dissolved radionuclides are transported through the Culebra.

Radionuclide transport through the Culebra is computed by the code SECOTP2D (Section PA-4.9) for partially-mined and fully-mined conditions (Section 6.4.6.2.3) as indicated in Table PA-25. These computations assume a 1 kg source of each radionuclide placed in the Culebra

between 0 and 50 years, and result in the fraction of each source $f_{m,k}(t)$, where m is the mining condition and k is the index for the radionuclide) reaching the LWB at each subsequent time t. For convenience, the time-ordering of the data from SECOTP2D is reversed so that the fraction $f_{m,k}(t)$ associated with year t = 200, for example, represents the release at the boundary at year 10,000 for a release occurring between 150 and 200 years.

The total release through the Culebra $R_{Cul,k}$ is calculated for the kth radionuclide by

$$R_{Cul,k} = \sum_{t_i \le t_m} r_k(t_i)\, f_{PM,k}(t_i) + \sum_{t_i > t_m} r_k(t_i)\, f_{FM,k}(t_i), \tag{274}$$

where $r_k(t_i)$ is the release of the kth radionuclide to the Culebra in kg at time t_i and $f_{PM,k}(t_i)$ and $f_{FM,k}(t_i)$ are the fractions of a unit source placed in the Culebra in the interval (t_{i-1}, t_i) that reaches the LWB by the end of the 10,000-year regulatory period, for partial mined and fully mined conditions within the LWB, respectively. The function $f_{m,k}(t)$ changes when mining is assumed to occur within the LWB; hence the sum in the equation above is evaluated in two parts, where t_{min} is the time that mining occurs. The total releases through the Culebra $f_{ST}(x_{st})$ is computed by converting the release of each radionuclide $R_{Cul,k}$ from kg to EPA units, then summing over all radionuclides.

PA-6.8.8 CCDF Construction

For each vector $x_{su,k}$ in the space of subjective uncertainty, the code CCDFGF samples a sequence $x_{st,i}$, i = 1, 2, …, nS of futures. In the CRA-2004 PA, nS = 10,000; this number of futures is sufficient to generate an adequate estimate of the mean CCDF for total releases for comparison with the boundary line specified in 40 CFR § 191.13, as demonstrated in Section PA-9.1. A release $f(x_{st,i})$ for each future is then constructed as described in Sections PA-6.8.1 through PA-6.8.7. Once the $f(x_{st,i})$ are evaluated, the CCDF can be approximated as indicated in Equation (275).

$$prob(Rel > R) = \int_{S_{St}} \delta_R\left[f(x_{st})\right] d_{st}(x_{st})\, dV_{st} \cong \sum_{i=1}^{nS} \delta_R\left[f(x_{st,i})\right] / nS \tag{275}$$

A binning technique is used to construct the desired CCDF (i.e., the consequence axis is divided into a sequence of bins and the number of values for $f(x_{st,i})$ falling in each bin is accumulated). In addition, all values for $f(x_{st,i})$ are saved and subsequently ordered to provide an alternative method for constructing the CCDFs. In addition to the total CCDF for all releases, it will be possible to obtain CCDFs for individual release modes (e.g., cuttings,

spallings, direct brine releases, to Culebra, through MBs, through Culebra). The logic for the production of the CCDFs is diagrammed in Figure PA-34.

The CCDF construction indicated in this section is for a single sample element $\boldsymbol{x}_{su,k}$ of the form indicated in conjunction with Equation (260). Repeated generation of CCDFs for individual sample elements $\boldsymbol{x}_{su,k}$, i.e. for the vectors representing epistemic uncertainty in the model results, will lead to the distribution of complete CCDFs.

PA-6.9 Sensitivity Analysis

Evaluation of one or more of the models discussed in Chapter PA-4.0 with the LHS in Equation (260) creates a mapping

$$\left\{\boldsymbol{x}_{su,k}, \boldsymbol{y}_{su,k}\right\}, \text{ k = 1, 2, …, nLHS} \tag{276}$$

from analysis inputs (i.e., $\boldsymbol{x}_{su,k}$) to analysis results (i.e., $\boldsymbol{y}\left(\boldsymbol{x}_{su,k}\right)$), where $\boldsymbol{y}_{su,k}$ denotes the results obtained with the model or models under consideration. A vector notation is used for y because, in general, a large number of predicted results are produced by each of the models used in the CRA-2004 PA. In addition, $\boldsymbol{y}\left(\boldsymbol{x}_{su,k}\right)$ could also correspond to a CCDF for normalized release constructed from model results associated with $\boldsymbol{x}_{su,k}$. Sensitivity analysis explores the mapping in Equation (276) to determine how the uncertainty in individual elements of $\boldsymbol{x}_{su}$ affects the uncertainty in individual elements of $\boldsymbol{y}\left(\boldsymbol{x}_{su}\right)$. Understanding how uncertainty in analysis inputs affects analysis results aids in understanding the current PA, and aids in improving the models for future PAs.

The presentation of results from each major model in the WIPP PA is accompanied by sensitivity analyses of the most important output of each major model. Where practical, sensitivity analysis results are based on a pooling of the results obtained for the three replicated LHSs (i.e., R1, R2, R3) discussed in Section PA-6.4. In other cases, the sensitivity analysis is based on the results for the first replicate (i.e., R1), and statistics are compared across the three replicates.

Three principle techniques are used in the sensitivity analysis: scatterplots; regression analyses to determine standardized regression coefficients and partial correlation coefficients; and stepwise regression analyses. Each technique is briefly discussed. A discussion of sensitivity analyses conducted for the CCA PA is provided in Helton et al. (1998).

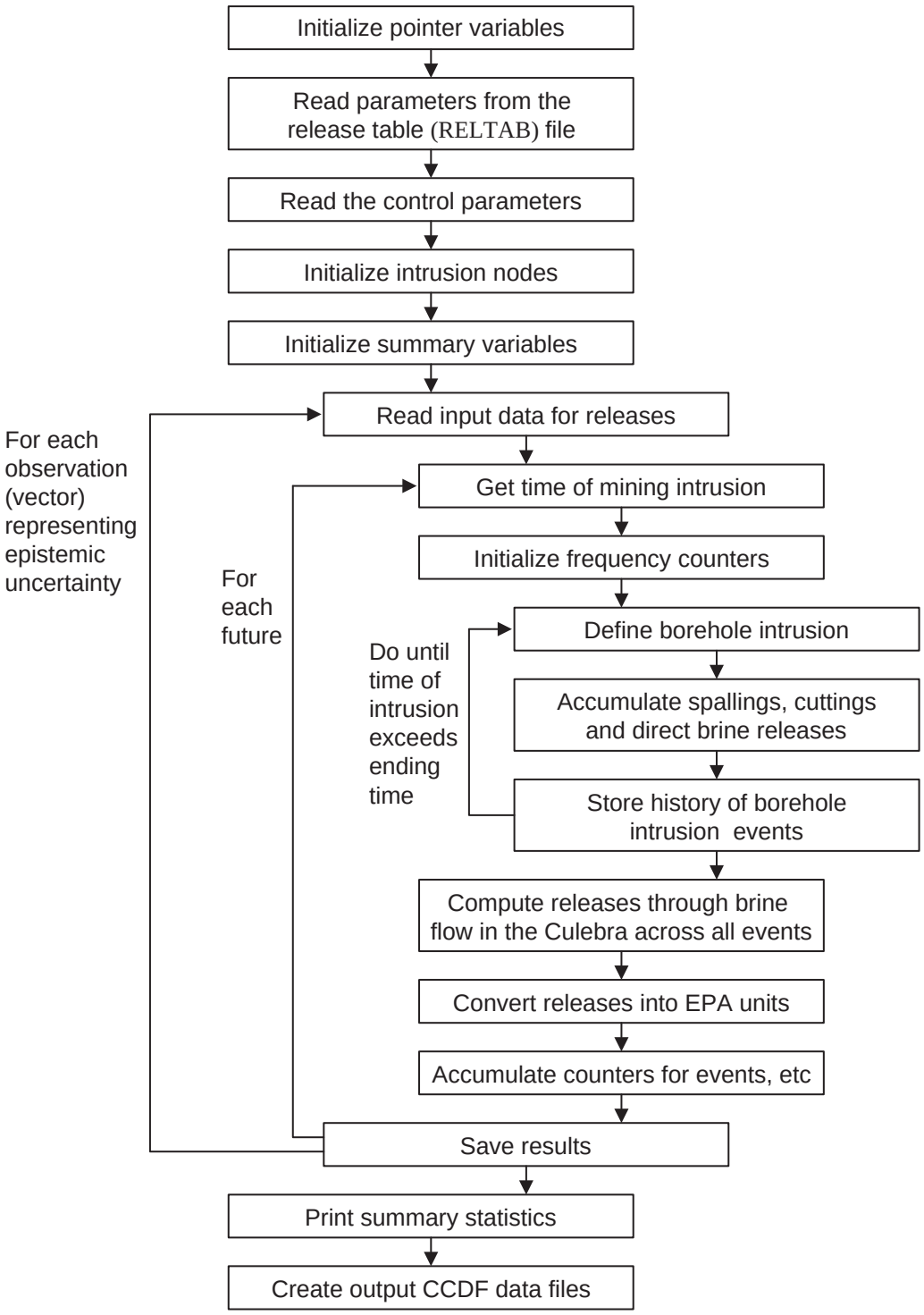

Figure PA-34. Processing of Input Data to Produce CCDFs.

PA-6.9.1 Scatterplots

Scatterplots are the simplest sensitivity analysis technique, performed by plotting the points

$$\left(x_{kj}, y_k\right), \text{ k = 1, 2, …, nLHS} \tag{277}$$

for each element x_j of x. The resulting plots can reveal relationships between y and the elements of x (i.e., the x_j). Scatterplots can be effective at revealing nonlinear relationships or threshold values, and at screening the elements of x for further investigation. The examination of such plots when Latin hypercube sampling is used can be particularly revealing due to the full stratification over the range of each input variable. Iman and Helton (1988) provide an example where the examination of scatterplots revealed a rather complex pattern of variable interactions.

PA-6.9.2 Regression Analysis

A more formal investigation of the mapping in Equation (276) can be based on regression analysis. In this approach, a model of the form

$$y = b_0 + \sum_{j=1}^{n} b_j x_j \tag{278}$$

is developed from the mapping between analysis inputs and analysis results shown in Equation (276), where the x_j are the input variables under consideration and the b_j are coefficients that must be determined. The coefficients b_j and other aspects of the construction of the regression model in Equation (278) can be used to indicate the importance of the individual variables x_j with respect to the uncertainty in y. The CRA-2004 PA employs the method of least squares to determine the coefficients b_j (Myers 1986).

Often the regression in Equation (278) is performed after the input and output variables are normalized to mean zero and standard deviation one. The resulting coefficients b_j are called standardized regression coefficients (SRCs). When the x_j are independent, the absolute value of the SRCs can be used to provide a measure of variable importance. Specifically, the coefficients provide a measure of importance based on the effect of moving each variable away from its expected value by a fixed fraction of its standard deviation while retaining all other variables at their expected values.

Partial correlation coefficients (PCCs) can also provide a measure of the linear relationships between the output variable y and the individual input variables. The PCC between y and an individual variable x_p is obtained from the use of a sequence of regression models. First, the following two regression models are constructed:

$$\hat{y} = b_0 + \sum_{\substack{j=1 \\ j \neq p}}^{n} b_j x_j \text{ and } \hat{x}_p = c_0 + \sum_{\substack{j=1 \\ j \neq p}}^{n} c_j x_j \ , \tag{279}$$

Then, the results of the two preceding regressions are used to define the new variables $y - \hat{y}$ and $x_p - \hat{x}_p$. By definition, the PCC between y and x_p is the correlation coefficient between $y - \hat{y}$

and $x_p - \hat{x}_p$. Thus, the PCC provides a measure of the linear relationship between y and x_p with the linear effects of the other variables removed.

Regression and correlation analyses often perform poorly when the relationships between the input and output variables are nonlinear. This is not surprising since such analyses are based on the assumption of linear relationships between variables. The problems associated with poor linear fits to nonlinear data can be avoided by use of the rank transformation (Iman and Conover 1979). The rank transformation is a simple concept: data are replaced with their corresponding ranks and then the usual regression and correlation procedures are performed on these ranks. Specifically, the smallest value of each variable is assigned the rank 1, the next largest value is assigned the rank 2, and so on up to the largest value, which is assigned the rank m, where m denotes the number of observations. The analysis is then performed with these ranks being used as the values for the input and output variables. A formal development of PCCs and the relationships between PCCs and SRCs is provided by Iman et al. (1985).

PA-6.9.3 Stepwise Regression Analysis

Stepwise regression analysis provides an alternative to constructing a regression model containing all the input variables. With this approach, a sequence of regression models is constructed. The first regression model contains the single input variable that has the largest impact on the uncertainty in the output variable (i.e., the input variable that has the largest correlation with the output variable y). The second regression model contains the two input variables that have the largest impact on the output variable: the input variable from the first step plus whichever of the remaining variables has the largest impact on the uncertainty not accounted for by the first variable (i.e., the input variable that has the largest correlation with the uncertainty in y that cannot be accounted for by the first variable). Additional models in the sequence are defined in the same manner until a point is reached at which further models are unable to meaningfully increase the amount of the uncertainty in the output variable that can be accounted for.

Stepwise regression analysis can provide insights on the importance of the individual variables. First, the order in which the variables are selected in the stepwise procedure provides an indication of their importance, with the most important variable being selected first, the next most important variable being selected second, and so on. Second, the R^2 values at successive steps of the analysis also provide a measure of variable importance by indicating how much of the uncertainty in the dependent variable can be accounted for by all variables selected through each step. When the input variables are uncorrelated, the differences in the R^2 values for the regression models constructed at successive steps equals the fraction of the total uncertainty in the output variable that can be accounted for by the individual input variables being added at each step. Third, the absolute values of the SRCs in the individual regression models provide an indication of variable importance. Further, the sign of an SRC indicates whether the input and output variable tend to increase and decrease together (a positive coefficient) or tend to move in opposite directions (a negative coefficient).

PA-7.0 RESULTS FOR THE UNDISTURBED REPOSITORY

The PA tabulates releases from the repository for undisturbed conditions. Releases to the accessible environment from the undisturbed repository fall under two sets of protection requirements. The first, as set forth 40 CFR § 191.15, protects individuals from radiological exposure; the second, in 40 CFR Part 191, Subpart C, protects groundwater resources from contamination. Chapter 8 describes how WIPP complies with these two requirements. This section supplements Chapter 8 by presenting flow (BRAGFLO) and transport (NUTS) results from modeling the undisturbed repository.

PA-7.1 Salado Flow

Flow in the Salado is computed by BRAGFLO (see Section PA-4.2). This section summarizes the Salado flow calculation results for the undisturbed scenario (S1). Pressure in the repository, brine saturation in the waste, and brine flow out of the repository are presented, along with sensitivity analyses that identify the uncertain parameters to which these results are most sensitive. The analysis package for Salado Flow (Stein and Zelinski 2003b) contains a detailed presentation on the BRAGFLO model, calculation results, and further sensitivity analyses.

PA-7.1.1 Pressure in the Repository

In undisturbed conditions, pressure strongly influences the extent to which contaminated brine might migrate from the repository to the accessible environment. In addition, pressure developed under undisturbed conditions is an initial condition for the models for spallings and DBR (Section PA-4.6 and Section PA-4.7, respectively).

The Salado flow model represents the repository as five regions in the numerical grid: three waste-filled regions (the Waste Panel, South RoR, and North RoR in Figure PA-8) and two excavated regions with no waste (Ops and Exp in Figure PA-8), which are combined in this analysis into the single nonwaste region. Figure PA-35 shows pressure in each region for the 100 realizations in Replicate R1. Pressures within the three waste-filled areas are very similar, because gas generation occurs in each region simultaneously. The pressure in the nonwaste region tends to be lower than in the waste-filled regions due to the intervening panel closures (CONC_PCS in Figure PA-8).

During the first 1,000 years, repository pressure may increase rapidly due to several factors: rapid initial creep closure of rooms (see Attachment PORSURF); initial inflow of brine causes gas generation due to corrosion; and availability of CPR material to produce gas by microbial degradation. Pressure generally approaches a steady-state value after 1,000 years as room closure ceases, brine inflow slows (thereby reducing gas generation by corrosion), and CPR materials are consumed.

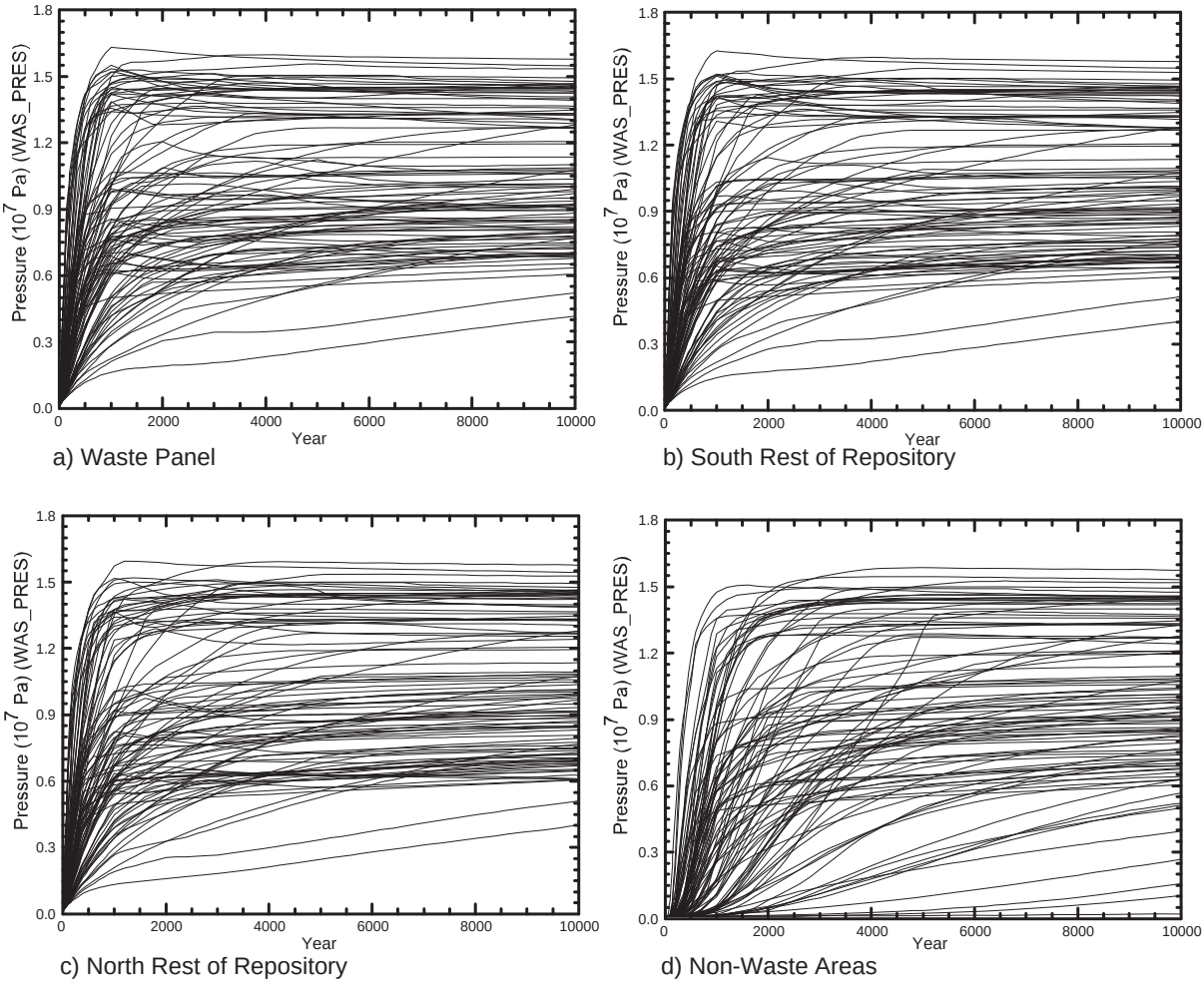

Figure PA-35. Pressure in the Excavated Areas, Replicate R1, Scenario S1.

Figure PA-36 shows the mean and 90th percentile values for pressure in each region. There is a consistent pattern of declining pressure from the waste panel through South RoR (SRR_PRES) and North RoR (NRR_PRES) to the nonwaste region (NWA_PRES). The differences in pressure reflect the slow migration of gas from waste-filled regions to the nonwaste regions where no gas is being produced. The 90th percentile pressures level off between 14 and 15 MPa indicating equilibrium between gas generation, which increases pressure, and pressure relief processes (e.g., fracturing, outward migration of fluids, and increased porosity of the excavated areas).

Sensitivity analyses are used to determine the importance of parameter uncertainty to the uncertainty in model results. Figure PA-37 shows partial rank correlation coefficients (PRCCs) resulting from regression between pressure in the waste panel (WAS_PRES) and the uncertain variables in the LHS (Section PA-5.0). The figure shows that uncertainty in the pressure in the waste panel is primarily determined by the sampled input parameter, WMICDFLG, which indicates whether microbial gas generation is active and what materials,

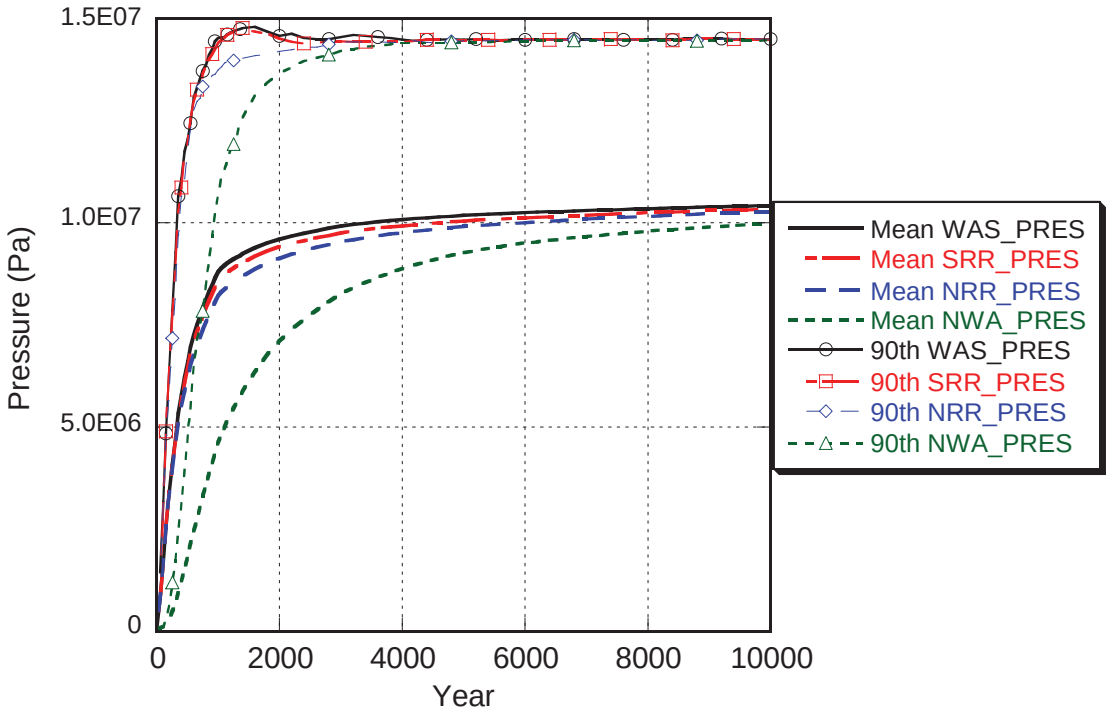

Figure PA-36. Mean and 90th Percentile Values for Pressure in Excavated Areas, Replicate R1, Scenario S1.

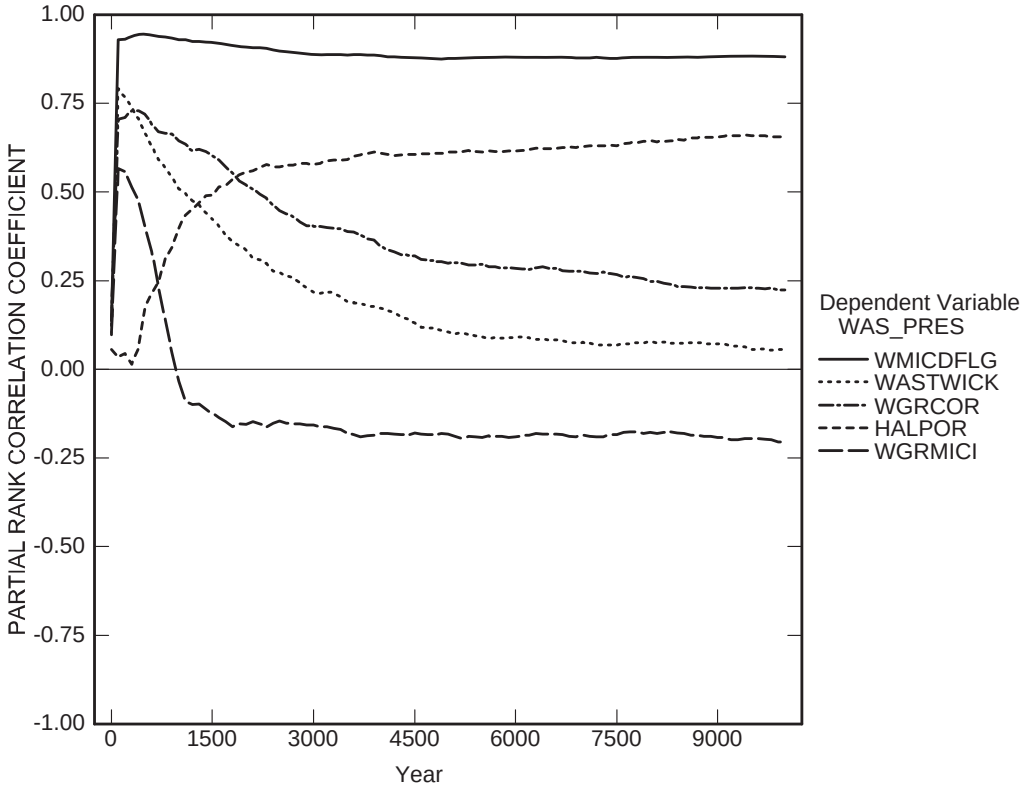

Figure PA-37. Primary Correlations of Pressure in the Waste Panel with Uncertain Parameters, Replicate R1, Scenario S1.

if any, are consumed. The positive correlation indicates that higher pressures result from higher values of WMICDFLG, which represent larger amounts of material available for gas production by microbial activity. The PRCC for WMICDFLG is approximately 0.85 throughout the 10,000-year calculation time, indicating that uncertainty in this parameter explains the variability in the waste panel pressure. Consequently, uncertainties in other parameters are not very significant; the other PRCCs in Figure PA-37 indicate that halite porosity (HALPOR), the inundated microbial gas generation rate (WGRMICI), the corrosion rate for steel (WGRCOR), and the waste wicking parameter (WASTWICK) determine the remaining variability in waste panel pressure.

Figure PA-38 compares statistics for pressure in the waste panel among the three replicates and shows that results for the three replicates are very similar. Mean pressures are nearly coincident; small differences between replicates are observable among the replicates at very high or very low pressures.

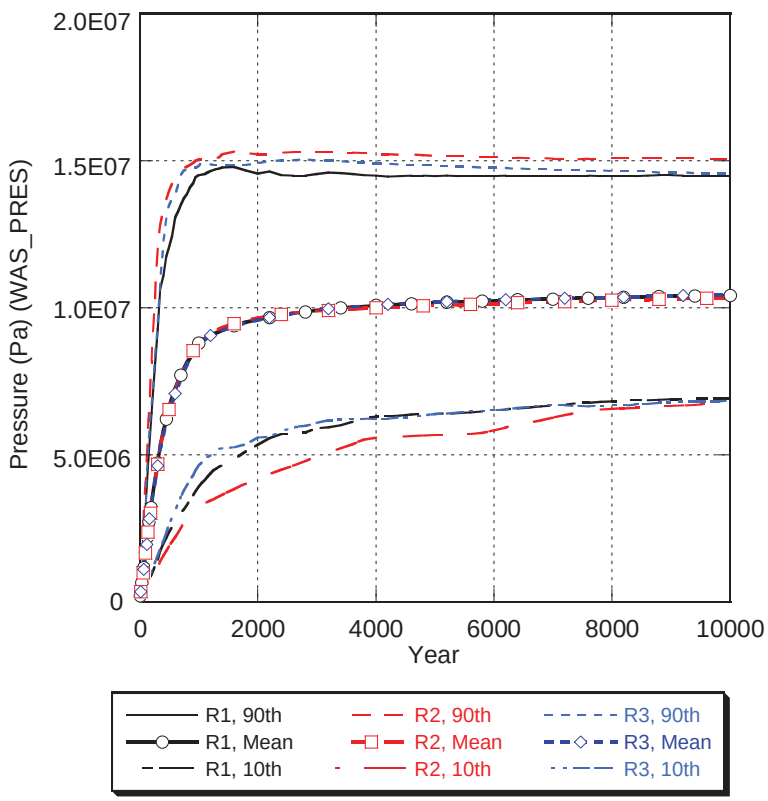

Figure PA-38. Comparison of Pressure in the Waste Panel Between All Replicates, Scenario S1.

PA-7.1.2 Brine Saturation in the Waste

Brine saturation is an important result of the model for Salado Flow, because gas generation processes, which tend to increase pressure, require brine. Brine saturation is also an initial condition in the model for DBR (Section PA-4.7).

Figure PA-39 shows brine saturation in the various excavated areas of the repository for the 100 realizations of Replicate 1. Brine saturation in the waste-filled areas is set initially to 0.015. Saturation increases very rapidly (in the first 100 years) in all excavated areas as brine flows toward the excavations, primarily from the DRZ above the excavation. Initially there is a large pressure differential between the DRZ and the excavated regions, and the relatively high permeability of the DRZ, compared to undisturbed halite, permits the rapid influx of brine. Brine inflow slows as the pressures equalize and as brine saturation in the DRZ decreases. Brine saturation in the waste decreases over time as brine is consumed by corrosion. Brine may also be driven out of the repository by high pressure.

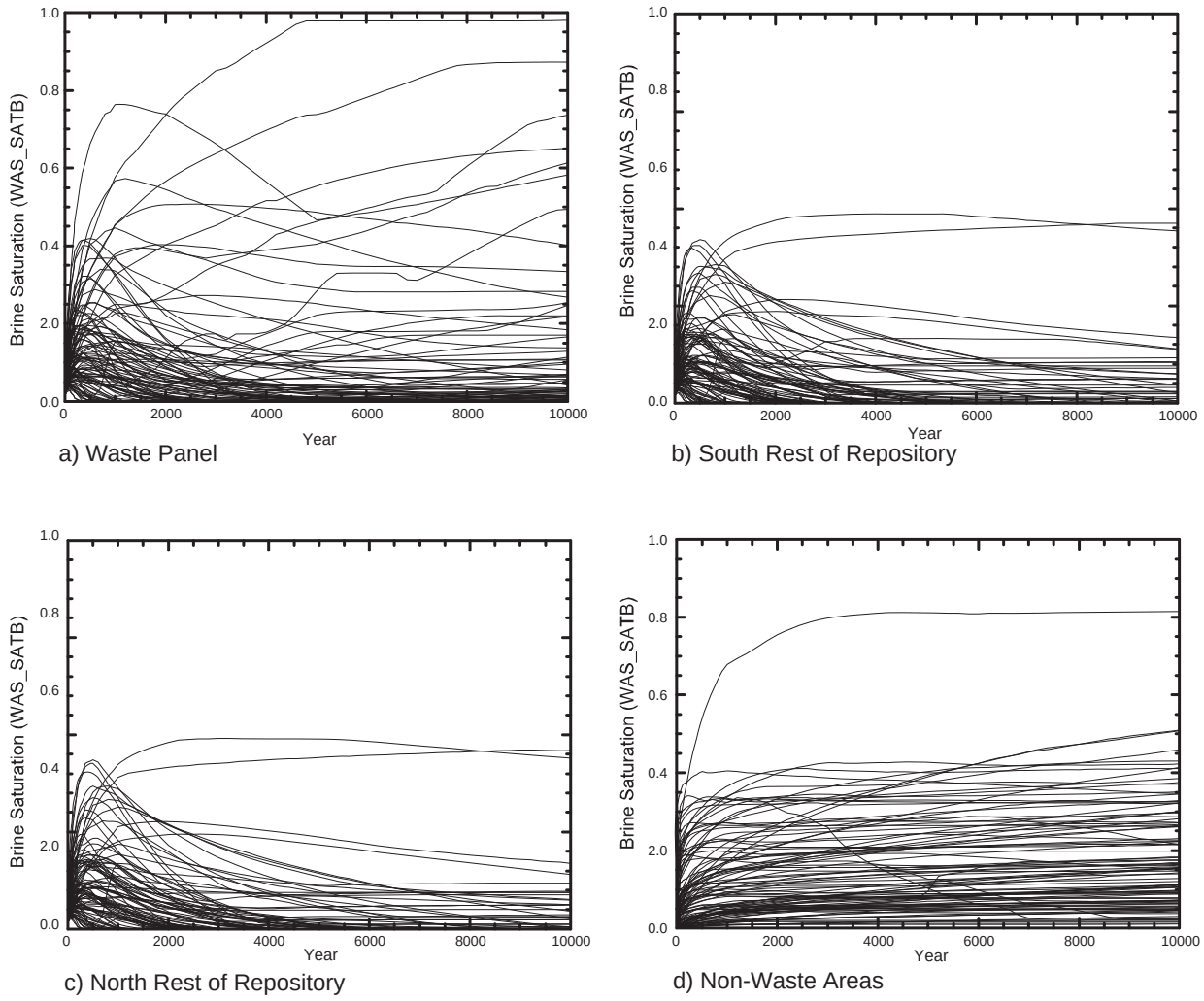

Figure PA-39. Brine Saturation in the Excavated Areas, Replicate R1, Scenario S1.

Figure PA-40 compares statistics for brine saturation between the different regions of the repository. Brine saturation in the waste panel (WAS_SATB) tends to be greater than in the rest of repository regions (SRR_SATB and NRR_SATB) due to the artificial two-dimensional modeling of the Salado; in the modeling grid (Figure PA-8), the waste panel has direct contact with the anhydrite MBs while the rest of repository regions do not. Brine saturation in the

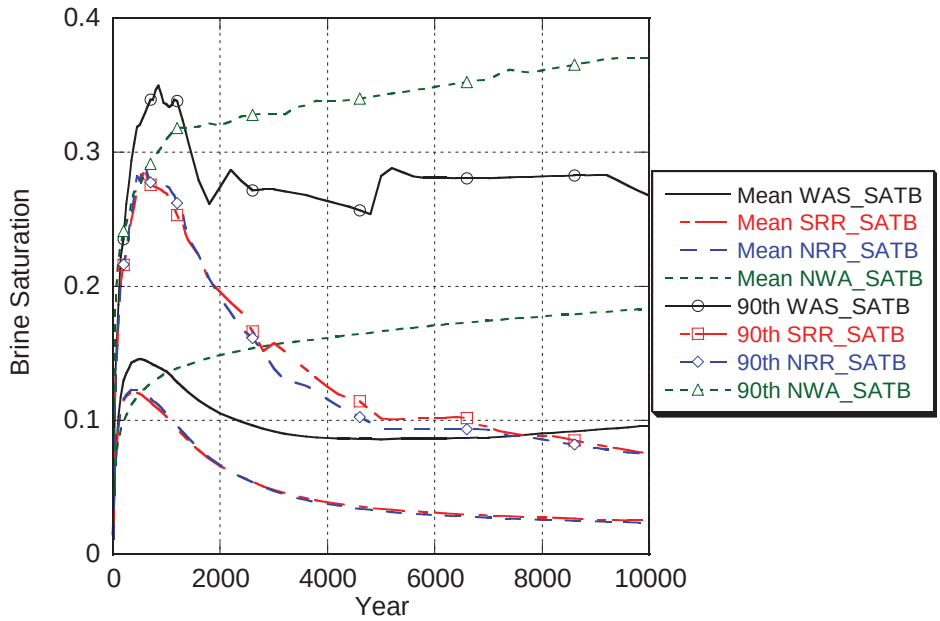

Figure PA-40. Mean and 90th Percentile Values for Brine Saturation in Excavated Areas, Replicate R1, Scenario S1.

non-waste region (NWA_SATB) is higher than in the waste-filled regions due to brine consumption in the waste regions, but also due to the panel closures. Brine that enters the experimental area flows down the stratigraphic gradient into the operations area, then ponds up against the panel closure separating the operations area from the waste filled regions.

Regression between the brine saturation in the waste panel (WAS_SATB) and the uncertain parameters in the LHS identifies a number of parameters that contribute to the uncertainty in brine saturation. The relative importance of these parameters varies over the 10,000-year modeling period, and none of the parameters is clearly dominant. Figure PA-41 shows positive correlations with halite porosity (HALPOR) and DRZ permeability (DRZPRM). Increases in halite porosity increase the volume of brine available in the material overlying the waste; increases in DRZ permeability accelerate drainage into the waste. Negative correlations are found between brine saturation and the corrosion rate (WGRCOR) and the wicking factor (WASTWICK) because increases in these two variables increase the rate at which brine is consumed by corrosion, thus decreasing saturation. The negative correlation between brine saturation and WMICDFLG, which becomes significant near the end of the simulation, indicates that increasing total gas generated (by adding microbial degradation of CPR material) eventually leads to less brine inflow and consequently lower saturation.

Figure PA-42 compares brine saturation statistics for the three replicates. The plots of the mean brine saturation are nearly coincident. Significant differences between replicates are evident at the high end of the saturation scale because there are only a few vectors in each replicate with high saturations.

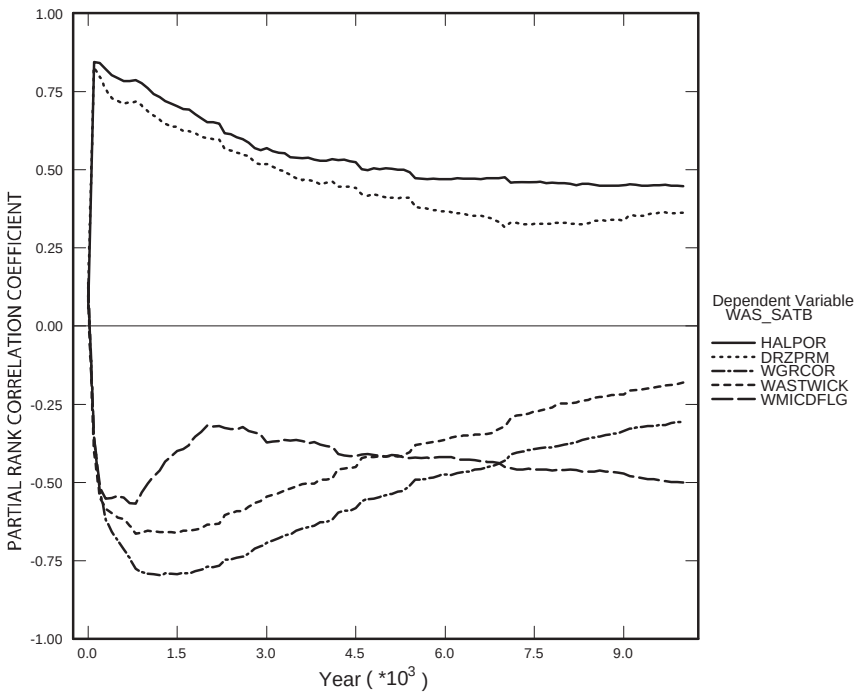

Figure PA-41. Primary Correlations of Brine Saturation in the Waste Panel with Uncertain Parameters, Replicate R1, Scenario S1.

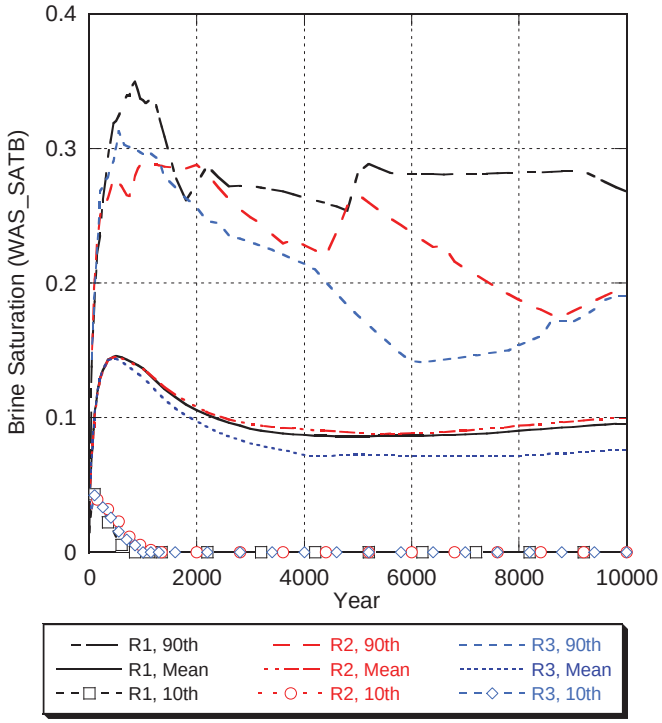

Figure PA-42. Comparison of Brine Saturation in the Waste Panel Between Replicates, Scenario S1.

PA-7.1.3 Brine Flow Out of the Repository

The anhydrite MBs and the shafts provide possible pathways for brine flow away from the repository in the undisturbed scenario (S1). The Salado flow model only tabulates the volume of brine crossing boundaries within the model grid; it does not identify whether the brine contains radionuclides from the waste. Transport is calculated separately from the flow and is discussed in Section PA-7.2.

Figure PA-43 shows cumulative brine outflow from the excavated regions of the repository (BRNREPOC). Brine flow out of the DRZ into the MBs is shown in Figure PA-44, and flow up the shaft to the bottom of the Culebra is shown in Figure PA-45. Comparison of total cumulative brine outflow into all MBs (BRAALOC, Figure PA-44) to total outflow (Figure PA-43) confirms that the primary path for brine outflow is along the MBs.

The distribution of brine flow among the potential pathways varies somewhat between vectors, but typically outflow along MB 139 to the south accounts for most of the total brine outflow. The dominance of MB 139 to the south as the primary conduit for brine outflow is illustrated in Table PA-26, which tabulates maximum brine outflow along each potential pathway for any vector in replicate R1. MB 139 is down the stratigraphic dip, and, being the lowest outflow pathway, it is most frequently saturated.

Figure PA-46 shows the volumes of brine that cross the LWB through the MBs. The largest outflow across the LWB is 433 m^3. Table PA-26 shows that a smaller volume of brine (50 m^3) may reach the Culebra through the shaft. Brine crossing the LWB or moving up the shaft does not necessarily indicate releases from the repository, since the brine may not have been in contact with the waste; the brine may have been present in the MBs at the start of the regulatory period. Section PA-7.2 presents the results of the transport calculations that determine the amount of radionuclides that be released by transport in brine.

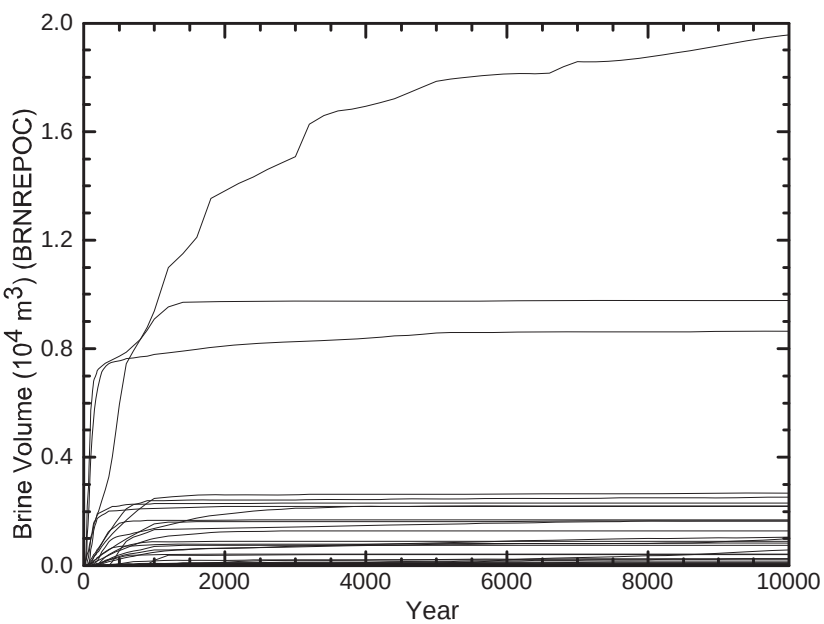

Figure PA-43. Brine Flow Away from the Repository, Replicate R1, Scenario S1.

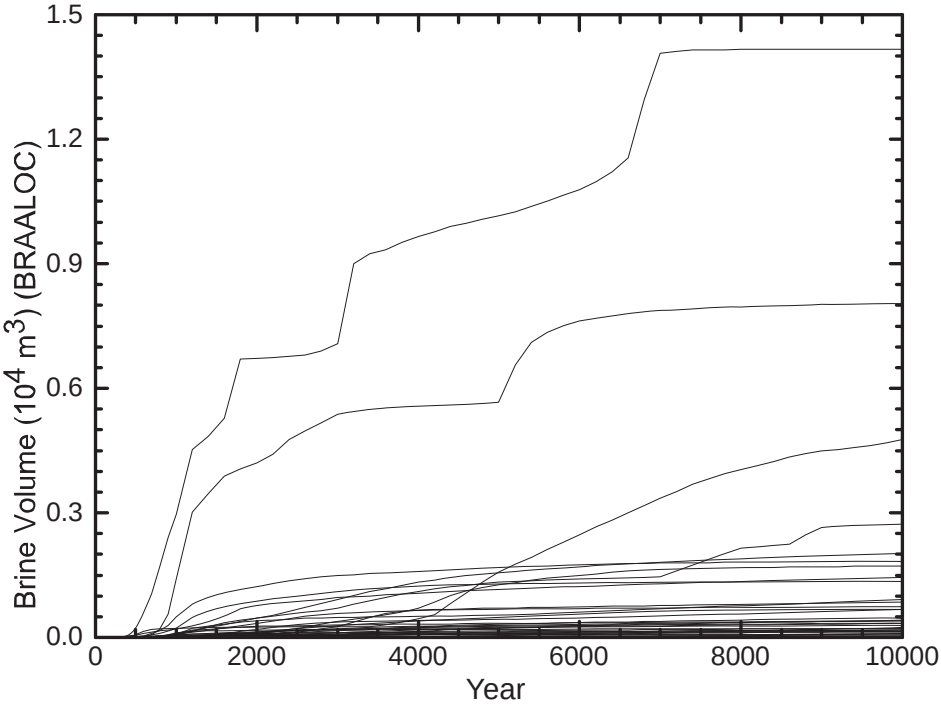

Figure PA-44. Brine Flow Away from the Repository Via All Marker Beds, Replicate R1, Scenario S1.

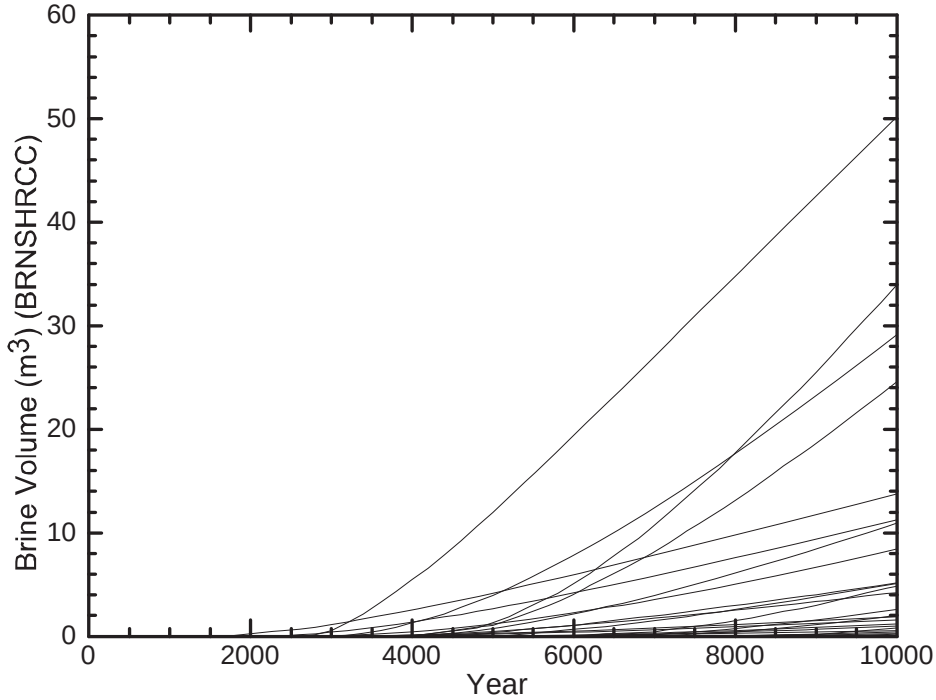

Figure PA-45. Brine Outflow Up the Shaft, Replicate R1, Scenario S1.

Table PA-26. Volume of Brine Outflow by Various Potential Pathways

Pathway for Brine Outflow	Maximum (m^3)
MB 138 North	432
MB 138 South	1,567
Anhydrite AB North	0
Anhydrite AB South	5
MB 139 North	1,832
MB 139 South	12,828
Shaft (to base of Culebra)	50

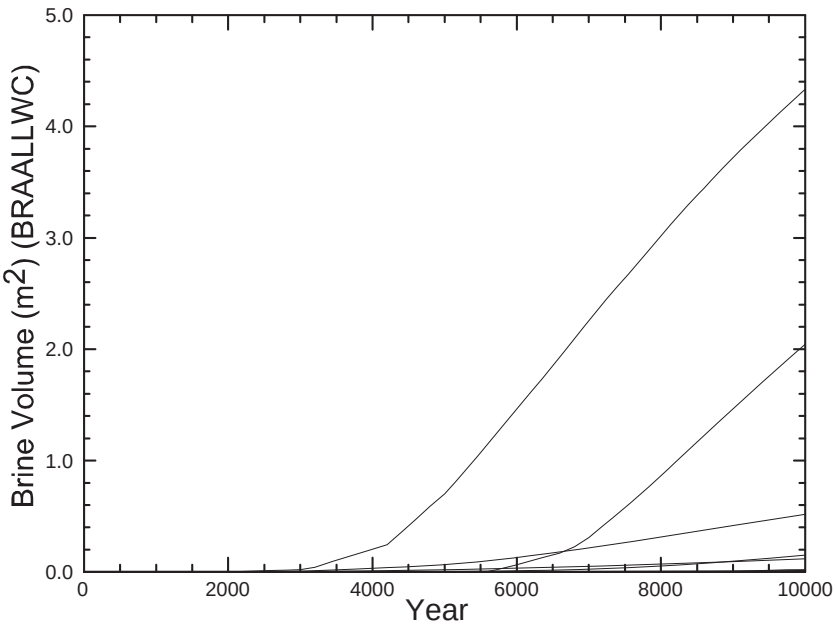

Figure PA-46. Brine Flow Via All MBs Across The LWBs, Replicate R1, Scenario S1.

Regression between total cumulative brine flow into the MBs (BRAALOC) and the uncertain parameters in the LHS (Figure PA-47) shows that uncertainty in brine outflow into the MBs is primarily determined by WMICDFLG, which indicates whether microbial gas generation is modeled and what materials, if any, are consumed. The positive correlation of WMICDFLG with BRAALOC is comparable to the correlation of WMICDFLG with pressure in the waste panel (WAS_PRES) indicating that increasing pressure correlates with increasing brine flow into the marker beds. The PRCC for WMICDFLG is approximately 0.85 throughout the 10,000-year calculation time, indicating that uncertainty in this parameter explains roughly 85% of the variability in BRAALOC. The porosity of halite (HALPOR) accounts for most of the remaining uncertainty. Increasing HALPOR means that more brine is available in the DRZ for inflow into the repository, and brine inflow is a necessary precursor to outflow. The influence of the other three parameters listed in Figure PA-47 is negligible.

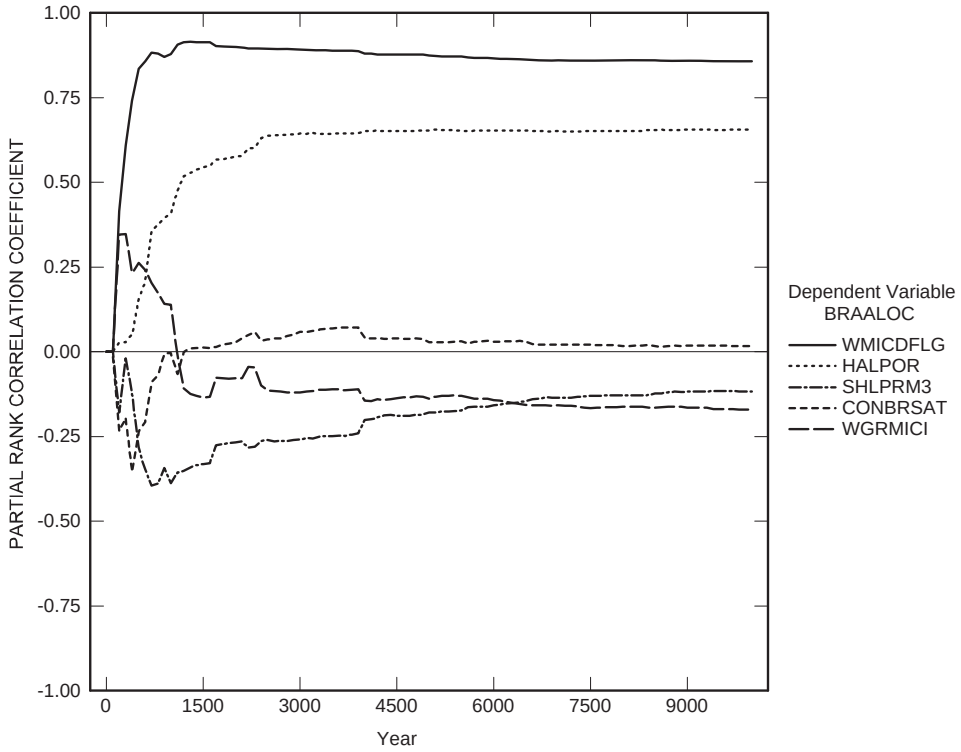

Figure PA-47. Primary Correlations of Total Cumulative Brine Flow Away from the Repository Through All MBs with Uncertain Parameters, Replicate R1, Scenario S1.

Figure PA-48 compares statistics of brine outflow from the repository for the three replicates, and shows that all three replicates produce similar results. The BRNREPOC provides a more valid basis for comparison among the replicates than the other outflow variables, because it has fewer vectors with zero values.

PA-7.2 Radionuclide Transport

Radionuclide transport in the undisturbed scenario is calculated by the code NUTS. Screening runs are used to determine which vectors have the potential to transport radionuclides to the accessible environment (see Section PA-6.7.2). Full transport simulations are run for all vectors that are screened in. This section summarizes the transport results for the undisturbed repository, both up the shaft to the Culebra, and through the Salado to the LWB. Lowry (2003) presents a detailed analysis of NUTS results for the CRA-2004 PA.

PA-7.2.1 Transport to the Culebra

No vectors showed any amount of radionuclide transported to the Culebra through the shafts from the undisturbed repository. Consequently, no radionuclides can transport through the Culebra to the LWB in undisturbed conditions.

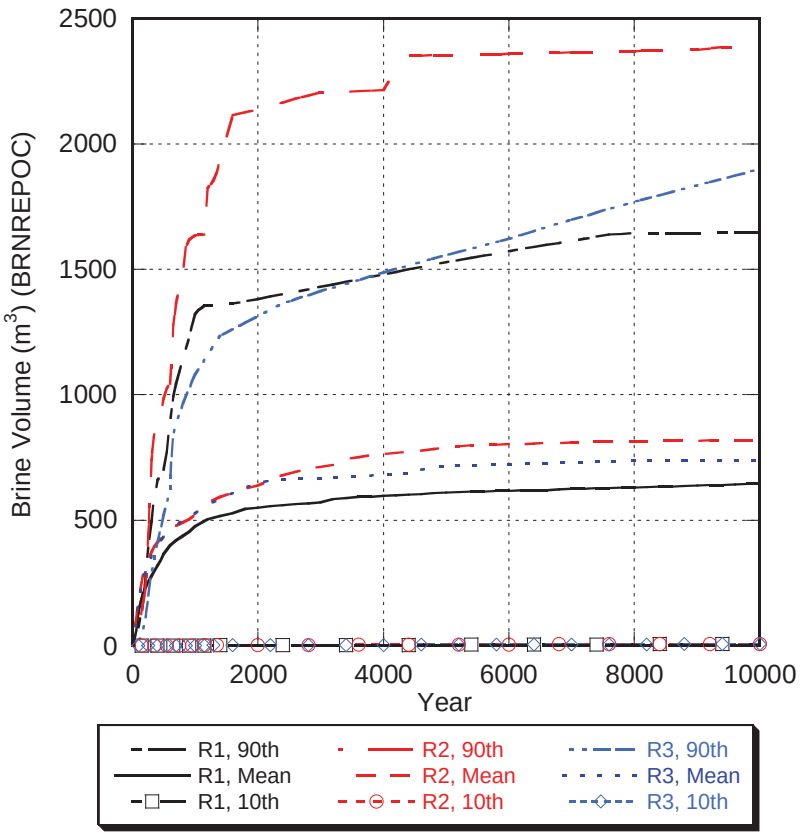

Figure PA-48. Comparison of Brine Flow Away from the Repository between Replicates, Scenario S1.

PA-7.2.2 Transport to the Land Withdrawal Boundary

In all three replicates (300 vectors) of the CRA-2004 PA, only one vector displayed non-zero releases across the LWB from the undisturbed repository. Vector 82 of Replicate R1 released a total of 2.89×10^{-15} EPA units out the southern anhydrite MB 139 over 10,000 years. The release is predominately ^{239}Pu. In this vector, quantities of all of the isotopes move through the MB about 677 m. However, at 984 m from the edge of the repository the concentration of ^{239}Pu decreases to less than 1×10^{-7} EPA units. The total distance from the repository edge to the LWB is 2,400 m. Thus, the non-zero release in this vector is indicative of numerical dispersion resulting from the coarse grid spacing between the repository and the LWB, rather than a probable transport of radionuclides.

The releases from the undisturbed scenario are insignificant when compared to releases from drilling intrusions (see Section PA-9.0). Consequently, releases in the undisturbed scenario are omitted from the calculation of total releases from the repository (see Section PA-9.0) to satisfy the containment requirements of 40 CPR Part 194. Chapter 8.0 demonstrates that WIPP complies with the individual protection requirements of 40 CFR § 191.15 and the groundwater protection requirements of 40 CFR Part 191, Subpart C.

PA-8.0 RESULTS FOR A DISTURBED REPOSITORY

The WIPP repository might be disturbed by exploratory drilling for natural resources during the 10,000-year regulatory period. Drilling could create additional pathways for radionuclide transport, especially in the Culebra, and could release material directly to the surface. In addition, mining for potash within the LWB might alter flow in the overlying geologic units and may accelerate transport through the Culebra. The disturbed scenarios used in PA modeling capture the range of possible releases resulting from drilling and mining.

As outlined in Section PA-6.8, total releases are computed by the code CCDFGF, which evaluates the function f in Equation (24) for each stochastically generated future of the repository. Total releases comprise transport releases and direct releases. Transport releases generally involve movement of radionuclides up an abandoned borehole into the Culebra, then through the Culebra to the LWB. Transport of radionuclides to the Culebra is computed using the codes NUTS and PANEL (see Section PA-4.3 and Section PA-4.4, respectively) using the brine flows computed by BRAGFLO. Transport through the Culebra is computed by the code SECOTP2D (see Section PA-4.9) using flow fields calculated by MODFLOW (see Section PA-4.8).

Direct releases occur at the time of a drilling intrusion and include releases of solids (cuttings, cavings, and spallings) computed using the code CUTTINGS_S (see Section PA-4.5 and Section PA-4.6) and direct releases of brine computed using BRAGFLO (see Section PA-4.7). Pressure and brine saturation within the waste are initial conditions to the models for direct releases. Results from the undisturbed repository (see Section PA-7.0) are used as the initial conditions for the first intrusion. To calculate initial conditions for subsequent intrusions, and to compute the source of radionuclides for transport in the Culebra, a set of drilling scenarios are used to calculate conditions within the repository after an intrusion, using BRAGFLO (Section PA-6.7.1).

This section first summarizes the scenarios used to represent drilling intrusions and the resulting repository conditions calculated by BRAGFLO. Next, transport releases are presented, followed by cuttings and cavings, spallings, and DBRs. Finally, total releases from the repository are summarized.

PA-8.1 Drilling Scenarios

As described in Section PA-3.9, the PA considers two types of drilling intrusions, E1 and E2. The E1 scenario represents the possibility that a borehole connects the repository with a pressurized brine reservoir located within the underlying Castile formation. The E2 scenario represents a borehole that does not connect the repository with an underlying brine reservoir. Repository conditions are calculated for the E1 scenario at 350 and 1,000 years, referred to as the BRAGFLO S2 and S3 scenarios, respectively. The BRAGFLO scenarios S4 and S5 represent E2 drilling events that occur at 350 and 1,000 years, respectively. An additional BRAGFLO scenario, S6, simulates the effects of an E2 intrusion at 800 years followed by an E1 intrusion 1,200 years later into the same panel. For more details on the BRAGFLO scenarios, see Section PA-6.7.1.

PA-8.2 Mining Scenarios

Long-term releases within the Culebra could be influenced by future mining activities that remove all the known potash reserves within the LWB and cause the transmissivity within the overlying Culebra to change. As outlined in Section PA-3.8, full mining of known potash reserves within the LWB in the absence of active and passive controls occurs with a probability specified as a Poisson process with a rate of 10^{-4} yr^{-1}. For any particular future $\boldsymbol{x}_{st}$ in S_{st}, this rate is used to define a time t_{min} at which full mining has occurred. As described in Section PA-6.8.7, flow fields are calculated for the Culebra for two conditions: partial mining, which assumes that all potash as been mined from reserves outside the LWB; and full mining, which assumes all reserves have been mined both inside and outside the LWB. Transport through the Culebra uses the partial mining flow fields prior to t_{min}, and the full mining flow fields after t_{min}.

PA-8.3 Salado Flow

This section summarizes the results of the Salado flow calculations for the disturbed scenarios. Stein and Zelinski (2003b) provide a detailed presentation on the BRAGFLO model, calculation results, and further sensitivity analyses

PA-8.3.1 Pressure in the Repository

Figure PA-49 shows pressure in the waste panel (WAS_PRES for area Waste Panel of Figure PA-8) for the 100 vectors of replicate R1 for each BRAGFLO scenario (Table PA-21). Scenario S1 represents undisturbed repository conditions; the pressure in the waste panel in scenario S1 (Figure PA-49a) is analyzed in Section PA-7.1. Before the drilling intrusions at 350 or 1,000 years, repository pressure increases as described in Section PA-7.1.

After the intrusion, pressure exhibits patterns that vary depending on the type of intrusion and upon sampled input variables related to the intrusion.

Scenarios S2 and S3 represent E1 intrusions at 350 and 1,000 years, respectively (Table PA-21). At the time of the intrusion, brine flow from the Castile brine reservoir leads to an increase in pressure (Figure PA-49b and c). However, pressure drops sharply 200 years after the intrusion when the borehole plugs above the repository fail (Table PA-5) and the permeability of the borehole generally increases. However, in vectors with low borehole permeability after plug failure, pressure does not change noticeably as a result of the borehole plug failure. Twelve hundred years after the drilling intrusion, the permeability of the borehole connecting the repository to the Castile is reduced by an order of magnitude because of creep closure (Table PA-5). This material change reduces pressure slightly in some vectors, but does not appear to have a significant effect on the pressure in most vectors.

Scenarios S4 and S5 represent E2 intrusions at 350 years and 1,000 years, respectively. The borehole plugs effectively prevent any change in repository pressure from the time of the intrusion until the borehole plugs fail (Figure PA-49d and e). As in the scenarios for E1 intrusions, pressure generally drops sharply when the plugs fail, except for vectors with low borehole permeability after plug failure.

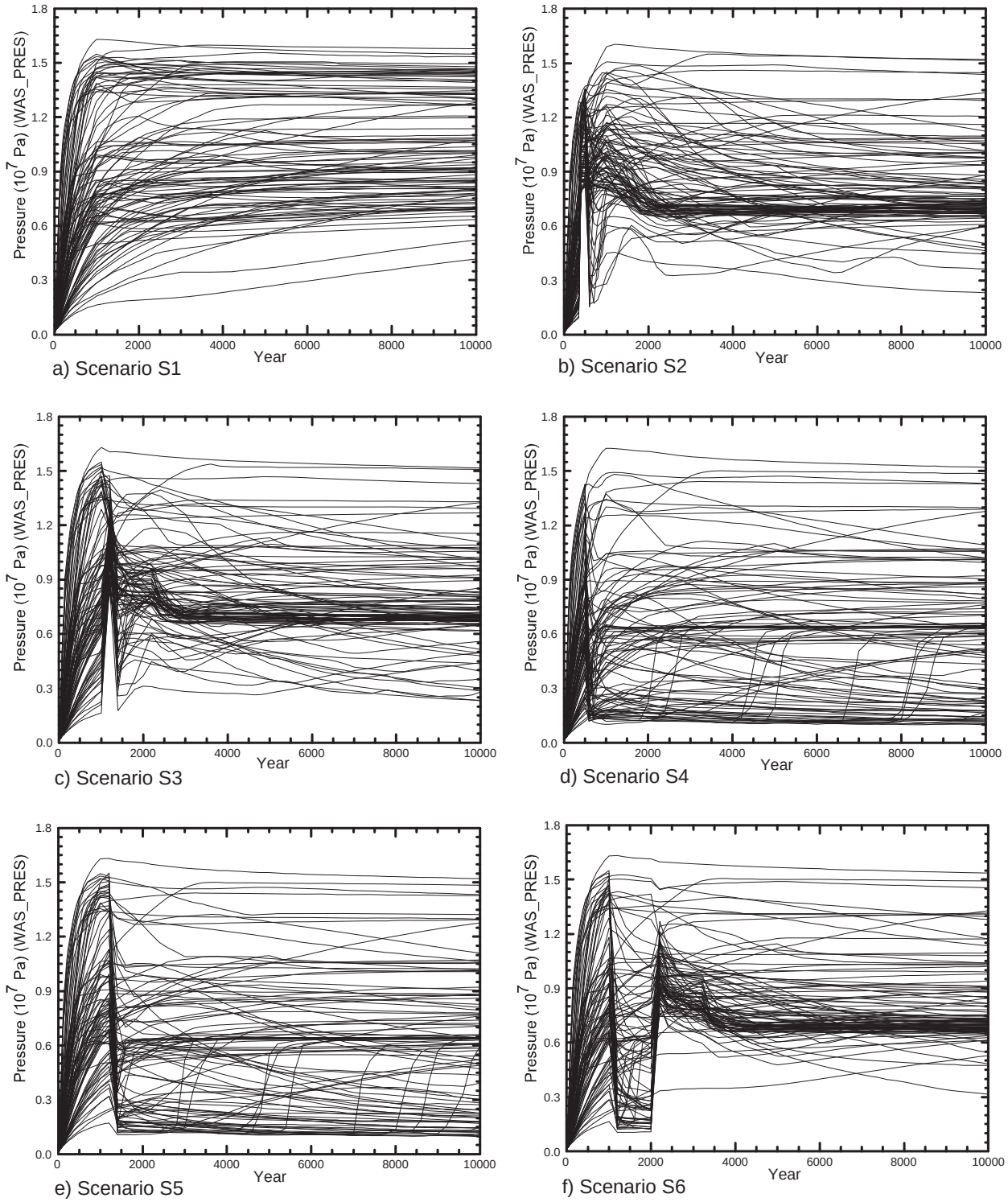

Figure PA-49. Pressure in the Waste Panel for All Scenarios, Replicate R1.

Scenario S6 represents two intrusions into the same panel: an E2 intrusion at 800 years followed by an E1 intrusion at 2000 years. Figure PA-49f shows pressure in the panel for the S6 scenario. The changes in pressure after the first intrusion are nearly identical to that observed in Scenario S5 (Figure PA-49e). In most vectors, the pressure decreases so much that there is a sharp increase in pressure at the time of the second intrusion, which connects the waste panel to the Castile brine reservoir. The changes in pressure after the second intrusion are very similar to those predicted after an E1 intrusion (Scenario S3, Figure PA-49c).

Figure PA-50 shows pressure in the rest of repository areas (SRR_PRES for area South RoR and NRR_PRES for area North RoR in Figure PA-8) and in the nonwaste areas (NWA_PRES averaged over areas Ops and Exp in Figure PA-8) for Scenarios S2 and S5, which represent E1 and E2 drilling intrusions into the waste panel at 350 and 1,000 years, respectively. In general, pressure in the rest of repository and nonwaste areas is not immediately affected by the intrusion. The presence of the Option D panel closures (see Section PA-4.2.8) inhibits flow of gas and brine between the intruded panel and adjoining areas, moderating the effects of the intrusion.

Figure PA-51 compares mean pressure in the waste panel among the scenarios. Pressure in the disturbed scenarios tends to be lower after the intrusion than pressure in the undisturbed scenario due to the borehole connection to the surface. By 2,000 years after the intrusion, the mean pressure after an E1 intrusion (Scenarios S2, S3, and S6) is about 80 percent of the mean pressure in undisturbed conditions (Scenario S1), and the mean pressure after an E2 intrusion (scenarios S4 and S5) is 60 percent of the mean pressure in undisturbed conditions.

Figure PA-52 illustrates the differences in pressure among the various excavated regions after an E1 intrusion at 350 years (Scenario S2). Following the intrusion, mean pressure in the waste panel (WAS_PRES) is temporarily higher than in the other repository regions. About 1,500 years after the intrusion, mean pressure in the South RoR (SRR_PRES) and North RoR (NRR_PRES) is approximately equal to mean pressure in the waste panel. Mean pressure in the nonwaste regions (NWA_PRES) is lower than pressure in the waste-filled regions until about 4,000 years after the intrusion. The delay in pressure equalization between different repository regions is due to the panel closures, which tend to prevent rapid exchange of brine and gas between regions (Hansen et al. 2002) unless pressure exceeds the fracture initiation pressure (approximately 12-14 MPa) after which pressure can rapidly equalize among the regions.

Regression between pressure in the waste panel for an E1 intrusion at 350 years (Scenario S2) and the uncertain parameters in the analysis (Section PA-5.2) shows that the uncertainty in the permeability of the borehole (BHPERM) is largely responsible for the uncertainty in pressure after the borehole plugs fail (Figure PA-53). Before the borehole plugs fail, pressure is most sensitive to variations in the initial pressure in the Castile (BPINTPRS) and the indicator for microbial gas generation (WMICDFLG). Increases in BPINTRS can increase brine flow from the Castile to the repository; larger values of WMICDFLG indicate the potential to generate additional gas as a consequence of the additional brine flowing into the

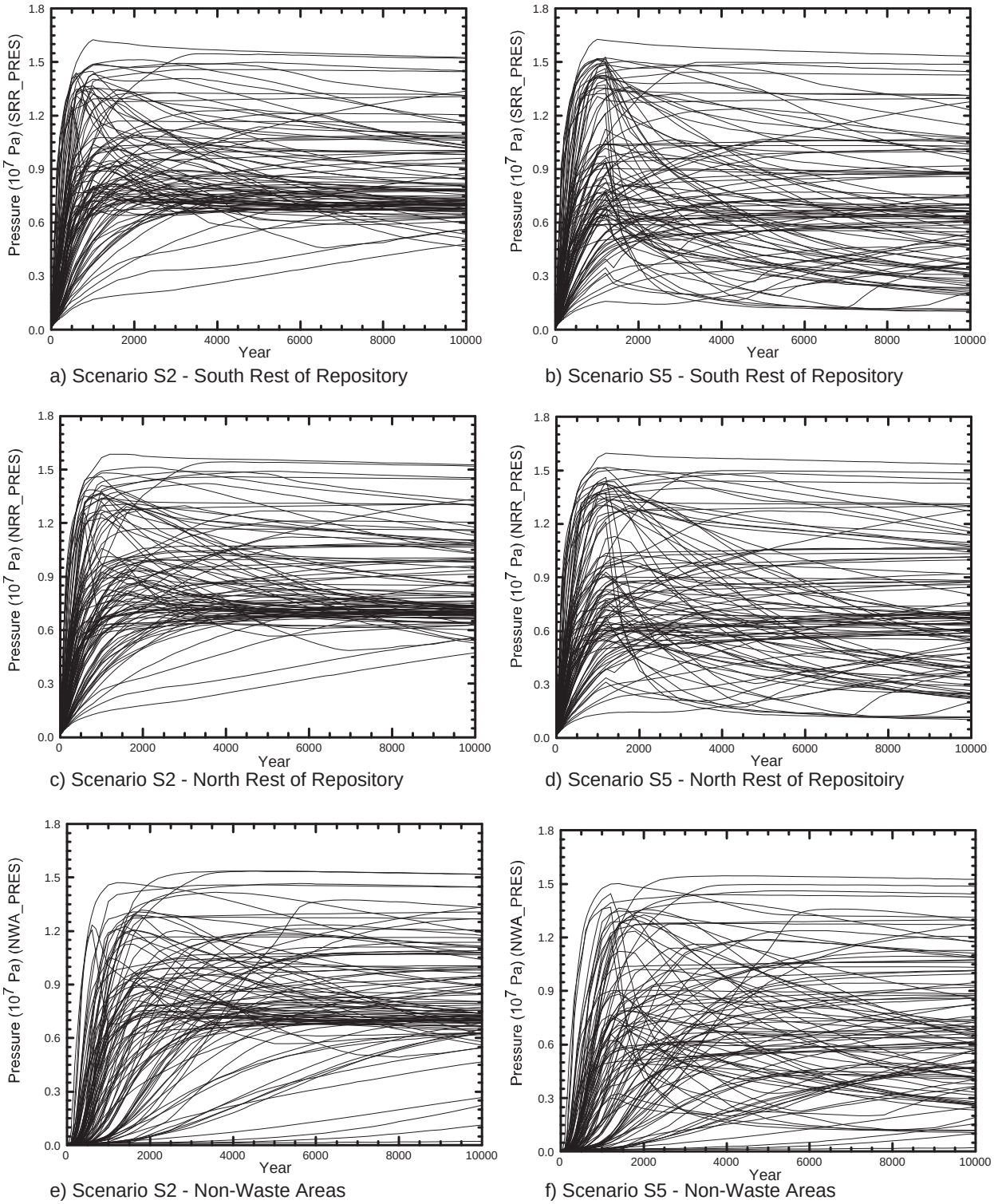

Figure PA-50. Pressure in Various Regions, Replicate R1, Scenarios S2 And S5.

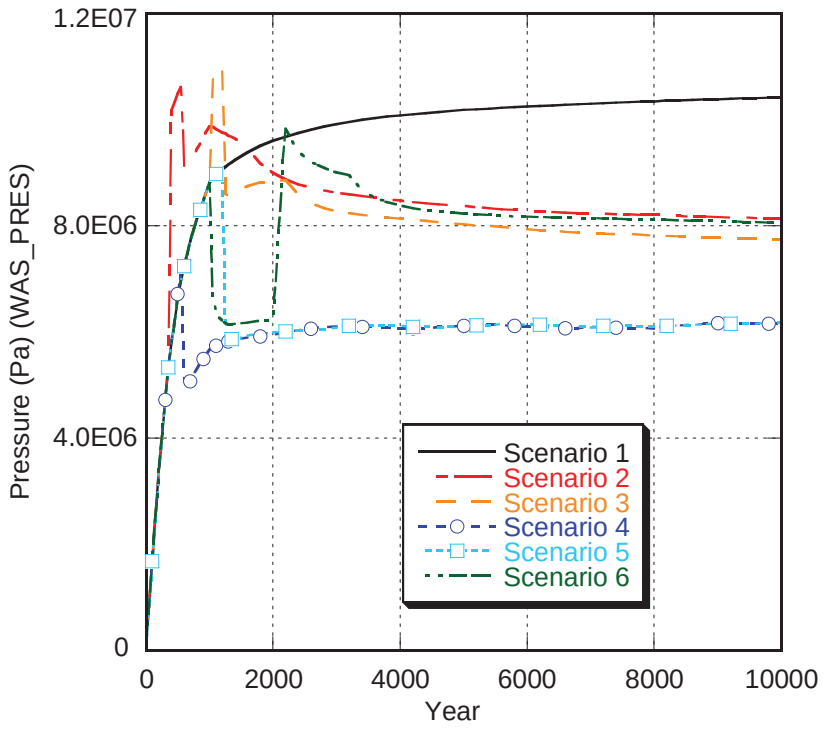

Figure PA-51. Mean Pressure in the Waste Panel for All Scenarios, Replicate R1

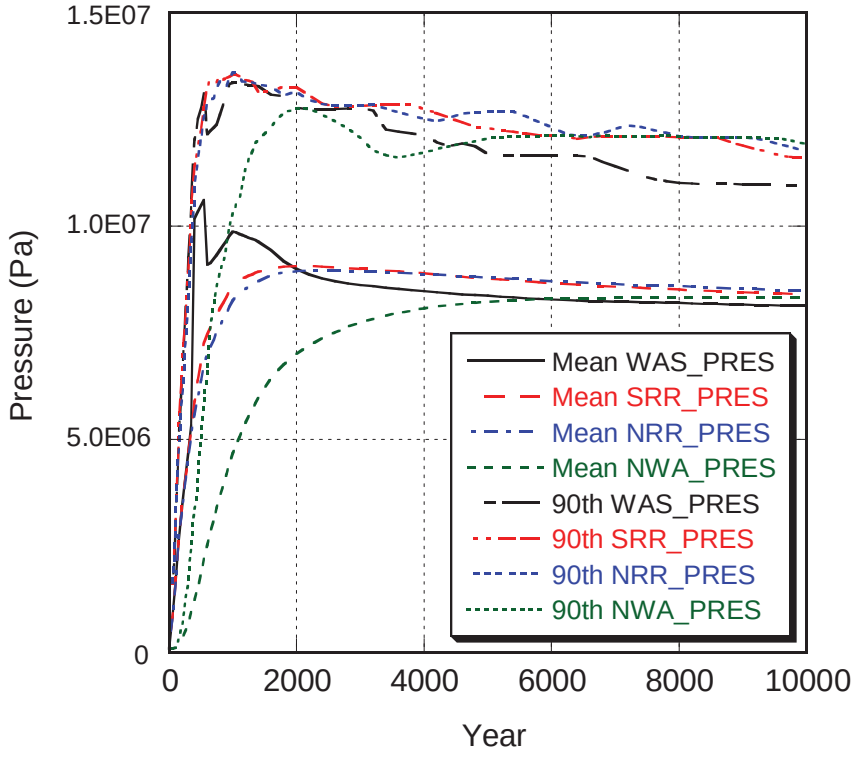

Figure PA-52. Mean And 90th Percentile Values For Pressure In The Excavated Regions Of The Repository, Replicate R1, Scenario S2.

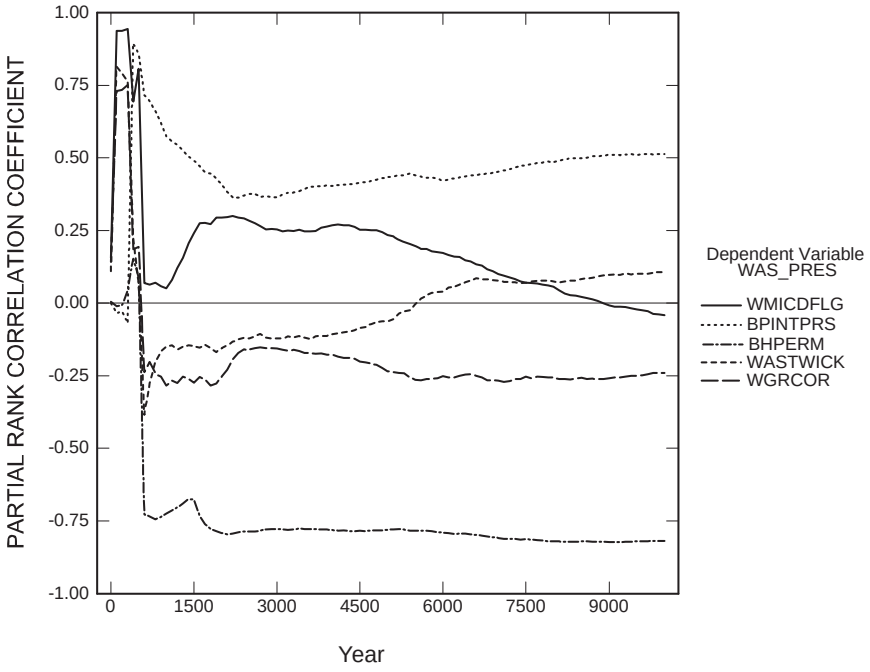

Figure PA-53. Primary Correlations For Pressure In The Waste Panel With Uncertain Parameters, Replicate R1, Scenario S2.

repository. Figure PA-54 shows the regression analysis results for an E2 intrusion at 1,000 years (Scenario S5). As in the analysis of Scenario S2, before the intrusion, the uncertainty in the indicator for microbial gas generation (WMICDFLG) is most important; after the borehole plugs fail, uncertainty in the permeability of borehole fill (BHPERM) is most important. Regression analyses for an E1 intrusion at 1,000 years and for an E2 intrusion at 350 years lead to similar conclusions (Stein and Zelinski, 2003b).

Figure PA-55 compares statistics for pressure in the waste panel for scenario S2 among the three replicates, and show that the three replicates produced statistically similar results.

PA-8.3.2 Brine Saturation

Brine saturation tends to increase after a drilling intrusion. Figure PA-56 shows brine saturation in the waste panel (WAS_SATB for area Waste Panel in Figure PA-8) for replicate R1 of each BRAGFLO scenario. In many vectors, the intruded panel becomes saturated after an E1 intrusion (Scenarios S2, S3, and S6). Depending on the borehole permeability and pressures in the repository and in the brine reservoir, quantities of brine can flow from the reservoir into the intruded panel, possibly filling the panel. In contrast, after an E2 intrusion (Scenarios S4 and S5) saturation increases for only a few vectors. An E2 intrusion tends to reduce the pressure in the intruded panel by releasing fluids (mainly gas) up the borehole (Figure PA-49). The reduced pressure in the waste permits an increase in brine inflow from the DRZ and the MBs. In addition, in some vectors brine can flow down the borehole from the Culebra into the intruded panel, depending on the permeability of the borehole.

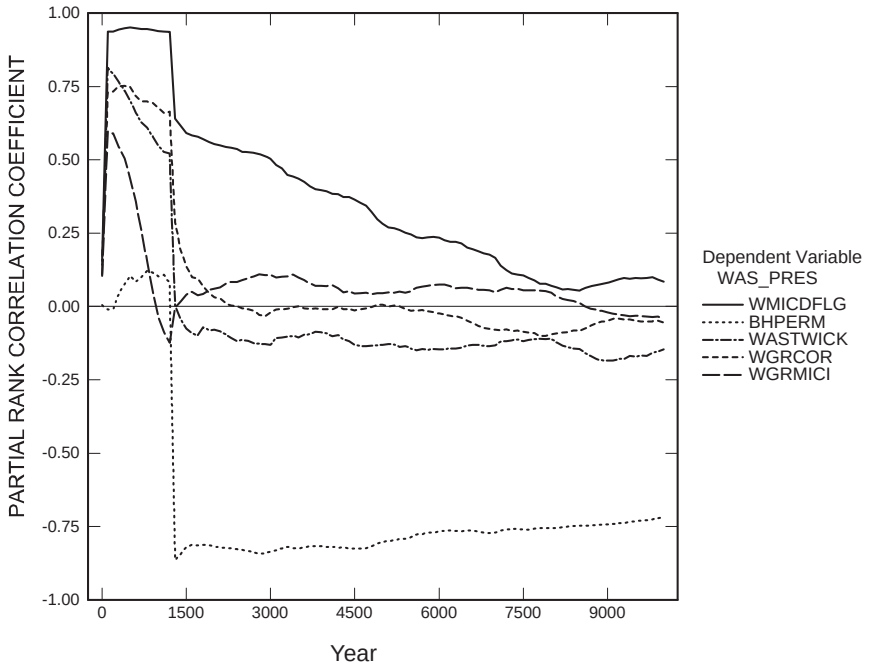

Figure PA-54. Primary Correlations For Pressure In The Waste Panel With Uncertain Parameters, Replicate R1, Scenario S5.

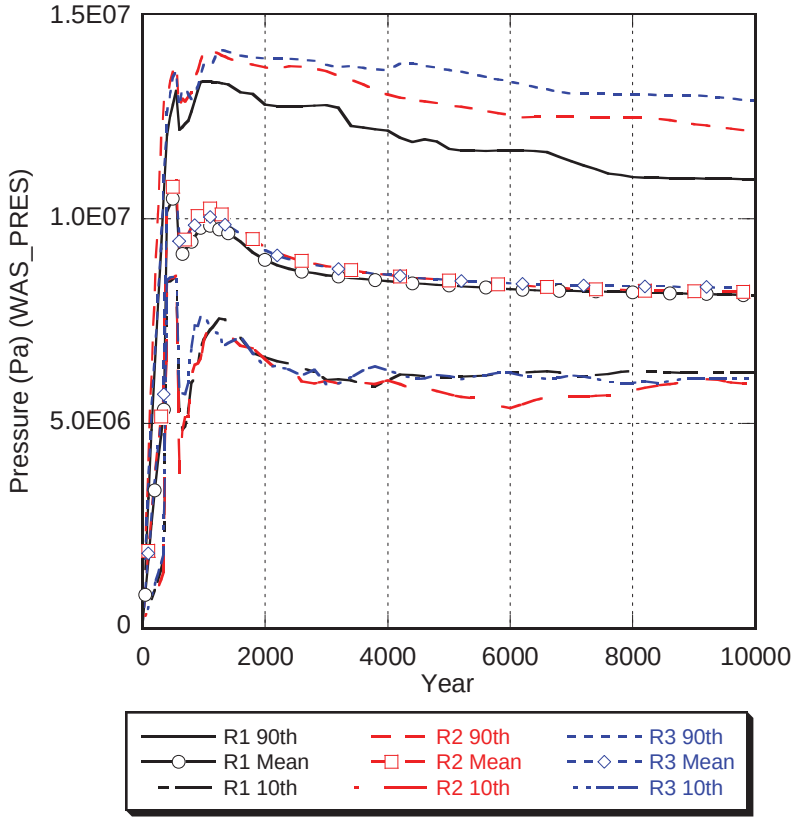

Figure PA-55. Statistics For Pressure in the Waste Panel For All Replicates, Scenario S2.

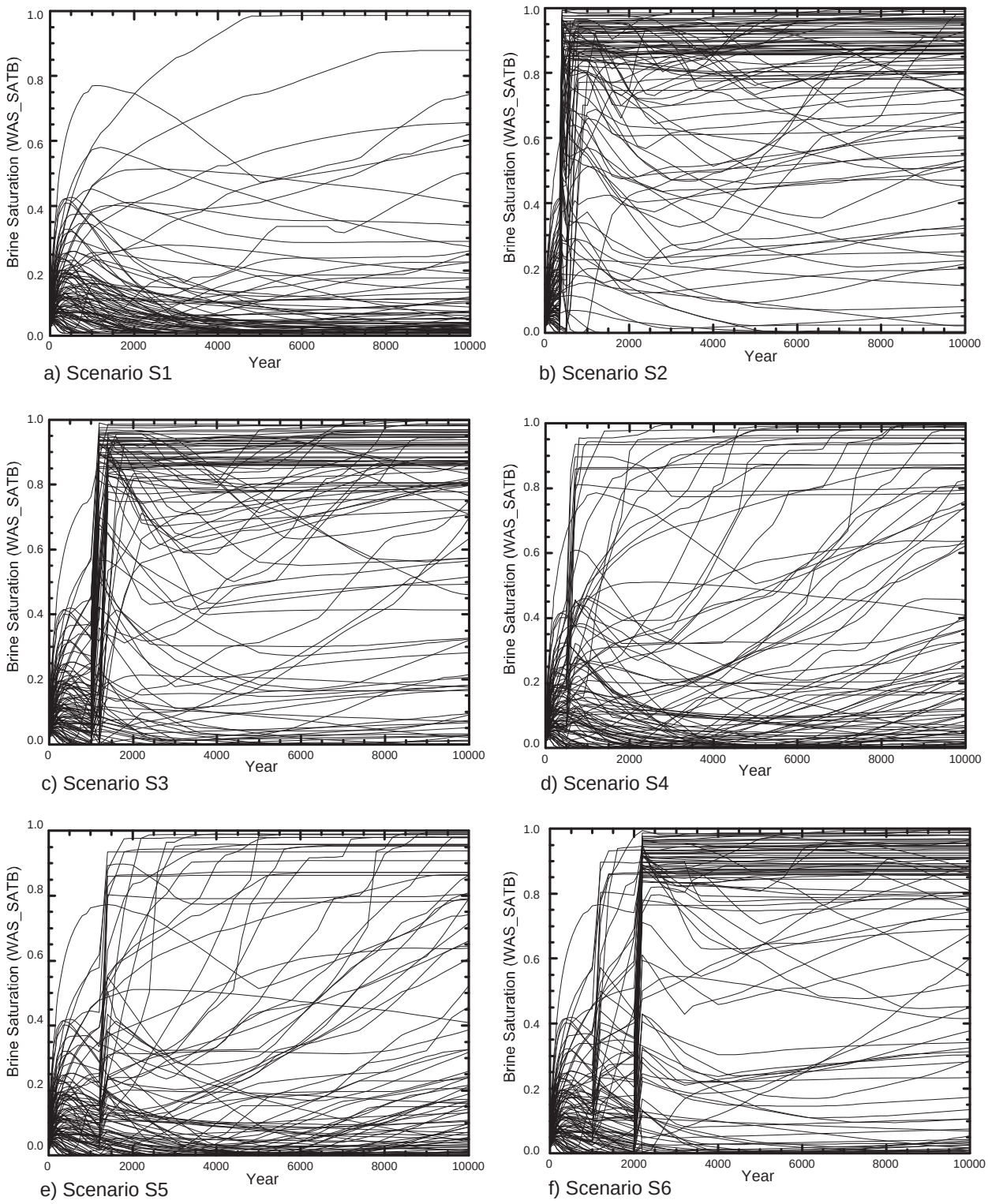

Figure PA-56. Brine Saturation in the Waste Panel for All Scenarios, Replicate R1.

Figure PA-57 compares the mean values for brine saturation in the waste panel (WAS_SATB) for each scenario. Brine saturation is highest after E1 intrusions (Scenarios S2, S3, and S6), but also increases somewhat after an E2 intrusion (Scenarios S4 and S5). However, saturation in other excavated areas is not generally increased. Figure PA-58 shows brine saturation in the rest of repository (SRR_SATB for area South RoR and NRR_SATB for area North RoR in Figure PA-8) and in the nonwaste areas (NWA_SATB averaged over areas Ops and Exp in Figure PA-8) for the Scenarios S2 and S5. Comparison of Figure PA-57 with Figure PA-39, which shows brine saturation in undisturbed conditions, reveals that brine saturation in unintruded regions is generally unaffected by the intrusion. The panel closures separating the intruded panel from these regions effectively prevent brine flow between excavated areas. In addition, the intruded panel is modeled as one of the panels at the southern end of the repository, and hence is down the stratigraphic dip from the other excavated regions.

Figure PA-58 also shows that brine saturation in the nonwaste areas (areas Ops and Exp in Figure PA-8) is somewhat higher than in the rest of repository areas (areas South RoR and North RoR in Figure PA-8). Brine saturation in the nonwaste areas is higher because of the lack of brine consuming corrosion processes in these areas and their position adjacent to the northern marker beds, which supply brine to the excavated area. The rest of repository areas have the lowest saturations because they are not connected to the brine reservoir, corrosion consumes brine in these regions, and their internal position in the two-dimensional grid (Figure PA-8) prevents direct flow of brine from the MBs.

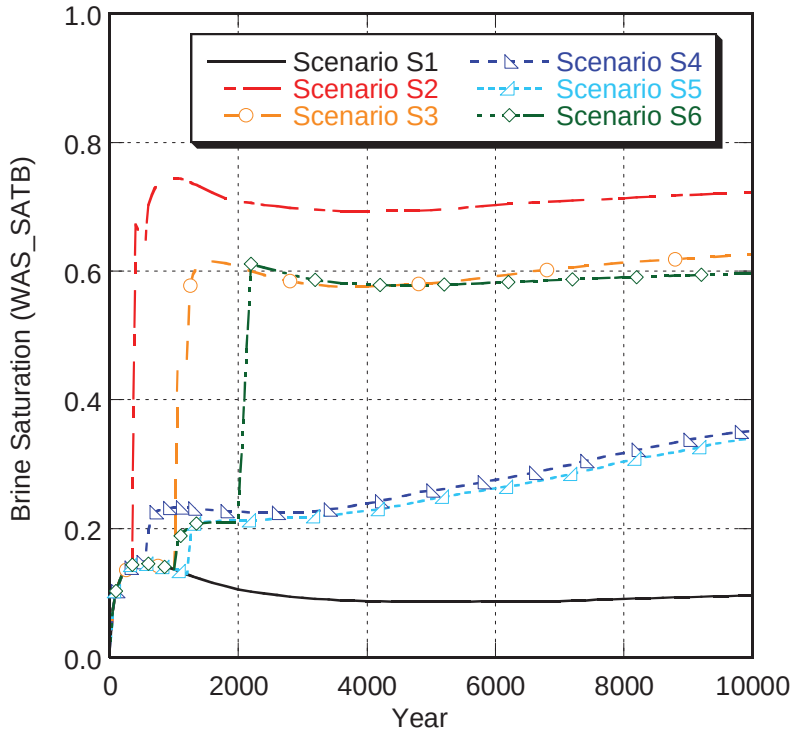

Figure PA-57. Mean Values for Brine Saturation in the Waste Panel for All Scenarios, Replicate R1.

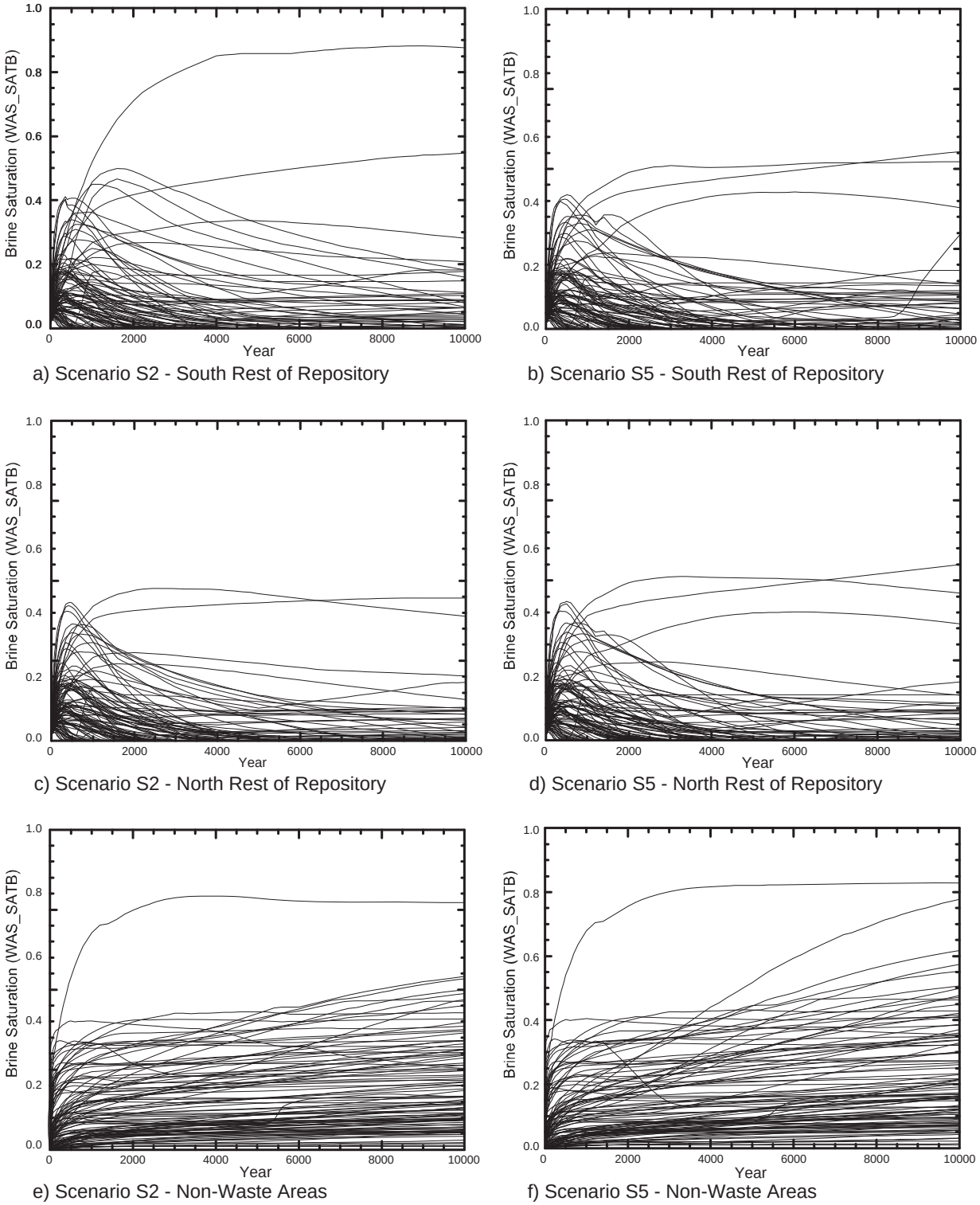

Figure PA-58. Brine Saturation in Excavated Areas, Replicate R1, Scenarios S2 and S5.

Figure PA-59 compares mean and 90th percentile brine saturations among the excavated areas for an E1 intrusion at 350 years (Scenario S2). Brine saturations in the waste panel are the highest due to the connection with the brine reservoir. Comparison of Figure PA-59 to Figure PA-40, which shows mean pressure for undisturbed conditions, indicates that brine saturation outside of the waste panel is very similar to the undisturbed Scenario S1.

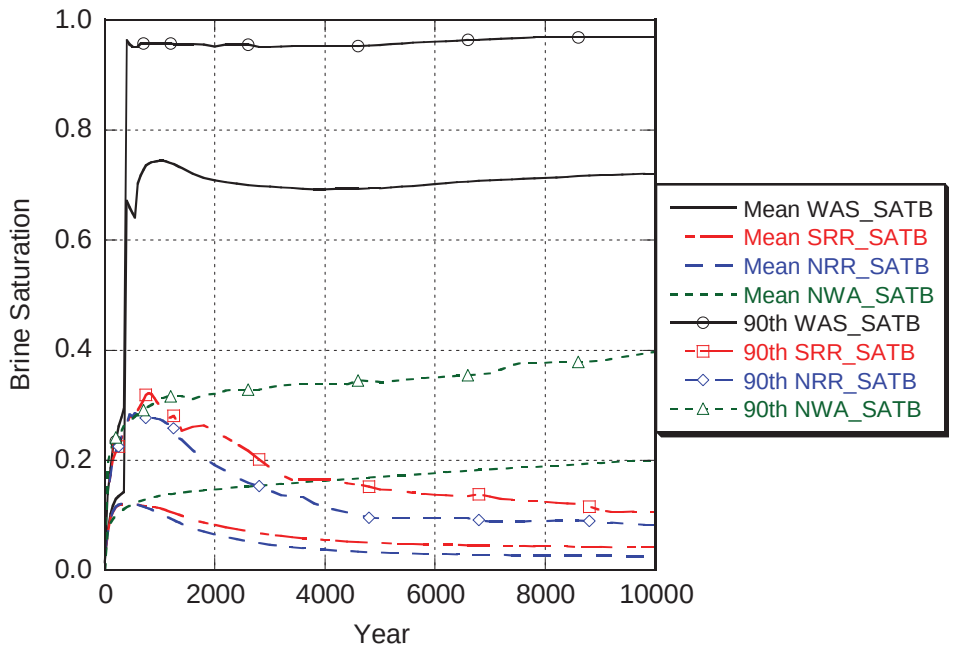

Figure PA-59. Statistics For Brine Saturation in Excavated Areas, Replicate R1, Scenario S2.

Figure PA-60 shows the results of the regression analysis between brine saturation in the waste panel (WAS_SATB) for the S2 scenario and the uncertain parameters in the analysis (Section PA-5.2). For most of the time after the intrusion, uncertainty in borehole permeability (BHPERM) is primarily responsible for the uncertainty in brine saturation, with increases in borehole permeability leading to increases in brine saturation. The indicator for microbial degradation (WMICDFLG), which has a negative correlation with the brine saturation in the waste panel, also has a significant influence throughout the 10,000-year modeling period. Because the S2 scenario models an intrusion at 350 years, much of the CPR material is still present in the waste. Additional brine entering the waste panel would saturate more of the waste and accelerate the degradation of the CPR material, increasing gas pressure, and in turn retarding brine inflow. Thus, the negative correlation between the indicator for microbial degradation and brine saturation is quite strong immediately after the intrusion, but decreases in importance at later times. Uncertainty in the other parameters in Figure PA-60 (HALPOR, DRZPRM, and WGRCOR, defined in Table PA-17), have relatively little influence on brine saturation. Regression analysis of waste saturation for the S3 scenario yields a similar result (Stein and Zelinski 2003b).

Figure PA-61 shows the results of the regression analysis between brine saturation in the waste panel (WAS_SATB) for the S5 scenario and the uncertain parameters in the analysis (Section PA-5.2). As with the S2 scenario, borehole permeability is the primary factor

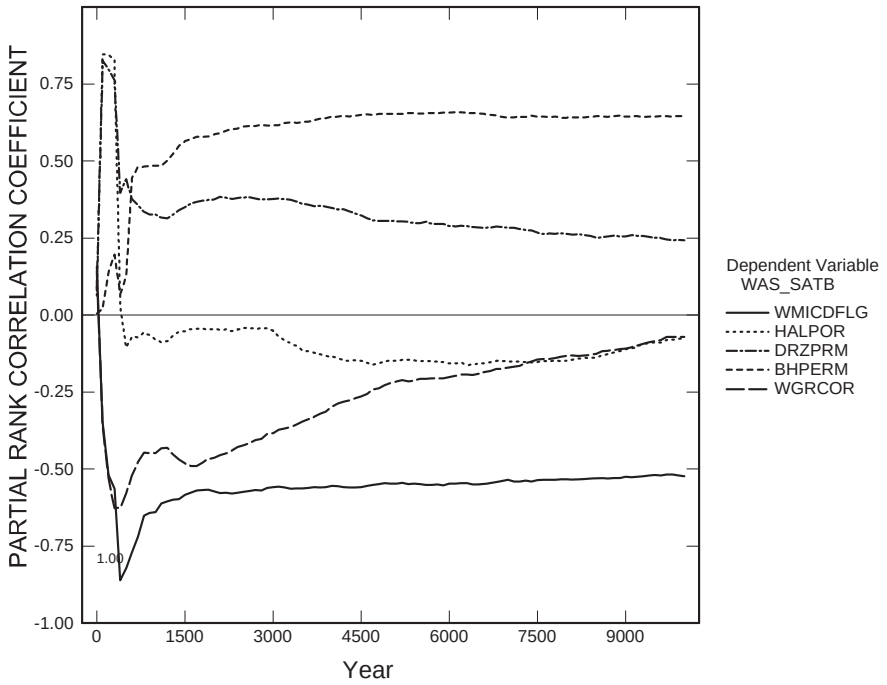

Figure PA-60. Primary Correlations for Brine Saturation in the Waste Panel with Uncertain Parameters, Replicate R1, Scenario S2.

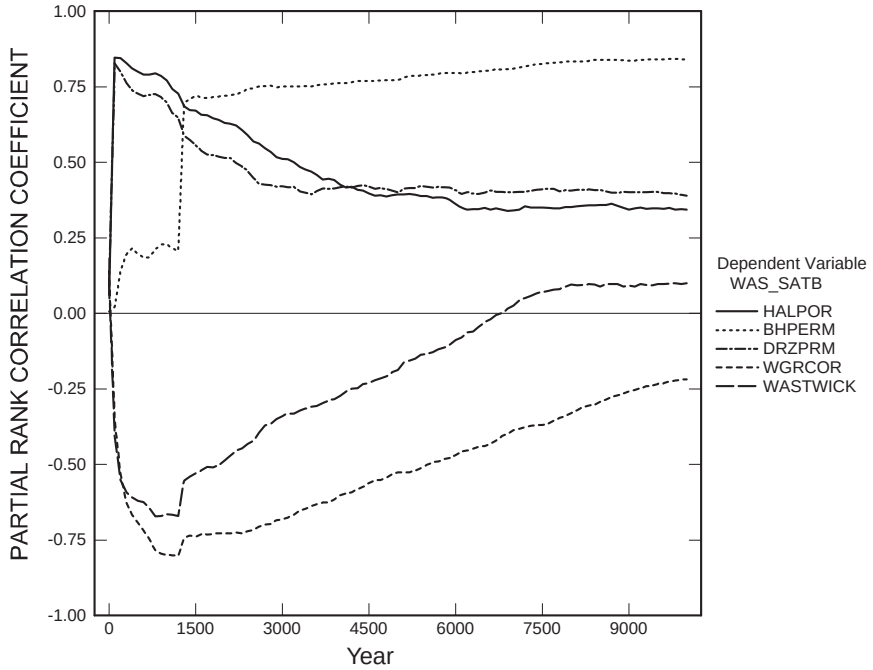

Figure PA-61. Primary Correlations of Brine Saturation in the Waste Panel with Uncertain Parameters, Replicate R1, Scenario S5.

influencing brine saturation in the waste panel (WAS_SATB) after the borehole plugs fail. Regression analysis of waste saturation for the S4 scenario yields a similar result (Stein and Zelinski 2003b).

Figure PA-62 compares statistics for brine saturation for the three replicates of the S2 scenario, and shows that the replicates produced similar results.

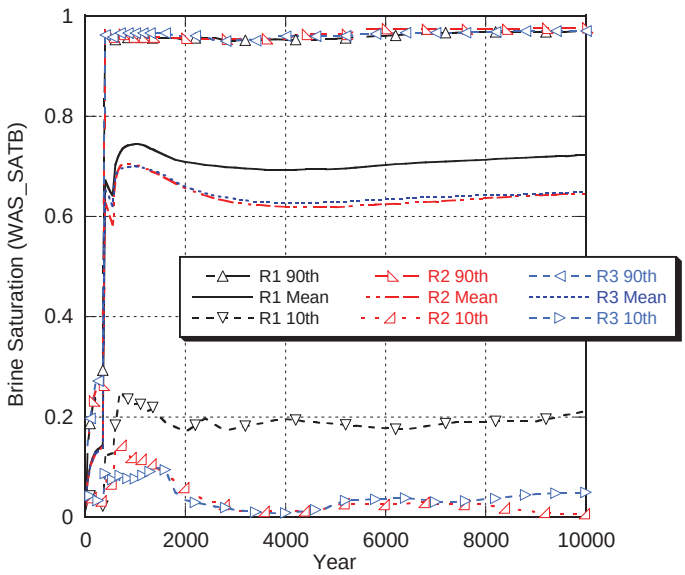

Figure PA-62. Statistics for Brine Saturation in the Waste Panel For All Replicates, Scenario S2.

PA-8.3.3 Brine Flow Out of the Repository

This section describes the flow of brine up a borehole to the Culebra. Brine flow to the Culebra is an important input to the calculations of long-term releases in the Culebra, described in Section PA-8.4.3. Direct brine flow up the borehole to the surface at the time of drilling is modeled separately in the DBR calculations, presented in Section PA-8.5.3.

Figure PA-63 shows cumulative brine flow out of the repository (BRNREPOC) and brine flow up a borehole to the Culebra (BRNBHRCC) for the five BRAGFLO scenarios that model drilling intrusions. The largest volumes of brine flow from the repository after E1 intrusions (Scenarios S2, S3, and S6), which is consistent with the higher brine saturation in the intruded panel (Figures PA-56b, PA-56c, and PA-56f, respectively). The similarity between the plots of BRNREPOC and BRNBHRCC indicate that nearly all the brine leaving the repository after an intrusion flows up the borehole to the Culebra. The few vectors that show brine flow out of the repository before the drilling intrusion generally have either very high pressures or very high DRZ permeability, allowing brine to flow from the repository into the MBs before the intrusion occurs. At 1,200 years after an E1 intrusion, the permeability of the borehole between the repository and the Castile is reduced by an order of magnitude because of creep closure (see Table PA-5), reducing brine flowing into the repository and causing a corresponding decrease in brine out of the repository.

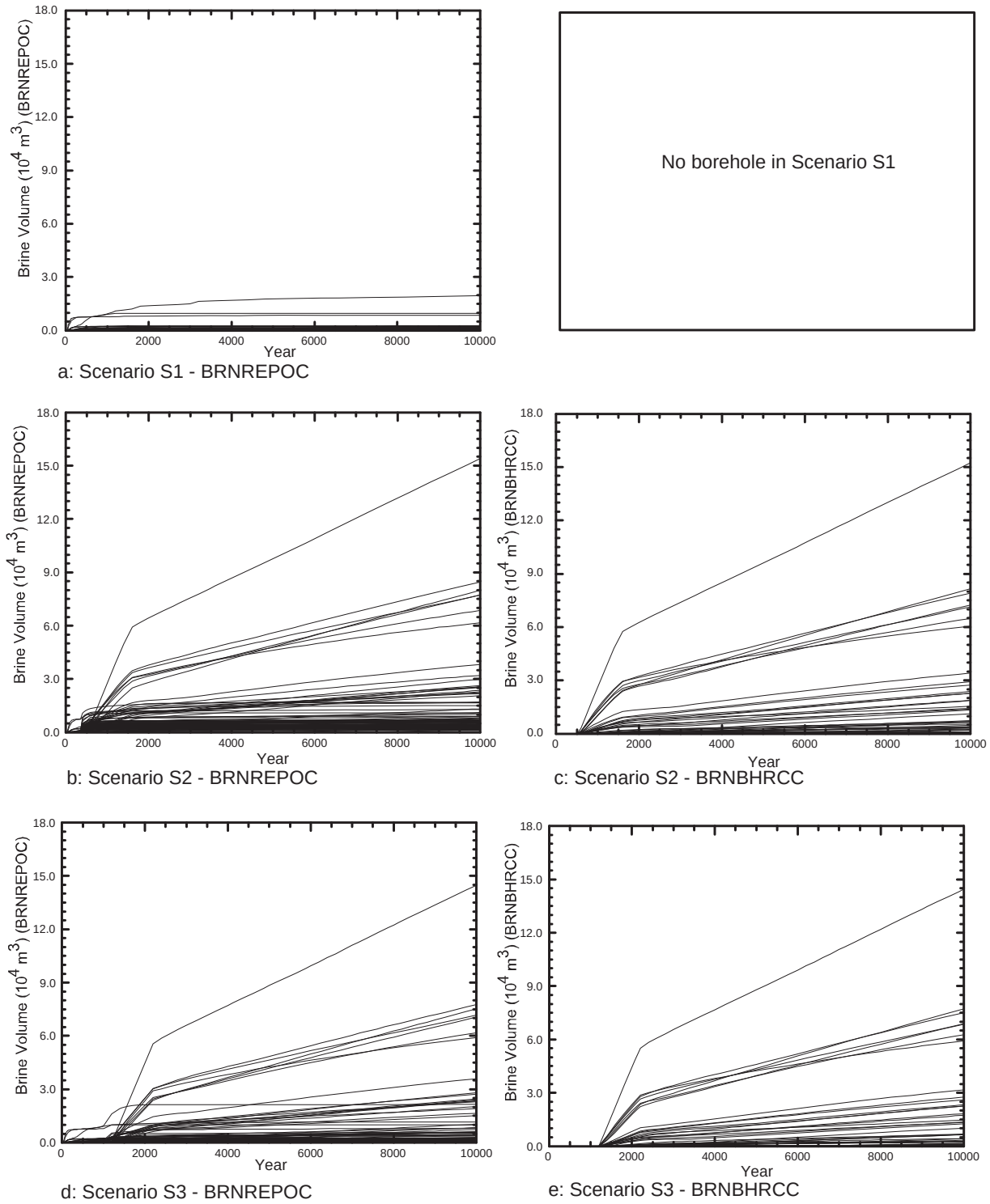

Figure PA-63. Total Cumulative Brine Outflow and Brine Flow Up the Borehole in All Scenarios, Replicate R1.

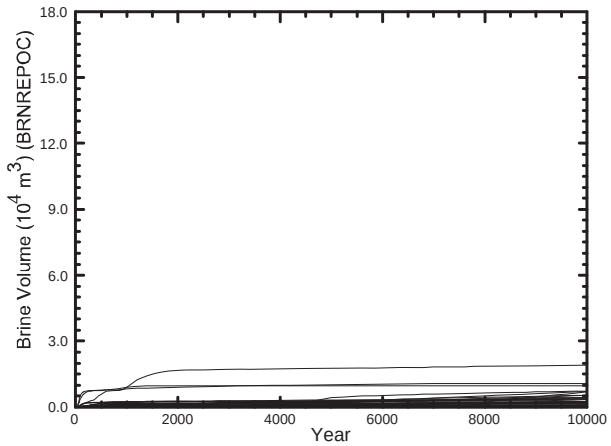

f) Scenario S4 - BRNREPOC

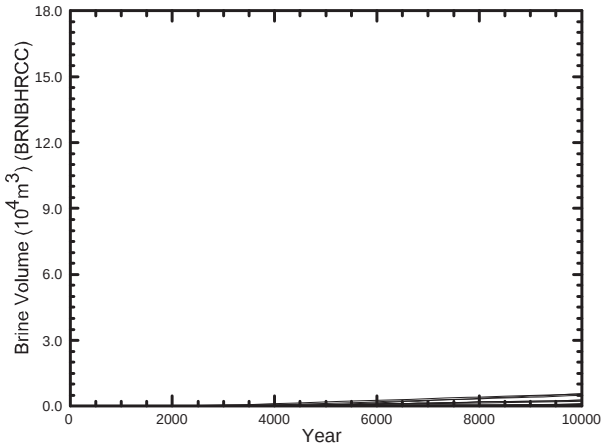

g) Scenario S4 - BRNBHRCC

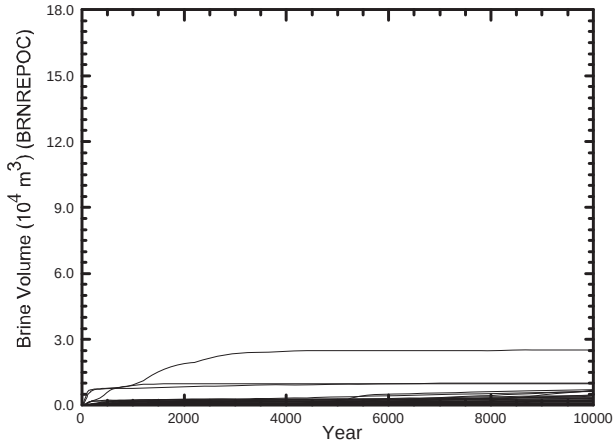

h) Scenario S5 - BRNREPOC

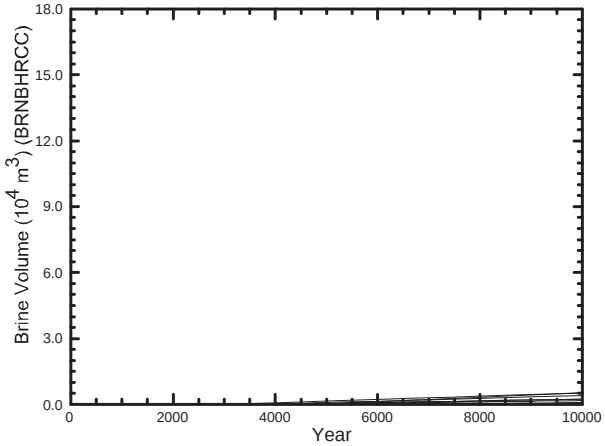

i) Scenario S5 - BRNBHRCC

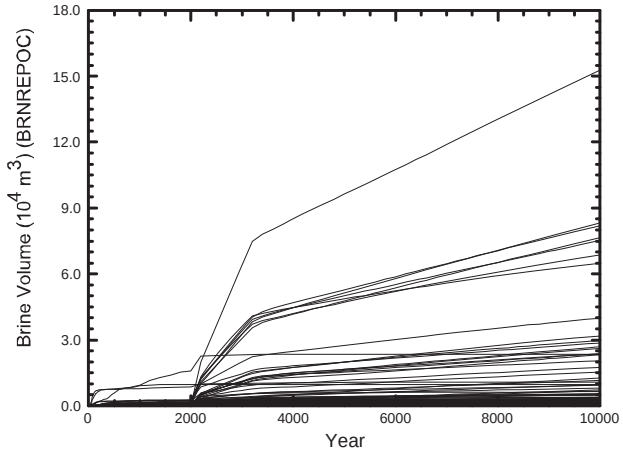

j) Scenario S6 - BRNREPOC

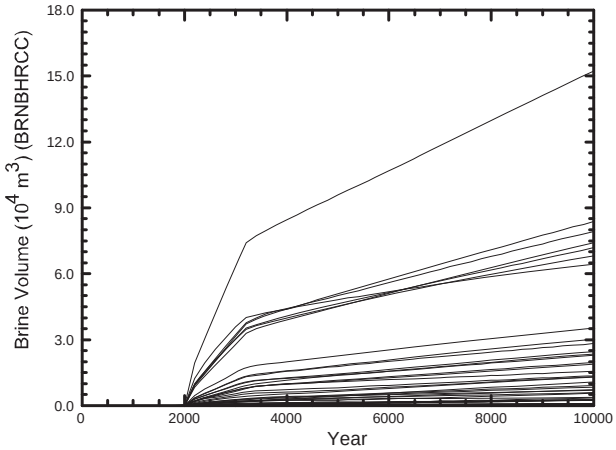

k) Scenario S6 - BRNBHRCC

Figure PA-63(cont). Total Cumulative Brine Outflow and Brine Flow Up the Borehole in All Scenarios, Replicate R1

Figure PA-64 shows the results of regression analysis between the brine flow up the borehole to the Culebra (BRNBHRCC) and the uncertain parameters in the analysis (Section PA-5.2). Before the intrusion, non-zero values of BRNBHRCC result from numerical error in the calculation; these values do not exceed 10^{-18} m^3 and thus the correlation to uncertainty in shaft permeability (SHUPRM) is not meaningful. Immediately after the intrusion, uncertainty in the permeability of the undegraded borehole plugs (PLGPRM) contributes most of the uncertainty in brine flow volumes. After the borehole plugs degrade (200 years after the intrusion), uncertainty in the permeability of the borehole (BHPERM) almost exclusively determines the uncertainty in brine volumes reaching the Culebra. The indicator for microbial degradation (WMICDFLG) is weakly correlated with the small amount of uncertainty that is not explained by the uncertainty in borehole permeability.

Figure PA-65 compares statistics for brine flow out of the repository for the three replicates of Scenario S2. The figure shows that brine flow results are very similar among replicates.

PA-8.4 Radionuclide Transport

In the disturbed scenarios, radionuclide transport in the Salado is calculated by the code NUTS (see Section PA-4.3). Transport from the Salado to the Culebra is calculated by NUTS and PANEL (see Section PA-4.3 and Section PA-4.4). Transport within the Culebra is calculated by SECOTP2D (see Section PA-4.9). For all transport calculations, mobilized concentrations of radionuclides in Salado and Castile brines are computed by the code PANEL (see Section PA-4.4).

This section summarizes the transport results for the disturbed scenarios. Detailed analysis of the NUTS results is presented in Lowry (2003). Garner (2003) provides analysis of the PANEL results; Kanney (2003) presents analysis of the SECOPT2D results.

PA-8.4.1 Radionuclide Source Term

The code PANEL calculates the source term for transport, which is the time-varying concentration of radioactivity mobilized in brine, either as dissolved isotopes or as isotopes sorbed to mobile colloids. Two different brines are considered: the interstitial brine present in the Salado Formation, which is magnesium rich; and the brine in the Castile Formation, which is sodium rich. Radionuclide solubility in the two brines can be considerably different. Before an E1 intrusion, performance assessment assumes that the brine in the repository is Salado brine. After an E1 intrusion, brine in the repository is assumed to be from the Castile.

Figure PA-66 and Figure PA-67 show the source term in Salado and Castile brines, respectively, as a function of time for all vectors in replicate R1. Concentrations are expressed as EPA units/m^3 to combine the radioactivity in different isotopes. Short-lived radionuclides, such as ^{238}Pu, decay rapidly in the first few years. After this initial decay, the source term is dominated by Am (Garner 2003); the concentration of Am is limited by its solubility until all the inventory of Am is in solution. After all Am is in solution, the total radionuclide concentration generally decreases as the Am decays, until the source term becomes dominated by Pu (Garner 2003). The horizontal lines in the figures indicate periods of time when the

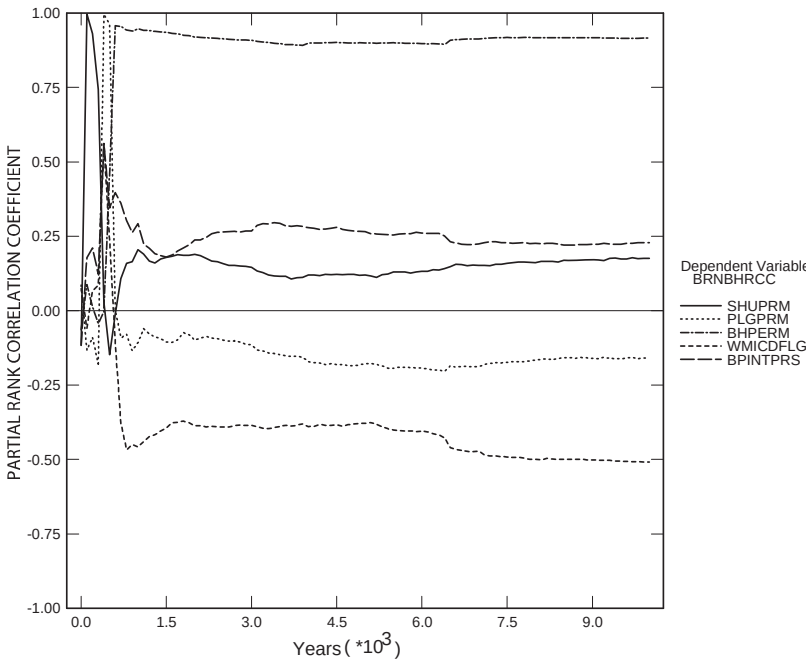

Figure PA-64. Primary Correlations for Cumulative Brine Flow Up the Borehole with Uncertain Parameters, Replicate R1, Scenario S2.

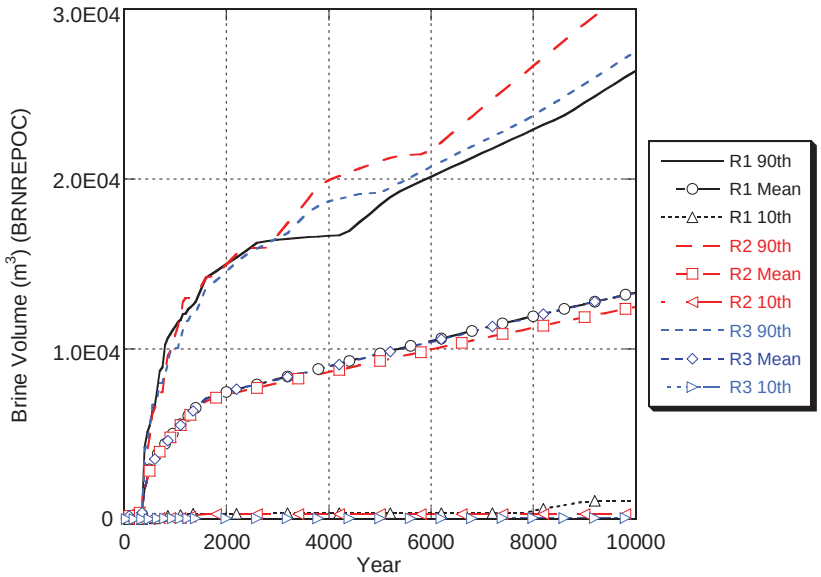

Figure PA-65. Statistics for Cumulative Brine Outflow in All Replicates, Scenario S2.

total radionuclide concentration is limited by the solubility of Am (before about 3,000 years) or Pu (after about 6,000 years). Thus, the uncertainty in total radionuclide concentration is determined by the uncertainty factors used in the calculation of solubilities for Am and Pu (see Table PA-9).

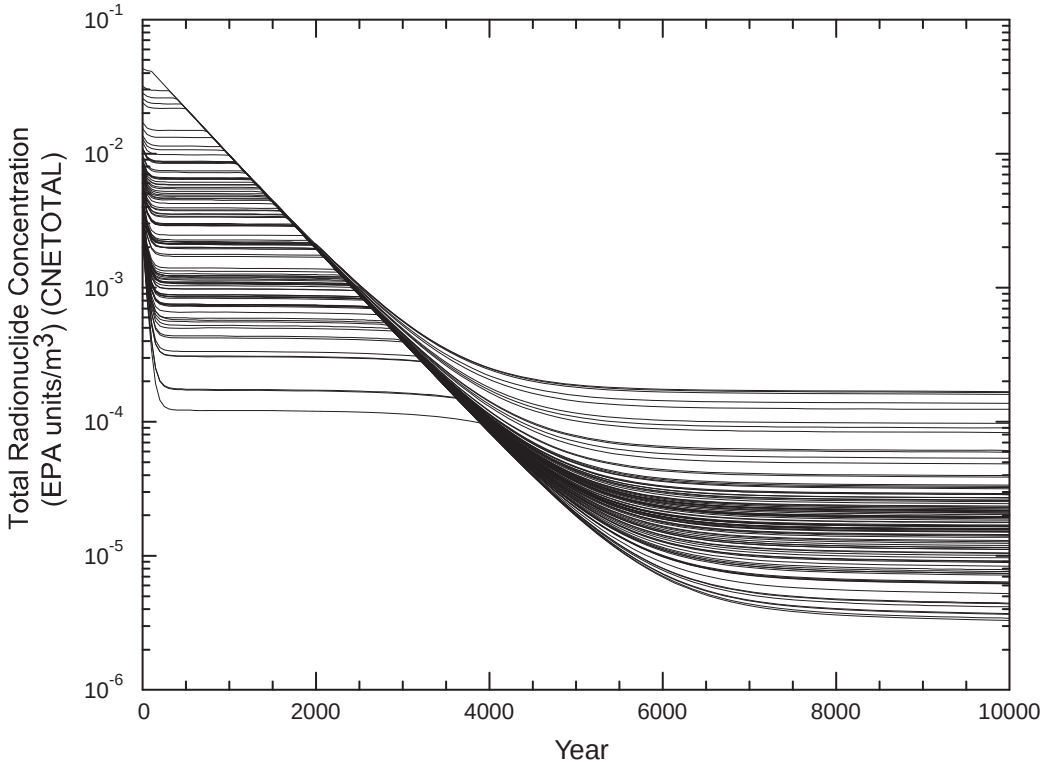

Figure PA-66. Total Mobilized Concentrations in Salado Brine.

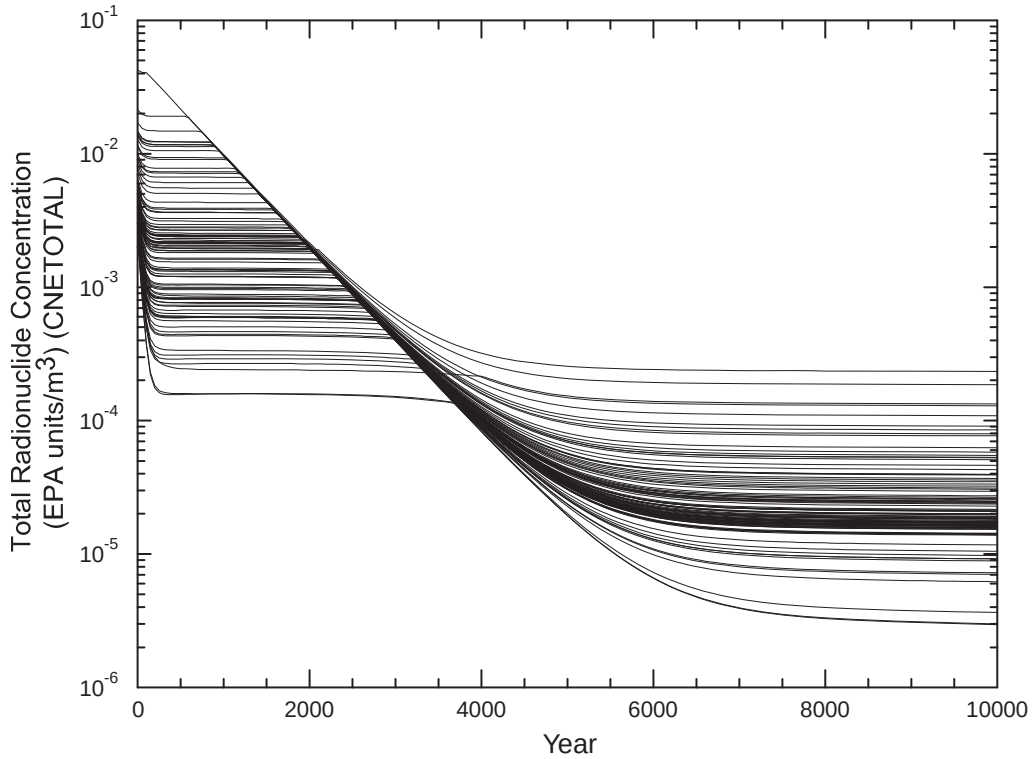

Figure PA-67. Total Mobilized Concentrations in Castile Brine.

PA-8.4.2 Transport through Marker Beds and Shaft

In the disturbed scenarios, none of the 300 realizations resulted in transport of radionuclides through the MBs and across the LWB (Lowry 2003). In addition, no realization showed transport of radionuclides through the shaft to the Culebra.

PA-8.4.3 Transport to the Culebra

In four of the disturbed scenarios (S2, S3, S4, and S5), transport to the Culebra is modeled with the code NUTS. In the multiple intrusion scenario (S6), the code PANEL is used to calculate transport to the Culebra. Figures PA-68 through PA-71 show cumulative radioactivity transported up the borehole to the Culebra. Transport to the Culebra is larger and occurs for more vectors in the S2 and S3 scenarios (E1 intrusions) than in the S4 or S5 scenarios (E2 intrusions). For most vectors that show significant transport, most of the transport occurs over a relatively short period of time, immediately after the borehole plugs fail.

Figure PA-72 shows total EPA units transported to the Culebra via the borehole in the S6 scenario. Almost no radionuclides are released after the E2 intrusion at 800 years; most transport occurs immediately following the E1 intrusion at 2,000 years.

Figure PA-73 and Figure PA-74 compare mean values among all three replicates for cumulative normalized releases up the borehole to the Culebra for scenarios S3 and S6, respectively. These figures show that the results from each replicate are very similar.

Sensitivity analysis of total radionuclides transported to the Culebra identified a strong linear relationship between the uncertainty in the total release to the Culebra and the uncertainty in the brine flow up the borehole (calculated by BRAGFLO; see Section PA-8.3.3). Figure PA-75 shows the relationship between total releases to the Culebra (EPATBHRC, calculated by NUTS; see Section PA-4.3) and brine flow up the borehole (BRNBHRCC, calculated by BRAGFLO; see Section PA-8.3.3) at 10,000 years after an E1 intrusion at 1,000 years (Scenario S3). Figure PA-76 shows the relationship between total releases to the Culebra (LDETOTAL, calculated by PANEL; see Section PA-4.4) and brine flow up the borehole (BRNBHRCC, calculated by BRAGFLO; see Section PA-8.3.3) at 10,000 years after the combination of an E2 intrusion at 800 years followed by an E1 intrusion in the same panel at 2,000 years (Scenario S6).

Sensitivity analysis (Section PA-8.3.3) identified borehole permeability (BHPERM) as the most important parameter contributing to the uncertainty in flow up the borehole (BRNBHRCC). Separate stepwise regression analyses (Lowry 2003; Garner 2003) confirmed the correlation between uncertainty in borehole permeability and releases to the Culebra. These analyses also identified the initial pressure in the brine pocket (BPINTPRS), indicator for microbial action (WMICDFLG), and steel corrosion rate (WGRCOR) as contributing to uncertainty in releases to the Culebra although the importance of these parameters is much less than that of borehole permeability.

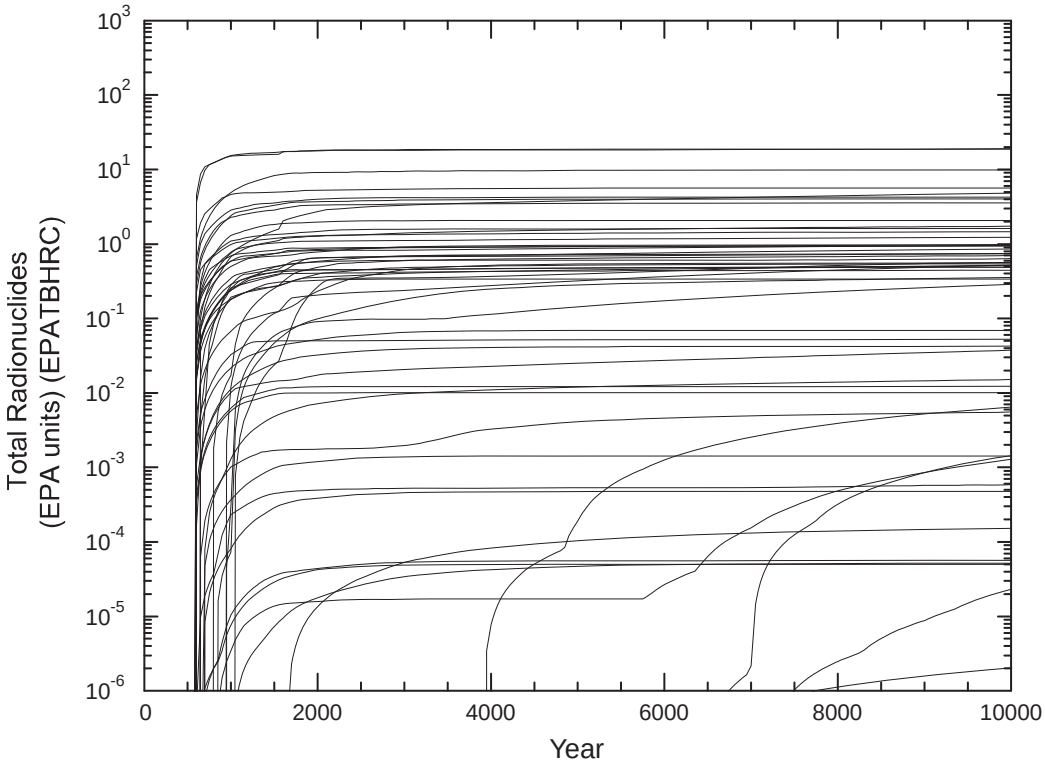

Figure PA-68. Cumulative Normalized Release Up the Borehole, Replicate R1, Scenario S2.

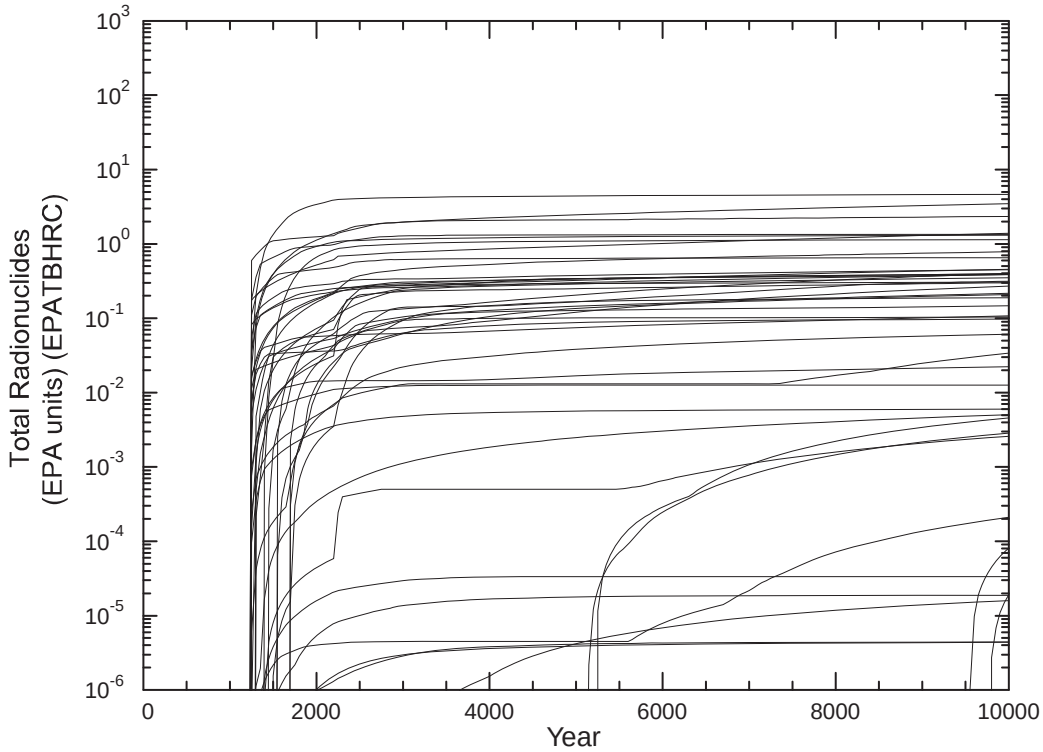

Figure PA-69. Cumulative Normalized Release Up the Borehole, Replicate R1, Scenario S3.

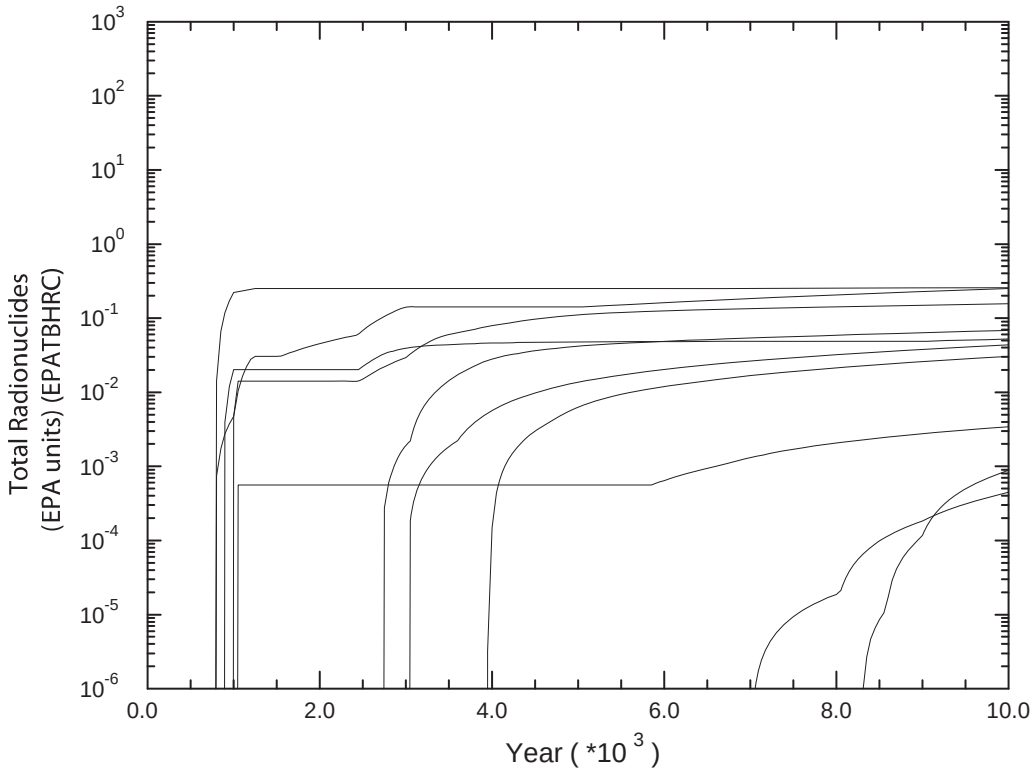

Figure PA-70. Cumulative Normalized Release Up the Borehole, Replicate R1, Scenario S4.

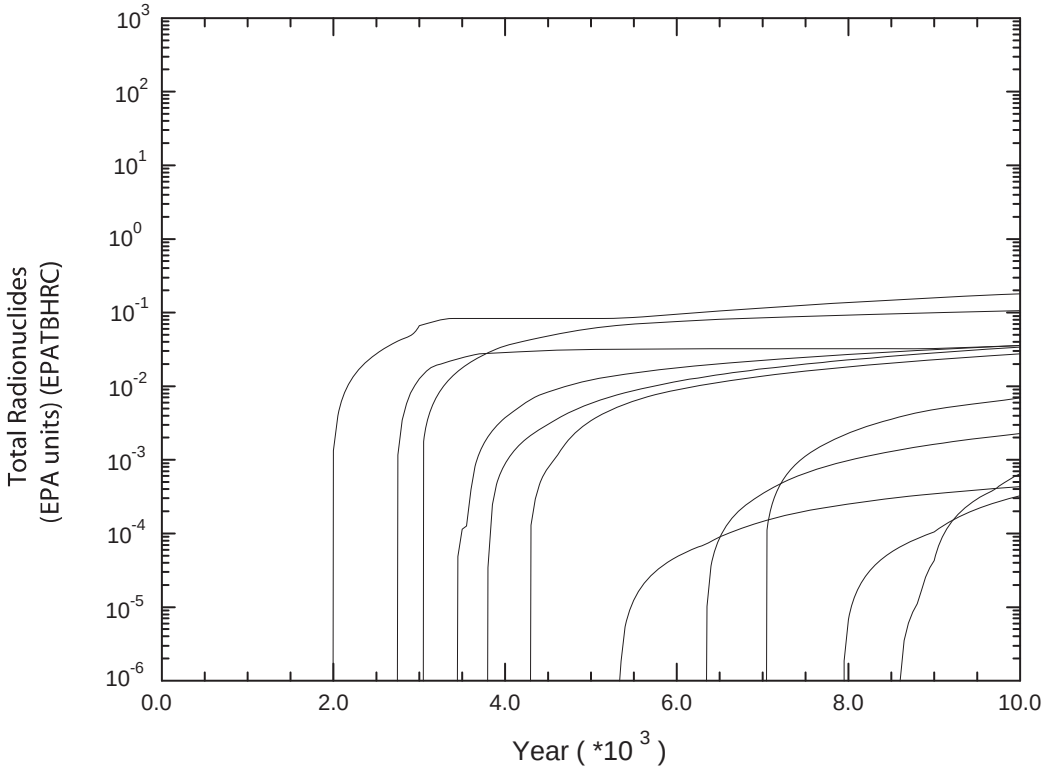

Figure PA-71. Cumulative Normalized Release Up the Borehole, Replicate R1, Scenario S5.

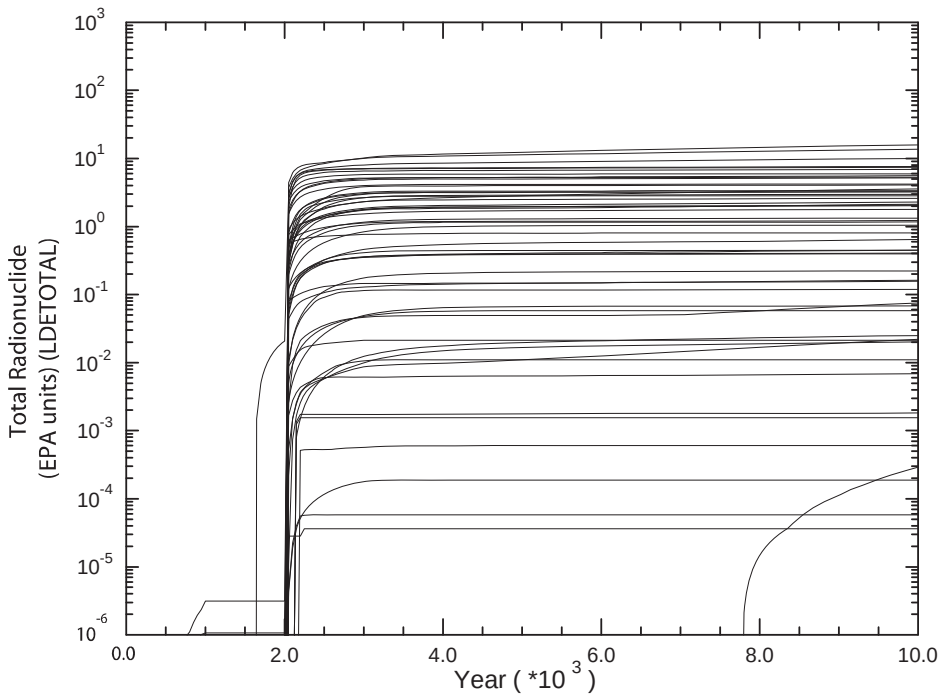

Figure PA-72. Cumulative Normalized Release Up the Borehole, Replicate R1, Scenario S6.

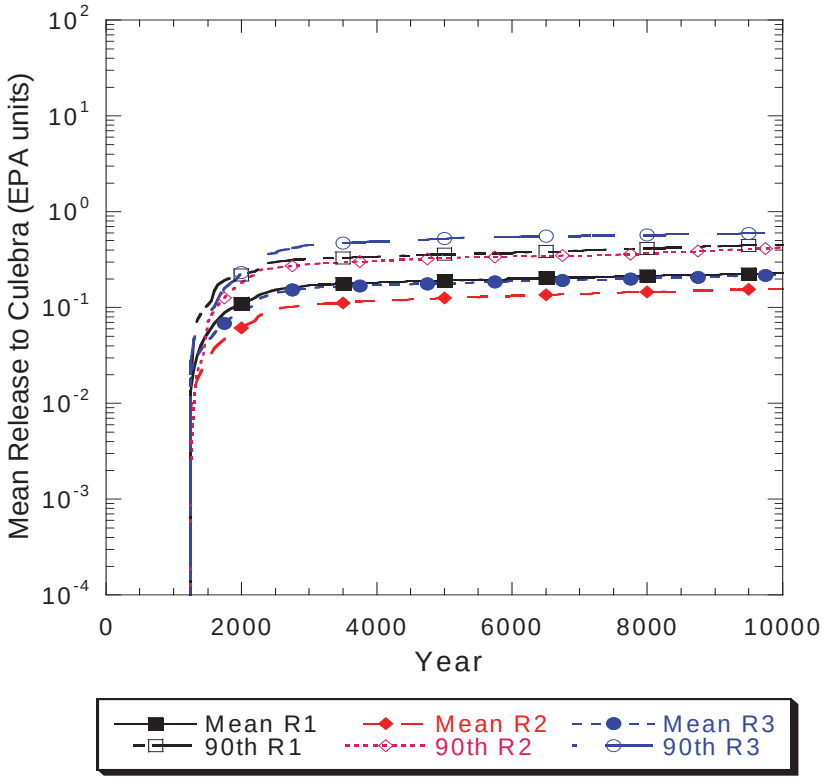

Figure PA-73. Mean Values for Cumulative Normalized Release Up the Borehole for All Replicates, Scenario S3.

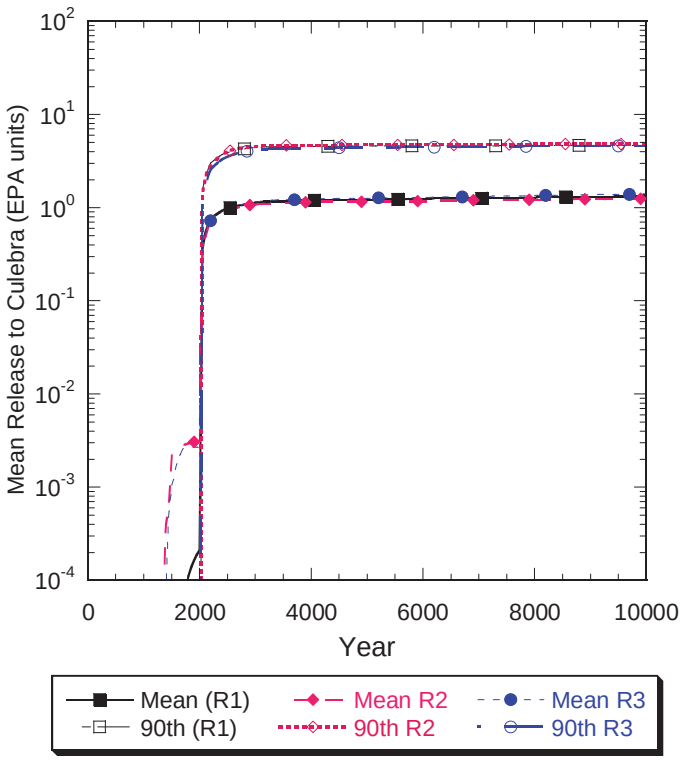

Figure PA-74. Mean Values for Cumulative Normalized Release Up Borehole for All Replicates, Scenario S6.

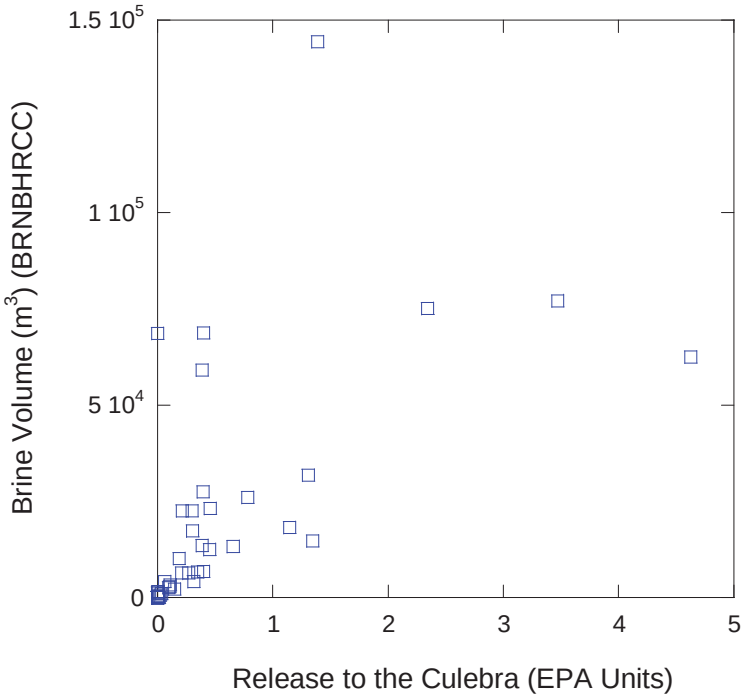

Figure PA-75. Comparison of Total Release to Culebra with Flow Up Borehole, Replicate 1 Scenario S3.

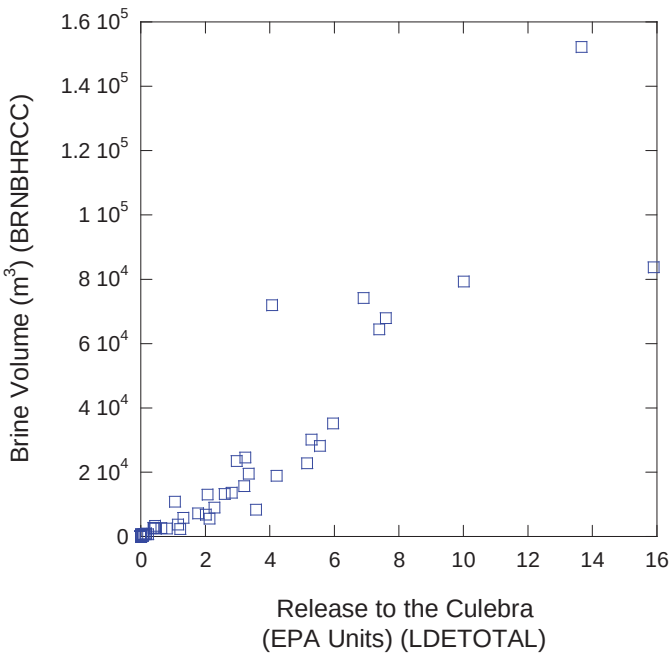

Figure PA-76. Comparison of Total Release to Culebra with Flow Up Borehole, Replicate 1 Scenario S3.

PA-8.4.4 Transport through the Culebra

Releases through the Culebra are calculated with the code SECOTP2D (see Section PA-4.9). As explained in Section PA-6.8.7, transport through the Culebra is calculated for a release of 1 kg of each of four radionuclides (^{241}Am, ^{234}U, ^{230}Th, and ^{239}Pu). Am is present as Am(III) and Th as Th(IV). Uranium may be present as either U(IV) or U(VI); plutonium may be present as Pu(III) or Pu(IV). The oxidation state of uranium and plutonium is an uncertain parameter (see WOXSTAT in Table PA-17). The total release of radionuclides across the LWB at the Culebra is calculated by the code CCDFGF by convoluting the SECOTP2D results with the transport to the Culebra calculated by NUTS and PANEL. This section discusses the SECOTP2D results; releases through the Culebra are presented in Section PA-9.5.

Transport calculations were performed for both partial-mining and full-mining scenarios. The partial-mining scenario assumes the extraction of all potash reserves outside the LWB while full mining assumes that all potash reserves both inside and outside the LWB are exploited. Flow fields in the Culebra are computed separately for each mining scenario by the code MODFLOW (see Section PA-4.8).

All SECOTP2D results, regardless of magnitude, are included in the calculation of releases through the Culebra. In practice, most non-zero releases computed by SECOTP2D are vanishingly small and result from numerical error (Kanney 2003). Consequently, the analysis of SECOTP2D results focused on realizations in which at least one billionth (10^{-9}) of the 1 kg source was transported to the land withdrawal boundary.

PA-8.4.4.1 Partial Mining Results

Under partial-mining conditions, only the ^{234}U species was transported beyond the LWB in any significant amount during the course of the 10,000-year simulation (Kanney 2003). Table PA-27 shows the eight vectors that resulted in releases greater than one billionth of the 1 kg source. Sensitivity analysis indicates that releases of ^{234}U are associated with the (VI) oxidation state. This result is reasonable because the matrix distribution coefficients for uranium in the (IV) state are much lower than for the (VI) state (see Section PA-5.2 and Attachment PAR, Table PAR-35).

Table PA-27. Releases of ^{234}U at LWB in Partial Mining Conditions

Replicate	Vector	^{234}U Release at LWB (fraction of 1 kg source)
3	54	0.479
3	84	0.177
3	38	0.0815
2	10	0.0711
1	58	0.0541
3	23	1.40×10^{-3}
1	8	2.36×10^{-4}
3	71	7.12×10^{-8}

PA-8.4.4.2 Full Mining Results

Under full-mining conditions, only the ^{234}U species was transported beyond the LWB in significant amounts during the course of the 10,000-year simulation. Table PA-28 shows the 18 vectors that resulted in releases greater than one billionth of the source of 1 kg. Sensitivity analysis indicates that releases of ^{234}U in the full mining conditions are also associated with the U(VI) oxidation state.

Two vectors showed releases of ^{239}Pu greater 1×10^{-9} kg. Replicate 2, vector 71 computed a release of 6.15×10^{-6} kg; replicate R1, vector 92 showed a release of 2.03×10^{-9} kg. No releases of ^{230}Th or ^{241}Am exceeded 1×10^{-9} kg.

PA-8.4.4.3 Additional Information

More detailed information on the results of the Culebra transport calculations can be found in the Analysis Package for the Culebra Transport Calculations: Compliance Recertification Application (Kanney 2003).

Table PA-28. Releases of ^{234}U at LWB in Full-Mining Conditions

Replicate	Vector	^{234}U Release at LWB (fraction of 1 kg source)
2	15	0.987
3	38	0.987
1	58	0.889
1	65	0.766
3	54	0.712
2	10	0.209
3	27	0.0269
1	90	0.0127
2	30	0.0123
1	31	6.18×10^{-3}
3	65	4.72×10^{-3}
3	66	1.80×10^{-4}
2	53	1.66×10^{-5}
3	67	1.59×10^{-7}
1	67	1.03×10^{-8}
3	42	4.53×10^{-9}
2	33	1.98×10^{-9}
2	24	1.61×10^{-9}

PA-8.5 Direct Releases

Direct releases occur at the time of a drilling intrusion, and include cuttings and cavings; spallings; and DBRs. This section presents analysis of the volume released by each mechanism.

PA-8.5.1 Cuttings and Cavings Volumes

Cuttings and cavings releases are solid waste material that is removed from the repository by the cutting of the drill bit and additional material that is sheared off the borehole wall by the circulation of the drilling fluid. Figure PA-77 shows the CCDFs for the total volume removed to the surface from cuttings and cavings for replicate R1. Figure PA-78 compares statistics for the CCDFs for cuttings and cavings volume for each replicate, and shows that the three replicates produced very similar results.

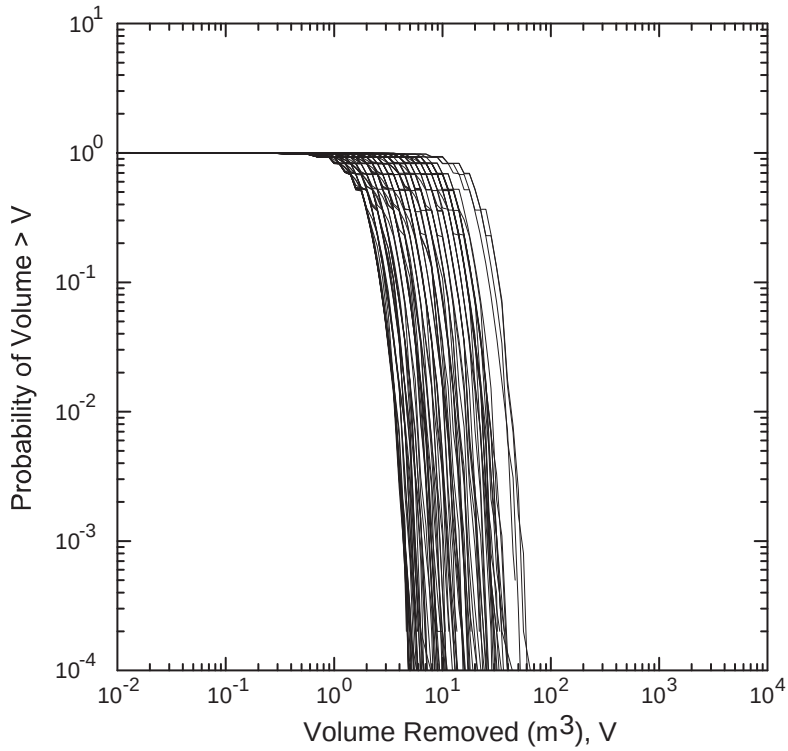

Figure PA-77. Total Volume Removed by Cuttings and Cavings, Replicate R1.

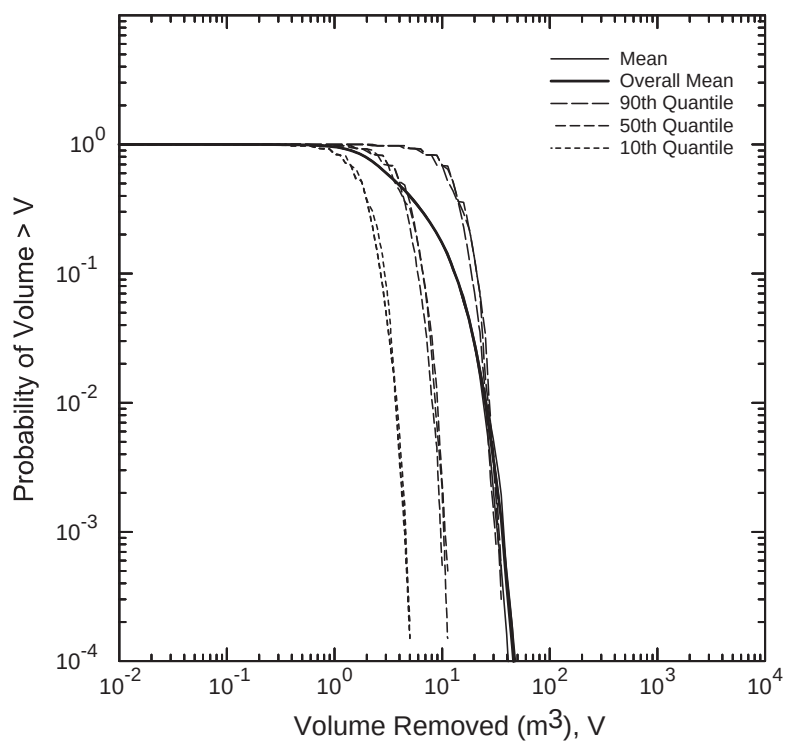

Figure PA-78. Statistics for Volumes Removed by Cuttings and Cavings, All Replicates.

Figure PA-79 shows that the uncertainty in cuttings and cavings volume arises primarily from the uncertainty in the shear strength of the waste (WTAUFAIL, see Table PA-17). The uncertainty in drill string angular velocity (DOMEGA) affects the calculation of cavings volume (Section PA-4.5), but is much less significant (Dunagan 2003a).

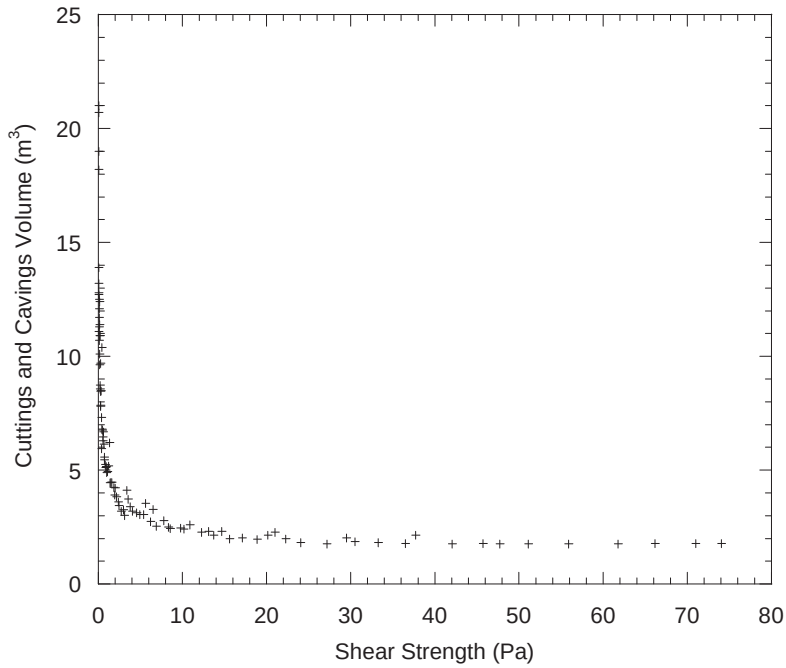

Figure PA-79. Sensitivity of Mean Cuttings and Cavings Volume to Waste Shear Strength.

PA-8.5.2 Spall Volumes

The volume of solid waste material released to the surface due to the spallings mechanism is calculated with the code DRSPALL. As outlined in Section PA-4.6.4, the code was run for each of 50 vectors in an LHS for DRSPALL, and for four values of repository pressure (10, 12, 14, and 14.8 MPa). Figure PA-80 shows the distribution of spall volumes for each value of repository pressure, ordered by increasing spall volume at 14.8 MPa. The maximum volume is 12.062 m^3 occurring at repository pressure of 14.8 MPa. At repository pressure at or below 10 MPa, no spallings occurred.

The distributions presented in Figure PA-80 are the volumes that could be removed by a single intrusion. As outlined in Section PA-4.6.4, the uncertainty in these volumes arises from four variables that are uncertain in the DRSPALL calculations: waste permeability; waste porosity; waste tensile strength; and waste particle diameter. Figure PA-81 and Figure PA-82 show the relationship between the spall volumes (SPALVOL) for the scenario with initial pressure of 14.8 MPa and the particle diameter (PARTDIAM) and the ratio of waste permeability to waste porosity (PERMPOR, from the term k'/ϕ in Equation (145)). Figure PA-81 and Figure PA-82 show that large spall volumes result from combinations of low values of particle diameter and low values for the ratio of waste permeability to waste porosity, and that uncertainty in these two parameters dominates the uncertainty in the spall volume from a single intrusion.

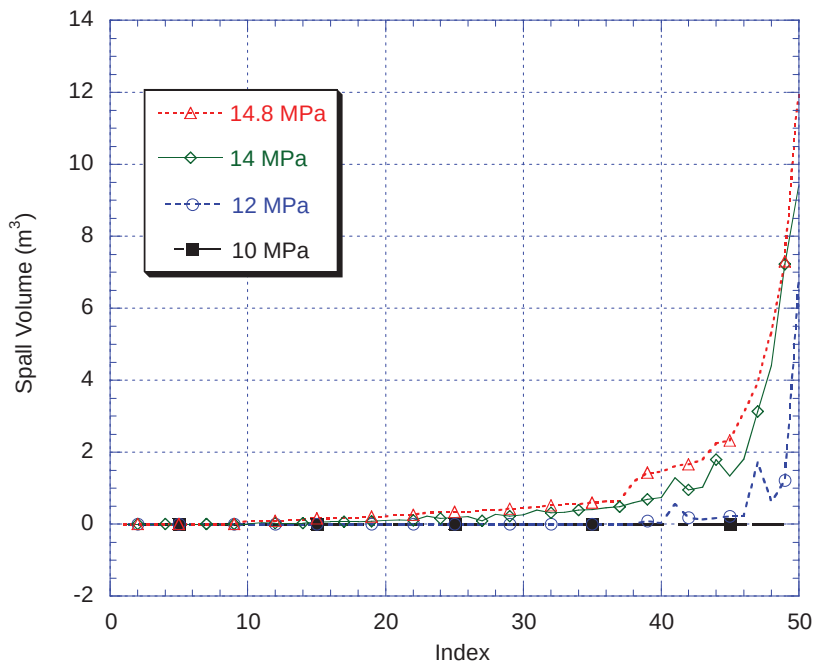

Figure PA-80. Spall Volume for a Single Intrusion (Ranked by Increasing Volume in the 14.8 MPa Scenario).

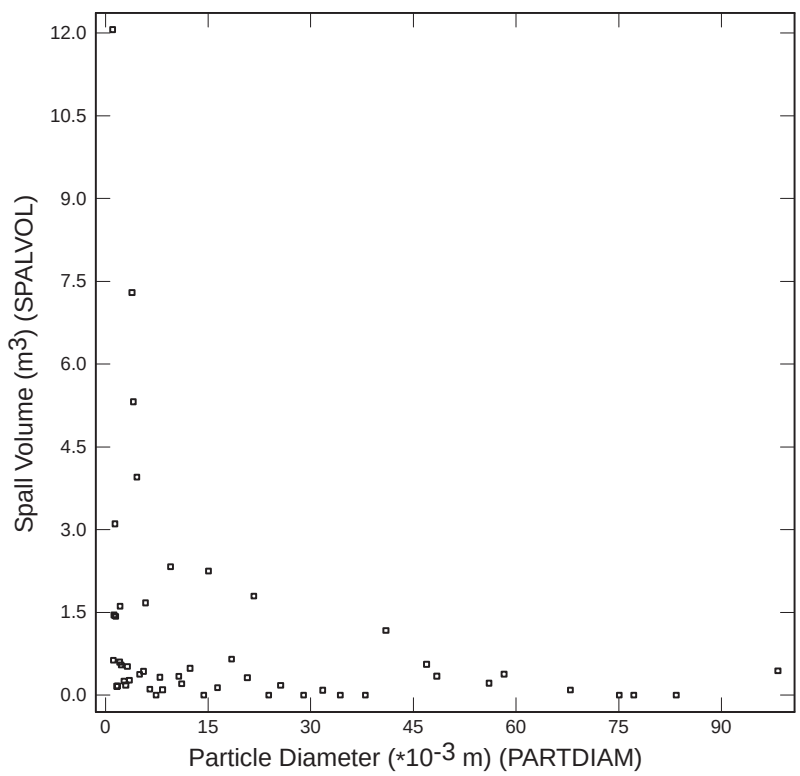

Figure PA-81. Sensitivity of Spall Volume for a Single Intrusion to Particle Diameter, 14.8 MPa Scenario.

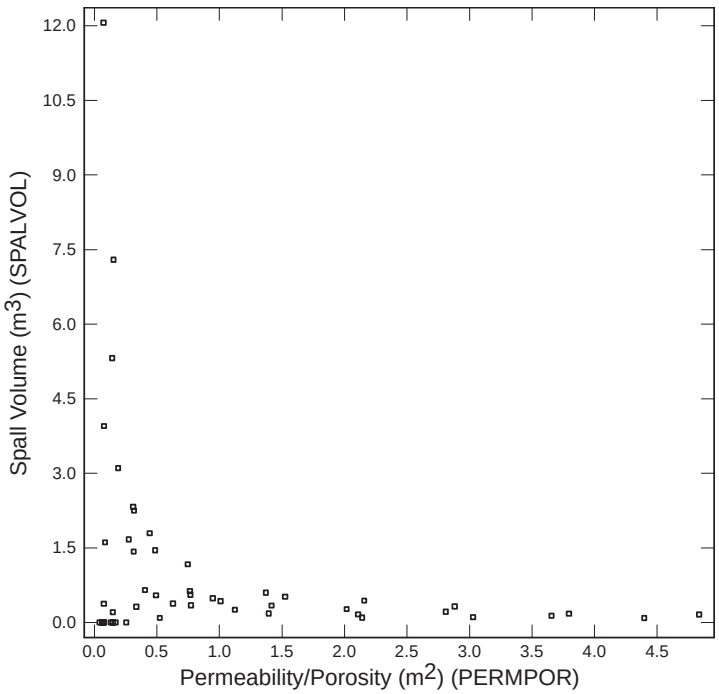

Figure PA-82. Sensitivity of Spall Volume for a Single Intrusion to *Waste Permeability / Waste Porosity* , 14.8 MPa Scenario.

The code CCDFGF stochastically generates futures for the repository and constructs the distribution of total volume removed by spallings for all intrusions (see Section PA-6.5 and Section PA-6.8). Figure PA-83 shows the CCDFs for the volume of material released (m^3) by spallings for replicate R1. Figure PA-84 compares statistics for the distribution of CCDFs for spall volume among the three replicates, and shows that the three replicates produce similar results. The median (50th quantile) and 10th quantile CCDFs do not plot on the scale of Figure PA-84 due to the large number of observations with spall volumes less than 0.01 m^3.

The distribution of spall volumes arises from the uncertain parameters used in the calculation of repository pressure (see Section PA-4.2) and the uncertain volume removed by a single intrusion (Figure PA-80). Section PA-7.1.1 and Section PA-8.3.1 identified three uncertain variables in the space for subjective uncertainty S_{su} that are primarily responsible for the uncertainty in repository pressure: borehole permeability (BHPERM); the indicator for microbial action (WMICDFLG); and the initial pressure in the Castile brine reservoir (BPINTPRS). Thus, these three variables may correlate to uncertainty in the total volume released by spalling.

In addition, the variable RNDSPALL (Table PA-17) in the LHS for the CRA-2004 PA (Equation (254)) assigns vectors from the LHS for DRSPALL (Section PA-4.6.4) to vectors in the LHS for the CRA-2004 PA. The variable RNDSPALL creates a mapping between the uncertain spall volumes in Figure PA-80 and the CCDFs in Figure PA-83. Thus, the spall volume (SPALVOL) for the 14.8 MPa scenario can be included in the sensitivity analysis for total spall volumes.

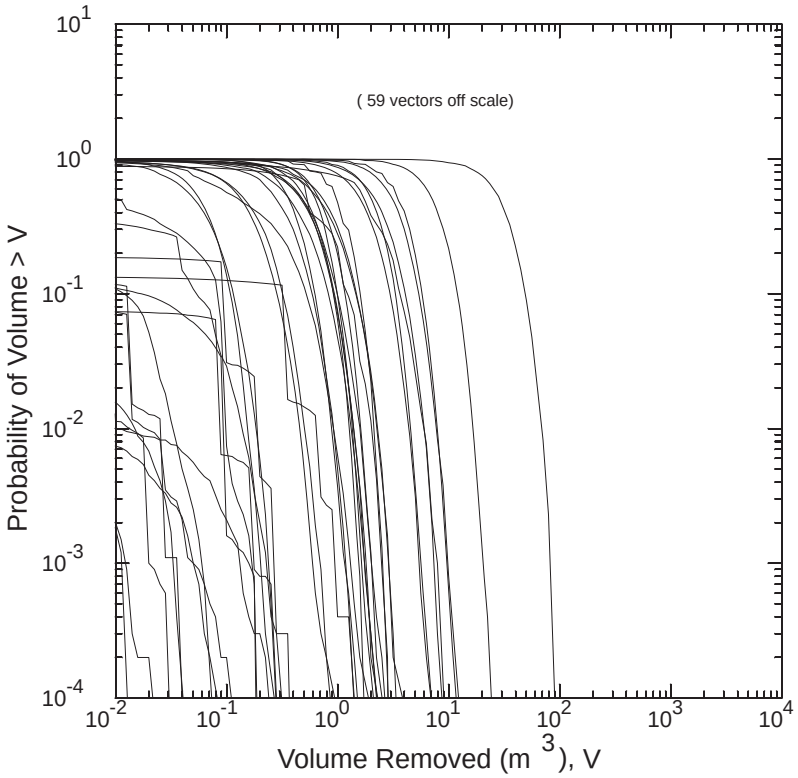

Figure PA-83. Total Volume Removed by Spallings, Replicate R1.

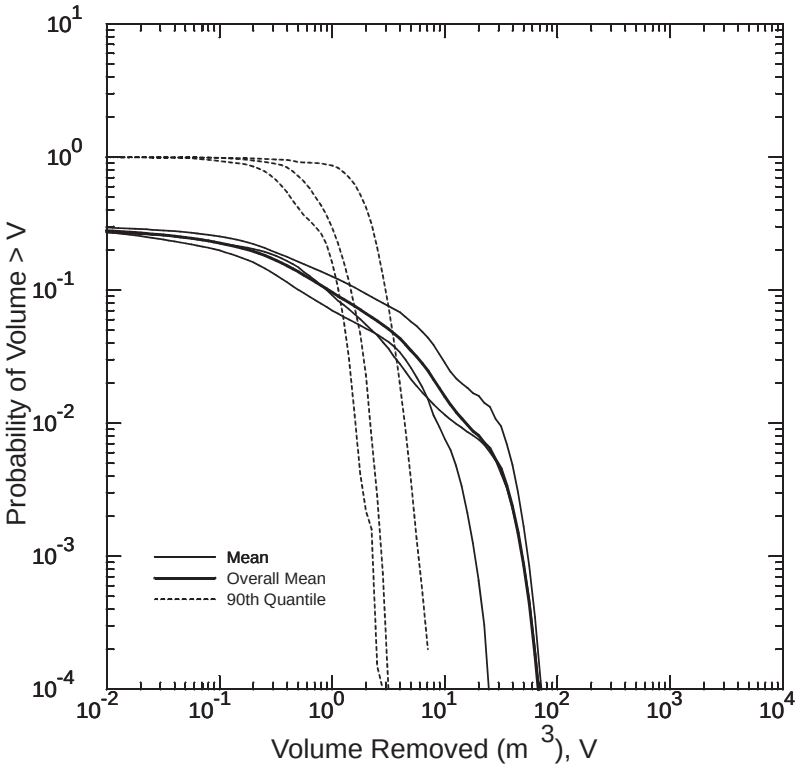

Figure PA-84. Statistics for Total Spall Volume, All Replicates.

Figure PA-85 demonstrates that the uncertainty in mean total spall volume arises primarily from the uncertainty in the indicator for microbial action (WMICDFLG) and the uncertainty in the spall volume from a single intrusion (SPALVOL). The indicator for microbial action (WMICDFLG) partitions the vectors into two sets of equal size: a set of vectors where microbial action occurs (WMICDFLG = 1 or 2) and a set where no microbial action is present (WMICDFLG = 0). Figure PA-80 shows that no spall releases are possible unless pressure exceeds 10 MPa. Figure PA-85 shows that when no microbial action is present, no spallings releases occur even when the spall volume from a single intrusion could be non-zero. Therefore, when no microbial action is present, repository pressure does not exceed the threshold for spall releases. In contrast, when microbial action is present (WMICDFLG = 1 or 2), Figure PA-85 shows that the uncertainty in total mean spall releases arises primarily from the uncertainty in the spall volume from a single release (SPALVOL).

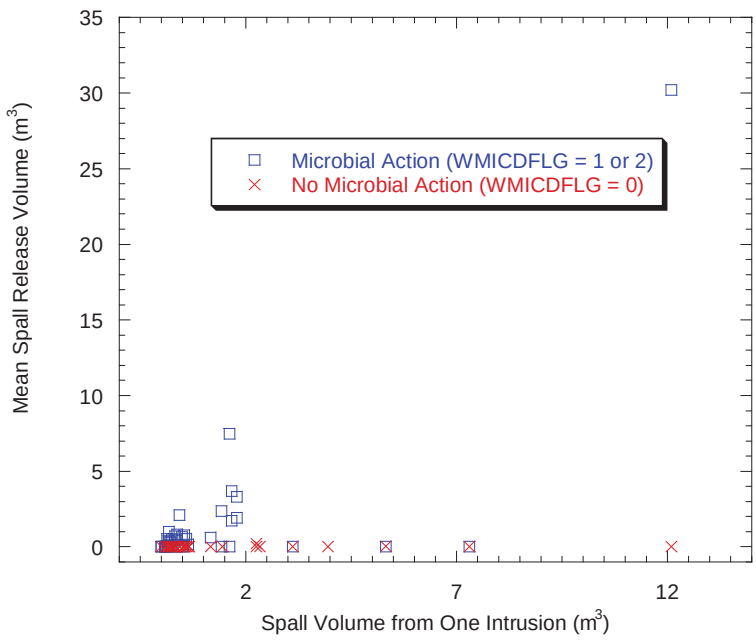

Figure PA-85. Sensitivity of Mean Total Spall Volume, Replicate R1.

PA-8.5.3 Direct Brine Release Volumes

DBRs to the surface can occur during or shortly after a drilling intrusion. For each element of the LHS, the code BRAGFLO (Section PA-4.7) calculates volumes of brine released for a total of 78 combinations of intrusion time, intrusion location, and initial conditions (Section PA-6.7.5) Initial conditions for the DBR calculations are computed by BRAGFLO for five scenarios (S1 through S5; see Section PA-6.7) Results from the S1 scenario represent undisturbed repository conditions; results from the S2 through S5 scenarios represent repository conditions that result after a drilling intrusion.

For replicate R1, only about eight percent of the 7,800 DBR calculations (100 vectors × 78 combinations) resulted in direct brine flow to the surface. The maximum DBR release is approximately 115 m^3. Only intrusions into a lower panel (see Section PA-4.7.1) resulted in

significant brine volume releases. In the S1 scenario, the lower panel represents an undisturbed panel at the south end of the repository. In the S2 and S3 scenarios, the lower panel represents any panel that has a previous E1 intrusion; in the S4 and S5 scenarios, the lower panel has a previous E2 intrusion.

Figure PA-86 shows probability plots of DBR volumes for Scenarios S1 through S5, lower intrusion, at the discrete times for which DBR is calculated. A probability plot displays the percentage of the vectors on the x-axis where release volumes are less than the value on the y-axis. Figure PA-86a shows DBR volumes for scenario S1 representing the initial intrusion at various times. Figure PA-86b and Figure PA-86c show DBR volumes for Scenarios S2 and S3, which represent a subsequent intrusion (at various times) into a panel that had an E1 intrusion at 350 years and 1,000 years, respectively. Figure PA-86d and Figure PA-86e show DBR volumes for Scenarios S4 and S5, which represent a subsequent intrusion (at various times) into a panel that had an E2 intrusion at 350 years and 1,000 years, respectively. Release volumes are larger and occur more frequently in the S2 and S3 scenarios, because the lower panel has much higher saturations after an E1 intrusion (Section PA-8.3.2).

Sensitivity analysis determined that DBR volume from a single intrusion is most sensitive to the initial pressure and brine saturation in the intruded panel (Stein 2003). The analysis is illustrated below for scenario S2; similar conclusions follow from analysis of the other scenarios. The initial pressure and brine saturation in the DBRs calculations are transferred from the Salado Flow calculations as described in Section PA-4.7.2. Thus, the uncertain parameters that are most influential to the uncertainty in pressure and brine saturation in the Salado Flow calculations (see Section PA-7.1 and Section PA-8.3) are also most influential in the uncertainty in DBR volumes.

The combination of relatively high pressure and brine saturation in the intruded panel is required for direct brine release to the surface. Figure PA-87 shows a scatter plot of pressure in the waste panel vs. DBR volumes for Scenario S2, lower intrusion with symbols indicating the value of the mobile brine saturation (defined as brine saturation S_b from the solution of Equation (25) minus residual brine saturation S_{br} in the waste (see Table PA-2)). The figure clearly shows that there are no releases until pressures exceed 8 MPa as indicated by the vertical line. Above 8 MPa, a significant number of vectors have zero releases, but these vectors have mobile brine saturations less than zero and thus no brine is available to be released. When mobile brine saturation approaches 1, relative permeability to gas becomes small enough that no gas flows into the well, and in these circumstances DBR releases end after three days (Equation (211)). Thus, in vectors with high mobile brine saturations, DBR releases increase proportionally with increases in pressure, as evidenced by the linear relationship between DBR volume and pressure for mobile brine saturation between 0.8 and 1.0. For vectors with mobile saturations between 0.2 and 0.8, both gas and brine can flow in the well, and the rate of gas flow can be high enough that the ending time of DBR releases may be as long as 11 days. Although brine may be flowing at slower rates in these vectors than in vectors with high mobile saturations, brine flow may continue longer and thus result in larger DBR volumes.

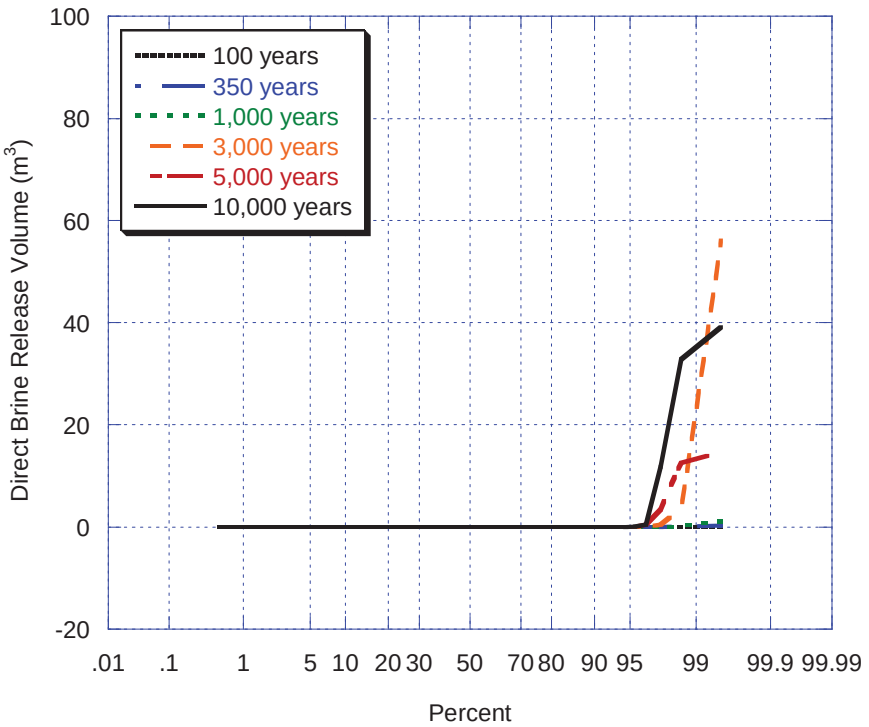

Figure PA-86a. DBRs for Initial Intrusions into Lower Panel (Scenario S1), Replicate R1.

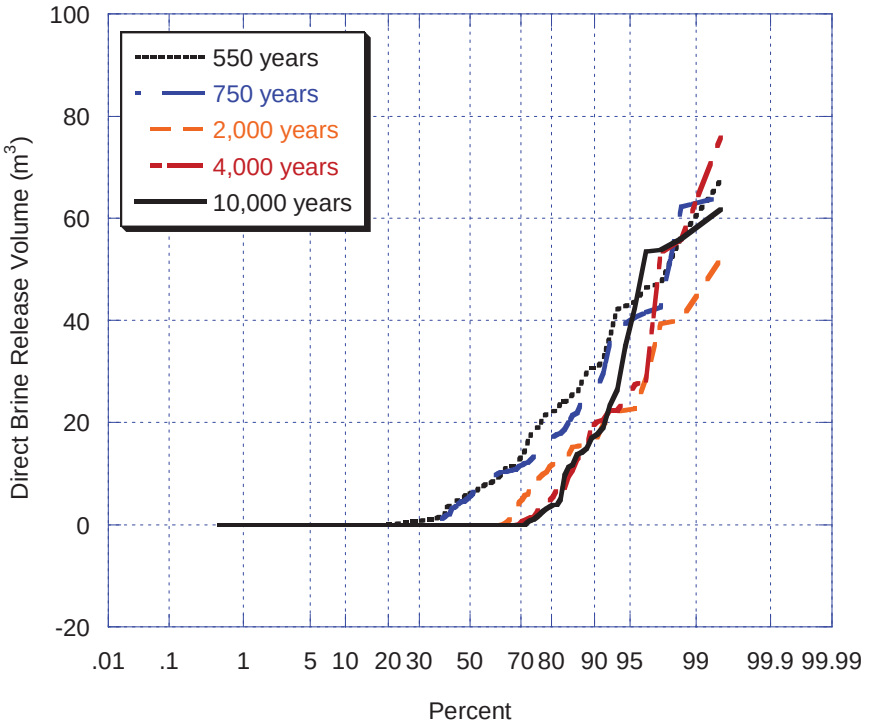

Figure PA-86b. DBRs for Subsequent Intrusions into Lower Panel After an E1 Intrusion at 350 Years (Scenario S2), Replicate R1.

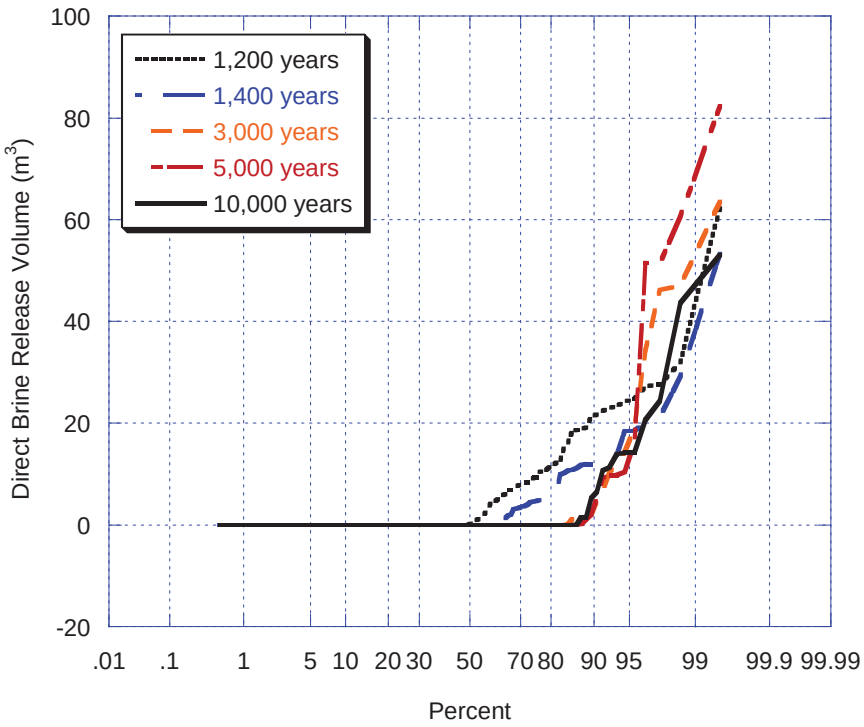

Figure PA-86c. DBRs for Subsequent Intrusions into Lower Panel After an E1 Intrusion at 1,000 Years (Scenario S3), Replicate R1.

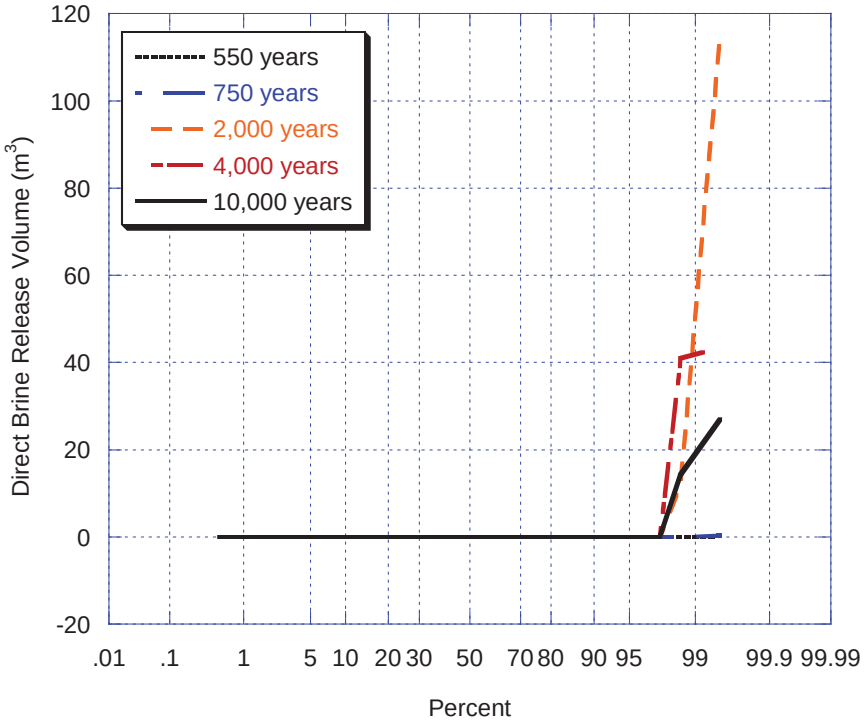

Figure PA-86d. DBRs for Subsequent Intrusions into Lower Panel After an E2 Intrusion at 350 Years (Scenario S4), Replicate R1.

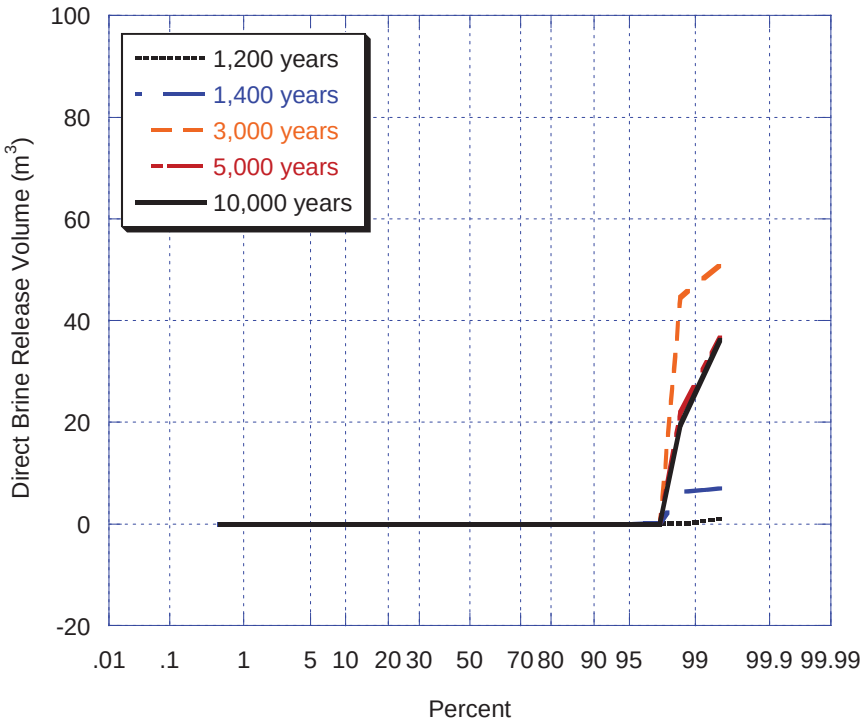

Figure PA-86e. DBRs for Subsequent Intrusions into Lower Panel After an E2 Intrusion at 1,000 Years (Scenario S5), Replicate R1.

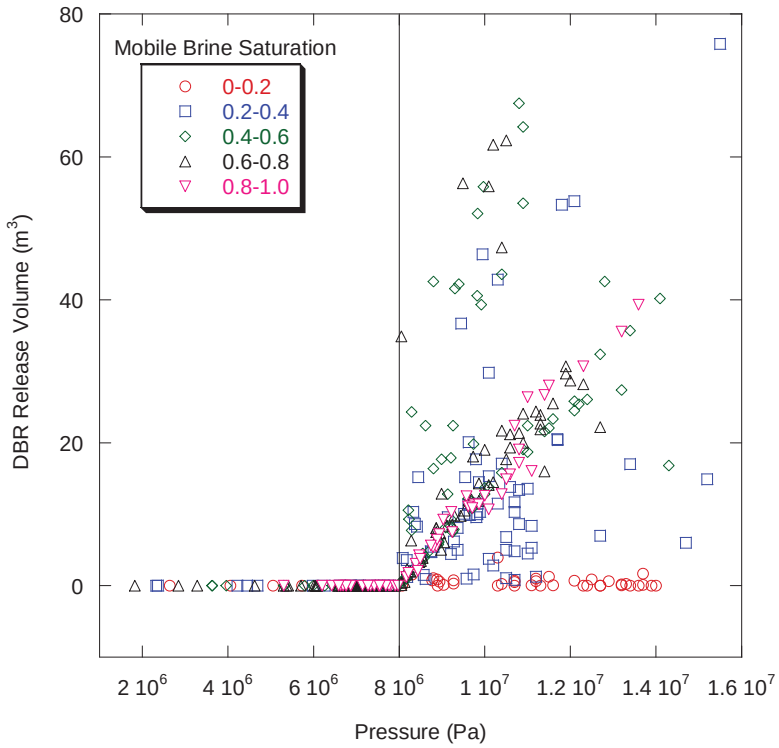

Figure PA-87. Sensitivity of DBR Volumes to Pressure, Replicate R1, Scenario S2, Lower Panel.

Figure PA-88 plots pressure against mobile brine saturation for the S2 scenario for all intrusion times with symbols indicating the range of DBR volumes. It is clear from Figure PA-88 that not all the variability in DBRs can be explained by pressure and saturation alone.

Borehole permeability can also be an important parameter controlling the volume of direct brine released. Borehole permeability is not a direct input to the DBR calculations, but this parameter affects conditions in the repository as modeled in the 10,000-year BRAGFLO calculations, which are used as initial conditions of the DBR model. Figure PA-89 shows a scatter plot of the log of borehole permeability against DBR volume for Scenario S2, lower intrusion with symbols indicating intrusion times. As borehole permeability decreases direct brine releases tend to increase, especially at late intrusion times (4,000 and 10,000 years). Helton et al. (1998) identified this same relationship in analysis of the CCA PA. Low values of borehole permeability tend to result in higher pressures following an E1 intrusion (Figure PA-53), which in turn lead to higher DBRs from subsequent intrusions.

The distributions presented in Figure PA-86 are for volumes of brine that could be released by a single intrusion. The code CCDFGF stochastically generates futures for the repository, specifying drilling times and locations, and constructs the distribution of total brine volume released (see Section PA-6.5 and Section PA-6.8). Figure PA-90 shows the CCDFs for the total brine volume released for replicate R1. Figure PA-91 compares the statistics for the CCDFs for total brine volume released among the three replicates, and shows that the three replicates produced similar results. Due to the number of observations which do not plot on the scale of Figure PA-90, the 10th quantiles do not appear on Figure PA-91.

Table PA-29 summarizes a stepwise regression analysis for mean total DBR volume. The uncertain parameters most important to uncertainty in total DBR volumes are those related to repository pressure (the indicator for microbial action (WMICDFLG) and the rate of steel corrosion (WGRCOR)) and brine saturation (the probability of an intrusion into the Castile brine reservoir (PBRINE), the pressure in the Castile brine reservoir (BPINTPRS), the permeability of the DRZ around the panel closures (DRZPCPRM), and the residual brine saturation in the waste (WRBRNSAT)). The linear regression model is not very effective at explaining the uncertainty in the total DBRs. The lack of resolution is due to the large number of vectors in which no direct brine releases occur; this conclusion was reached after analysis of the CCA PA (Helton et al. 1998).

PA-8.5.4 Additional Information

Dunagan (2003b) provides additional information about the cuttings and cavings releases calculated for the CRA-2004 PA. Additional information about the spallings releases is found in Lord et al. (2003) and Lord and Rudeen (2003). Stein (2003) provides detailed analysis of direct brine releases in the CRA-2004 PA.

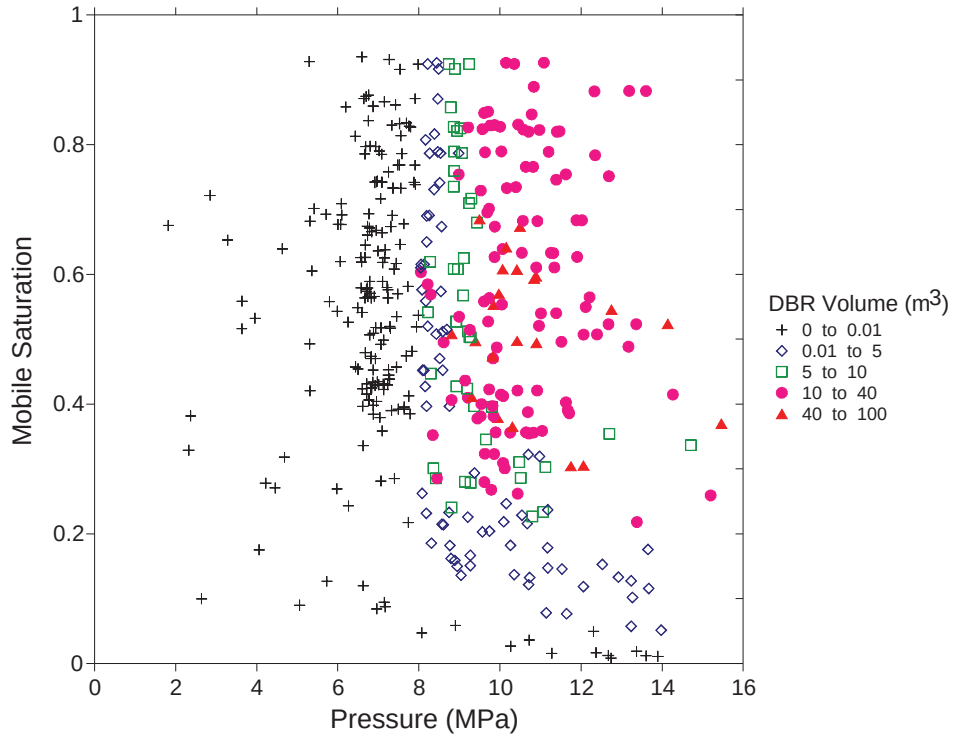

Figure PA-88. Sensitivity of DBR **Volumes to Pressure and Mobile Brine Saturation, Replicate R1, Scenario S2, Lower Panel.**

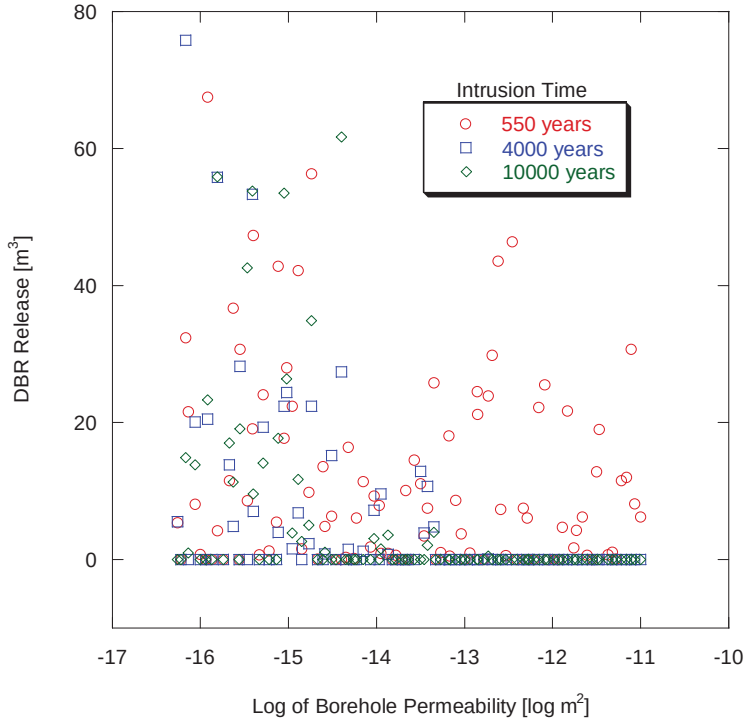

Figure PA-89. Sensitivity of DBR Volumes to Borehole Permeability, Replicate R1, Scenario S2, Lower Panel.

Table PA-29. Stepwise Regression Analysis for Mean Total DBR **Volume**

Step[1]	Expected Normalized Release		
	Variable[2]	SRRC[3]	R^2 [4]
1	WMICDFLG	–0.583	0.239
2	PBRINE	–0.385	0.378
3	BPINTPRS	0.389	0.515
4	WGRCOR	–0.190	0.553
5	DRZPCPRM	0.176	0.585
6	WRBRNSAT	–0.168	0.613

[1] Steps in stepwise regression analysis

[2] Variables listed in order of selection in regression analysis

[3] Standardized Rank Regression Coefficient in final regression model

[4] Cumulative R^2 value with entry of each variable into regression model

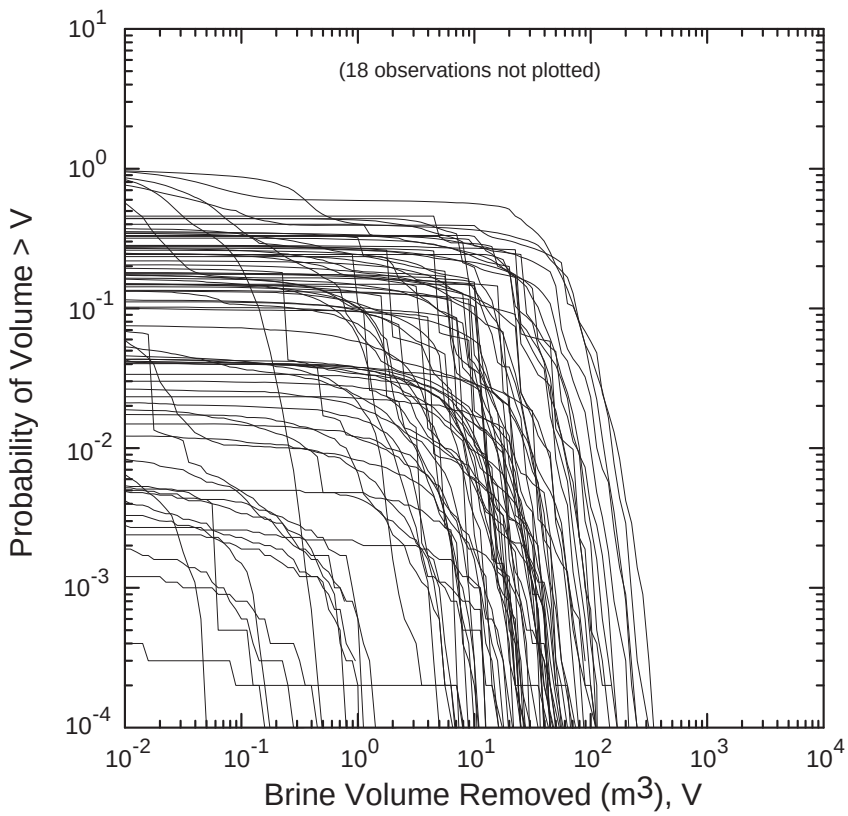

Figure PA-90. Total DBRs Volumes, Replicate R1.

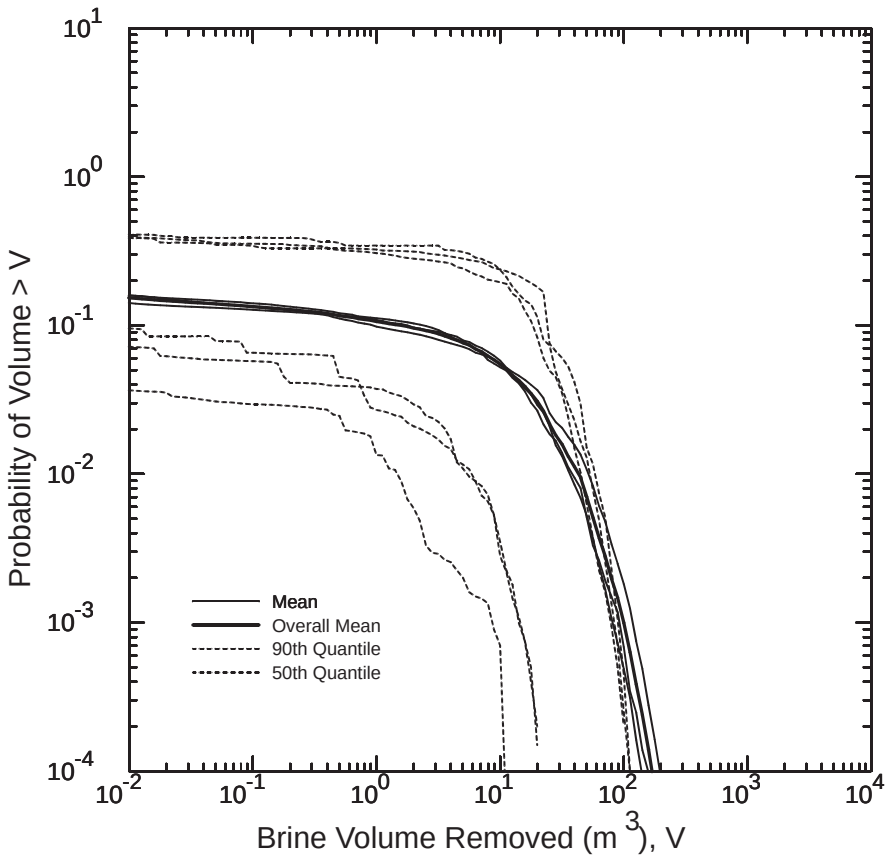

Figure PA-91. Statistics for Total DBR Volumes, All Replicates.

PA-9.0 NORMALIZED RELEASES

This section presents total normalized releases, followed by discussion of each of the four categories of releases that constitute the total release: cuttings and cavings; spallings; DBRs; and transport releases. Finally, this section concludes with a discussion of the sensitivity of total releases to uncertainty in parameter values.

PA-9.1 Total Releases

Figures PA-92, PA-93, and PA-94 show the CCDFs for total releases for replicates R1, R2, and R3 of the CRA-2004 PA. Each CCDF lies below and to the left of the limits specified in 40 CFR § 191.13(a). Thus, the WIPP continues to comply with the containment requirements of 40 CFR Part 191. The consistent increase in total releases at a probability of approximately 0.003 results from unlikely cuttings and cavings releases, as discussed in Section PA-9.6.1.

To compare the distributions of CCDFs among replicates and to demonstrate sufficiency of the sample size, mean and quantile CCDFs are computed. At each value for normalized release R on the abscissa, the CCDFs for a single replicate define 100 values for probability. The arithmetic mean of these 100 probabilities is the mean probability that release exceeds R; the curve defined by the mean probabilities for each value of R is the mean CCDF. The quantile CCDFs are defined analogously.

Figure PA-95 compares the mean, median, 90th and 10th quantiles for each replicate's distribution of CCDFs for total releases. Figure PA-95 shows that each replicate's distribution is quite similar, and shows qualitatively that the sample size of 100 in each replicate is sufficient to generate a stable distribution of outcomes.

Each of the mean and quantiles CCDFs in Figure PA-95 is an estimate of the true mean CCDF of the population of CCDFs. The overall mean CCDF is computed as the arithmetic mean of the three mean CCDFs from each replicate, and is an estimate of the true mean CCDF. To quantitatively determine the sufficiency of the sample size, a confidence interval is computed about the overall mean CCDF using Student's t-distribution. Figure PA-96 shows 95 percent confidence intervals about the overall mean, and provides quantitative confirmation of the sufficiency of the sample size, by displaying the overall mean together with the 0.95 confidence interval of the Student's t-distribution estimated from the individual means of the three independent replicates.

Figure PA-97, Figure PA-98, and Figure PA-99 show the mean CCDFs for each component of total releases, for replicates R1, R2, and R3, respectively. In each replicate, the location of the mean CCDF for total releases is dominated by the cuttings and cavings releases. The mean predicted released from spallings and direct brine are an order of magnitude less than mean releases for cuttings and cavings; therefore, these categories of releases make relatively little contribution to the location of the mean CCDF for total releases. Release by subsurface transport in the Salado or Culebra make essentially no contribution to total releases.

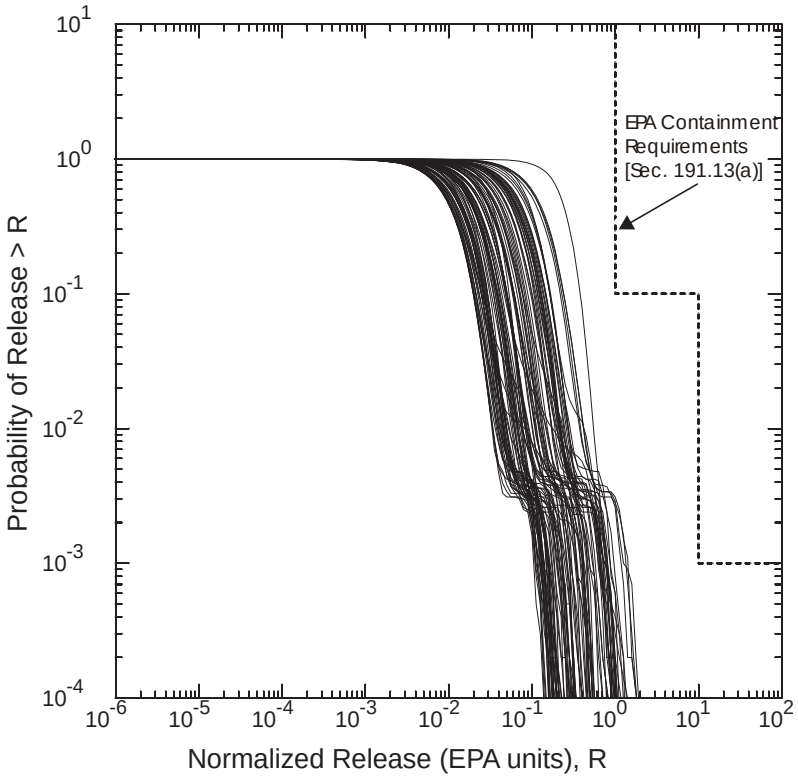

Figure PA-92. Total Normalized Releases, Replicate R1.

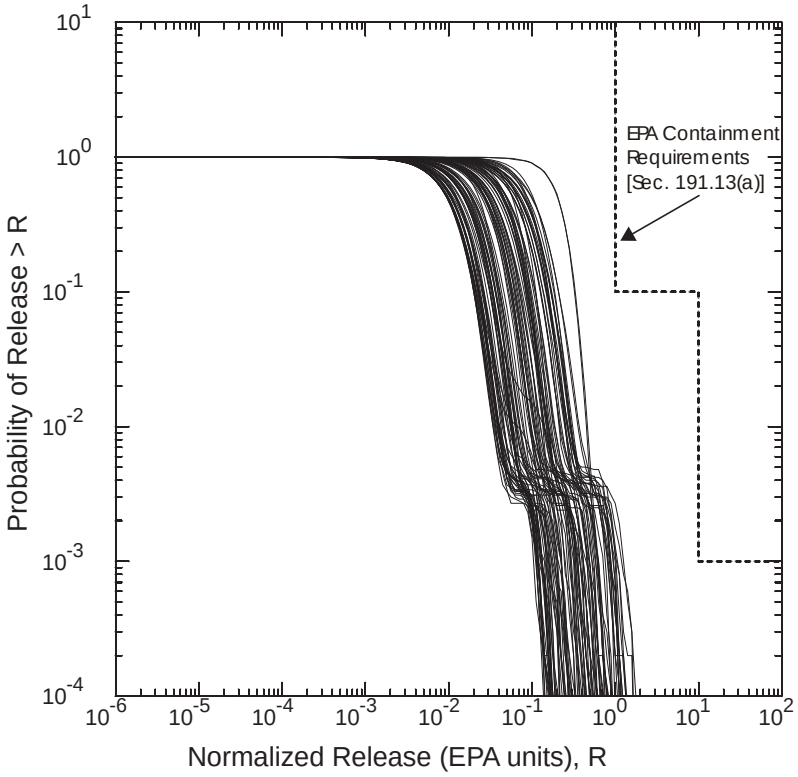

Figure PA-93. Total Normalized Releases, Replicate R2.

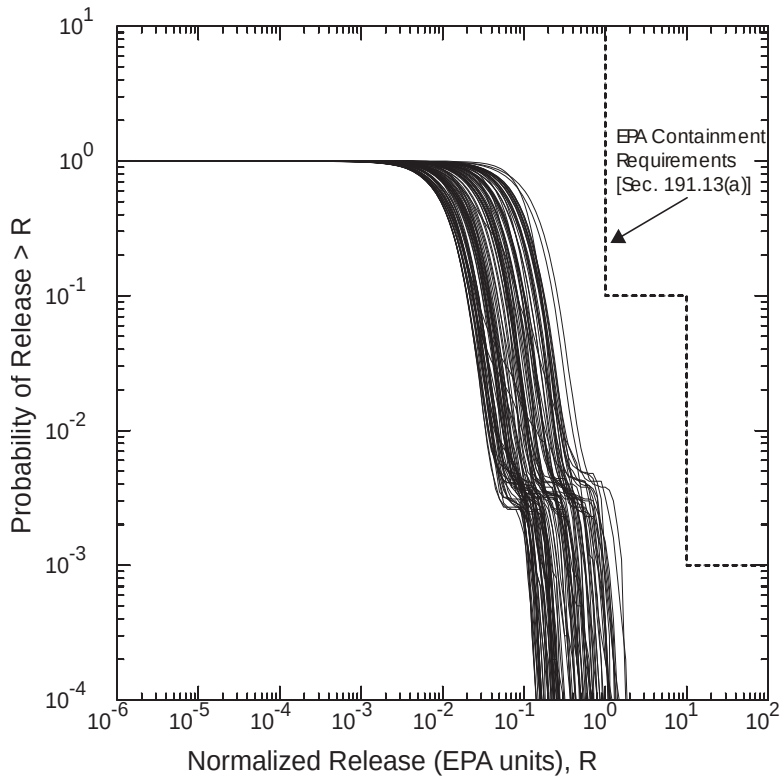

Figure PA-94. Total Normalized Releases, Replicate R3.

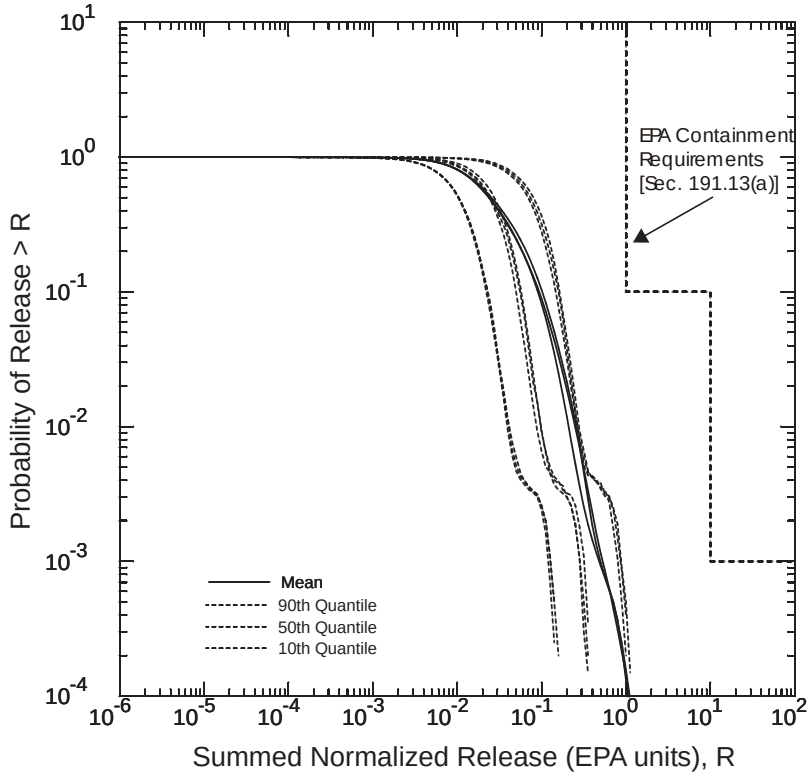

Figure PA-95. Mean and Quantiles CCDFs for Total Normalized Releases, All Replicates.

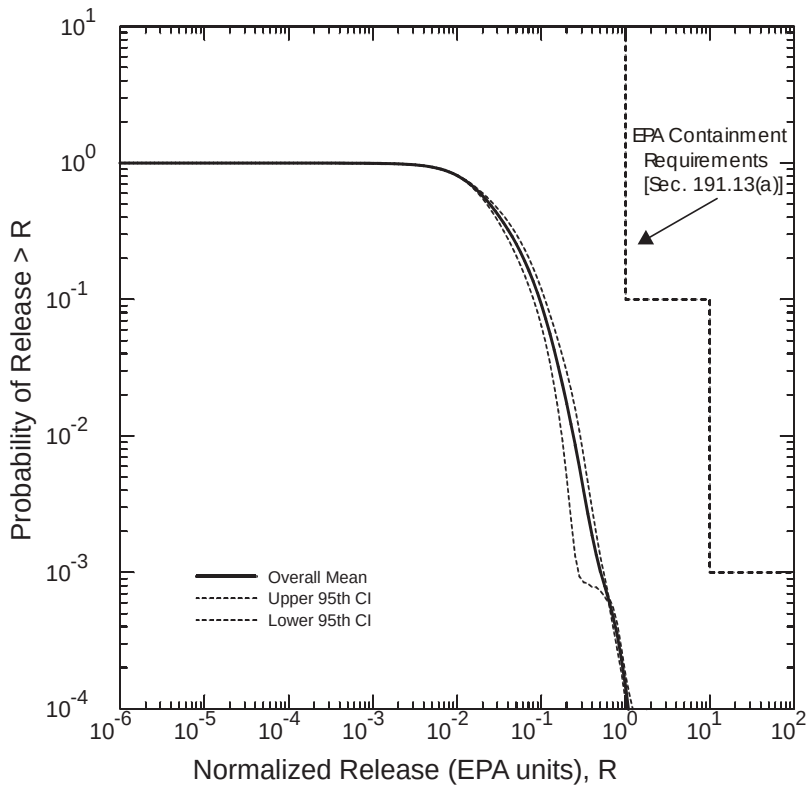

Figure PA-96. Confidence Interval on Overall Mean CCDF for Total Normalized Releases.

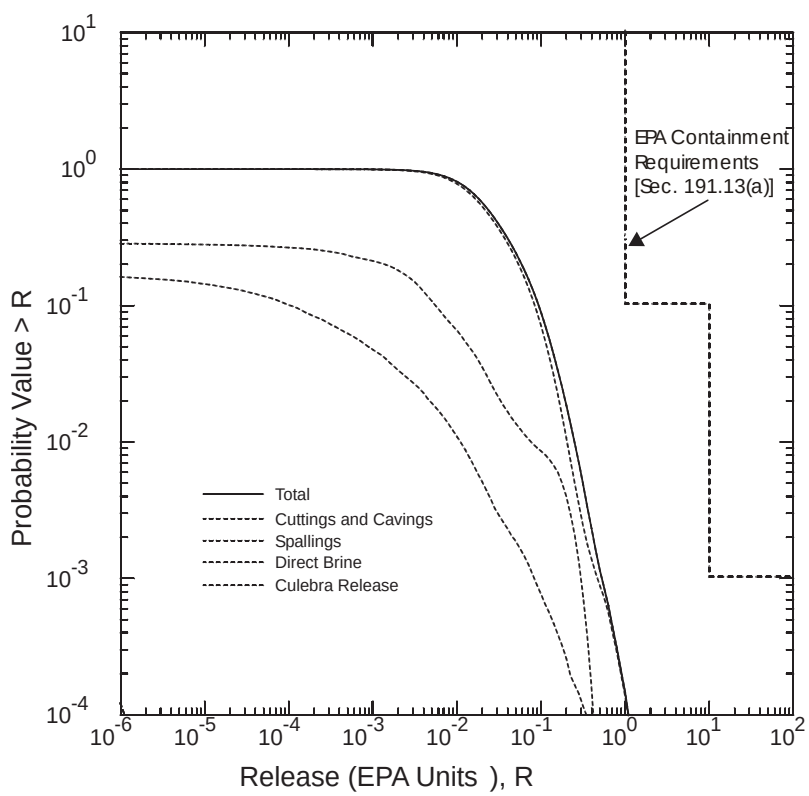

Figure PA-97. Mean CCDFs for Components of Total Normalized Releases, Replicate R1.

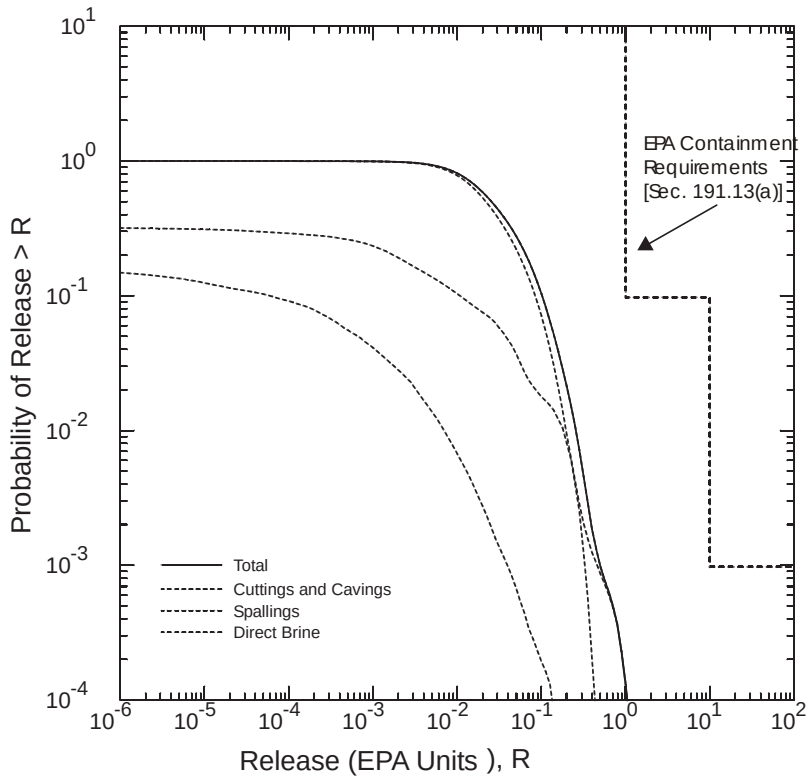

Figure PA-98. Mean CCDFs for Components of Total Normalized Releases, Replicate R2.

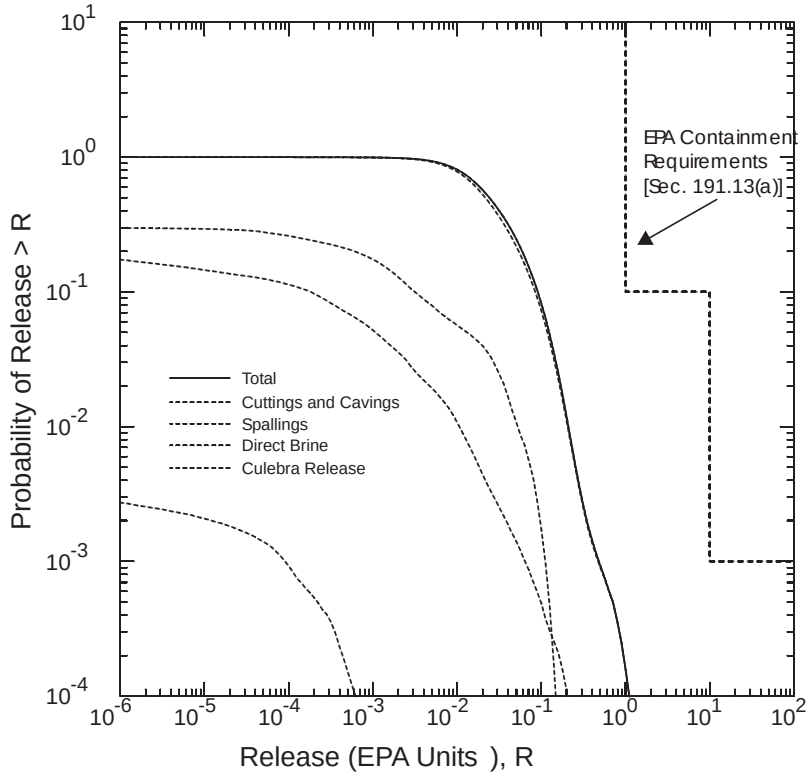

Figure PA-99. Mean CCDFs for Components of Total Normalized Releases, Replicate R3.

PA-9.2 Cuttings and Cavings Normalized Releases

Figures PA-100, PA-101, and PA-102 show the CCDFs for normalized releases due to cuttings and cavings for replicates R1, R2, and R3. The releases in each replicate are very similar; Figure PA-103 compares the mean and quantile CCDFs for cuttings and cavings releases for each replicate.

The increase in cuttings and cavings releases at a probability of 0.003 in each replicate is due to a few waste streams with very high radioactivity that are present in the updated inventory (Appendix DATA, Attachment F). These waste streams maintain significant radioactivity during the 10,000-year period. For example, a single waste stream (LA-TA-55-48, oil/vermiculate waste from ^{238}Pu heat source fabrication) has a concentration of radioactivity of 4.05 EPA units/m^3 at 100 years after repository closure, decaying to 1.95 EPA units/m^3 by 10,000 years (Fox 2003). This waste stream maintains high radioactivity concentration over time because it contains high quantities of longer-lived radioisotopes, principally ^{239}Pu and ^{240}Pu. The radioactivity concentrations in this waste stream can lead to cuttings and cavings releases exceeding 1 EPA unit for a single intrusion.

The volume of the LA-TA-55-48 waste stream (31 m^3) implies a probability of 31/168,500 = 0.00018 that this waste stream is selected as one of the three waste streams contributing to the cuttings and cavings release for a single intrusion at the probability of 10^2, which is below the EPA containment requirement. However, in any future of the repository, roughly six intrusions are expected (Dunagan 2003b), implying that 18 waste streams are selected for cuttings and cavings releases. The mean probability that the LA-TA-58-48 waste stream is selected at least once for cuttings and cavings releases is estimated to be

$$1-\left(1-0.00018\right)^{18}=0.0033\,;$$

thus, the increase in releases at a probability of about 0.003 in Figure PA-100, Figure PA-101, and Figure PA-102.

Figure PA-103 compares the mean, median, 90th, and 10th quantiles for each replicate's distribution of CCDFs for cuttings and cavings releases. The statistical measures of each replicate's distribution of CCDFs are quite similar, indicating that the sample size of 100 elements in each replicate is sufficient to estimate the distribution of CCDFs. Figure PA-104 shows the 95 percent confidence interval about the overall mean of the CCDFs for cuttings and cavings releases. The upper and lower confidence intervals nearly coincide with the overall mean, showing that the overall mean is estimated quite accurately.

Section PA-8.5.1 presents a sensitivity analysis for cuttings and cavings release volumes, and shows that the uncertainty in total cuttings and cavings volumes arises almost entirely from the uncertainty in waste shear strength (WTAUFAIL; see Table PA-17). Cuttings and cavings releases are computed by multiplying the volume released by the average concentration of radioactivity in the three selected CH-TRU waste streams (see Section PA-3.7). However, the uncertainty in the radioactivity in the cuttings and cavings materials is stochastic uncertainty, and is thus represented by the shape of the individual CCDFs in Figures PA-100, PA-101, and

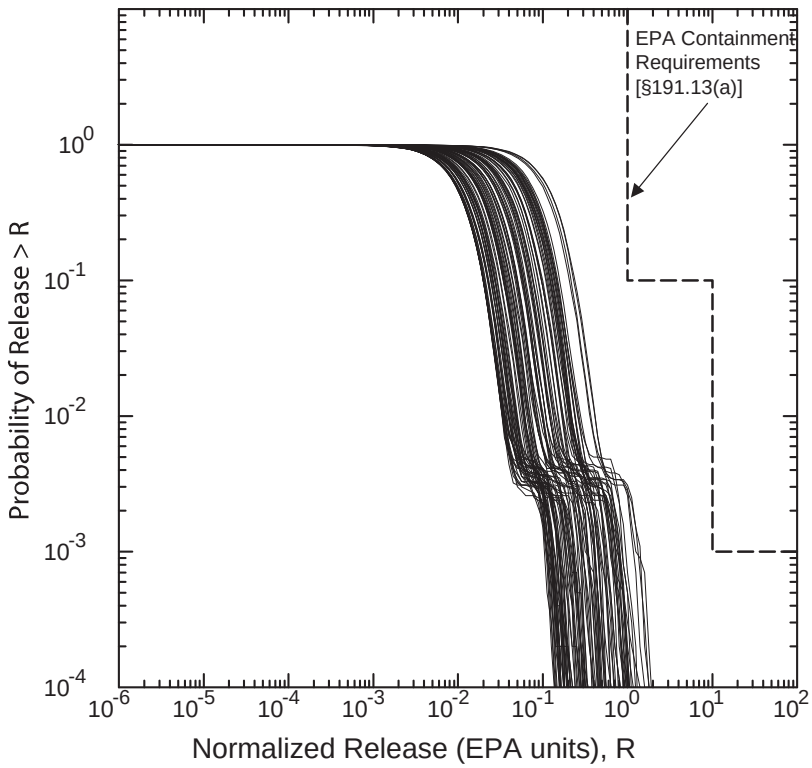

Figure PA-100. Cuttings and Cavings Releases, Replicate R1.

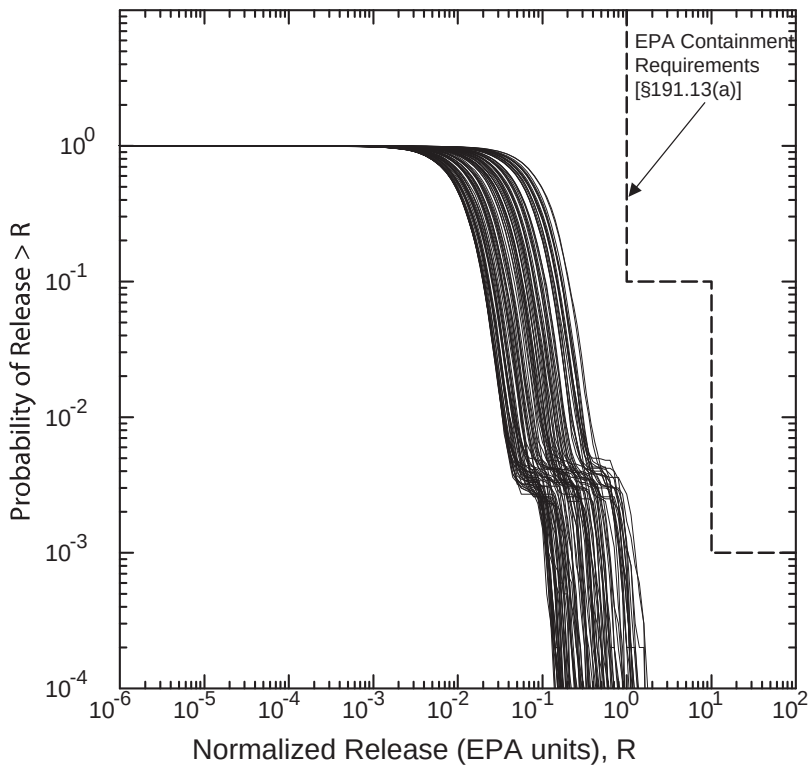

Figure PA-101. Cuttings and Cavings Releases, Replicate R2.

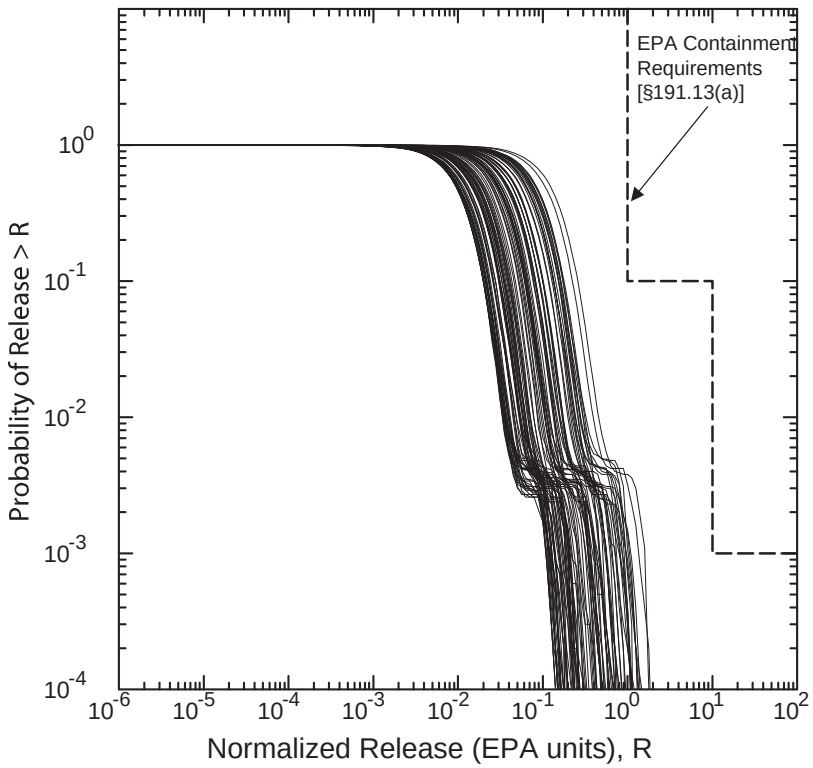

Figure PA-102. Cuttings and Cavings Releases, Replicate R3.

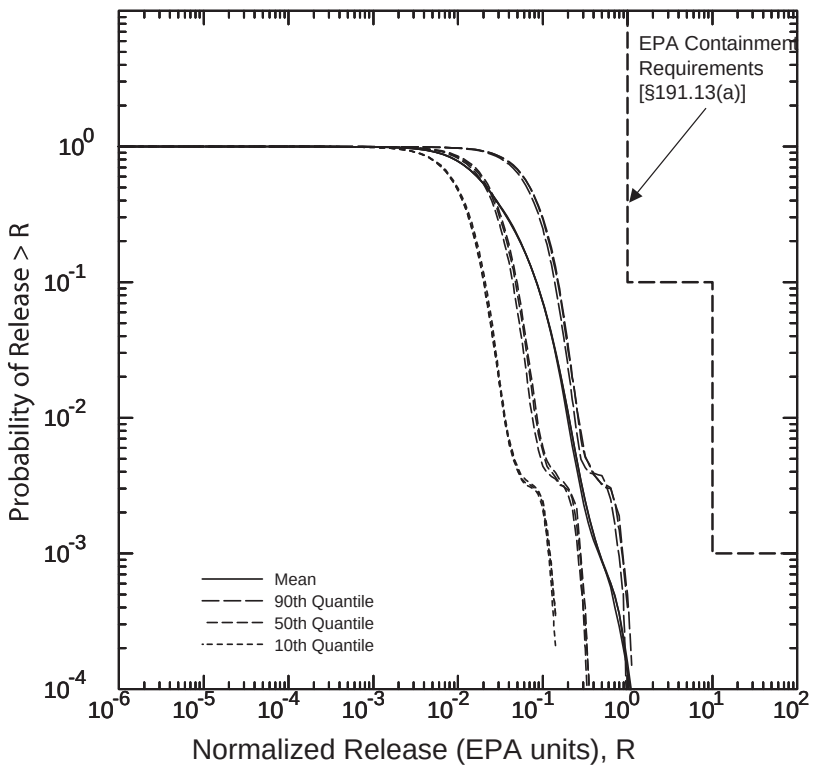

Figure PA-103. Mean and Quantile CCDFs for Cuttings and Cavings Releases, All Replicates.

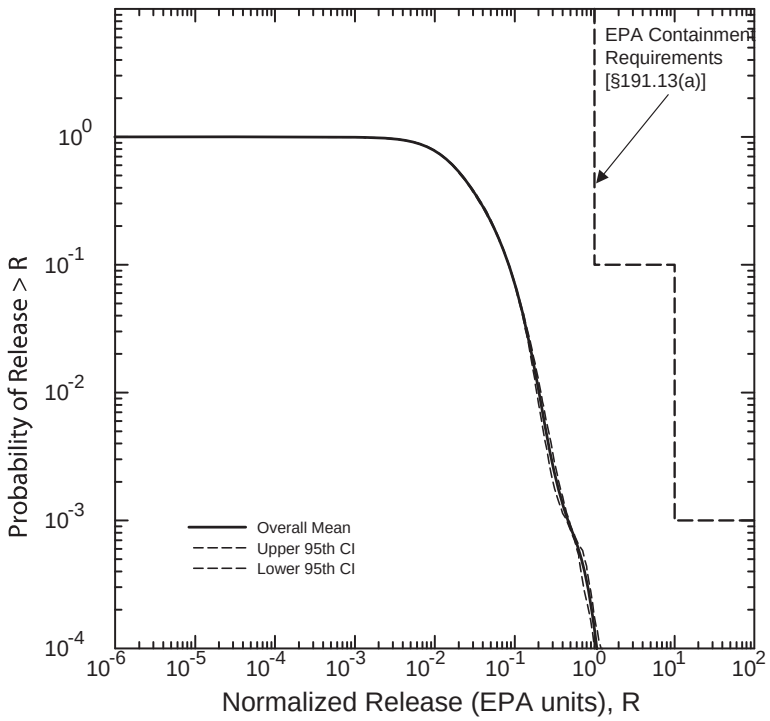

Figure PA-104. Confidence Interval on Overall Mean CCDF for Cuttings and Cavings Releases.

PA-102. Consequently, the uncertainty in mean cuttings and cavings releases is due to the subjective uncertain in the cuttings and cavings volume, as demonstrated in Figure PA-105, which demonstrates the high correlation between mean cuttings and cavings releases and the uncertainty in waste shear strength.

PA-9.3 Spallings Normalized Releases

Figures PA-106, PA-107, and PA-108 show the CCDFs for normalized releases due to spallings for replicates R1, R2, and R3. The releases for each replicate are very similar; Figure PA-109 compares the mean and quantile CCDFs for spallings releases for each replicate and indicates that the distribution of spallings releases are similar in each replicate. Figure PA-110 shows the 95 percent confidence interval about the overall mean of the CCDFs for spallings releases. Although the confidence interval for spallings releases is broader than that shown in Figure PA-104 for cuttings and cavings releases, the overall mean is quite similar to the upper confidence interval, particularly at low probabilities. This result provides confidence that the true mean CCDF for spallings releases does not lie far to the right of the overall mean computed from the three replicates, and thus remains far below the release limits.

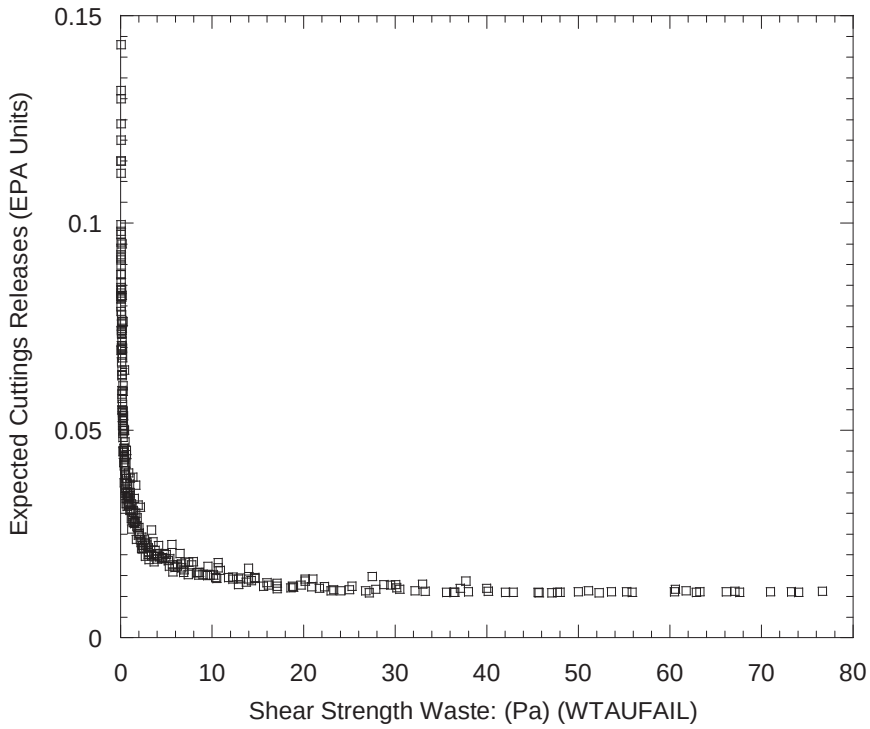

Figure PA-105. Uncertainty in Cuttings and Cavings Releases Due to Waste Shear Strength, All Replicates.

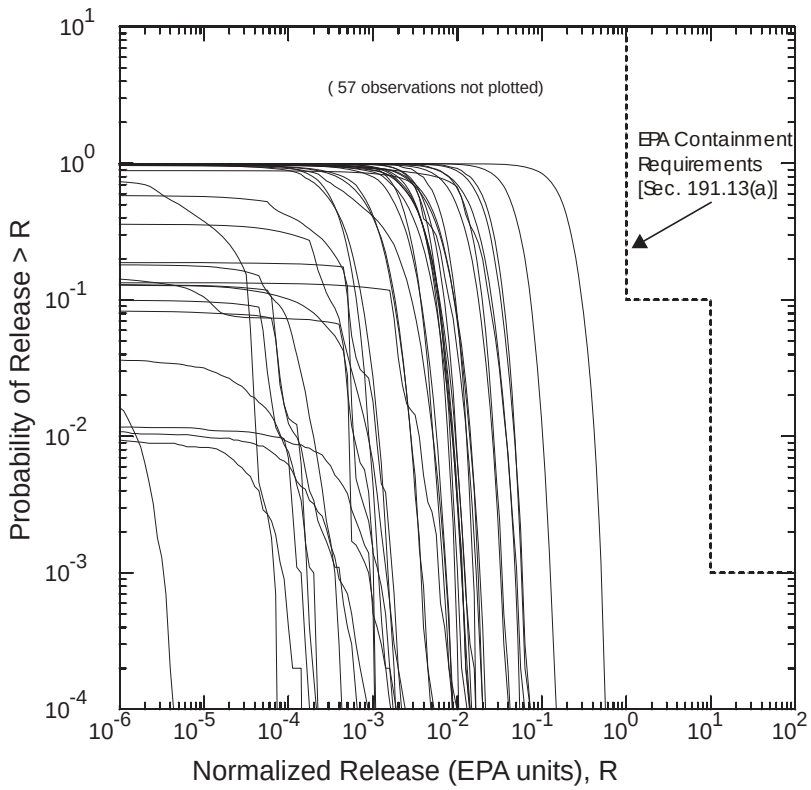

Figure PA-106. Spallings Releases, Replicate R1.

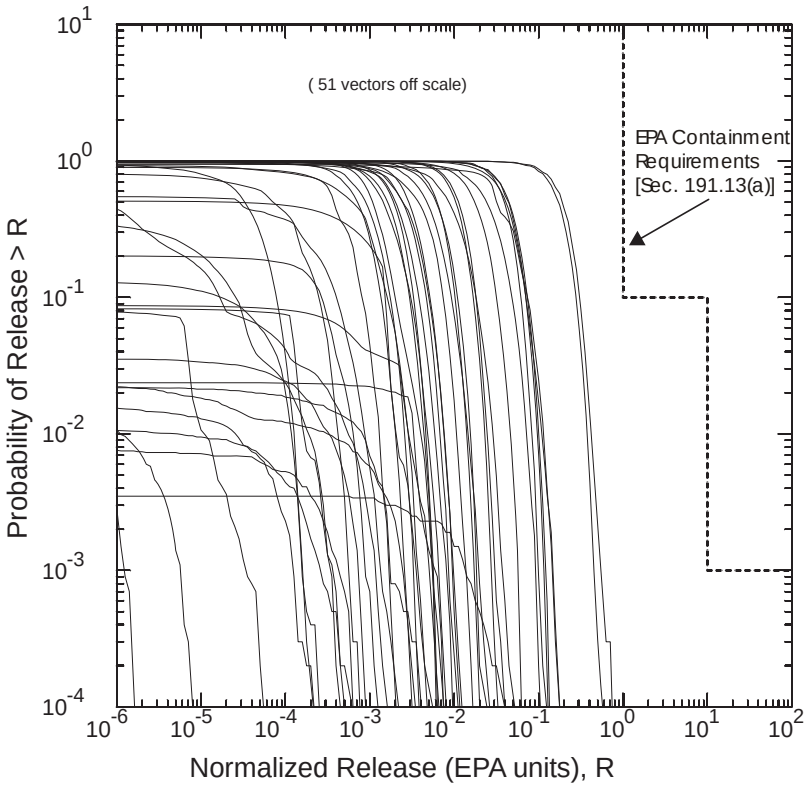

Figure PA-107. Spallings Releases, Replicate R2.

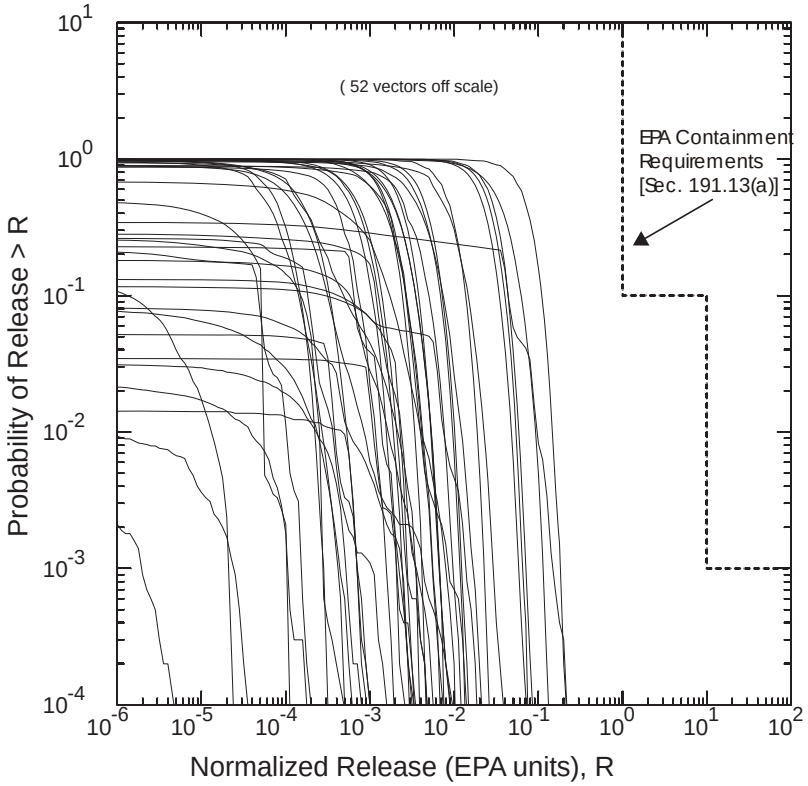

Figure PA-108. Spallings Releases, Replicate R3.

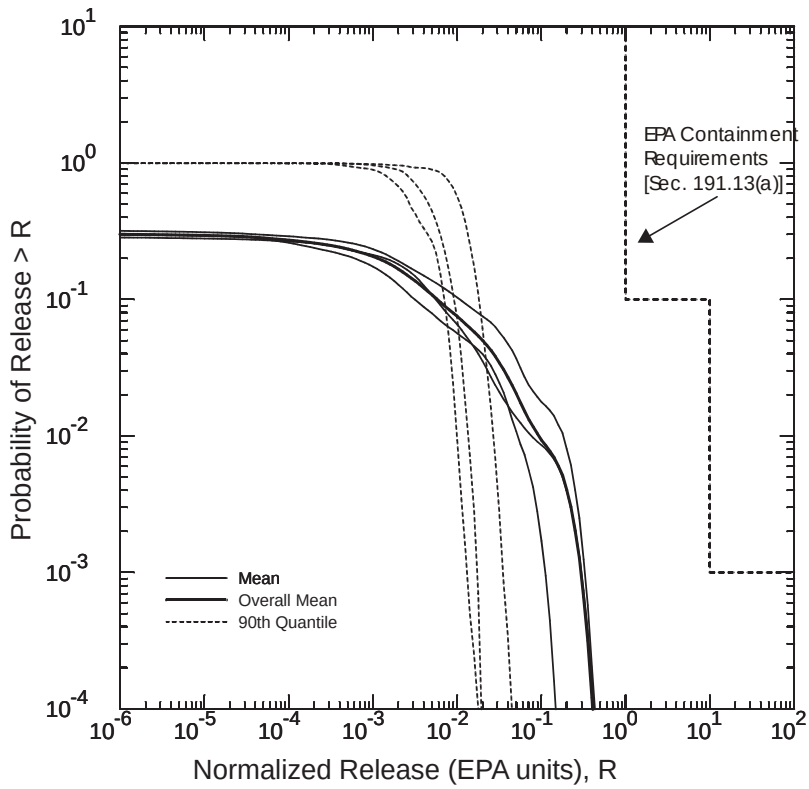

Figure PA-109. Mean and Quantile CCDFs for Spallings Releases, All Replicates.

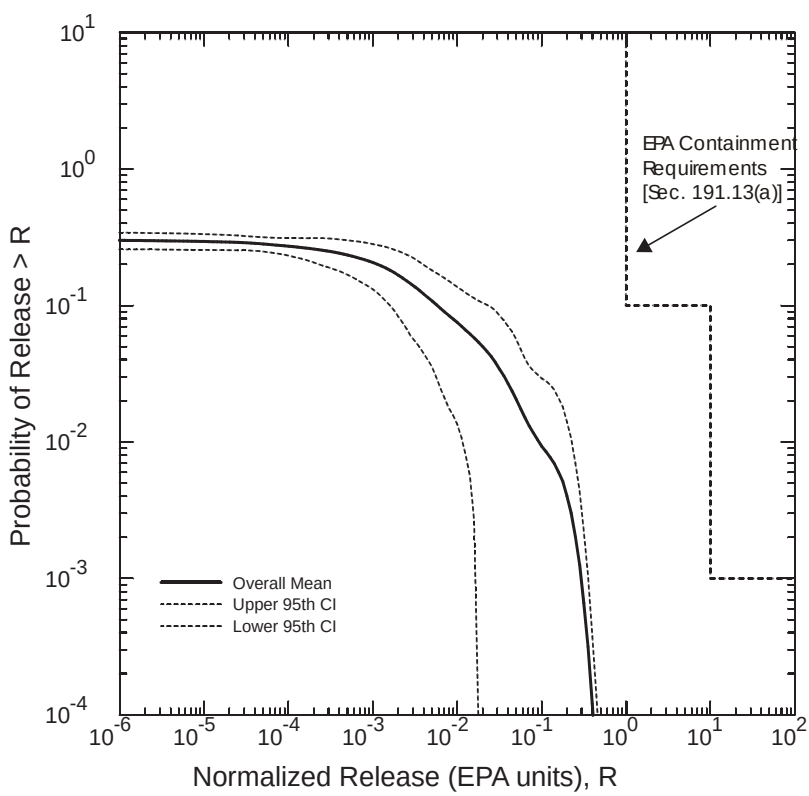

Figure PA-110. Confidence Interval on Overall Mean CCDF for Spallings Releases.

Section PA-8.5.2 presents a sensitivity analysis for spallings release volumes, and shows that the uncertainty in total spall volumes arises from the uncertainty in microbial action (WMICDFLG; see Table PA-17) and the uncertain spall volume from a single intrusion (see RNDSPALL in Table PA-17 and the discussion in Section PA-8.5.2). Since spall releases are computed by multiplying the volume released by the average concentration of radioactivity in the CH-TRU waste at the time of intrusion, the uncertainty in spalling releases is due to the same parameters that contribute to uncertainty in total spall volumes.

PA-9.4 Normalized Direct Brine Releases

Figures PA-111, PA-112, and PA-113 show the CCDFs for normalized direct brine releases for replicates R1, R2, and R3. The releases for each replicate are very similar; Figure PA-114 compares the mean and quantile CCDFs for each replicate; the 10th quantile for normalized DBRs does not plot on the scale of Figure PA-114. Figure PA-115 shows the 95 percent confidence interval about the overall mean of the CCDFs for DBRs, and shows that the overall mean is estimated reasonably well.

Section PA-8.5.3 provides an analysis identifying the sensitivity of the volume of brine released from a single intrusion to the uncertain parameters in the analysis. The sensitivity analysis showed that direct brine release volumes are most sensitive to uncertainty in pressure and brine saturation in the waste, which in turn, are most sensitive to microbial action in the waste (WMICDFLG; see Table PA-17) and borehole permeability (BHPERM).

As described in Section PA-6.8.5, DBRs are computed by multiplying the volume of brine released by the concentration of radionuclides in the brine. A stepwise regression analysis (summarized in Table PA-30) determined that the uncertainty in mean DBR is dominated by the parameters that influence the DBR volumes (WMIDFLG, the indicator for microbial action; BPINTPRS, the pressure in the Castile brine reservoir; PBRINE, the probability of an intrusion hitting the Castile brine reservoir; and WRBRNSAT, the residual brine saturation in the waste). The uncertainty in radionuclide concentration has a lesser influence on mean direct brine release, as only a single related parameter entered the analysis (WSOLAM3C, the uncertainty in the solubility of Am(III) in Castile brine). Figure PA-116 illustrates the sensitivity of mean DBR to DBR volume and to the most influential uncertain parameter, the indicator for microbial action (WMICDFLG). The figure shows that the mean DBRs is roughly proportional to the mean DBR volume among subsets of vectors with or without microbial action.

PA-9.5 Transport Normalized Releases

Figures PA-117 and PA-118 show the CCDFs for normalized releases due to transport through the Culebra for replicates R1 and R3. No transport releases larger than 10^{-6} EPA units occurred in replicate R2. Since the transport releases are small and statistically rare, no confidence intervals or sensitivity analyses are provided.

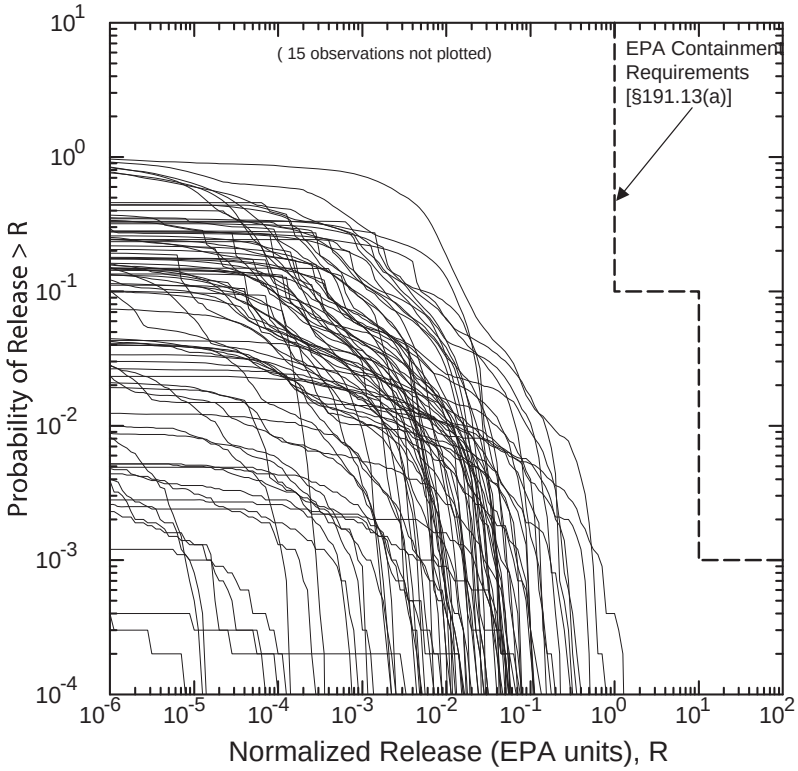

Figure PA-111. DBRs, Replicate R1.

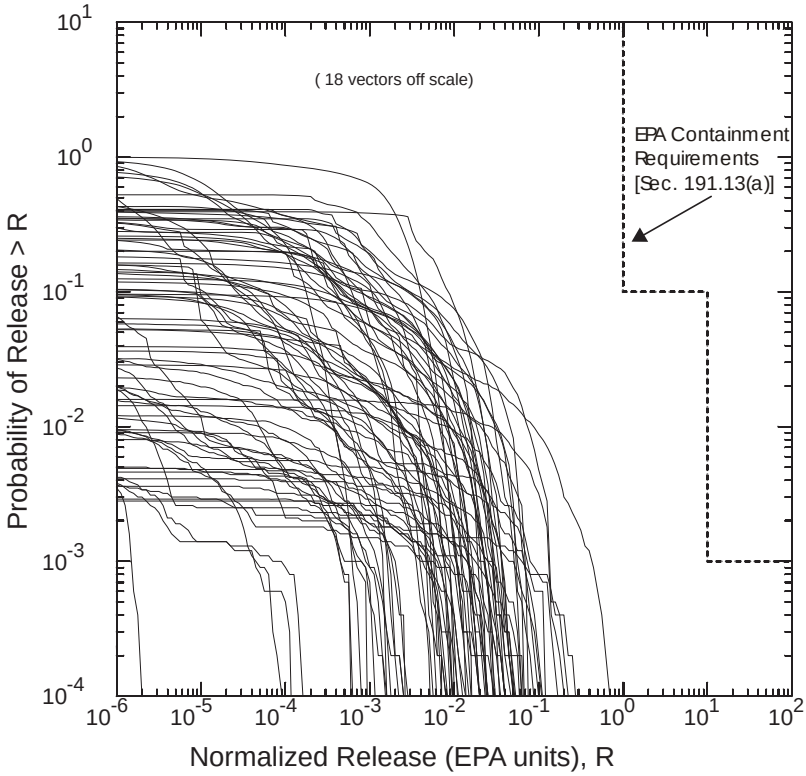

Figure PA-112. DBRs, Replicate R2.

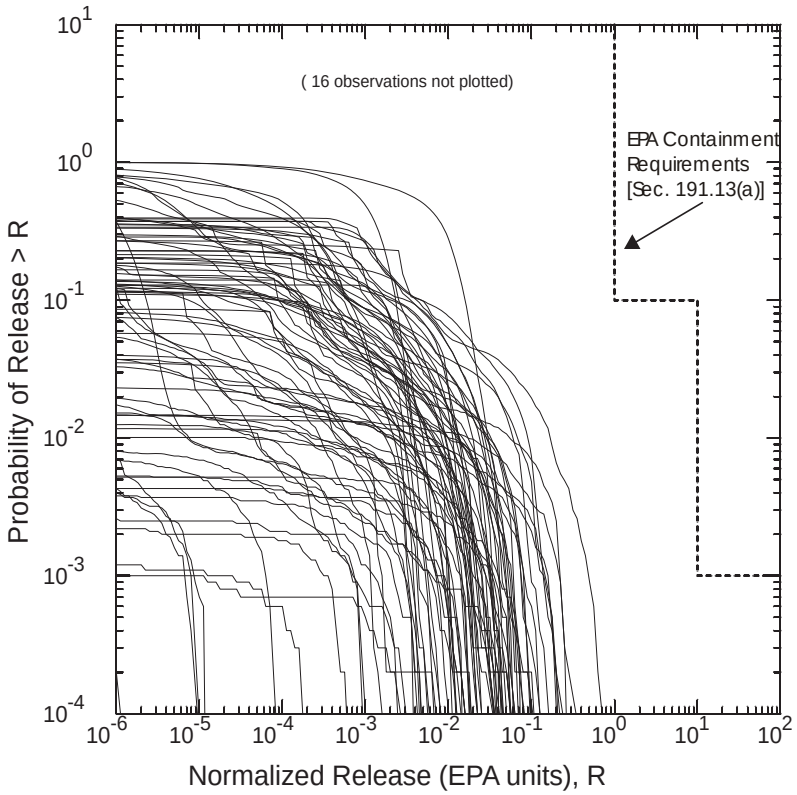

Figure PA-113. DBRs, Replicate R3.

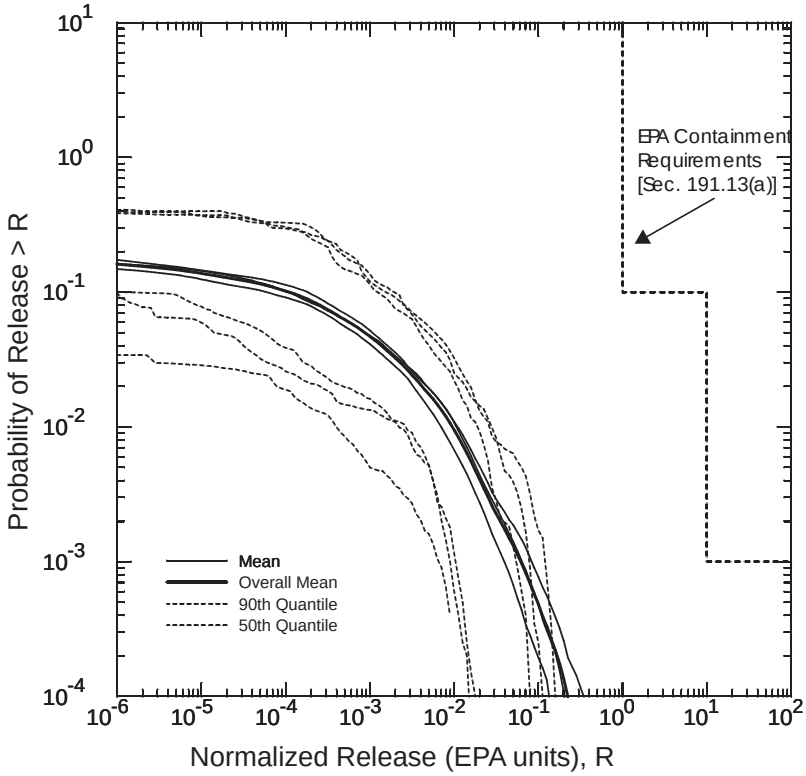

Figure PA-114. Mean and Quantile CCDFs for DBRs, All Replicates.

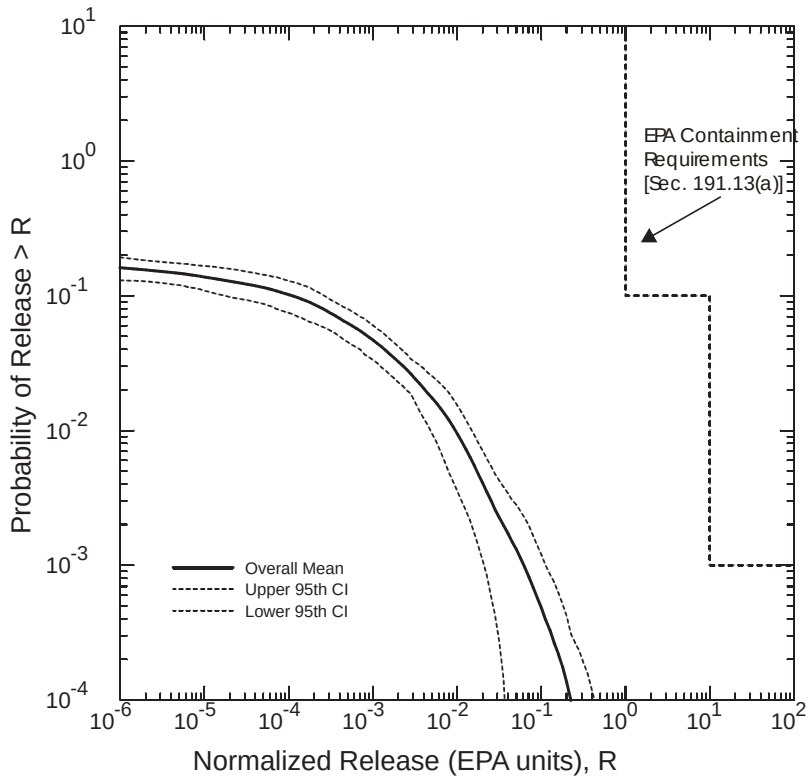

Figure PA-115. Confidence Interval on Overall Mean CCDF for DBRs.

Table PA-30. Stepwise Regression Analysis for Mean Total DBRs

	Expected Normalized Release		
Step[a]	Variable[b]	SRRC[c]	R^{2d}
1	WMICDFLG	-0.46784	0.15776
2	BPINTPRS	0.48223	0.34337
3	PBRINE	0.36000	0.47058
4	WSOLAM3C	0.29070	0.51608
5	WRBRNSAT	-0.15397	0.55481
6	CONGSSAT	-0.22426	0.57556
7	REPIPERM	-0.21496	0.60771
8	WGRCOR	-0.16265	0.63011
9	TENSLSTR	-0.14810	0.64990

[a] Steps in stepwise regression analysis

[b] Variables listed in order of selection in regression analysis

[c] Standardized Rank Regression Coefficient in final regression model

[d] Cumulative R^2 value with entry of each variable into regression model

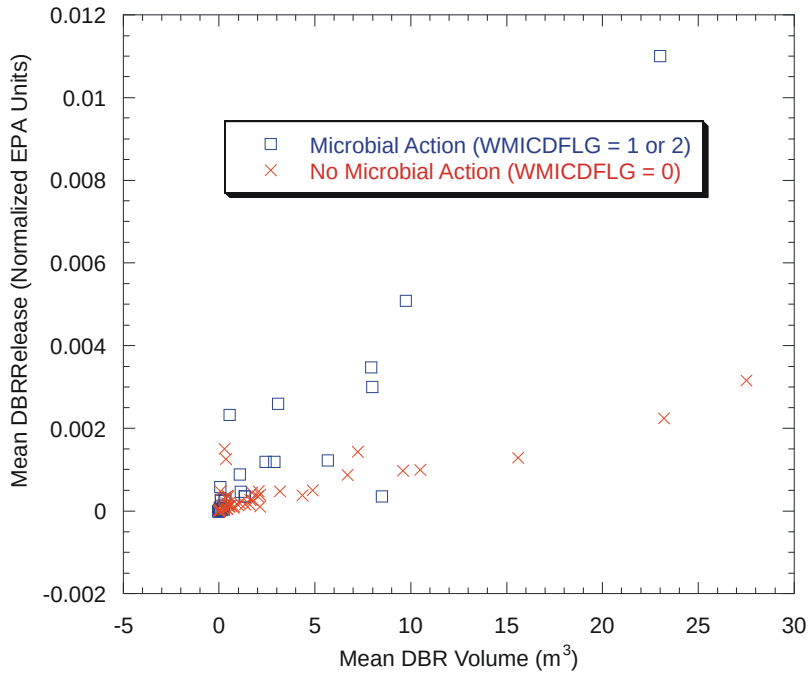

Figure PA-116. Sensitivity of DBRs.

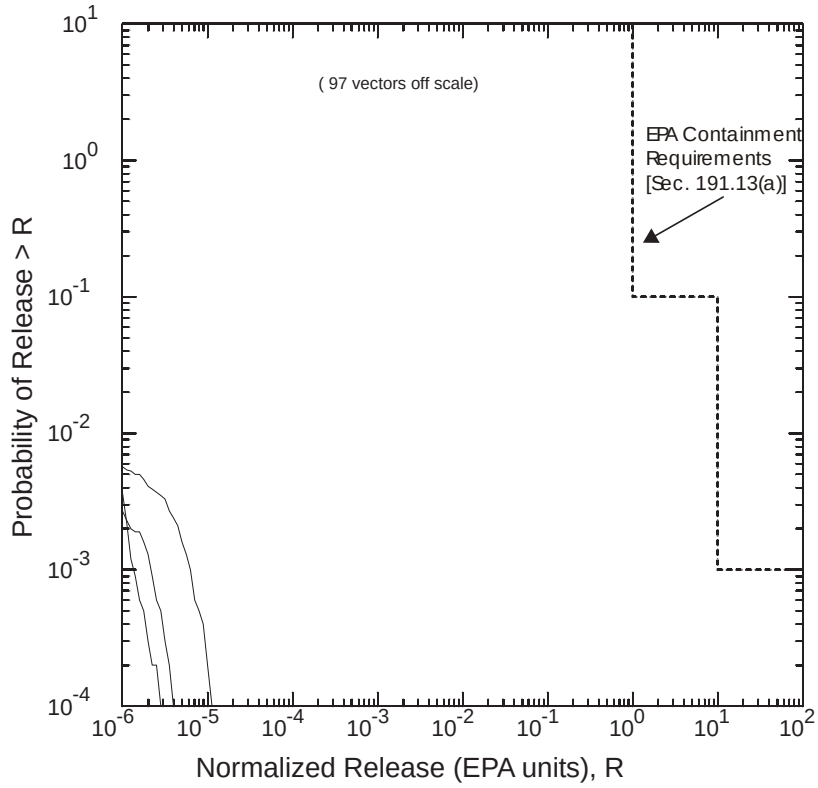

Figure PA-117. Transport Releases Through the Culebra, Replicate R1.

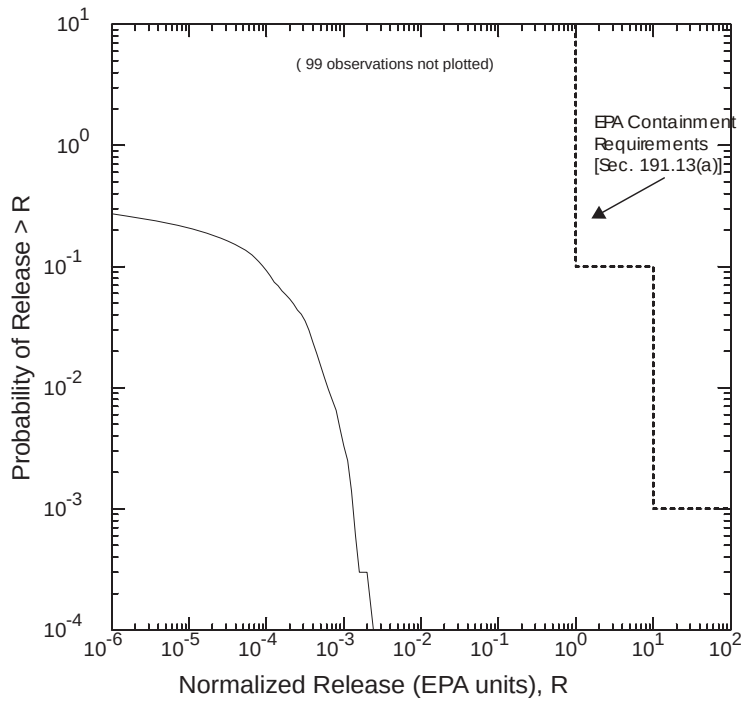

Figure PA-118. Transport Releases Through the Culebra, Replicate R3.

PA-9.6 Sensitivity Analysis for Total Normalized Releases

Uncertainty in total normalized releases is largely due to uncertainty in waste shear strength (WTAUFAIL; see Table PA-17). Table PA-31 lists the results of a stepwise regression between mean total normalized releases and the uncertain parameters in the analysis; waste shear strength (WTAUFAIL) is highly correlated with the uncertainty in mean total normalized releases. Figure PA-119 shows the relationship between the uncertainty in total releases and the uncertainty in WTAUFAIL for all replicates.

Table PA-31. Stepwise Regression Analysis for Mean Total Normalized Releases

	Expected Normalized Release		
Step[a]	Variable[b]	SRRC[c]	R^{2d}
1	WTAUFAIL	-0.95137	0.91345
2	WMICDFLG	0.11538	0.92727
3	DOMEGA	0.10735	0.93639
4	SPALLVOL	0.08003	0.94139
5	BPINTPRS	0.06271	0.94475
6	PLGPRM	0.05841	0.94802
7	SHLPRM3	-0.04728	0.95022

[a] Steps in stepwise regression analysis

[b] Variables listed in order of selection in regression analysis

[c] Standardized Rank Regression Coefficient in final regression model

[d] Cumulative R^2 value with entry of each variable into regression model

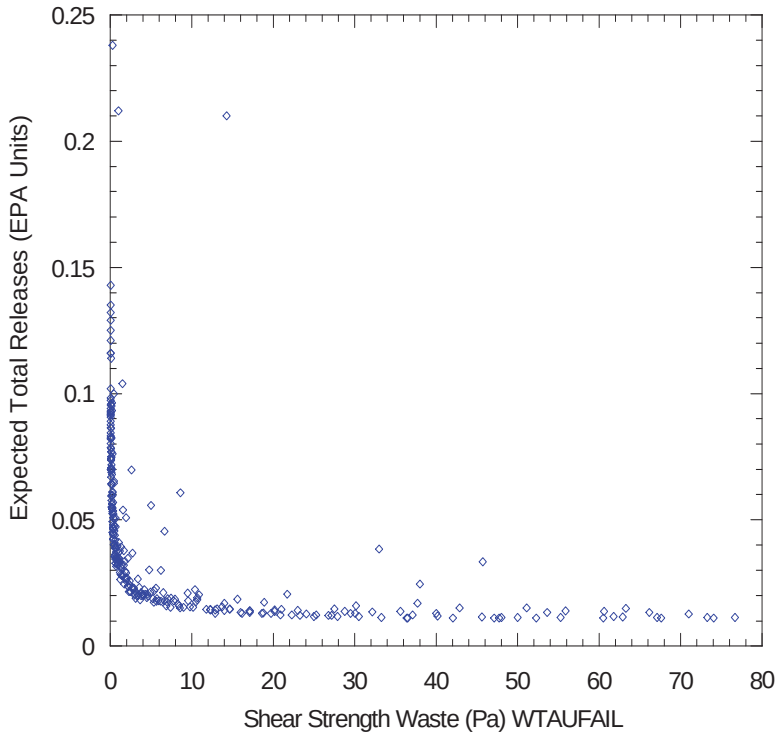

Figure PA-119. Uncertainty in Mean Total Releases Due to Waste Shear Strength, All Replicates.

As shown in Section PA-9.1, cuttings and cavings releases constitute most of the total releases from the repository. As shown in Section PA-8.5.1, most of the uncertainty in cuttings and cavings releases arises from uncertainty in waste shear strength (WTAUFAIL). Thus, uncertainty in WTAUFAIL dominates uncertainty in total releases.

The remaining uncertainty in total releases is primarily due to uncertainty in the spallings releases. Figure PA-120 compares total releases and cuttings and cavings releases for replicate R1, and shows that almost all of the total releases are due to cuttings and cavings. For replicate R1, Figure PA-121 shows the uncertainty in total releases that is not due to uncertainty in cuttings and cavings, and demonstrates that most of the remaining uncertainty arises from uncertainty in spallings releases. This figure shows that spallings releases account for almost all of the variability in the difference between the total releases and cuttings and cavings releases. The small amount of uncertainty in total releases that is not due to cuttings and cavings or spallings arises from uncertainty in the other components of total releases (i.e. DBR and transport releases). Since the three replicates are statistically similar (Figure PA-95), these conclusions hold for all replicates.

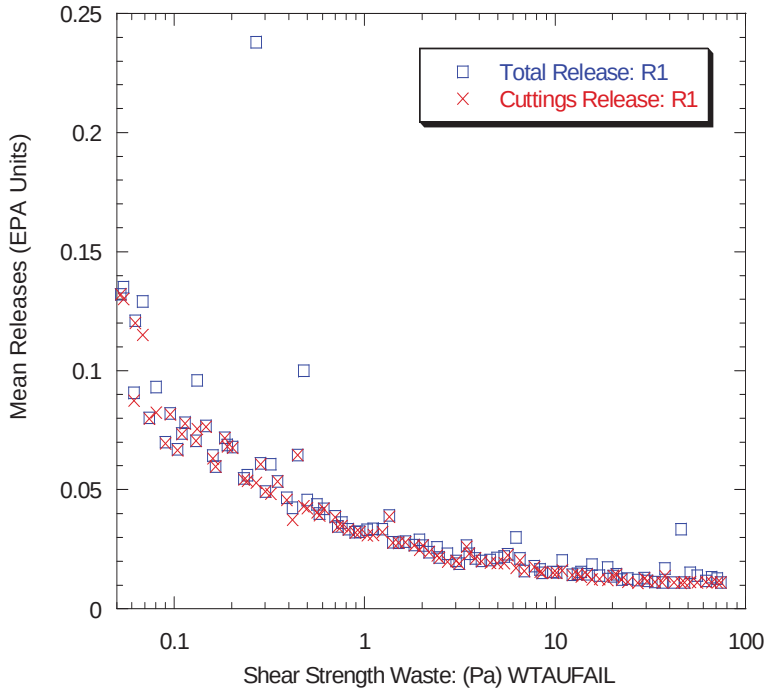

Figure PA-120. Comparison of Mean Total Releases to Mean Cuttings and Cavings Releases, Replicate R1.

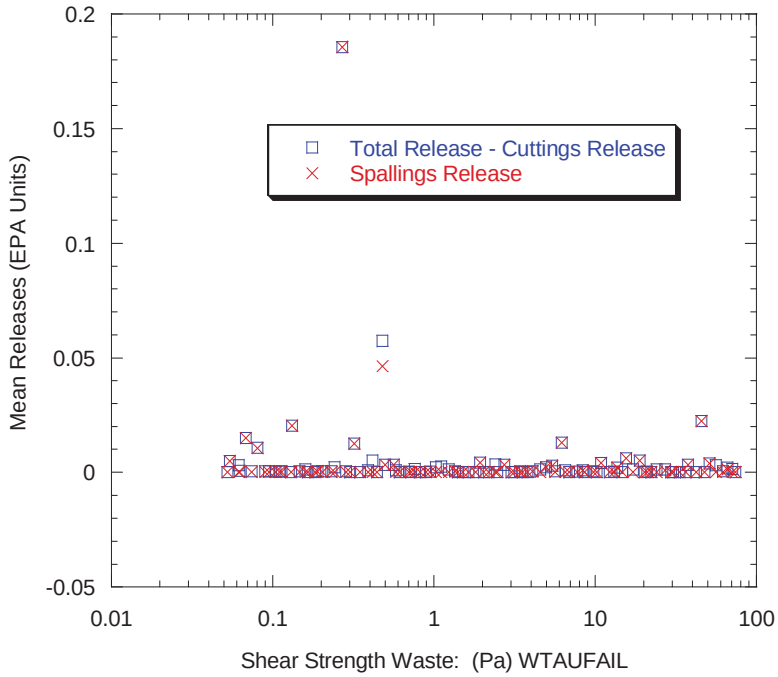

Figure PA-121. Comparison of Mean Total Releases Minus Mean Cuttings Releases to Spall Releases, Replicate R1.

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Appendix PA

Attachment MASS

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ACRONYMS AND ABBREVIATIONS

An	actinide
ASTP	Actinide Source Term Program
BSEP	Brine Sampling and Evaluation Program
CCDF	complementary cumulative distribution function
CH	contact-handled
CCA	Compliance Certification Application
CPR	cellulosic, plastic, and rubber
CRA	Compliance Recertification Application
DCCA	Draft Compliance Certification Application
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
DSEIS	Draft Supplement, Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
FEIS	Final Environmental Impact Statement
FEPs	features, events, and processes
FMT	Fracture-Matrix Transport
FSEIS	Final Supplemental Environmental Impact Statement
LANL	Los Alamos National Laboratory
LEFM	linear elastic fracture mechanics
LLNL	Lawrence Livermore National Laboratory
MB	marker bed
PA	performance assessment
PAVT	Performance Assessment Verification Test
QA	quality assurance
RH	remote-handled
RoR	Rest of Repository
SMC	Salado Mass Concrete
SNL	Sandia National Laboratories
SSBI	Small-Scale Brine Inflow
SWCF	Sandia National Laboratories WIPP Central Files
TDEM	Time Domain ElectroMagnetic
TRU	transuranic
WIPP	Waste Isolation Pilot Plant
WQSP	Water Quality Sampling Program

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MASS-1.0 INTRODUCTION

This attachment presents supplementary information to Appendix PA regarding the assumptions, simplifications, or approximations used in the models of the first recertification performance assessment (PA) of the Waste Isolation Pilot Plant (WIPP). Within this attachment, relevant issues in the formulation or development of the various types of models (for example, conceptual, mathematical, numerical, or computer code) used for the topic are discussed, and references to relevant historical information are included where appropriate.

Section MASS-2.0 contains a summary of changes in the PA since the Compliance Certification Application (CCA). Section MASS-3.0 includes a discussion of general modeling assumptions applicable to the disposal system as a whole, including a table of assumptions made in PA models, with cross-references. The remainder of this attachment discusses assumptions specific to the first recertification PA conceptual models. Historical development of the WIPP conceptual models that led to the PA used in the CCA is documented in CCA Appendix MASS-2.0.

MASS-2.0 SUMMARY OF CHANGES IN PERFORMANCE ASSESSMENT

Since the CCA, several concepts about the processes important to the performance of the WIPP have changed. Additionally, ongoing confirmatory experiments, monitoring results, and operational practices have generated information relevant to the conceptual models for the WIPP PA and provide additional support to the conceptual basis of the PA.

Changes that have occurred since the 1996 PA and new information that may be important to PA are as follows:

1. Features, events and processes (FEPs) assessment
   A. Inclusion of organic ligands in solubility calculations

2. Monitoring
   A. Changes resulting from Culebra water level investigations
   B. Drilling rate parameter change
   C. Changes in Borehole plugging configuration probabilities

3. Experimental Activities
   A. Magnesium-oxide investigations
   B. Changes resulting from actinide investigations

4. PA Models and Systems
   A. Administrative hardware and software updates
   B. Conceptual model changes
      i. Panels closures
      ii. Simplification of shafts
      iii. Grid refinements
      iv. North and South Rest of Repository (RoR)
   C. Spallings

D. Recalculation of Culebra T-fields
E. Performance Assessment Verification Test (PAVT) Baseline

5. Operational Considerations
   A. WIPP horizon moved up to Clay Seam G
   B. Waste inventory update
   C. Evaluation of waste structural impacts, emplacement, and homogeneity

A summary of each change is presented in this section. References to appropriate sections of this attachment are provided for those changes that impact modeling assumptions. Additional references are provided to other areas of the Compliance Recertification Application (CRA) discussing change implementation.

MASS-2.1 Features, Events, and Processes Assessment

Based on the PA methodology for WIPP (see Section 6.2), FEPs are important elements to help develop the conceptual models and modeling assumptions represented in PAs. The process used to develop and screen FEPs is outlined in Section 6.2. The results of the CCA FEPs screening was documented in CCA Appendix SCR. For the CRA, a reassessment of the baseline PA FEPs was conducted to determine if changes in WIPP activities and conditions changed the original FEPs descriptions, basis, or screening decisions. This assessment also determined if additional FEPs should be included in the CRA baseline. The reassessment results are documented in SNL (2003a) and have been used to develop Appendix PA, Attachment SCR. Changes to the FEPs' baseline include combining similar FEPs and deleting redundant or inclusive FEPs, separating general FEPs into more descriptive FEPs, and FEP screening decision changes.

MASS-2.2 Monitoring

Monitoring activities have continued since the certification of WIPP. These activities are used to validate assumptions and PA parameters, and also to detect substantial and detrimental deviation from expected repository performance. Monitoring, as discussed here, applies to the assurance requirement of 40 CFR §191.14(b) and the monitoring criteria at 40 CFR §194.42. Appendix MON details the monitoring program that meets these requirements. The monitoring program has led to three changes:

- Culebra water levels at some wells have exceeded the ranges used in the CCA steady-state T-field calibrations,
- The drilling rate for deep boreholes has increased since 1996, and
- The probabilities for borehole plug configurations have changed slightly since 1996.

The impacts and implementation of the new Culebra data are discussed in Section 2.2.1.4.1.2. and Appendix PA, Attachment TFIELD (see also MASS-2.4.2).

In the 2004 PA, two parameters have changed; the drilling rate and the probabilities for borehole plugging. The drilling rate for boreholes is discussed in Sections 6.0.2.3, 6.2.5.2; and Appendix DATA (Section DATA-2.0 and Attachment A). The probability for borehole plugging

configurations is discussed in Section 6.4.7.2. No changes are necessary to modeling assumptions to account for these parameter changes.

MASS-2.3 Experimental Activities

The EPA requires the recertification documentation to include an update of "additional analyses and results of laboratory experiments conducted by the Department or its contractors as part of the WIPP program" (40 CFR 194.15(a)(3)). The following discusses analyses and experiments conducted to support compliance determinations. Only the analyses with conclusions relevant to this recertification are discussed here; all ongoing and supportive experiments are presented in biannual reports previously submitted to Environmental Protection Agency (EPA) (SNL 2001a, 2001b; SNL 2002a, 2002b; and SNL 2003b).

MASS-2.3.1 Magnesium-Oxide Investigations

Experiments have been preformed to support implementation of magnesium oxide (MgO) as an engineered barrier. These experiments investigate hydration and carbonization of MgO to confirm its ability to sequester carbon dioxide (CO_2), buffer brine pH, and subsequently reduce actinide solubilities in the repository. The conclusions drawn from these activities are described in Appendix BARRIERS. Specifically, the incorporation of MgO in PA has not changed from the 1996 PA.

MASS-2.3.2 Actinide Investigations

An Actinide Source Term Program (ASTP) has continued to investigate actinide (An) speciation and solubilities since the certification of WIPP. These investigations include work relating to organic ligands and colloid effects on solubilities, and the appropriateness of the use of the oxidation state analogy. These activities are described in SNL (2001a, 2001b; SNL 2002a, 2002b; and SNL 2003b). The conclusions drawn from these activities and the changes to the 2004 PA are described in Appendix PA, Attachment SOTERM. Specifically, organic ligands are considered in the 2004 PA through the solubility calculations.

MASS-2.4 Performance Assessment Models and Systems

Changes have been made to the systems that are used to perform PAs. The PA hardware, operating systems, and parameter database were updated since the 1996 PA. These changes were necessary to replace obsolete hardware and operating systems and to increase PA capabilities. These changes were implemented and approved under applicable quality assurance (QA) requirements.

Additionally, conceptual model changes were necessary to implement new or different representations of physical systems in PA. Changes to conceptual models led to revised or replacement codes, which implement the conceptual models in PA. The following discusses these changes.

MASS-2.4.1 Administrative Hardware and Software Updates

The computer systems and operating systems have been upgraded since the 1996 PA because of increasing obsolescence of the operating system and hardware. New hardware is being used along with a newer operating system for the 2004 PA. All changes to these systems are performed under the appropriate QA program, and include testing, validation, and verification to ensure that there is no impact on PA implementation. A synopsis of the changes and references to the QA documentation are found in Long (2003).

MASS-2.4.2 Conceptual Model Changes

The certification decision by the EPA (1998a) included several conditions that the U.S. Department of Energy (DOE) was required to meet. In the first of these conditions, the EPA required the DOE to implement a specific design for the panel closure system (referred to as "Option D") and using Salado Mass Concrete (SMC). The DOE had included in the CCA four Options (A-D) for the panel closure design. The Option D design consisted of two components, a large concrete monolith and an explosion wall constructed of concrete blocks. The 1996 PA generically represented the closures in BRAGFLO and did not model a specific closure. The representation of the Option D closure has been incorporated into the BRAGFLO grid. The Option D closure modeling assumptions are discussed in Section MASS-19.0 and MASS-4.2. Panel closure implementation in PA is discussed in Appendix PA, Section PA-4.2.8.

To account for this design in PA, the conceptual model for Repository Fluid Flow, Disturbed Rock Zone (DRZ), and the Disposal System Geometry were revised and peer reviewed. Chapter 9 and Appendix PEER contain information on the conceptual model peer review. These conceptual models are implemented in BRAGFLO. See Section MASS-2.5.2 and MASS-4.2 for information on modeling assumptions and implementation of these conceptual models. Implementation of these conceptual model changes led to the following changes in BRAGFLO.

1. Implementation of Option D panel closures,
2. Simplification of the shaft seal model,
3. Refinement of grid outside the excavated area to improve computational accuracy and efficiency,
4. Increased Segmentation in the North RoR and South RoR.

MASS-2.4.3 Spallings Model

An EPA guidance letter on recertification requested the DOE implement a new spallings conceptual model (EPA 2002). The original conceptual model for spallings was peer reviewed during the first certification, but was deemed inadequate by the peer review panel. The DOE later derived a method to represent spallings that was deemed conservative by the peer reviewers and was used by DOE in the 1996 PA. Since the CCA, however, a more appropriate and representative spallings model has been developed, peer reviewed, and implemented in the 2004 PA. Results of the peer review are found in Chapter 9 and Appendix PEER. Modeling

assumptions concerning the Spallings model are detailed in Section MASS-16.1. Implementation of the spallings model is described in Appendix PA, Section PA-4.6.

No other conceptual models were revised for this recertification application.

MASS-2.4.4 Recalculation of Culebra T-fields

Water level rises in the Culebra have continued over recent years and the observed heads have exceeded the ranges of uncertainty established for the steady-state heads in many of the 32 wells used in the calibration of the transmissivity fields described in the CCA (SNL 2002b). Therefore, the DOE has recalculated T-Fields for the CRA using new Culebra data and geologic information (see Appendix PA, Attachment TFIELD; and Section 2.0). The DOE has implemented a program to identify other potential causes for the water-level rises (SNL 2003c).

MASS-2.4.5 Performance Assessment Verification Test Baseline

The EPA's PAVT parameters were incorporated into the 2004 PA parameter baseline (EPA 1998b, V-B-14). These parameters and a cross-reference of discussions concerning their incorporation into the 2004 PA are shown in Table 6-1.

MASS-2.5 Operational Considerations

Operational considerations are impacts to PA from changes to WIPP operations that the DOE has requested and the EPA has approved, or changes that have been mandated by the EPA.

MASS-2.5.1 Waste Isolation Pilot Plant Horizon Moved up to Clay Seam G

Operational changes to the repository design since the CCA include mining the repository horizon in the southern half of the waste panels at a different location than the northern half. Specifically, panels 3, 4, 5, 6, and 9 will be excavated at an elevation approximately 2.4 m above the level of panels 1, 2, 7, 8, and 10, and the operations and experimental areas. This change in horizon will bring the roof of the raised rooms to the level of the Clay Seam G. The change is expected to improve roof conditions and enhance operations and mine safety. The DOE submitted a planned change request to the EPA that described the change and presented an argument that the change would have minimal impact on long-term repository performance (DOE 2000). The EPA responded to the change request in a letter (EPA 2000) in which they agreed with DOE that the effects to long-term performance would be minimal. Further investigations led DOE to determine that no changes to the 2004 PA models were necessary to account for this change. Section MASS-20.0 discusses the justification for this determination.

MASS-2.5.2 Waste Inventory Update

The waste inventory used in the CCA was based on information contained in the TWBIR (CCA Appendix BIR). No waste had been emplaced in the repository at that time. Since 1996, waste has been emplaced in the repository and better estimates have been made of the existing and projected waste streams at the generator sites. The new waste information has been updated in the 2004 PA to include the emplaced, currently stored, and projected waste streams. This information was collected in the TWBID, Rev 2, with specific WIPP information detailed in

Appendix DATA, Attachment F. Inclusion of waste information in the 2004 PA is discussed in Appendix TRU WASTE.

MASS-2.5.3 Evaluation of Waste Structural Impacts, Emplacement, and Homogeneity

During the development of the CCA PA, the DOE choose to assume random placement of transuranic (TRU) waste in the WIPP, and developed conceptual and numerical models accordingly. The EPA reviewed these models and their results, and determined that DOE had modeled accurately random placement of waste in the disposal system. Since the time of the CCA, additional information about the waste and its emplacement has emerged and requires waste-related assumptions to be reevaluated. This evaluation is discussed in Section MASS-21.0.

MASS-3.0 GENERAL ASSUMPTIONS IN PERFORMANCE ASSESSMENT MODELS

Several assumptions are applied generally to the disposal system through the conceptual and mathematical models implemented in the major computer codes used in this PA. Several major assumptions are discussed here. A table of general assumptions is also presented in Section MASS-3.4.

MASS-3.1 Darcy's Law Applied to Fluid Flow Calculated by BRAGFLO, MODFLOW-2000, and SECOTP2D

A mathematical relationship expressing the flux of fluid as a function of hydraulic head gradients applied, commonly known as Darcy's Law, is applied to geologic media for all fluid-flow calculations. For details about the specific formulation of Darcy's Law used, refer to Appendix PA, Section PA-4.2 for the disposal system and Section PA-4.8 for the Culebra. Darcy's Law is not applied for flow up a borehole that is being drilled (see Section MASS-16.2; and Section 6.4.7.1.1 for more discussion of this topic).

Darcy's Law generally applies for flow models if certain conditions are satisfied: (1) the flow occurs in a porous medium with interconnected porosity, (2) flow velocities are low enough that viscous forces dominate inertial forces, and (3) a threshold hydraulic gradient is exceeded. In CCA Appendix MASS, these conditions were shown to be valid for the WIPP PA.

Darcy's Law assumes laminar flow, that is, there is no motion of the fluid at the fluid/solid interface. For liquids, it is reasonable to assume laminar flow under most conditions. For gases at low pressure, however, gas molecules near the solid interface may not have intimate contact with the solid and may have finite velocity, not necessarily zero. This effect, which results in additional flux of gas above that predicted by application of Darcy's Law, is known as the slip phenomenon, or Klinkenberg effect (Bear 1972, 128). A correction to Darcy's Law for the Klinkenberg effect is incorporated into the BRAGFLO model (see Appendix PA, Section PA-4.2).

Darcy flow for one and two phases implies that values for certain parameters must be specified. Some principal parameters relate to the properties of the fluid, others to the rock. Fluid properties in the Darcy flow model used for the WIPP are its density, viscosity, and compressibility. Rock properties in Darcy flow models are porosity, permeability, and

compressibility (pore, bulk, or rock). In BRAGFLO, other parameters are required to describe the interactions or interference between the two phases present in the model, gas and brine, because they can occupy the same pore space. In the WIPP application of Darcy flow models, compressibility of both the liquid and rock are related to porosity through a dependence on pressure. Fluid density, viscosity, and compressibility are functions of fluid composition, pressure, and temperature. In BRAGFLO, fluid viscosity is a function of pressure, but its density and compressibility are held constant. Fluid composition for the purposes of modeling flow and transport is assumed to be constant.

MASS-3.2 Hydrogen Gas as Surrogate for Waste-Generated Gas Physical Properties in BRAGFLO and DRSPALL

Hydrogen gas is produced by the corrosion of steel in the repository by water or brine. As in the CCA, the gas phase in the BRAGFLO model is assigned the properties of hydrogen because hydrogen will, under most conditions reasonable for the WIPP, be the dominant component of the gas phase. The model for spallings, DRSPALL, also assigns physical properties of hydrogen to the gas phase. In the CCA, the effect of assuming flow of pure H_2 instead of a mixture of gases (including H_2, CO_2, H_2S, and CH_4), was shown to be minor relative to the permeability variations in the surrounding formations.

Other gases may be produced by processes occurring in the repository. If microbial degradation occurs, a significant amount of carbon dioxide (CO_2) and methane (CH_4) will be generated by microbial degradation of cellulosics, and, perhaps, plastics and rubbers in the waste. The CO_2 produced, however, will react with the magnesium-oxide (MgO) engineered barrier and cementitious materials to form brucite ($Mg(OH_2)$), hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$), and calcite ($CaCO_3$) thus resulting in very low CO_2 fugacity in the repository. Although other gases exist in the disposal system, for BRAGFLO calculations it is assumed these gases are insignificant and are not included in the model.

With the average stoichiometry gas generation model, the total number of moles of gas generated will be the same whether the gas is considered to be pure H_2 or a mixture of several gases, because the generation of other gases is accounted for by specifying the stoichiometric factor y. Therefore, considering the moles of gas generated alone, the pressure buildup in the repository will be approximately the same, because the expected gases behave similarly to an ideal gas, even up to lithostatic pressures.

The effect of assuming pure H_2 instead of a mixture of gases (including H_2, CO_2, H_2S and CH_4) on flow behavior, and its resulting impact on the WIPP repository pressure is presented as follows:

Radial flow of a 100 percent saturated rock with nonideal gas is described by Darcy's Law (Amyx et al. 1960):

$$q_b = 1.988_10^{-5}\left[\frac{T_b z_b}{P_b}\frac{kh\left(P_e^2 - P_w^2\right)}{\mu_{avg} z_{avg} \ln\left(\frac{r_e}{r_w}\right)}\right], \qquad (2)$$

which can be rewritten:

$$P_e^2 - P_w^2 = \frac{q_b}{1.988_10^{-5}}\left[\frac{P_b}{T_b z_b}\frac{\mu_{avg} z_{avg} \ln\left(\frac{r_e}{r_w}\right)}{kh}\right], \qquad (3)$$

where:

q = gas flow rate, cubic feet per day at base (reference) conditions
T = temperature, K
P = pressure, pounds per square inch atmosphere
k = permeability, millidarcys
h = height, feet
μ = viscosity, centipoises
z = gas compressibility factor (a function of gas pressure and temperature)
r = radius, consistent units
e = external boundary (repository)
w = internal boundary (wellbore)
b = base or reference conditions for gas (temperature, pressure, compressibility factor)
avg = average properties between external and internal boundaries because u and z are functions of pressure which change with time.

This expression is very useful for looking at the relationships of gas properties (specifically μ and z [which is a function of the gas temperature and pressure]) and rock properties (namely k) on defining q and P.

In order to evaluate the effect of gas composition on q and P, a computer program developed by the National Institute of Standards and Technology (NIST) entitled SUPERTRAPP was used (NIST 1992). This computer program allows calculations of gas properties for 116 pure fluids and mixtures of up to 20 components for temperatures to 1,000 K and pressures to 300 megapascals. The computer program currently can evaluate hydrogen, CO_2, and water but does not have the capacity to evaluate brine (Friend and Huber 1994). Because such small quantities of H_2S are anticipated at the WIPP, its impact will be neglected.

Figure MASS-1 shows the relationship between gas viscosity H_2-CO_2 mixtures for various mole fractions of H_2 at pressures of 7 megapascals and 15 megapascals as determined from SUPERTRAPP. The viscosity at 50 percent mole fraction H_2 is 2.3 times greater than for 100 percent mole fraction H_2. As shown in Equation (2), viscosity has an inverse relationship to flow rate and, as shown in Equation (3), a direct relationship to the square of the repository pressure.

Hence viscosity differences that would result if gas properties other than those of hydrogen were incorporated would result in a decrease in flow rate and potentially higher pressures.

As shown in Figure MASS-2, the gas compressibility at 50 percent mole fraction H_2 is about 0.9 times that at 100 percent mole fraction H_2. Like viscosity, the gas compressibility factor is inversely related to flow rate and directly related to the square of the repository pressure. Hence changing composition from 100 percent to 50 percent H_2 would result in a slight increase in flow rate and a decrease in pressure. Therefore, the impact of variation in gas compressibility caused by composition is considered minor and so is neglected.

The viscosity and compressibility calculations described above for H_2-CO_2 mixtures were repeated for H_2-CH_4 mixtures for various mole fractions of H_2 at pressures of 7 MPa and 15 MPa (Kanney 2003). The variability of viscosity with the composition for the H_2-CH_4 mixtures is smaller than that observed for the H_2-CO_2 mixtures. For example, the gas viscosity of H_2-CH_4 at 50 percent mole fraction is only 1.6 times greater than that for 100 percent mole fraction H_2 at 15 MPa. The H_2-CH_4 mixtures are only slightly less compressible than the H_2-CO_2 mixtures. For example, the gas compressibility of H_2-CH_4 at 50 percent mole fraction is about 0.94 times that for 100 percent mole fraction H_2 at 15 MPa.

The absolute permeability of the surrounding formation plays a significant part with respect to both flow rate and pressure determinations. Because marker bed permeabilities range over four orders of magnitude (see Appendix PAR, Tables PAR-30 to PAR-32), these primary flow pathways will have a greater influence on pressure and flow rate determinations compared to either uncertainty in viscosity or gas compressibility effects.

It should also be noted that the BRAGFLO code includes a pressure-induced fracture model that will limit pressure increases in the repository (Schreiber 1997). For example, at high repository pressures, the factor of 2.3 pressure increase calculated here using the simplified Darcy's Law model is unlikely to be seen in the BRAGFLO results, since fracturing will lead to increased permeability, effectively limiting pressure increases.

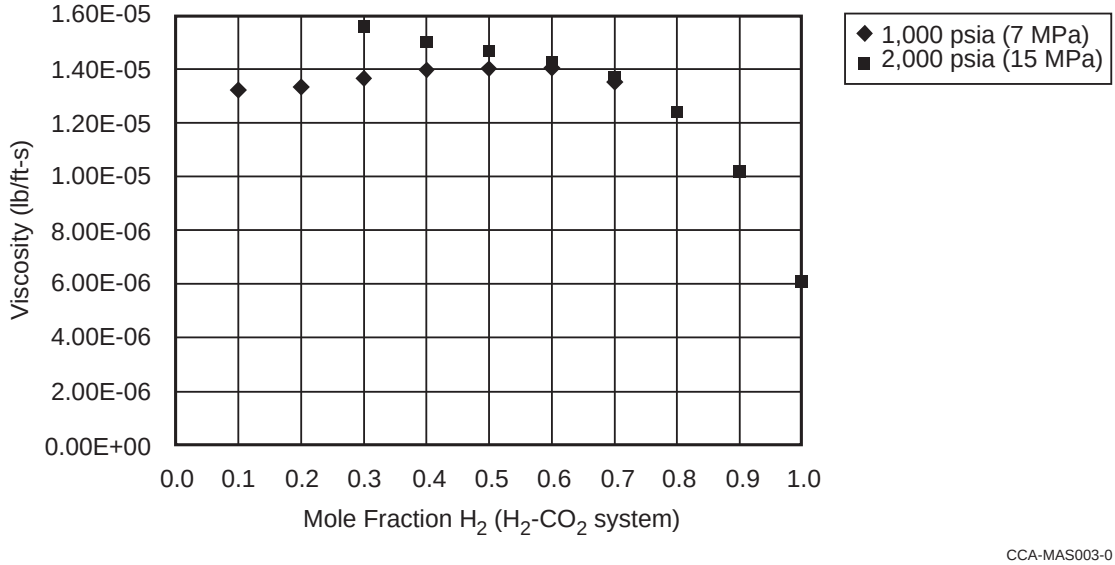

Figure MASS-1. Gas Viscosity as a Function of Mole Fraction H_2 at 7 Megapascals and 15 Megapascals Pressure

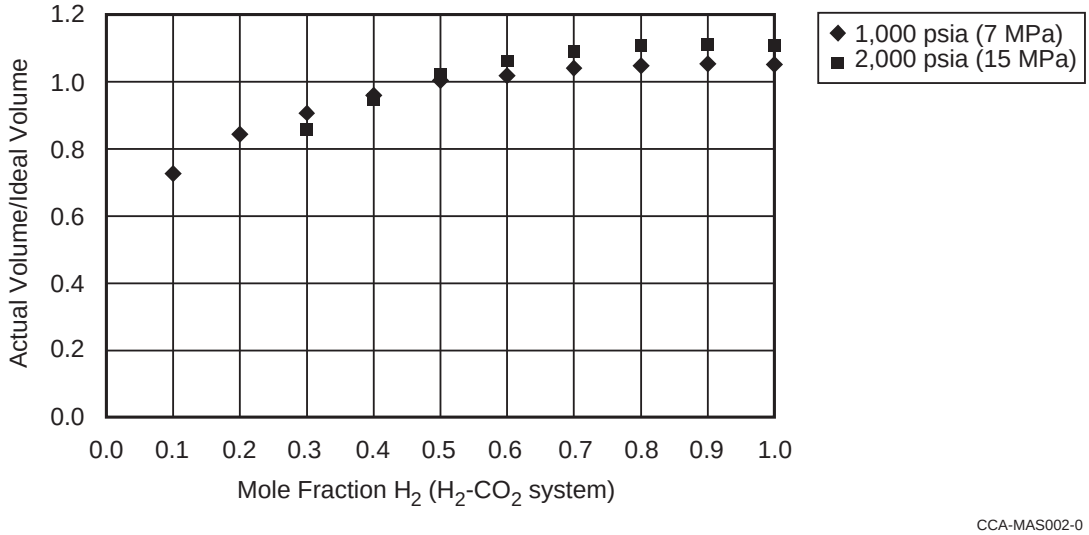

Figure MASS-2. Gas Compressibility as a Function of Mole Fraction H_2

MASS-3.3 Salado Brine as Surrogate for Liquid Phase Physical Properties in BRAGFLO

BRAGFLO models physical properties for all liquids as Salado brine properties. However, liquid in the modeled region may consist of (1) brine originally in the Salado, (2) liquid introduced in the excavation during construction, maintenance, and ventilation during the operational phase, (3) a very small amount of liquid introduced as a component of the waste, (4) liquid from overlying units, and (5) liquid from the Castile brine reservoir. However, for

BRAGFLO modeling it is assumed that the properties of all of these liquids are similar enough to Salado brine properties that the effect of variation in properties that may occur from liquids mixing is negligible. The variations in chemical properties of brine are accounted for as discussed in Section 6.4.3.4, and 6.4.3.5; and Appendix PA, Attachment SOTERM.

MASS-3.4 Table of General Modeling Assumptions

This section presents Table MASS-1, which lists modeling assumptions used in the PA. Table MASS-1 is a guide to general modeling assumptions used and provides some guidance for integrating the assumptions made with (a) the chapters or appendices in which they are discussed and (b) the code(s) that implement these assumptions.

The FEPs discussed in Appendix PA, Attachment SCR that are relevant to the assumptions are also indicated. The final column in the table indicates whether the DOE considers the assumption described to be reasonable or conservative. As discussed in Section 6.5, the DOE has not attempted to bias the overall results of the performance assessment toward a conservative outcome. However, where data or models are infeasible to obtain, or where effects on performance are not expected to be significant enough to justify development of a more complicated model, the DOE has chosen to use conservative assumptions. The designator R (reasonable) in the final column indicates that the DOE considers the assumption to be reasonable based on WIPP-specific data or information, data and information considered analogous to the WIPP disposal system, expert judgment, or other reasoning. The designator C (conservative) indicates the DOE considers the assumption made may overestimate a process or effect that may contribute to releases to the accessible environment. The regulatory designator (Reg) indicates that the assumption is based on regulations in 40 CFR Part 191, criteria in 40 CFR Part 194, or other regulatory guidance.

MASS-4.0 MODEL GEOMETRIES

This section presents supplementary information on the disposal system geometry.

MASS-4.1 Disposal System Geometry as Modeled in BRAGFLO

Overall, the conceptual model of the geometry of the disposal system is that the spatial effects of process interactions can be represented in two dimensions. The geometry used to represent the processes of long-term fluid flow in the Salado, flow between a borehole and overlying units, and flow within the repository (where processes coupled to fluid flow occur, such as creep closure and gas generation), is a vertical cross-section through the repository on a north-south axis. The dimension of this geometry in the direction perpendicular to the plane of the cross-section varies so that spatial effects of certain processes can be better represented, as discussed below.

Table MASS-1. General Modeling Assumptions

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
MASS-3.0 Some General Assumptions in Performance Assessment Models					
MASS-3.1 Darcy's Law Applied for Fluid Flow calculated by BRAGFLO, MODFLOW-2000, and SECOTP2D					
	1	BRAGFLO MODFLOW-2000	Flow is governed by mass conservation and Darcy's Law in porous media. Flow is laminar and fluids are Newtonian.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24) Brine inflow (W40)	R
	2	BRAGFLO	Two-phase flow in the porous media is by simultaneous immiscible displacement.	Fluid flow caused by gas production (W42)	R
	3	BRAGFLO	The Brooks-Corey or Van Genuchten/Parker equations represent interaction between brine and gas.	Fluid flow caused by gas production (W42)	R
	4	BRAGFLO	The Klinkenberg effect is included for flow of gases at low pressures.	Fluid flow caused by gas production (W42)	R
	5	BRAGFLO	Threshold displacement pressure for flow of gas into brine is constant.	Fluid flow caused by gas production (W42)	R
	6	BRAGFLO MODFLOW-2000 SECOTP2D	Fluid composition and compressibility are constant.	Saturated groundwater flow (N23) Fluid flow caused by gas production (W42)	R
MASS-3.2 Hydrogen Gas as Surrogate for Waste-Generated Gas Physical Properties in BRAGFLO					
	7	BRAGFLO DRSPALL	The gas phase is assigned the density and viscosity properties of hydrogen.	Fluid flow caused by gas production (W42)	R
MASS-3.3 Salado Brine as Surrogate for Liquid Phase Physical Properties in BRAGFLO					
	8	BRAGFLO	All liquid physical properties are assigned the properties of Salado brine.	Saturated groundwater flow (N23)	R
6.4.2 Model Geometries MASS-4.0 Model Geometries					
6.4.2.1 Disposal System Geometry MASS.4.1 Disposal System Geometry as Modeled in BRAGFLO					
		BRAGFLO	The disposal system is represented by a two-dimensional, north-south, vertical cross section.	Stratigraphy (N1) Physiography (N39)	R
		BRAGFLO	Flow in the disposal system is radially convergent or divergent centered on the repository, shaft, and borehole for disturbed performance.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24)	R
		BRAGFLO	Variable dip in the Salado is approximated by a 1 degree dip to the south.	Stratigraphy (N1)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
		BRAGFLO	Stratigraphical layers are parallel.	Stratigraphy (N1)	R
		BRAGFLO	The stratigraphy consists of units above the Dewey Lake, the Dewey Lake, the Forty niner, the Magenta, the Tamarisk, the Culebra, the Los Medaños, and the Salado (comprising impure halite, MB 138, anhydrites a and b [lumped together], and MB139). The dimensions of these units are constant. A Castile brine reservoir is included in all scenarios.	Stratigraphy (N1)	R
6.4.2.2 Culebra Geometry MASS-4.3 Historical Context of Culebra Geometries as Modeled in MODFLOW-2000 and SECOTP2D					
		MODFLOW-2000 SECOTP2D	The Culebra is represented by a two-dimensional, horizontal geometry for groundwater flow and radionuclide transport simulation.	Stratigraphy (N1)	R
		MODFLOW 2000 PEST	Transmissivity varies spatially. There is no vertical flow to or from the Culebra.	Groundwater recharge (N54) Groundwater discharge (N53)	R
		SECOTP2D	The regional flow field provides boundary conditions for local transport calculations.	Advection (W90)	R
6.4.3 The Repository MASS.5 BRAGFLO Geometry of the Repository					
		BRAGFLO	The repository comprises five regions separated by panel closures: the waste panel, a north RoR, a south RoR and the access drifts (separated by panel closures), the operations region, and the experimental region. Also, a single shaft region is modeled, and a borehole region is included for a borehole that intersects the separate waste panel. The dimensions of these regions are constant (see Figure 6-14).	Disposal geometry (W1)	R-C
		BRAGFLO	Long-term flow up plugged and abandoned boreholes is modeled as if all intrusions occur into a downdip (southern) panel.	Disposal geometry (W1)	C
		BRAGFLO	For each repository region the model geometry preserves design volume.	Disposal geometry (W1)	R
		BRAGFLO	Pillars individual drifts and rooms are not modeled for long-term performance, and containers provide	Disposal geometry (W1)	C

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			no barrier to fluid flow.		
		BRAGFLO	Long-term flow is radial to and from the borehole that intersects the waste disposal panel during disturbed performance.	Waste-induced borehole flow (H32)	R
		BRAGFLO	DRZ provides a pathway to Marker Beds		R
		BRAGFLO	Grid and material properties are consistent with the Option D design		R
6.4.3.1 Creep Closure MASS-6.0 Creep Closure Appendix PORSURF					
		SANTOS	Creep closure is modeled using a two-dimensional model of a single room. Room interactions are insignificant.	Salt creep (W20) Changes in the stress field Excavation-induced changes in stress (W19)	R
		SANTOS	Creep closure causes a decrease in room volume, which decreases waste porosity. The amount of creep closure is a function of time, gas pressure, and waste matrix strength.	Salt creep (W20) Changes in the stress field (W21) Consolidation of waste (W32) Pressurization (W26)	R
		BRAGFLO	Porosity of operations and experimental areas is fixed at a value representative of consolidated material.	Salt creep (W20)	R
6.4.3.2 Repository Fluid Flow MASS-7.0 Repository Fluid Flow					
		BRAGFLO	General assumptions 1 to 8.		See above
		BRAGFLO	The waste disposal region is assigned a constant permeability representative of average consolidated waste without backfill.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24)	R
MASS-7.1 Flow Interactions with the Creep Closure Model					
		BRAGFLO	The experimental and operations regions are assigned a constant permeability representative of unconsolidated material and a constant porosity representative of consolidated material.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24) Salt creep (N20)	R
MASS-7.2 Flow Interactions with the Gas Generation Model					
		BRAGFLO	For gas generation calculations, the effects of wicking are accounted for by assuming that brine in the	Wicking (W41)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			repository contacts waste to an extent greater than that calculated by the Darcy flow model used.		
6.4.3.3 Gas Generation MASS-8.0 Gas Generation Appendix TRU WASTE					
		BRAGFLO	Gas generation occurs by anoxic corrosion of steel containers, and Fe and Fe-base alloys in the waste, giving H_2, and microbial consumption of cellulosics and, perhaps, plastics and rubbers, giving mainly CO_2 and CH_4. Radiolysis, oxic reactions, and other gas generation mechanisms are insignificant. Gas generation is calculated using the average - stoichiometry model, and is dependent on brine availability.	Container material inventory (W5) Waste inventory (W2) Degradation Consumption of (W44) Gases from metal corrosion (W49)	R
		BRAGFLO	The anoxic corrosion rate is dependent on liquid saturation. Anoxic corrosion of steel continues until all the steel is consumed. Steel corrosion will not be passivated by microbially-generated gases CO_2 or H_2S. Brine is consumed by the corrosion reaction.	Brine inflow (W40) Gases from metal corrosion (W49) Consumption of organic material (W44)	R
		BRAGFLO	Laboratory-scale experimental measurements of gas generation rates at expected room temperatures are used to account for the effects of biofilms and chemical reactions.	Effects of biofilms on microbial gas generation (W48) Effects of temperature on microbial gas generation (W45) Chemical effects of corrosion (W51)	R
		BRAGFLO	The rate of microbial gas production is dependent on the amount of liquid present. It is assumed that microbial activity neither produces nor consumes water. Significant microbial activity occurs in half the simulations. In half of the simulations with microbial activity, microbes consume all of the cellulosics but none of the plastics and rubbers. In the other half of the simulations with microbial activity, microbes consume all of the cellulosics and all of the plastics and rubbers. Microbial production will	Brine inflow (W40) Consumption of CPR (W44) Waste inventory (W2)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			continue until all biodegradable CPR materials are consumed if brine is present. The MgO backfill will react with all of the CO_2 and remove it from the gaseous phase.		
		BRAGFLO	Gas dissolution in brine is of negligible consequence.	Fluid flow caused by gas production (W42)	R
		BRAGFLO	The gaseous phase is assigned the properties of hydrogen (general assumption 8).	Fluid flow caused by gas production (W42)	See above
6.4.3.4 Chemical Conditions in the Repository SOTERM-2.0 Conceptual Framework of Chemical Conditions					
		NUTS PANEL	Chemical conditions in the repository will be constant. Chemical equilibrium is assumed for all reactions that occur between brine in the repository, waste, and abundant minerals, with the exceptions of gas generation and redox reactions.	Speciation (W56) Redox kinetics (W66)	R
		NUTS PANEL	Brine and waste in the repository will contain a uniform mixture of dissolved and solid-state species. All actinides have instant access to all repository brine.	Heterogeneity of waste forms (W3) Speciation (W56)	C
		NUTS PANEL	No microenvironments that influence the overall chemical environment will persist.	Speciation (W56)	R
		NUTS PANEL	For the undisturbed performance and E2 scenarios, brine in the waste panels has the composition of Salado brine. For E1 and E1E2 scenarios, all brine in the waste panel intersected by the borehole has the composition of Castile brine.	Speciation (W56)	R
		NUTS PANEL	Chemical conditions in the waste panels will be reducing. However, a condition of redox disequilibrium will exist between the possible oxidation states of the actinide elements.	Redox kinetics (W56) Speciation (W56) Effects of metal corrosion (W64)	R
		NUTS PANEL	The pH and f_{CO2} in the waste panels will be controlled by the equilibrium between brucite and hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) (A result of this assumption is low f_{CO2} and mildly basic conditions).	Speciation (W56) Backfill chemical composition (W10)	R
6.4.3.5 Dissolved Actinide Source Term					

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
SOTERM-3.3 The FMT Computer Code					
		NUTS PANEL	Radionuclide dissolution to solubility limits is instantaneous.	Dissolution of waste (W58)	C
		NUTS PANEL	Six actinides (Th, U, Np, Pu, Am, and Cm) are considered in PANEL for calculations of radionuclide transport of brine (up a borehole). Four actinides (Th, U, Pu, and Am) are considered in NUTS for calculations of radionuclide transport in brine (porous materials) (Leigh 2003). Choice of radionuclides is discussed in Appendix TRU WASTE, Table TRU WASTE-9.	Waste inventory (W2)	R
		NUTS PANEL	The reducing conditions in the repository will eliminate significant concentrations of Np(VI), Pu(V), Pu(VI), and Am(V)species. Am and Cm will exist predominantly in the +III oxidation state, Th in the +IV oxidation state. It is assumed that the solubilities and K_ds of U, Np, and Pu will be dominated by one of the remaining oxidation states: U(IV) or U(VI), Np(IV or Np(V), and Pu(III) or Pu(IV).	Speciation (W56) Redox kinetics (W66)	R
		NUTS PANEL	For a given oxidation state, the different actinides exhibit similar chemical behavior and thus have similar solubilities.	Speciation (W56)	R
		NUTS PANEL	For undisturbed performance and for all aspects of disturbed performance except for cuttings and cavings releases, radionuclide-bearing compounds are distributed evenly throughout the disposal panel.	Waste inventory (W2) Heterogeneity of waste forms (W3)	R
		NUTS PANEL	Mobilization of actinides in the gas phase is negligible.	Dissolution of waste (W58)	R
		NUTS PANEL	Actinide concentrations in the repository will be inventory limited when the mass of an actinide becomes depleted such that the predicted solubilities cannot be achieved.	Dissolution of waste (W58)	R
6.4.3.6 Source Term for Colloidal Actinides					
		NUTS PANEL	Four types of colloids constitute the source term for colloidal actinides; microbes, humic substances, intrinsic	Colloid formation and stability (W79) Humic and fulvic acids	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			colloids, and mineral fragments.	(W70)	
		NUTS PANEL	The only intrinsic colloids that will form are those of the plutonium Pu(IV) polymer.	Colloid formation and stability (W79)	R
		NUTS PANEL	Concentrations of intrinsic colloids and mineral-fragment colloids are modeled as constants that were based on experimental observations. Humic and microbial colloidal actinide concentrations are modeled as proportional to dissolved actinide concentrations.	Colloid formation and stability (W79)	R
		NUTS PANEL	The maximum concentration of each actinide associated with each colloid type is constant.	Actinide sorption (W61)	R
6.4.4 Shafts and Shaft Seals MASS-12.0 Shafts and Shaft Seals					
		BRAGFLO	General Assumptions 1 to 8.		See above
		BRAGFLO	The four shafts connecting the repository to the surface are represented by a single shaft with a cross-section and volume equal to the total volume of the four real shafts and separated from the waste by less than the distance of the nearest real shaft.	Disposal geometry (W1)	R
		BRAGFLO	The seal system is represented by an upper and lower shaft region representing a composite of the actual materials in those regions.	Seal geometry (W6) Seal physical properties (W7)	R
		BRAGFLO	The shaft is surrounded by a DRZ which heals with time. The DRZ is represented through the composite permeabilities of the shaft system itself, rather than as a discrete zone. The effective permeability of shaft materials are adjusted at 200 years after closure to reflect consolidation and possible degradation. Permeabilities are constant for the shaft seal materials through the Rustler formation.	Salt creep (W20) Consolidation of seals (W36) DRZ (W18) Microbial growth on concrete (W76) Chemical degradation of seals (W74) Mechanical degradation of seals (W37)	R
		BRAGFLO	Concrete shaft components of the lower shaft are modeled as if they degrade after emplacement.	Mechanical degradation of seals	C
		NUTS	Radionuclides are not retarded by the	Actinide sorption (W61)	C

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			seals.	Speciation (W56)	
6.4.5 The Salado MASS-13.0 Salado					
		BRAGFLO	General Assumptions 1 to 8.		See above
6.4.5.1 Impure Halite MASS-13.1 High Threshold Pressure for Halite-Rich Salado Rock Units					
		BRAGFLO	Rock and hydrologic properties are constant.	Stratigraphy (N1)	R
6.4.5.2 Salado Interbeds MASS-13.3 The Fracture Model					
		BRAGFLO	Interbeds have a fracture-initiation pressure above which local fracturing and changes in porosity and permeability occur in response to changes in pore pressure. A power function relates the permeability increase to the porosity increase. A pressure is specified above which porosity and permeability do not change.	Disruption caused by gas effects (W25)	R
		BRAGFLO	Interbeds have identical physical properties; they differ only in position, thickness, and some fracture parameters.	Saturated groundwater flow (N23)	R
6.4.5.3 Disturbed Rock Zone MASS-13.4 Flow in the Disturbed Rock Zone					
		BRAGFLO	The permeability of the DRZ is sampled with the low value similar to intact halite and a high value representing a fractured material. The DRZ porosity is equal to the porosity of impure halite to plus 0.29 percent.	Disturbed rock zone (W18) Roof falls (W22) Gas explosions (W27) Seismic activity (N12) Underground boreholes (W39)	C-R
6.4.5.4 Actinide Transport in the Salado MASS-13.5 Actinide Transport in the Salado					
		NUTS	Dissolved actinides and colloidal actinides are transported by advection in the Salado. Diffusion and dispersion are assumed negligible.	Advection (W90) Diffusion (W91) Matrix diffusion (W92)	R
		NUTS	Sorption of actinides in the anhydrite interbeds, colloid retardation, colloid transport at higher than average velocities, co-precipitation of minerals containing actinides, channeled flow, and viscous fingering are not	Actinide sorption (W61) Colloid transport (W78) Colloid filtration (W80) Colloid sorption (W81) Fluid flow caused by gas production (W42)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			modeled.	Fracture flow (N25)	
		NUTS	Radionuclides having the same elemental form are grouped as discussed in Appendix TRU WASTE.	Radioactive decay and ingrowth (W12)	R
		NUTS	Sorption of actinides in the borehole is not modeled.	Actinide sorption (W61)	C
6.4.6 Units Above the Salado MASS-14.0 Geologic Units above the Salado					
		SECOTP2D	Above the Salado, lateral actinide transport to the accessible environment can occur only through the Culebra.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24) Solute transport (W77)	R
6.4.6.1 Los Medaños					
		MODFLOW-2000 BRAGFLO	The Los Medaños member of the Rustler Formation, Tamarisk, and Forty-niner are assumed to be impermeable.	Saturated groundwater flow (N23)	C
6.4.6.2 The Culebra MASS-15.0 Culebra Attachment TFIELD					
		MODFLOW-2000 SECOTP2D	General Assumptions 1, 6, and 8 (see first page of this table).		See above
		MODFLOW-2000 SECOTP2D	For fluid flow the Culebra is modeled as a uniform (single-porosity) porous medium. For radionuclide transport a double-porosity model is used (advection in high permeability features and diffusion and sorption in low-permeability features).	Saturated groundwater flow (N23) Fracture flow (N25) Advection (W90) Diffusion (W91)	R
		MODFLOW-2000	The Culebra flow field is determined from the observed hydraulic conditions and estimates of the effects of climate change and potash mining outside the controlled area, and does not change with time unless mining is predicted to occur in the disposal system in the future.	Saturated groundwater flow (N23) Climate change (N61) Precipitation (for example, rainfall) (N59) Temperature (N60) Changes in groundwater flow caused by mining (H37)	R
		BRAGFLO	The Culebra is assigned a single permeability to calculate brine flow into the unit from an intrusion borehole.	Natural borehole fluid flow (H31) Waste-induced borehole flow (H32)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
		MODFLOW-2000	Gas flow in the Culebra is not modeled. Gas from the repository does not affect fluid flow in the Culebra.	Saturated groundwater flow (N23) Fluid flow caused by gas production (W42)	R
		BRAGFLO MODFLOW-2000 SECOTP2D	Different thickness of the Culebra are assumed for BRAGFLO, MODFLOW-2000, and SECOTP2D calculations, although the transmissivities are consistent.	Effects of preferential pathways (N27)	R
		PEST	Uncertainty in the spatial variability of the Culebra transmissivity is accounted for by statistically generating many T-fields.	Saturated groundwater flow (N23) Fracture flow (N25) Shallow dissolution (N16)	R
		MODFLOW-2000 BRAGFLO	Potentiometric heads are set on the edges of the regional grid to represent flow in a portion of a much larger hydrologic system.	Groundwater recharge (N54) Groundwater discharge (N53) Changes in groundwater recharge and discharge (N56) Infiltration (N55)	R
6.4.6.2.1 Transport of Dissolved Actinides in the Culebra MASS-15.2 Dissolved Actinide Transport and Retardation in the Culebra					
		SECOTP2D	Dissolved actinides are transported by advection in high-permeability features and diffusion in low permeability features.	Solute transport (W77) Advection (W90) Diffusion (W91) Matrix diffusion (W92)	R
		SECOTP2D	Sorption occurs on dolomite in the matrix. Sorption on clays present in the Culebra is not modeled.	Actinide sorption (W61) Changes in sorptive surfaces (W63)	C
		SECOTP2D	Sorption is represented using a linear isotherm model.	Actinide sorption (W61) Kinetics of sorption (W62)	R
		SECOTP2D	The possible effects on sorption of the injection of brines from the Castile and Salado into the Culebra are accounted for in the distribution of actinide K_ds.	Actinide sorption (W61) Groundwater geochemistry (N36, N37) Natural borehole fluid flow (H31)	R
		SECOTP2D	Hydraulically-significant fractures are assumed to be present everywhere in the Culebra.	Advection (W90)	C
6.4.6.2.2 Transport of Colloidal Actinides in the Culebra MASS-15.3 Colloidal Actinide Transport and Retardation in the Culebra					

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
		SECOTP2D	Humic actinides are chemically retarded identically to dissolved actinides and are treated as dissolved actinides.	Advection (W90) Diffusion (W91) Colloid transport (W78) Microbial transport (W87)	R
		SECOTP2D	The concentration of intrinsic colloids is sufficiently low to justify elimination from PA transport calculations.		R
		SECOTP2D	Microbial colloids and mineral fragments are too large to undergo matrix diffusion. Filtration of these colloids occurs in high permeability features (which is modeled using a decay approach). Attenuation is so effective that associated actinides are assumed to be retained within the disposal system and are not transported in SECOTP2D.	Microbial transport (W87) Colloid sorption (W81)	R
6.4.6.2.3 Subsidence Due to Potash Mining MASS-15.4 Subsidence Caused by Potash Mining in the Culebra					
		MODFLOW-2000	The effect of potash mining is to increase the hydraulic conductivity in the Culebra by a factor from 1 to 1,000.	Potash mining (H13) Changes in groundwater flow caused by mining (H37)	Reg.
6.4.6.3 The Tamarisk					
		MODFLOW-2000 BRAGFLO	The Tamarisk is assumed to be impermeable.	Saturated groundwater flow (N23)	R
6.4.6.4 The Magenta					
		BRAGFLO	General Assumptions 1 to 8 (see first page of this table).		See above
		BRAGFLO	The Magenta permeability is set to the lowest value measured near to the center of the WIPP site. This increases the flow into the Culebra.	Saturated groundwater flow (N23)	R
		NUTS	No radionuclides entering the Magenta will reach the accessible environment. However, the volumes of brine and actinides entering and stored in the Magenta are modeled.	Solute transport (W77)	R
6.4.6.5 The Forty-niner					
		BRAGFLO	The Forty-niner is assumed to be impermeable.	Saturated groundwater flow (N23)	R
6.4.6.6 Dewey Lake					

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
		BRAGFLO	General Assumptions 1 to 8 (see first page of this table).		See above
		NUTS	The sorptive capacity of the Dewey Lake is sufficiently large to prevent any release over 10,000 years.	Saturated groundwater flow (N23) Actinide sorption (W61)	R
6.4.6.7 Supra-Dewey Lake Units					
		BRAGFLO	General Assumptions 1 to 8 (see first page of this table).		See above
		BRAGFLO	The units above the Dewey Lake are a single hydrostratigraphic unit.	Stratigraphy (N1)	R
		BRAGFLO	The units are thin and predominantly unsaturated.	Unsaturated groundwater flow (N24) Saturated groundwater flow (N23)	R
6.4.7 The Intrusion Borehole MASS-16.0 Intrusion Borehole					
6.4.7.1 Releases During Drilling					
		CUTTINGS_S BRAGFLO DRSPALL	Any actinides that enter the borehole are assumed to reach the surface.	—	C
MASS-16.1 Cuttings, Cavings, and Spall Releases during Drilling					
		BRAGFLO PANEL CUTTINGS_S DRSPALL	Future drilling practices will be the same as they are at present.	Oil and gas exploration (H1) Potash exploration (H2) Oil and gas exploitation (H4) Other resources (H8) Enhanced oil and gas recovery (H9)	Reg.
		CUTTINGS_S DRSPALL	Releases of particulate waste material are modeled (cuttings, cavings, and spallings). Releases are corrected for radioactive decay until the time of intrusion.	Drilling fluid flow (H21) Suspension of particles (W82) Cuttings (W84) Cavings (W85) Spallings (W86)	R
		CUTTINGS_S	Degraded waste properties are based on properties of marine clays, considered a worst case	Cavings (W85)	C
		DRSPALL	A hemispherical geometry with one-dimensional spherical symmetry defines the flow field and cavity in the waste	Spallings (W86)	**C**
		DRSPALL	Tensile strength, based on completely degraded waste surrogates, is felt to	Spallings (W86)	**C**

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			represent extreme, low-end tensile strengths because it does not account for several strengthening mechanisms		
		DRSPALL	Shape factor is 0.1, corresponding to particles that are easier to fluidize and entrain in the flow	Spallings (W86)	**C**
6.4.7.1.1 Direct Brine Release During Drilling MASS-16.2 Direct Brine Releases during Drilling					
		BRAGFLO PANEL	Brine containing actinides may flow to the surface during drilling. Direct brine release will have negligible effect on the long-term pressure and saturation in the waste panel.	Blowouts (W23)	R
		BRAGFLO	A two-dimensional grid (one degree dip) on the scale of the waste disposal region is used for direct brine release calculations.	Blowouts (H23)	R
		BRAGFLO CCDFGF	Calculation of direct brine release from several different locations provides reference results for the variation in release associated with location.	Blowouts (H23)	R
6.4.7.2 Long-Term Releases Following Drilling MASS-16.3 Long-Term Properties of the Abandoned Intrusion Borehole					
		BRAGFLO CCDFGF	Plugging and abandonment of future boreholes are assumed to be consistent with practices in the Delaware Basin.	Natural borehole fluid flow (H31) Waste-induced borehole flow (H32)	Reg.
6.4.7.2.1 Continuous Concrete Plug through the Salado and Castile					
		BRAGFLO CCDFGF	A continuous concrete plug is assumed to exist throughout the Salado and Castile. Long-term releases through a continuous plug are analogous to releases through a sealed shaft.	Natural borehole fluid flow (H31) Waste-induced borehole flow (H32)	Reg-R
6.4.7.2.2 The Two-Plug Configuration					
		BRAGFLO	A lower plug is located between the Castile brine reservoir and underlying formations. A second plug is located immediately above the Salado. The brine reservoir and waste panel are in direct communication though an open cased hole.	Natural borehole fluid flow (H31) Waste-induced borehole flow (H32)	Reg.-R
		BRAGFLO	The casing and upper concrete plug	Natural borehole fluid	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			are assumed to fail after 200 years, and the borehole is assumed to be filled with silty-sand like material. At 1,200 years after abandonment the permeability of the borehole below the waste panel is decreased by one order of magnitude as a result of salt creep.	flow (H31) Waste-induced borehole flow (H32)	
6.4.7.2.3 The Three-Plug Configuration					
		BRAGFLO	In addition to the two plug configuration, a third plug is placed within the Castile above the brine reservoir. The third plug is assumed not to fail over the regulatory time period.	Natural borehole fluid flow (H31) Waste-induced borehole flow (H32)	Reg.-R
6.4.8 Castile Brine Reservoir MASS-18.0 Castile Brine Reservoir					
		BRAGFLO	The Castile region is assigned a low permeability, which inhibits fluid flow. Brine occurrences in the Castile are bounded systems. Brine reservoirs under the waste panels are assumed to have limited extent and interconnectivity, with effective radii on the order of several hundred meters.	Brine reservoirs (N2)	R
6.4.9 Climate Change MASS-17.0 Climate Change					
		SECOTP2D	Climate-related factors are treated through recharge. A parameter called the Climate Index is used to scale the Culebra flux field.	Climate change (N61) Temperature (N60) Precipitation (for example, rainfall) (N59)	R
6.4.10 Initial and Boundary Conditions for Disposal System Modeling					
6.4.10.1 Disposal System Flow and Transport Modeling (BRAGFLO and NUTS)					
		BRAGFLO	There are no gradients for flow in the far-field of the Salado, and pressures are above hydrostatic, but below lithostatic. Excavation and waste emplacement result in partial drainage of the DRZ.	Saturated groundwater flow (N23) Brine inflow (W40)	R
		BRAGFLO	An initial water-table surface is set in the Dewey Lake at an elevation of 3,215 ft (980 m) above mean sea level. The initial pressures in the Salado are extrapolated from a sampled pressure in MB139 at the	Saturated groundwater flow (N23)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			shaft and are in hydrostatic equilibrium. The excavated region is assigned an initial pressure of one atmosphere. The liquid saturation of the waste-disposal region is consistent with the liquid saturation of emplaced waste. Other excavated regions are assigned zero liquid saturation, except the shaft which is fully saturated.		
		NUTS	Molecular transport boundary conditions are no diffusion or dispersion in the normal direction across far-field boundaries. Initial actinide concentrations are zero everywhere except in the waste.	Radionuclide decay and ingrowth (W12) Solute transport (W77)	R
6.4.10.2 Culebra Flow and Transport Modeling (MODFLOW-2000, SECOTP2D)					
		MODFLOW-2000	Constant head and no flow boundary conditions are set on the far-field boundaries of the flow model.	Saturated groundwater flow (N23)	R
		MODFLOW-2000	Initial actinide concentrations in the Culebra are zero.	Solute transport (W77)	R
6.4.10.3 Initial and Boundary Conditions for Other Computational Models					
		NUTS PANEL BRAGFLO (direct brine release) CUTTINGS_S	Initial and boundary conditions interpolated from previously executed BRAGFLO calculation.		R
6.4.12 Sequences of Future Events					
		CCDFGF	Each 10,000 year future (random sequence of future events) is generated by randomly and repeatedly sampling: the time between drilling events; the location of drilling events; the activity level of the waste penetrated by each drilling intrusion; the plug configuration of the borehole, and the penetration of a Castile brine reservoir, and by randomly sampling the occurrence of mining in the disposal system.	Oil and gas exploration (H1) Potash exploration (H2) Oil and gas exploitation (H4) Other resources (H8) Enhanced oil and gas recovery (H9) Natural borehole fluid flow (N31) Waste-induced borehole flow (H32)	Reg.-R
6.4.12.1 Active and Passive Institutional Controls in Performance Assessment Chapter 7.0					
		CCDFGF	Active institutional controls are effective for 100 years and completely eliminate possibility of		Reg.-R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			incompatible activities. No credit is taken for passive institutional controls.		
6.4.12.2 Number and Time of Drilling Intrusions					
		CCDFGF	Drilling may occur after 100 years according to a Poisson process.	Loss of records (H57) Oil and gas exploration (H1) Potash exploration (H2) Oil and gas exploitation (H4) Other resources (H8)	Reg.-R
6.4.12.3 Location of Intrusion Boreholes					
		CCDFGF	The waste disposal region is discretized with 144 regions with the probability of each region being intersected equal. A borehole can penetrate only one region.	Disposal geometry (W1)	R
6.4.12.4 Activity of the Intersected Waste Appendix TRU WASTE					
		CCDFGF	693 waste streams identified for contact-handled (CH)-TRU and all 86 remote-handled (RH)-TRU waste streams were grouped (binned) together into one equivalent or average (WIPP-scale) RH-TRU waste stream.	Heterogeneity of waste form (W3)	R
6.4.12.5 Diameter of the Intrusion Borehole CCA Appendix DEL					
		CUTTINGS_S	The diameter of the intrusion borehole is constant at 12.25 in. (31.12 cm).		Reg.-R
6.4.12.6 Probability of Intersecting a Brine Reservoir					
		CCDFGF	One brine reservoir is assumed to exist below the waste panels. The probability that a deep borehole intersects a brine reservoir below the waste panels is sampled uniformly from 0.01 to 0.60.	Brine reservoirs (N2)	R
6.4.12.7 Plug Configuration in the Abandoned Intrusion Borehole					
		CCDFGF	The two-plug configuration has a probability of 0.698. The three-plug configuration has a probability of 0.289. The continuous concrete plug has a probability of 0.015.		Reg.-R
6.4.12.8 Probability of Mining Occurring in the Land Withdrawal Area					

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
		CCDFGF	Mining in the disposal system occurs a maximum of once in 10,000 years (a 10^{-4} probability per year).		Reg.-R
6.4.13 Construction of a Single CCDF					
		CCDFGF	Deterministic calculations are executed with BRAGFLO, NUTS, MODFLOW-2000, SECOTP2D, CUTTINGS_S, and PANEL to generate reference conditions. These reference conditions are used to estimate the consequences associated with random sequences of future events. These are in turn used to develop CCDFs.		R
		CCDFGF	10,000 random sequences of future events are generated for each CCDF plotted.		R
6.4.13.1 Constructing Consequences of the Undisturbed Performance Scenario					
		CCDFGF	A BRAGFLO and NUTS calculation with undisturbed conditions is sufficient for estimating the consequences of the undisturbed performance scenario.		R
6.4.13.2 Scaling Methodology for Disturbed Performance Scenarios					
		CCDFGF	Consequences for random sequences of future events are constructed by scaling the consequences associated with deterministic calculations (reference conditions) to other times, generally by interpolation but sometimes by assuming either similarity or no consequence.		R
6.4.13.3 Estimating Long-Term Releases from the E1 Scenario					
		CCDFGF NUTS	Reference conditions are calculated or estimated for intrusions at 100, 350, 1,000, 3,000, 5,000, 7,000, and 9,000 years.	Waste-induced borehole flow (H32)	R
6.4.13.4 Estimating Long-Term Releases from the E2 Scenario					
		CCDFGF NUTS SECOTP2D	The methodology is similar to the methodology for the E1 scenario. For multiple E1 intrusions into the same panel, the additional source term to the Culebra for the second and subsequent intrusions is assumed to be negligible.	Waste-induced borehole flow (H32) Waste inventory (W2)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
6.4.13.5 Estimating Long-Term Releases from the E1E2 Scenario					
		CCDFGF PANEL	The concentration of actinides in liquid moving up the borehole assumes homogeneous mixing within the panel.	Waste-induced borehole flow (H32)	C
		PANEL	Any actinides that enter the borehole reach the Culebra.	Waste-induced borehole flow (H32)	C
		CCDFGF PANEL	Reference conditions are calculated or estimated for intrusion at 100, 300, 1,000, 2,000, 4,000, 6,000 and 9,000 years.	Oil and Gas Exploration (H1)	
6.4.13.6 Multiple Scenario Occurrences					
		CCDFGF PANEL	The panels are assumed not to be interconnected for long term brine flow.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24)	R
6.4.13.7 Estimating Releases During Drilling for All Scenarios					
		CCDFGF PANEL NUTS	Repository conditions will be dominated by Castile brine if any borehole connects to a brine reservoir.	Brine reservoirs (N2) Natural borehole fluid flow (H31)	R
		CUTTINGS_S PANEL CCDFGF	Depletion of actinides in parts of the repository that have been penetrated by boreholes is not accounted for in calculating the releases from subsequent intrusions at such locations.	Waste-induced borehole flow (N32) Waste inventory (W2)	C
6.4.13.8 Estimating Releases in the Culebra and the Impact of the Mining Scenario					
		CCDFGF MODFLOW-2000 SECOTP2D	Releases from intrusions at random times in the future are scaled from releases calculated at 100 years with a unit source of radionuclides in the Culebra.		R
		CCDFGF	Actinides in transit in the Culebra when mining occurs are transported in the flow field used for the undisturbed case. Actinides introduced subsequent to mining are transported in the flow field used for the disturbed case (that is, mined case).		R

* R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

Three other two-dimensional model geometries are used in performance assessment. For fluid flow and transport modeling in the Culebra, the geometry is a horizontal two-dimensional plane (see Sections 6.4.2 and 6.4.6.2). For modeling brine flow from the intruded panel to the borehole during drilling, the geometry is a two-dimensional, horizontal representation of a waste panel (see Section 6.4.7). For modeling brine flow that might occur between an E-type borehole and other boreholes penetrating the repository, the geometry used is a two-dimensional, horizontal representation of the entire repository (see Section 6.4.2). These geometries are mentioned here but not discussed in detail because they are components of other conceptual models requiring geometric assumptions.

The two-dimensional geometry developed for the Salado is based on the assumption that brine and gas flow will converge upon and diverge from the repository horizon. The impact of this conceptual model and its implementation in a two-dimensional grid has been compared to a model that does not make the assumption of convergent and divergent flow (see Attachment 4-1 for additional information). The conceptual model for the Salado includes the slight and variable dip of beds in the vicinity of the repository, which might affect fluid flow.

Above and below the repository, it is assumed that any flow between the borehole or shaft (see Section 6.4.3) and surrounding materials will converge or diverge. With respect to flow in units overlying the Salado, the only purpose of this conceptual model is to determine the quantity (flux) of fluid leaving or entering the borehole or shaft. Fluid movement through the units above the Salado is treated in a different conceptual model (see Section 6.4.6). Below the repository, the possible presence of a brine reservoir is considered to be important, so a hydrostratigraphic layer representing the Castile and a possible brine reservoir in it is included (see CCA Appendix MASS, Section MASS.4.2 for the disposal system geometry historical context prior to the CCA).

MASS-4.2 Change to Disposal System Geometry Since the CCA

Changes have been made to the disposal system geometry since the first WIPP certification. The disposal system geometry is specifically represented in BRAGFLO. This section describes the methodology used to create the two-dimensional BRAGFLO computational grid used for the 2004 PA calculations. The CRA-2004 grid is similar to that used for the CCA and PAVT, except for the differences that are described below.

The most important changes with respect to the CRA BRAGFLO grid are the implementation of the Option D panel closures and a simplified shaft seal model. Additional grid refinements have also been implemented to increase numerical accuracy and computational efficiency and to reduce numerical dispersion, but these refinements do not entail any changes to conceptual models. All conceptual model changes were approved by the Salado Flow Peer Review Panel in February 2003 (Caporuscio et al. 2003). For completeness, all changes from the CCA/PAVT grid are described here.

MASS-4.2.1 Baseline Grid Changes

The baseline grid used in the CCA and PAVT had (NX, NY) dimensions of (33, 31). The grid used for the CRA-2004 calculations has dimensions (68, 33). The specific changes that have been implemented in the CRA-2004 grid are listed below and then discussed in more detail in the

following sections. Logical grids for the CCA/PAVT and CRA are shown in Figures MASS-3 and MASS-4.

Changes implemented in the CRA-2004 Grid:

1. A simplified shaft seal model is implemented,
2. Option D type panel closures are implemented,
3. Segmentation of the waste regions is increased,
4. A grid flaring method is redefined and simplified,
5. X spacing of the grid beyond the repository to the north and south is refined, and
6. Layers above and below MB 139 have been made relatively thin (~1 m thick), and Y-spacing in Salado has been changed.

MASS-4.2.2 Simplified Shaft Seal Model

A shaft seal model is included in the CRA-2004 grid, but it is implemented in a simpler fashion than was used for the CCA and PAVT. A detailed description of the parameters used to define the simplified model is discussed in AP-094 (James and Stein 2002) and the resulting

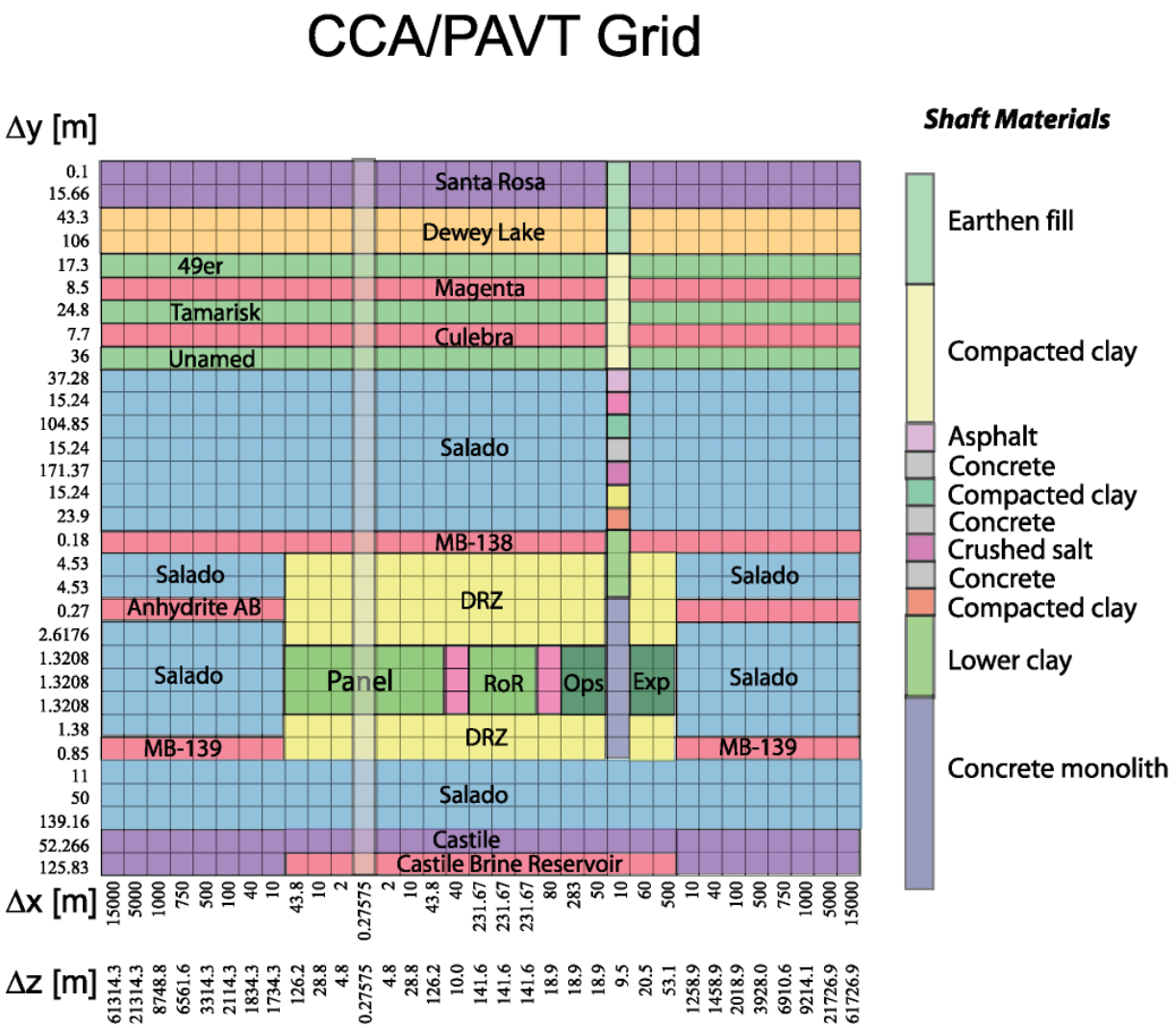

Figure MASS-3. Logical Grid Used for the 1996 WIPP PA BRAGFLO Calculations

analysis report (James and Stein 2003). The model that is used in the 2004 PA is described by Stein and Zelinski (2003a; 2003b), and was approved by the Salado Flow Peer Review panel (Caporuscio et al. 2003).

The new model does not alter the conceptual model of the shaft seal components as described in the CCA. Rather, it represents the behavior of seal components in the repository system model. Specifically, the original 11 separate material layers that defined the shaft model for the CCA were reduced to two layers each with properties equivalent to the composite effect of the original materials combined in series. Additionally, the six time intervals that were used to represent the evolution of the shaft seal materials over time were reduced to two intervals. The CRA and CCA shaft models are graphically compared in Figure MASS-5. The simplified shaft model was tested in the AP-106 calculations (Stein and Zelinski 2003a; 2003b), which supported the Salado Flow Peer Review. The results of this analysis demonstrated that brine flow through the simplified shaft model was comparable to brine flows seen through the

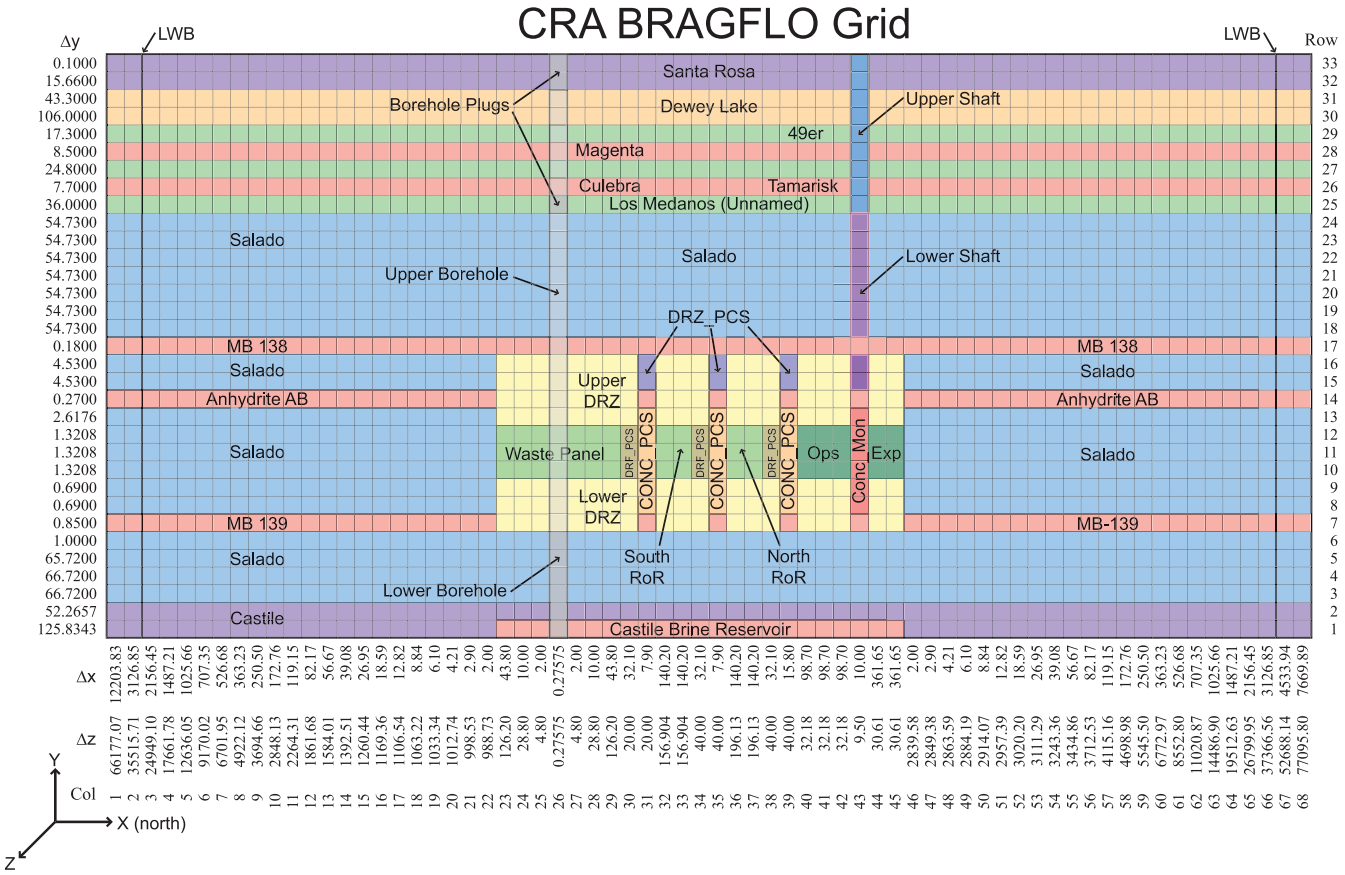

Figure MASS-4. Logical Grid Used for the 2004 PA BRAGFLO Calculations

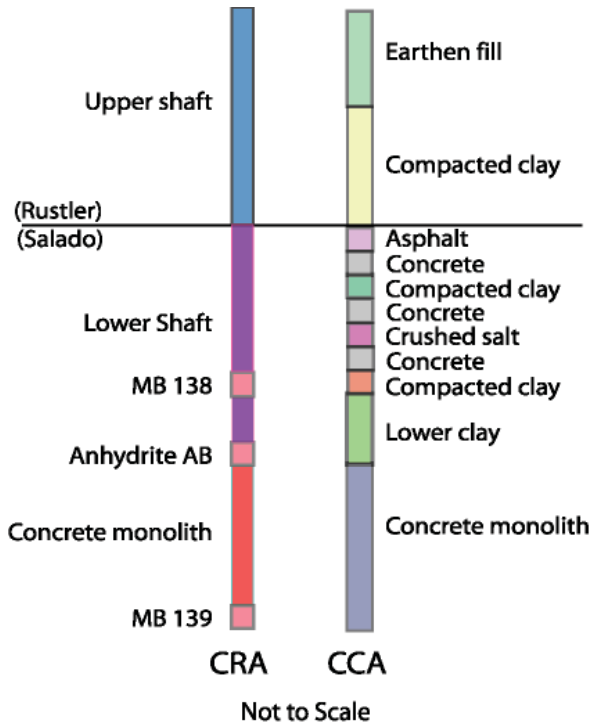

Figure MASS-5. Comparison of the Simplified Shaft (CRA-2004) and the Detailed Shaft (CCA) Models

detailed shaft model in the 1997 PAVT calculations. The conclusion remains that the shaft seals are very effective barriers to flow throughout the 10,000-year regulatory period.

MASS-4.2.3 Implementation of Option D Type Panel Closure

In the CCA, the DOE presented four options for panel closure designs (A through D). Upon reviewing the CCA, the EPA mandated the implementation of the Option D design. For CRA-2004, the true cross-sectional area of the Option D panel closures is represented in the flow model. In addition, to appropriately represent the effect of Option D geometry on repository fluid flow, the segmentation of the waste regions was increased in the grid. This change is described fully in MASS-4.2.4.

For CRA-2004, three sets of panel closures are included in the model domain. The southernmost set of closures represents a pair of closures separating a single waste panel from the other waste areas. The middle set of closures represents four panel closures that will be emplaced between the southern and northern extended panels. The northernmost set of panel closures represents two sets of four panel closures that will be emplaced between the waste regions and the shaft seals.

Each set of panel closures is represented in the CRA-2004 grid with four materials. Refer to Figure MASS-6.

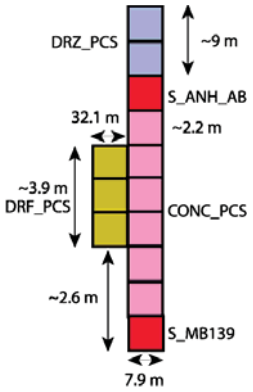

Figure MASS-6. Logical Grid Representation of the Option D Panel Closures for the CRA.

1. CONC_PCS: This material represents the concrete monolith, which has properties of SMC.

2. DRZ_PCS: This material represents the DRZ immediately above the concrete monolith that is expected to heal after the emplacement of the monolith.

3. DRF_PCS: This material represents the empty drift and explosion wall portion of the panel closure. This material has the same properties as WAS_AREA (including creep closure).

4. Marker bed materials: These materials are the same as those used to represent the anhydrite marker beds in other parts of the grid. Marker bed materials were used because they have permeability ranges very close to the material CONC_PCS and in the case when pressures near the panel closures exceed the fracture initiation pressure of the marker beds, fractures could extend around the concrete monolith out of the 2-D plane represented by the numerical grid. By using marker bed materials to represent the parts of the panel closures that intersect marker beds, both the permeability of the closure and the potential fracture behavior of marker bed material near the closures are represented.

Figure MASS-7 is a schematic diagram comparing the panel closure implementation in the CCA and CRA-2004 grids. Permeability ranges are indicated for all materials. Figure MASS-6 shows the 13 grid cells used to represent each set of Option D panel closures in the CRA-2004 BRAGFLO grid.

MASS-4.2.4 Increased Segmentation of Waste Regions in Grid

The CCA/PAVT grid divided the waste regions into two regions; a single panel in the southern end of the repository referred to as the Waste Panel, and a larger region containing the other nine panels referred to as the RoR. The Waste Panel is intersected by an intrusion borehole and is used to represent conditions in any panel that is intersected by a borehole. It is assumed that the Option D panel closures are effective at impeding flow between panels. Therefore, it was considered necessary to divide the RoR into northern and southern blocks

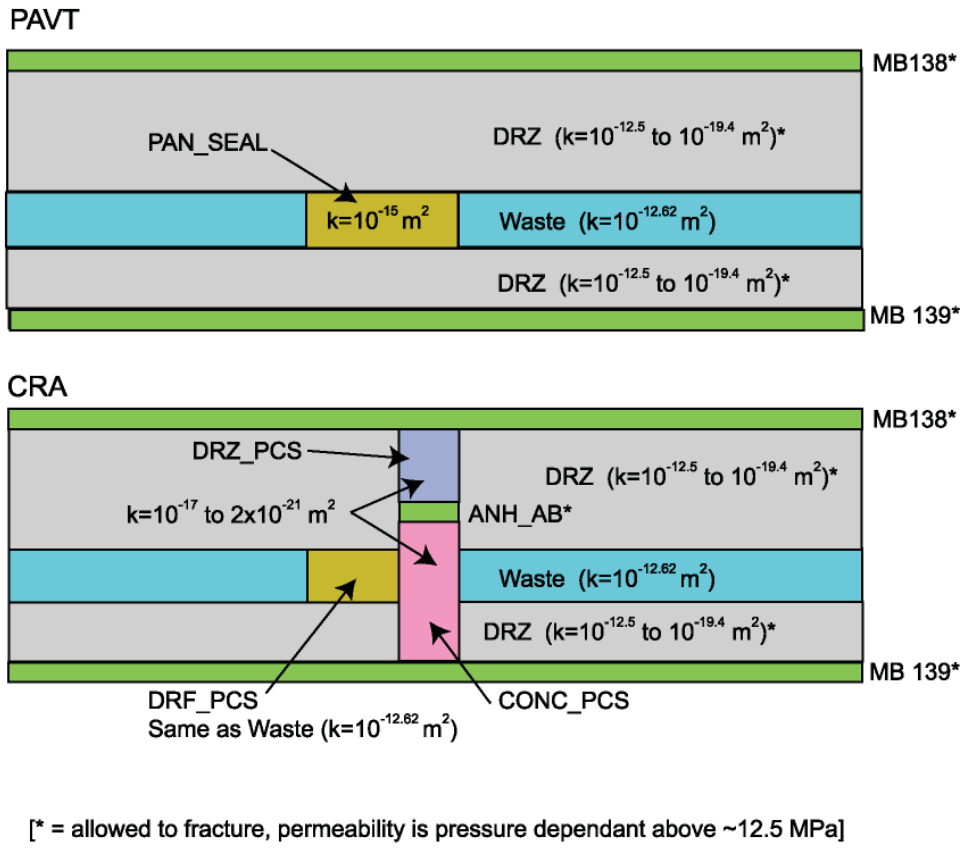

[* = allowed to fracture, permeability is pressure dependant above ~12.5 MPa]

Figure MASS-7. Schematic Comparison of the Representation of Panel Closures in the PAVT and CRA-2004.

separated by a set of panel closures. The south RoR block represents conditions in a panel directly adjacent to an intruded panel. The north RoR block represents conditions in a nonadjacent panel far from the intruded panel (has at least two panel closures between it and the intruded panel). This representation assumes that the effects of drilling intrusions will be damped in nonintruded panels and the degree of damping will depend on the proximity of the drilling intrusion and the number of panel closures separating the intruded panel from other regions of the repository. The delta Z dimensions of the RoR blocks were chosen so that the volume of the southern and northern RoR blocks were equivalent to four and five panels, respectively.

It should be noted that the total volume of the waste-filled areas represented in the CCA/PAVT grid (approximately 4.36×10^5 m^3) was found to be approximately 0.5 percent less than the designed volume (approximately 4.38×10^5 m^3) (Stein 2002). For CRA-2004, the larger correct volume has been used.

MASS-4.2.5 Redefined and Simplified Grid Flaring Method

Grid flaring is a method to represent 3-D volumes in a 2-D grid. Flaring is used when flows can be represented as divergent and convergent from the center of flaring. The CCA/PAVT grid used flaring at two different scales: locally around the borehole and shaft, and regionally to the north

and south of the excavated regions (around a point in the northern end of the RoR). For CRA-2004, the local flaring around the borehole is the same as in the CCA/PAVT grid. The local flaring around the shaft has been eliminated because it has been demonstrated not to be a release pathway. Likewise, the manner in which the regional flaring is calculated has been simplified.

The regional rectangular flaring occurs only for the grid blocks to the north and south of the excavated region. The CRA flaring is very similar to what was done for the CCA/PAVT grid; however the CRA flaring methodology is easier to implement. To define the flaring, it is assumed that looking from the top of the grid (x-z plane), the excavated regions of the grid can be approximated by a rectangle with length equal to the distance between the southern edge of the Waste Panel and the northern edge of the Experimental Area in the grid (x = 1830 m) and width, defined so that the area of the rectangle is equal to the total area of the excavated regions of the grid in the x-z plane (z = 80 m). In order to calculate the rectangular flaring for the grid cells outside the excavated regions, a centerline is defined to divides the flaring on the north and south. Because the waste panels are located in the southern part of the excavated area, the centerline is chosen to be the "center of waste" as the middle of the panel closure that separates the northern RoR from the southern RoR. The position of this center of the waste is described as the distances from the north and south edges of the gridded repository, DN and DS, respectively DN = 1378 m, DS = 452 m, DN + DS = 1830 m. Each flared grid block has length, Dx, and width, Dz. The block can be thought of as wrapped around the excavated area like half a rectangular onion, with the center at the center of waste (Figure MASS-8). Each Dz can be calculated from the preceding Dxs as follows.

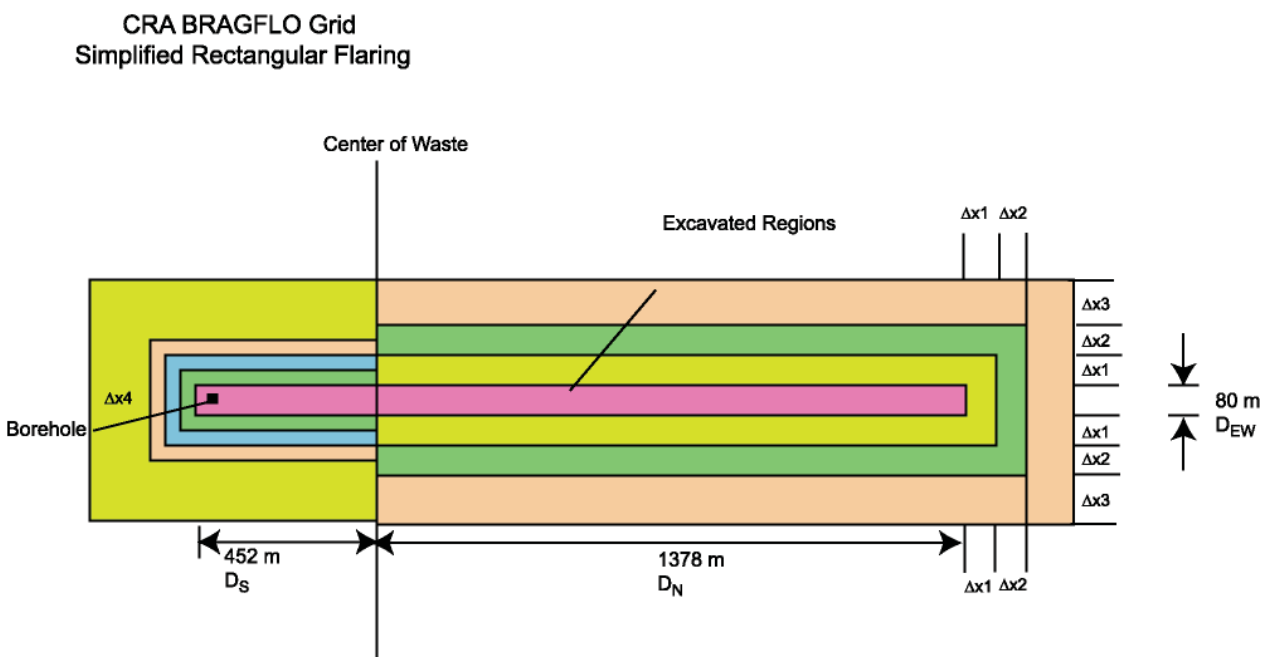

Figure MASS-8. CRA Flaring

For the northern end:

$$\Delta z_1 = 2D_N + D_{EW} + 2\Delta x_1$$

$$\Delta z_2 = 2D_N + D_{EW} + 4\Delta x_1 + 2\Delta x_2$$
$$\Delta z_3 = 2D_N + D_{EW} + 4\Delta x_1 + 4\Delta x_2 + 2\Delta x_3$$

Flaring for blocks wrapped around the southern end is the same with D_S substituted for D_N.

This method of rectangular flaring ensures that the grid accounts for all the volume surrounding the repository.

MASS-4.2.6 Refinement of the X-Spacing Outside the Repository

The grid blocks to the north and south of the excavated region will be refined in the x-direction from the baseline grid. The x-dimension of the grid cells immediately to the north and south of the repository start at 2 m and increases by a factor of 1.45. Exceptions to this are

$$\Delta z_n = 2D_N + D_{EW} + 4\sum_{i=1}^{n-1} \Delta x_i + 2\Delta x_n$$

made to ensure that the location of the Land Withdrawal Boundary (LWB) and the total extent of the grid matches that in the baseline grid. This refinement factor was chosen to reduce numerical dispersion caused by rapid increases in cell dimensions (Anderson and Woessner 1992; Wang and Anderson 1982).

MASS-4.2.7 Refinement of the Y-Spacing

In the y-direction, the grid spacing within layers representing the Salado has been changed from the CCA/PAVT. The CCA grid spacing in the Salado was dictated by the thickness of different shaft seal materials. Since the shaft is no longer represented in the model domain, the y spacing in the Salado is now uniform. In addition, two layers were added immediately above and below MB 139 to refine the grid spacing and reduce numerical dispersion. These changes result in a total of 33 y-divisions for the grid, and will increase the numerical accuracy of flow and transport calculations.

MASS-5.0 BRAGFLO GEOMETRY OF THE REPOSITORY

The repository geometry conceptual model is represented using the BRAGFLO code. As with the geometry of the disposal system discussed in Section 6.4.2.1 and earlier in this section, the principal process considered in setting up the repository geometry is fluid flow. Several features considered to be important in fluid flow are included in the conceptual model. The first is the overall dimension of the repository along the north-south trend of the cross section, as well as the major divisions within the repository (waste disposal region, operations region, and experimental region). The second is the volume of a single panel, because fluid flow to a borehole penetrating the repository can potentially access only the volume in a waste panel directly and other regions of the repository only by flow through or around a panel closure. The third is the physical dimensions of panel closures separating the single panel and the other major divisions of the repository.

Notably absent from the conceptual model for the long-term performance of the repository are pillars and individual drifts and rooms. These are excluded from the model for simplicity, and it is assumed that they have either negligible impact on fluid flow processes or, alternatively, that including them in the conceptual model would be beneficial to long-term performance because their presence could make flow paths more tortuous and decrease fluxes. This assumption includes lumping four and five of the 10 panels into the south RoR and north RoR regions respectively (see MASS-4.2.4).

The BRAGFLO model of the WIPP disposal system is a two-dimensional array of three-dimensional grid blocks. Each grid block has a finite length, width, height, volume, and surface area for its boundaries with neighboring grid blocks. The BRAGFLO two-dimensional grid is similar to any other two-dimensional grid used to treat flows, except that the grid-block dimension in the direction perpendicular (z-direction) to the plane of the grid varies from block to block as a function of the lateral direction (x-direction; see MASS-4.2.5). This allows the BRAGFLO grid to treat important geometric aspects of the WIPP disposal system, such as the very small intrusion borehole, the moderate-size shaft, and the larger controlled areas. The grid configurations used in the 1996 CCA PA and 1997 PAVT are shown in Figure MASS-3 while the 2004 PA grid is shown in Figure MASS-4.

MASS-5.1 Historical Context of the Repository Model

Several early models of repository fluid-flow behavior (models of radionuclide migration pathways, gas flow from the disposal area to the shaft, Salado brine flow through panel to borehole, effects of anhydrite layers on Salado brine flow through a panel, and flow from a brine reservoir through a disposal room) are summarized in a 1990 report (Rechard et al. 1990). In the preliminary performance assessment of 1992, all waste was lumped into a single region (WIPP Performance Assessment Department 1993). Because human intrusion boreholes were treated in detail for the 1996 performance assessment, it was necessary to model a single waste panel with a borehole surrounded by two-dimensional radial-flaring gridblocks. This approach is continued for the 2004 PA. The 1996 PA treated the remainder of the waste area as a single RoR. For the 2004 PA, the RoR is divided into two areas separated by a panel closure system. This change was made to more adequately simulate the effects of the Option D closure in impeding fluid flow between panels.

MASS-6.0 CREEP CLOSURE

The model used for creep closure of the repository is discussed in Appendix PA, Attachment PORSURF.4.11. Historical information is contained in CCA Appendix PORSURF.

MASS-7.0 REPOSITORY FLUID FLOW

This model represents the long-term flow behavior of liquid and gas in the repository and its interaction with other regions in which fluid flow may occur, such as the Salado, shafts, or intrusion borehole. This model is not used to represent the interaction of fluids in the repository with a borehole during drilling. Historical information on alternative conceptual models for brine inflow to the repository is contained in CCA Appendix MASS, Section MASS.7.

The third conceptual model for flow, the clay consolidation model, arises from observations made as part of the BSEP. On the basis of observations recorded during more than nine years of

The first principle in the conceptual model for fluid flow in the repository is that gas and brine can be both present and mobile (two-phase flow), governed by conservation of energy and mass and by Darcy's Law for their fluxes (see Appendix PA, Section PA-4.2). Consistent with typical concepts of two-phase flow, the phases can affect each other by impeding flow caused by partial saturation (relative permeability effects) and by affecting pressure caused by capillary forces (capillary pressure effects).

The flow of brine and gas in the repository is assumed to behave as two-phase, immiscible, Darcy flow (see Appendix PA, Section PA-4.2). BRAGFLO is used to simulate brine and gas flow in the repository and to incorporate the effects of disposal room closure and gas generation. Fluid flow in the repository is affected by the following factors:

- the geometrical association of pillars, rooms, and drifts; panel closure caused by creep; and possible borehole locations;
- the varied properties of the waste areas resulting from creep closure and heterogeneous contents;
- flow interactions with other parts of the disposal system; and
- reactions that generate gas.

The geometry of the panel around the intrusion borehole is consistent with the assumption that fluid flow there will occur directly toward or directly away from the borehole. The geometry represents a semi-circular volume north of the borehole and a semi-circular volume south of the borehole (representing the assumption of radial flow in a subregion of a two-dimensional representation of the repository.

Approximating convergent and divergent flow around the intrusion borehole creates a narrow neck in the otherwise fairly uniform width grid in the region representing the repository. In the undisturbed performance scenario and under certain conditions in other scenarios, flow in the repository may pass laterally through this neck. In reality, this neck does not exist. The presence in the model is expected to have a negligible or conservative impact on model predictions compared to predictions that would result from use of a more realistic model geometry. The time scale involved and the permeability contrast between the repository and surrounding rock are sufficient that lateral flow that may occur in the repository is restricted by the rate at which liquid gets into or out of the repository, rather than the rate at which it flows through the repository.

Gas generation is affected by the quantity of liquid in contact with metal. However, the distribution of fluid in the repository can be only approximated. For example, capillary action can create wicking that would increase the overall region in which gas generation occurs, but this cannot be modeled at the necessary resolution to fundamentally stimulate processes without undesirable effects on the duration of the model simulations. Therefore, as a bounding measure

for gas generation purposes, brine in the repository is distributed to an extent greater than actually estimated by the Darcy flow models used and values of parameters chosen.

Option D panel closures and the surrounding rocks are represented by a group of materials, which include:

1. SMC,
2. a material representing the empty drift and explosion wall,
3. a material representing healed DRZ, and
4. Marker beds.

SMC and healed DRZ materials are assigned permeability values that are sampled independently from a distribution ranging from 2×10^{-21} to 1×10^{-17} m^2. This value range is considered reasonable because the shape of the Option D closure assumes a compressive state and concrete permeability range similar to the tighter end of the 1997 PAVT permeability. This range captures the uncertainty in the long-term performance of the Option D panel closure design.

Modeling of flow within the repository is based on homogenizing the room contents into relatively large computational volumes. The approach ignores heterogeneities in disposal room contents that may influence gas and brine behavior in the room by causing fluid flow among channels or preferential paths in the waste, bypassing entire regions. Isolated regions could exist for several reasons:

- they may be isolated by low-permeability regions of waste that serve as barriers,
- connectivity with the interbeds may occur only at particular locations within the repository, or
- the repository dip may promote preferential gas flow in the upper regions of the waste.

For the CCA, the adequacy of the repository homogeneity assumption was examined in screening analyses DR-1 (Webb 1995) and DR-6 (Vaughn et al. 1995a). The analyses used an additional parameter in BRAGFLO to specify the minimum active (mobile) brine flow saturation (pseudo-residual brine saturation). Above this saturation, the normal descriptions of two-phase flow apply (that is, either the Brooks and Corey or van Genuchten and Parker relative permeability models). Below this minimum, brine is immobile, although it is available for reaction and may still be consumed during gas-generation reactions. The assumption of a minimum saturation limit was justified based on the presumed heterogeneity of the waste and the slight dip in the repository. The minimum active brine saturation was treated as an uncertain parameter and sampled uniformly between values 0.1 and 0.8 during the analysis. This saturation limit was applied uniformly throughout the disposal room to bound the impact of heterogeneities on flow (Webb 1995; Vaughn et al. 1995a). Results of this analysis showed that releases to the accessible environment in the baseline case (homogenization) are consistently higher.

The experimental and operations regions were represented in performance assessment (for the CCA) by a fixed porosity of 18.0 percent and a permeability of 10^{-11} m^2. The combination of low porosity and high permeability conservatively overestimated fluid flow through these regions and limit the capacity of these regions to store fluids, thus potentially overestimating releases to the environment. This conclusion was based on a screening analysis (Vaughn et al. 1995b) that examined the importance of permeability varying with porosity in closure regions (waste disposal region, experimental region, and operations region). To perform this analysis, a model for estimating the change in permeability with porosity in the closure regions was implemented in BRAGFLO. A series of BRAGFLO simulations was performed to determine whether permeability varying with porosity in the closure regions could enhance contaminant migration to the accessible environment. Two basic scenarios were considered in the screening analysis, undisturbed performance and disturbed performance. To assess the sensitivity of system performance on dynamic permeability in the closure regions, CCDFs of normalized contaminated brine releases were constructed and compared with the corresponding baseline conditional CCDFs. The baseline model treated permeabilities in the closure regions as fixed values. Results of this analysis showed that the inclusion of dynamic closure of the waste disposal region, experimental region, and operations region in BRAGFLO resulted in computed releases to the accessible environment that are essentially equivalent to the baseline case.

A separate analysis (Park and Hansen 2003) examined the possible effects of heterogeneity in waste container and waste material strength on room closure. The analysis of room closure found that the room porosity may vary widely depending on the type of waste container and on the emplacement of waste in the repository. However, analysis of a separate PA (Hansen et al. 2003a) found that PA results are relatively insensitive to the uncertainty in room closure and room porosity. The conclusions of the separate PA are summarized in Section MASS-21.0.

MASS-7.1 Flow Interactions with the Creep Closure Model

The dynamic effect of halite creep and room consolidation on room porosity is modeled only in the waste disposal region. Other parts of the repository, such as the experimental region and the operations region, are modeled assuming fixed (invariant with time) properties. In these regions, the permeability is held at a fixed high value representative of unconsolidated material, while the porosity is maintained at relatively low values associated with highly consolidated material. It is assumed that this combination of low porosity and high permeability conservatively overestimates flow through these regions and minimizes the capacity of this material to store fluids, thus maximizing the release to the environment. To examine the acceptability of this assumption, a screening analysis (Vaughn et al. 1995c) evaluated the effect of including closure of the experimental region and operations region. In this analysis, consolidation of the experimental region and operations region was implemented in BRAGFLO by relating pressure and time to porosity using a porosity-surface method. The porosity surface for the experimental region and operations region differs from the one used for consolidation of the disposal room and is based on an empty excavation (see Appendix PA, Attachment PORSURF). Results of the screening analysis showed that disregarding dynamic closure of the experimental region is acceptable because it is conservative: lower releases occur when closure of the experimental region and operations region is computed compared to simulations with time-invariant high permeability and low porosity.

MASS-7.2 Flow Interactions with the Gas Generation Model

Gas generation affects repository pressure, which in turn is an important parameter in other processes such as two-phase flow, creep closure, and fracturing of the interbeds and DRZ. Gas generation processes considered in performance assessment calculations include anoxic corrosion and microbial degradation. Radiolysis is excluded from performance assessment calculations on the basis of laboratory experiments and a screening analysis (Vaughn et al. 1995d) that concluded that radiolysis does not significantly affect repository performance.

In modeling gas generation, the effective liquid in a computational cell is the computed liquid in that cell plus an adjustment to account for the uncertainty associated with wicking by the waste (see Appendix PA, Section PA-4.2). Capillary action (wicking) is the ability of a material to carry a fluid by capillary forces above the level it would normally seek in response to gravity. Because the current gas-generation model computes substantially different gas-generation rates depending on whether the waste is wet or merely surrounded by water vapor, the physical extent of wetting could be important. A screening analysis (Vaughn et al. 1995e) examined wicking and concluded that it should be included in performance assessment calculations. The baseline gas-generation model in BRAGFLO accounts for corrosion of iron and microbial degradation of cellulosics. The net reaction rate of these processes depends directly on brine saturation: an increase in brine saturation will increase the net reaction rate by weighting the inundated portion more heavily and the slower humid portion less heavily. To simulate the effect of wicking on the net reaction rate, an effective brine saturation, which includes a wicking saturation contribution, is used to calculate reaction rates rather than the actual brine saturation. To account for uncertainty in the wicking saturation contribution, this contribution was sampled from a uniform distribution that ranged from 0.0 to 1.0 for each BRAGFLO simulation in the analysis.

MASS-8.0 GAS GENERATION

This model represents the possible generation of gas in the repository by corrosion of steel and microbial degradation of cellulosic, plastic, and rubber (CPR) materials. Additional discussion of this topic may be found in Appendix PA, Section PA-4.2.5 and Attachment SCR (FEPs W44 through W48, W53, and N71) and Section 6.4.3.3.

Gas will be produced in the repository by a variety of chemical reactions, principally those between brine, metals, microbes, CPR materials and by liberation of dissolved gases to the gaseous phase. The processes assumed for long-term performance are anoxic corrosion of steel waste containers and Fe-base metals in the waste and possible microbial consumption of CPR materials in the waste (a significant quantity of plastic is also present as drum liners). Anoxic-corrosion reactions between brine and steel are expected to occur and produce H_2; they are included in the conceptual model. Microbial consumption of cellulosics, plastics and rubbers, might occur. If it does, it may produce various gases, primarily CH_4 and CO_2. However, by reaction with the MgO backfill that will be emplaced to control the chemistry of the repository, CO_2 produced by microbial activity will be rapidly removed from the gaseous phase (see Appendix PA, Attachment SOTERM, Section SOTERM-2.2.2; and Section 6.4.3.4). Other gases such as N_2 and H_2S produced by microbial activity are insignificant in quantity (see CCA Appendix MASS, Attachment 8-1). Thus the conceptual model for gas generation assumes that

anoxic corrosion of steel will produce H_2; microbial consumption of CPR materials might occur and produce CH_4, CO_2, and other gases, but any CO_2 produced will be rapidly removed by reaction with MgO.

In the conceptual model, the rate of gas production in the repository by anoxic corrosion can be limited by several factors. Anoxic corrosion cannot occur unless brine (water) is present and in contact with steel. The corrosion rate is assumed to be dependent on brine saturation. Because anoxic corrosion consumes steel, the rate of gas production can be limited by the quantity of steel left in the repository. Because corrosion is a surface reaction, it proceeds at quantifiable rates per unit surface area of steel. In addition, anoxic corrosion consumes water. Because of these factors, the rate of gas generation in the repository can vary through time as conditions change. It is assumed that anoxic corrosion can occur in the repository as soon as the shafts are sealed.

Microbial consumption of CPR materials is limited by several factors, chiefly the long-term viability of microbes in the repository. Whether microbes consume plastics and rubbers is also important. The rate of microbial production is dependent on brine saturation. Because of uncertainty, however, it is assumed that there is no effect of microbial activity on brine (water) content in the repository.

A limited quantity of O_2 will be trapped in the panels after repository closure. However, this O_2 will be consumed quickly by both oxic corrosion and aerobic microbial activity, and reducing conditions will dominate in the repository over 10,000 years. The contribution of oxic corrosion and aerobic microbial activity to overall gas production is negligible. Thus, oxic reactions are not considered in the conceptual model for gas generation.

Addition of an MgO engineered barrier significantly reduces the impact of microbial production of CO_2 (see Appendix PA, Attachment SOTERM). As discussed in Section 6.4.3.4, the MgO backfill will react with carbon dioxide produced by microbial degradation and remove it from the gaseous phase.

Because the conceptual model comprises the general processes and interactions assumed to occur without direct reference to the mathematical equations used, no parameters are defined by this conceptual model. The mathematical model used to implement it, the average-stoichiometry model, is discussed in Section 6.4.3.3. The most important parameter in the average-stoichiometry model is the rate at which gas production occurs with brine and steel present, because this is the principal control on the total quantity of gas generated. The assumptions made about the principal reactions and their stoichiometries are also important, however, because they affect the quantity of gas created per unit quantity of steel and water reacted.

The feedback between the gas generation conceptual model and the repository fluid flow conceptual model is important to understand. Gas production cannot continue for long with the low initial quantity of liquid present in the waste, as specified by waste-acceptance criteria. For gas production to occur, brine must flow into the repository; for gas production to be sustained, brine consumed by gas production must be replenished. Gas production, however, tends to increase repository pressure and keep brine from flowing into it. Thus the rates at which various processes proceed are important in determining the conditions of the repository. There is

important feedback as well between the gas-generation model and other conceptual models through pressure effects, such as those calculating creep closure (Section 6.4.3.1), interbed fracturing (Section 6.4.5.2), two-phase flow (Section 6.4.3.2), and the radionuclide release associated with spalling and direct brine release during an inadvertent drilling intrusion (Section 6.4.7).

Single-process laboratory studies of anoxic corrosion of steels and Al-based materials by R. E. Westerman and his colleagues at Pacific Northwest National Laboratory (PNNL) from November 1989 through September 1995 have shown that the factor with the greatest effect on the rate of H_2 generation by anoxic corrosion is the quantity of brine in WIPP disposal rooms (see also CCA Appendix MASS, Attachment 8-2). This is because anoxic corrosion occurs rapidly under inundated conditions, but not at all under humid conditions. The pressure difference between WIPP disposal rooms and the far field and the porosity of the room contents also affect the extent of brine inflow and outflow and, hence, the anoxic-corrosion rate. Because the average-stoichiometry model is incorporated in BRAGFLO, gas production is coupled with brine and gas inflow and outflow. Moreover, because BRAGFLO uses a porosity surface to simulate room closure (Butcher and Mendenhall 1993), it also couples gas production to room closure. Telander and Westerman (1993, 1997) and subsequent studies of anoxic corrosion at PNNL have shown that pH, pressure, and the composition of the gaseous phase also affect the H_2 production rate.

The greatest uncertainty in modeling gas generation in WIPP disposal rooms is whether microbial gas generation will occur and, if so, to what extent it will occur and what its effects will be. The following sources of microbial uncertainty have been described:

- whether microorganisms capable of carrying out the potentially significant respiratory pathways identified by Brush (1990) (denitrification sulfate (SO_4^{2-}) reduction, and methanogenesis) will be present when the repository is filled and sealed,
- whether these microbes will survive for a significant fraction of the 10,000-year period of performance of the repository,
- whether sufficient H_2O will be present in the waste or brine,
- whether sufficient electron acceptors (oxidants) will be present and available,
- whether enough nutrients, especially N and P, will be present and available,
- whether microbes will consume significant quantities of plastics and rubbers during the 10,000-year period of performance of the repository, and
- the stoichiometry of the overall reaction for each significant respiratory pathway, especially the number of moles of electron acceptors, nutrients, gases, and H_2O consumed or produced per mole of substrate consumed.

With regard to the first five of these uncertainties, it has been concluded that, although significant microbial gas production is possible, it is by no means certain. To incorporate this uncertainty in PA, it is assumed that there is a probability of 0.50 for significant microbial

activity. In the event of significant microbial activity, microbes would consume 100 percent of the cellulosics in the repository. Furthermore, there is a probability of 0.50 that microbes would consume all of the plastics and rubbers after consuming all of the cellulosics. Thus, there is microbial consumption of all of the cellulosics, but no plastics or rubbers, in about 25 percent of the PA realizations (vectors); microbial consumption of all of the CPR materials in 25 percent of the vectors; and no microbial activity at all in the remaining 50 percent of the vectors (see CCA Appendix MASS, Attachment 8-3).

Single-process laboratory studies of microbial consumption of cellulosics by A.J. Francis and his colleagues at Brookhaven National Laboratory from May 1991 through September 2003 showed that if significant microbial activity occurs, the factor with the greatest effect on the microbial gas-generation rate is the quantity of brine in the repository (see Francis and Gillow 1994, 2000; Francis et al. 1997; Gillow and Francis 2001a, 2001b, 2002a, 2002b; CCA Appendix MASS, Attachment 8-2). This is because microbial gas production occurs rapidly under inundated conditions, but at much lower rates under humid conditions. These studies also found that inoculation with halophilic microbes from the WIPP site and nearby lakes, amendment with NO_3^- (an electron acceptor), amendment with nutrients, and addition of bentonite (a previously proposed backfill material) affect the rate or extent of microbial gas generation. Other factors that could affect the rate or extent of microbial gas generation, but which these studies did not quantify, are the pH; the dissolved or suspended concentrations of actinides or other heavy metals, which could inhibit or preclude microbial activity; and the concentrations of microbial byproducts, which could inhibit or preclude additional microbial activity. High pressure will not preclude or even inhibit microbial activity significantly, even when it increases to 150 atmospheres (lithostatic pressure at the depth of the repository).

Data summarized by Molecke (1979) imply that radiolysis of CPR materials will not be a significant, long-term gas-generation process in WIPP disposal rooms. (Radiolysis here refers to α radiolysis, the breaking of chemical bonds by α particles emitted during the radioactive decay of the actinide elements in TRU waste. Because molecular dissociation caused by other types of radiation will be insignificant in a TRU-waste repository such as the WIPP, this discussion considers only α radiolysis.) Based on calculations using the results of laboratory studies of brine radiolysis carried out for the WIPP by Reed et al. (1993) on estimates of the quantities of brine that could be present in the repository after filling and sealing, and on estimates of the solubilities of Pu, Am, Np, Th, and U summarized by Trauth et al. (1992), it was concluded that radiolysis of H_2O will not significantly affect the overall gas or H_2O content of the repository (see Appendix PA, Attachment SCR, FEP W52,).

Gas generation models are implemented in BRAGFLO with the assumption that the substrates (CPR materials and Fe-base metals) are homogeneously distributed throughout the waste. A separate PA (Hansen et al. 2003a) examined the possible effects of heterogeneity in substrate concentrations on PA results, and found that PA results are insensitive to the heterogeneity in substrate concentrations. The conclusions of the separate PA are summarized in Section MASS-21.0.

MASS-8.1 Historical Context of Gas Generation Modeling

See CCA Appendix MASS, Section MASS.8.1 for historical information that led to the CCA gas generation conceptual model.

MASS-9.0 CHEMICAL CONDITIONS

The models used for chemical conditions in the repository are discussed in Appendix BARRIERS and Appendix PA, Attachment SOTERM and Section 6.4.3.4.

MASS-10.0 DISSOLVED ACTINIDE SOURCE TERM

The models used for the dissolved actinide source term in the repository are discussed in Appendix PA, Attachments SOTERM and SCR and Section 6.4.3.5)

MASS-11.0 COLLOIDAL ACTINIDE SOURCE TERM

The models used for the colloidal actinide source term are discussed in Appendix PA, Attachment SOTERM (Section SOTERM.6) and Section 6.4.3.6.

MASS-12.0 SHAFTS AND SHAFT SEALS

The conceptual model for the shafts and shaft seals used in the performance assessment has been chosen to provide a reasonable and realistic basis for simulating long-term fluid flow through the shaft seal system and to allow evaluation of the effect that uncertainty about the long-term properties of the shaft seal system may have on cumulative radionuclide releases from the disposal system. The conceptual model and seal system design are also discussed in Section 6.4.4 and CCA Appendix SEAL (Section 2).

The conceptual model of the seals is based on results of detailed numerical models of the shaft seal system design. These models were developed to evaluate the performance of the shaft seal system under a range of conditions. Both fluid flow and structural response of the system have been evaluated. The principal uncertainties associated with the detailed models follow:

- reconsolidation of the crushed salt component,
- construction, permeability, and gas threshold pressure of the clay components, and
- damage, permeability, healing, and character of the Salado disturbed rock zones.

These uncertainties are also present in the performance assessment model and have been accounted for in the values specified for seal parameters. The consequences of uncertainty in seal component performance were a primary motivation in the development of the proposed seal system design. Although there is uncertainty in many of the materials and models, the shaft will be completely filled with high density, low permeability materials. The use of multiple materials

and components for each sealing function results in a robust system. Time dependency of the performance of seal components is incorporated directly into the model through temporal variation in seal properties.

The processes that can affect the performance of the shaft seals—structural, hydraulic, and coupled structural and hydrological—are discussed in some detail in CCA Appendix SEAL, Sections 7 and 8. Evaluation of these issues required the use of existing structural and both single-and two-phase flow codes. In addition, development of conceptual and numerical models for crushed salt reconsolidation, the disturbed rock zone, and the shaft seal system was required. These models have been reviewed by independent, qualified experts, are well documented, and have been developed within an accepted quality assurance program. Codes used in the analyses include SPECTROM-32 (structural) (Callahan 1994), SWIFT II (single-phase flow) (Reeves et al. 1986), and TOUGH2 (multi-phase flow) (Pruess 1991). These codes were selected for their capability to simulate the processes thought to affect seal performance. They are also well-documented, accepted, and widely used within the scientific community. The codes were modified to implement the conceptual models specific to the seals, and these modifications were made within a program that establishes criteria for assuring software quality.

The BRAGFLO model of the shaft seal system requires consistency with parameters associated with the surrounding system. The BRAGFLO shaft seal model implemented for the 2004 PA calculations grouped several shaft seal materials into two composite materials having properties derived from the combination of grouped materials in series. For example, the permeability of the material used to represent the lower portion of the shaft seal that lies in the Salado formation is derived from the permeability and thickness of the asphalt, concrete crushed salt, and clay layers of the seal in this horizon. This permeability changes after 200 years to incorporate the combined effects of the consolidation of these materials. The effects of the halite DRZ surrounding the shafts is included in the derivation of the composite properties used in the BRAGFLO model. A detailed description of the shaft model used in the 2004 PA BRAGFLO calculations can be found in James and Stein (2002 and 2003).

MASS-12.1 Historical Development of the Shaft Seals

The four shafts into the repository will be sealed after completion of disposal activities at the WIPP. The shaft seal system design has evolved over time (Stormont 1988; Nowak et al. 1990; DOE 1995). The Initial Reference Seal System Design proposed a two-component design to achieve a sealing strategy with two phases: concrete and clay seals formed a short-term seal, and a crushed salt seal formed long-term protection. The use of native rock (that is, crushed salt) as a permanent sealing material is considered the most effective means to eliminate the shafts as a preferred pathway for migration of hazardous constituents. Because some interim period must pass for the crushed salt to reconsolidate to sufficiently high densities, short-term seals were proposed as a means to prevent fluid migration during the interim. Estimates of this interim period ranged from 100 to 200 years.

Seal design changes and refinements have been incorporated into the conceptual model of the seals used by the DOE (Bertram-Howery et al. 1990; WIPP Performance Assessment Department 1991; Sandia WIPP Project 1992). Performance assessments conducted prior to 1992 addressed general sealing issues but did not include specific seal components.

Results of the scoping calculations using the DCCA model demonstrated that low-permeability materials were required for the shaft seals (DOE 1995, Appendix D). However, the simplicity of the conceptual model limited the applicability of results to the detailed seal system design.

The shaft seal design for the WIPP is presented in CCA Appendix SEAL (Sections 4 and 5).

MASS-13.0 SALADO

The purpose of this model is to reasonably represent the effects of fluid flow in the Salado on long-term performance of the disposal system. The conceptual model is also discussed in Section 6.4.5.

Fluid flow in the Salado is considered in the conceptual model of long-term disposal system performance for several reasons. First, some liquid could move from the Salado to the repository because of the considerable gradients that can form for liquid flow inward to the repository. This possibility is important because such fluid can interact with creep closure, gas generation, actinide solubilities, and other processes occurring in the repository. Second, gas generated in the repository is thought to be capable of fracturing the Salado interbeds under certain conditions, creating increased permeability channels that could be pathways for lateral transport. The pathway of lateral transport in intact Salado is also modeled, but it is considered unlikely to result in any significant radionuclide transport to the accessible environment boundary.

The fundamental principle in the conceptual model for fluid flow in the Salado is that it is a porous medium within which gas and brine can be both present and mobile (two-phase flow), governed by conservation of energy and mass, and by Darcy's Law for their fluxes (see Appendix PA, Sections PA-4.2). Consistent with typical concepts of two-phase flow, each phase can affect the other by impeding flow because of partial saturation (relative permeability effects) and by affecting pressure by capillary forces (capillary pressure effects). It is assumed that no waste-generated gas is present initially. Future states are modeled as producing gas by corrosion and microbial activities. Should high pressure develop over the regulatory period, it is allowed to access marker beds in the Salado.

Some variability in composition exists between different horizons of the Salado. The largest differences occur between the anhydrite-rich layers called interbeds and those dominated by halite. Within horizons dominated by halite, composition varies from nearly pure halite to halite plus several percent other minerals, in some instances including clay (see Chapter 2.0, Section 2.1.3.4). The Salado is modeled as impure halite except for those interbeds that intersect the DRZ near the repository. This conceptual model and an alternative model that explicitly represented all stratigraphically distinct layers of the Salado near the repository (Christian-Frear and Webb 1996) produced similar results.

From other modeling and theoretical considerations, flow between the Salado and the repository is expected to occur primarily through interbeds that intersect the DRZ. Because of the large surface areas between the interbeds and surrounding halite, the interbeds serve as conduits for the flow of brine in two directions: from halite to interbeds to the repository, or, for brine flowing out of the repository, from the repository into interbeds and then into halite. Because the repository is modeled as a relatively porous and permeable region, brine is considered most

likely (but not constrained) to leave the repository through MB139 below the repository because of the effect of gravity. If repository pressures become sufficiently high, gas is modeled to exit the repository via the marker beds in the proximity of the disposal room.

The effect of gravity may also be important in the Salado because of the slight and variable natural stratigraphic dip. For long-term performance modeling, the dip in the Salado within the domain is taken to be constant and 1 degree from the north to south.

Fluid flow in the Salado is conceptualized as occurring either convergently upon the repository, or divergently from it, as discussed in detail in Section 6.4.2.1. Because the repository is not conceptualized as homogeneous, implementing a geometry for the conceptual model of convergent or divergent flow in the Salado is somewhat complicated and is discussed in Section 6.4.2.1.

The conceptual model for Salado fluid flow has primary interactions with three other conceptual models. The interbed fracture conceptual model allows porosity and permeability of the interbeds to increase as a function of pressure. The repository fluid flow model is directly coupled to the Salado fluid flow model by the governing equations of flow in BRAGFLO (in the governing equations of the mathematical model, they cannot be distinguished), and it differs only in the region modeled and the parameters assigned to materials. The Salado model for actinide transport is directly coupled to the conceptual model for flow in the Salado through the process of advection.

MASS-13.1 High Threshold Pressure for Halite-Rich Salado Rock Units

A parameter used to describe the effects of two-phase flow is threshold pressure. The threshold pressure is important because it helps determine the ease with which gas can enter a liquid-saturated rock unit. For a brine-saturated rock, the threshold pressure is defined as “equal to the capillary pressure at which the relative permeability to the gas phase begins to rise from its zero value, corresponding to the incipient development of interconnected gas flow paths through the pore network” (Davies 1991, p. 9).

The threshold pressure, as well as other parameters used to describe two-phase characteristics, has not been measured for halite-rich rocks of the Salado. The Salado, however, is thought to be similar in pore structure to rocks for which threshold pressures have been measured (Davies 1991). Based on this observation, Davies (1991) postulated that the threshold pressure of the halite-rich rocks in the Salado could be estimated if an empirical correlation exists between rocks postulated to have similar pore structure.

Davies developed a correlation between threshold pressure and intrinsic permeability applicable to the Salado halites. (A similar correlation was developed for Salado anhydrites; subsequent testing confirmed that the correlation predicted threshold pressures accurately.) The correlation developed by Davies predicts threshold pressures in intact Salado halites on the order of 20 megapascals or greater (Davies 1991). This threshold pressure predicted by correlation is so high that for all practical and predictive purposes, no gas will flow into intact Salado halites (see Section 6.4.5.1).

Because threshold pressure helps control the flow of gas, and because the greatest volume of rock in the Salado is rich in halite, a high threshold pressure effectively limits the volume of gas that can be accommodated in the pore spaces of the host formation. Thus high threshold pressure is considered conservative as well as realistic, because if gas could flow into the pore spaces of Salado halite, repository pressures could be reduced dramatically.

MASS-13.2 Historical Context of the Salado Conceptual Model

See CRA Appendix MASS, Section MASS.13.2 for the historical information relating to the CCA Salado conceptual model. The Salado conceptual model is unchanged for CRA-2004.

MASS-13.3 The Fracture Model

The purpose of this model is to alter the porosity and permeability of the anhydrite interbeds and the DRZ if their pressure approaches lithostatic, simulating some of the hydraulic effects of fractures with the intent that unrealistically high pressures (in excess of lithostatic) do not occur in the repository or disposal system. The conceptual model is also discussed in Section 6.4.5.2.

In the 1992 preliminary performance assessment, repository pressures were shown to greatly exceed lithostatic pressure if a large quantity of gas was generated. Pressures within the waste repository and surrounding regions were predicted to be roughly 20 to 25 megapascals. It was expected that fracturing within the anhydrite marker beds would occur at pressures slightly below lithostatic pressure. An expert panel on fractures was convened to develop the conceptual bases for the fracturing within the anhydrite marker beds.

The porosity and permeability increases are conceptualized as occurring vertically throughout the affected interbed; in other words, throughout the porous medium as a whole rather than on discrete portions. This simplification facilitates numerical implementation and execution.

Two parametric behaviors must be quantified in the conceptual model. First, the change of porosity with pressure in the anhydrite marker beds must be specified. This is done with a relatively simple equation, described in Appendix PA, Section PA-4.2, that relates porosity change to pressure change using an assumption that the fracturing can be thought of as increasing the compressibility of interbeds. Parameters in the model are treated as fitting parameters and have little relation to physical behavior except that they affect the porosity change. The second parametric behavior is the change of permeability with pressure, which is incorporated by a functional dependence on the porosity change. It is assumed that a power function is appropriate for relating the magnitude of permeability increase to the magnitude of porosity increase. The parameter in this power function, an exponent, is also treated as a fitting parameter and can be set so that the behavior of permeability increase with porosity increase fits the desired behavior.

The fracture enhancement model assumes fracture propagation is uniform in the lateral direction to flow within the marker beds in the absence of dip. The 1-degree dip modeled in BRAGFLO may affect fracture propagation direction. That is, within the accuracy of the finite difference grid, a fracture will develop radially outward. This would not account for fracture fingering or a preferential fracturing direction; however, no existing evidence supports heterogeneous anhydrite

properties that would contribute to preferential fracture propagation. This evidence is discussed in CCA Appendix MASS, Attachment 13-2).

The maximum enhanced fracture porosity controls the storativity within the fracture. The extent of the migration of the gas front into the marker bed is sensitive to this storativity. The additional storativity caused by porosity enhancement will mitigate gas migration within the marker bed. The enhancement of permeability by marker-bed fracturing will make the gas more mobile and will contribute to longer gas-migration distances. Thus the effects of porosity enhancement at least partially counteract the effects of permeability enhancement in affecting the gas-migration distances.

Because intact anhydrite is partially fractured, the pressure at which porosity or permeability changes are initiated is close to the initial pressure within the anhydrite. The fracture treatment within the marker beds will not contribute to early brine drainage from the marker bed, because the pressures at these times are below the fracture initiation pressure.

The input data to the interbed fracture model (see Appendix PA, Attachment PAR) were chosen deterministically to produce the appropriate pressure and porosity response as predicted by a linear elastic fracture mechanics (LEFM) model, as discussed in Mendenhall and Gerstle (1993).

MASS-13.4 Flow in the Disturbed Rock Zone

The conceptual model for the DRZ around the waste disposal, operations, and experimental regions has been chosen to provide a reasonably conservative estimate of fluid flow between the repository and the intact halite and anhydrite marker beds. The conceptual model is also discussed in Section 6.4.5.3 of this application.

The conceptual model implemented in the performance assessment uses values for the permeability and porosity of the DRZ that do not vary with time. A screening analysis examined an alternative conceptual model for the DRZ in which permeability and porosity changed dynamically in response to changes in pressure (Vaughn et al. 1995). This analysis implemented a fracturing model in BRAGFLO for the DRZ. This fracturing model is identical to the existing anhydrite interbed alteration model. In this model, formation permeability and porosity depend on brine pressure as described by Freeze et al. (1995, 2-16 to 2-19) and Appendix PA, Section PA-4.2.1. This model permits the representation of two important formation alteration effects. First, pressure build-up caused by gas generation and creep closure within the waste will slightly increase porosity within the DRZ and offer additional fluid storage with lower pressures. Second, the accompanying increase in formation permeability will enhance fluid flow away from the DRZ. Because an increase in porosity tends to reduce outflow into the far field, parameter values for this analysis were selected so that the DRZ alteration model greatly increases permeability while only modestly increasing porosity.

Two basic scenarios were considered in the screening analysis by Vaughn et al. (1995), undisturbed performance and disturbed performance. Both scenarios included a 1-degree formation dip downward to the south. Intrusion event E1 is considered in the disturbed scenario and consists of a borehole that penetrates the repository and pressurized brine in the underlying Castile. Two variations of intrusion event E1 were examined, E1 updip and E1 downdip. In the

E1 updip event, the intruded panel region was located on the updip (north) end of the waste disposal region, whereas in the E1 downdip event, the intruded panel region is located on the downdip (south) end of the disposal region. These two different geometries permitted evaluation of the possibility of increased brine flow into the panel region caused by higher brine saturations downdip from the borehole and the potential for subsequent impacts on contaminant migration. To incorporate the effects of uncertainty in each case (E1 updip, E1 downdip, and undisturbed), a Latin hypercube sample size of 20 was used, for a total of 60 simulations. To assess the sensitivity of system performance on formation alteration of the DRZ, conditional CCDFs of normalized contaminated brine releases were constructed and compared with the corresponding baseline model conditional CCDFs that were computed with constant DRZ permeability and porosity values. Based on comparisons between conditional CCDFs, computed releases to the accessible environment were determined to be essentially equivalent between the two treatments.

Preliminary performance assessments considered alternative conceptual models that allowed for some lateral extent of the DRZ into the halite surrounding the waste disposal region and for the development of a transition zone between anhydrites a and b and MB 138 (SNL 1993, Figures 4.1-2 and 5.1.2; Davies et al. 1993; Gorham et al. 1992). The transition zone was envisioned as a region that had experienced some hydraulic depressurization and perhaps some elastic stress relief because of the excavation, but probably no irreversible rock damage and no large permeability changes. Modeling results indicated that including the lateral extent of the DRZ had no significant effect on fluid flow. Communication vertically to MB 138 was thought to be a potentially important process, however, and the model adopted for the performance assessment assumes that the DRZ extends upward to MB 138 and permeability is sampled over the same range used in the 1997 PAVT.

MASS-13.5 Actinide Transport in the Salado

The purpose of this model is to represent the transport of actinides in the Salado. The model for actinide transport in the Salado is implemented in the code NUTS. This model is also discussed in Section 6.4.5.4 and Appendix PA, Section PA-4.3.

Actinide transport in the Salado is conceptualized as occurring only by advection through the porous medium described in the Salado hydrology conceptual model. Advection is the movement of material with the bulk flow of fluid. Other processes that might disperse actinides, such as diffusion, hydrodynamic dispersion, and channeling in discrete fractures, are not included in the conceptual model.

Advection is a direct function of fluid flow, which is discussed in the conceptual model for Salado fluid flow.

This application of NUTS treats the transport of radionuclides within all the regions for which BRAGFLO computes brine and gas flow. The brine must pass through some part of the repository at some period in its history to become contaminated. While there, it is assumed to acquire radioactive constituents, which it then transports by advection to other regions outside the repository. NUTS uses BRAGFLO's velocity field, pressures, porosities, saturations, and other model parameters (including geometrical grid, residual saturation, material map, brine compressibility, and time step) averaged over a given number of time steps (20 for this

performance assessment calculation), which it takes as input for its transport calculations. Consequently, the results of NUTS are subject to all the uncertainties associated with BRAGFLO's conceptual model and parameterization, which will not be repeated here. Details of the source term are discussed in Appendix PA, Attachment SOTERM.

This application of NUTS disregards sorptive and other retarding effects throughout the entire flow region, even though retardation must occur at some level within the repository, the marker beds, and the anhydrite interbeds, and especially in zones with clay layers or clay as accessory minerals.

This application of NUTS neglects molecular dispersion, which leads to uncertainty. For materials of interest in the WIPP repository system, molecular diffusion coefficients are at a maximum on the order of 4×10^{-10} m^2 per second. Thus, the simplest scaling argument using a time scale of 10,000 years leads to a molecular diffusion (that is, mixing) length scale of approximately 33 ft (10 m), which is negligible compared to the lateral advection length scale of roughly 7,874 ft (2,400 m) (the lateral distance from the repository to the accessible environment).

This application of NUTS also neglects mechanical dispersion, which leads to additional uncertainty (see Section 6.4.5.4.2). Dispersion is quantified by dispersivities, which are empirical (tensor) factors that are proportional to flow velocity (to within geometrical factors related to flow direction). They account for both the downstream and cross-stream spreading of local extreme values in concentration of dissolved constituents. Physically, the spreading is caused by the fact that both the particle paths and velocity histories of once-neighboring particles can be vastly different because of material heterogeneities characterized by permeability variations. These variations arise from the irregular cross-sectional areas and tortuous nonhomogeneous, nonisotropic connectivity between pores. Because of its velocity dependence, the transverse component of mechanical dispersivity tends to transport dissolved constituents from regions of relatively rapid flow (where mechanical dispersion has a larger effect) to regions of slower flow (where mechanical dispersion has a smaller effect). In the downstream direction, dispersivity merely spreads constituents in the flow direction. Conceptually, ignoring lateral spreading assures that dissolved constituents will remain in the rapid part of the flow field, which assures their transport toward the boundary. Similarly, ignoring longitudinal dispersivity ignores the elongation of a feature in the flow direction, which ignores foreshortening (or lengthening) of arrival times. However, because the EPA release limits are time-integrated measures, the exact times of arrival are unimportant for constituents that arrive at the accessible environment within the assessment period (10,000 years).

Advection is therefore the only transport mechanism considered important, which underscores NUTS' reliance on BRAGFLO. Because the Darcy flows are given to NUTS as input, the maximum solubility limits for combined dissolved and colloidal components are the most important NUTS parameters. These components are described in Appendix PA, Attachment SOTERM.

MASS-14.0 GEOLOGIC UNITS ABOVE THE SALADO

The model for geologic units above the Salado was developed to provide a reasonable and realistic basis for simulations of fluid flow within the disposal system and detailed simulations of groundwater flow and radionuclide transport in the Culebra. The conceptual model for these units is also discussed in Section 6.4.6 of this application.

The conceptual model used in PA for the geologic units above the Salado is based on the overall concept of a groundwater basin, as introduced in Chapter 2.0 (Section 2.2.1.1) of this recertification application, and developed further in CCA Appendix MASS, Section MASS.14.2. The computer code SECOFL3D was used to evaluate the effect on regional-scale fluid flow by recharge and rock properties in the groundwater basin above the Salado (CCA Appendix MASS, Attachment 17-2). However, simpler models for this region are implemented in codes used in performance assessment. For example, in the BRAGFLO model, layer thicknesses, important material properties including porosity and permeability, and hydrologic properties such as pressure and initial fluid saturation are specified, but the model geometry and boundary conditions are not suited to groundwater basin modeling (nor is the BRAGFLO model used to make inferences about groundwater flow in the units above the Salado). In PA the Culebra is the only subsurface pathway modeled for radionuclide transport above the Salado, although the groundwater basin conceptual model includes other flow interactions. The Culebra model implemented in PA includes spatial variability in hydraulic conductivity and uncertainty and variability in physical and chemical transport processes. Thus, the geometries and properties of units in the different models applied to the units above the Salado by the DOE are chosen to be consistent with the purpose of the model.

The MODFLOW-2000 and SECOTP2D codes are used directly in PA to model fluid flow and transport in the Culebra. The assumptions made in these codes are discussed in Section 6.4.6.2 and Section MASS-15.0.

With respect to the units above the Salado, the BRAGFLO model is used only for determination of fluid fluxes between the shaft or intrusion borehole and hydrostratigraphic units. For this purpose, it does not need to resolve regional or local flow characteristics.

The basic stratigraphy and hydrology of the units above the Salado are described in Sections 2.1.3.5 through 2.1.3.10, and Section 2.2.1.4, respectively. Additional supporting information is contained in CCA Appendices GCR, HYDRO, and SUM. Details of the conceptual model for each unit are described in Sections 6.4.6.1 through 6.4.6.7.

MASS-14.1 Historical Context of the Units above the Salado Model

See CCA Appendix MASS, Section MASS.14.1 for historical information relating to the conceptual models for units above the Salado for the CCA. The conceptual models for the units above the Salado are unchanged for CRA-2004. However, CRA-2004 uses MODFLOW-2000 in place of SECOFL2D to model fluid flow in the Culebra.

MASS-14.2 Groundwater-Basin Conceptual Model

For a discussion on the groundwater-basin conceptual model, see CCA Appendix MASS, Section MASS.14.2.

MASS-15.0 CULEBRA

The conceptual model for groundwater flow in the Culebra (a) provides a reasonable and realistic basis for simulating radionuclide transport in the Culebra and (b) allows evaluation of the extent to which uncertainty about groundwater flow in the Culebra may contribute to uncertainty in the estimate of cumulative radionuclide releases from the disposal system. See Section 6.4.6.2 for additional references to other relevant discussions on this conceptual model.

The conceptual model used in performance assessment for groundwater flow in the Culebra treats the Culebra as a confined two-dimensional aquifer with constant thickness and spatially varying transmissivity (see CCA Appendix MASS, Attachment 15-7). Flow is modeled as single-phase (liquid) Darcy flow in a porous medium.

Basic stratigraphy and hydrology of the units above the Salado are described in Chapter 2.0, Sections 2.1 and 2.2. Additional supporting information is contained in CCA Appendices GCR, HYDRO, and SUM.

The conceptual model for flow in the Culebra is discussed in Section 6.4.6.2. Details of the calibration of the T-fields, based on available field data, are given in Appendix PA, Attachment TFIELD, Section TFIELD-4. Initial and boundary conditions used in the model are given in Section 6.4.10.2. A discussion of the adequacy of the two-dimensional assumption for PA calculations is included as Attachment 15-7 to CCA Appendix MASS.

The principal parameter used in the PA to characterize flow in the Culebra is an index parameter (the transmissivity index) used to select a single T-field for each Latin hypercube sample element from a set of calibrated fields, each of which is consistent with available data (see Appendix PAR).

MASS-15.1 Historical Context of the Culebra Model

Since the FEIS in 1980, the model used to describe flow and transport within the Culebra has changed significantly. In the FEIS, the Culebra and Magenta were combined and modeled as one layer referred to as the Rustler aquifers. In the modeling, the Rustler aquifers were assumed to be an isotropic porous medium with a uniform porosity of 0.10 (Lappin et al. 1989, Table K-2, K-18). A uniform T-field was assumed across the model domain except in Nash Draw. Regional flow was assumed to be toward the southwest discharging at Malaga Bend on the Pecos River. (There was no regulatory framework or boundary defined at this time.) Numerical modeling was not able to consider the possible effect of variations in brine density within the Rustler, so modeling used an equivalent freshwater head. Steady-state flow directions and rates were assumed. As for physical-transport characteristics, the Culebra was incorporated into the Rustler aquifers and assumed to be an isotropic, homogeneous porous medium.

Haug et al. (1987) calibrated a flow model to the H-3 pumping test (Beauheim 1987a) and the effects from the excavation of the shafts. Data from numerous new boreholes installed and tested since the 1980 study were included in this model. The boundaries of the model were not much larger than the extent of the WIPP site. Brine densities were also used as a calibration target. The brine densities were assigned at the boundaries and subsequently modified to match the observed fluid densities. Vertical leakage was included in an attempt to calibrate the brine densities. This attempt led to the recommendation that future modeling studies treat the Culebra as a leaky-confined aquifer. The T-field was estimated by kriging and modified by the addition of pilot points, which were located by trial and error. In this model, single- and double-porosity effects on the flow field were investigated. At the regional scale, the use of a double-porosity vs. single-porosity (matrix-only) conceptual model had little effect on the flow field.

A modeling study (LaVenue et al. 1990) conducted to support the DSEIS only slightly modified the conceptual model used by Haug et al. (1987). The differences in the conceptual model were the assumptions that brine density varied spatially but was held constant through time, and vertical leakage was not included. It was assumed that the brine concentrations could be considered to have changed little over the period of time modeled. The boundaries of the 1989 study were much larger than those of the 1987 study, extending approximately 18.6 mi (30 km) north and south and 12.4 mi (20 km) in east and west. The model grid was centered on the WIPP site. The boundaries were selected to include the region for which head data were available and to minimize the boundary effects during transient simulation of the H-3, WIPP-13, and H-11 pumping tests. Fixed heads were assigned around all four boundaries based upon the regional head values. Transmissivities were estimated by kriging and ranged over seven orders of magnitude in this study. Pilot points were added to modify the T-field during steady-state and transient calibration. Pilot-point locations were selected using an adjoint sensitivity analysis technique. The Culebra T-field were calibrated on the basis of 41 test locations. Transmissivity was recognized to vary by approximately three orders of magnitude within the WIPP site. Modern flow in Culebra was recognized as being predominantly north to south on the WIPP site, and strongly affected by a high-transmissivity zone in the southeastern portion of the WIPP site. Flow was calculated on the basis of a fully confined Culebra and boundary conditions applied at the WIPP site scale. As discussed in Lappin et al. (1989), local flow and transport behavior were affected by fracturing where the transmissivity is greater than approximately 10^{-6} m^2 per second. For physical transport, a double-porosity (matrix-diffusion) transport model for off-site transport from waste panels was assumed. Transport parameters were based on best estimates from nonsorbing tracer tests at three locations (Jones et al. 1992). It was assumed that the effective thickness was equal to the total thickness. Contaminant-transport calculations were one-dimensional.

The initial conditions for the Culebra flow field have been taken from the hydrographs of the WIPP boreholes. Prior to excavation of the salt handling shaft, the hydrographs showed little evidence of head change over the ten years preceding the shaft excavations. Head values were selected for each borehole with a hydrograph that preceded shaft excavation or that was located far from the shaft effects on the flow field. These data provided an estimate of the undisturbed head field and were subsequently used as initial conditions for the Culebra model's transient simulation.

In modeling the hydrologic characteristics of the Culebra, SNL (1992-1993) generated multiple T-field conditioned on hydraulic test data (point transmissivity data and transient head data) and then sampled those fields. This procedure addressed uncertainties in the location-specific values of the Culebra transmissivity. The geologic conceptual model was further revised to indicate that the degree of fracture flow was related to the degree of gypsum cement in the fractures. Contaminant-transport calculations were two-dimensional. The effective thickness of the Culebra was taken to be equal to the total thickness. A range of physical-transport parameters was used, as opposed to best estimates, to address the variability of physical-transport properties within the Culebra. The maximum fracture spacing was assumed to be equal to the total thickness of the Culebra (approximately 26 ft [8 m]). The fracture spacing used in modeling was a convenient modeling simplification based on the concept of through-going parallel fractures. Representing fracturing in terms of fracture spacing is a mechanism to ensure that the proper surface-to-volume ratios are used in estimating the role of matrix diffusion. Calculations considered the possibility of both single-porosity (fracture-flow-only) and double-porosity (matrix diffusion) behavior.

The main differences between the 1989 and 1992 models were the model boundary locations, boundary conditions, and the geostatistical approach used to develop and modify the T-field (LaVenue and RamaRao 1992). The 1992 model boundaries were rotated 38 degrees east to align with the axis of Nash Draw. This permitted the specification of a no-flow boundary condition along a portion of the western boundary, which was selected to coincide with the axis of Nash Draw. In addition, the northeastern corner of the model was treated as a no-flow boundary because of the low transmissivities in the area and the lack of any nearby regional heads to provide boundary head estimates. Transmissivities were simulated by conditional simulation. Pilot points were automatically located and assigned transmissivity values using an optimization routine during steady-state and transient-state calibration.

By 1994, the model of the Culebra's hydrologic characteristics was unchanged from that of December 1992. For the physical-transport characteristics, double-porosity transport was assumed, but the base case had large fracture spacing, effectively the same as the Culebra thickness. A single block size was assumed in each realization. Calculations still assumed an effective thickness equal to the total thickness.

For the 1996 CCA, the model of the Culebra's regional hydrologic characteristics had not changed from the 1994 model, although additional large-scale information from pumping at H-19 and small-scale information at Water Quality Sampling Program (WQSP) wells was incorporated into the calibration. Existing borehole-transmissivity interpretations were refined. The model of the physical-transport characteristics were changed on the basis of analysis of new data from H-19 and H-11 and reanalysis of previous tests of H-3, H-11, H-6. The Culebra was conceived of as a fractured porous medium with inherent local variability in the degree and scale of fracturing. Examination of core and shaft exposures revealed that there are multiple scales of porosity within the Culebra including fractures from microscale to large, vuggy zones, and inter-particle and inter-crystalline porosity. This variability leads to both lateral and vertical variations in permeability. Advection is believed to occur largely through fractures; however, in some areas it may also occur through vugs connected by small fractures and interparticle porosity. Diffusion occurs into all connected porosity. PA, rather than conceiving of transport in terms of fracture and matrix porosities, conceives the Culebra as being composed of advective and

diffusive porosities. Matrix diffusion is still believed to be effective and significant. The effective transport thickness is thought to be less than the total stratigraphic thickness. The available data suggest that the permeability of the upper portion of the Culebra is relatively low. Therefore the DOE has concluded that the Culebra is adequately represented by a double-porosity continuum model on the scale of PA calculations, and it is not necessary to use a discrete-fracture model on this scale.

For the 2004 PA, the method of defining the initial (pre-calibration) distribution of T within the Culebra has been revised to explicitly include the geologically zoned distribution of T first developed for the basin-scale model. Three zones are identified: an eastern zone in which halite is present in the Rustler members immediately above and/or below the Culebra and the Culebra transmissivity is consistently low (log T [m^2/s] < -5.4), a western zone in which dissolution of the upper Salado has occurred and the Culebra T is consistently high (log T [m^2/s] > -5.4), and an intermediate transition zone that includes most of the WIPP site. Areas of high T are distributed stochastically within 27.8 percent of the intermediate transition zone to represent the current uncertainty in their locations. Within each of the three zones, T is inversely correlated to the thickness of overburden above the Culebra.

The flow code used for the CRA T-fields was MODFLOW-2000 (Harbaugh et al. 2000). The model domain for CRA-2004 is similar in size (22.4 km [13.9 mi] wide by 30.7 km [19.1 mi] long) to that used for the CCA (approximately 22 km [13.7 mi] wide by 30 km [18.6 mi] long), but is oriented with the long axis extending north to south. The model domain was discretized into uniform 100-m [328-ft] by 100-m [328-ft] grid blocks. Constant-head conditions were prescribed for the eastern boundary of the model, as well as for the eastern portions of the northern and southern boundaries. Flow lines (no-flow boundaries) were prescribed from northeast to southwest down the axis of the northern part of Nash Draw, and from northwest to southeast down the southern arm of Nash Draw. Model cells in the northwest and southwest portions of the model domain beyond the flow lines were treated as inactive by MODFLOW-2000.

Implementation of the pilot-point method for T-field calibration was also revised for the CRA-2004 T-fields. Instead of using an adjoint-sensitivity approach to optimize the locations of the same number of pilot points as there were well locations, 100 pilot points were located to provide a relatively uniform distribution of wells and pilot points within the intermediate transition zone and near the borders of the other two zones. The regularization technique described by Doherty (2003) was used to prevent the large number of pilot points from causing numerical instability. PEST v. 5.5 (Doherty 2002) was used instead of GRASP to optimize T at pilot-point locations during the model-calibration process. The calibration process involved matching to heads measured in late 2000 and to transient heads at 40 wells resulting from seven major pumping tests.

Additional information on the T-field modeling performed for the 2004 PA is given in Chapter 6 and Appendix PA, Attachment TFIELD. Transport modeling for CRA-2004 was performed in the same manner as for the CCA.

MASS-15.2 Dissolved Actinide Transport and Retardation in the Culebra

The purpose of this model is to represent the effects of advective transport, physical retardation, and chemical retardation on the movement of actinides in the Culebra. This conceptual model is also discussed in Section 6.4.6.2.1.

The properties of the Culebra have been characterized by direct observation in outcrop, boreholes, and shafts (Holt and Powers 1984, 1986, 1988, 1990), field hydraulic testing and analysis (Beauheim 1987b), field tracer testing and analysis (Attachment 15-6; Jones et al. 1992; Mercer and Orr 1979), and laboratory testing and analysis (Papenguth and Behl 1996a, 1996b). The conceptual model for dissolved actinide transport in the Culebra is based on these observations, tests, and analyses. Because testing and analysis of the Culebra suggest that its upper portion does not play a significant role in transport, transport is modeled only for the lower portion of the Culebra.

The conceptual model for actinide transport in the Culebra has three principal components: advective transport, physical retardation, and chemical retardation. Two types of porosity are present—porosity in which advective transport occurs, and porosity that is relatively inactive in advective transport. This type of behavior is typically referred to as double porosity

Advective transport refers to the transport of actinides in those pores of the Culebra where the principal fluid flow occurs. This flow primarily occurs in fractures, but may also occur in microfractures connecting vugs in vuggy regions or other portions of the porosity of the Culebra that contain large pore-throat apertures (that is, high permeability regions). This mechanism includes the effects of diffusion and dispersion in advective porosity as well as the movement of actinides with the bulk fluid flow. Advective transport is thought to be controlled by hydraulic gradient, hydraulic conductivity, formation thickness, and advective porosity.

Physical retardation refers to the process of diffusion from advective porosity into diffusive porosity, that is, those portions of the porosity of the Culebra that are relatively inactive in advective transport. Once in the diffusive porosity, the transport of actinides is controlled by diffusion and sorption. Diffusion can be an important process for effectively retarding solutes by transferring mass from the porosity where advection (flow) is the dominant process into other portions of the rock. The properties that control the diffusion of actinides into the diffusive porosity are the surface-area-to-volume ratio of the matrix blocks, the tortuosity of the diffusive porosity, and actinide free-water diffusion coefficients (see CCA Appendix MASS, Attachment 15-3).

Chemical retardation refers to the sorption of actinides on minerals present in the Culebra. Sorption is thought to occur on dolomite grains, but will also occur on clay or other minerals. In the conceptual model, chemical retardation occurs only in the diffusive porosity, and adds to the effects of the physical retardation. The governing properties for sorption are described in a parametric expression of the degree to which dissolved actinides tend to sorb or remain in solution (in the mathematical model, a K_d or a linear isotherm is used), which requires the concentration of actinides in solution and the abundance of minerals on which sorption can occur (see CCA Appendix MASS, Attachment 15-1).

Advective porosity is thought to be a small percentage of the total volume of the Culebra. This porosity is interconnected and contains high-permeability features such as fractures or vuggy pore structures. In this advective porosity, little actual rock material is considered to exist (in other words, it is the fracture apertures and pore volumes without surrounding rock). In contrast, diffusive porosity makes up the major portion of the Culebra pore volume. It comprises lower-permeability features and most of the rock material. The rate at which diffusion removes solutes from advective porosity is a function of the surface area-to-volume ratio of the matrix blocks. For a given geometry of advective porosity assumed in a model (for example, parallel-plate fractures), this surface area-to-volume ratio can be expressed as a characteristic length, which is known as the matrix block length (for example, the thickness of a matrix slab between two parallel-plate fractures).

In summary, the conceptual model for dissolved actinide transport in the Culebra includes two types of porosity: advective porosity associated with high-permeability features of the Culebra, and diffusive porosity associated with lower-permeability features. These two types of porosity are distributed throughout the Culebra and are intertwined on a small scale; hence, mapping their regional extent or boundaries between them is not feasible. Advection, diffusion, and dispersion of dissolved actinides occur within the advective porosity. Diffusion (physical retardation) and sorption (chemical retardation) occur within the diffusive porosity. Advective porosity makes up a small portion of the overall pore volume of the Culebra; diffusion is an important process for transferring actinides into other portions of the rock in which there is a larger surface area for sorption. Because the upper portion of the Culebra has been observed to be relatively inactive in solute transport in tests, it is assumed to be unimportant and is not included in the conceptual model. Attachment 15-6 of CCA Appendix MASS contains additional information on the transport properties of the Culebra.

Several parameters are referred to or implied in the conceptual model as discussed in Section 6.4.6.2. For transport in advective porosity, the principal parameter is the porosity of the network, but because of links to the Culebra fluid flow model, the hydraulic gradient and hydraulic conductivity largely control the specific discharge calculated by MODFLOW-2000. Within diffusive porosity, the porosity, tortuosity, and diffusion coefficients for various actinides are important because of their effect on the rate of diffusion. A parameter called matrix block length, a measure of the surface area between the advective and diffusive porosities, is also important. The density of sorbing minerals and their sorption properties, expressed by K_d, are important in chemical retardation.

It is commonly assumed that there should be a relationship between the conductivity of advective porosity and its porosity and distribution, that is, that the fracture permeability, porosity, and aperture or spacing should be correlated. Data collected and analyzed at the WIPP do not support this assumption. There are no meaningful trends among these parameters for the data that have been collected. Therefore, values of these parameters are not correlated in the PA (see CCA Appendix MASS, Attachment 15-6, page 14 and Attachment 15-10).

Transport of actinides in the Culebra is coupled to several other conceptual models. An important coupling is to models for features that can introduce actinides to the Culebra, for example, the exploratory borehole, shafts and shaft seals, and dissolved actinide source term. The most important coupling is to the model for flow in the Culebra. Because transport in the

Culebra is one of the last processes to occur along this pathway prior to release, it does not feed back to other conceptual models in any significant manner. This conceptual model falls at the downstream end of the overall disposal system model, and thus has little or no impact on models that come before it.

MASS-15.2.1 Current Studies of Sorption in the Culebra

Several factors affect the sorption of Pu, Am, U, Th, and Np, the elements for which K_d values are required in PA for Culebra transport calculations (Ramsey 1996) including:

- the properties of the sorbents (solids) that will sorb actinides from solution,
- the composition of solutions that currently exist in the Culebra or could enter the Culebra after human intrusion into WIPP disposal rooms,
- the oxidation state of the sorbate (actinide elements) in the Culebra,
- dissolved actinide concentration,
- equilibration time, and
- direction of reaction (sorption versus desorption).

The two most important sorbents in the Culebra are dolomite, a carbonate mineral that constitutes most of the Culebra, and corrensite, an ordered mixture of chlorite and saponite associated with fracture surfaces and dispersed in the matrix (intact rock between the fractures) of the Culebra. Dolomite is important because it is by far the most abundant mineral in the Culebra. Corrensite is important because, although a minor constituent, it sorbs actinide elements more strongly than dolomite. The work of Sewards (1991) and Sewards et al. (1991, 1992) indicates that corrensite is associated with fracture surfaces and dispersed in the matrix at concentrations high enough to increase the retardation of Pu, Am, U, Th, and Np relative to that observed in laboratory studies with dolomite-rich rock. (Np was not transported in the 1996, the 2004 PA, or the 1997 PAVT, but K_ds were also determined for this element for completeness.) However, the DOE does not include K_ds for clay minerals in the ranges and probability distributions for the matrix K_ds used in PA calculations because laboratory data for clay-rich rock under expected Culebra conditions are insufficient at this time. Furthermore, the DOE does not take any credit for sorption by clay minerals associated with fracture surfaces. Omitting K_ds for clays is conservative.

The experimental basis for the ranges and probabilities of matrix distribution coefficients is documented in CCA MASS Attachment 15-1.

MASS-15.2.2 Historical Studies of Sorption in the Culebra

See CCA Appendix MASS, Section MASS.15.2.2 for historical information relating to the CCA Culebra conceptual model.

MASS-15.3 Colloidal Actinide Transport and Retardation in the Culebra

The purpose of this model is to represent the effects of colloidal actinide transport in the Culebra. This model is also discussed in Section 6.4.6.2.2 and Attachments 15-2, 15-8, and 15-9.

A particle is referred to as being in the colloidal state when the particle size lies roughly in the range between 1 nanometer and 1 micron. These particles are generally much larger than simple ions, and as a result, the transport behavior of colloids in groundwater systems can be quite different from that of dissolved species. In a groundwater system, colloids are essentially a third phase consisting of a mobile solid that can associate with or contain actinides and potentially increase transport rates slightly relative to the average groundwater velocity.

In the WIPP disposal system, for instance, colloids are often too large to pass through the small pore throats of diffusive porosity. Such colloids will be restricted to the advective portion of the flow system. Colloids may also be less reactive than dissolved actinides with the host rock. Therefore, even though a colloid is small enough to penetrate the diffusive porosity, the retardation coefficient associated with the colloid will in some cases be smaller than the retardation coefficient of the actinide associated with the colloid.

Colloid-facilitated actinide transport has not been included in the 1996 PA, the 2004 PA calculations, or the 1997 PAVT because of a lack of adequate information to model this phenomenon and demonstrate its impact on compliance (see, for example, SNL, 1992-1993, Vol. 1, 4-12, line 29). Transport of actinides by colloidal particles has been recognized only relatively recently as a phenomenon of potential importance to the performance of nuclear waste repositories (Jacquier 1991; Avogadro and de Marsily 1984). In fact, the study of colloid-facilitated contaminant transport is a relatively new topic to the geosciences in general. Nyhan et al. (1985) was one of the first investigations to demonstrate the potential importance of colloid-facilitated radionuclide transport. Since then, a number of researchers have investigated colloids as a potential transport mechanism (for example, McCarthy and Zachara 1989; Corapcioglu and Jiang 1993; Grindrod 1993; Ibaraki and Sudicky 1995). Grindrod (1993) and Ibaraki and Sudicky (1995) addressed the topic of colloid-facilitated transport through fractured porous media. Consequently, their work is most applicable to the colloid-transport problem in the Culebra.

Among the most sophisticated and rigorous numerical models developed are those by van der Lee et al. (1993, 1994) and Bennett et al. (1993). Many of the colloid-transport numerical models described in the literature focus on simulating solute transport through fractured media with double-porosity flow characteristics, and they have been generalized to include unique features of colloid transport (for example, Hwang et al. 1989; Grindrod and Worth 1990; Light et al. 1990; Smith and Delgueldre 1993; Harmand and Sardin 1994). Some numerical models, such as the population-balance model by Travis and Nuttall (1985), assume equilibrium colloid concentrations. That is, the loss of colloidal particles by attachment to the medium wall is compensated by the generation of new colloidal particles by various mechanisms such as condensation and entrainment. The modeling approach developed by Travis and Nuttall (1985) is similar to the double-porosity transport model.

MASS-15.3.1 Experimental Results

As discussed in Section 6.4.6.2.2, the four types of colloids and colloidal sized particles modeled to be introduced to the Culebra are microbes, mineral fragments, humic substances, and actinide intrinsic colloids. To investigate the impact of these four colloid types on radionuclide transport in the Culebra, an experimental program was developed and implemented at SNL with significant contributions from Lawrence Livermore National Laboratory (LLNL), Battelle National Laboratory, Los Alamos National Laboratory (LANL), and Florida State University. The intent of this experimental program was to develop parameter ranges and distributions for the conceptual models discussed above. With the exception of the Pu (IV) polymer, the experimental results indicated that colloid-facilitated actinide transport is not a viable mechanism for actinide transport in the Culebra. Furthermore, the potential amount of Pu (IV) polymer that could be introduced to the Culebra was found to be insignificant with respect to the EPA normalized release limit. Consequently, colloid-facilitated actinide transport was not simulated in the PA.

The experimental results and implications for PA modeling are summarized as follows:

- Mineral fragments and microbes are attenuated so effectively it was deemed unnecessary to include them in the transport calculations (see CCA Appendix MASS, Attachments 15-8 and 15-9).

- The total potential amount of Pu (IV) polymer introduced to the Culebra was found to be insignificant with respect to the EPA normalized release limit (Attachment 15-8). Therefore, the contribution of Pu (IV) polymer to the integrated discharge was disregarded in the PA.

- Under neutral to slightly basic brine conditions, the presence of humic substances in the brine did not influence the sorption behavior of dissolved actinides. Results indicate that at these geochemical conditions, humic substances were not effective complexants in the presence of dolomite (Attachment 15-8). Therefore, actinides associated with humic substances are assumed to disassociate upon entering the Culebra.

MASS-15.3.2 Indigenous Colloidal Transport

In an intrusion scenario at the WIPP, as dissolved actinide elements are introduced to the Culebra, it is possible that those dissolved actinides could sorb onto a separate population of indigenous mineral fragments, microbes, and humic substances. The physical and chemical behavior of these newly formed actinide-bearing colloidal particles will be nearly identical to the behavior of colloids introduced from the repository. Microbes and mineral fragments will be rapidly filtered out of the advective flow domain; hence, disregarding the interaction between dissolved actinides and these types of colloids is considered to be a conservative approach. Experimental results indicate that humic substances do not interact with dissolved actinides under the expected Culebra geochemical conditions. Consequently, the quantity of newly formed actinide-bearing humics will be insignificant.

MASS-15.3.3 Alternative Approaches Considered

As discussed above, results of experimental studies show that colloidal actinides are strongly attenuated or present in negligible concentrations, making it unnecessary to include them in PA simulations. The following section describes the three alternative transport conceptual models considered prior to the completion of these experimental results.

After the introduction of colloidal actinides and dissolved actinides into the Culebra, realistically a new equilibrium condition will be established, with the stipulation that the total concentration of actinide must be preserved. As in the repository, quantifying an equilibrium assemblage is not practicable.

Three approaches were considered to quantify colloid-facilitated actinide transport at the WIPP. First, the transport of one or more types of actinide-bearing colloidal particles in the Culebra could be assumed to be instantaneous. In other words, as actinides associated with that type of colloidal particle migrate to the Culebra from the repository, or are generated within the Culebra, the mass of actinides associated with those colloidal particles becomes part of the integrated release of actinides at the accessible environment boundary. This approach can be useful if the concentrations of actinides associated with one or more types of colloidal particles are very low. Treating colloid-facilitated actinide transport as instantaneous, however, is a significant shortcoming, because of the potentially large expected retardation effects of colloidal particles.

Second, SECOTP2D and supporting codes could be used to simulate the effects of one or more of the colloid retardation phenomena (Ramsey 1996). The double-porosity advection and diffusion equation solved by SECOTP2D can simulate colloid sorption in the matrix and to the fracture walls. The code can also model colloid filtration using the decay term of the governing equation. For colloids considered too large to diffuse into the matrix, matrix diffusion can be disabled by setting the matrix tortuosity to zero. This approach was used for some calculations completed in 1994. Specifically, microbes, because of their relatively large size, were excluded from matrix diffusion and limited to advective flow in fractures. Humic substances were allowed to diffuse into intercrystalline pores, but at a reduced rate relative to dissolved actinide species.

This approach requires a number of simplifying assumptions under the presumption they are conservative with respect to the integrated release of radionuclides. The first assumption is that the dissolved concentration will be greatest at the source point and therefore, the concentration of radionuclides associated with colloids will be greatest at the source as well. Second, a radionuclide associated with a colloid is assumed to remain fixed to that colloid throughout the simulation. Given these assumptions, the colloidal actinide concentration is no longer a function of the dissolved actinide concentration, and it is not necessary to solve the dissolved species transport problem and the colloid transport problem simultaneously. As a result, the standard advection-diffusion transport equation can be used to predict colloid transport and compute integrated colloid releases. Given the initial concentration of radionuclides sorbed to each specific type of colloid, the integrated colloid release can be converted to an integrated radionuclide release by postprocessing the colloid transport results. Radionuclide decay can also be accounted for in postprocessing.

The third assumption is that colloid-facilitated actinide transport could be quantified by a rigorous numerical modeling code developed for the WIPP. Such a rigorous transport model would address all physical and chemical processes that could affect the movement and fate of the four colloidal particle types, including colloid generation; interactions with solutes, the dispersant, and rock; advection; dispersion; diffusion; filtration; gravitational settling; attachment and detachment; adsorption and desorption; coagulation; flocculation; and peptization. Ideally, permeability reduction caused by pore clogging by colloids, which would affect solute transport as well, would also be considered. Currently available models do not include all of these processes (see CCA Appendix MASS, Attachments 15-2, 15-8, and 15-9).

The most practical approach to evaluating the transport of colloidal actinides is the second option presented above, using the SECOTP2D code. Where possible, the DOE considered reducing the number of phenomena treated in the transport code and address them in the source term. For example, the effect of ionic strength on colloid stability would have been included in the colloid source term. Retardation of colloidal particles was to be quantified using a retardation factor, and filtration was to be quantified through the decay term.

MASS-15.4 Subsidence Caused by Potash Mining in the Culebra

This model incorporates the effects of potash mining in the McNutt on disposal system performance (see Appendix PA, Attachment SCR, FEPs H13, H37, and H38). 40 CFR Part 194 provides a conceptual model and parts of a mathematical model for these effects. The DOE has implemented the EPA conceptual model to be consistent with EPA criteria and guidance. It is described in Section 6.4.6.2.3 of this recertification application. Additional information on the implementation of the mining subsidence model is available in Appendix PA, Attachment TFIELD, Section TFIELD-9.0; CCA Appendix MASS, Attachments 15-4 and 15-7; and Wallace (1996).

The principal parameter in this model is the range assigned to a factor by which hydraulic conductivity in the Culebra is increased (CCA Appendix MASS, Attachment 15-4). As allowed in supplementary information to 40 CFR Part 194, it is the only parameter changed to account for the effects of mining.

Mining in the McNutt has been considered in the performance of the WIPP since the original siting activities. Siting criteria for both the site abandoned in 1975 and the current site included setbacks from active mines. (See, for example, Section MASS-2.0.) The 1980 FEIS for the WIPP (DOE 1980) considered the possibility of an indirect dose arising from the effects of solution mining for potash or halite; it concluded that direct access of waste by solution mining for potash was not likely because of the methods that would be used to control the flow of solvent through the formation. See Appendix PA, Attachment SCR (FEPs H58 and H59).

Mining has been included in scenario development for the WIPP since the earliest work on this topic (for example, Hunter 1989; Marietta et al. 1989; Guzowski 1990; Tierney 1991; and WIPP Performance Assessment Division 1991). These early scenario developments considered both solution and room-and-pillar mining. The focus was generally on effects of mining outside the disposal system. The two primary effects of mining considered were changes in the hydraulic conductivity of the Culebra or other units and changes in recharge as a result of surface

subsidence. These mining effects were not formally incorporated into quantitative assessment of repository performance in preliminary PAs.

The inclusion of mining in PA satisfies the criteria of 40 CFR Part 194 to consider the effects of this activity on the disposal system.

MASS-16.0 INTRUSION BOREHOLE

The inclusion of intrusion boreholes in PA adds to the number of release pathways for radionuclides from the disposal system. Direct releases to the surface may occur during drilling as particulate material from cuttings, cavings, and spall are carried to the surface. Also, dissolved actinides may be carried to the surface in brine during drilling. Once abandoned, the borehole presents a possible long-term pathway for fluid flow, such as might occur between a hypothetical Castile brine reservoir, the repository, and overlying units. This topic is also addressed in Chapter 6.0, (Section 6.4.7) and Appendix PA Attachment SCR (FEPs H1 and H21).

MASS-16.1 Cuttings, Cavings, and Spall Releases during Drilling

These models estimate the quantity of actinides released as solids directly to the surface during drilling through the repository by three mechanisms: the drillbit boring through the waste (cuttings), the drilling fluid eroding the walls of the borehole (cavings), and high repository gas pressure causing solid material failure and entrainment into the drilling fluid in the wellbore (spallings). See Section 6.4.7.1 and references to other appendices cited in that section for additional information. Stochastic uncertainty with respect to parameters relevant to these release mechanisms is addressed in Section 6.4.12. The conceptual model for cuttings, cavings, and spallings is discussed in three parts because of the differing process by which the three types of material are produced.

Cuttings are materials removed to the surface through drilling mud by the direct mechanical action of the drill bit. The volume of waste removed to the surface is a function of the repository height and the drill bit area. The cuttings model has as a principal parameter the diameter of the drill bit (see Appendix DATA, Attachment A).

Cavings are materials introduced into the drilling mud by the erosive action of circulating drilling fluid on the waste in the walls of the borehole annulus. Erosion is driven solely by the shearing action of the drilling fluid (or mud) as it moves up the borehole annulus. Shearing may be caused by either laminar or turbulent flow. Repository-pressure effects on cavings, which are negligible, are covered by the spall process. The principal parameters in the cavings model are the properties of the drilling mud, drilling rates, the drill string angular velocity, and the shear resistance of the waste. See Appendix PA, Attachment PAR (Tables PAR-13 and PAR-18) for details on the sampled parameters used in the cavings model, the drill string angular velocity, and the effective shear resistance to erosion.

Spallings are solids introduced into the wellbore by the fluid pressure difference between the repository and the bottom of the wellbore. If the repository pressure is sufficiently high (~ >12 MPa) relative to the well bottom hole pressure (~8 MPa), the stress state in the repository may cause repository solids to fail in the vicinity of the wellbore. In turn, these solids may become

entrained in the gas flowing toward the well, ultimately to be carried up to the land surface, constituting a release. The principal parameters in the spallings model are the gas pressure in the repository when it is penetrated and properties of the waste such as permeability, tensile strength, and particle diameter. Because the release associated with spalling is sensitive to gas pressure in the repository, it is strongly coupled to the BRAGFLO-calculated conditions in the repository at the time of penetration.

MASS-16.1.1 Historical Context of Cuttings, Cavings and Spallings Models

Cuttings and cavings releases are straightforward. The analytical equations governing erosion (cavings) based on laminar and turbulent flow (Appendix PA, Section PA-4.5) have been implemented in the code CUTTINGS_S. Using selected input based on assumed physical properties of the waste and other drilling parameters, this code calculates the final caved diameter of the borehole that intersects the waste.

The various approaches used for spallings up to the CCA PA are documented in CCA Appendix MASS.16.1.1. Since the CCA PA, the spallings model has been extensively revised and has changed fundamentally from an end-state erosional model to a mechanically based coupled material failure and transport model (WIPP PA 2003a). This model is implemented in a new code, DRSPALL. The following discussion traces the historical steps from the CCA erosional model to DRSPALL.

According to the WIPP Conceptual Models Peer Review Report (CCA Section 9.3.1.2.7), the three primary objections to the erosional spallings model were; (1) channel flow scenario needed additional validation, (2) waste erosion resistance process and parameters had not been adequately evaluated, and (3) assumptions concerning waste degradation and strength. Though the strength value used, 1 lb/in^2, was consistent with the strength of soils, salt and clay mixtures, and similar mixtures with MgO (see CCA Appendix PEER, Section 2.6 for Berglund 1996), the peer review panel was not convinced of the applicability of this value in the model (Wilson et al. 1996b). Hansen et al. (1997) decided to revise the approach to estimating spall release and embarked on a two-part effort that sought to (1) derive mechanical strength estimates from laboratory measurements on surrogate WIPP wastes, and (2) develop a new mechanically-based model for spall that attempts to encompass the entire system response from bit penetration to near steady state rather than just the end state, as done in the erosional model. The results of the model development efforts were implemented in the code GASOUT (Hansen et al. 1997, Appendix C).

MASS-16.1.2 Waste Mechanistic Properties

The spalling event can occur only in cases that combine high pressure with highly degraded waste. A systematic approach was implemented to characterize the waste after compaction, corrosion, and microbial consumption through the used of waste surrogate materials. The primary emphasis of the waste surrogate testing was devoted to quantifying tensile strength, although many other characteristics, such as particle size, permeability, and heterogeneity, will greatly influence potential spall release. Utilizing a projected inventory of waste materials placed in the repository and assuming extensive degradation, recipes (mixtures) for surrogate products were determined. Surrogate recipes derived from corrosion of 50 percent and 100 percent of the

Fe-based inventory were fabricated and mechanically tested using standard laboratory procedures (Hansen et al. 1997).

Degraded waste strength was recognized as a key parameter in a WIPP spallings model (Wilson et al. 1996a, 1996b). Lacking, however, were compelling data to validate the value of tensile strength T_o = 1 lb/in^2 used in the CCA erosional model. In an attempt to build an understanding of the mechanical properties of degraded WIPP wastes, Hansen et al. (1997) developed a test methodology to construct and examine surrogate wastes. They scanned the inventory of WIPP wastes and prepared recipes for various surrogate wastes. A wide variety of materials were cut, shred, compressed, and aged in the laboratory to create specimens appropriate for standard laboratory measurements such as tensile and compression tests. Overall, results from 38 specimens were reported in Hansen et al. (1997) quantifying properties including tensile strength, cohesion, friction angle, Poisson's ratio, and Biot's constant. These data helped to make the case that the T_o = 1 lb/in^2 value used in the CCA was indeed conservative.

Subsurface processes leading to extensive degradation are based on several contributing conditions including ample brine availability, extensive microbial activity, corrosion, and the absence of cementation and salt encapsulation effects. Property values from these surrogate materials are selected to represent the worst-case response to the process being investigated (Hansen et al. 2003b). In terms of the degraded waste properties, the model is highly conservative.

MASS-16.1.3 New Mechanistic Model for Spall

In addition to the work on waste degradation, Hansen's team also laid the groundwork for a new approach to modeling the WIPP spallings process. Instead of focusing on the end state after penetration, as is done in the erosional model, the new effort sought to capture the system behavior from just before penetration through to the end state. In doing so, many more phenomena were included in the model. Considered in this new conceptual model was unsteady, convergent gas flow from the repository toward the wellbore that caused mechanical stress and potential failure of solids near the face of the wellbore. Pressure in the cavity at the point of penetration was balanced by the mud column in the wellbore and the repository pressure. This represented a more complex modeling approach, and was developed sufficiently to satisfy the peer review panel that convened in April, 1997 that the spallings release values used in the CCA were conservative (Wilson et al. 1997).

The new spall model, DRSPALL (WIPP PA 2003a) is based on a predecessor code called GASOUT (Hansen et al. 1997, Appendix C). DRSPALL builds upon GASOUT by:

1. Adding a wellbore flow model that transports mud, repository gas, and waste solids from repository level to the land surface; and

2. Adding a fluidized bed model that evaluates the potential for failed particulate waste to fluidize and become entrained in the wellbore flow.

The wellbore flow model in DRSPALL utilizes one-dimensional geometry with a compressible, viscous, isothermal, homogeneous mixture of mud, gas, and solids. Standard mass and momentum balance, friction loss, and slurry viscosity equations are used. Wellbore flow model

results were successfully verified against those from an independent commercial code for several test problems (WIPP PA 2003b).

DRSPALL applies the fluidized bed theory to determine the mobilization of failed material to the flow stream in the wellbore. If the escaping gas velocity exceeds the minimum fluidization velocity, failed material is fluidized and entrained for transport at the land surface. If gas velocity is too low to fluidize the bedded material, however, the cavity size is allowed to stabilize The spall volumes predicted by DRSPALL are based on conservative assumptions for material properties and for the flow geometry within the repository.

- The particle size distribution for spallings is based on a detailed analysis (Wang 1997) of data from an expert elicitation (DOE 1997). This analysis considered several limiting cases in developing a conservative distribution for mean particle size ranging from 1 mm to 10 cm (Hansen et al. 2003b).

- The shape factor for fluidization of particles has a potential range from 0 to 1.0. Smaller values of the shape factor denote particles that are less spherical, and therefore more easily fluidized and transported in the flow. The shape factor is conservatively set to a value of 0.1 for CRA-2004 (Lord 2003).

- The tensile strength of the waste assigned for the spalling process is uncertain, ranging from 0.12 MPa to 0.17 MPa (Hansen et al. 2003b). Tensile strength data was measured in laboratory experiments on surrogate materials that were chosen to conservatively represent highly degraded residuals from typical wastes. The given range is felt to represent extreme, low-end tensile strengths because it does not account for several strengthening mechanisms, such as MgO hydration and halite precipitation/cementation (Hansen et al. 1997).

- DRSPALL uses a hemispherical geometry (one-dimensional spherical symmetry) for the flow field and cavity in the waste. This conceptual model is appropriate when the drill bit first penetrates the repository. But as the drill bit passes completely through the compacted waste, the flow field will transition toward a cylindrically symmetric geometry. This transition is important because the largest spall release volumes are predicted to occur at late times, well after the drillbit has penetrated through the waste, and because the spall volumes predicted for a cylindrical geometry are less than for the hemispherical geometry (Lord et al. 2003).

In spite of this transition, the hemispherical geometry is used for the CRA-2004 spallings release calculations because it produces conservative results. Fifty calculations performed with DRSPALL in both the hemispherical and cylindrical flow geometries demonstrated that the spall volumes predicted with the hemispherical geometry are always larger than those for the cylindrical geometry (Lord and Rudeen 2003, Section 3.3 Sensitivity Analysis Report Part 2). In fact, the spall volumes are zero for all 50 realizations with a cylindrical geometry, which indicates that the likelihood of spalling is quite small in this geometry. It follows that the hemispherical geometry results in spall volumes that are conservative relative to the cylindrical geometry.

There is no consensus about how the driller will act as the drill approaches the waste horizon; that is, whether he or she will be able anticipate the presence of the gas-filled repository, or if he or she can or will control the drilling process once penetration occurs. For the WIPP intrusion scenarios, the conceptual model assumes the worst possible limiting situation, in which the borehole is driven through the waste by a driller without any knowledge of the existence of the repository, and the driller is unable or unwilling to control the subsequent gas release.

In summary, the conservative assumptions for waste properties, the waste flow geometry and the driller's actions provide very conservative spalling release volumes for CRA-2004 (see also Appendix PA, Section PA-4.6 for a description of the spallings model and Section 9.3.1.3.5.5 for the results of the new spallings model peer review).

MASS-16.1.4 Calculation of Cuttings, Cavings, and Spall Releases

As detailed in Appendix PA, Section PA-6.7, cuttings and cavings releases for intrusions into contact handled (CH)-TRU waste are computed by multiplying the volume released (calculated by the code CUTTINGS_S) with the radioactivity in three independently-selected waste streams, consistent with the conceptual assumption that waste is randomly placed within the repository. The effect of this assumption on PA results was examined in a separate PA (Hansen et al. 2003a) in which cuttings and cavings releases were computed by assuming that each intrusion encounters only a single waste stream. The differences in repository performance (determined by comparing the mean CCDFs for releases) were determined to be minor. For more details on the analysis, see Section MASS-21.0.

Because spallings may releases a relatively large volume of material (exceeding 4 m^3), spallings releases for intrusions into CH-TRU waste are computed by multiplying the volume of spalled material with the average concentration of radioactivity in the waste at the time of the intrusion. A separate PA (Hansen et al. 2003a) compared spallings releases computed using the average concentration of radioactivity in the waste to spallings releases computed by using the radioactivity of a single, randomly selected single waste stream. The analysis determined that the assumption had only a minor effect on the mean CCDF for releases. For more details on the analysis, see Section MASS-21.0.

MASS-16.2 Direct Brine Releases during Drilling

This model provides a series of calculations to estimate the quantity of brine released directly to the surface during drilling. Direct brine releases (DBRs) may occur when a driller penetrates the WIPP and unknowingly brings contaminated brine to the surface during drilling (these releases are not accounted for in the cuttings, cavings and spallings calculations, which model only the solids removed during drilling). Appendix PA, Section PA-4.7 described the DBR model used for the 2004 PA. CCA Appendix MASS, Attachment 16-2 describes the direct brine release model used for the 1996 PA. The conceptual model for DBRs is discussed in Section 6.4.7.1.1.

Uncertainty in the BRAGFLO direct-brine-release calculations is captured in the 10,000-year BRAGFLO calculations from which the initial and boundary conditions are derived. The model parameters that have the most influence on the direct brine releases are repository pressure and brine saturation at time of intrusion. Brine saturation is influenced by many factors, including

Salado and marker bed permeability and gas-generation rates (for undisturbed calculations). For E1 and E2 intrusions, Castile brine-reservoir pressure and volume and abandoned borehole permeabilities influence conditions for the second and subsequent intrusions. Dip in the repository (hence the location of intrusions), two-phase flow parameters (residual brine and gas saturation), time of intrusion, and duration of flow have lesser impacts on brine releases.

To account for changes in the BRAGFLO model (see Section MASS-2.0), the implementation of the DBR model has been adjusted for the CRA 2004-PA. Figure MASS-9 shows the DBR

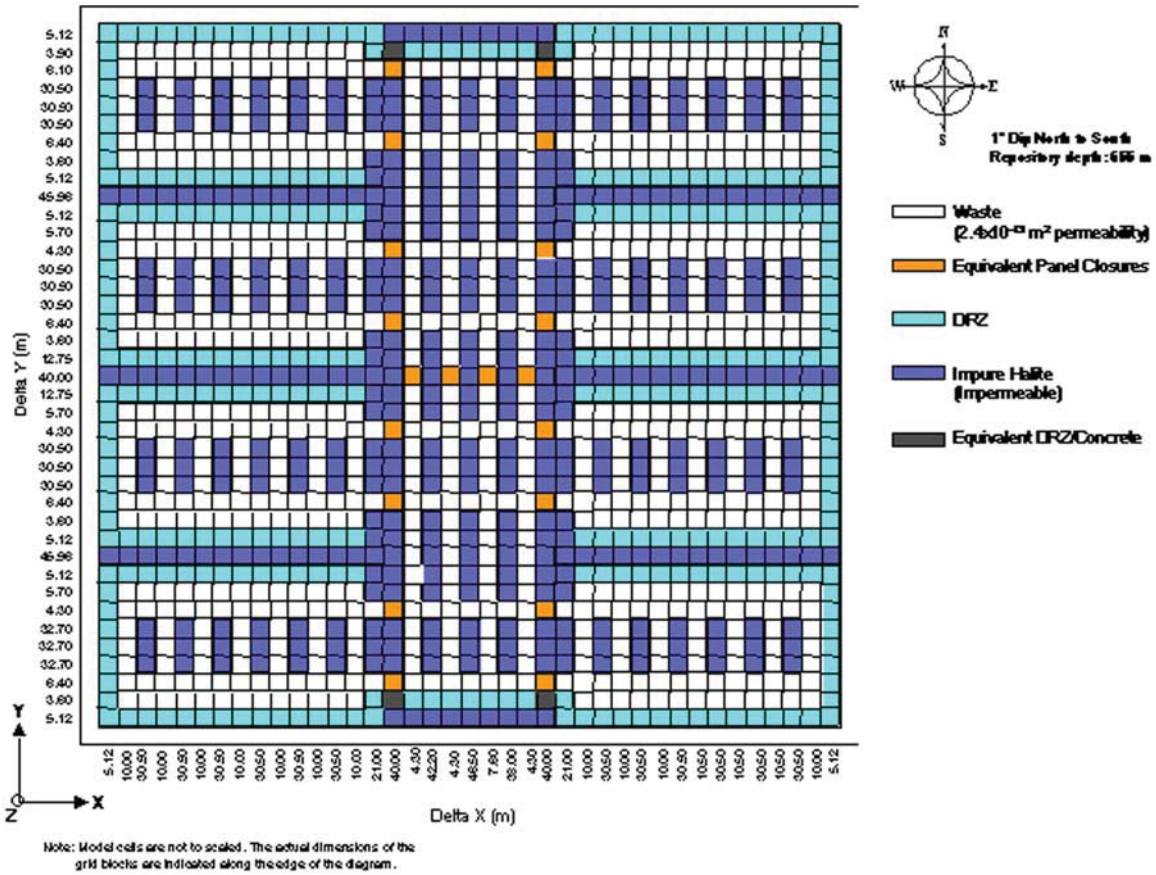

Figure MASS-9. Repository-Scale Horizontal BRAGFLO Mesh Used for Direct Brine Release Calculations

grid used in the 2004 PA. The grid dimensions and resolution are the same as in the CCA PA, but the material parameters assigned to the panel closures have been changed to be more consistent with the conceptual model for the Option D panel closures. In addition, the material parameters assigned to the DRZ have been changed to more consistently represent the DRZ. In the CCA PA, the pillars between rooms and the halite separating panels were assigned properties consistent with the DRZ material in the BRAGFLO grid. The DRZ permeability used in the CCA (10^{-15} m^2) was low enough that brine did not flow between panels during the 11-day DBR calculations. When the permeability of the DRZ was changed in the PAVT (from a constant value of 10^{-15} m^2 to a sampled value between $10^{-19.4}$ m^2 and $10^{-12.5}$ m^2), realizations with high

DRZ permeability allowed brine flow between panels during the 11-day period for DBR calculations. It is not reasonable to model the halite between panels as DRZ, since the DRZ would extend only a few meters into the 60-m thick ribs. Consequently, the material parameters assigned to cells separating panels were changed to be representative of undisturbed halite, rather than DRZ. Stein (2003b) provides details on the material parameters used in the DBR calculation and the rationale for the parameter values.

MASS-16.3 Long-Term Properties of the Abandoned Intrusion Borehole

The purpose of the model for the long-term properties of the intrusion borehole is to provide in BRAGFLO the physical properties relevant to fluid flow through a plugged and abandoned borehole that intersects the repository. The model includes several possible plugging and configuration patterns based on current practice in the Delaware Basin (CCA Appendix MASS, Attachment 16-1). Because plugging practice is closely controlled by state regulations, only the New Mexico portion of the Delaware Basin is considered. Section 6.4.7.2 of this application describes the properties assigned to the boreholes and the types of plug configurations considered in performance assessment.

The conceptual model for long-term flow up a plugged and abandoned borehole addresses the principal parameters in the intrusion borehole model for long-term flow: permeability, porosity, compressibility, and two-phase properties. Because these properties may change with time as the borehole plugs degrade, some types of boreholes have several defined stages for the evolution of borehole properties. No retardation of actinides or other transport-limiting effects in the borehole are assumed. This is considered a conservative assumption (see Table MASS-1).

Permeability, the most important borehole property, changes according to the stage of borehole degradation. The values assigned to other parameters are held constant for all stages and are set consistent with a borehole fill referred to as silty sand, consisting of the material that would naturally slough off the walls of the borehole or the remains of degraded plugs. The porosity of the plugged and abandoned borehole is set at a low value within the porosities expected of materials that will be in the borehole; the low value was chosen because smaller void volume in the borehole reduces storage in the borehole and slightly increases the total flux of fluids that may pass through it.

Predictions of the time-dependent permeability of plugged boreholes are based on three configurations for borehole plugs and two concepts of how the plug materials will be altered by fluids. The concepts include steel corrosion and concrete degradation. From the outside inward, the conceptual model for borehole plugs envisions concentric circles of ordinary portland cement as grout attaching the casing to the rock, low carbon steel (the casing), and a central disc of ordinary portland cement (the concrete plug). The bulk of the data used to predict the service lives of borehole plugs comes from the open literature on corrosion of low carbon steel and ordinary portland cement and from tabulated thermodynamic data bases.

Predictions of plug performance derived from the conceptual models are sensitive to both chemical and physical parameters. Key areas of uncertainty include the following:

- opened or closed nature of the physical and chemical systems,

- degree to which performance data from generic materials apply to WIPP-specific materials and conditions,
- conditions at the precise locations where WIPP plugs are emplaced, and
- physical dimensions of the plugs.

The conceptual models for predicting the time-dependent permeability of plugged boreholes recognize two types of systems: open and closed. Open systems are ones in which chemical components can be added or subtracted freely, whereas closed systems are ones in which the identity and amount of chemical components available for reaction are constant. In physical models, a closed system maintains a constant volume, while in open systems volume is unconstrained. The principal area of uncertainty in the conceptual models is the definition of the boundary between open and closed space. This boundary is significant because real systems are somewhere between totally open or closed, and open and closed systems result in very different expected performance lives for plugged boreholes.

In chemical systems, a very small addition or release of reacting components is insignificant, but a substantial change can have large effects: in open systems reactions proceed until the supply of reactants is exhausted. In open systems, equilibrium considerations may have little or no significance; hence treatment by equilibrium thermodynamics may be unenlightening. Similarly, in physical systems, a small amount of system expansion will have little effect on internal stresses, but unlimited expansion may cause the system to fail in tension.

MASS-16.3.1 Corrosion

There are many low-carbon-steel alloys, and not all corrode at the same rate in a given environment. However, because of the aggressive corrosion rate selected for the model, steel composition is not thought to introduce significant uncertainty about the rate. Corrosion of the casing steel has been modeled thermodynamically for plugged boreholes. Hydrogen is a common byproduct of corrosion. An equilibrium hydrogen pressure has been calculated for a number of potential reactions, using metallic iron to represent steel and pure water to represent brines. Attainment of equilibrium hydrogen pressure is taken to indicate cessation of corrosion. To reach equilibrium, the system must contain the hydrogen that is generated. The hydrostatic pressure of the brine column has been assumed to confine hydrogen when the pressure exceeds the equilibrium hydrogen pressure calculated for the corrosion reaction of interest.

Reactions most representative of corrosion of steel casing produce iron hydroxide corrosion products. Equilibrium hydrogen pressures for these reactions are exceeded by hydrostatic pressures at depths greater than about 1,100 ft (335 m). Corrosion of casing above this depth is treated as open; the casing corrodes until the supply of metallic iron is exhausted and the casing disintegrates. Without axial support supplied by the casing, the concrete plug also fails. In contrast, corrosion is assumed to take place in a closed system at depths greater than 1,100 ft (335 m). Hydrogen is not free to nucleate as a gas and leave the system. Although local perforations in the casing are expected, the casing does not disintegrate. It supports the concrete plugs, and permeability changes in the plugs are attributed to alteration of cement phases by the brine that flows through them.

The greatest uncertainty associated with composition is likely to arise from the thermodynamic calculations used in the model. Pure phases (Fe for steel and H_2O for brine) have been assumed so that hand calculations may be more readily performed. Various reactions and environments have been modeled without directly considering complexities in the chemical system (other than volatiles). Qualitatively, the added complexities are likely to have no substantial consequence on the ability of the brines to dissolve a pathway through the casing. However, system complexities might decrease the equilibrium hydrogen pressures calculated for the corrosion reactions or lead to unexpected reaction products.

Data supporting low-carbon-steel corrosion models come primarily from the literature. The empirical data support the assumption that general corrosion is the dominant mechanism for corrosion under oxic conditions and that pitting will occur under low oxygen (and high pH) or elevated carbon dioxide and hydrogen disulfide conditions. Corrosion rates are a function of the conditions under which corrosion occurs. Published data include rates as rapid as 3 mm per year, which is the value assumed in the model. Such rapid rates are not inconsistent with reports in the Delaware Basin of casing failures occurring from corrosion within months to years (CCA Appendix MASS, Attachment 16-3, B-17). Data from corrosion of steel enshrouded in concrete come from the literature on marine construction and the data base on reinforcing steels. These data support the assumption that steel encased in concrete cannot be assumed to corrode more slowly than exposed steel. This subject area is discussed in detail in CCA Appendix MASS, Attachment 16-3 (Section 3.2 and Appendix B).

MASS-16.3.2 Portland Cement Concrete

The cementitious materials used in hydrocarbon exploration are variable. The degree to which oil-field materials might perform differently from the cement mixtures investigated and reported in the literature is unknown. There is no standard mix formulation that specifies plugging cements precisely; the use of generic data is reasonable, because the vagaries of cement composition are implicitly included. The published empirical studies of concrete degradation include a large body of data for reacting solutions ranging from pure water to marine brines. Waters with higher chloride and magnesium contents cause greater reaction. This level of detail has not been factored into the model directly; rather, alteration by brines has been the favored source when extracting information on degradation.

Chemical alteration of cement phases by brine produces new solids with greater molar volumes than the unaltered, hardened cement phase. In a closed physical system, the alteration will lead to decreased internal porosity and consequent decrease in permeability. In an open physical system, alteration will lead to increased internal pore pressures that will eventually exceed the tensile strength of the concrete plug. The result is often seen on concrete sidewalks or other unreinforced concrete structures: without something to restrain expansion, the concrete cracks, increasing its porosity and permeability.

Current plugging practices create configurations that favor each model. Plugs installed to respond to the New Mexico Oil Conservation Division regulation R-111-P approach 2,000 ft (610 m) in length (State of New Mexico 1988). These plugs are judged to be long enough that they are self-confining. As a result, alteration of R-111-P plugs produces a situation in which performance is indistinguishable from the undisturbed rock. In contrast, plugs emplaced in

response to regulations of the U.S. Bureau of Land Management have a mean length near 40 m. This length is judged to be too short to provide self-confinement; alteration of the concrete results in fracturing and increased porosity and permeability in the plug. The plug length that changes the physical system from open to closed is undetermined. For both chemical and physical model elements, a closed system enhances performance.

Simulation of concrete plug degradation follows a model proposed by Berner (1990), in which the matrix degrades after dissolution and removal of soluble materials such as alkali salts. The model is grounded in empirical observations that concrete alteration sequentially removes excess alkalis, portlandite, and tobermorite or calcium-silicate-hydrate (CSH). Decreased strength attends removal of portlandite.

A critical amount of flow must occur before this degradation threshold is crossed. A volume equivalent to 100 pore volumes has been taken as the critical flow volume, based on values for common compositions of ordinary portland cement concrete (Berner 1990). Also following Berner, the model tracks the amount of flow as pore volumes, reasoning that flow occurs only through pores and that alteration is therefore limited to the solids that surround the pores. The model does not explicitly account for the strength of the concrete but instead makes the conservative assumption that physical failure occurs suddenly at the onset of chemical attack on CSH, that is, at approximately 100 pore volumes. As a result, initial porosity of the hardened concrete is a key parameter for timing plug degradation.

The initial permeability of hardened cement is directly related to the connected porosity that permits flow to occur. Initial permeability of ordinary portland cement is a strong function of the water:cement ratio of the mix. Higher water contents produce higher porosity and permeability. To simplify the analysis, the CCA used an initial plug permeability of 5×10^{-17} m^2. This value lies in the upper range of permeabilities reported for ordinary portland cement and is verified by field measurements made during a single field test of borehole plugging conducted for the DOE (CCA Appendix MASS, Attachment 16-3, C-4). In their review of the CCA, the EPA required the DOE to treat this parameter as uncertain (EPA 1998b, Section 5.17). DOE implemented log-uniform distribution of values ranging from 10^{-19} to 10^{-17} m^2. This distribution is used for the 2004 PA calculations.

The initial permeability of the concrete plug is an important parameter because water must penetrate and flow through the structure before it can alter the hardened plug. The lower the permeability, the longer it takes for 100 pore volumes to pass through the plug. Somewhat paradoxically, the lower the porosity, the smaller the volume of water needed before attack of the CSH begins, because the model decouples the relationship between porosity and permeability by holding permeability constant. In the real world, cement formulations with low water:cement ratios generally produce fewer alkalis and have both lower porosities and lower permeabilities. Less water must pass through the concrete body before onset of CSH degradation, but the lower permeabilities lead to a longer life. The simplified model is conservative: it holds the permeability constant at the upper end of the established range while allowing porosity to vary over the full range commonly encountered in ordinary portland cement. This accommodation reflects better knowledge of permeabilities than porosities in as-emplaced borehole plugs. The range in porosity modeled (5 to 40 percent) can create an order-of-magnitude spread in predicted performance life.

Data supporting the concrete degradation model come primarily from two sources: the international repository literature and journals on concrete construction (for example, dams or bridges). The international literature on repositories contains both models and empirical studies confirming that alteration of concrete will result in decreased porosities and permeabilities in closed systems. Experience for dams confirms this conclusion and confirms the diffusion-driven concrete alteration rates used in the model. The general concrete literature confirms the values of initial permeability and porosity of hardened concrete used in the model.

Observations made on cores recovered from potash mines near the WIPP confirm that alteration of concrete plugs is not extensive after decades of service. Qualitative data have been produced by recovery, microscopic inspection, and leach testing of concrete cores recovered from nearby potash mines. These data establish that plugs placed in boreholes will have low initial permeabilities and that plugs placed in the Salado will form tight interfaces at the borehole-rock interface and will not degrade substantially by contact with formation brines in the amounts and compositions that might reasonably be expected. See CCA Appendix MASS, Attachment 16-3 for the historical discussions of concrete plug alteration and creep closure of boreholes.

MASS-16.3.3 Borehole Configurations

The conceptual models for borehole plugs examine three basic possibilities: a continuous plug through the evaporite sequence, a plug below the brine reservoir horizon coupled with a plug between the repository and the Rustler, and three or more plugs with at least one intermediate plug between the brine reservoir and the repository and another between the repository and the Rustler. These possibilities represent simplifications of the plugging schemes documented in a 1996 survey during the 1996 CCA and verified by the Delaware Basin Drilling Surveillance Program (see Appendix DATA, Attachment A; and Sections 6.4.7.2.1 through 6.4.7.2.3). Since the CCA, plugging data show these three plug configurations continue to represent plugging patterns employed within the WIPP vicinity (WRES 2003, Attachment C).

As stated, the basis for these assumptions is a detailed survey of plugging practices in the Delaware Basin. The survey examined the lengths, locations, and intervals plugged, as well as the materials used for construction. The locations of plugs are determined partly by stratigraphic changes and partly by operational considerations during exploration and recovery. Variations in plug length and location affect pressure regimes and flow rates through plugs. The 120-ft (40-m) length of the plugs is the approximate mean value of approximately 188 plugs in the survey. Minimum lengths prescribed by regulations are 50 ft (15 m) above plus 50 ft (15 m) below casing transitions or recovery points. Additional plug lengths sometimes occur for unspecified reasons. When all else is equal, performance life is proportional to plug length. For conservatism, the model does not consider the longer plugs. In the conceptual model, all plugs are taken to be 120 ft (40 m) long. See CCA Appendix MASS, Attachment 16-3 (Section 5.0), for a more detailed discussion of plug performance.

The borehole permeability model was assembled beginning in February 1996. Initially, the model considered only the plug configuration stipulated by Oil Conservation Division regulations, but it was subsequently expanded to consider all regulations and practices documented in the New Mexico portion of the Delaware Basin, without specific consideration of their applicability to the WIPP in the future. The model was developed to be straightforward and

easy to understand. Use of hand calculations was favored over the use of complex computer codes. As a result, no detailed evaluation of potentially applicable codes was undertaken, and no screening of codes was performed.

CCA Appendix MASS, Attachment 16-3 describes the model and its predictions contains about 40 references with data that support the model. In general, these references support the plug configurations, steel corrosion mechanisms and rates, and concrete alteration processes that underpin the model. Additionally, the Delaware Basin Drilling Surveillance Program continuously monitors plugging practices in the WIPP vicinity (WRES 2003).

MASS-17.0 CLIMATE CHANGE

The purpose of this model is to allow quantitative consideration of the extent to which uncertainty about future climate may contribute to uncertainty in estimates of cumulative radionuclide releases from the disposal system. Consideration is limited to conditions that could result from reasonably possible natural climatic changes. The model is not intended to provide a quantitative prediction of future climate, nor is it intended to address uncertainty in system properties other than estimated cumulative radionuclide releases that may be affected by climate change. This model is also discussed in Section 6.4.9.

As discussed in CCA Appendix CLI, paleoclimatic data from the literature form the basis for reconstructing the climatic variability in southeastern New Mexico since late Pleistocene time, spanning the transition from full glacial conditions in North America (ice sheets as far south as the Northern Great Plains) to the present interglacial period. The wettest and coolest climate at the WIPP corresponded to periods of continental glaciation. During Holocene time (the past 10,000 years), the climate has been predominantly dry, like that of the present, with several wetter episodes.

Future climate at the WIPP may differ in the next 10,000 years from that of the present, but it should be bounded by the extremes of the late Pleistocene glaciation. For the purposes of performance assessment, the DOE assumes that uncertainty about future climate is adequately captured by considering two possible patterns: one in which the Holocene pattern of predominantly dry conditions alternating with wetter conditions continues; and one in which the climate becomes continuously wetter.

Effects of climatic change on the WIPP are limited in the performance assessment model to effects on groundwater flow in the Culebra. Flow (that is, specific discharge in the MODFLOW-2000 model) is increased from its present calibrated value by a sampled factor that ranges from 1.0 to 2.25 to simulate effects of wetter climates. Possible decreases in flow during drier climates are not considered. Justification for limiting the effects of climate change to flow in the Culebra is based on regional three-dimensional modeling that estimates the extent to which changes in recharge will alter the altitude of the water table and in turn affect flow in the Culebra and other units. Maximum recharge rates considered in the analysis result in a simulated water-table altitude at or near the ground surface throughout the region. Other effects of climatic change, including changes in temperature, wind, evapotranspiration, and vegetation, are not

modeled explicitly but are qualitatively included in this analysis through the consideration of the effects of varying recharge.

The climate change model is implemented through the use of a single parameter, the Climate Index. This parameter is a dimensionless factor by which the specific discharge in each grid block of the MODFLOW-2000domain is multiplied. It is a sampled parameter in the PA, with a bimodal distribution ranging from 1.00 to 1.25 and from 1.50 to 2.25. See Corbet (1995) and CCA Appendix MASS, Attachment 17-1 for a discussion of this distribution.

The climate change model used for performance assessment is predicated on the assumption that climate will change during the next 10,000 years. The extent of this change is uncertain, but it should be bounded by the changes that occurred in the past during the peaks of Pleistocene glaciation. Other conceptual models for climate change are not consistent with present scientific understanding of the Earth's climate or with the EPA's guidance to consider natural processes of climatic change (EPA 1996, pp. 5227-5228). For example, climate could be assumed to remain constant for 10,000 years, but this would be inconsistent with scientific understanding of climate. Alternatively, climate could be assumed to change to conditions unlike any known from the Pleistocene; however, no natural processes are known that could result in such change within 10,000 years.

As discussed in Corbet (1995) and CCA Appendix MASS, Attachment 17-1, the implementation of climate change in the performance assessment incorporates uncertainty about future climates within the range known from the Pleistocene. Alternative approaches to treating climate change in the performance assessment (that is, varying boundary conditions rather than specific discharge) are discussed in the following section. Past analyses performed using a different approach as part of the 1991 and 1992 preliminary performance assessments suggest that disposal system performance is not sensitive to climate change (Swift et al. 1994, p. 12).

MASS-17.1 Historical Context of the Climate Change Model

See CCA Appendix MASS, Section MASS.17.1 for historical information on the Climate Change model. This Climate Change model is unchanged for the 2004 PA.

MASS-18.0 CASTILE BRINE RESERVOIR

The conceptual model for the hypothetical brine reservoir is included in the performance assessment to estimate the extent to which uncertainty about the existence of a brine reservoir under the waste disposal region may contribute to uncertainty in the estimate of cumulative radionuclide releases from the disposal system. The conceptual model is not intended to provide a realistic approximation of an actual brine reservoir under the waste disposal region: data are insufficient to determine whether such a brine reservoir exists.

The Castile is treated as an impermeable unit in PA and plays no role in the analysis except to separate the Salado from the modeled brine reservoir in the BRAGFLO grid. In human-intrusion scenarios, the hypothetical brine reservoir can be penetrated by an intrusion borehole connecting it to the repository. The amount of brine that can enter the repository from the brine reservoir is

important to PA because brine is required for gas generation reactions to proceed and can transport radionuclides in solution, contributing to potential releases.

The properties of the hypothetical brine reservoir defined for PA include: permeability, porosity, pore volume, initial pressure, and various two-phase flow parameters. Values assigned for these properties were chosen to either be consistent with the available data from and analyses of borehole penetrations of brine reservoirs in the region, or to provide a reasonable response in the BRAGFLO model.

The treatment of the brine reservoir for the 2004 PA is different than that used in the 1996 CCA PA. The major changes to the brine reservoir representation were made by the EPA in their 1997 PAVT (EPA 1998b, V-B-14). In the 1997 PAVT, EPA defined new parameter ranges for bulk compressibility and total pore volume. The range of bulk compressibility was based on a reevaluation of field test data from the WIPP-12 borehole following the CCA (Beauheim 1997). Since the total volume of the grid cells used to represent the brine reservoir in BRAGFLO is fixed, the range of total pore volume was set by defining a range of "effective" porosity (pore volume = grid volume × effective porosity). This range of porosity values is not representative of the actual host rock rather it was chosen to produce a reasonable response in the BRAGFLO model by providing a predefined range of total pore volumes based on the field tests at WIPP-12.

For the 2003 WIPP PA, DOE has implemented this approach by assuming that the productivity ratio (PR) remains constant (2.0051×10^{-3} m^3/Pa). The productivity ratio is defined as:

$$PR = V \frac{C_r}{\phi},$$

where V is the grid volume of the brine reservoir (18,462,514 m^3), C_r is the bulk compressibility (2×10^{-11} to 1×10^{-10} Pa^{-1}), and φ is the effective porosity (0.1842 to 0.9208). The porosity range used in the CRA-2003 PA is slightly modified from that used by the EPA because the fixed-grid volume increased slightly from the volume assumed in the CCA BRAGFLO grid. In this approach, bulk compressibility and effective porosity are directly proportional (Stein 2003a). See Appendix PA, Section PA-4.2, for the details on the implementation in PA.

Basic geologic information about the Castile is given in Section 2.1.3.3. The hydrology of the known brine reservoirs is discussed in Section 2.2.1.2.2. The treatment of the hypothetical brine reservoir in the PA is discussed in Section 6.4.8, which also points to supplementary information included in this recertification application.

MASS-18.1 Historical Context of the Castile Brine Reservoir Model

See CCA Appendix MASS, Section MASS.18.1 for historical information on the Castile Brine Reservoir model.

MASS-19.0 OPTION D PANEL CLOSURES

The certification decision by the EPA (1998a) included several conditions that the DOE was required to meet. In the first of these conditions, the EPA required the DOE to implement a specific design for the panel closure system referred to as Option D and required the concrete monolith to be constructed using SMC. The DOE had included in the CCA four Options (A-D) for the panel closure design. The Option D design consisted of two components; a large monolith constructed of SMC and keyed into the surrounding DRZ, and an explosion wall constructed of concrete blocks, which is not keyed into the DRZ.

The PA calculations that supported the CCA and the subsequent 1997 PAVT calculations included generic panel closures in the BRAGFLO grid. These generic closures were not representative of the Option D design. Specifically, the Option D panel closures are designed to impede fluid flow (brine and gas) between panels over long-time scales. The generic panel closures included in the 1996 CCA and 1997 PAVT calculations were relatively permeable and allowed gas to flow freely between panels. In the 1996 CCA and 1997 PAVT PA calculations, a drilling intrusion into a single panel generally caused pressures in the entire repository to decrease.

Following the certification of the repository, the DOE updated the modeling of the panel closures in PA so that the mandated Option D design was adequately represented. A new panel closure representation was developed and presented to the Salado Flow Peer Review Panel in May 2002 and again in February 2003. The peer review panel approved the new conceptual models, which included the implementation of the Option D panel closures in the grid (Caporuscio et al. 2003).

In the CCA/PAVT BRAGFLO grid, only two panel closures were represented. For the 2004 PA, however, DOE included an additional set of panel closures. Preliminary tests of the Option D panel closure representation (Hansen et al. 2002) concluded that Option D panel closures were effective at impeding fluid flow between panels on the order of thousands of years, but that given enough time, pressures slowly equilibrated. These results suggest that the effect of a single intrusion event on pressures in other panels depends on the number of panel closures that lie between the intruded panel and the other panels. Therefore, DOE decided to divide the RoR region into two regions separated by a panel closure. This panel closure represents a set of four panel closures to be located between the northern and southern internal extended panels. The south RoR represents panels directly adjacent to an intruded panel and the north RoR represents panels that are farther away from the intruded panel (two sets of panel closures lie in between).

The DOE assumes that the effect of the Option D panel closures will be to impede fluid flow through and around the closures. Only the concrete monolith portion of the closure system is assumed to remain effective over the 10,000-year regulatory period. The explosion wall is assumed to effective only for a brief period during the operational period. The explosion wall and the open drift adjacent to the monolith are represented in the BRAGFLO grid by a column of grid cells with the properties of the waste area (e.g., high permeability) and include creep closure effects. The monolith is represented in the BRAGFLO grid by an adjacent column of grid cells with a length equal to the length of the monolith (7.9 m) multiplied by the number of panel closures in series and a width equal to the width of the monolith (10 m) multiplied by the number of panel closures in parallel. For instance, in Figure MASS-6, the southern panel closure in the

BRAGFLO grid represents a single set of two panel closures (in parallel) that separate a single external panel from the one of the two internal extended panels (9 and 10). The middle panel closure in the BRAGFLO grid represents a single set of four panel closures (in parallel) that separate the internal extended panels from one another. The northern panel closure in the BRAGFLO grid represents two sets (in series) of four panel closures (in parallel) that lie between the northern edge of the waste region and the shafts.

It is assumed in the modeling that the DRZ above the concrete monolith will heal and quickly attain a state of relatively low permeability. However, it is also assumed that if pressures exceed the fracture initiation pressure (~12.5 MPa), DRZ and anhydrite marker bed materials that intersect the waste room can fracture and allow gas or brine to circumvent the panel closures by flowing around the concrete monolith. This possibility is included in the implementation of the panel closures in the BRAGFLO by replacing the concrete monolith material with marker bed material everywhere the monolith intersects and cuts through the marker beds. This implementation is appropriate even at low pressures because the permeability range of the concrete and the marker beds is nearly equivalent. And at high pressures, fracturing is considered in these grid elements allowing fluids to flow, thus simulating the consequence of fractures extending around the monolith.

Additional information on panel closure effects on repository performances can be seen in the BRAGFLO Analysis package (SNL 2003c).

MASS-20.0 SUMMARY OF CLAY SEAM G MODELING ASSUMPTIONS

One of the changes to the repository design since the CCA is the raising of the repository horizon in the southern half of the waste panels. Specifically, Panels 3, 4, 5, 6, and 9 will be excavated at an elevation approximately 2.4 m above the level of Panels 1, 2, 7, 8, and 10, and the operations and experimental areas. This change in horizon will bring the roof of the raised rooms to the level of the Clay Seam G. The change is expected to improve roof conditions and enhance operations and mine safety. The DOE submitted a planned change request to EPA that described the change and presented an argument that the change would have minimal impact on long-term repository performance (DOE 2000). The EPA responded to the change request in a letter (EPA 2000) in which they agreed with the DOE that the effects to long-term performance would be minimal.

As part of the Salado Flow Peer Review in February 2003, the DOE did an impact assessment on the possible effects of the horizon change to PA to better demonstrate the minimal impact of this change on long-term performance. Two possible effects of this change on the results of PA were considered in this assessment.

First, it was considered that the horizon change might influence the creep-closure porosity surface calculated by the code SANTOS and used by BRAGFLO to determine the porosity of the waste rooms. This possibility was considered by simulating creep closure around a WIPP disposal room raised to Clay Seam G (Park 2002). The resulting Clay G porosity surface was then compared with the original porosity surface, which was used in the CCA. The differences

were shown to be so minor that long-term PA would not be significantly altered (Park and Holland 2003).

The second effect that was considered was the possibility that the thickness of the upper and lower DRZ, as represented in the BRAGFLO grid, might change due to the horizon change. Specifically, in the raised part of the repository, the lower DRZ might become thicker since the distance from the floor of the rooms to MB 139 will be greater than in the unraised part of the repository. A similar decrease in the thickness of the upper DRZ might occur as the roof of the rooms would be nearer to MB 138. Since the DRZ is assumed to be an important source of brine in BRAGFLO, these potential changes to the thickness of the DRZ might affect the amount of brine available to the waste in the raised panels. To assess whether such a change would affect long-term performance, DOE ran a single replicate of 100 undisturbed BRAGFLO vectors in which the total pore volume in the DRZ was adjusted to account for the thickness changes (Stein and Zelinski 2003a). Pressure and saturation results within the waste regions were compared to results assuming the original DRZ thicknesses. It was concluded from these comparisons that the effects of the DRZ thickness changes were very minor and not at all significant for long-term repository performance (Stein and Zelinski 2003b).

The results of the impact assessment were presented to the Salado Flow Peer Review panel in February 2003. The panel accepted the position that the repository horizon change was adequately represented by the impact assessment and need not be implemented explicitly in the BRAGFLO grid for PA calculations (Yew et al. 2003). Based on the results of this impact assessment and the acceptance of the Salado Flow Peer Review, the DOE has determined that it is not warranted to include the change in the repository horizon to Clay Seam G explicitly in the BRAGFLO grid.

MASS-21.0 EVALUATION OF WASTE STRUCTURAL IMPACTS, EMPLACEMENT AND HOMOGENEITY

During the development of the CCA PA, the DOE choose to assume random placement of TRU waste in the WIPP, and developed conceptual and numerical models accordingly. The EPA reviewed these models and their results, and determined that DOE had modeled accurately random placement of waste in the disposal system. Since the time of the CCA, additional information about the waste and its emplacement has emerged, and requires the assumption of random placement to be reevaluated. The waste inventory estimates have been updated since the CCA PA (see Appendix TRU WASTE), resulting in different estimates of important waste components, such as CPR materials. Additionally, the CCA PA assumed that all waste could be modeled as if the waste was emplaced in 55-gallon drums. However, the DOE is emplacing waste using several different types of waste containers, including standard waste boxes (SWBs) and pipe overpacks (Section 4.1). Waste has been shipped to WIPP in campaigns from the generator sites, resulting in waste emplacement that appears inconsistent with the representation of the waste as a homogeneous material. Finally, DOE plans to emplace waste types, such as supercompacted waste, that were not considered in the CCA inventory (DOE 2002). As a result of this new information and these proposed changes, DOE performed a separate analysis (Hansen et al. 2003a) to determine if the modeling assumptions used in PA continue to adequately represent the waste.

Many important waste characteristics, such as the radionuclide content and the mass of CPR materials, are directly incorporated in PA by means of waste material parameters. These parameters have been updated consistent with the inventory update (see Appendix TRU WASTE) and thus are represented in the 2004 PA. However, PA does not account for heterogeneity in waste materials or in waste containers. At the Idaho National Engineering and Environmental Laboratory, for instance, debris waste will be volume-reduced by supercompaction, resulting in a very dense waste form containing a high concentration of CPR material. In addition, the Pu residues from the Rocky Flats Environmental Technology Site have been packaged in pipe overpacks, which are more rigid than the typical 55-gallon drum assumed in the CCA. Additionally, PA assumes that waste is emplaced in a random or homogeneous manner. Actual waste emplacement is determined by the availability of waste at generator sites and the shipping schedules. Pipe overpacks occupy about 43 percent of the containers emplaced in Panel 1, suggesting that actual emplacement will not be statistically random.

The analysis reported in Hansen et al. (2003a) focused on potential effects of supercompacted waste and of waste in pipe overpacks on repository performance. Both waste types are structurally stiffer than the generic waste model used in the CCA PA, and the supercompacted waste in particular has high concentrations of CPR materials. The analysis began with a systematic reevaluation the baseline FEPs to identify specific components of PA that could be affected by supercompacted waste. The reassessment concluded that the FEPs “screened in” were adequate to represent the variety of waste types and containers, and that none of the “screened out” FEPs should be reconsidered for implementation. The FEPs assessment concluded that creep closure of the repository, chemical conditions of the waste, gas generation models, and waste mechanical properties could be affected by heterogeneities in the waste materials and waste containers. In addition, DOE determined that the assumption of random waste emplacement should be reevaluated.

Analysis of creep closure of waste-filled rooms, accounting for several types of waste materials and packaging, indicated that a wider range of long-term porosities could occur relative to that established in the CCA, given the uncertainties about the structural integrity of waste packages and their spatial arrangement in the repository (Park and Hansen 2003). For this reason, the analysis in Hansen et al. (2003a) treated creep closure as an uncertain variable. Sensitivity analysis showed that this additional uncertainty did not affect the results of PA in a significant way.

Chemical conditions also were reexamined under a range of possible waste arrangements. The assessment found that regardless of actual waste emplacement, the MgO would still be sufficient to maintain desired chemical conditions. Moreover, the constituents of supercompacted waste would not alter the reactions that determine chemical equilibrium and, consequently, no changes to actinide solubilities or to the gas generation models were warranted.

Supercompacted waste contains elevated amounts of CPR materials relative to other waste streams, and the future arrangement of this waste in the WIPP repository is uncertain. Thus, the analysis treated the spatial distribution of CPR materials as uncertain. However, sensitivity analysis demonstrated that uncertainty in the spatial distribution of CPR materials had little effect on PA results.

The representation of the waste properties also was considered; however, it was determined that no changes to permeability, shear strength, or tensile strength were warranted. Based on this evaluation, no changes to the models for direct releases were necessary.

Direct releases as a consequence of a drilling intrusion are calculated with the assumption of random waste emplacement in the repository. In addition, releases by spallings, DBR, and long-term radionuclide transport assume that radionuclides are homogeneously distributed throughout the waste. A sensitivity analysis determined that PA results are not greatly affected by the assumption of random waste emplacement or by the assumption that radionuclides are homogeneously distributed.

Based on the analysis reported in Hansen et al. (2003a), DOE concluded that:

1. Explicit representation of the specific features of supercompacted waste and of waste in pipe overpacks, such as structural rigidity, was not warranted in modeling, since PA results were relatively insensitive to the effects of such features.

2. PA results were not affected significantly by the assumption of nonrandom waste emplacement and the representation of these waste types as a homogeneous material.

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APPENDIX PA

ATTACHMENT PAR

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ACRONYMS AND ABBREVIATIONS

AIS	Air Intake Shaft
AMM	Asphalt mastic mix
CCA	Compliance Certification Application
CCDF	Complementary cumulative distribution function
CDF	Cumulative distribution function
CH	Contact-handled
DOE	Department of Energy
DRZ	Disturbed rock zone
EPA	Environmental Protection Agency
ERMS	Electronic Records Management System
FMT	Fracture matrix transport
GTFM	Graph Theoretic Field Model
ID	Identification number
LANL	Los Alamos National Laboratory
LHS	Latin hypercube sample
MB	Marker bed
MU	Map unit
PAVT	Performance Assessment Verification Test
PDF	Probability distribution function
PNL	Pacific Northwest Laboratory
QA	Quality Assurance
QAP	Quality Assurance Procedure
RH	Remote-handled
SMC	Salado Mass Concrete
SNL	Sandia National Laboratories
SSSPT	Small Scale Seal Performance Tests
SWCF	Sandia WIPP Central Files
TRU	Transuranic
TWBIR	Transuranic Waste Baseline Inventory Report
WES	Waterways Experiment Station
WIPP	Waste Isolation Pilot Plant

PAR 1.0 INTRODUCTION

This attachment contains information for the parameters used by performance assessment (PA) codes. Documentation, in the form of parameter sheets, is provided for the 64 parameters sampled by the Latin hypercube sample (LHS) code during the PA (see also Section 6.1.5 for discussion on probabilistic analyses and Section 6.1.5.2 for discussion on LHS). In addition, this attachment includes a listing of the sampled values for LHS sampled parameters (see Tables PAR-8 through PAR-11), four parameters sampled by LHS for the Spall model (see Tables PAR-12), the fixed-value parameters used in the PA codes (see Tables PAR-13 through PAR-49) and the parameters relating to the TRU waste inventory (see Tables PAR-50 through PAR-61). Additional information relevant to the use of these parameters in the PA is contained in Appendix PA; Appendix TRU WASTE provides details on the waste inventory.

Although the parameter development terminology used in this attachment is not the same as in Appendix PAR of the CCA, it is equivalent. Differences in terminology include; NP 9-2 rather than QAP 9-2, Parameter Data Entry Forms rather than Form 464's, material:property for identification rather than ID numbers, slightly different definintions for mean, median, and mode, and justification documents rather than parameter record package.

For additional information regarding all parameters, readers are referred to the parameter supporting information packages, which are contained in the Sandia National Laboratories (SNL) Waste Isolation Pilot Plant (WIPP) Records Center located at the SNL office in Carlsbad, New Mexico.

PAR 2.0 PARAMETER DEVELOPMENT PROCESS

The development of parameter values is controlled by the application of Nuclear Waste Management Program Procedure (NP) Parameters (NP 9-2). The process includes documentation of parameter development by those responsible for completion of a particular experimental investigation, development of a system design, or by staff involved in the PA modeling process. All of the references pertaining to parameter selection are contained within the three levels of parameter and data documentation: **(**1) Parameter Data Entry Form NP-9-2-1, (2) Analysis records packages, and (3) supporting data records packages.

The Parameter Data Entry Form is the highest-level record documenting parameter development that includes application of statistics and interpretations. The Parameter Data Entry Formsinclude a justification section, which is a pointer to supporting information including, where applicable, the Analysis plan and source document. All values provided in this attachment were derived from the WIPP PA parameter database. The numbers from the WIPP PA parameter database may differ slightly from those contained in the Parameter Data Entry Forms because of rounding.

The parameter supporting information package includes references to related information, such as Analysis Plans, SAND reports, test plans, and related ERMS file codes, and, where applicable, a summary on the experimental data collection (that is, method used, assumptions made in testing, and interpretation). The parameter supporting information packages point to the data records packages contain information such as the raw data, analysis, and data interpretation.

Each Parameter Data Entry Form, and parameter supporting information package are assigned unique Electronic Records Management System (ERMS) numbers. Copies of the Parameter Data Entry Forms, and parameter supporting information packages are maintained in the SNL WIPP Records Center.

PAR 3.0 PARAMETER DISTRIBUTIONS

Probability distributions are used to characterize the uncertainty concerning the value of a parameter. Numbers that characterize a particular distribution include the range, the mean, median, and mode (only for triangular distributions).

- Range. The range of a distribution can be denoted by (a,b), a pair of numbers in which a and b are minimum and maximum values of the parameter, respectively.

- Mean. The expectation of a random variable: i.e., the sum (or intergral) of the product of the variable and the PDF over the range of the variable. There is sample mean and mean: The mean, μ, of a distribution is one measure of the central tendency of a distribution, analogous to the arithmetic average of a series of numbers. The sample mean, $\bar{x}$, is the arithmetic average of value in an empirical data set.

- Median. The value of a random variable at which its CDF takes the value 0.5; i.e., the 50th percentile point.

- Mode. The value of a random variable at which its PDF takes its maximum value. The mode of a set of data is the value in the set that occurs most often.

PAR 3.1 Distribution Types And Applications

Distributions used to characterize uncertainty in parameters of the PA include: uniform, cumulative, triangular, Student's-t, delta, normal, log uniform, log cumulative, lognormal, and constant.

PAR 3.1.1 Uniform Distribution

Density Function: $$f(x) = \frac{1}{B - A} \qquad A \le x \le B \tag{1}$$

Distribution Function: $$F(x) = \frac{x - A}{B - A} \qquad A \le x \le B \tag{2}$$

Expected Value and Variance: $$E(X) = \frac{A + B}{2} \qquad V(X) = \frac{(B - A)^2}{12} \tag{3}$$

Median: $$X_{0.5} = \text{mean}$$

Use of the uniform distribution is appropriate when all that is known about a parameter is its range (a,b); the uniform distribution is the Maximum Entropy distribution under these circumstances (Tierney 1990).

PAR 3.1.2 Cumulative Distribution

A cumulative distribution (also called a constructed distribution) is described by a set of N ordered pairs:

$$(x_1 0), (x_2, P_2), (x_3, P_3), \ldots, (x_N, 1) \{\text{i.e., } P_1 = 0 \text{ and } P_N = 1 \text{ always}\} \tag{4}$$

where $x_1 < x_2 < x_3 < \ldots < x_N$ and $0 < P_2 < P_3 < \ldots < P_{N-1} < 1$

Because of the nature of the data, the PDF for this distribution takes the form:

$$P(\xi) = \begin{cases} 0 & \text{if } \xi < x1 \\ \dfrac{P_n - P_{n-1}}{x_n - x_{n-1}} & \text{if } x_{n-1} \le \xi \le x_n, n = 2,3,_, N \\ 0 & \text{if } \xi \ge x_N \end{cases} \tag{5}$$

and so the cumulative distribution function (CDF) takes the form:

$$P_r[X \le \xi] \approx II(\xi) = \begin{cases} 0 & \text{if } \xi < x_1 \\ P_{n-1} + \dfrac{(P_n - P_{n-1})(\xi - x_{n-1})}{(x_n - x_{n-1})} & \text{if } x_{n-1} \le \xi \le x_x \\ 1 & \text{if } \xi > x_N \end{cases} \quad n = 2,3,_, N \tag{6}$$

Expected Value:

$$E(X) = \sum_{n=2}^{N} (P_n - P_{n-1}) \frac{(x_n + x_{n-1})}{2} \tag{7}$$

Variance:

$$V(X) = \sum_{n=2}^{N} (P_n - P_{n-1}) \frac{(x_n^2 + x_n x_n - 1 + x_{n-1}^2)}{3} - \{E(X)\} \tag{8}$$

Median:

$$x_{0.50} = x_{m-1} + (x_m - x_{m-1}) \frac{(0.50 - P_{m-1})}{(P_m - P_{m-1})} \text{ where } P_{m-1} \le 0.50 < P_m \cdot \tag{9}$$

The cumulative distribution takes its name from the fact that it closely resembles the empirical CDF obtained by plotting the empirical percentiles of the data set (x_1,x_2,x_3, ..., x_N) (Blom 1989, p. 216). The cumulative distribution used here is the result of plotting the subjectively determined percentile points (x_1,P_1), (x_2,P_2), (x_3,P_3) ... , that arise in a formal elicitation of expert opinion concerning the form of the distribution of the parameter in question. A simple form of the cumulative distribution is used when the range (a,c) of the parameter is known and the analyst believes that his or her best estimate value, b, is also the median (or 50th percentile) of the

unknown distribution. In this case, the subjectively determined percentile points take the form: (a, 0.0), (b, 0.5), (c, 1.0) (Tierney 1990).

The cumulative distribution is the Maximum Entropy distribution associated with a set of percentile points (x_1,P_1), (x_2,P_2), ..., (x_N, P_N), no matter how that set of percentile points is obtained (that is, independent of whether the points are empirically or subjectively derived) (Tierney 1990).

PAR 3.1.3 Triangular Distribution

Density Function:

$$f(x) = \frac{2(x-a)}{(c-a)(b-a)} \qquad a \le x \le b$$

$$= \frac{2(c-x)}{(c-a)(c-b)} \qquad b \le x \le c \qquad (10)$$

Distribution Function:

$$F(x) = \frac{(x-a)^2}{(c-a)(b-a)} \qquad a \le x \le b$$

$$= \frac{(b-a)}{(c-a)} - \frac{(x+b-2c)(x-b)}{(c-a)(c-b)} \qquad b \le x \le c \qquad (11)$$

Expected Value:

$$E(X) = \frac{a+b+c}{3} \qquad (12)$$

Variance:

$$V(X) = \frac{a(a-b)+b(b-c)+c(c-a)}{18} \qquad (13)$$

Median:

$$X_{0.5} = a + \sqrt{\frac{(c-a)(b-a)}{2}} \quad \text{if } b \ge \frac{a+c}{2}$$

$$= c - \sqrt{\frac{(c-b)(c-a)}{2}} \quad \text{if } b \le \frac{a+c}{2} \qquad (14)$$

The triangular distribution is defined on the range (a,c) and has mode b. The mode can equal either of the two boundary values, which may simplify the computations above (Iman and Shortencarier 1984).

Use of the triangular distribution is appropriate when the range, (a,c), of the parameter is known and the analyst believes that his or her best estimate value, b, is also the mode (or most probable value) of the unknown distribution.

PAR 3.1.4 Student's-t Distribution

A Student's-t distribution is a Bayesian distribution for the unknown mean value of a parameter. Its use is appropriate when one has measured values of the parameter available (in contrast to values obtained subjectively through elicitation of professional opinion). If N denotes the number of measurements available, and $X_1, X_2, X_3, \ldots, X_N$ denote the values of the measurements, then the expected value or mean of the Student's-t distribution is the sample standard deviation divided by $\sqrt{N}$; the median value is equal to the mean value.

The Student's-t distribution applies when there are few measurements, say $3<N<10$. For large N, say $N>20$, there is little difference between the t-distribution and a normal distribution (see below) with the same mean and standard deviation.

In WIPP PA data characterized by Student's-t distribution are equally weighted. In other words, each measured value X_i is assigned a weight of 1/N, where N is the number of measurements.

PAR 3.1.5 Delta Distribution

The delta distribution is used to assign probabilities to the elements of some set of objects. For example, if the set consists of four alternative mathematical models of some phenomena and each model is labeled with one of the integers {1,2,3,4}, in other words,

$$M_1, M_2, M_3, M_4$$

then we might assign the vector of probabilities (p_1, p_2, p_3, p_4), where each p_i is a number between 0 and 1 and

$$p_1 + p_2 + p_3 + p_4 = 1. \tag{15}$$

The CDF associated with this delta distribution can be symbolically expressed by

$$F(x) = \sum_{n=1}^{4} p_n u(x-n). \tag{16}$$

The graph of this CDF can be visualized as an ascending staircase starting at zero level for x less than one, and having steps of height p_n at the points x = 1, 2, 3, 4.

The notion of mean value and variance still apply to a delta distribution, but the meanings of these quantities may require careful interpretation. If the M_n represents four different functions (say, discharge as a function of pressure), then it makes sense to talk about mean and variance functions. For the example of the four alternative mathematical models, the mean mathematical model is the linear combination

$$\overline{M} = \sum_{n=1}^{4} p_n M_n \tag{17}$$

and the variance of the models is similarly defined:

$$\Sigma^2 = \sum_{n=1}^{4} P_n \left(\overline{M} - M_n\right)^2 \tag{18}$$

The notion of median value is meaningless for a delta distribution.

PAR 3.1.6 Normal Distribution

Density function:

$$f\left(x\right) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{\frac{-x-\mu^2}{2\sigma^2}\right\} -\infty < x < \infty \tag{19}$$

Distribution function:

$$F\left(x\right) = \int_{-\infty}^{x} f\left(t\right) dt \; -\infty < x < \infty \tag{20}$$

Expected value and variance: $E\left(X\right) = \mu$ and $V\left(X\right) = \sigma^2$. (21)

The WIPP PA Program employs a truncated normal distribution where data are concentrated within an interval (lowrange, hirange) (Iman and Shortencarier 1984). The parameters of the truncated distribution can be expressed as follows:

$$E\left(X\right) = \mu = \frac{\left(\text{lowrange} + \text{hirange}\right)}{2} \quad V\left(X\right) = \sigma^2 = \left(\frac{\left(\text{lowrange} - \text{hirange}\right)}{6.18}\right)^2 \tag{22}$$

Median = mean (μ) and lowrange = 0.01 quantile, hirange = 0.99 quantile. The range of the random variable is arbitrarily set to (lowrange, hirange). Alternatively, the expected value μ and the standard deviation σ can be specified by the user of this distribution; in this case, the random variable takes on the range $\left(-\infty, \infty\right)$ and will need to be truncated to a finite interval and renormalized.

Use of the normal distribution is appropriate when it is known that the parameter is the sum of independent, identically-distributed random variables (this is seldom the case in practice) and there are a sufficient number of measurements of the parameter (N > 10) to make accurate, unbiased estimates of the mean (μ) and variance (σ^2) (Sandia WIPP Project 1992; Tierney 1990).

PAR 3.1.7 Log uniform Distribution

If X has a log uniform distribution on the interval from A to B where B > A > 0, then Y = $\log_{10}$ X has a uniform distribution from $\log_{10}$ A to $\log_{10}$ B (Iman and Shortencarier 1984).

Density Function:

$$f\left(x\right) = \frac{1}{x}\left(\ln B - \ln A\right) \qquad A < x < B \tag{23}$$

Distribution Function: $$F(x) = \frac{\ln x - \ln A}{\ln B - \ln A} \quad A < x < B \tag{24}$$

Expected Value: $$E(X) = \frac{B - A}{\ln B - \ln A} \tag{25}$$

Variance: $$V(X) = (B - A)\left[\frac{(\ln B - \ln A)(B + A) - 2(B - A)}{2(\ln B - \ln A)^2}\right] \tag{26}$$

Median: $$X_{0.5} = \sqrt{AB} \tag{27}$$

Use of the log uniform distribution is appropriate when all that is known about a parameter is its range (a,b) and B/A » 10; that is, the range (a,b) spans many orders of magnitude.

PAR 3.1.8 Log Cumulative Distribution

In this case, the independent variable is Y, where Y = log X. As with the cumulative distribution, this distribution is described by a set of N ordered pairs:

$$(y_p\, 0), (y_2, P_2), (y_3, P_3), \ldots, (y_N, 1) \; \{\text{that is}, P_1 = 0 \text{ and } P_N = 1 \text{ always}\} \tag{28}$$

where $y_1 < y_2 < y_3 < \ldots < y_N$ *and* $0 < P_2 < P_3 < \ldots < P_{N-1} < 1$

Because of the nature of the data, the PDF for this distribution takes the form:

$$P(\xi) = \begin{cases} 0 & \text{if } \xi < x1 \\ \dfrac{P_n - P_{n-1}}{\ln x_n - \ln x_{n-1}} \dfrac{1}{\xi} & \text{if } x_{n-1} \le \xi \le x_n, n = 2,3,_,N \\ 0 & \text{if } \xi \ge x_N \end{cases} \tag{29}$$

and so the CDF takes the form:

$$P_r X \le \xi = \begin{cases} 0 & \text{if } \xi < x_1 \\ P_{n-1} + \dfrac{(P_n - P_{n-1})(\ln\xi - \ln xn - 1)}{\ln x_{n-1} n x_{n-1}} & \text{if } \dfrac{x_{n-1} \le \xi \le x_x}{n - 2,3,_,N} \\ 1 & \text{if } \xi > x_N \end{cases} \tag{30}$$

Expected Value: $$E(X) = \sum_{n=2}^{N} (P_n - P_{nl}) \frac{(x_n - x_{n-1})}{\ln x_n - \ln x_{n-1}} \tag{31}$$

Variance: $$V(X) = \sum_{n=2}^{N} \frac{1}{2}(P_n - P_{n-1}) \frac{x_n^2 - x_{n-1}^2}{\ln x_n - \ln x_{n-1}} - \{E(X)\}^2 \quad (32)$$

Median:

$$X_{0.5} = 10^{**}\left\{x_{m-1} + (x_m - x_{m-1})\frac{(0.50 - P_{m-1})}{P_m - P_{m-1}}\right\} \text{ where } P_{m-1} \le 0.50 \le P_m . \quad (33)$$

PAR 3.1.9 Lognormal Distribution

If X ~ normal distribution with mean, μ, and variance, σ^2, and $Y = e^X$, the Y has a lognormal distribution. (34)

Density function: $$f(y) = \frac{1}{y\sigma\sqrt{2\pi}} \exp\left\{\frac{-(\ln y - \mu)}{2\sigma^2}\right\} \quad y > 0 \quad (35)$$

Distribution function: $$F(x) = \int_0^y f(t)\,dt \quad y > 0 \quad (36)$$

Expected value and variance:

$$E(Y) = \exp\left(\mu + \frac{\sigma^2}{2}\right) \quad V(Y) = \exp(2\mu + \sigma)\,[\exp(\sigma^2) - 1] \quad (37)$$

Median: $$X_{0.5} = e^{\mu} \quad (38)$$

As with the normal distribution, the lognormal distribution requires lowrange and hirange values. These values are in logarithmic form and are utilized in a normal distribution to determine a mean (μ) and a variance (σ^2), which in turn are used to identify the expected value and variance for the lognormal distribution (Iman and Shortencarier 1984).

PAR 3.1.10 Constants

Parameters may also be assigned a constant value in the PA parameter database. These parameters are tabulated at the end of the appendix.

PAR 4.0 PARAMETER CORRELATION

Parameter correlations used in PA are exclusively in LHS. Consequently, parameter correlations affect only sampled parameters described in the attached parameter sheets. Two types of parameter correlations are used. They are defined as explicit parameter correlation and induced parameter correlation. This section addresses the following criteria concerning parameter correlations, as specified in 40 CFR § 194.23(c)(6):

> (c) Documentation of all models and computer codes included, as part of any compliance application performance assessment calculation shall be provided. Such documentation shall include, but shall not be limited to:
>
> (6) An explanation of the manner in which models and computer codes incorporate the effects of parameter correlation.

Explicit parameter correlations are introduced or prohibited in LHS by the restricted pairing technique of Iman and Conover (1982). Three parameter correlations are specified in this PA through this technique. These correlations are all related to rock compressibility and permeability. In the Marker Bed (MB) 139 material region in BRAGFLO, rock compressibility (S_MB139:COMP_RCK) and intrinsic permeability (S_MB139:PRMX_LOG) are inverse-correlated with a correlation coefficient of -0.99. In the Salado Formation impure halite material region in BRAGFLO, rock compressibility (S_Halite:COMP_RCK) and intrinsic permeability (S_Halite:PRMX_LOG) are inverse correlated with a correlation coefficient of -0.99. In the Castile brine reservoir material region in BRAGFLO, rock compressibility (Castiler:COMP_RCK) and intrinsic permeability (Castiler:PRMX_LOG) are inverse correlated with a correlation coefficient of -0.75. Explicit parameter correlation is not used to correlate other sampled parameters.

Rock compressibilities and intrinsic permeabilities are correlated to be most consistent with interpretations of the hydraulic tests that have been performed in these units. In hydraulic testing, hydraulic diffusivity (the ratio of permeability to compressibility) is determined more precisely than either permeability or compressibility alone. Introducing the correlation of the permeability and compressibility parameters in PA better represents the knowledge of the formation gained from hydraulic testing than specifying no correlation whatsoever.

An induced correlation in PA is created when a parameter sampled in LHS (the underlying variable) is used to define the values of other parameters (defined variables). This is a prevalent method of correlation in this PA. For example, uncertainty in dissolved actinide oxidation states is represented in LHS by sampling the OXSTAT parameter (Global:OXSTAT). The results of this sampling are used in part to determine actinide solubilities (NUTS and PANEL), colloidal actinide concentrations (NUTS and PANEL), and K_D values (SECOTP2D) used for a particular vector. Selected examples of other induced parameter correlations include:

- the underlying variable x-direction permeability and the defined variables y- and z-direction permeabilities in many materials (BRAGFLO),
- the underlying variable x-direction permeability and defined variable threshold pressure in many materials (BRAGFLO),
- the underlying variable Lower Salado Clay permeability and the defined variable permeabilities of other clay members of the shaft seal system (BRAGFLO), and
- the underlying variable residual gas saturation (or other two-phase flow parameters) in many materials and the defined variable residual gas saturation (or other two-phase flow parameters) in other materials (BRAGFLO).

- the underlying variable americium properties and the defined variable curium properties (NUTS, PANEL, and SECOTP2D).

Where relevant, parameter sheets in this attachment contain information related to parameter correlation.

No correlations were used in this PA for certain parameters used to describe transport in the Culebra for which the possibility of correlation might be suspected. The treatment in PA is most consistent with available information, because, as discussed in CCA Appendix MASS (Attachments MASS 15-10 and 15-6, 14), correlation of well-to-well transmissivity versus well-to-well advective porosity and matrix block length is not evident in existing data, nor is the correlation between advective porosity and matrix block length.

There are four additional ways in which parameter correlations may be considered to be used in this PA, although they are not typically discussed as correlations per se. In a given LHS sample element, there is a correlation of 1 (100 percent) between the single observation of subjective uncertainty (the LHS sample for a complementary cumulative distribution function (CCDF)) with all of the sequences of random future events (scenarios) used to construct a CCDF. This is discussed in Section 6.1.

A correlation is made between the scenario being considered and the chemical properties (chemical composition) of brine in the repository (the physical properties viscosity and density are assumed to be the same for all scenarios). Brine composition affects actinide solubility. For undisturbed performance and E2 scenarios, brine composition is considered to be that of Salado brine. For the E1 and E1E2 scenarios, the brine composition is considered to be that of Castile brine. This is discussed in Section 6.4.3.4.

There are some correlations made in the construction of a CCDF regarding the similarity of events in a sequence of random future events. For example, the direct releases resulting from a third or later intrusion are determined from the calculated conditions following the second intrusion. This is discussed in Section 6.4.13.

Finally, there are also correlations among model parameters developed explicitly by the governing equations of computational models used. For example, the porosity of nodal blocks in BRAGFLO is a function of the initial porosity, pressure change, and compressibility. These types of relationships among parameters are documented in the Appendix PA.

PAR 5.0 KEY TO PARAMETER SHEETS

The parameter sheets included in this attachment contain a variety of information, some of which is extracted from the WIPP PA parameter database. Parameters are listed in the order in which they are retrieved from the WIPP PA parameter database. Eleven of the parameters retrieved from the database are dummy parameters and are not actually utilized by the code. Those parameters are therefore not are not listed or discussed in this section. Breaks in the numerical sequence of the parameters are due to dummy parameters.

Information presented in the parameter sheets is grouped into boxes labeled as follows:

PAR 5.1 Parameter(s)

The name of the parameter and the disposal system feature with which it is associated.

PAR 5.2 Parameter Description

The Parameter Description box defines the parameter and, where appropriate, explains the role of the parameter in the modeling.

PAR 5.3 Material and Property Name(s)

This box provides a link to the PA parameter database. The parameter label listed first is taken from the PA model parameter database and identifies the type of material in the disposal system being modeled (for example, S_MB139 means Salado MB139). The second label describes the PA model parameter name for the property of the material physical or operational meaning for the parameter (for example, SAT_RBRN means residual brine saturation).

PAR 5.4 Computational Code(s)

A list of the current computational models used by the PA Department that use this parameter.

PAR 5.5 Parameter Statistics

This box identifies the minimum and maximum for uniform distributions, the mode, minimum and maximum for Triangular distributions, the probability and the value associated with that probability for cumulative and delta distributions, and the measured values for the student's-t distribution. All values provided in this attachment were derived from the WIPP PA parameter database. These numbers may differ slightly from those contained in the Parameter Data Entry Forms because of rounding.

PAR 5.6 Units

The physical units of the parameters (usually expressed in metric units).

PAR 5.7 Distribution Type

This box identifies the type of parameter distribution (see PAR 3.1).

Data: The basis for the parameter values or parameter distribution is provided in this section. All values provided in this attachment were derived from the WIPP PA parameter database. These numbers may differ slightly from those contained in the Parameter Data Entry Forms because of rounding. The parameters are derived from the following kinds of data and information:

- Site-specific or waste-specific experimental data. These data includes information obtained from in situ experiments and research conducted at off-site laboratories (for example, permeability data, microbial gas generation). This category also includes

simulated waste experiments and may indicate correlations made with other material regions based on professional judgment.

- Waste-specific observational data. This category includes data obtained through observation or empirical analysis, such as semi-quantitative and qualitative visual characterization or acceptable knowledge of transuranic (TRU) waste (for example, waste components).

- Professional judgment. This category of information may involve the use of experimental or observational data from other non-WIPP contexts; interpreting information obtained from the general literature; or may be based on general engineering knowledge (see below).

- General Literature Data. This category of information includes that obtained from reports, journal articles, or handbooks relevant to systems or processes being modeled in the PA. It is often employed in conjunction with professional judgment.

- General Engineering Knowledge. This category of information identifies parameter values obtained from knowledge of standard engineering principles.

Readers are referred to justification documents and associated data packages maintained in the SNL WIPP Records Center for additional information.

PAR 5.8 Discussion

This box identifies the source(s) of parameter value(s) and the rationale for the parameter distribution and may clarify use of a particular parameter. Other relevant background information is also included in this section, where clarification is appropriate.

PAR 5.9 References

This box contains the references pertaining to parameter selection. The references are contained within the three levels of parameter and data documentation: (1) Parameter Data Entry Form, and (2) parameter supporting information packages. Selected references cited in the parameter supporting information packages are included in the parameter sheets to establish data quality.

PAR 6.0 EPAUNI OUTPUT DATA

Tables PAR-50 – 61 represent output files from the code EPAUNI Version 1.15A (for more information regarding EPAUNI output files, see Fox [2003]).

Table PAR-50 contains data from the EPAUNI output files EPU_CRA1_CH_UNIT2.OUT and EPU_CRA1_RH_UNIT2.OUT. The table contains waste stream volume and EPA units per m^3 for each of the CH-TRU and RH-TRU waste streams over each of the 10 time periods after closure (0, 100, 125, 175, 350, 1000, 3000, 5000, 7500, and 10,000 years). It also contains the probability of hitting each waste stream during a drilling intrusion at each of the 10 time periods after closure.

Tables PAR-51 – 60 contains data from the EPAUNI output file EPU_CRA1_CH_ ACTIVITY.DIA. The table contains activity information for each of the seven isotopes of concern for EPA unit calculations (^{241}Am, ^{244}Cm, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{234}U), the total activity used to calculate EPA units (called Total EPA Curies), and the EPA units for each CH-TRU waste stream. The code calculates these activities for each of the 10 time periods after closure (0, 100, 125, 175, 350, 1000, 3000, 5000, 7500, and 10,000 years) based on build-up and decay.

Table PAR-61 contains data from the EPAUNI output file EPU_CRA1_RH_ACTIVITY.DIA. The table contains activity information for each of the nine isotopes of concern for EPA unit calculations (^{241}Am, ^{244}Cm, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{234}U, ^{137}Cs, and ^{90}Sr), the total activity used to calculate EPA units (called Total EPA Curies), and the EPA units for each RH-TRU waste stream. The code calculates these activities for each of the 10 time periods after closure (0, 100, 125, 175, 350, 1000, 3000, 5000, 7500, and 10,000 years) based on build-up and decay.

PAR 7.0 PARAMETER SHEETS

Index of LHS Sampled Parameters:

Parameter #	Material Name	Property Name
Parameter 1	STEEL	CORRMCO2
Parameter 2	WAS_AREA	PROBDEG
Parameter 3	WAS_AREA	GRATMICI
Parameter 4	WAS_AREA	GRATMICH
Parameter 5	CELLULS	FBETA
Parameter 6	WAS_AREA	SAT_RGAS
Parameter 7	WAS_AREA	SAT_RBRN
Parameter 8	WAS_AREA	SAT_WICK
Parameter 9	DRZ_PCS	PRMX_LOG
Parameter 10	CONC_PCS	PRMX_LOG
Parameter 11	SOLU4	SOLCIM
Parameter 12	SOLTH4	SOLCIM
Parameter 14	CONC_PCS	SAT_RGAS
Parameter 15	CONC_PCS	SAT_RBRN
Parameter 16	CONC_PCS	PORE_DIS
Parameter 17	S_HALITE	POROSITY
Parameter 18	S_HALITE	PRMX_LOG
Parameter 19	S_HALITE	COMP_RCK
Parameter 20	S_MB139	PRMX_LOG
Parameter 21	S_MB139	COMP_RCK
Parameter 22	S_MB139	RELP_MOD
Parameter 23	S_MB139	SAT_RBRN
Parameter 24	S_MB139	SAT_RGAS
Parameter 25	S_MB139	PORE_DIS
Parameter 26	S_HALITE	PRESSURE
Parameter 27	CASTILER	PRESSURE
Parameter 28	CASTILER	PRMX_LOG
Parameter 29	CASTILER	COMP_RCK
Parameter 30	BH_SAND	PRMX_LOG
Parameter 31	DRZ_1	PRMX_LOG
Parameter 32	CONC_PLG	PRMX_LOG
Parameter 34	SOLAM3	SOLSIM
Parameter 35	SOLAM3	SOLCIM
Parameter 36	SOLPU3	SOLSIM
Parameter 37	SOLPU3	SOLCIM
Parameter 38	SOLPU4	SOLSIM

Index of LHS Sampled Parameters (continued):

Parameter #	Material Name	Property Name
Parameter 39	SOLPU4	SOLCIM
Parameter 40	SOLU4	SOLSIM
Parameter 41	SOLU6	SOLSIM
Parameter 42	SOLU6	SOLCIM
Parameter 43	SOLTH4	SOLSIM
Parameter 44	PHUMOX3	PHUMCIM
Parameter 45	GLOBAL	OXSTAT
Parameter 46	CULEBRA	MINP_FAC
Parameter 47	GLOBAL	TRANSIDX
Parameter 48	GLOBAL	CLIMTIDX
Parameter 49	CULEBRA	HMBLKLT
Parameter 50	CULEBRA	APOROS
Parameter 51	CULEBRA	DPOROS
Parameter 52	U+6	MKD_U
Parameter 53	U+4	MKD_U
Parameter 54	PU+3	MKD_PU
Parameter 55	PU+4	MKD_PU
Parameter 56	TH+4	MKD_TH
Parameter 57	AM+3	MKD_AM
Parameter 58	BOREHOLE	TAUFAIL
Parameter 60	GLOBAL	PBRINE
Parameter 61	BOREHOLE	DOMEGA
Parameter 62	SHFTU	SAT_RBRN
Parameter 63	SHFTU	SAT_RGAS
Parameter 64	SHFTU	PRMX_LOG
Parameter 65	SHFTL_T1	PRMX_LOG
Parameter 66	SHFTL_T2	PRMX_LOG
Parameter 75	SPALLMOD	RNDSPALL

Index of DRSPALL Sampled Parameters:

Material Name	Property Name
SPALLMOD	REPIPORE
SPALLMOD	REPIPERM
SPALLMOD	TENSLSTR
SPALLMOD	PARTDIAM

Refer to Table PAR-12 for the LHS Sampled Values for the Spall Model.

Parameter 1: Inundated Corrosion Rate for Steel Without CO_2 Present

Parameter Description:

This parameter is used to describe the rate of anoxic steel corrosion under brine-inundated conditions and with no CO_2 present (Appendix PA, Section PA-4.2).

Material and Property Name(s):

STEEL CORRMCO2

Computational Code: BRAGFLO

minimum	maximum
0.0	3.17×10^{-14}

Units: Meters/second

Distribution Type: Uniform

Data: Site- Specific Experimental Data

A discussion of the data associated with this parameter for the initial application may be found in Appendix PAR (DOE 1996). Justification for the change of this parameter for CRA may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the PA Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

Based on experimental results (Telander and Westerman 1993; 1997), steel is expected to corrode in the repository via the following reaction (Wang and Brush, 1996a, 1996b):

$$Fe^0 + 2H_2O \rightarrow Fe(OH)_2 + H_2$$

The rate of this reaction under a brine-inundated condition (no CO_2 present at all) is estimated to be 0 - 0.5 μm/year (0 - 1.59×10^{-14} m/s). This steel corrosion rate was estimated by DOE based on long-term anoxic steel corrosion experiments. Because of its uncertainty, this parameter was treated as a sampled variable in the CCA with a uniform distribution ranging from 0.0 to 1.59×10^{-14} m/s (see CCA Appendix PAR).

Subsequent to the CCA, the EPA questioned both the upper and lower bounds on DOE's assigned range of values for CORRMCO2. After evaluating the values DOE assigned to the steel corrosion rate, the EPA carefully examined experimental results. In all cases, except for the case of high pressure, the EPA, like the DOE, concluded that the steel corrosion rate used in the CCA was appropriate.

However, the EPA questioned the upper bound for the steel corrosion rate in the case of high pressures in the repository. Some experiments of six months duration conducted on steel immersed in brine under a hydrogen atmosphere indicated that the steel corrosion rate first

decreased at pressures from 2 to 70 atm and then increased at pressures from 70 to 127 atm (Telander and Westerman 1993). Because the repository may approach or exceed lithostatic pressure and because of the increase in the experimental corrosion rates at higher pressures, the EPA requested that DOE double the upper bound of the inundated corrosion rate to 3.17×10^{-14} m/s (EPA 1998). DOE has adopted this revised range for the rate of anoxic steel corrosion (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS 528582

Telander M. R. and Westerman, R.E. 1993. Hydrogen Generation by Metal Corrosion in Simulated Waste Isolation Pilot Plant Environments: Progress Report for the Period November 1989 through December 1992. SAND92-7347. Sandia National Laboratories. Albuquerque, NM.

Telander M. R. and Westerman, R.E. 1997. Hydrogen Generation by Metal Corrosion in Simulated Waste Isolation Pilot Plant Environments. SAND96-2538. Sandia National Laboratories. Albuquerque, NM.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Vols 1-XXI.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C. ERMS 525158.

Wang Y., and Brush L. H. 1996a. “Estimates Of Gas-Generation Parameters For The Long-Term WIPP PA” Memorandum to M. Tierney, 1/26/1996.. Sandia National Labs. Albuquerque, NM. ERMS 231943

Wang Y., and Brush L. H. 1996b. “Modify The Stoichiometric Factor Y In The BRAGFLO To Include The Effect Of MgO Added To WIPP Repository As A Backfill”. Memorandum to M. Tierney, 2/23/1996. Sandia National Labs. Albuquerque, NM. ERMS 232286.

Parameter 2: Probability of Microbial Degradation of Plastics and Rubbers in the Waste in the Event of Significant Microbial Gas Generation

Parameter Description:

This parameter is used to index alternative models of microbial degradation of plastics and rubbers in the waste in the repository in the event of significant microbial gas generation. It is a sampled parameter for the waste emplacement area and the waste, and the values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA PROBDEG)

Computational Code: BRAGFLO

Value	0	1.0	2.0
Percentiles	.50	.25	.25

Units: None

Distribution Type: Delta (see Figure PAR-1 for values.)

Data: General Engineering Knowledge - Professional Judgment

A discussion of the data associated with this parameter may be found in Tierney (1996) and the following parameter records package: Estimates of Gas Generation Parameters Required for BRAGFLO (ERMS #230819).

Discussion:

Cellulosics, plastics, and rubbers have been identified as the major organic materials to be emplaced in the WIPP repository (Appendix TRU WASTE) and could be degraded by microbes in 10,000 years. The occurrence of significant microbial gas generation in the repository will depend on: (1) whether microbes capable of consuming the emplaced organic materials will be present and active; (2) whether sufficient electron acceptors will be present and available; and (3) whether enough nutrients will be present and available. Considering uncertainties in evaluation of these factors and also in order to bracket all possible effects of gas generation on the WIPP PA, a probability of 50 percent is assigned to the occurrence of significant microbial gas generation (Wang and Brush 1996).

There are two factors that may potentially increase the biodegradability of these materials: long time scale and cometabolism. Over a time scale of 10,000 years, plastics and rubbers may change their chemical properties and therefore their biodegradability.

Cometabolism means that microbes degrade an organic compound, but do not use it or its constituent elements as a source of energy; these are derived from other substrates (Alexander 1994). In the WIPP repository, plastics and rubbers, which are resistant to biodegradation, may still be cometabolized with cellulosics and other more biodegradable organic compounds.

Because of these uncertainties, a probability of 50 percent is assigned to the biodegradation of plastics and rubbers in the event of significant microbial gas generation (Wang and Brush 1996).

The distribution for PROBDEG parameter is illustrated in Figure PAR-1. The parameter value ranges over the integers from 0 (no significant microbial gas generation) to 2 (significant microbial gas generation with degradation of plastics and rubbers); the third choice, a parameter value of 1, represents significant microbial gas generation without degradation of plastics and rubbers.

Parameter Data Entry Form ERMS: #234881

References:

Alexander, M. 1994. Biodegradation and Bioremediation. Academic Press, N.Y.

DOE/CAO. 1996. Transuranic Waste Baseline Inventory Report (Rev. 2). DOE/CAO-95-1121.

Tierney, M. 1996. Memorandum to File, Re: Reasons for choice of the PROBDEG parameter (id nos. 2824 and 2823) on February 22, 1996, March 29, 1996 (contained in ERMS 234881).

Wang, Y., and Brush, L. 1996. Memorandum to Martin Tierney, Re: Estimates of Gas-Generation Parameters for the Long-Term WIPP Performance Assessment, January 26, 1996. ERMS 231943.

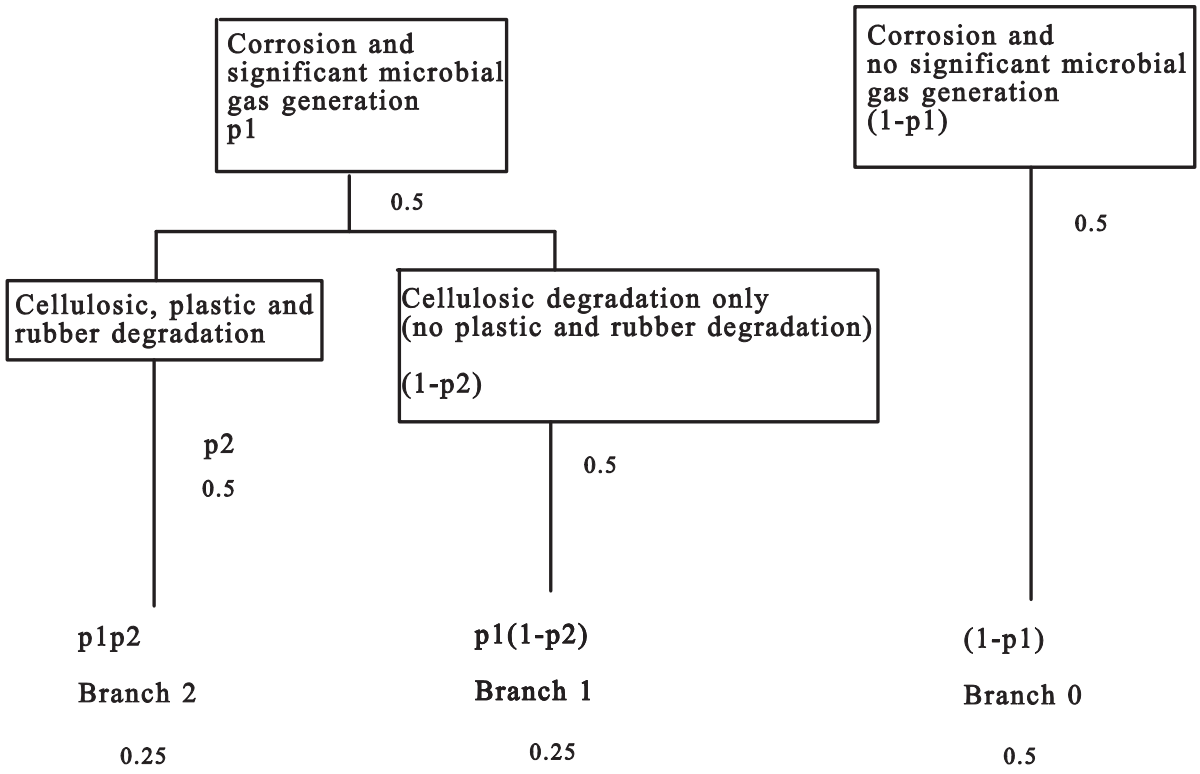

p1 = probability of occurrence of significant microbial gas generation (=50 percent)

p2 = probability of occurrence of plastics and rubber biodegradation in the event of significant gas generation (=50 percent)

Figure PAR-1. Logic Diagram for Possible Outcomes and Probabilities for the Parameter PROBDEG (modified from Tierney 1996)

Parameter 3: Biodegradation Rate of Cellulosics Under Brine-Inundated Conditions

Parameter Description:

This parameter is used to describe the rate of cellulosics biodegradation under anaerobic, brine-inundated conditions (see Appendix PA, Section PA-4.2). It is a sampled parameter for the waste emplacement area and the waste, and the values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA GRATMICI

Computational Code: BRAGFLO

minimum	maximum
3.171×10^{-10}	9.5129×10^{-9}

Units: Moles/(kilograms*second)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the parameter records package: Estimates of Gas Generation Required for BRAGFLO (ERMS #230819).

Discussion:

The maximum rate is estimated using the data obtained from both NO_3 - and nutrients-amended experiments, whereas the minimum rate is derived using the data obtained from the inoculated-only experiments without any nutrient and NO_3 amendment. The rates were calculated from the initial linear part of the experimental curve of CO_2 vs. time by assuming that cellulosics biodegradations in those experiments were nitrate- or nutrient-limited (Wang and Brush 1996).

Parameter Data Entry Form ERMS: #234928

References:

Wang, Y. and Brush, L. 1996. Memorandum to Martin Tierney, Re: Estimates of Gas-Generation Parameters for the Long-Term WIPP Performance Assessment, January 26, 1996. ERMS 231943.

Parameter 4: Biodegradation Rate of Cellulosics Under Humid Conditions

Parameter Description:

This parameter is used to describe the rate of cellulosics biodegradation under anaerobic, humid conditions (see Appendix PA, Section PA-4.2). It is a sampled parameter for the waste emplacement area and the waste, and the values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA GRATMICH

Computational Code: BRAGFLO

minimum	maximum
0.0	1.2684×10^{-9}

Units: Moles/(kilograms*second)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the parameter records package: Estimates of Gas Generation Required for BRAGFLO (ERMS #230819).

Discussion:

The maximum rate was estimated from cellulosics biodegradation experiments under anaerobic, humid conditions. The minimum rate is set to zero, corresponding to the cases where microbes become inactive because of water or nutrient stresses (Wang and Brush 1996).

Parameter Data Entry Form ERMS: #234923

References:

Wang, Y. and Brush, L. 1996. Memorandum to Martin Tierney, Re: Estimates of Gas-Generation Parameters for the Long-Term WIPP Performance Assessment, January 26, 1996. ERMS 231943.

Parameter 5: Factor β for Microbial Reaction Rates

Parameter Description:

Factor β is an index that characterizes the stoichiometry used to calculate the microbially generated gas, accounting for interaction with gases reacting with steel and steel corrosion products (see Appendix PA, Section PA-4.2).

Material and Property Name(s):

CELLULS FBETA)

Computational Code: BRAGFLO

minimum	maximum
0.0	1.0

Units: None

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the parameter records package: Estimates of Gas Generation Required for BRAGFLO (ERMS #230819).

Discussion:

Microbially generated gases CO_2 and H_2S may react with steel and steel corrosion products. Factor β characterizes the extent of CO_2 and H_2S consumption by those reactions: see Equation (18) in Wang and Brush 1996.

Parameter Data Entry Form ERMS: #231826

References:

Wang, Y. and Brush, L. 1996. Memorandum to Martin Tierney, Re: Estimates of Gas-Generation Parameters for the Long-Term WIPP Performance Assessment, January 26, 1996. ERMS #231943.

Parameter 6: Residual Gas Saturation - Repository

Parameter Description:

The residual (critical) gas saturation (S_{gr}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves. S_{gr} corresponds to the degree of waste-generated gas saturation necessary to create an incipient interconnected pathway in porous material, a condition required for porous rock to be permeable to gas. Below values of the S_{gr}, gas is immobile. It is a sampled parameter for the waste emplacement area and the waste. The values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA SAT_RGAS

Computational Code: BRAGFLO

minimum	maximum
0	0.15

Units: None

Distribution Type: Uniform

Data: General Literature and Professional Judgment

The parameter values are based on a November 15, 1995 Solutions Engineering letter report to D.M. Stoelzel of Sandia National Laboratories entitled “Critical (residual) Gas Saturation Recommendations for WIPP.”

Discussion:

Under conditions of chemical and biochemical gas generation and repository closure, gas saturation may increase to a level where the pore network in repository material regions becomes connected and gas permeability begins to increase. The lowest gas saturation at which continuous gas flow will occur is the residual (critical) gas saturation (S_{gr}). In a review of studies involving S_{gr}, Solutions Engineering (1996) reports values ranging from 0 to 27 percent. The assigned range for S_{gr} between 0 to 15 percent is consistent with recommendations in the Solutions Engineering report.

Parameter Data Entry Form ERMS: #234905

References:

Solutions Engineering. 1996. “Critical Gas Saturation Recommendations for WIPP.” Letter Report to D.M. Stoelzel, Sandia National Laboratories, November 15, 1995, Albuquerque, New Mexico. ERMS # 238769.

Parameter 7: Residual Brine Saturation – Waste Area

Parameter Description:

The residual brine saturation (S_{br}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves. Referred to also as S_{wr} (wetting phase) or S_{lr} (liquid phase), residual brine saturation is the point reached under high gas saturation conditions when brine is no longer continuous throughout the pore network and relative brine permeability becomes zero. Below the value of the S_{br}, brine is immobile. It is a sampled parameter for the waste emplacement area and the waste, and the values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA SAT_RBRN

Computational Code: BRAGFLO

minimum	maximum
0	0.55

Units: None

Distribution Type: Uniform

Data: General Literature and Professional Judgment

Two-phase flow parameters have not been measured for materials representing a collapsed empty, back-filled, or waste-filled room. Therefore, the parameter values are based on literature values for unconsolidated materials.

Discussion:

Brooks and Corey evaluated their two-phase characteristic equations against capillary pressure and relative permeability data obtained in laboratory experiments (Brooks and Corey 1964). Mualem (1976) proposed a modified procedure to that of Brooks and Corey for determining the wetting phase (S_{wr}) permeability curve by adding the constraint that the extrapolated curve should pass through the highest capillary pressure data point. Although their wetting phase relative permeability predictions are similar to each other and to the data, the Mualem procedure, in some cases, results in S_{wr} values less than those predicted by the Brooks and Corey model. Consequently, Table PAR-1 lists the Mualem (1976) residual wetting phase saturations to ensure that the potential for brine mobility is not underestimated. As indicated in Table PAR-1, single-phase liquid permeabilities of the Brooks and Corey materials are of the same order of magnitude as those assigned to waste disposal regions (10^{-13} m^2).

Table PAR-1. Brooks and Corey (1964) Materials Parameters - Unconsolidated Media[a]

Material	Permeability (m^2)[b]	Porosity	S_{wr}[c]
Volcanic Sand	1.1×10^{-11}	0.365	0.137
Fine Sand	2.85×10^{-12}	0.360	0.140
Glass Beads	1.05×10^{-11}	0.383	0.0783
Fragmented Mixture	1.50×10^{-11}	0.441	0.275
Fragmented Fox Hill Sandstone	1.61×10^{-11}	0.503	0.318
Touchet Silt Loam	5.00×10^{-13}	0.469	0.277
Poudre River Sand	2.26×10^{-11}	0.364	0.0824
Amarillo Silty Clay Loam	2.34×10^{-12}	0.455	0.242
Consolidated Berea Sandstone	4.81×10^{-13}	0.206	0.243
Consolidated Hygiene Sandstone	1.78×10^{-13}	0.250	0.560

a - Consolidated materials are identified in the material column
b - Single-phase liquid permeability
c - Mualem S_{wr} corrected for comparison to Brooks and Corey (1964)
S_{wr} - Wetting phase residual saturation

Parameter Data Entry Form ERMS: #234902

References:

Brooks, R.H., and Corey, A.T. 1964. Hydraulic Properties of Porous Media. Hydrology Paper No. 3. Fort Collins, CO: Colorado State University. NWM Library.

Mualem, Y. 1976. A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media. Water Resources Research. Vol. 12, no. 3, 513-522.

Vaughn, Palmer. 1996. Memo to Martin Tierney. RE: WAS_AREA and REPOSIT/SAT_RBRN Distribution, February 13, 1996. ERMS 234902.

Parameter 8: Wicking Saturation – Waste Area

Parameter Description:

The wicking saturation in the waste is used in the gas generation model (see Appendix PA, Section PA-4.2). It is a sampled parameter for the waste emplacement area and the waste, and the values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA SAT_WICK

Computational Code: BRAGFLO

minimum	maximum
0.0	1.0

Units: None

Distribution Type: Uniform

Data: Professional Judgment

The wicking parameter value varies from 0 (0 percent saturation) to 1.0 (100 percent saturation) and the parameter is assumed to be uniformly distributed.

Discussion:

Wicking is the ability of a material to carry a fluid by capillary action above the level it would normally seek in response to gravity. The use of a two-phase Darcy flow model in BRAGFLO includes possible effects of capillary action, but uncertainty remains about the extent to which the assumed homogeneous properties of the waste adequately characterize wicking. Because estimated rates of gas generation are higher for waste that is in direct contact with brine, brine saturation in the repository is adjusted in BRAGFLO to account for the possibility of wicking in the waste.

The adjustment is done as follows:

$$S_{b,eff} = S_b + S_w,$$

and

$$S_{b,eff} \leq 1.0,$$

where S_b is the brine saturation in the waste calculated by BRAGFLO, S_w is the wicking saturation that describes the additional amount of brine that may be present and in contact with the waste because of wicking, and $S_{b,eff}$ is the effective brine saturation used to determine the gas generation rates used in the analysis.

Parameter Data Entry Form ERMS: #234908

References:

N/A

Parameter 9: Log of Intrinsic Permeability – DRZ directly above the concrete portion of the panel closure

Parameter Description:

This parameter describes the permeability of cells immediately above the concrete part of the panel closures in the upper DRZ (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions. The permeability of these cells will be sampled to reflect the range expected for healed DRZ. This will capture the effect of rigid panel closures that include excavation of the DRZ immediately surrounding the concrete monolith that is emplaced quickly to prevent the further local development of DRZ, and healing of the DRZ due to compressive stresses imposed by creep closure around the rigid structure. In this way the panel closures are modeled as effective seals, including healing effects, in accordance with their design.

Material and Property Name(s):

DRZ_PCS PRMX_LOG
DRZ_PCS PRMY_LOG
DRZ_PCS PRMZ_LOG

Computational Code: BRAGFLO

mode	minimum	maximum
-18.75	-20.70	-17.0

Units: Log (meters squared)

Distribution Type: Triangular

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: Analysis Reports Relating to Analysis Plan AP-086 (ERMS 520523) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

Option D panel closures are designed to remove the DRZ above and below the panel entry drifts. Loose salt in the roof would also be taken down just prior to construction of the concrete monolith. The remaining salt surrounding the panel closure concrete would be subjected to compressive stresses, which would tighten any disturbed zones. Owing to the rounded configuration of Option D, the compressive stress state creates a situation very favorable for concrete: high compressive stresses and low stress differences. In turn, the compressive stresses developed within the salt will quickly heal any damage caused by construction excavation, thereby effectively eliminating the DRZ along the length of the panel closure. The volume of salt immediately above and below the rigid concrete monolith will likely approach the intrinsic permeability of Salado salt.

Undisturbed Salado salt is essentially impermeable. A low-end permeability would be immeasurably low (10^{-23} m^2, for example). The salt above and below the rigid monolith would assume relatively impermeable conditions. Permeability values employed are the same range as described for the concrete (2×10^{-21} to 10^{-17} m^2) (Stein 2002). The reason this range was selected rather than using the range approved for use with the intact halite is twofold. First, because the healed DRZ zone is relatively thin (9.06-m-thick in the model) small-scale heterogeneities including thin clay seams introduce uncertainties to how well this DRZ will impede flow. Second, the Panel Closure System will perform as a composite system that includes the healed DRZ, the concrete monolith, and the surrounding marker beds. In this system any flow will be focused through the highest permeability component of the system. In order that the PA calculations represent the uncertainties of exactly where any flow will occur during the regulatory period, we set the permeability range of the healed DRZ equal to the concrete so that there will be an equal probability of potential flow in either material. The permeability distributions can be implemented in PA by fitting a triangular distribution to the log of the permeability values described for concrete.

Parameter Data Entry Form ERMS: #520524

References:

Stein, J. 2002. Analysis Plan for Calculations of Salado Flow: Technical Baseline Migration (TBM), AP-086, February 13, 2002, ERMS #520612.

Parameter 10: Log of Intrinsic Permeability– Concrete portion of PCS

Parameter Description:

Log of the vertical and horizontal intrinsic permeability for the concrete portion of the Option D panel closure (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

CONC_PCS PRMX_LOG
CONC_PCS PRMY_LOG
CONC_PCS PRMZ_LOG

Computational Code: BRAGFLO

mode	minimum	maximum
-18.75	-20.70	-17.0

Units: Log (meters squared)

Distribution Type: Triangular

Data: Site- Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The distribution of permeability values for the concrete portion of the Option D panel closure is the same as were used for the concrete portion of the shaft seal in the original CCA (DOE 1996) shaft seal model (Stein 2002). The following justification is provided for permeability values used for the shaft seal concrete (see material CONC_T1, Appendix PAR in DOE 1996)

As reported by Repository Isolation Systems Department (1996), traditional freshwater concrete has been widely used for hydraulic applications such as water storage tanks, water and sewer systems, and massive dams because it has exceptionally low permeability (less than 10^{-20} m^2 upon hydration). Salado Mass Concrete (SMC) is a specially-designed, salt-saturated concrete mix (Wakeley et al. 1994; Wakeley et al. 1995).

Pfeifle, et al. (1996) performed two permeability tests on concrete specimens prepared from cores recovered from the WIPP SSSPT field experiments and one test on an SMC specimen prepared from a sample batched by the Waterways Experiment Station (WES). The specimens were tested as received with no attempts made to dry the specimens or to determine their moisture contents. Each test was performed using nitrogen gas as the permeant, flowmeters to measure gas flow, and fluid pressure gradients of 0.3, 0.6, or 0.75 megapascals. Attempts were made to apply Klinkenberg corrections to measured values of permeability, but

the range in pressure gradients used in the testing was not large enough to establish any particular trend when the permeability data were plotted as a function of reciprocal mean fluid pressure.

A total of 18 permeability measurements were made on the three specimens. Measured permeabilities of the specimens were all very low with a range from 2.1×10^{-21} m^2 to 7.51×10^{-21} m^2 with an average of 4.71×10^{-21} m^2. Knowles and Howard (1996) presented results of field permeability tests performed in the WIPP SSSPT boreholes during 1985-1987 and 1993-1995. Although individual seal system component material permeabilities for concrete, DRZ salt, and salt were not determined, overall seal system permeabilities were determined and ranged from 1.0×10^{-20} m^2 to 1.0×10^{-17} m^2 and from 1.0×10^{-23} m^2 to 1.0×10^{-19} m^2 for the 1985–1987 tests and the 1993-1995 tests, respectively. These ranges encompass the laboratory values measured by Pfeifle, et al. (1996).

The data described above were derived from gas permeability measurements in which no Klinkenberg corrections were applied to the measured values. The Klinkenberg corrections were expected to be small because of the low mean pressure gradients used in the tests.

The interface between the Salado salt and the SMC components may provide a flow path around the SMC components. This flow path is possible if a small aperture develops as the concrete is curing or if the interface degrades because of corrosive brines. If such a flow path occurs, the effective permeability of the SMC will increase. Because of this uncertainty, the upper bound permeability was assigned to a value of -17, which corresponds to a permeability of 1.0×10^{-17} m^2. This value was selected after an effective permeability calculation was performed. In this calculation, the interface zone was assumed to have a permeability of 1.0×10^{-14} m^2 and concrete permeabilities were varied from 1.0×10^{-23} to 1.0×10^{-19} m^2. Assuming the interface zone had a thickness of 0.001 times the shaft radius or smaller, the effective permeability of the concrete was about 1.0×10^{-17} m^2 regardless of the value selected for the permeability of the SMC seal.

Parameter Data Entry Form ERMS: #520524

References:

Knowles, M.K. and Howard, C.L. 1996. “Field and Laboratory Testing of Seal Materials Proposed for the Waste Isolation Pilot Plant,” Proceedings of the Waste Management 1996 Symposium. Tucson, AZ, February 25-29, 1996. SAND95-2082C. Albuquerque, NM: Sandia National Laboratories. ERMS #230945.

Pfeifle, T.W., Hansen, F.D., and Knowles, M.K. 1996. “Salt-Saturated Concrete Strength and Permeability,” Proceedings of the ASCE Fourth Materials Engineering Conference, Washington, DC, November 1996 (accepted for publication).

Repository Isolation Systems Department. 1996. Waste Isolation Pilot Plant Shaft Sealing System Compliance Submittal Design Report. SAND96-1326. Sandia National Laboratories. Albuquerque, NM. August 1996.

Stein, J. 2002. Analysis Plan for Calculations of Salado Flow: Technical Baseline Migration

(TBM), AP-086, February 13, 2002, ERMS #520612.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Vols 1-XXI.

Wakeley, L.D., Poole, T.S. and Burkes, J.P. 1994. Durability of Concrete Materials in High-Magnesium Brine. SAND93-7073. Albuquerque, NM: Sandia National Laboratories. WPO 10674.

Wakeley, L.D., Harrington, P.T., and Hansen, F.D. 1995. Variability in Properties of Salado Mass Concrete. SAND94-1495. Albuquerque, NM: Sandia National Laboratories. WPO 22744.

Parameter 11: Log of the Distribution of Solubility of U(IV) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for uranium in the +IV oxidation state in Castile brine.

Material and Property Name(s):

SOLU4 SOLCIM

Computational Code: PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: General Literature Data

For the CCA, solubilities were calculated using the Fracture Matrix Transport (FMT) code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of U(IV) in Castile brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Attachment SOTERM.

Parameter Data Entry Form ERMS: #529447

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 12: Log of the Distribution of Solubility of Th(IV) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for thorium in the +IV oxidation state in Castile brine.

Material and Property Name(s):

SOLTH4 SOLCIM

Computational Code: PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: General Literature Data

For the CCA, solubilities were calculated using the Fracture Matrix Transport (FMT) code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Th(IV) in Castile brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #529448

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 14: Residual Gas Saturation – Concrete Portion of PCS

Parameter Description:

The residual (critical) gas saturation (S_{gr}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves (see CCA Appendix PA, Figure 4.2.1). S_{gr} corresponds to the degree of waste-generated gas saturation necessary to create an incipient interconnected pathway in porous material, a condition required for porous rock to be permeable to gas.

Material and Property Name(s):

CONC_PCS SAT_RGAS

Computational Code: BRAGFLO

minimum	maximum
0	0.40

Units: None

Distribution Type: Uniform

Data: General Literature Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

This distribution is the same as were used in the original CCA shaft seal model. The initial gas saturation in the simplified shaft is a volume-weighted average of the initial gas saturations in the original shaft's subcomponents (James and Stein 2002; 2003). The following justification is provided for gas saturation values used for the CCA shaft seal subcomponents (see material SALT_T1, in Appendix PAR) DOE (1996).

A literature search was conducted to obtain residual saturation values for consolidated geologic materials, concrete, and asphalt in support of the CCA.

A single value of 0.18 was found for normal concrete (Mayer et al. 1992). Based on this value, a distribution was assumed for the seal components. The recommended value was 0.2, and the recommended range was 0.0 to 0.4 with a uniform distribution for all shaft seal materials.

Parameter Data Entry Form ERMS: #520524

References:

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Mayer, G., Jacobs, F., and Wittmann, F.H. 1992. "Experimental Determination and Numerical Simulation of the Permeability of Cementitious Materials," Nuclear Engineering and Design. Vol. 138, no. 2, 171-177.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

Parameter 15: Residual Brine Saturation – Concrete Portion of PCS

Parameter Description:

The residual brine saturation (S_{br}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves (see CCA Appendix PA, Figure 4.2.1). Referred to also as S_{wr} (wetting phase) or S_{lr} (liquid phase), residual brine saturation is the point reached under high gas saturation conditions when brine is no longer continuous throughout the pore network and relative brine permeability becomes zero.

Material and Property Name(s):

CONC_PCS SAT_RBRN

Computational Code: BRAGFLO

Value	0.0	0.20	0.60
Percentiles	0	0.50	1

Units: None

Distribution Type: Cumulative

Data: General Literature Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

This distribution is the same as were used for the original 1996 CCA shaft seal model. Recall that the initial brine saturation in the simplified shaft is a volume-weighted average of the initial brine saturations in the original shaft's subcomponents (James and Stein 2002, 2003). The following justification is provided for the residual brine saturation used for the CCA shaft components (see Material SALT_T1, CCA Appendix PAR in DOE [1996]).

A literature search was conducted to obtain residual liquid saturation values for consolidated geologic materials, concrete, and asphalt in support of the CCA. Residual liquid saturations for geologic materials were found in four references (Brooks and Corey 1964; Lappala et al. 1987; Parker et al. 1987; and Rawls et al. 1982). Brooks and Corey (1964) determined residual saturations for five unconsolidated samples based on measured values of liquid saturation as a function of capillary pressure. Lappala et al. (1987) determined residual moisture content for 11 soils by obtaining best fits to measured moisture content versus pressure head data using three models. The residual moisture contents determined for each soil using the three models were averaged and divided by the reported porosity to obtain a residual liquid saturation for each soil. Parker et al. (1987) fit their saturation-pressure relationship to observed data to obtain residual saturations for a sandy and clayey porous

media. Residual water contents reported by Rawls et al. (1982) for 11 soil texture classes were divided by the reported porosity to obtain residual saturations.

Mayer et al. (1992) reported a residual liquid saturation for normal concrete of 0.30. Data regarding residual liquid saturations in asphalt materials were not found in the literature.

The literature values of residual liquid saturation for geologic materials and concrete fall within the range of 0.0 to 0.6 with all but two values falling within the range of 0.0 to 0.4. It was recommended that a value of 0.2 be used for the residual liquid saturation of all seal components.

Parameter Data Entry Form ERMS: #520524

References:

Brooks, R.H., and Corey, A.T. 1964. Hydraulic Properties of Porous Media. Hydrology Paper No. 3. Fort Collins, CO: Colorado State University.

Lappala, E.G., Healy, R.W., and Weeks, E.P. 1987. Documentation of Computer Program VS2D to Solve the Equations of Fluid Flow in Variably Saturated Porous Media. Water-Resources Investigations Report 83-4099. Denver, CO: U.S. Geological Survey. Tech Library books collection: PC173.4.P67L31987.

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Mayer, G., Jacobs, F., and Wittmann, F.H. 1992. "Experimental Determination and Numerical Simulation of the Permeability of Cementitious Materials," Nuclear Engineering and Design. Vol. 138, no. 2, 171-177.

Parker, J.C., Lenhard, R.J., and Kuppusamy, T. 1987. "A Parametric Model for Constitutive Properties Governing Multiphase Flow in Porous Media," Water Resources Research. Vol. 23, no. 4, 618-624.

Rawls, W.J., Brakensiek, D.L., and Saxton, K.E. 1982. "Estimation of Soil Water Properties," Transactions of the ASAE. St. Joseph, MI: American Society of Agricultural Engineers. 1316-1328.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Vols 1-XXI.

Parameter 16: Pore Distribution Parameter in the Concrete portion of PCS

Parameter Description:

The Brooks-Corey pore size distribution parameter (λ) is used to calculate capillary pressure and relative permeabilities for gas and brine flow in the two-phase flow model (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter.

Material and Property Name(s):

CONC_PCS PORE_DIS

Computational Code: BRAGFLO

Value	0.11	0.94	8.1
Percentiles	0	0.50	1

Units: None

Distribution Type: Cumulative

Data: General Literature Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

This distribution of pore size values for the concrete portion of the Option D panel closure is the same as were used for the concrete portion of the shaft seal in the original 1996 CCA shaft seal model. (Stein, 2002) The following justification is provided for pore size distribution values used for the shaft seal (see material SALT_T1, CCA Appendix PAR)

A literature search was conducted to find pore distribution (that is, lambda) values for geologic materials and concrete. For geologic materials, 81 lambda values were found in 5 references (Brooks and Corey 1964; Mualem 1976; Rawls et al. 1982; Haverkamp and Parlange 1986; and Lappala et al. 1987). In addition, 38 lambda values were calculated from values of the van Genuchten parameter n found in 6 references (van Genuchten 1980; van Genuchten and Nielsen 1985; Hopmans and Overmars 1986; Parker et al. 1987; Stephens et al. 1988; and Wösten and van Genuchten 1988).

The total number of lambda values found in the literature or calculated from n values found in the literature was 119. In a few cases, different literature sources reported different values of lambda and/or n for the same materials. For this situation, the different lambda values were arithmetically averaged to obtain a single value for the material. This procedure yielded lambda values for a total of 85 different geologic materials.

The lambda values range from 0.11 to 11.67 and have a median of 0.94. Based on the shape of the histogram and CDF, it appears that the lambda values are log normally distributed. The Lilliefors test for normality (Iman and Conover 1983) was applied to the data to verify that the logarithm of the lambda values can be described by a normal distribution. The mean of the log lambda values was found to be -0.064 with a standard deviation of 1.08. The Lilliefors bounds represent the region within which 95 percent of normally distributed values will fall.

For concrete, a literature search yielded only one reference (Mayer et al. 1992). This reference indicates that the Corey (1954) relationships are appropriate for describing the two-phase characteristic curves for the normal concretes they tested. For asphalt materials, data regarding lambda values were not found in the literature.

Both a lognormal and cumulative distribution for this parameter was recommended for the seal components constructed from granular earth materials (that is, earthen fill, compacted clay, and reconsolidated crushed salt). A cumulative distribution is appropriate when the range (a, c) of the parameter is known and the best estimate value, b, is the median. The value recommended was 0.94, which is the median of the literature values for geologic materials. The recommended range for the distribution was 0.11 to 8.1. Consequently, a cumulative distribution is assigned. In the absence of literature data, the same lambda distribution type, value, and range were also recommended for the concrete and asphalt seal components.

Parameter Data Entry Form ERMS: #520524

References:

Brooks, R.H., and Corey, A.T. 1964. Hydraulic Properties of Porous Media. Hydrology Paper No. 3. Fort Collins, CO: Colorado State University.

Corey, A.T. 1954. “The Interrelation Between Gas and Oil Relative Permeabilities,” Producer's Monthly. Vol. XIX, no. 1, 38-41.

Haverkamp, R., and Parlange, J.Y. 1986. “Predicting the Water-Retention Curve From Particle-Size Distribution: 1. Sandy Soils Without Organic Matter,” Soil Science. Vol. 142, no. 6, 325-339.

Hopmans, J.W., and Overmars, B. 1986. “Presentation and Application of an Analytical Model to Describe Soil Hydraulic Properties,” Journal of Hydrology. Vol. 87, no. 1-2. 135-143.

Iman, R.L., and Conover, W.J. 1983. Modern Business Statistics. New York, NY: John Wiley & Sons, Inc.

Lappala, E.G., Healy, R.W., and Weeks, E.P. 1987. Documentation of Computer Program VS2D to Solve the Equations of Fluid Flow in Variably Saturated Porous Media. Water-Resources Investigations Report 83-4099. Denver, CO: U.S. Geological Survey.

Mayer, G., Jacobs, F., and Wittmann, F.H. 1992. “Experimental Determination and Numerical Simulation of the Permeability of Cementitious Materials,” Nuclear Engineering

and Design. Vol. 138, no. 2, 171-177.

Mualem, Y. 1976. "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media," Water Resources Research. Vol.12, no. 3, 513-522.

Parker, J.C., Lenhard, R.J., and Kuppusamy, T. 1987. "A Parametric Model for Constitutive Properties Governing Multiphase Flow in Porous Media," Water Resources Research. Vol. 23, no. 4, 618-624.

Rawls, W.J., Brakensiek, D.L., and Saxton, K.E. 1982. "Estimation of Soil Water Properties," Transactions of the ASAE. St. Joseph, MI: American Society of Agricultural Engineers. 1316-1328.

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

Stephens, D.B., Unruh, M., Havlena, J., Knowlton, R.G., Jr., Mattson, E., and Cox, W. 1988. "Vadose Zone Characterization of Low-Permeability Sediments Using Field Permeameters," Ground Water Monitoring Review. Vol. 8, no. 2, 59-66.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Vols 1-XXI.

van Genuchten, M. Th. 1980. "A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils," Soil Science Society of America Journal. Vol. 44, no. 5, 892-898.

van Genuchten, M. Th., and Nielsen, D.R. 1985. "On Describing and Predicting the Hydraulic Properties of Unsaturated Soils," Annales Geophysicae. Vol. 3, no. 5, 615-628.

Wösten, J.H.M., and van Genuchten, M. Th. 1988. "Using Texture and Other Soil Properties to Predict the Unsaturated Soil Hydraulic Functions," Soil Science Society of America Journal. Vol. 52, no. 6, 1762-1770.

Parameter 17: Effective Porosity - Halite

Parameter Description:

The effective porosity of Salado Formation halite and polyhalite refers to the ratio of the interconnected pore volume to the bulk volume.

Material and Property Name(s):

S_HALITE POROSITY

Computational Code: BRAGFLO

Value	1.0×10^{-3}	0.01	0.03
Percentiles	0	0.50	1

Units: None

Distribution Type: Cumulative

Data: Site-Specific Experimental Data

The effective porosity distribution of Salado halite is supported by three separate porosity calculations: (1) Skokan et al. (1989; p. 15) determined from electromagnetic and DC resistivity experiments, (2) drying experiments described in Powers et al. (1978; p. 7-30), and (3) drying experiments reported in Deal et al. (1993). The parameter records package associated with this parameter is: Halite Porosity (ERMS #230601).

Discussion:

The high value (0.03) for the range of porosity is suggested in Skokan et al. (1989; p.6,13), based on the low end (10 ohm) of the DC resistivity measurements registered in the underground repository. The low value (0.001) is suggested in Powers et al. (1978) based on drying experiments. The median value of 0.01 is suggested in Skokan et al. (1989; p.15). Deal et al. (1993) found an average value of 0.016 for total porosity from a different series of drying experiments.

Parameter Data Entry Form ERMS: #234387

References:

Deal, D.E., Abitz, R.J., Myers, J., Martin, M.L., Millgan, D.J., Sobocinski, R.W., Lipponer, P.P.J., and Belski, D.S. 1993. Brine Sampling and Evaluation Program, 1991 Report. DOE-WIPP-93-026. Carlsbad, NM: Westinghouse Electric Corporation, Waste Isolation Division.

Powers, D.W., Lambert, S.J., Shaffer, S.E., Hill, L.R., and Weart, W.D., eds. 1978. Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico. SAND78-1596. Albuquerque, NM: Sandia National Laboratories. Vols. 1-2.

V. 1 - ERMS #205448; V.2 - ERMS #226829 – #226830, original photos - ERMS #226859.

Skokan, C.K., Pfeifer, M.C., Keller, G.V., and Andersen, H.T. 1989. Studies of Electrical and Electromagnetic Methods for Characterizing Salt Properties at the WIPP Site, New Mexico. SAND87-7174. Albuquerque, NM: Sandia National Laboratories. ERMS #224033.

Parameter 18: Log of Intrinsic Permeability - Halite

Parameter Description:

The Salado Formation halite is assigned an intrinsic permeability intended to reflect the stratigraphic variability of Salado halite and far-field hydraulic conditions (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

S_HALITE PRMX_LOG
S_HALITE PRMY_LOG
S_HALITE PRMZ_LOG

Computational Code: BRAGFLO

minimum	maximum
-24.0	-21.0

Units: Log (m^2)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

The reported permeability range of undisturbed impure halite is based on four selected in situ hydraulic tests: three flow tests believed representative of far-field permeability and one flow test that measured permeability in a zone which included a range of halite lithologies. Computer-derived permeabilities based upon brine inflow data from Room Q fall within the range derived from flow tests. The reader is referred to the relevant parameter record package for more detail: Halite Permeability (ERMS #231218) Salado Halite Permeability from Room Q Analysis (ERMS #230721).

Discussion:

Impure halite denotes a broad range of lithologic types ranging from pure halite to lithologies with various degrees of impurities, including polyhalite, argillaceous and anhydrite halite. Far-field tests of the pure halite exist; however, far-field hydraulic tests data do not exist for relatively impure halites, which tend to show higher permeabilities in the near-field. Thus a range of permeability is specified, bounded by rounded low and high permeability values determined from the testing program.

Three hydraulic tests believed representative of far-field pure halite permeability were conducted in the present location of Room Q in map units with relatively low impurities: a halite with less than 0.5 percent impurity, a halite containing approximately one percent impurity and a halite and polyhalite zone with a one to two percent impurity. These tests are believed to represent the lower end of the permeability range for Salado halite (see Table

PAR-2). These units were tested before the large-scale brine inflow excavation was mined and at stratigraphic intervals located over 20 m (66 ft) from the excavation.

Although probably located within the influence of the DRZ, one flow test (C2H01-BGZ) was performed within map units 0-4. This permeability value in conjunction with Room Q model analysis determination of far-field permeability are used to bound the maximum permeability of Salado halite containing relatively high impurities.

A summary of selected interpretative results of these four flow and pressure tests is compiled in the attached table. A schematic representation of Salado map units near the disposal area horizon, adapted from Deal et. al. (1989), is attached for information purposes (see Figure PAR-2).

Parameter Data Entry Form ERMS: #234397

References:

Beauheim, R.L., Saulnier, G.J., Jr., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #226033.

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Albuquerque, NM: Sandia National Laboratories. ERMS #223378.

Davies, Peter and Rick Beauheim. 1996. Memo to Martin Tierney. RE: Changes to the parameter records package and form #464 for far-field permeability of Salado halites (id#s: 547, 548, and 549; idmtrl: S_HALITE; idpram: PRMX_LOG, PRMY_LOG, and PRMZ_LOG, respectively). March 7, 1996. ERMS #236772.

Deal, D.E., Abitz, R.J., Belski, D.S., and Case, J.B. 1989. Brine Sampling and Evaluation Program, 1988 Report. DOE-WIPP-89-015. Carlsbad, NM: Westinghouse Electric Corporation.

Jensen, A.L., Howard, C.L., Jones, R.L., and Peterson, T.P. 1993. Room Q Data Report: Test Borehole Data from April 1989 through November 1991. SAND92-1172. Albuquerque, NM: Sandia National Laboratories. ERMS #223548.

Saulnier, G.J., Jr., Domski, P.S., Palmer, J.B., Roberts, R.M., Stensrud, W.A., and Jensen, A.L. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Albuquerque, NM: Sandia National Laboratories. ERMS #225746

Stensrud, W.A., Dale, T.F., Domski, P.S., Palmer, J.B., Roberts, R.M., Fort, M.D., Saulnier, G.J., Jr., and Jensen, A.L. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Albuquerque, NM: Sandia National Laboratories. ERMS #226432.

Table PAR-2. Summary of Permeability Test-Interpretations Results from In Situ Permeability Tests Representing Undisturbed Impure Halite

Test Interval (meters from excavation)	Hole	Map unit(s)	Analysis Method	Permeability k (m^2)
20.13-21.03	QPPO5	MU 6	GTFM6.0	1.12×10^{-24}
23.35-24.20	QPP12	H3	GTFM6.0	2.69×10^{-22}
20.19-21.09	QPP15	MU O - MU PH-4	GTFM6.0	5.5×10^{-24}
4.50-5.58	C2H01-BGZ	MU O - MU 4	GTFM6.0	1.38×10^{-21}

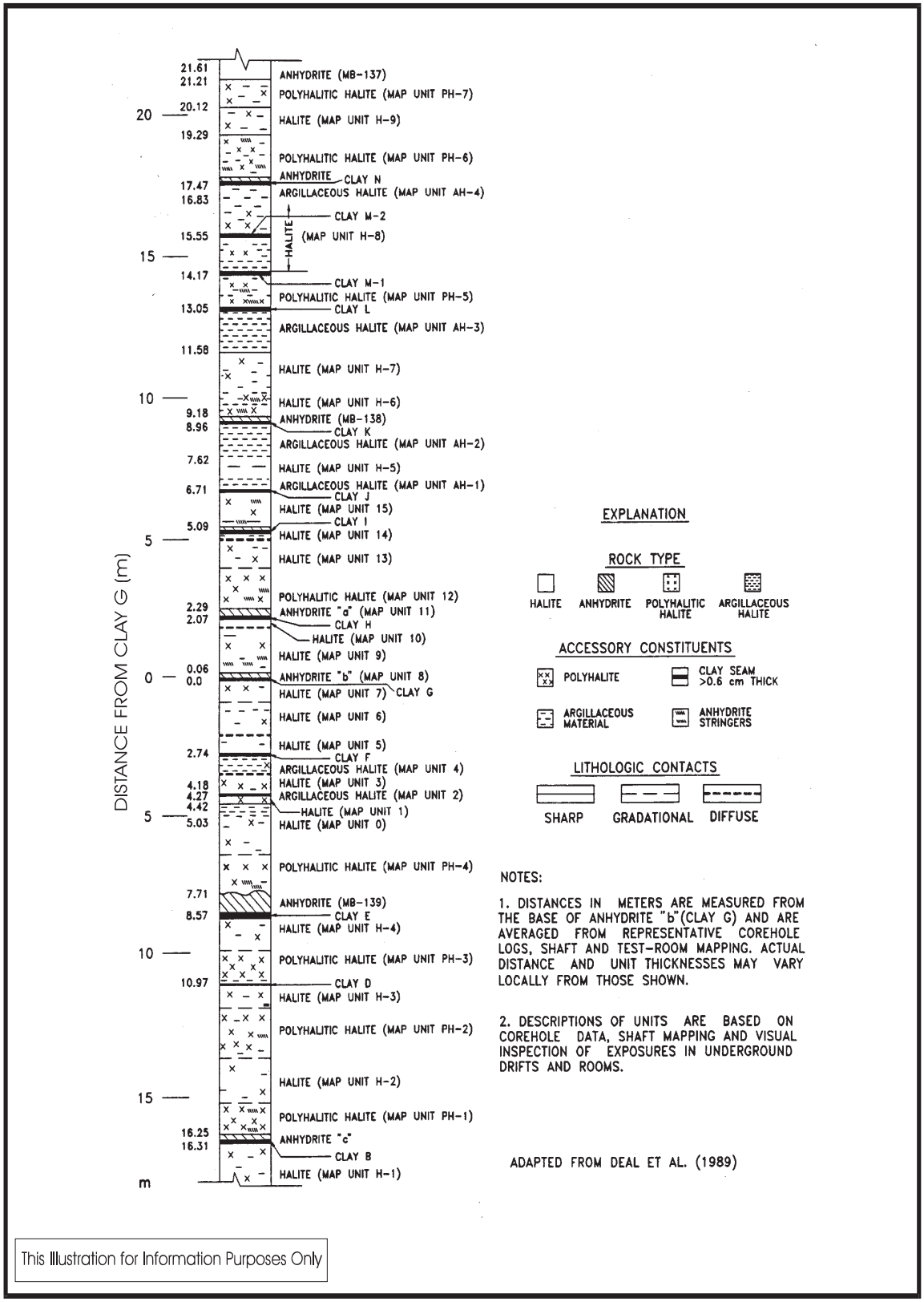

NMVP-6342-164-0

Figure PAR-2. Salado Map Units Near the Disposal Area Horizon

Parameter 19: Rock Compressibility - Halite

Parameter Description:

The rock (or bulk) compressibility of the Salado Formation halite is used to calculate the pore compressibility that is used in BRAGFLO. Pore compressibility is used to predict the effect of material compressibility on porosity and mass storage in the equation of state for flow through porous media as follows:

$$\varphi = \varphi_o \exp\left(c_p(p-p_o)\right)$$

where,

φ = porosity of solid matrix (cubic meters/cubic meters)
φ_o = porosity at reference pressure p_o
c_p = pore compressibility (pascals^{-1})
p = pore pressure (pascals)
p_o = reference pore pressure (pascals)

The rock compressibility is divided by effective porosity to calculate pore compressibility.

Material and Property Name(s):

S_HALITE COMP_RCK

Computational Code: BRAGFLO

minimum	maximum
2.94×10^{-12}	1.92×10^{-10}

Units: Pascals^{-1}

Distribution Type: Uniform

Data: Site-Specific Experimental Data

The parameter distribution for halite rock compressibility is based upon data from two hydraulic tests in Room Q: QPP05 and QPP15. Another data point calculated from sensitivity studies using brine inflow data from Room Q is within the range driven from the hydraulic tests. Parameter records packages associated with this parameter are: Halite Rock Compressibility (ERMS #231220) and Salado Halite Rock Compressibility from Room Q ANALYSIS (ERMS #230598).

The two in-situ hydraulic tests were conducted in the location of Room Q before the large-scale brine inflow excavation was mined (see Table PAR-3). Test intervals were located over 20 m (65 ft) from the excavation. Map units (MU) represented included MU 6 (halite) and MU 0 (halite)/MU PH-4 (polyhalite) within a radius of about 1 m (3.3 ft) of each borehole. Raw data included pressure, fluid volume, temperature, axial test-tool movement, and radial borehole closure.

Interpretation of all flow tests in the WIPP facility is based on the assumption that Darcy flow and borehole closure are the only forms of pressure/flow transmission during hydraulic tests. References related to data collection and interpretation are listed in the references section.

Parameter Data Entry Form ERMS: #234210

References:

Beauheim, R.L., Saulnier, G.J., Jr., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Watts Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #226003.

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Albuquerque, NM: Sandia National Laboratories. ERMS #223378.

Jensen, A.L., Howard, C.L., Jones, R.L., and Peterson, T.P. 1993. Room Q Data Report: Test Borehole Data from April 1989 through November 1991. SAND92-1172. Albuquerque, NM: Sandia National Laboratories. ERMS #223548

Saulnier, G.J., Jr., Domski, P.S., Palmer, J.B., Roberts, R.M., Stensrud, W.A., and Jensen, A.L. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Albuquerque, NM: Sandia National Laboratories. ERMS #225746

Stensrud, W.A., Dale, T.F., Domski, P.S., Palmer, J.B., Roberts, R.M., Fort, M.D., Saulnier, G.J., Jr., and Jensen, A.L. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Albuquerque, NM: Sandia National Laboratories. ERMS #226432.

Table PAR-3. Summary of Rock Compressibility Test-Interpretations Results from In Situ Permeability Tests for Undisturbed Halite and Polyhalite Map Units

Test Interval (meters from excavation)	Hole	Zone	Map Unit(s)	Analysis Method	Rock Compressibility C_r (1/pascal)	Formation Pore Pressure (megapascal)[1]
20.13-21.03 down	QPPO5 Room Q	undisturbed	MU 6	GTFM6.0	2.94×10^{-12}	13.89
20.19-21.09 down	QPP15 Room Q	undisturbed	MU 0 MU PH-4	GTFM6.0	1.92×10^{-10}	11.04

[1] Mean

Note: See Record Parameter Package for additional detail.

Parameter 20: Log of Intrinsic Permeability - Marker Bed 139

Parameter Description:

This parameter represents the intrinsic permeabilities for MB139.

Material and Property Name(s):

S_MB139 PRMX_LOG
S_MB139 PRMY_LOG
S_MB139 PRMZ_LOG

Computational Code: BRAGFLO

Measured Values:	-21.0	-19.2	-19.1	-18.8	-18.1	-17.1

Units: Log (meters squared)

Distribution Type: Student's-t

Data: Site-Specific Experimental Data and Laboratory-Measured Data

The reported parameter range of undisturbed Salado anhydrite permeabilities is based upon selected data collected from the following in situ hydraulic tests and measurements conducted in the laboratory: (1) five hydraulic tests conducted in the underground experimental area; and (2) 31 Klinkenberg-corrected gas permeabilities measured in the laboratory on specimens collected from MB139 core samples. Summary data tables are attached for both in situ and laboratory tests (see Table PAR-4 and Table PAR-5). Parameter records packages associated with this parameter are Anhydrite Permeability (x,y,z) (ERMS #231217); Salado Anhydrite Permeability in the X-Direction (ERMS #230603); Salado Anhydrite Permeability in the Y-Direction (ERMS 2 #30605); Salado Anhydrite Permeability in the Z-Direction (ERMS #230606).

Out of 15 borehole and field permeability tests conducted in MB140, MB139, MB138 and anhydrites a and b, 5 in situ hydraulic tests are considered representative of undisturbed anhydrite permeability. Located from about 10 to 24 m (33 to 79 ft) from the excavation, the test intervals for these five boreholes were outside of the DRZ. The radius of visibility ranged from 4 to 25 m (13 to 82 ft). The five successful tests are summarized as follows:

Borehole	Location	Map Unit	Testing Period
QPP03	Room Q	Anhydrite b	4/89 11/91
QPP13	Room Q	MB 139	4/89 11/91
C2H02	Room C2	MB 139	4/89 12/89
L4P51-C1	Room L4	MB 140	4/92 6/94
SCP01-A	Core Storage	MB 139	4/90 10/90

Klinkenberg-corrected gas permeability measured in the laboratory can be used as an equivalent measure of liquid permeability. Klinkenberg-corrected test specimen data exist

from six whole cores taken from MB139 in the northern experimental area: E1X07, E1X08, E1X10, E1X11 (E140 Drift), P3X10, and P3X11 (Room L3).

For purposes of parameterization, in situ test data are treated differently than laboratory-derived data. Uncertainty exists in regards to the spatial representativeness of the core samples. In situ hydraulic tests are considered representative of expected permeability conditions on the scale of the grid system used in the BRAGFLO mesh. Consequently, for the parameter distribution above, laboratory data from the 6 megapascals net effective stress are averaged as one data point, whereas each of the five hydraulic tests is considered an individual data point.

Parameter Data Entry Form ERMS: #234865

References:

Beauheim, R.L., Saulnier, G.J., Jr., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #2 26003.

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Albuquerque, NM; Sandia National Laboratories. ERMS #223378.

Howarth S.M., and Christian-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. Albuquerque, NM: Sandia National Laboratories. ERMS #238019

Jensen, A.L., Howard, C.L., Jones, R.L., and Peterson, T.P. 1993. Room Q Data Report: Test Borehole Data from April 1989 through November 1991. SAND92-1172. Albuquerque, NM: Sandia National Laboratories. ERMS #223548.

Saulnier, G.J., Jr., Domski, P.S., Palmer, J.B., Roberts, R.M., Stensrud, W.A., and Jensen, A.L. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Albuquerque, NM: Sandia National Laboratories. ERMS #225746.

Stensrud, W.A., T.F. Dale, P.S. Domski, J.B. Palmer, R.M. Roberts, M.D. Fort, G.J. Saulnier, Jr., and A.L. Jensen. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Albuquerque, NM: Sandia National Laboratories. ERMS #226432.

Table PAR-4. Summary of Test-Interpretations Results from In Situ Permeability Tests for Undisturbed Anhydrite Map Units

Test Interval (meters from excavation)	Hole	Zone	Map Unit	Analysis Method	Permeability k (m^2)	Formation Pore Pressure (megapascals)[1]
10.68-14.78 down	SCP01-A	undisturbed	MB139	GTFM6.0	1.4×10^{-19}	12.27
9.47-10.86 down	C2H02	undisturbed	MB139	GTFM6.0	1.0×10^{-21}	11.11
20.50-21.40 up	QPPO3	undisturbed	anhydrite b	GTFM6.0	7.6×10^{-20}	12.9
20.62-21.52 down	QPP13	undisturbed	MB139	GTFM6.0	6.0×10^{-20}	12.43
17.44-22.20 down	L4P51-C1	undisturbed	MB140	GTFM6.0	8.7×10^{-18}	9.38

[1] Mean

Note: See Record Parameter Package for additional detail.

Table PAR-5. Summary of MB139 Permeability Laboratory Test Results

	Permeability (pressure values are net effective stress)					
	Gas (Klinkenberg Corrected)			Log of Permeability		
	3.4 megapascals (m^2)	6 megapascals (m^2)	10 megapascals (m^2)	2 megapascals (m^2)	6 megapascals (m^2)	10 megapascals (m^2)
Minimum	1.5E-19	5.9E-20	5.0E-20	-18.84	-19.23	-19.30
Maximum	8.3E-16	3.0E-16	1.5E-16	-15.08	-15.52	-15.82
Sum	9.0E-16	3.4E-16	1.8E-16	-552.29	-524.43	-402.17
Points	31	29	22	31	29	22
Mean	2.9E-17	1.2E-17	8.0E-18	-17.82	-18.08	-18.28
Median	1.3E-18	5.7E-19	3.1E-19	-17.89	-18.24	-18.51
Std Deviation	1.5E-16	5.6E-17	3.2E-17	0.67	0.69	0.83
Variance	2.2E-32	3.2E-33	1.1E-33	0.45	0.48	0.69

Parameter 21: Rock Compressibility - Marker Bed 139

Parameter Description:

The rock (or bulk) compressibility of the Salado Formation Anhydrite Layers a and b MB139 is used to calculate the pore compressibility that is used in BRAGFLO. Pore compressibility is used to predict the effect of material compressibility on porosity and mass storage in the equation of state for flow through porous media as follows:

$$\varphi = \varphi_o \exp\left(c_p(p-p_o)\right)$$

where,

φ = porosity of solid matrix (cubic meters/cubic meters)
φ_o = porosity at reference pressure p_o
c_p = pore compressibility (pascals^{-1})
p = pore pressure (pascals)
p_o = reference pore pressure (pascals)

The rock compressibility is divided by effective porosity to calculate pore compressibility. It is a sampled parameter for MB139 and the values are then applied to MB138 and Anhydrite Layers a and b.

Material and Property Name(s):

S_MB139 COMP_RCK

Computational Code: BRAGFLO

Measured Values:	1.09×10^{-11}	1.09×10^{-11}	3.37×10^{-11}	2.75×10^{-10}

Units: Pascals^{-1}

Distribution Type: Student's-t

Data: Site-Specific Experimental Data

The parameter distribution for anhydrite rock compressibility is based upon data from four hydraulic tests in the underground WIPP facility (see Table PAR-6). The boreholes and map units tested include: C2H02 (MB139); QPP03 (Anhydrite b); QPP13 (MB139); and SCP01 (MB139). The parameter records package associated with this parameter is located at: WIPP: 1.2.07.1:PDD: QA:SALADO:PKG 19:Rock Compressibility (ERMS #231186).

The four successful tests include:

Borehole	Location	Start Date of Testing	End Date of Testing
QPP03	Room Q	4/89	11/91
QPP13	Room Q	4/89	11/91
C2H02	Room C2	4/89	11/89
SCP01-A	Core Storage	4/90	10/90

Raw data collected during hydraulic tests include pressure, fluid volume, temperature, axial test-tool movement, and radial borehole closure. Pressure/flow transmission during hydraulic tests is assumed to be a result of Darcy flow and borehole closure. The reader is referred to the anhydrite rock compressibility parameter record package for more detail.

Parameter Data Entry Form ERMS: #234574

References:

Beauheim, R.L., Saulnier, Jr., G.J., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #226003.

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Albuquerque, NM: Sandia National Laboratories. ERMS #223378.

Jensen, A.L., Howard, C.L., Jones, R.L., and Peterson, T.P. 1993. Room Q Data Report: Test Borehole Data from April 1989 through November 1991. SAND92-1172. Albuquerque, NM: Sandia National Laboratories. ERMS #223548.

Saulnier, Jr., G.J., Domski, P.S., Palmer, J.B., Roberts, R.M., Stensrud, W.A., and Jensen, A.L. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Albuquerque, NM: Sandia National Laboratories. ERMS #225746.

Stensrud, W.A., Dale, T.F., Domski, P.S., Palmer, J.B., Roberts, R.M., Fort, M.D., Saulnier, G.J., Jr., and Jensen, A.L. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Albuquerque, NM: Sandia National Laboratories. ERMS #226432.

Table PAR-6. Summary of Rock Compressibility Test-Interpretations Results from In Situ Permeability Tests for Undisturbed Anhydrite Marker Beds

Test Interval (meters from excavation)	Hole and Location	Zone	Map Unit(s)	Analysis Method	Rock Compressibility C_r (1/pascals)	Formation Pore Pressure (megapascals)[1]
9.47-10.86 down	C2H02	undisturbed	MB 139	GTFM6.0	1.09×10^{-11}	11.11
20.62-21.52 down	QPP13	undisturbed	MB 139	GTFM6.0	3.37×10^{-11}	12.43
10.68-14.78 down	SCP01	undisturbed	MB 139	GTFM6.0	1.09×10^{-11}	12.27
20.50-21.40 up	QPP03	undisturbed	Anhydrite b	GTFM6.0	2.75×10^{-10}	12.94

[1] Mean

Note: See Record Parameter Package for additional detail.

Parameter 22: Relative Permeability – Marker Bed 139

Parameter Description:

The relative permeability model number parameter is the flag used to select two-phase flow model for use in BRAGFLO. It is a sampled parameter for MB139 (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

S_MB139 RELP_MOD

Computational Code: BRAGFLO

Value	1.0	2.0	3.0	4.0
Percentiles	.50	0	0	.50

Units: None

Distribution Type: Delta

Data: Site-Specific Experimental Data

Site-specific experimental data was collected from whole core taken from six underground boreholes at the WIPP. The specimens first underwent permeability and porosity testing, then subsequent capillary pressure tests. Test data from MB 139 was applied to MB 138 and Anhydrite Layers a and b. All other material regions use the second modified Brooks-Corey two-phase flow model.

Assumptions made during testing were:

1) Cores were 100 percent saturated at initiation of capillary pressure tests.
2) Use of a 140° contact angle was appropriate for correcting mercury-air data to brine-air repository conditions.
3) Although tests were conducted at ambient conditions (no stress), the data are adequate to describe two-phase conditions at stress.

The following parameter records package is associated with the tests: Anhydrite Two-Phase Parameters, Appendix E for SAND94-0472 (ERMS #230643).

There are several two-phase relative permeability models described in Appendix BRAGFLO (DOE 1996), including the van Genuchten-Parker and the second modified Brooks-Corey. Interpretation of the experimental test results showed that either the second modified Brooks-Corey or the van Genuchten-Parker two-phase flow models could be used to describe the data.

Parameter Data Entry Form ERMS: #234500

References:

Howarth S.M., and Christian-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. Albuquerque, NM: Sandia National Laboratories. (ERMS #238019).

Webb, S.W. 1991. "Sensitivity Studies for Gas Release from the Waste Isolation Pilot Plant," Chapter 4.0 in Waste-Generated Gas at the Waste Isolation Pilot Plant: Papers Presented at the Nuclear Energy Agency Workshop on Gas Generation and Release from the Radioactive Waste Repositories, P.B. Davies et al., eds., SAND91-2378, November 1991. Albuquerque, NM: Sandia National Laboratories. (ERMS #228772).

Parameter 23: Residual Brine Saturation - Marker Bed 139

Parameter Description:

The residual brine saturation (S_{br}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves. Referred to also as S_{wr} (wetting phase) or S_{lr} (liquid phase), residual brine saturation is the point reached under high gas saturation conditions when brine is no longer continuous throughout the pore network and relative brine permeability becomes zero. It is a sampled parameter for MB139 (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

S_MB139 SAT_RBRN

Computational Code: BRAGFLO

Measured Values:	7.78×10^{-3}	0.069	0.070	0.073	0.109	0.174

Units: None

Distribution Type: Student's-t

Data: Site-Specific Experimental Data

Residual brine saturation parameter values for the marker beds are based on curve fit parameter values predicted from laboratory measurements of capillary pressure. The parameter records package associated with this parameter is: Anhydrite Two-Phase Parameters, Appendix E for SAND94-0472 (ERMS #230643).

Discussion:

Parameter values are based on curve fit capillary pressure data measured using a mercury injection technique. The two-phase flow program reports the results of curve-fitted measurements of capillary pressure on six MB samples (Howarth and Christian-Frear 1996). Specimens were collected from intact MB139 core samples taken from the experimental area of the repository.

Parameter Data Entry Form ERMS: #234506

References:

Howarth S.M., and Christian-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. Albuquerque, NM: Sandia National Laboratories. (ERMS #238019).

Parameter 24: Residual Gas Saturation - Marker Bed 139

Parameter Description:

The residual (critical) gas saturation (S_{gr}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves. S_{gr} corresponds to the degree of waste-generated gas saturation necessary to create an incipient interconnected pathway in porous material, a condition required for porous rock to be permeable to gas. It is a sampled parameter for MB139 (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

S_MB139 SAT_RGAS

Computational Code: BRAGFLO

Measured Values:	0.014	0.025	0.032	0.078	0.116	0.197

Units: None

Distribution: Student's-t

Data: Site-Specific Experimental Data

Residual gas saturation parameter values for the marker beds are based on curve-fitted laboratory measurements of capillary pressure. The parameter records package is associated with this parameter is: Anhydrite Two-Phase Parameters, Appendix E for SAND 94-0472 (ERMS #230643).

Discussion:

The two-phase flow program reports the results of curve-fitted measurements of capillary pressure on six marker bed samples tested using mercury injection (Howarth and Christian-Frear 1996). The samples were taken from intact MB139 core samples collected from the northern experimental area of the repository. The measurements were conducted at ambient conditions (no stress) and were assumed to be 100 percent saturated at the initiation of capillary pressure tests.

Parameter Data Entry Form ERMS: #234508

References:

Howarth S.M., and Christian-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. Albuquerque, NM: Sandia National Laboratories. ERMS #238019.

Parameter 25: Pore Distribution - Marker Bed 139

Parameter(s) Description:

The Brooks-Corey pore size distribution parameter (λ) is used to calculate capillary pressure and relative permeabilities for gas and brine flow in the two-phase flow model. It is a sampled parameter for MB139 (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

S_MB139 PORE_DIS

Computational Code: BRAGFLO

Measured Values:	0.491	0.558	0.652	0.655	0.665	0.842

Units: None

Distribution Type: Student's-t

Data: Site-Specific Experimental Data

Pore size distribution parameter values for all anhydrite units are based on curve fit values predicted from laboratory measurements of capillary pressure. The parameter records package associated with this parameter is retained in Anhydrite Two-Phase Parameters, Appendix E for SAND94-0472 (ERMS #230643).

Discussion:

Curve fit parameter values are derived from six specimens cut from intact MB139 core samples collected from the northern experimental area of the repository. Reported data and parameters are based on mercury injection capillary pressure tests (Howarth and Christian-Frear 1996).

Parameter Data Entry Form ERMS: #234859

References:

Howarth S.M., and Christian-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. Albuquerque, NM: Sandia National Laboratories. (ERMS #238019).

Parameter 26: Initial Pressure - Salado Halite

Parameter Description:

The initial brine far-field (undisturbed) pore pressure in the Salado halite is applied at an elevation consistent with the intersection of MB139 (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

S_HALITE PRESSURE

Computational Code: BRAGFLO

minimum	maximum
1.10×10^7	1.39×10^7

Units: Pascals

Distribution Type: Uniform

Data: Site-Specific Experimental Data

Two hydraulic tests were performed in boreholes in undisturbed halite in the underground WIPP repository. Both tests were performed in the area where Room Q would later be mined. The tests were undertaken in April-July, 1989. Pressure, fluid volume, temperature, axial test-tool movement, and radial borehole closure were measured during the hydraulic tests in undisturbed rock. The following parameter records package is associated with the tests: Halite Pressure (ERMS #231221).

Discussion:

It was assumed that Darcy flow and borehole closure were the only forms of pressure/flow transmission during the hydraulic tests in undisturbed halite. The uncertainty associated with the estimated parameter values is high. The distribution is based on the two data points provided in the data package and the calculated median is 1.247×10^7 pascals.

Parameter Data Entry Form ERMS: #234394

References:

Beauheim, R.L., Saulnier, G.J., Jr., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #226003.

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Albuquerque, NM: Sandia National Laboratories.

ERMS #223378.

Jensen, A.L., Howard, C.L., Jones, R.L., and Peterson, T.P. 1993. Room Q Data Report: Test Borehole Data from April 1989 through November 1991. SAND92-1172. Albuquerque, NM: Sandia National Laboratories. ERMS #223548.

Saulnier, G.J., Jr., Domski, P.S., Palmer, J.B., Roberts, R.M., Stensrud, W.A., and Jensen, A.L. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Albuquerque, NM: Sandia National Laboratories. ERMS #225746.

Stensrud, W.A., Dale, T.F., Domski, P.S., Palmer, J.B., Roberts, R.M., Fort, M.D., and Saulnier, G.J., Jr. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Albuquerque, NM: Sandia National Laboratories. ERMS #226432.

Parameter 27: Initial Pressure - Castile Brine Reservoir

Parameter Description:

Initial brine pore pressure in the Castile brine reservoir (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

CASTILER PRESSURE

Computational Code: BRAGFLO

mode	minimum	maximum
1.27×10^7	1.11×10^7	1.70×10^7

Units: Pascals

Distribution Type: Triangular

Data: Site-Specific Experimental Data and Professional Judgment

The parameter records package associated with this parameter is as follows: Castile Brine Reservoir Pressure (ERMS #231072).

Discussion:

All pressure measurements were adjusted to reflect formation pressure of the WIPP-12 reservoir. Pressure adjustments were made as follows:

$$P_a = P + \rho\, g\, (h - 140)\, 1 \times 10^{-6}$$

where:
- P_a = adjusted pressure (megapascals)
- P = measured/estimated pressure (megapascals)
- ρ = assumed density (kilograms per cubic meter)
- g = gravitational constant (9.8 Newtons per kilogram)
- h = brine reservoir elevation (meters above sea level)

Observed (measured and interpreted) Castile brine reservoir fluid pressures were compared with their corresponding lithostatic pressures; four locations (shown in Table PAR-7) were found to best represent the formation pressure. The measured values in Table PAR-7 are adjusted to reflect formation pressure at the depth of WIPP-12, which is representative of the depth of the BRAGFLO Castile Brine Reservoir. The pressure adjustment requires an assumption about pressure variation with depth in the Castile. Two bounding cases were used, hydrostatic and 85 percent of lithostatic; the adjusted pressure was calculated using the equation provided above. A brine density of 1,240 kg/m^3 (Reeves et al. 1989) was assumed for the hydrostatic variation; an average formation density of 2,040 kg/m^3 (Sandia WIPP Project 1992) was assumed for the lithostatic variation. The best-measured value (that is, the mode) is the brine reservoir pressure reported for WIPP-12 (12.7 megapascals). The maximum

brine reservoir pressure is 85 percent of lithostatic at WIPP-12 depth (17 megapascals). The minimum value is the lowest measured hydrostatic pressure (11.1 megapascals). Freeze and Larson (1996), attached to CCA Appendix MASS, Section 18 , provide more detail.

Parameter Data Entry Form ERMS: #231612

References:

Freeze, Geoff, and Larson, K. 1996. Memorandum to Martin Tierney Re: Initial Pressure in the Castile Brine Reservoir, March 20, 1996. ERMS #237148.

Lappin, A.R., Hunter, R.L., Garber, D.P., and Davies, P.B., eds. 1989. Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico, March 1989. SAND89-0462. Albuquerque, NM: Sandia National Laboratories. ERMS #224125.

Popielak, R.S., Beauheim, R.L., Black, S.R., Coons, W.E., Ellingson, C.T., and Olsen, R.L. 1983. Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico, DOE Report TME-3153.

Reeves, M., Freeze, G.A., Kelley, V.A., Pickens, J.F., Upton, D.T., and Davies, P.B. 1989. Regional Double-Porosity Solute Transport in the Culebra Dolomite under Brine-Reservoir-Breach Release Conditions: An Analysis of Parameter Sensitivity and Importance. SAND89-7069. Albuquerque, NM: Sandia National Laboratories. ERMS #224048.

Sandia WIPP Project. 1992. Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992: Volume 3, Model Parameters. SAND92-0700/3. Albuquerque, NM: Sandia National Laboratories. ERMS #223529.

Table PAR-7. Measured Castile Brine Reservoir Formation Pressures

Location	Pressure at Reservoir Depth (megapascals)	Pressure at WIPP-12 Depth with Hydrostatic Adjustment (megapascals)	Pressure at WIPP-12 Depth with 85% Lithostatic Adjustment (megapascals)
WIPP-12	12.7[(1)]	12.7	12.7
ERDA-6	14.1[(2)]	15.5	16.4
Belco	14.3[(2)]	14.5	14.5
Gulf Covington	13.6[(2)]	12.1	11.1

[(1)] from Reeves et al. 1989, Appendix A
[(2)] from Popielak et al. 1983, Table H.1

Parameter 28: Log of Intrinsic Permeability - Castile Brine Reservoir

Parameter Description:

The log of the intrinsic permeability of the Castile Brine Reservoir. It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

CASTILER PRMX_LOG
CASTILER PRMY_LOG
CASTILER PRMZ_LOG

Computational Code: BRAGFLO

mode	minimum	maximum
-11.80	-14.70	-9.80

Units: Log (meters squared)

Distribution Type: Triangular

Data: Site-Specific Experimental Data and Professional Judgment

Although several shorter flow tests were conducted to measure permeability of Castile brine reservoirs, only one test is considered representative of the long-term behavior of the brine reservoir behavior: the WIPP-12 Flow Test 3 (24,800 bbl produced, nine months recovery). The Graph Theoretic Field Model (GTFM) analysis of WIPP-12 Flow Test 3 (Reeves et al. 1989) is considered better than the Horner analysis because it considers the effects of pre-test borehole pumping history. The GTFM interpreted hydraulic conductivity from WIPP-12 Flow Test 3 therefore provides the basis for the mean permeability for the Castile brine reservoir. The other values from WIPP-12 and ERDA-6 were used to establish the permeability distribution.

Professional judgment was used to better define the data mean and range because of the shortage of directly relevant data points. The parameter records package associated with this parameter is as follows: Castile Brine Reservoir Permeability (ERMS #231070).

The GTFM analysis from WIPP-12 Flow Test 3 consists of a match to pressure response data and a match to flow rate data. The late time match to the pressure data are controlled primarily by the formation pressure and is not very sensitive to the hydraulic conductivity or the specific storage. To match the flow rate data, the GTFM interpreted hydraulic conductivity (K) is strongly correlated with the specified specific storage (S_s), where:

$$S_s = \rho g \, (C_R + \Phi\beta)$$

For Castile brine reservoir properties, specific storage is proportional to the bulk rock compressibility (C_R). The correlation between K and S_s is such that their product is

approximately a constant. For example, if the assumed specific storage (or rock compressibility) in GTFM is reduced by an order of magnitude, the interpreted hydraulic conductivity must increase by an order of magnitude to produce the same flow rate. The new combination of K and S_s will produce a different early-time pressure response, but will not impact the late-time match. For the GTFM analyses of the WIPP-12 Flow Tests, a rock compressibility of 1×10^{-9} pascals^{-1} was assumed. Because the mean rock compressibility for the Castile brine reservoir is 1×10^{-10} pascals^{-1}, the hydraulic conductivity required to reproduce the WIPP-12 flow is approximately 1×10^{-5} m/s (permeability of -11.81 log (square meters)). For all triangular distributions, the mode is the best estimate. GTFM analysis determines a hydraulic conductivity (with units of meters per second) based on pressure change, flow rate, and assumptions about fluid and formation properties. Conversions from meters per second to square meters were based on a conversion factor of 1.7×10^{-7} m^2 per (meters per second). The conversion factor is based on the assumed GTFM fluid properties.

Parameter Data Entry Form ERMS: #231613

References:

Popielak, R.S., Beauheim, R.L., Black, S.R., Coons, W.E., Ellingson, C.T., and Olsen, R.L. 1983. Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico. DOE Report TME-3153.

Reeves, M., Freeze, G.A., Kelley, V.A., Pickens, J.F., Upton, D.T., and Davies, P.B. 1989. Regional Double-Porosity Solute Transport in the Culebra Dolomite under Brine-Reservoir-Breach Release Conditions: An Analysis of Parameter Sensitivity and Importance. SAND89-7069. Albuquerque, NM: Sandia National Laboratories. ERMS #224048.

Parameter 29: Rock Compressibility - Castile Brine Reservoir

Parameter Description:

The rock (or bulk) compressibility of the Castile Brine Reservoir is used to calculate the pore compressibility, which is required for running BRAGFLO (see CCA Appendix PA, Figure 4.2.1). Pore compressibility is used to predict the effect of material compressibility on porosity and mass storage in the equation of state for flow through porous media as follows:

$$\phi = \phi_o \exp\left(c_p\left(p - p_o\right)\right)$$

where,

φ = porosity of solid matrix (cubic meters per cubic meters)
φ_o = porosity at reference pressure p_o
c_p = pore compressibility (pascals^{-1})
p = pore pressure (pascals)
p_o = reference pore pressure (pascals)

The rock compressibility is divided by effective porosity to calculate pore compressibility.

Material and Property Name(s):

CASTILER COMP_RCK

Computational Code: BRAGFLO

mode	minimum	maximum
4.00×10^{-11}	2.00×10^{-11}	1.00×10^{-10}

Units: Pascals^{-1}

Distribution Type: Triangular

Data: Site-Specific Experimental Data and Professional Judgment

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR in DOE (1996), parameter values were based on an analysis of data from WIPP-12. Rock compressibility values were determined by calculating the bulk modulus of anhydrite from the acoustic log of the Castile Anhydrite III unit found in WIPP-12. The DOE chose to use the acoustic log because it measures compressive wave travel time over short distances through relatively intact, undisturbed rock, then uses a correlation

between wave velocity and elastic rock properties to estimate bulk modulus. Various laboratory compression tests on anhydrite from other WIPP locations produced similar results for the bulk modulus (Popielak et al., 1983).

The estimated bulk modulus, K, for the intact Anhydrite III at WIPP-12 was 6.9×10^{10} pascals (10×10^{6} psi). Assuming uniaxial strain, the rock compressibility (C_R) can be estimated from the bulk modulus (K) and the shear modulus (G) of the rock:

$$C_R = \frac{1}{K + 4G/3}$$

No estimates for shear modulus for Anhydrite III were available. Beauheim et al. (1991) reported a value for G that was approximately 1/3 of K for Salado anhydrite. Using this estimate for G, the calculated intact rock compressibility is 1×10^{-11} pascals^{-1}.

The bulk modulus may be 2 to 10 times smaller for fractured rock (Popielak et al. 1983), corresponding to a 2 to 10 times increase in compressibility (assuming G changes accordingly). Beauheim et al. (1991) suggest that fracturing might result in a fourfold increase in rock compressibility. Using these adjustments for fractured rock, the calculated rock compressibility ranges from 2×10^{-11} pascals^{-1} to 1×10^{-10} pascals^{-1}, with an average value of 5×10^{-11} pascals^{-1}.

Hydraulic testing was performed in transition-zone (disturbed) Salado anhydrite and halite. Interpreted rock compressibilities for transition zone anhydrite ranged from 5×10^{-12} pascals^{-1} to 3×10^{-9} pascals^{-1}. Freeze and Cherry (1979) report a range for rock compressibility for fractured or jointed rock of 1×10^{-8} to 1×10^{-10} pascals^{-1} (DOE 1996).

Subsequent to the CCA PA calculations, EPA reviewed the CCA, and supporting information and references, and concluded that the compressibility parameter for the Castile Formation brine reservoir was not consistent with available information (EPA, 1998). Subsequent to the CCA, the field test data for the WIPP-12 borehole was re-examined and arrived at a revised range for rock compressibility. EPA regarded the re-analysis as a better estimate of the rock compressibility parameter than the value used in the CCA.

The Sandia National Laboratories Technical Library and Records Center undertook a key word-based (Castile rock compressibility) literature and records search to identify documentation/research that addresses the brine reservoir rock compressibility. Titles of all recent documents identified by the search were reviewed for relevancy; following this, abstracts and/or complete documents were reviewed to determine if information more recent than that cited in the CCA or PAVT was available. The literature and records search and review did not identify new information that would offer further support of, or otherwise refute the distributions and parameter ranges presented above. Consequently, rock compressibility is treated as a sampled variable having a triangular distribution and a revised range of 2×10^{-11} to 1×10^{-10} Pa^{-1} and a revised mode of 4×10^{-11} Pa^{-1}.

Parameter Data Entry Form ERMS: #522016

References:

Beauheim, R.L., Saulnier, G.J., Jr., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #226003.

Freeze, R.A., and Cherry, J.A. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

Popielak, R.S., Beauheim, R.L., Black, S.R., Coons, W.E., Ellingson, C.T., and Olsen, R.L. 1983. Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico. DOE Report TME-3153.

Reeves, M., Freeze, G.A., Kelley, V.A., Pickens, J.F., Upton, D.T., and Davies, P.B. 1989. Regional Double-Porosity Solute Transport in the Culebra Dolomite Under Brine-Reservoir-Breach Release Conditions: An Analysis of Parameter Sensitivity and Importance. SAND89-7069. Albuquerque, NM: Sandia National Laboratories. ERMS #224048.

U.S. Environmental Protection Agency (EPA). 1998. Response to Comments, Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with 40 CFR 191 Disposal Regulations: Certification Decision. Docket No. A-93-02, V-C-1. U.S. Environmental Protection Agency. Washington D.C.

Parameter 30: Log of Intrinsic Permeability - Intrusion Borehole Filled With Silty Sand

Parameter Description:

This parameter represents the log of the intrinsic permeability of the silty-sand-filled borehole in the human-intrusion scenario (see CCA Appendix PA, Figure 4.2.1). This permeability is representative of degraded concrete or material which may sluff into the borehole or spall from the sides. It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

BH_SAND PRMX_LOG
BH_SAND PRMY_LOG
BH_SAND PRMZ_LOG

Computational Code: BRAGFLO

minimum	maximum
-16.30	-11.00

Units: Log (meters squared)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR, this parameter represented the permeability of the silty-sand-filled borehole in the human-intrusion scenario. The permeability was representative of degraded concrete or material which may sluff into the borehole or spall from the sides. Three plug configurations with different permeabilities were associated with each configuration. Borehole materials and plug configurations were based on a review of regulations and practices, and the permeability predictions are based on models and data for steel corrosion and concrete alteration found in the literature (Thompson et al. 1996). Wherever possible, the predictions were calibrated by comparing predicted behavior to field data (Thompson et al. 1996).

The three plug configurations consisted of: a continuous concrete plug through the Salado and Castile which was assigned a probability of 0.015 (see Section 6.4.7.2.1), a two-plug configuration (a lower plug located between the Castile brine reservoir and underlying formations and an upper plug located in the Rustler immediately above the Salado), which was

assigned a probability of 0.696 (see Section 6.4.7.2.2), and a three-plug configuration (two plugs same as two-plug configuration and third plug located in the Castile above the brine reservoir and below the waste-disposal panel) which was assigned a probability of 0.289 (see Section 6.4.7.2.3).

The plugs were initially expected to have a tight permeability of 5×10^{-17} m^2 (Thompson et al. 1996). The continuous concrete plug was assumed not to degrade and had a permeability of 5×10^{-17} m^2 for the entire regulatory period. For the two-plug configuration, the permeability between the repository and the surface is 5×10^{-17} m^2 for the first 200 years and 10^{-14} to 10^{-11} m^2 after that; the permeability between the Castile and the repository is 10^{-14} to 10^{-11} m^2 up to 1,200 years and 10^{-15} to 10^{-12} m^2 after that. The three-plug configuration had the same material properties as the corresponding regions in the two-plug configuration and the third plug was assumed to behave as the lower plug in the two-plug configuration (DOE 1996).

Subsequent to the CCA PA calculations, EPA questioned the range of borehole sand permeabilities and the assumption that concrete borehole plugs would degrade to a more permeable material. The EPA (1997a) concluded that the lower bound for long-term borehole sand permeability proposed (10^{-14} m^2) should be closer to that of an undegraded borehole plug (5×10^{-17} m^2). The lower value was of interest to EPA because a lower permeability could result in increased gas pressures with consequent increases in brine and spallings releases during a human intrusion event.

The EPA also investigated drilling practices used in the petroleum industry and found literature values for cement permeability ranging from 9×10^{-21} to 1×10^{-16} m^2 (EPA 1997b). The EPA also found that filter cake and compacted, clay-based drilling muds could yield permeabilities of less than 9.9×10^{-22} m^2. In their considerations, the EPA noted that drilling mud used in the Delaware Basin boreholes might not have the permeability of clay-based solids; however, they noted that natural cuttings could contribute to lower borehole permeabilities than those assumed by the DOE. The EPA also postulated that the effective average permeability over an abandoned borehole could remain in the range of 9×10^{-21} to 1×10^{-16} m^2 over a period of hundreds of years or more if complete degradation does not occur throughout a plug configuration or if natural materials or mud were to provide additional layers with sealing properties.

With these findings, the EPA decided that the borehole sand permeabilities assigned in the CCA, while consistent with the broad range of available data, did not adequately represent the total range of permeability conditions that could exist. As a result, lower borehole sand permeabilities values are used. (Hansen and Leigh 2003)

Parameter Data Entry Form ERMS: #522016

References:

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

Thompson, T.W., Coons, W.E., Krumhansl, J.L., and Hansen, F.D. 1996. Inadvertent

Intrusion Borehole Permeability, Final Draft, July 8, 1996.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Vols 1-XXI.

U.S. Environmental Protection Agency (EPA). 1997a. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, III-B-14, U.S. Environmental Protection Agency. Washington D.C.

U.S. Environmental Protection Agency (EPA). 1997b. Compliance Application Review Documents for the Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations: Proposed Certification Decision. Docket No. A-93-02, III-B-2. U.S. Environmental Protection Agency. Washington D.C.

U.S. Environmental Protection Agency (EPA). 1998a. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C. ERMS #525158.

Parameter 31: Log of Intrinsic Permeability - Disturbed Rock Zone

Parameter Description:

This parameter represents the log of the intrinsic permeability of the disturbed rock zone (DRZ), 0-10,000 yrs (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

DRZ_1 PRMX_LOG
DRZ_1 PRMY_LOG
DRZ_1 PRMZ_LOG

Computational Code: BRAGFLO

minimum	maximum
-19.40	-12.50

Units: Log (meters squared)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

The grid used in CCA calculations implemented a DRZ of constant permeability (10^{-15} m^2) over a region 12 m above and 2.23 m below the disposal rooms. The grid was continuous above panel closure systems, such that the same permeability and thickness existed above and below the simulated panel closures. A more realistic representation of the DRZ over disposal rooms would include high permeability near the free surface of rooms, and reduction of permeability as a function of depth into the surrounding rock. Generally speaking, the DRZ extends greater distances above a room than below, and is relatively shallow into the ribs.

Subsequent to the CCA PA calculations, the EPA determined an alternate lower bound for DRZ permeability from measured gas permeability in anhydrite cores from MB139 (Howarth 1996; Beauheim 1996; Howarth and Christain-Frear 1994). The EPA concluded that a value of -19.4 for the log of the permeability was a more appropriate lower bound for the range of likely values. The EPA selected a value of -12.5 as an upper bound on the log of DRZ permeability based upon a sensitivity analysis (EPA 1998). The EPA also assigned a uniform distribution for the range of -19.4 to -12.5 based on the supposition that all the values are

equally likely. The geometric dimensions of the DRZ are the same in the CCA and the PAVT. The DOE has adopted this revised range for the DRZ permeability (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Beauheim, R.L. 1996. "Salado Package #16, (X, Y, Z) DRZ Permeability." Revision 1. Records Package. Sandia National Laboratories. Albuquerque, NM. ERMS #232038.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

Howarth, S.M. 1996. "[Salado Package #13], Salado Anhydrite Permeability in the X-Direction." Records Package. Sandia National Laboratories. Albuquerque, NM. ERMS #230603.

Howarth, S.M., and Christain-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. SAND94-0472 (Draft). Sandia National Laboratories. Albuquerque, NM. ERMS #238367.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 32: Log of Intrinsic Permeability – Concrete Plug

Parameter Description:

This parameter represents the log of the intrinsic permeability of the concrete plug, at the surface of the repository and in the Rustler (see CCA Appendix PA Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

CONC_PLG PRMX_LOG
CONC_PLG PRMY_LOG
CONC_PLG PRMZ_LOG

Computational Code: BRAGFLO

minimum	maximum
-19.00	-17.00

Units: Log (meters squared)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In preparation for the CCA, DOE developed a set of assumed plug configurations for boreholes drilled and abandoned in the future. Each assumed plug configuration involved several materials with varying degrees of integrity over the lifetime of the repository. One material used in the CCA PA borehole models was a concrete material. The DOE assumed that initially, the concrete plugs would be effective in limiting fluid flow in the borehole. However, for purposes of the CCA PA calculation, some plugs above the repository were assumed to degrade after 200 years of emplacement. From that point on, the borehole was assumed to be filled with a silty, sand-like material containing degraded concrete, corrosion products resulting from degradation of the casing, and material that sloughs off of the walls of the borehole.

In CCA Appendix PAR, borehole concrete permeability was set at a constant 5×10^{-17} m^2, based on results reported by Thompson et al. (1996). This value was directly measured for a concrete borehole plug at the WIPP site (Christensen and Hunter 1980).

Subsequent to the CCA PA calculations, EPA required the DOE to consider a range of values for the borehole concrete permeability (EPA 1998). The lower bound of the range chosen by EPA, – 1×10^{-19} m^2 – is more than two orders of magnitude lower than the lowest value measured for a WIPP borehole plug grout (5×10^{-17} m^2) as reported by Christensen and Hunter (1980). The EPA considered this to be a more conservative lower bound because a less permeable borehole plug may result in higher repository gas pressures and hence greater releases during a human intrusion event. The EPA chose an upper bound, 1×10^{-17} m^2, which was equal to the permeability of the concrete in the shaft seal systems. The EPA specified a uniform distribution over the permeability range (from 10^{-19} to 10^{-17}) (Froehlich 1997). The DOE has adopted this revised range for the borehole concrete permeability. (Hansen and Leigh 2003)

Parameter Data Entry Form ERMS: #522016

References:

Christensen, C.L. and Hunter, T.O. 1980. The Bell Canyon Test Results. SAND80-2414C. Sandia National Laboratories. Albuquerque, New Mexico.

Froehlich, G. 1997. “PAV1 Parameter Values.” Memorandum to C. Lattier. ERMS #246087. Sandia National Laboratories. Albuquerque, NM.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

Thompson, T.W., Coons, W.E., Krumhansl, J.L., and Hansen, F.D. 1996. Inadvertent Intrusion Borehole Permeability. Final Draft. Sandia National Laboratories. Carlsbad, NM.

U.S. Environmental Protection Agency (EPA). 1998a. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C. ERMS #525158.

Parameter 34: Log of the Distribution of Solubility of Am(III) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for americium in the +III oxidation state in Salado brine.

Material and Property Name(s):

SOLAM3 SOLSIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

For the CCA, solubilities were calculated using the Fracture Matrix Transport (FMT) code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Am (+III) in Salado brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237105

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 35: Log of the Distribution of Solubility of Am(III) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for americium in the +III oxidation state in Castile brine.

Material and Property Name(s):

SOLAM3 SOLCIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

For the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Am (+III) in Castile brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237106

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 36: Log of the Distribution of Solubility of Pu(III) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for plutonium in the +III oxidation state in Salado brine.

Material and Property Name(s):

SOLPU3 SOLSIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Pu (+III) in Salado brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: 237109

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 37: Log of the Distribution of Solubility of Pu(III) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for plutonium in the +III oxidation state in Castile brine.

Material and Property Name(s):

SOLPU3 SOLCIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Pu (+III) in Castile brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237108

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 38: Log of the Distribution of Solubility of Pu(IV) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for plutonium in the +IV oxidation state in Salado brine.

Material and Property Name(s):

SOLPU4 SOLSIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Pu(+IV) in Salado brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: 237110

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 39: Log of the Distribution of Solubility of Pu(IV) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for plutonium in the +IV oxidation state in Castile brine.

Material and Property Name(s):

SOLPU4 SOLCIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Pu(+IV) in Castile brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237111

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 40: Log of the Distribution of Solubility of U(IV) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for uranium in the +IV oxidation state in Salado brine.

Material and Property Name(s):

SOLU4 SOLSIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of U(+IV) in Salado brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: 237112

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996. Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 41: Log of the Distribution of Solubility of U(VI) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for uranium in the +VI oxidation state in Salado brine.

Material and Property Name(s):

SOLU6 SOLSIM)

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

Data on U(+VI) solubility in Salado brine was compiled by Hobart and Moore (1996), both from ongoing WIPP-directed research and from published literature. Project experimental data was from Reed et al. (1996) (see CCA Appendix SOTERM). Published data was from Yamazaki, et al (1992) and Pashalidas et al (1993). Based on these data, Hobart and Moore recommend a value for U(+VI) for use in performance assessment. Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

The solubility of U(+VI) in Salado brine is a function of pH, CO_2 fugacity, and other brine components. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237113

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791

Hobart, D.E., and Moore, R. 1996. Draft Analysis of Uranium (VI) Solubility Data for WIPP Performance Assessment, Sandia National Laboratories, March 28, 1996. ERMS #239856.

Hobart, D.E., and Moore, R. 1996. Analysis of Uranium (VI) Solubility Data for WIPP Performance Assessment: Implementation of Analysis Plan AP-028, Sandia National Laboratories, August 6, 1996. Contained in package ERMS #236488.

Pashalidis, I., Runde, W., Kim, J.I. 1993. "A Study of Solid-Liquid Phase Equilibria of Pu(VI) and U(VI) in Aqueous Carbonate Systems," Radiochim. Acta, 63, 141-146. ERMS #249861.

Reed, D.T., Wygmans, D.G., and Richmann, M.K. 1996. Stability of Pu(VI), Np(VI), and U(VI) in Simulated WIPP Brine, 3/13/96 Interim Report, Argonne National Laboratory Interim Report (personal communication). ERMS #235197.

Yamazaki, H., Lagerman, B., Symeopoulos, V., and Choppin, G. 1992. Solubility of Uranyl in Brine, Proceedings of the Third International High Level Radioactive Waste Management Conference, Las Vegas, NV, April 12-16, 1992, American Nuclear Society, La Grange Park, IL, and American Society of Engineers, New York. Located in: Vol. 2, p. 1607-1611. SAND92-7069C- ERMS #239678.

Parameter 42: Log of the Distribution of Solubility of U(VI) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for uranium in the +VI oxidation state in Castile brine.

Material and Property Name(s):

SOLU6 SOLCIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, data on U(+VI) solubility in Castile brine was compiled by Hobart and Moore (1996), both from ongoing WIPP-directed research and from published literature. Project experimental data was from Reed et al. (1996) (see Appendix PA, Attachment SOTERM). Published data was from Yamazaki, et al (1992) and Pashalidas et al (1993). Based on these data, Hobart and Moore recommend a value for U(+VI) for use in PA. Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

The solubility of U(+VI) in Castile brine is a function of pH, CO_2 fugacity, and other brine components. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237114

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Hobart, D.E., and Moore, R. 1996. Draft Analysis of Uranium (VI) Solubility Data for WIPP Performance Assessment, Sandia National Laboratories, March 28, 1996. ERMS #233703.

Reed, D.T., Wygmans, D.G., and Richmann, M.K. 1996. Stability of Pu(VI), Np(VI), and U(VI) in Simulated WIPP Brine, Argonne National Laboratory Interim Report (personal communication). 3/13/96 Interim Report contained in ERMS #235197.

Yamazaki, H., Lagerman, B., Symeopoulos, V., and Choppin, G. 1992. Solubility of Uranyl in Brine, Proceedings of the Third International High Level Radioactive Waste Management Conference, Las Vegas, NV, April 12-26, 1992, American Nuclear Society, La Grange Park and American Society of Engineers, New York. SAND92-7069C – ERMS #239678.

Parameter 43: Log of the Distribution of Solubility of Th(IV) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for thorium in the +IV oxidation state in Salado brine.

Material and Property Name(s):

SOLTH4 SOLSIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Th(+IV) in Salado brine assuming equilibrium conditions The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: 237115

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 44: Humic Proportionality Constant

Parameter Description:

The humic proportionality constant is used to calculate concentrations of actinides associated with mobile humic substances for actinide elements with oxidation state of +III, in the Castile brine.

Material and Property Name(s):

PHUMOX3 PHUMCIM

Computational Code(s): PANEL

Value	0.07	1.37	1.60
Percentiles	0	0.50	1.0

Units: None

Distribution Type: Cumulative

Data: Site-Specific Experimental Data

Experiments were conducted at Florida State University (Greg R. Choppin) and at SNL (Hans W. Papenguth and co-workers). These results, combined with WIPP-specific data on calcium and magnesium concentrations, formed the basis for this parameter distribution. The parameter records package associated with this parameter is located at: Mobile Colloidal Actinide Source Term 3, Humic Substances (ERMS #235855).

Discussion:

Humic substances encompass a broad variety of high-molecular-weight organic compounds that can mobilize actinides. To determine the concentration of actinides associated with humic substances, four pieces of information are required: (1) the concentration of reactive humic substance in the aqueous phase (that is, humic solubility); (2) the binding capacity of the humic substance; (3) actinide uptake (that is, actinide complexation constants); and (4) concentration of actinide ions in the aqueous phase (that is, actinide solubility). Quantification of actinide solubilities is described in Novak and Moore (1996). Collection of the other data, interpretation of that information, and development of parameter values for PA calculations is described in detail in Papenguth and Moore (1996). The humic proportionality constant is a combination of information from (1) and (3) above. This constant is multiplied by (4), the actinide concentration, to obtain the concentrations of actinides mobilized on humic colloids.

Further information on this parameter is found in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237683

References:

Novak, C.F., and Moore, R.C. 1996. Technical Memorandum to Malcolm Siegel, Re: Estimates of Dissolved Concentrations for +III, +IV, +V, and +VI Actinides in a Salado and a Castile Brine under Anticipated Repository Conditions, March 28, 1996. ERMS #236207.

Papenguth, Hans W. 1996. Memo to Christine T. Stockman. RE: Colloidal Actinide Source Term Parameters, Revision 2, April 22, 1996. ERMS #237522.

Papenguth, Hans W., and Moore, R.C. 1996. Mobile - Colloidal- Actinide Source Term, 3. Humic Substances, Sandia National Laboratories (ERMS #235855 Attachment A).

Parameter 45: Oxidation State Distribution Parameter

Parameter Description:

This parameter determines whether the repository environment is more reducing or less reducing for a particular realization.

Material and Property Name(s):

GLOBAL OXSTAT

Computational Code(s): PANEL

minimum	maximum
0	1.0

Units: None

Distribution Type: Uniform

Data: Site-Specific Experimental Data and Literature Research

Experimental results from Los Alamos National Laboratory, Pacific Northwest National Laboratory, and Argonne National Laboratories-East were used, as well as data from an extensive literature search. The parameter records package associated with this parameter is located at: Oxidation State Distribution (ERMS #235194).

Discussion:

The oxidation state distribution parameter is used to designate which oxidation states dominate the solubility. Actinides addressed are thorium, uranium, neptunium, plutonium, americium, and curium. Analysis of literature data demonstrated that certain actinides (that is, americium, thorium, curium) will exist only in one oxidation state given the expected WIPP repository conditions. Therefore, this distribution is not used with the PA for these actinides. Experimental evidence indicated that two oxidation states were possible for plutonium, uranium, and neptunium under the expected WIPP repository conditions. For these actinides, it is assumed that their solubilities and k_ds will be dominated by only one oxidation state, but it is uncertain which of two possible states will dominate. Therefore, in half of the realizations employing this parameter (if >0.5), the higher oxidation state solubilities and k_ds will be used, and in the other half of the realizations (if <0.5), the lower oxidation state solubilities and k_ds will be used (Weiner et al. 1996). Further information on this parameter is found in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237663

References:

Novak, C.F., and Moore, R.C. 1996. Technical Memorandum to Malcolm Siegel, Re: Estimates of Dissolved Concentrations for +III, +IV, +V, and +VI Actinides in a Salado and a Castile Brine under Anticipated Repository Conditions, March 28, 1996. ERMS #236207.

Stockman, Christine. 1996. Memo to Martin Tierney. RE: Implementation of Chemistry Parameters in PA. April 16, 1996. ERMS #237536.

Weiner, Ruth F., Hobart, D.E., Tait, C.D., and Clark, D.L. 1996. Analysis of Actinide Oxidation States in the WIPP. Contained in package ERMS #235194.

Parameter 46: Mining Transmissivity Multiplier

Parameter Description:

This parameter is a multiplier, which applies to the transmissivity in areas of the Culebra, which are located above areas of present and future potash mining.

Material and Property Name(s):

CULEBRA MINP_FAC

Computational Code: Routine Calculation

minimum	maximum
1.0	1000.0

Units: None

Distribution Type: Uniform

Data: Regulatory Basis

Data for the Mining Transmissivity Multiplier comes directly from the Preamble published in 40 CFR Part 194 (61 FR 5229). Based on its review of the literature, the EPA determined that mining can increase the conductivity of overlying formations by a factor of much as 1,000. Since the EPA does not specify a distribution for the multiplier, the DOE has assigned it a uniform distribution from 1 to 1,000 with a median value of 500.5. A discussion of the data associated with this parameter may be found in the following parameter records package: Mining Transmissivity Multiplier (ERMS #236489).

Discussion:

EPA's 40 CFR Part 194 requires that the DOE evaluate the consequences of mining in the McNutt on the performance of the WIPP (Larson 1996). The impacts of mining are taken into account by using a multiplier, which varies from 1 to 1,000 with a uniform distribution. The multiplier applies only to the transmissivity in the Culebra and it applies to areas that qualify under a range of criteria, including both mined areas and areas to be mined (Howard 1996).

In the PA, two cases are considered: (1) the partial mining case which includes all mining outside of the controlled area and (2) the full mining case which includes mining outside and inside of the controlled area. Everywhere that the Culebra is underlain by economical quantities of potash (see Section 2.3.1.1), the transmissivity is multiplied by the multiplier. The multiplier is applied uniformly over the entire mined area for a particular Tfield; however, the value of the multiplier changes for different Tfields. The partial mining case applies to all transmissivity vectors in the PA analysis. Starting from that initial condition, the full mining case has a 1 in 100 probability of occurring in any century over the 10,000 year regulatory

time frame (for any given Tfield).

Parameter Data Entry Form ERMS: #237666

References:

Howard, B. A. 1996. Memo from B. A. Howard to Mel Marietta, April 3, 1996, RE: Future Mining Events in the Performance Assessment. Attachment: Extent of Mining Position Paper, Revision 1. ERMS #238571.

Larson, Kurt. 1996. Memo to Mike Wallace, "Mining Transmissivity Multiplier—Area to be mined." April 25, 1996. ERMS #237455.

Wallace, M. 1996. Memo to M. Tierney, "Distribution for Non-Salado Parameter for SECOFL2D: Mining Transmissivity Multiplier," April 18, 1996. ERMS #239355.

Parameter 47: Culebra Transmissivity Field Index

Parameter Description:

This parameter is intended to incorporate uncertainty in the transmissivity field within the Culebra Dolomite Member of the Rustler Formation.

Material and Property Name(s):

GLOBAL TRANSIDX

Computational Code(s): SCMS Script

minimum	maximum
0.0	1.0

Units: None

Distribution Type: Uniform

Data: Professional Judgment - General Engineering Knowledge

No experimental data are associated with the transmissivity field index. The parameter is an index for selecting 1 of 100 transmissivity fields produced by PEST and MODFLOW. It varies uniformly from 0 to 1.

Discussion:

Using an approach known as conditioning, or making realizations of random fields coherent with measured information such as hydraulic head values, 100 equally likely Culebra transmissivity fields were generated (employing PEST and MODFLOW). After incorporating changes requested by EPA to account for future potash mining. Each realization was then converted to a flow field, using MODFLOW, assuming uniform Culebra thickness of 8 m and 16 percent effective porosity. TRANSDIX was used to sample on the interval (0,1). The result was mapped onto the integers 1-100 (the number of transmissivity fields) and the resulting integer was used to select a transmissivity field (Ruskauff 1996; Sandia WIPP Project 1992).

Parameter Data Entry Form ERMS: #233055

References:

Ruskauff, Greg. 1996. Memorandum to Martin Tierney, Re: Culebra Transmissivity Field Index, March 13, 1996. ERMS #235193

Sandia WIPP Project. 1992. Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992, Vol.3: Model Parameters. SAND92-0700/3. Albuquerque, NM: Sandia National Laboratories. ERMS #223529.

Parameter 48: Climate Index

Parameter Description:

A change in climate over the next 10,000 years could alter flow rates in the Culebra, thereby impacting radionuclide transport. The Climate Index is a multiplication factor to enhance the magnitude of flow in each realization of the Culebra flow field caused by changes in future climate.

Material and Property Name(s):

GLOBAL CLIMTIDX

Computational Code(s): PRESECOTP

Value	1	1.25	1.50	2.25
Percentiles	0	0.75	0.75	1

Units: None

Distribution Type: Cumulative

Data: General Literature and Professional Judgment

The parameter distribution was obtained by first surveying the available literature to obtain information that can be used to infer the annual precipitation rate since the end of the Pleistocene and for the next 10,000 years. Next, numerical simulations were performed to see how various assumed rates and temporal patterns of recharge would impact groundwater flow velocities in the Culebra within the WIPP site. The parameter records package associated with this parameter is located at: Climate Index (ERMS #236425).

Discussion:

The following main assumptions were used in the numerical simulations:

1. the groundwater basin conceptual model is applicable,
2. the lateral boundaries are flow divides (that is, no-flow boundaries) during the period simulated,
3. flow in the unsaturated zone can be neglected, and
4. the flow system was equilibrated to a recharge rate sufficient to maintain the water table near the land surface at the start of the simulations.

As described in the Climate Index Record Package (Corbet and Swift 1996), a step recharge function, which represents a radical disruption of the climate pattern of the Holocene, is unlikely and is assigned a 0.25 probability of occurrence and the Holocene recharge pattern is assigned a 0.75 probability of occurrence.

First, simulations were performed using a step recharge function for the pattern of future recharge. The results specify a uniform distribution between 1.5 and 2.25.

Next, six transient simulations using the Holocene pattern of future recharge were performed. The results specify a uniform distribution between 1.0 and 1.25.

Parameter Data Entry Form ERMS: #233031

References:

Corbet, T. and Swift, P. 1996. Memo to M. Tierney. Re: Distribution for Non-Salado Parameter for SECOFL2D: Climate Index, April 12, 1996. ERMS #237465.

Parameter 49: Culebra Half Matrix Block Length

Parameter Description:

This parameter is used to describe the half matrix block length (defined as one-half the thickness of a matrix slab between two parallel plates of fractures) for the Culebra dolomite. It is one of the parameters required in the SECOTP2D code for the double-porosity conceptualization of the Culebra (see also Appendix PA, Section PA-4.9).

Material and Property Name(s):

CULEBRA HMBLKLT

Computational Code(s): SECOTP2D

minimum	maximum
0.05	0.5

Units: Meters

Distribution Type: Uniform

Data: Professional Judgment - General Engineering Knowledge

The half matrix block length distribution is derived from numerical simulations of tracer test data. The data associated with this parameter are located in the following parameter records packages: Culebra Half Matrix Block Length (Culebra Transport Parameter) (ERMS #237225). Supporting data records packages for this parameter include: Tracer Test Interpretations, Simulations for Determination of Adective Porosity and Half Matrix Block Length parameters for CCA Calculations (ERMS #237450); Tracer Test Sample Analyses, H-19 Tracer Tests Conducted June 1995 through July 1995 (ERMS #237468); Tracer Test Sample Analyses, H-19 Tracer Tests Conducted December 1995 through April 1996 (ERMS #237452); and Tracer Test Sample Analyses, H-11 Tracer Tests Conducted February 1996 through March 1996 (ERMS #237467).

Discussion:

The half matrix block length is defined as one-half the thickness of a matrix slab between two parallel plates of fractures. Diffusive processes at the WIPP will cause some fraction of actinides, which are released from the repository, to diffuse from the advective porosity into the diffusive porosity (or matrix), thereby delaying and attenuating discharges at the site boundary. The larger the half matrix block length (smaller surface area for diffusion), the larger the release because there will be less diffusion and in turn less access to surface area for sorption (Meigs and McCord 1996; see CCA Appendix MASS).

The distribution of values for the half matrix block length is uniform, with values ranging from 0.05 to 0.5 m (that is, full matrix block length values from 0.1 to 1.0 m). This distribution

is based on numerical simulations of tracer test data from the H-3, H-11, and H-19 hydropads (Meigs and McCord 1996). Multiwell convergent flow tracer tests have been performed previously at H-3 and H-11 (Stensrud et al. 1989; Hydro Geo Chem, Inc. 1985). Additional tracer tests have been performed at H-11 and at H-19 (Beauheim et al. 1995). The 1995-96 tests at H-11 and H-19 consisted of single-well injection-withdrawal tests and multiwell convergent flow tests.

The matrix block length and the advective porosity are essentially fitting parameters inferred from comparing the results of numerical simulations of the tracer tests to the field data. Numerical simulations were performed with double-porosity models with both homogeneous and heterogeneous hydraulic conductivity fields. For the homogeneous approach, the field data was analyzed using the SWIFT-II transport code, and for the heterogeneous approach, the field data was analyzed using the THEMM code. Both modeling approaches yielded consistent results for each well-to-well path with regard to matrix block length (Meigs and McCord 1996).

Parameter Data Entry Form ERMS: #238356

References:

Beauheim, R. L., Meigs, L.C., Saulnier, G.J., and Stensrud, W.A. 1995. Culebra Transport Program Test Plan: Tracer Testing of the Culebra Dolomite Member of the Rustler Formation at the H-19 and H-11 Hydropads on the WIPP Site. ERMS #230156.

Hydro Geo Chem, Inc. 1985. WIPP Hydrology Program Waste Isolation Pilot Plant, SENM Hydrologic Data Report #1. SAND85-7206. Albuquerque, NM: Sandia National Laboratories. ERMS #228430.

Meigs, Lucy, and McCord, Jim. 1996. Memo to file. RE: Physical Transport in the Culebra Dolomite, July 11, 1996. ERMS #239167.

Stensrud, W.A., Bame, M.A., Lantz, K.D., Palmer, J.B., and Saulnier, G.J., Jr. 1989. WIPP Hydrology Program Waste Isolation Pilot Plant Southeastern New Mexico Hydrologic Data Report #8. SAND89-7056. Albuquerque, NM: Sandia National Laboratories. ERMS #228582.

Parameter 50: Culebra Advective Porosity

Parameter Description:

This parameter is used to describe the advective porosity (typically referred to as the fracture porosity) for the Culebra dolomite. It is one of the parameters required in the SECOTP2D code for the double-porosity conceptualization of the Culebra (see also Section 4.9).

Material and Property Name(s):

CULEBRA APOROS

Computational Code(s): SECOTP2D

minimum	maximum
1.0×10^{-4}	0.01

Units: None

Distribution Type: Log uniform

Data: Professional Judgment - General Engineering Knowledge

This porosity distribution is derived from numerical simulations of tracer test data. The data associated with this parameter are located in the following parameter records packages: Culebra Advective Porosity (Culebra Transport parameter) (ERMS #237227). Supporting data records packages for this parameter include: Tracer Test Interpretations, Simulations for Determination of Adective Porosity and Half Matrix Block Length parameters for CCA Calculations (ERMS #237450); Tracer Test Sample Analyses, H-19 Tracer Tests Conducted December 1995 through April 1996 (ERMS #237452); and Tracer Test Sample Analyses, H-11 Tracer Tests Conducted February 1996 through March 1996 (ERMS #237467).

Discussion:

The Culebra is a fractured dolomite with nonuniform properties and multiple scales of porosity, including fractures ranging from microscale to large, vuggy zones, inter-particle and inter-crystalline porosity. When the permeability contrast is significant between different scales of connected porosity, the total porosity of the system can be modeled by dividing it into the advective porosity (for example, fractures, and to some extent vugs connected by fractures, and interparticle porosity) and the diffusive (or matrix) porosity. The advective porosity refers to porosity through which most of the flow occurs (for example, fractures), while the diffusive porosity includes features such as intercrystalline porosity, and to some extent microfractures, vugs, and interparticle porosity, accessible to solutes only through diffusion. The advective porosity used for the PA simulations has been determined from evaluation of tracer test data (Meigs and McCord 1996). The diffusive porosity has been determined from laboratory measurements of core plugs, which do not contain large fractures

(Meigs and McCord 1996).

The distribution for the advective porosity is based on numerical simulations of tracer test data from the H-3, H-11, and H-19 hydropads (Meigs and McCord 1996). Multiwell convergent flow tests have been performed previously at H-3 and H-11 (Stensrud et al. 1989; Hydro Geo Chem, Inc. 1985). Additional tracer tests have been performed at H-11 and at H-19 (Beauheim et al. 1995). The recent tests at H-11 and H-19 consisted of single-well injection-withdrawal tests and multiwell convergent flow tests.

The advective porosity and the matrix block length are essentially fitting parameters inferred from comparing the results of numerical simulations of the tracer tests to the field data. Numerical simulations were performed with double-porosity models with both homogeneous and heterogeneous hydraulic conductivity fields. For the homogeneous approach, the field data was analyzed using the SWIFT-II transport code, and for the heterogeneous approach, the field data was analyzed using the THEMM code. Both modeling approaches yielded consistent results for each well-to-well path with regard to advective porosity (Meigs and McCord 1996).

Parameter Data Entry Form ERMS: #238358

References:

Beauheim, R. L., Meigs, L.C., Saulnier, G.J., and Stensrud, W.A. 1995. Culebra Transport Program Test Plan: Tracer Testing of the Culebra Dolomite Member of the Rustler Formation at the H-19 and H-11 Hydropads on the WIPP Site. ERMS #230156.

Hydro Geo Chem, Inc. 1985. WIPP Hydrology Program Waste Isolation Pilot Plant, SENM Hydrologic Data Report #1. SAND85-7206. Albuquerque, NM: Sandia National Laboratories. ERMS #228430.

Meigs, Lucy, and McCord, Jim. 1996. Memo to file. RE: Physical Transport in the Culebra Dolomite, July 11, 1996. ERMS #239167.

Stensrud, W.A., Bame, M.A., Lantz, K.D., Palmer, J.B., and Saulnier, G.J., Jr. 1989. WIPP Hydrology Program Waste Isolation Pilot Plant Southeastern New Mexico Hydrologic Data Report #8. SAND89-7056. Albuquerque, NM: Sandia National Laboratories. ERMS #28582.

Parameter 51: Culebra Diffusive Porosity

Parameter Description:

This parameter is used to describe the diffusive porosity (typically referred to as the matrix porosity) for the Culebra dolomite. It is one of the parameters required in the SECOTP2D code for the double-porosity conceptualization of the Culebra (see also Section PA-4.9).

Material and Property Name(s):

CULEBRA DPOROS

Computational Code(s): SECOTP2D

Value	0.10	0.11	0.12	0.16	0.18	0.19	0.25
Percentiles	0	0.10	0.25	0.50	0.75	0.90	1

Units: None

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Professional Judgment - General Engineering Knowledge

This porosity distribution is derived from laboratory measurements. The data associated with this parameter are located in the following parameter records packages: Culebra Diffusive Porosity (Culebra Transport Parameter) (ERMS #237228). Supporting data records packages for this parameter includes: Non-Salado Core Analyses Performed by Terra Tek (AA-2896) (ERMS #238234).

Discussion:

The Culebra is a fractured dolomite with nonuniform properties and multiple scales of porosity, including fractures ranging from microscale to large, vuggy zones and inter-particle and inter-crystalline porosity. When the permeability contrast is significant between different scales of connected porosity, the total porosity of the system can be modeled by dividing it into the advective (for example, fractures and, to some extent, vugs connected by fractures, and interparticle porosity) porosity and the diffusive (or matrix) porosity. The advective porosity refers to porosity through which most of the flow occurs, while the diffusive porosity includes features such as intercrystalline porosity and, to some extent, microfractures, vugs, and interparticle porosity accessible to solutes only through diffusion. The advective porosity to be used for the PA simulations has been determined from evaluation of tracer test data. The diffusive porosity has been determined from laboratory measurement of core plugs, which do not contain large fractures (Meigs and McCord 1996).

This diffusive porosity distribution is derived from laboratory measurements. Boyle's Law helium porosity measurements have been made from 103 Culebra core plugs from 17 locations as reported in Kelley and Saulnier (1990) as well as additional porosity measurements

completed by Terra Tek (ERMS #238234). The methodology used for porosity measurements are described in Kelley and Saulnier (1990). To account for areal averaging, individual porosity measurements from a borehole and/or hydropad were averaged to yield a borehole/hydropad average porosity. The averaged values were used to construct the distribution (Meigs and McCord 1996).

Parameter Data Entry Form ERMS: #238357

References:

Kelley, V. A., and Saulnier, G. 1990. Core Analyses for Selected Samples from the Culebra Dolomite at the Waste Isolation Pilot Plant Site. SAND90-7011. Albuquerque, NM: Sandia National Laboratories. ERMS #228629.

Meigs, Lucy, and McCord, Jim. 1996. Memo to file. RE: Physical Transport in the Culebra Dolomite, July 11, 1996. ERMS #239167.

Parameter 52: Matrix Distribution Coefficient for U(VI)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for uranium in the +VI oxidation state. K_d is the equilibrium ratio of the mass of U adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

U+6 MKD_U

Computational Code(s): SECOTP2D

minimum	maximum
3×10^{-5}	0.02

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved uranium. The experimental data did not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for uranium in the Culebra was set to zero, which was also conservative (DOE 1996). The laboratory sorption studies supporting the CCA values are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of K_ds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's K_ds are conservative (Brush 1996).

P.V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by samples of pure dolomite from Norway. Although this study did not yield K_ds for actual

samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP air intake shaft (AIS). This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density. Second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997, the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA 1998) than the uniform distribution specified by Brush and Storz (1996). The DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines,

Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 53: Matrix Distribution Coefficient for U(IV)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for uranium in the +IV oxidation state. K_d is the equilibrium ratio of the mass of uranium adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

U+4 MKD_U

Computational Code(s): SECOTP2D

minimum	maximum
0.70	10.0

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved uranium. The experimental data did not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for uranium in the Culebra was set to zero, which was also conservative (DOE 1996). The laboratory sorption studies are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of K_ds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's K_ds are conservative (Brush 1996).

P.V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by

samples of pure dolomite from Norway. Although this study did not yield K_ds for actual samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP AIS. This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density. Second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997, the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA 1998) than the uniform distribution specified by Brush and Storz (1996). The DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 54: Matrix Distribution Coefficient for Pu(III)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for plutonium in the +III oxidation state. K_d is the equilibrium ratio of the mass of plutonium adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

PU+3 MKD_PU

Computational Code(s): SECOTP2D

minimum	maximum
0.02	0.40

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved plutonium. The experimental data did not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for plutonium in the Culebra was set to zero, which was also conservative. (DOE 1996) The laboratory sorption studies are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of Kds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's Kds are conservative (Brush 1996).

P.V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by

samples of pure dolomite from Norway. Although this study did not yield K_ds for actual samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP AIS. This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density. Second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997, the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA 1998) than the uniform distribution specified by Brush and Storz (1996). The DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003)

Parameter Data Entry Form ERMS: #527707

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 55: Matrix Distribution Coefficient for Pu(IV)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for plutonium in the +IV oxidation state. K_d is the equilibrium ratio of the mass of plutonium adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

PU+4 MKD_PU

Computational Code(s): SECOTP2D

minimum	maximum
0.70	10.0

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved plutonium. The experimental data did not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for plutonium in the Culebra was set to zero, which was also conservative (DOE 1996). The laboratory sorption studies are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of K_ds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's K_ds are conservative (Brush 1996).

P. V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by samples of pure dolomite from Norway. Although this study did not yield K_ds for actual

samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP AIS. This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density. Second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997, the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA 1998) than the uniform distribution specified by Brush and Storz (1996). DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23: Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 56: Matrix Distribution Coefficient for Th(IV)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for thorium in the +IV oxidation state. K_d is the equilibrium ratio of the mass of thorium adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

TH+4 MKD_TH

Computational Code(s): SECOTP2D

minimum	maximum
0.70	10.0

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved thorium. The experimental data do not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for thorium in the Culebra was set to zero, which was also conservative (DOE 1996). The laboratory sorption studies are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of K_ds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's K_ds are conservative (Brush 1996).

P.V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by samples of pure dolomite from Norway. Although this study did not yield K_ds for actual

samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP AIS. This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density, and, second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997 the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA, 1998) than the uniform distribution specified by Brush and Storz (1996). The DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 57: Matrix Distribution Coefficient for Am(III)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for americium in the +III oxidation state. K_d is the equilibrium ratio of the mass of americium adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

AM+3 MKD_AM

Computational Code(s): SECOTP2D

minimum	maximum
0.02	0.40

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved americium. The experimental data did not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for americium in the Culebra was set to zero, which was also conservative (DOE 1996). The laboratory sorption studies are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of K_ds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's K_ds are conservative (Brush 1996).

P.V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by samples of pure dolomite from Norway. Although this study did not yield K_ds for actual

samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP AIS. This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density, and, second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997, the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA 1998) than the uniform distribution specified by Brush and Storz (1996). The DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #527706

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.
U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 58: Effective Shear Resistance to Erosion

Parameter Description:

This parameter describes the intrusion borehole's effective shear strength for erosion.

Material and Property Name(s):

BOREHOLE TAUFAIL

Computational Code: CUTTINGS_S

minimum	maximum
0.05	77.0

Units: Pascals

Distribution Type: Log uniform

Data: Professional Judgment

WIPP specific experimental data were not available for the effective shear resistance to erosion of the waste. Therefore, at the recommendation of the EPA, an estimation technique based on particle size distributions was used. A discussion of this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

The waste shear resistance was estimated based on particle size distributions as determined by an expert elicitation panel. The estimate used the Shield's parameter, which relies on a measure of the central point of a population of particles of various sizes, to determine the critical shear stress for an erodible, cohesionless sediment bed (Simon and Senturk 1992). With this approach, the calculated critical shear stresses ranged from 0.64 Pa to 77 Pa. For conservatism, the low value for waste shear resistance from the CCA PA was retained for the low value in the PAVT while the high value from the Shield's parameter method was used for the high value in the PAVT. The decision to use 0.05 Pa for the low value was supported by information that indicated that very fine-grained materials are not cohesionless as assumed in the Shield's parameter calculation. The information also showed that a lower bound of the critical shear stress for fine-grained cohesive sediments is on the order of the 0.05 Pa. (Parthenaides and Paaswell 1970) The high end of the range was considered appropriate for cohesionless particles and was retained based on the expert elicitation results. A log uniform distribution for the waste shear resistance was selected for the PAVT to provide equal

weighting over the three orders of magnitude in the range, 0.05 to 77 Pa.

Until additional experimental data becomes available, the range of values selected for the PAVT is certainly inclusive of any reasonable values for the shear strength of the waste. Therefore, DOE has adopted the PAVT values for the shear strength of the waste (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Simon, D.B. and Senturk, F. 1992. "Sediment Transport Technology Water and Sediment Dynamics." Water Resource Publication.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582.

Parameter 60: Probability of Hitting a Brine Reservoir

Parameter Description:

The parameter represents the probability of hitting a brine reservoir during a drilling intrusion.

Material and Property Name(s):

GLOBAL PBRINE

Computational Code: CCDFGF

minimum	maximum
0.01	0.60

Units: None

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , geophysical methods, geological structure analysis, and geostatistical correlation were performed to determine the probability of intersection of a borehole with both the waste disposal region and a pressurized brine reservoir in the Castile formation. The DOE estimated that there is a 0.08 probability that any random borehole that penetrates waste at the WIPP also would penetrate an underlying brine reservoir (DOE 1996).

During preparation of the CCA, DOE reexamined their time-domain electromagnetic geophysical survey and found that between 10 and 55 percent of the waste panel area may be underlain by relatively conductive units, possibly due to one or more brine reservoirs (Alumbaugh 1996). The data did not support a means to distinguish boundaries between possible brine reservoirs and non-reservoir areas. As a consequence, DOE assumed that only one reservoir existed below the waste panels.

The DOE also mapped the geologic structure of selected units within the Castile and Salado Formations to examine the relationship between identified brine intercepts and evaporite deformation. Studies indicated that many of the observed brine encounters in the Delaware Basin were associated with structural deformation in the Castile Formation (e.g. ERDA-6). The mapping exercise reaffirmed DOE's belief that much of the Castile Formation underlying the WIPP site is generally not deformed (and therefore, the likelihood of a brine reservoir

beneath the waste panels was expected to be low). However, DOE did not consider the results of this geologic structural analysis in quantifying the probability of a drilling intrusion intersecting a brine reservoir.

The DOE then conducted a geostatistical analysis to estimate the probability of drilling into a fractured reservoir in areas overlain by the waste disposal panels. The analysis was based on 354 drill holes and 27 brine reservoir intercepts within the vicinity of the WIPP. Geostatistical techniques were used to estimate the probabilities that a randomly placed drilling intrusion would encounter pressurized brine in the Castile Formation. The overall probability for the waste panel area was determined to be 0.08 (a probability of 0.08 that a drilling intrusion would intersect a waste panel and penetrate into a underlying, pressurized brine reservoir). This value was selected for the parameter PBRINE in the PA calculation.

The EPA reviewed the CCA and supporting documentation and concluded that the parameter PBRINE should be changed from a constant having a value of 0.08 to a uniform distribution represented by a range of 0.01 to 0.60 (median value of 0.305). The EPA believes that this range better reflects the uncertainty in the parameter and is a more appropriate representation of the concept of reasonable expectation than the fixed value of 0.08 used by DOE in the CCA (EPA 1998a).

In reaching its conclusion, EPA considered the possibility that the WIPP-12 brine reservoir may underlie the entire WIPP site and thus the probability of a drilling intrusion encountering the pressurized reservoir could approach certainty (100 percent). This would require the assumption that this reservoir is cylindrical in shape, which EPA considered unlikely because brine resides in vertical or subvertical fractures, and because of the nature of the results from the time domain electromagnetic soundings.

For these reasons, EPA agreed with DOE that there exists a significant uncertainty concerning the magnitude and extent of brine reservoirs beneath the waste panels, but questioned DOE's basis for the probability of encountering such a brine reservoir to be only eight percent, since other DOE-generated information indicated that this probability could be as high as 60 percent (EPA 1998a and 1998b).

EPA found that the most direct information on the presence of brine reservoirs was provided by the time domain electromagnetic information, which could be interpreted to indicate that brine reservoirs underlie as much as 55 percent of the repository. The EPA also found that these same data could be interpreted to mean that brine reservoirs may underlie as little as 10 percent of the repository.

Using the time domain electromagnetic information, EPA developed probability distributions for four cases involving either random or block models to correlate adjacent measurements and assumed either the base of the Castile Formation or the base of the Anhydrite III layer in the Castile Formation was the cutoff point above which brine reservoirs may exist (EPA 1998a and 1998b). EPA found that it made little difference whether the random model or block model was used to characterize correlation between the time domain electromagnetic measurements. However, the simulated probability distributions for encountering brine were highly sensitive to the geologic assumption of whether or not brine reservoirs exist below the bottom of the Anhydrite III layer. Using the base of the Castile Formation Anhydrite Layer III

as the lowermost stratigraphic layer below which no brine reservoirs occur, the simulations showed that the area beneath the WIPP containing brine reservoirs varies from one to six percent. However, if the base of the Castile Formation is the lowermost stratigraphic layer below which no brine reservoirs occur, the area of the excavated repository underlain by reservoirs increases to about 35 to 58 percent.

For these reasons, EPA selected one percent as the lower limit and 60 percent as the upper limit for the fraction of the excavated area underlain by brine reservoirs. The upper limit was slightly larger than the largest estimated value for this parameter, but was less than 100percent because it was unreasonable to assume that brine reservoirs must exist. The lower limit was equal to the smallest estimated value and was greater than zero because it was also unreasonable to assume with absolute certainty that a reservoir does not exist. A uniform distribution was mandated because the range of this parameter spans slightly more than an order of magnitude and the use of a uniform distribution conservatively biased the sampling toward the high end. The DOE has adopted the value for the probability of a drilling intrusion intersecting a brine reservoir in the Castile Formation beneath the WIPP (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #248783

References:

Alumbaugh, D.L. 1996. “Re-analysis of the Time Domain Electromagnetic (TDEM) Data Collected at the WIPP Site.” ERMS #245405. Sandia National Laboratories. Albuquerque, NM.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998a. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

U.S. Environmental Protection Agency (EPA). 1998b. Response to Comments, Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant’s Compliance with 40 CFR 191 Disposal Regulations: Certification Decision. Docket No. A-93-02, V-C-1. U.S. Environmental Protection Agency. Washington D.C.

Parameter 61: Drill String Angular Velocity

Parameter Description:

This parameter describes the drill string angular velocity. This value is required to calculate the fluid-generated shear stress.

Material and Property Name(s):

BOREHOLE DOMEGA

Computational Code: CUTTINGS_S

Value	4.2	6.3	8.4	10.5	12.6	14.7	16.8	18.8	20.9	23.0
Percentiles	0	0.15	0.65	0.80	0.90	0.95	0.97	0.98	0.99	1.0

Units: Radians/second

Distribution Type: Cumulative

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

The quantity of waste brought to the surface due to an inadvertent penetration of the repository by an exploratory drill bit depends upon three physical processes:

- Cuttings - waste contained in the cylindrical volume created by the cutting action of the drill bit passing through the waste.
- Cavings - waste that erodes from the borehole in response to movement of drilling fluid within the annulus between the drill collars and the borehole wall
- Spallings - waste forced into the drilling fluid due to pressurization of the repository by waste-generated gas. This requires a repository gas pressure that exceeds the hydrostatic pressure of the drilling mud.

The cavings component of direct surface release, after a waste disposal room is penetrated, consists of that quantity of waste material that is eroded from the borehole wall by the action of the flowing drilling fluid. The erosion process model describes the shearing action on the waste by the drilling fluid as it moves up the borehole annulus. The amount of material eroded from the borehole wall is dependent upon the magnitude of the fluid-generated shear

stress acting on the wall and the effective shear resistance to erosion of the compacted, decomposed waste. The drill string angular velocity is required to calculate the fluid-generated shear stress.

For the CCA, the DOE had information about the rotational velocities used in current practice when drilling through salt. Using this information, the DOE derived a median value based on a constructed cumulative distribution of the known, applicable rotational velocities for drilling in salt. The derived median value was 7.8 radians/second. The CCA PA calculation assigned a constant value of 7.8 radians/second to the drill string angular velocity.

In its review, the EPA found that the data used to derive the median drill string angular velocity encompassed a rather large range of values, from 4.2 to 23 radians/second. Because of this large range, the EPA questioned whether the PA model showed sensitivity to variations in drill string angular velocity over this range. The EPA performed a sensitivity analysis over the range of drill string angular velocities and observed a 60 percent change in cavings releases. As a result, the EPA determined that a constant value for drill string angular velocity did not sufficiently reflect the uncertainty due to the wide range of possible values. The EPA also found that the potential impact on repository performance was sufficient to warrant use of a range of values and required the DOE to treat the drill string angular velocity as a sampled variable with a constructed cumulative distribution with a minimum of 4.2 radians/second, a maximum of 23 radians/second, and a median of 7.77 radians/second. The data were based on a study of current drilling practices in salt, documented in EPA (1998). DOE has adopted the distribution for the drill angular velocity (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #231512

References:

EPA (U.S. Environmental Protection Agency). 1998. Technical Support Document for Section 194.23:Parameter Justification Report.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

Parameter 62: Residual Brine Saturation – Upper Portion of Simplified Shaft

Parameter Description:

The residual brine saturation (S_{br}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves (see CCA Appendix PA, Figure 4.2.1). Referred to also as S_{wr} (wetting phase) or S_{lr} (liquid phase), residual brine saturation is the point reached under high gas saturation conditions when brine is no longer continuous throughout the pore network and relative brine permeability becomes zero.

Material and Property Name(s):

SHFTU SAT_RBRN

Computational Code: BRAGFLO

Value	0	0.20	0.60
Percentiles	0	.50	1

Units: None

Distribution Type: Cumulative

Data: General Literature Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: CRA Parameter Package (ERMS #526660) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The values sampled for the material SHFTU are assigned to the other shaft seal materials (SHFTL_T1, SHFTL_T2, and CONC_MON). These distributions are the same as were used for the material SALT_T1 in DOE (1996) shaft seal model (James and Stein 2002, 2003).

A literature search was conducted to obtain residual liquid saturation values for consolidated geologic materials, concrete, and asphalt in support of the CCA. Residual liquid saturations for geologic materials were found in four references (Brooks and Corey 1964; Lappala et al. 1987; Parker et al. 1987; and Rawls et al. 1982). Brooks and Corey (1964) determined residual saturations for five unconsolidated samples based on measured values of liquid saturation as a function of capillary pressure. Lappala et al. (1987) determined residual moisture content for 11 soils by obtaining best fits to measured moisture content versus pressure head data using three models. The residual moisture contents determined for each soil using the three models were averaged and divided by the reported porosity to obtain a residual liquid saturation for each soil. Parker et al. (1987) fit their saturation-pressure relationship to observed data to obtain residual saturations for a sandy and clayey porous

media. Residual water contents reported by Rawls et al. (1982) for 11 soil texture classes were divided by the reported porosity to obtain residual saturations.

Mayer et al. (1992) reported a residual liquid saturation for normal concrete of 0.30. Data regarding residual liquid saturations in asphalt materials were not found in the literature.

The literature values of residual liquid saturation for geologic materials and concrete fall within the range of 0.0 to 0.6 with all but two values falling within the range of 0.0 to 0.4. It was recommended that a value of 0.2 be used for the residual liquid saturation of all seal components.

Parameter Data Entry Form ERMS: #527670

References:

Brooks, R.H., and Corey, A.T. 1964. Hydraulic Properties of Porous Media. Hydrology Paper No. 3. Fort Collins, CO: Colorado State University.

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Lappala, E.G., Healy, R.W., and Weeks, E.P. 1987. Documentation of Computer Program VS2D to Solve the Equations of Fluid Flow in Variably Saturated Porous Media. Water-Resources Investigations Report 83-4099. Denver, CO: U.S. Geological Survey. Tech Library books collection: PC173.4.P67L31987.

Mayer, G., Jacobs, F., and Wittmann, F.H. 1992. "Experimental Determination and Numerical Simulation of the Permeability of Cementitious Materials," Nuclear Engineering and Design. Vol. 138, no. 2, 171-177.

Parker, J.C., Lenhard, R.J., and Kuppusamy, T. 1987. "A Parametric Model for Constitutive Properties Governing Multiphase Flow in Porous Media," Water Resources Research. Vol. 23, no. 4, 618-624.

Rawls, W.J., Brakensiek, D.L., and Saxton, K.E. 1982. "Estimation of Soil Water Properties," Transactions of the ASAE. St. Joseph, MI: American Society of Agricultural Engineers. 1316-1328.

Parameter 63: Residual Gas Saturation – Upper Portion Simplified Shaft

Parameter Description:

The residual (critical) gas saturation (S_{gr}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves (see CCA Appendix PA, Figure 4.2.1). S_{gr} corresponds to the degree of waste-generated gas saturation necessary to create an incipient interconnected pathway in porous material; a condition required for porous rock to be permeable to gas.

Material and Property Name(s):

SHFTU SAT_RGAS

Computational Code: BRAGFLO

minimum	maximum
0	0.40

Units: None

Distribution Type: Uniform

Data: General Literature Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: CRA Parameter Package (ERMS #526660) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The values sampled for the material SHFTU are assigned to the other shaft seal materials (SHFTL_T1, SHFTL_T2, and CONC_MON). These distributions are the same as were used for the material SALT_T1 in DOE (1996) shaft seal model (James and Stein 2002; 2003).

A literature search was conducted to obtain residual saturation values for consolidated geologic materials, concrete, and asphalt in support of the CCA.

A single value of 0.18 was found for normal concrete (Mayer et al. 1992). Based on this value, a distribution was assumed for the seal components. The recommended value was 0.2, and the recommended range was 0.0 to 0.4 with a uniform distribution for all shaft seal materials.

Parameter Data Entry Form ERMS: #527671

References:

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Mayer, G., Jacobs, F., and Wittmann, F.H. 1992. "Experimental Determination and Numerical Simulation of the Permeability of Cementitious Materials," Nuclear Engineering and Design. Vol. 138, no. 2, 171-177.

Parameter 64: Log of Intrinsic Permeability – Upper Portion of Simplified Shaft

Parameter Description:

This parameter describes the permeability distribution for the shaft in the non-Salado formations (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

SHFTU PRMX_LOG

Computational Code: BRAGFLO

Value	-20.5	-20.0	-19.5	-19.0	-18.5	-18.0	-17.5	-17.0	-16.5
Percentiles	0	0.03	0.11	0.24	0.43	0.65	0.89	0.99	1

Units: Log (meters squared)

Distribution Type: Cumulative

Data:

A discussion of the data associated with this parameter may be found in the following parameter records packages: CRA Parameter Package (ERMS #526660) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The simplified shaft seal model (James and Stein 2002; 2003) was developed by combining the effects of the many different materials used in the baseline shaft seal model and representing these effects with fewer materials.

The permeability of the non-Salado portion of the simplified shaft was obtained by calculating the effective permeability of the materials above the Salado in the baseline shaft seal model (EARTH and CLAY_RUS). A cumulative distribution was fit to the resulting equivalent permeability data (James and Stein 2003).

Parameter Data Entry Form ERMS: #527656

References:

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Parameter 65: Log of Intrinsic Permeability – Lower Portion of Simplified Shaft (0-200 yrs)

Parameter Description:

This parameter describes the permeability distributions for the portion of the shaft in the Salado for the first 200 years of operation (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

SHFTL_T1 PRMX_LOG

Computational Code: BRAGFLO

Value	-20.0	-19.5	-19.0	-18.5	-18.0	-17.5	-17.0	-16.5
Percentiles	0	0.01	0.10	0.31	0.64	0.87	0.99	1

Units: Log (meters squared)

Distribution Type: Cumulative

Data: Site- Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: CRA Parameter Package (ERMS #526660) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The simplified shaft seal model (James and Stein 2002; 2003) was developed by combining the effects of the many different materials used in the baseline shaft seal model and representing these effects with fewer materials.

An analysis of the equivalent permeability data from the baseline shaft model used in the CCA indicates that the distributions for 0–10, 10–25, and 25–50 years are nearly identical (with mean equivalent permeabilities decreasing by 5 and 42 percent at 10 and 25 years, respectively). After 50 years, permeability progressively decreases between time intervals 25–50, 50–100, 100–200, and 200–400 years (with mean equivalent permeabilities decreasing by 133 percent, 604 percent, and 2507 percent at 50, 100, and 200 years, respectively). The final change occurs at 400 years and results in a very slight increase in effective permeability (mean equivalent permeability increases by 31 percent) because of increases in concrete permeability assumed for the 400–10,000 year period.

To capture the time-dependent behavior of the Salado composite material, there is a single permeability change at 200 years. A conservative choice for the distribution of the first 200

years is to average the distributions for the 0–10, 10–25, and 25–50 year intervals. Note that the 50–100 and 100–200 year intervals are not used. From 200 to 10,000 years, the distribution is defined as the average of the distributions from the baseline shaft seal model for the 200–400 and 400–10,000 year intervals. Because only the highest permeability data from the first 50 years is used to constrain the model for 200 years, this approach overestimates the permeability during the first 200 years and is thereby conservative. The permeability distributions can be implemented in PA by fitting a cumulative distribution to the data (James and Stein 2003).

Parameter Data Entry Form ERMS: #527672

References:

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Parameter 66: Log of Intrinsic Permeability – Lower Portion of Simplified Shaft (200-10,000 yrs)

Parameter Description:

This parameter describes the permeability distributions for the portion of the shaft in the Salado for the 200 to 10,000 years of operation (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

SHFTL_T2 PRMX_LOG

Computational Code: BRAGFLO

Value	-22.5	-22.0	-21.5	-21.0	-20.5	-20.0	-19.5	-19.0	-18.5	-18.0
Percentiles	0	0.02	0.08	0.17	0.31	0.53	0.70	0.87	0.97	1

Units: Log (meters squared)

Distribution Type: Cumulative

Data: Site- Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: CRA Parameter Package (ERMS #526660) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The simplified shaft seal model (James and Stein 2002; 2003) was developed by combining the effects of the many different materials used in the baseline shaft seal model and representing these effects with fewer materials.

An analysis of the equivalent permeability data from the baseline shaft model used in the CCA indicates that the distributions for 0–10, 10–25, and 25–50 years are nearly identical (with mean equivalent permeabilities decreasing by 5 and 42 percent at 10 and 25 years, respectively). After 50 years, permeability progressively decreases between time intervals 25–50, 50–100, 100–200, and 200–400 years (with mean equivalent permeabilities decreasing by 133, 604, and 2507 percent at 50, 100, and 200 years, respectively). The final change occurs at 400 years and results in a very slight increase in effective permeability (mean equivalent permeability increases by 31 percent) because of increases in concrete permeability assumed for the 400–10,000 year period.

To capture the time-dependent behavior of the Salado composite material from 200 to 10,000 years, the distribution is defined as the average of the distributions from the baseline shaft seal model for the 200–400 and 400–10,000 year intervals. Because only the highest permeability

data from the first 50 years is used to constrain the model for 200 years, this approach overestimates the permeability during the first 200 years and is thereby conservative. The permeability distributions are implemented in PA by fitting a cumulative distribution to the data. (James and Stein 2003)

Parameter Data Entry Form ERMS: #527682

References:

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Parameter 75: Index for Selecting Realizations for the SPALL Model

Parameter Description:

The index for selecting realizations in the SPALL model is used by CUTINGS_S to randomly match the 50 LHS elements (vectors) generated for DRSPALL to the 100 LHS elements (vectors) generated for BRAGFLO.

Material and Property Name(s):

SPALLMOD RNDSPALL

Computational Code: CUTTINGS_S

minimum	maximum
0.0	1.0

Units: None.

Distribution Type: Uniform

Data: Professional Judgment

The parameter distribution is uniform because each of the 50 unique sets of property values generated for DRSPALL is deemed equally probable.

Discussion:

Uncertainty in waste property values for DRSPALL is addressed by using LHS to sample on selected input parameters to create 50 equally probable, unique sets of input data (vectors). DRSPALL is then executed 50 times (once per vector) to create an array of 50 equally probable spall volumes for a selected repository pressure. When exercised over several pressures, a “spallings response surface” is thus created.

CUTTINGS_S must use a technique to map BRAGFLO vectors to DRSPALL vectors, since the vectors are created by independent LHS runs. CUTTINGS_S thus reads the RNDSPALL( ) value for a given BRAGFLO vector, multiplies it by 50, and takes the resulting integer value as the “index” of the DRSPALL vector associated with this BRAGFLO vector. Since there are 50 DRSPALL vectors and 100 BRAGFLO vectors, two BRAGFLO vectors will be mapped to one DRSPALL vector.

Parameter Data Entry Form ERMS: # NA

References:

NA

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied)

LHS#	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
1	STEEL	Generic steel in waste	CORRMCO2	Inundated corrosion rate for steel without CO2 present	Uniform	m/s	1.59E-14	1.59E-14	0.00E+00	3.17E-14	9.15E-15
2	WAS_AREA	Waste emplacement area and waste	PROBDEG	Probability of plastics and rubber biodegradation in event of microbial gas generation	Delta	NONE	2.00E+00	2.00E+00	0.00E+00	2.00E+00	0.00E+00
3	WAS_AREA	Waste emplacement area and waste	GRATMICI	Inundated biodegradation rate for cellulose	Uniform	moles/(kg*s)	4.92E-09	4.92E-09	3.17E-10	9.51E-09	2.65E-09
4	WAS_AREA	Waste emplacement area and waste	GRATMICH	Humid biodegredation rate for cellulose	Uniform	moles/(kg*s)	6.34E-10	6.34E-10	0.00E+00	1.27E-09	3.66E-10
5	CELLULS	Cellulose	FBETA	Factor beta for microbial reaction rates	Uniform	NONE	5.00E-01	5.00E-01	0.00E+00	1.00E+00	2.89E-01
6	WAS_AREA	Waste emplacement area and waste	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	7.50E-02	7.50E-02	0.00E+00	1.50E-01	4.33E-02
(6)	DRF_PCS	Drift/Explosion Wall Portion of PCS	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	7.50E-02	7.50E-02	0.00E+00	1.50E-01	4.33E-02
(6)	REPOSIT	Repository regions outside of panel region	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	7.50E-02	7.50E-02	0.00E+00	1.50E-02	4.33E-03
7	WAS_AREA	Waste emplacement area and waste	SAT_RBRN	Residual Brine Saturation	Uniform	NONE	2.76E-01	2.76E-01	0.00E+00	5.52E-01	1.59E-01
(7)	DRF_PCS		SAT_RBRN	Residual Brine Saturation	Uniform	NONE	2.76E-01	2.76E-01	0.00E+00	5.52E-01	1.59E-01
(7)	REPOSIT	Repository regions outside of panel region	SAT_RBRN	Residual Brine Saturation	Uniform	NONE	2.76E-01	2.76E-01	0.00E+00	5.52E-02	1.59E-02
8	WAS_AREA	Waste emplacement area and waste	SAT_WICK	Index for computing wicking	Uniform	NONE	5.00E-01	5.00E-01	0.00E+00	1.00E+00	2.89E-01
9	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	log(m^2)	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01
(9)	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	log(m^2)	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01
(9)	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	log(m^2)	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
10	3525	CONC_PCS	Concrete portion of PCS	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	log(m^2)	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01
(10)		CONC_PCS	Concrete portion of PCS	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	$\log(m^2)$	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01
(10)		CONC_PCS	Concrete portion of PCS	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	$\log(m^2)$	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01
11	3626	SOLU4	Solubility Multiplier for U+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
12	3627	SOLTH4	Solubility Multiplier for Th+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
14	3532	CONC_PCS	Concrete portion of PCS	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01	2.00E-01	0.00E+00	4.00E-01	1.16E-01
15	3531	CONC_PCS	Concrete portion of PCS	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.50E-01	2.00E-01	0.00E+00	6.00E-01	1.76E-01
16	3522	CONC_PCS	Concrete portion of PCS	PORE_DIS	Brooks-Corey pore distribution parameter	Cumulative	NONE	2.52E+00	9.40E-01	1.10E-01	8.10E+00	2.48E+00
17	544	S_HALITE	Salado halite, intact	POROSITY	Effective porosity	Cumulative	NONE	1.28E-02	1.00E-02	1.00E-03	3.00E-02	8.52E-03
18	547	S_HALITE	Salado halite, intact	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$\log(m^2)$	-2.25E+01	-2.25E+01	-2.40E+01	-2.10E+01	8.66E-01
(18)		S_HALITE	Salado halite, intact	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$\log(m^2)$	-2.25E+01	-2.25E+01	-2.40E+01	-2.10E+01	8.66E-01
(18)		S_HALITE	Salado halite, intact	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$\log(m^2)$	-2.25E+01	-2.25E+01	-2.40E+01	-2.10E+01	8.66E-01
19	541	S_HALITE	Salado halite, intact	COMP_RCK	Bulk Compressibility	Uniform	Pa^{-1}	9.75E-11	9.75E-11	2.94E-12	1.92E-10	5.46E-11
20	591	S_MB139	Salado marker bed 139, intact and fractured	PRMX_LOG	Log of intrinsic permeability, X-direction	Student	$\log(m^2)$	-1.89E+01	-1.89E+01	-2.10E+01	-1.71E+01	1.20E+00
(20)		S_MB139	Salado marker bed 139, intact and fractured	PRMY_LOG	Log of intrinsic permeability, Y-direction	Student	$\log(m^2)$	-1.89E+01	-1.89E+01	-2.10E+01	-1.71E+01	1.20E+00
(20)		S_MB139	Salado marker bed 139, intact and fractured	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Student	$\log(m^2)$	-1.89E+01	-1.89E+01	-2.10E+02	-1.71E+02	1.20E+01

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
21	580	S_MB139	Salado marker bed 139, intact and fractured	COMP_RCK	Bulk Compressibility	Student	Pa^{-1}	8.26E-11	8.26E-11	1.09E-11	2.75E-10	1.12E-10
22	596	S_MB139	Salado marker bed 139, intact and fractured	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00	4.00E+00	1.00E+00	4.00E+00	0.00E+00
23	598	S_MB139	Salado marker bed 139, intact and fractured	SAT_RBRN	Residual Brine Saturation	Student	NONE	8.36E-02	8.36E-02	7.78E-03	1.74E-01	5.01E-02
24	599	S_MB139	Salado marker bed 139, intact and fractured	SAT_RGAS	Residual Gas Saturation	Student	NONE	7.71E-02	7.71E-02	1.40E-02	1.97E-01	6.41E-02
25	587	S_MB139	Salado marker bed 139, intact and fractured	PORE_DIS	Brooks-Corey pore distribution parameter	Student	NONE	6.44E-01	6.44E-01	4.91E-01	8.42E-01	1.09E-01
26	546	S_HALITE	Salado halite, intact	PRESSURE	Brine far-field pore pressure	Uniform	Pa	1.25E+07	1.25E+07	1.10E+07	1.39E+07	8.23E+05
27	66	CASTILER	Castile Brine Reservoir	PRESSURE	Brine far-field pore pressure	Triangular	Pa	1.36E+07	1.27E+07	1.11E+07	1.70E+07	1.25E+06
28	67	CASTILER	Castile Brine Reservoir	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	$log(m^2)$	-1.21E+01	-1.18E+01	-1.47E+01	-9.80E+00	1.01E+00
(28)		CASTILER	Castile Brine Reservoir	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	$log(m^2)$	-1.21E+01	-1.18E+01	-1.47E+01	-9.80E+00	1.01E+00
(28)		CASTILER	Castile Brine Reservoir	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	$log(m^2)$	-1.21E+02	-1.18E+02	-1.47E+02	-9.80E+01	1.01E+01
29	61	CASTILER	Castile Brine Reservoir	COMP_RCK	Bulk Compressibility	Triangular	Pa^{-1}	5.30E-11	4.00E-11	2.00E-11	1.00E-10	1.70E-11
30	3184	BH_SAND	Borehole filled with silty sand	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$log(m^2)$	-1.37E+01	-1.37E+01	-1.63E+01	-1.10E+01	1.53E+00
(30)		BH_SAND	Borehole filled with silty sand	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$log(m^2)$	-1.37E+01	-1.37E+01	-1.63E+01	-1.10E+01	1.53E+00
(30)		BH_SAND	Borehole filled with silty sand	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$log(m^2)$	-1.37E+01	-1.37E+01	-1.63E+02	-1.10E+02	1.53E+01
31	198	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$log(m^2)$	-1.60E+01	-1.60E+01	-1.94E+01	-1.25E+01	2.00E+00
(31)		DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$log(m^2)$	-1.60E+01	-1.60E+01	-1.94E+01	-1.25E+01	2.00E+00
(31)		DRZ_2	Disturbed rock zone; time period 0 to 10,000 years	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$log(m^2)$	-1.60E+01	-1.60E+01	-1.94E+02	-1.25E+02	2.00E+01
32	3185	CONC_PLG	Concrete Plug, surface and Rustler	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$log(m^2)$	-1.80E+01	-1.80E+01	-1.90E+01	-1.70E+01	5.80E-01

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
(32)		CONC_PLG	Concrete Plug, surface and Rustler	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	log(m^2)	-1.80E+01	-1.80E+01	-1.90E+01	-1.70E+01	5.80E-01
(32)		CONC_PLG	Concrete Plug, surface and Rustler	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	log(m^2)	-1.80E+01	-1.80E+01	-1.90E+01	-1.70E+01	5.80E-01
34	3262	SOLAM3	Solubility Multiplier for Am+3	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
35	3263	SOLAM3	Solubility Multiplier for Am+3	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
36	3265	SOLPU3	Solubility Multiplier for Pu+3	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
37	3264	SOLPU3	Solubility Multiplier for Pu+3	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
38	3266	SOLPU4	Solubility Multiplier for Pu+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
39	3389	SOLPU4	Solubility Multiplier for Pu+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
40	3390	SOLU4	Solubility Multiplier for U+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
41	3391	SOLU6	Solubility Multiplier for U+6	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
42	3392	SOLU6	Solubility Multiplier for U+6	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
43	3393	SOLTH4	Solubility Multiplier for Th+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
44	3429	PHUMOX3	Proportionality Constant, +3 State, Humic Colloids	PHUMCIM	Proportionality Const., Humic Colloids, Castile Brine, MgO controls pH	Cumulative	NONE	1.10E+00	1.37E+00	6.50E-02	1.60E+00	4.69E-01
45	3417	GLOBAL	Information that applies globally	OXSTAT	Index for the Oxidation State	Uniform	NONE	5.00E-01	5.00E-01	0.00E+00	1.00E+00	2.89E-01
46	3419	CULEBRA	Culebra member of the Rustler formation	MINP_FAC	Mining Transmissivity Multiplier	Uniform	NONE	5.01E+02	5.01E+02	1.00E+00	1.00E+03	2.88E+02
47	225	GLOBAL	Information that applies globally	TRANSIDX	Index for selecting realizations of the Transmissivity Field	Uniform	NONE	5.00E-01	5.00E-01	0.00E+00	1.00E+00	2.89E-01
48	223	GLOBAL	Information that applies globally	CLIMTIDX	Climate Index	Cumulative	NONE	1.31E+00	1.17E+00	1.00E+00	2.25E+00	3.48E-01
49	3485	CULEBRA	Culebra member of the Rustler formation	HMBLKLT	Culebra Half Matrix-Block Length	Uniform	m	2.75E-01	2.75E-01	5.00E-02	5.00E-01	1.30E-01
50	3487	CULEBRA	Culebra member of the Rustler formation	APOROS	Culebra Advective Porosity	Log uniform	NONE	2.10E-03	1.00E-03	1.00E-04	1.00E-02	2.50E-03
51	3486	CULEBRA	Culebra member of the Rustler formation	DPOROS	Diffusive Porosity for Culebra Dolomite	Cumulative	NONE	1.60E-01	1.60E-01	1.00E-01	2.50E-01	3.50E-02
52	3475	U+6	Uranium VI	MKD_U	Matrix Partition Coefficient for Uranium	Log uniform	m^3/kg	3.10E-03	7.70E-04	3.00E-05	2.00E-02	4.60E-03
53	3479	U+4	Uranium IV	MKD_U	Matrix Partition Coefficient for Uranium	Log uniform	m^3/kg	3.50E+00	2.60E+00	7.00E-01	1.00E+01	2.50E+00

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
54	3480	PU+3	Plutonium III	MKD_PU	Matrix Partition Coefficient for Plutonium	Log uniform	m^3/kg	1.30E-01	9.00E-02	2.00E-02	4.00E-01	1.00E-01
55	3481	PU+4	Plutonium IV	MKD_PU	Matrix Partition Coefficient for Plutonium	Log uniform	m^3/kg	3.50E+00	2.60E+00	7.00E-01	1.00E+01	2.50E+00
56	3478	TH+4	Thorium IV	MKD_TH	Matrix Partition Coefficient for Thorium	Log uniform	m^3/kg	3.50E+00	2.60E+00	7.00E-01	1.00E+01	2.50E+00
58	2254	BOREHOLE	Borehole and Fill	TAUFAIL	Effective shear strength for erosion (rfail)	Log uniform	Pa	1.05E+01	1.96E+00	5.00E-02	7.70E+01	1.71E+01
60	3493	GLOBAL	Information that applies globally	PBRINE	Prob. that Drilling Intrusion In Excavated Area Encounters Pressurized Brine	Uniform	NONE	3.05E-01	3.05E-01	1.00E-02	6.00E-01	1.70E-01
61	27	BOREHOLE	Borehole and Fill	DOMEGA	Drill string angular velocity (0)	Cumulative	rad/s	8.63E+00	7.80E+00	4.20E+00	2.30E+01	3.16E+00
62	3560	SHFTU	Upper portion of simplified shaft	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.50E-01	2.00E-01	0.00E+00	6.00E-01	1.76E-01
(62)		CONC_MON	Concrete Monolith	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.50E-01	2.00E-01	0.00E+00	6.00E-01	1.76E-01
(62)		SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.50E-01	2.00E-01	0.00E+00	6.00E-01	1.76E-01
(62)		SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.50E-01	2.00E-01	0.00E+00	6.00E-01	1.76E-01
63	3561	SHFTU	Upper portion of simplified shaft	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01	2.00E-01	0.00E+00	4.00E-01	1.16E-01
(63)		CONC_MON	Concrete Monolith	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01	2.00E-01	0.00E+00	4.00E-01	1.16E-01
(63)		SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01	2.00E-01	0.00E+00	4.00E-01	1.16E-01
(63)		SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01	2.00E-01	0.00E+00	4.00E-01	1.16E-01
64	3557	SHFTU	Upper portion of simplified shaft	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	$log(m^2)$	-1.82E+01	-1.83E+01	-2.05E+01	-1.65E+01	7.94E-01
(64)		SHFTU	Upper portion of simplified shaft	PRMY_LOG	Log of intrinsic permeability, Y direction	Cumulative	$log(m^2)$	-1.82E+01	-1.83E+01	-2.05E+01	-1.65E+01	7.94E-01

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
(64)		SHFTU	Upper portion of simplified shaft	PRMZ_LOG	Log of intrinsic permeability, Z direction	Cumulative	log(m^2)	-1.82E+01	-1.83E+01	-2.05E+01	-1.65E+01	7.94E-01
65	3569	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	log(m^2)	-1.80E+01	-1.82E+01	-2.00E+01	-1.65E+01	5.97E-01
(65)		SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PRMY_LOG	Log of intrinsic permeability, Y-direction	Cumulative	log(m^2)	-1.80E+01	-1.82E+01	-2.00E+01	-1.65E+01	5.97E-01
(65)		SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Cumulative	log(m^2)	-1.80E+01	-1.82E+01	-2.00E+01	-1.65E+01	5.97E-01
66	3579	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	log(m^2)	-1.98E+01	-2.01E+01	-2.25E+01	-1.80E+01	9.37E-01
(66)		SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PRMY_LOG	Log of intrinsic permeability, Y-direction	Cumulative	log(m^2)	-1.98E+01	-2.01E+01	-2.25E+01	-1.80E+01	9.37E-01
(66)		SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Cumulative	log(m^2)	-1.98E+01	-2.01E+01	-2.25E+01	-1.80E+01	9.37E-01
75	NA	SPALLMOD	Material developed for DRSPALL	RNDSPALL	Index for selecting realizations of the SPALL model.	Uniform	NONE	0.50E+00	0.50E+00	0.00E+00	1.00E+00	2.89E-01

[1]For parameters with a triangular distribution, the value provided for the median is actually the mode

Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
1	1.09E-14	0.00E+00	8.17E-09	1.11E-10	5.59E-01	1.70E-02	9.33E-02	8.69E-01	-1.95E+01	-1.89E+01	-1.51E+00	5.78E-01	2.80E-01	3.06E-01	9.27E-01	2.33E-02	-2.23E+01	8.37E-11	-1.90E+01	9.76E-11	4.00E+00	1.08E-01	9.60E-02	5.73E-01
2	1.49E-14	2.00E+00	3.54E-09	6.47E-10	6.83E-02	1.48E-01	9.96E-02	7.30E-01	-1.75E+01	-1.73E+01	2.26E-01	-4.71E-01	1.44E-01	1.34E-01	7.95E-01	1.07E-02	-2.35E+01	1.57E-10	-1.86E+01	3.53E-11	1.00E+00	1.09E-01	5.56E-02	6.65E-01
3	1.20E-15	0.00E+00	2.31E-09	1.16E-09	3.07E-01	1.39E-01	1.86E-01	9.48E-01	-2.01E+01	-1.86E+01	-2.60E-01	8.41E-02	1.40E-01	3.83E-01	3.40E+00	5.58E-03	-2.26E+01	1.19E-10	-1.94E+01	1.41E-10	4.00E+00	1.15E-01	1.05E-01	6.62E-01
4	1.97E-14	2.00E+00	7.38E-09	1.15E-09	7.86E-02	6.79E-02	2.44E-01	8.75E-01	-1.93E+01	-1.89E+01	-4.15E-01	-2.73E-01	2.81E-02	7.63E-03	5.57E-01	4.73E-03	-2.35E+01	1.60E-10	-1.89E+01	8.13E-11	1.00E+00	1.23E-02	6.04E-02	7.43E-01
5	2.87E-14	1.00E+00	5.20E-09	9.97E-10	6.91E-01	3.89E-03	2.21E-01	5.80E-01	-1.83E+01	-2.02E+01	-6.54E-02	2.63E-04	4.01E-02	1.45E-03	7.79E+00	8.67E-03	-2.14E+01	4.39E-11	-1.87E+01	5.83E-11	4.00E+00	1.39E-01	7.07E-02	8.26E-01
6	1.89E-14	1.00E+00	1.98E-09	2.08E-10	9.77E-01	1.41E-01	1.16E-01	7.79E-01	-1.87E+01	-1.75E+01	-2.05E-02	2.69E-01	1.17E-01	4.16E-01	4.86E+00	2.54E-02	-2.33E+01	1.45E-10	-2.00E+01	2.33E-10	1.00E+00	9.22E-02	7.15E-02	7.31E-01
7	1.06E-14	0.00E+00	4.58E-09	6.89E-10	5.09E-01	8.61E-02	1.09E-01	4.52E-02	-1.82E+01	-1.92E+01	1.30E-01	-2.00E-01	1.72E-01	5.05E-02	4.65E+00	2.84E-02	-2.16E+01	4.62E-11	-1.83E+01	1.30E-11	4.00E+00	7.24E-02	8.48E-02	6.30E-01
8	2.51E-14	0.00E+00	3.13E-09	6.15E-10	1.39E-01	5.49E-03	3.35E-01	6.12E-01	-1.85E+01	-1.92E+01	1.55E-01	-1.32E-01	3.06E-01	1.85E-01	8.36E-01	1.54E-02	-2.12E+01	1.92E-11	-1.96E+01	1.96E-10	1.00E+00	7.25E-02	4.13E-02	6.83E-01
9	1.57E-14	1.00E+00	9.32E-09	2.58E-10	8.39E-01	1.28E-01	4.42E-01	6.82E-01	-1.99E+01	-2.01E+01	1.04E-01	-7.16E-02	3.91E-01	5.11E-01	5.64E+00	2.79E-02	-2.12E+01	1.66E-11	-1.84E+01	2.12E-11	1.00E+00	3.78E-02	1.29E-01	6.48E-01
10	2.41E-15	2.00E+00	2.78E-09	7.11E-10	4.32E-01	1.13E-01	3.22E-01	5.36E-01	-2.00E+01	-1.91E+01	2.45E-01	-4.41E-01	1.14E-01	1.65E-01	7.55E+00	5.91E-03	-2.34E+01	1.55E-10	-1.92E+01	1.21E-10	1.00E+00	9.86E-02	6.38E-02	5.82E-01
11	2.48E-14	0.00E+00	2.64E-09	8.21E-12	5.00E-01	7.27E-02	5.43E-01	5.85E-01	-1.85E+01	-1.88E+01	-3.44E-01	-2.34E-02	7.47E-02	1.98E-01	5.02E-01	4.49E-03	-2.38E+01	1.81E-10	-1.87E+01	3.63E-11	4.00E+00	8.44E-02	8.39E-02	6.26E-01
12	1.72E-14	1.00E+00	5.56E-09	1.26E-09	1.06E-01	8.71E-02	2.73E-01	3.35E-01	-1.88E+01	-1.84E+01	-6.84E-01	-4.63E-01	1.29E-01	5.62E-01	2.58E+00	2.00E-02	-2.28E+01	1.16E-10	-1.90E+01	8.81E-11	4.00E+00	5.25E-02	1.14E-01	6.60E-01
13	3.02E-14	0.00E+00	8.73E-09	2.03E-10	5.95E-01	8.05E-02	7.81E-02	9.05E-01	-1.89E+01	-1.86E+01	2.80E-01	-1.41E+00	2.12E-01	3.18E-01	3.66E+00	7.96E-03	-2.34E+01	1.49E-10	-1.86E+01	6.64E-11	4.00E+00	7.62E-02	9.41E-02	6.05E-01
14	3.64E-15	2.00E+00	4.90E-09	8.19E-10	3.17E-01	1.06E-01	2.08E-01	3.17E-02	-1.97E+01	-1.83E+01	-1.14E+00	-9.53E-01	2.58E-01	2.65E-01	4.43E+00	6.45E-03	-2.36E+01	1.73E-10	-1.87E+01	6.88E-11	4.00E+00	6.39E-02	1.08E-01	7.38E-01
15	3.16E-14	2.00E+00	6.82E-09	7.72E-10	2.69E-01	6.11E-02	5.19E-01	2.90E-01	-1.87E+01	-1.88E+01	-9.96E-01	2.45E-01	3.22E-01	6.69E-02	6.95E+00	1.43E-02	-2.37E+01	1.71E-10	-1.92E+01	1.23E-10	4.00E+00	7.96E-02	6.85E-02	5.25E-01
16	1.71E-14	1.00E+00	3.04E-09	1.66E-10	8.10E-02	7.56E-02	2.09E-02	9.34E-01	-1.88E+01	-1.87E+01	-1.31E-01	-9.54E-02	3.38E-01	1.06E-02	4.89E-01	9.05E-03	-2.11E+01	1.26E-11	-2.06E+01	2.75E-10	4.00E+00	8.36E-02	1.16E-01	6.16E-01
17	2.83E-14	1.00E+00	4.41E-09	2.67E-10	1.59E-01	1.01E-01	3.80E-01	7.45E-01	-1.87E+01	-1.89E+01	-3.87E-01	-4.89E-02	2.96E-01	2.57E-01	8.89E-01	3.30E-03	-2.25E+01	1.25E-10	-1.77E+01	1.09E-11	1.00E+00	7.83E-02	9.02E-02	5.96E-01
18	6.12E-15	2.00E+00	4.52E-09	1.20E-10	4.30E-02	9.56E-02	4.41E-01	3.54E-01	-1.89E+01	-1.79E+01	3.11E-02	-6.74E-02	2.52E-01	5.53E-01	3.35E+00	2.74E-03	-2.15E+01	2.44E-11	-2.10E+01	2.75E-10	1.00E+00	9.44E-02	1.13E-01	6.65E-01
19	1.37E-14	0.00E+00	5.15E-09	8.26E-10	8.23E-01	6.64E-02	3.60E-01	9.81E-01	-1.94E+01	-1.96E+01	5.41E-01	-3.04E-01	2.21E-01	1.77E-01	1.97E-01	1.23E-02	-2.13E+01	1.54E-11	-1.91E+01	1.29E-10	1.00E+00	1.11E-01	1.01E-01	6.38E-01
20	2.09E-14	0.00E+00	3.70E-09	4.86E-10	7.16E-01	3.15E-02	3.42E-01	9.98E-01	-1.89E+01	-1.83E+01	-1.85E+00	-7.91E-02	3.76E-01	5.72E-01	2.14E+00	2.20E-02	-2.19E+01	5.48E-11	-1.84E+01	1.09E-11	1.00E+00	8.57E-02	2.30E-02	6.55E-01
21	4.71E-16	0.00E+00	7.27E-09	1.08E-09	2.74E-01	1.44E-02	2.39E-01	8.22E-02	-1.84E+01	-1.81E+01	-9.06E-02	-4.91E-01	3.31E-01	3.91E-01	6.91E-01	1.46E-02	-2.15E+01	4.16E-11	-1.88E+01	7.41E-11	1.00E+00	1.01E-01	8.00E-02	5.67E-01
22	2.95E-14	2.00E+00	7.82E-09	1.28E-10	9.37E-01	1.11E-02	6.78E-03	8.23E-01	-1.85E+01	-1.80E+01	9.83E-01	-1.23E-02	2.75E-01	2.90E-01	2.71E+00	2.94E-02	-2.27E+01	1.22E-10	-1.88E+01	8.03E-11	4.00E+00	5.41E-02	8.70E-02	6.40E-01
23	7.20E-15	1.00E+00	3.91E-09	9.41E-11	4.76E-01	4.32E-02	2.54E-01	7.89E-01	-1.81E+01	-1.87E+01	-3.07E-02	3.72E-02	1.89E-01	1.55E-01	2.24E-01	9.37E-03	-2.13E+01	2.99E-11	-1.96E+01	1.90E-10	4.00E+00	8.82E-02	9.13E-02	6.78E-01
24	2.55E-14	0.00E+00	3.24E-09	3.05E-10	7.09E-01	2.49E-02	4.76E-01	4.42E-01	-1.86E+01	-1.95E+01	-5.29E-02	-7.85E-01	2.87E-01	1.00E-01	6.02E+00	3.77E-03	-2.38E+01	1.79E-10	-1.88E+01	9.32E-11	1.00E+00	8.41E-02	3.99E-02	6.18E-01
25	9.22E-16	0.00E+00	2.18E-09	5.57E-10	8.04E-01	6.99E-02	9.40E-02	3.78E-01	-1.87E+01	-1.76E+01	-5.87E-01	-3.98E-01	3.40E-01	7.19E-02	3.39E-01	1.19E-02	-2.32E+01	1.39E-10	-1.84E+01	2.80E-11	1.00E+00	1.33E-01	5.05E-02	6.08E-01
26	1.40E-14	2.00E+00	6.22E-09	6.14E-11	7.50E-01	6.98E-03	2.35E-01	2.93E-01	-1.93E+01	-1.84E+01	-9.76E-02	-2.32E-01	3.19E-01	2.76E-02	3.84E-01	1.09E-02	-2.37E+01	1.78E-10	-1.85E+01	3.33E-11	1.00E+00	8.77E-02	8.15E-02	6.55E-01
27	1.54E-14	2.00E+00	1.41E-09	5.69E-10	2.60E-02	7.13E-02	4.82E-01	4.81E-01	-1.91E+01	-1.84E+01	-7.98E-02	-1.69E-01	3.34E-01	2.96E-01	3.74E+00	1.66E-02	-2.36E+01	1.59E-10	-1.91E+01	9.89E-11	4.00E+00	6.13E-02	1.09E-01	6.96E-01
28	3.66E-17	1.00E+00	7.54E-09	7.40E-10	1.25E-01	1.26E-01	5.56E-02	2.56E-01	-1.83E+01	-1.98E+01	-1.35E-01	-2.27E-01	1.50E-01	4.87E-01	5.65E-01	2.51E-02	-2.24E+01	9.37E-11	-1.85E+01	2.45E-11	4.00E+00	9.83E-02	3.77E-02	5.90E-01
29	2.60E-14	2.00E+00	7.17E-09	8.58E-10	6.89E-01	1.22E-01	5.08E-02	4.56E-01	-1.95E+01	-1.90E+01	6.72E-01	-3.38E-01	4.94E-02	1.07E-01	1.05E+00	2.45E-02	-2.18E+01	4.79E-11	-1.90E+01	8.49E-11	1.00E+00	1.05E-01	1.40E-02	6.43E-01
30	1.44E-14	2.00E+00	9.12E-09	1.11E-09	4.50E-01	5.10E-02	2.78E-01	7.93E-01	-1.79E+01	-1.88E+01	6.05E-01	5.74E-02	6.39E-02	5.86E-02	3.14E+00	1.97E-02	-2.29E+01	1.18E-10	-1.91E+01	9.54E-11	1.00E+00	9.07E-02	1.07E-01	6.04E-01
31	4.92E-15	0.00E+00	8.45E-09	1.00E-09	4.44E-01	6.17E-02	4.64E-01	3.44E-01	-1.79E+01	-1.78E+01	7.47E-01	9.69E-01	3.50E-01	1.84E-02	4.76E+00	1.74E-02	-2.30E+01	1.11E-10	-1.81E+01	1.09E-11	1.00E+00	9.66E-02	5.20E-02	7.01E-01
32	1.03E-14	0.00E+00	7.69E-09	1.17E-09	3.85E-01	3.27E-02	3.92E-01	1.94E-01	-1.90E+01	-1.91E+01	-2.71E-02	-1.66E+00	2.32E-01	1.25E-01	7.04E+00	6.78E-03	-2.17E+01	3.64E-11	-1.97E+01	1.81E-10	4.00E+00	8.98E-02	5.41E-02	6.46E-01
33	1.47E-14	0.00E+00	6.98E-09	1.04E-09	8.48E-01	8.25E-02	4.31E-02	7.07E-01	-1.94E+01	-1.80E+01	-4.33E-01	-1.51E-01	3.88E-02	1.14E-01	7.95E+00	8.34E-03	-2.33E+01	1.53E-10	-1.83E+01	1.09E-11	4.00E+00	3.43E-02	6.73E-02	6.35E-01
34	1.17E-14	1.00E+00	7.58E-10	5.16E-10	3.60E-01	1.03E-01	3.72E-01	7.67E-01	-1.84E+01	-1.90E+01	-5.61E-02	6.53E-01	2.25E-01	4.92E-01	1.70E+00	2.80E-02	-2.26E+01	9.63E-11	-1.88E+01	8.27E-11	4.00E+00	8.29E-02	3.41E-02	6.10E-01
35	2.91E-14	0.00E+00	4.71E-09	1.02E-09	5.76E-01	9.04E-02	3.53E-01	6.42E-01	-1.81E+01	-1.74E+01	7.24E-02	-7.48E-01	1.80E-02	5.84E-01	6.40E+00	2.42E-03	-2.20E+01	7.01E-11	-1.86E+01	6.74E-11	4.00E+00	7.15E-02	6.13E-02	6.52E-01
36	1.75E-14	0.00E+00	6.53E-09	1.25E-09	6.56E-01	1.20E-01	4.75E-01	5.50E-01	-1.83E+01	-1.91E+01	1.10E+00	9.06E-01	1.58E-01	3.54E-01	3.05E+00	1.38E-02	-2.14E+01	2.83E-11	-1.82E+01	1.09E-11	4.00E+00	7.75E-02	1.06E-01	6.44E-01
37	2.06E-14	0.00E+00	4.92E-09	1.48E-10	1.46E-01	4.14E-02	5.35E-01	1.75E-01	-1.75E+01	-2.02E+01	-1.29E-02	-4.06E-03	2.07E-01	1.50E-01	3.24E-01	1.89E-02	-2.31E+01	1.30E-10	-1.91E+01	1.15E-10	1.00E+00	6.78E-02	7.63E-02	6.17E-01

Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
38	2.60E-14	0.00E+00	1.31E-09	9.67E-10	9.42E-01	1.44E-01	4.31E-01	4.27E-01	-1.88E+01	-1.94E+01	-2.13E-01	1.30E-01	1.88E-01	6.03E-02	4.10E+00	5.17E-03	-2.27E+01	9.82E-11	-1.94E+01	1.48E-10	4.00E+00	8.61E-02	8.44E-02	6.21E-01
39	2.17E-15	1.00E+00	3.26E-09	1.49E-11	5.87E-01	2.86E-02	1.12E-01	6.25E-01	-1.93E+01	-1.86E+01	1.44E-01	7.25E-01	2.68E-01	5.40E-02	4.02E+00	2.06E-03	-2.34E+01	1.64E-10	-1.86E+01	4.88E-11	4.00E+00	7.93E-02	9.59E-02	5.82E-01
40	4.45E-15	2.00E+00	8.32E-09	3.93E-10	8.12E-01	1.43E-01	5.20E-01	8.58E-01	-1.98E+01	-1.94E+01	-3.62E-02	-6.44E-01	2.16E-01	2.31E-01	7.25E-01	1.51E-02	-2.15E+01	2.75E-11	-1.80E+01	1.09E-11	1.00E+00	5.53E-02	4.27E-02	6.32E-01
41	1.25E-14	2.00E+00	6.07E-09	3.40E-10	9.03E-01	1.31E-01	5.39E-01	2.28E-01	-1.91E+01	-1.89E+01	4.42E-02	3.96E-01	2.94E-01	1.30E-01	5.29E+00	2.56E-02	-2.25E+01	1.06E-10	-2.01E+01	2.52E-10	4.00E+00	6.05E-02	1.70E-02	6.69E-01
42	1.22E-14	1.00E+00	5.21E-10	4.10E-10	7.83E-01	2.63E-02	4.45E-02	4.67E-01	-1.84E+01	-1.82E+01	-2.16E-01	-8.34E-02	4.74E-03	4.04E-02	4.26E-01	5.40E-03	-2.18E+01	4.02E-11	-1.95E+01	1.64E-10	4.00E+00	5.99E-02	6.27E-02	6.74E-01
43	1.40E-15	1.00E+00	8.60E-09	3.99E-10	4.26E-01	3.86E-02	4.19E-01	6.07E-01	-2.01E+01	-1.79E+01	-1.67E-01	-1.47E-02	2.88E-01	8.12E-02	4.68E-01	2.69E-02	-2.39E+01	1.90E-10	-1.95E+01	1.59E-10	4.00E+00	1.17E-01	9.15E-02	6.98E-01
44	2.77E-14	0.00E+00	8.93E-09	1.12E-09	6.31E-01	3.60E-02	1.95E-01	8.87E-01	-1.86E+01	-1.98E+01	-7.94E-01	7.29E-02	1.71E-01	4.55E-01	5.98E-01	1.64E-03	-2.17E+01	4.85E-11	-1.93E+01	1.43E-10	1.00E+00	1.02E-01	8.22E-02	7.70E-01
45	3.11E-14	2.00E+00	2.15E-09	7.09E-10	5.45E-01	5.43E-02	3.56E-01	1.17E-01	-1.87E+01	-1.83E+01	-3.08E-01	-6.91E-01	2.79E-01	4.08E-01	2.43E-01	2.40E-02	-2.24E+01	1.00E-10	-1.88E+01	5.46E-11	4.00E+00	9.10E-02	1.03E-01	5.93E-01
46	7.84E-15	1.00E+00	5.73E-09	4.58E-10	8.86E-01	4.45E-02	3.19E-01	4.15E-01	-1.85E+01	-1.93E+01	-7.37E-02	-1.26E-01	3.13E-01	3.68E-01	1.29E+00	1.04E-03	-2.27E+01	8.47E-11	-1.89E+01	8.79E-11	4.00E+00	5.01E-02	6.32E-02	7.18E-01
47	2.97E-15	1.00E+00	9.75E-10	1.10E-09	8.97E-01	1.32E-01	5.10E-01	8.44E-01	-1.79E+01	-1.88E+01	-1.78E-01	-1.89E-01	3.09E-01	1.35E-02	8.17E-01	1.84E-02	-2.22E+01	6.87E-11	-1.90E+01	1.09E-10	4.00E+00	4.19E-02	1.74E-01	7.25E-01
48	8.52E-15	0.00E+00	1.08E-09	3.24E-10	9.22E-02	1.15E-01	6.21E-02	7.54E-01	-1.96E+01	-1.87E+01	-4.72E-01	1.17E-01	6.91E-02	4.43E-02	6.27E-01	1.94E-02	-2.25E+01	7.72E-11	-1.71E+01	1.09E-11	4.00E+00	6.50E-02	6.69E-02	6.86E-01
49	8.98E-15	0.00E+00	5.55E-09	1.64E-10	2.23E-01	4.54E-02	3.10E-01	4.73E-01	-1.93E+01	-1.87E+01	-2.35E-01	-5.41E-01	2.38E-03	2.50E-01	6.63E+00	2.08E-02	-2.12E+01	2.30E-11	-1.91E+01	9.03E-11	1.00E+00	1.11E-01	9.35E-02	6.90E-01
50	2.31E-14	0.00E+00	8.04E-09	5.90E-10	1.66E-01	1.07E-01	2.27E-01	1.23E-01	-2.03E+01	-1.91E+01	3.69E-01	-4.22E-02	8.23E-02	3.37E-02	5.89E+00	2.88E-02	-2.21E+01	7.66E-11	-1.94E+01	1.39E-10	4.00E+00	4.49E-02	7.31E-02	6.82E-01
51	1.87E-14	2.00E+00	8.79E-09	2.96E-10	2.18E-01	1.10E-01	1.61E-01	1.34E-01	-1.83E+01	-1.89E+01	-1.87E-01	1.90E-01	2.15E-01	2.07E-01	1.79E-01	1.33E-03	-2.11E+01	7.04E-12	-1.81E+01	1.09E-11	4.00E+00	7.80E-02	8.83E-02	5.70E-01
52	9.60E-15	1.00E+00	6.89E-09	9.47E-10	3.44E-01	8.90E-02	4.06E-01	3.91E-01	-1.85E+01	-1.95E+01	7.75E-01	-2.03E-01	1.66E-01	4.11E-01	2.34E+00	8.39E-03	-2.32E+01	1.48E-10	-1.88E+01	7.33E-11	4.00E+00	8.01E-02	1.63E-01	6.80E-01
53	1.65E-14	1.00E+00	6.15E-09	5.01E-10	7.79E-01	3.55E-02	4.88E-01	9.28E-01	-1.92E+01	-1.80E+01	8.00E-01	1.14E+00	1.32E-01	5.24E-01	4.33E+00	3.45E-03	-2.37E+01	1.83E-10	-1.86E+01	4.34E-11	1.00E+00	7.05E-02	1.40E-02	6.39E-01
54	1.29E-14	0.00E+00	1.21E-09	7.82E-10	7.45E-01	1.00E-01	2.87E-01	3.68E-01	-1.91E+01	-1.88E+01	8.60E-01	-5.71E-01	1.99E-01	4.76E-01	1.92E+00	1.02E-02	-2.39E+01	1.88E-10	-1.84E+01	3.00E-11	4.00E+00	1.68E-01	2.62E-02	6.71E-01
55	2.34E-14	0.00E+00	1.71E-09	7.54E-10	1.90E-02	5.95E-02	4.30E-01	7.12E-01	-1.97E+01	-1.93E+01	-1.40E-01	-3.51E-01	3.56E-01	7.61E-02	7.19E+00	8.16E-03	-2.14E+01	1.14E-11	-1.96E+01	1.76E-10	1.00E+00	5.83E-02	4.86E-02	6.03E-01
56	1.20E-14	0.00E+00	2.81E-09	2.84E-10	7.63E-01	4.83E-02	2.97E-01	5.16E-01	-2.03E+01	-1.97E+01	5.89E-01	-1.07E+00	2.35E-01	1.41E-01	2.92E-01	3.10E-03	-2.35E+01	1.63E-10	-1.89E+01	6.31E-11	1.00E+00	7.38E-02	7.49E-02	6.33E-01
57	6.89E-15	0.00E+00	5.04E-09	9.63E-10	7.39E-01	5.05E-02	3.76E-02	2.08E-01	-1.76E+01	-1.99E+01	9.51E-02	-1.22E-01	2.03E-01	2.09E-01	1.55E+00	1.35E-02	-2.37E+01	1.68E-10	-1.87E+01	4.17E-11	1.00E+00	7.78E-03	7.64E-02	6.29E-01
58	2.46E-14	0.00E+00	4.79E-09	1.07E-09	2.09E-01	1.24E-01	4.62E-01	1.47E-01	-1.96E+01	-1.92E+01	1.48E-02	8.42E-01	1.55E-01	4.62E-01	3.07E-01	4.33E-03	-2.26E+01	1.03E-10	-1.98E+01	1.84E-10	4.00E+00	1.07E-01	6.01E-02	6.23E-01
59	1.92E-14	0.00E+00	4.05E-09	1.18E-09	5.22E-01	2.05E-02	3.98E-01	6.96E-01	-1.74E+01	-1.77E+01	-2.02E-01	4.44E-01	3.61E-01	1.11E-01	5.32E-01	2.65E-02	-2.18E+01	6.33E-11	-1.91E+01	1.11E-10	1.00E+00	4.84E-02	1.21E-01	6.22E-01
60	5.20E-15	0.00E+00	5.36E-09	6.80E-10	3.91E-01	2.18E-03	1.99E-01	6.58E-01	-1.90E+01	-1.85E+01	4.85E-01	2.56E-02	3.88E-01	3.46E-01	5.77E+00	9.59E-03	-2.23E+01	9.06E-11	-1.95E+01	1.69E-10	4.00E+00	1.22E-01	5.44E-02	6.76E-01
61	2.75E-14	0.00E+00	4.19E-09	2.74E-11	9.26E-01	5.75E-02	1.41E-01	2.65E-01	-1.72E+01	-2.00E+01	-1.97E-01	1.62E-02	9.74E-02	4.33E-01	3.92E+00	1.30E-02	-2.31E+01	1.34E-10	-1.93E+01	1.18E-10	1.00E+00	8.94E-02	1.53E-01	7.20E-01
62	1.59E-14	0.00E+00	8.06E-09	1.23E-09	2.51E-01	4.05E-02	2.77E-02	4.40E-01	-1.84E+01	-1.92E+01	6.55E-02	-3.61E-01	3.26E-01	5.52E-01	5.86E-01	6.28E-03	-2.17E+01	5.18E-11	-1.92E+01	1.32E-10	4.00E+00	6.64E-02	2.81E-02	5.99E-01
63	2.16E-14	0.00E+00	4.71E-10	9.88E-10	9.61E-01	7.36E-02	4.95E-01	5.22E-02	-1.78E+01	-1.85E+01	-1.10E-01	-8.60E-01	2.50E-01	8.53E-02	7.72E-01	2.75E-02	-2.29E+01	1.29E-10	-1.98E+01	2.21E-10	1.00E+00	9.51E-02	4.40E-02	6.51E-01
64	1.34E-14	2.00E+00	1.95E-09	5.43E-10	8.76E-01	9.33E-03	5.04E-01	4.04E-01	-1.91E+01	-1.75E+01	1.89E-01	-2.16E-01	5.98E-02	5.35E-01	6.59E-01	7.61E-03	-2.11E+01	6.57E-12	-1.87E+01	5.30E-11	4.00E+00	9.94E-02	7.79E-02	6.62E-01
65	1.63E-14	0.00E+00	2.55E-09	7.29E-10	6.25E-01	8.49E-02	2.68E-01	1.64E-01	-1.95E+01	-1.93E+01	-1.25E-01	-4.16E-02	3.97E-01	5.15E-01	2.44E+00	4.23E-03	-2.14E+01	3.77E-11	-1.93E+01	1.12E-10	1.00E+00	1.05E-01	7.48E-02	7.14E-01
66	2.27E-14	0.00E+00	4.17E-09	8.89E-10	5.20E-01	2.34E-02	4.50E-01	7.39E-01	-1.99E+01	-1.79E+01	9.40E-01	-1.80E-01	3.36E-02	3.73E-01	2.44E-01	2.04E-02	-2.39E+01	1.86E-10	-1.78E+01	1.09E-11	4.00E+00	6.90E-02	1.36E-01	6.57E-01
67	3.25E-15	2.00E+00	6.41E-10	1.06E-09	6.41E-01	1.38E-03	6.99E-02	8.04E-01	-1.81E+01	-2.05E+01	-1.92E-01	-1.13E-01	3.47E-01	1.40E-01	8.41E-01	7.10E-03	-2.33E+01	1.40E-10	-1.85E+01	1.76E-11	4.00E+00	9.61E-02	7.38E-02	6.25E-01
68	5.70E-15	2.00E+00	6.33E-09	4.35E-10	1.16E-01	1.08E-01	2.62E-01	5.07E-01	-1.81E+01	-1.97E+01	1.99E-01	-2.43E-01	2.67E-01	3.25E-01	6.88E-01	8.74E-03	-2.30E+01	1.32E-10	-1.87E+01	7.08E-11	4.00E+00	9.28E-02	6.94E-02	6.94E-01
69	2.63E-14	0.00E+00	6.44E-09	8.43E-10	6.07E-01	1.32E-02	1.28E-01	3.09E-01	-1.89E+01	-1.80E+01	-6.27E-01	-1.79E+00	3.82E-01	4.69E-01	2.88E+00	2.39E-02	-2.22E+01	7.94E-11	-1.85E+01	6.03E-11	1.00E+00	6.40E-02	8.06E-02	7.54E-01
70	2.72E-14	0.00E+00	2.39E-09	8.68E-10	9.31E-03	2.75E-02	1.91E-01	6.76E-01	-1.86E+01	-1.84E+01	-3.12E-03	1.49E-01	1.83E-01	9.69E-02	7.40E+00	2.30E-02	-2.21E+01	7.20E-11	-1.89E+01	1.01E-10	1.00E+00	7.67E-02	3.07E-02	5.53E-01
71	8.72E-15	0.00E+00	9.47E-09	1.80E-10	4.06E-01	1.20E-01	1.71E-01	3.21E-01	-1.73E+01	-1.93E+01	-8.82E-01	-2.38E-01	4.64E-02	5.01E-01	5.09E+00	9.70E-03	-2.23E+01	8.21E-11	-1.89E+01	7.61E-11	4.00E+00	1.04E-01	9.72E-02	6.49E-01
72	1.96E-14	2.00E+00	7.10E-09	1.21E-09	9.53E-01	7.52E-03	1.23E-01	6.04E-02	-1.91E+01	-1.82E+01	-2.24E-01	1.69E-01	1.04E-01	3.43E-01	1.36E-01	4.91E-03	-2.31E+01	1.09E-10	-1.92E+01	1.07E-10	1.00E+00	7.51E-02	8.91E-02	5.02E-01
73	2.00E-14	1.00E+00	8.55E-09	3.52E-10	4.68E-01	2.20E-02	3.65E-01	2.62E-02	-1.98E+01	-1.78E+01	-1.15E-01	4.65E-01	2.61E-01	2.38E-01	7.99E+00	4.00E-03	-2.13E+01	2.07E-11	-1.84E+01	4.02E-11	1.00E+00	1.29E-01	1.32E-01	6.42E-01
74	2.35E-14	0.00E+00	6.00E-09	3.72E-10	2.89E-01	1.18E-01	2.11E-01	5.48E-01	-1.94E+01	-2.01E+01	-4.50E-01	-1.06E-01	2.42E-01	2.06E-02	1.43E+00	9.99E-03	-2.24E+01	8.83E-11	-1.82E+01	1.09E-11	4.00E+00	1.20E-01	8.80E-02	6.68E-01
75	1.30E-14	0.00E+00	9.00E-09	8.00E-10	4.13E-01	4.66E-02	4.99E-01	5.21E-01	-1.80E+01	-1.90E+01	-3.24E-01	-1.57E-01	8.94E-03	1.81E-01	1.74E-01	2.61E-02	-2.34E+01	1.51E-10	-1.93E+01	1.35E-10	4.00E+00	8.21E-02	6.48E-02	5.36E-01
76	2.98E-14	2.00E+00	7.87E-09	6.27E-10	1.91E-01	1.26E-01	1.52E-02	9.19E-01	-1.92E+01	-1.83E+01	1.08E-01	-1.85E-01	3.01E-01	7.34E-02	4.54E-01	2.15E-03	-2.20E+01	5.72E-11	-1.90E+01	1.04E-10	4.00E+00	9.75E-02	1.01E-01	5.88E-01

Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
38	2.60E-14	0.00E+00	1.31E-09	9.67E-10	9.42E-01	1.44E-01	4.31E-01	4.27E-01	-1.88E+01	-1.94E+01	-2.13E-01	1.30E-01	1.88E-01	6.03E-02	4.10E+00	5.17E-03	-2.27E+01	9.82E-11	-1.94E+01	1.48E-10	4.00E+00	8.61E-02	8.44E-02	6.21E-01
39	2.17E-15	1.00E+00	3.26E-09	1.49E-11	5.87E-01	2.86E-02	1.12E-01	6.25E-01	-1.93E+01	-1.86E+01	1.44E-01	7.25E-01	2.68E-01	5.40E-02	4.02E+00	2.06E-03	-2.34E+01	1.64E-10	-1.86E+01	4.88E-11	4.00E+00	7.93E-02	9.59E-02	5.82E-01
40	4.45E-15	2.00E+00	8.32E-09	3.93E-10	8.12E-01	1.43E-01	5.20E-01	8.58E-01	-1.98E+01	-1.94E+01	-3.62E-02	-6.44E-01	2.16E-01	2.31E-01	7.25E-01	1.51E-02	-2.15E+01	2.75E-11	-1.80E+01	1.09E-11	1.00E+00	5.53E-02	4.27E-02	6.32E-01
41	1.25E-14	2.00E+00	6.07E-09	3.40E-10	9.03E-01	1.31E-01	5.39E-01	2.28E-01	-1.91E+01	-1.89E+01	4.42E-02	3.96E-01	2.94E-01	1.30E-01	5.29E+00	2.56E-02	-2.25E+01	1.06E-10	-2.01E+01	2.52E-10	4.00E+00	6.05E-02	1.70E-02	6.69E-01
42	1.22E-14	1.00E+00	5.21E-10	4.10E-10	7.83E-01	2.63E-02	4.45E-02	4.67E-01	-1.84E+01	-1.82E+01	-2.16E-01	-8.34E-02	4.74E-03	4.04E-02	4.26E-01	5.40E-03	-2.18E+01	4.02E-11	-1.95E+01	1.64E-10	4.00E+00	5.99E-02	6.27E-02	6.74E-01
43	1.40E-15	1.00E+00	8.60E-09	3.99E-10	4.26E-01	3.86E-02	4.19E-01	6.07E-01	-2.01E+01	-1.79E+01	-1.67E-01	-1.47E-02	2.88E-01	8.12E-02	4.68E-01	2.69E-02	-2.39E+01	1.90E-10	-1.95E+01	1.59E-10	4.00E+00	1.17E-01	9.15E-02	6.98E-01
44	2.77E-14	0.00E+00	8.93E-09	1.12E-09	6.31E-01	3.60E-02	1.95E-01	8.87E-01	-1.86E+01	-1.98E+01	-7.94E-01	7.29E-02	1.71E-01	4.55E-01	5.98E-01	1.64E-03	-2.17E+01	4.85E-11	-1.93E+01	1.43E-10	1.00E+00	1.02E-01	8.22E-02	7.70E-01
45	3.11E-14	2.00E+00	2.15E-09	7.09E-10	5.45E-01	5.43E-02	3.56E-01	1.17E-01	-1.87E+01	-1.83E+01	-3.08E-01	-6.91E-01	2.79E-01	4.08E-01	2.43E-01	2.40E-02	-2.24E+01	1.00E-10	-1.88E+01	5.46E-11	4.00E+00	9.10E-02	1.03E-01	5.93E-01
77	2.19E-14	1.00E+00	1.67E-09	4.78E-10	3.28E-01	1.42E-01	3.48E-01	9.68E-01	-1.82E+01	-1.87E+01	-8.34E-02	-9.39E-01	1.08E-01	1.57E-01	5.15E-01	2.80E-03	-2.25E+01	1.03E-10	-1.94E+01	1.49E-10	1.00E+00	6.29E-02	7.02E-02	5.43E-01
78	1.82E-14	1.00E+00	8.30E-09	4.10E-11	8.68E-01	1.16E-01	8.60E-02	2.42E-01	-1.82E+01	-1.92E+01	-5.54E-01	-2.95E-01	1.43E-02	1.22E-01	6.76E+00	1.81E-02	-2.20E+01	7.43E-11	-1.92E+01	1.32E-10	1.00E+00	1.15E-01	4.60E-02	5.86E-01
79	2.25E-14	2.00E+00	7.41E-09	9.03E-10	9.88E-01	6.49E-02	3.88E-01	5.68E-01	-1.99E+01	-1.94E+01	-2.47E-01	-1.41E-01	8.97E-02	1.64E-01	4.17E-01	1.27E-02	-2.31E+01	1.27E-10	-1.86E+01	5.56E-11	1.00E+00	1.25E-01	8.28E-02	6.87E-01
80	2.41E-14	0.00E+00	6.58E-09	5.82E-10	5.76E-02	9.63E-02	3.85E-01	1.09E-01	-1.88E+01	-1.71E+01	4.78E-02	-1.63E-01	1.23E-01	3.01E-02	2.64E-01	1.70E-02	-2.28E+01	1.08E-10	-1.90E+01	1.20E-10	1.00E+00	1.03E-01	7.72E-02	6.32E-01
81	4.08E-15	0.00E+00	1.80E-09	2.46E-10	5.62E-01	8.27E-02	1.76E-01	3.81E-01	-1.77E+01	-1.77E+01	1.75E-01	1.97E-01	6.46E-02	1.93E-01	4.02E-01	5.79E-03	-2.11E+01	8.70E-12	-1.83E+01	1.46E-11	4.00E+00	6.86E-02	7.89E-02	7.03E-01
82	9.33E-15	2.00E+00	1.45E-09	1.20E-09	7.27E-01	3.35E-02	3.06E-01	8.20E-01	-1.86E+01	-1.97E+01	-4.91E-01	7.72E-01	2.55E-02	3.94E-01	7.53E-01	2.17E-02	-2.19E+01	6.42E-11	-1.85E+01	4.67E-11	4.00E+00	1.27E-01	5.70E-02	6.07E-01
83	2.68E-14	0.00E+00	9.34E-09	4.30E-10	7.99E-01	1.35E-01	1.52E-01	5.97E-01	-1.76E+01	-1.77E+01	-4.03E-01	3.24E-01	3.92E-01	9.47E-02	9.07E-01	5.13E-03	-2.22E+01	6.60E-11	-1.82E+01	1.09E-11	1.00E+00	6.99E-02	3.64E-02	8.05E-01
84	1.78E-14	0.00E+00	3.82E-09	3.67E-10	3.75E-02	7.66E-02	5.25E-01	7.95E-03	-1.80E+01	-1.99E+01	2.34E-01	-5.64E-02	1.10E-01	1.20E-01	6.17E-01	2.53E-03	-2.32E+01	1.46E-10	-1.78E+01	1.09E-11	1.00E+00	1.12E-01	8.59E-02	6.75E-01
85	3.08E-14	1.00E+00	5.84E-09	9.26E-10	1.83E-01	1.34E-01	1.44E-01	2.79E-01	-1.88E+01	-1.86E+01	-7.46E-01	8.54E-01	1.95E-01	5.79E-01	7.17E-01	1.77E-02	-2.40E+01	1.92E-10	-1.99E+01	2.08E-10	1.00E+00	1.00E-01	5.74E-02	7.07E-01
86	1.80E-15	1.00E+00	9.18E-09	1.14E-09	3.63E-01	6.34E-02	2.50E-01	4.94E-01	-1.90E+01	-1.83E+01	-1.58E-01	2.12E-01	9.44E-02	1.74E-01	3.44E-01	1.46E-03	-2.29E+01	1.42E-10	-1.89E+01	7.85E-11	1.00E+00	5.74E-02	1.40E-02	7.09E-01
87	6.49E-15	1.00E+00	5.75E-09	8.80E-10	2.44E-01	9.22E-02	3.01E-01	8.96E-01	-1.96E+01	-1.96E+01	-2.42E-01	2.37E-01	1.41E-01	3.33E-01	1.98E+00	2.97E-02	-2.19E+01	5.89E-11	-1.80E+01	1.09E-11	1.00E+00	8.49E-02	9.31E-02	5.61E-01
88	4.38E-15	0.00E+00	7.65E-09	6.60E-10	9.10E-01	1.49E-01	1.58E-01	6.65E-01	-1.78E+01	-1.90E+01	1.39E-01	-4.12E-01	3.69E-01	9.17E-02	3.68E-01	7.35E-03	-2.21E+01	9.30E-11	-2.03E+01	2.75E-10	4.00E+00	9.19E-02	7.23E-02	5.77E-01
89	1.12E-14	2.00E+00	1.59E-09	7.92E-10	5.39E-01	7.81E-02	5.48E-01	8.36E-01	-1.86E+01	-1.82E+01	-1.33E+00	-2.53E-01	1.76E-01	1.44E-01	6.12E+00	7.77E-03	-2.16E+01	5.33E-11	-1.76E+01	1.09E-11	4.00E+00	8.89E-02	5.90E-02	6.00E-01
90	9.95E-15	2.00E+00	4.28E-09	1.04E-09	2.92E-01	9.43E-02	1.81E-01	9.53E-01	-1.80E+01	-2.04E+01	-1.73E-01	1.63E-01	1.26E-01	2.79E-01	5.40E+00	3.66E-03	-2.39E+01	1.76E-10	-1.93E+01	1.55E-10	1.00E+00	8.10E-02	1.41E-01	6.45E-01
91	2.11E-14	1.00E+00	8.43E-10	9.21E-10	6.63E-01	1.37E-01	2.84E-01	9.18E-02	-1.90E+01	-1.86E+01	-2.93E-01	-3.45E-02	8.46E-02	2.41E-01	7.88E-01	1.14E-02	-2.10E+01	4.70E-12	-1.81E+01	1.09E-11	1.00E+00	8.67E-02	9.98E-02	6.69E-01
92	3.05E-14	0.00E+00	2.46E-09	1.23E-09	8.52E-01	1.04E-01	7.38E-02	1.66E-02	-2.04E+01	-1.88E+01	-3.63E-01	5.03E-01	3.56E-01	3.86E-02	1.46E-01	7.26E-03	-2.30E+01	1.36E-10	-1.88E+01	9.40E-11	1.00E+00	9.37E-02	1.23E-01	6.28E-01
93	5.74E-15	2.00E+00	3.45E-09	2.37E-10	6.14E-01	1.30E-01	3.26E-01	8.00E-02	-1.90E+01	-1.96E+01	-9.14E-01	1.36E-01	2.46E-01	4.30E-01	6.55E-01	2.13E-02	-2.28E+01	1.13E-10	-1.92E+01	1.25E-10	1.00E+00	5.18E-02	4.78E-02	6.36E-01
94	8.23E-15	0.00E+00	5.38E-09	6.07E-10	9.91E-01	5.39E-02	4.11E-01	3.14E-01	-1.93E+01	-1.85E+01	-1.51E-01	-9.80E-02	5.56E-02	2.21E-01	7.30E+00	1.85E-03	-2.22E+01	8.67E-11	-1.95E+01	1.57E-10	1.00E+00	4.08E-02	9.90E-02	4.91E-01
95	2.81E-14	0.00E+00	3.36E-09	5.27E-10	3.31E-01	1.11E-01	4.55E-01	9.78E-01	-1.89E+01	-1.81E+01	2.06E-01	-3.88E-01	2.40E-01	2.85E-01	8.61E-01	1.58E-02	-2.29E+01	1.23E-10	-1.89E+01	6.14E-11	4.00E+00	1.49E-01	1.12E-01	6.14E-01
96	2.66E-15	0.00E+00	3.72E-09	2.19E-10	4.83E-01	9.84E-02	2.23E-01	2.37E-01	-1.78E+01	-1.82E+01	-4.64E-02	1.00E-01	3.77E-01	4.47E-01	6.38E+00	9.12E-03	-2.36E+01	1.67E-10	-1.82E+01	1.09E-11	1.00E+00	7.41E-02	1.25E-01	5.55E-01
97	2.94E-14	0.00E+00	8.88E-10	4.45E-10	6.74E-01	1.46E-01	2.48E-02	1.88E-01	-1.92E+01	-1.95E+01	4.26E-01	2.26E-01	3.65E-01	1.90E-01	1.11E+00	6.19E-03	-2.16E+01	3.20E-11	-1.74E+01	1.09E-11	4.00E+00	7.54E-02	1.40E-02	6.12E-01
98	7.47E-15	0.00E+00	2.98E-09	7.67E-11	1.80E-01	1.64E-02	1.38E-01	2.14E-01	-2.02E+01	-1.85E+01	-2.85E-01	6.08E-01	2.37E-02	1.68E-01	9.19E-01	6.59E-03	-2.16E+01	3.45E-11	-1.99E+01	2.48E-10	1.00E+00	2.69E-02	6.61E-02	6.59E-01
99	2.43E-14	1.00E+00	6.70E-09	7.50E-11	3.74E-01	1.84E-02	4.23E-01	6.35E-01	-1.97E+01	-2.00E+01	1.19E-03	-2.15E-01	1.60E-01	5.42E-01	1.22E-01	2.25E-02	-2.18E+01	6.00E-11	-1.87E+01	4.94E-11	4.00E+00	6.68E-02	5.16E-02	6.92E-01
100	2.13E-14	1.00E+00	4.08E-10	6.39E-10	2.38E-01	5.70E-02	4.29E-03	1.54E-01	-1.95E+01	-1.94E+01	3.01E-01	6.43E-02	7.67E-02	6.00E-01	5.12E+00	1.62E-02	-2.38E+01	1.72E-10	-1.90E+01	1.05E-10	1.00E+00	8.14E-02	1.17E-01	6.53E-01

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Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector Num.	S_HALITE PRESSURE	CASTILER PRESSURE	CASTILER PRMX_LOG	CASTILER COMP_RCK	BH_SAND PRMX_LOG	DRZ_1 PRMX_LOG	CONC_PLG PRMX_LOG	SOLAM3 SOLSIM	SOLAM3 SOLCIM	SOLPU3 SOLSIM	SOLPU3 SOLCIM	SOLPU4 SOLSIM	SOLPU4 SOLCIM	SOLU4 SOLSIM	SOLU6 SOLSIM	SOLU6 SOLCIM	SOLTH4 SOLSIM	PHUMOX3 PHUMCIM	GLOBAL OXSTAT	CULEBRA MINP_FAC	GLOBAL TRANSIDX	GLOBAL CLIMTIDX	CULEBRA HMBLKLT
1	1.27E+07	1.61E+07	-1.21E+01	6.60E-11	-1.56E+01	-1.53E+01	-1.83E+01	-2.01E-01	-6.30E-01	8.10E-02	-2.59E-01	1.37E-01	-1.94E+00	-4.22E-01	2.02E-01	-3.34E-02	-3.65E-01	1.44E+00	5.60E-01	2.98E+02	1.67E-01	1.23E+00	2.86E-01
2	1.22E+07	1.33E+07	-1.16E+01	5.79E-11	-1.22E+01	-1.80E+01	-1.83E+01	-9.92E-01	1.00E-02	-6.62E-01	4.83E-01	-3.87E-02	8.40E-01	-5.96E-02	-6.76E-02	-1.21E-01	-3.14E-01	1.41E+00	1.86E-01	2.09E+02	3.23E-01	1.75E+00	4.38E-01
3	1.27E+07	1.23E+07	-1.18E+01	5.32E-11	-1.35E+01	-1.42E+01	-1.84E+01	-1.38E-01	-5.31E-01	-1.22E-02	-4.38E-02	-1.46E-01	-4.45E-02	9.30E-01	-2.99E-01	-4.32E-01	-9.85E-02	2.22E-01	7.35E-01	5.39E+02	3.36E-01	1.13E+00	2.51E-01
4	1.32E+07	1.28E+07	-1.42E+01	8.88E-11	-1.24E+01	-1.45E+01	-1.83E+01	-3.15E-01	-4.96E-01	-1.90E-01	1.20E-01	-5.63E-02	-7.06E-01	-5.11E-02	-3.38E-02	6.11E-01	-1.98E+00	1.56E+00	9.76E-01	5.30E+01	1.91E-01	1.12E+00	4.27E-01
5	1.20E+07	1.45E+07	-1.23E+01	6.99E-11	-1.59E+01	-1.44E+01	-1.86E+01	2.38E-01	7.50E-01	-3.97E-02	6.16E-02	-1.65E+00	-1.56E-01	-3.26E-02	1.36E-01	4.60E-02	8.39E-01	1.38E+00	1.25E-01	5.70E+02	7.28E-01	1.65E+00	3.17E-01
6	1.18E+07	1.41E+07	-1.28E+01	6.49E-11	-1.18E+01	-1.50E+01	-1.87E+01	2.97E-01	4.80E-01	-1.28E-04	-7.09E-01	-2.95E-02	1.33E-01	-2.25E-01	-1.29E-01	-6.44E-02	7.86E-01	1.54E+00	4.65E-01	6.91E+02	1.26E-01	1.07E+00	5.75E-02
7	1.19E+07	1.33E+07	-1.18E+01	6.94E-11	-1.12E+01	-1.73E+01	-1.76E+01	-7.43E-02	9.08E-01	5.78E-01	1.73E-01	-1.20E-01	1.49E-01	-1.08E-01	-1.90E+00	1.13E-01	-5.54E-01	1.42E+00	6.22E-02	8.42E+01	6.73E-01	1.23E+00	3.13E-01
8	1.17E+07	1.21E+07	-1.02E+01	2.15E-11	-1.25E+01	-1.75E+01	-1.72E+01	-1.12E-01	-4.14E-01	-1.53E-01	9.37E-01	-3.22E-01	6.37E-02	1.24E+00	5.65E-01	2.05E-01	-1.42E-01	1.53E+00	5.34E-01	2.59E+02	5.56E-01	1.12E+00	1.82E-01
9	1.17E+07	1.51E+07	-1.20E+01	5.93E-11	-1.14E+01	-1.62E+01	-1.90E+01	-1.77E-01	-1.58E-01	-4.65E-01	-1.60E-01	-3.04E-01	-2.91E-01	-1.51E-01	-7.52E-01	-4.00E-03	-9.54E-01	1.53E-01	5.20E-01	1.00E+01	4.78E-01	1.24E+00	5.25E-02
10	1.38E+07	1.26E+07	-1.01E+01	2.46E-11	-1.19E+01	-1.27E+01	-1.76E+01	6.45E-01	-2.26E-01	9.98E-01	-9.46E-01	-1.32E-01	3.28E-01	2.52E-02	-3.89E-02	3.45E-01	-2.86E-01	1.52E+00	7.41E-01	6.43E+02	8.68E-01	1.16E+00	4.77E-01
11	1.14E+07	1.34E+07	-1.12E+01	4.30E-11	-1.37E+01	-1.47E+01	-1.80E+01	2.25E-01	-8.14E-02	-4.05E-01	-2.32E-01	-6.94E-01	-1.29E-01	-7.09E-01	-9.58E-01	9.06E-01	1.70E-01	1.58E+00	9.65E-01	6.61E+01	5.85E-01	1.13E+00	1.39E-01
12	1.28E+07	1.35E+07	-1.12E+01	5.04E-11	-1.36E+01	-1.41E+01	-1.75E+01	-3.69E-02	3.15E-02	-9.71E-02	1.59E-01	6.72E-03	-8.56E-02	-2.13E-01	2.84E-01	-1.36E-01	-4.75E-01	1.51E+00	1.94E-01	1.95E+02	9.56E-01	1.02E+00	1.63E-01
13	1.11E+07	1.29E+07	-1.33E+01	6.77E-11	-1.43E+01	-1.31E+01	-1.88E+01	-2.78E-01	-1.87E+00	-5.73E-02	7.76E-01	6.56E-02	-1.23E-01	-1.80E-01	1.71E-01	-2.44E-01	5.89E-01	9.61E-01	1.75E-01	8.21E+02	9.13E-01	1.17E+00	2.16E-01
14	1.25E+07	1.18E+07	-1.19E+01	4.03E-11	-1.56E+01	-1.32E+01	-1.79E+01	6.99E-02	2.76E-01	-7.76E-01	-3.30E-01	-1.30E+00	7.74E-03	1.68E-01	-1.16E-01	-9.50E-01	1.28E-01	1.58E+00	3.96E-01	9.41E+01	2.91E-01	1.17E+00	9.10E-02
15	1.12E+07	1.16E+07	-1.21E+01	4.56E-11	-1.38E+01	-1.34E+01	-1.81E+01	-4.08E-01	-1.93E-01	7.51E-01	-5.56E-02	1.69E-01	4.21E-01	1.18E-01	1.03E-01	7.04E-01	5.38E-02	1.00E+00	4.86E-02	2.29E+02	9.26E-02	1.05E+00	2.99E-01
16	1.29E+07	1.44E+07	-1.16E+01	4.53E-11	-1.46E+01	-1.39E+01	-1.77E+01	-1.71E-01	6.20E-01	1.40E-01	1.09E-01	3.20E-01	-1.79E-01	-1.34E-02	-2.00E-01	1.12E-02	-6.86E-02	5.73E-01	8.16E-01	4.74E+02	4.37E-01	1.09E+00	4.48E-01
17	1.18E+07	1.43E+07	-1.30E+01	7.60E-11	-1.13E+01	-1.53E+01	-1.89E+01	4.28E-01	-2.29E-01	-5.99E-01	5.38E-01	-9.78E-01	-2.27E-01	-2.41E-01	-6.41E-01	-7.84E-02	2.35E-01	1.57E+00	4.80E-01	9.05E+02	3.16E-01	1.05E+00	3.58E-01
18	1.16E+07	1.41E+07	-1.15E+01	6.18E-11	-1.36E+01	-1.76E+01	-1.71E+01	1.74E-01	-9.58E-02	2.44E-01	-1.09E-01	-3.98E-01	-1.66E+00	4.07E-02	2.03E-01	-5.92E-02	-2.09E-01	1.10E+00	2.18E-01	7.05E+02	2.07E-01	2.03E+00	4.90E-01
19	1.30E+07	1.25E+07	-1.23E+01	6.06E-11	-1.51E+01	-1.66E+01	-1.71E+01	9.65E-01	-3.89E-01	2.99E-01	2.41E-01	-2.67E-01	-3.29E-01	1.24E-01	-8.10E-01	-3.45E-01	-8.19E-01	1.57E+00	2.59E-01	1.19E+02	4.59E-01	1.10E+00	8.04E-02
20	1.37E+07	1.23E+07	-1.11E+01	3.37E-11	-1.13E+01	-1.54E+01	-1.77E+01	-2.93E-01	1.59E-01	-1.35E-01	-3.37E-02	-4.89E-01	2.10E-01	3.49E-01	9.36E-01	-3.86E-01	2.45E-01	1.39E+00	1.60E-02	4.50E+02	7.35E-02	1.96E+00	1.56E-01
21	1.21E+07	1.64E+07	-1.33E+01	7.39E-11	-1.22E+01	-1.65E+01	-1.82E+01	-5.45E-01	1.24E-01	2.18E-01	-5.19E-02	-1.75E+00	8.05E-02	6.12E-02	-3.54E-01	7.44E-02	9.19E-01	1.39E+00	6.29E-01	8.87E+02	1.85E-01	1.01E+00	2.36E-01
22	1.20E+07	1.54E+07	-1.22E+01	4.46E-11	-1.44E+01	-1.47E+01	-1.76E+01	9.19E-01	2.39E-01	1.77E-01	-2.40E-01	-4.66E-02	7.80E-01	7.53E-01	-1.48E-01	-2.86E-01	-3.90E-01	1.46E+00	8.22E-01	5.58E+02	6.44E-03	1.11E+00	4.93E-01
23	1.29E+07	1.32E+07	-1.16E+01	3.59E-11	-1.10E+01	-1.77E+01	-1.79E+01	-1.22E-01	-8.32E-01	-2.05E-01	-4.08E-01	-1.59E-01	-5.70E-02	-1.25E-01	7.91E-02	1.03E-01	-6.01E-01	1.42E+00	5.16E-02	5.08E+02	4.16E-01	1.02E+00	3.36E-01
24	1.30E+07	1.53E+07	-1.17E+01	4.17E-11	-1.52E+01	-1.92E+01	-1.75E+01	-9.12E-02	1.46E-02	-9.47E-01	-3.91E-01	9.48E-02	1.83E-01	8.13E-01	-1.92E-01	-2.00E-01	-4.18E-01	1.50E+00	9.97E-01	2.60E+01	4.66E-01	1.19E+00	6.06E-02
25	1.25E+07	1.28E+07	-1.07E+01	3.48E-11	-1.63E+01	-1.81E+01	-1.80E+01	-1.73E+00	-5.68E-02	4.69E-01	6.43E-01	2.01E-01	1.81E-02	-1.27E+00	-1.82E-01	2.17E-01	-2.34E-01	3.82E-01	6.69E-01	2.50E+02	1.51E-01	1.19E+00	6.48E-02
26	1.32E+07	1.45E+07	-1.13E+01	4.98E-11	-1.57E+01	-1.25E+01	-1.82E+01	-1.09E-01	-3.29E-01	1.07E-01	8.88E-01	2.49E-01	-7.26E-02	1.93E-01	1.86E-02	-7.84E-01	-7.57E-02	1.50E+00	5.00E-01	8.70E+02	7.53E-01	1.90E+00	1.31E-01
27	1.23E+07	1.49E+07	-1.12E+01	3.06E-11	-1.47E+01	-1.42E+01	-1.80E+01	-1.61E-01	-2.25E-02	-8.74E-01	-1.44E-01	9.38E-01	-3.77E-01	-1.65E-01	-1.15E+00	-5.65E-01	-5.61E-02	7.23E-01	5.91E-01	7.41E+02	5.00E-01	1.24E+00	1.52E-01
28	1.36E+07	1.28E+07	-1.34E+01	4.41E-11	-1.40E+01	-1.61E+01	-1.77E+01	7.78E-01	-1.46E-01	1.87E-02	3.42E-02	-1.49E-01	-4.59E-01	1.33E-01	-4.65E-01	2.64E-01	2.76E-01	1.16E+00	3.54E-01	5.14E+02	7.86E-01	1.08E+00	7.46E-02
29	1.37E+07	1.63E+07	-1.23E+01	6.73E-11	-1.59E+01	-1.36E+01	-1.88E+01	-8.92E-01	-6.75E-01	-1.82E-01	-2.25E-01	-9.08E-01	-1.00E-01	2.18E-01	-1.44E-01	-7.14E-02	-2.17E-02	1.53E+00	2.67E-01	7.90E+02	2.71E-01	1.93E+00	9.64E-02
30	1.27E+07	1.24E+07	-1.39E+01	8.52E-11	-1.20E+01	-1.51E+01	-1.78E+01	-1.27E-01	-1.85E-01	1.13E-01	-3.55E-01	2.55E-01	5.74E-01	-3.69E-01	-2.72E-01	-1.88E+00	-4.36E-02	7.77E-01	8.36E-01	4.69E+01	2.47E-01	1.04E+00	1.16E-01
31	1.30E+07	1.36E+07	-1.23E+01	6.37E-11	-1.12E+01	-1.54E+01	-1.78E+01	-3.17E-02	-1.39E+00	1.57E-01	-1.70E-01	1.79E-01	-1.46E-01	-7.62E-02	-2.46E-01	-4.90E-01	-1.92E-01	1.49E+00	9.24E-01	9.61E+02	9.33E-01	1.11E+00	3.81E-01
32	1.32E+07	1.60E+07	-1.28E+01	4.75E-11	-1.29E+01	-1.80E+01	-1.71E+01	-8.80E-02	-3.17E-01	-1.53E-01	4.34E-01	3.66E-01	-1.73E-01	8.60E-02	-2.31E-01	-1.56E-01	-1.59E+00	1.44E+00	2.93E-01	9.98E+02	6.95E-02	1.21E+00	1.89E-01
33	1.28E+07	1.24E+07	-1.05E+01	3.84E-11	-1.17E+01	-1.33E+01	-1.73E+01	1.79E-01	-2.40E-01	8.56E-01	-1.12E-01	5.78E-02	-8.23E-01	-1.14E-01	1.26E-01	-4.58E-02	2.15E-01	8.12E-01	3.85E-01	2.37E+02	8.28E-01	1.20E+00	3.39E-01
34	1.29E+07	1.66E+07	-1.17E+01	4.60E-11	-1.62E+01	-1.28E+01	-1.75E+01	3.33E-01	-2.04E-01	-7.01E-02	-1.75E-01	5.59E-01	9.89E-01	-4.49E-01	-3.24E-01	-5.44E-02	-2.97E-02	1.56E+00	5.03E-01	6.15E+02	7.74E-01	1.24E+00	2.02E-01
35	1.26E+07	1.52E+07	-1.24E+01	5.47E-11	-1.61E+01	-1.89E+01	-1.84E+01	1.33E+00	-1.44E-01	6.13E-01	-1.93E-01	1.15E-01	-4.45E-01	-1.42E-01	2.31E-01	-4.02E-02	-7.06E-01	9.40E-02	2.83E-01	1.45E+02	5.92E-01	1.11E+00	1.72E-01
36	1.33E+07	1.34E+07	-1.06E+01	2.93E-11	-1.61E+01	-1.67E+01	-1.84E+01	-6.61E-02	-3.46E-01	-1.96E+00	-8.79E-02	1.49E-01	8.66E-02	-3.19E-01	6.10E-01	2.02E-02	6.13E-01	1.38E+00	7.82E-01	3.46E+02	5.17E-01	1.15E+00	4.08E-01
37	1.37E+07	1.48E+07	-1.04E+01	5.09E-11	-1.54E+01	-1.44E+01	-1.84E+01	-2.13E-02	-1.31E-01	-5.17E-02	-6.39E-02	-2.47E-01	-5.87E-01	-3.95E-01	8.26E-01	-1.20E+00	3.43E-01	1.49E+00	3.13E-01	3.76E+02	3.92E-01	1.02E+00	4.43E-01
38	1.16E+07	1.48E+07	-1.08E+01	4.81E-11	-1.46E+01	-1.71E+01	-1.85E+01	-1.30E+00	-3.96E-01	6.69E-03	8.39E-02	-5.55E-01	-6.34E-01	2.05E-01	-1.55E+00	-2.19E-01	-1.30E-01	1.06E+00	9.20E-02	4.83E+02	1.01E-02	1.06E+00	4.69E-01
39	1.35E+07	1.17E+07	-1.14E+01	7.31E-11	-1.29E+01	-1.93E+01	-1.73E+01	6.80E-01	-6.11E-01	-3.22E-01	1.91E-01	-4.58E-01	-1.08E-01	-3.45E-01	-2.25E-01	7.99E-01	-7.68E-03	9.09E-01	4.36E-01	7.14E+02	6.61E-01	2.01E+00	2.26E-01
40	1.15E+07	1.39E+07	-1.19E+01	4.22E-11	-1.59E+01	-1.56E+01	-1.70E+01	-1.52E-01	-4.72E-01	2.13E-01	-8.92E-01	-6.11E-01	-3.63E-01	-7.73E-02	6.65E-02	2.01E-01	-1.66E-01	1.48E+00	7.60E-01	7.30E+02	6.26E-01	1.15E+00	3.56E-01
41	1.24E+07	1.14E+07	-1.19E+01	3.73E-11	-1.28E+01	-1.57E+01	-1.79E+01	-8.85E-01	-6.04E-03	-1.72E-01	6.61E-01	2.04E-01	-2.79E-01	-6.10E-01	7.68E-01	-2.31E-01	-4.29E-01	3.18E-01	6.55E-01	8.49E+02	5.60E-01	1.07E+00	1.69E-01
42	1.14E+07	1.22E+07	-1.26E+01	5.70E-11	-1.30E+01	-1.57E+01	-1.83E+01	3.82E-02	-1.75E+00	-1.07E-01	-5.29E-01	7.58E-02	-2.57E-03	-2.07E-01	-9.41E-01	-2.56E-01	-8.53E-02	1.47E+00	1.35E-01	8.39E+02	7.00E-01	1.16E+00	1.05E-01
43	1.19E+07	1.37E+07	-1.22E+01	4.28E-11	-1.25E+01	-1.73E+01	-1.87E+01	2.45E-01	-1.37E-01	-3.51E-01	-2.07E-01	6.57E-01	-2.31E-01	-2.13E-02	-4.09E-01	4.84E-01	5.15E-01	3.68E-01	2.31E-01	1.33E+02	4.23E-01	1.19E+00	4.67E-01
44	1.26E+07	1.44E+07	-1.20E+01	6.09E-11	-1.29E+01	-1.27E+01	-1.72E+01	-2.07E-01	3.83E-01	-3.62E-01	-8.02E-01	8.65E-01	-4.75E-01	-9.95E-01	-5.28E-01	-1.95E-02	-9.27E-02	1.48E+00	2.40E-01	9.72E+02	9.41E-01	2.14E+00	1.42E-01
45	1.36E+07	1.39E+07	-1.10E+01	2.98E-11	-1.16E+01	-1.63E+01	-1.74E+01	-3.67E-01	-9.37E-01	1.88E-01	-6.35E-01	-2.23E-01	-2.14E-01	6.85E-01	-3.08E-01	-1.12E-01	7.14E-01	9.29E-01	8.43E-01	5.75E+02	9.10E-01	1.63E+00	3.94E-01
46	1.24E+07	1.56E+07	-1.36E+01	8.39E-11	-1.11E+01	-1.69E+01	-1.83E+01	-4.14E-01	3.39E-01	1.15E+00	1.40E-01	-3.46E-01	5.22E-01	-2.96E-01	3.69E-01	-1.67E-01	-3.54E-02	1.11E+00	6.05E-01	4.91E+02	8.06E-01	1.12E+00	1.97E-01
47	1.19E+07	1.40E+07	-1.25E+01	6.26E-11	-1.57E+01	-1.31E+01	-1.74E+01	-3.54E-01	4.35E-01	-3.19E-01	9.90E-02	-6.28E-01	-9.57E-02	8.50E-01	5.58E-02	1.86E-01	-1.12E-01	1.43E+00	4.45E-01	3.94E+02	7.45E-01	1.13E+00	2.75E-01
48	1.18E+07	1.52E+07	-1.17E+01	5.16E-11	-1.50E+01	-1.37E+01	-1.71E+01	6.62E-03	-1.67E-02	-5.53E-01	-3.08E-01	1.64E-01	5.48E-02	7.16E-01	-8.53E-02	-4.09E-01	-2.22E-01	1.90E-01	4.18E-01	9.27E+02	1.43E-01	1.01E+00	3.44E-01
49	1.23E+07	1.47E+07	-1.13E+01	2.81E-11	-1.51E+01	-1.71E+01	-1.81E+01	-3.33E-01	-2.69E-01	3.80E-02	-1.58E-01	-4.74E-01	-1.89E-02	-1.92E+00	-5.87E-02	5.96E-01	-3.32E-01	5.50E-01	7.15E-01	4.26E+02	7.16E-01	1.25E+00	3.04E-01
50	1.34E+07	1.25E+07	-1.20E+01	5.88E-11	-1.43E+01	-1.90E+01	-1.77E+01	-5.72E-01	1.72E-01	-1.25E-01	7.99E-03	2.15E-02	-9.43E-01	-3.78E-01	8.86E-01	6.57E-02	9.88E-01	1.53E+00	6.46E-01	7.69E+02	3.77E-01	1.14E+00	1.33E-01
51	1.16E+07	1.40E+07	-1.03E+01	2.66E-11	-1.43E+01	-1.87E+01	-1.86E+01	-4.57E-02	9.91E-02	5.35E-01	-4.25E-01	-2.56E-02	-2.17E-01	9.65E-01	-1.81E-01	-5.42E-01	-5.34E-02	1.37E+00	9.60E-01	9.13E+02	6.49E-01	1.03E+00	7.23E-02
52	1.20E+07	1.38E+07	-1.17E+01	4.72E-11	-1.53E+01	-1.84E+01	-1.75E+01	1.06E-01	-1.18E+00	6.69E-01	-1.52E-01	5.38E-01	3.60E-01	-2.46E-01	-4.23E-01	-2.43E-01	1.01E+00	1.46E+00	2.79E-02	1.60E+02	8.13E-02	1.56E+00	2.83E-01
53	1.35E+07	1.42E+07	-1.15E+01	4.07E-11	-1.51E+01	-1.60E+01	-1.78E+01	-1.94E+00	-8.42E-02	-4.84E-02	-4.62E-01	-3.81E-01	-1.13E-01	5.82E-01	-5.89E-01	-4.54E-01	-1.39E-01	5.28E-01	3.34E-01	3.52E+02	3.48E-01	1.22E+00	2.70E-01

Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector Num.	S_HALITE PRESSURE	CASTILER PRESSURE	CASTILER PRMX_LOG	CASTILER COMP_RCK	BH_SAND PRMX_LOG	DRZ_1 PRMX_LOG	CONC_PLG PRMX_LOG	SOLAM3 SOLSIM	SOLAM3 SOLCIM	SOLPU3 SOLSIM	SOLPU3 SOLCIM	SOLPU4 SOLSIM	SOLPU4 SOLCIM	SOLU4 SOLSIM	SOLU6 SOLSIM	SOLU6 SOLCIM	SOLTH4 SOLSIM	PHUMOX3 PHUMCIM	GLOBAL OXSTAT	CULEBRA MINP_FAC	GLOBAL TRANSIDX	GLOBAL CLIMTIDX	CULEBRA HMBLKLT
54	1.31E+07	1.27E+07	-1.31E+01	7.75E-11	-1.26E+01	-1.46E+01	-1.72E+01	3.09E-02	-1.07E-01	-2.11E-01	-2.12E-01	-2.71E-01	-9.54E-01	-4.29E-01	-9.54E-02	-9.82E-02	4.69E-02	1.40E+00	8.55E-01	4.20E+02	4.97E-02	1.00E+00	3.89E-01
55	1.11E+07	1.37E+07	-1.16E+01	3.80E-11	-1.32E+01	-1.58E+01	-1.86E+01	3.73E-01	-7.73E-01	-2.41E-01	-1.85E-01	-1.23E+00	8.93E-01	-9.21E-01	-7.75E-02	-7.40E-01	2.05E-01	4.91E-01	5.77E-01	2.64E+02	8.87E-01	1.22E+00	3.29E-01
56	1.17E+07	1.43E+07	-1.29E+01	3.92E-11	-1.26E+01	-1.78E+01	-1.88E+01	8.51E-01	9.90E-01	-2.42E-02	1.84E-01	1.40E+00	-1.11E+00	8.22E-02	-2.28E-02	-1.29E-01	8.52E-01	1.01E+00	2.74E-01	8.13E+02	4.10E-01	1.18E+00	3.27E-01
57	1.14E+07	1.35E+07	-1.14E+01	4.14E-11	-1.35E+01	-1.91E+01	-1.89E+01	-2.12E-01	-2.87E-01	-1.18E-01	-1.90E+00	-1.19E-02	-3.08E-01	1.62E-01	3.04E-01	8.46E-01	-2.28E-01	1.41E+00	1.41E-01	5.21E+02	1.71E-01	2.16E+00	4.78E-01
58	1.25E+07	1.38E+07	-1.40E+01	7.16E-11	-1.27E+01	-1.34E+01	-1.76E+01	-1.85E-01	8.75E-01	3.43E-01	-2.91E-01	-8.33E-01	-2.46E-01	-1.68E-01	-2.08E-01	-4.27E-01	1.04E-01	1.55E+00	7.68E-01	3.26E+01	4.81E-01	2.25E+00	4.52E-01
59	1.33E+07	1.32E+07	-1.34E+01	4.66E-11	-1.56E+01	-1.84E+01	-1.74E+01	7.24E-01	8.84E-02	-4.35E-01	-2.84E-01	-2.32E-01	-4.01E-02	-1.56E+00	-1.01E-01	8.68E-01	-5.00E-01	1.47E+00	3.24E-01	9.32E+02	1.35E-01	1.60E+00	2.23E-01
60	1.15E+07	1.29E+07	-1.30E+01	4.86E-11	-1.23E+01	-1.68E+01	-1.81E+01	-7.91E-01	1.36E-01	-6.70E-02	-7.77E-01	-1.85E-01	2.28E-01	-8.16E-01	-3.58E-01	-1.16E-02	-1.72E-01	1.44E+00	8.75E-02	1.30E+02	9.81E-01	1.06E+00	2.05E-01
61	1.33E+07	1.25E+07	-1.19E+01	3.50E-11	-1.58E+01	-1.59E+01	-1.73E+01	-7.09E-01	7.89E-02	9.04E-01	-3.49E-02	1.02E-01	-2.38E-01	-1.02E-01	-4.96E-01	-1.48E-01	-1.49E-01	2.46E-01	9.09E-01	3.84E+02	9.29E-01	1.02E+00	3.24E-01
62	1.13E+07	1.20E+07	-1.07E+01	5.40E-11	-1.41E+01	-1.48E+01	-1.84E+01	-4.57E-01	5.85E-02	-2.17E-01	7.36E-02	9.92E-01	-9.55E-03	-1.68E-02	-4.58E-01	3.94E-01	9.17E-02	1.55E+00	5.88E-01	2.83E+02	2.63E-01	1.17E+00	2.65E-01
63	1.23E+07	1.27E+07	-1.09E+01	5.53E-11	-1.17E+01	-1.50E+01	-1.89E+01	8.37E-01	1.84E-01	-2.25E-01	-1.60E+00	-1.74E-01	-1.83E-01	4.60E-01	-7.82E-03	-3.61E-01	-2.37E-01	7.26E-02	4.81E-01	8.98E+02	8.51E-01	1.24E+00	2.58E-01
64	1.24E+07	1.12E+07	-1.30E+01	5.29E-11	-1.62E+01	-1.40E+01	-1.90E+01	-3.79E-01	-3.84E-02	-7.90E-02	2.02E-01	-1.94E-01	-5.05E-02	1.81E-01	-6.89E-01	1.65E-01	-1.96E-01	1.54E+00	7.96E-01	8.07E+02	3.62E-01	1.83E+00	4.57E-01
65	1.13E+07	1.23E+07	-1.13E+01	6.86E-11	-1.50E+01	-1.78E+01	-1.79E+01	2.13E-01	2.31E-01	-1.18E-01	-5.93E-01	6.16E-01	-2.43E-02	-2.17E-01	5.25E-01	-2.06E-01	-8.11E-02	1.57E+00	8.84E-01	4.33E+02	2.76E-02	1.07E+00	3.08E-01
66	1.23E+07	1.31E+07	-1.09E+01	3.62E-11	-1.15E+01	-1.77E+01	-1.82E+01	-8.03E-02	8.43E-01	2.36E-01	1.09E+00	-7.48E-01	1.29E-01	-7.32E-01	2.50E-01	-3.09E-01	-8.46E-01	8.72E-01	9.39E-01	9.40E+02	1.17E-01	2.05E+00	2.76E-01
67	1.31E+07	1.29E+07	-1.35E+01	7.87E-11	-1.34E+01	-1.38E+01	-1.76E+01	-2.41E-01	-1.19E-01	-2.61E-01	-7.77E-02	-2.06E-01	-5.09E-01	-1.33E-01	1.21E+00	-2.28E-01	1.53E-01	2.75E-01	8.94E-01	1.82E+02	3.53E-01	1.18E+00	2.93E-01
68	1.39E+07	1.37E+07	-1.10E+01	3.78E-11	-1.45E+01	-1.70E+01	-1.90E+01	-8.37E-03	1.07E-01	-1.78E-01	-1.35E-01	-8.41E-01	-2.65E-01	-6.65E-01	6.79E-03	-6.87E-01	-1.45E+00	6.97E-01	6.76E-03	7.38E+02	5.27E-01	1.14E+00	1.92E-01
69	1.35E+07	1.35E+07	-1.20E+01	4.94E-11	-1.32E+01	-1.65E+01	-1.87E+01	-2.16E-01	-8.43E-01	-2.48E-01	-2.47E-01	-5.19E-02	-6.82E-02	-1.11E+00	-8.37E-01	-1.61E-01	1.89E-01	1.27E+00	9.87E-01	5.81E+02	6.06E-01	1.09E+00	4.97E-01
70	1.36E+07	1.31E+07	-1.27E+01	7.09E-11	-1.49E+01	-1.70E+01	-1.84E+01	1.95E-01	7.79E-01	-2.07E-02	3.29E-01	-6.47E-03	-8.47E-01	2.93E-01	-1.48E+00	1.36E-01	1.41E-01	1.04E+00	6.75E-01	3.40E+02	5.46E-01	1.20E+00	1.01E-01
71	1.34E+07	1.19E+07	-1.27E+01	7.70E-11	-1.45E+01	-1.91E+01	-1.71E+01	-5.39E-02	6.68E-02	-1.59E+00	-7.47E-02	-8.12E-02	9.39E-01	1.45E-01	-2.21E-01	-8.42E-01	4.11E-01	7.55E-01	4.29E-01	7.74E+02	6.98E-01	1.86E+00	4.85E-01
72	1.34E+07	1.47E+07	-1.08E+01	5.22E-11	-1.37E+01	-1.30E+01	-1.81E+01	1.25E-01	-4.42E-02	-7.97E-01	4.21E-02	-2.17E-01	-1.91E-01	-3.33E-01	-4.62E-02	1.28E-01	-2.56E-01	6.60E-01	1.60E-01	1.04E+02	7.91E-01	1.04E+00	3.97E-01
73	1.21E+07	1.50E+07	-1.32E+01	8.18E-11	-1.27E+01	-1.29E+01	-1.72E+01	1.99E-02	-1.79E-01	-2.97E-01	-5.89E-03	-1.18E-01	1.91E-01	4.13E-01	1.11E-01	2.43E-01	-1.23E-01	1.28E-01	8.70E-01	6.10E+02	2.60E-01	1.54E+00	2.45E-01
74	1.21E+07	1.22E+07	-1.29E+01	6.43E-11	-1.60E+01	-1.82E+01	-1.89E+01	1.44E-01	-1.17E-02	8.35E-01	-8.42E-01	-9.38E-02	1.20E+00	-2.34E-01	4.32E-01	4.29E-01	-6.65E-01	1.20E+00	4.09E-01	7.55E+02	3.10E-01	1.03E+00	3.64E-01
75	1.12E+07	1.19E+07	-1.15E+01	5.15E-11	-1.33E+01	-1.41E+01	-1.78E+01	1.40E-01	4.23E-02	3.56E-01	-1.29E-01	-2.98E-01	1.06E-01	-1.26E-01	8.34E-02	-8.55E-02	-1.94E-02	4.45E-01	9.11E-01	6.30E+02	3.86E-01	2.19E+00	8.62E-02
76	1.37E+07	1.27E+07	-1.14E+01	3.90E-11	-1.21E+01	-1.44E+01	-1.88E+01	5.04E-02	6.93E-01	-4.47E-01	-1.18E+00	-7.01E-02	2.20E-01	-8.71E-02	2.21E-01	-1.79E-01	-3.40E-01	6.91E-01	6.81E-01	4.60E+02	4.92E-01	1.23E+00	8.43E-02
77	1.28E+07	1.59E+07	-1.36E+01	5.41E-11	-1.33E+01	-1.38E+01	-1.71E+01	-4.90E-01	5.15E-01	9.49E-02	-1.18E-01	-1.06E-01	1.56E-01	-8.62E-01	-5.49E-02	-1.45E-01	3.58E-01	2.71E-01	3.47E-01	4.03E+02	2.24E-01	1.15E+00	4.16E-01
78	1.12E+07	1.41E+07	-1.11E+01	3.15E-11	-1.15E+01	-1.51E+01	-1.75E+01	-2.34E-01	1.51E-01	-1.03E+00	5.23E-02	3.66E-02	-4.05E-01	-4.77E-01	1.62E-01	-1.52E+00	-8.95E-01	1.60E+00	5.64E-01	4.64E+02	1.04E-01	1.22E+00	3.74E-01
79	1.22E+07	1.57E+07	-1.08E+01	2.79E-11	-1.23E+01	-1.84E+01	-1.73E+01	-1.61E-02	5.58E-01	-9.17E-01	8.18E-01	-1.76E-02	4.66E-01	3.54E-01	-1.66E-02	1.12E+00	1.60E-01	1.31E+00	7.44E-02	3.08E+02	9.61E-01	1.05E+00	3.69E-01
80	1.15E+07	1.30E+07	-1.38E+01	8.14E-11	-1.40E+01	-1.88E+01	-1.74E+01	-7.59E-01	-1.70E-01	-4.17E-01	-1.32E+00	-1.99E-01	-7.23E-01	-4.20E-02	7.06E-01	5.93E-02	6.82E-02	8.23E-01	3.64E-01	5.43E+02	8.45E-01	1.09E+00	1.26E-01
81	1.16E+07	1.54E+07	-1.19E+01	5.67E-11	-1.21E+01	-1.61E+01	-1.80E+01	-4.30E-01	-1.97E-01	-1.96E-01	-3.61E-01	4.37E-01	-2.02E-01	6.04E-01	9.76E-01	1.72E-01	6.58E-01	1.41E+00	6.32E-01	1.87E+01	6.36E-01	1.71E+00	1.19E-01
82	1.11E+07	1.46E+07	-1.28E+01	3.97E-11	-1.18E+01	-1.88E+01	-1.87E+01	4.79E-01	-9.84E-01	-6.69E-01	2.31E-01	1.24E-01	-4.27E-01	4.81E-03	1.80E-01	-9.36E-01	-2.76E-01	1.26E+00	7.26E-01	2.15E+02	5.79E-01	1.11E+00	3.72E-01
83	1.31E+07	1.21E+07	-1.22E+01	3.31E-11	-1.49E+01	-1.74E+01	-1.78E+01	5.73E-01	-7.04E-02	-8.63E-02	1.50E-01	-2.42E-01	-1.31E+00	-1.58E-01	-4.43E-01	-2.72E-01	1.34E-02	4.11E-01	1.12E-01	7.36E+01	2.84E-01	1.21E+00	3.87E-01
84	1.25E+07	1.27E+07	-1.25E+01	3.66E-11	-1.19E+01	-1.26E+01	-1.82E+01	-9.74E-02	-2.11E-01	-1.65E-01	-1.47E-02	8.09E-01	1.74E-01	-5.53E-04	-1.60E-01	5.40E-01	-1.08E+00	3.47E-01	3.11E-02	3.17E+02	5.08E-02	1.20E+00	2.41E-01
85	1.27E+07	1.37E+07	-1.25E+01	6.29E-11	-1.38E+01	-1.83E+01	-1.82E+01	1.64E-01	-4.34E-01	1.55E-01	7.25E-01	-3.69E-01	-7.98E-02	2.44E-01	-1.19E-01	9.92E-01	-1.07E-01	1.35E+00	7.71E-01	9.59E+02	5.32E-01	1.04E+00	1.10E-01
86	1.11E+07	1.49E+07	-1.05E+01	3.41E-11	-1.53E+01	-1.55E+01	-1.79E+01	7.28E-02	2.21E-01	-1.04E-01	-2.57E-02	-2.09E-01	6.16E-01	-2.61E-01	-2.41E-01	-1.88E-01	-1.53E-01	1.17E+00	6.95E-01	6.86E+02	7.61E-01	1.04E+00	4.04E-01
87	1.13E+07	1.21E+07	-1.24E+01	4.89E-11	-1.39E+01	-1.62E+01	-1.85E+01	-6.37E-01	1.08E+00	6.00E-02	-4.98E-01	2.92E-02	-4.93E-01	-6.63E-02	-3.91E-01	-1.82E-01	2.84E-02	1.32E+00	6.13E-01	8.61E+02	8.19E-01	1.09E+00	4.60E-01
88	1.21E+07	1.30E+07	-1.31E+01	6.66E-11	-1.48E+01	-1.37E+01	-1.86E+01	5.34E-01	-3.75E-01	-2.84E-01	9.82E-01	-1.73E-01	2.65E-02	-1.83E-01	4.12E-02	-9.53E-02	1.09E-01	6.29E-01	9.47E-01	3.64E+02	7.40E-01	1.82E+00	3.47E-01
89	1.22E+07	1.32E+07	-1.31E+01	8.65E-11	-1.30E+01	-1.94E+01	-1.78E+01	-2.94E-03	-5.28E-02	4.45E-01	2.23E-01	7.81E-01	-1.37E-01	-2.01E-01	-7.15E-02	-4.81E-01	1.05E-02	1.40E+00	3.02E-01	6.60E+02	6.86E-01	1.72E+00	2.90E-01
90	1.31E+07	1.33E+07	-1.13E+01	3.21E-11	-1.16E+01	-1.85E+01	-1.85E+01	-1.09E+00	-2.20E-01	-3.39E-02	-4.32E-01	-1.64E-01	1.18E-01	5.70E-02	-2.61E-01	6.82E-01	1.98E-01	1.51E+00	8.68E-01	9.83E+02	2.14E-01	1.78E+00	1.45E-01
91	1.38E+07	1.31E+07	-1.18E+01	4.11E-11	-1.11E+01	-1.35E+01	-1.86E+01	1.10E-01	-2.48E-01	1.99E-01	5.75E-01	4.78E-01	-3.03E-02	-5.53E-01	1.48E-01	1.44E-01	4.71E-01	1.45E+00	7.06E-01	1.73E+02	3.49E-02	1.15E+00	1.61E-01
92	1.26E+07	1.42E+07	-1.25E+01	4.37E-11	-1.54E+01	-1.91E+01	-1.75E+01	-1.57E-01	-4.48E-01	7.19E-01	-2.16E-01	-1.32E-01	2.60E-01	-2.72E-01	-1.09E-01	-1.45E+00	-2.06E-01	1.51E+00	2.08E-01	5.91E+02	6.17E-01	2.09E+00	2.31E-01
93	1.35E+07	1.55E+07	-1.45E+01	9.02E-11	-1.39E+01	-1.72E+01	-1.89E+01	9.06E-02	-1.66E-01	5.41E-02	2.02E-02	2.31E-01	7.45E-01	5.44E-01	-4.34E-04	3.39E-02	-4.02E-01	1.21E+00	8.04E-01	3.23E+02	8.70E-01	2.12E+00	4.23E-01
94	1.37E+07	1.26E+07	-1.37E+01	7.94E-11	-1.42E+01	-1.64E+01	-1.81E+01	-2.65E-01	2.10E-01	-1.36E+00	-1.95E-01	2.14E-01	4.41E-02	-9.48E-02	-1.35E-01	8.73E-02	7.49E-02	1.43E+00	2.29E-01	8.56E+02	4.49E-01	1.01E+00	2.10E-01
95	1.32E+07	1.45E+07	-1.22E+01	7.43E-11	-1.31E+01	-1.86E+01	-1.88E+01	-4.74E-01	2.02E-01	2.56E-02	-9.36E-02	7.06E-01	-1.63E-01	2.29E-01	4.75E-01	-1.08E-01	-4.49E-01	1.59E+00	4.55E-01	2.72E+02	9.94E-01	1.06E+00	4.29E-01
96	1.15E+07	1.30E+07	-1.36E+01	5.78E-11	-1.55E+01	-1.30E+01	-1.85E+01	-5.58E-02	-2.84E-02	1.28E-01	-1.03E-01	-4.14E-01	-3.49E-01	1.02E-01	6.90E-01	-2.11E-01	-7.23E-01	1.59E+00	1.64E-01	6.52E+02	8.98E-01	1.20E+00	2.21E-01
97	1.19E+07	1.26E+07	-1.26E+01	5.60E-11	-1.23E+01	-1.58E+01	-1.70E+01	-1.88E-01	-1.14E-01	-4.87E-01	-7.75E-03	-9.75E-02	-1.43E-01	-4.88E-01	-2.05E-01	2.27E-01	-1.78E-01	8.99E-01	5.28E-01	7.90E+02	9.74E-01	1.52E+00	4.12E-01
98	1.38E+07	1.36E+07	-1.21E+01	4.46E-11	-1.42E+01	-1.79E+01	-1.87E+01	-1.43E-01	-6.32E-02	-1.44E-01	2.81E-01	-6.30E-02	2.41E-01	-4.15E-02	-1.65E-01	-6.48E-01	-2.19E-03	1.45E+00	3.77E-01	1.63E+02	8.38E-01	1.10E+00	4.33E-01
99	1.28E+07	1.18E+07	-1.41E+01	9.53E-11	-1.33E+01	-1.49E+01	-1.72E+01	-2.44E-01	-2.63E-01	-2.33E-01	-4.82E-01	-8.77E-02	6.82E-01	1.35E-02	-1.73E-01	-2.64E-02	-1.86E-01	4.76E-01	1.08E-01	6.73E+02	2.31E-01	1.08E+00	2.55E-01
100	1.12E+07	1.32E+07	-1.27E+01	6.01E-11	-1.47E+01	-1.67E+01	-1.74E+01	-2.26E-01	-1.01E-01	-3.86E-01	3.99E-01	-4.39E-01	-1.97E-01	-1.89E-01	2.74E-02	-3.24E-01	-2.49E-01	6.02E-01	5.41E-01	6.27E+02	6.54E-01	1.16E+00	1.78E-01

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Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
1	1.14E-03	1.20E-01	3.25E-03	2.06E+00	2.66E-02	1.53E+00	5.20E+00	3.89E-02	1.03E+00	4.85E-01	7.01E+00	3.86E-01	2.05E-01	-1.79E+01	-1.79E+01	-2.08E+01	1.66E-01
2	2.01E-04	1.72E-01	1.31E-02	4.61E+00	5.43E-02	5.02E+00	2.22E+00	2.04E-02	1.09E+01	2.00E-01	1.15E+01	5.10E-01	1.46E-01	-1.87E+01	-1.85E+01	-2.01E+01	3.58E-01
3	1.66E-03	1.41E-01	4.46E-04	2.23E+00	3.93E-02	8.22E+00	6.69E+00	2.64E-02	3.65E+01	3.73E-01	6.30E+00	1.90E-01	3.48E-01	-1.80E+01	-1.70E+01	-2.04E+01	1.71E-01
4	1.03E-04	1.46E-01	1.45E-02	1.88E+00	1.01E-01	2.28E+00	1.26E+00	6.96E-02	5.40E+00	3.24E-01	9.11E+00	3.69E-02	3.30E-01	-1.82E+01	-1.70E+01	-2.02E+01	3.26E-01
5	3.82E-04	1.80E-01	1.84E-03	4.78E+00	6.50E-02	1.50E+00	2.58E+00	1.81E-01	2.42E-01	1.73E-01	7.05E+00	2.54E-01	1.90E-01	-1.77E+01	-1.87E+01	-2.04E+01	5.72E-01
6	2.87E-04	1.45E-01	2.83E-04	6.97E+00	1.16E-01	4.20E+00	1.29E+00	6.56E-02	6.25E-02	3.30E-01	1.25E+01	5.28E-01	1.04E-01	-1.80E+01	-1.72E+01	-2.17E+01	8.18E-01
7	1.87E-04	1.10E-01	1.95E-03	3.77E+00	5.01E-02	2.72E+00	5.87E+00	1.20E-01	8.56E+00	1.26E-02	6.49E+00	2.36E-01	2.14E-01	-1.82E+01	-1.82E+01	-2.01E+01	6.89E-01
8	1.10E-04	1.11E-01	1.07E-04	8.51E-01	5.81E-02	8.05E+00	2.74E+00	2.20E-01	1.30E-01	5.88E-02	7.47E+00	2.75E-01	2.34E-02	-1.89E+01	-1.91E+01	-1.96E+01	3.26E-02
9	2.69E-03	1.85E-01	4.01E-03	2.64E+00	1.85E-01	3.77E+00	1.59E+00	2.36E-01	1.35E+00	1.80E-01	1.84E+01	5.47E-01	2.76E-01	-1.79E+01	-1.83E+01	-1.94E+01	7.45E-01
10	1.19E-03	1.65E-01	3.91E-03	2.57E+00	3.17E-02	8.66E-01	2.34E+00	7.87E-02	5.43E-02	2.09E-01	1.30E+01	2.22E-01	1.31E-01	-1.83E+01	-1.80E+01	-2.05E+01	9.88E-01
11	7.85E-04	1.24E-01	5.59E-05	7.83E+00	2.32E-02	5.39E+00	8.75E+00	5.81E-02	7.41E-02	4.18E-01	5.32E+00	2.84E-02	2.94E-01	-1.87E+01	-1.83E+01	-1.85E+01	8.25E-01
12	3.38E-03	1.90E-01	4.10E-04	8.59E+00	2.27E-01	6.40E+00	6.84E+00	1.02E-01	1.04E-01	4.75E-01	4.65E+00	1.71E-01	2.77E-01	-1.87E+01	-1.94E+01	-1.97E+01	1.57E-01
13	5.83E-03	1.80E-01	1.51E-03	1.47E+00	1.63E-01	1.20E+00	5.45E+00	1.58E-01	3.02E-01	9.01E-02	7.13E+00	8.40E-02	3.98E-01	-2.03E+01	-1.85E+01	-1.99E+01	9.18E-01
14	1.94E-03	1.76E-01	3.03E-04	2.98E+00	4.02E-02	6.56E+00	1.13E+00	8.38E-02	5.11E+01	4.69E-01	7.18E+00	5.97E-01	8.03E-02	-2.00E+01	-1.74E+01	-2.03E+01	5.63E-01
15	6.16E-03	1.81E-01	9.41E-04	4.29E+00	3.39E-01	9.10E-01	2.08E+00	2.50E-02	5.00E-01	3.90E-01	8.22E+00	5.86E-01	5.15E-02	-1.89E+01	-1.75E+01	-1.97E+01	3.82E-01
16	2.79E-03	1.74E-01	1.16E-03	9.95E+00	2.88E-01	1.44E+00	7.25E+00	9.41E-02	4.77E+01	1.09E-01	8.24E+00	3.66E-01	3.53E-01	-1.77E+01	-1.86E+01	-1.95E+01	2.28E-01
17	8.32E-04	1.15E-01	1.45E-04	7.95E-01	2.85E-02	4.98E+00	7.86E-01	2.13E-01	1.82E+00	5.75E-01	8.38E+00	0	1.32E-01	-1.81E+01	-1.92E+01	-1.99E+01	1.95E-01
18	6.56E-04	1.59E-01	8.99E-05	8.92E-01	1.78E-01	2.87E+00	1.36E+00	4.57E-02	5.62E-01	5.70E-01	8.14E+00	3.35E-01	3.05E-01	-1.98E+01	-1.74E+01	-1.99E+01	6.72E-01
19	4.02E-03	1.75E-01	7.07E-04	8.45E+00	1.47E-01	7.04E-01	7.31E-01	2.79E-02	6.90E+00	5.08E-01	6.02E+00	1.27E-01	1.41E-01	-1.83E+01	-1.84E+01	-2.00E+01	4.17E-01
20	1.65E-04	1.67E-01	5.77E-04	3.34E+00	3.33E-02	1.95E+00	7.43E+00	9.03E-02	1.51E+00	5.36E-01	8.19E+00	8.50E-03	3.24E-01	-1.88E+01	-1.81E+01	-1.90E+01	8.82E-01
21	5.78E-04	1.12E-01	2.08E-04	7.35E+00	3.73E-01	4.65E+00	1.37E+00	1.13E-01	3.43E+00	2.64E-01	1.56E+01	8.99E-02	2.53E-02	-2.03E+01	-1.73E+01	-2.07E+01	3.97E-01
22	3.21E-04	1.51E-01	1.10E-03	4.44E+00	3.02E-02	4.81E+00	1.63E+00	8.01E-02	4.80E-01	4.95E-01	7.93E+00	4.04E-01	3.95E-01	-1.84E+01	-1.85E+01	-1.93E+01	7.73E-02
23	4.06E-04	1.66E-01	4.29E-03	8.00E-01	1.95E-01	5.14E+00	1.53E+00	2.53E-01	2.46E+00	9.27E-02	5.57E+00	5.83E-01	1.55E-01	-1.90E+01	-1.84E+01	-2.14E+01	9.26E-01
24	2.22E-03	1.96E-01	1.02E-03	1.15E+00	3.99E-01	2.50E+00	3.56E+00	2.28E-02	6.11E-01	2.34E-01	9.71E+00	1.37E-01	3.59E-01	-1.92E+01	-1.80E+01	-2.07E+01	2.35E-01
25	1.39E-04	1.82E-01	5.15E-05	2.70E+00	2.78E-02	3.18E+00	1.04E+00	3.54E-01	8.20E-01	1.57E-01	6.78E+00	4.65E-01	3.92E-01	-1.91E+01	-1.89E+01	-2.11E+01	5.84E-01
26	4.53E-03	1.65E-01	7.55E-03	4.13E+00	1.69E-01	8.97E+00	9.99E-01	2.74E-02	3.20E-01	3.04E-02	7.37E+00	1.41E-01	4.70E-02	-1.74E+01	-1.75E+01	-2.18E+01	9.08E-01
27	1.06E-03	1.35E-01	2.13E-03	1.96E+00	1.38E-01	2.06E+00	8.21E-01	1.09E-01	1.94E+00	3.17E-01	7.06E+00	4.96E-03	1.02E-01	-1.75E+01	-1.84E+01	-1.98E+01	8.60E-01
28	3.07E-03	2.36E-01	1.48E-03	1.39E+00	9.94E-02	1.66E+00	2.93E+00	6.16E-02	2.03E-01	2.47E-01	1.13E+01	4.77E-01	1.68E-01	-1.78E+01	-1.76E+01	-1.82E+01	6.70E-02
29	3.65E-04	2.28E-01	2.37E-04	7.61E-01	5.90E-02	1.15E+00	3.85E+00	1.00E-01	1.56E+01	4.30E-01	4.98E+00	3.11E-01	5.72E-02	-1.84E+01	-1.88E+01	-1.86E+01	1.04E-01
30	1.16E-04	1.08E-01	3.37E-05	1.21E+00	2.53E-02	2.34E+00	3.39E+00	4.94E-02	6.22E+00	4.14E-01	7.28E+00	1.47E-01	2.19E-01	-1.92E+01	-1.80E+01	-2.05E+01	5.01E-01
31	7.69E-03	2.48E-01	9.54E-04	6.82E+00	4.76E-02	6.81E+00	4.51E+00	3.82E-01	2.95E+01	4.01E-01	1.20E+01	4.63E-01	2.52E-01	-1.88E+01	-1.77E+01	-1.97E+01	9.86E-02
32	3.25E-03	1.07E-01	1.66E-04	2.19E+00	2.92E-02	6.15E+00	1.84E+00	2.54E-02	7.59E-01	4.42E-01	7.53E+00	1.15E-01	3.65E-02	-1.76E+01	-1.83E+01	-2.07E+01	7.87E-01
33	1.95E-04	1.77E-01	9.51E-05	8.70E-01	3.12E-01	3.05E+00	3.16E+00	1.32E-01	4.45E-01	2.85E-01	2.23E+01	3.09E-03	1.86E-01	-1.84E+01	-1.82E+01	-2.13E+01	3.06E-01
34	4.73E-04	1.00E-01	4.04E-05	1.24E+00	2.35E-01	1.98E+00	6.21E+00	3.21E-02	5.59E+01	3.37E-01	1.05E+01	2.96E-01	2.25E-01	-1.85E+01	-1.78E+01	-2.05E+01	4.77E-02
35	1.77E-04	1.70E-01	8.71E-04	9.11E+00	3.44E-02	9.87E+00	4.28E+00	2.43E-01	3.05E+01	6.90E-02	8.01E+00	4.51E-01	4.14E-02	-1.79E+01	-1.81E+01	-1.96E+01	6.34E-01
36	2.13E-03	1.18E-01	8.57E-03	1.82E+00	4.32E-02	7.81E+00	1.90E+00	1.23E-01	8.98E-02	5.51E-01	4.40E+00	4.26E-01	2.66E-01	-1.80E+01	-1.71E+01	-2.12E+01	4.66E-01
37	1.30E-04	2.07E-01	3.23E-03	4.26E+00	1.44E-01	8.48E+00	1.75E+00	1.07E-01	6.62E+01	2.60E-01	1.40E+01	9.45E-02	2.82E-01	-1.94E+01	-1.80E+01	-2.00E+01	4.48E-01
38	1.76E-03	1.63E-01	5.29E-04	9.54E-01	6.17E-02	1.76E+00	7.50E+00	2.83E-01	1.90E-01	3.48E-01	1.03E+01	1.76E-01	6.78E-02	-1.76E+01	-1.83E+01	-2.19E+01	3.77E-01
39	1.46E-03	1.19E-01	2.81E-03	2.92E+00	1.99E-01	4.51E+00	5.05E+00	8.73E-02	2.23E+01	1.82E-01	7.79E+00	3.98E-01	8.59E-02	-1.91E+01	-1.73E+01	-1.90E+01	3.61E-01
40	4.25E-04	1.06E-01	1.63E-03	2.38E+00	9.28E-02	3.68E+00	8.19E+00	2.02E-01	4.57E+01	2.97E-01	8.09E+00	5.66E-01	2.85E-01	-1.86E+01	-1.94E+01	-2.15E+01	7.03E-01
41	2.60E-03	1.13E-01	1.42E-04	2.39E+00	4.13E-02	1.23E+00	1.41E+00	7.54E-02	1.37E+01	2.27E-02	6.52E+00	1.67E-02	7.65E-02	-1.92E+01	-1.81E+01	-1.87E+01	8.88E-02
42	3.88E-03	1.64E-01	6.34E-04	5.19E+00	2.70E-01	6.01E+00	2.29E+00	1.28E-01	2.10E+01	5.97E-01	1.37E+01	1.32E-01	2.03E-01	-1.82E+01	-1.99E+01	-1.98E+01	4.04E-01
43	3.11E-04	1.76E-01	1.84E-02	2.00E+00	3.63E-02	6.97E+00	9.22E+00	3.56E-02	9.52E-02	3.55E-01	7.25E+00	7.55E-02	3.22E-02	-1.93E+01	-1.95E+01	-2.01E+01	2.99E-02
44	3.38E-04	1.12E-01	5.64E-03	1.27E+00	6.37E-02	2.60E+00	1.66E+00	3.50E-02	1.84E-01	7.80E-02	1.10E+01	5.68E-01	2.42E-01	-1.99E+01	-1.76E+01	-1.93E+01	1.38E-01
45	8.17E-04	1.16E-01	2.62E-03	5.03E+00	2.50E-01	1.01E+00	1.19E+00	3.02E-01	1.89E+01	5.25E-01	6.04E+00	2.10E-01	3.45E-01	-1.70E+01	-1.76E+01	-2.24E+01	2.17E-01
46	1.32E-03	1.40E-01	1.35E-02	2.28E+00	2.12E-01	3.58E+00	9.50E-01	2.95E-02	4.17E-01	5.57E-01	4.21E+00	4.11E-01	3.41E-01	-1.74E+01	-1.81E+01	-1.92E+01	2.04E-01
47	6.48E-03	1.69E-01	7.41E-05	7.22E-01	3.76E-02	1.26E+00	7.72E+00	9.71E-02	1.24E+00	1.51E-01	1.01E+01	1.84E-01	3.12E-01	-1.86E+01	-1.77E+01	-1.91E+01	5.32E-01
48	1.58E-04	1.68E-01	1.26E-03	5.90E+00	2.99E-01	9.45E-01	7.04E-01	3.62E-01	6.16E-02	1.44E-01	5.30E+00	2.25E-01	2.60E-01	-1.96E+01	-1.78E+01	-1.89E+01	8.79E-01
49	3.66E-03	1.61E-01	1.29E-04	3.60E+00	1.67E-01	3.40E+00	9.35E-01	7.35E-02	3.90E-01	3.81E-01	7.83E+00	1.23E-01	3.75E-01	-1.97E+01	-1.81E+01	-2.06E+01	1.65E-02
50	5.25E-04	1.31E-01	4.87E-04	6.57E+00	5.32E-02	4.01E+00	1.93E+00	6.65E-02	7.77E+00	5.30E-01	9.95E+00	4.45E-01	3.65E-01	-1.81E+01	-1.90E+01	-2.10E+01	9.94E-01
51	2.33E-04	1.57E-01	4.99E-03	1.36E+00	2.18E-02	1.82E+00	8.76E+00	2.40E-02	6.84E-02	1.13E-01	1.22E+01	4.18E-02	3.39E-01	-1.85E+01	-1.76E+01	-1.93E+01	6.19E-01
52	2.69E-04	1.88E-01	2.73E-04	1.79E+00	2.42E-01	1.31E+00	3.77E+00	3.07E-01	1.65E-01	8.36E-02	6.21E+00	4.54E-02	9.37E-02	-1.77E+01	-1.79E+01	-1.88E+01	2.58E-01
53	4.46E-04	1.21E-01	4.67E-03	3.53E+00	1.27E-01	3.02E+00	8.77E-01	1.40E-01	5.62E+00	2.54E-01	1.62E+01	3.48E-01	2.45E-01	-1.82E+01	-1.93E+01	-1.81E+01	7.58E-01

Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
54	8.44E-03	1.14E-01	1.58E-02	1.12E+00	4.82E-02	1.12E+00	1.12E+00	5.14E-02	3.14E+00	3.86E-02	4.49E+00	1.12E-01	2.88E-01	-1.95E+01	-1.87E+01	-1.92E+01	5.56E-01
55	1.44E-03	1.50E-01	1.68E-02	5.54E+00	3.24E-02	1.06E+00	1.71E+00	5.68E-02	4.21E+01	1.66E-01	6.83E+00	2.80E-01	2.23E-01	-1.88E+01	-1.77E+01	-2.09E+01	2.45E-01
56	1.32E-04	1.58E-01	5.77E-05	9.37E-01	7.58E-02	1.69E+00	7.07E+00	2.18E-01	7.10E+01	2.93E-01	6.88E+00	5.58E-01	3.19E-01	-1.88E+01	-1.79E+01	-2.02E+01	5.50E-01
57	9.99E-03	1.48E-01	3.06E-05	6.16E+00	4.38E-02	2.17E+00	7.73E-01	2.21E-02	1.02E+01	1.61E-01	7.66E+00	1.17E-01	2.98E-01	-1.95E+01	-1.80E+01	-1.94E+01	4.57E-01
58	9.72E-04	1.72E-01	1.78E-04	8.21E+00	7.74E-02	1.60E+00	2.00E+00	2.70E-01	2.03E+00	1.60E-02	9.47E+00	1.05E-01	2.60E-01	-1.95E+01	-1.90E+01	-2.05E+01	2.88E-01
59	7.06E-04	2.12E-01	1.13E-02	1.71E+00	7.41E-02	9.14E-01	3.72E+00	1.99E-01	1.31E+01	2.39E-01	8.45E+00	6.43E-02	2.71E-01	-1.90E+01	-1.83E+01	-2.00E+01	9.57E-01
60	6.14E-04	1.83E-01	6.59E-04	7.10E-01	1.06E-01	3.54E+00	3.22E+00	1.39E-01	9.78E+00	4.28E-01	7.86E+00	1.47E-02	3.70E-01	-1.72E+01	-1.77E+01	-2.03E+01	9.38E-01
61	1.65E-03	1.86E-01	9.73E-03	1.58E+00	2.62E-02	2.25E+00	1.23E+00	4.14E-02	4.55E+00	5.87E-01	8.29E+00	2.58E-01	9.70E-03	-2.01E+01	-1.89E+01	-2.06E+01	6.58E-01
62	3.54E-03	1.55E-01	1.98E-02	7.26E+00	2.21E-02	9.79E-01	2.94E+00	3.21E-01	1.41E+00	5.91E-01	7.48E+00	1.58E-01	1.12E-01	-1.93E+01	-1.78E+01	-2.03E+01	7.66E-01
63	4.89E-04	1.28E-01	2.24E-03	2.47E+00	4.55E-02	4.41E+00	3.96E+00	5.43E-02	7.24E-01	4.39E-01	6.38E+00	1.64E-01	3.79E-01	-1.89E+01	-1.82E+01	-1.94E+01	2.94E-01
64	1.26E-03	1.83E-01	5.28E-03	3.44E+00	2.73E-01	5.59E+00	4.95E+00	1.53E-01	4.96E+00	2.18E-01	8.65E+00	2.02E-01	2.38E-01	-1.83E+01	-1.71E+01	-1.97E+01	4.83E-01
65	1.53E-03	2.24E-01	3.76E-04	1.05E+00	3.19E-01	3.35E+00	1.07E+00	1.76E-01	2.85E-01	2.28E-01	1.18E+01	1.96E-01	2.09E-01	-1.70E+01	-1.90E+01	-2.04E+01	1.46E-01
66	5.00E-03	1.78E-01	7.47E-04	1.18E+00	1.57E-01	8.03E-01	8.39E+00	4.63E-02	1.14E-01	5.01E-01	8.35E+00	3.77E-01	6.38E-02	-1.86E+01	-1.84E+01	-2.17E+01	1.19E-01
67	5.44E-03	1.11E-01	2.18E-04	5.33E+00	8.01E-02	2.80E+00	9.84E+00	2.32E-01	7.00E-01	5.19E-01	9.10E+00	5.34E-01	8.90E-02	-1.76E+01	-1.87E+01	-1.92E+01	5.21E-01
68	2.40E-04	1.30E-01	5.11E-04	8.77E+00	2.24E-01	7.36E-01	9.48E+00	3.24E-02	1.32E-01	5.45E-01	8.94E+00	1.03E-01	1.77E-01	-1.78E+01	-1.82E+01	-2.02E+01	5.10E-01
69	1.67E-04	1.60E-01	3.61E-05	3.12E+00	5.68E-02	8.49E-01	4.75E+00	3.04E-02	3.81E+00	4.25E-02	9.26E+00	4.91E-01	1.57E-02	-1.73E+01	-1.84E+01	-1.86E+01	7.31E-01
70	9.37E-03	1.17E-01	7.84E-04	1.03E+00	1.35E-01	9.63E+00	4.23E+00	6.40E-02	1.60E-01	2.42E-01	6.97E+00	3.38E-01	3.27E-01	-1.89E+01	-1.86E+01	-2.09E+01	8.49E-01
71	2.39E-03	1.15E-01	3.60E-03	8.35E-01	2.15E-01	1.58E+00	2.63E+00	5.36E-02	1.64E+00	1.33E-01	8.76E+00	4.21E-01	3.82E-01	-1.75E+01	-1.92E+01	-2.10E+01	6.26E-01
72	5.58E-04	1.71E-01	1.15E-04	7.42E-01	1.08E-01	6.36E+00	9.02E-01	4.32E-02	8.35E+00	1.39E-01	6.72E+00	1.77E-01	3.12E-01	-1.75E+01	-1.82E+01	-2.02E+01	8.61E-01
73	3.58E-04	1.84E-01	7.79E-05	5.65E+00	8.28E-02	1.43E+00	5.30E+00	6.03E-02	2.41E+01	4.54E-01	5.74E+00	9.62E-02	1.16E-01	-1.84E+01	-1.88E+01	-1.91E+01	9.78E-01
74	2.41E-03	1.03E-01	6.55E-03	1.07E+00	1.12E-01	5.79E+00	2.41E+00	1.60E-01	2.02E+01	2.11E-01	9.87E+00	2.01E-02	3.17E-02	-1.79E+01	-1.82E+01	-1.95E+01	6.61E-01
75	2.91E-04	1.29E-01	5.92E-03	9.82E-01	1.23E-01	1.36E+00	1.09E+00	2.72E-01	1.23E+01	3.61E-01	7.32E+00	5.18E-01	1.77E-02	-1.72E+01	-1.80E+01	-1.89E+01	6.93E-01
76	6.75E-03	1.82E-01	4.51E-05	1.43E+00	5.16E-02	1.83E+00	1.17E+00	3.76E-01	3.33E+01	1.88E-01	7.60E+00	5.74E-02	3.46E-03	-1.94E+01	-1.89E+01	-2.19E+01	5.08E-02
77	8.04E-03	2.20E-01	1.21E-02	1.31E+00	3.07E-02	9.44E+00	4.06E+00	4.85E-02	1.11E+00	2.71E-01	7.95E+00	2.98E-01	6.86E-02	-1.73E+01	-1.81E+01	-1.98E+01	8.37E-01
78	4.36E-03	1.87E-01	1.32E-03	3.99E+00	2.56E-01	7.18E+00	9.70E+00	3.26E-01	1.71E+01	4.11E-01	6.47E+00	7.01E-02	1.38E-01	-1.75E+01	-1.71E+01	-1.89E+01	6.00E-01
79	4.70E-03	1.43E-01	1.70E-03	9.34E+00	2.35E-02	3.24E+00	8.22E-01	1.91E-01	3.77E+01	3.99E-01	1.93E+01	2.43E-02	3.01E-01	-1.81E+01	-1.74E+01	-1.99E+01	2.72E-01
80	2.96E-03	1.16E-01	3.40E-04	3.90E+00	7.13E-02	1.91E+00	2.65E+00	1.73E-01	5.25E-02	2.78E-01	1.29E+01	2.66E-01	2.36E-01	-1.71E+01	-1.77E+01	-1.94E+01	1.21E-01
81	1.02E-03	1.53E-01	1.10E-02	2.13E+00	9.58E-02	7.49E-01	4.79E+00	2.15E-02	6.18E+01	3.02E-01	6.57E+00	3.46E-02	7.50E-03	-1.83E+01	-1.86E+01	-2.14E+01	7.75E-01
82	8.84E-04	1.89E-01	2.52E-04	6.35E+00	1.78E-01	1.18E+00	2.50E+00	3.43E-02	3.49E-01	5.18E-02	1.04E+01	4.97E-01	1.50E-01	-1.90E+01	-1.87E+01	-2.15E+01	9.67E-01
83	5.22E-03	1.02E-01	1.88E-04	4.63E+00	3.55E-01	2.74E+00	2.12E+00	1.65E-01	3.02E+00	3.69E-01	5.80E+00	1.33E-01	1.25E-01	-1.84E+01	-1.72E+01	-2.11E+01	3.45E-01
84	2.20E-04	1.39E-01	9.71E-05	3.71E+00	8.95E-02	1.39E+00	3.45E+00	1.16E-01	1.47E+01	5.81E-01	9.52E+00	4.38E-01	3.85E-01	-1.81E+01	-1.85E+01	-2.03E+01	4.91E-01
85	1.83E-03	1.95E-01	3.86E-04	1.66E+00	6.72E-02	8.38E-01	5.66E+00	3.84E-02	7.41E+01	1.28E-01	6.68E+00	1.85E-01	3.64E-01	-1.78E+01	-1.84E+01	-2.06E+01	7.29E-01
86	8.72E-03	1.22E-01	1.25E-04	3.05E+00	3.33E-01	1.07E+00	7.98E+00	1.46E-01	2.40E+00	3.86E-01	6.64E+00	3.24E-01	1.73E-01	-1.78E+01	-1.88E+01	-2.00E+01	8.06E-01
87	2.53E-04	1.86E-01	3.19E-04	1.48E+00	3.82E-01	7.65E+00	9.66E-01	2.10E-02	2.72E+01	5.16E-01	5.06E+00	6.09E-02	9.80E-02	-1.79E+01	-1.86E+01	-1.96E+01	4.80E-01
88	1.47E-04	1.36E-01	6.58E-05	6.41E+00	1.20E-01	4.33E+00	7.41E-01	4.06E-02	1.47E-01	5.59E-01	1.08E+01	7.99E-02	1.94E-01	-1.77E+01	-1.89E+01	-1.91E+01	9.00E-01
89	2.08E-03	1.89E-01	1.61E-04	2.78E+00	2.09E-02	1.03E+00	8.46E-01	1.88E-01	4.10E+00	3.10E-01	8.02E+00	1.52E-01	1.82E-01	-1.82E+01	-1.82E+01	-2.02E+01	2.66E-01
90	2.09E-04	1.73E-01	8.02E-05	9.56E+00	8.75E-02	9.06E+00	1.78E+00	2.59E-01	2.73E+00	6.89E-02	4.89E+00	1.56E-01	2.28E-01	-1.78E+01	-1.83E+01	-2.01E+01	6.41E-01
91	7.30E-03	1.07E-01	2.87E-03	1.54E+00	2.02E-01	5.47E+00	2.18E+00	4.43E-02	3.55E+00	1.20E-01	1.16E+01	1.64E-01	3.35E-01	-1.85E+01	-1.89E+01	-1.87E+01	4.22E-01
92	6.71E-04	1.18E-01	9.79E-03	2.85E+00	1.31E-01	7.29E+00	6.51E+00	3.09E-02	5.81E-01	4.79E-01	7.69E+00	3.16E-01	1.99E-01	-1.97E+01	-1.85E+01	-1.83E+01	7.96E-01
93	7.58E-04	1.62E-01	2.47E-03	9.93E-01	1.50E-01	4.10E+00	4.45E+00	3.97E-01	8.05E-02	4.92E-01	6.41E+00	4.83E-02	1.16E-01	-1.99E+01	-1.84E+01	-2.10E+01	7.16E-01
94	1.22E-04	1.33E-01	8.81E-03	7.91E+00	2.82E-01	7.99E-01	5.95E+00	8.58E-02	8.92E-01	1.96E-01	6.92E+00	2.45E-01	1.68E-01	-1.85E+01	-1.86E+01	-2.04E+01	3.30E-03
95	1.31E-03	1.05E-01	4.76E-05	3.26E+00	3.55E-01	2.13E+00	3.06E+00	2.96E-01	9.43E-01	4.48E-01	7.42E+00	4.86E-01	7.49E-02	-1.91E+01	-1.78E+01	-1.87E+01	9.42E-01
96	5.14E-04	1.26E-01	7.06E-03	5.83E+00	2.43E-02	2.54E+00	1.44E+00	7.11E-02	2.18E+00	4.98E-02	7.62E+00	1.96E-01	2.55E-01	-1.71E+01	-1.91E+01	-2.12E+01	1.89E-01
97	1.06E-04	2.40E-01	6.54E-05	4.88E+00	6.87E-02	3.93E+00	3.33E+00	2.34E-02	1.09E-01	4.60E-01	6.61E+00	3.68E-01	5.31E-02	-1.87E+01	-1.78E+01	-2.08E+01	3.13E-01
98	5.63E-03	1.79E-01	4.19E-05	1.61E+00	2.03E-02	7.63E-01	1.48E+00	1.26E-01	2.32E-01	3.20E-01	7.19E+00	5.40E-01	1.63E-01	-1.76E+01	-1.79E+01	-1.93E+01	4.31E-01
99	7.24E-03	1.68E-01	3.67E-05	7.52E+00	3.71E-02	8.64E+00	6.15E+00	3.73E-02	2.69E-01	1.00E-01	7.75E+00	5.55E-02	1.59E-01	-1.80E+01	-1.76E+01	-2.21E+01	5.92E-01
100	9.43E-04	1.03E-01	7.27E-03	1.75E+00	8.50E-02	2.39E+00	2.82E+00	3.35E-01	6.52E+00	3.46E-01	1.45E+01	8.22E-02	1.21E-01	-1.77E+01	-1.75E+01	-1.95E+01	3.38E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
1	7.81E-15	1.00E+00	7.04E-09	1.26E-09	3.94E-01	1.46E-02	3.19E-01	2.99E-01	-1.99E+01	-1.86E+01	-4.10E-01	6.99E-02	3.37E-01	8.32E-02	4.08E-01	2.84E-02	-2.31E+01	1.34E-10	-1.75E+01	1.09E-11	4.00E+00	4.16E-02	9.74E-02	5.88E-01
2	1.80E-14	2.00E+00	5.94E-09	8.62E-10	5.39E-01	1.27E-01	2.10E-01	7.62E-01	-1.84E+01	-2.00E+01	-2.93E-01	7.66E-01	1.48E-01	3.12E-01	1.58E+00	2.25E-03	-2.39E+01	1.81E-10	-1.93E+01	1.65E-10	4.00E+00	7.49E-02	1.08E-01	5.43E-01
3	1.84E-14	2.00E+00	7.66E-10	1.63E-10	5.98E-01	8.24E-02	1.13E-01	8.09E-01	-2.02E+01	-2.02E+01	-4.88E-01	-2.83E-01	1.37E-01	7.97E-02	4.28E+00	8.30E-03	-2.39E+01	1.84E-10	-1.85E+01	2.21E-11	4.00E+00	9.27E-02	8.77E-02	6.78E-01
4	1.11E-15	0.00E+00	7.18E-09	8.09E-10	2.35E-02	6.58E-02	5.24E-01	6.13E-01	-1.87E+01	-1.94E+01	-1.16E-01	1.02E+00	3.14E-01	1.29E-01	3.91E+00	2.27E-03	-2.37E+01	1.66E-10	-1.93E+01	1.38E-10	4.00E+00	1.26E-01	8.05E-02	6.45E-01
5	1.61E-14	2.00E+00	9.47E-09	5.32E-10	4.07E-01	9.18E-02	1.51E-01	8.41E-01	-1.90E+01	-1.91E+01	-3.64E-01	1.86E-01	2.72E-02	6.46E-02	7.78E+00	2.23E-02	-2.20E+01	5.29E-11	-1.86E+01	5.60E-11	4.00E+00	8.35E-02	1.13E-01	6.22E-01
6	1.75E-14	0.00E+00	1.46E-09	2.73E-10	4.31E-01	1.23E-01	5.11E-01	9.68E-01	-1.89E+01	-1.88E+01	2.54E-02	-9.70E-02	3.99E-01	3.76E-01	4.00E+00	2.02E-02	-2.29E+01	1.23E-10	-1.99E+01	2.10E-10	4.00E+00	8.15E-02	2.78E-02	6.31E-01
7	2.39E-14	1.00E+00	8.21E-09	2.10E-10	6.64E-01	1.74E-02	1.93E-01	1.65E-01	-1.80E+01	-1.93E+01	-1.65E-02	-1.09E-01	3.32E-01	1.64E-04	5.06E-01	1.50E-02	-2.12E+01	1.80E-11	-1.96E+01	1.62E-10	1.00E+00	6.12E-02	1.14E-01	6.37E-01
8	1.48E-14	0.00E+00	3.25E-09	8.26E-10	3.08E-01	6.42E-02	2.04E-01	7.69E-02	-1.93E+01	-1.90E+01	1.27E-01	-7.69E-01	5.14E-02	5.45E-01	2.79E+00	6.07E-03	-2.30E+01	1.37E-10	-1.97E+01	1.92E-10	4.00E+00	5.72E-02	9.50E-02	5.69E-01
9	2.50E-15	1.00E+00	8.73E-09	6.36E-10	5.13E-01	1.12E-01	3.05E-01	1.34E-01	-1.94E+01	-1.81E+01	-3.38E-01	8.83E-01	2.88E-01	1.60E-01	5.05E+00	4.89E-03	-2.17E+01	4.51E-11	-2.01E+01	2.69E-10	4.00E+00	8.62E-02	9.97E-02	7.05E-01
10	1.50E-15	0.00E+00	5.77E-09	9.66E-10	7.27E-01	3.11E-02	4.38E-01	4.49E-01	-1.79E+01	-1.91E+01	3.69E-01	-2.45E-01	2.58E-01	2.19E-01	7.31E-01	1.01E-02	-2.28E+01	1.18E-10	-1.87E+01	5.92E-11	1.00E+00	1.10E-01	1.40E-02	5.54E-01
11	2.77E-14	1.00E+00	2.11E-09	1.00E-09	8.49E-01	1.97E-03	2.61E-01	4.91E-01	-2.03E+01	-1.94E+01	-6.66E-02	6.43E-01	1.34E-01	5.69E-01	7.49E+00	1.47E-02	-2.14E+01	2.61E-11	-1.91E+01	9.93E-11	4.00E+00	9.43E-02	3.40E-02	6.72E-01
12	1.57E-14	1.00E+00	2.91E-09	1.20E-09	7.43E-01	1.02E-01	3.48E-01	2.04E-01	-1.89E+01	-1.80E+01	-1.38E+00	1.56E-01	3.75E-01	5.11E-01	1.11E+00	1.61E-02	-2.24E+01	1.05E-10	-1.84E+01	2.91E-11	4.00E+00	9.36E-02	5.99E-02	6.95E-01
13	6.99E-15	2.00E+00	5.85E-09	7.10E-10	4.95E-01	6.78E-02	2.30E-01	3.62E-01	-1.85E+01	-1.77E+01	-5.86E-02	5.80E-03	1.26E-01	3.07E-01	1.73E+00	1.10E-02	-2.32E+01	1.41E-10	-1.94E+01	1.35E-10	1.00E+00	5.52E-02	1.01E-01	6.58E-01
14	1.50E-14	0.00E+00	3.78E-09	1.18E-09	7.51E-01	1.94E-02	3.43E-02	4.21E-01	-1.75E+01	-1.96E+01	-1.16E+00	1.16E-01	2.08E-01	4.58E-01	5.58E-01	1.40E-03	-2.23E+01	7.24E-11	-1.83E+01	1.09E-11	1.00E+00	7.78E-03	9.09E-02	6.05E-01
15	1.66E-14	0.00E+00	5.70E-09	5.97E-10	9.73E-01	3.74E-02	4.60E-01	7.19E-01	-1.97E+01	-1.94E+01	-1.96E-01	-9.35E-03	2.09E-01	2.10E-01	3.44E-01	2.54E-02	-2.24E+01	8.22E-11	-1.81E+01	1.09E-11	1.00E+00	9.18E-02	1.31E-01	6.19E-01
16	1.75E-15	2.00E+00	6.59E-09	1.47E-10	7.91E-01	1.02E-01	1.29E-01	6.95E-01	-2.03E+01	-1.77E+01	-2.14E-01	-1.17E+00	4.49E-02	2.42E-01	2.50E+00	7.89E-03	-2.14E+01	2.83E-11	-1.93E+01	1.32E-10	4.00E+00	6.88E-02	3.83E-02	6.88E-01
17	9.22E-15	2.00E+00	9.01E-09	1.16E-10	4.50E-01	5.04E-02	1.97E-01	1.04E-01	-1.86E+01	-1.77E+01	-1.62E-01	-1.89E-01	1.50E-02	4.93E-01	3.84E-01	2.79E-02	-2.23E+01	9.34E-11	-1.90E+01	1.04E-10	4.00E+00	1.04E-01	7.78E-02	6.70E-01
18	2.74E-14	0.00E+00	4.05E-09	8.72E-10	1.94E-01	2.61E-02	1.00E-01	1.74E-01	-1.82E+01	-1.85E+01	5.34E-01	3.89E-01	1.68E-01	5.52E-02	4.27E-01	6.93E-03	-2.38E+01	1.79E-10	-1.90E+01	1.07E-10	1.00E+00	1.42E-01	6.30E-02	6.90E-01
19	3.03E-15	0.00E+00	5.31E-09	1.09E-10	2.26E-01	3.76E-02	7.91E-02	9.41E-01	-1.83E+01	-1.88E+01	3.03E-01	1.21E-01	7.83E-02	3.59E-01	6.66E+00	7.35E-03	-2.17E+01	6.99E-11	-1.88E+01	6.96E-11	1.00E+00	9.71E-02	1.21E-01	5.26E-01
20	2.43E-14	2.00E+00	7.60E-09	4.74E-10	4.61E-01	8.67E-02	3.67E-01	2.35E-01	-1.83E+01	-1.90E+01	-1.91E-01	-4.00E-01	3.43E-01	3.41E-01	4.12E+00	9.58E-03	-2.36E+01	1.75E-10	-2.00E+01	2.50E-10	1.00E+00	5.46E-02	9.80E-02	5.92E-01
21	5.43E-16	0.00E+00	6.42E-09	4.63E-10	5.51E-01	1.33E-01	4.04E-01	6.24E-01	-1.92E+01	-1.85E+01	-7.03E-03	-6.82E-01	2.18E-01	1.41E-01	7.22E-01	2.47E-03	-2.15E+01	3.36E-11	-1.89E+01	1.05E-10	1.00E+00	8.07E-02	7.16E-02	6.28E-01
22	6.63E-15	0.00E+00	3.62E-09	9.40E-10	5.72E-01	1.06E-01	4.24E-01	5.97E-01	-1.96E+01	-1.93E+01	-1.02E-01	-1.84E-01	2.56E-01	1.65E-01	2.37E-01	5.67E-03	-2.38E+01	1.77E-10	-1.87E+01	3.72E-11	4.00E+00	2.78E-02	1.04E-01	6.01E-01
23	1.98E-14	2.00E+00	4.18E-09	3.12E-10	3.57E-01	9.06E-02	5.36E-01	3.72E-02	-1.82E+01	-2.05E+01	-3.85E-01	7.08E-01	2.64E-01	4.55E-01	5.49E+00	9.92E-03	-2.15E+01	4.20E-11	-1.91E+01	1.16E-10	1.00E+00	7.39E-02	1.03E-01	7.08E-01
24	1.71E-14	0.00E+00	4.29E-09	5.58E-10	4.77E-01	5.14E-02	4.98E-01	5.20E-01	-1.91E+01	-1.95E+01	-1.50E-01	-2.19E-01	3.82E-01	1.37E-01	9.04E-01	4.99E-03	-2.31E+01	1.25E-10	-1.88E+01	9.61E-11	4.00E+00	7.75E-02	7.18E-02	7.10E-01
25	2.61E-14	0.00E+00	6.38E-09	5.95E-10	1.33E-01	8.70E-02	2.54E-01	3.14E-01	-1.93E+01	-1.83E+01	8.22E-02	-5.18E-03	6.96E-02	5.29E-01	1.78E-01	1.83E-02	-2.38E+01	1.87E-10	-1.84E+01	1.79E-11	4.00E+00	1.23E-01	1.01E-01	5.95E-01
26	3.17E-14	1.00E+00	5.61E-09	3.69E-10	8.82E-01	1.43E-01	4.30E-01	3.03E-01	-1.88E+01	-1.74E+01	-3.45E-01	-1.24E-01	2.66E-01	1.53E-01	1.38E+00	2.92E-03	-2.18E+01	4.04E-11	-1.83E+01	1.09E-11	1.00E+00	1.19E-01	8.22E-02	6.38E-01
27	9.53E-15	1.00E+00	7.34E-09	1.25E-09	6.57E-01	4.22E-02	1.47E-01	9.16E-01	-1.79E+01	-1.74E+01	1.74E-01	9.85E-01	2.97E-01	9.99E-02	4.45E-01	3.27E-03	-2.26E+01	1.02E-10	-1.96E+01	1.83E-10	4.00E+00	9.95E-02	7.45E-02	6.57E-01
28	1.38E-14	2.00E+00	8.33E-09	3.54E-10	8.92E-01	1.28E-01	3.95E-01	9.37E-01	-2.02E+01	-1.79E+01	1.17E+00	-7.99E-01	3.58E-01	4.08E-01	3.72E-01	9.00E-03	-2.18E+01	4.27E-11	-1.97E+01	1.96E-10	1.00E+00	7.84E-02	1.06E-01	6.43E-01
29	2.66E-14	1.00E+00	3.52E-09	9.96E-10	7.88E-01	1.17E-01	9.87E-02	7.36E-01	-1.86E+01	-1.85E+01	1.54E-01	2.43E-01	2.90E-01	2.24E-01	8.73E-01	1.65E-02	-2.33E+01	1.55E-10	-1.89E+01	7.43E-11	1.00E+00	1.32E-01	5.88E-02	6.29E-01
30	2.47E-14	0.00E+00	3.99E-09	9.38E-11	3.49E-02	6.00E-02	5.32E-01	2.89E-01	-1.92E+01	-2.01E+01	-9.28E-01	5.76E-02	2.95E-01	5.16E-01	3.50E+00	2.17E-02	-2.35E+01	1.56E-10	-1.78E+01	1.09E-11	1.00E+00	7.66E-02	1.45E-02	6.55E-01
31	2.36E-14	1.00E+00	6.07E-09	5.64E-10	9.30E-01	1.43E-03	3.41E-01	4.89E-01	-1.90E+01	-1.98E+01	-3.06E-01	-3.18E-01	2.29E-01	1.01E-01	8.31E-01	1.38E-02	-2.39E+01	1.89E-10	-1.95E+01	1.75E-10	4.00E+00	6.37E-02	9.24E-02	6.82E-01
32	2.27E-14	0.00E+00	2.22E-09	1.24E-09	9.25E-02	8.93E-02	2.89E-01	4.61E-01	-1.98E+01	-1.88E+01	2.13E-01	-6.88E-02	1.32E-01	3.27E-02	3.57E+00	9.80E-03	-2.32E+01	1.39E-10	-1.81E+01	1.09E-11	4.00E+00	8.01E-02	1.07E-01	6.42E-01
33	2.20E-14	0.00E+00	2.53E-09	6.76E-10	6.38E-01	1.04E-01	1.69E-01	5.41E-02	-2.00E+01	-1.96E+01	4.45E-01	-2.55E-01	1.91E-01	4.43E-01	6.80E-01	2.34E-02	-2.19E+01	6.71E-11	-1.95E+01	1.71E-10	1.00E+00	7.90E-02	5.72E-02	6.24E-01
34	2.02E-14	0.00E+00	2.39E-09	4.30E-10	3.32E-01	7.42E-03	2.99E-01	8.63E-02	-1.79E+01	-1.80E+01	-8.72E-02	-3.91E-01	3.07E-01	4.17E-01	2.84E+00	1.06E-03	-2.11E+01	1.23E-11	-1.80E+01	1.09E-11	4.00E+00	6.60E-02	4.80E-02	6.86E-01
35	8.32E-15	0.00E+00	1.40E-09	2.98E-11	4.21E-01	1.08E-01	1.21E-01	5.83E-01	-1.94E+01	-1.76E+01	-2.17E-01	3.03E-02	2.46E-01	1.88E-01	6.24E-01	2.61E-02	-2.18E+01	7.48E-11	-1.88E+01	6.67E-11	1.00E+00	7.61E-02	8.52E-02	6.67E-01
36	1.22E-14	0.00E+00	9.20E-09	1.22E-09	3.29E-01	7.86E-02	2.96E-01	3.49E-01	-1.95E+01	-1.91E+01	-4.58E-01	-2.10E-01	2.32E-01	5.01E-01	7.44E-01	1.72E-02	-2.12E+01	1.25E-11	-1.72E+01	1.09E-11	1.00E+00	8.85E-02	8.35E-02	6.32E-01
37	1.88E-14	0.00E+00	7.57E-09	9.81E-10	2.51E-01	4.03E-02	1.36E-01	6.68E-01	-1.88E+01	-1.93E+01	8.09E-01	-1.62E-01	8.96E-02	5.22E-01	6.50E+00	8.04E-03	-2.19E+01	5.81E-11	-1.87E+01	4.52E-11	4.00E+00	5.19E-02	7.89E-02	7.36E-01
38	2.86E-14	0.00E+00	2.48E-09	2.28E-10	9.82E-01	2.91E-02	3.84E-01	6.05E-01	-1.81E+01	-1.76E+01	4.88E-01	3.03E-01	2.20E-01	3.71E-01	2.14E-01	8.79E-03	-2.24E+01	8.42E-11	-1.86E+01	2.63E-11	1.00E+00	7.18E-02	8.66E-02	6.14E-01
39	1.15E-16	0.00E+00	4.75E-09	6.89E-10	2.88E-01	8.44E-03	3.23E-01	8.68E-01	-2.04E+01	-1.84E+01	-6.65E-01	1.72E-01	1.23E-01	1.48E-01	6.64E-01	7.18E-03	-2.34E+01	1.59E-10	-1.87E+01	4.38E-11	1.00E+00	8.94E-02	5.75E-02	5.73E-01
40	2.95E-14	1.00E+00	1.71E-09	5.11E-10	5.44E-01	9.63E-02	4.88E-01	1.59E-01	-1.92E+01	-1.92E+01	2.94E-01	-1.95E-02	1.59E-01	1.69E-01	8.51E-01	1.98E-02	-2.13E+01	2.11E-11	-2.07E+01	2.75E-10	4.00E+00	7.12E-02	7.64E-02	4.91E-01
41	9.14E-16	0.00E+00	8.25E-09	1.18E-09	3.18E-01	4.62E-02	4.84E-01	7.90E-01	-1.85E+01	-1.81E+01	2.38E-01	1.37E-01	1.07E-01	1.10E-01	3.35E+00	2.50E-02	-2.28E+01	1.26E-10	-1.90E+01	8.46E-11	1.00E+00	9.09E-02	5.57E-02	6.06E-01
42	3.00E-14	1.00E+00	3.32E-09	1.11E-09	3.46E-01	1.23E-01	6.82E-02	2.12E-01	-1.92E+01	-1.82E+01	-7.57E-01	-1.80E+00	4.07E-02	3.45E-01	5.21E+00	1.93E-02	-2.23E+01	9.98E-11	-1.90E+01	9.31E-11	1.00E+00	1.74E-01	6.13E-02	6.18E-01
43	1.42E-14	1.00E+00	9.68E-10	5.77E-10	5.30E-01	8.54E-02	1.14E-02	3.23E-01	-1.88E+01	-1.89E+01	-4.44E-01	5.75E-01	2.00E-02	2.64E-02	3.74E+00	5.30E-03	-2.33E+01	1.51E-10	-1.85E+01	6.18E-11	1.00E+00	8.07E-02	4.59E-02	6.13E-01
44	2.17E-15	0.00E+00	5.13E-09	5.54E-11	5.81E-01	2.01E-02	1.73E-01	1.46E-02	-1.95E+01	-1.81E+01	-1.85E-01	2.82E-01	1.70E-01	2.90E-01	7.08E+00	2.87E-02	-2.29E+01	1.14E-10	-1.88E+01	7.60E-11	1.00E+00	9.78E-02	1.36E-01	7.94E-01
45	2.24E-14	0.00E+00	8.41E-09	5.00E-10	3.75E-01	1.21E-01	1.40E-01	2.64E-01	-1.72E+01	-1.83E+01	-2.34E-02	5.49E-01	6.07E-02	3.33E-01	8.85E-01	1.89E-02	-2.13E+01	1.81E-11	-1.92E+01	1.27E-10	4.00E+00	4.74E-02	6.88E-02	5.78E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
46	2.57E-14	1.00E+00	1.20E-09	6.34E-10	6.14E-01	9.51E-02	4.67E-01	8.23E-01	-1.91E+01	-1.82E+01	1.32E-01	1.82E-02	2.40E-01	2.98E-01	8.19E-01	2.10E-02	-2.20E+01	8.47E-11	-1.86E+01	6.10E-11	1.00E+00	6.21E-02	5.34E-02	6.99E-01
47	6.85E-15	0.00E+00	4.62E-09	7.39E-10	1.16E-01	3.57E-02	4.89E-02	1.73E-03	-1.87E+01	-1.78E+01	-1.34E-01	-2.31E-01	2.49E-01	1.97E-01	4.79E+00	7.67E-03	-2.35E+01	1.65E-10	-1.92E+01	1.24E-10	1.00E+00	1.73E-02	7.37E-02	6.49E-01
48	1.64E-14	2.00E+00	8.08E-09	1.55E-13	7.13E-01	4.91E-02	4.09E-01	1.22E-01	-1.91E+01	-1.93E+01	5.46E-02	-1.73E-01	8.15E-02	1.76E-01	3.17E-01	5.94E-03	-2.24E+01	7.93E-11	-1.91E+01	1.14E-10	1.00E+00	8.29E-02	8.93E-02	7.21E-01
49	1.43E-14	1.00E+00	2.63E-09	1.10E-09	1.84E-01	7.58E-02	1.82E-01	4.57E-01	-1.87E+01	-1.78E+01	2.00E-01	-3.37E-02	3.25E-01	1.89E-01	2.64E-01	2.92E-02	-2.32E+01	1.45E-10	-1.86E+01	6.63E-11	4.00E+00	1.09E-01	9.16E-02	6.63E-01
50	7.31E-15	0.00E+00	4.49E-09	3.64E-10	8.86E-02	1.15E-01	5.51E-01	2.40E-02	-1.77E+01	-1.79E+01	-5.52E-01	-9.15E-01	9.65E-03	3.23E-01	8.03E-01	3.61E-03	-2.38E+01	1.76E-10	-1.85E+01	4.07E-11	1.00E+00	1.18E-01	7.50E-02	5.82E-01
51	1.19E-14	0.00E+00	6.73E-09	6.63E-10	9.17E-01	1.17E-01	5.25E-01	7.53E-01	-1.86E+01	-1.89E+01	6.76E-01	-1.53E-01	2.80E-01	5.87E-01	5.71E-01	1.05E-02	-2.35E+01	1.60E-10	-1.89E+01	8.78E-11	4.00E+00	1.15E-01	6.28E-02	6.69E-01
52	9.14E-15	2.00E+00	2.27E-09	3.37E-10	7.71E-01	5.70E-02	4.76E-01	1.92E-01	-1.82E+01	-1.83E+01	7.48E-01	9.00E-01	1.74E-01	1.34E-01	4.87E+00	5.70E-03	-2.36E+01	1.70E-10	-1.79E+01	1.09E-11	1.00E+00	4.58E-02	5.44E-02	7.27E-01
53	2.47E-14	0.00E+00	9.35E-09	2.38E-11	7.20E-02	1.13E-01	3.12E-01	8.82E-01	-1.96E+01	-1.86E+01	-2.78E-01	-1.41E-01	8.54E-02	4.70E-03	1.85E+00	2.14E-02	-2.30E+01	1.40E-10	-1.83E+01	1.09E-11	4.00E+00	6.69E-02	6.47E-02	7.34E-01
54	1.00E-14	0.00E+00	7.71E-09	9.11E-10	5.65E-01	1.46E-01	2.11E-02	3.76E-01	-1.85E+01	-2.00E+01	-2.26E-01	-4.78E-01	3.18E-01	2.02E-01	5.31E+00	1.22E-02	-2.22E+01	8.92E-11	-1.81E+01	1.09E-11	4.00E+00	1.02E-01	7.81E-02	5.97E-01
55	1.72E-14	1.00E+00	3.37E-09	3.85E-10	2.67E-01	1.30E-01	2.82E-01	2.42E-01	-1.95E+01	-1.95E+01	-2.34E-01	-4.18E-02	3.79E-01	4.76E-01	2.06E+00	1.71E-03	-2.11E+01	3.78E-12	-1.94E+01	1.25E-10	4.00E+00	1.06E-01	8.43E-02	6.83E-01
56	2.78E-15	2.00E+00	1.91E-09	1.16E-09	8.14E-01	1.09E-01	8.83E-02	5.51E-01	-1.88E+01	-1.97E+01	-1.80E-01	-5.89E-01	3.97E-02	1.50E-01	2.50E-01	8.52E-03	-2.20E+01	6.31E-11	-2.02E+01	2.75E-10	1.00E+00	8.42E-02	4.97E-02	6.80E-01
57	3.01E-14	0.00E+00	5.49E-09	1.09E-09	7.65E-01	1.37E-01	2.42E-01	9.65E-02	-1.93E+01	-1.94E+01	2.43E-01	-5.33E-02	3.72E-01	2.63E-01	6.93E+00	2.64E-02	-2.27E+01	9.37E-11	-1.88E+01	7.35E-11	1.00E+00	8.42E-02	1.09E-01	5.48E-01
58	5.96E-15	1.00E+00	5.04E-10	1.13E-09	4.74E-02	4.08E-02	3.63E-01	5.08E-01	-1.84E+01	-1.90E+01	1.29E-02	-8.72E-01	9.94E-02	4.87E-02	4.80E-01	4.03E-03	-2.33E+01	1.44E-10	-1.91E+01	9.73E-11	4.00E+00	1.13E-01	1.44E-01	7.70E-01
59	8.15E-15	0.00E+00	6.48E-10	9.60E-10	1.23E-01	5.71E-02	4.57E-01	7.47E-01	-1.78E+01	-1.87E+01	1.82E-01	-5.53E-01	3.03E-02	2.71E-01	1.65E-01	8.59E-03	-2.10E+01	5.69E-12	-1.86E+01	3.93E-11	4.00E+00	7.01E-02	1.97E-01	6.75E-01
60	1.95E-14	2.00E+00	5.05E-09	1.14E-09	6.07E-01	1.19E-01	5.07E-01	8.30E-01	-1.81E+01	-1.89E+01	8.34E-02	-1.27E-01	1.77E-01	6.01E-02	7.53E+00	2.47E-02	-2.16E+01	7.50E-11	-1.88E+01	5.31E-11	1.00E+00	6.96E-02	3.57E-02	6.73E-01
61	1.07E-14	0.00E+00	7.81E-09	1.15E-09	3.61E-01	1.31E-01	3.33E-01	7.23E-01	-1.86E+01	-1.81E+01	-4.12E-01	-2.01E-01	2.71E-01	1.25E-01	4.63E+00	1.13E-02	-2.25E+01	1.07E-10	-1.93E+01	1.44E-10	1.00E+00	6.00E-02	9.37E-02	7.16E-01
62	5.28E-15	0.00E+00	2.72E-09	9.32E-10	2.19E-01	1.47E-01	3.09E-02	4.71E-02	-1.88E+01	-1.98E+01	5.99E-01	-7.77E-02	3.61E-01	4.25E-01	5.71E+00	1.88E-02	-2.35E+01	1.48E-10	-1.95E+01	1.47E-10	4.00E+00	8.20E-02	4.95E-02	8.12E-01
63	1.28E-14	1.00E+00	1.14E-09	4.86E-10	7.36E-01	1.41E-01	5.44E-01	3.56E-01	-1.84E+01	-1.89E+01	-2.40E-01	1.92E-01	1.48E-01	9.56E-03	7.94E+00	5.49E-03	-2.19E+01	5.04E-11	-1.82E+01	1.09E-11	1.00E+00	4.33E-02	1.11E-01	6.39E-01
64	2.82E-14	0.00E+00	4.70E-09	7.19E-10	9.56E-01	2.55E-02	5.63E-02	6.38E-01	-1.89E+01	-2.02E+01	1.57E-01	-6.08E-02	6.57E-03	1.74E-01	3.23E+00	2.30E-02	-2.21E+01	9.05E-11	-1.98E+01	2.23E-10	1.00E+00	1.06E-01	1.18E-01	6.65E-01
65	1.81E-14	1.00E+00	6.94E-09	4.52E-10	4.46E-01	5.30E-02	1.55E-01	9.09E-01	-1.94E+01	-1.97E+01	9.95E-01	-2.91E-01	9.41E-02	2.84E-01	9.09E-01	3.79E-03	-2.13E+01	2.54E-11	-1.84E+01	3.40E-11	4.00E+00	9.88E-02	4.23E-02	6.55E-01
66	2.66E-14	2.00E+00	7.98E-10	7.90E-10	9.21E-01	9.52E-03	4.97E-01	1.88E-01	-1.85E+01	-1.84E+01	-2.46E-01	-2.27E-01	6.77E-02	2.80E-01	2.98E+00	3.02E-03	-2.26E+01	7.72E-11	-1.92E+01	9.42E-11	4.00E+00	9.02E-02	8.14E-02	5.36E-01
67	1.08E-14	0.00E+00	3.66E-10	1.70E-10	7.02E-01	2.75E-02	2.11E-01	9.97E-01	-1.84E+01	-1.80E+01	-7.12E-01	-3.52E-01	3.48E-01	5.38E-01	6.18E+00	1.43E-02	-2.34E+01	1.53E-10	-1.92E+01	1.54E-10	4.00E+00	3.74E-02	8.58E-02	6.34E-01
68	4.66E-15	2.00E+00	6.26E-09	1.06E-09	9.90E-01	4.69E-02	7.66E-02	4.40E-01	-1.95E+01	-1.84E+01	-4.55E-02	-1.36E-01	3.52E-01	3.93E-01	1.30E+00	1.30E-02	-2.37E+01	1.72E-10	-1.82E+01	1.29E-11	1.00E+00	7.56E-02	2.05E-02	6.53E-01
69	2.52E-14	0.00E+00	5.43E-09	1.03E-09	9.01E-01	6.63E-02	3.26E-01	6.60E-02	-2.01E+01	-1.91E+01	-3.94E-02	-3.58E-01	2.43E-01	4.55E-02	2.53E+00	6.67E-03	-2.25E+01	1.03E-10	-1.85E+01	4.77E-11	4.00E+00	9.65E-02	1.26E-01	6.60E-01
70	2.54E-14	2.00E+00	4.88E-09	1.08E-09	6.24E-02	7.05E-02	3.89E-01	8.10E-01	-1.88E+01	-1.71E+01	-1.74E+00	-4.90E-01	3.03E-01	5.60E-01	4.41E+00	2.06E-02	-2.22E+01	5.42E-11	-1.94E+01	1.40E-10	1.00E+00	5.95E-02	7.94E-02	6.51E-01
71	2.81E-14	0.00E+00	2.86E-09	1.83E-10	2.92E-01	3.22E-02	1.07E-01	1.11E-01	-1.90E+01	-1.88E+01	-8.72E-01	1.44E-01	3.85E-01	2.18E-02	1.37E-01	1.56E-02	-2.25E+01	9.76E-11	-2.10E+01	2.75E-10	1.00E+00	1.24E-01	4.36E-02	6.23E-01
72	3.61E-15	2.00E+00	7.49E-09	1.03E-09	1.46E-01	8.04E-02	5.18E-01	6.86E-01	-1.97E+01	-2.03E+01	-9.79E-01	-2.38E-01	2.14E-01	1.84E-01	4.20E-01	1.17E-02	-2.10E+01	8.27E-12	-1.93E+01	1.57E-10	1.00E+00	1.02E-01	6.58E-02	6.47E-01
73	3.05E-14	0.00E+00	6.87E-09	7.59E-10	5.42E-02	1.25E-01	3.47E-01	5.65E-01	-1.97E+01	-1.79E+01	3.95E-02	6.73E-01	7.27E-02	5.98E-02	6.52E-01	9.32E-03	-2.31E+01	1.19E-10	-1.96E+01	1.78E-10	1.00E+00	7.38E-02	1.40E-02	6.87E-01
74	2.14E-14	1.00E+00	8.86E-09	2.49E-10	8.09E-01	7.72E-02	4.70E-01	8.74E-01	-1.74E+01	-1.96E+01	-1.06E-01	-1.76E-01	2.82E-01	1.23E-01	2.76E-01	1.60E-02	-2.40E+01	1.86E-10	-1.84E+01	1.09E-11	4.00E+00	8.79E-02	4.41E-02	7.45E-01
75	2.92E-14	0.00E+00	8.53E-09	8.20E-10	9.44E-01	8.26E-02	4.44E-01	9.83E-01	-1.83E+01	-1.87E+01	-1.78E+00	-6.25E-01	1.87E-01	1.05E-01	7.83E-01	3.36E-03	-2.36E+01	1.62E-10	-1.98E+01	2.21E-10	4.00E+00	1.00E-01	8.87E-02	6.52E-01
76	2.18E-14	2.00E+00	4.37E-09	7.13E-11	1.54E-01	2.31E-02	4.33E-01	5.39E-01	-1.82E+01	-1.89E+01	-1.42E-01	-2.07E-01	1.17E-01	2.54E-01	6.75E+00	2.94E-02	-2.33E+01	1.49E-10	-1.90E+01	1.02E-10	4.00E+00	1.01E-01	3.93E-02	5.85E-01
77	3.08E-14	2.00E+00	8.90E-09	8.42E-10	2.74E-01	7.48E-02	4.17E-01	3.33E-01	-1.98E+01	-1.85E+01	7.59E-01	-1.50E-01	5.94E-02	4.35E-01	5.37E-01	1.70E-02	-2.30E+01	1.15E-10	-1.78E+01	1.09E-11	4.00E+00	5.24E-02	1.32E-01	6.49E-01
78	1.92E-14	2.00E+00	3.06E-09	6.54E-10	8.44E-04	1.13E-02	6.57E-02	9.26E-01	-1.73E+01	-1.85E+01	-9.05E-02	-9.95E-01	3.55E-01	6.95E-02	7.31E+00	2.26E-02	-2.17E+01	3.77E-11	-1.85E+01	3.19E-11	4.00E+00	1.35E-01	1.16E-01	6.11E-01
79	2.04E-14	0.00E+00	6.81E-09	4.96E-11	2.41E-01	1.10E-01	4.11E-02	7.03E-01	-1.81E+01	-1.98E+01	-1.21E-01	-4.50E-01	3.95E-01	5.59E-01	6.26E-01	2.72E-03	-2.16E+01	4.87E-11	-1.71E+01	1.09E-11	1.00E+00	7.27E-02	5.17E-02	6.61E-01
80	3.13E-14	0.00E+00	9.28E-09	2.57E-10	1.67E-01	9.40E-02	1.85E-01	4.75E-01	-1.89E+01	-1.82E+01	-2.54E-01	7.91E-02	3.30E-01	7.40E-02	4.73E-01	4.18E-03	-2.17E+01	6.88E-11	-1.89E+01	8.23E-11	1.00E+00	6.73E-02	6.95E-02	5.94E-01
81	1.11E-14	2.00E+00	8.04E-09	5.36E-10	6.20E-01	1.25E-02	4.01E-01	8.52E-01	-1.77E+01	-1.96E+01	-2.47E-03	2.17E-01	2.25E-01	9.11E-02	7.13E+00	4.42E-03	-2.11E+01	9.74E-12	-1.89E+01	8.43E-11	1.00E+00	9.49E-02	7.65E-02	6.29E-01
82	8.62E-15	1.00E+00	4.09E-09	6.10E-10	8.30E-01	1.34E-01	2.34E-01	6.51E-01	-1.77E+01	-1.86E+01	9.15E-01	-1.50E+00	1.98E-01	1.60E-01	8.05E+00	1.36E-02	-2.40E+01	1.91E-10	-1.89E+01	9.07E-11	4.00E+00	8.71E-02	9.62E-02	6.26E-01
83	4.32E-15	2.00E+00	2.03E-09	7.33E-10	6.42E-01	1.39E-01	1.26E-01	7.86E-01	-1.80E+01	-1.86E+01	-5.23E-02	9.20E-02	3.23E-01	9.59E-02	1.94E-01	2.69E-02	-2.15E+01	3.68E-11	-1.90E+01	8.82E-11	4.00E+00	8.77E-02	9.46E-02	6.76E-01
84	2.94E-14	1.00E+00	8.63E-09	1.21E-09	4.12E-01	7.16E-02	2.20E-01	9.00E-01	-1.89E+01	-1.87E+01	-6.95E-02	4.35E-02	2.12E-02	5.82E-01	9.25E-01	1.34E-03	-2.26E+01	1.09E-10	-1.86E+01	5.42E-11	4.00E+00	1.08E-01	6.71E-02	7.53E-01
85	2.09E-14	0.00E+00	1.83E-09	7.73E-10	8.52E-01	7.25E-02	3.54E-01	6.70E-01	-1.76E+01	-1.87E+01	-4.81E-01	-2.74E-02	3.49E-02	1.16E-01	2.19E+00	2.98E-02	-2.16E+01	3.17E-11	-1.91E+01	1.22E-10	4.00E+00	4.91E-02	7.29E-02	7.02E-01
86	2.33E-14	2.00E+00	1.66E-09	1.05E-09	4.85E-01	2.13E-02	2.79E-01	2.59E-01	-1.80E+01	-1.88E+01	6.76E-02	-1.66E+00	2.03E-01	1.63E-02	5.96E-01	4.45E-03	-2.22E+01	8.79E-11	-1.91E+01	1.20E-10	4.00E+00	8.55E-02	5.30E-02	6.97E-01
87	3.98E-15	0.00E+00	6.56E-09	4.12E-10	8.73E-01	9.81E-02	4.50E-01	2.77E-01	-1.83E+01	-1.91E+01	-1.58E-01	-8.98E-02	1.50E-03	3.65E-01	6.36E+00	9.23E-03	-2.21E+01	5.73E-11	-1.88E+01	7.88E-11	1.00E+00	1.12E-01	3.13E-02	5.86E-01
88	2.29E-14	0.00E+00	1.53E-09	4.41E-10	2.34E-01	1.44E-01	2.26E-03	9.58E-01	-1.90E+01	-1.89E+01	2.90E-03	1.03E-01	1.92E-01	3.85E-01	1.06E+00	6.28E-03	-2.28E+01	1.29E-10	-1.90E+01	7.95E-11	1.00E+00	6.43E-02	1.24E-01	6.44E-01
89	6.22E-15	1.00E+00	6.14E-09	9.16E-10	2.01E-01	1.42E-01	3.77E-01	2.21E-01	-1.81E+01	-2.04E+01	2.25E-01	-1.14E-01	1.08E-01	1.17E-01	1.44E-01	2.43E-02	-2.19E+01	6.49E-11	-1.94E+01	1.32E-10	4.00E+00	2.98E-02	1.40E-02	5.60E-01
90	3.46E-15	0.00E+00	8.81E-10	7.76E-10	9.66E-01	1.00E-01	1.61E-01	4.04E-01	-1.78E+01	-1.92E+01	-8.31E-01	8.44E-01	1.42E-01	4.67E-01	7.69E-01	2.38E-02	-2.13E+01	2.21E-11	-1.84E+01	2.27E-11	4.00E+00	1.54E-01	9.02E-02	6.41E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
91	1.24E-14	0.00E+00	5.21E-09	4.04E-10	6.94E-01	4.64E-03	2.74E-01	3.96E-01	-1.92E+01	-1.75E+01	6.40E-01	-4.19E-01	3.09E-01	1.34E-02	5.99E+00	4.65E-03	-2.14E+01	2.94E-11	-1.87E+01	6.42E-11	4.00E+00	9.05E-02	2.35E-02	5.67E-01
92	2.72E-14	1.00E+00	3.10E-09	8.79E-10	1.79E-01	6.19E-02	8.99E-02	7.75E-01	-1.99E+01	-1.87E+01	-3.45E-02	4.80E-01	5.39E-02	4.20E-02	5.55E+00	2.06E-03	-2.27E+01	1.11E-10	-1.92E+01	1.11E-10	1.00E+00	5.81E-02	1.40E-02	6.36E-01
93	1.31E-14	2.00E+00	7.24E-09	8.94E-10	6.82E-01	5.50E-02	2.61E-02	3.89E-01	-1.91E+01	-1.92E+01	-1.32E-01	-3.29E-01	3.67E-01	3.91E-02	2.32E+00	2.73E-02	-2.21E+01	4.71E-11	-1.80E+01	1.09E-11	1.00E+00	7.07E-02	6.44E-02	6.09E-01
94	1.52E-14	1.00E+00	3.87E-09	2.40E-10	8.37E-01	5.98E-02	2.68E-01	5.73E-01	-1.93E+01	-1.90E+01	1.03E-01	-9.91E-02	1.62E-01	8.66E-02	3.29E-01	1.77E-02	-2.12E+01	1.52E-11	-1.83E+01	1.45E-11	4.00E+00	9.33E-02	8.25E-02	7.14E-01
95	5.51E-15	2.00E+00	3.72E-09	1.98E-10	6.75E-01	1.35E-01	2.51E-01	4.14E-01	-1.87E+01	-1.84E+01	-2.05E-01	2.14E-01	1.52E-01	2.34E-01	5.79E-01	1.80E-03	-2.27E+01	1.20E-10	-1.87E+01	7.19E-11	1.00E+00	1.05E-01	1.61E-01	6.20E-01
96	1.02E-14	0.00E+00	7.92E-09	2.95E-10	5.00E-01	3.30E-02	5.10E-02	5.43E-01	-1.75E+01	-1.99E+01	-5.96E-01	-4.34E-01	1.04E-01	1.94E-01	3.00E-01	1.27E-02	-2.36E+01	1.68E-10	-1.88E+01	5.05E-11	1.00E+00	7.82E-02	6.10E-02	6.65E-01
97	4.84E-15	0.00E+00	9.07E-09	1.33E-10	8.68E-01	4.44E-02	9.54E-03	1.47E-01	-1.86E+01	-1.83E+01	-1.71E-01	2.28E-01	2.72E-01	4.83E-01	6.98E-01	7.11E-03	-2.32E+01	1.32E-10	-1.90E+01	1.09E-10	4.00E+00	8.52E-02	6.66E-02	6.00E-01
98	2.11E-14	1.00E+00	1.30E-09	3.27E-10	1.51E-02	1.51E-02	2.22E-01	9.70E-01	-1.87E+01	-1.92E+01	-7.83E-02	4.09E-01	1.16E-01	5.99E-01	1.24E-01	2.57E-02	-2.27E+01	9.72E-11	-1.91E+01	1.12E-10	1.00E+00	6.48E-02	7.06E-02	6.16E-01
99	1.33E-14	0.00E+00	4.94E-09	2.92E-10	1.05E-01	3.19E-03	3.74E-01	5.24E-01	-1.97E+01	-1.99E+01	8.93E-01	-7.59E-02	3.91E-01	4.03E-01	5.92E+00	7.57E-03	-2.29E+01	1.31E-10	-1.95E+01	1.50E-10	1.00E+00	1.16E-01	1.56E-01	6.07E-01
100	1.17E-14	0.00E+00	4.43E-10	8.42E-11	3.88E-01	1.49E-01	2.43E-01	6.43E-01	-1.99E+01	-1.86E+01	1.13E-01	-3.99E-02	1.81E-01	2.99E-02	5.18E-01	6.44E-03	-2.21E+01	6.08E-11	-1.77E+01	1.09E-11	4.00E+00	9.55E-02	6.86E-02	5.01E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector Num.	S_HALITE PRESSURE	CASTILER PRESSURE	CASTILER PRMX_LOG	CASTILER COMP_RCK	BH_SAND PRMX_LOG	DRZ_1 PRMX_LOG	CONC_PLG PRMX_LOG	SOLAM3 SOLSIM	SOLAM3 SOLCIM	SOLPU3 SOLSIM	SOLPU3 SOLCIM	SOLPU4 SOLSIM	SOLPU4 SOLCIM	SOLU4 SOLSIM	SOLU6 SOLSIM	SOLU6 SOLCIM	SOLTH4 SOLSIM	PHUMOX3 PHUMCIM	GLOBAL OXSTAT	CULEBRA MINP_FAC	GLOBAL TRANSIDX	GLOBAL CLIMTIDX	CULEBRA HMBLKLT
1	1.20E+07	1.29E+07	-1.15E+01	6.02E-11	-1.33E+01	-1.74E+01	-1.71E+01	-1.01E-01	-4.84E-01	3.55E-01	2.39E-01	1.88E-01	2.12E-01	-4.98E-01	2.49E-01	-1.48E-01	-7.50E-01	1.46E+00	8.42E-01	7.97E+02	5.39E-01	1.01E+00	4.79E-01
2	1.28E+07	1.21E+07	-1.43E+01	6.75E-11	-1.37E+01	-1.62E+01	-1.78E+01	8.79E-01	-1.21E+00	8.65E-01	1.47E-01	-2.34E-03	3.53E-01	-1.95E-01	2.82E-03	1.23E-01	-4.53E-01	1.41E+00	6.50E-01	4.76E+02	8.09E-02	1.06E+00	1.93E-01
3	1.12E+07	1.32E+07	-1.12E+01	3.64E-11	-1.49E+01	-1.48E+01	-1.71E+01	3.64E-01	-4.19E-01	-7.16E-02	-4.14E-01	9.07E-01	-7.40E-01	-2.06E-01	-3.58E-01	-1.24E+00	-1.90E-01	1.41E+00	1.44E-01	9.89E+01	7.78E-01	2.10E+00	3.45E-01
4	1.29E+07	1.52E+07	-1.27E+01	7.45E-11	-1.53E+01	-1.57E+01	-1.73E+01	-2.81E-01	-1.35E-01	-1.23E+00	-1.32E+00	-2.57E-01	-2.34E-01	-9.56E-03	-1.03E-01	-1.73E-01	1.26E-01	1.07E-01	3.58E-01	9.38E+02	4.94E-01	1.06E+00	1.14E-01
5	1.29E+07	1.26E+07	-1.10E+01	2.35E-11	-1.22E+01	-1.83E+01	-1.84E+01	4.07E-01	8.67E-02	-1.80E-01	-1.01E-01	8.78E-02	-1.17E-01	6.41E-01	-4.03E-01	-3.88E-03	-1.67E-01	3.73E-01	1.95E-01	9.89E+02	5.94E-01	1.07E+00	4.30E-01
6	1.19E+07	1.23E+07	-1.24E+01	6.88E-11	-1.36E+01	-1.42E+01	-1.85E+01	-9.67E-01	4.85E-01	-7.99E-01	-2.12E-01	7.49E-01	4.59E-02	-7.74E-01	-2.49E-01	1.53E-01	-9.49E-01	9.88E-01	5.89E-02	8.65E+02	5.85E-01	1.04E+00	3.90E-01
7	1.38E+07	1.57E+07	-1.13E+01	3.17E-11	-1.32E+01	-1.45E+01	-1.77E+01	5.62E-02	-2.35E-01	5.03E-02	8.40E-01	-1.04E-01	1.18E-01	5.24E-02	-1.68E-01	-7.84E-01	-2.70E-01	1.40E+00	6.17E-01	8.19E+02	2.36E-01	1.17E+00	3.09E-01
8	1.34E+07	1.30E+07	-1.07E+01	4.03E-11	-1.52E+01	-1.65E+01	-1.90E+01	1.91E-01	-2.24E-02	-7.75E-01	1.07E+00	-3.54E-02	-2.20E-02	-3.86E-01	9.23E-01	-1.75E-01	-1.56E-02	1.42E+00	3.32E-01	6.53E+02	9.06E-01	1.87E+00	6.32E-02
9	1.28E+07	1.62E+07	-1.16E+01	2.97E-11	-1.11E+01	-1.63E+01	-1.71E+01	-2.54E-01	8.63E-01	7.05E-01	-3.29E-01	-4.19E-02	1.92E-01	-3.20E-03	1.91E-02	9.26E-01	-6.01E-02	1.29E+00	5.40E-01	2.83E+02	5.72E-01	1.15E+00	7.35E-02
10	1.20E+07	1.19E+07	-1.17E+01	3.96E-11	-1.10E+01	-1.81E+01	-1.89E+01	9.39E-01	3.65E-01	-1.01E-01	-4.57E-01	2.43E-01	2.33E-03	-1.06E-01	9.85E-02	4.64E-02	2.49E-01	9.60E-01	8.64E-01	7.29E+02	6.57E-01	1.20E+00	3.73E-01
11	1.33E+07	1.31E+07	-1.18E+01	3.84E-11	-1.29E+01	-1.35E+01	-1.74E+01	-5.40E-02	8.44E-01	1.07E-01	-1.71E-01	-1.86E-01	3.44E-01	1.31E-01	2.63E-02	-2.37E-01	-5.12E-01	1.43E+00	5.62E-01	3.40E+02	5.09E-01	1.17E+00	2.55E-01
12	1.37E+07	1.27E+07	-1.10E+01	2.77E-11	-1.61E+01	-1.77E+01	-1.75E+01	7.76E-01	4.48E-02	1.22E-02	-1.58E-01	-2.74E-01	1.70E-01	-1.91E+00	-3.24E-01	-3.49E-01	-1.84E-01	7.59E-01	5.96E-01	4.88E+02	9.33E-01	1.14E+00	2.45E-01
13	1.23E+07	1.49E+07	-1.33E+01	5.62E-11	-1.57E+01	-1.26E+01	-1.88E+01	-1.51E+00	6.92E-01	1.36E+00	3.28E-02	-1.51E-01	-1.84E-02	-6.64E-01	-7.33E-04	-5.26E-01	4.32E-01	1.44E+00	7.62E-02	6.08E+02	7.42E-01	1.23E+00	3.31E-01
14	1.13E+07	1.23E+07	-1.02E+01	2.65E-11	-1.39E+01	-1.51E+01	-1.72E+01	-2.32E-01	9.41E-01	-2.43E-01	-3.54E-01	-2.43E-01	-1.94E-01	9.97E-01	-4.12E-01	-2.15E-02	-1.20E-01	1.52E+00	4.46E-01	5.15E+02	4.05E-02	1.12E+00	1.23E-01
15	1.28E+07	1.40E+07	-1.40E+01	6.48E-11	-1.44E+01	-1.90E+01	-1.87E+01	-4.06E-01	9.99E-01	-1.54E-02	1.36E-01	-1.98E-02	-4.49E-01	-8.56E-01	-1.32E-01	-2.06E-01	7.88E-01	1.34E+00	9.10E-01	2.41E+02	5.29E-01	1.18E+00	2.20E-01
16	1.39E+07	1.51E+07	-1.10E+01	4.33E-11	-1.48E+01	-1.83E+01	-1.81E+01	-3.41E-01	-6.98E-02	-4.96E-01	-2.64E-01	1.63E-01	-2.05E-01	-7.01E-01	-9.39E-01	-5.92E-02	-8.56E-01	8.60E-01	5.84E-01	3.84E+02	3.16E-01	1.59E+00	3.21E-01
17	1.16E+07	1.14E+07	-1.09E+01	3.43E-11	-1.17E+01	-1.87E+01	-1.90E+01	-2.93E-01	-2.51E-01	-2.51E-01	-1.92E-01	-1.81E+00	5.08E-02	2.17E-01	-9.64E-02	-7.80E-02	-1.90E-05	1.47E+00	8.03E-01	3.29E+01	1.85E-01	1.08E+00	1.55E-01
18	1.19E+07	1.39E+07	-1.05E+01	3.21E-11	-1.28E+01	-1.72E+01	-1.85E+01	-1.44E-01	7.26E-01	-1.54E-03	2.54E-03	-8.20E-02	2.42E-01	-8.56E-02	-2.31E-02	-4.88E-01	1.41E-01	1.54E-01	2.07E-01	3.65E+02	7.95E-01	1.15E+00	2.70E-01
19	1.16E+07	1.20E+07	-1.19E+01	5.49E-11	-1.25E+01	-1.85E+01	-1.76E+01	-2.19E-01	-1.09E-01	1.79E-01	7.12E-01	9.81E-02	-6.93E-01	-9.17E-02	-4.48E-01	-2.01E-01	5.72E-01	5.57E-01	8.87E-01	5.59E+02	9.96E-01	1.53E+00	4.94E-01
20	1.17E+07	1.46E+07	-1.30E+01	4.96E-11	-1.37E+01	-1.60E+01	-1.89E+01	5.12E-03	-2.47E-01	1.17E-02	-8.66E-01	8.03E-01	2.27E-01	2.33E-01	-1.98E-01	1.75E-01	3.13E-01	1.09E+00	6.48E-01	5.92E+02	8.90E-01	1.96E+00	3.16E-01
21	1.14E+07	1.15E+07	-1.25E+01	4.56E-11	-1.32E+01	-1.37E+01	-1.84E+01	-7.16E-02	3.39E-02	8.72E-02	-3.37E-02	9.51E-01	-2.45E-01	-1.59E-01	-1.74E-01	-1.89E+00	-6.40E-01	5.83E-01	4.80E-01	9.52E+02	1.10E-01	1.04E+00	2.36E-01
22	1.25E+07	1.33E+07	-1.21E+01	6.18E-11	-1.16E+01	-1.49E+01	-1.89E+01	-6.73E-02	-3.64E-03	-3.98E-01	-4.07E-01	-4.44E-01	-2.25E-01	4.38E-01	-2.90E-01	1.97E-01	-1.38E-01	1.57E+00	6.72E-01	9.42E+02	8.75E-01	1.21E+00	4.33E-01
23	1.12E+07	1.59E+07	-1.12E+01	3.70E-11	-1.18E+01	-1.88E+01	-1.87E+01	-3.80E-02	-3.43E-01	-3.73E-01	-5.54E-02	-2.12E-01	-1.06E+00	-4.05E-01	2.27E-01	-3.02E-01	-2.92E-01	1.56E+00	6.30E-01	3.45E+02	6.46E-02	1.09E+00	3.56E-01
24	1.38E+07	1.16E+07	-1.20E+01	8.05E-11	-1.13E+01	-1.50E+01	-1.83E+01	-3.76E-01	-1.87E-01	5.59E-01	-2.14E-02	-2.07E-01	-2.19E-01	-1.34E-01	-2.72E-01	-3.77E-01	-1.70E+00	1.25E-01	9.87E-01	2.35E+02	4.74E-01	2.06E+00	1.71E-01
25	1.31E+07	1.53E+07	-1.33E+01	7.59E-11	-1.25E+01	-1.30E+01	-1.88E+01	-2.00E-01	1.84E-01	4.63E-01	-7.25E-01	-6.48E-02	-3.96E-01	-9.38E-01	1.37E-01	-2.85E-01	-1.53E-01	1.40E+00	4.88E-01	1.60E+02	2.97E-01	1.07E+00	2.77E-01
26	1.25E+07	1.19E+07	-1.03E+01	3.81E-11	-1.14E+01	-1.32E+01	-1.80E+01	-1.67E-01	-4.42E-01	-1.07E-01	6.74E-01	-8.64E-01	2.23E-01	-3.10E-01	-8.69E-02	-4.02E-02	3.99E-02	1.05E+00	1.17E-02	7.08E+02	6.00E-01	1.03E+00	4.72E-01
27	1.27E+07	1.34E+07	-1.27E+01	6.56E-11	-1.54E+01	-1.92E+01	-1.78E+01	-5.56E-02	-9.70E-01	-6.35E-01	7.77E-01	-5.56E-02	-6.45E-03	9.60E-02	-8.45E-01	-7.37E-02	-1.75E-01	3.21E-01	4.49E-02	1.30E+02	3.99E-01	1.24E+00	3.75E-01
28	1.30E+07	1.41E+07	-1.06E+01	3.31E-11	-1.60E+01	-1.39E+01	-1.83E+01	7.27E-01	-8.75E-02	2.18E-01	-3.08E-01	1.54E-01	-1.65E+00	3.25E-01	8.86E-01	1.40E-01	-4.88E-01	4.86E-01	2.51E-01	2.22E+02	5.53E-01	1.07E+00	4.25E-01
29	1.36E+07	1.21E+07	-1.32E+01	6.27E-11	-1.35E+01	-1.36E+01	-1.83E+01	-7.59E-01	-1.18E-01	6.72E-01	-6.79E-01	-4.80E-01	-1.38E-01	1.01E+00	-2.95E-02	-6.64E-02	-1.96E+00	1.31E+00	8.10E-01	6.79E+02	6.60E-01	1.19E+00	1.89E-01
30	1.31E+07	1.40E+07	-1.22E+01	4.77E-11	-1.54E+01	-1.87E+01	-1.83E+01	-5.51E-01	1.66E-01	1.70E-01	-1.67E-02	-3.37E-01	1.86E-01	2.02E-02	-1.91E-01	2.28E-02	1.14E-01	1.24E+00	3.15E-03	3.11E+02	1.91E-01	1.20E+00	1.73E-01
31	1.11E+07	1.36E+07	-1.22E+01	6.40E-11	-1.57E+01	-1.41E+01	-1.86E+01	-7.02E-01	4.09E-01	2.60E-02	-3.63E-01	-2.89E-01	-4.41E-01	6.80E-02	-1.20E-01	-3.18E-01	-2.57E-02	2.37E-01	7.32E-01	4.64E+02	7.82E-01	1.03E+00	4.99E-01
32	1.25E+07	1.18E+07	-1.29E+01	5.29E-11	-1.59E+01	-1.71E+01	-1.82E+01	9.12E-02	-9.85E-02	5.37E-01	-2.06E-01	-1.53E-01	-5.20E-01	1.99E-01	-7.55E-02	9.60E-01	1.77E-01	1.49E+00	2.61E-02	5.36E+02	7.54E-01	1.22E+00	3.84E-01
33	1.12E+07	1.28E+07	-1.28E+01	5.14E-11	-1.47E+01	-1.59E+01	-1.70E+01	-1.24E-02	7.95E-02	-2.16E-01	-1.98E-01	-1.30E+00	4.49E-01	1.59E-01	-1.85E-01	7.04E-01	-4.33E-01	6.04E-01	6.39E-01	9.18E+02	8.85E-01	1.22E+00	1.60E-01
34	1.17E+07	1.65E+07	-1.22E+01	4.59E-11	-1.29E+01	-1.89E+01	-1.80E+01	2.31E-01	-4.08E-01	9.51E-01	-2.46E-01	2.31E-01	-8.01E-01	-2.99E-01	-1.08E-01	-1.61E-01	-1.16E-01	4.56E-01	3.00E-01	8.28E+02	3.42E-01	1.03E+00	3.41E-01
35	1.26E+07	1.33E+07	-1.43E+01	9.49E-11	-1.34E+01	-1.66E+01	-1.84E+01	1.65E-01	-8.11E-01	-1.24E-01	-6.40E-01	-5.36E-01	-1.46E-01	8.94E-01	-5.79E-02	-7.06E-01	1.39E+00	1.52E+00	4.07E-01	5.48E+02	3.28E-02	1.10E+00	2.25E-01
36	1.23E+07	1.25E+07	-1.25E+01	5.56E-11	-1.46E+01	-1.54E+01	-1.75E+01	-1.51E-02	-2.95E-02	-1.89E-01	-2.21E-01	1.28E+00	9.51E-01	8.04E-01	-4.20E-02	-1.33E+00	-7.62E-02	8.00E-01	5.51E-01	8.68E+00	2.73E-01	1.81E+00	4.68E-01
37	1.15E+07	1.30E+07	-1.36E+01	7.82E-11	-1.27E+01	-1.58E+01	-1.88E+01	1.51E-01	-2.12E-01	-2.00E+00	-1.24E-01	2.12E-01	6.82E-02	1.85E-01	2.89E-01	-1.67E+00	-5.84E-01	1.06E+00	3.68E-02	8.06E+02	3.33E-01	1.01E+00	1.13E-01
38	1.12E+07	1.42E+07	-1.39E+01	5.82E-11	-1.32E+01	-1.82E+01	-1.78E+01	2.18E-01	9.60E-02	-3.39E-01	-1.30E-01	-1.01E-01	-5.20E-02	-3.39E-01	-5.71E-01	1.57E-01	-9.18E-01	1.17E+00	6.81E-01	1.97E+02	6.94E-01	1.18E+00	3.15E-01
39	1.34E+07	1.60E+07	-1.15E+01	5.91E-11	-1.31E+01	-1.79E+01	-1.81E+01	-1.28E-01	-1.42E-01	-3.47E-02	3.63E-01	3.17E-01	-6.18E-02	1.50E-01	-1.48E-01	3.02E-02	5.34E-01	1.56E+00	2.27E-01	3.80E+02	1.24E-01	1.11E+00	1.33E-01
40	1.14E+07	1.20E+07	-1.01E+01	5.23E-11	-1.63E+01	-1.90E+01	-1.78E+01	-1.98E-03	-1.98E-01	7.97E-01	-2.70E-01	1.58E-02	5.91E-01	-1.83E-01	-2.28E-01	-1.83E-01	2.35E-01	1.20E+00	5.37E-01	4.97E+02	8.37E-01	1.05E+00	7.86E-02
41	1.26E+07	1.31E+07	-1.04E+01	2.89E-11	-1.55E+01	-1.48E+01	-1.77E+01	1.08E+00	-1.49E-01	-7.68E-02	-4.77E-01	-1.58E+00	-2.82E-01	3.87E-02	5.81E-01	-2.13E-01	-2.33E-01	1.55E+00	2.72E-01	4.08E+02	4.42E-01	2.22E+00	4.55E-01
42	1.22E+07	1.44E+07	-1.23E+01	5.31E-11	-1.24E+01	-1.84E+01	-1.77E+01	-1.07E+00	-1.78E-01	6.06E-02	5.22E-01	5.90E-02	-1.89E+00	7.52E-01	-2.50E-01	-2.16E-01	-2.16E-01	1.54E+00	7.45E-01	3.07E+02	9.79E-01	1.02E+00	1.98E-01
43	1.21E+07	1.26E+07	-1.20E+01	5.72E-11	-1.21E+01	-1.43E+01	-1.84E+01	2.44E-01	-1.24E-02	-2.78E-01	-2.40E-01	4.47E-01	1.51E-01	-7.80E-01	1.51E-01	3.09E-01	-3.31E-02	1.54E+00	7.19E-01	7.61E+02	8.46E-01	1.19E+00	4.15E-01
44	1.37E+07	1.22E+07	-1.24E+01	7.76E-11	-1.40E+01	-1.64E+01	-1.81E+01	3.16E-01	1.97E-02	-4.27E-01	-7.93E-01	1.20E-01	-3.76E-02	-2.38E-01	-6.79E-02	7.88E-01	-2.57E-01	1.37E+00	7.67E-01	8.81E+02	6.47E-01	1.70E+00	2.95E-01
45	1.31E+07	1.47E+07	-1.28E+01	7.92E-11	-1.38E+01	-1.43E+01	-1.72E+01	-4.40E-02	5.57E-01	2.08E-01	-2.00E+00	7.63E-02	-6.36E-01	8.55E-02	-2.38E-01	-5.99E-01	-1.27E-01	1.50E+00	4.51E-01	5.79E+02	8.57E-01	1.75E+00	9.82E-02
46	1.32E+07	1.23E+07	-1.18E+01	3.76E-11	-1.24E+01	-1.29E+01	-1.85E+01	1.26E-01	2.25E-01	-2.46E-01	4.74E-01	5.34E-01	-2.99E-01	-1.77E-02	6.70E-02	-1.41E-01	-1.66E-01	1.45E+00	3.25E-01	7.83E+01	1.43E-01	1.79E+00	9.44E-02
47	1.19E+07	1.17E+07	-1.13E+01	3.57E-11	-1.30E+01	-1.55E+01	-1.75E+01	-1.81E+00	-9.25E-01	3.94E-02	-2.87E-01	-1.34E-01	1.23E-01	-4.23E-01	-5.52E-02	-1.21E-01	-2.09E-01	1.46E+00	4.38E-01	1.08E+02	2.22E-01	1.89E+00	3.81E-01
48	1.33E+07	1.28E+07	-1.22E+01	7.18E-11	-1.43E+01	-1.94E+01	-1.71E+01	-2.39E-01	8.00E-01	8.22E-01	8.76E-01	-2.17E-01	-1.40E-01	2.45E-01	6.37E-01	-2.48E-01	-3.49E-01	1.50E+00	1.09E-01	6.94E+02	4.17E-01	1.25E+00	4.63E-01
49	1.27E+07	1.64E+07	-1.16E+01	4.90E-11	-1.51E+01	-1.53E+01	-1.79E+01	-4.22E-01	-1.47E+00	-2.36E-01	7.69E-02	2.67E-01	8.94E-02	9.00E-01	-3.56E-01	-1.10E-01	-1.23E+00	1.53E+00	7.04E-01	8.60E+02	8.16E-01	1.16E+00	4.47E-01
50	1.35E+07	1.29E+07	-1.25E+01	7.29E-11	-1.23E+01	-1.33E+01	-1.72E+01	5.39E-01	6.15E-02	-8.57E-02	1.04E-01	-3.47E-02	-8.95E-02	-7.09E-02	-3.91E-01	-4.36E-01	-4.05E-01	1.44E+00	6.61E-01	7.50E+02	7.17E-01	1.10E+00	2.16E-01
51	1.22E+07	1.35E+07	-1.14E+01	3.03E-11	-1.49E+01	-1.69E+01	-1.70E+01	3.89E-02	-1.57E-01	-5.07E-01	-2.29E-01	-2.27E-01	1.31E-02	-5.82E-01	8.31E-01	-4.64E-01	8.18E-01	1.59E+00	9.44E-01	1.88E+02	5.16E-01	1.09E+00	2.62E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector Num.	S_HALITE PRESSURE	CASTILER PRESSURE	CASTILER PRMX_LOG	CASTILER COMP_RCK	BH_SAND PRMX_LOG	DRZ_1 PRMX_LOG	CONC_PLG PRMX_LOG	SOLAM3 SOLSIM	SOLAM3 SOLCIM	SOLPU3 SOLSIM	SOLPU3 SOLCIM	SOLPU4 SOLSIM	SOLPU4 SOLCIM	SOLU4 SOLSIM	SOLU6 SOLSIM	SOLU6 SOLCIM	SOLTH4 SOLSIM	PHUMOX3 PHUMCIM	GLOBAL OXSTAT	CULEBRA MINP_FAC	GLOBAL TRANSIDX	GLOBAL CLIMTIDX	CULEBRA HMBLKLT
52	1.36E+07	1.24E+07	-1.20E+01	4.39E-11	-1.62E+01	-1.38E+01	-1.78E+01	-7.98E-02	-7.68E-02	-3.89E-01	2.11E-01	-1.80E-01	-2.38E-01	2.63E-01	-1.09E+00	-4.68E-02	7.36E-01	1.44E+00	3.93E-01	8.34E+02	3.78E-01	1.14E+00	4.23E-01
53	1.10E+07	1.37E+07	-1.37E+01	4.64E-11	-1.58E+01	-1.38E+01	-1.80E+01	1.04E-01	2.41E-01	-5.48E-02	4.47E-01	-3.64E-01	5.08E-01	-2.14E-01	4.26E-02	6.50E-01	-8.06E-01	1.02E+00	6.98E-01	4.53E+02	6.77E-01	1.08E+00	1.64E-01
54	1.18E+07	1.56E+07	-1.31E+01	8.38E-11	-1.55E+01	-1.75E+01	-1.82E+01	-1.22E-01	1.36E-01	-9.19E-02	-6.75E-02	-1.18E+00	1.42E-01	-1.43E+00	1.20E-01	2.67E-01	-6.75E-01	7.73E-01	1.14E-01	4.32E+01	7.63E-02	1.17E+00	4.44E-01
55	1.11E+07	1.28E+07	-1.34E+01	6.66E-11	-1.52E+01	-1.62E+01	-1.80E+01	-4.33E-01	1.08E-01	-1.58E+00	-6.59E-03	-8.79E-02	-4.45E-02	3.57E-01	-2.21E-01	1.10E-01	-1.02E-01	1.58E+00	1.70E-01	5.84E+02	9.87E-01	1.65E+00	4.03E-01
56	1.30E+07	1.47E+07	-1.26E+01	5.40E-11	-1.39E+01	-1.86E+01	-1.81E+01	4.88E-01	1.45E-01	1.43E-01	3.59E-02	-6.02E-01	9.40E-01	-1.11E-01	-1.73E+00	-2.56E-01	8.92E-02	9.24E-01	9.94E-02	1.41E+02	4.05E-01	1.24E+00	2.52E-01
57	1.38E+07	1.34E+07	-1.23E+01	4.52E-11	-1.42E+01	-1.78E+01	-1.85E+01	-1.67E-01	-3.04E-01	-2.07E-01	1.51E-02	6.87E-01	-8.67E-01	8.72E-03	5.47E-01	2.40E-01	4.64E-01	8.23E-01	8.21E-01	9.07E+02	1.61E-02	1.73E+00	1.78E-01
58	1.30E+07	1.38E+07	-1.30E+01	4.21E-11	-1.35E+01	-1.76E+01	-1.86E+01	3.01E-02	-4.55E-01	2.26E-01	-4.29E-01	-1.63E-01	-6.85E-02	-2.35E-01	6.72E-01	-2.81E-02	-3.08E-01	1.42E+00	4.30E-01	2.57E+02	9.30E-01	1.05E+00	6.39E-02
59	1.34E+07	1.22E+07	-1.18E+01	3.47E-11	-1.59E+01	-1.85E+01	-1.77E+01	-1.45E+00	1.23E-01	-2.96E-01	-1.08E-02	-9.56E-02	-9.37E-02	-1.62E-01	5.27E-02	6.80E-01	-2.43E-01	8.95E-01	5.71E-01	7.34E+02	2.42E-01	1.13E+00	2.84E-01
60	1.21E+07	1.42E+07	-1.19E+01	6.32E-11	-1.34E+01	-1.74E+01	-1.85E+01	-3.33E-01	-2.39E-01	7.87E-02	1.17E-01	6.10E-01	1.61E-01	-6.71E-02	1.87E-01	-3.95E-01	1.73E-03	2.70E-01	3.78E-01	6.30E+02	7.02E-01	2.18E+00	7.24E-02
61	1.14E+07	1.48E+07	-1.14E+01	4.85E-11	-1.36E+01	-1.41E+01	-1.77E+01	-3.27E-02	-9.63E-02	-9.12E-01	-1.79E-01	-1.73E-01	-1.95E-01	-2.80E-01	1.99E-01	1.89E-01	2.75E-01	1.39E+00	5.25E-01	1.71E+02	7.34E-01	1.01E+00	3.53E-01
62	1.24E+07	1.38E+07	-1.21E+01	6.97E-11	-1.51E+01	-1.46E+01	-1.83E+01	5.64E-01	-1.27E-01	9.15E-01	1.71E-01	-2.47E-01	-4.15E-01	5.70E-01	-1.53E-01	-1.32E-01	8.50E-01	3.38E-01	8.53E-01	7.01E+01	2.84E-01	1.08E+00	4.52E-01
63	1.28E+07	1.43E+07	-1.11E+01	3.88E-11	-1.12E+01	-1.63E+01	-1.82E+01	-2.28E-01	-8.73E-01	2.02E-01	-2.34E-01	-4.53E-01	-1.77E-01	-4.59E-02	3.83E-01	-8.69E-02	-1.97E-01	1.36E+00	2.65E-01	5.11E+01	9.48E-01	1.59E+00	2.80E-01
64	1.34E+07	1.45E+07	-1.26E+01	5.41E-11	-1.15E+01	-1.67E+01	-1.79E+01	-2.14E-02	-1.64E+00	-1.70E-01	-4.87E-01	4.35E-02	8.46E-01	-4.51E-01	-4.88E-01	-4.76E-01	-4.41E-02	1.48E+00	1.84E-01	9.24E+02	6.34E-01	1.02E+00	3.06E-01
65	1.27E+07	1.44E+07	-1.09E+01	4.16E-11	-1.20E+01	-1.27E+01	-1.72E+01	-9.38E-01	-2.04E-01	6.14E-01	-3.84E-01	1.12E-01	-3.06E-02	-2.50E-01	1.56E-01	2.05E-01	5.09E-02	1.53E+00	8.43E-02	9.63E+02	1.10E-01	1.85E+00	4.84E-01
66	1.32E+07	1.36E+07	-1.41E+01	9.26E-11	-1.57E+01	-1.34E+01	-1.80E+01	6.21E-01	-4.62E-02	-1.65E-01	-8.90E-02	-2.01E-01	-3.40E-01	-2.29E-01	-3.14E-01	2.37E-01	-1.50E-01	7.15E-01	1.21E-01	1.19E+02	1.34E-01	1.08E+00	3.97E-01
67	1.30E+07	1.39E+07	-1.25E+01	4.93E-11	-1.15E+01	-1.72E+01	-1.72E+01	5.97E-02	-3.63E-01	-1.33E-01	2.35E-01	-4.96E-01	6.04E-01	7.40E-01	9.56E-01	-7.75E-01	1.95E-01	4.64E-01	4.16E-01	2.75E+02	8.61E-01	1.11E+00	3.51E-01
68	1.13E+07	1.53E+07	-1.24E+01	8.26E-11	-1.17E+01	-1.70E+01	-1.81E+01	1.12E-01	5.08E-02	-2.12E-01	6.34E-01	-1.90E-01	-4.93E-01	-1.45E-01	-1.15E-01	5.06E-01	-1.48E+00	1.47E+00	3.83E-01	7.75E+02	8.29E-01	1.12E+00	5.01E-02
69	1.27E+07	1.47E+07	-1.17E+01	5.10E-11	-1.19E+01	-1.78E+01	-1.89E+01	1.80E-02	6.17E-01	-4.57E-01	-4.66E-02	-1.12E-01	3.18E-02	4.53E-01	-1.00E-02	-1.59E-01	2.24E-01	1.38E+00	2.46E-01	6.61E+02	6.11E-01	2.08E+00	4.41E-01
70	1.16E+07	1.37E+07	-1.34E+01	7.12E-11	-1.18E+01	-1.77E+01	-1.79E+01	-1.77E-01	1.92E-01	4.25E-01	1.20E-01	-2.35E-02	7.63E-02	-1.32E-01	-2.10E-01	2.26E-01	6.17E-01	6.80E-01	8.76E-01	9.97E+02	9.38E-02	1.23E+00	3.26E-01
71	1.24E+07	1.25E+07	-1.13E+01	3.50E-11	-1.22E+01	-1.66E+01	-1.79E+01	2.85E-01	-3.60E-02	-3.26E-01	-8.98E-01	4.61E-01	-1.04E-01	-1.02E-01	3.28E-01	-3.25E-01	6.28E-02	1.43E+00	2.12E-01	8.49E+02	2.45E-02	1.16E+00	4.11E-01
72	1.18E+07	1.24E+07	-1.29E+01	6.82E-11	-1.44E+01	-1.26E+01	-1.88E+01	2.13E-01	-2.83E-01	2.97E-01	6.73E-02	-4.13E-01	-1.24E-01	-5.46E-02	-6.55E-01	-9.28E-02	-6.69E-02	1.57E+00	6.03E-01	7.86E+02	3.28E-01	1.09E+00	1.81E-01
73	1.21E+07	1.38E+07	-1.20E+01	4.44E-11	-1.49E+01	-1.55E+01	-1.75E+01	-2.46E-01	-5.47E-02	-2.29E-01	5.66E-01	3.57E-01	-1.71E-01	-9.58E-01	-4.77E-01	-9.78E-01	7.63E-02	1.58E+00	9.01E-01	4.47E+02	6.22E-01	1.13E+00	2.98E-01
74	1.24E+07	1.30E+07	-1.07E+01	4.47E-11	-1.41E+01	-1.81E+01	-1.86E+01	-1.89E-01	-2.24E-01	3.22E-01	2.82E-01	1.78E-01	7.46E-01	3.32E-02	-3.90E-02	5.54E-02	3.46E-02	1.58E+00	7.78E-01	7.54E+02	6.81E-01	1.52E+00	1.43E-01
75	1.33E+07	1.32E+07	-1.21E+01	5.01E-11	-1.53E+01	-1.69E+01	-1.76E+01	-4.52E-01	-5.44E-01	-1.59E-01	-5.78E-01	-7.05E-01	-3.04E-01	-1.24E-01	-8.13E-02	-1.02E-01	1.54E-01	1.47E+00	3.16E-01	5.67E+02	2.63E-01	2.00E+00	1.39E-01
76	1.35E+07	1.29E+07	-1.23E+01	5.59E-11	-1.20E+01	-1.50E+01	-1.74E+01	-1.50E-01	-1.70E-01	-8.39E-01	1.62E-01	7.07E-02	-1.06E-01	1.24E-01	-1.64E-01	8.19E-01	1.57E-01	6.14E-01	1.54E-01	2.44E+01	4.56E-01	1.04E+00	4.76E-01
77	1.20E+07	1.41E+07	-1.38E+01	8.79E-11	-1.19E+01	-1.60E+01	-1.73E+01	-1.06E-01	-4.64E-01	-6.99E-01	-1.67E+00	-1.40E-01	7.60E-01	-2.50E-01	-5.19E-01	-3.69E-01	1.50E-02	5.35E-01	3.67E-01	4.15E+02	4.30E-01	2.15E+00	1.20E-01
78	1.15E+07	1.44E+07	-1.19E+01	6.00E-11	-1.56E+01	-1.58E+01	-1.79E+01	9.72E-01	1.32E+00	-1.83E-01	-5.94E-02	-7.29E-01	-7.06E-02	-4.69E-01	-1.41E-01	-4.18E-01	-2.27E-01	1.51E+00	5.03E-01	6.50E+02	3.06E-01	2.23E+00	2.40E-01
79	1.39E+07	1.45E+07	-1.17E+01	4.25E-11	-1.60E+01	-1.80E+01	-1.87E+01	1.42E-01	-6.94E-01	-1.29E-01	-5.01E-01	-7.04E-02	9.77E-02	-1.76E-01	-7.52E-01	-1.28E-01	-8.74E-02	1.55E+00	9.30E-01	8.95E+02	9.51E-01	1.19E+00	3.62E-01
80	1.33E+07	1.32E+07	-1.18E+01	4.80E-11	-1.29E+01	-1.73E+01	-1.75E+01	8.23E-01	1.75E-01	-3.13E-01	-3.59E-02	-4.94E-02	-9.09E-01	-2.75E-02	1.69E-01	3.83E-01	-3.86E-01	1.38E+00	5.20E-01	8.68E+01	7.23E-01	1.11E+00	1.50E-01
81	1.35E+07	1.33E+07	-1.31E+01	8.48E-11	-1.40E+01	-1.52E+01	-1.87E+01	-3.15E-01	2.36E-01	1.27E-01	-1.86E-01	2.15E-01	2.82E-01	1.76E-01	-2.01E-02	1.01E-01	-7.76E-02	1.59E+00	7.27E-01	1.69E+01	9.61E-01	1.00E+00	2.30E-01
82	1.23E+07	1.36E+07	-1.16E+01	3.99E-11	-1.27E+01	-1.92E+01	-1.73E+01	-1.58E-01	5.22E-01	-6.53E-02	-7.62E-02	-1.27E-01	-1.26E-01	7.63E-02	-8.16E-01	-2.24E-01	-3.64E-01	1.60E+00	2.33E-01	6.18E+02	2.63E-04	1.03E+00	1.45E-01
83	1.18E+07	1.17E+07	-1.28E+01	7.40E-11	-1.13E+01	-1.91E+01	-1.74E+01	-6.63E-01	-6.04E-02	-2.77E-02	-1.24E+00	5.60E-01	-5.97E-01	-1.62E+00	-4.35E-01	9.07E-02	2.09E-01	1.49E+00	1.37E-01	1.69E+02	5.68E-01	1.22E+00	2.71E-01
84	1.22E+07	1.34E+07	-1.12E+01	4.07E-11	-1.14E+01	-1.46E+01	-1.82E+01	8.23E-02	-2.21E-01	-4.07E-02	-9.57E-02	-3.43E-01	-3.80E-01	-1.68E-01	-9.80E-01	5.51E-01	9.32E-01	7.39E-01	7.80E-01	6.83E+02	4.29E-01	1.21E+00	4.06E-01
85	1.15E+07	1.50E+07	-1.08E+01	4.18E-11	-1.42E+01	-1.28E+01	-1.89E+01	1.83E-01	-1.62E-01	-5.86E-02	-8.04E-02	2.45E-02	-3.34E-01	-6.03E-02	-1.35E+00	-9.31E-03	-4.21E-01	1.12E+00	9.39E-01	2.05E+02	1.51E-01	1.17E+00	1.99E-01
86	1.29E+07	1.42E+07	-1.27E+01	6.98E-11	-1.30E+01	-1.28E+01	-1.72E+01	-1.84E-01	-1.15E-01	-9.48E-01	2.16E-01	7.51E-01	-1.39E-02	2.09E-01	7.82E-01	1.18E+00	6.62E-01	1.52E+00	8.94E-01	3.22E+02	2.14E-01	1.25E+00	2.10E-01
87	1.11E+07	1.55E+07	-1.17E+01	4.08E-11	-1.62E+01	-1.68E+01	-1.73E+01	-2.04E-01	-1.81E+00	-1.17E-01	-1.40E-01	7.79E-03	-8.05E-02	-3.84E-02	7.07E-01	4.92E-01	-9.28E-02	2.86E-01	9.52E-01	6.37E+02	2.50E-01	1.15E+00	3.68E-01
88	1.37E+07	1.31E+07	-1.13E+01	6.39E-11	-1.38E+01	-1.40E+01	-1.76E+01	1.74E-01	2.55E-01	-4.34E-02	9.44E-02	-1.24E-01	1.11E+00	-1.21E+00	2.11E-01	4.32E-01	-1.01E-02	1.40E+00	9.62E-01	3.59E+02	5.66E-02	1.06E+00	3.37E-01
89	1.36E+07	1.52E+07	-1.36E+01	6.14E-11	-1.11E+01	-1.51E+01	-1.76E+01	-1.11E-01	1.16E-02	-4.78E-01	3.33E-01	-8.02E-01	-1.60E-01	-1.46E-01	-2.06E-01	-2.35E-01	-1.41E-01	6.48E-01	1.73E-01	4.35E+02	7.67E-01	1.22E+00	4.88E-01
90	1.25E+07	1.35E+07	-1.19E+01	4.72E-11	-1.45E+01	-1.37E+01	-1.82E+01	-8.01E-01	-2.93E-01	-1.40E-01	1.96E-01	-1.36E-02	-1.56E-01	-4.39E-01	4.84E-01	-1.90E-01	-3.36E-01	1.39E+00	3.01E-01	9.71E+02	3.65E-01	1.94E+00	2.33E-01
91	1.23E+07	1.39E+07	-1.30E+01	5.77E-11	-1.47E+01	-1.44E+01	-1.89E+01	-5.85E-01	-6.09E-01	1.16E-01	-9.60E-01	-9.26E-01	8.68E-01	-3.65E-01	-2.32E-01	-1.11E-01	1.05E-01	1.48E+00	7.91E-01	3.96E+02	1.64E-01	1.12E+00	2.07E-01
92	1.26E+07	1.26E+07	-1.35E+01	7.65E-11	-1.50E+01	-1.93E+01	-1.85E+01	-8.50E-01	-6.51E-02	-4.42E-01	-1.09E-01	-6.38E-01	-9.66E-01	-2.21E-01	1.13E+00	-6.55E-01	-4.72E-01	1.14E+00	9.98E-01	4.22E+02	2.03E-01	1.63E+00	2.90E-01
93	1.36E+07	1.26E+07	-1.14E+01	3.08E-11	-1.45E+01	-1.31E+01	-1.74E+01	-4.89E-01	-1.50E-02	-6.05E-01	-1.14E-01	-9.71E-01	-1.42E+00	-5.01E-01	-1.29E-01	-9.38E-01	9.66E-01	4.19E-01	4.99E-01	7.16E+02	9.12E-01	1.01E+00	5.72E-02
94	1.13E+07	1.25E+07	-1.38E+01	8.84E-11	-1.24E+01	-1.47E+01	-1.71E+01	6.79E-01	-3.35E-01	2.49E-01	1.89E-01	-3.83E-01	-2.55E-01	1.17E-01	4.15E-01	-4.96E-02	3.58E-01	3.83E-01	4.70E-01	8.71E+02	4.62E-01	1.20E+00	8.37E-02
95	1.18E+07	1.50E+07	-1.16E+01	5.19E-11	-1.48E+01	-1.31E+01	-1.82E+01	-4.80E-01	3.39E-01	-1.50E+00	4.89E-02	-2.32E-01	6.64E-01	5.20E-01	1.12E-01	-8.82E-01	-1.06E-01	1.73E-01	9.78E-01	5.01E+02	3.55E-01	1.19E+00	3.95E-01
96	1.32E+07	1.27E+07	-1.15E+01	4.31E-11	-1.59E+01	-1.54E+01	-1.75E+01	-3.60E-01	-1.88E-01	-1.52E-01	-1.34E-01	8.87E-01	-1.82E-01	-8.03E-02	7.29E-02	8.70E-01	-5.51E-02	6.88E-02	3.41E-01	2.97E+02	4.86E-01	1.13E+00	1.27E-01
97	1.14E+07	1.30E+07	-1.32E+01	5.87E-11	-1.43E+01	-1.30E+01	-1.87E+01	-8.88E-02	-6.61E-01	-9.81E-03	9.95E-01	1.94E-01	-2.10E-01	-1.91E-01	8.93E-02	5.99E-02	-3.80E-02	1.50E+00	6.94E-02	2.13E+02	8.10E-01	2.03E+00	1.05E-01
98	1.20E+07	1.55E+07	-1.04E+01	3.33E-11	-1.21E+01	-1.56E+01	-1.87E+01	-9.27E-02	-3.87E-01	1.36E-01	-1.49E-01	-4.00E-01	-4.67E-01	-3.04E-02	2.24E-01	2.15E-04	-2.42E-01	9.31E-01	2.82E-01	5.27E+02	5.46E-01	1.16E+00	2.60E-01
99	1.17E+07	1.28E+07	-1.11E+01	3.69E-11	-1.16E+01	-1.35E+01	-1.73E+01	-2.12E-01	-7.67E-01	-1.96E-01	9.02E-01	-3.17E-01	-3.65E-01	-3.39E-01	-1.84E+00	8.00E-02	-2.07E-01	1.21E+00	8.33E-01	1.45E+02	1.77E-01	1.24E+00	1.02E-01
100	1.17E+07	1.58E+07	-1.08E+01	2.50E-11	-1.26E+01	-1.67E+01	-1.86E+01	-1.36E-01	2.12E-01	1.58E-01	-1.66E-01	1.38E-01	4.67E-01	6.85E-01	-6.92E-01	-1.72E-02	1.89E-01	2.19E-01	7.54E-01	2.64E+02	3.86E-01	1.11E+00	8.70E-02

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
1	1.45E-03	1.89E-01	2.64E-03	2.30E+00	2.61E-02	8.04E-01	2.47E+00	1.12E-01	4.20E+00	3.31E-01	1.20E+01	2.99E-01	2.15E-01	-1.89E+01	-1.83E+01	-1.96E+01	3.99E-01
2	1.31E-03	1.12E-01	1.96E-03	9.56E-01	2.48E-01	1.08E+00	4.44E+00	5.16E-02	2.30E+01	5.23E-02	5.70E+00	9.75E-02	5.30E-02	-1.82E+01	-1.79E+01	-1.91E+01	1.75E-01
3	1.44E-04	1.57E-01	1.28E-03	9.36E-01	1.38E-01	1.74E+00	1.14E+00	3.80E-01	3.59E-01	5.66E-01	6.91E+00	3.20E-01	2.27E-01	-1.77E+01	-1.89E+01	-2.04E+01	3.87E-01
4	2.72E-03	1.61E-01	1.01E-02	1.48E+00	6.93E-02	1.63E+00	1.62E+00	8.31E-02	5.43E-02	5.39E-01	9.59E+00	1.20E-01	1.32E-01	-1.79E+01	-1.89E+01	-1.95E+01	1.61E-02
5	6.07E-03	1.80E-01	1.72E-03	5.24E+00	9.60E-02	7.07E+00	8.54E+00	1.58E-01	1.77E+00	5.85E-01	8.73E+00	3.97E-01	3.24E-01	-2.02E+01	-1.73E+01	-2.02E+01	1.64E-01
6	3.49E-03	1.53E-01	1.14E-04	7.25E-01	1.88E-01	8.39E-01	8.46E+00	2.13E-01	5.53E+01	2.61E-01	8.09E+00	2.73E-01	3.69E-01	-1.86E+01	-1.75E+01	-2.17E+01	1.00E+00
7	2.56E-04	1.84E-01	2.48E-04	1.14E+00	3.77E-01	9.87E-01	1.16E+00	2.80E-02	3.26E-01	5.06E-01	6.15E+00	1.37E-03	2.37E-01	-1.98E+01	-1.91E+01	-2.11E+01	4.53E-01
8	3.32E-04	1.42E-01	2.18E-04	6.46E+00	4.46E-02	1.02E+00	6.52E+00	3.58E-01	3.56E+01	5.49E-01	7.13E+00	2.90E-01	3.86E-01	-1.93E+01	-1.88E+01	-2.01E+01	8.99E-01
9	4.07E-04	1.19E-01	1.89E-03	6.72E+00	4.70E-02	9.58E-01	1.49E+00	7.89E-02	5.71E+00	2.66E-01	4.64E+00	5.56E-01	2.19E-01	-1.96E+01	-1.75E+01	-2.10E+01	8.30E-01
10	1.60E-04	1.87E-01	7.98E-05	8.00E-01	2.01E-01	7.09E+00	8.92E-01	1.29E-01	8.79E-01	3.13E-01	1.26E+01	1.79E-02	1.83E-01	-1.91E+01	-1.86E+01	-1.93E+01	4.69E-01
11	1.48E-04	1.90E-01	4.77E-03	7.65E+00	5.12E-02	8.88E-01	2.28E+00	5.32E-02	2.02E+01	2.42E-02	1.31E+01	1.64E-01	1.95E-01	-1.74E+01	-1.92E+01	-1.91E+01	8.18E-01
12	7.89E-03	1.04E-01	4.09E-03	7.54E-01	3.52E-01	3.97E+00	9.63E-01	3.34E-02	2.75E+01	5.57E-01	2.06E+01	1.66E-01	4.22E-02	-1.76E+01	-1.77E+01	-2.03E+01	4.07E-01
13	4.68E-03	1.82E-01	5.02E-04	7.11E-01	1.23E-01	9.20E+00	2.42E+00	2.98E-02	1.21E-01	4.67E-01	7.50E+00	2.68E-01	2.84E-01	-1.87E+01	-1.83E+01	-1.91E+01	9.45E-01
14	2.41E-03	1.88E-01	2.11E-03	9.09E-01	4.19E-02	8.01E+00	1.59E+00	1.21E-01	2.35E+00	5.08E-02	7.99E+00	6.50E-02	3.73E-01	-1.84E+01	-1.77E+01	-1.99E+01	2.70E-01
15	5.92E-03	1.68E-01	3.09E-05	1.30E+00	2.02E-02	4.49E+00	8.61E-01	2.58E-01	8.43E+00	1.94E-01	7.38E+00	5.96E-01	2.43E-02	-1.83E+01	-1.87E+01	-2.12E+01	5.40E-02
16	9.08E-04	1.70E-01	3.91E-04	1.91E+00	8.99E-02	3.83E+00	1.78E+00	1.46E-01	2.91E+00	8.06E-02	9.08E+00	8.64E-03	1.46E-01	-1.81E+01	-1.85E+01	-2.00E+01	1.43E-01
17	8.68E-04	1.08E-01	5.90E-04	8.27E-01	1.25E-01	1.31E+00	7.82E-01	8.67E-02	4.81E-01	2.78E-01	6.65E+00	1.29E-01	9.74E-02	-1.78E+01	-1.87E+01	-1.97E+01	9.76E-01
18	2.09E-04	2.08E-01	2.32E-04	6.15E+00	3.12E-01	1.97E+00	4.37E+00	6.47E-02	1.86E+01	4.62E-01	5.43E+00	5.42E-02	1.99E-02	-1.81E+01	-1.73E+01	-1.94E+01	7.11E-01
19	2.77E-03	1.13E-01	2.76E-03	3.92E+00	2.46E-01	5.44E+00	6.07E+00	2.77E-01	3.01E+01	1.33E-01	1.30E+01	4.94E-02	3.52E-01	-2.00E+01	-1.87E+01	-1.96E+01	5.48E-01
20	7.97E-03	2.03E-01	3.22E-04	2.85E+00	2.30E-02	1.49E+00	7.15E-01	1.52E-01	6.94E+00	4.30E-01	7.21E+00	2.50E-02	3.63E-01	-1.70E+01	-1.74E+01	-1.92E+01	8.80E-02
21	4.72E-04	1.23E-01	1.45E-02	4.27E+00	3.81E-02	1.23E+00	1.38E+00	5.01E-02	1.19E-01	7.00E-02	6.39E+00	2.18E-01	2.09E-01	-1.87E+01	-1.94E+01	-1.99E+01	6.48E-01
22	1.08E-03	1.38E-01	7.12E-04	1.36E+00	1.60E-01	1.20E+00	5.02E+00	2.15E-02	4.02E+01	5.82E-01	4.84E+00	4.99E-01	8.93E-03	-1.93E+01	-1.81E+01	-1.98E+01	1.31E-01
23	7.75E-04	1.70E-01	9.31E-05	4.39E+00	1.92E-01	3.41E+00	4.65E+00	1.58E-01	1.43E+01	2.78E-02	7.74E+00	3.52E-01	3.14E-01	-1.94E+01	-1.89E+01	-1.94E+01	5.83E-01
24	4.37E-04	1.19E-01	1.63E-03	1.52E+00	2.12E-02	2.78E+00	6.30E+00	3.09E-01	4.08E-01	3.98E-01	7.32E+00	1.03E-01	2.08E-01	-1.90E+01	-1.77E+01	-1.93E+01	6.70E-01
25	2.30E-04	1.68E-01	1.55E-02	1.11E+00	1.49E-01	1.19E+00	4.56E+00	2.20E-01	1.06E-01	3.70E-02	8.63E+00	8.34E-02	2.76E-01	-1.99E+01	-1.70E+01	-1.93E+01	7.16E-02
26	3.70E-03	1.80E-01	5.99E-05	6.31E+00	4.62E-02	8.50E-01	1.77E+00	1.01E-01	7.57E-01	3.63E-01	9.22E+00	1.38E-01	1.12E-01	-1.77E+01	-1.77E+01	-1.90E+01	1.82E-01
27	6.44E-04	1.58E-01	1.69E-04	1.45E+00	2.45E-02	3.09E+00	2.20E+00	1.39E-01	1.29E+01	1.38E-01	4.56E+00	8.95E-02	2.54E-01	-1.81E+01	-1.93E+01	-1.95E+01	7.85E-01
28	1.13E-03	1.83E-01	8.97E-04	2.58E+00	1.35E-01	7.51E+00	5.26E+00	2.23E-02	9.96E-01	1.92E-02	9.91E+00	4.67E-01	9.41E-02	-1.83E+01	-1.88E+01	-1.96E+01	3.63E-01
29	1.58E-03	1.77E-01	4.04E-05	3.81E+00	2.87E-01	2.16E+00	8.85E-01	1.66E-01	1.56E+00	3.77E-01	7.90E+00	5.77E-01	3.99E-01	-1.88E+01	-1.94E+01	-2.02E+01	3.09E-01
30	1.01E-03	1.84E-01	1.13E-02	9.20E+00	3.31E-01	2.28E+00	3.31E+00	6.96E-02	6.70E+00	3.88E-01	9.24E+00	1.25E-02	3.07E-01	-1.84E+01	-1.91E+01	-2.05E+01	1.02E-01
31	1.32E-03	1.10E-01	8.75E-04	9.86E+00	1.42E-01	6.20E+00	1.30E+00	2.27E-01	2.10E+00	1.15E-01	8.52E+00	3.07E-02	3.12E-02	-1.78E+01	-1.79E+01	-2.06E+01	8.53E-01
32	6.04E-04	1.00E-01	3.50E-03	1.65E+00	3.96E-02	9.18E-01	7.26E-01	3.90E-02	8.42E-01	2.03E-01	8.12E+00	1.15E-01	3.17E-01	-1.91E+01	-1.82E+01	-2.03E+01	7.72E-01
33	4.29E-04	1.78E-01	3.53E-04	9.70E-01	3.28E-02	3.86E+00	5.37E+00	3.46E-01	3.66E+00	4.46E-02	4.98E+00	2.39E-02	2.36E-02	-1.97E+01	-1.89E+01	-1.92E+01	2.27E-01
34	8.45E-03	1.34E-01	2.85E-04	1.25E+00	1.44E-01	1.26E+00	1.27E+00	2.69E-01	1.21E+00	1.53E-01	6.96E+00	1.74E-01	2.43E-01	-1.89E+01	-1.81E+01	-1.89E+01	7.07E-01
35	5.60E-03	1.77E-01	8.58E-03	1.09E+00	5.81E-02	1.69E+00	5.52E+00	3.94E-01	7.67E+01	4.55E-01	9.51E+00	1.25E-01	2.48E-01	-1.79E+01	-1.85E+01	-1.88E+01	6.17E-01
36	2.03E-04	1.61E-01	4.25E-04	4.76E+00	3.89E-01	4.57E+00	5.62E+00	1.26E-01	1.05E+01	3.73E-01	6.51E+00	5.09E-01	1.14E-01	-1.79E+01	-1.70E+01	-1.92E+01	9.27E-01
37	2.54E-03	1.42E-01	4.85E-05	2.90E+00	3.70E-02	2.47E+00	1.10E+00	8.89E-02	2.70E-01	2.57E-01	7.42E+00	4.57E-01	1.03E-01	-1.76E+01	-1.78E+01	-1.97E+01	9.71E-02
38	7.31E-03	1.72E-01	6.06E-04	5.66E+00	2.60E-01	1.01E+00	7.84E+00	4.06E-02	6.91E-02	4.01E-01	7.71E+00	1.06E-01	2.70E-01	-1.81E+01	-1.77E+01	-2.08E+01	8.82E-01
39	7.00E-04	1.72E-01	3.65E-05	3.60E+00	2.00E-01	2.84E+00	3.37E+00	5.93E-02	1.81E-01	2.47E-01	6.59E+00	1.35E-01	6.28E-02	-1.82E+01	-1.78E+01	-1.99E+01	8.00E-01
40	1.41E-03	1.90E-01	1.02E-03	2.21E+00	2.64E-01	5.71E+00	2.86E+00	1.18E-01	5.36E-02	2.29E-01	5.55E+00	5.37E-01	8.23E-02	-1.87E+01	-1.81E+01	-2.05E+01	1.99E-01
41	8.16E-04	1.81E-01	1.22E-03	5.14E+00	1.02E-01	1.35E+00	2.05E+00	3.27E-01	1.98E-01	2.40E-01	6.74E+00	2.00E-01	3.58E-01	-1.76E+01	-1.76E+01	-2.20E+01	5.29E-01
42	3.15E-03	1.65E-01	1.66E-02	1.79E+00	3.12E-02	1.39E+00	8.20E+00	2.59E-02	6.08E-01	3.52E-01	4.33E+00	1.18E-01	7.00E-02	-1.75E+01	-1.80E+01	-2.02E+01	4.84E-01
43	1.81E-03	1.55E-01	1.10E-02	8.52E+00	6.24E-02	8.67E+00	4.77E+00	2.93E-02	9.15E-02	2.94E-01	7.05E+00	1.11E-01	1.37E-01	-1.77E+01	-1.97E+01	-1.94E+01	9.58E-01
44	4.40E-03	1.46E-01	7.58E-03	7.81E+00	7.91E-02	2.53E+00	1.08E+00	3.21E-02	7.51E-01	1.77E-01	5.06E+00	1.72E-01	2.97E-01	-1.86E+01	-1.71E+01	-1.87E+01	6.28E-01
45	7.45E-04	1.41E-01	1.43E-03	2.12E+00	6.29E-02	9.13E-01	8.88E+00	2.17E-01	1.09E+00	4.10E-01	1.47E+01	2.55E-01	4.41E-03	-1.77E+01	-1.87E+01	-1.98E+01	8.31E-01
46	7.12E-03	1.73E-01	9.70E-03	3.96E+00	4.00E-02	1.46E+00	1.69E+00	2.93E-01	3.41E+00	5.34E-01	6.44E+00	3.43E-02	2.09E-03	-2.04E+01	-1.83E+01	-2.15E+01	1.15E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
47	2.16E-03	1.18E-01	3.56E-05	7.92E+00	2.64E-02	3.35E+00	7.28E+00	4.34E-02	1.55E-01	4.26E-01	1.35E+01	1.89E-01	8.86E-02	-1.85E+01	-1.81E+01	-2.08E+01	2.60E-01
48	2.66E-04	1.79E-01	4.39E-03	7.88E-01	2.74E-02	3.55E+00	3.21E+00	7.18E-02	2.61E+00	5.41E-01	8.27E+00	1.47E-01	3.77E-01	-1.76E+01	-1.79E+01	-2.00E+01	5.13E-01
49	4.05E-03	1.66E-01	6.78E-04	4.36E+00	5.49E-02	8.49E+00	2.19E+00	2.49E-01	2.17E+00	3.89E-01	1.74E+01	2.47E-01	1.23E-01	-1.92E+01	-1.85E+01	-1.90E+01	9.16E-01
50	9.96E-04	1.75E-01	3.35E-05	5.37E+00	2.92E-01	6.71E+00	1.05E+00	3.32E-02	6.71E+01	1.40E-01	6.78E+00	5.24E-01	2.34E-01	-1.86E+01	-1.88E+01	-1.96E+01	4.26E-01
51	5.47E-03	1.15E-01	2.22E-03	6.69E+00	3.13E-02	3.46E+00	7.22E+00	5.87E-02	2.24E-01	5.92E-01	5.99E+00	6.22E-02	3.93E-01	-1.82E+01	-1.83E+01	-1.84E+01	4.98E-01
52	1.17E-04	1.21E-01	7.34E-05	1.40E+00	4.92E-02	1.87E+00	9.65E+00	1.79E-01	3.64E-01	6.77E-02	5.29E+00	4.83E-01	1.69E-01	-1.77E+01	-1.75E+01	-2.00E+01	5.78E-01
53	3.27E-04	2.31E-01	8.97E-05	1.36E+00	5.70E-02	8.23E+00	7.02E+00	9.49E-02	3.98E+00	5.01E-01	7.94E+00	3.89E-01	1.06E-01	-1.80E+01	-1.86E+01	-1.80E+01	5.62E-01
54	3.76E-04	1.15E-01	5.58E-03	1.01E+00	7.42E-02	4.26E+00	2.96E+00	1.92E-01	6.26E-02	3.22E-01	6.36E+00	4.77E-01	3.02E-01	-2.01E+01	-1.84E+01	-2.00E+01	7.35E-01
55	1.70E-04	1.14E-01	5.27E-05	7.18E+00	2.36E-01	4.14E+00	8.24E-01	6.10E-02	1.63E-01	2.88E-01	9.73E+00	1.50E-01	1.27E-01	-1.98E+01	-1.74E+01	-1.90E+01	2.65E-01
56	8.87E-03	1.50E-01	5.35E-03	5.77E+00	2.19E-01	2.66E+00	4.04E+00	3.19E-01	1.95E+00	2.75E-01	1.57E+01	5.73E-01	1.77E-01	-1.95E+01	-1.80E+01	-1.82E+01	3.47E-01
57	3.58E-04	1.86E-01	7.46E-05	2.55E+00	2.31E-01	2.92E+00	2.59E+00	3.05E-01	9.75E-02	5.19E-01	8.30E+00	3.92E-02	1.31E-02	-1.78E+01	-1.80E+01	-1.88E+01	9.87E-01
58	9.19E-04	1.89E-01	4.17E-05	3.73E+00	8.09E-02	5.33E+00	9.48E+00	3.66E-01	2.80E-01	1.48E-01	1.09E+01	1.86E-01	2.62E-01	-1.73E+01	-1.84E+01	-2.15E+01	4.48E-01
59	2.26E-04	1.74E-01	1.80E-02	2.07E+00	3.24E-01	5.87E+00	1.53E+00	5.55E-02	4.80E+01	4.78E-01	8.17E+00	2.00E-01	1.41E-01	-1.71E+01	-1.82E+01	-2.03E+01	2.15E-01
60	1.83E-04	1.13E-01	3.73E-03	2.16E+00	2.49E-02	7.82E+00	3.62E+00	2.02E-02	7.44E+00	2.17E-01	1.16E+01	2.36E-01	3.40E-01	-1.80E+01	-1.76E+01	-1.85E+01	2.34E-01
61	2.41E-04	2.25E-01	1.41E-02	3.02E+00	4.25E-02	2.63E+00	7.57E-01	2.39E-01	4.56E+01	3.37E-01	7.08E+00	1.82E-01	1.73E-01	-1.88E+01	-1.90E+01	-2.04E+01	7.66E-01
62	5.96E-04	1.63E-01	1.03E-04	2.42E+00	1.16E-01	6.12E+00	3.69E+00	2.07E-02	6.29E+01	3.07E-01	7.30E+00	4.10E-02	2.04E-01	-1.85E+01	-1.84E+01	-2.22E+01	2.09E-01
63	6.91E-04	1.71E-01	4.79E-03	8.81E-01	1.65E-01	6.63E+00	2.08E+00	2.05E-01	6.25E+00	1.83E-01	7.88E+00	4.27E-01	1.51E-01	-1.78E+01	-1.81E+01	-2.01E+01	8.78E-01
64	1.09E-04	1.47E-01	2.95E-03	1.03E+00	8.92E-02	1.88E+00	1.03E+00	9.81E-02	2.79E+01	2.45E-01	7.82E+00	2.80E-01	2.94E-01	-1.82E+01	-1.71E+01	-2.14E+01	5.40E-01
65	9.81E-03	1.16E-01	1.06E-04	5.57E+00	1.19E-01	3.11E+00	1.47E+00	2.86E-01	6.05E+01	5.29E-01	4.44E+00	2.32E-01	1.66E-01	-1.75E+01	-1.83E+01	-1.98E+01	2.47E-01
66	1.52E-04	1.85E-01	7.27E-03	9.51E+00	2.19E-02	5.88E+00	1.01E+00	3.69E-02	3.22E+01	5.98E-01	7.78E+00	3.47E-01	3.33E-01	-1.94E+01	-1.85E+01	-1.99E+01	7.59E-01
67	1.63E-03	1.82E-01	8.06E-04	3.12E+00	9.47E-02	2.40E+00	4.91E+00	2.48E-02	5.89E-02	1.75E-01	6.63E+00	2.09E-01	2.44E-01	-1.96E+01	-1.76E+01	-2.10E+01	3.27E-01
68	1.76E-04	1.17E-01	4.67E-04	1.19E+00	3.38E-01	7.44E+00	2.87E+00	1.35E-01	9.51E+00	5.64E-01	6.84E+00	9.54E-02	2.68E-01	-1.73E+01	-1.80E+01	-2.12E+01	3.54E-01
69	5.01E-03	1.05E-01	3.12E-03	1.22E+00	2.25E-01	7.03E-01	9.80E+00	2.73E-02	5.22E-01	1.17E-01	1.19E+01	4.16E-01	2.82E-01	-1.74E+01	-1.95E+01	-2.01E+01	3.46E-02
70	1.25E-04	1.11E-01	5.90E-03	5.91E+00	3.75E-01	4.73E+00	4.12E+00	3.37E-01	2.08E-01	3.44E-01	6.30E+00	4.92E-01	3.08E-01	-1.72E+01	-1.90E+01	-2.11E+01	3.79E-01
71	2.19E-03	1.08E-01	6.77E-03	1.26E+00	2.22E-02	9.51E+00	7.97E+00	4.67E-02	1.18E+01	4.50E-01	7.47E+00	5.88E-01	1.56E-01	-1.83E+01	-1.85E+01	-2.14E+01	6.61E-01
72	4.25E-03	1.86E-01	1.23E-04	2.51E+00	3.50E-02	1.16E+00	9.13E+00	3.05E-02	6.69E-01	3.03E-01	1.24E+01	4.78E-03	3.31E-01	-1.79E+01	-1.72E+01	-2.19E+01	9.03E-01
73	3.09E-04	1.06E-01	1.95E-04	1.86E+00	1.04E-01	1.56E+00	7.77E-01	1.76E-01	1.06E+00	2.08E-01	1.05E+01	1.53E-01	3.55E-01	-1.94E+01	-1.84E+01	-2.04E+01	1.56E-01
74	3.47E-03	1.28E-01	1.96E-02	8.25E+00	9.91E-02	1.67E+00	1.99E+00	1.87E-01	1.40E+01	1.24E-02	7.60E+00	4.49E-01	4.97E-02	-1.89E+01	-1.83E+01	-2.04E+01	6.37E-01
75	3.00E-04	1.26E-01	4.51E-05	3.24E+00	1.79E-01	3.69E+00	2.56E+00	4.18E-02	5.23E+00	1.66E-01	8.36E+00	7.40E-02	6.00E-02	-1.86E+01	-1.82E+01	-1.87E+01	9.68E-01
76	2.33E-03	1.75E-01	1.58E-04	7.72E-01	7.68E-02	3.25E+00	1.40E+00	7.51E-02	8.44E-02	9.60E-02	1.11E+01	4.46E-01	1.58E-01	-1.80E+01	-1.86E+01	-2.08E+01	2.94E-01
77	6.33E-03	1.57E-01	4.52E-04	1.73E+00	1.12E-01	9.41E+00	3.87E+00	2.32E-02	2.09E+01	1.27E-01	7.23E+00	4.79E-02	3.24E-01	-1.95E+01	-1.92E+01	-2.25E+01	7.95E-01
78	1.70E-03	1.67E-01	6.91E-05	1.95E+00	2.97E-02	7.61E-01	1.90E+00	3.50E-02	1.62E+01	6.03E-02	6.52E+00	1.79E-01	3.95E-02	-1.83E+01	-1.81E+01	-2.02E+01	4.11E-01
79	1.33E-04	1.97E-01	1.11E-03	2.69E+00	3.56E-02	2.06E+00	1.25E+00	4.46E-02	1.31E-01	3.25E-01	6.98E+00	5.31E-01	1.60E-01	-1.85E+01	-1.82E+01	-2.07E+01	8.65E-01
80	2.82E-04	1.03E-01	3.77E-04	7.45E+00	7.05E-02	8.83E+00	5.89E+00	2.46E-01	2.53E+01	1.04E-01	8.95E+00	5.75E-02	3.41E-01	-1.75E+01	-1.72E+01	-2.07E+01	4.88E-02
81	3.26E-03	1.04E-01	2.57E-04	2.01E+00	8.54E-02	5.00E+00	3.83E+00	9.53E-02	1.27E+00	5.71E-01	7.17E+00	7.91E-02	4.51E-02	-1.81E+01	-1.90E+01	-2.05E+01	3.31E-01
82	5.01E-04	1.50E-01	9.95E-04	6.96E+00	4.81E-02	6.49E+00	1.96E+00	4.90E-02	3.01E-01	4.87E-01	2.17E+01	1.93E-01	6.77E-02	-1.90E+01	-1.79E+01	-2.06E+01	7.25E-01
83	1.31E-04	2.49E-01	5.70E-05	8.99E+00	1.69E-01	7.80E-01	5.86E+00	2.69E-02	8.64E+00	3.54E-01	7.67E+00	1.57E-01	2.72E-01	-1.84E+01	-1.84E+01	-1.95E+01	6.28E-02
84	3.90E-04	2.16E-01	1.48E-03	1.07E+00	2.86E-02	4.31E+00	6.66E+00	1.06E-01	1.49E-01	4.45E-01	1.02E+01	4.35E-01	1.36E-01	-1.91E+01	-1.85E+01	-2.16E+01	5.93E-01
85	1.23E-03	1.28E-01	1.34E-04	2.74E+00	1.30E-01	1.11E+00	3.11E+00	5.53E-02	2.39E-01	4.88E-01	6.17E+00	3.72E-01	3.91E-01	-1.78E+01	-1.84E+01	-1.86E+01	2.24E-02
86	1.91E-03	1.65E-01	3.41E-03	8.44E-01	2.09E-01	2.24E+00	2.74E+00	8.14E-02	4.30E-01	1.06E-01	1.13E+01	4.11E-01	3.47E-01	-1.93E+01	-1.74E+01	-1.91E+01	4.31E-01
87	5.05E-04	1.30E-01	1.47E-04	1.63E+00	3.34E-02	7.28E-01	7.52E+00	3.78E-02	5.23E+01	2.85E-01	1.01E+01	3.06E-01	3.40E-02	-1.84E+01	-1.83E+01	-2.13E+01	4.74E-01
88	2.97E-03	1.37E-01	6.37E-05	4.96E+00	6.66E-02	2.95E+00	2.72E+00	1.41E-01	1.39E+00	1.89E-01	1.02E+01	1.41E-01	1.91E-01	-1.72E+01	-1.86E+01	-1.98E+01	6.57E-01
89	1.89E-03	1.33E-01	6.52E-03	9.38E+00	5.24E-02	5.02E+00	1.21E+00	1.15E-01	7.49E-02	2.23E-01	6.69E+00	3.79E-01	1.17E-01	-1.69E+01	-1.78E+01	-2.03E+01	6.82E-01
90	3.83E-03	1.62E-01	3.02E-04	3.43E+00	6.51E-02	9.81E+00	3.03E+00	1.10E-01	5.47E-01	8.52E-02	5.81E+00	6.87E-02	7.73E-02	-1.88E+01	-1.80E+01	-2.10E+01	1.26E-01
91	1.10E-04	1.18E-01	8.63E-03	4.71E+00	1.58E-01	4.81E+00	6.87E+00	1.99E-01	1.70E+01	4.16E-01	8.20E+00	3.23E-01	1.87E-01	-1.90E+01	-1.78E+01	-2.01E+01	6.66E-03
92	9.53E-03	2.36E-01	2.44E-03	3.08E+00	3.61E-01	1.55E+00	9.21E-01	2.45E-02	3.06E+00	4.17E-01	7.59E+00	5.14E-01	2.56E-01	-1.85E+01	-1.73E+01	-2.02E+01	6.02E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
93	1.18E-03	1.44E-01	7.46E-04	3.46E+00	1.07E-01	2.34E+00	4.18E+00	6.68E-02	3.80E+01	9.03E-02	6.85E+00	3.44E-01	3.67E-01	-1.87E+01	-1.82E+01	-1.87E+01	6.94E-01
94	5.30E-04	1.10E-01	2.03E-04	8.68E+00	2.75E-01	2.00E+00	8.08E-01	9.16E-02	7.83E-02	5.16E-01	1.40E+01	4.05E-01	8.43E-02	-1.84E+01	-1.79E+01	-2.09E+01	9.36E-01
95	1.93E-04	1.32E-01	1.32E-03	1.59E+00	8.33E-02	1.06E+00	1.67E+00	1.69E-01	1.69E+00	4.40E-01	1.14E+01	2.57E-01	2.24E-01	-1.80E+01	-1.78E+01	-2.18E+01	2.85E-01
96	5.11E-03	1.15E-01	1.26E-04	4.16E+00	1.77E-01	7.46E-01	3.54E+00	6.43E-02	5.72E-01	4.94E-01	7.52E+00	3.68E-01	2.90E-01	-1.92E+01	-1.88E+01	-2.07E+01	5.54E-01
97	5.70E-04	2.40E-01	1.27E-02	3.33E+00	6.05E-02	1.40E+00	1.33E+00	7.37E-02	1.07E+01	1.60E-01	1.59E+01	5.47E-01	2.31E-01	-1.76E+01	-1.82E+01	-2.09E+01	3.19E-01
98	1.04E-04	1.01E-01	1.85E-04	1.75E+00	2.90E-02	2.11E+00	1.85E+00	2.39E-02	4.78E+00	4.75E-01	1.05E+01	3.35E-01	7.58E-02	-1.89E+01	-1.81E+01	-1.85E+01	5.01E-01
99	6.86E-03	1.62E-01	1.24E-02	2.32E+00	2.98E-01	5.22E+00	2.33E+00	3.63E-02	2.76E+00	3.65E-01	8.04E+00	5.66E-01	1.99E-01	-1.71E+01	-1.82E+01	-1.95E+01	7.44E-01
100	2.08E-03	1.24E-01	5.50E-04	4.55E+00	2.39E-02	1.79E+00	9.67E-01	4.57E-02	4.59E+00	2.12E-01	8.35E+00	8.74E-02	3.81E-01	-1.80E+01	-1.76E+01	-2.04E+01	8.41E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector Num.	STEEL CORRMCO2	WAS_AREA PROBDEG	WAS_AREA GRATMICI	WAS_AREA GRATMICH	CELLULS FBETA	WAS_AREA SAT_RGAS	WAS_AREA SAT_RBRN	WAS_AREA SAT_WICK	DRZ_PCS PRMX_LOG	CONC_PCS PRMX_LOG	SOLU4 SOLCIM	SOLTH4 SOLCIM	CONC_PCS SAT_RGAS	CONC_PCS SAT_RBRN	CONC_PCS PORE_DIS	S_HALITE POROSITY	S_HALITE PRMX_LOG	S_HALITE COMP_RCK	S_MB139 PRMX_LOG	S_MB139 COMP_RCK	S_MB139 RELP_MOD	S_MB139 SAT_RBRN	S_MB139 SAT_RGAS	S_MB139 PORE_DIS
1	1.50E-15	0.00E+00	3.32E-09	4.55E-10	8.57E-01	9.81E-02	2.56E-01	6.81E-01	-1.75E+01	-1.85E+01	-1.38E-01	2.26E-02	7.95E-02	1.28E-01	1.48E-01	9.34E-03	-2.15E+01	3.76E-11	-1.88E+01	7.45E-11	4.00E+00	7.44E-02	1.40E-02	6.93E-01
2	1.76E-14	0.00E+00	2.90E-09	3.12E-10	7.11E-01	8.22E-02	4.02E-01	4.09E-01	-2.02E+01	-1.93E+01	1.31E-01	-3.43E-01	6.38E-02	1.17E-01	6.59E+00	2.24E-02	-2.27E+01	1.08E-10	-1.94E+01	1.31E-10	4.00E+00	9.81E-02	8.59E-02	6.95E-01
3	2.13E-14	2.00E+00	9.41E-09	1.12E-09	1.33E-01	5.13E-02	9.78E-02	6.32E-01	-1.84E+01	-1.87E+01	-4.24E-02	6.71E-02	1.96E-01	5.93E-01	5.11E-01	4.04E-03	-2.30E+01	1.17E-10	-1.89E+01	7.27E-11	1.00E+00	5.62E-02	8.65E-02	6.75E-01
4	2.54E-14	2.00E+00	5.78E-09	1.25E-09	3.16E-01	1.11E-01	1.90E-01	7.96E-01	-1.88E+01	-1.77E+01	1.17E+00	-1.57E-01	1.31E-01	3.93E-01	7.30E+00	1.14E-02	-2.35E+01	1.68E-10	-1.84E+01	1.09E-11	1.00E+00	9.59E-02	6.68E-02	6.23E-01
5	2.45E-14	0.00E+00	7.65E-09	1.05E-09	3.13E-02	1.29E-01	1.20E-01	5.55E-01	-1.80E+01	-1.77E+01	6.66E-02	-2.71E-01	2.20E-01	1.41E-01	2.74E+00	1.81E-02	-2.22E+01	7.83E-11	-1.81E+01	1.09E-11	4.00E+00	1.17E-01	5.03E-02	6.18E-01
6	4.30E-15	0.00E+00	9.18E-09	3.44E-10	4.73E-01	6.58E-02	1.45E-01	3.80E-01	-1.85E+01	-1.93E+01	9.84E-01	8.37E-01	9.38E-02	6.59E-02	5.56E-01	8.31E-03	-2.17E+01	3.55E-11	-1.95E+01	1.62E-10	4.00E+00	1.03E-01	4.41E-02	6.61E-01
7	1.13E-14	1.00E+00	7.43E-09	4.25E-10	3.22E-01	7.76E-03	3.12E-01	5.68E-02	-1.87E+01	-1.79E+01	7.24E-01	7.85E-01	3.60E-01	1.38E-01	3.38E-01	1.99E-02	-2.26E+01	1.03E-10	-1.87E+01	4.86E-11	4.00E+00	8.64E-02	1.11E-01	6.84E-01
8	7.27E-15	2.00E+00	6.29E-09	1.21E-10	1.80E-01	9.21E-02	4.67E-01	5.81E-01	-1.93E+01	-1.91E+01	-2.44E-01	-2.03E-01	3.30E-01	1.71E-01	6.93E+00	1.28E-02	-2.14E+01	1.80E-11	-1.92E+01	1.08E-10	4.00E+00	1.29E-01	9.64E-02	6.67E-01
9	2.94E-14	1.00E+00	8.46E-09	4.67E-10	2.58E-01	1.35E-01	5.34E-01	1.26E-01	-1.91E+01	-1.86E+01	-1.28E-01	-1.27E-01	3.56E-01	7.09E-02	4.04E-01	1.13E-03	-2.34E+01	1.40E-10	-1.84E+01	3.47E-11	4.00E+00	6.27E-02	6.51E-02	5.82E-01
10	1.29E-14	0.00E+00	3.37E-09	2.06E-10	7.92E-01	3.17E-02	1.73E-01	5.49E-01	-1.85E+01	-1.88E+01	-5.62E-01	-1.06E-01	7.50E-03	3.55E-01	7.68E+00	6.96E-03	-2.34E+01	1.56E-10	-1.96E+01	1.65E-10	1.00E+00	1.06E-01	1.40E-02	6.46E-01
11	2.25E-14	2.00E+00	5.91E-09	2.27E-10	4.84E-01	6.24E-02	4.15E-01	9.14E-02	-1.88E+01	-2.03E+01	-6.04E-02	-3.93E-01	2.69E-01	3.49E-01	3.52E+00	4.43E-03	-2.18E+01	6.23E-11	-1.88E+01	6.72E-11	4.00E+00	8.52E-02	1.18E-01	6.76E-01
12	3.13E-14	2.00E+00	1.17E-09	1.17E-09	6.41E-01	7.06E-02	1.02E-01	7.53E-01	-1.86E+01	-1.93E+01	-9.18E-03	-2.43E-01	1.99E-01	3.02E-01	2.72E-01	3.56E-03	-2.24E+01	7.08E-11	-1.85E+01	3.11E-11	1.00E+00	9.40E-02	6.17E-02	6.39E-01
13	6.29E-16	0.00E+00	5.43E-09	1.09E-09	4.97E-01	1.83E-02	4.86E-01	4.65E-01	-1.98E+01	-2.02E+01	4.41E-01	-3.80E-01	2.12E-01	9.81E-02	1.23E+00	7.95E-03	-2.29E+01	1.30E-10	-1.95E+01	1.68E-10	4.00E+00	4.20E-02	7.41E-02	6.48E-01
14	5.73E-15	0.00E+00	6.56E-09	1.21E-09	9.11E-01	1.07E-01	3.28E-01	4.92E-01	-1.81E+01	-1.96E+01	-2.15E-01	-1.77E-01	3.20E-01	1.16E-01	7.77E-01	1.72E-02	-2.38E+01	1.78E-10	-1.94E+01	1.12E-10	1.00E+00	8.20E-02	1.20E-01	5.46E-01
15	3.16E-14	0.00E+00	7.23E-10	1.12E-09	4.52E-01	4.22E-02	5.21E-01	2.51E-02	-1.81E+01	-1.82E+01	-2.65E-02	-1.13E-01	2.43E-01	2.06E-01	7.58E+00	6.90E-03	-2.27E+01	1.06E-10	-1.89E+01	8.42E-11	4.00E+00	5.80E-02	1.22E-01	5.90E-01
16	2.89E-14	0.00E+00	4.61E-09	3.61E-10	8.39E-01	5.75E-02	2.76E-01	3.01E-01	-1.74E+01	-1.80E+01	-5.43E-01	7.66E-02	2.01E-01	4.95E-02	5.93E+00	1.44E-02	-2.37E+01	1.73E-10	-1.90E+01	8.17E-11	4.00E+00	4.63E-02	4.27E-02	6.59E-01
17	3.09E-14	1.00E+00	5.54E-09	7.81E-10	6.97E-01	1.41E-02	2.26E-01	8.89E-01	-1.88E+01	-1.95E+01	-6.13E-01	5.08E-01	3.87E-01	2.24E-01	7.11E-01	2.01E-02	-2.14E+01	3.42E-11	-1.92E+01	1.56E-10	1.00E+00	1.43E-01	9.51E-02	5.94E-01
18	1.51E-14	0.00E+00	2.85E-09	5.63E-10	4.47E-01	1.06E-01	3.40E-01	1.39E-01	-1.91E+01	-1.86E+01	-1.09E-01	-6.01E-01	3.00E-01	4.89E-01	5.85E-01	7.14E-03	-2.39E+01	1.86E-10	-1.96E+01	1.84E-10	4.00E+00	1.19E-01	5.45E-02	7.06E-01
19	1.62E-14	1.00E+00	2.29E-09	1.19E-09	2.78E-01	1.42E-01	2.97E-02	1.01E-01	-1.88E+01	-1.89E+01	-3.62E-01	-3.81E-02	2.61E-02	8.52E-02	5.26E-01	2.74E-02	-2.23E+01	9.07E-11	-2.01E+01	2.75E-10	1.00E+00	8.91E-02	5.74E-02	6.74E-01
20	2.08E-14	1.00E+00	7.58E-09	8.59E-10	8.60E-01	1.23E-01	1.27E-01	2.09E-01	-1.97E+01	-1.74E+01	-1.66E-01	-1.48E+00	1.55E-01	4.29E-02	8.35E-01	2.28E-03	-2.32E+01	1.39E-10	-1.93E+01	1.36E-10	1.00E+00	7.06E-02	8.77E-02	6.55E-01
21	1.41E-14	0.00E+00	8.72E-09	8.75E-10	5.12E-01	7.93E-02	4.09E-01	3.35E-01	-2.00E+01	-1.94E+01	-1.82E+00	-1.37E-01	1.72E-01	2.10E-01	5.63E-01	2.24E-02	-2.28E+01	1.13E-10	-1.88E+01	7.69E-11	4.00E+00	1.07E-01	4.77E-02	6.72E-01
22	1.44E-14	1.00E+00	5.21E-09	1.16E-09	8.26E-01	2.51E-02	8.22E-02	5.16E-01	-2.03E+01	-1.77E+01	-4.99E-02	-2.54E-01	2.11E-01	4.26E-01	5.58E+00	1.78E-02	-2.13E+01	1.32E-11	-1.78E+01	1.09E-11	4.00E+00	8.42E-02	3.97E-02	6.60E-01
23	4.46E-15	1.00E+00	7.04E-09	5.12E-10	9.31E-01	7.29E-02	4.80E-01	8.31E-01	-1.84E+01	-1.98E+01	-8.07E-02	-2.24E-01	3.08E-01	3.78E-01	6.40E-01	3.88E-03	-2.30E+01	1.30E-10	-1.83E+01	1.94E-11	4.00E+00	5.75E-02	5.66E-02	6.01E-01
24	9.99E-15	0.00E+00	3.93E-09	7.97E-10	5.58E-01	9.01E-02	1.37E-01	4.84E-03	-1.82E+01	-1.92E+01	1.18E-01	-1.87E-02	3.25E-01	2.88E-01	6.49E-01	2.72E-02	-2.31E+01	1.24E-10	-2.06E+01	2.75E-10	4.00E+00	6.35E-02	4.60E-02	6.05E-01
25	1.39E-14	2.00E+00	4.48E-09	6.92E-10	9.86E-01	8.68E-02	5.41E-01	1.50E-02	-2.01E+01	-1.89E+01	2.15E-01	-4.92E-01	1.27E-01	4.96E-01	4.83E-01	9.04E-03	-2.17E+01	5.36E-11	-1.87E+01	5.56E-11	4.00E+00	1.12E-01	7.37E-02	6.27E-01
26	2.11E-14	1.00E+00	8.84E-09	6.51E-10	9.70E-01	7.60E-02	4.97E-01	2.41E-01	-1.86E+01	-1.92E+01	-1.37E+00	-9.98E-02	6.52E-02	5.66E-01	6.16E+00	2.55E-02	-2.19E+01	4.72E-11	-1.83E+01	1.09E-11	1.00E+00	2.11E-02	1.08E-01	6.13E-01
27	3.99E-15	1.00E+00	6.37E-09	8.16E-10	3.85E-01	1.18E-01	4.62E-01	6.67E-01	-1.87E+01	-1.97E+01	5.24E-01	-1.62E-01	4.88E-02	1.97E-01	1.87E+00	3.04E-03	-2.35E+01	1.49E-10	-1.89E+01	9.02E-11	1.00E+00	1.11E-01	6.61E-02	6.58E-01
28	9.15E-15	2.00E+00	5.19E-09	1.06E-09	6.60E-01	9.72E-02	1.79E-01	5.93E-01	-2.04E+01	-1.87E+01	-1.90E-01	-7.36E-01	3.81E-01	4.33E-01	5.46E+00	2.98E-02	-2.29E+01	1.15E-10	-2.00E+01	2.18E-10	1.00E+00	7.35E-02	2.84E-02	6.47E-01
29	7.86E-15	0.00E+00	2.75E-09	5.83E-10	7.77E-01	7.66E-02	4.76E-01	2.15E-01	-1.81E+01	-1.84E+01	-2.98E-02	2.22E-01	2.99E-01	3.86E-02	3.73E+00	2.41E-02	-2.24E+01	1.00E-10	-1.90E+01	9.76E-11	1.00E+00	1.00E-01	7.84E-02	6.09E-01
30	1.28E-16	2.00E+00	1.34E-09	1.03E-09	5.47E-02	1.16E-01	4.16E-02	4.56E-01	-1.96E+01	-1.89E+01	3.09E-01	4.06E-01	1.76E-01	1.55E-01	6.19E-01	3.28E-03	-2.14E+01	2.23E-11	-1.92E+01	1.42E-10	4.00E+00	5.03E-02	7.21E-02	4.91E-01
31	2.95E-14	1.00E+00	4.37E-09	4.90E-10	7.86E-01	5.28E-02	5.93E-02	3.25E-01	-1.98E+01	-2.00E+01	-1.51E-01	1.34E+00	3.91E-01	4.66E-01	2.46E-01	1.01E-02	-2.16E+01	4.22E-11	-1.75E+01	1.09E-11	4.00E+00	9.73E-02	1.09E-01	5.82E-01
32	5.13E-15	0.00E+00	8.98E-10	8.99E-10	4.30E-01	1.00E-01	5.29E-01	6.52E-01	-1.80E+01	-1.86E+01	-7.84E-01	8.62E-01	3.18E-01	3.85E-01	6.59E-01	5.79E-03	-2.37E+01	1.71E-10	-1.87E+01	4.59E-11	1.00E+00	8.46E-02	7.95E-02	7.32E-01
33	2.61E-14	0.00E+00	3.18E-09	1.02E-09	6.20E-01	1.31E-01	1.22E-01	3.12E-01	-1.91E+01	-1.91E+01	4.74E-01	1.24E-01	8.90E-02	1.51E-01	8.45E-01	2.71E-03	-2.20E+01	5.59E-11	-1.94E+01	1.44E-10	1.00E+00	6.45E-02	7.51E-02	7.24E-01
34	2.70E-14	1.00E+00	5.36E-09	2.45E-10	4.26E-02	2.76E-02	3.25E-01	1.54E-01	-1.79E+01	-1.93E+01	-8.67E-01	-4.34E-01	2.20E-01	7.89E-03	3.21E-01	1.58E-03	-2.20E+01	7.26E-11	-1.96E+01	2.30E-10	4.00E+00	6.78E-02	1.72E-02	6.21E-01
35	6.75E-15	0.00E+00	1.53E-09	9.83E-10	5.87E-01	9.57E-02	4.39E-01	9.39E-01	-1.77E+01	-1.84E+01	2.26E-01	-1.77E+00	2.34E-01	5.56E-01	3.65E-01	6.29E-03	-2.12E+01	1.56E-11	-1.93E+01	1.26E-10	1.00E+00	8.00E-02	1.97E-01	7.53E-01
36	1.55E-14	2.00E+00	1.71E-09	8.37E-10	6.83E-01	3.71E-03	1.39E-01	5.27E-01	-1.90E+01	-1.83E+01	-7.11E-01	-1.92E-01	3.67E-01	2.53E-01	6.90E-01	5.02E-03	-2.37E+01	1.81E-10	-1.88E+01	6.91E-11	1.00E+00	1.14E-01	6.03E-02	8.42E-01
37	1.81E-14	0.00E+00	4.87E-09	1.22E-09	9.49E-01	4.07E-02	2.27E-01	9.88E-01	-1.91E+01	-1.96E+01	7.83E-01	-1.72E-01	2.83E-01	1.77E-03	7.50E+00	1.43E-02	-2.38E+01	1.76E-10	-1.87E+01	6.63E-11	1.00E+00	1.02E-01	6.00E-02	7.42E-01
38	2.19E-14	2.00E+00	3.80E-09	6.11E-11	1.89E-02	1.77E-02	3.81E-01	6.28E-01	-1.83E+01	-1.89E+01	2.11E-01	-2.09E-01	1.67E-01	5.93E-02	5.01E+00	2.92E-03	-2.39E+01	1.87E-10	-1.71E+01	1.09E-11	4.00E+00	5.99E-02	6.71E-02	6.51E-01
39	6.40E-15	2.00E+00	3.90E-10	4.13E-10	8.78E-01	1.50E-01	2.98E-01	2.33E-01	-2.00E+01	-1.81E+01	-2.16E-01	-5.84E-02	7.06E-02	4.83E-01	4.30E+00	1.35E-03	-2.29E+01	1.26E-10	-1.93E+01	1.48E-10	1.00E+00	6.59E-02	3.24E-02	6.16E-01
40	2.31E-14	1.00E+00	7.20E-09	6.99E-10	6.70E-01	1.02E-01	3.54E-01	9.72E-01	-1.95E+01	-1.85E+01	-4.90E-01	-7.92E-01	2.85E-01	1.91E-01	2.79E-01	1.75E-02	-2.34E+01	1.64E-10	-1.94E+01	1.28E-10	1.00E+00	7.45E-02	7.60E-02	5.73E-01
41	1.15E-14	1.00E+00	3.85E-09	8.02E-10	3.59E-01	3.40E-02	8.64E-02	7.13E-02	-1.81E+01	-1.82E+01	-7.73E-01	-3.39E-01	2.59E-01	5.42E-02	5.74E+00	1.88E-02	-2.10E+01	4.83E-12	-1.73E+01	1.09E-11	1.00E+00	4.71E-02	9.16E-02	7.14E-01
42	2.99E-14	2.00E+00	2.38E-09	5.00E-10	8.41E-01	1.04E-01	3.92E-01	3.62E-01	-1.89E+01	-1.88E+01	-8.84E-02	6.95E-01	5.74E-02	1.62E-01	1.39E-01	1.50E-02	-2.16E+01	4.44E-11	-1.87E+01	6.23E-11	4.00E+00	2.48E-02	7.69E-02	6.78E-01
43	2.52E-14	0.00E+00	8.19E-09	9.29E-10	9.67E-02	5.88E-02	2.07E-01	1.67E-01	-1.85E+01	-1.94E+01	9.20E-02	-6.80E-01	2.38E-01	1.93E-01	2.98E-01	2.33E-02	-2.31E+01	1.36E-10	-1.91E+01	1.18E-10	1.00E+00	8.81E-02	9.48E-02	7.41E-01
44	2.49E-14	0.00E+00	9.11E-09	1.42E-11	1.55E-01	1.12E-01	1.61E-02	2.77E-01	-1.97E+01	-1.87E+01	-3.13E-01	5.03E-02	3.16E-01	2.58E-01	4.14E+00	1.62E-02	-2.26E+01	9.41E-11	-1.84E+01	1.34E-11	1.00E+00	9.34E-02	4.14E-02	6.92E-01
45	8.42E-16	0.00E+00	8.96E-09	5.41E-10	3.32E-01	5.05E-02	2.04E-01	3.85E-01	-1.92E+01	-1.80E+01	-3.52E-01	7.18E-01	2.50E-01	5.07E-01	9.35E-01	9.77E-03	-2.40E+01	1.91E-10	-1.95E+01	1.78E-10	1.00E+00	8.67E-02	8.39E-02	7.01E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
46	9.68E-15	1.00E+00	3.60E-09	8.26E-10	8.93E-01	2.03E-02	2.35E-01	7.15E-01	-1.95E+01	-1.79E+01	8.12E-01	2.43E-01	2.75E-01	2.01E-02	8.83E-01	5.98E-03	-2.15E+01	2.77E-11	-1.85E+01	5.08E-11	4.00E+00	1.33E-01	8.50E-02	6.50E-01
47	1.34E-14	0.00E+00	8.67E-09	7.36E-10	3.69E-01	6.75E-02	1.61E-01	4.83E-02	-1.89E+01	-2.01E+01	-2.23E-01	5.67E-01	2.39E-02	1.65E-01	6.29E+00	1.90E-02	-2.11E+01	8.40E-12	-1.88E+01	8.94E-11	1.00E+00	7.30E-02	1.13E-01	6.32E-01
48	1.84E-14	0.00E+00	8.33E-09	4.01E-10	5.08E-01	1.02E-01	2.11E-01	1.71E-01	-1.77E+01	-1.86E+01	-4.06E-02	1.19E-01	1.63E-01	5.51E-01	3.11E+00	5.64E-03	-2.25E+01	9.93E-11	-1.86E+01	5.47E-11	1.00E+00	1.26E-01	6.35E-02	5.72E-01
49	2.80E-15	2.00E+00	1.30E-09	2.80E-10	1.05E-01	3.07E-02	7.64E-02	7.85E-01	-1.73E+01	-1.85E+01	-9.08E-01	-2.19E-01	3.46E-01	2.57E-02	8.95E-01	3.49E-03	-2.13E+01	1.94E-11	-1.86E+01	3.61E-11	1.00E+00	9.98E-02	1.03E-01	5.35E-01
50	2.84E-14	0.00E+00	4.77E-09	1.91E-10	2.37E-01	1.09E-01	5.44E-01	4.33E-01	-1.93E+01	-2.05E+01	6.27E-01	-6.60E-01	2.44E-01	2.85E-02	1.91E-01	2.87E-02	-2.25E+01	9.36E-11	-1.84E+01	1.09E-11	1.00E+00	8.55E-02	2.16E-02	7.04E-01
51	9.36E-15	2.00E+00	8.59E-09	2.60E-10	2.05E-01	1.34E-01	3.63E-01	9.52E-01	-1.84E+01	-1.76E+01	-3.33E-01	1.99E-01	1.85E-01	3.18E-01	5.28E+00	2.48E-02	-2.14E+01	2.98E-11	-1.91E+01	9.86E-11	4.00E+00	6.96E-02	7.14E-02	7.86E-01
52	1.07E-14	0.00E+00	5.71E-09	5.01E-11	7.53E-02	3.68E-02	4.49E-01	6.47E-01	-1.95E+01	-2.00E+01	7.25E-02	-4.25E-02	1.36E-02	1.76E-01	4.43E+00	1.54E-02	-2.36E+01	1.45E-10	-1.91E+01	1.24E-10	1.00E+00	1.09E-01	7.88E-02	6.12E-01
53	7.31E-15	0.00E+00	8.08E-09	1.50E-10	8.07E-01	4.46E-02	2.52E-01	1.99E-01	-1.86E+01	-1.89E+01	5.54E-01	1.90E-01	1.72E-01	4.72E-01	7.00E-01	2.17E-02	-2.40E+01	1.88E-10	-1.79E+01	1.09E-11	4.00E+00	5.24E-02	1.36E-01	6.20E-01
54	2.73E-14	0.00E+00	6.42E-09	5.49E-10	9.69E-01	1.25E-01	2.39E-02	5.06E-01	-1.71E+01	-1.94E+01	2.76E-01	-1.97E-01	3.13E-02	3.73E-01	4.01E+00	4.20E-03	-2.16E+01	5.13E-11	-1.89E+01	9.28E-11	1.00E+00	7.83E-02	1.00E-01	6.25E-01
55	8.01E-15	1.00E+00	5.09E-09	3.32E-10	1.40E-01	7.03E-02	2.38E-01	2.69E-01	-1.78E+01	-1.95E+01	-1.96E-01	-4.17E-01	3.41E-01	4.66E-02	7.92E-01	1.22E-02	-2.19E+01	6.36E-11	-1.80E+01	1.09E-11	1.00E+00	8.13E-02	1.40E-02	6.11E-01
56	2.68E-14	0.00E+00	4.91E-10	8.68E-10	3.44E-01	4.66E-02	3.20E-01	9.49E-01	-1.99E+01	-1.97E+01	-1.14E+00	2.29E-01	5.29E-02	3.07E-01	4.10E-01	1.05E-02	-2.12E+01	8.90E-12	-1.85E+01	1.09E-11	1.00E+00	7.74E-02	2.48E-02	6.36E-01
57	1.67E-14	0.00E+00	6.02E-09	1.24E-09	4.68E-01	7.43E-02	2.79E-01	3.14E-02	-1.90E+01	-2.00E+01	-1.77E-01	-1.16E+00	2.30E-01	2.46E-01	1.70E+00	8.17E-03	-2.35E+01	1.66E-10	-1.87E+01	5.88E-11	4.00E+00	9.51E-02	8.91E-02	5.20E-01
58	1.30E-14	2.00E+00	3.53E-09	6.19E-10	9.55E-01	2.96E-02	1.14E-01	7.77E-01	-1.82E+01	-1.81E+01	1.88E-01	-1.87E-01	7.54E-02	1.23E-01	7.73E-01	2.92E-02	-2.33E+01	1.42E-10	-1.88E+01	6.09E-11	4.00E+00	1.58E-01	9.29E-02	5.53E-01
59	2.28E-14	0.00E+00	3.65E-09	6.43E-11	1.70E-01	1.07E-02	1.94E-01	8.46E-01	-1.96E+01	-1.83E+01	9.03E-01	-9.32E-02	3.79E-01	4.15E-01	3.88E-01	2.61E-02	-2.21E+01	6.81E-11	-1.92E+01	1.10E-10	1.00E+00	4.11E-02	7.28E-02	4.91E-01
60	1.23E-14	1.00E+00	2.53E-09	4.81E-10	8.85E-01	6.13E-02	4.70E-02	1.14E-01	-1.82E+01	-1.83E+01	1.57E-01	-3.05E-01	3.90E-02	1.55E-02	9.85E-01	2.58E-02	-2.23E+01	8.18E-11	-1.86E+01	4.46E-11	4.00E+00	6.67E-02	8.28E-02	7.15E-01
61	1.92E-14	2.00E+00	2.23E-09	7.11E-10	2.67E-01	8.73E-02	4.26E-01	4.15E-01	-1.78E+01	-1.99E+01	-6.26E-02	3.42E-01	1.18E-01	4.55E-01	2.99E+00	9.49E-03	-2.39E+01	1.82E-10	-1.80E+01	1.09E-11	4.00E+00	9.68E-02	5.62E-02	6.98E-01
62	5.50E-15	2.00E+00	4.92E-09	3.83E-10	5.26E-01	1.39E-01	5.05E-01	3.44E-01	-1.84E+01	-1.91E+01	-2.83E-01	-1.24E-01	3.57E-01	3.63E-01	7.08E+00	5.44E-03	-2.10E+01	4.63E-12	-1.91E+01	1.04E-10	1.00E+00	9.91E-02	6.81E-02	7.76E-01
63	3.38E-15	1.00E+00	6.10E-09	3.18E-10	5.38E-01	1.13E-01	1.70E-01	7.67E-01	-1.97E+01	-1.85E+01	-3.84E-01	-5.29E-02	1.33E-01	1.87E-01	2.26E-01	6.60E-03	-2.37E+01	1.83E-10	-1.81E+01	1.09E-11	4.00E+00	7.78E-03	1.14E-01	7.21E-01
64	1.04E-14	0.00E+00	6.65E-10	1.10E-09	3.05E-01	1.33E-01	1.78E-02	4.29E-01	-1.89E+01	-1.99E+01	-1.40E-01	6.42E-01	9.75E-02	4.07E-01	3.86E+00	7.32E-03	-2.34E+01	1.59E-10	-1.79E+01	1.09E-11	4.00E+00	1.74E-01	1.00E-01	6.63E-01
65	2.31E-14	1.00E+00	8.26E-09	5.31E-10	5.78E-01	1.27E-01	8.96E-02	9.06E-01	-1.86E+01	-1.88E+01	-4.04E-01	-9.15E-01	1.51E-01	7.42E-02	6.05E-01	1.46E-03	-2.15E+01	3.96E-11	-2.09E+01	2.75E-10	4.00E+00	1.22E-01	9.37E-02	6.44E-01
66	2.42E-14	0.00E+00	1.99E-09	4.37E-10	1.25E-01	9.43E-02	5.49E-01	8.91E-01	-1.93E+01	-1.82E+01	1.99E-01	-3.24E-02	2.63E-01	1.81E-01	1.96E-01	1.19E-02	-2.11E+01	1.11E-11	-1.95E+01	1.49E-10	1.00E+00	9.13E-02	8.83E-02	6.52E-01
67	1.96E-14	1.00E+00	1.48E-09	2.72E-11	2.19E-01	1.21E-01	6.61E-02	1.40E-01	-1.91E+01	-1.81E+01	-4.71E-01	-5.23E-01	2.95E-01	4.47E-01	4.33E-01	2.29E-02	-2.38E+01	1.74E-10	-1.92E+01	1.39E-10	4.00E+00	9.21E-02	8.24E-02	6.01E-01
68	2.40E-14	0.00E+00	4.36E-09	1.08E-09	2.85E-01	6.78E-04	5.01E-01	6.10E-01	-1.99E+01	-1.75E+01	-1.55E+00	-2.45E-02	2.26E-01	1.58E-01	2.24E+00	1.72E-03	-2.33E+01	1.49E-10	-1.97E+01	1.90E-10	4.00E+00	1.08E-01	1.72E-01	6.53E-01
69	1.74E-15	1.00E+00	6.95E-09	9.06E-10	8.35E-02	8.98E-02	4.08E-01	8.71E-01	-1.93E+01	-1.97E+01	-1.18E-01	-4.98E-03	9.51E-04	7.70E-02	7.57E-01	9.90E-03	-2.18E+01	6.07E-11	-1.89E+01	7.85E-11	1.00E+00	1.01E-01	1.51E-01	5.60E-01
70	1.24E-14	0.00E+00	1.09E-09	5.91E-10	1.13E-01	4.63E-02	4.24E-01	9.17E-01	-1.90E+01	-1.74E+01	-1.67E-01	-1.48E-01	1.04E-01	5.77E-01	6.77E+00	2.96E-02	-2.21E+01	6.67E-11	-1.82E+01	2.15E-11	4.00E+00	7.20E-02	5.85E-02	6.04E-01
71	2.18E-14	0.00E+00	6.74E-09	1.19E-09	6.59E-01	1.57E-02	1.06E-01	8.30E-01	-1.85E+01	-1.90E+01	-1.23E-01	3.14E-02	1.04E-01	1.25E-01	7.29E-01	6.09E-03	-2.21E+01	8.32E-11	-1.85E+01	2.80E-11	1.00E+00	6.53E-02	6.38E-02	6.66E-01
72	3.02E-14	0.00E+00	8.68E-10	1.66E-10	2.26E-01	2.36E-02	4.74E-03	9.66E-01	-1.82E+01	-2.02E+01	-2.50E-01	-3.69E-01	3.57E-02	5.35E-01	4.93E+00	8.51E-03	-2.36E+01	1.64E-10	-1.92E+01	1.34E-10	4.00E+00	8.07E-02	1.26E-01	7.09E-01
73	1.57E-14	1.00E+00	6.66E-09	2.32E-10	6.19E-01	5.61E-02	3.03E-01	5.75E-01	-2.05E+01	-1.88E+01	-1.53E-01	-1.00E+00	8.49E-02	1.47E-01	3.29E+00	1.28E-02	-2.13E+01	2.52E-11	-1.76E+01	1.09E-11	1.00E+00	6.97E-02	8.05E-02	6.68E-01
74	3.07E-14	2.00E+00	4.20E-09	1.86E-10	8.11E-01	3.84E-02	3.52E-01	2.29E-01	-1.94E+01	-1.90E+01	8.83E-01	9.89E-01	1.84E-01	3.41E-01	2.41E+00	6.40E-03	-2.15E+01	3.21E-11	-2.02E+01	1.97E-10	1.00E+00	7.16E-02	9.82E-02	6.88E-01
75	2.91E-15	1.00E+00	7.72E-09	1.13E-09	2.11E-02	1.41E-01	3.80E-01	4.79E-01	-1.88E+01	-1.81E+01	-1.01E-01	9.14E-01	2.89E-01	6.30E-02	7.83E+00	7.66E-03	-2.19E+01	4.97E-11	-1.89E+01	7.99E-11	4.00E+00	8.03E-02	7.09E-02	6.41E-01
76	1.69E-14	0.00E+00	5.58E-10	7.48E-10	2.42E-01	1.38E-01	3.34E-01	8.59E-01	-1.90E+01	-1.94E+01	6.78E-01	2.08E-01	3.04E-01	5.22E-01	9.17E-01	4.31E-03	-2.31E+01	1.43E-10	-1.86E+01	6.44E-11	1.00E+00	6.03E-02	6.24E-02	6.40E-01
77	2.04E-14	0.00E+00	3.02E-09	9.13E-10	4.12E-01	1.48E-01	6.84E-02	6.96E-01	-1.80E+01	-1.92E+01	4.79E-02	1.69E-01	3.76E-01	4.58E-01	5.05E-01	2.79E-02	-2.25E+01	9.56E-11	-1.90E+01	1.14E-10	4.00E+00	1.12E-01	1.06E-01	6.86E-01
78	2.59E-14	0.00E+00	1.89E-09	1.64E-10	3.98E-01	4.93E-02	1.51E-01	8.97E-02	-1.86E+01	-1.78E+01	3.55E-01	-2.34E-01	1.41E-01	3.33E-01	6.40E+00	1.39E-02	-2.11E+01	2.15E-11	-1.98E+01	2.06E-10	1.00E+00	8.35E-02	6.87E-02	6.30E-01
79	2.78E-14	0.00E+00	7.30E-09	1.01E-09	2.96E-01	1.23E-01	3.88E-01	9.29E-01	-1.92E+01	-1.90E+01	-2.43E-01	-7.66E-02	1.91E-01	1.88E-02	8.12E-01	2.47E-02	-2.24E+01	1.11E-10	-1.90E+01	9.40E-11	4.00E+00	5.06E-02	1.02E-01	6.33E-01
80	1.61E-14	0.00E+00	1.69E-09	6.74E-10	9.03E-01	6.43E-02	2.68E-01	3.51E-01	-1.94E+01	-1.78E+01	-1.83E-01	2.85E-01	2.05E-01	3.56E-02	6.03E+00	5.19E-03	-2.33E+01	1.61E-10	-1.87E+01	5.17E-11	4.00E+00	9.05E-02	5.40E-02	5.98E-01
81	1.90E-14	2.00E+00	3.13E-09	9.65E-10	6.08E-02	1.05E-02	4.73E-01	6.03E-02	-1.83E+01	-1.72E+01	-9.37E-02	-6.30E-02	1.75E-02	5.70E-01	1.17E-01	8.83E-03	-2.32E+01	1.33E-10	-1.91E+01	1.05E-10	4.00E+00	9.26E-02	7.02E-02	6.07E-01
82	1.73E-14	1.00E+00	6.94E-09	6.06E-10	7.68E-01	8.52E-02	4.53E-01	9.91E-01	-1.79E+01	-1.92E+01	1.43E-01	-6.98E-02	3.93E-01	1.07E-01	8.05E+00	1.67E-02	-2.36E+01	1.50E-10	-1.98E+01	2.48E-10	1.00E+00	3.66E-02	5.12E-02	5.96E-01
83	3.80E-15	0.00E+00	4.04E-09	8.90E-11	9.22E-01	2.16E-02	2.17E-01	4.47E-01	-1.94E+01	-1.91E+01	2.41E-02	1.49E-01	4.07E-02	1.76E-01	8.62E-01	4.87E-03	-2.22E+01	8.59E-11	-1.93E+01	1.53E-10	4.00E+00	7.94E-02	8.97E-02	6.26E-01
84	8.34E-15	0.00E+00	2.52E-09	1.17E-11	7.53E-01	1.44E-01	6.88E-03	7.20E-01	-1.96E+01	-1.90E+01	2.28E-02	-2.95E-01	3.99E-01	2.76E-01	2.66E+00	2.02E-03	-2.29E+01	1.20E-10	-1.91E+01	8.53E-11	4.00E+00	6.14E-02	1.07E-01	5.86E-01
85	2.50E-15	2.00E+00	5.58E-09	1.05E-10	7.33E-01	7.34E-03	2.60E-01	2.82E-01	-1.87E+01	-1.87E+01	1.74E-01	-8.70E-01	2.79E-01	2.81E-01	4.56E+00	7.69E-03	-2.22E+01	7.40E-11	-1.83E+01	2.46E-11	4.00E+00	1.03E-01	9.09E-02	6.90E-01
86	4.90E-15	0.00E+00	6.11E-09	9.43E-10	5.51E-03	6.86E-02	3.61E-02	4.84E-01	-1.95E+01	-1.83E+01	2.42E-01	-1.64E+00	1.59E-01	1.12E-01	4.56E-01	2.08E-02	-2.21E+01	7.98E-11	-1.82E+01	1.09E-11	4.00E+00	8.30E-02	8.40E-02	6.28E-01
87	6.18E-15	2.00E+00	6.85E-09	8.18E-11	5.67E-01	2.68E-02	1.60E-01	8.62E-01	-1.87E+01	-1.96E+01	-4.11E-01	1.37E-01	1.00E-02	5.14E-01	4.71E-01	1.58E-02	-2.27E+01	1.21E-10	-1.90E+01	8.71E-11	1.00E+00	8.75E-02	3.59E-02	5.45E-01
88	2.02E-14	0.00E+00	8.99E-09	2.95E-10	4.35E-01	1.19E-01	2.88E-01	8.16E-01	-1.90E+01	-1.74E+01	1.07E-01	1.17E-02	1.14E-01	1.36E-01	2.91E+00	2.59E-03	-2.27E+01	1.23E-10	-1.85E+01	4.13E-11	1.00E+00	8.85E-02	1.32E-01	6.81E-01
89	2.64E-14	2.00E+00	4.17E-09	2.68E-10	3.74E-01	7.99E-02	3.72E-01	5.39E-01	-1.83E+01	-1.86E+01	-1.76E-02	9.35E-02	1.48E-01	9.48E-02	2.22E+00	1.95E-02	-2.26E+01	1.04E-10	-1.97E+01	2.56E-10	4.00E+00	7.59E-02	1.31E-01	6.56E-01
90	1.19E-14	0.00E+00	7.32E-09	1.27E-09	1.96E-01	1.28E-02	2.86E-01	2.58E-01	-1.89E+01	-1.98E+01	-6.79E-03	-4.60E-01	3.37E-01	5.86E-01	7.16E+00	2.12E-03	-2.12E+01	2.71E-11	-1.88E+01	7.03E-11	4.00E+00	7.80E-02	5.31E-02	6.31E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
91	2.82E-14	0.00E+00	7.81E-09	1.32E-10	7.43E-01	5.46E-02	3.06E-01	7.08E-01	-1.76E+01	-1.84E+01	-7.52E-02	-2.47E-01	8.13E-02	2.37E-01	4.70E+00	2.66E-02	-2.18E+01	5.94E-11	-1.90E+01	1.02E-10	4.00E+00	9.45E-02	8.11E-02	5.66E-01
92	2.87E-14	2.00E+00	9.48E-09	6.32E-10	4.01E-01	1.44E-01	4.44E-01	6.18E-01	-1.92E+01	-1.83E+01	1.38E-01	9.71E-02	2.56E-01	2.67E-01	1.57E+00	1.36E-02	-2.31E+01	1.53E-10	-1.91E+01	1.17E-10	1.00E+00	1.16E-01	3.41E-02	5.76E-01
93	1.80E-14	2.00E+00	2.67E-09	3.76E-10	7.24E-01	4.00E-02	5.11E-01	6.70E-01	-1.85E+01	-1.84E+01	1.73E-04	-8.59E-02	1.37E-01	8.22E-02	2.42E-01	1.12E-02	-2.30E+01	1.09E-10	-1.84E+01	3.04E-11	1.00E+00	1.27E-01	3.72E-02	6.64E-01
94	1.01E-15	2.00E+00	1.00E-09	9.56E-10	1.86E-01	4.58E-03	1.85E-01	2.98E-01	-1.79E+01	-1.96E+01	-2.32E-01	4.40E-02	3.71E-01	9.16E-02	2.03E+00	2.81E-02	-2.28E+01	1.33E-10	-1.99E+01	1.74E-10	1.00E+00	7.64E-02	1.16E-01	6.71E-01
95	1.98E-14	1.00E+00	2.09E-09	6.68E-10	5.42E-01	1.46E-01	3.69E-01	1.85E-01	-2.00E+01	-1.88E+01	-9.87E-01	4.57E-01	2.64E-01	1.12E-02	5.10E+00	2.14E-02	-2.32E+01	1.56E-10	-1.82E+01	1.09E-11	1.00E+00	8.99E-02	1.40E-01	5.90E-01
96	1.47E-14	0.00E+00	7.93E-09	9.90E-10	5.91E-01	2.90E-03	2.47E-01	7.39E-01	-1.87E+01	-1.89E+01	-2.06E-01	-1.15E-02	3.33E-01	3.25E-01	3.49E+00	4.66E-03	-2.20E+01	7.59E-11	-1.89E+01	9.58E-11	1.00E+00	7.56E-02	1.40E-02	6.37E-01
97	8.78E-15	0.00E+00	1.83E-09	7.69E-10	6.32E-01	8.37E-02	4.34E-01	5.60E-01	-1.89E+01	-1.79E+01	3.62E-02	1.67E-01	1.10E-01	2.22E-01	1.20E+00	2.05E-02	-2.17E+01	5.55E-11	-1.89E+01	1.08E-10	4.00E+00	5.50E-02	4.87E-02	6.43E-01
98	2.37E-14	0.00E+00	9.27E-09	1.15E-09	7.01E-01	3.56E-02	5.00E-02	8.06E-01	-1.92E+01	-1.87E+01	-2.86E-01	3.58E-01	1.23E-01	1.01E-01	3.59E-01	8.60E-03	-2.25E+01	8.90E-11	-1.93E+01	1.21E-10	1.00E+00	3.29E-02	7.75E-02	6.79E-01
99	1.09E-14	1.00E+00	4.65E-09	7.51E-10	6.06E-01	1.28E-01	5.14E-01	7.41E-01	-1.75E+01	-1.91E+01	-4.43E-01	-4.81E-01	4.53E-02	4.22E-01	1.45E+00	2.38E-02	-2.23E+01	8.70E-11	-1.86E+01	3.92E-11	4.00E+00	6.84E-02	1.04E-01	6.35E-01
100	2.07E-15	0.00E+00	7.96E-09	6.35E-10	9.99E-01	1.14E-01	3.43E-01	3.98E-01	-1.76E+01	-1.80E+01	-4.61E-01	-1.44E-01	3.51E-01	5.39E-01	1.65E-01	9.19E-03	-2.19E+01	4.63E-11	-1.83E+01	1.09E-11	1.00E+00	1.05E-01	9.71E-02	6.17E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector Num.	S_HALITE PRESSURE	CASTILER PRESSURE	CASTILER PRMX_LOG	CASTILER COMP_RCK	BH_SAND PRMX_LOG	DRZ_1 PRMX_LOG	CONC_PLG PRMX_LOG	SOLAM3 SOLSIM	SOLAM3 SOLCIM	SOLPU3 SOLSIM	SOLPU3 SOLCIM	SOLPU4 SOLSIM	SOLPU4 SOLCIM	SOLU4 SOLSIM	SOLU6 SOLSIM	SOLU6 SOLCIM	SOLTH4 SOLSIM	PHUMOX3 PHUMCIM	GLOBAL OXSTAT	CULEBRA MINP_FAC	GLOBAL TRANSIDX	GLOBAL CLIMTIDX	CULEBRA HMBLKLT
1	1.31E+07	1.41E+07	-1.32E+01	4.35E-11	-1.38E+01	-1.51E+01	-1.73E+01	-1.97E+00	1.98E-01	-3.81E-01	-1.94E-02	-1.81E-01	-7.97E-01	6.61E-02	-1.83E-01	-4.80E-01	-4.56E-01	1.40E+00	2.34E-01	1.35E+01	4.49E-01	1.00E+00	1.44E-01
2	1.19E+07	1.41E+07	-1.01E+01	3.45E-11	-1.33E+01	-1.34E+01	-1.88E+01	-2.10E-01	-1.31E-01	6.16E-02	-6.85E-02	9.58E-01	1.11E-01	-4.63E-01	-1.78E+00	-2.12E-01	-1.44E-01	1.45E+00	8.50E-01	2.02E+02	8.04E-01	1.07E+00	4.04E-01
3	1.22E+07	1.34E+07	-1.27E+01	4.20E-11	-1.50E+01	-1.66E+01	-1.86E+01	8.67E-02	5.27E-01	-1.10E-02	-7.58E-02	1.42E-01	-3.97E-01	-3.17E-01	2.42E-01	2.72E-01	-1.28E-01	1.37E+00	4.30E-01	9.36E+02	5.24E-01	1.10E+00	3.71E-01
4	1.24E+07	1.48E+07	-1.35E+01	6.39E-11	-1.54E+01	-1.89E+01	-1.83E+01	-2.21E-01	-9.25E-01	5.33E-02	-5.83E-01	-1.67E-01	-3.29E-01	2.30E-01	-2.60E-01	1.54E-01	-4.23E-01	1.49E+00	4.07E-01	8.57E+01	8.63E-01	1.19E+00	4.40E-01
5	1.27E+07	1.57E+07	-1.25E+01	4.61E-11	-1.17E+01	-1.67E+01	-1.81E+01	3.05E-01	2.87E-02	-4.96E-01	1.95E-01	7.33E-01	-2.45E-01	-1.67E-01	-2.50E-01	-1.15E-01	-2.97E-01	3.89E-01	6.06E-01	3.92E+02	1.57E-03	1.09E+00	1.37E-01
6	1.19E+07	1.44E+07	-1.15E+01	6.13E-11	-1.62E+01	-1.82E+01	-1.70E+01	-1.81E-01	-4.18E-01	2.15E-01	-2.27E-01	-1.08E-01	-5.36E-01	-1.56E+00	-7.90E-02	-1.89E-02	-7.90E-02	1.15E+00	2.55E-01	3.07E+02	3.87E-01	1.03E+00	2.66E-01
7	1.35E+07	1.36E+07	-1.19E+01	4.94E-11	-1.31E+01	-1.26E+01	-1.86E+01	9.55E-01	4.47E-02	1.20E+00	-1.42E-01	-3.57E-01	-2.12E-01	-9.92E-02	9.24E-01	-6.48E-01	3.89E-02	6.23E-01	3.99E-01	4.79E+02	3.24E-02	1.16E+00	2.93E-01
8	1.28E+07	1.27E+07	-1.31E+01	5.67E-11	-1.32E+01	-1.89E+01	-1.79E+01	-5.28E-01	-1.49E-01	4.23E-01	-3.56E-01	2.28E-03	3.79E-01	-6.69E-01	2.27E-01	2.38E-01	-2.40E-01	1.20E+00	2.03E-01	2.17E+02	2.13E-01	1.17E+00	3.67E-01
9	1.25E+07	1.45E+07	-1.03E+01	2.40E-11	-1.46E+01	-1.86E+01	-1.83E+01	-2.48E-01	2.09E-01	-2.03E-01	-6.03E-02	-1.31E-02	-1.46E-01	4.60E-01	-1.64E-01	9.12E-01	1.75E-01	1.50E+00	6.68E-01	7.78E+01	9.33E-02	1.23E+00	1.16E-01
10	1.36E+07	1.24E+07	-1.09E+01	4.74E-11	-1.57E+01	-1.34E+01	-1.78E+01	7.70E-01	-7.47E-02	4.75E-01	-1.16E-01	6.32E-02	-4.28E-01	8.37E-02	2.79E-02	5.45E-01	5.82E-01	1.40E+00	9.72E-01	2.38E+02	8.78E-01	1.15E+00	3.51E-01
11	1.12E+07	1.43E+07	-1.43E+01	7.31E-11	-1.39E+01	-1.29E+01	-1.87E+01	-1.86E-03	5.79E-01	-7.49E-01	-3.08E-01	-2.23E-01	-1.46E+00	9.80E-01	-8.41E-02	-1.72E-01	-2.71E-01	9.82E-01	1.30E-01	7.25E+02	6.34E-01	1.51E+00	2.30E-01
12	1.35E+07	1.44E+07	-1.27E+01	5.24E-11	-1.43E+01	-1.28E+01	-1.81E+01	-1.38E-01	-9.70E-01	8.14E-01	3.85E-02	3.52E-02	6.74E-01	-4.11E-01	6.52E-01	9.71E-02	-2.04E-01	9.62E-01	3.08E-02	6.48E+02	6.85E-01	1.99E+00	9.71E-02
13	1.12E+07	1.34E+07	-1.16E+01	3.15E-11	-1.29E+01	-1.78E+01	-1.84E+01	-4.18E-01	-4.40E-01	6.25E-01	9.31E-02	9.47E-01	5.13E-02	2.80E-01	3.68E-01	-1.93E-01	-8.85E-01	8.65E-01	1.02E-01	9.97E+02	5.41E-01	1.20E+00	3.52E-01
14	1.19E+07	1.53E+07	-1.36E+01	7.46E-11	-1.51E+01	-1.82E+01	-1.73E+01	2.34E-01	8.90E-02	-5.64E-02	5.01E-01	2.39E-01	2.89E-01	5.04E-01	-3.89E-02	1.22E-01	-9.03E-01	1.51E+00	4.73E-01	1.24E+02	7.57E-01	1.11E+00	3.91E-01
15	1.28E+07	1.23E+07	-1.24E+01	7.15E-11	-1.39E+01	-1.39E+01	-1.80E+01	-1.71E-01	8.81E-01	-1.28E+00	2.13E-01	-1.30E-01	-2.97E-01	-4.27E-01	-2.35E-01	9.21E-02	-6.55E-01	1.11E+00	5.76E-01	1.38E+02	5.19E-01	1.01E+00	1.09E-01
16	1.36E+07	1.56E+07	-1.17E+01	5.58E-11	-1.37E+01	-1.87E+01	-1.88E+01	3.50E-01	-2.90E-01	-6.11E-01	-1.48E-01	-9.76E-02	6.05E-02	-2.33E-01	-2.90E-02	-9.61E-01	4.07E-01	1.36E+00	1.23E-01	8.35E+02	1.76E-01	1.24E+00	4.70E-01
17	1.16E+07	1.51E+07	-1.14E+01	4.83E-11	-1.21E+01	-1.43E+01	-1.71E+01	-2.37E-01	-2.03E-01	9.64E-02	-4.76E-01	1.22E-01	-1.22E+00	3.20E-01	-1.36E-01	-7.65E-02	-5.55E-01	2.56E-01	8.28E-01	8.02E+02	5.84E-01	2.02E+00	3.62E-01
18	1.36E+07	1.21E+07	-1.13E+01	3.97E-11	-1.52E+01	-1.35E+01	-1.73E+01	-4.82E-01	6.82E-01	-8.95E-02	1.28E-02	-2.50E-03	-1.59E-01	2.49E-01	-4.60E-02	-2.74E-01	-2.16E-01	1.56E+00	3.76E-01	9.68E+01	9.33E-01	2.25E+00	1.77E-01
19	1.24E+07	1.27E+07	-1.18E+01	5.44E-11	-1.57E+01	-1.49E+01	-1.84E+01	3.25E-02	6.64E-02	5.82E-01	-3.03E-01	-4.97E-01	5.24E-01	1.24E+00	-9.59E-02	9.76E-01	-6.74E-02	3.52E-01	4.89E-01	3.40E+01	7.17E-01	1.04E+00	1.87E-01
20	1.35E+07	1.30E+07	-1.19E+01	4.30E-11	-1.45E+01	-1.69E+01	-1.72E+01	-4.58E-01	-3.32E-01	-2.68E-01	1.11E+00	-2.60E-01	-9.59E-01	-6.08E-01	-4.37E-01	-2.48E-01	7.10E-02	7.01E-01	8.71E-01	8.41E+02	9.06E-01	1.16E+00	5.00E-01
21	1.17E+07	1.38E+07	-1.23E+01	6.42E-11	-1.28E+01	-1.91E+01	-1.87E+01	-2.68E-01	-7.94E-03	-4.02E-02	-5.45E-01	-3.57E-01	-4.61E-01	-9.54E-01	7.79E-01	-1.95E-01	1.24E-01	1.41E+00	9.59E-01	2.48E+01	3.72E-01	1.00E+00	1.67E-01
22	1.20E+07	1.39E+07	-1.18E+01	5.31E-11	-1.28E+01	-1.31E+01	-1.75E+01	7.18E-01	-1.18E-01	-1.88E-01	1.20E-01	-1.83E+00	1.72E-01	-3.16E-02	8.99E-02	4.09E-01	-7.59E-01	1.01E+00	9.66E-01	1.59E+02	1.18E-01	1.25E+00	1.92E-01
23	1.27E+07	1.55E+07	-1.22E+01	4.20E-11	-1.61E+01	-1.59E+01	-1.85E+01	-1.02E-01	-4.87E-01	7.26E-01	4.82E-01	-1.14E-01	6.01E-01	7.71E-02	-3.33E-01	-1.51E+00	-1.12E+00	1.45E+00	9.90E-01	1.46E+02	6.48E-01	1.15E+00	2.22E-01
24	1.32E+07	1.27E+07	-1.21E+01	4.69E-11	-1.36E+01	-1.26E+01	-1.85E+01	6.39E-02	-2.18E-02	2.11E-01	-4.98E-02	-1.79E-01	-2.08E-01	-2.50E-01	-5.53E-01	8.13E-01	-9.02E-02	1.53E+00	1.79E-01	8.27E+02	6.67E-01	1.12E+00	3.43E-01
25	1.15E+07	1.41E+07	-1.24E+01	7.72E-11	-1.59E+01	-1.65E+01	-1.85E+01	-7.05E-02	1.70E-01	-9.30E-01	-6.42E-01	8.89E-02	-1.36E-01	-1.33E-01	-1.07E-01	-4.86E-03	9.74E-01	4.39E-01	1.52E-01	2.61E+02	5.25E-02	1.87E+00	4.77E-01
26	1.35E+07	1.19E+07	-1.12E+01	3.56E-11	-1.15E+01	-1.37E+01	-1.71E+01	-1.39E+00	-9.51E-02	1.89E-01	-2.39E-01	2.51E-01	7.19E-02	1.73E-01	-1.19E-01	-5.37E-01	-1.73E-01	1.39E+00	4.16E-01	2.94E+02	1.60E-02	1.75E+00	2.67E-01
27	1.21E+07	1.22E+07	-1.19E+01	5.12E-11	-1.46E+01	-1.57E+01	-1.86E+01	-4.94E-02	1.33E-01	-8.35E-01	1.79E-01	-2.76E-01	8.39E-01	-2.24E-01	-1.31E-01	-4.53E-01	6.52E-01	1.49E+00	5.60E-01	9.16E+02	1.98E-01	1.09E+00	1.52E-01
28	1.32E+07	1.48E+07	-1.30E+01	9.02E-11	-1.10E+01	-1.63E+01	-1.87E+01	3.77E-02	2.45E-01	2.27E-01	7.44E-01	-8.04E-01	-1.67E+00	-2.13E-01	-2.05E-01	-5.79E-01	-1.49E-01	1.42E+00	3.08E-01	8.61E+02	4.57E-01	1.20E+00	7.78E-02
29	1.34E+07	1.28E+07	-1.11E+01	3.29E-11	-1.16E+01	-1.64E+01	-1.87E+01	6.30E-03	-4.76E-01	-5.07E-01	1.38E-01	6.96E-01	-7.39E-01	-1.18E-01	6.28E-01	6.96E-02	5.07E-02	1.60E+00	6.75E-01	6.25E+02	2.77E-01	2.11E+00	3.04E-01
30	1.31E+07	1.47E+07	-1.28E+01	8.22E-11	-1.27E+01	-1.36E+01	-1.87E+01	-3.85E-01	-9.84E-02	-1.74E-01	-1.75E+00	2.35E-01	-2.36E-01	-7.55E-02	-1.90E-01	2.22E-01	-4.84E-01	1.59E+00	8.82E-01	7.38E+02	1.85E-01	1.17E+00	3.95E-01
31	1.36E+07	1.49E+07	-1.22E+01	6.06E-11	-1.35E+01	-1.48E+01	-1.86E+01	-3.53E-01	-2.01E-01	-6.96E-01	9.78E-01	6.23E-01	-9.39E-02	-7.46E-01	2.09E-01	-3.63E-01	4.95E-01	1.56E+00	2.92E-01	2.42E+02	9.95E-01	1.04E+00	1.26E-01
32	1.21E+07	1.32E+07	-1.17E+01	6.61E-11	-1.22E+01	-1.60E+01	-1.73E+01	-1.90E-01	-2.27E-01	-4.70E-02	-8.17E-01	-8.60E-01	-7.02E-01	-1.85E+00	-1.04E+00	-1.10E-01	-1.22E-01	8.35E-01	6.42E-02	5.49E+02	6.24E-01	2.14E+00	1.83E-01
33	1.13E+07	1.31E+07	-1.29E+01	6.65E-11	-1.21E+01	-1.40E+01	-1.73E+01	-6.90E-01	4.39E-01	-1.11E-01	-2.32E-01	1.99E-01	-1.18E-01	1.42E-01	-3.16E-01	-1.99E+00	1.06E-01	9.38E-01	6.17E-01	3.49E+02	8.37E-01	1.93E+00	3.30E-01
34	1.20E+07	1.38E+07	-1.33E+01	9.10E-11	-1.31E+01	-1.66E+01	-1.78E+01	-6.91E-02	-4.11E-01	7.98E-01	1.69E-01	3.96E-01	-2.74E-01	2.14E-01	-3.99E-01	7.97E-01	1.83E-01	1.47E+00	3.27E-01	2.85E+02	6.11E-01	1.20E+00	1.97E-01
35	1.18E+07	1.30E+07	-1.04E+01	4.28E-11	-1.29E+01	-1.41E+01	-1.90E+01	1.23E-01	-1.20E-01	7.80E-02	1.46E-01	-1.51E-02	-8.16E-02	3.65E-02	-1.05E-03	-2.27E-01	-1.98E-01	1.52E+00	2.80E-01	1.87E+02	7.25E-01	1.01E+00	2.53E-01
36	1.28E+07	1.38E+07	-1.28E+01	8.48E-11	-1.41E+01	-1.92E+01	-1.76E+01	9.83E-02	-1.65E-01	-9.52E-02	6.62E-01	8.44E-01	9.77E-01	-6.18E-02	-2.11E-01	1.40E-02	-4.33E-01	1.38E+00	1.96E-01	1.94E+02	1.66E-01	1.60E+00	1.19E-01
37	1.11E+07	1.23E+07	-1.12E+01	4.16E-11	-1.49E+01	-1.54E+01	-1.77E+01	5.25E-02	2.87E-01	5.50E-01	-4.83E-01	5.09E-01	-2.11E-02	-3.57E-01	-4.12E-01	-1.87E-01	2.04E-01	1.48E+00	4.39E-01	8.94E+02	1.41E-01	1.14E+00	1.74E-01
38	1.18E+07	1.33E+07	-1.20E+01	5.15E-11	-1.54E+01	-1.30E+01	-1.80E+01	-1.14E-01	-1.19E+00	3.09E-01	3.27E-02	-9.11E-01	-4.78E-01	-4.30E-02	-4.86E-02	-3.89E-01	-1.37E-01	5.68E-01	6.93E-01	3.56E+02	4.85E-01	1.04E+00	8.20E-02
39	1.34E+07	1.53E+07	-1.28E+01	5.75E-11	-1.26E+01	-1.45E+01	-1.75E+01	1.13E-01	-8.56E-01	-7.65E-02	2.15E-01	2.37E-02	-3.17E-01	1.22E-01	8.63E-01	-1.19E-01	1.31E-01	7.87E-01	7.47E-02	8.57E+02	7.25E-02	1.06E+00	2.00E-01
40	1.14E+07	1.47E+07	-1.06E+01	4.67E-11	-1.25E+01	-1.28E+01	-1.80E+01	-7.80E-01	3.74E-01	-2.23E-01	-9.69E-01	4.96E-01	-1.75E-01	-8.52E-01	8.39E-01	8.88E-01	-2.48E-01	8.99E-01	8.62E-02	6.72E+02	4.32E-01	1.05E+00	3.98E-01
41	1.14E+07	1.51E+07	-1.15E+01	5.72E-11	-1.55E+01	-1.88E+01	-1.90E+01	-1.72E+00	-1.67E-01	8.57E-02	-2.46E-01	5.12E-02	-8.81E-02	-5.46E-02	-1.07E-02	1.86E-01	-4.81E-02	1.57E+00	4.93E-01	7.43E+02	8.11E-01	1.21E+00	1.49E-01
42	1.14E+07	1.49E+07	-1.24E+01	7.82E-11	-1.49E+01	-1.61E+01	-1.76E+01	-1.08E-01	-7.62E-01	-2.92E-01	-1.36E-02	-8.38E-02	1.07E-01	1.63E-01	-9.66E-01	-4.08E-01	1.62E-01	1.07E+00	7.86E-01	7.07E+02	2.02E-01	1.10E+00	3.39E-01
43	1.38E+07	1.54E+07	-1.10E+01	3.52E-11	-1.24E+01	-1.90E+01	-1.88E+01	-1.24E-01	-5.34E-01	-2.21E-01	-1.30E-01	-2.04E-01	-4.93E-02	-1.63E-01	-9.82E-02	-1.32E-01	-2.16E-02	7.59E-02	8.41E-01	4.29E+02	8.96E-01	1.25E+00	4.34E-01
44	1.11E+07	1.45E+07	-1.19E+01	6.87E-11	-1.44E+01	-1.29E+01	-1.80E+01	-1.80E-01	-4.03E-02	-3.55E-01	5.62E-01	-1.35E-01	2.04E-01	7.59E-01	-4.92E-01	1.72E-01	6.67E-03	1.43E+00	5.43E-02	9.26E+02	7.65E-01	1.18E+00	3.37E-01
45	1.25E+07	1.59E+07	-1.23E+01	4.54E-11	-1.48E+01	-1.33E+01	-1.82E+01	-4.24E-02	-2.36E-01	-1.98E+00	-3.97E-01	1.02E+00	8.50E-01	3.20E-02	1.45E-01	-2.04E-01	-1.16E-01	1.49E-01	4.51E-01	1.68E+02	2.70E-01	1.04E+00	3.82E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector	S_HALITE	CASTILER	CASTILER	CASTILER	BH_SAND	DRZ_1	CONC_PLG	SOLAM3	SOLAM3	SOLPU3	SOLPU3	SOLPU4	SOLPU4	SOLU4	SOLU6	SOLU6	SOLTH4	PHUMOX3	GLOBAL	CULEBRA	GLOBAL	GLOBAL	CULEBRA
Num.	PRESSURE	PRESSURE	PRMX_LOG	COMP_RCK	PRMX_LOG	PRMX_LOG	PRMX_LOG	SOLSIM	SOLCIM	SOLSIM	SOLCIM	SOLSIM	SOLCIM	SOLSIM	SOLSIM	SOLCIM	SOLSIM	PHUMCIM	OXSTAT	MINP_FAC	TRANSIDX	CLIMTIDX	HMBLKLT
46	1.32E+07	1.54E+07	-1.09E+01	3.64E-11	-1.38E+01	-1.68E+01	-1.78E+01	-3.07E-02	7.90E-01	-1.60E-01	1.10E-01	-9.61E-01	9.24E-01	8.57E-01	-4.62E-01	1.99E-01	-2.11E-01	1.40E+00	3.83E-01	7.66E+02	3.17E-01	1.23E+00	4.86E-01
47	1.11E+07	1.24E+07	-1.18E+01	4.47E-11	-1.57E+01	-1.72E+01	-1.75E+01	1.58E-01	6.07E-03	-1.15E-01	7.79E-01	3.03E-01	-2.58E-01	-3.03E-01	9.85E-02	-9.46E-02	-6.04E-01	4.15E-01	9.45E-01	4.82E+02	4.99E-01	1.68E+00	3.12E-01
48	1.18E+07	1.16E+07	-1.14E+01	3.93E-11	-1.47E+01	-1.31E+01	-1.89E+01	-7.70E-01	3.47E-01	1.16E-01	8.02E-01	-4.20E-01	4.87E-01	-1.77E-01	-1.15E-01	-8.67E-01	-1.79E-01	9.03E-01	1.67E-01	4.49E+02	6.91E-01	1.13E+00	4.25E-01
49	1.30E+07	1.31E+07	-1.20E+01	3.80E-11	-1.20E+01	-1.44E+01	-1.81E+01	8.41E-01	9.80E-01	1.44E-01	-9.71E-02	8.69E-01	4.39E-02	-9.24E-01	-7.06E-01	-1.27E-01	2.17E-01	2.45E-01	3.68E-01	5.03E+02	7.34E-01	1.11E+00	2.82E-01
50	1.27E+07	1.32E+07	-1.26E+01	4.40E-11	-1.19E+01	-1.85E+01	-1.85E+01	4.62E-01	-6.02E-02	-2.45E-01	-2.15E-01	-6.62E-02	-1.27E-01	-1.46E-01	-1.70E-01	2.04E-01	-4.77E-01	1.47E+00	2.68E-01	3.27E+02	3.07E-01	1.15E+00	2.35E-01
51	1.13E+07	1.68E+07	-1.12E+01	2.96E-11	-1.20E+01	-1.32E+01	-1.79E+01	8.64E-01	2.24E-01	-1.03E-01	-3.21E-02	-1.65E-01	-6.37E-02	-2.38E-01	-2.27E-01	7.87E-02	-4.05E-03	1.43E+00	8.65E-01	3.74E+02	9.78E-01	1.72E+00	2.41E-01
52	1.39E+07	1.65E+07	-1.26E+01	7.35E-11	-1.34E+01	-1.48E+01	-1.84E+01	-2.84E-01	2.33E-02	-1.29E-01	-1.55E-01	1.48E-01	-4.05E-02	-1.05E-01	-5.78E-02	3.93E-02	-4.09E-01	5.98E-01	4.62E-01	6.52E+02	5.72E-01	2.05E+00	7.00E-02
53	1.37E+07	1.42E+07	-1.13E+01	6.47E-11	-1.19E+01	-1.71E+01	-1.82E+01	-1.97E-01	2.32E-01	9.80E-01	-3.75E-01	-2.19E-01	-6.08E-01	6.50E-01	-2.99E-01	-5.42E-02	-2.29E-01	1.53E+00	9.16E-01	8.17E+02	4.09E-01	1.06E+00	2.20E-01
54	1.26E+07	1.59E+07	-1.18E+01	7.00E-11	-1.13E+01	-1.76E+01	-1.86E+01	9.03E-01	1.30E-01	-2.06E-02	-1.06E-03	4.61E-02	3.42E-01	-2.64E-01	-3.43E-01	-1.80E-01	-1.91E-01	1.24E+00	6.38E-01	5.18E+02	6.75E-02	1.81E+00	2.46E-01
55	1.23E+07	1.28E+07	-1.08E+01	4.07E-11	-1.12E+01	-1.41E+01	-1.70E+01	-9.30E-02	-1.77E-01	-8.26E-01	6.92E-04	-2.01E-01	1.60E-01	1.87E-01	7.05E-02	-1.61E-01	-3.45E-01	1.52E+00	8.19E-01	6.91E+02	3.41E-01	1.24E+00	4.52E-01
56	1.17E+07	1.18E+07	-1.16E+01	3.78E-11	-1.40E+01	-1.50E+01	-1.89E+01	2.24E-01	-3.51E-01	1.67E-01	-2.82E-01	2.23E-01	-4.41E-01	8.10E-01	-2.01E-01	-9.06E-01	-3.84E-01	4.69E-01	6.87E-01	6.70E+02	4.18E-01	1.14E+00	4.60E-01
57	1.12E+07	1.37E+07	-1.31E+01	6.71E-11	-1.11E+01	-1.79E+01	-1.72E+01	5.84E-01	-1.99E+00	-2.01E-01	-1.34E-01	-5.20E-01	2.47E-01	-8.06E-01	-2.84E-01	-2.17E-01	8.40E-02	3.01E-01	8.05E-01	8.85E+02	9.49E-01	1.08E+00	2.86E-01
58	1.26E+07	1.26E+07	-1.30E+01	5.39E-11	-1.45E+01	-1.58E+01	-1.88E+01	-9.30E-01	-2.40E-01	-1.08E+00	-3.22E-01	-2.68E-02	-9.12E-01	5.86E-02	-6.09E-01	-1.32E-02	3.63E-01	1.70E-01	5.28E-01	4.93E+02	5.08E-01	1.21E+00	5.43E-02
59	1.27E+07	1.21E+07	-1.32E+01	6.91E-11	-1.59E+01	-1.58E+01	-1.79E+01	-8.37E-02	-2.60E-01	-3.18E-01	-3.81E-02	7.55E-02	1.94E-01	1.50E-01	1.74E-01	-4.29E-02	3.14E-01	1.27E+00	7.94E-01	3.64E+02	6.58E-01	1.91E+00	4.58E-01
60	1.15E+07	1.35E+07	-1.36E+01	6.22E-11	-1.22E+01	-1.72E+01	-1.81E+01	-2.25E-01	1.61E-01	1.58E-01	-9.77E-02	-2.48E-01	-1.67E-01	-1.03E+00	1.05E+00	-2.43E-01	-1.83E-01	1.29E+00	1.12E-01	5.43E+00	8.56E-01	1.58E+00	4.78E-01
61	1.17E+07	1.35E+07	-1.36E+01	5.83E-11	-1.33E+01	-1.57E+01	-1.82E+01	-1.23E+00	9.83E-02	1.35E-01	-8.28E-02	-1.67E+00	2.37E-01	-1.90E-01	-2.40E-02	6.52E-01	5.47E-01	1.42E+00	5.94E-01	9.67E+02	2.22E-01	1.22E+00	4.28E-01
62	1.38E+07	1.39E+07	-1.40E+01	9.43E-11	-1.48E+01	-1.78E+01	-1.76E+01	-4.38E-01	-5.16E-02	-3.11E-02	-4.38E-01	-8.06E-02	5.84E-01	9.84E-02	-2.16E-01	-2.54E-02	2.47E-01	6.90E-01	9.88E-01	9.74E+02	8.84E-01	1.03E+00	2.99E-01
63	1.22E+07	1.13E+07	-1.30E+01	6.19E-11	-1.23E+01	-1.37E+01	-1.82E+01	1.86E-01	-1.41E-01	-4.76E-01	-4.66E-02	-4.24E-02	2.26E-01	-4.41E-01	-3.71E-01	3.19E-01	-3.61E-01	1.38E-01	6.27E-01	5.76E+02	4.70E-01	2.17E+00	6.28E-02
64	1.29E+07	1.26E+07	-1.17E+01	4.01E-11	-1.14E+01	-1.55E+01	-1.77E+01	-4.93E-01	-6.16E-01	-1.59E-01	5.57E-02	-7.24E-02	-1.86E-01	-1.95E-02	-1.57E-01	1.10E-01	-9.81E-01	1.51E+00	3.17E-01	4.03E+02	3.37E-01	1.07E+00	4.90E-01
65	1.22E+07	1.29E+07	-1.14E+01	3.91E-11	-1.44E+01	-1.51E+01	-1.89E+01	-1.57E-01	-1.52E+00	-4.40E-01	-1.62E-01	-7.44E-01	-3.71E-01	1.13E-01	2.19E-01	-1.11E+00	-1.53E-01	1.55E+00	7.58E-01	7.56E+02	2.42E-02	1.97E+00	5.74E-02
66	1.33E+07	1.28E+07	-1.38E+01	8.31E-11	-1.18E+01	-1.73E+01	-1.81E+01	-8.11E-02	4.88E-01	1.91E-01	8.81E-01	-6.04E-02	1.38E-01	9.32E-03	-6.34E-02	-8.39E-02	-6.09E-02	6.41E-01	7.28E-01	5.98E+02	4.69E-01	1.03E+00	4.11E-01
67	1.21E+07	1.29E+07	-1.39E+01	4.79E-11	-1.41E+01	-1.75E+01	-1.83E+01	1.46E-01	1.54E-01	9.28E-01	-7.34E-01	1.76E-01	-1.08E-01	-2.70E-01	-1.49E+00	-1.29E+00	-1.10E-01	1.41E+00	9.38E-01	3.34E+02	8.90E-02	1.54E+00	4.65E-01
68	1.16E+07	1.42E+07	-1.25E+01	5.54E-11	-1.53E+01	-1.60E+01	-1.79E+01	-3.58E-01	-3.08E-03	3.97E-01	6.11E-01	-1.33E+00	-1.22E-01	-1.24E-01	8.28E-02	3.58E-01	-2.30E-01	1.44E+00	7.15E-01	5.90E+02	4.97E-02	1.12E+00	4.45E-01
69	1.28E+07	1.62E+07	-1.24E+01	5.27E-11	-1.40E+01	-1.39E+01	-1.77E+01	1.37E-01	-2.75E-01	-4.13E-03	2.76E-01	-4.10E-01	-2.20E-01	-1.81E-01	-1.80E-01	-1.48E-01	1.13E+00	1.46E+00	1.47E-01	5.61E+01	8.27E-01	2.08E+00	2.15E-01
70	1.11E+07	1.31E+07	-1.33E+01	8.13E-11	-1.60E+01	-1.92E+01	-1.74E+01	2.07E-01	-2.11E-01	-1.22E-01	1.60E-01	1.05E-01	-1.63E-01	-3.63E-02	-3.79E-01	-2.64E-01	3.32E-02	1.58E+00	4.42E-02	4.63E+02	6.09E-01	1.84E+00	1.62E-01
71	1.38E+07	1.22E+07	-1.22E+01	5.93E-11	-1.63E+01	-1.77E+01	-1.81E+01	-3.24E-01	6.29E-01	-1.67E-01	-1.70E-01	4.05E-01	-2.24E-01	-5.33E-01	5.40E-01	-2.82E-02	-6.97E-02	5.55E-01	9.04E-01	9.02E+02	8.44E-01	2.19E+00	2.77E-01
72	1.32E+07	1.46E+07	-1.22E+01	5.06E-11	-1.13E+01	-1.77E+01	-1.71E+01	-1.62E-01	8.30E-02	-3.32E-01	-2.52E-01	1.86E-01	-1.71E-03	6.18E-01	7.08E-01	-3.61E-02	8.47E-01	1.57E+00	5.82E-01	2.25E+02	4.26E-01	1.07E+00	4.50E-01
73	1.38E+07	1.39E+07	-1.10E+01	2.45E-11	-1.42E+01	-1.54E+01	-1.76E+01	-1.47E-01	-6.70E-01	-7.42E-02	-2.21E-01	-4.70E-01	-1.83E-02	-1.44E-01	-1.49E-01	-6.72E-02	1.43E-01	1.38E+00	1.17E-02	6.15E+02	7.78E-01	1.10E+00	3.85E-01
74	1.12E+07	1.23E+07	-1.11E+01	2.78E-11	-1.12E+01	-1.85E+01	-1.76E+01	-1.39E-02	-3.12E-01	2.30E-02	7.66E-02	-9.26E-02	-7.41E-02	-9.70E-02	1.33E-01	1.31E-01	-2.04E-02	1.19E+00	5.34E-01	4.56E+01	3.66E-01	1.23E+00	7.46E-02
75	1.33E+07	1.17E+07	-1.23E+01	7.64E-11	-1.27E+01	-1.81E+01	-1.88E+01	-3.70E-02	-3.62E-01	-4.03E-01	-8.55E-02	-1.24E-01	-6.22E-02	4.06E-01	9.71E-01	-7.09E-01	-2.54E-01	7.43E-01	3.38E-01	2.77E+02	6.80E-01	1.79E+00	3.76E-01
76	1.21E+07	1.36E+07	-1.17E+01	5.47E-11	-1.53E+01	-1.75E+01	-1.82E+01	-2.33E-01	-6.81E-02	1.28E-01	-1.06E-01	-1.52E-01	-1.44E-01	-4.72E-01	-1.62E-02	-9.90E-02	7.33E-01	3.60E-01	9.22E-01	1.06E+02	1.54E-01	1.23E+00	2.97E-01
77	1.29E+07	1.25E+07	-1.09E+01	3.06E-11	-1.56E+01	-1.81E+01	-1.73E+01	2.44E-01	-8.65E-02	-1.49E-01	3.72E-01	-3.89E-01	-3.83E-01	-6.66E-02	1.96E-01	5.77E-02	8.87E-01	1.33E+00	7.64E-01	9.84E+02	2.51E-01	1.08E+00	1.70E-01
78	1.17E+07	1.61E+07	-1.20E+01	3.65E-11	-1.61E+01	-1.46E+01	-1.71E+01	-3.12E-01	-2.18E-01	-6.44E-02	-1.86E-01	-1.41E-01	-2.91E-02	-1.31E+00	4.20E-01	-2.86E-01	-1.56E+00	1.48E+00	3.52E-01	9.40E+02	3.56E-01	1.09E+00	9.15E-02
79	1.31E+07	1.31E+07	-1.44E+01	8.64E-11	-1.58E+01	-1.26E+01	-1.75E+01	2.04E-02	8.31E-01	-2.31E-01	-8.52E-01	-7.17E-01	4.50E-01	-6.44E-01	3.07E-01	-2.31E-01	-4.15E-02	1.59E+00	6.47E-01	5.62E+02	1.37E-01	1.64E+00	4.21E-01
80	1.16E+07	1.44E+07	-1.27E+01	4.10E-11	-1.17E+01	-1.83E+01	-1.89E+01	-1.45E-01	9.32E-01	1.04E-02	-1.97E-01	-2.42E-01	-2.39E-01	9.02E-01	4.15E-03	1.59E-01	-3.02E-02	2.01E-01	7.32E-01	8.71E+02	9.80E-01	1.12E+00	6.61E-02
81	1.13E+07	1.33E+07	-1.01E+01	2.61E-11	-1.16E+01	-1.80E+01	-1.76E+01	-1.28E-01	-2.97E-02	-2.53E-01	-1.56E+00	-2.84E-02	7.11E-01	-1.13E-02	4.56E-01	-4.99E-01	6.44E-01	1.58E+00	7.01E-01	9.56E+02	9.60E-01	1.15E+00	2.06E-01
82	1.15E+07	1.35E+07	-1.21E+01	4.45E-11	-1.18E+01	-1.47E+01	-1.72E+01	-3.93E-01	-1.50E-02	-2.41E-01	7.05E-02	-1.91E-01	1.89E-02	5.78E-01	5.60E-01	-3.53E-01	9.37E-01	5.25E-01	6.53E-01	1.73E+02	9.23E-01	1.11E+00	2.10E-01
83	1.23E+07	1.15E+07	-1.26E+01	6.27E-11	-1.14E+01	-1.73E+01	-1.80E+01	1.38E+00	-1.91E-01	-4.49E-01	-1.24E-01	-4.33E-01	7.96E-01	-3.58E-01	5.81E-02	6.29E-01	-1.64E-01	1.54E+00	5.64E-01	5.51E+02	9.10E-01	1.13E+00	1.57E-01
84	1.20E+07	1.30E+07	-1.04E+01	3.44E-11	-1.55E+01	-1.93E+01	-1.83E+01	-5.96E-02	5.11E-02	-3.66E-01	-1.09E+00	-1.24E+00	3.55E-02	-3.25E-01	1.15E-01	4.96E-01	-6.67E-01	1.09E+00	5.13E-01	3.12E+02	5.52E-01	1.21E+00	3.26E-01
85	1.23E+07	1.20E+07	-1.41E+01	7.93E-11	-1.51E+01	-1.53E+01	-1.72E+01	2.63E-01	-1.09E-01	-1.43E-01	-2.44E-02	7.78E-01	-1.95E+00	-7.91E-02	1.88E-01	-7.30E-02	2.63E-01	1.44E+00	7.78E-01	7.95E+02	1.24E-01	1.05E+00	2.49E-01
86	1.25E+07	1.21E+07	-1.07E+01	5.03E-11	-1.24E+01	-1.65E+01	-1.71E+01	-8.76E-01	1.89E-01	4.38E-02	2.31E-01	-4.92E-02	9.42E-02	3.80E-01	1.29E-01	-4.45E-01	2.02E-01	2.94E-01	3.45E-01	4.15E+02	2.40E-01	1.12E+00	1.03E-01
87	1.18E+07	1.37E+07	-1.16E+01	4.59E-11	-1.31E+01	-1.94E+01	-1.84E+01	-2.87E-01	1.28E+00	-1.82E-01	9.41E-01	-5.65E-01	-2.01E-01	-1.32E-01	-2.38E-01	-3.38E-01	-3.21E-01	1.39E+00	9.86E-02	6.88E+02	2.95E-01	1.17E+00	3.20E-01
88	1.26E+07	1.26E+07	-1.37E+01	7.08E-11	-1.11E+01	-1.56E+01	-1.77E+01	-2.03E-01	-5.67E-01	-1.37E-01	-1.79E-01	1.62E-01	-8.55E-01	-2.73E-02	-1.65E+00	2.31E-01	-5.53E-02	1.54E+00	4.45E-01	3.85E+02	7.01E-01	1.19E+00	4.10E-01
89	1.34E+07	1.29E+07	-1.13E+01	4.96E-11	-1.49E+01	-1.88E+01	-1.74E+01	1.95E-01	-7.97E-02	-5.38E-02	-4.56E-01	-3.37E-01	-9.86E-02	1.94E-01	-6.17E-01	-7.53E-01	-1.41E+00	1.02E-01	5.50E-03	7.11E+02	7.98E-01	1.14E+00	3.58E-01
90	1.37E+07	1.34E+07	-1.15E+01	3.07E-11	-1.37E+01	-1.69E+01	-1.72E+01	6.26E-01	7.25E-01	-2.13E-01	-1.27E+00	-2.36E-01	6.32E-03	-1.99E-01	-7.79E-01	-4.21E-01	1.67E-02	1.47E+00	2.29E-01	6.50E+01	6.00E-01	1.20E+00	1.08E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector	S_HALITE	CASTILER	CASTILER	CASTILER	BH_SAND	DRZ_1	CONC_PLG	SOLAM3	SOLAM3	SOLPU3	SOLPU3	SOLPU4	SOLPU4	SOLU4	SOLU6	SOLU6	SOLTH4	PHUMOX3	GLOBAL	CULEBRA	GLOBAL	GLOBAL	CULEBRA
Num.	PRESSURE	PRESSURE	PRMX_LOG	COMP_RCK	PRMX_LOG	PRMX_LOG	PRMX_LOG	SOLSIM	SOLCIM	SOLSIM	SOLCIM	SOLSIM	SOLCIM	SOLSIM	SOLSIM	SOLCIM	SOLSIM	PHUMCIM	OXSTAT	MINP_FAC	TRANSIDX	CLIMTIDX	HMBLKLT
91	1.30E+07	1.25E+07	-1.34E+01	7.55E-11	-1.26E+01	-1.43E+01	-1.87E+01	-9.83E-01	-8.06E-01	2.79E-02	-9.44E-01	-2.90E-01	1.30E+00	-2.02E-01	-1.42E-01	5.74E-01	-1.04E-01	4.94E-01	5.04E-01	4.58E+02	3.24E-01	1.08E+00	1.29E-01
92	1.25E+07	1.18E+07	-1.21E+01	4.90E-11	-1.34E+01	-1.71E+01	-1.84E+01	-1.19E-02	-1.57E-01	6.67E-01	1.05E-01	5.91E-01	1.21E-01	-3.84E-01	1.89E-02	-1.56E-01	-3.39E-01	1.58E+00	5.43E-01	6.32E+02	7.83E-01	1.17E+00	3.17E-01
93	1.30E+07	1.37E+07	-1.21E+01	5.98E-11	-1.35E+01	-1.38E+01	-1.75E+01	6.56E-01	-1.36E-01	-1.73E+00	-4.19E-01	-3.11E-01	-4.83E-01	-1.54E-01	1.61E-01	-3.13E-01	-1.97E+00	1.50E+00	9.00E-01	5.35E+02	9.60E-01	1.06E+00	3.07E-01
94	1.23E+07	1.43E+07	-1.18E+01	3.71E-11	-1.50E+01	-1.42E+01	-1.85E+01	-5.64E-01	-1.45E+00	-9.58E-01	4.24E-01	-6.21E-01	1.53E-01	-8.57E-02	-7.40E-01	-1.45E-01	-1.17E-02	1.50E+00	8.33E-01	2.58E+02	1.03E-01	1.22E+00	2.58E-01
95	1.29E+07	1.33E+07	-1.08E+01	3.22E-11	-1.60E+01	-1.62E+01	-1.74E+01	5.18E-01	1.08E-01	2.54E-01	-3.84E-01	1.10E-01	1.89E-01	2.34E-02	-7.33E-02	-7.95E-01	1.10E-01	1.45E+00	2.16E-01	5.26E+02	5.40E-01	1.02E+00	1.34E-01
96	1.24E+07	1.25E+07	-1.13E+01	3.87E-11	-1.30E+01	-1.44E+01	-1.89E+01	1.68E-01	-4.62E-01	-2.65E-02	-2.05E-01	-4.61E-01	-3.55E-01	-2.22E-01	-4.76E-01	2.65E-02	7.52E-01	1.04E+00	2.10E-02	1.12E+02	2.90E-01	1.02E+00	4.92E-01
97	1.33E+07	1.50E+07	-1.05E+01	2.83E-11	-1.23E+01	-1.53E+01	-1.79E+01	-6.55E-01	-4.72E-02	2.48E-01	3.38E-01	2.11E-01	-8.93E-03	-4.85E-01	-8.80E-01	7.34E-01	7.73E-02	8.07E-01	7.46E-01	6.09E+02	2.34E-01	1.19E+00	2.26E-01
98	1.37E+07	1.19E+07	-1.34E+01	5.88E-11	-1.43E+01	-1.84E+01	-1.77E+01	-2.35E-02	-1.84E-01	-4.28E-01	-1.91E-01	-1.56E-01	-4.80E-02	2.19E-01	-9.05E-01	3.45E-03	-9.13E-02	1.55E+00	1.85E-01	7.72E+02	3.92E-01	1.02E+00	8.74E-02
99	1.31E+07	1.27E+07	-1.06E+01	3.35E-11	-1.62E+01	-1.62E+01	-1.78E+01	4.42E-01	-2.47E-01	-5.67E-01	2.38E-01	-3.56E-02	-6.53E-01	-6.57E-03	2.56E-01	1.39E+00	-8.26E-01	7.53E-01	2.85E-01	7.84E+02	5.65E-01	1.18E+00	4.17E-01
100	1.14E+07	1.40E+07	-1.29E+01	6.82E-11	-1.36E+01	-1.50E+01	-1.74E+01	7.31E-02	-3.79E-01	8.72E-01	-7.14E-01	-2.15E-01	-1.90E-01	7.32E-01	4.37E-02	-5.74E-02	2.28E-01	1.23E+00	2.40E-01	4.35E+02	7.42E-01	1.70E+00	2.73E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
1	9.77E-03	1.53E-01	3.78E-04	1.16E+00	8.85E-02	2.00E+00	7.03E+00	3.78E-01	1.88E+01	3.39E-01	6.77E+00	1.24E-01	1.01E-01	-1.97E+01	-1.86E+01	-2.07E+01	5.98E-02
2	1.72E-04	1.12E-01	3.13E-03	7.50E-01	3.49E-01	3.31E+00	1.49E+00	3.73E-01	1.86E-01	5.73E-01	5.65E+00	1.60E-01	1.60E-01	-1.75E+01	-1.81E+01	-1.93E+01	1.10E-01
3	8.34E-03	1.65E-01	2.26E-04	9.07E+00	2.94E-01	7.13E-01	8.83E+00	2.00E-01	8.53E-02	5.47E-01	7.53E+00	5.14E-01	9.65E-02	-1.80E+01	-1.87E+01	-1.97E+01	1.74E-01
4	1.61E-03	1.85E-01	3.03E-04	3.60E+00	2.09E-02	6.79E+00	2.27E+00	2.96E-01	5.36E+00	5.95E-01	6.10E+00	4.31E-01	1.25E-01	-1.77E+01	-1.73E+01	-2.02E+01	4.04E-02
5	1.61E-04	2.42E-01	1.57E-02	1.45E+00	4.73E-02	4.48E+00	7.70E-01	1.33E-01	1.31E+00	7.67E-02	7.19E+00	3.45E-01	2.94E-01	-1.79E+01	-1.84E+01	-2.00E+01	3.22E-01
6	8.55E-04	1.10E-01	1.32E-02	5.05E+00	5.16E-02	3.88E+00	1.94E+00	1.09E-01	1.66E+00	4.66E-01	1.97E+01	7.67E-02	2.47E-01	-1.74E+01	-1.81E+01	-1.98E+01	6.52E-01
7	1.58E-03	1.85E-01	3.23E-04	8.75E-01	2.04E-01	1.23E+00	6.89E+00	1.78E-01	6.76E+01	2.69E-01	6.90E+00	3.63E-01	3.09E-01	-1.83E+01	-1.78E+01	-1.86E+01	9.08E-01
8	6.74E-03	1.81E-01	2.60E-04	6.61E+00	2.50E-01	5.88E+00	1.76E+00	7.82E-02	4.29E+01	5.07E-01	4.30E+00	1.89E-02	9.05E-02	-1.87E+01	-1.80E+01	-1.86E+01	2.43E-01
9	1.00E-03	1.20E-01	7.93E-04	1.19E+00	5.65E-02	4.55E+00	1.02E+00	5.32E-02	4.50E+00	9.84E-02	7.48E+00	5.01E-01	1.07E-01	-1.99E+01	-1.83E+01	-2.03E+01	4.45E-01
10	6.44E-03	1.86E-01	2.29E-03	2.12E+00	2.59E-01	1.38E+00	1.25E+00	1.71E-01	3.41E+00	1.67E-01	6.17E+00	3.32E-01	2.58E-01	-2.00E+01	-1.82E+01	-2.11E+01	8.71E-01
11	7.83E-03	1.74E-01	3.29E-03	3.24E+00	1.03E-01	2.19E+00	9.11E-01	9.49E-02	2.63E-01	4.43E-02	8.25E+00	1.05E-01	1.69E-01	-1.73E+01	-1.83E+01	-2.02E+01	8.05E-01
12	1.24E-04	1.62E-01	7.17E-03	8.40E-01	3.17E-02	1.52E+00	6.64E+00	7.65E-02	2.51E-01	4.17E-01	7.90E+00	1.85E-01	2.86E-01	-1.87E+01	-1.76E+01	-1.90E+01	2.17E-01
13	1.06E-03	1.58E-01	1.45E-03	1.69E+00	5.24E-02	1.71E+00	8.06E-01	2.88E-02	2.19E-01	5.14E-01	7.17E+00	5.50E-01	3.18E-01	-1.86E+01	-1.72E+01	-1.98E+01	9.84E-01
14	1.22E-03	1.02E-01	6.60E-04	1.48E+00	6.16E-02	8.89E-01	1.57E+00	2.66E-02	2.68E+01	1.29E-01	5.91E+00	1.46E-02	2.91E-01	-1.96E+01	-1.88E+01	-2.08E+01	6.10E-01
15	9.40E-03	1.35E-01	1.09E-02	8.10E+00	2.48E-02	1.81E+00	5.91E+00	4.20E-02	2.88E+01	5.81E-01	1.23E+01	4.03E-01	3.43E-01	-1.87E+01	-1.82E+01	-1.91E+01	6.38E-01
16	3.20E-03	1.87E-01	2.08E-04	1.35E+00	1.68E-01	9.60E-01	3.55E+00	2.28E-02	4.00E+01	2.03E-01	1.35E+01	3.73E-02	1.68E-01	-1.82E+01	-1.80E+01	-1.94E+01	3.57E-02
17	7.90E-04	1.51E-01	1.33E-03	1.84E+00	2.45E-01	3.81E+00	4.32E+00	5.75E-02	3.02E+01	3.60E-01	9.72E+00	0	6.91E-02	-1.88E+01	-1.80E+01	-2.00E+01	8.85E-01
18	3.02E-03	2.22E-01	2.21E-04	5.63E+00	8.24E-02	4.64E+00	5.32E+00	3.63E-02	4.02E+00	2.27E-01	6.52E+00	4.92E-02	3.13E-01	-1.77E+01	-1.78E+01	-1.92E+01	1.85E-01
19	8.13E-03	1.30E-01	2.38E-03	4.38E+00	1.41E-01	1.56E+00	2.87E+00	3.48E-02	1.17E+00	2.49E-01	8.22E+00	2.01E-01	2.20E-01	-1.84E+01	-1.71E+01	-2.08E+01	9.20E-01
20	2.47E-03	1.48E-01	4.07E-03	2.92E+00	3.92E-02	2.32E+00	2.14E+00	1.83E-01	1.59E+01	1.51E-02	7.76E+00	1.41E-01	5.35E-02	-1.79E+01	-1.75E+01	-1.89E+01	9.75E-01
21	1.90E-03	1.17E-01	4.79E-03	7.13E-01	3.39E-02	3.95E+00	5.00E+00	2.74E-02	5.31E-02	3.43E-01	1.61E+01	1.36E-01	3.47E-01	-1.80E+01	-1.85E+01	-2.02E+01	4.92E-01
22	5.09E-04	1.16E-01	7.06E-04	9.93E+00	3.75E-02	4.82E+00	9.64E-01	1.14E-01	4.20E-01	2.73E-01	8.16E+00	1.01E-02	1.72E-01	-1.79E+01	-1.82E+01	-1.88E+01	8.97E-01
23	3.96E-03	1.93E-01	1.30E-03	3.30E+00	2.89E-02	1.94E+00	2.05E+00	1.36E-01	1.07E+01	3.83E-01	1.25E+01	2.71E-01	1.98E-01	-1.81E+01	-1.80E+01	-1.92E+01	9.30E-01
24	1.05E-04	1.37E-01	3.12E-05	1.09E+00	6.44E-02	1.11E+00	1.12E+00	8.74E-02	1.47E+01	4.09E-01	9.37E+00	6.98E-02	2.05E-01	-1.87E+01	-1.88E+01	-1.92E+01	5.54E-01
25	2.58E-04	1.85E-01	7.73E-04	7.45E+00	1.07E-01	9.90E-01	2.66E+00	2.02E-01	1.16E-01	4.90E-01	1.01E+01	1.12E-01	2.13E-01	-2.00E+01	-1.87E+01	-2.17E+01	2.51E-01
26	1.88E-04	1.16E-01	9.60E-04	7.52E+00	1.31E-01	3.20E+00	4.47E+00	9.50E-02	2.89E+00	4.22E-01	8.30E+00	5.35E-01	3.01E-01	-1.70E+01	-1.76E+01	-2.13E+01	7.29E-01
27	2.80E-04	1.10E-01	5.74E-05	3.16E+00	1.15E-01	9.67E+00	2.25E+00	2.39E-02	7.33E+01	5.19E-01	9.93E+00	6.56E-02	2.43E-01	-1.89E+01	-1.76E+01	-1.82E+01	4.55E-01
28	2.72E-03	1.12E-01	1.13E-02	2.14E+00	4.32E-02	1.17E+00	2.62E+00	1.01E-01	5.12E-01	5.60E-01	6.96E+00	2.91E-01	8.75E-02	-2.02E+01	-1.81E+01	-1.97E+01	1.21E-01
29	5.41E-03	1.39E-01	5.65E-04	9.29E-01	2.22E-02	4.90E+00	4.62E+00	3.47E-01	7.92E-02	2.22E-01	7.39E+00	5.64E-02	2.60E-02	-1.85E+01	-1.89E+01	-1.95E+01	9.96E-01
30	4.85E-03	1.88E-01	8.64E-04	7.30E-01	1.24E-01	2.57E+00	4.76E+00	1.31E-01	1.23E+01	5.23E-02	7.98E+00	4.12E-01	3.57E-01	-1.78E+01	-1.89E+01	-2.04E+01	7.97E-01
31	1.78E-03	1.72E-01	2.42E-04	8.73E+00	3.15E-01	7.19E+00	1.28E+00	3.34E-02	5.31E-01	1.18E-01	4.80E+00	4.32E-01	3.07E-01	-1.95E+01	-1.85E+01	-2.01E+01	4.63E-01
32	1.68E-03	1.67E-01	7.45E-05	3.36E+00	2.31E-02	1.43E+00	9.89E-01	3.23E-01	1.97E+01	4.52E-01	7.98E+00	5.38E-01	3.29E-01	-1.97E+01	-1.79E+01	-2.10E+01	6.16E-01
33	1.13E-04	1.64E-01	1.08E-04	5.84E+00	2.77E-01	5.60E+00	8.29E+00	3.90E-01	1.29E+01	6.78E-02	8.06E+00	2.77E-01	3.90E-01	-1.83E+01	-1.89E+01	-1.99E+01	7.07E-01
34	1.16E-04	1.98E-01	5.31E-03	9.53E+00	3.00E-01	2.69E+00	1.32E+00	6.18E-02	3.98E-01	5.36E-01	1.02E+01	3.71E-01	4.03E-02	-1.82E+01	-1.86E+01	-1.89E+01	1.42E-01
35	1.91E-03	1.83E-01	1.79E-03	2.67E+00	1.05E-01	8.99E+00	1.38E+00	4.93E-02	1.40E+01	3.14E-01	1.57E+01	4.56E-01	7.74E-02	-1.78E+01	-1.99E+01	-2.05E+01	4.00E-01
36	2.54E-03	1.42E-01	1.63E-03	1.37E+00	2.12E-01	8.07E+00	1.83E+00	3.64E-01	5.00E+00	2.37E-01	1.05E+01	3.80E-01	1.46E-01	-1.85E+01	-1.78E+01	-2.03E+01	9.41E-01
37	4.06E-03	1.79E-01	4.63E-03	7.00E+00	1.50E-01	1.89E+00	9.07E+00	4.72E-02	7.43E-01	1.77E-02	7.26E+00	9.19E-02	6.72E-02	-1.95E+01	-1.89E+01	-2.01E+01	2.92E-01
38	9.79E-04	1.14E-01	3.73E-05	3.97E+00	6.78E-02	2.27E+00	3.26E+00	2.37E-01	9.94E-02	8.66E-02	7.30E+00	2.14E-02	3.64E-01	-1.92E+01	-1.79E+01	-2.10E+01	4.11E-01
39	1.26E-03	1.40E-01	6.37E-04	2.42E+00	2.36E-01	9.01E+00	3.29E+00	5.96E-02	1.99E-01	2.93E-01	9.10E+00	1.29E-01	1.50E-01	-1.74E+01	-1.82E+01	-1.95E+01	1.94E-01
40	2.40E-04	1.83E-01	9.55E-05	2.53E+00	2.38E-02	4.31E+00	2.47E+00	1.67E-01	4.70E+01	4.79E-02	8.11E+00	1.50E-01	1.86E-01	-1.89E+01	-1.74E+01	-2.06E+01	2.27E-01
41	6.16E-04	2.35E-01	6.01E-03	2.22E+00	1.86E-01	9.70E-01	4.08E+00	1.22E-01	6.33E+01	4.38E-01	8.64E+00	4.80E-03	1.77E-01	-1.76E+01	-1.71E+01	-2.20E+01	6.89E-01
42	5.33E-04	1.04E-01	4.56E-04	9.10E-01	8.66E-02	1.64E+00	7.08E+00	3.17E-02	1.71E+01	5.52E-01	4.45E+00	2.11E-01	3.84E-02	-1.82E+01	-1.76E+01	-2.08E+01	8.68E-01
43	6.63E-04	1.06E-01	3.24E-05	3.92E+00	7.99E-02	3.42E+00	7.40E-01	3.39E-01	3.71E+01	4.98E-01	1.08E+01	1.18E-01	2.25E-01	-1.78E+01	-1.95E+01	-2.01E+01	5.10E-01
44	9.02E-03	1.14E-01	1.14E-04	1.16E+00	2.77E-02	4.24E+00	8.42E+00	5.15E-02	1.73E+00	3.90E-01	5.20E+00	2.62E-01	1.53E-01	-1.70E+01	-1.88E+01	-1.99E+01	5.27E-01
45	1.18E-03	1.73E-01	7.74E-03	7.18E+00	7.24E-02	3.50E+00	5.16E+00	5.47E-02	5.94E+00	5.01E-01	6.74E+00	1.13E-01	1.89E-01	-1.89E+01	-1.83E+01	-1.96E+01	8.14E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector	CULEBRA	CULEBRA	U+6	U+4	PU+3	PU+4	TH+4	AM+3	BOREHOLE	GLOBAL	BOREHOLE	SHFTU	SHFTU	SHFTU	SHFTL_T1	SHFTL_T2	SPALLMOD
Num.	APOROS	DPOROS	MKD_U	MKD_U	MKD_PU	MKD_PU	MKD_TH	MKD_AM	TAUFAIL	PBRINE	DOMEGA	SAT_RBRN	SAT_RGAS	PRMX_LOG	PRMX_LOG	PRMX_LOG	RNDSPALL
46	3.38E-03	1.73E-01	1.72E-04	4.89E+00	3.28E-02	8.28E-01	2.35E+00	8.52E-02	3.47E-01	4.80E-01	8.89E+00	4.68E-01	2.81E-01	-1.84E+01	-1.90E+01	-2.05E+01	1.53E-01
47	4.38E-04	1.89E-01	4.26E-04	1.05E+00	2.79E-02	6.40E+00	2.13E+00	3.10E-01	5.68E+00	1.41E-01	7.31E+00	1.33E-01	2.78E-01	-1.93E+01	-1.77E+01	-1.80E+01	3.82E-03
48	2.72E-04	1.80E-01	4.29E-03	7.93E-01	3.67E-02	1.76E+00	1.19E+00	1.19E-01	5.53E-02	2.60E-01	1.18E+01	3.06E-01	2.33E-02	-1.90E+01	-1.77E+01	-2.18E+01	8.28E-01
49	1.42E-03	1.01E-01	3.02E-03	5.23E+00	5.88E-02	3.12E+00	2.53E+00	6.63E-02	3.11E-01	4.59E-01	7.80E+00	4.65E-02	2.52E-01	-1.80E+01	-1.80E+01	-2.06E+01	6.73E-01
50	7.05E-04	1.59E-01	4.97E-04	6.74E+00	9.89E-02	2.08E+00	7.97E+00	1.91E-01	1.05E-01	1.52E-01	6.31E+00	1.99E-01	4.00E-01	-1.88E+01	-1.76E+01	-1.98E+01	8.36E-01
51	3.32E-04	1.68E-01	8.50E-05	2.60E+00	2.31E-01	2.72E+00	1.64E+00	3.99E-02	6.83E-01	2.15E-01	1.34E+01	5.69E-01	1.19E-01	-2.04E+01	-1.79E+01	-2.04E+01	8.55E-01
52	3.57E-03	1.19E-01	2.01E-03	6.26E+00	4.79E-02	1.51E+00	3.04E+00	4.43E-02	7.97E+00	7.38E-02	1.26E+01	5.89E-01	1.07E-02	-1.71E+01	-1.77E+01	-2.13E+01	2.07E-01
53	2.29E-04	1.60E-01	1.00E-02	9.46E+00	9.73E-02	7.65E+00	4.72E+00	5.57E-02	8.73E-01	2.28E-01	7.64E+00	3.34E-02	1.10E-01	-1.91E+01	-1.87E+01	-1.93E+01	4.34E-01
54	3.69E-03	1.33E-01	1.19E-04	1.79E+00	1.37E-01	9.43E+00	5.48E+00	6.97E-02	9.18E-02	1.97E-01	7.89E+00	3.21E-01	3.70E-01	-1.90E+01	-1.69E+01	-2.09E+01	3.47E-01
55	4.44E-03	1.69E-01	5.68E-03	1.96E+00	1.75E-01	5.10E+00	5.66E+00	2.41E-01	1.83E+00	5.94E-01	1.15E+01	5.63E-01	1.64E-01	-1.84E+01	-1.92E+01	-1.94E+01	3.62E-01
56	5.04E-03	1.11E-01	1.03E-03	8.80E+00	2.99E-02	7.05E+00	1.53E+00	3.00E-02	5.00E+01	1.73E-01	8.47E+00	2.36E-01	5.63E-02	-1.92E+01	-1.84E+01	-2.01E+01	6.54E-02
57	7.25E-03	2.50E-01	6.30E-05	2.81E+00	2.67E-01	1.45E+00	3.69E+00	1.84E-01	9.01E+00	1.38E-01	7.08E+00	2.40E-01	1.21E-01	-1.81E+01	-1.83E+01	-2.15E+01	5.75E-01
58	1.47E-03	1.66E-01	1.60E-04	2.26E+00	3.34E-01	5.28E+00	9.43E-01	4.29E-02	1.51E+00	3.78E-01	1.39E+01	3.88E-01	2.65E-01	-1.76E+01	-1.81E+01	-1.94E+01	9.50E-01
59	1.75E-04	1.32E-01	1.90E-02	1.62E+00	3.54E-02	2.48E+00	1.34E+00	2.56E-01	7.06E+00	1.87E-01	1.07E+01	1.74E-01	1.43E-01	-1.98E+01	-1.77E+01	-2.11E+01	1.12E-01
60	1.94E-04	1.08E-01	6.68E-03	7.80E+00	5.38E-02	2.63E+00	3.53E+00	2.57E-02	2.22E+00	1.08E-01	6.70E+00	5.97E-01	1.29E-02	-1.80E+01	-1.85E+01	-2.01E+01	7.49E-01
61	4.67E-04	1.22E-01	1.50E-02	1.41E+00	4.38E-02	9.75E+00	8.51E-01	3.81E-02	1.04E+01	3.58E-01	6.88E+00	6.25E-02	4.48E-02	-1.83E+01	-1.94E+01	-2.09E+01	7.11E-01
62	1.57E-04	1.77E-01	2.64E-03	4.53E+00	2.15E-02	1.26E+00	2.95E+00	3.08E-02	4.68E-01	2.87E-02	8.35E+00	5.58E-01	3.22E-01	-1.94E+01	-1.82E+01	-1.88E+01	5.45E-01
63	3.86E-04	1.74E-01	1.42E-02	1.59E+00	4.96E-02	7.82E-01	3.75E+00	1.04E-01	1.00E+00	2.76E-01	1.16E+01	2.67E-02	1.81E-01	-1.77E+01	-1.94E+01	-2.03E+01	1.40E-01
64	3.26E-04	1.47E-01	1.92E-04	3.80E+00	2.79E-01	8.09E-01	3.17E+00	4.62E-02	1.73E-01	3.10E-01	2.14E+01	9.23E-02	5.13E-02	-1.92E+01	-1.75E+01	-1.93E+01	3.08E-01
65	3.67E-04	1.13E-01	3.64E-03	8.31E+00	3.11E-02	7.34E-01	1.92E+00	1.62E-01	7.42E+00	5.30E-01	5.41E+00	1.79E-01	2.54E-01	-1.88E+01	-1.84E+01	-2.04E+01	6.64E-01
66	1.14E-03	1.78E-01	4.81E-05	2.48E+00	9.45E-02	1.21E+00	7.63E+00	2.10E-01	2.03E-01	3.00E-01	1.20E+01	1.66E-03	1.38E-01	-1.76E+01	-1.74E+01	-2.05E+01	7.87E-01
67	5.84E-04	2.31E-01	1.43E-04	4.06E+00	5.82E-02	8.19E+00	7.85E+00	2.50E-02	2.06E+00	5.55E-01	8.12E+00	2.20E-01	2.19E-01	-1.89E+01	-1.86E+01	-2.16E+01	7.60E-01
68	2.00E-04	1.44E-01	5.45E-04	9.67E-01	3.62E-01	6.56E+00	7.31E+00	1.50E-01	3.82E-01	2.44E-01	6.48E+00	4.95E-01	3.00E-01	-1.82E+01	-1.88E+01	-2.09E+01	2.74E-01
69	8.18E-04	1.71E-01	2.06E-03	2.79E+00	2.40E-02	7.45E+00	9.93E+00	8.29E-02	2.73E+00	5.27E-01	7.44E+00	1.24E-01	6.11E-02	-1.86E+01	-1.85E+01	-1.97E+01	6.00E-01
70	4.31E-04	1.63E-01	6.92E-05	1.74E+00	1.12E-01	1.66E+00	4.19E+00	7.46E-02	1.08E+00	3.90E-02	1.10E+01	2.81E-01	3.40E-01	-1.78E+01	-1.92E+01	-1.85E+01	9.63E-01
71	4.32E-03	1.65E-01	5.35E-05	1.11E+00	4.10E-02	4.06E+00	3.93E+00	2.40E-02	5.86E-02	5.86E-01	6.99E+00	1.93E-01	3.50E-01	-1.79E+01	-1.90E+01	-2.00E+01	5.89E-01
72	3.61E-04	1.43E-01	1.34E-04	1.24E+00	2.05E-02	8.65E-01	9.14E-01	2.77E-01	4.28E+00	3.32E-01	7.59E+00	8.12E-02	3.87E-01	-1.83E+01	-1.87E+01	-1.95E+01	5.31E-01
73	5.51E-03	1.70E-01	8.06E-03	9.55E-01	3.87E-01	2.21E+00	3.40E+00	1.15E-01	3.30E+01	4.27E-01	1.46E+01	1.54E-01	3.94E-01	-1.99E+01	-1.84E+01	-2.05E+01	3.16E-01
74	6.30E-03	2.05E-01	7.47E-05	8.47E-01	4.23E-02	1.09E+00	1.73E+00	2.21E-02	9.58E+00	1.77E-01	1.12E+01	1.62E-01	3.55E-02	-1.83E+01	-1.84E+01	-2.02E+01	4.88E-01
75	2.36E-04	1.17E-01	8.24E-05	5.95E+00	3.08E-01	3.65E+00	2.03E+00	1.49E-01	3.35E-01	2.57E-01	5.05E+00	8.64E-02	2.01E-01	-1.91E+01	-1.82E+01	-2.19E+01	5.12E-01
76	2.22E-03	1.29E-01	9.07E-03	1.54E+00	3.99E-01	7.65E-01	7.83E-01	1.27E-01	1.24E+00	2.94E-01	5.01E+00	4.81E-01	7.57E-02	-1.78E+01	-1.87E+01	-1.87E+01	7.36E-01
77	8.80E-04	1.79E-01	1.77E-02	3.51E+00	7.67E-02	5.18E+00	6.53E+00	2.28E-01	2.50E+01	2.85E-01	6.44E+00	3.93E-01	2.73E-01	-1.75E+01	-1.75E+01	-2.14E+01	3.78E-01
78	4.06E-04	1.55E-01	1.08E-03	5.51E+00	1.96E-01	3.08E+00	1.15E+00	3.67E-02	6.30E-01	4.46E-01	7.82E+00	4.36E-02	2.63E-01	-1.95E+01	-1.91E+01	-2.14E+01	8.46E-01
79	7.10E-03	1.55E-01	1.26E-04	2.06E+00	3.75E-01	7.70E+00	7.10E-01	1.57E-01	1.46E+00	3.95E-01	9.58E+00	2.53E-01	1.35E-01	-1.81E+01	-1.73E+01	-1.96E+01	3.98E-01
80	1.37E-04	1.15E-01	4.85E-04	1.26E+00	1.57E-01	6.13E+00	5.85E+00	2.65E-01	5.36E+01	4.71E-01	1.01E+01	4.72E-01	3.25E-01	-1.85E+01	-1.84E+01	-1.95E+01	1.65E-01
81	5.79E-03	1.09E-01	6.40E-03	6.48E+00	9.11E-02	2.89E+00	2.39E+00	2.83E-01	7.47E-02	1.26E-01	7.41E+00	1.65E-01	1.31E-01	-1.86E+01	-1.71E+01	-1.87E+01	2.87E-01
82	5.56E-04	1.90E-01	2.69E-03	3.72E+00	1.94E-01	2.10E+00	4.05E+00	9.09E-02	1.41E-01	5.68E-01	9.10E+00	9.87E-02	2.33E-01	-1.76E+01	-1.79E+01	-2.07E+01	4.72E-01
83	3.13E-04	1.82E-01	9.49E-03	4.25E+00	7.00E-02	5.57E+00	1.08E+00	1.43E-01	3.64E+01	4.30E-01	5.78E+00	3.58E-01	3.35E-01	-1.77E+01	-1.81E+01	-2.23E+01	3.39E-01
84	6.47E-04	1.26E-01	4.63E-05	3.10E+00	1.22E-01	6.28E+00	9.40E+00	8.06E-02	1.28E-01	3.24E-01	8.37E+00	3.39E-01	8.38E-02	-1.81E+01	-1.75E+01	-1.91E+01	5.62E-01
85	1.36E-03	1.06E-01	3.46E-05	1.29E+00	4.52E-02	1.13E+00	1.46E+00	2.21E-01	6.65E+00	4.01E-01	7.71E+00	5.80E-01	1.87E-02	-1.84E+01	-1.71E+01	-2.15E+01	7.17E-02
86	9.15E-04	1.76E-01	4.35E-05	1.03E+00	7.45E-02	2.79E+00	1.42E+00	2.06E-02	3.08E+00	3.72E-01	6.60E+00	4.43E-01	1.92E-01	-1.93E+01	-1.86E+01	-2.04E+01	3.54E-01
87	2.98E-04	1.88E-01	1.83E-03	4.73E+00	2.18E-01	8.99E-01	1.16E+00	2.49E-01	2.17E+01	2.09E-01	6.59E+00	1.69E-01	2.69E-01	-1.81E+01	-1.77E+01	-1.91E+01	7.77E-01
88	2.32E-03	1.18E-01	1.22E-02	1.67E+00	2.26E-01	9.36E-01	1.78E+00	2.16E-02	8.82E-01	4.83E-01	7.03E+00	1.92E-01	3.80E-01	-1.93E+01	-1.72E+01	-1.90E+01	6.98E-01
89	4.77E-03	1.61E-01	1.69E-02	8.19E-01	6.38E-02	8.48E+00	1.07E+00	1.05E-01	6.47E-02	1.10E-01	6.39E+00	1.45E-01	2.40E-01	-1.85E+01	-1.90E+01	-2.00E+01	2.64E-01
90	1.27E-04	1.05E-01	3.76E-03	7.59E-01	1.79E-01	1.32E+00	6.31E+00	4.81E-02	2.33E+01	1.02E-01	6.67E+00	7.37E-02	6.83E-03	-1.77E+01	-1.79E+01	-2.06E+01	3.84E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector	CULEBRA	CULEBRA	U+6	U+4	PU+3	PU+4	TH+4	AM+3	BOREHOLE	GLOBAL	BOREHOLE	SHFTU	SHFTU	SHFTU	SHFTL_T1	SHFTL_T2	SPALLMOD
Num.	APOROS	DPOROS	MKD_U	MKD_U	MKD_PU	MKD_PU	MKD_TH	MKD_AM	TAUFAIL	PBRINE	DOMEGA	SAT_RBRN	SAT_RGAS	PRMX_LOG	PRMX_LOG	PRMX_LOG	RNDSPALL
91	2.08E-03	1.50E-01	9.73E-05	1.89E+00	1.17E-01	1.04E+00	8.65E+00	3.30E-01	2.32E+00	8.90E-02	5.55E+00	4.62E-01	3.03E-02	-1.91E+01	-1.93E+01	-1.84E+01	4.29E-01
92	2.11E-03	1.01E-01	3.86E-04	4.48E+00	1.59E-01	1.33E+00	5.03E+00	6.48E-02	6.05E+01	5.94E-02	1.74E+01	3.13E-01	3.79E-01	-1.71E+01	-1.93E+01	-2.18E+01	8.03E-02
93	1.01E-04	2.16E-01	3.39E-04	9.96E-01	1.65E-01	1.05E+00	2.75E+00	2.08E-02	5.88E-01	3.52E-01	4.63E+00	2.31E-01	1.14E-01	-1.72E+01	-1.80E+01	-2.02E+01	2.30E-01
94	7.45E-04	1.20E-01	1.21E-03	6.05E+00	1.45E-01	2.43E+00	6.07E+00	2.82E-02	1.40E-01	2.20E-02	9.41E+00	5.26E-01	3.64E-01	-1.80E+01	-1.78E+01	-1.99E+01	1.85E-02
95	2.16E-04	1.83E-01	1.79E-04	4.86E+00	2.59E-02	7.43E-01	8.22E-01	2.98E-01	7.98E-01	4.56E-01	7.67E+00	5.09E-01	9.28E-02	-1.75E+01	-1.84E+01	-1.96E+01	6.25E-01
96	4.83E-04	1.76E-01	1.54E-03	5.34E+00	2.69E-02	5.78E+00	2.85E+00	3.96E-02	2.49E+00	1.59E-01	6.34E+00	4.19E-01	3.74E-01	-1.73E+01	-1.81E+01	-1.92E+01	9.38E-01
97	2.82E-03	1.68E-01	5.78E-05	8.05E+00	3.50E-02	1.85E+00	8.89E-01	3.27E-02	2.76E-01	1.85E-01	4.59E+00	3.18E-02	2.28E-01	-1.72E+01	-1.83E+01	-2.12E+01	9.44E-02
98	1.47E-04	2.13E-01	4.07E-05	2.97E+00	7.87E-02	8.72E+00	1.60E+00	2.17E-01	6.88E-02	3.19E-01	8.68E+00	1.80E-01	2.47E-03	-1.89E+01	-1.83E+01	-2.03E+01	6.47E-01
99	1.39E-04	1.27E-01	9.04E-04	2.34E+00	3.41E-01	3.56E+00	9.57E+00	6.38E-02	3.78E+00	3.65E-01	6.81E+00	2.98E-01	2.10E-01	-1.86E+01	-1.85E+01	-1.98E+01	7.63E-01
100	3.11E-03	1.23E-01	2.88E-04	2.02E+00	1.32E-01	2.97E+00	7.32E-01	7.16E-02	1.54E-01	1.49E-01	7.10E+00	1.04E-01	3.54E-01	-1.76E+01	-1.82E+01	-1.88E+01	2.98E-02

Table PAR-12. LHS Sampled Values for the Spall Model (50 vectors) Only 1 Replicate

Vector Num.	Parameter			
	SPALLMOD REPIPORE	SPALLMOD REPIPERM	SPALLMOD TENSLSTR	SPALLMOD PARTDIAM
1	5.17E-01	3.97E-13	1.38E+05	4.69E-02
2	3.77E-01	5.77E-14	1.25E+05	3.88E-03
3	6.24E-01	3.90E-14	1.47E+05	7.72E-02
4	6.41E-01	5.49E-14	1.39E+05	2.13E-03
5	4.91E-01	7.22E-14	1.52E+05	1.11E-02
6	6.32E-01	8.81E-13	1.66E+05	2.96E-03
7	5.69E-01	4.28E-14	1.64E+05	2.39E-02
8	6.04E-01	2.42E-14	1.55E+05	3.80E-02
9	5.33E-01	7.55E-13	1.30E+05	1.07E-02
10	6.12E-01	1.03E-13	1.60E+05	7.51E-02
11	4.85E-01	3.05E-13	1.23E+05	5.82E-02
12	5.38E-01	2.81E-13	1.31E+05	6.79E-02
13	4.52E-01	1.27E-12	1.50E+05	5.60E-02
14	4.70E-01	1.72E-12	1.65E+05	1.64E-02
15	4.96E-01	1.00E-12	1.37E+05	3.51E-03
16	3.59E-01	2.74E-14	1.54E+05	4.60E-03
17	4.61E-01	3.46E-14	1.44E+05	4.98E-03
18	3.51E-01	2.62E-13	1.63E+05	4.10E-02
19	4.46E-01	6.33E-14	1.26E+05	4.06E-03
20	5.85E-01	1.96E-13	1.44E+05	2.08E-02
21	4.36E-01	1.10E-13	1.21E+05	8.34E-02
22	6.02E-01	1.82E-12	1.29E+05	6.48E-03
23	3.73E-01	1.18E-13	1.67E+05	1.50E-02
24	4.62E-01	3.53E-13	1.50E+05	1.16E-03
25	5.88E-01	1.24E-12	1.33E+05	1.76E-03

Vector Num.	Parameter			
	SPALLMOD REPIPORE	SPALLMOD REPIPERM	SPALLMOD TENSLSTR	SPALLMOD PARTDIAM
26	3.97E-01	1.76E-13	1.48E+05	2.17E-02
27	6.18E-01	4.75E-14	1.53E+05	3.43E-02
28	4.37E-01	2.13E-13	1.42E+05	1.24E-03
29	4.77E-01	4.51E-13	1.47E+05	1.23E-02
30	4.02E-01	2.89E-14	1.39E+05	1.04E-03
31	5.20E-01	1.64E-13	1.55E+05	1.51E-03
32	6.51E-01	1.39E-12	1.62E+05	8.34E-03
33	6.38E-01	7.16E-13	1.35E+05	2.73E-03
34	3.68E-01	5.05E-13	1.58E+05	2.06E-03
35	3.85E-01	8.31E-13	1.29E+05	9.83E-02
36	5.11E-01	1.40E-13	1.59E+05	5.84E-03
37	5.45E-01	8.09E-14	1.27E+05	1.44E-02
38	4.21E-01	2.04E-12	1.34E+05	1.64E-03
39	5.94E-01	4.58E-13	1.70E+05	4.84E-02
40	5.63E-01	7.35E-14	1.22E+05	2.89E-02
41	5.26E-01	2.31E-12	1.43E+05	3.17E-02
42	4.30E-01	6.55E-13	1.26E+05	3.18E-03
43	3.92E-01	1.13E-12	1.35E+05	7.96E-03
44	4.08E-01	1.55E-12	1.69E+05	2.56E-02
45	5.51E-01	2.23E-13	1.45E+05	1.84E-02
46	5.79E-01	5.84E-13	1.21E+05	5.57E-03
47	5.03E-01	9.51E-14	1.61E+05	1.40E-03
48	4.14E-01	1.28E-13	1.68E+05	9.49E-03
49	5.58E-01	3.53E-14	1.41E+05	7.40E-03
50	6.57E-01	3.24E-13	1.56E+05	2.32E-03

Table PAR-13. Borehole, Blowout and Drill Mud Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BLOWOUT	Material for direct brine release calculations	GAS_MIN	Gas rate cut-off	Constant	mscf/day	1.00E+02
	BLOWOUT	Material for direct brine release calculations	HREPO	Height of repository at burial time in CUTTINGS model	Constant	m	3.96E+00
	BLOWOUT	Material for direct brine release calculations	MAXFLOW	Maximum blowout flow	Constant	s	9.50E+05
	BLOWOUT	Material for direct brine release calculations	MINFLOW	Minimum blowout flow	Constant	s	2.59E+05
	BLOWOUT	Material for direct brine release calculations	PARTDIA	Waste Particle Diameter in CUTTINGS Model	Log uniform	m	2.80E-03
	BLOWOUT	Material for direct brine release calculations	RE_CAST	External drainage radius for the Castile formation	Constant	m	1.14E+02
	BLOWOUT	Material for direct brine release calculations	RGAS	Gas Constant for Hydrogen	Constant	N*m/kg/K	4.12E+03
	BLOWOUT	Material for direct brine release calculations	RHOS	Waste Particle Density in CUTTINGS_S Model	Constant	kg/m^3	2.65E+03
	BLOWOUT	Material for direct brine release calculations	THCK_CAS	Thickness of the Castile Brine Reservoir	Constant	m	1.26E+02
	BLOWOUT	Material for direct brine release calculations	TREPO	Temperature of repository in CUTTINGS model	Constant	K	3.00E+02
	BOREHOLE	Borehole and Fill	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	BOREHOLE	Borehole and Fill	COLDIA	Drill collar diameter in CUTTINGS model	Constant	m	2.03E-01
	BOREHOLE	Borehole and Fill	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	2.64E-09
	BOREHOLE	Borehole and Fill	DIAMMOD	Modern or current diameter	Constant	m	3.11E-01
	BOREHOLE	Borehole and Fill	DOMEGA	Drill string angular velocity (0)	Cumulative	rad/s	Sampled Value
	BOREHOLE	Borehole and Fill	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	BOREHOLE	Borehole and Fill	L1	Drill collar length in CUTTINGS model	Constant	m	1.83E+02
	BOREHOLE	Borehole and Fill	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	BOREHOLE	Borehole and Fill	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	BOREHOLE	Borehole and Fill	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	BOREHOLE	Borehole and Fill	PIPED	Drill pipe diameter in CUTTINGS model	Constant	m	1.14E-01

Table PAR-13. Borehole, Blowout and Drill Mud Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BOREHOLE	Borehole and Fill	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	BOREHOLE	Borehole and Fill	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	9.40E-01
	BOREHOLE	Borehole and Fill	POROSITY	Effective porosity	Constant	NONE	5.00E-02
	BOREHOLE	Borehole and Fill	PRMX_LOG	Log of intrinsic permeability, X-direction	Normal	$\log(m^2)$	-1.25E+01
	BOREHOLE	Borehole and Fill	PRMY_LOG	Log of intrinsic permeability, Y-direction	Normal	$\log(m^2)$	-1.25E+01
	BOREHOLE	Borehole and Fill	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Normal	$\log(m^2)$	-1.25E+01
	BOREHOLE	Borehole and Fill	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	BOREHOLE	Borehole and Fill	SAT_RBRN	Residual Brine Saturation	Constant	NONE	2.00E-01
	BOREHOLE	Borehole and Fill	SAT_RGAS	Residual Gas Saturation	Constant	NONE	2.00E-01
	BOREHOLE	Borehole and Fill	TAUFAIL	Effective shear strength for erosion (rfail)	Log uniform	Pa	Sampled Value
	BOREHOLE	Borehole and Fill	WUF	Unit of Waste	Constant	Curies	2.48E+00
	DRILLMUD	Drilling Mud	DNSFLUID	Brine Density	Cumulative	kg/m^3	1.21E+03
	DRILLMUD	Drilling Mud	VISCO	Viscosity	Cumulative	Pa*s	9.17E-03
	DRILLMUD	Drilling Mud	YLDSTRSS	Yield Stress Point	Cumulative	Pa	4.40E+00

Table PAR-14. Borehole (Concrete Plug) Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CONC_PLG	Concrete Plug, surface and Rustler	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	3.80E-10
	CONC_PLG	Concrete Plug, surface and Rustler	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CONC_PLG	Concrete Plug, surface and Rustler	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CONC_PLG	Concrete Plug, surface and Rustler	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	9.40E-01
	CONC_PLG	Concrete Plug, surface and Rustler	POROSITY	Effective porosity	Constant	NONE	3.20E-01
	CONC_PLG	Concrete Plug, surface and Rustler	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$\log(m^2)$	-1.80E+01
	CONC_PLG	Concrete Plug, surface and Rustler	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$\log(m^2)$	-1.80E+01
	CONC_PLG	Concrete Plug, surface and Rustler	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-15. Borehole (Open) Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BH_OPEN	Borehole Unrestricted	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	BH_OPEN	Borehole Unrestricted	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	BH_OPEN	Borehole Unrestricted	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	BH_OPEN	Borehole Unrestricted	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	BH_OPEN	Borehole Unrestricted	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	BH_OPEN	Borehole Unrestricted	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	BH_OPEN	Borehole Unrestricted	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	BH_OPEN	Borehole Unrestricted	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	BH_OPEN	Borehole Unrestricted	POROSITY	Effective porosity	Constant	NONE	3.20E-01
	BH_OPEN	Borehole Unrestricted	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$log(m^2)$	-9.00E+00
	BH_OPEN	Borehole Unrestricted	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$log(m^2)$	-9.00E+00
	BH_OPEN	Borehole Unrestricted	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$log(m^2)$	-9.00E+00
	BH_OPEN	Borehole Unrestricted	RELP_MOD	Model number, relative permeability model	Constant	NONE	5.00E+00
	BH_OPEN	Borehole Unrestricted	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	BH_OPEN	Borehole Unrestricted	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-16. Borehole (Silty Sand) Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BH_SAND	Borehole filled with silty sand	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	BH_SAND	Borehole filled with silty sand	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	BH_SAND	Borehole filled with silty sand	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	BH_SAND	Borehole filled with silty sand	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	BH_SAND	Borehole filled with silty sand	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	BH_SAND	Borehole filled with silty sand	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	BH_SAND	Borehole filled with silty sand	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	BH_SAND	Borehole filled with silty sand	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	9.40E-01
	BH_SAND	Borehole filled with silty sand	POROSITY	Effective porosity	Constant	NONE	3.20E-01
	BH_SAND	Borehole filled with silty sand	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$log(m^2)$	Sampled Value
	BH_SAND	Borehole filled with silty sand	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$log(m^2)$	Applied Value See BH_SAND PRMX_LOG
	BH_SAND	Borehole filled with silty sand	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$log(m^2)$	Applied Value See BH_SAND PRMX_LOG
	BH_SAND	Borehole filled with silty sand	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	BH_SAND	Borehole filled with silty sand	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	BH_SAND	Borehole filled with silty sand	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-17. Borehole (Creep) Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BH_CREEP	Creep Borehole Fill	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	BH_CREEP	Creep Borehole Fill	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	BH_CREEP	Creep Borehole Fill	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	BH_CREEP	Creep Borehole Fill	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	BH_CREEP	Creep Borehole Fill	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	BH_CREEP	Creep Borehole Fill	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	BH_CREEP	Creep Borehole Fill	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	BH_CREEP	Creep Borehole Fill	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	9.40E-01
	BH_CREEP	Creep Borehole Fill	POROSITY	Effective porosity	Constant	NONE	3.20E-01
	BH_CREEP	Creep Borehole Fill	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$log(m^2)$	-1.35E+01
	BH_CREEP	Creep Borehole Fill	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$log(m^2)$	-1.35E+01
	BH_CREEP	Creep Borehole Fill	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$log(m^2)$	-1.35E+01
	BH_CREEP	Creep Borehole Fill	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	BH_CREEP	Creep Borehole Fill	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	BH_CREEP	Creep Borehole Fill	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-18. DRSPALL Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SPALLMOD	Material developed for DRSPALL	ANNUROUG	Absolute wall roughness of wellbore annulus	Constant	m	5.00E-05
	SPALLMOD	Material developed for DRSPALL	BIOTBETA	Biot's beta for waste	Constant	NONE	1.00E+00
	SPALLMOD	Material developed for DRSPALL	COHESION	Cohesion of waste	Constant	Pa	1.40E+05
	SPALLMOD	Material developed for DRSPALL	DDZPERM	Permeability of drilling-damaged zone (DDZ)	Constant	m2	1.00E-14
	SPALLMOD	Material developed for DRSPALL	DDZTHICK	Thickness of drilling-damaged zone (DDZ)	Constant	m	1.60E-01
	SPALLMOD	Material developed for DRSPALL	DRILRATE	Drill penetration rate through Salado	Constant	m/s	4.45E-03
	SPALLMOD	Material developed for DRSPALL	DRZPERM	DRZ Permeability for DRSPALL	Constant	m^2	1.00E-15
	SPALLMOD	Material developed for DRSPALL	FFSTRESS	Isotropic in-situ stress in waste area	Constant	Pa	1.49E+07
	SPALLMOD	Material developed for DRSPALL	FRICTANG	Friction angle of waste	Constant	deg	4.58E+01
	SPALLMOD	Material developed for DRSPALL	MUDPRATE	Typical volumetric mud pumping rate for drilling in Salado	Constant	(m3)/s	2.02E-02
	SPALLMOD	Material developed for DRSPALL	MUDSOLMX	Solids volume fraction in drill mud that causes choking of flow	Constant	NONE	6.15E-01
	SPALLMOD	Material developed for DRSPALL	MUDSOLVE	Exponent on mud slurry viscosity power law	Constant	NONE	-1.50E+00
	SPALLMOD	Material developed for DRSPALL	PARTDIAM	Particle diameter of disaggregated waste	Loguniform	m	1.00E-02
	SPALLMOD	Material developed for DRSPALL	PIPEID	Inner diameter of drill pipe (where OD = 0.1143 m)	Constant	m	9.72E-02
	SPALLMOD	Material developed for DRSPALL	PIPEROUG	Absolute wall roughness of drill pipe	Constant	m	5.00E-05
	SPALLMOD	Material developed for DRSPALL	POISRAT	Poisson's ratio for waste	Constant	NONE	3.80E-01
	SPALLMOD	Material developed for DRSPALL	REFPRS	Atmospheric pressure at sea level	Constant	Pa	1.02E+05
	SPALLMOD	Material developed for DRSPALL	REPIPERM	Waste permeability to gas local to intrusion borehole	Loguniform	m2	2.40E-13

Table PAR-18. DRSPALL Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SPALLMOD	Material developed for DRSPALL	REPOSTOP	Elevation of roof in excavated area	Constant	m	3.85E+02
	SPALLMOD	Material developed for DRSPALL	SALTDENS	Density of solid cuttings from the Salado	Constant	kg/m3	2.18E+03
	SPALLMOD	Material developed for DRSPALL	SHAPEFAC	Shape factor for disaggregated waste particles	Constant	NONE	1.00E-01
	SPALLMOD	Material developed for DRSPALL	STPDVOLR	Mud ejection rate that turns off drilling	Constant	$(m^3)/s$	1.00E+03
	SPALLMOD	Material developed for DRSPALL	STPPVOLR	Mud ejection rate that turns off mud pump	Constant	$(m^3)/s$	1.00E+03
	SPALLMOD	Material developed for DRSPALL	SURFELEV	Elevation of land surface at WIPP site	Constant	m	1.04E+03
	SPALLMOD	Material developed for DRSPALL	TENSLSTR	Tensile strength of waste	Uniform	Pa	1.45E+05

Table PAR-19. Shaft Material Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CONC_MON	Concrete Monolith	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	CONC_MON	Concrete Monolith	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	6.00E-11
	CONC_MON	Concrete Monolith	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CONC_MON	Concrete Monolith	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CONC_MON	Concrete Monolith	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	CONC_MON	Concrete Monolith	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	CONC_MON	Concrete Monolith	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CONC_MON	Concrete Monolith	PORE_DIS	Brooks-Corey pore distribution parameter	Cumulative	NONE	9.40E-01
	CONC_MON	Concrete Monolith	POROSITY	Effective porosity	Constant	NONE	5.00E-02
	CONC_MON	Concrete Monolith	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$log(m^2)$	-1.40E+01
	CONC_MON	Concrete Monolith	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$log(m^2)$	-1.40E+01
	CONC_MON	Concrete Monolith	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$log(m^2)$	-1.40E+01
	CONC_MON	Concrete Monolith	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CONC_MON	Concrete Monolith	SAT_IBRN	Initial Brine Saturation	Constant	NONE	1.00E+00
	CONC_MON	Concrete Monolith	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.00E-01
	CONC_MON	Concrete Monolith	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	COMP_POR	Pore volume compressibility	Constant	Pa^{-1}	4.28E-09
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01

Table PAR-19. Shaft Material Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	POROSITY	Effective porosity	Constant	NONE	1.13E-01
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	$\log(m^2)$	Sampled Value
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	SAT_IBRN	Initial Brine Saturation	Constant	NONE	5.34E-01
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	COMP_POR	Pore volume compressibility	Constant	Pa^{-1}	4.28E-09
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	POROSITY	Effective porosity	Constant	NONE	1.13E-01
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	$\log(m^2)$	Sampled Value
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	SAT_IBRN	Initial Brine Saturation	Constant	NONE	5.34E-01
	SHFTU	Upper portion of simplified shaft	COMP_POR	Pore volume compressibility	Constant	Pa^{-1}	2.05E-08
	SHFTU	Upper portion of simplified shaft	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	SHFTU	Upper portion of simplified shaft	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	SHFTU	Upper portion of simplified shaft	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01

Table PAR-19. Shaft Material Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SHFTU	Upper portion of simplified shaft	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	SHFTU	Upper portion of simplified shaft	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	SHFTU	Upper portion of simplified shaft	POROSITY	Effective porosity	Constant	NONE	2.91E-01
	SHFTU	Upper portion of simplified shaft	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	$\log(m^2)$	Sampled Value
	SHFTU	Upper portion of simplified shaft	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	SHFTU	Upper portion of simplified shaft	SAT_IBRN	Initial Brine Saturation	Constant	NONE	7.96E-01
	SHFTU	Upper portion of simplified shaft	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	Sampled Value
	SHFTU	Upper portion of simplified shaft	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	Sampled Value

Table PAR-20. Panel Closure Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CONC_PCS	Concrete portion of PCS	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	CONC_PCS	Concrete portion of PCS	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	6.00E-11
	CONC_PCS	Concrete portion of PCS	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CONC_PCS	Concrete portion of PCS	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CONC_PCS	Concrete portion of PCS	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	CONC_PCS	Concrete portion of PCS	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	CONC_PCS	Concrete portion of PCS	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CONC_PCS	Concrete portion of PCS	PORE_DIS	Brooks-Corey pore distribution parameter	Cumulative	NONE	Sampled Value
	CONC_PCS	Concrete portion of PCS	POROSITY	Effective porosity	Constant	NONE	5.00E-02
	CONC_PCS	Concrete portion of PCS	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	$log(m^2)$	Sampled Value
	CONC_PCS	Concrete portion of PCS	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	$log(m^2)$	Applied Value See CONC_PCS PRMX_LOG
	CONC_PCS	Concrete portion of PCS	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	$log(m^2)$	Applied Value See CONC_PCS PRMX_LOG
	CONC_PCS	Concrete portion of PCS	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CONC_PCS	Concrete portion of PCS	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	Sampled Value
	CONC_PCS	Concrete portion of PCS	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	Sampled Value
	DRZ_PCS	DRZ directly above concrete portion of panel closure	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	DRZ_PCS	DRZ directly above concrete portion of panel closure	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	7.41E-10
	DRZ_PCS	DRZ directly above concrete portion of panel closure	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00

Table PAR-20. Panel Closure Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	DRZ_PCS	DRZ directly above concrete portion of panel closure	POROSITY	Effective porosity	Cumulative	NONE	1.29E-02
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	$\log(m^2)$	Sampled Value
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	$\log(m^2)$	Applied Value See DRZ_PCS PRMX_LOG
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	$\log(m^2)$	Applied Value See DRZ_PCS PRMX_LOG
	DRZ_PCS	DRZ directly above concrete portion of panel closure	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	DRZ_PCS	DRZ directly above concrete portion of panel closure	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-21. Santa Rosa Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SANTAROS	Santa Rosa Formation	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	SANTAROS	Santa Rosa Formation	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	1.00E-08
	SANTAROS	Santa Rosa Formation	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	SANTAROS	Santa Rosa Formation	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	SANTAROS	Santa Rosa Formation	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	SANTAROS	Santa Rosa Formation	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	SANTAROS	Santa Rosa Formation	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	SANTAROS	Santa Rosa Formation	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	6.44E-01
	SANTAROS	Santa Rosa Formation	POROSITY	Effective porosity	Constant	NONE	1.75E-01
	SANTAROS	Santa Rosa Formation	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	SANTAROS	Santa Rosa Formation	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.00E+01
	SANTAROS	Santa Rosa Formation	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.00E+01
	SANTAROS	Santa Rosa Formation	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.00E+01
	SANTAROS	Santa Rosa Formation	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	SANTAROS	Santa Rosa Formation	SAT_IBRN	Initial Brine Saturation	Constant	NONE	8.36E-02
	SANTAROS	Santa Rosa Formation	SAT_RBRN	Residual Brine Saturation	Constant	NONE	8.36E-02
	SANTAROS	Santa Rosa Formation	SAT_RGAS	Residual Gas Saturation	Constant	NONE	7.71E-02

Table PAR-22. Dewey Lake Formation

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	DEWYLAKE	Dewey Lake Red Beds	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	DEWYLAKE	Dewey Lake Red Beds	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	1.00E-08
	DEWYLAKE	Dewey Lake Red Beds	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	DEWYLAKE	Dewey Lake Red Beds	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	DEWYLAKE	Dewey Lake Red Beds	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	DEWYLAKE	Dewey Lake Red Beds	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	DEWYLAKE	Dewey Lake Red Beds	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	DEWYLAKE	Dewey Lake Red Beds	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	6.44E-01
	DEWYLAKE	Dewey Lake Red Beds	POROSITY	Effective porosity	Student	NONE	1.43E-01
	DEWYLAKE	Dewey Lake Red Beds	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.63E+01
	DEWYLAKE	Dewey Lake Red Beds	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.63E+01
	DEWYLAKE	Dewey Lake Red Beds	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.63E+01
	DEWYLAKE	Dewey Lake Red Beds	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	DEWYLAKE	Dewey Lake Red Beds	SAL_USAT	Average saturation, unsaturated zones	Constant	NONE	8.36E-02
	DEWYLAKE	Dewey Lake Red Beds	SAT_IBRN	Initial Brine Saturation	Constant	NONE	1.00E+00
	DEWYLAKE	Dewey Lake Red Beds	SAT_RBRN	Residual Brine Saturation	Constant	NONE	8.36E-02
	DEWYLAKE	Dewey Lake Red Beds	SAT_RGAS	Residual Gas Saturation	Constant	NONE	7.71E-02

Table PAR-23. Forty-Niner Member of the Rustler Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	FORTYNIN	Forty Niner Member	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	FORTYNIN	Forty Niner Member	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	FORTYNIN	Forty Niner Member	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	FORTYNIN	Forty Niner Member	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	FORTYNIN	Forty Niner Member	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	FORTYNIN	Forty Niner Member	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	FORTYNIN	Forty Niner Member	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	FORTYNIN	Forty Niner Member	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	FORTYNIN	Forty Niner Member	POROSITY	Effective porosity	Student	NONE	8.20E-02
	FORTYNIN	Forty Niner Member	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$log(m^2)$	-3.50E+01
	FORTYNIN	Forty Niner Member	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$log(m^2)$	-3.50E+01
	FORTYNIN	Forty Niner Member	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$log(m^2)$	-3.50E+01
	FORTYNIN	Forty Niner Member	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	FORTYNIN	Forty Niner Member	SAT_RBRN	Residual Brine Saturation	Constant	NONE	2.00E-01
	FORTYNIN	Forty Niner Member	SAT_RGAS	Residual Gas Saturation	Constant	NONE	2.00E-01

Table PAR-24. Magenta Member of the Rustler Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	MAGENTA	Magenta Member	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	MAGENTA	Magenta Member	COMP_RCK	Bulk Compressibility	Student	Pa^{-1}	2.64E-10
	MAGENTA	Magenta Member	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	MAGENTA	Magenta Member	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	MAGENTA	Magenta Member	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	MAGENTA	Magenta Member	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	MAGENTA	Magenta Member	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	MAGENTA	Magenta Member	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	6.44E-01
	MAGENTA	Magenta Member	POROSITY	Effective porosity	Student	NONE	1.38E-01
	MAGENTA	Magenta Member	PRESSURE	Brine far-field pore pressure	Constant	Pa	9.47E+05
	MAGENTA	Magenta Member	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.52E+01
	MAGENTA	Magenta Member	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.52E+01
	MAGENTA	Magenta Member	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.52E+01
	MAGENTA	Magenta Member	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	MAGENTA	Magenta Member	SAT_RBRN	Residual Brine Saturation	Constant	NONE	8.36E-02
	MAGENTA	Magenta Member	SAT_RGAS	Residual Gas Saturation	Constant	NONE	7.71E-02

Table PAR-25. Tamarisk Member of the Rustler Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	TAMARISK	Tamarisk Member	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	TAMARISK	Tamarisk Member	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	TAMARISK	Tamarisk Member	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	TAMARISK	Tamarisk Member	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	TAMARISK	Tamarisk Member	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	TAMARISK	Tamarisk Member	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	TAMARISK	Tamarisk Member	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	TAMARISK	Tamarisk Member	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	TAMARISK	Tamarisk Member	POROSITY	Effective porosity	Student	NONE	6.40E-02
	TAMARISK	Tamarisk Member	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$log(m^2)$	-3.50E+01
	TAMARISK	Tamarisk Member	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$log(m^2)$	-3.50E+01
	TAMARISK	Tamarisk Member	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$log(m^2)$	-3.50E+01
	TAMARISK	Tamarisk Member	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	TAMARISK	Tamarisk Member	SAT_RBRN	Residual Brine Saturation	Constant	NONE	2.00E-01
	TAMARISK	Tamarisk Member	SAT_RGAS	Residual Gas Saturation	Constant	NONE	2.00E-01

Table PAR-26. Culebra Member of the Rustler Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CULEBRA	Culebra member of the Rustler formation	APOROS	Culebra Advective Porosity	Log uniform	NONE	Sampled Value
	CULEBRA	Culebra member of the Rustler formation	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	CULEBRA	Culebra member of the Rustler formation	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	1.00E-10
	CULEBRA	Culebra member of the Rustler formation	DISP_L	Longitudinal dispersivity	Constant	m	0.00E+00
	CULEBRA	Culebra member of the Rustler formation	DISPT_L	Transverse dispersivity	Constant	m	0.00E+00
	CULEBRA	Culebra member of the Rustler formation	DNSGRAIN	Material Grain Density	Constant	kg/m^3	2.82E+03
	CULEBRA	Culebra member of the Rustler formation	DPOROS	Diffusive Porosity for Culebra Dolomite	Cumulative	NONE	Sampled Value
	CULEBRA	Culebra member of the Rustler formation	DTORT	Diffusive Tortuosity	Constant	NONE	1.10E-01
	CULEBRA	Culebra member of the Rustler formation	FTORT	Fracture Tortuosity	Constant	NONE	1.00E+00
	CULEBRA	Culebra member of the Rustler formation	HMBLKLT	Culebra Half Matrix-Block Length	Uniform	m	Sampled Value
	CULEBRA	Culebra member of the Rustler formation	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CULEBRA	Culebra member of the Rustler formation	MINP_FAC	Mining Transmissivity Multiplier	Uniform	NONE	Sampled Value
	CULEBRA	Culebra member of the Rustler formation	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CULEBRA	Culebra member of the Rustler formation	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	CULEBRA	Culebra member of the Rustler formation	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	CULEBRA	Culebra member of the Rustler formation	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CULEBRA	Culebra member of the Rustler formation	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	6.44E-01

Table PAR-26. Culebra Member of the Rustler Formation Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CULEBRA	Culebra member of the Rustler formation	POROSITY	Effective porosity	Constant	NONE	1.51E-01
	CULEBRA	Culebra member of the Rustler formation	PRESSURE	Brine far-field pore pressure	Constant	Pa	9.14E+05
	CULEBRA	Culebra member of the Rustler formation	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.31E+01
	CULEBRA	Culebra member of the Rustler formation	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.31E+01
	CULEBRA	Culebra member of the Rustler formation	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.31E+01
	CULEBRA	Culebra member of the Rustler formation	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CULEBRA	Culebra member of the Rustler formation	SAT_IBRN	Initial Brine Saturation	Constant	NONE	1.00E+00
	CULEBRA	Culebra member of the Rustler formation	SAT_RBRN	Residual Brine Saturation	Constant	NONE	8.36E-02
	CULEBRA	Culebra member of the Rustler formation	SAT_RGAS	Residual Gas Saturation	Constant	NONE	7.71E-02
	CULEBRA	Culebra member of the Rustler formation	SKIN_RES	Skin Resistance	Constant	NONE	0.00E+00

Table PAR-27. Los Medanos (Unnamed Lower) Member of the Rustler Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	UNNAMED	Unnamed Lower Member of Rustler Formation	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	UNNAMED	Unnamed Lower Member of Rustler Formation	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	UNNAMED	Unnamed Lower Member of Rustler Formation	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	UNNAMED	Unnamed Lower Member of Rustler Formation	POROSITY	Effective porosity	Student	NONE	1.81E-01
	UNNAMED	Unnamed Lower Member of Rustler Formation	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-3.50E+01
	UNNAMED	Unnamed Lower Member of Rustler Formation	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-3.50E+01
	UNNAMED	Unnamed Lower Member of Rustler Formation	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-3.50E+01
	UNNAMED	Unnamed Lower Member of Rustler Formation	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	SAT_RBRN	Residual Brine Saturation	Constant	NONE	2.00E-01
	UNNAMED	Unnamed Lower Member of Rustler Formation	SAT_RGAS	Residual Gas Saturation	Constant	NONE	2.00E-01

Table PAR-28. Salado Formation – Intact Halite – Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_HALITE	Salado halite, intact	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	S_HALITE	Salado halite, intact	COMP_RCK	Bulk Compressibility	Uniform	Pa^{-1}	Sampled Value
	S_HALITE	Salado halite, intact	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	S_HALITE	Salado halite, intact	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	S_HALITE	Salado halite, intact	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	S_HALITE	Salado halite, intact	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	S_HALITE	Salado halite, intact	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	S_HALITE	Salado halite, intact	PORE_DIS	Brooks-Corey pore distribution parameter	Cumulative	NONE	7.00E-01
	S_HALITE	Salado halite, intact	POROSITY	Effective porosity	Cumulative	NONE	Sampled Value
	S_HALITE	Salado halite, intact	PRESSURE	Brine far-field pore pressure	Uniform	Pa	Sampled Value
	S_HALITE	Salado halite, intact	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$\log(m^2)$	Sampled Value
	S_HALITE	Salado halite, intact	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$\log(m^2)$	Applied Value See S_HALITE PRMX_LOG
	S_HALITE	Salado halite, intact	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$\log(m^2)$	Applied Value See S_HALITE PRMX_LOG
	S_HALITE	Salado halite, intact	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00
	S_HALITE	Salado halite, intact	SAT_RBRN	Residual Brine Saturation	Uniform	NONE	3.00E-01
	S_HALITE	Salado halite, intact	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01

Table PAR-29. Salado Formation – Brine – Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BRINESAL	Salado Brine	COMPRES	Brine Compressibility	Constant	Pa^{-1}	3.10E-10
	BRINESAL	Salado Brine	DNSFLUID	Brine Density	Constant	kg/m^3	1.22E+03
	BRINESAL	Salado Brine	REF_PRES	Reference pressure for porosity	Constant	Pa	1.01E+05
	BRINESAL	Salado Brine	REF_TEMP	Reference Temperature	Constant	K	3.00E+02
	BRINESAL	Salado Brine	VISCO	Viscosity	Constant	Pa*s	2.10E-03
	BRINESAL	Salado Brine	WTF	Mass fraction of salt in brine	Student	NONE	3.24E-01

Table PAR-30. Salado Formation – Marker Bed 138 – Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_MB138	Salado marker bed 138, intact and fractured	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	COMP_RCK	Bulk Compressibility	Student	Pa^{-1}	8.26E-11
	S_MB138	Salado marker bed 138, intact and fractured	DPHIMAX	Incremental increase in porosity relative to intact conditions	Constant	NONE	3.90E-02
	S_MB138	Salado marker bed 138, intact and fractured	IFRX	Index for fracture perm. enhancement in X-direction	Constant	NONE	1.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	IFRY	Index for fracture perm. enhancement in Y-direction	Constant	NONE	1.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	IFRZ	Index for fracture perm. enhancement in Z-direction	Constant	NONE	0.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	KMAXLOG	Log of Maximum Permeability in Altered Anhydrite Flow Model Anhydrites	Constant	$log(m^2)$	-9.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	S_MB138	Salado marker bed 138, intact and fractured	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	S_MB138	Salado marker bed 138, intact and fractured	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	S_MB138	Salado marker bed 138, intact and fractured	PF_DELTA	Incremental pressure for full fracture development	Constant	Pa	3.80E+06
	S_MB138	Salado marker bed 138, intact and fractured	PI_DELTA	Fracture initiation pressure increment	Constant	Pa	2.00E+05
	S_MB138	Salado marker bed 138, intact and fractured	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	S_MB138	Salado marker bed 138, intact and fractured	PORE_DIS	Brooks-Corey pore distribution parameter	Student	NONE	6.44E-01
	S_MB138	Salado marker bed 138, intact and fractured	POROSITY	Effective porosity	Student	NONE	1.10E-02
	S_MB138	Salado marker bed 138, intact and fractured	PRMX_LOG	Log of intrinsic permeability, X-direction	Student	$log(m^2)$	-1.89E+01
	S_MB138	Salado marker bed 138, intact and fractured	PRMY_LOG	Log of intrinsic permeability, Y-direction	Student	$log(m^2)$	-1.89E+01

Table PAR-30. Salado Formation – Marker Bed 138 – Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_MB138	Salado marker bed 138, intact and fractured	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Student	$\log(m^2)$	-1.89E+01
	S_MB138	Salado marker bed 138, intact and fractured	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	SAT_RBRN	Residual Brine Saturation	Student	NONE	8.36E-02
	S_MB138	Salado marker bed 138, intact and fractured	SAT_RGAS	Residual Gas Saturation	Student	NONE	7.71E-02
	S_MB139	Salado marker bed 139, intact and fractured	COMP_RCK	Bulk Compressibility	Student	Pa^{-1}	Sampled Value

Table PAR-31. Salado Formation – Marker Bed 139 – Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CONC_PLG	Concrete Plug, surface and Rustler	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	log(m^2)	Sampled Value
	S_MB139	Salado marker bed 139, intact and fractured	BKLINK	Klinkenberg B Correction Parameters for H2 gas	Constant	Pa	2.71E-01
	S_MB139	Salado marker bed 139, intact and fractured	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	DPHIMAX	Incremental increase in porosity relative to intact conditions	Constant	NONE	3.90E-02
	S_MB139	Salado marker bed 139, intact and fractured	EXPKLINK	Klinkenberg b correction parameters for H2 gas	Constant	NONE	-3.41E-01
	S_MB139	Salado marker bed 139, intact and fractured	IFRX	Index for fracture perm. enhancement in X-direction	Constant	NONE	1.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	IFRY	Index for fracture perm. enhancement in Y-direction	Constant	NONE	1.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	IFRZ	Index for fracture perm. enhancement in Z-direction	Constant	NONE	0.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	KMAXLOG	Log of Maximum Permeability in Altered Anhydrite Flow Model Anhydrites	Constant	log(m^2)	-9.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	S_MB139	Salado marker bed 139, intact and fractured	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	S_MB139	Salado marker bed 139, intact and fractured	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	S_MB139	Salado marker bed 139, intact and fractured	PF_DELTA	Incremental pressure for full fracture development	Constant	Pa	3.80E+06
	S_MB139	Salado marker bed 139, intact and fractured	PI_DELTA	Fracture initiation pressure increment	Constant	Pa	2.00E+05
	S_MB139	Salado marker bed 139, intact and fractured	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	S_MB139	Salado marker bed 139, intact and fractured	PORE_DIS	Brooks-Corey pore distribution parameter	Student	NONE	Sampled Value
	S_MB139	Salado marker bed 139, intact and fractured	POROSITY	Effective porosity	Student	NONE	1.10E-02

Table PAR-31. Salado Formation – Marker Bed 139 – Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_MB139	Salado marker bed 139, intact and fractured	PRMX_LOG	Log of intrinsic permeability, X-direction	Student	$\log(m^2)$	Sampled Value
	S_MB139	Salado marker bed 139, intact and fractured	PRMY_LOG	Log of intrinsic permeability, Y-direction	Student	$\log(m^2)$	-1.89E+01
	S_MB139	Salado marker bed 139, intact and fractured	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Student	$\log(m^2)$	-1.89E+01
	S_MB139	Salado marker bed 139, intact and fractured	RELP_MOD	Model number, relative permeability model	Delta	NONE	Sampled Value
	S_MB139	Salado marker bed 139, intact and fractured	SAT_RBRN	Residual Brine Saturation	Student	NONE	Sampled Value
	S_MB139	Salado marker bed 139, intact and fractured	SAT_RGAS	Residual Gas Saturation	Student	NONE	Sampled Value

Table PAR-32. Salado Formation – Anhydrite a and b, Intact and Fractured – Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	COMP_RCK	Bulk Compressibility	Student	Pa^{-1}	8.26E-11
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	DPHIMAX	Incremental increase in porosity relative to intact conditions	Constant	NONE	2.39E-01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	IFRX	Index for fracture perm. enhancement in X-direction	Constant	NONE	1.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	IFRY	Index for fracture perm. enhancement in Y-direction	Constant	NONE	1.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	IFRZ	Index for fracture perm. enhancement in Z-direction	Constant	NONE	0.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	KMAXLOG	Log of Maximum Permeability in Altered Anhydrite Flow Model Anhydrites	Constant	$log(m^2)$	-9.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PF_DELTA	Incremental pressure for full fracture development	Constant	Pa	3.80E+06
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PI_DELTA	Fracture initiation pressure increment	Constant	Pa	2.00E+05
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PORE_DIS	Brooks-Corey pore distribution parameter	Student	NONE	6.44E-01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	POROSITY	Effective porosity	Student	NONE	1.10E-02
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PRMX_LOG	Log of intrinsic permeability, X-direction	Student	$log(m^2)$	-1.89E+01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PRMY_LOG	Log of intrinsic permeability, Y-direction	Student	$log(m^2)$	-1.89E+01

Table PAR-32. Salado Formation – Anhydrite a and b, Intact and Fractured – Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Student	log(m^2)	-1.89E+01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	SAT_RBRN	Residual Brine Saturation	Student	NONE	8.36E-02
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	SAT_RGAS	Residual Gas Saturation	Student	NONE	7.71E-02

Table PAR-33. Disturbed Rock Zone Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	7.41E-10
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	POROSITY	Effective porosity	Cumulative	NONE	1.29E-02
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.70E+01
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.70E+01
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.70E+01
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	7.41E-10
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00

Table PAR-33. Disturbed Rock Zone Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	POROSITY	Effective porosity	Cumulative	NONE	1.29E-02
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$\log(m^2)$	Sampled Value
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$\log(m^2)$	Applied Value See DRZ-1 PRMX_LOG
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$\log(m^2)$	Applied Value See DRZ_1 PRMX_LOG
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-34. Waste Area and Waste Material Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	WAS_AREA	Waste emplacement area and waste	ABSROUGH	Absolute roughness of material	Uniform	m	2.50E-02
	WAS_AREA	Waste emplacement area and waste	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	WAS_AREA	Waste emplacement area and waste	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	WAS_AREA	Waste emplacement area and waste	DCELLCHW	Average density of cellulosics in CH waste	Constant	kg/m^3	5.80E+01
	WAS_AREA	Waste emplacement area and waste	DCELLRHW	Average density of cellulosics in RH waste	Constant	kg/m^3	4.50E+00
	WAS_AREA	Waste emplacement area and waste	DIRNCCHW	Bulk density of iron containers, CH waste	Constant	kg/m^3	1.70E+02
	WAS_AREA	Waste emplacement area and waste	DIRNCRHW	Bulk density of iron containers, RH waste	Constant	kg/m^3	4.80E+02
	WAS_AREA	Waste emplacement area and waste	DIRONCHW	Average density of iron-based material in CH waste	Constant	kg/m^3	1.10E+02
	WAS_AREA	Waste emplacement area and waste	DIRONRHW	Average density of iron-based material in RH waste	Constant	kg/m^3	1.10E+02
	WAS_AREA	Waste emplacement area and waste	DPLASCHW	Average density of plastics in CH waste	Constant	kg/m^3	4.20E+01
	WAS_AREA	Waste emplacement area and waste	DPLASRHW	Average density of plastics in CH waste	Constant	kg/m^3	4.90E+00
	WAS_AREA	Waste emplacement area and waste	DPLSCCHW	Bulk density of plastic liners, CH waste	Constant	kg/m^3	1.60E+01
	WAS_AREA	Waste emplacement area and waste	DPLSCRHW	Bulk density of plastic liners, RH waste	Constant	kg/m^3	1.40E+00
	WAS_AREA	Waste emplacement area and waste	DRUBBCHW	Average density of rubber in CH waste	Constant	kg/m^3	1.40E+01
	WAS_AREA	Waste emplacement area and waste	DRUBBRHW	Average density of rubber in RH waste	Constant	kg/m^3	3.10E+00
	WAS_AREA	Waste emplacement area and waste	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	WAS_AREA	Waste emplacement area and waste	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	WAS_AREA	Waste emplacement area and waste	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00

Table PAR-34. Waste Area and Waste Material Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	WAS_AREA	Waste emplacement area and waste	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	WAS_AREA	Waste emplacement area and waste	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	WAS_AREA	Waste emplacement area and waste	PORE_DIS	Brooks-Corey pore distribution parameter	Cumulative	NONE	2.89E+00
	WAS_AREA	Waste emplacement area and waste	POROSITY	Effective porosity	Constant	NONE	8.48E-01
	WAS_AREA	Waste emplacement area and waste	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.26E+01
	WAS_AREA	Waste emplacement area and waste	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.26E+01
	WAS_AREA	Waste emplacement area and waste	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.26E+01
	WAS_AREA	Waste emplacement area and waste	PROBDEG	Probability of plastics and rubber biodegradation in event of microbial gas generation	Delta	NONE	Sampled Value
	WAS_AREA	Waste emplacement area and waste	PTHRESH	Capillary threshold displacement pressure	Constant	Pa	8.00E+06
	WAS_AREA	Waste emplacement area and waste	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	WAS_AREA	Waste emplacement area and waste	SAT_IBRN	Initial Brine Saturation	Constant	NONE	1.50E-02
	WAS_AREA	Waste emplacement area and waste	SAT_RBRN	Residual Brine Saturation	Uniform	NONE	Sampled Value
	WAS_AREA	Waste emplacement area and waste	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	Sampled Value
	WAS_AREA	Waste emplacement area and waste	SAT_WICK	Index for computing wicking	Uniform	NONE	Sampled Value
	WAS_AREA	Waste emplacement area and waste	VOLCHW	BIR total volume of CH waste	Constant	m^3	1.69E+05
	WAS_AREA	Waste emplacement area and waste	VOLRHW	BIR total volume of RH waste	Constant	m^3	7.08E+03

Table PAR-35 Waste Chemistry Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	AM	Americium	CAPMIC	Maximum Concentration of Actinide on Microbe Colloids	Constant	moles/liter	1.00E+00
	AM	Americium	CONCINT	Actinide Concentration with Mobile Actinide Intrinsic Colloids	Constant	moles/liter	0.00E+00
	AM	Americium	CONCMIN	Actinide Concentration with Mobile Mineral Fragment Colloids	Constant	moles/liter	2.60E-08
	AM	Americium	PROPMIC	Moles of Actinide Mobilized on Microbe Colloids per Moles Dissolved	Constant	NONE	3.60E+00
	AM+3	Americium III	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	3.00E-10
	AM+3	Americium III	MKD_AM	Matrix Partition Coefficient for Americium	Log uniform	m^3/kg	Sampled Value
	NP	Neptunium	CAPHUM	Maximum Concentration of Actinide with Mobile Humic Colloids	Constant	moles/liter	1.10E-05
	NP	Neptunium	CAPMIC	Maximum Concentration of Actinide on Microbe Colloids	Constant	moles/liter	2.70E-03
	NP	Neptunium	CONCINT	Actinide Concentration with Mobile Actinide Intrinsic Colloids	Constant	moles/liter	0.00E+00
	NP	Neptunium	CONCMIN	Actinide Concentration with Mobile Mineral Fragment Colloids	Constant	moles/liter	2.60E-08
	NP	Neptunium	PROPMIC	Moles of Actinide Mobilized on Microbe Colloids per Moles Dissolved	Constant	NONE	1.20E+01
	PHUMOX3	Proportionality Constant, +3 State, Humic Colloids	PHUMCIM	Proportionality Const., Humic Colloids, Castile Brine, MgO controls pH	Cumulative	NONE	Sampled Value
	PHUMOX3	Proportionality Constant, +3 State, Humic Colloids	PHUMSIM	Proportionality Const. Of Actinides in Salado Brine w/Humic Colloids, Inorganic	Constant	NONE	1.90E-01
	PHUMOX4	Proportionality constant with humic colloids for a	PHUMCIM	Proportionality Const., Humic Colloids, Castile Brine, MgO controls pH	Constant	NONE	6.30E+00
	PHUMOX4	Proportionality constant with humic colloids for a	PHUMSIM	Proportionality Const. Of Actinides in Salado Brine w/Humic Colloids, Inorganic	Constant	NONE	6.30E+00
	PHUMOX5	Proportionality constant with humic colloids for a	PHUMCIM	Proportionality Const., Humic Colloids, Castile Brine, MgO controls pH	Constant	NONE	7.40E-03

Table PAR-35. Waste Chemistry Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	PHUMOX5	Proportionality constant with humic colloids for a	PHUMSIM	Proportionality Const. Of Actinides in Salado Brine w/Humic Colloids, Inorganic	Constant	NONE	9.10E-04
	PHUMOX6	Proportionality constant with humic colloids for a	PHUMCIM	Proportionality Const., Humic Colloids, Castile Brine, MgO controls pH	Constant	NONE	5.10E-01
	PHUMOX6	Proportionality constant with humic colloids for a	PHUMSIM	Proportionality Const. Of Actinides in Salado Brine w/Humic Colloids, Inorganic	Constant	NONE	1.20E-01
	PU	Plutonium	CAPHUM	Maximum Concentration of Actinide with Mobile Humic Colloids	Constant	moles/liter	1.10E-05
	PU	Plutonium	CAPMIC	Maximum Concentration of Actinide on Microbe Colloids	Constant	moles/liter	6.80E-05
	PU	Plutonium	CONCINT	Actinide Concentration with Mobile Actinide Intrinsic Colloids	Constant	moles/liter	1.00E-09
	PU	Plutonium	CONCMIN	Actinide Concentration with Mobile Mineral Fragment Colloids	Constant	moles/liter	2.60E-08
	PU	Plutonium	PROPMIC	Moles of Actinide Mobilized on Microbe Colloids per Moles Dissolved	Constant	NONE	3.00E-01
	PU+3	Plutonium III	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	3.00E-10
	PU+3	Plutonium III	MKD_PU	Matrix Partition Coefficient for Plutonium	Log uniform	m^3/kg	Sampled Value
	PU+4	Plutonium IV	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	1.53E-10
	PU+4	Plutonium IV	MKD_PU	Matrix Partition Coefficient for Plutonium	Log uniform	m^3/kg	Sampled Value
	SOLAM3	Solubility Multiplier for Am+3	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLAM3	Solubility Multiplier for Am+3	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLMOD3	Oxidation state III model	SOLCOC	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	1.77E-07
	SOLMOD3	Oxidation state III model	SOLCOH	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	1.69E-07

Table PAR-35. Waste Chemistry Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SOLMOD3	Oxidation state III model	SOLSOC	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	3.07E-07
	SOLMOD3	Oxidation state III model	SOLSOH	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	3.07E-07
	SOLMOD4	Oxidation state IV model	SOLCOC	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	5.84E-09
	SOLMOD4	Oxidation state IV model	SOLCOH	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	2.47E-08
	SOLMOD4	Oxidation state IV model	SOLSOC	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	1.24E-08
	SOLMOD4	Oxidation state IV model	SOLSOH	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	1.19E-08
	SOLMOD5	Oxidation state V model	SOLCOC	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	2.13E-05
	SOLMOD5	Oxidation state V model	SOLCOH	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	5.08E-06
	SOLMOD5	Oxidation state V model	SOLSOC	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	9.72E-07
	SOLMOD5	Oxidation state V model	SOLSOH	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	1.02E-06
	SOLMOD6	Oxidation state VI model	SOLCOC	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	8.80E-06
	SOLMOD6	Oxidation state VI model	SOLCOH	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	8.80E-06
	SOLMOD6	Oxidation state VI model	SOLSOC	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	8.70E-06
	SOLMOD6	Oxidation state VI model	SOLSOH	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	8.70E-06

Table PAR-35. Waste Chemistry Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SOLPU3	Solubility Multiplier for Pu+3	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLPU3	Solubility Multiplier for Pu+3	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLPU4	Solubility Multiplier for Pu+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLPU4	Solubility Multiplier for Pu+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLTH4	Solubility Multiplier for Th+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLTH4	Solubility Multiplier for Th+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLU4	Solubility Multiplier for U+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLU4	Solubility Multiplier for U+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLU6	Solubility Multiplier for U+6	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLU6	Solubility Multiplier for U+6	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value

Table PAR-35. Waste Chemistry Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	TH	Thorium	CAPHUM	Maximum Concentration of Actinide with Mobile Humic Colloids	Constant	moles/liter	1.10E-05
	TH	Thorium	CAPMIC	Maximum Concentration of Actinide on Microbe Colloids	Constant	moles/liter	1.90E-03
	TH	Thorium	CONCINT	Actinide Concentration with Mobile Actinide Intrinsic Colloids	Constant	moles/liter	0.00E+00
	TH	Thorium	CONCMIN	Actinide Concentration with Mobile Mineral Fragment Colloids	Constant	moles/liter	2.60E-08
	TH	Thorium	PROPMIC	Moles of Actinide Mobilized on Microbe Colloids per Moles Dissolved	Constant	NONE	3.10E+00
	TH+4	Thorium IV	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	1.53E-10
	TH+4	Thorium IV	MKD_TH	Matrix Partition Coefficient for Thorium	Log uniform	m^3/kg	Sampled Value
	U	Uranium	CAPHUM	Maximum Concentration of Actinide with Mobile Humic Colloids	Constant	moles/liter	1.10E-05
	U	Uranium	CAPMIC	Maximum Concentration of Actinide on Microbe Colloids	Constant	moles/liter	2.10E-03
	U	Uranium	CONCINT	Actinide Concentration with Mobile Actinide Intrinsic Colloids	Constant	moles/liter	0.00E+00
	U	Uranium	CONCMIN	Actinide Concentration with Mobile Mineral Fragment Colloids	Constant	moles/liter	2.60E-08
	U	Uranium	PROPMIC	Moles of Actinide Mobilized on Microbe Colloids per Moles Dissolved	Constant	NONE	2.10E-03
	U+4	Uranium IV	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	1.53E-10
	U+4	Uranium IV	MKD_U	Matrix Partition Coefficient for Uranium	Log uniform	m^3/kg	Sampled Value
	U+6	Uranium VI	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	4.26E-10
	U+6	Uranium VI	MKD_U	Matrix Partition Coefficient for Uranium	Log uniform	m^3/kg	Sampled Value

Table PAR-36. Radionuclide Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	AM241	Americium 241	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.41E-01
	AM241	Americium 241	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	AM241	Americium 241	HALFLIFE	Halflife	Constant	s	1.36E+10
	AM243	Americium 243	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.43E-01
	AM243	Americium 243	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	AM243	Americium 243	HALFLIFE	Halflife	Constant	s	2.33E+11
	CF252	Californium 252	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.52E-01
	CF252	Californium 252	EPAREL	EPA Release Limit	Constant	Curies/wuf	0.00E+00
	CF252	Californium 252	HALFLIFE	Halflife	Constant	s	8.33E+07
	CM243	Curium 243	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.43E-01
	CM243	Curium 243	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	CM243	Curium 243	HALFLIFE	Halflife	Constant	s	8.99E+08
	CM244	Curium 244	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.44E-01
	CM244	Curium 244	EPAREL	EPA Release Limit	Constant	Curies/wuf	0.00E+00
	CM244	Curium 244	HALFLIFE	Halflife	Constant	s	5.72E+08
	CM245	Curium 245	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.45E-01
	CM245	Curium 245	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	CM245	Curium 245	HALFLIFE	Halflife	Constant	s	2.68E+11
	CM248	Curium 248	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.48E-01
	CM248	Curium 248	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	CM248	Curium 248	HALFLIFE	Halflife	Constant	s	1.07E+13
	CS137	Cesium 137	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	1.37E-01
	CS137	Cesium 137	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+03
	CS137	Cesium 137	HALFLIFE	Halflife	Constant	s	9.47E+08
	NP237	Neptunium 237	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.37E-01
	NP237	Neptunium 237	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	NP237	Neptunium 237	HALFLIFE	Halflife	Constant	s	6.75E+13
	PA231	Protactinium 231	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.31E-01
	PA231	Protactinium 231	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PA231	Protactinium 231	HALFLIFE	Halflife	Constant	s	1.03E+12
	PB210	Lead 210	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.10E-01
	PB210	Lead 210	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02

Table PAR-36. Radionuclide Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	PB210	Lead 210	HALFLIFE	Halflife	Constant	s	7.04E+08
	PM147	Promethium 147	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	1.47E-01
	PM147	Promethium 147	EPAREL	EPA Release Limit	Constant	Curies/wuf	0.00E+00
	PM147	Promethium 147	HALFLIFE	Halflife	Constant	s	8.28E+07
	PU238	Plutonium 238	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.38E-01
	PU238	Plutonium 238	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PU238	Plutonium 238	HALFLIFE	Halflife	Constant	s	2.77E+09
	PU239	Plutonium 239	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.39E-01
	PU239	Plutonium 239	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PU239	Plutonium 239	HALFLIFE	Halflife	Constant	s	7.59E+11
	PU240	Plutonium 240	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.40E-01
	PU240	Plutonium 240	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PU240	Plutonium 240	HALFLIFE	Halflife	Constant	s	2.06E+11
	PU241	Plutonium 241	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.41E-01
	PU241	Plutonium 241	EPAREL	EPA Release Limit	Constant	Curies/wuf	0.00E+00
	PU241	Plutonium 241	HALFLIFE	Halflife	Constant	s	4.54E+08
	PU242	Plutonium 242	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.42E-01
	PU242	Plutonium 242	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PU242	Plutonium 242	HALFLIFE	Halflife	Constant	s	1.22E+13
	PU244	Plutonium 244	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.44E-01
	PU244	Plutonium 244	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PU244	Plutonium 244	HALFLIFE	Halflife	Constant	s	2.61E+15
	RA226	Radium 226	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.26E-01
	RA226	Radium 226	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	RA226	Radium 226	HALFLIFE	Halflife	Constant	s	5.05E+10
	RA228	Radium 228	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.28E-01
	RA228	Radium 228	EPAREL	EPA Release Limit	Constant	Curies/wuf	0.00E+00
	RA228	Radium 228	HALFLIFE	Halflife	Constant	s	2.11E+08
	SR90	Strontium 90	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	8.99E-02
	SR90	Strontium 90	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+03
	SR90	Strontium 90	HALFLIFE	Halflife	Constant	s	9.19E+08
	TH229	Thorium 229	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.29E-01
	TH229	Thorium 229	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02

Table PAR-36. Radionuclide Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	TH229	Thorium 229	HALFLIFE	Halflife	Constant	s	2.32E+11
	TH230	Thorium 230	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.30E-01
	TH230	Thorium 230	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+01
	TH230	Thorium 230	HALFLIFE	Halflife	Constant	s	2.43E+12
	TH232	Thorium 232	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.32E-01
	TH232	Thorium 232	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+01
	TH232	Thorium 232	HALFLIFE	Halflife	Constant	s	4.43E+17
	U233	Uranium 233	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.33E-01
	U233	Uranium 233	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	U233	Uranium 233	HALFLIFE	Halflife	Constant	s	5.00E+12
	U234	Uranium 234	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.34E-01
	U234	Uranium 234	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	U234	Uranium 234	HALFLIFE	Halflife	Constant	s	7.72E+12
	U235	Uranium 235	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.35E-01
	U235	Uranium 235	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	U235	Uranium 235	HALFLIFE	Halflife	Constant	s	2.22E+16
	U236	Uranium 236	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.36E-01
	U236	Uranium 236	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	U236	Uranium 236	HALFLIFE	Halflife	Constant	s	7.39E+14
	U238	Uranium 238	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.38E-01
	U238	Uranium 238	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	U238	Uranium 238	HALFLIFE	Halflife	Constant	s	1.41E+17

Table PAR-37. Isotope Inventory

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	AM241	Americium 241	INVCHD	Inventory of Contact Handled Design	Constant	Curies	4.42E+05
	AM241	Americium 241	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.58E+04
	AM241L	Americium 241 Lumped with Plutonium 241	INVCHD	Inventory of Contact Handled Design	Constant	Curies	4.59E+05
	AM241L	Americium 241 Lumped with Plutonium 241	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.66E+04
	AM243	Americium 243	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.10E+01
	AM243	Americium 243	INVRHD	Inventory of Remote Handled Design	Constant	Curies	7.42E-01
	CF252	Californium 252	INVCHD	Inventory of Contact Handled Design	Constant	Curies	4.64E-05
	CF252	Californium 252	INVRHD	Inventory of Remote Handled Design	Constant	Curies	3.95E-06
	CM243	Curium 243	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.82E-01
	CM243	Curium 243	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.25E-01
	CM244	Curium 244	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.43E+03
	CM244	Curium 244	INVRHD	Inventory of Remote Handled Design	Constant	Curies	7.94E+01
	CM245	Curium 245	INVCHD	Inventory of Contact Handled Design	Constant	Curies	8.59E-03
	CM245	Curium 245	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.06E-02
	CM248	Curium 248	INVCHD	Inventory of Contact Handled Design	Constant	Curies	9.14E-02
	CM248	Curium 248	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.83E-03
	CS137	Cesium 137	INVCHD	Inventory of Contact Handled Design	Constant	Curies	4.61E+03
	CS137	Cesium 137	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.74E+05
	NP237	Neptunium 237	INVCHD	Inventory of Contact Handled Design	Constant	Curies	9.25E+00
	NP237	Neptunium 237	INVRHD	Inventory of Remote Handled Design	Constant	Curies	8.22E-01
	PA231	Protactinium 231	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.21E+00
	PA231	Protactinium 231	INVRHD	Inventory of Remote Handled Design	Constant	Curies	6.55E-04
	PB210	Lead 210	INVCHD	Inventory of Contact Handled Design	Constant	Curies	4.94E+00
	PB210	Lead 210	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.42E-05
	PM147	Promethium 147	INVCHD	Inventory of Contact Handled Design	Constant	Curies	3.86E-04
	PM147	Promethium 147	INVRHD	Inventory of Remote Handled Design	Constant	Curies	7.47E-02
	PU238	Plutonium 238	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.25E+06
	PU238	Plutonium 238	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.80E+03
	PU238L	Plutonium 238 Equals Plutonium 238 Inventory	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.25E+06

Table PAR-37. Isotope Inventory — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	PU238L	Plutonium 238 Equals Plutonium 238 Inventory	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.80E+03
	PU239	Plutonium 239	INVCHD	Inventory of Contact Handled Design	Constant	Curies	6.59E+05
	PU239	Plutonium 239	INVRHD	Inventory of Remote Handled Design	Constant	Curies	5.37E+03
	PU239L	Plutonium 239 Lumped with Plutonium 240 and Pluton	INVCHD	Inventory of Contact Handled Design	Constant	Curies	7.66E+05
	PU239L	Plutonium 239 Lumped with Plutonium 240 and Pluton	INVRHD	Inventory of Remote Handled Design	Constant	Curies	7.05E+03
	PU240	Plutonium 240	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.07E+05
	PU240	Plutonium 240	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.67E+03
	PU241	Plutonium 241	INVCHD	Inventory of Contact Handled Design	Constant	Curies	5.14E+05
	PU241	Plutonium 241	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.39E+04
	PU242	Plutonium 242	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.66E+01
	PU242	Plutonium 242	INVRHD	Inventory of Remote Handled Design	Constant	Curies	4.74E-01
	PU244	Plutonium 244	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.32E-06
	PU244	Plutonium 244	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.10E-03
	RA226	Radium 226	INVCHD	Inventory of Contact Handled Design	Constant	Curies	6.28E+00
	RA226	Radium 226	INVRHD	Inventory of Remote Handled Design	Constant	Curies	4.99E-05
	RA228	Radium 228	INVCHD	Inventory of Contact Handled Design	Constant	Curies	7.63E+00
	RA228	Radium 228	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.51E-01
	SR90	Strontium 90	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.68E+04
	SR90	Strontium 90	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.15E+05
	TH229	Thorium 229	INVCHD	Inventory of Contact Handled Design	Constant	Curies	5.25E+00
	TH229	Thorium 229	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.39E-01
	TH230	Thorium 230	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.69E-01
	TH230	Thorium 230	INVRHD	Inventory of Remote Handled Design	Constant	Curies	6.67E-03
	TH230L	Thorium 230 Lumped with Thorium 229	INVCHD	Inventory of Contact Handled Design	Constant	Curies	5.42E+00
	TH230L	Thorium 230 Lumped with Thorium 229	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.46E-01
	TH232	Thorium 232	INVCHD	Inventory of Contact Handled Design	Constant	Curies	6.61E+00
	TH232	Thorium 232	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.18E-01

Table PAR-37. Isotope Inventory — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	U233	Uranium 233	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.24E+03
	U233	Uranium 233	INVRHD	Inventory of Remote Handled Design	Constant	Curies	3.41E+01
	U234	Uranium 234	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.97E+02
	U234	Uranium 234	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.20E+01
	U234L	Uranium 234 Lumped with Uranium 233	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.54E+03
	U234L	Uranium 234 Lumped with Uranium 233	INVRHD	Inventory of Remote Handled Design	Constant	Curies	5.61E+01
	U235	Uranium 235	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.34E+00
	U235	Uranium 235	INVRHD	Inventory of Remote Handled Design	Constant	Curies	9.42E-01
	U236	Uranium 236	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.31E-01
	U236	Uranium 236	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.42E+00
	U238	Uranium 238	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.44E+01
	U238	Uranium 238	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.30E+02

Table PAR-38. Waste Container Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	REFCON	Reference Constant	ASDRUM	Surface area of corrodible metal per drum	Constant	m^2	6.00E+00
	REFCON	Reference Constant	DRROOM	Number of drums, per room, in ideal packing	Constant	NONE	6.80E+03

Table PAR-39. Stoichiometric Gas Generation Model Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	STEEL	Generic steel in waste	CORRMCO2	Inundated corrosion rate for steel without CO2 present	Uniform	m/s	Sampled Value
	STEEL	Generic steel in waste	HUMCORR	Humid corrosion rate for steel	Constant	m/s	0.00E+00
	STEEL	Generic steel in waste	STOIFX	Stoichiometric factor - X	Constant	NONE	1.00E+00
	SULFATE	Sulfate	QINIT	Initial quantity of material in waste	Constant	moles	6.59E+06
	WAS_AREA	Waste emplacement area and waste	DCELLCHW	Average density of cellulosics in CH waste	Constant	kg/m^3	5.80E+01
	WAS_AREA	Waste emplacement area and waste	DCELLRHW	Average density of cellulosics in RH waste	Constant	kg/m^3	4.50E+00
	WAS_AREA	Waste emplacement area and waste	DIRNCCHW	Bulk density of iron containers, CH waste	Constant	kg/m^3	1.70E+02
	WAS_AREA	Waste emplacement area and waste	DIRNCRHW	Bulk density of iron containers, RH waste	Constant	kg/m^3	4.80E+02
	WAS_AREA	Waste emplacement area and waste	DIRONCHW	Average density of iron-based material in CH waste	Constant	kg/m^3	1.10E+02
	WAS_AREA	Waste emplacement area and waste	DIRONRHW	Average density of iron-based material in RH waste	Constant	kg/m^3	1.10E+02
	WAS_AREA	Waste emplacement area and waste	DPLASCHW	Average density of plastics in CH waste	Constant	kg/m^3	4.20E+01
	WAS_AREA	Waste emplacement area and waste	DPLASRHW	Average density of plastics in RH waste	Constant	kg/m^3	4.90E+00
	WAS_AREA	Waste emplacement area and waste	DPLSCCHW	Bulk density of plastic liners, CH waste	Constant	kg/m^3	1.60E+01
	WAS_AREA	Waste emplacement area and waste	DPLSCRHW	Bulk density of plastic liners, RH waste	Constant	kg/m^3	1.40E+00
	WAS_AREA	Waste emplacement area and waste	DRUBBCHW	Average density of rubber in CH waste	Constant	kg/m^3	1.40E+01
	WAS_AREA	Waste emplacement area and waste	DRUBBRHW	Average density of rubber in RH waste	Constant	kg/m^3	3.10E+00
	WAS_AREA	Waste emplacement area and waste	GRATMICH	Humid biodegredation rate for cellulose	Uniform	moles/(kg*s)	Sampled Value
	WAS_AREA	Waste emplacement area and waste	GRATMICI	Inundated biodegradation rate for cellulose	Uniform	moles/(kg*s)	Sampled Value

Table PAR-40. Predisposal Cavities (Waste Area) Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CAVITY_1	Cavity for Waste Areas	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	CAVITY_1	Cavity for Waste Areas	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	CAVITY_1	Cavity for Waste Areas	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CAVITY_1	Cavity for Waste Areas	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CAVITY_1	Cavity for Waste Areas	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	CAVITY_1	Cavity for Waste Areas	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	CAVITY_1	Cavity for Waste Areas	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CAVITY_1	Cavity for Waste Areas	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	CAVITY_1	Cavity for Waste Areas	POROSITY	Effective porosity	Constant	NONE	1.00E+00
	CAVITY_1	Cavity for Waste Areas	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	CAVITY_1	Cavity for Waste Areas	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_1	Cavity for Waste Areas	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_1	Cavity for Waste Areas	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_1	Cavity for Waste Areas	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CAVITY_1	Cavity for Waste Areas	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_1	Cavity for Waste Areas	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_1	Cavity for Waste Areas	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	CAVITY_2	Cavity for Non-waste Areas	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CAVITY_2	Cavity for Non-waste Areas	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CAVITY_2	Cavity for Non-waste Areas	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	CAVITY_2	Cavity for Non-waste Areas	POROSITY	Effective porosity	Constant	NONE	1.00E+00
	CAVITY_2	Cavity for Non-waste Areas	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05

Table PAR-40. Predisposal Cavities (Waste Area) Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CAVITY_2	Cavity for Non-waste Areas	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_2	Cavity for Non-waste Areas	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_2	Cavity for Non-waste Areas	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_2	Cavity for Non-waste Areas	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CAVITY_2	Cavity for Non-waste Areas	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00
	CAVITY_3	Cavity for Shaft	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	CAVITY_3	Cavity for Shaft	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	CAVITY_3	Cavity for Shaft	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CAVITY_3	Cavity for Shaft	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CAVITY_3	Cavity for Shaft	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	CAVITY_3	Cavity for Shaft	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	CAVITY_3	Cavity for Shaft	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CAVITY_3	Cavity for Shaft	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	CAVITY_3	Cavity for Shaft	POROSITY	Effective porosity	Constant	NONE	1.00E+00
	CAVITY_3	Cavity for Shaft	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	CAVITY_3	Cavity for Shaft	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_3	Cavity for Shaft	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_3	Cavity for Shaft	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_3	Cavity for Shaft	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CAVITY_3	Cavity for Shaft	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_3	Cavity for Shaft	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_3	Cavity for Shaft	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00
	CAVITY_4	Cavity for Borehole	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	CAVITY_4	Cavity for Borehole	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	CAVITY_4	Cavity for Borehole	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CAVITY_4	Cavity for Borehole	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CAVITY_4	Cavity for Borehole	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00

Table PAR-40. Predisposal Cavities (Waste Area) Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CAVITY_4	Cavity for Borehole	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	CAVITY_4	Cavity for Borehole	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CAVITY_4	Cavity for Borehole	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	CAVITY_4	Cavity for Borehole	POROSITY	Effective porosity	Constant	NONE	1.00E+00
	CAVITY_4	Cavity for Borehole	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	CAVITY_4	Cavity for Borehole	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_4	Cavity for Borehole	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_4	Cavity for Borehole	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_4	Cavity for Borehole	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CAVITY_4	Cavity for Borehole	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_4	Cavity for Borehole	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_4	Cavity for Borehole	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-41. Operations Region Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	OPS_AREA	Operations Region	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	OPS_AREA	Operations Region	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	OPS_AREA	Operations Region	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	OPS_AREA	Operations Region	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	OPS_AREA	Operations Region	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	OPS_AREA	Operations Region	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	OPS_AREA	Operations Region	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	OPS_AREA	Operations Region	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	OPS_AREA	Operations Region	POROSITY	Effective porosity	Constant	NONE	1.80E-01
	OPS_AREA	Operations Region	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	OPS_AREA	Operations Region	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$log(m^2)$	-1.10E+01
	OPS_AREA	Operations Region	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$log(m^2)$	-1.10E+01
	OPS_AREA	Operations Region	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$log(m^2)$	-1.10E+01
	OPS_AREA	Operations Region	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	OPS_AREA	Operations Region	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	OPS_AREA	Operations Region	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	OPS_AREA	Operations Region	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-42. Area Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	EXP_AREA	Experimental Area	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	EXP_AREA	Experimental Area	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	EXP_AREA	Experimental Area	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	EXP_AREA	Experimental Area	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	EXP_AREA	Experimental Area	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	EXP_AREA	Experimental Area	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	EXP_AREA	Experimental Area	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	EXP_AREA	Experimental Area	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	EXP_AREA	Experimental Area	POROSITY	Effective porosity	Constant	NONE	1.80E-01
	EXP_AREA	Experimental Area	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	EXP_AREA	Experimental Area	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.10E+01
	EXP_AREA	Experimental Area	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.10E+01
	EXP_AREA	Experimental Area	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.10E+01
	EXP_AREA	Experimental Area	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	EXP_AREA	Experimental Area	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	EXP_AREA	Experimental Area	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	EXP_AREA	Experimental Area	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-43. Castile Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	IMPERM_Z	Impermeable Zones	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	IMPERM_Z	Impermeable Zones	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	IMPERM_Z	Impermeable Zones	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0
	IMPERM_Z	Impermeable Zones	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	IMPERM_Z	Impermeable Zones	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	IMPERM_Z	Impermeable Zones	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	IMPERM_Z	Impermeable Zones	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	IMPERM_Z	Impermeable Zones	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	IMPERM_Z	Impermeable Zones	POROSITY	Effective porosity	Constant	NONE	5.00E-03
	IMPERM_Z	Impermeable Zones	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-3.50E+01
	IMPERM_Z	Impermeable Zones	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-3.50E+01
	IMPERM_Z	Impermeable Zones	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-3.50E+01
	IMPERM_Z	Impermeable Zones	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	IMPERM_Z	Impermeable Zones	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	IMPERM_Z	Impermeable Zones	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-44. Castile Brine Reservoir Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CASTILER	Castile Brine Reservoir	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	CASTILER	Castile Brine Reservoir	COMP_RCK	Bulk Compressibility	Triangular	Pa^{-1}	Sampled Value
	CASTILER	Castile Brine Reservoir	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CASTILER	Castile Brine Reservoir	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CASTILER	Castile Brine Reservoir	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	CASTILER	Castile Brine Reservoir	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	CASTILER	Castile Brine Reservoir	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CASTILER	Castile Brine Reservoir	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	CASTILER	Castile Brine Reservoir	POROSITY	Effective porosity	Student	NONE	8.70E-03
	CASTILER	Castile Brine Reservoir	PRESSURE	Brine far-field pore pressure	Triangular	Pa	1.27E+07
	CASTILER	Castile Brine Reservoir	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	$\log(m^2)$	-1.18E+01
	CASTILER	Castile Brine Reservoir	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	$\log(m^2)$	-1.18E+01
	CASTILER	Castile Brine Reservoir	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	$\log(m^2)$	-1.18E+01
	CASTILER	Castile Brine Reservoir	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CASTILER	Castile Brine Reservoir	SAT_IBRN	Initial Brine Saturation	Constant	NONE	1.00E+00
	CASTILER	Castile Brine Reservoir	SAT_RBRN	Residual Brine Saturation	Constant	NONE	2.00E-01
	CASTILER	Castile Brine Reservoir	SAT_RGAS	Residual Gas Saturation	Constant	NONE	2.00E-01

Table PAR-45. Reference Constants

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	REFCON	Reference Constant	ABERM	Area of Berm Placed Over Waste Panel	Constant	m^2	6.29E+05
	REFCON	Reference Constant	ACF_CH4	Acentric Factors - CH4	Constant	NONE	1.00E-02
	REFCON	Reference Constant	ACF_CO2	Acentric Factors - CO2	Constant	NONE	2.31E-01
	REFCON	Reference Constant	ACF_H2	Acentric Factors - H2	Constant	NONE	0.00E+00
	REFCON	Reference Constant	ACF_H2S	Acentric Factors - H2S	Constant	NONE	1.00E-01
	REFCON	Reference Constant	ACF_N2	Acentric Factors - N2	Constant	NONE	4.50E-02
	REFCON	Reference Constant	ACF_O2	Acentric Factors - O2	Constant	NONE	1.90E-02
	REFCON	Reference Constant	AREA_CH	Area For CH Waste Disposal in CDFGF Model	Constant	m^2	1.12E+05
	REFCON	Reference Constant	AREA_RH	Area For RH Waste Disposal in CDFGF Model	Constant	m^2	1.58E+04
	REFCON	Reference Constant	AREA_ZRO	Area in Waste Panels Not Used For Disposal (CCDFGF Model)	Constant	m^2	4.13E+03
	REFCON	Reference Constant	ATMPA	Conversion from std. atmosphere to Pa	Constant	Pa/atm	1.01E+05
	REFCON	Reference Constant	AVOGADRO	Avogadro's number	Constant	$mole^{-1}$	6.02E+23
	REFCON	Reference Constant	BIP_11	H2:H2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_12	H2:CO2 - Binary Interaction Parameter	Constant	NONE	-3.43E-01
	REFCON	Reference Constant	BIP_13	H2:CH4 - Binary Interaction Parameter	Constant	NONE	-2.22E-02
	REFCON	Reference Constant	BIP_14	H2:N2 - Binary Interaction Parameter	Constant	NONE	9.78E-02
	REFCON	Reference Constant	BIP_15	H2:H2S - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_16	H2:O2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_21	CO2:H2 - Binary Interaction Parameter	Constant	NONE	-3.43E-01
	REFCON	Reference Constant	BIP_22	CO2:CO2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_23	CO2:CH4 - Binary Interaction Parameter	Constant	NONE	9.33E-02
	REFCON	Reference Constant	BIP_24	CO2:N2 - Binary Interaction Parameter	Constant	NONE	-3.15E-02
	REFCON	Reference Constant	BIP_25	CO2:H2S - Binary Interaction Parameter	Constant	NONE	9.89E-02

Table PAR-45. Reference Constants — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	REFCON	Reference Constant	BIP_26	CO2:O2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_31	CH4:H2 - Binary Interaction Parameter	Constant	NONE	-2.22E-02
	REFCON	Reference Constant	BIP_32	CH4:CO2 - Binary Interaction Parameter	Constant	NONE	9.33E-02
	REFCON	Reference Constant	BIP_33	CH4:CH4 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_34	CH4:N2 - Binary Interaction Parameter	Constant	NONE	2.78E-02
	REFCON	Reference Constant	BIP_35	CH4:H2S - Binary Interaction Parameter	Constant	NONE	8.50E-02
	REFCON	Reference Constant	BIP_36	CH4:O2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_41	N2:H2 - Binary Interaction Parameter	Constant	NONE	9.78E-02
	REFCON	Reference Constant	BIP_42	N2:CO2 - Binary Interaction Parameter	Constant	NONE	-3.15E-02
	REFCON	Reference Constant	BIP_43	N2:CH4 - Binary Interaction Parameter	Constant	NONE	2.78E-02
	REFCON	Reference Constant	BIP_44	N2:N2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_45	N2:H2S - Binary Interaction Parameter	Constant	NONE	1.70E-01
	REFCON	Reference Constant	BIP_46	N2:O2 - Binary Interaction Parameter	Constant	NONE	-7.80E-03
	REFCON	Reference Constant	BIP_51	H2S:H2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_52	H2S:CO2 - Binary Interaction Parameter	Constant	NONE	9.89E-02
	REFCON	Reference Constant	BIP_53	H2S:CH4 - Binary Interaction Parameter	Constant	NONE	8.50E-02
	REFCON	Reference Constant	BIP_54	H2S:N2 - Binary Interaction Parameter	Constant	NONE	1.70E-01
	REFCON	Reference Constant	BIP_55	H2S:H2S - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_56	H2S:O2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_61	O2:H2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_62	O2:CO2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_63	O2:CH4 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_64	O2:N2 - Binary Interaction Parameter	Constant	NONE	-7.80E-03
	REFCON	Reference Constant	BIP_65	O2:H2S - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_66	O2:O2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	CITOBQ	Curie to Becquerel Conversion	Constant	Bq/Curies	3.70E+10
	REFCON	Reference Constant	DARM2	Conversion from darcy to m^2	Constant	m^2/darcy	9.87E-13

Table PAR-45. Reference Constants — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	REFCON	Reference Constant	DAYSEC	Conversion from days to seconds	Constant	s/day	8.64E+04
	REFCON	Reference Constant	FTM	Conversion from feet to meter	Constant	m/ft	3.05E-01
	REFCON	Reference Constant	FVRW	Fraction of Emplaced RH Volume Occupied by RH Waste in CCDFGF Model	Constant	NONE	1.00E+00
	REFCON	Reference Constant	FVW	Fraction of Repository Volume Occupied By Waste In CCDFGF Model	Constant	NONE	3.86E-01
	REFCON	Reference Constant	GRAVACC	Standard gravitational acceleration	Constant	m/s^2	9.81E+00
	REFCON	Reference Constant	HRH	Emplaced Height of Remote Handled Waste in CCDFGF Model	Constant	m	5.09E-01
	REFCON	Reference Constant	MW_CELL	Carbon Normalized Molecular Weight of Cellulose	Constant	kg/mole	2.70E-02
	REFCON	Reference Constant	MW_CH4	Molecular Weight of CH4	Constant	kg/mole	1.60E-02
	REFCON	Reference Constant	MW_CO2	Molecular Weight of CO2	Constant	kg/mole	4.40E-02
	REFCON	Reference Constant	MW_FE	Molecular Weight - FE	Constant	kg/mole	5.58E-02
	REFCON	Reference Constant	MW_H2	Molecular Weight - H2	Constant	kg/mole	2.02E-03
	REFCON	Reference Constant	MW_H2O	Molecular Weight - H2O	Constant	kg/mole	1.80E-02
	REFCON	Reference Constant	MW_H2S	Molecular Weight of H2S	Constant	kg/mole	3.41E-02
	REFCON	Reference Constant	MW_N2	Molecular Weight of N2	Constant	kg/mole	2.80E-02
	REFCON	Reference Constant	MW_NACL	Molecular Weight of NaCl	Constant	kg/mole	5.84E-02
	REFCON	Reference Constant	MW_O2	Molecular Weight of O2	Constant	kg/mole	3.20E-02
	REFCON	Reference Constant	OMEGAA	Constants for RKS EOS	Constant	NONE	4.27E-01
	REFCON	Reference Constant	OMEGAB	Constants for RDS EOS	Constant	NONE	8.66E-02
	REFCON	Reference Constant	PC_CH4	Critical Pressure of CH4	Constant	Pa	4.62E+06
	REFCON	Reference Constant	PC_CO2	Critical Pressure of CO2	Constant	Pa	7.38E+06
	REFCON	Reference Constant	PC_H2	Critical Pressure of H2	Constant	Pa	2.05E+06
	REFCON	Reference Constant	PC_H2S	Critical Pressure of H2S	Constant	Pa	9.01E+06
	REFCON	Reference Constant	PC_N2	Critical Pressure of N2	Constant	Pa	3.39E+06
	REFCON	Reference Constant	PC_O2	Critical Pressure of O2	Constant	Pa	5.08E+06
	REFCON	Reference Constant	PI	Mathematical constant: PI	Constant	NONE	3.14E+00
	REFCON	Reference Constant	PSIPA	Conversion from psi to pascal	Constant	$Pa*in^2/lb$	6.89E+03
	REFCON	Reference Constant	R	Gas constant R	Constant	J/mole*K	8.31E+00

Table PAR-45. Reference Constants — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	REFCON	Reference Constant	SECYR	Seconds to years Conversion	Constant	yr/s	3.17E-08
	REFCON	Reference Constant	TC_CH4	Critical temperature: Methane (CH4)	Constant	K	1.91E+02
	REFCON	Reference Constant	TC_CO2	Critical temperature: Carbon Dioxide (CO2)	Constant	K	3.04E+02
	REFCON	Reference Constant	TC_H2	Critical temperature: Hydrogen (H2)	Constant	K	4.36E+01
	REFCON	Reference Constant	TC_H2S	Critical temperature: Hydrogen Sulfide (H2S)	Constant	K	3.74E+02
	REFCON	Reference Constant	TC_N2	Critical temperature: Nitrogen (N2)	Constant	K	1.26E+02
	REFCON	Reference Constant	TC_O2	Critical temperature: Oxygen (O2)	Constant	K	1.55E+02
	REFCON	Reference Constant	VOLWP	Uncompacted Volume of Waste Panels In CCDFGF Model	Constant	m^3	4.36E+05
	REFCON	Reference Constant	VPANLEX	Excavated volume of one panel	Constant	m^3	4.61E+04
	REFCON	Reference Constant	VREPOS	Excavated storage volume of repository	Constant	m^3	4.38E+05
	REFCON	Reference Constant	VROOM	Volume of one room in repository	Constant	m^3	3.64E+03
	REFCON	Reference Constant	YRSEC	Conversion from mean solar or tropical year to seconds	Constant	s/yr	3.16E+07

Table PAR-46. Global Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	GLOBAL	Information that applies globally	FPICD	PIC multiplicative factor for human intrusion by drilling	Constant	NONE	1.00E+00
	GLOBAL	Information that applies globally	FPICM	PIC multiplicative factor for human intrusion by mining	Constant	NONE	1.00E+00
	GLOBAL	Information that applies globally	LAMBDAD	Drilling Rate Per Unit Area	Constant	(km^{-2}) (yr^{-1})	5.25E-03
	GLOBAL	Information that applies globally	MINERT	Mining rate from 40 CFR 194	Constant	yr^{-1}	1.00E-04
	GLOBAL	Information that applies globally	ONEPLG	Probability of having Plug Pattern 1	Constant	NONE	1.50E-02
	GLOBAL	Information that applies globally	PLGPAT	Index for Plugging Pattern After Drilling Intrusion	Delta	NONE	0.00E+00
	GLOBAL	Information that applies globally	TA	Time Active Institutional Controls at WIPP Site Are Effective	Constant	yr	1.00E+02
	GLOBAL	Information that applies globally	THREEPLG	Probability of having Plug Pattern 3	Constant	NONE	2.89E-01
	GLOBAL	Information that applies globally	TPICD	Time over which passive institutional controls reduce rate of drilling	Constant	yr	6.00E+02
	GLOBAL	Information that applies globally	TPICM	Time over which passive institutional controls reduce rate of mining	Constant	yr	6.00E+02
	GLOBAL	Information that applies globally	TWOPLG	Probability of having Plug Pattern 2	Constant	NONE	6.96E-01

Table PAR-47. Listing of Parameters Used in BRAGFLO Which Differ From the PA Parameter Database

Database Material	Database Property	Modeling value used	Distribution type	Database value	Units
REPOSIT	DCELLCHW	5.80E+01	CONSTANT	5.40E+01	kg/m^3
REPOSIT	DCELLRHW	4.50E+00	CONSTANT	1.70E+01	kg/m^3
REPOSIT	DIRNCCHW	1.70E+02	CONSTANT	1.39E+02	kg/m^3
REPOSIT	DIRNCRHW	4.80E+02	CONSTANT	2.59E+03	kg/m^3
REPOSIT	DIRONCHW	1.10E+02	CONSTANT	1.70E+02	kg/m^3
REPOSIT	DIRONRHW	1.10E+02	CONSTANT	1.00E+02	kg/m^3
REPOSIT	DPLASCHW	4.20E+01	CONSTANT	3.40E+01	kg/m^3
REPOSIT	DPLSCCHW	1.60E+01	CONSTANT	2.60E+01	kg/m^3
REPOSIT	DRUBBCHW	1.40E+01	CONSTANT	1.00E+01	kg/m^3
REPOSIT	DRUBBRHW	3.10E+00	CONSTANT	3.30E+00	kg/m^3
SHFTL_T1	PCT_A	0.00E+00	CONSTANT	5.60E-01	Pa
SHFTL_T1	PCT_EXP	0.00E+00	CONSTANT	-3.46E-01	NONE
SHFTL_T1	SAT_IBRN	9.99E-01	CONSTANT	5.34E-01	NONE
SHFTL_T2	PCT_A	0.00E+00	CONSTANT	5.60E-01	Pa
SHFTL_T2	PCT_EXP	0.00E+00	CONSTANT	-3.46E-01	NONE
SHFTL_T2	SAT_IBRN	9.99E-01	CONSTANT	5.34E-01	NONE
SHFTU	PCT_A	0.00E+00	CONSTANT	5.60E-01	Pa
SHFTU	PCT_EXP	0.00E+00	CONSTANT	-3.46E-01	NONE
SHFTU	SAT_IBRN	9.99E-01	CONSTANT	7.96E-01	NONE

Table PAR-48. Listing of Parameters Used in DRSPALL Not in the PA Parameter Database

Database Material	Database Property	Modeling value used	Distribution type
SPALLMOD	CHARLEN	0.02E+00	Constant
SPALLMOD	DRZTCK	0.85E+00	Constant
SPALLMOD	EXITPLEN	0.00E+00	Constant
SPALLMOD	EXITPDIA	20.32E-02	Constant
SPALLMOD	FRCHBETA	1.15E-06	Constant
SPALLMOD	INITBAR	0.15E+00	Constant
SPALLMOD	MAXPPRES	27.50E+06	Constant
SPALLMOD	REPOSTCK	0.00E+00	Constant
SPALLMOD	REPOTRAD	1.92E+01	Constant
SPALLMOD	STPDTIME	1.00E+03	Constant

Table PAR-49. Reference Thicknesses for Hydrostratigraphic Units in BRAGFLO

Hydrostratigraphic Unit	Total Hydrostratigraphic Unit Thickness (meters)	Geologic Units Combined as Units Above Dewey Lake	Geologic Unit Thickness (meters)
Units above Dewey Lake	15.76[1]	Surficial Sediments Mescalero Caliche Gatuña Santa Rosa	0 - 3 0 – 4.6[2] 0 – [2.7 – 9.0][3] 0 – [0.6 – 64.0][4]
Dewey Lake	149.3		
Forty-niner	17.3		
Magenta	8.5		
Tamarisk	24.8		
Culebra	7.7		
Unnamed lower Member	36.0		
Impure Halite	600.3		
Marker Bed 138			
Anhydrite Layers and b	0.27		
Marker Bed 139	0.85		
Castile	78.5		

[1] Thicknesses of supra-Dewey Lake hydrostratigraphic unit relates to the ranges of total thickness of geologic units as determined for the following quadrants of the land withdrawal area:

Northwest – 6.0 m (H-6) – 22 m (WIPP-13)
Southwest – 6.0 m (P-6) – 12 m (H-14)
Southeast – 11.3 m (ERDA-9) – 47 m (H-15)
Northeast – 21 m (WIPP-21) – 67 m (H-5)

Source: Sanchez and McCasland, 1994, Assessment of Solid Waste Management Units: NMED/DOE/AIP-94/1, New Mexico Environment Department, Santa Fe, New Mexico, p. 4-1 – 4-28.

[2] Mescalero caliche engulfs local bedrock; thickness of unit is accounted for in bedrock unit thickness of geologic units above Dewey Lake.

[3] Gatuña thickness is variable; generally thickest on west half of land withdrawal area and absent on east side. Range includes AIS shaft (2.7 m) and H-14 (9.0 m).

[4] Santa Rosa is generally absent on west half of land withdrawal area; thickens to east. Range includes AIS shaft (0.6 m) and H-5 (64 m).

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
AE-T001	2.30E+02	1.36E-03	7.57E-03	7.21E-03	7.13E-03	6.99E-03	6.61E-03	5.82E-03	4.96E-03	4.46E-03	3.94E-03	3.50E-03
AE-T003	5.21E+01	3.09E-04	7.84E-03	7.68E-03	7.63E-03	7.54E-03	7.30E-03	6.76E-03	5.99E-03	5.46E-03	4.89E-03	4.41E-03
AW-N026.82	2.10E-01	1.25E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	1.46E+01	8.68E-05	2.67E-02	1.93E-02	1.82E-02	1.65E-02	1.39E-02	1.28E-02	1.21E-02	1.14E-02	1.06E-02	9.87E-03
AW-T033.1325	5.35E+01	3.17E-04	2.67E-02	1.93E-02	1.82E-02	1.65E-02	1.39E-02	1.28E-02	1.21E-02	1.14E-02	1.06E-02	9.86E-03
AW-W049	1.80E+01	1.07E-04	1.73E-04	1.73E-04	1.73E-04	1.72E-04	1.72E-04	1.68E-04	1.59E-04	1.50E-04	1.40E-04	1.30E-04
BCLCH-MT01	5.24E+00	3.11E-05	1.10E+00	5.23E-01	4.36E-01	3.05E-01	1.03E-01	3.03E-02	2.51E-02	2.30E-02	2.09E-02	1.90E-02
BT-T002	1.86E+01	1.10E-04	1.60E-04	7.45E-05	6.16E-05	4.24E-05	1.25E-05	1.58E-06	9.01E-07	8.23E-07	7.65E-07	7.19E-07
ET-C1-B55	8.40E-01	4.99E-06	7.41E-04	6.88E-04	6.75E-04	6.52E-04	5.92E-04	4.77E-04	3.84E-04	3.46E-04	3.08E-04	2.76E-04
ET-C1-D139	2.10E-01	1.25E-06	4.13E-04	3.83E-04	3.76E-04	3.64E-04	3.30E-04	2.67E-04	2.16E-04	1.94E-04	1.73E-04	1.55E-04
ET-C2-SEFOR	1.25E+00	7.42E-06	1.18E-03	1.10E-03	1.08E-03	1.04E-03	9.24E-04	6.84E-04	5.18E-04	4.70E-04	4.23E-04	3.82E-04
FM-MOX-MT02	4.20E-01	2.49E-06	2.46E-08	2.11E-08	2.01E-08	1.85E-08	1.45E-08	7.76E-09	4.03E-09	3.51E-09	3.09E-09	2.75E-09
FM-MOX-T01	6.86E+00	4.07E-05	2.49E-08	2.13E-08	2.03E-08	1.87E-08	1.46E-08	7.84E-09	4.06E-09	3.54E-09	3.12E-09	2.78E-09
IN-BN-510	1.99E+04	1.18E-01	1.81E-02	1.35E-02	1.28E7-02	1.18E-02	9.95E-03	8.73E-03	7.89E-03	7.37E-03	6.80E-03	6.27E-03
IN-GEM-01	2.05E+02	1.22E-03	2.85E-03	2.58E-03	2.52E-03	2.40E-03	2.07E-03	1.39E-03	9.65E-04	8.78E-04	7.97E-04	7.27E-04
IN-GEM-02	4.87E+01	2.89E-04	2.84E-03	2.58E-03	2.52E-03	2.40E-03	2.07E-03	1.39E-03	9.65E-04	8.78E-04	7.98E-04	7.27E-04
IN-W157.144	7.46E+02	4.43E-03	2.58E-03	2.51E-03	2.48E-03	2.44E-03	2.31E-03	2.04E-03	1.78E-03	1.64E-03	1.49E-03	1.36E-03
IN-W163.1007	1.15E+01	6.81E-05	4.69E-02	4.61E-02	4.58E-02	4.52E-02	4.36E-02	4.01E-02	3.58E-02	3.30E-02	3.00E-02	2.73E-02
IN-W164.153	4.79E+00	2.84E-05	1.07E-03	1.05E-03	1.05E-03	1.03E-03	9.94E-04	9.14E-04	8.16E-04	7.52E-04	6.83E-04	6.23E-04
IN-W167.149	3.83E+02	2.28E-03	2.24E-03	2.19E-03	2.17E-03	2.14E-03	2.05E-03	1.86E-03	1.65E-03	1.52E-03	1.38E-03	1.26E-03
IN-W174.154	4.31E+02	2.56E-03	1.91E-02	8.70E-03	7.15E-03	4.84E-03	1.26E-03	6.68E-05	5.25E-05	4.65E-05	4.04E-05	3.56E-05
IN-W177.156	8.03E+02	4.77E-03	2.17E-02	9.88E-03	8.11E-03	5.47E-03	1.39E-03	2.82E-05	1.95E-05	1.90E-05	1.83E-05	1.77E-05
IN-W179.158	2.00E+03	1.19E-02	8.71E-03	3.96E-03	3.25E-03	2.19E-03	5.53E-04	8.05E-06	4.70E-06	4.65E-06	4.59E-06	4.53E-06
IN-W181.162	8.03E+01	4.77E-04	8.42E-04	8.28E-04	8.22E-04	8.12E-04	7.82E-04	7.19E-04	6.42E-04	5.92E-04	5.38E-04	4.90E-04

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
IN-W188.160	1.49E+02	8.85E-04	3.06E-03	3.01E-03	2.99E-03	2.95E-03	2.84E-03	2.61E-03	2.33E-03	2.15E-03	1.95E-03	1.78E-03
IN-W216.98	1.27E+04	7.57E-02	4.60E-02	3.96E-02	3.81E-02	3.54E-02	2.73E-02	1.12E-02	2.58E-03	2.07E-03	1.87E-03	1.70E-03
IN-W218.909	2.08E+03	1.24E-02	1.69E-03	1.49E-03	1.44E-03	1.36E-03	1.10E-03	5.98E-04	3.12E-04	2.79E-04	2.53E-04	2.31E-04
IN-W219.110	3.95E+00	2.35E-05	7.04E-03	6.92E-03	6.88E-03	6.79E-03	6.54E-03	6.02E-03	5.37E-03	4.95E-03	4.50E-03	4.10E-03
IN-W219.914	1.89E+00	1.12E-05	2.32E-03	2.28E-03	2.27E-03	2.24E-03	2.16E-03	1.99E-03	1.77E-03	1.63E-03	1.48E-03	1.35E-03
IN-W220.114	1.89E+03	1.12E-02	1.19E-02	1.03E-02	9.99E-03	9.32E-03	7.37E-03	3.47E-03	1.34E-03	1.17E-03	1.06E-03	9.65E-04
IN-W221.927	3.92E+01	2.33E-04	4.32E-03	4.25E-03	4.22E-03	4.17E-03	4.02E-03	3.69E-03	3.30E-03	3.04E-03	2.76E-03	2.52E-03
IN-W222.116	2.59E+02	1.54E-03	2.21E-02	2.18E-02	2.16E-02	2.13E-02	2.06E-02	1.89E-02	1.69E-02	1.55E-02	1.41E-02	1.29E-02
IN-W228.101	8.06E+03	4.79E-02	8.50E-04	7.54E-04	7.32E-04	6.90E-04	5.68E-04	3.23E-04	1.82E-04	1.63E-04	1.48E-04	1.35E-04
IN-W240.931	3.97E+02	2.36E-03	6.63E-03	6.44E-03	6.38E-03	6.27E-03	5.95E-03	5.29E-03	4.62E-03	4.26E-03	3.87E-03	3.53E-03
IN-W243.808	7.73E+02	4.59E-03	5.68E-03	5.55E-03	5.51E-03	5.42E-03	5.19E-03	4.69E-03	4.14E-03	3.82E-03	3.47E-03	3.16E-03
IN-W245.301	7.52E+02	4.47E-03	1.09E-02	1.07E-02	1.07E-02	1.05E-02	1.01E-02	9.31E-03	8.30E-03	7.65E-03	6.95E-03	6.34E-03
IN-W247.810	7.62E+02	4.52E-03	5.27E-03	5.18E-03	5.14E-03	5.07E-03	4.89E-03	4.49E-03	4.01E-03	3.70E-03	3.36E-03	3.06E-03
IN-W249.527	6.68E+00	3.97E-05	7.39E-01	3.40E-01	2.80E-01	1.91E-01	5.38E-02	7.91E-03	7.23E-03	6.84E-03	6.39E-03	5.97E-03
IN-W263.520	2.80E+02	1.66E-03	1.95E-03	9.49E-04	8.01E-04	5.80E-04	2.36E-04	1.20E-04	1.12E-04	1.06E-04	9.87E-05	9.19E-05
IN-W267.1005	1.15E+01	6.81E-05	8.48E-02	8.34E-02	8.28E-02	8.18E-02	7.88E-02	7.25E-02	6.47E-02	5.96E-02	5.42E-02	4.94E-02
IN-W309.609	7.73E+03	4.59E-02	2.28E-03	2.22E-03	2.20E-03	2.16E-03	2.05E-03	1.83E-03	1.61E-03	1.48E-03	1.34E-03	1.23E-03
IN-W315.601	3.44E+01	2.04E-04	1.04E-01	8.85E-02	8.51E-02	7.87E-02	5.98E-02	2.21E-02	2.34E-03	1.43E-03	1.27E-03	1.15E-03
IN-W319.584	4.79E+00	2.84E-05	3.12E-02	3.07E-02	3.05E-02	3.01E-02	2.90E-02	2.67E-02	2.38E-02	2.19E-02	1.99E-02	1.82E-02
IN-W321.1023	1.15E+01	6.81E-05	1.13E-01	1.11E-01	1.10E-01	1.09E-01	1.05E-01	9.64E-02	8.60E-02	7.93E-02	7.21E-02	6.57E-02
IN-W322.851	1.89E+00	1.12E-05	2.35E-02	2.34E-02	2.33E-02	2.33E-02	2.31E-02	2.25E-02	2.08E-02	1.92E-02	1.75E-02	1.60E-02
IN-W322.952	1.66E+00	9.85E-06	7.12E-02	7.09E-02	7.08E-02	7.07E-02	7.01E-02	6.83E-02	6.30E-02	5.82E-02	5.30E-02	4.84E-02
IN-W323.562	1.89E+00	1.12E-05	2.73E-03	1.62E-03	1.45E-03	1.19E-03	7.68E-04	5.58E-04	4.90E-04	4.61E-04	4.29E-04	3.99E-04
IN-W323.951	2.10E-01	1.25E-06	7.77E-03	7.58E-03	7.49E-03	7.32E-03	6.86E-03	5.96E-03	5.24E-03	4.93E-03	4.59E-03	4.27E-03
IN-W332.661	4.79E+00	2.84E-05	1.06E-02	4.86E-03	4.01E-03	2.74E-03	7.71E-04	1.15E-04	1.05E-04	9.92E-05	9.27E-05	8.66E-05
IN-W337.673	2.10E-01	1.25E-06	7.04E-02	7.01E-02	7.00E-02	6.99E-02	6.94E-02	6.75E-02	6.23E-02	5.76E-02	5.24E-02	4.79E-02
IN-W337.957	1.89E+00	1.12E-05	2.35E-02	2.34E-02	2.33E-02	2.33E-02	2.31E-02	2.25E-02	2.08E-02	1.92E-02	1.75E-02	1.60E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
IN-W341.671	2.10E-01	1.25E-06	3.74E-02	3.73E-02	3.73E-02	3.72E-02	3.70E-02	3.64E-02	3.43E-02	3.24E-02	3.01E-02	2.81E-02
IN-W341.954	1.89E+00	1.12E-05	1.25E-02	1.25E-02	1.25E-02	1.24E-02	1.24E-02	1.21E-02	1.15E-02	1.08E-02	1.01E-02	9.37E-03
IN-W342.652	1.89E+00	1.12E-05	9.31E-03	7.94E-03	7.63E-03	7.05E-03	5.35E-03	1.94E-03	1.54E-04	7.72E-05	6.91E-05	6.42E-05
IN-W342.953	4.20E-01	2.49E-06	2.80E-02	2.39E-02	2.30E-02	2.12E-02	1.61E-02	5.83E-03	4.62E-04	2.33E-04	2.08E-04	1.93E-04
IN-W347.818	1.54E+02	9.14E-04	6.19E-03	6.13E-03	6.12E-03	6.09E-03	6.00E-03	5.68E-03	4.87E-03	4.21E-03	3.53E-03	3.00E-03
IN-W348.1012	2.29E+01	1.36E-04	9.16E-02	9.03E-02	9.00E-02	8.96E-02	8.86E-02	8.61E-02	7.92E-02	7.32E-02	6.65E-02	6.06E-02
IN-W353.917	2.10E-01	1.25E-06	4.80E-04	4.78E-04	4.78E-04	4.77E-04	4.75E-04	4.66E-04	4.40E-04	4.15E-04	3.86E-04	3.60E-04
IN-W357.1022	4.79E+00	2.84E-05	8.61E-04	8.48E-04	8.46E-04	8.42E-04	8.33E-04	8.09E-04	7.45E-04	6.88E-04	6.25E-04	5.70E-04
IN-W358.854	1.89E+00	1.12E-05	6.61E-01	3.07E-01	2.54E-01	1.75E-01	5.26E-02	1.14E-02	9.61E-03	8.33E-03	7.02E-03	5.99E-03
IN-W358.855	3.33E+00	1.98E-05	2.00E+00	9.28E-01	7.68E-01	5.29E-01	1.59E-01	3.44E-02	2.90E-02	2.51E-02	2.12E-02	1.81E-02
IN-W358.948	2.10E-01	1.25E-06	6.62E+00	3.07E+00	2.54E+00	1.75E+00	5.26E-01	1.14E-01	9.59E-02	8.31E-02	7.02E-02	5.98E-02
IN-W361.1021	1.15E+01	6.81E-05	3.47E-02	3.42E-02	3.41E-02	3.39E-02	3.36E-02	3.26E-02	3.00E-02	2.77E-02	2.52E-02	2.30E-02
IN-W362.1020	4.59E+01	2.72E-04	1.13E-01	1.12E-01	1.11E-01	1.11E-01	1.10E-01	1.06E-01	9.79E-02	9.04E-02	8.22E-02	7.49E-02
IN-W363.1019	4.79E+00	2.84E-05	5.15E-02	5.07E-02	5.06E-02	5.03E-02	4.98E-02	4.83E-02	4.45E-02	4.11E-02	3.73E-02	3.41E-02
IN-W364.1011	4.79E+00	2.84E-05	8.46E-02	8.33E-02	8.31E-02	8.27E-02	8.18E-02	7.94E-02	7.31E-02	6.75E-02	6.14E-02	5.60E-02
IN-W365.1010	1.15E+01	6.81E-05	1.32E-01	1.16E-01	1.13E-01	1.06E-01	8.64E-02	4.72E-02	2.50E-02	2.23E-02	2.03E-02	1.85E-02
IN-W366.841	1.63E+01	9.65E-05	1.70E-02	1.68E-02	1.67E-02	1.66E-02	1.64E-02	1.58E-02	1.45E-02	1.34E-02	1.22E-02	1.11E-02
IN-W372.832	1.89E+00	1.12E-05	9.31E-03	7.94E-03	7.63E-03	7.05E-03	5.35E-03	1.94E-03	1.54E-04	7.72E-05	6.91E-05	6.42E-05
IN-W375.1096	2.00E+02	1.19E-03	5.04E-04	4.97E-04	4.96E-04	4.93E-04	4.88E-04	4.74E-04	4.36E-04	4.03E-04	3.66E-04	3.34E-04
KN-B234TRU	4.14E+02	2.46E-03	5.43E-03	5.13E-03	5.06E-03	4.93E-03	4.59E-03	3.91E-03	3.31E-03	3.02E-03	2.71E-03	2.46E-03
LA-IT-00-01	9.78E+00	5.81E-05	2.50E-03	1.64E-03	1.50E-03	1.28E-03	8.53E-04	4.25E-04	2.33E-04	2.13E-04	1.97E-04	1.83E-04
LA-OS-00-01	6.96E+01	4.13E-04	8.91E+00	4.20E+00	3.49E+00	2.44E+00	7.77E-01	1.34E-01	7.16E-02	6.57E-02	6.13E-02	5.73E-02
LA-PX-00-01	6.20E-01	3.68E-06	8.94E-04	8.56E-04	8.48E-04	8.33E-04	7.95E-04	7.23E-04	6.41E-04	5.91E-04	5.36E-04	4.89E-04
LA-SL-00-01	4.20E-01	2.49E-06	2.73E-03	2.04E-03	1.93E-03	1.78E-03	1.53E-03	1.43E-03	1.35E-03	1.27E-03	1.18E-03	1.10E-03
LA-TA-03-12	2.21E+02	1.31E-03	6.98E-05	3.91E-05	3.44E-05	2.75E-05	1.63E-05	1.10E-05	9.35E-06	8.53E-06	7.67E-06	6.94E-06
LA-TA-03-13	4.64E+01	2.75E-04	9.34E-04	4.73E-04	4.05E-04	3.01E-04	1.39E-04	7.55E-05	6.50E-05	5.98E-05	5.43E-05	4.96E-05
LA-TA-03-19	1.80E+02	1.07E-03	3.73E-04	1.95E-04	1.69E-04	1.29E-04	6.54E-05	3.95E-05	3.39E-05	3.11E-05	2.81E-05	2.55E-05

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
LA-TA-03-20	3.01E+01	1.79E-04	1.06E-03	5.56E-04	4.80E-04	3.66E-04	1.86E-04	1.10E-04	9.30E-05	8.48E-05	7.63E-05	6.89E-05
LA-TA-03-24	3.00E+01	1.78E-04	3.82E-03	1.86E-03	1.57E-03	1.13E-03	4.47E-04	1.97E-04	1.69E-04	1.55E-04	1.40E-04	1.27E-04
LA-TA-03-26	2.43E+01	1.44E-04	6.31E-04	5.30E-04	5.15E-04	4.92E-04	4.54E-04	4.33E-04	4.07E-04	3.84E-04	3.57E-04	3.31E-04
LA-TA-03-28	5.84E+00	3.47E-05	4.32E-04	2.89E-04	2.67E-04	2.35E-04	1.85E-04	1.66E-04	1.56E-04	1.48E-04	1.37E-04	1.28E-04
LA-TA-03-30	8.30E-01	4.93E-06	3.70E-02	3.58E-02	3.55E-02	3.50E-02	3.36E-02	3.10E-02	2.76E-02	2.53E-02	2.29E-02	2.08E-02
LA-TA-03-31	2.10E-01	1.25E-06	4.28E-04	2.86E-04	2.65E-04	2.33E-04	1.84E-04	1.64E-04	1.55E-04	1.46E-04	1.36E-04	1.27E-04
LA-TA-03-40	2.66E+02	1.58E-03	1.15E-06	9.73E-07	9.46E-07	9.06E-07	8.41E-07	8.05E-07	7.60E-07	7.17E-07	6.68E-07	6.21E-07
LA-TA-03-42	3.00E+02	1.78E-03	5.40E-08	4.99E-08	4.93E-08	4.83E-08	4.67E-08	4.52E-08	4.26E-08	4.01E-08	3.73E-08	3.47E-08
LA-TA-21-06	2.26E+02	1.34E-03	1.08E-03	5.02E-04	4.16E-04	2.89E-04	9.06E-05	2.30E-05	2.00E-05	1.84E-05	1.67E-05	1.52E-05
LA-TA-21-12	2.64E+02	1.57E-03	5.50E-03	2.54E-03	2.10E-03	1.44E-03	4.16E-04	7.04E-05	6.07E-05	5.59E-05	5.08E-05	4.63E-05
LA-TA-21-13	1.62E+01	9.63E-05	3.66E-04	3.22E-04	3.12E-04	2.94E-04	2.39E-04	1.30E-04	6.94E-05	6.33E-05	5.88E-05	5.48E-05
LA-TA-21-14	7.90E+00	4.69E-05	5.75E-03	3.85E-03	3.57E-03	3.15E-03	2.49E-03	2.23E-03	2.10E-03	1.98E-03	1.85E-03	1.72E-03
LA-TA-21-15	3.54E+00	2.10E-05	2.00E-03	1.97E-03	1.96E-03	1.94E-03	1.90E-03	1.81E-03	1.65E-03	1.53E-03	1.40E-03	1.28E-03
LA-TA-21-16	7.17E+01	4.25E-04	8.25E-04	8.06E-04	8.01E-04	7.93E-04	7.71E-04	7.22E-04	6.51E-04	6.00E-04	5.44E-04	4.96E-04
LA-TA-21-40	1.02E+03	6.07E-03	5.24E-06	3.09E-06	2.77E-06	2.29E-06	1.55E-06	1.28E-06	1.21E-06	1.14E-06	1.06E-06	9.87E-07
LA-TA-21-41	4.15E+01	2.46E-04	6.88E-05	6.86E-05	6.86E-05	6.85E-05	6.81E-05	6.69E-05	6.31E-05	5.96E-05	5.54E-05	5.16E-05
LA-TA-21-42	6.91E+02	4.10E-03	3.01E-06	1.96E-06	1.80E-06	1.57E-06	1.19E-06	1.01E-06	9.27E-07	8.68E-07	8.02E-07	7.41E-07
LA-TA-21-43	2.53E+03	1.50E-02	1.12E-03	1.09E-03	1.09E-03	1.08E-03	1.05E-03	9.83E-04	8.87E-04	8.17E-04	7.42E-04	6.76E-04
LA-TA-21-44	1.38E+02	8.18E-04	3.45E-03	3.40E-03	3.39E-03	3.38E-03	3.35E-03	3.28E-03	3.09E-03	2.92E-03	2.71E-03	2.53E-03
LA-TA-48-01	6.20E-01	3.68E-06	4.60E-03	4.49E-03	4.45E-03	4.39E-03	4.21E-03	3.76E-03	3.04E-03	2.55E-03	2.07E-03	1.69E-03
LA-TA-49-01	9.62E+01	5.71E-04	3.67E-03	3.58E-03	3.55E-03	3.50E-03	3.35E-03	3.00E-03	2.43E-03	2.04E-03	1.65E-03	1.35E-03
LA-TA-50-10	1.04E+00	6.174E-06	3.37E-04	2.97E-04	2.90E-04	2.78E-04	2.47E-04	1.97E-04	1.64E-04	1.54E-04	1.43E-04	1.33E-04
LA-TA-50-11	8.57E+00	5.087E-05	3.00E-04	2.93E-04	2.91E-04	2.88E-04	2.80E-04	2.62E-04	2.37E-04	2.18E-04	1.99E-04	1.81E-04
LA-TA-50-15	1.59E+02	9.446E-04	5.12E-05	3.02E-05	2.70E-05	2.22E-05	1.45E-05	1.07E-05	9.35E-06	8.61E-06	7.83E-06	7.14E-06
LA-TA-50-17	2.16E+02	1.284E-03	6.80E-04	6.20E-04	6.07E-04	5.84E-04	5.19E-04	3.94E-04	3.14E-04	2.94E-04	2.73E-04	2.54E-04
LA-TA-50-18	9.84E+01	5.842E-04	1.70E-04	1.60E-04	1.58E-04	1.54E-04	1.45E-04	1.27E-04	1.12E-04	1.05E-04	9.80E-05	9.12E-05
LA-TA-50-19	1.18E+03	7.003E-03	2.72E-06	2.42E-06	2.36E-06	2.26E-06	2.00E-06	1.55E-06	1.26E-06	1.18E-06	1.09E-06	1.02E-06

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
LA-TA-50-20	6.20E-01	3.680E-06	1.21E-04	1.12E-04	1.10E-04	1.07E-04	9.57E-05	7.31E-05	5.85E-05	5.48E-05	5.10E-05	4.75E-05
LA-TA-50-40	2.45E+01	1.456E-04	3.48E-06	3.31E-06	3.27E-06	3.19E-06	2.99E-06	2.59E-06	2.20E-06	1.99E-06	1.77E-06	1.59E-06
LA-TA-50-41	3.59E+01	2.132E-04	7.14E-06	7.04E-06	7.00E-06	6.94E-06	6.76E-06	6.35E-06	5.74E-06	5.29E-06	4.80E-06	4.38E-06
LA-TA-55-19	3.24E+03	1.925E-02	5.35E-05	5.14E-05	5.09E-05	4.99E-05	4.74E-05	4.23E-05	3.69E-05	3.39E-05	3.06E-05	2.78E-05
LA-TA-55-20	6.30E+02	3.738E-03	5.95E-03	5.81E-03	5.77E-03	5.69E-03	5.48E-03	5.02E-03	4.47E-03	4.11E-03	3.73E-03	3.40E-03
LA-TA-55-21	9.90E+01	5.876E-04	2.80E-04	2.72E-04	2.69E-04	2.65E-04	2.53E-04	2.28E-04	2.01E-04	1.85E-04	1.68E-04	1.53E-04
LA-TA-55-22	1.42E+01	8.417E-05	6.71E-03	6.46E-03	6.41E-03	6.30E-03	6.04E-03	5.53E-03	4.92E-03	4.54E-03	4.12E-03	3.75E-03
LA-TA-55-23	1.25E+01	7.408E-05	5.56E-03	5.33E-03	5.27E-03	5.17E-03	4.91E-03	4.40E-03	3.87E-03	3.56E-03	3.23E-03	2.94E-03
LA-TA-55-24	1.25E+00	7.420E-06	2.65E-02	2.60E-02	2.58E-02	2.55E-02	2.46E-02	2.25E-02	2.01E-02	1.85E-02	1.68E-02	1.53E-02
LA-TA-55-25	2.26E+01	1.344E-04	7.32E-03	7.17E-03	7.12E-03	7.02E-03	6.75E-03	6.19E-03	5.51E-03	5.07E-03	4.61E-03	4.20E-03
LA-TA-55-28	3.74E+00	2.220E-05	1.40E-02	1.36E-02	1.35E-02	1.33E-02	1.27E-02	1.16E-02	1.03E-02	9.44E-03	8.57E-03	7.81E-03
LA-TA-55-30	3.31E+03	1.966E-02	2.75E-04	2.64E-04	2.62E-04	2.57E-04	2.44E-04	2.18E-04	1.91E-04	1.75E-04	1.59E-04	1.45E-04
LA-TA-55-32	4.78E+00	2.837E-05	3.81E-02	2.53E-02	2.34E-02	2.04E-02	1.55E-02	1.26E-02	1.09E-02	1.00E-02	9.02E-03	8.18E-03
LA-TA-55-33	6.66E+00	3.953E-05	1.55E-03	1.49E-03	1.47E-03	1.44E-03	1.36E-03	1.20E-03	1.04E-03	9.50E-04	8.56E-04	7.76E-04
LA-TA-55-34	2.68E+02	1.591E-03	5.24E-03	5.09E-03	5.05E-03	4.98E-03	4.77E-03	4.34E-03	3.84E-03	3.53E-03	3.20E-03	2.91E-03
LA-TA-55-38	8.48E+02	5.035E-03	9.74E-04	8.73E-04	8.50E-04	8.06E-04	6.80E-04	4.27E-04	2.75E-04	2.48E-04	2.25E-04	2.04E-04
LA-TA-55-39	2.91E+00	1.727E-05	1.50E-01	1.47E-01	1.46E-01	1.44E-01	1.39E-01	1.28E-01	1.14E-01	1.05E-01	9.56E-02	8.72E-02
LA-TA-55-41	4.37E+01	2.594E-04	4.32E-02	3.84E-02	3.72E-02	3.51E-02	2.90E-02	1.68E-02	9.76E-03	8.77E-03	7.95E-03	7.25E-03
LA-TA-55-43	6.49E+01	3.853E-04	1.32E-02	6.00E-03	4.93E-03	3.33E-03	8.52E-04	2.44E-05	1.69E-05	1.59E-05	1.49E-05	1.40E-05
LA-TA-55-44	2.31E+02	1.369E-03	8.81E-03	4.04E-03	3.33E-03	2.27E-03	6.24E-04	6.82E-05	5.64E-05	5.21E-05	4.76E-05	4.36E-05
LA-TA-55-48	3.10E+01	1.841E-04	4.31E+00	4.05E+00	3.99E+00	3.88E+00	3.60E+00	3.09E+00	2.62E+00	2.38E+00	2.14E+00	1.93E+00
LA-TA-55-49	1.83E+01	1.086E-04	5.84E-01	2.72E-01	2.25E-01	1.55E-01	4.71E-02	9.66E-03	7.98E-03	7.33E-03	6.66E-03	6.07E-03
LA-TA-55-53	2.16E+02	1.284E-03	7.70E-03	7.43E-03	7.36E-03	7.24E-03	6.88E-03	6.13E-03	5.36E-03	4.94E-03	4.48E-03	4.09E-03
LA-TA-55-56	9.47E+02	5.622E-03	3.26E-03	2.75E-03	2.67E-03	2.53E-03	2.28E-03	2.03E-03	1.79E-03	1.65E-03	1.49E-03	1.36E-03
LA-TA-55-60	2.11E+02	1.254E-03	3.73E-06	3.11E-06	3.00E-06	2.82E-06	2.44E-06	1.97E-06	1.62E-06	1.48E-06	1.33E-06	1.20E-06
LA-TA-55-61	2.27E+02	1.344E-03	8.17E-06	5.84E-06	5.47E-06	4.91E-06	3.96E-06	3.32E-06	2.89E-06	2.64E-06	2.37E-06	2.15E-06
LA-TA-55-62	7.36E+01	4.368E-04	2.58E-06	2.46E-06	2.43E-06	2.37E-06	2.21E-06	1.91E-06	1.62E-06	1.47E-06	1.30E-06	1.17E-06

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
LA-TA-55-63	5.66E+00	3.360E-05	7.19E-05	7.08E-05	7.05E-05	6.98E-05	6.80E-05	6.40E-05	5.78E-05	5.33E-05	4.84E-05	4.41E-05
LL-M001	3.40E+01	2.018E-04	3.26E-02	2.71E-02	2.60E-02	2.42E-02	2.01E-02	1.42E-02	1.05E-02	9.40E-03	8.38E-03	7.52E-03
LL-T001	3.83E+02	2.273E-03	1.36E-02	1.33E-02	1.31E-02	1.27E-02	1.15E-02	8.96E-03	7.05E-03	6.36E-03	5.67E-03	5.09E-03
LL-T002	2.08E+03	1.235E-02	2.53E-02	2.39E-02	2.35E-02	2.26E-02	2.03E-02	1.57E-02	1.23E-02	1.11E-02	9.95E-03	8.96E-03
LL-T003	1.06E+03	6.303E-03	1.71E-03	1.53E-03	1.48E-03	1.40E-03	1.20E-03	8.46E-04	6.07E-04	5.35E-04	4.67E-04	4.11E-04
LL-T004	3.24E+01	1.922E-04	3.24E-02	3.04E-02	2.97E-02	2.84E-02	2.47E-02	1.76E-02	1.26E-02	1.11E-02	9.70E-03	8.53E-03
LL-T005	1.13E+03	6.691E-03	4.57E-03	4.08E-03	3.95E-03	3.72E-03	3.13E-03	2.07E-03	1.39E-03	1.22E-03	1.06E-03	9.31E-04
LL-W018	2.11E+00	1.253E-05	2.17E-04	2.16E-04	2.12E-04	2.04E-04	1.81E-04	1.31E-04	9.27E-05	7.86E-05	6.53E-05	5.47E-05
LL-W019	1.82E+01	1.080E-04	1.27E-02	1.21E-02	1.19E-02	1.14E-02	9.96E-03	6.99E-03	4.93E-03	4.34E-03	3.77E-03	3.32E-03
LL-W034	2.10E+01	1.245E-04	4.18E-03	3.72E-03	3.60E-03	3.39E-03	2.84E-03	1.88E-03	1.26E-03	1.10E-03	9.59E-04	8.42E-04
MC-W001	2.50E+00	1.484E-05	3.44E-04	3.09E-04	3.01E-04	2.85E-04	2.39E-04	1.45E-04	9.16E-05	8.46E-05	7.87E-05	7.32E-05
MU-W002	1.46E+00	8.667E-06	5.84E-03	5.00E-03	4.80E-03	4.45E-03	3.39E-03	1.29E-03	1.80E-04	1.28E-04	1.17E-04	1.09E-04
NT-JAS-01	9.56E+02	5.676E-03	1.71E-03	1.53E-03	1.49E-03	1.40E-03	1.20E-03	8.47E-04	6.08E-04	5.36E-04	4.68E-04	4.11E-04
NT-W001	6.32E+02	3.753E-03	2.09E-02	2.02E-02	2.01E-02	1.99E-02	1.93E-02	1.82E-02	1.68E-02	1.59E-02	1.47E-02	1.37E-02
NT-W021	5.67E+00	3.366E-05	3.23E-02	3.17E-02	3.15E-02	3.11E-02	3.01E-02	2.78E-02	2.48E-02	2.29E-02	2.08E-02	1.90E-02
OR-W201	1.21E+02	7.183E-04	4.28E-01	3.74E-01	3.60E-01	3.36E-01	2.78E-01	1.82E-01	1.21E-01	1.06E-01	9.15E-02	8.00E-02
OR-W202	5.86E+02	3.480E-03	5.86E-02	3.35E-02	2.96E-02	2.38E-02	1.41E-02	8.48E-03	6.30E-03	5.53E-03	4.78E-03	4.17E-03
OR-W203	2.00E+02	1.189E-03	9.60E-05	8.18E-05	7.88E-05	7.36E-05	6.13E-05	4.15E-05	2.68E-05	2.15E-05	1.66E-05	1.28E-05
OR-W204	3.86E+01	2.290E-04	2.35E-04	1.67E-04	1.56E-04	1.40E-04	1.09E-04	8.04E-05	6.29E-05	5.61E-05	4.93E-05	4.36E-05
PA-A015	1.76E+01	1.046E-04	9.74E-05	9.71E-05	9.71E-05	9.69E-05	9.64E-05	9.46E-05	8.93E-05	8.43E-05	7.85E-05	7.30E-05
RF-MT0001	8.15E+00	4.838E-05	1.05E+00	9.10E-01	8.78E-01	8.19E-01	6.46E-01	3.01E-01	1.13E-01	9.72E-02	8.81E-02	8.03E-02
RF-MT0002	6.30E-01	3.740E-06	1.04E+00	9.05E-01	8.74E-01	8.15E-01	6.43E-01	2.99E-01	1.12E-01	9.69E-02	8.77E-02	8.00E-02
RF-MT0003	1.67E+00	9.913E-06	1.19E-02	1.17E-02	1.16E-02	1.14E-02	1.10E-02	1.01E-02	9.03E-03	8.33E-03	7.56E-03	6.90E-03
RF-MT0007	8.30E-01	4.927E-06	1.05E-02	9.37E-03	9.10E-03	8.59E-03	7.09E-03	4.07E-03	2.33E-03	2.09E-03	1.90E-03	1.73E-03
RF-MT0089	4.20E-01	2.493E-06	4.72E-04	4.63E-04	4.59E-04	4.53E-04	4.37E-04	4.02E-04	3.59E-04	3.31E-04	3.01E-04	2.74E-04
RF-MT0090	2.50E+00	1.484E-05	2.03E-01	1.98E-01	1.97E-01	1.94E-01	1.88E-01	1.73E-01	1.55E-01	1.43E-01	1.30E-01	1.18E-01
RF-MT0091	1.49E+02	8.835E-04	2.27E-01	2.21E-01	2.20E-01	2.17E-01	2.10E-01	1.94E-01	1.74E-01	1.60E-01	1.46E-01	1.33E-01

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-MT0092	2.15E+01	1.274E-04	2.26E-01	2.20E-01	2.19E-01	2.16E-01	2.09E-01	1.93E-01	1.73E-01	1.60E-01	1.45E-01	1.32E-01
RF-MT0093	2.34E+01	1.386E-04	2.28E-01	2.22E-01	2.20E-01	2.18E-01	2.10E-01	1.93E-01	1.72E-01	1.59E-01	1.44E-01	1.31E-01
RF-MT0097	1.46E+00	8.667E-06	1.85E-01	1.80E-01	1.79E-01	1.77E-01	1.71E-01	1.57E-01	1.41E-01	1.30E-01	1.19E-01	1.08E-01
RF-MT0099	6.30E-01	3.740E-06	4.71E-04	4.62E-04	4.59E-04	4.53E-04	4.36E-04	4.02E-04	3.59E-04	3.31E-04	3.00E-04	2.74E-04
RF-MT0290	1.90E+01	1.126E-04	3.88E-02	3.80E-02	3.77E-02	3.72E-02	3.59E-02	3.30E-02	2.95E-02	2.72E-02	2.47E-02	2.25E-02
RF-MT-0292	2.40E+01	1.423E-04	3.88E-02	3.81E-02	3.78E-02	3.73E-02	3.59E-02	3.31E-02	2.95E-02	2.72E-02	2.47E-02	2.26E-02
RF-MT-0299	3.11E+01	1.844E-04	1.13E+00	1.06E+00	1.05E+00	1.01E+00	9.18E-01	7.27E-01	5.87E-01	5.39E-01	4.89E-01	4.46E-01
RF-MT0302	4.20E-01	2.493E-06	2.65E-03	2.57E-03	2.55E-03	2.51E-03	2.38E-03	2.13E-03	1.87E-03	1.72E-03	1.56E-03	1.42E-03
RF-MT0320	7.09E+00	4.209E-05	1.60E-01	1.54E-01	1.53E-01	1.50E-01	1.41E-01	1.24E-01	1.07E-01	9.89E-02	8.99E-02	8.20E-02
RF-MT0321	4.16E+01	2.469E-04	1.03E-02	9.72E-03	9.58E-03	9.32E-03	8.59E-03	7.09E-03	5.90E-03	5.42E-03	4.92E-03	4.49E-03
RF-MT-0328	3.24E+00	1.923E-05	1.25E-02	1.21E-02	1.19E-02	1.17E-02	1.10E-02	9.54E-03	8.23E-03	7.57E-03	6.88E-03	6.28E-03
RF-MT0330	4.88E+00	2.897E-05	1.49E-01	1.45E-01	1.44E-01	1.43E-01	1.37E-01	1.26E-01	1.12E-01	1.03E-01	9.31E-02	8.48E-02
RF-MT-0331	2.46E+01	1.460E-04	1.35E-01	1.31E-01	1.30E-01	1.28E-01	1.22E-01	1.09E-01	9.59E-02	8.84E-02	8.03E-02	7.33E-02
RF-MT0332	1.46E+00	8.667E-06	4.76E-04	4.66E-04	4.63E-04	4.57E-04	4.40E-04	4.05E-04	3.62E-04	3.34E-04	3.03E-04	2.77E-04
RF-MT-0335	8.30E-01	4.927E-06	4.63E-02	4.50E-02	4.45E-02	4.38E-02	4.17E-02	3.74E-02	3.29E-02	3.03E-02	2.75E-02	2.51E-02
RF-MT0336	1.43E+01	8.483E-05	1.91E-01	1.85E-01	1.83E-01	1.80E-01	1.72E-01	1.54E-01	1.35E-01	1.25E-01	1.13E-01	1.03E-01
RF-MT0337	1.40E+01	8.293E-05	1.17E-01	1.14E-01	1.13E-01	1.11E-01	1.06E-01	9.56E-02	8.43E-02	7.77E-02	7.06E-02	6.44E-02
RF-MT0339	2.60E+02	1.544E-03	1.44E-02	1.40E-02	1.38E-02	1.36E-02	1.29E-02	1.14E-02	9.94E-03	9.16E-03	8.32E-03	7.59E-03
RF-MT-0342	4.20E-01	2.493E-06	7.61E-02	7.42E-02	7.36E-02	7.26E-02	6.98E-02	6.38E-02	5.68E-02	5.24E-02	4.76E-02	4.34E-02
RF-MT0371	2.04E+01	1.213E-04	3.39E-01	3.28E-01	3.24E-01	3.18E-01	3.00E-01	2.64E-01	2.29E-01	2.11E-01	1.92E-01	1.75E-01
RF-MT-0372	1.46E+00	8.667E-06	3.03E-02	2.96E-02	2.93E-02	2.89E-02	2.77E-02	2.52E-02	2.23E-02	2.06E-02	1.87E-02	1.71E-02
RF-MT0373	3.96E+00	2.351E-05	2.02E-01	1.98E-01	1.96E-01	1.94E-01	1.87E-01	1.73E-01	1.54E-01	1.42E-01	1.29E-01	1.18E-01
RF-MT0374	6.30E-01	3.740E-06	2.73E-02	2.65E-02	2.63E-02	2.58E-02	2.46E-02	2.19E-02	1.92E-02	1.77E-02	1.61E-02	1.47E-02
RF-MT0376	2.10E-01	1.247E-06	7.85E-02	7.65E-02	7.59E-02	7.48E-02	7.17E-02	6.51E-02	5.76E-02	5.31E-02	4.82E-02	4.40E-02
RF-MT0377	7.44E+01	4.418E-04	1.08E-01	1.05E-01	1.04E-01	1.02E-01	9.69E-02	8.65E-02	7.58E-02	6.98E-02	6.34E-02	5.79E-02
RF-MT0378	6.30E-01	3.740E-06	1.69E-01	1.65E-01	1.64E-01	1.61E-01	1.54E-01	1.40E-01	1.24E-01	1.14E-01	1.03E-01	9.43E-02
RF-MT0419	4.79E+00	2.843E-05	2.33E-02	2.24E-02	2.22E-02	2.17E-02	2.04E-02	1.77E-02	1.52E-02	1.40E-02	1.27E-02	1.16E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-MT0420	8.30E-01	4.927E-06	2.34E-02	2.25E-02	2.22E-02	2.17E-02	2.04E-02	1.77E-02	1.52E-02	1.40E-02	1.27E-02	1.16E-02
RF-MT0423	1.04E+00	6.174E-06	2.40E-01	2.32E-01	2.31E-01	2.27E-01	2.18E-01	1.97E-01	1.74E-01	1.61E-01	1.46E-01	1.33E-01
RF-MT0425	2.10E-01	1.247E-06	2.31E-02	2.22E-02	2.20E-02	2.15E-02	2.02E-02	1.75E-02	1.50E-02	1.38E-02	1.26E-02	1.15E-02
RF-MT-0438	6.30E-01	3.740E-06	1.19E-01	1.16E-01	1.15E-01	1.14E-01	1.09E-01	9.98E-02	8.87E-02	8.18E-02	7.43E-02	6.78E-02
RF-MT0440	2.29E+00	1.359E-05	1.19E-02	1.17E-02	1.16E-02	1.14E-02	1.10E-02	1.00E-02	8.88E-03	8.18E-03	7.43E-03	6.78E-03
RF-MT0442	8.30E-01	4.927E-06	1.15E-02	1.12E-02	1.11E-02	1.09E-02	1.04E-02	9.46E-03	8.37E-03	7.72E-03	7.01E-03	6.40E-03
RF-MT0443	1.94E+01	1.151E-04	7.36E-03	7.20E-03	7.15E-03	7.05E-03	6.79E-03	6.24E-03	5.57E-03	5.13E-03	4.66E-03	4.25E-03
RF-MT0444	4.51E+01	2.675E-04	1.65E-02	1.60E-02	1.59E-02	1.56E-02	1.48E-02	1.32E-02	1.15E-02	1.06E-02	9.66E-03	8.81E-03
RF-MT0480	1.19E+02	7.076E-04	1.76E-02	1.70E-02	1.68E-02	1.65E-02	1.57E-02	1.40E-02	1.23E-02	1.13E-02	1.03E-02	9.36E-03
RF-MT0488	5.25E+02	3.114E-03	6.00E-03	5.81E-03	5.76E-03	5.65E-03	5.35E-03	4.74E-03	4.13E-03	3.81E-03	3.46E-03	3.16E-03
RF-MT0490	1.89E+00	1.122E-05	9.36E-03	9.12E-03	9.04E-03	8.90E-03	8.50E-03	7.68E-03	6.78E-03	6.25E-03	5.68E-03	5.18E-03
RF-MT-0491	6.30E-01	3.740E-06	1.44E-03	1.38E-03	1.36E-03	1.33E-03	1.25E-03	1.08E-03	9.24E-04	8.50E-04	7.73E-04	7.05E-04
RF-MT0523A	1.08E+01	6.435E-05	6.59E-02	6.33E-02	6.26E-02	6.12E-02	5.74E-02	4.95E-02	4.24E-02	3.90E-02	3.55E-02	3.23E-02
RF-MT0523B	1.08E+01	6.435E-05	6.59E-02	6.33E-02	6.26E-02	6.12E-02	5.74E-02	4.95E-02	4.24E-02	3.90E-02	3.55E-02	3.23E-02
RF-MT0523C	1.08E+01	6.435E-05	6.59E-02	6.33E-02	6.26E-02	6.12E-02	5.74E-02	4.95E-02	4.24E-02	3.90E-02	3.55E-02	3.23E-02
RF-MT0523D	1.08E+01	6.435E-05	6.59E-02	6.33E-02	6.26E-02	6.12E-02	5.74E-02	4.95E-02	4.24E-02	3.90E-02	3.55E-02	3.23E-02
RF-MT0523E	1.08E+01	6.435E-05	6.59E-02	6.33E-02	6.26E-02	6.12E-02	5.74E-02	4.95E-02	4.24E-02	3.90E-02	3.55E-02	3.23E-02
RF-MT0531	2.10E-01	1.247E-06	4.71E-04	4.62E-04	4.58E-04	4.52E-04	4.36E-04	4.01E-04	3.58E-04	3.30E-04	3.00E-04	2.74E-04
RF-MT0532E	1.56E+01	9.278E-05	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.38E-02	7.73E-02	6.42E-02	5.90E-02	5.36E-02	4.89E-02
RF-MT0532F	1.56E+01	9.278E-05	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.38E-02	7.73E-02	6.42E-02	5.90E-02	5.36E-02	4.89E-02
RF-MT0541	4.38E+00	2.600E-05	8.77E-03	8.02E-03	7.84E-03	7.50E-03	6.52E-03	4.54E-03	3.28E-03	2.99E-03	2.72E-03	2.48E-03
RF-MT0545	2.10E-01	1.247E-06	4.29E-03	4.21E-03	4.18E-03	4.12E-03	3.97E-03	3.66E-03	3.27E-03	3.01E-03	2.74E-03	2.50E-03
RF-MT0800	6.25E+01	3.709E-04	7.85E-02	6.78E-02	6.53E-02	6.07E-02	4.73E-02	2.04E-02	6.00E-03	5.02E-03	4.54E-03	4.14E-03
RF-MT0801	1.03E+02	6.082E-04	8.77E-03	8.02E-03	7.84E-03	7.50E-03	6.52E-03	4.54E-03	3.28E-03	2.99E-03	2.72E-03	2.48E-03
RF-MT0803	2.29E+00	1.359E-05	8.79E-03	8.04E-03	7.85E-03	7.51E-03	6.53E-03	4.54E-03	3.28E-03	2.99E-03	2.72E-03	2.48E-03
RF-MT0806	2.10E-01	1.247E-06	2.01E-01	1.96E-01	1.95E-01	1.93E-01	1.86E-01	1.72E-01	1.54E-01	1.42E-01	1.29E-01	1.17E-01
RF-MT0807	8.42E+01	4.997E-04	2.69E-03	2.56E-03	2.53E-03	2.47E-03	2.29E-03	1.94E-03	1.64E-03	1.50E-03	1.37E-03	1.25E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-MT0816	4.20E-01	2.493E-06	7.03E-02	6.77E-02	6.69E-02	6.55E-02	6.16E-02	5.35E-02	4.62E-02	4.25E-02	3.86E-02	3.52E-02
RF-MT-0823	2.10E-01	1.247E-06	6.55E-02	6.29E-02	6.22E-02	6.08E-02	5.70E-02	4.91E-02	4.21E-02	3.88E-02	3.52E-02	3.21E-02
RF-MT0827	1.05E+01	6.257E-05	7.08E-02	6.81E-02	6.74E-02	6.60E-02	6.20E-02	5.40E-02	4.65E-02	4.28E-02	3.89E-02	3.55E-02
RF-MT0831	5.99E+01	3.557E-04	3.12E-02	3.03E-02	3.00E-02	2.95E-02	2.81E-02	2.52E-02	2.21E-02	2.04E-02	1.85E-02	1.69E-02
RF-MT0832	1.94E+02	1.153E-03	4.13E-02	3.96E-02	3.92E-02	3.83E-02	3.59E-02	3.10E-02	2.66E-02	2.45E-02	2.22E-02	2.03E-02
RF-MT0833	1.21E+02	7.173E-04	1.95E-02	1.87E-02	1.84E-02	1.80E-02	1.69E-02	1.45E-02	1.24E-02	1.14E-02	1.03E-02	9.42E-03
RF-MT0855	1.67E+00	9.913E-06	5.09E-04	4.99E-04	4.95E-04	4.89E-04	4.71E-04	4.34E-04	3.87E-04	3.57E-04	3.24E-04	2.96E-04
RF-MT0857	2.10E-01	1.247E-06	2.01E-01	1.96E-01	1.95E-01	1.93E-01	1.86E-01	1.71E-01	1.53E-01	1.41E-01	1.28E-01	1.17E-01
RF-MT0H61	7.71E+00	4.577E-05	2.03E-01	1.98E-01	1.97E-01	1.94E-01	1.88E-01	1.73E-01	1.55E-01	1.43E-01	1.30E-01	1.18E-01
RF-MT2116	2.08E+00	1.235E-05	4.12E-02	3.96E-02	3.91E-02	3.83E-02	3.59E-02	3.09E-02	2.65E-02	2.44E-02	2.22E-02	2.02E-02
RF-MT3010	5.58E+01	3.315E-04	1.38E-02	1.34E-02	1.33E-02	1.30E-02	1.24E-02	1.11E-02	9.80E-03	9.03E-03	8.20E-03	7.48E-03
RF-MT3011	5.03E+02	2.987E-03	9.78E-03	9.47E-03	9.37E-03	9.20E-03	8.71E-03	7.71E-03	6.72E-03	6.18E-03	5.62E-03	5.12E-03
RF-MT420P	1.61E+02	9.554E-04	2.32E-01	2.26E-01	2.24E-01	2.21E-01	2.13E-01	1.94E-01	1.72E-01	1.59E-01	1.44E-01	1.32E-01
RF-MT532A	3.86E+01	2.290E-04	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.38E-02	7.73E-02	6.43E-02	5.91E-02	5.37E-02	4.90E-02
RF-MT532B	1.73E+02	1.028E-03	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.38E-02	7.73E-02	6.43E-02	5.91E-02	5.37E-02	4.90E-02
RF-MT532C	3.47E+02	2.061E-03	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.37E-02	7.73E-02	6.43E-02	5.90E-02	5.36E-02	4.89E-02
RF-MT532D	2.19E+00	1.300E-05	1.12E-01	1.07E-01	1.05E-01	1.02E-01	9.40E-02	7.75E-02	6.45E-02	5.92E-02	5.38E-02	4.91E-02
RF-TT0069	2.10E-01	1.247E-06	1.12E-02	1.09E-02	1.07E-02	1.06E-02	1.00E-02	8.89E-03	7.77E-03	7.16E-03	6.50E-03	5.93E-03
RF-TT0200	6.30E-01	3.740E-06	1.58E-01	1.53E-01	1.51E-01	1.48E-01	1.40E-01	1.23E-01	1.06E-01	9.79E-02	8.90E-02	8.11E-02
RF-TT0299	2.10E-01	1.247E-06	1.12E+00	1.06E+00	1.04E+00	1.01E+00	9.11E-01	7.23E-01	5.84E-01	5.35E-01	4.86E-01	4.44E-01
RF-TT0300	4.31E+01	2.557E-04	1.11E-01	1.08E-01	1.08E-01	1.06E-01	1.01E-01	9.19E-02	8.13E-02	7.50E-02	6.81E-02	6.21E-02
RF-TT0301	5.84E+00	3.467E-05	1.12E-01	1.09E-01	1.08E-01	1.06E-01	1.02E-01	9.22E-02	8.16E-02	7.52E-02	6.84E-02	6.23E-02
RF-TT0302	9.91E+00	5.883E-05	2.67E-03	2.60E-03	2.57E-03	2.53E-03	2.40E-03	2.15E-03	1.88E-03	1.73E-03	1.57E-03	1.44E-03
RF-TT0303	1.25E+00	7.420E-06	1.17E-01	1.13E-01	1.12E-01	1.10E-01	1.04E-01	9.19E-02	8.01E-02	7.38E-02	6.71E-02	6.12E-02
RF-TT0310	3.13E+00	1.858E-05	2.00E-01	1.95E-01	1.93E-01	1.90E-01	1.81E-01	1.64E-01	1.45E-01	1.33E-01	1.21E-01	1.10E-01
RF-TT0312	5.80E+01	3.440E-04	2.38E-01	2.31E-01	2.29E-01	2.25E-01	2.15E-01	1.93E-01	1.70E-01	1.56E-01	1.42E-01	1.30E-01
RF-TT0317	2.10E-01	1.247E-06	5.78E-02	5.67E-02	5.63E-02	5.55E-02	5.35E-02	4.92E-02	4.39E-02	4.05E-02	3.68E-02	3.35E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-TT0320	2.80E+01	1.664E-04	1.60E-01	1.54E-01	1.53E-01	1.50E-01	1.41E-01	1.24E-01	1.07E-01	9.89E-02	8.99E-02	8.20E-02
RF-TT0330	1.71E+01	1.014E-04	1.49E-01	1.46E-01	1.45E-01	1.43E-01	1.37E-01	1.26E-01	1.12E-01	1.03E-01	9.33E-02	8.50E-02
RF-TT-0331	7.15E+01	4.244E-04	1.35E-01	1.31E-01	1.30E-01	1.28E-01	1.22E-01	1.09E-01	9.58E-02	8.83E-02	8.02E-02	7.32E-02
RF-TT-0334	4.70E+00	2.790E-05	1.21E+00	1.18E+00	1.17E+00	1.16E+00	1.11E+00	1.02E+00	9.07E-01	8.37E-01	7.60E-01	6.93E-01
RF-TT0335	1.11E+02	6.600E-04	4.61E-02	4.47E-02	4.43E-02	4.36E-02	4.15E-02	3.72E-02	3.27E-02	3.01E-02	2.74E-02	2.49E-02
RF-TT0336	2.38E+01	1.412E-04	1.91E-01	1.85E-01	1.83E-01	1.80E-01	1.72E-01	1.54E-01	1.35E-01	1.25E-01	1.13E-01	1.03E-01
RF-TT0337	4.91E+01	2.915E-04	1.17E-01	1.14E-01	1.13E-01	1.11E-01	1.06E-01	9.56E-02	8.43E-02	7.77E-02	7.06E-02	6.44E-02
RF-TT0338	1.53E+02	9.092E-04	1.49E-01	1.44E-01	1.43E-01	1.40E-01	1.34E-01	1.20E-01	1.05E-01	9.71E-02	8.83E-02	8.05E-02
RF-TT0340	7.30E+00	4.333E-05	3.87E-02	3.80E-02	3.77E-02	3.72E-02	3.59E-02	3.30E-02	2.95E-02	2.72E-02	2.47E-02	2.25E-02
RF-TT0342	2.21E+01	1.312E-04	7.66E-02	7.47E-02	7.41E-02	7.31E-02	7.03E-02	6.43E-02	5.72E-02	5.27E-02	4.79E-02	4.37E-02
RF-TT0360	6.30E-01	3.740E-06	1.33E-01	1.29E-01	1.28E-01	1.25E-01	1.18E-01	1.04E-01	9.05E-02	8.33E-02	7.57E-02	6.90E-02
RF-TT0368	1.25E+01	7.426E-05	1.35E-01	1.30E-01	1.29E-01	1.26E-01	1.19E-01	1.05E-01	9.14E-02	8.42E-02	7.65E-02	6.97E-02
RF-TT0370	1.71E+01	1.014E-04	2.14E-01	2.07E-01	2.05E-01	2.01E-01	1.91E-01	1.70E-01	1.49E-01	1.37E-01	1.25E-01	1.14E-01
RF-TT0371	2.10E-01	1.247E-06	3.36E-01	3.25E-01	3.21E-01	3.15E-01	2.98E-01	2.62E-01	2.27E-01	2.09E-01	1.90E-01	1.73E-01
RF-TT0372	4.20E-01	2.493E-06	3.01E-02	2.93E-02	2.91E-02	2.87E-02	2.75E-02	2.50E-02	2.22E-02	2.04E-02	1.86E-02	1.69E-02
RF-TT0374	1.14E+01	6.749E-05	2.75E-02	2.67E-02	2.65E-02	2.60E-02	2.47E-02	2.21E-02	1.94E-02	1.78E-02	1.62E-02	1.48E-02
RF-TT0375A	3.05E+00	1.811E-05	1.56E-03	1.53E-03	1.52E-03	1.50E-03	1.44E-03	1.33E-03	1.19E-03	1.09E-03	9.93E-04	9.05E-04
RF-TT0375B	3.05E+00	1.811E-05	1.56E-03	1.53E-03	1.52E-03	1.50E-03	1.44E-03	1.33E-03	1.19E-03	1.09E-03	9.93E-04	9.05E-04
RF-TT0376	1.15E+01	6.803E-05	7.92E-02	7.72E-02	7.66E-02	7.54E-02	7.23E-02	6.56E-02	5.81E-02	5.35E-02	4.86E-02	4.43E-02
RF-TT0377	3.86E+00	2.291E-05	1.08E-01	1.05E-01	1.04E-01	1.02E-01	9.68E-02	8.64E-02	7.57E-02	6.98E-02	6.34E-02	5.78E-02
RF-TT0391	4.20E-01	2.493E-06	2.43E-01	2.37E-01	2.35E-01	2.31E-01	2.21E-01	1.99E-01	1.76E-01	1.62E-01	1.47E-01	1.34E-01
RF-TT0392	2.10E-01	1.247E-06	2.41E-01	2.35E-01	2.34E-01	2.31E-01	2.23E-01	2.05E-01	1.84E-01	1.69E-01	1.54E-01	1.40E-01
RF-TT0393	1.11E+01	6.559E-05	2.34E-01	2.27E-01	2.25E-01	2.21E-01	2.09E-01	1.86E-01	1.63E-01	1.50E-01	1.36E-01	1.24E-01
RF-TT0398	4.20E-01	2.493E-06	2.24E-01	2.19E-01	2.17E-01	2.15E-01	2.07E-01	1.92E-01	1.71E-01	1.58E-01	1.44E-01	1.31E-01
RF-TT0409	2.10E-01	1.247E-06	2.49E-01	2.41E-01	2.39E-01	2.35E-01	2.24E-01	2.01E-01	1.77E-01	1.63E-01	1.48E-01	1.35E-01
RF-TT0412	2.10E-01	1.247E-06	2.49E-01	2.41E-01	2.39E-01	2.35E-01	2.24E-01	2.01E-01	1.77E-01	1.63E-01	1.48E-01	1.35E-01
RF-TT0414	6.46E+00	3.835E-05	2.51E-01	2.43E-01	2.40E-01	2.37E-01	2.26E-01	2.03E-01	1.78E-01	1.64E-01	1.49E-01	1.36E-01

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-TT0430	2.10E-01	1.247E-06	3.20E-03	3.14E-03	3.12E-03	3.08E-03	2.96E-03	2.73E-03	2.44E-03	2.25E-03	2.04E-03	1.86E-03
RF-TT0431	2.28E+01	1.355E-04	7.26E-03	7.12E-03	7.06E-03	6.97E-03	6.71E-03	6.18E-03	5.51E-03	5.08E-03	4.62E-03	4.21E-03
RF-TT0438	7.21E+01	4.279E-04	1.20E-01	1.17E-01	1.16E-01	1.14E-01	1.10E-01	1.00E-01	8.90E-02	8.21E-02	7.46E-02	6.80E-02
RF-TT0440	7.17E+01	4.259E-04	1.19E-02	1.16E-02	1.15E-02	1.14E-02	1.09E-02	9.98E-03	8.87E-03	8.17E-03	7.42E-03	6.76E-03
RF-TT0441	1.45E+02	8.605E-04	2.16E-02	2.10E-02	2.08E-02	2.04E-02	1.94E-02	1.73E-02	1.51E-02	1.39E-02	1.27E-02	1.15E-02
RF-TT0442	4.86E+01	2.886E-04	1.14E-02	1.11E-02	1.10E-02	1.09E-02	1.04E-02	9.42E-03	8.34E-03	7.69E-03	6.98E-03	6.37E-03
RF-TT0443	1.97E+00	1.169E-05	7.36E-03	7.20E-03	7.15E-03	7.05E-03	6.79E-03	6.24E-03	5.57E-03	5.13E-03	4.66E-03	4.25E-03
RF-TT0479	1.04E+00	6.174E-06	1.40E-01	1.38E-01	1.37E-01	1.35E-01	1.30E-01	1.20E-01	1.07E-01	9.84E-02	8.94E-02	8.16E-02
RF-TT0480	3.70E+02	2.196E-03	1.76E-02	1.70E-02	1.69E-02	1.66E-02	1.57E-02	1.40E-02	1.23E-02	1.13E-02	1.03E-02	9.38E-03
RF-TT0481	2.10E-01	1.247E-06	1.74E-02	1.69E-02	1.67E-02	1.64E-02	1.56E-02	1.39E-02	1.22E-02	1.12E-02	1.02E-02	9.29E-03
RF-TT0483	8.30E-01	4.927E-06	2.18E-02	2.13E-02	2.12E-02	2.09E-02	2.01E-02	1.85E-02	1.66E-02	1.53E-02	1.39E-02	1.27E-02
RF-TT0484	9.80E+00	5.817E-05	7.91E-03	7.72E-03	7.66E-03	7.54E-03	7.22E-03	6.55E-03	5.80E-03	5.35E-03	4.86E-03	4.43E-03
RF-TT0485	5.42E+00	3.217E-05	9.31E-04	9.03E-04	8.94E-04	8.78E-04	8.33E-04	7.41E-04	6.48E-04	5.97E-04	5.42E-04	4.94E-04
RF-TT0486	1.44E+01	8.536E-05	2.08E-03	2.02E-03	2.00E-03	1.96E-03	1.86E-03	1.66E-03	1.45E-03	1.33E-03	1.21E-03	1.11E-03
RF-TT0487	2.82E+00	1.674E-05	4.12E-02	3.96E-02	3.91E-02	3.83E-02	3.59E-02	3.10E-02	2.65E-02	2.44E-02	2.22E-02	2.02E-02
RF-TT0489	9.38E+00	5.568E-05	4.80E-03	4.66E-03	4.62E-03	4.54E-03	4.32E-03	3.86E-03	3.39E-03	3.12E-03	2.83E-03	2.58E-03
RF-TT0490	3.02E+02	1.790E-03	9.37E-03	9.12E-03	9.05E-03	8.90E-03	8.51E-03	7.69E-03	6.79E-03	6.26E-03	5.68E-03	5.18E-03
RF-TT0491	2.96E+01	1.754E-04	1.44E-03	1.39E-03	1.37E-03	1.34E-03	1.26E-03	1.08E-03	9.29E-04	8.55E-04	7.77E-04	7.08E-04
RF-TT0492	1.89E+00	1.122E-05	1.13E-02	1.10E-02	1.09E-02	1.07E-02	1.02E-02	9.19E-03	8.10E-03	7.46E-03	6.78E-03	6.18E-03
RF-TT0523A	1.46E+00	8.667E-06	6.58E-02	6.32E-02	6.25E-02	6.11E-02	5.72E-02	4.94E-02	4.23E-02	3.89E-02	3.54E-02	3.23E-02
RF-TT0523B	1.46E+00	8.667E-06	6.58E-02	6.32E-02	6.25E-02	6.11E-02	5.72E-02	4.94E-02	4.23E-02	3.89E-02	3.54E-02	3.23E-02
RF-TT0523C	1.46E+00	8.667E-06	6.58E-02	6.32E-02	6.25E-02	6.11E-02	5.72E-02	4.94E-02	4.23E-02	3.89E-02	3.54E-02	3.23E-02
RF-TT0523D	1.46E+00	8.667E-06	6.58E-02	6.32E-02	6.25E-02	6.11E-02	5.72E-02	4.94E-02	4.23E-02	3.89E-02	3.54E-02	3.23E-02
RF-TT0523E	1.46E+00	8.667E-06	6.58E-02	6.32E-02	6.25E-02	6.11E-02	5.72E-02	4.94E-02	4.23E-02	3.89E-02	3.54E-02	3.23E-02
RF-TT0532A	1.66E+01	9.830E-05	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.39E-02	7.74E-02	6.43E-02	5.91E-02	5.37E-02	4.90E-02
RF-TT0532B	1.66E+01	9.830E-05	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.39E-02	7.74E-02	6.43E-02	5.91E-02	5.37E-02	4.90E-02
RF-TT0541	2.10E-01	1.247E-06	3.85E-02	3.78E-02	3.75E-02	3.70E-02	3.57E-02	3.29E-02	2.93E-02	2.71E-02	2.46E-02	2.24E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-TT0545	4.20E-01	2.493E-06	4.28E-03	4.20E-03	4.17E-03	4.11E-03	3.96E-03	3.65E-03	3.26E-03	3.00E-03	2.73E-03	2.49E-03
RF-TT0601	2.71E+00	1.609E-05	1.35E-01	1.30E-01	1.29E-01	1.26E-01	1.19E-01	1.05E-01	9.14E-02	8.42E-02	7.64E-02	6.97E-02
RF-TT0802	5.71E+01	3.387E-04	5.52E-01	5.28E-01	5.21E-01	5.09E-01	4.74E-01	4.03E-01	3.42E-01	3.15E-01	2.86E-01	2.61E-01
RF-TT0809	4.70E+00	2.790E-05	5.51E-01	5.27E-01	5.20E-01	5.08E-01	4.73E-01	4.03E-01	3.42E-01	3.15E-01	2.86E-01	2.61E-01
RF-TT0821	2.48E+02	1.470E-03	3.57E-02	3.46E-02	3.43E-02	3.38E-02	3.22E-02	2.89E-02	2.55E-02	2.35E-02	2.13E-02	1.94E-02
RF-TT0822	2.60E+02	1.540E-03	2.78E-02	2.67E-02	2.64E-02	2.59E-02	2.43E-02	2.11E-02	1.82E-02	1.68E-02	1.52E-02	1.39E-02
RF-TT0823	2.10E-01	1.247E-06	6.55E-02	6.29E-02	6.22E-02	6.08E-02	5.70E-02	4.91E-02	4.21E-02	3.88E-02	3.52E-02	3.21E-02
RF-TT0824	1.24E+03	7.339E-03	1.48E-02	1.43E-02	1.42E-02	1.40E-02	1.32E-02	1.18E-02	1.03E-02	9.48E-03	8.62E-03	7.86E-03
RF-TT0825	6.34E+02	3.760E-03	2.22E-02	2.15E-02	2.12E-02	2.08E-02	1.97E-02	1.74E-02	1.51E-02	1.39E-02	1.27E-02	1.15E-02
RF-TT0832	2.12E+02	1.257E-03	4.11E-02	3.95E-02	3.90E-02	3.82E-02	3.58E-02	3.09E-02	2.65E-02	2.44E-02	2.21E-02	2.02E-02
RF-TT0854	2.82E+00	1.674E-05	2.24E-03	2.20E-03	2.19E-03	2.16E-03	2.08E-03	1.91E-03	1.71E-03	1.57E-03	1.43E-03	1.30E-03
RF-TT0886	2.10E-01	1.247E-06	4.27E-03	4.19E-03	4.16E-03	4.10E-03	3.95E-03	3.64E-03	3.25E-03	3.00E-03	2.72E-03	2.48E-03
RF-TT2216	3.13E+00	1.858E-05	4.12E-02	3.96E-02	3.91E-02	3.83E-02	3.59E-02	3.10E-02	2.66E-02	2.44E-02	2.22E-02	2.03E-02
RF-TT3010	7.13E+02	4.235E-03	1.38E-02	1.34E-02	1.33E-02	1.30E-02	1.24E-02	1.12E-02	9.81E-03	9.04E-03	8.21E-03	7.49E-03
RF-TT3011	2.18E+03	1.293E-02	9.78E-03	9.47E-03	9.37E-03	9.19E-03	8.71E-03	7.70E-03	6.71E-03	6.18E-03	5.62E-03	5.12E-03
RF-TT301U	1.56E+01	9.278E-05	1.41E-01	1.37E-01	1.36E-01	1.34E-01	1.28E-01	1.15E-01	1.02E-01	9.38E-02	8.52E-02	7.77E-02
RF-TT310P	2.71E+00	1.609E-05	2.64E-01	2.57E-01	2.55E-01	2.51E-01	2.41E-01	2.20E-01	1.95E-01	1.80E-01	1.64E-01	1.50E-01
RF-TT338S	4.20E-01	2.493E-06	5.77E-02	5.66E-02	5.62E-02	5.54E-02	5.34E-02	4.91E-02	4.38E-02	4.04E-02	3.67E-02	3.35E-02
RF-TT390P	4.20E-01	2.493E-06	2.83E-01	2.76E-01	2.74E-01	2.70E-01	2.60E-01	2.37E-01	2.11E-01	1.95E-01	1.77E-01	1.62E-01
RF-TT391P	2.27E+01	1.349E-04	2.45E-01	2.38E-01	2.36E-01	2.33E-01	2.23E-01	2.01E-01	1.77E-01	1.63E-01	1.48E-01	1.35E-01
RF-TT392P	6.52E+01	3.873E-04	2.42E-01	2.37E-01	2.35E-01	2.32E-01	2.24E-01	2.07E-01	1.85E-01	1.70E-01	1.55E-01	1.41E-01
RF-TT393R	1.25E+01	7.426E-05	1.93E-01	1.88E-01	1.87E-01	1.85E-01	1.79E-01	1.65E-01	1.48E-01	1.36E-01	1.24E-01	1.13E-01
RF-TT394P	6.20E-01	3.680E-06	3.19E-01	3.09E-01	3.06E-01	3.02E-01	2.88E-01	2.58E-01	2.27E-01	2.10E-01	1.91E-01	1.74E-01
RF-TT395P	8.30E-01	4.927E-06	3.19E-01	3.09E-01	3.06E-01	3.01E-01	2.87E-01	2.58E-01	2.27E-01	2.10E-01	1.91E-01	1.74E-01
RF-TT396P	2.10E-01	1.247E-06	3.15E-01	3.05E-01	3.02E-01	2.98E-01	2.84E-01	2.55E-01	2.24E-01	2.07E-01	1.88E-01	1.72E-01
RF-TT398P	4.32E+01	2.561E-04	2.26E-01	2.20E-01	2.19E-01	2.16E-01	2.09E-01	1.93E-01	1.73E-01	1.60E-01	1.45E-01	1.32E-01
RF-TT398R	6.98E+01	4.145E-04	3.41E-01	3.18E-01	3.13E-01	3.03E-01	2.74E-01	2.16E-01	1.73E-01	1.59E-01	1.45E-01	1.32E-01

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-TT411R	7.71E+00	4.577E-05	2.51E-01	2.43E-01	2.40E-01	2.37E-01	2.26E-01	2.03E-01	1.78E-01	1.64E-01	1.49E-01	1.36E-01
RF-TT429R	2.08E+00	1.235E-05	5.41E-01	4.86E-01	4.73E-01	4.49E-01	3.80E-01	2.39E-01	1.55E-01	1.41E-01	1.28E-01	1.17E-01
RF-TT433X	6.30E-01	3.740E-06	5.44E-01	4.87E-01	4.73E-01	4.49E-01	3.77E-01	2.31E-01	1.46E-01	1.32E-01	1.20E-01	1.10E-01
RF-TT436R	7.09E+00	4.209E-05	4.41E-01	4.03E-01	3.95E-01	3.78E-01	3.30E-01	2.33E-01	1.71E-01	1.56E-01	1.42E-01	1.29E-01
RF-TT454X	4.20E-01	2.493E-06	4.37E-01	4.01E-01	3.92E-01	3.76E-01	3.28E-01	2.32E-01	1.70E-01	1.55E-01	1.41E-01	1.29E-01
RL-T101	5.68E+02	3.371E-03	8.44E-03	8.41E-03	8.36E-03	8.27E-03	8.02E-03	7.46E-03	6.71E-03	6.19E-03	5.63E-03	5.13E-03
RL-T102	2.00E+02	1.188E-03	3.06E-07	3.05E-07	3.03E-07	3.00E-07	2.91E-07	2.71E-07	2.44E-07	2.25E-07	2.04E-07	1.87E-07
RL-T103	9.96E+01	5.914E-04	2.39E-02	2.32E-02	2.30E-02	2.25E-02	2.14E-02	1.90E-02	1.67E-02	1.54E-02	1.40E-02	1.28E-02
RL-T104	4.99E+00	2.962E-05	1.75E-05	1.74E-05	1.73E-05	1.71E-05	1.66E-05	1.55E-05	1.39E-05	1.28E-05	1.16E-05	1.06E-05
RL-T105	8.04E+01	4.773E-04	4.12E-04	4.10E-04	4.08E-04	4.03E-04	3.91E-04	3.64E-04	3.27E-04	3.02E-04	2.74E-04	2.50E-04
RL-T106	8.11E+00	4.814E-05	3.99E-03	3.97E-03	3.95E-03	3.90E-03	3.78E-03	3.52E-03	3.17E-03	2.92E-03	2.66E-03	2.42E-03
RL-T107	6.16E+03	3.654E-02	6.39E-02	3.69E-02	3.28E-02	2.66E-02	1.69E-02	1.29E-02	1.16E-02	1.07E-02	9.69E-03	8.84E-03
RL-T108	1.93E+02	1.143E-03	5.33E-04	3.85E-04	3.62E-04	3.26E-04	2.68E-04	2.34E-04	2.10E-04	1.94E-04	1.76E-04	1.61E-04
RL-T109	1.97E+01	1.171E-04	3.44E-03	3.42E-03	3.40E-03	3.36E-03	3.26E-03	3.03E-03	2.72E-03	2.51E-03	2.28E-03	2.08E-03
RL-T110	4.94E+02	2.933E-03	1.59E-02	1.57E-02	1.56E-02	1.54E-02	1.49E-02	1.39E-02	1.25E-02	1.15E-02	1.04E-02	9.52E-03
RL-T112	1.38E+02	8.176E-04	9.67E-03	9.10E-03	8.96E-03	8.71E-03	8.08E-03	6.94E-03	5.95E-03	5.48E-03	4.98E-03	4.55E-03
RL-T113	4.28E+01	2.541E-04	8.16E-05	7.97E-05	7.91E-05	7.79E-05	7.50E-05	6.97E-05	6.27E-05	5.78E-05	5.26E-05	4.80E-05
RL-T114	1.96E+01	1.162E-04	2.62E-02	2.61E-02	2.59E-02	2.57E-02	2.49E-02	2.32E-02	2.08E-02	1.92E-02	1.75E-02	1.59E-02
RL-T115	1.03E+03	6.087E-03	7.38E-03	7.19E-03	7.12E-03	6.99E-03	6.64E-03	5.95E-03	5.23E-03	4.82E-03	4.38E-03	4.00E-03
RL-T116	1.10E+01	6.542E-05	7.62E-02	7.59E-02	7.54E-02	7.46E-02	7.23E-02	6.73E-02	6.05E-02	5.58E-02	5.08E-02	4.63E-02
RL-T118	2.62E+02	1.555E-03	4.11E-03	3.82E-03	3.75E-03	3.64E-03	3.37E-03	2.94E-03	2.55E-03	2.35E-03	2.13E-03	1.95E-03
RL-T120	1.34E+02	7.943E-04	2.11E-03	2.05E-03	2.03E-03	1.99E-03	1.88E-03	1.67E-03	1.47E-03	1.35E-03	1.23E-03	1.12E-03
RL-T122	2.93E+01	1.739E-04	1.22E-03	1.21E-03	1.21E-03	1.19E-03	1.16E-03	1.10E-03	1.01E-03	9.42E-04	8.73E-04	8.12E-04
RL-T123	6.20E-01	3.680E-06	1.41E-01	1.41E-01	1.40E-01	1.38E-01	1.34E-01	1.25E-01	1.12E-01	1.04E-01	9.41E-02	8.59E-02
RL-T125	1.52E+01	9.011E-05	2.60E-01	2.50E-01	2.44E-01	2.33E-01	2.04E-01	1.52E-01	1.15E-01	1.03E-01	9.18E-02	8.20E-02
RL-T127	2.84E+02	1.683E-03	2.36E-02	2.29E-02	2.26E-02	2.21E-02	2.07E-02	1.79E-02	1.53E-02	1.41E-02	1.28E-02	1.17E-02
RL-T128	4.20E-01	2.493E-06	6.46E-03	5.50E-03	5.29E-03	4.88E-03	3.68E-03	1.30E-03	5.28E-05	2.36E-06	2.49E-07	1.93E-07

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-T129	2.88E+01	1.707E-04	1.66E-02	8.96E-03	7.81E-03	6.08E-03	3.37E-03	2.32E-03	2.08E-03	1.92E-03	1.75E-03	1.59E-03
RL-T130	2.10E-01	1.247E-06	7.60E-04	7.57E-04	7.53E-04	7.45E-04	7.22E-04	6.73E-04	6.05E-04	5.58E-04	5.08E-04	4.63E-04
RL-T131	3.02E+01	1.790E-04	1.16E-03	1.12E-03	1.11E-03	1.09E-03	1.03E-03	9.14E-04	8.01E-04	7.38E-04	6.71E-04	6.13E-04
RL-T132	2.87E+01	1.704E-04	5.36E-01	5.34E-01	5.31E-01	5.25E-01	5.09E-01	4.74E-01	4.26E-01	3.93E-01	3.58E-01	3.26E-01
RL-T133	2.10E-01	1.247E-06	1.24E-03	1.22E-03	1.22E-03	1.20E-03	1.16E-03	1.07E-03	9.56E-04	8.82E-04	8.02E-04	7.31E-04
RL-T134	2.10E-01	1.247E-06	3.16E-03	3.14E-03	3.12E-03	3.09E-03	3.00E-03	2.79E-03	2.51E-03	2.31E-03	2.10E-03	1.92E-03
RL-T135	4.20E-01	2.493E-06	7.43E-03	7.39E-03	7.35E-03	7.27E-03	7.05E-03	6.57E-03	5.91E-03	5.46E-03	4.96E-03	4.53E-03
RL-T137	1.52E+02	9.001E-04	1.79E-01	1.73E-01	1.72E-01	1.68E-01	1.59E-01	1.41E-01	1.24E-01	1.14E-01	1.04E-01	9.47E-02
RL-T140	1.38E+02	8.198E-04	2.02E-01	1.95E-01	1.92E-01	1.88E-01	1.77E-01	1.55E-01	1.35E-01	1.24E-01	1.12E-01	1.02E-01
RL-T143	4.04E+02	2.396E-03	9.15E-04	9.11E-04	9.06E-04	8.96E-04	8.69E-04	8.09E-04	7.28E-04	6.71E-04	6.10E-04	5.57E-04
RL-T145	7.11E+02	4.222E-03	1.48E-03	1.47E-03	1.46E-03	1.45E-03	1.40E-03	1.31E-03	1.18E-03	1.09E-03	9.86E-04	9.00E-04
RL-W407	4.89E+02	2.901E-03	5.11E-03	5.03E-03	4.99E-03	4.93E-03	4.76E-03	4.39E-03	3.92E-03	3.62E-03	3.29E-03	3.00E-03
RL-W408	3.80E+00	2.256E-05	2.65E-06	2.62E-06	2.60E-06	2.57E-06	2.48E-06	2.28E-06	2.04E-06	1.88E-06	1.71E-06	1.56E-06
RL-W415	8.41E+01	4.993E-04	2.65E-06	2.62E-06	2.60E-06	2.57E-06	2.48E-06	2.28E-06	2.04E-06	1.88E-06	1.71E-06	1.56E-06
RL-W418	1.73E+01	1.025E-04	5.55E-05	5.47E-05	5.44E-05	5.37E-05	5.18E-05	4.78E-05	4.27E-05	3.94E-05	3.58E-05	3.26E-05
RL-W437	1.60E+03	9.502E-03	5.10E-03	5.02E-03	4.99E-03	4.93E-03	4.76E-03	4.39E-03	3.92E-03	3.62E-03	3.29E-03	3.00E-03
RL-W438	5.31E+00	3.152E-05	2.65E-06	2.62E-06	2.60E-06	2.57E-06	2.48E-06	2.29E-06	2.04E-06	1.88E-06	1.71E-06	1.56E-06
RL-W439	1.25E+04	7.427E-02	2.39E-02	2.33E-02	2.30E-02	2.26E-02	2.14E-02	1.91E-02	1.67E-02	1.54E-02	1.40E-02	1.28E-02
RL-W443	1.41E+03	8.365E-03	5.11E-03	5.03E-03	5.00E-03	4.94E-03	4.76E-03	4.39E-03	3.93E-03	3.62E-03	3.29E-03	3.00E-03
RL-W444	1.05E+03	6.205E-03	5.11E-03	5.03E-03	5.00E-03	4.94E-03	4.77E-03	4.39E-03	3.93E-03	3.62E-03	3.29E-03	3.00E-03
RL-W447	9.87E+00	5.859E-05	6.09E-05	6.02E-05	5.98E-05	5.90E-05	5.69E-05	5.24E-05	4.68E-05	4.32E-05	3.93E-05	3.58E-05
RL-W448	1.68E+00	9.973E-06	2.65E-06	2.62E-06	2.60E-06	2.57E-06	2.48E-06	2.28E-06	2.04E-06	1.88E-06	1.71E-06	1.56E-06
RL-W449	1.05E+00	6.233E-06	4.78E-03	4.09E-03	3.93E-03	3.64E-03	2.77E-03	1.04E-03	1.31E-04	8.76E-05	7.83E-05	7.14E-05
RL-W450	8.40E-01	4.986E-06	8.01E-05	7.92E-05	7.87E-05	7.77E-05	7.50E-05	6.91E-05	6.17E-05	5.69E-05	5.17E-05	4.72E-05
RL-W451	4.20E-01	2.493E-06	2.28E-05	2.25E-05	2.24E-05	2.21E-05	2.13E-05	1.96E-05	1.75E-05	1.62E-05	1.47E-05	1.34E-05
RL-W452	7.60E+00	4.511E-05	5.55E-05	5.48E-05	5.44E-05	5.37E-05	5.19E-05	4.78E-05	4.27E-05	3.94E-05	3.58E-05	3.27E-05
RL-W453	2.10E-01	1.247E-06	5.77E-04	5.68E-04	5.65E-04	5.58E-04	5.39E-04	4.96E-04	4.44E-04	4.09E-04	3.72E-04	3.40E-04

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W454	2.10E-01	1.247E-06	8.07E-03	7.94E-03	7.89E-03	7.80E-03	7.53E-03	6.94E-03	6.20E-03	5.72E-03	5.20E-03	4.74E-03
RL-W455	2.10E-01	1.247E-06	2.13E-03	2.10E-03	2.09E-03	2.07E-03	1.99E-03	1.84E-03	1.64E-03	1.51E-03	1.38E-03	1.26E-03
RL-W456	9.03E+00	5.360E-05	6.59E-03	6.49E-03	6.45E-03	6.37E-03	6.15E-03	5.67E-03	5.07E-03	4.67E-03	4.25E-03	3.87E-03
RL-W457	6.30E-01	3.740E-06	9.17E-03	9.03E-03	8.97E-03	8.86E-03	8.56E-03	7.89E-03	7.05E-03	6.50E-03	5.91E-03	5.39E-03
RL-W458	2.10E-01	1.247E-06	2.43E-02	2.32E-02	2.26E-02	2.16E-02	1.90E-02	1.42E-02	1.07E-02	9.60E-03	8.50E-03	7.58E-03
RL-W459	6.12E+00	3.633E-05	1.29E-02	1.25E-02	1.23E-02	1.19E-02	1.10E-02	9.30E-03	7.83E-03	7.16E-03	6.46E-03	5.86E-03
RL-W460	2.10E-01	1.247E-06	5.11E-03	5.03E-03	4.99E-03	4.93E-03	4.76E-03	4.39E-03	3.92E-03	3.62E-03	3.29E-03	3.00E-03
RL-W461	4.20E-01	2.493E-06	3.11E-04	2.65E-04	2.55E-04	2.35E-04	1.77E-04	6.26E-05	2.53E-06	1.03E-07	1.86E-09	3.38E-11
RL-W462	2.10E-01	1.247E-06	1.44E-03	1.42E-03	1.42E-03	1.40E-03	1.35E-03	1.24E-03	1.11E-03	1.02E-03	9.31E-04	8.49E-04
RL-W463	4.20E-01	2.493E-06	3.75E-03	3.69E-03	3.67E-03	3.62E-03	3.50E-03	3.23E-03	2.88E-03	2.66E-03	2.42E-03	2.21E-03
RL-W464	4.20E-01	2.493E-06	1.73E-03	1.70E-03	1.69E-03	1.67E-03	1.61E-03	1.49E-03	1.33E-03	1.22E-03	1.11E-03	1.02E-03
RL-W465	8.40E-01	4.986E-06	5.75E-03	5.67E-03	5.63E-03	5.56E-03	5.37E-03	4.95E-03	4.42E-03	4.08E-03	3.71E-03	3.38E-03
RL-W466	1.41E+01	8.352E-05	4.71E-03	4.64E-03	4.61E-03	4.56E-03	4.40E-03	4.05E-03	3.62E-03	3.34E-03	3.04E-03	2.77E-03
RL-W467	1.26E+00	7.480E-06	2.68E-03	2.64E-03	2.62E-03	2.59E-03	2.50E-03	2.31E-03	2.06E-03	1.90E-03	1.73E-03	1.58E-03
RL-W468	2.10E-01	1.247E-06	8.23E-05	8.11E-05	8.06E-05	7.96E-05	7.68E-05	7.08E-05	6.33E-05	5.84E-05	5.30E-05	4.84E-05
RL-W469	1.26E+00	7.480E-06	5.58E-03	5.50E-03	5.46E-03	5.40E-03	5.21E-03	4.80E-03	4.29E-03	3.96E-03	3.60E-03	3.28E-03
RL-W470	2.10E-01	1.247E-06	2.60E-01	2.50E-01	2.44E-01	2.33E-01	2.04E-01	1.52E-01	1.15E-01	1.03E-01	9.17E-02	8.19E-02
RL-W474	1.89E+00	1.122E-05	8.51E-04	6.19E-04	5.79E-04	5.11E-04	3.60E-04	1.46E-04	3.89E-05	3.09E-05	2.68E-05	2.35E-05
RL-W476	4.78E+00	2.837E-05	2.72E-03	2.68E-03	2.66E-03	2.63E-03	2.54E-03	2.35E-03	2.10E-03	1.93E-03	1.76E-03	1.60E-03
RL-W480	4.20E-01	2.493E-06	4.93E-03	4.86E-03	4.82E-03	4.77E-03	4.60E-03	4.24E-03	3.79E-03	3.49E-03	3.18E-03	2.90E-03
RL-W481	6.30E-01	3.740E-06	5.15E-03	5.08E-03	5.05E-03	4.98E-03	4.81E-03	4.43E-03	3.96E-03	3.65E-03	3.32E-03	3.03E-03
RL-W482	2.50E+00	1.484E-05	2.06E-01	1.98E-01	1.90E-01	1.75E-01	1.32E-01	4.65E-02	2.14E-03	3.09E-04	1.98E-04	1.67E-04
RL-W483	1.04E+00	6.174E-06	3.70E-02	3.56E-02	3.42E-02	3.15E-02	2.36E-02	8.34E-03	3.80E-04	5.19E-05	3.24E-05	2.72E-05
RL-W484	8.40E-01	4.986E-06	6.14E-04	5.79E-04	5.70E-04	5.55E-04	5.10E-04	4.18E-04	3.47E-04	3.18E-04	2.89E-04	2.63E-04
RL-W485	2.10E-01	1.247E-06	2.27E-04	2.15E-04	2.12E-04	2.08E-04	1.96E-04	1.73E-04	1.50E-04	1.38E-04	1.25E-04	1.14E-04
RL-W486	2.10E-01	1.247E-06	9.57E-05	9.07E-05	8.96E-05	8.78E-05	8.28E-05	7.28E-05	6.32E-05	5.81E-05	5.27E-05	4.81E-05
RL-W487	2.10E-01	1.247E-06	1.42E-02	1.36E-02	1.35E-02	1.32E-02	1.24E-02	1.08E-02	9.27E-03	8.50E-03	7.69E-03	6.99E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W488	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	2.10E-01	1.247E-06	1.53E-02	1.50E-02	1.49E-02	1.47E-02	1.42E-02	1.30E-02	1.16E-02	1.07E-02	9.72E-03	8.87E-03
RL-W490	1.90E+00	1.128E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	2.10E-01	1.247E-06	2.32E-03	2.16E-03	2.11E-03	2.03E-03	1.82E-03	1.47E-03	1.22E-03	1.12E-03	1.02E-03	9.27E-04
RL-W492	2.10E-01	1.247E-06	3.21E-04	3.16E-04	3.13E-04	3.09E-04	2.97E-04	2.73E-04	2.43E-04	2.24E-04	2.04E-04	1.86E-04
RL-W493	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.75E+01	4.600E-04	5.27E-03	4.68E-03	4.43E-03	3.99E-03	2.88E-03	1.01E-03	6.38E-05	2.31E-05	1.88E-05	1.66E-05
RL-W495	4.20E-01	2.493E-06	1.43E-02	1.41E-02	1.36E-02	1.25E-02	9.36E-03	3.32E-03	1.73E-04	4.18E-05	3.20E-05	2.81E-05
RL-W496	2.10E-01	1.247E-06	1.92E-01	1.86E-01	1.78E-01	1.63E-01	1.22E-01	4.28E-02	1.99E-03	3.14E-04	2.16E-04	1.89E-04
RL-W497	2.10E-01	1.247E-06	2.61E-02	2.41E-02	2.36E-02	2.27E-02	2.05E-02	1.65E-02	1.34E-02	1.21E-02	1.08E-02	9.71E-03
RL-W498	7.14E+02	4.237E-03	7.57E-05	7.47E-05	7.42E-05	7.33E-05	7.07E-05	6.52E-05	5.82E-05	5.37E-05	4.88E-05	4.45E-05
RL-W499	2.10E-01	1.247E-06	2.31E-06	2.28E-06	2.26E-06	2.23E-06	2.16E-06	1.99E-06	1.77E-06	1.64E-06	1.49E-06	1.36E-06
RL-W500	2.10E-01	1.247E-06	1.05E-04	1.02E-04	1.01E-04	9.88E-05	9.34E-05	8.28E-05	7.24E-05	6.67E-05	6.07E-05	5.54E-05
RL-W501	5.44E+01	3.231E-04	1.42E-02	1.37E-02	1.35E-02	1.32E-02	1.24E-02	1.08E-02	9.29E-03	8.52E-03	7.71E-03	7.00E-03
RL-W502	3.15E+00	1.870E-05	8.20E-05	8.09E-05	8.03E-05	7.93E-05	7.66E-05	7.06E-05	6.31E-05	5.82E-05	5.29E-05	4.82E-05
RL-W503	4.20E-01	2.493E-06	2.39E-02	2.32E-02	2.30E-02	2.25E-02	2.13E-02	1.90E-02	1.67E-02	1.54E-02	1.40E-02	1.28E-02
RL-W504	2.10E-01	1.247E-06	1.42E-02	1.36E-02	1.35E-02	1.32E-02	1.24E-02	1.08E-02	9.27E-03	8.50E-03	7.69E-03	6.99E-03
RL-W505	2.10E-01	1.247E-06	1.25E-03	1.24E-03	1.23E-03	1.21E-03	1.17E-03	1.08E-03	9.66E-04	8.91E-04	8.10E-04	7.39E-04
RL-W506	6.30E-01	3.740E-06	1.40E-04	1.37E-04	1.36E-04	1.34E-04	1.29E-04	1.19E-04	1.06E-04	9.76E-05	8.87E-05	8.09E-05
RL-W507	6.30E-01	3.740E-06	1.48E-05	1.46E-05	1.45E-05	1.44E-05	1.39E-05	1.28E-05	1.14E-05	1.05E-05	9.56E-06	8.73E-06
RL-W508	6.30E-01	3.740E-06	1.79E-01	1.73E-01	1.72E-01	1.68E-01	1.59E-01	1.41E-01	1.24E-01	1.14E-01	1.04E-01	9.46E-02
RL-W509	4.83E+00	2.867E-05	2.01E-01	1.94E-01	1.92E-01	1.88E-01	1.76E-01	1.55E-01	1.34E-01	1.23E-01	1.12E-01	1.02E-01
RL-W510	3.36E+00	1.995E-05	2.73E-02	2.65E-02	2.62E-02	2.56E-02	2.42E-02	2.15E-02	1.88E-02	1.73E-02	1.58E-02	1.44E-02
RL-W511	5.29E+01	3.141E-04	2.17E-01	2.12E-01	2.10E-01	2.07E-01	1.98E-01	1.80E-01	1.59E-01	1.47E-01	1.34E-01	1.22E-01
RL-W512	3.13E+01	1.857E-04	2.44E-01	2.35E-01	2.33E-01	2.28E-01	2.16E-01	1.91E-01	1.66E-01	1.53E-01	1.38E-01	1.26E-01
RL-W513	8.79E+03	5.219E-02	3.79E-02	3.30E-02	3.18E-02	2.98E-02	2.49E-02	1.65E-02	1.14E-02	1.02E-02	9.02E-03	8.07E-03
RL-W514	4.20E-01	2.493E-06	9.14E-05	9.00E-05	8.94E-05	8.84E-05	8.53E-05	7.86E-05	7.02E-05	6.48E-05	5.89E-05	5.37E-05

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W515	8.02E+00	4.761E-05	1.86E-04	1.84E-04	1.83E-04	1.80E-04	1.74E-04	1.60E-04	1.43E-04	1.32E-04	1.20E-04	1.10E-04
RL-W516	2.66E+01	1.579E-04	7.78E-05	7.67E-05	7.62E-05	7.53E-05	7.26E-05	6.69E-05	5.98E-05	5.52E-05	5.01E-05	4.57E-05
RL-W517	2.10E-01	1.247E-06	8.76E-11	8.65E-11	8.59E-11	8.48E-11	8.19E-11	7.54E-11	6.74E-11	6.22E-11	5.65E-11	5.16E-11
RL-W518	8.40E-01	4.986E-06	3.65E-02	3.53E-02	3.49E-02	3.41E-02	3.21E-02	2.82E-02	2.45E-02	2.25E-02	2.05E-02	1.86E-02
RL-W519	1.68E+00	9.973E-06	5.57E-03	5.48E-03	5.45E-03	5.38E-03	5.19E-03	4.79E-03	4.28E-03	3.95E-03	3.59E-03	3.27E-03
RL-W520	4.20E-01	2.493E-06	2.44E-03	2.41E-03	2.39E-03	2.36E-03	2.28E-03	2.10E-03	1.88E-03	1.73E-03	1.57E-03	1.44E-03
RL-W521	2.10E-01	1.247E-06	9.10E-05	8.97E-05	8.91E-05	8.80E-05	8.49E-05	7.83E-05	6.99E-05	6.45E-05	5.86E-05	5.35E-05
RL-W522	2.31E+00	1.371E-05	7.55E-02	7.15E-02	7.03E-02	6.82E-02	6.27E-02	5.25E-02	4.40E-02	4.03E-02	3.64E-02	3.30E-02
RL-W523	2.10E-01	1.247E-06	1.36E-01	1.19E-01	1.15E-01	1.07E-01	8.93E-02	5.84E-02	3.92E-02	3.48E-02	3.07E-02	2.73E-02
RL-W524	2.73E+00	1.621E-05	5.60E-02	5.09E-02	4.96E-02	4.73E-02	4.16E-02	3.14E-02	2.43E-02	2.20E-02	1.97E-02	1.78E-02
RL-W525	6.30E-01	3.740E-06	2.31E-02	2.15E-02	2.11E-02	2.03E-02	1.83E-02	1.48E-02	1.20E-02	1.09E-02	9.84E-03	8.90E-03
RL-W526	1.44E+01	8.518E-05	7.38E-03	7.18E-03	7.11E-03	6.98E-03	6.63E-03	5.94E-03	5.23E-03	4.82E-03	4.38E-03	4.00E-03
RL-W527	2.10E-01	1.247E-06	5.47E-02	5.30E-02	5.24E-02	5.14E-02	4.87E-02	4.35E-02	3.82E-02	3.51E-02	3.19E-02	2.91E-02
RL-W528	5.26E+00	3.122E-05	3.07E-01	2.64E-01	2.54E-01	2.37E-01	1.94E-01	1.19E-01	7.33E-02	6.36E-02	5.51E-02	4.81E-02
RL-W529	1.90E+00	1.128E-05	2.12E-03	2.05E-03	2.03E-03	1.99E-03	1.88E-03	1.68E-03	1.47E-03	1.35E-03	1.23E-03	1.12E-03
RL-W530	4.20E-01	2.493E-06	1.10E-01	1.07E-01	1.06E-01	1.03E-01	9.77E-02	8.67E-02	7.59E-02	6.99E-02	6.35E-02	5.80E-02
RL-W531	5.47E+00	3.247E-05	1.73E-01	1.44E-01	1.38E-01	1.27E-01	1.01E-01	5.88E-02	3.45E-02	3.01E-02	2.64E-02	2.33E-02
RL-W532	3.04E+01	1.805E-04	4.55E-04	4.48E-04	4.45E-04	4.40E-04	4.25E-04	3.91E-04	3.50E-04	3.23E-04	2.93E-04	2.67E-04
RL-W533	3.80E+00	2.256E-05	1.15E-03	1.12E-03	1.11E-03	1.09E-03	1.03E-03	9.13E-04	8.00E-04	7.37E-04	6.70E-04	6.12E-04
RL-W534	2.10E-01	1.247E-06	1.84E-06	1.81E-06	1.80E-06	1.78E-06	1.72E-06	1.58E-06	1.41E-06	1.30E-06	1.19E-06	1.08E-06
RL-W535	2.38E+01	1.410E-04	3.21E-02	2.99E-02	2.94E-02	2.83E-02	2.56E-02	2.07E-02	1.70E-02	1.55E-02	1.40E-02	1.27E-02
RL-W536	6.51E+00	3.864E-05	3.15E-03	3.03E-03	2.99E-03	2.92E-03	2.73E-03	2.37E-03	2.04E-03	1.88E-03	1.70E-03	1.55E-03
RL-W537	5.04E+00	2.992E-05	2.18E-01	2.12E-01	2.11E-01	2.08E-01	1.99E-01	1.81E-01	1.60E-01	1.48E-01	1.35E-01	1.23E-01
RL-W538	1.68E+00	9.973E-06	2.92E-06	2.88E-06	2.86E-06	2.82E-06	2.72E-06	2.51E-06	2.24E-06	2.07E-06	1.88E-06	1.72E-06
RL-W539	4.20E-01	2.493E-06	1.29E-03	1.27E-03	1.26E-03	1.25E-03	1.20E-03	1.11E-03	9.91E-04	9.15E-04	8.31E-04	7.58E-04
RL-W540	3.09E+01	1.832E-04	1.14E-02	1.04E-02	1.02E-02	9.72E-03	8.61E-03	6.67E-03	5.28E-03	4.80E-03	4.32E-03	3.90E-03
RL-W541	6.30E-01	3.740E-06	2.49E-03	2.46E-03	2.44E-03	2.41E-03	2.33E-03	2.14E-03	1.92E-03	1.77E-03	1.61E-03	1.47E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W542	3.99E+00	2.369E-05	1.13E-02	1.10E-02	1.08E-02	1.06E-02	1.00E-02	8.84E-03	7.71E-03	7.10E-03	6.44E-03	5.88E-03
RL-W543	4.01E+00	2.380E-05	5.74E-05	5.66E-05	5.62E-05	5.55E-05	5.36E-05	4.94E-05	4.41E-05	4.07E-05	3.70E-05	3.37E-05
RL-W544	2.10E-01	1.247E-06	1.46E-02	1.41E-02	1.40E-02	1.36E-02	1.28E-02	1.13E-02	9.77E-03	8.98E-03	8.14E-03	7.41E-03
RL-W545	3.80E+00	2.256E-05	3.63E-04	3.57E-04	3.55E-04	3.51E-04	3.38E-04	3.12E-04	2.79E-04	2.57E-04	2.34E-04	2.13E-04
RL-W546	8.40E-01	4.986E-06	7.21E-05	7.11E-05	7.06E-05	6.98E-05	6.73E-05	6.21E-05	5.55E-05	5.12E-05	4.65E-05	4.24E-05
RL-W547	5.61E+01	3.333E-04	2.75E-08	2.71E-08	2.69E-08	2.66E-08	2.56E-08	2.36E-08	2.11E-08	1.95E-08	1.77E-08	1.62E-08
RL-W548	4.20E-01	2.493E-06	3.17E-06	3.13E-06	3.11E-06	3.07E-06	2.96E-06	2.73E-06	2.44E-06	2.25E-06	2.04E-06	1.87E-06
RL-W549	4.00E+00	2.374E-05	2.59E-02	2.41E-02	2.37E-02	2.28E-02	2.07E-02	1.69E-02	1.39E-02	1.27E-02	1.15E-02	1.04E-02
RL-W550	4.41E+00	2.618E-05	2.20E-01	2.14E-01	2.13E-01	2.10E-01	2.01E-01	1.83E-01	1.62E-01	1.49E-01	1.36E-01	1.24E-01
RL-W551	1.56E+01	9.248E-05	7.89E-02	7.59E-02	7.51E-02	7.37E-02	6.96E-02	6.11E-02	5.29E-02	4.86E-02	4.40E-02	4.01E-02
RL-W552	8.40E-01	4.986E-06	9.84E-04	9.71E-04	9.64E-04	9.52E-04	9.19E-04	8.47E-04	7.57E-04	6.98E-04	6.35E-04	5.79E-04
RL-W553	4.20E-01	2.493E-06	1.74E-04	1.73E-04	1.72E-04	1.70E-04	1.64E-04	1.51E-04	1.35E-04	1.24E-04	1.13E-04	1.03E-04
RL-W554	9.50E+00	5.639E-05	1.23E-04	1.21E-04	1.20E-04	1.19E-04	1.15E-04	1.06E-04	9.45E-05	8.72E-05	7.92E-05	7.23E-05
RL-W555	1.20E+01	7.141E-05	4.47E-05	4.40E-05	4.38E-05	4.32E-05	4.17E-05	3.84E-05	3.44E-05	3.17E-05	2.88E-05	2.63E-05
RL-W563	2.10E-01	1.247E-06	2.37E-02	2.30E-02	2.27E-02	2.22E-02	2.10E-02	1.87E-02	1.63E-02	1.51E-02	1.37E-02	1.25E-02
RL-W564	1.26E+00	7.480E-06	2.54E-03	2.48E-03	2.45E-03	2.40E-03	2.27E-03	2.01E-03	1.76E-03	1.62E-03	1.47E-03	1.35E-03
RL-W565	2.10E-01	1.247E-06	2.37E-03	2.34E-03	2.32E-03	2.30E-03	2.22E-03	2.04E-03	1.82E-03	1.68E-03	1.53E-03	1.40E-03
RL-W566	2.31E+00	1.371E-05	3.17E-03	3.12E-03	3.10E-03	3.06E-03	2.96E-03	2.72E-03	2.43E-03	2.25E-03	2.04E-03	1.86E-03
RL-W567	2.10E-01	1.247E-06	2.83E-01	2.80E-01	2.69E-01	2.47E-01	1.85E-01	6.59E-02	3.77E-03	1.13E-03	9.00E-04	7.90E-04
RL-W568	3.74E+00	2.220E-05	3.05E-01	3.05E-01	2.93E-01	2.69E-01	2.02E-01	7.31E-02	5.86E-03	2.82E-03	2.37E-03	2.08E-03
RL-W569	2.10E+00	1.247E-05	4.47E-04	4.43E-04	4.24E-04	3.90E-04	2.92E-04	1.03E-04	5.32E-06	1.28E-06	1.03E-06	9.45E-07
RL-W570	4.20E-01	2.493E-06	1.25E-03	1.24E-03	1.23E-03	1.21E-03	1.17E-03	1.08E-03	9.66E-04	8.91E-04	8.10E-04	7.39E-04
RL-W571	1.25E+01	7.408E-05	2.05E-02	1.95E-02	1.88E-02	1.74E-02	1.37E-02	7.00E-03	3.27E-03	2.84E-03	2.52E-03	2.25E-03
RL-W572	2.29E+00	1.359E-05	8.02E-05	7.95E-05	7.65E-05	7.09E-05	5.48E-05	2.38E-05	7.36E-06	6.32E-06	5.84E-06	5.43E-06
RL-W573	1.50E+01	8.892E-05	1.45E-01	1.43E-01	1.37E-01	1.26E-01	9.47E-02	3.39E-02	2.21E-03	8.41E-04	6.91E-04	6.09E-04
RL-W574	8.19E+01	4.861E-04	1.14E-01	1.12E-01	1.08E-01	9.91E-02	7.44E-02	2.65E-02	1.66E-03	5.87E-04	4.79E-04	4.22E-04
RL-W575	2.84E+02	1.687E-03	2.16E-01	2.12E-01	2.03E-01	1.87E-01	1.40E-01	5.03E-02	3.54E-03	1.50E-03	1.26E-03	1.12E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W576	4.11E+01	2.438E-04	1.06E-01	1.05E-01	1.01E-01	9.28E-02	6.96E-02	2.49E-02	1.57E-03	5.67E-04	4.64E-04	4.09E-04
RL-W579	4.20E-01	2.493E-06	1.25E-03	1.10E-03	1.06E-03	9.99E-04	8.10E-04	4.35E-04	2.24E-04	1.99E-04	1.81E-04	1.65E-04
RL-W580	2.11E+00	1.253E-05	3.69E-04	3.67E-04	3.67E-04	3.66E-04	3.64E-04	3.55E-04	3.28E-04	3.05E-04	2.79E-04	2.56E-04
RL-W581	4.20E-01	2.493E-06	1.06E-02	9.01E-03	8.66E-03	7.99E-03	6.04E-03	2.13E-03	8.61E-05	3.49E-06	6.33E-08	1.15E-09
RL-W582	2.10E-01	1.247E-06	3.13E-04	2.82E-04	2.75E-04	2.64E-04	2.32E-04	1.75E-04	1.33E-04	1.20E-04	1.06E-04	9.49E-05
RL-W583	2.10E-01	1.247E-06	8.10E-04	7.98E-04	7.93E-04	7.83E-04	7.56E-04	6.97E-04	6.22E-04	5.74E-04	5.22E-04	4.76E-04
RL-W584	2.10E-01	1.247E-06	7.84E-03	7.14E-03	7.00E-03	6.76E-03	6.18E-03	5.17E-03	4.30E-03	3.88E-03	3.45E-03	3.09E-03
RL-W585	4.20E-01	2.493E-06	2.22E-02	2.10E-02	2.06E-02	2.00E-02	1.83E-02	1.53E-02	1.27E-02	1.14E-02	1.02E-02	9.07E-03
RL-W586	2.10E-01	1.247E-06	1.28E-05	1.26E-05	1.25E-05	1.24E-05	1.19E-05	1.10E-05	9.83E-06	9.07E-06	8.24E-06	7.52E-06
RL-W587	4.20E-01	2.493E-06	1.36E-04	1.34E-04	1.34E-04	1.32E-04	1.27E-04	1.17E-04	1.05E-04	9.67E-05	8.79E-05	8.02E-05
RL-W588	2.10E-01	1.247E-06	6.32E-03	5.77E-03	5.66E-03	5.48E-03	5.04E-03	4.31E-03	3.63E-03	3.28E-03	2.92E-03	2.61E-03
RL-W589	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	6.20E-01	3.680E-06	1.80E-02	1.55E-02	1.46E-02	1.31E-02	9.34E-03	3.31E-03	2.93E-04	1.49E-04	1.22E-04	1.03E-04
RL-W591	2.10E-01	1.247E-06	2.34E-01	2.30E-01	2.20E-01	2.02E-01	1.51E-01	5.32E-02	2.75E-03	6.25E-04	4.55E-04	3.85E-04
RL-W592	2.50E+00	1.484E-05	9.91E-02	9.13E-02	8.69E-02	7.91E-02	5.85E-02	2.17E-02	2.76E-03	1.76E-03	1.48E-03	1.27E-03
RL-W593	6.20E-01	3.680E-06	4.13E-04	4.10E-04	4.09E-04	4.08E-04	4.02E-04	3.83E-04	3.30E-04	2.86E-04	2.41E-04	2.05E-04
RL-W594	2.50E+00	1.484E-05	8.63E-02	7.56E-02	7.25E-02	6.67E-02	5.00E-02	1.77E-02	8.18E-04	1.22E-04	7.89E-05	6.66E-05
RL-W595	6.20E-01	3.680E-06	2.26E-03	1.67E-03	1.55E-03	1.36E-03	9.74E-04	5.44E-04	3.13E-04	2.64E-04	2.21E-04	1.86E-04
RL-W596	9.45E+00	5.610E-05	2.27E-05	1.96E-05	1.85E-05	1.65E-05	1.18E-05	4.20E-06	3.58E-07	1.78E-07	1.44E-07	1.23E-07
RL-W597	3.12E+00	1.852E-05	1.03E-01	9.82E-02	9.40E-02	8.62E-02	6.45E-02	2.34E-02	2.00E-03	9.94E-04	8.09E-04	6.89E-04
RL-W598	8.74E+00	5.188E-05	5.18E-02	4.30E-02	4.04E-02	3.59E-02	2.53E-02	8.95E-03	8.60E-04	4.69E-04	3.88E-04	3.33E-04
RL-W599	2.10E-01	1.247E-06	7.86E-02	7.70E-02	7.37E-02	6.76E-02	5.04E-02	1.78E-02	9.19E-04	2.09E-04	1.52E-04	1.28E-04
RL-W600	8.60E-01	5.105E-06	9.17E-09	9.03E-09	8.97E-09	8.86E-09	8.55E-09	7.88E-09	7.04E-09	6.50E-09	5.90E-09	5.39E-09
RL-W601	1.31E+00	7.776E-06	3.02E-05	3.00E-05	2.98E-05	2.95E-05	2.84E-05	2.62E-05	2.34E-05	2.16E-05	1.96E-05	1.79E-05
RL-W602	2.79E+00	1.656E-05	1.24E-02	1.22E-02	1.21E-02	1.20E-02	1.16E-02	1.07E-02	9.53E-03	8.79E-03	7.99E-03	7.29E-03
RL-W603	7.60E+00	4.511E-05	2.62E-02	2.59E-02	2.57E-02	2.54E-02	2.45E-02	2.26E-02	2.02E-02	1.86E-02	1.69E-02	1.54E-02
RL-W604	2.10E-01	1.247E-06	8.03E-04	7.56E-04	7.43E-04	7.19E-04	6.52E-04	5.25E-04	4.22E-04	3.80E-04	3.38E-04	3.02E-04

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W605	2.10E-01	1.247E-06	5.06E-04	5.03E-04	5.00E-04	4.94E-04	4.76E-04	4.39E-04	3.92E-04	3.62E-04	3.29E-04	3.00E-04
RL-W606	2.10E-01	1.247E-06	2.04E-04	2.03E-04	2.02E-04	1.99E-04	1.92E-04	1.77E-04	1.58E-04	1.46E-04	1.33E-04	1.21E-04
RL-W607	2.10E-01	1.247E-06	1.36E-04	1.28E-04	1.26E-04	1.22E-04	1.10E-04	8.87E-05	7.13E-05	6.42E-05	5.71E-05	5.11E-05
RL-W608	6.12E+00	3.633E-05	3.26E-05	2.67E-05	2.54E-05	2.31E-05	1.76E-05	9.29E-06	4.67E-06	3.96E-06	3.38E-06	2.92E-06
RL-W610	3.80E+00	2.256E-05	4.95E-02	4.88E-02	4.85E-02	4.79E-02	4.62E-02	4.26E-02	3.81E-02	3.51E-02	3.19E-02	2.91E-02
RL-W612	9.89E+00	5.871E-05	4.61E-05	4.54E-05	4.51E-05	4.45E-05	4.30E-05	3.97E-05	3.55E-05	3.28E-05	2.98E-05	2.72E-05
RL-W615	1.89E+00	1.122E-05	7.20E-04	7.18E-04	7.18E-04	7.17E-04	7.13E-04	7.00E-04	6.61E-04	6.24E-04	5.81E-04	5.40E-04
RL-W622	1.89E+00	1.122E-05	3.93E-06	3.87E-06	3.84E-06	3.80E-06	3.66E-06	3.38E-06	3.02E-06	2.79E-06	2.53E-06	2.31E-06
RL-W625	2.10E-01	1.247E-06	4.65E-04	4.27E-04	4.15E-04	3.94E-04	3.47E-04	2.71E-04	2.11E-04	1.86E-04	1.61E-04	1.40E-04
RL-W626	2.10E-01	1.247E-06	1.80E-02	1.62E-02	1.58E-02	1.50E-02	1.30E-02	9.36E-03	6.88E-03	6.14E-03	5.42E-03	4.82E-03
RL-W627	2.10E-01	1.247E-06	3.72E-05	3.61E-05	3.45E-05	3.17E-05	2.36E-05	8.29E-06	3.58E-07	3.52E-08	2.05E-08	1.89E-08
RL-W628	2.10E-01	1.247E-06	1.02E-04	1.01E-04	9.98E-05	9.86E-05	9.52E-05	8.77E-05	7.84E-05	7.23E-05	6.57E-05	6.00E-05
RL-W629	2.10E-01	1.247E-06	6.84E-06	6.76E-06	6.71E-06	6.63E-06	6.40E-06	5.90E-06	5.27E-06	4.86E-06	4.42E-06	4.03E-06
RL-W630	4.20E-01	2.493E-06	4.00E-02	3.93E-02	3.90E-02	3.85E-02	3.72E-02	3.43E-02	3.07E-02	2.83E-02	2.57E-02	2.34E-02
RL-W631	4.20E-01	2.493E-06	6.04E-04	6.00E-04	5.96E-04	5.89E-04	5.68E-04	5.24E-04	4.68E-04	4.32E-04	3.92E-04	3.58E-04
RL-W632	2.10E-01	1.247E-06	2.16E-01	2.13E-01	2.11E-01	2.05E-01	1.90E-01	1.59E-01	1.33E-01	1.21E-01	1.09E-01	9.88E-02
RL-W633	2.10E-01	1.247E-06	2.06E-04	1.86E-04	1.79E-04	1.66E-04	1.31E-04	6.61E-05	2.95E-05	2.50E-05	2.17E-05	1.90E-05
RL-W634	2.10E-01	1.247E-06	1.96E-04	1.95E-04	1.95E-04	1.95E-04	1.94E-04	1.90E-04	1.80E-04	1.69E-04	1.58E-04	1.47E-04
RL-W635	1.54E+01	9.136E-05	2.19E-02	1.78E-02	1.68E-02	1.51E-02	1.11E-02	5.44E-03	2.40E-03	2.00E-03	1.69E-03	1.45E-03
RL-W636	1.05E+00	6.233E-06	2.52E-03	2.27E-03	2.18E-03	2.02E-03	1.60E-03	8.04E-04	3.57E-04	3.03E-04	2.63E-04	2.30E-04
RL-W637	6.30E-01	3.740E-06	2.35E-05	1.88E-05	1.78E-05	1.63E-05	1.31E-05	9.24E-06	6.74E-06	5.90E-06	5.11E-06	4.45E-06
RL-W638	4.01E+00	2.380E-05	7.65E-05	6.65E-05	6.35E-05	5.83E-05	4.52E-05	2.29E-05	1.05E-05	8.95E-06	7.74E-06	6.77E-06
RL-W639	6.30E-01	3.740E-06	1.44E-04	1.42E-04	1.41E-04	1.39E-04	1.34E-04	1.24E-04	1.11E-04	1.02E-04	9.28E-05	8.46E-05
RL-W640	2.10E-01	1.247E-06	1.46E-02	1.43E-02	1.42E-02	1.41E-02	1.36E-02	1.25E-02	1.12E-02	1.03E-02	9.38E-03	8.55E-03
RL-W641	5.46E+00	3.241E-05	6.60E-03	5.42E-03	5.20E-03	4.83E-03	4.05E-03	3.02E-03	2.35E-03	2.12E-03	1.90E-03	1.71E-03
RL-W642	1.68E+00	9.973E-06	2.20E-04	1.98E-04	1.94E-04	1.84E-04	1.57E-04	1.03E-04	7.10E-05	6.59E-05	6.12E-05	5.70E-05
RL-W643	1.68E+00	9.973E-06	6.61E-03	5.43E-03	5.20E-03	4.84E-03	4.06E-03	3.03E-03	2.35E-03	2.12E-03	1.90E-03	1.71E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W644	8.40E-01	4.986E-06	2.63E-04	2.63E-04	2.62E-04	2.62E-04	2.61E-04	2.56E-04	2.42E-04	2.28E-04	2.12E-04	1.97E-04
RL-W645	1.47E+00	8.726E-06	4.28E-04	4.22E-04	4.19E-04	4.13E-04	3.97E-04	3.63E-04	3.23E-04	2.97E-04	2.70E-04	2.46E-04
RL-W646	4.20E-01	2.493E-06	5.81E-04	5.49E-04	5.40E-04	5.23E-04	4.77E-04	3.89E-04	3.16E-04	2.85E-04	2.54E-04	2.27E-04
RL-W647	2.10E-01	1.247E-06	1.21E-02	7.30E-03	6.56E-03	5.44E-03	3.60E-03	2.59E-03	2.19E-03	2.03E-03	1.86E-03	1.70E-03
RL-W648	2.10E-01	1.247E-06	3.47E-05	2.70E-05	2.52E-05	2.21E-05	1.56E-05	7.19E-06	2.88E-06	2.35E-06	1.96E-06	1.66E-06
RL-W649	1.90E+00	1.128E-05	1.41E-05	1.10E-05	1.02E-05	8.99E-06	6.35E-06	2.92E-06	1.17E-06	9.55E-07	7.98E-07	6.74E-07
RL-W653	4.20E-01	2.493E-06	1.30E-05	1.29E-05	1.28E-05	1.26E-05	1.22E-05	1.12E-05	1.00E-05	9.24E-06	8.40E-06	7.66E-06
RL-W654	2.10E-01	1.247E-06	1.44E-04	1.42E-04	1.41E-04	1.39E-04	1.34E-04	1.24E-04	1.10E-04	1.02E-04	9.25E-05	8.44E-05
RL-W655	1.46E+00	8.667E-06	6.54E-01	6.09E-01	5.81E-01	5.30E-01	3.92E-01	1.38E-01	7.07E-03	1.57E-03	1.13E-03	9.47E-04
RL-W656	3.12E+00	1.852E-05	1.13E+00	1.13E+00	1.09E+00	1.01E+00	7.57E-01	2.68E-01	1.19E-02	1.39E-03	8.30E-04	7.17E-04
RL-W657	1.49E+01	8.821E-05	1.27E-01	1.23E-01	1.18E-01	1.09E-01	8.15E-02	2.87E-02	1.31E-03	1.84E-04	1.16E-04	9.76E-05
RL-W659	4.20E-01	2.493E-06	5.67E-01	5.35E-01	5.12E-01	4.69E-01	3.50E-01	1.23E-01	5.78E-03	9.38E-04	6.37E-04	5.49E-04
RL-W660	2.08E+00	1.235E-05	6.77E-01	6.18E-01	5.89E-01	5.36E-01	3.94E-01	1.40E-01	9.25E-03	3.49E-03	2.76E-03	2.34E-03
RL-W661	2.10E-01	1.247E-06	6.07E-02	6.06E-02	5.82E-02	5.36E-02	4.04E-02	1.43E-02	6.35E-04	7.38E-05	4.05E-05	3.19E-05
RL-W662	2.10E-01	1.247E-06	2.07E-03	1.92E-03	1.85E-03	1.70E-03	1.28E-03	4.52E-04	2.27E-05	4.71E-06	3.37E-06	2.85E-06
RL-W665	8.53E+00	5.064E-05	6.95E-01	6.32E-01	6.00E-01	5.42E-01	3.93E-01	1.36E-01	6.70E-03	1.31E-03	9.39E-04	8.12E-04
RL-W666	1.46E+00	8.667E-06	6.31E-02	6.09E-02	5.84E-02	5.38E-02	4.05E-02	1.44E-02	8.28E-04	2.49E-04	1.96E-04	1.70E-04
RL-W668	4.27E+01	2.535E-04	2.47E-04	2.13E-04	2.05E-04	1.91E-04	1.48E-04	6.28E-05	1.72E-05	1.42E-05	1.28E-05	1.16E-05
RL-W669	1.26E+00	7.480E-06	6.60E-03	5.42E-03	5.20E-03	4.83E-03	4.05E-03	3.02E-03	2.35E-03	2.12E-03	1.90E-03	1.71E-03
RL-W670	2.10E-01	1.247E-06	9.28E-04	7.99E-04	7.70E-04	7.15E-04	5.55E-04	2.36E-04	6.48E-05	5.34E-05	4.81E-05	4.36E-05
RL-W671	9.45E+00	5.610E-05	2.99E-03	2.69E-03	2.58E-03	2.37E-03	1.78E-03	6.29E-04	2.88E-05	4.16E-06	2.73E-06	2.37E-06
RL-W672	9.45E+00	5.610E-05	2.03E-02	1.83E-02	1.75E-02	1.61E-02	1.21E-02	4.27E-03	1.96E-04	2.83E-05	1.86E-05	1.61E-05
RL-W673	4.91E+01	2.917E-04	3.77E-03	3.39E-03	3.25E-03	2.99E-03	2.25E-03	7.93E-04	3.64E-05	5.26E-06	3.46E-06	3.00E-06
RL-W674	3.33E+01	1.979E-04	1.39E-03	1.38E-03	1.38E-03	1.38E-03	1.36E-03	1.33E-03	1.25E-03	1.18E-03	1.10E-03	1.02E-03
RL-W675	2.10E-01	1.247E-06	2.15E-02	1.73E-02	1.64E-02	1.49E-02	1.16E-02	6.72E-03	3.99E-03	3.47E-03	3.01E-03	2.64E-03
RL-W676	4.41E+00	2.618E-05	1.58E-04	1.55E-04	1.54E-04	1.52E-04	1.47E-04	1.37E-04	1.25E-04	1.17E-04	1.09E-04	1.01E-04
RL-W677	3.15E+00	1.870E-05	8.32E-02	7.45E-02	7.17E-02	6.66E-02	5.27E-02	2.66E-02	1.20E-02	1.02E-02	8.81E-03	7.73E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W678	4.20E-01	2.493E-06	2.65E-03	2.48E-03	2.40E-03	2.24E-03	1.86E-03	1.20E-03	7.86E-04	6.87E-04	5.97E-04	5.23E-04
RL-W679	3.80E+00	2.256E-05	1.36E-03	1.22E-03	1.17E-03	1.09E-03	8.62E-04	4.34E-04	1.93E-04	1.64E-04	1.42E-04	1.24E-04
RL-W680	2.10E-01	1.247E-06	7.34E-06	5.94E-06	5.58E-06	4.99E-06	3.67E-06	1.79E-06	7.83E-07	6.46E-07	5.42E-07	4.60E-07
RL-W681	2.10E-01	1.247E-06	1.67E-05	1.62E-05	1.60E-05	1.57E-05	1.48E-05	1.33E-05	1.15E-05	1.04E-05	9.24E-06	8.27E-06
RL-W685	1.43E+02	8.484E-04	9.04E-05	8.90E-05	8.84E-05	8.74E-05	8.43E-05	7.77E-05	6.95E-05	6.41E-05	5.83E-05	5.32E-05
RL-W689	2.10E-01	1.247E-06	2.27E-04	1.91E-04	1.83E-04	1.69E-04	1.28E-04	4.95E-05	8.53E-06	6.50E-06	5.99E-06	5.57E-06
RL-W690	4.20E-01	2.493E-06	2.73E-02	2.69E-02	2.67E-02	2.64E-02	2.55E-02	2.35E-02	2.10E-02	1.94E-02	1.77E-02	1.61E-02
RL-W691	2.10E-01	1.247E-06	1.27E-03	1.25E-03	1.24E-03	1.22E-03	1.18E-03	1.09E-03	9.75E-04	8.99E-04	8.17E-04	7.46E-04
RL-W692	4.20E-01	2.493E-06	2.50E-02	2.47E-02	2.45E-02	2.42E-02	2.34E-02	2.16E-02	1.93E-02	1.78E-02	1.62E-02	1.48E-02
RL-W693	6.20E-01	3.680E-06	2.10E-02	2.07E-02	2.05E-02	2.03E-02	1.96E-02	1.81E-02	1.62E-02	1.49E-02	1.36E-02	1.24E-02
RL-W694	2.29E+00	1.359E-05	5.99E-02	5.90E-02	5.86E-02	5.79E-02	5.59E-02	5.16E-02	4.62E-02	4.26E-02	3.87E-02	3.53E-02
RL-W695	8.40E-01	4.986E-06	2.89E-05	2.63E-05	2.57E-05	2.46E-05	2.13E-05	1.46E-05	1.07E-05	9.93E-06	9.24E-06	8.59E-06
RL-W696	2.10E-01	1.247E-06	2.22E-04	2.03E-04	1.97E-04	1.87E-04	1.63E-04	1.22E-04	9.22E-05	8.09E-05	7.00E-05	6.10E-05
RL-W697	2.10E-01	1.247E-06	9.38E-02	5.10E-02	4.44E-02	3.43E-02	1.67E-02	4.43E-03	3.39E-04	1.66E-04	1.48E-04	1.39E-04
RL-W698	2.10E-01	1.247E-06	1.82E-03	1.55E-03	1.49E-03	1.37E-03	1.04E-03	3.67E-04	1.54E-05	1.15E-06	5.19E-07	4.73E-07
RL-W699	4.20E-01	2.493E-06	1.99E-04	1.97E-04	1.90E-04	1.77E-04	1.39E-04	6.34E-05	2.28E-05	1.98E-05	1.81E-05	1.67E-05
RL-W700	1.26E+00	7.480E-06	1.44E-04	1.42E-04	1.41E-04	1.39E-04	1.34E-04	1.24E-04	1.10E-04	1.02E-04	9.25E-05	8.44E-05
RL-W702	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	4.20E-01	2.493E-06	6.60E-03	5.42E-03	5.19E-03	4.83E-03	4.05E-03	3.02E-03	2.34E-03	2.12E-03	1.90E-03	1.71E-03
RL-W705	6.20E-01	3.680E-06	7.63E-05	7.51E-05	7.47E-05	7.38E-05	7.12E-05	6.57E-05	5.88E-05	5.42E-05	4.93E-05	4.50E-05
RL-W706	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	1.87E+00	1.110E-05	9.01E-04	8.88E-04	8.82E-04	8.71E-04	8.41E-04	7.76E-04	6.94E-04	6.40E-04	5.82E-04	5.31E-04
RL-W708	6.20E-01	3.680E-06	4.12E-04	4.06E-04	4.03E-04	3.98E-04	3.85E-04	3.55E-04	3.17E-04	2.93E-04	2.66E-04	2.43E-04
RL-W709	2.10E-01	1.247E-06	4.20E-01	4.14E-01	4.11E-01	4.06E-01	3.92E-01	3.62E-01	3.24E-01	2.98E-01	2.71E-01	2.48E-01
RL-W710	2.10E-01	1.247E-06	2.51E-05	2.47E-05	2.45E-05	2.42E-05	2.34E-05	2.16E-05	1.93E-05	1.78E-05	1.62E-05	1.48E-05
RL-W711	2.10E-01	1.247E-06	7.83E-03	7.71E-03	7.66E-03	7.57E-03	7.31E-03	6.75E-03	6.04E-03	5.57E-03	5.06E-03	4.62E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W712	2.10E-01	1.247E-06	1.01E-02	9.97E-03	9.91E-03	9.79E-03	9.45E-03	8.72E-03	7.80E-03	7.19E-03	6.54E-03	5.97E-03
RL-W713	2.10E-01	1.247E-06	8.73E-03	8.60E-03	8.54E-03	8.44E-03	8.15E-03	7.52E-03	6.72E-03	6.20E-03	5.64E-03	5.14E-03
RL-W714	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	4.20E-01	2.493E-06	7.41E-05	7.30E-05	7.25E-05	7.16E-05	6.91E-05	6.37E-05	5.69E-05	5.25E-05	4.77E-05	4.36E-05
RL-W716	8.40E-01	4.986E-06	3.86E-04	3.80E-04	3.78E-04	3.73E-04	3.60E-04	3.32E-04	2.97E-04	2.74E-04	2.49E-04	2.27E-04
RL-W717	2.10E-01	1.247E-06	3.86E-04	3.80E-04	3.78E-04	3.73E-04	3.60E-04	3.32E-04	2.97E-04	2.74E-04	2.49E-04	2.27E-04
RL-W718	4.20E-01	2.493E-06	3.40E-05	3.35E-05	3.33E-05	3.29E-05	3.17E-05	2.92E-05	2.61E-05	2.41E-05	2.19E-05	2.00E-05
RL-W719	4.20E-01	2.493E-06	1.54E-04	1.51E-04	1.50E-04	1.49E-04	1.43E-04	1.32E-04	1.18E-04	1.09E-04	9.91E-05	9.04E-05
RL-W720	2.52E+00	1.496E-05	1.58E-04	1.56E-04	1.55E-04	1.53E-04	1.48E-04	1.36E-04	1.22E-04	1.12E-04	1.02E-04	9.31E-05
RL-W721	2.31E+00	1.371E-05	1.17E-04	1.15E-04	1.14E-04	1.13E-04	1.09E-04	1.01E-04	8.98E-05	8.28E-05	7.53E-05	6.87E-05
RL-W723	6.20E-01	3.680E-06	1.48E-03	1.45E-03	1.44E-03	1.43E-03	1.38E-03	1.27E-03	1.14E-03	1.05E-03	9.54E-04	8.71E-04
RL-W724	3.33E+00	1.977E-05	1.82E-03	1.79E-03	1.78E-03	1.76E-03	1.70E-03	1.57E-03	1.40E-03	1.29E-03	1.17E-03	1.07E-03
RL-W725	1.25E+00	7.420E-06	1.53E-03	1.51E-03	1.50E-03	1.48E-03	1.43E-03	1.32E-03	1.18E-03	1.09E-03	9.91E-04	9.04E-04
RL-W726	1.66E+00	9.854E-06	9.12E-04	8.98E-04	8.92E-04	8.82E-04	8.52E-04	7.86E-04	7.03E-04	6.49E-04	5.90E-04	5.38E-04
RL-W727	6.24E+00	3.704E-05	1.49E-03	1.46E-03	1.45E-03	1.44E-03	1.39E-03	1.28E-03	1.15E-03	1.06E-03	9.60E-04	8.76E-04
RL-W728	8.32E+00	4.939E-05	1.02E-03	1.00E-03	9.96E-04	9.84E-04	9.51E-04	8.78E-04	7.85E-04	7.24E-04	6.58E-04	6.01E-04
RL-W729	2.91E+00	1.727E-05	1.34E-03	1.32E-03	1.31E-03	1.30E-03	1.25E-03	1.16E-03	1.03E-03	9.53E-04	8.66E-04	7.90E-04
RL-W730	1.20E+02	7.100E-04	1.65E-03	1.41E-03	1.35E-03	1.25E-03	9.41E-04	3.32E-04	1.34E-05	5.43E-07	9.86E-09	1.79E-10
RL-W731	2.10E-01	1.247E-06	8.99E-06	8.92E-06	8.90E-06	8.87E-06	8.77E-06	8.50E-06	7.96E-06	7.51E-06	6.99E-06	6.50E-06
RL-W732	6.46E+01	3.835E-04	1.21E-02	1.18E-02	1.17E-02	1.14E-02	1.09E-02	9.73E-03	8.56E-03	7.89E-03	7.18E-03	6.55E-03
RL-W733	6.30E-01	3.740E-06	1.44E-02	1.39E-02	1.37E-02	1.34E-02	1.26E-02	1.12E-02	9.72E-03	8.93E-03	8.10E-03	7.38E-03
RL-W734	4.20E-01	2.493E-06	7.27E-02	7.02E-02	6.94E-02	6.79E-02	6.42E-02	5.72E-02	5.01E-02	4.61E-02	4.18E-02	3.81E-02
RL-W735	2.10E-01	1.247E-06	1.15E-01	1.11E-01	1.09E-01	1.07E-01	1.01E-01	8.98E-02	7.84E-02	7.21E-02	6.53E-02	5.95E-02
RL-W736	2.10E-01	1.247E-06	8.42E-05	8.09E-05	8.00E-05	7.83E-05	7.31E-05	6.20E-05	5.24E-05	4.81E-05	4.35E-05	3.96E-05
RL-W737	8.40E-01	4.986E-06	2.68E-02	2.59E-02	2.56E-02	2.51E-02	2.37E-02	2.12E-02	1.85E-02	1.70E-02	1.55E-02	1.41E-02
RL-W738	2.31E+00	1.371E-05	3.25E-02	3.13E-02	3.09E-02	3.02E-02	2.84E-02	2.50E-02	2.17E-02	2.00E-02	1.81E-02	1.64E-02
RL-W739	2.10E-01	1.247E-06	5.02E-02	4.90E-02	4.86E-02	4.79E-02	4.61E-02	4.24E-02	3.79E-02	3.49E-02	3.17E-02	2.89E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W740	1.32E+01	7.853E-05	2.25E-02	2.18E-02	2.15E-02	2.11E-02	1.98E-02	1.73E-02	1.50E-02	1.38E-02	1.25E-02	1.13E-02
RL-W741	1.05E+00	6.233E-06	1.74E-01	1.51E-01	1.46E-01	1.37E-01	1.13E-01	7.33E-02	4.83E-02	4.26E-02	3.73E-02	3.30E-02
RL-W742	2.10E-01	1.247E-06	8.97E-02	8.65E-02	8.54E-02	8.34E-02	7.82E-02	6.80E-02	5.87E-02	5.40E-02	4.90E-02	4.47E-02
RL-W743	2.10E-01	1.247E-06	7.53E-05	6.88E-05	6.74E-05	6.47E-05	5.70E-05	4.17E-05	3.22E-05	3.01E-05	2.80E-05	2.60E-05
RL-W744	2.10E-01	1.247E-06	3.21E-03	3.19E-03	3.18E-03	3.17E-03	3.14E-03	3.01E-03	2.66E-03	2.37E-03	2.06E-03	1.81E-03
RL-W745	2.10E-01	1.247E-06	4.72E-04	4.65E-04	4.62E-04	4.56E-04	4.41E-04	4.06E-04	3.63E-04	3.35E-04	3.04E-04	2.78E-04
RL-W746	4.20E-01	2.493E-06	9.07E-04	8.94E-04	8.88E-04	8.77E-04	8.47E-04	7.80E-04	6.97E-04	6.43E-04	5.85E-04	5.33E-04
RL-W747	2.10E-01	1.247E-06	4.91E-03	4.84E-03	4.81E-03	4.75E-03	4.59E-03	4.23E-03	3.78E-03	3.48E-03	3.17E-03	2.89E-03
RL-W748	1.32E+01	7.853E-05	6.58E-02	6.34E-02	6.08E-02	5.59E-02	4.18E-02	1.48E-02	7.87E-04	1.94E-04	1.44E-04	1.23E-04
RL-W749	3.78E+00	2.244E-05	2.36E-03	2.33E-03	2.31E-03	2.28E-03	2.21E-03	2.04E-03	1.82E-03	1.68E-03	1.53E-03	1.39E-03
RL-W750	4.20E-01	2.493E-06	3.18E+00	3.03E+00	2.90E+00	2.67E+00	2.00E+00	7.09E-01	3.83E-02	9.91E-03	7.44E-03	6.33E-03
RL-W751	2.10E-01	1.247E-06	5.74E+00	5.47E+00	5.25E+00	4.82E+00	3.61E+00	1.28E+00	6.92E-02	1.79E-02	1.34E-02	1.14E-02
RL-W752	9.87E+00	5.859E-05	5.31E-02	5.06E-02	4.85E-02	4.46E-02	3.34E-02	1.18E-02	6.40E-04	1.66E-04	1.24E-04	1.06E-04
RL-W753	1.22E+01	7.212E-05	5.80E-01	5.53E-01	5.30E-01	4.87E-01	3.65E-01	1.29E-01	6.99E-03	1.81E-03	1.36E-03	1.16E-03
RP-W754	1.48E+03	8.810E-03	5.71E-03	5.65E-03	5.63E-03	5.61E-03	5.53E-03	5.32E-03	4.94E-03	4.62E-03	4.26E-03	3.93E-03
RP-W755	2.45E+03	1.453E-02	3.21E-03	3.10E-03	3.07E-03	3.02E-03	2.87E-03	2.56E-03	2.26E-03	2.11E-03	1.95E-03	1.80E-03
SA-T001	5.41E+00	3.211E-05	3.02E-03	2.86E-03	2.83E-03	2.77E-03	2.62E-03	2.33E-03	2.09E-03	1.96E-03	1.82E-03	1.70E-03
SA-W134	1.60E+01	9.510E-05	2.52E-03	2.13E-03	2.04E-03	1.90E-03	1.52E-03	8.35E-04	4.55E-04	4.07E-04	3.71E-04	3.39E-04
SA-W134M	2.08E+00	1.235E-05	2.52E-03	2.13E-03	2.05E-03	1.90E-03	1.52E-03	8.36E-04	4.56E-04	4.09E-04	3.72E-04	3.40E-04
T001-221F-HET	2.25E+03	1.338E-02	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.83E-02	4.54E-02	4.22E-02	3.91E-02
T001-221H-HET	4.07E+03	2.415E-02	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.83E-02	4.54E-02	4.22E-02	3.92E-02
T001-235F-HET	2.34E+02	1.389E-03	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.78E-02	5.20E-02	4.83E-02	4.54E-02	4.22E-02	3.91E-02
T001-772F-HET	2.02E+03	1.198E-02	2.76E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.83E-02	4.55E-02	4.22E-02	3.92E-02
T001-773A-CLAS	2.26E+01	1.344E-04	2.76E-01	1.55E-01	1.37E-01	1.10E-01	6.80E-02	5.21E-02	4.84E-02	4.55E-02	4.23E-02	3.92E-02
T001-773A-HET	2.61E+02	1.551E-03	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.78E-02	5.20E-02	4.83E-02	4.54E-02	4.22E-02	3.92E-02
W006-773A-VIT	6.20E-01	3.680E-06	3.49E+00	3.48E+00	3.48E+00	3.47E+00	3.45E+00	3.39E+00	3.20E+00	3.02E+00	2.81E+00	2.62E+00
W026-221F-HET	7.86E+02	4.665E-03	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.81E-02	5.23E-02	4.86E-02	4.57E-02	4.24E-02	3.94E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
W026-221H-HET	5.88E+02	3.488E-03	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.84E-02	4.55E-02	4.22E-02	3.92E-02
W026-235F-HET	9.15E+00	5.432E-05	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.83E-02	4.55E-02	4.22E-02	3.92E-02
W026-772F-HET	2.50E+00	1.484E-05	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.78E-02	5.19E-02	4.82E-02	4.54E-02	4.21E-02	3.91E-02
W026-773A-HET	4.07E+01	2.414E-04	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.83E-02	4.55E-02	4.22E-02	3.92E-02
W027-221F-HET	3.05E+03	1.811E-02	2.47E-01	1.42E-01	1.26E-01	1.03E-01	6.60E-02	5.19E-02	4.83E-02	4.54E-02	4.22E-02	3.92E-02
W027-221H-HET	1.34E+03	7.925E-03	2.46E-01	1.42E-01	1.26E-01	1.03E-01	6.61E-02	5.21E-02	4.84E-02	4.55E-02	4.23E-02	3.92E-02
W027-235F-HET	4.02E+02	2.385E-03	2.46E-01	1.42E-01	1.26E-01	1.03E-01	6.60E-02	5.20E-02	4.83E-02	4.55E-02	4.22E-02	3.92E-02
W027-772F-HET	7.30E+02	4.332E-03	2.46E-01	1.42E-01	1.26E-01	1.03E-01	6.60E-02	5.20E-02	4.83E-02	4.55E-02	4.22E-02	3.92E-02
W027-773A-HET	1.09E+03	6.463E-03	2.46E-01	1.42E-01	1.26E-01	1.03E-01	6.59E-02	5.19E-02	4.82E-02	4.54E-02	4.21E-02	3.91E-02
W027-999-HET	1.24E+03	7.387E-03	2.46E-01	1.42E-01	1.26E-01	1.03E-01	6.60E-02	5.19E-02	4.83E-02	4.54E-02	4.22E-02	3.91E-02
W053-773A-VIT	6.20E-01	3.680E-06	2.59E+00	2.59E+00	2.58E+00	2.58E+00	2.57E+00	2.52E+00	2.38E+00	2.25E+00	2.09E+00	1.94E+00
WP-INW169.001	1.70E+01	1.010E-04	5.53E-03	5.38E-03	5.33E-03	5.25E-03	5.00E-03	4.49E-03	3.95E-03	3.64E-03	3.31E-03	3.02E-03
WP-INW198.001	4.47E+01	2.655E-04	3.58E-03	3.50E-03	3.47E-03	3.43E-03	3.30E-03	3.02E-03	2.68E-03	2.48E-03	2.25E-03	2.05E-03
WP-INW211.001	2.86E+02	1.699E-03	5.34E-02	5.21E-02	5.17E-02	5.09E-02	4.87E-02	4.41E-02	3.89E-02	3.59E-02	3.26E-02	2.98E-02
WP-INW216.001-	8.88E+02	5.273E-03	1.17E-01	1.01E-01	9.73E-02	9.04E-02	7.02E-02	2.98E-02	8.13E-03	6.73E-03	6.08E-03	5.55E-03
WP-INW216.001-	3.09E+02	1.832E-03	9.25E-02	7.98E-02	7.69E-02	7.14E-02	5.54E-02	2.35E-02	6.34E-03	5.24E-03	4.74E-03	4.33E-03
WP-INW218.001-	7.57E+02	4.492E-03	4.13E-03	3.77E-03	3.68E-03	3.52E-03	3.05E-03	2.10E-03	1.50E-03	1.37E-03	1.25E-03	1.14E-03
WP-INW218.001-	2.50E+01	1.483E-04	1.73E-03	1.69E-03	1.67E-03	1.64E-03	1.56E-03	1.40E-03	1.23E-03	1.13E-03	1.03E-03	9.41E-04
WP-INW222.001	3.02E+01	1.795E-04	1.42E-02	1.37E-02	1.36E-02	1.34E-02	1.27E-02	1.13E-02	9.90E-03	9.12E-03	8.29E-03	7.56E-03
WP-INW243.001	6.72E+01	3.989E-04	1.38E-02	1.33E-02	1.32E-02	1.29E-02	1.22E-02	1.08E-02	9.35E-03	8.62E-03	7.83E-03	7.14E-03
WP-INW247.001R	1.08E+02	6.432E-04	1.54E-02	1.49E-02	1.48E-02	1.46E-02	1.39E-02	1.26E-02	1.11E-02	1.03E-02	9.32E-03	8.50E-03
WP-INW276.001	1.03E+01	6.108E-05	1.54E-02	1.50E-02	1.49E-02	1.47E-02	1.42E-02	1.30E-02	1.16E-02	1.07E-02	9.71E-03	8.86E-03
WP-INW276.002	1.62E+01	9.599E-05	1.46E-02	1.42E-02	1.41E-02	1.39E-02	1.34E-02	1.22E-02	1.09E-02	1.00E-02	9.10E-03	8.30E-03
WP-INW276.003	1.86E+02	1.103E-03	4.73E-02	4.60E-02	4.57E-02	4.50E-02	4.32E-02	3.94E-02	3.51E-02	3.23E-02	2.94E-02	2.68E-02
WP-INW276.004	4.66E+01	2.767E-04	4.06E-02	3.94E-02	3.91E-02	3.85E-02	3.68E-02	3.34E-02	2.95E-02	2.72E-02	2.47E-02	2.26E-02
WP-INW296.001-	1.09E+01	6.482E-05	4.67E-02	4.50E-02	4.46E-02	4.37E-02	4.13E-02	3.64E-02	3.17E-02	2.92E-02	2.65E-02	2.42E-02
WP-INW296.001-	8.11E+01	4.812E-04	2.15E-02	2.08E-02	2.06E-02	2.03E-02	1.93E-02	1.72E-02	1.51E-02	1.39E-02	1.26E-02	1.15E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
WP-LA-TA-55-19	5.88E+00	3.490E-05	3.01E-03	2.74E-03	2.68E-03	2.58E-03	2.33E-03	1.90E-03	1.58E-03	1.45E-03	1.31E-03	1.20E-03
WP-LA-TA-55-19	7.52E+01	4.464E-04	1.84E-02	1.76E-02	1.74E-02	1.71E-02	1.62E-02	1.44E-02	1.25E-02	1.15E-02	1.05E-02	9.53E-03
WP-LA-TA-55-43	1.90E+02	1.127E-03	6.86E-03	3.13E-03	2.57E-03	1.74E-03	4.49E-04	1.72E-05	1.22E-05	1.13E-05	1.05E-05	9.76E-06
WP-RF001.01	4.77E+02	2.832E-03	5.32E-03	5.14E-03	5.10E-03	5.01E-03	4.77E-03	4.28E-03	3.76E-03	3.46E-03	3.15E-03	2.87E-03
WP-RF002.01-A	3.51E+02	2.082E-03	8.18E-03	7.94E-03	7.87E-03	7.73E-03	7.35E-03	6.57E-03	5.77E-03	5.31E-03	4.83E-03	4.40E-03
WP-RF002.01-B	2.10E-01	1.247E-06	1.45E-02	1.41E-02	1.40E-02	1.38E-02	1.31E-02	1.18E-02	1.04E-02	9.59E-03	8.71E-03	7.95E-03
WP-RF003.01	2.32E+02	1.379E-03	2.27E-01	2.21E-01	2.20E-01	2.16E-01	2.07E-01	1.88E-01	1.66E-01	1.53E-01	1.39E-01	1.27E-01
WP-RF004.01	5.67E+00	3.366E-05	5.21E-03	5.09E-03	5.06E-03	4.99E-03	4.80E-03	4.41E-03	3.93E-03	3.62E-03	3.29E-03	3.00E-03
WP-RF005.01	1.21E+02	7.155E-04	3.68E-01	3.41E-01	3.35E-01	3.23E-01	2.88E-01	2.19E-01	1.70E-01	1.56E-01	1.42E-01	1.29E-01
WP-RF005.02	7.83E+01	4.650E-04	4.93E-01	4.46E-01	4.35E-01	4.14E-01	3.54E-01	2.32E-01	1.58E-01	1.43E-01	1.30E-01	1.19E-01
WP-RF006.01	2.21E+02	1.311E-03	2.17E-01	2.10E-01	2.08E-01	2.05E-01	1.96E-01	1.78E-01	1.57E-01	1.45E-01	1.32E-01	1.20E-01
WP-RF008.01	8.00E+01	4.749E-04	1.77E-01	1.72E-01	1.71E-01	1.68E-01	1.60E-01	1.44E-01	1.27E-01	1.17E-01	1.06E-01	9.70E-02
WP-RF009.01	1.30E+03	7.711E-03	3.87E-01	3.58E-01	3.51E-01	3.38E-01	3.01E-01	2.24E-01	1.72E-01	1.58E-01	1.43E-01	1.31E-01
WP-RF010.01	5.55E+01	3.295E-04	8.55E-03	8.33E-03	8.25E-03	8.11E-03	7.72E-03	6.91E-03	6.06E-03	5.58E-03	5.07E-03	4.63E-03
WP-RF029.01-A	4.89E+01	2.902E-04	1.82E-03	1.77E-03	1.75E-03	1.71E-03	1.61E-03	1.40E-03	1.21E-03	1.11E-03	1.01E-03	9.23E-04
WP-RF029.01-B	1.88E+01	1.116E-04	4.58E-03	4.34E-03	4.28E-03	4.15E-03	3.79E-03	3.05E-03	2.50E-03	2.30E-03	2.08E-03	1.90E-03
WP-RF118.01	1.27E+03	7.559E-03	2.45E-01	2.39E-01	2.36E-01	2.32E-01	2.22E-01	2.00E-01	1.76E-01	1.62E-01	1.47E-01	1.35E-01
WP-RLMPDT.001	7.35E+00	4.363E-05	6.87E-03	6.59E-03	6.50E-03	6.35E-03	5.95E-03	5.19E-03	4.48E-03	4.11E-03	3.72E-03	3.39E-03
WP-RLNPDT.002	9.07E+01	5.385E-04	5.79E-03	5.54E-03	5.46E-03	5.32E-03	4.95E-03	4.22E-03	3.59E-03	3.29E-03	2.98E-03	2.71E-03
WP-SR2001.001.	6.17E+01	3.665E-04	6.39E-04	6.15E-04	6.08E-04	5.98E-04	5.72E-04	5.28E-04	4.74E-04	4.38E-04	3.99E-04	3.65E-04
WP-SR-W027-221	1.41E+02	8.377E-04	9.96E-04	9.50E-04	9.37E-04	9.14E-04	8.53E-04	7.39E-04	6.34E-04	5.82E-04	5.27E-04	4.79E-04
CH Total	1.685E+05	1.000E+00										
RH Total	7.078E+03	1.000E+00	3.477E-02	1.475E-02	1.344E-02	1.189E-02	9.480E-03	5.767E-03	3.612E-03	3.248E-03	2.930E-03	2.658E-03

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	8.48E+01	0.00E+00	1.38E+01	2.09E+02	1.24E+02	5.12E+01	1.47E-02	4.31E+02	1.74E+00
AE-T003	1.00E+01	0.00E+00	1.84E+00	6.45E+01	2.49E+01	2.81E+01	3.03E-04	1.01E+02	4.09E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	4.67E-02	0.00E+00	4.88E+01	4.76E+01	2.87E-01	5.47E-02	5.53E-03	9.67E+01	3.90E-01
AW-T033.1325	1.71E-01	0.00E+00	1.79E+02	1.74E+02	1.05E+00	2.00E-01	2.03E-02	3.54E+02	1.43E+00
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.72E-01	0.00E+00	0.00E+00	0.00E+00	7.72E-01	3.11E-03
BCLCH-MT01	1.53E+01	0.00E+00	1.38E+03	2.87E+01	7.51E+00	7.72E+01	1.43E-01	1.43E+03	5.78E+00
BT-T002	1.20E-02	7.43E-04	7.22E-01	7.24E-04	1.48E-03	3.39E-02	2.06E-03	7.39E-01	2.98E-03
ET-C1-B55	5.30E-02	0.00E+00	8.23E-03	6.20E-02	3.09E-02	5.98E-02	2.37E-04	1.54E-01	6.22E-04
ET-C1-D139	7.28E-03	0.00E+00	1.14E-03	8.72E-03	4.35E-03	7.95E-03	1.80E-07	2.15E-02	8.66E-05
ET-C2-SEFOR	1.83E-01	0.00E+00	0.00E+00	1.37E-01	4.59E-02	1.23E-01	0.00E+00	3.66E-01	1.47E-03
FM-MOX-MT02	1.63E-06	0.00E+00	4.60E-07	3.00E-07	1.78E-07	4.27E-06	5.60E-11	2.56E-06	1.03E-08
FM-MOX-T01	2.68E-05	0.00E+00	7.59E-06	4.94E-06	2.94E-06	7.03E-05	9.24E-10	4.23E-05	1.71E-07
IN-BN-510	7.07E+03	0.00E+00	3.91E+04	3.97E+04	3.36E+03	1.68E+01	6.00E+00	8.92E+04	3.60E+02
IN-GEM-01	8.90E+01	0.00E+00	7.76E-01	4.46E+01	1.02E+01	1.19E+01	8.01E-05	1.45E+02	5.83E-01
IN-GEM-02	2.11E+01	0.00E+00	1.85E-01	1.06E+01	2.42E+00	2.81E+00	1.91E-05	3.43E+01	1.38E-01
IN-W157.144	9.87E+01	0.00E+00	7.52E+00	3.03E+02	6.85E+01	2.10E+02	1.15E-03	4.77E+02	1.93E+00
IN-W163.1007	1.59E+01	0.00E+00	2.32E+00	9.39E+01	2.12E+01	6.47E+01	3.56E-04	1.33E+02	5.38E-01
IN-W164.153	1.52E-01	0.00E+00	2.21E-02	8.94E-01	2.02E-01	6.19E-01	3.39E-06	1.27E+00	5.12E-03
IN-W167.149	3.12E+01	0.00E+00	3.60E+00	1.45E+02	3.28E+01	1.00E+02	5.51E-04	2.13E+02	8.57E-01
IN-W174.154	0.00E+00	0.00E+00	2.04E+03	1.95E+00	3.84E+00	0.00E+00	3.12E-01	2.04E+03	8.23E+00
IN-W177.156	2.11E-02	0.00E+00	4.33E+03	1.83E+00	1.12E-02	8.62E-02	6.62E-01	4.33E+03	1.75E+01
IN-W179.158	1.42E-01	0.00E+00	4.31E+03	1.06E-01	5.50E-02	5.79E-01	6.60E-01	4.31E+03	1.74E+01
IN-W181.162	2.02E+00	0.00E+00	2.94E-01	1.18E+01	2.67E+00	8.21E+00	4.50E-05	1.68E+01	6.76E-02
IN-W188.160	1.36E+01	0.00E+00	1.97E+00	7.96E+01	1.79E+01	5.53E+01	3.02E-04	1.13E+02	4.56E-01
IN-W216.98	1.37E+05	0.00E+00	1.61E+02	6.49E+03	1.48E+03	4.52E+03	2.46E-02	1.46E+05	5.87E+02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	6.91E+02	0.00E+00	3.57E+00	1.44E+02	3.26E+01	1.00E+02	5.48E-04	8.71E+02	3.51E+00
IN-W219.110	8.27E-01	0.00E+00	1.20E-01	4.86E+00	1.10E+00	3.36E+00	1.84E-05	6.90E+00	2.78E-02
IN-W219.914	1.30E-01	0.00E+00	1.90E-02	7.66E-01	1.73E-01	5.32E-01	2.90E-06	1.09E+00	4.39E-03
IN-W220.114	4.90E+03	0.00E+00	1.27E+01	5.49E+02	1.21E+02	3.54E+02	1.94E-03	5.58E+03	2.25E+01
IN-W221.927	5.05E+00	0.00E+00	7.34E-01	2.96E+01	6.68E+00	2.06E+01	1.12E-04	4.20E+01	1.70E-01
IN-W222.116	1.72E+02	0.00E+00	2.49E+01	9.99E+02	2.26E+02	6.94E+02	3.81E-03	1.42E+03	5.73E+00
IN-W228.101	1.29E+03	0.00E+00	8.08E+00	3.27E+02	7.38E+01	2.27E+02	1.24E-03	1.70E+03	6.85E+00
IN-W240.931	1.28E+02	0.00E+00	1.03E+01	4.20E+02	9.44E+01	2.87E+02	1.58E-03	6.52E+02	2.63E+00
IN-W243.808	1.73E+02	0.00E+00	1.81E+01	7.32E+02	1.65E+02	5.08E+02	2.77E-03	1.09E+03	4.39E+00
IN-W245.301	2.48E+02	0.00E+00	3.56E+01	1.43E+03	3.24E+02	9.92E+02	5.45E-03	2.04E+03	8.21E+00
IN-W247.810	1.21E+02	0.00E+00	1.73E+01	6.98E+02	1.59E+02	4.84E+02	2.65E-03	9.95E+02	4.01E+00
IN-W249.527	0.00E+00	0.00E+00	1.21E+03	1.24E+01	0.00E+00	0.00E+00	1.86E-01	1.22E+03	4.94E+00
IN-W263.520	3.45E-02	0.00E+00	1.27E+02	8.42E+00	1.34E-02	1.40E-01	1.94E-02	1.35E+02	5.45E-01
IN-W267.1005	2.88E+01	0.00E+00	4.20E+00	1.70E+02	3.84E+01	1.18E+02	6.44E-04	2.41E+02	9.73E-01
IN-W309.609	8.14E+02	0.00E+00	7.04E+01	2.84E+03	6.42E+02	1.97E+03	1.08E-02	4.36E+03	1.76E+01
IN-W315.601	8.69E+02	0.00E+00	2.94E-01	1.19E+01	2.68E+00	8.21E+00	4.51E-05	8.84E+02	3.57E+00
IN-W319.584	4.44E+00	0.00E+00	6.45E-01	2.61E+01	5.91E+00	1.81E+01	9.87E-05	3.71E+01	1.50E-01
IN-W321.1023	3.84E+01	0.00E+00	5.59E+00	2.26E+02	5.10E+01	1.56E+02	8.57E-04	3.21E+02	1.29E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	9.11E+00	1.88E+00	0.00E+00	0.00E+00	1.10E+01	4.43E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.43E+01	5.02E+00	0.00E+00	0.00E+00	2.93E+01	1.18E-01
IN-W323.562	8.20E-02	0.00E+00	9.48E-01	2.49E-01	0.00E+00	3.34E-01	1.45E-04	1.28E+00	5.16E-03
IN-W323.951	9.68E-02	0.00E+00	1.13E-02	2.97E-01	0.00E+00	3.94E-01	1.73E-06	4.05E-01	1.63E-03
IN-W332.661	0.00E+00	0.00E+00	1.24E+01	1.29E-01	0.00E+00	0.00E+00	1.91E-03	1.26E+01	5.06E-02
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	3.04E+00	6.28E-01	0.00E+00	0.00E+00	3.67E+00	1.48E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	9.11E+00	1.88E+00	0.00E+00	0.00E+00	1.10E+01	4.43E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.95E+00	0.00E+00	0.00E+00	0.00E+00	1.95E+00	7.86E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.86E+00	0.00E+00	0.00E+00	0.00E+00	5.86E+00	2.36E-02
IN-W342.652	4.32E+00	0.00E+00	0.00E+00	4.02E-02	1.04E-17	0.00E+00	0.00E+00	4.36E+00	1.76E-02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W342.953	2.89E+00	0.00E+00	0.00E+00	2.69E-02	6.96E-18	0.00E+00	0.00E+00	2.92E+00	1.18E-02
IN-W347.818	2.26E+00	0.00E+00	0.00E+00	8.25E+01	1.52E+02	0.00E+00	1.58E-08	2.36E+02	9.53E-01
IN-W348.1012	1.20E-01	0.00E+00	1.03E+01	4.17E+02	9.43E+01	0.00E+00	1.57E-03	5.21E+02	2.10E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.50E-02	0.00E+00	0.00E+00	0.00E+00	2.50E-02	1.01E-04
IN-W357.1022	0.00E+00	0.00E+00	2.02E-02	8.18E-01	1.84E-01	0.00E+00	3.09E-06	1.02E+00	4.12E-03
IN-W358.854	0.00E+00	0.00E+00	3.04E+02	1.88E+00	3.62E+00	0.00E+00	3.94E-02	3.10E+02	1.25E+00
IN-W358.855	0.00E+00	0.00E+00	1.62E+03	9.99E+00	1.92E+01	0.00E+00	2.10E-01	1.65E+03	6.66E+00
IN-W358.948	0.00E+00	0.00E+00	3.39E+02	2.09E+00	4.01E+00	0.00E+00	4.39E-02	3.45E+02	1.39E+00
IN-W361.1021	3.18E-02	0.00E+00	1.96E+00	7.89E+01	1.78E+01	0.00E+00	3.00E-04	9.88E+01	3.98E-01
IN-W362.1020	0.00E+00	0.00E+00	2.56E+01	1.03E+03	2.34E+02	0.00E+00	3.93E-03	1.29E+03	5.20E+00
IN-W363.1019	0.00E+00	0.00E+00	1.20E+00	4.89E+01	1.11E+01	0.00E+00	1.85E-04	6.11E+01	2.47E-01
IN-W364.1011	0.00E+00	0.00E+00	1.99E+00	8.03E+01	1.81E+01	0.00E+00	3.05E-04	1.01E+02	4.05E-01
IN-W365.1010	2.96E+02	0.00E+00	1.58E+00	6.34E+01	1.44E+01	0.00E+00	2.42E-04	3.76E+02	1.52E+00
IN-W366.841	1.05E+00	0.00E+00	1.34E+00	5.41E+01	1.23E+01	0.00E+00	2.06E-04	6.87E+01	2.77E-01
IN-W372.832	4.32E+00	0.00E+00	0.00E+00	4.02E-02	1.04E-17	0.00E+00	0.00E+00	4.36E+00	1.76E-02
IN-W375.1096	0.00E+00	0.00E+00	4.96E-01	2.00E+01	4.52E+00	0.00E+00	7.59E-05	2.50E+01	1.01E-01
KN-B234TRU	1.50E+02	0.00E+00	1.90E+01	2.91E+02	9.77E+01	1.10E+02	3.91E-03	5.57E+02	2.25E+00
LA-IT-00-01	2.23E+00	4.79E-01	3.23E+00	5.85E-01	1.13E-02	2.11E-08	6.88E-04	6.06E+00	2.44E-02
LA-OS-00-01	4.97E+03	0.00E+00	1.48E+05	1.23E+03	0.00E+00	0.00E+00	1.58E+01	1.54E+05	6.20E+02
LA-PX-00-01	1.95E-02	0.00E+00	6.22E-03	9.04E-02	2.12E-02	3.49E-02	7.82E-07	1.37E-01	5.54E-04
LA-SL-00-01	0.00E+00	0.00E+00	1.31E-01	1.53E-01	0.00E+00	0.00E+00	2.74E-05	2.84E-01	1.15E-03
LA-TA-03-12	2.06E-01	0.00E+00	3.04E+00	4.36E-01	1.52E-01	2.07E-01	6.95E-04	3.83E+00	1.55E-02
LA-TA-03-13	2.66E-01	0.00E+00	9.63E+00	6.80E-01	1.60E-01	2.74E-01	1.53E-03	1.07E+01	4.33E-02
LA-TA-03-19	5.42E-01	0.00E+00	1.44E+01	1.33E+00	3.84E-01	4.24E-01	3.27E-03	1.66E+01	6.70E-02
LA-TA-03-20	2.92E-01	0.00E+00	6.82E+00	5.86E-01	2.06E-01	3.47E-01	1.39E-03	7.90E+00	3.19E-02
LA-TA-03-24	3.95E-01	0.00E+00	2.66E+01	1.09E+00	3.30E-01	3.60E-01	6.15E-03	2.84E+01	1.14E-01
LA-TA-03-26	1.98E-02	0.00E+00	1.10E+00	2.64E+00	4.32E-02	3.15E-02	1.12E-03	3.80E+00	1.53E-02
LA-TA-03-28	0.00E+00	0.00E+00	3.79E-01	2.47E-01	0.00E+00	0.00E+00	8.43E-05	6.26E-01	2.52E-03

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-03-30	8.72E-01	0.00E+00	2.70E-01	5.03E+00	1.46E+00	1.65E+00	5.89E-05	7.62E+00	3.07E-02
LA-TA-03-31	0.00E+00	0.00E+00	1.35E-02	8.79E-03	0.00E+00	0.00E+00	3.01E-06	2.23E-02	9.00E-05
LA-TA-03-40	0.00E+00	0.00E+00	2.14E-02	5.47E-02	0.00E+00	0.00E+00	4.84E-06	7.60E-02	3.07E-04
LA-TA-03-42	2.01E-05	0.00E+00	5.35E-04	3.42E-03	4.50E-05	3.45E-05	1.21E-07	4.02E-03	1.62E-05
LA-TA-21-06	1.98E-01	0.00E+00	5.89E+01	9.56E-01	2.92E-01	3.56E-01	1.31E-02	6.03E+01	2.43E-01
LA-TA-21-12	7.23E-01	0.00E+00	3.55E+02	3.32E+00	9.91E-01	1.22E+00	7.89E-02	3.60E+02	1.45E+00
LA-TA-21-13	1.18E+00	0.00E+00	0.00E+00	2.94E-01	0.00E+00	0.00E+00	0.00E+00	1.47E+00	5.93E-03
LA-TA-21-14	1.76E-04	0.00E+00	6.77E+00	4.49E+00	5.23E-05	4.95E-04	8.77E-04	1.13E+01	4.54E-02
LA-TA-21-15	1.07E-01	0.00E+00	1.86E-02	1.39E+00	2.37E-01	2.01E-01	4.05E-06	1.75E+00	7.06E-03
LA-TA-21-16	1.25E+00	0.00E+00	2.87E-01	1.06E+01	2.53E+00	2.12E+00	6.52E-05	1.47E+01	5.91E-02
LA-TA-21-40	1.65E-04	0.00E+00	9.94E-01	3.33E-01	3.68E-04	8.49E-05	3.54E-04	1.33E+00	5.35E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	7.08E-01	0.00E+00	0.00E+00	0.00E+00	7.08E-01	2.86E-03
LA-TA-21-42	1.71E-02	0.00E+00	3.23E-01	1.64E-01	1.12E-02	2.76E-03	1.30E-04	5.15E-01	2.08E-03
LA-TA-21-43	5.98E+01	0.00E+00	1.07E+01	5.11E+02	1.22E+02	2.19E+01	4.25E-03	7.03E+02	2.83E+00
LA-TA-21-44	2.80E-01	0.00E+00	2.25E+00	1.15E+02	3.06E-01	3.09E-01	6.07E-04	1.18E+02	4.75E-01
LA-TA-48-01	9.31E-02	2.26E+00	8.47E-03	1.18E-01	4.87E-01	2.55E-02	3.06E-06	7.07E-01	2.85E-03
LA-TA-49-01	1.15E+01	2.80E+02	1.04E+00	1.46E+01	6.04E+01	3.15E+00	3.78E-04	8.75E+01	3.53E-01
LA-TA-50-10	3.11E-02	0.00E+00	9.86E-03	4.59E-02	0.00E+00	0.00E+00	1.20E-06	8.68E-02	3.50E-04
LA-TA-50-11	5.84E-02	0.00E+00	1.01E-02	4.66E-01	1.04E-01	2.53E-02	3.52E-06	6.38E-01	2.57E-03
LA-TA-50-15	1.14E-01	0.00E+00	1.49E+00	3.40E-01	7.62E-02	1.00E-01	2.75E-04	2.02E+00	8.15E-03
LA-TA-50-17	1.71E+01	0.00E+00	1.21E+00	1.82E+01	4.29E-04	9.15E-03	5.63E-04	3.65E+01	1.47E-01
LA-TA-50-18	1.02E+00	0.00E+00	1.60E-01	2.97E+00	5.34E-06	2.70E-04	3.63E-05	4.14E+00	1.67E-02
LA-TA-50-19	3.24E-01	0.00E+00	7.13E-02	3.95E-01	4.57E-03	3.34E-03	4.30E-05	7.95E-01	3.21E-03
LA-TA-50-20	8.90E-03	0.00E+00	0.00E+00	9.73E-03	0.00E+00	0.00E+00	0.00E+00	1.86E-02	7.51E-05
LA-TA-50-40	4.64E-03	0.00E+00	9.63E-04	1.06E-02	4.95E-03	1.07E-02	1.93E-07	2.12E-02	8.53E-05
LA-TA-50-41	4.69E-03	0.00E+00	9.71E-04	4.70E-02	1.10E-02	1.91E-02	1.49E-07	6.36E-02	2.56E-04
LA-TA-55-19	7.92E+00	0.00E+00	1.28E+00	2.64E+01	7.45E+00	1.08E+01	1.80E-03	4.30E+01	1.74E-01
LA-TA-55-20	1.24E+02	0.00E+00	1.46E+01	6.37E+02	1.54E+02	2.70E+02	9.64E-02	9.29E+02	3.75E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-21	1.11E+00	6.67E-04	1.68E-01	4.52E+00	1.09E+00	2.23E+00	2.50E-05	6.88E+00	2.78E-02
LA-TA-55-22	3.02E+00	0.00E+00	9.48E-01	1.59E+01	3.73E+00	6.90E+00	1.41E-04	2.36E+01	9.51E-02
LA-TA-55-23	2.84E+00	0.00E+00	7.92E-01	1.09E+01	2.70E+00	6.79E+00	1.15E-04	1.72E+01	6.94E-02
LA-TA-55-24	1.05E+00	0.00E+00	1.24E-01	5.72E+00	1.34E+00	3.24E+00	1.56E-05	8.22E+00	3.32E-02
LA-TA-55-25	5.35E+00	0.00E+00	7.25E-01	2.84E+01	6.65E+00	1.66E+01	9.11E-05	4.11E+01	1.66E-01
LA-TA-55-28	1.83E+00	0.00E+00	4.02E-01	8.71E+00	2.06E+00	5.38E+00	5.20E-05	1.30E+01	5.25E-02
LA-TA-55-30	4.36E+01	6.32E-06	4.81E+00	1.43E+02	3.46E+01	3.94E+01	1.27E-03	2.26E+02	9.11E-01
LA-TA-55-32	3.48E+00	0.00E+00	2.69E+01	1.13E+01	3.50E+00	4.91E+00	6.27E-03	4.51E+01	1.82E-01
LA-TA-55-33	5.22E-01	0.00E+00	6.94E-02	1.49E+00	4.76E-01	6.90E-01	1.36E-05	2.56E+00	1.03E-02
LA-TA-55-34	5.24E+01	0.00E+00	6.42E+00	2.31E+02	5.88E+01	8.32E+01	4.03E-03	3.48E+02	1.41E+00
LA-TA-55-38	1.38E+02	0.00E+00	2.11E+00	5.10E+01	1.38E+01	1.94E+01	2.11E-03	2.05E+02	8.26E-01
LA-TA-55-39	1.35E+01	0.00E+00	1.56E+00	7.60E+01	1.71E+01	3.41E+01	2.20E-04	1.08E+02	4.36E-01
LA-TA-55-41	3.48E+02	0.00E+00	3.23E+00	9.43E+01	2.26E+01	4.29E+01	4.95E-04	4.68E+02	1.89E+00
LA-TA-55-43	1.18E-01	0.00E+00	2.12E+02	1.42E-01	4.98E-02	3.77E-01	2.91E-02	2.12E+02	8.56E-01
LA-TA-55-44	1.10E+00	0.00E+00	4.99E+02	2.63E+00	7.32E-01	1.11E+00	9.97E-02	5.04E+02	2.03E+00
LA-TA-55-48	7.99E+03	0.00E+00	1.97E+03	1.69E+04	6.32E+03	1.16E+04	3.69E-01	3.32E+04	1.34E+02
LA-TA-55-49	1.75E+01	0.00E+00	2.59E+03	3.09E+01	8.70E+00	1.36E+01	5.07E-01	2.65E+03	1.07E+01
LA-TA-55-53	8.20E+01	0.00E+00	5.36E+00	2.64E+02	6.18E+01	7.46E+01	1.01E-03	4.13E+02	1.67E+00
LA-TA-55-56	8.77E+01	0.00E+00	2.00E+02	3.82E+02	9.61E+01	1.73E+02	3.23E-02	7.65E+02	3.09E+00
LA-TA-55-60	4.73E-02	0.00E+00	5.04E-02	7.19E-02	2.56E-02	1.02E-01	9.84E-06	1.95E-01	7.87E-04
LA-TA-55-61	4.03E-02	0.00E+00	2.32E-01	1.39E-01	4.72E-02	9.88E-02	4.34E-05	4.59E-01	1.85E-03
LA-TA-55-62	1.04E-02	0.00E+00	2.21E-03	2.33E-02	1.12E-02	2.66E-02	4.22E-07	4.71E-02	1.90E-04
LA-TA-55-63	7.50E-03	0.00E+00	1.49E-03	7.46E-02	1.73E-02	2.61E-02	2.47E-07	1.01E-01	4.07E-04
LL-M001	1.08E+02	3.03E+01	6.50E+01	6.99E+01	3.16E+01	2.06E+02	6.71E-03	2.75E+02	1.11E+00
LL-T001	5.20E+02	0.00E+00	0.00E+00	5.34E+02	2.41E+02	1.60E+03	0.00E+00	1.30E+03	5.22E+00
LL-T002	5.20E+03	0.00E+00	5.17E+02	5.18E+03	2.13E+03	1.41E+04	5.34E-02	1.30E+04	5.25E+01
LL-T003	2.02E+02	0.00E+00	5.79E+01	1.05E+02	8.49E+01	5.57E+02	5.97E-03	4.49E+02	1.81E+00
LL-T004	1.28E+02	0.00E+00	1.19E+01	6.66E+01	5.35E+01	3.54E+02	1.23E-03	2.60E+02	1.05E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
LL-T005	6.79E+02	1.32E+03	1.40E+02	2.48E+02	2.11E+02	1.31E+03	1.44E-02	1.28E+03	5.15E+00
LL-W018	5.25E-02	0.00E+00	0.00E+00	1.85E-02	4.27E-02	2.68E-01	0.00E+00	1.14E-01	4.58E-04
LL-W019	3.08E+01	0.00E+00	0.00E+00	1.44E+01	1.21E+01	7.84E+01	0.00E+00	5.72E+01	2.31E-01
LL-W034	1.16E+01	2.23E+01	2.45E+00	4.20E+00	3.50E+00	2.23E+01	2.53E-04	2.17E+01	8.77E-02
MC-W001	1.53E-01	0.00E+00	0.00E+00	6.05E-02	0.00E+00	4.03E-02	0.00E+00	2.14E-01	8.61E-04
MU-W002	2.06E+00	0.00E+00	0.00E+00	5.26E-02	0.00E+00	0.00E+00	2.67E-12	2.11E+00	8.52E-03
NT-JAS-01	1.82E+02	0.00E+00	5.21E+01	9.47E+01	7.64E+01	5.02E+02	5.38E-03	4.05E+02	1.63E+00
NT-W001	2.98E+02	6.82E-01	1.04E+02	2.86E+03	1.91E+01	3.51E+01	2.23E-02	3.28E+03	1.32E+01
NT-W021	5.17E+00	0.00E+00	7.46E-01	3.22E+01	7.36E+00	1.80E+01	1.23E-04	4.54E+01	1.83E-01
OR-W201	6.29E+03	4.70E+01	2.24E+03	2.16E+03	2.13E+03	1.88E+04	4.38E+01	1.29E+04	5.18E+01
OR-W202	9.74E+02	9.78E+02	6.45E+03	5.54E+02	5.42E+02	6.04E+02	1.12E+00	8.52E+03	3.44E+01
OR-W203	2.14E+00	3.41E+01	9.24E-01	2.49E-02	1.68E+00	1.53E+00	1.57E-04	4.77E+00	1.92E-02
OR-W204	4.88E-01	1.41E-04	1.05E+00	4.24E-01	2.87E-01	0.00E+00	1.78E-04	2.25E+00	9.06E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.26E-01	0.00E+00	0.00E+00	0.00E+00	4.26E-01	1.72E-03
RF-MT0001	1.87E+03	0.00E+00	6.51E+00	1.96E+02	4.48E+01	1.38E+02	9.71E-04	2.12E+03	8.53E+00
RF-MT0002	1.44E+02	0.00E+00	4.99E-01	1.51E+01	3.44E+00	1.06E+01	7.45E-05	1.63E+02	6.56E-01
RF-MT0003	5.72E-01	0.00E+00	1.14E-01	3.45E+00	7.87E-01	2.42E+00	1.71E-05	4.92E+00	1.98E-02
RF-MT0007	1.64E+00	0.00E+00	0.00E+00	4.30E-01	9.80E-02	2.81E-01	0.00E+00	2.17E+00	8.74E-03
RF-MT0089	5.64E-03	0.00E+00	1.14E-03	3.45E-02	7.86E-03	2.42E-02	1.70E-07	4.91E-02	1.98E-04
RF-MT0090	1.56E+01	0.00E+00	1.62E+00	8.85E+01	2.00E+01	2.42E+01	2.41E-04	1.26E+02	5.07E-01
RF-MT0091	9.49E+02	0.00E+00	1.64E+02	5.92E+03	1.35E+03	2.00E+03	2.75E-02	8.37E+03	3.38E+01
RF-MT0092	1.36E+02	0.00E+00	2.07E+01	8.47E+02	1.96E+02	2.76E+02	3.08E-03	1.20E+03	4.84E+00
RF-MT0093	1.69E+02	0.00E+00	2.13E+01	9.14E+02	2.15E+02	2.36E+02	3.17E-03	1.32E+03	5.32E+00
RF-MT0097	8.44E+00	0.00E+00	9.40E-01	4.78E+01	9.79E+00	1.29E+01	1.40E-04	6.69E+01	2.70E-01
RF-MT0099	8.48E-03	0.00E+00	1.72E-03	5.17E-02	1.18E-02	3.64E-02	2.56E-07	7.36E-02	2.97E-04
RF-MT0290	2.10E+01	0.00E+00	4.25E+00	1.28E+02	2.92E+01	9.02E+01	6.33E-04	1.82E+02	7.35E-01
RF-MT-0292	2.65E+01	0.00E+00	5.37E+00	1.62E+02	3.69E+01	1.14E+02	8.01E-04	2.31E+02	9.30E-01
RF-MT-0299	3.48E+03	0.00E+00	1.38E+02	4.15E+03	9.47E+02	2.94E+03	2.05E-02	8.71E+03	3.51E+01

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0302	5.09E-02	0.00E+00	5.45E-03	1.79E-01	4.10E-02	1.14E-01	1.77E-05	2.76E-01	1.11E-03
RF-MT0320	6.16E+01	0.00E+00	5.65E+00	1.74E+02	3.98E+01	1.15E+02	8.55E-04	2.81E+02	1.13E+00
RF-MT0321	3.55E+01	0.00E+00	1.69E+00	5.60E+01	1.27E+01	3.21E+01	2.66E-03	1.06E+02	4.27E-01
RF-MT-0328	2.39E+00	0.00E+00	2.02E-01	6.08E+00	1.39E+00	4.29E+00	3.69E-04	1.01E+01	4.06E-02
RF-MT0330	2.50E+01	0.00E+00	2.21E+00	1.23E+02	3.03E+01	4.03E+01	3.30E-04	1.80E+02	7.27E-01
RF-MT-0331	1.50E+02	0.00E+00	1.38E+01	5.41E+02	1.21E+02	2.34E+02	2.28E-02	8.25E+02	3.33E+00
RF-MT0332	1.98E-02	0.00E+00	4.01E-03	1.21E-01	2.75E-02	8.51E-02	5.98E-07	1.72E-01	6.94E-04
RF-MT-0335	1.70E+00	0.00E+00	1.84E-01	6.22E+00	1.43E+00	3.47E+00	5.70E-04	9.54E+00	3.85E-02
RF-MT0336	1.22E+02	0.00E+00	1.22E+01	4.42E+02	1.01E+02	2.04E+02	3.64E-03	6.76E+02	2.73E+00
RF-MT0337	6.94E+01	0.00E+00	6.70E+00	2.70E+02	6.05E+01	9.94E+01	4.85E-03	4.06E+02	1.64E+00
RF-MT0339	1.87E+02	0.00E+00	1.83E+01	5.92E+02	1.34E+02	3.60E+02	1.98E-02	9.30E+02	3.75E+00
RF-MT-0342	1.08E+00	0.00E+00	1.53E-01	5.47E+00	1.23E+00	2.64E+00	8.13E-05	7.92E+00	3.20E-02
RF-MT0371	3.70E+02	0.00E+00	3.54E+01	1.07E+03	2.43E+02	7.52E+02	6.58E-03	1.72E+03	6.93E+00
RF-MT-0372	1.57E+00	0.00E+00	2.49E-01	7.45E+00	1.70E+00	4.65E+00	2.77E-04	1.10E+01	4.43E-02
RF-MT0373	2.47E+01	0.00E+00	2.56E+00	1.40E+02	3.17E+01	3.84E+01	3.83E-04	1.99E+02	8.02E-01
RF-MT0374	7.77E-01	0.00E+00	9.16E-02	2.77E+00	6.31E-01	1.94E+00	1.70E-05	4.27E+00	1.72E-02
RF-MT0376	6.20E-01	0.00E+00	7.40E-02	2.76E+00	6.39E-01	1.43E+00	2.61E-05	4.09E+00	1.65E-02
RF-MT0377	3.66E+02	0.00E+00	4.26E+01	1.29E+03	2.93E+02	9.04E+02	1.66E-02	1.99E+03	8.03E+00
RF-MT0378	4.04E+00	0.00E+00	5.90E-01	1.78E+01	4.06E+00	1.25E+01	8.79E-05	2.65E+01	1.07E-01
RF-MT0419	6.77E+00	0.00E+00	5.51E-01	1.66E+01	3.79E+00	1.17E+01	8.21E-05	2.77E+01	1.12E-01
RF-MT0420	1.18E+00	0.00E+00	9.55E-02	2.88E+00	6.58E-01	2.03E+00	1.43E-05	4.81E+00	1.94E-02
RF-MT0423	1.03E+01	0.00E+00	7.77E-01	4.16E+01	9.20E+00	8.06E+00	1.16E-04	6.19E+01	2.49E-01
RF-MT0425	2.95E-01	0.00E+00	2.39E-02	7.20E-01	1.64E-01	5.08E-01	3.57E-06	1.20E+00	4.85E-03
RF-MT-0438	2.66E+00	0.00E+00	3.14E-01	1.28E+01	2.89E+00	5.04E+00	6.00E-05	1.87E+01	7.52E-02
RF-MT0440	9.57E-01	0.00E+00	1.13E-01	4.64E+00	1.08E+00	2.07E+00	1.82E-04	6.78E+00	2.74E-02
RF-MT0442	3.65E-01	0.00E+00	4.87E-02	1.59E+00	3.62E-01	7.69E-01	1.02E-04	2.36E+00	9.53E-03
RF-MT0443	4.26E+00	0.00E+00	8.00E-01	2.47E+01	5.63E+00	1.61E+01	2.78E-04	3.54E+01	1.43E-01
RF-MT0444	3.47E+01	0.00E+00	3.92E+00	1.19E+02	2.70E+01	8.32E+01	6.08E-04	1.85E+02	7.44E-01

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0480	9.77E+01	0.00E+00	1.10E+01	3.34E+02	7.62E+01	2.14E+02	4.11E-03	5.19E+02	2.09E+00
RF-MT0488	1.56E+02	0.00E+00	1.65E+01	4.96E+02	1.13E+02	3.49E+02	3.34E-02	7.81E+02	3.15E+00
RF-MT0490	6.97E-01	0.00E+00	9.55E-02	2.93E+00	6.69E-01	1.93E+00	2.55E-05	4.39E+00	1.77E-02
RF-MT-0491	5.68E-02	0.00E+00	4.37E-03	1.33E-01	3.02E-02	9.02E-02	2.66E-06	2.24E-01	9.04E-04
RF-MT0523A	4.49E+01	0.00E+00	3.47E+00	1.05E+02	2.39E+01	7.35E+01	7.74E-04	1.77E+02	7.15E-01
RF-MT0523B	4.49E+01	0.00E+00	3.47E+00	1.05E+02	2.39E+01	7.35E+01	7.74E-04	1.77E+02	7.15E-01
RF-MT0523C	4.49E+01	0.00E+00	3.47E+00	1.05E+02	2.39E+01	7.35E+01	7.74E-04	1.77E+02	7.15E-01
RF-MT0523D	4.49E+01	0.00E+00	3.47E+00	1.05E+02	2.39E+01	7.35E+01	7.74E-04	1.77E+02	7.15E-01
RF-MT0523E	4.49E+01	0.00E+00	3.47E+00	1.05E+02	2.39E+01	7.35E+01	7.74E-04	1.77E+02	7.15E-01
RF-MT0531	2.82E-03	0.00E+00	5.72E-04	1.72E-02	3.93E-03	1.22E-02	8.53E-08	2.45E-02	9.88E-05
RF-MT0532E	1.46E+02	0.00E+00	7.43E+00	2.29E+02	5.21E+01	1.57E+02	2.22E-03	4.34E+02	1.75E+00
RF-MT0532F	1.46E+02	0.00E+00	7.43E+00	2.29E+02	5.21E+01	1.57E+02	2.22E-03	4.34E+02	1.75E+00
RF-MT0541	5.43E+00	0.00E+00	1.07E-01	3.25E+00	7.40E-01	2.29E+00	1.60E-05	9.52E+00	3.84E-02
RF-MT0545	2.57E-02	0.00E+00	5.19E-03	1.57E-01	3.57E-02	1.10E-01	7.74E-07	2.23E-01	9.01E-04
RF-MT0800	1.12E+03	0.00E+00	2.57E+00	7.74E+01	1.76E+01	5.47E+01	8.67E-04	1.22E+03	4.90E+00
RF-MT0801	1.27E+02	0.00E+00	2.52E+00	7.60E+01	1.73E+01	5.34E+01	3.76E-04	2.23E+02	8.99E-01
RF-MT0803	2.85E+00	0.00E+00	5.63E-02	1.70E+00	3.87E-01	1.20E+00	8.40E-06	4.99E+00	2.01E-02
RF-MT0806	1.29E+00	0.00E+00	1.35E-01	7.38E+00	1.66E+00	2.02E+00	2.02E-05	1.05E+01	4.22E-02
RF-MT0807	1.65E+01	0.00E+00	1.04E+00	3.14E+01	7.17E+00	2.21E+01	1.55E-04	5.61E+01	2.26E-01
RF-MT0816	1.74E+00	0.00E+00	1.47E-01	4.43E+00	1.01E+00	3.13E+00	2.19E-05	7.32E+00	2.95E-02
RF-MT-0823	8.65E-01	0.00E+00	6.68E-02	2.02E+00	4.60E-01	1.41E+00	1.49E-05	3.41E+00	1.38E-02
RF-MT0827	4.38E+01	0.00E+00	3.71E+00	1.12E+02	2.55E+01	7.89E+01	5.54E-04	1.85E+02	7.46E-01
RF-MT0831	8.16E+01	0.00E+00	1.02E+01	3.03E+02	6.92E+01	2.08E+02	1.38E-02	4.64E+02	1.87E+00
RF-MT0832	5.05E+02	0.00E+00	3.69E+01	1.18E+03	2.68E+02	7.42E+02	3.89E-02	1.99E+03	8.02E+00
RF-MT0833	1.54E+02	0.00E+00	1.10E+01	3.41E+02	7.77E+01	2.23E+02	1.08E-02	5.83E+02	2.35E+00
RF-MT0855	2.42E-02	0.00E+00	4.90E-03	1.48E-01	3.37E-02	1.04E-01	7.31E-07	2.11E-01	8.49E-04
RF-MT0857	1.29E+00	0.00E+00	1.34E-01	7.36E+00	1.66E+00	2.02E+00	2.01E-05	1.05E+01	4.22E-02
RF-MT0H61	4.80E+01	0.00E+00	4.99E+00	2.73E+02	6.18E+01	7.48E+01	7.45E-04	3.88E+02	1.56E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT2116	5.42E+00	0.00E+00	3.96E-01	1.26E+01	2.87E+00	7.95E+00	4.17E-04	2.13E+01	8.58E-02
RF-MT3010	3.27E+01	0.00E+00	4.12E+00	1.25E+02	2.87E+01	8.53E+01	1.01E-03	1.90E+02	7.68E-01
RF-MT3011	2.47E+02	0.00E+00	2.56E+01	7.71E+02	1.76E+02	5.44E+02	1.16E-02	1.22E+03	4.92E+00
RF-MT420P	1.35E+03	0.00E+00	1.30E+02	6.34E+03	1.45E+03	1.78E+03	2.94E-02	9.27E+03	3.74E+01
RF-MT532A	3.59E+02	0.00E+00	1.83E+01	5.66E+02	1.29E+02	3.86E+02	5.46E-03	1.07E+03	4.32E+00
RF-MT532B	1.61E+03	0.00E+00	8.23E+01	2.54E+03	5.78E+02	1.74E+03	2.45E-02	4.81E+03	1.94E+01
RF-MT532C	3.23E+03	0.00E+00	1.65E+02	5.09E+03	1.16E+03	3.47E+03	4.93E-02	9.64E+03	3.89E+01
RF-MT532D	2.05E+01	0.00E+00	1.04E+00	3.22E+01	7.32E+00	2.19E+01	3.10E-04	6.10E+01	2.46E-01
RF-TT0069	1.13E-01	0.00E+00	1.24E-02	3.73E-01	8.50E-02	2.64E-01	7.54E-05	5.83E-01	2.35E-03
RF-TT0200	5.43E+00	0.00E+00	4.99E-01	1.53E+01	3.51E+00	1.01E+01	7.55E-05	2.47E+01	9.97E-02
RF-TT0299	2.33E+01	0.00E+00	9.24E-01	2.79E+01	6.36E+00	1.96E+01	1.38E-04	5.85E+01	2.36E-01
RF-TT0300	1.79E+02	0.00E+00	2.63E+01	8.00E+02	1.83E+02	4.78E+02	1.23E-02	1.19E+03	4.80E+00
RF-TT0301	2.42E+01	0.00E+00	3.57E+00	1.09E+02	2.49E+01	6.47E+01	1.67E-03	1.62E+02	6.52E-01
RF-TT0302	1.21E+00	0.00E+00	1.30E-01	4.26E+00	9.73E-01	2.72E+00	4.18E-04	6.57E+00	2.65E-02
RF-TT0303	7.31E+00	0.00E+00	7.58E-01	2.29E+01	5.21E+00	1.61E+01	1.15E-03	3.62E+01	1.46E-01
RF-TT0310	2.47E+01	0.00E+00	3.56E+00	1.03E+02	2.42E+01	5.89E+01	7.16E-04	1.55E+02	6.27E-01
RF-TT0312	6.00E+02	0.00E+00	6.42E+01	2.25E+03	5.08E+02	1.24E+03	1.14E-02	3.42E+03	1.38E+01
RF-TT0317	3.53E-01	0.00E+00	6.98E-02	2.11E+00	4.80E-01	1.48E+00	1.04E-05	3.01E+00	1.21E-02
RF-TT0320	2.44E+02	0.00E+00	2.24E+01	6.87E+02	1.58E+02	4.54E+02	3.39E-03	1.11E+03	4.48E+00
RF-TT0330	8.75E+01	0.00E+00	7.74E+00	4.32E+02	1.06E+02	1.41E+02	1.16E-03	6.32E+02	2.55E+00
RF-TT-0331	4.36E+02	0.00E+00	4.00E+01	1.57E+03	3.51E+02	6.79E+02	6.62E-02	2.40E+03	9.66E+00
RF-TT-0334	1.76E+02	0.00E+00	3.24E+01	9.75E+02	2.22E+02	6.88E+02	4.83E-03	1.41E+03	5.67E+00
RF-TT0335	2.28E+02	0.00E+00	2.45E+01	8.29E+02	1.90E+02	4.63E+02	7.59E-02	1.27E+03	5.13E+00
RF-TT0336	2.04E+02	0.00E+00	2.04E+01	7.34E+02	1.67E+02	3.39E+02	6.06E-03	1.13E+03	4.54E+00
RF-TT0337	2.44E+02	0.00E+00	2.35E+01	9.48E+02	2.12E+02	3.49E+02	1.70E-02	1.43E+03	5.76E+00
RF-TT0338	1.03E+03	0.00E+00	8.54E+01	3.70E+03	8.29E+02	1.56E+03	2.10E-02	5.64E+03	2.28E+01
RF-TT0340	8.08E+00	0.00E+00	1.63E+00	4.92E+01	1.13E+01	3.47E+01	2.43E-04	7.01E+01	2.83E-01
RF-TT0342	5.73E+01	0.00E+00	8.16E+00	2.90E+02	6.49E+01	1.40E+02	4.32E-03	4.20E+02	1.69E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0360	4.44E+00	0.00E+00	4.14E-01	1.30E+01	3.00E+00	8.25E+00	6.81E-05	2.09E+01	8.41E-02
RF-TT0368	8.89E+01	0.00E+00	8.31E+00	2.61E+02	6.01E+01	1.65E+02	1.37E-03	4.18E+02	1.69E+00
RF-TT0370	1.75E+02	0.00E+00	1.79E+01	5.81E+02	1.33E+02	3.51E+02	1.05E-02	9.06E+02	3.65E+00
RF-TT0371	3.78E+00	0.00E+00	3.61E-01	1.09E+01	2.48E+00	7.67E+00	6.71E-05	1.75E+01	7.06E-02
RF-TT0372	4.48E-01	0.00E+00	7.11E-02	2.13E+00	4.86E-01	1.33E+00	7.90E-05	3.13E+00	1.26E-02
RF-TT0374	1.42E+01	0.00E+00	1.67E+00	5.03E+01	1.15E+01	3.54E+01	3.09E-04	7.75E+01	3.13E-01
RF-TT0375A	1.40E-01	0.00E+00	2.75E-02	8.26E-01	1.88E-01	5.83E-01	4.10E-06	1.18E+00	4.77E-03
RF-TT0375B	1.40E-01	0.00E+00	2.75E-02	8.26E-01	1.88E-01	5.83E-01	4.10E-06	1.18E+00	4.77E-03
RF-TT0376	3.41E+01	0.00E+00	4.07E+00	1.52E+02	3.51E+01	7.89E+01	1.44E-03	2.25E+02	9.08E-01
RF-TT0377	1.90E+01	0.00E+00	2.21E+00	6.67E+01	1.53E+01	4.69E+01	8.60E-04	1.03E+02	4.16E-01
RF-TT0391	4.32E+00	0.00E+00	3.11E-01	1.69E+01	3.80E+00	8.21E+00	4.64E-05	2.53E+01	1.02E-01
RF-TT0392	1.53E+00	0.00E+00	1.96E-01	8.82E+00	2.00E+00	2.85E+00	2.94E-05	1.26E+01	5.06E-02
RF-TT0393	1.23E+02	0.00E+00	1.37E+01	4.11E+02	9.38E+01	2.89E+02	2.04E-03	6.41E+02	2.59E+00
RF-TT0398	2.73E+00	0.00E+00	3.60E-01	1.65E+01	3.73E+00	5.38E+00	5.39E-05	2.33E+01	9.40E-02
RF-TT0409	2.36E+00	0.00E+00	1.69E-01	8.51E+00	1.92E+00	2.07E+00	2.58E-05	1.30E+01	5.23E-02
RF-TT0412	2.36E+00	0.00E+00	1.69E-01	8.51E+00	1.92E+00	2.07E+00	2.58E-05	1.30E+01	5.23E-02
RF-TT0414	7.32E+01	0.00E+00	5.21E+00	2.64E+02	5.95E+01	6.41E+01	7.97E-04	4.02E+02	1.62E+00
RF-TT0430	1.92E-02	0.00E+00	3.89E-03	1.17E-01	2.67E-02	8.25E-02	5.81E-07	1.67E-01	6.72E-04
RF-TT0431	4.81E+00	0.00E+00	9.48E-01	2.88E+01	6.57E+00	1.96E+01	3.64E-04	4.11E+01	1.66E-01
RF-TT0438	3.06E+02	0.00E+00	3.61E+01	1.47E+03	3.33E+02	5.81E+02	6.91E-03	2.14E+03	8.64E+00
RF-TT0440	2.99E+01	0.00E+00	3.51E+00	1.45E+02	3.38E+01	6.49E+01	5.69E-03	2.12E+02	8.55E-01
RF-TT0441	1.46E+02	0.00E+00	1.65E+01	5.01E+02	1.15E+02	3.45E+02	7.08E-03	7.78E+02	3.14E+00
RF-TT0442	2.13E+01	0.00E+00	2.84E+00	9.26E+01	2.11E+01	4.50E+01	5.95E-03	1.38E+02	5.56E-01
RF-TT0443	4.33E-01	0.00E+00	8.16E-02	2.51E+00	5.71E-01	1.63E+00	2.82E-05	3.59E+00	1.45E-02
RF-TT0479	4.17E+00	0.00E+00	8.47E-01	2.54E+01	5.80E+00	1.79E+01	1.26E-04	3.62E+01	1.46E-01
RF-TT0480	3.03E+02	0.00E+00	3.42E+01	1.04E+03	2.36E+02	6.67E+02	1.27E-02	1.61E+03	6.50E+00
RF-TT0481	1.71E-01	0.00E+00	1.93E-02	5.84E-01	1.34E-01	3.75E-01	7.18E-06	9.07E-01	3.66E-03
RF-TT0483	5.14E-01	0.00E+00	1.04E-01	3.13E+00	7.15E-01	2.21E+00	1.72E-02	4.48E+00	1.81E-02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0484	2.84E+00	0.00E+00	4.31E-01	1.30E+01	2.97E+00	9.17E+00	1.76E-04	1.92E+01	7.76E-02
RF-TT0485	2.40E-01	0.00E+00	2.66E-02	8.01E-01	1.83E-01	5.66E-01	2.82E-04	1.25E+00	5.05E-03
RF-TT0486	1.42E+00	0.00E+00	1.58E-01	4.76E+00	1.09E+00	3.34E+00	2.51E-04	7.42E+00	2.99E-02
RF-TT0487	7.34E+00	0.00E+00	5.36E-01	1.71E+01	3.89E+00	1.08E+01	5.64E-04	2.88E+01	1.16E-01
RF-TT0489	2.02E+00	0.00E+00	2.41E-01	7.25E+00	1.65E+00	5.12E+00	1.37E-04	1.12E+01	4.50E-02
RF-TT0490	1.11E+02	0.00E+00	1.53E+01	4.68E+02	1.07E+02	3.06E+02	4.07E-03	7.00E+02	2.82E+00
RF-TT0491	2.68E+00	0.00E+00	2.07E-01	6.26E+00	1.43E+00	4.27E+00	1.26E-04	1.06E+01	4.27E-02
RF-TT0492	8.64E-01	0.00E+00	1.17E-01	3.50E+00	7.99E-01	2.46E+00	1.74E-05	5.28E+00	2.13E-02
RF-TT0523A	6.05E+00	0.00E+00	4.68E-01	1.41E+01	3.22E+00	9.90E+00	1.04E-04	2.38E+01	9.60E-02
RF-TT0523B	6.05E+00	0.00E+00	4.68E-01	1.41E+01	3.22E+00	9.90E+00	1.04E-04	2.38E+01	9.60E-02
RF-TT0523C	6.05E+00	0.00E+00	4.68E-01	1.41E+01	3.22E+00	9.90E+00	1.04E-04	2.38E+01	9.60E-02
RF-TT0523D	6.05E+00	0.00E+00	4.68E-01	1.41E+01	3.22E+00	9.90E+00	1.04E-04	2.38E+01	9.60E-02
RF-TT0523E	6.05E+00	0.00E+00	4.68E-01	1.41E+01	3.22E+00	9.90E+00	1.04E-04	2.38E+01	9.60E-02
RF-TT0532A	1.55E+02	0.00E+00	7.84E+00	2.43E+02	5.52E+01	1.66E+02	2.34E-03	4.60E+02	1.86E+00
RF-TT0532B	1.55E+02	0.00E+00	7.84E+00	2.43E+02	5.52E+01	1.66E+02	2.34E-03	4.60E+02	1.86E+00
RF-TT0541	2.30E-01	0.00E+00	4.67E-02	1.41E+00	3.21E-01	9.92E-01	6.97E-06	2.01E+00	8.09E-03
RF-TT0545	5.14E-02	0.00E+00	1.04E-02	3.13E-01	7.15E-02	2.21E-01	1.55E-06	4.46E-01	1.80E-03
RF-TT0601	1.92E+01	0.00E+00	1.79E+00	5.65E+01	1.31E+01	3.58E+01	2.95E-04	9.05E+01	3.65E-01
RF-TT0802	2.19E+03	0.00E+00	1.48E+02	4.46E+03	1.02E+03	3.13E+03	2.20E-02	7.81E+03	3.15E+01
RF-TT0809	1.80E+02	0.00E+00	1.21E+01	3.67E+02	8.33E+01	2.57E+02	1.81E-03	6.42E+02	2.59E+00
RF-TT0821	3.81E+02	0.00E+00	4.40E+01	1.44E+03	3.29E+02	7.65E+02	1.75E-01	2.19E+03	8.84E+00
RF-TT0822	4.27E+02	0.00E+00	3.43E+01	1.08E+03	2.45E+02	6.82E+02	1.88E-01	1.79E+03	7.20E+00
RF-TT0823	8.65E-01	0.00E+00	6.68E-02	2.02E+00	4.60E-01	1.41E+00	1.49E-05	3.41E+00	1.38E-02
RF-TT0824	8.74E+02	0.00E+00	9.40E+01	2.91E+03	6.63E+02	1.93E+03	7.66E-02	4.54E+03	1.83E+01
RF-TT0825	7.36E+02	0.00E+00	6.79E+01	2.19E+03	4.98E+02	1.28E+03	9.12E-02	3.49E+03	1.41E+01
RF-TT0832	5.50E+02	0.00E+00	4.02E+01	1.28E+03	2.92E+02	8.08E+02	4.24E-02	2.16E+03	8.71E+00
RF-TT0854	1.81E-01	0.00E+00	3.67E-02	1.10E+00	2.52E-01	7.78E-01	7.53E-04	1.57E+00	6.33E-03
RF-TT0886	2.57E-02	0.00E+00	5.18E-03	1.56E-01	3.57E-02	1.10E-01	7.73E-07	2.22E-01	8.97E-04

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT2216	8.12E+00	0.00E+00	5.94E-01	1.90E+01	4.31E+00	1.19E+01	6.25E-04	3.20E+01	1.29E-01
RF-TT3010	4.18E+02	0.00E+00	5.26E+01	1.60E+03	3.66E+02	1.09E+03	1.29E-02	2.44E+03	9.82E+00
RF-TT3011	1.07E+03	0.00E+00	1.11E+02	3.34E+03	7.62E+02	2.36E+03	5.03E-02	5.28E+03	2.13E+01
RF-TT301U	8.76E+01	0.00E+00	1.17E+01	3.63E+02	8.41E+01	2.31E+02	1.91E-03	5.46E+02	2.20E+00
RF-TT310P	2.60E+01	0.00E+00	3.05E+00	1.22E+02	2.64E+01	4.84E+01	4.59E-04	1.77E+02	7.15E-01
RF-TT338S	7.05E-01	0.00E+00	1.40E-01	4.21E+00	9.61E-01	2.96E+00	2.09E-05	6.01E+00	2.42E-02
RF-TT390P	4.29E+00	0.00E+00	3.79E-01	2.05E+01	4.30E+00	7.39E+00	8.53E-05	2.94E+01	1.19E-01
RF-TT391P	2.35E+02	0.00E+00	1.70E+01	9.20E+02	2.06E+02	4.48E+02	2.54E-03	1.38E+03	5.56E+00
RF-TT392P	4.77E+02	0.00E+00	6.13E+01	2.76E+03	6.27E+02	8.89E+02	9.19E-03	3.92E+03	1.58E+01
RF-TT393R	7.01E+01	0.00E+00	1.04E+01	4.22E+02	9.65E+01	1.44E+02	1.73E-03	5.99E+02	2.41E+00
RF-TT394P	8.96E+00	0.00E+00	6.44E-01	3.26E+01	6.89E+00	1.04E+01	1.03E-04	4.91E+01	1.98E-01
RF-TT395P	1.20E+01	0.00E+00	8.62E-01	4.36E+01	9.20E+00	1.38E+01	1.38E-04	6.56E+01	2.65E-01
RF-TT396P	2.99E+00	0.00E+00	2.15E-01	1.09E+01	2.30E+00	3.45E+00	3.45E-05	1.64E+01	6.61E-02
RF-TT398P	2.82E+02	0.00E+00	3.73E+01	1.71E+03	3.86E+02	5.55E+02	5.57E-03	2.41E+03	9.73E+00
RF-TT398R	2.45E+03	0.00E+00	6.93E+01	2.76E+03	6.24E+02	1.08E+03	1.03E-02	5.90E+03	2.38E+01
RF-TT411R	8.74E+01	0.00E+00	6.22E+00	3.15E+02	7.11E+01	7.65E+01	9.52E-04	4.79E+02	1.93E+00
RF-TT429R	1.89E+02	0.00E+00	1.34E+00	7.29E+01	1.62E+01	1.34E+01	1.99E-04	2.79E+02	1.13E+00
RF-TT433X	5.94E+01	0.00E+00	3.70E-01	2.10E+01	4.20E+00	5.29E+00	5.52E-05	8.50E+01	3.43E-01
RF-TT436R	4.33E+02	0.00E+00	5.35E+00	2.75E+02	6.19E+01	1.02E+02	7.98E-04	7.75E+02	3.13E+00
RF-TT454X	2.54E+01	0.00E+00	3.15E-01	1.62E+01	3.65E+00	6.02E+00	4.70E-05	4.56E+01	1.84E-01
RL-T101	1.01E+02	0.00E+00	1.91E+01	8.74E+02	1.95E+02	8.51E+02	1.97E-03	1.19E+03	4.80E+00
RL-T102	1.28E-03	0.00E+00	2.43E-04	1.12E-02	2.49E-03	1.08E-02	1.18E-06	1.52E-02	6.13E-05
RL-T103	1.01E+02	0.00E+00	2.31E+01	3.82E+02	8.47E+01	4.52E+02	2.39E-03	5.91E+02	2.38E+00
RL-T104	1.83E-03	0.00E+00	3.47E-04	1.59E-02	3.57E-03	1.55E-02	6.84E-08	2.16E-02	8.72E-05
RL-T105	7.05E-01	0.00E+00	1.31E-01	6.03E+00	1.35E+00	5.85E+00	5.83E-05	8.22E+00	3.31E-02
RL-T106	6.77E-01	0.00E+00	1.29E-01	5.90E+00	1.32E+00	5.72E+00	1.33E-05	8.02E+00	3.23E-02
RL-T107	1.86E+03	0.00E+00	7.57E+04	1.63E+04	3.63E+03	1.57E+04	8.66E+00	9.75E+04	3.93E+02
RL-T108	1.07E+00	0.00E+00	1.31E+01	9.27E+00	2.07E+00	9.00E+00	1.38E-03	2.55E+01	1.03E-01

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T109	1.48E+00	0.00E+00	2.69E-01	1.23E+01	2.75E+00	1.19E+01	2.33E-02	1.68E+01	6.78E-02
RL-T110	1.65E+02	0.00E+00	5.13E+01	1.41E+03	3.16E+02	1.37E+03	1.37E+00	1.94E+03	7.83E+00
RL-T112	7.92E+01	0.00E+00	2.17E+01	1.87E+02	4.18E+01	1.82E+02	7.38E-01	3.30E+02	1.33E+00
RL-T113	7.07E-02	0.00E+00	4.19E-02	6.15E-01	1.38E-01	5.98E-01	4.32E-06	8.66E-01	3.49E-03
RL-T114	1.08E+01	0.00E+00	2.04E+00	9.35E+01	2.09E+01	9.09E+01	2.11E-04	1.27E+02	5.13E-01
RL-T115	3.07E+02	0.00E+00	6.62E+01	1.23E+03	2.75E+02	1.34E+03	4.20E-01	1.88E+03	7.57E+00
RL-T116	1.77E+01	0.00E+00	3.36E+00	1.53E+02	3.43E+01	1.49E+02	5.65E-02	2.08E+02	8.40E-01
RL-T118	5.35E+01	0.00E+00	2.68E+01	1.52E+02	3.40E+01	1.48E+02	8.36E-01	2.67E+02	1.08E+00
RL-T120	1.24E+01	0.00E+00	2.81E+00	4.50E+01	9.97E+00	5.19E+01	2.91E-04	7.01E+01	2.83E-01
RL-T122	6.24E-01	0.00E+00	1.19E-01	5.42E+00	1.22E+00	5.27E+00	1.46E+00	8.83E+00	3.56E-02
RL-T123	1.84E+00	0.00E+00	3.48E-01	1.59E+01	3.57E+00	1.55E+01	5.97E-02	2.17E+01	8.75E-02
RL-T125	3.88E+02	0.00E+00	8.62E+01	3.33E+02	1.71E+02	2.42E+03	8.90E-03	9.79E+02	3.95E+00
RL-T127	4.21E+02	0.00E+00	2.17E+01	9.94E+02	2.22E+02	9.64E+02	8.22E-02	1.66E+03	6.69E+00
RL-T128	6.73E-01	0.00E+00	5.27E-07	2.42E-05	5.39E-06	2.34E-05	5.43E-11	6.73E-01	2.71E-03
RL-T129	1.56E+00	0.00E+00	1.00E+02	1.37E+01	3.04E+00	1.32E+01	1.80E-02	1.19E+02	4.78E-01
RL-T130	3.32E-03	0.00E+00	6.33E-04	2.91E-02	6.49E-03	2.81E-02	8.31E-05	3.96E-02	1.60E-04
RL-T131	1.53E+00	0.00E+00	3.46E-01	5.54E+00	1.23E+00	6.34E+00	8.27E-03	8.64E+00	3.48E-02
RL-T132	3.22E+02	0.00E+00	6.10E+01	2.81E+03	6.27E+02	2.72E+03	2.51E-01	3.82E+03	1.54E+01
RL-T133	7.14E-03	0.00E+00	9.79E-04	4.61E-02	1.03E-02	3.86E-02	1.01E-07	6.44E-02	2.60E-04
RL-T134	1.39E-02	0.00E+00	2.63E-03	1.21E-01	2.69E-02	1.17E-01	2.72E-07	1.64E-01	6.63E-04
RL-T135	6.49E-02	0.00E+00	1.24E-02	5.66E-01	1.27E-01	5.49E-01	4.15E-03	7.74E-01	3.12E-03
RL-T137	1.19E+03	0.00E+00	2.70E+02	4.31E+03	9.57E+02	4.99E+03	3.40E-02	6.72E+03	2.71E+01
RL-T140	1.45E+03	0.00E+00	2.56E+02	4.17E+03	1.03E+03	4.24E+03	2.62E+01	6.92E+03	2.79E+01
RL-T143	7.73E+00	0.00E+00	1.47E+00	6.73E+01	1.51E+01	6.54E+01	3.88E-02	9.16E+01	3.70E-01
RL-T145	2.20E+01	0.00E+00	4.19E+00	1.92E+02	4.28E+01	1.86E+02	9.00E-02	2.61E+02	1.05E+00
RL-W407	7.19E+01	0.00E+00	8.93E+00	4.40E+02	9.83E+01	2.83E+02	9.22E-04	6.19E+02	2.50E+00
RL-W408	2.85E-04	0.00E+00	3.77E-05	1.78E-03	3.98E-04	1.46E-03	3.90E-09	2.50E-03	1.01E-05
RL-W415	6.29E-03	0.00E+00	8.31E-04	3.94E-02	8.79E-03	3.21E-02	8.58E-08	5.53E-02	2.23E-04

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W418	2.75E-02	0.00E+00	3.50E-03	1.69E-01	3.78E-02	1.20E-01	3.62E-07	2.38E-01	9.58E-04
RL-W437	2.36E+02	0.00E+00	2.94E+01	1.44E+03	3.22E+02	9.28E+02	3.03E-03	2.03E+03	8.17E+00
RL-W438	3.99E-04	0.00E+00	5.27E-05	2.49E-03	5.55E-04	2.04E-03	5.44E-09	3.49E-03	1.41E-05
RL-W439	1.27E+04	0.00E+00	2.91E+03	4.80E+04	1.07E+04	5.68E+04	3.00E-01	7.43E+04	2.99E+02
RL-W443	2.08E+02	0.00E+00	2.59E+01	1.27E+03	2.83E+02	8.17E+02	2.67E-03	1.79E+03	7.20E+00
RL-W444	1.54E+02	0.00E+00	1.92E+01	9.41E+02	2.10E+02	6.07E+02	1.98E-03	1.33E+03	5.34E+00
RL-W447	1.71E-02	0.00E+00	2.26E-03	1.06E-01	2.38E-02	8.72E-02	2.33E-07	1.49E-01	6.01E-04
RL-W448	1.26E-04	0.00E+00	1.67E-05	7.86E-04	1.75E-04	6.45E-04	1.72E-09	1.10E-03	4.45E-06
RL-W449	1.22E+00	0.00E+00	6.11E-04	2.25E-02	5.02E-03	1.17E-02	6.31E-08	1.25E+00	5.02E-03
RL-W450	1.90E-03	0.00E+00	2.52E-04	1.19E-02	2.65E-03	9.73E-03	2.60E-08	1.67E-02	6.73E-05
RL-W451	2.71E-04	0.00E+00	3.59E-05	1.69E-03	3.78E-04	1.39E-03	3.70E-09	2.37E-03	9.57E-06
RL-W452	1.21E-02	0.00E+00	1.55E-03	7.44E-02	1.66E-02	5.27E-02	1.60E-07	1.05E-01	4.22E-04
RL-W453	3.49E-03	0.00E+00	4.35E-04	2.14E-02	4.76E-03	1.37E-02	4.49E-08	3.01E-02	1.21E-04
RL-W454	4.88E-02	0.00E+00	6.08E-03	2.99E-01	6.67E-02	1.92E-01	6.28E-07	4.20E-01	1.69E-03
RL-W455	1.29E-02	0.00E+00	1.64E-03	7.90E-02	1.76E-02	5.62E-02	1.69E-07	1.11E-01	4.48E-04
RL-W456	1.71E+00	0.00E+00	2.14E-01	1.05E+01	2.34E+00	6.92E+00	2.21E-05	1.48E+01	5.95E-02
RL-W457	1.66E-01	0.00E+00	2.08E-02	1.02E+00	2.27E-01	6.71E-01	2.15E-06	1.43E+00	5.78E-03
RL-W458	5.06E-01	0.00E+00	1.06E-01	4.19E-01	2.33E-01	2.70E+00	1.10E-05	1.26E+00	5.10E-03
RL-W459	4.83E+00	0.00E+00	1.10E+00	1.04E+01	3.18E+00	2.68E+01	1.13E-04	1.95E+01	7.86E-02
RL-W460	3.09E-02	0.00E+00	3.85E-03	1.89E-01	4.23E-02	1.22E-01	3.98E-07	2.66E-01	1.07E-03
RL-W461	3.24E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.24E-02	1.31E-04
RL-W462	8.64E-03	0.00E+00	1.12E-03	5.35E-02	1.20E-02	3.99E-02	1.15E-07	7.52E-02	3.03E-04
RL-W463	4.53E-02	0.00E+00	5.65E-03	2.78E-01	6.20E-02	1.79E-01	5.84E-07	3.91E-01	1.58E-03
RL-W464	2.10E-02	0.00E+00	2.60E-03	1.28E-01	2.85E-02	8.23E-02	2.69E-07	1.80E-01	7.26E-04
RL-W465	1.38E-01	0.00E+00	1.76E-02	8.51E-01	1.90E-01	5.96E-01	1.82E-06	1.20E+00	4.83E-03
RL-W466	1.90E+00	0.00E+00	2.40E-01	1.17E+01	2.61E+00	7.93E+00	2.48E-05	1.64E+01	6.63E-02
RL-W467	9.63E-02	0.00E+00	1.24E-02	5.96E-01	1.33E-01	4.35E-01	1.27E-06	8.37E-01	3.37E-03
RL-W468	4.92E-04	0.00E+00	6.36E-05	3.05E-03	6.81E-04	2.27E-03	6.57E-09	4.28E-03	1.73E-05

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W469	2.02E-01	0.00E+00	2.56E-02	1.24E+00	2.78E-01	8.36E-01	2.64E-06	1.75E+00	7.04E-03
RL-W470	5.39E+00	0.00E+00	1.19E+00	4.60E+00	2.37E+00	3.36E+01	1.23E-04	1.35E+01	5.46E-02
RL-W474	2.48E-01	0.00E+00	1.31E-01	1.05E-02	8.97E-03	0.00E+00	1.36E-05	3.99E-01	1.61E-03
RL-W476	3.66E-01	0.00E+00	4.72E-02	2.30E+00	5.15E-01	1.52E+00	4.87E-06	3.23E+00	1.30E-02
RL-W480	5.93E-02	0.00E+00	7.56E-03	3.65E-01	8.16E-02	2.59E-01	7.81E-07	5.13E-01	2.07E-03
RL-W481	9.31E-02	0.00E+00	1.19E-02	5.73E-01	1.28E-01	4.07E-01	1.23E-06	8.05E-01	3.25E-03
RL-W482	1.24E+02	0.00E+00	3.95E+00	7.28E-02	1.36E-01	5.40E+02	4.08E-04	1.28E+02	5.15E-01
RL-W483	9.23E+00	0.00E+00	3.07E-01	4.72E-03	9.63E-03	4.03E+01	3.17E-05	9.55E+00	3.85E-02
RL-W484	4.38E-02	0.00E+00	2.47E-03	6.58E-02	1.58E-02	3.34E-02	2.55E-07	1.28E-01	5.15E-04
RL-W485	2.63E-03	0.00E+00	3.50E-04	7.12E-03	1.70E-03	0.00E+00	3.61E-08	1.18E-02	4.76E-05
RL-W486	1.11E-03	0.00E+00	1.48E-04	3.01E-03	7.17E-04	0.00E+00	1.52E-08	4.98E-03	2.01E-05
RL-W487	1.71E-01	0.00E+00	1.90E-02	4.31E-01	1.19E-01	3.11E-01	1.96E-06	7.39E-01	2.98E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	9.31E-02	0.00E+00	1.79E-02	5.58E-01	1.27E-01	5.02E-01	1.84E-06	7.95E-01	3.21E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	3.47E-02	0.00E+00	1.51E-02	5.85E-02	1.29E-02	1.82E-01	1.56E-06	1.21E-01	4.88E-04
RL-W492	2.00E-03	0.00E+00	3.71E-04	1.17E-02	2.64E-03	1.05E-02	3.83E-08	1.67E-02	6.74E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.91E+01	0.00E+00	2.15E+01	2.95E-01	2.52E-01	4.20E+02	2.22E-03	1.01E+02	4.08E-01
RL-W495	1.43E+00	0.00E+00	5.85E-02	2.83E-03	2.25E-03	7.65E+00	6.04E-06	1.49E+00	6.02E-03
RL-W496	9.30E+00	0.00E+00	6.73E-01	9.29E-03	7.47E-03	4.95E+01	6.95E-05	9.99E+00	4.03E-02
RL-W497	4.14E-01	0.00E+00	1.33E-01	5.58E-01	2.53E-01	1.30E+00	1.37E-05	1.36E+00	5.47E-03
RL-W498	1.55E+00	0.00E+00	1.97E-01	9.53E+00	2.13E+00	6.75E+00	2.04E-05	1.34E+01	5.41E-02
RL-W499	1.39E-05	0.00E+00	1.77E-06	8.54E-05	1.91E-05	6.07E-05	1.83E-10	1.20E-04	4.85E-07
RL-W500	9.90E-04	0.00E+00	2.20E-04	3.49E-03	7.75E-04	4.27E-03	2.27E-08	5.47E-03	2.21E-05
RL-W501	4.43E+01	0.00E+00	4.90E+00	1.12E+02	3.07E+01	8.06E+01	5.06E-04	1.92E+02	7.73E-01
RL-W502	7.40E-03	0.00E+00	9.48E-04	4.56E-02	1.02E-02	3.24E-02	9.78E-08	6.41E-02	2.58E-04
RL-W503	4.27E-01	0.00E+00	9.71E-02	1.61E+00	3.57E-01	1.90E+00	1.00E-05	2.49E+00	1.00E-02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W504	1.71E-01	0.00E+00	1.90E-02	4.31E-01	1.19E-01	3.11E-01	1.96E-06	7.39E-01	2.98E-03
RL-W505	7.21E-03	0.00E+00	9.94E-04	4.66E-02	1.04E-02	3.90E-02	1.03E-07	6.51E-02	2.63E-04
RL-W506	2.69E-03	0.00E+00	3.91E-04	1.53E-02	3.42E-03	1.17E-02	4.03E-08	2.18E-02	8.79E-05
RL-W507	2.68E-04	0.00E+00	3.42E-05	1.65E-03	3.68E-04	1.17E-03	3.53E-09	2.32E-03	9.35E-06
RL-W508	4.94E+00	0.00E+00	1.12E+00	1.79E+01	3.98E+00	2.07E+01	1.15E-04	2.79E+01	1.13E-01
RL-W509	5.06E+01	0.00E+00	8.93E+00	1.46E+02	3.58E+01	1.49E+02	9.22E-04	2.41E+02	9.72E-01
RL-W510	4.09E+00	0.00E+00	9.16E-01	1.45E+01	3.22E+00	1.77E+01	9.46E-05	2.27E+01	9.16E-02
RL-W511	4.45E+02	0.00E+00	4.42E+01	1.94E+03	4.25E+02	9.64E+02	4.91E-03	2.85E+03	1.15E+01
RL-W512	4.01E+02	0.00E+00	2.98E+01	1.17E+03	2.91E+02	4.93E+02	3.08E-03	1.89E+03	7.63E+00
RL-W513	4.19E+04	0.00E+00	1.21E+04	1.91E+04	9.49E+03	7.82E+04	1.25E+00	8.26E+04	3.33E+02
RL-W514	1.10E-03	0.00E+00	1.39E-04	6.76E-03	1.52E-03	4.57E-03	1.44E-08	9.52E-03	3.84E-05
RL-W515	4.28E-02	0.00E+00	5.45E-03	2.64E-01	5.88E-02	1.87E-01	5.63E-07	3.71E-01	1.50E-03
RL-W516	5.94E-02	0.00E+00	7.57E-03	3.65E-01	8.16E-02	2.59E-01	7.82E-07	5.13E-01	2.07E-03
RL-W517	5.25E-10	0.00E+00	6.77E-11	3.25E-09	7.25E-10	2.42E-09	6.99E-15	4.56E-09	1.84E-11
RL-W518	1.54E+00	0.00E+00	2.85E-01	4.66E+00	1.13E+00	5.21E+00	2.94E-05	7.61E+00	3.07E-02
RL-W519	2.69E-01	0.00E+00	3.38E-02	1.65E+00	3.68E-01	1.10E+00	3.49E-06	2.32E+00	9.35E-03
RL-W520	2.90E-02	0.00E+00	3.81E-03	1.81E-01	4.04E-02	1.41E-01	3.93E-07	2.54E-01	1.02E-03
RL-W521	5.48E-04	0.00E+00	6.98E-05	3.37E-03	7.53E-04	2.40E-03	7.21E-09	4.74E-03	1.91E-05
RL-W522	1.20E+01	0.00E+00	2.59E+00	2.23E+01	6.39E+00	3.47E+01	2.68E-04	4.32E+01	1.74E-01
RL-W523	3.72E+00	0.00E+00	9.86E-01	1.48E+00	9.00E-01	6.88E+00	1.02E-04	7.09E+00	2.86E-02
RL-W524	1.53E+01	0.00E+00	3.77E+00	1.36E+01	5.27E+00	3.28E+01	3.90E-04	3.79E+01	1.53E-01
RL-W525	1.22E+00	0.00E+00	2.56E-01	1.61E+00	5.33E-01	2.57E+00	2.64E-05	3.61E+00	1.46E-02
RL-W526	4.29E+00	0.00E+00	9.24E-01	1.72E+01	3.85E+00	1.87E+01	9.54E-05	2.63E+01	1.06E-01
RL-W527	4.66E-01	0.00E+00	1.34E-01	1.82E+00	4.33E-01	2.19E+00	1.38E-05	2.85E+00	1.15E-02
RL-W528	2.31E+02	0.00E+00	5.68E+01	5.80E+01	5.56E+01	3.34E+02	5.86E-03	4.01E+02	1.62E+00
RL-W529	1.76E-01	0.00E+00	3.99E-02	6.39E-01	1.42E-01	7.37E-01	4.12E-06	9.97E-01	4.02E-03
RL-W530	2.07E+00	0.00E+00	4.63E-01	7.30E+00	1.62E+00	8.96E+00	4.78E-05	1.15E+01	4.62E-02
RL-W531	1.34E+02	0.00E+00	4.64E+01	3.16E+01	2.28E+01	2.38E+02	4.79E-03	2.34E+02	9.45E-01

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W532	3.95E-01	0.00E+00	5.05E-02	2.44E+00	5.44E-01	1.73E+00	5.21E-06	3.43E+00	1.38E-02
RL-W533	1.92E-01	0.00E+00	4.36E-02	6.97E-01	1.55E-01	7.99E-01	4.50E-06	1.09E+00	4.39E-03
RL-W534	1.10E-05	0.00E+00	1.41E-06	6.80E-05	1.53E-05	4.82E-05	1.45E-10	9.57E-05	3.86E-07
RL-W535	6.15E+01	0.00E+00	1.39E+01	8.72E+01	2.67E+01	1.47E+02	1.44E-03	1.89E+02	7.63E-01
RL-W536	1.19E+00	0.00E+00	1.87E-01	3.03E+00	6.88E-01	3.36E+00	2.25E-05	5.09E+00	2.05E-02
RL-W537	4.12E+01	0.00E+00	4.23E+00	1.86E+02	4.09E+01	9.41E+01	4.63E-04	2.72E+02	1.10E+00
RL-W538	1.40E-04	0.00E+00	1.79E-05	8.64E-04	1.93E-04	6.13E-04	1.84E-09	1.22E-03	4.90E-06
RL-W539	1.54E-02	0.00E+00	2.01E-03	9.55E-02	2.13E-02	7.46E-02	2.08E-07	1.34E-01	5.41E-04
RL-W540	3.24E+01	0.00E+00	8.85E+00	3.44E+01	1.19E+01	7.16E+01	9.14E-04	8.75E+01	3.53E-01
RL-W541	4.46E-02	0.00E+00	5.80E-03	2.77E-01	6.18E-02	2.10E-01	5.99E-07	3.89E-01	1.57E-03
RL-W542	2.11E+00	0.00E+00	4.31E-01	7.00E+00	1.62E+00	8.62E+00	4.45E-05	1.12E+01	4.50E-02
RL-W543	6.59E-03	0.00E+00	8.39E-04	4.06E-02	9.07E-03	2.89E-02	8.66E-08	5.71E-02	2.30E-04
RL-W544	1.51E-01	0.00E+00	3.43E-02	4.62E-01	1.16E-01	5.74E-01	3.54E-06	7.62E-01	3.07E-03
RL-W545	3.95E-02	0.00E+00	5.03E-03	2.43E-01	5.43E-02	1.72E-01	5.19E-07	3.42E-01	1.38E-03
RL-W546	1.73E-03	0.00E+00	2.21E-04	1.07E-02	2.38E-03	7.54E-03	2.28E-08	1.50E-02	6.06E-05
RL-W547	4.42E-05	0.00E+00	5.64E-06	2.72E-04	6.08E-05	1.93E-04	5.82E-10	3.82E-04	1.54E-06
RL-W548	3.80E-05	0.00E+00	4.89E-06	2.35E-04	5.25E-05	1.73E-04	5.05E-10	3.30E-04	1.33E-06
RL-W549	7.98E+00	0.00E+00	1.97E+00	1.21E+01	3.61E+00	2.19E+01	2.03E-04	2.56E+01	1.03E-01
RL-W550	3.67E+01	0.00E+00	3.72E+00	1.64E+02	3.61E+01	8.25E+01	4.03E-04	2.40E+02	9.69E-01
RL-W551	6.74E+01	0.00E+00	5.50E+00	1.85E+02	4.70E+01	8.77E+01	5.68E-04	3.05E+02	1.23E+00
RL-W552	2.35E-02	0.00E+00	3.04E-03	1.46E-01	3.25E-02	1.10E-01	3.14E-07	2.05E-01	8.26E-04
RL-W553	1.94E-03	0.00E+00	2.87E-04	1.30E-02	2.90E-03	1.38E-02	2.97E-08	1.81E-02	7.31E-05
RL-W554	3.34E-02	0.00E+00	4.26E-03	2.06E-01	4.60E-02	1.46E-01	4.40E-07	2.90E-01	1.17E-03
RL-W555	1.54E-02	0.00E+00	1.97E-03	9.48E-02	2.11E-02	6.73E-02	2.03E-07	1.33E-01	5.38E-04
RL-W563	2.23E-01	0.00E+00	4.92E-02	7.86E-01	1.74E-01	9.17E-01	5.07E-06	1.23E+00	4.97E-03
RL-W564	1.41E-01	0.00E+00	3.26E-02	5.09E-01	1.13E-01	7.05E-01	3.37E-06	7.95E-01	3.21E-03
RL-W565	1.42E-02	0.00E+00	1.83E-03	8.78E-02	1.96E-02	6.54E-02	1.89E-07	1.24E-01	4.98E-04
RL-W566	2.09E-01	0.00E+00	2.69E-02	1.29E+00	2.89E-01	9.30E-01	2.77E-06	1.81E+00	7.31E-03

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W567	1.40E+01	0.00E+00	6.87E-01	3.97E-02	3.21E-02	7.89E+01	7.09E-05	1.48E+01	5.95E-02
RL-W568	2.65E+02	0.00E+00	1.45E+01	1.88E+00	1.50E+00	1.63E+03	1.49E-03	2.83E+02	1.14E+00
RL-W569	2.21E-01	0.00E+00	1.09E-02	6.26E-04	5.08E-05	1.25E+00	1.12E-06	2.33E-01	9.39E-04
RL-W570	1.48E-02	0.00E+00	1.90E-03	9.31E-02	2.07E-02	6.15E-02	1.96E-07	1.31E-01	5.27E-04
RL-W571	4.58E+01	0.00E+00	6.46E+00	7.55E+00	3.79E+00	2.49E+02	6.67E-04	6.36E+01	2.56E-01
RL-W572	3.95E-02	0.00E+00	1.93E-03	4.07E-03	9.07E-05	2.23E-01	2.00E-07	4.56E-02	1.84E-04
RL-W573	5.10E+02	0.00E+00	2.48E+01	2.23E+00	1.67E+00	2.83E+03	2.56E-03	5.38E+02	2.17E+00
RL-W574	2.18E+03	0.00E+00	1.07E+02	8.51E+00	6.20E+00	1.23E+04	1.11E-02	2.31E+03	9.30E+00
RL-W575	1.43E+04	0.00E+00	7.22E+02	8.14E+01	4.95E+01	7.74E+04	7.45E-02	1.52E+04	6.12E+01
RL-W576	1.03E+03	0.00E+00	5.04E+01	4.15E+00	2.99E+00	5.81E+03	5.20E-03	1.08E+03	4.37E+00
RL-W579	1.03E-01	0.00E+00	1.33E-03	2.08E-02	4.65E-03	2.05E-02	1.37E-07	1.30E-01	5.24E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.66E-01	2.71E-02	0.00E+00	0.00E+00	1.93E-01	7.78E-04
RL-W581	1.10E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.10E+00	4.44E-03
RL-W582	7.09E-03	0.00E+00	1.13E-03	5.32E-03	2.76E-03	3.32E-03	1.16E-07	1.63E-02	6.57E-05
RL-W583	4.91E-03	0.00E+00	6.12E-04	3.00E-02	6.71E-03	1.93E-02	6.32E-08	4.22E-02	1.70E-04
RL-W584	1.07E-01	0.00E+00	4.02E-02	1.75E-01	8.59E-02	9.71E-02	4.14E-06	4.08E-01	1.65E-03
RL-W585	5.57E-01	0.00E+00	2.14E-01	1.02E+00	5.22E-01	2.96E+00	2.20E-05	2.31E+00	9.32E-03
RL-W586	7.74E-05	0.00E+00	9.63E-06	4.74E-04	1.06E-04	3.04E-04	9.94E-10	6.66E-04	2.69E-06
RL-W587	1.65E-03	0.00E+00	2.08E-04	1.01E-02	2.26E-03	6.84E-03	2.15E-08	1.42E-02	5.73E-05
RL-W588	7.48E-02	0.00E+00	3.39E-02	1.48E-01	7.24E-02	8.17E-02	3.50E-06	3.29E-01	1.33E-03
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	2.01E+00	0.00E+00	7.22E-01	1.14E-02	2.03E-02	1.07E+01	7.45E-05	2.77E+00	1.12E-02
RL-W591	1.14E+01	0.00E+00	8.16E-01	1.41E-02	2.63E-02	6.47E+01	8.42E-05	1.22E+01	4.92E-02
RL-W592	5.10E+01	0.00E+00	8.93E+00	6.53E-01	8.51E-01	2.61E+02	9.22E-04	6.14E+01	2.48E-01
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.36E-02	4.00E-02	0.00E+00	0.00E+00	6.35E-02	2.56E-04
RL-W594	5.18E+01	0.00E+00	1.61E+00	2.92E-02	5.40E-02	6.54E+01	1.66E-04	5.35E+01	2.16E-01
RL-W595	1.21E-01	0.00E+00	1.68E-01	2.00E-02	3.93E-02	6.47E-01	1.73E-05	3.48E-01	1.40E-03
RL-W596	3.95E-02	0.00E+00	1.31E-02	2.06E-04	3.69E-04	1.94E-01	1.35E-06	5.32E-02	2.14E-04

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W597	7.25E+01	0.00E+00	5.74E+00	3.99E-01	6.69E-01	3.62E+02	5.92E-04	7.93E+01	3.20E-01
RL-W598	7.70E+01	0.00E+00	3.39E+01	5.56E-01	8.34E-01	3.75E+02	3.50E-03	1.12E+02	4.52E-01
RL-W599	3.81E+00	0.00E+00	2.73E-01	4.70E-03	8.79E-03	2.16E+01	2.82E-05	4.09E+00	1.65E-02
RL-W600	2.28E-07	0.00E+00	2.84E-08	1.39E-06	3.11E-07	8.96E-07	2.93E-12	1.96E-06	7.89E-09
RL-W601	1.05E-03	0.00E+00	1.55E-04	7.03E-03	1.58E-03	7.50E-03	1.60E-08	9.82E-03	3.96E-05
RL-W602	9.85E-01	0.00E+00	1.27E-01	6.09E+00	1.37E+00	4.54E+00	1.32E-05	8.57E+00	3.46E-02
RL-W603	5.68E+00	0.00E+00	7.35E-01	3.52E+01	7.86E+00	2.61E+01	7.58E-05	4.94E+01	1.99E-01
RL-W604	1.43E-02	0.00E+00	1.93E-03	1.71E-02	8.47E-03	3.11E-02	1.99E-07	4.18E-02	1.69E-04
RL-W605	2.83E-03	0.00E+00	4.19E-04	1.89E-02	4.23E-03	2.02E-02	4.32E-08	2.64E-02	1.06E-04
RL-W606	1.14E-03	0.00E+00	1.69E-04	7.61E-03	1.70E-03	8.14E-03	1.74E-08	1.06E-02	4.29E-05
RL-W607	2.43E-03	0.00E+00	3.26E-04	2.89E-03	1.44E-03	5.25E-03	3.37E-08	7.08E-03	2.85E-05
RL-W608	2.83E-02	0.00E+00	1.27E-02	3.76E-03	4.65E-03	8.06E-02	1.31E-06	4.94E-02	1.99E-04
RL-W610	5.43E+00	0.00E+00	6.77E-01	3.32E+01	7.42E+00	2.14E+01	6.99E-05	4.67E+01	1.88E-01
RL-W612	1.28E-02	0.00E+00	1.64E-03	8.05E-02	1.80E-02	5.06E-02	1.69E-07	1.13E-01	4.56E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.38E-01	0.00E+00	0.00E+00	0.00E+00	3.38E-01	1.36E-03
RL-W622	2.14E-04	0.00E+00	2.67E-05	1.31E-03	2.92E-04	8.42E-04	2.76E-09	1.84E-03	7.42E-06
RL-W625	6.88E-03	0.00E+00	4.06E-03	6.68E-03	6.60E-03	4.57E-02	4.19E-07	2.42E-02	9.77E-05
RL-W626	4.27E-01	0.00E+00	9.24E-02	2.62E-01	1.58E-01	7.97E-01	9.54E-06	9.39E-01	3.78E-03
RL-W627	1.81E-03	0.00E+00	1.24E-04	1.24E-06	0.00E+00	9.47E-03	1.27E-08	1.94E-03	7.82E-06
RL-W628	6.14E-04	0.00E+00	7.76E-05	3.78E-03	8.43E-04	2.55E-03	8.01E-09	5.31E-03	2.14E-05
RL-W629	4.07E-05	0.00E+00	5.34E-06	2.54E-04	5.66E-05	1.98E-04	5.51E-10	3.56E-04	1.44E-06
RL-W630	4.49E-01	0.00E+00	9.94E-02	2.94E+00	6.83E-01	2.14E+00	1.03E-05	4.17E+00	1.68E-02
RL-W631	6.77E-03	0.00E+00	1.00E-03	4.51E-02	1.01E-02	4.82E-02	1.03E-07	6.29E-02	2.54E-04
RL-W632	3.17E+00	0.00E+00	1.35E-01	5.96E+00	1.96E+00	1.60E+01	1.40E-05	1.12E+01	4.53E-02
RL-W633	8.20E-03	0.00E+00	7.84E-04	9.35E-04	8.29E-04	1.97E-02	8.10E-08	1.08E-02	4.33E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	1.02E-02	0.00E+00	0.00E+00	0.00E+00	1.02E-02	4.11E-05
RL-W635	4.62E+01	0.00E+00	2.65E+01	4.34E+00	6.51E+00	1.99E+02	2.73E-03	8.35E+01	3.37E-01
RL-W636	5.00E-01	0.00E+00	5.00E-02	5.67E-02	5.03E-02	1.21E+00	5.16E-06	6.57E-01	2.65E-03

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W637	1.14E-03	0.00E+00	1.27E-03	6.37E-04	6.28E-04	4.35E-03	1.32E-07	3.68E-03	1.48E-05
RL-W638	5.10E-02	0.00E+00	1.30E-02	6.24E-03	5.90E-03	1.62E-01	1.34E-06	7.61E-02	3.07E-04
RL-W639	2.60E-03	0.00E+00	3.32E-04	1.60E-02	3.57E-03	1.13E-02	3.42E-08	2.25E-02	9.06E-05
RL-W640	8.78E-02	0.00E+00	1.10E-02	5.39E-01	1.21E-01	3.64E-01	1.14E-06	7.58E-01	3.06E-03
RL-W641	2.86E+00	0.00E+00	2.42E+00	2.59E+00	1.07E+00	5.85E+00	2.50E-04	8.94E+00	3.60E-02
RL-W642	5.97E-02	0.00E+00	2.52E-04	3.16E-02	1.62E-04	2.53E-03	2.60E-08	9.17E-02	3.70E-04
RL-W643	8.80E-01	0.00E+00	7.46E-01	7.97E-01	3.29E-01	1.80E+00	7.70E-05	2.75E+00	1.11E-02
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.49E-02	0.00E+00	0.00E+00	0.00E+00	5.49E-02	2.21E-04
RL-W645	1.95E-02	0.00E+00	3.36E-03	1.08E-01	2.54E-02	9.84E-02	3.46E-07	1.56E-01	6.30E-04
RL-W646	1.91E-02	0.00E+00	3.00E-03	2.58E-02	1.26E-02	4.78E-02	3.09E-07	6.05E-02	2.44E-04
RL-W647	5.30E-02	0.00E+00	4.48E-01	1.10E-01	1.74E-02	1.60E-01	4.63E-05	6.29E-01	2.53E-03
RL-W648	8.61E-04	0.00E+00	7.66E-04	6.00E-05	1.19E-04	5.12E-03	7.90E-08	1.81E-03	7.28E-06
RL-W649	3.16E-03	0.00E+00	2.82E-03	2.21E-04	4.36E-04	1.88E-02	2.91E-07	6.64E-03	2.68E-05
RL-W653	1.56E-04	0.00E+00	2.02E-05	9.65E-04	2.15E-04	7.18E-04	2.08E-09	1.36E-03	5.47E-06
RL-W654	8.63E-04	0.00E+00	1.10E-04	5.32E-03	1.19E-03	3.77E-03	1.14E-08	7.48E-03	3.01E-05
RL-W655	2.10E+02	0.00E+00	2.61E+01	2.11E-01	4.99E-01	1.01E+03	2.69E-03	2.37E+02	9.54E-01
RL-W656	8.59E+02	0.00E+00	1.17E+01	4.96E-01	5.13E-01	4.80E+03	1.21E-03	8.71E+02	3.51E+00
RL-W657	4.50E+02	0.00E+00	1.73E+01	2.44E-01	4.88E-01	2.12E+03	1.79E-03	4.68E+02	1.89E+00
RL-W659	5.50E+01	0.00E+00	3.91E+00	4.70E-02	5.85E-02	2.40E+02	4.03E-04	5.90E+01	2.38E-01
RL-W660	3.00E+02	0.00E+00	4.70E+01	8.66E-01	1.56E+00	1.37E+03	4.85E-03	3.49E+02	1.41E+00
RL-W661	3.10E+00	0.00E+00	5.88E-02	4.18E-04	3.82E-03	1.66E+01	6.07E-06	3.16E+00	1.28E-02
RL-W662	1.04E-01	0.00E+00	3.50E-03	1.07E-04	1.92E-04	3.41E-01	3.62E-07	1.08E-01	4.34E-04
RL-W665	1.19E+03	0.00E+00	2.80E+02	1.31E+00	1.76E+00	6.77E+03	2.89E-02	1.47E+03	5.93E+00
RL-W666	2.20E+01	0.00E+00	6.87E-01	5.49E-02	5.80E-02	9.79E+01	7.09E-05	2.28E+01	9.21E-02
RL-W668	2.41E+00	0.00E+00	2.16E-02	1.45E-01	4.13E-02	2.31E-01	2.23E-06	2.62E+00	1.06E-02
RL-W669	6.59E-01	0.00E+00	5.60E-01	5.97E-01	2.46E-01	1.35E+00	5.78E-05	2.06E+00	8.32E-03
RL-W670	4.45E-02	0.00E+00	3.98E-04	2.68E-03	7.63E-04	4.29E-03	4.11E-08	4.83E-02	1.95E-04
RL-W671	6.80E+00	0.00E+00	2.04E-01	4.91E-03	5.12E-03	1.41E+01	2.11E-05	7.01E+00	2.83E-02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W672	4.62E+01	0.00E+00	1.39E+00	3.35E-02	3.48E-02	9.56E+01	1.44E-04	4.76E+01	1.92E-01
RL-W673	4.45E+01	0.00E+00	1.34E+00	3.24E-02	3.36E-02	9.22E+01	1.38E-04	4.59E+01	1.85E-01
RL-W674	1.38E-01	0.00E+00	5.97E-02	1.12E+01	9.77E-02	6.43E-01	6.16E-06	1.15E+01	4.63E-02
RL-W675	5.44E-01	0.00E+00	3.30E-01	1.31E-01	1.14E-01	1.57E+00	3.41E-05	1.12E+00	4.51E-03
RL-W676	2.14E-02	0.00E+00	1.98E-03	1.47E-01	2.14E-03	4.65E-02	2.04E-07	1.72E-01	6.95E-04
RL-W677	4.94E+01	0.00E+00	4.91E+00	5.74E+00	5.00E+00	1.12E+02	5.07E-04	6.50E+01	2.62E-01
RL-W678	1.38E-01	0.00E+00	4.10E-02	5.16E-02	4.56E-02	8.79E-01	4.23E-06	2.76E-01	1.11E-03
RL-W679	9.78E-01	0.00E+00	9.16E-02	1.11E-01	9.83E-02	2.25E+00	9.46E-06	1.28E+00	5.16E-03
RL-W680	2.04E-04	0.00E+00	1.29E-04	1.74E-05	3.14E-05	9.67E-04	1.33E-08	3.82E-04	1.54E-06
RL-W681	1.17E-04	0.00E+00	5.23E-05	4.67E-04	2.33E-04	8.04E-04	5.39E-09	8.69E-04	3.51E-06
RL-W685	3.72E-01	0.00E+00	4.64E-02	2.28E+00	5.08E-01	1.47E+00	4.79E-06	3.21E+00	1.29E-02
RL-W689	1.09E-02	0.00E+00	5.58E-04	3.87E-04	0.00E+00	1.41E-03	5.76E-08	1.19E-02	4.78E-05
RL-W690	3.24E-01	0.00E+00	4.10E-02	2.03E+00	4.52E-01	1.28E+00	4.23E-06	2.84E+00	1.15E-02
RL-W691	7.51E-03	0.00E+00	9.55E-04	4.70E-02	1.05E-02	2.96E-02	9.86E-08	6.59E-02	2.66E-04
RL-W692	2.97E-01	0.00E+00	3.78E-02	1.86E+00	4.15E-01	1.17E+00	3.90E-06	2.61E+00	1.05E-02
RL-W693	3.68E-01	0.00E+00	4.67E-02	2.30E+00	5.13E-01	1.44E+00	4.82E-06	3.23E+00	1.30E-02
RL-W694	3.86E+00	0.00E+00	4.90E-01	2.43E+01	5.38E+00	1.52E+01	5.06E-05	3.40E+01	1.37E-01
RL-W695	3.63E-03	0.00E+00	0.00E+00	2.39E-03	0.00E+00	0.00E+00	0.00E+00	6.02E-03	2.43E-05
RL-W696	4.01E-03	0.00E+00	1.79E-03	2.91E-03	2.88E-03	2.09E-02	1.84E-07	1.16E-02	4.67E-05
RL-W697	1.09E+00	0.00E+00	3.78E+00	6.92E-03	9.54E-04	0.00E+00	3.90E-04	4.88E+00	1.97E-02
RL-W698	9.47E-02	0.00E+00	0.00E+00	3.29E-05	0.00E+00	0.00E+00	0.00E+00	9.48E-02	3.82E-04
RL-W699	1.80E-02	0.00E+00	2.52E-04	2.20E-03	2.59E-04	8.77E-02	2.60E-08	2.07E-02	8.37E-05
RL-W700	5.19E-03	0.00E+00	6.60E-04	3.19E-02	7.13E-03	2.27E-02	6.81E-08	4.48E-02	1.81E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	2.20E-01	0.00E+00	1.86E-01	1.99E-01	8.22E-02	4.50E-01	1.92E-05	6.87E-01	2.77E-03
RL-W705	1.33E-03	0.00E+00	1.72E-04	8.35E-03	1.87E-03	5.53E-03	1.77E-08	1.17E-02	4.73E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W707	4.75E-02	0.00E+00	6.10E-03	2.98E-01	6.66E-02	1.97E-01	6.30E-07	4.18E-01	1.69E-03
RL-W708	7.17E-03	0.00E+00	9.24E-04	4.52E-02	1.01E-02	2.98E-02	9.54E-08	6.33E-02	2.55E-04
RL-W709	2.48E+00	0.00E+00	3.18E-01	1.56E+01	3.48E+00	1.03E+01	3.29E-05	2.19E+01	8.82E-02
RL-W710	1.48E-04	0.00E+00	1.90E-05	9.31E-04	2.07E-04	6.15E-04	1.96E-09	1.31E-03	5.26E-06
RL-W711	4.62E-02	0.00E+00	5.94E-03	2.91E-01	6.49E-02	1.92E-01	6.13E-07	4.08E-01	1.64E-03
RL-W712	5.98E-02	0.00E+00	7.69E-03	3.76E-01	8.39E-02	2.49E-01	7.94E-07	5.27E-01	2.13E-03
RL-W713	5.17E-02	0.00E+00	6.64E-03	3.24E-01	7.26E-02	2.14E-01	6.85E-07	4.55E-01	1.83E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	8.97E-04	0.00E+00	1.12E-04	5.49E-03	1.23E-03	3.54E-03	1.15E-08	7.72E-03	3.11E-05
RL-W716	9.35E-03	0.00E+00	1.17E-03	5.72E-02	1.28E-02	3.69E-02	1.20E-07	8.04E-02	3.24E-04
RL-W717	2.33E-03	0.00E+00	2.91E-04	1.43E-02	3.19E-03	9.19E-03	3.01E-08	2.01E-02	8.11E-05
RL-W718	4.12E-04	0.00E+00	5.13E-05	2.52E-03	5.62E-04	1.62E-03	5.30E-09	3.54E-03	1.43E-05
RL-W719	1.86E-03	0.00E+00	2.31E-04	1.14E-02	2.54E-03	7.33E-03	2.39E-08	1.60E-02	6.46E-05
RL-W720	1.15E-02	0.00E+00	1.44E-03	7.03E-02	1.58E-02	4.52E-02	1.48E-07	9.90E-02	3.99E-04
RL-W721	7.79E-03	0.00E+00	9.71E-04	4.76E-02	1.07E-02	3.06E-02	1.00E-07	6.70E-02	2.70E-04
RL-W723	2.58E-02	0.00E+00	3.28E-03	1.62E-01	3.61E-02	1.02E-01	3.38E-07	2.27E-01	9.15E-04
RL-W724	1.72E-01	0.00E+00	2.18E-02	1.07E+00	2.40E-01	6.75E-01	2.25E-06	1.50E+00	6.06E-03
RL-W725	5.42E-02	0.00E+00	6.88E-03	3.39E-01	7.57E-02	2.13E-01	7.10E-07	4.76E-01	1.92E-03
RL-W726	4.27E-02	0.00E+00	5.43E-03	2.68E-01	5.97E-02	1.68E-01	5.60E-07	3.76E-01	1.51E-03
RL-W727	2.62E-01	0.00E+00	3.33E-02	1.64E+00	3.67E-01	1.03E+00	3.44E-06	2.30E+00	9.28E-03
RL-W728	2.38E-01	0.00E+00	3.04E-02	1.50E+00	3.34E-01	9.39E-01	3.13E-06	2.10E+00	8.47E-03
RL-W729	1.10E-01	0.00E+00	1.41E-02	6.89E-01	1.55E-01	4.33E-01	1.45E-06	9.68E-01	3.90E-03
RL-W730	4.89E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.89E+01	1.97E-01
RL-W731	1.58E-05	0.00E+00	0.00E+00	4.51E-04	1.85E-06	0.00E+00	0.00E+00	4.68E-04	1.89E-06
RL-W732	3.08E+01	0.00E+00	8.00E+00	1.27E+02	2.82E+01	1.55E+02	8.26E-04	1.94E+02	7.82E-01
RL-W733	4.16E-01	0.00E+00	1.04E-01	1.38E+00	3.43E-01	1.69E+00	1.07E-05	2.24E+00	9.04E-03
RL-W734	1.31E+00	0.00E+00	3.47E-01	4.76E+00	1.16E+00	5.02E+00	3.58E-05	7.57E+00	3.05E-02
RL-W735	1.08E+00	0.00E+00	2.65E-01	3.71E+00	9.22E-01	3.90E+00	2.73E-05	5.97E+00	2.41E-02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W736	1.29E-03	0.00E+00	5.65E-07	2.46E-03	6.36E-04	1.19E-03	5.83E-11	4.39E-03	1.77E-05
RL-W737	9.66E-01	0.00E+00	2.42E-01	3.52E+00	8.58E-01	3.36E+00	2.49E-05	5.58E+00	2.25E-02
RL-W738	3.62E+00	0.00E+00	8.31E-01	1.12E+01	2.96E+00	1.22E+01	8.58E-05	1.86E+01	7.50E-02
RL-W739	3.06E-01	0.00E+00	7.33E-02	1.82E+00	4.16E-01	1.11E+00	7.57E-06	2.61E+00	1.05E-02
RL-W740	1.53E+01	0.00E+00	2.69E+00	4.43E+01	1.16E+01	5.59E+01	2.77E-04	7.38E+01	2.98E-01
RL-W741	2.43E+01	0.00E+00	6.32E+00	8.62E+00	6.14E+00	4.20E+01	6.52E-04	4.53E+01	1.83E-01
RL-W742	1.02E+00	0.00E+00	1.90E-01	2.80E+00	6.61E-01	3.60E+00	1.96E-05	4.67E+00	1.88E-02
RL-W743	2.06E-03	0.00E+00	5.17E-05	1.81E-03	0.00E+00	0.00E+00	5.33E-09	3.92E-03	1.58E-05
RL-W744	0.00E+00	0.00E+00	0.00E+00	9.02E-02	7.69E-02	0.00E+00	0.00E+00	1.67E-01	6.74E-04
RL-W745	2.83E-03	0.00E+00	3.61E-04	1.75E-02	3.90E-03	1.24E-02	3.73E-08	2.46E-02	9.91E-05
RL-W746	1.09E-02	0.00E+00	1.39E-03	6.71E-02	1.51E-02	4.76E-02	1.44E-07	9.45E-02	3.81E-04
RL-W747	2.95E-02	0.00E+00	3.77E-03	1.82E-01	4.07E-02	1.29E-01	3.89E-07	2.56E-01	1.03E-03
RL-W748	2.05E+02	0.00E+00	1.06E+01	3.02E-01	4.97E-01	9.71E+02	1.09E-03	2.16E+02	8.71E-01
RL-W749	2.50E-01	0.00E+00	3.23E-02	1.58E+00	3.52E-01	1.04E+00	3.33E-06	2.21E+00	8.92E-03
RL-W750	3.14E+02	0.00E+00	1.60E+01	4.95E-01	8.12E-01	1.37E+03	1.65E-03	3.31E+02	1.33E+00
RL-W751	2.83E+02	0.00E+00	1.45E+01	4.45E-01	7.37E-01	1.24E+03	1.49E-03	2.99E+02	1.21E+00
RL-W752	1.23E+02	0.00E+00	6.28E+00	1.94E-01	3.20E-01	5.38E+02	6.48E-04	1.30E+02	5.24E-01
RL-W753	1.66E+03	0.00E+00	8.47E+01	2.61E+00	4.30E+00	7.24E+03	8.74E-03	1.75E+03	7.05E+00
RP-W754	7.86E+01	0.00E+00	1.07E+01	1.86E+03	1.53E+02	6.69E+01	3.54E-01	2.10E+03	8.47E+00
RP-W755	4.27E+02	0.00E+00	6.42E+00	1.39E+03	1.16E+02	4.99E+01	1.26E+01	1.95E+03	7.86E+00
SA-T001	8.62E-01	1.40E+00	1.54E-01	3.03E+00	1.41E-02	0.00E+00	2.05E-05	4.06E+00	1.64E-02
SA-W134	6.99E+00	5.44E-04	1.05E+00	1.38E+00	4.38E-01	1.27E+00	1.67E-01	1.00E+01	4.04E-02
SA-W134M	9.08E-01	7.05E-05	1.36E-01	1.80E-01	5.68E-02	1.65E-01	2.16E-02	1.30E+00	5.25E-03
T001-221F-HET	1.56E+03	0.00E+00	1.23E+05	2.88E+04	7.12E+02	4.18E+03	1.83E+01	1.54E+05	6.20E+02
T001-221H-HET	2.80E+03	0.00E+00	2.21E+05	5.20E+04	1.29E+03	7.54E+03	3.30E+01	2.77E+05	1.12E+03
T001-235F-HET	1.61E+02	0.00E+00	1.27E+04	2.99E+03	7.39E+01	4.33E+02	1.90E+00	1.60E+04	6.44E+01
T001-772F-HET	1.39E+03	0.00E+00	1.10E+05	2.58E+04	6.37E+02	3.73E+03	1.64E+01	1.38E+05	5.57E+02
T001-773A-CLAS	1.56E+01	0.00E+00	1.24E+03	2.90E+02	7.15E+00	4.20E+01	1.84E-01	1.55E+03	6.24E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
T001-773A-HET	1.80E+02	0.00E+00	1.42E+04	3.34E+03	8.25E+01	4.84E+02	2.12E+00	1.78E+04	7.18E+01
W006-773A-VIT	2.63E-03	0.00E+00	0.00E+00	5.37E+02	0.00E+00	0.00E+00	0.00E+00	5.37E+02	2.16E+00
W026-221F-HET	5.42E+02	0.00E+00	4.28E+04	1.01E+04	2.48E+02	1.46E+03	6.39E+00	5.37E+04	2.17E+02
W026-221H-HET	4.05E+02	0.00E+00	3.20E+04	7.51E+03	1.85E+02	1.09E+03	4.77E+00	4.01E+04	1.62E+02
W026-235F-HET	6.31E+00	0.00E+00	4.99E+02	1.17E+02	2.89E+00	1.70E+01	7.44E-02	6.25E+02	2.52E+00
W026-772F-HET	1.73E+00	0.00E+00	1.36E+02	3.19E+01	7.87E-01	4.63E+00	2.03E-02	1.70E+02	6.87E-01
W026-773A-HET	2.80E+01	0.00E+00	2.21E+03	5.20E+02	1.29E+01	7.52E+01	3.30E-01	2.77E+03	1.12E+01
W027-221F-HET	2.15E+03	0.00E+00	1.45E+05	3.90E+04	9.61E+02	2.38E+03	3.27E+01	1.87E+05	7.52E+02
W027-221H-HET	9.41E+02	0.00E+00	6.31E+04	1.71E+04	4.21E+02	1.04E+03	1.43E+01	8.15E+04	3.29E+02
W027-235F-HET	2.83E+02	0.00E+00	1.90E+04	5.14E+03	1.27E+02	3.13E+02	4.31E+00	2.45E+04	9.88E+01
W027-772F-HET	5.15E+02	0.00E+00	3.45E+04	9.32E+03	2.30E+02	5.68E+02	7.82E+00	4.46E+04	1.80E+02
W027-773A-HET	7.67E+02	0.00E+00	5.14E+04	1.39E+04	3.43E+02	8.49E+02	1.17E+01	6.64E+04	2.68E+02
W027-999-HET	8.77E+02	0.00E+00	5.88E+04	1.59E+04	3.92E+02	9.69E+02	1.33E+01	7.60E+04	3.06E+02
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.99E+02	0.00E+00	0.00E+00	0.00E+00	3.99E+02	1.61E+00
WP-INW169.001	4.16E+00	0.00E+00	3.71E-01	1.54E+01	3.43E+00	8.55E+00	2.03E-04	2.33E+01	9.41E-02
WP-INW198.001	5.38E+00	0.00E+00	6.46E-01	2.76E+01	6.10E+00	1.40E+01	1.49E-04	3.97E+01	1.60E-01
WP-INW211.001	6.05E+02	0.00E+00	6.07E+01	2.56E+03	5.66E+02	1.59E+03	8.24E-03	3.79E+03	1.53E+01
WP-INW216.001-	2.40E+04	0.00E+00	3.49E+01	1.48E+03	3.29E+02	8.79E+02	2.81E-01	2.58E+04	1.04E+02
WP-INW216.001-	6.58E+03	0.00E+00	9.40E+00	4.01E+02	8.87E+01	2.38E+02	2.86E-02	7.08E+03	2.86E+01
WP-INW218.001-	4.53E+02	0.00E+00	6.15E+00	2.58E+02	5.72E+01	1.59E+02	3.87E-01	7.75E+02	3.12E+00
WP-INW218.001-	1.96E+00	0.00E+00	1.69E-01	7.01E+00	1.56E+00	4.50E+00	3.74E-02	1.07E+01	4.33E-02
WP-INW222.001	2.04E+01	0.00E+00	1.83E+00	6.85E+01	1.54E+01	3.82E+01	7.62E-04	1.06E+02	4.28E-01
WP-INW243.001	5.00E+01	0.00E+00	3.94E+00	1.44E+02	3.23E+01	7.72E+01	1.27E-03	2.30E+02	9.28E-01
WP-INW247.001R	6.57E+01	0.00E+00	9.16E+00	2.76E+02	6.28E+01	1.34E+02	1.02E-03	4.13E+02	1.67E+00
WP-INW276.001	4.97E+00	0.00E+00	8.93E-01	2.73E+01	6.22E+00	1.13E+01	1.09E-04	3.94E+01	1.59E-01
WP-INW276.002	7.91E+00	0.00E+00	1.34E+00	4.01E+01	9.33E+00	1.70E+01	1.65E-04	5.87E+01	2.37E-01
WP-INW276.003	3.01E+02	0.00E+00	4.99E+01	1.49E+03	3.40E+02	7.16E+02	5.60E-03	2.18E+03	8.79E+00
WP-INW276.004	7.26E+01	0.00E+00	1.06E+01	3.15E+02	7.18E+01	1.51E+02	1.24E-03	4.70E+02	1.89E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-INW296.001-	2.71E+01	0.00E+00	2.51E+00	7.90E+01	1.79E+01	3.88E+01	2.96E-04	1.27E+02	5.10E-01
WP-INW296.001-	8.09E+01	0.00E+00	8.85E+00	2.80E+02	6.34E+01	1.40E+02	1.27E-03	4.33E+02	1.75E+00
WP-LA-TA-55-19	1.38E+00	0.00E+00	4.12E-01	2.09E+00	5.05E-01	1.39E+00	2.68E-03	4.39E+00	1.77E-02
WP-LA-TA-55-19	6.44E+01	0.00E+00	1.38E+01	2.13E+02	5.20E+01	1.38E+02	8.86E-02	3.43E+02	1.38E+00
WP-LA-TA-55-43	3.46E-01	0.00E+00	3.22E+02	3.23E-01	1.37E-01	1.24E+00	5.98E-02	3.23E+02	1.30E+00
WP-RF001.01	1.15E+02	0.00E+00	1.12E+01	4.10E+02	9.34E+01	1.39E+02	1.05E-02	6.30E+02	2.54E+00
WP-RF002.01-A	1.29E+02	0.00E+00	1.49E+01	4.62E+02	1.06E+02	3.06E+02	1.93E-02	7.11E+02	2.87E+00
WP-RF002.01-B	1.32E-01	0.00E+00	1.03E-02	5.00E-01	1.14E-01	1.93E-01	1.26E-06	7.56E-01	3.05E-03
WP-RF003.01	2.00E+03	0.00E+00	2.40E+02	8.82E+03	2.01E+03	5.06E+03	3.31E-02	1.31E+04	5.27E+01
WP-RF004.01	9.18E-01	0.00E+00	1.61E-01	5.09E+00	1.17E+00	2.89E+00	1.44E-04	7.33E+00	2.96E-02
WP-RF005.01	5.15E+03	0.00E+00	1.22E+02	4.67E+03	1.06E+03	2.01E+03	1.44E-02	1.10E+04	4.43E+01
WP-RF005.02	6.11E+03	0.00E+00	6.30E+01	2.79E+03	6.27E+02	1.03E+03	7.71E-03	9.58E+03	3.87E+01
WP-RF006.01	1.91E+03	0.00E+00	2.29E+02	7.93E+03	1.81E+03	2.61E+03	4.92E-02	1.19E+04	4.79E+01
WP-RF008.01	5.73E+02	0.00E+00	8.16E+01	2.32E+03	5.39E+02	1.73E+03	9.68E-03	3.51E+03	1.42E+01
WP-RF009.01	6.15E+04	0.00E+00	1.00E+03	5.09E+04	1.14E+04	1.98E+04	1.24E-01	1.25E+05	5.03E+02
WP-RF010.01	2.08E+01	0.00E+00	2.54E+00	7.68E+01	1.75E+01	6.11E+01	9.93E-04	1.18E+02	4.75E-01
WP-RF029.01-A	5.03E+00	0.00E+00	4.78E-01	1.35E+01	3.09E+00	1.40E+01	7.79E-04	2.21E+01	8.91E-02
WP-RF029.01-B	7.85E+00	0.00E+00	3.78E-01	1.07E+01	2.44E+00	1.11E+01	2.29E-03	2.14E+01	8.61E-02
WP-RF118.01	1.27E+04	0.00E+00	1.90E+03	5.14E+04	1.15E+04	3.64E+04	4.11E-01	7.74E+04	3.12E+02
WP-RLMPDT.001	2.69E+00	0.00E+00	5.55E-01	7.35E+00	1.91E+00	7.99E+00	5.94E-05	1.25E+01	5.05E-02
WP-RLNPDT.002	3.33E+01	0.00E+00	5.29E+00	7.22E+01	1.94E+01	9.17E+01	5.85E-04	1.30E+02	5.25E-01
WP-SR2001.001.	9.89E-01	0.00E+00	6.08E-01	6.82E+00	1.36E+00	4.99E+00	6.72E-05	9.78E+00	3.94E-02
WP-SR-W027-221	7.82E+00	0.00E+00	1.79E+00	1.96E+01	5.47E+00	2.25E+01	1.86E-01	3.49E+01	1.41E-01
Total	4.42E+05	2.72E+03	1.25E+06	6.60E+05	1.07E+05	5.15E+05	2.97E+02	2.46E+06	9.92E+03

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	7.37E+01	0.00E+00	6.27E+00	2.08E+02	1.22E+02	4.16E-01	1.74E-02	4.11E+02	1.66E+00
AE-T003	9.34E+00	0.00E+00	8.35E-01	6.44E+01	2.47E+01	2.28E-01	6.64E-04	9.92E+01	4.00E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	4.14E-02	0.00E+00	2.21E+01	4.74E+01	2.84E-01	4.44E-04	1.51E-02	6.99E+01	2.82E-01
AW-T033.1325	1.51E-01	0.00E+00	8.11E+01	1.73E+02	1.04E+00	1.62E-03	5.52E-02	2.56E+02	1.03E+00
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.70E-01	0.00E+00	0.00E+00	0.00E+00	7.70E-01	3.11E-03
BCLCH-MT01	1.53E+01	0.00E+00	6.27E+02	2.86E+01	7.44E+00	6.26E-01	4.14E-01	6.79E+02	2.74E+00
BT-T002	1.12E-02	1.62E-05	3.28E-01	7.22E-04	1.47E-03	2.75E-04	2.21E-03	3.43E-01	1.39E-03
ET-C1-B55	4.69E-02	0.00E+00	3.74E-03	6.19E-02	3.06E-02	4.85E-04	2.38E-04	1.43E-01	5.78E-04
ET-C1-D139	6.43E-03	0.00E+00	5.18E-04	8.70E-03	4.30E-03	6.45E-05	4.03E-07	1.99E-02	8.04E-05
ET-C2-SEFOR	1.59E-01	0.00E+00	0.00E+00	1.37E-01	4.55E-02	9.95E-04	0.00E+00	3.41E-01	1.38E-03
FM-MOX-MT02	1.51E-06	0.00E+00	2.09E-07	2.99E-07	1.77E-07	3.46E-08	1.46E-10	2.19E-06	8.84E-09
FM-MOX-T01	2.49E-05	0.00E+00	3.44E-06	4.92E-06	2.91E-06	5.71E-07	2.41E-09	3.62E-05	1.46E-07
IN-BN-510	6.02E+03	0.00E+00	1.78E+04	3.96E+04	3.32E+03	1.36E-01	1.37E+01	6.67E+04	2.69E+02
IN-GEM-01	7.62E+01	0.00E+00	3.52E-01	4.44E+01	1.01E+01	9.62E-02	2.32E-04	1.31E+02	5.28E-01
IN-GEM-02	1.81E+01	0.00E+00	8.39E-02	1.06E+01	2.40E+00	2.28E-02	5.53E-05	3.11E+01	1.26E-01
IN-W157.144	9.02E+01	0.00E+00	3.41E+00	3.02E+02	6.78E+01	1.71E+00	2.63E-03	4.63E+02	1.87E+00
IN-W163.1007	1.54E+01	0.00E+00	1.05E+00	9.36E+01	2.10E+01	5.25E-01	8.11E-04	1.31E+02	5.29E-01
IN-W164.153	1.48E-01	0.00E+00	1.01E-02	8.92E-01	2.00E-01	5.03E-03	7.73E-06	1.25E+00	5.04E-03
IN-W167.149	2.95E+01	0.00E+00	1.63E+00	1.44E+02	3.24E+01	8.14E-01	1.26E-03	2.08E+02	8.39E-01
IN-W174.154	0.00E+00	0.00E+00	9.24E+02	1.94E+00	3.80E+00	0.00E+00	7.11E-01	9.30E+02	3.75E+00
IN-W177.156	2.05E-02	0.00E+00	1.96E+03	1.82E+00	1.10E-02	6.99E-04	1.51E+00	1.97E+03	7.93E+00
IN-W179.158	1.38E-01	0.00E+00	1.96E+03	1.06E-01	5.44E-02	4.70E-03	1.50E+00	1.96E+03	7.90E+00
IN-W181.162	1.96E+00	0.00E+00	1.33E-01	1.18E+01	2.64E+00	6.66E-02	1.03E-04	1.65E+01	6.65E-02
IN-W188.160	1.32E+01	0.00E+00	8.95E-01	7.94E+01	1.78E+01	4.49E-01	6.89E-04	1.11E+02	4.48E-01
IN-W216.98	1.17E+05	0.00E+00	7.30E+01	6.48E+03	1.46E+03	3.67E+01	5.61E-02	1.25E+05	5.05E+02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	5.92E+02	0.00E+00	1.62E+00	1.44E+02	3.23E+01	8.12E-01	1.25E-03	7.69E+02	3.10E+00
IN-W219.110	8.02E-01	0.00E+00	5.46E-02	4.84E+00	1.09E+00	2.73E-02	4.20E-05	6.78E+00	2.74E-02
IN-W219.914	1.27E-01	0.00E+00	8.60E-03	7.64E-01	1.72E-01	4.31E-03	6.62E-06	1.07E+00	4.32E-03
IN-W220.114	4.18E+03	0.00E+00	5.75E+00	5.47E+02	1.19E+02	2.87E+00	4.42E-03	4.85E+03	1.96E+01
IN-W221.927	4.90E+00	0.00E+00	3.33E-01	2.95E+01	6.61E+00	1.67E-01	2.56E-04	4.13E+01	1.67E-01
IN-W222.116	1.67E+02	0.00E+00	1.13E+01	9.96E+02	2.24E+02	5.64E+00	8.67E-03	1.40E+03	5.64E+00
IN-W228.101	1.11E+03	0.00E+00	3.67E+00	3.26E+02	7.30E+01	1.84E+00	2.82E-03	1.51E+03	6.08E+00
IN-W240.931	1.17E+02	0.00E+00	4.69E+00	4.18E+02	9.34E+01	2.33E+00	3.61E-03	6.33E+02	2.55E+00
IN-W243.808	1.62E+02	0.00E+00	8.21E+00	7.30E+02	1.64E+02	4.12E+00	6.32E-03	1.06E+03	4.29E+00
IN-W245.301	2.40E+02	0.00E+00	1.61E+01	1.43E+03	3.21E+02	8.05E+00	1.24E-02	2.00E+03	8.07E+00
IN-W247.810	1.17E+02	0.00E+00	7.86E+00	6.96E+02	1.57E+02	3.93E+00	6.05E-03	9.78E+02	3.94E+00
IN-W249.527	0.00E+00	0.00E+00	5.50E+02	1.24E+01	0.00E+00	0.00E+00	4.23E-01	5.63E+02	2.27E+00
IN-W263.520	3.34E-02	0.00E+00	5.75E+01	8.40E+00	1.32E-02	1.14E-03	4.42E-02	6.60E+01	2.66E-01
IN-W267.1005	2.80E+01	0.00E+00	1.91E+00	1.69E+02	3.80E+01	9.55E-01	1.47E-03	2.37E+02	9.57E-01
IN-W309.609	7.51E+02	0.00E+00	3.20E+01	2.83E+03	6.35E+02	1.60E+01	2.46E-02	4.25E+03	1.71E+01
IN-W315.601	7.41E+02	0.00E+00	1.34E-01	1.19E+01	2.65E+00	6.66E-02	1.03E-04	7.55E+02	3.05E+00
IN-W319.584	4.30E+00	0.00E+00	2.93E-01	2.60E+01	5.85E+00	1.47E-01	2.25E-04	3.65E+01	1.47E-01
IN-W321.1023	3.72E+01	0.00E+00	2.54E+00	2.25E+02	5.05E+01	1.27E+00	1.95E-03	3.15E+02	1.27E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	9.09E+00	1.86E+00	0.00E+00	0.00E+00	1.10E+01	4.42E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.42E+01	4.97E+00	0.00E+00	0.00E+00	2.92E+01	1.18E-01
IN-W323.562	7.96E-02	0.00E+00	4.30E-01	2.48E-01	0.00E+00	2.71E-03	3.31E-04	7.58E-01	3.06E-03
IN-W323.951	9.39E-02	0.00E+00	5.11E-03	2.96E-01	0.00E+00	3.20E-03	3.93E-06	3.95E-01	1.59E-03
IN-W332.661	0.00E+00	0.00E+00	5.64E+00	1.29E-01	0.00E+00	0.00E+00	4.34E-03	5.77E+00	2.33E-02
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	3.03E+00	6.21E-01	0.00E+00	0.00E+00	3.65E+00	1.47E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	9.09E+00	1.86E+00	0.00E+00	0.00E+00	1.10E+01	4.42E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.94E+00	0.00E+00	0.00E+00	0.00E+00	1.94E+00	7.83E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.84E+00	0.00E+00	0.00E+00	0.00E+00	5.84E+00	2.35E-02
IN-W342.652	3.68E+00	0.00E+00	0.00E+00	4.01E-02	1.03E-17	0.00E+00	0.00E+00	3.72E+00	1.50E-02
IN-W342.953	2.46E+00	0.00E+00	0.00E+00	2.68E-02	6.88E-18	0.00E+00	0.00E+00	2.49E+00	1.00E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W347.818	1.93E+00	0.00E+00	0.00E+00	8.23E+01	1.50E+02	0.00E+00	1.58E-08	2.34E+02	9.44E-01
IN-W348.1012	1.02E-01	0.00E+00	4.65E+00	4.15E+02	9.33E+01	0.00E+00	3.58E-03	5.14E+02	2.07E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.49E-02	0.00E+00	0.00E+00	0.00E+00	2.49E-02	1.00E-04
IN-W357.1022	0.00E+00	0.00E+00	9.17E-03	8.16E-01	1.82E-01	0.00E+00	7.05E-06	1.01E+00	4.06E-03
IN-W358.854	0.00E+00	0.00E+00	1.38E+02	1.87E+00	3.58E+00	0.00E+00	9.91E-02	1.44E+02	5.80E-01
IN-W358.855	0.00E+00	0.00E+00	7.37E+02	9.96E+00	1.90E+01	0.00E+00	5.28E-01	7.66E+02	3.09E+00
IN-W358.948	0.00E+00	0.00E+00	1.54E+02	2.08E+00	3.96E+00	0.00E+00	1.10E-01	1.60E+02	6.45E-01
IN-W361.1021	2.71E-02	0.00E+00	8.88E-01	7.87E+01	1.77E+01	0.00E+00	6.83E-04	9.73E+01	3.92E-01
IN-W362.1020	0.00E+00	0.00E+00	1.16E+01	1.03E+03	2.32E+02	0.00E+00	8.95E-03	1.27E+03	5.12E+00
IN-W363.1019	0.00E+00	0.00E+00	5.46E-01	4.87E+01	1.10E+01	0.00E+00	4.20E-04	6.02E+01	2.43E-01
IN-W364.1011	0.00E+00	0.00E+00	9.02E-01	8.01E+01	1.80E+01	0.00E+00	6.94E-04	9.90E+01	3.99E-01
IN-W365.1010	2.53E+02	0.00E+00	7.16E-01	6.33E+01	1.42E+01	0.00E+00	5.50E-04	3.31E+02	1.33E+00
IN-W366.841	8.98E-01	0.00E+00	6.10E-01	5.39E+01	1.21E+01	0.00E+00	4.69E-04	6.75E+01	2.72E-01
IN-W372.832	3.68E+00	0.00E+00	0.00E+00	4.01E-02	1.03E-17	0.00E+00	0.00E+00	3.72E+00	1.50E-02
IN-W375.1096	0.00E+00	0.00E+00	2.25E-01	1.99E+01	4.47E+00	0.00E+00	1.73E-04	2.46E+01	9.93E-02
KN-B234TRU	1.31E+02	0.00E+00	8.60E+00	2.90E+02	9.66E+01	8.92E-01	7.62E-03	5.26E+02	2.12E+00
LA-IT-00-01	1.90E+00	1.04E-02	1.47E+00	5.83E-01	1.25E-02	1.71E-10	1.32E-03	3.97E+00	1.60E-02
LA-OS-00-01	4.23E+03	0.00E+00	6.70E+04	1.23E+03	0.00E+00	0.00E+00	4.47E+01	7.25E+04	2.92E+02
LA-PX-00-01	1.77E-02	0.00E+00	2.82E-03	9.02E-02	2.10E-02	2.84E-04	2.00E-06	1.32E-01	5.31E-04
LA-SL-00-01	0.00E+00	0.00E+00	5.96E-02	1.52E-01	0.00E+00	0.00E+00	5.32E-05	2.12E-01	8.55E-04
LA-TA-03-12	1.81E-01	0.00E+00	1.38E+00	4.34E-01	1.50E-01	1.68E-03	1.29E-03	2.15E+00	8.65E-03
LA-TA-03-13	2.35E-01	0.00E+00	4.37E+00	6.78E-01	1.58E-01	2.23E-03	3.41E-03	5.45E+00	2.20E-02
LA-TA-03-19	4.74E-01	0.00E+00	6.52E+00	1.33E+00	3.80E-01	3.44E-03	6.09E-03	8.71E+00	3.51E-02
LA-TA-03-20	2.59E-01	0.00E+00	3.10E+00	5.84E-01	2.04E-01	2.82E-03	2.73E-03	4.14E+00	1.67E-02
LA-TA-03-24	3.47E-01	0.00E+00	1.21E+01	1.09E+00	3.26E-01	2.92E-03	1.14E-02	1.38E+01	5.58E-02
LA-TA-03-26	1.78E-02	0.00E+00	4.97E-01	2.63E+00	4.27E-02	2.56E-04	1.34E-03	3.19E+00	1.29E-02
LA-TA-03-28	0.00E+00	0.00E+00	1.72E-01	2.46E-01	0.00E+00	0.00E+00	1.59E-04	4.18E-01	1.69E-03
LA-TA-03-30	7.90E-01	0.00E+00	1.23E-01	5.01E+00	1.44E+00	1.34E-02	1.12E-04	7.36E+00	2.97E-02
LA-TA-03-31	0.00E+00	0.00E+00	6.13E-03	8.77E-03	0.00E+00	0.00E+00	5.65E-06	1.49E-02	6.01E-05

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-03-40	0.00E+00	0.00E+00	9.69E-03	5.45E-02	0.00E+00	0.00E+00	9.03E-06	6.42E-02	2.59E-04
LA-TA-03-42	1.82E-05	0.00E+00	2.43E-04	3.41E-03	4.45E-05	2.80E-07	2.26E-07	3.71E-03	1.50E-05
LA-TA-21-06	1.79E-01	0.00E+00	2.67E+01	9.53E-01	2.89E-01	2.89E-03	2.46E-02	2.82E+01	1.14E-01
LA-TA-21-12	6.51E-01	0.00E+00	1.61E+02	3.31E+00	9.80E-01	9.92E-03	1.49E-01	1.66E+02	6.70E-01
LA-TA-21-13	1.00E+00	0.00E+00	0.00E+00	2.93E-01	0.00E+00	0.00E+00	0.00E+00	1.30E+00	5.23E-03
LA-TA-21-14	1.65E-04	0.00E+00	3.07E+00	4.47E+00	5.18E-05	4.02E-06	2.20E-03	7.55E+00	3.04E-02
LA-TA-21-15	9.71E-02	0.00E+00	8.46E-03	1.39E+00	2.35E-01	1.63E-03	7.71E-06	1.73E+00	6.96E-03
LA-TA-21-16	1.13E+00	0.00E+00	1.30E-01	1.06E+01	2.51E+00	1.72E-02	1.21E-04	1.43E+01	5.77E-02
LA-TA-21-40	1.43E-04	0.00E+00	4.51E-01	3.32E-01	3.64E-04	6.89E-07	5.48E-04	7.84E-01	3.16E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	7.06E-01	0.00E+00	0.00E+00	0.00E+00	7.06E-01	2.85E-03
LA-TA-21-42	1.46E-02	0.00E+00	1.47E-01	1.63E-01	1.10E-02	2.24E-05	1.93E-04	3.36E-01	1.35E-03
LA-TA-21-43	5.16E+01	0.00E+00	4.86E+00	5.09E+02	1.20E+02	1.77E-01	6.35E-03	6.86E+02	2.77E+00
LA-TA-21-44	2.47E-01	0.00E+00	1.02E+00	1.15E+02	3.03E-01	2.51E-03	1.05E-03	1.16E+02	4.68E-01
LA-TA-48-01	8.00E-02	4.91E-02	3.84E-03	1.18E-01	4.88E-01	2.07E-04	4.72E-06	6.90E-01	2.78E-03
LA-TA-49-01	9.88E+00	6.10E+00	4.72E-01	1.45E+01	6.05E+01	2.56E-02	5.82E-04	8.54E+01	3.44E-01
LA-TA-50-10	2.65E-02	0.00E+00	4.48E-03	4.57E-02	0.00E+00	0.00E+00	3.13E-06	7.67E-02	3.09E-04
LA-TA-50-11	5.05E-02	0.00E+00	4.58E-03	4.64E-01	1.03E-01	2.05E-04	5.50E-06	6.22E-01	2.51E-03
LA-TA-50-15	9.96E-02	0.00E+00	6.77E-01	3.39E-01	7.54E-02	8.12E-04	5.67E-04	1.19E+00	4.80E-03
LA-TA-50-17	1.46E+01	0.00E+00	5.50E-01	1.81E+01	4.24E-04	7.43E-05	8.00E-04	3.33E+01	1.34E-01
LA-TA-50-18	8.66E-01	0.00E+00	7.26E-02	2.96E+00	5.29E-06	2.19E-06	6.77E-05	3.90E+00	1.57E-02
LA-TA-50-19	2.76E-01	0.00E+00	3.24E-02	3.94E-01	4.53E-03	2.71E-05	5.69E-05	7.07E-01	2.85E-03
LA-TA-50-20	7.58E-03	0.00E+00	0.00E+00	9.70E-03	0.00E+00	0.00E+00	0.00E+00	1.73E-02	6.97E-05
LA-TA-50-40	4.26E-03	0.00E+00	4.37E-04	1.06E-02	4.90E-03	8.70E-05	3.81E-07	2.02E-02	8.13E-05
LA-TA-50-41	4.55E-03	0.00E+00	4.41E-04	4.68E-02	1.09E-02	1.55E-04	3.39E-07	6.27E-02	2.53E-04
LA-TA-55-19	7.06E+00	0.00E+00	5.82E-01	2.63E+01	7.37E+00	8.77E-02	2.05E-03	4.13E+01	1.67E-01
LA-TA-55-20	1.13E+02	0.00E+00	6.63E+00	6.36E+02	1.52E+02	2.19E+00	9.92E-02	9.08E+02	3.66E+00
LA-TA-55-21	1.01E+00	1.45E-05	7.61E-02	4.50E+00	1.08E+00	1.81E-02	5.79E-05	6.67E+00	2.69E-02
LA-TA-55-22	2.77E+00	0.00E+00	4.30E-01	1.58E+01	3.69E+00	5.60E-02	3.27E-04	2.27E+01	9.17E-02
LA-TA-55-23	2.61E+00	0.00E+00	3.60E-01	1.09E+01	2.67E+00	5.52E-02	2.70E-04	1.65E+01	6.66E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-24	9.85E-01	0.00E+00	5.64E-02	5.70E+00	1.32E+00	2.63E-02	4.00E-05	8.06E+00	3.25E-02
LA-TA-55-25	5.04E+00	0.00E+00	3.29E-01	2.83E+01	6.58E+00	1.35E-01	2.33E-04	4.02E+01	1.62E-01
LA-TA-55-28	1.72E+00	0.00E+00	1.82E-01	8.69E+00	2.04E+00	4.37E-02	1.31E-04	1.26E+01	5.09E-02
LA-TA-55-30	3.83E+01	1.38E-07	2.18E+00	1.43E+02	3.42E+01	3.20E-01	2.21E-03	2.17E+02	8.76E-01
LA-TA-55-32	3.11E+00	0.00E+00	1.22E+01	1.13E+01	3.46E+00	3.98E-02	1.15E-02	3.00E+01	1.21E-01
LA-TA-55-33	4.65E-01	0.00E+00	3.15E-02	1.48E+00	4.71E-01	5.60E-03	2.71E-05	2.45E+00	9.89E-03
LA-TA-55-34	4.71E+01	0.00E+00	2.91E+00	2.30E+02	5.82E+01	6.75E-01	5.29E-03	3.38E+02	1.36E+00
LA-TA-55-38	1.18E+02	0.00E+00	9.59E-01	5.08E+01	1.36E+01	1.57E-01	2.52E-03	1.84E+02	7.40E-01
LA-TA-55-39	1.25E+01	0.00E+00	7.09E-01	7.58E+01	1.70E+01	2.77E-01	5.26E-04	1.06E+02	4.27E-01
LA-TA-55-41	2.98E+02	0.00E+00	1.47E+00	9.40E+01	2.24E+01	3.48E-01	1.13E-03	4.16E+02	1.68E+00
LA-TA-55-43	1.12E-01	0.00E+00	9.62E+01	1.42E-01	4.93E-02	3.06E-03	7.07E-02	9.66E+01	3.90E-01
LA-TA-55-44	9.70E-01	0.00E+00	2.27E+02	2.62E+00	7.24E-01	9.05E-03	1.98E-01	2.31E+02	9.32E-01
LA-TA-55-48	7.14E+03	0.00E+00	8.95E+02	1.68E+04	6.25E+03	9.45E+01	7.55E-01	3.11E+04	1.26E+02
LA-TA-55-49	1.53E+01	0.00E+00	1.18E+03	3.08E+01	8.61E+00	1.11E-01	1.02E+00	1.23E+03	4.97E+00
LA-TA-55-53	7.20E+01	0.00E+00	2.43E+00	2.63E+02	6.11E+01	6.05E-01	2.06E-03	3.99E+02	1.61E+00
LA-TA-55-56	7.97E+01	0.00E+00	9.06E+01	3.81E+02	9.51E+01	1.40E+00	7.14E-02	6.46E+02	2.61E+00
LA-TA-55-60	4.32E-02	0.00E+00	2.29E-02	7.17E-02	2.53E-02	8.25E-04	1.97E-05	1.63E-01	6.58E-04
LA-TA-55-61	3.72E-02	0.00E+00	1.05E-01	1.39E-01	4.67E-02	8.02E-04	8.89E-05	3.28E-01	1.32E-03
LA-TA-55-62	9.63E-03	0.00E+00	1.00E-03	2.32E-02	1.10E-02	2.16E-04	8.54E-07	4.49E-02	1.81E-04
LA-TA-55-63	7.15E-03	0.00E+00	6.77E-04	7.44E-02	1.72E-02	2.12E-04	5.39E-07	9.94E-02	4.01E-04
LL-M001	9.81E+01	6.59E-01	2.95E+01	6.97E+01	3.13E+01	1.68E+00	1.94E-02	2.29E+02	9.22E-01
LL-T001	4.90E+02	0.00E+00	0.00E+00	5.32E+02	2.39E+02	1.30E+01	0.00E+00	1.26E+03	5.08E+00
LL-T002	4.84E+03	0.00E+00	2.35E+02	5.16E+03	2.11E+03	1.14E+02	1.55E-01	1.23E+04	4.98E+01
LL-T003	1.88E+02	0.00E+00	2.63E+01	1.05E+02	8.40E+01	4.52E+00	1.73E-02	4.03E+02	1.63E+00
LL-T004	1.20E+02	0.00E+00	5.39E+00	6.65E+01	5.30E+01	2.87E+00	3.55E-03	2.44E+02	9.85E-01
LL-T005	6.17E+02	2.87E+01	6.35E+01	2.47E+02	2.12E+02	1.06E+01	4.18E-02	1.14E+03	4.60E+00
LL-W018	5.25E-02	0.00E+00	0.00E+00	1.84E-02	4.22E-02	2.18E-03	0.00E+00	1.13E-01	4.56E-04
LL-W019	2.85E+01	0.00E+00	0.00E+00	1.44E+01	1.19E+01	6.37E-01	0.00E+00	5.48E+01	2.21E-01
LL-W034	1.05E+01	4.85E-01	1.11E+00	4.18E+00	3.52E+00	1.81E-01	7.32E-04	1.94E+01	7.80E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
MC-W001	1.32E-01	0.00E+00	0.00E+00	6.04E-02	0.00E+00	3.27E-04	0.00E+00	1.92E-01	7.74E-04
MU-W002	1.76E+00	0.00E+00	0.00E+00	5.24E-02	0.00E+00	0.00E+00	2.67E-12	1.81E+00	7.29E-03
NT-JAS-01	1.70E+02	0.00E+00	2.37E+01	9.44E+01	7.56E+01	4.07E+00	1.56E-02	3.63E+02	1.47E+00
NT-W001	2.55E+02	1.48E-02	4.72E+01	2.85E+03	1.89E+01	2.85E-01	4.27E-02	3.17E+03	1.28E+01
NT-W021	4.92E+00	0.00E+00	3.38E-01	3.21E+01	7.28E+00	1.46E-01	2.70E-04	4.46E+01	1.80E-01
OR-W201	5.90E+03	1.02E+00	1.02E+03	2.15E+03	2.11E+03	1.53E+02	4.43E+01	1.12E+04	4.53E+01
OR-W202	8.47E+02	2.13E+01	2.93E+03	5.52E+02	5.39E+02	4.91E+00	2.38E+00	4.87E+03	1.96E+01
OR-W203	1.87E+00	7.42E-01	4.20E-01	2.48E-02	1.76E+00	1.25E-02	3.38E-04	4.07E+00	1.64E-02
OR-W204	4.16E-01	3.08E-06	4.76E-01	4.22E-01	2.84E-01	0.00E+00	3.83E-04	1.60E+00	6.45E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.24E-01	0.00E+00	0.00E+00	0.00E+00	4.24E-01	1.71E-03
RF-MT0001	1.60E+03	0.00E+00	2.95E+00	1.95E+02	4.43E+01	1.12E+00	2.25E-03	1.84E+03	7.41E+00
RF-MT0002	1.23E+02	0.00E+00	2.27E-01	1.50E+01	3.40E+00	8.61E-02	1.72E-04	1.41E+02	5.70E-01
RF-MT0003	5.58E-01	0.00E+00	5.18E-02	3.44E+00	7.79E-01	1.97E-02	3.94E-05	4.83E+00	1.95E-02
RF-MT0007	1.40E+00	0.00E+00	0.00E+00	4.28E-01	9.69E-02	2.28E-03	0.00E+00	1.93E+00	7.78E-03
RF-MT0089	5.51E-03	0.00E+00	5.18E-04	3.44E-02	7.78E-03	1.97E-04	3.94E-07	4.82E-02	1.94E-04
RF-MT0090	1.40E+01	0.00E+00	7.33E-01	8.83E+01	1.98E+01	1.97E-01	5.58E-04	1.23E+02	4.95E-01
RF-MT0091	8.67E+02	0.00E+00	7.44E+01	5.90E+03	1.33E+03	1.62E+01	5.96E-02	8.17E+03	3.29E+01
RF-MT0092	1.24E+02	0.00E+00	9.38E+00	8.45E+02	1.94E+02	2.24E+00	7.13E-03	1.17E+03	4.73E+00
RF-MT0093	1.51E+02	0.00E+00	9.66E+00	9.12E+02	2.13E+02	1.91E+00	7.34E-03	1.29E+03	5.18E+00
RF-MT0097	7.56E+00	0.00E+00	4.27E-01	4.76E+01	9.68E+00	1.05E-01	3.24E-04	6.53E+01	2.63E-01
RF-MT0099	8.28E-03	0.00E+00	7.79E-04	5.15E-02	1.16E-02	2.96E-04	5.92E-07	7.22E-02	2.91E-04
RF-MT0290	2.05E+01	0.00E+00	1.93E+00	1.28E+02	2.89E+01	7.32E-01	1.47E-03	1.79E+02	7.21E-01
RF-MT-0292	2.59E+01	0.00E+00	2.44E+00	1.61E+02	3.65E+01	9.26E-01	1.85E-03	2.26E+02	9.12E-01
RF-MT-0299	3.05E+03	0.00E+00	6.24E+01	4.13E+03	9.37E+02	2.38E+01	4.75E-02	8.19E+03	3.30E+01
RF-MT0302	4.67E-02	0.00E+00	2.48E-03	1.78E-01	4.05E-02	9.26E-04	1.87E-05	2.68E-01	1.08E-03
RF-MT0320	5.58E+01	0.00E+00	2.56E+00	1.73E+02	3.94E+01	9.31E-01	1.96E-03	2.71E+02	1.09E+00
RF-MT0321	3.12E+01	0.00E+00	7.65E-01	5.58E+01	1.25E+01	2.61E-01	2.99E-03	1.00E+02	4.04E-01
RF-MT-0328	2.16E+00	0.00E+00	9.17E-02	6.07E+00	1.37E+00	3.48E-02	4.08E-04	9.69E+00	3.91E-02
RF-MT0330	2.25E+01	0.00E+00	1.01E+00	1.23E+02	3.00E+01	3.27E-01	7.64E-04	1.76E+02	7.10E-01

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT-0331	1.35E+02	0.00E+00	6.24E+00	5.39E+02	1.19E+02	1.90E+00	2.55E-02	7.99E+02	3.22E+00
RF-MT0332	1.93E-02	0.00E+00	1.82E-03	1.21E-01	2.72E-02	6.91E-04	1.38E-06	1.69E-01	6.81E-04
RF-MT-0335	1.55E+00	0.00E+00	8.35E-02	6.21E+00	1.41E+00	2.82E-02	6.06E-04	9.25E+00	3.73E-02
RF-MT0336	1.10E+02	0.00E+00	5.53E+00	4.40E+02	9.96E+01	1.65E+00	6.03E-03	6.55E+02	2.64E+00
RF-MT0337	6.20E+01	0.00E+00	3.04E+00	2.69E+02	5.99E+01	8.07E-01	6.16E-03	3.94E+02	1.59E+00
RF-MT0339	1.70E+02	0.00E+00	8.28E+00	5.90E+02	1.32E+02	2.92E+00	2.34E-02	9.00E+02	3.63E+00
RF-MT-0342	9.97E-01	0.00E+00	6.94E-02	5.45E+00	1.21E+00	2.14E-02	1.11E-04	7.73E+00	3.12E-02
RF-MT0371	3.37E+02	0.00E+00	1.61E+01	1.07E+03	2.41E+02	6.11E+00	1.35E-02	1.66E+03	6.69E+00
RF-MT-0372	1.47E+00	0.00E+00	1.13E-01	7.43E+00	1.69E+00	3.78E-02	3.26E-04	1.07E+01	4.32E-02
RF-MT0373	2.21E+01	0.00E+00	1.16E+00	1.40E+02	3.14E+01	3.11E-01	8.85E-04	1.94E+02	7.83E-01
RF-MT0374	7.19E-01	0.00E+00	4.16E-02	2.76E+00	6.24E-01	1.58E-02	3.50E-05	4.14E+00	1.67E-02
RF-MT0376	5.70E-01	0.00E+00	3.36E-02	2.75E+00	6.32E-01	1.16E-02	4.06E-05	3.99E+00	1.61E-02
RF-MT0377	3.38E+02	0.00E+00	1.94E+01	1.29E+03	2.90E+02	7.34E+00	2.50E-02	1.93E+03	7.79E+00
RF-MT0378	3.80E+00	0.00E+00	2.68E-01	1.77E+01	4.01E+00	1.02E-01	2.03E-04	2.58E+01	1.04E-01
RF-MT0419	6.11E+00	0.00E+00	2.50E-01	1.65E+01	3.75E+00	9.50E-02	1.90E-04	2.66E+01	1.07E-01
RF-MT0420	1.06E+00	0.00E+00	4.34E-02	2.87E+00	6.51E-01	1.65E-02	3.30E-05	4.63E+00	1.87E-02
RF-MT0423	9.03E+00	0.00E+00	3.53E-01	4.14E+01	9.10E+00	6.54E-02	2.68E-04	5.99E+01	2.42E-01
RF-MT0425	2.66E-01	0.00E+00	1.09E-02	7.18E-01	1.63E-01	4.12E-03	8.26E-06	1.16E+00	4.67E-03
RF-MT-0438	2.41E+00	0.00E+00	1.42E-01	1.28E+01	2.86E+00	4.09E-02	1.21E-04	1.82E+01	7.32E-02
RF-MT0440	8.76E-01	0.00E+00	5.11E-02	4.62E+00	1.07E+00	1.68E-02	2.04E-04	6.61E+00	2.67E-02
RF-MT0442	3.33E-01	0.00E+00	2.21E-02	1.58E+00	3.58E-01	6.25E-03	1.12E-04	2.30E+00	9.26E-03
RF-MT0443	4.10E+00	0.00E+00	3.63E-01	2.46E+01	5.57E+00	1.30E-01	4.34E-04	3.46E+01	1.40E-01
RF-MT0444	3.20E+01	0.00E+00	1.78E+00	1.19E+02	2.67E+01	6.75E-01	1.38E-03	1.79E+02	7.22E-01
RF-MT0480	8.95E+01	0.00E+00	5.01E+00	3.33E+02	7.54E+01	1.74E+00	6.27E-03	5.03E+02	2.03E+00
RF-MT0488	1.43E+02	0.00E+00	7.47E+00	4.94E+02	1.11E+02	2.84E+00	3.66E-02	7.56E+02	3.05E+00
RF-MT0490	6.49E-01	0.00E+00	4.34E-02	2.92E+00	6.62E-01	1.57E-02	4.42E-05	4.27E+00	1.72E-02
RF-MT-0491	5.10E-02	0.00E+00	1.98E-03	1.33E-01	2.99E-02	7.32E-04	3.52E-06	2.15E-01	8.68E-04
RF-MT0523A	4.04E+01	0.00E+00	1.58E+00	1.05E+02	2.37E+01	5.97E-01	1.45E-03	1.70E+02	6.86E-01
RF-MT0523B	4.04E+01	0.00E+00	1.58E+00	1.05E+02	2.37E+01	5.97E-01	1.45E-03	1.70E+02	6.86E-01

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0523C	4.04E+01	0.00E+00	1.58E+00	1.05E+02	2.37E+01	5.97E-01	1.45E-03	1.70E+02	6.86E-01
RF-MT0523D	4.04E+01	0.00E+00	1.58E+00	1.05E+02	2.37E+01	5.97E-01	1.45E-03	1.70E+02	6.86E-01
RF-MT0523E	4.04E+01	0.00E+00	1.58E+00	1.05E+02	2.37E+01	5.97E-01	1.45E-03	1.70E+02	6.86E-01
RF-MT0531	2.76E-03	0.00E+00	2.59E-04	1.71E-02	3.89E-03	9.86E-05	1.97E-07	2.40E-02	9.69E-05
RF-MT0532E	1.29E+02	0.00E+00	3.37E+00	2.28E+02	5.16E+01	1.27E+00	3.67E-03	4.12E+02	1.66E+00
RF-MT0532F	1.29E+02	0.00E+00	3.37E+00	2.28E+02	5.16E+01	1.27E+00	3.67E-03	4.12E+02	1.66E+00
RF-MT0541	4.69E+00	0.00E+00	4.86E-02	3.24E+00	7.32E-01	1.86E-02	3.70E-05	8.71E+00	3.51E-02
RF-MT0545	2.51E-02	0.00E+00	2.36E-03	1.56E-01	3.53E-02	8.96E-04	1.79E-06	2.19E-01	8.84E-04
RF-MT0800	9.54E+02	0.00E+00	1.17E+00	7.72E+01	1.75E+01	4.44E-01	1.37E-03	1.05E+03	4.23E+00
RF-MT0801	1.10E+02	0.00E+00	1.14E+00	7.58E+01	1.72E+01	4.33E-01	8.69E-04	2.04E+02	8.22E-01
RF-MT0803	2.46E+00	0.00E+00	2.56E-02	1.69E+00	3.83E-01	9.71E-03	1.94E-05	4.56E+00	1.84E-02
RF-MT0806	1.16E+00	0.00E+00	6.13E-02	7.36E+00	1.65E+00	1.64E-02	4.66E-05	1.02E+01	4.13E-02
RF-MT0807	1.47E+01	0.00E+00	4.72E-01	3.13E+01	7.09E+00	1.79E-01	3.59E-04	5.35E+01	2.16E-01
RF-MT0816	1.57E+00	0.00E+00	6.66E-02	4.41E+00	9.96E-01	2.54E-02	5.07E-05	7.05E+00	2.84E-02
RF-MT-0823	7.78E-01	0.00E+00	3.03E-02	2.01E+00	4.56E-01	1.15E-02	2.80E-05	3.28E+00	1.32E-02
RF-MT0827	3.96E+01	0.00E+00	1.69E+00	1.12E+02	2.52E+01	6.40E-01	1.28E-03	1.78E+02	7.18E-01
RF-MT0831	7.56E+01	0.00E+00	4.62E+00	3.02E+02	6.84E+01	1.69E+00	1.57E-02	4.51E+02	1.82E+00
RF-MT0832	4.52E+02	0.00E+00	1.67E+01	1.18E+03	2.65E+02	6.02E+00	4.61E-02	1.91E+03	7.70E+00
RF-MT0833	1.37E+02	0.00E+00	5.01E+00	3.40E+02	7.69E+01	1.81E+00	1.30E-02	5.59E+02	2.25E+00
RF-MT0855	2.36E-02	0.00E+00	2.22E-03	1.47E-01	3.33E-02	8.46E-04	1.69E-06	2.07E-01	8.33E-04
RF-MT0857	1.16E+00	0.00E+00	6.10E-02	7.34E+00	1.65E+00	1.64E-02	4.64E-05	1.02E+01	4.12E-02
RF-MT0H61	4.31E+01	0.00E+00	2.27E+00	2.72E+02	6.11E+01	6.07E-01	1.72E-03	3.78E+02	1.53E+00
RF-MT2116	4.84E+00	0.00E+00	1.80E-01	1.26E+01	2.84E+00	6.45E-02	4.94E-04	2.04E+01	8.23E-02
RF-MT3010	3.03E+01	0.00E+00	1.87E+00	1.25E+02	2.84E+01	6.92E-01	1.81E-03	1.85E+02	7.47E-01
RF-MT3011	2.26E+02	0.00E+00	1.16E+01	7.69E+02	1.75E+02	4.42E+00	1.66E-02	1.18E+03	4.76E+00
RF-MT420P	1.20E+03	0.00E+00	5.89E+01	6.33E+03	1.43E+03	1.44E+01	5.48E-02	9.02E+03	3.64E+01
RF-MT532A	3.17E+02	0.00E+00	8.32E+00	5.64E+02	1.27E+02	3.13E+00	9.05E-03	1.02E+03	4.10E+00
RF-MT532B	1.42E+03	0.00E+00	3.74E+01	2.53E+03	5.72E+02	1.41E+01	4.06E-02	4.56E+03	1.84E+01
RF-MT532C	2.85E+03	0.00E+00	7.51E+01	5.07E+03	1.14E+03	2.82E+01	8.17E-02	9.14E+03	3.69E+01

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT532D	1.81E+01	0.00E+00	4.72E-01	3.21E+01	7.24E+00	1.77E-01	5.14E-04	5.78E+01	2.33E-01
RF-TT0069	1.04E-01	0.00E+00	5.61E-03	3.72E-01	8.41E-02	2.14E-03	7.78E-05	5.65E-01	2.28E-03
RF-TT0200	4.92E+00	0.00E+00	2.26E-01	1.52E+01	3.47E+00	8.21E-02	1.73E-04	2.39E+01	9.62E-02
RF-TT0299	2.04E+01	0.00E+00	4.20E-01	2.78E+01	6.29E+00	1.59E-01	3.19E-04	5.49E+01	2.22E-01
RF-TT0300	1.66E+02	0.00E+00	1.20E+01	7.98E+02	1.81E+02	3.88E+00	1.74E-02	1.16E+03	4.67E+00
RF-TT0301	2.25E+01	0.00E+00	1.62E+00	1.09E+02	2.47E+01	5.25E-01	2.37E-03	1.57E+02	6.35E-01
RF-TT0302	1.11E+00	0.00E+00	5.89E-02	4.24E+00	9.62E-01	2.21E-02	4.44E-04	6.38E+00	2.57E-02
RF-TT0303	6.69E+00	0.00E+00	3.44E-01	2.28E+01	5.16E+00	1.31E-01	1.30E-03	3.50E+01	1.41E-01
RF-TT0310	2.28E+01	0.00E+00	1.61E+00	1.03E+02	2.40E+01	4.78E-01	1.41E-03	1.51E+02	6.09E-01
RF-TT0312	5.47E+02	0.00E+00	2.92E+01	2.24E+03	5.03E+02	1.01E+01	2.39E-02	3.32E+03	1.34E+01
RF-TT0317	3.44E-01	0.00E+00	3.17E-02	2.10E+00	4.75E-01	1.20E-02	2.41E-05	2.95E+00	1.19E-02
RF-TT0320	2.21E+02	0.00E+00	1.02E+01	6.85E+02	1.56E+02	3.69E+00	7.77E-03	1.07E+03	4.32E+00
RF-TT0330	7.86E+01	0.00E+00	3.51E+00	4.30E+02	1.05E+02	1.15E+00	2.67E-03	6.17E+02	2.49E+00
RF-TT-0331	3.91E+02	0.00E+00	1.82E+01	1.56E+03	3.47E+02	5.52E+00	7.40E-02	2.32E+03	9.36E+00
RF-TT-0334	1.70E+02	0.00E+00	1.47E+01	9.72E+02	2.20E+02	5.58E+00	1.12E-02	1.38E+03	5.55E+00
RF-TT0335	2.07E+02	0.00E+00	1.11E+01	8.27E+02	1.88E+02	3.76E+00	8.07E-02	1.23E+03	4.98E+00
RF-TT0336	1.83E+02	0.00E+00	9.24E+00	7.32E+02	1.66E+02	2.75E+00	1.01E-02	1.09E+03	4.40E+00
RF-TT0337	2.18E+02	0.00E+00	1.07E+01	9.45E+02	2.10E+02	2.84E+00	2.16E-02	1.38E+03	5.58E+00
RF-TT0338	9.24E+02	0.00E+00	3.88E+01	3.69E+03	8.20E+02	1.27E+01	3.78E-02	5.47E+03	2.21E+01
RF-TT0340	7.89E+00	0.00E+00	7.40E-01	4.90E+01	1.11E+01	2.82E-01	5.63E-04	6.88E+01	2.77E-01
RF-TT0342	5.28E+01	0.00E+00	3.70E+00	2.89E+02	6.42E+01	1.13E+00	5.92E-03	4.10E+02	1.65E+00
RF-TT0360	4.03E+00	0.00E+00	1.88E-01	1.30E+01	2.97E+00	6.70E-02	1.49E-04	2.01E+01	8.12E-02
RF-TT0368	8.05E+01	0.00E+00	3.77E+00	2.60E+02	5.95E+01	1.34E+00	2.99E-03	4.04E+02	1.63E+00
RF-TT0370	1.59E+02	0.00E+00	8.14E+00	5.79E+02	1.31E+02	2.85E+00	1.40E-02	8.77E+02	3.54E+00
RF-TT0371	3.44E+00	0.00E+00	1.64E-01	1.09E+01	2.46E+00	6.23E-02	1.38E-04	1.69E+01	6.82E-02
RF-TT0372	4.20E-01	0.00E+00	3.23E-02	2.12E+00	4.81E-01	1.08E-02	9.30E-05	3.06E+00	1.23E-02
RF-TT0374	1.31E+01	0.00E+00	7.58E-01	5.01E+01	1.13E+01	2.87E-01	6.36E-04	7.53E+01	3.04E-01
RF-TT0375A	1.36E-01	0.00E+00	1.25E-02	8.24E-01	1.86E-01	4.73E-03	9.48E-06	1.16E+00	4.67E-03
RF-TT0375B	1.36E-01	0.00E+00	1.25E-02	8.24E-01	1.86E-01	4.73E-03	9.48E-06	1.16E+00	4.67E-03

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0376	3.14E+01	0.00E+00	1.85E+00	1.51E+02	3.47E+01	6.40E-01	2.24E-03	2.19E+02	8.85E-01
RF-TT0377	1.76E+01	0.00E+00	1.01E+00	6.66E+01	1.51E+01	3.81E-01	1.29E-03	1.00E+02	4.04E-01
RF-TT0391	3.92E+00	0.00E+00	1.41E-01	1.68E+01	3.76E+00	6.66E-02	1.08E-04	2.47E+01	9.94E-02
RF-TT0392	1.38E+00	0.00E+00	8.88E-02	8.80E+00	1.98E+00	2.31E-02	6.77E-05	1.23E+01	4.94E-02
RF-TT0393	1.14E+02	0.00E+00	6.20E+00	4.09E+02	9.28E+01	2.35E+00	4.72E-03	6.22E+02	2.51E+00
RF-TT0398	2.48E+00	0.00E+00	1.64E-01	1.64E+01	3.69E+00	4.37E-02	1.25E-04	2.28E+01	9.18E-02
RF-TT0409	2.07E+00	0.00E+00	7.65E-02	8.49E+00	1.90E+00	1.68E-02	5.88E-05	1.25E+01	5.06E-02
RF-TT0412	2.07E+00	0.00E+00	7.65E-02	8.49E+00	1.90E+00	1.68E-02	5.88E-05	1.25E+01	5.06E-02
RF-TT0414	6.42E+01	0.00E+00	2.37E+00	2.63E+02	5.89E+01	5.20E-01	1.82E-03	3.89E+02	1.57E+00
RF-TT0430	1.88E-02	0.00E+00	1.77E-03	1.17E-01	2.64E-02	6.70E-04	1.34E-06	1.64E-01	6.59E-04
RF-TT0431	4.67E+00	0.00E+00	4.30E-01	2.87E+01	6.50E+00	1.59E-01	5.49E-04	4.03E+01	1.62E-01
RF-TT0438	2.78E+02	0.00E+00	1.64E+01	1.46E+03	3.29E+02	4.71E+00	1.40E-02	2.09E+03	8.42E+00
RF-TT0440	2.74E+01	0.00E+00	1.59E+00	1.44E+02	3.34E+01	5.27E-01	6.38E-03	2.07E+02	8.34E-01
RF-TT0441	1.35E+02	0.00E+00	7.47E+00	4.99E+02	1.13E+02	2.80E+00	1.03E-02	7.55E+02	3.04E+00
RF-TT0442	1.94E+01	0.00E+00	1.29E+00	9.24E+01	2.09E+01	3.65E-01	6.51E-03	1.34E+02	5.40E-01
RF-TT0443	4.16E-01	0.00E+00	3.70E-02	2.50E+00	5.65E-01	1.32E-02	4.42E-05	3.52E+00	1.42E-02
RF-TT0479	4.07E+00	0.00E+00	3.84E-01	2.53E+01	5.74E+00	1.45E-01	2.92E-04	3.55E+01	1.43E-01
RF-TT0480	2.78E+02	0.00E+00	1.55E+01	1.04E+03	2.34E+02	5.41E+00	1.94E-02	1.56E+03	6.30E+00
RF-TT0481	1.56E-01	0.00E+00	8.74E-03	5.82E-01	1.32E-01	3.04E-03	1.10E-05	8.79E-01	3.54E-03
RF-TT0483	5.02E-01	0.00E+00	4.72E-02	3.12E+00	7.07E-01	1.79E-02	1.72E-02	4.39E+00	1.77E-02
RF-TT0484	2.69E+00	0.00E+00	1.96E-01	1.30E+01	2.94E+00	7.45E-02	2.60E-04	1.88E+01	7.57E-02
RF-TT0485	2.21E-01	0.00E+00	1.21E-02	7.99E-01	1.81E-01	4.59E-03	2.87E-04	1.21E+00	4.89E-03
RF-TT0486	1.31E+00	0.00E+00	7.16E-02	4.74E+00	1.08E+00	2.71E-02	2.82E-04	7.20E+00	2.90E-02
RF-TT0487	6.56E+00	0.00E+00	2.43E-01	1.70E+01	3.85E+00	8.75E-02	6.69E-04	2.77E+01	1.12E-01
RF-TT0489	1.87E+00	0.00E+00	1.09E-01	7.23E+00	1.64E+00	4.16E-02	1.84E-04	1.09E+01	4.38E-02
RF-TT0490	1.03E+02	0.00E+00	6.94E+00	4.66E+02	1.06E+02	2.49E+00	7.07E-03	6.82E+02	2.75E+00
RF-TT0491	2.41E+00	0.00E+00	9.38E-02	6.25E+00	1.41E+00	3.46E-02	1.67E-04	1.02E+01	4.10E-02
RF-TT0492	8.08E-01	0.00E+00	5.29E-02	3.49E+00	7.91E-01	2.00E-02	4.02E-05	5.14E+00	2.07E-02
RF-TT0523A	5.44E+00	0.00E+00	2.12E-01	1.41E+01	3.19E+00	8.04E-02	1.96E-04	2.29E+01	9.23E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0523B	5.44E+00	0.00E+00	2.12E-01	1.41E+01	3.19E+00	8.04E-02	1.96E-04	2.29E+01	9.23E-02
RF-TT0523C	5.44E+00	0.00E+00	2.12E-01	1.41E+01	3.19E+00	8.04E-02	1.96E-04	2.29E+01	9.23E-02
RF-TT0523D	5.44E+00	0.00E+00	2.12E-01	1.41E+01	3.19E+00	8.04E-02	1.96E-04	2.29E+01	9.23E-02
RF-TT0523E	5.44E+00	0.00E+00	2.12E-01	1.41E+01	3.19E+00	8.04E-02	1.96E-04	2.29E+01	9.23E-02
RF-TT0532A	1.36E+02	0.00E+00	3.56E+00	2.42E+02	5.46E+01	1.35E+00	3.88E-03	4.37E+02	1.76E+00
RF-TT0532B	1.36E+02	0.00E+00	3.56E+00	2.42E+02	5.46E+01	1.35E+00	3.88E-03	4.37E+02	1.76E+00
RF-TT0541	2.25E-01	0.00E+00	2.12E-02	1.41E+00	3.18E-01	8.05E-03	1.61E-05	1.97E+00	7.94E-03
RF-TT0545	5.02E-02	0.00E+00	4.72E-03	3.12E-01	7.07E-02	1.79E-03	3.59E-06	4.37E-01	1.76E-03
RF-TT0601	1.74E+01	0.00E+00	8.14E-01	5.63E+01	1.29E+01	2.91E-01	6.47E-04	8.75E+01	3.53E-01
RF-TT0802	1.95E+03	0.00E+00	6.70E+01	4.44E+03	1.01E+03	2.54E+01	5.09E-02	7.47E+03	3.01E+01
RF-TT0809	1.60E+02	0.00E+00	5.50E+00	3.66E+02	8.24E+01	2.09E+00	4.18E-03	6.14E+02	2.48E+00
RF-TT0821	3.47E+02	0.00E+00	2.00E+01	1.44E+03	3.25E+02	6.21E+00	1.83E-01	2.13E+03	8.58E+00
RF-TT0822	3.84E+02	0.00E+00	1.55E+01	1.08E+03	2.43E+02	5.53E+00	1.94E-01	1.72E+03	6.93E+00
RF-TT0823	7.78E-01	0.00E+00	3.03E-02	2.01E+00	4.56E-01	1.15E-02	2.80E-05	3.28E+00	1.32E-02
RF-TT0824	8.00E+02	0.00E+00	4.27E+01	2.90E+03	6.56E+02	1.56E+01	9.50E-02	4.40E+03	1.77E+01
RF-TT0825	6.64E+02	0.00E+00	3.08E+01	2.18E+03	4.93E+02	1.04E+01	1.05E-01	3.37E+03	1.36E+01
RF-TT0832	4.92E+02	0.00E+00	1.83E+01	1.28E+03	2.89E+02	6.56E+00	5.02E-02	2.07E+03	8.36E+00
RF-TT0854	1.77E-01	0.00E+00	1.66E-02	1.10E+00	2.50E-01	6.32E-03	7.60E-04	1.54E+00	6.21E-03
RF-TT0886	2.51E-02	0.00E+00	2.35E-03	1.55E-01	3.53E-02	8.94E-04	1.79E-06	2.18E-01	8.80E-04
RF-TT2216	7.26E+00	0.00E+00	2.70E-01	1.89E+01	4.26E+00	9.69E-02	7.42E-04	3.07E+01	1.24E-01
RF-TT3010	3.88E+02	0.00E+00	2.39E+01	1.59E+03	3.62E+02	8.86E+00	2.32E-02	2.37E+03	9.55E+00
RF-TT3011	9.79E+02	0.00E+00	5.04E+01	3.33E+03	7.54E+02	1.91E+01	7.20E-02	5.11E+03	2.06E+01
RF-TT301U	8.14E+01	0.00E+00	5.32E+00	3.62E+02	8.32E+01	1.88E+00	4.21E-03	5.32E+02	2.14E+00
RF-TT310P	2.35E+01	0.00E+00	1.39E+00	1.22E+02	2.61E+01	3.93E-01	1.06E-03	1.73E+02	6.96E-01
RF-TT338S	6.87E-01	0.00E+00	6.35E-02	4.19E+00	9.51E-01	2.40E-02	4.82E-05	5.90E+00	2.38E-02
RF-TT390P	3.87E+00	0.00E+00	1.72E-01	2.04E+01	4.25E+00	6.00E-02	1.60E-04	2.87E+01	1.16E-01
RF-TT391P	2.14E+02	0.00E+00	7.72E+00	9.18E+02	2.04E+02	3.64E+00	5.87E-03	1.34E+03	5.42E+00
RF-TT392P	4.32E+02	0.00E+00	2.78E+01	2.75E+03	6.20E+02	7.22E+00	2.12E-02	3.83E+03	1.54E+01
RF-TT393R	6.39E+01	0.00E+00	4.72E+00	4.20E+02	9.55E+01	1.17E+00	3.77E-03	5.85E+02	2.36E+00

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT394P	7.93E+00	0.00E+00	2.92E-01	3.25E+01	6.81E+00	8.40E-02	2.29E-04	4.75E+01	1.92E-01
RF-TT395P	1.06E+01	0.00E+00	3.91E-01	4.34E+01	9.10E+00	1.12E-01	3.07E-04	6.36E+01	2.56E-01
RF-TT396P	2.65E+00	0.00E+00	9.76E-02	1.09E+01	2.28E+00	2.80E-02	7.67E-05	1.59E+01	6.41E-02
RF-TT398P	2.57E+02	0.00E+00	1.69E+01	1.70E+03	3.82E+02	4.51E+00	1.29E-02	2.36E+03	9.51E+00
RF-TT398R	2.12E+03	0.00E+00	3.14E+01	2.75E+03	6.17E+02	8.79E+00	2.39E-02	5.51E+03	2.22E+01
RF-TT411R	7.67E+01	0.00E+00	2.82E+00	3.14E+02	7.03E+01	6.21E-01	2.17E-03	4.64E+02	1.87E+00
RF-TT429R	1.61E+02	0.00E+00	6.06E-01	7.27E+01	1.60E+01	1.08E-01	4.61E-04	2.51E+02	1.01E+00
RF-TT433X	5.08E+01	0.00E+00	1.68E-01	2.09E+01	4.15E+00	4.30E-02	1.28E-04	7.60E+01	3.07E-01
RF-TT436R	3.72E+02	0.00E+00	2.43E+00	2.74E+02	6.12E+01	8.30E-01	1.85E-03	7.09E+02	2.86E+00
RF-TT454X	2.18E+01	0.00E+00	1.43E-01	1.61E+01	3.61E+00	4.89E-02	1.09E-04	4.17E+01	1.68E-01
RL-T101	1.11E+02	0.00E+00	8.67E+00	8.72E+02	1.93E+02	6.91E+00	5.72E-03	1.18E+03	4.78E+00
RL-T102	1.40E-03	0.00E+00	1.10E-04	1.12E-02	2.47E-03	8.77E-05	1.22E-06	1.51E-02	6.10E-05
RL-T103	9.94E+01	0.00E+00	1.05E+01	3.81E+02	8.38E+01	3.67E+00	6.92E-03	5.74E+02	2.32E+00
RL-T104	2.01E-03	0.00E+00	1.58E-04	1.58E-02	3.53E-03	1.26E-04	1.36E-07	2.15E-02	8.68E-05
RL-T105	7.71E-01	0.00E+00	5.96E-02	6.02E+00	1.33E+00	4.75E-02	8.40E-05	8.18E+00	3.30E-02
RL-T106	7.43E-01	0.00E+00	5.85E-02	5.88E+00	1.30E+00	4.65E-02	3.86E-05	7.98E+00	3.22E-02
RL-T107	2.04E+03	0.00E+00	3.44E+04	1.62E+04	3.59E+03	1.28E+02	2.35E+01	5.63E+04	2.27E+02
RL-T108	1.17E+00	0.00E+00	5.92E+00	9.25E+00	2.05E+00	7.31E-02	3.93E-03	1.84E+01	7.42E-02
RL-T109	1.61E+00	0.00E+00	1.22E-01	1.23E+01	2.72E+00	9.69E-02	2.34E-02	1.67E+01	6.75E-02
RL-T110	1.80E+02	0.00E+00	2.33E+01	1.41E+03	3.13E+02	1.11E+01	1.38E+00	1.92E+03	7.75E+00
RL-T112	7.28E+01	0.00E+00	9.84E+00	1.86E+02	4.13E+01	1.47E+00	7.42E-01	3.11E+02	1.25E+00
RL-T113	7.76E-02	0.00E+00	1.90E-02	6.14E-01	1.36E-01	4.85E-03	1.25E-05	8.46E-01	3.41E-03
RL-T114	1.18E+01	0.00E+00	9.27E-01	9.32E+01	2.07E+01	7.38E-01	6.11E-04	1.27E+02	5.11E-01
RL-T115	3.01E+02	0.00E+00	3.00E+01	1.23E+03	2.72E+02	1.09E+01	4.33E-01	1.83E+03	7.37E+00
RL-T116	1.94E+01	0.00E+00	1.52E+00	1.52E+02	3.39E+01	1.21E+00	5.72E-02	2.07E+02	8.36E-01
RL-T118	4.98E+01	0.00E+00	1.22E+01	1.51E+02	3.36E+01	1.20E+00	8.41E-01	2.48E+02	1.00E+00
RL-T120	1.21E+01	0.00E+00	1.28E+00	4.48E+01	9.86E+00	4.21E-01	8.42E-04	6.80E+01	2.74E-01
RL-T122	6.85E-01	0.00E+00	5.39E-02	5.40E+00	1.20E+00	4.28E-02	1.46E+00	8.80E+00	3.55E-02
RL-T123	2.02E+00	0.00E+00	1.58E-01	1.58E+01	3.53E+00	1.26E-01	5.98E-02	2.16E+01	8.71E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T125	4.01E+02	0.00E+00	3.91E+01	3.32E+02	1.70E+02	1.97E+01	2.58E-02	9.42E+02	3.80E+00
RL-T127	3.87E+02	0.00E+00	9.84E+00	9.91E+02	2.20E+02	7.83E+00	8.65E-02	1.61E+03	6.48E+00
RL-T128	5.73E-01	0.00E+00	2.39E-07	2.41E-05	5.34E-06	1.90E-07	1.58E-10	5.73E-01	2.31E-03
RL-T129	1.71E+00	0.00E+00	4.55E+01	1.37E+01	3.01E+00	1.07E-01	3.77E-02	6.39E+01	2.58E-01
RL-T130	3.65E-03	0.00E+00	2.87E-04	2.90E-02	6.42E-03	2.28E-04	8.32E-05	3.94E-02	1.59E-04
RL-T131	1.48E+00	0.00E+00	1.57E-01	5.52E+00	1.21E+00	5.15E-02	8.33E-03	8.38E+00	3.38E-02
RL-T132	3.53E+02	0.00E+00	2.77E+01	2.80E+03	6.20E+02	2.21E+01	2.63E-01	3.80E+03	1.53E+01
RL-T133	7.20E-03	0.00E+00	4.44E-04	4.59E-02	1.02E-02	3.13E-04	2.93E-07	6.37E-02	2.57E-04
RL-T134	1.52E-02	0.00E+00	1.20E-03	1.21E-01	2.66E-02	9.52E-04	7.88E-07	1.64E-01	6.60E-04
RL-T135	7.12E-02	0.00E+00	5.61E-03	5.64E-01	1.25E-01	4.45E-03	4.15E-03	7.70E-01	3.11E-03
RL-T137	1.16E+03	0.00E+00	1.22E+02	4.29E+03	9.47E+02	4.05E+01	8.68E-02	6.52E+03	2.63E+01
RL-T140	1.36E+03	0.00E+00	1.16E+02	4.15E+03	1.02E+03	3.44E+01	2.63E+01	6.67E+03	2.69E+01
RL-T143	8.49E+00	0.00E+00	6.66E-01	6.71E+01	1.49E+01	5.31E-01	3.90E-02	9.12E+01	3.68E-01
RL-T145	2.42E+01	0.00E+00	1.90E+00	1.91E+02	4.23E+01	1.51E+00	9.08E-02	2.60E+02	1.05E+00
RL-W407	6.95E+01	0.00E+00	4.05E+00	4.38E+02	9.72E+01	2.30E+00	2.67E-03	6.09E+02	2.46E+00
RL-W408	2.85E-04	0.00E+00	1.71E-05	1.77E-03	3.94E-04	1.18E-05	1.13E-08	2.47E-03	9.95E-06
RL-W415	6.29E-03	0.00E+00	3.77E-04	3.93E-02	8.70E-03	2.61E-04	2.49E-07	5.46E-02	2.20E-04
RL-W418	2.69E-02	0.00E+00	1.59E-03	1.68E-01	3.74E-02	9.74E-04	1.05E-06	2.34E-01	9.45E-04
RL-W437	2.28E+02	0.00E+00	1.33E+01	1.44E+03	3.19E+02	7.53E+00	8.78E-03	1.99E+03	8.04E+00
RL-W438	3.99E-04	0.00E+00	2.39E-05	2.48E-03	5.49E-04	1.65E-05	1.58E-08	3.45E-03	1.39E-05
RL-W439	1.25E+04	0.00E+00	1.32E+03	4.78E+04	1.06E+04	4.61E+02	8.69E-01	7.22E+04	2.91E+02
RL-W443	2.01E+02	0.00E+00	1.17E+01	1.27E+03	2.80E+02	6.63E+00	7.74E-03	1.76E+03	7.09E+00
RL-W444	1.49E+02	0.00E+00	8.71E+00	9.38E+02	2.08E+02	4.92E+00	5.74E-03	1.30E+03	5.26E+00
RL-W447	1.71E-02	0.00E+00	1.03E-03	1.06E-01	2.36E-02	7.08E-04	6.76E-07	1.47E-01	5.94E-04
RL-W448	1.26E-04	0.00E+00	7.58E-06	7.84E-04	1.74E-04	5.24E-06	5.00E-09	1.09E-03	4.40E-06
RL-W449	1.04E+00	0.00E+00	2.77E-04	2.24E-02	4.97E-03	9.50E-05	1.83E-07	1.07E+00	4.29E-03
RL-W450	1.90E-03	0.00E+00	1.14E-04	1.19E-02	2.62E-03	7.90E-05	7.53E-08	1.65E-02	6.65E-05
RL-W451	2.72E-04	0.00E+00	1.63E-05	1.68E-03	3.74E-04	1.13E-05	1.07E-08	2.35E-03	9.46E-06
RL-W452	1.18E-02	0.00E+00	7.02E-04	7.42E-02	1.65E-02	4.28E-04	4.62E-07	1.03E-01	4.16E-04

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W453	3.37E-03	0.00E+00	1.97E-04	2.13E-02	4.71E-03	1.12E-04	1.30E-07	2.96E-02	1.19E-04
RL-W454	4.71E-02	0.00E+00	2.76E-03	2.98E-01	6.60E-02	1.56E-03	1.82E-06	4.14E-01	1.67E-03
RL-W455	1.26E-02	0.00E+00	7.44E-04	7.88E-02	1.75E-02	4.56E-04	4.90E-07	1.10E-01	4.42E-04
RL-W456	1.66E+00	0.00E+00	9.73E-02	1.05E+01	2.32E+00	5.62E-02	6.41E-05	1.45E+01	5.86E-02
RL-W457	1.61E-01	0.00E+00	9.45E-03	1.02E+00	2.25E-01	5.45E-03	6.23E-06	1.41E+00	5.69E-03
RL-W458	5.09E-01	0.00E+00	4.83E-02	4.17E-01	2.31E-01	2.19E-02	3.18E-05	1.21E+00	4.86E-03
RL-W459	4.90E+00	0.00E+00	4.97E-01	1.04E+01	3.15E+00	2.18E-01	3.28E-04	1.89E+01	7.62E-02
RL-W460	2.99E-02	0.00E+00	1.75E-03	1.88E-01	4.18E-02	9.88E-04	1.15E-06	2.62E-01	1.06E-03
RL-W461	2.76E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.76E-02	1.11E-04
RL-W462	8.52E-03	0.00E+00	5.08E-04	5.33E-02	1.18E-02	3.24E-04	3.35E-07	7.42E-02	2.99E-04
RL-W463	4.38E-02	0.00E+00	2.57E-03	2.77E-01	6.13E-02	1.45E-03	1.69E-06	3.85E-01	1.55E-03
RL-W464	2.02E-02	0.00E+00	1.18E-03	1.28E-01	2.82E-02	6.68E-04	7.78E-07	1.77E-01	7.14E-04
RL-W465	1.35E-01	0.00E+00	8.00E-03	8.49E-01	1.88E-01	4.84E-03	5.27E-06	1.18E+00	4.76E-03
RL-W466	1.85E+00	0.00E+00	1.09E-01	1.17E+01	2.58E+00	6.44E-02	7.18E-05	1.62E+01	6.53E-02
RL-W467	9.47E-02	0.00E+00	5.61E-03	5.94E-01	1.31E-01	3.53E-03	3.69E-06	8.25E-01	3.33E-03
RL-W468	4.85E-04	0.00E+00	2.89E-05	3.04E-03	6.74E-04	1.84E-05	1.90E-08	4.23E-03	1.70E-05
RL-W469	1.97E-01	0.00E+00	1.16E-02	1.24E+00	2.75E-01	6.79E-03	7.64E-06	1.72E+00	6.93E-03
RL-W470	5.57E+00	0.00E+00	5.39E-01	4.58E+00	2.35E+00	2.73E-01	3.55E-04	1.30E+01	5.26E-02
RL-W474	2.11E-01	0.00E+00	5.96E-02	1.05E-02	8.88E-03	0.00E+00	3.93E-05	2.90E-01	1.17E-03
RL-W476	3.56E-01	0.00E+00	2.14E-02	2.29E+00	5.10E-01	1.23E-02	1.41E-05	3.18E+00	1.28E-02
RL-W480	5.80E-02	0.00E+00	3.43E-03	3.64E-01	8.08E-02	2.11E-03	2.26E-06	5.06E-01	2.04E-03
RL-W481	9.12E-02	0.00E+00	5.39E-03	5.71E-01	1.26E-01	3.31E-03	3.55E-06	7.94E-01	3.20E-03
RL-W482	1.21E+02	0.00E+00	1.79E+00	7.26E-02	1.34E-01	4.38E+00	1.18E-03	1.23E+02	4.96E-01
RL-W483	9.04E+00	0.00E+00	1.39E-01	4.70E-03	9.53E-03	3.27E-01	9.18E-05	9.19E+00	3.71E-02
RL-W484	3.83E-02	0.00E+00	1.12E-03	6.57E-02	1.56E-02	2.71E-04	7.39E-07	1.21E-01	4.86E-04
RL-W485	2.24E-03	0.00E+00	1.59E-04	7.10E-03	1.69E-03	0.00E+00	1.05E-07	1.12E-02	4.51E-05
RL-W486	9.47E-04	0.00E+00	6.70E-05	3.00E-03	7.09E-04	0.00E+00	4.41E-08	4.72E-03	1.90E-05
RL-W487	1.55E-01	0.00E+00	8.60E-03	4.29E-01	1.17E-01	2.52E-03	5.67E-06	7.10E-01	2.86E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W489	9.38E-02	0.00E+00	8.11E-03	5.56E-01	1.25E-01	4.07E-03	5.34E-06	7.83E-01	3.16E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	3.48E-02	0.00E+00	6.84E-03	5.83E-02	1.27E-02	1.48E-03	4.51E-06	1.13E-01	4.54E-04
RL-W492	2.01E-03	0.00E+00	1.69E-04	1.17E-02	2.61E-03	8.51E-05	1.11E-07	1.65E-02	6.63E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.96E+01	0.00E+00	9.76E+00	2.94E-01	2.50E-01	3.41E+00	6.44E-03	8.99E+01	3.63E-01
RL-W495	1.44E+00	0.00E+00	2.65E-02	2.82E-03	2.23E-03	6.21E-02	1.75E-05	1.47E+00	5.94E-03
RL-W496	9.36E+00	0.00E+00	3.06E-01	9.27E-03	7.39E-03	4.02E-01	2.01E-04	9.68E+00	3.90E-02
RL-W497	3.90E-01	0.00E+00	6.03E-02	5.56E-01	2.51E-01	1.05E-02	3.97E-05	1.26E+00	5.07E-03
RL-W498	1.51E+00	0.00E+00	8.95E-02	9.50E+00	2.11E+00	5.48E-02	5.90E-05	1.32E+01	5.33E-02
RL-W499	1.36E-05	0.00E+00	8.04E-07	8.52E-05	1.89E-05	4.92E-07	5.30E-10	1.19E-04	4.78E-07
RL-W500	9.67E-04	0.00E+00	9.98E-05	3.48E-03	7.67E-04	3.46E-05	6.58E-08	5.31E-03	2.14E-05
RL-W501	4.01E+01	0.00E+00	2.22E+00	1.12E+02	3.04E+01	6.54E-01	1.47E-03	1.84E+02	7.43E-01
RL-W502	7.25E-03	0.00E+00	4.30E-04	4.54E-02	1.01E-02	2.63E-04	2.83E-07	6.32E-02	2.55E-04
RL-W503	4.19E-01	0.00E+00	4.41E-02	1.60E+00	3.53E-01	1.55E-02	2.90E-05	2.42E+00	9.76E-03
RL-W504	1.55E-01	0.00E+00	8.60E-03	4.29E-01	1.17E-01	2.52E-03	5.67E-06	7.10E-01	2.86E-03
RL-W505	7.27E-03	0.00E+00	4.51E-04	4.64E-02	1.03E-02	3.17E-04	2.97E-07	6.44E-02	2.60E-04
RL-W506	2.63E-03	0.00E+00	1.77E-04	1.52E-02	3.38E-03	9.48E-05	1.17E-07	2.14E-02	8.64E-05
RL-W507	2.62E-04	0.00E+00	1.55E-05	1.64E-03	3.64E-04	9.50E-06	1.02E-08	2.29E-03	9.21E-06
RL-W508	4.81E+00	0.00E+00	5.08E-01	1.78E+01	3.94E+00	1.68E-01	3.35E-04	2.71E+01	1.09E-01
RL-W509	4.74E+01	0.00E+00	4.05E+00	1.45E+02	3.54E+01	1.21E+00	2.67E-03	2.32E+02	9.37E-01
RL-W510	4.00E+00	0.00E+00	4.16E-01	1.44E+01	3.19E+00	1.44E-01	2.74E-04	2.20E+01	8.89E-02
RL-W511	4.07E+02	0.00E+00	2.01E+01	1.93E+03	4.20E+02	7.83E+00	1.36E-02	2.78E+03	1.12E+01
RL-W512	3.56E+02	0.00E+00	1.35E+01	1.17E+03	2.88E+02	4.00E+00	8.92E-03	1.82E+03	7.35E+00
RL-W513	3.80E+04	0.00E+00	5.50E+03	1.90E+04	9.39E+03	6.35E+02	3.62E+00	7.19E+04	2.90E+02
RL-W514	1.07E-03	0.00E+00	6.31E-05	6.74E-03	1.50E-03	3.71E-05	4.16E-08	9.38E-03	3.78E-05
RL-W515	4.19E-02	0.00E+00	2.48E-03	2.63E-01	5.82E-02	1.52E-03	1.63E-06	3.66E-01	1.47E-03
RL-W516	5.81E-02	0.00E+00	3.44E-03	3.64E-01	8.08E-02	2.11E-03	2.27E-06	5.06E-01	2.04E-03
RL-W517	5.18E-10	0.00E+00	3.07E-11	3.24E-09	7.17E-10	1.97E-11	2.03E-14	4.50E-09	1.82E-11

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W518	1.46E+00	0.00E+00	1.29E-01	4.64E+00	1.11E+00	4.23E-02	8.53E-05	7.35E+00	2.96E-02
RL-W519	2.61E-01	0.00E+00	1.53E-02	1.64E+00	3.64E-01	8.92E-03	1.01E-05	2.28E+00	9.21E-03
RL-W520	2.88E-02	0.00E+00	1.73E-03	1.80E-01	3.99E-02	1.15E-03	1.14E-06	2.51E-01	1.01E-03
RL-W521	5.37E-04	0.00E+00	3.17E-05	3.36E-03	7.46E-04	1.95E-05	2.09E-08	4.67E-03	1.88E-05
RL-W522	1.12E+01	0.00E+00	1.18E+00	2.22E+01	6.32E+00	2.82E-01	7.76E-04	4.09E+01	1.65E-01
RL-W523	3.37E+00	0.00E+00	4.48E-01	1.47E+00	8.90E-01	5.58E-02	2.95E-04	6.18E+00	2.49E-02
RL-W524	1.40E+01	0.00E+00	1.71E+00	1.36E+01	5.22E+00	2.66E-01	1.13E-03	3.45E+01	1.39E-01
RL-W525	1.11E+00	0.00E+00	1.16E-01	1.60E+00	5.28E-01	2.09E-02	7.64E-05	3.36E+00	1.35E-02
RL-W526	4.20E+00	0.00E+00	4.20E-01	1.71E+01	3.81E+00	1.52E-01	2.77E-04	2.56E+01	1.03E-01
RL-W527	4.60E-01	0.00E+00	6.06E-02	1.81E+00	4.28E-01	1.77E-02	4.00E-05	2.76E+00	1.11E-02
RL-W528	2.06E+02	0.00E+00	2.58E+01	5.78E+01	5.50E+01	2.71E+00	1.70E-02	3.45E+02	1.39E+00
RL-W529	1.72E-01	0.00E+00	1.81E-02	6.38E-01	1.40E-01	5.98E-03	1.19E-05	9.67E-01	3.90E-03
RL-W530	2.02E+00	0.00E+00	2.10E-01	7.28E+00	1.61E+00	7.27E-02	1.39E-04	1.11E+01	4.48E-02
RL-W531	1.21E+02	0.00E+00	2.11E+01	3.15E+01	2.26E+01	1.93E+00	1.39E-02	1.96E+02	7.90E-01
RL-W532	3.87E-01	0.00E+00	2.29E-02	2.43E+00	5.38E-01	1.40E-02	1.51E-05	3.38E+00	1.36E-02
RL-W533	1.87E-01	0.00E+00	1.98E-02	6.95E-01	1.53E-01	6.49E-03	1.30E-05	1.06E+00	4.26E-03
RL-W534	1.08E-05	0.00E+00	6.38E-07	6.78E-05	1.51E-05	3.91E-07	4.21E-10	9.44E-05	3.81E-07
RL-W535	5.66E+01	0.00E+00	6.31E+00	8.70E+01	2.64E+01	1.19E+00	4.16E-03	1.76E+02	7.11E-01
RL-W536	1.11E+00	0.00E+00	8.50E-02	3.02E+00	6.80E-01	2.73E-02	5.92E-05	4.89E+00	1.97E-02
RL-W537	3.78E+01	0.00E+00	1.92E+00	1.85E+02	4.04E+01	7.64E-01	1.29E-03	2.65E+02	1.07E+00
RL-W538	1.37E-04	0.00E+00	8.11E-06	8.62E-04	1.91E-04	4.98E-06	5.34E-09	1.20E-03	4.83E-06
RL-W539	1.52E-02	0.00E+00	9.13E-04	9.52E-02	2.11E-02	6.05E-04	6.02E-07	1.33E-01	5.34E-04
RL-W540	2.97E+01	0.00E+00	4.02E+00	3.43E+01	1.17E+01	5.81E-01	2.65E-03	7.97E+01	3.21E-01
RL-W541	4.41E-02	0.00E+00	2.63E-03	2.76E-01	6.11E-02	1.71E-03	1.74E-06	3.84E-01	1.55E-03
RL-W542	2.05E+00	0.00E+00	1.96E-01	6.98E+00	1.61E+00	6.99E-02	1.29E-04	1.08E+01	4.37E-02
RL-W543	6.45E-03	0.00E+00	3.81E-04	4.05E-02	8.97E-03	2.35E-04	2.51E-07	5.63E-02	2.27E-04
RL-W544	1.45E-01	0.00E+00	1.55E-02	4.60E-01	1.14E-01	4.66E-03	1.03E-05	7.36E-01	2.97E-03
RL-W545	3.86E-02	0.00E+00	2.28E-03	2.42E-01	5.37E-02	1.40E-03	1.51E-06	3.37E-01	1.36E-03
RL-W546	1.69E-03	0.00E+00	1.00E-04	1.07E-02	2.36E-03	6.12E-05	6.60E-08	1.48E-02	5.97E-05

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W547	4.33E-05	0.00E+00	2.56E-06	2.71E-04	6.02E-05	1.57E-06	1.69E-09	3.77E-04	1.52E-06
RL-W548	3.74E-05	0.00E+00	2.22E-06	2.34E-04	5.20E-05	1.40E-06	1.46E-09	3.26E-04	1.31E-06
RL-W549	7.44E+00	0.00E+00	8.92E-01	1.21E+01	3.57E+00	1.77E-01	5.88E-04	2.40E+01	9.66E-02
RL-W550	3.37E+01	0.00E+00	1.69E+00	1.63E+02	3.57E+01	6.70E-01	1.13E-03	2.35E+02	9.45E-01
RL-W551	5.99E+01	0.00E+00	2.50E+00	1.84E+02	4.65E+01	7.12E-01	1.65E-03	2.93E+02	1.18E+00
RL-W552	2.32E-02	0.00E+00	1.38E-03	1.45E-01	3.22E-02	8.89E-04	9.11E-07	2.02E-01	8.15E-04
RL-W553	2.06E-03	0.00E+00	1.30E-04	1.30E-02	2.87E-03	1.12E-04	8.60E-08	1.80E-02	7.26E-05
RL-W554	3.27E-02	0.00E+00	1.94E-03	2.05E-01	4.56E-02	1.19E-03	1.28E-06	2.85E-01	1.15E-03
RL-W555	1.51E-02	0.00E+00	8.92E-04	9.45E-02	2.09E-02	5.46E-04	5.88E-07	1.31E-01	5.30E-04
RL-W563	2.16E-01	0.00E+00	2.23E-02	7.84E-01	1.73E-01	7.45E-03	1.47E-05	1.20E+00	4.82E-03
RL-W564	1.41E-01	0.00E+00	1.48E-02	5.07E-01	1.11E-01	5.72E-03	9.76E-06	7.74E-01	3.12E-03
RL-W565	1.40E-02	0.00E+00	8.32E-04	8.76E-02	1.94E-02	5.31E-04	5.48E-07	1.22E-01	4.91E-04
RL-W566	2.05E-01	0.00E+00	1.22E-02	1.29E+00	2.86E-01	7.55E-03	8.04E-06	1.79E+00	7.21E-03
RL-W567	1.42E+01	0.00E+00	3.12E-01	3.96E-02	3.18E-02	6.40E-01	2.05E-04	1.46E+01	5.89E-02
RL-W568	2.73E+02	0.00E+00	6.56E+00	1.87E+00	1.48E+00	1.32E+01	4.32E-03	2.83E+02	1.14E+00
RL-W569	2.25E-01	0.00E+00	4.94E-03	6.25E-04	5.03E-05	1.01E-02	3.25E-06	2.31E-01	9.29E-04
RL-W570	1.44E-02	0.00E+00	8.64E-04	9.29E-02	2.05E-02	4.99E-04	5.69E-07	1.29E-01	5.19E-04
RL-W571	4.62E+01	0.00E+00	2.93E+00	7.53E+00	3.75E+00	2.02E+00	1.93E-03	6.04E+01	2.44E-01
RL-W572	4.01E-02	0.00E+00	8.78E-04	4.06E-03	8.97E-05	1.81E-03	5.79E-07	4.51E-02	1.82E-04
RL-W573	5.16E+02	0.00E+00	1.12E+01	2.22E+00	1.66E+00	2.30E+01	7.41E-03	5.31E+02	2.14E+00
RL-W574	2.22E+03	0.00E+00	4.86E+01	8.49E+00	6.13E+00	1.00E+02	3.21E-02	2.28E+03	9.21E+00
RL-W575	1.45E+04	0.00E+00	3.28E+02	8.12E+01	4.90E+01	6.28E+02	2.16E-01	1.49E+04	6.01E+01
RL-W576	1.04E+03	0.00E+00	2.29E+01	4.13E+00	2.96E+00	4.71E+01	1.51E-02	1.07E+03	4.32E+00
RL-W579	8.84E-02	0.00E+00	6.03E-04	2.07E-02	4.61E-03	1.66E-04	3.97E-07	1.14E-01	4.61E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.65E-01	2.68E-02	0.00E+00	0.00E+00	1.92E-01	7.75E-04
RL-W581	9.39E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.39E-01	3.79E-03
RL-W582	6.14E-03	0.00E+00	5.11E-04	5.30E-03	2.73E-03	2.70E-05	3.37E-07	1.47E-02	5.92E-05
RL-W583	4.74E-03	0.00E+00	2.78E-04	2.99E-02	6.64E-03	1.57E-04	1.83E-07	4.15E-02	1.68E-04
RL-W584	9.43E-02	0.00E+00	1.82E-02	1.74E-01	8.50E-02	7.88E-04	1.20E-05	3.72E-01	1.50E-03

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W585	5.60E-01	0.00E+00	9.69E-02	1.02E+00	5.17E-01	2.40E-02	6.39E-05	2.19E+00	8.83E-03
RL-W586	7.48E-05	0.00E+00	4.37E-06	4.72E-04	1.05E-04	2.47E-06	2.88E-09	6.56E-04	2.65E-06
RL-W587	1.60E-03	0.00E+00	9.45E-05	1.01E-02	2.24E-03	5.55E-05	6.23E-08	1.40E-02	5.64E-05
RL-W588	6.61E-02	0.00E+00	1.54E-02	1.47E-01	7.16E-02	6.63E-04	1.01E-05	3.01E-01	1.21E-03
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	2.03E+00	0.00E+00	3.28E-01	1.14E-02	2.01E-02	8.70E-02	2.16E-04	2.39E+00	9.63E-03
RL-W591	1.16E+01	0.00E+00	3.70E-01	1.41E-02	2.60E-02	5.25E-01	2.44E-04	1.20E+01	4.82E-02
RL-W592	5.10E+01	0.00E+00	4.05E+00	6.52E-01	8.42E-01	2.12E+00	2.67E-03	5.66E+01	2.28E-01
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.35E-02	3.95E-02	0.00E+00	0.00E+00	6.31E-02	2.54E-04
RL-W594	4.60E+01	0.00E+00	7.30E-01	2.91E-02	5.35E-02	5.31E-01	4.81E-04	4.69E+01	1.89E-01
RL-W595	1.21E-01	0.00E+00	7.61E-02	1.99E-02	3.89E-02	5.25E-03	5.02E-05	2.56E-01	1.03E-03
RL-W596	3.93E-02	0.00E+00	5.92E-03	2.05E-04	3.65E-04	1.58E-03	3.90E-06	4.58E-02	1.85E-04
RL-W597	7.23E+01	0.00E+00	2.61E+00	3.98E-01	6.62E-01	2.94E+00	1.72E-03	7.59E+01	3.06E-01
RL-W598	7.65E+01	0.00E+00	1.54E+01	5.54E-01	8.25E-01	3.04E+00	1.01E-02	9.32E+01	3.76E-01
RL-W599	3.87E+00	0.00E+00	1.24E-01	4.68E-03	8.70E-03	1.76E-01	8.18E-05	4.01E+00	1.62E-02
RL-W600	2.20E-07	0.00E+00	1.29E-08	1.39E-06	3.08E-07	7.27E-09	8.48E-12	1.93E-06	7.76E-09
RL-W601	1.12E-03	0.00E+00	7.05E-05	7.01E-03	1.56E-03	6.09E-05	4.65E-08	9.76E-03	3.93E-05
RL-W602	9.71E-01	0.00E+00	5.78E-02	6.08E+00	1.35E+00	3.69E-02	3.81E-05	8.46E+00	3.41E-02
RL-W603	5.60E+00	0.00E+00	3.34E-01	3.51E+01	7.78E+00	2.12E-01	2.20E-04	4.88E+01	1.97E-01
RL-W604	1.31E-02	0.00E+00	8.74E-04	1.70E-02	8.38E-03	2.52E-04	5.76E-07	3.94E-02	1.59E-04
RL-W605	3.00E-03	0.00E+00	1.90E-04	1.88E-02	4.18E-03	1.64E-04	1.25E-07	2.62E-02	1.06E-04
RL-W606	1.21E-03	0.00E+00	7.65E-05	7.59E-03	1.69E-03	6.61E-05	5.04E-08	1.06E-02	4.26E-05
RL-W607	2.22E-03	0.00E+00	1.48E-04	2.88E-03	1.42E-03	4.26E-05	9.76E-08	6.67E-03	2.69E-05
RL-W608	2.65E-02	0.00E+00	5.75E-03	3.75E-03	4.61E-03	6.54E-04	3.79E-06	4.06E-02	1.64E-04
RL-W610	5.25E+00	0.00E+00	3.07E-01	3.31E+01	7.34E+00	1.74E-01	2.03E-04	4.60E+01	1.85E-01
RL-W612	1.24E-02	0.00E+00	7.44E-04	8.03E-02	1.79E-02	4.11E-04	4.90E-07	1.11E-01	4.49E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.37E-01	0.00E+00	0.00E+00	0.00E+00	3.37E-01	1.36E-03
RL-W622	2.07E-04	0.00E+00	1.21E-05	1.31E-03	2.89E-04	6.84E-06	7.99E-09	1.81E-03	7.31E-06
RL-W625	7.19E-03	0.00E+00	1.84E-03	6.67E-03	6.53E-03	3.71E-04	1.22E-06	2.22E-02	8.96E-05

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W626	3.87E-01	0.00E+00	4.20E-02	2.61E-01	1.56E-01	6.47E-03	2.77E-05	8.46E-01	3.41E-03
RL-W627	1.82E-03	0.00E+00	5.61E-05	1.24E-06	0.00E+00	7.69E-05	3.69E-08	1.88E-03	7.57E-06
RL-W628	5.97E-04	0.00E+00	3.52E-05	3.77E-03	8.34E-04	2.07E-05	2.32E-08	5.23E-03	2.11E-05
RL-W629	4.04E-05	0.00E+00	2.42E-06	2.53E-04	5.60E-05	1.61E-06	1.60E-09	3.52E-04	1.42E-06
RL-W630	4.45E-01	0.00E+00	4.51E-02	2.93E+00	6.76E-01	1.74E-02	2.97E-05	4.09E+00	1.65E-02
RL-W631	7.17E-03	0.00E+00	4.55E-04	4.49E-02	9.96E-03	3.91E-04	3.00E-07	6.25E-02	2.52E-04
RL-W632	3.17E+00	0.00E+00	6.13E-02	5.94E+00	1.94E+00	1.30E-01	4.04E-05	1.11E+01	4.48E-02
RL-W633	7.56E-03	0.00E+00	3.56E-04	9.32E-04	8.20E-04	1.60E-04	2.35E-07	9.67E-03	3.90E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	1.02E-02	0.00E+00	0.00E+00	0.00E+00	1.02E-02	4.10E-05
RL-W635	4.51E+01	0.00E+00	1.20E+01	4.32E+00	6.44E+00	1.62E+00	7.92E-03	6.79E+01	2.74E-01
RL-W636	4.61E-01	0.00E+00	2.27E-02	5.65E-02	4.98E-02	9.83E-03	1.50E-05	5.90E-01	2.38E-03
RL-W637	1.10E-03	0.00E+00	5.78E-04	6.36E-04	6.21E-04	3.53E-05	3.81E-07	2.93E-03	1.18E-05
RL-W638	4.82E-02	0.00E+00	5.89E-03	6.23E-03	5.84E-03	1.32E-03	3.88E-06	6.61E-02	2.67E-04
RL-W639	2.54E-03	0.00E+00	1.51E-04	1.59E-02	3.53E-03	9.20E-05	9.92E-08	2.22E-02	8.94E-05
RL-W640	8.53E-02	0.00E+00	5.01E-03	5.37E-01	1.19E-01	2.96E-03	3.30E-06	7.47E-01	3.01E-03
RL-W641	2.61E+00	0.00E+00	1.10E+00	2.58E+00	1.06E+00	4.75E-02	7.25E-04	7.34E+00	2.96E-02
RL-W642	5.09E-02	0.00E+00	1.14E-04	3.15E-02	1.60E-04	2.05E-05	7.53E-08	8.27E-02	3.33E-04
RL-W643	8.02E-01	0.00E+00	3.39E-01	7.95E-01	3.25E-01	1.46E-02	2.23E-04	2.26E+00	9.12E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.47E-02	0.00E+00	0.00E+00	0.00E+00	5.47E-02	2.21E-04
RL-W645	1.95E-02	0.00E+00	1.52E-03	1.08E-01	2.52E-02	7.99E-04	1.00E-06	1.54E-01	6.20E-04
RL-W646	1.77E-02	0.00E+00	1.36E-03	2.57E-02	1.24E-02	3.88E-04	8.97E-07	5.72E-02	2.31E-04
RL-W647	4.98E-02	0.00E+00	2.03E-01	1.10E-01	1.73E-02	1.30E-03	1.34E-04	3.80E-01	1.53E-03
RL-W648	8.82E-04	0.00E+00	3.48E-04	5.99E-05	1.17E-04	4.16E-05	2.29E-07	1.41E-03	5.67E-06
RL-W649	3.24E-03	0.00E+00	1.28E-03	2.20E-04	4.31E-04	1.53E-04	8.43E-07	5.17E-03	2.09E-05
RL-W653	1.54E-04	0.00E+00	9.17E-06	9.62E-04	2.13E-04	5.83E-06	6.04E-09	1.34E-03	5.40E-06
RL-W654	8.45E-04	0.00E+00	5.01E-05	5.30E-03	1.17E-03	3.06E-05	3.30E-08	7.37E-03	2.97E-05
RL-W655	2.08E+02	0.00E+00	1.18E+01	2.10E-01	4.94E-01	8.18E+00	7.81E-03	2.21E+02	8.90E-01
RL-W656	8.71E+02	0.00E+00	5.32E+00	4.94E-01	5.08E-01	3.90E+01	3.51E-03	8.77E+02	3.54E+00
RL-W657	4.45E+02	0.00E+00	7.86E+00	2.43E-01	4.83E-01	1.72E+01	5.18E-03	4.54E+02	1.83E+00

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W659	5.38E+01	0.00E+00	1.77E+00	4.68E-02	5.79E-02	1.95E+00	1.17E-03	5.57E+01	2.25E-01
RL-W660	2.95E+02	0.00E+00	2.13E+01	8.64E-01	1.54E+00	1.11E+01	1.41E-02	3.19E+02	1.29E+00
RL-W661	3.12E+00	0.00E+00	2.67E-02	4.16E-04	3.78E-03	1.35E-01	1.76E-05	3.15E+00	1.27E-02
RL-W662	9.83E-02	0.00E+00	1.59E-03	1.07E-04	1.90E-04	2.77E-03	1.05E-06	1.00E-01	4.04E-04
RL-W665	1.21E+03	0.00E+00	1.27E+02	1.31E+00	1.75E+00	5.50E+01	8.39E-02	1.34E+03	5.39E+00
RL-W666	2.16E+01	0.00E+00	3.12E-01	5.47E-02	5.74E-02	7.95E-01	2.05E-04	2.20E+01	8.89E-02
RL-W668	2.06E+00	0.00E+00	9.80E-03	1.44E-01	4.08E-02	1.88E-03	6.46E-06	2.26E+00	9.10E-03
RL-W669	6.01E-01	0.00E+00	2.54E-01	5.96E-01	2.44E-01	1.10E-02	1.68E-04	1.70E+00	6.83E-03
RL-W670	3.80E-02	0.00E+00	1.81E-04	2.67E-03	7.55E-04	3.48E-05	1.19E-07	4.16E-02	1.68E-04
RL-W671	6.20E+00	0.00E+00	9.27E-02	4.89E-03	5.07E-03	1.14E-01	6.11E-05	6.30E+00	2.54E-02
RL-W672	4.21E+01	0.00E+00	6.31E-01	3.34E-02	3.44E-02	7.76E-01	4.16E-04	4.28E+01	1.73E-01
RL-W673	4.06E+01	0.00E+00	6.06E-01	3.23E-02	3.32E-02	7.48E-01	4.00E-04	4.13E+01	1.67E-01
RL-W674	1.36E-01	0.00E+00	2.71E-02	1.12E+01	9.66E-02	5.22E-03	1.79E-05	1.14E+01	4.60E-02
RL-W675	5.09E-01	0.00E+00	1.50E-01	1.31E-01	1.12E-01	1.27E-02	9.87E-05	9.02E-01	3.64E-03
RL-W676	1.96E-02	0.00E+00	8.99E-04	1.46E-01	2.12E-03	3.78E-04	5.92E-07	1.69E-01	6.82E-04
RL-W677	4.53E+01	0.00E+00	2.23E+00	5.72E+00	4.95E+00	9.10E-01	1.47E-03	5.82E+01	2.35E-01
RL-W678	1.43E-01	0.00E+00	1.86E-02	5.14E-02	4.52E-02	7.13E-03	1.23E-05	2.58E-01	1.04E-03
RL-W679	8.98E-01	0.00E+00	4.16E-02	1.11E-01	9.72E-02	1.83E-02	2.74E-05	1.15E+00	4.63E-03
RL-W680	2.02E-04	0.00E+00	5.85E-05	1.73E-05	3.11E-05	7.85E-06	3.86E-08	3.09E-04	1.25E-06
RL-W681	1.23E-04	0.00E+00	2.37E-05	4.65E-04	2.31E-04	6.52E-06	1.56E-08	8.43E-04	3.40E-06
RL-W685	3.60E-01	0.00E+00	2.11E-02	2.27E+00	5.03E-01	1.19E-02	1.39E-05	3.16E+00	1.27E-02
RL-W689	9.33E-03	0.00E+00	2.53E-04	3.86E-04	0.00E+00	1.14E-05	1.67E-07	9.97E-03	4.02E-05
RL-W690	3.13E-01	0.00E+00	1.86E-02	2.02E+00	4.47E-01	1.04E-02	1.23E-05	2.80E+00	1.13E-02
RL-W691	7.26E-03	0.00E+00	4.34E-04	4.68E-02	1.04E-02	2.40E-04	2.86E-07	6.49E-02	2.62E-04
RL-W692	2.87E-01	0.00E+00	1.72E-02	1.85E+00	4.10E-01	9.48E-03	1.13E-05	2.57E+00	1.04E-02
RL-W693	3.55E-01	0.00E+00	2.12E-02	2.29E+00	5.08E-01	1.17E-02	1.40E-05	3.18E+00	1.28E-02
RL-W694	3.73E+00	0.00E+00	2.22E-01	2.42E+01	5.33E+00	1.23E-01	1.47E-04	3.35E+01	1.35E-01
RL-W695	3.09E-03	0.00E+00	0.00E+00	2.38E-03	0.00E+00	0.00E+00	0.00E+00	5.47E-03	2.21E-05
RL-W696	4.02E-03	0.00E+00	8.11E-04	2.90E-03	2.85E-03	1.69E-04	5.34E-07	1.06E-02	4.27E-05

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W697	9.31E-01	0.00E+00	1.72E+00	6.90E-03	9.44E-04	0.00E+00	1.13E-03	2.66E+00	1.07E-02
RL-W698	8.07E-02	0.00E+00	0.00E+00	3.28E-05	0.00E+00	0.00E+00	0.00E+00	8.07E-02	3.26E-04
RL-W699	1.79E-02	0.00E+00	1.14E-04	2.19E-03	2.56E-04	7.12E-04	7.53E-08	2.05E-02	8.26E-05
RL-W700	5.08E-03	0.00E+00	3.00E-04	3.18E-02	7.05E-03	1.84E-04	1.98E-07	4.42E-02	1.78E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	2.00E-01	0.00E+00	8.46E-02	1.98E-01	8.14E-02	3.65E-03	5.58E-05	5.64E-01	2.28E-03
RL-W705	1.29E-03	0.00E+00	7.79E-05	8.33E-03	1.85E-03	4.49E-05	5.13E-08	1.16E-02	4.66E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	4.62E-02	0.00E+00	2.77E-03	2.97E-01	6.59E-02	1.60E-03	1.83E-06	4.12E-01	1.66E-03
RL-W708	6.98E-03	0.00E+00	4.20E-04	4.50E-02	9.96E-03	2.42E-04	2.77E-07	6.24E-02	2.52E-04
RL-W709	2.41E+00	0.00E+00	1.45E-01	1.55E+01	3.44E+00	8.35E-02	9.53E-05	2.15E+01	8.69E-02
RL-W710	1.44E-04	0.00E+00	8.64E-06	9.29E-04	2.05E-04	4.99E-06	5.69E-09	1.29E-03	5.19E-06
RL-W711	4.50E-02	0.00E+00	2.70E-03	2.90E-01	6.42E-02	1.56E-03	1.78E-06	4.02E-01	1.62E-03
RL-W712	5.82E-02	0.00E+00	3.49E-03	3.75E-01	8.30E-02	2.02E-03	2.30E-06	5.19E-01	2.09E-03
RL-W713	5.02E-02	0.00E+00	3.01E-03	3.23E-01	7.18E-02	1.74E-03	1.99E-06	4.48E-01	1.81E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	8.67E-04	0.00E+00	5.08E-05	5.47E-03	1.21E-03	2.87E-05	3.35E-08	7.60E-03	3.06E-05
RL-W716	9.04E-03	0.00E+00	5.29E-04	5.70E-02	1.26E-02	2.99E-04	3.49E-07	7.92E-02	3.19E-04
RL-W717	2.25E-03	0.00E+00	1.32E-04	1.43E-02	3.16E-03	7.46E-05	8.71E-08	1.98E-02	7.98E-05
RL-W718	3.98E-04	0.00E+00	2.33E-05	2.51E-03	5.56E-04	1.32E-05	1.54E-08	3.49E-03	1.41E-05
RL-W719	1.79E-03	0.00E+00	1.05E-04	1.14E-02	2.52E-03	5.95E-05	6.92E-08	1.58E-02	6.36E-05
RL-W720	1.11E-02	0.00E+00	6.52E-04	7.01E-02	1.56E-02	3.67E-04	4.30E-07	9.75E-02	3.93E-04
RL-W721	7.52E-03	0.00E+00	4.41E-04	4.74E-02	1.06E-02	2.49E-04	2.90E-07	6.59E-02	2.66E-04
RL-W723	2.49E-02	0.00E+00	1.49E-03	1.61E-01	3.57E-02	8.25E-04	9.80E-07	2.24E-01	9.01E-04
RL-W724	1.66E-01	0.00E+00	9.91E-03	1.07E+00	2.38E-01	5.48E-03	6.53E-06	1.48E+00	5.97E-03
RL-W725	5.24E-02	0.00E+00	3.12E-03	3.38E-01	7.49E-02	1.73E-03	2.06E-06	4.68E-01	1.89E-03
RL-W726	4.12E-02	0.00E+00	2.46E-03	2.67E-01	5.91E-02	1.36E-03	1.62E-06	3.70E-01	1.49E-03
RL-W727	2.53E-01	0.00E+00	1.51E-02	1.63E+00	3.63E-01	8.37E-03	9.97E-06	2.27E+00	9.13E-03

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W728	2.30E-01	0.00E+00	1.38E-02	1.49E+00	3.30E-01	7.62E-03	9.08E-06	2.07E+00	8.34E-03
RL-W729	1.06E-01	0.00E+00	6.38E-03	6.87E-01	1.53E-01	3.51E-03	4.21E-06	9.53E-01	3.84E-03
RL-W730	4.17E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.17E+01	1.68E-01
RL-W731	1.34E-05	0.00E+00	0.00E+00	4.49E-04	1.83E-06	0.00E+00	0.00E+00	4.65E-04	1.87E-06
RL-W732	3.08E+01	0.00E+00	3.63E+00	1.27E+02	2.79E+01	1.26E+00	2.39E-03	1.89E+02	7.61E-01
RL-W733	4.04E-01	0.00E+00	4.72E-02	1.38E+00	3.39E-01	1.37E-02	3.11E-05	2.17E+00	8.73E-03
RL-W734	1.26E+00	0.00E+00	1.58E-01	4.74E+00	1.14E+00	4.07E-02	1.04E-04	7.31E+00	2.95E-02
RL-W735	1.03E+00	0.00E+00	1.20E-01	3.70E+00	9.12E-01	3.17E-02	7.92E-05	5.76E+00	2.32E-02
RL-W736	1.13E-03	0.00E+00	2.56E-07	2.45E-03	6.29E-04	9.69E-06	1.69E-10	4.21E-03	1.70E-05
RL-W737	9.21E-01	0.00E+00	1.10E-01	3.51E+00	8.49E-01	2.73E-02	7.23E-05	5.39E+00	2.17E-02
RL-W738	3.44E+00	0.00E+00	3.77E-01	1.12E+01	2.93E+00	9.90E-02	2.49E-04	1.79E+01	7.22E-02
RL-W739	2.93E-01	0.00E+00	3.33E-02	1.81E+00	4.11E-01	8.99E-03	2.19E-05	2.55E+00	1.03E-02
RL-W740	1.47E+01	0.00E+00	1.22E+00	4.41E+01	1.14E+01	4.54E-01	8.04E-04	7.14E+01	2.88E-01
RL-W741	2.19E+01	0.00E+00	2.87E+00	8.60E+00	6.07E+00	3.41E-01	1.89E-03	3.94E+01	1.59E-01
RL-W742	9.74E-01	0.00E+00	8.64E-02	2.79E+00	6.54E-01	2.92E-02	5.69E-05	4.50E+00	1.82E-02
RL-W743	1.76E-03	0.00E+00	2.34E-05	1.80E-03	0.00E+00	0.00E+00	1.55E-08	3.58E-03	1.45E-05
RL-W744	0.00E+00	0.00E+00	0.00E+00	9.00E-02	7.61E-02	0.00E+00	0.00E+00	1.66E-01	6.70E-04
RL-W745	2.77E-03	0.00E+00	1.64E-04	1.74E-02	3.86E-03	1.00E-04	1.08E-07	2.42E-02	9.77E-05
RL-W746	1.07E-02	0.00E+00	6.31E-04	6.69E-02	1.49E-02	3.86E-04	4.16E-07	9.31E-02	3.76E-04
RL-W747	2.89E-02	0.00E+00	1.71E-03	1.81E-01	4.02E-02	1.05E-03	1.13E-06	2.52E-01	1.02E-03
RL-W748	2.03E+02	0.00E+00	4.79E+00	3.01E-01	4.92E-01	7.88E+00	3.16E-03	2.08E+02	8.39E-01
RL-W749	2.43E-01	0.00E+00	1.47E-02	1.57E+00	3.48E-01	8.42E-03	9.66E-06	2.18E+00	8.79E-03
RL-W750	3.07E+02	0.00E+00	7.26E+00	4.93E-01	8.04E-01	1.12E+01	4.79E-03	3.16E+02	1.27E+00
RL-W751	2.77E+02	0.00E+00	6.56E+00	4.43E-01	7.29E-01	1.01E+01	4.32E-03	2.85E+02	1.15E+00
RL-W752	1.21E+02	0.00E+00	2.85E+00	1.93E-01	3.17E-01	4.37E+00	1.88E-03	1.24E+02	5.00E-01
RL-W753	1.62E+03	0.00E+00	3.84E+01	2.60E+00	4.25E+00	5.88E+01	2.53E-02	1.67E+03	6.72E+00
RP-W754	6.89E+01	0.00E+00	4.86E+00	1.85E+03	1.51E+02	5.43E-01	3.56E-01	2.08E+03	8.38E+00
RP-W755	3.65E+02	0.00E+00	2.92E+00	1.39E+03	1.14E+02	4.05E-01	1.26E+01	1.88E+03	7.58E+00
SA-T001	7.34E-01	3.06E-02	6.98E-02	3.02E+00	1.77E-02	0.00E+00	5.06E-05	3.84E+00	1.55E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
SA-W134	5.99E+00	1.18E-05	4.76E-01	1.38E+00	4.33E-01	1.03E-02	1.67E-01	8.44E+00	3.40E-02
SA-W134M	7.78E-01	1.54E-06	6.17E-02	1.79E-01	5.62E-02	1.34E-03	2.16E-02	1.10E+00	4.42E-03
T001-221F-HET	1.45E+03	0.00E+00	5.57E+04	2.87E+04	7.04E+02	3.39E+01	4.24E+01	8.66E+04	3.49E+02
T001-221H-HET	2.61E+03	0.00E+00	1.01E+05	5.18E+04	1.27E+03	6.12E+01	7.64E+01	1.56E+05	6.30E+02
T001-235F-HET	1.50E+02	0.00E+00	5.78E+03	2.98E+03	7.31E+01	3.51E+00	4.40E+00	8.99E+03	3.62E+01
T001-772F-HET	1.29E+03	0.00E+00	5.01E+04	2.57E+04	6.30E+02	3.03E+01	3.81E+01	7.77E+04	3.13E+02
T001-773A-CLAS	1.45E+01	0.00E+00	5.61E+02	2.89E+02	7.07E+00	3.41E-01	4.26E-01	8.71E+02	3.51E+00
T001-773A-HET	1.67E+02	0.00E+00	6.45E+03	3.33E+03	8.17E+01	3.93E+00	4.91E+00	1.00E+04	4.05E+01
W006-773A-VIT	2.24E-03	0.00E+00	0.00E+00	5.35E+02	0.00E+00	0.00E+00	0.00E+00	5.35E+02	2.16E+00
W026-221F-HET	5.04E+02	0.00E+00	1.94E+04	1.01E+04	2.46E+02	1.18E+01	1.48E+01	3.03E+04	1.22E+02
W026-221H-HET	3.77E+02	0.00E+00	1.45E+04	7.49E+03	1.83E+02	8.84E+00	1.10E+01	2.26E+04	9.11E+01
W026-235F-HET	5.87E+00	0.00E+00	2.26E+02	1.17E+02	2.86E+00	1.38E-01	1.72E-01	3.52E+02	1.42E+00
W026-772F-HET	1.61E+00	0.00E+00	6.17E+01	3.18E+01	7.79E-01	3.76E-02	4.69E-02	9.59E+01	3.87E-01
W026-773A-HET	2.60E+01	0.00E+00	1.01E+03	5.18E+02	1.27E+01	6.11E-01	7.64E-01	1.56E+03	6.30E+00
W027-221F-HET	1.90E+03	0.00E+00	6.56E+04	3.89E+04	9.51E+02	1.93E+01	6.10E+01	1.07E+05	4.33E+02
W027-221H-HET	8.32E+02	0.00E+00	2.86E+04	1.70E+04	4.16E+02	8.44E+00	2.67E+01	4.69E+04	1.89E+02
W027-235F-HET	2.50E+02	0.00E+00	8.60E+03	5.12E+03	1.25E+02	2.54E+00	8.02E+00	1.41E+04	5.69E+01
W027-772F-HET	4.55E+02	0.00E+00	1.57E+04	9.30E+03	2.28E+02	4.61E+00	1.46E+01	2.56E+04	1.03E+02
W027-773A-HET	6.78E+02	0.00E+00	2.33E+04	1.39E+04	3.39E+02	6.89E+00	2.17E+01	3.82E+04	1.54E+02
W027-999-HET	7.76E+02	0.00E+00	2.67E+04	1.58E+04	3.88E+02	7.86E+00	2.49E+01	4.37E+04	1.76E+02
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.98E+02	0.00E+00	0.00E+00	0.00E+00	3.98E+02	1.60E+00
WP-INW169.001	3.79E+00	0.00E+00	1.68E-01	1.53E+01	3.39E+00	6.94E-02	2.76E-04	2.27E+01	9.15E-02
WP-INW198.001	4.99E+00	0.00E+00	2.93E-01	2.75E+01	6.04E+00	1.14E-01	2.75E-04	3.88E+01	1.57E-01
WP-INW211.001	5.62E+02	0.00E+00	2.75E+01	2.55E+03	5.60E+02	1.29E+01	2.01E-02	3.70E+03	1.49E+01
WP-INW216.001-	2.04E+04	0.00E+00	1.58E+01	1.47E+03	3.25E+02	7.13E+00	2.87E-01	2.22E+04	8.97E+01
WP-INW216.001-	5.62E+03	0.00E+00	4.27E+00	4.00E+02	8.78E+01	1.93E+00	3.04E-02	6.11E+03	2.46E+01
WP-INW218.001-	3.91E+02	0.00E+00	2.79E+00	2.57E+02	5.66E+01	1.29E+00	3.88E-01	7.07E+02	2.85E+00
WP-INW218.001-	1.80E+00	0.00E+00	7.68E-02	6.99E+00	1.54E+00	3.65E-02	3.74E-02	1.04E+01	4.21E-02
WP-INW222.001	1.85E+01	0.00E+00	8.28E-01	6.83E+01	1.52E+01	3.10E-01	1.12E-03	1.03E+02	4.15E-01

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-INW243.001	4.48E+01	0.00E+00	1.79E+00	1.44E+02	3.20E+01	6.26E-01	2.05E-03	2.22E+02	8.95E-01
WP-INW247.001R	5.99E+01	0.00E+00	4.16E+00	2.75E+02	6.21E+01	1.09E+00	2.82E-03	4.01E+02	1.62E+00
WP-INW276.001	4.56E+00	0.00E+00	4.05E-01	2.72E+01	6.15E+00	9.20E-02	2.84E-04	3.83E+01	1.55E-01
WP-INW276.002	7.24E+00	0.00E+00	6.10E-01	4.00E+01	9.23E+00	1.38E-01	4.28E-04	5.70E+01	2.30E-01
WP-INW276.003	2.77E+02	0.00E+00	2.27E+01	1.48E+03	3.36E+02	5.81E+00	1.54E-02	2.12E+03	8.55E+00
WP-INW276.004	6.62E+01	0.00E+00	4.79E+00	3.14E+02	7.10E+01	1.23E+00	3.31E-03	4.56E+02	1.84E+00
WP-INW296.001-	2.42E+01	0.00E+00	1.14E+00	7.88E+01	1.78E+01	3.15E-01	7.88E-04	1.22E+02	4.92E-01
WP-INW296.001-	7.30E+01	0.00E+00	4.02E+00	2.79E+02	6.27E+01	1.13E+00	3.00E-03	4.19E+02	1.69E+00
WP-LA-TA-55-19	1.22E+00	0.00E+00	1.87E-01	2.08E+00	5.00E-01	1.13E-02	2.76E-03	3.99E+00	1.61E-02
WP-LA-TA-55-19	5.89E+01	0.00E+00	6.27E+00	2.12E+02	5.15E+01	1.12E+00	9.13E-02	3.29E+02	1.33E+00
WP-LA-TA-55-43	3.31E-01	0.00E+00	1.46E+02	3.22E-01	1.35E-01	1.00E-02	1.23E-01	1.47E+02	5.94E-01
WP-RF001.01	1.02E+02	0.00E+00	5.08E+00	4.08E+02	9.24E+01	1.13E+00	1.27E-02	6.08E+02	2.45E+00
WP-RF002.01-A	1.19E+02	0.00E+00	6.77E+00	4.60E+02	1.05E+02	2.49E+00	2.23E-02	6.91E+02	2.78E+00
WP-RF002.01-B	1.18E-01	0.00E+00	4.69E-03	4.98E-01	1.12E-01	1.56E-03	3.28E-06	7.33E-01	2.96E-03
WP-RF003.01	1.85E+03	0.00E+00	1.09E+02	8.80E+03	1.99E+03	4.11E+01	8.01E-02	1.27E+04	5.14E+01
WP-RF004.01	8.66E-01	0.00E+00	7.30E-02	5.07E+00	1.15E+00	2.35E-02	1.75E-04	7.16E+00	2.89E-02
WP-RF005.01	4.45E+03	0.00E+00	5.53E+01	4.65E+03	1.05E+03	1.64E+01	3.83E-02	1.02E+04	4.11E+01
WP-RF005.02	5.23E+03	0.00E+00	2.86E+01	2.78E+03	6.20E+02	8.39E+00	2.01E-02	8.66E+03	3.49E+01
WP-RF006.01	1.70E+03	0.00E+00	1.04E+02	7.91E+03	1.80E+03	2.12E+01	9.41E-02	1.15E+04	4.64E+01
WP-RF008.01	5.38E+02	0.00E+00	3.70E+01	2.31E+03	5.34E+02	1.40E+01	2.57E-02	3.42E+03	1.38E+01
WP-RF009.01	5.30E+04	0.00E+00	4.55E+02	5.07E+04	1.12E+04	1.61E+02	3.20E-01	1.15E+05	4.65E+02
WP-RF010.01	1.95E+01	0.00E+00	1.15E+00	7.66E+01	1.74E+01	4.96E-01	1.49E-03	1.15E+02	4.62E-01
WP-RF029.01-A	4.69E+00	0.00E+00	2.17E-01	1.35E+01	3.06E+00	1.14E-01	8.73E-04	2.14E+01	8.63E-02
WP-RF029.01-B	7.01E+00	0.00E+00	1.72E-01	1.07E+01	2.42E+00	8.99E-02	2.36E-03	2.03E+01	8.17E-02
WP-RF118.01	1.19E+04	0.00E+00	8.64E+02	5.12E+04	1.13E+04	2.96E+02	7.84E-01	7.53E+04	3.04E+02
WP-RLMPDT.001	2.53E+00	0.00E+00	2.52E-01	7.33E+00	1.89E+00	6.49E-02	1.68E-04	1.20E+01	4.84E-02
WP-RLNPDT.002	3.10E+01	0.00E+00	2.40E+00	7.20E+01	1.92E+01	7.45E-01	1.62E-03	1.25E+02	5.03E-01
WP-SR2001.001.	9.87E-01	0.00E+00	2.76E-01	6.80E+00	1.34E+00	4.05E-02	1.86E-04	9.41E+00	3.79E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-SR-W027-221	7.32E+00	0.00E+00	8.11E-01	1.95E+01	5.41E+00	1.83E-01	1.87E-01	3.33E+01	1.34E-01
Total	3.92E+05	5.91E+01	5.68E+05	6.58E+05	1.06E+05	4.18E+03	5.42E+02	1.72E+06	6.95E+03

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	7.09E+01	0.00E+00	5.15E+00	2.08E+02	1.22E+02	1.25E-01	1.78E-02	4.06E+02	1.64E+00
AE-T003	8.98E+00	0.00E+00	6.86E-01	6.43E+01	2.46E+01	6.84E-02	7.17E-04	9.86E+01	3.97E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	3.98E-02	0.00E+00	1.82E+01	4.74E+01	2.83E-01	1.33E-04	1.65E-02	6.59E+01	2.66E-01
AW-T033.1325	1.46E-01	0.00E+00	6.65E+01	1.73E+02	1.03E+00	4.87E-04	6.05E-02	2.41E+02	9.72E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.70E-01	0.00E+00	0.00E+00	0.00E+00	7.70E-01	3.10E-03
BCLCH-MT01	1.47E+01	0.00E+00	5.15E+02	2.86E+01	7.42E+00	1.88E-01	4.54E-01	5.66E+02	2.28E+00
BT-T002	1.08E-02	6.22E-06	2.69E-01	7.22E-04	1.46E-03	8.25E-05	2.23E-03	2.84E-01	1.15E-03
ET-C1-B55	4.50E-02	0.00E+00	3.07E-03	6.18E-02	3.05E-02	1.46E-04	2.39E-04	1.41E-01	5.67E-04
ET-C1-D139	6.18E-03	0.00E+00	4.25E-04	8.69E-03	4.29E-03	1.94E-05	4.37E-07	1.96E-02	7.90E-05
ET-C2-SEFOR	1.53E-01	0.00E+00	0.00E+00	1.36E-01	4.53E-02	2.99E-04	0.00E+00	3.35E-01	1.35E-03
FM-MOX-MT02	1.45E-06	0.00E+00	1.71E-07	2.99E-07	1.76E-07	1.04E-08	1.60E-10	2.10E-06	8.45E-09
FM-MOX-T01	2.39E-05	0.00E+00	2.83E-06	4.92E-06	2.90E-06	1.71E-07	2.63E-09	3.46E-05	1.40E-07
IN-BN-510	5.79E+03	0.00E+00	1.46E+04	3.95E+04	3.31E+03	4.09E-02	1.48E+01	6.32E+04	2.55E+02
IN-GEM-01	7.32E+01	0.00E+00	2.89E-01	4.44E+01	1.00E+01	2.89E-02	2.55E-04	1.28E+02	5.16E-01
IN-GEM-02	1.74E+01	0.00E+00	6.89E-02	1.06E+01	2.39E+00	6.84E-03	6.07E-05	3.04E+01	1.23E-01
IN-W157.144	8.67E+01	0.00E+00	2.80E+00	3.02E+02	6.76E+01	5.12E-01	2.84E-03	4.59E+02	1.85E+00
IN-W163.1007	1.48E+01	0.00E+00	8.65E-01	9.36E+01	2.10E+01	1.58E-01	8.78E-04	1.30E+02	5.25E-01
IN-W164.153	1.42E-01	0.00E+00	8.25E-03	8.91E-01	2.00E-01	1.51E-03	8.38E-06	1.24E+00	5.00E-03
IN-W167.149	2.84E+01	0.00E+00	1.34E+00	1.44E+02	3.24E+01	2.44E-01	1.36E-03	2.06E+02	8.32E-01
IN-W174.154	0.00E+00	0.00E+00	7.58E+02	1.94E+00	3.79E+00	0.00E+00	7.70E-01	7.65E+02	3.08E+00
IN-W177.156	1.97E-02	0.00E+00	1.61E+03	1.82E+00	1.10E-02	2.10E-04	1.64E+00	1.62E+03	6.51E+00
IN-W179.158	1.33E-01	0.00E+00	1.61E+03	1.06E-01	5.43E-02	1.41E-03	1.63E+00	1.61E+03	6.48E+00
IN-W181.162	1.88E+00	0.00E+00	1.09E-01	1.18E+01	2.64E+00	2.00E-02	1.11E-04	1.64E+01	6.60E-02
IN-W188.160	1.27E+01	0.00E+00	7.35E-01	7.93E+01	1.77E+01	1.35E-01	7.46E-04	1.10E+02	4.45E-01
IN-W216.98	1.13E+05	0.00E+00	5.99E+01	6.47E+03	1.46E+03	1.10E+01	6.08E-02	1.21E+05	4.86E+02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	5.68E+02	0.00E+00	1.33E+00	1.43E+02	3.22E+01	2.44E-01	1.35E-03	7.45E+02	3.01E+00
IN-W219.110	7.71E-01	0.00E+00	4.49E-02	4.84E+00	1.08E+00	8.20E-03	4.55E-05	6.74E+00	2.72E-02
IN-W219.914	1.22E-01	0.00E+00	7.06E-03	7.64E-01	1.71E-01	1.30E-03	7.17E-06	1.06E+00	4.29E-03
IN-W220.114	4.02E+03	0.00E+00	4.72E+00	5.47E+02	1.19E+02	8.62E-01	4.79E-03	4.69E+03	1.89E+01
IN-W221.927	4.71E+00	0.00E+00	2.73E-01	2.95E+01	6.59E+00	5.01E-02	2.78E-04	4.10E+01	1.66E-01
IN-W222.116	1.60E+02	0.00E+00	9.26E+00	9.96E+02	2.23E+02	1.69E+00	9.40E-03	1.39E+03	5.60E+00
IN-W228.101	1.06E+03	0.00E+00	3.01E+00	3.26E+02	7.28E+01	5.54E-01	3.06E-03	1.46E+03	5.90E+00
IN-W240.931	1.12E+02	0.00E+00	3.85E+00	4.18E+02	9.31E+01	7.00E-01	3.91E-03	6.28E+02	2.53E+00
IN-W243.808	1.56E+02	0.00E+00	6.74E+00	7.30E+02	1.63E+02	1.24E+00	6.85E-03	1.06E+03	4.26E+00
IN-W245.301	2.31E+02	0.00E+00	1.33E+01	1.42E+03	3.20E+02	2.42E+00	1.35E-02	1.99E+03	8.01E+00
IN-W247.810	1.12E+02	0.00E+00	6.45E+00	6.96E+02	1.56E+02	1.18E+00	6.55E-03	9.71E+02	3.92E+00
IN-W249.527	0.00E+00	0.00E+00	4.51E+02	1.23E+01	0.00E+00	0.00E+00	4.58E-01	4.64E+02	1.87E+00
IN-W263.520	3.22E-02	0.00E+00	4.72E+01	8.39E+00	1.32E-02	3.42E-04	4.79E-02	5.57E+01	2.24E-01
IN-W267.1005	2.69E+01	0.00E+00	1.57E+00	1.69E+02	3.79E+01	2.87E-01	1.59E-03	2.36E+02	9.50E-01
IN-W309.609	7.22E+02	0.00E+00	2.62E+01	2.83E+03	6.33E+02	4.79E+00	2.66E-02	4.21E+03	1.70E+01
IN-W315.601	7.12E+02	0.00E+00	1.10E-01	1.19E+01	2.65E+00	2.00E-02	1.11E-04	7.26E+02	2.93E+00
IN-W319.584	4.14E+00	0.00E+00	2.40E-01	2.60E+01	5.83E+00	4.40E-02	2.44E-04	3.62E+01	1.46E-01
IN-W321.1023	3.58E+01	0.00E+00	2.08E+00	2.25E+02	5.04E+01	3.81E-01	2.12E-03	3.13E+02	1.26E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	9.08E+00	1.86E+00	0.00E+00	0.00E+00	1.09E+01	4.41E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.42E+01	4.96E+00	0.00E+00	0.00E+00	2.92E+01	1.18E-01
IN-W323.562	7.65E-02	0.00E+00	3.53E-01	2.48E-01	0.00E+00	8.15E-04	3.59E-04	6.78E-01	2.73E-03
IN-W323.951	9.03E-02	0.00E+00	4.20E-03	2.96E-01	0.00E+00	9.61E-04	4.26E-06	3.90E-01	1.57E-03
IN-W332.661	0.00E+00	0.00E+00	4.63E+00	1.28E-01	0.00E+00	0.00E+00	4.70E-03	4.76E+00	1.92E-02
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	3.03E+00	6.20E-01	0.00E+00	0.00E+00	3.65E+00	1.47E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	9.08E+00	1.86E+00	0.00E+00	0.00E+00	1.09E+01	4.41E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.94E+00	0.00E+00	0.00E+00	0.00E+00	1.94E+00	7.83E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.83E+00	0.00E+00	0.00E+00	0.00E+00	5.83E+00	2.35E-02
IN-W342.652	3.54E+00	0.00E+00	0.00E+00	4.00E-02	1.02E-17	0.00E+00	0.00E+00	3.58E+00	1.44E-02
IN-W342.953	2.36E+00	0.00E+00	0.00E+00	2.68E-02	6.87E-18	0.00E+00	0.00E+00	2.39E+00	9.64E-03

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W347.818	1.85E+00	0.00E+00	0.00E+00	8.22E+01	1.50E+02	0.00E+00	1.58E-08	2.34E+02	9.42E-01
IN-W348.1012	9.80E-02	0.00E+00	3.82E+00	4.15E+02	9.30E+01	0.00E+00	3.88E-03	5.12E+02	2.07E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.49E-02	0.00E+00	0.00E+00	0.00E+00	2.49E-02	1.00E-04
IN-W357.1022	0.00E+00	0.00E+00	7.52E-03	8.15E-01	1.82E-01	0.00E+00	7.64E-06	1.01E+00	4.05E-03
IN-W358.854	0.00E+00	0.00E+00	1.13E+02	1.87E+00	3.57E+00	0.00E+00	1.08E-01	1.19E+02	4.80E-01
IN-W358.855	0.00E+00	0.00E+00	6.05E+02	9.96E+00	1.90E+01	0.00E+00	5.76E-01	6.34E+02	2.56E+00
IN-W358.948	0.00E+00	0.00E+00	1.26E+02	2.08E+00	3.95E+00	0.00E+00	1.20E-01	1.32E+02	5.34E-01
IN-W361.1021	2.60E-02	0.00E+00	7.29E-01	7.86E+01	1.76E+01	0.00E+00	7.40E-04	9.70E+01	3.91E-01
IN-W362.1020	0.00E+00	0.00E+00	9.55E+00	1.03E+03	2.31E+02	0.00E+00	9.69E-03	1.27E+03	5.11E+00
IN-W363.1019	0.00E+00	0.00E+00	4.49E-01	4.87E+01	1.09E+01	0.00E+00	4.56E-04	6.01E+01	2.42E-01
IN-W364.1011	0.00E+00	0.00E+00	7.41E-01	8.00E+01	1.79E+01	0.00E+00	7.52E-04	9.87E+01	3.98E-01
IN-W365.1010	2.43E+02	0.00E+00	5.87E-01	6.32E+01	1.42E+01	0.00E+00	5.96E-04	3.21E+02	1.29E+00
IN-W366.841	8.63E-01	0.00E+00	5.01E-01	5.39E+01	1.21E+01	0.00E+00	5.08E-04	6.73E+01	2.71E-01
IN-W372.832	3.54E+00	0.00E+00	0.00E+00	4.00E-02	1.02E-17	0.00E+00	0.00E+00	3.58E+00	1.44E-02
IN-W375.1096	0.00E+00	0.00E+00	1.85E-01	1.99E+01	4.46E+00	0.00E+00	1.88E-04	2.46E+01	9.90E-02
KN-B234TRU	1.26E+02	0.00E+00	7.06E+00	2.90E+02	9.64E+01	2.68E-01	8.17E-03	5.19E+02	2.09E+00
LA-IT-00-01	1.83E+00	4.00E-03	1.20E+00	5.82E-01	1.25E-02	5.14E-11	1.42E-03	3.63E+00	1.46E-02
LA-OS-00-01	4.07E+03	0.00E+00	5.50E+04	1.22E+03	0.00E+00	0.00E+00	4.90E+01	6.03E+04	2.43E+02
LA-PX-00-01	1.70E-02	0.00E+00	2.32E-03	9.01E-02	2.10E-02	8.51E-05	2.18E-06	1.30E-01	5.26E-04
LA-SL-00-01	0.00E+00	0.00E+00	4.89E-02	1.52E-01	0.00E+00	0.00E+00	5.70E-05	2.01E-01	8.12E-04
LA-TA-03-12	1.74E-01	0.00E+00	1.13E+00	4.34E-01	1.50E-01	5.04E-04	1.38E-03	1.89E+00	7.62E-03
LA-TA-03-13	2.26E-01	0.00E+00	3.59E+00	6.78E-01	1.57E-01	6.68E-04	3.69E-03	4.65E+00	1.88E-02
LA-TA-03-19	4.56E-01	0.00E+00	5.35E+00	1.32E+00	3.79E-01	1.03E-03	6.51E-03	7.52E+00	3.03E-02
LA-TA-03-20	2.49E-01	0.00E+00	2.54E+00	5.83E-01	2.04E-01	8.46E-04	2.93E-03	3.58E+00	1.44E-02
LA-TA-03-24	3.33E-01	0.00E+00	9.90E+00	1.09E+00	3.26E-01	8.77E-04	1.21E-02	1.17E+01	4.70E-02
LA-TA-03-26	1.71E-02	0.00E+00	4.08E-01	2.63E+00	4.26E-02	7.68E-05	1.37E-03	3.10E+00	1.25E-02
LA-TA-03-28	0.00E+00	0.00E+00	1.41E-01	2.46E-01	0.00E+00	0.00E+00	1.70E-04	3.87E-01	1.56E-03
LA-TA-03-30	7.60E-01	0.00E+00	1.01E-01	5.01E+00	1.44E+00	4.02E-03	1.20E-04	7.30E+00	2.95E-02
LA-TA-03-31	0.00E+00	0.00E+00	5.03E-03	8.76E-03	0.00E+00	0.00E+00	6.05E-06	1.38E-02	5.57E-05

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-03-40	0.00E+00	0.00E+00	7.96E-03	5.45E-02	0.00E+00	0.00E+00	9.65E-06	6.24E-02	2.52E-04
LA-TA-03-42	1.75E-05	0.00E+00	1.99E-04	3.41E-03	4.44E-05	8.41E-08	2.42E-07	3.67E-03	1.48E-05
LA-TA-21-06	1.72E-01	0.00E+00	2.19E+01	9.53E-01	2.88E-01	8.67E-04	2.63E-02	2.34E+01	9.42E-02
LA-TA-21-12	6.26E-01	0.00E+00	1.32E+02	3.31E+00	9.78E-01	2.98E-03	1.59E-01	1.37E+02	5.54E-01
LA-TA-21-13	9.64E-01	0.00E+00	0.00E+00	2.93E-01	0.00E+00	0.00E+00	0.00E+00	1.26E+00	5.07E-03
LA-TA-21-14	1.58E-04	0.00E+00	2.52E+00	4.47E+00	5.16E-05	1.21E-06	2.40E-03	7.00E+00	2.82E-02
LA-TA-21-15	9.33E-02	0.00E+00	6.94E-03	1.38E+00	2.34E-01	4.89E-04	8.25E-06	1.72E+00	6.93E-03
LA-TA-21-16	1.08E+00	0.00E+00	1.07E-01	1.06E+01	2.50E+00	5.16E-03	1.30E-04	1.42E+01	5.74E-02
LA-TA-21-40	1.37E-04	0.00E+00	3.70E-01	3.32E-01	3.63E-04	2.07E-07	5.77E-04	7.03E-01	2.83E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	7.06E-01	0.00E+00	0.00E+00	0.00E+00	7.06E-01	2.85E-03
LA-TA-21-42	1.40E-02	0.00E+00	1.20E-01	1.63E-01	1.10E-02	6.74E-06	2.02E-04	3.09E-01	1.25E-03
LA-TA-21-43	4.95E+01	0.00E+00	3.99E+00	5.09E+02	1.20E+02	5.33E-02	6.66E-03	6.82E+02	2.75E+00
LA-TA-21-44	2.38E-01	0.00E+00	8.39E-01	1.15E+02	3.02E-01	7.52E-04	1.11E-03	1.16E+02	4.67E-01
LA-TA-48-01	7.69E-02	1.89E-02	3.15E-03	1.18E-01	4.87E-01	6.21E-05	4.97E-06	6.85E-01	2.76E-03
LA-TA-49-01	9.49E+00	2.34E+00	3.88E-01	1.45E+01	6.03E+01	7.68E-03	6.13E-04	8.47E+01	3.42E-01
LA-TA-50-10	2.54E-02	0.00E+00	3.67E-03	4.57E-02	0.00E+00	0.00E+00	3.42E-06	7.48E-02	3.02E-04
LA-TA-50-11	4.85E-02	0.00E+00	3.76E-03	4.64E-01	1.02E-01	6.16E-05	5.79E-06	6.18E-01	2.49E-03
LA-TA-50-15	9.57E-02	0.00E+00	5.56E-01	3.39E-01	7.52E-02	2.44E-04	6.11E-04	1.07E+00	4.30E-03
LA-TA-50-17	1.40E+01	0.00E+00	4.51E-01	1.81E+01	4.23E-04	2.23E-05	8.36E-04	3.26E+01	1.31E-01
LA-TA-50-18	8.32E-01	0.00E+00	5.96E-02	2.96E+00	5.27E-06	6.58E-07	7.23E-05	3.85E+00	1.55E-02
LA-TA-50-19	2.66E-01	0.00E+00	2.66E-02	3.93E-01	4.51E-03	8.15E-06	5.90E-05	6.90E-01	2.78E-03
LA-TA-50-20	7.28E-03	0.00E+00	0.00E+00	9.70E-03	0.00E+00	0.00E+00	0.00E+00	1.70E-02	6.85E-05
LA-TA-50-40	4.10E-03	0.00E+00	3.59E-04	1.06E-02	4.89E-03	2.61E-05	4.09E-07	1.99E-02	8.02E-05
LA-TA-50-41	4.38E-03	0.00E+00	3.62E-04	4.68E-02	1.08E-02	4.65E-05	3.67E-07	6.23E-02	2.51E-04
LA-TA-55-19	6.78E+00	0.00E+00	4.77E-01	2.63E+01	7.35E+00	2.63E-02	2.09E-03	4.09E+01	1.65E-01
LA-TA-55-20	1.09E+02	0.00E+00	5.44E+00	6.35E+02	1.52E+02	6.58E-01	9.97E-02	9.01E+02	3.63E+00
LA-TA-55-21	9.73E-01	5.58E-06	6.25E-02	4.50E+00	1.07E+00	5.43E-03	6.28E-05	6.61E+00	2.66E-02
LA-TA-55-22	2.67E+00	0.00E+00	3.53E-01	1.58E+01	3.68E+00	1.68E-02	3.55E-04	2.25E+01	9.08E-02
LA-TA-55-23	2.51E+00	0.00E+00	2.95E-01	1.09E+01	2.67E+00	1.66E-02	2.93E-04	1.63E+01	6.58E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-24	9.47E-01	0.00E+00	4.63E-02	5.69E+00	1.32E+00	7.89E-03	4.36E-05	8.01E+00	3.23E-02
LA-TA-55-25	4.85E+00	0.00E+00	2.70E-01	2.83E+01	6.56E+00	4.04E-02	2.54E-04	4.00E+01	1.61E-01
LA-TA-55-28	1.65E+00	0.00E+00	1.50E-01	8.68E+00	2.04E+00	1.31E-02	1.42E-04	1.25E+01	5.05E-02
LA-TA-55-30	3.68E+01	5.28E-08	1.79E+00	1.42E+02	3.41E+01	9.61E-02	2.35E-03	2.15E+02	8.67E-01
LA-TA-55-32	2.98E+00	0.00E+00	1.00E+01	1.13E+01	3.45E+00	1.20E-02	1.23E-02	2.77E+01	1.12E-01
LA-TA-55-33	4.47E-01	0.00E+00	2.58E-02	1.48E+00	4.70E-01	1.68E-03	2.92E-05	2.43E+00	9.78E-03
LA-TA-55-34	4.52E+01	0.00E+00	2.39E+00	2.30E+02	5.80E+01	2.03E-01	5.48E-03	3.36E+02	1.35E+00
LA-TA-55-38	1.14E+02	0.00E+00	7.87E-01	5.08E+01	1.36E+01	4.72E-02	2.58E-03	1.79E+02	7.21E-01
LA-TA-55-39	1.20E+01	0.00E+00	5.82E-01	7.58E+01	1.69E+01	8.30E-02	5.72E-04	1.05E+02	4.24E-01
LA-TA-55-41	2.86E+02	0.00E+00	1.20E+00	9.40E+01	2.23E+01	1.04E-01	1.22E-03	4.04E+02	1.63E+00
LA-TA-55-43	1.07E-01	0.00E+00	7.90E+01	1.41E-01	4.92E-02	9.19E-04	7.68E-02	7.94E+01	3.20E-01
LA-TA-55-44	9.32E-01	0.00E+00	1.86E+02	2.62E+00	7.22E-01	2.72E-03	2.12E-01	1.91E+02	7.68E-01
LA-TA-55-48	6.87E+03	0.00E+00	7.35E+02	1.68E+04	6.24E+03	2.84E+01	8.13E-01	3.07E+04	1.24E+02
LA-TA-55-49	1.47E+01	0.00E+00	9.66E+02	3.08E+01	8.59E+00	3.32E-02	1.09E+00	1.02E+03	4.12E+00
LA-TA-55-53	6.92E+01	0.00E+00	2.00E+00	2.63E+02	6.10E+01	1.82E-01	2.22E-03	3.95E+02	1.59E+00
LA-TA-55-56	7.66E+01	0.00E+00	7.44E+01	3.80E+02	9.48E+01	4.20E-01	7.72E-02	6.26E+02	2.53E+00
LA-TA-55-60	4.15E-02	0.00E+00	1.88E-02	7.17E-02	2.53E-02	2.48E-04	2.12E-05	1.57E-01	6.34E-04
LA-TA-55-61	3.57E-02	0.00E+00	8.65E-02	1.38E-01	4.66E-02	2.41E-04	9.56E-05	3.07E-01	1.24E-03
LA-TA-55-62	9.26E-03	0.00E+00	8.22E-04	2.32E-02	1.10E-02	6.48E-05	9.18E-07	4.43E-02	1.79E-04
LA-TA-55-63	6.87E-03	0.00E+00	5.56E-04	7.44E-02	1.71E-02	6.37E-05	5.83E-07	9.89E-02	3.99E-04
LL-M001	9.43E+01	2.53E-01	2.42E+01	6.97E+01	3.13E+01	5.03E-01	2.13E-02	2.20E+02	8.85E-01
LL-T001	4.71E+02	0.00E+00	0.00E+00	5.32E+02	2.38E+02	3.90E+00	0.00E+00	1.24E+03	5.00E+00
LL-T002	4.65E+03	0.00E+00	1.93E+02	5.16E+03	2.11E+03	3.43E+01	1.70E-01	1.21E+04	4.88E+01
LL-T003	1.81E+02	0.00E+00	2.16E+01	1.05E+02	8.38E+01	1.36E+00	1.90E-02	3.91E+02	1.58E+00
LL-T004	1.15E+02	0.00E+00	4.43E+00	6.64E+01	5.28E+01	8.62E-01	3.90E-03	2.39E+02	9.62E-01
LL-T005	5.93E+02	1.10E+01	5.21E+01	2.47E+02	2.12E+02	3.19E+00	4.59E-02	1.10E+03	4.45E+00
LL-W018	5.05E-02	0.00E+00	0.00E+00	1.84E-02	4.21E-02	6.53E-04	0.00E+00	1.11E-01	4.48E-04
LL-W019	2.74E+01	0.00E+00	0.00E+00	1.43E+01	1.19E+01	1.91E-01	0.00E+00	5.36E+01	2.16E-01
LL-W034	1.01E+01	1.87E-01	9.11E-01	4.18E+00	3.51E+00	5.43E-02	8.03E-04	1.87E+01	7.55E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
MC-W001	1.26E-01	0.00E+00	0.00E+00	6.03E-02	0.00E+00	9.82E-05	0.00E+00	1.87E-01	7.53E-04
MU-W002	1.69E+00	0.00E+00	0.00E+00	5.24E-02	0.00E+00	0.00E+00	2.67E-12	1.74E+00	7.01E-03
NT-JAS-01	1.63E+02	0.00E+00	1.94E+01	9.44E+01	7.54E+01	1.22E+00	1.71E-02	3.52E+02	1.42E+00
NT-W001	2.45E+02	5.70E-03	3.88E+01	2.85E+03	1.89E+01	8.56E-02	4.58E-02	3.15E+03	1.27E+01
NT-W021	4.73E+00	0.00E+00	2.78E-01	3.21E+01	7.26E+00	4.38E-02	2.91E-04	4.43E+01	1.79E-01
OR-W201	5.67E+03	3.93E-01	8.33E+02	2.15E+03	2.11E+03	4.59E+01	4.43E+01	1.08E+04	4.36E+01
OR-W202	8.14E+02	8.18E+00	2.40E+03	5.52E+02	5.37E+02	1.47E+00	2.57E+00	4.31E+03	1.74E+01
OR-W203	1.79E+00	2.85E-01	3.44E-01	2.48E-02	1.75E+00	3.74E-03	3.65E-04	3.92E+00	1.58E-02
OR-W204	4.00E-01	1.18E-06	3.91E-01	4.22E-01	2.83E-01	0.00E+00	4.14E-04	1.50E+00	6.03E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.24E-01	0.00E+00	0.00E+00	0.00E+00	4.24E-01	1.71E-03
RF-MT0001	1.53E+03	0.00E+00	2.43E+00	1.95E+02	4.42E+01	3.37E-01	2.44E-03	1.78E+03	7.16E+00
RF-MT0002	1.18E+02	0.00E+00	1.86E-01	1.50E+01	3.39E+00	2.59E-02	1.87E-04	1.37E+02	5.51E-01
RF-MT0003	5.37E-01	0.00E+00	4.25E-02	3.43E+00	7.77E-01	5.90E-03	4.28E-05	4.79E+00	1.93E-02
RF-MT0007	1.35E+00	0.00E+00	0.00E+00	4.28E-01	9.67E-02	6.84E-04	0.00E+00	1.87E+00	7.56E-03
RF-MT0089	5.30E-03	0.00E+00	4.25E-04	3.43E-02	7.76E-03	5.90E-05	4.27E-07	4.78E-02	1.93E-04
RF-MT0090	1.34E+01	0.00E+00	6.02E-01	8.82E+01	1.98E+01	5.90E-02	6.05E-04	1.22E+02	4.92E-01
RF-MT0091	8.33E+02	0.00E+00	6.11E+01	5.89E+03	1.33E+03	4.87E+00	6.44E-02	8.12E+03	3.27E+01
RF-MT0092	1.19E+02	0.00E+00	7.70E+00	8.44E+02	1.94E+02	6.74E-01	7.73E-03	1.17E+03	4.70E+00
RF-MT0093	1.45E+02	0.00E+00	7.93E+00	9.11E+02	2.12E+02	5.74E-01	7.96E-03	1.28E+03	5.15E+00
RF-MT0097	7.27E+00	0.00E+00	3.50E-01	4.76E+01	9.66E+00	3.14E-02	3.52E-04	6.49E+01	2.62E-01
RF-MT0099	7.96E-03	0.00E+00	6.39E-04	5.15E-02	1.16E-02	8.88E-05	6.42E-07	7.17E-02	2.89E-04
RF-MT0290	1.98E+01	0.00E+00	1.58E+00	1.27E+02	2.88E+01	2.20E-01	1.59E-03	1.78E+02	7.16E-01
RF-MT-0292	2.49E+01	0.00E+00	2.00E+00	1.61E+02	3.64E+01	2.78E-01	2.01E-03	2.25E+02	9.06E-01
RF-MT-0299	2.93E+03	0.00E+00	5.12E+01	4.13E+03	9.34E+02	7.15E+00	5.15E-02	8.05E+03	3.25E+01
RF-MT0302	4.49E-02	0.00E+00	2.03E-03	1.78E-01	4.04E-02	2.78E-04	1.89E-05	2.66E-01	1.07E-03
RF-MT0320	5.37E+01	0.00E+00	2.10E+00	1.73E+02	3.92E+01	2.79E-01	2.13E-03	2.68E+02	1.08E+00
RF-MT0321	3.00E+01	0.00E+00	6.28E-01	5.58E+01	1.25E+01	7.83E-02	3.04E-03	9.89E+01	3.99E-01
RF-MT-0328	2.08E+00	0.00E+00	7.52E-02	6.06E+00	1.37E+00	1.04E-02	4.14E-04	9.58E+00	3.86E-02
RF-MT0330	2.16E+01	0.00E+00	8.25E-01	1.22E+02	2.99E+01	9.82E-02	8.29E-04	1.75E+02	7.05E-01

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT-0331	1.30E+02	0.00E+00	5.12E+00	5.39E+02	1.19E+02	5.69E-01	2.59E-02	7.92E+02	3.19E+00
RF-MT0332	1.86E-02	0.00E+00	1.49E-03	1.21E-01	2.71E-02	2.07E-04	1.50E-06	1.68E-01	6.76E-04
RF-MT-0335	1.49E+00	0.00E+00	6.86E-02	6.20E+00	1.41E+00	8.46E-03	6.11E-04	9.17E+00	3.70E-02
RF-MT0336	1.06E+02	0.00E+00	4.54E+00	4.40E+02	9.93E+01	4.96E-01	6.38E-03	6.49E+02	2.62E+00
RF-MT0337	5.96E+01	0.00E+00	2.50E+00	2.69E+02	5.97E+01	2.42E-01	6.36E-03	3.91E+02	1.58E+00
RF-MT0339	1.63E+02	0.00E+00	6.80E+00	5.89E+02	1.32E+02	8.77E-01	2.39E-02	8.91E+02	3.59E+00
RF-MT-0342	9.58E-01	0.00E+00	5.70E-02	5.45E+00	1.21E+00	6.42E-03	1.16E-04	7.67E+00	3.09E-02
RF-MT0371	3.24E+02	0.00E+00	1.32E+01	1.07E+03	2.40E+02	1.83E+00	1.46E-02	1.64E+03	6.62E+00
RF-MT-0372	1.41E+00	0.00E+00	9.29E-02	7.43E+00	1.68E+00	1.13E-02	3.33E-04	1.06E+01	4.28E-02
RF-MT0373	2.13E+01	0.00E+00	9.55E-01	1.39E+02	3.13E+01	9.35E-02	9.59E-04	1.93E+02	7.78E-01
RF-MT0374	6.91E-01	0.00E+00	3.41E-02	2.76E+00	6.23E-01	4.74E-03	3.76E-05	4.11E+00	1.66E-02
RF-MT0376	5.48E-01	0.00E+00	2.76E-02	2.75E+00	6.30E-01	3.49E-03	4.28E-05	3.95E+00	1.59E-02
RF-MT0377	3.25E+02	0.00E+00	1.59E+01	1.28E+03	2.89E+02	2.20E+00	2.62E-02	1.91E+03	7.72E+00
RF-MT0378	3.66E+00	0.00E+00	2.20E-01	1.77E+01	4.00E+00	3.05E-02	2.21E-04	2.56E+01	1.03E-01
RF-MT0419	5.87E+00	0.00E+00	2.05E-01	1.65E+01	3.74E+00	2.85E-02	2.06E-04	2.63E+01	1.06E-01
RF-MT0420	1.02E+00	0.00E+00	3.56E-02	2.87E+00	6.49E-01	4.96E-03	3.58E-05	4.57E+00	1.84E-02
RF-MT0423	8.67E+00	0.00E+00	2.89E-01	4.14E+01	9.08E+00	1.96E-02	2.91E-04	5.95E+01	2.40E-01
RF-MT0425	2.56E-01	0.00E+00	8.91E-03	7.18E-01	1.62E-01	1.24E-03	8.95E-06	1.14E+00	4.62E-03
RF-MT-0438	2.32E+00	0.00E+00	1.17E-01	1.27E+01	2.85E+00	1.23E-02	1.31E-04	1.80E+01	7.27E-02
RF-MT0440	8.42E-01	0.00E+00	4.20E-02	4.62E+00	1.06E+00	5.06E-03	2.07E-04	6.57E+00	2.65E-02
RF-MT0442	3.20E-01	0.00E+00	1.81E-02	1.58E+00	3.57E-01	1.88E-03	1.13E-04	2.28E+00	9.19E-03
RF-MT0443	3.94E+00	0.00E+00	2.98E-01	2.46E+01	5.56E+00	3.91E-02	4.58E-04	3.44E+01	1.39E-01
RF-MT0444	3.08E+01	0.00E+00	1.46E+00	1.19E+02	2.67E+01	2.03E-01	1.49E-03	1.77E+02	7.15E-01
RF-MT0480	8.60E+01	0.00E+00	4.11E+00	3.33E+02	7.52E+01	5.22E-01	6.59E-03	4.98E+02	2.01E+00
RF-MT0488	1.38E+02	0.00E+00	6.13E+00	4.94E+02	1.11E+02	8.51E-01	3.71E-02	7.49E+02	3.02E+00
RF-MT0490	6.24E-01	0.00E+00	3.56E-02	2.92E+00	6.60E-01	4.70E-03	4.70E-05	4.24E+00	1.71E-02
RF-MT-0491	4.90E-02	0.00E+00	1.63E-03	1.32E-01	2.98E-02	2.20E-04	3.64E-06	2.13E-01	8.58E-04
RF-MT0523A	3.88E+01	0.00E+00	1.29E+00	1.05E+02	2.36E+01	1.79E-01	1.56E-03	1.68E+02	6.78E-01
RF-MT0523B	3.88E+01	0.00E+00	1.29E+00	1.05E+02	2.36E+01	1.79E-01	1.56E-03	1.68E+02	6.78E-01

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0523C	3.88E+01	0.00E+00	1.29E+00	1.05E+02	2.36E+01	1.79E-01	1.56E-03	1.68E+02	6.78E-01
RF-MT0523D	3.88E+01	0.00E+00	1.29E+00	1.05E+02	2.36E+01	1.79E-01	1.56E-03	1.68E+02	6.78E-01
RF-MT0523E	3.88E+01	0.00E+00	1.29E+00	1.05E+02	2.36E+01	1.79E-01	1.56E-03	1.68E+02	6.78E-01
RF-MT0531	2.65E-03	0.00E+00	2.13E-04	1.71E-02	3.88E-03	2.96E-05	2.14E-07	2.39E-02	9.62E-05
RF-MT0532E	1.24E+02	0.00E+00	2.77E+00	2.28E+02	5.14E+01	3.82E-01	3.89E-03	4.06E+02	1.64E+00
RF-MT0532F	1.24E+02	0.00E+00	2.77E+00	2.28E+02	5.14E+01	3.82E-01	3.89E-03	4.06E+02	1.64E+00
RF-MT0541	4.51E+00	0.00E+00	3.99E-02	3.24E+00	7.30E-01	5.59E-03	4.01E-05	8.51E+00	3.43E-02
RF-MT0545	2.41E-02	0.00E+00	1.93E-03	1.56E-01	3.52E-02	2.69E-04	1.94E-06	2.18E-01	8.77E-04
RF-MT0800	9.16E+02	0.00E+00	9.58E-01	7.72E+01	1.74E+01	1.33E-01	1.45E-03	1.01E+03	4.08E+00
RF-MT0801	1.05E+02	0.00E+00	9.37E-01	7.58E+01	1.71E+01	1.30E-01	9.42E-04	1.99E+02	8.03E-01
RF-MT0803	2.37E+00	0.00E+00	2.10E-02	1.69E+00	3.82E-01	2.91E-03	2.11E-05	4.46E+00	1.80E-02
RF-MT0806	1.12E+00	0.00E+00	5.03E-02	7.36E+00	1.64E+00	4.92E-03	5.06E-05	1.02E+01	4.10E-02
RF-MT0807	1.41E+01	0.00E+00	3.88E-01	3.13E+01	7.07E+00	5.38E-02	3.90E-04	5.28E+01	2.13E-01
RF-MT0816	1.51E+00	0.00E+00	5.47E-02	4.41E+00	9.93E-01	7.62E-03	5.49E-05	6.97E+00	2.81E-02
RF-MT-0823	7.47E-01	0.00E+00	2.49E-02	2.01E+00	4.54E-01	3.45E-03	2.99E-05	3.24E+00	1.31E-02
RF-MT0827	3.81E+01	0.00E+00	1.38E+00	1.12E+02	2.52E+01	1.92E-01	1.39E-03	1.76E+02	7.10E-01
RF-MT0831	7.26E+01	0.00E+00	3.79E+00	3.02E+02	6.83E+01	5.07E-01	1.60E-02	4.46E+02	1.80E+00
RF-MT0832	4.34E+02	0.00E+00	1.37E+01	1.18E+03	2.65E+02	1.81E+00	4.72E-02	1.89E+03	7.61E+00
RF-MT0833	1.32E+02	0.00E+00	4.11E+00	3.40E+02	7.67E+01	5.43E-01	1.33E-02	5.52E+02	2.23E+00
RF-MT0855	2.27E-02	0.00E+00	1.83E-03	1.47E-01	3.32E-02	2.54E-04	1.83E-06	2.05E-01	8.27E-04
RF-MT0857	1.12E+00	0.00E+00	5.01E-02	7.34E+00	1.64E+00	4.91E-03	5.03E-05	1.01E+01	4.09E-02
RF-MT0H61	4.14E+01	0.00E+00	1.86E+00	2.72E+02	6.10E+01	1.82E-01	1.87E-03	3.76E+02	1.52E+00
RF-MT2116	4.66E+00	0.00E+00	1.48E-01	1.25E+01	2.83E+00	1.94E-02	5.06E-04	2.02E+01	8.14E-02
RF-MT3010	2.92E+01	0.00E+00	1.53E+00	1.24E+02	2.83E+01	2.08E-01	1.93E-03	1.84E+02	7.40E-01
RF-MT3011	2.17E+02	0.00E+00	9.55E+00	7.69E+02	1.74E+02	1.33E+00	1.74E-02	1.17E+03	4.72E+00
RF-MT420P	1.16E+03	0.00E+00	4.83E+01	6.32E+03	1.43E+03	4.33E+00	5.86E-02	8.95E+03	3.61E+01
RF-MT532A	3.05E+02	0.00E+00	6.83E+00	5.63E+02	1.27E+02	9.40E-01	9.59E-03	1.00E+03	4.04E+00
RF-MT532B	1.37E+03	0.00E+00	3.07E+01	2.53E+03	5.70E+02	4.23E+00	4.30E-02	4.50E+03	1.81E+01
RF-MT532C	2.74E+03	0.00E+00	6.16E+01	5.07E+03	1.14E+03	8.46E+00	8.65E-02	9.01E+03	3.63E+01

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT532D	1.74E+01	0.00E+00	3.88E-01	3.21E+01	7.22E+00	5.33E-02	5.45E-04	5.70E+01	2.30E-01
RF-TT0069	9.97E-02	0.00E+00	4.60E-03	3.71E-01	8.39E-02	6.42E-04	7.81E-05	5.60E-01	2.26E-03
RF-TT0200	4.73E+00	0.00E+00	1.86E-01	1.52E+01	3.46E+00	2.47E-02	1.88E-04	2.36E+01	9.52E-02
RF-TT0299	1.96E+01	0.00E+00	3.44E-01	2.78E+01	6.28E+00	4.78E-02	3.46E-04	5.40E+01	2.18E-01
RF-TT0300	1.60E+02	0.00E+00	9.81E+00	7.97E+02	1.81E+02	1.16E+00	1.82E-02	1.15E+03	4.63E+00
RF-TT0301	2.16E+01	0.00E+00	1.33E+00	1.09E+02	2.46E+01	1.58E-01	2.47E-03	1.56E+02	6.29E-01
RF-TT0302	1.07E+00	0.00E+00	4.83E-02	4.24E+00	9.60E-01	6.63E-03	4.47E-04	6.32E+00	2.55E-02
RF-TT0303	6.43E+00	0.00E+00	2.82E-01	2.28E+01	5.14E+00	3.92E-02	1.32E-03	3.47E+01	1.40E-01
RF-TT0310	2.19E+01	0.00E+00	1.33E+00	1.03E+02	2.39E+01	1.44E-01	1.52E-03	1.50E+02	6.04E-01
RF-TT0312	5.26E+02	0.00E+00	2.39E+01	2.24E+03	5.02E+02	3.02E+00	2.58E-02	3.29E+03	1.33E+01
RF-TT0317	3.31E-01	0.00E+00	2.60E-02	2.10E+00	4.74E-01	3.61E-03	2.61E-05	2.93E+00	1.18E-02
RF-TT0320	2.12E+02	0.00E+00	8.33E+00	6.85E+02	1.55E+02	1.11E+00	8.42E-03	1.06E+03	4.28E+00
RF-TT0330	7.55E+01	0.00E+00	2.89E+00	4.30E+02	1.04E+02	3.44E-01	2.90E-03	6.13E+02	2.47E+00
RF-TT-0331	3.76E+02	0.00E+00	1.49E+01	1.56E+03	3.46E+02	1.66E+00	7.52E-02	2.30E+03	9.27E+00
RF-TT-0334	1.64E+02	0.00E+00	1.21E+01	9.72E+02	2.19E+02	1.68E+00	1.21E-02	1.37E+03	5.51E+00
RF-TT0335	1.99E+02	0.00E+00	9.14E+00	8.26E+02	1.88E+02	1.13E+00	8.14E-02	1.22E+03	4.93E+00
RF-TT0336	1.76E+02	0.00E+00	7.58E+00	7.32E+02	1.65E+02	8.25E-01	1.06E-02	1.08E+03	4.36E+00
RF-TT0337	2.09E+02	0.00E+00	8.77E+00	9.45E+02	2.10E+02	8.51E-01	2.23E-02	1.37E+03	5.53E+00
RF-TT0338	8.88E+02	0.00E+00	3.18E+01	3.68E+03	8.18E+02	3.80E+00	4.02E-02	5.42E+03	2.19E+01
RF-TT0340	7.59E+00	0.00E+00	6.08E-01	4.90E+01	1.11E+01	8.46E-02	6.11E-04	6.83E+01	2.75E-01
RF-TT0342	5.08E+01	0.00E+00	3.04E+00	2.89E+02	6.40E+01	3.40E-01	6.16E-03	4.07E+02	1.64E+00
RF-TT0360	3.87E+00	0.00E+00	1.54E-01	1.29E+01	2.96E+00	2.01E-02	1.61E-04	1.99E+01	8.03E-02
RF-TT0368	7.74E+01	0.00E+00	3.10E+00	2.60E+02	5.93E+01	4.03E-01	3.24E-03	4.00E+02	1.61E+00
RF-TT0370	1.53E+02	0.00E+00	6.68E+00	5.78E+02	1.31E+02	8.56E-01	1.46E-02	8.69E+02	3.50E+00
RF-TT0371	3.31E+00	0.00E+00	1.35E-01	1.09E+01	2.45E+00	1.87E-02	1.48E-04	1.67E+01	6.75E-02
RF-TT0372	4.04E-01	0.00E+00	2.65E-02	2.12E+00	4.80E-01	3.24E-03	9.50E-05	3.03E+00	1.22E-02
RF-TT0374	1.26E+01	0.00E+00	6.22E-01	5.01E+01	1.13E+01	8.62E-02	6.85E-04	7.46E+01	3.01E-01
RF-TT0375A	1.31E-01	0.00E+00	1.02E-02	8.23E-01	1.86E-01	1.42E-03	1.03E-05	1.15E+00	4.64E-03
RF-TT0375B	1.31E-01	0.00E+00	1.02E-02	8.23E-01	1.86E-01	1.42E-03	1.03E-05	1.15E+00	4.64E-03

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0376	3.01E+01	0.00E+00	1.52E+00	1.51E+02	3.46E+01	1.92E-01	2.36E-03	2.18E+02	8.77E-01
RF-TT0377	1.69E+01	0.00E+00	8.25E-01	6.65E+01	1.51E+01	1.14E-01	1.36E-03	9.93E+01	4.00E-01
RF-TT0391	3.77E+00	0.00E+00	1.16E-01	1.68E+01	3.75E+00	2.00E-02	1.17E-04	2.45E+01	9.86E-02
RF-TT0392	1.33E+00	0.00E+00	7.29E-02	8.79E+00	1.98E+00	6.95E-03	7.34E-05	1.22E+01	4.91E-02
RF-TT0393	1.09E+02	0.00E+00	5.09E+00	4.09E+02	9.26E+01	7.05E-01	5.11E-03	6.16E+02	2.48E+00
RF-TT0398	2.38E+00	0.00E+00	1.34E-01	1.64E+01	3.68E+00	1.31E-02	1.35E-04	2.26E+01	9.12E-02
RF-TT0409	1.99E+00	0.00E+00	6.28E-02	8.48E+00	1.90E+00	5.04E-03	6.37E-05	1.24E+01	5.01E-02
RF-TT0412	1.99E+00	0.00E+00	6.28E-02	8.48E+00	1.90E+00	5.04E-03	6.37E-05	1.24E+01	5.01E-02
RF-TT0414	6.17E+01	0.00E+00	1.94E+00	2.63E+02	5.87E+01	1.56E-01	1.97E-03	3.85E+02	1.55E+00
RF-TT0430	1.80E-02	0.00E+00	1.45E-03	1.17E-01	2.64E-02	2.01E-04	1.46E-06	1.62E-01	6.55E-04
RF-TT0431	4.49E+00	0.00E+00	3.53E-01	2.87E+01	6.48E+00	4.78E-02	5.77E-04	4.00E+01	1.61E-01
RF-TT0438	2.67E+02	0.00E+00	1.35E+01	1.46E+03	3.29E+02	1.42E+00	1.50E-02	2.07E+03	8.36E+00
RF-TT0440	2.63E+01	0.00E+00	1.31E+00	1.44E+02	3.33E+01	1.58E-01	6.48E-03	2.05E+02	8.28E-01
RF-TT0441	1.29E+02	0.00E+00	6.13E+00	4.99E+02	1.13E+02	8.41E-01	1.08E-02	7.47E+02	3.01E+00
RF-TT0442	1.87E+01	0.00E+00	1.06E+00	9.23E+01	2.09E+01	1.10E-01	6.59E-03	1.33E+02	5.36E-01
RF-TT0443	4.00E-01	0.00E+00	3.04E-02	2.50E+00	5.64E-01	3.97E-03	4.66E-05	3.49E+00	1.41E-02
RF-TT0479	3.92E+00	0.00E+00	3.15E-01	2.53E+01	5.72E+00	4.37E-02	3.17E-04	3.52E+01	1.42E-01
RF-TT0480	2.67E+02	0.00E+00	1.27E+01	1.04E+03	2.33E+02	1.62E+00	2.04E-02	1.55E+03	6.24E+00
RF-TT0481	1.50E-01	0.00E+00	7.18E-03	5.81E-01	1.32E-01	9.14E-04	1.15E-05	8.71E-01	3.51E-03
RF-TT0483	4.83E-01	0.00E+00	3.88E-02	3.12E+00	7.05E-01	5.38E-03	1.72E-02	4.36E+00	1.76E-02
RF-TT0484	2.58E+00	0.00E+00	1.61E-01	1.29E+01	2.93E+00	2.24E-02	2.72E-04	1.86E+01	7.51E-02
RF-TT0485	2.12E-01	0.00E+00	9.92E-03	7.98E-01	1.81E-01	1.38E-03	2.88E-04	1.20E+00	4.85E-03
RF-TT0486	1.26E+00	0.00E+00	5.87E-02	4.74E+00	1.07E+00	8.15E-03	2.87E-04	7.13E+00	2.87E-02
RF-TT0487	6.31E+00	0.00E+00	2.00E-01	1.70E+01	3.84E+00	2.63E-02	6.85E-04	2.74E+01	1.10E-01
RF-TT0489	1.80E+00	0.00E+00	8.97E-02	7.23E+00	1.63E+00	1.25E-02	1.91E-04	1.08E+01	4.33E-02
RF-TT0490	9.94E+01	0.00E+00	5.70E+00	4.66E+02	1.05E+02	7.47E-01	7.51E-03	6.76E+02	2.73E+00
RF-TT0491	2.31E+00	0.00E+00	7.70E-02	6.24E+00	1.41E+00	1.04E-02	1.73E-04	1.00E+01	4.05E-02
RF-TT0492	7.77E-01	0.00E+00	4.34E-02	3.48E+00	7.89E-01	6.01E-03	4.36E-05	5.09E+00	2.05E-02
RF-TT0523A	5.23E+00	0.00E+00	1.74E-01	1.40E+01	3.18E+00	2.41E-02	2.10E-04	2.26E+01	9.12E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0523B	5.23E+00	0.00E+00	1.74E-01	1.40E+01	3.18E+00	2.41E-02	2.10E-04	2.26E+01	9.12E-02
RF-TT0523C	5.23E+00	0.00E+00	1.74E-01	1.40E+01	3.18E+00	2.41E-02	2.10E-04	2.26E+01	9.12E-02
RF-TT0523D	5.23E+00	0.00E+00	1.74E-01	1.40E+01	3.18E+00	2.41E-02	2.10E-04	2.26E+01	9.12E-02
RF-TT0523E	5.23E+00	0.00E+00	1.74E-01	1.40E+01	3.18E+00	2.41E-02	2.10E-04	2.26E+01	9.12E-02
RF-TT0532A	1.31E+02	0.00E+00	2.92E+00	2.42E+02	5.45E+01	4.04E-01	4.10E-03	4.30E+02	1.74E+00
RF-TT0532B	1.31E+02	0.00E+00	2.92E+00	2.42E+02	5.45E+01	4.04E-01	4.10E-03	4.30E+02	1.74E+00
RF-TT0541	2.17E-01	0.00E+00	1.74E-02	1.40E+00	3.17E-01	2.42E-03	1.75E-05	1.95E+00	7.88E-03
RF-TT0545	4.83E-02	0.00E+00	3.88E-03	3.12E-01	7.05E-02	5.38E-04	3.89E-06	4.34E-01	1.75E-03
RF-TT0601	1.68E+01	0.00E+00	6.68E-01	5.63E+01	1.29E+01	8.72E-02	6.99E-04	8.66E+01	3.49E-01
RF-TT0802	1.88E+03	0.00E+00	5.50E+01	4.44E+03	1.00E+03	7.62E+00	5.52E-02	7.37E+03	2.97E+01
RF-TT0809	1.54E+02	0.00E+00	4.51E+00	3.65E+02	8.22E+01	6.27E-01	4.53E-03	6.06E+02	2.45E+00
RF-TT0821	3.34E+02	0.00E+00	1.64E+01	1.43E+03	3.25E+02	1.86E+00	1.84E-01	2.11E+03	8.50E+00
RF-TT0822	3.69E+02	0.00E+00	1.28E+01	1.08E+03	2.42E+02	1.66E+00	1.95E-01	1.70E+03	6.85E+00
RF-TT0823	7.47E-01	0.00E+00	2.49E-02	2.01E+00	4.54E-01	3.45E-03	2.99E-05	3.24E+00	1.31E-02
RF-TT0824	7.69E+02	0.00E+00	3.50E+01	2.90E+03	6.54E+02	4.69E+00	9.77E-02	4.36E+03	1.76E+01
RF-TT0825	6.39E+02	0.00E+00	2.53E+01	2.18E+03	4.92E+02	3.11E+00	1.06E-01	3.34E+03	1.35E+01
RF-TT0832	4.73E+02	0.00E+00	1.50E+01	1.27E+03	2.88E+02	1.97E+00	5.14E-02	2.05E+03	8.27E+00
RF-TT0854	1.70E-01	0.00E+00	1.37E-02	1.10E+00	2.49E-01	1.90E-03	7.61E-04	1.53E+00	6.16E-03
RF-TT0886	2.41E-02	0.00E+00	1.93E-03	1.55E-01	3.52E-02	2.68E-04	1.94E-06	2.17E-01	8.73E-04
RF-TT2216	6.98E+00	0.00E+00	2.21E-01	1.89E+01	4.25E+00	2.91E-02	7.59E-04	3.04E+01	1.22E-01
RF-TT3010	3.73E+02	0.00E+00	1.96E+01	1.59E+03	3.61E+02	2.66E+00	2.47E-02	2.35E+03	9.46E+00
RF-TT3011	9.41E+02	0.00E+00	4.14E+01	3.33E+03	7.52E+02	5.74E+00	7.52E-02	5.06E+03	2.04E+01
RF-TT301U	7.82E+01	0.00E+00	4.37E+00	3.61E+02	8.30E+01	5.64E-01	4.55E-03	5.27E+02	2.13E+00
RF-TT310P	2.26E+01	0.00E+00	1.14E+00	1.21E+02	2.61E+01	1.18E-01	1.15E-03	1.71E+02	6.91E-01
RF-TT338S	6.60E-01	0.00E+00	5.21E-02	4.19E+00	9.48E-01	7.21E-03	5.23E-05	5.85E+00	2.36E-02
RF-TT390P	3.72E+00	0.00E+00	1.41E-01	2.04E+01	4.24E+00	1.80E-02	1.71E-04	2.85E+01	1.15E-01
RF-TT391P	2.05E+02	0.00E+00	6.34E+00	9.17E+02	2.04E+02	1.09E+00	6.36E-03	1.33E+03	5.37E+00
RF-TT392P	4.15E+02	0.00E+00	2.28E+01	2.75E+03	6.19E+02	2.17E+00	2.30E-02	3.80E+03	1.53E+01
RF-TT393R	6.14E+01	0.00E+00	3.88E+00	4.20E+02	9.52E+01	3.50E-01	4.07E-03	5.81E+02	2.34E+00

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT394P	7.62E+00	0.00E+00	2.40E-01	3.25E+01	6.80E+00	2.52E-02	2.48E-04	4.71E+01	1.90E-01
RF-TT395P	1.02E+01	0.00E+00	3.21E-01	4.34E+01	9.08E+00	3.37E-02	3.32E-04	6.30E+01	2.54E-01
RF-TT396P	2.55E+00	0.00E+00	8.01E-02	1.09E+01	2.27E+00	8.41E-03	8.29E-05	1.58E+01	6.35E-02
RF-TT398P	2.47E+02	0.00E+00	1.39E+01	1.70E+03	3.81E+02	1.35E+00	1.40E-02	2.34E+03	9.45E+00
RF-TT398R	2.03E+03	0.00E+00	2.58E+01	2.75E+03	6.16E+02	2.64E+00	2.59E-02	5.42E+03	2.19E+01
RF-TT411R	7.37E+01	0.00E+00	2.32E+00	3.14E+02	7.01E+01	1.86E-01	2.35E-03	4.60E+02	1.85E+00
RF-TT429R	1.55E+02	0.00E+00	4.98E-01	7.27E+01	1.59E+01	3.25E-02	5.00E-04	2.44E+02	9.84E-01
RF-TT433X	4.88E+01	0.00E+00	1.38E-01	2.09E+01	4.14E+00	1.29E-02	1.38E-04	7.40E+01	2.98E-01
RF-TT436R	3.57E+02	0.00E+00	1.99E+00	2.74E+02	6.11E+01	2.49E-01	2.00E-03	6.94E+02	2.80E+00
RF-TT454X	2.10E+01	0.00E+00	1.17E-01	1.61E+01	3.60E+00	1.47E-02	1.18E-04	4.08E+01	1.65E-01
RL-T101	1.06E+02	0.00E+00	7.12E+00	8.71E+02	1.93E+02	2.07E+00	6.27E-03	1.18E+03	4.75E+00
RL-T102	1.35E-03	0.00E+00	9.06E-05	1.12E-02	2.46E-03	2.63E-05	1.23E-06	1.51E-02	6.07E-05
RL-T103	9.56E+01	0.00E+00	8.62E+00	3.80E+02	8.36E+01	1.10E+00	7.60E-03	5.68E+02	2.29E+00
RL-T104	1.93E-03	0.00E+00	1.29E-04	1.58E-02	3.52E-03	3.77E-05	1.47E-07	2.14E-02	8.63E-05
RL-T105	7.42E-01	0.00E+00	4.89E-02	6.01E+00	1.33E+00	1.43E-02	8.79E-05	8.13E+00	3.28E-02
RL-T106	7.15E-01	0.00E+00	4.80E-02	5.87E+00	1.30E+00	1.39E-02	4.23E-05	7.94E+00	3.20E-02
RL-T107	1.97E+03	0.00E+00	2.82E+04	1.62E+04	3.58E+03	3.83E+01	2.57E+01	5.00E+04	2.02E+02
RL-T108	1.12E+00	0.00E+00	4.86E+00	9.24E+00	2.05E+00	2.19E-02	4.31E-03	1.73E+01	6.97E-02
RL-T109	1.55E+00	0.00E+00	1.00E-01	1.22E+01	2.71E+00	2.91E-02	2.34E-02	1.66E+01	6.71E-02
RL-T110	1.74E+02	0.00E+00	1.91E+01	1.40E+03	3.12E+02	3.34E+00	1.38E+00	1.91E+03	7.70E+00
RL-T112	6.99E+01	0.00E+00	8.07E+00	1.86E+02	4.12E+01	4.42E-01	7.43E-01	3.06E+02	1.23E+00
RL-T113	7.47E-02	0.00E+00	1.56E-02	6.13E-01	1.36E-01	1.46E-03	1.37E-05	8.39E-01	3.38E-03
RL-T114	1.14E+01	0.00E+00	7.61E-01	9.32E+01	2.07E+01	2.21E-01	6.71E-04	1.26E+02	5.08E-01
RL-T115	2.89E+02	0.00E+00	2.47E+01	1.22E+03	2.71E+02	3.26E+00	4.35E-01	1.81E+03	7.30E+00
RL-T116	1.86E+01	0.00E+00	1.25E+00	1.52E+02	3.38E+01	3.63E-01	5.73E-02	2.06E+02	8.31E-01
RL-T118	4.79E+01	0.00E+00	9.98E+00	1.51E+02	3.35E+01	3.60E-01	8.41E-01	2.44E+02	9.82E-01
RL-T120	1.16E+01	0.00E+00	1.05E+00	4.48E+01	9.84E+00	1.26E-01	9.24E-04	6.73E+01	2.71E-01
RL-T122	6.59E-01	0.00E+00	4.43E-02	5.40E+00	1.20E+00	1.29E-02	1.46E+00	8.76E+00	3.53E-02
RL-T123	1.94E+00	0.00E+00	1.30E-01	1.58E+01	3.52E+00	3.78E-02	5.98E-02	2.15E+01	8.66E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T125	3.86E+02	0.00E+00	3.21E+01	3.32E+02	1.69E+02	5.90E+00	2.83E-02	9.19E+02	3.70E+00
RL-T127	3.72E+02	0.00E+00	8.07E+00	9.91E+02	2.19E+02	2.35E+00	8.71E-02	1.59E+03	6.41E+00
RL-T128	5.50E-01	0.00E+00	1.96E-07	2.41E-05	5.32E-06	5.69E-08	1.73E-10	5.50E-01	2.22E-03
RL-T129	1.65E+00	0.00E+00	3.73E+01	1.36E+01	3.00E+00	3.22E-02	4.06E-02	5.57E+01	2.24E-01
RL-T130	3.51E-03	0.00E+00	2.36E-04	2.90E-02	6.40E-03	6.84E-05	8.32E-05	3.92E-02	1.58E-04
RL-T131	1.43E+00	0.00E+00	1.29E-01	5.52E+00	1.21E+00	1.55E-02	8.34E-03	8.29E+00	3.34E-02
RL-T132	3.40E+02	0.00E+00	2.27E+01	2.80E+03	6.19E+02	6.63E+00	2.65E-01	3.78E+03	1.52E+01
RL-T133	6.93E-03	0.00E+00	3.65E-04	4.59E-02	1.01E-02	9.40E-05	3.21E-07	6.33E-02	2.55E-04
RL-T134	1.47E-02	0.00E+00	9.81E-04	1.21E-01	2.66E-02	2.86E-04	8.64E-07	1.63E-01	6.56E-04
RL-T135	6.85E-02	0.00E+00	4.60E-03	5.63E-01	1.25E-01	1.34E-03	4.15E-03	7.66E-01	3.09E-03
RL-T137	1.11E+03	0.00E+00	1.00E+02	4.29E+03	9.44E+02	1.22E+01	9.47E-02	6.45E+03	2.60E+01
RL-T140	1.30E+03	0.00E+00	9.55E+01	4.15E+03	1.01E+03	1.03E+01	2.63E+01	6.59E+03	2.66E+01
RL-T143	8.17E+00	0.00E+00	5.47E-01	6.71E+01	1.49E+01	1.59E-01	3.91E-02	9.07E+01	3.66E-01
RL-T145	2.32E+01	0.00E+00	1.56E+00	1.91E+02	4.22E+01	4.53E-01	9.09E-02	2.58E+02	1.04E+00
RL-W407	6.68E+01	0.00E+00	3.33E+00	4.38E+02	9.70E+01	6.89E-01	2.93E-03	6.05E+02	2.44E+00
RL-W408	2.74E-04	0.00E+00	1.41E-05	1.77E-03	3.92E-04	3.55E-06	1.24E-08	2.45E-03	9.89E-06
RL-W415	6.05E-03	0.00E+00	3.10E-04	3.92E-02	8.67E-03	7.83E-05	2.73E-07	5.43E-02	2.19E-04
RL-W418	2.59E-02	0.00E+00	1.31E-03	1.68E-01	3.73E-02	2.92E-04	1.15E-06	2.33E-01	9.38E-04
RL-W437	2.19E+02	0.00E+00	1.09E+01	1.43E+03	3.18E+02	2.26E+00	9.64E-03	1.98E+03	7.99E+00
RL-W438	3.83E-04	0.00E+00	1.97E-05	2.48E-03	5.48E-04	4.96E-06	1.73E-08	3.43E-03	1.38E-05
RL-W439	1.20E+04	0.00E+00	1.08E+03	4.78E+04	1.05E+04	1.38E+02	9.54E-01	7.14E+04	2.88E+02
RL-W443	1.93E+02	0.00E+00	9.63E+00	1.26E+03	2.79E+02	1.99E+00	8.49E-03	1.75E+03	7.04E+00
RL-W444	1.43E+02	0.00E+00	7.15E+00	9.38E+02	2.08E+02	1.48E+00	6.30E-03	1.30E+03	5.22E+00
RL-W447	1.64E-02	0.00E+00	8.42E-04	1.06E-01	2.35E-02	2.13E-04	7.42E-07	1.46E-01	5.90E-04
RL-W448	1.21E-04	0.00E+00	6.22E-06	7.83E-04	1.73E-04	1.57E-06	5.48E-09	1.08E-03	4.37E-06
RL-W449	9.97E-01	0.00E+00	2.28E-04	2.24E-02	4.96E-03	2.85E-05	2.01E-07	1.02E+00	4.13E-03
RL-W450	1.83E-03	0.00E+00	9.37E-05	1.19E-02	2.62E-03	2.37E-05	8.26E-08	1.64E-02	6.61E-05
RL-W451	2.61E-04	0.00E+00	1.34E-05	1.68E-03	3.73E-04	3.38E-06	1.18E-08	2.33E-03	9.39E-06
RL-W452	1.14E-02	0.00E+00	5.76E-04	7.42E-02	1.64E-02	1.29E-04	5.07E-07	1.03E-01	4.13E-04

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W453	3.24E-03	0.00E+00	1.62E-04	2.13E-02	4.70E-03	3.35E-05	1.43E-07	2.94E-02	1.19E-04
RL-W454	4.53E-02	0.00E+00	2.27E-03	2.98E-01	6.58E-02	4.68E-04	2.00E-06	4.11E-01	1.66E-03
RL-W455	1.21E-02	0.00E+00	6.11E-04	7.87E-02	1.74E-02	1.37E-04	5.38E-07	1.09E-01	4.39E-04
RL-W456	1.59E+00	0.00E+00	7.99E-02	1.05E+01	2.31E+00	1.69E-02	7.04E-05	1.44E+01	5.82E-02
RL-W457	1.55E-01	0.00E+00	7.75E-03	1.02E+00	2.24E-01	1.63E-03	6.83E-06	1.40E+00	5.65E-03
RL-W458	4.90E-01	0.00E+00	3.96E-02	4.17E-01	2.30E-01	6.58E-03	3.49E-05	1.18E+00	4.75E-03
RL-W459	4.71E+00	0.00E+00	4.08E-01	1.04E+01	3.14E+00	6.53E-02	3.60E-04	1.86E+01	7.50E-02
RL-W460	2.87E-02	0.00E+00	1.44E-03	1.88E-01	4.17E-02	2.97E-04	1.27E-06	2.60E-01	1.05E-03
RL-W461	2.65E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.65E-02	1.07E-04
RL-W462	8.19E-03	0.00E+00	4.17E-04	5.33E-02	1.18E-02	9.71E-05	3.67E-07	7.37E-02	2.97E-04
RL-W463	4.21E-02	0.00E+00	2.11E-03	2.77E-01	6.12E-02	4.35E-04	1.86E-06	3.82E-01	1.54E-03
RL-W464	1.95E-02	0.00E+00	9.69E-04	1.27E-01	2.81E-02	2.01E-04	8.54E-07	1.76E-01	7.10E-04
RL-W465	1.30E-01	0.00E+00	6.57E-03	8.48E-01	1.88E-01	1.45E-03	5.79E-06	1.17E+00	4.73E-03
RL-W466	1.78E+00	0.00E+00	8.94E-02	1.17E+01	2.58E+00	1.93E-02	7.88E-05	1.61E+01	6.49E-02
RL-W467	9.10E-02	0.00E+00	4.60E-03	5.93E-01	1.31E-01	1.06E-03	4.05E-06	8.20E-01	3.31E-03
RL-W468	4.67E-04	0.00E+00	2.37E-05	3.04E-03	6.72E-04	5.54E-06	2.09E-08	4.20E-03	1.69E-05
RL-W469	1.89E-01	0.00E+00	9.52E-03	1.23E+00	2.74E-01	2.04E-03	8.39E-06	1.71E+00	6.89E-03
RL-W470	5.35E+00	0.00E+00	4.43E-01	4.58E+00	2.34E+00	8.20E-02	3.90E-04	1.27E+01	5.13E-02
RL-W474	2.03E-01	0.00E+00	4.89E-02	1.05E-02	8.85E-03	0.00E+00	4.31E-05	2.71E-01	1.09E-03
RL-W476	3.42E-01	0.00E+00	1.76E-02	2.29E+00	5.09E-01	3.70E-03	1.55E-05	3.16E+00	1.27E-02
RL-W480	5.58E-02	0.00E+00	2.82E-03	3.63E-01	8.06E-02	6.32E-04	2.48E-06	5.03E-01	2.03E-03
RL-W481	8.76E-02	0.00E+00	4.43E-03	5.70E-01	1.26E-01	9.92E-04	3.90E-06	7.88E-01	3.18E-03
RL-W482	1.16E+02	0.00E+00	1.47E+00	7.26E-02	1.34E-01	1.32E+00	1.30E-03	1.18E+02	4.76E-01
RL-W483	8.69E+00	0.00E+00	1.14E-01	4.70E-03	9.50E-03	9.82E-02	1.01E-04	8.82E+00	3.56E-02
RL-W484	3.68E-02	0.00E+00	9.20E-04	6.56E-02	1.55E-02	8.15E-05	8.11E-07	1.19E-01	4.79E-04
RL-W485	2.15E-03	0.00E+00	1.30E-04	7.10E-03	1.68E-03	0.00E+00	1.15E-07	1.11E-02	4.46E-05
RL-W486	9.10E-04	0.00E+00	5.50E-05	3.00E-03	7.07E-04	0.00E+00	4.84E-08	4.67E-03	1.88E-05
RL-W487	1.48E-01	0.00E+00	7.06E-03	4.29E-01	1.17E-01	7.57E-04	6.22E-06	7.02E-01	2.83E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W489	9.03E-02	0.00E+00	6.65E-03	5.56E-01	1.25E-01	1.22E-03	5.86E-06	7.77E-01	3.13E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	3.35E-02	0.00E+00	5.61E-03	5.82E-02	1.27E-02	4.44E-04	4.95E-06	1.10E-01	4.44E-04
RL-W492	1.93E-03	0.00E+00	1.38E-04	1.17E-02	2.61E-03	2.55E-05	1.22E-07	1.63E-02	6.58E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.66E+01	0.00E+00	8.01E+00	2.94E-01	2.49E-01	1.02E+00	7.06E-03	8.51E+01	3.43E-01
RL-W495	1.39E+00	0.00E+00	2.18E-02	2.82E-03	2.22E-03	1.86E-02	1.92E-05	1.41E+00	5.70E-03
RL-W496	9.00E+00	0.00E+00	2.51E-01	9.26E-03	7.37E-03	1.21E-01	2.21E-04	9.27E+00	3.74E-02
RL-W497	3.75E-01	0.00E+00	4.95E-02	5.56E-01	2.50E-01	3.16E-03	4.36E-05	1.23E+00	4.96E-03
RL-W498	1.46E+00	0.00E+00	7.35E-02	9.50E+00	2.11E+00	1.65E-02	6.48E-05	1.31E+01	5.30E-02
RL-W499	1.31E-05	0.00E+00	6.60E-07	8.51E-05	1.89E-05	1.48E-07	5.81E-10	1.18E-04	4.75E-07
RL-W500	9.30E-04	0.00E+00	8.19E-05	3.47E-03	7.65E-04	1.04E-05	7.22E-08	5.25E-03	2.12E-05
RL-W501	3.85E+01	0.00E+00	1.83E+00	1.12E+02	3.03E+01	1.96E-01	1.61E-03	1.82E+02	7.34E-01
RL-W502	6.97E-03	0.00E+00	3.53E-04	4.54E-02	1.00E-02	7.89E-05	3.11E-07	6.28E-02	2.53E-04
RL-W503	4.03E-01	0.00E+00	3.62E-02	1.60E+00	3.52E-01	4.64E-03	3.19E-05	2.39E+00	9.65E-03
RL-W504	1.48E-01	0.00E+00	7.06E-03	4.29E-01	1.17E-01	7.57E-04	6.22E-06	7.02E-01	2.83E-03
RL-W505	7.00E-03	0.00E+00	3.70E-04	4.64E-02	1.02E-02	9.50E-05	3.26E-07	6.40E-02	2.58E-04
RL-W506	2.53E-03	0.00E+00	1.46E-04	1.52E-02	3.37E-03	2.85E-05	1.28E-07	2.13E-02	8.58E-05
RL-W507	2.52E-04	0.00E+00	1.27E-05	1.64E-03	3.63E-04	2.85E-06	1.12E-08	2.27E-03	9.15E-06
RL-W508	4.63E+00	0.00E+00	4.17E-01	1.78E+01	3.92E+00	5.06E-02	3.67E-04	2.68E+01	1.08E-01
RL-W509	4.56E+01	0.00E+00	3.33E+00	1.45E+02	3.53E+01	3.62E-01	2.93E-03	2.30E+02	9.26E-01
RL-W510	3.84E+00	0.00E+00	3.41E-01	1.44E+01	3.18E+00	4.31E-02	3.01E-04	2.18E+01	8.79E-02
RL-W511	3.91E+02	0.00E+00	1.65E+01	1.93E+03	4.19E+02	2.35E+00	1.49E-02	2.76E+03	1.11E+01
RL-W512	3.42E+02	0.00E+00	1.11E+01	1.17E+03	2.87E+02	1.20E+00	9.79E-03	1.81E+03	7.28E+00
RL-W513	3.65E+04	0.00E+00	4.51E+03	1.90E+04	9.36E+03	1.91E+02	3.98E+00	6.94E+04	2.80E+02
RL-W514	1.03E-03	0.00E+00	5.18E-05	6.74E-03	1.50E-03	1.11E-05	4.56E-08	9.32E-03	3.76E-05
RL-W515	4.03E-02	0.00E+00	2.03E-03	2.63E-01	5.80E-02	4.55E-04	1.79E-06	3.63E-01	1.46E-03
RL-W516	5.59E-02	0.00E+00	2.82E-03	3.63E-01	8.06E-02	6.32E-04	2.49E-06	5.03E-01	2.03E-03
RL-W517	4.98E-10	0.00E+00	2.52E-11	3.24E-09	7.15E-10	5.90E-12	2.22E-14	4.47E-09	1.80E-11

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W518	1.41E+00	0.00E+00	1.06E-01	4.64E+00	1.11E+00	1.27E-02	9.36E-05	7.26E+00	2.93E-02
RL-W519	2.51E-01	0.00E+00	1.26E-02	1.64E+00	3.63E-01	2.68E-03	1.11E-05	2.27E+00	9.15E-03
RL-W520	2.77E-02	0.00E+00	1.42E-03	1.80E-01	3.98E-02	3.44E-04	1.25E-06	2.49E-01	1.01E-03
RL-W521	5.16E-04	0.00E+00	2.60E-05	3.36E-03	7.44E-04	5.85E-06	2.29E-08	4.64E-03	1.87E-05
RL-W522	1.08E+01	0.00E+00	9.66E-01	2.22E+01	6.30E+00	8.46E-02	8.52E-04	4.03E+01	1.62E-01
RL-W523	3.24E+00	0.00E+00	3.67E-01	1.47E+00	8.88E-01	1.68E-02	3.24E-04	5.97E+00	2.41E-02
RL-W524	1.34E+01	0.00E+00	1.41E+00	1.35E+01	5.20E+00	7.99E-02	1.24E-03	3.36E+01	1.35E-01
RL-W525	1.07E+00	0.00E+00	9.52E-02	1.60E+00	5.26E-01	6.27E-03	8.39E-05	3.29E+00	1.33E-02
RL-W526	4.04E+00	0.00E+00	3.44E-01	1.71E+01	3.80E+00	4.56E-02	3.03E-04	2.53E+01	1.02E-01
RL-W527	4.43E-01	0.00E+00	4.98E-02	1.81E+00	4.27E-01	5.33E-03	4.39E-05	2.73E+00	1.10E-02
RL-W528	1.98E+02	0.00E+00	2.12E+01	5.77E+01	5.49E+01	8.15E-01	1.86E-02	3.32E+02	1.34E+00
RL-W529	1.65E-01	0.00E+00	1.49E-02	6.37E-01	1.40E-01	1.80E-03	1.31E-05	9.57E-01	3.86E-03
RL-W530	1.94E+00	0.00E+00	1.72E-01	7.28E+00	1.60E+00	2.18E-02	1.52E-04	1.10E+01	4.43E-02
RL-W531	1.16E+02	0.00E+00	1.73E+01	3.15E+01	2.25E+01	5.80E-01	1.53E-02	1.87E+02	7.55E-01
RL-W532	3.72E-01	0.00E+00	1.88E-02	2.43E+00	5.37E-01	4.21E-03	1.66E-05	3.36E+00	1.35E-02
RL-W533	1.80E-01	0.00E+00	1.62E-02	6.95E-01	1.52E-01	1.95E-03	1.43E-05	1.04E+00	4.21E-03
RL-W534	1.04E-05	0.00E+00	5.24E-07	6.78E-05	1.51E-05	1.18E-07	4.62E-10	9.38E-05	3.78E-07
RL-W535	5.44E+01	0.00E+00	5.18E+00	8.69E+01	2.64E+01	3.58E-01	4.56E-03	1.73E+02	6.97E-01
RL-W536	1.07E+00	0.00E+00	6.97E-02	3.02E+00	6.79E-01	8.20E-03	6.47E-05	4.83E+00	1.95E-02
RL-W537	3.63E+01	0.00E+00	1.57E+00	1.85E+02	4.03E+01	2.29E-01	1.41E-03	2.63E+02	1.06E+00
RL-W538	1.32E-04	0.00E+00	6.65E-06	8.61E-04	1.91E-04	1.49E-06	5.86E-09	1.19E-03	4.80E-06
RL-W539	1.47E-02	0.00E+00	7.49E-04	9.52E-02	2.11E-02	1.82E-04	6.60E-07	1.32E-01	5.31E-04
RL-W540	2.85E+01	0.00E+00	3.30E+00	3.42E+01	1.17E+01	1.74E-01	2.91E-03	7.78E+01	3.14E-01
RL-W541	4.24E-02	0.00E+00	2.16E-03	2.76E-01	6.10E-02	5.12E-04	1.91E-06	3.81E-01	1.54E-03
RL-W542	1.97E+00	0.00E+00	1.61E-01	6.98E+00	1.60E+00	2.10E-02	1.42E-04	1.07E+01	4.32E-02
RL-W543	6.20E-03	0.00E+00	3.13E-04	4.04E-02	8.95E-03	7.05E-05	2.75E-07	5.59E-02	2.25E-04
RL-W544	1.40E-01	0.00E+00	1.28E-02	4.60E-01	1.14E-01	1.40E-03	1.12E-05	7.27E-01	2.93E-03
RL-W545	3.72E-02	0.00E+00	1.88E-03	2.42E-01	5.36E-02	4.20E-04	1.65E-06	3.35E-01	1.35E-03
RL-W546	1.63E-03	0.00E+00	8.22E-05	1.07E-02	2.35E-03	1.84E-05	7.24E-08	1.47E-02	5.93E-05

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W547	4.16E-05	0.00E+00	2.10E-06	2.71E-04	6.00E-05	4.70E-07	1.85E-09	3.75E-04	1.51E-06
RL-W548	3.60E-05	0.00E+00	1.82E-06	2.34E-04	5.18E-05	4.21E-07	1.61E-09	3.24E-04	1.31E-06
RL-W549	7.15E+00	0.00E+00	7.32E-01	1.21E+01	3.56E+00	5.33E-02	6.45E-04	2.35E+01	9.47E-02
RL-W550	3.24E+01	0.00E+00	1.39E+00	1.63E+02	3.56E+01	2.01E-01	1.24E-03	2.33E+02	9.38E-01
RL-W551	5.76E+01	0.00E+00	2.05E+00	1.84E+02	4.64E+01	2.14E-01	1.81E-03	2.90E+02	1.17E+00
RL-W552	2.23E-02	0.00E+00	1.13E-03	1.45E-01	3.21E-02	2.67E-04	1.00E-06	2.01E-01	8.10E-04
RL-W553	1.98E-03	0.00E+00	1.07E-04	1.29E-02	2.86E-03	3.37E-05	9.43E-08	1.79E-02	7.21E-05
RL-W554	3.15E-02	0.00E+00	1.59E-03	2.05E-01	4.54E-02	3.56E-04	1.40E-06	2.84E-01	1.14E-03
RL-W555	1.45E-02	0.00E+00	7.32E-04	9.45E-02	2.09E-02	1.64E-04	6.45E-07	1.31E-01	5.26E-04
RL-W563	2.08E-01	0.00E+00	1.83E-02	7.83E-01	1.72E-01	2.24E-03	1.61E-05	1.18E+00	4.77E-03
RL-W564	1.35E-01	0.00E+00	1.22E-02	5.07E-01	1.11E-01	1.72E-03	1.07E-05	7.65E-01	3.09E-03
RL-W565	1.34E-02	0.00E+00	6.83E-04	8.75E-02	1.94E-02	1.59E-04	6.02E-07	1.21E-01	4.88E-04
RL-W566	1.97E-01	0.00E+00	1.00E-02	1.28E+00	2.85E-01	2.27E-03	8.82E-06	1.78E+00	7.16E-03
RL-W567	1.37E+01	0.00E+00	2.56E-01	3.95E-02	3.17E-02	1.92E-01	2.25E-04	1.40E+01	5.64E-02
RL-W568	2.63E+02	0.00E+00	5.38E+00	1.87E+00	1.48E+00	3.97E+00	4.74E-03	2.72E+02	1.10E+00
RL-W569	2.16E-01	0.00E+00	4.05E-03	6.24E-04	5.02E-05	3.04E-03	3.57E-06	2.21E-01	8.91E-04
RL-W570	1.39E-02	0.00E+00	7.09E-04	9.28E-02	2.05E-02	1.50E-04	6.25E-07	1.28E-01	5.15E-04
RL-W571	4.44E+01	0.00E+00	2.41E+00	7.53E+00	3.74E+00	6.06E-01	2.12E-03	5.81E+01	2.34E-01
RL-W572	3.86E-02	0.00E+00	7.20E-04	4.05E-03	8.95E-05	5.43E-04	6.35E-07	4.34E-02	1.75E-04
RL-W573	4.97E+02	0.00E+00	9.23E+00	2.22E+00	1.65E+00	6.89E+00	8.13E-03	5.10E+02	2.06E+00
RL-W574	2.14E+03	0.00E+00	3.99E+01	8.48E+00	6.12E+00	3.01E+01	3.52E-02	2.19E+03	8.83E+00
RL-W575	1.39E+04	0.00E+00	2.69E+02	8.11E+01	4.89E+01	1.89E+02	2.37E-01	1.43E+04	5.77E+01
RL-W576	1.00E+03	0.00E+00	1.88E+01	4.13E+00	2.95E+00	1.42E+01	1.66E-02	1.03E+03	4.15E+00
RL-W579	8.50E-02	0.00E+00	4.95E-04	2.07E-02	4.59E-03	4.99E-05	4.36E-07	1.11E-01	4.47E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.65E-01	2.68E-02	0.00E+00	0.00E+00	1.92E-01	7.74E-04
RL-W581	9.02E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.02E-01	3.64E-03
RL-W582	5.90E-03	0.00E+00	4.20E-04	5.30E-03	2.72E-03	8.09E-06	3.70E-07	1.43E-02	5.78E-05
RL-W583	4.56E-03	0.00E+00	2.28E-04	2.99E-02	6.62E-03	4.71E-05	2.01E-07	4.13E-02	1.66E-04
RL-W584	9.07E-02	0.00E+00	1.50E-02	1.74E-01	8.48E-02	2.37E-04	1.32E-05	3.65E-01	1.47E-03

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W585	5.39E-01	0.00E+00	7.96E-02	1.02E+00	5.15E-01	7.21E-03	7.01E-05	2.15E+00	8.67E-03
RL-W586	7.19E-05	0.00E+00	3.59E-06	4.72E-04	1.04E-04	7.42E-07	3.16E-09	6.52E-04	2.63E-06
RL-W587	1.54E-03	0.00E+00	7.75E-05	1.01E-02	2.23E-03	1.67E-05	6.83E-08	1.39E-02	5.61E-05
RL-W588	6.35E-02	0.00E+00	1.26E-02	1.47E-01	7.14E-02	1.99E-04	1.11E-05	2.95E-01	1.19E-03
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	1.95E+00	0.00E+00	2.69E-01	1.14E-02	2.01E-02	2.61E-02	2.37E-04	2.25E+00	9.07E-03
RL-W591	1.11E+01	0.00E+00	3.04E-01	1.40E-02	2.60E-02	1.58E-01	2.68E-04	1.15E+01	4.62E-02
RL-W592	4.91E+01	0.00E+00	3.33E+00	6.51E-01	8.40E-01	6.37E-01	2.93E-03	5.39E+01	2.17E-01
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.35E-02	3.94E-02	0.00E+00	0.00E+00	6.29E-02	2.54E-04
RL-W594	4.42E+01	0.00E+00	5.99E-01	2.91E-02	5.33E-02	1.59E-01	5.28E-04	4.49E+01	1.81E-01
RL-W595	1.17E-01	0.00E+00	6.25E-02	1.99E-02	3.88E-02	1.58E-03	5.51E-05	2.38E-01	9.60E-04
RL-W596	3.78E-02	0.00E+00	4.86E-03	2.05E-04	3.64E-04	4.74E-04	4.28E-06	4.32E-02	1.74E-04
RL-W597	6.95E+01	0.00E+00	2.14E+00	3.97E-01	6.60E-01	8.83E-01	1.88E-03	7.27E+01	2.93E-01
RL-W598	7.35E+01	0.00E+00	1.26E+01	5.54E-01	8.23E-01	9.14E-01	1.11E-02	8.75E+01	3.53E-01
RL-W599	3.72E+00	0.00E+00	1.02E-01	4.68E-03	8.67E-03	5.27E-02	8.98E-05	3.84E+00	1.55E-02
RL-W600	2.11E-07	0.00E+00	1.06E-08	1.38E-06	3.07E-07	2.18E-09	9.31E-12	1.91E-06	7.71E-09
RL-W601	1.07E-03	0.00E+00	5.79E-05	7.01E-03	1.55E-03	1.83E-05	5.10E-08	9.69E-03	3.91E-05
RL-W602	9.34E-01	0.00E+00	4.75E-02	6.07E+00	1.35E+00	1.11E-02	4.18E-05	8.40E+00	3.39E-02
RL-W603	5.38E+00	0.00E+00	2.74E-01	3.50E+01	7.76E+00	6.37E-02	2.41E-04	4.85E+01	1.95E-01
RL-W604	1.26E-02	0.00E+00	7.18E-04	1.70E-02	8.36E-03	7.57E-05	6.32E-07	3.87E-02	1.56E-04
RL-W605	2.88E-03	0.00E+00	1.56E-04	1.88E-02	4.17E-03	4.91E-05	1.37E-07	2.60E-02	1.05E-04
RL-W606	1.16E-03	0.00E+00	6.28E-05	7.59E-03	1.68E-03	1.98E-05	5.53E-08	1.05E-02	4.23E-05
RL-W607	2.13E-03	0.00E+00	1.22E-04	2.88E-03	1.42E-03	1.28E-05	1.07E-07	6.55E-03	2.64E-05
RL-W608	2.55E-02	0.00E+00	4.72E-03	3.74E-03	4.59E-03	1.96E-04	4.16E-06	3.85E-02	1.55E-04
RL-W610	5.04E+00	0.00E+00	2.52E-01	3.31E+01	7.32E+00	5.21E-02	2.22E-04	4.57E+01	1.84E-01
RL-W612	1.19E-02	0.00E+00	6.11E-04	8.02E-02	1.78E-02	1.23E-04	5.38E-07	1.11E-01	4.46E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.37E-01	0.00E+00	0.00E+00	0.00E+00	3.37E-01	1.36E-03
RL-W622	1.99E-04	0.00E+00	9.95E-06	1.30E-03	2.88E-04	2.05E-06	8.77E-09	1.80E-03	7.26E-06
RL-W625	6.92E-03	0.00E+00	1.51E-03	6.66E-03	6.51E-03	1.11E-04	1.33E-06	2.16E-02	8.71E-05

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W626	3.72E-01	0.00E+00	3.44E-02	2.61E-01	1.55E-01	1.94E-03	3.03E-05	8.22E-01	3.32E-03
RL-W627	1.75E-03	0.00E+00	4.60E-05	1.23E-06	0.00E+00	2.31E-05	4.05E-08	1.80E-03	7.25E-06
RL-W628	5.74E-04	0.00E+00	2.89E-05	3.76E-03	8.32E-04	6.21E-06	2.55E-08	5.20E-03	2.10E-05
RL-W629	3.89E-05	0.00E+00	1.99E-06	2.53E-04	5.59E-05	4.83E-07	1.75E-09	3.50E-04	1.41E-06
RL-W630	4.28E-01	0.00E+00	3.70E-02	2.93E+00	6.74E-01	5.22E-03	3.26E-05	4.07E+00	1.64E-02
RL-W631	6.90E-03	0.00E+00	3.73E-04	4.49E-02	9.93E-03	1.18E-04	3.29E-07	6.21E-02	2.50E-04
RL-W632	3.04E+00	0.00E+00	5.03E-02	5.93E+00	1.94E+00	3.91E-02	4.44E-05	1.10E+01	4.42E-02
RL-W633	7.26E-03	0.00E+00	2.92E-04	9.32E-04	8.18E-04	4.81E-05	2.58E-07	9.31E-03	3.75E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	1.02E-02	0.00E+00	0.00E+00	0.00E+00	1.02E-02	4.09E-05
RL-W635	4.34E+01	0.00E+00	9.87E+00	4.32E+00	6.42E+00	4.86E-01	8.69E-03	6.40E+01	2.58E-01
RL-W636	4.43E-01	0.00E+00	1.86E-02	5.64E-02	4.97E-02	2.95E-03	1.64E-05	5.68E-01	2.29E-03
RL-W637	1.05E-03	0.00E+00	4.75E-04	6.35E-04	6.20E-04	1.06E-05	4.18E-07	2.78E-03	1.12E-05
RL-W638	4.63E-02	0.00E+00	4.83E-03	6.22E-03	5.82E-03	3.95E-04	4.26E-06	6.32E-02	2.55E-04
RL-W639	2.44E-03	0.00E+00	1.24E-04	1.59E-02	3.52E-03	2.76E-05	1.09E-07	2.20E-02	8.88E-05
RL-W640	8.21E-02	0.00E+00	4.11E-03	5.37E-01	1.19E-01	8.88E-04	3.62E-06	7.42E-01	2.99E-03
RL-W641	2.50E+00	0.00E+00	9.03E-01	2.58E+00	1.05E+00	1.43E-02	7.96E-04	7.04E+00	2.84E-02
RL-W642	4.89E-02	0.00E+00	9.37E-05	3.15E-02	1.59E-04	6.16E-06	8.26E-08	8.06E-02	3.25E-04
RL-W643	7.71E-01	0.00E+00	2.78E-01	7.94E-01	3.25E-01	4.39E-03	2.45E-04	2.17E+00	8.74E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.47E-02	0.00E+00	0.00E+00	0.00E+00	5.47E-02	2.20E-04
RL-W645	1.87E-02	0.00E+00	1.25E-03	1.08E-01	2.51E-02	2.40E-04	1.10E-06	1.53E-01	6.15E-04
RL-W646	1.70E-02	0.00E+00	1.12E-03	2.57E-02	1.24E-02	1.16E-04	9.84E-07	5.62E-02	2.27E-04
RL-W647	4.79E-02	0.00E+00	1.67E-01	1.10E-01	1.72E-02	3.90E-04	1.47E-04	3.42E-01	1.38E-03
RL-W648	8.48E-04	0.00E+00	2.85E-04	5.98E-05	1.17E-04	1.25E-05	2.51E-07	1.31E-03	5.29E-06
RL-W649	3.12E-03	0.00E+00	1.05E-03	2.20E-04	4.30E-04	4.59E-05	9.26E-07	4.82E-03	1.94E-05
RL-W653	1.48E-04	0.00E+00	7.52E-06	9.62E-04	2.12E-04	1.75E-06	6.63E-09	1.33E-03	5.36E-06
RL-W654	8.13E-04	0.00E+00	4.11E-05	5.30E-03	1.17E-03	9.19E-06	3.62E-08	7.32E-03	2.95E-05
RL-W655	2.00E+02	0.00E+00	9.72E+00	2.10E-01	4.93E-01	2.45E+00	8.57E-03	2.11E+02	8.49E-01
RL-W656	8.38E+02	0.00E+00	4.37E+00	4.94E-01	5.07E-01	1.17E+01	3.85E-03	8.43E+02	3.40E+00
RL-W657	4.28E+02	0.00E+00	6.45E+00	2.43E-01	4.82E-01	5.18E+00	5.69E-03	4.35E+02	1.75E+00

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W659	5.18E+01	0.00E+00	1.46E+00	4.68E-02	5.77E-02	5.85E-01	1.28E-03	5.33E+01	2.15E-01
RL-W660	2.84E+02	0.00E+00	1.75E+01	8.63E-01	1.53E+00	3.34E+00	1.54E-02	3.04E+02	1.23E+00
RL-W661	3.00E+00	0.00E+00	2.19E-02	4.16E-04	3.77E-03	4.05E-02	1.93E-05	3.03E+00	1.22E-02
RL-W662	9.45E-02	0.00E+00	1.31E-03	1.07E-04	1.90E-04	8.30E-04	1.15E-06	9.61E-02	3.88E-04
RL-W665	1.16E+03	0.00E+00	1.04E+02	1.30E+00	1.74E+00	1.65E+01	9.20E-02	1.27E+03	5.12E+00
RL-W666	2.08E+01	0.00E+00	2.56E-01	5.47E-02	5.72E-02	2.39E-01	2.25E-04	2.12E+01	8.53E-02
RL-W668	1.98E+00	0.00E+00	8.04E-03	1.44E-01	4.07E-02	5.64E-04	7.09E-06	2.17E+00	8.76E-03
RL-W669	5.78E-01	0.00E+00	2.09E-01	5.95E-01	2.43E-01	3.29E-03	1.84E-04	1.63E+00	6.55E-03
RL-W670	3.65E-02	0.00E+00	1.48E-04	2.67E-03	7.53E-04	1.04E-05	1.31E-07	4.01E-02	1.62E-04
RL-W671	5.96E+00	0.00E+00	7.61E-02	4.89E-03	5.06E-03	3.43E-02	6.71E-05	6.04E+00	2.44E-02
RL-W672	4.05E+01	0.00E+00	5.18E-01	3.34E-02	3.43E-02	2.33E-01	4.56E-04	4.11E+01	1.66E-01
RL-W673	3.90E+01	0.00E+00	4.98E-01	3.23E-02	3.31E-02	2.25E-01	4.39E-04	3.96E+01	1.60E-01
RL-W674	1.31E-01	0.00E+00	2.23E-02	1.12E+01	9.64E-02	1.57E-03	1.96E-05	1.14E+01	4.60E-02
RL-W675	4.90E-01	0.00E+00	1.23E-01	1.30E-01	1.12E-01	3.82E-03	1.08E-04	8.55E-01	3.45E-03
RL-W676	1.88E-02	0.00E+00	7.38E-04	1.46E-01	2.12E-03	1.13E-04	6.50E-07	1.68E-01	6.77E-04
RL-W677	4.35E+01	0.00E+00	1.83E+00	5.71E+00	4.94E+00	2.73E-01	1.61E-03	5.60E+01	2.26E-01
RL-W678	1.38E-01	0.00E+00	1.53E-02	5.14E-02	4.50E-02	2.14E-03	1.35E-05	2.50E-01	1.01E-03
RL-W679	8.63E-01	0.00E+00	3.41E-02	1.11E-01	9.70E-02	5.48E-03	3.01E-05	1.11E+00	4.46E-03
RL-W680	1.94E-04	0.00E+00	4.80E-05	1.73E-05	3.10E-05	2.36E-06	4.23E-08	2.91E-04	1.17E-06
RL-W681	1.19E-04	0.00E+00	1.95E-05	4.65E-04	2.30E-04	1.96E-06	1.72E-08	8.33E-04	3.36E-06
RL-W685	3.46E-01	0.00E+00	1.73E-02	2.27E+00	5.02E-01	3.57E-03	1.53E-05	3.13E+00	1.26E-02
RL-W689	8.96E-03	0.00E+00	2.08E-04	3.85E-04	0.00E+00	3.43E-06	1.83E-07	9.55E-03	3.85E-05
RL-W690	3.01E-01	0.00E+00	1.53E-02	2.02E+00	4.46E-01	3.11E-03	1.35E-05	2.78E+00	1.12E-02
RL-W691	6.98E-03	0.00E+00	3.56E-04	4.68E-02	1.03E-02	7.21E-05	3.14E-07	6.45E-02	2.60E-04
RL-W692	2.76E-01	0.00E+00	1.41E-02	1.85E+00	4.09E-01	2.85E-03	1.24E-05	2.55E+00	1.03E-02
RL-W693	3.41E-01	0.00E+00	1.74E-02	2.29E+00	5.07E-01	3.52E-03	1.53E-05	3.16E+00	1.27E-02
RL-W694	3.59E+00	0.00E+00	1.83E-01	2.42E+01	5.31E+00	3.70E-02	1.61E-04	3.33E+01	1.34E-01
RL-W695	2.97E-03	0.00E+00	0.00E+00	2.38E-03	0.00E+00	0.00E+00	0.00E+00	5.35E-03	2.16E-05
RL-W696	3.86E-03	0.00E+00	6.65E-04	2.90E-03	2.84E-03	5.08E-05	5.86E-07	1.03E-02	4.14E-05

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W697	8.94E-01	0.00E+00	1.41E+00	6.90E-03	9.41E-04	0.00E+00	1.24E-03	2.31E+00	9.32E-03
RL-W698	7.75E-02	0.00E+00	0.00E+00	3.28E-05	0.00E+00	0.00E+00	0.00E+00	7.75E-02	3.13E-04
RL-W699	1.72E-02	0.00E+00	9.37E-05	2.19E-03	2.56E-04	2.14E-04	8.26E-08	1.98E-02	7.97E-05
RL-W700	4.88E-03	0.00E+00	2.46E-04	3.18E-02	7.03E-03	5.54E-05	2.17E-07	4.39E-02	1.77E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	1.92E-01	0.00E+00	6.94E-02	1.98E-01	8.11E-02	1.10E-03	6.12E-05	5.41E-01	2.18E-03
RL-W705	1.24E-03	0.00E+00	6.39E-05	8.32E-03	1.85E-03	1.35E-05	5.64E-08	1.15E-02	4.63E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	4.44E-02	0.00E+00	2.27E-03	2.97E-01	6.57E-02	4.79E-04	2.00E-06	4.09E-01	1.65E-03
RL-W708	6.71E-03	0.00E+00	3.44E-04	4.50E-02	9.93E-03	7.26E-05	3.03E-07	6.20E-02	2.50E-04
RL-W709	2.32E+00	0.00E+00	1.19E-01	1.55E+01	3.43E+00	2.51E-02	1.05E-04	2.14E+01	8.63E-02
RL-W710	1.38E-04	0.00E+00	7.09E-06	9.28E-04	2.05E-04	1.50E-06	6.25E-09	1.28E-03	5.15E-06
RL-W711	4.32E-02	0.00E+00	2.21E-03	2.90E-01	6.40E-02	4.67E-04	1.95E-06	3.99E-01	1.61E-03
RL-W712	5.59E-02	0.00E+00	2.86E-03	3.74E-01	8.28E-02	6.06E-04	2.52E-06	5.16E-01	2.08E-03
RL-W713	4.83E-02	0.00E+00	2.47E-03	3.23E-01	7.16E-02	5.22E-04	2.18E-06	4.45E-01	1.79E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	8.34E-04	0.00E+00	4.17E-05	5.47E-03	1.21E-03	8.62E-06	3.67E-08	7.55E-03	3.04E-05
RL-W716	8.69E-03	0.00E+00	4.34E-04	5.69E-02	1.26E-02	8.98E-05	3.83E-07	7.87E-02	3.17E-04
RL-W717	2.17E-03	0.00E+00	1.09E-04	1.42E-02	3.15E-03	2.24E-05	9.56E-08	1.97E-02	7.93E-05
RL-W718	3.83E-04	0.00E+00	1.91E-05	2.51E-03	5.55E-04	3.95E-06	1.69E-08	3.47E-03	1.40E-05
RL-W719	1.72E-03	0.00E+00	8.62E-05	1.14E-02	2.51E-03	1.79E-05	7.60E-08	1.57E-02	6.32E-05
RL-W720	1.07E-02	0.00E+00	5.35E-04	7.01E-02	1.55E-02	1.10E-04	4.72E-07	9.68E-02	3.91E-04
RL-W721	7.23E-03	0.00E+00	3.62E-04	4.74E-02	1.05E-02	7.47E-05	3.19E-07	6.55E-02	2.64E-04
RL-W723	2.40E-02	0.00E+00	1.22E-03	1.61E-01	3.56E-02	2.48E-04	1.08E-06	2.22E-01	8.95E-04
RL-W724	1.59E-01	0.00E+00	8.13E-03	1.07E+00	2.37E-01	1.65E-03	7.17E-06	1.47E+00	5.93E-03
RL-W725	5.04E-02	0.00E+00	2.56E-03	3.38E-01	7.48E-02	5.20E-04	2.26E-06	4.65E-01	1.88E-03
RL-W726	3.97E-02	0.00E+00	2.02E-03	2.67E-01	5.89E-02	4.09E-04	1.78E-06	3.67E-01	1.48E-03
RL-W727	2.43E-01	0.00E+00	1.24E-02	1.63E+00	3.62E-01	2.51E-03	1.09E-05	2.25E+00	9.07E-03

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W728	2.21E-01	0.00E+00	1.13E-02	1.49E+00	3.30E-01	2.29E-03	9.97E-06	2.06E+00	8.29E-03
RL-W729	1.02E-01	0.00E+00	5.24E-03	6.87E-01	1.52E-01	1.06E-03	4.62E-06	9.47E-01	3.82E-03
RL-W730	4.00E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.00E+01	1.61E-01
RL-W731	1.29E-05	0.00E+00	0.00E+00	4.49E-04	1.83E-06	0.00E+00	0.00E+00	4.64E-04	1.87E-06
RL-W732	2.96E+01	0.00E+00	2.98E+00	1.26E+02	2.78E+01	3.78E-01	2.63E-03	1.87E+02	7.53E-01
RL-W733	3.88E-01	0.00E+00	3.88E-02	1.37E+00	3.38E-01	4.11E-03	3.42E-05	2.14E+00	8.62E-03
RL-W734	1.21E+00	0.00E+00	1.29E-01	4.74E+00	1.14E+00	1.22E-02	1.14E-04	7.22E+00	2.91E-02
RL-W735	9.92E-01	0.00E+00	9.87E-02	3.69E+00	9.10E-01	9.50E-03	8.69E-05	5.69E+00	2.30E-02
RL-W736	1.09E-03	0.00E+00	2.10E-07	2.45E-03	6.28E-04	2.91E-06	1.85E-10	4.17E-03	1.68E-05
RL-W737	8.85E-01	0.00E+00	9.00E-02	3.50E+00	8.47E-01	8.20E-03	7.93E-05	5.33E+00	2.15E-02
RL-W738	3.30E+00	0.00E+00	3.10E-01	1.12E+01	2.92E+00	2.97E-02	2.73E-04	1.77E+01	7.13E-02
RL-W739	2.82E-01	0.00E+00	2.73E-02	1.81E+00	4.10E-01	2.70E-03	2.41E-05	2.53E+00	1.02E-02
RL-W740	1.41E+01	0.00E+00	1.00E+00	4.41E+01	1.14E+01	1.36E-01	8.82E-04	7.06E+01	2.85E-01
RL-W741	2.10E+01	0.00E+00	2.36E+00	8.59E+00	6.06E+00	1.02E-01	2.08E-03	3.80E+01	1.53E-01
RL-W742	9.37E-01	0.00E+00	7.09E-02	2.79E+00	6.52E-01	8.77E-03	6.25E-05	4.45E+00	1.79E-02
RL-W743	1.69E-03	0.00E+00	1.92E-05	1.80E-03	0.00E+00	0.00E+00	1.70E-08	3.51E-03	1.42E-05
RL-W744	0.00E+00	0.00E+00	0.00E+00	8.99E-02	7.59E-02	0.00E+00	0.00E+00	1.66E-01	6.69E-04
RL-W745	2.66E-03	0.00E+00	1.35E-04	1.74E-02	3.85E-03	3.01E-05	1.19E-07	2.41E-02	9.70E-05
RL-W746	1.03E-02	0.00E+00	5.18E-04	6.69E-02	1.49E-02	1.16E-04	4.56E-07	9.25E-02	3.73E-04
RL-W747	2.78E-02	0.00E+00	1.40E-03	1.81E-01	4.01E-02	3.14E-04	1.24E-06	2.51E-01	1.01E-03
RL-W748	1.95E+02	0.00E+00	3.94E+00	3.01E-01	4.91E-01	2.37E+00	3.47E-03	2.00E+02	8.04E-01
RL-W749	2.34E-01	0.00E+00	1.20E-02	1.57E+00	3.47E-01	2.53E-03	1.06E-05	2.17E+00	8.73E-03
RL-W750	2.95E+02	0.00E+00	5.96E+00	4.93E-01	8.02E-01	3.35E+00	5.25E-03	3.03E+02	1.22E+00
RL-W751	2.67E+02	0.00E+00	5.38E+00	4.43E-01	7.27E-01	3.02E+00	4.74E-03	2.73E+02	1.10E+00
RL-W752	1.16E+02	0.00E+00	2.34E+00	1.93E-01	3.16E-01	1.31E+00	2.06E-03	1.19E+02	4.79E-01
RL-W753	1.56E+03	0.00E+00	3.15E+01	2.60E+00	4.24E+00	1.77E+01	2.78E-02	1.60E+03	6.44E+00
RP-W754	6.62E+01	0.00E+00	3.99E+00	1.85E+03	1.51E+02	1.63E-01	3.56E-01	2.07E+03	8.36E+00
RP-W755	3.51E+02	0.00E+00	2.39E+00	1.38E+03	1.14E+02	1.22E-01	1.26E+01	1.86E+03	7.51E+00
SA-T001	7.05E-01	1.17E-02	5.73E-02	3.02E+00	1.77E-02	0.00E+00	5.51E-05	3.80E+00	1.53E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
SA-W134	5.76E+00	4.55E-06	3.91E-01	1.37E+00	4.32E-01	3.10E-03	1.67E-01	8.12E+00	3.27E-02
SA-W134M	7.48E-01	5.90E-07	5.06E-02	1.79E-01	5.61E-02	4.03E-04	2.16E-02	1.06E+00	4.25E-03
T001-221F-HET	1.39E+03	0.00E+00	4.57E+04	2.87E+04	7.02E+02	1.02E+01	4.59E+01	7.65E+04	3.09E+02
T001-221H-HET	2.51E+03	0.00E+00	8.25E+04	5.18E+04	1.27E+03	1.84E+01	8.29E+01	1.38E+05	5.57E+02
T001-235F-HET	1.44E+02	0.00E+00	4.75E+03	2.98E+03	7.29E+01	1.06E+00	4.77E+00	7.94E+03	3.20E+01
T001-772F-HET	1.24E+03	0.00E+00	4.11E+04	2.57E+04	6.29E+02	9.09E+00	4.13E+01	6.87E+04	2.77E+02
T001-773A-CLAS	1.40E+01	0.00E+00	4.60E+02	2.89E+02	7.05E+00	1.02E-01	4.62E-01	7.70E+02	3.11E+00
T001-773A-HET	1.61E+02	0.00E+00	5.30E+03	3.33E+03	8.14E+01	1.18E+00	5.32E+00	8.87E+03	3.58E+01
W006-773A-VIT	2.15E-03	0.00E+00	0.00E+00	5.35E+02	0.00E+00	0.00E+00	0.00E+00	5.35E+02	2.16E+00
W026-221F-HET	4.84E+02	0.00E+00	1.59E+04	1.01E+04	2.45E+02	3.55E+00	1.60E+01	2.67E+04	1.08E+02
W026-221H-HET	3.62E+02	0.00E+00	1.19E+04	7.49E+03	1.83E+02	2.65E+00	1.20E+01	2.00E+04	8.05E+01
W026-235F-HET	5.64E+00	0.00E+00	1.86E+02	1.17E+02	2.85E+00	4.13E-02	1.87E-01	3.11E+02	1.25E+00
W026-772F-HET	1.54E+00	0.00E+00	5.06E+01	3.18E+01	7.77E-01	1.13E-02	5.09E-02	8.48E+01	3.42E-01
W026-773A-HET	2.50E+01	0.00E+00	8.25E+02	5.18E+02	1.27E+01	1.83E-01	8.29E-01	1.38E+03	5.57E+00
W027-221F-HET	1.83E+03	0.00E+00	5.38E+04	3.88E+04	9.48E+02	5.80E+00	6.52E+01	9.55E+04	3.85E+02
W027-221H-HET	7.99E+02	0.00E+00	2.35E+04	1.70E+04	4.15E+02	2.53E+00	2.85E+01	4.18E+04	1.68E+02
W027-235F-HET	2.40E+02	0.00E+00	7.06E+03	5.12E+03	1.25E+02	7.62E-01	8.57E+00	1.26E+04	5.06E+01
W027-772F-HET	4.37E+02	0.00E+00	1.29E+04	9.29E+03	2.27E+02	1.38E+00	1.56E+01	2.28E+04	9.20E+01
W027-773A-HET	6.52E+02	0.00E+00	1.92E+04	1.38E+04	3.38E+02	2.07E+00	2.32E+01	3.40E+04	1.37E+02
W027-999-HET	7.45E+02	0.00E+00	2.19E+04	1.58E+04	3.87E+02	2.36E+00	2.66E+01	3.89E+04	1.57E+02
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.97E+02	0.00E+00	0.00E+00	0.00E+00	3.97E+02	1.60E+00
WP-INW169.001	3.64E+00	0.00E+00	1.38E-01	1.53E+01	3.38E+00	2.08E-02	2.87E-04	2.25E+01	9.07E-02
WP-INW198.001	4.79E+00	0.00E+00	2.41E-01	2.75E+01	6.02E+00	3.42E-02	2.94E-04	3.85E+01	1.55E-01
WP-INW211.001	5.40E+02	0.00E+00	2.26E+01	2.55E+03	5.59E+02	3.88E+00	2.19E-02	3.67E+03	1.48E+01
WP-INW216.001-	1.96E+04	0.00E+00	1.30E+01	1.47E+03	3.25E+02	2.14E+00	2.88E-01	2.14E+04	8.64E+01
WP-INW216.001-	5.39E+03	0.00E+00	3.50E+00	3.99E+02	8.75E+01	5.80E-01	3.07E-02	5.88E+03	2.37E+01
WP-INW218.001-	3.75E+02	0.00E+00	2.29E+00	2.57E+02	5.65E+01	3.88E-01	3.88E-01	6.91E+02	2.79E+00
WP-INW218.001-	1.73E+00	0.00E+00	6.31E-02	6.99E+00	1.53E+00	1.10E-02	3.74E-02	1.04E+01	4.17E-02
WP-INW222.001	1.78E+01	0.00E+00	6.80E-01	6.83E+01	1.52E+01	9.30E-02	1.17E-03	1.02E+02	4.11E-01

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-INW243.001	4.31E+01	0.00E+00	1.47E+00	1.43E+02	3.19E+01	1.88E-01	2.16E-03	2.20E+02	8.86E-01
WP-INW247.001R	5.75E+01	0.00E+00	3.41E+00	2.75E+02	6.20E+01	3.26E-01	3.09E-03	3.98E+02	1.60E+00
WP-INW276.001	4.39E+00	0.00E+00	3.33E-01	2.72E+01	6.14E+00	2.76E-02	3.10E-04	3.80E+01	1.53E-01
WP-INW276.002	6.95E+00	0.00E+00	5.01E-01	3.99E+01	9.21E+00	4.15E-02	4.68E-04	5.66E+01	2.28E-01
WP-INW276.003	2.67E+02	0.00E+00	1.86E+01	1.48E+03	3.35E+02	1.74E+00	1.68E-02	2.10E+03	8.48E+00
WP-INW276.004	6.37E+01	0.00E+00	3.94E+00	3.14E+02	7.08E+01	3.68E-01	3.61E-03	4.52E+02	1.82E+00
WP-INW296.001-	2.33E+01	0.00E+00	9.35E-01	7.87E+01	1.77E+01	9.45E-02	8.61E-04	1.21E+02	4.87E-01
WP-INW296.001-	7.02E+01	0.00E+00	3.30E+00	2.79E+02	6.26E+01	3.41E-01	3.26E-03	4.15E+02	1.67E+00
WP-LA-TA-55-19	1.17E+00	0.00E+00	1.53E-01	2.08E+00	4.99E-01	3.38E-03	2.77E-03	3.90E+00	1.57E-02
WP-LA-TA-55-19	5.66E+01	0.00E+00	5.15E+00	2.12E+02	5.13E+01	3.36E-01	9.17E-02	3.25E+02	1.31E+00
WP-LA-TA-55-43	3.18E-01	0.00E+00	1.20E+02	3.22E-01	1.35E-01	3.01E-03	1.32E-01	1.21E+02	4.88E-01
WP-RF001.01	9.82E+01	0.00E+00	4.17E+00	4.08E+02	9.22E+01	3.39E-01	1.30E-02	6.03E+02	2.43E+00
WP-RF002.01-A	1.14E+02	0.00E+00	5.56E+00	4.60E+02	1.04E+02	7.47E-01	2.27E-02	6.84E+02	2.76E+00
WP-RF002.01-B	1.14E-01	0.00E+00	3.85E-03	4.98E-01	1.12E-01	4.69E-04	3.58E-06	7.27E-01	2.93E-03
WP-RF003.01	1.78E+03	0.00E+00	8.94E+01	8.79E+03	1.99E+03	1.23E+01	8.71E-02	1.26E+04	5.10E+01
WP-RF004.01	8.33E-01	0.00E+00	5.99E-02	5.07E+00	1.15E+00	7.05E-03	1.80E-04	7.11E+00	2.87E-02
WP-RF005.01	4.27E+03	0.00E+00	4.54E+01	4.65E+03	1.04E+03	4.91E+00	4.18E-02	1.00E+04	4.04E+01
WP-RF005.02	5.03E+03	0.00E+00	2.35E+01	2.78E+03	6.19E+02	2.52E+00	2.19E-02	8.45E+03	3.41E+01
WP-RF006.01	1.63E+03	0.00E+00	8.54E+01	7.90E+03	1.79E+03	6.37E+00	1.01E-01	1.14E+04	4.60E+01
WP-RF008.01	5.17E+02	0.00E+00	3.04E+01	2.31E+03	5.32E+02	4.20E+00	2.80E-02	3.39E+03	1.37E+01
WP-RF009.01	5.09E+04	0.00E+00	3.73E+02	5.07E+04	1.12E+04	4.83E+01	3.50E-01	1.13E+05	4.56E+02
WP-RF010.01	1.88E+01	0.00E+00	9.46E-01	7.66E+01	1.73E+01	1.49E-01	1.56E-03	1.14E+02	4.58E-01
WP-RF029.01-A	4.51E+00	0.00E+00	1.78E-01	1.34E+01	3.05E+00	3.41E-02	8.87E-04	2.12E+01	8.54E-02
WP-RF029.01-B	6.73E+00	0.00E+00	1.41E-01	1.07E+01	2.41E+00	2.70E-02	2.37E-03	1.99E+01	8.04E-02
WP-RF118.01	1.14E+04	0.00E+00	7.09E+02	5.12E+04	1.13E+04	8.88E+01	8.40E-01	7.46E+04	3.01E+02
WP-RLMPDT.001	2.43E+00	0.00E+00	2.07E-01	7.33E+00	1.89E+00	1.95E-02	1.84E-04	1.19E+01	4.78E-02
WP-RLNPDT.002	2.98E+01	0.00E+00	1.97E+00	7.20E+01	1.92E+01	2.24E-01	1.78E-03	1.23E+02	4.96E-01
WP-SR2001.001.	9.50E-01	0.00E+00	2.27E-01	6.80E+00	1.34E+00	1.22E-02	2.04E-04	9.31E+00	3.76E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-SR-W027-221	7.03E+00	0.00E+00	6.65E-01	1.95E+01	5.40E+00	5.48E-02	1.87E-01	3.28E+01	1.32E-01
Total	3.76E+05	2.27E+01	4.66E+05	6.57E+05	1.05E+05	1.25E+03	5.78E+02	1.61E+06	6.47E+03

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	6.54E+01	0.00E+00	3.47E+00	2.08E+02	1.21E+02	1.12E-02	1.84E-02	3.98E+02	1.61E+00
AE-T003	8.29E+00	0.00E+00	4.62E-01	6.42E+01	2.45E+01	6.16E-03	7.97E-04	9.74E+01	3.93E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	3.67E-02	0.00E+00	1.22E+01	4.73E+01	2.82E-01	1.20E-05	1.86E-02	5.99E+01	2.42E-01
AW-T033.1325	1.34E-01	0.00E+00	4.48E+01	1.73E+02	1.03E+00	4.39E-05	6.82E-02	2.19E+02	8.83E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.68E-01	0.00E+00	0.00E+00	0.00E+00	7.68E-01	3.10E-03
BCLCH-MT01	1.36E+01	0.00E+00	3.47E+02	2.85E+01	7.38E+00	1.69E-02	5.14E-01	3.97E+02	1.60E+00
BT-T002	9.96E-03	9.17E-07	1.81E-01	7.21E-04	1.46E-03	7.43E-06	2.26E-03	1.96E-01	7.89E-04
ET-C1-B55	4.16E-02	0.00E+00	2.07E-03	6.17E-02	3.03E-02	1.31E-05	2.39E-04	1.36E-01	5.48E-04
ET-C1-D139	5.70E-03	0.00E+00	2.87E-04	8.68E-03	4.27E-03	1.75E-06	4.86E-07	1.89E-02	7.64E-05
ET-C2-SEFOR	1.41E-01	0.00E+00	0.00E+00	1.36E-01	4.51E-02	2.69E-05	0.00E+00	3.22E-01	1.30E-03
FM-MOX-MT02	1.34E-06	0.00E+00	1.15E-07	2.98E-07	1.75E-07	9.36E-10	1.80E-10	1.93E-06	7.77E-09
FM-MOX-T01	2.21E-05	0.00E+00	1.90E-06	4.91E-06	2.89E-06	1.54E-08	2.96E-09	3.18E-05	1.28E-07
IN-BN-510	5.34E+03	0.00E+00	9.82E+03	3.95E+04	3.30E+03	3.69E-03	1.65E+01	5.79E+04	2.34E+02
IN-GEM-01	6.75E+01	0.00E+00	1.95E-01	4.43E+01	9.98E+00	2.60E-03	2.89E-04	1.22E+02	4.92E-01
IN-GEM-02	1.60E+01	0.00E+00	4.64E-02	1.05E+01	2.38E+00	6.16E-04	6.87E-05	2.90E+01	1.17E-01
IN-W157.144	8.00E+01	0.00E+00	1.89E+00	3.01E+02	6.72E+01	4.62E-02	3.17E-03	4.50E+02	1.82E+00
IN-W163.1007	1.37E+01	0.00E+00	5.83E-01	9.34E+01	2.08E+01	1.42E-02	9.80E-04	1.29E+02	5.18E-01
IN-W164.153	1.31E-01	0.00E+00	5.56E-03	8.90E-01	1.99E-01	1.36E-04	9.34E-06	1.23E+00	4.94E-03
IN-W167.149	2.62E+01	0.00E+00	9.03E-01	1.44E+02	3.22E+01	2.20E-02	1.52E-03	2.03E+02	8.20E-01
IN-W174.154	0.00E+00	0.00E+00	5.11E+02	1.94E+00	3.77E+00	0.00E+00	8.59E-01	5.17E+02	2.09E+00
IN-W177.156	1.82E-02	0.00E+00	1.09E+03	1.82E+00	1.10E-02	1.89E-05	1.83E+00	1.09E+03	4.39E+00
IN-W179.158	1.22E-01	0.00E+00	1.08E+03	1.05E-01	5.40E-02	1.27E-04	1.82E+00	1.08E+03	4.37E+00
IN-W181.162	1.74E+00	0.00E+00	7.37E-02	1.17E+01	2.62E+00	1.80E-03	1.24E-04	1.62E+01	6.52E-02
IN-W188.160	1.17E+01	0.00E+00	4.95E-01	7.92E+01	1.76E+01	1.21E-02	8.32E-04	1.09E+02	4.40E-01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W216.98	1.04E+05	0.00E+00	4.04E+01	6.46E+03	1.45E+03	9.93E-01	6.78E-02	1.12E+05	4.51E+02
IN-W218.909	5.25E+02	0.00E+00	8.97E-01	1.43E+02	3.20E+01	2.20E-02	1.51E-03	7.01E+02	2.83E+00
IN-W219.110	7.12E-01	0.00E+00	3.02E-02	4.83E+00	1.08E+00	7.39E-04	5.08E-05	6.65E+00	2.68E-02
IN-W219.914	1.12E-01	0.00E+00	4.76E-03	7.62E-01	1.70E-01	1.17E-04	7.99E-06	1.05E+00	4.23E-03
IN-W220.114	3.71E+03	0.00E+00	3.18E+00	5.46E+02	1.18E+02	7.76E-02	5.34E-03	4.38E+03	1.76E+01
IN-W221.927	4.35E+00	0.00E+00	1.84E-01	2.94E+01	6.56E+00	4.52E-03	3.10E-04	4.05E+01	1.63E-01
IN-W222.116	1.48E+02	0.00E+00	6.24E+00	9.94E+02	2.22E+02	1.52E-01	1.05E-02	1.37E+03	5.53E+00
IN-W228.101	9.81E+02	0.00E+00	2.03E+00	3.25E+02	7.24E+01	4.99E-02	3.41E-03	1.38E+03	5.56E+00
IN-W240.931	1.04E+02	0.00E+00	2.59E+00	4.18E+02	9.26E+01	6.30E-02	4.36E-03	6.17E+02	2.49E+00
IN-W243.808	1.44E+02	0.00E+00	4.54E+00	7.29E+02	1.62E+02	1.12E-01	7.64E-03	1.04E+03	4.19E+00
IN-W245.301	2.13E+02	0.00E+00	8.93E+00	1.42E+03	3.18E+02	2.18E-01	1.50E-02	1.96E+03	7.91E+00
IN-W247.810	1.04E+02	0.00E+00	4.35E+00	6.95E+02	1.56E+02	1.06E-01	7.31E-03	9.58E+02	3.87E+00
IN-W249.527	0.00E+00	0.00E+00	3.04E+02	1.23E+01	0.00E+00	0.00E+00	5.11E-01	3.17E+02	1.28E+00
IN-W263.520	2.97E-02	0.00E+00	3.18E+01	8.38E+00	1.31E-02	3.08E-05	5.34E-02	4.03E+01	1.62E-01
IN-W267.1005	2.48E+01	0.00E+00	1.06E+00	1.69E+02	3.77E+01	2.58E-02	1.77E-03	2.33E+02	9.38E-01
IN-W309.609	6.66E+02	0.00E+00	1.77E+01	2.82E+03	6.30E+02	4.32E-01	2.97E-02	4.14E+03	1.67E+01
IN-W315.601	6.57E+02	0.00E+00	7.39E-02	1.18E+01	2.63E+00	1.80E-03	1.24E-04	6.71E+02	2.71E+00
IN-W319.584	3.82E+00	0.00E+00	1.62E-01	2.59E+01	5.80E+00	3.97E-03	2.72E-04	3.57E+01	1.44E-01
IN-W321.1023	3.31E+01	0.00E+00	1.40E+00	2.25E+02	5.01E+01	3.43E-02	2.36E-03	3.09E+02	1.25E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	9.07E+00	1.85E+00	0.00E+00	0.00E+00	1.09E+01	4.40E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.42E+01	4.93E+00	0.00E+00	0.00E+00	2.91E+01	1.17E-01
IN-W323.562	7.07E-02	0.00E+00	2.38E-01	2.48E-01	0.00E+00	7.34E-05	4.00E-04	5.56E-01	2.24E-03
IN-W323.951	8.34E-02	0.00E+00	2.83E-03	2.95E-01	0.00E+00	8.66E-05	4.75E-06	3.81E-01	1.54E-03
IN-W332.661	0.00E+00	0.00E+00	3.12E+00	1.28E-01	0.00E+00	0.00E+00	5.24E-03	3.25E+00	1.31E-02
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	3.02E+00	6.16E-01	0.00E+00	0.00E+00	3.64E+00	1.47E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	9.07E+00	1.85E+00	0.00E+00	0.00E+00	1.09E+01	4.40E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.94E+00	0.00E+00	0.00E+00	0.00E+00	1.94E+00	7.82E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.83E+00	0.00E+00	0.00E+00	0.00E+00	5.83E+00	2.35E-02
IN-W342.652	3.27E+00	0.00E+00	0.00E+00	4.00E-02	1.02E-17	0.00E+00	0.00E+00	3.31E+00	1.33E-02
IN-W342.953	2.18E+00	0.00E+00	0.00E+00	2.67E-02	6.83E-18	0.00E+00	0.00E+00	2.21E+00	8.90E-03
IN-W347.818	1.71E+00	0.00E+00	0.00E+00	8.21E+01	1.49E+02	0.00E+00	1.58E-08	2.33E+02	9.38E-01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W348.1012	9.04E-02	0.00E+00	2.57E+00	4.15E+02	9.26E+01	0.00E+00	4.33E-03	5.10E+02	2.06E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.49E-02	0.00E+00	0.00E+00	0.00E+00	2.49E-02	1.00E-04
IN-W357.1022	0.00E+00	0.00E+00	5.07E-03	8.14E-01	1.81E-01	0.00E+00	8.52E-06	1.00E+00	4.03E-03
IN-W358.854	0.00E+00	0.00E+00	7.64E+01	1.87E+00	3.55E+00	0.00E+00	1.21E-01	8.20E+01	3.30E-01
IN-W358.855	0.00E+00	0.00E+00	4.07E+02	9.94E+00	1.89E+01	0.00E+00	6.46E-01	4.37E+02	1.76E+00
IN-W358.948	0.00E+00	0.00E+00	8.50E+01	2.08E+00	3.93E+00	0.00E+00	1.35E-01	9.11E+01	3.68E-01
IN-W361.1021	2.40E-02	0.00E+00	4.91E-01	7.85E+01	1.75E+01	0.00E+00	8.25E-04	9.66E+01	3.89E-01
IN-W362.1020	0.00E+00	0.00E+00	6.43E+00	1.02E+03	2.30E+02	0.00E+00	1.08E-02	1.26E+03	5.08E+00
IN-W363.1019	0.00E+00	0.00E+00	3.02E-01	4.86E+01	1.09E+01	0.00E+00	5.08E-04	5.98E+01	2.41E-01
IN-W364.1011	0.00E+00	0.00E+00	4.99E-01	7.99E+01	1.78E+01	0.00E+00	8.39E-04	9.82E+01	3.96E-01
IN-W365.1010	2.24E+02	0.00E+00	3.96E-01	6.31E+01	1.41E+01	0.00E+00	6.65E-04	3.02E+02	1.22E+00
IN-W366.841	7.97E-01	0.00E+00	3.37E-01	5.38E+01	1.20E+01	0.00E+00	5.67E-04	6.70E+01	2.70E-01
IN-W372.832	3.27E+00	0.00E+00	0.00E+00	4.00E-02	1.02E-17	0.00E+00	0.00E+00	3.31E+00	1.33E-02
IN-W375.1096	0.00E+00	0.00E+00	1.24E-01	1.99E+01	4.43E+00	0.00E+00	2.09E-04	2.44E+01	9.85E-02
KN-B234TRU	1.16E+02	0.00E+00	4.76E+00	2.89E+02	9.59E+01	2.41E-02	9.00E-03	5.06E+02	2.04E+00
LA-IT-00-01	1.69E+00	5.91E-04	8.11E-01	5.82E-01	1.24E-02	4.63E-12	1.56E-03	3.09E+00	1.25E-02
LA-OS-00-01	3.75E+03	0.00E+00	3.70E+04	1.22E+03	0.00E+00	0.00E+00	5.54E+01	4.21E+04	1.70E+02
LA-PX-00-01	1.57E-02	0.00E+00	1.56E-03	9.00E-02	2.08E-02	7.67E-06	2.45E-06	1.28E-01	5.16E-04
LA-SL-00-01	0.00E+00	0.00E+00	3.29E-02	1.52E-01	0.00E+00	0.00E+00	6.27E-05	1.85E-01	7.46E-04
LA-TA-03-12	1.61E-01	0.00E+00	7.62E-01	4.33E-01	1.49E-01	4.55E-05	1.51E-03	1.51E+00	6.08E-03
LA-TA-03-13	2.08E-01	0.00E+00	2.42E+00	6.77E-01	1.57E-01	6.02E-05	4.11E-03	3.46E+00	1.40E-02
LA-TA-03-19	4.21E-01	0.00E+00	3.61E+00	1.32E+00	3.77E-01	9.32E-05	7.13E-03	5.73E+00	2.31E-02
LA-TA-03-20	2.30E-01	0.00E+00	1.71E+00	5.83E-01	2.03E-01	7.62E-05	3.22E-03	2.73E+00	1.10E-02
LA-TA-03-24	3.08E-01	0.00E+00	6.67E+00	1.08E+00	3.24E-01	7.90E-05	1.33E-02	8.40E+00	3.39E-02
LA-TA-03-26	1.58E-02	0.00E+00	2.75E-01	2.62E+00	4.24E-02	6.92E-06	1.42E-03	2.96E+00	1.19E-02
LA-TA-03-28	0.00E+00	0.00E+00	9.51E-02	2.46E-01	0.00E+00	0.00E+00	1.86E-04	3.41E-01	1.37E-03
LA-TA-03-30	7.01E-01	0.00E+00	6.78E-02	5.00E+00	1.43E+00	3.62E-04	1.32E-04	7.20E+00	2.90E-02
LA-TA-03-31	0.00E+00	0.00E+00	3.39E-03	8.75E-03	0.00E+00	0.00E+00	6.63E-06	1.22E-02	4.90E-05
LA-TA-03-40	0.00E+00	0.00E+00	5.36E-03	5.44E-02	0.00E+00	0.00E+00	1.06E-05	5.98E-02	2.41E-04
LA-TA-03-42	1.61E-05	0.00E+00	1.34E-04	3.40E-03	4.41E-05	7.58E-09	2.65E-07	3.59E-03	1.45E-05
LA-TA-21-06	1.59E-01	0.00E+00	1.48E+01	9.51E-01	2.87E-01	7.81E-05	2.89E-02	1.62E+01	6.53E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-12	5.78E-01	0.00E+00	8.91E+01	3.30E+00	9.72E-01	2.68E-04	1.74E-01	9.41E+01	3.79E-01
LA-TA-21-13	8.90E-01	0.00E+00	0.00E+00	2.92E-01	0.00E+00	0.00E+00	0.00E+00	1.18E+00	4.77E-03
LA-TA-21-14	1.46E-04	0.00E+00	1.70E+00	4.46E+00	5.14E-05	1.09E-07	2.70E-03	6.17E+00	2.49E-02
LA-TA-21-15	8.62E-02	0.00E+00	4.68E-03	1.38E+00	2.33E-01	4.41E-05	9.06E-06	1.71E+00	6.88E-03
LA-TA-21-16	9.98E-01	0.00E+00	7.21E-02	1.05E+01	2.49E+00	4.65E-04	1.42E-04	1.41E+01	5.68E-02
LA-TA-21-40	1.27E-04	0.00E+00	2.50E-01	3.31E-01	3.61E-04	1.86E-08	6.21E-04	5.82E-01	2.35E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	7.05E-01	0.00E+00	0.00E+00	0.00E+00	7.05E-01	2.84E-03
LA-TA-21-42	1.30E-02	0.00E+00	8.11E-02	1.63E-01	1.10E-02	6.07E-07	2.17E-04	2.68E-01	1.08E-03
LA-TA-21-43	4.57E+01	0.00E+00	2.69E+00	5.08E+02	1.19E+02	4.80E-03	7.12E-03	6.76E+02	2.73E+00
LA-TA-21-44	2.19E-01	0.00E+00	5.65E-01	1.14E+02	3.00E-01	6.78E-05	1.21E-03	1.15E+02	4.65E-01
LA-TA-48-01	7.10E-02	2.78E-03	2.13E-03	1.17E-01	4.85E-01	5.60E-06	5.34E-06	6.75E-01	2.72E-03
LA-TA-49-01	8.76E+00	3.45E-01	2.61E-01	1.45E+01	6.00E+01	6.92E-04	6.58E-04	8.36E+01	3.37E-01
LA-TA-50-10	2.35E-02	0.00E+00	2.48E-03	4.56E-02	0.00E+00	0.00E+00	3.85E-06	7.16E-02	2.89E-04
LA-TA-50-11	4.48E-02	0.00E+00	2.53E-03	4.63E-01	1.02E-01	5.55E-06	6.23E-06	6.12E-01	2.47E-03
LA-TA-50-15	8.83E-02	0.00E+00	3.74E-01	3.38E-01	7.48E-02	2.20E-05	6.75E-04	8.76E-01	3.53E-03
LA-TA-50-17	1.29E+01	0.00E+00	3.04E-01	1.81E+01	4.21E-04	2.01E-06	8.88E-04	3.13E+01	1.26E-01
LA-TA-50-18	7.68E-01	0.00E+00	4.02E-02	2.95E+00	5.24E-06	5.93E-08	7.93E-05	3.76E+00	1.52E-02
LA-TA-50-19	2.45E-01	0.00E+00	1.79E-02	3.93E-01	4.49E-03	7.34E-07	6.21E-05	6.60E-01	2.66E-03
LA-TA-50-20	6.72E-03	0.00E+00	0.00E+00	9.68E-03	0.00E+00	0.00E+00	0.00E+00	1.64E-02	6.62E-05
LA-TA-50-40	3.78E-03	0.00E+00	2.42E-04	1.05E-02	4.86E-03	2.35E-06	4.51E-07	1.94E-02	7.83E-05
LA-TA-50-41	4.04E-03	0.00E+00	2.44E-04	4.67E-02	1.08E-02	4.19E-06	4.09E-07	6.18E-02	2.49E-04
LA-TA-55-19	6.26E+00	0.00E+00	3.22E-01	2.62E+01	7.31E+00	2.37E-03	2.15E-03	4.01E+01	1.62E-01
LA-TA-55-20	1.01E+02	0.00E+00	3.66E+00	6.34E+02	1.51E+02	5.93E-02	1.00E-01	8.89E+02	3.59E+00
LA-TA-55-21	8.98E-01	8.23E-07	4.21E-02	4.49E+00	1.07E+00	4.89E-04	7.01E-05	6.50E+00	2.62E-02
LA-TA-55-22	2.46E+00	0.00E+00	2.38E-01	1.58E+01	3.66E+00	1.52E-03	3.96E-04	2.22E+01	8.94E-02
LA-TA-55-23	2.32E+00	0.00E+00	1.99E-01	1.08E+01	2.65E+00	1.49E-03	3.28E-04	1.60E+01	6.45E-02
LA-TA-55-24	8.74E-01	0.00E+00	3.12E-02	5.69E+00	1.31E+00	7.10E-04	4.90E-05	7.90E+00	3.19E-02
LA-TA-55-25	4.47E+00	0.00E+00	1.82E-01	2.82E+01	6.53E+00	3.64E-03	2.86E-04	3.94E+01	1.59E-01
LA-TA-55-28	1.53E+00	0.00E+00	1.01E-01	8.67E+00	2.03E+00	1.18E-03	1.60E-04	1.23E+01	4.97E-02
LA-TA-55-30	3.40E+01	7.79E-09	1.21E+00	1.42E+02	3.40E+01	8.66E-03	2.56E-03	2.11E+02	8.52E-01
LA-TA-55-32	2.76E+00	0.00E+00	6.74E+00	1.12E+01	3.43E+00	1.08E-03	1.35E-02	2.42E+01	9.75E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-33	4.13E-01	0.00E+00	1.74E-02	1.48E+00	4.68E-01	1.52E-04	3.22E-05	2.38E+00	9.59E-03
LA-TA-55-34	4.17E+01	0.00E+00	1.61E+00	2.30E+02	5.77E+01	1.83E-02	5.75E-03	3.31E+02	1.33E+00
LA-TA-55-38	1.05E+02	0.00E+00	5.30E-01	5.07E+01	1.35E+01	4.25E-03	2.67E-03	1.70E+02	6.84E-01
LA-TA-55-39	1.11E+01	0.00E+00	3.92E-01	7.57E+01	1.68E+01	7.48E-03	6.40E-04	1.04E+02	4.19E-01
LA-TA-55-41	2.64E+02	0.00E+00	8.11E-01	9.38E+01	2.22E+01	9.41E-03	1.36E-03	3.81E+02	1.54E+00
LA-TA-55-43	9.92E-02	0.00E+00	5.32E+01	1.41E-01	4.89E-02	8.28E-05	8.61E-02	5.36E+01	2.16E-01
LA-TA-55-44	8.60E-01	0.00E+00	1.25E+02	2.61E+00	7.18E-01	2.45E-04	2.34E-01	1.30E+02	5.23E-01
LA-TA-55-48	6.34E+03	0.00E+00	4.95E+02	1.68E+04	6.20E+03	2.56E+00	8.99E-01	2.98E+04	1.20E+02
LA-TA-55-49	1.36E+01	0.00E+00	6.51E+02	3.07E+01	8.54E+00	2.99E-03	1.20E+00	7.05E+02	2.84E+00
LA-TA-55-53	6.39E+01	0.00E+00	1.35E+00	2.62E+02	6.07E+01	1.64E-02	2.45E-03	3.88E+02	1.57E+00
LA-TA-55-56	7.07E+01	0.00E+00	5.01E+01	3.80E+02	9.43E+01	3.79E-02	8.59E-02	5.95E+02	2.40E+00
LA-TA-55-60	3.83E-02	0.00E+00	1.27E-02	7.16E-02	2.51E-02	2.23E-05	2.34E-05	1.48E-01	5.96E-04
LA-TA-55-61	3.30E-02	0.00E+00	5.83E-02	1.38E-01	4.64E-02	2.17E-05	1.06E-04	2.76E-01	1.11E-03
LA-TA-55-62	8.55E-03	0.00E+00	5.54E-04	2.32E-02	1.10E-02	5.83E-06	1.01E-06	4.32E-02	1.74E-04
LA-TA-55-63	6.35E-03	0.00E+00	3.74E-04	7.43E-02	1.70E-02	5.74E-06	6.48E-07	9.80E-02	3.95E-04
LL-M001	8.70E+01	3.73E-02	1.63E+01	6.96E+01	3.11E+01	4.53E-02	2.42E-02	2.04E+02	8.23E-01
LL-T001	4.34E+02	0.00E+00	0.00E+00	5.31E+02	2.37E+02	3.51E-01	0.00E+00	1.20E+03	4.85E+00
LL-T002	4.29E+03	0.00E+00	1.30E+02	5.15E+03	2.09E+03	3.09E+00	1.92E-01	1.17E+04	4.70E+01
LL-T003	1.67E+02	0.00E+00	1.45E+01	1.04E+02	8.34E+01	1.22E-01	2.15E-02	3.69E+02	1.49E+00
LL-T004	1.06E+02	0.00E+00	2.98E+00	6.63E+01	5.25E+01	7.76E-02	4.42E-03	2.28E+02	9.19E-01
LL-T005	5.47E+02	1.63E+00	3.51E+01	2.47E+02	2.11E+02	2.88E-01	5.20E-02	1.04E+03	4.19E+00
LL-W018	4.66E-02	0.00E+00	0.00E+00	1.84E-02	4.19E-02	5.88E-05	0.00E+00	1.07E-01	4.31E-04
LL-W019	2.53E+01	0.00E+00	0.00E+00	1.43E+01	1.18E+01	1.72E-02	0.00E+00	5.14E+01	2.07E-01
LL-W034	9.35E+00	2.75E-02	6.14E-01	4.18E+00	3.49E+00	4.89E-03	9.10E-04	1.76E+01	7.11E-02
MC-W001	1.17E-01	0.00E+00	0.00E+00	6.02E-02	0.00E+00	8.85E-06	0.00E+00	1.77E-01	7.13E-04
MU-W002	1.56E+00	0.00E+00	0.00E+00	5.23E-02	0.00E+00	0.00E+00	2.67E-12	1.61E+00	6.49E-03
NT-JAS-01	1.50E+02	0.00E+00	1.31E+01	9.42E+01	7.50E+01	1.10E-01	1.94E-02	3.33E+02	1.34E+00
NT-W001	2.26E+02	8.41E-04	2.61E+01	2.84E+03	1.88E+01	7.72E-03	5.03E-02	3.11E+03	1.26E+01
NT-W021	4.37E+00	0.00E+00	1.87E-01	3.20E+01	7.22E+00	3.95E-03	3.24E-04	4.38E+01	1.77E-01
OR-W201	5.24E+03	5.80E-02	5.61E+02	2.15E+03	2.09E+03	4.14E+00	4.44E+01	1.01E+04	4.07E+01
OR-W202	7.51E+02	1.21E+00	1.62E+03	5.51E+02	5.34E+02	1.33E-01	2.85E+00	3.46E+03	1.40E+01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
OR-W203	1.66E+00	4.20E-02	2.32E-01	2.48E-02	1.74E+00	3.37E-04	4.05E-04	3.66E+00	1.47E-02
OR-W204	3.69E-01	1.74E-07	2.63E-01	4.22E-01	2.82E-01	0.00E+00	4.60E-04	1.34E+00	5.39E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.24E-01	0.00E+00	0.00E+00	0.00E+00	4.24E-01	1.71E-03
RF-MT0001	1.42E+03	0.00E+00	1.63E+00	1.95E+02	4.39E+01	3.04E-02	2.72E-03	1.66E+03	6.68E+00
RF-MT0002	1.09E+02	0.00E+00	1.25E-01	1.50E+01	3.38E+00	2.33E-03	2.09E-04	1.27E+02	5.14E-01
RF-MT0003	4.95E-01	0.00E+00	2.87E-02	3.43E+00	7.73E-01	5.32E-04	4.77E-05	4.73E+00	1.91E-02
RF-MT0007	1.25E+00	0.00E+00	0.00E+00	4.27E-01	9.62E-02	6.16E-05	0.00E+00	1.77E+00	7.13E-03
RF-MT0089	4.89E-03	0.00E+00	2.87E-04	3.43E-02	7.72E-03	5.32E-06	4.77E-07	4.72E-02	1.90E-04
RF-MT0090	1.24E+01	0.00E+00	4.05E-01	8.81E+01	1.97E+01	5.32E-03	6.75E-04	1.21E+02	4.86E-01
RF-MT0091	7.69E+02	0.00E+00	4.11E+01	5.89E+03	1.32E+03	4.39E-01	7.15E-02	8.02E+03	3.23E+01
RF-MT0092	1.10E+02	0.00E+00	5.19E+00	8.43E+02	1.93E+02	6.07E-02	8.63E-03	1.15E+03	4.64E+00
RF-MT0093	1.34E+02	0.00E+00	5.34E+00	9.10E+02	2.11E+02	5.18E-02	8.89E-03	1.26E+03	5.08E+00
RF-MT0097	6.71E+00	0.00E+00	2.36E-01	4.75E+01	9.61E+00	2.83E-03	3.92E-04	6.41E+01	2.58E-01
RF-MT0099	7.35E-03	0.00E+00	4.31E-04	5.14E-02	1.15E-02	8.00E-06	7.17E-07	7.07E-02	2.85E-04
RF-MT0290	1.82E+01	0.00E+00	1.07E+00	1.27E+02	2.87E+01	1.98E-02	1.78E-03	1.75E+02	7.07E-01
RF-MT-0292	2.30E+01	0.00E+00	1.35E+00	1.61E+02	3.62E+01	2.50E-02	2.24E-03	2.22E+02	8.93E-01
RF-MT-0299	2.71E+03	0.00E+00	3.45E+01	4.13E+03	9.29E+02	6.45E-01	5.75E-02	7.80E+03	3.14E+01
RF-MT0302	4.14E-02	0.00E+00	1.37E-03	1.78E-01	4.02E-02	2.50E-05	1.91E-05	2.61E-01	1.05E-03
RF-MT0320	4.95E+01	0.00E+00	1.42E+00	1.73E+02	3.90E+01	2.52E-02	2.37E-03	2.63E+02	1.06E+00
RF-MT0321	2.77E+01	0.00E+00	4.23E-01	5.57E+01	1.24E+01	7.06E-03	3.12E-03	9.62E+01	3.88E-01
RF-MT-0328	1.92E+00	0.00E+00	5.07E-02	6.05E+00	1.36E+00	9.41E-04	4.23E-04	9.38E+00	3.78E-02
RF-MT0330	1.99E+01	0.00E+00	5.56E-01	1.22E+02	2.97E+01	8.85E-03	9.25E-04	1.73E+02	6.96E-01
RF-MT-0331	1.20E+02	0.00E+00	3.45E+00	5.38E+02	1.18E+02	5.13E-02	2.65E-02	7.79E+02	3.14E+00
RF-MT0332	1.71E-02	0.00E+00	1.01E-03	1.20E-01	2.70E-02	1.87E-05	1.67E-06	1.65E-01	6.67E-04
RF-MT-0335	1.38E+00	0.00E+00	4.62E-02	6.19E+00	1.40E+00	7.62E-04	6.19E-04	9.02E+00	3.64E-02
RF-MT0336	9.74E+01	0.00E+00	3.06E+00	4.39E+02	9.88E+01	4.47E-02	6.91E-03	6.39E+02	2.58E+00
RF-MT0337	5.50E+01	0.00E+00	1.68E+00	2.68E+02	5.94E+01	2.18E-02	6.65E-03	3.85E+02	1.55E+00
RF-MT0339	1.51E+02	0.00E+00	4.58E+00	5.89E+02	1.31E+02	7.90E-02	2.47E-02	8.75E+02	3.53E+00
RF-MT-0342	8.85E-01	0.00E+00	3.84E-02	5.44E+00	1.20E+00	5.79E-04	1.22E-04	7.56E+00	3.05E-02
RF-MT0371	2.99E+02	0.00E+00	8.89E+00	1.06E+03	2.39E+02	1.65E-01	1.61E-02	1.61E+03	6.49E+00
RF-MT-0372	1.30E+00	0.00E+00	6.26E-02	7.42E+00	1.67E+00	1.02E-03	3.44E-04	1.05E+01	4.22E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0373	1.96E+01	0.00E+00	6.43E-01	1.39E+02	3.11E+01	8.42E-03	1.07E-03	1.91E+02	7.68E-01
RF-MT0374	6.38E-01	0.00E+00	2.30E-02	2.75E+00	6.19E-01	4.27E-04	4.16E-05	4.03E+00	1.63E-02
RF-MT0376	5.06E-01	0.00E+00	1.86E-02	2.74E+00	6.27E-01	3.15E-04	4.60E-05	3.90E+00	1.57E-02
RF-MT0377	3.00E+02	0.00E+00	1.07E+01	1.28E+03	2.88E+02	1.99E-01	2.81E-02	1.88E+03	7.58E+00
RF-MT0378	3.37E+00	0.00E+00	1.48E-01	1.77E+01	3.98E+00	2.75E-03	2.46E-04	2.52E+01	1.02E-01
RF-MT0419	5.42E+00	0.00E+00	1.38E-01	1.65E+01	3.72E+00	2.57E-03	2.30E-04	2.58E+01	1.04E-01
RF-MT0420	9.42E-01	0.00E+00	2.40E-02	2.86E+00	6.46E-01	4.47E-04	3.99E-05	4.48E+00	1.80E-02
RF-MT0423	8.00E+00	0.00E+00	1.95E-01	4.14E+01	9.03E+00	1.77E-03	3.25E-04	5.86E+01	2.36E-01
RF-MT0425	2.36E-01	0.00E+00	6.00E-03	7.17E-01	1.61E-01	1.12E-04	1.00E-05	1.12E+00	4.52E-03
RF-MT-0438	2.14E+00	0.00E+00	7.88E-02	1.27E+01	2.84E+00	1.11E-03	1.44E-04	1.78E+01	7.17E-02
RF-MT0440	7.77E-01	0.00E+00	2.83E-02	4.61E+00	1.06E+00	4.55E-04	2.12E-04	6.47E+00	2.61E-02
RF-MT0442	2.95E-01	0.00E+00	1.22E-02	1.58E+00	3.55E-01	1.69E-04	1.15E-04	2.24E+00	9.05E-03
RF-MT0443	3.64E+00	0.00E+00	2.01E-01	2.46E+01	5.53E+00	3.52E-03	4.92E-04	3.39E+01	1.37E-01
RF-MT0444	2.84E+01	0.00E+00	9.84E-01	1.18E+02	2.65E+01	1.83E-02	1.66E-03	1.74E+02	7.02E-01
RF-MT0480	7.94E+01	0.00E+00	2.77E+00	3.32E+02	7.48E+01	4.71E-02	7.07E-03	4.89E+02	1.97E+00
RF-MT0488	1.27E+02	0.00E+00	4.13E+00	4.93E+02	1.11E+02	7.67E-02	3.78E-02	7.35E+02	2.96E+00
RF-MT0490	5.76E-01	0.00E+00	2.40E-02	2.91E+00	6.56E-01	4.23E-04	5.11E-05	4.17E+00	1.68E-02
RF-MT-0491	4.52E-02	0.00E+00	1.10E-03	1.32E-01	2.96E-02	1.98E-05	3.83E-06	2.08E-01	8.39E-04
RF-MT0523A	3.58E+01	0.00E+00	8.71E-01	1.04E+02	2.35E+01	1.61E-02	1.71E-03	1.65E+02	6.64E-01
RF-MT0523B	3.58E+01	0.00E+00	8.71E-01	1.04E+02	2.35E+01	1.61E-02	1.71E-03	1.65E+02	6.64E-01
RF-MT0523C	3.58E+01	0.00E+00	8.71E-01	1.04E+02	2.35E+01	1.61E-02	1.71E-03	1.65E+02	6.64E-01
RF-MT0523D	3.58E+01	0.00E+00	8.71E-01	1.04E+02	2.35E+01	1.61E-02	1.71E-03	1.65E+02	6.64E-01
RF-MT0523E	3.58E+01	0.00E+00	8.71E-01	1.04E+02	2.35E+01	1.61E-02	1.71E-03	1.65E+02	6.64E-01
RF-MT0531	2.45E-03	0.00E+00	1.44E-04	1.71E-02	3.85E-03	2.67E-06	2.39E-07	2.36E-02	9.49E-05
RF-MT0532E	1.14E+02	0.00E+00	1.87E+00	2.28E+02	5.12E+01	3.44E-02	4.21E-03	3.95E+02	1.59E+00
RF-MT0532F	1.14E+02	0.00E+00	1.87E+00	2.28E+02	5.12E+01	3.44E-02	4.21E-03	3.95E+02	1.59E+00
RF-MT0541	4.16E+00	0.00E+00	2.69E-02	3.23E+00	7.26E-01	5.03E-04	4.48E-05	8.14E+00	3.28E-02
RF-MT0545	2.23E-02	0.00E+00	1.30E-03	1.56E-01	3.50E-02	2.42E-05	2.17E-06	2.15E-01	8.66E-04
RF-MT0800	8.46E+02	0.00E+00	6.45E-01	7.70E+01	1.73E+01	1.20E-02	1.56E-03	9.41E+02	3.79E+00
RF-MT0801	9.73E+01	0.00E+00	6.32E-01	7.57E+01	1.70E+01	1.17E-02	1.05E-03	1.91E+02	7.69E-01
RF-MT0803	2.18E+00	0.00E+00	1.41E-02	1.69E+00	3.80E-01	2.63E-04	2.35E-05	4.27E+00	1.72E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0806	1.03E+00	0.00E+00	3.39E-02	7.35E+00	1.63E+00	4.44E-04	5.65E-05	1.00E+01	4.05E-02
RF-MT0807	1.30E+01	0.00E+00	2.61E-01	3.12E+01	7.03E+00	4.85E-03	4.35E-04	5.15E+01	2.08E-01
RF-MT0816	1.39E+00	0.00E+00	3.68E-02	4.40E+00	9.88E-01	6.87E-04	6.13E-05	6.82E+00	2.75E-02
RF-MT-0823	6.90E-01	0.00E+00	1.68E-02	2.01E+00	4.52E-01	3.11E-04	3.28E-05	3.17E+00	1.28E-02
RF-MT0827	3.52E+01	0.00E+00	9.32E-01	1.11E+02	2.50E+01	1.73E-02	1.55E-03	1.73E+02	6.95E-01
RF-MT0831	6.70E+01	0.00E+00	2.55E+00	3.01E+02	6.79E+01	4.56E-02	1.65E-02	4.39E+02	1.77E+00
RF-MT0832	4.01E+02	0.00E+00	9.26E+00	1.17E+03	2.63E+02	1.63E-01	4.88E-02	1.85E+03	7.44E+00
RF-MT0833	1.22E+02	0.00E+00	2.77E+00	3.39E+02	7.63E+01	4.89E-02	1.38E-02	5.40E+02	2.18E+00
RF-MT0855	2.10E-02	0.00E+00	1.23E-03	1.47E-01	3.31E-02	2.29E-05	2.05E-06	2.02E-01	8.16E-04
RF-MT0857	1.03E+00	0.00E+00	3.37E-02	7.33E+00	1.63E+00	4.43E-04	5.62E-05	1.00E+01	4.04E-02
RF-MT0H61	3.82E+01	0.00E+00	1.25E+00	2.71E+02	6.07E+01	1.64E-02	2.09E-03	3.72E+02	1.50E+00
RF-MT2116	4.30E+00	0.00E+00	9.94E-02	1.25E+01	2.82E+00	1.75E-03	5.23E-04	1.97E+01	7.96E-02
RF-MT3010	2.69E+01	0.00E+00	1.03E+00	1.24E+02	2.82E+01	1.87E-02	2.11E-03	1.80E+02	7.27E-01
RF-MT3011	2.01E+02	0.00E+00	6.43E+00	7.67E+02	1.73E+02	1.20E-01	1.85E-02	1.15E+03	4.63E+00
RF-MT420P	1.07E+03	0.00E+00	3.26E+01	6.31E+03	1.42E+03	3.91E-01	6.42E-02	8.83E+03	3.56E+01
RF-MT532A	2.81E+02	0.00E+00	4.60E+00	5.63E+02	1.26E+02	8.47E-02	1.04E-02	9.75E+02	3.93E+00
RF-MT532B	1.26E+03	0.00E+00	2.07E+01	2.53E+03	5.67E+02	3.81E-01	4.66E-02	4.38E+03	1.76E+01
RF-MT532C	2.53E+03	0.00E+00	4.15E+01	5.06E+03	1.14E+03	7.62E-01	9.37E-02	8.77E+03	3.54E+01
RF-MT532D	1.60E+01	0.00E+00	2.61E-01	3.20E+01	7.18E+00	4.80E-03	5.90E-04	5.55E+01	2.24E-01
RF-TT0069	9.21E-02	0.00E+00	3.10E-03	3.71E-01	8.35E-02	5.79E-05	7.87E-05	5.50E-01	2.22E-03
RF-TT0200	4.37E+00	0.00E+00	1.25E-01	1.52E+01	3.44E+00	2.22E-03	2.09E-04	2.32E+01	9.33E-02
RF-TT0299	1.81E+01	0.00E+00	2.32E-01	2.77E+01	6.24E+00	4.31E-03	3.86E-04	5.23E+01	2.11E-01
RF-TT0300	1.48E+02	0.00E+00	6.61E+00	7.96E+02	1.80E+02	1.05E-01	1.94E-02	1.13E+03	4.56E+00
RF-TT0301	2.00E+01	0.00E+00	8.97E-01	1.08E+02	2.45E+01	1.42E-02	2.63E-03	1.54E+02	6.20E-01
RF-TT0302	9.86E-01	0.00E+00	3.26E-02	4.24E+00	9.55E-01	5.98E-04	4.53E-04	6.21E+00	2.50E-02
RF-TT0303	5.94E+00	0.00E+00	1.90E-01	2.28E+01	5.12E+00	3.53E-03	1.35E-03	3.40E+01	1.37E-01
RF-TT0310	2.02E+01	0.00E+00	8.93E-01	1.02E+02	2.38E+01	1.29E-02	1.67E-03	1.47E+02	5.94E-01
RF-TT0312	4.85E+02	0.00E+00	1.61E+01	2.24E+03	4.99E+02	2.72E-01	2.86E-02	3.24E+03	1.31E+01
RF-TT0317	3.05E-01	0.00E+00	1.75E-02	2.10E+00	4.72E-01	3.26E-04	2.92E-05	2.89E+00	1.17E-02
RF-TT0320	1.96E+02	0.00E+00	5.61E+00	6.84E+02	1.55E+02	9.97E-02	9.40E-03	1.04E+03	4.19E+00
RF-TT0330	6.97E+01	0.00E+00	1.94E+00	4.29E+02	1.04E+02	3.10E-02	3.24E-03	6.05E+02	2.44E+00

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT-0331	3.47E+02	0.00E+00	1.00E+01	1.56E+03	3.44E+02	1.49E-01	7.69E-02	2.26E+03	9.12E+00
RF-TT-0334	1.51E+02	0.00E+00	8.13E+00	9.70E+02	2.18E+02	1.51E-01	1.35E-02	1.35E+03	5.43E+00
RF-TT0335	1.84E+02	0.00E+00	6.16E+00	8.25E+02	1.87E+02	1.02E-01	8.25E-02	1.20E+03	4.85E+00
RF-TT0336	1.63E+02	0.00E+00	5.11E+00	7.31E+02	1.64E+02	7.43E-02	1.15E-02	1.06E+03	4.29E+00
RF-TT0337	1.93E+02	0.00E+00	5.91E+00	9.43E+02	2.08E+02	7.67E-02	2.33E-02	1.35E+03	5.45E+00
RF-TT0338	8.19E+02	0.00E+00	2.14E+01	3.68E+03	8.14E+02	3.43E-01	4.40E-02	5.33E+03	2.15E+01
RF-TT0340	7.01E+00	0.00E+00	4.09E-01	4.89E+01	1.11E+01	7.62E-03	6.82E-04	6.74E+01	2.72E-01
RF-TT0342	4.69E+01	0.00E+00	2.05E+00	2.88E+02	6.37E+01	3.06E-02	6.51E-03	4.01E+02	1.62E+00
RF-TT0360	3.57E+00	0.00E+00	1.04E-01	1.29E+01	2.95E+00	1.81E-03	1.79E-04	1.95E+01	7.88E-02
RF-TT0368	7.14E+01	0.00E+00	2.09E+00	2.59E+02	5.90E+01	3.63E-02	3.60E-03	3.92E+02	1.58E+00
RF-TT0370	1.41E+02	0.00E+00	4.50E+00	5.78E+02	1.30E+02	7.72E-02	1.53E-02	8.53E+02	3.44E+00
RF-TT0371	3.05E+00	0.00E+00	9.06E-02	1.08E+01	2.44E+00	1.68E-03	1.64E-04	1.64E+01	6.62E-02
RF-TT0372	3.73E-01	0.00E+00	1.79E-02	2.12E+00	4.77E-01	2.92E-04	9.81E-05	2.99E+00	1.20E-02
RF-TT0374	1.16E+01	0.00E+00	4.19E-01	5.00E+01	1.13E+01	7.76E-03	7.58E-04	7.33E+01	2.96E-01
RF-TT0375A	1.21E-01	0.00E+00	6.90E-03	8.22E-01	1.85E-01	1.28E-04	1.15E-05	1.14E+00	4.58E-03
RF-TT0375B	1.21E-01	0.00E+00	6.90E-03	8.22E-01	1.85E-01	1.28E-04	1.15E-05	1.14E+00	4.58E-03
RF-TT0376	2.78E+01	0.00E+00	1.02E+00	1.51E+02	3.44E+01	1.73E-02	2.53E-03	2.14E+02	8.64E-01
RF-TT0377	1.56E+01	0.00E+00	5.56E-01	6.64E+01	1.50E+01	1.03E-02	1.46E-03	9.75E+01	3.93E-01
RF-TT0391	3.48E+00	0.00E+00	7.82E-02	1.68E+01	3.73E+00	1.80E-03	1.30E-04	2.41E+01	9.71E-02
RF-TT0392	1.23E+00	0.00E+00	4.91E-02	8.78E+00	1.97E+00	6.26E-04	8.19E-05	1.20E+01	4.85E-02
RF-TT0393	1.01E+02	0.00E+00	3.43E+00	4.09E+02	9.21E+01	6.35E-02	5.71E-03	6.05E+02	2.44E+00
RF-TT0398	2.20E+00	0.00E+00	9.04E-02	1.64E+01	3.66E+00	1.18E-03	1.51E-04	2.24E+01	9.01E-02
RF-TT0409	1.84E+00	0.00E+00	4.23E-02	8.47E+00	1.89E+00	4.54E-04	7.10E-05	1.22E+01	4.94E-02
RF-TT0412	1.84E+00	0.00E+00	4.23E-02	8.47E+00	1.89E+00	4.54E-04	7.10E-05	1.22E+01	4.94E-02
RF-TT0414	5.70E+01	0.00E+00	1.31E+00	2.62E+02	5.84E+01	1.41E-02	2.20E-03	3.79E+02	1.53E+00
RF-TT0430	1.67E-02	0.00E+00	9.77E-04	1.16E-01	2.62E-02	1.81E-05	1.63E-06	1.60E-01	6.46E-04
RF-TT0431	4.14E+00	0.00E+00	2.38E-01	2.86E+01	6.45E+00	4.31E-03	6.18E-04	3.95E+01	1.59E-01
RF-TT0438	2.46E+02	0.00E+00	9.06E+00	1.46E+03	3.27E+02	1.28E-01	1.66E-02	2.04E+03	8.24E+00
RF-TT0440	2.43E+01	0.00E+00	8.81E-01	1.44E+02	3.32E+01	1.43E-02	6.63E-03	2.03E+02	8.16E-01
RF-TT0441	1.20E+02	0.00E+00	4.13E+00	4.98E+02	1.13E+02	7.58E-02	1.15E-02	7.34E+02	2.96E+00
RF-TT0442	1.73E+01	0.00E+00	7.13E-01	9.22E+01	2.07E+01	9.88E-03	6.71E-03	1.31E+02	5.28E-01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0443	3.69E-01	0.00E+00	2.05E-02	2.50E+00	5.61E-01	3.58E-04	5.01E-05	3.45E+00	1.39E-02
RF-TT0479	3.62E+00	0.00E+00	2.13E-01	2.53E+01	5.69E+00	3.93E-03	3.54E-04	3.48E+01	1.40E-01
RF-TT0480	2.46E+02	0.00E+00	8.58E+00	1.03E+03	2.32E+02	1.46E-01	2.19E-02	1.52E+03	6.13E+00
RF-TT0481	1.39E-01	0.00E+00	4.83E-03	5.81E-01	1.31E-01	8.23E-05	1.24E-05	8.55E-01	3.45E-03
RF-TT0483	4.46E-01	0.00E+00	2.61E-02	3.11E+00	7.01E-01	4.85E-04	1.72E-02	4.30E+00	1.74E-02
RF-TT0484	2.39E+00	0.00E+00	1.08E-01	1.29E+01	2.92E+00	2.01E-03	2.91E-04	1.83E+01	7.39E-02
RF-TT0485	1.96E-01	0.00E+00	6.69E-03	7.97E-01	1.80E-01	1.24E-04	2.89E-04	1.18E+00	4.76E-03
RF-TT0486	1.16E+00	0.00E+00	3.96E-02	4.73E+00	1.07E+00	7.34E-04	2.94E-04	7.00E+00	2.82E-02
RF-TT0487	5.82E+00	0.00E+00	1.35E-01	1.70E+01	3.82E+00	2.37E-03	7.08E-04	2.68E+01	1.08E-01
RF-TT0489	1.66E+00	0.00E+00	6.04E-02	7.22E+00	1.62E+00	1.12E-03	2.02E-04	1.06E+01	4.26E-02
RF-TT0490	9.18E+01	0.00E+00	3.84E+00	4.65E+02	1.05E+02	6.73E-02	8.18E-03	6.66E+02	2.68E+00
RF-TT0491	2.14E+00	0.00E+00	5.19E-02	6.23E+00	1.40E+00	9.36E-04	1.82E-04	9.82E+00	3.96E-02
RF-TT0492	7.17E-01	0.00E+00	2.92E-02	3.48E+00	7.85E-01	5.41E-04	4.87E-05	5.01E+00	2.02E-02
RF-TT0523A	4.82E+00	0.00E+00	1.17E-01	1.40E+01	3.16E+00	2.17E-03	2.30E-04	2.21E+01	8.92E-02
RF-TT0523B	4.82E+00	0.00E+00	1.17E-01	1.40E+01	3.16E+00	2.17E-03	2.30E-04	2.21E+01	8.92E-02
RF-TT0523C	4.82E+00	0.00E+00	1.17E-01	1.40E+01	3.16E+00	2.17E-03	2.30E-04	2.21E+01	8.92E-02
RF-TT0523D	4.82E+00	0.00E+00	1.17E-01	1.40E+01	3.16E+00	2.17E-03	2.30E-04	2.21E+01	8.92E-02
RF-TT0523E	4.82E+00	0.00E+00	1.17E-01	1.40E+01	3.16E+00	2.17E-03	2.30E-04	2.21E+01	8.92E-02
RF-TT0532A	1.21E+02	0.00E+00	1.97E+00	2.42E+02	5.42E+01	3.64E-02	4.45E-03	4.19E+02	1.69E+00
RF-TT0532B	1.21E+02	0.00E+00	1.97E+00	2.42E+02	5.42E+01	3.64E-02	4.45E-03	4.19E+02	1.69E+00
RF-TT0541	2.00E-01	0.00E+00	1.17E-02	1.40E+00	3.15E-01	2.18E-04	1.95E-05	1.93E+00	7.78E-03
RF-TT0545	4.46E-02	0.00E+00	2.61E-03	3.11E-01	7.01E-02	4.85E-05	4.35E-06	4.29E-01	1.73E-03
RF-TT0601	1.55E+01	0.00E+00	4.50E-01	5.62E+01	1.28E+01	7.86E-03	7.77E-04	8.49E+01	3.42E-01
RF-TT0802	1.73E+03	0.00E+00	3.70E+01	4.43E+03	9.98E+02	6.87E-01	6.16E-02	7.20E+03	2.90E+01
RF-TT0809	1.42E+02	0.00E+00	3.04E+00	3.65E+02	8.18E+01	5.65E-02	5.06E-03	5.92E+02	2.39E+00
RF-TT0821	3.08E+02	0.00E+00	1.11E+01	1.43E+03	3.23E+02	1.68E-01	1.86E-01	2.07E+03	8.36E+00
RF-TT0822	3.41E+02	0.00E+00	8.60E+00	1.07E+03	2.41E+02	1.50E-01	1.97E-01	1.66E+03	6.71E+00
RF-TT0823	6.90E-01	0.00E+00	1.68E-02	2.01E+00	4.52E-01	3.11E-04	3.28E-05	3.17E+00	1.28E-02
RF-TT0824	7.10E+02	0.00E+00	2.36E+01	2.89E+03	6.51E+02	4.23E-01	1.02E-01	4.28E+03	1.73E+01
RF-TT0825	5.89E+02	0.00E+00	1.70E+01	2.18E+03	4.89E+02	2.80E-01	1.09E-01	3.27E+03	1.32E+01
RF-TT0832	4.36E+02	0.00E+00	1.01E+01	1.27E+03	2.87E+02	1.77E-01	5.31E-02	2.01E+03	8.09E+00

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0854	1.57E-01	0.00E+00	9.20E-03	1.09E+00	2.48E-01	1.71E-04	7.62E-04	1.51E+00	6.08E-03
RF-TT0886	2.23E-02	0.00E+00	1.30E-03	1.55E-01	3.50E-02	2.42E-05	2.16E-06	2.14E-01	8.62E-04
RF-TT2216	6.44E+00	0.00E+00	1.49E-01	1.89E+01	4.23E+00	2.62E-03	7.85E-04	2.97E+01	1.20E-01
RF-TT3010	3.44E+02	0.00E+00	1.32E+01	1.59E+03	3.59E+02	2.40E-01	2.70E-02	2.31E+03	9.30E+00
RF-TT3011	8.69E+02	0.00E+00	2.79E+01	3.32E+03	7.48E+02	5.18E-01	8.01E-02	4.97E+03	2.00E+01
RF-TT301U	7.22E+01	0.00E+00	2.94E+00	3.61E+02	8.26E+01	5.08E-02	5.06E-03	5.19E+02	2.09E+00
RF-TT310P	2.09E+01	0.00E+00	7.66E-01	1.21E+02	2.59E+01	1.06E-02	1.28E-03	1.69E+02	6.81E-01
RF-TT338S	6.10E-01	0.00E+00	3.51E-02	4.19E+00	9.43E-01	6.49E-04	5.84E-05	5.77E+00	2.33E-02
RF-TT390P	3.43E+00	0.00E+00	9.51E-02	2.04E+01	4.22E+00	1.62E-03	1.87E-04	2.81E+01	1.13E-01
RF-TT391P	1.89E+02	0.00E+00	4.27E+00	9.16E+02	2.03E+02	9.83E-02	7.11E-03	1.31E+03	5.29E+00
RF-TT392P	3.83E+02	0.00E+00	1.54E+01	2.74E+03	6.15E+02	1.95E-01	2.57E-02	3.76E+03	1.52E+01
RF-TT393R	5.67E+01	0.00E+00	2.61E+00	4.20E+02	9.47E+01	3.16E-02	4.52E-03	5.74E+02	2.31E+00
RF-TT394P	7.04E+00	0.00E+00	1.62E-01	3.24E+01	6.76E+00	2.27E-03	2.76E-04	4.64E+01	1.87E-01
RF-TT395P	9.42E+00	0.00E+00	2.16E-01	4.33E+01	9.03E+00	3.04E-03	3.70E-04	6.20E+01	2.50E-01
RF-TT396P	2.35E+00	0.00E+00	5.40E-02	1.08E+01	2.26E+00	7.58E-04	9.23E-05	1.55E+01	6.25E-02
RF-TT398P	2.28E+02	0.00E+00	9.36E+00	1.70E+03	3.79E+02	1.22E-01	1.56E-02	2.32E+03	9.34E+00
RF-TT398R	1.88E+03	0.00E+00	1.74E+01	2.74E+03	6.12E+02	2.38E-01	2.90E-02	5.25E+03	2.12E+01
RF-TT411R	6.80E+01	0.00E+00	1.56E+00	3.13E+02	6.98E+01	1.68E-02	2.62E-03	4.53E+02	1.82E+00
RF-TT429R	1.43E+02	0.00E+00	3.35E-01	7.26E+01	1.59E+01	2.93E-03	5.58E-04	2.32E+02	9.34E-01
RF-TT433X	4.50E+01	0.00E+00	9.28E-02	2.09E+01	4.12E+00	1.16E-03	1.55E-04	7.01E+01	2.83E-01
RF-TT436R	3.30E+02	0.00E+00	1.34E+00	2.73E+02	6.08E+01	2.24E-02	2.24E-03	6.65E+02	2.68E+00
RF-TT454X	1.94E+01	0.00E+00	7.89E-02	1.61E+01	3.58E+00	1.32E-03	1.32E-04	3.91E+01	1.58E-01
RL-T101	9.82E+01	0.00E+00	4.80E+00	8.70E+02	1.92E+02	1.87E-01	7.11E-03	1.17E+03	4.70E+00
RL-T102	1.25E-03	0.00E+00	6.10E-05	1.11E-02	2.45E-03	2.37E-06	1.24E-06	1.49E-02	6.00E-05
RL-T103	8.83E+01	0.00E+00	5.81E+00	3.80E+02	8.32E+01	9.93E-02	8.61E-03	5.57E+02	2.25E+00
RL-T104	1.79E-03	0.00E+00	8.71E-05	1.58E-02	3.50E-03	3.40E-06	1.62E-07	2.12E-02	8.54E-05
RL-T105	6.85E-01	0.00E+00	3.29E-02	6.00E+00	1.32E+00	1.28E-03	9.36E-05	8.04E+00	3.24E-02
RL-T106	6.60E-01	0.00E+00	3.24E-02	5.87E+00	1.29E+00	1.26E-03	4.79E-05	7.85E+00	3.17E-02
RL-T107	1.82E+03	0.00E+00	1.90E+04	1.62E+04	3.56E+03	3.45E+00	2.90E+01	4.06E+04	1.64E+02
RL-T108	1.04E+00	0.00E+00	3.28E+00	9.23E+00	2.04E+00	1.98E-03	4.88E-03	1.56E+01	6.28E-02
RL-T109	1.43E+00	0.00E+00	6.74E-02	1.22E+01	2.70E+00	2.62E-03	2.34E-02	1.65E+01	6.63E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T110	1.60E+02	0.00E+00	1.29E+01	1.40E+03	3.10E+02	3.01E-01	1.38E+00	1.89E+03	7.61E+00
RL-T112	6.46E+01	0.00E+00	5.44E+00	1.86E+02	4.10E+01	3.99E-02	7.44E-01	2.98E+02	1.20E+00
RL-T113	6.90E-02	0.00E+00	1.05E-02	6.12E-01	1.35E-01	1.31E-04	1.56E-05	8.27E-01	3.33E-03
RL-T114	1.05E+01	0.00E+00	5.13E-01	9.30E+01	2.05E+01	2.00E-02	7.60E-04	1.25E+02	5.02E-01
RL-T115	2.67E+02	0.00E+00	1.66E+01	1.22E+03	2.70E+02	2.94E-01	4.37E-01	1.78E+03	7.16E+00
RL-T116	1.72E+01	0.00E+00	8.42E-01	1.52E+02	3.37E+01	3.27E-02	5.74E-02	2.04E+02	8.22E-01
RL-T118	4.42E+01	0.00E+00	6.73E+00	1.51E+02	3.34E+01	3.24E-02	8.43E-01	2.36E+02	9.53E-01
RL-T120	1.07E+01	0.00E+00	7.06E-01	4.47E+01	9.78E+00	1.14E-02	1.05E-03	6.59E+01	2.66E-01
RL-T122	6.08E-01	0.00E+00	2.98E-02	5.39E+00	1.19E+00	1.16E-03	1.46E+00	8.68E+00	3.50E-02
RL-T123	1.79E+00	0.00E+00	8.73E-02	1.58E+01	3.50E+00	3.41E-03	5.98E-02	2.13E+01	8.57E-02
RL-T125	3.56E+02	0.00E+00	2.16E+01	3.31E+02	1.68E+02	5.32E-01	3.21E-02	8.77E+02	3.54E+00
RL-T127	3.43E+02	0.00E+00	5.44E+00	9.89E+02	2.18E+02	2.12E-01	8.80E-02	1.56E+03	6.27E+00
RL-T128	5.08E-01	0.00E+00	1.32E-07	2.41E-05	5.29E-06	5.13E-09	1.96E-10	5.08E-01	2.05E-03
RL-T129	1.52E+00	0.00E+00	2.51E+01	1.36E+01	2.98E+00	2.90E-03	4.49E-02	4.33E+01	1.75E-01
RL-T130	3.24E-03	0.00E+00	1.59E-04	2.89E-02	6.37E-03	6.16E-06	8.32E-05	3.88E-02	1.56E-04
RL-T131	1.32E+00	0.00E+00	8.67E-02	5.51E+00	1.20E+00	1.39E-03	8.35E-03	8.12E+00	3.28E-02
RL-T132	3.14E+02	0.00E+00	1.53E+01	2.79E+03	6.15E+02	5.98E-01	2.68E-01	3.74E+03	1.51E+01
RL-T133	6.40E-03	0.00E+00	2.46E-04	4.58E-02	1.01E-02	8.47E-06	3.64E-07	6.25E-02	2.52E-04
RL-T134	1.35E-02	0.00E+00	6.61E-04	1.20E-01	2.64E-02	2.57E-05	9.79E-07	1.61E-01	6.49E-04
RL-T135	6.33E-02	0.00E+00	3.10E-03	5.63E-01	1.24E-01	1.20E-04	4.15E-03	7.57E-01	3.05E-03
RL-T137	1.03E+03	0.00E+00	6.76E+01	4.28E+03	9.39E+02	1.10E+00	1.06E-01	6.32E+03	2.55E+01
RL-T140	1.20E+03	0.00E+00	6.43E+01	4.15E+03	1.01E+03	9.32E-01	2.63E+01	6.45E+03	2.60E+01
RL-T143	7.54E+00	0.00E+00	3.68E-01	6.70E+01	1.48E+01	1.44E-02	3.91E-02	8.97E+01	3.62E-01
RL-T145	2.15E+01	0.00E+00	1.05E+00	1.91E+02	4.20E+01	4.08E-02	9.11E-02	2.55E+02	1.03E+00
RL-W407	6.17E+01	0.00E+00	2.24E+00	4.37E+02	9.65E+01	6.21E-02	3.32E-03	5.98E+02	2.41E+00
RL-W408	2.53E-04	0.00E+00	9.47E-06	1.77E-03	3.90E-04	3.20E-07	1.40E-08	2.42E-03	9.77E-06
RL-W415	5.59E-03	0.00E+00	2.09E-04	3.92E-02	8.63E-03	7.06E-06	3.09E-07	5.36E-02	2.16E-04
RL-W418	2.39E-02	0.00E+00	8.79E-04	1.68E-01	3.71E-02	2.64E-05	1.30E-06	2.30E-01	9.27E-04
RL-W437	2.03E+02	0.00E+00	7.37E+00	1.43E+03	3.16E+02	2.04E-01	1.09E-02	1.96E+03	7.89E+00
RL-W438	3.54E-04	0.00E+00	1.32E-05	2.48E-03	5.45E-04	4.47E-07	1.96E-08	3.39E-03	1.37E-05
RL-W439	1.11E+04	0.00E+00	7.29E+02	4.77E+04	1.05E+04	1.25E+01	1.08E+00	7.00E+04	2.82E+02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W443	1.78E+02	0.00E+00	6.49E+00	1.26E+03	2.78E+02	1.79E-01	9.62E-03	1.73E+03	6.96E+00
RL-W444	1.32E+02	0.00E+00	4.81E+00	9.36E+02	2.06E+02	1.33E-01	7.13E-03	1.28E+03	5.16E+00
RL-W447	1.52E-02	0.00E+00	5.67E-04	1.05E-01	2.34E-02	1.92E-05	8.40E-07	1.45E-01	5.83E-04
RL-W448	1.12E-04	0.00E+00	4.19E-06	7.82E-04	1.72E-04	1.42E-07	6.21E-09	1.07E-03	4.32E-06
RL-W449	9.20E-01	0.00E+00	1.53E-04	2.24E-02	4.93E-03	2.57E-06	2.27E-07	9.47E-01	3.82E-03
RL-W450	1.69E-03	0.00E+00	6.32E-05	1.18E-02	2.60E-03	2.14E-06	9.36E-08	1.62E-02	6.53E-05
RL-W451	2.41E-04	0.00E+00	9.01E-06	1.68E-03	3.71E-04	3.04E-07	1.33E-08	2.30E-03	9.28E-06
RL-W452	1.05E-02	0.00E+00	3.88E-04	7.41E-02	1.63E-02	1.16E-05	5.75E-07	1.01E-01	4.08E-04
RL-W453	2.99E-03	0.00E+00	1.09E-04	2.13E-02	4.68E-03	3.02E-06	1.62E-07	2.91E-02	1.17E-04
RL-W454	4.18E-02	0.00E+00	1.53E-03	2.97E-01	6.55E-02	4.22E-05	2.26E-06	4.06E-01	1.64E-03
RL-W455	1.12E-02	0.00E+00	4.11E-04	7.86E-02	1.73E-02	1.23E-05	6.09E-07	1.08E-01	4.34E-04
RL-W456	1.47E+00	0.00E+00	5.38E-02	1.04E+01	2.30E+00	1.52E-03	7.97E-05	1.43E+01	5.75E-02
RL-W457	1.43E-01	0.00E+00	5.22E-03	1.01E+00	2.23E-01	1.47E-04	7.74E-06	1.39E+00	5.59E-03
RL-W458	4.52E-01	0.00E+00	2.67E-02	4.17E-01	2.29E-01	5.93E-04	3.96E-05	1.12E+00	4.53E-03
RL-W459	4.35E+00	0.00E+00	2.75E-01	1.03E+01	3.12E+00	5.88E-03	4.07E-04	1.81E+01	7.29E-02
RL-W460	2.65E-02	0.00E+00	9.67E-04	1.88E-01	4.15E-02	2.67E-05	1.43E-06	2.57E-01	1.04E-03
RL-W461	2.45E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.45E-02	9.87E-05
RL-W462	7.56E-03	0.00E+00	2.81E-04	5.32E-02	1.17E-02	8.75E-06	4.16E-07	7.28E-02	2.93E-04
RL-W463	3.89E-02	0.00E+00	1.42E-03	2.76E-01	6.09E-02	3.92E-05	2.10E-06	3.78E-01	1.52E-03
RL-W464	1.80E-02	0.00E+00	6.53E-04	1.27E-01	2.80E-02	1.81E-05	9.68E-07	1.74E-01	7.01E-04
RL-W465	1.20E-01	0.00E+00	4.43E-03	8.47E-01	1.87E-01	1.31E-04	6.56E-06	1.16E+00	4.67E-03
RL-W466	1.64E+00	0.00E+00	6.02E-02	1.16E+01	2.56E+00	1.74E-03	8.92E-05	1.59E+01	6.41E-02
RL-W467	8.41E-02	0.00E+00	3.10E-03	5.93E-01	1.30E-01	9.55E-05	4.59E-06	8.10E-01	3.27E-03
RL-W468	4.31E-04	0.00E+00	1.60E-05	3.03E-03	6.68E-04	4.99E-07	2.37E-08	4.15E-03	1.67E-05
RL-W469	1.75E-01	0.00E+00	6.41E-03	1.23E+00	2.73E-01	1.84E-04	9.50E-06	1.69E+00	6.80E-03
RL-W470	4.94E+00	0.00E+00	2.98E-01	4.57E+00	2.33E+00	7.39E-03	4.42E-04	1.21E+01	4.90E-02
RL-W474	1.87E-01	0.00E+00	3.29E-02	1.04E-02	8.81E-03	0.00E+00	4.88E-05	2.40E-01	9.66E-04
RL-W476	3.16E-01	0.00E+00	1.19E-02	2.29E+00	5.06E-01	3.33E-04	1.76E-05	3.12E+00	1.26E-02
RL-W480	5.15E-02	0.00E+00	1.90E-03	3.63E-01	8.01E-02	5.69E-05	2.81E-06	4.96E-01	2.00E-03
RL-W481	8.09E-02	0.00E+00	2.98E-03	5.70E-01	1.25E-01	8.94E-05	4.42E-06	7.79E-01	3.14E-03
RL-W482	1.07E+02	0.00E+00	9.92E-01	7.25E-02	1.33E-01	1.19E-01	1.47E-03	1.09E+02	4.38E-01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W483	8.02E+00	0.00E+00	7.70E-02	4.69E-03	9.45E-03	8.85E-03	1.14E-04	8.11E+00	3.27E-02
RL-W484	3.39E-02	0.00E+00	6.20E-04	6.55E-02	1.55E-02	7.34E-06	9.18E-07	1.16E-01	4.66E-04
RL-W485	1.99E-03	0.00E+00	8.77E-05	7.09E-03	1.67E-03	0.00E+00	1.30E-07	1.08E-02	4.37E-05
RL-W486	8.40E-04	0.00E+00	3.70E-05	2.99E-03	7.03E-04	0.00E+00	5.49E-08	4.57E-03	1.84E-05
RL-W487	1.37E-01	0.00E+00	4.76E-03	4.28E-01	1.16E-01	6.82E-05	7.05E-06	6.87E-01	2.77E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	8.33E-02	0.00E+00	4.48E-03	5.55E-01	1.24E-01	1.10E-04	6.64E-06	7.67E-01	3.09E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	3.09E-02	0.00E+00	3.78E-03	5.82E-02	1.26E-02	4.00E-05	5.60E-06	1.06E-01	4.25E-04
RL-W492	1.78E-03	0.00E+00	9.32E-05	1.16E-02	2.59E-03	2.30E-06	1.38E-07	1.61E-02	6.49E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.07E+01	0.00E+00	5.40E+00	2.93E-01	2.48E-01	9.22E-02	8.00E-03	7.67E+01	3.09E-01
RL-W495	1.28E+00	0.00E+00	1.47E-02	2.81E-03	2.21E-03	1.68E-03	2.18E-05	1.30E+00	5.24E-03
RL-W496	8.31E+00	0.00E+00	1.69E-01	9.25E-03	7.33E-03	1.09E-02	2.50E-04	8.50E+00	3.43E-02
RL-W497	3.46E-01	0.00E+00	3.33E-02	5.55E-01	2.49E-01	2.85E-04	4.94E-05	1.18E+00	4.77E-03
RL-W498	1.34E+00	0.00E+00	4.95E-02	9.48E+00	2.09E+00	1.48E-03	7.34E-05	1.30E+01	5.23E-02
RL-W499	1.21E-05	0.00E+00	4.44E-07	8.50E-05	1.88E-05	1.33E-08	6.59E-10	1.16E-04	4.69E-07
RL-W500	8.59E-04	0.00E+00	5.52E-05	3.47E-03	7.61E-04	9.36E-07	8.17E-08	5.14E-03	2.07E-05
RL-W501	3.56E+01	0.00E+00	1.23E+00	1.11E+02	3.01E+01	1.77E-02	1.82E-03	1.78E+02	7.19E-01
RL-W502	6.43E-03	0.00E+00	2.38E-04	4.53E-02	9.98E-03	7.10E-06	3.52E-07	6.20E-02	2.50E-04
RL-W503	3.72E-01	0.00E+00	2.44E-02	1.60E+00	3.50E-01	4.18E-04	3.61E-05	2.35E+00	9.46E-03
RL-W504	1.37E-01	0.00E+00	4.76E-03	4.28E-01	1.16E-01	6.82E-05	7.05E-06	6.87E-01	2.77E-03
RL-W505	6.46E-03	0.00E+00	2.50E-04	4.63E-02	1.02E-02	8.56E-06	3.70E-07	6.32E-02	2.55E-04
RL-W506	2.34E-03	0.00E+00	9.80E-05	1.52E-02	3.36E-03	2.56E-06	1.45E-07	2.10E-02	8.47E-05
RL-W507	2.33E-04	0.00E+00	8.58E-06	1.64E-03	3.61E-04	2.57E-07	1.27E-08	2.24E-03	9.04E-06
RL-W508	4.27E+00	0.00E+00	2.81E-01	1.78E+01	3.90E+00	4.55E-03	4.16E-04	2.63E+01	1.06E-01
RL-W509	4.21E+01	0.00E+00	2.24E+00	1.45E+02	3.51E+01	3.27E-02	3.32E-03	2.25E+02	9.06E-01
RL-W510	3.55E+00	0.00E+00	2.30E-01	1.44E+01	3.16E+00	3.89E-03	3.41E-04	2.14E+01	8.61E-02
RL-W511	3.61E+02	0.00E+00	1.11E+01	1.93E+03	4.17E+02	2.12E-01	1.68E-02	2.72E+03	1.10E+01
RL-W512	3.16E+02	0.00E+00	7.49E+00	1.16E+03	2.86E+02	1.08E-01	1.11E-02	1.77E+03	7.15E+00
RL-W513	3.37E+04	0.00E+00	3.04E+03	1.90E+04	9.31E+03	1.72E+01	4.51E+00	6.51E+04	2.62E+02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W514	9.51E-04	0.00E+00	3.49E-05	6.73E-03	1.49E-03	1.00E-06	5.17E-08	9.20E-03	3.71E-05
RL-W515	3.72E-02	0.00E+00	1.37E-03	2.62E-01	5.77E-02	4.10E-05	2.03E-06	3.59E-01	1.45E-03
RL-W516	5.16E-02	0.00E+00	1.90E-03	3.63E-01	8.01E-02	5.69E-05	2.82E-06	4.96E-01	2.00E-03
RL-W517	4.60E-10	0.00E+00	1.70E-11	3.23E-09	7.11E-10	5.32E-13	2.52E-14	4.42E-09	1.78E-11
RL-W518	1.30E+00	0.00E+00	7.15E-02	4.63E+00	1.11E+00	1.14E-03	1.06E-04	7.11E+00	2.87E-02
RL-W519	2.32E-01	0.00E+00	8.48E-03	1.64E+00	3.61E-01	2.41E-04	1.26E-05	2.24E+00	9.04E-03
RL-W520	2.56E-02	0.00E+00	9.55E-04	1.80E-01	3.96E-02	3.10E-05	1.42E-06	2.46E-01	9.92E-04
RL-W521	4.76E-04	0.00E+00	1.75E-05	3.35E-03	7.40E-04	5.27E-07	2.60E-08	4.58E-03	1.85E-05
RL-W522	9.95E+00	0.00E+00	6.51E-01	2.22E+01	6.27E+00	7.62E-03	9.65E-04	3.90E+01	1.57E-01
RL-W523	2.99E+00	0.00E+00	2.48E-01	1.47E+00	8.83E-01	1.51E-03	3.67E-04	5.59E+00	2.26E-02
RL-W524	1.24E+01	0.00E+00	9.47E-01	1.35E+01	5.18E+00	7.20E-03	1.40E-03	3.20E+01	1.29E-01
RL-W525	9.85E-01	0.00E+00	6.41E-02	1.60E+00	5.23E-01	5.65E-04	9.50E-05	3.17E+00	1.28E-02
RL-W526	3.73E+00	0.00E+00	2.32E-01	1.71E+01	3.78E+00	4.11E-03	3.44E-04	2.48E+01	1.00E-01
RL-W527	4.09E-01	0.00E+00	3.35E-02	1.81E+00	4.25E-01	4.80E-04	4.97E-05	2.68E+00	1.08E-02
RL-W528	1.83E+02	0.00E+00	1.43E+01	5.77E+01	5.46E+01	7.34E-02	2.11E-02	3.09E+02	1.25E+00
RL-W529	1.52E-01	0.00E+00	1.00E-02	6.36E-01	1.39E-01	1.62E-04	1.48E-05	9.37E-01	3.78E-03
RL-W530	1.79E+00	0.00E+00	1.16E-01	7.27E+00	1.60E+00	1.97E-03	1.72E-04	1.08E+01	4.34E-02
RL-W531	1.07E+02	0.00E+00	1.17E+01	3.14E+01	2.24E+01	5.22E-02	1.73E-02	1.73E+02	6.96E-01
RL-W532	3.44E-01	0.00E+00	1.27E-02	2.43E+00	5.34E-01	3.79E-04	1.88E-05	3.32E+00	1.34E-02
RL-W533	1.66E-01	0.00E+00	1.09E-02	6.94E-01	1.52E-01	1.76E-04	1.62E-05	1.02E+00	4.12E-03
RL-W534	9.60E-06	0.00E+00	3.53E-07	6.77E-05	1.50E-05	1.06E-08	5.23E-10	9.26E-05	3.73E-07
RL-W535	5.03E+01	0.00E+00	3.49E+00	8.68E+01	2.62E+01	3.23E-02	5.17E-03	1.67E+02	6.72E-01
RL-W536	9.84E-01	0.00E+00	4.70E-02	3.01E+00	6.75E-01	7.39E-04	7.28E-05	4.72E+00	1.90E-02
RL-W537	3.35E+01	0.00E+00	1.06E+00	1.85E+02	4.01E+01	2.07E-02	1.60E-03	2.60E+02	1.05E+00
RL-W538	1.22E-04	0.00E+00	4.48E-06	8.60E-04	1.90E-04	1.35E-07	6.64E-09	1.18E-03	4.74E-06
RL-W539	1.35E-02	0.00E+00	5.05E-04	9.50E-02	2.09E-02	1.64E-05	7.48E-07	1.30E-01	5.24E-04
RL-W540	2.63E+01	0.00E+00	2.22E+00	3.42E+01	1.16E+01	1.57E-02	3.29E-03	7.44E+01	3.00E-01
RL-W541	3.92E-02	0.00E+00	1.46E-03	2.75E-01	6.07E-02	4.61E-05	2.16E-06	3.77E-01	1.52E-03
RL-W542	1.82E+00	0.00E+00	1.08E-01	6.97E+00	1.60E+00	1.89E-03	1.60E-04	1.05E+01	4.23E-02
RL-W543	5.73E-03	0.00E+00	2.11E-04	4.04E-02	8.90E-03	6.35E-06	3.12E-07	5.52E-02	2.23E-04
RL-W544	1.29E-01	0.00E+00	8.60E-03	4.59E-01	1.14E-01	1.26E-04	1.27E-05	7.10E-01	2.86E-03

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W545	3.43E-02	0.00E+00	1.26E-03	2.42E-01	5.33E-02	3.78E-05	1.87E-06	3.30E-01	1.33E-03
RL-W546	1.50E-03	0.00E+00	5.54E-05	1.06E-02	2.34E-03	1.66E-06	8.20E-08	1.45E-02	5.86E-05
RL-W547	3.84E-05	0.00E+00	1.42E-06	2.70E-04	5.97E-05	4.23E-08	2.10E-09	3.70E-04	1.49E-06
RL-W548	3.32E-05	0.00E+00	1.23E-06	2.34E-04	5.16E-05	3.79E-08	1.82E-09	3.20E-04	1.29E-06
RL-W549	6.60E+00	0.00E+00	4.93E-01	1.20E+01	3.54E+00	4.80E-03	7.31E-04	2.27E+01	9.14E-02
RL-W550	2.99E+01	0.00E+00	9.34E-01	1.63E+02	3.54E+01	1.81E-02	1.40E-03	2.29E+02	9.25E-01
RL-W551	5.32E+01	0.00E+00	1.38E+00	1.84E+02	4.62E+01	1.92E-02	2.05E-03	2.85E+02	1.15E+00
RL-W552	2.06E-02	0.00E+00	7.64E-04	1.45E-01	3.19E-02	2.40E-05	1.13E-06	1.98E-01	8.00E-04
RL-W553	1.83E-03	0.00E+00	7.21E-05	1.29E-02	2.85E-03	3.04E-06	1.07E-07	1.77E-02	7.13E-05
RL-W554	2.90E-02	0.00E+00	1.07E-03	2.05E-01	4.52E-02	3.20E-05	1.59E-06	2.80E-01	1.13E-03
RL-W555	1.34E-02	0.00E+00	4.93E-04	9.43E-02	2.07E-02	1.48E-05	7.31E-07	1.29E-01	5.20E-04
RL-W563	1.92E-01	0.00E+00	1.23E-02	7.82E-01	1.71E-01	2.01E-04	1.83E-05	1.16E+00	4.67E-03
RL-W564	1.25E-01	0.00E+00	8.19E-03	5.06E-01	1.11E-01	1.55E-04	1.21E-05	7.50E-01	3.02E-03
RL-W565	1.24E-02	0.00E+00	4.60E-04	8.74E-02	1.93E-02	1.44E-05	6.82E-07	1.20E-01	4.82E-04
RL-W566	1.82E-01	0.00E+00	6.74E-03	1.28E+00	2.84E-01	2.04E-04	9.99E-06	1.76E+00	7.08E-03
RL-W567	1.26E+01	0.00E+00	1.72E-01	3.95E-02	3.15E-02	1.73E-02	2.55E-04	1.29E+01	5.19E-02
RL-W568	2.43E+02	0.00E+00	3.63E+00	1.87E+00	1.47E+00	3.58E-01	5.37E-03	2.50E+02	1.01E+00
RL-W569	2.00E-01	0.00E+00	2.73E-03	6.23E-04	4.99E-05	2.74E-04	4.04E-06	2.03E-01	8.19E-04
RL-W570	1.28E-02	0.00E+00	4.78E-04	9.27E-02	2.04E-02	1.35E-05	7.08E-07	1.26E-01	5.09E-04
RL-W571	4.10E+01	0.00E+00	1.62E+00	7.52E+00	3.72E+00	5.46E-02	2.40E-03	5.39E+01	2.17E-01
RL-W572	3.56E-02	0.00E+00	4.85E-04	4.05E-03	8.90E-05	4.89E-05	7.19E-07	4.02E-02	1.62E-04
RL-W573	4.58E+02	0.00E+00	6.22E+00	2.22E+00	1.64E+00	6.21E-01	9.21E-03	4.69E+02	1.89E+00
RL-W574	1.97E+03	0.00E+00	2.69E+01	8.47E+00	6.09E+00	2.71E+00	3.99E-02	2.01E+03	8.12E+00
RL-W575	1.28E+04	0.00E+00	1.81E+02	8.10E+01	4.86E+01	1.70E+01	2.68E-01	1.32E+04	5.30E+01
RL-W576	9.26E+02	0.00E+00	1.27E+01	4.13E+00	2.94E+00	1.28E+00	1.87E-02	9.45E+02	3.81E+00
RL-W579	7.84E-02	0.00E+00	3.33E-04	2.07E-02	4.57E-03	4.50E-06	4.94E-07	1.04E-01	4.19E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.65E-01	2.66E-02	0.00E+00	0.00E+00	1.92E-01	7.73E-04
RL-W581	8.32E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.32E-01	3.36E-03
RL-W582	5.44E-03	0.00E+00	2.83E-04	5.29E-03	2.71E-03	7.29E-07	4.19E-07	1.37E-02	5.53E-05
RL-W583	4.21E-03	0.00E+00	1.54E-04	2.98E-02	6.58E-03	4.24E-06	2.28E-07	4.08E-02	1.64E-04
RL-W584	8.37E-02	0.00E+00	1.01E-02	1.74E-01	8.43E-02	2.13E-05	1.49E-05	3.52E-01	1.42E-03

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W585	4.98E-01	0.00E+00	5.36E-02	1.01E+00	5.13E-01	6.49E-04	7.94E-05	2.08E+00	8.38E-03
RL-W586	6.64E-05	0.00E+00	2.42E-06	4.71E-04	1.04E-04	6.68E-08	3.58E-09	6.44E-04	2.60E-06
RL-W587	1.42E-03	0.00E+00	5.22E-05	1.00E-02	2.22E-03	1.50E-06	7.74E-08	1.37E-02	5.54E-05
RL-W588	5.86E-02	0.00E+00	8.50E-03	1.47E-01	7.10E-02	1.79E-05	1.26E-05	2.85E-01	1.15E-03
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	1.80E+00	0.00E+00	1.81E-01	1.13E-02	2.00E-02	2.35E-03	2.69E-04	2.01E+00	8.12E-03
RL-W591	1.03E+01	0.00E+00	2.05E-01	1.40E-02	2.58E-02	1.42E-02	3.03E-04	1.05E+01	4.24E-02
RL-W592	4.53E+01	0.00E+00	2.24E+00	6.50E-01	8.36E-01	5.74E-02	3.32E-03	4.90E+01	1.98E-01
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.35E-02	3.92E-02	0.00E+00	0.00E+00	6.27E-02	2.53E-04
RL-W594	4.08E+01	0.00E+00	4.04E-01	2.90E-02	5.30E-02	1.44E-02	5.98E-04	4.13E+01	1.67E-01
RL-W595	1.08E-01	0.00E+00	4.21E-02	1.99E-02	3.85E-02	1.42E-04	6.24E-05	2.08E-01	8.40E-04
RL-W596	3.49E-02	0.00E+00	3.28E-03	2.05E-04	3.62E-04	4.27E-05	4.85E-06	3.88E-02	1.56E-04
RL-W597	6.42E+01	0.00E+00	1.44E+00	3.97E-01	6.56E-01	7.95E-02	2.13E-03	6.67E+01	2.69E-01
RL-W598	6.79E+01	0.00E+00	8.50E+00	5.53E-01	8.19E-01	8.23E-02	1.26E-02	7.78E+01	3.14E-01
RL-W599	3.44E+00	0.00E+00	6.86E-02	4.67E-03	8.63E-03	4.75E-03	1.02E-04	3.52E+00	1.42E-02
RL-W600	1.95E-07	0.00E+00	7.11E-09	1.38E-06	3.05E-07	1.97E-10	1.05E-11	1.89E-06	7.62E-09
RL-W601	9.90E-04	0.00E+00	3.90E-05	7.00E-03	1.55E-03	1.65E-06	5.78E-08	9.57E-03	3.86E-05
RL-W602	8.62E-01	0.00E+00	3.20E-02	6.06E+00	1.34E+00	9.97E-04	4.74E-05	8.30E+00	3.35E-02
RL-W603	4.97E+00	0.00E+00	1.84E-01	3.50E+01	7.72E+00	5.74E-03	2.73E-04	4.79E+01	1.93E-01
RL-W604	1.16E-02	0.00E+00	4.83E-04	1.70E-02	8.32E-03	6.82E-06	7.16E-07	3.74E-02	1.51E-04
RL-W605	2.66E-03	0.00E+00	1.05E-04	1.88E-02	4.15E-03	4.43E-06	1.56E-07	2.57E-02	1.04E-04
RL-W606	1.08E-03	0.00E+00	4.23E-05	7.58E-03	1.67E-03	1.79E-06	6.27E-08	1.04E-02	4.18E-05
RL-W607	1.97E-03	0.00E+00	8.19E-05	2.87E-03	1.41E-03	1.15E-06	1.21E-07	6.33E-03	2.55E-05
RL-W608	2.35E-02	0.00E+00	3.18E-03	3.74E-03	4.57E-03	1.77E-05	4.71E-06	3.50E-02	1.41E-04
RL-W610	4.66E+00	0.00E+00	1.70E-01	3.30E+01	7.28E+00	4.70E-03	2.52E-04	4.51E+01	1.82E-01
RL-W612	1.10E-02	0.00E+00	4.11E-04	8.01E-02	1.77E-02	1.11E-05	6.09E-07	1.09E-01	4.40E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.36E-01	0.00E+00	0.00E+00	0.00E+00	3.36E-01	1.36E-03
RL-W622	1.83E-04	0.00E+00	6.71E-06	1.30E-03	2.87E-04	1.85E-07	9.94E-09	1.78E-03	7.17E-06
RL-W625	6.39E-03	0.00E+00	1.02E-03	6.65E-03	6.48E-03	1.00E-05	1.51E-06	2.05E-02	8.28E-05
RL-W626	3.43E-01	0.00E+00	2.32E-02	2.60E-01	1.55E-01	1.75E-04	3.44E-05	7.81E-01	3.15E-03
RL-W627	1.62E-03	0.00E+00	3.10E-05	1.23E-06	0.00E+00	2.08E-06	4.59E-08	1.65E-03	6.65E-06

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W628	5.30E-04	0.00E+00	1.95E-05	3.76E-03	8.28E-04	5.60E-07	2.89E-08	5.14E-03	2.07E-05
RL-W629	3.59E-05	0.00E+00	1.34E-06	2.53E-04	5.56E-05	4.35E-08	1.98E-09	3.45E-04	1.39E-06
RL-W630	3.95E-01	0.00E+00	2.50E-02	2.92E+00	6.70E-01	4.71E-04	3.70E-05	4.01E+00	1.62E-02
RL-W631	6.37E-03	0.00E+00	2.51E-04	4.48E-02	9.88E-03	1.06E-05	3.73E-07	6.13E-02	2.47E-04
RL-W632	2.81E+00	0.00E+00	3.39E-02	5.93E+00	1.93E+00	3.52E-03	5.03E-05	1.07E+01	4.31E-02
RL-W633	6.70E-03	0.00E+00	1.97E-04	9.30E-04	8.14E-04	4.33E-06	2.92E-07	8.65E-03	3.49E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	1.01E-02	0.00E+00	0.00E+00	0.00E+00	1.01E-02	4.09E-05
RL-W635	4.01E+01	0.00E+00	6.65E+00	4.31E+00	6.39E+00	4.38E-02	9.85E-03	5.74E+01	2.32E-01
RL-W636	4.09E-01	0.00E+00	1.26E-02	5.64E-02	4.94E-02	2.66E-04	1.86E-05	5.27E-01	2.13E-03
RL-W637	9.72E-04	0.00E+00	3.20E-04	6.34E-04	6.16E-04	9.55E-07	4.74E-07	2.54E-03	1.03E-05
RL-W638	4.27E-02	0.00E+00	3.26E-03	6.21E-03	5.79E-03	3.56E-05	4.82E-06	5.80E-02	2.34E-04
RL-W639	2.26E-03	0.00E+00	8.32E-05	1.59E-02	3.50E-03	2.49E-06	1.23E-07	2.18E-02	8.77E-05
RL-W640	7.58E-02	0.00E+00	2.77E-03	5.36E-01	1.18E-01	8.00E-05	4.10E-06	7.33E-01	2.95E-03
RL-W641	2.31E+00	0.00E+00	6.08E-01	2.58E+00	1.05E+00	1.28E-03	9.01E-04	6.54E+00	2.64E-02
RL-W642	4.51E-02	0.00E+00	6.32E-05	3.14E-02	1.59E-04	5.55E-07	9.36E-08	7.68E-02	3.10E-04
RL-W643	7.11E-01	0.00E+00	1.87E-01	7.93E-01	3.23E-01	3.95E-04	2.78E-04	2.02E+00	8.13E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.46E-02	0.00E+00	0.00E+00	0.00E+00	5.46E-02	2.20E-04
RL-W645	1.73E-02	0.00E+00	8.42E-04	1.07E-01	2.50E-02	2.16E-05	1.25E-06	1.50E-01	6.07E-04
RL-W646	1.57E-02	0.00E+00	7.52E-04	2.57E-02	1.23E-02	1.05E-05	1.12E-06	5.44E-02	2.20E-04
RL-W647	4.42E-02	0.00E+00	1.13E-01	1.09E-01	1.71E-02	3.51E-05	1.67E-04	2.83E-01	1.14E-03
RL-W648	7.83E-04	0.00E+00	1.92E-04	5.97E-05	1.16E-04	1.12E-06	2.85E-07	1.15E-03	4.65E-06
RL-W649	2.88E-03	0.00E+00	7.08E-04	2.20E-04	4.28E-04	4.13E-06	1.05E-06	4.24E-03	1.71E-05
RL-W653	1.36E-04	0.00E+00	5.07E-06	9.60E-04	2.11E-04	1.58E-07	7.51E-09	1.31E-03	5.29E-06
RL-W654	7.50E-04	0.00E+00	2.77E-05	5.29E-03	1.16E-03	8.28E-07	4.10E-08	7.23E-03	2.92E-05
RL-W655	1.85E+02	0.00E+00	6.55E+00	2.10E-01	4.90E-01	2.21E-01	9.70E-03	1.92E+02	7.74E-01
RL-W656	7.73E+02	0.00E+00	2.94E+00	4.93E-01	5.04E-01	1.05E+00	4.36E-03	7.77E+02	3.14E+00
RL-W657	3.95E+02	0.00E+00	4.35E+00	2.43E-01	4.79E-01	4.66E-01	6.44E-03	4.00E+02	1.61E+00
RL-W659	4.78E+01	0.00E+00	9.80E-01	4.67E-02	5.74E-02	5.27E-02	1.45E-03	4.89E+01	1.97E-01
RL-W660	2.62E+02	0.00E+00	1.18E+01	8.62E-01	1.53E+00	3.01E-01	1.75E-02	2.76E+02	1.11E+00
RL-W661	2.77E+00	0.00E+00	1.48E-02	4.16E-04	3.75E-03	3.65E-03	2.19E-05	2.79E+00	1.13E-02
RL-W662	8.72E-02	0.00E+00	8.79E-04	1.06E-04	1.89E-04	7.48E-05	1.30E-06	8.84E-02	3.57E-04

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W665	1.07E+03	0.00E+00	7.04E+01	1.30E+00	1.73E+00	1.49E+00	1.04E-01	1.15E+03	4.62E+00
RL-W666	1.92E+01	0.00E+00	1.72E-01	5.46E-02	5.69E-02	2.15E-02	2.55E-04	1.95E+01	7.85E-02
RL-W668	1.83E+00	0.00E+00	5.42E-03	1.44E-01	4.05E-02	5.08E-05	8.03E-06	2.02E+00	8.14E-03
RL-W669	5.33E-01	0.00E+00	1.41E-01	5.94E-01	2.42E-01	2.96E-04	2.08E-04	1.51E+00	6.09E-03
RL-W670	3.37E-02	0.00E+00	1.00E-04	2.66E-03	7.49E-04	9.41E-07	1.48E-07	3.72E-02	1.50E-04
RL-W671	5.50E+00	0.00E+00	5.13E-02	4.88E-03	5.03E-03	3.09E-03	7.60E-05	5.56E+00	2.24E-02
RL-W672	3.74E+01	0.00E+00	3.49E-01	3.33E-02	3.41E-02	2.10E-02	5.17E-04	3.78E+01	1.52E-01
RL-W673	3.60E+01	0.00E+00	3.35E-01	3.22E-02	3.30E-02	2.02E-02	4.97E-04	3.64E+01	1.47E-01
RL-W674	1.21E-01	0.00E+00	1.50E-02	1.11E+01	9.59E-02	1.41E-04	2.22E-05	1.14E+01	4.58E-02
RL-W675	4.52E-01	0.00E+00	8.28E-02	1.30E-01	1.12E-01	3.44E-04	1.23E-04	7.77E-01	3.13E-03
RL-W676	1.74E-02	0.00E+00	4.97E-04	1.46E-01	2.10E-03	1.02E-05	7.37E-07	1.66E-01	6.70E-04
RL-W677	4.02E+01	0.00E+00	1.23E+00	5.71E+00	4.91E+00	2.46E-02	1.83E-03	5.21E+01	2.10E-01
RL-W678	1.27E-01	0.00E+00	1.03E-02	5.13E-02	4.48E-02	1.93E-04	1.53E-05	2.34E-01	9.42E-04
RL-W679	7.97E-01	0.00E+00	2.30E-02	1.10E-01	9.65E-02	4.94E-04	3.41E-05	1.03E+00	4.14E-03
RL-W680	1.80E-04	0.00E+00	3.24E-05	1.73E-05	3.08E-05	2.12E-07	4.79E-08	2.60E-04	1.05E-06
RL-W681	1.10E-04	0.00E+00	1.31E-05	4.64E-04	2.29E-04	1.76E-07	1.94E-08	8.16E-04	3.29E-06
RL-W685	3.19E-01	0.00E+00	1.17E-02	2.27E+00	4.99E-01	3.22E-04	1.73E-05	3.10E+00	1.25E-02
RL-W689	8.27E-03	0.00E+00	1.40E-04	3.85E-04	0.00E+00	3.09E-07	2.07E-07	8.80E-03	3.55E-05
RL-W690	2.78E-01	0.00E+00	1.03E-02	2.02E+00	4.43E-01	2.80E-04	1.53E-05	2.75E+00	1.11E-02
RL-W691	6.44E-03	0.00E+00	2.40E-04	4.67E-02	1.03E-02	6.49E-06	3.55E-07	6.37E-02	2.57E-04
RL-W692	2.55E-01	0.00E+00	9.49E-03	1.85E+00	4.07E-01	2.56E-04	1.41E-05	2.52E+00	1.02E-02
RL-W693	3.15E-01	0.00E+00	1.17E-02	2.29E+00	5.04E-01	3.17E-04	1.74E-05	3.12E+00	1.26E-02
RL-W694	3.31E+00	0.00E+00	1.23E-01	2.42E+01	5.28E+00	3.34E-03	1.82E-04	3.29E+01	1.33E-01
RL-W695	2.74E-03	0.00E+00	0.00E+00	2.38E-03	0.00E+00	0.00E+00	0.00E+00	5.12E-03	2.06E-05
RL-W696	3.57E-03	0.00E+00	4.48E-04	2.89E-03	2.83E-03	4.58E-06	6.64E-07	9.74E-03	3.93E-05
RL-W697	8.25E-01	0.00E+00	9.49E-01	6.89E-03	9.36E-04	0.00E+00	1.41E-03	1.78E+00	7.19E-03
RL-W698	7.15E-02	0.00E+00	0.00E+00	3.27E-05	0.00E+00	0.00E+00	0.00E+00	7.16E-02	2.89E-04
RL-W699	1.59E-02	0.00E+00	6.32E-05	2.19E-03	2.54E-04	1.92E-05	9.36E-08	1.84E-02	7.42E-05
RL-W700	4.51E-03	0.00E+00	1.66E-04	3.17E-02	7.00E-03	4.99E-06	2.46E-07	4.34E-02	1.75E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W704	1.78E-01	0.00E+00	4.68E-02	1.98E-01	8.07E-02	9.88E-05	6.93E-05	5.03E-01	2.03E-03
RL-W705	1.15E-03	0.00E+00	4.31E-05	8.31E-03	1.84E-03	1.21E-06	6.38E-08	1.13E-02	4.57E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	4.10E-02	0.00E+00	1.53E-03	2.96E-01	6.54E-02	4.31E-05	2.27E-06	4.04E-01	1.63E-03
RL-W708	6.19E-03	0.00E+00	2.32E-04	4.49E-02	9.88E-03	6.54E-06	3.44E-07	6.12E-02	2.47E-04
RL-W709	2.14E+00	0.00E+00	7.99E-02	1.55E+01	3.41E+00	2.26E-03	1.18E-04	2.11E+01	8.53E-02
RL-W710	1.28E-04	0.00E+00	4.78E-06	9.27E-04	2.04E-04	1.35E-07	7.08E-09	1.26E-03	5.09E-06
RL-W711	3.99E-02	0.00E+00	1.49E-03	2.89E-01	6.37E-02	4.21E-05	2.21E-06	3.94E-01	1.59E-03
RL-W712	5.16E-02	0.00E+00	1.93E-03	3.74E-01	8.24E-02	5.46E-05	2.86E-06	5.10E-01	2.06E-03
RL-W713	4.46E-02	0.00E+00	1.67E-03	3.22E-01	7.12E-02	4.71E-05	2.47E-06	4.40E-01	1.77E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	7.70E-04	0.00E+00	2.81E-05	5.46E-03	1.20E-03	7.76E-07	4.16E-08	7.46E-03	3.01E-05
RL-W716	8.02E-03	0.00E+00	2.92E-04	5.69E-02	1.25E-02	8.09E-06	4.33E-07	7.77E-02	3.13E-04
RL-W717	2.00E-03	0.00E+00	7.31E-05	1.42E-02	3.13E-03	2.02E-06	1.08E-07	1.94E-02	7.83E-05
RL-W718	3.53E-04	0.00E+00	1.29E-05	2.51E-03	5.52E-04	3.56E-07	1.91E-08	3.42E-03	1.38E-05
RL-W719	1.59E-03	0.00E+00	5.81E-05	1.13E-02	2.50E-03	1.61E-06	8.61E-08	1.55E-02	6.24E-05
RL-W720	9.86E-03	0.00E+00	3.61E-04	7.00E-02	1.55E-02	9.93E-06	5.34E-07	9.57E-02	3.86E-04
RL-W721	6.68E-03	0.00E+00	2.44E-04	4.73E-02	1.05E-02	6.73E-06	3.61E-07	6.47E-02	2.61E-04
RL-W723	2.21E-02	0.00E+00	8.23E-04	1.61E-01	3.54E-02	2.23E-05	1.22E-06	2.19E-01	8.85E-04
RL-W724	1.47E-01	0.00E+00	5.48E-03	1.06E+00	2.36E-01	1.48E-04	8.12E-06	1.45E+00	5.86E-03
RL-W725	4.65E-02	0.00E+00	1.73E-03	3.37E-01	7.44E-02	4.68E-05	2.56E-06	4.60E-01	1.85E-03
RL-W726	3.66E-02	0.00E+00	1.36E-03	2.66E-01	5.86E-02	3.69E-05	2.02E-06	3.63E-01	1.46E-03
RL-W727	2.24E-01	0.00E+00	8.36E-03	1.63E+00	3.60E-01	2.26E-04	1.24E-05	2.22E+00	8.96E-03
RL-W728	2.04E-01	0.00E+00	7.62E-03	1.49E+00	3.28E-01	2.06E-04	1.13E-05	2.03E+00	8.19E-03
RL-W729	9.44E-02	0.00E+00	3.53E-03	6.86E-01	1.52E-01	9.50E-05	5.23E-06	9.36E-01	3.77E-03
RL-W730	3.70E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.70E+01	1.49E-01
RL-W731	1.19E-05	0.00E+00	0.00E+00	4.48E-04	1.82E-06	0.00E+00	0.00E+00	4.62E-04	1.86E-06
RL-W732	2.73E+01	0.00E+00	2.01E+00	1.26E+02	2.77E+01	3.41E-02	2.98E-03	1.83E+02	7.39E-01
RL-W733	3.58E-01	0.00E+00	2.61E-02	1.37E+00	3.37E-01	3.70E-04	3.87E-05	2.09E+00	8.44E-03
RL-W734	1.12E+00	0.00E+00	8.71E-02	4.73E+00	1.14E+00	1.10E-03	1.29E-04	7.08E+00	2.85E-02
RL-W735	9.16E-01	0.00E+00	6.65E-02	3.69E+00	9.05E-01	8.56E-04	9.85E-05	5.58E+00	2.25E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W736	1.01E-03	0.00E+00	1.42E-07	2.45E-03	6.24E-04	2.62E-07	2.10E-10	4.08E-03	1.64E-05
RL-W737	8.17E-01	0.00E+00	6.06E-02	3.50E+00	8.42E-01	7.39E-04	8.98E-05	5.22E+00	2.11E-02
RL-W738	3.05E+00	0.00E+00	2.09E-01	1.11E+01	2.91E+00	2.68E-03	3.09E-04	1.73E+01	6.98E-02
RL-W739	2.60E-01	0.00E+00	1.84E-02	1.81E+00	4.08E-01	2.43E-04	2.73E-05	2.50E+00	1.01E-02
RL-W740	1.30E+01	0.00E+00	6.74E-01	4.40E+01	1.14E+01	1.23E-02	9.99E-04	6.91E+01	2.79E-01
RL-W741	1.94E+01	0.00E+00	1.59E+00	8.58E+00	6.03E+00	9.22E-03	2.35E-03	3.56E+01	1.44E-01
RL-W742	8.65E-01	0.00E+00	4.78E-02	2.78E+00	6.49E-01	7.90E-04	7.08E-05	4.34E+00	1.75E-02
RL-W743	1.56E-03	0.00E+00	1.30E-05	1.80E-03	0.00E+00	0.00E+00	1.92E-08	3.37E-03	1.36E-05
RL-W744	0.00E+00	0.00E+00	0.00E+00	8.98E-02	7.55E-02	0.00E+00	0.00E+00	1.65E-01	6.67E-04
RL-W745	2.46E-03	0.00E+00	9.06E-05	1.74E-02	3.83E-03	2.72E-06	1.34E-07	2.38E-02	9.59E-05
RL-W746	9.47E-03	0.00E+00	3.49E-04	6.68E-02	1.48E-02	1.04E-05	5.17E-07	9.14E-02	3.69E-04
RL-W747	2.57E-02	0.00E+00	9.45E-04	1.81E-01	3.99E-02	2.83E-05	1.40E-06	2.47E-01	9.98E-04
RL-W748	1.80E+02	0.00E+00	2.65E+00	3.00E-01	4.88E-01	2.13E-01	3.93E-03	1.83E+02	7.39E-01
RL-W749	2.16E-01	0.00E+00	8.11E-03	1.57E+00	3.45E-01	2.28E-04	1.20E-05	2.14E+00	8.63E-03
RL-W750	2.73E+02	0.00E+00	4.02E+00	4.92E-01	7.97E-01	3.02E-01	5.95E-03	2.78E+02	1.12E+00
RL-W751	2.46E+02	0.00E+00	3.63E+00	4.42E-01	7.23E-01	2.72E-01	5.37E-03	2.51E+02	1.01E+00
RL-W752	1.07E+02	0.00E+00	1.58E+00	1.93E-01	3.14E-01	1.18E-01	2.33E-03	1.09E+02	4.40E-01
RL-W753	1.44E+03	0.00E+00	2.13E+01	2.59E+00	4.22E+00	1.59E+00	3.15E-02	1.47E+03	5.92E+00
RP-W754	6.11E+01	0.00E+00	2.69E+00	1.85E+03	1.50E+02	1.47E-02	3.57E-01	2.06E+03	8.32E+00
RP-W755	3.24E+02	0.00E+00	1.61E+00	1.38E+03	1.14E+02	1.10E-02	1.26E+01	1.83E+03	7.39E+00
SA-T001	6.51E-01	1.73E-03	3.86E-02	3.01E+00	1.76E-02	0.00E+00	6.18E-05	3.72E+00	1.50E-02
SA-W134	5.31E+00	6.71E-07	2.63E-01	1.37E+00	4.30E-01	2.80E-04	1.67E-01	7.55E+00	3.04E-02
SA-W134M	6.90E-01	8.70E-08	3.41E-02	1.79E-01	5.58E-02	3.63E-05	2.16E-02	9.80E-01	3.95E-03
T001-221F-HET	1.29E+03	0.00E+00	3.08E+04	2.86E+04	6.99E+02	9.17E-01	5.13E+01	6.15E+04	2.48E+02
T001-221H-HET	2.31E+03	0.00E+00	5.56E+04	5.17E+04	1.26E+03	1.66E+00	9.25E+01	1.11E+05	4.47E+02
T001-235F-HET	1.33E+02	0.00E+00	3.20E+03	2.97E+03	7.25E+01	9.50E-02	5.32E+00	6.38E+03	2.57E+01
T001-772F-HET	1.15E+03	0.00E+00	2.77E+04	2.57E+04	6.25E+02	8.19E-01	4.61E+01	5.51E+04	2.22E+02
T001-773A-CLAS	1.29E+01	0.00E+00	3.10E+02	2.88E+02	7.01E+00	9.22E-03	5.16E-01	6.19E+02	2.49E+00
T001-773A-HET	1.48E+02	0.00E+00	3.57E+03	3.32E+03	8.10E+01	1.06E-01	5.94E+00	7.12E+03	2.87E+01
W006-773A-VIT	1.99E-03	0.00E+00	0.00E+00	5.34E+02	0.00E+00	0.00E+00	0.00E+00	5.34E+02	2.15E+00
W026-221F-HET	4.47E+02	0.00E+00	1.07E+04	1.00E+04	2.44E+02	3.19E-01	1.79E+01	2.15E+04	8.67E+01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W026-221H-HET	3.34E+02	0.00E+00	8.03E+03	7.48E+03	1.82E+02	2.39E-01	1.34E+01	1.60E+04	6.47E+01
W026-235F-HET	5.21E+00	0.00E+00	1.25E+02	1.16E+02	2.84E+00	3.72E-03	2.08E-01	2.50E+02	1.01E+00
W026-772F-HET	1.42E+00	0.00E+00	3.41E+01	3.17E+01	7.73E-01	1.02E-03	5.68E-02	6.81E+01	2.75E-01
W026-773A-HET	2.31E+01	0.00E+00	5.56E+02	5.17E+02	1.26E+01	1.65E-02	9.25E-01	1.11E+03	4.47E+00
W027-221F-HET	1.69E+03	0.00E+00	3.63E+04	3.88E+04	9.43E+02	5.22E-01	7.15E+01	7.77E+04	3.13E+02
W027-221H-HET	7.38E+02	0.00E+00	1.58E+04	1.70E+04	4.13E+02	2.28E-01	3.13E+01	3.40E+04	1.37E+02
W027-235F-HET	2.22E+02	0.00E+00	4.76E+03	5.11E+03	1.24E+02	6.87E-02	9.40E+00	1.02E+04	4.12E+01
W027-772F-HET	4.04E+02	0.00E+00	8.65E+03	9.28E+03	2.26E+02	1.25E-01	1.71E+01	1.86E+04	7.49E+01
W027-773A-HET	6.02E+02	0.00E+00	1.29E+04	1.38E+04	3.37E+02	1.86E-01	2.55E+01	2.77E+04	1.12E+02
W027-999-HET	6.88E+02	0.00E+00	1.48E+04	1.58E+04	3.85E+02	2.13E-01	2.91E+01	3.17E+04	1.28E+02
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.97E+02	0.00E+00	0.00E+00	0.00E+00	3.97E+02	1.60E+00
WP-INW169.001	3.36E+00	0.00E+00	9.30E-02	1.53E+01	3.37E+00	1.88E-03	3.03E-04	2.21E+01	8.92E-02
WP-INW198.001	4.43E+00	0.00E+00	1.62E-01	2.74E+01	5.99E+00	3.08E-03	3.22E-04	3.80E+01	1.53E-01
WP-INW211.001	4.99E+02	0.00E+00	1.52E+01	2.55E+03	5.56E+02	3.49E-01	2.45E-02	3.61E+03	1.46E+01
WP-INW216.001-	1.81E+04	0.00E+00	8.75E+00	1.47E+03	3.23E+02	1.93E-01	2.90E-01	1.99E+04	8.03E+01
WP-INW216.001-	4.98E+03	0.00E+00	2.36E+00	3.99E+02	8.71E+01	5.22E-02	3.11E-02	5.47E+03	2.20E+01
WP-INW218.001-	3.46E+02	0.00E+00	1.54E+00	2.57E+02	5.62E+01	3.49E-02	3.88E-01	6.61E+02	2.67E+00
WP-INW218.001-	1.60E+00	0.00E+00	4.25E-02	6.98E+00	1.53E+00	9.88E-04	3.74E-02	1.02E+01	4.11E-02
WP-INW222.001	1.64E+01	0.00E+00	4.58E-01	6.82E+01	1.51E+01	8.37E-03	1.25E-03	1.00E+02	4.04E-01
WP-INW243.001	3.98E+01	0.00E+00	9.88E-01	1.43E+02	3.17E+01	1.69E-02	2.33E-03	2.16E+02	8.69E-01
WP-INW247.001R	5.31E+01	0.00E+00	2.30E+00	2.74E+02	6.16E+01	2.94E-02	3.49E-03	3.91E+02	1.58E+00
WP-INW276.001	4.05E+00	0.00E+00	2.24E-01	2.71E+01	6.11E+00	2.49E-03	3.49E-04	3.75E+01	1.51E-01
WP-INW276.002	6.42E+00	0.00E+00	3.37E-01	3.99E+01	9.16E+00	3.74E-03	5.26E-04	5.58E+01	2.25E-01
WP-INW276.003	2.46E+02	0.00E+00	1.25E+01	1.48E+03	3.34E+02	1.57E-01	1.90E-02	2.07E+03	8.36E+00
WP-INW276.004	5.88E+01	0.00E+00	2.65E+00	3.13E+02	7.04E+01	3.32E-02	4.07E-03	4.45E+02	1.79E+00
WP-INW296.001-	2.15E+01	0.00E+00	6.30E-01	7.86E+01	1.76E+01	8.52E-03	9.70E-04	1.18E+02	4.77E-01
WP-INW296.001-	6.48E+01	0.00E+00	2.22E+00	2.78E+02	6.22E+01	3.07E-02	3.65E-03	4.08E+02	1.64E+00
WP-LA-TA-55-19	1.08E+00	0.00E+00	1.03E-01	2.08E+00	4.96E-01	3.05E-04	2.79E-03	3.76E+00	1.52E-02
WP-LA-TA-55-19	5.22E+01	0.00E+00	3.47E+00	2.12E+02	5.11E+01	3.03E-02	9.23E-02	3.19E+02	1.29E+00
WP-LA-TA-55-43	2.93E-01	0.00E+00	8.09E+01	3.21E-01	1.34E-01	2.72E-04	1.46E-01	8.18E+01	3.30E-01
WP-RF001.01	9.07E+01	0.00E+00	2.81E+00	4.08E+02	9.17E+01	3.05E-02	1.35E-02	5.93E+02	2.39E+00

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF002.01-A	1.06E+02	0.00E+00	3.74E+00	4.59E+02	1.04E+02	6.73E-02	2.33E-02	6.72E+02	2.71E+00
WP-RF002.01-B	1.05E-01	0.00E+00	2.59E-03	4.97E-01	1.12E-01	4.23E-05	4.03E-06	7.16E-01	2.89E-03
WP-RF003.01	1.64E+03	0.00E+00	6.02E+01	8.78E+03	1.98E+03	1.11E+00	9.76E-02	1.25E+04	5.02E+01
WP-RF004.01	7.69E-01	0.00E+00	4.04E-02	5.06E+00	1.15E+00	6.35E-04	1.87E-04	7.01E+00	2.83E-02
WP-RF005.01	3.94E+03	0.00E+00	3.06E+01	4.64E+03	1.04E+03	4.42E-01	4.72E-02	9.65E+03	3.89E+01
WP-RF005.02	4.64E+03	0.00E+00	1.58E+01	2.77E+03	6.15E+02	2.27E-01	2.46E-02	8.04E+03	3.24E+01
WP-RF006.01	1.51E+03	0.00E+00	5.75E+01	7.89E+03	1.78E+03	5.74E-01	1.11E-01	1.12E+04	4.53E+01
WP-RF008.01	4.77E+02	0.00E+00	2.05E+01	2.31E+03	5.29E+02	3.79E-01	3.16E-02	3.33E+03	1.34E+01
WP-RF009.01	4.70E+04	0.00E+00	2.51E+02	5.06E+04	1.12E+04	4.35E+00	3.93E-01	1.09E+05	4.40E+02
WP-RF010.01	1.73E+01	0.00E+00	6.37E-01	7.64E+01	1.72E+01	1.34E-02	1.68E-03	1.12E+02	4.50E-01
WP-RF029.01-A	4.16E+00	0.00E+00	1.20E-01	1.34E+01	3.03E+00	3.07E-03	9.07E-04	2.07E+01	8.36E-02
WP-RF029.01-B	6.22E+00	0.00E+00	9.49E-02	1.06E+01	2.40E+00	2.43E-03	2.39E-03	1.94E+01	7.80E-02
WP-RF118.01	1.06E+04	0.00E+00	4.78E+02	5.11E+04	1.13E+04	8.00E+00	9.23E-01	7.34E+04	2.96E+02
WP-RLMPDT.001	2.24E+00	0.00E+00	1.39E-01	7.32E+00	1.88E+00	1.76E-03	2.09E-04	1.16E+01	4.67E-02
WP-RLNPDT.002	2.75E+01	0.00E+00	1.33E+00	7.19E+01	1.91E+01	2.01E-02	2.01E-03	1.20E+02	4.83E-01
WP-SR2001.001.	8.77E-01	0.00E+00	1.53E-01	6.79E+00	1.33E+00	1.10E-03	2.31E-04	9.15E+00	3.69E-02
WP-SR-W027-221	6.49E+00	0.00E+00	4.48E-01	1.95E+01	5.37E+00	4.94E-03	1.87E-01	3.20E+01	1.29E-01
Total	3.47E+05	3.35E+00	3.14E+05	6.56E+05	1.05E+05	1.13E+02	6.33E+02	1.42E+06	5.74E+03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	4.94E+01	0.00E+00	8.71E-01	2.07E+02	1.19E+02	2.47E-06	1.94E-02	3.76E+02	1.52E+00
AE-T003	6.26E+00	0.00E+00	1.16E-01	6.39E+01	2.40E+01	1.35E-06	9.21E-04	9.43E+01	3.80E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	2.77E-02	0.00E+00	3.07E+00	4.71E+01	2.77E-01	2.63E-09	2.19E-02	5.05E+01	2.04E-01
AW-T033.1325	1.01E-01	0.00E+00	1.13E+01	1.72E+02	1.01E+00	9.63E-09	8.03E-02	1.85E+02	7.44E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.65E-01	0.00E+00	0.00E+00	0.00E+00	7.65E-01	3.08E-03
BCLCH-MT01	1.02E+01	0.00E+00	8.71E+01	2.84E+01	7.24E+00	3.72E-06	6.07E-01	1.34E+02	5.39E-01
BT-T002	7.52E-03	1.13E-09	4.55E-02	7.17E-04	1.43E-03	1.63E-09	2.31E-03	5.75E-02	2.32E-04
ET-C1-B55	3.14E-02	0.00E+00	5.19E-04	6.14E-02	2.98E-02	2.88E-09	2.39E-04	1.23E-01	4.97E-04
ET-C1-D139	4.31E-03	0.00E+00	7.19E-05	8.63E-03	4.19E-03	3.83E-10	5.63E-07	1.72E-02	6.94E-05
ET-C2-SEFOR	1.07E-01	0.00E+00	0.00E+00	1.36E-01	4.43E-02	5.91E-09	0.00E+00	2.86E-01	1.16E-03
FM-MOX-MT02	1.01E-06	0.00E+00	2.90E-08	2.97E-07	1.72E-07	2.06E-13	2.10E-10	1.51E-06	6.08E-09
FM-MOX-T01	1.67E-05	0.00E+00	4.78E-07	4.89E-06	2.83E-06	3.39E-12	3.47E-09	2.49E-05	1.00E-07
IN-BN-510	4.03E+03	0.00E+00	2.47E+03	3.93E+04	3.24E+03	8.10E-07	1.92E+01	4.90E+04	1.98E+02
IN-GEM-01	5.10E+01	0.00E+00	4.89E-02	4.41E+01	9.80E+00	5.71E-07	3.41E-04	1.05E+02	4.23E-01
IN-GEM-02	1.21E+01	0.00E+00	1.16E-02	1.05E+01	2.33E+00	1.35E-07	8.12E-05	2.49E+01	1.01E-01
IN-W157.144	6.04E+01	0.00E+00	4.74E-01	3.00E+02	6.60E+01	1.01E-05	3.68E-03	4.27E+02	1.72E+00
IN-W163.1007	1.03E+01	0.00E+00	1.46E-01	9.30E+01	2.05E+01	3.12E-06	1.14E-03	1.24E+02	5.00E-01
IN-W164.153	9.90E-02	0.00E+00	1.39E-03	8.85E-01	1.95E-01	2.99E-08	1.08E-05	1.18E+00	4.76E-03
IN-W167.149	1.98E+01	0.00E+00	2.27E-01	1.43E+02	3.16E+01	4.83E-06	1.76E-03	1.95E+02	7.86E-01
IN-W174.154	0.00E+00	0.00E+00	1.28E+02	1.93E+00	3.70E+00	0.00E+00	9.95E-01	1.35E+02	5.44E-01
IN-W177.156	1.37E-02	0.00E+00	2.73E+02	1.81E+00	1.08E-02	4.15E-09	2.12E+00	2.76E+02	1.12E+00
IN-W179.158	9.24E-02	0.00E+00	2.72E+02	1.05E-01	5.30E-02	2.79E-08	2.11E+00	2.74E+02	1.10E+00
IN-W181.162	1.31E+00	0.00E+00	1.85E-02	1.17E+01	2.57E+00	3.96E-07	1.44E-04	1.56E+01	6.28E-02
IN-W188.160	8.82E+00	0.00E+00	1.24E-01	7.88E+01	1.73E+01	2.67E-06	9.65E-04	1.05E+02	4.24E-01
IN-W216.98	7.84E+04	0.00E+00	1.01E+01	6.43E+03	1.42E+03	2.18E-04	7.86E-02	8.63E+04	3.48E+02

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	3.96E+02	0.00E+00	2.25E-01	1.42E+02	3.14E+01	4.82E-06	1.75E-03	5.70E+02	2.30E+00
IN-W219.110	5.38E-01	0.00E+00	7.58E-03	4.81E+00	1.06E+00	1.62E-07	5.89E-05	6.41E+00	2.58E-02
IN-W219.914	8.48E-02	0.00E+00	1.19E-03	7.59E-01	1.67E-01	2.56E-08	9.27E-06	1.01E+00	4.08E-03
IN-W220.114	2.80E+03	0.00E+00	7.97E-01	5.43E+02	1.16E+02	1.70E-05	6.19E-03	3.46E+03	1.40E+01
IN-W221.927	3.28E+00	0.00E+00	4.62E-02	2.93E+01	6.43E+00	9.92E-07	3.59E-04	3.90E+01	1.57E-01
IN-W222.116	1.12E+02	0.00E+00	1.57E+00	9.89E+02	2.18E+02	3.35E-05	1.22E-02	1.32E+03	5.32E+00
IN-W228.101	7.41E+02	0.00E+00	5.09E-01	3.23E+02	7.11E+01	1.10E-05	3.95E-03	1.14E+03	4.58E+00
IN-W240.931	7.84E+01	0.00E+00	6.51E-01	4.15E+02	9.09E+01	1.38E-05	5.05E-03	5.85E+02	2.36E+00
IN-W243.808	1.09E+02	0.00E+00	1.14E+00	7.25E+02	1.59E+02	2.45E-05	8.85E-03	9.94E+02	4.01E+00
IN-W245.301	1.61E+02	0.00E+00	2.24E+00	1.41E+03	3.12E+02	4.78E-05	1.74E-02	1.89E+03	7.62E+00
IN-W247.810	7.83E+01	0.00E+00	1.09E+00	6.91E+02	1.53E+02	2.33E-05	8.47E-03	9.23E+02	3.72E+00
IN-W249.527	0.00E+00	0.00E+00	7.63E+01	1.23E+01	0.00E+00	0.00E+00	5.93E-01	8.92E+01	3.60E-01
IN-W263.520	2.24E-02	0.00E+00	7.97E+00	8.34E+00	1.29E-02	6.77E-09	6.19E-02	1.64E+01	6.62E-02
IN-W267.1005	1.88E+01	0.00E+00	2.65E-01	1.68E+02	3.70E+01	5.67E-06	2.06E-03	2.24E+02	9.04E-01
IN-W309.609	5.03E+02	0.00E+00	4.44E+00	2.81E+03	6.18E+02	9.48E-05	3.45E-02	3.94E+03	1.59E+01
IN-W315.601	4.96E+02	0.00E+00	1.85E-02	1.18E+01	2.58E+00	3.96E-07	1.44E-04	5.10E+02	2.06E+00
IN-W319.584	2.89E+00	0.00E+00	4.06E-02	2.58E+01	5.70E+00	8.71E-07	3.15E-04	3.44E+01	1.39E-01
IN-W321.1023	2.50E+01	0.00E+00	3.52E-01	2.24E+02	4.92E+01	7.54E-06	2.74E-03	2.98E+02	1.20E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	9.02E+00	1.82E+00	0.00E+00	0.00E+00	1.08E+01	4.37E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.40E+01	4.84E+00	0.00E+00	0.00E+00	2.89E+01	1.16E-01
IN-W323.562	5.34E-02	0.00E+00	5.97E-02	2.46E-01	0.00E+00	1.61E-08	4.64E-04	3.60E-01	1.45E-03
IN-W323.951	6.30E-02	0.00E+00	7.09E-04	2.94E-01	0.00E+00	1.90E-08	5.51E-06	3.57E-01	1.44E-03
IN-W332.661	0.00E+00	0.00E+00	7.83E-01	1.28E-01	0.00E+00	0.00E+00	6.08E-03	9.16E-01	3.70E-03
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	3.01E+00	6.05E-01	0.00E+00	0.00E+00	3.61E+00	1.46E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	9.02E+00	1.82E+00	0.00E+00	0.00E+00	1.08E+01	4.37E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.93E+00	0.00E+00	0.00E+00	0.00E+00	1.93E+00	7.78E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.80E+00	0.00E+00	0.00E+00	0.00E+00	5.80E+00	2.34E-02
IN-W342.652	2.47E+00	0.00E+00	0.00E+00	3.98E-02	9.99E-18	0.00E+00	0.00E+00	2.51E+00	1.01E-02
IN-W342.953	1.65E+00	0.00E+00	0.00E+00	2.66E-02	6.70E-18	0.00E+00	0.00E+00	1.67E+00	6.75E-03
IN-W347.818	1.29E+00	0.00E+00	0.00E+00	8.17E+01	1.46E+02	0.00E+00	1.58E-08	2.29E+02	9.23E-01
IN-W348.1012	6.83E-02	0.00E+00	6.46E-01	4.12E+02	9.09E+01	0.00E+00	5.02E-03	5.04E+02	2.03E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.47E-02	0.00E+00	0.00E+00	0.00E+00	2.47E-02	9.97E-05
IN-W357.1022	0.00E+00	0.00E+00	1.27E-03	8.10E-01	1.78E-01	0.00E+00	9.88E-06	9.89E-01	3.99E-03
IN-W358.854	0.00E+00	0.00E+00	1.92E+01	1.86E+00	3.49E+00	0.00E+00	1.42E-01	2.47E+01	9.95E-02
IN-W358.855	0.00E+00	0.00E+00	1.02E+02	9.89E+00	1.85E+01	0.00E+00	7.55E-01	1.31E+02	5.30E-01
IN-W358.948	0.00E+00	0.00E+00	2.13E+01	2.07E+00	3.86E+00	0.00E+00	1.58E-01	2.74E+01	1.11E-01
IN-W361.1021	1.82E-02	0.00E+00	1.23E-01	7.81E+01	1.72E+01	0.00E+00	9.57E-04	9.55E+01	3.85E-01
IN-W362.1020	0.00E+00	0.00E+00	1.61E+00	1.02E+03	2.26E+02	0.00E+00	1.25E-02	1.25E+03	5.02E+00
IN-W363.1019	0.00E+00	0.00E+00	7.58E-02	4.84E+01	1.07E+01	0.00E+00	5.89E-04	5.91E+01	2.38E-01
IN-W364.1011	0.00E+00	0.00E+00	1.25E-01	7.95E+01	1.75E+01	0.00E+00	9.73E-04	9.71E+01	3.92E-01
IN-W365.1010	1.69E+02	0.00E+00	9.93E-02	6.28E+01	1.38E+01	0.00E+00	7.71E-04	2.46E+02	9.91E-01
IN-W366.841	6.02E-01	0.00E+00	8.46E-02	5.35E+01	1.18E+01	0.00E+00	6.57E-04	6.60E+01	2.66E-01
IN-W372.832	2.47E+00	0.00E+00	0.00E+00	3.98E-02	9.99E-18	0.00E+00	0.00E+00	2.51E+00	1.01E-02
IN-W375.1096	0.00E+00	0.00E+00	3.12E-02	1.98E+01	4.35E+00	0.00E+00	2.42E-04	2.42E+01	9.74E-02
KN-B234TRU	8.76E+01	0.00E+00	1.19E+00	2.88E+02	9.41E+01	5.30E-06	1.03E-02	4.71E+02	1.90E+00
LA-IT-00-01	1.27E+00	7.29E-07	2.04E-01	5.79E-01	1.22E-02	1.02E-15	1.77E-03	2.07E+00	8.35E-03
LA-OS-00-01	2.83E+03	0.00E+00	9.30E+03	1.22E+03	0.00E+00	0.00E+00	6.53E+01	1.34E+04	5.41E+01
LA-PX-00-01	1.18E-02	0.00E+00	3.92E-04	8.95E-02	2.05E-02	1.68E-09	2.87E-06	1.22E-01	4.93E-04
LA-SL-00-01	0.00E+00	0.00E+00	8.27E-03	1.51E-01	0.00E+00	0.00E+00	7.15E-05	1.60E-01	6.44E-04
LA-TA-03-12	1.22E-01	0.00E+00	1.91E-01	4.31E-01	1.46E-01	9.98E-09	1.72E-03	8.92E-01	3.60E-03
LA-TA-03-13	1.57E-01	0.00E+00	6.07E-01	6.74E-01	1.54E-01	1.32E-08	4.76E-03	1.60E+00	6.44E-03
LA-TA-03-19	3.18E-01	0.00E+00	9.05E-01	1.32E+00	3.70E-01	2.05E-08	8.10E-03	2.92E+00	1.18E-02
LA-TA-03-20	1.73E-01	0.00E+00	4.30E-01	5.80E-01	1.99E-01	1.67E-08	3.68E-03	1.39E+00	5.58E-03
LA-TA-03-24	2.32E-01	0.00E+00	1.67E+00	1.08E+00	3.18E-01	1.74E-08	1.51E-02	3.32E+00	1.34E-02
LA-TA-03-26	1.19E-02	0.00E+00	6.90E-02	2.61E+00	4.16E-02	1.52E-09	1.49E-03	2.74E+00	1.10E-02
LA-TA-03-28	0.00E+00	0.00E+00	2.39E-02	2.44E-01	0.00E+00	0.00E+00	2.12E-04	2.68E-01	1.08E-03
LA-TA-03-30	5.30E-01	0.00E+00	1.70E-02	4.98E+00	1.40E+00	7.95E-08	1.50E-04	6.92E+00	2.79E-02
LA-TA-03-31	0.00E+00	0.00E+00	8.51E-04	8.70E-03	0.00E+00	0.00E+00	7.54E-06	9.56E-03	3.86E-05
LA-TA-03-40	0.00E+00	0.00E+00	1.35E-03	5.41E-02	0.00E+00	0.00E+00	1.20E-05	5.55E-02	2.24E-04
LA-TA-03-42	1.22E-05	0.00E+00	3.37E-05	3.38E-03	4.33E-05	1.66E-12	3.01E-07	3.47E-03	1.40E-05
LA-TA-21-06	1.20E-01	0.00E+00	3.71E+00	9.47E-01	2.81E-01	1.72E-08	3.29E-02	5.09E+00	2.05E-02
LA-TA-21-12	4.37E-01	0.00E+00	2.24E+01	3.28E+00	9.55E-01	5.89E-08	1.98E-01	2.72E+01	1.10E-01

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-13	6.72E-01	0.00E+00	0.00E+00	2.91E-01	0.00E+00	0.00E+00	0.00E+00	9.63E-01	3.88E-03
LA-TA-21-14	1.10E-04	0.00E+00	4.27E-01	4.44E+00	5.04E-05	2.39E-11	3.15E-03	4.87E+00	1.96E-02
LA-TA-21-15	6.51E-02	0.00E+00	1.17E-03	1.38E+00	2.29E-01	9.68E-09	1.03E-05	1.67E+00	6.73E-03
LA-TA-21-16	7.54E-01	0.00E+00	1.81E-02	1.05E+01	2.44E+00	1.02E-07	1.62E-04	1.37E+01	5.52E-02
LA-TA-21-40	9.57E-05	0.00E+00	6.26E-02	3.29E-01	3.54E-04	4.09E-12	6.87E-04	3.93E-01	1.59E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	7.01E-01	0.00E+00	0.00E+00	0.00E+00	7.01E-01	2.83E-03
LA-TA-21-42	9.78E-03	0.00E+00	2.04E-02	1.62E-01	1.08E-02	1.33E-10	2.38E-04	2.03E-01	8.20E-04
LA-TA-21-43	3.45E+01	0.00E+00	6.75E-01	5.05E+02	1.17E+02	1.05E-06	7.84E-03	6.58E+02	2.65E+00
LA-TA-21-44	1.66E-01	0.00E+00	1.42E-01	1.14E+02	2.95E-01	1.49E-08	1.36E-03	1.14E+02	4.61E-01
LA-TA-48-01	5.36E-02	3.43E-06	5.33E-04	1.17E-01	4.76E-01	1.23E-09	5.91E-06	6.47E-01	2.61E-03
LA-TA-49-01	6.62E+00	4.26E-04	6.56E-02	1.44E+01	5.89E+01	1.52E-07	7.28E-04	8.00E+01	3.23E-01
LA-TA-50-10	1.77E-02	0.00E+00	6.21E-04	4.54E-02	0.00E+00	0.00E+00	4.52E-06	6.38E-02	2.57E-04
LA-TA-50-11	3.38E-02	0.00E+00	6.36E-04	4.61E-01	9.99E-02	1.22E-09	6.91E-06	5.95E-01	2.40E-03
LA-TA-50-15	6.67E-02	0.00E+00	9.39E-02	3.36E-01	7.35E-02	4.82E-09	7.76E-04	5.71E-01	2.30E-03
LA-TA-50-17	9.76E+00	0.00E+00	7.63E-02	1.80E+01	4.13E-04	4.41E-10	9.70E-04	2.78E+01	1.12E-01
LA-TA-50-18	5.80E-01	0.00E+00	1.01E-02	2.94E+00	5.15E-06	1.30E-11	9.00E-05	3.53E+00	1.42E-02
LA-TA-50-19	1.85E-01	0.00E+00	4.49E-03	3.91E-01	4.41E-03	1.61E-10	6.69E-05	5.85E-01	2.36E-03
LA-TA-50-20	5.08E-03	0.00E+00	0.00E+00	9.63E-03	0.00E+00	0.00E+00	0.00E+00	1.47E-02	5.93E-05
LA-TA-50-40	2.86E-03	0.00E+00	6.07E-05	1.05E-02	4.77E-03	5.16E-10	5.16E-07	1.82E-02	7.33E-05
LA-TA-50-41	3.05E-03	0.00E+00	6.12E-05	4.65E-02	1.06E-02	9.20E-10	4.75E-07	6.02E-02	2.43E-04
LA-TA-55-19	4.73E+00	0.00E+00	8.07E-02	2.61E+01	7.17E+00	5.21E-07	2.23E-03	3.81E+01	1.54E-01
LA-TA-55-20	7.59E+01	0.00E+00	9.20E-01	6.31E+02	1.48E+02	1.30E-05	1.01E-01	8.56E+02	3.45E+00
LA-TA-55-21	6.78E-01	1.02E-09	1.06E-02	4.47E+00	1.05E+00	1.07E-07	8.14E-05	6.21E+00	2.50E-02
LA-TA-55-22	1.86E+00	0.00E+00	5.97E-02	1.57E+01	3.59E+00	3.33E-07	4.60E-04	2.12E+01	8.56E-02
LA-TA-55-23	1.75E+00	0.00E+00	4.99E-02	1.08E+01	2.60E+00	3.27E-07	3.81E-04	1.52E+01	6.12E-02
LA-TA-55-24	6.60E-01	0.00E+00	7.83E-03	5.66E+00	1.29E+00	1.56E-07	5.74E-05	7.61E+00	3.07E-02
LA-TA-55-25	3.38E+00	0.00E+00	4.56E-02	2.81E+01	6.41E+00	7.98E-07	3.35E-04	3.79E+01	1.53E-01
LA-TA-55-28	1.15E+00	0.00E+00	2.53E-02	8.63E+00	1.99E+00	2.59E-07	1.87E-04	1.18E+01	4.75E-02
LA-TA-55-30	2.57E+01	9.61E-12	3.03E-01	1.41E+02	3.33E+01	1.90E-06	2.88E-03	2.01E+02	8.09E-01
LA-TA-55-32	2.08E+00	0.00E+00	1.69E+00	1.12E+01	3.37E+00	2.37E-07	1.53E-02	1.83E+01	7.39E-02
LA-TA-55-33	3.12E-01	0.00E+00	4.37E-03	1.47E+00	4.59E-01	3.33E-08	3.68E-05	2.25E+00	9.07E-03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-34	3.15E+01	0.00E+00	4.04E-01	2.29E+02	5.67E+01	4.01E-06	6.18E-03	3.17E+02	1.28E+00
LA-TA-55-38	7.92E+01	0.00E+00	1.33E-01	5.04E+01	1.33E+01	9.33E-07	2.82E-03	1.43E+02	5.77E-01
LA-TA-55-39	8.37E+00	0.00E+00	9.83E-02	7.53E+01	1.65E+01	1.64E-06	7.45E-04	1.00E+02	4.04E-01
LA-TA-55-41	1.99E+02	0.00E+00	2.04E-01	9.34E+01	2.18E+01	2.07E-06	1.58E-03	3.15E+02	1.27E+00
LA-TA-55-43	7.49E-02	0.00E+00	1.34E+01	1.40E-01	4.80E-02	1.82E-08	1.00E-01	1.37E+01	5.53E-02
LA-TA-55-44	6.50E-01	0.00E+00	3.15E+01	2.60E+00	7.05E-01	5.37E-08	2.67E-01	3.57E+01	1.44E-01
LA-TA-55-48	4.79E+03	0.00E+00	1.24E+02	1.67E+04	6.09E+03	5.61E-04	1.03E+00	2.77E+04	1.12E+02
LA-TA-55-49	1.02E+01	0.00E+00	1.63E+02	3.06E+01	8.38E+00	6.56E-07	1.38E+00	2.14E+02	8.63E-01
LA-TA-55-53	4.82E+01	0.00E+00	3.38E-01	2.61E+02	5.95E+01	3.59E-06	2.81E-03	3.69E+02	1.49E+00
LA-TA-55-56	5.34E+01	0.00E+00	1.26E+01	3.78E+02	9.26E+01	8.32E-06	9.93E-02	5.37E+02	2.16E+00
LA-TA-55-60	2.90E-02	0.00E+00	3.18E-03	7.12E-02	2.47E-02	4.90E-09	2.68E-05	1.28E-01	5.16E-04
LA-TA-55-61	2.49E-02	0.00E+00	1.46E-02	1.38E-01	4.55E-02	4.76E-09	1.21E-04	2.23E-01	8.98E-04
LA-TA-55-62	6.46E-03	0.00E+00	1.39E-04	2.31E-02	1.08E-02	1.28E-09	1.16E-06	4.04E-02	1.63E-04
LA-TA-55-63	4.79E-03	0.00E+00	9.39E-05	7.39E-02	1.67E-02	1.26E-09	7.48E-07	9.55E-02	3.85E-04
LL-M001	6.57E+01	4.61E-05	4.10E+00	6.92E+01	3.05E+01	9.95E-06	2.86E-02	1.70E+02	6.84E-01
LL-T001	3.28E+02	0.00E+00	0.00E+00	5.28E+02	2.32E+02	7.72E-05	0.00E+00	1.09E+03	4.39E+00
LL-T002	3.24E+03	0.00E+00	3.26E+01	5.12E+03	2.06E+03	6.79E-04	2.27E-01	1.05E+04	4.22E+01
LL-T003	1.26E+02	0.00E+00	3.65E+00	1.04E+02	8.18E+01	2.69E-05	2.54E-02	3.15E+02	1.27E+00
LL-T004	8.01E+01	0.00E+00	7.49E-01	6.60E+01	5.16E+01	1.70E-05	5.22E-03	1.98E+02	8.00E-01
LL-T005	4.13E+02	2.01E-03	8.81E+00	2.45E+02	2.07E+02	6.31E-05	6.14E-02	8.74E+02	3.53E+00
LL-W018	3.52E-02	0.00E+00	0.00E+00	1.83E-02	4.11E-02	1.29E-08	0.00E+00	9.46E-02	3.82E-04
LL-W019	1.91E+01	0.00E+00	0.00E+00	1.42E+01	1.16E+01	3.78E-06	0.00E+00	4.50E+01	1.81E-01
LL-W034	7.06E+00	3.39E-05	1.54E-01	4.15E+00	3.43E+00	1.07E-06	1.07E-03	1.48E+01	5.97E-02
MC-W001	8.81E-02	0.00E+00	0.00E+00	5.99E-02	0.00E+00	1.94E-09	0.00E+00	1.48E-01	5.97E-04
MU-W002	1.18E+00	0.00E+00	0.00E+00	5.20E-02	0.00E+00	0.00E+00	2.67E-12	1.23E+00	4.95E-03
NT-JAS-01	1.14E+02	0.00E+00	3.28E+00	9.38E+01	7.37E+01	2.42E-05	2.29E-02	2.84E+02	1.15E+00
NT-W001	1.71E+02	1.04E-06	6.56E+00	2.83E+03	1.84E+01	1.69E-06	5.73E-02	3.02E+03	1.22E+01
NT-W021	3.30E+00	0.00E+00	4.70E-02	3.19E+01	7.09E+00	8.67E-07	3.74E-04	4.23E+01	1.71E-01
OR-W201	3.96E+03	7.15E-05	1.41E+02	2.14E+03	2.06E+03	9.08E-04	4.45E+01	8.33E+03	3.36E+01
OR-W202	5.68E+02	1.49E-03	4.07E+02	5.48E+02	5.25E+02	2.91E-05	3.29E+00	2.05E+03	8.27E+00
OR-W203	1.25E+00	5.19E-05	5.82E-02	2.46E-02	1.71E+00	7.40E-08	4.67E-04	3.05E+00	1.23E-02

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
OR-W204	2.79E-01	2.15E-10	6.60E-02	4.19E-01	2.77E-01	0.00E+00	5.30E-04	1.04E+00	4.20E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.21E-01	0.00E+00	0.00E+00	0.00E+00	4.21E-01	1.70E-03
RF-MT0001	1.07E+03	0.00E+00	4.10E-01	1.94E+02	4.31E+01	6.66E-06	3.16E-03	1.31E+03	5.27E+00
RF-MT0002	8.22E+01	0.00E+00	3.15E-02	1.49E+01	3.31E+00	5.11E-07	2.42E-04	1.01E+02	4.05E-01
RF-MT0003	3.74E-01	0.00E+00	7.19E-03	3.41E+00	7.59E-01	1.17E-07	5.54E-05	4.55E+00	1.84E-02
RF-MT0007	9.40E-01	0.00E+00	0.00E+00	4.25E-01	9.44E-02	1.35E-08	0.00E+00	1.46E+00	5.89E-03
RF-MT0089	3.69E-03	0.00E+00	7.19E-05	3.41E-02	7.58E-03	1.17E-09	5.54E-07	4.55E-02	1.83E-04
RF-MT0090	9.37E+00	0.00E+00	1.02E-01	8.76E+01	1.93E+01	1.17E-06	7.84E-04	1.16E+02	4.69E-01
RF-MT0091	5.81E+02	0.00E+00	1.03E+01	5.86E+03	1.30E+03	9.64E-05	8.26E-02	7.74E+03	3.12E+01
RF-MT0092	8.32E+01	0.00E+00	1.30E+00	8.39E+02	1.89E+02	1.33E-05	1.00E-02	1.11E+03	4.49E+00
RF-MT0093	1.01E+02	0.00E+00	1.34E+00	9.05E+02	2.07E+02	1.14E-05	1.03E-02	1.22E+03	4.90E+00
RF-MT0097	5.07E+00	0.00E+00	5.92E-02	4.73E+01	9.43E+00	6.21E-07	4.56E-04	6.18E+01	2.49E-01
RF-MT0099	5.55E-03	0.00E+00	1.08E-04	5.11E-02	1.13E-02	1.76E-09	8.33E-07	6.81E-02	2.75E-04
RF-MT0290	1.38E+01	0.00E+00	2.68E-01	1.27E+02	2.81E+01	4.35E-06	2.06E-03	1.69E+02	6.81E-01
RF-MT-0292	1.74E+01	0.00E+00	3.38E-01	1.60E+02	3.55E+01	5.50E-06	2.60E-03	2.14E+02	8.61E-01
RF-MT-0299	2.04E+03	0.00E+00	8.66E+00	4.11E+03	9.12E+02	1.42E-04	6.67E-02	7.07E+03	2.85E+01
RF-MT0302	3.13E-02	0.00E+00	3.43E-04	1.77E-01	3.95E-02	5.50E-09	1.95E-05	2.48E-01	1.00E-03
RF-MT0320	3.74E+01	0.00E+00	3.56E-01	1.72E+02	3.83E+01	5.53E-06	2.75E-03	2.48E+02	1.00E+00
RF-MT0321	2.09E+01	0.00E+00	1.06E-01	5.54E+01	1.22E+01	1.55E-06	3.23E-03	8.86E+01	3.57E-01
RF-MT-0328	1.45E+00	0.00E+00	1.27E-02	6.02E+00	1.34E+00	2.07E-07	4.36E-04	8.82E+00	3.56E-02
RF-MT0330	1.51E+01	0.00E+00	1.39E-01	1.22E+02	2.92E+01	1.94E-06	1.07E-03	1.66E+02	6.70E-01
RF-MT-0331	9.03E+01	0.00E+00	8.66E-01	5.35E+02	1.16E+02	1.13E-05	2.74E-02	7.42E+02	2.99E+00
RF-MT0332	1.29E-02	0.00E+00	2.52E-04	1.20E-01	2.65E-02	4.10E-09	1.94E-06	1.59E-01	6.43E-04
RF-MT-0335	1.04E+00	0.00E+00	1.16E-02	6.16E+00	1.37E+00	1.67E-07	6.31E-04	8.59E+00	3.46E-02
RF-MT0336	7.36E+01	0.00E+00	7.68E-01	4.37E+02	9.70E+01	9.81E-06	7.73E-03	6.09E+02	2.45E+00
RF-MT0337	4.16E+01	0.00E+00	4.22E-01	2.67E+02	5.83E+01	4.79E-06	7.10E-03	3.67E+02	1.48E+00
RF-MT0339	1.14E+02	0.00E+00	1.15E+00	5.86E+02	1.29E+02	1.74E-05	2.59E-02	8.29E+02	3.34E+00
RF-MT-0342	6.68E-01	0.00E+00	9.64E-03	5.41E+00	1.18E+00	1.27E-07	1.33E-04	7.27E+00	2.93E-02
RF-MT0371	2.26E+02	0.00E+00	2.23E+00	1.06E+03	2.34E+02	3.63E-05	1.85E-02	1.52E+03	6.13E+00
RF-MT-0372	9.85E-01	0.00E+00	1.57E-02	7.38E+00	1.64E+00	2.24E-07	3.60E-04	1.00E+01	4.04E-02
RF-MT0373	1.48E+01	0.00E+00	1.61E-01	1.39E+02	3.05E+01	1.85E-06	1.24E-03	1.84E+02	7.42E-01

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0374	4.82E-01	0.00E+00	5.77E-03	2.74E+00	6.08E-01	9.37E-08	4.78E-05	3.84E+00	1.55E-02
RF-MT0376	3.82E-01	0.00E+00	4.66E-03	2.73E+00	6.16E-01	6.91E-08	5.10E-05	3.73E+00	1.51E-02
RF-MT0377	2.27E+02	0.00E+00	2.69E+00	1.28E+03	2.82E+02	4.36E-05	3.09E-02	1.79E+03	7.21E+00
RF-MT0378	2.55E+00	0.00E+00	3.71E-02	1.76E+01	3.91E+00	6.03E-07	2.86E-04	2.41E+01	9.72E-02
RF-MT0419	4.09E+00	0.00E+00	3.47E-02	1.64E+01	3.65E+00	5.64E-07	2.67E-04	2.42E+01	9.76E-02
RF-MT0420	7.12E-01	0.00E+00	6.02E-03	2.85E+00	6.34E-01	9.80E-08	4.63E-05	4.20E+00	1.69E-02
RF-MT0423	6.05E+00	0.00E+00	4.89E-02	4.11E+01	8.86E+00	3.88E-07	3.77E-04	5.61E+01	2.26E-01
RF-MT0425	1.78E-01	0.00E+00	1.51E-03	7.13E-01	1.59E-01	2.45E-08	1.16E-05	1.05E+00	4.24E-03
RF-MT-0438	1.62E+00	0.00E+00	1.98E-02	1.27E+01	2.79E+00	2.43E-07	1.65E-04	1.71E+01	6.89E-02
RF-MT0440	5.87E-01	0.00E+00	7.09E-03	4.59E+00	1.04E+00	1.00E-07	2.19E-04	6.22E+00	2.51E-02
RF-MT0442	2.23E-01	0.00E+00	3.07E-03	1.57E+00	3.49E-01	3.71E-08	1.18E-04	2.15E+00	8.66E-03
RF-MT0443	2.75E+00	0.00E+00	5.04E-02	2.44E+01	5.43E+00	7.74E-07	5.46E-04	3.27E+01	1.32E-01
RF-MT0444	2.15E+01	0.00E+00	2.47E-01	1.18E+02	2.60E+01	4.01E-06	1.93E-03	1.65E+02	6.67E-01
RF-MT0480	6.00E+01	0.00E+00	6.95E-01	3.30E+02	7.35E+01	1.03E-05	7.81E-03	4.65E+02	1.87E+00
RF-MT0488	9.60E+01	0.00E+00	1.04E+00	4.91E+02	1.09E+02	1.68E-05	3.89E-02	6.96E+02	2.81E+00
RF-MT0490	4.35E-01	0.00E+00	6.02E-03	2.90E+00	6.44E-01	9.30E-08	5.75E-05	3.98E+00	1.61E-02
RF-MT-0491	3.42E-02	0.00E+00	2.75E-04	1.32E-01	2.91E-02	4.35E-09	4.12E-06	1.95E-01	7.87E-04
RF-MT0523A	2.71E+01	0.00E+00	2.19E-01	1.04E+02	2.31E+01	3.54E-06	1.94E-03	1.54E+02	6.22E-01
RF-MT0523B	2.71E+01	0.00E+00	2.19E-01	1.04E+02	2.31E+01	3.54E-06	1.94E-03	1.54E+02	6.22E-01
RF-MT0523C	2.71E+01	0.00E+00	2.19E-01	1.04E+02	2.31E+01	3.54E-06	1.94E-03	1.54E+02	6.22E-01
RF-MT0523D	2.71E+01	0.00E+00	2.19E-01	1.04E+02	2.31E+01	3.54E-06	1.94E-03	1.54E+02	6.22E-01
RF-MT0523E	2.71E+01	0.00E+00	2.19E-01	1.04E+02	2.31E+01	3.54E-06	1.94E-03	1.54E+02	6.22E-01
RF-MT0531	1.85E-03	0.00E+00	3.60E-05	1.70E-02	3.78E-03	5.86E-10	2.77E-07	2.27E-02	9.15E-05
RF-MT0532E	8.63E+01	0.00E+00	4.68E-01	2.27E+02	5.02E+01	7.55E-06	4.71E-03	3.64E+02	1.47E+00
RF-MT0532F	8.63E+01	0.00E+00	4.68E-01	2.27E+02	5.02E+01	7.55E-06	4.71E-03	3.64E+02	1.47E+00
RF-MT0541	3.14E+00	0.00E+00	6.75E-03	3.21E+00	7.13E-01	1.11E-07	5.20E-05	7.08E+00	2.85E-02
RF-MT0545	1.68E-02	0.00E+00	3.27E-04	1.55E-01	3.44E-02	5.32E-09	2.52E-06	2.07E-01	8.34E-04
RF-MT0800	6.39E+02	0.00E+00	1.62E-01	7.67E+01	1.70E+01	2.63E-06	1.73E-03	7.33E+02	2.95E+00
RF-MT0801	7.35E+01	0.00E+00	1.59E-01	7.53E+01	1.67E+01	2.57E-06	1.22E-03	1.66E+02	6.68E-01
RF-MT0803	1.65E+00	0.00E+00	3.55E-03	1.68E+00	3.73E-01	5.76E-08	2.73E-05	3.71E+00	1.49E-02
RF-MT0806	7.78E-01	0.00E+00	8.51E-03	7.31E+00	1.60E+00	9.74E-08	6.55E-05	9.70E+00	3.91E-02

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0807	9.84E+00	0.00E+00	6.56E-02	3.11E+01	6.91E+00	1.06E-06	5.05E-04	4.79E+01	1.93E-01
RF-MT0816	1.05E+00	0.00E+00	9.25E-03	4.38E+00	9.70E-01	1.51E-07	7.12E-05	6.41E+00	2.59E-02
RF-MT-0823	5.21E-01	0.00E+00	4.21E-03	2.00E+00	4.44E-01	6.82E-08	3.73E-05	2.97E+00	1.20E-02
RF-MT0827	2.66E+01	0.00E+00	2.34E-01	1.11E+02	2.46E+01	3.80E-06	1.80E-03	1.62E+02	6.54E-01
RF-MT0831	5.06E+01	0.00E+00	6.41E-01	3.00E+02	6.67E+01	1.00E-05	1.72E-02	4.18E+02	1.68E+00
RF-MT0832	3.03E+02	0.00E+00	2.32E+00	1.17E+03	2.58E+02	3.57E-05	5.13E-02	1.73E+03	6.98E+00
RF-MT0833	9.20E+01	0.00E+00	6.95E-01	3.37E+02	7.49E+01	1.07E-05	1.45E-02	5.05E+02	2.04E+00
RF-MT0855	1.59E-02	0.00E+00	3.09E-04	1.46E-01	3.25E-02	5.02E-09	2.38E-06	1.95E-01	7.86E-04
RF-MT0857	7.77E-01	0.00E+00	8.46E-03	7.29E+00	1.60E+00	9.72E-08	6.52E-05	9.68E+00	3.90E-02
RF-MT0H61	2.89E+01	0.00E+00	3.15E-01	2.70E+02	5.95E+01	3.61E-06	2.42E-03	3.59E+02	1.45E+00
RF-MT2116	3.25E+00	0.00E+00	2.50E-02	1.25E+01	2.77E+00	3.83E-07	5.50E-04	1.85E+01	7.46E-02
RF-MT3010	2.03E+01	0.00E+00	2.59E-01	1.24E+02	2.77E+01	4.11E-06	2.39E-03	1.72E+02	6.93E-01
RF-MT3011	1.52E+02	0.00E+00	1.61E+00	7.64E+02	1.70E+02	2.62E-05	2.02E-02	1.09E+03	4.38E+00
RF-MT420P	8.05E+02	0.00E+00	8.17E+00	6.28E+03	1.39E+03	8.57E-05	7.29E-02	8.49E+03	3.42E+01
RF-MT532A	2.13E+02	0.00E+00	1.16E+00	5.60E+02	1.24E+02	1.86E-05	1.16E-02	8.97E+02	3.62E+00
RF-MT532B	9.53E+02	0.00E+00	5.19E+00	2.51E+03	5.57E+02	8.37E-05	5.21E-02	4.03E+03	1.62E+01
RF-MT532C	1.91E+03	0.00E+00	1.04E+01	5.03E+03	1.11E+03	1.67E-04	1.05E-01	8.07E+03	3.25E+01
RF-MT532D	1.21E+01	0.00E+00	6.56E-02	3.19E+01	7.05E+00	1.05E-06	6.60E-04	5.11E+01	2.06E-01
RF-TT0069	6.95E-02	0.00E+00	7.78E-04	3.69E-01	8.19E-02	1.27E-08	7.94E-05	5.21E-01	2.10E-03
RF-TT0200	3.30E+00	0.00E+00	3.14E-02	1.51E+01	3.38E+00	4.88E-07	2.43E-04	2.18E+01	8.81E-02
RF-TT0299	1.37E+01	0.00E+00	5.82E-02	2.76E+01	6.13E+00	9.46E-07	4.48E-04	4.75E+01	1.91E-01
RF-TT0300	1.12E+02	0.00E+00	1.66E+00	7.92E+02	1.77E+02	2.30E-05	2.11E-02	1.08E+03	4.36E+00
RF-TT0301	1.51E+01	0.00E+00	2.25E-01	1.08E+02	2.40E+01	3.12E-06	2.87E-03	1.47E+02	5.93E-01
RF-TT0302	7.45E-01	0.00E+00	8.17E-03	4.21E+00	9.37E-01	1.31E-07	4.62E-04	5.90E+00	2.38E-02
RF-TT0303	4.49E+00	0.00E+00	4.78E-02	2.27E+01	5.02E+00	7.76E-07	1.40E-03	3.22E+01	1.30E-01
RF-TT0310	1.53E+01	0.00E+00	2.24E-01	1.02E+02	2.33E+01	2.84E-06	1.91E-03	1.41E+02	5.67E-01
RF-TT0312	3.67E+02	0.00E+00	4.05E+00	2.23E+03	4.90E+02	5.98E-05	3.29E-02	3.09E+03	1.24E+01
RF-TT0317	2.31E-01	0.00E+00	4.40E-03	2.09E+00	4.63E-01	7.15E-08	3.39E-05	2.79E+00	1.12E-02
RF-TT0320	1.48E+02	0.00E+00	1.41E+00	6.81E+02	1.52E+02	2.19E-05	1.09E-02	9.82E+02	3.96E+00
RF-TT0330	5.27E+01	0.00E+00	4.88E-01	4.27E+02	1.02E+02	6.80E-06	3.76E-03	5.82E+02	2.35E+00
RF-TT-0331	2.62E+02	0.00E+00	2.52E+00	1.55E+03	3.38E+02	3.27E-05	7.96E-02	2.16E+03	8.69E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT-0334	1.14E+02	0.00E+00	2.04E+00	9.65E+02	2.14E+02	3.32E-05	1.57E-02	1.30E+03	5.22E+00
RF-TT0335	1.39E+02	0.00E+00	1.55E+00	8.21E+02	1.83E+02	2.23E-05	8.41E-02	1.15E+03	4.62E+00
RF-TT0336	1.23E+02	0.00E+00	1.28E+00	7.27E+02	1.61E+02	1.63E-05	1.29E-02	1.01E+03	4.08E+00
RF-TT0337	1.46E+02	0.00E+00	1.48E+00	9.39E+02	2.05E+02	1.68E-05	2.49E-02	1.29E+03	5.20E+00
RF-TT0338	6.19E+02	0.00E+00	5.38E+00	3.66E+03	7.99E+02	7.52E-05	4.97E-02	5.08E+03	2.05E+01
RF-TT0340	5.29E+00	0.00E+00	1.03E-01	4.87E+01	1.09E+01	1.67E-06	7.91E-04	6.49E+01	2.62E-01
RF-TT0342	3.54E+01	0.00E+00	5.14E-01	2.87E+02	6.25E+01	6.72E-06	7.06E-03	3.85E+02	1.55E+00
RF-TT0360	2.70E+00	0.00E+00	2.61E-02	1.29E+01	2.89E+00	3.98E-07	2.07E-04	1.85E+01	7.45E-02
RF-TT0368	5.40E+01	0.00E+00	5.23E-01	2.58E+02	5.79E+01	7.96E-06	4.16E-03	3.71E+02	1.49E+00
RF-TT0370	1.07E+02	0.00E+00	1.13E+00	5.75E+02	1.28E+02	1.69E-05	1.65E-02	8.10E+02	3.27E+00
RF-TT0371	2.31E+00	0.00E+00	2.28E-02	1.08E+01	2.39E+00	3.70E-07	1.88E-04	1.55E+01	6.25E-02
RF-TT0372	2.82E-01	0.00E+00	4.48E-03	2.11E+00	4.69E-01	6.40E-08	1.03E-04	2.86E+00	1.15E-02
RF-TT0374	8.77E+00	0.00E+00	1.05E-01	4.98E+01	1.10E+01	1.70E-06	8.70E-04	6.97E+01	2.81E-01
RF-TT0375A	9.14E-02	0.00E+00	1.73E-03	8.18E-01	1.82E-01	2.81E-08	1.33E-05	1.09E+00	4.41E-03
RF-TT0375B	9.14E-02	0.00E+00	1.73E-03	8.18E-01	1.82E-01	2.81E-08	1.33E-05	1.09E+00	4.41E-03
RF-TT0376	2.10E+01	0.00E+00	2.56E-01	1.50E+02	3.38E+01	3.80E-06	2.81E-03	2.05E+02	8.28E-01
RF-TT0377	1.18E+01	0.00E+00	1.39E-01	6.61E+01	1.47E+01	2.26E-06	1.60E-03	9.27E+01	3.74E-01
RF-TT0391	2.63E+00	0.00E+00	1.96E-02	1.67E+01	3.66E+00	3.96E-07	1.51E-04	2.30E+01	9.28E-02
RF-TT0392	9.26E-01	0.00E+00	1.23E-02	8.73E+00	1.93E+00	1.37E-07	9.51E-05	1.16E+01	4.68E-02
RF-TT0393	7.61E+01	0.00E+00	8.61E-01	4.07E+02	9.04E+01	1.39E-05	6.63E-03	5.74E+02	2.31E+00
RF-TT0398	1.66E+00	0.00E+00	2.27E-02	1.63E+01	3.59E+00	2.59E-07	1.75E-04	2.16E+01	8.71E-02
RF-TT0409	1.39E+00	0.00E+00	1.06E-02	8.43E+00	1.85E+00	9.97E-08	8.24E-05	1.17E+01	4.71E-02
RF-TT0412	1.39E+00	0.00E+00	1.06E-02	8.43E+00	1.85E+00	9.97E-08	8.24E-05	1.17E+01	4.71E-02
RF-TT0414	4.30E+01	0.00E+00	3.28E-01	2.61E+02	5.73E+01	3.09E-06	2.55E-03	3.62E+02	1.46E+00
RF-TT0430	1.26E-02	0.00E+00	2.45E-04	1.16E-01	2.57E-02	3.98E-09	1.89E-06	1.54E-01	6.22E-04
RF-TT0431	3.13E+00	0.00E+00	5.97E-02	2.85E+01	6.33E+00	9.45E-07	6.82E-04	3.80E+01	1.53E-01
RF-TT0438	1.86E+02	0.00E+00	2.28E+00	1.45E+03	3.21E+02	2.80E-05	1.90E-02	1.96E+03	7.92E+00
RF-TT0440	1.83E+01	0.00E+00	2.21E-01	1.43E+02	3.26E+01	3.13E-06	6.87E-03	1.95E+02	7.84E-01
RF-TT0441	9.02E+01	0.00E+00	1.04E+00	4.96E+02	1.10E+02	1.66E-05	1.26E-02	6.97E+02	2.81E+00
RF-TT0442	1.30E+01	0.00E+00	1.79E-01	9.17E+01	2.04E+01	2.17E-06	6.90E-03	1.25E+02	5.05E-01
RF-TT0443	2.79E-01	0.00E+00	5.14E-03	2.48E+00	5.50E-01	7.85E-08	5.56E-05	3.32E+00	1.34E-02

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0479	2.73E+00	0.00E+00	5.33E-02	2.51E+01	5.59E+00	8.64E-07	4.11E-04	3.35E+01	1.35E-01
RF-TT0480	1.86E+02	0.00E+00	2.15E+00	1.03E+03	2.28E+02	3.21E-05	2.42E-02	1.44E+03	5.82E+00
RF-TT0481	1.05E-01	0.00E+00	1.21E-03	5.78E-01	1.29E-01	1.81E-08	1.36E-05	8.12E-01	3.28E-03
RF-TT0483	3.37E-01	0.00E+00	6.56E-03	3.10E+00	6.89E-01	1.06E-07	1.72E-02	4.15E+00	1.67E-02
RF-TT0484	1.80E+00	0.00E+00	2.72E-02	1.29E+01	2.86E+00	4.42E-07	3.20E-04	1.76E+01	7.08E-02
RF-TT0485	1.48E-01	0.00E+00	1.68E-03	7.93E-01	1.77E-01	2.73E-08	2.90E-04	1.12E+00	4.52E-03
RF-TT0486	8.77E-01	0.00E+00	9.93E-03	4.71E+00	1.05E+00	1.61E-07	3.04E-04	6.64E+00	2.68E-02
RF-TT0487	4.40E+00	0.00E+00	3.38E-02	1.69E+01	3.75E+00	5.20E-07	7.44E-04	2.51E+01	1.01E-01
RF-TT0489	1.25E+00	0.00E+00	1.52E-02	7.18E+00	1.59E+00	2.47E-07	2.18E-04	1.00E+01	4.05E-02
RF-TT0490	6.93E+01	0.00E+00	9.64E-01	4.63E+02	1.03E+02	1.48E-05	9.21E-03	6.36E+02	2.56E+00
RF-TT0491	1.61E+00	0.00E+00	1.30E-02	6.20E+00	1.37E+00	2.06E-07	1.96E-04	9.20E+00	3.71E-02
RF-TT0492	5.42E-01	0.00E+00	7.34E-03	3.46E+00	7.70E-01	1.19E-07	5.65E-05	4.78E+00	1.93E-02
RF-TT0523A	3.64E+00	0.00E+00	2.95E-02	1.40E+01	3.10E+00	4.77E-07	2.61E-04	2.07E+01	8.36E-02
RF-TT0523B	3.64E+00	0.00E+00	2.95E-02	1.40E+01	3.10E+00	4.77E-07	2.61E-04	2.07E+01	8.36E-02
RF-TT0523C	3.64E+00	0.00E+00	2.95E-02	1.40E+01	3.10E+00	4.77E-07	2.61E-04	2.07E+01	8.36E-02
RF-TT0523D	3.64E+00	0.00E+00	2.95E-02	1.40E+01	3.10E+00	4.77E-07	2.61E-04	2.07E+01	8.36E-02
RF-TT0523E	3.64E+00	0.00E+00	2.95E-02	1.40E+01	3.10E+00	4.77E-07	2.61E-04	2.07E+01	8.36E-02
RF-TT0532A	9.14E+01	0.00E+00	4.94E-01	2.40E+02	5.32E+01	7.99E-06	4.97E-03	3.86E+02	1.55E+00
RF-TT0532B	9.14E+01	0.00E+00	4.94E-01	2.40E+02	5.32E+01	7.99E-06	4.97E-03	3.86E+02	1.55E+00
RF-TT0541	1.51E-01	0.00E+00	2.94E-03	1.40E+00	3.09E-01	4.78E-08	2.26E-05	1.86E+00	7.49E-03
RF-TT0545	3.37E-02	0.00E+00	6.56E-04	3.10E-01	6.89E-02	1.06E-08	5.05E-06	4.13E-01	1.66E-03
RF-TT0601	1.17E+01	0.00E+00	1.13E-01	5.59E+01	1.26E+01	1.73E-06	8.98E-04	8.03E+01	3.24E-01
RF-TT0802	1.31E+03	0.00E+00	9.30E+00	4.41E+03	9.80E+02	1.51E-04	7.16E-02	6.71E+03	2.71E+01
RF-TT0809	1.08E+02	0.00E+00	7.63E-01	3.63E+02	8.03E+01	1.24E-05	5.88E-03	5.52E+02	2.22E+00
RF-TT0821	2.33E+02	0.00E+00	2.77E+00	1.42E+03	3.17E+02	3.69E-05	1.89E-01	1.98E+03	7.97E+00
RF-TT0822	2.57E+02	0.00E+00	2.16E+00	1.07E+03	2.36E+02	3.29E-05	1.99E-01	1.56E+03	6.31E+00
RF-TT0823	5.21E-01	0.00E+00	4.21E-03	2.00E+00	4.44E-01	6.82E-08	3.73E-05	2.97E+00	1.20E-02
RF-TT0824	5.36E+02	0.00E+00	5.92E+00	2.88E+03	6.39E+02	9.29E-05	1.08E-01	4.06E+03	1.64E+01
RF-TT0825	4.45E+02	0.00E+00	4.28E+00	2.17E+03	4.80E+02	6.16E-05	1.14E-01	3.10E+03	1.25E+01
RF-TT0832	3.30E+02	0.00E+00	2.53E+00	1.27E+03	2.81E+02	3.89E-05	5.58E-02	1.88E+03	7.58E+00
RF-TT0854	1.19E-01	0.00E+00	2.31E-03	1.09E+00	2.43E-01	3.75E-08	7.64E-04	1.45E+00	5.86E-03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0886	1.68E-02	0.00E+00	3.26E-04	1.54E-01	3.44E-02	5.31E-09	2.51E-06	2.06E-01	8.30E-04
RF-TT2216	4.87E+00	0.00E+00	3.74E-02	1.88E+01	4.15E+00	5.75E-07	8.24E-04	2.79E+01	1.12E-01
RF-TT3010	2.60E+02	0.00E+00	3.31E+00	1.58E+03	3.52E+02	5.26E-05	3.05E-02	2.20E+03	8.86E+00
RF-TT3011	6.56E+02	0.00E+00	7.00E+00	3.30E+03	7.35E+02	1.14E-04	8.75E-02	4.70E+03	1.90E+01
RF-TT301U	5.45E+01	0.00E+00	7.39E-01	3.59E+02	8.11E+01	1.12E-05	5.85E-03	4.95E+02	2.00E+00
RF-TT310P	1.58E+01	0.00E+00	1.92E-01	1.21E+02	2.55E+01	2.33E-06	1.48E-03	1.62E+02	6.54E-01
RF-TT338S	4.60E-01	0.00E+00	8.81E-03	4.16E+00	9.26E-01	1.43E-07	6.78E-05	5.56E+00	2.24E-02
RF-TT390P	2.59E+00	0.00E+00	2.39E-02	2.03E+01	4.14E+00	3.56E-07	2.13E-04	2.70E+01	1.09E-01
RF-TT391P	1.43E+02	0.00E+00	1.07E+00	9.11E+02	1.99E+02	2.16E-05	8.25E-03	1.25E+03	5.06E+00
RF-TT392P	2.89E+02	0.00E+00	3.86E+00	2.73E+03	6.04E+02	4.29E-05	2.98E-02	3.63E+03	1.46E+01
RF-TT393R	4.28E+01	0.00E+00	6.56E-01	4.17E+02	9.30E+01	6.93E-06	5.22E-03	5.54E+02	2.23E+00
RF-TT394P	5.31E+00	0.00E+00	4.06E-02	3.22E+01	6.64E+00	4.99E-07	3.19E-04	4.42E+01	1.78E-01
RF-TT395P	7.11E+00	0.00E+00	5.43E-02	4.31E+01	8.86E+00	6.67E-07	4.28E-04	5.92E+01	2.39E-01
RF-TT396P	1.78E+00	0.00E+00	1.36E-02	1.08E+01	2.22E+00	1.66E-07	1.07E-04	1.48E+01	5.96E-02
RF-TT398P	1.72E+02	0.00E+00	2.35E+00	1.69E+03	3.72E+02	2.68E-05	1.81E-02	2.24E+03	9.02E+00
RF-TT398R	1.42E+03	0.00E+00	4.36E+00	2.73E+03	6.01E+02	5.22E-05	3.36E-02	4.75E+03	1.92E+01
RF-TT411R	5.14E+01	0.00E+00	3.92E-01	3.12E+02	6.85E+01	3.69E-06	3.04E-03	4.32E+02	1.74E+00
RF-TT429R	1.08E+02	0.00E+00	8.41E-02	7.22E+01	1.56E+01	6.44E-07	6.48E-04	1.96E+02	7.89E-01
RF-TT433X	3.40E+01	0.00E+00	2.33E-02	2.08E+01	4.04E+00	2.55E-07	1.79E-04	5.88E+01	2.37E-01
RF-TT436R	2.49E+02	0.00E+00	3.37E-01	2.72E+02	5.96E+01	4.93E-06	2.60E-03	5.81E+02	2.34E+00
RF-TT454X	1.46E+01	0.00E+00	1.98E-02	1.60E+01	3.52E+00	2.90E-07	1.53E-04	3.42E+01	1.38E-01
RL-T101	7.42E+01	0.00E+00	1.20E+00	8.65E+02	1.88E+02	4.10E-05	8.39E-03	1.13E+03	4.55E+00
RL-T102	9.41E-04	0.00E+00	1.53E-05	1.11E-02	2.40E-03	5.21E-10	1.26E-06	1.44E-02	5.82E-05
RL-T103	6.67E+01	0.00E+00	1.46E+00	3.78E+02	8.16E+01	2.18E-05	1.02E-02	5.28E+02	2.13E+00
RL-T104	1.35E-03	0.00E+00	2.19E-05	1.57E-02	3.44E-03	7.46E-10	1.85E-07	2.05E-02	8.28E-05
RL-T105	5.17E-01	0.00E+00	8.27E-03	5.97E+00	1.30E+00	2.82E-07	1.02E-04	7.80E+00	3.14E-02
RL-T106	4.99E-01	0.00E+00	8.12E-03	5.84E+00	1.27E+00	2.76E-07	5.66E-05	7.61E+00	3.07E-02
RL-T107	1.37E+03	0.00E+00	4.77E+03	1.61E+04	3.50E+03	7.57E-04	3.41E+01	2.58E+04	1.04E+02
RL-T108	7.84E-01	0.00E+00	8.22E-01	9.18E+00	2.00E+00	4.34E-07	5.76E-03	1.28E+01	5.16E-02
RL-T109	1.08E+00	0.00E+00	1.69E-02	1.22E+01	2.65E+00	5.75E-07	2.34E-02	1.59E+01	6.43E-02
RL-T110	1.21E+02	0.00E+00	3.23E+00	1.40E+03	3.04E+02	6.61E-05	1.38E+00	1.83E+03	7.36E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T112	4.88E+01	0.00E+00	1.37E+00	1.85E+02	4.02E+01	8.75E-06	7.45E-01	2.76E+02	1.11E+00
RL-T113	5.21E-02	0.00E+00	2.64E-03	6.09E-01	1.33E-01	2.88E-08	1.84E-05	7.97E-01	3.21E-03
RL-T114	7.92E+00	0.00E+00	1.29E-01	9.26E+01	2.02E+01	4.38E-06	8.97E-04	1.21E+02	4.87E-01
RL-T115	2.02E+02	0.00E+00	4.17E+00	1.22E+03	2.65E+02	6.45E-05	4.42E-01	1.69E+03	6.81E+00
RL-T116	1.30E+01	0.00E+00	2.11E-01	1.51E+02	3.30E+01	7.19E-06	5.76E-02	1.98E+02	7.97E-01
RL-T118	3.34E+01	0.00E+00	1.69E+00	1.50E+02	3.28E+01	7.12E-06	8.44E-01	2.19E+02	8.83E-01
RL-T120	8.10E+00	0.00E+00	1.77E-01	4.45E+01	9.60E+00	2.50E-06	1.24E-03	6.24E+01	2.52E-01
RL-T122	4.59E-01	0.00E+00	7.49E-03	5.36E+00	1.17E+00	2.54E-07	1.46E+00	8.46E+00	3.41E-02
RL-T123	1.35E+00	0.00E+00	2.19E-02	1.57E+01	3.44E+00	7.48E-07	5.98E-02	2.06E+01	8.31E-02
RL-T125	2.69E+02	0.00E+00	5.43E+00	3.29E+02	1.65E+02	1.17E-04	3.79E-02	7.69E+02	3.10E+00
RL-T127	2.59E+02	0.00E+00	1.37E+00	9.84E+02	2.14E+02	4.65E-05	8.94E-02	1.46E+03	5.88E+00
RL-T128	3.84E-01	0.00E+00	3.32E-08	2.39E-05	5.20E-06	1.13E-12	2.31E-10	3.84E-01	1.55E-03
RL-T129	1.15E+00	0.00E+00	6.31E+00	1.36E+01	2.93E+00	6.36E-07	5.17E-02	2.40E+01	9.67E-02
RL-T130	2.45E-03	0.00E+00	3.99E-05	2.88E-02	6.25E-03	1.35E-09	8.32E-05	3.76E-02	1.52E-04
RL-T131	9.95E-01	0.00E+00	2.18E-02	5.48E+00	1.18E+00	3.06E-07	8.37E-03	7.69E+00	3.10E-02
RL-T132	2.37E+02	0.00E+00	3.85E+00	2.78E+03	6.04E+02	1.31E-04	2.72E-01	3.63E+03	1.46E+01
RL-T133	4.83E-03	0.00E+00	6.16E-05	4.56E-02	9.89E-03	1.86E-09	4.30E-07	6.04E-02	2.44E-04
RL-T134	1.02E-02	0.00E+00	1.66E-04	1.20E-01	2.59E-02	5.65E-09	1.16E-06	1.56E-01	6.29E-04
RL-T135	4.78E-02	0.00E+00	7.78E-04	5.60E-01	1.22E-01	2.64E-08	4.15E-03	7.35E-01	2.96E-03
RL-T137	7.77E+02	0.00E+00	1.70E+01	4.26E+03	9.22E+02	2.41E-04	1.25E-01	5.98E+03	2.41E+01
RL-T140	9.08E+02	0.00E+00	1.61E+01	4.12E+03	9.89E+02	2.05E-04	2.63E+01	6.06E+03	2.45E+01
RL-T143	5.70E+00	0.00E+00	9.25E-02	6.67E+01	1.45E+01	3.15E-06	3.92E-02	8.70E+01	3.51E-01
RL-T145	1.62E+01	0.00E+00	2.64E-01	1.90E+02	4.12E+01	8.97E-06	9.13E-02	2.48E+02	9.99E-01
RL-W407	4.66E+01	0.00E+00	5.63E-01	4.35E+02	9.47E+01	1.36E-05	3.92E-03	5.77E+02	2.33E+00
RL-W408	1.91E-04	0.00E+00	2.38E-06	1.76E-03	3.83E-04	7.02E-11	1.66E-08	2.34E-03	9.42E-06
RL-W415	4.22E-03	0.00E+00	5.23E-05	3.90E-02	8.47E-03	1.55E-09	3.65E-07	5.17E-02	2.09E-04
RL-W418	1.81E-02	0.00E+00	2.21E-04	1.67E-01	3.64E-02	5.78E-09	1.54E-06	2.22E-01	8.94E-04
RL-W437	1.53E+02	0.00E+00	1.85E+00	1.42E+03	3.10E+02	4.47E-05	1.29E-02	1.89E+03	7.62E+00
RL-W438	2.67E-04	0.00E+00	3.32E-06	2.46E-03	5.35E-04	9.81E-11	2.32E-08	3.27E-03	1.32E-05
RL-W439	8.37E+03	0.00E+00	1.83E+02	4.75E+04	1.03E+04	2.74E-03	1.28E+00	6.63E+04	2.67E+02
RL-W443	1.35E+02	0.00E+00	1.63E+00	1.26E+03	2.73E+02	3.94E-05	1.14E-02	1.67E+03	6.71E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W444	9.97E+01	0.00E+00	1.21E+00	9.32E+02	2.03E+02	2.92E-05	8.42E-03	1.24E+03	4.98E+00
RL-W447	1.14E-02	0.00E+00	1.42E-04	1.05E-01	2.30E-02	4.20E-09	9.92E-07	1.39E-01	5.62E-04
RL-W448	8.46E-05	0.00E+00	1.05E-06	7.78E-04	1.69E-04	3.11E-11	7.33E-09	1.03E-03	4.17E-06
RL-W449	6.95E-01	0.00E+00	3.85E-05	2.23E-02	4.84E-03	5.64E-10	2.68E-07	7.22E-01	2.91E-03
RL-W450	1.28E-03	0.00E+00	1.59E-05	1.18E-02	2.55E-03	4.69E-10	1.11E-07	1.56E-02	6.30E-05
RL-W451	1.82E-04	0.00E+00	2.26E-06	1.67E-03	3.64E-04	6.68E-11	1.58E-08	2.22E-03	8.95E-06
RL-W452	7.92E-03	0.00E+00	9.74E-05	7.37E-02	1.60E-02	2.54E-09	6.79E-07	9.77E-02	3.94E-04
RL-W453	2.26E-03	0.00E+00	2.74E-05	2.12E-02	4.59E-03	6.62E-10	1.91E-07	2.80E-02	1.13E-04
RL-W454	3.16E-02	0.00E+00	3.83E-04	2.96E-01	6.42E-02	9.25E-09	2.67E-06	3.92E-01	1.58E-03
RL-W455	8.43E-03	0.00E+00	1.03E-04	7.82E-02	1.70E-02	2.71E-09	7.20E-07	1.04E-01	4.18E-04
RL-W456	1.11E+00	0.00E+00	1.35E-02	1.04E+01	2.26E+00	3.34E-07	9.41E-05	1.38E+01	5.55E-02
RL-W457	1.08E-01	0.00E+00	1.31E-03	1.01E+00	2.19E-01	3.23E-08	9.14E-06	1.34E+00	5.39E-03
RL-W458	3.42E-01	0.00E+00	6.70E-03	4.14E-01	2.25E-01	1.30E-07	4.67E-05	9.87E-01	3.98E-03
RL-W459	3.28E+00	0.00E+00	6.90E-02	1.03E+01	3.06E+00	1.29E-06	4.81E-04	1.67E+01	6.74E-02
RL-W460	2.00E-02	0.00E+00	2.43E-04	1.87E-01	4.07E-02	5.87E-09	1.69E-06	2.48E-01	1.00E-03
RL-W461	1.85E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.85E-02	7.45E-05
RL-W462	5.71E-03	0.00E+00	7.04E-05	5.29E-02	1.15E-02	1.92E-09	4.91E-07	7.02E-02	2.83E-04
RL-W463	2.94E-02	0.00E+00	3.56E-04	2.75E-01	5.97E-02	8.60E-09	2.48E-06	3.64E-01	1.47E-03
RL-W464	1.36E-02	0.00E+00	1.64E-04	1.27E-01	2.75E-02	3.97E-09	1.14E-06	1.68E-01	6.77E-04
RL-W465	9.05E-02	0.00E+00	1.11E-03	8.43E-01	1.83E-01	2.87E-08	7.74E-06	1.12E+00	4.51E-03
RL-W466	1.24E+00	0.00E+00	1.51E-02	1.16E+01	2.52E+00	3.82E-07	1.05E-04	1.53E+01	6.19E-02
RL-W467	6.35E-02	0.00E+00	7.78E-04	5.90E-01	1.28E-01	2.10E-08	5.42E-06	7.82E-01	3.15E-03
RL-W468	3.25E-04	0.00E+00	4.01E-06	3.02E-03	6.56E-04	1.10E-10	2.79E-08	4.00E-03	1.61E-05
RL-W469	1.32E-01	0.00E+00	1.61E-03	1.23E+00	2.68E-01	4.03E-08	1.12E-05	1.63E+00	6.56E-03
RL-W470	3.73E+00	0.00E+00	7.49E-02	4.55E+00	2.29E+00	1.62E-06	5.22E-04	1.06E+01	4.29E-02
RL-W474	1.41E-01	0.00E+00	8.27E-03	1.04E-02	8.64E-03	0.00E+00	5.76E-05	1.69E-01	6.81E-04
RL-W476	2.39E-01	0.00E+00	2.97E-03	2.28E+00	4.97E-01	7.31E-08	2.07E-05	3.01E+00	1.22E-02
RL-W480	3.89E-02	0.00E+00	4.77E-04	3.61E-01	7.87E-02	1.25E-08	3.32E-06	4.79E-01	1.93E-03
RL-W481	6.11E-02	0.00E+00	7.49E-04	5.67E-01	1.23E-01	1.96E-08	5.22E-06	7.52E-01	3.03E-03
RL-W482	8.12E+01	0.00E+00	2.49E-01	7.21E-02	1.31E-01	2.60E-05	1.74E-03	8.16E+01	3.29E-01
RL-W483	6.06E+00	0.00E+00	1.93E-02	4.67E-03	9.28E-03	1.94E-06	1.35E-04	6.09E+00	2.46E-02

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W484	2.56E-02	0.00E+00	1.56E-04	6.52E-02	1.52E-02	1.61E-09	1.09E-06	1.06E-01	4.28E-04
RL-W485	1.50E-03	0.00E+00	2.20E-05	7.05E-03	1.64E-03	0.00E+00	1.54E-07	1.02E-02	4.12E-05
RL-W486	6.34E-04	0.00E+00	9.30E-06	2.98E-03	6.91E-04	0.00E+00	6.48E-08	4.31E-03	1.74E-05
RL-W487	1.04E-01	0.00E+00	1.19E-03	4.26E-01	1.14E-01	1.50E-08	8.32E-06	6.45E-01	2.60E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	6.29E-02	0.00E+00	1.13E-03	5.52E-01	1.22E-01	2.42E-08	7.84E-06	7.38E-01	2.98E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	2.34E-02	0.00E+00	9.49E-04	5.79E-02	1.24E-02	8.78E-09	6.62E-06	9.46E-02	3.81E-04
RL-W492	1.35E-03	0.00E+00	2.34E-05	1.16E-02	2.55E-03	5.05E-10	1.63E-07	1.55E-02	6.25E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	5.34E+01	0.00E+00	1.36E+00	2.92E-01	2.43E-01	2.02E-05	9.45E-03	5.53E+01	2.23E-01
RL-W495	9.66E-01	0.00E+00	3.68E-03	2.80E-03	2.17E-03	3.69E-07	2.57E-05	9.75E-01	3.93E-03
RL-W496	6.28E+00	0.00E+00	4.24E-02	9.20E-03	7.19E-03	2.39E-06	2.96E-04	6.34E+00	2.56E-02
RL-W497	2.62E-01	0.00E+00	8.37E-03	5.52E-01	2.44E-01	6.25E-08	5.83E-05	1.07E+00	4.30E-03
RL-W498	1.02E+00	0.00E+00	1.24E-02	9.44E+00	2.06E+00	3.25E-07	8.66E-05	1.25E+01	5.05E-02
RL-W499	9.11E-06	0.00E+00	1.12E-07	8.46E-05	1.84E-05	2.92E-12	7.78E-10	1.12E-04	4.53E-07
RL-W500	6.49E-04	0.00E+00	1.38E-05	3.45E-03	7.47E-04	2.06E-10	9.65E-08	4.86E-03	1.96E-05
RL-W501	2.69E+01	0.00E+00	3.09E-01	1.11E+02	2.96E+01	3.88E-06	2.15E-03	1.68E+02	6.76E-01
RL-W502	4.86E-03	0.00E+00	5.97E-05	4.51E-02	9.80E-03	1.56E-09	4.16E-07	5.98E-02	2.41E-04
RL-W503	2.81E-01	0.00E+00	6.12E-03	1.59E+00	3.44E-01	9.17E-08	4.26E-05	2.22E+00	8.96E-03
RL-W504	1.04E-01	0.00E+00	1.19E-03	4.26E-01	1.14E-01	1.50E-08	8.32E-06	6.45E-01	2.60E-03
RL-W505	4.88E-03	0.00E+00	6.26E-05	4.61E-02	9.99E-03	1.88E-09	4.37E-07	6.10E-02	2.46E-04
RL-W506	1.77E-03	0.00E+00	2.46E-05	1.51E-02	3.29E-03	5.63E-10	1.72E-07	2.02E-02	8.15E-05
RL-W507	1.76E-04	0.00E+00	2.15E-06	1.63E-03	3.54E-04	5.64E-11	1.50E-08	2.16E-03	8.73E-06
RL-W508	3.23E+00	0.00E+00	7.04E-02	1.77E+01	3.83E+00	1.00E-06	4.91E-04	2.48E+01	1.00E-01
RL-W509	3.18E+01	0.00E+00	5.63E-01	1.44E+02	3.45E+01	7.17E-06	3.92E-03	2.11E+02	8.52E-01
RL-W510	2.68E+00	0.00E+00	5.77E-02	1.43E+01	3.10E+00	8.53E-07	4.02E-04	2.02E+01	8.14E-02
RL-W511	2.73E+02	0.00E+00	2.78E+00	1.92E+03	4.09E+02	4.65E-05	1.98E-02	2.60E+03	1.05E+01
RL-W512	2.39E+02	0.00E+00	1.88E+00	1.16E+03	2.80E+02	2.38E-05	1.31E-02	1.68E+03	6.77E+00
RL-W513	2.55E+04	0.00E+00	7.63E+02	1.89E+04	9.14E+03	3.77E-03	5.32E+00	5.43E+04	2.19E+02
RL-W514	7.18E-04	0.00E+00	8.76E-06	6.70E-03	1.46E-03	2.20E-10	6.11E-08	8.88E-03	3.58E-05

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W515	2.81E-02	0.00E+00	3.43E-04	2.61E-01	5.67E-02	9.00E-09	2.39E-06	3.46E-01	1.40E-03
RL-W516	3.90E-02	0.00E+00	4.77E-04	3.61E-01	7.87E-02	1.25E-08	3.33E-06	4.79E-01	1.93E-03
RL-W517	3.47E-10	0.00E+00	4.27E-12	3.21E-09	6.98E-10	1.17E-16	2.97E-14	4.26E-09	1.72E-11
RL-W518	9.82E-01	0.00E+00	1.80E-02	4.61E+00	1.09E+00	2.51E-07	1.25E-04	6.69E+00	2.70E-02
RL-W519	1.75E-01	0.00E+00	2.13E-03	1.63E+00	3.54E-01	5.30E-08	1.48E-05	2.16E+00	8.72E-03
RL-W520	1.93E-02	0.00E+00	2.40E-04	1.79E-01	3.89E-02	6.80E-09	1.67E-06	2.38E-01	9.58E-04
RL-W521	3.60E-04	0.00E+00	4.40E-06	3.33E-03	7.26E-04	1.16E-10	3.07E-08	4.42E-03	1.78E-05
RL-W522	7.52E+00	0.00E+00	1.63E-01	2.21E+01	6.16E+00	1.67E-06	1.14E-03	3.59E+01	1.45E-01
RL-W523	2.26E+00	0.00E+00	6.21E-02	1.46E+00	8.67E-01	3.32E-07	4.33E-04	4.65E+00	1.88E-02
RL-W524	9.36E+00	0.00E+00	2.38E-01	1.35E+01	5.08E+00	1.58E-06	1.66E-03	2.81E+01	1.13E-01
RL-W525	7.44E-01	0.00E+00	1.61E-02	1.59E+00	5.14E-01	1.24E-07	1.12E-04	2.87E+00	1.16E-02
RL-W526	2.82E+00	0.00E+00	5.82E-02	1.70E+01	3.71E+00	9.02E-07	4.06E-04	2.36E+01	9.51E-02
RL-W527	3.09E-01	0.00E+00	8.41E-03	1.80E+00	4.17E-01	1.05E-07	5.87E-05	2.53E+00	1.02E-02
RL-W528	1.38E+02	0.00E+00	3.58E+00	5.74E+01	5.36E+01	1.61E-05	2.49E-02	2.53E+02	1.02E+00
RL-W529	1.15E-01	0.00E+00	2.51E-03	6.33E-01	1.36E-01	3.55E-08	1.75E-05	8.87E-01	3.58E-03
RL-W530	1.36E+00	0.00E+00	2.92E-02	7.23E+00	1.57E+00	4.32E-07	2.03E-04	1.02E+01	4.11E-02
RL-W531	8.09E+01	0.00E+00	2.93E+00	3.13E+01	2.20E+01	1.15E-05	2.04E-02	1.37E+02	5.53E-01
RL-W532	2.60E-01	0.00E+00	3.18E-03	2.41E+00	5.24E-01	8.33E-08	2.22E-05	3.20E+00	1.29E-02
RL-W533	1.26E-01	0.00E+00	2.74E-03	6.90E-01	1.49E-01	3.85E-08	1.91E-05	9.68E-01	3.90E-03
RL-W534	7.25E-06	0.00E+00	8.85E-08	6.74E-05	1.47E-05	2.32E-12	6.17E-10	8.94E-05	3.60E-07
RL-W535	3.80E+01	0.00E+00	8.76E-01	8.63E+01	2.57E+01	7.09E-06	6.11E-03	1.51E+02	6.09E-01
RL-W536	7.43E-01	0.00E+00	1.18E-02	3.00E+00	6.63E-01	1.62E-07	8.54E-05	4.41E+00	1.78E-02
RL-W537	2.53E+01	0.00E+00	2.66E-01	1.84E+02	3.94E+01	4.53E-06	1.88E-03	2.49E+02	1.00E+00
RL-W538	9.21E-05	0.00E+00	1.13E-06	8.56E-04	1.86E-04	2.95E-11	7.84E-09	1.14E-03	4.58E-06
RL-W539	1.02E-02	0.00E+00	1.27E-04	9.46E-02	2.06E-02	3.59E-09	8.83E-07	1.26E-01	5.06E-04
RL-W540	1.99E+01	0.00E+00	5.58E-01	3.40E+01	1.14E+01	3.45E-06	3.89E-03	6.59E+01	2.66E-01
RL-W541	2.96E-02	0.00E+00	3.65E-04	2.74E-01	5.95E-02	1.01E-08	2.55E-06	3.64E-01	1.47E-03
RL-W542	1.37E+00	0.00E+00	2.72E-02	6.93E+00	1.57E+00	4.15E-07	1.89E-04	9.90E+00	3.99E-02
RL-W543	4.33E-03	0.00E+00	5.28E-05	4.02E-02	8.74E-03	1.39E-09	3.68E-07	5.33E-02	2.15E-04
RL-W544	9.74E-02	0.00E+00	2.16E-03	4.57E-01	1.11E-01	2.77E-08	1.50E-05	6.68E-01	2.69E-03
RL-W545	2.59E-02	0.00E+00	3.17E-04	2.40E-01	5.23E-02	8.30E-09	2.21E-06	3.19E-01	1.29E-03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W546	1.13E-03	0.00E+00	1.39E-05	1.06E-02	2.30E-03	3.64E-10	9.69E-08	1.40E-02	5.66E-05
RL-W547	2.90E-05	0.00E+00	3.55E-07	2.69E-04	5.86E-05	9.30E-12	2.48E-09	3.57E-04	1.44E-06
RL-W548	2.51E-05	0.00E+00	3.08E-07	2.32E-04	5.06E-05	8.33E-12	2.15E-09	3.08E-04	1.24E-06
RL-W549	4.98E+00	0.00E+00	1.24E-01	1.20E+01	3.48E+00	1.05E-06	8.63E-04	2.06E+01	8.29E-02
RL-W550	2.26E+01	0.00E+00	2.34E-01	1.62E+02	3.48E+01	3.98E-06	1.65E-03	2.20E+02	8.86E-01
RL-W551	4.02E+01	0.00E+00	3.46E-01	1.83E+02	4.53E+01	4.22E-06	2.42E-03	2.69E+02	1.08E+00
RL-W552	1.56E-02	0.00E+00	1.92E-04	1.44E-01	3.13E-02	5.28E-09	1.34E-06	1.92E-01	7.72E-04
RL-W553	1.38E-03	0.00E+00	1.81E-05	1.29E-02	2.79E-03	6.67E-10	1.26E-07	1.71E-02	6.88E-05
RL-W554	2.19E-02	0.00E+00	2.69E-04	2.04E-01	4.44E-02	7.03E-09	1.87E-06	2.70E-01	1.09E-03
RL-W555	1.01E-02	0.00E+00	1.24E-04	9.39E-02	2.04E-02	3.24E-09	8.63E-07	1.24E-01	5.02E-04
RL-W563	1.45E-01	0.00E+00	3.10E-03	7.78E-01	1.68E-01	4.42E-08	2.16E-05	1.10E+00	4.41E-03
RL-W564	9.43E-02	0.00E+00	2.06E-03	5.03E-01	1.09E-01	3.40E-08	1.43E-05	7.08E-01	2.86E-03
RL-W565	9.37E-03	0.00E+00	1.16E-04	8.69E-02	1.89E-02	3.15E-09	8.05E-07	1.15E-01	4.65E-04
RL-W566	1.37E-01	0.00E+00	1.69E-03	1.28E+00	2.79E-01	4.48E-08	1.18E-05	1.69E+00	6.83E-03
RL-W567	9.53E+00	0.00E+00	4.33E-02	3.93E-02	3.09E-02	3.80E-06	3.02E-04	9.65E+00	3.89E-02
RL-W568	1.83E+02	0.00E+00	9.10E-01	1.86E+00	1.44E+00	7.85E-05	6.34E-03	1.88E+02	7.56E-01
RL-W569	1.51E-01	0.00E+00	6.85E-04	6.20E-04	4.90E-05	6.02E-08	4.78E-06	1.52E-01	6.14E-04
RL-W570	9.67E-03	0.00E+00	1.20E-04	9.22E-02	2.00E-02	2.96E-09	8.36E-07	1.22E-01	4.92E-04
RL-W571	3.10E+01	0.00E+00	4.07E-01	7.48E+00	3.65E+00	1.20E-05	2.84E-03	4.25E+01	1.72E-01
RL-W572	2.69E-02	0.00E+00	1.22E-04	4.03E-03	8.74E-05	1.07E-08	8.49E-07	3.11E-02	1.26E-04
RL-W573	3.46E+02	0.00E+00	1.56E+00	2.21E+00	1.61E+00	1.36E-04	1.09E-02	3.52E+02	1.42E+00
RL-W574	1.49E+03	0.00E+00	6.75E+00	8.43E+00	5.97E+00	5.95E-04	4.71E-02	1.51E+03	6.09E+00
RL-W575	9.70E+03	0.00E+00	4.55E+01	8.06E+01	4.77E+01	3.73E-03	3.17E-01	9.87E+03	3.98E+01
RL-W576	6.99E+02	0.00E+00	3.18E+00	4.11E+00	2.88E+00	2.80E-04	2.21E-02	7.09E+02	2.86E+00
RL-W579	5.92E-02	0.00E+00	8.37E-05	2.06E-02	4.49E-03	9.87E-10	5.83E-07	8.44E-02	3.40E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.64E-01	2.61E-02	0.00E+00	0.00E+00	1.90E-01	7.67E-04
RL-W581	6.29E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.29E-01	2.54E-03
RL-W582	4.11E-03	0.00E+00	7.09E-05	5.26E-03	2.66E-03	1.60E-10	4.95E-07	1.21E-02	4.88E-05
RL-W583	3.18E-03	0.00E+00	3.86E-05	2.97E-02	6.46E-03	9.32E-10	2.69E-07	3.94E-02	1.59E-04
RL-W584	6.32E-02	0.00E+00	2.53E-03	1.73E-01	8.28E-02	4.68E-09	1.76E-05	3.22E-01	1.30E-03
RL-W585	3.76E-01	0.00E+00	1.35E-02	1.01E+00	5.03E-01	1.43E-07	9.38E-05	1.90E+00	7.67E-03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W586	5.02E-05	0.00E+00	6.07E-07	4.69E-04	1.02E-04	1.47E-11	4.23E-09	6.21E-04	2.51E-06
RL-W587	1.07E-03	0.00E+00	1.31E-05	9.99E-03	2.18E-03	3.30E-10	9.14E-08	1.33E-02	5.35E-05
RL-W588	4.43E-02	0.00E+00	2.13E-03	1.46E-01	6.97E-02	3.94E-09	1.49E-05	2.63E-01	1.06E-03
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	1.36E+00	0.00E+00	4.55E-02	1.13E-02	1.96E-02	5.16E-07	3.17E-04	1.44E+00	5.79E-03
RL-W591	7.75E+00	0.00E+00	5.14E-02	1.40E-02	2.54E-02	3.12E-06	3.58E-04	7.84E+00	3.16E-02
RL-W592	3.42E+01	0.00E+00	5.63E-01	6.47E-01	8.20E-01	1.26E-05	3.92E-03	3.63E+01	1.46E-01
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.33E-02	3.85E-02	0.00E+00	0.00E+00	6.19E-02	2.49E-04
RL-W594	3.08E+01	0.00E+00	1.01E-01	2.89E-02	5.21E-02	3.15E-06	7.06E-04	3.10E+01	1.25E-01
RL-W595	8.14E-02	0.00E+00	1.06E-02	1.98E-02	3.78E-02	3.12E-08	7.37E-05	1.50E-01	6.04E-04
RL-W596	2.64E-02	0.00E+00	8.22E-04	2.04E-04	3.55E-04	9.37E-09	5.73E-06	2.78E-02	1.12E-04
RL-W597	4.85E+01	0.00E+00	3.62E-01	3.95E-01	6.44E-01	1.75E-05	2.52E-03	4.99E+01	2.01E-01
RL-W598	5.13E+01	0.00E+00	2.13E+00	5.50E-01	8.04E-01	1.81E-05	1.49E-02	5.48E+01	2.21E-01
RL-W599	2.60E+00	0.00E+00	1.72E-02	4.65E-03	8.47E-03	1.04E-06	1.20E-04	2.63E+00	1.06E-02
RL-W600	1.47E-07	0.00E+00	1.79E-09	1.38E-06	3.00E-07	4.32E-14	1.25E-11	1.82E-06	7.35E-09
RL-W601	7.48E-04	0.00E+00	9.78E-06	6.96E-03	1.52E-03	3.62E-10	6.82E-08	9.24E-03	3.73E-05
RL-W602	6.51E-01	0.00E+00	8.02E-03	6.03E+00	1.32E+00	2.19E-07	5.59E-05	8.01E+00	3.23E-02
RL-W603	3.75E+00	0.00E+00	4.63E-02	3.48E+01	7.58E+00	1.26E-06	3.23E-04	4.62E+01	1.86E-01
RL-W604	8.78E-03	0.00E+00	1.21E-04	1.69E-02	8.16E-03	1.50E-09	8.46E-07	3.40E-02	1.37E-04
RL-W605	2.01E-03	0.00E+00	2.64E-05	1.87E-02	4.07E-03	9.72E-10	1.84E-07	2.48E-02	1.00E-04
RL-W606	8.12E-04	0.00E+00	1.06E-05	7.54E-03	1.64E-03	3.93E-10	7.40E-08	1.00E-02	4.03E-05
RL-W607	1.49E-03	0.00E+00	2.06E-05	2.86E-03	1.38E-03	2.53E-10	1.43E-07	5.75E-03	2.32E-05
RL-W608	1.78E-02	0.00E+00	7.97E-04	3.72E-03	4.49E-03	3.88E-09	5.56E-06	2.68E-02	1.08E-04
RL-W610	3.52E+00	0.00E+00	4.27E-02	3.28E+01	7.15E+00	1.03E-06	2.97E-04	4.35E+01	1.76E-01
RL-W612	8.30E-03	0.00E+00	1.03E-04	7.97E-02	1.74E-02	2.44E-09	7.20E-07	1.06E-01	4.25E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.34E-01	0.00E+00	0.00E+00	0.00E+00	3.34E-01	1.35E-03
RL-W622	1.38E-04	0.00E+00	1.68E-06	1.30E-03	2.81E-04	4.06E-11	1.17E-08	1.72E-03	6.92E-06
RL-W625	4.82E-03	0.00E+00	2.56E-04	6.62E-03	6.36E-03	2.20E-09	1.78E-06	1.81E-02	7.28E-05
RL-W626	2.59E-01	0.00E+00	5.82E-03	2.59E-01	1.52E-01	3.84E-08	4.06E-05	6.76E-01	2.73E-03
RL-W627	1.22E-03	0.00E+00	7.78E-06	1.23E-06	0.00E+00	4.57E-10	5.42E-08	1.23E-03	4.96E-06
RL-W628	4.01E-04	0.00E+00	4.89E-06	3.74E-03	8.12E-04	1.23E-10	3.41E-08	4.96E-03	2.00E-05

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W629	2.71E-05	0.00E+00	3.36E-07	2.51E-04	5.46E-05	9.54E-12	2.34E-09	3.33E-04	1.34E-06
RL-W630	2.98E-01	0.00E+00	6.26E-03	2.91E+00	6.58E-01	1.03E-07	4.37E-05	3.87E+00	1.56E-02
RL-W631	4.81E-03	0.00E+00	6.31E-05	4.46E-02	9.70E-03	2.32E-09	4.40E-07	5.92E-02	2.39E-04
RL-W632	2.12E+00	0.00E+00	8.51E-03	5.90E+00	1.89E+00	7.73E-07	5.93E-05	9.92E+00	4.00E-02
RL-W633	5.06E-03	0.00E+00	4.94E-05	9.26E-04	7.99E-04	9.51E-10	3.45E-07	6.84E-03	2.76E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	1.01E-02	0.00E+00	0.00E+00	0.00E+00	1.01E-02	4.07E-05
RL-W635	3.03E+01	0.00E+00	1.67E+00	4.29E+00	6.27E+00	9.61E-06	1.16E-02	4.25E+01	1.71E-01
RL-W636	3.09E-01	0.00E+00	3.15E-03	5.61E-02	4.85E-02	5.84E-08	2.20E-05	4.17E-01	1.68E-03
RL-W637	7.34E-04	0.00E+00	8.02E-05	6.31E-04	6.05E-04	2.10E-10	5.59E-07	2.05E-03	8.27E-06
RL-W638	3.23E-02	0.00E+00	8.17E-04	6.18E-03	5.69E-03	7.81E-09	5.70E-06	4.50E-02	1.81E-04
RL-W639	1.70E-03	0.00E+00	2.09E-05	1.58E-02	3.44E-03	5.46E-10	1.46E-07	2.10E-02	8.46E-05
RL-W640	5.72E-02	0.00E+00	6.95E-04	5.33E-01	1.16E-01	1.76E-08	4.84E-06	7.07E-01	2.85E-03
RL-W641	1.75E+00	0.00E+00	1.53E-01	2.56E+00	1.03E+00	2.82E-07	1.06E-03	5.49E+00	2.21E-02
RL-W642	3.41E-02	0.00E+00	1.59E-05	3.13E-02	1.56E-04	1.22E-10	1.11E-07	6.55E-02	2.64E-04
RL-W643	5.37E-01	0.00E+00	4.70E-02	7.89E-01	3.17E-01	8.68E-08	3.28E-04	1.69E+00	6.82E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.43E-02	0.00E+00	0.00E+00	0.00E+00	5.43E-02	2.19E-04
RL-W645	1.31E-02	0.00E+00	2.11E-04	1.07E-01	2.45E-02	4.74E-09	1.47E-06	1.45E-01	5.83E-04
RL-W646	1.19E-02	0.00E+00	1.89E-04	2.55E-02	1.21E-02	2.30E-09	1.32E-06	4.97E-02	2.00E-04
RL-W647	3.34E-02	0.00E+00	2.82E-02	1.09E-01	1.68E-02	7.72E-09	1.97E-04	1.87E-01	7.56E-04
RL-W648	5.92E-04	0.00E+00	4.82E-05	5.94E-05	1.14E-04	2.47E-10	3.36E-07	8.14E-04	3.28E-06
RL-W649	2.18E-03	0.00E+00	1.78E-04	2.19E-04	4.20E-04	9.07E-10	1.24E-06	2.99E-03	1.21E-05
RL-W653	1.03E-04	0.00E+00	1.27E-06	9.55E-04	2.07E-04	3.46E-11	8.87E-09	1.27E-03	5.11E-06
RL-W654	5.67E-04	0.00E+00	6.95E-06	5.26E-03	1.14E-03	1.82E-10	4.84E-08	6.98E-03	2.81E-05
RL-W655	1.40E+02	0.00E+00	1.64E+00	2.09E-01	4.81E-01	4.85E-05	1.15E-02	1.42E+02	5.72E-01
RL-W656	5.84E+02	0.00E+00	7.39E-01	4.91E-01	4.95E-01	2.31E-04	5.15E-03	5.86E+02	2.36E+00
RL-W657	2.98E+02	0.00E+00	1.09E+00	2.41E-01	4.71E-01	1.02E-04	7.61E-03	3.00E+02	1.21E+00
RL-W659	3.61E+01	0.00E+00	2.46E-01	4.65E-02	5.64E-02	1.16E-05	1.72E-03	3.64E+01	1.47E-01
RL-W660	1.98E+02	0.00E+00	2.96E+00	8.58E-01	1.50E+00	6.60E-05	2.06E-02	2.03E+02	8.20E-01
RL-W661	2.09E+00	0.00E+00	3.70E-03	4.13E-04	3.68E-03	8.02E-07	2.58E-05	2.10E+00	8.48E-03
RL-W662	6.59E-02	0.00E+00	2.21E-04	1.06E-04	1.85E-04	1.64E-08	1.54E-06	6.64E-02	2.68E-04
RL-W665	8.10E+02	0.00E+00	1.77E+01	1.30E+00	1.70E+00	3.26E-04	1.23E-01	8.30E+02	3.35E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W666	1.45E+01	0.00E+00	4.33E-02	5.43E-02	5.59E-02	4.72E-06	3.02E-04	1.47E+01	5.91E-02
RL-W668	1.38E+00	0.00E+00	1.36E-03	1.43E-01	3.98E-02	1.12E-08	9.48E-06	1.57E+00	6.31E-03
RL-W669	4.03E-01	0.00E+00	3.53E-02	5.92E-01	2.37E-01	6.51E-08	2.46E-04	1.27E+00	5.11E-03
RL-W670	2.55E-02	0.00E+00	2.51E-05	2.65E-03	7.36E-04	2.07E-10	1.75E-07	2.89E-02	1.16E-04
RL-W671	4.15E+00	0.00E+00	1.29E-02	4.86E-03	4.94E-03	6.79E-07	8.97E-05	4.18E+00	1.68E-02
RL-W672	2.82E+01	0.00E+00	8.76E-02	3.31E-02	3.35E-02	4.61E-06	6.11E-04	2.84E+01	1.14E-01
RL-W673	2.72E+01	0.00E+00	8.41E-02	3.21E-02	3.24E-02	4.44E-06	5.87E-04	2.74E+01	1.10E-01
RL-W674	9.13E-02	0.00E+00	3.76E-03	1.11E+01	9.41E-02	3.10E-08	2.62E-05	1.13E+01	4.54E-02
RL-W675	3.41E-01	0.00E+00	2.08E-02	1.30E-01	1.10E-01	7.55E-08	1.45E-04	6.01E-01	2.43E-03
RL-W676	1.31E-02	0.00E+00	1.25E-04	1.45E-01	2.07E-03	2.24E-09	8.70E-07	1.61E-01	6.48E-04
RL-W677	3.04E+01	0.00E+00	3.09E-01	5.68E+00	4.82E+00	5.40E-06	2.16E-03	4.12E+01	1.66E-01
RL-W678	9.61E-02	0.00E+00	2.58E-03	5.10E-02	4.40E-02	4.24E-08	1.80E-05	1.94E-01	7.81E-04
RL-W679	6.02E-01	0.00E+00	5.77E-03	1.10E-01	9.47E-02	1.09E-07	4.02E-05	8.12E-01	3.28E-03
RL-W680	1.36E-04	0.00E+00	8.12E-06	1.72E-05	3.03E-05	4.66E-11	5.66E-08	1.91E-04	7.71E-07
RL-W681	8.28E-05	0.00E+00	3.29E-06	4.62E-04	2.25E-04	3.87E-11	2.30E-08	7.73E-04	3.12E-06
RL-W685	2.41E-01	0.00E+00	2.93E-03	2.26E+00	4.90E-01	7.07E-08	2.04E-05	2.99E+00	1.21E-02
RL-W689	6.25E-03	0.00E+00	3.51E-05	3.83E-04	0.00E+00	6.78E-11	2.45E-07	6.67E-03	2.69E-05
RL-W690	2.10E-01	0.00E+00	2.58E-03	2.01E+00	4.35E-01	6.15E-08	1.80E-05	2.66E+00	1.07E-02
RL-W691	4.86E-03	0.00E+00	6.02E-05	4.65E-02	1.01E-02	1.43E-09	4.20E-07	6.15E-02	2.48E-04
RL-W692	1.92E-01	0.00E+00	2.38E-03	1.84E+00	4.00E-01	5.63E-08	1.66E-05	2.43E+00	9.81E-03
RL-W693	2.38E-01	0.00E+00	2.94E-03	2.28E+00	4.95E-01	6.96E-08	2.05E-05	3.01E+00	1.21E-02
RL-W694	2.50E+00	0.00E+00	3.09E-02	2.40E+01	5.19E+00	7.32E-07	2.15E-04	3.18E+01	1.28E-01
RL-W695	2.07E-03	0.00E+00	0.00E+00	2.36E-03	0.00E+00	0.00E+00	0.00E+00	4.43E-03	1.79E-05
RL-W696	2.70E-03	0.00E+00	1.13E-04	2.88E-03	2.78E-03	1.01E-09	7.84E-07	8.46E-03	3.41E-05
RL-W697	6.23E-01	0.00E+00	2.38E-01	6.85E-03	9.19E-04	0.00E+00	1.66E-03	8.71E-01	3.51E-03
RL-W698	5.40E-02	0.00E+00	0.00E+00	3.25E-05	0.00E+00	0.00E+00	0.00E+00	5.41E-02	2.18E-04
RL-W699	1.20E-02	0.00E+00	1.59E-05	2.18E-03	2.50E-04	4.22E-09	1.11E-07	1.45E-02	5.83E-05
RL-W700	3.41E-03	0.00E+00	4.16E-05	3.16E-02	6.87E-03	1.10E-09	2.90E-07	4.19E-02	1.69E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	1.34E-01	0.00E+00	1.17E-02	1.97E-01	7.92E-02	2.17E-08	8.19E-05	4.22E-01	1.70E-03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W705	8.67E-04	0.00E+00	1.08E-05	8.27E-03	1.81E-03	2.67E-10	7.54E-08	1.10E-02	4.42E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	3.10E-02	0.00E+00	3.85E-04	2.95E-01	6.42E-02	9.47E-09	2.68E-06	3.90E-01	1.57E-03
RL-W708	4.68E-03	0.00E+00	5.82E-05	4.47E-02	9.70E-03	1.44E-09	4.06E-07	5.91E-02	2.39E-04
RL-W709	1.62E+00	0.00E+00	2.01E-02	1.54E+01	3.35E+00	4.96E-07	1.40E-04	2.04E+01	8.23E-02
RL-W710	9.65E-05	0.00E+00	1.20E-06	9.22E-04	2.00E-04	2.96E-11	8.36E-09	1.22E-03	4.92E-06
RL-W711	3.01E-02	0.00E+00	3.74E-04	2.88E-01	6.25E-02	9.23E-09	2.61E-06	3.81E-01	1.54E-03
RL-W712	3.90E-02	0.00E+00	4.84E-04	3.72E-01	8.09E-02	1.20E-08	3.38E-06	4.92E-01	1.99E-03
RL-W713	3.37E-02	0.00E+00	4.18E-04	3.21E-01	6.99E-02	1.03E-08	2.92E-06	4.25E-01	1.71E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	5.81E-04	0.00E+00	7.04E-06	5.43E-03	1.18E-03	1.70E-10	4.91E-08	7.20E-03	2.90E-05
RL-W716	6.06E-03	0.00E+00	7.34E-05	5.66E-02	1.23E-02	1.78E-09	5.12E-07	7.50E-02	3.02E-04
RL-W717	1.51E-03	0.00E+00	1.83E-05	1.41E-02	3.07E-03	4.43E-10	1.28E-07	1.88E-02	7.56E-05
RL-W718	2.67E-04	0.00E+00	3.23E-06	2.49E-03	5.42E-04	7.81E-11	2.25E-08	3.30E-03	1.33E-05
RL-W719	1.20E-03	0.00E+00	1.46E-05	1.13E-02	2.45E-03	3.53E-10	1.02E-07	1.49E-02	6.03E-05
RL-W720	7.45E-03	0.00E+00	9.05E-05	6.96E-02	1.52E-02	2.18E-09	6.31E-07	9.23E-02	3.72E-04
RL-W721	5.04E-03	0.00E+00	6.12E-05	4.71E-02	1.03E-02	1.48E-09	4.26E-07	6.25E-02	2.52E-04
RL-W723	1.67E-02	0.00E+00	2.06E-04	1.60E-01	3.48E-02	4.90E-09	1.44E-06	2.12E-01	8.55E-04
RL-W724	1.11E-01	0.00E+00	1.38E-03	1.06E+00	2.31E-01	3.25E-08	9.58E-06	1.40E+00	5.65E-03
RL-W725	3.51E-02	0.00E+00	4.33E-04	3.35E-01	7.30E-02	1.03E-08	3.02E-06	4.44E-01	1.79E-03
RL-W726	2.77E-02	0.00E+00	3.42E-04	2.65E-01	5.75E-02	8.10E-09	2.38E-06	3.51E-01	1.41E-03
RL-W727	1.70E-01	0.00E+00	2.10E-03	1.62E+00	3.53E-01	4.97E-08	1.46E-05	2.15E+00	8.66E-03
RL-W728	1.54E-01	0.00E+00	1.91E-03	1.48E+00	3.22E-01	4.52E-08	1.33E-05	1.96E+00	7.91E-03
RL-W729	7.13E-02	0.00E+00	8.85E-04	6.82E-01	1.49E-01	2.09E-08	6.17E-06	9.04E-01	3.64E-03
RL-W730	2.79E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.79E+01	1.13E-01
RL-W731	9.00E-06	0.00E+00	0.00E+00	4.46E-04	1.79E-06	0.00E+00	0.00E+00	4.57E-04	1.84E-06
RL-W732	2.06E+01	0.00E+00	5.04E-01	1.26E+02	2.72E+01	7.48E-06	3.51E-03	1.74E+02	7.01E-01
RL-W733	2.71E-01	0.00E+00	6.56E-03	1.37E+00	3.30E-01	8.13E-08	4.57E-05	1.97E+00	7.95E-03
RL-W734	8.47E-01	0.00E+00	2.19E-02	4.71E+00	1.11E+00	2.42E-07	1.52E-04	6.69E+00	2.70E-02
RL-W735	6.92E-01	0.00E+00	1.67E-02	3.67E+00	8.88E-01	1.88E-07	1.16E-04	5.27E+00	2.12E-02
RL-W736	7.60E-04	0.00E+00	3.56E-08	2.43E-03	6.13E-04	5.75E-11	2.48E-10	3.81E-03	1.54E-05

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W737	6.17E-01	0.00E+00	1.52E-02	3.48E+00	8.27E-01	1.62E-07	1.06E-04	4.94E+00	1.99E-02
RL-W738	2.30E+00	0.00E+00	5.23E-02	1.11E+01	2.85E+00	5.88E-07	3.65E-04	1.63E+01	6.57E-02
RL-W739	1.96E-01	0.00E+00	4.62E-03	1.80E+00	4.00E-01	5.34E-08	3.22E-05	2.40E+00	9.68E-03
RL-W740	9.82E+00	0.00E+00	1.69E-01	4.38E+01	1.11E+01	2.70E-06	1.18E-03	6.50E+01	2.62E-01
RL-W741	1.47E+01	0.00E+00	3.98E-01	8.54E+00	5.92E+00	2.02E-06	2.78E-03	2.95E+01	1.19E-01
RL-W742	6.53E-01	0.00E+00	1.20E-02	2.77E+00	6.37E-01	1.74E-07	8.36E-05	4.07E+00	1.64E-02
RL-W743	1.18E-03	0.00E+00	3.25E-06	1.79E-03	0.00E+00	0.00E+00	2.27E-08	2.97E-03	1.20E-05
RL-W744	0.00E+00	0.00E+00	0.00E+00	8.93E-02	7.41E-02	0.00E+00	0.00E+00	1.63E-01	6.59E-04
RL-W745	1.86E-03	0.00E+00	2.28E-05	1.73E-02	3.76E-03	5.96E-10	1.59E-07	2.29E-02	9.25E-05
RL-W746	7.15E-03	0.00E+00	8.76E-05	6.65E-02	1.45E-02	2.29E-09	6.11E-07	8.82E-02	3.56E-04
RL-W747	1.94E-02	0.00E+00	2.37E-04	1.80E-01	3.92E-02	6.22E-09	1.65E-06	2.39E-01	9.63E-04
RL-W748	1.36E+02	0.00E+00	6.65E-01	2.99E-01	4.79E-01	4.68E-05	4.64E-03	1.37E+02	5.54E-01
RL-W749	1.63E-01	0.00E+00	2.04E-03	1.56E+00	3.39E-01	5.00E-08	1.42E-05	2.07E+00	8.33E-03
RL-W750	2.06E+02	0.00E+00	1.01E+00	4.90E-01	7.83E-01	6.62E-05	7.03E-03	2.08E+02	8.39E-01
RL-W751	1.86E+02	0.00E+00	9.10E-01	4.40E-01	7.10E-01	5.97E-05	6.34E-03	1.88E+02	7.58E-01
RL-W752	8.08E+01	0.00E+00	3.95E-01	1.92E-01	3.08E-01	2.59E-05	2.76E-03	8.17E+01	3.29E-01
RL-W753	1.09E+03	0.00E+00	5.33E+00	2.58E+00	4.14E+00	3.49E-04	3.72E-02	1.10E+03	4.43E+00
RP-W754	4.62E+01	0.00E+00	6.75E-01	1.84E+03	1.47E+02	3.22E-06	3.57E-01	2.03E+03	8.20E+00
RP-W755	2.44E+02	0.00E+00	4.05E-01	1.38E+03	1.11E+02	2.41E-06	1.26E+01	1.74E+03	7.03E+00
SA-T001	4.92E-01	2.14E-06	9.69E-03	3.00E+00	1.73E-02	0.00E+00	7.22E-05	3.52E+00	1.42E-02
SA-W134	4.01E+00	8.27E-10	6.60E-02	1.37E+00	4.22E-01	6.14E-08	1.67E-01	6.03E+00	2.43E-02
SA-W134M	5.21E-01	1.07E-10	8.56E-03	1.78E-01	5.47E-02	7.97E-09	2.16E-02	7.84E-01	3.16E-03
T001-221F-HET	9.71E+02	0.00E+00	7.73E+03	2.85E+04	6.86E+02	2.01E-04	5.95E+01	3.79E+04	1.53E+02
T001-221H-HET	1.75E+03	0.00E+00	1.39E+04	5.14E+04	1.24E+03	3.64E-04	1.07E+02	6.85E+04	2.76E+02
T001-235F-HET	1.01E+02	0.00E+00	8.02E+02	2.96E+03	7.12E+01	2.09E-05	6.18E+00	3.94E+03	1.59E+01
T001-772F-HET	8.66E+02	0.00E+00	6.95E+03	2.55E+04	6.14E+02	1.80E-04	5.35E+01	3.40E+04	1.37E+02
T001-773A-CLAS	9.73E+00	0.00E+00	7.78E+01	2.87E+02	6.89E+00	2.02E-06	5.99E-01	3.82E+02	1.54E+00
T001-773A-HET	1.12E+02	0.00E+00	8.95E+02	3.30E+03	7.95E+01	2.33E-05	6.90E+00	4.40E+03	1.77E+01
W006-773A-VIT	1.50E-03	0.00E+00	0.00E+00	5.31E+02	0.00E+00	0.00E+00	0.00E+00	5.31E+02	2.14E+00
W026-221F-HET	3.38E+02	0.00E+00	2.70E+03	9.99E+03	2.39E+02	7.01E-05	2.08E+01	1.33E+04	5.36E+01
W026-221H-HET	2.53E+02	0.00E+00	2.02E+03	7.44E+03	1.79E+02	5.25E-05	1.55E+01	9.90E+03	3.99E+01

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W026-235F-HET	3.93E+00	0.00E+00	3.14E+01	1.16E+02	2.79E+00	8.17E-07	2.42E-01	1.54E+02	6.21E-01
W026-772F-HET	1.08E+00	0.00E+00	8.56E+00	3.16E+01	7.59E-01	2.23E-07	6.59E-02	4.20E+01	1.69E-01
W026-773A-HET	1.75E+01	0.00E+00	1.39E+02	5.14E+02	1.24E+01	3.63E-06	1.07E+00	6.85E+02	2.76E+00
W027-221F-HET	1.28E+03	0.00E+00	9.10E+03	3.86E+04	9.26E+02	1.15E-04	8.12E+01	5.00E+04	2.01E+02
W027-221H-HET	5.57E+02	0.00E+00	3.97E+03	1.69E+04	4.05E+02	5.01E-05	3.55E+01	2.19E+04	8.82E+01
W027-235F-HET	1.68E+02	0.00E+00	1.19E+03	5.08E+03	1.22E+02	1.51E-05	1.07E+01	6.58E+03	2.65E+01
W027-772F-HET	3.05E+02	0.00E+00	2.17E+03	9.23E+03	2.22E+02	2.74E-05	1.94E+01	1.20E+04	4.82E+01
W027-773A-HET	4.54E+02	0.00E+00	3.24E+03	1.38E+04	3.30E+02	4.09E-05	2.89E+01	1.78E+04	7.18E+01
W027-999-HET	5.20E+02	0.00E+00	3.70E+03	1.57E+04	3.77E+02	4.67E-05	3.31E+01	2.04E+04	8.21E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.95E+02	0.00E+00	0.00E+00	0.00E+00	3.95E+02	1.59E+00
WP-INW169.001	2.54E+00	0.00E+00	2.33E-02	1.52E+01	3.30E+00	4.12E-07	3.28E-04	2.11E+01	8.51E-02
WP-INW198.001	3.34E+00	0.00E+00	4.07E-02	2.73E+01	5.88E+00	6.77E-07	3.66E-04	3.66E+01	1.47E-01
WP-INW211.001	3.77E+02	0.00E+00	3.82E+00	2.53E+03	5.46E+02	7.66E-05	2.86E-02	3.46E+03	1.39E+01
WP-INW216.001-	1.37E+04	0.00E+00	2.20E+00	1.46E+03	3.17E+02	4.24E-05	2.92E-01	1.55E+04	6.24E+01
WP-INW216.001-	3.76E+03	0.00E+00	5.92E-01	3.97E+02	8.55E+01	1.15E-05	3.17E-02	4.24E+03	1.71E+01
WP-INW218.001-	2.62E+02	0.00E+00	3.87E-01	2.55E+02	5.51E+01	7.66E-06	3.88E-01	5.73E+02	2.31E+00
WP-INW218.001-	1.21E+00	0.00E+00	1.07E-02	6.94E+00	1.50E+00	2.17E-07	3.74E-02	9.69E+00	3.91E-02
WP-INW222.001	1.24E+01	0.00E+00	1.15E-01	6.79E+01	1.48E+01	1.84E-06	1.38E-03	9.51E+01	3.84E-01
WP-INW243.001	3.00E+01	0.00E+00	2.48E-01	1.42E+02	3.11E+01	3.72E-06	2.60E-03	2.04E+02	8.22E-01
WP-INW247.001R	4.01E+01	0.00E+00	5.77E-01	2.73E+02	6.05E+01	6.45E-06	4.10E-03	3.74E+02	1.51E+00
WP-INW276.001	3.06E+00	0.00E+00	5.63E-02	2.70E+01	5.99E+00	5.46E-07	4.09E-04	3.61E+01	1.46E-01
WP-INW276.002	4.85E+00	0.00E+00	8.46E-02	3.97E+01	8.99E+00	8.20E-07	6.17E-04	5.36E+01	2.16E-01
WP-INW276.003	1.86E+02	0.00E+00	3.15E+00	1.47E+03	3.28E+02	3.45E-05	2.24E-02	1.99E+03	8.03E+00
WP-INW276.004	4.44E+01	0.00E+00	6.65E-01	3.12E+02	6.91E+01	7.28E-06	4.78E-03	4.26E+02	1.72E+00
WP-INW296.001-	1.62E+01	0.00E+00	1.58E-01	7.82E+01	1.73E+01	1.87E-06	1.14E-03	1.12E+02	4.51E-01
WP-INW296.001-	4.89E+01	0.00E+00	5.58E-01	2.77E+02	6.11E+01	6.73E-06	4.24E-03	3.88E+02	1.56E+00
WP-LA-TA-55-19	8.15E-01	0.00E+00	2.59E-02	2.07E+00	4.87E-01	6.69E-08	2.82E-03	3.40E+00	1.37E-02
WP-LA-TA-55-19	3.95E+01	0.00E+00	8.71E-01	2.11E+02	5.01E+01	6.65E-06	9.32E-02	3.01E+02	1.22E+00
WP-LA-TA-55-43	2.22E-01	0.00E+00	2.03E+01	3.20E-01	1.32E-01	5.96E-08	1.68E-01	2.11E+01	8.53E-02
WP-RF001.01	6.85E+01	0.00E+00	7.04E-01	4.06E+02	9.00E+01	6.70E-06	1.42E-02	5.65E+02	2.28E+00
WP-RF002.01-A	7.97E+01	0.00E+00	9.39E-01	4.57E+02	1.02E+02	1.48E-05	2.43E-02	6.39E+02	2.58E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF002.01-B	7.91E-02	0.00E+00	6.51E-04	4.95E-01	1.10E-01	9.29E-09	4.73E-06	6.84E-01	2.76E-03
WP-RF003.01	1.24E+03	0.00E+00	1.51E+01	8.73E+03	1.94E+03	2.44E-04	1.14E-01	1.19E+04	4.81E+01
WP-RF004.01	5.81E-01	0.00E+00	1.01E-02	5.03E+00	1.12E+00	1.39E-07	1.98E-04	6.75E+00	2.72E-02
WP-RF005.01	2.98E+03	0.00E+00	7.68E+00	4.62E+03	1.02E+03	9.71E-05	5.54E-02	8.62E+03	3.48E+01
WP-RF005.02	3.50E+03	0.00E+00	3.97E+00	2.76E+03	6.04E+02	4.98E-05	2.89E-02	6.87E+03	2.77E+01
WP-RF006.01	1.14E+03	0.00E+00	1.44E+01	7.85E+03	1.75E+03	1.26E-04	1.26E-01	1.08E+04	4.34E+01
WP-RF008.01	3.61E+02	0.00E+00	5.14E+00	2.30E+03	5.20E+02	8.32E-05	3.71E-02	3.18E+03	1.28E+01
WP-RF009.01	3.55E+04	0.00E+00	6.31E+01	5.03E+04	1.10E+04	9.55E-04	4.61E-01	9.69E+04	3.91E+02
WP-RF010.01	1.31E+01	0.00E+00	1.60E-01	7.61E+01	1.69E+01	2.94E-06	1.85E-03	1.06E+02	4.28E-01
WP-RF029.01-A	3.14E+00	0.00E+00	3.01E-02	1.34E+01	2.98E+00	6.75E-07	9.39E-04	1.95E+01	7.86E-02
WP-RF029.01-B	4.69E+00	0.00E+00	2.38E-02	1.06E+01	2.35E+00	5.34E-07	2.41E-03	1.77E+01	7.12E-02
WP-RF118.01	7.98E+03	0.00E+00	1.20E+02	5.08E+04	1.10E+04	1.76E-03	1.05E+00	7.00E+04	2.82E+02
WP-RLMPDT.001	1.69E+00	0.00E+00	3.50E-02	7.28E+00	1.84E+00	3.85E-07	2.46E-04	1.09E+01	4.38E-02
WP-RLNPDT.002	2.08E+01	0.00E+00	3.33E-01	7.15E+01	1.87E+01	4.42E-06	2.36E-03	1.11E+02	4.49E-01
WP-SR2001.001.	6.62E-01	0.00E+00	3.83E-02	6.76E+00	1.31E+00	2.41E-07	2.72E-04	8.76E+00	3.53E-02
WP-SR-W027-221	4.90E+00	0.00E+00	1.13E-01	1.94E+01	5.27E+00	1.09E-06	1.87E-01	2.99E+01	1.20E-01
Total	2.62E+05	4.13E-03	7.88E+04	6.53E+05	1.03E+05	2.48E-02	7.17E+02	1.10E+06	4.43E+03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	1.74E+01	0.00E+00	5.13E-03	2.03E+02	1.11E+02	6.37E-20	1.96E-02	3.32E+02	1.34E+00
AE-T003	2.21E+00	0.00E+00	6.83E-04	6.27E+01	2.24E+01	3.49E-20	9.61E-04	8.73E+01	3.52E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	9.78E-03	0.00E+00	1.81E-02	4.62E+01	2.58E-01	6.79E-23	2.30E-02	4.65E+01	1.88E-01
AW-T033.1325	3.58E-02	0.00E+00	6.63E-02	1.69E+02	9.41E-01	2.48E-22	8.41E-02	1.70E+02	6.86E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.50E-01	0.00E+00	0.00E+00	0.00E+00	7.50E-01	3.03E-03
BCLCH-MT01	3.61E+00	0.00E+00	5.13E-01	2.79E+01	6.76E+00	9.59E-20	6.37E-01	3.94E+01	1.59E-01
BT-T002	2.65E-03	1.78E-20	2.68E-04	7.04E-04	1.33E-03	4.21E-23	2.32E-03	7.27E-03	2.93E-05
ET-C1-B55	1.11E-02	0.00E+00	3.05E-06	6.03E-02	2.78E-02	7.43E-23	2.39E-04	9.94E-02	4.01E-04
ET-C1-D139	1.52E-03	0.00E+00	4.24E-07	8.47E-03	3.91E-03	9.88E-24	5.88E-07	1.39E-02	5.61E-05
ET-C2-SEFOR	3.76E-02	0.00E+00	0.00E+00	1.33E-01	4.13E-02	1.52E-22	0.00E+00	2.12E-01	8.54E-04
FM-MOX-MT02	3.57E-07	0.00E+00	1.71E-10	2.91E-07	1.60E-07	5.30E-27	2.20E-10	8.09E-07	3.26E-09
FM-MOX-T01	5.89E-06	0.00E+00	2.82E-09	4.80E-06	2.64E-06	8.74E-26	3.64E-09	1.33E-05	5.38E-08
IN-BN-510	1.42E+03	0.00E+00	1.45E+01	3.85E+04	3.02E+03	2.09E-20	2.00E+01	4.30E+04	1.73E+02
IN-GEM-01	1.80E+01	0.00E+00	2.88E-04	4.33E+01	9.14E+00	1.47E-20	3.58E-04	7.04E+01	2.84E-01
IN-GEM-02	4.27E+00	0.00E+00	6.86E-05	1.03E+01	2.18E+00	3.49E-21	8.52E-05	1.67E+01	6.75E-02
IN-W157.144	2.13E+01	0.00E+00	2.79E-03	2.94E+02	6.16E+01	2.61E-19	3.84E-03	3.77E+02	1.52E+00
IN-W163.1007	3.65E+00	0.00E+00	8.61E-04	9.13E+01	1.91E+01	8.04E-20	1.19E-03	1.14E+02	4.60E-01
IN-W164.153	3.49E-02	0.00E+00	8.21E-06	8.69E-01	1.82E-01	7.70E-22	1.13E-05	1.09E+00	4.38E-03
IN-W167.149	6.98E+00	0.00E+00	1.33E-03	1.41E+02	2.95E+01	1.25E-19	1.84E-03	1.77E+02	7.15E-01
IN-W174.154	0.00E+00	0.00E+00	7.55E-01	1.89E+00	3.45E+00	0.00E+00	1.04E+00	7.14E+00	2.88E-02
IN-W177.156	4.85E-03	0.00E+00	1.61E+00	1.78E+00	1.00E-02	1.07E-22	2.21E+00	5.61E+00	2.26E-02
IN-W179.158	3.26E-02	0.00E+00	1.60E+00	1.03E-01	4.95E-02	7.19E-22	2.20E+00	3.98E+00	1.61E-02
IN-W181.162	4.62E-01	0.00E+00	1.09E-04	1.15E+01	2.40E+00	1.02E-20	1.50E-04	1.43E+01	5.77E-02
IN-W188.160	3.11E+00	0.00E+00	7.32E-04	7.74E+01	1.61E+01	6.87E-20	1.01E-03	9.66E+01	3.90E-01
IN-W216.98	2.77E+04	0.00E+00	5.96E-02	6.31E+03	1.33E+03	5.62E-18	8.21E-02	3.53E+04	1.42E+02

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	1.40E+02	0.00E+00	1.33E-03	1.40E+02	2.93E+01	1.24E-19	1.83E-03	3.09E+02	1.25E+00
IN-W219.110	1.90E-01	0.00E+00	4.47E-05	4.72E+00	9.86E-01	4.18E-21	6.15E-05	5.89E+00	2.38E-02
IN-W219.914	2.99E-02	0.00E+00	7.03E-06	7.45E-01	1.56E-01	6.60E-22	9.68E-06	9.30E-01	3.75E-03
IN-W220.114	9.87E+02	0.00E+00	4.70E-03	5.33E+02	1.09E+02	4.39E-19	6.46E-03	1.63E+03	6.57E+00
IN-W221.927	1.16E+00	0.00E+00	2.72E-04	2.87E+01	6.01E+00	2.56E-20	3.75E-04	3.59E+01	1.45E-01
IN-W222.116	3.94E+01	0.00E+00	9.22E-03	9.71E+02	2.04E+02	8.63E-19	1.27E-02	1.21E+03	4.89E+00
IN-W228.101	2.61E+02	0.00E+00	3.00E-03	3.17E+02	6.63E+01	2.82E-19	4.12E-03	6.45E+02	2.60E+00
IN-W240.931	2.76E+01	0.00E+00	3.83E-03	4.08E+02	8.49E+01	3.57E-19	5.28E-03	5.20E+02	2.10E+00
IN-W243.808	3.84E+01	0.00E+00	6.71E-03	7.12E+02	1.49E+02	6.31E-19	9.24E-03	8.99E+02	3.62E+00
IN-W245.301	5.67E+01	0.00E+00	1.32E-02	1.39E+03	2.91E+02	1.23E-18	1.82E-02	1.74E+03	7.00E+00
IN-W247.810	2.76E+01	0.00E+00	6.43E-03	6.79E+02	1.43E+02	6.02E-19	8.84E-03	8.49E+02	3.42E+00
IN-W249.527	0.00E+00	0.00E+00	4.49E-01	1.20E+01	0.00E+00	0.00E+00	6.19E-01	1.31E+01	5.28E-02
IN-W263.520	7.91E-03	0.00E+00	4.70E-02	8.18E+00	1.20E-02	1.74E-22	6.47E-02	8.32E+00	3.35E-02
IN-W267.1005	6.62E+00	0.00E+00	1.56E-03	1.65E+02	3.45E+01	1.46E-19	2.15E-03	2.06E+02	8.31E-01
IN-W309.609	1.77E+02	0.00E+00	2.61E-02	2.76E+03	5.77E+02	2.45E-18	3.60E-02	3.51E+03	1.42E+01
IN-W315.601	1.75E+02	0.00E+00	1.09E-04	1.16E+01	2.41E+00	1.02E-20	1.50E-04	1.89E+02	7.62E-01
IN-W319.584	1.02E+00	0.00E+00	2.39E-04	2.53E+01	5.32E+00	2.25E-20	3.29E-04	3.17E+01	1.28E-01
IN-W321.1023	8.80E+00	0.00E+00	2.07E-03	2.19E+02	4.59E+01	1.94E-19	2.86E-03	2.74E+02	1.11E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	8.85E+00	1.69E+00	0.00E+00	0.00E+00	1.06E+01	4.25E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.36E+01	4.52E+00	0.00E+00	0.00E+00	2.81E+01	1.13E-01
IN-W323.562	1.88E-02	0.00E+00	3.52E-04	2.42E-01	0.00E+00	4.15E-22	4.84E-04	2.61E-01	1.05E-03
IN-W323.951	2.22E-02	0.00E+00	4.18E-06	2.88E-01	0.00E+00	4.90E-22	5.75E-06	3.11E-01	1.25E-03
IN-W332.661	0.00E+00	0.00E+00	4.61E-03	1.25E-01	0.00E+00	0.00E+00	6.35E-03	1.36E-01	5.49E-04
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	2.95E+00	5.65E-01	0.00E+00	0.00E+00	3.52E+00	1.42E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	8.85E+00	1.69E+00	0.00E+00	0.00E+00	1.06E+01	4.25E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.89E+00	0.00E+00	0.00E+00	0.00E+00	1.89E+00	7.63E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.69E+00	0.00E+00	0.00E+00	0.00E+00	5.69E+00	2.29E-02
IN-W342.652	8.70E-01	0.00E+00	0.00E+00	3.90E-02	9.32E-18	0.00E+00	0.00E+00	9.09E-01	3.66E-03
IN-W342.953	5.81E-01	0.00E+00	0.00E+00	2.61E-02	6.26E-18	0.00E+00	0.00E+00	6.07E-01	2.45E-03
IN-W347.818	4.55E-01	0.00E+00	0.00E+00	8.02E+01	1.36E+02	0.00E+00	1.58E-08	2.17E+02	8.75E-01
IN-W348.1012	2.41E-02	0.00E+00	3.80E-03	4.05E+02	8.48E+01	0.00E+00	5.24E-03	4.90E+02	1.97E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.43E-02	0.00E+00	0.00E+00	0.00E+00	2.43E-02	9.79E-05
IN-W357.1022	0.00E+00	0.00E+00	7.49E-06	7.95E-01	1.66E-01	0.00E+00	1.03E-05	9.61E-01	3.87E-03
IN-W358.854	0.00E+00	0.00E+00	1.13E-01	1.83E+00	3.25E+00	0.00E+00	1.48E-01	5.34E+00	2.15E-02
IN-W358.855	0.00E+00	0.00E+00	6.02E-01	9.71E+00	1.73E+01	0.00E+00	7.91E-01	2.84E+01	1.15E-01
IN-W358.948	0.00E+00	0.00E+00	1.26E-01	2.03E+00	3.60E+00	0.00E+00	1.65E-01	5.92E+00	2.39E-02
IN-W361.1021	6.40E-03	0.00E+00	7.26E-04	7.67E+01	1.60E+01	0.00E+00	9.99E-04	9.27E+01	3.74E-01
IN-W362.1020	0.00E+00	0.00E+00	9.51E-03	1.00E+03	2.11E+02	0.00E+00	1.31E-02	1.21E+03	4.88E+00
IN-W363.1019	0.00E+00	0.00E+00	4.47E-04	4.75E+01	9.95E+00	0.00E+00	6.15E-04	5.74E+01	2.32E-01
IN-W364.1011	0.00E+00	0.00E+00	7.38E-04	7.81E+01	1.63E+01	0.00E+00	1.02E-03	9.44E+01	3.81E-01
IN-W365.1010	5.96E+01	0.00E+00	5.85E-04	6.16E+01	1.29E+01	0.00E+00	8.05E-04	1.34E+02	5.41E-01
IN-W366.841	2.12E-01	0.00E+00	4.98E-04	5.25E+01	1.10E+01	0.00E+00	6.86E-04	6.38E+01	2.57E-01
IN-W372.832	8.70E-01	0.00E+00	0.00E+00	3.90E-02	9.32E-18	0.00E+00	0.00E+00	9.09E-01	3.66E-03
IN-W375.1096	0.00E+00	0.00E+00	1.84E-04	1.94E+01	4.06E+00	0.00E+00	2.53E-04	2.35E+01	9.47E-02
KN-B234TRU	3.09E+01	0.00E+00	7.03E-03	2.83E+02	8.78E+01	1.37E-19	1.07E-02	4.01E+02	1.62E+00
LA-IT-00-01	4.49E-01	1.14E-17	1.20E-03	5.68E-01	1.14E-02	2.62E-29	1.84E-03	1.03E+00	4.16E-03
LA-OS-00-01	1.00E+03	0.00E+00	5.47E+01	1.19E+03	0.00E+00	0.00E+00	6.85E+01	2.32E+03	9.34E+00
LA-PX-00-01	4.17E-03	0.00E+00	2.31E-06	8.79E-02	1.91E-02	4.34E-23	3.01E-06	1.11E-01	4.48E-04
LA-SL-00-01	0.00E+00	0.00E+00	4.87E-05	1.49E-01	0.00E+00	0.00E+00	7.43E-05	1.49E-01	5.99E-04
LA-TA-03-12	4.29E-02	0.00E+00	1.13E-03	4.23E-01	1.36E-01	2.57E-22	1.78E-03	6.05E-01	2.44E-03
LA-TA-03-13	5.54E-02	0.00E+00	3.57E-03	6.61E-01	1.43E-01	3.41E-22	4.97E-03	8.69E-01	3.50E-03
LA-TA-03-19	1.12E-01	0.00E+00	5.33E-03	1.29E+00	3.45E-01	5.27E-22	8.41E-03	1.76E+00	7.10E-03
LA-TA-03-20	6.11E-02	0.00E+00	2.53E-03	5.69E-01	1.86E-01	4.31E-22	3.83E-03	8.22E-01	3.31E-03
LA-TA-03-24	8.20E-02	0.00E+00	9.85E-03	1.06E+00	2.97E-01	4.47E-22	1.56E-02	1.46E+00	5.90E-03
LA-TA-03-26	4.20E-03	0.00E+00	4.06E-04	2.56E+00	3.88E-02	3.92E-23	1.51E-03	2.61E+00	1.05E-02
LA-TA-03-28	0.00E+00	0.00E+00	1.41E-04	2.40E-01	0.00E+00	0.00E+00	2.20E-04	2.40E-01	9.68E-04
LA-TA-03-30	1.87E-01	0.00E+00	1.00E-04	4.88E+00	1.31E+00	2.05E-21	1.55E-04	6.38E+00	2.57E-02
LA-TA-03-31	0.00E+00	0.00E+00	5.01E-06	8.54E-03	0.00E+00	0.00E+00	7.83E-06	8.56E-03	3.45E-05
LA-TA-03-40	0.00E+00	0.00E+00	7.92E-06	5.31E-02	0.00E+00	0.00E+00	1.25E-05	5.31E-02	2.14E-04
LA-TA-03-42	4.29E-06	0.00E+00	1.99E-07	3.32E-03	4.04E-05	4.29E-26	3.13E-07	3.37E-03	1.36E-05
LA-TA-21-06	4.23E-02	0.00E+00	2.18E-02	9.29E-01	2.63E-01	4.42E-22	3.41E-02	1.29E+00	5.20E-03
LA-TA-21-12	1.54E-01	0.00E+00	1.32E-01	3.22E+00	8.91E-01	1.52E-21	2.06E-01	4.61E+00	1.86E-02

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-13	2.37E-01	0.00E+00	0.00E+00	2.85E-01	0.00E+00	0.00E+00	0.00E+00	5.22E-01	2.11E-03
LA-TA-21-14	3.89E-05	0.00E+00	2.51E-03	4.36E+00	4.71E-05	6.15E-25	3.30E-03	4.36E+00	1.76E-02
LA-TA-21-15	2.30E-02	0.00E+00	6.91E-06	1.35E+00	2.13E-01	2.50E-22	1.07E-05	1.59E+00	6.39E-03
LA-TA-21-16	2.66E-01	0.00E+00	1.07E-04	1.03E+01	2.28E+00	2.63E-21	1.68E-04	1.28E+01	5.17E-02
LA-TA-21-40	3.38E-05	0.00E+00	3.69E-04	3.23E-01	3.31E-04	1.06E-25	7.08E-04	3.25E-01	1.31E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	6.88E-01	0.00E+00	0.00E+00	0.00E+00	6.88E-01	2.78E-03
LA-TA-21-42	3.45E-03	0.00E+00	1.20E-04	1.59E-01	1.00E-02	3.44E-24	2.45E-04	1.73E-01	6.98E-04
LA-TA-21-43	1.22E+01	0.00E+00	3.98E-03	4.96E+02	1.09E+02	2.72E-20	8.07E-03	6.18E+02	2.49E+00
LA-TA-21-44	5.84E-02	0.00E+00	8.36E-04	1.12E+02	2.75E-01	3.84E-22	1.41E-03	1.12E+02	4.52E-01
LA-TA-48-01	1.89E-02	5.39E-17	3.14E-06	1.15E-01	4.44E-01	3.17E-23	6.08E-06	5.77E-01	2.33E-03
LA-TA-49-01	2.33E+00	6.69E-15	3.86E-04	1.42E+01	5.50E+01	3.92E-21	7.50E-04	7.15E+01	2.88E-01
LA-TA-50-10	6.25E-03	0.00E+00	3.66E-06	4.46E-02	0.00E+00	0.00E+00	4.73E-06	5.08E-02	2.05E-04
LA-TA-50-11	1.19E-02	0.00E+00	3.75E-06	4.52E-01	9.32E-02	3.14E-23	7.13E-06	5.58E-01	2.25E-03
LA-TA-50-15	2.35E-02	0.00E+00	5.53E-04	3.30E-01	6.86E-02	1.24E-22	8.08E-04	4.24E-01	1.71E-03
LA-TA-50-17	3.44E+00	0.00E+00	4.49E-04	1.77E+01	3.85E-04	1.14E-23	9.95E-04	2.11E+01	8.51E-02
LA-TA-50-18	2.05E-01	0.00E+00	5.94E-05	2.88E+00	4.80E-06	3.36E-25	9.35E-05	3.09E+00	1.25E-02
LA-TA-50-19	6.53E-02	0.00E+00	2.65E-05	3.83E-01	4.11E-03	4.15E-24	6.84E-05	4.53E-01	1.83E-03
LA-TA-50-20	1.79E-03	0.00E+00	0.00E+00	9.46E-03	0.00E+00	0.00E+00	0.00E+00	1.13E-02	4.53E-05
LA-TA-50-40	1.01E-03	0.00E+00	3.57E-07	1.03E-02	4.46E-03	1.33E-23	5.37E-07	1.58E-02	6.35E-05
LA-TA-50-41	1.08E-03	0.00E+00	3.60E-07	4.56E-02	9.86E-03	2.37E-23	4.96E-07	5.66E-02	2.28E-04
LA-TA-55-19	1.67E+00	0.00E+00	4.75E-04	2.56E+01	6.70E+00	1.34E-20	2.26E-03	3.40E+01	1.37E-01
LA-TA-55-20	2.68E+01	0.00E+00	5.42E-03	6.19E+02	1.38E+02	3.36E-19	1.01E-01	7.84E+02	3.16E+00
LA-TA-55-21	2.39E-01	1.59E-20	6.22E-05	4.39E+00	9.77E-01	2.77E-21	8.50E-05	5.60E+00	2.26E-02
LA-TA-55-22	6.55E-01	0.00E+00	3.52E-04	1.54E+01	3.35E+00	8.58E-21	4.80E-04	1.94E+01	7.84E-02
LA-TA-55-23	6.18E-01	0.00E+00	2.94E-04	1.06E+01	2.43E+00	8.44E-21	3.98E-04	1.36E+01	5.50E-02
LA-TA-55-24	2.33E-01	0.00E+00	4.61E-05	5.55E+00	1.20E+00	4.02E-21	6.00E-05	6.99E+00	2.82E-02
LA-TA-55-25	1.19E+00	0.00E+00	2.69E-04	2.76E+01	5.98E+00	2.06E-20	3.50E-04	3.47E+01	1.40E-01
LA-TA-55-28	4.06E-01	0.00E+00	1.49E-04	8.47E+00	1.86E+00	6.68E-21	1.96E-04	1.07E+01	4.33E-02
LA-TA-55-30	9.05E+00	1.51E-22	1.78E-03	1.39E+02	3.11E+01	4.90E-20	2.99E-03	1.79E+02	7.22E-01
LA-TA-55-32	7.34E-01	0.00E+00	9.97E-03	1.10E+01	3.15E+00	6.10E-21	1.59E-02	1.49E+01	6.00E-02
LA-TA-55-33	1.10E-01	0.00E+00	2.57E-05	1.45E+00	4.29E-01	8.58E-22	3.83E-05	1.99E+00	8.00E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-34	1.11E+01	0.00E+00	2.38E-03	2.24E+02	5.29E+01	1.03E-19	6.32E-03	2.88E+02	1.16E+00
LA-TA-55-38	2.79E+01	0.00E+00	7.84E-04	4.95E+01	1.24E+01	2.41E-20	2.86E-03	8.98E+01	3.62E-01
LA-TA-55-39	2.95E+00	0.00E+00	5.79E-04	7.39E+01	1.54E+01	4.23E-20	7.78E-04	9.22E+01	3.72E-01
LA-TA-55-41	7.03E+01	0.00E+00	1.20E-03	9.16E+01	2.04E+01	5.33E-20	1.65E-03	1.82E+02	7.35E-01
LA-TA-55-43	2.64E-02	0.00E+00	7.87E-02	1.38E-01	4.48E-02	4.69E-22	1.05E-01	3.93E-01	1.58E-03
LA-TA-55-44	2.29E-01	0.00E+00	1.85E-01	2.55E+00	6.58E-01	1.39E-21	2.78E-01	3.90E+00	1.57E-02
LA-TA-55-48	1.69E+03	0.00E+00	7.32E-01	1.64E+04	5.68E+03	1.45E-17	1.07E+00	2.38E+04	9.59E+01
LA-TA-55-49	3.61E+00	0.00E+00	9.62E-01	3.00E+01	7.83E+00	1.69E-20	1.43E+00	4.38E+01	1.77E-01
LA-TA-55-53	1.70E+01	0.00E+00	1.99E-03	2.56E+02	5.56E+01	9.27E-20	2.93E-03	3.29E+02	1.33E+00
LA-TA-55-56	1.88E+01	0.00E+00	7.40E-02	3.71E+02	8.64E+01	2.14E-19	1.04E-01	4.76E+02	1.92E+00
LA-TA-55-60	1.02E-02	0.00E+00	1.87E-05	6.99E-02	2.30E-02	1.26E-22	2.79E-05	1.03E-01	4.16E-04
LA-TA-55-61	8.79E-03	0.00E+00	8.61E-05	1.35E-01	4.25E-02	1.23E-22	1.26E-04	1.86E-01	7.52E-04
LA-TA-55-62	2.28E-03	0.00E+00	8.18E-07	2.26E-02	1.00E-02	3.30E-23	1.21E-06	3.49E-02	1.41E-04
LA-TA-55-63	1.69E-03	0.00E+00	5.53E-07	7.25E-02	1.56E-02	3.25E-23	7.80E-07	8.98E-02	3.62E-04
LL-M001	2.32E+01	7.23E-16	2.41E-02	6.80E+01	2.85E+01	2.57E-19	3.00E-02	1.20E+02	4.83E-01
LL-T001	1.16E+02	0.00E+00	0.00E+00	5.18E+02	2.17E+02	1.99E-18	0.00E+00	8.51E+02	3.43E+00
LL-T002	1.14E+03	0.00E+00	1.92E-01	5.03E+03	1.92E+03	1.75E-17	2.38E-01	8.09E+03	3.26E+01
LL-T003	4.45E+01	0.00E+00	2.15E-02	1.02E+02	7.64E+01	6.92E-19	2.67E-02	2.23E+02	8.98E-01
LL-T004	2.83E+01	0.00E+00	4.41E-03	6.48E+01	4.81E+01	4.39E-19	5.48E-03	1.41E+02	5.69E-01
LL-T005	1.46E+02	3.15E-14	5.19E-02	2.41E+02	1.93E+02	1.63E-18	6.44E-02	5.80E+02	2.34E+00
LL-W018	1.24E-02	0.00E+00	0.00E+00	1.80E-02	3.84E-02	3.33E-22	0.00E+00	6.87E-02	2.77E-04
LL-W019	6.73E+00	0.00E+00	0.00E+00	1.40E+01	1.09E+01	9.75E-20	0.00E+00	3.16E+01	1.27E-01
LL-W034	2.49E+00	5.32E-16	9.08E-04	4.08E+00	3.20E+00	2.77E-20	1.13E-03	9.77E+00	3.94E-02
MC-W001	3.11E-02	0.00E+00	0.00E+00	5.88E-02	0.00E+00	5.01E-23	0.00E+00	8.99E-02	3.62E-04
MU-W002	4.15E-01	0.00E+00	0.00E+00	5.11E-02	0.00E+00	0.00E+00	2.66E-12	4.66E-01	1.88E-03
NT-JAS-01	4.01E+01	0.00E+00	1.93E-02	9.20E+01	6.88E+01	6.23E-19	2.40E-02	2.01E+02	8.10E-01
NT-W001	6.01E+01	1.63E-17	3.86E-02	2.78E+03	1.72E+01	4.37E-20	5.95E-02	2.85E+03	1.15E+01
NT-W021	1.16E+00	0.00E+00	2.77E-04	3.13E+01	6.62E+00	2.23E-20	3.90E-04	3.90E+01	1.57E-01
OR-W201	1.40E+03	1.12E-15	8.30E-01	2.10E+03	1.92E+03	2.34E-17	4.45E+01	5.46E+03	2.20E+01
OR-W202	2.00E+02	2.34E-14	2.39E+00	5.38E+02	4.90E+02	7.51E-19	3.42E+00	1.23E+03	4.97E+00
OR-W203	4.41E-01	8.14E-16	3.43E-04	2.42E-02	1.60E+00	1.91E-21	4.87E-04	2.06E+00	8.32E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
OR-W204	9.82E-02	3.37E-21	3.89E-04	4.12E-01	2.58E-01	0.00E+00	5.53E-04	7.69E-01	3.10E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.14E-01	0.00E+00	0.00E+00	0.00E+00	4.14E-01	1.67E-03
RF-MT0001	3.77E+02	0.00E+00	2.41E-03	1.90E+02	4.03E+01	1.72E-19	3.30E-03	6.07E+02	2.45E+00
RF-MT0002	2.90E+01	0.00E+00	1.85E-04	1.47E+01	3.09E+00	1.32E-20	2.53E-04	4.67E+01	1.89E-01
RF-MT0003	1.32E-01	0.00E+00	4.24E-05	3.35E+00	7.08E-01	3.01E-21	5.79E-05	4.19E+00	1.69E-02
RF-MT0007	3.32E-01	0.00E+00	0.00E+00	4.17E-01	8.81E-02	3.49E-22	0.00E+00	8.37E-01	3.38E-03
RF-MT0089	1.30E-03	0.00E+00	4.24E-07	3.35E-02	7.07E-03	3.01E-23	5.79E-07	4.19E-02	1.69E-04
RF-MT0090	3.31E+00	0.00E+00	5.99E-04	8.60E+01	1.80E+01	3.01E-20	8.19E-04	1.07E+02	4.33E-01
RF-MT0091	2.05E+02	0.00E+00	6.08E-02	5.75E+03	1.21E+03	2.49E-18	8.61E-02	7.16E+03	2.89E+01
RF-MT0092	2.93E+01	0.00E+00	7.66E-03	8.23E+02	1.77E+02	3.44E-19	1.05E-02	1.03E+03	4.15E+00
RF-MT0093	3.57E+01	0.00E+00	7.89E-03	8.88E+02	1.94E+02	2.93E-19	1.08E-02	1.12E+03	4.51E+00
RF-MT0097	1.79E+00	0.00E+00	3.49E-04	4.64E+01	8.80E+00	1.60E-20	4.76E-04	5.70E+01	2.30E-01
RF-MT0099	1.96E-03	0.00E+00	6.37E-07	5.02E-02	1.06E-02	4.53E-23	8.70E-07	6.27E-02	2.53E-04
RF-MT0290	4.86E+00	0.00E+00	1.58E-03	1.24E+02	2.63E+01	1.12E-19	2.15E-03	1.55E+02	6.27E-01
RF-MT-0292	6.12E+00	0.00E+00	1.99E-03	1.57E+02	3.32E+01	1.42E-19	2.72E-03	1.97E+02	7.93E-01
RF-MT-0299	7.21E+02	0.00E+00	5.10E-02	4.03E+03	8.52E+02	3.65E-18	6.97E-02	5.60E+03	2.26E+01
RF-MT0302	1.10E-02	0.00E+00	2.02E-06	1.74E-01	3.68E-02	1.42E-22	1.96E-05	2.22E-01	8.94E-04
RF-MT0320	1.32E+01	0.00E+00	2.10E-03	1.69E+02	3.58E+01	1.43E-19	2.87E-03	2.18E+02	8.79E-01
RF-MT0321	7.37E+00	0.00E+00	6.25E-04	5.44E+01	1.14E+01	4.00E-20	3.26E-03	7.31E+01	2.95E-01
RF-MT-0328	5.10E-01	0.00E+00	7.49E-05	5.91E+00	1.25E+00	5.33E-21	4.40E-04	7.67E+00	3.09E-02
RF-MT0330	5.31E+00	0.00E+00	8.21E-04	1.19E+02	2.73E+01	5.01E-20	1.12E-03	1.52E+02	6.13E-01
RF-MT-0331	3.18E+01	0.00E+00	5.10E-03	5.25E+02	1.09E+02	2.90E-19	2.77E-02	6.66E+02	2.68E+00
RF-MT0332	4.56E-03	0.00E+00	1.49E-06	1.18E-01	2.47E-02	1.06E-22	2.03E-06	1.47E-01	5.92E-04
RF-MT-0335	3.67E-01	0.00E+00	6.83E-05	6.05E+00	1.28E+00	4.31E-21	6.34E-04	7.70E+00	3.10E-02
RF-MT0336	2.59E+01	0.00E+00	4.52E-03	4.29E+02	9.05E+01	2.53E-19	7.99E-03	5.46E+02	2.20E+00
RF-MT0337	1.47E+01	0.00E+00	2.49E-03	2.62E+02	5.44E+01	1.24E-19	7.24E-03	3.31E+02	1.34E+00
RF-MT0339	4.01E+01	0.00E+00	6.77E-03	5.75E+02	1.20E+02	4.47E-19	2.63E-02	7.35E+02	2.96E+00
RF-MT-0342	2.36E-01	0.00E+00	5.68E-05	5.31E+00	1.10E+00	3.28E-21	1.36E-04	6.65E+00	2.68E-02
RF-MT0371	7.97E+01	0.00E+00	1.31E-02	1.04E+03	2.19E+02	9.35E-19	1.92E-02	1.34E+03	5.39E+00
RF-MT-0372	3.47E-01	0.00E+00	9.25E-05	7.24E+00	1.53E+00	5.78E-21	3.65E-04	9.12E+00	3.68E-02
RF-MT0373	5.23E+00	0.00E+00	9.51E-04	1.36E+02	2.85E+01	4.77E-20	1.30E-03	1.70E+02	6.84E-01

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0374	1.70E-01	0.00E+00	3.40E-05	2.69E+00	5.67E-01	2.42E-21	4.97E-05	3.43E+00	1.38E-02
RF-MT0376	1.35E-01	0.00E+00	2.75E-05	2.68E+00	5.75E-01	1.78E-21	5.26E-05	3.39E+00	1.37E-02
RF-MT0377	8.00E+01	0.00E+00	1.58E-02	1.25E+03	2.64E+02	1.12E-18	3.18E-02	1.60E+03	6.44E+00
RF-MT0378	8.99E-01	0.00E+00	2.19E-04	1.73E+01	3.65E+00	1.56E-20	2.99E-04	2.18E+01	8.80E-02
RF-MT0419	1.44E+00	0.00E+00	2.04E-04	1.61E+01	3.41E+00	1.45E-20	2.79E-04	2.10E+01	8.45E-02
RF-MT0420	2.51E-01	0.00E+00	3.54E-05	2.80E+00	5.92E-01	2.53E-21	4.84E-05	3.64E+00	1.47E-02
RF-MT0423	2.13E+00	0.00E+00	2.88E-04	4.04E+01	8.27E+00	1.00E-20	3.94E-04	5.08E+01	2.05E-01
RF-MT0425	6.28E-02	0.00E+00	8.87E-06	7.00E-01	1.48E-01	6.31E-22	1.21E-05	9.11E-01	3.67E-03
RF-MT-0438	5.70E-01	0.00E+00	1.16E-04	1.24E+01	2.60E+00	6.26E-21	1.72E-04	1.56E+01	6.29E-02
RF-MT0440	2.07E-01	0.00E+00	4.18E-05	4.50E+00	9.68E-01	2.58E-21	2.21E-04	5.68E+00	2.29E-02
RF-MT0442	7.87E-02	0.00E+00	1.81E-05	1.54E+00	3.25E-01	9.56E-22	1.19E-04	1.95E+00	7.85E-03
RF-MT0443	9.69E-01	0.00E+00	2.97E-04	2.40E+01	5.06E+00	2.00E-20	5.63E-04	3.00E+01	1.21E-01
RF-MT0444	7.56E+00	0.00E+00	1.46E-03	1.16E+02	2.43E+01	1.03E-19	2.01E-03	1.47E+02	5.94E-01
RF-MT0480	2.12E+01	0.00E+00	4.09E-03	3.24E+02	6.86E+01	2.66E-19	8.04E-03	4.14E+02	1.67E+00
RF-MT0488	3.39E+01	0.00E+00	6.11E-03	4.82E+02	1.01E+02	4.34E-19	3.92E-02	6.17E+02	2.49E+00
RF-MT0490	1.54E-01	0.00E+00	3.54E-05	2.84E+00	6.02E-01	2.40E-21	5.96E-05	3.60E+00	1.45E-02
RF-MT-0491	1.20E-02	0.00E+00	1.62E-06	1.29E-01	2.72E-02	1.12E-22	4.22E-06	1.68E-01	6.79E-04
RF-MT0523A	9.54E+00	0.00E+00	1.29E-03	1.02E+02	2.15E+01	9.13E-20	2.01E-03	1.33E+02	5.36E-01
RF-MT0523B	9.54E+00	0.00E+00	1.29E-03	1.02E+02	2.15E+01	9.13E-20	2.01E-03	1.33E+02	5.36E-01
RF-MT0523C	9.54E+00	0.00E+00	1.29E-03	1.02E+02	2.15E+01	9.13E-20	2.01E-03	1.33E+02	5.36E-01
RF-MT0523D	9.54E+00	0.00E+00	1.29E-03	1.02E+02	2.15E+01	9.13E-20	2.01E-03	1.33E+02	5.36E-01
RF-MT0523E	9.54E+00	0.00E+00	1.29E-03	1.02E+02	2.15E+01	9.13E-20	2.01E-03	1.33E+02	5.36E-01
RF-MT0531	6.52E-04	0.00E+00	2.12E-07	1.67E-02	3.53E-03	1.51E-23	2.90E-07	2.09E-02	8.42E-05
RF-MT0532E	3.04E+01	0.00E+00	2.76E-03	2.22E+02	4.69E+01	1.95E-19	4.87E-03	3.00E+02	1.21E+00
RF-MT0532F	3.04E+01	0.00E+00	2.76E-03	2.22E+02	4.69E+01	1.95E-19	4.87E-03	3.00E+02	1.21E+00
RF-MT0541	1.11E+00	0.00E+00	3.98E-05	3.16E+00	6.65E-01	2.85E-21	5.43E-05	4.93E+00	1.99E-02
RF-MT0545	5.93E-03	0.00E+00	1.93E-06	1.52E-01	3.21E-02	1.37E-22	2.63E-06	1.90E-01	7.68E-04
RF-MT0800	2.25E+02	0.00E+00	9.54E-04	7.52E+01	1.59E+01	6.79E-20	1.79E-03	3.16E+02	1.28E+00
RF-MT0801	2.59E+01	0.00E+00	9.34E-04	7.39E+01	1.56E+01	6.63E-20	1.28E-03	1.15E+02	4.65E-01
RF-MT0803	5.81E-01	0.00E+00	2.09E-05	1.65E+00	3.48E-01	1.49E-21	2.85E-05	2.58E+00	1.04E-02
RF-MT0806	2.74E-01	0.00E+00	5.01E-05	7.17E+00	1.50E+00	2.51E-21	6.85E-05	8.95E+00	3.61E-02

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0807	3.47E+00	0.00E+00	3.86E-04	3.05E+01	6.45E+00	2.74E-20	5.27E-04	4.04E+01	1.63E-01
RF-MT0816	3.71E-01	0.00E+00	5.45E-05	4.30E+00	9.05E-01	3.89E-21	7.44E-05	5.58E+00	2.25E-02
RF-MT-0823	1.84E-01	0.00E+00	2.48E-05	1.96E+00	4.14E-01	1.76E-21	3.88E-05	2.56E+00	1.03E-02
RF-MT0827	9.36E+00	0.00E+00	1.38E-03	1.09E+02	2.30E+01	9.80E-20	1.88E-03	1.41E+02	5.69E-01
RF-MT0831	1.79E+01	0.00E+00	3.77E-03	2.94E+02	6.22E+01	2.58E-19	1.74E-02	3.74E+02	1.51E+00
RF-MT0832	1.07E+02	0.00E+00	1.37E-02	1.15E+03	2.41E+02	9.21E-19	5.20E-02	1.49E+03	6.02E+00
RF-MT0833	3.25E+01	0.00E+00	4.09E-03	3.31E+02	6.99E+01	2.77E-19	1.47E-02	4.33E+02	1.75E+00
RF-MT0855	5.59E-03	0.00E+00	1.82E-06	1.44E-01	3.03E-02	1.29E-22	2.48E-06	1.80E-01	7.24E-04
RF-MT0857	2.74E-01	0.00E+00	4.98E-05	7.15E+00	1.50E+00	2.51E-21	6.81E-05	8.93E+00	3.60E-02
RF-MT0H61	1.02E+01	0.00E+00	1.85E-03	2.65E+02	5.56E+01	9.29E-20	2.53E-03	3.31E+02	1.33E+00
RF-MT2116	1.14E+00	0.00E+00	1.47E-04	1.22E+01	2.58E+00	9.88E-21	5.57E-04	1.60E+01	6.44E-02
RF-MT3010	7.17E+00	0.00E+00	1.53E-03	1.21E+02	2.58E+01	1.06E-19	2.48E-03	1.54E+02	6.22E-01
RF-MT3011	5.34E+01	0.00E+00	9.51E-03	7.49E+02	1.59E+02	6.76E-19	2.07E-02	9.62E+02	3.88E+00
RF-MT420P	2.84E+02	0.00E+00	4.81E-02	6.16E+03	1.30E+03	2.21E-18	7.57E-02	7.75E+03	3.12E+01
RF-MT532A	7.49E+01	0.00E+00	6.80E-03	5.49E+02	1.16E+02	4.79E-19	1.20E-02	7.40E+02	2.98E+00
RF-MT532B	3.36E+02	0.00E+00	3.05E-02	2.47E+03	5.20E+02	2.16E-18	5.39E-02	3.32E+03	1.34E+01
RF-MT532C	6.74E+02	0.00E+00	6.14E-02	4.94E+03	1.04E+03	4.31E-18	1.08E-01	6.66E+03	2.68E+01
RF-MT532D	4.26E+00	0.00E+00	3.86E-04	3.13E+01	6.58E+00	2.72E-20	6.82E-04	4.21E+01	1.70E-01
RF-TT0069	2.45E-02	0.00E+00	4.58E-06	3.62E-01	7.65E-02	3.28E-22	7.96E-05	4.63E-01	1.87E-03
RF-TT0200	1.16E+00	0.00E+00	1.85E-04	1.49E+01	3.16E+00	1.26E-20	2.54E-04	1.92E+01	7.73E-02
RF-TT0299	4.83E+00	0.00E+00	3.43E-04	2.71E+01	5.72E+00	2.44E-20	4.68E-04	3.76E+01	1.52E-01
RF-TT0300	3.93E+01	0.00E+00	9.77E-03	7.78E+02	1.65E+02	5.94E-19	2.17E-02	9.82E+02	3.96E+00
RF-TT0301	5.31E+00	0.00E+00	1.33E-03	1.06E+02	2.24E+01	8.04E-20	2.94E-03	1.34E+02	5.38E-01
RF-TT0302	2.63E-01	0.00E+00	4.81E-05	4.14E+00	8.75E-01	3.38E-21	4.64E-04	5.27E+00	2.13E-02
RF-TT0303	1.58E+00	0.00E+00	2.81E-04	2.22E+01	4.69E+00	2.00E-20	1.42E-03	2.85E+01	1.15E-01
RF-TT0310	5.39E+00	0.00E+00	1.32E-03	1.00E+02	2.18E+01	7.32E-20	1.99E-03	1.27E+02	5.13E-01
RF-TT0312	1.29E+02	0.00E+00	2.38E-02	2.18E+03	4.57E+02	1.54E-18	3.43E-02	2.77E+03	1.12E+01
RF-TT0317	8.13E-02	0.00E+00	2.59E-05	2.05E+00	4.32E-01	1.84E-21	3.54E-05	2.56E+00	1.03E-02
RF-TT0320	5.22E+01	0.00E+00	8.30E-03	6.68E+02	1.42E+02	5.65E-19	1.14E-02	8.62E+02	3.47E+00
RF-TT0330	1.86E+01	0.00E+00	2.87E-03	4.19E+02	9.50E+01	1.75E-19	3.92E-03	5.33E+02	2.15E+00
RF-TT-0331	9.24E+01	0.00E+00	1.48E-02	1.52E+03	3.16E+02	8.44E-19	8.04E-02	1.93E+03	7.79E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT-0334	4.02E+01	0.00E+00	1.20E-02	9.47E+02	2.00E+02	8.55E-19	1.64E-02	1.19E+03	4.79E+00
RF-TT0335	4.90E+01	0.00E+00	9.10E-03	8.06E+02	1.71E+02	5.75E-19	8.45E-02	1.03E+03	4.14E+00
RF-TT0336	4.33E+01	0.00E+00	7.55E-03	7.14E+02	1.51E+02	4.21E-19	1.33E-02	9.07E+02	3.66E+00
RF-TT0337	5.14E+01	0.00E+00	8.73E-03	9.21E+02	1.91E+02	4.34E-19	2.54E-02	1.16E+03	4.69E+00
RF-TT0338	2.18E+02	0.00E+00	3.17E-02	3.59E+03	7.46E+02	1.94E-18	5.15E-02	4.56E+03	1.84E+01
RF-TT0340	1.87E+00	0.00E+00	6.05E-04	4.78E+01	1.01E+01	4.31E-20	8.26E-04	5.98E+01	2.41E-01
RF-TT0342	1.25E+01	0.00E+00	3.03E-03	2.82E+02	5.84E+01	1.73E-19	7.23E-03	3.52E+02	1.42E+00
RF-TT0360	9.51E-01	0.00E+00	1.54E-04	1.26E+01	2.70E+00	1.03E-20	2.16E-04	1.63E+01	6.56E-02
RF-TT0368	1.90E+01	0.00E+00	3.08E-03	2.53E+02	5.41E+01	2.05E-19	4.33E-03	3.26E+02	1.32E+00
RF-TT0370	3.76E+01	0.00E+00	6.66E-03	5.64E+02	1.19E+02	4.37E-19	1.69E-02	7.21E+02	2.91E+00
RF-TT0371	8.13E-01	0.00E+00	1.34E-04	1.06E+01	2.23E+00	9.53E-21	1.96E-04	1.36E+01	5.49E-02
RF-TT0372	9.93E-02	0.00E+00	2.64E-05	2.07E+00	4.37E-01	1.65E-21	1.04E-04	2.60E+00	1.05E-02
RF-TT0374	3.09E+00	0.00E+00	6.19E-04	4.88E+01	1.03E+01	4.39E-20	9.06E-04	6.22E+01	2.51E-01
RF-TT0375A	3.22E-02	0.00E+00	1.02E-05	8.03E-01	1.69E-01	7.24E-22	1.39E-05	1.00E+00	4.05E-03
RF-TT0375B	3.22E-02	0.00E+00	1.02E-05	8.03E-01	1.69E-01	7.24E-22	1.39E-05	1.00E+00	4.05E-03
RF-TT0376	7.41E+00	0.00E+00	1.51E-03	1.48E+02	3.16E+01	9.80E-20	2.89E-03	1.87E+02	7.52E-01
RF-TT0377	4.16E+00	0.00E+00	8.21E-04	6.48E+01	1.37E+01	5.83E-20	1.65E-03	8.27E+01	3.34E-01
RF-TT0391	9.27E-01	0.00E+00	1.16E-04	1.64E+01	3.42E+00	1.02E-20	1.58E-04	2.08E+01	8.37E-02
RF-TT0392	3.27E-01	0.00E+00	7.26E-05	8.57E+00	1.80E+00	3.54E-21	9.93E-05	1.07E+01	4.31E-02
RF-TT0393	2.68E+01	0.00E+00	5.07E-03	3.99E+02	8.44E+01	3.60E-19	6.92E-03	5.10E+02	2.06E+00
RF-TT0398	5.86E-01	0.00E+00	1.34E-04	1.60E+01	3.35E+00	6.68E-21	1.83E-04	2.00E+01	8.05E-02
RF-TT0409	4.90E-01	0.00E+00	6.25E-05	8.27E+00	1.73E+00	2.57E-21	8.60E-05	1.05E+01	4.23E-02
RF-TT0412	4.90E-01	0.00E+00	6.25E-05	8.27E+00	1.73E+00	2.57E-21	8.60E-05	1.05E+01	4.23E-02
RF-TT0414	1.52E+01	0.00E+00	1.93E-03	2.56E+02	5.35E+01	7.96E-20	2.66E-03	3.25E+02	1.31E+00
RF-TT0430	4.44E-03	0.00E+00	1.44E-06	1.14E-01	2.40E-02	1.03E-22	1.97E-06	1.42E-01	5.73E-04
RF-TT0431	1.10E+00	0.00E+00	3.52E-04	2.80E+01	5.91E+00	2.44E-20	7.02E-04	3.50E+01	1.41E-01
RF-TT0438	6.56E+01	0.00E+00	1.34E-02	1.43E+03	2.99E+02	7.22E-19	1.98E-02	1.79E+03	7.23E+00
RF-TT0440	6.47E+00	0.00E+00	1.30E-03	1.41E+02	3.04E+01	8.07E-20	6.93E-03	1.78E+02	7.16E-01
RF-TT0441	3.18E+01	0.00E+00	6.11E-03	4.86E+02	1.03E+02	4.29E-19	1.30E-02	6.21E+02	2.51E+00
RF-TT0442	4.59E+00	0.00E+00	1.05E-03	9.00E+01	1.90E+01	5.59E-20	6.95E-03	1.14E+02	4.58E-01
RF-TT0443	9.84E-02	0.00E+00	3.03E-05	2.44E+00	5.14E-01	2.02E-21	5.73E-05	3.05E+00	1.23E-02

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0479	9.63E-01	0.00E+00	3.14E-04	2.47E+01	5.22E+00	2.23E-20	4.29E-04	3.08E+01	1.24E-01
RF-TT0480	6.56E+01	0.00E+00	1.27E-02	1.01E+03	2.12E+02	8.28E-19	2.49E-02	1.29E+03	5.19E+00
RF-TT0481	3.69E-02	0.00E+00	7.15E-06	5.67E-01	1.20E-01	4.66E-22	1.41E-05	7.24E-01	2.92E-03
RF-TT0483	1.19E-01	0.00E+00	3.86E-05	3.04E+00	6.43E-01	2.74E-21	1.72E-02	3.82E+00	1.54E-02
RF-TT0484	6.35E-01	0.00E+00	1.60E-04	1.26E+01	2.67E+00	1.14E-20	3.29E-04	1.59E+01	6.42E-02
RF-TT0485	5.22E-02	0.00E+00	9.88E-06	7.79E-01	1.65E-01	7.03E-22	2.91E-04	9.96E-01	4.02E-03
RF-TT0486	3.09E-01	0.00E+00	5.85E-05	4.62E+00	9.77E-01	4.15E-21	3.07E-04	5.91E+00	2.38E-02
RF-TT0487	1.55E+00	0.00E+00	1.99E-04	1.66E+01	3.50E+00	1.34E-20	7.54E-04	2.17E+01	8.73E-02
RF-TT0489	4.42E-01	0.00E+00	8.93E-05	7.05E+00	1.49E+00	6.37E-21	2.23E-04	8.98E+00	3.62E-02
RF-TT0490	2.44E+01	0.00E+00	5.68E-03	4.54E+02	9.59E+01	3.81E-19	9.53E-03	5.75E+02	2.32E+00
RF-TT0491	5.69E-01	0.00E+00	7.66E-05	6.09E+00	1.28E+00	5.30E-21	2.00E-04	7.94E+00	3.20E-02
RF-TT0492	1.91E-01	0.00E+00	4.32E-05	3.40E+00	7.19E-01	3.06E-21	5.90E-05	4.31E+00	1.74E-02
RF-TT0523A	1.29E+00	0.00E+00	1.73E-04	1.37E+01	2.90E+00	1.23E-20	2.71E-04	1.79E+01	7.21E-02
RF-TT0523B	1.29E+00	0.00E+00	1.73E-04	1.37E+01	2.90E+00	1.23E-20	2.71E-04	1.79E+01	7.21E-02
RF-TT0523C	1.29E+00	0.00E+00	1.73E-04	1.37E+01	2.90E+00	1.23E-20	2.71E-04	1.79E+01	7.21E-02
RF-TT0523D	1.29E+00	0.00E+00	1.73E-04	1.37E+01	2.90E+00	1.23E-20	2.71E-04	1.79E+01	7.21E-02
RF-TT0523E	1.29E+00	0.00E+00	1.73E-04	1.37E+01	2.90E+00	1.23E-20	2.71E-04	1.79E+01	7.21E-02
RF-TT0532A	3.22E+01	0.00E+00	2.91E-03	2.36E+02	4.97E+01	2.06E-19	5.14E-03	3.18E+02	1.28E+00
RF-TT0532B	3.22E+01	0.00E+00	2.91E-03	2.36E+02	4.97E+01	2.06E-19	5.14E-03	3.18E+02	1.28E+00
RF-TT0541	5.32E-02	0.00E+00	1.73E-05	1.37E+00	2.89E-01	1.23E-21	2.37E-05	1.71E+00	6.90E-03
RF-TT0545	1.19E-02	0.00E+00	3.86E-06	3.04E-01	6.43E-02	2.74E-22	5.27E-06	3.80E-01	1.53E-03
RF-TT0601	4.12E+00	0.00E+00	6.66E-04	5.49E+01	1.17E+01	4.45E-20	9.36E-04	7.07E+01	2.85E-01
RF-TT0802	4.61E+02	0.00E+00	5.47E-02	4.33E+03	9.14E+02	3.89E-18	7.47E-02	5.71E+03	2.30E+01
RF-TT0809	3.79E+01	0.00E+00	4.49E-03	3.56E+02	7.49E+01	3.20E-19	6.14E-03	4.69E+02	1.89E+00
RF-TT0821	8.20E+01	0.00E+00	1.63E-02	1.40E+03	2.96E+02	9.51E-19	1.90E-01	1.78E+03	7.16E+00
RF-TT0822	9.07E+01	0.00E+00	1.27E-02	1.05E+03	2.21E+02	8.47E-19	1.99E-01	1.36E+03	5.48E+00
RF-TT0823	1.84E-01	0.00E+00	2.48E-05	1.96E+00	4.14E-01	1.76E-21	3.88E-05	2.56E+00	1.03E-02
RF-TT0824	1.89E+02	0.00E+00	3.49E-02	2.83E+03	5.96E+02	2.39E-18	1.10E-01	3.61E+03	1.46E+01
RF-TT0825	1.57E+02	0.00E+00	2.52E-02	2.13E+03	4.48E+02	1.59E-18	1.15E-01	2.73E+03	1.10E+01
RF-TT0832	1.16E+02	0.00E+00	1.49E-02	1.24E+03	2.63E+02	1.00E-18	5.66E-02	1.62E+03	6.54E+00
RF-TT0854	4.18E-02	0.00E+00	1.36E-05	1.07E+00	2.27E-01	9.67E-22	7.64E-04	1.34E+00	5.39E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0886	5.93E-03	0.00E+00	1.92E-06	1.51E-01	3.21E-02	1.37E-22	2.62E-06	1.90E-01	7.64E-04
RF-TT2216	1.72E+00	0.00E+00	2.20E-04	1.84E+01	3.87E+00	1.48E-20	8.36E-04	2.40E+01	9.69E-02
RF-TT3010	9.16E+01	0.00E+00	1.95E-02	1.55E+03	3.29E+02	1.36E-18	3.16E-02	1.97E+03	7.96E+00
RF-TT3011	2.31E+02	0.00E+00	4.12E-02	3.24E+03	6.86E+02	2.93E-18	8.99E-02	4.16E+03	1.68E+01
RF-TT301U	1.92E+01	0.00E+00	4.35E-03	3.52E+02	7.57E+01	2.88E-19	6.10E-03	4.47E+02	1.80E+00
RF-TT310P	5.56E+00	0.00E+00	1.13E-03	1.18E+02	2.38E+01	6.02E-20	1.55E-03	1.48E+02	5.96E-01
RF-TT338S	1.62E-01	0.00E+00	5.19E-05	4.09E+00	8.64E-01	3.68E-21	7.08E-05	5.11E+00	2.06E-02
RF-TT390P	9.13E-01	0.00E+00	1.41E-04	1.99E+01	3.86E+00	9.19E-21	2.21E-04	2.47E+01	9.95E-02
RF-TT391P	5.05E+01	0.00E+00	6.31E-03	8.94E+02	1.86E+02	5.57E-19	8.62E-03	1.13E+03	4.56E+00
RF-TT392P	1.02E+02	0.00E+00	2.27E-02	2.68E+03	5.64E+02	1.11E-18	3.11E-02	3.35E+03	1.35E+01
RF-TT393R	1.51E+01	0.00E+00	3.86E-03	4.10E+02	8.68E+01	1.79E-19	5.45E-03	5.12E+02	2.06E+00
RF-TT394P	1.87E+00	0.00E+00	2.39E-04	3.17E+01	6.19E+00	1.29E-20	3.33E-04	3.97E+01	1.60E-01
RF-TT395P	2.51E+00	0.00E+00	3.20E-04	4.23E+01	8.27E+00	1.72E-20	4.46E-04	5.31E+01	2.14E-01
RF-TT396P	6.26E-01	0.00E+00	7.98E-05	1.06E+01	2.07E+00	4.29E-21	1.11E-04	1.33E+01	5.35E-02
RF-TT398P	6.06E+01	0.00E+00	1.38E-02	1.66E+03	3.47E+02	6.90E-19	1.89E-02	2.07E+03	8.34E+00
RF-TT398R	5.00E+02	0.00E+00	2.57E-02	2.68E+03	5.61E+02	1.35E-18	3.51E-02	3.74E+03	1.51E+01
RF-TT411R	1.81E+01	0.00E+00	2.31E-03	3.06E+02	6.39E+01	9.51E-20	3.18E-03	3.88E+02	1.56E+00
RF-TT429R	3.81E+01	0.00E+00	4.96E-04	7.09E+01	1.45E+01	1.66E-20	6.77E-04	1.23E+02	4.98E-01
RF-TT433X	1.20E+01	0.00E+00	1.37E-04	2.04E+01	3.77E+00	6.58E-21	1.87E-04	3.62E+01	1.46E-01
RF-TT436R	8.78E+01	0.00E+00	1.99E-03	2.67E+02	5.57E+01	1.27E-19	2.71E-03	4.10E+02	1.66E+00
RF-TT454X	5.15E+00	0.00E+00	1.17E-04	1.57E+01	3.28E+00	7.48E-21	1.59E-04	2.42E+01	9.74E-02
RL-T101	2.62E+01	0.00E+00	7.09E-03	8.49E+02	1.76E+02	1.06E-18	8.80E-03	1.05E+03	4.24E+00
RL-T102	3.32E-04	0.00E+00	9.02E-08	1.09E-02	2.24E-03	1.34E-23	1.26E-06	1.35E-02	5.42E-05
RL-T103	2.35E+01	0.00E+00	8.59E-03	3.71E+02	7.62E+01	5.62E-19	1.07E-02	4.71E+02	1.90E+00
RL-T104	4.76E-04	0.00E+00	1.29E-07	1.54E-02	3.21E-03	1.92E-23	1.93E-07	1.91E-02	7.71E-05
RL-T105	1.82E-01	0.00E+00	4.87E-05	5.86E+00	1.21E+00	7.27E-21	1.05E-04	7.26E+00	2.93E-02
RL-T106	1.76E-01	0.00E+00	4.78E-05	5.73E+00	1.18E+00	7.11E-21	5.94E-05	7.09E+00	2.86E-02
RL-T107	4.84E+02	0.00E+00	2.81E+01	1.58E+04	3.26E+03	1.95E-17	3.57E+01	1.96E+04	7.92E+01
RL-T108	2.77E-01	0.00E+00	4.84E-03	9.01E+00	1.86E+00	1.12E-20	6.04E-03	1.12E+01	4.50E-02
RL-T109	3.81E-01	0.00E+00	9.97E-05	1.19E+01	2.47E+00	1.48E-20	2.34E-02	1.48E+01	5.98E-02
RL-T110	4.27E+01	0.00E+00	1.90E-02	1.37E+03	2.84E+02	1.70E-18	1.38E+00	1.70E+03	6.84E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T112	1.72E+01	0.00E+00	8.04E-03	1.82E+02	3.76E+01	2.26E-19	7.44E-01	2.37E+02	9.56E-01
RL-T113	1.84E-02	0.00E+00	1.55E-05	5.98E-01	1.24E-01	7.43E-22	1.93E-05	7.40E-01	2.98E-03
RL-T114	2.79E+00	0.00E+00	7.58E-04	9.09E+01	1.88E+01	1.13E-19	9.41E-04	1.13E+02	4.54E-01
RL-T115	7.11E+01	0.00E+00	2.46E-02	1.19E+03	2.47E+02	1.66E-18	4.42E-01	1.51E+03	6.10E+00
RL-T116	4.58E+00	0.00E+00	1.25E-03	1.49E+02	3.08E+01	1.85E-19	5.76E-02	1.84E+02	7.42E-01
RL-T118	1.18E+01	0.00E+00	9.94E-03	1.48E+02	3.06E+01	1.84E-19	8.43E-01	1.91E+02	7.69E-01
RL-T120	2.86E+00	0.00E+00	1.04E-03	4.37E+01	8.96E+00	6.45E-20	1.30E-03	5.55E+01	2.24E-01
RL-T122	1.62E-01	0.00E+00	4.41E-05	5.26E+00	1.09E+00	6.55E-21	1.46E+00	7.97E+00	3.22E-02
RL-T123	4.77E-01	0.00E+00	1.29E-04	1.54E+01	3.21E+00	1.93E-20	5.97E-02	1.92E+01	7.73E-02
RL-T125	9.49E+01	0.00E+00	3.20E-02	3.23E+02	1.54E+02	3.01E-18	3.97E-02	5.72E+02	2.31E+00
RL-T127	9.14E+01	0.00E+00	8.04E-03	9.66E+02	2.00E+02	1.20E-18	8.98E-02	1.26E+03	5.07E+00
RL-T128	1.35E-01	0.00E+00	1.95E-10	2.35E-05	4.85E-06	2.90E-26	2.43E-10	1.35E-01	5.46E-04
RL-T129	4.06E-01	0.00E+00	3.72E-02	1.33E+01	2.73E+00	1.64E-20	5.38E-02	1.65E+01	6.67E-02
RL-T130	8.63E-04	0.00E+00	2.35E-07	2.83E-02	5.84E-03	3.49E-23	8.31E-05	3.50E-02	1.41E-04
RL-T131	3.51E-01	0.00E+00	1.28E-04	5.38E+00	1.10E+00	7.88E-21	8.37E-03	6.84E+00	2.76E-02
RL-T132	8.36E+01	0.00E+00	2.26E-02	2.73E+03	5.64E+02	3.38E-18	2.72E-01	3.38E+03	1.36E+01
RL-T133	1.70E-03	0.00E+00	3.63E-07	4.48E-02	9.23E-03	4.79E-23	4.51E-07	5.57E-02	2.25E-04
RL-T134	3.60E-03	0.00E+00	9.77E-07	1.18E-01	2.42E-02	1.46E-22	1.21E-06	1.45E-01	5.86E-04
RL-T135	1.69E-02	0.00E+00	4.58E-06	5.49E-01	1.14E-01	6.82E-22	4.14E-03	6.84E-01	2.76E-03
RL-T137	2.74E+02	0.00E+00	1.00E-01	4.18E+03	8.61E+02	6.21E-18	1.30E-01	5.32E+03	2.14E+01
RL-T140	3.20E+02	0.00E+00	9.51E-02	4.05E+03	9.23E+02	5.27E-18	2.62E+01	5.32E+03	2.14E+01
RL-T143	2.01E+00	0.00E+00	5.45E-04	6.54E+01	1.35E+01	8.12E-20	3.92E-02	8.10E+01	3.27E-01
RL-T145	5.72E+00	0.00E+00	1.55E-03	1.86E+02	3.85E+01	2.31E-19	9.13E-02	2.31E+02	9.30E-01
RL-W407	1.64E+01	0.00E+00	3.31E-03	4.27E+02	8.84E+01	3.52E-19	4.12E-03	5.32E+02	2.15E+00
RL-W408	6.73E-05	0.00E+00	1.40E-08	1.73E-03	3.58E-04	1.81E-24	1.74E-08	2.15E-03	8.68E-06
RL-W415	1.49E-03	0.00E+00	3.08E-07	3.83E-02	7.91E-03	4.00E-23	3.83E-07	4.76E-02	1.92E-04
RL-W418	6.36E-03	0.00E+00	1.30E-06	1.64E-01	3.40E-02	1.49E-22	1.61E-06	2.04E-01	8.24E-04
RL-W437	5.39E+01	0.00E+00	1.09E-02	1.40E+03	2.90E+02	1.15E-18	1.35E-02	1.74E+03	7.02E+00
RL-W438	9.43E-05	0.00E+00	1.96E-08	2.42E-03	4.99E-04	2.53E-24	2.43E-08	3.01E-03	1.21E-05
RL-W439	2.95E+03	0.00E+00	1.08E+00	4.66E+04	9.59E+03	7.06E-17	1.34E+00	5.91E+04	2.39E+02
RL-W443	4.75E+01	0.00E+00	9.59E-03	1.23E+03	2.55E+02	1.02E-18	1.19E-02	1.54E+03	6.19E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W444	3.52E+01	0.00E+00	7.12E-03	9.14E+02	1.89E+02	7.54E-19	8.84E-03	1.14E+03	4.59E+00
RL-W447	4.04E-03	0.00E+00	8.38E-07	1.03E-01	2.14E-02	1.08E-22	1.04E-06	1.28E-01	5.18E-04
RL-W448	2.98E-05	0.00E+00	6.19E-09	7.64E-04	1.58E-04	8.02E-25	7.69E-09	9.52E-04	3.84E-06
RL-W449	2.45E-01	0.00E+00	2.27E-07	2.18E-02	4.52E-03	1.45E-23	2.82E-07	2.71E-01	1.09E-03
RL-W450	4.50E-04	0.00E+00	9.34E-08	1.16E-02	2.38E-03	1.21E-23	1.16E-07	1.44E-02	5.80E-05
RL-W451	6.42E-05	0.00E+00	1.33E-08	1.64E-03	3.40E-04	1.72E-24	1.65E-08	2.04E-03	8.24E-06
RL-W452	2.79E-03	0.00E+00	5.73E-07	7.23E-02	1.50E-02	6.55E-23	7.12E-07	9.01E-02	3.63E-04
RL-W453	7.97E-04	0.00E+00	1.61E-07	2.08E-02	4.29E-03	1.71E-23	2.00E-07	2.59E-02	1.04E-04
RL-W454	1.11E-02	0.00E+00	2.26E-06	2.90E-01	6.00E-02	2.39E-22	2.80E-06	3.61E-01	1.46E-03
RL-W455	2.97E-03	0.00E+00	6.08E-07	7.68E-02	1.59E-02	6.98E-23	7.55E-07	9.56E-02	3.86E-04
RL-W456	3.92E-01	0.00E+00	7.95E-05	1.02E+01	2.11E+00	8.60E-21	9.88E-05	1.27E+01	5.12E-02
RL-W457	3.80E-02	0.00E+00	7.72E-06	9.90E-01	2.04E-01	8.34E-22	9.59E-06	1.23E+00	4.97E-03
RL-W458	1.20E-01	0.00E+00	3.95E-05	4.07E-01	2.10E-01	3.36E-21	4.90E-05	7.37E-01	2.97E-03
RL-W459	1.16E+00	0.00E+00	4.06E-04	1.01E+01	2.86E+00	3.33E-20	5.05E-04	1.41E+01	5.69E-02
RL-W460	7.07E-03	0.00E+00	1.43E-06	1.84E-01	3.80E-02	1.51E-22	1.78E-06	2.29E-01	9.22E-04
RL-W461	6.52E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.52E-03	2.63E-05
RL-W462	2.01E-03	0.00E+00	4.15E-07	5.19E-02	1.08E-02	4.95E-23	5.15E-07	6.47E-02	2.61E-04
RL-W463	1.04E-02	0.00E+00	2.10E-06	2.70E-01	5.58E-02	2.22E-22	2.61E-06	3.36E-01	1.36E-03
RL-W464	4.78E-03	0.00E+00	9.65E-07	1.24E-01	2.56E-02	1.02E-22	1.20E-06	1.55E-01	6.24E-04
RL-W465	3.19E-02	0.00E+00	6.54E-06	8.27E-01	1.71E-01	7.40E-22	8.12E-06	1.03E+00	4.15E-03
RL-W466	4.37E-01	0.00E+00	8.90E-05	1.14E+01	2.35E+00	9.85E-21	1.11E-04	1.41E+01	5.70E-02
RL-W467	2.24E-02	0.00E+00	4.58E-06	5.79E-01	1.19E-01	5.41E-22	5.69E-06	7.20E-01	2.90E-03
RL-W468	1.15E-04	0.00E+00	2.36E-08	2.96E-03	6.12E-04	2.82E-24	2.93E-08	3.69E-03	1.49E-05
RL-W469	4.65E-02	0.00E+00	9.48E-06	1.20E+00	2.50E-01	1.04E-21	1.18E-05	1.50E+00	6.05E-03
RL-W470	1.32E+00	0.00E+00	4.41E-04	4.47E+00	2.13E+00	4.18E-20	5.48E-04	7.92E+00	3.19E-02
RL-W474	4.99E-02	0.00E+00	4.87E-05	1.02E-02	8.07E-03	0.00E+00	6.05E-05	6.83E-02	2.75E-04
RL-W476	8.41E-02	0.00E+00	1.75E-05	2.23E+00	4.63E-01	1.89E-21	2.18E-05	2.78E+00	1.12E-02
RL-W480	1.37E-02	0.00E+00	2.81E-06	3.54E-01	7.34E-02	3.22E-22	3.49E-06	4.41E-01	1.78E-03
RL-W481	2.16E-02	0.00E+00	4.41E-06	5.56E-01	1.15E-01	5.06E-22	5.48E-06	6.93E-01	2.79E-03
RL-W482	2.86E+01	0.00E+00	1.47E-03	7.08E-02	1.22E-01	6.71E-19	1.82E-03	2.88E+01	1.16E-01
RL-W483	2.14E+00	0.00E+00	1.14E-04	4.58E-03	8.66E-03	5.01E-20	1.41E-04	2.15E+00	8.67E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W484	9.04E-03	0.00E+00	9.16E-07	6.40E-02	1.42E-02	4.15E-23	1.14E-06	8.72E-02	3.52E-04
RL-W485	5.29E-04	0.00E+00	1.30E-07	6.92E-03	1.53E-03	0.00E+00	1.61E-07	8.98E-03	3.62E-05
RL-W486	2.24E-04	0.00E+00	5.47E-08	2.92E-03	6.45E-04	0.00E+00	6.80E-08	3.79E-03	1.53E-05
RL-W487	3.65E-02	0.00E+00	7.03E-06	4.18E-01	1.07E-01	3.86E-22	8.73E-06	5.62E-01	2.26E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	2.22E-02	0.00E+00	6.63E-06	5.42E-01	1.14E-01	6.23E-22	8.23E-06	6.78E-01	2.73E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	8.24E-03	0.00E+00	5.59E-06	5.68E-02	1.16E-02	2.26E-22	6.94E-06	7.66E-02	3.09E-04
RL-W492	4.75E-04	0.00E+00	1.38E-07	1.14E-02	2.38E-03	1.30E-23	1.71E-07	1.42E-02	5.73E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	1.88E+01	0.00E+00	7.98E-03	2.86E-01	2.27E-01	5.22E-19	9.91E-03	1.94E+01	7.81E-02
RL-W495	3.41E-01	0.00E+00	2.17E-05	2.75E-03	2.03E-03	9.51E-21	2.70E-05	3.46E-01	1.39E-03
RL-W496	2.21E+00	0.00E+00	2.50E-04	9.03E-03	6.71E-03	6.15E-20	3.10E-04	2.23E+00	8.99E-03
RL-W497	9.22E-02	0.00E+00	4.93E-05	5.42E-01	2.28E-01	1.61E-21	6.12E-05	8.62E-01	3.47E-03
RL-W498	3.58E-01	0.00E+00	7.32E-05	9.26E+00	1.92E+00	8.39E-21	9.09E-05	1.15E+01	4.65E-02
RL-W499	3.21E-06	0.00E+00	6.57E-10	8.30E-05	1.72E-05	7.54E-26	8.16E-10	1.03E-04	4.17E-07
RL-W500	2.29E-04	0.00E+00	8.15E-08	3.39E-03	6.97E-04	5.30E-24	1.01E-07	4.31E-03	1.74E-05
RL-W501	9.47E+00	0.00E+00	1.82E-03	1.09E+02	2.76E+01	1.00E-19	2.26E-03	1.46E+02	5.88E-01
RL-W502	1.71E-03	0.00E+00	3.52E-07	4.43E-02	9.14E-03	4.02E-23	4.37E-07	5.51E-02	2.22E-04
RL-W503	9.90E-02	0.00E+00	3.60E-05	1.56E+00	3.21E-01	2.37E-21	4.47E-05	1.98E+00	8.00E-03
RL-W504	3.65E-02	0.00E+00	7.03E-06	4.18E-01	1.07E-01	3.86E-22	8.73E-06	5.62E-01	2.26E-03
RL-W505	1.72E-03	0.00E+00	3.69E-07	4.52E-02	9.32E-03	4.85E-23	4.58E-07	5.63E-02	2.27E-04
RL-W506	6.23E-04	0.00E+00	1.45E-07	1.49E-02	3.07E-03	1.45E-23	1.80E-07	1.86E-02	7.48E-05
RL-W507	6.20E-05	0.00E+00	1.27E-08	1.60E-03	3.31E-04	1.45E-24	1.58E-08	1.99E-03	8.04E-06
RL-W508	1.14E+00	0.00E+00	4.15E-04	1.74E+01	3.58E+00	2.58E-20	5.15E-04	2.21E+01	8.91E-02
RL-W509	1.12E+01	0.00E+00	3.31E-03	1.42E+02	3.22E+01	1.85E-19	4.12E-03	1.85E+02	7.46E-01
RL-W510	9.45E-01	0.00E+00	3.40E-04	1.41E+01	2.90E+00	2.20E-20	4.22E-04	1.79E+01	7.22E-02
RL-W511	9.61E+01	0.00E+00	1.64E-02	1.88E+03	3.82E+02	1.20E-18	2.07E-02	2.36E+03	9.52E+00
RL-W512	8.41E+01	0.00E+00	1.11E-02	1.14E+03	2.62E+02	6.13E-19	1.37E-02	1.48E+03	5.97E+00
RL-W513	8.98E+03	0.00E+00	4.49E+00	1.85E+04	8.53E+03	9.72E-17	5.58E+00	3.61E+04	1.45E+02
RL-W514	2.53E-04	0.00E+00	5.16E-08	6.57E-03	1.36E-03	5.67E-24	6.41E-08	8.19E-03	3.30E-05

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W515	9.90E-03	0.00E+00	2.02E-06	2.56E-01	5.29E-02	2.32E-22	2.51E-06	3.19E-01	1.29E-03
RL-W516	1.37E-02	0.00E+00	2.81E-06	3.54E-01	7.34E-02	3.22E-22	3.49E-06	4.42E-01	1.78E-03
RL-W517	1.22E-10	0.00E+00	2.51E-14	3.16E-09	6.52E-10	3.01E-30	3.12E-14	3.93E-09	1.58E-11
RL-W518	3.46E-01	0.00E+00	1.06E-04	4.52E+00	1.01E+00	6.47E-21	1.31E-04	5.88E+00	2.37E-02
RL-W519	6.17E-02	0.00E+00	1.25E-05	1.60E+00	3.31E-01	1.37E-21	1.56E-05	1.99E+00	8.04E-03
RL-W520	6.82E-03	0.00E+00	1.41E-06	1.76E-01	3.63E-02	1.75E-22	1.75E-06	2.19E-01	8.82E-04
RL-W521	1.27E-04	0.00E+00	2.59E-08	3.27E-03	6.78E-04	2.98E-24	3.22E-08	4.08E-03	1.64E-05
RL-W522	2.65E+00	0.00E+00	9.62E-04	2.17E+01	5.75E+00	4.31E-20	1.20E-03	3.01E+01	1.21E-01
RL-W523	7.96E-01	0.00E+00	3.66E-04	1.44E+00	8.09E-01	8.55E-21	4.55E-04	3.04E+00	1.23E-02
RL-W524	3.30E+00	0.00E+00	1.40E-03	1.32E+01	4.74E+00	4.07E-20	1.74E-03	2.13E+01	8.57E-02
RL-W525	2.62E-01	0.00E+00	9.48E-05	1.56E+00	4.80E-01	3.20E-21	1.18E-04	2.31E+00	9.29E-03
RL-W526	9.94E-01	0.00E+00	3.43E-04	1.67E+01	3.46E+00	2.33E-20	4.26E-04	2.12E+01	8.53E-02
RL-W527	1.09E-01	0.00E+00	4.96E-05	1.77E+00	3.89E-01	2.72E-21	6.16E-05	2.27E+00	9.13E-03
RL-W528	4.87E+01	0.00E+00	2.11E-02	5.63E+01	5.00E+01	4.15E-19	2.62E-02	1.55E+02	6.25E-01
RL-W529	4.06E-02	0.00E+00	1.48E-05	6.21E-01	1.27E-01	9.16E-22	1.84E-05	7.89E-01	3.18E-03
RL-W530	4.78E-01	0.00E+00	1.72E-04	7.10E+00	1.46E+00	1.11E-20	2.13E-04	9.04E+00	3.64E-02
RL-W531	2.85E+01	0.00E+00	1.72E-02	3.07E+01	2.05E+01	2.96E-19	2.14E-02	7.98E+01	3.22E-01
RL-W532	9.15E-02	0.00E+00	1.87E-05	2.37E+00	4.89E-01	2.15E-21	2.33E-05	2.95E+00	1.19E-02
RL-W533	4.43E-02	0.00E+00	1.62E-05	6.78E-01	1.39E-01	9.93E-22	2.01E-05	8.61E-01	3.47E-03
RL-W534	2.56E-06	0.00E+00	5.22E-10	6.61E-05	1.37E-05	5.99E-26	6.48E-10	8.24E-05	3.32E-07
RL-W535	1.34E+01	0.00E+00	5.16E-03	8.47E+01	2.40E+01	1.83E-19	6.41E-03	1.22E+02	4.93E-01
RL-W536	2.62E-01	0.00E+00	6.94E-05	2.94E+00	6.19E-01	4.18E-21	8.94E-05	3.82E+00	1.54E-02
RL-W537	8.93E+00	0.00E+00	1.57E-03	1.81E+02	3.68E+01	1.17E-19	1.97E-03	2.26E+02	9.12E-01
RL-W538	3.25E-05	0.00E+00	6.63E-09	8.40E-04	1.74E-04	7.62E-25	8.23E-09	1.05E-03	4.22E-06
RL-W539	3.61E-03	0.00E+00	7.46E-07	9.28E-02	1.92E-02	9.27E-23	9.27E-07	1.16E-01	4.66E-04
RL-W540	7.02E+00	0.00E+00	3.28E-03	3.34E+01	1.07E+01	8.90E-20	4.08E-03	5.11E+01	2.06E-01
RL-W541	1.04E-02	0.00E+00	2.15E-06	2.69E-01	5.56E-02	2.61E-22	2.67E-06	3.35E-01	1.35E-03
RL-W542	4.85E-01	0.00E+00	1.60E-04	6.81E+00	1.46E+00	1.07E-20	1.99E-04	8.75E+00	3.53E-02
RL-W543	1.53E-03	0.00E+00	3.11E-07	3.94E-02	8.16E-03	3.60E-23	3.87E-07	4.91E-02	1.98E-04
RL-W544	3.44E-02	0.00E+00	1.27E-05	4.49E-01	1.04E-01	7.14E-22	1.58E-05	5.87E-01	2.37E-03
RL-W545	9.14E-03	0.00E+00	1.87E-06	2.36E-01	4.89E-02	2.14E-22	2.32E-06	2.94E-01	1.19E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W546	4.00E-04	0.00E+00	8.18E-08	1.04E-02	2.14E-03	9.37E-24	1.02E-07	1.29E-02	5.21E-05
RL-W547	1.02E-05	0.00E+00	2.09E-09	2.64E-04	5.47E-05	2.40E-25	2.60E-09	3.29E-04	1.33E-06
RL-W548	8.84E-06	0.00E+00	1.82E-09	2.28E-04	4.72E-05	2.15E-25	2.25E-09	2.84E-04	1.15E-06
RL-W549	1.76E+00	0.00E+00	7.29E-04	1.18E+01	3.25E+00	2.72E-20	9.05E-04	1.68E+01	6.75E-02
RL-W550	7.96E+00	0.00E+00	1.38E-03	1.59E+02	3.25E+01	1.03E-19	1.73E-03	2.00E+02	8.05E-01
RL-W551	1.42E+01	0.00E+00	2.04E-03	1.80E+02	4.23E+01	1.09E-19	2.53E-03	2.36E+02	9.52E-01
RL-W552	5.49E-03	0.00E+00	1.13E-06	1.42E-01	2.92E-02	1.36E-22	1.40E-06	1.76E-01	7.11E-04
RL-W553	4.87E-04	0.00E+00	1.07E-07	1.26E-02	2.61E-03	1.72E-23	1.32E-07	1.57E-02	6.34E-05
RL-W554	7.73E-03	0.00E+00	1.58E-06	2.00E-01	4.14E-02	1.81E-22	1.97E-06	2.49E-01	1.00E-03
RL-W555	3.56E-03	0.00E+00	7.29E-07	9.21E-02	1.90E-02	8.36E-23	9.05E-07	1.15E-01	4.62E-04
RL-W563	5.11E-02	0.00E+00	1.82E-05	7.64E-01	1.57E-01	1.14E-21	2.27E-05	9.72E-01	3.92E-03
RL-W564	3.33E-02	0.00E+00	1.21E-05	4.94E-01	1.01E-01	8.76E-22	1.50E-05	6.29E-01	2.54E-03
RL-W565	3.30E-03	0.00E+00	6.80E-07	8.53E-02	1.77E-02	8.12E-23	8.45E-07	1.06E-01	4.29E-04
RL-W566	4.85E-02	0.00E+00	9.97E-06	1.25E+00	2.60E-01	1.16E-21	1.24E-05	1.56E+00	6.29E-03
RL-W567	3.36E+00	0.00E+00	2.55E-04	3.85E-02	2.89E-02	9.80E-20	3.16E-04	3.43E+00	1.38E-02
RL-W568	6.47E+01	0.00E+00	5.36E-03	1.83E+00	1.35E+00	2.02E-18	6.66E-03	6.78E+01	2.74E-01
RL-W569	5.32E-02	0.00E+00	4.03E-06	6.09E-04	4.57E-05	1.55E-21	5.01E-06	5.39E-02	2.17E-04
RL-W570	3.41E-03	0.00E+00	7.06E-07	9.05E-02	1.86E-02	7.64E-23	8.77E-07	1.13E-01	4.54E-04
RL-W571	1.09E+01	0.00E+00	2.40E-03	7.34E+00	3.41E+00	3.09E-19	2.98E-03	2.17E+01	8.74E-02
RL-W572	9.49E-03	0.00E+00	7.17E-07	3.95E-03	8.16E-05	2.77E-22	8.91E-07	1.35E-02	5.45E-05
RL-W573	1.22E+02	0.00E+00	9.19E-03	2.17E+00	1.51E+00	3.52E-18	1.14E-02	1.26E+02	5.07E-01
RL-W574	5.25E+02	0.00E+00	3.98E-02	8.27E+00	5.58E+00	1.53E-17	4.94E-02	5.39E+02	2.17E+00
RL-W575	3.42E+03	0.00E+00	2.68E-01	7.91E+01	4.46E+01	9.61E-17	3.32E-01	3.54E+03	1.43E+01
RL-W576	2.47E+02	0.00E+00	1.87E-02	4.03E+00	2.69E+00	7.22E-18	2.32E-02	2.53E+02	1.02E+00
RL-W579	2.09E-02	0.00E+00	4.93E-07	2.02E-02	4.19E-03	2.55E-23	6.12E-07	4.53E-02	1.83E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.61E-01	2.44E-02	0.00E+00	0.00E+00	1.86E-01	7.48E-04
RL-W581	2.22E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.22E-01	8.94E-04
RL-W582	1.45E-03	0.00E+00	4.18E-07	5.16E-03	2.48E-03	4.13E-24	5.19E-07	9.10E-03	3.67E-05
RL-W583	1.12E-03	0.00E+00	2.27E-07	2.91E-02	6.03E-03	2.40E-23	2.82E-07	3.63E-02	1.46E-04
RL-W584	2.23E-02	0.00E+00	1.49E-05	1.70E-01	7.73E-02	1.21E-22	1.85E-05	2.70E-01	1.09E-03
RL-W585	1.33E-01	0.00E+00	7.92E-05	9.90E-01	4.70E-01	3.68E-21	9.84E-05	1.59E+00	6.42E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W586	1.77E-05	0.00E+00	3.57E-09	4.60E-04	9.50E-05	3.78E-25	4.44E-09	5.73E-04	2.31E-06
RL-W587	3.79E-04	0.00E+00	7.72E-08	9.80E-03	2.04E-03	8.50E-24	9.59E-08	1.22E-02	4.93E-05
RL-W588	1.56E-02	0.00E+00	1.26E-05	1.44E-01	6.51E-02	1.02E-22	1.56E-05	2.24E-01	9.05E-04
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	4.80E-01	0.00E+00	2.68E-04	1.11E-02	1.83E-02	1.33E-20	3.33E-04	5.09E-01	2.05E-03
RL-W591	2.73E+00	0.00E+00	3.03E-04	1.37E-02	2.37E-02	8.04E-20	3.76E-04	2.77E+00	1.12E-02
RL-W592	1.21E+01	0.00E+00	3.31E-03	6.35E-01	7.66E-01	3.25E-19	4.12E-03	1.35E+01	5.43E-02
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.29E-02	3.59E-02	0.00E+00	0.00E+00	5.89E-02	2.37E-04
RL-W594	1.09E+01	0.00E+00	5.96E-04	2.83E-02	4.86E-02	8.12E-20	7.41E-04	1.10E+01	4.42E-02
RL-W595	2.87E-02	0.00E+00	6.22E-05	1.94E-02	3.53E-02	8.04E-22	7.73E-05	8.36E-02	3.37E-04
RL-W596	9.30E-03	0.00E+00	4.84E-06	2.00E-04	3.32E-04	2.42E-22	6.01E-06	9.84E-03	3.97E-05
RL-W597	1.71E+01	0.00E+00	2.13E-03	3.87E-01	6.02E-01	4.50E-19	2.64E-03	1.81E+01	7.29E-02
RL-W598	1.81E+01	0.00E+00	1.26E-02	5.40E-01	7.50E-01	4.66E-19	1.56E-02	1.94E+01	7.82E-02
RL-W599	9.16E-01	0.00E+00	1.01E-04	4.56E-03	7.91E-03	2.69E-20	1.26E-04	9.28E-01	3.74E-03
RL-W600	5.20E-08	0.00E+00	1.05E-11	1.35E-06	2.80E-07	1.11E-27	1.31E-11	1.68E-06	6.78E-09
RL-W601	2.64E-04	0.00E+00	5.76E-08	6.83E-03	1.42E-03	9.32E-24	7.16E-08	8.51E-03	3.43E-05
RL-W602	2.30E-01	0.00E+00	4.73E-05	5.92E+00	1.23E+00	5.65E-21	5.87E-05	7.38E+00	2.98E-02
RL-W603	1.32E+00	0.00E+00	2.73E-04	3.42E+01	7.07E+00	3.25E-20	3.39E-04	4.26E+01	1.72E-01
RL-W604	3.10E-03	0.00E+00	7.15E-07	1.66E-02	7.62E-03	3.86E-23	8.87E-07	2.73E-02	1.10E-04
RL-W605	7.09E-04	0.00E+00	1.55E-07	1.84E-02	3.80E-03	2.51E-23	1.93E-07	2.29E-02	9.22E-05
RL-W606	2.86E-04	0.00E+00	6.25E-08	7.40E-03	1.53E-03	1.01E-23	7.77E-08	9.22E-03	3.72E-05
RL-W607	5.24E-04	0.00E+00	1.21E-07	2.81E-03	1.29E-03	6.52E-24	1.50E-07	4.62E-03	1.86E-05
RL-W608	6.26E-03	0.00E+00	4.70E-06	3.65E-03	4.19E-03	1.00E-22	5.83E-06	1.41E-02	5.69E-05
RL-W610	1.24E+00	0.00E+00	2.51E-04	3.22E+01	6.67E+00	2.66E-20	3.12E-04	4.01E+01	1.62E-01
RL-W612	2.93E-03	0.00E+00	6.08E-07	7.82E-02	1.62E-02	6.29E-23	7.55E-07	9.74E-02	3.93E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.28E-01	0.00E+00	0.00E+00	0.00E+00	3.28E-01	1.32E-03
RL-W622	4.88E-05	0.00E+00	9.91E-09	1.27E-03	2.63E-04	1.05E-24	1.23E-08	1.58E-03	6.38E-06
RL-W625	1.70E-03	0.00E+00	1.51E-06	6.49E-03	5.93E-03	5.67E-23	1.87E-06	1.41E-02	5.70E-05
RL-W626	9.14E-02	0.00E+00	3.43E-05	2.54E-01	1.42E-01	9.91E-22	4.26E-05	4.87E-01	1.97E-03
RL-W627	4.31E-04	0.00E+00	4.58E-08	1.20E-06	0.00E+00	1.18E-23	5.69E-08	4.32E-04	1.74E-06
RL-W628	1.41E-04	0.00E+00	2.88E-08	3.67E-03	7.58E-04	3.17E-24	3.58E-08	4.57E-03	1.84E-05

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W629	9.56E-06	0.00E+00	1.98E-09	2.47E-04	5.09E-05	2.46E-25	2.46E-09	3.07E-04	1.24E-06
RL-W630	1.05E-01	0.00E+00	3.69E-05	2.85E+00	6.14E-01	2.66E-21	4.58E-05	3.57E+00	1.44E-02
RL-W631	1.70E-03	0.00E+00	3.72E-07	4.38E-02	9.05E-03	5.99E-23	4.62E-07	5.45E-02	2.20E-04
RL-W632	7.49E-01	0.00E+00	5.01E-05	5.79E+00	1.77E+00	1.99E-20	6.23E-05	8.30E+00	3.35E-02
RL-W633	1.79E-03	0.00E+00	2.91E-07	9.09E-04	7.46E-04	2.45E-23	3.61E-07	3.44E-03	1.39E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	9.90E-03	0.00E+00	0.00E+00	0.00E+00	9.90E-03	3.99E-05
RL-W635	1.07E+01	0.00E+00	9.82E-03	4.21E+00	5.85E+00	2.48E-19	1.22E-02	2.08E+01	8.37E-02
RL-W636	1.09E-01	0.00E+00	1.86E-05	5.50E-02	4.53E-02	1.51E-21	2.30E-05	2.09E-01	8.44E-04
RL-W637	2.59E-04	0.00E+00	4.73E-07	6.19E-04	5.65E-04	5.41E-24	5.87E-07	1.44E-03	5.82E-06
RL-W638	1.14E-02	0.00E+00	4.81E-06	6.07E-03	5.31E-03	2.01E-22	5.98E-06	2.28E-02	9.18E-05
RL-W639	6.01E-04	0.00E+00	1.23E-07	1.55E-02	3.21E-03	1.41E-23	1.53E-07	1.93E-02	7.80E-05
RL-W640	2.02E-02	0.00E+00	4.09E-06	5.23E-01	1.09E-01	4.53E-22	5.08E-06	6.52E-01	2.63E-03
RL-W641	6.16E-01	0.00E+00	8.99E-04	2.51E+00	9.59E-01	7.27E-21	1.12E-03	4.09E+00	1.65E-02
RL-W642	1.20E-02	0.00E+00	9.34E-08	3.07E-02	1.45E-04	3.14E-24	1.16E-07	4.28E-02	1.73E-04
RL-W643	1.90E-01	0.00E+00	2.77E-04	7.75E-01	2.96E-01	2.24E-21	3.44E-04	1.26E+00	5.08E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.33E-02	0.00E+00	0.00E+00	0.00E+00	5.33E-02	2.15E-04
RL-W645	4.60E-03	0.00E+00	1.25E-06	1.05E-01	2.29E-02	1.22E-22	1.55E-06	1.32E-01	5.34E-04
RL-W646	4.18E-03	0.00E+00	1.11E-06	2.50E-02	1.13E-02	5.94E-23	1.38E-06	4.05E-02	1.63E-04
RL-W647	1.18E-02	0.00E+00	1.66E-04	1.07E-01	1.57E-02	1.99E-22	2.07E-04	1.35E-01	5.43E-04
RL-W648	2.09E-04	0.00E+00	2.84E-07	5.83E-05	1.07E-04	6.37E-24	3.53E-07	3.74E-04	1.51E-06
RL-W649	7.67E-04	0.00E+00	1.05E-06	2.15E-04	3.92E-04	2.34E-23	1.30E-06	1.38E-03	5.55E-06
RL-W653	3.63E-05	0.00E+00	7.49E-09	9.38E-04	1.94E-04	8.92E-25	9.30E-09	1.17E-03	4.71E-06
RL-W654	2.00E-04	0.00E+00	4.09E-08	5.16E-03	1.07E-03	4.69E-24	5.08E-08	6.43E-03	2.59E-05
RL-W655	4.92E+01	0.00E+00	9.68E-03	2.05E-01	4.49E-01	1.25E-18	1.20E-02	4.99E+01	2.01E-01
RL-W656	2.06E+02	0.00E+00	4.35E-03	4.82E-01	4.62E-01	5.97E-18	5.40E-03	2.07E+02	8.35E-01
RL-W657	1.05E+02	0.00E+00	6.43E-03	2.37E-01	4.39E-01	2.64E-18	7.98E-03	1.06E+02	4.27E-01
RL-W659	1.27E+01	0.00E+00	1.45E-03	4.56E-02	5.26E-02	2.98E-19	1.80E-03	1.28E+01	5.17E-02
RL-W660	6.98E+01	0.00E+00	1.74E-02	8.42E-01	1.40E+00	1.70E-18	2.17E-02	7.21E+01	2.91E-01
RL-W661	7.39E-01	0.00E+00	2.18E-05	4.06E-04	3.43E-03	2.07E-20	2.71E-05	7.42E-01	2.99E-03
RL-W662	2.32E-02	0.00E+00	1.30E-06	1.04E-04	1.73E-04	4.23E-22	1.61E-06	2.35E-02	9.48E-05
RL-W665	2.86E+02	0.00E+00	1.04E-01	1.27E+00	1.59E+00	8.42E-18	1.29E-01	2.89E+02	1.16E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W666	5.11E+00	0.00E+00	2.55E-04	5.33E-02	5.22E-02	1.22E-19	3.16E-04	5.22E+00	2.10E-02
RL-W668	4.87E-01	0.00E+00	8.01E-06	1.41E-01	3.71E-02	2.88E-22	9.95E-06	6.65E-01	2.68E-03
RL-W669	1.42E-01	0.00E+00	2.08E-04	5.81E-01	2.21E-01	1.68E-21	2.58E-04	9.44E-01	3.81E-03
RL-W670	8.98E-03	0.00E+00	1.48E-07	2.60E-03	6.87E-04	5.33E-24	1.84E-07	1.23E-02	4.95E-05
RL-W671	1.47E+00	0.00E+00	7.58E-05	4.77E-03	4.61E-03	1.75E-20	9.41E-05	1.47E+00	5.94E-03
RL-W672	9.95E+00	0.00E+00	5.16E-04	3.25E-02	3.13E-02	1.19E-19	6.41E-04	1.00E+01	4.04E-02
RL-W673	9.60E+00	0.00E+00	4.96E-04	3.15E-02	3.02E-02	1.15E-19	6.16E-04	9.66E+00	3.90E-02
RL-W674	3.22E-02	0.00E+00	2.22E-05	1.09E+01	8.78E-02	7.99E-22	2.75E-05	1.10E+01	4.43E-02
RL-W675	1.20E-01	0.00E+00	1.22E-04	1.27E-01	1.02E-01	1.95E-21	1.52E-04	3.50E-01	1.41E-03
RL-W676	4.62E-03	0.00E+00	7.35E-07	1.43E-01	1.93E-03	5.78E-23	9.13E-07	1.49E-01	6.02E-04
RL-W677	1.07E+01	0.00E+00	1.82E-03	5.57E+00	4.50E+00	1.39E-19	2.26E-03	2.08E+01	8.38E-02
RL-W678	3.39E-02	0.00E+00	1.52E-05	5.01E-02	4.11E-02	1.09E-21	1.89E-05	1.25E-01	5.04E-04
RL-W679	2.12E-01	0.00E+00	3.40E-05	1.08E-01	8.84E-02	2.80E-21	4.22E-05	4.09E-01	1.65E-03
RL-W680	4.78E-05	0.00E+00	4.78E-08	1.69E-05	2.82E-05	1.20E-24	5.94E-08	9.31E-05	3.75E-07
RL-W681	2.92E-05	0.00E+00	1.94E-08	4.53E-04	2.10E-04	9.99E-25	2.41E-08	6.92E-04	2.79E-06
RL-W685	8.50E-02	0.00E+00	1.72E-05	2.21E+00	4.57E-01	1.82E-21	2.14E-05	2.76E+00	1.11E-02
RL-W689	2.20E-03	0.00E+00	2.07E-07	3.76E-04	0.00E+00	1.75E-24	2.57E-07	2.58E-03	1.04E-05
RL-W690	7.40E-02	0.00E+00	1.52E-05	1.97E+00	4.06E-01	1.59E-21	1.89E-05	2.45E+00	9.88E-03
RL-W691	1.72E-03	0.00E+00	3.54E-07	4.56E-02	9.41E-03	3.68E-23	4.40E-07	5.68E-02	2.29E-04
RL-W692	6.78E-02	0.00E+00	1.40E-05	1.81E+00	3.73E-01	1.45E-21	1.74E-05	2.25E+00	9.06E-03
RL-W693	8.40E-02	0.00E+00	1.73E-05	2.23E+00	4.62E-01	1.80E-21	2.15E-05	2.78E+00	1.12E-02
RL-W694	8.82E-01	0.00E+00	1.82E-04	2.36E+01	4.84E+00	1.89E-20	2.26E-04	2.93E+01	1.18E-01
RL-W695	7.30E-04	0.00E+00	0.00E+00	2.32E-03	0.00E+00	0.00E+00	0.00E+00	3.05E-03	1.23E-05
RL-W696	9.50E-04	0.00E+00	6.63E-07	2.83E-03	2.59E-03	2.59E-23	8.23E-07	6.37E-03	2.57E-05
RL-W697	2.20E-01	0.00E+00	1.40E-03	6.73E-03	8.58E-04	0.00E+00	1.74E-03	2.31E-01	9.29E-04
RL-W698	1.91E-02	0.00E+00	0.00E+00	3.19E-05	0.00E+00	0.00E+00	0.00E+00	1.91E-02	7.70E-05
RL-W699	4.24E-03	0.00E+00	9.34E-08	2.14E-03	2.33E-04	1.09E-22	1.16E-07	6.61E-03	2.66E-05
RL-W700	1.20E-03	0.00E+00	2.45E-07	3.10E-02	6.41E-03	2.82E-23	3.04E-07	3.86E-02	1.56E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	4.73E-02	0.00E+00	6.91E-05	1.93E-01	7.40E-02	5.59E-22	8.59E-05	3.15E-01	1.27E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W705	3.06E-04	0.00E+00	6.37E-08	8.12E-03	1.69E-03	6.87E-24	7.91E-08	1.01E-02	4.08E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	1.09E-02	0.00E+00	2.26E-06	2.89E-01	5.99E-02	2.44E-22	2.81E-06	3.60E-01	1.45E-03
RL-W708	1.65E-03	0.00E+00	3.43E-07	4.39E-02	9.05E-03	3.70E-23	4.26E-07	5.46E-02	2.20E-04
RL-W709	5.70E-01	0.00E+00	1.18E-04	1.51E+01	3.13E+00	1.28E-20	1.47E-04	1.88E+01	7.60E-02
RL-W710	3.40E-05	0.00E+00	7.06E-09	9.05E-04	1.86E-04	7.64E-25	8.77E-09	1.13E-03	4.54E-06
RL-W711	1.06E-02	0.00E+00	2.20E-06	2.83E-01	5.84E-02	2.38E-22	2.74E-06	3.52E-01	1.42E-03
RL-W712	1.38E-02	0.00E+00	2.85E-06	3.65E-01	7.55E-02	3.09E-22	3.54E-06	4.54E-01	1.83E-03
RL-W713	1.19E-02	0.00E+00	2.46E-06	3.15E-01	6.53E-02	2.66E-22	3.06E-06	3.92E-01	1.58E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	2.05E-04	0.00E+00	4.15E-08	5.33E-03	1.10E-03	4.39E-24	5.15E-08	6.64E-03	2.68E-05
RL-W716	2.14E-03	0.00E+00	4.32E-07	5.55E-02	1.15E-02	4.58E-23	5.37E-07	6.91E-02	2.79E-04
RL-W717	5.33E-04	0.00E+00	1.08E-07	1.39E-02	2.87E-03	1.14E-23	1.34E-07	1.73E-02	6.97E-05
RL-W718	9.41E-05	0.00E+00	1.90E-08	2.45E-03	5.06E-04	2.01E-24	2.37E-08	3.05E-03	1.23E-05
RL-W719	4.24E-04	0.00E+00	8.59E-08	1.11E-02	2.29E-03	9.11E-24	1.07E-07	1.38E-02	5.56E-05
RL-W720	2.63E-03	0.00E+00	5.33E-07	6.83E-02	1.42E-02	5.62E-23	6.62E-07	8.51E-02	3.43E-04
RL-W721	1.78E-03	0.00E+00	3.60E-07	4.62E-02	9.59E-03	3.81E-23	4.47E-07	5.76E-02	2.32E-04
RL-W723	5.89E-03	0.00E+00	1.22E-06	1.57E-01	3.25E-02	1.26E-22	1.51E-06	1.96E-01	7.89E-04
RL-W724	3.92E-02	0.00E+00	8.10E-06	1.04E+00	2.16E-01	8.39E-22	1.01E-05	1.29E+00	5.22E-03
RL-W725	1.24E-02	0.00E+00	2.55E-06	3.29E-01	6.81E-02	2.65E-22	3.17E-06	4.10E-01	1.65E-03
RL-W726	9.75E-03	0.00E+00	2.01E-06	2.60E-01	5.37E-02	2.09E-22	2.50E-06	3.24E-01	1.31E-03
RL-W727	5.98E-02	0.00E+00	1.24E-05	1.59E+00	3.30E-01	1.28E-21	1.54E-05	1.98E+00	7.99E-03
RL-W728	5.45E-02	0.00E+00	1.13E-05	1.46E+00	3.00E-01	1.17E-21	1.40E-05	1.81E+00	7.30E-03
RL-W729	2.52E-02	0.00E+00	5.22E-06	6.70E-01	1.39E-01	5.38E-22	6.48E-06	8.34E-01	3.36E-03
RL-W730	9.84E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.84E+00	3.97E-02
RL-W731	3.17E-06	0.00E+00	0.00E+00	4.38E-04	1.67E-06	0.00E+00	0.00E+00	4.43E-04	1.79E-06
RL-W732	7.27E+00	0.00E+00	2.97E-03	1.23E+02	2.54E+01	1.93E-19	3.69E-03	1.56E+02	6.29E-01
RL-W733	9.54E-02	0.00E+00	3.86E-05	1.34E+00	3.08E-01	2.10E-21	4.80E-05	1.74E+00	7.03E-03
RL-W734	2.99E-01	0.00E+00	1.29E-04	4.62E+00	1.04E+00	6.23E-21	1.60E-04	5.96E+00	2.40E-02
RL-W735	2.44E-01	0.00E+00	9.82E-05	3.60E+00	8.29E-01	4.85E-21	1.22E-04	4.68E+00	1.89E-02
RL-W736	2.68E-04	0.00E+00	2.10E-10	2.39E-03	5.72E-04	1.48E-24	2.60E-10	3.23E-03	1.30E-05

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W737	2.18E-01	0.00E+00	8.96E-05	3.42E+00	7.72E-01	4.18E-21	1.11E-04	4.41E+00	1.78E-02
RL-W738	8.12E-01	0.00E+00	3.08E-04	1.09E+01	2.66E+00	1.52E-20	3.83E-04	1.44E+01	5.79E-02
RL-W739	6.92E-02	0.00E+00	2.72E-05	1.77E+00	3.74E-01	1.38E-21	3.38E-05	2.21E+00	8.91E-03
RL-W740	3.46E+00	0.00E+00	9.97E-04	4.30E+01	1.04E+01	6.95E-20	1.24E-03	5.69E+01	2.29E-01
RL-W741	5.17E+00	0.00E+00	2.35E-03	8.38E+00	5.52E+00	5.22E-20	2.91E-03	1.91E+01	7.69E-02
RL-W742	2.30E-01	0.00E+00	7.06E-05	2.72E+00	5.94E-01	4.47E-21	8.77E-05	3.54E+00	1.43E-02
RL-W743	4.15E-04	0.00E+00	1.92E-08	1.76E-03	0.00E+00	0.00E+00	2.38E-08	2.17E-03	8.76E-06
RL-W744	0.00E+00	0.00E+00	0.00E+00	8.77E-02	6.92E-02	0.00E+00	0.00E+00	1.57E-01	6.33E-04
RL-W745	6.55E-04	0.00E+00	1.34E-07	1.70E-02	3.51E-03	1.54E-23	1.66E-07	2.12E-02	8.53E-05
RL-W746	2.52E-03	0.00E+00	5.16E-07	6.52E-02	1.35E-02	5.91E-23	6.41E-07	8.13E-02	3.28E-04
RL-W747	6.83E-03	0.00E+00	1.40E-06	1.77E-01	3.66E-02	1.60E-22	1.74E-06	2.20E-01	8.87E-04
RL-W748	4.79E+01	0.00E+00	3.92E-03	2.93E-01	4.47E-01	1.21E-18	4.87E-03	4.86E+01	1.96E-01
RL-W749	5.75E-02	0.00E+00	1.20E-05	1.53E+00	3.16E-01	1.29E-21	1.49E-05	1.91E+00	7.69E-03
RL-W750	7.26E+01	0.00E+00	5.94E-03	4.81E-01	7.31E-01	1.71E-18	7.37E-03	7.38E+01	2.98E-01
RL-W751	6.56E+01	0.00E+00	5.36E-03	4.32E-01	6.62E-01	1.54E-18	6.66E-03	6.67E+01	2.69E-01
RL-W752	2.85E+01	0.00E+00	2.33E-03	1.88E-01	2.88E-01	6.68E-19	2.89E-03	2.90E+01	1.17E-01
RL-W753	3.84E+02	0.00E+00	3.14E-02	2.53E+00	3.86E+00	9.00E-18	3.90E-02	3.90E+02	1.57E+00
RP-W754	1.63E+01	0.00E+00	3.98E-03	1.81E+03	1.37E+02	8.31E-20	3.57E-01	1.96E+03	7.90E+00
RP-W755	8.62E+01	0.00E+00	2.38E-03	1.35E+03	1.04E+02	6.21E-20	1.26E+01	1.55E+03	6.26E+00
SA-T001	1.73E-01	3.35E-17	5.70E-05	2.94E+00	1.61E-02	0.00E+00	7.55E-05	3.13E+00	1.26E-02
SA-W134	1.42E+00	1.30E-20	3.89E-04	1.34E+00	3.94E-01	1.58E-21	1.67E-01	3.32E+00	1.34E-02
SA-W134M	1.84E-01	1.68E-21	5.04E-05	1.75E-01	5.11E-02	2.06E-22	2.16E-02	4.31E-01	1.74E-03
T001-221F-HET	3.43E+02	0.00E+00	4.55E+01	2.80E+04	6.40E+02	5.19E-18	6.22E+01	2.91E+04	1.17E+02
T001-221H-HET	6.16E+02	0.00E+00	8.21E+01	5.05E+04	1.16E+03	9.37E-18	1.12E+02	5.24E+04	2.12E+02
T001-235F-HET	3.55E+01	0.00E+00	4.73E+00	2.90E+03	6.64E+01	5.38E-19	6.45E+00	3.02E+03	1.22E+01
T001-772F-HET	3.06E+02	0.00E+00	4.09E+01	2.50E+04	5.73E+02	4.63E-18	5.59E+01	2.60E+04	1.05E+02
T001-773A-CLAS	3.43E+00	0.00E+00	4.58E-01	2.82E+02	6.43E+00	5.22E-20	6.26E-01	2.92E+02	1.18E+00
T001-773A-HET	3.95E+01	0.00E+00	5.27E+00	3.24E+03	7.42E+01	6.02E-19	7.20E+00	3.37E+03	1.36E+01
W006-773A-VIT	5.29E-04	0.00E+00	0.00E+00	5.21E+02	0.00E+00	0.00E+00	0.00E+00	5.21E+02	2.10E+00
W026-221F-HET	1.19E+02	0.00E+00	1.59E+01	9.80E+03	2.23E+02	1.81E-18	2.17E+01	1.02E+04	4.11E+01
W026-221H-HET	8.91E+01	0.00E+00	1.19E+01	7.30E+03	1.67E+02	1.35E-18	1.62E+01	7.58E+03	3.06E+01

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W026-235F-HET	1.39E+00	0.00E+00	1.85E-01	1.14E+02	2.60E+00	2.11E-20	2.53E-01	1.18E+02	4.76E-01
W026-772F-HET	3.79E-01	0.00E+00	5.04E-02	3.10E+01	7.08E-01	5.75E-21	6.89E-02	3.22E+01	1.30E-01
W026-773A-HET	6.15E+00	0.00E+00	8.21E-01	5.05E+02	1.16E+01	9.35E-20	1.12E+00	5.24E+02	2.12E+00
W027-221F-HET	4.50E+02	0.00E+00	5.36E+01	3.79E+04	8.64E+02	2.96E-18	8.43E+01	3.93E+04	1.59E+02
W027-221H-HET	1.97E+02	0.00E+00	2.34E+01	1.66E+04	3.78E+02	1.29E-18	3.68E+01	1.72E+04	6.95E+01
W027-235F-HET	5.91E+01	0.00E+00	7.03E+00	4.99E+03	1.14E+02	3.89E-19	1.11E+01	5.18E+03	2.09E+01
W027-772F-HET	1.08E+02	0.00E+00	1.28E+01	9.06E+03	2.07E+02	7.06E-19	2.01E+01	9.40E+03	3.79E+01
W027-773A-HET	1.60E+02	0.00E+00	1.91E+01	1.35E+04	3.08E+02	1.06E-18	3.00E+01	1.40E+04	5.65E+01
W027-999-HET	1.83E+02	0.00E+00	2.18E+01	1.54E+04	3.52E+02	1.20E-18	3.43E+01	1.60E+04	6.46E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.87E+02	0.00E+00	0.00E+00	0.00E+00	3.87E+02	1.56E+00
WP-INW169.001	8.95E-01	0.00E+00	1.37E-04	1.50E+01	3.08E+00	1.06E-20	3.35E-04	1.89E+01	7.63E-02
WP-INW198.001	1.18E+00	0.00E+00	2.40E-04	2.68E+01	5.49E+00	1.74E-20	3.79E-04	3.35E+01	1.35E-01
WP-INW211.001	1.33E+02	0.00E+00	2.25E-02	2.49E+03	5.09E+02	1.98E-18	2.99E-02	3.13E+03	1.26E+01
WP-INW216.001-	4.82E+03	0.00E+00	1.29E-02	1.44E+03	2.96E+02	1.09E-18	2.92E-01	6.56E+03	2.64E+01
WP-INW216.001-	1.33E+03	0.00E+00	3.49E-03	3.89E+02	7.98E+01	2.96E-19	3.19E-02	1.80E+03	7.24E+00
WP-INW218.001-	9.22E+01	0.00E+00	2.28E-03	2.50E+02	5.15E+01	1.98E-19	3.88E-01	3.95E+02	1.59E+00
WP-INW218.001-	4.25E-01	0.00E+00	6.28E-05	6.81E+00	1.40E+00	5.59E-21	3.74E-02	8.68E+00	3.50E-02
WP-INW222.001	4.36E+00	0.00E+00	6.77E-04	6.66E+01	1.38E+01	4.74E-20	1.41E-03	8.48E+01	3.42E-01
WP-INW243.001	1.06E+01	0.00E+00	1.46E-03	1.40E+02	2.90E+01	9.59E-20	2.68E-03	1.79E+02	7.24E-01
WP-INW247.001R	1.41E+01	0.00E+00	3.40E-03	2.68E+02	5.65E+01	1.66E-19	4.30E-03	3.39E+02	1.37E+00
WP-INW276.001	1.08E+00	0.00E+00	3.31E-04	2.65E+01	5.59E+00	1.41E-20	4.28E-04	3.32E+01	1.34E-01
WP-INW276.002	1.71E+00	0.00E+00	4.98E-04	3.89E+01	8.39E+00	2.11E-20	6.46E-04	4.90E+01	1.98E-01
WP-INW276.003	6.56E+01	0.00E+00	1.85E-02	1.45E+03	3.06E+02	8.90E-19	2.35E-02	1.82E+03	7.33E+00
WP-INW276.004	1.57E+01	0.00E+00	3.92E-03	3.06E+02	6.45E+01	1.88E-19	5.01E-03	3.86E+02	1.56E+00
WP-INW296.001-	5.72E+00	0.00E+00	9.31E-04	7.68E+01	1.61E+01	4.82E-20	1.19E-03	9.86E+01	3.98E-01
WP-INW296.001-	1.73E+01	0.00E+00	3.28E-03	2.72E+02	5.70E+01	1.74E-19	4.43E-03	3.46E+02	1.40E+00
WP-LA-TA-55-19	2.87E-01	0.00E+00	1.53E-04	2.03E+00	4.55E-01	1.73E-21	2.82E-03	2.77E+00	1.12E-02
WP-LA-TA-55-19	1.39E+01	0.00E+00	5.13E-03	2.07E+02	4.68E+01	1.72E-19	9.33E-02	2.68E+02	1.08E+00
WP-LA-TA-55-43	7.81E-02	0.00E+00	1.20E-01	3.14E-01	1.23E-01	1.54E-21	1.75E-01	8.09E-01	3.26E-03
WP-RF001.01	2.42E+01	0.00E+00	4.15E-03	3.98E+02	8.40E+01	1.73E-19	1.45E-02	5.06E+02	2.04E+00
WP-RF002.01-A	2.81E+01	0.00E+00	5.53E-03	4.49E+02	9.50E+01	3.81E-19	2.46E-02	5.72E+02	2.31E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF002.01-B	2.79E-02	0.00E+00	3.83E-06	4.85E-01	1.02E-01	2.39E-22	4.95E-06	6.15E-01	2.48E-03
WP-RF003.01	4.36E+02	0.00E+00	8.90E-02	8.57E+03	1.81E+03	6.29E-18	1.19E-01	1.08E+04	4.36E+01
WP-RF004.01	2.05E-01	0.00E+00	5.96E-05	4.94E+00	1.05E+00	3.60E-21	2.01E-04	6.20E+00	2.50E-02
WP-RF005.01	1.05E+03	0.00E+00	4.52E-02	4.53E+03	9.50E+02	2.50E-18	5.80E-02	6.53E+03	2.63E+01
WP-RF005.02	1.24E+03	0.00E+00	2.34E-02	2.71E+03	5.64E+02	1.28E-18	3.02E-02	4.51E+03	1.82E+01
WP-RF006.01	4.01E+02	0.00E+00	8.50E-02	7.71E+03	1.63E+03	3.25E-18	1.31E-01	9.74E+03	3.93E+01
WP-RF008.01	1.27E+02	0.00E+00	3.03E-02	2.25E+03	4.85E+02	2.14E-18	3.88E-02	2.86E+03	1.16E+01
WP-RF009.01	1.25E+04	0.00E+00	3.72E-01	4.94E+04	1.02E+04	2.46E-17	4.82E-01	7.21E+04	2.91E+02
WP-RF010.01	4.61E+00	0.00E+00	9.42E-04	7.47E+01	1.58E+01	7.59E-20	1.90E-03	9.50E+01	3.83E-01
WP-RF029.01-A	1.11E+00	0.00E+00	1.77E-04	1.31E+01	2.78E+00	1.74E-20	9.48E-04	1.70E+01	6.85E-02
WP-RF029.01-B	1.66E+00	0.00E+00	1.40E-04	1.04E+01	2.20E+00	1.38E-20	2.42E-03	1.42E+01	5.74E-02
WP-RF118.01	2.81E+03	0.00E+00	7.06E-01	4.99E+04	1.03E+04	4.53E-17	1.09E+00	6.30E+04	2.54E+02
WP-RLMPDT.001	5.97E-01	0.00E+00	2.06E-04	7.14E+00	1.72E+00	9.93E-21	2.58E-04	9.46E+00	3.82E-02
WP-RLNPDT.002	7.33E+00	0.00E+00	1.96E-03	7.02E+01	1.75E+01	1.14E-19	2.48E-03	9.50E+01	3.83E-01
WP-SR2001.001.	2.34E-01	0.00E+00	2.26E-04	6.63E+00	1.22E+00	6.21E-21	2.85E-04	8.08E+00	3.26E-02
WP-SR-W027-221	1.73E+00	0.00E+00	6.63E-04	1.90E+01	4.92E+00	2.80E-20	1.86E-01	2.59E+01	1.04E-01
Total	9.25E+04	6.49E-14	4.64E+02	6.41E+05	9.60E+04	6.40E-16	7.43E+02	8.31E+05	3.35E+03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	7.05E-01	0.00E+00	7.06E-10	1.92E+02	8.99E+01	9.83E-62	1.95E-02	2.82E+02	1.14E+00
AE-T003	8.94E-02	0.00E+00	9.40E-11	5.92E+01	1.81E+01	5.39E-62	9.56E-04	7.74E+01	3.12E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	3.96E-04	0.00E+00	2.49E-09	4.36E+01	2.09E-01	1.05E-64	2.28E-02	4.39E+01	1.77E-01
AW-T033.1325	1.45E-03	0.00E+00	9.12E-09	1.59E+02	7.61E-01	3.83E-64	8.37E-02	1.60E+02	6.46E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.08E-01	0.00E+00	0.00E+00	0.00E+00	7.08E-01	2.86E-03
BCLCH-MT01	1.46E-01	0.00E+00	7.06E-08	2.63E+01	5.47E+00	1.48E-61	6.34E-01	3.26E+01	1.31E-01
BT-T002	1.07E-04	1.01E-53	3.69E-11	6.64E-04	1.08E-03	6.50E-65	2.30E-03	4.15E-03	1.68E-05
ET-C1-B55	4.48E-04	0.00E+00	4.20E-13	5.69E-02	2.25E-02	1.15E-64	2.38E-04	8.01E-02	3.23E-04
ET-C1-D139	6.15E-05	0.00E+00	5.83E-14	8.00E-03	3.16E-03	1.53E-65	5.85E-07	1.12E-02	4.53E-05
ET-C2-SEFOR	1.52E-03	0.00E+00	0.00E+00	1.26E-01	3.34E-02	2.35E-64	0.00E+00	1.61E-01	6.47E-04
FM-MOX-MT02	1.44E-08	0.00E+00	2.35E-17	2.75E-07	1.30E-07	8.18E-69	2.19E-10	4.19E-07	1.69E-09
FM-MOX-T01	2.38E-07	0.00E+00	3.87E-16	4.53E-06	2.14E-06	1.35E-67	3.62E-09	6.91E-06	2.79E-08
IN-BN-510	5.76E+01	0.00E+00	2.00E-06	3.64E+04	2.44E+03	3.22E-62	1.99E+01	3.89E+04	1.57E+02
IN-GEM-01	7.28E-01	0.00E+00	3.96E-11	4.09E+01	7.40E+00	2.27E-62	3.56E-04	4.90E+01	1.98E-01
IN-GEM-02	1.73E-01	0.00E+00	9.44E-12	9.71E+00	1.76E+00	5.39E-63	8.47E-05	1.17E+01	4.70E-02
IN-W157.144	8.62E-01	0.00E+00	3.84E-10	2.78E+02	4.98E+01	4.03E-61	3.82E-03	3.28E+02	1.32E+00
IN-W163.1007	1.48E-01	0.00E+00	1.19E-10	8.61E+01	1.54E+01	1.24E-61	1.18E-03	1.02E+02	4.10E-01
IN-W164.153	1.41E-03	0.00E+00	1.13E-12	8.20E-01	1.47E-01	1.19E-63	1.12E-05	9.69E-01	3.91E-03
IN-W167.149	2.83E-01	0.00E+00	1.84E-10	1.33E+02	2.39E+01	1.93E-61	1.83E-03	1.57E+02	6.33E-01
IN-W174.154	0.00E+00	0.00E+00	1.04E-07	1.79E+00	2.79E+00	0.00E+00	1.03E+00	5.61E+00	2.26E-02
IN-W177.156	1.96E-04	0.00E+00	2.21E-07	1.68E+00	8.12E-03	1.65E-64	2.20E+00	3.88E+00	1.57E-02
IN-W179.158	1.32E-03	0.00E+00	2.20E-07	9.71E-02	4.00E-02	1.11E-63	2.19E+00	2.33E+00	9.38E-03
IN-W181.162	1.87E-02	0.00E+00	1.50E-11	1.08E+01	1.94E+00	1.58E-62	1.49E-04	1.28E+01	5.15E-02
IN-W188.160	1.26E-01	0.00E+00	1.01E-10	7.30E+01	1.31E+01	1.06E-61	1.00E-03	8.62E+01	3.48E-01
IN-W216.98	1.12E+03	0.00E+00	8.21E-09	5.96E+03	1.07E+03	8.68E-60	8.17E-02	8.15E+03	3.29E+01
IN-W218.909	5.65E+00	0.00E+00	1.82E-10	1.32E+02	2.37E+01	1.92E-61	1.82E-03	1.61E+02	6.51E-01
IN-W219.110	7.67E-03	0.00E+00	6.15E-12	4.45E+00	7.98E-01	6.46E-63	6.11E-05	5.26E+00	2.12E-02
IN-W219.914	1.21E-03	0.00E+00	9.67E-13	7.03E-01	1.26E-01	1.02E-63	9.62E-06	8.30E-01	3.35E-03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W220.114	4.00E+01	0.00E+00	6.46E-10	5.03E+02	8.77E+01	6.79E-61	6.43E-03	6.31E+02	2.54E+00
IN-W221.927	4.69E-02	0.00E+00	3.75E-11	2.71E+01	4.86E+00	3.95E-62	3.73E-04	3.20E+01	1.29E-01
IN-W222.116	1.59E+00	0.00E+00	1.27E-09	9.16E+02	1.65E+02	1.33E-60	1.26E-02	1.08E+03	4.37E+00
IN-W228.101	1.06E+01	0.00E+00	4.12E-10	3.00E+02	5.37E+01	4.36E-61	4.10E-03	3.64E+02	1.47E+00
IN-W240.931	1.12E+00	0.00E+00	5.27E-10	3.85E+02	6.87E+01	5.51E-61	5.25E-03	4.55E+02	1.83E+00
IN-W243.808	1.55E+00	0.00E+00	9.24E-10	6.72E+02	1.20E+02	9.75E-61	9.19E-03	7.94E+02	3.20E+00
IN-W245.301	2.29E+00	0.00E+00	1.82E-09	1.31E+03	2.36E+02	1.90E-60	1.81E-02	1.55E+03	6.24E+00
IN-W247.810	1.12E+00	0.00E+00	8.84E-10	6.41E+02	1.15E+02	9.29E-61	8.80E-03	7.57E+02	3.05E+00
IN-W249.527	0.00E+00	0.00E+00	6.19E-08	1.14E+01	0.00E+00	0.00E+00	6.15E-01	1.20E+01	4.83E-02
IN-W263.520	3.20E-04	0.00E+00	6.46E-09	7.73E+00	9.72E-03	2.69E-64	6.43E-02	7.80E+00	3.15E-02
IN-W267.1005	2.68E-01	0.00E+00	2.15E-10	1.56E+02	2.79E+01	2.26E-61	2.13E-03	1.84E+02	7.42E-01
IN-W309.609	7.18E+00	0.00E+00	3.60E-09	2.60E+03	4.67E+02	3.78E-60	3.58E-02	3.08E+03	1.24E+01
IN-W315.601	7.08E+00	0.00E+00	1.50E-11	1.09E+01	1.95E+00	1.58E-62	1.50E-04	1.99E+01	8.04E-02
IN-W319.584	4.12E-02	0.00E+00	3.29E-11	2.39E+01	4.30E+00	3.47E-62	3.27E-04	2.83E+01	1.14E-01
IN-W321.1023	3.56E-01	0.00E+00	2.86E-10	2.07E+02	3.71E+01	3.00E-61	2.84E-03	2.45E+02	9.86E-01
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	8.36E+00	1.37E+00	0.00E+00	0.00E+00	9.73E+00	3.92E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.23E+01	3.65E+00	0.00E+00	0.00E+00	2.59E+01	1.05E-01
IN-W323.562	7.61E-04	0.00E+00	4.84E-11	2.28E-01	0.00E+00	6.42E-64	4.81E-04	2.29E-01	9.25E-04
IN-W323.951	8.99E-04	0.00E+00	5.75E-13	2.72E-01	0.00E+00	7.57E-64	5.72E-06	2.73E-01	1.10E-03
IN-W332.661	0.00E+00	0.00E+00	6.34E-10	1.18E-01	0.00E+00	0.00E+00	6.31E-03	1.25E-01	5.02E-04
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	2.79E+00	4.57E-01	0.00E+00	0.00E+00	3.24E+00	1.31E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	8.36E+00	1.37E+00	0.00E+00	0.00E+00	9.73E+00	3.92E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.79E+00	0.00E+00	0.00E+00	0.00E+00	1.79E+00	7.21E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.37E+00	0.00E+00	0.00E+00	0.00E+00	5.37E+00	2.17E-02
IN-W342.652	3.52E-02	0.00E+00	0.00E+00	3.68E-02	7.54E-18	0.00E+00	0.00E+00	7.20E-02	2.90E-04
IN-W342.953	2.35E-02	0.00E+00	0.00E+00	2.47E-02	5.06E-18	0.00E+00	0.00E+00	4.82E-02	1.94E-04
IN-W347.818	1.84E-02	0.00E+00	0.00E+00	7.57E+01	1.10E+02	0.00E+00	1.57E-08	1.86E+02	7.50E-01
IN-W348.1012	9.74E-04	0.00E+00	5.23E-10	3.82E+02	6.86E+01	0.00E+00	5.21E-03	4.51E+02	1.82E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.29E-02	0.00E+00	0.00E+00	0.00E+00	2.29E-02	9.24E-05
IN-W357.1022	0.00E+00	0.00E+00	1.03E-12	7.51E-01	1.34E-01	0.00E+00	1.03E-05	8.85E-01	3.57E-03
IN-W358.854	0.00E+00	0.00E+00	1.55E-08	1.72E+00	2.63E+00	0.00E+00	1.48E-01	4.50E+00	1.82E-02

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W358.855	0.00E+00	0.00E+00	8.29E-08	9.16E+00	1.40E+01	0.00E+00	7.86E-01	2.39E+01	9.66E-02
IN-W358.948	0.00E+00	0.00E+00	1.73E-08	1.92E+00	2.92E+00	0.00E+00	1.64E-01	4.99E+00	2.01E-02
IN-W361.1021	2.59E-04	0.00E+00	9.99E-11	7.24E+01	1.30E+01	0.00E+00	9.94E-04	8.54E+01	3.44E-01
IN-W362.1020	0.00E+00	0.00E+00	1.31E-09	9.44E+02	1.70E+02	0.00E+00	1.30E-02	1.11E+03	4.49E+00
IN-W363.1019	0.00E+00	0.00E+00	6.15E-11	4.48E+01	8.05E+00	0.00E+00	6.12E-04	5.29E+01	2.13E-01
IN-W364.1011	0.00E+00	0.00E+00	1.02E-10	7.37E+01	1.32E+01	0.00E+00	1.01E-03	8.69E+01	3.50E-01
IN-W365.1010	2.41E+00	0.00E+00	8.05E-11	5.82E+01	1.04E+01	0.00E+00	8.01E-04	7.10E+01	2.87E-01
IN-W366.841	8.58E-03	0.00E+00	6.86E-11	4.96E+01	8.92E+00	0.00E+00	6.83E-04	5.85E+01	2.36E-01
IN-W372.832	3.52E-02	0.00E+00	0.00E+00	3.68E-02	7.54E-18	0.00E+00	0.00E+00	7.20E-02	2.90E-04
IN-W375.1096	0.00E+00	0.00E+00	2.53E-11	1.83E+01	3.29E+00	0.00E+00	2.52E-04	2.16E+01	8.72E-02
KN-B234TRU	1.25E+00	0.00E+00	9.67E-10	2.67E+02	7.11E+01	2.11E-61	1.06E-02	3.39E+02	1.37E+00
LA-IT-00-01	1.82E-02	6.52E-51	1.65E-10	5.36E-01	9.20E-03	4.05E-71	1.83E-03	5.65E-01	2.28E-03
LA-OS-00-01	4.05E+01	0.00E+00	7.53E-06	1.13E+03	0.00E+00	0.00E+00	6.82E+01	1.24E+03	4.98E+00
LA-PX-00-01	1.69E-04	0.00E+00	3.18E-13	8.29E-02	1.54E-02	6.70E-65	2.99E-06	9.86E-02	3.97E-04
LA-SL-00-01	0.00E+00	0.00E+00	6.70E-12	1.40E-01	0.00E+00	0.00E+00	7.39E-05	1.40E-01	5.66E-04
LA-TA-03-12	1.74E-03	0.00E+00	1.55E-10	4.00E-01	1.10E-01	3.97E-64	1.77E-03	5.13E-01	2.07E-03
LA-TA-03-13	2.24E-03	0.00E+00	4.92E-10	6.24E-01	1.16E-01	5.26E-64	4.94E-03	7.47E-01	3.01E-03
LA-TA-03-19	4.53E-03	0.00E+00	7.34E-10	1.22E+00	2.79E-01	8.14E-64	8.36E-03	1.51E+00	6.09E-03
LA-TA-03-20	2.47E-03	0.00E+00	3.48E-10	5.37E-01	1.50E-01	6.66E-64	3.81E-03	6.93E-01	2.80E-03
LA-TA-03-24	3.32E-03	0.00E+00	1.36E-09	9.99E-01	2.40E-01	6.91E-64	1.56E-02	1.26E+00	5.07E-03
LA-TA-03-26	1.70E-04	0.00E+00	5.59E-11	2.42E+00	3.14E-02	6.05E-65	1.50E-03	2.45E+00	9.89E-03
LA-TA-03-28	0.00E+00	0.00E+00	1.94E-11	2.26E-01	0.00E+00	0.00E+00	2.19E-04	2.27E-01	9.14E-04
LA-TA-03-30	7.56E-03	0.00E+00	1.38E-11	4.61E+00	1.06E+00	3.17E-63	1.55E-04	5.68E+00	2.29E-02
LA-TA-03-31	0.00E+00	0.00E+00	6.90E-13	8.06E-03	0.00E+00	0.00E+00	7.79E-06	8.07E-03	3.26E-05
LA-TA-03-40	0.00E+00	0.00E+00	1.09E-12	5.01E-02	0.00E+00	0.00E+00	1.24E-05	5.01E-02	2.02E-04
LA-TA-03-42	1.74E-07	0.00E+00	2.73E-14	3.13E-03	3.27E-05	6.62E-68	3.11E-07	3.17E-03	1.28E-05
LA-TA-21-06	1.71E-03	0.00E+00	3.01E-09	8.77E-01	2.12E-01	6.83E-64	3.39E-02	1.13E+00	4.54E-03
LA-TA-21-12	6.23E-03	0.00E+00	1.81E-08	3.04E+00	7.21E-01	2.34E-63	2.05E-01	3.97E+00	1.60E-02
LA-TA-21-13	9.59E-03	0.00E+00	0.00E+00	2.69E-01	0.00E+00	0.00E+00	0.00E+00	2.79E-01	1.13E-03
LA-TA-21-14	1.58E-06	0.00E+00	3.46E-10	4.12E+00	3.81E-05	9.50E-67	3.28E-03	4.12E+00	1.66E-02
LA-TA-21-15	9.29E-04	0.00E+00	9.52E-13	1.27E+00	1.73E-01	3.85E-64	1.07E-05	1.45E+00	5.84E-03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-16	1.08E-02	0.00E+00	1.47E-11	9.71E+00	1.84E+00	4.07E-63	1.67E-04	1.16E+01	4.66E-02
LA-TA-21-40	1.37E-06	0.00E+00	5.08E-11	3.05E-01	2.68E-04	1.63E-67	7.04E-04	3.06E-01	1.23E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	6.50E-01	0.00E+00	0.00E+00	0.00E+00	6.50E-01	2.62E-03
LA-TA-21-42	1.40E-04	0.00E+00	1.65E-11	1.50E-01	8.12E-03	5.31E-66	2.44E-04	1.59E-01	6.40E-04
LA-TA-21-43	4.93E-01	0.00E+00	5.47E-10	4.68E+02	8.85E+01	4.20E-62	8.03E-03	5.57E+02	2.25E+00
LA-TA-21-44	2.36E-03	0.00E+00	1.15E-10	1.05E+02	2.23E-01	5.92E-64	1.40E-03	1.06E+02	4.26E-01
LA-TA-48-01	7.65E-04	3.07E-50	4.32E-13	1.08E-01	3.59E-01	4.89E-65	6.05E-06	4.68E-01	1.89E-03
LA-TA-49-01	9.44E-02	3.81E-48	5.31E-11	1.34E+01	4.45E+01	6.05E-63	7.46E-04	5.80E+01	2.34E-01
LA-TA-50-10	2.53E-04	0.00E+00	5.04E-13	4.21E-02	0.00E+00	0.00E+00	4.70E-06	4.23E-02	1.71E-04
LA-TA-50-11	4.82E-04	0.00E+00	5.15E-13	4.27E-01	7.54E-02	4.85E-65	7.09E-06	5.03E-01	2.03E-03
LA-TA-50-15	9.52E-04	0.00E+00	7.61E-11	3.12E-01	5.55E-02	1.92E-64	8.03E-04	3.69E-01	1.49E-03
LA-TA-50-17	1.39E-01	0.00E+00	6.19E-11	1.67E+01	3.12E-04	1.76E-65	9.90E-04	1.68E+01	6.78E-02
LA-TA-50-18	8.28E-03	0.00E+00	8.17E-12	2.72E+00	3.89E-06	5.18E-67	9.30E-05	2.73E+00	1.10E-02
LA-TA-50-19	2.64E-03	0.00E+00	3.64E-12	3.62E-01	3.33E-03	6.42E-66	6.80E-05	3.68E-01	1.48E-03
LA-TA-50-20	7.25E-05	0.00E+00	0.00E+00	8.93E-03	0.00E+00	0.00E+00	0.00E+00	9.00E-03	3.63E-05
LA-TA-50-40	4.08E-05	0.00E+00	4.92E-14	9.71E-03	3.60E-03	2.06E-65	5.34E-07	1.34E-02	5.39E-05
LA-TA-50-41	4.35E-05	0.00E+00	4.96E-14	4.31E-02	7.98E-03	3.66E-65	4.93E-07	5.11E-02	2.06E-04
LA-TA-55-19	6.75E-02	0.00E+00	6.54E-11	2.42E+01	5.42E+00	2.07E-62	2.24E-03	2.97E+01	1.20E-01
LA-TA-55-20	1.08E+00	0.00E+00	7.45E-10	5.85E+02	1.12E+02	5.18E-61	1.01E-01	6.98E+02	2.81E+00
LA-TA-55-21	9.68E-03	9.08E-54	8.56E-12	4.14E+00	7.90E-01	4.28E-63	8.45E-05	4.94E+00	1.99E-02
LA-TA-55-22	2.65E-02	0.00E+00	4.84E-11	1.46E+01	2.71E+00	1.32E-62	4.78E-04	1.73E+01	6.98E-02
LA-TA-55-23	2.50E-02	0.00E+00	4.04E-11	9.99E+00	1.97E+00	1.30E-62	3.96E-04	1.20E+01	4.83E-02
LA-TA-55-24	9.42E-03	0.00E+00	6.34E-12	5.24E+00	9.72E-01	6.21E-63	5.97E-05	6.22E+00	2.51E-02
LA-TA-55-25	4.82E-02	0.00E+00	3.70E-11	2.60E+01	4.84E+00	3.18E-62	3.48E-04	3.09E+01	1.25E-01
LA-TA-55-28	1.64E-02	0.00E+00	2.05E-11	7.99E+00	1.50E+00	1.03E-62	1.95E-04	9.51E+00	3.83E-02
LA-TA-55-30	3.66E-01	8.60E-56	2.45E-10	1.31E+02	2.52E+01	7.57E-62	2.97E-03	1.57E+02	6.31E-01
LA-TA-55-32	2.97E-02	0.00E+00	1.37E-09	1.04E+01	2.55E+00	9.42E-63	1.58E-02	1.30E+01	5.22E-02
LA-TA-55-33	4.45E-03	0.00E+00	3.54E-12	1.37E+00	3.47E-01	1.32E-63	3.81E-05	1.72E+00	6.92E-03
LA-TA-55-34	4.50E-01	0.00E+00	3.28E-10	2.12E+02	4.28E+01	1.60E-61	6.28E-03	2.55E+02	1.03E+00
LA-TA-55-38	1.13E+00	0.00E+00	1.08E-10	4.67E+01	1.00E+01	3.71E-62	2.84E-03	5.79E+01	2.33E-01
LA-TA-55-39	1.20E-01	0.00E+00	7.97E-11	6.97E+01	1.25E+01	6.54E-62	7.74E-04	8.23E+01	3.32E-01

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-41	2.85E+00	0.00E+00	1.65E-10	8.65E+01	1.65E+01	8.23E-62	1.64E-03	1.06E+02	4.27E-01
LA-TA-55-43	1.07E-03	0.00E+00	1.08E-08	1.30E-01	3.63E-02	7.24E-64	1.04E-01	2.72E-01	1.10E-03
LA-TA-55-44	9.27E-03	0.00E+00	2.55E-08	2.41E+00	5.32E-01	2.14E-63	2.77E-01	3.23E+00	1.30E-02
LA-TA-55-48	6.83E+01	0.00E+00	1.01E-07	1.55E+04	4.60E+03	2.23E-59	1.07E+00	2.02E+04	8.13E+01
LA-TA-55-49	1.46E-01	0.00E+00	1.32E-07	2.83E+01	6.33E+00	2.61E-62	1.43E+00	3.62E+01	1.46E-01
LA-TA-55-53	6.88E-01	0.00E+00	2.74E-10	2.42E+02	4.50E+01	1.43E-61	2.91E-03	2.88E+02	1.16E+00
LA-TA-55-56	7.62E-01	0.00E+00	1.02E-08	3.50E+02	6.99E+01	3.31E-61	1.03E-01	4.21E+02	1.70E+00
LA-TA-55-60	4.13E-04	0.00E+00	2.57E-12	6.60E-02	1.86E-02	1.95E-64	2.77E-05	8.51E-02	3.43E-04
LA-TA-55-61	3.56E-04	0.00E+00	1.19E-11	1.27E-01	3.44E-02	1.90E-64	1.26E-04	1.62E-01	6.54E-04
LA-TA-55-62	9.21E-05	0.00E+00	1.13E-13	2.14E-02	8.12E-03	5.10E-65	1.20E-06	2.96E-02	1.19E-04
LA-TA-55-63	6.84E-05	0.00E+00	7.61E-14	6.85E-02	1.26E-02	5.02E-65	7.76E-07	8.11E-02	3.27E-04
LL-M001	9.38E-01	4.12E-49	3.32E-09	6.42E+01	2.31E+01	3.96E-61	2.98E-02	8.82E+01	3.56E-01
LL-T001	4.68E+00	0.00E+00	0.00E+00	4.89E+02	1.76E+02	3.07E-60	0.00E+00	6.70E+02	2.70E+00
LL-T002	4.63E+01	0.00E+00	2.64E-08	4.75E+03	1.55E+03	2.70E-59	2.37E-01	6.35E+03	2.56E+01
LL-T003	1.80E+00	0.00E+00	2.95E-09	9.62E+01	6.18E+01	1.07E-60	2.65E-02	1.60E+02	6.44E-01
LL-T004	1.14E+00	0.00E+00	6.07E-10	6.11E+01	3.89E+01	6.79E-61	5.45E-03	1.01E+02	4.08E-01
LL-T005	5.90E+00	1.80E-47	7.14E-09	2.27E+02	1.56E+02	2.51E-60	6.41E-02	3.90E+02	1.57E+00
LL-W018	5.03E-04	0.00E+00	0.00E+00	1.70E-02	3.10E-02	5.14E-64	0.00E+00	4.85E-02	1.96E-04
LL-W019	2.72E-01	0.00E+00	0.00E+00	1.32E+01	8.77E+00	1.51E-61	0.00E+00	2.22E+01	8.97E-02
LL-W034	1.01E-01	3.03E-49	1.25E-10	3.85E+00	2.59E+00	4.28E-62	1.12E-03	6.54E+00	2.64E-02
MC-W001	1.26E-03	0.00E+00	0.00E+00	5.55E-02	0.00E+00	7.73E-65	0.00E+00	5.68E-02	2.29E-04
MU-W002	1.68E-02	0.00E+00	0.00E+00	4.82E-02	0.00E+00	0.00E+00	2.65E-12	6.50E-02	2.62E-04
NT-JAS-01	1.62E+00	0.00E+00	2.66E-09	8.69E+01	5.56E+01	9.62E-61	2.39E-02	1.44E+02	5.81E-01
NT-W001	2.43E+00	9.28E-51	5.31E-09	2.62E+03	1.39E+01	6.74E-62	5.92E-02	2.64E+03	1.06E+01
NT-W021	4.71E-02	0.00E+00	3.81E-11	2.95E+01	5.35E+00	3.45E-62	3.88E-04	3.49E+01	1.41E-01
OR-W201	5.65E+01	6.40E-49	1.14E-07	1.98E+03	1.55E+03	3.62E-59	4.43E+01	3.63E+03	1.47E+01
OR-W202	8.10E+00	1.33E-47	3.30E-07	5.08E+02	3.96E+02	1.16E-60	3.41E+00	9.15E+02	3.69E+00
OR-W203	1.78E-02	4.64E-49	4.72E-11	2.28E-02	1.29E+00	2.94E-63	4.85E-04	1.33E+00	5.38E-03
OR-W204	3.98E-03	1.92E-54	5.35E-11	3.89E-01	2.09E-01	0.00E+00	5.50E-04	6.02E-01	2.43E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	3.90E-01	0.00E+00	0.00E+00	0.00E+00	3.90E-01	1.57E-03
RF-MT0001	1.53E+01	0.00E+00	3.32E-10	1.80E+02	3.26E+01	2.65E-61	3.28E-03	2.27E+02	9.17E-01

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0002	1.17E+00	0.00E+00	2.55E-11	1.38E+01	2.50E+00	2.04E-62	2.52E-04	1.75E+01	7.06E-02
RF-MT0003	5.34E-03	0.00E+00	5.83E-12	3.16E+00	5.73E-01	4.65E-63	5.76E-05	3.74E+00	1.51E-02
RF-MT0007	1.34E-02	0.00E+00	0.00E+00	3.94E-01	7.13E-02	5.39E-64	0.00E+00	4.79E-01	1.93E-03
RF-MT0089	5.27E-05	0.00E+00	5.83E-14	3.16E-02	5.72E-03	4.65E-65	5.75E-07	3.74E-02	1.51E-04
RF-MT0090	1.34E-01	0.00E+00	8.25E-11	8.12E+01	1.46E+01	4.65E-62	8.14E-04	9.59E+01	3.87E-01
RF-MT0091	8.29E+00	0.00E+00	8.37E-09	5.43E+03	9.79E+02	3.84E-60	8.56E-02	6.41E+03	2.59E+01
RF-MT0092	1.19E+00	0.00E+00	1.06E-09	7.77E+02	1.43E+02	5.31E-61	1.04E-02	9.21E+02	3.71E+00
RF-MT0093	1.45E+00	0.00E+00	1.09E-09	8.39E+02	1.57E+02	4.52E-61	1.07E-02	9.97E+02	4.02E+00
RF-MT0097	7.23E-02	0.00E+00	4.80E-11	4.38E+01	7.12E+00	2.47E-62	4.73E-04	5.10E+01	2.06E-01
RF-MT0099	7.93E-05	0.00E+00	8.76E-14	4.74E-02	8.56E-03	6.99E-65	8.65E-07	5.60E-02	2.26E-04
RF-MT0290	1.97E-01	0.00E+00	2.17E-10	1.17E+02	2.12E+01	1.73E-61	2.14E-03	1.39E+02	5.59E-01
RF-MT-0292	2.48E-01	0.00E+00	2.74E-10	1.49E+02	2.68E+01	2.19E-61	2.70E-03	1.76E+02	7.08E-01
RF-MT-0299	2.92E+01	0.00E+00	7.02E-09	3.80E+03	6.89E+02	5.63E-60	6.93E-02	4.52E+03	1.82E+01
RF-MT0302	4.47E-04	0.00E+00	2.78E-13	1.64E-01	2.98E-02	2.19E-64	1.95E-05	1.94E-01	7.84E-04
RF-MT0320	5.34E-01	0.00E+00	2.88E-10	1.59E+02	2.89E+01	2.20E-61	2.86E-03	1.89E+02	7.62E-01
RF-MT0321	2.98E-01	0.00E+00	8.60E-11	5.13E+01	9.21E+00	6.17E-62	3.24E-03	6.08E+01	2.45E-01
RF-MT-0328	2.06E-02	0.00E+00	1.03E-11	5.58E+00	1.01E+00	8.23E-63	4.38E-04	6.61E+00	2.67E-02
RF-MT0330	2.15E-01	0.00E+00	1.13E-10	1.13E+02	2.20E+01	7.73E-62	1.12E-03	1.35E+02	5.44E-01
RF-MT-0331	1.29E+00	0.00E+00	7.02E-10	4.96E+02	8.77E+01	4.48E-61	2.75E-02	5.85E+02	2.36E+00
RF-MT0332	1.85E-04	0.00E+00	2.05E-13	1.11E-01	2.00E-02	1.63E-64	2.02E-06	1.31E-01	5.29E-04
RF-MT-0335	1.48E-02	0.00E+00	9.40E-12	5.71E+00	1.04E+00	6.66E-63	6.31E-04	6.76E+00	2.73E-02
RF-MT0336	1.05E+00	0.00E+00	6.23E-10	4.05E+02	7.32E+01	3.91E-61	7.95E-03	4.79E+02	1.93E+00
RF-MT0337	5.93E-01	0.00E+00	3.42E-10	2.47E+02	4.40E+01	1.91E-61	7.20E-03	2.92E+02	1.18E+00
RF-MT0339	1.62E+00	0.00E+00	9.32E-10	5.43E+02	9.72E+01	6.91E-61	2.61E-02	6.41E+02	2.59E+00
RF-MT-0342	9.53E-03	0.00E+00	7.81E-12	5.01E+00	8.92E-01	5.06E-63	1.35E-04	5.91E+00	2.39E-02
RF-MT0371	3.23E+00	0.00E+00	1.81E-09	9.81E+02	1.77E+02	1.44E-60	1.91E-02	1.16E+03	4.68E+00
RF-MT-0372	1.41E-02	0.00E+00	1.27E-11	6.84E+00	1.24E+00	8.92E-63	3.63E-04	8.09E+00	3.26E-02
RF-MT0373	2.12E-01	0.00E+00	1.31E-10	1.28E+02	2.31E+01	7.36E-62	1.29E-03	1.52E+02	6.11E-01
RF-MT0374	6.87E-03	0.00E+00	4.68E-12	2.54E+00	4.59E-01	3.73E-63	4.95E-05	3.00E+00	1.21E-02
RF-MT0376	5.45E-03	0.00E+00	3.78E-12	2.53E+00	4.65E-01	2.75E-63	5.23E-05	3.00E+00	1.21E-02
RF-MT0377	3.24E+00	0.00E+00	2.18E-09	1.18E+03	2.13E+02	1.74E-60	3.16E-02	1.40E+03	5.64E+00

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0378	3.64E-02	0.00E+00	3.01E-11	1.63E+01	2.95E+00	2.40E-62	2.97E-04	1.93E+01	7.78E-02
RF-MT0419	5.84E-02	0.00E+00	2.81E-11	1.52E+01	2.76E+00	2.25E-62	2.77E-04	1.80E+01	7.27E-02
RF-MT0420	1.02E-02	0.00E+00	4.88E-12	2.64E+00	4.79E-01	3.90E-63	4.81E-05	3.13E+00	1.26E-02
RF-MT0423	8.63E-02	0.00E+00	3.97E-11	3.81E+01	6.69E+00	1.55E-62	3.91E-04	4.49E+01	1.81E-01
RF-MT0425	2.54E-03	0.00E+00	1.22E-12	6.61E-01	1.20E-01	9.75E-64	1.21E-05	7.83E-01	3.16E-03
RF-MT-0438	2.30E-02	0.00E+00	1.60E-11	1.17E+01	2.10E+00	9.66E-63	1.71E-04	1.39E+01	5.59E-02
RF-MT0440	8.37E-03	0.00E+00	5.75E-12	4.25E+00	7.83E-01	3.98E-63	2.20E-04	5.04E+00	2.03E-02
RF-MT0442	3.18E-03	0.00E+00	2.49E-12	1.46E+00	2.63E-01	1.48E-63	1.19E-04	1.72E+00	6.95E-03
RF-MT0443	3.92E-02	0.00E+00	4.08E-11	2.26E+01	4.10E+00	3.08E-62	5.60E-04	2.68E+01	1.08E-01
RF-MT0444	3.06E-01	0.00E+00	2.00E-10	1.09E+02	1.97E+01	1.60E-61	2.00E-03	1.29E+02	5.20E-01
RF-MT0480	8.56E-01	0.00E+00	5.63E-10	3.06E+02	5.55E+01	4.11E-61	8.00E-03	3.62E+02	1.46E+00
RF-MT0488	1.37E+00	0.00E+00	8.41E-10	4.55E+02	8.19E+01	6.70E-61	3.90E-02	5.38E+02	2.17E+00
RF-MT0490	6.21E-03	0.00E+00	4.88E-12	2.69E+00	4.87E-01	3.70E-63	5.92E-05	3.18E+00	1.28E-02
RF-MT-0491	4.87E-04	0.00E+00	2.23E-13	1.22E-01	2.20E-02	1.73E-64	4.19E-06	1.44E-01	5.82E-04
RF-MT0523A	3.86E-01	0.00E+00	1.77E-10	9.62E+01	1.74E+01	1.41E-61	2.00E-03	1.14E+02	4.60E-01
RF-MT0523B	3.86E-01	0.00E+00	1.77E-10	9.62E+01	1.74E+01	1.41E-61	2.00E-03	1.14E+02	4.60E-01
RF-MT0523C	3.86E-01	0.00E+00	1.77E-10	9.62E+01	1.74E+01	1.41E-61	2.00E-03	1.14E+02	4.60E-01
RF-MT0523D	3.86E-01	0.00E+00	1.77E-10	9.62E+01	1.74E+01	1.41E-61	2.00E-03	1.14E+02	4.60E-01
RF-MT0523E	3.86E-01	0.00E+00	1.77E-10	9.62E+01	1.74E+01	1.41E-61	2.00E-03	1.14E+02	4.60E-01
RF-MT0531	2.64E-05	0.00E+00	2.92E-14	1.58E-02	2.86E-03	2.33E-65	2.88E-07	1.87E-02	7.52E-05
RF-MT0532E	1.23E+00	0.00E+00	3.79E-10	2.10E+02	3.79E+01	3.01E-61	4.84E-03	2.49E+02	1.00E+00
RF-MT0532F	1.23E+00	0.00E+00	3.79E-10	2.10E+02	3.79E+01	3.01E-61	4.84E-03	2.49E+02	1.00E+00
RF-MT0541	4.48E-02	0.00E+00	5.47E-12	2.98E+00	5.38E-01	4.40E-63	5.40E-05	3.56E+00	1.44E-02
RF-MT0545	2.40E-04	0.00E+00	2.65E-13	1.44E-01	2.60E-02	2.12E-64	2.62E-06	1.70E-01	6.86E-04
RF-MT0800	9.12E+00	0.00E+00	1.31E-10	7.10E+01	1.28E+01	1.05E-61	1.78E-03	9.30E+01	3.75E-01
RF-MT0801	1.05E+00	0.00E+00	1.29E-10	6.97E+01	1.26E+01	1.02E-61	1.27E-03	8.34E+01	3.36E-01
RF-MT0803	2.35E-02	0.00E+00	2.87E-12	1.56E+00	2.81E-01	2.30E-63	2.84E-05	1.86E+00	7.51E-03
RF-MT0806	1.11E-02	0.00E+00	6.90E-12	6.77E+00	1.21E+00	3.88E-63	6.81E-05	7.99E+00	3.22E-02
RF-MT0807	1.40E-01	0.00E+00	5.31E-11	2.88E+01	5.21E+00	4.24E-62	5.24E-04	3.41E+01	1.38E-01
RF-MT0816	1.50E-02	0.00E+00	7.49E-12	4.06E+00	7.32E-01	6.00E-63	7.40E-05	4.81E+00	1.94E-02
RF-MT-0823	7.44E-03	0.00E+00	3.41E-12	1.85E+00	3.35E-01	2.71E-63	3.85E-05	2.19E+00	8.85E-03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0827	3.79E-01	0.00E+00	1.90E-10	1.03E+02	1.86E+01	1.51E-61	1.87E-03	1.22E+02	4.90E-01
RF-MT0831	7.23E-01	0.00E+00	5.19E-10	2.78E+02	5.03E+01	3.99E-61	1.73E-02	3.29E+02	1.33E+00
RF-MT0832	4.32E+00	0.00E+00	1.88E-09	1.08E+03	1.95E+02	1.42E-60	5.17E-02	1.28E+03	5.16E+00
RF-MT0833	1.31E+00	0.00E+00	5.63E-10	3.13E+02	5.66E+01	4.28E-61	1.47E-02	3.70E+02	1.49E+00
RF-MT0855	2.26E-04	0.00E+00	2.50E-13	1.36E-01	2.45E-02	2.00E-64	2.47E-06	1.60E-01	6.47E-04
RF-MT0857	1.11E-02	0.00E+00	6.86E-12	6.75E+00	1.21E+00	3.87E-63	6.77E-05	7.98E+00	3.22E-02
RF-MT0H61	4.12E-01	0.00E+00	2.55E-10	2.50E+02	4.50E+01	1.44E-61	2.52E-03	2.96E+02	1.19E+00
RF-MT2116	4.63E-02	0.00E+00	2.02E-11	1.16E+01	2.09E+00	1.53E-62	5.54E-04	1.37E+01	5.52E-02
RF-MT3010	2.90E-01	0.00E+00	2.10E-10	1.15E+02	2.09E+01	1.64E-61	2.46E-03	1.36E+02	5.47E-01
RF-MT3011	2.16E+00	0.00E+00	1.31E-09	7.07E+02	1.28E+02	1.05E-60	2.06E-02	8.38E+02	3.38E+00
RF-MT420P	1.15E+01	0.00E+00	6.62E-09	5.82E+03	1.05E+03	3.41E-60	7.53E-02	6.88E+03	2.78E+01
RF-MT532A	3.03E+00	0.00E+00	9.36E-10	5.19E+02	9.35E+01	7.40E-61	1.19E-02	6.15E+02	2.48E+00
RF-MT532B	1.36E+01	0.00E+00	4.20E-09	2.33E+03	4.21E+02	3.33E-60	5.36E-02	2.76E+03	1.11E+01
RF-MT532C	2.73E+01	0.00E+00	8.45E-09	4.66E+03	8.41E+02	6.66E-60	1.08E-01	5.53E+03	2.23E+01
RF-MT532D	1.73E-01	0.00E+00	5.31E-11	2.95E+01	5.32E+00	4.20E-62	6.78E-04	3.50E+01	1.41E-01
RF-TT0069	9.92E-04	0.00E+00	6.30E-13	3.42E-01	6.19E-02	5.06E-64	7.91E-05	4.05E-01	1.63E-03
RF-TT0200	4.71E-02	0.00E+00	2.55E-11	1.40E+01	2.55E+00	1.94E-62	2.52E-04	1.66E+01	6.70E-02
RF-TT0299	1.95E-01	0.00E+00	4.72E-11	2.56E+01	4.63E+00	3.77E-62	4.66E-04	3.04E+01	1.23E-01
RF-TT0300	1.59E+00	0.00E+00	1.34E-09	7.34E+02	1.33E+02	9.17E-61	2.16E-02	8.69E+02	3.50E+00
RF-TT0301	2.15E-01	0.00E+00	1.82E-10	9.99E+01	1.81E+01	1.24E-61	2.93E-03	1.18E+02	4.77E-01
RF-TT0302	1.06E-02	0.00E+00	6.62E-12	3.90E+00	7.08E-01	5.22E-63	4.61E-04	4.62E+00	1.86E-02
RF-TT0303	6.40E-02	0.00E+00	3.87E-11	2.10E+01	3.79E+00	3.09E-62	1.41E-03	2.48E+01	1.00E-01
RF-TT0310	2.18E-01	0.00E+00	1.82E-10	9.44E+01	1.76E+01	1.13E-61	1.98E-03	1.12E+02	4.53E-01
RF-TT0312	5.23E+00	0.00E+00	3.28E-09	2.06E+03	3.70E+02	2.38E-60	3.41E-02	2.44E+03	9.83E+00
RF-TT0317	3.29E-03	0.00E+00	3.56E-12	1.93E+00	3.50E-01	2.85E-63	3.52E-05	2.29E+00	9.22E-03
RF-TT0320	2.11E+00	0.00E+00	1.14E-09	6.31E+02	1.15E+02	8.72E-61	1.13E-02	7.47E+02	3.01E+00
RF-TT0330	7.52E-01	0.00E+00	3.95E-10	3.96E+02	7.69E+01	2.71E-61	3.90E-03	4.74E+02	1.91E+00
RF-TT-0331	3.74E+00	0.00E+00	2.04E-09	1.44E+03	2.55E+02	1.30E-60	7.99E-02	1.70E+03	6.85E+00
RF-TT-0334	1.63E+00	0.00E+00	1.65E-09	8.94E+02	1.62E+02	1.32E-60	1.63E-02	1.06E+03	4.27E+00
RF-TT0335	1.98E+00	0.00E+00	1.25E-09	7.61E+02	1.39E+02	8.88E-61	8.40E-02	9.01E+02	3.63E+00
RF-TT0336	1.75E+00	0.00E+00	1.04E-09	6.74E+02	1.22E+02	6.50E-61	1.33E-02	7.97E+02	3.21E+00

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0337	2.08E+00	0.00E+00	1.20E-09	8.70E+02	1.54E+02	6.70E-61	2.53E-02	1.03E+03	4.14E+00
RF-TT0338	8.83E+00	0.00E+00	4.36E-09	3.39E+03	6.03E+02	2.99E-60	5.13E-02	4.00E+03	1.61E+01
RF-TT0340	7.55E-02	0.00E+00	8.33E-11	4.51E+01	8.19E+00	6.66E-62	8.22E-04	5.34E+01	2.15E-01
RF-TT0342	5.05E-01	0.00E+00	4.16E-10	2.66E+02	4.72E+01	2.68E-61	7.19E-03	3.14E+02	1.26E+00
RF-TT0360	3.85E-02	0.00E+00	2.11E-11	1.19E+01	2.18E+00	1.58E-62	2.15E-04	1.41E+01	5.70E-02
RF-TT0368	7.70E-01	0.00E+00	4.24E-10	2.39E+02	4.37E+01	3.17E-61	4.31E-03	2.84E+02	1.14E+00
RF-TT0370	1.52E+00	0.00E+00	9.16E-10	5.32E+02	9.64E+01	6.74E-61	1.68E-02	6.30E+02	2.54E+00
RF-TT0371	3.29E-02	0.00E+00	1.84E-11	9.99E+00	1.81E+00	1.47E-62	1.95E-04	1.18E+01	4.77E-02
RF-TT0372	4.02E-03	0.00E+00	3.63E-12	1.95E+00	3.54E-01	2.55E-63	1.04E-04	2.31E+00	9.31E-03
RF-TT0374	1.25E-01	0.00E+00	8.52E-11	4.61E+01	8.34E+00	6.79E-62	9.01E-04	5.46E+01	2.20E-01
RF-TT0375A	1.30E-03	0.00E+00	1.40E-12	7.58E-01	1.37E-01	1.12E-63	1.39E-05	8.96E-01	3.61E-03
RF-TT0375B	1.30E-03	0.00E+00	1.40E-12	7.58E-01	1.37E-01	1.12E-63	1.39E-05	8.96E-01	3.61E-03
RF-TT0376	3.00E-01	0.00E+00	2.08E-10	1.39E+02	2.55E+01	1.51E-61	2.88E-03	1.65E+02	6.66E-01
RF-TT0377	1.68E-01	0.00E+00	1.13E-10	6.12E+01	1.11E+01	9.01E-62	1.64E-03	7.25E+01	2.92E-01
RF-TT0391	3.75E-02	0.00E+00	1.59E-11	1.55E+01	2.76E+00	1.58E-62	1.57E-04	1.83E+01	7.37E-02
RF-TT0392	1.32E-02	0.00E+00	9.99E-12	8.09E+00	1.46E+00	5.47E-63	9.88E-05	9.56E+00	3.86E-02
RF-TT0393	1.09E+00	0.00E+00	6.98E-10	3.77E+02	6.82E+01	5.55E-61	6.89E-03	4.46E+02	1.80E+00
RF-TT0398	2.37E-02	0.00E+00	1.84E-11	1.51E+01	2.71E+00	1.03E-62	1.82E-04	1.79E+01	7.20E-02
RF-TT0409	1.98E-02	0.00E+00	8.60E-12	7.81E+00	1.40E+00	3.97E-63	8.55E-05	9.23E+00	3.72E-02
RF-TT0412	1.98E-02	0.00E+00	8.60E-12	7.81E+00	1.40E+00	3.97E-63	8.55E-05	9.23E+00	3.72E-02
RF-TT0414	6.14E-01	0.00E+00	2.66E-10	2.42E+02	4.33E+01	1.23E-61	2.65E-03	2.86E+02	1.15E+00
RF-TT0430	1.80E-04	0.00E+00	1.99E-13	1.07E-01	1.94E-02	1.58E-64	1.96E-06	1.27E-01	5.11E-04
RF-TT0431	4.47E-02	0.00E+00	4.84E-11	2.64E+01	4.78E+00	3.76E-62	6.98E-04	3.12E+01	1.26E-01
RF-TT0438	2.66E+00	0.00E+00	1.84E-09	1.35E+03	2.42E+02	1.11E-60	1.97E-02	1.59E+03	6.42E+00
RF-TT0440	2.62E-01	0.00E+00	1.79E-10	1.33E+02	2.46E+01	1.25E-61	6.89E-03	1.58E+02	6.36E-01
RF-TT0441	1.29E+00	0.00E+00	8.41E-10	4.59E+02	8.34E+01	6.62E-61	1.29E-02	5.44E+02	2.19E+00
RF-TT0442	1.86E-01	0.00E+00	1.45E-10	8.50E+01	1.54E+01	8.64E-62	6.91E-03	1.01E+02	4.05E-01
RF-TT0443	3.98E-03	0.00E+00	4.16E-12	2.30E+00	4.16E-01	3.13E-63	5.70E-05	2.72E+00	1.10E-02
RF-TT0479	3.90E-02	0.00E+00	4.32E-11	2.33E+01	4.22E+00	3.44E-62	4.26E-04	2.75E+01	1.11E-01
RF-TT0480	2.65E+00	0.00E+00	1.74E-09	9.53E+02	1.72E+02	1.28E-60	2.48E-02	1.13E+03	4.55E+00
RF-TT0481	1.50E-03	0.00E+00	9.83E-13	5.35E-01	9.72E-02	7.20E-64	1.40E-05	6.34E-01	2.56E-03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0483	4.80E-03	0.00E+00	5.31E-12	2.87E+00	5.20E-01	4.24E-63	1.71E-02	3.41E+00	1.38E-02
RF-TT0484	2.57E-02	0.00E+00	2.20E-11	1.19E+01	2.16E+00	1.76E-62	3.27E-04	1.41E+01	5.69E-02
RF-TT0485	2.11E-03	0.00E+00	1.36E-12	7.35E-01	1.33E-01	1.09E-63	2.89E-04	8.71E-01	3.51E-03
RF-TT0486	1.25E-02	0.00E+00	8.05E-12	4.36E+00	7.90E-01	6.42E-63	3.05E-04	5.17E+00	2.08E-02
RF-TT0487	6.28E-02	0.00E+00	2.74E-11	1.57E+01	2.83E+00	2.07E-62	7.50E-04	1.86E+01	7.48E-02
RF-TT0489	1.79E-02	0.00E+00	1.23E-11	6.65E+00	1.20E+00	9.83E-63	2.21E-04	7.88E+00	3.18E-02
RF-TT0490	9.89E-01	0.00E+00	7.81E-10	4.29E+02	7.76E+01	5.88E-61	9.48E-03	5.07E+02	2.05E+00
RF-TT0491	2.30E-02	0.00E+00	1.06E-11	5.75E+00	1.04E+00	8.18E-63	1.99E-04	6.81E+00	2.74E-02
RF-TT0492	7.73E-03	0.00E+00	5.95E-12	3.21E+00	5.82E-01	4.73E-63	5.87E-05	3.80E+00	1.53E-02
RF-TT0523A	5.20E-02	0.00E+00	2.39E-11	1.29E+01	2.34E+00	1.90E-62	2.70E-04	1.53E+01	6.18E-02
RF-TT0523B	5.20E-02	0.00E+00	2.39E-11	1.29E+01	2.34E+00	1.90E-62	2.70E-04	1.53E+01	6.18E-02
RF-TT0523C	5.20E-02	0.00E+00	2.39E-11	1.29E+01	2.34E+00	1.90E-62	2.70E-04	1.53E+01	6.18E-02
RF-TT0523D	5.20E-02	0.00E+00	2.39E-11	1.29E+01	2.34E+00	1.90E-62	2.70E-04	1.53E+01	6.18E-02
RF-TT0523E	5.20E-02	0.00E+00	2.39E-11	1.29E+01	2.34E+00	1.90E-62	2.70E-04	1.53E+01	6.18E-02
RF-TT0532A	1.30E+00	0.00E+00	4.00E-10	2.23E+02	4.02E+01	3.18E-61	5.11E-03	2.64E+02	1.07E+00
RF-TT0532B	1.30E+00	0.00E+00	4.00E-10	2.23E+02	4.02E+01	3.18E-61	5.11E-03	2.64E+02	1.07E+00
RF-TT0541	2.15E-03	0.00E+00	2.38E-12	1.29E+00	2.34E-01	1.90E-63	2.35E-05	1.53E+00	6.16E-03
RF-TT0545	4.80E-04	0.00E+00	5.31E-13	2.87E-01	5.20E-02	4.24E-64	5.24E-06	3.39E-01	1.37E-03
RF-TT0601	1.67E-01	0.00E+00	9.16E-11	5.18E+01	9.50E+00	6.87E-62	9.31E-04	6.14E+01	2.48E-01
RF-TT0802	1.87E+01	0.00E+00	7.53E-09	4.09E+03	7.40E+02	6.00E-60	7.43E-02	4.85E+03	1.95E+01
RF-TT0809	1.53E+00	0.00E+00	6.19E-10	3.36E+02	6.06E+01	4.94E-61	6.11E-03	3.99E+02	1.61E+00
RF-TT0821	3.32E+00	0.00E+00	2.25E-09	1.32E+03	2.39E+02	1.47E-60	1.89E-01	1.56E+03	6.30E+00
RF-TT0822	3.67E+00	0.00E+00	1.75E-09	9.90E+02	1.78E+02	1.31E-60	1.98E-01	1.17E+03	4.73E+00
RF-TT0823	7.44E-03	0.00E+00	3.41E-12	1.85E+00	3.35E-01	2.71E-63	3.85E-05	2.19E+00	8.85E-03
RF-TT0824	7.66E+00	0.00E+00	4.80E-09	2.67E+03	4.82E+02	3.70E-60	1.09E-01	3.16E+03	1.27E+01
RF-TT0825	6.35E+00	0.00E+00	3.47E-09	2.01E+03	3.63E+02	2.45E-60	1.15E-01	2.38E+03	9.58E+00
RF-TT0832	4.70E+00	0.00E+00	2.05E-09	1.17E+03	2.12E+02	1.55E-60	5.63E-02	1.39E+03	5.61E+00
RF-TT0854	1.69E-03	0.00E+00	1.87E-12	1.01E+00	1.83E-01	1.49E-63	7.59E-04	1.19E+00	4.81E-03
RF-TT0886	2.40E-04	0.00E+00	2.64E-13	1.43E-01	2.60E-02	2.11E-64	2.61E-06	1.69E-01	6.82E-04
RF-TT2216	6.94E-02	0.00E+00	3.03E-11	1.74E+01	3.13E+00	2.29E-62	8.32E-04	2.06E+01	8.31E-02
RF-TT3010	3.71E+00	0.00E+00	2.68E-09	1.47E+03	2.66E+02	2.09E-60	3.15E-02	1.74E+03	7.00E+00

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT3011	9.37E+00	0.00E+00	5.67E-09	3.06E+03	5.55E+02	4.52E-60	8.94E-02	3.63E+03	1.46E+01
RF-TT301U	7.78E-01	0.00E+00	5.99E-10	3.33E+02	6.12E+01	4.44E-61	6.07E-03	3.95E+02	1.59E+00
RF-TT310P	2.25E-01	0.00E+00	1.56E-10	1.12E+02	1.92E+01	9.29E-62	1.54E-03	1.31E+02	5.29E-01
RF-TT338S	6.57E-03	0.00E+00	7.14E-12	3.86E+00	6.99E-01	5.68E-63	7.04E-05	4.56E+00	1.84E-02
RF-TT390P	3.70E-02	0.00E+00	1.94E-11	1.88E+01	3.13E+00	1.42E-62	2.20E-04	2.20E+01	8.85E-02
RF-TT391P	2.04E+00	0.00E+00	8.68E-10	8.44E+02	1.50E+02	8.60E-61	8.57E-03	9.96E+02	4.02E+00
RF-TT392P	4.13E+00	0.00E+00	3.13E-09	2.53E+03	4.56E+02	1.71E-60	3.09E-02	2.99E+03	1.21E+01
RF-TT393R	6.11E-01	0.00E+00	5.31E-10	3.87E+02	7.02E+01	2.76E-61	5.42E-03	4.58E+02	1.85E+00
RF-TT394P	7.58E-02	0.00E+00	3.29E-11	2.99E+01	5.01E+00	1.99E-62	3.31E-04	3.50E+01	1.41E-01
RF-TT395P	1.02E-01	0.00E+00	4.40E-11	4.00E+01	6.69E+00	2.66E-62	4.44E-04	4.68E+01	1.89E-01
RF-TT396P	2.53E-02	0.00E+00	1.10E-11	9.99E+00	1.68E+00	6.62E-63	1.11E-04	1.17E+01	4.71E-02
RF-TT398P	2.45E+00	0.00E+00	1.90E-09	1.57E+03	2.81E+02	1.07E-60	1.88E-02	1.85E+03	7.46E+00
RF-TT398R	2.02E+01	0.00E+00	3.54E-09	2.53E+03	4.54E+02	2.08E-60	3.49E-02	3.00E+03	1.21E+01
RF-TT411R	7.33E-01	0.00E+00	3.18E-10	2.89E+02	5.17E+01	1.47E-61	3.16E-03	3.41E+02	1.38E+00
RF-TT429R	1.54E+00	0.00E+00	6.82E-11	6.69E+01	1.18E+01	2.56E-62	6.73E-04	8.02E+01	3.23E-01
RF-TT433X	4.85E-01	0.00E+00	1.89E-11	1.92E+01	3.05E+00	1.02E-62	1.86E-04	2.28E+01	9.19E-02
RF-TT436R	3.55E+00	0.00E+00	2.73E-10	2.52E+02	4.50E+01	1.96E-61	2.70E-03	3.01E+02	1.21E+00
RF-TT454X	2.09E-01	0.00E+00	1.61E-11	1.49E+01	2.65E+00	1.16E-62	1.59E-04	1.77E+01	7.14E-02
RL-T101	1.06E+00	0.00E+00	9.75E-10	8.02E+02	1.42E+02	1.63E-60	8.76E-03	9.45E+02	3.81E+00
RL-T102	1.34E-05	0.00E+00	1.24E-14	1.03E-02	1.81E-03	2.07E-65	1.25E-06	1.21E-02	4.88E-05
RL-T103	9.51E-01	0.00E+00	1.18E-09	3.50E+02	6.16E+01	8.68E-61	1.06E-02	4.13E+02	1.66E+00
RL-T104	1.92E-05	0.00E+00	1.77E-14	1.46E-02	2.60E-03	2.97E-65	1.91E-07	1.72E-02	6.93E-05
RL-T105	7.38E-03	0.00E+00	6.70E-12	5.54E+00	9.79E-01	1.12E-62	1.05E-04	6.52E+00	2.63E-02
RL-T106	7.12E-03	0.00E+00	6.58E-12	5.41E+00	9.57E-01	1.10E-62	5.91E-05	6.37E+00	2.57E-02
RL-T107	1.96E+01	0.00E+00	3.87E-06	1.49E+04	2.64E+03	3.01E-59	3.55E+01	1.76E+04	7.11E+01
RL-T108	1.12E-02	0.00E+00	6.66E-10	8.50E+00	1.51E+00	1.73E-62	6.01E-03	1.00E+01	4.04E-02
RL-T109	1.54E-02	0.00E+00	1.37E-11	1.13E+01	2.00E+00	2.29E-62	2.32E-02	1.33E+01	5.37E-02
RL-T110	1.73E+00	0.00E+00	2.62E-09	1.29E+03	2.30E+02	2.63E-60	1.37E+00	1.53E+03	6.15E+00
RL-T112	6.96E-01	0.00E+00	1.11E-09	1.71E+02	3.04E+01	3.48E-61	7.40E-01	2.03E+02	8.19E-01
RL-T113	7.44E-04	0.00E+00	2.14E-12	5.65E-01	1.00E-01	1.15E-63	1.92E-05	6.65E-01	2.68E-03
RL-T114	1.13E-01	0.00E+00	1.04E-10	8.58E+01	1.52E+01	1.74E-61	9.36E-04	1.01E+02	4.08E-01

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T115	2.88E+00	0.00E+00	3.38E-09	1.13E+03	2.00E+02	2.57E-60	4.40E-01	1.33E+03	5.37E+00
RL-T116	1.86E-01	0.00E+00	1.71E-10	1.40E+02	2.49E+01	2.86E-61	5.73E-02	1.65E+02	6.67E-01
RL-T118	4.77E-01	0.00E+00	1.37E-09	1.39E+02	2.47E+01	2.83E-61	8.38E-01	1.65E+02	6.67E-01
RL-T120	1.16E-01	0.00E+00	1.44E-10	4.12E+01	7.25E+00	9.95E-62	1.29E-03	4.86E+01	1.96E-01
RL-T122	6.56E-03	0.00E+00	6.07E-12	4.97E+00	8.85E-01	1.01E-62	1.45E+00	7.31E+00	2.95E-02
RL-T123	1.93E-02	0.00E+00	1.78E-11	1.46E+01	2.60E+00	2.98E-62	5.94E-02	1.72E+01	6.95E-02
RL-T125	3.84E+00	0.00E+00	4.40E-09	3.05E+02	1.25E+02	4.65E-60	3.95E-02	4.34E+02	1.75E+00
RL-T127	3.70E+00	0.00E+00	1.11E-09	9.12E+02	1.62E+02	1.85E-60	8.93E-02	1.08E+03	4.34E+00
RL-T128	5.48E-03	0.00E+00	2.69E-17	2.22E-05	3.92E-06	4.48E-68	2.41E-10	5.50E-03	2.22E-05
RL-T129	1.64E-02	0.00E+00	5.11E-09	1.26E+01	2.21E+00	2.53E-62	5.35E-02	1.48E+01	5.98E-02
RL-T130	3.49E-05	0.00E+00	3.23E-14	2.67E-02	4.72E-03	5.39E-65	8.26E-05	3.15E-02	1.27E-04
RL-T131	1.42E-02	0.00E+00	1.76E-11	5.08E+00	8.92E-01	1.22E-62	8.32E-03	5.99E+00	2.42E-02
RL-T132	3.39E+00	0.00E+00	3.12E-09	2.58E+03	4.56E+02	5.22E-60	2.71E-01	3.04E+03	1.22E+01
RL-T133	6.89E-05	0.00E+00	5.00E-14	4.22E-02	7.47E-03	7.40E-65	4.49E-07	4.98E-02	2.01E-04
RL-T134	1.46E-04	0.00E+00	1.34E-13	1.11E-01	1.96E-02	2.25E-64	1.21E-06	1.31E-01	5.27E-04
RL-T135	6.82E-04	0.00E+00	6.30E-13	5.19E-01	9.21E-02	1.05E-63	4.12E-03	6.16E-01	2.48E-03
RL-T137	1.11E+01	0.00E+00	1.38E-08	3.95E+03	6.96E+02	9.58E-60	1.30E-01	4.66E+03	1.88E+01
RL-T140	1.30E+01	0.00E+00	1.31E-08	3.82E+03	7.47E+02	8.14E-60	2.61E+01	4.61E+03	1.86E+01
RL-T143	8.13E-02	0.00E+00	7.49E-11	6.18E+01	1.10E+01	1.25E-61	3.89E-02	7.28E+01	2.94E-01
RL-T145	2.31E-01	0.00E+00	2.14E-10	1.76E+02	3.11E+01	3.57E-61	9.08E-02	2.07E+02	8.36E-01
RL-W407	6.65E-01	0.00E+00	4.56E-10	4.03E+02	7.15E+01	5.43E-61	4.09E-03	4.75E+02	1.92E+00
RL-W408	2.73E-06	0.00E+00	1.93E-15	1.63E-03	2.89E-04	2.80E-66	1.73E-08	1.92E-03	7.76E-06
RL-W415	6.02E-05	0.00E+00	4.24E-14	3.61E-02	6.40E-03	6.17E-65	3.81E-07	4.26E-02	1.72E-04
RL-W418	2.58E-04	0.00E+00	1.79E-13	1.55E-01	2.75E-02	2.30E-64	1.61E-06	1.83E-01	7.36E-04
RL-W437	2.18E+00	0.00E+00	1.50E-09	1.32E+03	2.34E+02	1.78E-60	1.35E-02	1.56E+03	6.27E+00
RL-W438	3.82E-06	0.00E+00	2.69E-15	2.28E-03	4.04E-04	3.91E-66	2.42E-08	2.69E-03	1.08E-05
RL-W439	1.20E+02	0.00E+00	1.48E-07	4.40E+04	7.76E+03	1.09E-58	1.33E+00	5.19E+04	2.09E+02
RL-W443	1.92E+00	0.00E+00	1.32E-09	1.16E+03	2.06E+02	1.57E-60	1.19E-02	1.37E+03	5.53E+00
RL-W444	1.42E+00	0.00E+00	9.79E-10	8.63E+02	1.53E+02	1.16E-60	8.79E-03	1.02E+03	4.10E+00
RL-W447	1.63E-04	0.00E+00	1.15E-13	9.71E-02	1.73E-02	1.67E-64	1.04E-06	1.15E-01	4.62E-04
RL-W448	1.21E-06	0.00E+00	8.52E-16	7.21E-04	1.28E-04	1.24E-66	7.65E-09	8.50E-04	3.43E-06

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W449	9.91E-03	0.00E+00	3.12E-14	2.06E-02	3.65E-03	2.25E-65	2.80E-07	3.42E-02	1.38E-04
RL-W450	1.82E-05	0.00E+00	1.29E-14	1.09E-02	1.93E-03	1.87E-65	1.15E-07	1.29E-02	5.18E-05
RL-W451	2.60E-06	0.00E+00	1.83E-15	1.55E-03	2.75E-04	2.66E-66	1.64E-08	1.83E-03	7.36E-06
RL-W452	1.13E-04	0.00E+00	7.89E-14	6.83E-02	1.21E-02	1.01E-64	7.08E-07	8.05E-02	3.25E-04
RL-W453	3.22E-05	0.00E+00	2.22E-14	1.96E-02	3.47E-03	2.64E-65	1.99E-07	2.31E-02	9.32E-05
RL-W454	4.51E-04	0.00E+00	3.10E-13	2.74E-01	4.85E-02	3.69E-64	2.79E-06	3.23E-01	1.30E-03
RL-W455	1.20E-04	0.00E+00	8.37E-14	7.25E-02	1.28E-02	1.08E-64	7.51E-07	8.54E-02	3.45E-04
RL-W456	1.59E-02	0.00E+00	1.09E-11	9.62E+00	1.70E+00	1.33E-62	9.82E-05	1.13E+01	4.57E-02
RL-W457	1.54E-03	0.00E+00	1.06E-12	9.35E-01	1.65E-01	1.29E-63	9.54E-06	1.10E+00	4.44E-03
RL-W458	4.87E-03	0.00E+00	5.43E-12	3.84E-01	1.70E-01	5.18E-63	4.88E-05	5.59E-01	2.25E-03
RL-W459	4.69E-02	0.00E+00	5.59E-11	9.53E+00	2.31E+00	5.14E-62	5.02E-04	1.19E+01	4.80E-02
RL-W460	2.86E-04	0.00E+00	1.97E-13	1.73E-01	3.07E-02	2.34E-64	1.77E-06	2.04E-01	8.24E-04
RL-W461	2.64E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.64E-04	1.06E-06
RL-W462	8.15E-05	0.00E+00	5.71E-14	4.90E-02	8.70E-03	7.65E-65	5.13E-07	5.78E-02	2.33E-04
RL-W463	4.19E-04	0.00E+00	2.89E-13	2.55E-01	4.51E-02	3.43E-64	2.59E-06	3.00E-01	1.21E-03
RL-W464	1.94E-04	0.00E+00	1.33E-13	1.17E-01	2.07E-02	1.58E-64	1.19E-06	1.38E-01	5.57E-04
RL-W465	1.29E-03	0.00E+00	9.00E-13	7.81E-01	1.39E-01	1.14E-63	8.08E-06	9.21E-01	3.71E-03
RL-W466	1.77E-02	0.00E+00	1.23E-11	1.07E+01	1.90E+00	1.52E-62	1.10E-04	1.26E+01	5.10E-02
RL-W467	9.06E-04	0.00E+00	6.30E-13	5.46E-01	9.64E-02	8.35E-64	5.66E-06	6.44E-01	2.60E-03
RL-W468	4.64E-06	0.00E+00	3.25E-15	2.80E-03	4.95E-04	4.36E-66	2.92E-08	3.30E-03	1.33E-05
RL-W469	1.88E-03	0.00E+00	1.30E-12	1.14E+00	2.02E-01	1.60E-63	1.17E-05	1.34E+00	5.41E-03
RL-W470	5.33E-02	0.00E+00	6.07E-11	4.22E+00	1.73E+00	6.46E-62	5.45E-04	6.00E+00	2.42E-02
RL-W474	2.02E-03	0.00E+00	6.70E-12	9.62E-03	6.53E-03	0.00E+00	6.02E-05	1.82E-02	7.35E-05
RL-W476	3.40E-03	0.00E+00	2.41E-12	2.11E+00	3.75E-01	2.91E-63	2.16E-05	2.49E+00	1.00E-02
RL-W480	5.55E-04	0.00E+00	3.86E-13	3.35E-01	5.94E-02	4.98E-64	3.47E-06	3.94E-01	1.59E-03
RL-W481	8.72E-04	0.00E+00	6.07E-13	5.25E-01	9.28E-02	7.81E-64	5.45E-06	6.19E-01	2.50E-03
RL-W482	1.16E+00	0.00E+00	2.02E-10	6.68E-02	9.86E-02	1.04E-60	1.81E-03	1.33E+00	5.34E-03
RL-W483	8.65E-02	0.00E+00	1.57E-11	4.33E-03	7.00E-03	7.73E-62	1.41E-04	9.79E-02	3.95E-04
RL-W484	3.66E-04	0.00E+00	1.26E-13	6.04E-02	1.15E-02	6.42E-65	1.13E-06	7.22E-02	2.91E-04
RL-W485	2.14E-05	0.00E+00	1.78E-14	6.53E-03	1.24E-03	0.00E+00	1.60E-07	7.80E-03	3.14E-05
RL-W486	9.05E-06	0.00E+00	7.53E-15	2.76E-03	5.21E-04	0.00E+00	6.76E-08	3.29E-03	1.33E-05

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W487	1.48E-03	0.00E+00	9.67E-13	3.95E-01	8.63E-02	5.96E-64	8.68E-06	4.83E-01	1.95E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	8.98E-04	0.00E+00	9.12E-13	5.11E-01	9.21E-02	9.62E-64	8.19E-06	6.04E-01	2.44E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	3.33E-04	0.00E+00	7.69E-13	5.36E-02	9.35E-03	3.50E-64	6.91E-06	6.33E-02	2.55E-04
RL-W492	1.92E-05	0.00E+00	1.90E-14	1.07E-02	1.92E-03	2.01E-65	1.70E-07	1.27E-02	5.11E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.62E-01	0.00E+00	1.10E-09	2.70E-01	1.83E-01	8.06E-61	9.86E-03	1.23E+00	4.94E-03
RL-W495	1.38E-02	0.00E+00	2.99E-12	2.59E-03	1.64E-03	1.47E-62	2.68E-05	1.81E-02	7.28E-05
RL-W496	8.96E-02	0.00E+00	3.44E-11	8.52E-03	5.43E-03	9.50E-62	3.09E-04	1.04E-01	4.19E-04
RL-W497	3.73E-03	0.00E+00	6.78E-12	5.11E-01	1.84E-01	2.49E-63	6.09E-05	6.99E-01	2.82E-03
RL-W498	1.45E-02	0.00E+00	1.01E-11	8.74E+00	1.55E+00	1.30E-62	9.04E-05	1.03E+01	4.16E-02
RL-W499	1.30E-07	0.00E+00	9.04E-17	7.84E-05	1.39E-05	1.16E-67	8.12E-10	9.24E-05	3.73E-07
RL-W500	9.26E-06	0.00E+00	1.12E-14	3.20E-03	5.64E-04	8.18E-66	1.01E-07	3.77E-03	1.52E-05
RL-W501	3.83E-01	0.00E+00	2.50E-10	1.03E+02	2.23E+01	1.55E-61	2.25E-03	1.25E+02	5.06E-01
RL-W502	6.93E-05	0.00E+00	4.84E-14	4.18E-02	7.40E-03	6.21E-65	4.34E-07	4.93E-02	1.99E-04
RL-W503	4.01E-03	0.00E+00	4.96E-12	1.48E+00	2.60E-01	3.65E-63	4.45E-05	1.74E+00	7.01E-03
RL-W504	1.48E-03	0.00E+00	9.67E-13	3.95E-01	8.63E-02	5.96E-64	8.68E-06	4.83E-01	1.95E-03
RL-W505	6.96E-05	0.00E+00	5.08E-14	4.27E-02	7.54E-03	7.48E-65	4.56E-07	5.03E-02	2.03E-04
RL-W506	2.52E-05	0.00E+00	1.99E-14	1.40E-02	2.49E-03	2.24E-65	1.79E-07	1.65E-02	6.67E-05
RL-W507	2.51E-06	0.00E+00	1.74E-15	1.51E-03	2.68E-04	2.25E-66	1.57E-08	1.78E-03	7.19E-06
RL-W508	4.61E-02	0.00E+00	5.71E-11	1.64E+01	2.89E+00	3.98E-62	5.13E-04	1.93E+01	7.80E-02
RL-W509	4.53E-01	0.00E+00	4.56E-10	1.34E+02	2.60E+01	2.85E-61	4.09E-03	1.60E+02	6.46E-01
RL-W510	3.83E-02	0.00E+00	4.68E-11	1.33E+01	2.34E+00	3.40E-62	4.20E-04	1.57E+01	6.32E-02
RL-W511	3.89E+00	0.00E+00	2.26E-09	1.78E+03	3.09E+02	1.85E-60	2.06E-02	2.09E+03	8.43E+00
RL-W512	3.41E+00	0.00E+00	1.52E-09	1.07E+03	2.12E+02	9.46E-61	1.37E-02	1.29E+03	5.19E+00
RL-W513	3.63E+02	0.00E+00	6.19E-07	1.75E+04	6.90E+03	1.50E-58	5.55E+00	2.48E+04	9.99E+01
RL-W514	1.03E-05	0.00E+00	7.10E-15	6.20E-03	1.10E-03	8.76E-66	6.37E-08	7.32E-03	2.95E-05
RL-W515	4.01E-04	0.00E+00	2.78E-13	2.42E-01	4.28E-02	3.58E-64	2.50E-06	2.85E-01	1.15E-03
RL-W516	5.56E-04	0.00E+00	3.87E-13	3.35E-01	5.94E-02	4.98E-64	3.47E-06	3.94E-01	1.59E-03
RL-W517	4.95E-12	0.00E+00	3.46E-21	2.98E-09	5.27E-10	4.65E-72	3.10E-14	3.51E-09	1.42E-11

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W518	1.40E-02	0.00E+00	1.46E-11	4.27E+00	8.19E-01	9.99E-63	1.31E-04	5.10E+00	2.06E-02
RL-W519	2.50E-03	0.00E+00	1.73E-12	1.51E+00	2.68E-01	2.11E-63	1.55E-05	1.78E+00	7.19E-03
RL-W520	2.76E-04	0.00E+00	1.94E-13	1.66E-01	2.94E-02	2.71E-64	1.74E-06	1.96E-01	7.88E-04
RL-W521	5.14E-06	0.00E+00	3.56E-15	3.09E-03	5.48E-04	4.61E-66	3.20E-08	3.64E-03	1.47E-05
RL-W522	1.07E-01	0.00E+00	1.32E-10	2.04E+01	4.65E+00	6.66E-62	1.19E-03	2.52E+01	1.02E-01
RL-W523	3.22E-02	0.00E+00	5.04E-11	1.36E+00	6.55E-01	1.32E-62	4.52E-04	2.04E+00	8.24E-03
RL-W524	1.34E-01	0.00E+00	1.93E-10	1.25E+01	3.84E+00	6.29E-62	1.73E-03	1.64E+01	6.63E-02
RL-W525	1.06E-02	0.00E+00	1.30E-11	1.48E+00	3.88E-01	4.94E-63	1.17E-04	1.87E+00	7.56E-03
RL-W526	4.02E-02	0.00E+00	4.72E-11	1.58E+01	2.80E+00	3.59E-62	4.24E-04	1.86E+01	7.50E-02
RL-W527	4.40E-03	0.00E+00	6.82E-12	1.67E+00	3.15E-01	4.20E-63	6.12E-05	1.99E+00	8.01E-03
RL-W528	1.97E+00	0.00E+00	2.90E-09	5.32E+01	4.05E+01	6.42E-61	2.60E-02	9.56E+01	3.86E-01
RL-W529	1.64E-03	0.00E+00	2.04E-12	5.87E-01	1.03E-01	1.42E-63	1.83E-05	6.91E-01	2.79E-03
RL-W530	1.93E-02	0.00E+00	2.36E-11	6.70E+00	1.18E+00	1.72E-62	2.12E-04	7.90E+00	3.19E-02
RL-W531	1.15E+00	0.00E+00	2.37E-09	2.90E+01	1.66E+01	4.57E-61	2.13E-02	4.67E+01	1.89E-01
RL-W532	3.70E-03	0.00E+00	2.58E-12	2.24E+00	3.96E-01	3.32E-63	2.31E-05	2.64E+00	1.06E-02
RL-W533	1.79E-03	0.00E+00	2.22E-12	6.40E-01	1.12E-01	1.53E-63	2.00E-05	7.54E-01	3.04E-03
RL-W534	1.03E-07	0.00E+00	7.18E-17	6.24E-05	1.11E-05	9.25E-68	6.44E-10	7.36E-05	2.97E-07
RL-W535	5.42E-01	0.00E+00	7.10E-10	8.00E+01	1.94E+01	2.82E-61	6.37E-03	1.00E+02	4.03E-01
RL-W536	1.06E-02	0.00E+00	9.56E-12	2.78E+00	5.00E-01	6.46E-63	8.90E-05	3.29E+00	1.33E-02
RL-W537	3.61E-01	0.00E+00	2.16E-10	1.70E+02	2.97E+01	1.81E-61	1.96E-03	2.01E+02	8.09E-01
RL-W538	1.31E-06	0.00E+00	9.12E-16	7.93E-04	1.41E-04	1.18E-66	8.19E-09	9.35E-04	3.77E-06
RL-W539	1.46E-04	0.00E+00	1.03E-13	8.76E-02	1.55E-02	1.43E-64	9.22E-07	1.03E-01	4.16E-04
RL-W540	2.84E-01	0.00E+00	4.52E-10	3.15E+01	8.63E+00	1.37E-61	4.06E-03	4.04E+01	1.63E-01
RL-W541	4.22E-04	0.00E+00	2.96E-13	2.54E-01	4.50E-02	4.03E-64	2.66E-06	2.99E-01	1.21E-03
RL-W542	1.96E-02	0.00E+00	2.20E-11	6.42E+00	1.18E+00	1.65E-62	1.98E-04	7.63E+00	3.08E-02
RL-W543	6.17E-05	0.00E+00	4.28E-14	3.72E-02	6.60E-03	5.55E-65	3.84E-07	4.39E-02	1.77E-04
RL-W544	1.39E-03	0.00E+00	1.75E-12	4.23E-01	8.41E-02	1.10E-63	1.57E-05	5.09E-01	2.05E-03
RL-W545	3.70E-04	0.00E+00	2.57E-13	2.23E-01	3.95E-02	3.31E-64	2.31E-06	2.63E-01	1.06E-03
RL-W546	1.62E-05	0.00E+00	1.13E-14	9.81E-03	1.73E-03	1.45E-65	1.01E-07	1.16E-02	4.66E-05
RL-W547	4.14E-07	0.00E+00	2.88E-16	2.49E-04	4.42E-05	3.70E-67	2.58E-09	2.94E-04	1.19E-06
RL-W548	3.58E-07	0.00E+00	2.50E-16	2.15E-04	3.82E-05	3.32E-67	2.24E-09	2.54E-04	1.02E-06

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W549	7.11E-02	0.00E+00	1.00E-10	1.11E+01	2.63E+00	4.20E-62	9.01E-04	1.38E+01	5.56E-02
RL-W550	3.22E-01	0.00E+00	1.90E-10	1.50E+02	2.63E+01	1.58E-61	1.72E-03	1.77E+02	7.13E-01
RL-W551	5.73E-01	0.00E+00	2.81E-10	1.70E+02	3.42E+01	1.68E-61	2.52E-03	2.04E+02	8.24E-01
RL-W552	2.22E-04	0.00E+00	1.55E-13	1.34E-01	2.36E-02	2.10E-64	1.40E-06	1.58E-01	6.36E-04
RL-W553	1.97E-05	0.00E+00	1.47E-14	1.19E-02	2.11E-03	2.66E-65	1.32E-07	1.40E-02	5.66E-05
RL-W554	3.13E-04	0.00E+00	2.18E-13	1.89E-01	3.35E-02	2.80E-64	1.95E-06	2.23E-01	8.98E-04
RL-W555	1.44E-04	0.00E+00	1.00E-13	8.70E-02	1.54E-02	1.29E-64	9.01E-07	1.03E-01	4.13E-04
RL-W563	2.07E-03	0.00E+00	2.51E-12	7.21E-01	1.27E-01	1.76E-63	2.25E-05	8.50E-01	3.43E-03
RL-W564	1.35E-03	0.00E+00	1.67E-12	4.66E-01	8.19E-02	1.35E-63	1.50E-05	5.50E-01	2.22E-03
RL-W565	1.34E-04	0.00E+00	9.36E-14	8.06E-02	1.43E-02	1.25E-64	8.40E-07	9.50E-02	3.83E-04
RL-W566	1.96E-03	0.00E+00	1.37E-12	1.18E+00	2.10E-01	1.79E-63	1.23E-05	1.39E+00	5.62E-03
RL-W567	1.36E-01	0.00E+00	3.51E-11	3.64E-02	2.34E-02	1.51E-61	3.15E-04	1.96E-01	7.91E-04
RL-W568	2.62E+00	0.00E+00	7.37E-10	1.72E+00	1.09E+00	3.13E-60	6.62E-03	5.43E+00	2.19E-02
RL-W569	2.15E-03	0.00E+00	5.55E-13	5.75E-04	3.70E-05	2.40E-63	4.98E-06	2.77E-03	1.12E-05
RL-W570	1.38E-04	0.00E+00	9.71E-14	8.54E-02	1.51E-02	1.18E-64	8.72E-07	1.01E-01	4.06E-04
RL-W571	4.42E-01	0.00E+00	3.30E-10	6.93E+00	2.76E+00	4.77E-61	2.96E-03	1.01E+01	4.08E-02
RL-W572	3.84E-04	0.00E+00	9.87E-14	3.73E-03	6.60E-05	4.28E-64	8.86E-07	4.18E-03	1.69E-05
RL-W573	4.94E+00	0.00E+00	1.27E-09	2.04E+00	1.22E+00	5.43E-60	1.14E-02	8.21E+00	3.31E-02
RL-W574	2.12E+01	0.00E+00	5.47E-09	7.81E+00	4.51E+00	2.37E-59	4.91E-02	3.36E+01	1.36E-01
RL-W575	1.38E+02	0.00E+00	3.68E-08	7.47E+01	3.60E+01	1.49E-58	3.31E-01	2.49E+02	1.01E+00
RL-W576	9.98E+00	0.00E+00	2.57E-09	3.80E+00	2.18E+00	1.11E-59	2.31E-02	1.60E+01	6.44E-02
RL-W579	8.45E-04	0.00E+00	6.78E-14	1.91E-02	3.39E-03	3.93E-65	6.09E-07	2.33E-02	9.39E-05
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.52E-01	1.97E-02	0.00E+00	0.00E+00	1.72E-01	6.93E-04
RL-W581	8.97E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.97E-03	3.62E-05
RL-W582	5.87E-05	0.00E+00	5.75E-14	4.88E-03	2.01E-03	6.37E-66	5.16E-07	6.94E-03	2.80E-05
RL-W583	4.54E-05	0.00E+00	3.12E-14	2.75E-02	4.88E-03	3.71E-65	2.81E-07	3.24E-02	1.31E-04
RL-W584	9.02E-04	0.00E+00	2.05E-12	1.60E-01	6.25E-02	1.86E-64	1.84E-05	2.24E-01	9.02E-04
RL-W585	5.36E-03	0.00E+00	1.09E-11	9.35E-01	3.80E-01	5.68E-63	9.79E-05	1.32E+00	5.32E-03
RL-W586	7.16E-07	0.00E+00	4.92E-16	4.34E-04	7.69E-05	5.84E-67	4.41E-09	5.12E-04	2.06E-06
RL-W587	1.53E-05	0.00E+00	1.06E-14	9.26E-03	1.65E-03	1.31E-65	9.54E-08	1.09E-02	4.40E-05
RL-W588	6.32E-04	0.00E+00	1.73E-12	1.36E-01	5.26E-02	1.57E-64	1.55E-05	1.89E-01	7.62E-04

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	1.94E-02	0.00E+00	3.69E-11	1.05E-02	1.48E-02	2.06E-62	3.31E-04	4.50E-02	1.81E-04
RL-W591	1.11E-01	0.00E+00	4.16E-11	1.29E-02	1.91E-02	1.24E-61	3.74E-04	1.43E-01	5.77E-04
RL-W592	4.88E-01	0.00E+00	4.56E-10	5.99E-01	6.19E-01	5.02E-61	4.09E-03	1.71E+00	6.90E-03
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.16E-02	2.91E-02	0.00E+00	0.00E+00	5.07E-02	2.04E-04
RL-W594	4.40E-01	0.00E+00	8.21E-11	2.68E-02	3.93E-02	1.25E-61	7.37E-04	5.07E-01	2.04E-03
RL-W595	1.16E-03	0.00E+00	8.56E-12	1.83E-02	2.86E-02	1.24E-63	7.69E-05	4.81E-02	1.94E-04
RL-W596	3.76E-04	0.00E+00	6.66E-13	1.89E-04	2.68E-04	3.73E-64	5.98E-06	8.39E-04	3.38E-06
RL-W597	6.92E-01	0.00E+00	2.93E-10	3.66E-01	4.87E-01	6.95E-61	2.63E-03	1.55E+00	6.24E-03
RL-W598	7.32E-01	0.00E+00	1.73E-09	5.10E-01	6.07E-01	7.20E-61	1.55E-02	1.86E+00	7.51E-03
RL-W599	3.71E-02	0.00E+00	1.40E-11	4.31E-03	6.40E-03	4.15E-62	1.25E-04	4.79E-02	1.93E-04
RL-W600	2.10E-09	0.00E+00	1.45E-18	1.27E-06	2.26E-07	1.72E-69	1.30E-11	1.50E-06	6.06E-09
RL-W601	1.07E-05	0.00E+00	7.93E-15	6.45E-03	1.15E-03	1.44E-65	7.12E-08	7.61E-03	3.07E-05
RL-W602	9.29E-03	0.00E+00	6.50E-12	5.59E+00	9.93E-01	8.72E-63	5.84E-05	6.59E+00	2.66E-02
RL-W603	5.36E-02	0.00E+00	3.75E-11	3.23E+01	5.72E+00	5.02E-62	3.37E-04	3.80E+01	1.53E-01
RL-W604	1.25E-04	0.00E+00	9.83E-14	1.57E-02	6.16E-03	5.96E-65	8.83E-07	2.20E-02	8.86E-05
RL-W605	2.87E-05	0.00E+00	2.14E-14	1.73E-02	3.07E-03	3.87E-65	1.92E-07	2.04E-02	8.24E-05
RL-W606	1.16E-05	0.00E+00	8.60E-15	6.98E-03	1.24E-03	1.56E-65	7.72E-08	8.23E-03	3.32E-05
RL-W607	2.12E-05	0.00E+00	1.67E-14	2.65E-03	1.04E-03	1.01E-65	1.50E-07	3.71E-03	1.50E-05
RL-W608	2.53E-04	0.00E+00	6.46E-13	3.45E-03	3.39E-03	1.55E-64	5.80E-06	7.09E-03	2.86E-05
RL-W610	5.02E-02	0.00E+00	3.46E-11	3.04E+01	5.40E+00	4.10E-62	3.10E-04	3.59E+01	1.45E-01
RL-W612	1.18E-04	0.00E+00	8.37E-14	7.39E-02	1.31E-02	9.71E-65	7.51E-07	8.71E-02	3.51E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.10E-01	0.00E+00	0.00E+00	0.00E+00	3.10E-01	1.25E-03
RL-W622	1.98E-06	0.00E+00	1.36E-15	1.20E-03	2.12E-04	1.62E-66	1.22E-08	1.42E-03	5.71E-06
RL-W625	6.88E-05	0.00E+00	2.07E-13	6.13E-03	4.80E-03	8.76E-65	1.86E-06	1.10E-02	4.44E-05
RL-W626	3.70E-03	0.00E+00	4.72E-12	2.40E-01	1.15E-01	1.53E-63	4.24E-05	3.58E-01	1.45E-03
RL-W627	1.74E-05	0.00E+00	6.30E-15	1.14E-06	0.00E+00	1.82E-65	5.66E-08	1.86E-05	7.51E-08
RL-W628	5.72E-06	0.00E+00	3.96E-15	3.46E-03	6.13E-04	4.89E-66	3.56E-08	4.08E-03	1.65E-05
RL-W629	3.87E-07	0.00E+00	2.72E-16	2.33E-04	4.12E-05	3.80E-67	2.45E-09	2.74E-04	1.11E-06
RL-W630	4.26E-03	0.00E+00	5.08E-12	2.69E+00	4.97E-01	4.11E-63	4.56E-05	3.20E+00	1.29E-02
RL-W631	6.86E-05	0.00E+00	5.11E-14	4.13E-02	7.32E-03	9.25E-65	4.59E-07	4.87E-02	1.97E-04

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W632	3.03E-02	0.00E+00	6.90E-12	5.46E+00	1.43E+00	3.08E-62	6.19E-05	6.92E+00	2.79E-02
RL-W633	7.23E-05	0.00E+00	4.00E-14	8.58E-04	6.03E-04	3.79E-65	3.60E-07	1.53E-03	6.18E-06
RL-W634	0.00E+00	0.00E+00	0.00E+00	9.35E-03	0.00E+00	0.00E+00	0.00E+00	9.35E-03	3.77E-05
RL-W635	4.32E-01	0.00E+00	1.35E-09	3.98E+00	4.74E+00	3.82E-61	1.21E-02	9.16E+00	3.69E-02
RL-W636	4.41E-03	0.00E+00	2.55E-12	5.20E-02	3.66E-02	2.32E-63	2.29E-05	9.30E-02	3.75E-04
RL-W637	1.05E-05	0.00E+00	6.50E-14	5.85E-04	4.57E-04	8.35E-66	5.84E-07	1.05E-03	4.24E-06
RL-W638	4.61E-04	0.00E+00	6.62E-13	5.73E-03	4.29E-03	3.11E-64	5.94E-06	1.05E-02	4.23E-05
RL-W639	2.43E-05	0.00E+00	1.69E-14	1.47E-02	2.60E-03	2.18E-65	1.52E-07	1.73E-02	6.97E-05
RL-W640	8.17E-04	0.00E+00	5.63E-13	4.94E-01	8.77E-02	6.99E-64	5.05E-06	5.83E-01	2.35E-03
RL-W641	2.49E-02	0.00E+00	1.24E-10	2.37E+00	7.76E-01	1.12E-62	1.11E-03	3.18E+00	1.28E-02
RL-W642	4.87E-04	0.00E+00	1.29E-14	2.90E-02	1.18E-04	4.85E-66	1.15E-07	2.96E-02	1.19E-04
RL-W643	7.67E-03	0.00E+00	3.81E-11	7.31E-01	2.39E-01	3.45E-63	3.42E-04	9.79E-01	3.95E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.03E-02	0.00E+00	0.00E+00	0.00E+00	5.03E-02	2.03E-04
RL-W645	1.86E-04	0.00E+00	1.71E-13	9.90E-02	1.85E-02	1.89E-64	1.54E-06	1.18E-01	4.74E-04
RL-W646	1.69E-04	0.00E+00	1.53E-13	2.36E-02	9.14E-03	9.17E-65	1.37E-06	3.30E-02	1.33E-04
RL-W647	4.77E-04	0.00E+00	2.29E-11	1.01E-01	1.27E-02	3.07E-64	2.05E-04	1.14E-01	4.60E-04
RL-W648	8.44E-06	0.00E+00	3.91E-14	5.51E-05	8.63E-05	9.83E-66	3.51E-07	1.50E-04	6.05E-07
RL-W649	3.10E-05	0.00E+00	1.44E-13	2.03E-04	3.17E-04	3.61E-65	1.29E-06	5.52E-04	2.23E-06
RL-W653	1.47E-06	0.00E+00	1.03E-15	8.85E-04	1.57E-04	1.38E-66	9.25E-09	1.04E-03	4.21E-06
RL-W654	8.09E-06	0.00E+00	5.63E-15	4.88E-03	8.63E-04	7.24E-66	5.05E-08	5.75E-03	2.32E-05
RL-W655	1.99E+00	0.00E+00	1.33E-09	1.93E-01	3.63E-01	1.93E-60	1.20E-02	2.56E+00	1.03E-02
RL-W656	8.34E+00	0.00E+00	5.99E-10	4.55E-01	3.73E-01	9.21E-60	5.37E-03	9.17E+00	3.70E-02
RL-W657	4.26E+00	0.00E+00	8.84E-10	2.24E-01	3.55E-01	4.08E-60	7.94E-03	4.84E+00	1.95E-02
RL-W659	5.15E-01	0.00E+00	1.99E-10	4.31E-02	4.26E-02	4.61E-61	1.79E-03	6.03E-01	2.43E-03
RL-W660	2.82E+00	0.00E+00	2.40E-09	7.95E-01	1.13E+00	2.63E-60	2.15E-02	4.77E+00	1.92E-02
RL-W661	2.99E-02	0.00E+00	3.00E-12	3.83E-04	2.78E-03	3.19E-62	2.69E-05	3.31E-02	1.33E-04
RL-W662	9.40E-04	0.00E+00	1.79E-13	9.81E-05	1.40E-04	6.54E-64	1.61E-06	1.18E-03	4.76E-06
RL-W665	1.16E+01	0.00E+00	1.43E-08	1.20E+00	1.28E+00	1.30E-59	1.29E-01	1.42E+01	5.71E-02
RL-W666	2.07E-01	0.00E+00	3.51E-11	5.03E-02	4.22E-02	1.88E-61	3.15E-04	3.00E-01	1.21E-03
RL-W668	1.97E-02	0.00E+00	1.10E-12	1.33E-01	3.00E-02	4.44E-64	9.90E-06	1.83E-01	7.36E-04
RL-W669	5.75E-03	0.00E+00	2.86E-11	5.48E-01	1.79E-01	2.59E-63	2.57E-04	7.33E-01	2.96E-03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W670	3.63E-04	0.00E+00	2.03E-14	2.46E-03	5.55E-04	8.23E-66	1.83E-07	3.38E-03	1.36E-05
RL-W671	5.93E-02	0.00E+00	1.04E-11	4.50E-03	3.73E-03	2.70E-62	9.36E-05	6.76E-02	2.73E-04
RL-W672	4.03E-01	0.00E+00	7.10E-11	3.07E-02	2.53E-02	1.83E-61	6.37E-04	4.59E-01	1.85E-03
RL-W673	3.88E-01	0.00E+00	6.82E-11	2.97E-02	2.44E-02	1.77E-61	6.12E-04	4.43E-01	1.79E-03
RL-W674	1.30E-03	0.00E+00	3.05E-12	1.03E+01	7.11E-02	1.23E-63	2.74E-05	1.03E+01	4.17E-02
RL-W675	4.87E-03	0.00E+00	1.69E-11	1.20E-01	8.27E-02	3.01E-63	1.51E-04	2.08E-01	8.38E-04
RL-W676	1.87E-04	0.00E+00	1.01E-13	1.35E-01	1.56E-03	8.92E-65	9.08E-07	1.37E-01	5.50E-04
RL-W677	4.33E-01	0.00E+00	2.51E-10	5.26E+00	3.64E+00	2.15E-61	2.25E-03	9.34E+00	3.76E-02
RL-W678	1.37E-03	0.00E+00	2.09E-12	4.73E-02	3.32E-02	1.69E-63	1.88E-05	8.19E-02	3.30E-04
RL-W679	8.59E-03	0.00E+00	4.68E-12	1.02E-01	7.15E-02	4.32E-63	4.20E-05	1.82E-01	7.33E-04
RL-W680	1.94E-06	0.00E+00	6.58E-15	1.59E-05	2.28E-05	1.86E-66	5.91E-08	4.08E-05	1.64E-07
RL-W681	1.18E-06	0.00E+00	2.67E-15	4.28E-04	1.70E-04	1.54E-66	2.40E-08	5.99E-04	2.42E-06
RL-W685	3.44E-03	0.00E+00	2.37E-12	2.09E+00	3.70E-01	2.81E-63	2.13E-05	2.46E+00	9.93E-03
RL-W689	8.91E-05	0.00E+00	2.85E-14	3.55E-04	0.00E+00	2.70E-66	2.56E-07	4.44E-04	1.79E-06
RL-W690	2.99E-03	0.00E+00	2.09E-12	1.86E+00	3.29E-01	2.45E-63	1.88E-05	2.19E+00	8.84E-03
RL-W691	6.94E-05	0.00E+00	4.88E-14	4.31E-02	7.61E-03	5.68E-65	4.38E-07	5.08E-02	2.05E-04
RL-W692	2.74E-03	0.00E+00	1.93E-12	1.70E+00	3.02E-01	2.24E-63	1.73E-05	2.01E+00	8.10E-03
RL-W693	3.40E-03	0.00E+00	2.38E-12	2.11E+00	3.73E-01	2.77E-63	2.14E-05	2.48E+00	1.00E-02
RL-W694	3.57E-02	0.00E+00	2.50E-11	2.23E+01	3.92E+00	2.92E-62	2.25E-04	2.62E+01	1.06E-01
RL-W695	2.95E-05	0.00E+00	0.00E+00	2.19E-03	0.00E+00	0.00E+00	0.00E+00	2.22E-03	8.95E-06
RL-W696	3.85E-05	0.00E+00	9.12E-14	2.67E-03	2.10E-03	4.00E-65	8.19E-07	4.80E-03	1.94E-05
RL-W697	8.89E-03	0.00E+00	1.93E-10	6.35E-03	6.94E-04	0.00E+00	1.73E-03	1.77E-02	7.13E-05
RL-W698	7.71E-04	0.00E+00	0.00E+00	3.02E-05	0.00E+00	0.00E+00	0.00E+00	8.01E-04	3.23E-06
RL-W699	1.71E-04	0.00E+00	1.29E-14	2.02E-03	1.89E-04	1.68E-64	1.15E-07	2.38E-03	9.58E-06
RL-W700	4.86E-05	0.00E+00	3.37E-14	2.92E-02	5.18E-03	4.36E-65	3.03E-07	3.45E-02	1.39E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	1.91E-03	0.00E+00	9.52E-12	1.82E-01	5.98E-02	8.64E-64	8.54E-05	2.44E-01	9.85E-04
RL-W705	1.24E-05	0.00E+00	8.76E-15	7.66E-03	1.36E-03	1.06E-65	7.87E-08	9.04E-03	3.64E-05
RL-W706		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707		4.42E-04	0.00E+00	3.12E-13	2.73E-01	4.84E-02	3.77E-64	2.80E-06	3.22E-01

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W708		6.67E-05	0.00E+00	4.72E-14	4.14E-02	7.32E-03	5.72E-65	4.24E-07	4.88E-02
RL-W709		2.31E-02	0.00E+00	1.63E-11	1.43E+01	2.53E+00	1.97E-62	1.46E-04	1.69E+01
RL-W710		1.38E-06	0.00E+00	9.71E-16	8.54E-04	1.51E-04	1.18E-66	8.72E-09	1.01E-03
RL-W711		4.30E-04	0.00E+00	3.03E-13	2.67E-01	4.72E-02	3.68E-64	2.72E-06	3.14E-01
RL-W712		5.57E-04	0.00E+00	3.93E-13	3.45E-01	6.11E-02	4.77E-64	3.52E-06	4.06E-01
RL-W713		4.81E-04	0.00E+00	3.39E-13	2.97E-01	5.28E-02	4.11E-64	3.04E-06	3.50E-01
RL-W714		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715		8.30E-06	0.00E+00	5.71E-15	5.03E-03	8.92E-04	6.79E-66	5.13E-08	5.93E-03
RL-W716		8.64E-05	0.00E+00	5.95E-14	5.24E-02	9.28E-03	7.07E-65	5.34E-07	6.18E-02
RL-W717		2.16E-05	0.00E+00	1.49E-14	1.31E-02	2.32E-03	1.76E-65	1.34E-07	1.55E-02
RL-W718		3.81E-06	0.00E+00	2.62E-15	2.31E-03	4.09E-04	3.11E-66	2.35E-08	2.72E-03
RL-W719		1.72E-05	0.00E+00	1.18E-14	1.05E-02	1.85E-03	1.41E-65	1.06E-07	1.23E-02
RL-W720		1.06E-04	0.00E+00	7.34E-14	6.45E-02	1.15E-02	8.68E-65	6.59E-07	7.61E-02
RL-W721		7.20E-05	0.00E+00	4.96E-14	4.36E-02	7.76E-03	5.88E-65	4.45E-07	5.15E-02
RL-W723		2.39E-04	0.00E+00	1.67E-13	1.49E-01	2.63E-02	1.95E-64	1.50E-06	1.75E-01
RL-W724		1.59E-03	0.00E+00	1.11E-12	9.81E-01	1.75E-01	1.30E-63	1.00E-05	1.16E+00
RL-W725		5.01E-04	0.00E+00	3.51E-13	3.11E-01	5.51E-02	4.09E-64	3.15E-06	3.66E-01
RL-W726		3.95E-04	0.00E+00	2.77E-13	2.46E-01	4.34E-02	3.22E-64	2.49E-06	2.89E-01
RL-W727		2.42E-03	0.00E+00	1.70E-12	1.50E+00	2.67E-01	1.98E-63	1.53E-05	1.77E+00
RL-W728		2.20E-03	0.00E+00	1.55E-12	1.38E+00	2.43E-01	1.80E-63	1.39E-05	1.62E+00
RL-W729		1.02E-03	0.00E+00	7.18E-13	6.32E-01	1.12E-01	8.31E-64	6.44E-06	7.46E-01
RL-W730		3.98E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.98E-01
RL-W731		1.28E-07	0.00E+00	0.00E+00	4.13E-04	1.35E-06	0.00E+00	0.00E+00	4.15E-04
RL-W732		2.94E-01	0.00E+00	4.08E-10	1.16E+02	2.05E+01	2.98E-61	3.67E-03	1.37E+02
RL-W733		3.86E-03	0.00E+00	5.31E-12	1.27E+00	2.49E-01	3.24E-63	4.77E-05	1.52E+00
RL-W734		1.21E-02	0.00E+00	1.77E-11	4.36E+00	8.41E-01	9.62E-63	1.59E-04	5.22E+00
RL-W735		9.87E-03	0.00E+00	1.35E-11	3.40E+00	6.71E-01	7.48E-63	1.21E-04	4.08E+00
RL-W736		1.08E-05	0.00E+00	2.88E-17	2.25E-03	4.63E-04	2.29E-66	2.59E-10	2.73E-03
RL-W737		8.81E-03	0.00E+00	1.23E-11	3.23E+00	6.24E-01	6.46E-63	1.11E-04	3.86E+00
RL-W738		3.29E-02	0.00E+00	4.24E-11	1.03E+01	2.15E+00	2.34E-62	3.81E-04	1.25E+01
RL-W739		2.80E-03	0.00E+00	3.74E-12	1.67E+00	3.02E-01	2.13E-63	3.36E-05	1.97E+00

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W740		1.40E-01	0.00E+00	1.37E-10	4.06E+01	8.41E+00	1.07E-61	1.23E-03	4.92E+01
RL-W741		2.09E-01	0.00E+00	3.23E-10	7.91E+00	4.47E+00	8.06E-62	2.90E-03	1.26E+01
RL-W742		9.32E-03	0.00E+00	9.71E-12	2.57E+00	4.81E-01	6.91E-63	8.72E-05	3.06E+00
RL-W743		1.68E-05	0.00E+00	2.64E-15	1.66E-03	0.00E+00	0.00E+00	2.37E-08	1.68E-03
RL-W744		0.00E+00	0.00E+00	0.00E+00	8.28E-02	5.60E-02	0.00E+00	0.00E+00	1.39E-01
RL-W745		2.65E-05	0.00E+00	1.84E-14	1.60E-02	2.84E-03	2.37E-65	1.66E-07	1.89E-02
RL-W746		1.02E-04	0.00E+00	7.10E-14	6.16E-02	1.10E-02	9.13E-65	6.37E-07	7.26E-02
RL-W747		2.76E-04	0.00E+00	1.92E-13	1.67E-01	2.96E-02	2.48E-64	1.73E-06	1.97E-01
RL-W748	1.94E+00	0.00E+00	5.39E-10	2.77E-01	3.62E-01	1.86E-60	4.84E-03	2.58E+00	1.04E-02
RL-W749	2.33E-03	0.00E+00	1.65E-12	1.45E+00	2.56E-01	1.99E-63	1.48E-05	1.71E+00	6.88E-03
RL-W750	2.94E+00	0.00E+00	8.17E-10	4.54E-01	5.91E-01	2.64E-60	7.33E-03	3.99E+00	1.61E-02
RL-W751	2.65E+00	0.00E+00	7.37E-10	4.08E-01	5.36E-01	2.38E-60	6.62E-03	3.60E+00	1.45E-02
RL-W752	1.15E+00	0.00E+00	3.20E-10	1.78E-01	2.33E-01	1.03E-60	2.88E-03	1.57E+00	6.32E-03
RL-W753	1.55E+01	0.00E+00	4.32E-09	2.39E+00	3.13E+00	1.39E-59	3.88E-02	2.11E+01	8.50E-02
RP-W754	6.59E-01	0.00E+00	5.47E-10	1.70E+03	1.11E+02	1.28E-61	3.55E-01	1.82E+03	7.32E+00
RP-W755	3.49E+00	0.00E+00	3.28E-10	1.27E+03	8.41E+01	9.58E-62	1.25E+01	1.37E+03	5.54E+00
SA-T001	7.01E-03	1.91E-50	7.85E-12	2.78E+00	1.31E-02	0.00E+00	7.51E-05	2.80E+00	1.13E-02
SA-W134	5.73E-02	7.40E-54	5.35E-11	1.27E+00	3.18E-01	2.44E-63	1.66E-01	1.81E+00	7.28E-03
SA-W134M	7.44E-03	9.60E-55	6.94E-12	1.65E-01	4.13E-02	3.18E-64	2.15E-02	2.35E-01	9.48E-04
T001-221F-HET	1.39E+01	0.00E+00	6.26E-06	2.64E+04	5.18E+02	8.02E-60	6.18E+01	2.70E+04	1.09E+02
T001-221H-HET	2.49E+01	0.00E+00	1.13E-05	4.77E+04	9.35E+02	1.45E-59	1.12E+02	4.87E+04	1.97E+02
T001-235F-HET	1.44E+00	0.00E+00	6.50E-07	2.74E+03	5.37E+01	8.31E-61	6.42E+00	2.80E+03	1.13E+01
T001-772F-HET	1.24E+01	0.00E+00	5.63E-06	2.36E+04	4.63E+02	7.16E-60	5.56E+01	2.42E+04	9.75E+01
T001-773A-CLAS	1.39E-01	0.00E+00	6.30E-08	2.66E+02	5.20E+00	8.06E-62	6.22E-01	2.72E+02	1.10E+00
T001-773A-HET	1.60E+00	0.00E+00	7.26E-07	3.06E+03	6.00E+01	9.29E-61	7.16E+00	3.13E+03	1.26E+01
W006-773A-VIT	2.14E-05	0.00E+00	0.00E+00	4.92E+02	0.00E+00	0.00E+00	0.00E+00	4.92E+02	1.98E+00
W026-221F-HET	4.82E+00	0.00E+00	2.19E-06	9.26E+03	1.81E+02	2.79E-60	2.16E+01	9.46E+03	3.82E+01
W026-221H-HET	3.60E+00	0.00E+00	1.63E-06	6.89E+03	1.35E+02	2.09E-60	1.61E+01	7.05E+03	2.84E+01
W026-235F-HET	5.61E-02	0.00E+00	2.55E-08	1.07E+02	2.10E+00	3.25E-62	2.51E-01	1.10E+02	4.42E-01
W026-772F-HET	1.54E-02	0.00E+00	6.94E-09	2.92E+01	5.73E-01	8.88E-63	6.85E-02	2.99E+01	1.21E-01
W026-773A-HET	2.49E-01	0.00E+00	1.13E-07	4.77E+02	9.35E+00	1.44E-61	1.12E+00	4.87E+02	1.97E+00

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W027-221F-HET	1.82E+01	0.00E+00	7.37E-06	3.57E+04	6.99E+02	4.57E-60	8.39E+01	3.65E+04	1.47E+02
W027-221H-HET	7.95E+00	0.00E+00	3.22E-06	1.57E+04	3.06E+02	1.99E-60	3.66E+01	1.60E+04	6.46E+01
W027-235F-HET	2.39E+00	0.00E+00	9.67E-07	4.71E+03	9.21E+01	6.00E-61	1.10E+01	4.82E+03	1.94E+01
W027-772F-HET	4.35E+00	0.00E+00	1.76E-06	8.55E+03	1.68E+02	1.09E-60	2.00E+01	8.74E+03	3.53E+01
W027-773A-HET	6.48E+00	0.00E+00	2.63E-06	1.27E+04	2.49E+02	1.63E-60	2.99E+01	1.30E+04	5.25E+01
W027-999-HET	7.42E+00	0.00E+00	3.00E-06	1.46E+04	2.85E+02	1.86E-60	3.42E+01	1.49E+04	6.01E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.66E+02	0.00E+00	0.00E+00	0.00E+00	3.66E+02	1.47E+00
WP-INW169.001	3.62E-02	0.00E+00	1.89E-11	1.41E+01	2.49E+00	1.64E-62	3.33E-04	1.66E+01	6.71E-02
WP-INW198.001	4.77E-02	0.00E+00	3.30E-11	2.53E+01	4.44E+00	2.69E-62	3.77E-04	2.98E+01	1.20E-01
WP-INW211.001	5.37E+00	0.00E+00	3.10E-09	2.35E+03	4.12E+02	3.05E-60	2.98E-02	2.76E+03	1.11E+01
WP-INW216.001-	1.95E+02	0.00E+00	1.78E-09	1.36E+03	2.39E+02	1.69E-60	2.91E-01	1.79E+03	7.22E+00
WP-INW216.001-	5.37E+01	0.00E+00	4.80E-10	3.68E+02	6.45E+01	4.57E-61	3.17E-02	4.86E+02	1.96E+00
WP-INW218.001-	3.73E+00	0.00E+00	3.14E-10	2.36E+02	4.16E+01	3.05E-61	3.86E-01	2.82E+02	1.14E+00
WP-INW218.001-	1.72E-02	0.00E+00	8.64E-12	6.43E+00	1.13E+00	8.64E-63	3.72E-02	7.62E+00	3.07E-02
WP-INW222.001	1.77E-01	0.00E+00	9.32E-11	6.29E+01	1.12E+01	7.32E-62	1.41E-03	7.42E+01	2.99E-01
WP-INW243.001	4.29E-01	0.00E+00	2.01E-10	1.32E+02	2.35E+01	1.48E-61	2.67E-03	1.56E+02	6.29E-01
WP-INW247.001R	5.72E-01	0.00E+00	4.68E-10	2.53E+02	4.57E+01	2.57E-61	4.28E-03	2.99E+02	1.21E+00
WP-INW276.001	4.36E-02	0.00E+00	4.56E-11	2.50E+01	4.52E+00	2.18E-62	4.26E-04	2.96E+01	1.19E-01
WP-INW276.002	6.92E-02	0.00E+00	6.86E-11	3.68E+01	6.79E+00	3.27E-62	6.42E-04	4.36E+01	1.76E-01
WP-INW276.003	2.65E+00	0.00E+00	2.55E-09	1.37E+03	2.47E+02	1.37E-60	2.33E-02	1.62E+03	6.51E+00
WP-INW276.004	6.33E-01	0.00E+00	5.39E-10	2.89E+02	5.22E+01	2.90E-61	4.99E-03	3.42E+02	1.38E+00
WP-INW296.001-	2.32E-01	0.00E+00	1.28E-10	7.25E+01	1.31E+01	7.44E-62	1.19E-03	8.58E+01	3.46E-01
WP-INW296.001-	6.98E-01	0.00E+00	4.52E-10	2.57E+02	4.61E+01	2.68E-61	4.41E-03	3.03E+02	1.22E+00
WP-LA-TA-55-19	1.16E-02	0.00E+00	2.10E-11	1.92E+00	3.68E-01	2.67E-63	2.81E-03	2.30E+00	9.26E-03
WP-LA-TA-55-19	5.63E-01	0.00E+00	7.06E-10	1.95E+02	3.79E+01	2.65E-61	9.28E-02	2.34E+02	9.42E-01
WP-LA-TA-55-43	3.16E-03	0.00E+00	1.65E-08	2.96E-01	9.93E-02	2.37E-63	1.74E-01	5.73E-01	2.31E-03
WP-RF001.01	9.77E-01	0.00E+00	5.71E-10	3.76E+02	6.79E+01	2.67E-61	1.44E-02	4.45E+02	1.79E+00
WP-RF002.01-A	1.14E+00	0.00E+00	7.61E-10	4.23E+02	7.69E+01	5.88E-61	2.45E-02	5.01E+02	2.02E+00
WP-RF002.01-B	1.13E-03	0.00E+00	5.27E-13	4.58E-01	8.27E-02	3.70E-64	4.92E-06	5.42E-01	2.19E-03
WP-RF003.01	1.77E+01	0.00E+00	1.23E-08	8.09E+03	1.47E+03	9.71E-60	1.18E-01	9.57E+03	3.86E+01
WP-RF004.01	8.28E-03	0.00E+00	8.21E-12	4.66E+00	8.48E-01	5.55E-63	2.00E-04	5.52E+00	2.23E-02

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF005.01	4.25E+01	0.00E+00	6.23E-09	4.28E+03	7.69E+02	3.87E-60	5.77E-02	5.09E+03	2.05E+01
WP-RF005.02	5.00E+01	0.00E+00	3.22E-09	2.56E+03	4.56E+02	1.98E-60	3.01E-02	3.06E+03	1.24E+01
WP-RF006.01	1.62E+01	0.00E+00	1.17E-08	7.28E+03	1.32E+03	5.02E-60	1.30E-01	8.61E+03	3.47E+01
WP-RF008.01	5.15E+00	0.00E+00	4.16E-09	2.13E+03	3.92E+02	3.31E-60	3.86E-02	2.52E+03	1.02E+01
WP-RF009.01	5.06E+02	0.00E+00	5.11E-08	4.66E+04	8.27E+03	3.80E-59	4.80E-01	5.54E+04	2.24E+02
WP-RF010.01	1.87E-01	0.00E+00	1.30E-10	7.05E+01	1.28E+01	1.17E-61	1.89E-03	8.34E+01	3.36E-01
WP-RF029.01-A	4.49E-02	0.00E+00	2.44E-11	1.24E+01	2.25E+00	2.69E-62	9.43E-04	1.47E+01	5.91E-02
WP-RF029.01-B	6.70E-02	0.00E+00	1.93E-11	9.81E+00	1.78E+00	2.13E-62	2.40E-03	1.17E+01	4.70E-02
WP-RF118.01	1.14E+02	0.00E+00	9.71E-08	4.71E+04	8.34E+03	6.99E-59	1.09E+00	5.56E+04	2.24E+02
WP-RLMPDT.001	2.42E-02	0.00E+00	2.84E-11	6.75E+00	1.39E+00	1.53E-62	2.57E-04	8.16E+00	3.29E-02
WP-RLNPDT.002	2.97E-01	0.00E+00	2.70E-10	6.63E+01	1.41E+01	1.76E-61	2.46E-03	8.07E+01	3.25E-01
WP-SR2001.001.	9.45E-03	0.00E+00	3.10E-11	6.26E+00	9.86E-01	9.58E-63	2.83E-04	7.26E+00	2.93E-02
WP-SR-W027-221	7.00E-02	0.00E+00	9.12E-11	1.80E+01	3.98E+00	4.32E-62	1.85E-01	2.22E+01	8.95E-02
Total	3.74E+03	3.70E-47	6.38E-05	6.05E+05	7.76E+04	9.88E-58	7.39E+02	6.87E+05	2.77E+03

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	2.85E-02	0.00E+00	9.71E-17	1.81E+02	7.27E+01	0.00E+00	1.94E-02	2.54E+02	1.02E+00
AE-T003	3.62E-03	0.00E+00	1.29E-17	5.59E+01	1.47E+01	0.00E+00	9.50E-04	7.06E+01	2.85E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	1.60E-05	0.00E+00	3.43E-16	4.12E+01	1.69E-01	0.00E+00	2.27E-02	4.14E+01	1.67E-01
AW-T033.1325	5.86E-05	0.00E+00	1.26E-15	1.51E+02	6.16E-01	0.00E+00	8.32E-02	1.51E+02	6.10E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	6.69E-01	0.00E+00	0.00E+00	0.00E+00	6.69E-01	2.70E-03
BCLCH-MT01	5.91E-03	0.00E+00	9.71E-15	2.48E+01	4.42E+00	0.00E+00	6.30E-01	2.99E+01	1.21E-01
BT-T002	4.34E-06	5.77E-87	5.07E-18	6.27E-04	8.72E-04	0.00E+00	2.29E-03	3.80E-03	1.53E-05
ET-C1-B55	1.81E-05	0.00E+00	5.78E-20	5.37E-02	1.82E-02	0.00E+00	2.36E-04	7.22E-02	2.91E-04
ET-C1-D139	2.49E-06	0.00E+00	8.02E-21	7.55E-03	2.56E-03	0.00E+00	5.81E-07	1.01E-02	4.08E-05
ET-C2-SEFOR	6.16E-05	0.00E+00	0.00E+00	1.19E-01	2.70E-02	0.00E+00	0.00E+00	1.46E-01	5.87E-04
FM-MOX-MT02	5.84E-10	0.00E+00	3.23E-24	2.60E-07	1.05E-07	0.00E+00	2.18E-10	3.65E-07	1.47E-09
FM-MOX-T01	9.64E-09	0.00E+00	5.33E-23	4.27E-06	1.73E-06	0.00E+00	3.60E-09	6.02E-06	2.43E-08
IN-BN-510	2.33E+00	0.00E+00	2.75E-13	3.43E+04	1.98E+03	0.00E+00	1.98E+01	3.63E+04	1.47E+02
IN-GEM-01	2.95E-02	0.00E+00	5.45E-18	3.86E+01	5.98E+00	0.00E+00	3.54E-04	4.46E+01	1.80E-01
IN-GEM-02	7.00E-03	0.00E+00	1.30E-18	9.17E+00	1.43E+00	0.00E+00	8.42E-05	1.06E+01	4.28E-02
IN-W157.144	3.49E-02	0.00E+00	5.28E-17	2.62E+02	4.03E+01	0.00E+00	3.80E-03	3.03E+02	1.22E+00
IN-W163.1007	5.97E-03	0.00E+00	1.63E-17	8.13E+01	1.25E+01	0.00E+00	1.17E-03	9.38E+01	3.78E-01
IN-W164.153	5.72E-05	0.00E+00	1.56E-19	7.74E-01	1.19E-01	0.00E+00	1.12E-05	8.93E-01	3.60E-03
IN-W167.149	1.14E-02	0.00E+00	2.53E-17	1.25E+02	1.93E+01	0.00E+00	1.82E-03	1.45E+02	5.84E-01
IN-W174.154	0.00E+00	0.00E+00	1.43E-14	1.69E+00	2.26E+00	0.00E+00	1.03E+00	4.97E+00	2.01E-02
IN-W177.156	7.94E-06	0.00E+00	3.04E-14	1.58E+00	6.57E-03	0.00E+00	2.18E+00	3.77E+00	1.52E-02
IN-W179.158	5.34E-05	0.00E+00	3.03E-14	9.17E-02	3.24E-02	0.00E+00	2.18E+00	2.30E+00	9.28E-03
IN-W181.162	7.57E-04	0.00E+00	2.06E-18	1.02E+01	1.57E+00	0.00E+00	1.48E-04	1.18E+01	4.75E-02
IN-W188.160	5.10E-03	0.00E+00	1.39E-17	6.90E+01	1.06E+01	0.00E+00	9.96E-04	7.95E+01	3.21E-01
IN-W216.98	4.53E+01	0.00E+00	1.13E-15	5.62E+03	8.68E+02	0.00E+00	8.12E-02	6.54E+03	2.64E+01

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	2.29E-01	0.00E+00	2.51E-17	1.25E+02	1.92E+01	0.00E+00	1.80E-03	1.44E+02	5.81E-01
IN-W219.110	3.11E-04	0.00E+00	8.46E-19	4.20E+00	6.45E-01	0.00E+00	6.08E-05	4.85E+00	1.96E-02
IN-W219.914	4.90E-05	0.00E+00	1.33E-19	6.64E-01	1.02E-01	0.00E+00	9.57E-06	7.66E-01	3.09E-03
IN-W220.114	1.62E+00	0.00E+00	8.89E-17	4.75E+02	7.10E+01	0.00E+00	6.39E-03	5.48E+02	2.21E+00
IN-W221.927	1.90E-03	0.00E+00	5.16E-18	2.56E+01	3.93E+00	0.00E+00	3.71E-04	2.95E+01	1.19E-01
IN-W222.116	6.45E-02	0.00E+00	1.75E-16	8.65E+02	1.33E+02	0.00E+00	1.26E-02	9.98E+02	4.03E+00
IN-W228.101	4.28E-01	0.00E+00	5.67E-17	2.83E+02	4.34E+01	0.00E+00	4.08E-03	3.27E+02	1.32E+00
IN-W240.931	4.53E-02	0.00E+00	7.26E-17	3.63E+02	5.55E+01	0.00E+00	5.22E-03	4.19E+02	1.69E+00
IN-W243.808	6.28E-02	0.00E+00	1.27E-16	6.34E+02	9.74E+01	0.00E+00	9.14E-03	7.32E+02	2.95E+00
IN-W245.301	9.28E-02	0.00E+00	2.50E-16	1.24E+03	1.91E+02	0.00E+00	1.80E-02	1.43E+03	5.76E+00
IN-W247.810	4.52E-02	0.00E+00	1.22E-16	6.05E+02	9.33E+01	0.00E+00	8.75E-03	6.98E+02	2.82E+00
IN-W249.527	0.00E+00	0.00E+00	8.51E-15	1.07E+01	0.00E+00	0.00E+00	6.12E-01	1.13E+01	4.57E-02
IN-W263.520	1.30E-05	0.00E+00	8.89E-16	7.29E+00	7.86E-03	0.00E+00	6.39E-02	7.36E+00	2.97E-02
IN-W267.1005	1.08E-02	0.00E+00	2.95E-17	1.47E+02	2.26E+01	0.00E+00	2.12E-03	1.70E+02	6.84E-01
IN-W309.609	2.91E-01	0.00E+00	4.95E-16	2.46E+03	3.78E+02	0.00E+00	3.56E-02	2.84E+03	1.14E+01
IN-W315.601	2.87E-01	0.00E+00	2.07E-18	1.03E+01	1.58E+00	0.00E+00	1.49E-04	1.22E+01	4.90E-02
IN-W319.584	1.67E-03	0.00E+00	4.53E-18	2.26E+01	3.48E+00	0.00E+00	3.26E-04	2.61E+01	1.05E-01
IN-W321.1023	1.44E-02	0.00E+00	3.93E-17	1.96E+02	3.00E+01	0.00E+00	2.82E-03	2.26E+02	9.10E-01
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	7.89E+00	1.11E+00	0.00E+00	0.00E+00	9.00E+00	3.63E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.10E+01	2.96E+00	0.00E+00	0.00E+00	2.40E+01	9.67E-02
IN-W323.562	3.08E-05	0.00E+00	6.66E-18	2.15E-01	0.00E+00	0.00E+00	4.79E-04	2.16E-01	8.71E-04
IN-W323.951	3.64E-05	0.00E+00	7.91E-20	2.57E-01	0.00E+00	0.00E+00	5.69E-06	2.57E-01	1.04E-03
IN-W332.661	0.00E+00	0.00E+00	8.73E-17	1.12E-01	0.00E+00	0.00E+00	6.28E-03	1.18E-01	4.75E-04
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	2.63E+00	3.70E-01	0.00E+00	0.00E+00	3.00E+00	1.21E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	7.89E+00	1.11E+00	0.00E+00	0.00E+00	9.00E+00	3.63E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.69E+00	0.00E+00	0.00E+00	0.00E+00	1.69E+00	6.80E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.07E+00	0.00E+00	0.00E+00	0.00E+00	5.07E+00	2.04E-02
IN-W342.652	1.42E-03	0.00E+00	0.00E+00	3.48E-02	6.10E-18	0.00E+00	0.00E+00	3.62E-02	1.46E-04
IN-W342.953	9.51E-04	0.00E+00	0.00E+00	2.33E-02	4.09E-18	0.00E+00	0.00E+00	2.42E-02	9.77E-05
IN-W347.818	7.45E-04	0.00E+00	0.00E+00	7.15E+01	8.92E+01	0.00E+00	1.56E-08	1.61E+02	6.48E-01
IN-W348.1012	3.94E-05	0.00E+00	7.20E-17	3.61E+02	5.55E+01	0.00E+00	5.18E-03	4.16E+02	1.68E+00

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.16E-02	0.00E+00	0.00E+00	0.00E+00	2.16E-02	8.72E-05
IN-W357.1022	0.00E+00	0.00E+00	1.42E-19	7.09E-01	1.09E-01	0.00E+00	1.02E-05	8.17E-01	3.29E-03
IN-W358.854	0.00E+00	0.00E+00	2.14E-15	1.63E+00	2.13E+00	0.00E+00	1.47E-01	3.90E+00	1.57E-02
IN-W358.855	0.00E+00	0.00E+00	1.14E-14	8.65E+00	1.13E+01	0.00E+00	7.82E-01	2.08E+01	8.37E-02
IN-W358.948	0.00E+00	0.00E+00	2.38E-15	1.81E+00	2.36E+00	0.00E+00	1.63E-01	4.33E+00	1.75E-02
IN-W361.1021	1.05E-05	0.00E+00	1.38E-17	6.83E+01	1.05E+01	0.00E+00	9.88E-04	7.88E+01	3.18E-01
IN-W362.1020	0.00E+00	0.00E+00	1.80E-16	8.91E+02	1.38E+02	0.00E+00	1.29E-02	1.03E+03	4.15E+00
IN-W363.1019	0.00E+00	0.00E+00	8.46E-18	4.23E+01	6.51E+00	0.00E+00	6.08E-04	4.88E+01	1.97E-01
IN-W364.1011	0.00E+00	0.00E+00	1.40E-17	6.96E+01	1.07E+01	0.00E+00	1.00E-03	8.02E+01	3.24E-01
IN-W365.1010	9.76E-02	0.00E+00	1.11E-17	5.49E+01	8.45E+00	0.00E+00	7.96E-04	6.35E+01	2.56E-01
IN-W366.841	3.47E-04	0.00E+00	9.44E-18	4.68E+01	7.21E+00	0.00E+00	6.79E-04	5.40E+01	2.18E-01
IN-W372.832	1.42E-03	0.00E+00	0.00E+00	3.48E-02	6.10E-18	0.00E+00	0.00E+00	3.62E-02	1.46E-04
IN-W375.1096	0.00E+00	0.00E+00	3.48E-18	1.73E+01	2.66E+00	0.00E+00	2.50E-04	2.00E+01	8.05E-02
KN-B234TRU	5.06E-02	0.00E+00	1.33E-16	2.52E+02	5.75E+01	0.00E+00	1.06E-02	3.09E+02	1.25E+00
LA-IT-00-01	7.35E-04	3.71E-84	2.27E-17	5.06E-01	7.44E-03	0.00E+00	1.82E-03	5.16E-01	2.08E-03
LA-OS-00-01	1.64E+00	0.00E+00	1.04E-12	1.06E+03	0.00E+00	0.00E+00	6.78E+01	1.13E+03	4.57E+00
LA-PX-00-01	6.83E-06	0.00E+00	4.37E-20	7.83E-02	1.25E-02	0.00E+00	2.97E-06	9.08E-02	3.66E-04
LA-SL-00-01	0.00E+00	0.00E+00	9.22E-19	1.32E-01	0.00E+00	0.00E+00	7.35E-05	1.32E-01	5.34E-04
LA-TA-03-12	7.02E-05	0.00E+00	2.13E-17	3.77E-01	8.92E-02	0.00E+00	1.76E-03	4.68E-01	1.89E-03
LA-TA-03-13	9.08E-05	0.00E+00	6.77E-17	5.89E-01	9.38E-02	0.00E+00	4.91E-03	6.88E-01	2.77E-03
LA-TA-03-19	1.84E-04	0.00E+00	1.01E-16	1.15E+00	2.26E-01	0.00E+00	8.31E-03	1.39E+00	5.58E-03
LA-TA-03-20	1.00E-04	0.00E+00	4.79E-17	5.07E-01	1.21E-01	0.00E+00	3.79E-03	6.32E-01	2.55E-03
LA-TA-03-24	1.34E-04	0.00E+00	1.87E-16	9.43E-01	1.94E-01	0.00E+00	1.55E-02	1.15E+00	4.65E-03
LA-TA-03-26	6.87E-06	0.00E+00	7.69E-18	2.28E+00	2.54E-02	0.00E+00	1.50E-03	2.31E+00	9.32E-03
LA-TA-03-28	0.00E+00	0.00E+00	2.66E-18	2.14E-01	0.00E+00	0.00E+00	2.17E-04	2.14E-01	8.63E-04
LA-TA-03-30	3.06E-04	0.00E+00	1.90E-18	4.35E+00	8.56E-01	0.00E+00	1.54E-04	5.21E+00	2.10E-02
LA-TA-03-31	0.00E+00	0.00E+00	9.49E-20	7.61E-03	0.00E+00	0.00E+00	7.75E-06	7.62E-03	3.07E-05
LA-TA-03-40	0.00E+00	0.00E+00	1.50E-19	4.73E-02	0.00E+00	0.00E+00	1.23E-05	4.73E-02	1.91E-04
LA-TA-03-42	7.03E-09	0.00E+00	3.76E-21	2.96E-03	2.65E-05	0.00E+00	3.09E-07	2.99E-03	1.20E-05
LA-TA-21-06	6.92E-05	0.00E+00	4.14E-16	8.28E-01	1.72E-01	0.00E+00	3.37E-02	1.03E+00	4.17E-03
LA-TA-21-12	2.52E-04	0.00E+00	2.49E-15	2.87E+00	5.83E-01	0.00E+00	2.03E-01	3.66E+00	1.48E-02

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-13	3.88E-04	0.00E+00	0.00E+00	2.54E-01	0.00E+00	0.00E+00	0.00E+00	2.55E-01	1.03E-03
LA-TA-21-14	6.37E-08	0.00E+00	4.76E-17	3.88E+00	3.08E-05	0.00E+00	3.26E-03	3.89E+00	1.57E-02
LA-TA-21-15	3.76E-05	0.00E+00	1.31E-19	1.20E+00	1.40E-01	0.00E+00	1.06E-05	1.34E+00	5.41E-03
LA-TA-21-16	4.35E-04	0.00E+00	2.02E-18	9.17E+00	1.49E+00	0.00E+00	1.66E-04	1.07E+01	4.30E-02
LA-TA-21-40	5.53E-08	0.00E+00	6.98E-18	2.88E-01	2.16E-04	0.00E+00	7.00E-04	2.89E-01	1.17E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	6.13E-01	0.00E+00	0.00E+00	0.00E+00	6.13E-01	2.47E-03
LA-TA-21-42	5.65E-06	0.00E+00	2.27E-18	1.42E-01	6.57E-03	0.00E+00	2.42E-04	1.49E-01	6.00E-04
LA-TA-21-43	1.99E-02	0.00E+00	7.53E-17	4.42E+02	7.16E+01	0.00E+00	7.98E-03	5.14E+02	2.07E+00
LA-TA-21-44	9.57E-05	0.00E+00	1.58E-17	9.95E+01	1.80E-01	0.00E+00	1.40E-03	9.97E+01	4.02E-01
LA-TA-48-01	3.10E-05	1.75E-83	5.95E-20	1.02E-01	2.91E-01	0.00E+00	6.02E-06	3.93E-01	1.58E-03
LA-TA-49-01	3.82E-03	2.17E-81	7.31E-18	1.26E+01	3.60E+01	0.00E+00	7.41E-04	4.86E+01	1.96E-01
LA-TA-50-10	1.02E-05	0.00E+00	6.93E-20	3.97E-02	0.00E+00	0.00E+00	4.68E-06	3.97E-02	1.60E-04
LA-TA-50-11	1.95E-05	0.00E+00	7.09E-20	4.03E-01	6.10E-02	0.00E+00	7.05E-06	4.64E-01	1.87E-03
LA-TA-50-15	3.85E-05	0.00E+00	1.05E-17	2.94E-01	4.49E-02	0.00E+00	7.99E-04	3.40E-01	1.37E-03
LA-TA-50-17	5.63E-03	0.00E+00	8.51E-18	1.57E+01	2.52E-04	0.00E+00	9.84E-04	1.58E+01	6.35E-02
LA-TA-50-18	3.35E-04	0.00E+00	1.12E-18	2.57E+00	3.14E-06	0.00E+00	9.24E-05	2.57E+00	1.04E-02
LA-TA-50-19	1.07E-04	0.00E+00	5.01E-19	3.42E-01	2.69E-03	0.00E+00	6.76E-05	3.45E-01	1.39E-03
LA-TA-50-20	2.93E-06	0.00E+00	0.00E+00	8.43E-03	0.00E+00	0.00E+00	0.00E+00	8.43E-03	3.40E-05
LA-TA-50-40	1.65E-06	0.00E+00	6.77E-21	9.17E-03	2.92E-03	0.00E+00	5.31E-07	1.21E-02	4.87E-05
LA-TA-50-41	1.76E-06	0.00E+00	6.82E-21	4.07E-02	6.45E-03	0.00E+00	4.90E-07	4.71E-02	1.90E-04
LA-TA-55-19	2.73E-03	0.00E+00	9.00E-18	2.28E+01	4.38E+00	0.00E+00	2.23E-03	2.72E+01	1.10E-01
LA-TA-55-20	4.39E-02	0.00E+00	1.03E-16	5.52E+02	9.03E+01	0.00E+00	1.00E-01	6.42E+02	2.59E+00
LA-TA-55-21	3.92E-04	5.17E-87	1.18E-18	3.91E+00	6.39E-01	0.00E+00	8.41E-05	4.55E+00	1.84E-02
LA-TA-55-22	1.07E-03	0.00E+00	6.66E-18	1.38E+01	2.19E+00	0.00E+00	4.75E-04	1.60E+01	6.43E-02
LA-TA-55-23	1.01E-03	0.00E+00	5.57E-18	9.43E+00	1.59E+00	0.00E+00	3.94E-04	1.10E+01	4.44E-02
LA-TA-55-24	3.81E-04	0.00E+00	8.73E-19	4.95E+00	7.86E-01	0.00E+00	5.94E-05	5.74E+00	2.31E-02
LA-TA-55-25	1.95E-03	0.00E+00	5.09E-18	2.46E+01	3.91E+00	0.00E+00	3.46E-04	2.85E+01	1.15E-01
LA-TA-55-28	6.65E-04	0.00E+00	2.82E-18	7.54E+00	1.21E+00	0.00E+00	1.93E-04	8.76E+00	3.53E-02
LA-TA-55-30	1.48E-02	4.90E-89	3.38E-17	1.24E+02	2.04E+01	0.00E+00	2.95E-03	1.44E+02	5.81E-01
LA-TA-55-32	1.20E-03	0.00E+00	1.89E-16	9.78E+00	2.06E+00	0.00E+00	1.57E-02	1.19E+01	4.78E-02
LA-TA-55-33	1.80E-04	0.00E+00	4.87E-19	1.29E+00	2.80E-01	0.00E+00	3.79E-05	1.57E+00	6.33E-03

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-34	1.82E-02	0.00E+00	4.51E-17	2.00E+02	3.46E+01	0.00E+00	6.25E-03	2.35E+02	9.45E-01
LA-TA-55-38	4.57E-02	0.00E+00	1.48E-17	4.41E+01	8.09E+00	0.00E+00	2.83E-03	5.23E+01	2.11E-01
LA-TA-55-39	4.84E-03	0.00E+00	1.10E-17	6.58E+01	1.01E+01	0.00E+00	7.70E-04	7.59E+01	3.06E-01
LA-TA-55-41	1.15E-01	0.00E+00	2.27E-17	8.17E+01	1.33E+01	0.00E+00	1.63E-03	9.51E+01	3.83E-01
LA-TA-55-43	4.33E-05	0.00E+00	1.49E-15	1.23E-01	2.93E-02	0.00E+00	1.04E-01	2.56E-01	1.03E-03
LA-TA-55-44	3.75E-04	0.00E+00	3.51E-15	2.28E+00	4.31E-01	0.00E+00	2.75E-01	2.98E+00	1.20E-02
LA-TA-55-48	2.76E+00	0.00E+00	1.39E-14	1.46E+04	3.72E+03	0.00E+00	1.06E+00	1.83E+04	7.40E+01
LA-TA-55-49	5.91E-03	0.00E+00	1.82E-14	2.67E+01	5.12E+00	0.00E+00	1.42E+00	3.33E+01	1.34E-01
LA-TA-55-53	2.79E-02	0.00E+00	3.77E-17	2.28E+02	3.64E+01	0.00E+00	2.89E-03	2.65E+02	1.07E+00
LA-TA-55-56	3.08E-02	0.00E+00	1.40E-15	3.31E+02	5.65E+01	0.00E+00	1.03E-01	3.87E+02	1.56E+00
LA-TA-55-60	1.67E-05	0.00E+00	3.54E-19	6.23E-02	1.51E-02	0.00E+00	2.75E-05	7.74E-02	3.12E-04
LA-TA-55-61	1.44E-05	0.00E+00	1.63E-18	1.20E-01	2.78E-02	0.00E+00	1.25E-04	1.48E-01	5.98E-04
LA-TA-55-62	3.73E-06	0.00E+00	1.55E-20	2.02E-02	6.57E-03	0.00E+00	1.20E-06	2.67E-02	1.08E-04
LA-TA-55-63	2.77E-06	0.00E+00	1.05E-20	6.46E-02	1.02E-02	0.00E+00	7.71E-07	7.48E-02	3.02E-04
LL-M001	3.80E-02	2.35E-82	4.57E-16	6.06E+01	1.86E+01	0.00E+00	2.96E-02	7.93E+01	3.20E-01
LL-T001	1.90E-01	0.00E+00	0.00E+00	4.62E+02	1.42E+02	0.00E+00	0.00E+00	6.04E+02	2.44E+00
LL-T002	1.87E+00	0.00E+00	3.63E-15	4.48E+03	1.26E+03	0.00E+00	2.36E-01	5.74E+03	2.31E+01
LL-T003	7.28E-02	0.00E+00	4.07E-16	9.08E+01	5.00E+01	0.00E+00	2.64E-02	1.41E+02	5.68E-01
LL-T004	4.63E-02	0.00E+00	8.35E-17	5.77E+01	3.15E+01	0.00E+00	5.42E-03	8.93E+01	3.60E-01
LL-T005	2.39E-01	1.02E-80	9.82E-16	2.15E+02	1.26E+02	0.00E+00	6.37E-02	3.41E+02	1.38E+00
LL-W018	2.03E-05	0.00E+00	0.00E+00	1.60E-02	2.51E-02	0.00E+00	0.00E+00	4.11E-02	1.66E-04
LL-W019	1.10E-02	0.00E+00	0.00E+00	1.25E+01	7.10E+00	0.00E+00	0.00E+00	1.96E+01	7.89E-02
LL-W034	4.08E-03	1.73E-82	1.72E-17	3.63E+00	2.09E+00	0.00E+00	1.12E-03	5.73E+00	2.31E-02
MC-W001	5.09E-05	0.00E+00	0.00E+00	5.24E-02	0.00E+00	0.00E+00	0.00E+00	5.25E-02	2.12E-04
MU-W002	6.79E-04	0.00E+00	0.00E+00	4.55E-02	0.00E+00	0.00E+00	2.63E-12	4.62E-02	1.86E-04
NT-JAS-01	6.56E-02	0.00E+00	3.66E-16	8.20E+01	4.50E+01	0.00E+00	2.38E-02	1.27E+02	5.12E-01
NT-W001	9.85E-02	5.29E-84	7.31E-16	2.47E+03	1.13E+01	0.00E+00	5.89E-02	2.49E+03	1.00E+01
NT-W021	1.91E-03	0.00E+00	5.24E-18	2.79E+01	4.33E+00	0.00E+00	3.86E-04	3.22E+01	1.30E-01
OR-W201	2.28E+00	3.65E-82	1.57E-14	1.87E+03	1.26E+03	0.00E+00	4.40E+01	3.17E+03	1.28E+01
OR-W202	3.28E-01	7.59E-81	4.53E-14	4.79E+02	3.20E+02	0.00E+00	3.39E+00	8.03E+02	3.24E+00
OR-W203	7.22E-04	2.64E-82	6.49E-18	2.15E-02	1.05E+00	0.00E+00	4.82E-04	1.07E+00	4.31E-03

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
OR-W204	1.61E-04	1.10E-87	7.37E-18	3.67E-01	1.69E-01	0.00E+00	5.47E-04	5.36E-01	2.16E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	3.69E-01	0.00E+00	0.00E+00	0.00E+00	3.69E-01	1.49E-03
RF-MT0001	6.17E-01	0.00E+00	4.57E-17	1.70E+02	2.63E+01	0.00E+00	3.26E-03	1.97E+02	7.92E-01
RF-MT0002	4.75E-02	0.00E+00	3.51E-18	1.31E+01	2.02E+00	0.00E+00	2.50E-04	1.51E+01	6.10E-02
RF-MT0003	2.16E-04	0.00E+00	8.02E-19	2.99E+00	4.63E-01	0.00E+00	5.72E-05	3.45E+00	1.39E-02
RF-MT0007	5.43E-04	0.00E+00	0.00E+00	3.72E-01	5.77E-02	0.00E+00	0.00E+00	4.30E-01	1.74E-03
RF-MT0089	2.13E-06	0.00E+00	8.02E-21	2.99E-02	4.63E-03	0.00E+00	5.72E-07	3.45E-02	1.39E-04
RF-MT0090	5.41E-03	0.00E+00	1.14E-17	7.67E+01	1.18E+01	0.00E+00	8.10E-04	8.84E+01	3.57E-01
RF-MT0091	3.35E-01	0.00E+00	1.15E-15	5.12E+03	7.92E+02	0.00E+00	8.51E-02	5.91E+03	2.38E+01
RF-MT0092	4.80E-02	0.00E+00	1.45E-16	7.34E+02	1.16E+02	0.00E+00	1.04E-02	8.49E+02	3.42E+00
RF-MT0093	5.85E-02	0.00E+00	1.50E-16	7.92E+02	1.27E+02	0.00E+00	1.07E-02	9.18E+02	3.70E+00
RF-MT0097	2.93E-03	0.00E+00	6.60E-18	4.14E+01	5.76E+00	0.00E+00	4.71E-04	4.71E+01	1.90E-01
RF-MT0099	3.21E-06	0.00E+00	1.21E-20	4.47E-02	6.92E-03	0.00E+00	8.60E-07	5.17E-02	2.08E-04
RF-MT0290	7.95E-03	0.00E+00	2.98E-17	1.11E+02	1.72E+01	0.00E+00	2.13E-03	1.28E+02	5.16E-01
RF-MT-0292	1.00E-02	0.00E+00	3.77E-17	1.40E+02	2.17E+01	0.00E+00	2.69E-03	1.62E+02	6.53E-01
RF-MT-0299	1.18E+00	0.00E+00	9.66E-16	3.59E+03	5.57E+02	0.00E+00	6.89E-02	4.15E+03	1.67E+01
RF-MT0302	1.81E-05	0.00E+00	3.83E-20	1.55E-01	2.41E-02	0.00E+00	1.93E-05	1.79E-01	7.22E-04
RF-MT0320	2.16E-02	0.00E+00	3.97E-17	1.51E+02	2.34E+01	0.00E+00	2.84E-03	1.74E+02	7.01E-01
RF-MT0321	1.21E-02	0.00E+00	1.18E-17	4.84E+01	7.45E+00	0.00E+00	3.22E-03	5.59E+01	2.25E-01
RF-MT-0328	8.35E-04	0.00E+00	1.42E-18	5.27E+00	8.15E-01	0.00E+00	4.35E-04	6.09E+00	2.45E-02
RF-MT0330	8.69E-03	0.00E+00	1.56E-17	1.06E+02	1.78E+01	0.00E+00	1.11E-03	1.24E+02	5.01E-01
RF-MT-0331	5.21E-02	0.00E+00	9.66E-17	4.68E+02	7.10E+01	0.00E+00	2.74E-02	5.39E+02	2.17E+00
RF-MT0332	7.47E-06	0.00E+00	2.82E-20	1.05E-01	1.62E-02	0.00E+00	2.01E-06	1.21E-01	4.87E-04
RF-MT-0335	6.00E-04	0.00E+00	1.29E-18	5.39E+00	8.39E-01	0.00E+00	6.27E-04	6.23E+00	2.51E-02
RF-MT0336	4.25E-02	0.00E+00	8.57E-17	3.82E+02	5.92E+01	0.00E+00	7.90E-03	4.42E+02	1.78E+00
RF-MT0337	2.40E-02	0.00E+00	4.71E-17	2.34E+02	3.56E+01	0.00E+00	7.16E-03	2.69E+02	1.09E+00
RF-MT0339	6.57E-02	0.00E+00	1.28E-16	5.12E+02	7.86E+01	0.00E+00	2.60E-02	5.91E+02	2.38E+00
RF-MT-0342	3.86E-04	0.00E+00	1.08E-18	4.73E+00	7.21E-01	0.00E+00	1.34E-04	5.45E+00	2.20E-02
RF-MT0371	1.31E-01	0.00E+00	2.49E-16	9.26E+02	1.43E+02	0.00E+00	1.90E-02	1.07E+03	4.31E+00
RF-MT-0372	5.69E-04	0.00E+00	1.75E-18	6.45E+00	1.00E+00	0.00E+00	3.61E-04	7.46E+00	3.01E-02
RF-MT0373	8.57E-03	0.00E+00	1.80E-17	1.21E+02	1.87E+01	0.00E+00	1.28E-03	1.40E+02	5.64E-01

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0374	2.78E-04	0.00E+00	6.44E-19	2.40E+00	3.71E-01	0.00E+00	4.92E-05	2.77E+00	1.12E-02
RF-MT0376	2.21E-04	0.00E+00	5.20E-19	2.39E+00	3.76E-01	0.00E+00	5.20E-05	2.76E+00	1.11E-02
RF-MT0377	1.31E-01	0.00E+00	3.00E-16	1.12E+03	1.72E+02	0.00E+00	3.15E-02	1.29E+03	5.20E+00
RF-MT0378	1.47E-03	0.00E+00	4.14E-18	1.54E+01	2.39E+00	0.00E+00	2.95E-04	1.78E+01	7.17E-02
RF-MT0419	2.36E-03	0.00E+00	3.87E-18	1.44E+01	2.23E+00	0.00E+00	2.76E-04	1.66E+01	6.69E-02
RF-MT0420	4.11E-04	0.00E+00	6.71E-19	2.49E+00	3.87E-01	0.00E+00	4.79E-05	2.88E+00	1.16E-02
RF-MT0423	3.49E-03	0.00E+00	5.46E-18	3.60E+01	5.41E+00	0.00E+00	3.89E-04	4.14E+01	1.67E-01
RF-MT0425	1.03E-04	0.00E+00	1.68E-19	6.24E-01	9.68E-02	0.00E+00	1.20E-05	7.21E-01	2.91E-03
RF-MT-0438	9.33E-04	0.00E+00	2.20E-18	1.11E+01	1.70E+00	0.00E+00	1.70E-04	1.28E+01	5.15E-02
RF-MT0440	3.39E-04	0.00E+00	7.91E-19	4.01E+00	6.34E-01	0.00E+00	2.19E-04	4.65E+00	1.87E-02
RF-MT0442	1.29E-04	0.00E+00	3.42E-19	1.38E+00	2.13E-01	0.00E+00	1.18E-04	1.59E+00	6.41E-03
RF-MT0443	1.59E-03	0.00E+00	5.62E-18	2.14E+01	3.31E+00	0.00E+00	5.57E-04	2.47E+01	9.95E-02
RF-MT0444	1.24E-02	0.00E+00	2.76E-17	1.03E+02	1.59E+01	0.00E+00	1.99E-03	1.19E+02	4.79E-01
RF-MT0480	3.46E-02	0.00E+00	7.75E-17	2.89E+02	4.49E+01	0.00E+00	7.95E-03	3.34E+02	1.35E+00
RF-MT0488	5.55E-02	0.00E+00	1.16E-16	4.29E+02	6.63E+01	0.00E+00	3.88E-02	4.95E+02	2.00E+00
RF-MT0490	2.51E-04	0.00E+00	6.71E-19	2.54E+00	3.94E-01	0.00E+00	5.89E-05	2.93E+00	1.18E-02
RF-MT-0491	1.97E-05	0.00E+00	3.07E-20	1.15E-01	1.78E-02	0.00E+00	4.17E-06	1.33E-01	5.36E-04
RF-MT0523A	1.56E-02	0.00E+00	2.44E-17	9.08E+01	1.41E+01	0.00E+00	1.99E-03	1.05E+02	4.23E-01
RF-MT0523B	1.56E-02	0.00E+00	2.44E-17	9.08E+01	1.41E+01	0.00E+00	1.99E-03	1.05E+02	4.23E-01
RF-MT0523C	1.56E-02	0.00E+00	2.44E-17	9.08E+01	1.41E+01	0.00E+00	1.99E-03	1.05E+02	4.23E-01
RF-MT0523D	1.56E-02	0.00E+00	2.44E-17	9.08E+01	1.41E+01	0.00E+00	1.99E-03	1.05E+02	4.23E-01
RF-MT0523E	1.56E-02	0.00E+00	2.44E-17	9.08E+01	1.41E+01	0.00E+00	1.99E-03	1.05E+02	4.23E-01
RF-MT0531	1.07E-06	0.00E+00	4.02E-21	1.49E-02	2.31E-03	0.00E+00	2.86E-07	1.72E-02	6.93E-05
RF-MT0532E	4.98E-02	0.00E+00	5.22E-17	1.98E+02	3.07E+01	0.00E+00	4.82E-03	2.29E+02	9.23E-01
RF-MT0532F	4.98E-02	0.00E+00	5.22E-17	1.98E+02	3.07E+01	0.00E+00	4.82E-03	2.29E+02	9.23E-01
RF-MT0541	1.82E-03	0.00E+00	7.53E-19	2.81E+00	4.35E-01	0.00E+00	5.37E-05	3.25E+00	1.31E-02
RF-MT0545	9.72E-06	0.00E+00	3.65E-20	1.36E-01	2.10E-02	0.00E+00	2.60E-06	1.57E-01	6.32E-04
RF-MT0800	3.69E-01	0.00E+00	1.81E-17	6.70E+01	1.04E+01	0.00E+00	1.77E-03	7.78E+01	3.14E-01
RF-MT0801	4.24E-02	0.00E+00	1.77E-17	6.58E+01	1.02E+01	0.00E+00	1.26E-03	7.61E+01	3.07E-01
RF-MT0803	9.52E-04	0.00E+00	3.96E-19	1.47E+00	2.28E-01	0.00E+00	2.82E-05	1.70E+00	6.85E-03
RF-MT0806	4.49E-04	0.00E+00	9.49E-19	6.39E+00	9.80E-01	0.00E+00	6.77E-05	7.37E+00	2.97E-02

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0807	5.68E-03	0.00E+00	7.31E-18	2.72E+01	4.22E+00	0.00E+00	5.22E-04	3.14E+01	1.27E-01
RF-MT0816	6.08E-04	0.00E+00	1.03E-18	3.83E+00	5.92E-01	0.00E+00	7.35E-05	4.43E+00	1.78E-02
RF-MT-0823	3.01E-04	0.00E+00	4.69E-19	1.75E+00	2.71E-01	0.00E+00	3.83E-05	2.02E+00	8.14E-03
RF-MT0827	1.53E-02	0.00E+00	2.61E-17	9.69E+01	1.50E+01	0.00E+00	1.86E-03	1.12E+02	4.51E-01
RF-MT0831	2.92E-02	0.00E+00	7.15E-17	2.62E+02	4.07E+01	0.00E+00	1.72E-02	3.03E+02	1.22E+00
RF-MT0832	1.75E-01	0.00E+00	2.59E-16	1.02E+03	1.58E+02	0.00E+00	5.14E-02	1.18E+03	4.75E+00
RF-MT0833	5.32E-02	0.00E+00	7.75E-17	2.95E+02	4.58E+01	0.00E+00	1.46E-02	3.41E+02	1.37E+00
RF-MT0855	9.15E-06	0.00E+00	3.44E-20	1.28E-01	1.98E-02	0.00E+00	2.46E-06	1.48E-01	5.96E-04
RF-MT0857	4.49E-04	0.00E+00	9.44E-19	6.38E+00	9.80E-01	0.00E+00	6.73E-05	7.36E+00	2.97E-02
RF-MT0H61	1.67E-02	0.00E+00	3.51E-17	2.36E+02	3.64E+01	0.00E+00	2.50E-03	2.73E+02	1.10E+00
RF-MT2116	1.87E-03	0.00E+00	2.78E-18	1.09E+01	1.69E+00	0.00E+00	5.51E-04	1.26E+01	5.08E-02
RF-MT3010	1.17E-02	0.00E+00	2.89E-17	1.08E+02	1.69E+01	0.00E+00	2.45E-03	1.25E+02	5.04E-01
RF-MT3011	8.75E-02	0.00E+00	1.80E-16	6.68E+02	1.04E+02	0.00E+00	2.05E-02	7.72E+02	3.11E+00
RF-MT420P	4.65E-01	0.00E+00	9.11E-16	5.49E+03	8.51E+02	0.00E+00	7.49E-02	6.34E+03	2.56E+01
RF-MT532A	1.23E-01	0.00E+00	1.29E-16	4.90E+02	7.57E+01	0.00E+00	1.19E-02	5.65E+02	2.28E+00
RF-MT532B	5.51E-01	0.00E+00	5.78E-16	2.20E+03	3.40E+02	0.00E+00	5.33E-02	2.54E+03	1.02E+01
RF-MT532C	1.10E+00	0.00E+00	1.16E-15	4.40E+03	6.80E+02	0.00E+00	1.07E-01	5.09E+03	2.05E+01
RF-MT532D	6.98E-03	0.00E+00	7.31E-18	2.79E+01	4.31E+00	0.00E+00	6.74E-04	3.22E+01	1.30E-01
RF-TT0069	4.02E-05	0.00E+00	8.68E-20	3.23E-01	5.00E-02	0.00E+00	7.87E-05	3.73E-01	1.50E-03
RF-TT0200	1.91E-03	0.00E+00	3.50E-18	1.32E+01	2.07E+00	0.00E+00	2.51E-04	1.53E+01	6.17E-02
RF-TT0299	7.90E-03	0.00E+00	6.49E-18	2.41E+01	3.74E+00	0.00E+00	4.63E-04	2.79E+01	1.12E-01
RF-TT0300	6.44E-02	0.00E+00	1.85E-16	6.93E+02	1.08E+02	0.00E+00	2.14E-02	8.01E+02	3.23E+00
RF-TT0301	8.70E-03	0.00E+00	2.51E-17	9.43E+01	1.47E+01	0.00E+00	2.91E-03	1.09E+02	4.39E-01
RF-TT0302	4.30E-04	0.00E+00	9.11E-19	3.69E+00	5.73E-01	0.00E+00	4.58E-04	4.26E+00	1.72E-02
RF-TT0303	2.59E-03	0.00E+00	5.33E-18	1.98E+01	3.07E+00	0.00E+00	1.40E-03	2.29E+01	9.23E-02
RF-TT0310	8.82E-03	0.00E+00	2.50E-17	8.91E+01	1.43E+01	0.00E+00	1.97E-03	1.03E+02	4.17E-01
RF-TT0312	2.12E-01	0.00E+00	4.51E-16	1.95E+03	2.99E+02	0.00E+00	3.39E-02	2.25E+03	9.06E+00
RF-TT0317	1.33E-04	0.00E+00	4.91E-19	1.83E+00	2.83E-01	0.00E+00	3.50E-05	2.11E+00	8.50E-03
RF-TT0320	8.55E-02	0.00E+00	1.57E-16	5.95E+02	9.27E+01	0.00E+00	1.13E-02	6.88E+02	2.77E+00
RF-TT0330	3.04E-02	0.00E+00	5.44E-17	3.74E+02	6.22E+01	0.00E+00	3.88E-03	4.36E+02	1.76E+00
RF-TT-0331	1.51E-01	0.00E+00	2.81E-16	1.36E+03	2.07E+02	0.00E+00	7.95E-02	1.57E+03	6.31E+00

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT-0334	6.58E-02	0.00E+00	2.28E-16	8.44E+02	1.31E+02	0.00E+00	1.62E-02	9.75E+02	3.93E+00
RF-TT0335	8.03E-02	0.00E+00	1.72E-16	7.18E+02	1.12E+02	0.00E+00	8.35E-02	8.30E+02	3.35E+00
RF-TT0336	7.09E-02	0.00E+00	1.43E-16	6.36E+02	9.85E+01	0.00E+00	1.32E-02	7.35E+02	2.96E+00
RF-TT0337	8.42E-02	0.00E+00	1.65E-16	8.21E+02	1.25E+02	0.00E+00	2.51E-02	9.46E+02	3.82E+00
RF-TT0338	3.57E-01	0.00E+00	6.00E-16	3.20E+03	4.88E+02	0.00E+00	5.10E-02	3.69E+03	1.49E+01
RF-TT0340	3.06E-03	0.00E+00	1.15E-17	4.26E+01	6.63E+00	0.00E+00	8.17E-04	4.92E+01	1.98E-01
RF-TT0342	2.05E-02	0.00E+00	5.73E-17	2.51E+02	3.82E+01	0.00E+00	7.15E-03	2.89E+02	1.17E+00
RF-TT0360	1.56E-03	0.00E+00	2.91E-18	1.13E+01	1.77E+00	0.00E+00	2.14E-04	1.30E+01	5.25E-02
RF-TT0368	3.12E-02	0.00E+00	5.84E-17	2.26E+02	3.54E+01	0.00E+00	4.29E-03	2.61E+02	1.05E+00
RF-TT0370	6.15E-02	0.00E+00	1.26E-16	5.03E+02	7.80E+01	0.00E+00	1.67E-02	5.81E+02	2.34E+00
RF-TT0371	1.33E-03	0.00E+00	2.54E-18	9.43E+00	1.46E+00	0.00E+00	1.94E-04	1.09E+01	4.39E-02
RF-TT0372	1.63E-04	0.00E+00	5.00E-19	1.84E+00	2.86E-01	0.00E+00	1.03E-04	2.13E+00	8.59E-03
RF-TT0374	5.07E-03	0.00E+00	1.17E-17	4.35E+01	6.75E+00	0.00E+00	8.96E-04	5.03E+01	2.03E-01
RF-TT0375A	5.28E-05	0.00E+00	1.93E-19	7.15E-01	1.11E-01	0.00E+00	1.38E-05	8.26E-01	3.33E-03
RF-TT0375B	5.28E-05	0.00E+00	1.93E-19	7.15E-01	1.11E-01	0.00E+00	1.38E-05	8.26E-01	3.33E-03
RF-TT0376	1.21E-02	0.00E+00	2.86E-17	1.32E+02	2.07E+01	0.00E+00	2.86E-03	1.52E+02	6.14E-01
RF-TT0377	6.81E-03	0.00E+00	1.56E-17	5.78E+01	8.97E+00	0.00E+00	1.63E-03	6.68E+01	2.69E-01
RF-TT0391	1.52E-03	0.00E+00	2.19E-18	1.46E+01	2.24E+00	0.00E+00	1.56E-04	1.69E+01	6.80E-02
RF-TT0392	5.35E-04	0.00E+00	1.38E-18	7.64E+00	1.18E+00	0.00E+00	9.82E-05	8.82E+00	3.56E-02
RF-TT0393	4.39E-02	0.00E+00	9.60E-17	3.56E+02	5.52E+01	0.00E+00	6.85E-03	4.11E+02	1.66E+00
RF-TT0398	9.59E-04	0.00E+00	2.53E-18	1.43E+01	2.19E+00	0.00E+00	1.81E-04	1.65E+01	6.64E-02
RF-TT0409	8.02E-04	0.00E+00	1.18E-18	7.37E+00	1.13E+00	0.00E+00	8.51E-05	8.50E+00	3.43E-02
RF-TT0412	8.02E-04	0.00E+00	1.18E-18	7.37E+00	1.13E+00	0.00E+00	8.51E-05	8.50E+00	3.43E-02
RF-TT0414	2.49E-02	0.00E+00	3.66E-17	2.28E+02	3.50E+01	0.00E+00	2.63E-03	2.63E+02	1.06E+00
RF-TT0430	7.27E-06	0.00E+00	2.73E-20	1.01E-01	1.57E-02	0.00E+00	1.95E-06	1.17E-01	4.72E-04
RF-TT0431	1.81E-03	0.00E+00	6.66E-18	2.49E+01	3.87E+00	0.00E+00	6.94E-04	2.88E+01	1.16E-01
RF-TT0438	1.08E-01	0.00E+00	2.54E-16	1.27E+03	1.96E+02	0.00E+00	1.96E-02	1.47E+03	5.92E+00
RF-TT0440	1.06E-02	0.00E+00	2.47E-17	1.25E+02	1.99E+01	0.00E+00	6.85E-03	1.45E+02	5.86E-01
RF-TT0441	5.21E-02	0.00E+00	1.16E-16	4.33E+02	6.75E+01	0.00E+00	1.28E-02	5.01E+02	2.02E+00
RF-TT0442	7.52E-03	0.00E+00	2.00E-17	8.02E+01	1.24E+01	0.00E+00	6.88E-03	9.26E+01	3.74E-01
RF-TT0443	1.61E-04	0.00E+00	5.73E-19	2.17E+00	3.36E-01	0.00E+00	5.67E-05	2.51E+00	1.01E-02

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0479	1.58E-03	0.00E+00	5.95E-18	2.20E+01	3.41E+00	0.00E+00	4.24E-04	2.54E+01	1.02E-01
RF-TT0480	1.07E-01	0.00E+00	2.40E-16	9.00E+02	1.39E+02	0.00E+00	2.47E-02	1.04E+03	4.19E+00
RF-TT0481	6.05E-05	0.00E+00	1.35E-19	5.05E-01	7.86E-02	0.00E+00	1.39E-05	5.84E-01	2.35E-03
RF-TT0483	1.94E-04	0.00E+00	7.31E-19	2.71E+00	4.21E-01	0.00E+00	1.70E-02	3.15E+00	1.27E-02
RF-TT0484	1.04E-03	0.00E+00	3.03E-18	1.13E+01	1.75E+00	0.00E+00	3.26E-04	1.30E+01	5.24E-02
RF-TT0485	8.54E-05	0.00E+00	1.87E-19	6.94E-01	1.08E-01	0.00E+00	2.87E-04	8.02E-01	3.23E-03
RF-TT0486	5.06E-04	0.00E+00	1.11E-18	4.12E+00	6.39E-01	0.00E+00	3.04E-04	4.76E+00	1.92E-02
RF-TT0487	2.54E-03	0.00E+00	3.77E-18	1.48E+01	2.29E+00	0.00E+00	7.46E-04	1.71E+01	6.89E-02
RF-TT0489	7.24E-04	0.00E+00	1.69E-18	6.28E+00	9.74E-01	0.00E+00	2.20E-04	7.26E+00	2.93E-02
RF-TT0490	4.00E-02	0.00E+00	1.08E-16	4.05E+02	6.28E+01	0.00E+00	9.43E-03	4.68E+02	1.89E+00
RF-TT0491	9.31E-04	0.00E+00	1.45E-18	5.42E+00	8.39E-01	0.00E+00	1.98E-04	6.26E+00	2.53E-02
RF-TT0492	3.13E-04	0.00E+00	8.18E-19	3.03E+00	4.70E-01	0.00E+00	5.84E-05	3.50E+00	1.41E-02
RF-TT0523A	2.10E-03	0.00E+00	3.28E-18	1.22E+01	1.89E+00	0.00E+00	2.68E-04	1.41E+01	5.68E-02
RF-TT0523B	2.10E-03	0.00E+00	3.28E-18	1.22E+01	1.89E+00	0.00E+00	2.68E-04	1.41E+01	5.68E-02
RF-TT0523C	2.10E-03	0.00E+00	3.28E-18	1.22E+01	1.89E+00	0.00E+00	2.68E-04	1.41E+01	5.68E-02
RF-TT0523D	2.10E-03	0.00E+00	3.28E-18	1.22E+01	1.89E+00	0.00E+00	2.68E-04	1.41E+01	5.68E-02
RF-TT0523E	2.10E-03	0.00E+00	3.28E-18	1.22E+01	1.89E+00	0.00E+00	2.68E-04	1.41E+01	5.68E-02
RF-TT0532A	5.28E-02	0.00E+00	5.51E-17	2.10E+02	3.25E+01	0.00E+00	5.08E-03	2.43E+02	9.79E-01
RF-TT0532B	5.28E-02	0.00E+00	5.51E-17	2.10E+02	3.25E+01	0.00E+00	5.08E-03	2.43E+02	9.79E-01
RF-TT0541	8.72E-05	0.00E+00	3.28E-19	1.22E+00	1.89E-01	0.00E+00	2.34E-05	1.41E+00	5.68E-03
RF-TT0545	1.94E-05	0.00E+00	7.31E-20	2.71E-01	4.21E-02	0.00E+00	5.21E-06	3.13E-01	1.26E-03
RF-TT0601	6.75E-03	0.00E+00	1.26E-17	4.89E+01	7.68E+00	0.00E+00	9.26E-04	5.66E+01	2.28E-01
RF-TT0802	7.55E-01	0.00E+00	1.04E-15	3.86E+03	5.98E+02	0.00E+00	7.39E-02	4.46E+03	1.80E+01
RF-TT0809	6.21E-02	0.00E+00	8.51E-17	3.18E+02	4.90E+01	0.00E+00	6.07E-03	3.67E+02	1.48E+00
RF-TT0821	1.34E-01	0.00E+00	3.09E-16	1.25E+03	1.94E+02	0.00E+00	1.88E-01	1.44E+03	5.81E+00
RF-TT0822	1.49E-01	0.00E+00	2.41E-16	9.34E+02	1.44E+02	0.00E+00	1.97E-01	1.08E+03	4.35E+00
RF-TT0823	3.01E-04	0.00E+00	4.69E-19	1.75E+00	2.71E-01	0.00E+00	3.83E-05	2.02E+00	8.14E-03
RF-TT0824	3.10E-01	0.00E+00	6.60E-16	2.52E+03	3.90E+02	0.00E+00	1.09E-01	2.91E+03	1.17E+01
RF-TT0825	2.57E-01	0.00E+00	4.77E-16	1.90E+03	2.93E+02	0.00E+00	1.14E-01	2.19E+03	8.82E+00
RF-TT0832	1.90E-01	0.00E+00	2.83E-16	1.11E+03	1.72E+02	0.00E+00	5.60E-02	1.28E+03	5.16E+00
RF-TT0854	6.85E-05	0.00E+00	2.58E-19	9.52E-01	1.48E-01	0.00E+00	7.55E-04	1.10E+00	4.44E-03

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0886	9.71E-06	0.00E+00	3.64E-20	1.35E-01	2.10E-02	0.00E+00	2.60E-06	1.56E-01	6.29E-04
RF-TT2216	2.81E-03	0.00E+00	4.17E-18	1.64E+01	2.53E+00	0.00E+00	8.27E-04	1.90E+01	7.65E-02
RF-TT3010	1.50E-01	0.00E+00	3.69E-16	1.38E+03	2.15E+02	0.00E+00	3.13E-02	1.60E+03	6.45E+00
RF-TT3011	3.79E-01	0.00E+00	7.80E-16	2.89E+03	4.49E+02	0.00E+00	8.89E-02	3.34E+03	1.35E+01
RF-TT301U	3.15E-02	0.00E+00	8.24E-17	3.14E+02	4.95E+01	0.00E+00	6.03E-03	3.64E+02	1.47E+00
RF-TT310P	9.10E-03	0.00E+00	2.14E-17	1.06E+02	1.55E+01	0.00E+00	1.53E-03	1.21E+02	4.88E-01
RF-TT338S	2.66E-04	0.00E+00	9.82E-19	3.64E+00	5.65E-01	0.00E+00	7.00E-05	4.21E+00	1.70E-02
RF-TT390P	1.50E-03	0.00E+00	2.66E-18	1.77E+01	2.53E+00	0.00E+00	2.18E-04	2.03E+01	8.17E-02
RF-TT391P	8.26E-02	0.00E+00	1.20E-16	7.97E+02	1.21E+02	0.00E+00	8.52E-03	9.18E+02	3.70E+00
RF-TT392P	1.67E-01	0.00E+00	4.31E-16	2.39E+03	3.69E+02	0.00E+00	3.08E-02	2.76E+03	1.11E+01
RF-TT393R	2.47E-02	0.00E+00	7.31E-17	3.65E+02	5.68E+01	0.00E+00	5.39E-03	4.22E+02	1.70E+00
RF-TT394P	3.07E-03	0.00E+00	4.52E-18	2.82E+01	4.05E+00	0.00E+00	3.30E-04	3.23E+01	1.30E-01
RF-TT395P	4.11E-03	0.00E+00	6.06E-18	3.77E+01	5.41E+00	0.00E+00	4.41E-04	4.31E+01	1.74E-01
RF-TT396P	1.03E-03	0.00E+00	1.51E-18	9.43E+00	1.36E+00	0.00E+00	1.10E-04	1.08E+01	4.35E-02
RF-TT398P	9.93E-02	0.00E+00	2.62E-16	1.48E+03	2.27E+02	0.00E+00	1.87E-02	1.71E+03	6.88E+00
RF-TT398R	8.18E-01	0.00E+00	4.87E-16	2.39E+03	3.67E+02	0.00E+00	3.47E-02	2.76E+03	1.11E+01
RF-TT411R	2.97E-02	0.00E+00	4.37E-17	2.73E+02	4.18E+01	0.00E+00	3.14E-03	3.14E+02	1.27E+00
RF-TT429R	6.23E-02	0.00E+00	9.38E-18	6.32E+01	9.50E+00	0.00E+00	6.69E-04	7.27E+01	2.93E-01
RF-TT433X	1.96E-02	0.00E+00	2.60E-18	1.82E+01	2.47E+00	0.00E+00	1.85E-04	2.07E+01	8.33E-02
RF-TT436R	1.44E-01	0.00E+00	3.76E-17	2.38E+02	3.64E+01	0.00E+00	2.68E-03	2.75E+02	1.11E+00
RF-TT454X	8.44E-03	0.00E+00	2.21E-18	1.40E+01	2.15E+00	0.00E+00	1.58E-04	1.62E+01	6.52E-02
RL-T101	4.28E-02	0.00E+00	1.34E-16	7.57E+02	1.15E+02	0.00E+00	8.71E-03	8.72E+02	3.52E+00
RL-T102	5.44E-07	0.00E+00	1.71E-21	9.69E-03	1.47E-03	0.00E+00	1.24E-06	1.12E-02	4.50E-05
RL-T103	3.85E-02	0.00E+00	1.63E-16	3.31E+02	4.99E+01	0.00E+00	1.06E-02	3.80E+02	1.53E+00
RL-T104	7.79E-07	0.00E+00	2.44E-21	1.38E-02	2.10E-03	0.00E+00	1.90E-07	1.59E-02	6.39E-05
RL-T105	2.99E-04	0.00E+00	9.22E-19	5.23E+00	7.92E-01	0.00E+00	1.04E-04	6.02E+00	2.43E-02
RL-T106	2.88E-04	0.00E+00	9.06E-19	5.10E+00	7.74E-01	0.00E+00	5.88E-05	5.88E+00	2.37E-02
RL-T107	7.92E-01	0.00E+00	5.32E-13	1.41E+04	2.14E+03	0.00E+00	3.53E+01	1.63E+04	6.56E+01
RL-T108	4.53E-04	0.00E+00	9.17E-17	8.03E+00	1.22E+00	0.00E+00	5.98E-03	9.25E+00	3.73E-02
RL-T109	6.24E-04	0.00E+00	1.89E-18	1.06E+01	1.62E+00	0.00E+00	2.31E-02	1.23E+01	4.95E-02
RL-T110	6.99E-02	0.00E+00	3.60E-16	1.22E+03	1.86E+02	0.00E+00	1.36E+00	1.41E+03	5.67E+00

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T112	2.82E-02	0.00E+00	1.52E-16	1.62E+02	2.46E+01	0.00E+00	7.35E-01	1.87E+02	7.55E-01
RL-T113	3.01E-05	0.00E+00	2.94E-19	5.33E-01	8.09E-02	0.00E+00	1.91E-05	6.14E-01	2.48E-03
RL-T114	4.57E-03	0.00E+00	1.44E-17	8.10E+01	1.23E+01	0.00E+00	9.31E-04	9.33E+01	3.76E-01
RL-T115	1.16E-01	0.00E+00	4.65E-16	1.06E+03	1.62E+02	0.00E+00	4.37E-01	1.23E+03	4.95E+00
RL-T116	7.51E-03	0.00E+00	2.36E-17	1.32E+02	2.02E+01	0.00E+00	5.69E-02	1.53E+02	6.15E-01
RL-T118	1.93E-02	0.00E+00	1.88E-16	1.32E+02	2.00E+01	0.00E+00	8.33E-01	1.52E+02	6.14E-01
RL-T120	4.68E-03	0.00E+00	1.98E-17	3.89E+01	5.87E+00	0.00E+00	1.28E-03	4.48E+01	1.81E-01
RL-T122	2.65E-04	0.00E+00	8.35E-19	4.69E+00	7.16E-01	0.00E+00	1.44E+00	6.84E+00	2.76E-02
RL-T123	7.81E-04	0.00E+00	2.44E-18	1.38E+01	2.10E+00	0.00E+00	5.90E-02	1.59E+01	6.42E-02
RL-T125	1.55E-01	0.00E+00	6.06E-16	2.88E+02	1.01E+02	0.00E+00	3.93E-02	3.89E+02	1.57E+00
RL-T127	1.50E-01	0.00E+00	1.52E-16	8.61E+02	1.31E+02	0.00E+00	8.87E-02	9.92E+02	4.00E+00
RL-T128	2.22E-04	0.00E+00	3.70E-24	2.09E-05	3.17E-06	0.00E+00	2.40E-10	2.46E-04	9.91E-07
RL-T129	6.64E-04	0.00E+00	7.04E-16	1.19E+01	1.79E+00	0.00E+00	5.32E-02	1.37E+01	5.52E-02
RL-T130	1.41E-06	0.00E+00	4.45E-21	2.52E-02	3.82E-03	0.00E+00	8.21E-05	2.91E-02	1.17E-04
RL-T131	5.74E-04	0.00E+00	2.43E-18	4.79E+00	7.21E-01	0.00E+00	8.27E-03	5.52E+00	2.23E-02
RL-T132	1.37E-01	0.00E+00	4.29E-16	2.43E+03	3.69E+02	0.00E+00	2.69E-01	2.80E+03	1.13E+01
RL-T133	2.79E-06	0.00E+00	6.88E-21	3.99E-02	6.04E-03	0.00E+00	4.46E-07	4.59E-02	1.85E-04
RL-T134	5.90E-06	0.00E+00	1.85E-20	1.05E-01	1.58E-02	0.00E+00	1.20E-06	1.21E-01	4.86E-04
RL-T135	2.76E-05	0.00E+00	8.68E-20	4.90E-01	7.45E-02	0.00E+00	4.10E-03	5.68E-01	2.29E-03
RL-T137	4.49E-01	0.00E+00	1.89E-15	3.73E+03	5.63E+02	0.00E+00	1.29E-01	4.29E+03	1.73E+01
RL-T140	5.24E-01	0.00E+00	1.80E-15	3.61E+03	6.04E+02	0.00E+00	2.60E+01	4.24E+03	1.71E+01
RL-T143	3.29E-03	0.00E+00	1.03E-17	5.83E+01	8.86E+00	0.00E+00	3.87E-02	6.72E+01	2.71E-01
RL-T145	9.36E-03	0.00E+00	2.94E-17	1.66E+02	2.52E+01	0.00E+00	9.02E-02	1.91E+02	7.72E-01
RL-W407	2.69E-02	0.00E+00	6.27E-17	3.81E+02	5.78E+01	0.00E+00	4.07E-03	4.39E+02	1.77E+00
RL-W408	1.10E-07	0.00E+00	2.65E-22	1.54E-03	2.34E-04	0.00E+00	1.72E-08	1.77E-03	7.15E-06
RL-W415	2.44E-06	0.00E+00	5.84E-21	3.41E-02	5.17E-03	0.00E+00	3.79E-07	3.93E-02	1.58E-04
RL-W418	1.04E-05	0.00E+00	2.46E-20	1.46E-01	2.22E-02	0.00E+00	1.60E-06	1.68E-01	6.79E-04
RL-W437	8.83E-02	0.00E+00	2.06E-16	1.25E+03	1.89E+02	0.00E+00	1.34E-02	1.44E+03	5.79E+00
RL-W438	1.54E-07	0.00E+00	3.71E-22	2.15E-03	3.27E-04	0.00E+00	2.40E-08	2.48E-03	1.00E-05
RL-W439	4.84E+00	0.00E+00	2.04E-14	4.15E+04	6.28E+03	0.00E+00	1.32E+00	4.78E+04	1.93E+02
RL-W443	7.77E-02	0.00E+00	1.82E-16	1.10E+03	1.67E+02	0.00E+00	1.18E-02	1.27E+03	5.10E+00

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W444	5.76E-02	0.00E+00	1.35E-16	8.15E+02	1.24E+02	0.00E+00	8.74E-03	9.39E+02	3.79E+00
RL-W447	6.61E-06	0.00E+00	1.59E-20	9.17E-02	1.40E-02	0.00E+00	1.03E-06	1.06E-01	4.26E-04
RL-W448	4.89E-08	0.00E+00	1.17E-22	6.81E-04	1.03E-04	0.00E+00	7.61E-09	7.84E-04	3.16E-06
RL-W449	4.01E-04	0.00E+00	4.29E-21	1.95E-02	2.96E-03	0.00E+00	2.79E-07	2.28E-02	9.20E-05
RL-W450	7.37E-07	0.00E+00	1.77E-21	1.03E-02	1.56E-03	0.00E+00	1.15E-07	1.19E-02	4.78E-05
RL-W451	1.05E-07	0.00E+00	2.52E-22	1.46E-03	2.22E-04	0.00E+00	1.64E-08	1.68E-03	6.79E-06
RL-W452	4.58E-06	0.00E+00	1.09E-20	6.45E-02	9.80E-03	0.00E+00	7.04E-07	7.43E-02	2.99E-04
RL-W453	1.31E-06	0.00E+00	3.06E-21	1.85E-02	2.80E-03	0.00E+00	1.98E-07	2.13E-02	8.60E-05
RL-W454	1.82E-05	0.00E+00	4.27E-20	2.59E-01	3.92E-02	0.00E+00	2.77E-06	2.98E-01	1.20E-03
RL-W455	4.87E-06	0.00E+00	1.15E-20	6.84E-02	1.04E-02	0.00E+00	7.47E-07	7.88E-02	3.18E-04
RL-W456	6.41E-04	0.00E+00	1.51E-18	9.08E+00	1.38E+00	0.00E+00	9.77E-05	1.05E+01	4.22E-02
RL-W457	6.23E-05	0.00E+00	1.46E-19	8.82E-01	1.34E-01	0.00E+00	9.49E-06	1.02E+00	4.10E-03
RL-W458	1.97E-04	0.00E+00	7.48E-19	3.63E-01	1.37E-01	0.00E+00	4.85E-05	5.00E-01	2.02E-03
RL-W459	1.90E-03	0.00E+00	7.69E-18	9.00E+00	1.87E+00	0.00E+00	4.99E-04	1.09E+01	4.38E-02
RL-W460	1.16E-05	0.00E+00	2.71E-20	1.64E-01	2.49E-02	0.00E+00	1.76E-06	1.88E-01	7.60E-04
RL-W461	1.07E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.07E-05	4.30E-08
RL-W462	3.30E-06	0.00E+00	7.86E-21	4.63E-02	7.04E-03	0.00E+00	5.10E-07	5.33E-02	2.15E-04
RL-W463	1.70E-05	0.00E+00	3.97E-20	2.41E-01	3.65E-02	0.00E+00	2.58E-06	2.77E-01	1.12E-03
RL-W464	7.83E-06	0.00E+00	1.83E-20	1.11E-01	1.68E-02	0.00E+00	1.19E-06	1.28E-01	5.14E-04
RL-W465	5.23E-05	0.00E+00	1.24E-19	7.37E-01	1.12E-01	0.00E+00	8.03E-06	8.49E-01	3.42E-03
RL-W466	7.15E-04	0.00E+00	1.69E-18	1.01E+01	1.54E+00	0.00E+00	1.09E-04	1.17E+01	4.70E-02
RL-W467	3.67E-05	0.00E+00	8.68E-20	5.16E-01	7.80E-02	0.00E+00	5.63E-06	5.94E-01	2.39E-03
RL-W468	1.88E-07	0.00E+00	4.47E-22	2.64E-03	4.01E-04	0.00E+00	2.90E-08	3.04E-03	1.23E-05
RL-W469	7.62E-05	0.00E+00	1.80E-19	1.07E+00	1.64E-01	0.00E+00	1.16E-05	1.24E+00	4.99E-03
RL-W470	2.16E-03	0.00E+00	8.35E-18	3.98E+00	1.40E+00	0.00E+00	5.42E-04	5.38E+00	2.17E-02
RL-W474	8.17E-05	0.00E+00	9.22E-19	9.08E-03	5.28E-03	0.00E+00	5.98E-05	1.45E-02	5.85E-05
RL-W476	1.38E-04	0.00E+00	3.32E-19	1.99E+00	3.03E-01	0.00E+00	2.15E-05	2.29E+00	9.25E-03
RL-W480	2.25E-05	0.00E+00	5.31E-20	3.16E-01	4.80E-02	0.00E+00	3.45E-06	3.64E-01	1.47E-03
RL-W481	3.53E-05	0.00E+00	8.35E-20	4.96E-01	7.51E-02	0.00E+00	5.42E-06	5.71E-01	2.30E-03
RL-W482	4.69E-02	0.00E+00	2.78E-17	6.31E-02	7.98E-02	0.00E+00	1.80E-03	1.92E-01	7.72E-04
RL-W483	3.50E-03	0.00E+00	2.16E-18	4.08E-03	5.67E-03	0.00E+00	1.40E-04	1.34E-02	5.40E-05

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W484	1.48E-05	0.00E+00	1.74E-20	5.70E-02	9.27E-03	0.00E+00	1.13E-06	6.63E-02	2.67E-04
RL-W485	8.67E-07	0.00E+00	2.46E-21	6.17E-03	1.00E-03	0.00E+00	1.59E-07	7.17E-03	2.89E-05
RL-W486	3.66E-07	0.00E+00	1.04E-21	2.60E-03	4.22E-04	0.00E+00	6.72E-08	3.03E-03	1.22E-05
RL-W487	5.98E-05	0.00E+00	1.33E-19	3.73E-01	6.98E-02	0.00E+00	8.64E-06	4.43E-01	1.79E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	3.64E-05	0.00E+00	1.26E-19	4.83E-01	7.45E-02	0.00E+00	8.14E-06	5.57E-01	2.25E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	1.35E-05	0.00E+00	1.06E-19	5.06E-02	7.57E-03	0.00E+00	6.87E-06	5.82E-02	2.35E-04
RL-W492	7.78E-07	0.00E+00	2.61E-21	1.01E-02	1.55E-03	0.00E+00	1.69E-07	1.17E-02	4.71E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	3.08E-02	0.00E+00	1.51E-16	2.55E-01	1.48E-01	0.00E+00	9.80E-03	4.44E-01	1.79E-03
RL-W495	5.58E-04	0.00E+00	4.11E-19	2.45E-03	1.33E-03	0.00E+00	2.67E-05	4.36E-03	1.76E-05
RL-W496	3.62E-03	0.00E+00	4.73E-18	8.05E-03	4.39E-03	0.00E+00	3.07E-04	1.64E-02	6.60E-05
RL-W497	1.51E-04	0.00E+00	9.33E-19	4.83E-01	1.49E-01	0.00E+00	6.05E-05	6.32E-01	2.55E-03
RL-W498	5.86E-04	0.00E+00	1.39E-18	8.25E+00	1.26E+00	0.00E+00	8.99E-05	9.51E+00	3.83E-02
RL-W499	5.26E-09	0.00E+00	1.24E-23	7.40E-05	1.13E-05	0.00E+00	8.07E-10	8.52E-05	3.44E-07
RL-W500	3.75E-07	0.00E+00	1.54E-21	3.02E-03	4.56E-04	0.00E+00	1.00E-07	3.48E-03	1.40E-05
RL-W501	1.55E-02	0.00E+00	3.44E-17	9.69E+01	1.81E+01	0.00E+00	2.23E-03	1.15E+02	4.64E-01
RL-W502	2.81E-06	0.00E+00	6.66E-21	3.95E-02	5.98E-03	0.00E+00	4.32E-07	4.54E-02	1.83E-04
RL-W503	1.62E-04	0.00E+00	6.82E-19	1.39E+00	2.10E-01	0.00E+00	4.42E-05	1.60E+00	6.46E-03
RL-W504	5.98E-05	0.00E+00	1.33E-19	3.73E-01	6.98E-02	0.00E+00	8.64E-06	4.43E-01	1.79E-03
RL-W505	2.82E-06	0.00E+00	6.98E-21	4.03E-02	6.10E-03	0.00E+00	4.53E-07	4.64E-02	1.87E-04
RL-W506	1.02E-06	0.00E+00	2.74E-21	1.32E-02	2.01E-03	0.00E+00	1.78E-07	1.53E-02	6.15E-05
RL-W507	1.01E-07	0.00E+00	2.40E-22	1.43E-03	2.16E-04	0.00E+00	1.56E-08	1.64E-03	6.63E-06
RL-W508	1.86E-03	0.00E+00	7.86E-18	1.55E+01	2.34E+00	0.00E+00	5.10E-04	1.78E+01	7.19E-02
RL-W509	1.83E-02	0.00E+00	6.27E-17	1.26E+02	2.11E+01	0.00E+00	4.07E-03	1.47E+02	5.94E-01
RL-W510	1.55E-03	0.00E+00	6.44E-18	1.25E+01	1.89E+00	0.00E+00	4.18E-04	1.44E+01	5.82E-02
RL-W511	1.57E-01	0.00E+00	3.10E-16	1.68E+03	2.50E+02	0.00E+00	2.05E-02	1.93E+03	7.78E+00
RL-W512	1.38E-01	0.00E+00	2.10E-16	1.01E+03	1.71E+02	0.00E+00	1.36E-02	1.18E+03	4.77E+00
RL-W513	1.47E+01	0.00E+00	8.51E-14	1.65E+04	5.58E+03	0.00E+00	5.52E+00	2.21E+04	8.92E+01
RL-W514	4.15E-07	0.00E+00	9.77E-22	5.86E-03	8.92E-04	0.00E+00	6.34E-08	6.75E-03	2.72E-05

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W515	1.62E-05	0.00E+00	3.83E-20	2.28E-01	3.46E-02	0.00E+00	2.48E-06	2.63E-01	1.06E-03
RL-W516	2.25E-05	0.00E+00	5.32E-20	3.16E-01	4.80E-02	0.00E+00	3.45E-06	3.64E-01	1.47E-03
RL-W517	2.00E-13	0.00E+00	4.76E-28	2.81E-09	4.26E-10	0.00E+00	3.09E-14	3.24E-09	1.31E-11
RL-W518	5.67E-04	0.00E+00	2.00E-18	4.03E+00	6.63E-01	0.00E+00	1.30E-04	4.70E+00	1.89E-02
RL-W519	1.01E-04	0.00E+00	2.37E-19	1.43E+00	2.16E-01	0.00E+00	1.54E-05	1.64E+00	6.63E-03
RL-W520	1.12E-05	0.00E+00	2.67E-20	1.57E-01	2.38E-02	0.00E+00	1.73E-06	1.80E-01	7.27E-04
RL-W521	2.08E-07	0.00E+00	4.91E-22	2.92E-03	4.43E-04	0.00E+00	3.18E-08	3.36E-03	1.35E-05
RL-W522	4.34E-03	0.00E+00	1.82E-17	1.93E+01	3.76E+00	0.00E+00	1.18E-03	2.31E+01	9.30E-02
RL-W523	1.30E-03	0.00E+00	6.93E-18	1.28E+00	5.30E-01	0.00E+00	4.50E-04	1.81E+00	7.31E-03
RL-W524	5.41E-03	0.00E+00	2.65E-17	1.18E+01	3.10E+00	0.00E+00	1.72E-03	1.49E+01	6.00E-02
RL-W525	4.30E-04	0.00E+00	1.80E-18	1.39E+00	3.14E-01	0.00E+00	1.16E-04	1.71E+00	6.88E-03
RL-W526	1.63E-03	0.00E+00	6.49E-18	1.49E+01	2.26E+00	0.00E+00	4.21E-04	1.72E+01	6.91E-02
RL-W527	1.78E-04	0.00E+00	9.38E-19	1.57E+00	2.55E-01	0.00E+00	6.09E-05	1.83E+00	7.38E-03
RL-W528	7.97E-02	0.00E+00	3.99E-16	5.02E+01	3.27E+01	0.00E+00	2.59E-02	8.30E+01	3.35E-01
RL-W529	6.64E-05	0.00E+00	2.80E-19	5.54E-01	8.33E-02	0.00E+00	1.82E-05	6.37E-01	2.57E-03
RL-W530	7.83E-04	0.00E+00	3.25E-18	6.32E+00	9.56E-01	0.00E+00	2.11E-04	7.28E+00	2.94E-02
RL-W531	4.67E-02	0.00E+00	3.26E-16	2.73E+01	1.34E+01	0.00E+00	2.12E-02	4.08E+01	1.65E-01
RL-W532	1.50E-04	0.00E+00	3.55E-19	2.11E+00	3.20E-01	0.00E+00	2.30E-05	2.43E+00	9.80E-03
RL-W533	7.25E-05	0.00E+00	3.06E-19	6.04E-01	9.09E-02	0.00E+00	1.99E-05	6.95E-01	2.80E-03
RL-W534	4.19E-09	0.00E+00	9.88E-24	5.89E-05	8.97E-06	0.00E+00	6.41E-10	6.79E-05	2.74E-07
RL-W535	2.19E-02	0.00E+00	9.77E-17	7.55E+01	1.57E+01	0.00E+00	6.34E-03	9.13E+01	3.68E-01
RL-W536	4.29E-04	0.00E+00	1.32E-18	2.62E+00	4.05E-01	0.00E+00	8.85E-05	3.03E+00	1.22E-02
RL-W537	1.46E-02	0.00E+00	2.97E-17	1.61E+02	2.41E+01	0.00E+00	1.95E-03	1.85E+02	7.46E-01
RL-W538	5.32E-08	0.00E+00	1.26E-22	7.48E-04	1.14E-04	0.00E+00	8.14E-09	8.62E-04	3.48E-06
RL-W539	5.90E-06	0.00E+00	1.41E-20	8.27E-02	1.26E-02	0.00E+00	9.17E-07	9.53E-02	3.84E-04
RL-W540	1.15E-02	0.00E+00	6.22E-17	2.98E+01	6.98E+00	0.00E+00	4.04E-03	3.68E+01	1.48E-01
RL-W541	1.71E-05	0.00E+00	4.08E-20	2.40E-01	3.64E-02	0.00E+00	2.64E-06	2.76E-01	1.11E-03
RL-W542	7.94E-04	0.00E+00	3.03E-18	6.06E+00	9.56E-01	0.00E+00	1.96E-04	7.02E+00	2.83E-02
RL-W543	2.50E-06	0.00E+00	5.89E-21	3.51E-02	5.34E-03	0.00E+00	3.82E-07	4.05E-02	1.63E-04
RL-W544	5.63E-05	0.00E+00	2.41E-19	4.00E-01	6.80E-02	0.00E+00	1.56E-05	4.68E-01	1.89E-03
RL-W545	1.50E-05	0.00E+00	3.54E-20	2.10E-01	3.20E-02	0.00E+00	2.29E-06	2.42E-01	9.77E-04

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W546	6.55E-07	0.00E+00	1.55E-21	9.26E-03	1.40E-03	0.00E+00	1.01E-07	1.07E-02	4.30E-05
RL-W547	1.68E-08	0.00E+00	3.96E-23	2.35E-04	3.58E-05	0.00E+00	2.57E-09	2.71E-04	1.09E-06
RL-W548	1.45E-08	0.00E+00	3.44E-23	2.03E-04	3.09E-05	0.00E+00	2.23E-09	2.34E-04	9.44E-07
RL-W549	2.88E-03	0.00E+00	1.38E-17	1.05E+01	2.12E+00	0.00E+00	8.95E-04	1.26E+01	5.08E-02
RL-W550	1.30E-02	0.00E+00	2.61E-17	1.42E+02	2.12E+01	0.00E+00	1.71E-03	1.63E+02	6.58E-01
RL-W551	2.32E-02	0.00E+00	3.86E-17	1.60E+02	2.77E+01	0.00E+00	2.51E-03	1.88E+02	7.57E-01
RL-W552	8.99E-06	0.00E+00	2.14E-20	1.26E-01	1.91E-02	0.00E+00	1.39E-06	1.45E-01	5.86E-04
RL-W553	7.97E-07	0.00E+00	2.02E-21	1.13E-02	1.71E-03	0.00E+00	1.31E-07	1.30E-02	5.22E-05
RL-W554	1.27E-05	0.00E+00	3.00E-20	1.78E-01	2.71E-02	0.00E+00	1.94E-06	2.05E-01	8.28E-04
RL-W555	5.83E-06	0.00E+00	1.38E-20	8.21E-02	1.24E-02	0.00E+00	8.95E-07	9.45E-02	3.81E-04
RL-W563	8.37E-05	0.00E+00	3.45E-19	6.81E-01	1.03E-01	0.00E+00	2.24E-05	7.84E-01	3.16E-03
RL-W564	5.45E-05	0.00E+00	2.29E-19	4.40E-01	6.63E-02	0.00E+00	1.49E-05	5.07E-01	2.04E-03
RL-W565	5.41E-06	0.00E+00	1.29E-20	7.60E-02	1.16E-02	0.00E+00	8.35E-07	8.76E-02	3.53E-04
RL-W566	7.94E-05	0.00E+00	1.89E-19	1.12E+00	1.70E-01	0.00E+00	1.23E-05	1.29E+00	5.19E-03
RL-W567	5.51E-03	0.00E+00	4.82E-18	3.43E-02	1.89E-02	0.00E+00	3.13E-04	5.91E-02	2.38E-04
RL-W568	1.06E-01	0.00E+00	1.02E-16	1.63E+00	8.80E-01	0.00E+00	6.58E-03	2.62E+00	1.06E-02
RL-W569	8.71E-05	0.00E+00	7.64E-20	5.42E-04	2.99E-05	0.00E+00	4.96E-06	6.64E-04	2.68E-06
RL-W570	5.58E-06	0.00E+00	1.34E-20	8.06E-02	1.22E-02	0.00E+00	8.67E-07	9.28E-02	3.74E-04
RL-W571	1.79E-02	0.00E+00	4.54E-17	6.54E+00	2.23E+00	0.00E+00	2.95E-03	8.79E+00	3.54E-02
RL-W572	1.55E-05	0.00E+00	1.36E-20	3.52E-03	5.34E-05	0.00E+00	8.81E-07	3.59E-03	1.45E-05
RL-W573	2.00E-01	0.00E+00	1.74E-16	1.93E+00	9.85E-01	0.00E+00	1.13E-02	3.13E+00	1.26E-02
RL-W574	8.60E-01	0.00E+00	7.53E-16	7.37E+00	3.65E+00	0.00E+00	4.88E-02	1.19E+01	4.81E-02
RL-W575	5.60E+00	0.00E+00	5.07E-15	7.05E+01	2.92E+01	0.00E+00	3.29E-01	1.06E+02	4.26E-01
RL-W576	4.04E-01	0.00E+00	3.54E-16	3.59E+00	1.76E+00	0.00E+00	2.30E-02	5.78E+00	2.33E-02
RL-W579	3.42E-05	0.00E+00	9.33E-21	1.80E-02	2.74E-03	0.00E+00	6.05E-07	2.08E-02	8.37E-05
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.44E-01	1.60E-02	0.00E+00	0.00E+00	1.60E-01	6.43E-04
RL-W581	3.63E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.63E-04	1.46E-06
RL-W582	2.37E-06	0.00E+00	7.91E-21	4.60E-03	1.63E-03	0.00E+00	5.13E-07	6.23E-03	2.51E-05
RL-W583	1.84E-06	0.00E+00	4.30E-21	2.60E-02	3.95E-03	0.00E+00	2.79E-07	2.99E-02	1.21E-04
RL-W584	3.65E-05	0.00E+00	2.82E-19	1.51E-01	5.06E-02	0.00E+00	1.83E-05	2.02E-01	8.15E-04
RL-W585	2.17E-04	0.00E+00	1.50E-18	8.82E-01	3.07E-01	0.00E+00	9.73E-05	1.19E+00	4.80E-03

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W586	2.90E-08	0.00E+00	6.77E-23	4.10E-04	6.22E-05	0.00E+00	4.39E-09	4.72E-04	1.90E-06
RL-W587	6.20E-07	0.00E+00	1.46E-21	8.74E-03	1.33E-03	0.00E+00	9.49E-08	1.01E-02	4.06E-05
RL-W588	2.56E-05	0.00E+00	2.38E-19	1.28E-01	4.26E-02	0.00E+00	1.54E-05	1.71E-01	6.88E-04
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	7.85E-04	0.00E+00	5.07E-18	9.86E-03	1.20E-02	0.00E+00	3.29E-04	2.29E-02	9.25E-05
RL-W591	4.47E-03	0.00E+00	5.73E-18	1.22E-02	1.55E-02	0.00E+00	3.72E-04	3.25E-02	1.31E-04
RL-W592	1.98E-02	0.00E+00	6.27E-17	5.66E-01	5.01E-01	0.00E+00	4.07E-03	1.09E+00	4.40E-03
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.04E-02	2.35E-02	0.00E+00	0.00E+00	4.39E-02	1.77E-04
RL-W594	1.78E-02	0.00E+00	1.13E-17	2.53E-02	3.18E-02	0.00E+00	7.33E-04	7.56E-02	3.05E-04
RL-W595	4.70E-05	0.00E+00	1.18E-18	1.73E-02	2.31E-02	0.00E+00	7.64E-05	4.05E-02	1.63E-04
RL-W596	1.52E-05	0.00E+00	9.17E-20	1.78E-04	2.17E-04	0.00E+00	5.95E-06	4.16E-04	1.68E-06
RL-W597	2.80E-02	0.00E+00	4.03E-17	3.45E-01	3.94E-01	0.00E+00	2.62E-03	7.69E-01	3.10E-03
RL-W598	2.96E-02	0.00E+00	2.38E-16	4.81E-01	4.91E-01	0.00E+00	1.54E-02	1.02E+00	4.10E-03
RL-W599	1.50E-03	0.00E+00	1.92E-18	4.07E-03	5.17E-03	0.00E+00	1.25E-04	1.09E-02	4.38E-05
RL-W600	8.51E-11	0.00E+00	1.99E-25	1.20E-06	1.83E-07	0.00E+00	1.29E-11	1.39E-06	5.59E-09
RL-W601	4.32E-07	0.00E+00	1.09E-21	6.09E-03	9.27E-04	0.00E+00	7.08E-08	7.02E-03	2.83E-05
RL-W602	3.76E-04	0.00E+00	8.95E-19	5.28E+00	8.04E-01	0.00E+00	5.80E-05	6.08E+00	2.45E-02
RL-W603	2.17E-03	0.00E+00	5.16E-18	3.05E+01	4.63E+00	0.00E+00	3.35E-04	3.51E+01	1.42E-01
RL-W604	5.07E-06	0.00E+00	1.35E-20	1.48E-02	4.99E-03	0.00E+00	8.78E-07	1.98E-02	7.98E-05
RL-W605	1.16E-06	0.00E+00	2.94E-21	1.64E-02	2.49E-03	0.00E+00	1.91E-07	1.88E-02	7.60E-05
RL-W606	4.69E-07	0.00E+00	1.18E-21	6.59E-03	1.00E-03	0.00E+00	7.68E-08	7.60E-03	3.06E-05
RL-W607	8.59E-07	0.00E+00	2.29E-21	2.50E-03	8.45E-04	0.00E+00	1.49E-07	3.35E-03	1.35E-05
RL-W608	1.03E-05	0.00E+00	8.89E-20	3.25E-03	2.74E-03	0.00E+00	5.77E-06	6.01E-03	2.42E-05
RL-W610	2.03E-03	0.00E+00	4.76E-18	2.87E+01	4.36E+00	0.00E+00	3.09E-04	3.31E+01	1.33E-01
RL-W612	4.79E-06	0.00E+00	1.15E-20	6.97E-02	1.06E-02	0.00E+00	7.47E-07	8.04E-02	3.24E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	2.92E-01	0.00E+00	0.00E+00	0.00E+00	2.92E-01	1.18E-03
RL-W622	7.99E-08	0.00E+00	1.88E-22	1.13E-03	1.72E-04	0.00E+00	1.22E-08	1.31E-03	5.26E-06
RL-W625	2.79E-06	0.00E+00	2.85E-20	5.79E-03	3.88E-03	0.00E+00	1.85E-06	9.68E-03	3.90E-05
RL-W626	1.50E-04	0.00E+00	6.49E-19	2.27E-01	9.27E-02	0.00E+00	4.21E-05	3.20E-01	1.29E-03
RL-W627	7.05E-07	0.00E+00	8.68E-22	1.07E-06	0.00E+00	0.00E+00	5.63E-08	1.83E-06	7.40E-09
RL-W628	2.31E-07	0.00E+00	5.45E-22	3.27E-03	4.96E-04	0.00E+00	3.54E-08	3.77E-03	1.52E-05

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W629	1.57E-08	0.00E+00	3.75E-23	2.20E-04	3.33E-05	0.00E+00	2.43E-09	2.53E-04	1.02E-06
RL-W630	1.72E-04	0.00E+00	6.98E-19	2.54E+00	4.02E-01	0.00E+00	4.53E-05	2.95E+00	1.19E-02
RL-W631	2.78E-06	0.00E+00	7.04E-21	3.90E-02	5.92E-03	0.00E+00	4.57E-07	4.49E-02	1.81E-04
RL-W632	1.23E-03	0.00E+00	9.49E-19	5.16E+00	1.16E+00	0.00E+00	6.16E-05	6.31E+00	2.55E-02
RL-W633	2.92E-06	0.00E+00	5.51E-21	8.10E-04	4.88E-04	0.00E+00	3.57E-07	1.30E-03	5.25E-06
RL-W634	0.00E+00	0.00E+00	0.00E+00	8.82E-03	0.00E+00	0.00E+00	0.00E+00	8.82E-03	3.56E-05
RL-W635	1.75E-02	0.00E+00	1.86E-16	3.75E+00	3.83E+00	0.00E+00	1.21E-02	7.61E+00	3.07E-02
RL-W636	1.78E-04	0.00E+00	3.51E-19	4.91E-02	2.96E-02	0.00E+00	2.28E-05	7.89E-02	3.18E-04
RL-W637	4.24E-07	0.00E+00	8.95E-21	5.52E-04	3.70E-04	0.00E+00	5.80E-07	9.22E-04	3.72E-06
RL-W638	1.86E-05	0.00E+00	9.11E-20	5.41E-03	3.47E-03	0.00E+00	5.91E-06	8.90E-03	3.59E-05
RL-W639	9.84E-07	0.00E+00	2.33E-21	1.38E-02	2.10E-03	0.00E+00	1.51E-07	1.59E-02	6.43E-05
RL-W640	3.30E-05	0.00E+00	7.75E-20	4.66E-01	7.10E-02	0.00E+00	5.03E-06	5.37E-01	2.17E-03
RL-W641	1.01E-03	0.00E+00	1.70E-17	2.24E+00	6.28E-01	0.00E+00	1.10E-03	2.87E+00	1.16E-02
RL-W642	1.97E-05	0.00E+00	1.77E-21	2.73E-02	9.50E-05	0.00E+00	1.15E-07	2.75E-02	1.11E-04
RL-W643	3.10E-04	0.00E+00	5.24E-18	6.90E-01	1.94E-01	0.00E+00	3.40E-04	8.85E-01	3.57E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	4.75E-02	0.00E+00	0.00E+00	0.00E+00	4.75E-02	1.92E-04
RL-W645	7.54E-06	0.00E+00	2.36E-20	9.34E-02	1.50E-02	0.00E+00	1.53E-06	1.08E-01	4.37E-04
RL-W646	6.85E-06	0.00E+00	2.11E-20	2.23E-02	7.39E-03	0.00E+00	1.37E-06	2.97E-02	1.20E-04
RL-W647	1.93E-05	0.00E+00	3.15E-18	9.52E-02	1.03E-02	0.00E+00	2.04E-04	1.06E-01	4.26E-04
RL-W648	3.42E-07	0.00E+00	5.38E-21	5.20E-05	6.98E-05	0.00E+00	3.49E-07	1.23E-04	4.94E-07
RL-W649	1.26E-06	0.00E+00	1.98E-20	1.91E-04	2.56E-04	0.00E+00	1.29E-06	4.50E-04	1.82E-06
RL-W653	5.95E-08	0.00E+00	1.42E-22	8.36E-04	1.27E-04	0.00E+00	9.20E-09	9.62E-04	3.88E-06
RL-W654	3.27E-07	0.00E+00	7.75E-22	4.60E-03	6.98E-04	0.00E+00	5.03E-08	5.30E-03	2.14E-05
RL-W655	8.06E-02	0.00E+00	1.83E-16	1.83E-01	2.94E-01	0.00E+00	1.19E-02	5.69E-01	2.29E-03
RL-W656	3.37E-01	0.00E+00	8.24E-17	4.29E-01	3.02E-01	0.00E+00	5.34E-03	1.07E+00	4.33E-03
RL-W657	1.72E-01	0.00E+00	1.22E-16	2.11E-01	2.87E-01	0.00E+00	7.89E-03	6.79E-01	2.74E-03
RL-W659	2.08E-02	0.00E+00	2.74E-17	4.07E-02	3.44E-02	0.00E+00	1.78E-03	9.77E-02	3.94E-04
RL-W660	1.14E-01	0.00E+00	3.30E-16	7.50E-01	9.15E-01	0.00E+00	2.14E-02	1.80E+00	7.26E-03
RL-W661	1.21E-03	0.00E+00	4.13E-19	3.62E-04	2.25E-03	0.00E+00	2.68E-05	3.84E-03	1.55E-05
RL-W662	3.81E-05	0.00E+00	2.46E-20	9.26E-05	1.13E-04	0.00E+00	1.60E-06	2.45E-04	9.90E-07
RL-W665	4.68E-01	0.00E+00	1.97E-15	1.13E+00	1.04E+00	0.00E+00	1.28E-01	2.77E+00	1.12E-02

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W666	8.37E-03	0.00E+00	4.82E-18	4.75E-02	3.41E-02	0.00E+00	3.13E-04	9.03E-02	3.64E-04
RL-W668	7.97E-04	0.00E+00	1.52E-19	1.25E-01	2.43E-02	0.00E+00	9.84E-06	1.51E-01	6.07E-04
RL-W669	2.33E-04	0.00E+00	3.93E-18	5.17E-01	1.45E-01	0.00E+00	2.55E-04	6.63E-01	2.67E-03
RL-W670	1.47E-05	0.00E+00	2.80E-21	2.32E-03	4.49E-04	0.00E+00	1.82E-07	2.78E-03	1.12E-05
RL-W671	2.40E-03	0.00E+00	1.44E-18	4.25E-03	3.02E-03	0.00E+00	9.31E-05	9.75E-03	3.93E-05
RL-W672	1.63E-02	0.00E+00	9.77E-18	2.90E-02	2.05E-02	0.00E+00	6.34E-04	6.64E-02	2.68E-04
RL-W673	1.57E-02	0.00E+00	9.38E-18	2.80E-02	1.98E-02	0.00E+00	6.09E-04	6.41E-02	2.59E-04
RL-W674	5.27E-05	0.00E+00	4.20E-19	9.69E+00	5.75E-02	0.00E+00	2.72E-05	9.75E+00	3.93E-02
RL-W675	1.97E-04	0.00E+00	2.32E-18	1.13E-01	6.69E-02	0.00E+00	1.50E-04	1.81E-01	7.28E-04
RL-W676	7.57E-06	0.00E+00	1.39E-20	1.27E-01	1.26E-03	0.00E+00	9.03E-07	1.28E-01	5.18E-04
RL-W677	1.75E-02	0.00E+00	3.45E-17	4.97E+00	2.94E+00	0.00E+00	2.24E-03	7.93E+00	3.20E-02
RL-W678	5.55E-05	0.00E+00	2.88E-19	4.46E-02	2.69E-02	0.00E+00	1.87E-05	7.16E-02	2.89E-04
RL-W679	3.48E-04	0.00E+00	6.44E-19	9.60E-02	5.78E-02	0.00E+00	4.18E-05	1.54E-01	6.22E-04
RL-W680	7.83E-08	0.00E+00	9.06E-22	1.51E-05	1.85E-05	0.00E+00	5.88E-08	3.37E-05	1.36E-07
RL-W681	4.78E-08	0.00E+00	3.67E-22	4.04E-04	1.37E-04	0.00E+00	2.38E-08	5.41E-04	2.18E-06
RL-W685	1.39E-04	0.00E+00	3.26E-19	1.97E+00	2.99E-01	0.00E+00	2.12E-05	2.27E+00	9.16E-03
RL-W689	3.61E-06	0.00E+00	3.92E-21	3.35E-04	0.00E+00	0.00E+00	2.54E-07	3.39E-04	1.37E-06
RL-W690	1.21E-04	0.00E+00	2.88E-19	1.76E+00	2.66E-01	0.00E+00	1.87E-05	2.02E+00	8.15E-03
RL-W691	2.81E-06	0.00E+00	6.71E-21	4.07E-02	6.16E-03	0.00E+00	4.35E-07	4.68E-02	1.89E-04
RL-W692	1.11E-04	0.00E+00	2.66E-19	1.61E+00	2.44E-01	0.00E+00	1.72E-05	1.85E+00	7.47E-03
RL-W693	1.38E-04	0.00E+00	3.28E-19	1.99E+00	3.02E-01	0.00E+00	2.13E-05	2.29E+00	9.24E-03
RL-W694	1.44E-03	0.00E+00	3.44E-18	2.10E+01	3.17E+00	0.00E+00	2.23E-04	2.42E+01	9.75E-02
RL-W695	1.20E-06	0.00E+00	0.00E+00	2.07E-03	0.00E+00	0.00E+00	0.00E+00	2.07E-03	8.34E-06
RL-W696	1.56E-06	0.00E+00	1.26E-20	2.52E-03	1.70E-03	0.00E+00	8.14E-07	4.22E-03	1.70E-05
RL-W697	3.60E-04	0.00E+00	2.66E-17	6.00E-03	5.61E-04	0.00E+00	1.72E-03	8.64E-03	3.48E-05
RL-W698	3.12E-05	0.00E+00	0.00E+00	2.85E-05	0.00E+00	0.00E+00	0.00E+00	5.97E-05	2.41E-07
RL-W699	6.94E-06	0.00E+00	1.77E-21	1.90E-03	1.53E-04	0.00E+00	1.15E-07	2.06E-03	8.32E-06
RL-W700	1.97E-06	0.00E+00	4.64E-21	2.76E-02	4.19E-03	0.00E+00	3.01E-07	3.18E-02	1.28E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	7.74E-05	0.00E+00	1.31E-18	1.72E-01	4.84E-02	0.00E+00	8.49E-05	2.21E-01	8.90E-04

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W705	5.01E-07	0.00E+00	1.21E-21	7.23E-03	1.10E-03	0.00E+00	7.82E-08	8.34E-03	3.36E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	1.79E-05	0.00E+00	4.29E-20	2.58E-01	3.92E-02	0.00E+00	2.78E-06	2.97E-01	1.20E-03
RL-W708	2.70E-06	0.00E+00	6.49E-21	3.91E-02	5.92E-03	0.00E+00	4.21E-07	4.50E-02	1.82E-04
RL-W709	9.34E-04	0.00E+00	2.24E-18	1.35E+01	2.05E+00	0.00E+00	1.45E-04	1.55E+01	6.27E-02
RL-W710	5.57E-08	0.00E+00	1.34E-22	8.06E-04	1.22E-04	0.00E+00	8.67E-09	9.28E-04	3.74E-06
RL-W711	1.74E-05	0.00E+00	4.17E-20	2.52E-01	3.82E-02	0.00E+00	2.71E-06	2.90E-01	1.17E-03
RL-W712	2.25E-05	0.00E+00	5.40E-20	3.25E-01	4.94E-02	0.00E+00	3.50E-06	3.75E-01	1.51E-03
RL-W713	1.95E-05	0.00E+00	4.67E-20	2.80E-01	4.27E-02	0.00E+00	3.03E-06	3.23E-01	1.30E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	3.36E-07	0.00E+00	7.86E-22	4.75E-03	7.21E-04	0.00E+00	5.10E-08	5.47E-03	2.21E-05
RL-W716	3.50E-06	0.00E+00	8.18E-21	4.95E-02	7.51E-03	0.00E+00	5.31E-07	5.70E-02	2.30E-04
RL-W717	8.73E-07	0.00E+00	2.05E-21	1.24E-02	1.88E-03	0.00E+00	1.33E-07	1.43E-02	5.75E-05
RL-W718	1.54E-07	0.00E+00	3.61E-22	2.18E-03	3.31E-04	0.00E+00	2.34E-08	2.51E-03	1.01E-05
RL-W719	6.94E-07	0.00E+00	1.63E-21	9.86E-03	1.50E-03	0.00E+00	1.06E-07	1.14E-02	4.58E-05
RL-W720	4.30E-06	0.00E+00	1.01E-20	6.09E-02	9.27E-03	0.00E+00	6.55E-07	7.02E-02	2.83E-04
RL-W721	2.91E-06	0.00E+00	6.82E-21	4.12E-02	6.28E-03	0.00E+00	4.42E-07	4.75E-02	1.91E-04
RL-W723	9.65E-06	0.00E+00	2.30E-20	1.40E-01	2.12E-02	0.00E+00	1.49E-06	1.61E-01	6.51E-04
RL-W724	6.42E-05	0.00E+00	1.53E-19	9.26E-01	1.41E-01	0.00E+00	9.95E-06	1.07E+00	4.30E-03
RL-W725	2.03E-05	0.00E+00	4.83E-20	2.93E-01	4.46E-02	0.00E+00	3.14E-06	3.38E-01	1.36E-03
RL-W726	1.60E-05	0.00E+00	3.81E-20	2.32E-01	3.51E-02	0.00E+00	2.47E-06	2.67E-01	1.08E-03
RL-W727	9.79E-05	0.00E+00	2.34E-19	1.42E+00	2.16E-01	0.00E+00	1.52E-05	1.64E+00	6.59E-03
RL-W728	8.92E-05	0.00E+00	2.13E-19	1.30E+00	1.97E-01	0.00E+00	1.38E-05	1.49E+00	6.03E-03
RL-W729	4.12E-05	0.00E+00	9.88E-20	5.97E-01	9.09E-02	0.00E+00	6.41E-06	6.88E-01	2.77E-03
RL-W730	1.61E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.61E-02	6.50E-05
RL-W731	5.20E-09	0.00E+00	0.00E+00	3.90E-04	1.09E-06	0.00E+00	0.00E+00	3.91E-04	1.58E-06
RL-W732	1.19E-02	0.00E+00	5.62E-17	1.10E+02	1.66E+01	0.00E+00	3.65E-03	1.27E+02	5.10E-01
RL-W733	1.56E-04	0.00E+00	7.31E-19	1.19E+00	2.02E-01	0.00E+00	4.74E-05	1.40E+00	5.63E-03
RL-W734	4.89E-04	0.00E+00	2.44E-18	4.12E+00	6.80E-01	0.00E+00	1.58E-04	4.80E+00	1.94E-02
RL-W735	3.99E-04	0.00E+00	1.86E-18	3.21E+00	5.43E-01	0.00E+00	1.21E-04	3.75E+00	1.51E-02
RL-W736	4.39E-07	0.00E+00	3.97E-24	2.13E-03	3.74E-04	0.00E+00	2.57E-10	2.50E-03	1.01E-05

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W737	3.57E-04	0.00E+00	1.70E-18	3.05E+00	5.05E-01	0.00E+00	1.10E-04	3.55E+00	1.43E-02
RL-W738	1.33E-03	0.00E+00	5.84E-18	9.69E+00	1.74E+00	0.00E+00	3.79E-04	1.14E+01	4.61E-02
RL-W739	1.13E-04	0.00E+00	5.15E-19	1.57E+00	2.45E-01	0.00E+00	3.34E-05	1.82E+00	7.34E-03
RL-W740	5.67E-03	0.00E+00	1.89E-17	3.83E+01	6.80E+00	0.00E+00	1.23E-03	4.51E+01	1.82E-01
RL-W741	8.47E-03	0.00E+00	4.44E-17	7.47E+00	3.61E+00	0.00E+00	2.88E-03	1.11E+01	4.47E-02
RL-W742	3.77E-04	0.00E+00	1.34E-18	2.42E+00	3.89E-01	0.00E+00	8.67E-05	2.81E+00	1.13E-02
RL-W743	6.79E-07	0.00E+00	3.63E-22	1.57E-03	0.00E+00	0.00E+00	2.35E-08	1.57E-03	6.32E-06
RL-W744	0.00E+00	0.00E+00	0.00E+00	7.81E-02	4.53E-02	0.00E+00	0.00E+00	1.23E-01	4.98E-04
RL-W745	1.07E-06	0.00E+00	2.54E-21	1.51E-02	2.29E-03	0.00E+00	1.65E-07	1.74E-02	7.03E-05
RL-W746	4.13E-06	0.00E+00	9.77E-21	5.81E-02	8.86E-03	0.00E+00	6.34E-07	6.70E-02	2.70E-04
RL-W747	1.12E-05	0.00E+00	2.65E-20	1.57E-01	2.39E-02	0.00E+00	1.72E-06	1.81E-01	7.31E-04
RL-W748	7.84E-02	0.00E+00	7.42E-17	2.61E-01	2.93E-01	0.00E+00	4.81E-03	6.37E-01	2.57E-03
RL-W749	9.41E-05	0.00E+00	2.27E-19	1.37E+00	2.07E-01	0.00E+00	1.47E-05	1.57E+00	6.35E-03
RL-W750	1.19E-01	0.00E+00	1.12E-16	4.28E-01	4.78E-01	0.00E+00	7.29E-03	1.03E+00	4.16E-03
RL-W751	1.07E-01	0.00E+00	1.02E-16	3.85E-01	4.33E-01	0.00E+00	6.58E-03	9.32E-01	3.76E-03
RL-W752	4.67E-02	0.00E+00	4.41E-17	1.68E-01	1.88E-01	0.00E+00	2.86E-03	4.06E-01	1.64E-03
RL-W753	6.28E-01	0.00E+00	5.95E-16	2.26E+00	2.53E+00	0.00E+00	3.86E-02	5.45E+00	2.20E-02
RP-W754	2.67E-02	0.00E+00	7.53E-17	1.61E+03	8.97E+01	0.00E+00	3.53E-01	1.70E+03	6.85E+00
RP-W755	1.41E-01	0.00E+00	4.51E-17	1.20E+03	6.80E+01	0.00E+00	1.24E+01	1.28E+03	5.17E+00
SA-T001	2.84E-04	1.09E-83	1.08E-18	2.62E+00	1.06E-02	0.00E+00	7.47E-05	2.63E+00	1.06E-02
SA-W134	2.32E-03	4.22E-87	7.37E-18	1.19E+00	2.58E-01	0.00E+00	1.65E-01	1.62E+00	6.53E-03
SA-W134M	3.01E-04	5.47E-88	9.55E-19	1.56E-01	3.34E-02	0.00E+00	2.14E-02	2.11E-01	8.50E-04
T001-221F-HET	5.61E-01	0.00E+00	8.62E-13	2.49E+04	4.19E+02	0.00E+00	6.15E+01	2.54E+04	1.02E+02
T001-221H-HET	1.01E+00	0.00E+00	1.56E-12	4.50E+04	7.57E+02	0.00E+00	1.11E+02	4.59E+04	1.85E+02
T001-235F-HET	5.81E-02	0.00E+00	8.95E-14	2.59E+03	4.35E+01	0.00E+00	6.38E+00	2.64E+03	1.06E+01
T001-772F-HET	5.00E-01	0.00E+00	7.75E-13	2.23E+04	3.75E+02	0.00E+00	5.52E+01	2.28E+04	9.17E+01
T001-773A-CLAS	5.62E-03	0.00E+00	8.68E-15	2.51E+02	4.21E+00	0.00E+00	6.19E-01	2.56E+02	1.03E+00
T001-773A-HET	6.48E-02	0.00E+00	9.98E-14	2.89E+03	4.86E+01	0.00E+00	7.12E+00	2.95E+03	1.19E+01
W006-773A-VIT	8.67E-07	0.00E+00	0.00E+00	4.65E+02	0.00E+00	0.00E+00	0.00E+00	4.65E+02	1.87E+00
W026-221F-HET	1.95E-01	0.00E+00	3.01E-13	8.74E+03	1.46E+02	0.00E+00	2.14E+01	8.91E+03	3.59E+01
W026-221H-HET	1.46E-01	0.00E+00	2.25E-13	6.51E+03	1.09E+02	0.00E+00	1.60E+01	6.63E+03	2.67E+01

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W026-235F-HET	2.27E-03	0.00E+00	3.50E-15	1.01E+02	1.70E+00	0.00E+00	2.50E-01	1.03E+02	4.16E-01
W026-772F-HET	6.21E-04	0.00E+00	9.55E-16	2.76E+01	4.63E-01	0.00E+00	6.81E-02	2.81E+01	1.13E-01
W026-773A-HET	1.01E-02	0.00E+00	1.56E-14	4.50E+02	7.57E+00	0.00E+00	1.11E+00	4.59E+02	1.85E+00
W027-221F-HET	7.36E-01	0.00E+00	1.02E-12	3.37E+04	5.65E+02	0.00E+00	8.34E+01	3.44E+04	1.39E+02
W027-221H-HET	3.22E-01	0.00E+00	4.43E-13	1.48E+04	2.48E+02	0.00E+00	3.64E+01	1.51E+04	6.08E+01
W027-235F-HET	9.68E-02	0.00E+00	1.33E-13	4.45E+03	7.45E+01	0.00E+00	1.10E+01	4.53E+03	1.83E+01
W027-772F-HET	1.76E-01	0.00E+00	2.42E-13	8.07E+03	1.36E+02	0.00E+00	1.99E+01	8.23E+03	3.32E+01
W027-773A-HET	2.62E-01	0.00E+00	3.61E-13	1.20E+04	2.02E+02	0.00E+00	2.97E+01	1.23E+04	4.94E+01
W027-999-HET	3.00E-01	0.00E+00	4.13E-13	1.38E+04	2.31E+02	0.00E+00	3.40E+01	1.40E+04	5.65E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.45E+02	0.00E+00	0.00E+00	0.00E+00	3.45E+02	1.39E+00
WP-INW169.001	1.47E-03	0.00E+00	2.60E-18	1.33E+01	2.02E+00	0.00E+00	3.32E-04	1.53E+01	6.19E-02
WP-INW198.001	1.93E-03	0.00E+00	4.54E-18	2.39E+01	3.59E+00	0.00E+00	3.75E-04	2.75E+01	1.11E-01
WP-INW211.001	2.17E-01	0.00E+00	4.26E-16	2.22E+03	3.33E+02	0.00E+00	2.96E-02	2.55E+03	1.03E+01
WP-INW216.001-	7.90E+00	0.00E+00	2.45E-16	1.28E+03	1.94E+02	0.00E+00	2.89E-01	1.48E+03	5.98E+00
WP-INW216.001-	2.17E+00	0.00E+00	6.60E-17	3.47E+02	5.22E+01	0.00E+00	3.15E-02	4.01E+02	1.62E+00
WP-INW218.001-	1.51E-01	0.00E+00	4.32E-17	2.23E+02	3.37E+01	0.00E+00	3.83E-01	2.57E+02	1.04E+00
WP-INW218.001-	6.96E-04	0.00E+00	1.19E-18	6.07E+00	9.15E-01	0.00E+00	3.70E-02	7.03E+00	2.83E-02
WP-INW222.001	7.15E-03	0.00E+00	1.28E-17	5.93E+01	9.03E+00	0.00E+00	1.40E-03	6.84E+01	2.76E-01
WP-INW243.001	1.73E-02	0.00E+00	2.77E-17	1.25E+02	1.90E+01	0.00E+00	2.65E-03	1.44E+02	5.79E-01
WP-INW247.001R	2.32E-02	0.00E+00	6.44E-17	2.39E+02	3.70E+01	0.00E+00	4.25E-03	2.76E+02	1.11E+00
WP-INW276.001	1.77E-03	0.00E+00	6.27E-18	2.36E+01	3.66E+00	0.00E+00	4.24E-04	2.73E+01	1.10E-01
WP-INW276.002	2.80E-03	0.00E+00	9.44E-18	3.47E+01	5.49E+00	0.00E+00	6.38E-04	4.02E+01	1.62E-01
WP-INW276.003	1.07E-01	0.00E+00	3.51E-16	1.29E+03	2.00E+02	0.00E+00	2.32E-02	1.49E+03	6.00E+00
WP-INW276.004	2.56E-02	0.00E+00	7.42E-17	2.73E+02	4.22E+01	0.00E+00	4.96E-03	3.15E+02	1.27E+00
WP-INW296.001-	9.37E-03	0.00E+00	1.76E-17	6.84E+01	1.06E+01	0.00E+00	1.18E-03	7.90E+01	3.19E-01
WP-INW296.001-	2.83E-02	0.00E+00	6.22E-17	2.42E+02	3.73E+01	0.00E+00	4.39E-03	2.80E+02	1.13E+00
WP-LA-TA-55-19	4.71E-04	0.00E+00	2.89E-18	1.81E+00	2.97E-01	0.00E+00	2.79E-03	2.11E+00	8.50E-03
WP-LA-TA-55-19	2.28E-02	0.00E+00	9.71E-17	1.84E+02	3.06E+01	0.00E+00	9.23E-02	2.15E+02	8.67E-01
WP-LA-TA-55-43	1.28E-04	0.00E+00	2.26E-15	2.79E-01	8.04E-02	0.00E+00	1.73E-01	5.33E-01	2.15E-03
WP-RF001.01	3.96E-02	0.00E+00	7.86E-17	3.55E+02	5.50E+01	0.00E+00	1.43E-02	4.10E+02	1.65E+00
WP-RF002.01-A	4.60E-02	0.00E+00	1.05E-16	4.00E+02	6.22E+01	0.00E+00	2.43E-02	4.62E+02	1.86E+00

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF002.01-B	4.57E-05	0.00E+00	7.26E-20	4.33E-01	6.69E-02	0.00E+00	4.90E-06	5.00E-01	2.01E-03
WP-RF003.01	7.15E-01	0.00E+00	1.69E-15	7.64E+03	1.19E+03	0.00E+00	1.18E-01	8.82E+03	3.56E+01
WP-RF004.01	3.35E-04	0.00E+00	1.13E-18	4.40E+00	6.86E-01	0.00E+00	1.99E-04	5.09E+00	2.05E-02
WP-RF005.01	1.72E+00	0.00E+00	8.57E-16	4.04E+03	6.22E+02	0.00E+00	5.74E-02	4.66E+03	1.88E+01
WP-RF005.02	2.02E+00	0.00E+00	4.43E-16	2.41E+03	3.69E+02	0.00E+00	2.99E-02	2.79E+03	1.12E+01
WP-RF006.01	6.57E-01	0.00E+00	1.61E-15	6.87E+03	1.07E+03	0.00E+00	1.30E-01	7.94E+03	3.20E+01
WP-RF008.01	2.08E-01	0.00E+00	5.73E-16	2.01E+03	3.17E+02	0.00E+00	3.84E-02	2.33E+03	9.37E+00
WP-RF009.01	2.05E+01	0.00E+00	7.04E-15	4.40E+04	6.69E+03	0.00E+00	4.77E-01	5.07E+04	2.05E+02
WP-RF010.01	7.55E-03	0.00E+00	1.78E-17	6.65E+01	1.03E+01	0.00E+00	1.88E-03	7.69E+01	3.10E-01
WP-RF029.01-A	1.82E-03	0.00E+00	3.36E-18	1.17E+01	1.82E+00	0.00E+00	9.37E-04	1.35E+01	5.44E-02
WP-RF029.01-B	2.71E-03	0.00E+00	2.66E-18	9.26E+00	1.44E+00	0.00E+00	2.39E-03	1.07E+01	4.31E-02
WP-RF118.01	4.61E+00	0.00E+00	1.34E-14	4.45E+04	6.75E+03	0.00E+00	1.08E+00	5.12E+04	2.07E+02
WP-RLMPDT.001	9.78E-04	0.00E+00	3.90E-18	6.37E+00	1.13E+00	0.00E+00	2.55E-04	7.49E+00	3.02E-02
WP-RLNPDT.002	1.20E-02	0.00E+00	3.72E-17	6.25E+01	1.14E+01	0.00E+00	2.45E-03	7.40E+01	2.98E-01
WP-SR2001.001.	3.82E-04	0.00E+00	4.27E-18	5.91E+00	7.98E-01	0.00E+00	2.82E-04	6.71E+00	2.70E-02
WP-SR-W027-221	2.83E-03	0.00E+00	1.26E-17	1.70E+01	3.22E+00	0.00E+00	1.84E-01	2.04E+01	8.21E-02
Total	1.52E+02	2.11E-80	8.79E-12	5.71E+05	6.28E+04	0.00E+00	7.35E+02	6.35E+05	2.56E+03

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	5.18E-04	0.00E+00	2.57E-25	1.68E+02	5.58E+01	0.00E+00	1.93E-02	2.24E+02	9.03E-01
AE-T003	6.56E-05	0.00E+00	3.43E-26	5.20E+01	1.13E+01	0.00E+00	9.44E-04	6.33E+01	2.55E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	2.91E-07	0.00E+00	9.08E-25	3.83E+01	1.30E-01	0.00E+00	2.26E-02	3.85E+01	1.55E-01
AW-T033.1325	1.06E-06	0.00E+00	3.33E-24	1.40E+02	4.73E-01	0.00E+00	8.26E-02	1.41E+02	5.67E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	6.22E-01	0.00E+00	0.00E+00	0.00E+00	6.22E-01	2.51E-03
BCLCH-MT01	1.07E-04	0.00E+00	2.57E-23	2.31E+01	3.39E+00	0.00E+00	6.26E-01	2.71E+01	1.09E-01
BT-T002	7.88E-08	0.00E+00	1.35E-26	5.84E-04	6.69E-04	0.00E+00	2.28E-03	3.53E-03	1.42E-05
ET-C1-B55	3.29E-07	0.00E+00	1.53E-28	5.00E-02	1.40E-02	0.00E+00	2.35E-04	6.42E-02	2.59E-04
ET-C1-D139	4.52E-08	0.00E+00	2.13E-29	7.03E-03	1.96E-03	0.00E+00	5.77E-07	8.99E-03	3.63E-05
ET-C2-SEFOR	1.12E-06	0.00E+00	0.00E+00	1.10E-01	2.07E-02	0.00E+00	0.00E+00	1.31E-01	5.28E-04
FM-MOX-MT02	1.06E-11	0.00E+00	8.56E-33	2.42E-07	8.05E-08	0.00E+00	2.16E-10	3.22E-07	1.30E-09
FM-MOX-T01	1.75E-10	0.00E+00	1.41E-31	3.98E-06	1.33E-06	0.00E+00	3.57E-09	5.31E-06	2.14E-08
IN-BN-510	4.23E-02	0.00E+00	7.29E-22	3.20E+04	1.52E+03	0.00E+00	1.96E+01	3.35E+04	1.35E+02
IN-GEM-01	5.35E-04	0.00E+00	1.45E-26	3.59E+01	4.59E+00	0.00E+00	3.51E-04	4.05E+01	1.63E-01
IN-GEM-02	1.27E-04	0.00E+00	3.44E-27	8.53E+00	1.09E+00	0.00E+00	8.36E-05	9.63E+00	3.88E-02
IN-W157.144	6.33E-04	0.00E+00	1.40E-25	2.44E+02	3.09E+01	0.00E+00	3.77E-03	2.75E+02	1.11E+00
IN-W163.1007	1.08E-04	0.00E+00	4.32E-26	7.57E+01	9.58E+00	0.00E+00	1.16E-03	8.53E+01	3.44E-01
IN-W164.153	1.04E-06	0.00E+00	4.12E-28	7.20E-01	9.13E-02	0.00E+00	1.11E-05	8.12E-01	3.27E-03
IN-W167.149	2.08E-04	0.00E+00	6.70E-26	1.17E+02	1.48E+01	0.00E+00	1.80E-03	1.32E+02	5.30E-01
IN-W174.154	0.00E+00	0.00E+00	3.79E-23	1.57E+00	1.73E+00	0.00E+00	1.02E+00	4.32E+00	1.74E-02
IN-W177.156	1.44E-07	0.00E+00	8.06E-23	1.47E+00	5.04E-03	0.00E+00	2.17E+00	3.65E+00	1.47E-02
IN-W179.158	9.69E-07	0.00E+00	8.03E-23	8.53E-02	2.48E-02	0.00E+00	2.16E+00	2.27E+00	9.16E-03
IN-W181.162	1.38E-05	0.00E+00	5.47E-27	9.50E+00	1.21E+00	0.00E+00	1.47E-04	1.07E+01	4.32E-02
IN-W188.160	9.25E-05	0.00E+00	3.67E-26	6.42E+01	8.10E+00	0.00E+00	9.89E-04	7.23E+01	2.91E-01
IN-W216.98	8.22E-01	0.00E+00	2.99E-24	5.23E+03	6.66E+02	0.00E+00	8.06E-02	5.90E+03	2.38E+01
IN-W218.909	4.15E-03	0.00E+00	6.65E-26	1.16E+02	1.47E+01	0.00E+00	1.79E-03	1.31E+02	5.27E-01
IN-W219.110	5.64E-06	0.00E+00	2.24E-27	3.91E+00	4.95E-01	0.00E+00	6.04E-05	4.41E+00	1.78E-02
IN-W219.914	8.89E-07	0.00E+00	3.53E-28	6.17E-01	7.83E-02	0.00E+00	9.50E-06	6.96E-01	2.81E-03

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W220.114	2.94E-02	0.00E+00	2.36E-25	4.42E+02	5.45E+01	0.00E+00	6.35E-03	4.96E+02	2.00E+00
IN-W221.927	3.44E-05	0.00E+00	1.37E-26	2.38E+01	3.02E+00	0.00E+00	3.68E-04	2.68E+01	1.08E-01
IN-W222.116	1.17E-03	0.00E+00	4.63E-25	8.05E+02	1.02E+02	0.00E+00	1.25E-02	9.07E+02	3.66E+00
IN-W228.101	7.76E-03	0.00E+00	1.50E-25	2.63E+02	3.33E+01	0.00E+00	4.05E-03	2.97E+02	1.20E+00
IN-W240.931	8.21E-04	0.00E+00	1.92E-25	3.38E+02	4.26E+01	0.00E+00	5.18E-03	3.81E+02	1.54E+00
IN-W243.808	1.14E-03	0.00E+00	3.37E-25	5.90E+02	7.47E+01	0.00E+00	9.08E-03	6.65E+02	2.68E+00
IN-W245.301	1.69E-03	0.00E+00	6.62E-25	1.15E+03	1.46E+02	0.00E+00	1.78E-02	1.30E+03	5.23E+00
IN-W247.810	8.21E-04	0.00E+00	3.23E-25	5.63E+02	7.15E+01	0.00E+00	8.68E-03	6.34E+02	2.56E+00
IN-W249.527	0.00E+00	0.00E+00	2.26E-23	9.98E+00	0.00E+00	0.00E+00	6.08E-01	1.06E+01	4.27E-02
IN-W263.520	2.35E-07	0.00E+00	2.36E-24	6.79E+00	6.03E-03	0.00E+00	6.35E-02	6.86E+00	2.76E-02
IN-W267.1005	1.97E-04	0.00E+00	7.82E-26	1.37E+02	1.73E+01	0.00E+00	2.11E-03	1.54E+02	6.22E-01
IN-W309.609	5.27E-03	0.00E+00	1.31E-24	2.29E+03	2.90E+02	0.00E+00	3.53E-02	2.58E+03	1.04E+01
IN-W315.601	5.20E-03	0.00E+00	5.48E-27	9.58E+00	1.21E+00	0.00E+00	1.48E-04	1.08E+01	4.35E-02
IN-W319.584	3.03E-05	0.00E+00	1.20E-26	2.10E+01	2.67E+00	0.00E+00	3.23E-04	2.37E+01	9.55E-02
IN-W321.1023	2.62E-04	0.00E+00	1.04E-25	1.82E+02	2.30E+01	0.00E+00	2.80E-03	2.05E+02	8.27E-01
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	7.34E+00	8.50E-01	0.00E+00	0.00E+00	8.19E+00	3.30E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	1.96E+01	2.27E+00	0.00E+00	0.00E+00	2.18E+01	8.80E-02
IN-W323.562	5.59E-07	0.00E+00	1.76E-26	2.00E-01	0.00E+00	0.00E+00	4.75E-04	2.01E-01	8.10E-04
IN-W323.951	6.60E-07	0.00E+00	2.10E-28	2.39E-01	0.00E+00	0.00E+00	5.65E-06	2.39E-01	9.64E-04
IN-W332.661	0.00E+00	0.00E+00	2.31E-25	1.04E-01	0.00E+00	0.00E+00	6.23E-03	1.10E-01	4.44E-04
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	2.45E+00	2.84E-01	0.00E+00	0.00E+00	2.73E+00	1.10E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	7.34E+00	8.50E-01	0.00E+00	0.00E+00	8.19E+00	3.30E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.57E+00	0.00E+00	0.00E+00	0.00E+00	1.57E+00	6.33E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	4.72E+00	0.00E+00	0.00E+00	0.00E+00	4.72E+00	1.90E-02
IN-W342.652	2.59E-05	0.00E+00	0.00E+00	3.24E-02	4.68E-18	0.00E+00	0.00E+00	3.24E-02	1.31E-04
IN-W342.953	1.73E-05	0.00E+00	0.00E+00	2.17E-02	3.14E-18	0.00E+00	0.00E+00	2.17E-02	8.74E-05
IN-W347.818	1.35E-05	0.00E+00	0.00E+00	6.65E+01	6.84E+01	0.00E+00	1.55E-08	1.35E+02	5.44E-01
IN-W348.1012	7.16E-07	0.00E+00	1.91E-25	3.36E+02	4.26E+01	0.00E+00	5.14E-03	3.78E+02	1.53E+00

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.01E-02	0.00E+00	0.00E+00	0.00E+00	2.01E-02	8.12E-05
IN-W357.1022	0.00E+00	0.00E+00	3.76E-28	6.59E-01	8.32E-02	0.00E+00	1.01E-05	7.43E-01	2.99E-03
IN-W358.854	0.00E+00	0.00E+00	5.67E-24	1.51E+00	1.63E+00	0.00E+00	1.46E-01	3.29E+00	1.33E-02
IN-W358.855	0.00E+00	0.00E+00	3.02E-23	8.05E+00	8.68E+00	0.00E+00	7.76E-01	1.75E+01	7.06E-02
IN-W358.948	0.00E+00	0.00E+00	6.31E-24	1.68E+00	1.81E+00	0.00E+00	1.62E-01	3.65E+00	1.47E-02
IN-W361.1021	1.90E-07	0.00E+00	3.64E-26	6.36E+01	8.05E+00	0.00E+00	9.81E-04	7.17E+01	2.89E-01
IN-W362.1020	0.00E+00	0.00E+00	4.77E-25	8.29E+02	1.06E+02	0.00E+00	1.29E-02	9.35E+02	3.77E+00
IN-W363.1019	0.00E+00	0.00E+00	2.24E-26	3.94E+01	5.00E+00	0.00E+00	6.04E-04	4.44E+01	1.79E-01
IN-W364.1011	0.00E+00	0.00E+00	3.70E-26	6.47E+01	8.19E+00	0.00E+00	9.97E-04	7.29E+01	2.94E-01
IN-W365.1010	1.77E-03	0.00E+00	2.94E-26	5.11E+01	6.48E+00	0.00E+00	7.91E-04	5.76E+01	2.32E-01
IN-W366.841	6.31E-06	0.00E+00	2.50E-26	4.36E+01	5.53E+00	0.00E+00	6.74E-04	4.91E+01	1.98E-01
IN-W372.832	2.59E-05	0.00E+00	0.00E+00	3.24E-02	4.68E-18	0.00E+00	0.00E+00	3.24E-02	1.31E-04
IN-W375.1096	0.00E+00	0.00E+00	9.23E-27	1.61E+01	2.04E+00	0.00E+00	2.49E-04	1.81E+01	7.31E-02
KN-B234TRU	9.18E-04	0.00E+00	3.53E-25	2.34E+02	4.41E+01	0.00E+00	1.05E-02	2.78E+02	1.12E+00
LA-IT-00-01	1.34E-05	0.00E+00	6.02E-26	4.71E-01	5.71E-03	0.00E+00	1.81E-03	4.78E-01	1.93E-03
LA-OS-00-01	2.97E-02	0.00E+00	2.75E-21	9.90E+02	0.00E+00	0.00E+00	6.73E+01	1.06E+03	4.26E+00
LA-PX-00-01	1.24E-07	0.00E+00	1.16E-28	7.29E-02	9.58E-03	0.00E+00	2.95E-06	8.24E-02	3.32E-04
LA-SL-00-01	0.00E+00	0.00E+00	2.44E-27	1.23E-01	0.00E+00	0.00E+00	7.30E-05	1.23E-01	4.97E-04
LA-TA-03-12	1.27E-06	0.00E+00	5.65E-26	3.51E-01	6.84E-02	0.00E+00	1.75E-03	4.21E-01	1.70E-03
LA-TA-03-13	1.65E-06	0.00E+00	1.79E-25	5.48E-01	7.20E-02	0.00E+00	4.88E-03	6.25E-01	2.52E-03
LA-TA-03-19	3.33E-06	0.00E+00	2.68E-25	1.07E+00	1.73E-01	0.00E+00	8.25E-03	1.25E+00	5.05E-03
LA-TA-03-20	1.82E-06	0.00E+00	1.27E-25	4.72E-01	9.31E-02	0.00E+00	3.76E-03	5.69E-01	2.29E-03
LA-TA-03-24	2.44E-06	0.00E+00	4.95E-25	8.77E-01	1.49E-01	0.00E+00	1.54E-02	1.04E+00	4.20E-03
LA-TA-03-26	1.25E-07	0.00E+00	2.04E-26	2.13E+00	1.95E-02	0.00E+00	1.48E-03	2.15E+00	8.65E-03
LA-TA-03-28	0.00E+00	0.00E+00	7.06E-27	1.99E-01	0.00E+00	0.00E+00	2.16E-04	1.99E-01	8.03E-04
LA-TA-03-30	5.55E-06	0.00E+00	5.03E-27	4.05E+00	6.57E-01	0.00E+00	1.53E-04	4.71E+00	1.90E-02
LA-TA-03-31	0.00E+00	0.00E+00	2.52E-28	7.08E-03	0.00E+00	0.00E+00	7.69E-06	7.09E-03	2.86E-05
LA-TA-03-40	0.00E+00	0.00E+00	3.98E-28	4.40E-02	0.00E+00	0.00E+00	1.23E-05	4.40E-02	1.78E-04

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-03-42	1.28E-10	0.00E+00	9.96E-30	2.75E-03	2.03E-05	0.00E+00	3.07E-07	2.77E-03	1.12E-05
LA-TA-21-06	1.26E-06	0.00E+00	1.10E-24	7.70E-01	1.32E-01	0.00E+00	3.35E-02	9.36E-01	3.77E-03
LA-TA-21-12	4.58E-06	0.00E+00	6.61E-24	2.67E+00	4.47E-01	0.00E+00	2.02E-01	3.32E+00	1.34E-02
LA-TA-21-13	7.04E-06	0.00E+00	0.00E+00	2.37E-01	0.00E+00	0.00E+00	0.00E+00	2.37E-01	9.54E-04
LA-TA-21-14	1.16E-09	0.00E+00	1.26E-25	3.61E+00	2.36E-05	0.00E+00	3.24E-03	3.62E+00	1.46E-02
LA-TA-21-15	6.82E-07	0.00E+00	3.47E-28	1.12E+00	1.07E-01	0.00E+00	1.05E-05	1.23E+00	4.94E-03
LA-TA-21-16	7.90E-06	0.00E+00	5.35E-27	8.53E+00	1.14E+00	0.00E+00	1.65E-04	9.68E+00	3.90E-02
LA-TA-21-40	1.00E-09	0.00E+00	1.85E-26	2.68E-01	1.66E-04	0.00E+00	6.96E-04	2.69E-01	1.08E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	5.71E-01	0.00E+00	0.00E+00	0.00E+00	5.71E-01	2.30E-03
LA-TA-21-42	1.03E-07	0.00E+00	6.02E-27	1.32E-01	5.04E-03	0.00E+00	2.41E-04	1.37E-01	5.54E-04
LA-TA-21-43	3.62E-04	0.00E+00	2.00E-25	4.11E+02	5.49E+01	0.00E+00	7.92E-03	4.66E+02	1.88E+00
LA-TA-21-44	1.74E-06	0.00E+00	4.19E-26	9.26E+01	1.38E-01	0.00E+00	1.39E-03	9.27E+01	3.74E-01
LA-TA-48-01	5.62E-07	0.00E+00	1.58E-28	9.50E-02	2.23E-01	0.00E+00	5.97E-06	3.18E-01	1.28E-03
LA-TA-49-01	6.93E-05	0.00E+00	1.94E-26	1.18E+01	2.76E+01	0.00E+00	7.36E-04	3.94E+01	1.59E-01
LA-TA-50-10	1.86E-07	0.00E+00	1.84E-28	3.70E-02	0.00E+00	0.00E+00	4.64E-06	3.70E-02	1.49E-04
LA-TA-50-11	3.54E-07	0.00E+00	1.88E-28	3.75E-01	4.68E-02	0.00E+00	7.00E-06	4.22E-01	1.70E-03
LA-TA-50-15	6.99E-07	0.00E+00	2.78E-26	2.74E-01	3.44E-02	0.00E+00	7.93E-04	3.09E-01	1.25E-03
LA-TA-50-17	1.02E-04	0.00E+00	2.26E-26	1.47E+01	1.94E-04	0.00E+00	9.77E-04	1.47E+01	5.91E-02
LA-TA-50-18	6.08E-06	0.00E+00	2.98E-27	2.39E+00	2.41E-06	0.00E+00	9.18E-05	2.39E+00	9.64E-03
LA-TA-50-19	1.94E-06	0.00E+00	1.33E-27	3.18E-01	2.07E-03	0.00E+00	6.71E-05	3.20E-01	1.29E-03
LA-TA-50-20	5.32E-08	0.00E+00	0.00E+00	7.84E-03	0.00E+00	0.00E+00	0.00E+00	7.84E-03	3.16E-05
LA-TA-50-40	3.00E-08	0.00E+00	1.79E-29	8.53E-03	2.24E-03	0.00E+00	5.27E-07	1.08E-02	4.34E-05
LA-TA-50-41	3.20E-08	0.00E+00	1.81E-29	3.78E-02	4.95E-03	0.00E+00	4.87E-07	4.28E-02	1.73E-04
LA-TA-55-19	4.96E-05	0.00E+00	2.39E-26	2.13E+01	3.36E+00	0.00E+00	2.22E-03	2.46E+01	9.93E-02
LA-TA-55-20	7.96E-04	0.00E+00	2.72E-25	5.14E+02	6.93E+01	0.00E+00	9.95E-02	5.83E+02	2.35E+00
LA-TA-55-21	7.11E-06	0.00E+00	3.12E-27	3.64E+00	4.91E-01	0.00E+00	8.35E-05	4.13E+00	1.67E-02
LA-TA-55-22	1.95E-05	0.00E+00	1.76E-26	1.28E+01	1.68E+00	0.00E+00	4.71E-04	1.45E+01	5.84E-02
LA-TA-55-23	1.84E-05	0.00E+00	1.48E-26	8.77E+00	1.22E+00	0.00E+00	3.91E-04	9.99E+00	4.03E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-24	6.92E-06	0.00E+00	2.31E-27	4.60E+00	6.03E-01	0.00E+00	5.90E-05	5.21E+00	2.10E-02
LA-TA-55-25	3.54E-05	0.00E+00	1.35E-26	2.29E+01	3.00E+00	0.00E+00	3.44E-04	2.59E+01	1.04E-01
LA-TA-55-28	1.21E-05	0.00E+00	7.48E-27	7.02E+00	9.31E-01	0.00E+00	1.92E-04	7.95E+00	3.21E-02
LA-TA-55-30	2.69E-04	0.00E+00	8.95E-26	1.15E+02	1.56E+01	0.00E+00	2.93E-03	1.31E+02	5.27E-01
LA-TA-55-32	2.18E-05	0.00E+00	5.00E-25	9.10E+00	1.58E+00	0.00E+00	1.56E-02	1.07E+01	4.31E-02
LA-TA-55-33	3.27E-06	0.00E+00	1.29E-27	1.20E+00	2.15E-01	0.00E+00	3.76E-05	1.42E+00	5.70E-03
LA-TA-55-34	3.30E-04	0.00E+00	1.19E-25	1.86E+02	2.66E+01	0.00E+00	6.20E-03	2.13E+02	8.57E-01
LA-TA-55-38	8.30E-04	0.00E+00	3.93E-26	4.11E+01	6.21E+00	0.00E+00	2.81E-03	4.73E+01	1.91E-01
LA-TA-55-39	8.78E-05	0.00E+00	2.91E-26	6.13E+01	7.74E+00	0.00E+00	7.64E-04	6.90E+01	2.78E-01
LA-TA-55-41	2.09E-03	0.00E+00	6.02E-26	7.60E+01	1.02E+01	0.00E+00	1.62E-03	8.62E+01	3.48E-01
LA-TA-55-43	7.85E-07	0.00E+00	3.95E-24	1.14E-01	2.25E-02	0.00E+00	1.03E-01	2.40E-01	9.67E-04
LA-TA-55-44	6.81E-06	0.00E+00	9.30E-24	2.12E+00	3.30E-01	0.00E+00	2.73E-01	2.72E+00	1.10E-02
LA-TA-55-48	5.02E-02	0.00E+00	3.67E-23	1.36E+04	2.85E+03	0.00E+00	1.05E+00	1.65E+04	6.64E+01
LA-TA-55-49	1.07E-04	0.00E+00	4.83E-23	2.49E+01	3.93E+00	0.00E+00	1.41E+00	3.02E+01	1.22E-01
LA-TA-55-53	5.06E-04	0.00E+00	9.98E-26	2.13E+02	2.79E+01	0.00E+00	2.87E-03	2.40E+02	9.69E-01
LA-TA-55-56	5.60E-04	0.00E+00	3.72E-24	3.08E+02	4.34E+01	0.00E+00	1.02E-01	3.51E+02	1.42E+00
LA-TA-55-60	3.04E-07	0.00E+00	9.39E-28	5.80E-02	1.16E-02	0.00E+00	2.74E-05	6.96E-02	2.80E-04
LA-TA-55-61	2.61E-07	0.00E+00	4.32E-27	1.12E-01	2.13E-02	0.00E+00	1.24E-04	1.33E-01	5.38E-04
LA-TA-55-62	6.77E-08	0.00E+00	4.11E-29	1.88E-02	5.04E-03	0.00E+00	1.19E-06	2.38E-02	9.60E-05
LA-TA-55-63	5.02E-08	0.00E+00	2.78E-29	6.01E-02	7.83E-03	0.00E+00	7.66E-07	6.80E-02	2.74E-04
LL-M001	6.89E-04	0.00E+00	1.21E-24	5.64E+01	1.43E+01	0.00E+00	2.94E-02	7.07E+01	2.85E-01
LL-T001	3.44E-03	0.00E+00	0.00E+00	4.30E+02	1.09E+02	0.00E+00	0.00E+00	5.39E+02	2.17E+00
LL-T002	3.40E-02	0.00E+00	9.63E-24	4.17E+03	9.63E+02	0.00E+00	2.34E-01	5.13E+03	2.07E+01
LL-T003	1.32E-03	0.00E+00	1.08E-24	8.45E+01	3.83E+01	0.00E+00	2.62E-02	1.23E+02	4.96E-01
LL-T004	8.40E-04	0.00E+00	2.21E-25	5.37E+01	2.42E+01	0.00E+00	5.38E-03	7.79E+01	3.14E-01
LL-T005	4.33E-03	0.00E+00	2.60E-24	2.00E+02	9.70E+01	0.00E+00	6.33E-02	2.97E+02	1.20E+00
LL-W018	3.69E-07	0.00E+00	0.00E+00	1.49E-02	1.93E-02	0.00E+00	0.00E+00	3.42E-02	1.38E-04
LL-W019	2.00E-04	0.00E+00	0.00E+00	1.16E+01	5.45E+00	0.00E+00	0.00E+00	1.70E+01	6.87E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LL-W034	7.40E-05	0.00E+00	4.56E-26	3.38E+00	1.61E+00	0.00E+00	1.11E-03	4.99E+00	2.01E-02
MC-W001	9.23E-07	0.00E+00	0.00E+00	4.88E-02	0.00E+00	0.00E+00	0.00E+00	4.88E-02	1.97E-04
MU-W002	1.23E-05	0.00E+00	0.00E+00	4.23E-02	0.00E+00	0.00E+00	2.61E-12	4.24E-02	1.71E-04
NT-JAS-01	1.19E-03	0.00E+00	9.70E-25	7.63E+01	3.45E+01	0.00E+00	2.36E-02	1.11E+02	4.47E-01
NT-W001	1.79E-03	0.00E+00	1.94E-24	2.30E+03	8.64E+00	0.00E+00	5.84E-02	2.31E+03	9.32E+00
NT-W021	3.46E-05	0.00E+00	1.39E-26	2.59E+01	3.32E+00	0.00E+00	3.83E-04	2.92E+01	1.18E-01
OR-W201	4.15E-02	0.00E+00	4.17E-23	1.74E+03	9.63E+02	0.00E+00	4.37E+01	2.75E+03	1.11E+01
OR-W202	5.95E-03	0.00E+00	1.20E-22	4.46E+02	2.46E+02	0.00E+00	3.36E+00	6.95E+02	2.80E+00
OR-W203	1.31E-05	0.00E+00	1.72E-26	2.00E-02	8.02E-01	0.00E+00	4.79E-04	8.23E-01	3.32E-03
OR-W204	2.92E-06	0.00E+00	1.95E-26	3.41E-01	1.30E-01	0.00E+00	5.43E-04	4.71E-01	1.90E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	3.43E-01	0.00E+00	0.00E+00	0.00E+00	3.43E-01	1.38E-03
RF-MT0001	1.12E-02	0.00E+00	1.21E-25	1.58E+02	2.02E+01	0.00E+00	3.24E-03	1.78E+02	7.18E-01
RF-MT0002	8.62E-04	0.00E+00	9.30E-27	1.22E+01	1.55E+00	0.00E+00	2.49E-04	1.37E+01	5.53E-02
RF-MT0003	3.92E-06	0.00E+00	2.13E-27	2.78E+00	3.56E-01	0.00E+00	5.68E-05	3.13E+00	1.26E-02
RF-MT0007	9.86E-06	0.00E+00	0.00E+00	3.46E-01	4.42E-02	0.00E+00	0.00E+00	3.90E-01	1.57E-03
RF-MT0089	3.87E-08	0.00E+00	2.13E-29	2.78E-02	3.55E-03	0.00E+00	5.68E-07	3.13E-02	1.26E-04
RF-MT0090	9.82E-05	0.00E+00	3.01E-26	7.13E+01	9.04E+00	0.00E+00	8.04E-04	8.04E+01	3.24E-01
RF-MT0091	6.09E-03	0.00E+00	3.05E-24	4.77E+03	6.07E+02	0.00E+00	8.45E-02	5.37E+03	2.17E+01
RF-MT0092	8.72E-04	0.00E+00	3.85E-25	6.83E+02	8.86E+01	0.00E+00	1.03E-02	7.71E+02	3.11E+00
RF-MT0093	1.06E-03	0.00E+00	3.96E-25	7.37E+02	9.72E+01	0.00E+00	1.06E-02	8.34E+02	3.36E+00
RF-MT0097	5.31E-05	0.00E+00	1.75E-26	3.85E+01	4.42E+00	0.00E+00	4.67E-04	4.29E+01	1.73E-01
RF-MT0099	5.82E-08	0.00E+00	3.20E-29	4.16E-02	5.31E-03	0.00E+00	8.54E-07	4.69E-02	1.89E-04
RF-MT0290	1.44E-04	0.00E+00	7.91E-26	1.03E+02	1.32E+01	0.00E+00	2.11E-03	1.16E+02	4.69E-01
RF-MT-0292	1.82E-04	0.00E+00	9.99E-26	1.30E+02	1.67E+01	0.00E+00	2.67E-03	1.47E+02	5.93E-01
RF-MT-0299	2.14E-02	0.00E+00	2.56E-24	3.34E+03	4.28E+02	0.00E+00	6.84E-02	3.77E+03	1.52E+01
RF-MT0302	3.28E-07	0.00E+00	1.02E-28	1.44E-01	1.85E-02	0.00E+00	1.92E-05	1.63E-01	6.56E-04
RF-MT0320	3.92E-04	0.00E+00	1.05E-25	1.40E+02	1.80E+01	0.00E+00	2.82E-03	1.58E+02	6.37E-01
RF-MT0321	2.19E-04	0.00E+00	3.14E-26	4.51E+01	5.71E+00	0.00E+00	3.20E-03	5.08E+01	2.05E-01

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT-0328	1.52E-05	0.00E+00	3.76E-27	4.90E+00	6.25E-01	0.00E+00	4.32E-04	5.53E+00	2.23E-02
RF-MT0330	1.58E-04	0.00E+00	4.12E-26	9.90E+01	1.37E+01	0.00E+00	1.10E-03	1.13E+02	4.54E-01
RF-MT-0331	9.46E-04	0.00E+00	2.56E-25	4.36E+02	5.45E+01	0.00E+00	2.72E-02	4.90E+02	1.98E+00
RF-MT0332	1.36E-07	0.00E+00	7.46E-29	9.74E-02	1.24E-02	0.00E+00	1.99E-06	1.10E-01	4.43E-04
RF-MT-0335	1.09E-05	0.00E+00	3.43E-27	5.02E+00	6.43E-01	0.00E+00	6.23E-04	5.66E+00	2.28E-02
RF-MT0336	7.71E-04	0.00E+00	2.27E-25	3.56E+02	4.55E+01	0.00E+00	7.85E-03	4.01E+02	1.62E+00
RF-MT0337	4.36E-04	0.00E+00	1.25E-25	2.17E+02	2.73E+01	0.00E+00	7.11E-03	2.45E+02	9.87E-01
RF-MT0339	1.19E-03	0.00E+00	3.40E-25	4.77E+02	6.03E+01	0.00E+00	2.58E-02	5.37E+02	2.17E+00
RF-MT-0342	7.00E-06	0.00E+00	2.85E-27	4.40E+00	5.53E-01	0.00E+00	1.33E-04	4.96E+00	2.00E-02
RF-MT0371	2.37E-03	0.00E+00	6.59E-25	8.61E+02	1.10E+02	0.00E+00	1.89E-02	9.71E+02	3.92E+00
RF-MT-0372	1.03E-05	0.00E+00	4.64E-27	6.01E+00	7.69E-01	0.00E+00	3.59E-04	6.78E+00	2.73E-02
RF-MT0373	1.56E-04	0.00E+00	4.77E-26	1.13E+02	1.43E+01	0.00E+00	1.28E-03	1.27E+02	5.12E-01
RF-MT0374	5.05E-06	0.00E+00	1.71E-27	2.23E+00	2.85E-01	0.00E+00	4.89E-05	2.52E+00	1.01E-02
RF-MT0376	4.00E-06	0.00E+00	1.38E-27	2.22E+00	2.88E-01	0.00E+00	5.16E-05	2.51E+00	1.01E-02
RF-MT0377	2.38E-03	0.00E+00	7.94E-25	1.04E+03	1.32E+02	0.00E+00	3.12E-02	1.17E+03	4.72E+00
RF-MT0378	2.67E-05	0.00E+00	1.10E-26	1.43E+01	1.83E+00	0.00E+00	2.93E-04	1.62E+01	6.52E-02
RF-MT0419	4.29E-05	0.00E+00	1.03E-26	1.34E+01	1.71E+00	0.00E+00	2.74E-04	1.51E+01	6.08E-02
RF-MT0420	7.46E-06	0.00E+00	1.78E-27	2.32E+00	2.97E-01	0.00E+00	4.75E-05	2.62E+00	1.06E-02
RF-MT0423	6.34E-05	0.00E+00	1.45E-26	3.35E+01	4.15E+00	0.00E+00	3.87E-04	3.76E+01	1.52E-01
RF-MT0425	1.87E-06	0.00E+00	4.45E-28	5.80E-01	7.42E-02	0.00E+00	1.19E-05	6.55E-01	2.64E-03
RF-MT-0438	1.69E-05	0.00E+00	5.84E-27	1.03E+01	1.31E+00	0.00E+00	1.69E-04	1.16E+01	4.68E-02
RF-MT0440	6.15E-06	0.00E+00	2.10E-27	3.74E+00	4.86E-01	0.00E+00	2.17E-04	4.22E+00	1.70E-02
RF-MT0442	2.34E-06	0.00E+00	9.07E-28	1.28E+00	1.63E-01	0.00E+00	1.17E-04	1.44E+00	5.82E-03
RF-MT0443	2.88E-05	0.00E+00	1.49E-26	1.99E+01	2.54E+00	0.00E+00	5.53E-04	2.24E+01	9.04E-02
RF-MT0444	2.25E-04	0.00E+00	7.30E-26	9.58E+01	1.22E+01	0.00E+00	1.97E-03	1.08E+02	4.35E-01
RF-MT0480	6.29E-04	0.00E+00	2.05E-25	2.69E+02	3.44E+01	0.00E+00	7.90E-03	3.03E+02	1.22E+00
RF-MT0488	1.01E-03	0.00E+00	3.07E-25	3.99E+02	5.09E+01	0.00E+00	3.85E-02	4.50E+02	1.82E+00
RF-MT0490	4.56E-06	0.00E+00	1.78E-27	2.36E+00	3.02E-01	0.00E+00	5.85E-05	2.66E+00	1.07E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT-0491	3.58E-07	0.00E+00	8.13E-29	1.07E-01	1.36E-02	0.00E+00	4.14E-06	1.21E-01	4.87E-04
RF-MT0523A	2.84E-04	0.00E+00	6.46E-26	8.45E+01	1.08E+01	0.00E+00	1.98E-03	9.53E+01	3.84E-01
RF-MT0523B	2.84E-04	0.00E+00	6.46E-26	8.45E+01	1.08E+01	0.00E+00	1.98E-03	9.53E+01	3.84E-01
RF-MT0523C	2.84E-04	0.00E+00	6.46E-26	8.45E+01	1.08E+01	0.00E+00	1.98E-03	9.53E+01	3.84E-01
RF-MT0523D	2.84E-04	0.00E+00	6.46E-26	8.45E+01	1.08E+01	0.00E+00	1.98E-03	9.53E+01	3.84E-01
RF-MT0523E	2.84E-04	0.00E+00	6.46E-26	8.45E+01	1.08E+01	0.00E+00	1.98E-03	9.53E+01	3.84E-01
RF-MT0531	1.94E-08	0.00E+00	1.06E-29	1.39E-02	1.77E-03	0.00E+00	2.84E-07	1.56E-02	6.30E-05
RF-MT0532E	9.04E-04	0.00E+00	1.38E-25	1.84E+02	2.35E+01	0.00E+00	4.78E-03	2.08E+02	8.38E-01
RF-MT0532F	9.04E-04	0.00E+00	1.38E-25	1.84E+02	2.35E+01	0.00E+00	4.78E-03	2.08E+02	8.38E-01
RF-MT0541	3.29E-05	0.00E+00	2.00E-27	2.62E+00	3.34E-01	0.00E+00	5.33E-05	2.95E+00	1.19E-02
RF-MT0545	1.76E-07	0.00E+00	9.66E-29	1.26E-01	1.61E-02	0.00E+00	2.58E-06	1.43E-01	5.75E-04
RF-MT0800	6.70E-03	0.00E+00	4.79E-26	6.24E+01	7.96E+00	0.00E+00	1.75E-03	7.04E+01	2.84E-01
RF-MT0801	7.70E-04	0.00E+00	4.69E-26	6.13E+01	7.83E+00	0.00E+00	1.25E-03	6.91E+01	2.79E-01
RF-MT0803	1.73E-05	0.00E+00	1.05E-27	1.37E+00	1.75E-01	0.00E+00	2.80E-05	1.54E+00	6.22E-03
RF-MT0806	8.15E-06	0.00E+00	2.52E-27	5.95E+00	7.51E-01	0.00E+00	6.72E-05	6.70E+00	2.70E-02
RF-MT0807	1.03E-04	0.00E+00	1.94E-26	2.53E+01	3.24E+00	0.00E+00	5.18E-04	2.85E+01	1.15E-01
RF-MT0816	1.10E-05	0.00E+00	2.73E-27	3.57E+00	4.55E-01	0.00E+00	7.30E-05	4.02E+00	1.62E-02
RF-MT-0823	5.46E-06	0.00E+00	1.24E-27	1.63E+00	2.08E-01	0.00E+00	3.81E-05	1.83E+00	7.40E-03
RF-MT0827	2.78E-04	0.00E+00	6.91E-26	9.02E+01	1.15E+01	0.00E+00	1.85E-03	1.02E+02	4.10E-01
RF-MT0831	5.31E-04	0.00E+00	1.89E-25	2.44E+02	3.12E+01	0.00E+00	1.70E-02	2.75E+02	1.11E+00
RF-MT0832	3.17E-03	0.00E+00	6.87E-25	9.50E+02	1.21E+02	0.00E+00	5.11E-02	1.07E+03	4.32E+00
RF-MT0833	9.65E-04	0.00E+00	2.05E-25	2.75E+02	3.51E+01	0.00E+00	1.45E-02	3.10E+02	1.25E+00
RF-MT0855	1.66E-07	0.00E+00	9.13E-29	1.19E-01	1.52E-02	0.00E+00	2.44E-06	1.34E-01	5.42E-04
RF-MT0857	8.15E-06	0.00E+00	2.50E-27	5.93E+00	7.51E-01	0.00E+00	6.69E-05	6.68E+00	2.70E-02
RF-MT0H61	3.02E-04	0.00E+00	9.30E-26	2.20E+02	2.79E+01	0.00E+00	2.49E-03	2.48E+02	9.99E-01
RF-MT2116	3.40E-05	0.00E+00	7.38E-27	1.01E+01	1.30E+00	0.00E+00	5.47E-04	1.14E+01	4.61E-02
RF-MT3010	2.13E-04	0.00E+00	7.66E-26	1.01E+02	1.30E+01	0.00E+00	2.43E-03	1.14E+02	4.58E-01
RF-MT3011	1.59E-03	0.00E+00	4.77E-25	6.21E+02	7.96E+01	0.00E+00	2.04E-02	7.01E+02	2.83E+00

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT420P	8.44E-03	0.00E+00	2.42E-24	5.11E+03	6.52E+02	0.00E+00	7.44E-02	5.76E+03	2.32E+01
RF-MT532A	2.23E-03	0.00E+00	3.41E-25	4.56E+02	5.80E+01	0.00E+00	1.18E-02	5.14E+02	2.07E+00
RF-MT532B	9.99E-03	0.00E+00	1.53E-24	2.05E+03	2.61E+02	0.00E+00	5.29E-02	2.31E+03	9.30E+00
RF-MT532C	2.00E-02	0.00E+00	3.08E-24	4.10E+03	5.22E+02	0.00E+00	1.06E-01	4.62E+03	1.86E+01
RF-MT532D	1.27E-04	0.00E+00	1.94E-26	2.59E+01	3.30E+00	0.00E+00	6.70E-04	2.92E+01	1.18E-01
RF-TT0069	7.29E-07	0.00E+00	2.30E-28	3.00E-01	3.84E-02	0.00E+00	7.81E-05	3.39E-01	1.37E-03
RF-TT0200	3.46E-05	0.00E+00	9.28E-27	1.23E+01	1.58E+00	0.00E+00	2.49E-04	1.39E+01	5.61E-02
RF-TT0299	1.44E-04	0.00E+00	1.72E-26	2.25E+01	2.87E+00	0.00E+00	4.60E-04	2.53E+01	1.02E-01
RF-TT0300	1.17E-03	0.00E+00	4.90E-25	6.45E+02	8.28E+01	0.00E+00	2.13E-02	7.28E+02	2.93E+00
RF-TT0301	1.58E-04	0.00E+00	6.65E-26	8.77E+01	1.13E+01	0.00E+00	2.89E-03	9.90E+01	3.99E-01
RF-TT0302	7.81E-06	0.00E+00	2.42E-27	3.43E+00	4.39E-01	0.00E+00	4.55E-04	3.87E+00	1.56E-02
RF-TT0303	4.70E-05	0.00E+00	1.41E-26	1.84E+01	2.35E+00	0.00E+00	1.39E-03	2.08E+01	8.38E-02
RF-TT0310	1.60E-04	0.00E+00	6.62E-26	8.29E+01	1.09E+01	0.00E+00	1.95E-03	9.39E+01	3.78E-01
RF-TT0312	3.84E-03	0.00E+00	1.20E-24	1.81E+03	2.30E+02	0.00E+00	3.37E-02	2.04E+03	8.23E+00
RF-TT0317	2.42E-06	0.00E+00	1.30E-27	1.70E+00	2.17E-01	0.00E+00	3.47E-05	1.92E+00	7.72E-03
RF-TT0320	1.55E-03	0.00E+00	4.17E-25	5.54E+02	7.11E+01	0.00E+00	1.12E-02	6.25E+02	2.52E+00
RF-TT0330	5.52E-04	0.00E+00	1.44E-25	3.48E+02	4.77E+01	0.00E+00	3.85E-03	3.95E+02	1.60E+00
RF-TT-0331	2.75E-03	0.00E+00	7.45E-25	1.26E+03	1.58E+02	0.00E+00	7.89E-02	1.42E+03	5.74E+00
RF-TT-0334	1.20E-03	0.00E+00	6.03E-25	7.86E+02	1.00E+02	0.00E+00	1.61E-02	8.86E+02	3.57E+00
RF-TT0335	1.46E-03	0.00E+00	4.57E-25	6.68E+02	8.59E+01	0.00E+00	8.30E-02	7.54E+02	3.04E+00
RF-TT0336	1.29E-03	0.00E+00	3.79E-25	5.92E+02	7.56E+01	0.00E+00	1.31E-02	6.67E+02	2.69E+00
RF-TT0337	1.53E-03	0.00E+00	4.38E-25	7.64E+02	9.58E+01	0.00E+00	2.49E-02	8.60E+02	3.47E+00
RF-TT0338	6.49E-03	0.00E+00	1.59E-24	2.98E+03	3.74E+02	0.00E+00	5.06E-02	3.35E+03	1.35E+01
RF-TT0340	5.55E-05	0.00E+00	3.04E-26	3.96E+01	5.09E+00	0.00E+00	8.12E-04	4.47E+01	1.80E-01
RF-TT0342	3.71E-04	0.00E+00	1.52E-25	2.33E+02	2.93E+01	0.00E+00	7.10E-03	2.63E+02	1.06E+00
RF-TT0360	2.83E-05	0.00E+00	7.71E-27	1.05E+01	1.35E+00	0.00E+00	2.12E-04	1.18E+01	4.77E-02
RF-TT0368	5.66E-04	0.00E+00	1.55E-25	2.10E+02	2.71E+01	0.00E+00	4.26E-03	2.37E+02	9.57E-01
RF-TT0370	1.12E-03	0.00E+00	3.34E-25	4.68E+02	5.98E+01	0.00E+00	1.66E-02	5.28E+02	2.13E+00

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0371	2.42E-05	0.00E+00	6.72E-27	8.77E+00	1.12E+00	0.00E+00	1.93E-04	9.90E+00	3.99E-02
RF-TT0372	2.95E-06	0.00E+00	1.33E-27	1.72E+00	2.20E-01	0.00E+00	1.02E-04	1.93E+00	7.80E-03
RF-TT0374	9.19E-05	0.00E+00	3.11E-26	4.05E+01	5.18E+00	0.00E+00	8.90E-04	4.57E+01	1.84E-01
RF-TT0375A	9.58E-07	0.00E+00	5.12E-28	6.66E-01	8.50E-02	0.00E+00	1.37E-05	7.51E-01	3.03E-03
RF-TT0375B	9.58E-07	0.00E+00	5.12E-28	6.66E-01	8.50E-02	0.00E+00	1.37E-05	7.51E-01	3.03E-03
RF-TT0376	2.20E-04	0.00E+00	7.58E-26	1.22E+02	1.58E+01	0.00E+00	2.84E-03	1.38E+02	5.57E-01
RF-TT0377	1.24E-04	0.00E+00	4.12E-26	5.38E+01	6.88E+00	0.00E+00	1.62E-03	6.07E+01	2.45E-01
RF-TT0391	2.76E-05	0.00E+00	5.80E-27	1.36E+01	1.71E+00	0.00E+00	1.55E-04	1.53E+01	6.18E-02
RF-TT0392	9.70E-06	0.00E+00	3.64E-27	7.11E+00	9.04E-01	0.00E+00	9.75E-05	8.01E+00	3.23E-02
RF-TT0393	7.97E-04	0.00E+00	2.55E-25	3.31E+02	4.23E+01	0.00E+00	6.80E-03	3.73E+02	1.51E+00
RF-TT0398	1.74E-05	0.00E+00	6.71E-27	1.33E+01	1.68E+00	0.00E+00	1.79E-04	1.50E+01	6.03E-02
RF-TT0409	1.46E-05	0.00E+00	3.14E-27	6.86E+00	8.68E-01	0.00E+00	8.45E-05	7.73E+00	3.12E-02
RF-TT0412	1.46E-05	0.00E+00	3.14E-27	6.86E+00	8.68E-01	0.00E+00	8.45E-05	7.73E+00	3.12E-02
RF-TT0414	4.51E-04	0.00E+00	9.70E-26	2.13E+02	2.69E+01	0.00E+00	2.61E-03	2.39E+02	9.65E-01
RF-TT0430	1.32E-07	0.00E+00	7.25E-29	9.42E-02	1.21E-02	0.00E+00	1.94E-06	1.06E-01	4.28E-04
RF-TT0431	3.28E-05	0.00E+00	1.76E-26	2.32E+01	2.97E+00	0.00E+00	6.89E-04	2.62E+01	1.05E-01
RF-TT0438	1.95E-03	0.00E+00	6.72E-25	1.18E+03	1.50E+02	0.00E+00	1.95E-02	1.33E+03	5.38E+00
RF-TT0440	1.92E-04	0.00E+00	6.54E-26	1.17E+02	1.53E+01	0.00E+00	6.81E-03	1.32E+02	5.32E-01
RF-TT0441	9.46E-04	0.00E+00	3.07E-25	4.03E+02	5.18E+01	0.00E+00	1.27E-02	4.55E+02	1.84E+00
RF-TT0442	1.37E-04	0.00E+00	5.29E-26	7.46E+01	9.54E+00	0.00E+00	6.83E-03	8.42E+01	3.39E-01
RF-TT0443	2.93E-06	0.00E+00	1.52E-27	2.02E+00	2.58E-01	0.00E+00	5.63E-05	2.28E+00	9.19E-03
RF-TT0479	2.86E-05	0.00E+00	1.58E-26	2.05E+01	2.62E+00	0.00E+00	4.21E-04	2.31E+01	9.30E-02
RF-TT0480	1.95E-03	0.00E+00	6.36E-25	8.37E+02	1.07E+02	0.00E+00	2.45E-02	9.44E+02	3.81E+00
RF-TT0481	1.10E-06	0.00E+00	3.59E-28	4.70E-01	6.03E-02	0.00E+00	1.38E-05	5.30E-01	2.14E-03
RF-TT0483	3.53E-06	0.00E+00	1.94E-27	2.52E+00	3.23E-01	0.00E+00	1.69E-02	2.86E+00	1.15E-02
RF-TT0484	1.89E-05	0.00E+00	8.03E-27	1.05E+01	1.34E+00	0.00E+00	3.23E-04	1.18E+01	4.76E-02
RF-TT0485	1.55E-06	0.00E+00	4.96E-28	6.46E-01	8.28E-02	0.00E+00	2.85E-04	7.29E-01	2.94E-03
RF-TT0486	9.19E-06	0.00E+00	2.94E-27	3.83E+00	4.91E-01	0.00E+00	3.01E-04	4.32E+00	1.74E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0487	4.61E-05	0.00E+00	9.98E-27	1.38E+01	1.76E+00	0.00E+00	7.41E-04	1.55E+01	6.26E-02
RF-TT0489	1.31E-05	0.00E+00	4.48E-27	5.84E+00	7.47E-01	0.00E+00	2.19E-04	6.59E+00	2.66E-02
RF-TT0490	7.26E-04	0.00E+00	2.85E-25	3.77E+02	4.82E+01	0.00E+00	9.36E-03	4.25E+02	1.71E+00
RF-TT0491	1.69E-05	0.00E+00	3.85E-27	5.05E+00	6.43E-01	0.00E+00	1.96E-04	5.69E+00	2.30E-02
RF-TT0492	5.68E-06	0.00E+00	2.17E-27	2.82E+00	3.61E-01	0.00E+00	5.79E-05	3.18E+00	1.28E-02
RF-TT0523A	3.82E-05	0.00E+00	8.71E-27	1.14E+01	1.45E+00	0.00E+00	2.66E-04	1.28E+01	5.16E-02
RF-TT0523B	3.82E-05	0.00E+00	8.71E-27	1.14E+01	1.45E+00	0.00E+00	2.66E-04	1.28E+01	5.16E-02
RF-TT0523C	3.82E-05	0.00E+00	8.71E-27	1.14E+01	1.45E+00	0.00E+00	2.66E-04	1.28E+01	5.16E-02
RF-TT0523D	3.82E-05	0.00E+00	8.71E-27	1.14E+01	1.45E+00	0.00E+00	2.66E-04	1.28E+01	5.16E-02
RF-TT0523E	3.82E-05	0.00E+00	8.71E-27	1.14E+01	1.45E+00	0.00E+00	2.66E-04	1.28E+01	5.16E-02
RF-TT0532A	9.58E-04	0.00E+00	1.46E-25	1.96E+02	2.49E+01	0.00E+00	5.05E-03	2.21E+02	8.89E-01
RF-TT0532B	9.58E-04	0.00E+00	1.46E-25	1.96E+02	2.49E+01	0.00E+00	5.05E-03	2.21E+02	8.89E-01
RF-TT0541	1.58E-06	0.00E+00	8.69E-28	1.14E+00	1.45E-01	0.00E+00	2.32E-05	1.28E+00	5.16E-03
RF-TT0545	3.53E-07	0.00E+00	1.94E-28	2.52E-01	3.23E-02	0.00E+00	5.18E-06	2.84E-01	1.15E-03
RF-TT0601	1.22E-04	0.00E+00	3.34E-26	4.55E+01	5.89E+00	0.00E+00	9.19E-04	5.14E+01	2.07E-01
RF-TT0802	1.37E-02	0.00E+00	2.75E-24	3.59E+03	4.59E+02	0.00E+00	7.34E-02	4.05E+03	1.63E+01
RF-TT0809	1.13E-03	0.00E+00	2.26E-25	2.95E+02	3.76E+01	0.00E+00	6.03E-03	3.33E+02	1.34E+00
RF-TT0821	2.44E-03	0.00E+00	8.20E-25	1.16E+03	1.49E+02	0.00E+00	1.86E-01	1.31E+03	5.27E+00
RF-TT0822	2.70E-03	0.00E+00	6.38E-25	8.69E+02	1.11E+02	0.00E+00	1.96E-01	9.80E+02	3.95E+00
RF-TT0823	5.46E-06	0.00E+00	1.24E-27	1.63E+00	2.08E-01	0.00E+00	3.81E-05	1.83E+00	7.40E-03
RF-TT0824	5.62E-03	0.00E+00	1.75E-24	2.34E+03	2.99E+02	0.00E+00	1.08E-01	2.64E+03	1.07E+01
RF-TT0825	4.67E-03	0.00E+00	1.26E-24	1.76E+03	2.25E+02	0.00E+00	1.13E-01	1.99E+03	8.02E+00
RF-TT0832	3.45E-03	0.00E+00	7.49E-25	1.03E+03	1.32E+02	0.00E+00	5.56E-02	1.16E+03	4.69E+00
RF-TT0854	1.24E-06	0.00E+00	6.83E-28	8.86E-01	1.14E-01	0.00E+00	7.50E-04	1.00E+00	4.03E-03
RF-TT0886	1.76E-07	0.00E+00	9.65E-29	1.26E-01	1.61E-02	0.00E+00	2.58E-06	1.42E-01	5.71E-04
RF-TT2216	5.10E-05	0.00E+00	1.11E-26	1.53E+01	1.94E+00	0.00E+00	8.21E-04	1.72E+01	6.95E-02
RF-TT3010	2.72E-03	0.00E+00	9.79E-25	1.29E+03	1.65E+02	0.00E+00	3.11E-02	1.45E+03	5.86E+00
RF-TT3011	6.88E-03	0.00E+00	2.07E-24	2.69E+03	3.44E+02	0.00E+00	8.82E-02	3.03E+03	1.22E+01

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT301U	5.72E-04	0.00E+00	2.18E-25	2.92E+02	3.80E+01	0.00E+00	5.99E-03	3.30E+02	1.33E+00
RF-TT310P	1.65E-04	0.00E+00	5.68E-26	9.82E+01	1.19E+01	0.00E+00	1.52E-03	1.10E+02	4.44E-01
RF-TT338S	4.83E-06	0.00E+00	2.60E-27	3.39E+00	4.34E-01	0.00E+00	6.95E-05	3.82E+00	1.54E-02
RF-TT390P	2.72E-05	0.00E+00	7.06E-27	1.65E+01	1.94E+00	0.00E+00	2.17E-04	1.84E+01	7.44E-02
RF-TT391P	1.50E-03	0.00E+00	3.17E-25	7.41E+02	9.31E+01	0.00E+00	8.46E-03	8.35E+02	3.37E+00
RF-TT392P	3.03E-03	0.00E+00	1.14E-24	2.22E+03	2.83E+02	0.00E+00	3.05E-02	2.51E+03	1.01E+01
RF-TT393R	4.49E-04	0.00E+00	1.94E-25	3.40E+02	4.36E+01	0.00E+00	5.35E-03	3.83E+02	1.55E+00
RF-TT394P	5.57E-05	0.00E+00	1.20E-26	2.62E+01	3.11E+00	0.00E+00	3.27E-04	2.94E+01	1.18E-01
RF-TT395P	7.46E-05	0.00E+00	1.61E-26	3.51E+01	4.15E+00	0.00E+00	4.38E-04	3.93E+01	1.58E-01
RF-TT396P	1.86E-05	0.00E+00	4.01E-27	8.77E+00	1.04E+00	0.00E+00	1.09E-04	9.81E+00	3.96E-02
RF-TT398P	1.80E-03	0.00E+00	6.94E-25	1.38E+03	1.74E+02	0.00E+00	1.86E-02	1.55E+03	6.25E+00
RF-TT398R	1.49E-02	0.00E+00	1.29E-24	2.22E+03	2.82E+02	0.00E+00	3.45E-02	2.50E+03	1.01E+01
RF-TT411R	5.39E-04	0.00E+00	1.16E-25	2.54E+02	3.21E+01	0.00E+00	3.12E-03	2.86E+02	1.15E+00
RF-TT429R	1.13E-03	0.00E+00	2.49E-26	5.88E+01	7.29E+00	0.00E+00	6.64E-04	6.61E+01	2.66E-01
RF-TT433X	3.56E-04	0.00E+00	6.88E-27	1.69E+01	1.89E+00	0.00E+00	1.84E-04	1.88E+01	7.58E-02
RF-TT436R	2.61E-03	0.00E+00	9.96E-26	2.21E+02	2.79E+01	0.00E+00	2.66E-03	2.49E+02	1.01E+00
RF-TT454X	1.53E-04	0.00E+00	5.86E-27	1.30E+01	1.65E+00	0.00E+00	1.57E-04	1.47E+01	5.92E-02
RL-T101	7.77E-04	0.00E+00	3.56E-25	7.04E+02	8.82E+01	0.00E+00	8.65E-03	7.93E+02	3.20E+00
RL-T102	9.87E-09	0.00E+00	4.53E-30	9.02E-03	1.13E-03	0.00E+00	1.24E-06	1.01E-02	4.09E-05
RL-T103	6.99E-04	0.00E+00	4.31E-25	3.08E+02	3.83E+01	0.00E+00	1.05E-02	3.46E+02	1.39E+00
RL-T104	1.41E-08	0.00E+00	6.46E-30	1.28E-02	1.61E-03	0.00E+00	1.89E-07	1.44E-02	5.81E-05
RL-T105	5.42E-06	0.00E+00	2.44E-27	4.86E+00	6.07E-01	0.00E+00	1.03E-04	5.47E+00	2.21E-02
RL-T106	5.23E-06	0.00E+00	2.40E-27	4.75E+00	5.94E-01	0.00E+00	5.83E-05	5.34E+00	2.16E-02
RL-T107	1.44E-02	0.00E+00	1.41E-21	1.31E+04	1.64E+03	0.00E+00	3.51E+01	1.48E+04	5.97E+01
RL-T108	8.22E-06	0.00E+00	2.43E-25	7.47E+00	9.36E-01	0.00E+00	5.93E-03	8.41E+00	3.39E-02
RL-T109	1.13E-05	0.00E+00	5.00E-27	9.90E+00	1.24E+00	0.00E+00	2.29E-02	1.12E+01	4.50E-02
RL-T110	1.27E-03	0.00E+00	9.54E-25	1.14E+03	1.43E+02	0.00E+00	1.35E+00	1.28E+03	5.16E+00
RL-T112	5.11E-04	0.00E+00	4.04E-25	1.51E+02	1.89E+01	0.00E+00	7.30E-01	1.70E+02	6.86E-01

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T113	5.46E-07	0.00E+00	7.79E-28	4.96E-01	6.21E-02	0.00E+00	1.89E-05	5.58E-01	2.25E-03
RL-T114	8.30E-05	0.00E+00	3.80E-26	7.54E+01	9.45E+00	0.00E+00	9.24E-04	8.48E+01	3.42E-01
RL-T115	2.11E-03	0.00E+00	1.23E-24	9.90E+02	1.24E+02	0.00E+00	4.34E-01	1.12E+03	4.50E+00
RL-T116	1.36E-04	0.00E+00	6.25E-26	1.23E+02	1.55E+01	0.00E+00	5.65E-02	1.39E+02	5.59E-01
RL-T118	3.50E-04	0.00E+00	4.99E-25	1.22E+02	1.53E+01	0.00E+00	8.28E-01	1.39E+02	5.59E-01
RL-T120	8.49E-05	0.00E+00	5.24E-26	3.62E+01	4.50E+00	0.00E+00	1.27E-03	4.07E+01	1.64E-01
RL-T122	4.82E-06	0.00E+00	2.21E-27	4.36E+00	5.49E-01	0.00E+00	1.43E+00	6.34E+00	2.56E-02
RL-T123	1.42E-05	0.00E+00	6.48E-27	1.28E+01	1.61E+00	0.00E+00	5.86E-02	1.45E+01	5.83E-02
RL-T125	2.82E-03	0.00E+00	1.61E-24	2.68E+02	7.74E+01	0.00E+00	3.90E-02	3.46E+02	1.39E+00
RL-T127	2.72E-03	0.00E+00	4.04E-25	8.01E+02	1.00E+02	0.00E+00	8.81E-02	9.01E+02	3.64E+00
RL-T128	4.02E-06	0.00E+00	9.81E-33	1.95E-05	2.43E-06	0.00E+00	2.38E-10	2.59E-05	1.05E-07
RL-T129	1.21E-05	0.00E+00	1.87E-24	1.10E+01	1.37E+00	0.00E+00	5.29E-02	1.25E+01	5.02E-02
RL-T130	2.56E-08	0.00E+00	1.18E-29	2.34E-02	2.93E-03	0.00E+00	8.15E-05	2.64E-02	1.07E-04
RL-T131	1.04E-05	0.00E+00	6.44E-27	4.46E+00	5.53E-01	0.00E+00	8.21E-03	5.02E+00	2.03E-02
RL-T132	2.49E-03	0.00E+00	1.14E-24	2.26E+03	2.83E+02	0.00E+00	2.67E-01	2.55E+03	1.03E+01
RL-T133	5.06E-08	0.00E+00	1.82E-29	3.71E-02	4.64E-03	0.00E+00	4.43E-07	4.17E-02	1.68E-04
RL-T134	1.07E-07	0.00E+00	4.90E-29	9.74E-02	1.22E-02	0.00E+00	1.19E-06	1.10E-01	4.42E-04
RL-T135	5.01E-07	0.00E+00	2.30E-28	4.56E-01	5.71E-02	0.00E+00	4.07E-03	5.17E-01	2.08E-03
RL-T137	8.14E-03	0.00E+00	5.02E-24	3.47E+03	4.32E+02	0.00E+00	1.28E-01	3.90E+03	1.57E+01
RL-T140	9.52E-03	0.00E+00	4.77E-24	3.36E+03	4.64E+02	0.00E+00	2.58E+01	3.85E+03	1.55E+01
RL-T143	5.97E-05	0.00E+00	2.73E-26	5.43E+01	6.79E+00	0.00E+00	3.85E-02	6.11E+01	2.46E-01
RL-T145	1.70E-04	0.00E+00	7.79E-26	1.55E+02	1.93E+01	0.00E+00	8.96E-02	1.74E+02	7.01E-01
RL-W407	4.88E-04	0.00E+00	1.66E-25	3.54E+02	4.44E+01	0.00E+00	4.04E-03	3.99E+02	1.61E+00
RL-W408	2.00E-09	0.00E+00	7.03E-31	1.43E-03	1.80E-04	0.00E+00	1.71E-08	1.61E-03	6.50E-06
RL-W415	4.43E-08	0.00E+00	1.55E-29	3.17E-02	3.97E-03	0.00E+00	3.76E-07	3.57E-02	1.44E-04
RL-W418	1.89E-07	0.00E+00	6.52E-29	1.36E-01	1.71E-02	0.00E+00	1.59E-06	1.53E-01	6.17E-04
RL-W437	1.60E-03	0.00E+00	5.47E-25	1.16E+03	1.45E+02	0.00E+00	1.33E-02	1.31E+03	5.26E+00
RL-W438	2.80E-09	0.00E+00	9.82E-31	2.00E-03	2.51E-04	0.00E+00	2.39E-08	2.26E-03	9.09E-06

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W439	8.78E-02	0.00E+00	5.41E-23	3.86E+04	4.82E+03	0.00E+00	1.31E+00	4.35E+04	1.75E+02
RL-W443	1.41E-03	0.00E+00	4.82E-25	1.02E+03	1.28E+02	0.00E+00	1.17E-02	1.15E+03	4.64E+00
RL-W444	1.05E-03	0.00E+00	3.57E-25	7.58E+02	9.49E+01	0.00E+00	8.68E-03	8.53E+02	3.44E+00
RL-W447	1.20E-07	0.00E+00	4.21E-29	8.53E-02	1.08E-02	0.00E+00	1.02E-06	9.61E-02	3.87E-04
RL-W448	8.87E-10	0.00E+00	3.11E-31	6.34E-04	7.92E-05	0.00E+00	7.56E-09	7.13E-04	2.87E-06
RL-W449	7.28E-06	0.00E+00	1.14E-29	1.81E-02	2.27E-03	0.00E+00	2.77E-07	2.04E-02	8.22E-05
RL-W450	1.34E-08	0.00E+00	4.69E-30	9.58E-03	1.20E-03	0.00E+00	1.14E-07	1.08E-02	4.35E-05
RL-W451	1.91E-09	0.00E+00	6.68E-31	1.36E-03	1.71E-04	0.00E+00	1.62E-08	1.53E-03	6.17E-06
RL-W452	8.30E-08	0.00E+00	2.88E-29	6.00E-02	7.51E-03	0.00E+00	6.99E-07	6.75E-02	2.72E-04
RL-W453	2.37E-08	0.00E+00	8.10E-30	1.72E-02	2.15E-03	0.00E+00	1.97E-07	1.94E-02	7.81E-05
RL-W454	3.31E-07	0.00E+00	1.13E-28	2.41E-01	3.01E-02	0.00E+00	2.75E-06	2.71E-01	1.09E-03
RL-W455	8.84E-08	0.00E+00	3.05E-29	6.37E-02	7.96E-03	0.00E+00	7.42E-07	7.16E-02	2.89E-04
RL-W456	1.16E-05	0.00E+00	3.99E-27	8.45E+00	1.06E+00	0.00E+00	9.70E-05	9.51E+00	3.84E-02
RL-W457	1.13E-06	0.00E+00	3.88E-28	8.21E-01	1.03E-01	0.00E+00	9.42E-06	9.24E-01	3.72E-03
RL-W458	3.58E-06	0.00E+00	1.98E-27	3.37E-01	1.05E-01	0.00E+00	4.81E-05	4.43E-01	1.79E-03
RL-W459	3.44E-05	0.00E+00	2.04E-26	8.37E+00	1.44E+00	0.00E+00	4.96E-04	9.81E+00	3.96E-02
RL-W460	2.10E-07	0.00E+00	7.17E-29	1.52E-01	1.91E-02	0.00E+00	1.74E-06	1.71E-01	6.90E-04
RL-W461	1.94E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.94E-07	7.81E-10
RL-W462	5.99E-08	0.00E+00	2.08E-29	4.31E-02	5.40E-03	0.00E+00	5.06E-07	4.85E-02	1.95E-04
RL-W463	3.08E-07	0.00E+00	1.05E-28	2.24E-01	2.80E-02	0.00E+00	2.56E-06	2.52E-01	1.02E-03
RL-W464	1.42E-07	0.00E+00	4.84E-29	1.03E-01	1.29E-02	0.00E+00	1.18E-06	1.16E-01	4.67E-04
RL-W465	9.49E-07	0.00E+00	3.28E-28	6.86E-01	8.59E-02	0.00E+00	7.98E-06	7.72E-01	3.11E-03
RL-W466	1.30E-05	0.00E+00	4.47E-27	9.42E+00	1.18E+00	0.00E+00	1.09E-04	1.06E+01	4.27E-02
RL-W467	6.66E-07	0.00E+00	2.30E-28	4.80E-01	5.98E-02	0.00E+00	5.59E-06	5.40E-01	2.18E-03
RL-W468	3.41E-09	0.00E+00	1.18E-30	2.46E-03	3.07E-04	0.00E+00	2.88E-08	2.76E-03	1.11E-05
RL-W469	1.38E-06	0.00E+00	4.76E-28	9.98E-01	1.26E-01	0.00E+00	1.16E-05	1.12E+00	4.53E-03
RL-W470	3.91E-05	0.00E+00	2.21E-26	3.70E+00	1.07E+00	0.00E+00	5.38E-04	4.77E+00	1.93E-02
RL-W474	1.48E-06	0.00E+00	2.44E-27	8.45E-03	4.05E-03	0.00E+00	5.94E-05	1.26E-02	5.07E-05

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W476	2.50E-06	0.00E+00	8.79E-28	1.85E+00	2.33E-01	0.00E+00	2.14E-05	2.08E+00	8.40E-03
RL-W480	4.08E-07	0.00E+00	1.41E-28	2.94E-01	3.69E-02	0.00E+00	3.42E-06	3.31E-01	1.33E-03
RL-W481	6.41E-07	0.00E+00	2.21E-28	4.61E-01	5.76E-02	0.00E+00	5.38E-06	5.19E-01	2.09E-03
RL-W482	8.51E-04	0.00E+00	7.36E-26	5.87E-02	6.12E-02	0.00E+00	1.79E-03	1.23E-01	4.94E-04
RL-W483	6.35E-05	0.00E+00	5.71E-27	3.80E-03	4.35E-03	0.00E+00	1.39E-04	8.35E-03	3.37E-05
RL-W484	2.69E-07	0.00E+00	4.60E-29	5.31E-02	7.11E-03	0.00E+00	1.12E-06	6.02E-02	2.43E-04
RL-W485	1.57E-08	0.00E+00	6.51E-30	5.74E-03	7.69E-04	0.00E+00	1.58E-07	6.51E-03	2.63E-05
RL-W486	6.65E-09	0.00E+00	2.75E-30	2.42E-03	3.24E-04	0.00E+00	6.68E-08	2.75E-03	1.11E-05
RL-W487	1.09E-06	0.00E+00	3.53E-28	3.47E-01	5.36E-02	0.00E+00	8.57E-06	4.01E-01	1.62E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	6.60E-07	0.00E+00	3.33E-28	4.49E-01	5.71E-02	0.00E+00	8.08E-06	5.06E-01	2.04E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	2.45E-07	0.00E+00	2.81E-28	4.71E-02	5.80E-03	0.00E+00	6.82E-06	5.29E-02	2.13E-04
RL-W492	1.41E-08	0.00E+00	6.91E-30	9.42E-03	1.19E-03	0.00E+00	1.68E-07	1.06E-02	4.28E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	5.60E-04	0.00E+00	4.01E-25	2.38E-01	1.14E-01	0.00E+00	9.73E-03	3.62E-01	1.46E-03
RL-W495	1.01E-05	0.00E+00	1.09E-27	2.28E-03	1.02E-03	0.00E+00	2.65E-05	3.33E-03	1.34E-05
RL-W496	6.58E-05	0.00E+00	1.25E-26	7.49E-03	3.37E-03	0.00E+00	3.05E-04	1.12E-02	4.53E-05
RL-W497	2.74E-06	0.00E+00	2.47E-27	4.49E-01	1.14E-01	0.00E+00	6.01E-05	5.64E-01	2.27E-03
RL-W498	1.06E-05	0.00E+00	3.67E-27	7.68E+00	9.63E-01	0.00E+00	8.93E-05	8.64E+00	3.49E-02
RL-W499	9.55E-11	0.00E+00	3.30E-32	6.88E-05	8.64E-06	0.00E+00	8.01E-10	7.75E-05	3.12E-07
RL-W500	6.80E-09	0.00E+00	4.09E-30	2.81E-03	3.50E-04	0.00E+00	9.95E-08	3.16E-03	1.27E-05
RL-W501	2.82E-04	0.00E+00	9.13E-26	9.02E+01	1.39E+01	0.00E+00	2.22E-03	1.04E+02	4.19E-01
RL-W502	5.09E-08	0.00E+00	1.76E-29	3.67E-02	4.59E-03	0.00E+00	4.29E-07	4.13E-02	1.67E-04
RL-W503	2.94E-06	0.00E+00	1.81E-27	1.30E+00	1.61E-01	0.00E+00	4.39E-05	1.46E+00	5.88E-03
RL-W504	1.09E-06	0.00E+00	3.53E-28	3.47E-01	5.36E-02	0.00E+00	8.57E-06	4.01E-01	1.62E-03
RL-W505	5.11E-08	0.00E+00	1.85E-29	3.75E-02	4.68E-03	0.00E+00	4.50E-07	4.22E-02	1.70E-04
RL-W506	1.85E-08	0.00E+00	7.27E-30	1.23E-02	1.54E-03	0.00E+00	1.77E-07	1.39E-02	5.59E-05

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W507	1.84E-09	0.00E+00	6.36E-31	1.33E-03	1.66E-04	0.00E+00	1.55E-08	1.49E-03	6.03E-06
RL-W508	3.38E-05	0.00E+00	2.08E-26	1.44E+01	1.80E+00	0.00E+00	5.06E-04	1.62E+01	6.53E-02
RL-W509	3.33E-04	0.00E+00	1.66E-25	1.18E+02	1.62E+01	0.00E+00	4.04E-03	1.34E+02	5.39E-01
RL-W510	2.81E-05	0.00E+00	1.71E-26	1.17E+01	1.45E+00	0.00E+00	4.15E-04	1.31E+01	5.29E-02
RL-W511	2.86E-03	0.00E+00	8.23E-25	1.56E+03	1.92E+02	0.00E+00	2.03E-02	1.75E+03	7.07E+00
RL-W512	2.50E-03	0.00E+00	5.55E-25	9.42E+02	1.31E+02	0.00E+00	1.35E-02	1.07E+03	4.33E+00
RL-W513	2.67E-01	0.00E+00	2.26E-22	1.54E+04	4.28E+03	0.00E+00	5.48E+00	1.97E+04	7.93E+01
RL-W514	7.53E-09	0.00E+00	2.59E-30	5.45E-03	6.84E-04	0.00E+00	6.29E-08	6.13E-03	2.47E-05
RL-W515	2.94E-07	0.00E+00	1.02E-28	2.13E-01	2.66E-02	0.00E+00	2.47E-06	2.39E-01	9.64E-04
RL-W516	4.08E-07	0.00E+00	1.41E-28	2.94E-01	3.69E-02	0.00E+00	3.43E-06	3.31E-01	1.33E-03
RL-W517	3.64E-15	0.00E+00	1.26E-36	2.62E-09	3.27E-10	0.00E+00	3.06E-14	2.94E-09	1.19E-11
RL-W518	1.03E-05	0.00E+00	5.31E-27	3.75E+00	5.09E-01	0.00E+00	1.29E-04	4.26E+00	1.72E-02
RL-W519	1.83E-06	0.00E+00	6.29E-28	1.33E+00	1.66E-01	0.00E+00	1.53E-05	1.49E+00	6.03E-03
RL-W520	2.03E-07	0.00E+00	7.09E-29	1.46E-01	1.82E-02	0.00E+00	1.72E-06	1.64E-01	6.61E-04
RL-W521	3.77E-09	0.00E+00	1.30E-30	2.71E-03	3.40E-04	0.00E+00	3.16E-08	3.05E-03	1.23E-05
RL-W522	7.88E-05	0.00E+00	4.83E-26	1.80E+01	2.88E+00	0.00E+00	1.17E-03	2.08E+01	8.40E-02
RL-W523	2.37E-05	0.00E+00	1.84E-26	1.19E+00	4.06E-01	0.00E+00	4.46E-04	1.60E+00	6.44E-03
RL-W524	9.81E-05	0.00E+00	7.03E-26	1.10E+01	2.38E+00	0.00E+00	1.71E-03	1.33E+01	5.38E-02
RL-W525	7.80E-06	0.00E+00	4.76E-27	1.30E+00	2.41E-01	0.00E+00	1.16E-04	1.54E+00	6.20E-03
RL-W526	2.95E-05	0.00E+00	1.72E-26	1.39E+01	1.74E+00	0.00E+00	4.18E-04	1.56E+01	6.28E-02
RL-W527	3.24E-06	0.00E+00	2.49E-27	1.47E+00	1.95E-01	0.00E+00	6.04E-05	1.66E+00	6.70E-03
RL-W528	1.45E-03	0.00E+00	1.06E-24	4.67E+01	2.51E+01	0.00E+00	2.57E-02	7.18E+01	2.90E-01
RL-W529	1.21E-06	0.00E+00	7.43E-28	5.15E-01	6.39E-02	0.00E+00	1.81E-05	5.79E-01	2.34E-03
RL-W530	1.42E-05	0.00E+00	8.62E-27	5.88E+00	7.33E-01	0.00E+00	2.09E-04	6.62E+00	2.67E-02
RL-W531	8.48E-04	0.00E+00	8.65E-25	2.54E+01	1.03E+01	0.00E+00	2.10E-02	3.58E+01	1.44E-01
RL-W532	2.72E-06	0.00E+00	9.40E-28	1.96E+00	2.46E-01	0.00E+00	2.28E-05	2.21E+00	8.91E-03
RL-W533	1.32E-06	0.00E+00	8.11E-28	5.62E-01	6.97E-02	0.00E+00	1.97E-05	6.32E-01	2.55E-03
RL-W534	7.60E-11	0.00E+00	2.62E-32	5.48E-05	6.88E-06	0.00E+00	6.36E-10	6.17E-05	2.49E-07

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W535	3.98E-04	0.00E+00	2.59E-25	7.03E+01	1.21E+01	0.00E+00	6.29E-03	8.23E+01	3.32E-01
RL-W536	7.79E-06	0.00E+00	3.49E-27	2.44E+00	3.11E-01	0.00E+00	8.78E-05	2.75E+00	1.11E-02
RL-W537	2.65E-04	0.00E+00	7.87E-26	1.50E+02	1.85E+01	0.00E+00	1.94E-03	1.68E+02	6.78E-01
RL-W538	9.65E-10	0.00E+00	3.33E-31	6.96E-04	8.73E-05	0.00E+00	8.08E-09	7.84E-04	3.16E-06
RL-W539	1.07E-07	0.00E+00	3.75E-29	7.70E-02	9.63E-03	0.00E+00	9.10E-07	8.66E-02	3.49E-04
RL-W540	2.09E-04	0.00E+00	1.65E-25	2.77E+01	5.36E+00	0.00E+00	4.01E-03	3.31E+01	1.33E-01
RL-W541	3.10E-07	0.00E+00	1.08E-28	2.23E-01	2.79E-02	0.00E+00	2.63E-06	2.51E-01	1.01E-03
RL-W542	1.44E-05	0.00E+00	8.03E-27	5.64E+00	7.33E-01	0.00E+00	1.95E-04	6.38E+00	2.57E-02
RL-W543	4.53E-08	0.00E+00	1.56E-29	3.27E-02	4.10E-03	0.00E+00	3.80E-07	3.68E-02	1.48E-04
RL-W544	1.02E-06	0.00E+00	6.38E-28	3.72E-01	5.22E-02	0.00E+00	1.55E-05	4.24E-01	1.71E-03
RL-W545	2.72E-07	0.00E+00	9.37E-29	1.96E-01	2.45E-02	0.00E+00	2.28E-06	2.20E-01	8.88E-04
RL-W546	1.19E-08	0.00E+00	4.11E-30	8.61E-03	1.08E-03	0.00E+00	9.98E-08	9.69E-03	3.91E-05
RL-W547	3.04E-10	0.00E+00	1.05E-31	2.19E-04	2.75E-05	0.00E+00	2.55E-09	2.46E-04	9.94E-07
RL-W548	2.63E-10	0.00E+00	9.11E-32	1.89E-04	2.37E-05	0.00E+00	2.21E-09	2.13E-04	8.58E-07
RL-W549	5.22E-05	0.00E+00	3.66E-26	9.74E+00	1.63E+00	0.00E+00	8.89E-04	1.14E+01	4.59E-02
RL-W550	2.37E-04	0.00E+00	6.93E-26	1.32E+02	1.63E+01	0.00E+00	1.70E-03	1.48E+02	5.98E-01
RL-W551	4.21E-04	0.00E+00	1.02E-25	1.49E+02	2.12E+01	0.00E+00	2.49E-03	1.70E+02	6.86E-01
RL-W552	1.63E-07	0.00E+00	5.67E-29	1.18E-01	1.47E-02	0.00E+00	1.38E-06	1.32E-01	5.33E-04
RL-W553	1.45E-08	0.00E+00	5.35E-30	1.05E-02	1.31E-03	0.00E+00	1.30E-07	1.18E-02	4.75E-05
RL-W554	2.30E-07	0.00E+00	7.94E-29	1.66E-01	2.08E-02	0.00E+00	1.93E-06	1.87E-01	7.53E-04
RL-W555	1.06E-07	0.00E+00	3.66E-29	7.64E-02	9.54E-03	0.00E+00	8.89E-07	8.59E-02	3.47E-04
RL-W563	1.52E-06	0.00E+00	9.15E-28	6.34E-01	7.87E-02	0.00E+00	2.22E-05	7.12E-01	2.87E-03
RL-W564	9.89E-07	0.00E+00	6.07E-28	4.10E-01	5.09E-02	0.00E+00	1.48E-05	4.61E-01	1.86E-03
RL-W565	9.82E-08	0.00E+00	3.41E-29	7.08E-02	8.86E-03	0.00E+00	8.29E-07	7.96E-02	3.21E-04
RL-W566	1.44E-06	0.00E+00	5.00E-28	1.04E+00	1.31E-01	0.00E+00	1.22E-05	1.17E+00	4.71E-03
RL-W567	9.99E-05	0.00E+00	1.28E-26	3.20E-02	1.45E-02	0.00E+00	3.11E-04	4.69E-02	1.89E-04
RL-W568	1.92E-03	0.00E+00	2.69E-25	1.51E+00	6.75E-01	0.00E+00	6.54E-03	2.20E+00	8.86E-03
RL-W569	1.58E-06	0.00E+00	2.03E-28	5.05E-04	2.30E-05	0.00E+00	4.92E-06	5.34E-04	2.15E-06

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W570	1.01E-07	0.00E+00	3.54E-29	7.50E-02	9.36E-03	0.00E+00	8.61E-07	8.44E-02	3.40E-04
RL-W571	3.25E-04	0.00E+00	1.20E-25	6.09E+00	1.71E+00	0.00E+00	2.92E-03	7.80E+00	3.15E-02
RL-W572	2.82E-07	0.00E+00	3.60E-29	3.28E-03	4.10E-05	0.00E+00	8.75E-07	3.32E-03	1.34E-05
RL-W573	3.63E-03	0.00E+00	4.61E-25	1.80E+00	7.56E-01	0.00E+00	1.12E-02	2.57E+00	1.04E-02
RL-W574	1.56E-02	0.00E+00	2.00E-24	6.86E+00	2.80E+00	0.00E+00	4.85E-02	9.72E+00	3.92E-02
RL-W575	1.02E-01	0.00E+00	1.34E-23	6.56E+01	2.24E+01	0.00E+00	3.27E-01	8.84E+01	3.56E-01
RL-W576	7.33E-03	0.00E+00	9.39E-25	3.34E+00	1.35E+00	0.00E+00	2.28E-02	4.72E+00	1.90E-02
RL-W579	6.21E-07	0.00E+00	2.47E-29	1.67E-02	2.10E-03	0.00E+00	6.01E-07	1.89E-02	7.60E-05
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.34E-01	1.22E-02	0.00E+00	0.00E+00	1.46E-01	5.88E-04
RL-W581	6.59E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.59E-06	2.66E-08
RL-W582	4.31E-08	0.00E+00	2.10E-29	4.28E-03	1.25E-03	0.00E+00	5.10E-07	5.53E-03	2.23E-05
RL-W583	3.33E-08	0.00E+00	1.14E-29	2.42E-02	3.03E-03	0.00E+00	2.77E-07	2.72E-02	1.10E-04
RL-W584	6.62E-07	0.00E+00	7.48E-28	1.41E-01	3.88E-02	0.00E+00	1.82E-05	1.80E-01	7.25E-04
RL-W585	3.94E-06	0.00E+00	3.98E-27	8.21E-01	2.36E-01	0.00E+00	9.66E-05	1.06E+00	4.26E-03
RL-W586	5.26E-10	0.00E+00	1.79E-31	3.82E-04	4.77E-05	0.00E+00	4.36E-09	4.29E-04	1.73E-06
RL-W587	1.13E-08	0.00E+00	3.88E-30	8.13E-03	1.02E-03	0.00E+00	9.42E-08	9.15E-03	3.69E-05
RL-W588	4.64E-07	0.00E+00	6.31E-28	1.19E-01	3.27E-02	0.00E+00	1.53E-05	1.52E-01	6.12E-04
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	1.43E-05	0.00E+00	1.35E-26	9.18E-03	9.18E-03	0.00E+00	3.27E-04	1.87E-02	7.54E-05
RL-W591	8.12E-05	0.00E+00	1.52E-26	1.14E-02	1.19E-02	0.00E+00	3.69E-04	2.37E-02	9.55E-05
RL-W592	3.59E-04	0.00E+00	1.66E-25	5.27E-01	3.84E-01	0.00E+00	4.04E-03	9.15E-01	3.69E-03
RL-W593	0.00E+00	0.00E+00	0.00E+00	1.90E-02	1.80E-02	0.00E+00	0.00E+00	3.70E-02	1.49E-04
RL-W594	3.23E-04	0.00E+00	2.99E-26	2.35E-02	2.44E-02	0.00E+00	7.27E-04	4.89E-02	1.97E-04
RL-W595	8.54E-07	0.00E+00	3.12E-27	1.61E-02	1.77E-02	0.00E+00	7.59E-05	3.39E-02	1.37E-04
RL-W596	2.76E-07	0.00E+00	2.43E-28	1.66E-04	1.67E-04	0.00E+00	5.90E-06	3.39E-04	1.37E-06
RL-W597	5.08E-04	0.00E+00	1.07E-25	3.21E-01	3.02E-01	0.00E+00	2.60E-03	6.26E-01	2.53E-03
RL-W598	5.37E-04	0.00E+00	6.31E-25	4.48E-01	3.77E-01	0.00E+00	1.53E-02	8.40E-01	3.39E-03
RL-W599	2.72E-05	0.00E+00	5.09E-27	3.78E-03	3.97E-03	0.00E+00	1.24E-04	7.90E-03	3.19E-05

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W600	1.55E-12	0.00E+00	5.28E-34	1.12E-06	1.40E-07	0.00E+00	1.28E-11	1.26E-06	5.08E-09
RL-W601	7.84E-09	0.00E+00	2.89E-30	5.67E-03	7.11E-04	0.00E+00	7.03E-08	6.38E-03	2.57E-05
RL-W602	6.83E-06	0.00E+00	2.37E-27	4.91E+00	6.16E-01	0.00E+00	5.76E-05	5.53E+00	2.23E-02
RL-W603	3.93E-05	0.00E+00	1.37E-26	2.83E+01	3.55E+00	0.00E+00	3.32E-04	3.19E+01	1.29E-01
RL-W604	9.20E-08	0.00E+00	3.59E-29	1.38E-02	3.83E-03	0.00E+00	8.72E-07	1.76E-02	7.09E-05
RL-W605	2.11E-08	0.00E+00	7.79E-30	1.52E-02	1.91E-03	0.00E+00	1.89E-07	1.71E-02	6.90E-05
RL-W606	8.51E-09	0.00E+00	3.14E-30	6.13E-03	7.69E-04	0.00E+00	7.63E-08	6.90E-03	2.78E-05
RL-W607	1.56E-08	0.00E+00	6.07E-30	2.33E-03	6.48E-04	0.00E+00	1.48E-07	2.97E-03	1.20E-05
RL-W608	1.86E-07	0.00E+00	2.36E-28	3.03E-03	2.10E-03	0.00E+00	5.73E-06	5.13E-03	2.07E-05
RL-W610	3.69E-05	0.00E+00	1.26E-26	2.67E+01	3.35E+00	0.00E+00	3.06E-04	3.01E+01	1.21E-01
RL-W612	8.70E-08	0.00E+00	3.05E-29	6.49E-02	8.14E-03	0.00E+00	7.42E-07	7.30E-02	2.95E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	2.72E-01	0.00E+00	0.00E+00	0.00E+00	2.72E-01	1.10E-03
RL-W622	1.45E-09	0.00E+00	4.98E-31	1.06E-03	1.32E-04	0.00E+00	1.21E-08	1.19E-03	4.78E-06
RL-W625	5.06E-08	0.00E+00	7.56E-29	5.39E-03	2.98E-03	0.00E+00	1.84E-06	8.37E-03	3.37E-05
RL-W626	2.72E-06	0.00E+00	1.72E-27	2.11E-01	7.11E-02	0.00E+00	4.18E-05	2.82E-01	1.14E-03
RL-W627	1.28E-08	0.00E+00	2.30E-30	9.98E-07	0.00E+00	0.00E+00	5.59E-08	1.07E-06	4.30E-09
RL-W628	4.20E-09	0.00E+00	1.45E-30	3.04E-03	3.81E-04	0.00E+00	3.51E-08	3.42E-03	1.38E-05
RL-W629	2.84E-10	0.00E+00	9.94E-32	2.05E-04	2.56E-05	0.00E+00	2.41E-09	2.30E-04	9.28E-07
RL-W630	3.13E-06	0.00E+00	1.85E-27	2.37E+00	3.08E-01	0.00E+00	4.50E-05	2.68E+00	1.08E-02
RL-W631	5.04E-08	0.00E+00	1.87E-29	3.63E-02	4.55E-03	0.00E+00	4.53E-07	4.09E-02	1.65E-04
RL-W632	2.23E-05	0.00E+00	2.52E-27	4.80E+00	8.86E-01	0.00E+00	6.12E-05	5.68E+00	2.29E-02
RL-W633	5.31E-08	0.00E+00	1.46E-29	7.54E-04	3.74E-04	0.00E+00	3.55E-07	1.13E-03	4.55E-06
RL-W634	0.00E+00	0.00E+00	0.00E+00	8.21E-03	0.00E+00	0.00E+00	0.00E+00	8.21E-03	3.31E-05
RL-W635	3.17E-04	0.00E+00	4.93E-25	3.49E+00	2.94E+00	0.00E+00	1.20E-02	6.44E+00	2.60E-02
RL-W636	3.24E-06	0.00E+00	9.31E-28	4.56E-02	2.27E-02	0.00E+00	2.26E-05	6.84E-02	2.76E-04
RL-W637	7.69E-09	0.00E+00	2.37E-29	5.14E-04	2.84E-04	0.00E+00	5.76E-07	7.98E-04	3.22E-06
RL-W638	3.38E-07	0.00E+00	2.42E-28	5.03E-03	2.66E-03	0.00E+00	5.87E-06	7.70E-03	3.11E-05
RL-W639	1.79E-08	0.00E+00	6.18E-30	1.29E-02	1.61E-03	0.00E+00	1.50E-07	1.45E-02	5.84E-05

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W640	6.00E-07	0.00E+00	2.05E-28	4.34E-01	5.45E-02	0.00E+00	4.99E-06	4.88E-01	1.97E-03
RL-W641	1.83E-05	0.00E+00	4.51E-26	2.09E+00	4.82E-01	0.00E+00	1.10E-03	2.57E+00	1.04E-02
RL-W642	3.57E-07	0.00E+00	4.69E-30	2.54E-02	7.29E-05	0.00E+00	1.14E-07	2.55E-02	1.03E-04
RL-W643	5.63E-06	0.00E+00	1.39E-26	6.42E-01	1.49E-01	0.00E+00	3.38E-04	7.91E-01	3.19E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	4.42E-02	0.00E+00	0.00E+00	0.00E+00	4.42E-02	1.78E-04
RL-W645	1.37E-07	0.00E+00	6.25E-29	8.69E-02	1.15E-02	0.00E+00	1.52E-06	9.84E-02	3.97E-04
RL-W646	1.24E-07	0.00E+00	5.58E-29	2.08E-02	5.67E-03	0.00E+00	1.36E-06	2.64E-02	1.07E-04
RL-W647	3.50E-07	0.00E+00	8.34E-27	8.86E-02	7.87E-03	0.00E+00	2.03E-04	9.66E-02	3.90E-04
RL-W648	6.20E-09	0.00E+00	1.43E-29	4.84E-05	5.36E-05	0.00E+00	3.47E-07	1.02E-04	4.12E-07
RL-W649	2.28E-08	0.00E+00	5.25E-29	1.78E-04	1.97E-04	0.00E+00	1.28E-06	3.76E-04	1.52E-06
RL-W653	1.08E-09	0.00E+00	3.76E-31	7.78E-04	9.72E-05	0.00E+00	9.14E-09	8.75E-04	3.53E-06
RL-W654	5.94E-09	0.00E+00	2.05E-30	4.28E-03	5.36E-04	0.00E+00	4.99E-08	4.82E-03	1.94E-05
RL-W655	1.46E-03	0.00E+00	4.86E-25	1.70E-01	2.25E-01	0.00E+00	1.18E-02	4.09E-01	1.65E-03
RL-W656	6.12E-03	0.00E+00	2.18E-25	3.99E-01	2.32E-01	0.00E+00	5.31E-03	6.42E-01	2.59E-03
RL-W657	3.13E-03	0.00E+00	3.23E-25	1.96E-01	2.21E-01	0.00E+00	7.84E-03	4.28E-01	1.73E-03
RL-W659	3.78E-04	0.00E+00	7.27E-26	3.78E-02	2.64E-02	0.00E+00	1.77E-03	6.64E-02	2.68E-04
RL-W660	2.07E-03	0.00E+00	8.75E-25	6.98E-01	7.02E-01	0.00E+00	2.13E-02	1.42E+00	5.74E-03
RL-W661	2.20E-05	0.00E+00	1.10E-27	3.37E-04	1.72E-03	0.00E+00	2.66E-05	2.11E-03	8.50E-06
RL-W662	6.91E-07	0.00E+00	6.52E-29	8.61E-05	8.68E-05	0.00E+00	1.59E-06	1.75E-04	7.07E-07
RL-W665	8.49E-03	0.00E+00	5.22E-24	1.06E+00	7.96E-01	0.00E+00	1.27E-01	1.99E+00	8.01E-03
RL-W666	1.52E-04	0.00E+00	1.28E-26	4.42E-02	2.62E-02	0.00E+00	3.11E-04	7.08E-02	2.86E-04
RL-W668	1.45E-05	0.00E+00	4.02E-28	1.17E-01	1.86E-02	0.00E+00	9.77E-06	1.35E-01	5.46E-04
RL-W669	4.22E-06	0.00E+00	1.04E-26	4.81E-01	1.11E-01	0.00E+00	2.53E-04	5.93E-01	2.39E-03
RL-W670	2.67E-07	0.00E+00	7.42E-30	2.16E-03	3.45E-04	0.00E+00	1.80E-07	2.50E-03	1.01E-05
RL-W671	4.35E-05	0.00E+00	3.80E-27	3.95E-03	2.31E-03	0.00E+00	9.24E-05	6.40E-03	2.58E-05
RL-W672	2.96E-04	0.00E+00	2.59E-26	2.70E-02	1.57E-02	0.00E+00	6.29E-04	4.36E-02	1.76E-04
RL-W673	2.85E-04	0.00E+00	2.49E-26	2.61E-02	1.52E-02	0.00E+00	6.04E-04	4.21E-02	1.70E-04
RL-W674	9.57E-07	0.00E+00	1.11E-27	9.02E+00	4.41E-02	0.00E+00	2.70E-05	9.06E+00	3.65E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W675	3.58E-06	0.00E+00	6.15E-27	1.06E-01	5.13E-02	0.00E+00	1.49E-04	1.57E-01	6.33E-04
RL-W676	1.37E-07	0.00E+00	3.69E-29	1.18E-01	9.67E-04	0.00E+00	8.96E-07	1.19E-01	4.81E-04
RL-W677	3.18E-04	0.00E+00	9.14E-26	4.62E+00	2.26E+00	0.00E+00	2.22E-03	6.88E+00	2.78E-02
RL-W678	1.01E-06	0.00E+00	7.64E-28	4.15E-02	2.06E-02	0.00E+00	1.86E-05	6.22E-02	2.51E-04
RL-W679	6.31E-06	0.00E+00	1.71E-27	8.94E-02	4.44E-02	0.00E+00	4.15E-05	1.34E-01	5.39E-04
RL-W680	1.42E-09	0.00E+00	2.40E-30	1.40E-05	1.42E-05	0.00E+00	5.83E-08	2.82E-05	1.14E-07
RL-W681	8.68E-10	0.00E+00	9.73E-31	3.76E-04	1.05E-04	0.00E+00	2.37E-08	4.81E-04	1.94E-06
RL-W685	2.53E-06	0.00E+00	8.65E-28	1.84E+00	2.30E-01	0.00E+00	2.10E-05	2.07E+00	8.33E-03
RL-W689	6.55E-08	0.00E+00	1.04E-29	3.12E-04	0.00E+00	0.00E+00	2.52E-07	3.12E-04	1.26E-06
RL-W690	2.20E-06	0.00E+00	7.64E-28	1.63E+00	2.04E-01	0.00E+00	1.86E-05	1.84E+00	7.41E-03
RL-W691	5.10E-08	0.00E+00	1.78E-29	3.78E-02	4.73E-03	0.00E+00	4.32E-07	4.26E-02	1.72E-04
RL-W692	2.02E-06	0.00E+00	7.04E-28	1.50E+00	1.87E-01	0.00E+00	1.71E-05	1.68E+00	6.79E-03
RL-W693	2.50E-06	0.00E+00	8.69E-28	1.85E+00	2.32E-01	0.00E+00	2.11E-05	2.08E+00	8.40E-03
RL-W694	2.62E-05	0.00E+00	9.13E-27	1.96E+01	2.43E+00	0.00E+00	2.22E-04	2.20E+01	8.87E-02
RL-W695	2.17E-08	0.00E+00	0.00E+00	1.92E-03	0.00E+00	0.00E+00	0.00E+00	1.92E-03	7.76E-06
RL-W696	2.83E-08	0.00E+00	3.33E-29	2.34E-03	1.30E-03	0.00E+00	8.08E-07	3.64E-03	1.47E-05
RL-W697	6.53E-06	0.00E+00	7.04E-26	5.58E-03	4.31E-04	0.00E+00	1.71E-03	7.73E-03	3.12E-05
RL-W698	5.66E-07	0.00E+00	0.00E+00	2.65E-05	0.00E+00	0.00E+00	0.00E+00	2.71E-05	1.09E-07
RL-W699	1.26E-07	0.00E+00	4.69E-30	1.77E-03	1.17E-04	0.00E+00	1.14E-07	1.89E-03	7.61E-06
RL-W700	3.57E-08	0.00E+00	1.23E-29	2.57E-02	3.22E-03	0.00E+00	2.99E-07	2.89E-02	1.17E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	1.41E-06	0.00E+00	3.47E-27	1.60E-01	3.71E-02	0.00E+00	8.43E-05	1.97E-01	7.96E-04
RL-W705	9.09E-09	0.00E+00	3.20E-30	6.73E-03	8.46E-04	0.00E+00	7.77E-08	7.58E-03	3.06E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	3.24E-07	0.00E+00	1.14E-28	2.40E-01	3.01E-02	0.00E+00	2.76E-06	2.70E-01	1.09E-03
RL-W708	4.90E-08	0.00E+00	1.72E-29	3.64E-02	4.55E-03	0.00E+00	4.18E-07	4.09E-02	1.65E-04
RL-W709	1.70E-05	0.00E+00	5.93E-27	1.26E+01	1.57E+00	0.00E+00	1.44E-04	1.41E+01	5.70E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W710	1.01E-09	0.00E+00	3.54E-31	7.50E-04	9.36E-05	0.00E+00	8.61E-09	8.44E-04	3.40E-06
RL-W711	3.16E-07	0.00E+00	1.11E-28	2.34E-01	2.93E-02	0.00E+00	2.69E-06	2.64E-01	1.06E-03
RL-W712	4.09E-07	0.00E+00	1.43E-28	3.03E-01	3.79E-02	0.00E+00	3.48E-06	3.41E-01	1.37E-03
RL-W713	3.53E-07	0.00E+00	1.24E-28	2.61E-01	3.28E-02	0.00E+00	3.01E-06	2.94E-01	1.18E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	6.09E-09	0.00E+00	2.08E-30	4.42E-03	5.53E-04	0.00E+00	5.06E-08	4.97E-03	2.01E-05
RL-W716	6.35E-08	0.00E+00	2.17E-29	4.60E-02	5.76E-03	0.00E+00	5.27E-07	5.18E-02	2.09E-04
RL-W717	1.58E-08	0.00E+00	5.42E-30	1.15E-02	1.44E-03	0.00E+00	1.32E-07	1.30E-02	5.22E-05
RL-W718	2.80E-09	0.00E+00	9.56E-31	2.03E-03	2.54E-04	0.00E+00	2.32E-08	2.28E-03	9.20E-06
RL-W719	1.26E-08	0.00E+00	4.31E-30	9.18E-03	1.15E-03	0.00E+00	1.05E-07	1.03E-02	4.16E-05
RL-W720	7.81E-08	0.00E+00	2.68E-29	5.67E-02	7.11E-03	0.00E+00	6.50E-07	6.38E-02	2.57E-04
RL-W721	5.29E-08	0.00E+00	1.81E-29	3.83E-02	4.82E-03	0.00E+00	4.39E-07	4.31E-02	1.74E-04
RL-W723	1.75E-07	0.00E+00	6.10E-29	1.30E-01	1.63E-02	0.00E+00	1.48E-06	1.47E-01	5.92E-04
RL-W724	1.17E-06	0.00E+00	4.06E-28	8.61E-01	1.08E-01	0.00E+00	9.88E-06	9.70E-01	3.91E-03
RL-W725	3.68E-07	0.00E+00	1.28E-28	2.73E-01	3.42E-02	0.00E+00	3.11E-06	3.07E-01	1.24E-03
RL-W726	2.90E-07	0.00E+00	1.01E-28	2.16E-01	2.70E-02	0.00E+00	2.46E-06	2.43E-01	9.79E-04
RL-W727	1.78E-06	0.00E+00	6.20E-28	1.32E+00	1.66E-01	0.00E+00	1.51E-05	1.49E+00	5.99E-03
RL-W728	1.62E-06	0.00E+00	5.65E-28	1.21E+00	1.51E-01	0.00E+00	1.37E-05	1.36E+00	5.48E-03
RL-W729	7.48E-07	0.00E+00	2.62E-28	5.55E-01	6.97E-02	0.00E+00	6.36E-06	6.25E-01	2.52E-03
RL-W730	2.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.93E-04	1.18E-06
RL-W731	9.43E-11	0.00E+00	0.00E+00	3.63E-04	8.37E-07	0.00E+00	0.00E+00	3.64E-04	1.47E-06
RL-W732	2.16E-04	0.00E+00	1.49E-25	1.02E+02	1.27E+01	0.00E+00	3.62E-03	1.15E+02	4.64E-01
RL-W733	2.84E-06	0.00E+00	1.94E-27	1.11E+00	1.55E-01	0.00E+00	4.71E-05	1.27E+00	5.10E-03
RL-W734	8.88E-06	0.00E+00	6.46E-27	3.83E+00	5.22E-01	0.00E+00	1.57E-04	4.35E+00	1.76E-02
RL-W735	7.25E-06	0.00E+00	4.93E-27	2.99E+00	4.16E-01	0.00E+00	1.20E-04	3.40E+00	1.37E-02
RL-W736	7.96E-09	0.00E+00	1.05E-32	1.98E-03	2.87E-04	0.00E+00	2.56E-10	2.27E-03	9.14E-06
RL-W737	6.47E-06	0.00E+00	4.50E-27	2.83E+00	3.87E-01	0.00E+00	1.09E-04	3.22E+00	1.30E-02
RL-W738	2.42E-05	0.00E+00	1.55E-26	9.02E+00	1.34E+00	0.00E+00	3.76E-04	1.04E+01	4.17E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W739	2.06E-06	0.00E+00	1.37E-27	1.47E+00	1.88E-01	0.00E+00	3.32E-05	1.65E+00	6.66E-03
RL-W740	1.03E-04	0.00E+00	5.00E-26	3.57E+01	5.22E+00	0.00E+00	1.22E-03	4.09E+01	1.65E-01
RL-W741	1.54E-04	0.00E+00	1.18E-25	6.95E+00	2.77E+00	0.00E+00	2.86E-03	9.72E+00	3.92E-02
RL-W742	6.84E-06	0.00E+00	3.54E-27	2.25E+00	2.98E-01	0.00E+00	8.61E-05	2.55E+00	1.03E-02
RL-W743	1.23E-08	0.00E+00	9.62E-31	1.46E-03	0.00E+00	0.00E+00	2.34E-08	1.46E-03	5.88E-06
RL-W744	0.00E+00	0.00E+00	0.00E+00	7.27E-02	3.47E-02	0.00E+00	0.00E+00	1.07E-01	4.33E-04
RL-W745	1.95E-08	0.00E+00	6.72E-30	1.41E-02	1.76E-03	0.00E+00	1.63E-07	1.59E-02	6.39E-05
RL-W746	7.50E-08	0.00E+00	2.59E-29	5.41E-02	6.79E-03	0.00E+00	6.29E-07	6.09E-02	2.46E-04
RL-W747	2.03E-07	0.00E+00	7.01E-29	1.47E-01	1.84E-02	0.00E+00	1.70E-06	1.65E-01	6.65E-04
RL-W748	1.42E-03	0.00E+00	1.97E-25	2.43E-01	2.25E-01	0.00E+00	4.78E-03	4.74E-01	1.91E-03
RL-W749	1.71E-06	0.00E+00	6.02E-28	1.27E+00	1.59E-01	0.00E+00	1.46E-05	1.43E+00	5.77E-03
RL-W750	2.16E-03	0.00E+00	2.98E-25	3.99E-01	3.67E-01	0.00E+00	7.24E-03	7.75E-01	3.12E-03
RL-W751	1.95E-03	0.00E+00	2.69E-25	3.58E-01	3.33E-01	0.00E+00	6.54E-03	6.99E-01	2.82E-03
RL-W752	8.47E-04	0.00E+00	1.17E-25	1.56E-01	1.44E-01	0.00E+00	2.84E-03	3.04E-01	1.23E-03
RL-W753	1.14E-02	0.00E+00	1.58E-24	2.10E+00	1.94E+00	0.00E+00	3.83E-02	4.09E+00	1.65E-02
RP-W754	4.84E-04	0.00E+00	2.00E-25	1.50E+03	6.88E+01	0.00E+00	3.50E-01	1.57E+03	6.32E+00
RP-W755	2.56E-03	0.00E+00	1.20E-25	1.12E+03	5.22E+01	0.00E+00	1.23E+01	1.18E+03	4.77E+00
SA-T001	5.15E-06	0.00E+00	2.86E-27	2.44E+00	8.10E-03	0.00E+00	7.41E-05	2.45E+00	9.87E-03
SA-W134	4.21E-05	0.00E+00	1.95E-26	1.11E+00	1.98E-01	0.00E+00	1.64E-01	1.47E+00	5.94E-03
SA-W134M	5.46E-06	0.00E+00	2.53E-27	1.45E-01	2.57E-02	0.00E+00	2.12E-02	1.92E-01	7.73E-04
T001-221F-HET	1.02E-02	0.00E+00	2.29E-21	2.32E+04	3.21E+02	0.00E+00	6.11E+01	2.36E+04	9.50E+01
T001-221H-HET	1.83E-02	0.00E+00	4.12E-21	4.19E+04	5.80E+02	0.00E+00	1.10E+02	4.26E+04	1.72E+02
T001-235F-HET	1.05E-03	0.00E+00	2.37E-22	2.41E+03	3.33E+01	0.00E+00	6.34E+00	2.45E+03	9.87E+00
T001-772F-HET	9.08E-03	0.00E+00	2.05E-21	2.08E+04	2.88E+02	0.00E+00	5.49E+01	2.11E+04	8.51E+01
T001-773A-CLAS	1.02E-04	0.00E+00	2.30E-23	2.33E+02	3.23E+00	0.00E+00	6.14E-01	2.37E+02	9.57E-01
T001-773A-HET	1.18E-03	0.00E+00	2.65E-22	2.69E+03	3.73E+01	0.00E+00	7.07E+00	2.73E+03	1.10E+01
W006-773A-VIT	1.57E-08	0.00E+00	0.00E+00	4.32E+02	0.00E+00	0.00E+00	0.00E+00	4.32E+02	1.74E+00
W026-221F-HET	3.54E-03	0.00E+00	7.97E-22	8.13E+03	1.12E+02	0.00E+00	2.13E+01	8.26E+03	3.33E+01

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W026-221H-HET	2.65E-03	0.00E+00	5.96E-22	6.05E+03	8.37E+01	0.00E+00	1.59E+01	6.15E+03	2.48E+01
W026-235F-HET	4.12E-05	0.00E+00	9.28E-24	9.42E+01	1.31E+00	0.00E+00	2.48E-01	9.57E+01	3.86E-01
W026-772F-HET	1.13E-05	0.00E+00	2.53E-24	2.57E+01	3.56E-01	0.00E+00	6.76E-02	2.61E+01	1.05E-01
W026-773A-HET	1.83E-04	0.00E+00	4.12E-23	4.19E+02	5.80E+00	0.00E+00	1.10E+00	4.26E+02	1.72E+00
W027-221F-HET	1.34E-02	0.00E+00	2.69E-21	3.14E+04	4.34E+02	0.00E+00	8.28E+01	3.19E+04	1.29E+02
W027-221H-HET	5.84E-03	0.00E+00	1.17E-21	1.38E+04	1.90E+02	0.00E+00	3.62E+01	1.40E+04	5.64E+01
W027-235F-HET	1.76E-03	0.00E+00	3.53E-22	4.14E+03	5.71E+01	0.00E+00	1.09E+01	4.21E+03	1.70E+01
W027-772F-HET	3.19E-03	0.00E+00	6.42E-22	7.51E+03	1.04E+02	0.00E+00	1.98E+01	7.63E+03	3.08E+01
W027-773A-HET	4.76E-03	0.00E+00	9.57E-22	1.12E+04	1.55E+02	0.00E+00	2.95E+01	1.14E+04	4.59E+01
W027-999-HET	5.45E-03	0.00E+00	1.10E-21	1.28E+04	1.77E+02	0.00E+00	3.37E+01	1.30E+04	5.25E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.21E+02	0.00E+00	0.00E+00	0.00E+00	3.21E+02	1.30E+00
WP-INW169.001	2.66E-05	0.00E+00	6.90E-27	1.24E+01	1.55E+00	0.00E+00	3.29E-04	1.39E+01	5.62E-02
WP-INW198.001	3.50E-05	0.00E+00	1.20E-26	2.22E+01	2.75E+00	0.00E+00	3.72E-04	2.50E+01	1.01E-01
WP-INW211.001	3.95E-03	0.00E+00	1.13E-24	2.06E+03	2.56E+02	0.00E+00	2.94E-02	2.32E+03	9.34E+00
WP-INW216.001-	1.43E-01	0.00E+00	6.49E-25	1.19E+03	1.49E+02	0.00E+00	2.87E-01	1.34E+03	5.40E+00
WP-INW216.001-	3.94E-02	0.00E+00	1.75E-25	3.23E+02	4.01E+01	0.00E+00	3.13E-02	3.63E+02	1.46E+00
WP-INW218.001-	2.74E-03	0.00E+00	1.15E-25	2.08E+02	2.58E+01	0.00E+00	3.81E-01	2.34E+02	9.43E-01
WP-INW218.001-	1.26E-05	0.00E+00	3.15E-27	5.65E+00	7.02E-01	0.00E+00	3.67E-02	6.39E+00	2.58E-02
WP-INW222.001	1.30E-04	0.00E+00	3.40E-26	5.52E+01	6.93E+00	0.00E+00	1.39E-03	6.22E+01	2.51E-01
WP-INW243.001	3.15E-04	0.00E+00	7.33E-26	1.16E+02	1.46E+01	0.00E+00	2.63E-03	1.31E+02	5.26E-01
WP-INW247.001R	4.20E-04	0.00E+00	1.71E-25	2.22E+02	2.84E+01	0.00E+00	4.22E-03	2.51E+02	1.01E+00
WP-INW276.001	3.21E-05	0.00E+00	1.66E-26	2.20E+01	2.81E+00	0.00E+00	4.21E-04	2.48E+01	9.99E-02
WP-INW276.002	5.08E-05	0.00E+00	2.50E-26	3.23E+01	4.21E+00	0.00E+00	6.34E-04	3.65E+01	1.47E-01
WP-INW276.003	1.95E-03	0.00E+00	9.30E-25	1.20E+03	1.53E+02	0.00E+00	2.30E-02	1.35E+03	5.46E+00
WP-INW276.004	4.65E-04	0.00E+00	1.97E-25	2.54E+02	3.24E+01	0.00E+00	4.92E-03	2.86E+02	1.15E+00
WP-INW296.001-	1.70E-04	0.00E+00	4.67E-26	6.37E+01	8.10E+00	0.00E+00	1.17E-03	7.18E+01	2.89E-01
WP-INW296.001-	5.13E-04	0.00E+00	1.65E-25	2.25E+02	2.86E+01	0.00E+00	4.35E-03	2.54E+02	1.02E+00
WP-LA-TA-55-19	8.54E-06	0.00E+00	7.66E-27	1.68E+00	2.28E-01	0.00E+00	2.77E-03	1.91E+00	7.72E-03

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-LA-TA-55-19	4.14E-04	0.00E+00	2.57E-25	1.72E+02	2.35E+01	0.00E+00	9.16E-02	1.95E+02	7.86E-01
WP-LA-TA-55-43	2.32E-06	0.00E+00	6.00E-24	2.60E-01	6.16E-02	0.00E+00	1.72E-01	4.93E-01	1.99E-03
WP-RF001.01	7.18E-04	0.00E+00	2.08E-25	3.30E+02	4.22E+01	0.00E+00	1.42E-02	3.72E+02	1.50E+00
WP-RF002.01-A	8.36E-04	0.00E+00	2.78E-25	3.72E+02	4.77E+01	0.00E+00	2.42E-02	4.20E+02	1.69E+00
WP-RF002.01-B	8.29E-07	0.00E+00	1.92E-28	4.03E-01	5.13E-02	0.00E+00	4.86E-06	4.54E-01	1.83E-03
WP-RF003.01	1.30E-02	0.00E+00	4.47E-24	7.11E+03	9.09E+02	0.00E+00	1.17E-01	8.02E+03	3.23E+01
WP-RF004.01	6.09E-06	0.00E+00	2.99E-27	4.10E+00	5.27E-01	0.00E+00	1.97E-04	4.62E+00	1.86E-02
WP-RF005.01	3.12E-02	0.00E+00	2.27E-24	3.76E+03	4.77E+02	0.00E+00	5.69E-02	4.24E+03	1.71E+01
WP-RF005.02	3.67E-02	0.00E+00	1.17E-24	2.25E+03	2.83E+02	0.00E+00	2.97E-02	2.53E+03	1.02E+01
WP-RF006.01	1.19E-02	0.00E+00	4.27E-24	6.39E+03	8.19E+02	0.00E+00	1.29E-01	7.21E+03	2.91E+01
WP-RF008.01	3.78E-03	0.00E+00	1.52E-24	1.87E+03	2.43E+02	0.00E+00	3.81E-02	2.11E+03	8.51E+00
WP-RF009.01	3.72E-01	0.00E+00	1.87E-23	4.10E+04	5.13E+03	0.00E+00	4.74E-01	4.61E+04	1.86E+02
WP-RF010.01	1.37E-04	0.00E+00	4.73E-26	6.19E+01	7.92E+00	0.00E+00	1.87E-03	6.98E+01	2.82E-01
WP-RF029.01-A	3.30E-05	0.00E+00	8.89E-27	1.09E+01	1.40E+00	0.00E+00	9.31E-04	1.23E+01	4.95E-02
WP-RF029.01-B	4.92E-05	0.00E+00	7.04E-27	8.61E+00	1.10E+00	0.00E+00	2.37E-03	9.72E+00	3.92E-02
WP-RF118.01	8.36E-02	0.00E+00	3.54E-23	4.14E+04	5.18E+03	0.00E+00	1.07E+00	4.66E+04	1.88E+02
WP-RLMPDT.001	1.78E-05	0.00E+00	1.03E-26	5.93E+00	8.64E-01	0.00E+00	2.53E-04	6.79E+00	2.74E-02
WP-RLNPDT.002	2.18E-04	0.00E+00	9.85E-26	5.82E+01	8.77E+00	0.00E+00	2.43E-03	6.70E+01	2.70E-01
WP-SR2001.001.	6.94E-06	0.00E+00	1.13E-26	5.50E+00	6.12E-01	0.00E+00	2.80E-04	6.11E+00	2.46E-02
WP-SR-W027-221	5.14E-05	0.00E+00	3.33E-26	1.58E+01	2.47E+00	0.00E+00	1.83E-01	1.84E+01	7.43E-02
Total	2.75E+00	0.00E+00	2.33E-20	5.31E+05	4.82E+04	0.00E+00	7.30E+02	5.80E+05	2.34E+03

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	9.40E-06	0.00E+00	6.82E-34	1.57E+02	4.28E+01	0.00E+00	1.91E-02	1.99E+02	8.04E-01
AE-T003	1.19E-06	0.00E+00	9.08E-35	4.84E+01	8.63E+00	0.00E+00	9.37E-04	5.70E+01	2.30E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	5.28E-09	0.00E+00	2.41E-33	3.57E+01	9.94E-02	0.00E+00	2.24E-02	3.58E+01	1.44E-01
AW-T033.1325	1.93E-08	0.00E+00	8.82E-33	1.30E+02	3.62E-01	0.00E+00	8.20E-02	1.31E+02	5.27E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	5.79E-01	0.00E+00	0.00E+00	0.00E+00	5.79E-01	2.34E-03
BCLCH-MT01	1.95E-06	0.00E+00	6.82E-32	2.15E+01	2.60E+00	0.00E+00	6.21E-01	2.47E+01	9.97E-02
BT-T002	1.43E-09	0.00E+00	3.57E-35	5.43E-04	5.13E-04	0.00E+00	2.26E-03	3.32E-03	1.34E-05
ET-C1-B55	5.97E-09	0.00E+00	4.06E-37	4.65E-02	1.07E-02	0.00E+00	2.33E-04	5.75E-02	2.32E-04
ET-C1-D139	8.20E-10	0.00E+00	5.63E-38	6.54E-03	1.51E-03	0.00E+00	5.73E-07	8.05E-03	3.24E-05
ET-C2-SEFOR	2.03E-08	0.00E+00	0.00E+00	1.03E-01	1.59E-02	0.00E+00	0.00E+00	1.19E-01	4.78E-04
FM-MOX-MT02	1.92E-13	0.00E+00	2.27E-41	2.25E-07	6.18E-08	0.00E+00	2.15E-10	2.87E-07	1.16E-09
FM-MOX-T01	3.18E-12	0.00E+00	3.75E-40	3.70E-06	1.02E-06	0.00E+00	3.55E-09	4.72E-06	1.90E-08
IN-BN-510	7.67E-04	0.00E+00	1.93E-30	2.97E+04	1.16E+03	0.00E+00	1.95E+01	3.09E+04	1.25E+02
IN-GEM-01	9.70E-06	0.00E+00	3.83E-35	3.34E+01	3.52E+00	0.00E+00	3.49E-04	3.69E+01	1.49E-01
IN-GEM-02	2.30E-06	0.00E+00	9.12E-36	7.94E+00	8.39E-01	0.00E+00	8.30E-05	8.78E+00	3.54E-02
IN-W157.144	1.15E-05	0.00E+00	3.71E-34	2.27E+02	2.37E+01	0.00E+00	3.74E-03	2.51E+02	1.01E+00
IN-W163.1007	1.97E-06	0.00E+00	1.15E-34	7.04E+01	7.35E+00	0.00E+00	1.16E-03	7.78E+01	3.14E-01
IN-W164.153	1.88E-08	0.00E+00	1.09E-36	6.70E-01	7.01E-02	0.00E+00	1.10E-05	7.41E-01	2.99E-03
IN-W167.149	3.77E-06	0.00E+00	1.78E-34	1.09E+02	1.14E+01	0.00E+00	1.79E-03	1.20E+02	4.84E-01
IN-W174.154	0.00E+00	0.00E+00	1.00E-31	1.46E+00	1.33E+00	0.00E+00	1.01E+00	3.80E+00	1.53E-02
IN-W177.156	2.61E-09	0.00E+00	2.14E-31	1.37E+00	3.87E-03	0.00E+00	2.15E+00	3.53E+00	1.42E-02
IN-W179.158	1.76E-08	0.00E+00	2.13E-31	7.94E-02	1.91E-02	0.00E+00	2.15E+00	2.24E+00	9.05E-03
IN-W181.162	2.50E-07	0.00E+00	1.45E-35	8.84E+00	9.25E-01	0.00E+00	1.46E-04	9.76E+00	3.94E-02
IN-W188.160	1.68E-06	0.00E+00	9.74E-35	5.97E+01	6.21E+00	0.00E+00	9.82E-04	6.59E+01	2.66E-01
IN-W216.98	1.49E-02	0.00E+00	7.93E-33	4.87E+03	5.11E+02	0.00E+00	8.00E-02	5.38E+03	2.17E+01
IN-W218.909	7.54E-05	0.00E+00	1.76E-34	1.08E+02	1.13E+01	0.00E+00	1.78E-03	1.19E+02	4.81E-01
IN-W219.110	1.02E-07	0.00E+00	5.94E-36	3.64E+00	3.80E-01	0.00E+00	5.99E-05	4.02E+00	1.62E-02
IN-W219.914	1.61E-08	0.00E+00	9.35E-37	5.75E-01	6.01E-02	0.00E+00	9.43E-06	6.35E-01	2.56E-03
IN-W220.114	5.33E-04	0.00E+00	6.25E-34	4.11E+02	4.18E+01	0.00E+00	6.30E-03	4.53E+02	1.83E+00

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W221.927	6.25E-07	0.00E+00	3.62E-35	2.22E+01	2.31E+00	0.00E+00	3.65E-04	2.45E+01	9.87E-02
IN-W222.116	2.13E-05	0.00E+00	1.23E-33	7.49E+02	7.84E+01	0.00E+00	1.24E-02	8.27E+02	3.34E+00
IN-W228.101	1.41E-04	0.00E+00	3.99E-34	2.45E+02	2.55E+01	0.00E+00	4.02E-03	2.71E+02	1.09E+00
IN-W240.931	1.49E-05	0.00E+00	5.10E-34	3.15E+02	3.27E+01	0.00E+00	5.14E-03	3.47E+02	1.40E+00
IN-W243.808	2.07E-05	0.00E+00	8.93E-34	5.49E+02	5.73E+01	0.00E+00	9.01E-03	6.06E+02	2.45E+00
IN-W245.301	3.06E-05	0.00E+00	1.76E-33	1.07E+03	1.12E+02	0.00E+00	1.77E-02	1.18E+03	4.77E+00
IN-W247.810	1.49E-05	0.00E+00	8.55E-34	5.24E+02	5.49E+01	0.00E+00	8.62E-03	5.79E+02	2.33E+00
IN-W249.527	0.00E+00	0.00E+00	5.98E-32	9.29E+00	0.00E+00	0.00E+00	6.03E-01	9.89E+00	3.99E-02
IN-W263.520	4.27E-09	0.00E+00	6.25E-33	6.31E+00	4.63E-03	0.00E+00	6.30E-02	6.38E+00	2.57E-02
IN-W267.1005	3.57E-06	0.00E+00	2.07E-34	1.27E+02	1.33E+01	0.00E+00	2.09E-03	1.41E+02	5.67E-01
IN-W309.609	9.57E-05	0.00E+00	3.48E-33	2.13E+03	2.22E+02	0.00E+00	3.51E-02	2.35E+03	9.47E+00
IN-W315.601	9.44E-05	0.00E+00	1.45E-35	8.91E+00	9.29E-01	0.00E+00	1.47E-04	9.84E+00	3.97E-02
IN-W319.584	5.49E-07	0.00E+00	3.18E-35	1.96E+01	2.05E+00	0.00E+00	3.21E-04	2.16E+01	8.71E-02
IN-W321.1023	4.75E-06	0.00E+00	2.76E-34	1.69E+02	1.77E+01	0.00E+00	2.78E-03	1.87E+02	7.54E-01
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	6.83E+00	6.52E-01	0.00E+00	0.00E+00	7.48E+00	3.02E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	1.82E+01	1.74E+00	0.00E+00	0.00E+00	1.99E+01	8.04E-02
IN-W323.562	1.02E-08	0.00E+00	4.68E-35	1.87E-01	0.00E+00	0.00E+00	4.72E-04	1.87E-01	7.54E-04
IN-W323.951	1.20E-08	0.00E+00	5.56E-37	2.23E-01	0.00E+00	0.00E+00	5.61E-06	2.23E-01	8.97E-04
IN-W332.661	0.00E+00	0.00E+00	6.13E-34	9.66E-02	0.00E+00	0.00E+00	6.19E-03	1.03E-01	4.15E-04
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	2.28E+00	2.18E-01	0.00E+00	0.00E+00	2.50E+00	1.01E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	6.83E+00	6.52E-01	0.00E+00	0.00E+00	7.48E+00	3.02E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.46E+00	0.00E+00	0.00E+00	0.00E+00	1.46E+00	5.89E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	4.39E+00	0.00E+00	0.00E+00	0.00E+00	4.39E+00	1.77E-02
IN-W342.652	4.69E-07	0.00E+00	0.00E+00	3.01E-02	3.59E-18	0.00E+00	0.00E+00	3.01E-02	1.21E-04
IN-W342.953	3.13E-07	0.00E+00	0.00E+00	2.02E-02	2.41E-18	0.00E+00	0.00E+00	2.02E-02	8.13E-05
IN-W347.818	2.45E-07	0.00E+00	0.00E+00	6.19E+01	5.25E+01	0.00E+00	1.54E-08	1.14E+02	4.61E-01
IN-W348.1012	1.30E-08	0.00E+00	5.06E-34	3.12E+02	3.27E+01	0.00E+00	5.11E-03	3.45E+02	1.39E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	1.87E-02	0.00E+00	0.00E+00	0.00E+00	1.87E-02	7.55E-05
IN-W357.1022	0.00E+00	0.00E+00	9.97E-37	6.14E-01	6.39E-02	0.00E+00	1.01E-05	6.77E-01	2.73E-03
IN-W358.854	0.00E+00	0.00E+00	1.50E-32	1.41E+00	1.25E+00	0.00E+00	1.45E-01	2.81E+00	1.13E-02
IN-W358.855	0.00E+00	0.00E+00	8.01E-32	7.49E+00	6.66E+00	0.00E+00	7.71E-01	1.49E+01	6.02E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W358.948	0.00E+00	0.00E+00	1.67E-32	1.57E+00	1.39E+00	0.00E+00	1.61E-01	3.11E+00	1.26E-02
IN-W361.1021	3.45E-09	0.00E+00	9.66E-35	5.92E+01	6.18E+00	0.00E+00	9.74E-04	6.54E+01	2.64E-01
IN-W362.1020	0.00E+00	0.00E+00	1.27E-33	7.72E+02	8.11E+01	0.00E+00	1.28E-02	8.53E+02	3.44E+00
IN-W363.1019	0.00E+00	0.00E+00	5.94E-35	3.66E+01	3.83E+00	0.00E+00	5.99E-04	4.05E+01	1.63E-01
IN-W364.1011	0.00E+00	0.00E+00	9.81E-35	6.02E+01	6.28E+00	0.00E+00	9.90E-04	6.65E+01	2.68E-01
IN-W365.1010	3.22E-05	0.00E+00	7.78E-35	4.76E+01	4.97E+00	0.00E+00	7.85E-04	5.25E+01	2.12E-01
IN-W366.841	1.14E-07	0.00E+00	6.63E-35	4.05E+01	4.25E+00	0.00E+00	6.69E-04	4.48E+01	1.81E-01
IN-W372.832	4.69E-07	0.00E+00	0.00E+00	3.01E-02	3.59E-18	0.00E+00	0.00E+00	3.01E-02	1.21E-04
IN-W375.1096	0.00E+00	0.00E+00	2.45E-35	1.50E+01	1.56E+00	0.00E+00	2.47E-04	1.65E+01	6.67E-02
KN-B234TRU	1.67E-05	0.00E+00	9.35E-34	2.18E+02	3.38E+01	0.00E+00	1.04E-02	2.52E+02	1.02E+00
LA-IT-00-01	2.42E-07	0.00E+00	1.59E-34	4.38E-01	4.38E-03	0.00E+00	1.80E-03	4.44E-01	1.79E-03
LA-OS-00-01	5.39E-04	0.00E+00	7.28E-30	9.21E+02	0.00E+00	0.00E+00	6.68E+01	9.88E+02	3.98E+00
LA-PX-00-01	2.25E-09	0.00E+00	3.07E-37	6.78E-02	7.35E-03	0.00E+00	2.93E-06	7.51E-02	3.03E-04
LA-SL-00-01	0.00E+00	0.00E+00	6.48E-36	1.15E-01	0.00E+00	0.00E+00	7.25E-05	1.15E-01	4.62E-04
LA-TA-03-12	2.31E-08	0.00E+00	1.50E-34	3.27E-01	5.25E-02	0.00E+00	1.74E-03	3.81E-01	1.54E-03
LA-TA-03-13	2.99E-08	0.00E+00	4.75E-34	5.10E-01	5.52E-02	0.00E+00	4.85E-03	5.70E-01	2.30E-03
LA-TA-03-19	6.04E-08	0.00E+00	7.09E-34	9.96E-01	1.33E-01	0.00E+00	8.20E-03	1.14E+00	4.59E-03
LA-TA-03-20	3.30E-08	0.00E+00	3.37E-34	4.39E-01	7.15E-02	0.00E+00	3.73E-03	5.14E-01	2.07E-03
LA-TA-03-24	4.42E-08	0.00E+00	1.31E-33	8.17E-01	1.14E-01	0.00E+00	1.53E-02	9.46E-01	3.81E-03
LA-TA-03-26	2.27E-09	0.00E+00	5.40E-35	1.98E+00	1.50E-02	0.00E+00	1.47E-03	1.99E+00	8.04E-03
LA-TA-03-28	0.00E+00	0.00E+00	1.87E-35	1.85E-01	0.00E+00	0.00E+00	2.14E-04	1.85E-01	7.47E-04
LA-TA-03-30	1.01E-07	0.00E+00	1.33E-35	3.77E+00	5.04E-01	0.00E+00	1.52E-04	4.27E+00	1.72E-02
LA-TA-03-31	0.00E+00	0.00E+00	6.67E-37	6.59E-03	0.00E+00	0.00E+00	7.64E-06	6.60E-03	2.66E-05
LA-TA-03-40	0.00E+00	0.00E+00	1.05E-36	4.10E-02	0.00E+00	0.00E+00	1.22E-05	4.10E-02	1.65E-04
LA-TA-03-42	2.31E-12	0.00E+00	2.64E-38	2.56E-03	1.56E-05	0.00E+00	3.05E-07	2.58E-03	1.04E-05
LA-TA-21-06	2.28E-08	0.00E+00	2.91E-33	7.17E-01	1.01E-01	0.00E+00	3.33E-02	8.51E-01	3.43E-03
LA-TA-21-12	8.30E-08	0.00E+00	1.75E-32	2.49E+00	3.43E-01	0.00E+00	2.01E-01	3.03E+00	1.22E-02
LA-TA-21-13	1.28E-07	0.00E+00	0.00E+00	2.20E-01	0.00E+00	0.00E+00	0.00E+00	2.20E-01	8.88E-04
LA-TA-21-14	2.10E-11	0.00E+00	3.34E-34	3.36E+00	1.81E-05	0.00E+00	3.22E-03	3.37E+00	1.36E-02
LA-TA-21-15	1.24E-08	0.00E+00	9.20E-37	1.04E+00	8.22E-02	0.00E+00	1.04E-05	1.12E+00	4.53E-03
LA-TA-21-16	1.43E-07	0.00E+00	1.42E-35	7.94E+00	8.77E-01	0.00E+00	1.64E-04	8.82E+00	3.56E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-40	1.82E-11	0.00E+00	4.91E-35	2.49E-01	1.27E-04	0.00E+00	6.91E-04	2.50E-01	1.01E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	5.31E-01	0.00E+00	0.00E+00	0.00E+00	5.31E-01	2.14E-03
LA-TA-21-42	1.86E-09	0.00E+00	1.59E-35	1.23E-01	3.87E-03	0.00E+00	2.39E-04	1.27E-01	5.12E-04
LA-TA-21-43	6.57E-06	0.00E+00	5.29E-34	3.83E+02	4.21E+01	0.00E+00	7.87E-03	4.25E+02	1.71E+00
LA-TA-21-44	3.15E-08	0.00E+00	1.11E-34	8.61E+01	1.06E-01	0.00E+00	1.38E-03	8.63E+01	3.48E-01
LA-TA-48-01	1.02E-08	0.00E+00	4.18E-37	8.84E-02	1.71E-01	0.00E+00	5.93E-06	2.59E-01	1.05E-03
LA-TA-49-01	1.26E-06	0.00E+00	5.14E-35	1.09E+01	2.12E+01	0.00E+00	7.31E-04	3.21E+01	1.30E-01
LA-TA-50-10	3.37E-09	0.00E+00	4.87E-37	3.44E-02	0.00E+00	0.00E+00	4.61E-06	3.44E-02	1.39E-04
LA-TA-50-11	6.43E-09	0.00E+00	4.98E-37	3.49E-01	3.59E-02	0.00E+00	6.95E-06	3.85E-01	1.55E-03
LA-TA-50-15	1.27E-08	0.00E+00	7.36E-35	2.55E-01	2.64E-02	0.00E+00	7.88E-04	2.82E-01	1.14E-03
LA-TA-50-17	1.86E-06	0.00E+00	5.98E-35	1.36E+01	1.48E-04	0.00E+00	9.70E-04	1.36E+01	5.50E-02
LA-TA-50-18	1.10E-07	0.00E+00	7.90E-36	2.23E+00	1.85E-06	0.00E+00	9.11E-05	2.23E+00	8.97E-03
LA-TA-50-19	3.52E-08	0.00E+00	3.52E-36	2.96E-01	1.58E-03	0.00E+00	6.66E-05	2.98E-01	1.20E-03
LA-TA-50-20	9.66E-10	0.00E+00	0.00E+00	7.30E-03	0.00E+00	0.00E+00	0.00E+00	7.30E-03	2.94E-05
LA-TA-50-40	5.44E-10	0.00E+00	4.75E-38	7.94E-03	1.72E-03	0.00E+00	5.23E-07	9.66E-03	3.89E-05
LA-TA-50-41	5.81E-10	0.00E+00	4.79E-38	3.52E-02	3.80E-03	0.00E+00	4.83E-07	3.90E-02	1.57E-04
LA-TA-55-19	9.00E-07	0.00E+00	6.32E-35	1.98E+01	2.58E+00	0.00E+00	2.20E-03	2.24E+01	9.01E-02
LA-TA-55-20	1.45E-05	0.00E+00	7.21E-34	4.78E+02	5.32E+01	0.00E+00	9.88E-02	5.31E+02	2.14E+00
LA-TA-55-21	1.29E-07	0.00E+00	8.28E-36	3.39E+00	3.76E-01	0.00E+00	8.29E-05	3.76E+00	1.52E-02
LA-TA-55-22	3.54E-07	0.00E+00	4.68E-35	1.19E+01	1.29E+00	0.00E+00	4.68E-04	1.32E+01	5.32E-02
LA-TA-55-23	3.33E-07	0.00E+00	3.91E-35	8.17E+00	9.36E-01	0.00E+00	3.88E-04	9.10E+00	3.67E-02
LA-TA-55-24	1.26E-07	0.00E+00	6.13E-36	4.29E+00	4.63E-01	0.00E+00	5.85E-05	4.75E+00	1.91E-02
LA-TA-55-25	6.43E-07	0.00E+00	3.58E-35	2.13E+01	2.30E+00	0.00E+00	3.41E-04	2.36E+01	9.51E-02
LA-TA-55-28	2.19E-07	0.00E+00	1.98E-35	6.53E+00	7.15E-01	0.00E+00	1.91E-04	7.25E+00	2.92E-02
LA-TA-55-30	4.88E-06	0.00E+00	2.37E-34	1.07E+02	1.20E+01	0.00E+00	2.91E-03	1.19E+02	4.80E-01
LA-TA-55-32	3.96E-07	0.00E+00	1.33E-33	8.46E+00	1.21E+00	0.00E+00	1.55E-02	9.69E+00	3.91E-02
LA-TA-55-33	5.93E-08	0.00E+00	3.42E-36	1.12E+00	1.65E-01	0.00E+00	3.74E-05	1.28E+00	5.17E-03
LA-TA-55-34	6.00E-06	0.00E+00	3.17E-34	1.73E+02	2.04E+01	0.00E+00	6.16E-03	1.93E+02	7.80E-01
LA-TA-55-38	1.51E-05	0.00E+00	1.04E-34	3.82E+01	4.76E+00	0.00E+00	2.79E-03	4.30E+01	1.73E-01
LA-TA-55-39	1.59E-06	0.00E+00	7.70E-35	5.70E+01	5.94E+00	0.00E+00	7.59E-04	6.29E+01	2.54E-01
LA-TA-55-41	3.79E-05	0.00E+00	1.59E-34	7.07E+01	7.84E+00	0.00E+00	1.61E-03	7.86E+01	3.17E-01

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-43	1.43E-08	0.00E+00	1.05E-32	1.06E-01	1.73E-02	0.00E+00	1.02E-01	2.26E-01	9.11E-04
LA-TA-55-44	1.24E-07	0.00E+00	2.47E-32	1.97E+00	2.53E-01	0.00E+00	2.71E-01	2.50E+00	1.01E-02
LA-TA-55-48	9.11E-04	0.00E+00	9.74E-32	1.27E+04	2.19E+03	0.00E+00	1.05E+00	1.49E+04	5.99E+01
LA-TA-55-49	1.95E-06	0.00E+00	1.28E-31	2.32E+01	3.01E+00	0.00E+00	1.40E+00	2.76E+01	1.11E-01
LA-TA-55-53	9.18E-06	0.00E+00	2.65E-34	1.98E+02	2.14E+01	0.00E+00	2.85E-03	2.19E+02	8.84E-01
LA-TA-55-56	1.02E-05	0.00E+00	9.85E-33	2.86E+02	3.33E+01	0.00E+00	1.01E-01	3.20E+02	1.29E+00
LA-TA-55-60	5.51E-09	0.00E+00	2.49E-36	5.39E-02	8.87E-03	0.00E+00	2.72E-05	6.28E-02	2.53E-04
LA-TA-55-61	4.74E-09	0.00E+00	1.15E-35	1.04E-01	1.64E-02	0.00E+00	1.23E-04	1.21E-01	4.86E-04
LA-TA-55-62	1.23E-09	0.00E+00	1.09E-37	1.75E-02	3.87E-03	0.00E+00	1.18E-06	2.13E-02	8.60E-05
LA-TA-55-63	9.12E-10	0.00E+00	7.36E-38	5.60E-02	6.01E-03	0.00E+00	7.61E-07	6.20E-02	2.50E-04
LL-M001	1.25E-05	0.00E+00	3.21E-33	5.24E+01	1.10E+01	0.00E+00	2.92E-02	6.34E+01	2.56E-01
LL-T001	6.24E-05	0.00E+00	0.00E+00	4.00E+02	8.35E+01	0.00E+00	0.00E+00	4.84E+02	1.95E+00
LL-T002	6.17E-04	0.00E+00	2.55E-32	3.88E+03	7.39E+02	0.00E+00	2.32E-01	4.62E+03	1.86E+01
LL-T003	2.40E-05	0.00E+00	2.86E-33	7.87E+01	2.94E+01	0.00E+00	2.60E-02	1.08E+02	4.36E-01
LL-T004	1.52E-05	0.00E+00	5.86E-34	5.00E+01	1.85E+01	0.00E+00	5.34E-03	6.85E+01	2.76E-01
LL-T005	7.86E-05	0.00E+00	6.90E-33	1.86E+02	7.44E+01	0.00E+00	6.28E-02	2.60E+02	1.05E+00
LL-W018	6.70E-09	0.00E+00	0.00E+00	1.39E-02	1.48E-02	0.00E+00	0.00E+00	2.86E-02	1.15E-04
LL-W019	3.63E-06	0.00E+00	0.00E+00	1.08E+01	4.18E+00	0.00E+00	0.00E+00	1.50E+01	6.03E-02
LL-W034	1.34E-06	0.00E+00	1.21E-34	3.15E+00	1.23E+00	0.00E+00	1.10E-03	4.38E+00	1.77E-02
MC-W001	1.68E-08	0.00E+00	0.00E+00	4.54E-02	0.00E+00	0.00E+00	0.00E+00	4.54E-02	1.83E-04
MU-W002	2.24E-07	0.00E+00	0.00E+00	3.94E-02	0.00E+00	0.00E+00	2.60E-12	3.94E-02	1.59E-04
NT-JAS-01	2.16E-05	0.00E+00	2.57E-33	7.10E+01	2.65E+01	0.00E+00	2.34E-02	9.75E+01	3.93E-01
NT-W001	3.24E-05	0.00E+00	5.14E-33	2.14E+03	6.63E+00	0.00E+00	5.80E-02	2.15E+03	8.67E+00
NT-W021	6.28E-07	0.00E+00	3.68E-35	2.41E+01	2.55E+00	0.00E+00	3.80E-04	2.67E+01	1.08E-01
OR-W201	7.53E-04	0.00E+00	1.10E-31	1.62E+03	7.39E+02	0.00E+00	4.34E+01	2.40E+03	9.68E+00
OR-W202	1.08E-04	0.00E+00	3.19E-31	4.15E+02	1.89E+02	0.00E+00	3.34E+00	6.07E+02	2.45E+00
OR-W203	2.38E-07	0.00E+00	4.56E-35	1.87E-02	6.15E-01	0.00E+00	4.75E-04	6.34E-01	2.56E-03
OR-W204	5.30E-08	0.00E+00	5.17E-35	3.18E-01	9.94E-02	0.00E+00	5.39E-04	4.18E-01	1.68E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	3.19E-01	0.00E+00	0.00E+00	0.00E+00	3.19E-01	1.29E-03
RF-MT0001	2.03E-04	0.00E+00	3.21E-34	1.47E+02	1.55E+01	0.00E+00	3.22E-03	1.62E+02	6.55E-01
RF-MT0002	1.56E-05	0.00E+00	2.47E-35	1.13E+01	1.19E+00	0.00E+00	2.47E-04	1.25E+01	5.04E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0003	7.12E-08	0.00E+00	5.63E-36	2.58E+00	2.73E-01	0.00E+00	5.64E-05	2.86E+00	1.15E-02
RF-MT0007	1.79E-07	0.00E+00	0.00E+00	3.22E-01	3.39E-02	0.00E+00	0.00E+00	3.56E-01	1.44E-03
RF-MT0089	7.03E-10	0.00E+00	5.63E-38	2.58E-02	2.72E-03	0.00E+00	5.64E-07	2.86E-02	1.15E-04
RF-MT0090	1.78E-06	0.00E+00	7.97E-35	6.64E+01	6.94E+00	0.00E+00	7.98E-04	7.33E+01	2.96E-01
RF-MT0091	1.11E-04	0.00E+00	8.09E-33	4.43E+03	4.66E+02	0.00E+00	8.39E-02	4.90E+03	1.98E+01
RF-MT0092	1.58E-05	0.00E+00	1.02E-33	6.35E+02	6.80E+01	0.00E+00	1.02E-02	7.03E+02	2.84E+00
RF-MT0093	1.93E-05	0.00E+00	1.05E-33	6.85E+02	7.46E+01	0.00E+00	1.05E-02	7.60E+02	3.06E+00
RF-MT0097	9.64E-07	0.00E+00	4.64E-35	3.58E+01	3.39E+00	0.00E+00	4.64E-04	3.92E+01	1.58E-01
RF-MT0099	1.06E-09	0.00E+00	8.47E-38	3.87E-02	4.07E-03	0.00E+00	8.48E-07	4.28E-02	1.73E-04
RF-MT0290	2.62E-06	0.00E+00	2.10E-34	9.59E+01	1.01E+01	0.00E+00	2.10E-03	1.06E+02	4.27E-01
RF-MT-0292	3.30E-06	0.00E+00	2.65E-34	1.21E+02	1.28E+01	0.00E+00	2.65E-03	1.34E+02	5.41E-01
RF-MT-0299	3.89E-04	0.00E+00	6.78E-33	3.11E+03	3.28E+02	0.00E+00	6.79E-02	3.44E+03	1.39E+01
RF-MT0302	5.95E-09	0.00E+00	2.69E-37	1.34E-01	1.42E-02	0.00E+00	1.91E-05	1.48E-01	5.98E-04
RF-MT0320	7.12E-06	0.00E+00	2.79E-34	1.30E+02	1.38E+01	0.00E+00	2.80E-03	1.44E+02	5.81E-01
RF-MT0321	3.98E-06	0.00E+00	8.32E-35	4.20E+01	4.38E+00	0.00E+00	3.18E-03	4.63E+01	1.87E-01
RF-MT-0328	2.75E-07	0.00E+00	9.97E-36	4.56E+00	4.80E-01	0.00E+00	4.29E-04	5.04E+00	2.03E-02
RF-MT0330	2.86E-06	0.00E+00	1.09E-34	9.21E+01	1.05E+01	0.00E+00	1.09E-03	1.03E+02	4.14E-01
RF-MT-0331	1.72E-05	0.00E+00	6.78E-34	4.05E+02	4.18E+01	0.00E+00	2.70E-02	4.47E+02	1.80E+00
RF-MT0332	2.46E-09	0.00E+00	1.98E-37	9.06E-02	9.53E-03	0.00E+00	1.98E-06	1.00E-01	4.04E-04
RF-MT-0335	1.98E-07	0.00E+00	9.08E-36	4.67E+00	4.94E-01	0.00E+00	6.18E-04	5.16E+00	2.08E-02
RF-MT0336	1.40E-05	0.00E+00	6.02E-34	3.31E+02	3.49E+01	0.00E+00	7.79E-03	3.66E+02	1.48E+00
RF-MT0337	7.91E-06	0.00E+00	3.31E-34	2.02E+02	2.10E+01	0.00E+00	7.06E-03	2.23E+02	9.00E-01
RF-MT0339	2.16E-05	0.00E+00	9.01E-34	4.43E+02	4.63E+01	0.00E+00	2.56E-02	4.90E+02	1.98E+00
RF-MT-0342	1.27E-07	0.00E+00	7.55E-36	4.10E+00	4.25E-01	0.00E+00	1.32E-04	4.52E+00	1.82E-02
RF-MT0371	4.30E-05	0.00E+00	1.75E-33	8.02E+02	8.42E+01	0.00E+00	1.88E-02	8.86E+02	3.57E+00
RF-MT-0372	1.87E-07	0.00E+00	1.23E-35	5.59E+00	5.90E-01	0.00E+00	3.56E-04	6.18E+00	2.49E-02
RF-MT0373	2.82E-06	0.00E+00	1.27E-34	1.05E+02	1.10E+01	0.00E+00	1.27E-03	1.16E+02	4.67E-01
RF-MT0374	9.16E-08	0.00E+00	4.52E-36	2.08E+00	2.19E-01	0.00E+00	4.85E-05	2.29E+00	9.25E-03
RF-MT0376	7.26E-08	0.00E+00	3.65E-36	2.07E+00	2.21E-01	0.00E+00	5.12E-05	2.29E+00	9.23E-03
RF-MT0377	4.31E-05	0.00E+00	2.10E-33	9.66E+02	1.02E+02	0.00E+00	3.10E-02	1.07E+03	4.31E+00
RF-MT0378	4.85E-07	0.00E+00	2.91E-35	1.33E+01	1.41E+00	0.00E+00	2.91E-04	1.47E+01	5.94E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0419	7.79E-07	0.00E+00	2.72E-35	1.24E+01	1.31E+00	0.00E+00	2.72E-04	1.38E+01	5.54E-02
RF-MT0420	1.35E-07	0.00E+00	4.71E-36	2.16E+00	2.28E-01	0.00E+00	4.72E-05	2.39E+00	9.62E-03
RF-MT0423	1.15E-06	0.00E+00	3.83E-35	3.12E+01	3.19E+00	0.00E+00	3.84E-04	3.44E+01	1.39E-01
RF-MT0425	3.39E-08	0.00E+00	1.18E-36	5.40E-01	5.70E-02	0.00E+00	1.18E-05	5.97E-01	2.41E-03
RF-MT-0438	3.07E-07	0.00E+00	1.55E-35	9.59E+00	1.00E+00	0.00E+00	1.68E-04	1.06E+01	4.27E-02
RF-MT0440	1.12E-07	0.00E+00	5.56E-36	3.48E+00	3.73E-01	0.00E+00	2.16E-04	3.85E+00	1.55E-02
RF-MT0442	4.25E-08	0.00E+00	2.40E-36	1.19E+00	1.25E-01	0.00E+00	1.16E-04	1.32E+00	5.31E-03
RF-MT0443	5.23E-07	0.00E+00	3.95E-35	1.85E+01	1.95E+00	0.00E+00	5.49E-04	2.05E+01	8.25E-02
RF-MT0444	4.08E-06	0.00E+00	1.94E-34	8.91E+01	9.36E+00	0.00E+00	1.96E-03	9.85E+01	3.97E-01
RF-MT0480	1.14E-05	0.00E+00	5.44E-34	2.50E+02	2.64E+01	0.00E+00	7.84E-03	2.77E+02	1.12E+00
RF-MT0488	1.83E-05	0.00E+00	8.13E-34	3.72E+02	3.90E+01	0.00E+00	3.82E-02	4.11E+02	1.66E+00
RF-MT0490	8.28E-08	0.00E+00	4.71E-36	2.20E+00	2.32E-01	0.00E+00	5.81E-05	2.43E+00	9.78E-03
RF-MT-0491	6.50E-09	0.00E+00	2.15E-37	9.96E-02	1.05E-02	0.00E+00	4.11E-06	1.10E-01	4.44E-04
RF-MT0523A	5.15E-06	0.00E+00	1.71E-34	7.87E+01	8.29E+00	0.00E+00	1.96E-03	8.69E+01	3.51E-01
RF-MT0523B	5.15E-06	0.00E+00	1.71E-34	7.87E+01	8.29E+00	0.00E+00	1.96E-03	8.69E+01	3.51E-01
RF-MT0523C	5.15E-06	0.00E+00	1.71E-34	7.87E+01	8.29E+00	0.00E+00	1.96E-03	8.69E+01	3.51E-01
RF-MT0523D	5.15E-06	0.00E+00	1.71E-34	7.87E+01	8.29E+00	0.00E+00	1.96E-03	8.69E+01	3.51E-01
RF-MT0523E	5.15E-06	0.00E+00	1.71E-34	7.87E+01	8.29E+00	0.00E+00	1.96E-03	8.69E+01	3.51E-01
RF-MT0531	3.52E-10	0.00E+00	2.82E-38	1.29E-02	1.36E-03	0.00E+00	2.82E-07	1.42E-02	5.74E-05
RF-MT0532E	1.64E-05	0.00E+00	3.67E-34	1.72E+02	1.81E+01	0.00E+00	4.75E-03	1.90E+02	7.65E-01
RF-MT0532F	1.64E-05	0.00E+00	3.67E-34	1.72E+02	1.81E+01	0.00E+00	4.75E-03	1.90E+02	7.65E-01
RF-MT0541	5.98E-07	0.00E+00	5.29E-36	2.43E+00	2.56E-01	0.00E+00	5.30E-05	2.69E+00	1.09E-02
RF-MT0545	3.20E-09	0.00E+00	2.56E-37	1.18E-01	1.24E-02	0.00E+00	2.56E-06	1.30E-01	5.24E-04
RF-MT0800	1.22E-04	0.00E+00	1.27E-34	5.81E+01	6.11E+00	0.00E+00	1.74E-03	6.42E+01	2.59E-01
RF-MT0801	1.40E-05	0.00E+00	1.24E-34	5.70E+01	6.01E+00	0.00E+00	1.24E-03	6.30E+01	2.54E-01
RF-MT0803	3.14E-07	0.00E+00	2.78E-36	1.27E+00	1.34E-01	0.00E+00	2.78E-05	1.41E+00	5.68E-03
RF-MT0806	1.48E-07	0.00E+00	6.67E-36	5.54E+00	5.77E-01	0.00E+00	6.68E-05	6.11E+00	2.47E-02
RF-MT0807	1.87E-06	0.00E+00	5.14E-35	2.35E+01	2.48E+00	0.00E+00	5.14E-04	2.60E+01	1.05E-01
RF-MT0816	2.00E-07	0.00E+00	7.24E-36	3.32E+00	3.49E-01	0.00E+00	7.25E-05	3.67E+00	1.48E-02
RF-MT-0823	9.91E-08	0.00E+00	3.30E-36	1.51E+00	1.60E-01	0.00E+00	3.78E-05	1.67E+00	6.74E-03
RF-MT0827	5.05E-06	0.00E+00	1.83E-34	8.39E+01	8.84E+00	0.00E+00	1.83E-03	9.27E+01	3.74E-01

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0831	9.63E-06	0.00E+00	5.02E-34	2.27E+02	2.40E+01	0.00E+00	1.69E-02	2.51E+02	1.01E+00
RF-MT0832	5.76E-05	0.00E+00	1.82E-33	8.84E+02	9.29E+01	0.00E+00	5.07E-02	9.77E+02	3.94E+00
RF-MT0833	1.75E-05	0.00E+00	5.44E-34	2.55E+02	2.69E+01	0.00E+00	1.44E-02	2.82E+02	1.14E+00
RF-MT0855	3.02E-09	0.00E+00	2.42E-37	1.11E-01	1.17E-02	0.00E+00	2.42E-06	1.23E-01	4.94E-04
RF-MT0857	1.48E-07	0.00E+00	6.63E-36	5.52E+00	5.77E-01	0.00E+00	6.64E-05	6.10E+00	2.46E-02
RF-MT0H61	5.49E-06	0.00E+00	2.47E-34	2.05E+02	2.14E+01	0.00E+00	2.47E-03	2.26E+02	9.11E-01
RF-MT2116	6.17E-07	0.00E+00	1.96E-35	9.44E+00	9.94E-01	0.00E+00	5.43E-04	1.04E+01	4.21E-02
RF-MT3010	3.87E-06	0.00E+00	2.03E-34	9.36E+01	9.94E+00	0.00E+00	2.42E-03	1.04E+02	4.18E-01
RF-MT3011	2.88E-05	0.00E+00	1.27E-33	5.78E+02	6.11E+01	0.00E+00	2.02E-02	6.39E+02	2.58E+00
RF-MT420P	1.53E-04	0.00E+00	6.40E-33	4.76E+03	5.01E+02	0.00E+00	7.38E-02	5.26E+03	2.12E+01
RF-MT532A	4.04E-05	0.00E+00	9.05E-34	4.24E+02	4.45E+01	0.00E+00	1.17E-02	4.69E+02	1.89E+00
RF-MT532B	1.81E-04	0.00E+00	4.06E-33	1.90E+03	2.00E+02	0.00E+00	5.25E-02	2.10E+03	8.48E+00
RF-MT532C	3.64E-04	0.00E+00	8.16E-33	3.81E+03	4.00E+02	0.00E+00	1.06E-01	4.21E+03	1.70E+01
RF-MT532D	2.30E-06	0.00E+00	5.14E-35	2.41E+01	2.53E+00	0.00E+00	6.65E-04	2.67E+01	1.08E-01
RF-TT0069	1.32E-08	0.00E+00	6.09E-37	2.79E-01	2.94E-02	0.00E+00	7.76E-05	3.09E-01	1.25E-03
RF-TT0200	6.28E-07	0.00E+00	2.46E-35	1.15E+01	1.22E+00	0.00E+00	2.47E-04	1.27E+01	5.11E-02
RF-TT0299	2.60E-06	0.00E+00	4.56E-35	2.09E+01	2.20E+00	0.00E+00	4.57E-04	2.31E+01	9.32E-02
RF-TT0300	2.12E-05	0.00E+00	1.30E-33	6.00E+02	6.35E+01	0.00E+00	2.11E-02	6.64E+02	2.68E+00
RF-TT0301	2.87E-06	0.00E+00	1.76E-34	8.17E+01	8.63E+00	0.00E+00	2.87E-03	9.03E+01	3.64E-01
RF-TT0302	1.42E-07	0.00E+00	6.40E-36	3.19E+00	3.37E-01	0.00E+00	4.52E-04	3.53E+00	1.42E-02
RF-TT0303	8.54E-07	0.00E+00	3.74E-35	1.72E+01	1.81E+00	0.00E+00	1.38E-03	1.90E+01	7.65E-02
RF-TT0310	2.91E-06	0.00E+00	1.76E-34	7.72E+01	8.39E+00	0.00E+00	1.94E-03	8.55E+01	3.45E-01
RF-TT0312	6.98E-05	0.00E+00	3.17E-33	1.69E+03	1.76E+02	0.00E+00	3.34E-02	1.86E+03	7.51E+00
RF-TT0317	4.39E-08	0.00E+00	3.45E-36	1.58E+00	1.66E-01	0.00E+00	3.45E-05	1.75E+00	7.04E-03
RF-TT0320	2.82E-05	0.00E+00	1.10E-33	5.15E+02	5.45E+01	0.00E+00	1.11E-02	5.70E+02	2.30E+00
RF-TT0330	1.00E-05	0.00E+00	3.82E-34	3.24E+02	3.66E+01	0.00E+00	3.83E-03	3.60E+02	1.45E+00
RF-TT-0331	4.98E-05	0.00E+00	1.97E-33	1.18E+03	1.22E+02	0.00E+00	7.83E-02	1.30E+03	5.23E+00
RF-TT-0334	2.17E-05	0.00E+00	1.60E-33	7.31E+02	7.70E+01	0.00E+00	1.60E-02	8.08E+02	3.26E+00
RF-TT0335	2.64E-05	0.00E+00	1.21E-33	6.22E+02	6.59E+01	0.00E+00	8.24E-02	6.88E+02	2.77E+00
RF-TT0336	2.34E-05	0.00E+00	1.00E-33	5.51E+02	5.80E+01	0.00E+00	1.30E-02	6.09E+02	2.45E+00
RF-TT0337	2.78E-05	0.00E+00	1.16E-33	7.11E+02	7.35E+01	0.00E+00	2.48E-02	7.84E+02	3.16E+00

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0338	1.18E-04	0.00E+00	4.22E-33	2.77E+03	2.87E+02	0.00E+00	5.02E-02	3.06E+03	1.23E+01
RF-TT0340	1.01E-06	0.00E+00	8.05E-35	3.69E+01	3.90E+00	0.00E+00	8.06E-04	4.08E+01	1.64E-01
RF-TT0342	6.74E-06	0.00E+00	4.03E-34	2.17E+02	2.25E+01	0.00E+00	7.05E-03	2.40E+02	9.67E-01
RF-TT0360	5.13E-07	0.00E+00	2.04E-35	9.74E+00	1.04E+00	0.00E+00	2.11E-04	1.08E+01	4.35E-02
RF-TT0368	1.03E-05	0.00E+00	4.10E-34	1.96E+02	2.08E+01	0.00E+00	4.23E-03	2.16E+02	8.72E-01
RF-TT0370	2.03E-05	0.00E+00	8.85E-34	4.35E+02	4.59E+01	0.00E+00	1.65E-02	4.81E+02	1.94E+00
RF-TT0371	4.39E-07	0.00E+00	1.78E-35	8.17E+00	8.60E-01	0.00E+00	1.91E-04	9.02E+00	3.64E-02
RF-TT0372	5.36E-08	0.00E+00	3.51E-36	1.60E+00	1.69E-01	0.00E+00	1.02E-04	1.76E+00	7.11E-03
RF-TT0374	1.67E-06	0.00E+00	8.24E-35	3.77E+01	3.97E+00	0.00E+00	8.83E-04	4.17E+01	1.68E-01
RF-TT0375A	1.74E-08	0.00E+00	1.36E-36	6.20E-01	6.52E-02	0.00E+00	1.36E-05	6.85E-01	2.76E-03
RF-TT0375B	1.74E-08	0.00E+00	1.36E-36	6.20E-01	6.52E-02	0.00E+00	1.36E-05	6.85E-01	2.76E-03
RF-TT0376	4.00E-06	0.00E+00	2.01E-34	1.14E+02	1.22E+01	0.00E+00	2.82E-03	1.26E+02	5.08E-01
RF-TT0377	2.24E-06	0.00E+00	1.09E-34	5.00E+01	5.28E+00	0.00E+00	1.61E-03	5.53E+01	2.23E-01
RF-TT0391	5.00E-07	0.00E+00	1.54E-35	1.27E+01	1.32E+00	0.00E+00	1.54E-04	1.40E+01	5.64E-02
RF-TT0392	1.76E-07	0.00E+00	9.66E-36	6.61E+00	6.94E-01	0.00E+00	9.68E-05	7.31E+00	2.95E-02
RF-TT0393	1.45E-05	0.00E+00	6.75E-34	3.08E+02	3.25E+01	0.00E+00	6.75E-03	3.40E+02	1.37E+00
RF-TT0398	3.16E-07	0.00E+00	1.78E-35	1.24E+01	1.29E+00	0.00E+00	1.78E-04	1.37E+01	5.50E-02
RF-TT0409	2.64E-07	0.00E+00	8.32E-36	6.38E+00	6.66E-01	0.00E+00	8.39E-05	7.05E+00	2.84E-02
RF-TT0412	2.64E-07	0.00E+00	8.32E-36	6.38E+00	6.66E-01	0.00E+00	8.39E-05	7.05E+00	2.84E-02
RF-TT0414	8.19E-06	0.00E+00	2.57E-34	1.98E+02	2.06E+01	0.00E+00	2.59E-03	2.18E+02	8.81E-01
RF-TT0430	2.39E-09	0.00E+00	1.92E-37	8.76E-02	9.25E-03	0.00E+00	1.92E-06	9.69E-02	3.91E-04
RF-TT0431	5.95E-07	0.00E+00	4.68E-35	2.16E+01	2.28E+00	0.00E+00	6.84E-04	2.39E+01	9.62E-02
RF-TT0438	3.54E-05	0.00E+00	1.78E-33	1.10E+03	1.15E+02	0.00E+00	1.93E-02	1.22E+03	4.91E+00
RF-TT0440	3.49E-06	0.00E+00	1.73E-34	1.09E+02	1.17E+01	0.00E+00	6.76E-03	1.20E+02	4.85E-01
RF-TT0441	1.72E-05	0.00E+00	8.13E-34	3.75E+02	3.97E+01	0.00E+00	1.26E-02	4.15E+02	1.67E+00
RF-TT0442	2.48E-06	0.00E+00	1.40E-34	6.94E+01	7.32E+00	0.00E+00	6.78E-03	7.68E+01	3.10E-01
RF-TT0443	5.31E-08	0.00E+00	4.03E-36	1.88E+00	1.98E-01	0.00E+00	5.59E-05	2.08E+00	8.38E-03
RF-TT0479	5.20E-07	0.00E+00	4.18E-35	1.90E+01	2.01E+00	0.00E+00	4.18E-04	2.10E+01	8.48E-02
RF-TT0480	3.54E-05	0.00E+00	1.69E-33	7.79E+02	8.18E+01	0.00E+00	2.43E-02	8.61E+02	3.47E+00
RF-TT0481	1.99E-08	0.00E+00	9.51E-37	4.37E-01	4.63E-02	0.00E+00	1.37E-05	4.84E-01	1.95E-03
RF-TT0483	6.40E-08	0.00E+00	5.14E-36	2.35E+00	2.48E-01	0.00E+00	1.68E-02	2.61E+00	1.05E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0484	3.43E-07	0.00E+00	2.13E-35	9.74E+00	1.03E+00	0.00E+00	3.21E-04	1.08E+01	4.34E-02
RF-TT0485	2.81E-08	0.00E+00	1.32E-36	6.01E-01	6.35E-02	0.00E+00	2.83E-04	6.65E-01	2.68E-03
RF-TT0486	1.67E-07	0.00E+00	7.78E-36	3.57E+00	3.76E-01	0.00E+00	2.99E-04	3.94E+00	1.59E-02
RF-TT0487	8.37E-07	0.00E+00	2.65E-35	1.28E+01	1.35E+00	0.00E+00	7.36E-04	1.42E+01	5.71E-02
RF-TT0489	2.39E-07	0.00E+00	1.19E-35	5.44E+00	5.73E-01	0.00E+00	2.17E-04	6.01E+00	2.42E-02
RF-TT0490	1.32E-05	0.00E+00	7.55E-34	3.51E+02	3.69E+01	0.00E+00	9.29E-03	3.88E+02	1.56E+00
RF-TT0491	3.07E-07	0.00E+00	1.02E-35	4.70E+00	4.94E-01	0.00E+00	1.95E-04	5.19E+00	2.09E-02
RF-TT0492	1.03E-07	0.00E+00	5.75E-36	2.62E+00	2.77E-01	0.00E+00	5.75E-05	2.90E+00	1.17E-02
RF-TT0523A	6.93E-07	0.00E+00	2.31E-35	1.06E+01	1.12E+00	0.00E+00	2.65E-04	1.17E+01	4.71E-02
RF-TT0523B	6.93E-07	0.00E+00	2.31E-35	1.06E+01	1.12E+00	0.00E+00	2.65E-04	1.17E+01	4.71E-02
RF-TT0523C	6.93E-07	0.00E+00	2.31E-35	1.06E+01	1.12E+00	0.00E+00	2.65E-04	1.17E+01	4.71E-02
RF-TT0523D	6.93E-07	0.00E+00	2.31E-35	1.06E+01	1.12E+00	0.00E+00	2.65E-04	1.17E+01	4.71E-02
RF-TT0523E	6.93E-07	0.00E+00	2.31E-35	1.06E+01	1.12E+00	0.00E+00	2.65E-04	1.17E+01	4.71E-02
RF-TT0532A	1.74E-05	0.00E+00	3.87E-34	1.82E+02	1.91E+01	0.00E+00	5.01E-03	2.01E+02	8.11E-01
RF-TT0532B	1.74E-05	0.00E+00	3.87E-34	1.82E+02	1.91E+01	0.00E+00	5.01E-03	2.01E+02	8.11E-01
RF-TT0541	2.87E-08	0.00E+00	2.30E-36	1.06E+00	1.11E-01	0.00E+00	2.31E-05	1.17E+00	4.71E-03
RF-TT0545	6.40E-09	0.00E+00	5.14E-37	2.35E-01	2.48E-02	0.00E+00	5.14E-06	2.59E-01	1.05E-03
RF-TT0601	2.22E-06	0.00E+00	8.85E-35	4.23E+01	4.52E+00	0.00E+00	9.13E-04	4.68E+01	1.89E-01
RF-TT0802	2.49E-04	0.00E+00	7.28E-33	3.34E+03	3.52E+02	0.00E+00	7.29E-02	3.69E+03	1.49E+01
RF-TT0809	2.05E-05	0.00E+00	5.98E-34	2.75E+02	2.89E+01	0.00E+00	5.99E-03	3.04E+02	1.23E+00
RF-TT0821	4.42E-05	0.00E+00	2.17E-33	1.08E+03	1.14E+02	0.00E+00	1.85E-01	1.19E+03	4.81E+00
RF-TT0822	4.89E-05	0.00E+00	1.69E-33	8.09E+02	8.49E+01	0.00E+00	1.94E-01	8.94E+02	3.61E+00
RF-TT0823	9.91E-08	0.00E+00	3.30E-36	1.51E+00	1.60E-01	0.00E+00	3.78E-05	1.67E+00	6.74E-03
RF-TT0824	1.02E-04	0.00E+00	4.64E-33	2.18E+03	2.30E+02	0.00E+00	1.07E-01	2.41E+03	9.72E+00
RF-TT0825	8.47E-05	0.00E+00	3.35E-33	1.64E+03	1.73E+02	0.00E+00	1.12E-01	1.81E+03	7.31E+00
RF-TT0832	6.27E-05	0.00E+00	1.99E-33	9.59E+02	1.01E+02	0.00E+00	5.52E-02	1.06E+03	4.27E+00
RF-TT0854	2.26E-08	0.00E+00	1.81E-36	8.24E-01	8.73E-02	0.00E+00	7.45E-04	9.12E-01	3.68E-03
RF-TT0886	3.20E-09	0.00E+00	2.56E-37	1.17E-01	1.24E-02	0.00E+00	2.56E-06	1.29E-01	5.21E-04
RF-TT2216	9.26E-07	0.00E+00	2.93E-35	1.42E+01	1.49E+00	0.00E+00	8.15E-04	1.57E+01	6.34E-02
RF-TT3010	4.94E-05	0.00E+00	2.60E-33	1.20E+03	1.27E+02	0.00E+00	3.08E-02	1.33E+03	5.34E+00
RF-TT3011	1.25E-04	0.00E+00	5.48E-33	2.50E+03	2.64E+02	0.00E+00	8.76E-02	2.77E+03	1.12E+01

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT301U	1.04E-05	0.00E+00	5.79E-34	2.72E+02	2.91E+01	0.00E+00	5.95E-03	3.01E+02	1.21E+00
RF-TT310P	3.00E-06	0.00E+00	1.51E-34	9.14E+01	9.15E+00	0.00E+00	1.51E-03	1.01E+02	4.05E-01
RF-TT338S	8.76E-08	0.00E+00	6.90E-36	3.15E+00	3.33E-01	0.00E+00	6.91E-05	3.49E+00	1.41E-02
RF-TT390P	4.93E-07	0.00E+00	1.87E-35	1.54E+01	1.49E+00	0.00E+00	2.15E-04	1.68E+01	6.79E-02
RF-TT391P	2.72E-05	0.00E+00	8.39E-34	6.90E+02	7.15E+01	0.00E+00	8.40E-03	7.61E+02	3.07E+00
RF-TT392P	5.51E-05	0.00E+00	3.02E-33	2.07E+03	2.17E+02	0.00E+00	3.03E-02	2.29E+03	9.21E+00
RF-TT393R	8.15E-06	0.00E+00	5.14E-34	3.16E+02	3.34E+01	0.00E+00	5.31E-03	3.50E+02	1.41E+00
RF-TT394P	1.01E-06	0.00E+00	3.18E-35	2.44E+01	2.39E+00	0.00E+00	3.25E-04	2.68E+01	1.08E-01
RF-TT395P	1.35E-06	0.00E+00	4.25E-35	3.27E+01	3.19E+00	0.00E+00	4.35E-04	3.58E+01	1.45E-01
RF-TT396P	3.38E-07	0.00E+00	1.06E-35	8.17E+00	7.97E-01	0.00E+00	1.09E-04	8.96E+00	3.61E-02
RF-TT398P	3.27E-05	0.00E+00	1.84E-33	1.28E+03	1.34E+02	0.00E+00	1.84E-02	1.41E+03	5.70E+00
RF-TT398R	2.70E-04	0.00E+00	3.42E-33	2.07E+03	2.16E+02	0.00E+00	3.42E-02	2.28E+03	9.21E+00
RF-TT411R	9.77E-06	0.00E+00	3.07E-34	2.36E+02	2.46E+01	0.00E+00	3.10E-03	2.61E+02	1.05E+00
RF-TT429R	2.05E-05	0.00E+00	6.59E-35	5.47E+01	5.59E+00	0.00E+00	6.60E-04	6.03E+01	2.43E-01
RF-TT433X	6.47E-06	0.00E+00	1.82E-35	1.57E+01	1.45E+00	0.00E+00	1.83E-04	1.72E+01	6.93E-02
RF-TT436R	4.74E-05	0.00E+00	2.64E-34	2.06E+02	2.14E+01	0.00E+00	2.64E-03	2.27E+02	9.17E-01
RF-TT454X	2.78E-06	0.00E+00	1.55E-35	1.21E+01	1.26E+00	0.00E+00	1.55E-04	1.34E+01	5.40E-02
RL-T101	1.41E-05	0.00E+00	9.43E-34	6.55E+02	6.77E+01	0.00E+00	8.58E-03	7.23E+02	2.92E+00
RL-T102	1.79E-10	0.00E+00	1.20E-38	8.39E-03	8.63E-04	0.00E+00	1.23E-06	9.25E-03	3.73E-05
RL-T103	1.27E-05	0.00E+00	1.14E-33	2.86E+02	2.93E+01	0.00E+00	1.04E-02	3.16E+02	1.27E+00
RL-T104	2.57E-10	0.00E+00	1.71E-38	1.19E-02	1.24E-03	0.00E+00	1.88E-07	1.32E-02	5.30E-05
RL-T105	9.84E-08	0.00E+00	6.48E-36	4.52E+00	4.66E-01	0.00E+00	1.03E-04	4.99E+00	2.01E-02
RL-T106	9.49E-08	0.00E+00	6.36E-36	4.42E+00	4.56E-01	0.00E+00	5.79E-05	4.88E+00	1.97E-02
RL-T107	2.61E-04	0.00E+00	3.74E-30	1.22E+04	1.26E+03	0.00E+00	3.48E+01	1.35E+04	5.44E+01
RL-T108	1.49E-07	0.00E+00	6.44E-34	6.95E+00	7.18E-01	0.00E+00	5.89E-03	7.68E+00	3.10E-02
RL-T109	2.05E-07	0.00E+00	1.33E-35	9.21E+00	9.53E-01	0.00E+00	2.28E-02	1.02E+01	4.11E-02
RL-T110	2.30E-05	0.00E+00	2.53E-33	1.06E+03	1.09E+02	0.00E+00	1.35E+00	1.17E+03	4.71E+00
RL-T112	9.28E-06	0.00E+00	1.07E-33	1.40E+02	1.45E+01	0.00E+00	7.25E-01	1.55E+02	6.26E-01
RL-T113	9.91E-09	0.00E+00	2.07E-36	4.61E-01	4.76E-02	0.00E+00	1.88E-05	5.09E-01	2.05E-03
RL-T114	1.51E-06	0.00E+00	1.01E-34	7.01E+01	7.25E+00	0.00E+00	9.18E-04	7.74E+01	3.12E-01
RL-T115	3.84E-05	0.00E+00	3.27E-33	9.21E+02	9.53E+01	0.00E+00	4.31E-01	1.02E+03	4.10E+00

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T116	2.47E-06	0.00E+00	1.66E-34	1.15E+02	1.19E+01	0.00E+00	5.61E-02	1.27E+02	5.10E-01
RL-T118	6.36E-06	0.00E+00	1.32E-33	1.14E+02	1.18E+01	0.00E+00	8.22E-01	1.26E+02	5.10E-01
RL-T120	1.54E-06	0.00E+00	1.39E-34	3.37E+01	3.45E+00	0.00E+00	1.26E-03	3.72E+01	1.50E-01
RL-T122	8.74E-08	0.00E+00	5.86E-36	4.06E+00	4.21E-01	0.00E+00	1.42E+00	5.90E+00	2.38E-02
RL-T123	2.57E-07	0.00E+00	1.72E-35	1.19E+01	1.24E+00	0.00E+00	5.82E-02	1.32E+01	5.32E-02
RL-T125	5.12E-05	0.00E+00	4.25E-33	2.49E+02	5.94E+01	0.00E+00	3.87E-02	3.09E+02	1.25E+00
RL-T127	4.93E-05	0.00E+00	1.07E-33	7.45E+02	7.70E+01	0.00E+00	8.75E-02	8.22E+02	3.32E+00
RL-T128	7.30E-08	0.00E+00	2.60E-41	1.81E-05	1.87E-06	0.00E+00	2.37E-10	2.01E-05	8.09E-08
RL-T129	2.19E-07	0.00E+00	4.94E-33	1.03E+01	1.05E+00	0.00E+00	5.25E-02	1.14E+01	4.58E-02
RL-T130	4.65E-10	0.00E+00	3.12E-38	2.18E-02	2.25E-03	0.00E+00	8.10E-05	2.41E-02	9.73E-05
RL-T131	1.89E-07	0.00E+00	1.71E-35	4.15E+00	4.25E-01	0.00E+00	8.16E-03	4.58E+00	1.85E-02
RL-T132	4.51E-05	0.00E+00	3.01E-33	2.11E+03	2.17E+02	0.00E+00	2.66E-01	2.32E+03	9.36E+00
RL-T133	9.19E-10	0.00E+00	4.83E-38	3.45E-02	3.56E-03	0.00E+00	4.40E-07	3.81E-02	1.54E-04
RL-T134	1.94E-09	0.00E+00	1.30E-37	9.06E-02	9.32E-03	0.00E+00	1.18E-06	1.00E-01	4.03E-04
RL-T135	9.10E-09	0.00E+00	6.09E-37	4.24E-01	4.38E-02	0.00E+00	4.04E-03	4.72E-01	1.90E-03
RL-T137	1.48E-04	0.00E+00	1.33E-32	3.23E+03	3.31E+02	0.00E+00	1.27E-01	3.56E+03	1.44E+01
RL-T140	1.73E-04	0.00E+00	1.27E-32	3.12E+03	3.56E+02	0.00E+00	2.56E+01	3.51E+03	1.41E+01
RL-T143	1.08E-06	0.00E+00	7.24E-35	5.05E+01	5.21E+00	0.00E+00	3.82E-02	5.57E+01	2.25E-01
RL-T145	3.08E-06	0.00E+00	2.07E-34	1.44E+02	1.48E+01	0.00E+00	8.90E-02	1.59E+02	6.40E-01
RL-W407	8.87E-06	0.00E+00	4.41E-34	3.30E+02	3.40E+01	0.00E+00	4.01E-03	3.64E+02	1.47E+00
RL-W408	3.63E-11	0.00E+00	1.86E-39	1.33E-03	1.38E-04	0.00E+00	1.70E-08	1.47E-03	5.93E-06
RL-W415	8.03E-10	0.00E+00	4.10E-38	2.95E-02	3.05E-03	0.00E+00	3.73E-07	3.26E-02	1.31E-04
RL-W418	3.43E-09	0.00E+00	1.73E-37	1.27E-01	1.31E-02	0.00E+00	1.57E-06	1.40E-01	5.63E-04
RL-W437	2.91E-05	0.00E+00	1.45E-33	1.08E+03	1.12E+02	0.00E+00	1.32E-02	1.19E+03	4.80E+00
RL-W438	5.09E-11	0.00E+00	2.60E-39	1.87E-03	1.92E-04	0.00E+00	2.37E-08	2.06E-03	8.30E-06
RL-W439	1.59E-03	0.00E+00	1.43E-31	3.60E+04	3.69E+03	0.00E+00	1.31E+00	3.97E+04	1.60E+02
RL-W443	2.56E-05	0.00E+00	1.28E-33	9.51E+02	9.80E+01	0.00E+00	1.16E-02	1.05E+03	4.23E+00
RL-W444	1.90E-05	0.00E+00	9.47E-34	7.06E+02	7.28E+01	0.00E+00	8.62E-03	7.78E+02	3.14E+00
RL-W447	2.18E-09	0.00E+00	1.12E-37	7.94E-02	8.25E-03	0.00E+00	1.02E-06	8.77E-02	3.53E-04
RL-W448	1.61E-11	0.00E+00	8.24E-40	5.90E-04	6.08E-05	0.00E+00	7.50E-09	6.50E-04	2.62E-06
RL-W449	1.32E-07	0.00E+00	3.02E-38	1.69E-02	1.74E-03	0.00E+00	2.75E-07	1.86E-02	7.50E-05

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W450	2.43E-10	0.00E+00	1.24E-38	8.91E-03	9.18E-04	0.00E+00	1.13E-07	9.83E-03	3.96E-05
RL-W451	3.46E-11	0.00E+00	1.77E-39	1.27E-03	1.31E-04	0.00E+00	1.61E-08	1.40E-03	5.63E-06
RL-W452	1.51E-09	0.00E+00	7.63E-38	5.58E-02	5.77E-03	0.00E+00	6.94E-07	6.16E-02	2.48E-04
RL-W453	4.30E-10	0.00E+00	2.15E-38	1.60E-02	1.65E-03	0.00E+00	1.95E-07	1.77E-02	7.13E-05
RL-W454	6.01E-09	0.00E+00	3.00E-37	2.24E-01	2.31E-02	0.00E+00	2.73E-06	2.47E-01	9.96E-04
RL-W455	1.60E-09	0.00E+00	8.09E-38	5.93E-02	6.11E-03	0.00E+00	7.36E-07	6.54E-02	2.64E-04
RL-W456	2.11E-07	0.00E+00	1.06E-35	7.87E+00	8.11E-01	0.00E+00	9.63E-05	8.68E+00	3.50E-02
RL-W457	2.05E-08	0.00E+00	1.03E-36	7.64E-01	7.87E-02	0.00E+00	9.35E-06	8.43E-01	3.40E-03
RL-W458	6.50E-08	0.00E+00	5.25E-36	3.14E-01	8.08E-02	0.00E+00	4.78E-05	3.95E-01	1.59E-03
RL-W459	6.25E-07	0.00E+00	5.40E-35	7.79E+00	1.10E+00	0.00E+00	4.92E-04	8.89E+00	3.59E-02
RL-W460	3.81E-09	0.00E+00	1.90E-37	1.42E-01	1.46E-02	0.00E+00	1.73E-06	1.56E-01	6.30E-04
RL-W461	3.52E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.52E-09	1.42E-11
RL-W462	1.09E-09	0.00E+00	5.52E-38	4.01E-02	4.14E-03	0.00E+00	5.03E-07	4.42E-02	1.78E-04
RL-W463	5.59E-09	0.00E+00	2.79E-37	2.08E-01	2.15E-02	0.00E+00	2.54E-06	2.30E-01	9.26E-04
RL-W464	2.58E-09	0.00E+00	1.28E-37	9.59E-02	9.87E-03	0.00E+00	1.17E-06	1.06E-01	4.26E-04
RL-W465	1.72E-08	0.00E+00	8.70E-37	6.38E-01	6.59E-02	0.00E+00	7.92E-06	7.04E-01	2.84E-03
RL-W466	2.36E-07	0.00E+00	1.18E-35	8.76E+00	9.04E-01	0.00E+00	1.08E-04	9.67E+00	3.90E-02
RL-W467	1.21E-08	0.00E+00	6.09E-37	4.46E-01	4.59E-02	0.00E+00	5.55E-06	4.92E-01	1.99E-03
RL-W468	6.19E-11	0.00E+00	3.14E-39	2.29E-03	2.36E-04	0.00E+00	2.86E-08	2.52E-03	1.02E-05
RL-W469	2.51E-08	0.00E+00	1.26E-36	9.29E-01	9.63E-02	0.00E+00	1.15E-05	1.03E+00	4.13E-03
RL-W470	7.10E-07	0.00E+00	5.86E-35	3.45E+00	8.22E-01	0.00E+00	5.34E-04	4.27E+00	1.72E-02
RL-W474	2.69E-08	0.00E+00	6.48E-36	7.87E-03	3.11E-03	0.00E+00	5.90E-05	1.10E-02	4.45E-05
RL-W476	4.54E-08	0.00E+00	2.33E-36	1.72E+00	1.79E-01	0.00E+00	2.12E-05	1.90E+00	7.67E-03
RL-W480	7.40E-09	0.00E+00	3.73E-37	2.73E-01	2.83E-02	0.00E+00	3.40E-06	3.02E-01	1.22E-03
RL-W481	1.16E-08	0.00E+00	5.86E-37	4.29E-01	4.42E-02	0.00E+00	5.34E-06	4.73E-01	1.91E-03
RL-W482	1.54E-05	0.00E+00	1.95E-34	5.46E-02	4.70E-02	0.00E+00	1.78E-03	1.03E-01	4.17E-04
RL-W483	1.15E-06	0.00E+00	1.51E-35	3.54E-03	3.34E-03	0.00E+00	1.38E-04	7.01E-03	2.83E-05
RL-W484	4.87E-09	0.00E+00	1.22E-37	4.94E-02	5.45E-03	0.00E+00	1.11E-06	5.48E-02	2.21E-04
RL-W485	2.86E-10	0.00E+00	1.73E-38	5.34E-03	5.90E-04	0.00E+00	1.57E-07	5.93E-03	2.39E-05
RL-W486	1.21E-10	0.00E+00	7.28E-39	2.26E-03	2.48E-04	0.00E+00	6.63E-08	2.50E-03	1.01E-05
RL-W487	1.97E-08	0.00E+00	9.35E-37	3.23E-01	4.11E-02	0.00E+00	8.51E-06	3.64E-01	1.47E-03

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	1.20E-08	0.00E+00	8.82E-37	4.18E-01	4.38E-02	0.00E+00	8.03E-06	4.62E-01	1.86E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	4.44E-09	0.00E+00	7.44E-37	4.38E-02	4.45E-03	0.00E+00	6.77E-06	4.83E-02	1.95E-04
RL-W492	2.56E-10	0.00E+00	1.83E-38	8.76E-03	9.15E-04	0.00E+00	1.67E-07	9.68E-03	3.90E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	1.02E-05	0.00E+00	1.06E-33	2.21E-01	8.73E-02	0.00E+00	9.67E-03	3.18E-01	1.28E-03
RL-W495	1.84E-07	0.00E+00	2.89E-36	2.12E-03	7.80E-04	0.00E+00	2.63E-05	2.93E-03	1.18E-05
RL-W496	1.19E-06	0.00E+00	3.32E-35	6.97E-03	2.59E-03	0.00E+00	3.03E-04	9.86E-03	3.97E-05
RL-W497	4.97E-08	0.00E+00	6.55E-36	4.18E-01	8.77E-02	0.00E+00	5.97E-05	5.06E-01	2.04E-03
RL-W498	1.93E-07	0.00E+00	9.74E-36	7.15E+00	7.39E-01	0.00E+00	8.86E-05	7.89E+00	3.18E-02
RL-W499	1.73E-12	0.00E+00	8.74E-41	6.40E-05	6.63E-06	0.00E+00	7.96E-10	7.07E-05	2.85E-07
RL-W500	1.23E-10	0.00E+00	1.09E-38	2.61E-03	2.69E-04	0.00E+00	9.88E-08	2.88E-03	1.16E-05
RL-W501	5.11E-06	0.00E+00	2.42E-34	8.39E+01	1.06E+01	0.00E+00	2.20E-03	9.45E+01	3.81E-01
RL-W502	9.24E-10	0.00E+00	4.68E-38	3.42E-02	3.52E-03	0.00E+00	4.26E-07	3.77E-02	1.52E-04
RL-W503	5.34E-08	0.00E+00	4.79E-36	1.21E+00	1.24E-01	0.00E+00	4.36E-05	1.33E+00	5.36E-03
RL-W504	1.97E-08	0.00E+00	9.35E-37	3.23E-01	4.11E-02	0.00E+00	8.51E-06	3.64E-01	1.47E-03
RL-W505	9.28E-10	0.00E+00	4.91E-38	3.49E-02	3.59E-03	0.00E+00	4.47E-07	3.85E-02	1.55E-04
RL-W506	3.36E-10	0.00E+00	1.93E-38	1.15E-02	1.18E-03	0.00E+00	1.76E-07	1.26E-02	5.10E-05
RL-W507	3.34E-11	0.00E+00	1.69E-39	1.24E-03	1.27E-04	0.00E+00	1.54E-08	1.36E-03	5.50E-06
RL-W508	6.14E-07	0.00E+00	5.52E-35	1.34E+01	1.38E+00	0.00E+00	5.03E-04	1.48E+01	5.96E-02
RL-W509	6.04E-06	0.00E+00	4.41E-34	1.09E+02	1.24E+01	0.00E+00	4.01E-03	1.22E+02	4.91E-01
RL-W510	5.10E-07	0.00E+00	4.52E-35	1.09E+01	1.12E+00	0.00E+00	4.12E-04	1.20E+01	4.83E-02
RL-W511	5.19E-05	0.00E+00	2.18E-33	1.45E+03	1.47E+02	0.00E+00	2.02E-02	1.60E+03	6.45E+00
RL-W512	4.54E-05	0.00E+00	1.47E-33	8.76E+02	1.01E+02	0.00E+00	1.34E-02	9.77E+02	3.94E+00
RL-W513	4.84E-03	0.00E+00	5.98E-31	1.43E+04	3.29E+03	0.00E+00	5.44E+00	1.76E+04	7.10E+01
RL-W514	1.37E-10	0.00E+00	6.86E-39	5.07E-03	5.25E-04	0.00E+00	6.25E-08	5.60E-03	2.26E-05
RL-W515	5.34E-09	0.00E+00	2.69E-37	1.98E-01	2.04E-02	0.00E+00	2.45E-06	2.18E-01	8.80E-04
RL-W516	7.41E-09	0.00E+00	3.74E-37	2.73E-01	2.83E-02	0.00E+00	3.40E-06	3.02E-01	1.22E-03
RL-W517	6.60E-17	0.00E+00	3.34E-45	2.43E-09	2.51E-10	0.00E+00	3.04E-14	2.69E-09	1.08E-11
RL-W518	1.87E-07	0.00E+00	1.41E-35	3.49E+00	3.90E-01	0.00E+00	1.28E-04	3.88E+00	1.57E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W519	3.33E-08	0.00E+00	1.67E-36	1.24E+00	1.27E-01	0.00E+00	1.52E-05	1.36E+00	5.50E-03
RL-W520	3.68E-09	0.00E+00	1.88E-37	1.36E-01	1.40E-02	0.00E+00	1.71E-06	1.50E-01	6.03E-04
RL-W521	6.85E-11	0.00E+00	3.45E-39	2.52E-03	2.61E-04	0.00E+00	3.14E-08	2.79E-03	1.12E-05
RL-W522	1.43E-06	0.00E+00	1.28E-34	1.67E+01	2.21E+00	0.00E+00	1.17E-03	1.89E+01	7.63E-02
RL-W523	4.30E-07	0.00E+00	4.87E-35	1.11E+00	3.12E-01	0.00E+00	4.43E-04	1.42E+00	5.73E-03
RL-W524	1.78E-06	0.00E+00	1.86E-34	1.02E+01	1.83E+00	0.00E+00	1.70E-03	1.20E+01	4.85E-02
RL-W525	1.42E-07	0.00E+00	1.26E-35	1.21E+00	1.85E-01	0.00E+00	1.15E-04	1.39E+00	5.61E-03
RL-W526	5.36E-07	0.00E+00	4.56E-35	1.29E+01	1.33E+00	0.00E+00	4.15E-04	1.42E+01	5.73E-02
RL-W527	5.87E-08	0.00E+00	6.59E-36	1.36E+00	1.50E-01	0.00E+00	6.00E-05	1.51E+00	6.10E-03
RL-W528	2.63E-05	0.00E+00	2.80E-33	4.34E+01	1.93E+01	0.00E+00	2.55E-02	6.27E+01	2.53E-01
RL-W529	2.19E-08	0.00E+00	1.97E-36	4.79E-01	4.90E-02	0.00E+00	1.79E-05	5.28E-01	2.13E-03
RL-W530	2.58E-07	0.00E+00	2.28E-35	5.48E+00	5.63E-01	0.00E+00	2.08E-04	6.04E+00	2.44E-02
RL-W531	1.54E-05	0.00E+00	2.29E-33	2.37E+01	7.91E+00	0.00E+00	2.09E-02	3.16E+01	1.27E-01
RL-W532	4.94E-08	0.00E+00	2.49E-36	1.83E+00	1.89E-01	0.00E+00	2.27E-05	2.02E+00	8.13E-03
RL-W533	2.39E-08	0.00E+00	2.15E-36	5.23E-01	5.35E-02	0.00E+00	1.96E-05	5.76E-01	2.32E-03
RL-W534	1.38E-12	0.00E+00	6.94E-41	5.10E-05	5.28E-06	0.00E+00	6.32E-10	5.63E-05	2.27E-07
RL-W535	7.22E-06	0.00E+00	6.86E-34	6.54E+01	9.25E+00	0.00E+00	6.25E-03	7.47E+01	3.01E-01
RL-W536	1.41E-07	0.00E+00	9.24E-36	2.27E+00	2.38E-01	0.00E+00	8.72E-05	2.51E+00	1.01E-02
RL-W537	4.82E-06	0.00E+00	2.09E-34	1.39E+02	1.42E+01	0.00E+00	1.93E-03	1.54E+02	6.19E-01
RL-W538	1.75E-11	0.00E+00	8.82E-40	6.48E-04	6.70E-05	0.00E+00	8.03E-09	7.15E-04	2.88E-06
RL-W539	1.95E-09	0.00E+00	9.93E-38	7.16E-02	7.39E-03	0.00E+00	9.04E-07	7.90E-02	3.19E-04
RL-W540	3.79E-06	0.00E+00	4.37E-34	2.58E+01	4.11E+00	0.00E+00	3.98E-03	2.99E+01	1.21E-01
RL-W541	5.63E-09	0.00E+00	2.86E-37	2.08E-01	2.14E-02	0.00E+00	2.61E-06	2.29E-01	9.23E-04
RL-W542	2.61E-07	0.00E+00	2.13E-35	5.25E+00	5.63E-01	0.00E+00	1.94E-04	5.81E+00	2.34E-02
RL-W543	8.23E-10	0.00E+00	4.14E-38	3.04E-02	3.14E-03	0.00E+00	3.77E-07	3.36E-02	1.35E-04
RL-W544	1.85E-08	0.00E+00	1.69E-36	3.46E-01	4.00E-02	0.00E+00	1.54E-05	3.86E-01	1.56E-03
RL-W545	4.93E-09	0.00E+00	2.48E-37	1.82E-01	1.88E-02	0.00E+00	2.26E-06	2.01E-01	8.10E-04
RL-W546	2.16E-10	0.00E+00	1.09E-38	8.02E-03	8.25E-04	0.00E+00	9.91E-08	8.84E-03	3.56E-05
RL-W547	5.52E-12	0.00E+00	2.78E-40	2.04E-04	2.11E-05	0.00E+00	2.53E-09	2.25E-04	9.06E-07
RL-W548	4.77E-12	0.00E+00	2.42E-40	1.76E-04	1.82E-05	0.00E+00	2.20E-09	1.94E-04	7.83E-07
RL-W549	9.48E-07	0.00E+00	9.70E-35	9.06E+00	1.25E+00	0.00E+00	8.83E-04	1.03E+01	4.16E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W550	4.30E-06	0.00E+00	1.84E-34	1.23E+02	1.25E+01	0.00E+00	1.69E-03	1.35E+02	5.46E-01
RL-W551	7.64E-06	0.00E+00	2.71E-34	1.39E+02	1.63E+01	0.00E+00	2.47E-03	1.55E+02	6.25E-01
RL-W552	2.96E-09	0.00E+00	1.50E-37	1.09E-01	1.13E-02	0.00E+00	1.37E-06	1.21E-01	4.86E-04
RL-W553	2.63E-10	0.00E+00	1.42E-38	9.74E-03	1.00E-03	0.00E+00	1.29E-07	1.07E-02	4.33E-05
RL-W554	4.17E-09	0.00E+00	2.10E-37	1.54E-01	1.60E-02	0.00E+00	1.92E-06	1.70E-01	6.87E-04
RL-W555	1.92E-09	0.00E+00	9.70E-38	7.11E-02	7.32E-03	0.00E+00	8.83E-07	7.84E-02	3.16E-04
RL-W563	2.76E-08	0.00E+00	2.43E-36	5.90E-01	6.04E-02	0.00E+00	2.21E-05	6.50E-01	2.62E-03
RL-W564	1.80E-08	0.00E+00	1.61E-36	3.81E-01	3.90E-02	0.00E+00	1.47E-05	4.20E-01	1.70E-03
RL-W565	1.78E-09	0.00E+00	9.05E-38	6.58E-02	6.80E-03	0.00E+00	8.24E-07	7.26E-02	2.93E-04
RL-W566	2.61E-08	0.00E+00	1.33E-36	9.66E-01	1.00E-01	0.00E+00	1.21E-05	1.07E+00	4.30E-03
RL-W567	1.81E-06	0.00E+00	3.39E-35	2.97E-02	1.11E-02	0.00E+00	3.09E-04	4.12E-02	1.66E-04
RL-W568	3.49E-05	0.00E+00	7.13E-34	1.41E+00	5.18E-01	0.00E+00	6.49E-03	1.93E+00	7.79E-03
RL-W569	2.87E-08	0.00E+00	5.37E-37	4.70E-04	1.76E-05	0.00E+00	4.89E-06	4.92E-04	1.99E-06
RL-W570	1.84E-09	0.00E+00	9.39E-38	6.98E-02	7.18E-03	0.00E+00	8.55E-07	7.70E-02	3.11E-04
RL-W571	5.90E-06	0.00E+00	3.19E-34	5.66E+00	1.31E+00	0.00E+00	2.90E-03	6.98E+00	2.81E-02
RL-W572	5.12E-09	0.00E+00	9.54E-38	3.05E-03	3.14E-05	0.00E+00	8.69E-07	3.08E-03	1.24E-05
RL-W573	6.59E-05	0.00E+00	1.22E-33	1.67E+00	5.80E-01	0.00E+00	1.11E-02	2.26E+00	9.12E-03
RL-W574	2.83E-04	0.00E+00	5.29E-33	6.38E+00	2.15E+00	0.00E+00	4.82E-02	8.58E+00	3.46E-02
RL-W575	1.85E-03	0.00E+00	3.56E-32	6.11E+01	1.72E+01	0.00E+00	3.24E-01	7.85E+01	3.17E-01
RL-W576	1.33E-04	0.00E+00	2.49E-33	3.11E+00	1.04E+00	0.00E+00	2.27E-02	4.17E+00	1.68E-02
RL-W579	1.13E-08	0.00E+00	6.55E-38	1.56E-02	1.61E-03	0.00E+00	5.97E-07	1.72E-02	6.93E-05
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.24E-01	9.39E-03	0.00E+00	0.00E+00	1.34E-01	5.39E-04
RL-W581	1.20E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.20E-07	4.82E-10
RL-W582	7.82E-10	0.00E+00	5.56E-38	3.99E-03	9.56E-04	0.00E+00	5.06E-07	4.94E-03	1.99E-05
RL-W583	6.05E-10	0.00E+00	3.02E-38	2.25E-02	2.32E-03	0.00E+00	2.75E-07	2.48E-02	1.00E-04
RL-W584	1.20E-08	0.00E+00	1.98E-36	1.31E-01	2.98E-02	0.00E+00	1.80E-05	1.61E-01	6.49E-04
RL-W585	7.15E-08	0.00E+00	1.05E-35	7.64E-01	1.81E-01	0.00E+00	9.60E-05	9.45E-01	3.81E-03
RL-W586	9.54E-12	0.00E+00	4.75E-40	3.55E-04	3.66E-05	0.00E+00	4.33E-09	3.92E-04	1.58E-06
RL-W587	2.04E-10	0.00E+00	1.03E-38	7.57E-03	7.84E-04	0.00E+00	9.35E-08	8.35E-03	3.37E-05
RL-W588	8.43E-09	0.00E+00	1.67E-36	1.11E-01	2.51E-02	0.00E+00	1.52E-05	1.36E-01	5.48E-04
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W590	2.59E-07	0.00E+00	3.57E-35	8.54E-03	7.04E-03	0.00E+00	3.25E-04	1.59E-02	6.41E-05
RL-W591	1.47E-06	0.00E+00	4.03E-35	1.06E-02	9.11E-03	0.00E+00	3.66E-04	2.00E-02	8.08E-05
RL-W592	6.51E-06	0.00E+00	4.41E-34	4.90E-01	2.95E-01	0.00E+00	4.01E-03	7.89E-01	3.18E-03
RL-W593	0.00E+00	0.00E+00	0.00E+00	1.77E-02	1.38E-02	0.00E+00	0.00E+00	3.15E-02	1.27E-04
RL-W594	5.87E-06	0.00E+00	7.93E-35	2.19E-02	1.87E-02	0.00E+00	7.22E-04	4.13E-02	1.67E-04
RL-W595	1.55E-08	0.00E+00	8.28E-36	1.50E-02	1.36E-02	0.00E+00	7.54E-05	2.87E-02	1.16E-04
RL-W596	5.02E-09	0.00E+00	6.44E-37	1.54E-04	1.28E-04	0.00E+00	5.86E-06	2.88E-04	1.16E-06
RL-W597	9.22E-06	0.00E+00	2.83E-34	2.99E-01	2.32E-01	0.00E+00	2.58E-03	5.33E-01	2.15E-03
RL-W598	9.75E-06	0.00E+00	1.67E-33	4.17E-01	2.89E-01	0.00E+00	1.52E-02	7.21E-01	2.91E-03
RL-W599	4.94E-07	0.00E+00	1.35E-35	3.52E-03	3.05E-03	0.00E+00	1.23E-04	6.69E-03	2.70E-05
RL-W600	2.81E-14	0.00E+00	1.40E-42	1.04E-06	1.08E-07	0.00E+00	1.27E-11	1.15E-06	4.63E-09
RL-W601	1.42E-10	0.00E+00	7.67E-39	5.27E-03	5.45E-04	0.00E+00	6.98E-08	5.82E-03	2.35E-05
RL-W602	1.24E-07	0.00E+00	6.29E-36	4.57E+00	4.73E-01	0.00E+00	5.72E-05	5.04E+00	2.03E-02
RL-W603	7.14E-07	0.00E+00	3.63E-35	2.64E+01	2.72E+00	0.00E+00	3.30E-04	2.91E+01	1.17E-01
RL-W604	1.67E-09	0.00E+00	9.51E-38	1.28E-02	2.93E-03	0.00E+00	8.65E-07	1.57E-02	6.35E-05
RL-W605	3.83E-10	0.00E+00	2.07E-38	1.42E-02	1.46E-03	0.00E+00	1.88E-07	1.56E-02	6.30E-05
RL-W606	1.55E-10	0.00E+00	8.32E-39	5.71E-03	5.90E-04	0.00E+00	7.57E-08	6.30E-03	2.54E-05
RL-W607	2.83E-10	0.00E+00	1.61E-38	2.17E-03	4.97E-04	0.00E+00	1.47E-07	2.66E-03	1.07E-05
RL-W608	3.38E-09	0.00E+00	6.25E-37	2.82E-03	1.61E-03	0.00E+00	5.69E-06	4.43E-03	1.79E-05
RL-W610	6.69E-07	0.00E+00	3.34E-35	2.49E+01	2.57E+00	0.00E+00	3.04E-04	2.74E+01	1.11E-01
RL-W612	1.58E-09	0.00E+00	8.09E-38	6.04E-02	6.25E-03	0.00E+00	7.36E-07	6.66E-02	2.69E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	2.53E-01	0.00E+00	0.00E+00	0.00E+00	2.53E-01	1.02E-03
RL-W622	2.63E-11	0.00E+00	1.32E-39	9.81E-04	1.01E-04	0.00E+00	1.20E-08	1.08E-03	4.37E-06
RL-W625	9.18E-10	0.00E+00	2.01E-37	5.01E-03	2.29E-03	0.00E+00	1.83E-06	7.30E-03	2.94E-05
RL-W626	4.93E-08	0.00E+00	4.56E-36	1.96E-01	5.45E-02	0.00E+00	4.15E-05	2.51E-01	1.01E-03
RL-W627	2.32E-10	0.00E+00	6.09E-39	9.29E-07	0.00E+00	0.00E+00	5.55E-08	9.85E-07	3.97E-09
RL-W628	7.62E-11	0.00E+00	3.83E-39	2.83E-03	2.92E-04	0.00E+00	3.49E-08	3.12E-03	1.26E-05
RL-W629	5.16E-12	0.00E+00	2.63E-40	1.90E-04	1.96E-05	0.00E+00	2.40E-09	2.10E-04	8.46E-07
RL-W630	5.68E-08	0.00E+00	4.91E-36	2.20E+00	2.37E-01	0.00E+00	4.47E-05	2.44E+00	9.83E-03
RL-W631	9.15E-10	0.00E+00	4.94E-38	3.38E-02	3.49E-03	0.00E+00	4.50E-07	3.73E-02	1.50E-04
RL-W632	4.04E-07	0.00E+00	6.67E-36	4.46E+00	6.80E-01	0.00E+00	6.07E-05	5.14E+00	2.07E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W633	9.63E-10	0.00E+00	3.87E-38	7.01E-04	2.87E-04	0.00E+00	3.52E-07	9.89E-04	3.99E-06
RL-W634	0.00E+00	0.00E+00	0.00E+00	7.64E-03	0.00E+00	0.00E+00	0.00E+00	7.64E-03	3.08E-05
RL-W635	5.76E-06	0.00E+00	1.31E-33	3.25E+00	2.25E+00	0.00E+00	1.19E-02	5.52E+00	2.23E-02
RL-W636	5.87E-08	0.00E+00	2.47E-36	4.25E-02	1.74E-02	0.00E+00	2.25E-05	5.99E-02	2.42E-04
RL-W637	1.40E-10	0.00E+00	6.29E-38	4.78E-04	2.18E-04	0.00E+00	5.72E-07	6.96E-04	2.81E-06
RL-W638	6.14E-09	0.00E+00	6.40E-37	4.68E-03	2.04E-03	0.00E+00	5.83E-06	6.73E-03	2.71E-05
RL-W639	3.24E-10	0.00E+00	1.64E-38	1.20E-02	1.24E-03	0.00E+00	1.49E-07	1.32E-02	5.33E-05
RL-W640	1.09E-08	0.00E+00	5.44E-37	4.04E-01	4.18E-02	0.00E+00	4.96E-06	4.46E-01	1.80E-03
RL-W641	3.32E-07	0.00E+00	1.20E-34	1.94E+00	3.69E-01	0.00E+00	1.09E-03	2.31E+00	9.32E-03
RL-W642	6.49E-09	0.00E+00	1.24E-38	2.37E-02	5.59E-05	0.00E+00	1.13E-07	2.37E-02	9.57E-05
RL-W643	1.02E-07	0.00E+00	3.68E-35	5.98E-01	1.14E-01	0.00E+00	3.35E-04	7.12E-01	2.87E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	4.11E-02	0.00E+00	0.00E+00	0.00E+00	4.11E-02	1.66E-04
RL-W645	2.48E-09	0.00E+00	1.66E-37	8.09E-02	8.80E-03	0.00E+00	1.51E-06	8.97E-02	3.62E-04
RL-W646	2.26E-09	0.00E+00	1.48E-37	1.93E-02	4.35E-03	0.00E+00	1.35E-06	2.37E-02	9.55E-05
RL-W647	6.36E-09	0.00E+00	2.21E-35	8.24E-02	6.04E-03	0.00E+00	2.01E-04	8.86E-02	3.57E-04
RL-W648	1.13E-10	0.00E+00	3.78E-38	4.50E-05	4.11E-05	0.00E+00	3.44E-07	8.64E-05	3.49E-07
RL-W649	4.14E-10	0.00E+00	1.39E-37	1.66E-04	1.51E-04	0.00E+00	1.27E-06	3.18E-04	1.28E-06
RL-W653	1.96E-11	0.00E+00	9.97E-40	7.24E-04	7.46E-05	0.00E+00	9.07E-09	7.98E-04	3.22E-06
RL-W654	1.08E-10	0.00E+00	5.44E-39	3.99E-03	4.11E-04	0.00E+00	4.96E-08	4.40E-03	1.77E-05
RL-W655	2.65E-05	0.00E+00	1.29E-33	1.58E-01	1.73E-01	0.00E+00	1.17E-02	3.43E-01	1.38E-03
RL-W656	1.11E-04	0.00E+00	5.79E-34	3.72E-01	1.78E-01	0.00E+00	5.27E-03	5.55E-01	2.24E-03
RL-W657	5.68E-05	0.00E+00	8.55E-34	1.83E-01	1.69E-01	0.00E+00	7.78E-03	3.60E-01	1.45E-03
RL-W659	6.87E-06	0.00E+00	1.93E-34	3.52E-02	2.03E-02	0.00E+00	1.76E-03	5.72E-02	2.31E-04
RL-W660	3.77E-05	0.00E+00	2.32E-33	6.49E-01	5.39E-01	0.00E+00	2.11E-02	1.21E+00	4.88E-03
RL-W661	3.98E-07	0.00E+00	2.90E-36	3.13E-04	1.32E-03	0.00E+00	2.64E-05	1.66E-03	6.70E-06
RL-W662	1.25E-08	0.00E+00	1.73E-37	8.02E-05	6.66E-05	0.00E+00	1.57E-06	1.48E-04	5.98E-07
RL-W665	1.54E-04	0.00E+00	1.38E-32	9.81E-01	6.11E-01	0.00E+00	1.26E-01	1.72E+00	6.93E-03
RL-W666	2.76E-06	0.00E+00	3.39E-35	4.11E-02	2.01E-02	0.00E+00	3.09E-04	6.15E-02	2.48E-04
RL-W668	2.63E-07	0.00E+00	1.07E-36	1.09E-01	1.43E-02	0.00E+00	9.70E-06	1.23E-01	4.96E-04
RL-W669	7.66E-08	0.00E+00	2.76E-35	4.48E-01	8.53E-02	0.00E+00	2.52E-04	5.33E-01	2.15E-03
RL-W670	4.85E-09	0.00E+00	1.97E-38	2.01E-03	2.64E-04	0.00E+00	1.79E-07	2.27E-03	9.16E-06

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W671	7.90E-07	0.00E+00	1.01E-35	3.68E-03	1.77E-03	0.00E+00	9.18E-05	5.55E-03	2.24E-05
RL-W672	5.37E-06	0.00E+00	6.86E-35	2.51E-02	1.21E-02	0.00E+00	6.25E-04	3.78E-02	1.52E-04
RL-W673	5.18E-06	0.00E+00	6.59E-35	2.43E-02	1.16E-02	0.00E+00	6.00E-04	3.65E-02	1.47E-04
RL-W674	1.74E-08	0.00E+00	2.95E-36	8.39E+00	3.38E-02	0.00E+00	2.68E-05	8.42E+00	3.40E-02
RL-W675	6.49E-08	0.00E+00	1.63E-35	9.81E-02	3.94E-02	0.00E+00	1.48E-04	1.38E-01	5.55E-04
RL-W676	2.49E-09	0.00E+00	9.77E-38	1.10E-01	7.42E-04	0.00E+00	8.90E-07	1.11E-01	4.47E-04
RL-W677	5.78E-06	0.00E+00	2.42E-34	4.30E+00	1.73E+00	0.00E+00	2.21E-03	6.04E+00	2.43E-02
RL-W678	1.83E-08	0.00E+00	2.02E-36	3.87E-02	1.58E-02	0.00E+00	1.84E-05	5.45E-02	2.20E-04
RL-W679	1.15E-07	0.00E+00	4.52E-36	8.31E-02	3.40E-02	0.00E+00	4.12E-05	1.17E-01	4.73E-04
RL-W680	2.58E-11	0.00E+00	6.36E-39	1.30E-05	1.09E-05	0.00E+00	5.79E-08	2.40E-05	9.66E-08
RL-W681	1.58E-11	0.00E+00	2.58E-39	3.50E-04	8.08E-05	0.00E+00	2.35E-08	4.31E-04	1.74E-06
RL-W685	4.59E-08	0.00E+00	2.29E-36	1.71E+00	1.76E-01	0.00E+00	2.09E-05	1.88E+00	7.60E-03
RL-W689	1.19E-09	0.00E+00	2.75E-38	2.90E-04	0.00E+00	0.00E+00	2.51E-07	2.90E-04	1.17E-06
RL-W690	3.99E-08	0.00E+00	2.02E-36	1.52E+00	1.56E-01	0.00E+00	1.84E-05	1.68E+00	6.76E-03
RL-W691	9.25E-10	0.00E+00	4.71E-38	3.52E-02	3.62E-03	0.00E+00	4.29E-07	3.88E-02	1.57E-04
RL-W692	3.66E-08	0.00E+00	1.87E-36	1.39E+00	1.44E-01	0.00E+00	1.70E-05	1.54E+00	6.20E-03
RL-W693	4.53E-08	0.00E+00	2.30E-36	1.72E+00	1.78E-01	0.00E+00	2.10E-05	1.90E+00	7.66E-03
RL-W694	4.76E-07	0.00E+00	2.42E-35	1.82E+01	1.86E+00	0.00E+00	2.20E-04	2.01E+01	8.09E-02
RL-W695	3.94E-10	0.00E+00	0.00E+00	1.79E-03	0.00E+00	0.00E+00	0.00E+00	1.79E-03	7.22E-06
RL-W696	5.13E-10	0.00E+00	8.82E-38	2.18E-03	9.98E-04	0.00E+00	8.03E-07	3.18E-03	1.28E-05
RL-W697	1.19E-07	0.00E+00	1.87E-34	5.19E-03	3.30E-04	0.00E+00	1.70E-03	7.22E-03	2.91E-05
RL-W698	1.03E-08	0.00E+00	0.00E+00	2.46E-05	0.00E+00	0.00E+00	0.00E+00	2.47E-05	9.94E-08
RL-W699	2.29E-09	0.00E+00	1.24E-38	1.65E-03	8.98E-05	0.00E+00	1.13E-07	1.74E-03	7.01E-06
RL-W700	6.48E-10	0.00E+00	3.26E-38	2.39E-02	2.47E-03	0.00E+00	2.97E-07	2.64E-02	1.06E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	2.55E-08	0.00E+00	9.20E-36	1.49E-01	2.85E-02	0.00E+00	8.37E-05	1.78E-01	7.16E-04
RL-W705	1.65E-10	0.00E+00	8.47E-39	6.26E-03	6.49E-04	0.00E+00	7.71E-08	6.91E-03	2.79E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	5.89E-09	0.00E+00	3.01E-37	2.23E-01	2.31E-02	0.00E+00	2.74E-06	2.46E-01	9.93E-04
RL-W708	8.90E-10	0.00E+00	4.56E-38	3.39E-02	3.49E-03	0.00E+00	4.15E-07	3.73E-02	1.51E-04

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W709	3.08E-07	0.00E+00	1.57E-35	1.17E+01	1.21E+00	0.00E+00	1.43E-04	1.29E+01	5.20E-02
RL-W710	1.84E-11	0.00E+00	9.39E-40	6.98E-04	7.18E-05	0.00E+00	8.55E-09	7.70E-04	3.11E-06
RL-W711	5.73E-09	0.00E+00	2.93E-37	2.18E-01	2.25E-02	0.00E+00	2.67E-06	2.40E-01	9.70E-04
RL-W712	7.42E-09	0.00E+00	3.80E-37	2.82E-01	2.91E-02	0.00E+00	3.45E-06	3.11E-01	1.25E-03
RL-W713	6.41E-09	0.00E+00	3.28E-37	2.43E-01	2.51E-02	0.00E+00	2.98E-06	2.68E-01	1.08E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	1.11E-10	0.00E+00	5.52E-39	4.11E-03	4.25E-04	0.00E+00	5.03E-08	4.54E-03	1.83E-05
RL-W716	1.15E-09	0.00E+00	5.75E-38	4.29E-02	4.42E-03	0.00E+00	5.23E-07	4.73E-02	1.91E-04
RL-W717	2.88E-10	0.00E+00	1.44E-38	1.07E-02	1.11E-03	0.00E+00	1.31E-07	1.18E-02	4.77E-05
RL-W718	5.08E-11	0.00E+00	2.53E-39	1.89E-03	1.95E-04	0.00E+00	2.31E-08	2.08E-03	8.40E-06
RL-W719	2.29E-10	0.00E+00	1.14E-38	8.54E-03	8.80E-04	0.00E+00	1.04E-07	9.42E-03	3.80E-05
RL-W720	1.42E-09	0.00E+00	7.09E-38	5.27E-02	5.45E-03	0.00E+00	6.46E-07	5.82E-02	2.35E-04
RL-W721	9.60E-10	0.00E+00	4.79E-38	3.57E-02	3.69E-03	0.00E+00	4.36E-07	3.94E-02	1.59E-04
RL-W723	3.18E-09	0.00E+00	1.62E-37	1.21E-01	1.25E-02	0.00E+00	1.47E-06	1.34E-01	5.40E-04
RL-W724	2.11E-08	0.00E+00	1.08E-36	8.02E-01	8.32E-02	0.00E+00	9.81E-06	8.85E-01	3.57E-03
RL-W725	6.68E-09	0.00E+00	3.40E-37	2.54E-01	2.62E-02	0.00E+00	3.09E-06	2.80E-01	1.13E-03
RL-W726	5.26E-09	0.00E+00	2.68E-37	2.01E-01	2.07E-02	0.00E+00	2.44E-06	2.21E-01	8.93E-04
RL-W727	3.23E-08	0.00E+00	1.64E-36	1.23E+00	1.27E-01	0.00E+00	1.50E-05	1.36E+00	5.47E-03
RL-W728	2.94E-08	0.00E+00	1.50E-36	1.12E+00	1.16E-01	0.00E+00	1.36E-05	1.24E+00	5.00E-03
RL-W729	1.36E-08	0.00E+00	6.94E-37	5.17E-01	5.35E-02	0.00E+00	6.32E-06	5.70E-01	2.30E-03
RL-W730	5.31E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.31E-06	2.14E-08
RL-W731	1.71E-12	0.00E+00	0.00E+00	3.38E-04	6.42E-07	0.00E+00	0.00E+00	3.39E-04	1.37E-06
RL-W732	3.92E-06	0.00E+00	3.95E-34	9.51E+01	9.77E+00	0.00E+00	3.59E-03	1.05E+02	4.23E-01
RL-W733	5.15E-08	0.00E+00	5.14E-36	1.03E+00	1.19E-01	0.00E+00	4.68E-05	1.15E+00	4.65E-03
RL-W734	1.61E-07	0.00E+00	1.71E-35	3.57E+00	4.00E-01	0.00E+00	1.56E-04	3.97E+00	1.60E-02
RL-W735	1.32E-07	0.00E+00	1.31E-35	2.78E+00	3.19E-01	0.00E+00	1.19E-04	3.10E+00	1.25E-02
RL-W736	1.45E-10	0.00E+00	2.79E-41	1.84E-03	2.20E-04	0.00E+00	2.54E-10	2.06E-03	8.32E-06
RL-W737	1.17E-07	0.00E+00	1.19E-35	2.64E+00	2.97E-01	0.00E+00	1.09E-04	2.93E+00	1.18E-02
RL-W738	4.38E-07	0.00E+00	4.10E-35	8.39E+00	1.03E+00	0.00E+00	3.73E-04	9.42E+00	3.80E-02
RL-W739	3.73E-08	0.00E+00	3.62E-36	1.36E+00	1.44E-01	0.00E+00	3.29E-05	1.51E+00	6.08E-03
RL-W740	1.87E-06	0.00E+00	1.33E-34	3.32E+01	4.00E+00	0.00E+00	1.21E-03	3.72E+01	1.50E-01

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W741	2.79E-06	0.00E+00	3.12E-34	6.46E+00	2.13E+00	0.00E+00	2.84E-03	8.59E+00	3.47E-02
RL-W742	1.24E-07	0.00E+00	9.39E-36	2.10E+00	2.29E-01	0.00E+00	8.55E-05	2.33E+00	9.38E-03
RL-W743	2.24E-10	0.00E+00	2.55E-39	1.36E-03	0.00E+00	0.00E+00	2.32E-08	1.36E-03	5.47E-06
RL-W744	0.00E+00	0.00E+00	0.00E+00	6.76E-02	2.67E-02	0.00E+00	0.00E+00	9.43E-02	3.80E-04
RL-W745	3.54E-10	0.00E+00	1.78E-38	1.31E-02	1.35E-03	0.00E+00	1.62E-07	1.45E-02	5.83E-05
RL-W746	1.36E-09	0.00E+00	6.86E-38	5.03E-02	5.21E-03	0.00E+00	6.25E-07	5.56E-02	2.24E-04
RL-W747	3.69E-09	0.00E+00	1.86E-37	1.36E-01	1.41E-02	0.00E+00	1.69E-06	1.50E-01	6.07E-04
RL-W748	2.58E-05	0.00E+00	5.21E-34	2.26E-01	1.72E-01	0.00E+00	4.75E-03	4.03E-01	1.63E-03
RL-W749	3.10E-08	0.00E+00	1.59E-36	1.18E+00	1.22E-01	0.00E+00	1.45E-05	1.31E+00	5.26E-03
RL-W750	3.92E-05	0.00E+00	7.90E-34	3.71E-01	2.81E-01	0.00E+00	7.19E-03	6.59E-01	2.66E-03
RL-W751	3.54E-05	0.00E+00	7.13E-34	3.33E-01	2.55E-01	0.00E+00	6.49E-03	5.95E-01	2.40E-03
RL-W752	1.54E-05	0.00E+00	3.10E-34	1.45E-01	1.11E-01	0.00E+00	2.82E-03	2.59E-01	1.04E-03
RL-W753	2.07E-04	0.00E+00	4.18E-33	1.96E+00	1.49E+00	0.00E+00	3.80E-02	3.48E+00	1.40E-02
RP-W754	8.78E-06	0.00E+00	5.29E-34	1.39E+03	5.28E+01	0.00E+00	3.48E-01	1.45E+03	5.83E+00
RP-W755	4.65E-05	0.00E+00	3.17E-34	1.04E+03	4.00E+01	0.00E+00	1.23E+01	1.09E+03	4.41E+00
SA-T001	9.35E-08	0.00E+00	7.59E-36	2.27E+00	6.22E-03	0.00E+00	7.36E-05	2.28E+00	9.18E-03
SA-W134	7.63E-07	0.00E+00	5.17E-35	1.03E+00	1.52E-01	0.00E+00	1.63E-01	1.35E+00	5.44E-03
SA-W134M	9.91E-08	0.00E+00	6.71E-36	1.35E-01	1.97E-02	0.00E+00	2.11E-02	1.76E-01	7.08E-04
T001-221F-HET	1.85E-04	0.00E+00	6.06E-30	2.16E+04	2.47E+02	0.00E+00	6.06E+01	2.19E+04	8.82E+01
T001-221H-HET	3.32E-04	0.00E+00	1.09E-29	3.90E+04	4.45E+02	0.00E+00	1.09E+02	3.95E+04	1.59E+02
T001-235F-HET	1.91E-05	0.00E+00	6.29E-31	2.24E+03	2.56E+01	0.00E+00	6.29E+00	2.27E+03	9.16E+00
T001-772F-HET	1.65E-04	0.00E+00	5.44E-30	1.93E+04	2.21E+02	0.00E+00	5.45E+01	1.96E+04	7.90E+01
T001-773A-CLAS	1.85E-06	0.00E+00	6.09E-32	2.17E+02	2.48E+00	0.00E+00	6.10E-01	2.20E+02	8.88E-01
T001-773A-HET	2.13E-05	0.00E+00	7.01E-31	2.50E+03	2.86E+01	0.00E+00	7.02E+00	2.54E+03	1.02E+01
W006-773A-VIT	2.86E-10	0.00E+00	0.00E+00	4.02E+02	0.00E+00	0.00E+00	0.00E+00	4.02E+02	1.62E+00
W026-221F-HET	6.42E-05	0.00E+00	2.11E-30	7.57E+03	8.60E+01	0.00E+00	2.11E+01	7.67E+03	3.09E+01
W026-221H-HET	4.81E-05	0.00E+00	1.58E-30	5.63E+03	6.42E+01	0.00E+00	1.58E+01	5.71E+03	2.30E+01
W026-235F-HET	7.48E-07	0.00E+00	2.46E-32	8.76E+01	1.00E+00	0.00E+00	2.46E-01	8.89E+01	3.58E-01
W026-772F-HET	2.05E-07	0.00E+00	6.71E-33	2.39E+01	2.73E-01	0.00E+00	6.71E-02	2.42E+01	9.77E-02
W026-773A-HET	3.32E-06	0.00E+00	1.09E-31	3.90E+02	4.45E+00	0.00E+00	1.09E+00	3.95E+02	1.59E+00
W027-221F-HET	2.43E-04	0.00E+00	7.13E-30	2.92E+04	3.33E+02	0.00E+00	8.22E+01	2.96E+04	1.20E+02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W027-221H-HET	1.06E-04	0.00E+00	3.11E-30	1.28E+04	1.46E+02	0.00E+00	3.59E+01	1.30E+04	5.24E+01
W027-235F-HET	3.19E-05	0.00E+00	9.35E-31	3.85E+03	4.38E+01	0.00E+00	1.08E+01	3.91E+03	1.57E+01
W027-772F-HET	5.80E-05	0.00E+00	1.70E-30	6.99E+03	7.97E+01	0.00E+00	1.96E+01	7.09E+03	2.86E+01
W027-773A-HET	8.65E-05	0.00E+00	2.54E-30	1.04E+04	1.19E+02	0.00E+00	2.93E+01	1.06E+04	4.26E+01
W027-999-HET	9.89E-05	0.00E+00	2.90E-30	1.19E+04	1.36E+02	0.00E+00	3.35E+01	1.21E+04	4.87E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	2.99E+02	0.00E+00	0.00E+00	0.00E+00	2.99E+02	1.21E+00
WP-INW169.001	4.83E-07	0.00E+00	1.83E-35	1.15E+01	1.19E+00	0.00E+00	3.27E-04	1.27E+01	5.13E-02
WP-INW198.001	6.36E-07	0.00E+00	3.19E-35	2.07E+01	2.11E+00	0.00E+00	3.70E-04	2.28E+01	9.19E-02
WP-INW211.001	7.16E-05	0.00E+00	2.99E-33	1.92E+03	1.96E+02	0.00E+00	2.92E-02	2.11E+03	8.52E+00
WP-INW216.001-	2.60E-03	0.00E+00	1.72E-33	1.11E+03	1.14E+02	0.00E+00	2.85E-01	1.22E+03	4.93E+00
WP-INW216.001-	7.15E-04	0.00E+00	4.64E-34	3.00E+02	3.07E+01	0.00E+00	3.11E-02	3.31E+02	1.34E+00
WP-INW218.001-	4.98E-05	0.00E+00	3.04E-34	1.93E+02	1.98E+01	0.00E+00	3.78E-01	2.13E+02	8.61E-01
WP-INW218.001-	2.29E-07	0.00E+00	8.36E-36	5.26E+00	5.39E-01	0.00E+00	3.64E-02	5.83E+00	2.35E-02
WP-INW222.001	2.35E-06	0.00E+00	9.01E-35	5.14E+01	5.32E+00	0.00E+00	1.38E-03	5.67E+01	2.29E-01
WP-INW243.001	5.71E-06	0.00E+00	1.94E-34	1.08E+02	1.12E+01	0.00E+00	2.61E-03	1.19E+02	4.80E-01
WP-INW247.001R	7.63E-06	0.00E+00	4.52E-34	2.07E+02	2.18E+01	0.00E+00	4.19E-03	2.29E+02	9.21E-01
WP-INW276.001	5.82E-07	0.00E+00	4.41E-35	2.05E+01	2.15E+00	0.00E+00	4.18E-04	2.26E+01	9.11E-02
WP-INW276.002	9.22E-07	0.00E+00	6.63E-35	3.00E+01	3.23E+00	0.00E+00	6.29E-04	3.33E+01	1.34E-01
WP-INW276.003	3.54E-05	0.00E+00	2.47E-33	1.12E+03	1.18E+02	0.00E+00	2.29E-02	1.23E+03	4.98E+00
WP-INW276.004	8.44E-06	0.00E+00	5.21E-34	2.36E+02	2.49E+01	0.00E+00	4.89E-03	2.61E+02	1.05E+00
WP-INW296.001-	3.09E-06	0.00E+00	1.24E-34	5.93E+01	6.21E+00	0.00E+00	1.16E-03	6.55E+01	2.64E-01
WP-INW296.001-	9.31E-06	0.00E+00	4.37E-34	2.10E+02	2.20E+01	0.00E+00	4.32E-03	2.32E+02	9.34E-01
WP-LA-TA-55-19	1.55E-07	0.00E+00	2.03E-35	1.57E+00	1.75E-01	0.00E+00	2.75E-03	1.74E+00	7.03E-03
WP-LA-TA-55-19	7.51E-06	0.00E+00	6.82E-34	1.60E+02	1.80E+01	0.00E+00	9.10E-02	1.78E+02	7.16E-01
WP-LA-TA-55-43	4.22E-08	0.00E+00	1.59E-32	2.42E-01	4.73E-02	0.00E+00	1.71E-01	4.60E-01	1.85E-03
WP-RF001.01	1.30E-05	0.00E+00	5.52E-34	3.07E+02	3.23E+01	0.00E+00	1.41E-02	3.40E+02	1.37E+00
WP-RF002.01-A	1.52E-05	0.00E+00	7.36E-34	3.46E+02	3.66E+01	0.00E+00	2.40E-02	3.83E+02	1.54E+00
WP-RF002.01-B	1.51E-08	0.00E+00	5.10E-37	3.75E-01	3.94E-02	0.00E+00	4.83E-06	4.14E-01	1.67E-03
WP-RF003.01	2.35E-04	0.00E+00	1.18E-32	6.61E+03	6.97E+02	0.00E+00	1.16E-01	7.31E+03	2.95E+01
WP-RF004.01	1.10E-07	0.00E+00	7.93E-36	3.81E+00	4.04E-01	0.00E+00	1.96E-04	4.22E+00	1.70E-02
WP-RF005.01	5.66E-04	0.00E+00	6.02E-33	3.50E+03	3.66E+02	0.00E+00	5.65E-02	3.86E+03	1.56E+01

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF005.02	6.67E-04	0.00E+00	3.11E-33	2.09E+03	2.17E+02	0.00E+00	2.95E-02	2.31E+03	9.30E+00
WP-RF006.01	2.17E-04	0.00E+00	1.13E-32	5.95E+03	6.28E+02	0.00E+00	1.28E-01	6.58E+03	2.65E+01
WP-RF008.01	6.86E-05	0.00E+00	4.03E-33	1.74E+03	1.87E+02	0.00E+00	3.79E-02	1.93E+03	7.76E+00
WP-RF009.01	6.75E-03	0.00E+00	4.94E-32	3.81E+04	3.94E+03	0.00E+00	4.70E-01	4.21E+04	1.70E+02
WP-RF010.01	2.49E-06	0.00E+00	1.25E-34	5.76E+01	6.08E+00	0.00E+00	1.85E-03	6.37E+01	2.57E-01
WP-RF029.01-A	5.98E-07	0.00E+00	2.36E-35	1.01E+01	1.07E+00	0.00E+00	9.24E-04	1.12E+01	4.51E-02
WP-RF029.01-B	8.93E-07	0.00E+00	1.87E-35	8.02E+00	8.46E-01	0.00E+00	2.36E-03	8.86E+00	3.57E-02
WP-RF118.01	1.52E-03	0.00E+00	9.39E-32	3.85E+04	3.97E+03	0.00E+00	1.06E+00	4.25E+04	1.71E+02
WP-RLMPDT.001	3.22E-07	0.00E+00	2.74E-35	5.51E+00	6.63E-01	0.00E+00	2.52E-04	6.18E+00	2.49E-02
WP-RLNPDT.002	3.95E-06	0.00E+00	2.61E-34	5.42E+01	6.73E+00	0.00E+00	2.41E-03	6.09E+01	2.46E-01
WP-SR2001.001.	1.26E-07	0.00E+00	3.00E-35	5.12E+00	4.70E-01	0.00E+00	2.78E-04	5.59E+00	2.25E-02
WP-SR-W027-221	9.33E-07	0.00E+00	8.82E-35	1.47E+01	1.90E+00	0.00E+00	1.82E-01	1.68E+01	6.76E-02
Total	4.99E-02	0.00E+00	6.17E-29	4.95E+05	3.70E+04	0.00E+00	7.25E+02	5.32E+05	2.15E+03

Table PAR-61. Isotopes Activity, Total Activity and EPA Units for RH-TRU Waste Streams

Time	RH Total										
	AM241 (Ci)	CM244 (Ci) Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci) Non-E	U234 (Ci)	CS137 (Ci)	SR90 (Ci)	EPA (Ci)	EPA Unit
0 Years	1.58E+04	7.93E+01	2.80E+03	5.38E+03	1.68E+03	2.40E+04	2.20E+01	2.39E+05	1.15E+05	3.41E+01	6.10E+04
100 Years	1.41E+04	1.73E+00	1.27E+03	5.36E+03	1.66E+03	1.95E+02	2.25E+01	2.37E+04	1.06E+04	3.41E+01	2.59E+04
125 Years	1.36E+04	6.63E-01	1.04E+03	5.36E+03	1.65E+03	5.85E+01	2.26E+01	1.33E+04	5.86E+03	3.41E+01	2.36E+04
175 Years	1.25E+04	9.79E-02	7.04E+02	5.35E+03	1.64E+03	5.27E+00	2.27E+01	4.19E+03	1.78E+03	3.41E+01	2.09E+04
350 Years	9.46E+03	1.21E-04	1.77E+02	5.32E+03	1.61E+03	1.16E-03	2.29E+01	7.34E+01	2.77E+01	3.40E+01	1.66E+04
1000 Years	3.34E+03	1.89E-15	1.04E+00	5.22E+03	1.51E+03	2.98E-17	2.29E+01	2.21E-05	5.29E-06	3.40E+01	1.01E+04
3000 Years	1.35E+02	1.08E-48	1.43E-07	4.93E+03	1.22E+03	4.61E-59	2.28E+01	1.88E-25	1.12E-26	3.37E+01	6.34E+03
5000 Years	5.46E+00	6.15E-82	1.97E-14	4.65E+03	9.86E+02	0.00E+00	2.27E+01	1.61E-45	2.38E-47	3.34E+01	5.70E+03
7500 Years	9.92E-02	0.00E+00	5.22E-23	4.33E+03	7.56E+02	0.00E+00	2.25E+01	1.32E-70	3.42E-73	3.30E+01	5.14E+03
10000 Years	1.80E-03	0.00E+00	1.38E-31	4.03E+03	5.80E+02	0.00E+00	2.24E+01	0.00E+00	0.00E+00	3.26E+01	4.67E+03

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APPENDIX PA

ATTACHMENT PORSURF

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PORSURF.1 INTRODUCTION

Creep closure of the excavation and the presence of either brine or gas in the waste disposal region both influence time-dependent changes in void volume in the waste disposal area. As a consequence, these processes influence two-phase fluid flow of brine and gases through the waste and its capacity for storing fluids. For the performance assessment (PA), a porosity surface method is used to indirectly couple mechanical closure and gas generation with two-phase fluid flow calculations implemented in the BRAGFLO code (Appendix PA, Section PA 4.2). The porosity surface approach is used because current codes are not capable of fully coupling creep closure, waste consolidation, brine availability, and gas production and migration with computational efficiency. The porosity surface method incorporates the results of closure calculations obtained from the SANTOS code, a quasistatic, large deformation finite-element structural analysis code (Stone 1997). The adequacy of the method is documented in Freeze (1996), who concludes that the approximation is valid so long as the rate of room pressurization in final calculations is bounded by the room pressurization history that was used to develop the porosity surface.

The porosity surface used in the CRA-2004 PA is the same surface that was used for the CCA PA. Consequently, the models and parameters used to calculate this surface are unchanged from the CCA PA. For information on the porosity surface used in the CCA PA, see CCA Appendix PORSURF.

A separate analysis considered the potential effects on repository performance of uncertainty in the porosity surface (Appendix PA, Attachment MASS, Section MASS.2.0). Uncertainty in the porosity surface can arise from heterogeneity in the rigidity of waste packages, and from uncertain spatial arrangement of waste in the repository. The analysis considered four porosity surfaces, including the surface from the CCA, which represented various bounding combinations of waste package rigidity and waste initial porosity. The analysis concluded that uncertainty in porosity surface did not have significant effects on repository performance, and recommended the continued use of the CCA porosity surface in PA.

PORSURF.2 CREEP CLOSURE METHOD

Creep closure is accounted for in BRAGFLO by changing the porosity of the waste disposal area according to a table of porosity values, termed the porosity surface. The porosity surface is generated using the nonlinear finite element code, SANTOS. Disposal room porosity is calculated over time, varying the rate of gas generation and the gas production potential, to construct a three-dimensional porosity surface representing changes in porosity as a function of pressure and time over the 10,000-year simulation period.

The completed porosity surface is compiled in tabular form and is used in the solution of the gas and brine mass balance equations presented in Appendix PA Section PA-4.2.1. Porosity is interpolated from the porosity surface corresponding to the calculated gas pressure at time level t_n. The porosity surface is then accessed iteratively for the remainder of the simulation at the end of each BRAGFLO time step t_{n+1}. The closure data provided by SANTOS can be viewed as a series of surfaces, with any gas generation history computed by BRAGFLO constrained to fall

on this surface. Various techniques described in Freeze et al. (1995) were used to check the validity of this approach, and it was found to be a reasonable representation of the behavior observed in the complex models.

In SANTOS, gas pressure in the disposal room is computed from the ideal gas law by the following relationship:

$$p_g = \frac{NRT}{V},$$

where N is the mass of gas in moles at a given time, R is the universal gas constant (8.23 m^3 Pa/ mole °K), T is the absolute temperature in degrees Kelvin (constant at 300° K), and V is the current free volume of the room. The mass of gas is computed as

$$N = r(t, f) \times Ndrums \times t\ ,$$

where $r(t, f)$ is the gas generation rate (moles/drum/yr) at time t for the scaling factor f and Ndrums is the number of drums of waste in the room (6804 drums per room). The base gas generation rate in SANTOS is

$$r(t,1) = \begin{cases} 2\ mol/drum/yr & 0 \le t \le 550\ yr \\ 1\ mol/drum/yr & 550\ yr \le t \le 1050\ yr \\ 0\ mol/drum/yr & 1050\ yr \le t \end{cases}.$$

The base gas generation rate $r(t,1)$ is representative of relatively high gas production rates from both microbial degradation of cellulosic, plastic and rubber materials and from anoxic corrosion of Fe-base metals (Butcher 1997b). To provide a range of SANTOS results that spans the possible range of pressure computed by BRAGFLO, the gas generation rate is varied by the scaling factor f. Thirteen values of f are used to construct the porosity surface: f = 0.0, 0.025, 0.05, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1.0, 1.2, 1.6, and 2.0. The condition of f = 0 represents the state of the repository when no gas is produced; f = 2 represents twice the base gas generation rate. The gas generation rate for each case is computed by

$$r(t, f) = f \times r(t,1).$$

The gas generation potentials and rates used in SANTOS are not the same as are used in BRAGFLO, the PA model for two-phase flow in the repository (see Appendix PA, Section PA-4.2). In SANTOS, gas generation is included to introduce a range of values for gas pressure during room closure, thereby capturing the effects of gas pressure on room closure; the use of the scaling factor f ensures that SANTOS results span a wide range of possible gas generation rates and potentials. In contrast, the BRAGFLO code computes the amount of gas generated at each time step, using a stoichiometric model that accounts for the inventory of gas-generation substrates, the saturation of the waste material, and the uncertain parameters in the gas generation model.

PORSURF.3 CONCEPTUAL MODEL FOR POROSITY SURFACE

The ability of salt to deform with time, eliminate voids, and create an impermeable salt barrier around the waste was one of the principal reasons for locating the WIPP repository in a bedded salt formation. The creep closure process is a complex and interdependent series of events starting after a region within the repository is excavated. Immediately upon excavation, the equilibrium state of the rock surrounding the repository is disturbed, and the rock begins to deform and return to equilibrium. Eventually, at equilibrium, deformation ceases, and the waste region has undergone as much compaction as is possible under the prevailing lithostatic stress field.

Creep closure of the excavation begins immediately and causes the volume of the cavity to become smaller. If the room were empty, rather than partially filled with waste, closure would proceed to the point where the void volume created by the excavation would be eliminated and the surrounding halite would return to its undisturbed, uniform stress state. In a waste-filled room, the rock will contact the waste and the rate of closure will decrease as the waste compacts and stiffens; eventually, closure will cease when the waste can take the full overburden load without further deformation. Initially, unconsolidated waste can support only small loads, but as the room continues to close after contact with the waste, the waste will consolidate and support a greater portion of the weight of the overburden. Consolidation will continue until mechanical equilibrium is reached.

The presence of gas in the room will retard the closure process due to the build-up of pressure. As the waste consolidates, pore volume is reduced and pore pressure increases (using the ideal gas law). In this process, the waste can be considered to be a skeleton structure immersed in a pore fluid (the gas). As the pore pressure increases, less of the weight of the overburden is carried by the skeleton, and more support is provided by the gas. If the gas pressure increases to lithostatic pressure, the pore pressure alone is sufficient to support the overburden.

PORSURF.4 SANTOS NUMERICAL ANALYSES

Computation of repository creep closure is a particularly challenging structural engineering problem, because the rock surrounding the repository continually deforms with time until equilibrium is reached. Not only is the deformation of the salt inelastic, but it also involves larger deformations than are customarily addressed with conventional structural deformation codes. In addition, the formation surrounding the repository is not homogeneous in composition, containing various parting planes and interbeds with different properties than the salt.

Deformation of the waste is also nonlinear, with large strains, and the response of a waste-filled room is complicated by the presence of gas. These complex characteristics of the materials comprising the repository and its surroundings require the use of highly specialized constitutive models. Appropriate models have been built into the SANTOS code over a number of years. Principal components of the SANTOS model include:

1. Disposal Room Configuration and Idealized Stratigraphy. Disposal room dimensions, computational configuration, and idealized stratigraphy are defined in Attachment 1 to

CCA Appendix PORSURF. The idealized stratigraphy is reproduced in Figure PORSURF-1 of this Attachment.

2. Discretized Finite Element Model. A two-dimensional plane strain model, as shown in Figure PORSURF-2, is used for the SANTOS analyses. The discretized model represents the room as one of an infinite number of rooms located at the repository horizon. The model contains 1,680 quadrilateral uniform-strain elements and 1,805 nodal points. Contact surfaces between the stored waste and the surfaces of the room are addressed. Justification for this model and additional detail on initial and boundary conditions is provided in Attachment 1 to CCA Appendix PORSURF.

3. Geomechanical Model. Mechanical material response models and their corresponding property values are assigned to each region of the configuration. These models include:

   A. a combined transient-secondary creep constitutive model for clean and argillaceous halite;

   B. an inelastic constitutive model for anhydrite; and

   C. a volumetric plasticity model for waste.

   Material properties are provided in CCA Appendix PORSURF.

The results of the SANTOS calculations are illustrated in Figures PORSURF-3 and PORSURF-4. Figure PORSURF-3 shows disposal room porosity as a function of time for various values of the gas generation scaling factor f. Figure PORSURF-4 shows disposal room pressure as a function of time for various values of f. When f = 0, no gas is present in the disposal room, thus, disposal room pressure is identically zero for all times, and this pressure curve is omitted from Figure PORSURF-4.

PORSURF.5 IMPLEMENTATION OF POROSITY SURFACE IN BRAGFLO

As outlined in Section PORSURF.3, the SANTOS program is used to determine time-dependent porosities and pressures in the repository under different rates of gas generation determined by the scaling factor f. Calculation with each value of f results in the porosity and pressure curves in Figures PORSURF-3 and PORSURF-4.

The porosities calculated by SANTOS are defined relative to a dynamically changing excavated volume. In contrast, BRAGFLO assumes a fixed excavated volume, with the effects of closure accounted for by a dynamically changing porosity. The pressures in Figure PORSURF-4 are pressures calculated by SANTOS, as outlined above. However, the porosities in Figure PORSURF-3 are the porosities used in BRAGFLO and are obtained from the true porosities calculated by SANTOS by correcting for the repository closure. Specifically,

$$\phi_S V_S = \phi_B V_B ,$$

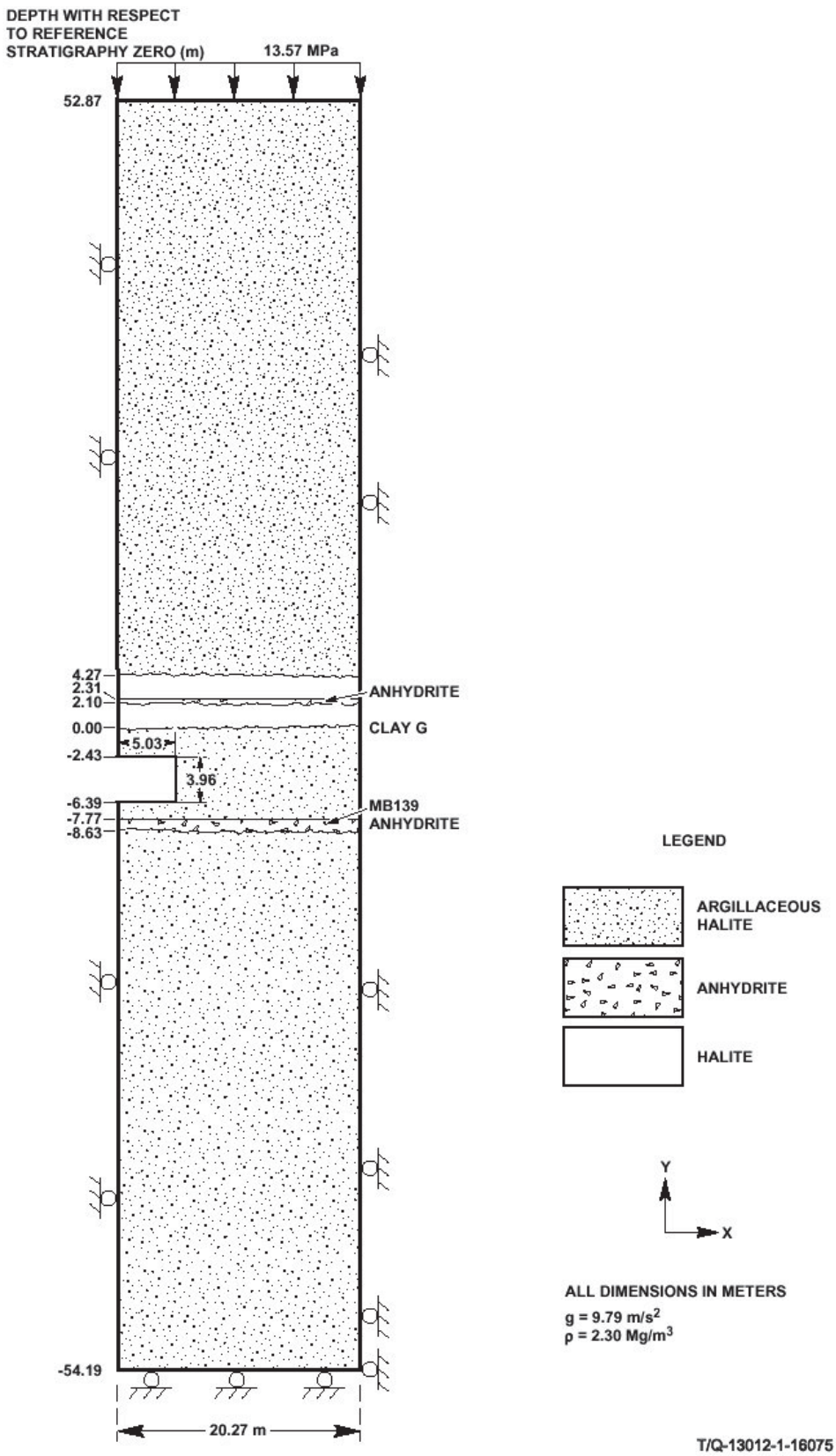

Figure PORSURF-1. Stratigraphy for the Porosity Surface Calculations.

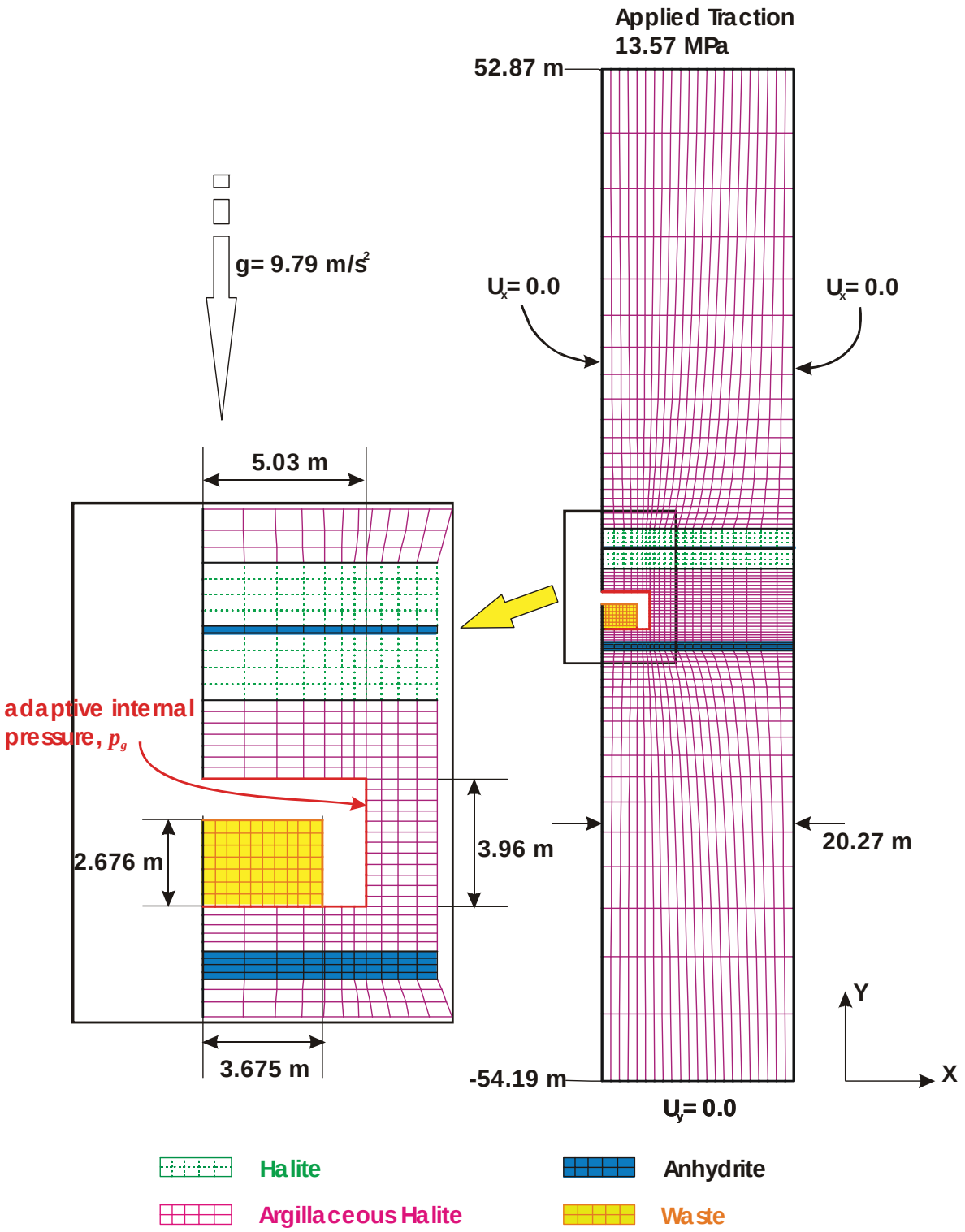

Figure PORSURF-2. Mesh Discretization and Boundary Conditions used for the Porosity Surface Calculations.

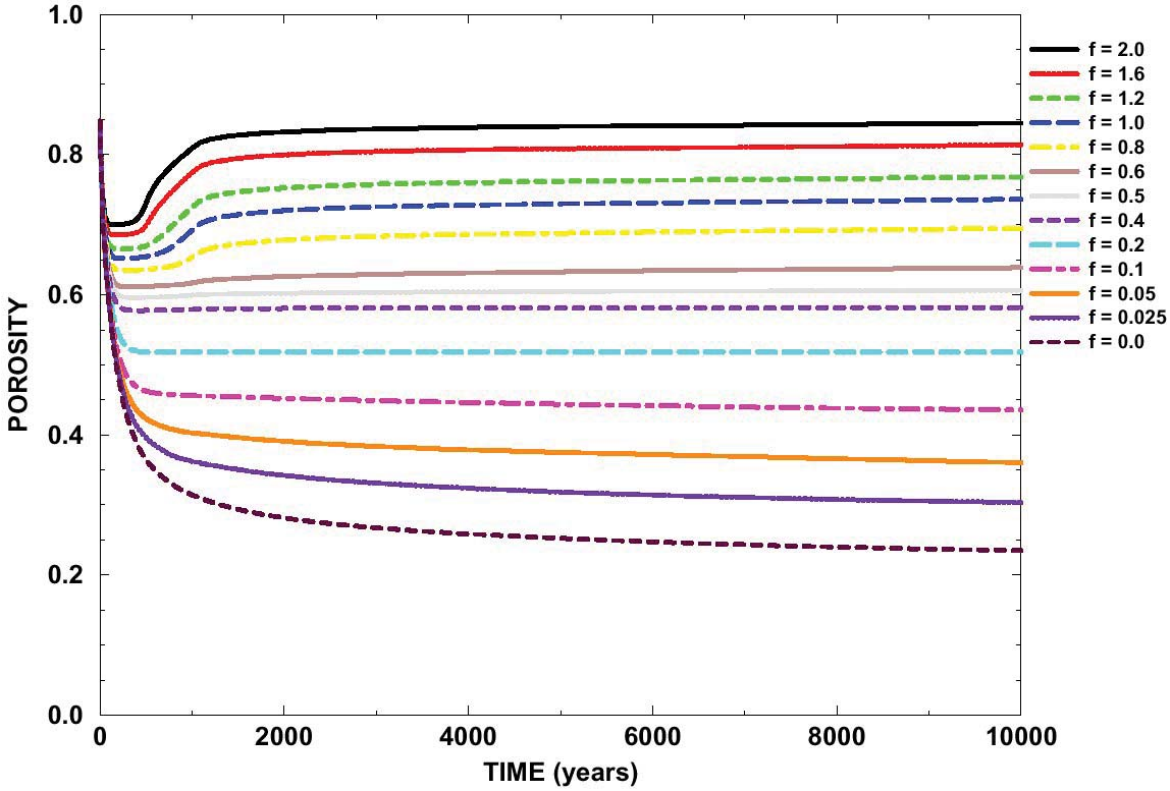

Figure PORSURF-3. Disposal Room Porosity for Various Values of the Scale Factor (f).

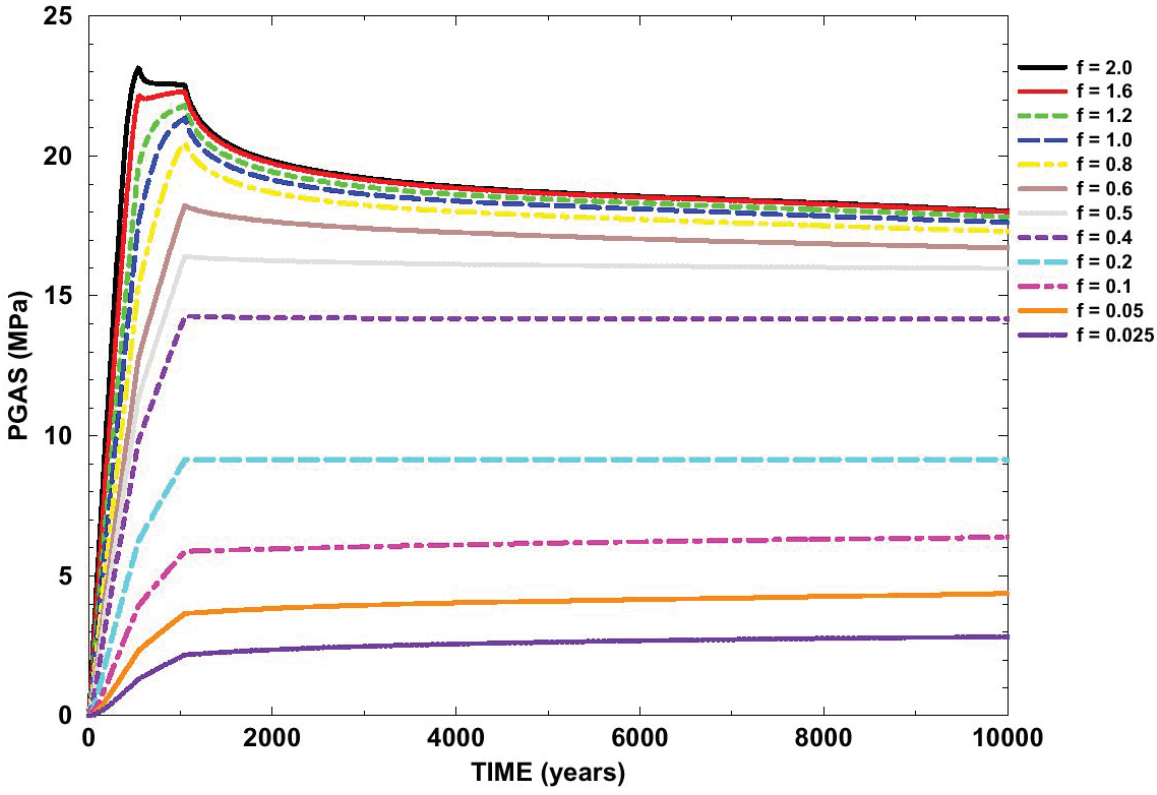

Figure PORSURF-4. Disposal Room Pressure for Various Values of the Scale Factor (f).

where ϕ_S and ϕ_B are the porosities associated with SANTOS and BRAGFLO and V_S and V_B are the total volume per excavated room as represented in SANTOS and BRAGFLO. Note that while V_S changes with time, V_B does not. This formulation conserves the total pore volume in the waste areas between SANTOS and BRAGFLO calculations.

Brine pressures $p_b(t)$ obtained in the waste disposal regions are used in conjunction with the results in Figures PORSURF-3 and PORSURF-4 to estimate porosity in the waste-filled regions for the BRAGFLO calculations. Given a value for $p_b(t)$, values f_1 and f_2 are determined such that

$$p(t, f_1) \le p_b(t) < p(t, f_2),$$

where $p(t, f_i)$ denotes the pressure (Pa) at time t obtained with gas generation rate $r_{f_i}(t)$. An f value associated with $p_b(t)$ is then given by

$$\hat{f} = f_1 + \left(\frac{p_b(t) - p(t, f_1)}{p(t, f_2) - p(t, f_1)} \right) (f_2 - f_1),$$

with $\hat{f}$ being estimated by linear interpolation on f_1 and f_2. With $\hat{f}$ determined, a corresponding porosity $\hat{\phi}$ for use with $p_b(t)$ is obtained from the porosity results in Figure PORSURF-3. Specifically,

$$\hat{\phi} = \phi(t, f_1) + \left(\frac{\hat{f} - f_1}{f_2 - f_1} \right) \left(\phi(t, f_2) - \phi(t, f_1) \right),$$

where $\phi(t, f_i)$ denotes the porosity at time t obtained with gas generation rate $r_{f_i}(t)$.

PORSURF.6 DYNAMIC CLOSURE OF THE NORTH-END AND HALLWAYS

The porosity surface method is not used to model the north end of the repository occupied by the experimental and operational regions. During development of the CCA PA, a supporting analysis compared brine and gas flow results for two models for closure of the north end of the repository: a dynamic closure model, and a baseline model, in which the porosity and permeability of these regions were held constant (Vaughn et al. 1995). The study examined the effect of these two approaches on brine releases to the accessible environment for both disturbed and undisturbed conditions, as well the effects on brine pressures and brine saturations in the modeled regions. The study concluded that the baseline case (assuming constant low porosity and high permeability) consistently led to either similar or more conservative brine pressures and brine saturations, thereby overestimating potential releases relative to the dynamic consolidation case. Consequently, PA uses the simplifying case of constant porosity and permeability in the northern end of the repository, rather than modeling dynamic closure of these areas.

PORSURF.7 ADDITIONAL INFORMATION

The following attachments were included in CCA Appendix PORSURF to document additional details of the porosity surface method:

1. Attachment 1 to Appendix PORSURF of the CCA, Proposed Model for the Final Porosity Surface Calculations. This memo documents preliminary configuration and constitutive property values for the final porosity surface calculations. Tables in the memo include elastic and creep properties for clean halite and argillaceous halite, volumetric strain data and material constants used in the volumetric-plasticity model for waste, and elastic and Drucker-Prager constants assigned to anhydrite Marker Bed 139. This attachment was supplemented and updated subsequent to the CCA by Butcher (1997a; 1997b).

2. Attachment 2 to Appendix PORSURF of the CCA, Baseline Inventory Assumptions for the Final Porosity Surface Calculations. This memo discusses the effect of changes in the Transuranic Waste Baseline Inventory Report (TWBIR) on the SANTOS analyses.

3. Attachment 3 to Appendix PORSURF of the CCA, Corrosion and Microbial Gas Generation Potentials. This memo discusses the rationale for the base gas production potentials of 1,050 moles/drum for corrosion and 550 moles/drum for microbial decay in the SANTOS analyses.

4. Attachment 4 to Appendix PORSURF of the CCA, Resolution of Remaining Issues for the Final Disposal Room Calculations. This memo provides additional detail on the disposal room elevation, determination of plastic constants for transuranic (TRU) waste, and determination of SANTOS input constants for clean halite, argillaceous halite, and anhydrite.

5. Attachment 5 to Appendix PORSURF of the CCA, Sample SANTOS Input File for Disposal Room Analysis. A representative sample input file is provided in this attachment. The only difference between this input file and the file used in the CCA calculations (see Stone 1997) is a subroutine modifying the gas generation variable.

6. Attachment 6 to Appendix PORSURF of the CCA, Final Porosity Surface Data. This attachment provides SANTOS results for selected gas generation scaling factors f = 2.0, f = 1.0, and f = 0.5. This attachment was updated and published as a formal SAND report (Stone 1997) subsequent to submittal of the CCA.

7. Attachment 7 to Appendix PORSURF of the CCA, SANTOS - A Two-Dimensional Finite Element Program for the Quasistatic, Large Deformation, Inelastic Response of Solids. This report provides documentation on the SANTOS code.

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APPENDIX PA

ATTACHMENT SCR

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ACRONYMS AND ABBREVIATIONS

AMWTP	Advanced Mixed Waste Treatment Plant
BNL	Brookhaven National Laboratory
CAG	Compliance Application Guidance
CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CDF	cumulative distribution function
CFR	Code of Federal Regulations
CH	contact-handled
CRA	Compliance Recertification Application
DBDSP	Delaware Basin Drilling Surveillance Program
DFR	driving force ratio
DOE	U.S. Department of Energy
DP	disturbed performance
DRZ	disturbed rock zone
EDTA	ethylene diamine tetra-acetate
EPA	Environmental Protection Agency
EP	event and process
ERMS	Electronic Record Management System
FEP	feature, event, and process
FGE	fissile gram equivalent
FLAC	Fast Lagranian Analysis of Continua
FMT	Fracture-Matrix Transport
FSU	Florida State University
H	human
HC	historical and current human activities
HCN	historic, current and near future human activities
LWA	Land Withdrawal Act
MB	marker bed
MgO	magnesium oxide
MPI	Mississippi Potash Inc.
N	natural
NMBMMR	New Mexico Bureau of Mines and Mineral Resources
NORM	naturally occurring radioactive material
PA	performance assessment
PAVT	performance assessment verification test
RH	remote-handled
RTC	Response to Comments Document
SKI	Statens Kärnkraftinspektion
SMC	Salado mass concrete
SNL	Sandia National Laboratories
SO-C	screened-out consequence
SO-P	screened-out probability
SO-R	screened-out regulatory
T	transmissitivity

TDS	total dissolved solids
TRU	transuranic
TSD	Technical Support Document
TWBIR	Transuranic Waste Baseline Inventory Report
UP	undisturbed performance
VOC	volatile organic compound
W	waste and repository-induced
WIPP	Waste Isolation Pilot Plant
WPO	WIPP Project Office

SCR-1.0 INTRODUCTION

The United States Department of Energy (DOE) has developed the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico for the disposal of transuranic wastes generated by defense programs. In May of 1998, the Environmental Protection Agency (EPA) certified that the WIPP would meet the disposal standards (EPA 1998a) established in Title 40 Code of Federal Regulations (CFR) Part 191, Subparts B and C (EPA 1993), thereby allowing the WIPP to begin waste disposal operations. This certification was based on performance assessment (PA) calculations that were included in the DOE's Compliance Certification Application (CCA). These calculations demonstrate that the cumulative releases of radionuclides to the accessible environment will not exceed those allowed by the EPA standard.

The WIPP Land Withdrawal Act (LWA) (U.S. Congress 1992) requires the WIPP to be recertified (demonstrate continued compliance with the disposal standards) every five years. As such, the DOE has prepared a Compliance Recertification Application (CRA-2004) which demonstrates that the WIPP continues to comply with EPA's requirements for radioactive waste disposal. The CRA-2004 includes any changes to the WIPP long-term compliance baseline since the CCA.

To assure that PA calculations account for important aspects of the disposal system, features, events, and processes (FEPs) considered to be potentially important to the disposal system are identified. These FEPs are used as a tool for determining what phenomena and components of the disposal system can and should be dealt with in PA calculations. For the WIPP CCA, a systematic process was used to compile, analyze, screen, and document FEPs for use in PA. The FEP screening process used in the CCA has also been used for the CRA-2004 and is described in detail in Section 6.2. For the CRA-2004, this process focused on evaluating any new information that may have impacts or present inconsistencies to those screening arguments and decisions presented in the CCA. Changes and updates as a result of this evaluation are described in the *FEPs Reassessment for Recertification Report* (Wagner et al. 2003).

Wagner et al. (2003) concluded that of the original 237 FEPs included in the CCA, 106 have not changed, 120 FEPs required updates to their FEP descriptions and/or screening arguments, and seven of the original baseline FEPs screening decisions required a change from their original screening decision. Four of the original baseline FEPs have been deleted or combined with other closely related FEPs. Finally, two new FEPs have been added to the baseline. These two FEPs were previously addressed in an existing FEP; they have been separated for clarity. Table SCR-1 summarizes the changes in the FEP baseline since the CCA.

Table SCR-1. FEPs Change Summary Since CCA

EPA FEP I.D.	FEP Name	Summary of Change
FEPs Combined with other FEPs		
N17	Lateral ***Dissolution***	Combined with N16, ***Shallow Dissolution.*** N17 removed from baseline.

Table SCR-1. FEPs Change Summary Since CCA - Continued

EPA FEP I.D.	FEP Name	Summary of Change
N19	***Solution Chimneys***	Combined with N20, *Breccia Pipes*. N19 removed from Baseline.
H33	***Flow Through Undetected Boreholes***	Combined with H31, *Natural Borehole Fluid Flow*. H33 removed from baseline.
W38	***Investigation Boreholes***	Addressed in H31, *Natural Borehole Fluid Flow*, and H33, *"Flow Through Undetected Boreholes."* W38 removed from baseline.
FEPs With Changed Screening Decisions		
W50	***Galvanic Coupling***	SO-P to SO-C
W68	***Organic Complexation***	SO-C to UP
W69	***Organic Ligands***	SO-C to UP
H27	***Liquid Waste Disposal***	SO-R to SO-C
H28	***Enhanced Oil and Gas Production***	SO-R to SO-C
H29	***Hydrocarbon Storage***	SO-R to SO-C
H41	***Surface Disruptions***	SO-C to UP (HCN)
New FEPs for CRA		
H58	***Solution Mining for Potash***	Separated from H13, *Potash Mining.*
H59	***Solution Mining for Other Resources***	Separated from H13, *Potash Mining.*

SCR-2.0 BASIS FOR FEATURES, EVENTS, AND PROCESSES SCREENING PROCESS

SCR-2.1 Requirement for Features, Events, and Processes

The origin of FEPs is related to the EPA's radioactive waste disposal standard's requirement to use PA methodology. The DOE was required to demonstrate that the WIPP complied with the Containment Requirements of 40 CFR § 191.13 (EPA 1993). These requirements state that the DOE must use PA to demonstrate that the probabilities of cumulative radionuclide releases from the disposal system during the 10,000 years following closure will fall below specified limits. The PA analyses supporting this determination must be quantitative and must consider uncertainties caused by all *Significant Processes and Events* that may affect the disposal system, including inadvertent human intrusion into the repository during the future. The scope of PA is further defined by EPA at 40 CFR § 194.32 (EPA 1996a), which states:

> Any compliance application(s) shall include information which:
>
> (1) Identifies all potential processes, events or sequences and combinations of processes and events that may occur during the regulatory time frame and may affect the disposal system;

(2) Identifies the processes, events or sequences and combinations of processes and events included in performance assessments; and

(3) Documents why any processes, events or sequences and combinations of processes and events identified pursuant to paragraph (e)(1) of this section were not included in performance assessment results provided in any compliance application.

Therefore, the PA methodology includes a process that compiles a comprehensive list of the FEPs that are relevant to disposal system performance. Those FEPs shown by screening analysis to have the potential to affect performance are represented in scenarios and quantitative calculations using a system of linked computer models to describe the interaction of the repository with the natural system, both with and without human intrusion. For the CCA, the DOE first compiled a comprehensive list of FEPs which was then subjected to a screening process that eventually lead to the set of FEPs used in PA to demonstrate WIPP's compliance with the long-term disposal standards.

SCR-2.2 Features, Events, and Processes List Development for the CCA

As a starting point, the DOE assembled a list of potentially relevant FEPs from the compilation developed by Stenhouse et al. (1993) for the Swedish Nuclear Power Inspectorate Statens Kärnkraftinspektion (SKI). The SKI list was based on a series of FEP lists developed for other disposal programs and is considered the best-documented and most comprehensive starting point for the WIPP. For the SKI study, an initial raw FEP list was compiled based on nine different FEP identification studies.

The compilers of the SKI list eliminated a number of FEPs as irrelevant to the particular disposal concept under consideration in Sweden. These FEPs were reinstated for the WIPP effort, and several FEPs on the SKI list were subdivided to facilitate screening for the WIPP. Finally, to ensure comprehensiveness, other FEPs specific to the WIPP were added based on review of key project documents and broad examination of the preliminary WIPP list by both project participants and stakeholders. The initial unedited list is contained in Appendix SCR, Attachment 1. The initial unedited FEP list was restructured and revised to derive the comprehensive WIPP FEP list used in the CCA. The number of FEPs was reduced to 237 in the CCA to avoid the ambiguities caused by the use of a generic list. Restructuring the list did not remove any substantive issues from the discussion. As discussed in more detail in Attachment 1, the following steps were used to reduce the initial unedited list to the appropriate WIPP FEP list used in the CCA.

- References to subsystems were eliminated because the SKI subsystem classification was not appropriate for the WIPP disposal concept. For example, in contrast to the Swedish disposal concept, canister integrity does not have a role in post-operational performance of the WIPP, and the terms near-field, far-field, and biosphere are not unequivocally defined for the WIPP site.

- Duplicate FEPs were eliminated. Duplicate FEPs arose in the SKI list because individual FEPs could act in different subsystems. FEPs had a single entry in the CCA list whether they were applicable to several parts of the disposal system or to a single part only, for

example, the FEP ***Gas Effects***. Disruption appears in the seals, backfill, waste, canister, and near-field subsystems in the initial FEP list. These FEPs are represented by the single FEP, ***Disruption Due to Gas Effects***.

- FEPs that are not relevant to the WIPP design or inventory were eliminated. Examples include FEPs related to high-level waste, copper canisters, and bentonite backfill.

- FEPs relating to engineering design changes were eliminated because they were not relevant to a compliance application based on the DOE's design for the WIPP. Examples of such FEPs are ***Design Modifications: Canister and Design Modification: Geometry***.

- FEPs relating to constructional, operational, and decommissioning errors were eliminated. The DOE has administrative and quality control procedures to ensure that the facility will be constructed, operated, and decommissioned properly.

- Detailed FEPs relating to processes in the surface environment were aggregated into a small number of generalized FEPs. For example, the SKI list includes the biosphere FEPs ***Inhalation of Salt Particles***, ***Smoking***, ***Showers and Humidifiers***, ***Inhalation and Biotic Material***, ***Household Dust and Fumes***, ***Deposition (Wet and Dry***), ***Inhalation and Soils and Sediments***, ***Inhalation and Gases and Vapors (Indoor and Outdoor***), and ***Suspension in Air***, which are represented by the FEP ***Inhalation***.

- FEPs relating to the containment of hazardous metals, volatile organic compounds (VOCs), and other chemicals that are not regulated by 40 CFR Part 191 were not included.

- A few FEPs have been renamed to be consistent with terms used to describe specific WIPP processes (for example, ***Wicking***, ***Brine Inflow***).

These steps resulted in a list of 237 WIPP-relevant FEPs retained for further consideration in the first certification PA. The 237 were screened to determine which would be included in the PA models and scenarios for the CCA.

SCR-2.3 Criteria for Screening of Features, Events, and Processes and Categorization of Retained Features, Events, and Processes

The purpose of FEP screening is to identify those FEPs that should be accounted for in PA calculations, and those FEPs that need not be considered further. The DOE's process of removing FEPs from consideration in PA calculations involved the structured application of explicit screening criteria. The criteria used to screen out FEPs are explicit regulatory exclusions (SO-R), probability (SO-P), or consequence (SO-C). All three criteria are derived from regulatory requirements. FEPs not screened as SO-R, SO-P, or SO-C were retained for inclusion in PA calculations and are classified as either undisturbed performance (UP) or disturbed performance (DP) FEPs.

SCR-2.3.1 Regulation (SO-R)

Specific FEP screening criteria are stated in 40 CFR Part 191 and Part 194. Such screening criteria relating to the applicability of particular FEPs represent screening decisions made by the EPA. That is, in the process of developing and demonstrating the feasibility of the 40 CFR Part 191 standard and the 40 CFR Part 194 criteria, the EPA considered and made conclusions on the relevance, consequence, and/or probability of occurrence of particular FEPs. In so doing, it allowed some FEPs to be eliminated from consideration.

SCR-2.3.2 Probability of Occurrence of a Feature, Event, and Process Leading to Significant Release of Radionuclides (SO-P)

Low-probability events can be excluded on the basis of the criterion provided in 40 CFR § 194.32(d), which states, "performance assessments need not consider processes and events that have less than one chance in 10,000 of occurring over 10,000 years" (EPA 1996a). In practice, for most FEPs screened out on the basis of low probability of occurrence, it has not been possible to estimate a meaningful quantitative probability. In the absence of quantitative probability estimates, a qualitative argument was used.

SCR-2.3.3 Potential Consequences Associated with the Occurrence of the Features, Events, and Processes (SO-C)

The DOE recognizes two uses for this criterion:

1. FEPs can be eliminated from PA calculations on the basis of insignificant consequence. Consequence can refer to effects on the repository or site or to radiological consequence. In particular, 40 CFR § 194.34(a) states: "The results of performance assessments shall be assembled into 'complementary, cumulative distribution functions' (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events" (EPA 1996a). The DOE has omitted events and processes from PA calculations where there is a reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed by such omissions.

2. FEPs that are potentially beneficial to subsystem performance may be eliminated from PA calculations if necessary to simplify the analysis. This argument may be used when there is uncertainty as to exactly how the FEP should be incorporated into assessment calculations or when incorporation would incur unreasonable difficulties.

In some cases, the effects of the occurrence of a particular event or process, although not necessarily insignificant, can be shown to lie within the range of uncertainty of another FEP already accounted for in the PA calculations. In such cases, the event or process may be considered to be included in PA calculations implicitly, within the range of uncertainty associated with the included FEP.

Although some FEPs could be eliminated from PA calculations on the basis of more than one criterion, the most practical screening criterion was used for classification. In particular, a regulatory screening classification was used in preference to a probability or consequence

screening classification. FEPs that have not been screened out based on any of the three criteria were included in the PA.

SCR-2.3.4 Undisturbed Performance (UP) Features, Events, and Processes

FEPs classified as UP are accounted for in calculations of undisturbed performance of the disposal system. Undisturbed performance is defined in 40 CFR § 191.12 as "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events" (EPA 1993). The UP FEPs are accounted for in the PA calculations to evaluate compliance with the Containment Requirements in 40 CFR § 191.13. Undisturbed PA calculations are also used to demonstrate compliance with the individual and groundwater protection requirements of 40 CFR § 191.15 and 40 CFR 191 Subpart C, respectively.

SCR-2.3.5 Disturbed Performance (DP) Features, Events, and Processes

The FEPs classified as DP are accounted for only in assessment calculations for disturbed performance. The DP FEPs that remain following the screening process relate to the potential disruptive effects of future drilling and mining events in the controlled area. Consideration of both DP and UP FEPs is required to evaluate compliance with 40 CFR § 191.13.

SCR-2.4 Features, Events, and Processes Categories and Timeframes

In the following sections, FEPs are discussed under the categories Natural (N) FEPs, Human-Initiated (H) Events and Processes (EPs), and Waste- and Repository-Induced (W) FEPs. The FEPs are also considered within time frames during which they may occur. Due to the regulatory requirements concerning human activities, two time periods were used when evaluating Human-Initiated EPs. These timeframes were defined as Historical, Current, and Near-Future Human Activities (HCN) and Future Human Activities (Future). These time frames are also discussed in the following section.

SCR-2.4.1 Description of Natural Features, Events, and Processes

Natural FEPs are those that relate to hydrologic, geologic, and climate conditions that have the potential to affect long-term performance of the WIPP disposal system over the regulatory timeframe. These FEPs do not include the impacts of other human related activities such as the effect of boreholes on FEPs related to natural changes in groundwater chemistry. Only natural events and processes are included within the screening process.

Consistent with 40 CFR § 194.32(d), the DOE has screened out several natural FEPs from PA calculations on the basis of a low probability of occurrence at or near the WIPP site. In particular, natural events for which there is no evidence indicating that they have occurred within the Delaware Basin have been screened on this basis. For FEPs analysis, the probabilities of occurrence of these events are assumed to be zero. Quantitative, nonzero probabilities for such events, based on numbers of occurrences, cannot be ascribed without considering regions much larger than the Delaware Basin, thus neglecting established geological understanding of the events and processes that occur within particular geographical provinces.

In considering the overall geological setting of the Delaware Basin, the DOE has eliminated many FEPs from PA calculations on the basis of low consequence. Events and processes that have had little effect on the characteristics of the region in the past are expected to be of low consequence for the regulatory time period.

SCR-2.4.2 Description of Human-Initiated Events and Processes

Human-Initiated EPs (Human EPs) are those associated with human activities in the past, present, and future. The EPA provided guidance in their regulations concerning which human activities are to be considered, the severity, and the manner in which to include them in the future predictions.

The scope of PAs is clarified with respect to human-initiated events and processes in 40 CFR § 194.32. At 40 CFR § 194.32(a), the EPA states:

> Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.

Thus, PAs must include consideration of human EPs relating to mining and drilling activities that might take place during the regulatory time frame. In particular, PAs must consider the potential effects of such activities that might take place within the controlled area at a time when institutional controls cannot be assumed to completely eliminate the possibility of human intrusion.

Further criteria concerning the scope of PAs are provided at 40 CFR § 194.32(c):

> Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

In order to implement the criteria in 40 CFR § 194.32 relating to the scope of PAs, the DOE has divided human activities into three categories: (1) human activities that are currently taking place and those that took place prior to the time of the compliance application; (2) human activities that might be initiated in the near future after submission of the compliance application; and (3) human activities that might be initiated after repository closure. The first two categories of EPs are considered under undisturbed performance, and EPs in the third category lead to disturbed performance conditions. A description of these three categories follows.

1. Historical and current human activities (HC) include resource extraction activities that have historically taken place and are currently taking place outside the controlled area. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. Current human activities taking place within the controlled area are essentially those associated with development of the WIPP repository. Historic human activities include existing boreholes.

2. Near-future human activities include resource extraction activities that may be expected to occur outside the controlled area based on existing plans and leases. Thus, the near future includes the expected lives of existing mines and oil and gas fields, and the expected lives of new mines and oil and gas fields that the DOE expects will be developed based on existing plans and leases. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. The only human activities that are expected to occur within the controlled area in the near future are those associated with development of the WIPP repository. The DOE expects that any activity initiated in the near future, based on existing plans and leases, will be initiated prior to repository closure. Activities initiated prior to repository closure are assumed to continue until their completion.

3. Future human activities include activities that might be initiated within or outside the controlled area after repository closure. This includes drilling and mining for resources within the disposal system at a time when institutional controls cannot be assumed to completely eliminate the possibility of such activities. Future human activities could influence the transport of contaminants within and outside the disposal system by directly removing waste from the disposal system or altering the geological, hydrological, or geochemical characteristics of the disposal system.

SCR-2.4.2.1 Scope of Future Human Activities in Performance Assessment

Performance assessments must consider the effects of future human activities on the performance of the disposal system. The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), which limits the scope of consideration of future human actions in PAs to mining and drilling.

SCR-2.4.2.1.1 Criteria Concerning Future Mining

The EPA provides the following additional criteria concerning the type of future mining that should be considered by the DOE in 40 CFR § 194.32(b):

> Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.

Thus, consideration of future mining may be limited to mining within the controlled area at the locations of resources that are similar in quality and type to those currently extracted from the Delaware Basin. Potash is the only resource that has been identified within the controlled area in quality similar to that currently mined from underground deposits elsewhere in the Delaware Basin. The hydrogeological impacts of future potash mining within the controlled area are accounted for in calculations of the disturbed performance of the disposal system. Consistent

with 40 CFR § 194.32(b), all economically recoverable resources in the vicinity of the disposal system (outside the controlled area) are assumed to be extracted in the near future.

SCR-2.4.2.1.2 Criteria Concerning Future Drilling

With respect to consideration of future drilling, in the preamble to 40 CFR Part 194, the EPA

> …reasoned that while the resources drilled for today may not be the same as those drilled for in the future, the present rates at which these boreholes are drilled can nonetheless provide an estimate of the future rate at which boreholes will be drilled.

Criteria concerning the consideration of future deep and shallow drilling in PAs are provided in 40 CFR § 194.33. The EPA also provides a criterion in 40 CFR § 194.33(d) concerning the use of future boreholes subsequent to drilling.

> With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

Thus, PAs need not consider the effects of techniques used for resource extraction and recovery that would occur subsequent to the drilling of a borehole in the future. Theses activities are screened SO-R.

The EPA provides an additional criterion that limits the severity of human intrusion scenarios that must be considered in PAs. In 40 CFR § 194.33(b)(1) the EPA states that:

> Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario.

SCR-2.4.2.1.3 Screening of Future Human Event and Processes

Future Human EPs accounted for in PA calculations for the WIPP are those associated with mining and deep drilling within the controlled area at a time when institutional controls cannot be assumed to eliminate completely the possibility of such activities. All other future Human EPs, if not eliminated from PA calculations based on regulation, have been eliminated based on low consequence or low probability. For example, the effects of future shallow drilling within the controlled area were eliminated from CCA PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-2.4.3 Description of Waste- and Repository-Induced Features, Events, and Processes

The waste- and repository-induced FEPs are those that relate specifically to the waste material, waste containers, shaft seals, MgO backfill, panel closures, repository structures, and investigation boreholes. All FEPs related to radionuclide chemistry and radionuclide migration are included in this category. The FEPs related to radionuclide transport resulting from future borehole intersections of the WIPP excavation are defined as waste- and repository-induced FEPs.

SCR-3.0 FEATURES, EVENTS, AND PROCESSES BASELINE FOR RECERTIFICATION

The reassessment of FEPs (Wagner et al. 2003) results in a new FEPs baseline for CRA-2004. As discussed in Section SCR.1, 106 of the original 237 WIPP FEPs have not changed. Additionally, 120 FEPs required updates to their FEP descriptions and/or screening arguments. Seven of the original baseline FEPs screening decisions have changed from their original screening decision. Four of the original baseline FEPs have been deleted or combined with other closely related FEPs. Finally, two new FEPs have been added to the baseline. These two FEPs were previously accounted for in a broader FEP. Table SCR-2 outlines the results of the assessment, and subsequent sections of this document present the actual screening decisions and supporting arguments. Those FEPs not separated by gridlines in the first column of Table SCR-2 have been addressed by group, due to close similarity with other FEPs within that group. This grouping process was formerly used in the CCA, and also by the EPA in their Technical Support Document (TSD) for §194.32 (EPA 1998c).

Table SCR-2. FEPs Reassessment Results

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N1	***Stratigraphy***	No	No change	UP
N2	***Brine Reservoirs***	No	No change	DP
N3	***Changes in Regional Stress***	No	Additional information added to FEP text, no change to italicized text.	SO-C
N4	***Regional Tectonics***	No	Additional information added to FEP text, no change to italicized text.	SO-C
N5	***Regional Uplift and Subsidence***	No	Additional information added to FEP text, no change to italicized text.	SO-C
N6	***Salt Deformation***	No	No change	SO-P
N7	***Diapirism***	No	No change	SO-P
N8	***Formation of Fractures***	No	Original FEP text revised and replaced, reference to other FEP removed from italicized text	SO-P UP (Repository)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N9	***Changes in Fracture Properties***	No	Original FEP text revised and replaced, reference to other FEP removed from italicized text	SO-C UP (Near Repository)
N10	***Formation of New Faults***	No	Additional information added to FEP text, no change to italicized text.	SO-P
N11	***Fault Movement***	No	Additional information added to FEP text, no change to italicized text.	SO-P
N12	***Seismic Activity***	No	No change	UP
N13	***Volcanic Activity***	No	Italicized text changed, FEP text unchanged	SO-P
N14	***Magmatic Activity***	No	No changes	SO-C
N15	***Metamorphic Activity***	No	No changes	SO-P
N16	***Shallow Dissolution***	No	N16 and N17 (***Lateral Dissolution***) combined, N17 deleted from baseline. FEP text modified and additional information added.	UP
N17	***Lateral Dissolution***	No	Combined with N16 (***Shallow Dissolution***) - Deleted from baseline – see N16	NA
N19	***Solution Chimneys***	No	Combined with N20 and deleted from baseline	NA
N18	***Deep Dissolution***	No	Both italicized and FEP text revised.	SO-P
N20	***Breccia Pipes***	No	N20 and N19 (***Solution Chimneys***) combined, Both italicized and FEP text revised.	SO-P
N21	***Collapse Breccias***	No	Both italicized and FEP text revised.	SO-P

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N22	***Fracture Infills***	No	No changes	SO-C - Beneficial
N23	***Saturated Groundwater Flow***	No	No change	UP
N24	***Unsaturated Groundwater Flow***	No	No change	UP SO-C in Culebra
N25	***Fracture Flow***	No	No change	UP
N27	***Effects of Preferential Pathways***	No	No change	UP UP in Salado and Culebra
N26	***Density effects on Groundwater Flow***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N28	***Thermal effects on Groundwater Flow***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N29	***Saline Intrusion [Hydrogeological Effects]***	No	Reference to other FEPs removed from the italicized text. FEP text unchanged.	SO-P
N30	***Freshwater Intrusion [Hydrogeological effects]***	No	Reference to other FEPs removed from the italicized text. FEP text unchanged.	SO-P
N31	***Hydrological Response to Earthquakes***	No	Reference to other FEPs removed from the italicized text. FEP text unchanged.	SO-C
N32	***Natural Gas Intrusion***	No	Reference to other FEPs removed from the italicized text. FEP text unchanged.	SO-P
N33	***Groundwater Geochemistry***	No	No change	UP
N34	***Saline Intrusion (Geochemical Effects)***	No	FEP N34 and N38 described together. Screening Argument revised and replaced, italicized text revised to remove reference to other FEPs	SO-C

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N38	***Effects of Dissolution***	No	FEP N34 and N38 are described together. Screening Argument revised and replaced, italicized text revised to remove reference to other FEPs	SO-C
N35	***Freshwater Intrusion (Geochemical Effects)***	No	FEP N35, N36 and N37 are described together. Screening Argument revised and replaced, italicized text revised to remove reference to other FEPs	SO-C
N36	***Changes in Groundwater Eh***	No	FEP N35, N36 and N37 are described together. Screening Argument revised and replaced, italicized text revised to remove reference to other FEPs	SO-C
N37	***Changes in Groundwater pH***	No	FEP N35, N36 and N37 are described together. Screening Argument revised and replaced, italicized text revised to remove reference to other FEPs	SO-C
N39	***Physiography***	No	No change	UP
N40	***Impact of a Large Meteorite***	No	No change	SO-P
N41	***Mechanical Weathering***	No	No change	SO-C
N42	***Chemical Weathering***	No	No change	SO-C
N43	***Aeolian Erosion***	No	No change	SO-C
N44	***Fluvial Erosion***	No	No change	SO-C
N45	***Mass Wasting [Erosion]***	No	No change	SO-C
N46	***Aeolian Deposition***	No	No change	SO-C
N47	***Fluvial Deposition***	No	No change	SO-C
N48	***Lacustrine Deposition***	No	No change	SO-C
N49	***Mass Wasting [Deposition]***	No	No change	SO-C

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N50	***Soil Development***	No	Clarification text added to the FEP text	SO-C
N51	***Stream and River Flow***	No	No change	SO-C
N52	***Surface Water Bodies***	No	No change	SO-C
N53	***Groundwater Discharge***	No	No change	UP
N54	***Groundwater Recharge***	No	No change	UP
N55	***Infiltration***	No	No change	UP
N56	***Changes in Groundwater Recharge and Discharge***	No	No change	UP
N57	***Lake Formation***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N58	***River Flooding***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N59	***Precipitation (e.g. Rainfall)***	No	No change	UP
N60	***Temperature***	No	No change	UP
N61	***Climate Change***	No	No change	UP
N62	***Glaciation***	No	No change	SO-P
N63	***Permafrost***	No	No change	SO-P
N64	***Seas and Oceans***	No	No change	SO-C
N65	***Estuaries***	No	No change	SO-C
N66	***Coastal Erosion***	No	No change	SO-C
N67	***Marine Sediment Transport and Deposition***	No	No change	SO-C
N68	***Sea Level Changes***	No	No change	SO-C
N69	***Plants***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N70	***Animals***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N71	***Microbes***	No	Additional information added to FEP text, reference to other FEPs removed from italicized text.	SO-C (UP - for colloidal effects and gas generation)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N72	***Natural Ecological Deevelopment***	No	No change	SO-C
W1	***Disposal Geometry***	No	No change	UP
W2	***Waste Inventory***	No	No change	UP
W3	***Heterogeneity of Waste Forms***	No	No change	DP
W4	***Container Form***	No	Both italicized and FEP text revised	SO-C
W5	***Container Material Inventory***	No	No change	UP
W6	***Seal Geometry***	No	No change	UP
W7	***Seal Physical Properties***	No	No change	UP
W8	***Seal Chemical Composition***	No	Both italicized and FEP text revised	SO-C Beneficial SO-C
W9	***Backfill Physical Properties***	No	Both italicized and FEP text revised	SO-C
W10	***Backfill Chemical Composition***	No	No change	UP
W11	***Post-Closure Monitoring***	No	Additional information added to FEP text.	SO-C
W12	***Radionuclide Decay and In-Growth***	No	No change	UP
W13	***Heat from Radioactive Decay***	No	No change to Italicized text, new concluding paragraph added to FEP text.	SO-C
W14	***Nuclear Criticality: Heat***	No	No change to Italicized text, additional information added to FEP text.	SO-P
W15	***Radiological Effects on Waste***	No	No change to Italicized text, FEP text revised.	SO-C
W16	***Radiological Effects on Containers***	No	No change to Italicized text, FEP text revised.	SO-C
W17	***Radiological Effects on Seals***	No	No change	SO-C
W18	***Disturbed Rock Zone (DRZ)***	No	No change	UP

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W19	***Excavation-Induced Changes in Stress***	No	No change	UP
W20	***Salt Creep***	No	No change	UP
W21	***Changes in the Stress Field***	No	No change	UP
W22	***Roof Falls***	No	No change	UP
W23	***Subsidence***	No	Minor changes to FEPs text, no changes to italicized text.	SO-C
W24	***Large Scale Rock Fracturing***	No	Minor changes to FEPs text, no changes to italicized text.	SO-P
W25	***Disruption Due to Gas Effects***	No	No change	UP
W26	***Pressurization***	No	No change	UP
W27	***Gas Explosions***	No	No change	UP
W28	***Nuclear Explosions***	No	Reference to other FEPs removed from italicized text, FEP text revised.	SO-P
W29	***Thermal Effects on Material Properties***	No	Additional information added to FEP text, grouped with similar FEPs; italicized text unchanged	SO-C
W30	***Thermally-Induced Stress Changes***	No	Additional information added to FEP text, grouped with similar FEPs; italicized text unchanged	SO-C
W31	***Differing Thermal Expansion of Repository Components***	No	Additional information added to FEP text, grouped with similar FEPs; italicized text unchanged	SO-C
W72	***Exothermic Reactions***	No	Additional information added to FEP text, grouped with similar FEPs; italicized text unchanged	SO-C

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W73	***Concrete Hydration***	No	Additional information added to FEP text, grouped with similar FEPs; italicized text unchanged	SO-C
W32	***Consolidation of Waste***	No	No change	UP
W36	***Consolidation of Seals***	No	No change	UP
W37	***Mechanical Degradation of Seals***	No	No change	UP
W39	***Underground Boreholes***	No	No change	UP
W33	***Movement of Containers***	No	Reference to other FEPs removed from italicized text, FEP text revised	SO-C
W34	***Container Integrity***	No	Reference to other FEPs removed from italicized text, FEP text revised	SO-C Beneficial
W35	***Mechanical Effects of Backfill***	No	Both italicized and FEP text revised.	SO-C
W38	***Investigation Boreholes***	Yes	Encompassed in FEPS H31 and W33, FEP H38 deleted from baseline.	NA
W40	***Brine Inflow***	No	No change	UP
W41	***Wicking***	No	No change	UP
W42	***Fluid Flow Due to Gas Production***	No	No change	UP
W43	***Convection***	No	Reference to other FEPs removed from italicized text, FEP text revised	SO-C
W44	***Degradation of Organic Material***	No	No change	UP
W45	***Effects of Temperature on Microbial Gas Generation***	No	No change	UP
W48	***Effects of Biofilms on Microbial Gas Generation***	No	No change	UP
W46	***Effects of Pressure on Microbial Gas Generation***	No	Reference to other FEPs removed from italicized text, FEP text revised	SO-C

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W47	***Effects of Radiation on Microbial Gas Generation***	No	Reference to other FEPs removed from italicized text, FEP text revised	SO-C
W49	***Gases from Metal Corrosion***	No	No change	UP
W51	***Chemical Effects of Corrosion***	No	No change	UP
W50	***Galvanic Coupling (Within the Repository)***	Yes	Decision changed from SO-P to SO-C. Both italicized and FEP text revised.	SO-C
W52	***Radiolysis of Brine***	No	Both italicized and FEP text revised.	SO-C
W53	***Radiolysis of Cellulose***	No	FEP text revised	SO-C
W54	***Helium Gas Production***	No	Both italicized and FEP text revised.	SO-C
W55	***Radioactive Gases***	No	Reference to other FEPs removed from italicized text, no change to FEP text	SO-C
W56	***Speciation***	No	No change	UP UP in disposal rooms and Culebra. SO-C elsewhere, and beneficial SO-C in cementitious seals
W57	***Kinetics of Speciation***	No	Both italicized and FEP text revised.	SO-C
W58	***Dissolution of Waste***	No	No change	UP
W59	***Precipitation of Secondary Minerals***	No	Both italicized and FEP text revised.	SO-C-Beneficial
W60	***Kinetics of Precipitation and Dissolution***	No	Both italicized and FEP text revised.	SO-C
W61	***Actinide Sorption***	No	No change	UP
W62	***Kinetics of Sorption***	No	No change	UP
W63	***Changes in Sorptive Surfaces***	No	No change	UP
W64	***Effects of Metal Corrosion***	No	No change	UP
W65	***Reduction-Oxidation Fronts***	No	Reference to other FEPs removed from FEP and italicized text	SO-P

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W66	***Reduction-Oxidation Kinetics***	No	No change	UP
W67	***Localized Reducing Zones***	No	Changes to FEPs text, no changes to italicized text.	SO-C
W68	***Organic Complexation***	Yes	Decision changed from SO-C to UP. Both italicized and FEP text revised.	UP
W69	***Organic Ligands***	Yes	Decision changed from SO-C to UP. Both italicized and FEP text revised.	UP
W71	***Kinetics of Organic Complexation***	No	Both italicized and FEP text revised.	SO-C
W70	***Humic and Flvic Acids***	No	No change	UP
W74	***Chemical Degradation of Seals***	No	No change	UP
W76	***Microbial Growth on Concrete***	No	No change	UP
W75	***Chemical Degradation of Backfill***	No	FEP text unchanged, reference to other FEPs removed from FEP and italicized text	SO-C
W77	***Solute Transport***	No	No change	UP
W78	***Colloid Transport***	No	No change	UP
W79	***Colloid Formation and Stability***	No	No change	UP
W80	***Colloid Filtration***	No	No change	UP
W81	***Colloid Sorption***	No	No change	UP
W82	***Suspensions of Particles***	No	No change	DP
W83	***Rinse***	No	No change	SO-C
W84	***Cuttings***	No	No change	DP
W85	***Cavings***	No	No change	DP
W86	***Spallings***	No	No change	DP
W87	***Microbial Transport***	No	No change	UP
W88	***Biofilms***	No	Both italicized and FEP text revised.	SO-C Beneficial

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W89	***Transport of Radioactive Gases***	No	No change to Italicized text, additional information added to FEP text.	SO-C
W90	***Advection***	No	No change	UP
W91	***Diffusion***	No	No change	UP
W92	***Matrix Diffusion***	No	No change	UP
W93	***Soret Effect***	No	No changes	SO-C
W94	***Electrochemical Effects***	No	Both italicized and FEP text revised.	SO-C
W95	***Galvanic Coupling (Outside the Repository)***	No	Reference to other FEPs removed from italicized text, no change to FEP text	SO-P
W96	***Electrophoresis***	No	Both italicized and FEP text revised.	SO-C
W97	***Chemical Gradients***	No	Reference to other FEPs removed from italicized text, additional information added to FEP text.	SO-C
W98	***Osmotic Processes***	No	Reference to other FEPs removed from italicized text, FEP text revised.	SO-C
W99	***Alpha Recoil***	No	Reference to other FEPs removed from italicized text, FEP text revised.	SO-C
W100	***Enhanced Diffusion***	No	Both italicized and FEP text revised.	SO-C
W101	***Plant Uptake***	No	No changes	SO-R
W102	***Animal Uptake***	No	No changes	SO-R
W103	***Accumulation in Soils***	No	No changes	SO-C
W104	***Ingestion***	No	No changes	SO-R
W105	***Inhalation***	No	No changes	SO-R
W106	***Irradiation***	No	No changes	SO-R
W107	***Dermal Sorption***	No	No changes	SO-R
W108	***Injection***	No	No changes	SO-R

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H1	***Oil and Gas Exploration***	No	Updated	SO-C (HCN) DP (Future)
H2	***Potash Exploration***	No	Updated	SO-C (HCN) DP (Future)
H4	***Oil and Gas Exploitation***	No	Updated	SO-C (HCN) DP (Future)
H8	***Other Resources***	No	Updated	SO-C (HCN) DP (Future)
H9	***Enhanced Oil and Gas Recovery***	No	Updated	SO-C (HCN) DP (Future)
H3	***Water Resources Exploration***	No	Both italicized and FEP text revised.	SO-C (HCN) SO-C (Future)
H5	***Groundwater Exploitation***	No	Both italicized and FEP text revised.	SO-C (HCN) SO-C (Future)
H6	***Archaeological Investigations***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H7	***Geothermal***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H10	***Liquid Waste Disposal***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H11	***Hydrocarbon Storage***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H12	***Deliberate Drilling Intrusion***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H13	***Conventional Underground Potash Mining*** ***Formerly Called "Potash Mining"***	No	Name changed from "Potash Mining" to "Conventional Underground Potash Mining." Both italicized and FEP text revised.	UP (HCN) DP (Future)
H14	***Other Resources***	No	Both italicized and FEP text revised.	SO-C (HCN) SO-R (Future)
H15	***Tunneling***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H16	***Construction of Underground Facilities (for Example Storage, Disposal, Accommodation)***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H17	***Archaeological Excavations***	No	Both italicized and FEP text revised.	SO-C (HCN) SO-R (Future)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H18	***Deliberate Mining Intrusion***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H19	***Explosions for Resource Recovery***	No	Both italicized and FEP text revised.	SO-C (HCN) SO-R (Future)
H20	***Underground Nuclear Device Testing***	No	No changes	SO-C (HCN) SO-R (Future)
H21	***Drilling Fluid Flow***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) DP (Future)
H22	***Drilling Fluid Loss***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) DP (Future)
H23	***Blowouts***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) DP (Future)
H24	***Drilling-Induced Geochemical Changes***	No	Reference to other FEPs removed from FEP and italicized text	UP (HCN) DP (Future)
H25	***Oil and Gas Extraction***	No	No changes	SO-C (HCN) SO-R (Future)
H26	***Groundwater Extraction***	No	No changes	SO-C (HCN) SO-R (Future)
H27	***Liquid Waste Disposal***	Yes	Additional information added to the original FEP text. Screening changed in italicized text from SO-R to SO-C (future).	SO-C (HCN) SO-C (Future)
H28	***Enhanced Oil and Gas Production***	Yes	Additional information added to the original FEP text. Screening changed in italicized text from SO-R to SO-C (future).	SO-C (HCN) SO-C (Future)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H29	***Hydrocarbon Storage***	Yes	Additional information added to the original FEP text. Screening changed in italicized text from SO-R to SO-C (future).	SO-C (HCN) SO-C (Future)
H30	***Fluid-injection Induced Geochemical Changes***	No	Reference to other FEPs removed from FEP and italicized text.	UP (HCN) SO-R (Future)
H31	***Natural Borehole Fluid Flow***	No	H31 and H33 combined. Both FEP text and italicized text revised to include H33.	SO-C (HCN) DP (Future)
H33	***Flow Through Undetected Boreholes***	Yes	Combined with H31 and deleted from FEPs baseline.	NA
H32	***Waste-Induced Borehole Flow***	No	Both FEP text and italicized text revised.	SO-R (HCN) DP (Future)
H34	***Borehole-Induced Solution and Subsidence***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	SO-C (HCN) SO-C (Future)
H35	***Borehole-Induced Mineralization***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	SO-C (HCN) SO-C (Future)
H36	***Borehole-Induced Geochemical Changes***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	UP (HCN) DP (Future)
H37	***Changes in Groundwater Flow Due to Mining***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	UP (HCN) DP (Future)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H38	***Changes in Geochemistry Due to Mining***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	SO-C (HCN) SO-R (Future)
H39	***Changes in Groundwater Flow Due to Explosions***	No	No changes	SO-C (HCN) SO-R (Future)
H40	***Land Use Changes***	No	Reference to other FEPs removed from italicized text, additional information added to FEP text.	SO-R (HCN) SO-R (Future)
H41	***Surface Disruptions***	Yes	Reference to other FEPs removed from italicized text, additional information added to FEP text.	UP (HCN) SO-R (Future)
H42	***Damming of Streams or Rivers***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) SO-R (Future)
H43	***Reservoirs***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) SO-R (Future)
H44	***Irrigation***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) SO-R (Future)
H45	***Lake Usage***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	SO-R (HCN) SO-R (Future)
H46	***Altered Soil or Surface Water Chemistry by Human Activities***	No	Reference to other FEPs removed from FEP and italicized text.	SO-C (HCN) SO-R (Future)
H47	***Greenhouse Gas Effects***	No	No changes	SO-R (HCN) SO-R (Future)
H48	***Acid Rain***	No	No changes	SO-R (HCN) SO-R (Future)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H49	***Damage to the Ozone Layer***	No	No changes	SO-R (HCN) SO-R (Future)
H50	***Coastal Water Use***	No	No changes	SO-R (HCN) SO-R (Future)
H51	***Sea water Use***	No	No changes	SO-R (HCN) SO-R (Future)
H52	***Estuarine Water Use***	No	No changes	SO-R (HCN) SO-R (Future)
H53	***Arable Farming***	No	No changes	SO-C (HCN) SO-R (Future)
H54	***Ranching***	No	No changes	SO-C (HCN) SO-R (Future)
H55	***Fish Farming***	No	No changes	SO-R (HCN) SO-R (Future)
H56	***Demographic Change and Urban Development***	No	Reference to other FEPs removed from FEP and italicized text.	SO-R (HCN) SO-R (Future)
H57	***Loss of Records***	No	Additional information added to FEP text, italicized text modified to remove reference to another FEP.	NA (HCN) DP (Future)
H58	***Solution Mining for Potash***	Yes	New FEP, ***Solution Mining*** was contained in various other FEPs – see H13	SO-R (HCN) SO-R (Future)
H59	***Solution Mining for Other Resources***	Yes	New FEP, ***Solution Mining*** was contained in various other FEPs – see H13	SO-C (HCN) SO-C (Future)

SCR-4.0 SCREENING OF NATURAL FEPS

This section presents the screening arguments and decisions for natural FEPs. Natural FEPs may be important to the performance of the disposal system. Screening of natural FEPs is done in the absence of human influences on the FEPs. Table SCR-2 provides information regarding the changes to these FEPs since the CCA. Of the 72 natural FEPs, 32 remain completely unchanged, 38 were updated to include additional information or were edited for clarity and completeness, and two were deleted from the baseline by combining with other more appropriate FEPs. No screening decisions (classifications) for natural FEPs were changed.

SCR-4.1 Geological FEPs

SCR-4.1.1 Stratigraphy

SCR-4.1.1.1 FEP Number: N1 and N2
FEP Title: ***Stratigraphy*** (N1)
Brine Reservoir (N2)

SCR-4.1.1.1.1 Screening Decision: UP

The stratigraphy of the geological formations in the region of the WIPP is accounted for in PA calculations. The presence of brine reservoirs in the Castile Formation is accounted for in PA calculations.

SCR-4.1.1.1.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-4.1.1.1.3 Screening Argument

The ***Stratigraphy*** and geology of the region around the WIPP, including the distribution and characteristics of pressurized ***Brine Reservoirs*** in the Castile Formation (hereafter referred to as the Castile), are discussed in detail in Section 2.1.3. The stratigraphy of the geological formations in the region of the WIPP is accounted for in PA calculations through the setup of the model geometries (Section 6.4.2). The presence of brine reservoirs is accounted for in the treatment of inadvertent drilling (Sections 6.4.12.6 and 6.4.8).

SCR-4.1.2 Tectonics

SCR-4.1.2.1 FEP Number: N3, N4, and N5
FEP Title: ***Regional Tectonics*** (N3)
Change in Regional Stress (N4)
Regional Uplift and Subsidence (N5)

SCR-4.1.2.1.1 Screening Decision: SO-C

The effects of regional tectonics, regional uplift and subsidence, and changes in regional stress have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.1.2.1.2 Summary of New Information

The DOE's screening designations for WIPP regional tectonics, changes in regional stress, regional uplift and subsidence appears to be technically valid. DOE described the WIPP site as located in an area with no evidence of significant tectonic activity, and with a low level of stress in the region. The WIPP is located in an area of tectonic quiescence. Seismic monitoring

conducted for the WIPP since the CCA continues to record small events at distance from the WIPP, and these events are mainly in areas associated with hydrocarbon production. Two nearby events (magnitude 3.5, 10/97, and magnitude 2.8, 12/98) are related to rockfalls in the Nash Draw mine and are not tectonic in origin (DOE 1999). These events did not cause any damage at the WIPP. There are no known nearby active faults, and one of the main tectonic features is a slight eastward dip to pre-Cenozoic formations within the basin. There is no geologic evidence of continuing tilting. These studies show short-term benchmark movements consistent with the basin tilt.

SCR-4.1.2.1.3 Screening Argument

Regional Tectonics encompasses two related issues of concern: the overall level of regional stress and whether any significant ***Changes in Regional Stress*** might occur.

The tectonic setting and structural features of the area around the WIPP are described in Section 2.1.5. In summary, there is no geological evidence for Quaternary regional tectonics in the Delaware Basin. The eastward tilting of the region has been dated as mid-Miocene to Pliocene by King (1948, pp. 120 - 121) and is associated with the uplift of the Guadalupe Mountains to the west. Fault zones along the eastern margin of the basin, where it flanks the Central Basin Platform, were active during the Late Permian. Evidence for this includes the displacement of the Rustler Formation (hereafter referred to as the Rustler) observed by Holt and Powers (1988, pp. 4 - 14) and the thinning of the Dewey Lake Redbeds (hereafter referred to as the Dewey Lake) reported by Schiel (1994). There is, however, no surface displacement along the trend of these fault zones, indicating that there has been no significant Quaternary movement. Other faults identified within the evaporite sequence of the Delaware Basin are inferred by Barrows' figures in Borns et al. (1983, pp. 58 - 60) to be the result of salt deformation rather than regional tectonic processes. According to Muehlberger et al. (1978, p. 338), the nearest faults on which Quaternary movement has been identified lie to the west of the Guadalupe Mountains and are of minor regional significance. The effects of regional tectonics and changes in regional stress have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

There are no reported stress measurements from the Delaware Basin, but a low level of regional stress has been inferred from the geological setting of the area (see Section 2.1.5). The inferred low level of regional stress and the lack of Quaternary tectonic activity indicate that regional tectonics and any changes in regional stress will be minor and therefore of low consequence to the performance of the disposal system. Even if rates of regional tectonic movement experienced over the past 10 million years continue, the extent of ***Regional Uplift and Subsidence*** over the next 10,000 years would only be about several feet (approximately 1 m). This amount of uplift or subsidence would not lead to a breach of the Salado because the salt would deform plastically to accommodate this slow rate of movement. Uniform regional uplift or a small increase in regional dip consistent with this past rate could give rise to downcutting by rivers and streams in the region. The extent of this downcutting would be little more than the extent of uplift, and reducing the overburden by 1 or 2 m would have no significant effect on groundwater flow or contaminant transport in units above or below the Salado. Thus, the effects of ***Regional Uplift and Subsidence*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.1.2.1.4 Tectonic Setting and Site Structural Features

The DOE has screened out, on the basis of either probability or consequence or both, all tectonic, magmatic, and structural related processes. The screening discussions can be found in CCA Appendix SCR. The information needed for this screening is included here and covers regional tectonic processes such as subsidence and uplift and basin tilting, magmatic processes such as igneous intrusion and events such as volcanism, and structural processes such as faulting, and loading and unloading of the rocks because of long-term sedimentation or erosion. Discussions of structural events, such as earthquakes, are considered to the extent that they may create new faults or activate old faults. The seismicity of the area is considered in Section 2.6 for the purposes of determining seismic design parameters for the facility.

SCR-4.1.2.1.5 Tectonics

The processes and features included in this section are those more traditionally considered part of tectonics-processes that develop the broad-scale features of the earth. Salt dissolution is a different process that can develop some features resembling those of tectonics.

Most broad-scale structural elements of the area around the WIPP developed during the Late Paleozoic (Appendix CCA GCR, pp. 3-58 to 3-77). There is little historical or geological evidence of significant tectonic activity in the vicinity, and the level of stress in the region is low. The entire region tilted slightly during the Tertiary, and activity related to Basin and Range tectonics formed major structures southwest of the area. Seismic activity is specifically addressed in a separate section.

Broad subsidence began in the area as early as the Ordovician, developing a sag called the Tobosa Basin. By Late Pennsylvanian to Early Permian time, the Central Basin Platform developed (Figure 2-19), separating the Tobosa Basin into two parts: the Delaware Basin to the west and the Midland Basin to the east. The Permian Basin refers to the collective set of depositional basins in the area during the Permian Period. Southwest of the Delaware Basin, the Diablo Platform began developing either in the Late Pennsylvanian or Early Permian. The Marathon Uplift and Ouachita tectonic belt limited the southern extent of the Delaware Basin.

According to Brokaw et al. (1972, p. 30), pre-Ochoan sedimentary rocks in the Delaware Basin show evidence of gentle downwarping during deposition, while Ochoan and younger rocks do not. A relatively uniform eastward tilt, generally from about 14 to 19 m/km (75 to 100 ft/mi), has been superimposed on the sedimentary sequence. P.B. King (1948, pp. 108 and 121) generally attributes the uplift of the Guadalupe and Delaware mountains along the west side of the Delaware Basin to the later Cenozoic, though he also notes that some faults along the west margin of the Guadalupe Mountains have displaced Quaternary gravels.

P.B. King (1948, p. 144) also infers the uplift from the Pliocene-age deposits of the Llano Estacado. Subsequent studies of the Ogallala of the Llano Estacado show that it varies in age from Miocene (about 12 million years before present) to Pliocene (Hawley 1993). This is the most likely range for uplift of the Guadalupe Mountains and broad tilting to the east of the Delaware Basin sequence.

Analysis of the present regional stress field indicates that the Delaware Basin lies within the Southern Great Plains stress province. This province is a transition zone between the extensional stress regime to the west and the region of compressive stress to the east. An interpretation by Zoback and Zoback (1991, p. 350) of the available data indicates that the level of stress in the Southern Great Plains stress province is low. Changes to the tectonic setting, such as the development of subduction zones and a consequent change in the driving forces, would take much longer than 10,000 years to occur.

To the west of the Southern Great Plains province is the Basin and Range province, or Cordilleran Extension province, where according to Zoback and Zoback (1991, pp. 348-351) normal faulting is the characteristic style of deformation. The eastern boundary of the Basin and Range province is marked by the Rio Grande Rift. Sanford et al. (1991, p. 230) note that, as a geological structure, the Rift extends beyond the relatively narrow geomorphological feature seen at the surface, with a magnetic anomaly at least 500 km (300 mi) wide. On this basis, the Rio Grande Rift can be regarded as a system of axial grabens along a major north-south trending structural uplift (a continuation of the Southern Rocky Mountains). The magnetic anomaly extends beneath the Southern Great Plains stress province, and regional-scale uplift of about 1,000 m (3,300 ft) over the past 10 million years also extends into eastern New Mexico.

To the east of the Southern Great Plains province is the large Mid-Plate province that encompasses central and eastern regions of the conterminous United States and the Atlantic basin west of the Mid-Atlantic Ridge. The Mid-Plate province is characterized by low levels of paleo- and historic seismicity. Where Quaternary faulting has occurred, it is generally strike-slip and appears to be associated with the reactivation of older structural elements.

Zoback et al. (1991) report no stress measurements from the Delaware Basin. The stress field in the Southern Great Plains stress province has been defined from borehole measurements in west Texas and from volcanic lineaments in northern New Mexico. These measurements were interpreted by Zoback and Zoback (1991, p. 353) to indicate that the least principal horizontal stress is oriented north-northeast and south-southwest and that most of the province is characterized by an extensional stress regime.

There is an abrupt change between the orientation of the least principal horizontal stress in the Southern Great Plains and the west-northwest orientation of the least principal horizontal stress characteristic of the Rio Grande Rift. In addition to the geological indications of a transition zone as described above, Zoback and Zoback (1980, p. 6134) point out that there is also evidence for a sharp boundary between these two provinces. This is reinforced by the change in crustal thickness from about 40 km (24 mi) beneath the Colorado Plateau to about 50 km (30 mi) or more beneath the Southern Great Plains east of the Rio Grande Rift. The base of the crust within the Rio Grande Rift is poorly defined but is shallower than that of the Colorado Plateau (Thompson and Zoback 1979, p. 152). There is also markedly lower heat flow in the Southern Great Plains (typically < 60 m Wm-2) reported by Blackwell et al. (1991, p. 428) compared with that in the Rio Grande Rift (typically > 80 m Wm-2) reported by Reiter et al. (1991, p. 463).

On the eastern boundary of the Southern Great Plains province, there is only a small rotation in the direction of the least principal horizontal stress. There is, however, a change from an extensional, normal faulting regime to a compressive, strike-slip faulting regime in the Mid-Plate

province. According to Zoback and Zoback (1980, p. 6134), the available data indicate that this change is not abrupt and that the Southern Great Plains province can be viewed as a marginal part of the Mid-Plate province.

SCR-4.1.3 Structural FEPs

SCR-4.1.3.1 Deformation

SCR-4.1.3.1.1 FEP Number: N6 and N7
FEP Title: ***Salt Deformation*** (N6)
Diapirism (N7)

SCR-4.1.3.1.1.1 *Screening Decision: SO-P*

Natural salt deformation and diapirism at the WIPP site over the next 10,000 years on a scale severe enough to significantly affect performance of the disposal system has been eliminated from PA calculations on the basis of low probability of occurrence.

SCR-4.1.3.1.1.2 *Summary of New Information*

The DOE presented extensive evidence that some of the evaporites in the northern Delaware Basin have been deformed and proposed that the likely mechanism for deformation is gravity foundering of the more dense anhydrites in less dense halite (e.g., Anderson and Powers 1978; Jones 1981; Borns et al. 1983; Borns 1987). Diapirism occurs when the deformation is penetrative, i.e., halite beds disrupt overlying anhydrites. As Anderson and Powers (1978) suggested, this may have happened northeast of the WIPP at the location of drillhole ERDA-6. This is the only location where diapirism has been suggested for the evaporites of the northern Delaware Basin. The geologic situation suggests that deformation occurred before the Miocene-Pliocene Ogallala Formation was deposited (Jones 1981). Mechanical modeling is consistent with salt deformation occurring over about 700,000 years to form the deformed features known in the northern part of the WIPP site (Borns et al. 1983). The DOE drew the conclusion that evaporites at the WIPP site deform too slowly to affect performance of the disposal system.

Because brine reservoirs appear to be associated with deformation, Powers et al. (1996) prepared detailed structure elevation maps of various units from the base of the Castile Formation upward through the evaporites in the northern Delaware Basin. Drillholes are far more numerous for this study than at the time of the study by Anderson and Powers (1978). Subdivisions of the Castile appear to be continuous in the vicinity of ERDA 6 and at ERDA 6. There is little justification for interpreting diapiric piercement at that site. The location and distribution of evaporite deformation in the area of the WIPP site is similar to that proposed by earlier studies (e.g., Anderson and Powers 1978; Borns et al. 1983; Borns and Shaffer 1985).

Surface domal features at the northwestern end of Nash Draw were of undetermined origin prior to WIPP investigations (e.g., Vine 1963), but extensive geophysical studies were conducted of these features as part of early WIPP studies (see Powers 1996). Two of the domal features were drilled, demonstrating that they had a solution-collapse origin (breccia pipes) and were not related in any way to salt diapirism (Snyder and Gard 1982).

A more recent study of structure for the Culebra Dolomite Member of the Rustler Formation (Powers 2002) shows that the larger deformation associated with deeper units is reflected by the Culebra, although the structural relief is muted. In addition, evaporite deformation in the northern part of the WIPP site, associated with the area earlier termed the "disturbed zone" (Powers et al. 1978), is hardly observable on a map of Culebra structure (Powers 2002). There is no evidence of more recent deformation at the WIPP site based on such maps.

These findings are consistent with the DOE position in the CCA that diapirism can be eliminated from PA calculations on the basis of low probability of occurrence. Although this discussion includes more recent information, the FEPs screening decision remains unchanged.

SCR-4.1.3.1.1.3 *Screening Argument*

SCR-4.1.3.1.1.3.1 *Deformation*

Deformed salt in the lower Salado and upper strata of the Castile has been encountered in a number of boreholes around the WIPP site; the extent of existing salt deformation is summarized in Section 2.1.6.1, and further detail is provided in CCA Appendix DEF.

A number of mechanisms may result in ***Salt Deformation***: in massive salt deposits, buoyancy effects or ***Diapirism*** may cause salt to rise through denser, overlying units; and in bedded salt with anhydrite or other interbeds, gravity foundering of the interbeds into the halite may take place. Results from rock mechanics modeling studies (see CCA Appendix DEF) indicate that the time scale for the deformation process is such that significant natural deformation is unlikely to occur at the WIPP site over any time frame significant to waste isolation. Thus, natural ***Salt Deformation*** and ***Diapirism*** severe enough to alter existing patterns of groundwater flow or the behavior of the disposal system over the regulatory period has been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.3.2 Fracture Development

SCR-4.1.3.2.1 FEP Number: N8
FEP Title: ***Formation of Fractures***

SCR-4.1.3.2.1.1 *Screening Decision: SO-P, UP (Repository)*

The formation of fractures has been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 years. The formation of fractures near the repository is accounted for in PA via treatment of the DRZ.

SCR-4.1.3.2.1.2 *Summary of New Information*

The screening argument for formation of fractures has been revised to reflect recent studies. The screening statement has been updated to reflect the formation of fractures near the repository (DRZ).

SCR-4.1.3.2.1.3 *Screening Argument*

The ***Formation of Fractures*** requires larger changes in stress than are required for changes to the properties of existing fractures to overcome the shear and tensile strength of the rock. It has been concluded from the regional tectonic setting of the Delaware Basin that no significant changes in regional stress are expected over the regulatory period. The EPA agrees that fracture formation in the Rustler is likely a result of halite dissolution and subsequent overlying unit fracturing loading/unloading, as well as the syn- and post-depositional processes. Intraformational post-depositional dissolution of the Rustler Formation has been ruled out as a major contributor to Rustler salt distribution and thus to new fracture formation based on work by Holt and Powers (ibid., DOE 1996a: Appendix DEF, Section DEF3.2) and Powers and Holt (1999, 2000), who believe that depositional facies and syndepositional dissolution account for most of the patterns on halite distribution in the Rustler. The argument against developing new fractures in the Rustler during the regulatory period appears reasonable. The formation of new fracture sets in the Culebra has therefore been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 years.

Repository-induced fracturing of the DRZ and Salado interbeds is accounted for in PA calculations.

A mechanism such as salt diapirism could develop fracturing in the Salado, but there is little evidence of diapirism in the Delaware Basin. Salt deformation has occurred in the vicinity of the WIPP, and fractures have developed in deeper Castile anhydrites as a consequence. Deformation rates are slow, and it is highly unlikely that this process will induce significant new fractures in the Salado during the regulatory time period. Surface domal features at the northwestern end of Nash Draw were of undetermined origin prior to WIPP investigations (e.g., Vine 1963), but extensive geophysical studies were conducted of these features as part of early WIPP studies (see Powers 1996). Two of the domal features were drilled, demonstrating that they had a solution-collapse origin (breccia pipes) and were not related in any way to salt diapirism (Snyder and Gard 1982).

The argument against developing new fractures within the Salado Formation during the regulatory period via regional stress therefore appears reasonable. Editorial changes for clarity are suggested, as well as separating the two FEPs into discrete arguments. Although the discussion of fracture development has been revised to include more recent information, the screening decision remains unchanged.

SCR-4.1.3.2.2 FEP Number: N9
FEP Title: ***Changes in Fracture Properties***

SCR-4.1.3.2.2.1 *Screening Decision: SO-C, UP (near repository)*

Naturally-induced changes in fracture properties that may affect groundwater flow or radionuclide transport in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. ***Changes in Fracture Properties*** *near the repository are accounted for in PA calculations through treatment of the DRZ.*

SCR-4.1.3.2.2.2 *Summary of New Information*

The screening argument has been updated with additional information that addresses the treatment of fractures in the near field. The screening decision has not changed.

SCR-4.1.3.2.2.3 *Screening Argument*

Groundwater flow in the region of the WIPP and transport of any released radionuclides may take place along fractures. The rate of flow and the extent of transport will be influenced by fracture characteristics. ***Changes in Fracture Properties*** could arise through natural changes in the local stress field; for example, through tectonic processes, erosion or sedimentation changing the amount of overburden, dissolution of soluble minerals along beds in the Rustler or upper Salado, or dissolution or precipitation of minerals in fractures.

Tectonic processes and features (N3 ***Changes in Regional Stress***; N4 ***Tectonics***; N5 ***Regional Uplift and Subsidence***; N6 ***Salt Deformation***; N7 ***Diapirism***) have been screened out of PA. These processes are not expected to change the character of fractures significantly during the regulatory period.

Surface erosion or deposition (e.g., FEPs N41-N49) are not expected to change significantly the overburden on the Culebra during the regulatory period. The relationship between Culebra transmissivity (T) and depth is significant (Holt, 2002; Holt and Powers, 2002), but the potential change to Culebra T based on deposition or erosion from these processes over the regulatory period is insignificant.

Shallow dissolution (FEP N16), where soluble beds from the upper Salado or Rustler are removed by groundwater, has been extensively considered. There are no direct effects on the Salado at depths of the repository. Extensive study of the upper Salado and Rustler halite units (Holt and Powers 1988; CCA Appendix FAC; Powers and Holt 1999, 2000; Powers 2002) indicates little potential for dissolution at the WIPP site during the regulatory period. Existing fracture properties are expressed through the relationship between Culebra T values and geologic factors at and near the WIPP site (Holt 2002; Holt and Powers 2002). These will be incorporated in PA (see N16, ***Shallow Dissolution***).

Mineral precipitation within fractures (N22) is expected to be beneficial to performance, and it has been screened out on the basis of low consequence. Natural dissolution of fracture fillings within the Culebra is incorporated within FEP N16 (***Shallow Dissolution***). There is no new information on the distribution of fracture fillings within the Culebra. The effects of fracture fillings are also expected to be represented in the distribution of Culebra T values around the WIPP site and are thus incorporated into PA.

Repository induced fracturing of the DRZ and Salado interbeds is accounted for in PA calculations (UP), and is discussed further in FEPs W18 and W19.

SCR-4.1.3.2.3 FEP Number(s): N10 and N11
FEP Title(s): ***Formation of New Faults*** (N10)
Fault Movement (N11)

SCR-4.1.3.2.3.1 *Screening Decision: SO-P*

The naturally induced fault movement and formation of new faults of sufficient magnitude to significantly affect the performance of the disposal system have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-4.1.3.2.3.2 *Summary of New Information*

No changes have been made to the FEP screening decision. However, the screening argument text was revised to include information on seismic monitoring since the CCA and the nearby rockfalls of non-tectonic origin in potash mines.

SCR-4.1.3.2.3.3 *Screening Argument*

Faults are present in the Delaware Basin in both the units underlying the Salado and in the Permian evaporite sequence (see Section 2.1.5.3). According to Powers et al. (1978, included in CCA Appendix GCR), there is evidence that movement along faults within the pre-Permian units affected the thickness of Early Permian strata, but these faults did not exert a structural control on the deposition of the Castile, the Salado, or the Rustler. Fault zones along the margins of the Delaware Basin were active during the Late Permian Period. Along the eastern margin, where the Delaware Basin flanks the Central Basin Platform, Holt and Powers (1988, included in CCA Appendix FAC) note that there is displacement of the Rustler, and Schiel (1994) notes that there is thinning of the Dewey Lake. There is, however, no surface displacement along the trend of these fault zones, indicating that there has been no significant Quaternary movement. Muehlberger et al. (1978, p. 338) note that the nearest faults on which Quaternary movement has been identified lie to the west of the Guadalupe Mountains.

The WIPP is located in an area of tectonic quiescence. Seismic monitoring conducted for the WIPP since the CCA continues to record small events at distance from the WIPP, and these events are mainly in areas associated with hydrocarbon production. Two nearby events (magnitude 3.5, 10/97, and magnitude 2.8, 12/98) are related to rockfalls in the Nash Draw mine and are not tectonic in origin (DOE 1999). These events did not cause any damage at the WIPP. The absence of Quaternary fault scarps and the general tectonic setting and understanding of its evolution indicate that large-scale, tectonically-induced ***Fault Movement*** within the Delaware Basin can be eliminated from PA calculations on the basis of low probability over 10,000 years. The stable tectonic setting also allows the ***Formation of New Faults*** within the basin over the next 10,000 years to be eliminated from PA calculations on the basis of low probability of occurrence.

Evaporite dissolution at or near the WIPP site has the potential for developing fractures in the overlying beds. Three zones (top of Salado, M1/H1 of the Los Medaños Member, and M2/H2 of the Los Medaños Member) with halite underlie the Culebra Dolomite Member at the site (Powers 2002). The upper Salado is present across the site, and there is no indication that dissolution of this area will occur in the regulatory period or cause faulting at the site. The Los

Medaños units show both mudflat facies and halite-bearing facies within or adjacent to the WIPP site (Powers 2002). Although the distribution of halite in the Rustler is mainly due to depositional facies and syndepositional dissolution (Holt and Powers 1988; Powers and Holt 1999, 2000), the possibility of past or future halite dissolution along the margins cannot be ruled out (Holt and Powers 1988; Beauheim and Holt 1999). If halite in the lower Rustler has been dissolved along the depositional margin, it has not occurred recently or has been of no consequence, as there is no indication on the surface or in Rustler structure of new (or old) faults in this area (e.g., Powers et al. 1978; Powers 2002).

The absence of Quaternary fault scarps and the general tectonic setting and understanding of its evolution indicate that large-scale, tectonically-induced fault movement within the Delaware Basin can be eliminated from PA calculations on the basis of low probability over 10,000 years. The stable tectonic setting also allows the ***Formation of New Faults*** within the basin over the next 10,000 years to be eliminated from PA calculations on the basis of low probability of occurrence.

SCR-4.1.3.2.4 FEP Number: N12
FEP Title: ***Seismic Activity***

SCR-4.1.3.2.4.1 *Screening Decision: UP*

The postclosure effects of seismic activity on the repository and the DRZ are accounted for in PA calculations.

SCR-4.1.3.2.4.2 *Summary of New Information*

No new information has been identified for this FEP. Any changes in the implementation of seismic activity within PA are discussed in Section 6.0.

SCR-4.1.3.2.4.3 *Screening Argument*

The following subsections present the screening argument for seismic activity (groundshaking).

SCR-4.1.3.2.4.4 *Causes of Seismic Activity*

Seismic Activity describes transient ground motion that may be generated by several energy sources. There are two possible causes of ***Seismic Activity*** that could potentially affect the WIPP site: natural- and human-induced. Natural seismic activity is caused by fault movement (earthquakes) when the buildup of strain in rock is released through sudden rupture or movement. Human-induced seismic activity may result from a variety of surface and subsurface activities, such as ***Explosions*** (H19 and H20), ***Mining*** (H13, H14, H58, and H59), ***Fluid Injection*** (H28), and ***Fluid Withdrawal*** (H25).

SCR-4.1.3.2.4.5 *Groundshaking*

Ground vibration and the consequent shaking of buildings and other structures are the most obvious effects of seismic activity. Once the repository and shafts have been sealed, however,

existing surface structures will be dismantled. Postclosure PAs are concerned with the effects of seismic activity on the closed repository.

In regions of low and moderate seismic activity, such as the Delaware Basin, rocks behave elastically in response to the passage of seismic waves, and there are no long-term changes in rock properties. The effects of earthquakes beyond the DRZ have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. An inelastic response, such as cracking, is only possible where there are free surfaces, as in the roof and walls of the repository prior to closure by creep. ***Seismic Activity*** could, therefore, have an effect on the properties of the DRZ.

An assessment of the extent of damage in underground excavations caused by groundshaking largely depends on observations from mines and tunnels. Because such excavations tend to take place in rock types more brittle than halite, these observations cannot be related directly to the behavior of the WIPP. According to Wallner (1981, 244), the DRZ in brittle rock types is likely to be more highly fractured and hence more prone to spalling and rockfalls than an equivalent zone in salt. Relationships between groundshaking and subsequent damage observed in mines will therefore be conservative with respect to the extent of damage induced at the WIPP by seismic activity.

Dowding and Rozen (1978) classified damage in underground structures following seismic activity and found that no damage (cracks, spalling, or rockfalls) occurred at accelerations below 0.2 gravities and that only minor damage occurred at accelerations up to 0.4 gravities. Lenhardt (1988, p. 392) showed that a magnitude 3 earthquake would have to be within 1 km (0.6 mi) of a mine to result in falls of loose rock. The risk of seismic activity in the region of the WIPP reaching these thresholds is discussed below.

SCR-4.1.3.2.4.6 *Seismic Risk in the Region of the WIPP*

Prior to the introduction of a seismic monitoring network in 1960, most recorded earthquakes in New Mexico were associated with the Rio Grande Rift, although small earthquakes were detected in other parts of the region. In addition to continued activity in the Rio Grande Rift, the instrumental record has shown a significant amount of seismic activity originating from the Central Basin Platform and a number of small earthquakes in the Los Medaños area. Seismic activity in the Rio Grande Rift is associated with extensional tectonics in that area. Seismic activity in the Central Basin Platform may be associated with natural earthquakes, but there are also indications that this activity occurs in association with oil-field activities such as fluid injection. Small earthquakes in the Los Medaños region have not been precisely located, but may be the result of mining activity in the region. Section 2.6.2 contains additional discussion of seismic activity and risk in the WIPP region.

The instrumental record was used as the basis of a seismic risk study primarily intended for design calculations of surface facilities rather than for postclosure PAs. The use of this study to define probable ground accelerations in the WIPP region over the next 10,000 years is based on the assumptions that hydrocarbon extraction and potash mining will continue in the region and that the regional tectonic setting precludes major changes over the next 10,000 years.

Three source regions were used in calculating seismic risk: the Rio Grande Rift, the Central Basin Platform, and part of the Delaware Basin province (including the Los Medaños). Using conservative assumptions about the maximum magnitude event in each zone, the study indicated a return period of about 10,000 years (annual probability of occurrence of 10^{-4}) for events producing ground accelerations of 0.1 gravities. Ground accelerations of 0.2 gravities would have an annual probability of occurrence of about 5×10^{16}.

The results of the seismic risk study and the observations of damage in mines due to groundshaking give an estimated annual probability of occurrence of between 10^{-6} and 10^{-8} for events that could increase the permeability of the DRZ. The DRZ is accounted for in PA calculations as a zone of permanently high permeability (see Section 6.4.5.3); this treatment is considered to account for the effects of any potential seismic activity.

SCR-4.1.4 Crustal Process

SCR-4.1.4.1 FEP Number: N13
FEP Title: ***Volcanic Activity***

SCR-4.1.4.1.1 Screening Decision: SO-P

Volcanic Activity *has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-4.1.4.1.2 Summary of New Information

No new information has been identified for this FEP. Editorial changes were made to the screening decision to remove reference to other FEPs. No changes have been made to the description or screening argument.

SCR-4.1.4.1.3 Screening Argument

The Paleozoic and younger stratigraphic sequences within the Delaware Basin are devoid of locally derived volcanic rocks. Volcanic ashes (dated at 13 million years and 0.6 million years) do occur in the Gatuña Formation (hereafter referred to as the Gatuña), but these are not locally derived. Within eastern New Mexico and northern, central, and western Texas, the closest Tertiary volcanic rocks with notable areal extent or tectonic significance to the WIPP are approximately 160 km (100 mi) to the south in the Davis Mountains volcanic area. The closest Quaternary volcanic rocks are 250 km (150 mi) to the northwest in the Sacramento Mountains. No volcanic rocks are exposed at the surface within the Delaware Basin.

Volcanic Activity is associated with particular tectonic settings: constructive and destructive plate margins, regions of intraplate rifting, and isolated hot-spots in intraplate regions. The tectonic setting of the WIPP site and the Delaware Basin is remote from plate margins, and the absence of past volcanic activity indicates the absence of a major hot spot in the region. Intraplate rifting has taken place along the Rio Grande some 200 km (120 mi) west of the WIPP site during the Tertiary and Quaternary Periods. Igneous activity along this rift valley is comprised of sheet lavas intruded on by a host of small-to-large plugs, sills, and other intrusive bodies. However, the geological setting of the WIPP site within the large and stable Delaware

Basin allows volcanic activity in the region of the WIPP repository to be eliminated from performance calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.4.2 FEP Number: N14
FEP Title: ***Magmatic Activity***

SCR-4.1.4.2.1 Screening Decision: SO-C

*The effects of **Magmatic Activity** have been eliminated from the PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.1.4.2.2 Summary of New Information

No new information has been identified for this FEP. Editorial changes were made to the screening decision to remove reference to other FEPs. No changes have been made to the description or screening argument.

SCR-4.1.4.2.3 Screening Argument

Magmatic *Activity* is defined as the subsurface intrusion of igneous rocks into country rock. Deep intrusive igneous rocks crystallize at depths of several kilometers (several miles) and have no surface or near-surface expression until considerable erosion has taken place. Alternatively, intrusive rocks may form from magma that has risen to near the surface or in the vents that give rise to volcanoes and lava flows. Magma near the surface may be intruded along subvertical and subhorizontal discontinuities (forming dikes and sills, respectively), and magma in volcanic vents may solidify as plugs. The formation of such features close to a repository or the existence of a recently intruded rock mass could impose thermal stresses inducing new fractures or altering the hydraulic characteristics of existing fractures.

The principal area of magmatic activity in New Mexico is the Rio Grande Rift, where extensive intrusions occurred during the Tertiary and Quaternary Periods. The Rio Grande Rift, however, is in a different tectonic province than the Delaware Basin, and its magmatic activity is related to the extensional stress regime and high heat flow in that region.

Within the Delaware Basin, there is a single identified outcrop of a lamprophyre dike about 70 km (40 mi) southwest of the WIPP (see Section 2.1.5.4 and CCA Appendix GCR for more detail). Closer to the WIPP site, similar rocks have been exposed within potash mines some 15 km (10 mi) to the northwest, and igneous rocks have been reported from petroleum exploration boreholes. Material from the subsurface exposures has been dated at around 35 million years. Some recrystallization of the host rocks took place alongside the intrusion, and there is evidence that minor fracture development and fluid migration also occurred along the margins of the intrusion. However, the fractures have been sealed, and there is no evidence that the dike acted as a conduit for continued fluid flow.

Aeromagnetic surveys of the Delaware Basin have shown anomalies that lie on a linear southwest-northeast trend that coincides with the surface and subsurface exposures of magmatic rocks. There is a strong indication therefore of a dike or a closely related set of dikes extending

for at least 120 km (70 mi) across the region (see Section 2.1.5.4). The aeromagnetic survey conducted to delineate the dike showed a magnetic anomaly that is several kilometers (several miles) wide at depth and narrows to a thin trace near the surface. This pattern is interpreted as the result of an extensive dike swarm at depths of less than approximately 4.0 km (2.5 mi) near the Precambrian basement, from which a limited number of dikes have extended towards the surface.

Magmatic Activity has taken place in the vicinity of the WIPP site in the past, but the igneous rocks have cooled over a long period. Any enhanced fracturing or conduits for fluid flow have been sealed by salt creep and mineralization. Continuing magmatic activity in the Rio Grande Rift is too remote from the WIPP location to be of consequence to the performance of the disposal system. Thus, the effects of magmatic activity have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.1.4.2.4 FEP Number: N15
FEP Title: **Metamorphic Activity**

SCR-4.1.4.2.4.1 *Screening Decision: SO-P*

Metamorphic Activity *has been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.*

SCR-4.1.4.2.4.2 *Summary of New Information*

No new information has been identified for this FEP. Editorial changes were made to the screening decision to remove reference to other FEPs. No changes have been made to the description or screening argument.

SCR-4.1.4.2.4.3 *Screening Argument*

Metamorphic Activity, that is, solid-state recrystallization changes to rock properties and geologic structures through the effects of heat and/or pressure, requires depths of burial much greater than the depth of the repository. Regional tectonics that would result in the burial of the repository to the depths at which the repository would be affected by ***Metamorphic Activity*** have been eliminated from PA calculations on the basis of low probability of occurrence; therefore, metamorphic activity has also been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.5 Geochemical Processes

SCR-4.1.5.1 FEP Number: N16
FEP Title: ***Shallow Dissolution (including lateral dissolution)***

SCR-4.1.5.1.1 Screening Decision: UP

Shallow Dissolution *is accounted for in PA calculations.*

SCR-4.1.5.1.2 Summary of New Information

In the vicinity of the WIPP site, the processes described in CCA Appendix SCR as ***Shallow Dissolution*** (N16) and ***Lateral Dissolution*** (N17) extensively overlap. As a result, N16 and N17 have been combined and N17 has been deleted from the FEPs baseline. FEP N16 has been modified to account for the deletion of N17. For CRA-2004, all of these interrelated processes, and their attendant features, are considered as part of shallow dissolution, which is accounted for in PA calculations.

SCR-4.1.5.1.3 Screening Argument

This section discusses a variety of styles of dissolution that have been active in the region of the WIPP or in the Delaware Basin. A distinction has been drawn between ***Shallow Dissolution***, involving circulation of groundwater and mineral dissolution, in the Rustler and at the top of the Salado in the region of the WIPP; and deep dissolution taking place in the Castile and the base of the Salado. Dissolution will initially enhance porosities, but continued dissolution may lead to compaction of the affected units with a consequent reduction in porosity. Compaction may result in fracturing of overlying brittle units and increased permeability. Extensive dissolution may create cavities (karst) and result in the total collapse of overlying units. This topic is discussed further in Section 2.1.6.2.

SCR-4.1.5.1.4 Shallow Dissolution

In the region around WIPP, ***Shallow Dissolution*** by groundwater flow has removed soluble minerals from the upper Salado as well as the Rustler to form Nash Draw; extensive solution within the closed draw has created karst features including caves and dolines in the sulfate beds of the Rustler (see Lee, 1925; Bachman, 1980, 1985, 1987a). An alluvial doline drilled at WIPP 33, about 850 m (2800 ft) west of the WIPP site boundary, is the nearest karst feature known in the vicinity of the site. Upper Salado halite dissolution in Nash Draw resulted in propagating fracturing upward through the overlying Rustler (Holt and Powers 1988). The margin of dissolution of halite from the upper Salado has commonly been placed west of the WIPP site, near, but east of, Livingston Ridge, the eastern boundary of Nash Draw. Halite occurs in the Rustler east of Livingston Ridge, with the margin generally progressively eastward in higher stratigraphic units (e.g., Snyder 1985; Powers and Holt 1995). The distribution of halite in the Rustler has commonly been attributed to ***Shallow Dissolution*** (e.g., Powers et al. 1978; Lambert, 1983; Bachman 1985; Lowenstein 1987). During early studies for the WIPP, the variability of transmissivity of the Culebra in the vicinity of the WIPP was commonly attributed to the effects of dissolution of Rustler halite and changes in fracturing as a consequence.

After a detailed sedimentologic and stratigraphic investigation of WIPP cores, shafts, and geophysical logs from the region around WIPP, the distribution of halite in the Rustler was attributed to depositional and syndepositional processes rather than post-depositional dissolution (Holt and Powers 1988; Powers and Holt 2000). Rustler exposures in shafts for the WIPP revealed extensive sedimentary structures in clastic units (Holt and Powers 1984, 1986, 1990), and the suite of features in these beds led these investigators (Holt and Powers 1988; Powers and Holt 1990, 2000) to reinterpret the clastic units. They conclude that the clastic facies represent mainly mudflat facies tracts adjacent to a salt pan. Although some halite likely was deposited in

mudflat areas proximal to the salt pan, it was largely removed by syndepositional dissolution, as indicated by soil structures, soft sediment deformation, bedding, and small-scale vertical relationships (Holt and Powers 1988; Powers and Holt 1990, 1999, 2000). The depositional margins of halite in the Rustler are the likely points for past or future dissolution (e.g., Holt and Powers 1988; Beauheim and Holt 1990). Cores from drillholes at the H-19 drillpad near the Tamarisk Member halite margin show evidence of some dissolution of halite in the Tamarisk (Mercer et al. 1998), consistent with these predictions. The distribution of Culebra T values is not considered related to dissolution of Rustler halite, and other geological factors (e.g., depth, upper Salado dissolution) correlate well with Culebra transmissivity (e.g., Powers and Holt 1995; Holt and Powers 2002).

Since the CCA was completed, the WIPP has conducted additional work on ***Shallow Dissolution***, principally of the upper Salado, and its possible relationship to the distribution of T values for the Culebra as determined through testing of WIPP hydrology wells.

AP-088 (Beauheim 2002) noted that potentiometric surface values for the Culebra in many monitoring wells were outside the uncertainty ranges used to calibrate models of steady-state heads for the unit. AP-088 directed the analysis of the relationship between geological factors and values of T at Culebra wells. The relationship between geological factors, including dissolution of the upper Salado as well as limited dissolution in the Rustler, and Culebra T is being used to evaluate differences between assuming steady-state Culebra heads and changing heads.

Task 1 for AP-088 (Powers 2002) evaluated geological factors, including shallow dissolution in the vicinity of the WIPP site that related to Culebra T. A much more extensive drillhole geological database was developed than was previously available, utilizing sources of data from WIPP, potash exploration, and oil and gas exploration and development. The principal findings related to shallow dissolution are: 1) a relatively narrow zone (~ 200-400 m wide) could be defined as the margin of dissolution of the upper Salado in much of the area around WIPP: 2) the upper Salado dissolution margin commonly underlies surface escarpments such as Livingston Ridge; and 3) there are possible extensions or reentrants of incipient upper Salado dissolution extending eastward from the general dissolution margin. The WIPP site proper is not affected by this process.

Culebra T correlates well with depth or overburden, which affects fracture apertures (Powers and Holt 1995, Holt and Powers 2002; Holt 2002). Dissolution of the upper Salado appears to increase T by one or more orders of magnitude (Holt 2002). Because there is no indication of upper Salado dissolution at the WIPP site, Holt (2002) did not include this factor for the WIPP site in estimates of base T values for the WIPP site and surroundings.

There is no new work since the CCA on the distribution of fracture fillings in the Culebra or on dissolution of the fillings. The effects of this process are represented in the distribution of Culebra T values around the WIPP site.

New work regarding shallow dissolution does not change the inclusion of the effects in the T field for the Culebra within PA calculations. The new work provides a firmer basis for understanding the effects of shallow dissolution as represented in PA.

The effects of ***Shallow Dissolution*** (including the impacts of lateral dissolution) have been included in PA calculations.

SCR-4.1.5.2 FEP Number: N17 (removed from baseline)
FEP Title: ***Lateral Dissolution***

SCR-4.1.5.2.1 Summary of New Information

FEP N17 ***Lateral Dissolution*** is so similar to FEP N16 ***Shallow Dissolution*** as features and processes that they are better treated as a single FEP N16, ***Shallow Dissolution***. Therefore, N17 has been deleted from the FEPs baseline and the text for N16 has been modified to address the combination of N16 and N17 into one FEP N16. ***Shallow Dissolution*** is accounted for in PA calculations and encompasses the nature and characteristics of lateral dissolution.

SCR-4.1.5.3 FEP Number: N18, N20 and N21
FEP Title: ***Deep Dissolution*** (N18)
Breccia Pipes (N20)
Collapse Breccias (N21)

SCR-4.1.5.3.1 Screening Decision: SO-P

Deep Dissolution *and the formation of associated features (for example,* ***Solution Chimneys****,* ***Breccia Pipes****,* ***Collapse Breccias****) at the WIPP site have been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.*

SCR-4.1.5.3.2 Summary of New Information

The DOE limited ***Deep Dissolution*** to processes involving dissolution of the Castile or basal Salado Formations and associated features such as ***Breccia Pipes*** (also known as ***Solution Chimneys***) with this process. The DOE found that deep dissolution is a process that may be operating in the Delaware Basin, but the process is limited by the hydraulic and geochemical characteristics of the expected source of water in the Delaware Mountain Group underlying the evaporite formations. Investigations of the WIPP site have not found evidence of specific features (e.g., ***Breccia Pipes, Solution Collapse***, or ***Solution Chimneys***) associated with deep dissolution. The EPA also concluded that the mechanism may be operating in the Delaware Basin, and that there is little evidence of deep dissolution at the WIPP site. The EPA concluded that the rate or magnitude of this process is not high enough that it is likely to threaten integrity of the WIPP over the next 10,000 years. These conclusions appear reasonable. The original description and screening arguments as presented in the CCA remain valid. The FEP discussion has been modified to clarify the arguments and the original screening decision as presented in the CCA has been revised to remove reference to other FEPs.

SCR-4.1.5.3.3 Screening Argument

This section discusses a variety of styles of dissolution that have been active in the region of the WIPP or in the Delaware Basin. A distinction has been drawn between ***Shallow Dissolution***, involving circulation of groundwater and mineral dissolution in the Rustler and at the top of the Salado in the region of the WIPP, and ***Deep Dissolution*** taking place in the Castile and the base

of the Salado. Dissolution will initially enhance porosities, but continued dissolution may lead to compaction of the affected units with a consequent reduction in porosity. Compaction may result in fracturing of overlying brittle units and increased permeability. Extensive dissolution may create cavities (karst) and result in the total collapse of overlying units. This topic is discussed further in Section 2.1.6.2.

SCR-4.1.5.3.4 Deep Dissolution

Deep Dissolution refers to the dissolution of salt or other evaporite minerals in a formation at depth (see Section 2.1.6.2). Deep dissolution is distinguished from shallow and lateral dissolution not only by depth, but also by the origin of the water. Dissolution by groundwater from deep water-bearing zones can lead to the formation of cavities. Collapse of overlying beds leads to the formation of ***Collapse Breccias*** if the overlying rocks are brittle or to deformation if the overlying rocks are ductile. If dissolution is extensive, ***Breccia Pipes*** or ***Solution Chimneys*** may form above the cavity. These pipes may reach the surface or pass upwards into fractures and then into microcracks that do not extend to the surface. ***Breccia Pipes*** may also form through the downward percolation of meteoric waters, as discussed earlier. ***Deep Dissolution*** is of concern because it could accelerate contaminant transport through the creation of vertical flow paths that bypass low-permeability units in the Rustler. If dissolution occurred within or beneath the waste panels themselves, there could be increased circulation of groundwater through the waste, as well as a breach of the Salado host rock.

Features identified as being the result of ***Deep Dissolution*** are present along the northern and eastern margins of the Delaware Basin. In addition to features that have a surface expression or that appear within potash mine workings, ***Deep Dissolution*** has been cited by Anderson et al. (1972, p. 81) as the cause of lateral variability within evaporite sequences in the lower Salado.

Exposures of the McNutt Potash Member of the Salado within a mine near Nash Draw have shown a breccia pipe containing cemented brecciated fragments of formations higher in the stratigraphic sequence. At the surface, this feature is marked by a dome, and similar domes have been interpreted as dissolution features. The depth of dissolution has not been confirmed, but the collapse structures led Anderson (1978, p. 52) and Snyder et al. (1982, p. 65) to postulate dissolution of the Capitan Limestone at depth; collapse of the Salado, Rustler, and younger formations; and subsequent dissolution and hydration by downward percolating waters. San Simon Sink (see Section 2.1.6.2), some 35 km (20 mi) east-southeast of the WIPP site, has also been interpreted as a ***Solution Chimneys***. Subsidence has occurred there in historical times according to Nicholson and Clebsch (1961, p. 14), suggesting that dissolution at depth is still taking place. Whether this is the result of downwards-percolating surface water or of deep groundwater has not been confirmed. The association of these dissolution features with the inner margin of the Capitan Reef suggest that they owe their origins, if not their continued development, to groundwaters derived from the Capitan Limestone.

SCR-4.1.5.3.5 Dissolution within the Castile and Lower Salado Formations

The Castile contains sequences of varved anhydrite and carbonate (that is, laminae deposited on a cyclical basis) that can be correlated between several boreholes. On the basis of these deposits, a basin-wide uniformity in the depositional environment of the Castile evaporites was assumed.

The absence of varves from all or part of a sequence and the presence of brecciated anhydrite beds have been interpreted by Anderson et al. (1972) as evidence of dissolution. Holt and Powers (CCA Appendix FAC) have questioned the assumption of a uniform depositional environment and contend that the anhydrite beds are lateral equivalents of halite sequences without significant postdepositional dissolution. Wedges of brecciated anhydrite along the margin of the Castile have been interpreted by Robinson and Powers (1987, p. 78) as gravity-driven clastic deposits, rather than the result of ***Deep Dissolution***.

Localized depressions at the top of the Castile and inclined geophysical marker units at the base of the Salado have been interpreted by Davies (1983, p. 45) as the result of ***Deep Dissolution*** and subsequent collapse or deformation of overlying rocks. The postulated cause of this dissolution was circulation of undersaturated groundwaters from the Bell Canyon Formation (hereafter referred to as the Bell Canyon). Additional boreholes (notably WIPP-13, WIPP-32, and DOE-2) and geophysical logging led Borns and Shaffer (1985) to conclude that the features interpreted by Davies as being dissolution features are the result of irregularities at the top of the Bell Canyon. These irregularities led to localized depositional thickening of the Castile and lower Salado sediments.

SCR-4.1.5.3.6 Collapse Breccias at Basin Margins

Collapse Breccias are present at several places around the margins of the Delaware Basin. Their formation is attributed to relatively fresh groundwater from the Capitan Limestone that forms the margin of the basin. ***Collapse Breccias*** corresponding to features on geophysical records that have been ascribed to ***Deep Dissolution*** have not been found in boreholes away from the margins. These features have been reinterpreted as the result of early dissolution prior to the deposition of the Salado.

SCR-4.1.5.3.7 Summary of Deep Dissolution

Deep Dissolution features have been identified within the Delaware Basin, but only in marginal areas underlain by Capitan Reef. There is a low probability that deep dissolution will occur sufficiently close to the waste panels over the regulatory period to affect groundwater flow in the immediate region of the WIPP. ***Deep Dissolution*** at the WIPP site has therefore been eliminated from *PA* calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.5.4 FEP Number: N19 (removed from baseline)
FEP Title: ***Solution Chimneys***

SCR-4.1.5.4.1 Screening Decision: NA

SCR-4.1.5.4.2 Summary of New Information

Solution Chimneys (N19) and ***Breccia Pipes*** (N20) are equivalent as used in the CCA and supporting documents for the WIPP. Neither the DOE nor the EPA discussions supporting the original certification make a clear distinction between the two. These FEPs have been combined and are addressed in FEP N20 ***Breccia Pipes***. The screening arguments have not changed as a result of consolidation.

SCR-4.1.5.5 FEP Number: N22
FEP Title: ***Fracture Infill***

SCR-4.1.5.5.1 Screening Decision: SO-C - Beneficial

*The effects of **Fracture Infills** have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-4.1.5.5.2 Summary of New Information

No new information has been identified that related to the screening of this FEP. No changes have been made.

SCR-4.1.5.5.3 Screening Argument

SCR-4.1.5.5.3.1 Mineralization

Precipitation of minerals as ***Fracture Infills*** can reduce hydraulic conductivities. The distribution of infilled fractures in the Culebra closely parallels the spatial variability of lateral transmissivity in the Culebra. The secondary gypsum veins in the Rustler have not been dated. Strontium isotope studies (Siegel et al. 1991, pp. 5-53 to 5-57) indicate that the infilling minerals are locally derived from the host rock rather than extrinsically derived, and it is inferred that they reflect an early phase of mineralization and are not associated with recent meteoric waters.

Stable isotope geochemistry in the Rustler has also provided information on mineral stabilities in these strata. Both Chapman (1986, p. 31) and Lambert and Harvey (1987, p. 207) imply that the mineralogical characteristics of units above the Salado have been stable or subject to only minor changes under the various recharge conditions that have existed during the past 0.6 million years—the period since the formation of the Mescalero caliche and the establishment of a pattern of climate change and associated changes in recharge that led to present-day hydrogeological conditions. No changes in climate are expected other than those experienced during this period, and for this reason, no changes are expected in the mineralogical characteristics other than those expressed by the existing variability of fracture infills and diagenetic textures. Formation of ***Fracture Infills*** will reduce transmissivities and will therefore be of beneficial consequence to the performance of the disposal system.

SCR-4.2 Subsurface Hydrological Features, Events, and Processes

SCR-4.2.1 Groundwater Characteristics

SCR-4.2.1.1 FEP Number: N23, N24, N25 and N27
FEP Title: ***Saturated Groundwater Flow*** *(N23)*
Unsaturated Groundwater Flow *(N24)*
Fracture Flow *(N25)*
Effects of Preferential Pathways *(N27)*

SCR-4.2.1.1.1 Screening Decision: UP

Saturated ***Groundwater Flow***, ***Unsaturated Groundwater Flow***, ***Fracture Flow***, *and the* ***Effects of Preferential Pathways*** *are accounted for in PA calculations.*

SCR-4.2.1.1.2 Summary of New Information

No new information related to the screening of these FEPs has been identified. These FEPs continue to be accounted for in PA.

SCR-4.2.1.1.3 Screening Argument

Saturated Groundwater Flow, ***Unsaturated Groundwater Flow,*** and ***Fracture Flow*** are accounted for in PA calculations. Groundwater flow is discussed in Sections 2.2.1, 6.4.5, and 6.4.6.

The hydrogeologic properties of the Culebra are also spatially variable. This variability, including the ***Effects of Preferential Pathways***, is accounted for in PA calculations in the estimates of transmissivity and aquifer thickness.

SCR-4.2.1.2 FEP Number: N26
FEP Title: ***Density Effect on Groundwater Flow***

SCR-4.2.1.2.1 Screening Decision: SO-C

Density Effects on Groundwater Flow *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.2.1.2.2 Summary of New Information

The effects of natural density variations on groundwater flow have been screened out on the basis of low consequence. Editorial changes have been made to the FEP description, argument, and screening decision.

SCR-4.2.1.2.3 Screening Argument

The most transmissive unit in the Rustler, and hence the most significant potential pathway for transport of radionuclides to the accessible environment, is the Culebra. The properties of Culebra groundwaters are not homogeneous, and spatial variations in groundwater density

(Section 2.2.1.4.1.2) could influence the rate and direction of groundwater flow. A comparison of the gravity-driven flow component and the pressure-driven component in the Culebra, however, shows that only in the region to the south of the WIPP are head gradients low enough for density gradients to be significant (Davies 1989, p. 53). Accounting for this variability would rotate groundwater flow vectors towards the east (down-dip) and hence fluid in the high transmissivity zone would move away from the zone. Excluding brine density variations within the Culebra from PA calculations is therefore a conservative assumption, and ***Density Effects on Groundwater Flow*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2 Changes in Groundwater Flow

SCR-4.2.2.1 FEP Number: N28
FEP Title: ***Thermal Effects on Groundwater Flow***

SCR-4.2.2.1.1 Screening Decision: SO-C

*Natural **Thermal Effects on Groundwater Flow** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-4.2.2.1.2 Screening Argument

The geothermal gradient in the region of the WIPP has been measured at about 30°C (54°F) per kilometer (50°C [90°F] per mile). Given the generally low permeability in the region, and the limited thickness of units in which groundwater flow occurs (for example the Culebra), natural convection will be too weak to have a significant effect on groundwater flow. No natural FEPs have been identified that could significantly alter the temperature distribution of the disposal system or give rise to ***Thermal Effects on Groundwater Flow***. Such effects have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2.2 FEP Number: N29
FEP Title: ***Saline Intrusion (hydrogeological effects)***

SCR-4.2.2.2.1 Screening Decision: SO-P

*Changes in groundwater flow arising from **Saline Intrusion** has been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 years.*

SCR-4.2.2.2.2 Summary of New Information

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-4.2.2.2.3 Screening Argument

No natural events or processes have been identified that could result in ***Saline Intrusion*** into units above the Salado or cause a significant increase in fluid density. Natural ***Saline Intrusion*** has therefore been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years. ***Saline Intrusion*** arising from human events such as drilling into a pressurized brine pocket is discussed in FEPs H21 through H24.

SCR-4.2.2.3 FEP Number: N30
FEP Title: ***Freshwater Intrusion (hydrogeological effects)***

SCR-4.2.2.3.1 Screening Decision: SO-P

*Changes in groundwater flow arising **Freshwater Intrusion** have been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 years.*

SCR-4.2.2.3.2 Summary

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-4.2.2.3.2.1 *Screening Argument*

A number of FEPs, including ***Climate Change***, can result in changes in infiltration and recharge (see discussions for FEPs N53 through N55). These changes will affect the height of the water table and hence could affect groundwater flow in the Rustler through changes in head gradients. The generally low transmissivity of the Dewey Lake and the Rustler, however, will prevent any significant changes in groundwater density from occurring within the Culebra over the timescales for which increased precipitation and recharge are anticipated. No other natural events or processes have been identified that could result in ***Freshwater Intrusion*** into units above the Salado or cause a significant decrease in fluid density. ***Freshwater Intrusion*** has therefore been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.2.2.4 FEP Number: N31
FEP Title: ***Hydrological Response to Earthquakes***

SCR-4.2.2.4.1 Screening Decision: SO-C

*A **Hydrological Response to Earthquakes** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.2.2.4.2 Summary of New Information

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-4.2.2.4.3 Screening Argument

SCR-4.2.2.4.3.1 *Hydrological Effects of Seismic Activity*

There are a variety of ***Hydrological Response to Earthquakes***. Some of these responses, such as changes in surface-water flow directions, result directly from fault movement. Others, such as changes in subsurface water chemistry and temperature, probably result from changes in flow pathways along the fault or fault zone. According to Bredehoeft et al. (1987, p. 139), further away from the region of fault movement, two types of changes to groundwater levels may take place as a result of changes in fluid pressure:

- The passage of seismic waves through a rock mass causes a volume change, inducing a transient response in the fluid pressure, which may be observed as a short-lived fluctuation of the water level in wells, or

- Changes in volume strain can cause long-term changes in water level. A buildup of strain occurs prior to rupture and is released during an earthquake. The consequent change in fluid pressure may be manifested by the drying up or reactivation of springs some distance from the region of the epicenter.

Fluid pressure changes induced by the transmission of seismic waves can produce changes of up to several meters (several yards) in groundwater levels in wells, even at distances of thousands of kilometers from the epicenter. These changes are temporary, however, and levels typically return to pre-earthquake levels in a few hours or days. Changes in fluid pressure arising from changes in volume strain persist for much longer periods, but they are only potentially consequential in tectonic regimes where there is a significant buildup of strain. The regional tectonics of the Delaware Basin indicate that such a buildup has a low probability of occurring over the next 10,000 years (see FEPs N3 and N4).

The expected level of seismic activity in the region of the WIPP will be of low consequence to the performance of the disposal system in terms of groundwater flow or contaminant transport. Changes in groundwater levels resulting from more distant earthquakes will be too short in duration to be significant. Thus, the ***Hydrological Response to Earthquakes*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2.5 FEP Number: N32
FEP Title: ***Natural Gas Intrusion***

SCR-4.2.2.5.1 Screening decision: SO-P

Changes in groundwater flow arising from natural gas intrusion have been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 years.

SCR-4.2.2.5.2 Summary of New Information

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-4.2.2.5.2.1 *Screening Argument*

Hydrocarbon resources are present in formations beneath the WIPP (Section 2.3.1.2), and natural gas is extracted from the Morrow Formation. These reserves are, however, some 4,200 m (14,000 ft) below the surface, and no natural events or processes have been identified that could result in ***Natural Gas Intrusion*** into the Salado or the units above. ***Natural Gas Intrusion*** has therefore been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.3 Subsurface Geochemical Features, Events, and Processes

SCR-4.3.1 Groundwater Geochemistry

SCR-4.3.1.1 FEP Number: N33
FEP Title: ***Groundwater Geochemistry***

SCR-4.3.1.1.1 Screening Decision: UP

Groundwater Geochemistry *in the hydrological units of the disposal system is accounted for in PA calculations.*

SCR-4.3.1.1.2 Summary of New Information

No new information related to the screening of these FEPs has been identified. These FEPs continue to be accounted for in PA.

SCR-4.3.1.1.3 Screening Argument

The most important aspect of ***Groundwater Geochemistry*** in the region of the WIPP in terms of chemical retardation and colloid stability is salinity. ***Groundwater Geochemistr***y is discussed in detail in Sections 2.2 and 2.4 and summarized here. The Delaware Mountain Group, Castile, and Salado contain basinal brines. Waters in the Castile and Salado are at or near halite saturation. Above the Salado, groundwaters are also relatively saline, and groundwater quality is poor in all of the permeable units. Waters from the Culebra vary spatially in salinity and chemistry. They range from saline sodium chloride-rich waters to brackish calcium sulfate-rich waters. In addition, a range of magnesium to calcium ratios has been observed, and some waters reflect the influence of potash mining activities, having elevated potassium to sodium ratios. Waters from the Santa Rosa are generally of better quality than any of those from the Rustler. Salado and Castile brine geochemistry is accounted for in PA calculations of the actinide source term (Section 6.4.3.4). Culebra brine geochemistry is accounted for in the retardation factors used in PA calculations of actinide transport (see Section 6.4.6.2).

SCR-4.3.1.2 FEP Number(s): N34 and N38
FEP Title(s): ***Saline Intrusion*** (geochemical effects) (N34)
Effects of Dissolution (N38)

SCR-4.3.1.2.1 Screening Decision: SO-C

*The effects of **Saline Intrusion** and dissolution on groundwater chemistry have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.3.1.2.2 Summary of New Information

The conclusion that "No natural events or processes have been identified that could result in saline intrusion into units above the Salado" (DOE 1996a, Appendix SCR) remains valid. The possibility that dissolution might result in an increase in the salinity of low-to-moderate-ionic-strength groundwaters in the Culebra also appears unlikely.

Nevertheless, ***Saline Intrusion*** and dissolution, in the unlikely event that they occur, would not affect the predicted transport of radionuclides in the Culebra because results obtained from laboratory studies (Brush 1996) with saline solutions were largely used to predict radionuclide transport for the CCA PA and the Performance Assessment Verification Test (PAVT). These results will also be used for the CRA-2004 PA.

SCR-4.3.1.2.3 Screening Argument

Saline Intrusion and ***Effects of Dissolution*** are considered together in this discussion because dissolution of minerals such as halite (NaCl), anhydrite ($CaSO_4$), or gypsum ($CaSO_4 \cdot 2H_2O$) (N38) could – in the most extreme case – increase the salinity of groundwaters in the Culebra Member of the Rustler Formation to levels characteristic of those expected after ***Saline Intrusion*** (N34).

No natural events or processes have been identified that could result in saline intrusion into units above the Salado. Injection of Castile-Formation or Salado brines into the Culebra as a result of human intrusion, an anthropogenically induced event, was included in the PA calculations for the CCA and the EPA's PAVT, and is included in the CRA-2004 PA. Laboratory studies carried out to evaluate radionuclide transport in the Culebra following human intrusion produced data that can also be used to evaluate the consequences of natural saline intrusion.

The possibility that dissolution of halite, anhydrite, or gypsum might result in an increase in the salinity of low-to-moderate-ionic-strength groundwaters in the Culebra also appears unlikely, despite the presence of halite in the Los Medaños under most of the WIPP Site (Siegel and Lambert 1991, Figure 1-13), including the expected Culebra off-site transport pathway (the direction of flow from the point(s) at which brines from the repository would enter the Culebra in the event of human intrusion to the south or south-southeast and eventually to the boundary of the WIPP site). (The Los Medaños Member of the Rustler, formerly referred to as the unnamed lower member of the Rustler, underlies the Culebra.) A dissolution-induced increase in the salinity of Culebra groundwaters is unlikely because: (1) the dissolution of halite is known to be rapid; (2) (moderate-ionic-strength) groundwaters along the off-site transport pathway (and at many other locations in the Culebra) have had sufficient time to dissolve significant quantities of

halite, if this mineral is present in the subjacent Los Medaños and if Culebra fluids have been in contact with it; and (3) the lack of high-ionic-strength groundwaters along the offsite transport pathway (and elsewhere in the Culebra) implies that halite is present in the Los Medaños but Culebra fluids have not contacted it, or that halite is not present in the Los Medaños. Because halite dissolves so rapidly if contacted by undersaturated solutions, this conclusion does not depend on the nature and timing of Culebra recharge (i.e., whether the Rustler has been a closed hydrologic system for several thousand to a few tens of thousands of years, or is subject to significant modern recharge).

Nevertheless, saline intrusion would not affect the predicted transport of thorium (Th), uranium (U), plutonium (Pu), and americium (Am) in the Culebra. This is because: (1) the laboratory studies that quantified the retardation of Th, U, Pu, and Am for the CCA PA were carried out with both moderate-ionic-strength solutions representative of Culebra groundwaters along the expected offsite transport pathway, and with high-ionic-strength solutions representative of brines from the Castile and the Salado (Brush 1996; Brush and Storz 1996); and (2) the results obtained with the saline (Castile and Salado) solutions were – for the most part – used to predict the transport of Pu(III) and Am(III); Th(IV), U(IV), Np(IV) and Pu(IV); and U(VI). The results obtained with the saline solutions were used for these actinide oxidation states because the extent to which saline and Culebra brines will mix along the offsite transport pathway in the Culebra was unclear at the time of the CCA PA; therefore, Brush (1996) and Brush and Storz (1996) recommended that PA use the results that predict less retardation. In the case of Pu(III) and Am(III); Th(IV), U(IV), Np(IV) and Pu(IV); and U(VI), the K_ds obtained with the saline solutions were somewhat lower than those obtained with the Culebra fluids. The K_ds recommended by Brush and Storz (1996) were used for the CRA-2004 PA. These K_ds are also based mainly on results obtained with saline solutions.

Finally, it is important to reiterate that the use of results from laboratory studies with saline solutions to predict radionuclide transport in the Culebra for the CCA PA, the PAVT, and the CRA PA implements the effects of saline intrusion caused by human intrusion, not natural ***Saline Intrusion***. The conclusions that natural ***Saline Intrusion*** is unlikely, that significant dissolution is unlikely, and that these events or processes would have no significant consequence – in the unlikely event that they occur – continue to be valid.

SCR-4.3.1.3 FEP Number: N35, N36 and N37
FEP Title: ***Freshwater Intrusion*** (Geochemical Effects) (N35)
Change in Groundwater Eh (N36)
Changes in Groundwater pH (N37)

SCR-4.3.1.3.1 Screening Decision: SO-C

*The effects of **Freshwater Intrusion** on groundwater chemistry have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Changes in **Groundwater** Eh and pH have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.3.1.3.2 Summary of New Information

The most likely mechanism for (natural) ***Freshwater Intrusion*** into the Culebra, ***Changes in Groundwater Eh***, ***Changes in Groundwater pH*** is (natural) recharge of the Culebra. There is still considerable uncertainty regarding the extent and timing of recharge of the Culebra. If recharge occurs mainly during periods of high precipitation (pluvials) associated with periods of continental glaciation, the consequences of such recharge are probably already reflected in the ranges of geochemical conditions currently observed in the Culebra as a whole, as well as along the likely offsite transport pathway. Therefore, the occurrence of another pluvial during the 10,000-year WIPP regulatory period would have no significant, additional consequence for the long-term performance of the repository. If, on the other hand, significant recharge occurs throughout both phases of the glacial-interglacial cycles, the conclusion that the effects of pluvial and modern recharge are inconsequential (are already reflected by existing variations in geochemical conditions) is also still valid.

The decision to screenout FEPs N35, N36, and N37 on the basis of low consequence for the long-term performance of the WIPP remains valid. However, the following discussion provides additional justification for this decision. FEPs N35, N36, and N37 are considered together in this discussion because the same process is the most likely cause, and perhaps the only plausible cause, for all three of these events or changes in these important geochemical properties of groundwaters in the Culebra Member of the Rustler Formation. To summarize, the original screening argument for these FEPs has been modified to provide a more robust basis for the low consequence decision, and ***Effects of Dissolution*** (N38) have been removed from this set of FEPs and is now addressed jointly with ***Saline Intrusion*** (N34).

SCR-4.3.1.3.3 Screening Argument

Natural changes in the groundwater chemistry of the Culebra and other units that resulted from ***Saline Intrusion*** or ***Freshwater Intrusion*** could potentially affect chemical retardation and the stability of colloids. Changes in ***Groundwater Eh*** and ***Groundwater pH*** could also affect the migration of radionuclides (see FEPs W65 to W70). No natural EPs have been identified that could result in ***Saline Intrusion*** into units above the Salado, and the magnitude of any natural temporal variation due to the effects of dissolution on groundwater chemistry, or due to changes in recharge, is likely to be no greater than the present spatial variation. These FEPs related to the effects of future natural changes in groundwater chemistry have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The most likely mechanism for (natural) ***freshwater intrusion*** into the Culebra (FEP N35), ***Changes in Groundwater*** Eh (N36), and ***Changes in Groundwater*** pH (N37) is (natural) recharge of the Culebra. (Other FEPs consider possible anthropogenically induced recharge). These three FEPs are closely related because an increase in the rate of recharge could reduce the ionic strength(s) of Culebra groundwaters, possibly enough to saturate the Culebra with (essentially) fresh water, at least temporarily. Such a change in ionic strength could, if enough atmospheric oxygen remained in solution, also increase the Eh of Culebra groundwaters enough to oxidize plutonium from the relatively immobile +III and +IV oxidation states (Pu(III) and Pu(IV)) – the oxidation states expected under current conditions (Brush 1996; Brush and Storz 1996) – to the relatively mobile +V and +VI oxidation states (Pu(V) and Pu(VI)). Similarly,

recharge of the Culebra with freshwater could also change the pH of Culebra groundwaters from the currently observed range of about 6 to 7 to mildy acidic values, thus (possibly) decreasing the retardation of dissolved Pu and Am. (These changes in ionic strength, Eh, and pH could also affect mobilities of Th, U, and neptunium (Np), but the long-term performance of the WIPP is much less sensitive to the mobilities of these radioelements than to those of Pu and Am.)

There is still considerable uncertainty regarding the extent and timing of recharge of the Culebra. Lambert (1986), Lambert and Carter (1987), Lambert and Harvey (1987), and Lambert (1991) used a variety of stable and radiogenic, isotopic-dating techniques to conclude that the Rustler (and the Dewey Lake Formation) have been closed hydrologic systems for several thousand to a few tens of thousands of years. In other words, the last significant recharge of the Rustler occurred during the late Pleistocene in response to higher levels of precipitation and infiltration associated with the most recent continental glaciation of North America, and the current flow field in the Culebra is the result of the slow discharge of groundwater from this unit. Other investigators have agreed that it is possible that Pleistocene recharge has contributed to present-day flow patterns in the Culebra, but that current patterns are also consistent with significant current recharge (Haug et al. 1987; Davies 1989). Still others (Chapman 1986, 1988) have rejected Lambert's interpretations in favor of exclusively modern recharge, at least in some areas. For example, the low-salinity of Hydrochemical Zone B south of the WIPP site could represent dilution of Culebra groundwater with significant quantities of recently introduced meteoric water (see Siegel et al. 1991, pp. 2-57 – 2-62 and Figure 2-17 for definitions and locations of the four hydrochemical facies in the Culebra in and around the WIPP site).

The current program to explain the cause(s) of the rising water levels observed in Culebra monitoring wells may elucidate the nature and timing of recharge. However, the justification of this screening decision does not depend on how this issue is resolved. If recharge occurs mainly during periods of high precipitation (pluvials) associated with periods of continental glaciation, the consequences of such recharge are probably already reflected in the ranges of geochemical conditions currently observed in the Culebra as a whole, as well as along the likely offsite transport pathway (the direction of flow from the point(s) at which brines from the repository would enter the Culebra in the event of human intrusion to the south or south-southeast and eventually to the boundary of the WIPP site). Hence, the effects of recharge, (possible) freshwater intrusion, and (possible) concomitant changes in groundwater Eh and pH can be screened out on the basis of low consequence to the performance of the far-field barrier. The reasons for the conclusion that the effects of pluvial recharge are inconsequential (are already included among existing variations in geochemical conditions) are: (1) as many as 50 continental glaciations and associated pluvials have occurred since the late Pliocene Epoch 2.5 million years ago (2.5 Ma BP); (2) the glaciations and pluvials that have occurred since about 0.5 to 1 Ma BP have been significantly more severe than those that occurred prior to 1 Ma BP (see, for example, Servant 2001); (3) the studies that quantified the retardation of Th, U, Pu, and Am for the WIPP CCA PA calculations and the EPA's PAVT were carried out under conditions that encompass those observed along the likely Culebra offsite transport pathway (Brush 1996; Brush and Storz 1996); and (4) these studies demonstrated that conditions in the Culebra are favorable for retardation of actinides despite the effects of as many as 50 periods of recharge.

It is also worth noting that the choice of the most recent glacial maximum as an upper limit for possible climatic changes during the 10,000 year WIPP regulatory period (Swift 1991 CCA

Appendix CLI) established conservative upper limits for precipitation and recharge of the Culebra at the WIPP site. The review by Swift (1991), later incorporated in CCA Appendix CLI, provides evidence that precipitation in New Mexico did not attain its maximum level (about 60-100 percent of current precipitation) until a few thousand years before the last glacial maximum. Swift pointed out that:

> Prior to the last glacial maximum 22 to 18 ka BP, evidence from mid- Wisconsin faunal assemblages in caves in southern New Mexico, including the presence of extralimital species such as the desert tortoise that are now restricted to warmer climates, suggests warm summers and mild, relatively dry winters (Harris 1987, 1988). Lacustrine evidence confirms the interpretation that conditions prior to and during the glacial advance that were generally drier than those at the glacial maximum. Permanent water did not appear in what was later to be a major lake in the Estancia Valley in central New Mexico until sometime before 24 ka BP (Bachhuber 1989). Late-Pleistocene lake levels in the San Agustin Plains in western New Mexico remained low until approximately 26.4 ka BP, and the $\delta^{18}O$ record from ostracode shells suggests that mean annual temperatures at that location did not decrease significantly until approximately 22 ka BP (Phillips et al. 1992).

Therefore, it is likely that precipitation and recharge did not attain levels characteristic of the most recent glacial maximum until about 70,000 to 75,000 years after the last glaciations had begun. High-resolution, deep-sea $\delta^{18}O$ data (and other data) reviewed by Servant (2001, Figures 1 and 2) support the conclusion that, although the volume of ice incorporated in continental ice sheets can expand rapidly at the start of a glaciation rapidly, attainment of maximum volume does not occur until a few thousand or a few tens of thousands of years prior to the termination of the approximately 100,000-year glaciations that have occurred during the last 0.5-1 Ma BP. Therefore, it is unlikely that precipitation and recharge will reach their maximum levels during the 10,000-year regulatory period.

If, on the other hand, significant recharge occurs throughout both phases of the glacial-interglacial cycles, the conclusion that the effects of pluvial and modern recharge are inconsequential (are already reflected by existing variations in geochemical conditions) is also still valid.

SCR-4.3.1.4 FEP Number: N38
FEP Title: ***Effects of Dissolution***

SCR-4.3.1.4.1 Screening Decision: SO-C

See discussion in ***Saline Intrusion*** (N34).

SCR-4.4 Geomorphological Features, Events, and Processes

SCR-4.4.1 Physiography

SCR-4.4.1.1 FEP Number: N39
FEP Title: ***Physiography***

SCR-4.4.1.1.1 Screening Decision: UP

*Relevant aspects of the **physiography**, geomorphology, and topography of the region around the WIPP are accounted for in PA calculations.*

SCR-4.4.1.1.2 Summary of New Information

No new information has been identified related to this FEP. No changes have been made.

SCR-4.4.1.1.3 Screening Argument

Physiography and geomorphology are discussed in detail in Section 2.1.4, and are accounted for in the setup of the PA calculations (Section 6.4.2).

SCR-4.4.1.2 FEP Number: N40
FEP Title: ***Impact of a Large Meteorite***

SCR-4.4.1.2.1 Screening Decision: SO-P

*Disruption arising from the **Impact of a Large Meteorite** has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-4.4.1.3 Summary of New Information

No new information has been identified related to this FEP. No changes have been made.

SCR-4.4.1.4 Screening Argument

Meteors frequently enter the earth's atmosphere, but most of these are small and burn up before reaching the ground. Of those that reach the ground, most produce only small impact craters that would have no effect on the postclosure integrity of a repository 650 m (2,150 ft) below the ground surface. While the depth of a crater may be only one-eighth of its diameter, the depth of the disrupted and brecciated material is typically one-third of the overall crater diameter (Grieve 1987, p. 248). Direct disruption of waste at the WIPP would only occur with a crater larger than 1.8 km (1.1 mi) in diameter. Even if waste were not directly disrupted, the ***impact of a large meteorite*** could create a zone of fractured rocks beneath and around the crater. The extent of such a zone would depend on the rock type. For sedimentary rocks, the zone may extend to a depth of half the crater diameter or more (Dence et al. 1977, p. 263). The impact of a meteorite causing a crater larger than 1 km (0.6 mi) in diameter could thus fracture the Salado above the repository.

Geological evidence for meteorite impacts on earth is rare because many meteorites fall into the oceans and erosion and sedimentation serve to obscure craters that form on land. Dietz (1961) estimated that meteorites that cause craters larger than 1 km (0.6 mi) in diameter strike the earth at the rate of about one every 10,000 years (equivalent to about 2×10^{-13} impacts per square kilometer per year). Using observations from the Canadian Shield, Hartmann (1965, p. 161) estimated a frequency of between 0.8×10^{-13} and 17×10^{-13} per square kilometer per year for impacts causing craters larger than 1 km (0.6 mi). Frequencies estimated for larger impacts in studies reported by Grieve (1987, p. 263) can be extrapolated to give a rate of about 1.3×10^{-12} per square kilometer per year for craters larger than 1 km (0.6 mi). It is commonly assumed that meteorite impacts are randomly distributed across the earth's surface, although Halliday (1964, pp. 267-277) calculated that the rate of impact in polar regions would be some 50 to 60 percent of that in equatorial regions. The frequencies reported by Grieve (1987) would correspond to an overall rate of about 1 per 1,000 years on the basis of a random distribution.

Assuming the higher estimated impact rate of 17×10^{-13} impacts per square kilometer per year for impacts leading to fracturing of sufficient extent to affect a deep repository and assuming a repository footprint of 1.4 km × 1.6 km (0.9 mi × 1.0 mi) for the WIPP yields a frequency of about 4×10^{-12} impacts per year for a direct hit above the repository. This impact frequency is several orders of magnitude below the screening limit of 10^{-4} per 10,000 years provided in 40 CFR § 194.32(d).

Meteorite hits directly above the repository footprint are not the only impacts of concern, however, because large craters may disrupt the waste panels even if the center of the crater is outside the repository area. It is possible to calculate the frequency of meteorite impacts that could disrupt a deep repository such as the WIPP by using the conservative model of a cylinder of rock fractured to a depth equal to one-half the crater diameter, as shown in CCA Appendix SCR, Figure SCR-1. The area within which a meteorite could impact the repository is calculated by

$$S_D = \left(L + 2 \times \frac{D}{2}\right) \times \left(W + 2 \times \frac{D}{2}\right), \tag{1}$$

Where

L = length of the repository footprint (kilometers),
W = width of the repository footprint (kilometers),
D = diameter of the impact crater (kilometers), and
S_D = area of the region where the crater would disrupt the repository (square kilometers).

There are insufficient data on meteorites that have struck the earth to derive a distribution function for the size of craters directly. Using meteorite impacts on the moon as an analogy, however, Grieve (1987, p. 257) derived the following distribution function:

$$F_D \propto D^{-18} \tag{2}$$

where

F_D = frequency of impacts resulting in craters larger than D (impacts per square kilometer per year).

If f(D) denotes the frequency of impacts giving craters of diameter D, then the frequency of impacts giving craters larger than D is

$$FD = \int_{D}^{\infty} f\ (D)\, d\, D \tag{3}$$

and

$$f\ (D) = F_1 \times 1.8 \times D^{-28}, \tag{4}$$

where

F_1 = frequency of impacts resulting in craters larger than 1 km (impacts per square kilometer per year), and

$f(D)$ = frequency of impacts resulting in craters of diameter D (impacts per square kilometer per year).

The overall frequency of meteorite impacts that could disrupt or fracture the repository is thus given by

$$N = \int_{2h}^{\infty} f\ (D) \times S_D\, dD, \tag{5}$$

Where

h = depth to repository (kilometers),

N = frequency of impacts leading to disruption of the repository (impacts per year), and

$$N = 1.8F_1 \left[1.8\ LW(2h)^{-18} + 0.8(L + W)\,(2h)^{-0.8} - 0.2(2h)^{0.2}\right] \tag{6}$$

If it is assumed that the repository is located at a depth of 650 m (2,150 ft) and has a footprint area of 1.4 km × 1.6 km (0.9 mi × 1.0 mi) and that meteorites creating craters larger than 1 km in diameter hit the earth at a frequency (F_1) of 17×10^{-13} impacts per square kilometer per year, then Equation (6) gives a frequency of approximately 1.3×10^{-11} impacts per year for impacts disrupting the repository. If impacts are randomly distributed over time, this corresponds to a probability of 1.3×10^{-7} over 10,000 years.

Similar calculations have been performed that indicate rates of impact of between 10^{-12} and 10^{-13} per year for meteorites large enough to disrupt a deep repository (see, for example, Hartmann 1979, Kärnbränslesakerhet 1978, Claiborne and Gera 1974, Cranwell et al. 1990, and Thorne

1992). Meteorite impact can thus be eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

Assuming a random or nearly random distribution of meteorite impacts, cratering at any location is inevitable given sufficient time. Although repository depth and host-rock lithology may reduce the consequences of a ***Meteorite Impact***, there are no repository locations or engineered systems that can reduce the probability of impact over 10,000 years.

SCR-4.4.1.5 FEP Number: N41 and N42
FEP Title(s): ***Mechanical Weathering*** (N41)
Chemical Weathering (N42)

SCR-4.4.1.5.1 Screening Decision: SO-C

The effects of ***Chemical and Mechanical Weathering*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.4.1.5.2 Summary of New Information

No new information has been identified related to these FEPs. No changes have been made.

SCR-4.4.1.5.3 Screening Argument

Mechanical Weathering and ***Chemical Weathering*** are assumed to be occurring at or near the surface around the WIPP site, through processes such as exfoliation and leaching. The extent of these processes is limited and they will contribute little to the overall rate of erosion in the area or to the availability of material for other erosional processes. The effects of ***Chemical and Mechanical Weathering*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.4.1.6 FEP Number: N43, N44 & N45
FEP Title: ***Aeolian Erosion*** (N43)
Fluvial Erosion (N44)
Mass Wasting (N45

SCR-4.4.1.6.1 Screening Decision: SO-C

The effects of ***Fluvial and Aeolian Erosion and Mass W asting*** *in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.4.1.6.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. No changes have been made.

SCR-4.4.1.6.3 Screening Argument

The geomorphological regime on the Mescalero Plain (Los Medaños) in the region of the WIPP is dominated by aeolian processes. Dunes are present in the area, and although some are stabilized by vegetation, ***Aeolian Erosion*** will occur as they migrate across the area. Old dunes will be replaced by new dunes, and no significant changes in the overall thickness of aeolian material are likely to occur.

Currently, precipitation in the region of the WIPP is too low (about 33 cm [13 in.] per year) to cause perennial streams, and the relief in the area is too low for extensive sheet flood erosion during storms. An increase in precipitation to around 61 cm (24 in.) per year in cooler climatic conditions could result in perennial streams, but the nature of the relief and the presence of dissolution hollows and sinks will ensure that these streams remain small. Significant ***Fluvial Erosion*** is not expected during the next 10,000 years.

Mass Wasting (the downslope movement of material caused by the direct effect of gravity) is important only in terms of sediment erosion in regions of steep slopes. In the vicinity of the WIPP, Mass ***Wasting*** will be insignificant under the climatic conditions expected over the next 10,000 years.

Erosion from wind, water, and mass wasting will continue in the WIPP region throughout the next 10,000 years at rates similar to those occurring at present. These rates are too low to affect the performance of the disposal system significantly. Thus, the effects of ***Fluvial*** and ***Aeolian Erosion*** and Mass ***Wasting*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.4.1.7 FEP Number: N50
FEP Title: **Soil Development**

SCR-4.4.1.7.1 Screening Decision: SO-C

Soil Development *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.4.1.7.2 Summary of New Information

No new information has been identified related to the screening of this FEP. Editorial changes have been made.

SCR-4.4.1.7.3 Screening Argument

The Mescalero caliche is a well-developed calcareous remnant of an extensive soil profile across the WIPP site and adjacent areas. Although this unit may be up to 3 m (10 ft) thick, it is not continuous and does not prevent infiltration to the underlying formations. At Nash Draw, this caliche, dated in Lappin et al. (1989, pp. 2-4) at 410,000 to 510,000 years old, is present in collapse blocks, indicating some growth of Nash Draw in the late Pleistocene. Localized gypsite spring deposits about 25,000 years old occur along the eastern flank of Nash Draw, but the springs are not currently active. The Berino soil, interpreted as 333,000 years old (Rosholt and

McKinney 1980, Table 5), is a thin soil horizon above the Mescalero caliche. The persistence of these soils on the Livingston Ridge and the lack of deformation indicates the relative stability of the WIPP region over the past half-million years.

Continued growth of caliche may occur in the future but will be of low consequence in terms of its effect on infiltration. Other soils in the area are not extensive enough to affect the amount of infiltration that reaches underlying aquifers. ***Soil Development*** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5 Surface Hydrological Features, Events, and Processes

SCR-4.5.1 Depositional Processes

SCR-4.5.1.1 FEP Number: N46, N47, N48 and N49
FEP Title: ***Aeolian Deposition*** (N46)
Fluvial Deposition (47)
Lacustrine Deposition (N48)
Mass Waste (Deposition) (N49)

SCR-4.5.1.1.1 Screening Decision: SO-C

*The effects of **Aeolian**, **Fluvial**, **and Lacustrine** deposition and sedimentation in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.5.1.1.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. No changes have been made.

SCR-4.5.1.1.3 Screening Argument

The geomorphological regime on the Mescalero Plain (Los Medaños) in the region of the WIPP is dominated by aeolian processes, but although some dunes are stabilized by vegetation, no significant changes in the overall thickness of aeolian material are expected to occur. Vegetational changes during periods of wetter climate may further stabilize the dune fields, but ***Aeolian Deposition*** is not expected to significantly increase the overall thickness of the superficial deposits.

The limited extent of water courses in the region of the WIPP, under both present-day conditions and under the expected climatic conditions, will restrict the amount of ***Fluvial Deposition*** and ***Lacustrine Deposition*** in the region.

Mass Wasting (Deposition) may be significant if it results in dams or modifies streams. In the region around the WIPP, the Pecos River forms a significant water course some 19 km (12 mi) away, but the broadness of its valley precludes either significant mass wasting or the formation of large impoundments.

Sedimentation from wind, water, and Mass ***Wasting*** is expected to continue in the WIPP region throughout the next 10,000 years at the low rates similar to those occurring at present. These rates are too low to significantly affect the performance of the disposal system. Thus, the effects of ***Aeolian***, ***Fluvial***, ***and Lacustrine Deposition*** and sedimentation resulting from Mass ***Wasting*** have been eliminated from PA calculations on the basis of low consequence.

SCR-4.5.2 Streams and Lakes

SCR-4.5.2.1 FEPs Number: N51
FEPs Title: ***Stream and River Flow***

SCR-4.5.2.1.1 Screening Decision: SO-C

Stream and River Flow *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.5.2.1.2 Summary of New Information

No new information has been identified related to the screening of this FEP. No changes have been made.

SCR-4.5.2.1.3 Screening Argument

No perennial streams are present at the WIPP site, and there is no evidence in the literature indicating that such features existed at this location since the Pleistocene (see, for example, Powers et al. 1978; and Bachman 1974, 1981, and 1987b). The Pecos River is approximately 19 km (12 mi) from the WIPP site and more than 90 m (300 ft) lower in elevation. ***Stream and River Flow*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5.2.2 FEP Number: N52
FEP Title: ***Surface Water Bodies***

SCR-4.5.2.2.1 Screening Decision: SO-C

The effects of ***Surface Water Bodies*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.5.2.2.2 Summary of New Information

No new information has been identified related to the screening of this FEP. No changes have been made.

SCR-4.5.2.2.3 Screening Argument

No standing ***Surface Water Bodies*** are present at the WIPP site, and there is no evidence in the literature indicating that such features existed at this location during or after the Pleistocene (see, for example, Powers et al. 1978; and Bachman 1974, 1981, and 1987b). In Nash Draw, lakes

and spoil ponds associated with potash mines are located at elevations 30 m (100 ft) below the elevation of the land surface at the location of the waste panels. There is no evidence in the literature to suggest that Nash Draw was formed by stream erosion or was at any time the location of a deep body of standing water, although shallow playa lakes have existed there at various times. Based on these factors, the formation of large lakes is unlikely and the formation of smaller lakes and ponds is of little consequence to the performance of the disposal system. The effects of ***Surface Water Bodies*** have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5.3 Groundwater Recharge and Discharge

SCR-4.5.3.1 FEP Number: N53, N54, and N55
FEP Title: ***Groundwater Discharge*** (N53)
Groundwater Recharge (N54)
Infiltration (N55)

SCR-4.5.3.1.1 Screening Decision: UP

Groundwater Recharge, Infiltration, and ***Groundwater Discharge*** *are accounted for in PA calculations.*

SCR-4.5.3.1.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-4.5.3.1.3 Screening Argument

The groundwater basin described in Section 2.2.1.4 is governed by flow from areas where the water table is high to areas where the water table is low. The height of the water table is governed by the amount of ***Groundwater Recharge*** reaching the water table, which in turn is a function of the vertical hydraulic conductivity and the partitioning of precipitation between evapotranspiration, runoff, and ***Infiltration***. Flow within the Rustler is also governed by the amount of ***Groundwater Discharge*** that takes place from the basin. In the region around the WIPP, the principal discharge areas are along Nash Draw and the Pecos River. Groundwater flow modeling accounts for infiltration, recharge, and discharge (Sections 2.2.1.4 and 6.4.10.2).

SCR-4.5.3.2 FEP Number: N56
FEP Title: ***Changes in Groundwater Recharge and Discharge***

SCR-4.5.3.2.1 Screening Decision: UP

Changes in ***Groundwater Recharge and Discharge*** *arising as a result of climate change are accounted for in PA calculations.*

SCR-4.5.3.2.2 Summary of New Information

No information has become available that would change the screening decision for this FEP. Changes in the implementation (if any) of this FEP within PA are addressed in Chapter 6.0. This FEP has been separated from N57 and N58 for editorial purposes.

SCR-4.5.3.2.3 Screening Argument

Changes in recharge may affect groundwater flow and radionuclide transport in units such as the Culebra and Magenta dolomites. Changes in the surface environment driven by natural climate change are expected to occur over the next 10,000 years (see FEPs N59 to N63). Groundwater basin modeling (Section 2.2.1.4) indicates that a change in recharge will affect the height of the water table in the area of the WIPP, and that this will in turn affect the direction and rate of groundwater flow.

The present-day water table in the vicinity of the WIPP is within the Dewey Lake at about 980 m (3,215 ft) above mean sea level (Section 2.2.1.4.2.1). An increase in recharge relative to present-day conditions would raise the water table, potentially as far as the local ground surface. Similarly, a decrease in recharge could result in a lowering of the water table. The low transmissivity of the Dewey Lake and the Rustler ensures that any such lowering of the water table will be at a slow rate, and lateral discharge from the groundwater basin is expected to persist for several thousand years after any decrease in recharge. Under the anticipated changes in climate over the next 10,000 years, the water table will not fall below the base of the Dewey Lake, and dewatering of the Culebra is not expected to occur during this period (Section 2.2.1.4).

Changes in Groundwater Recharge and Discharge are accounted for in PA calculations through definition of the boundary conditions for flow and transport in the Culebra (Section 6.4.9).

SCR-4.5.3.3 FEP Number: N57 & N58
FEP Title: ***Lake Formation*** (N57)
River Flooding (N58)

SCR-4.5.3.3.1 Screening Decision: SO-C

The effects of ***River Flooding and Lake Formation*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.5.3.3.2 Summary of New Information

The original text in CCA Appendix SCR has been modified only to remove reference to other FEPs. No substantive changes have been made to the FEP descriptions, screening arguments, or screening decision.

SCR-4.5.3.3.3 Screening Argument

Intermittent flooding of stream channels and the formation of shallow lakes will occur in the WIPP region over the next 10,000 years. These may have a short-lived and local effect on the height of the water table, but are unlikely to affect groundwater flow in the Culebra.

Future occurrences of playa lakes or other longer-term floods will be remote from the WIPP and will have little consequence on system performance in terms of groundwater flow at the site. There is no reason to believe that any impoundments or lakes could form over the WIPP site itself. Thus, ***River Flooding*** and ***Lake Formation*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.6 Climate Events and Processes

SCR-4.6.1 Climate and Climate Changes

SCR-4.6.1.1 FEP Number: N59 and N60
FEP Title: ***Precipitation*** (N59)
Temperature (N60)

SCR-4.6.1.1.1 Screening Decision: UP

Precipitation and temperature are accounted for in PA calculations.

SCR-4.6.1.1.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-4.6.1.1.3 Screening Argument

The climate and meteorology of the region around the WIPP are described in, Section 2.5.2. Precipitation in the region is low (about 33 cm (13 in.) per year) and temperatures are moderate with a mean annual temperature of about 63°F (17°C). ***Precipitation*** and ***Temperature*** are important controls on the amount of recharge that reaches the groundwater system and are accounted for in PA calculations by use of a sampled parameter for scaling flow velocity in the Culebra (Section 6.4.9 and Appendix PA, Attachment PAR).

SCR-4.6.1.2 FEP Number: N61
FEP Title: ***Climate Change***

SCR-4.6.1.2.1 Screening Decision: UP

Climate Change *is accounted for in PA calculations.*

SCR-4.6.1.2.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-4.6.1.2.3 Screening Argument

Climate Changes are instigated by changes in the earth's orbit, which affect the amount of insolation, and by feedback mechanisms within the atmosphere and hydrosphere. Models of these mechanisms, combined with interpretations of the geological record, suggest that the climate will become cooler and wetter in the WIPP region during the next 10,000 years as a result of natural causes. Other changes, such as fluctuations in radiation intensity from the sun and variability within the many feedback mechanisms, will modify this climatic response to orbital changes. The available evidence suggests that these changes will be less extreme than those arising from orbital fluctuations.

The effect of a change to cooler and wetter conditions is considered to be an increase in the amount of recharge, which in turn will affect the height of the water table (see FEPs N53 through N56). The height of the water table across the groundwater basin is an important control on the rate and direction of groundwater flow within the Culebra (see Section 2.2.1.4), and hence potentially on transport of radionuclides released to the Culebra through the shafts or intrusion boreholes. ***Climate Change*** is accounted for in PA calculations through a sampled parameter used to scale groundwater flow velocity in the Culebra (Section 6.4.9 and Appendix PA, Attachment PAR).

SCR-4.6.1.3 FEP Number: N62 and N63
FEP Title: ***Glaciation*** (N62)
Permafrost (N63)

SCR-4.6.1.3.1 Screening Decision: SO-P

Glaciation *and the effects of* ***Permafrost*** *have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-4.6.1.3.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. No changes have been made.

SCR-4.6.1.3.3 Screening Argument

No evidence exists to suggest that the northern part of the Delaware Basin has been covered by continental glaciers at any time since the beginning of the Paleozoic Era. During the maximum extent of continental glaciation in the Pleistocene Epoch, glaciers extended into northeastern Kansas at their closest approach to southeastern New Mexico. There is no evidence that alpine glaciers formed in the region of the WIPP during the Pleistocene glacial periods.

According to the theory that relates the periodicity of climate change to perturbations in the earth's orbit, a return to a full glacial cycle within the next 10,000 years is highly unlikely (Imbrie and Imbrie 1980, 951).

Thus, ***Glaciation*** has been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years. Similarly, a number of processes associated with the proximity of an ice sheet or valley glacier, such as ***Permafrost*** and accelerated slope erosion (solifluction) have been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.7 Marine Features, Events, and Process

SCR-4.7.1 Seas, Sedimentation, and Level Changes

SCR-4.7.1.1 FEP Number(s): N64 and N65
FEP Title(s): ***Seas and Oceans*** (N64)
Estuaries (N65)

SCR-4.7.1.1 Screening Decision: SO-C

*The effects of **Estuaries**, seas, and oceans have has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.7.1.1.2 Summary of New Information

No new information has been identified related to this FEP. No changes have been made.

SCR-4.7.1.1.3 Screening Argument

The WIPP site is more than 800 km (480 mi) from the Pacific Ocean and from the Gulf of Mexico. ***Estuaries*** and ***Seas and Oceans*** have therefore been eliminated from PA calculations on the basis of low consequence to the disposal system.

SCR-4.7.1.2 FEPs Number(s): N66 and N67
FEPs Title(s): ***Coastal Erosion*** (N66)
Marine Sediment Transport and Deposition (N67)

SCR-4.7.1.2.1 Screening Decision: SO-C

*The effects of **Coastal Erosion**,* and ***Marine Sediment Transport and Deposition*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.7.1.2.2 Summary of New Information

No new information has been identified related to these FEPs. No changes have been made.

SCR-4.7.1.2.3 Screening Argument

The WIPP site is more than 800 km (480 mi) from the Pacific Ocean and Gulf of Mexico. The effects of ***Coastal Erosion***, and ***Marine Sediment Transport and Deposition*** have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.7.1.3 FEP Number: N68
FEP Title: ***Sea Level Changes***

SCR-4.7.1.3.1 Screening Decision: SO-C

*The effects of both short-term and long-term **Sea Level Changes** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.7.1.3.2 Summary of New Information

No new information has been identified relating to the screening of this FEP. No changes have been made.

SCR-4.7.1.3.3 Screening Argument

The WIPP site is some 1,036 m (3,400 ft) above sea level. Global ***Sea Level Changes*** may result in sea levels as much as 140 m (460 ft) below that of the present day during glacial periods, according to Chappell and Shackleton (1986, p. 138). This can have marked effects on coastal aquifers. During the next 10,000 years, the global sea level can be expected to drop towards this glacial minimum, but this will not affect the groundwater system in the vicinity of the WIPP. Short-term changes in sea level, brought about by events such as meteorite impact, tsunamis, seiches, and hurricanes may raise water levels by several tens of meters. Such events have a maximum duration of a few days and will have no effect on the surface or groundwater systems at the WIPP site. Anthropogenic-induced global warming has been conjectured by Warrick and Oerlemans (1990, p. 278) to result in longer-term sea level rise. The magnitude of this rise, however, is not expected to be more than a few meters, and such a variation will have no effect on the groundwater system in the WIPP region. Thus, the effects of both short-term and long-term ***Sea Level Changes*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.8 Ecological Features, Events, and Process

SCR-4.8.1 Flora and Fauna

SCR-4.8.1.1 FEP Number(s): N69 and N70
FEP Title(s): ***Plants*** (N69)
Animals (N70)

SCR-4.8.1.1.1 Screening Decision: SO-C

*The effects of the natural **Plants and Animals**, (flora and fauna) in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.8.1.1.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. Only editorial changes have been made.

SCR-4.8.1.1.3 Screening Argument

The terrestrial and aquatic ecology of the region around the WIPP is described in Section 2.4.1. The ***Plants*** in the region are predominantly shrubs and grasses. The most conspicuous ***Animals*** in the area are jackrabbits and cottontail rabbits. The effects of this flora and fauna in the region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.8.1.2 FEP Number: N71
FEP Title: ***Microbes***

SCR-4.8.1.2.1 Screening Decision: SO-C
UP for colloidal effects and gas generation

*The effects of **Microbes** on the region of the WIPP has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.8.1.2.2 Summary of New Information

Microbes can be important in soil development. As dissolved actinide elements are introduced to the Culebra, it is possible that those dissolved actinides can sorb onto ***Microbes***. However, due to the size effect, ***Microbes*** will be rapidly filtered out of the advective flow domain; hence, the effect of ***Microbes*** on radionuclide transport in the Culebra will be insignificant. The original screening decision remains valid. Additional information has been included to support the screening argument.

SCR-4.8.1.2.3 Screening Argument

Microbes are presumed to be present with the thin soil horizons. Gillow et al. (2000) characterized the microbial distribution in Culebra groundwater at the WIPP site. Culebra groundwater contained $1.51 \pm 1.08 \times 10^5$ cells/ml. The dimension of the cells are 0.75 μm in length and 0.58 μm in width, right at the upper limit of colloidal particle size. Gillow et al. (2000) also found that at pH 5.0, Culebra denitrifier CDn ($0.90 \pm 0.02 \times 10^8$ cells/ml) removed 32 percent of the uranium added to sorption experiments, which is equivalent to 180 ± 10 mg U/g of dry cells. Another isolate from WIPP (Halomonas sp.) ($3.55 \pm 0.11 \times 10^8$ cells/ml) sorbed 79 percent of the added uranium. Due to their large sizes, microbial cells as colloidal particles will be rapidly filtered out in the Culebra formation. Therefore, the original FEP screening decision that ***Microbes*** in groundwater have an insignificant impact on radionuclide transport in the Culebra formation remains valid. A similar conclusion has also been arrived for Sweden repository environments (Pedersen 1999).

SCR-4.8.1.3 FEP Number: N72
FEP Title: ***Natural Ecological Development***

SCR-4.8.1.3.1 Screening Decision: SO-C

The effects of ***Natural Ecological Development*** *likely to occur in the region of the WIPP have been eliminated from* PA *calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.8.1.3.2 Summary of New Information

No new information has been identified related to the screening of this FEP. No changes have been made.

SCR-4.8.1.3.3 Screening Argument

The region around the WIPP is sparsely vegetated as a result of the climate and poor soil quality. Wetter periods are expected during the regulatory period, but botanical records indicate that, even under these conditions, dense vegetation will not be present in the region (Swift 1992; see CCA Appendix CLI, p. 17). The effects of the indigenous fauna are of low consequence to the performance of the disposal system and no natural events or processes have been identified that would lead to a change in this fauna that would be of consequence to system performance. ***Natural Ecological Development*** in the region of the WIPP has therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.0 SCREENING OF HUMAN-INITIATED EPS

The following section presents screening arguments and decisions for human-initiated EPs. Table SCR-2 provides summary information regarding changes to human-initiated EPs since the CCA. Of the 57 human-initiated EPs, 13 remain unchanged, 39 were updated with new information or were edited for clarity and completeness, 4 screening decisions were changed, 1

EP was deleted from the baseline by combining with other more appropriate EPs, and 2 EPs were added.

SCR-5.1 Human Induced Geological Events and Process

SCR-5.1.1 Drilling

SCR-5.1.1.1 FEP Number: H1, H2, H4, H8, and H9
FEP Title: ***Oil and Gas Exploration*** (H1)
Potash Exploration (H2)
Oil and Gas Exploitation (H4)
Other Resources (drilling for) (H8)
Enhanced Oil and Gas Recovery (drilling for) (H9)

SCR-5.1.1.1.1 Screening Decision: SO-C (HCN)
DP (Future)

The effects of historical, current, and near-future drilling associated with ***Oil and Gas Exploration, Potash Exploration, Oil and G as Exploitation, Drilling for Other Resources,*** *and* ***Enhanced Oil*** *and* ***Gas Recovery*** *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system (see screening discussion for H21, H22, and H23). Oil and gas exploration, potash exploration, oil and gas exploitation, drilling for other resources, and enhanced oil and gas recovery in the future is accounted for in disturbed performance scenarios through incorporation of the rate of future drilling as specified in 40 CFR § 194.33.*

SCR-5.1.1.1.2 Summary of New Information

Regulations require that drilling for resources in the future be considered in PA calculations. As such, deep drilling associated with ***Oil and Gas Exploration, Potash Exploration, Oil and Gas Exploration*** drilling for ***Other Resources***, and ***Enhanced Oil*** *and* ***Gas Recovery*** in the future is accounted for in the PA in DP scenarios via the drilling rate as calculated by the method prescribed by the EPA. For HCN time frames, deep drilling for ***Oil and Gas Exploration, Potash Exploration, Oil and Gas Exploitation,*** and drilling for ***Other Resources*** has been screened out based on consequence. Additionally, ***Drilling for the Purposes of Enhanced Oil*** *and* ***Gas Recovery*** has been screened out based on consequence because the process of drilling does not vary depending on the intended use of the borehole, be it for resource recovery, reservoir stimulation, or for other purposes such as geologic characterization and exploration. The screening decision of SO-C for HCN for these FEPs is largely based on the screening of FEPs H21 ***Drilling Fluid Flow***, H22 ***Drilling Fluid Loss***, and H23 ***Blowouts***. Because these activities are currently taking place, and will not occur within the land withdrawal boundary during the current time period nor in the near future (due to active institutional controls), the only possible impact to the repository could be from ***Drilling Fluid Flow, Fluid Loss, or Blowout*** in boreholes outside the WIPP land withdrawal boundary. The specific effects are discussed in detail within the screening discussions for FEPs H21, H22, and H23.

SCR-5.1.1.1.3 Historical, Current, and Near-Future Human EPs

Resource exploration and exploitation are the most common reasons for drilling in the Delaware Basin and are the most likely reasons for drilling in the near future. The WIPP location has been evaluated for the occurrence of natural resources in economic quantities. Powers et al. (1978) (CCA Appendix GCR, Chapter 8) investigated the potential for exploitation of potash, hydrocarbons, caliche, gypsum, salt, uranium, sulfur, and lithium. Also, in 1995, the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) performed a reevaluation of the mineral resources at and within 1.6 km (1 mi) around the WIPP site. While some resources do exist at the WIPP site, for the HCN timeframes, such drilling is assumed to only occur outside the WIPP site boundary. This assumption is based on current federal ownership and management of the WIPP during operations, and assumed effectiveness of institutional controls for the 100-year period immediately following site closure.

Drilling associated with ***Oil and Gas Exploration*** and ***Oil and Gas Exploitation*** currently takes place in the vicinity of the WIPP. For example, gas is extracted from reservoirs in the Morrow Formation, some 4,200 m (14,000 ft) below the surface, and oil is extracted from shallower units within the Delaware Mountain Group, some 2,150 to 2,450 m (7,000 to 8,000 ft) below the surface.

Potash resources in the vicinity of the WIPP are discussed in Section 2.3.1.1. Throughout the Carlsbad Potash District, commercial quantities of potash are restricted to the McNutt, which forms part of the Salado above the repository horizon. ***Potash Exploration*** and evaluation boreholes have been drilled within and outside the controlled area. Such drilling will continue outside the WIPP land withdrawal boundary, but no longer occurs within the boundary due to transfer of rights and controls to the DOE. Moreover, drilling for the evaluation of potash resources within the boundary will not occur throughout the time period of active institutional controls.

Drilling for Other Resources has taken place within the Delaware Basin. For example, sulfur extraction using the Frasch process began in 1969 and continued for three decades at the Culberson County Rustler Springs mine near Orla, Texas. In addition, brine wells have been in operation in and about the Delaware Basin for at least as long. Solution mining processes for sulfur, salt (brine), potash, or any other mineral are not addressed in this FEP; only the drilling of the borehole is addressed here. Resource extraction through solution mining and any potential effects are evaluated in H58, solution mining. Nonetheless, the drilling activity associated with the production of other resources is not notably different than drilling for petroleum exploration and exploitation.

Drilling for the purposes of reservoir stimulation and subsequent ***Enhanced Oil*** *and* ***Gas Recovery*** does take place within the Delaware Basin, although systematic, planned waterflooding has not taken place near the WIPP. Instead, injection near WIPP consists of single-point injectors, rather than broad, grid-type waterflood projects (Hall et al. 2003). In the vicinity of the WIPP, fluid injection usually takes place using boreholes initially drilled as producing wells. Therefore, regardless of the initial intent of a deep borehole, whether in search of petroleum reserves or as an injection point, the drilling event and associated processes are virtually the same. These drilling related processes are addressed more fully in H21 ***Drilling***

Fluid Flow, H22 ***Drilling Fluid Loss***, and H23 ***Blowouts***. Discussion on the effects subsequent to drilling a borehole for the purpose of enhancing oil and gas recovery is discussed in FEP H28, ***Enhanced Oil and Gas Production***.

In summary, drilling associated with ***Oil and Gas Exploration, Potash Exploration, Oil and Gas Exploitation, Enhanced Oil*** *and* ***Gas Recovery,*** and drilling associated with ***Other Resources*** has taken place and is expected to continue in the Delaware Basin. The potential effects of existing and possible near-future boreholes on fluid flow and radionuclide transport within the disposal system are discussed in FEPs H25 through H36, where low consequence screening arguments are provided.

SCR-5.1.1.1.4 Future Human EPs

Criteria in 40 CFR § 194.33 require the DOE to examine the historical rate of drilling for resources in the Delaware Basin. Thus, consistent with 40 CFR § 194.33(b)(3)(i), the DOE has used the historical record of deep drilling associated with ***Oil and Gas Exploration, Potash Exploration, Oil and Gas Exploitation, Enhanced Oil*** *and* ***Gas Recovery,*** and ***Drilling Associated With Other*** resources (sulfur exploration) in the Delaware Basin in calculations to determine the rate of future deep drilling in the Delaware Basin (see Appendix DEL, Appendix DATA; and Chapter 6.3.2).

SCR-5.1.1.2 FEP Number(s): H3 and H5
FEP Title(s): ***Water Resources Exploration*** (H3)
Groundwater Exploitation (H5)

SCR-5.1.1.2.1 Screening Decision: SO-C (HCN)
SO-C (Future)

The effects of HCN drilling associated with ***Water Resources Exploration*** *and* ***Groundwater Exploitation*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Historical shallow drilling associated with* ***Water Resources Exploration*** *and* ***Groundwater Exploitation*** *is accounted for in calculations to determine the rate of future shallow drilling.*

SCR-5.1.1.2.2 Summary of New Information

In the screening of FEPs conducted for the CCA, FEP H3 and H5 were screened out based on low consequence (SO-C) for the long-term performance of the WIPP. The CCA screening decision and argument applied to both the HCN and future time periods and remain valid for the CRA; however, additional justification for this conclusion has been provided.

SCR-5.1.1.2.3 Screening Argument

Drilling associated with ***Water Resources Exploration*** and ***Groundwater Exploitation*** has taken place and is expected to continue in the Delaware Basin. For the most part, water resources in the vicinity of the WIPP are scarce. Elsewhere in the Delaware Basin, potable water occurs in places while some communities rely solely on groundwater sources for drinking water. Even though ***Water Resources Exploration*** and ***Groundwater Exploitation*** occur in the Basin, all

such exploration/exploitation is confined to shallow drilling that extends no deeper than the Rustler Formation and thus will not impact repository performance because of the limited drilling anticipated in the future and the sizeable thickness of low permeability Salado salt between the waste panels and the shallow groundwaters. Given the limited groundwater resources and minimal consequence of shallow drilling on performance, the effects of HCN and future drilling associated with ***Water Resources Exploration*** and ***Groundwater Exploitation*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Thus, the screening argument remains the same as given previously in the CCA.

Although shallow drilling for ***Water Resources Exploration*** and ***Groundwater Exploitation*** have been eliminated from PA calculations, the Delaware Basin Drilling Surveillance Program (DBDSP) continues to collect drilling data related to water resources, as well as other shallow drilling activities. As shown in the DBDSP 2002 Annual Report (DOE 2002), the total number of shallow water wells in the Delaware Basin is currently 2,296 compared to 2,331 shallow water wells reported in the CCA, a decrease of 35 wells (attributed primarily to the reclassification of water wells to other types of shallow boreholes). Based on these data, the shallow drilling rate for ***Water Resources Exploration*** and ***Groundwater Exploitation*** is essentially the same as reported in the CCA. The distribution of groundwater wells in the Delaware Basin was included in CCA Appendix USDW, Section USDW.3.

SCR-5.1.1.2.4 Historical, Current, and Near-Future Human EPs

Water is currently extracted from formations above the Salado, as discussed in CCA Section 2.3.1.3. The distribution of groundwater wells in the Delaware Basin is included in CCA Appendix USDW, Section USDW.3. ***Water Resources Exploration*** and ***Groundwater Exploitation*** are expected to continue in the Delaware Basin.

In summary, drilling associated with ***Water Resources Exploration, Groundwater Exploitation***, ***Potash Exploration***, ***Oil and Gas Exploration***, ***Oil and Gas Exploitation***, ***Enhanced Oil and Gas Recovery***, and drilling to explore ***Other Resources*** has taken place and is expected to continue in the Delaware Basin. The potential effects of existing and possible near-future boreholes on fluid flow and radionuclide transport within the disposal system are discussed in Section SCR.5.2, where low consequence screening arguments are provided.

SCR-5.1.1.2.5 Future Human EPs

Criteria in 40 CFR § 194.33 require that, to calculate the rates of future shallow and deep drilling in the Delaware Basin, the DOE should examine the historical rate of drilling for resources in the Delaware Basin.

Shallow drilling associated with water, potash, sulfur, oil, and gas extraction has taken place in the Delaware Basin over the past 100 years. However, of these resources, only water and potash are present at shallow depths (less than 655 m (2,150 ft) below the surface) within the controlled area. Thus, consistent with 40 CFR § 194.33(b)(4), the DOE accounts for this drilling through the use of the historical record of shallow drilling associated with ***Water Resources Exploration***,

Potash Exploration, and ***Groundwater Exploitation***, in calculations to determine the rate of future shallow drilling in the Delaware Basin.

SCR-5.1.1.3 FEP Number: H6, H7, H10, H11, and H12
FEP Title: ***Archeology*** (H6)
Geothermal Energy Production (H7)
Liquid Waste Disposal (H10)
Hydrocarbon Storage (H11)
Deliberate Drilling Intrusion (H12)

SCR-5.1.1.3.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Drilling associated with ***Archeology, Geothermal Energy Production, Liquid Waste Disposal, Hydrocarbon Storage,*** *and* ***Deliberate Drilling Intrusion*** *have been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.1.3.2 Summary of New Information

Based on current Delaware Basin data (Appendix DATA, Attachment A), the regulatory exclusion based on the "future states assumption" continues to be valid; i.e., no drilling for geothermal, archeological, liquid waste disposal, or hydrocarbon storage has occurred. Only editorial changes have been made.

SCR-5.1.1.3.3 Screening Argument

SCR-5.1.1.3.3.1 *Historic, Current, and Near-Future EPs*

No drilling associated with ***Archeology*** or ***Geothermal Energy Production,*** has taken place in the Delaware Basin. Consistent with the future states assumptions in 40 CFR § 194.25(a), such drilling activities have been eliminated from PA calculations on regulatory grounds.

While numerous archeological sites exist at and near the WIPP site, drilling for archeological purposes has not occurred. Archeological investigations have only involved shallow surface disruptions, and do not require deeper investigation by any method, drilling or otherwise. Geothermal energy is not considered to be a potentially exploitable resource because economically attractive geothermal conditions do not exist in the northern Delaware Basin.

Oil and gas production byproducts are disposed of underground in the WIPP region, but such liquid waste disposal does not involve drilling of additional boreholes (see H27); therefore drilling of boreholes for the explicit purpose of disposal has not occurred.

Hydrocarbon Storage takes place in the Delaware Basin, but it involves gas injection through existing boreholes into depleted reservoirs (see, for example, Burton et al. 1993, 66-67). Therefore, drilling of boreholes for the explicit purpose of ***Hydrocarbon Storage*** has not occurred.

Consistent with 40 CFR § 194.33(b)(1), all near-future Human EPs relating to ***Deliberate Drilling Intrusion*** into the WIPP excavation have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.1.3.4 Future Human EPs

Consistent with 40 CFR § 194.33 and the future states assumptions in 40 CFR § 194.25(a), drilling for purposes other than resource recovery (such as WIPP site investigation), and drilling activities that have not taken place in the Delaware Basin over the past 100 years, need not be considered in determining future drilling rates. Thus, drilling associated with archeological investigations***, Geothermal Energy Production, Liquid Waste Disposal, Hydrocarbon Storage***, and ***Deliberate Drilling Intrusion*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2 Excavation Activities

SCR-5.1.2.1 FEP Number: H13
FEP Title: ***Conventional Underground Potash Mining***

SCR-5.1.2.1.1 Screening Decision: UP (HCN)
DP (Future)

As prescribed by 40 CFR § 194.32 (b), the effects of HCN and future ***Conventional Underground Potash Mining*** *are accounted for in PA calculations (see also FEP H37).*

SCR-5.1.2.1.2 Summary of New Information

The name of this FEP has been changed to more specifically identify the mining process. Previously, H13 was generically titled ***Potash Mining***, which broadly included all mining mechanisms and techniques such as conventional, strip or surface, and solution mining. ***Solution Mining*** for potash is addressed in FEP H58, and ***Solution Mining for brine***, ***other Minerals***, or for the ***Creation of Storage Cavities***, is addressed in FEP H59.

SCR-5.1.2.1.3 Screening Argument

Potash is the only known economically viable resource in the vicinity of the WIPP that is recovered by underground mining (see Section 2.3.1). Potash is mined by conventional techniques extensively in the region east of Carlsbad and up to 2.4 km (1.5 mi) from the boundaries of the controlled area of the WIPP. According to existing plans and leases (see Section 2.3.1.1), potash mining is expected to continue in the vicinity of the WIPP in the near future. The DOE assumes that all economically recoverable potash in the vicinity of the disposal system will be extracted in the near future, although there are no economical reserves above the WIPP waste panels (Griswold and Griswold 1999).

In summary, ***Conventional Underground Potash Mining*** is currently taking place and is expected to continue in the vicinity of the WIPP in the near future. The potential effects of HCN, and future ***Conventional Underground Potash Mining*** are accounted for in PA calculations as prescribed by 40 CFR § 194.32 (b), and as further described in the Supplementary

Information to 40 CFR 194, Subpart C, "Compliance Certification and Recertification" and in the Compliance Application Guidance (CAG), Subpart C, § 194.32, Scope of Performance Assessments.

SCR-5.1.2.2 FEP Number: H14
FEP Title: ***Other Resources (mining for)***

SCR-5.1.2.2.1 Screening Decision: SO-C (HCN)
SO-R (Future)

*HCN **Mining for Other Resources** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future **Mining for Other Resources** has been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.2.2.2 Summary of New Information

Since the CCA, no changes in the resources sought via mining have occurred. Therefore, the screening decision for mining for other resources have not changed. Minimal changes to the screening argument have been made for clarity and completeness.

SCR-5.1.2.2.3 Screening Argument

Potash is the only known economically viable resource in the vicinity of the WIPP that is recovered by underground mining. Potash is mined extensively in the region east of Carlsbad and up to 5 km (3.1 mi) from the boundaries of the controlled area. According to existing plans and leases, *potash mining* is expected to continue in the vicinity of the WIPP in the near future. The DOE assumes that all economically recoverable potash in the vicinity of the disposal system will be extracted in the near future. Excavation for resources other than potash and archaeological excavations have taken place or are currently taking place in the Delaware Basin. These activities have not altered the geology of the controlled area significantly, and have been eliminated from PA calculations for the HCN timeframe on the basis of low consequence to the performance of the disposal system.

Potash is the only resource that has been identified within the controlled area in quality similar to that currently mined elsewhere in the Delaware Basin. Future ***M ining for Other Resources*** has been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.3 FEP Number: H15 and H16
FEP Title: ***Tunneling*** (H15)
Construction of Underground Facilities (H16)

SCR-5.1.2.3.1 Screening Decision: SO-R (HCN)
SO-R (Future)

*Consistent with 40 CFR § 194.33(b)(1), near-future human-initiated events and processes relating to **Tunneling** into the WIPP excavation and **construction of underground facilities** have been eliminated from PA calculations on regulatory grounds. Furthermore, consistent with 40 CFR § 194.33(b)(1), future human-initiated EPs relating to **Tunneling** into the WIPP*

*excavation and **Construction of Underground Facilities** have been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.2.3.2 Summary

This FEP has been screened out according to the regulatory criteria in 40 CFR 194.25 (a) (characteristics of the future remain what they are at the time the compliance application). Potash mining, which includes ***Tunneling***, has taken place in the Northern Delaware Basin and potash mining is accounted for in PA calculations. The FEP description, screening argument, and screening decision remain unchanged.

SCR-5.1.2.3.3 Screening Argument

No ***Tunneling*** or ***Construction of Underground Facilities*** (for example, storage, disposal, accommodation [that is, dwellings]) has taken place in the Delaware Basin. Mining for potash occurs (a form of ***Tunneling***), but is addressed specifically in FEP H-13. Gas storage does take place in the Delaware Basin, but it involves injection through boreholes into depleted reservoirs, and not excavation (see, for example, Burton et al. 1993, pp. 66-67).

On April 26, 2001, the DOE formally requested approval the installation of the OMNISita astrophysics experiment in the core storage alcove of the WIPP underground. The purpose of the project is to develop a prototype neutrino detector to test proof of concept principles and measure background cosmic radiation levels within the WIPP underground. EPA approved the request on August 29, 2001. This project does not require additional ***Tunneling*** or excavation beyond the current repository footprint, and therefore does not impact the screening argument for this FEP.

Because ***Tunneling*** and ***Construction of Underground Facilities*** (other than WIPP) have not taken place in the Delaware Basin, and consistent with the future states assumptions in 40 CFR § 194.25(a), such excavation activities have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.4 FEP Number: H17
FEP Title: ***Archeological Excavations***

SCR-5.1.2.4.1 Screening Decision: SO-C (HCN)
SO-R (Future)

*HCN **Archaeological Excavations** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future **Archaeological Excavations** into the disposal system have been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.2.4.2 Summary of New Information

The original description for this FEP and screening argument remain valid; only editorial changes have been made.

SCR-5.1.2.4.3 Screening Argument

Archeological Excavations have occurred at or near the WIPP, but involved only minor surface disturbances. These ***Archaeological Excavations*** may continue into the foreseeable future as other archeological sites are discovered. These activities have not altered the geology of the controlled area significantly, and have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system for the HCN timeframe.

Also, consistent with 40 CFR § 194.32(a), which limits the scope of consideration of future human actions to mining and drilling, future ***Archaeological Excavations*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.5 FEP Number: H18
FEP Title: ***Deliberate Mining Intrusion***

SCR-5.1.2.5.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Consistent with 40 CFR § 194.33(b)(1), near-future human-initiated EPs relating to ***Deliberate Mining Intrusion*** *into the WIPP excavation have been eliminated from PA calculations on regulatory grounds. Furthermore, consistent with 40 CFR § 194.33(b)(1), future human-initiated EPs relating to* ***Deliberate Mining Intrusion*** *into the WIPP excavation have been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.2.5.2 Summary of New Information

No changes have been to this FEP.

SCR-5.1.2.5.3 Screening Argument

Consistent with 40 CFR § 194.33(b)(1), all future Human related EPs relating to ***Deliberate Mining Intrusion*** into the WIPP excavation have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.3 Subsurface Explosions

SCR-5.1.3.1 FEPs Number: H19
FEP Title: ***Explosions for Resource Recovery***

SCR-5.1.3.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Historical underground ***Explosions for Resource Recovery*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future underground explosions for resource recovery have been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.3.1.2 Summary of New Information

The original screening argument and decision for this FEP remain valid. Additional text has been added to describe the past use of explosives in potash mining in the Delaware Basin. This additional information is provided for completeness, and does not affect the screening argument or decision.

SCR-5.1.3.1.3 Screening Argument

This section discusses subsurface explosions associated with resource recovery that may result in pathways for fluid flow between hydraulically conductive horizons. The potential effects of explosions on the hydrological characteristics of the disposal system are discussed in H39.

SCR-5.1.3.1.4 Historical, Current, and Near-Future Human EPs

Neither small-scale nor regional-scale explosive techniques to enhance formation hydraulic conductivity form a part of current mainstream oil- and gas-production technology. Instead, controlled perforating and hydrofracturing are used to improve the performance of oil and gas boreholes in the Delaware Basin. However, small-scale explosions have been used in the past to fracture oil- and natural-gas-bearing units to enhance resource recovery. The size of explosion used to fracture an oil- or gas-bearing unit is limited by the need to contain the damage within the unit being exploited. In the area surrounding the WIPP, the stratigraphic units with oil and gas resources are too deep for explosions to affect the performance of the disposal system. Thus, the effects of ***Explosions for Resource Recovery*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Potash mining is currently taking place and is expected to continue in the vicinity of the WIPP in the near future. Potash is mined extensively in the region east of Carlsbad and up to 2.4 km (1.3 mi) from the boundaries of the controlled area. In earlier years conventional drill, blast, load, and rail-haulage methods were used. Today, continuous miners similar to those used in coal-mining have been adapted to fit the potash-salt formations. Hence, drilling and blasting technology is not used in the present day potash mines. Thus, the effects of ***Explosions for Resource Recovery*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Consistent with 40 CFR § 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, future underground ***explosions for resource recovery*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.3.2 FEPs Number: H20
FEP Title: ***Underground Nuclear Device Testing***

SCR-5.1.3.2.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Historical ***Underground Nuclear Device Testing*** *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future* ***Underground Nuclear Device Testing*** *has been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.3.2.2 Summary of New Information

No new information has been identified related to this FEP. No changes have been made.

SCR-5.1.3.2.3 Screening Argument

SCR-5.1.3.2.3.1 *Historical, Current, and Near-Future Human EPs*

The Delaware Basin has been used for an isolated nuclear test. This test, Project Gnome (Rawson et al. 1965), took place in 1961 at a location approximately 13 km (8 mi) southwest of the WIPP waste disposal region. Project Gnome was decommissioned in 1979.

The primary objective of Project Gnome was to study the effects of an underground nuclear explosion in salt. The Gnome experiment involved the detonation of a 3.1 kiloton nuclear device at a depth of 360 m (1,190 ft) in the bedded salt of the Salado. The explosion created an approximately spherical cavity of about 27,000 m^3 (950,000 ft^3) and caused surface displacements in a radius of 360 m (1,180 ft). No earth tremors perceptible to humans were reported at distances over 40 km (25 mi) from the explosion. A zone of increased permeability was observed to extend at least 46 m (150 ft) laterally from and 105 m (344 ft) above the point of the explosion. The test had no significant effects on the geological characteristics of the WIPP disposal system. Thus, historical ***Underground Nuclear Device Testing*** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. There are no existing plans for ***Underground Nuclear Device Testing*** in the vicinity of the WIPP in the near future.

SCR-5.1.3.2.3.2 *Future Human EPs*

The criterion in 40 CFR § 194.32(a), relating to the scope of PAs, limits the consideration of future human actions to mining and drilling. Therefore, future ***Underground Nuclear Device Testing*** has been eliminated from PA calculations on regulatory grounds.

SCR-5.2 Subsurface Hydrological and Geochemical Events and Processes

SCR-5.2.1 Borehole Fluid Flow

SCR-5.2.1.1 FEP Number: H21
FEP Title: ***Drilling Fluid Flow***

SCR-5.2.1.1.1 Screening Decision: SO-C (HCN)
DP (Future)

Drilling Fluid Flow *associated with historical, current, near-future, and future boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The possibility of a future deep borehole penetrating a waste panel, such that drilling-induced flow results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations. The possibility of a deep borehole penetrating both the waste disposal region and a Castile brine reservoir is accounted for in PA calculations.*

SCR-5.2.1.1.2 Summary of New Information

No new information is available for this FEP. However, the screening argument has been revised for clarity and editorial purposes.

SCR-5.2.1.1.3 Screening Argument

Borehole circulation fluid could be lost to thief zones encountered during drilling, or fluid could flow from pressurized zones through the borehole to the land surface (blowout) or to a thief zone. Such drilling-related EPs could influence groundwater flow and, potentially, radionuclide transport in the affected units. Future drilling within the controlled area could result in direct releases of radionuclides to the land surface or transport of radionuclides between hydraulically conductive units.

Movement of brine from a pressurized zone, through a borehole into potential thief zones such as the Salado interbeds or the Culebra, could result in geochemical changes and altered radionuclide migration rates in these units.

SCR-5.2.1.1.3.1 *Historical, Current, and Near-Future Human EPs*

Drilling *Fluid Flow* is a short-term event that can result in the flow of pressurized fluid from one geologic stratum to another. However, long-term flow through abandoned boreholes would have a greater hydrological impact in the Culebra than a short-term event like drilling-induced flow outside the controlled area. Wallace (1996a) analyzed the potential effects of flow through abandoned boreholes in the future within the controlled area, and concluded that interconnections between the Culebra and deep units could be eliminated from PA calculations on the basis of low consequence. Thus, the HCN of ***Drilling Fluid Flow*** associated with boreholes outside the controlled area has been screened out on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H25 through H36, drilling associated with **Water Resources Exploration, Groundwater Exploitation, Potash Exploration, Oil and Gas Exploration, Oil and Gas Exploitation, Enhanced Oil and Gas Recovery,** and **Drilling to Explore Other Resources** has taken place or is currently taking place outside the controlled area in the Delaware Basin. These drilling activities are expected to continue in the vicinity of the WIPP in the near future.

SCR-5.2.1.1.3.2 *Future Human EPs*

For the future, drill holes may intersect the waste disposal region and their effects could be more profound. Thus, the possibility of a future borehole penetrating a waste panel, so that ***Drilling Fluid Flow*** and, potentially, ***Blowout***, results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations.

The units intersected by the borehole may provide sources for fluid flow (brine, oil, or gas) to the waste panel during drilling. In the vicinity of the WIPP, the Castile that underlies the Salado contains isolated volumes of brine at fluid pressures greater than hydrostatic. A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. The possibility of a deep borehole penetrating both a waste panel and a brine reservoir is accounted for in PA calculations.

A future borehole that is drilled through a disposal room wall, but does not intersect waste, could penetrate a brine reservoir underlying the waste disposal region. Such an event would depressurize the brine reservoir to some extent, and thus would affect the consequences of any subsequent intersections of the reservoir. The possibility for a borehole to depressurize a brine reservoir underlying the waste disposal region is accounted for in PA calculations.

Penetration of an underpressurized unit underlying the Salado could result in flow and radionuclide transport from the waste panel to the underlying unit during drilling, although drillers would minimize such fluid loss to a thief zone through the injection of materials to reduce permeability or through the use of casing and cementing. Also, the permeabilities of formations underlying the Salado are less than the permeability of the Culebra (Wallace 1996a). Thus, the consequences associated with radionuclide transport to an underpressurized unit below the waste panels during drilling will be less significant, in terms of disposal system performance, than the consequences associated with radionuclide transport to the land surface or to the Culebra during drilling. Through this comparison, drilling events that result in penetration of underpressurized units below the waste-disposal region have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

In evaluating the potential consequences of **Drilling Fluid Loss** to a waste panel, two types of drilling events need to be considered – those that intercept pressurized fluid in underlying formations such as the Castile (defined in CCA Section 6.3.2.2 as E1 events), and those that do not (E2 events). A possible hydrological effect would be to make a greater volume of brine available for gas generation processes and thereby increase gas volumes at particular times in the future. As discussed in CCA Section 6.4.12.6, of boreholes that intersect a waste panel in the future, 8 percent are assumed to be E1 events and 92 percent are E2 events. For either type of drilling event, on the basis of current drilling practices, the driller is assumed to pass through the

repository rapidly. Relatively small amounts of drilling fluid loss may not be noticed and may not give rise to concern. Larger fluid losses would lead to the driller injecting materials to reduce permeability, or to the borehole being cased and cemented, to limit the loss of drilling fluid.

For boreholes that intersect pressurized brine reservoirs, the volume of fluid available to flow up a borehole will be significantly greater than the volume of any drilling fluid that could be lost. This greater volume of brine is accounted for in PA calculations, and is allowed to enter the disposal room (see CCA Section 6.4.7). Thus, the effects of **Drilling Fluid Loss** will be small by comparison to the potential flow of brine from pressurized brine reservoirs. Therefore, the effects of drilling fluid loss for E1 drilling events have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

For boreholes that do not intersect pressurized brine reservoirs the treatment of the disposal room implicitly accounts for the potential for greater gas generation resulting from **Drilling Fluid Loss**. Thus, the hydrological effects of drilling fluid loss for E2 drilling events are accounted for in PA calculations within the conceptual model of the disposal room for drilling intrusions.

SCR-5.2.1.2 FEP Number: H22
FEP Title: ***Drilling Fluid Loss***

SCR-5.2.1.2.1 Screening Decision: SO-C (HCN)
DP (Future)

Drilling Fluid Loss *associated with HCN, and future boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The possibility of a future* **Drilling Fluid Loss** *into waste panels is accounted for in PA calculations.*

SCR-5.2.1.2.2 Summary of New Information

No new information is available for this FEP. However, the screening argument has been revised for clarity and editorial purposes.

SCR-5.2.1.2.3 Screening Argument

Drilling Fluid lLoss is a short-term event that can result in the flow of pressurized fluid from one geologic stratum to another. Large fluid losses would lead a driller to inject materials to reduce permeability, or it would lead to the borehole being cased and cemented to limit the loss of drilling fluid. Assuming such operations are successful, **Drilling Fluid Loss** in the near future outside the controlled area will not significantly affect the hydrology of the disposal system. Thus, **Drilling Fluid Loss** associated with historical, current, and near-future boreholes has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The consequences of **Drilling Fluid Loss** into waste panels in the future is accounted for in PA calculations for E1 and E2 events.

SCR-5.2.1.2.3.1 *Historical, Current, and Near-Future Human EPs*

Drilling Fluid Flow will not affect hydraulic conditions in the disposal system significantly unless there is substantial **Drilling Fluid Loss** to a thief zone, such as the Culebra. Typically, zones into which significant borehole circulation fluid is lost are isolated through injection of materials to reduce permeability or through casing and cementing programs. Assuming such operations are successful, **Drilling Fluid Loss** in the near future outside the controlled area will not affect the hydrology of the disposal system significantly and be of no consequence.

SCR-5.2.1.2.3.2 *Future Human EPs*

The consequences of drilling within the controlled area in the future will primarily depend on the location of the borehole. Potentially, future deep drilling could penetrate the waste disposal region. Hydraulic and geochemical conditions in the waste panel could be affected as a result of **Drilling Fluid Loss** to the panel.

Penetration of an under pressurized unit underlying the Salado could result in flow and radionuclide transport from the waste panel to the underlying unit during drilling, although drillers would minimize such fluid loss to a thief zone through the injection of materials to reduce permeability or through the use of casing and cementing. Also, the permeabilities of formations underlying the Salado are less than the permeability of the Culebra (Wallace 1996a). Thus, the consequences associated with radionuclide transport to an underpressurized unit below the waste panels during drilling will be less significant, in terms of disposal system performance, than the consequences associated with radionuclide transport to the land surface or to the Culebra during drilling. Through this comparison, drilling events that result in penetration of under pressurized units below the waste-disposal region have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

For boreholes that do not intersect pressurized brine reservoirs (but do penetrate the waste-disposal region) the treatment of the disposal room implicitly accounts for the potential for greater gas generation resulting from drilling fluid loss. Thus, the hydrological effects of **Drilling Fluid Loss** for E2 drilling events are accounted for in PA calculations within the conceptual model of the disposal room for drilling intrusions.

SCR-5.2.1.3 FEP Number: H23
FEP Title: ***Blowouts***

SCR-5.2.1.3.1 Screening Decision: SO-C (HCN)
DP (Future)

Blowouts *associated with HCN, and future boreholes that do not intersect the waste disposal region, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The possibility of a future deep borehole penetrating a waste panel, such that drilling-induced flow results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations. The possibility of a deep borehole penetrating both the waste disposal region and a Castile brine reservoir is accounted for in PA calculations.*

SCR-5.2.1.3.2 Summary of New Information

No new information is available for this FEP. However, the screening argument has been revised for clarity and editorial purposes.

SCR-5.2.1.3.3 Screening Argument

Blowouts are short-term events that can result in the flow of pressurized fluid from one geologic stratum to another. For the near future, a ***Blowout*** may occur in the vicinity of the WIPP but is not likely to affect the disposal system because of the distance from the well to the waste panels, assuming that passive and active institutional controls are in place which restrict borehole installation to outside the WIPP boundary. ***Blowouts*** associated with HCN, and future boreholes that do not intersect the waste disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. For the future, the drill holes may intersect the waste disposal region and these effects could be more profound. Thus, ***Blowouts*** are included in the assessment of future activities.

The consequences of ***Blowout*** in the future are accounted for in PA calculations.

Fluid could flow from pressurized zones through the borehole to the land surface (***Blowout***) or to a thief zone. Such drilling-related EPs could influence groundwater flow and, potentially, radionuclide transport in the affected units. Movement of brine from a pressurized zone, through a borehole, into potential thief zones such as the Salado interbeds or the Culebra, could result in geochemical changes and altered radionuclide migration rates in these units.

SCR-5.2.1.3.3.1 *Historical, Current, and Near-Future Human EPs*

Drilling associated with ***Water Resources Exploration, Groundwater Exploitation, Potash Exploration, Oil and Gas Exploration, Oil and Gas Exploitation, Enhanced Oil and Gas Recovery,*** and ***Drilling to Explore Other Resources*** has taken place or is currently taking place outside the controlled area in the Delaware Basin. These drilling activities are expected to continue in the vicinity of the WIPP in the near future.

Naturally occurring brine and gas pockets have been encountered during drilling in the Delaware Basin. Brine pockets have been intersected in the Castile (as discussed in Section 2.2.1.3) and in the Salado above the WIPP horizon (Section 2.2.1.2.2). Gas ***Blowouts*** have occurred during drilling in the Salado. Usually, such events result in brief interruptions in drilling while the intersected fluid pocket is allowed to depressurize through flow to the surface (for a period lasting from a few hours to a few days). Drilling then restarts with an increased drilling mud weight. Under these conditions, ***Blowouts*** in the near future will cause isolated hydraulic disturbances, but will not affect the hydrology of the disposal system significantly.

Potentially, the most significant disturbance to the disposal system could occur if an uncontrolled ***Blowout*** during drilling resulted in substantial flow through the borehole from a pressurized zone to a thief zone. For example, if a borehole penetrates a brine reservoir in the Castile, brine could flow through the borehole to the Culebra, and, as a result, could affect hydraulic conditions in the Culebra. The potential effects of such an event can be compared to the effects of long-term fluid flow from deep overpressurized units to the Culebra through abandoned boreholes. Wallace

(1996a) analyzed the potential effects of flow through abandoned boreholes in the future within the controlled area and concluded that interconnections between the Culebra and deep units could be eliminated from PA calculations on the basis of low consequence. Long-term flow through abandoned boreholes would have a greater hydrological impact in the Culebra than short-term drilling-induced flow outside the controlled area. Thus, the effects of fluid flow during drilling in the near future have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

In summary, ***Blowouts*** associated with historical, current, and near-future boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.3.3.2 *Future Human EPs - Boreholes that Intersect the Waste Disposal Region*

The consequences of drilling within the controlled area in the future will primarily depend on the location of the borehole. Potentially, future deep drilling could penetrate the waste disposal region. If the borehole intersects the waste in the disposal rooms, radionuclides could be transported as a result of ***Drilling Fluid Flow***: releases to the accessible environment may occur as material entrained in the circulating drilling fluid is brought to the surface. Also, during drilling, contaminated brine may flow up the borehole and reach the surface, depending on fluid pressure within the waste disposal panels; ***Blowout*** conditions could prevail if the waste panel were sufficiently pressurized at the time of intrusion.

SCR-5.2.1.3.3.3 *Hydraulic Effects of Drilling-Induced Flow*

The possibility of a future borehole penetrating a waste panel, so that ***Drilling Fluid Flow*** and, potentially, ***Blowout***, results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations.

The units intersected by the borehole may provide sources for fluid flow (brine, oil, or gas) to the waste panel during drilling. In the vicinity of the WIPP, the Castile that underlies the Salado contains isolated volumes of brine at fluid pressures greater than hydrostatic. A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. The possibility of a deep borehole penetrating both a waste panel and a brine reservoir is accounted for in PA calculations.

Future boreholes could affect the hydraulic conditions in the disposal system. Intersection of pockets of pressurized gas and brine would likely result in short-term, isolated hydraulic disturbances, and will not affect the hydrology of the disposal system significantly. Potentially, the most significant hydraulic disturbance to the disposal system could occur if an uncontrolled ***Blowout*** during drilling resulted in substantial flow through the borehole from a pressurized zone to a thief zone. For example, if a borehole penetrates a brine reservoir in the Castile, brine could flow through the borehole to the Culebra, and, as a result, could affect hydraulic conditions in the Culebra. The potential effects of such an event can be compared to the effects of long-term fluid flow from deep overpressurized units to the Culebra through abandoned boreholes. Wallace (1996a) analyzed the potential effects of such interconnections in the future within the controlled

area concluded that flow through abandoned boreholes between the Culebra and deep units could be eliminated from PA calculations on the basis of low consequence.

SCR-5.2.1.4 FEP Number: H24
FEP Title: ***Drilling Induced Geochemical Changes***

SCR-5.2.1.4.1 Screening Decision: UP (HCN)
DP (Future)

Drilling Induced Geochemical Changes *that occur within the controlled area as a result of HCN, and future drilling-induced flow are accounted for in PA calculations.*

SCR-5.2.1.4.2 Summary of New Information

No new information is available for this FEP. However, the screening argument has been revised for clarity and editorial purposes.

SCR-5.2.1.4.3 Screening Argument

Borehole circulation fluid could be lost to thief zones encountered during drilling, or fluid could flow from pressurized zones through the borehole to the land surface (***Blowout***) or to a thief zone. Such drilling-related EPs could influence groundwater flow and, potentially, radionuclide transport in the affected units. Future drilling within the controlled area could result in direct releases of radionuclides to the land surface or transport of radionuclides between hydraulically conductive units.

Movement of brine from a pressurized zone, through a borehole, into potential thief zones such as the Salado interbeds or the Culebra, could result in geochemical changes and altered radionuclide migration rates in these units.

SCR-5.2.1.4.3.1 *Historical, Current, and Near-Future Human EPs*

Drilling associated with resource exploration, exploitation, and recovery has taken place or is currently taking place outside the controlled area in the Delaware Basin. These drilling activities are expected to continue in the vicinity of the WIPP in the near future. Chemical changes induced by such drilling are discussed below.

SCR-5.2.1.4.3.2 *Geochemical effects of drilling-induced flow*

Radionuclide migration rates are governed by the coupled effects of hydrological and geochemical processes (see discussions in FEPs W77 through W100). Human EPs outside the controlled area could affect the geochemistry of units within the controlled area if they occur sufficiently close to the edge of the controlled area. Movement of brine from a pressurized reservoir in the Castile through a borehole into potential thief zones, such as the Salado interbeds or the Culebra, could cause ***Drilling-Induced Geochemical Changes*** resulting in altered radionuclide migration rates in these units through their effects on colloid transport and sorption (colloid transport may enhance radionuclide migration, while radionuclide migration may be retarded by sorption).

The treatment of colloids in PA calculations is described in Sections 6.4.3.6 and 6.4.6.2.2. The repository and its contents provide the main source of colloids in the disposal system. By comparison, Castile brines have relatively low total colloid concentrations. Therefore, changes in colloid transport in units within the controlled area as a result of HCN drilling-induced flow have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Sorption within the Culebra is accounted for in PA calculations as discussed in Section 6.4.6.2. The sorption model comprises an equilibrium, sorption isotherm approximation, employing distribution coefficients (Kds) applicable to dolomite in the Culebra (Appendix PA, Attachment MASS, Section MASS.15.2; and PAVT). The CDFs of distribution coefficients used are derived from a suite of experimental studies that include measurements of K_ds for actinides in a range of chemical systems including Culebra and Castile brines, Culebra brines, and Salado brines. Therefore, any changes in sorption geochemistry in the Culebra within the controlled area as a result of HCN drilling-induced flow are accounted for in PA calculations.

Sorption within the Dewey Lake is accounted for in PA calculations, as discussed in Section 6.4.6.6. It is assumed that the sorptive capacity of the Dewey Lake is sufficiently large to prevent any radionuclides that enter the Dewey Lake from being released over 10,000 years (Wallace et al. 1995). Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The effects of changes in sorption in the Dewey Lake and other units within the controlled area as a result of HCN drilling-induced flow have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.4.3.3 *Future Human EPs - Boreholes that Intersect the Waste Disposal Region*

The consequences of drilling within the controlled area in the future will primarily depend on the location of the borehole. Potentially, future deep drilling could penetrate the waste disposal region. If the borehole intersects the waste in the disposal rooms, radionuclides could be transported as a result of **Drilling *Fluid Flow*** and geochemical conditions in the waste panel could be affected as a result of ***Drilling-Induced Geochemical Changes.***

SCR-5.2.1.4.3.4 *Geochemical Effects of Drilling-Induced Flow*

Drilling Fluid Loss to a waste panel could modify the chemistry of disposal room brines in a manner that would affect the solubility of radionuclides and the source term available for subsequent transport from the disposal room. The majority of drilling fluids used are likely to be locally derived, and their bulk chemistry will be similar to fluids currently present in the disposal system. In addition, the presence of the MgO chemical conditioner in the disposal rooms will buffer the chemistry across a range of fluid compositions, as discussed in detail in Appendix PA, Attachment SOTERM. Furthermore, for E1 drilling events, the volume of Castile brine that flows into the disposal room will be greater than that of any drilling fluids; Castile brine chemistry is accounted for in PA calculations. Thus, the effects on radionuclide solubility of ***Drilling Fluid Loss*** to the disposal room have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Movement of brine from a pressurized reservoir in the Castile through a borehole into thief zones, such as the Salado interbeds or the Culebra, could result in geochemical changes in the receiving units, and thus alter radionuclide migration rates in these units through their effects on colloid transport and sorption.

The repository and its contents provide the main source of colloids in the disposal system. Thus, colloid transport in the Culebra within the controlled area as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region are accounted for in PA calculations, as described in Sections 6.4.3.6 and 6.4.6.2.1. The Culebra is the most transmissive unit in the disposal system and it is the most likely unit through which significant radionuclide transport could occur. Therefore, colloid transport in units other than the Culebra, as a result of ***Drilling Fluid Loss*** associated with boreholes that intersect the waste disposal region, has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21, H22, and H23, sorption within the Culebra is accounted for in PA calculations. The sorption model used incorporates the effects of changes in sorption in the Culebra as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region.

Consistent with the screening discussion in FEPs H21, H22, and H23, the effects of changes in sorption in the Dewey Lake inside the controlled area as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-5.2.1.4.3.5 *Future Human EPs - Boreholes That Do Not Intersect the Waste Disposal Region*

Future boreholes that do not intersect the waste disposal region could nevertheless encounter contaminated material by intersecting a region into which radionuclides have migrated from the disposal panels, or could affect hydrogeological conditions within the disposal system. Consistent with the containment requirements in 40 CFR § 191.13(a), PAs need not evaluate the effects of the intersection of contaminated material outside the controlled area.

Movement of brine from a pressurized reservoir in the Castile, through a borehole, into thief zones such as the Salado interbeds or the Culebra, could result in ***Drilling-Induced Geochemical Changes*** and altered radionuclide migration rates in these units.

SCR-5.2.1.4.3.6 *Geochemical Effects of Drilling-Induced Flow*

Movement of brine from a pressurized reservoir in the Castile through a borehole into thief zones, such as the Salado interbeds or the Culebra, could cause geochemical changes resulting in altered radionuclide migration rates in these units through their effects on colloid transport and sorption.

The contents of the waste disposal panels provide the main source of colloids in the disposal system. Thus, consistent with the discussion in FEPs H21, H22, and H23, colloid transport as a result of drilling-induced flow associated with future boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21, H22, and H23, sorption within the Culebra is accounted for in PA calculations. The sorption model accounts for the effects of changes in sorption in the Culebra as a result of drilling-induced flow associated with boreholes that do not intersect the waste disposal region.

Consistent with the screening discussion in FEPs H21, H22, and H23, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of drilling-induced flow associated with boreholes that do not intersect the waste disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

In summary, the effects of ***Drilling-Induced Geochemical Changes*** that occur within the controlled area as a result of historical, current, near-future, and future drilling-induced flow are accounted for in PA calculations. Those that occur outside the controlled area have been eliminated from PA calculations.

SCR-5.2.1.5 FEP Number(s): H25 and H26
FEP Title(s): ***Oil and Gas Extraction***
Groundwater Extraction

SCR-5.2.1.5.1 Screening Decision: SO-C (HCN)
SO-R (Future)

HCN ***Groundwater, Oil,*** and ***Gas Extraction*** *outside the controlled area has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.* ***Groundwater, Oil,*** and ***Gas Extraction*** *through future boreholes has been eliminated from PA calculations on regulatory grounds.*

SCR-5.2.1.5.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. Delaware Basin monitoring information (see Appendix DATA, Attachment A) does not indicate any changes in oil, gas, or water extraction that would require modification to these screening arguments or decisions. No changes have been made.

SCR-5.2.1.5.2.1 *Screening Argument*

The extraction of fluid could alter fluid-flow patterns in the target horizons, or in overlying units as a result of a failed borehole casing. Also, the removal of confined fluid from oil- or gas-bearing units can cause compaction in some geologic settings, potentially resulting in subvertical fracturing and surface subsidence.

SCR-5.2.1.5.2.2 *Historical, Current, and Near-Future Human EPs*

As discussed in FEPs H25 through H36, water, oil, and gas production are the only activities involving fluid extraction through boreholes that have taken place or are currently taking place in the vicinity of the WIPP. These activities are expected to continue in the vicinity of the WIPP in the near future.

Groundwater Extraction outside the controlled area from formations above the Salado could affect groundwater flow. The Dewey Lake contains a productive zone of saturation south of the WIPP site. Several wells operated by the J.C. Mills Ranch south of the WIPP produce water from the Dewey Lake to supply livestock (see Section 2.2.1.4.2.1). Also, water has been extracted from the Culebra at the Engle Well approximately 9.66 km (6 mi) south of the controlled area to provide water for livestock. No water wells in other areas in the vicinity of the WIPP are expected to be drilled in the near future because of the high concentrations of total dissolved solids in the groundwater.

If contaminated water intersects a well while it is producing, then contaminants could be pumped to the surface. Consistent with the containment requirements in 40 CFR § 191.13(a), PAs need not evaluate radiation doses that might result from such an event. However, compliance assessments must include any such events in dose calculations for evaluating compliance with the individual protection requirements in 40 CFR § 191.15. As discussed in Chapter 8.0, under undisturbed conditions, there are no calculated radionuclide releases to units containing producing wells.

Pumping from wells at the J.C. Mills Ranch may have resulted in reductions in hydraulic head in the Dewey Lake within southern regions of the controlled area, leading to increased hydraulic head gradients. However, these changes in the groundwater flow conditions in the Dewey Lake will have no significant effects on the performance of the disposal system, primarily because of the sorptive capacity of the Dewey Lake (see Section 6.4.6.6). Retardation of any radionuclides that enter the Dewey Lake will be such that no radionuclides will migrate through the Dewey Lake to the accessible environment within the 10,000-year regulatory period.

The effects of ***Groundwater Extraction*** from the Culebra from a well 9.66 km (6 mi) south of the controlled area have been evaluated by Wallace (1996b), using an analytical solution for Darcian fluid flow in a continuous porous medium. Wallace (1996b) showed that such a well pumping at about 0.5 g (1.9 L) per minute for 10,000 years will induce a hydraulic head gradient across the controlled area of about 4×10^{-5}. The hydraulic head gradient across the controlled area currently ranges from between 0.001 to 0.007. Therefore, pumping from the Engle Well will have only minor effects on the hydraulic head gradient within the controlled area even if pumping were to continue for 10,000 years. Thus, the effects of HCN ***Groundwater Extraction*** outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Oil and Gas Extraction outside the controlled area could affect the hydrology of the disposal system. However, the horizons that act as oil and gas reservoirs are sufficiently below the repository for changes in fluid-flow patterns to be of low consequence, unless there is fluid leakage through a failed borehole casing. Also, ***Oil and Gas Extraction*** horizons in the

Delaware Basin are well-lithified rigid strata, so oil and gas extraction is not likely to result in compaction and subsidence (Brausch et al. 1982, pp. 52, 61). Furthermore, the plasticity of the salt formations in the Delaware Basin will limit the extent of any fracturing caused by compaction of underlying units. Thus, neither the extraction of gas from reservoirs in the Morrow Formation (some 4,200 m (14,000 ft) below the surface), nor extraction of oil from the shallower units within the Delaware Mountain Group (about 1,250 to 2,450 m (about 4,000 to 8,000 ft) below the surface) will lead to compaction and subsidence. In summary, historical, current, and near-future ***Oil and Gas Extraction*** outside the controlled area has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.5.2.3 *Future Human EPs*

Consistent with 40 CFR § 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, ***Groundwater Extraction*** and ***Oil and Gas Extraction*** through future boreholes have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.6 FEP Number(s): H27, H28 and H29
FEP Title(s): ***Liquid Waste Disposal*** (H27)
Enhanced Oil and Gas Production (H28)
Hydrocarbon Storage (H29)

SCR-5.2.1.6.1 Screening Decision: SO-C (HCN)
SO-C (Future)

*The hydrological effects of HCN fluid injection (**Liquid Waste Disposal, Enhanced Oil** and **Gas Production,** and **Hydrocarbon Storage**) through boreholes outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Geochemical changes that occur inside the controlled area as a result of fluid flow associated with HCN fluid injection are accounted for in PA calculations. **Liquid Waste Disposal, Enhanced Oil and Gas Production,** and **Hydrocarbon Storage** in the future have been eliminated from PA calculations based on low consequence.*

SCR-5.2.1.6.2 Summary of New Information

Fluid injection modeling conducted since the CCA has demonstrated that injection of fluids will not have a significant effect upon the WIPP's ability to contain radioactive materials (Stoelzel and Swift 1997). The results of this modeling justify changing the screening decision for these FEPs from SO-R to SO-C for the future timeframe. Neither hydraulic fracturing nor waterflooding conducted in wells outside the controlled area have the potential to affect the disposal system in any significant way. The screening argument for this FEP has been updated to include references and conclusions from Steolzel and Swift. The hydrological effects of HCN, and future ***Hydrocarbon Storage*** (H29) have been screened out on the basis of low consequence. Only one hydrocarbon (gas) storage facility is operating in the Delaware Basin, and it is too far away to have any effect on groundwater at the WIPP under any circumstances. No changes have been made to the FEP description, although the screening decision for the future time period has

been changed from SO-R to SO-C; the screening argument has been modified slightly to include citation of a recent survey.

SCR-5.2.1.6.3 Screening Argument

The injection of fluids could alter fluid-flow patterns in the target horizons or, if there is accidental leakage through a borehole casing in any other intersected hydraulically conductive zone. Injection of fluids through a leaking borehole could also result in geochemical changes and altered radionuclide migration rates in the thief units.

SCR-5.2.1.6.3.1 *Historical, Current, and Near-Future Human EPs*

The only historical and current activities involving fluid injection through boreholes in the Delaware Basin are ***Enhanced Oil and Gas Production*** (waterflooding or carbon dioxide (CO_2) injection), ***Hydrocarbon Storage*** (gas reinjection), and ***Liquid Waste Disposal*** (by-products from oil and gas production). These fluid injection activities are expected to continue in the vicinity of the WIPP in the near future.

Hydraulic fracturing of oil- or gas-bearing units is currently used to improve the performance of hydrocarbon reservoirs in the Delaware Basin. Fracturing is induced during a short period of high-pressure fluid injection, resulting in increased hydraulic conductivity near the borehole. Normally, this controlled fracturing is confined to the pay zone and is unlikely to affect overlying strata.

Secondary production techniques, such as waterflooding, that are used to maintain reservoir pressure and displace oil are currently employed in hydrocarbon reservoirs in the Delaware Basin (Brausch et al. 1982, pp. 29-30). Tertiary recovery techniques, such as ***Carbon Dioxide*** miscible flooding, have been implemented with limited success in the Delaware Basin, but CO_2 miscible flooding is not an attractive recovery method for reservoirs near WIPP (Melzer 2003). Even if ***Carbon Dioxide*** flooding were to occur the effects (if any) would be very similar to those associated with waterflooding.

Reinjection of gas for storage currently takes place at one location in the Delaware Basin in a depleted gas field in the Morrow Formation at the Washington Ranch near Carlsbad Caverns (Burton et al. 1993, pp. 66-67; CCA Appendix DATA, Attachment A). This field is too far from the WIPP site to have any effect on WIPP groundwaters under any circumstances. Disposal of liquid by-products from oil and gas production involves injection of fluid into depleted reservoirs. Such fluid injection techniques result in repressurization of the depleted target reservoir and mitigates any effects of fluid withdrawal.

The most significant effects of fluid injection would arise from substantial and uncontrolled fluid leakage through a failed borehole casing. The highly saline environment of some units can promote rapid corrosion of well casings and may result in fluid loss from boreholes.

SCR-5.2.1.6.3.2 *Hydraulic Effects of Leakage through Injection Boreholes*

The Vacuum Field (located in the Capitan Reef, some 30 km [20 mi] northeast of the WIPP site) and the Rhodes-Yates Field (located in the back reef of the Capitan, some 70 km (45 mi)

southeast of the WIPP site) have been waterflooded for 40 years with confirmed leaking wells, which have resulted in brine entering the Salado and other formations above the Salado (see, for example, Silva 1994, pp. 67-68). Currently, saltwater disposal takes place in the vicinity of the WIPP into formations below the Castile. However, leakages from saltwater disposal wells or waterflood wells in the near future in the vicinity of the WIPP are unlikely to occur because of the following:

- There are significant differences between the geology and lithology in the vicinity of the disposal system and that of the Vacuum and Rhodes-Yates Fields. The WIPP is located in the Delaware Basin in a fore-reef environment, where a thick zone of anhydrite and halite (the Castile) exists. In the vicinity of the WIPP, oil is produced from the Brushy Canyon Formation at depths greater than 2100 m (7,000 ft). By contrast, the Castile is not present at either the Vacuum or the Rhodes-Yates Field, which lie outside the Delaware Basin. Oil production at the Vacuum Field is from the San Andres and Grayburg Formations at depths of approximately 1400 m (4,500 ft), and oil production at the Rhodes-Yates Field is from the Yates and Seven Rivers Formations at depths of approximately 900 m (3,000 ft). Waterflooding at the Rhodes-Yates Field involves injection into a zone only 60 m (200 ft) below the Salado. There are more potential thief zones below the Salado near the WIPP than at the Rhodes-Yates or Vacuum Fields; the Salado in the vicinity of the WIPP is therefore less likely to receive any fluid that leaks from an injection borehole. Additionally, the oil pools in the vicinity of the WIPP are characterized by channel sands with thin net pay zones, low permeabilities, high irreducible water saturations, and high residual oil saturations. Therefore, waterflooding of oil fields in the vicinity of the WIPP on the scale of that undertaken in the Vacuum or the Rhodes-Yates Field is unlikely.

- New Mexico state regulations require the emplacement of a salt isolation casing string for all wells drilled in the potash enclave, which includes the WIPP area, to reduce the possibility of petroleum wells leaking into the Salado. Also, injection pressures are not allowed to exceed the pressure at which the rocks fracture. The injection pressure gradient must be kept below 4.5×10^3 pascals per meter above hydrostatic if fracture pressures are unknown. Such controls on fluid injection pressures limit the potential magnitude of any leakages from injection boreholes.

- Recent improvements in well completion practices and reservoir operations management have reduced the occurrences of leakages from injection wells. For example, injection pressures during waterflooding are typically kept below about 23×10^3 pascals per meter to avoid fracture initiation. Also, wells are currently completed using cemented and perforated casing, rather than the open-hole completions used in the early Rhodes-Yates wells. A recent report (Hall et al. 2003) concludes that injection well operations near WIPP have a very low failure rate, and that failures, although rare, are remedied quickly.

Any injection well leakages that do occur in the vicinity of the WIPP in the near future are more likely to be associated with liquid waste disposal than waterflooding. Disposal typically involves fluid injection though old and potentially corroded well casings and does not include monitoring to the same extent as waterflooding. Such fluid injection could affect the performance of the

disposal system if sufficient fluid leaked into the Salado interbeds to affect the rate of brine flow into the waste disposal panels.

Stoelzel and O'Brien (1996) evaluated the potential effects on the disposal system of leakage from a hypothetical salt water disposal borehole near the WIPP. Stoelzel and O'Brien (1996) used the two-dimensional BRAGFLO model (vertical north-south cross-section) to simulate saltwater disposal to the north and to the south of the disposal system. The disposal system model included the waste disposal region, the marker beds and anhydrite intervals near the excavation horizon, and the rock strata associated with local oil and gas developments. A worst case simulation was run using high values of borehole and anhydrite permeability and a low value of halite permeability to encourage flow to the disposal panels via the anhydrite. Also, the boreholes were assumed to be plugged immediately above the Salado (consistent with the plugging configurations described in Section 6.4.7.2). Saltwater disposal into the Upper Bell Canyon was simulated, with annular leakage through the Salado. A total of approximately 7×10^5 m^3 (2.47×10^7 ft^3) of brine was injected through the boreholes during a 50-year simulated disposal period. In this time, approximately 50 m^3 (1765.5 ft^3) of brine entered the anhydrite interval at the horizon of the waste disposal region. For the next 200 years the boreholes were assumed to be abandoned (with open-hole permeabilities of 1×10^{-9} m^2 (4×10^{-8} in.)). Cement plugs (of permeability 1×10^{-17} m^2 (4×10^{-16} in.)) were assumed to be placed at the injection interval and at the top of the Salado. Subsequently, the boreholes were prescribed the permeability of silty sand (see Section 6.4.7.2), and the simulation was continued until the end of the 10,000-year regulatory period. During this period, approximately 400 m^3 (14,124 ft^3) of brine entered the waste disposal region from the anhydrite interval. This value of cumulative brine inflow is within the bounds of the values generated by PA calculations for the undisturbed performance scenario. During the disposal well simulation, leakage from the injection boreholes would have had no significant effect on the inflow rate at the waste panels.

Stoelzel and Swift (1997) expanded on Stoelzel and O'Brien's (1996) work by considering injection for a longer period of time (up to 150 years) and into deeper horizons at higher pressures. They developed two computational models (a modified cross-sectional model and an axisymmetric radial model) that are alternatives to the cross-sectional model used by Stoelzel and O'Brien (1996). Rather than repeat the conservative and bounding approach used by Stoelzel and O'Brien (1996), Stoelzel and Swift (1997) focused on reasonable and realistic conditions for most aspects of the modeling, including setting parameters that were sampled in the CCA at their median values. Model results indicate that, for the cases considered, the largest volume of brine entering MB139 (the primary pathway to the WIPP) from the borehole is approximately 1,500 m^3 (52,974 ft^3), which is a small enough volume that it would not affect Stoelzel and O'Brien's (1996) conclusion even if it somehow all reached the WIPP. Other cases showed from 0 to 600 m^3 (21,190 ft^3) of brine entering MB139 from the injection well. In all cases, high-permeability fractures created in the Castile and Salado anhydrite layers by the modeled injection pressures were restricted to less than 400 m (1,312 ft) from the wellbore, and did not extend more than 250 m in MB138 and MB139.

No flow entered MB139, nor was fracturing of the unit calculated to occur away from the borehole, in cases in which leaks in the cement sheath had permeabilities of $1 \times 10^{-12.5}$ m^2 (corresponding to the median value used to characterize fully degraded boreholes in the CCA) or lower. The cases modeled in which flow entered MB139 from the borehole and fracturing

occurred away from the borehole required injection pressures conservatively higher than any currently in use near the WIPP and either 150 years of leakage through a fully degraded cement sheath or 10 years of simultaneous tubing and casing leaks from a waterflood operation. These conditions are not likely to occur in the future. If leaks like these do occur from brine injection near the WIPP, however, results of the Stoelzel and Swift (1997) modeling study indicate that they will not affect the performance of the repository.

Thus, the hydraulic effects of leakage through HCN boreholes outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.6.3.3 *Effects of Density Changes Resulting from Leakage Through Injection Boreholes*

Leakage through a failed borehole casing during a fluid injection operation in the vicinity of the WIPP could alter fluid density in the affected unit, which could result in changes in fluid flow rates and directions within the disposal system. Disposal of oil and gas production by-products through boreholes could increase fluid densities in transmissive units affected by leakage in the casing. Operations such as waterflooding use fluids derived from the target reservoir, or fluids with a similar composition, to avoid scaling and other reactions. Therefore, the effects of leakage from waterflood boreholes would be similar to leakage from disposal wells.

Denser fluids have a tendency to sink relative to less dense fluids, and, if the hydrogeological unit concerned has a dip, there will be a tendency for the dense fluid to travel in the downdip direction. If this direction is the same as the direction of the groundwater pressure gradient, there would be an increase in flow velocity, and conversely, if the downdip direction is opposed to the direction of the groundwater pressure gradient, there would be a decrease in flow velocity. In general terms, taking account of density-related flow will cause a rotation of the flow vector towards the downdip direction that is dependent on the density contrast and the dip.

Wilmot and Galson (1996) showed that brine density changes in the Culebra resulting from leakage through an injection borehole outside the controlled area will not affect fluid flow in the Culebra significantly. Potash mining activities assumed on the basis of regulatory criteria to occur in the near future outside the controlled area will have a more significant effect on modeled Culebra hydrology. The distribution of existing leases suggests that near-future mining will take place to the north, west, and south of the controlled area (see Section 2.3.1.1). The effects of such potash mining are accounted for in calculations of undisturbed performance of the disposal system (through an increase in the transmissivity of the Culebra above the mined region, as discussed in FEPs H37, H38, and H39). Groundwater modeling that accounts for potash mining shows a change in the fluid pressure distribution, and a consequent shift of flow directions towards the west in the Culebra within the controlled area (Wallace 1996c). A localized increase in fluid density in the Culebra resulting from leakage from an injection borehole would rotate the flow vector towards the downdip direction (towards the east).

Wilmot and Galson (1996) compared the relative magnitudes of the freshwater head gradient and the gravitational gradient and showed that the density effect is of low consequence to the

performance of the disposal system. According to Darcy's Law, flow in an isotropic porous medium is governed by the gradient of fluid pressure and a gravitational term

$$\bar{v} - -\frac{k}{\mu}\left[\nabla p - \rho \bar{g}\right], \tag{7}$$

where

v	=	Darcy velocity vector	(m s^{-1})
k	=	intrinsic permeability	(m^2)
μ	=	fluid viscosity	(pa s)
∇p	=	gradient of fluid pressure	(pa m^{-1})
ρ	=	fluid density	(kg m^{-3})
g	=	gravitational acceleration vector	(m s^{-2})

The relationship between the gravity-driven flow component and the pressure-driven component can be shown by expressing the velocity vector in terms of a freshwater head gradient and a density-related elevation gradient

$$\bar{v} = -K\left[\nabla H_f + \frac{\Delta\rho}{\rho_f}\nabla E\right], \tag{8}$$

where

K	=	hydraulic conductivity	(m s^{-1})
∇H_f	=	gradient of freshwater head	
$\Delta\rho$	=	difference between actual fluid density and reference fluid density	(kg m^{-3})
ρ_f	=	density of freshwater	(kg m^{-3})
∇E	=	gradient of elevation	

Davies (1989, p. 28) defined a driving force ratio (DFR) to assess the potential significance of the density gradient

$$\mathrm{DFR} = \frac{\Delta\rho\left|\nabla E\right|}{\rho_f\left|\nabla H_f\right|} \tag{9}$$

and concluded that a DFR of 0.5 can be considered an approximate threshold at which density-related gravity effects may become significant (Davies 1989, p. 28).

The dip of the Culebra in the vicinity of the WIPP is about 0.44° or 8 m/km (26 ft/mi) to the east (Davies 1989, p. 42). According to Davies (1989, pp. 47 - 48), freshwater head gradients in the Culebra between the waste panels and the southwestern and western boundaries of the accessible environment range from 4 m/km (13 ft/mi) to 7 m/km (23 ft/mi). Only small changes in gradient arise from the calculated effects of near-future mining. Culebra brines have densities ranging

from 998 to 1,158 kg/m^3 (998 to 1,158 ppm) (Cauffman et al. 1990, Table E1.b). Assuming the density of fluid leaking from a waterflood borehole or a disposal well to be 1,215 kg/m^3 (1,215 ppm) (a conservative high value similar to the density of Castile brine [Popielak et al. 1983, Table C-2]), leads to a DFR of between 0.07 and 0.43. These values of the DFR show that density-related effects caused by leakage of brine into the Culebra during fluid injection operations are not significant.

In summary, the effects of HCN fluid injection (***Liquid Waste Disposal, Enhanced Oil and Gas Production,*** and ***Hydrocarbon Storage)*** through boreholes outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.6.3.4 *Geochemical Effects of Leakage through Injection Boreholes*

Injection of fluids through a leaking borehole could affect the geochemical conditions in thief zones, such as the Salado interbeds or the Culebra. Such ***Fluid Injection-Induced Geochemical Changes*** could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area through their effects on colloid transport and sorption.

The majority of fluids injected (for example, during brine disposal) have been extracted locally during production activities. Because they have been derived locally, their compositions are similar to fluids currently present in the disposal system, and they will have low total colloid concentrations compared to those in the waste disposal panels (see FEPs discussion for H21 through H24). The repository will remain the main source of colloids in the disposal system. Therefore, colloid transport as a result of HCN fluid injection has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21 through H24, sorption within the Culebra is accounted for in PA calculations. The sorption model used accounts for the effects of any changes in sorption in the Culebra as a result of leakage through HCN injection boreholes.

Consistent with the screening discussion in FEPs H21 through H24, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of leakage through HCN injection boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

Nonlocally derived fluids could be used during hydraulic fracturing operations. However, such fluid injection operations would be carefully controlled to minimize leakage to thief zones. Therefore, any potential geochemical effects of such leakages have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.6.3.5 *Future Human EPs*

Consistent with 40 CFR § 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole within the site boundary.

Liquid Waste dDisposal (by-products from oil and gas production), ***Enhanced Oil and Gas Production***, and ***Hydrocarbon Storage*** are techniques associated with resource recovery and are expected to continue into the future outside the site boundary. Analyses have shown that these activities have little consequence on repository performance (Stoelzel and Swift 1997). Therefore, activities such as ***Liquid Waste Disposal, Enhanced Oil and Gas Production,*** and ***Hydrocarbon Storage*** have been eliminated from PA calculations on the basis of low consequence.

SCR-5.2.1.7 FEP Number: H30
FEP Title: ***Fluid Injection-Induced Geochemical Changes***

SCR-5.2.1.7.1 Screening Decision: UP (HCN)
SO-R (Future)

Geochemical changes that occur inside the controlled area as a result of fluid flow associated with HCN fluid injection are accounted for in PA calculations. ***Liquid Waste dDisposal****,* ***Enhanced Oil and Gas Production****, and* ***Hydrocarbon Storage*** *involving future boreholes have been eliminated from PA calculations on regulatory grounds.*

SCR-5.2.1.7.2 Summary of New Information

No new information regarding this FEP has been identified. The screening argument has been enhanced; the screening decisions have not changed.

SCR-5.2.1.7.3 Screening Argument

The injection of fluids could alter fluid-flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone. Injection of fluids through a leaking borehole could also result in geochemical changes and altered radionuclide migration rates in the thief units.

SCR-5.2.1.7.3.1 *Geochemical Effects of Leakage through Injection Boreholes*

Injection of fluids through a leaking borehole could affect the geochemical conditions in thief zones, such as the Salado interbeds or the Culebra. Such ***Fluid Injection-Induced Geochemical Changes*** could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area through their effects on colloid transport and sorption.

The majority of fluids injected (for example, during brine disposal) have been extracted locally during production activities. Because they have been derived locally, their compositions are similar to fluids currently present in the disposal system, and they will have low total colloid concentrations compared to those in the waste disposal panels (see FEPs H21 through H24). The repository will remain the main source of colloids in the disposal system. Therefore, colloid transport as a result of HCN fluid injection has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21 through H24, sorption within the Culebra is accounted for in PA calculations. The sorption model used accounts for the effects of any changes in sorption in the Culebra as a result of leakage through HCN injection boreholes.

Consistent with the screening discussion in FEPs H21 through H24, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of leakage through HCN injection boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

Non-locally derived fluids could be used during hydraulic fracturing operations. However, such fluid injection operations would be carefully controlled to minimize leakage to thief zones. Therefore, any potential geochemical effects of such leakages have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.7.3.2 *Future Human EPs*

Consistent with 40 CFR § 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. ***Liquid Waste dDisposal*** (by-products from oil and gas production), ***Enhanced Oil and Gas Production***, and ***Hydrocarbon Storage*** are techniques associated with resource recovery. Therefore, the use of future boreholes for such activities and fluid injection-induced geochemical changes have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.8 FEP Number: H31 and H33
FEP Title: ***Natural Borehole Fluid Flow*** (H31)
Flow Through Undetected Boreholes (H33)

SCR-5.2.1.8.1 Screening Decision: SO-C (HCN)
SO-C (Future, holes not penetrating waste panels)
DP (Future, holes through waste panels)

The effects of natural fluid flow through existing or near-future abandoned boreholes, known or unknown, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Natural borehole flow through a future borehole that intersects a waste panel is accounted for in PA calculations. The effects of natural borehole flow through a future borehole that does not intersect the waste-disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.8.2 Summary of New Information

Natural Borehole Fluid Flow and ***Flow Through Undetected Boreholes*** have been combined because knowledge of a borehole's existence has no impact on its effects. ***Flow Through Undetected Boreholes*** has been deleted from the baseline and the description of ***Natural Borehole Fluid Flow*** was changed to include unknown boreholes. The screening argument has been modified to simplify and improve clarity.

SCR-5.2.1.8.3 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Movement of fluids through abandoned boreholes could result in borehole-induced geochemical changes in the receiving units such as the Salado interbeds or Culebra, and thus alter radionuclide migration rates in these units.

Potentially, boreholes could provide pathways for surface-derived water or groundwater to percolate through low-permeability strata and into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns. Also, fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation.

SCR-5.2.1.8.3.1 *Historical, Current, and Near-Future Human EPs*

SCR-5.2.1.8.3.2 *Abandoned water, potash, oil, and gas exploration and production boreholes exist within and outside the controlled area. Most of these boreholes have been plugged in some way, but some have simply been abandoned. Over time, even the boreholes that have been plugged may provide hydraulic connections among the units they penetrate as the plugs degrade. The DOE assumes that records of past and present drilling activities in New Mexico are largely accurate and that evidence of most boreholes would be included in these records. However, the potential effects of boreholes do not change depending on whether we know of their existence or not, hence* **Flow Through Undetected Boreholes** *and* **Flow Through Undetected Boreholes** *can be evaluated together.*

SCR-5.2.1.8.3.3 *Hydraulic Effects of Flow through Abandoned Boreholes*

Fluid flow and radionuclide transport within the Culebra could be affected if deep boreholes result in hydraulic connections between the Culebra and deep overpressurized or underpressurized units, or if boreholes provide interconnections for flow between shallow units.

SCR-5.2.1.8.3.4 *Connections Between the Culebra and Deeper Units*

Fluid flow and radionuclide transport within the Culebra could be affected if deep boreholes result in hydraulic connections between the Culebra and deep overpressurized or underpressurized units. Over the past 80 years, a large number of deep boreholes have been drilled within and around the controlled area (see Section 6.4.12.2). The effects on the performance of the disposal system of long-term hydraulic connections between the Culebra and deep units depends on the locations of the boreholes. In some cases, changes in the Culebra flow field caused by interconnections with deep units could decrease lateral radionuclide travel times to the accessible environment.

As part of an analysis to determine the impact of such interconnections, Wallace (1996a) gathered information on the pressures, permeabilities, and thicknesses of potential oil- or gas-bearing sedimentary units; such units exist to a depth of about 5,500 m (18,044 ft) in the vicinity of the WIPP. Of these units, the Atoka, some 4,000 m (13,123 ft) below the land surface, has the highest documented pressure of about 64×10^6 pascals (9,600 psi), with permeability of about 2×10^{-14} m^2 (2.1×10^{-13} ft^2) and thickness of about 210 m (689 ft). The Strawn, 3,900 m (12,795 ft) below the land surface, has the lowest pressures (35×10^6 pascals (5,000 psi), which is lower than hydrostatic) and highest permeability (10^{-13} m^2 (1.1×10^{-12} ft^2)) of the deep units, with a thickness of about 90 m (295 ft).

PA calculations indicate that the shortest radionuclide travel times to the accessible environment through the Culebra occur when flow in the Culebra in the disposal system is from north to south. Wallace (1996a) ran the steady-state SECOFL2D model with the PA data that generated the shortest radionuclide travel times (with and without mining in the controlled area) but perturbed the flow field by placing a borehole connecting the Atoka to the Culebra just north of the waste disposal panels and a borehole connecting the Culebra to the Strawn just south of the controlled area. The borehole locations were selected to coincide with the end points of the fastest flow paths modeled, which represents an unlikely worst-case condition. Although the Atoka is primarily a gas-bearing unit, Wallace (1996a) assumed that the unit is brine saturated. This assumption is conservative because it prevents two-phase flow from occurring in the Culebra, which would decrease the water permeability and thereby increase transport times. He further conservatively assumed that the pressure in the Atoka would not have been depleted by production before the well was plugged and abandoned. He also conservatively assumed that all flow from the Atoka would enter the Culebra and not intermediate or shallower units, and that flow from the Culebra could somehow enter the Strawn despite intermediate zones having higher pressures than the Culebra. The fluid flux through each borehole was determined using Darcy's Law, assuming a borehole hydraulic conductivity of 10^{-4} m/s (for a permeability of about 10^{-11} m^2 (1.1×10^{-10} ft^2)) representing silty sand, a borehole radius of 0.25 m (.82 ft), and a fluid pressure in the Culebra of 0.88×10^6 pascals (132 psi) at a depth of about 200 m (650 ft). With these parameters, the Atoka was calculated to transmit water to the Culebra at about 1.4×10^{-5} m^3/s (0.22 gpm), and the Strawn was calculated to receive water from the Culebra at about 1.5×10^{-6} m^3/s (0.024 gpm).

Travel times through the Culebra to the accessible environment were calculated using the SECOFL2D velocity fields for particles released to the Culebra above the waste panels, assuming no retardation by sorption or diffusion into the rock matrix. Mean Darcy velocities were then determined from the distance each radionuclide traveled, the time taken to reach the accessible environment, and the effective Culebra porosity. The results show that, at worst, interconnections between the Culebra and deep units under the unrealistically conservative assumptions listed above could cause less than a twofold increase in the largest mean Darcy velocity expected in the Culebra in the absence of such interconnections.

These effects can be compared to the potential effects of climate change on gradients and flow velocities through the Culebra. As discussed in Section 6.4.9 (and Corbet and Knupp 1996), the maximum effect of a future wetter climate would be to raise the water table to the ground surface. This would raise heads and gradients in all units above the Salado. For the Culebra, the

maximum change in gradient was estimated to be about a factor of 2.1. The effect of climate change is incorporated in compliance calculations through the Climate Index, which is used as a multiplier for Culebra groundwater velocities. The Climate Index has a bimodal distribution, with the range from 1.00 to 1.25 having a 75 percent probability, and the range from 1.50 to 2.25 having a 25 percent probability. Because implementation of the Climate Index leads to radionuclide releases through the Culebra that are orders of magnitude lower than the regulatory limits, the effects of flow between the Culebra and deeper units through abandoned boreholes can be screened out on the basis of low consequence.

SCR-5.2.1.8.3.5 *Connections Between the Culebra and Shallower Units*

Abandoned boreholes could also provide interconnections for long-term fluid flow between shallow units (overlying the Salado). Abandoned boreholes could provide pathways for downward flow of water from the Dewey Lake and/or Magenta to the Culebra because the Culebra hydraulic head is lower than the hydraulic heads of these units. Magenta freshwater heads are as much as 45 m (148 ft) higher than Culebra freshwater heads. Because the Culebra is generally at least one order of magnitude more transmissive than the Magenta at any location, a connection between the Magenta and Culebra would cause proportionally more drawdown in the Magenta head than rise in the Culebra head. For example, for a one order of magnitude difference in transmissivity and a 45-m (148-ft) difference in head, the Magenta head would decrease by approximately 40 m (131 ft) while the Culebra head increased by 5 m (16 ft). This head increase in the Culebra would also be a localized effect, decreasing with radial distance from the leaking borehole. The primary flow direction in the Culebra across the WIPP site is from north to south, with the Culebra head decreasing by approximately 20 m (66 ft) across this distance. A 5-m (16-ft) increase in Culebra head at the northern WIPP boundary would, therefore, increase gradients by at most 25 percent.

The Dewey Lake freshwater head at the WQSP-6 pad is 55 m (180 ft) higher than the Culebra freshwater head. Leakage from the Dewey Lake could have a greater effect on Culebra head than leakage from the Magenta if the difference in transmissivity between the Dewey Lake and Culebra observed at the WQSP-6 pad, where the Dewey Lake is two orders of magnitude more transmissive than the Culebra (Beauheim and Ruskauff 1998), persists over a wide region. However, the saturated, highly transmissive zone in the Dewey Lake has only been observed south of the WIPP disposal panels. A connection between the Dewey Lake and the Culebra south of the panels would tend to decrease the north-south gradient in the Culebra across the site, not increase it.

In any case, leakage of water from overlying units into the Culebra could not increase Culebra heads and gradients as much as might result from climate change, discussed above. Because implementation of the Climate Index leads to radionuclide releases through the Culebra that are orders of magnitude lower than the regulatory limits, the effects of flow between the Culebra and shallower units through abandoned boreholes can be screened out on the basis of low consequence.

SCR-5.2.1.8.3.6 *Changes in Fluid Density Resulting from Flow Through Abandoned Boreholes*

Leakage from historical, current, and near-future abandoned boreholes that penetrate pressurized brine pockets in the Castile could give rise to fluid density changes in affected units. Wilmot and Galson (1996) showed that brine density changes in the Culebra resulting from leakage through an abandoned borehole would not have a significant effect on the Culebra flow field. A localized increase in fluid density in the Culebra resulting from leakage from an abandoned borehole would rotate the flow vector towards the downdip direction (towards the east). A comparison of the relative magnitudes of the freshwater head gradient and the gravitational gradient, based on an analysis similar to that presented in Sections SCR.5.2.1 (FEPs H27, H28, and H29), shows that the density effect is of low consequence to the performance of the disposal system.

SCR-5.2.1.8.3.7 *Future Human EPs*

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete, the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.8.3.8 *Hydraulic Effects of Flow Through Abandoned Boreholes*

A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. Long-term ***Natural Borehole Flow*** through such a borehole is accounted for in PA calculations (see Section 6.4.8).

Deep abandoned boreholes that intersect the Salado interbeds near the waste disposal panels could provide pathways for long-term radionuclide transport from the waste panels to the land surface or to overlying units. The potential significance of such events were assessed by WIPP PA Department (1991, B-26 to B-27), which examined single-phase flow and transport between the waste panels and a borehole intersecting MB139 outside the DRZ. The analysis assumed an in situ pressure of 11 megapascals in MB139, a borehole pressure of 6.5 megapascals (975 psi) (hydrostatic) at MB139, and a constant pressure of 18 megapascals (2,700 psi) as a source term in the waste panels representing gas generation. Also, MB139 was assigned a permeability of approximately 3×10^{-20} m^2 (3.2×10^{-19} ft^2) and a porosity of 0.01 percent. The disturbed zone was assumed to exist in MB139 directly beneath the repository only and was assigned a permeability of 1.0×10^{-17} m^2 (1.1×10^{-16} ft^2) and a porosity of 0.055 percent. Results showed that the rate of flow through a borehole located just 0.25 m (0.8 ft) outside the DRZ would be more than two orders of magnitude less than the rate of flow through a borehole located within the DRZ because of the contrast in permeability. Thus, any releases of radionuclides to the accessible environment through deep boreholes that do not intersect waste panels would be insignificant compared to the releases that would result from transport through boreholes that

intersect waste panels. Thus, radionuclide transport through deep boreholes that do not intersect waste panels has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.8.3.9 *Fluid Flow and Radionuclide Transport in the Culebra*

Fluid flow and radionuclide transport within the Culebra could be affected if future boreholes result in hydraulic connections between the Culebra and either deeper or shallower units. Over the 10,000-year regulatory period, a large number of deep boreholes could be drilled within and around the controlled area (see Section 6.4.12.2). The effects on the performance of the disposal system of long-term hydraulic connections between the Culebra and deeper or shallower units would be the same as those discussed above for historic, current, and near-future conditions. Thus, the effects of flow between the Culebra and deeper or shallower units through abandoned future boreholes can be screened out on the basis of low consequence.

SCR-5.2.1.8.3.10 *Changes in Fluid Density Resulting from Flow Through Abandoned Boreholes*

A future borehole that intersects a pressurized brine reservoir in the Castile could also provide a source for brine flow to the Culebra in the event of borehole casing leakage, with a consequent localized increase in fluid density in the Culebra. The effect of such a change in fluid density would be to increase any density-driven component of groundwater flow. If the downdip direction, along which the density-driven component would be directed, is different from the direction of the groundwater pressure gradient, there would be a slight rotation of the flow vector towards the downdip direction. The groundwater modeling presented by Davies (1989, p. 50) indicates that a borehole that intersects a pressurized brine pocket and causes a localized increase in fluid density in the Culebra above the waste panels would result in a rotation of the flow vector slightly towards the east. However, the magnitude of this effect would be small in comparison to the magnitude of the pressure gradient (see screening argument for FEPS H27, H28, and H29 where this effect is screened out on the basis of low consequence.

SCR-5.2.1.9 FEP Number: H32
FEP Title: ***Waste-Induced Borehold Flow***

SCR-5.2.1.9.1 Screening Decision: SO-R (HCN)
DP (Future)

Waste-induced flow through boreholes drilled in the near future has been eliminated from PA calculations on regulatory grounds. ***Waste-Induced Borehole Flow*** *and* ***Natural Borehole Flow*** *through a future borehole that intersects a waste panel are accounted for in PA calculations.*

SCR-5.2.1.9.2 Summary of New Information

SCR-5.2.1.9.3 No new information has been identified for this FEP. This discussion for this FEP has been modified for editorial purposes.

SCR-5.2.1.9.4 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Continued resource exploration and production in the near future will result in the occurrence of many more abandoned boreholes in the vicinity of the controlled area. Institutional controls will prevent drilling (other than that associated with the WIPP development) from taking place within the controlled area in the near future. Therefore, no boreholes will intersect the waste disposal region in the near future, and ***Waste-Induced Borehole Flow*** in the near future has been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.9.4.1 *Future Human EPs*

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.9.4.2 *Hydraulic Effects of Flow Through Abandoned Boreholes*

An abandoned future borehole that intersects a waste panel could provide a connection for contaminant transport away from the repository horizon. If the borehole has degraded casing and/or plugs, and the fluid pressure within the waste panel is sufficient, radionuclides could be transported to the land surface. Additionally, if brine flows through the borehole to overlying units, such as the Culebra, it may carry dissolved and colloidal actinides that can be transported laterally to the accessible environment by natural groundwater flow in the overlying units. Long-term ***Waste-Induced Borehole Flow*** is accounted for in PA calculations (see Section 6.4.7.2).

SCR-5.2.1.10 FEP Number: H34
FEP Title: ***Borehole-Induced Solution and Subsidence***

SCR-5.2.1.10.1 Screening Decision: SO-C (HCN)
SO-C (Future)

The effects of ***Borehole-Induced Solution and Subsidence*** *associated with existing, near-future, and future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-5.2.1.10.2 Summary of New Information

The original description and screening arguments for ***Borehole-Induced Solution and Subsidence*** around existing and future boreholes remain unchanged and valid. The change in hydraulic conductivity within the Culebra from ***Borehole-Induced Solution and Subsidence*** along the flow path will have no significant affect on the long-term performance of the disposal system. The effects have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The FEP description and screening arguments have been revised to include new information related to borehole-induced subsidence by recognizing new and developing sinks in the region.

SCR-5.2.1.10.3 Screening Argument

Potentially, boreholes could provide pathways for surface-derived water or groundwater to percolate through low-permeability strata and into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns. Also, fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation.

SCR-5.2.1.10.3.1 *Historical, Current, and Near-Future Human EPs*

SCR-5.2.1.10.3.1.1 *Borehole-Induced Solution and Subsidence*

During the period covered by HCN FEPs, drilling within the land withdrawn for the WIPP will be controlled, and boreholes will be plugged according to existing regulations. Under these circumstances and during this time period, ***Borehole-Induced Solution and Subsidence*** at WIPP is eliminated from PA calculations on the basis of no consequence to the disposal system.

Outside the area withdrawn for the WIPP, drilling has been regulated, but conditions of historical and existing boreholes are highly variable. ***Borehole-Induced Solution and Subsidence*** may occur in these areas, although it is expected to be limited and should not affect the disposal system, as discussed in the following paragraphs.

Three features are required for significant ***Borehole-Induced Solution and Subsidence*** to occur: a borehole, an energy gradient to drive unsaturated (with respect to halite) water through the evaporite-bearing formations, and a conduit to allow migration of brine away from the site of dissolution. Without these features, minor amounts of halite might be dissolved in the immediate

vicinity of a borehole, but percolating water would become saturated with respect to halite and stagnant in the bottom of the drillhole, preventing further dissolution.

At, and in the vicinity of, the WIPP site, drillholes penetrating into, but not through, the evaporite-bearing formations have little potential for dissolution. Brines coming from the Salado and Castile, for example, have high total dissolved solids (TDS) and are likely to precipitate halite, not dissolve more halite during passage through the borehole. Water infiltrating from the surface or near-surface units may not be saturated with halite. For drillholes with a total depth in halite-bearing formations, there is little potential for dissolution because the halite-bearing units have very low permeability and provide little outlet for the brine created as the infiltrating water fills the drillhole. ERDA 9 is the deepest drillhole in the immediate vicinity of the waste panels at WIPP; the bottom of the drillhole is in the uppermost Castile Formation, with no known outlet for brine at the bottom.

Drillholes penetrating through the evaporite-bearing formations provide possible pathways for circulation of water. Underlying units in the vicinity of the WIPP site with sufficient potentiometric levels or pressures to reach or move upward through the halite units generally have one of two characteristics: (1) high-salinity brines, which limit or eliminate the potential for dissolution of evaporites, or (2) are gas-producers. Wallace et al. (1982) analyzed natural processes of dissolution of the evaporites by water from the underlying Bell Canyon Formation. They concluded that brine removal in the Bell Canyon is slow, limiting the movement of dissolution fronts or the creation of natural collapse features. Existing drillholes that are within the boundaries of the withdrawn land and also penetrate through the evaporites are not located in the immediate vicinity of the waste panels or WIPP workings.

There are three examples in the region that appear to demonstrate the process for ***Borehole-Induced Solution and Subsidence***, but the geohydrologic setting and drillhole completions differ from those at or near the WIPP.

An example of ***Borehole-Induced Solution and Subsidence*** occurred in 1980 about 160 km (100 mi) southeast of the WIPP site (outside the Delaware Basin) at the Wink Sink (Baumgardner et al. 1982; Johnson 1989); percolation of shallow groundwater through abandoned boreholes, dissolution of the Salado, and subsidence of overlying units led to a surface collapse feature 110 m (360 ft) in width and 34 m (110 ft) deep. At Wink Sink, the Salado is underlain by the Tansill, Yates, and Capitan Formations, which contain vugs and solution cavities through which brine could migrate. Also, the hydraulic head of the Santa Rosa (the uppermost aquifer) is greater than those of the deep aquifers (Tansill, Yates, and Capitan Formations), suggesting downward flow if a connection were established. A second sink (Wink Sink 2) formed in May 2002, near the earlier sink (Johnson et al., in press). Its origin is similar to the earlier sink. By February 2003, Wink Sink 2 had enlarged by surface collapse to a length of about 305 m (1000 ft) and a width of about 198 m (650 ft).

A similar, though smaller, surface collapse occurred in 1998 northwest of Jal, New Mexico (Powers 2000). The most likely cause of collapse appears to be dissolution of Rustler, and possibly Salado, halite as relatively low salinity water from the Capitan Reef circulated through breaks in the casing of a deep water supply well. Much of the annulus behind the casing through the evaporite section was uncemented, and work in the well at one time indicated bent and

ruptured casing. The surface collapse occurred quickly, and the sink was initially about 23 m (75 ft) across and a little more than 30 m (100 ft) deep. By 2001, the surface diameter was about 37 m (120 ft), and the sink was filled with collapse debris to about 18 m (60 ft) below the ground level (Powers, in press).

The sinkholes near Wink, Texas, and Jal, New Mexico, occurred above the Capitan Reef (which is by definition outside the Delaware Basin), and the low salinity water and relatively high potentiometric levels of the Capitan Reef appear to be integral parts of the process that formed these sinkholes. They are reviewed as examples of the process of evaporite dissolution and subsidence related to circulation in drillholes. Nevertheless, the factors of significant low salinity water and high potentiometric levels in units below the evaporites do not appear to apply at the WIPP site.

Beauheim (1986) considered the direction of natural fluid flow through boreholes in the vicinity of the WIPP. Beauheim (1986, p. 72) examined hydraulic heads measured using drill stem tests in the Bell Canyon and the Culebra at well DOE-2 and concluded that the direction of flow in a cased borehole open only to the Bell Canyon and the Culebra would be upward. Bell Canyon waters in the vicinity of the WIPP site are saline brines (e.g., Lambert 1978; Beauheim et al. 1983; Mercer et al. 1987), limiting the potential for dissolution of the overlying evaporites. However, dissolution of halite in the Castile and the Salado would increase the relative density of the fluid in an open borehole, causing a reduction in the rate of upward flow. Potentially, the direction of borehole fluid flow could reverse, but such a flow could be sustained only if sufficient driving pressure, porosity, and permeability exist for fluid to flow laterally within the Bell Canyon. A further potential sink for Salado-derived brine is the Capitan Limestone. However, the subsurface extent of the Capitan Reef is approximately 16 km (10 mi) from the WIPP at its closest point, and this unit will not provide a sink for brine derived from boreholes in the vicinity of the controlled area. A similar screening argument is made for natural deep dissolution in the vicinity of the WIPP (see N16, N17, and N18).

The effects of ***Borehole-Induced Solution and Subsidence*** through a waste panel are considered below. The principal effects of ***Borehole-Induced Solution and Subsidence*** in the remaining parts of the disposal system should be to change the hydraulic properties of the Culebra and other rocks in the system. The features are local (limited lateral dimensions) and commonly nearly circular. If subsidence occurs along the expected travel path and the transmissivity of the Culebra is increased, as in the calculations conducted by Wallace (1996c), the travel times should increase. If the transmissivity along the expected flow path decreased locally due to such a feature, the flow path should be lengthened by travel around the feature. Thus, the effects of ***Borehole-Induced Solution and Subsidence*** around existing abandoned boreholes, and boreholes drilled and abandoned in the near-future, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.10.3.2 *Future Human EPs*

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially,

contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.10.3.2.1 *Borehole-Induced Solution and Subsidence*

Future boreholes that do not intersect the WIPP excavation do not differ in long-term behavior or consequences from existing boreholes, and can be eliminated from PA on the basis of low consequence to the performance of the disposal system.

The condition of more apparent concern is a future borehole that intersects the WIPP excavation. Seals and casings are assumed to degrade, connecting the excavation to various units. For a drillhole intersecting the excavation, but not connecting to a brine reservoir or to formations below the evaporites, downward flow is limited by the open volume of the disposal room(s), which is dependent with time, gas generation, or brine inflow to the disposal system from the Salado.

Maximum dissolution, and maximum increase in borehole diameter, will occur at the top of the Salado; dissolution will decrease with depth as the percolating water becomes salt saturated. Eventually, degraded casing and concrete plug products, clays, and other materials will fill the borehole. Long-term flow through a borehole that intersects a waste panel is accounted for in disturbed performance calculations by assuming that the borehole is eventually filled by such materials, which have the properties of a silty sand (see Section 6.4.7.2). However, these calculations assume that the borehole diameter does not increase with time. Under the conditions assumed in the SCR for the CCA for an E2 drilling event at 1,000 years, about 1,000 m^3 (35,316 ft^3) would be dissolved from the lower Rustler and upper Salado Formations. If the dissolved area is approximately cylindrical or conical around the borehole, and the collapse/subsidence propagates upward as occurred in breccia pipes (e.g., Snyder and Gard 1982), the diameter of the collapsed or subsided area through the Culebra and other units would be a few tens of meters across. Changes in hydraulic parameters for this small zone should slow travel times for any hypothesized radionuclide release, as discussed for HCN occurrences. This does not change the argument for low consequence due to ***Borehole-Induced Solution and Subsidence*** for these circumstances.

If a drillhole through a waste panel and into deeper evaporites intercepts a Castile brine reservoir, the brine has little or no capability of dissolving additional halite. The Castile brine flow is considered elsewhere as part of disturbed performance. There is, however, no ***Borehole-Induced Solution and Subsidence*** under this circumstance, and therefore there is no effect on performance due to this EP.

If a borehole intercepts a waste panel and also interconnects with formations below the evaporite section, fluid flow up or down is determined by several conditions and may change over a period of time (e.g., as dissolution increases the fluid density in the borehole. Fluid flow downward is not a concern for performance, as fluid velocities in units such as the Bell Canyon are slow and should not be of concern for performance (e.g., II-G-12, 3.12.3.3.). For dissolution at the top of the evaporite section (as with boreholes considered under HCN), the process can develop a localized area around the borehole in which the hydraulic parameters for the Culebra and other

units are altered. As with boreholes considered for HCN, the local change in hydraulic parameters, if it occurs along the expected flow path, would be expected to cause little change in travel time and should increase the travel time.

In summary, the effects of ***Borehole-Induced Solution and Subsidence*** around future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.11 FEP Number: H35
FEP Title: ***Borehole Induced Mineralization***

SCR-5.2.1.11.1 Screening Decision: SO-C (HCN)
SO-C (Future)

The effects of ***Borehole -Induced Mineralization****, associated with existing, near-future, and future abandoned boreholes, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-5.2.1.11.2 Summary of New Information

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. Movement of compositionally different groundwater into the Culebra may lead to mineral precipitation, potentially changing porosity and permeability within the unit, and affecting contaminant transport. The potential effects of borehole-induced brine movement into the Culebra dolomite and mineral precipitation/ dissolution are discussed in FEPs H31 through H36. The original FEP description was slightly modified to include an evaluation of the effects of mineral precipitation on matrix diffusion.

SCR-5.2.1.11.3 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Movement of fluids through abandoned boreholes could result in ***Borehole*-Induced Geochemical Changes** in the receiving units, such as the Salado interbeds or Culebra, and thus alter radionuclide migration rates in these units.

Potentially, boreholes could provide pathways for surface-derived water or groundwater to percolate through low-permeability strata and into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns. Also, fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation.

SCR-5.2.1.11.3.1 *Borehole-Induced Mineralization*

Fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation. For example:

- Limited calcite precipitation may occur as the waters mix in the Culebra immediately surrounding the borehole, and calcite dissolution may occur as the brines migrate away from the borehole due to variations in water chemistry along the flow path.

- Gypsum may be dissolved as the waters mix in the Culebra immediately surrounding the borehole but may precipitate as the waters migrate through the Culebra.

The effects of these mass transfer processes on groundwater flow depend on the original permeability structure of the Culebra rocks and the location of the mass transfer. The volumes of minerals that may precipitate and/or dissolve in the Culebra as a result of the injection of Castile or Salado brine through a borehole will not affect the existing spatial variability in the permeability field significantly.

Predicted radionuclide transport rates in the Culebra assume that the dolomite matrix is diffusively accessed by the contaminants. The possible inhibition of matrix diffusion by secondary mineral precipitation on fracture walls, due to mixing between brines and Culebra porewater, was addressed by Wang (1998). Wang showed that the volume of secondary minerals precipitated due to this mechanism was too small to significantly affect matrix porosity and accessibility.

Consequently, the effects of ***Borehole -Induced Mineralization*** on permeability and groundwater flow within the Culebra, as a result of brines introduced via any existing abandoned boreholes, and boreholes drilled and abandoned in the near-future, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.11.4 Future Human EPs

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.11.4.1 *Borehole-Induced Mineralization*

Fluid flow between hydraulically conductive horizons through a future borehole may result in changes in permeability in the affected units through mineral precipitation. However, the effects of mineral precipitation as a result of flow through a future borehole in the controlled area will be similar to the effects of mineral precipitation as a result of flow through an existing or near-future borehole (see FEP H32 and H33). Thus, ***Borehole-Induced Mineralization*** associated

with flow through a future borehole has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.12 FEP Number: H36
FEP Title: ***Borehole-Induced Geochemical Changes***

SCR-5.2.1.12.1 Screening Decision: UP (HCN)
DP (Future)
SO-C for units other than the Culebra

Geochemical changes that occur inside the controlled area as a result of long-term flow associated with HCN, and future abandoned boreholes are accounted for in PA calculations.

SCR-5.2.1.12.2 Summary of New Information

No new information has been identified. This FEP has been modified for editorial purposes.

SCR-5.2.1.12.3 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Movement of fluids through abandoned boreholes could result in ***Borehole*-Induced Geochemical Changes** in the receiving units such as the Salado interbeds or Culebra, and thus alter radionuclide migration rates in these units.

SCR-5.2.1.12.3.1 *Geochemical Effects of Borehole Flow*

Movement of fluids through abandoned boreholes could result in ***Borehole*-Induced Geochemical Changes** in the receiving units such as the Salado interbeds or Culebra. Such geochemical changes could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area, or if they occur as a result of flow through existing boreholes within the controlled area through their effects on colloid transport and sorption.

The contents of the waste disposal panels provide the main source of colloids in the disposal system. Thus, consistent with the discussion for ***Borehole*-Induced Geochemical Changes** (H24), colloid transport as a result of flow through existing and near-future abandoned boreholes has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in H24, sorption within the Culebra is accounted for in PA calculations. The sorption model used accounts for the effects of changes in sorption in the Culebra as a result of flow through existing and near-future abandoned boreholes.

Consistent with the screening discussion in H24, the effects of changes in sorption in the Dewey Lake inside the controlled area as a result of flow through existing and near-future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-5.2.1.12.4 Future Human EPs

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.12.4.1 *Geochemical Effects of Flow Through Abandoned Boreholes*

Movement of fluids through abandoned boreholes could result in ***Borehole*-Induced Geochemical Changes** in the receiving units, such as the Salado interbeds or Culebra. Such geochemical changes could alter radionuclide migration rates within the disposal system in the affected units through their effects on colloid transport and sorption.

The waste disposal panels provide the main source of colloids in the disposal system. Colloid transport within the Culebra as a result of long-term flow associated with future abandoned boreholes that intersect the waste disposal region are accounted for in PA calculations, as described in Sections 6.4.3.6 and 6.4.6.2.1. Consistent with the discussion in H24, colloid transport as a result of flow through future abandoned boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The Culebra is the most transmissive unit in the disposal system and it is the most likely unit through which significant radionuclide transport could occur. Therefore, colloid transport in units other than the Culebra, as a result of flow through future abandoned boreholes, has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in H24, sorption within the Culebra is accounted for in PA calculations. The sorption model accounts for the effects of changes in sorption in the Culebra as a result of flow through future abandoned boreholes.

Consistent with the screening discussion in H24, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of flow through future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-5.2.2 Excavation-Induced Flow

SCR-5.2.2.1 FEP Number: H37
FEP Title: ***Changes in Groundwater Flow due to Mining***

SCR-5.2.2.1.1 Screening Decision: UP (HCN)
DP (Future)

Changes in groundwater flow due to HCN, and future potash mining are accounted for in PA calculations.

SCR-5.2.2.1.2 Summary of New Information

Changes in groundwater flow due to HCN, and future mining are included in PA calculations of groundwater flow and transport through the Culebra. The FEP description and screening argument have been modified slightly to reflect recent activities, but the screening decision is unchanged.

SCR-5.2.2.1.3 Screening Argument

Excavation activities may result in hydrological disturbances of the disposal system. Subsidence associated with excavations may affect groundwater flow patterns through increased hydraulic conductivity within and between units. Fluid flow associated with excavation activities may also result in changes in brine density and geochemistry in the disposal system.

SCR-5.2.2.1.3.1 *Historical, Current, and Near-Future Human EPs*

Currently, potash mining is the only excavation activity currently taking place in the vicinity of the WIPP that could affect hydrogeological or geochemical conditions in the disposal system. Potash is mined in the region east of Carlsbad and up to 5 km (3.1 mi) from the boundaries of the controlled area. Mining of the McNutt in the Salado is expected to continue in the vicinity of the WIPP (see Section 2.3.1.1): the DOE assumes that all economically recoverable potash in the vicinity of the WIPP (outside the controlled area) will be extracted in the near future.

SCR-5.2.2.1.3.2 *Hydrogeological Effects of Mining*

Potash mining in the Delaware Basin typically involves constructing vertical shafts to the elevation of the ore zone and then extracting the minerals in an excavation that follows the trend of the ore body. Potash has been extracted using conventional room and pillar mining, secondary mining where pillars are removed, and modified long-wall mining methods. Mining techniques used include drilling and blasting (used for mining langbeinite) and continuous mining (commonly used for mining sylvite). The DOE (Westinghouse 1994, pp. 2-17 to 2-19) reported investigations of subsidence associated with potash mining operations located near the WIPP. The reported maximum total subsidence at potash mines is about 1.5 m (5 ft), representing up to 66 percent of initial excavation height, with an observed angle of draw from the vertical at the edge of the excavation of 58 degrees. The DOE (Westinghouse 1994 pp. 2-22 to 2-23) found no evidence that subsidence over local potash mines had caused fracturing sufficient to connect the mining horizon to water-bearing units or the surface. However,

subsidence and fracturing associated with mining in the McNutt in the vicinity of the WIPP may allow increased recharge to the Rustler units and affect the lateral hydraulic conductivity of overlying units, such as the Culebra, which could influence the direction and magnitude of fluid flow within the disposal system. Such ***Changes in Groundwater Flow Due to Mining*** are accounted for in calculations of undisturbed performance of the disposal system. The effects of any increased recharge that may be occurring are in effect included by using heads measured in 2000 (which should reflect that recharge) to calibrate Culebra transmissivity fields and calculate transport through those fields (Beauheim 2002). Changes (increases) in Culebra transmissivity are incorporated directly in the modeling of flow and transport in the Culebra (see Section 6.4.6.2.3).

Potash mining, and the associated processing outside the controlled area, have changed fluid densities within the Culebra, as demonstrated by the areas of higher densities around boreholes WIPP-27 and WIPP-29 (Davies 1989, p. 43). Transient groundwater flow calculations (Davies 1989, pp. 77 - 81) show that brine density variations to the west of the WIPP site caused by historical and current potash processing operations will not persist because the rate of groundwater flow in this area is fast enough to flush the high density groundwaters to the Pecos River. These calculations also show that accounting for the existing brine density variations in the region east of the WIPP site, where hydraulic conductivities are low, would have little effect on the direction or rate of groundwater flow. Therefore, changes in fluid densities from historical and current Human EPs have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The distribution of existing leases and potash grades suggests that near-future mining will take place to the north, west, and south of the controlled area (see CCA Appendix DEL). A localized increase in fluid density in the Culebra, in the mined region or elsewhere outside the controlled area, would rotate the flow vector towards the downdip direction (towards the east). A comparison of the relative magnitudes of the pressure gradient and the density gradient (based on an analysis identical to that presented for fluid leakage to the Culebra through boreholes) shows that the density effect is of low consequence to the performance of the disposal system.

SCR-5.2.2.1.4 Future Human EPs

Consistent with 40 CFR § 194.32(b), consideration of future mining may be limited to potash mining within the disposal system. Within the controlled area, the McNutt provides the only potash of appropriate quality. The extent of possible future potash mining within the controlled area is discussed in Section 2.3.1.1. Criteria concerning the consequence modeling of future mining are provided in 40 CFR § 194.32(b): the effects of future mining may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system. Thus, consistent with 40 CFR § 194.32(b), ***Changes in Groundwater Flow Due to Mining*** within the controlled area are accounted for in calculations of the disturbed performance of the disposal system (see Section 6.4.6.2.3).

SCR-5.2.2.2 FEP Number: H38
FEP Title: ***Changes in Geochemistry Due to Mining***

SCR-5.2.2.2.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Changes in geochemistry due to HCN potash mining have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Changes in geochemistry due to future mining have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.2.2.2 Summary of New Information

The only natural resource being mined underground currently near WIPP is potash in the McNutt, and it is the only mineral considered for future mining. Potash mining is also the only excavation activity currently taking place in the vicinity of the WIPP that could affect hydrogeological or geochemical conditions in the disposal system. It appears unlikely that underground mining will impact the site geochemistry during the time of passive institutional controls, and a conclusion of no near-term consequence is screened from future events as per 40 CFR § 194.25. Changes have been made to the screening argument. However, the screening decision remains the same.

SCR-5.2.2.2.3 Screening Argument

SCR-5.2.2.2.3.1 *Historical, Current, and Near-Future Human EPs*

Potash mining is the only excavation activity currently taking place in the vicinity of the WIPP that could affect hydrogeological or geochemical conditions in the disposal system. Potash is mined in the region east of Carlsbad and up to 5 km (1.5 mi) from the boundaries of the controlled area. Mining of the McNutt in the Salado is expected to continue in the vicinity of the WIPP (see Section 2.3.1.1): the DOE assumes that all economically recoverable potash in the vicinity of the WIPP (outside the controlled area) will be extracted in the near future.

SCR-5.2.2.2.3.2 *Geochemical Effects of Mining*

Fluid flow associated with excavation activities may result in geochemical disturbances of the disposal system. Some waters from the Culebra reflect the influence of current potash mining, having elevated potassium to sodium ratios. However, potash mining has had no significant effect on the geochemical characteristics of the disposal system. Solution mining, which involves the injection of freshwater to dissolve the ore body, can be used for extracting sylvite. The impact on the WIPP of neighboring potash mines was examined in greater detail by D'Appolonia (1982). D'Appolonia noted that attempts to solution mine sylvite in the Delaware Basin failed due to low ore grade, thinness of the ore beds, and problems with heating and pumping injection water. See discussion for potash mining FEP H13. Thus, ***Changes in Groundwater Flow Due to Mining*** (HCN) have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.2.2.3.3 *Future Human EPs*

Consistent with 40 CFR § 194.32(b), consideration of future mining may be limited to potash mining within the disposal system. Within the controlled area, the McNutt provides the only potash of appropriate quality. The extent of possible future potash mining within the controlled area is discussed in Section 2.3.1.1. Criteria concerning the consequence modeling of future mining are provided in 40 CFR § 194.32(b): the effects of future mining may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system. Thus, consistent with 40 CFR § 194.32(b), changes in groundwater flow due to mining within the controlled area are accounted for in calculations of the disturbed performance of the disposal system (see Section 6.4.6.2.3). Other potential effects, such as ***Changes in Groundwater Flow Due to Mining***, have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.2.3 FEP Number H58
FEP Title: ***Solution Mining for Potash***

SCR-5.2.2.3.1 Screening Decision: SO-R (HCN)
SO-R (future)

HCN, and future ***Solution Mining*** for ***Potash*** *has been eliminated from PA calculations on regulatory grounds. HCN, and future solution mining for other resources have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-5.2.2.3.2 Summary of New Information

In the CCA, ***Solution Mining for Potash*** was not identified as a separate FEP, although all components of the solution mining process were accounted for in FEPs screening, albeit in a piecemeal fashion. For example, the drilling of the borehole necessary for solution injection or effluent recovery is addressed in FEP H8, ***Drilling For Other Resources***, mainly because the physical and mechanical effects of the drilling activity do not vary based on the type of resource being sought, nor on the final intended use of the borehole; e.g., disposal well, injection well, solution mining, or oil and gas extraction. The removal of an ore as a result of solution mining is ultimately the same as if conventional mining processes had removed the ore. Potash mining using conventional methods is addressed in FEP H13, ***Conventional Underground Potash Mining***. The ultimate effect of such ore body removal is believed to be the eventual subsidence of the overlying units and the associated impact upon hydraulic conductivity. This has been demonstrated to have a negligible effect on performance of the WIPP, and is in fact accounted for in PA by EPA's requisite treatment of potash mining above the waste area.

Although the original FEP baseline considered different types of mineral and petroleum resource exploration/exploitation, it did not initially consider the possibility of brine mining (solution mining), even though this has occurred in the Delaware Basin. EPA noted this oversight in their March 1997 letter requesting additional information regarding the CCA (EPA 1997). In response to this request, the DOE submitted two memos (Hicks 1997a, 1997b) that addressed both ***Solution Mining for Potash*** and solution mining for brine. In EPA's TSD for §194.32, "Scope of Performance Assessments," EPA noted that these memos adequately supported the screening decisions presented in the CCA.

For CRA-2004, solution mining has been explicitly represented within the FEPs baseline through the additions of FEP H58***, Solution Mining for Potash*** and FEP H59, ***Solution Mining for Other Resources***. The reassessment of these EPs confirms that no significant developments have occurred since the CCA, and the arguments used by Hicks remain valid. The creation of these FEPs will aid in clarifying and separating the activities related to solution mining from conventional mining for potash as addressed in FEP H13.

SCR-5.2.2.3.3 Screening Argument

Currently, no ***Solution Mining for Potash*** occurs in the Carlsbad Potash District (CPD). The prospect of using solution-mining techniques for extracting potash has been identified in the region, but has not been implemented. A pilot plant for secondary solution mining of sylvite in the Clayton Basin, just north of the Delaware Basin was permitted, and concept planning took place during the mid-1990s and was noted by the EPA in their Response to Comments to the CCA (EPA 1998b). Five years later, this pilot project has yet to begin. Therefore, it is premature to consider this an operational solution mining activity. More importantly, the proposed site is outside the Delaware Basin.

The potash reserves evaluated by Griswold and Griswold (1999) and NMBMMR (1995) at WIPP are of economic importance in only two ore zones; the 4th and the 10th and contain two minerals of economic importance, langbeinite and sylvite. The ore in the 10th ore zone is primarily sylvite with some langbeinite and the ore in the 4th zone is langbeinite with some sylvite. Langbeinite falls between gypsum and polyhalite in solubility and dissolves at a rate 1000 times slower than sylvite (Heyn 1997). Halite, the predominate gangue mineral present, is much more soluble than the langbeinite. Due to the insolubility of langbeinite, sylvite is the only ore that could be mined using a solution mining process. Mining for sylvite by solutioning would cause the langbeinite to be lost because conventional mining could not be done in conjunction with a solution mining process.

Communiqués with IMC Global (Heyn 1997, Prichard 2003), indicate that rock temperature is critical to the success of a solution-mining endeavor. IMC Global's solution mines in Michigan and Saskatchewan are at depths around 914 m (3,000 ft) or greater, at which rock temperatures are higher. The ore zones at WIPP are shallow, at depths of 457 to 549 m (1500 to 1800 ft), with fairly cool rock temperatures. David Prichard of IMC Global states that solution mining is energy intensive and the cool temperature of the rock would add to the energy costs. In addition, variable concentrations of confounding minerals (such as kainite and leonite) will cause problems with the brine chemistry.

Typically, solution mining is used for potash:

- when deposits are at depths in excess of 914 m (3000 ft) and rock temperatures are high or are geologically too complex to mine profitably using conventional underground mining techniques;

- to recover the potash pillars at the end of a mine's life; or

- when a mine is unintentionally flooded with waters from underlying or overlying rock strata and conventional mining is no longer feasible.

Douglas W. Heyn (chief chemist of IMC Kalium) provided written testimony to EPA related to the Agency's rulemaking activities on the CCA. Heyn concluded that "the rational choice for extracting WIPP potash ore reserves would be by conventional room and pillar mechanical means" (Heyn 1997). It is the opinion of IMC Global that no company will ever attempt solution mining of the ores in or near the WIPP (Heyn 1997, Prichard 2003).

The impact on the WIPP of neighboring potash mines was examined in detail by D'Appolonia (1982) and evaluated the possible effects of ***Solution Mining for Potash*** or other evaporite minerals. According to D'Appolonia (1982), and in agreement with Heyn (1997) of IMC Global Inc, solution mining of langbeinite is not technically feasible because the ore is less soluble than the surrounding evaporite minerals. Solution mining of sylvite was unsuccessfully attempted in the past by the Potash Company of America and Continental Potash, both ore bodies currently owned by Mississippi Chemical. Failure of solution mining was attributed to low ore grade, thinness of the ore beds, and problems with heating and pumping injection water. Unavailability of water in the area would also impede implementation of this technique. For these reasons, solution mining is not currently used in the Carlsbad Potash District.

Serious technical and economic obstacles exist that render ***Solution Mining for Potash*** very unlikely in the vicinity of the WIPP. Expectedly, no operational example of this technology exists in the CPD; that is, ***Solution Mining for Potash*** in not considered a current practice in the area. For this reason, consideration of solution mining on the disposal system in the future may be excluded on regulatory grounds. For example, the EPA stated in their Response to Comments, Section 8, Issue GG (EPA 1998b):

> …However, the Agency emphasizes that, in accordance with the WIPP compliance criteria, solution mining does not need to be included in the PA. As previously discussed, potash solution mining is not an ongoing activity in the Delaware Basin. Section 194.32(b) of the rule limits assessment of mining effects to excavation mining. Thus the solution mining scenarios proposed are excluded on regulatory grounds after repository closure. Prior to or soon after disposal, solution mining is an activity that could be considered under Section 194.32(c). However, DOE found that potash solution mining is not an ongoing activity in the Delaware Basin; and one pilot project examining solution mining in the Basin is not substantive evidence that such mining is expected to occur in the near future. (Even if mining were assumed to occur in the near future, the proposed scenarios would not be possible because, even though solution mining might occur, there would be no intruding borehole to provide a pathway into the repository: active institutional controls would preclude such drilling during the first 100 years after disposal.) Furthermore, Section 194.33(d) states that PA need not analyze the effects of techniques used for resource recovery (e.g. solution mining) after a borehole is drilled in the future.

No new data or information has become available that compromise, reduce, or invalidate the project's position on whether ***Solution Mining for Potash*** should be included in the PA calculations. Therefore, conventional mining activities will continue to be incorporated into the WIPP PA as directed by the EPA Compliance Application Guidance (CAG) (EPA 1996c). It remains to be seen if a viable potash solution mining project (or others like it) ever progress beyond the planning phase. Construction of a facility for solution mining is an expensive undertaking, and its use as a final recovery method implies that marginal (residual) ore quantities

are available. Because the Carlsbad Potash District mines are in their mature stages (declining) of production, the significant financing required for a solution mining facility may not become available. Nonetheless, at the time of this FEP reassessment, this technology is not being employed. Therefore, a screening based on the future states assumption at 40 CFR § 194.25(a) is appropriate for this mining technique. Further, the proposed site is outside the Delaware Basin making it outside the scope of consideration.

SCR-5.2.2.4 FEP Number: H59
FEP Title: ***Solution Mining for Other Resources***

SCR-5.2.2.4.1 Screening Decision: SO-C (HCN)
SO-C (future)

HCN, and future ***Solution Mining for Potash*** *has been eliminated from PA calculations on regulatory grounds. HCN, and future* ***Solution Mining for Other Resources*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-5.2.2.4.2 Summary of New Information

See summary for H58.

SCR-5.2.2.4.3 Screening Argument

Brine wells (solution mining for brine) exist within the Delaware Basin, although none within the vicinity of the WIPP. Sulfur extraction using the Frasch process began in 1969 and continued for three decades at the Culberson County Rustler Springs mine near Orla, Texas. Solution mining for the purposes of creating a storage cavity has not occurred within the New Mexico portion of the Delaware Basin.

SCR-5.2.2.4.4 Solution Mining for Brine

Oil and gas reserves in the Delaware Basin are located in structures within the Delaware Mountain Group and lower stratigraphic units. Boreholes drilled to reach these horizons pass through the Salado and Castile Formations that comprise thick halite and other evaporite units. To avoid dissolution of the halite units during drilling and prior to casing of the borehole, the fluid used for lubrication, rotating the drilling-bit cutters, and transporting cuttings (drilling mud) must be saturated with respect to halite. Most oil- and gas-field drilling operations in the Delaware Basin therefore use saturated brine (10 to 10.5 pounds per gallon) as a drilling fluid until reaching the Bell Canyon Formation, where intermediate casing is set.

One method of providing saturated brine for drilling operations is solution mining, whereby fresh water is pumped into the Salado Formation, allowed to reach saturation with respect to halite, and then recovered. This manufactured brine is then transported to the drilling site by water tanker.

Two principal techniques are used for solution mining; single-borehole operations, and doublet or two-borehole operations.

In single-borehole operations, a borehole is drilled into the upper part of the halite unit. After casing and cementing this portion of the borehole, the borehole is extended, uncased into the halite formation. An inner pipe is installed from the surface to the base of this uncased portion of the borehole. During operation, fresh water is pumped down the annulus of the borehole. This dissolves halite over the uncased portion of the borehole, and saturated brine is forced up the inner tube to the surface.

In doublet operations, a pair of boreholes are drilled, cased and cemented into the upper part of the halite unit. The base of the production well is set some feet below the base of the injection well. In the absence of natural fractures or other connections between the boreholes, hydrofracturing is used to induce fractures around the injection well. During operation, fresh water is pumped down the injection well. This initially dissolves halite from the walls of the fractures and the resulting brine is then pumped from the production well. After a period of operation a cavity develops between the boreholes as the halite between fractures is removed. Because of its lower density, fresh water injected into this cavity will rise to the top and dissolve halite from the roof of the cavity. As the brine density increases it sinks within the cavern and saturated brine is extracted from the production well.

SCR-5.2.2.4.4.1 *Current Brine Wells within the Vicinity of WIPP*

Brine wells are classified as Class II injection wells. In the Delaware Basin, the process includes injecting fresh water into a salt formation to create a saturated brine solution which is then extracted and utilized as a drilling agent. These wells are tracked by the Delaware Basin Drilling Surveillance Program on a continuing basis. Supplemental information provided to the EPA in 1997 showed 11 brine wells in the Delaware Basin. Since that time, additional information has shown that there are 15 brine wells within the Delaware basin, of which four are plugged and abandoned. This results in 11 currently active brine wells. Table SCR-3 provides information on these wells.

Table SCR-3. Delaware Basin Brine Well Status

County	Location	API No.	Well Name and No.	Operator	Status
Eddy	22S-26E-36	3001521842	City of Carlsbad #WS-1	Key Energy Services	Brine Well
Eddy	22S-27E-03	3001520331	Tracy #3	Ray Westall	Plugged Brine Well
Eddy	22S-27E-17	3001522574	Eugenie #WS-1	I & W Inc	Brine Well
Eddy	22S-27E-17	3001523031	Eugenie #WS-2	I & W Inc	Plugged Brine Well
Loving	Blk 29-03	4230110142	Lineberry Brine Station #1	Chance Properties	Brine Well
Loving	Blk 01-82	4230130680	Chapman Ford #BR1	Herricks & Son Co.	Plugged Brine Well
Loving	Blk 33-80	4230180318	Mentone Brine Station #1D	Basic Energy Services	Brine Well
Loving	Blk 29-28	4230180319	East Mentone Brine Station #1	Permian Brine Sales, Inc.	Plugged Brine Well

Table SCR-3. Delaware Basin Brine Well Status — Continued

County	Location	API No.	Well Name and No.	Operator	Status
Loving	Blk 01-83	4230180320	North Mentone #1	Chance Properties	Brine Well
Reeves	Blk 56-30	4238900408	Orla Brine Station #1D	Mesquite SWD Inc.	Brine Well
Reeves	Blk 04-08	4238920100	North Pecos Brine Station #WD-1	Chance Properties	Brine Well
Reeves	Blk 07-21	4238980476	Coyanosa Brine Station #1	Chance Properties	Brine Well
Ward	Blk 17-20	4247531742	Pyote Brine Station #WD-1	Chance Properties	Brine Well
Ward	Blk 01-13	4247534514	Quito West Unit #207	Seaboard Oil Co.	Brine Well
Ward	Blk 34-174	4247582265	Barstow Brine Station #1	Chance Properties	Brine Well

While these wells are within the Delaware Basin, none are within the vicinity of the WIPP. The nearest brine well to the WIPP is the Eugenie #WS-1, located within the city limits of Carlsbad, New Mexico. This well is approximately 48 km (30 mi) from the WIPP site.

SCR-5.2.2.4.5 Solution Mining for Other Minerals

Currently, there are no ongoing solution mining activities within the vicinity of WIPP. The Rustler Springs sulfur mine located in Culberson County, Texas, began operations in 1969 and continued until it was officially closed in 1999. This mine used the Frasch process to extract molten sulfur (Cunningham 1999).

SCR-5.2.2.4.6 Solution Mining for Gas Storage

No gas storage cavities have been solution mined within the New Mexico portion of the Delaware Basin. Five gas storage facilities exist within the general vicinity of the WIPP; however only one is within the Delaware basin. This one New Mexico Delaware Basin facility uses a depleted gas reservoir for storage and containment; it was not solution mined (Appendix DATA).

SCR-5.2.2.4.7 Solution Mining for Disposal

Solution mining can be used to create a disposal cavity in bedded salt. Such disposal cavities can be used for the disposal of naturally occurring radioactive material (NORM) or other wastes. No such cavities have been mined or operated within the vicinity of the WIPP.

SCR-5.2.2.4.8 Effects of Solution Mining

SCR-5.2.2.4.8.1 *Subsidence*

Regardless of whether the single-borehole or two-borehole technique is used for solution mining, the result is a subsurface cavity which could collapse and lead to subsidence of overlying strata. Gray (1991) quoted earlier analyses that show cavity stability is relatively high if the cavity has

at least 15 m (50 ft) of overburden per million cubic feet of cavity volume (26.9 m per 50,000 m^3). There are two studies - discussed below - of the size of solution mining cavities in the Carlsbad region. These studies concern the Carlsbad Eugenie Brine Wells and the Carlsbad Brine Well and show that neither of these cavities are currently close to this critical ratio, but that subsidence in the future, given continued brine extraction, is a possibility.

Hickerson (1991) considered the potential for subsidence resulting from operation of the Carlsbad Eugenie Brine wells, where fresh water is injected into a salt section at a depth of 178 m (583 ft) and brine is recovered through a borehole at a depth of 179 m (587 ft). The boreholes are 100 m (327 ft) apart. Hickerson noted that the fresh water, being less dense than brine, tends to move upwards, causing the dissolution cavern to grow preferentially upwards. Thus, the dissolution cavern at the Carlsbad Eugenie Brine wells is approximately triangular in cross-section, being bounded by the top of the salt section and larger near the injection well. Hickerson estimated that brine production from 1979 until 1991 had created a cavern of about 9.6×10^4 m^3 (3.4×10^6 ft^3). The size of this cavern was estimated as 107 m (350 ft) by 47 m (153 ft) at the upper surface of the cavern with a depth of 39 m (127 ft).

Gray (1991) investigated the potential for collapse and subsidence at the Carlsbad Brine Well. Based on estimated production rates between 1976 and 1991, approximately 9.6×10^4 m^3 (3.4×10^6 ft^3) of salt has been dissolved at this site. The well depth is 216 m (710 ft) and thus there are about 64 m (210 ft) of overburden per million cubic feet of capacity (112 m of overburden per 50,000 m^3 of capacity).

Gray (1991) also estimated the time required for the cavity at the Carlsbad Brine Well to reach the critical ratio. At an average cavity growth rate of 6.4×10^3 m^3 per year (2.25×10^5 ft^3 per year), a further 50 years of operation would be required before cavity stability was reduced to levels of concern. A similar calculation for the Carlsbad Eugenie Brine well, based on an overburden of 140 m (460 ft) and an estimated average cavity growth rate of 7.9×10^3 m^3 per year (2.8×10^5 ft^3 per year), shows that a further 15 years of operation is required before the cavity reaches the critical ratio.

SCR-5.2.2.4.8.2 *Hydrogeological Effects*

In regions where solution mining takes place, the hydrogeology could be affected in a number ways:

- Subsidence above a large dissolution cavity could change the vertical and lateral hydraulic conductivity of overlying units.
- Extraction of fresh water from aquifers for solution mining could cause local changes in pressure gradients.
- Loss of injected fresh water or extracted brine to overlying units could cause local changes in pressure gradients.

The potential for subsidence to take place above solution mining operations in the region of Carlsbad is discussed above. Some subsidence could occur in the future if brine operations

continue at existing wells. Resulting fracturing may change permeabilities locally in overlying formations. However, because of the restricted scale of the solution mining at a particular site, and the distances between such wells, such fracturing will have no significant effect on hydrogeology near the WIPP.

Solution mining operations in the Delaware Basin extract water from shallow aquifers so that, even if large drawdowns are permitted, the effects on the hydrogeology will be limited to a relatively small area around the operation. Since all the active operations are more than 32 km (20 mi) from the WIPP, there will be no significant effects on the hydrogeology near the WIPP.

Discharge plans for solution mining operations typically include provision for annual mechanical integrity tests at one and one-half the normal operating pressure for four hours (OCD 1994). Thus, the potential for loss of integrity and consequent leakage of freshwater or brine to overlying formations is low. If, despite these annual tests, large water losses did take place, from either injection or production wells, the result would be low brine yields and remedial actions would most likely be taken by the operators.

SCR-5.2.2.4.8.3 *Geochemical Effects*

Solution mining operations could affect the geochemistry of surface or subsurface water near the operation if there were brine leakage from storage tanks or production wells. Discharge plans for solution mining operations specify the measures to be taken to prevent leakage and to mitigate the effects of any that do take place. These measures include berms around tanks and annual mechanical integrity testing of wells (OCD 1994). The potential for changes in geochemistry is therefore low, and any brine losses that did take place would be limited by remedial actions taken by the operator. In the event of leakage from a production well, the effect on geochemistry of overlying formation waters would be localized and, given the distance of such wells from the WIPP site, such leakage would have no significant effect on geochemistry near the WIPP.

SCR-5.2.2.4.9 Conclusion of Low Consequence

Brine production through solution mining takes place in the Delaware Basin, and the DOE assumes it will continue in the near future.

Despite oil and gas exploration and production taking place in the vicinity of the WIPP site, the nearest operating solution mine is more than 32 km (20 mi) from the WIPP site. These locations are too far from the WIPP site for any changes in hydrogeology or geochemistry, from subsidence or fresh water or brine leakage, to affect the performance of the disposal system. Thus, the effects of historical, current, near-future, and future ***Solution Mining for Other Resources*** in the Delaware Basin can be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.3 Explosion-Induced Flow

SCR-5.2.3.1 FEP Number: H39
FEPs Title: ***Changes in Groundwater Flow due to Explosions***

SCR-5.2.3.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Changes in groundwater flow due to historical explosions have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Changes in groundwater flow due to future explosions have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.3.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.2.3.1.3 Screening Argument

SCR-5.2.3.1.3.1 *Historical, Current, and Near-Future Human EPs*

The small-scale explosions that have been used in the Delaware Basin to fracture oil- and natural-gas-bearing units to enhance resource recovery have been too deep to have disturbed the hydrology of the disposal system (see FEP H19).

Also, as discussed in ***Underground Nuclear Device Testing*** (H20), the Delaware Basin has been used for an isolated nuclear test (Project Gnome), approximately 13 km (8 mi) southwest of the WIPP waste disposal region. An induced zone of increased permeability was observed to extend 46 m (150 ft) laterally from the point of the explosion. The increase in permeability was primarily associated with motions and separations along bedding planes, the major pre-existing weaknesses in the rock. This region of increased permeability is too far from the WIPP site to have had a significant effect on the hydrological characteristics of the disposal system. Thus, ***Changes in Groundwater Flow Due to Explosions*** in the past have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.3.1.3.2 *Future Human EPs*

The criterion in 40 CFR § 194.32(a) relating to the scope of PAs limits the consideration of future human actions to mining and drilling. Also, consistent with 40 CFR § 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, ***Changes in Groundwater Flow Due to Explosions*** in the future have been eliminated from PA calculations on regulatory grounds.

SCR-5.3 Geomorphological Events and Processes

SCR-5.3.1 Land Use Changes

SCR-5.3.1.1 FEP Number: H40
FEP Title: ***Land Use Changes***

SCR-5.3.1.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Land Use Changes *have been eliminated from PA calculations on regulatory grounds.*

SCR-5.3.1.1.2 Summary of New Information

The Delaware Basin monitoring program monitors land use activities in the WIPP vicinity. This program has not identified new planned uses for land in the vicinity of the WIPP (DOE 2002). This FEP discussion has been updated with additional information about industrial land uses in the region.

SCR-5.3.1.1.3 Screening Argument

This section discusses surface activities that could affect the geomorphological characteristics of the disposal system and result in changes in infiltration and recharge conditions. The potential effects of water use and control on disposal system performance are discussed in FEPs H42 through H46.

SCR-5.3.1.1.4 Historical, Current, and Near-Future Human EPs

Surface activities that take place at present in the vicinity of the WIPP site include those associated with potash mining, oil and gas reservoir development, water extraction, and grazing. Additionally, a number of archeological investigations have taken place within the controlled area that were aimed at protecting and preserving cultural resources. Elsewhere in the Delaware Basin, sand, gravel, and caliche are produced through surface quarrying. The only surface activity that has the potential to affect the disposal system is potash tailings, salt tailings (both potash and WIPP) and effluent disposal. Potash tailings ponds may act as sources of focused recharge to the Dewey Lake and Rustler units.

Three potash tailings piles/ponds are in operation that might be influencing groundwater flow at the WIPP site. These are the Mississippi Potash Inc. (MPI) East tailings pile, approximately 10 km (6 mi) due north of the WIPP, the MPI West tailings pile in the northwest arm of Nash Draw, and the IMC Kalium tailings pile, approximately 10 km (6 mi) due west of the WIPP in Nash Draw. These tailings piles have been in operation for decades—disposal at the MPI East site, the youngest of the piles, began in 1965. Brine disposal at these locations affects Rustler groundwaters in Nash Draw, as shown by the hydrochemical facies D waters described by Siegel et al. (1991, p. 2-61). Brine disposal also affects heads in Nash Draw, and these head effects likely propagate to the WIPP site as well. These effects, however, predate water-level monitoring for the WIPP and have been implicitly included when defining boundary heads for Culebra flow models. The Culebra transmissivity fields developed for the CRA used water

levels measured in 2000 to define model boundary conditions. Thus, the effects of brine disposal at the tailings piles can be considered to be included in PA calculations. These effects are expected to continue in the near future.

The Delaware Basin monitoring program monitors land use activities in the WIPP vicinity. This program has not identified new planned uses for land in the vicinity of the WIPP (DOE 2002). Therefore, consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), ***Land Use Changes*** in the near future in the vicinity of the WIPP have been eliminated from PA calculations on regulatory grounds.

SCR-5.3.1.1.5 Future Human EPs

The criterion in 40 CFR § 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and PAs "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions." Therefore, no future ***Land Use Changes*** need be considered in the vicinity of the WIPP, and they have been eliminated from PA calculations on regulatory grounds.

SCR-5.3.1.2 FEP Number: H41
FEP Title: ***Surface Disruptions***

Future ***Surface Disruptions*** not affecting hydrogeologic or geologic conditions have been eliminated from PA calculations on regulatory grounds. Future tailings ponds, if situated in Nash Draw, are expected to change Culebra (and Magenta) heads, similar to existing ones. Future tailings ponds outside of Nash Draw would not be expected to alter Culebra heads because leakage from the ponds would not be able to propagate through the low-permeability lower Dewey Lake clastics and Rustler anhydrites overlying the Culebra during the 100 years or less that such a pond might be in operation. Because PA calculations already include the present-day effects of tailings ponds in Nash Draw on heads, as well as the effects of future potash mining on the permeability of the Culebra (which has much greater potential to alter flow than changes in head), future potash tailings ponds may be screened out on the basis of low consequence.

SCR-5.3.1.2.1 Screening Decision: UP (HCN)
SO-R (Future)

*The effects of HCN **Surface Disruptions** have been screened out on the basis of low consequence if they have no potential to affect the disposal system, or are implicitly included in PA calculations when they might affect the disposal system. The effects of future **Surface Disruptions** have been eliminated from PA calculations on regulatory grounds.*

SCR-5.3.1.2.2 Summary of New Information

The screening argument for ***Surface Disruptions*** has changed. Per the original screening decision, surface activities in the vicinity of the WIPP site have disrupted the surface, but most surface activities have no potential to affect the disposal system and are, therefore, screened out on the basis of low consequence. However, the effects of the activity capable of altering the

disposal system (disposal of potash effluent) are included in our modeling of current conditions (i.e., heads) at and around the site. Therefore, the screening decision has been changed from SO-C to UP for HCN. Discussion regarding these anthropogenic effects is found in Section 2.2.1.4.2.2 of the CRA. There are no planned changes to land use in the vicinity of the WIPP in the near future, and future events that might disrupt the surface at the WIPP site are screened out on the basis of regulatory criteria.

SCR-5.3.1.2.3 Screening Argument

This section discusses surface activities that could affect the geomorphological characteristics of the disposal system and result in changes in infiltration and recharge conditions. The potential effects of water use and control on disposal system performance are discussed in FEPs H42 through H46.

SCR-5.3.1.2.4 Historical, Current, and Near-Future Human EPs

Surface activities that take place at present in the vicinity of the WIPP site include those associated with potash mining, oil and gas reservoir development, water extraction, and grazing. Additionally, a number of ***Archeological Investigations*** have taken place within the controlled area that were aimed at protecting and preserving cultural resources. Elsewhere in the Delaware Basin, sand, gravel, and caliche are produced through surface quarrying. The only surface activity that has the potential to affect the disposal system is potash tailings, salt tailings (both potash and WIPP) and effluent disposal. Potash tailings ponds may act as sources of focused recharge to the Dewey Lake and Rustler units.

Three potash tailings piles/ponds are in operation that might be influencing groundwater flow at the WIPP site. These are the Mississippi Potash Inc. (MPI) East tailings pile, approximately 10 km (6 mi) due north of the WIPP, the MPI West tailings pile in the northwest arm of Nash Draw, and the IMC Kalium tailings pile, approximately 10 km (6 mi) due west of the WIPP in Nash Draw. These tailings piles have been in operation for decades—disposal at the MPI East site, the youngest of the piles, began in 1965. Brine disposal at these locations affects Rustler groundwaters in Nash Draw, as shown by the hydrochemical facies D waters described by Siegel et al. (1991, p. 2-61). Brine disposal also affects heads in Nash Draw, and these head effects likely propagate to the WIPP site as well. These effects, however, predate water-level monitoring for the WIPP and have been implicitly included when defining boundary heads for Culebra flow models. The Culebra transmissivity fields developed for the CRA used water levels measured in 2000 to define model boundary conditions. Thus, the effects of brine disposal at the tailings piles can be considered to be included in PA calculations. These effects are expected to continue in the near future.

The Delaware Basin monitoring program monitors land use activities in the WIPP vicinity. This program has not identified new planned uses for land in the vicinity of the WIPP (DOE 2002). Therefore, consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), ***Land Use Changes*** in the near future in the vicinity of the WIPP have been eliminated from PA calculations on regulatory grounds.

SCR-5.3.1.2.5 Future Human EPs

The criterion in 40 CFR § 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and PAs "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions." Therefore, no future ***Land Use Changes*** need be considered in the vicinity of the WIPP, and they have been eliminated from PA calculations on regulatory grounds.

Future ***Surface Disruptions*** not affecting hydrogeologic or geologic conditions have been eliminated from PA calculations on regulatory grounds. Future tailings ponds, if situated in Nash Draw, are expected to change Culebra (and Magenta) heads, similar to existing ones. Future tailings ponds outside of Nash Draw would not be expected to alter Culebra heads because leakage from the ponds would not be able to propagate through the low-permeability lower Dewey Lake clastics and Rustler anhydrites overlying the Culebra during the 100 years or less that such a pond might be in operation. Because PA calculations already include the present-day effects of tailings ponds in Nash Draw on heads, as well as the effects of future potash mining on the permeability of the Culebra (which has much greater potential to alter flow than changes in head), future potash tailings ponds may be screened out on the basis of low consequence.

SCR-5.4 Surface Hydrological Events and Processes

SCR-5.4.1 Water Control and Use

SCR-5.4.1.1 FEP Number(s): H42, H43, and H44
FEP Title(s): ***Damming of Streams and Rivers*** (H42)
Reservoirs (H43)
Irrigation (H44)

SCR-5.4.1.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

The effects of HCN ***Damming of Streams and Rivers, Reservoirs,*** *and* ***Irrigation*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future* ***Damming of Streams and Rivers, Reservoirs,*** *and* ***Irrigation*** *have been eliminated from PA calculations on regulatory grounds.*

SCR-5.4.1.1.2 Summary of New Information

No new information has been identified related to these FEPs. Changes have been made for editorial purposes.

SCR-5.4.1.1.3 Screening Argument

Irrigation and damming, as well as other forms of water control and use, could lead to localized changes in recharge, possibly leading to increased heads locally, thereby affecting flow directions and velocities in the Rustler and Dewey Lake.

SCR-5.4.1.1.4 Historical, Current, and Near-Future Human EPs

In the WIPP area, two topographically low features, the Pecos River and Nash Draw, are sufficiently large to warrant consideration for damming. Dams and ***Reservoirs*** already exist along the Pecos River. However, the Pecos River is far enough from the waste panels (19 km [12 mi]) that the effects of ***Damming of Streams and Rivers,*** and ***Reservoirs*** can be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Nash Draw is not currently dammed, and based on current hydrological and climatic conditions, there is no reason to believe it will be dammed in the near future.

Irrigation uses water from rivers, lakes, impoundments, and wells to supplement the rainfall in an area to grow crops. ***Irrigation*** in arid environments needs to be efficient and involves the spreading of a relatively thin layer of water for uptake by plants, so little water would be expected to infiltrate beyond the root zone. However, some water added to the surface may infiltrate and reach the water table, affecting groundwater flow patterns. ***Irrigation*** currently takes place on a small scale within the Delaware Basin but not in the vicinity of the WIPP, and the extent of ***Irrigation*** is not expected to change in the near future. Such ***Irrigation*** has no significant effect on the characteristics of the disposal system. Thus, the effects of ***Irrigation*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.4.1.1.5 Future Human EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future ***Damming of Streams and Rivers, Reservoirs,*** *and* ***Irrigation*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.4.1.2 FEP Number: H45
FEP Title: ***Lake Usage***

SCR-5.4.1.2.1 Screening Decision: SO-R (HCN)
SO-R (Future)

The effects of ***Lake Usage*** *have been eliminated from PA calculations on regulatory grounds.*

SCR-5.4.1.2.2 Summary of New Information

No new information has been identified related to this FEP. Changes have been made for editorial purposes.

SCR-5.4.1.2.3 Screening Argument

Irrigation and damming, as well as other forms of water control and use, could lead to localized changes in recharge, possibly leading to increased heads locally, thereby affecting flow directions and velocities in the Rustler and Dewey Lake. Surface activities, such as those associated with potash mining, could also affect soil and surface water chemistry. Note that the potential effects of geomorphological changes through land use are discussed in H40 and H41.

SCR-5.4.1.2.4 Historical, Current, and Near-Future Human EPs

As discussed in Section 2.2.2, there are no major natural lakes or ponds within 8 km (5 mi) of the site. To the northwest, west, and southwest, Red Lake, Lindsey Lake, and Laguna Grande de la Sal are more than 8 km (5 mi) from the site, at elevations of 914 to 1,006 m (3,000 to 3,300 ft). Laguna Gatuña, Laguna Tonto, Laguna Plata, and Laguna Toston are playas more than 16 km (10 mi) north and are at elevations of 1,050 m (3,450 ft) or higher.

Waters from these lakes are of limited use. Therefore human activities associated with lakes have been screened out of PA calculations based on regulatory grounds supported by 194.32(c) and 194.54(b).

SCR-5.4.1.2.5 Future Human EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future ***Lake Usage*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.4.1.3 FEP Number: H46
FEP Title: ***Altered Soil or Surface Water Chemistry by Human Activities***

SCR-5.4.1.3.1 Screening Decision: SO-C (HCN)
SO-R (Future)

The effects of HCN ***Altered Soil or Surface Water Chemistry by Human Activities*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future* ***Altered Soil or Surface Water Chemistry by Human Activities*** *have been eliminated from PA calculations on regulatory grounds.*

SCR-5.4.1.3.2 Summary of New Information

No new information has been identified related to this FEP. Changes have been made for editorial purposes.

SCR-5.4.1.3.3 Screening Argument

Irrigation and damming, as well as other forms of water control and use, could lead to localized changes in recharge, possibly leading to increased heads locally, thereby affecting flow directions and velocities in the Rustler and Dewey Lake. Surface activities, such as those associated with potash mining, could also affect soil and surface water chemistry.

SCR-5.4.1.3.4 Historical, Current, and Near-Future Human EPs

Potash mining effluent and runoff from oil fields have altered soil and surface water chemistry in the vicinity of the WIPP. However, the performance of the disposal will not be sensitive to soil and surface water chemistry. Therefore, ***Altered Soil or Surface Water Chemistry by Human Activities*** has been eliminated from PA calculations on the basis of low consequence to the

performance of the disposal system. The effects of effluent from potash processing on groundwater flow are discussed in H37.

SCR-5.4.1.3.5 Future Human EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a) that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future ***Altered Soil or Surface Water Chemistry by Human Activities*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.5 Climatic Events and Processes

SCR-5.5.1 Anthropogenic Climate Change

SCR-5.5.1.1 FEP Number(s): H47, H48, and H49
FEP Title: ***Greenhouse Gas Effects*** (H47)
Acid Rain (H48)
Damage to the Ozone (N49)

SCR-5.5.1.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

*The effects of anthropogenic climate change (**Acid Rain**, **Greenhouse Gas Effects**, and **Damage to the Ozone** layer) have been eliminated from PA calculations on regulatory grounds.*

SCR-5.5.1.1.2 Summary of New Information

No new information has been identified related to this FEP. Changes have been made for editorial purposes.

SCR-5.5.1.1.3 Anthropogenic Climate Change

The effects of the current climate and natural climatic change are accounted for in PA calculations, as discussed in Section 6.4.9. However, human activities may also affect the future climate and thereby influence groundwater recharge in the WIPP region. The effects of anthropogenic climate change may be on a local to regional scale (***Acid Rain*** *(H48)*) or on a regional to global scale (***Greenhouse Gas Effects*** *(H47)* and ***Damage to the Ozone*** layer *(H49)*). Of these anthropogenic effects, only the ***Greenhouse Gas Effect*** could influence groundwater recharge in the WIPP region. However, consistent with the future states assumptions in 40 CFR § 194.25, compliance assessments and PAs need not consider indirect anthropogenic effects on disposal system performance. Therefore, the effects of anthropogenic climate change have been eliminated from PA calculations on regulatory grounds.

SCR-5.6 Marine Events and Processes

SCR-5.6.1 Marine Activities

SCR-5.6.1.1.1 FEP Number(s): H50, H51 & H52
FEP Title(s): ***Costal Water Use*** (H50)
Seawater Use (H51)
Estuarine Water (H52)

SCR-5.6.1.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

*HCN, and future **Coastal Water Use, Seawater Use,** and **Estuarine Water** use have been eliminated from PA calculations on regulatory grounds.*

SCR-5.6.1.1.2 Summary of New Information

No new information has been identified related to this FEP. Changes have been made for editorial purposes.

SCR-5.6.1.1.3 Screening Argument

This section discusses the potential for Human EPs related to marine activities to affect infiltration and recharge conditions in the vicinity of the WIPP.

SCR-5.6.1.1.4 Historical, Current, and Near-Future Human EPs

The WIPP site is more than 800 km (480 mi) from the nearest seas, and hydrological conditions in the vicinity of the WIPP have not been affected by marine activities. Furthermore, consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), consideration of HCN human activities is limited to those activities that have occurred or are expected to occur in the vicinity of the disposal system. Therefore, Human EPs related to marine activities (such as ***Coastal Water Use, Seawater Use,*** *and* ***Estuarine Water*** use) have been eliminated from PA calculations on regulatory grounds.

SCR-5.6.1.1.5 Future Human EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a) that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future marine activities (such as ***Coastal Water Use, Seawater Use,*** *and* ***Estuarine Water*** use) have been eliminated from PA calculations on regulatory grounds.

SCR-5.7 Ecological Events and Processes

SCR-5.7.1 Agricultural Activities

SCR-5.7.1.1 FEP Number(s): H53, H54, and H55
FEP Title(s): ***Arable Farming*** (H53)

Ranching (H54)
Fish Farming (H55)

SCR-5.7.1.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

*The effects of HCN **Ranching** and **Arable Farming** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The effects of changes in future **Ranching** and **Arable Farming** practices have been eliminated from PA calculations on regulatory grounds. **Fish Farming** has been eliminated from PA calculations on regulatory grounds.*

SCR-5.7.1.1.2 Summary of New Information

No new information has been identified related to these FEPs.

SCR-5.7.1.1.3 Screening Argument

Agricultural activities could affect infiltration and recharge conditions in the vicinity of the WIPP. Also, application of acids, oxidants, and nitrates during agricultural practice could alter groundwater geochemistry.

SCR-5.7.1.1.4 Historical, Current, and Near-Future Human EPs

Grazing leases exist for all land sections immediately surrounding the WIPP and grazing occurs within the controlled area (see Section 2.3.2.2). Although grazing and related crop production have had some control on the vegetation at the WIPP site, these activities are unlikely to have affected subsurface hydrological or geochemical conditions. The climate, soil quality, and lack of suitable water sources all mitigate against agricultural development of the region in the near future. Therefore, the effects of HCN ***Ranching*** *and* ***Arable Farming*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), agricultural activities, such as ***Fish Farming***, that have not taken place and are not expected to take place in the near future in the vicinity of the WIPP have been eliminated from PA calculations on regulatory grounds.

SCR-5.7.1.1.5 Future Human EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a) that limit the scope of consideration of future human activities in PAs to mining and drilling. Also, the criterion in 40 CFR § 194.25(a) concerned with predictions of the future states of society requires that compliance assessments and PAs “shall assume that characteristics of the future remain what they are at the time the compliance application is prepared.” Therefore, the effects of changes in future agricultural practices (such as ***Ranching***, ***Arable Farming***, and ***Fish Farming***) have been eliminated from PA calculations on regulatory grounds.

SCR-5.7.2 Social and Technological Development

SCR-5.7.2.1 FEP Number: H56
FEP Title: ***Demographic Change and Urban Development***

SCR-5.7.2.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Demographic Change and Urban Development *in the near future and in the future have been eliminated from PA calculations on regulatory grounds.*

SCR-5.7.2.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.7.2.1.3 Screening Argument

Social and technological changes in the future could result in the development of new communities and new activities in the vicinity of the WIPP that could have an impact on the performance of the disposal system.

Demography in the WIPP vicinity is discussed in Section 2.3.2.1. The community nearest to the WIPP site is the town of Loving, 29 km (18 mi) west-southwest of the site center. There are no existing plans for urban developments in the vicinity of the WIPP in the near future. Furthermore, the criterion in 40 CFR § 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and PAs "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared." Therefore, ***Demographic Change and Urban Development*** in the vicinity of the WIPP and technological developments have been eliminated from PA calculations on regulatory grounds.

SCR-5.7.2.2 FEP Number: H57
FEP Title: ***Loss of Records***

SCR-5.7.2.2.1 Screening Decision: NA (HCN)
DP (Future)

Loss of Records *in the future is accounted for in PA calculations.*

SCR-5.7.2.2.2 Summary of New Information

No new information has been identified for this FEP. Changes have been made for editorial purposes.

SCR-5.7.2.2.3 Screening Argument

Human activities will be prevented from occurring within the controlled area in the near future. However, PAs must consider the potential effects of human activities that might take place within the controlled area at a time when institutional controls cannot be assumed to eliminate

completely the possibility of human intrusion. Consistent with 40 CFR § 194.41(b), the DOE assumes no credit for active institutional controls for more than 100 years after disposal. Also, consistent with 40 CFR § 194.43(c), the DOE originally assumed in the CCA that passive institutional controls do not eliminate the likelihood of future human intrusion entirely. The provisions at 40 CFR 194.43(c) allow credit for passive institutional controls by reducing the likelihood of human intrusions for several hundred years. In DOE (1996a), the DOE took credit for these controls that include records retention by reducing the probability of intrusion for the first 600 years after active controls cease. EPA disallowed this credit during the original certification (EPA 1998a). DOE no longer takes credit for passive institutional controls in PA, effectively assuming that all public records and archives relating to the repository are lost 100 years after closure. Therefore, DOE continues to include the ***Loss of Records*** FEP within PA and does not include credit for passive institutional controls.

SCR-6.0 WASTE AND REPOSITORY-INDUCED FEPS

This section presents screening arguments and decisions for waste- and repository-induced FEPs. Of the original 108 waste- and repository-induced FEPs, 61 remain unchanged, 43 were updated with new information or were edited for clarity and completeness, three screening decisions were changed, and one FEP was deleted from the baseline by combining with other, more appropriate FEPs.

SCR-6.1 Waste and Repository Characteristics

SCR-6.1.1 Repository Characteristics

SCR-6.1.1.1 FEP Number: W1
FEP Title: ***Disposal Geometry***

SCR-6.1.1.1.1 Screening Decision: UP

*The WIPP repository **Disposal Geometry** is accounted for in PA calculations.*

SCR-6.1.1.1.2 Summary of New Information

Representation of the repository within the PA has changed since the CCA; however, the screening argument and decision remain unchanged. **Disposal *Geometry*** is accounted for in PA calculations.

SCR-6.1.1.2 Screening Argument

Disposal *Geometry* is described in Chapter 3, Section 3.2 and is accounted for in the setup of PA calculations (Section 6.4.2).

SCR-6.1.2 Waste Characteristics

SCR-6.1.2.1 FEP Number: W2 and W3
FEP Title: ***Waste Inventory***
Heterogeneity of Waste Forms

SCR-6.1.2.1.1 Screening Decision: UP

*The **Waste Inventory** and **Heterogeneity of Waste Forms** are accounted for in PA calculations.*

SCR-6.1.2.1.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.1.2.1.3 Screening Argument

Waste characteristics, comprising the ***Waste Inventory*** and the ***Heterogeneity of Waste Forms***, are described in Chapter 4.0. The waste inventory is accounted for in PA calculations in deriving the dissolved actinide source term and gas generation rates (Sections 6.4.3.5 and 6.4.3.3). The distribution of contact-handled (CH) and remote-handled (RH) transuranic (TRU) waste within the repository leads to room scale heterogeneity of the waste forms, which is accounted for in PA calculations when considering the potential activity of waste material encountered during inadvertent borehole intrusion (Section 6.4.7).

SCR-6.1.3 Container Characteristics

SCR-6.1.3.1 FEP Number: W4
FEP Title: ***Container Form***

SCR-6.1.3.1.1 Screening Decision: SO-C - Beneficial

*The **Container Form** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.1.3.1.2 Summary of New Information

The inventories of container materials (i.e., steel and plastic liners) are included in WIPP long-term PAs as input parameters of the gas generation model (Wang and Brush 1996). The ***Container Form*** has been eliminated from PA calculations on the basis of its beneficial effect on retarding radionuclide release. The PAs assume instantaneous container failure and waste dissolution according to the source-term model. The screening argument has been modified to incorporate additional information, although the screening decision has not changed.

SCR-6.1.3.1.3 Screening Argument

As in the CCA, the CRA calculations show that a significant fraction of steel and other Fe-base materials will remain undegraded over 10,000 years (see Helton et al. 1998). For all undisturbed cases, at least 30 percent of the steels will remain uncorroded at the end of 10,000 years. In addition, it is assumed in both CCA and CRA-2004 calculations that there is no microbial degradation of plastic container materials in 75 percent of PA realizations (Wang and Brush 1996). All these undegraded container materials will (1) prevent the contact between brine and radionuclides; (2) decrease the rate and extent of radionuclide transport due to high tortuosity along the flow pathways and, as a result, increase opportunities for metallic Fe and corrosion products to beneficially reduce radionuclides to lower oxidation states. Therefore, the container form can be eliminated on the basis of its beneficial effect on retarding radionuclide transport. Both CCA and CRA assume instantaneous container failure and waste dissolution according to the source-term model. In CCA Appendix WCL, a minimum quantity of metallic Fe was specified to ensure sufficient reactants to reduce radionuclides to lower and less soluble oxidation states. This requirement is met as long as there are no substantial changes in container materials. The 2003 update to the TWBIR Revision 3 (Appendix DATA, Attachment F) indicates that the density of steel in container materials currently reported by the sites has an average value of 170 kg/m^3. This is an increase over what was reported for the CCA (139 to 230 kg/m^3)(8.6 to 14.3 lb/ft^3). Therefore, the current inventory estimates indicate that there is a sufficient quantity of metallic iron to ensure reduction of radionuclides to lower and less soluble oxidation states. The 2003 update to the TWBIR Revision 3 (Appendix DATA, Attachment F) indicates that the density of plastic liners currently reported by the sites has an average value of 16 kg/m3. This is a decrease from 26 to 21 kg/m^3 (1.6 to 1.3 lb/ft^3) reported in the CCA.

SCR-6.1.3.2 FEP Number: W5
FEP Title: ***Container Material Inventory***

SCR-6.1.3.2.1 Screening Decision: UP

*The **Container Material Inventory** is accounted for in PA calculations.*

SCR-6.1.3.2.2 Summary of New Information

No new information has been identified that relates to the screening of this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA; however, the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.1.3.2.3 Screening Argument

The ***Container Material Inventory*** is described in Chapter 4.0, and is accounted for in PA calculations through the estimation of gas generation rates (Section 6.4.3.3).

SCR-6.1.4 Seal Characteristics

SCR-6.1.4.1 FEP Number: W6 and W7
FEP Title: ***Seal Geometry*** (W6)
Seal Physical Properties (W7)

SCR-6.1.4.1.1 Screening Decision: UP

*The **Seal Geometry** and **Seal Physical Properties** are accounted for in PA calculations.*

SCR-6.1.4.1.2 Summary of New Information

No new information has been identified that relates to the screening of these FEPs. Since these FEP are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation are described in Section 6.4.4.

SCR-6.1.4.1.3 Screening Argument

Seal (shaft seals, panel closures, and drift closures) characteristics, including ***Seal Geometry*** and ***Seal Physical Properties***, are described in Section 3.3.2 and are accounted for in PA calculations through the representation of the seal system in BRAGFLO and the permeabilities assigned to the seal materials (Section 6.4.4).

SCR-6.1.4.2 FEPs Number: W8
FEP Title: ***Seal Chemical Composition***

SCR-6.1.4.2.1 Screening Decision: SO-C Beneficial

*The **Seal Chemical Composition** has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-6.1.4.2.2 Summary of New Information

In the CCA, ***Seal Chemical Composition*** was screened out on the basis of predicted beneficial consequences, which are not credited in PA calculations. Recent publications provide support for the screening argument that chemical interactions between the cement seals and the brine will be of beneficial consequence to the performance of the disposal system, through sorption and sequestration of radionuclides. Ignoring adsorption simplifies the PA calculations, and is expected to produce somewhat more conservative results. However, because little or no upward flow is predicted to occur through the seals, the overall effect on PA results may not be significant.

The original FEP description has been modified slightly to include supporting evidence for the argument that chemical interactions between the cement seals and the brine will be of beneficial consequence to the performance of the disposal system.

SCR-6.1.4.2.3 Screening Argument

Seal (shaft seals, panel closures, and drift closures) characteristics, including ***Seal Geometry*** and ***Seal Physical Properties***, are described in CCA Chapter 3.0 and are accounted for in PA calculations through the representation of the seal system in BRAGFLO and the permeabilities assigned to the seal materials. The effect of shaft ***Seal Chemical Composition*** on actinide speciation and mobility has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.1.4.2.4 Repository Seals

Certain repository materials have the potential to interact with groundwater and significantly alter the chemical speciation of any radionuclides present. In particular, extensive use of cementitious materials in the seals may have the capacity to buffer groundwaters to extremely high pH (for example, Bennett et al. 1992, pp. 315 - 325). At high pH values, the speciation and adsorption behavior of many radionuclides is such that their dissolved concentrations are reduced in comparison with near-neutral waters. This effect reduces the migration of radionuclides in dissolved form.

Several recent publications describe strong actinide (or actinide analog) sorption by cement (Altenheinhaese et al. 1994; Wierczinski et al. 1998; Pointeau et al. 2001), or sequestration by incorporation into cement alteration phases (Gougar et al. 1996, Dickson and Glasser 2000). These provide support for the screening argument that chemical interactions between the cement seals and the brine will be of beneficial consequence to the performance of the disposal system.

The effects of cementitious seals on groundwater chemistry have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.1.5 Backfill Characteristics

SCR-6.1.5.1 FEP Number: W9
FEP Title: ***Backfill Physical Properties***

SCR-6.1.5.1.1 Screening Decision: SO-C

Backfill Physical Properties *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.1.5.1.2 Summary of New Information

No new information related to this FEP has been identified. Changes have been made for editorial purposes.

SCR-6.1.5.1.3 Screening Argument

A chemical backfill is being added to the disposal room to buffer the chemical environment. The backfill characteristics were previously described in CCA Appendix BACK with additional information contained in Appendix BARRIERS. The mechanical and thermal effects of backfill

are discussed in W35 and W72 respectively, where they have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Backfill will result in an initial permeability for the disposal room lower than that of an empty cavity, so neglecting the hydrological effects of backfill is a conservative assumption with regard to brine inflow and radionuclide migration. Thus, ***Backfill Physical Properties*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.1.5.2 FEP Number: W10
FEP Title: ***Backfill Chemical Composition***

SCR-6.1.5.2.1 Screening Decision: UP

*The **Backfill Chemical Composition** is accounted for in PA calculations.*

SCR-6.1.5.2.2 Summary of New Information

No new information related to this FEP has been identified. Changes have been made for editorial purposes.

SCR-6.1.5.2.3 Screening Argument

A chemical backfill is added to the disposal room to buffer the chemical environment. The backfill characteristics are described in Section 6.4.3.4. The mechanical and thermal effects of backfill are discussed in FEP W35 and FEP W72, respectively, where they have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. ***Backfill Chemical Composition*** is accounted for in PA calculations in deriving the dissolved and colloidal actinide source terms (Section 6.4.3).

SCR-6.1.6 Post-Closure Monitoring Characteristics

SCR-6.1.6.1 FEPs Number: W11
FEP Title: ***Post-Closure Monitoring***

SCR-6.1.6.1.1 Screening Decision: SO-C

*The potential effects of **Post-Closure Monitoring** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.1.6.1.2 Summary of New Information

The FEP screening argument has been modified to include reference to 40 CFR 194.42(d). Compliance with this requirement ensures that ***Post-Closure Monitoring*** is not detrimental to the performance of the repository. No changes have been proposed to the ***Post-Closure Monitoring*** program as presented in the CCA. The pre-closure monitoring program has not identified a condition relating to the act of monitoring that would be detrimental to the performance of the repository after closure (Annual Site Environmental Reports and Annual Compliance Monitoring Parameter Assessments). No changes have been made to the FEP description, screening argument, or screening decision.

SCR-6.1.6.1.3 Screening Argument

Post-Closure Monitoring is required by 40 CFR § 191.14(b) as an assurance requirement to "detect substantial and detrimental deviations from expected performance." The DOE has designed the monitoring program (see CCA Appendix MON) so that the monitoring methods employed are not detrimental to the performance of the disposal system (40 CFR 194.42(d)). Non-intrusive monitoring techniques are used so that ***Post-Closure Monitoring*** would not impact containment or require remedial activities. In summary, the effects of monitoring have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.2 Radiological Features, Events, and Processes

SCR-6.2.1 Radioactive Decay and Heat

SCR-6.2.1.1 FEP Number: W12
FEP Title: ***Radionuclide Decay and Ingrowth***

SCR-6.2.1.1.1 Screening Decision: UP

Radionuclide Decay and Ingrowth *are accounted for in PA calculations.*

SCR-6.2.1.1.2 Summary of New Information

No new information related to this FEP has been identified. No changes have been made.

SCR-6.2.1.1.3 Screening Argument

Radionuclide Decay and Ingrowth are accounted for in PA calculations (see Section 6.4.12.4).

SCR-6.2.1.2 FEP Number: W13
FEP Title: ***Heat From Radioactive Decay***

SCR-6.2.1.2.1 Screening Decision: SO-C

The effects of temperature increases as a result of radioactive decay have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.2.1.2.2 Summary of New Information

WIPP transportation restrictions do not allow the thermal load of the WIPP to exceed 10 kW/acre (NRC 2002). Transportation requirements restrict the thermal load from RH-TRU waste containers to no more than 300 watts per container (NRC 2002). However, the limit on the surface dose equivalent rate of the RH-TRU containers (1,000 rem/hr) is more restrictive and equates to a thermal load of only about 60 watts per container. Based on the thermal loads permitted, the maximum temperature rise in the repository from radioactive decay heat should be less than 2°C (3.6°F). The 2003 update to the TWBIR Revision 3 (Appendix DATA, Attachment F) indicates that the radionuclide inventory is lower than previously estimated for the CCA.

Thus, all CRA radioactive decay heating screening arguments are bounded by the previous CCA screening arguments.

SCR-6.2.1.3 Screening Argument

Radioactive decay of the waste emplaced in the repository will generate heat. The importance of ***Heat from Radioactive Decay*** depends on the effects that the induced temperature changes would have on mechanics (W29 - W31), fluid flow (W40 and W41), and geochemical processes (W44 through W75). For example, extreme temperature increases could result in thermally induced fracturing, regional uplift, or thermally driven flow of gas and brine in the vicinity of the repository.

The design basis for the WIPP requires that the thermal loading does not exceed 10 kW per acre. Transportation restrictions also require that the thermal power generated by waste in an RH-TRU container shall not exceed 300 watts (NRC 2002).

The DOE has conducted numerous studies related to ***Heat from Radioactive Decay***. The following presents a brief summary of these past analyses. First, a numerical study to calculate induced temperature distributions and regional uplift is reported in DOE (1980 pp. 9-149 to 9-150). This study involved estimation of the thermal power of CH-TRU waste containers. The DOE (1980 pp. 9-149) analysis assumed the following:

- All CH-TRU waste drums and boxes contain the maximum permissible quantity of plutonium. The fissionable radionuclide content for CH-TRU waste containers was assumed to be no greater than 200 grams per 0.21 m^3 (7 ounces per 7.4 ft^3) drum and 350 grams per 1.8 m^3 (12.3 ounces per 63.6 ft^3) standard waste box (plutonium-239 fissile gram equivalents).

- The plutonium in CH-TRU waste containers is weapons grade material producing heat at 0.0024 watts per gram. Thus, the thermal power of a drum is approximately 0.5 watts and that of a box is approximately 0.8 watts.

- Approximately 3.7×10^5 m^3 (1.3×10^7 ft^3) of CH-TRU waste are distributed within a repository enclosing an area of 7.3×10^5 m^2 (7.9×10^6 ft^2). This is a conservative assumption in terms of quantity and density of waste within the repository, because the maximum capacity of the WIPP is 1.756×10^5 m^3 (6.2×10^6 ft^3) for all waste (as specified by the Land Withdrawal Act [LWA]) to be placed in an enclosed area of approximately 5.1×10^5 m^2 (16 mi^2).

- Half of the CH-TRU waste volume is placed in drums and half in boxes so that the repository will contain approximately 900,000 drums and 900,000 boxes. Thus, a calculated thermal power of 0.7 watts per square meter (2.8 kW/acre) of heat is generated by the CH-TRU waste.

- Insufficient RH-TRU waste would be emplaced in the repository to influence the total thermal load.

Under these assumptions, Thorne and Rudeen (1981) estimated the long-term temperature response of the disposal system to waste emplacement. Calculations assumed a uniform initial power density of 2.8 kW/acre (0.7 W/m^2) which decreases over time. Thorne and Rudeen (1981) attributed this thermal load to RH-TRU waste, but the DOE (1980), more appropriately, attributed this thermal load to CH-TRU waste based on the assumptions listed above. Thorne and Rudeen (1981) estimated the maximum rise in temperature at the center of a repository to be 1.6°C (2.9°F) at 80 years after waste emplacement.

More recently, Sanchez and Trellue (1996) estimated the maximum thermal power of an RH-TRU waste container. The Sanchez and Trellue (1996) analysis involved inverse shielding calculations to evaluate the thermal power of an RH-TRU container corresponding to the maximum permissible surface dose of 1000 rem per hour. The following calculational steps were taken in the Sanchez and Trellue (1996) analysis:

- Calculate the absorbed dose rate for gamma radiation corresponding to the maximum surface dose equivalent rate of 1000 rem per hour. Beta and alpha radiation are not included in this calculation because such particles will not penetrate the waste matrix or the container in significant quantities. Neutrons are not included in the analysis because the maximum dose rate from neutrons is 270 millirem per hour, and the corresponding neutron heating rate will be insignificant.

- Calculate the exposure rate for gamma radiation corresponding to the absorbed dose rate for gamma radiation.

- Calculate the gamma flux density at the surface of a RH-TRU container corresponding to the exposure rate for gamma radiation. Assuming the gamma energy is 1.0 megaelectron volts, the maximum allowable gamma flux density at the surface of a RH-TRU container is about 5.8×10^8 gamma rays per square centimeter per second.

- Determine the distributed gamma source strength, or gamma activity, in an RH-TRU container from the surface gamma flux density. The source is assumed to be shielded such that the gamma flux is attenuated by the container and by absorbing material in the container. The level of shielding depends on the matrix density. Scattering of the gamma flux, with loss of energy, is also accounted for in this calculation through inclusion of a gamma buildup factor. The distributed gamma source strength is determined assuming a uniform source in a right cylindrical container. The maximum total gamma source (gamma curies) is then calculated for a RH-TRU container containing 0.89 m^3 (31.4 ft^3) of waste. For the waste of greatest expected density (about 6,000 kg/m^3 (360 lb/ft^3), the gamma source is about 2×10^4 Ci/m^3 (566 Ci/ft^3).

- Calculate the total curie load of a RH-TRU container (including alpha and beta radiation) from the gamma load. The ratio of the total curie load to the gamma curie load was estimated through examination of the radionuclide inventory presented in CCA Appendix BIR. The gamma curie load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of total curie load to gamma curie load of RH-TRU waste was calculated to be 1.01.

- Calculate the thermal load of a RH-TRU container from the total curie load. The ratio of thermal load to curie load was estimated through examination of the radionuclide inventory presented in CCA Appendix BIR. The thermal load and the total curie load for each radionuclide listed in the WIPP inventory were summed. Based on these summed loads the ratio of thermal load to curie load of RH-TRU waste was calculated to be about 0.0037 watts per curie. For a gamma source of 2×10^4 Ci/m^3 (566 Ci/ft^3), the maximum permissible thermal load of a RH-TRU container is about 70 W/m^3 (2 W/ft^3). Thus, the maximum thermal load of a RH-TRU container is about 60 W, and the transportation limit of 300 W will not be achieved.

Note that Sanchez and Trellue (1996) calculated the average thermal load for a RH-TRU container to be less than 1 W. Also, the total RH-TRU heat load is less than 10 percent of the total heat load in the WIPP. Thus, the total thermal load of the RH-TRU waste will not significantly affect the average rise in temperature in the repository resulting from decay of CH-TRU waste.

Temperature increases will be greater at locations where the thermal power of an RH-TRU container is 60 W, if any such containers are emplaced. Sanchez and Trellue (1996) estimated the temperature increase at the surface of a 60 W RH-TRU waste container. Their analysis involved solution of a steady-state thermal conduction problem with a constant heat source term of 70 W/m^3 (2 W/ft^3). These conditions represent conservative assumptions because the thermal load will decrease with time as the radioactive waste decays. The temperature increase at the surface of the container was calculated to be about 3°C (5.4°F).

In summary, analysis has shown that the average temperature increase in the WIPP repository, due to radioactive decay of the emplaced CH- and RH-TRU waste, will be less than 2°C (3.6°F). Temperature increases of about 3°C (5.4°F) may occur in the vicinity of RH-TRU containers with the highest allowable thermal load of about 60 watts (based on the maximum allowable surface dose equivalent for RH-TRU containers). Potential heat generation from nuclear criticality is discussed in W14 and exothermic reactions and the effects of repository temperature changes on mechanics are discussed in the set of FEPs grouped as W29, W30, W31, W72, and W73. These FEPs have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The previous FEPs screening arguments for the CCA used a bounding radioactivity heat load of 0.5 watts/drum for the CH-TRU waste containers. With a total CH-TRU volume of 168,500 m^3 (~5,950,000 ft^3) this corresponds to approximately 810,000 55-gallon drum equivalents with a corresponding heat load of > 400 kW used for the CCA FEPs screening arguments. From Sanchez and Trellue (1996), it can be seen that a realistic assessment of the heat load, based on radionuclide inventory data in the Transuranic Waste Baseline Inventory Report (TWBIR) is less than 100 kW. Thus, the CCA FEPs incorporate a factor of safety of at least four.

Since the 2003 update to the TWBIR Revision 3 (Appendix DATA, Attachment F) indicates that the radionuclide inventory is lower than that previously estimated for the CCA), all CRA-2004 radioactive decay heating screening arguments are bounded by the previous CCA screening arguments. Verification of the fact that heat loads for the CRA-2004 are less than those for the

CCA is provided in Djordjevic (2003). Djordjevic (2003) is a recalculation of the work of Sanchez and Trellue (1996) using radionuclide data from Appendix DATA, Attachment F.

SCR-6.2.1.4 FEPs Number: W14
FEPs Title: ***Nuclear Criticality: Heat***

SCR-6.2.1.4.1 Screening Decision: SO-P

Nuclear Criticality *has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-6.2.1.4.2 Summary of New Information

Heat generated via **Nuclear Criticality** was screened out based on the low probability that a criticality event would occur. The updated information for the WIPP disposal inventory of fissile material (Appendix DATA, Attachment F; Leigh 2003a) indicates that the expected WIPP-scale quantity is 43 percent lower than previously estimated in CCA TWBIR Rev 3. Thus, all CRA-2004 criticality screening arguments are conservatively bounded by the previous CCA screening arguments (Rechard et al. 1996, 2000, and 2001).

SCR-6.2.1.4.3 Screening Argument

Nuclear **Criticality** refers to a sustained fission reaction that may occur if fissile radionuclides reach both a sufficiently high concentration and total mass (where the latter parameter includes the influence of enrichment of the fissile radionuclides). In the subsurface, the primary effect of a nuclear reaction is the production of heat.

Nuclear criticality (near and far field) was eliminated from PA calculations for the WIPP for waste contaminated with TRU radionuclides. The probability for criticality within the repository is low (there are no mechanisms for concentrating fissile radionuclides dispersed amongst the waste). Possible mechanisms for concentration in the waste disposal region include high solubility, compaction, sorption, and precipitation. First, the maximum solubility of ^{239}Pu in the WIPP repository, the most abundant fissile radionuclide, is orders of magnitude lower than necessary to create a critical solution. The same is true for ^{235}U, the other primary fissile radionuclide. Second, the waste is assumed to be compacted by repository processes to one fourth its original volume. This compaction is still an order of magnitude too disperse (many orders of magnitude too disperse if neutron absorbers that prevent criticality (for example, ^{238}U) are included). Third, any potential sorbents in the waste would be fairly uniformly distributed throughout the waste disposal region; consequently, concentration of fissile radionuclides in localized areas through sorption is improbable. Fourth, precipitation requires significant localized changes in brine chemistry; small local variations are insufficient to separate substantial amounts of ^{239}Pu from other actinides in the waste disposal region (for example, 11 times more ^{238}U is present than ^{239}Pu).

Criticality away from the repository (following an inadvertent human intrusion) has a low probability because (1) the amount of fissile material transported from the repository is small; (2) host rock media have small porosities (insufficient for generation of sizable precipitation zone); and (3) no credible mechanism exists for the concentrating fissile material during transport (the

natural tendency is for transported to be dispersed). As discussed in Section 6.4.6.2 and CCA Appendix PA, Attachment MASS Section MASS.15, the dolomite porosity consists of intergranular porosity, vugs, microscopic fractures, and macroscopic fractures. As discussed in Section 6.4.5.2, porosity in the marker beds consists of partially healed fractures that may dilate as pressure increases. Advective flow in both units occurs mostly through macroscopic fractures. Consequently, any potential deposition through precipitation or sorption is constrained by the depth to which precipitation and sorption occur away from fractures. This geometry is not favorable for fission reactions and eliminates the possibility of criticality. Thus, **Nuclear Criticality** has been eliminated from PA calculations on the basis of low probability of occurrence.

Screening arguments made in Rechard et al. (1996) are represented in greater detail in Rechard et al. (2000, 2001). A major finding among the analysis results in the screening arguments is the determination that fissile material would need to be reconcentrated by three orders of magnitude in order to be considered in a criticality scenario. These previous arguments were based on radionuclide information from Revision 3 of the TWBIR (DOE 1996b). Of the 135 radionuclides presented in that TWBIR database, only 17 are possible contributors to fissile material. Table SCR-4 identifies these nuclides along with their conversion factors for specific activity and ^{239}Pu fissile gram equivalents (^{239}Pu fissile gram equivalent (FGE) per ANSI/ANS-18.5).

Radioactivity inventories for the fissile radionuclides used in the CCA and CRA-2004 are presented in Table SCR-5. Also shown in Table SCR-5 are the corresponding FGE inventories. Key amongst the information presented in this table is updated information for the WIPP disposal inventory of fissile material (Appendix DATA, Attachment F; Leigh 2003a) indicates that the expected WIPP-scale quantity is 43 percent lower than previously estimated in TWBIR Rev. 3. Thus, all CRA-2004 criticality screening arguments are conservatively bounded by the previous CCA screening arguments (Rechard et al. 1996, 2000, and 2001).

SCR-6.2.2 Radiological Effects on Material Properties

SCR-6.2.2.1 FEP Number: W15, W16, and W17
FEP Title: ***Radiological Effects on Waste*** (W15)
Radiological Effects on Containers (W16)
Radiological Effects on Seals (W17)

SCR-6.2.2.1.1 Screening Decision: SO-C

Radiological Effects on the Properties of the Waste, Container, and Seals *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.2.2.1.2 Summary of New Information

The FEPs screening argument has been updated by referencing new radiological waste data. The screening decision for these FEPs has not been affected or changed by these new data.

Table SCR-4. Properties of Fissile Radionuclides in the Actinide Series

Nuclide ID	Atomic Number	Atomic Number	Half-Life(1) (sec)	Mass Excess Value(2) (MeV)	Atomic Weight(3) (gm/mole)	Specific Activity(4) (Ci/gm)	Fissile Gram Equivalent Factor(5) (^{239}Pu)
^{233}U	92	233	5.0020E+12	36.914	233.040	9.6763E-03	1.00E+00
^{235}U	92	235	2.2210E+16	40.916	235.044	2.1611E-06	1.00E+00
^{237}Np	93	237	6.7530E+13	44.868	237.048	7.0476E-04	1.50E-02
^{238}Pu	94	238	2.7690E+09	46.160	238.050	1.7115E+01	1.13E-01
^{239}Pu	94	239	7.5940E+11	48.585	239.052	6.2146E-02	1.00E+00
^{240}Pu	94	240	2.0630E+11	50.122	240.054	2.2781E-01	2.25E-02
^{241}Pu	94	241	4.5440E+08	52.952	241.057	1.0300E+02	2.25E+00
^{242}Pu	94	242	1.2210E+13	54.714	242.059	3.8171E-03	7.50E-03
^{241}Am	95	241	1.3640E+10	52.931	241.057	3.4312E+00	1.87E-02
^{242m}Am	95	242	4.7970E+09	55.513	242.060	9.7159E+00	3.46E+01
^{243}Am	95	243	2.3290E+11	57.171	243.061	1.9929E-01	1.29E-02
^{243}Cm	96	243	8.9940E+08	57.177	243.061	5.1607E+01	5.00E+00
^{244}Cm	96	244	5.7150E+08	58.449	244.063	8.0883E+01	9.00E-02
^{245}Cm	96	245	2.6820E+11	60.998	245.065	1.7165E-01	1.50E+01
^{247}Cm	96	247	4.9230E+14	65.528	247.070	9.2752E-05	5.00E-01
^{249}Cf	98	249	1.1060E+10	69.718	249.075	4.0953E+00	4.50E+01
^{251}Cf	98	251	2.8340E+10	74.128	251.080	1.5855E+00	9.00E+01

1 Half-life data originally taken from ORIGEN2 decay library (Croff 1980). Data values presented in Ref. Sanchez 1996 (WIPP WPO# 037404).
2 Mass excess values originally taken from Nuclear Wallet Cards (Tuli 1985). Data values presented in Ref. Sanchez 1996 (WIPP WPO# 037404).
3 Atomic weight calculated from: ATWT (AMU) = AN (atomic mass number) – ME (mass difference in MeV, ME of C^{12} = 0) / 931.4943 (MeV per AMU, Parrington et al. 1996, pg. 58).
4 Specific Activity calculated from: A'= (Na ln(2))/(ATWT half-life), Ref. Turner 1992, pg. 64 and A (Ci/gm) = A'(Bq/gm) / 3.7E+10 (Bq/Ci), Turner 1992, pg. 43, where Na = Avogadro's number = 6.02213676E+23 (atom/mole, Parrington, pg.59).
5 FGE (^{239}Pu based) data values from NuPac 1989 (TRUPACT-II SAR/Table 10.1/pg. 1.3.7-51 (data originally from Ref. ANSI/ANS-8.15 1981).

Table SCR-5. Fissile Equivalents of Radionuclides in the Actinide Series

Nuclide ID	Radioactivity Inventory(1) (Ci)				Nuclide Fissile Mass(2) (FGE-^{239}Pu)			
	TWBIR 3 (1995)	TWBIR 3 (2033)	2003 UpDate (2002)	2003 UpDate (2033)	TWBIR 3 (1995)	TWBIR 3 (2033)	2003 UpDate (2002)	2003 UpDate (2033)
^{233}U	1.95E+03	1.95E+03	1.27E+03	1.27E+03	2.02E+05	2.02E+05	1.31E+05	1.32E+05
^{235}U	1.74E+01	1.75E+01	2.26E+00	2.28E+00	8.05E+06	8.10E+06	1.05E+06	1.06E+06
^{237}Np	5.90E+01	6.49E+01	5.46E+00	1.01E+01	1.26E+03	1.38E+03	1.16E+02	2.14E+02
^{238}Pu	2.61E+06	1.94E+06	1.61E+06	1.25E+06	1.72E+04	1.28E+04	1.07E+04	8.27E+03
^{239}Pu	7.96E+05	7.95E+05	6.66E+05	6.64E+05	1.28E+07	1.28E+07	1.07E+07	1.07E+07
^{240}Pu	2.15E+05	2.14E+05	1.09E+05	1.09E+05	2.12E+04	2.11E+04	1.07E+04	1.07E+04
^{241}Pu	2.45E+06	3.94E+05	2.51E+06	5.38E+05	5.35E+04	8.61E+03	5.49E+04	1.18E+04

Table SCR-5. Fissile Equivalents of Radionuclides in the Actinide Series — Continued

Nuclide ID	Radioactivity Inventory[1] (Ci)				Nuclide Fissile Mass[2] (FGE-^{239}Pu)			
	TWBIR 3 (1995)	TWBIR 3 (2033)	2003 UpDate (2002)	2003 UpDate (2033)	TWBIR 3 (1995)	TWBIR 3 (2033)	2003 UpDate (2002)	2003 UpDate (2033)
^{242}Pu	1.17E+03	1.17E+03	2.71E+01	2.71E+01	2.30E+03	2.30E+03	5.33E+01	5.32E+01
^{241}Am	4.48E+05	4.88E+05	4.15E+05	4.58E+05	2.44E+03	2.66E+03	2.26E+03	2.50E+03
^{242m}Am	1.75E+00	1.47E+00	2.44E-01	2.11E-01	6.23E+00	5.23E+00	8.67E-01	7.50E-01
^{243}Am	3.26E+01	3.25E+01	2.18E+01	2.17E+01	2.11E+00	2.10E+00	1.41E+00	1.41E+00
^{243}Cm	5.23E+01	2.07E+01	8.87E-01	4.07E-01	5.07E+00	2.01E+00	8.59E-02	3.94E-02
^{244}Cm	3.18E+04	7.44E+03	1.18E+04	2.51E+03	3.54E+01	8.28E+00	1.32E+01	2.79E+00
^{245}Cm	1.15E-02	1.15E-02	1.90E-02	1.92E-02	1.00E+00	1.00E+00	1.66E+00	1.68E+00
^{247}Cm	3.21E-09	9.51E-09	9.44E+00	9.45E+00	1.73E-05	5.13E-05	5.09E+04	5.09E+04
^{249}Cf	6.87E-02	6.38E-02	7.72E-02	7.24E-02	7.55E-01	7.01E-01	8.48E-01	7.96E-01
^{251}Cf	3.78E-03	3.67E-03	5.23E-04	5.10E-04	2.15E-01	2.08E-01	2.97E-02	2.90E-02
				Σ	2.11E+07	2.12E+07	1.20E+07	1.20E+07

[1] TWBIR Rev. 3 data values originally from DOE 1996b. Data values presented in Sanchez 1997, pp. 27-30. TWBIR 2003 Update 2002 (beginning of calendar year) data from Appendix DATA, Attachment F. TWBIR 2002 Update 2033 (end of calendar year) data from Leigh 2003a.

[2] ^{239}Pu Fissile Gram Equivalents calculated from: FGE(^{239}Pu) = Inventory (Ci) * FGE Factor (from Table 1) / A'(Ci/gm, from Table 1).

SCR-6.2.2.1.3 Screening Argument

Ionizing radiation can change the physical properties of many materials. Strong radiation fields could lead to damage of waste matrices, brittleness of the metal containers, and disruption of any crystalline structure in the seals. The low level of activity of the waste in the WIPP is unlikely to generate a strong radiation field. According to the new *inventory* data, the total radionuclide inventory decreased from 7.44×10^6 (DOE 1996b) to 6.66×10^6 curies (Appendix DATA, Attachment F), about a 10 percent decrease. Such a small decrease will not change the original screening argument. In addition, PA calculations assume instantaneous container failure and waste dissolution according to the source-term model (see Sections 6.4.3.4, 6.4.3.5, and 6.4.3.6. Therefore, ***Radiological Effects on the Properties of the Waste, Container, and Seals*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3 Geological and Mechanical Features, Events, and Processes

SCR-6.3.1 Excavation-Induced Changes

SCR-6.3.1.1 FEP Number: W18 and W19
FEP Title: ***Disturbed Rock Zone*** (W18)
Excavation-Induced Change in Stress (W19)

SCR-6.3.1.1.1 Screening Decision: UP

Excavation-induced host rock fracturing through formation of a disturbed rock zone (*DRZ*) *and changes in stress are accounted for in PA calculations.*

SCR-6.3.1.1.2 Summary of New Information

No new information has been identified relating to these two FEPs. No changes have been made since the CRA.

SCR-6.3.1.1.3 Screening Argument

Construction of the repository has caused local ***excavation-induced changes in stress*** in the surrounding rock as discussed in Section 3.3.1.5. This has led to failure of intact rock around the opening, creating a DRZ of fractures. On completion of the WIPP excavation, the extent of the induced stress field perturbation will be sufficient to have caused dilation and fracturing in the anhydrite layers a and b, MB139, and, possibly, MB138. The creation of the DRZ around the excavation and the disturbance of the anhydrite layers and marker beds will alter the permeability and effective porosity of the rock around the repository, providing enhanced pathways for flow of gas and brine between the waste-filled rooms and the nearby interbeds. This excavation-induced, host-rock fracturing is accounted for in PA calculations (Section 6.4.5.3).

The DRZ around repository shafts could provide pathways for flow from the repository to hydraulically conductive units above the repository horizon. The effectiveness of long-term shaft seals is dependent upon the seals providing sufficient backstress for salt creep to heal the DRZ around them, so that connected flow paths out of the repository horizon will cease to exist. These factors are considered in the current seal design.

SCR-6.3.1.2 FEP Number: W20 and W21
FEP Title: ***Salt Creep*** (W20)
Change in the Stress Field (W21)

SCR-6.3.1.2.1 Screening Decision: UP

Salt Creep *in the Salado and resultant* ***Changes in the Stress Field*** *are accounted for in PA calculations.*

SCR-6.3.1.2.2 Summary of New Information

No new information has been identified relating to these two FEPs. No changes have been made since CRA-2004.

SCR-6.3.1.2.3 Screening Argument

Salt Creep will lead to ***Changes in the Stress Field***, compaction of the waste and containers, and consolidation of the long-term components of the sealing system. It will also tend to close fractures in the DRZ, leading to reductions in porosity and permeability, increases in pore fluid

pressure, and reductions in fluid flow rates in the repository. ***Salt Creep*** in the Salado is accounted for in PA calculations (Section 6.4.3.1). The long-term repository seal system relies on the consolidation of the crushed-salt seal material and healing of the DRZ around the seals to achieve a low permeability under stresses induced by salt creep. Seal performance is discussed further in FEPs W36 and W37.

SCR-6.3.1.3 FEP Number: W22
FEP Title: ***Roof Falls***

SCR-6.3.1.3.1 Screening Decision: UP

The potential effects of roof falls on flow paths are accounted for in PA calculations.

SCR-6.3.1.3.2 Summary of New Information

No new information has been identified relating to this FEP. No changes have been made since the CRA.

SCR-6.3.1.3.3 Screening Argument

Instability of the DRZ could to lead to localized ***Roof Falls*** in the first few hundred years. If instability of the DRZ causes roof falls, development of the DRZ may be sufficient to disrupt the anhydrite layers above the repository, which may create a zone of rock containing anhydrite extending from the interbeds toward a waste-filled room. Fracture development is most likely to be induced as the rock stress and strain distributions evolve because of creep. In the long term, the effects of roof falls in the repository are likely to be minor because **Salt *Creep*** will reduce the void space and the potential for ***Roof Falls*** as well as leading to healing of any roof material that has fallen into the rooms. However, because of uncertainty in the process by which the disposal room DRZ heals, the flow model used in the PA assumes that a higher permeability zone remains for the long term. Thus, the potential effects of ***Roof Falls*** on flow paths are accounted for in PA calculations through appropriate ranges of the parameters describing the DRZ.

SCR-6.3.1.4 FEP Number(s): W23 and W24
FEP Title(s): ***Subsidence*** (W23)
Large Scale Rock Fracturing (W24)

SCR-6.3.1.4.1 Screening Decision(s): SO-C (W23)
SO-P (W24)

*Fracturing within units overlying the Salado and surface displacement caused by **Subsidence** associated with repository closure have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The potential for excavation or repository-induced **Subsidence** to create **Large-Scale Rock Fracturing** and fluid flow paths between the repository and units overlying the Salado has been eliminated from PA calculations on the basis of the low probability of occurrence over 10,000 years.*

SCR-6.3.1.4.2 Summary of New Information

The DOE acknowledges that proximal ***Roof Falls*** (see W22, Appendix SCR, Section SCR.2.3.3) will occur and minor subsidence of stratigraphic units overlying the Salado at WIPP could occur. Subsidence of geologic formations overlying the WIPP due to ***Salt Creep*** is shown to be only modestly perturbed and the consequence is captured by the uncertainty employed in the PA. ***Roof Falls*** and large-scale ***Subsidence*** have therefore been screened out of the PA calculations based upon low consequence. The potential effects of ***Roof Falls*** on flow paths are accounted for in PA calculations through appropriate ranges of the parameters describing the DRZ. Continuous survey data, reported annually, reaffirm that ***Subsidence*** is minimal and near the accuracy of the survey itself (COMPs, annual reports). Changes for clarity and editorial purposes have been made to the screening argument.

SCR-6.3.1.4.3 Screening Argument

Instability of the DRZ could to lead to localized ***Roof Falls*** in the first few hundred years. If instability of the DRZ causes ***Roof Falls***, development of the DRZ may be sufficient to disrupt the anhydrite layers above the repository, which may create a zone of rock containing anhydrite extending from the interbeds toward a waste-filled room. Fracture development is most likely to be induced as the rock stress and strain distributions evolve because of creep and the local lithologies. In the long term, the effects of ***Roof Falls*** in the repository are likely to be minor because ***Salt Creep*** will reduce the void space and the potential for roof falls as well as leading to healing of any roof material that has fallen into the rooms. Because of uncertainty in the process by which the disposal room DRZ heals, the flow model used in the PA assumed that a higher permeability zone remained for the long term. The PAVT modified the DRZ permeability to a sampled range. Thus, the potential effects of ***Roof Falls*** on flow paths are accounted for in PA calculations through appropriate ranges of the parameters describing the DRZ.

The amount of ***Subsidence*** that can occur as a result of ***Salt Creep*** closure or roof collapse in the WIPP excavation depends primarily on the volume of excavated rock, the initial and compressed porosities of the various emplaced materials (waste, backfill, panel and drift closures, and seals), the amount of inward creep of the repository walls, and the gas and fluid pressures within the repository. The DOE (Westinghouse 1994) has analyzed potential excavation-induced subsidence with the primary objective of determining the geomechanical advantage of backfilling the WIPP excavation. The DOE (Westinghouse 1994, pp. 3-4 to 3-23) used mass conservation calculations, the influence function method, the National Coal Board empirical method, and the two-dimensional, finite-difference code, Fast Lagrangian Analysis of Continua (FLAC) to estimate ***Subsidence*** for conditions ranging from no backfill to emplacement of a highly compacted crushed salt backfill. The DOE (Westinghouse 1994, pp. 2-17 to 2-23) also investigated ***Subsidence*** at potash mines located near the WIPP site to gain insight into the expected ***Subsidence*** conditions at the WIPP and to calibrate the subsidence calculation methods.

Subsidence over potash mines will be much greater than subsidence over the WIPP because of the significant differences in stratigraphic position, depth, extraction ratio, and layout. The WIPP site is located stratigraphically lower than the lowest potash mine, which is near the base of the McNutt Potash Member (hereafter called the McNutt). At the WIPP site, the base of the

McNutt is about 150 m (490 ft) above the repository horizon. Also, the WIPP rock extraction ratio in the waste disposal region will be about 22 percent, as compared to 65 percent for the lowest extraction ratios within potash mines investigated by the DOE (Westinghouse 1994, p. 2-17).

The DOE (Westinghouse 1994, p. 2-22) reported the maximum total ***Subsidence*** at potash mines to be about 1.5 m (5 ft). This level of ***Subsidence*** has been observed to have caused surface fractures. However, the DOE (Westinghouse 1994, p. 2-23) found no evidence that ***Subsidence*** over potash mines had caused fracturing sufficient to connect the mining horizon to water-bearing units or the landsurface. The level of disturbance caused by ***Subsidence*** above the WIPP repository will be less than that associated with potash mining and thus, by analogy, will not create fluid flow paths between the repository and the overlying units.

The various ***Subsidence*** calculation methods used by the DOE (Westinghouse 1994, pp. 3-4 to 3-23) provided similar and consistent results, which support the premise that ***Subsidence*** over the WIPP will be less than ***Subsidence*** over potash mines. Estimates of maximum ***Subsidence*** at the land surface for the cases of no backfill and highly compacted backfill are 0.62 m (2 ft) and 0.52 m (1.7 ft), respectively. The mass conservation method gave the upper bound estimate of ***Subsidence*** in each case. The surface topography in the WIPP area varies by more than 3 m (10 ft), so the expected amount of repository-induced ***Subsidence*** will not create a basin, and will not affect surface hydrology significantly. The DOE (Westinghouse 1994, Table 3-13) also estimated ***Subsidence*** at the depth of the Culebra using the FLAC model, for the case of an empty repository (containing no waste or backfill). The FLAC analysis assumed the Salado to be halite and the Culebra to have anhydrite material parameters.

Maximum ***Subsidence*** at the Culebra was estimated to be 0.56 m (1.8 ft). The vertical strain was concentrated in the Salado above the repository. Vertical strain was less than 0.01 percent in units overlying the Salado and was close to zero in the Culebra (Westinghouse 1994, Figure 3-40). The maximum horizontal displacement in the Culebra was estimated to be 0.02 m (0.08 ft), with a maximum tensile horizontal strain of 0.007 percent. The DOE (Westinghouse 1994, 4-1 to 4-2) concluded that the induced strains in the Culebra will be uniformly distributed because no large-scale faults or discontinuities are present in the vicinity of the WIPP. Furthermore, strains of this magnitude would not be expected to cause extensive fracturing.

At the WIPP site, the Culebra hydraulic conductivity varies spatially over approximately four orders of magnitude, from 1×10^{-8} m (3.2×10^{-8} ft) per second (0.4 m (1.3 ft) per year) to 1×10^{-5} m (3.2×10^{-5} ft) per second (Appendix PA, Attachment TFIELD). Where transmissive horizontal fractures exist, hydraulic conductivity in the Culebra is dominated by flow through the fractures. An induced tensile vertical strain may result in an increase in fracture aperture and corresponding increases in hydraulic conductivity. The magnitude of increase in hydraulic conductivity can be estimated by approximating the hydrological behavior of the Culebra with a simple conceptual model of fluid flow through a series of parallel fractures with uniform properties. A conservative estimate of the change in hydraulic conductivity can be made by assuming that all the vertical strain is translated to fracture opening (and none to rock expansion). This method for evaluating changes in hydraulic conductivity is similar to that used by the EPA in estimating the effects of subsidence caused by potash mining (Peake 1996; EPA 1996b).

The equivalent porous medium hydraulic conductivity, *K* (meters per second), of a system of parallel fractures can be calculated assuming the cubic law for fluid flow (Witherspoon et al. 1980):

$$K = \frac{w^3 \rho g N}{12 \mu 2}, \tag{10}$$

where *w* is the fracture aperture, ρ is the fluid density (taken to be 1,000 kg/m^3), *g* is the acceleration due to gravity (9.79 m (32 ft) per second squared), μ is the fluid viscosity (taken as 0.001 pascal seconds), *D* is the effective Culebra thickness (7.7 m (26.3 ft)), and *N* is the number of fractures. For 10 fractures with a fracture aperture, *w*, of 6×10^{-5} m (2×10^{-4} ft), the Culebra hydraulic conductivity, *K*, is approximately 7 m per year (2×10^{-7} m (6.5×10^{-7} ft) per second). The values of the parameters used in this calculation are within the range of those expected for the Culebra at the WIPP site (Appendix PA, Attachment TFIELD).

The amount of opening of each fracture as a result of subsidence-induced tensile vertical strain, ε, (assuming rigid rock) is $D\varepsilon/N$ meters. Thus, for a vertical strain of 0.0001, the fracture aperture, *w*, becomes approximately 1.4×10^{-4} m. The Culebra hydraulic conductivity, *K*, then increases to approximately 85 m (279 ft) per year (2.7×10^{-6} m (8.9×10^{-6} ft) per second). Thus, on the basis of a conservative estimate of vertical strain, the hydraulic conductivity of the Culebra may increase by an order of magnitude. In the PA calculations, multiple realizations of the Culebra transmissivity field are generated as a means of accounting for spatial variability and uncertainty (Appendix TFIELD). A change in hydraulic conductivity of one order of magnitude through vertical strain is within the range of uncertainty incorporated in the Culebra transmissivity field through these multiple realizations. Thus, changes in the horizontal component of Culebra hydraulic conductivity resulting from repository-induced subsidence have been eliminated from PA calculations on the basis of low consequence.

A similar calculation can be performed to estimate the change in vertical hydraulic conductivity in the Culebra as a result of a horizontal strain of 0.00007 m/m (Westinghouse 1994, p. 3-20). Assuming this strain to be distributed over about 1,000 fractures (neglecting rock expansion), with zero initial aperture, in a lateral extent of the Culebra of about 800 m (2,625 ft) (Westinghouse 1994, Figure 3-39), then the subsidence-induced fracture aperture is approximately 6×10^{-5} m (1.9×10^{-4} ft). Using the values for ρ, *g*, and μ, above, the vertical hydraulic conductivity of the Culebra can then be calculated, through an equation similar to above, to be 7 m (23 ft) per year (2×10^{-7} m (6.5×10^{-7} ft) per second). Thus, vertical hydraulic conductivity in the Culebra may be created as a result of repository-induced ***Subsidence***, although this is expected to be insignificant.

In summary, as a result of observations of ***Subsidence*** associated with potash mines in the vicinity of the WIPP, the potential for ***Subsidence*** to create fluid flow paths between the repository and units overlying the Salado has been eliminated from PA calculations on the basis of low probability. The effects of repository-induced ***Subsidence*** on hydraulic conductivity in the Culebra have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3.2 Effects of Fluid Pressure Changes

SCR-6.3.2.1 FEP Number: W25 and W26
FEP Title: ***Disruption Due to Gas Effects*** (W25)
Pressurization (W26)

SCR-6.3.2.1.1 Screening Decision: UP

*The mechanical effects of gas generation through **Pressurization** and **Disruption Due to Gas** flow are accounted for in PA calculations.*

SCR-6.3.2.1.2 Summary of New Information

No new information has been identified relating to these FEPs. No changes have been made.

SCR-6.3.2.1.3 Screening Argument

The mechanical effects of gas generation, including the slowing of creep closure of the repository due to gas ***Pressurization***, and the fracturing of interbeds in the Salado through ***Disruption Due to Gas Effects*** are accounted for in PA calculations (Sections 6.4.5.2 and 6.4.3.1).

SCR-6.3.3 Effects of Explosions

SCR-6.3.3.1 FEP Number: W27
FEP Title: ***Gas Explosions***

SCR-6.3.3.1.1 Screening Decision: UP

*The potential effects of **Gas Explosions** are accounted for in PA calculations.*

SCR-6.3.3.1.2 Summary of New Information

No new information has been identified related to this FEP. Only editorial changes have been made to this FEP.

Explosive gas mixtures could collect in the head space above the waste in a closed panel. The most explosive gas mixture potentially generated will be a mixture of hydrogen, methane, and oxygen which will convert to CO_2 and water on ignition. This means that there is little likelihood of a ***Gas Explosion***in the long term, because the rooms and panels are expected to become anoxic and oxygen depleted. Compaction through salt creep will also greatly reduce any void space in which the gas can accumulate. Analysis (see Appendix BARRIERS**,** Attachment PCS) indicates that the most explosive mixture of hydrogen, methane, and oxygen will be present in the void space approximately 20 years after panel-closure emplacement. This possibility of an explosion prior to the occurrence of anoxic conditions is considered in the design of the operational panel closure. The effect of such an explosion on the DRZ is expected to be no more severe than a ***Roof Fall*** which is accounted for in the PA calculations (FEP W22).

SCR-6.3.3.2 FEP Number: W28
FEP Title: ***Nuclear Explosions***

SCR-6.3.3.2.1 Screening Decision: SO-P

Nuclear Explosions *have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-6.3.3.2.2 Summary of New Information

Editorial changes have been made for clarity as well as separating the two FEPs within the original SCR text into discrete arguments. Additional information is referenced to support the conclusions.

SCR-6.3.3.2.3 Screening Argument

Nuclear explosions have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years. For a ***Nuclear Explosions*** to occur, a critical mass of Pu would have to undergo rapid compression to a high density. Even if a critical mass of Pu could form in the system, there is no mechanism for rapid compression. Radioactivity inventories for the fissile radionuclides used in DOE (1996a) and CRA-2004 are presented in Table SCR-6. The updated information for the WIPP disposal inventory of fissile material (Appendix DATA, Attachment F; Leigh 2003a) indicates that the expected WIPP-scale quantity is 43 percent lower than previously estimated in TWBIR Rev. 3 (DOE 1996b). Thus, all CRA-2004 criticality screening arguments are conservatively bounded by the previous CCA screening arguments (Rechard et al. 1996, 2000, and 2001).

SCR-6.3.4 Thermal Effects

SCR-6.3.4.1 FEP Number: W29, W30, W31, W72, and W73
FEP Title: ***Thermal Effects on Material Properties*** (W29)
Thermally-Induced Stress Changes (W30)
Differing Thermal Expansion of Repository Components (W31)
Exothermic Reactions (W72)
Concrete Hydration (W73)

SCR-6.3.4.1.1 Screening Decision: SO-C

The effects of ***Thermally Induced Stress, Differing Thermal Expansion of Components,*** *and* ***Thermal Effects on Material Properties*** *in the repository have been eliminated from PA calculations on the basis of low consequence to performance of the disposal system.*

The thermal effects of exothermic reactions, including ***Concrete Hydration****, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.3.4.1.2 Summary of New Information

All potential sources of heat and elevated temperature have been evaluated and found not to produce high enough temperature changes to affect the repository's performance. Sources of heat within the repository include radioactive decay and exothermic chemical reactions such as backfill hydration and metal corrosion. The rates of these exothermic reactions are limited by the availability of brine in the repository. ***Concrete Hydration*** in the seals is a significant source of heat, but it is relatively short-lived. Energy released by the hydration of the seal concrete could raise the temperature of the concrete to approximately 53°C (127°F), and that of the surrounding salt to approximately 38°C (100°F), one week after seal emplacement. Elevated temperatures will persist for a short period of time, perhaps a few years or a few decades. The thermal stresses from these temperatures and the temperatures in the concrete itself have been calculated to be below the design compressive strength for the concrete. Thus, thermal stresses should not degrade the long-term performance of the seals. In general, the various sources of heat do not appear to be great enough to jeopardize the performance of the disposal system.

The original FEP descriptions have been changed slightly to include the effects of water release during carbonation of the backfill, and the effects of formation of metastable hydrated carbonate minerals.

SCR-6.3.4.1.3 Screening Argument

Thermally Induced Stress could result in pathways for groundwater flow in the DRZ, in the anhydrite layers and marker beds, and through seals, or it could enhance existing pathways. Conversely, elevated temperatures will accelerate the rate of ***Salt Creep*** and mitigate fracture development. Thermal expansion could also result in uplift of the rock and ground surface overlying the repository, and thermal buoyancy forces could lift the waste upward in the salt rock.

The distributions of thermal stress and strain changes depend on the induced temperature field and the ***Differing Thermal Expansion of Components*** of the repository, which depends on the components' elastic properties. Potentially***, Thermal Effects on Material Properties*** (such as permeability and porosity) could affect the behavior of the repository.

Radioactive decay (W13), ***Nuclear Criticality*** (W14), and ***Exothermic Reactions*** (W72 and W73) are three possible sources of heat in the WIPP repository. According to the new inventory data, the total radionuclide inventory decreases increases from 7.44 × 106 (DOE 1996b) to 6.66 × 106 curies (Appendix DATA, Attachment F), about a 10 percent decrease. Such a small change will not result in a significant deviation from the possible temperature rise predicted in the CCA. Exothermic reactions in the WIPP repository include MgO hydration, MgO carbonation, Al corrosion, and ***Cement Hydration*** (Bennett et al. 1996). Wang (1996) has shown that the temperature rise by an individual reaction is proportional to $\sqrt{VM}$, where V is the maximum rate of brine inflow into a waste panel for a reaction limited by brine inflow (or a specified maximum reaction rate for a reaction limited by its own kinetics) and M is the quantity of the reactant. MgO hydration, cement hydration, and Al corrosion are assumed to be limited by brine inflow, because they all consume water and have high reaction rates. For these reactions, the calculated temperature rises need to be updated for the changes in both brine inflow rate and

waste inventory. According to the CRA-2004 PA calculations, the average brine inflow rate upon a human intrusion is 156 m^3/year (204 yd^3/year), with a maximum value of 332 m^3/year (434 yd^3/year). In the CCA, the maximum brine inflow rate was assumed to be 200 m^3/year (261 yd^3/year). With the new rate of 332 m^3/year (434 yd^3/year), it is estimated that the temperature rise by each exothermic reaction is increased by 29 percent if the quantity of reactant remains the same. Changes in the amounts of reactants are tabulated in Table SCR-6.

Table SCR-6. Changes in Inventory Quantities from the CCA to the CRA

Inventory	CCA	CRA	Change
MgO (tons)	85,600[1]	72,760 (because of the elimination of mini-sacks)[a]	–15%
Cellulosics (tons)	5,940[2]	8,120[3]	37%
Plastics (tons)	3,740[2]	8,120[3]	117%
Rubber (tons)	1,100[2]	1,960[3]	78%
Aluminum alloys (tons)	1,980[2]	1,960[3]	–1%
Cement (tons)	8,540[2]	9,971[5]	17%

[1] U.S. DOE (2001)
[2] U.S. DOE (1996b). Only CH wastes are considered. Total volume of CH wastes is 1.1×10^5 m^3. This is not scaled to WIPP disposal volume.
[3] Appendix DATA, Attachment F. Only CH wastes are considered. Total volume of CH waste is 1.4 x 10^5 m^3. This is not scaled to WIPP disposal volume.
[4] This estimate is derived from data in Leigh (2003b) includes both reacted and unreacted cement. (1.2e7 kg x 1.4e5/168485 /1000 kg/ton = 9971 tons cement)

Similarly, MgO carbonation, which consumes ***Carbon Dioxide***, is limited by ***Carbon Dioxide*** generation from microbial degradation. Given a biodegradation rate constant, the total CO_2 generated per year is proportional to the total quantity of biodegradable materials in the repository. The inventory of biodegradable materials has been changed from 13,398 (5,940 + 1.7 × 3,740 + 1,100)1 tons to 23,884 (8,120 + 1.7 × 8,120 + 1,960)1 tons of equivalent cellulosics (Wang and Brush 1996a and 1996b). This increase in biodegradeable materials corresponds to a proportional increase in CO_2 generation. For MgO carbonation and microbial degradation, the calculated temperature rises have been updated for the changes in both microbial gas generation and waste inventory and are presented in Table SCR-7.

Temperature rises (^oC) by exothermic reactions are revised as follows:

Table SCR-7. CCA and CRA Exothermic Temperature Rises

Reactant	CCA[1]	CRA1
MgO hydration	< 4.5	< 4.7
Backfill Carbonation	< 0.6	< 0.7
Microbial degradation	< 0.8	< 1.4
Aluminum corrosion	< 6.0	< 6.8
Cement hydration	< 2.0	< 2.5

[1] All values are shown in degrees Celsius

[1] The 1.7 molar conversion rate for plastic is based on analyses presented in Wang and Brush (1996a and ***1996***b).

For the CCA conditions following a drilling event, aluminum corrosion could, at most, result in a short-lived (two years) temperature increase of about 6°C (10.8°F) above ambient room temperature (about 27°C (80°F)) (Bennett et al. 1996). A temperature rise of 6°C (10.8°F) represented the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously. Revised maximum temperature rises by exothermic reactions for CRA-2004 are still less than 10°C (18°F) (as shown in Table SCR-7). Such small temperature changes cannot affect material properties. Thus, ***Thermal Effects on Material Properties*** in the repository have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3.5 Mechanical Effects on Material Properties

SCR-6.3.5.1 FEP Number: W32, W36, W37 and W39
FEP Title: ***Consolidation of Waste*** (W32)
Consolidation of Seals (W36)
Mechanical Degradation of Seals (W37)
Underground Boreholes (W39)

SCR-6.3.5.1.1 Screening Decision: UP

Consolidation of Waste *is accounted for in PA calculations.* ***Consolidation of Seals*** *and* ***Mechanical Degradation of Seals*** *are accounted for in PA calculations. Flow through isolated, unsealed* ***Underground Boreholes*** *is accounted for in PA calculations.*

SCR-6.3.5.1.2 Summary of New Information

No new information has been identified for these FEPs; however, because they are accounted for (UP) in PA, the implementation may differ from that used the CCA**)**. No information has been identified that would change the screening decision of UP. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.3.6.1.3 Screening Argument

Consolidation of Waste is accounted for in PA calculations in the modeling of creep closure of the disposal room (Section 6.4.3.1).

Mechanical Degradation of Seals and ***Consolidation of Seals*** are accounted for in PA calculations through the permeability range assumed for the seal system (Section 6.4.4).

The site investigation program has also involved the drilling of boreholes from within the excavated part of the repository. Following their use for monitoring or other purposes, these ***Underground Boreholes*** will be sealed where practical, and ***Salt Creep*** will also serve to consolidate the seals and to close the boreholes. Any boreholes that remain unsealed will connect the repository to anhydrite interbeds within the Salado, and thus provide potential pathways for radionuclide transport. PA calculations account for fluid flow to and from the interbeds by assuming that the DRZ has a permanently enhanced permeability that allows flow of repository brines into specific anhydrite layers and interbeds. This treatment is also considered to account for the effects of any unsealed boreholes.

SCR-6.3.5.2 FEP Number: W33
FEP Title: ***Movement of Containers***

SCR-6.3.5.2.1 Screening Decision: SO-C

Movement of Containers *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.3.5.2.2 Summary of New Information

Movement of Containers has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The FEP description has been updated to reflect new waste inventory data (waste density).

SCR-6.3.5.2.3 Screening Argument

Movement of Waste Containers placed in salt may occur as a result two buoyancy mechanisms (Dawson and Tillerson 1978): (1) the density contrast between the waste container and the surrounding salt, and (2) the temperature contrast between a salt volume that includes a heat source and the surrounding unheated salt. When the density of the waste container is greater than the density of the surrounding salt, the container sinks relative to the salt; whereas when the salt density is greater than the container density, the container rises relative to the salt. Similarly, when a discrete volume of salt within a large salt mass is heated, the heat raises the temperature of the discrete volume above that of the surrounding salt thereby inducing density contrasts and buoyant forces that initiate upward flow of the heated salt volume. In a repository setting, the source of the heat may be radioactive decay of the waste itself or exothermic reactions of the backfill materials and waste constituents, e.g., MgO hydration, MgO carbonation, aluminum corrosion, cement hydration, and calcium oxide hydration.

For the CCA, the density of the compacted waste and the grain density of the halite in the Salado were assumed to be 2,000 kg/m^3 and 2,163 kg/m^3, respectively. Because this density contrast is small, the movement of containers relative to the salt was considered minimal, particularly when drag forces on the waste containers were also considered. In addition, vertical movement initiated in response to thermally-induced density changes for high-level waste containers of a similar density to those at the WIPP were calculated to be approximately 0.35 m (1 ft) (Dawson and Tillerson 1978, p. 22). This calculated movement was considered conservative given that containers at the WIPP will generate much less heat and will, therefore, move less. As a result, container movement was eliminated from PA calculations on the basis of low consequences to the performance of the disposal system.

The calculations performed for DOE (1996a) were based on estimates of the waste inventory. However, with the initiation of waste disposal, actual waste inventory is tracked and future waste stream inventories have been refined. Based on an evaluation of these data, two factors may affect the conclusions reached in DOE (1996a) concerning container movement.

The first factor is changes in density of the waste form. For the most part, waste density will remain as assumed in the CCA. According to new *inventory* data (Appendix DATA, Attachment F), the revised waste density has changed by at most 10 percent (lower). Some future waste

streams may however be more highly compacted, perhaps having a density roughly three times greater than that assumed in the CCA. In calculations of container movement, Dawson and Tillerson (1978, p. 22) varied container density by nearly a factor of three (from 2,000 kg/m^3 (125 lb/ft^3) to 5,800 kg/m^3 (362 lb/ft^3)) and found that an individual dense container could move vertically as much as about 28 m (92 ft). Given the geologic environment of the WIPP, a container would likely encounter a dense stiff unit (such as an anhydrite stringer) that would arrest further movement far short of this upper bound; however, because of the massive thickness of the Salado salt, even a movement of 28 m (92 ft) would have little impact on performance.

The second inventory factor that could affect container movement is the composition of the waste (and backfills) relative to its heat production. Radioactive decay, ***Nuclear Criticality***, and exothermic reactions are three possible sources of heat in the WIPP repository. According to the new inventory data, the total radionuclide inventory decreases from 7.44×10^6 (CCA) to 6.66×10^6 curies (Appendix DATA, Attachment F), about a 10 percent decrease. Such a small change will not result in a significant deviation from the possible temperature rise predicted in the CCA. As shown in Section SCR.6.3.4 (FEPs W72 and W73), temperature rises from exothermic reactions are quite small (see Table SCR-7). Note that the revised maximum temperature rises by exothermic reactions are still less than 10°C (18°F).

Based on the small differences between the temperature and density assumed in the CCA compared to those determined using *new inventory* data (Appendix DATA, Attachment F), the conclusion about the importance of container movement reported in the CCA will not be affected, even when more highly compacted future waste streams are considered. Also, the effects of the revised maximum temperature rise and higher density future waste streams on container movement are competing factors (high density waste will sink, whereas the higher temperature waste-salt volume will rise) that may result in even less movement. Therefore, ***Movement of Waste Containers*** has been eliminated from PA calculations on the basis of low consequence.

SCR-6.3.5.3 FEP Number: W34
FEP Title: ***Container Integrity***

SCR-6.3.6.3.1 Screening Decision: SO-C Beneficial

Container Integrity *has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-6.3.5.3.2 Summary of New Information

No new information has been identified relating to this FEP. Editorial changes have been made to the FEP screening argument.

SCR-6.3.5.3.3 Screening Argument

Container Integrity is required only for waste transportation. As in the CCA, the CRA-2004 calculations show that a significant fraction of steel and other Fe-base materials will remain undegraded over 10,000 years (see Helton et al. 1998). For all undisturbed cases, at least 30 percent of the steels will remain uncorroded at the end of 10,000 years. In addition, it is assumed

in both CCA and CRA-2004 calculations that there is no microbial degradation of plastic container materials in 75 percent of PA realizations (Wang and Brush 1996). All these undegraded container materials will (1) prevent the contact between brine and radionuclides; and (2) decrease the rate and extent of radionuclide transport due to high tortuosity along the flow pathways and, as a result, increase opportunities for metallic iron and corrosion products to beneficially reduce radionuclides to lower oxidation states. Therefore, the ***Container Integrity*** can be eliminated on the basis of its beneficial effect on retarding radionuclide transport. Both ***CCA*** and CRA-2004 assume instantaneous container failure and waste dissolution according to the source-term model.

SCR-6.3.5.4 FEP Number: W35
FEP Title: ***Mechanical Effects of Backfill***

SCR-6.3.5.4.1 Screening Decision: SO-C

*The **Mechanical Effects of Backfill** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.3.5.4.2 Summary of New Information

In 2001, MgO mini-sacks were eliminated from the repository, which decreases the backfill to waste volume ratio (EPA 2001). Although the backfill will provide additional resistance to creep closure, most of the resistance will be provided by the waste. Therefore, inclusion of backfill would not significantly reduce the total ***Subsidence*** in the waste rooms, and screening based on low consequence is appropriate. The screening argument has been updated to reflect the elimination of minisacks.

SCR-6.3.5.4.3 Screening Argument

The chemical conditioners or backfill added to the disposal room will act to resist creep closure. However, calculations have shown that because of the high porosity and low stiffness of the waste and the high waste to potential backfill volume, inclusion of backfill does not significantly decrease the total subsidence in the waste emplacement area or disposal room (Westinghouse 1994). Since 2001, DOE has eliminated MgO mini sacks from the repository reducing the total inventory from 85,600 short tons to 74,000 short tons, which further reduces the potential backfill volume (EPA 2001). Therefore, the ***Mechanical Effects of Backfill*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3.5.5 FEP Number: W38
FEP Title: ***Investigation Boreholes***

SCR-6.3.5.5.1 Screening Decision: NA

SCR-6.3.5.5.2 Summary of New Information

The effects of ***Investigation Boreholes*** (whether sealed or not) that penetrate the disposal horizon but do not intersect the waste panels are encompassed by the arguments made in ***Natural***

Borehole Fluid Flow (H31) and ***Flow Through Undetected Boreholes*** (H33). FEP W38 has been deleted from the FEPs baseline because it is redundant. The effects of drillholes drilled from the underground are accounted for in PA by assumptions about the permeability of the DRZ. ***Natural Borehole Fluid Flow*** (H31) and ***Flow Through Undetected Boreholes*** (H33) encompass the effects of W38. Therefore, W38, ***Investigation Boreholes,*** has been deleted from the FEPs Baseline.

SCR-6.4 Subsurface Hydrological and Fluid Dynamic Features, Events, and Processes

SCR-6.4.1 Repository-Induced Flow

SCR-6.4.1.1 FEP Number: W40 and W41
FEP Title: ***Brine Inflow*** (W40)
Wicking (W41)

SCR-6.4.1.1.1 Screening Decision: UP

Two-phase brine and gas flow and capillary rise (wicking) in the repository and the Salado are accounted for in PA calculations.

SCR-6.4.1.1.2 Summary of New Information

No new information has been identified related to these FEPs. No changes have been made to the screening decisions or screening arguments.

SCR-6.4.1.1.3 Screening Argument

Brine Inflow to the repository may occur through the DRZ, impure halite, anhydrite layers, or clay layers. Pressurization of the repository through gas generation could limit the amount of brine that flows into the rooms and drifts. Two-phase flow of brine and gas in the repository and the Salado is accounted for in PA calculations (Section 6.4.3.2).

Capillary rise (or ***Wicking***) is a potential mechanism for liquid migration through unsaturated zones in the repository. Capillary rise in the waste material could affect gas generation rates, which are dependent on water availability. Potential releases due to drilling intrusion are also influenced by brine saturations and therefore by ***Wicking***. Capillary rise is therefore accounted for in PA calculations (Section 6.4.3.2).

SCR-6.4.2 Effects of Gas Generation

SCR-6.4.2.1 FEP Number: W42
FEP Title: ***Fluid Flow Due to Gas Production***

SCR-6.4.2.1.1 Screening Decision: UP

Fluid flow in the repository and Salado due to gas production is accounted for in PA calculations.

SCR-6.4.2.1.2 Summary of New Information

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-6.4.2.1.3 Screening Argument

Pressurization of the repository through gas generation could limit the amount of brine that flows into the rooms and drifts. Gas may flow from the repository through the DRZ, impure halite, anhydrite layers, or clay layers. The amount of water available for reactions and microbial activity will impact the amounts and types of gases produced (W44 through W55). Gas generation rates, and therefore repository pressure, may change as the water content of the repository changes. Pressure changes and ***Fluid Flow Due to Gas Production*** in the repository and the Salado are accounted for in PA calculations through modeling the two-phase flow (Section 6.4.3.2).

SCR-6.4.3 Thermal Effects

SCR-6.4.3.1 FEP Number: W43
FEP Title: ***Convection***

SCR-6.4.3.1.1 Screening Decision: SO-C

Convection *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.4.3.1.2 Summary of New Information

No new information has been identified relative to the screening of this FEP. The FEP description has been updated and modified for editorial purposes.

SCR-6.4.3.1.3 Screening Argument

Temperature differentials in the repository could initiate ***Convection.*** The resulting thermally-induced brine flow or thermally-induced two-phase flow could influence contaminant transport. Potentially, thermal gradients in the disposal rooms could drive the movement of water vapor. For example, temperature increases around waste located at the edges of the rooms could cause evaporation of water entering from the DRZ. This water vapor could condense on cooler waste containers in the rooms and could contribute to brine formation, corrosion, and gas generation.

Nuclear Criticality (W13), ***Radioactive Decay*** (W14), and ***Exothermic Reactions*** (W72) are three possible sources of heat in the WIPP repository.

The characteristic velocity, Vi, for convective flow of fluid component I in an unsaturated porous medium is given by (from Hicks 1996);

$$V_i \approx -\frac{k_i}{\mu_i}(\alpha_i \rho_{i0} g \Delta T), \qquad (11)$$

where α_i (per degree) is the coefficient of expansion of the ith component, k_i is the intrinsic permeability (square meters), μ_i is the fluid viscosity (pascal second), ρ_{i0} (kilograms per cubic meter) is the fluid density at a reference point, g is the acceleration of gravity, and ΔT is the change in temperature. This velocity may be evaluated for the brine and gas phases expected in the waste disposal region.

For a temperature increase of 10°C (18°F), the characteristic velocity for convective flow of brine in the DRZ around the concrete shaft seals is approximately 7×10^{-4} m (2.3×10^{-3} ft) per year (2×10^{-11} m (6.6×10^{-11} ft) per second), and the characteristic velocity for convective flow of gas in the DRZ is approximately 1×10^{-3} m (3.2×10^{-3} ft) per year (3×10^{-11} m (9.8×10^{-11} ft) per second) (Hicks 1996). For a temperature increase of 25°C (45°F), the characteristic velocity for convective flow of brine in the concrete seals is approximately 2×10^{-7} m (6.5×10^{-7} ft) per year (6×10^{-15} m (1.9×10^{-14} ft) per second), and the characteristic velocity for convective flow of gas in the concrete seals is approximately 3×10^{-7} m (9.8×10^{-7} ft) per year (8×10^{-15} m (2.6×10^{-4} ft) per second) (Hicks 1996). These values of Darcy velocity are much smaller than the expected values associated with ***Brine Inflow*** to the disposal rooms of fluid flow resulting from gas generation. In addition, the buoyancy forces generated by smaller temperature contrasts in the DRZ, resulting from backfill and ***Concrete Hydration*** and ***Radioactive Decay***, will be short-lived and insignificant compared to the other driving forces for fluid flow. The short-term concrete seals will be designed to function as barriers to fluid flow for at least 100 years after emplacement, and seal permeability will be minimized (Wakeley et al. 1995). Thus, temperature increases associated with ***Concrete Hydration*** will not result in significant buoyancy driven fluid flow through the concrete seal system. In summary, temperature changes in the disposal system will not cause significant thermal ***cConvection***. Furthermore, the induced temperature gradients will be insufficient to generate water vapor and drive significant moisture migration.

Temperature effects on fluid viscosity would be most significant in the DRZ surrounding the hydrating concrete seals (where temperatures of approximately 38°C (100°F) are expected). The viscosity of pure water decreases by about 19 percent over a temperature range of between 27°C (80°F) and 38°C (100°F) (Batchelor 1973, p. 596). Although at a temperature of 27°C (80°F), the viscosity of Salado brine is about twice that of pure water (Rechard et al. 1990, a-19), the magnitude of the variation in brine viscosity between 27°C (80°F) and 38°C (100°F) will be similar to the magnitude of the variation in viscosity of pure water. The viscosity of air over this temperature range varies by less than seven percent (Batchelor 1973, p. 594) and the viscosity of gas in the waste disposal region over this temperature range is also likely to vary by less than seven percent. The Darcy fluid flow velocity for a porous medium is inversely proportional to the fluid viscosity. Thus, increases in brine and gas flow rates may occur as a result of viscosity variations in the vicinity of the concrete seals. However, these viscosity variations will persist only for a short period in which temperatures are elevated, and, thus, the expected variations in brine and gas viscosity in the waste disposal region will not affect the long-term performance of the disposal system significantly.

For the CCA conditions following a drilling event, aluminum corrosion could, at most, result in a short-lived (two years) temperature increase of about 6°C (10.8°F). A temperature rise of 6°C (10.8°F) represented the maximum that could occur as a result of any combination of

Exothermic Reactions occurring simultaneously. Revised maximum temperature rises by ***Exothermic Reactions*** for CRA-2004 are still less than 10 ^{o}C (18°F) (as shown in Table SCR-7). Such small temperature changes cannot affect material properties.

In summary, temperature changes in the disposal system will not cause significant thermally-induced two-phase flow. Thermal ***cConvection*** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5 Geochemical and Chemical Features, Events, and Processes

SCR-6.5.1 Gas Generation

SCR-6.5.1.1 FEP Number: W44, W45, and W48
FEP Titles: ***Degradation of Organic Material*** (W44)
Effects of Temperature on Microbial Gas Generation (W45)
Effects of Biofilms on Microbial Gas Generation (W48)

SCR-6.5.1.1.1 Screening Decision: UP

Microbial gas generation from degradation of organic material is accounted for in PA calculations, and the ***Effects of Temperature and Biofilm Formation on Microbial Gas Generation*** *are incorporated in the gas generation rates used.*

SCR-6.5.1.1.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. Editorial changes have been made to the screening argument. The screening decision remains unchanged.

SCR-6.5.1.1.3 Screening Argument

Microbial breakdown of cellulosic material, and possibly plastics and other synthetic materials, will produce mainly CO_2, but also nitrogen oxide, nitrogen, hydrogen sulfide, hydrogen, and methane. The rate of microbial gas production will depend upon the nature of the microbial populations established, the prevailing conditions, and the substrates present. Microbial gas generation from ***Degradation of Organic Material*** is accounted for in PA calculations.

The following subsections discuss the effects of temperature, pressure, radiation, and biofilms on gas production rates via their control of microbial gas generation processes.

SCR-6.5.1.1.3.1 *Effects of Temperature on Microbial Gas Generation*

Calculations and experimental studies of induced temperature distributions within the repository have been undertaken and are described in FEPs W29, W30, and W31. Numerical analysis suggests that the average temperature increase in the WIPP repository caused by radioactive decay of the emplaced CH- and RH-TRU waste is likely to be less than 3°C (5.4°F) (FEP W13).

Temperature increases resulting from ***Exothermic Reactions*** are discussed in FEPs W72 and W73. Potentially the most significant ***Exothermic Reactions*** are ***Concrete Hydration***, backfill

hydration, and aluminum corrosion. Hydration of the seal concrete could raise the temperature of the concrete to approximately 53°C (127°F) and that of the surrounding salt to approximately 38°C (100°F) one week after seal emplacement (W73).

As discussed in FEPs W72 and W73, the maximum temperature rise in the disposal panels as a consequence of backfill hydration will be less than 5.3°C (9.5°F), resulting from ***Brine Inflow*** following a drilling intrusion into a waste disposal panel. Note that active institutional controls will prevent drilling within the controlled area for 100 years after disposal. By this time, any heat generation by radioactive decay and concrete seal hydration will have decreased substantially, and the temperatures in the disposal panels will have reduced to close to initial values.

Under similar conditions following a drilling event, aluminum corrosion could, at most, result in a short-lived (two years) temperature rise of about 7.9°C (14.2°F) (see W72). These calculated maximum heat generation rates resulting from aluminum corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability; each calculation assumes that all available brine is consumed by the reaction of concern. Thus, the temperature rise of 10°C (18°F) represents the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously.

Relatively few data exist on the ***Effects of Temperature on Microbial Gas Generation*** under expected WIPP conditions. Molecke (1979, p. 4) summarized microbial gas generation rates observed during a range of experiments. Increases in temperature from ambient up to 40°C (104°F) or 50°C (122°F) were reported to increase gas production, mainly via the degradation of cellulosic waste under either aerobic or anaerobic conditions (Molecke 1979, p. 7). Above 70°C (158°F), however, gas generation rates were generally observed to decrease. The experiments were conducted over a range of temperatures and chemical conditions and for different substrates, representing likely states within the repository. Gas generation rates were presented as ranges with upper and lower bounds as estimates of uncertainty (Molecke 1979, p. 7). Later experiments reported by Francis and Gillow (1994) support the gas generation rate data reported by Molecke (1979). These experiments investigated microbial gas generation under a wide range of possible conditions in the repository. These conditions included the presence of microbial inoculum, humid or inundated conditions, cellulosic substrates, additional nutrients, electron acceptors, bentonite, and initially oxic or anoxic conditions. These experiments were carried out at a reference temperature of 30°C (86°F), based on the average temperature expected in the repository. Gas generation rates used in the PA calculations have been derived from available experimental data and are described in Section 6.4.3.3. The effects of temperature on microbial gas generation are implicitly incorporated in the gas generation rates used.

SCR-6.5.1.1.3.2 *Effects of Biofilms on Microbial Gas Generation*

The location of microbial activity within the repository is likely to be controlled by the availability of substrates and nutrients. Biofilms may develop on surfaces where nutrients are concentrated. They consist of one or more layers of cells with extracellular polymeric material and serve to maintain an optimum environment for growth. Within such a biofilm ecosystem,

nutrient retention and recycling maximize microbe numbers on the surface (see, for example, Stroes-Gascoyne and West 1994, pp. 9 – 10).

Biofilms can form on almost any moist surface, but their development is likely to be restricted in porous materials. Even so, their development is possible at locations throughout the disposal system. The ***Effects of Biofilms on Microbial Gas Generation*** may affect disposal system performance through control of microbial population size and their effects on radionuclide transport.

Molecke (1979, p. 4) summarized microbial gas generation rates observed during a range of experimental studies. The experiments were conducted over a range of temperatures and chemical conditions and for different substrates representing likely states within the repository. However, the effect of biofilm formation in these experiments was uncertain. Molecke (1979, p. 7), presented gas generation rates as ranges, with upper and lower bounds as estimates of uncertainty. Later experiments reported by Francis and Gillow (1994) support the gas generation rate data reported by Molecke (1979). Their experiments investigated microbial gas generation under a wide range of possible conditions in the repository. These conditions included the presence of microbial inoculum, humid or inundated conditions, cellulosic substrates, additional nutrients, electron acceptors, bentonite, and initially oxic or anoxic conditions. Under the more favorable conditions for microbial growth established during the experiments, the development of populations of halophilic microbes and associated biofilms was evidenced by observation of an extracellular, carotenoid pigment, bacterioruberin, in the culture bottles (Francis and Gillow 1994, p. 59). Gas generation rates used in the PA calculations have been derived from available experimental data and are described in Section 6.4.3.3. The ***Effects of Biofilms on Microbial Gas Generation*** rates are implicitly incorporated in the gas generation rates.

Biofilms may also influence contaminant transport rates through their capacity to retain and thus retard both the microbes themselves and radionuclides. This effect is not accounted for in PA calculations, but is considered potentially beneficial to calculated disposal system performance. Microbial transport is discussed in FEP W87.

SCR-6.5.1.2 FEP Number: W46
FEP Title: ***Effects of Pressure on Microbial Gas Generation***

SCR-6.5.1.2.1 Screening Decision: SO-C

*The **Effects of Pressure on Microbial Gas Generation** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.2.2 Summary of New Information

The FEP screening argument has been updated, however the screening decision has not changed.

SCR-6.5.1.2.3 Screening Argument

Directly relevant to WIPP conditions, the gas generation experiments with actual waste components at Argonne National Laboratory provide no indication of any enhancement of pressured nitrogen atmosphere (2150 psia) on microbial gas generation (Felicione et al. 2001). In

addition, microbial breakdown of cellulosic material, and possibly plastics and other synthetic materials in the repository, will produce mainly CO_2 and methane with minor amounts of nitrogen oxide, nitrogen, and hydrogen sulfide. The accumulation of these gaseous species will contribute the total pressure in the repository. Increases in the partial pressures of these reaction products could potentially limit gas generation reactions. However, such an effect is not taken into account in WIPP PA calculations. The rate of microbial gas production will depend upon the nature of the microbial populations established, the prevailing conditions, and the substrates present. Microbial gas generation from ***Degradation of Organic Material*** (W44) is accounted for in PA calculations.

Chemical reactions may occur depending on, among other things, the concentrations of available reactants, the presence of catalysts and the accumulation of reaction products, the biological activity, and the prevailing conditions (for example, temperature and pressure). Reactions that involve the production or consumption of gases are often particularly influenced by pressure because of the high molar volume of gases. The effect of high total pressures on chemical reactions is generally to reduce or limit further gas generation.

Few data exist from which the ***Effects of Pressure on Microbial Gas Generation*** reactions that may occur in the WIPP can be assessed and quantified. Studies of microbial activity in deep-sea environments suggest (for example, Kato et al. 1994, p. 94) that microbial gas generation reactions are less likely to be limited by increasing pressures in the disposal rooms than are inorganic gas generation reactions (for example, corrosion). Consequently, the ***Effects of Pressure on Microbial Gas Generation*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.3 FEP Number: W47
FEP Title: ***Effects of Radiation on Microbial Gas Generation***

SCR-6.5.1.3.1 Screening Decision: SO-C

*The **Effects of Radiation on Microbial Gas Generation** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.3.2 Summary of New Information

The FEP screening argument has been updated to reflect the new radionuclide inventory, although the screening decision has not changed.

SCR-6.5.1.3.3 Screening Argument

Radiation may slow down microbial gas generation rates, but such an effect is not taken into account in WIPP PA calculations. According to the new *inventory* data, the total radionuclide inventory decreases from 7.44×10^6 (DOE 1996b) to 6.66×10^6 curies (Appendix DATA, Attachment F), about a 10 percent decrease Such a small change will not affect the original screening argument.

Experiments investigating microbial gas generation rates suggest that the effects of alpha radiation from TRU waste is not likely to have significant effects on microbial activity (Barnhart

et al. 1980; Francis 1985). Consequently, the ***Effects of Radiation on Microbial Gas Generation*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.4 FEP Number: W49 and W51
FEP Title: ***Gasses from Metal Corrosion***
Chemical Effects of Corrosion

SCR-6.5.1.4.1 Screening Decision: UP

Gas generation from metal corrosion is accounted for in PA calculations, and the effects of chemical changes from metal corrosion are incorporated in the gas generation rates used.

SCR-6.5.1.4.2 Summary of New Information

No new information has been identified related to these FEPs. They have been modified only from an editorial perspective, and have not changed since the CCA.

SCR-6.5.1.4.3 Screening Argument

Oxic corrosion of waste drums and metallic waste will occur at early times following closure of the repository and will deplete its oxygen content. Anoxic corrosion will follow the oxic phase and will produce hydrogen, while consuming water. ***Gases from Metal Corrosion*** are accounted for in PA calculations.

The predominant ***Chemical Effect of Corrosion*** reactions on the environment of disposal rooms will be to lower the oxidation state of the brines and maintain reducing conditions.

Molecke (1979, p. 4) summarized gas generation rates that were observed during a range of experiments. The experiments were conducted over a range of temperatures and chemical conditions representing likely states within the repository. Later experiments reported by Telander and Westerman (1993) support the gas generation rate data reported by Molecke (1979). Their experiments investigated gas generation from corrosion under a wide range of possible conditions in the repository. The studies included corrosion of low-carbon steel waste packaging materials in synthetic brines, representative of intergranular Salado brines at the repository horizon, under anoxic (reducing) conditions.

Gas generation rates used in the PA calculations have been derived from available experimental data and are described in Section 6.4.3.3. The effects of chemical changes from metal corrosion are, therefore, accounted for in PA calculations.

SCR-6.5.1.5 FEP Number: W50
FEP Title: ***Galvanic Coupling*** (within the repository)

SCR-6.5.1.5.1 Screening Decision: SO-C

*The effects of **Galvanic Coupling** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.5.2 Summary of New Information

The original screening argument confused ***Galvanic Coupling*** internal and external to the repository (see W95). As such, the original screening decision for ***Galvanic Coupling*** was screened out on probability however, it is more appropriate to screen this FEP on consequence. The screening decision has therefore been changes to SO-C and a clear distinction between which FEP considers internal and external coupling was included in the FEP discussions.

Consideration ***Galvanic Coupling*** (W50), is restricted to consideration of effects between or among materials within the repository. ***Galvanic Coupling*** with materials outside the repository is considered in ***Galvanic Coupling*** (W95).

Galvanic Coupling (within the repository) is unlikely to occur on a large scale. On a very small scale, ***Galvanic Coupling*** could occur whenever two dissimilar metals are in contact and a conducting medium is present. However, the resulting corrosion would cause the same effects as the other corrosion processes already included in the assessments. Thus, ***Galvanic Coupling***, as a distinct corrosion mechanism, would have negligible effects on repository performance.

Galvanic Coupling has been screened out on the basis of low consequence. No new information has become available that affects the screening argument; the FEP screening argument and screening decision remain unchanged.

SCR-6.5.1.5.3 Screening Argument

Galvanic Coupling (i.e. establishing an electrical current through chemical processes) could lead to the propagation of electric potential gradients between metals in the waste form, canisters, and other metals external to the waste form, potentially influencing corrosion processes, gas generation rates and chemical migration.

Metallic ore bodies external to the repository are nonexistent (CCA Appendix GCR) and therefore galvanic coupling between the waste and metals external to the repository would not occur. However, a variety of metals will be present within the repository as waste metals and containers, creating a potential for formation of galvanic cells over short distances. As an example, the presence of copper could influence rates of hydrogen gas production resulting from the corrosion of iron. The interactions between metals depend upon their physical disposition and the prevailing solution conditions, including pH and salinity. Good physical and electrical contact between the metals is critical to the establishment of galvanic cells.

Consequently, given the preponderance of iron over other metals within the repository and the likely passivation of many nonferrous materials, the influence of these electrochemical interactions on corrosion, and therefore gas generation, is expected to be minimal. Therefore, the effects of ***Galvanic Coupling*** have been eliminated from PA calculations on the basis of low consequence.

SCR-6.5.1.6 FEP Number: W52
FEP Title: ***Radiolysis of Brine***

SCR-6.5.1.6.1 Screening Decision: SO-C

*Gas generation from **Radiolysis of Brine** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.6.2 Summary of New Information

No new information is available relative to this FEP and screening decision. The screening argument has been modified for editorial purposes.

SCR-6.5.1.6.3 Screening Argument

Radiolysis of Brine in the WIPP disposal rooms, and of water in the waste, will lead to the production of gases and may significantly affect the oxygen content of the rooms. This in turn will affect the prevailing chemical conditions and potentially the concentrations of radionuclides that may be mobilized in the brines.

The overall reaction for the radiolysis of water in the waste and brine is

$$H_2O = H_2 + \tfrac{1}{2} O_2 \qquad (12)$$

However, the production of intermediate oxygen-bearing species that may subsequently undergo reduction will lead to reduced oxygen gas yields. The remainder of this section is concerned with the physical effects of gas generation by radiolysis of brine.

Reed et al. (1993) studied radiolytic gas generation during experiments lasting between 155 and 182 days. These experiments involved both synthetic brines similar to those sampled from the Salado at the WIPP repository horizon, and brines occurring in reservoirs in the Castile, as well as real brines sampled from the Salado in the repository workings. The brines were spiked with ^{239}Pu(VI) at concentrations between 6.9×10^{-9} and 3.4×10^{-4} molal. During these relatively short-term experiments, hydrogen gas was observed as the product of radiolysis. Oxygen gas was not observed; this was attributed to the formation of intermediate oxygen-bearing species. However, given sufficient exposure to alpha-emission, oxygen production may reach 50 percent that of hydrogen.

An estimate of the potential rate of gas generation due to the radiolysis of brine, R_{RAD}, can be made by making the following assumptions:

- Gas production occurs following the reaction above, so that 1.5 moles of gas are generated for each mole of water consumed.
- Gas production occurs as a result of the alpha decay of ^{239}Pu.
- ^{239}Puconcentrations in the disposal room brines are controlled by solubility equilibria.

- All of the dissolved plutonium is ^{239}Pu.

R_{RAD} is then given by

$$R_{RAD} = \frac{Y_g C_{Pu} SA_{Pu} \overline{E}_\alpha V_B}{N_D N_A} \tag{13}$$

$$R_{RAD} = \frac{\left(\frac{1.5 \text{ molecule gas}}{\text{molecule } H_2O}\right)\left(3.15\times10^{7}\ \frac{\text{sec}}{\text{yr}}\right)\left(3\times10^{-4}\ \frac{\text{mol}}{\text{L}}\right)\left(5.42\times10^{11}\ \frac{\text{Bq}}{\text{mol}}\right)\left(5.15\times10^{6}\ \frac{\text{eV}}{\text{dis}}\right)\left(\frac{0.015\ H_2O}{100\ \text{eV}}\right)\left(4.36\times10^{8}\text{L}\right)}{\left(8\times10^{5}\ \text{drums}\right)\left(6.022\times10^{23}\ \frac{\text{molecules}}{\text{mole}}\right)} \tag{14}$$

R = rate of gas production (moles per drum per year)
Y_g = radiolytic gas yield, in number of moles of gas produced per number of water molecules consumed
C_{Pu} = maximum dissolved concentration of plutonium (molar)
SA_{Pu} = specific activity of ^{239}Pu (5.42×10^{11} becquerels per mole)
$\overline{E}_\alpha$ = average energy of α-particles emitted during ^{239}Pu decay (5.15×10^{6} eV)
G = number of water molecules split per 100 eV of energy transferred from alpha-particles
V_B = volume of brine in the repository (liters)
N_D = number of CH drums in the repository (~8×10^{5})
N_A = Avogadro constant (6.022×10^{23} molecules per mole)

The value of G used in this calculation has been set at 0.015, the upper limit of the range of values observed (0.011 to 0.015) during experimental studies of the effects of radiation on WIPP brines (Reed et al. 1993). A maximum estimate of the volume of brine that could potentially be present in the disposal region has been made from its excavated volume of 436,000 m^3 (520,266 yd^3). This estimate, in particular, is considered to be highly conservative because it makes no allowance for creep closure of the excavation, or for the volume of waste and backfill that will be emplaced, and takes no account of factors that may limit brine inflow. These parameter values lead to an estimate of the potential rate of gas production due to the ***Radiolysis of Brine*** of 0.6 moles per drum per year.

Assuming ideal gas behavior and repository conditions of 30°C (86°F) and 14.8 MPa (lithostatic pressure), this is equivalent to approximately 6.8×10^{4} liters (1.8×10^{4} gallons) per year.

Potential gas production rates from other processes that will occur in the repository are significantly greater than this. For example, under water-saturated conditions, microbial degradation of cellulosic waste has the potential to yield between 1.3×10^{6} and 3.8×10^{7} liters (3.4×10^{5} and 1.0×10^{7} gallons) per year; anoxic corrosion of steels has the potential to yield up to 6.3×10^{5} liters (1.6×10^{5} gallons) per year.

In addition to the assessment of the potential rate of gas generation by ***Radiolysis of Brine*** given above, a study of the likely consequences on disposal system performance has been undertaken by Vaughn et al. (1995). A model was implemented in BRAGFLO to estimate radiolytic gas generation in the disposal region according to the equation above.

A set of BRAGFLO simulations was performed to assess the magnitude of the influence of the ***Radiolysis of Brine*** on contaminant migration to the accessible environment. The calculations considered radiolysis of water by 15 isotopes of Th, Pu, U, and Am. Conditional complementary cumulative distribution functions (CCDFs) of normalized contaminated brine releases to the Culebra via a human intrusion borehole and the shaft system, as well as releases to the subsurface boundary of the accessible environment via the Salado interbeds, were constructed and compared to the corresponding baseline CCDFs calculated excluding radiolysis. The comparisons indicated that ***Radiolysis of Brine*** does not significantly affect releases to the Culebra or the subsurface boundary of the accessible environment under disturbed or undisturbed conditions (Vaughn et al. 1995). Although the analysis of Vaughn et al. (1995) used data that are different than those used in the PA calculations, estimates of total gas volumes in the repository are similar to those considered in the analysis performed by Vaughn et al. (1995).

Therefore, gas generation by ***Radiolysis of Brine*** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.7 FEP Number: W53
FEP Title: ***Radiolysis of Cellulose***

SCR-6.5.1.7.1 Screening Decision: SO-C

*Gas generation from **Radiolysis of Cellulose** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.7.2 Summary of New Information

This FEP has been updated with new inventory data related to cellulose content. In addition, the screening argument has been modified by the inclusion of gas generation information from the WIPP transportation program.

SCR-6.5.1.7.3 Screening Argument

Molecke (1979) compared experimental data on gas production rates caused by ***Radiolysis of Cellulose*** and other waste materials with gas generation rates by other processes including bacterial (microbial) waste degradation. The comparative gas generation rates reported by Molecke (1979, p. 4) are given in terms of most probable ranges, using units of moles per year per drum, for drums of 0.21 m^3 (0.27 yd^3) in volume. A most probable range of 0.005 to 0.011 moles per year per drum is reported for gas generation due to radiolysis of cellulosic material (Molecke 1979, p. 4). As a comparison, a most probable range of 0.0 to 5.5 moles per year per drum is reported for gas generation by bacterial degradation of waste.

The data reported by Molecke (1979) are consistent with more recent gas generation investigations made under the WIPP program, and indicate that radiolysis of cellulosic materials

will generate significantly less gas than other gas generation processes. Gas generation from radiolysis of cellulosics therefore can be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Radiolytic gas generation is controlled by the radioactivity of wastes and the waste properties. According to the new *inventory* data, the total radionuclide inventory decreases from 7.44×10^6 (DOE 1996b) to 6.66×10^6 curies (Appendix DATA, Attachment F), about a 10 percent decrease. Interestingly, the radionuclide inventory in the CH-TRU waste, which accounts for the most volume of WIPP wastes, decreases from 6.42×10^6 (DOE 1996b) to 5.33×10^6 curies (Appendix DATA, Attachment F). Such a small change will not affect radiolytic gas generation. However, the new inventory data indicates a 7 percent increase in the density of cellulose in waste materials (Appendix DATA, Attachment F). Because the additional cellulose component is mainly derived from the Advanced Mixed Waste Treatment Plant (AMWTP) wastes, which have relatively low radioactivity, the increase in total cellulose quantity will not significantly affect the prediction of total radiolytic gas generation.

Radiolytic gas generation is also limited by transportation requirements, which state that the hydrogen generated in the innermost layer of confinement must be no more than five percent over 60 days (DOE 2000). Thus, the maximum rate allowed for transportation is 0.201 m^3 per drum × five percent × 1000 L/m^3 per 60 days × 365 days per year = 61 L per drum per year, smaller than the maximum microbial gas generation rate. Note that this estimate is very conservative and the actual rates are even smaller. It is a general consensus within the international research community that the effect of radiolytic gas generation on the long-term performance of a low/intermediate level waste repository is negligible (Rodwell et al. 1999).

SCR-6.5.1.8 FEP Number: W54
FEP Title: ***Helium Gas Production***

SCR-6.5.1.8.1 Screening Decision: SO-C

Gas generation from helium production has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.8.2 Summary of New Information

The updated information for the WIPP disposal inventory indicates that the expected WIPP-scale radionuclide activity (2.48 million curies of TRU isotopes) is less than previously estimated in TWBIR Rev 3 (DOE 1996b). Thus, the ***Helium Gas Production*** argument for CRA-2004 is conservatively bounded by the previous CCA screening argument. The FEP screening argument and screening decision remain unchanged except for editorial changes.

SCR-6.5.1.8.3 Screening Argument

Helium Gas Production will occur by the reduction of α-particles (helium nuclei) emitted from the waste. The maximum amount of helium that could be produced can be calculated from the number α-particles generated during radioactive decay. The α-particles are converted to helium gas by the following reaction:

$$^{4}He^{2+} + 2e^{-} \rightarrow He(g) \tag{15}$$

For the screening argument used in the CCA, the inventory (I) that may be emplaced in the repository is approximately 4.07 million curies or 1.5×10^{17} becquerels (see CCA Appendix BIR). Assuming that the inventory continues to yield α-particles at this rate throughout the 10,000-year regulatory period the maximum rate of helium gas produced (R_{He}) may be calculated from

$$R_{He} = \frac{1\left(\frac{1\ \text{He atom}}{\alpha - \text{decay}}\right)}{N_A} \tag{16}$$

R_{He} is the rate of ***Helium Gas Production*** in the repository (mole per second)

I is the waste inventory, 1.5×10^{17} becquerels, assuming that 1 becquerel is equal to 1 α-decay per second, and N_A is Avogadro constant (6.022×10^{23} atoms per mole). These assumptions regarding the inventory lead to maximum estimates for helium production because some of the radionuclides will decay by beta and gamma emission.

R_{He} is approximately 5.5×10^{-7} moles per second based on an alpha-emitting inventory of 4.07 million curies. Assuming ideal gas behavior and repository conditions of 30°C (86°F) and 14.8 MPa or 146 atm (lithostatic pressure), yields approximately 1.3 liters (0.34 gallons) per year.

Gas production rates by microbial degradation of organic materials and anoxic corrosion of steel are likely to be significantly greater than 1.3 liters per year. For example, anoxic corrosion of steels is estimated to yield 0 to 6.3×10^{5} liters of hydrogen per year (Section 6.4, Appendix PA, Attachment MASS). Even if gas production by ***Microbes*** and corrosion was minimal and helium production dominated gas generation, the effects would be of low consequence because of the low total volume.

The effects of ***Helium Gas Production*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.9 FEP Number: W55
FEP Title: ***Radioactive Gases***

SCR-6.5.1.9.1 Screening Decision: SO-C

*The formation and transport of **Radioactive Gases** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.9.2 Summary of New Information

No new information has become available that affects the screening argument; the FEP screening decision remains unchanged. Additional information has been added to the screening discussions.

SCR-6.5.1.9.3 Screening Argument

Based on the composition of the anticipated waste inventory as described in Appendix DATA, Attachment F, the ***Radioactive Gases*** that will be generated in the repository are radon and carbon-14 labeled CO_2 and methane (CH_4).

Appendix DATA, Attachment F indicates that a small amount of carbon-14, 0.73 grams, or 3.26 curies, will be disposed in the WIPP. This amount is insignificant in comparison with the 40 CFR § 191.13 cumulative release limit for carbon-14.

Notwithstanding this comparison, consideration of transport of ***Radioactive Gases*** could potentially be necessary in respect of the 40 CFR § 191.15 individual protection requirements. carbon-14 may partition into CO_2 and methane formed during microbial degradation of cellulosic and other organic wastes (for example, rubbers and plastics). However, total fugacities of CO_2 in the repository are expected to be very low because of the action of the MgO backfill which will lead to incorporation of CO_2 in solid magnesite. Similarly, interaction of CO_2 with cementitious wastes will limit CO_2 fugacities by the formation of solid calcium carbonate. Thus, because of the formation of solid carbonate phases in the repository, significant transport of carbon-14 as carbon dioxide-14 has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Potentially significant volumes of methane may be produced during the microbial degradation of cellulosic waste. However, volumes of methane-14 will be small given the low total inventory of carbon-14, and the tendency of carbon-14 to be incorporated into solid carbonate phases in the repository. Therefore, although transport of carbon-14 could occur as methane-14, this effect has been eliminated from the current PA calculations on the basis of low consequence to the performance of the disposal system.

Radon gas will contain proportions of the alpha emitters ^{219}Rn, ^{220}Rn, and ^{222}Rn. All of these have short half-lives, but ^{222}Rn is potentially the most important because it is produced from the abundant waste isotope, ^{238}Pu, and because it has the longest half-life of the radon isotopes ($\approx$ 4 days). ^{222}radon will exhibit secular equilibrium with its parent ^{226}Rn, which has a half-life of 1600 years. Consequently, ^{222}Rn will be produced throughout the 10,000-year regulatory time period. Conservative analysis of the potential ^{222}Rn inventory suggests activities of less than 716 curies at 10,000 years (Bennett 1996).

Direct comparison of the estimated level of ^{222}Rn activity with the release limits specified in 40 CFR § 191.13 cannot be made because the release limits do not cover radionuclides with half-lives less than 20 years. For this reason, production of radon gas can be eliminated from the PA calculations on regulatory grounds. Notwithstanding this regulatory argument, the small potential radon inventory means that the formation and transport of radon gas can also be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.2 Speciation

SCR-6.5.2.1 FEP Number: W56
FEP Title: ***Speciation***

SCR-6.5.2.1.1 Screening Decision: UP – Disposal Room
UP – Culebra
SO-C – Beneficial – Shaft Seals

*Chemical **Speciation** is accounted for in PA calculations in the estimates of radionuclide solubility in the disposal rooms, and the degree of chemical retardation estimated during contaminant transport. The effects of cementitious seals on chemical **Speciation** have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-6.5.2.1.2 Summary of New Information

No new information has been identified related to the screening of this FEP. It has been modified for editorial purposes.

SCR-6.5.2.1.3 Screening Argument

Chemical ***Speciation*** refers to the form in which elements occur under a particular set of chemical or environmental conditions. Conditions affecting chemical ***Speciation*** include the temperature, pressure, and salinity (ionic strength) of the water in question. The importance of chemical speciation lies in its control of the geochemical reactions likely to occur and the consequences for actinide mobility.

SCR-6.5.2.1.3.1 *Disposal Room*

The concentrations of radionuclides that dissolve in any brines present in the disposal rooms after repository closure will depend on the stability of the chemical species that form under the prevailing conditions (for example, temperature, pressure, and ionic strength). The method used to derive radionuclide solubilities in the disposal rooms (see Section 6.4.3.5) considers the expected conditions. The MgO backfill will buffer pH values in the disposal room to between 9 and 10. Thus, chemical ***Speciation*** is accounted for in PA calculations in the estimates of radionuclide solubility in the disposal rooms.

SCR-6.5.2.1.3.2 *Repository Seals*

Certain repository materials have the potential to interact with groundwater and significantly alter the chemical ***Speciation*** of any radionuclides present. In particular, extensive use of cementitious materials in the seals may have the capacity to buffer groundwaters to extremely high pH (for example, Bennett et al. 1992, pp. 315 – 325). At high pH values, the ***Speciation*** and adsorption behavior of many radionuclides is such that their dissolved concentrations are reduced in comparison with near-neutral waters. This effect reduces the migration of radionuclides in dissolved form. The effects of cementitious seals on groundwater chemistry

have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.2.1.3.3 *Culebra*

Chemical ***Speciation*** will affect actinide retardation in the Culebra. The dependence of actinide retardation on ***Speciation*** in the Culebra is accounted for in PA calculations by sampling over ranges of distribution coefficients (K_ds). The ranges of K_ds are based on the range of groundwater compositions and ***Speciation*** in the Culebra, including consideration of nonradionuclide solutes. The methodology used to simulate sorption in the Culebra is described in Section 6.4.6.2.1.

SCR-6.5.2.2 FEP Number: W57
FEP Title: ***Kinetics of Speciation***

SCR-6.5.2.2.1 Screening Decision: SO-C

The effects of reaction kinetics in chemical speciation reactions have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.2.2.2 Summary of New Information

No new information that would change the screening argument has arisen since the submission of the CCA. The original screening discussions have been edited for clarity of expression.

SCR-6.5.2.2.3 Screening Argument

Chemical ***Speciation*** of actinides describes the composition and relative distribution of dissolved species, such as the hydrated metal ion, or complexes, whether with organic or inorganic ligands. Conditions affecting chemical ***Speciation*** include temperature, ionic strength, ligand concentration and pH of the solution. Some ligands, such as hydroxide, may act to decrease actinide solubility, while others, such as citrate, frequently have the opposite influence, often increasing actinide solubility.

SCR-6.5.2.2.4 Disposal Room Equilibrium Conditions

The concentrations of radionuclides that can be dissolved in brines within the disposal rooms will depend on the thermodynamic stabilities and solubilities of the respective metal complexes. The Fracture-Matrix Transport (FMT) calculations and database input used to determine the brine solubilities of radionuclides takes into account the expected conditions, including temperature, ionic strength, pH, and ligand concentration. The chemical ***Speciation*** at equilibrium is accounted for in PA calculations in the estimates of radionuclide solubility in the disposal rooms.

SCR-6.5.2.2.5 Kinetics of Complex Formation

The waste that is emplaced within the WIPP contains radionuclides, including actinides or actinide bearing materials in solid phases, e.g. metal oxides, salts, coprecipitated solids, and

contaminated objects. In the event of contact with brine, the solution phase concentration of dissolved radionuclides is controlled both by the solution composition, and by the kinetics of dissolution of the solid phases, effectively approaching equilibrium from undersaturation. Solution complexation reactions of most metal ions with common inorganic ligands, such as carbonate and hydroxide, and with organic ligands such as acetate, citrate, oxalate, and ethylene diamine tetra-acetate (EDTA) are kinetically very fast, reaching equilibrium in fractions of a second, an inconsequentially short time increment on the scale of the 10,000-year regulatory period. Reactions of these types are generally so fast that special techniques must be adopted to measure the reaction rates; as a practical matter, the reaction rate is limited by the mixing rate when metal solutions are combined with ligand solutions. As a result, the rate of approach to an equilibrium distribution of solution species takes place much more rapidly than dissolution, making the dissolution reaction the rate limiting step. The effects of reaction kinetics in aqueous systems are discussed by Lasaga et al. (1994) who suggest that in contrast to many heterogeneous reactions, homogeneous aqueous geochemical ***Speciation*** reactions involving relatively small inorganic species occur rapidly and are accurately described by thermodynamic equilibrium models that neglect explicit consideration of reaction kinetics.

For that reason, the rate at which solution species approach equilibrium distribution is of no consequence to repository performance. ***Kinetics of Chemical Speciation*** may be eliminated from PA calculations on the basis of no consequence.

SCR-6.5.3 Precipitation and Dissolution

SCR-6.5.3.1 FEP Number: W58, W59, and W60
FEP Title: ***Dissolution of Waste*** (W58)
Precipitation of Secondary Minerals (W59)
Kinetics of Precipitation and Dissolution (W60)

SCR-6.5.3.1.1 Screening Decision: UP – W58
SO-C Beneficial – W59
SO-C – W60

Waste dissolution and the release of radionuclides in the disposal rooms are accounted for in PA calculations. The formation of radionuclide bearing precipitates from groundwaters and brines and the associated retardation of contaminants have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The effect of reaction kinetics in controlling the rate of waste dissolution within the disposal rooms has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.3.1.2 Summary of New Information

Precipitation of Secondary Minerals in the disposal room and in geologic units will lead to reductions in nuclide concentrations via the sequestration of radionuclides by coprecipitation and by encapsulation of radionuclide precipitates, and will retard radionuclide transport through sorption. Within the disposal room, metal oxides/oxy-hydroxides will form by corrosion of waste packages and waste components; brucite will form by hydration of MgO backfill;

carbonate minerals will form by carbonation of MgO backfill and cement phases; secondary cement alteration phases will form through brine-cement waste form interactions; and chloride and sulfate minerals will be precipitated due to water uptake during hydration and corrosion reactions. In geologic units above the repository, iron oxides/oxy-hydroxides, carbonates, sulfates may form as groundwaters mix. Mineral precipitation in geologic units above the repository is assumed to be uniform, and in addition to sorbing or sequestering radionuclides, will be beneficial by reducing permeability and slowing the groundwater flow.

During the original WIPP Certification, the EPA questioned the screening argument for ***Kinetics of Precipitation and Dissolution***. The EPA stated in EPA TSD Scope of Performance Assessment regarding ***Kinetics of Precipitation and Dissolution:***

> The screening argument in SCR.2.5.3 appears reasonable to EPA. Initially, EPA thought the argument appeared questionable because the CCA assumed that precipitation reactions are always rapid and complete. As a result, the EPA questioned the gas pressures in the repository, the chemical conditions, and the actinide solubilities. The DOE has since submitted experimental results indicating that the predicted reactions occur and time frames are somewhat rapid. The EPA reconsidered this assessment and concluded that the precipitation assumptions are necessary (and conservative), and are supported by experimental data.

Other than that stated above, no new information that would change the screening argument has arisen since the submission of the CCA. The original text has been edited for clarity of expression.

SCR-6.5.3.1.3 Screening Argument

Dissolution of Waste and ***Precipitation of Secondary Minerals*** control the concentrations of radionuclides in brines and can influence rates of contaminant transport. Waste dissolution is accounted for in PA calculations. The formation of radionuclide-bearing precipitates from groundwaters and brines and the associated retardation of contaminants have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

At low temperatures, precipitation and dissolution reactions are caused by changes in fluid chemistry that result in chemical undersaturation or oversaturation (Bruno and Sandino 1987). Precipitation can be divided into two stages: nucleation and crystal growth. Following nucleation, growth rates depend on the rates of surface processes and the transport of materials to the growth site. Mineral dissolution often depends on whether a surface reaction or transport of material away from the reaction site act as the rate controlling process. The former case may cause selective dissolution along crystallographically controlled features, whereas the latter may induce rapid bulk dissolution (Berner 1981). Thus, a range of kinetic behaviors will be exhibited by different mineral precipitation and dissolution reactions in geochemical systems.

SCR-6.5.3.1.3.1 *Disposal Room*

The waste that is emplaced within the WIPP contains radionuclides, including actinides or actinide-bearing materials in solid phases, e.g. metal oxides, salts, coprecipitated solids, and contaminated objects. In the event of contact with brine, the solution phase concentration of dissolved radionuclides is controlled both by the solution composition, and by the kinetics of

dissolution of the solid phases, effectively approaching equilibrium from undersaturation. Solution complexation reactions of most metal ions with common inorganic ligands, such as carbonated and hydroxide, and with organic ligands such as acetate, citrate, oxalate, and EDTA are kinetically very fast, reaching equilibrium in less than one second, which is infinitesimally small on the time scale of the 10,000 year regulatory period. The rate at which thermodynamic equilibrium is approached between solution composition and the solubility controlling solid phases will be limited by rate of dissolution of the solid materials in the waste. As a result, until equilibrium is reached, the solution concentration of the actinides will be lower than the concentration that is predicted based upon equilibrium of the solution phase components with the solubility limiting solid phases. The WIPP actinide source term model, which describes interactions of the waste and brine, is described in detail in Section 6.4.3.5. The assumption of instantaneous equilibrium in waste dissolution reactions is a conservative approach, yielding maximum concentration estimates for radionuclides in the disposal rooms because a time weighted average resulting from a kinetically accurate estimate of solution compositions would have lower concentrations at early times. Waste dissolution at the thermodynamic equilibrium solubility limit is accounted for in PA calculations. However, the ***Kinetics of Dissolution*** within the disposal rooms has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.3.1.3.2 *Geological Units*

During groundwater flow, radionuclide precipitation processes that occur will lead to reduced contaminant transport. No credit is given in PA calculations to the potentially beneficial occurrence of ***Precipitation of Secondary Minerals***. The formation of radionuclide-bearing precipitates from groundwaters and brines and the associated retardation of contaminants have been eliminated from PA calculations on the basis of beneficial consequence to disposal system performance. As a result ***Kinetics of Precipitation*** also has been eliminated from PA calculations because no credit is taken for precipitation reactions.

SCR-6.5.4 Sorption

SCR-6.5.4.1 FEP Number: W61, W62, and W63
FEP Title: ***Actinide Sorption*** (W61)
Kinetics of Sorption (W62)
Changes in Sorptive Surfaces (W63)

SCR-6.5.4.1.1 Screening Decision: UP – (W61, W62) In the Culebra & Dewey Lake
SO-C – Beneficial – (W61, W61) In the Disposal Room, Shaft Seals, Panel Closures, Other Geologic Units
UP – (W63)

Sorption within the disposal rooms, which would serve to reduce radionuclide concentrations, has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The effects of sorption processes in shaft seals and panel closures have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. Sorption within the Culebra and the Dewey Lake is accounted for in PA calculations. Sorption processes within other geological units of the

disposal system have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. Mobile adsorbents (for example, microbes and humic acids), and the sorption of radionuclides at their surfaces, are accounted for in PA calculations in the estimates of the concentrations of actinides that may be carried. The potential effects of reaction kinetics in adsorption processes and of ***Changes in Sorptive Surfaces*** *are accounted for in PA calculations.*

SCR-6.5.4.1.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.5.4.1.3 Screening Argument

Sorption may be defined as the accumulation of matter at the interface between a solid and an aqueous solution. Within PA calculations, including those made for the WIPP, the use of isotherm representations of ***Actinide Sorption*** prevails because of their computational simplicity in comparison with other models (Serne 1992, pp. 238 – 239).

The mechanisms that control the ***Kinetics of Sorption*** processes are, in general, poorly understood. Often, sorption of inorganic ions on mineral surfaces is a two-step process consisting of a short period (typically minutes) of diffusion-controlled, rapid uptake, followed by slower processes (typically weeks to months) including surface rearrangement, aggregation and precipitation, and solid solution formation (Davis and Kent 1990, 202). Available data concerning rates of sorption reactions involving the important radionuclides indicate that, in general, a range of kinetic behavior is to be expected.

The relevance to the WIPP of sorption reaction kinetics lies in their effects on chemical transport. Sorption of waste contaminants to static surfaces of the disposal system such as seals and host rocks acts to retard chemical transport. Sorption of waste contaminants to potentially mobile surfaces, such as colloids, however, may act to enhance chemical transport, particularly if the kinetics of contaminant desorption are slow or the process is irreversible (nonequilibrium).

The following subsections discuss sorption in the disposal rooms, shaft seals, panel closures, the Culebra, and other geological units of the WIPP disposal system. Sorption on colloids, ***Microbes***, and particulate material is also discussed.

SCR-6.5.4.1.3.1 *Disposal Room*

The concentrations of radionuclides that dissolve in waters entering the disposal room will be controlled by a combination of sorption and dissolution reactions. However, because sorption processes are surface phenomena, the amount of material that is likely to be involved in sorption mass transfer processes will be small relative to that involved in the bulk dissolution of waste. WIPP PA calculations therefore assume that dissolution reactions control radionuclide concentrations. Sorption on waste, containers, and backfill within the disposal rooms, which would serve to reduce radionuclide concentrations, has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.4.1.4 Shaft Seals and Panel Closures

Chapter 3.0 and CCA Appendix SEAL describe the seals that are to be placed at various locations in the access shafts and waste panel access tunnels. The materials to be used include crushed salt, bentonite clay, and cementitious grouts. Of these, the latter two in particular possess significant sorption capacities. No credit is given for the influence of sorption processes that may occur in seal materials and their likely beneficial effects on radionuclide migration rates. The effects of sorption processes in shaft seals and panel closures have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.4.1.4.1 *Culebra*

Sorption within the Culebra is accounted for in PA calculations as discussed in Section 6.4.6.2. The model used comprises an equilibrium, sorption isotherm approximation, employing constructed cumulative distribution functions (CDFs) of distribution coefficients (K_ds) applicable to dolomite in the Culebra. The potential effects of reaction kinetics in adsorption processes are encompassed in the ranges of K_ds used. The geochemical speciation of the Culebra groundwaters and the effects of ***Changes in Sorptive Surfaces*** are implicitly accounted for in PA calculations for the WIPP in the ranges of K_ds used.

SCR-6.5.4.1.4.2 *Other Geological Units*

During groundwater flow, any radionuclide sorption processes that occur between dissolved or colloidal actinides and rock surfaces will lead to reduced rates of contaminant transport. The sorptive capacity of the Dewey Lake is sufficiently large to prevent any radionuclides that enter it from being released to the accessible environment over 10,000 years (Wallace et al. 1995). Thus, sorption within the Dewey Lake is accounted for in PA calculations as discussed in Section 6.4.6.6. No credit is given to the potentially beneficial occurrence of sorption in other geological units outside the Culebra. Sorption processes within other geological units of the disposal system have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.4.1.4.3 *Sorption on Colloids, Microbes, and Particulate Material*

The interactions of sorption processes with colloidal, microbial, or particulate transport are complex. Neglecting sorption of contaminants on immobile surfaces in the repository shafts and Salado (for example, the clays of the Salado interbeds) is a conservative approach because it leads to overestimated transport rates. However, neglecting sorption on potentially mobile adsorbents (for example, microbes and humic acids) cannot be shown to be conservative with respect to potential releases, because mobile adsorbents may act to transport radionuclides sorbed to them. Consequently, the concentrations of actinides that may be carried by mobile adsorbents are accounted for in PA calculations (see Section 6.4.3.6).

SCR-6.5.5 Reduction-Oxidation Chemistry

SCR-6.5.5.1 FEP Number: W64 and W66
FEP Title: ***Effects of Metal Corrosion Reduction-Oxidation Kinetics***

SCR-6.5.5.1.1 Screening Decision: UP

The effects of reduction-oxidation reactions related to metal corrosion on reduction-oxidation conditions are accounted for in PA calculations. Reduction-oxidation reaction kinetics are accounted for in PA calculations.

SCR-6.5.5.1.2 Summary of New Information

No new information has been identified for these FEPs. The screening arguments have not changed. Editorial changes have been made to the discussion.

SCR-6.5.5.1.3 Screening Argument

SCR-6.5.5.1.3.1 *Reduction-Oxidation Kinetics*

In general, investigation of the reduction-oxidation couples present in aqueous geochemical systems suggests that most reduction-oxidation reactions are not in thermodynamic equilibrium (Wolery 1992, 27). The lack of data characterizing the rates of reactions among trace element reduction-oxidation couples leads to uncertainty in elemental speciation. This uncertainty in ***Reduction-Oxidation Kinetics*** is accounted for in PA calculations in the dissolved actinide source term model (see Section 6.4.3.5), which estimates the probabilities that particular actinides occur in certain oxidation states.

SCR-6.5.5.1.3.2 *Corrosion*

Other than gas generation, which is discussed in FEPs W44 through W55, the main ***Effect of Metal Corrosion*** will be to influence the chemical conditions that prevail within the repository. Ferrous metals will be the most abundant metals in the WIPP, and these will corrode on contact with any brines entering the repository. Initially, corrosion will occur under oxic conditions owing to the atmospheric oxygen present in the repository at the time of closure. However, consumption of the available oxygen by corrosion reactions will rapidly lead to anoxic (reducing) conditions. These changes and controls on conditions within the repository will affect the chemical ***Speciation*** of the brines and may affect the oxidation states of the actinides present. Changes to the oxidation states of the actinides will lead to changes in the concentrations that may be mobilized during brine flow. The oxidation states of the actinides are accounted for in PA calculations by the use of parameters that describe probabilities that the actinides exist in particular oxidation states and, as a result, the likely actinide concentrations. Therefore, the ***Effect of Metal Corrosion*** are accounted for in PA calculations.

SCR-6.5.5.2 FEP Number: W65
FEP Title: ***Reduction-Oxidation Fronts***

SCR-6.5.5.2.1 Screening Dec*ision: SO-P*

The migration of ***Reduction-Oxidation Fronts*** *through the repository has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-6.5.5.2.2 Summary of New Information

Large-scale reduction-oxidation fronts have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years. There is no new information that would change the screening decision. Editorial changes have been made to the FEP text to remove reference to other FEP descriptions, screening arguments and screening decisions.

SCR-6.5.5.2.3 Screening Argument

The development of ***Reduction-Oxidation Fronts*** in the disposal system may affect the chemistry and migration of radionuclides. ***Reduction-Oxidation Fronts*** separate regions that may be characterized, in broad terms, as having different oxidation potentials. On either side of a ***Reduction-Oxidation Fronts***, the behavior of reduction-oxidation-sensitive elements may be controlled by different geochemical reactions. Elements that exhibit the greatest range of oxidation states (for example, uranium, neptunium, and plutonium) will be the most affected by ***Reduction-Oxidation Fronts*** development and migration. The migration of ***Reduction-Oxidation Fronts*** may occur as a result of diffusion processes, or in response to groundwater flow, but will be restricted by the occurrence of heterogeneous buffering reactions (for example, mineral dissolution and precipitation reactions). Indeed, these buffering reactions cause the typically sharp, distinct nature of reduction-oxidation fronts.

Of greater significance is the possibility that the flow of fluids having different oxidation potentials from those established within the repository might lead to the development and migration of a large-scale ***Reduction-Oxidation Fronts***. ***Reduction-Oxidation Fronts*** have been observed in natural systems to be the loci for both the mobilization and concentration of radionuclides, such as uranium. For example, during investigations at two uranium deposits at Poços de Caldas, Brazil, uranium was observed by Waber (1991) to be concentrated along ***Reduction-Oxidation Fronts*** at the onset of reducing conditions by its precipitation as uranium oxide. In contrast, studies of the Alligator Rivers uranium deposit in Australia by Snelling (1992) indicated that the movement of the relatively oxidized weathered zone downwards through the primary ore body as the deposit was eroded and gradually exhumed led to the formation of secondary uranyl-silicate minerals and the mobilization of uranium in its more soluble uranium (VI) form in near-surface waters. The geochemical evidence from these sites suggests that the ***Reduction-Oxidation Fronts*** had migrated only slowly, at most on the order of a few tens of meters per million years. These rates of migration were controlled by a range of factors, including the rates of erosion, infiltration of oxidizing waters, geochemical reactions, and diffusion processes.

The migration of large-scale ***Reduction-Oxidation Fronts*** through the repository as a result of regional fluid flow is considered unlikely over the regulatory period on the basis of comparison

with the slow rates of ***Reduction-Oxidation Fronts*** migration suggested by natural system studies. This comparison is considered conservative because the relatively impermeable nature of the Salado suggests that ***Reduction-Oxidation Fronts*** migration rates at the WIPP are likely to be slower than those observed in the more permeable lithologies of the natural systems studied. Large-scale ***Reduction-Oxidation Fronts*** have therefore been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-6.5.5.3 FEP Number: W67
FEP Title: ***Localized Reducing Zones***

SCR-6.5.5.3.1 Screening Decision: SO-C

*The formation of **Localized Reducing Zones** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.5.3.2 Summary of New Information

The FEP screening argument has been modified from that presented the CCA to include a more complete description of the description has been updated.

SCR-6.5.5.3.3 Screening Argument

The dominant reduction reactions in the repository include steel corrosion and microbial degradation. The following bounding calculation shows that molecular diffusion alone will be sufficient to mix brine chemistry over a distance of meters and therefore the formation of ***Localized Reducing Zones*** in the repository is of low consequence.

The diffusion of a chemical species in a porous medium can be described by Fick's equation (e.g., Richardson and McSween 1989, p.132):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial X}\left(D_{eff}\ \frac{\partial C}{\partial X}\right) \tag{17}$$

where C is the concentration of the diffusing chemical species; t is the time; X is the distance; and D_{eff} is the effective diffusivity of the chemical species in a given porous medium. D_{eff} is related to the porosity (ϕ) of the medium by (e.g., Oelkers, 1996):

$$D_{eff} = \phi^2 D \tag{18}$$

where D is the diffusivity of the species in pure solution. The D values for most aqueous species at room temperatures fall into a narrow range, and 10^{-5} cm^2 (1.5×10^{-6} in^2) per second is a good approximation (e.g., Richardson and McSween 1989, p.138). From the WIPP PA calculations (Bean et al. 1996, p.7-29; WIPP PA Department, 1993, Equation B-8), the porosity in the WIPP waste panels after room closure is calculated to be 0.4 to 0.7. From Equation (19), the effective diffusivity D_{eff} in the waste is estimated to be $2 \sim 5 \times 10^{-6}$ cm^2 (7×10^{-7} in^2) per second (= $6 \sim 16 \times 10^{-3}$ m^2/year).

Given a time scale of T, the typical diffusion penetration distance (L) can be determined by scaling:

$$L = \sqrt{D_{eff}\,T}\ . \tag{19}$$

Using Equation (20), the diffusion penetration distance in the WIPP can be calculated as a function of diffusion time, as shown in Figure SCR-1.

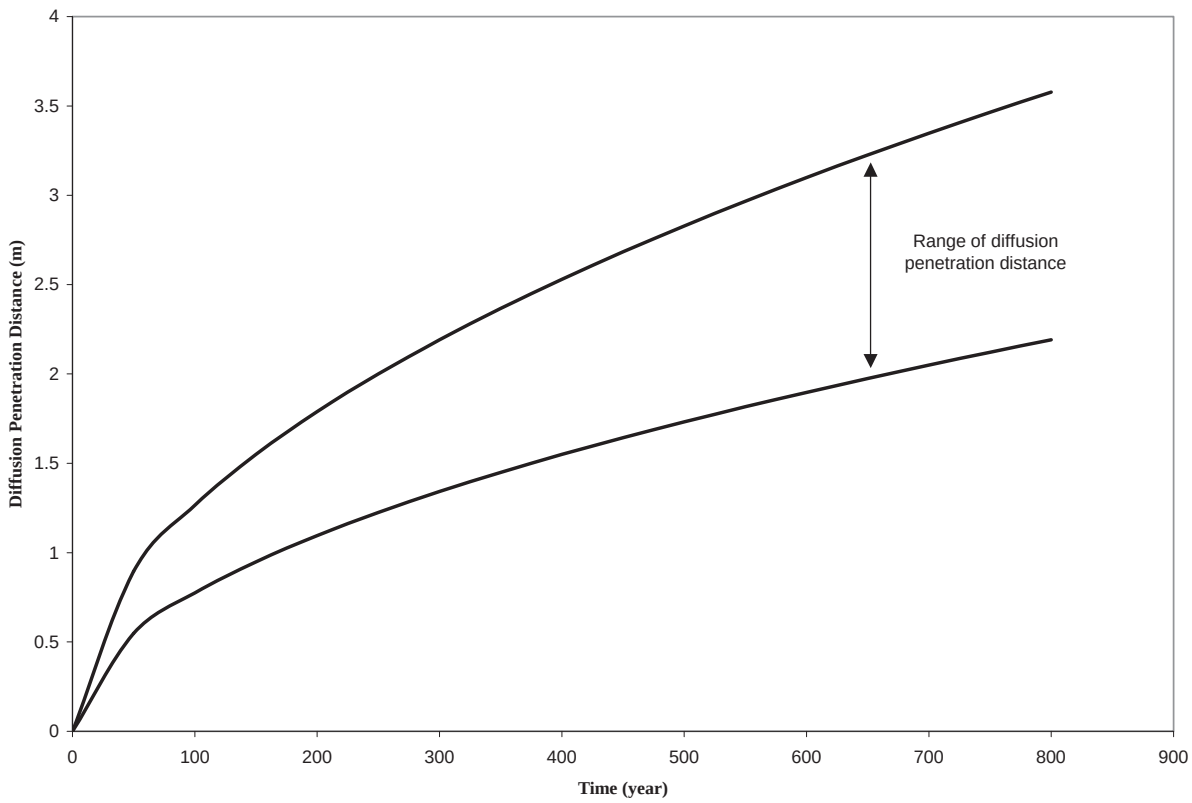

Figure SCR-1. Diffusion Penetration Distance in the WIPP as a Function of Diffusion Time

Direct brine release requires the repository gas pressure to be at least 8 MPA (Stoelzel et al. 1996). The CRA calculations show that it will take at least 100 years for the repository pressure to reach this critical value by gas generation processes. Over this time scale, according to Equation (20) and Figure SCR-1, molecular diffusion alone can mix brine composition effectively at least over a distance of ~ 1 m (3.3 ft).

The above calculation assumes diffusion only through liquid water. This assumption is applicable to steel corrosion, the humid rate of which is zero. Note that microbial reactions can also consume or release gaseous species. The diffusion of a gaseous species is much faster than an aqueous one. Thus, molecular diffusion can homogenize microbial reactions even at a much large scale.

The height of waste stacks in the repository after room closure (h) can be calculated by:

$$h = \frac{h_0 (1 - \phi_0)}{1 - \phi} \tag{20}$$

where h_0 and ϕ_0 are the initial height of waste stacks and the initial porosity of wastes, which are assumed to be 4 m and 0.88, respectively, in the WIPP PA. For ϕ = 0.4 - 0.7, h is estimated to be 0.8 to 1.4 m. This means that molecular diffusion alone can homogenize redox reaction in the vertical dimension of the repository. Therefore, the formation of localized reducing zone is unlikely. The general repository environment will become reducing shortly after room closure, due to metal corrosion and microbial reactions. Therefore, ***Localized Reducing Zones*** can be eliminated from PA calculations on the basis of low consequence to the disposal system.

SCR-6.5.6 Organic Complexation

SCR-6.5.6.1 FEP Number: W68, W69, and W71
FEP Title: ***Organic Complexation*** (W68)
Organic Ligands (W69)
Kinetics of Organic Complexation (W71)

SCR-6.5.6.1.1 Screening Decision: UP W68 and W69
SO-C W71

*The effects of anthropogenic **Organic Complexation** reactions, including the effects of **Organic Ligands**, humic, and fulvic acids, have been incorporated in the PA calculations. The kinetics of organic ligand complexation is screened out because the rate at which **Organic Ligands** are complexed to actinide is so fast that it has no consequence to repository performance.*

SCR-6.5.6.1.2 Summary of New Information

The ***Organic Complexation*** was screened out for the CCA PA, on the basis that transition metals (in particular **iron**, **nickel**, **chromium**, **vanadium**, and **manganese**, present in waste drum steel) would compete effectively with the actinides for the binding sites on the organic ligands, thus preventing significant complexation of actinides organics. Although the CRA-2004 calculations include the effects of ***Organic Ligands*** (acetate, citrate, EDTA, and oxalate) on actinide solubility calculations, based on a revised thermodynamic database, the rate at which ***Organic Ligands*** are complexed to actinides is of no consequence to repository performance. Kinetics of ***Organic Ligands*** complexation may be eliminated from PA calculations on the basis of no consequence.

SCR-6.5.6.1.3 Screening Argument

From a PA standpoint, the most important actinides are Th, U, Np, Pu, and Am. Dissolved thorium, uranium, neptunium, plutonium, and americium will speciate essentially entirely as Th(IV), U(IV) or U(VI), Np(IV) or Np(V), Pu(III) or Pu(IV), and Am(III) under the strongly reducing conditions expected due to the presence of Fe(II) and microbes. (Section SOTERM-33 – SOTERM-36).

Some ***Organic Ligands*** can increase the actinide solubilities. An estimate of the complexing agents in the transuranic solidified waste forms scheduled for disposal in WIPP is presented in Appendix DATA, Attachment F Table DATA-F-3.2-24. Acetate, citrate, oxalate, and EDTA were determined to be the only water-soluble and actinide complexing organic ligands present in significant quantities in the TWBIR. These ligands and their complexation with actinides (Th(IV), U(VI), Np(V), and Am(III)) in a variety of ionic strength media were studied at Florida State University (FSU) (Choppin et al. 2001). The FSU studies showed that acetate, citrate, oxalate, and EDTA are capable of significantly enhancing dissolved actinide concentrations. Lactate behavior was also studied at FSU because it appeared in the preliminary inventory of nonradioactive constituents of the TRU waste to be emplaced in the WIPP (Brush 1990); lactate did not appear in the TWBIR, nor does it appear in the 2003 update to the TWBIR (Appendix DATA, Attachment F).

The solubility of the actinides is calculated using FMT, a computer code for calculating actinide concentration limits based on thermodynamic parameters. The parameters for FMT are derived both from experimental investigations specifically designed to provide parameter values for this model and from the published literature.

- Although the FSU experimental work on ***Organic Ligands*** complexation showed that acetate, citrate, oxalate, and EDTA are capable of significantly enhancing dissolved actinide concentrations, SNL did not include the results in the FMT calculations for the CCA PA because (1) the thermodynamic database for ***Organic Complexation*** of actinides was not considered adequate at the time, and (2) side-calculations using thermodynamic data for low-ionic-strength NaCl solutions showed that transition metals (in particular iron, nickel, chromium, vanadium, and manganese present in waste drum steel) would compete effectively with the actinides for the binding sites on the ***Organic Ligands***, thus preventing significant complexation of actinides organics (Appendix PA, Attachment SOTERM , Sections SOTERM-36 - SOTERM-41).

The CRA-2004 calculations include the effects of organic ligands (acetate, citrate, EDTA, and oxalate) on actinide solubilities in the FMT calculations (Brush and Xiong 2003). The FMT database includes all of the results of experimental studies (Choppin et al. 2001) required to predict the complexation of dissolved An(III), An(IV), and An(V) species by acetate, citrate, EDTA, and oxalate (Giambalvo 2002a, ***2002***b).

Solution complexation reactions of most metal ions with common inorganic ligands, such as carbonate and hydroxide, and with organic ligands, such as acetate, citrate, oxalate, and EDTA, are kinetically very fast, reaching equilibrium in fractions of a second, an inconsequentially short time increment on the scale of the 10,000-year regulatory period. Reactions of these types are generally so fast that special techniques must be adopted to measure the reaction rates; as a practical matter, the reaction rate is limited by the mixing rate when metal solutions are combined with ligand solutions.

For that reason, the rate at which ***Organic Ligands*** are complexed to actinide is of no consequence to repository performance. ***Kinetics of Organic Complexation*** may be eliminated from PA calculations on the basis of no consequence.

SCR-6.5.6.2 FEP Number: W70
FEP Title: ***Humic and Fulvic Acids***

SCR-6.5.6.2.1 Screening Decision: UP

The presence of ***Humic and Fulvic Acids*** *is incorporated in PA calculations.*

SCR-6.5.6.2.2 Summary of New Information

No new information has been identified for this FEP. Editorial changes have been made to the discussion.

SCR-6.5.6.2.3 Screening Argument

The occurrence of ***Humic and Fulvic Acids*** is incorporated in PA calculations in the models for radionuclide transport by humic colloids (see Section 6.4.6.2.2).

SCR-6.5.7 Chemical Effects on Material Properties

SCR-6.5.7.1 FEP Number: W74 and W76
FEP Title: ***Chemical Degradation of Seals*** (W74)
Microbial Growth on Concrete (W76)

SCR-6.5.7.1.1 Screening Decision: UP

The effects of ***Chemical Degradation of Seals*** *and of* ***Microbial Growth on Concrete*** *are accounted for in PA calculations.*

SCR-6.5.7.1.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in DOE (1996a); however the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.5.7.1.3 Screening Argument

The concrete used in the seal systems will degrade due to chemical reaction with the infiltrating groundwater. Degradation could lead to an increase in permeability of the seal system. The main uncertainties with regard to cement degradation rates at the WIPP are the effects of groundwater chemistry, the exact nature of the cementitious phases present, and the rates of brine infiltration. The PA calculations take a conservative approach to these uncertainties by assuming a large increase in permeability of the concrete seals only a few hundred years after closure. These permeability values are based on seal design considerations and consider the potential effects of degradation processes. Therefore, the effects of ***Chemical Degradation of Seals*** are accounted for in PA calculations through the CDFs used for seal material permeabilities.

Concrete can be inhabited by alkalophilic bacteria, which could produce acids, thereby accelerating the seal degradation process. Nitrification processes, which will produce nitric acid, tend to be aerobic, and will be further limited at the WIPP by the low availability of ammonium in the brines (Pedersen and Karlsson 1995, 75). Because of the limitations on growth because of the chemical conditions, it is likely that the effects of ***Microbial Growth on Concrete*** will be small. The effects of such microbial activity on seal properties are, therefore, implicitly accounted for in PA calculations through the CDFs used for seal material permeabilities.

SCR-6.5.7.2 FEP Number: W75
FEP Title: ***Chemical Degradation of Backfill***

SCR-6.5.7.2.1 Screening Decision: SO-C

The effects on material properties of the ***Chemical Degradation of Backfill*** *have been eliminated from PA calculations on the basis of low consequence.*

SCR-6.5.7.2.2 Summary of New Information

As MgO degrades chemically, its physical properties change. Previously, DOE provided a paper by Bynum et al. (1997), which summarizes the experimental results pertaining to chemical degradation of backfill acquired by 1997. The most current MgO data, obtained after the CCA, are summarized in the 2001 MRS Proceedings paper by Snider (2001). The current data show that new MgO will essentially behave as it was designed. Changes have been made to the FEP discussion to reference new experimental results and for editorial purposes.

SCR-6.5.7.2.3 Screening Argument

Degradation of the chemical conditioners or backfill added to the disposal room is a prerequisite of their function in buffering the chemical environment of the disposal room. However, the chemical reactions (Snider 2001) and dissolution involved will change the physical properties of the material. Because the mechanical and hydraulic characteristics of the backfill have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system, the effects of the ***Chemical Degradation of Backfill*** on material properties have been eliminated from PA calculations on the same basis.

SCR-6.6 Contaminant Transport Mode Features, Events, and Processes

SCR-6.6.1 Solute and Colloid Transport

SCR-6.6.1.1 FEP Number: W77
FEP Title: ***Solute Transport***

SCR-6.6.1.1.1 Screening Decision: UP

Transport of dissolved radionuclides is accounted for in PA calculations.

SCR-6.6.1.1.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Sections 6.4.5.4 and 6.4.6.2.1.

SCR-6.6.1.1.3 Screening Argument

Solute Transport may occur by advection, dispersion, and diffusion down chemical potential gradients, and is accounted for in PA calculations (Sections 6.4.5.4 and 6.4.6.2.1).

SCR-6.6.1.2 FEP Number: W78, W79, W80, and W81
FEP Title: ***Colloidal Transport*** (W78)
Colloidal Formation and Stability (W79)
Colloidal Filtration (W80)
Colloidal Sorption (W81)

SCR-6.6.1.2.1 Screening Decision: UP

Formation of colloids, transport of colloidal radionuclides, and colloid retardation through filtration and sorption are accounted for in PA calculations.

SCR-6.6.1.2.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation (if any) are described in Sections 6.4.3.6 and 6.4.6.2.2.

SCR-6.6.1.2.3 Screening Argument

Colloids typically have sizes of between 1 nm and 1 μm and may form stable dispersions in groundwaters. ***Colloid Formation and Stability*** depends on their composition and the prevailing chemical conditions (for example, salinity). Depending on their size, ***Colloid Transport*** may occur at different rates than those of fully dissolved species. They may be physically excluded from fine porous media, and their migration may be accelerated through fractured media in channels where velocities are greatest. However, they can also interact with the host rocks during transport and become retarded. These interactions may be of a chemical or physical nature and include electrostatic effects, leading to ***Colloid Sorption,*** and sieving leading to ***Colloid Filtration*** and pore blocking. ***Colloid Formation and Stability*** is accounted for in PA calculations through estimates of colloid numbers in the disposal room based on the prevailing chemical conditions (Section 6.4.3.6). Colloid sorption, filtration, and transport in the Culebra are accounted for in PA calculations (Section 6.4.6.2.2).

SCR-6.6.2 Particle Transport

SCR-6.6.2.1 FEP Number: W82, W83,W84, W85, and W86
FEP Title: ***Suspension of Particles*** (W82)
Rinse (W83)
Cuttings (W84)
Cavings (W85)
Spallings (W86)

SCR-6.6.2.1.1 Screening Decision: DP W82, W84, W85, W86
SO-C W83

The formation of particulates through **Rinse** *and subsequent transport of radionuclides in groundwater and brine has been eliminated from PA calculations for undisturbed conditions on the basis of low consequence to the performance of the disposal system. The transport of radionuclides as particulates (**Cuttings, Cavings**, and **Spallings**) during penetration of the repository by a borehole, is accounted for in PA calculations.*

SCR-6.6.2.1.2 Summary of New Information

Suspensions of Particles larger than colloids are generally unstable and do not persist for very long. The **Rinse** process likely cannot occur under undisturbed conditions because brine flow would not be rapid enough to create a suspension of particles and transport them to the accessible environment. The only reasonable conditions under which suspensions could be formed would be during a drilling event with particles of waste suspended in the drilling fluid are carried to the surface. This effect is covered in PA. Editorial changes have been made to the discussion.

SCR-6.6.2.1.3 Screening Argument

Suspensions of Particles that have sizes larger than colloids are unstable because the particles undergo gravitational settling. It is unlikely that brine flow will be rapid enough within the WIPP disposal rooms to generate particulate suspensions through **Rinse** and transport under undisturbed conditions. Mobilization of suspensions would effect a local and minor redistribution of radionuclides within the room and would not result in increased radionuclide transport from the repository. The formation of particulates through **Rinse** and transport of radionuclides in groundwater and brine has been eliminated from PA calculations for undisturbed conditions on the basis of low consequence to the performance of the disposal system.

Inadvertent human intrusion into the repository by a borehole could result in transport of waste material to the ground surface through drilling-induced flow and blowouts (FEPs H21 and H23). This waste could include material intersected by the drill bit (***Cuttings***), material eroded from the borehole wall by circulating drilling fluid (***Cavings***), and material that enters the borehole as the repository depressurizes (***Spallings***). Transport of radionuclides by these materials and in brine is accounted for in PA calculations and is discussed in Section 6.4.7.1.

SCR-6.6.3 Microbial Transport

SCR-6.6.3.1 FEP Number: W87
FEP Title: ***Microbial Transport***

SCR-6.6.3.1.1 Screening Decision: UP

Transport of radionuclides bound to microbes is accounted for in PA calculations.

SCR-6.6.3.1.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.6.3.1.3 Screening Argument

Microbes will be introduced into the disposal rooms during the operational phase of the repository and will also occur naturally in geological units throughout the disposal system. Because of their colloidal size, microbes, and any radionuclides bound to them, may be transported at different rates than radionuclides in solution. ***Microbial Transport*** of radionuclides is accounted for in PA calculations (Section 6.4.6.2.2).

SCR-6.6.3.2 FEP Number: W88
FEP Title: ***Biofilms***

SCR-6.6.3.2.1 Screening Decision: SO-C Beneficial

*The effects of **Biofilms** on microbial transport have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-6.6.3.2.2 Summary of New Information

The effects of ***Biofilms*** on ***Microbial Transport*** have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The discussion of this FEP has been updated with recent experimental work.

SCR-6.6.3.2.3 Screening Argument

Microbes will be introduced into the disposal rooms during the operational phase of the repository and will also occur naturally in geological units throughout the disposal system.

Biofilms may influence microbial and radionuclide transport rates through their capacity to retain, and therefore retard, both the microbes themselves and radionuclides. The formation of ***Biofilms*** in deep subsurface environments such as in the WIPP is controversial. Since the microbial degradation experiments at Brookhaven National Laboratory (BNL) bracket expected repository conditions, the potential effect of ***Biofilms*** formation on microbial degradation and transport, if any, has been captured in the PA parameters derived from those experiments

(Francis and Gillow 1994; Francis et. al 1997; Francis and Gillow 2000; Gillow and Francis 2001a; Gillow and Francis 2001b; Gillow and Francis 2002a; Gillow and Francis 2002b). As a matter of fact, no apparent formation of stable biofilms was observed in the BNL experiments. The formation of ***Biofilms*** tends to reduce cell suspension and mobility. This effect has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.6.4 Gas Transport

SCR-6.6.4.1 FEP Number: W89
FEP Title: ***Transport of Radioactive Gases***

SCR-6.6.4.1.1 Screening Decision: SO-C

*The **Transport of Radioactive Gases** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.6.4.1.2 Summary of New Information

This FEP discussion has been updated to include recent inventory information. The screening decision has not changed.

SCR-6.6.4.1.3 Screening Argument

The production and potential ***Transport of Radioactive Gases*** are eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Transportable radioactive gases are comprised mainly of isotopes of radon and carbon-14. Radon gases are eliminated from PA because their inventory is small (<20 Ci; Appendix DATA, Attachment F) and their half-lives are short (<4 days), resulting in insignificant potential for release from the repository. The updated information for the WIPP disposal inventory of carbon-14 (Appendix DATA, Attachment F) indicates that the expected WIPP-scale quantity (3.3 Ci) is 70 percent lower than previously estimated (~13 Ci) in the TWBIR Rev 3 (DOE 1996b). Thus, all CRA-2004 screening arguments for carbon-14 are conservatively bounded by the previous CCA screening arguments.

SCR-6.7 Contaminant Transport Processes

SCR-6.7.1 Advection

SCR-6.7.1.1 FEP Number: W90
FEP Title: ***Advection***

SCR-6.7.1.1.1 Screening Decision: UP

***Advection** of contaminants is accounted for in PA calculations.*

SCR-6.7.1.1.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.7.1.1.3 Screening Argument

Advection (that is, the transport of dissolved and solid material by flowing fluid) is accounted for in PA calculations (Sections 6.4.5.4 and 6.4.6.2).

SCR-6.7.2 Diffusion

SCR-6.7.2.1 FEP Number: W91 and W92
FEP Title: ***Diffusion*** (W91)
Matrix Diffusion (W92)

SCR-6.7.2.1.1 Screening Decision: UP

Diffusion *of contaminants and retardation by* ***Matrix Diffusion*** *are accounted for in PA calculations.*

SCR-6.7.2.1.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.7.2.1.3 Screening Argument

Diffusion (that is, the movement of molecules or particles both parallel to and transverse to the direction of advection in response to Brownian forces) and, more specifically ***matrix diffusion***, whereby movement is transverse to the direction of advection within a fracture and into the surrounding rock matrix, are accounted for in PA calculations (Section 6.4.6.2).

SCR-6.7.3 Thermochemical Transport Phenomena

SCR-6.7.3.1 FEP Number: W93
FEP Title: ***Soret Effect***

SCR-6.7.3.1.1 Screening Decision: SO-C

The effects of thermochemical transport phenomena (the ***Soret Effect****) have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.7.3.1.2 Summary of New Information

There is no new information available that affects the screening decision; only minor editorial changes have been made to the FEP discussion.

SCR-6.7.3.1.3 Screening Argument

According to Fick's law, the diffusion flux of a solute is proportional to the solute concentration gradient. In the presence of a temperature gradient there will also be a solute flux proportional to the temperature gradient (the ***Soret Effect***). Thus, the total solute flux, J, in a liquid phase may be expressed as

$$J = - DVC - NDVT, \tag{21}$$

where C is the solute concentration, T is the temperature of the liquid, D is the solute diffusion coefficient, and

$$N = S_T C(1-C), \tag{22}$$

in which S_T is the Soret coefficient. The mass conservation equation for solute diffusion in a liquid is then

$$\frac{\partial C}{\partial t} = \nabla \bullet \left(D\nabla C + ND\nabla T\right). \tag{23}$$

When temperature gradients exist in solutions with both light and heavy solute molecules, the heavier molecules tend to concentrate in the colder regions of the solution. Typically, large temperature gradients are required for Soret diffusion to be significant compared to Fickian diffusion.

Radioactive Decay, ***Nuclear Criticality***, and ***Exothermic Reactions*** are three possible sources of heat in the WIPP repository. The DOE (1980) estimated that radioactive decay of CH-TRU waste will result in a maximum temperature rise at the center of the repository of 1.6°C (2.9°F) at 80 years after waste emplacement. Sanchez and Trellue (1996) have shown that the total thermal load of RH-TRU waste will not significantly affect the average temperature increase in the repository. Temperature increases of about 3°C (5.4°F) may occur at the locations of RH-TRU containers with maximum thermal power (60 W). Such temperature increases are likely to be short-lived on the time scale of the 10,000 year regulatory period because of the rapid decay of heat-producing nuclides in RH-TRU waste, such as ^{137}Cs, ^{90}Sr, ^{241}Pu, and ^{147}Pm, whose half-lives are approximately 30, 29, 14, and 3 years, respectively. Soret diffusion generated by such temperature gradients will be negligible compared to other radionuclide transport mechanisms.

Temperature increases resulting from exothermic reactions are discussed in W72. Potentially the most significant exothermic reactions are **Concrete Hydration**, backfill hydration, and **Aluminum Corrosion**. Hydration of the seal concrete could raise the temperature of the concrete to approximately 50°C (122°F) and that of the surrounding salt to approximately 38°C (100°F) one week after seal emplacement.

However, the concrete seals will act as barriers to fluid flow for at least 100 years after emplacement, and seal permeability will be minimized (Wakeley et al. 1995). As a result, short-term temperature increases associated with concrete hydration will not result in significant Soret diffusion through the seal system.

The maximum temperature rise in the disposal panels will be less than 5°C (9°F) as a consequence of backfill hydration. Note that active institutional controls will prevent drilling within the controlled area for 100 years after disposal. Heat generation by radioactive decay and concrete seal hydration will have decreased substantially after 100 years, and the temperatures in the disposal panels will have decreased nearly to the temperature of the undisturbed host rock.

If the repository were to be inundated following a drilling intrusion, aluminum corrosion could, at most, result in a short-lived (two years) temperature increase of about 6°C (10.8°F). These calculated maximum heat generation rates resulting from aluminum corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability; each calculation assumes that all available brine is consumed by the reaction of concern. Thus, the temperature rise of 6°C (10.8°F) represents the maximum that could occur as a result of a combination of exothermic reactions occurring simultaneously. Temperature increases of this magnitude will not result in significant Soret diffusion within the disposal system.

The limited magnitude and spatial scale of temperature gradients in the disposal system indicate that Soret diffusion will be insignificant, allowing the effects of thermochemical transport (***Soret Effect***) to be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.4 Electrochemical Transport Phenomena

SCR-6.7.4.1 FEP Number: W94
FEP Title: ***Electrochemical Effects***

SCR-6.7.4.1.1 Screening Decision: SO-C

The effects of electrochemical transport phenomena caused by electrochemical reactions have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.4.1.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.4.1.3 Screening Argument

The variety of waste metals and metal packaging in the repository may allow galvanic cells spanning short distances to be established. The interactions among the metals depend upon their physical characteristics and the chemical conditions in the repository. For example, good physical and electrical contact, which is critical to the establishment of galvanic cells, may be impeded by electrically nonconductive waste materials. Additionally, in order to establish a galvanic cell, it is necessary that the metals have different values for standard reduction potentials. For example, a galvanic cell is not expected to be formed by contact of two segments of metals with identical compositions. As a result, galvanic cells can only be established by contact of dissimilar metals, as might happen due to contact between a waste drum and the contents, or between contents within a waste package. The localized nature of electrochemical

transport is restricted to the size scale over which galvanic cells can develop, i.e., on the order of size of waste packages. Since the possible range of transport is restricted by the physical extent of galvanic activity, ***Electrochemical Effects*** cannot act as long-range transport mechanisms for radionuclides and therefore are of no consequence to the performance of the repository.

SCR-6.7.4.2 FEP Number: W95
FEP Title: ***Galvanic Coupling***

SCR-6.7.4.2.1 Screening Decision: SO-P

*The effects of **Galvanic Coupling** between the waste and metals external to the repository on transport have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-6.7.4.2.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.4.2.3 Screening Argument

With regard to the WIPP, ***Galvanic Coupling*** refers to the establishment of galvanic cells between metals in the waste form, canisters, and other metals external to the waste form.

Long range electric potential gradients may exist in the subsurface as a result of groundwater flow and electrochemical reactions. The development of electric potential gradients may be associated with the weathering of sulfide ore bodies, variations in rock properties at geological contacts, bioelectric activity associated with organic matter, natural corrosion reactions, and temperature gradients in groundwater. With the exception of mineralization potentials associated with metal sulfide ores, the magnitude of electric potentials is usually less than about 100 millivolts and the potentials tend to average to zero over distances of several thousand feet (Telford et al. 1976). Metals external to the waste form can include natural metallic ore bodies in the host rock. However, metallic ore bodies and metallic sulfide ores do not exist in the region of the repository (CCA Appendix GCR). As a result, galvanic coupling between the waste and metallic materials outside the repository cannot occur. Therefore, ***Galvanic Coupling*** is eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-6.7.4.3 FEP Number: W96
FEP Title: ***Electrophoresis***

SCR-6.7.4.3.1 Screening Decision: SO-C

*The effects of electrochemical transport phenomena caused by **Electrophoresis** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.7.4.3.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.4.3.3 Screening Argument

Long range (in terms of distance) electric potential gradients may exist in the subsurface as a result of groundwater flow and electrochemical reactions. The development of potentials may be associated with the weathering of sulfide ore bodies, variations in rock properties at geological contacts, bioelectric activity associated with organic matter, natural corrosion reactions, and temperature gradients in groundwater. With the exception of mineralization potentials associated with metal sulfide ores, the magnitude of such potentials is usually less than about 100 millivolts and the potentials tend to average to zero over distances of several thousand feet (Telford et al. 1976, p. 458). Short range potential gradients due to corrosion of metals within the waste may be set up over distances that are restricted to the size scale of the waste packages.

A variety of metals will be present within the repository as waste metals and metal packaging, which may allow electrochemical cells to be established over short distances. The types of interactions that will occur depend on the metals involved, their physical characteristics, and the prevailing solution conditions. Electrochemical cells that may be established will be small relative to the size of the repository, limiting the extent to which migration of contaminants by ***Electrophoresis*** can occur. The electric field gradients will be of small magnitude and confined to regions of electrochemical activity in the area immediately surrounding the waste material. As a result, ***Electrophoretic Effects*** on migration behavior due to both long and short range potential gradients have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.5 Physiochemical Transport Phenomena

SCR-6.7.5.1 FEP Number: W97
FEP Title: ***Chemical Gradients***

SCR-6.7.5.1.1 Screening Decision: SO-C

*The effects of enhanced diffusion across **Chemical Gradients** have been eliminated from PAs on the basis of low consequence to the performance of the disposal system.*

SCR-6.7.5.1.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.5.1.3 Screening Argument

Chemical Gradients within the disposal system, whether induced naturally or resulting from repository material and waste emplacement, may influence the transport of contaminants. Gradients will exist at interfaces between different repository materials and between repository

and geological materials. Distinct chemical regimes will be established within concrete seals and adjoining host rocks. Similarly, ***Chemical Gradients*** will exist between the waste and the surrounding rocks of the Salado. Other ***Chemical Gradients*** may exist due to the juxtaposition of relatively dilute groundwaters and brines or between groundwaters with different compositions. Natural gradients currently exist between different groundwaters in the Culebra.

Enhanced diffusion is a possible consequence of ***Chemical Gradients*** that occur at material boundaries. However, the distances over which enhanced diffusion could occur will be small in comparison to the size of the disposal system. Processes that may be induced by ***Chemical Gradients*** at material boundaries include the formation or destabilization of colloids. For example, cementitious materials that will be emplaced in the WIPP as part of the waste and the seals contain colloidal-sized materials, such as calcium-silicate-hydrate gels, and alkaline pore fluids. ***Chemical Gradients*** will exist between the pore fluids in the cementitious materials and the less alkaline surroundings. Chemical interactions at these interfaces may lead to the generation of colloids of the inorganic, mineral fragment type. Colloidal compositions may include calcium and magnesium oxides, calcium hydroxide, calcium-aluminum silicates, calcium-silicate-hydrate gels, and silica. Experimental investigations of the stability of inorganic, mineral fragment colloidal dispersions have been carried out as part of the WIPP colloid-facilitated actinide transport program (Papenguth and Behl 1996). Results of the investigations indicate that the salinities of the WIPP brines are sufficient to cause destabilization of mineral fragment colloidal dispersions. Therefore, concentrations of colloidal suspensions originating from concrete within the repository are expected to be extremely low, and are considered in PA calculations.

SCR-6.7.5.2 FEP Number: W98
FEP Title: ***Osmotic Processes***

SCR-6.7.5.2.1 Screening Decision: SO-C

*The effects of **Osmotic Processes** have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-6.7.5.2.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.5.2.3 Screening Argument

Osmotic Processes, i.e., diffusion of water through a semi permeable or differentially permeable membrane in response to a concentration gradient, may occur at interfaces between waters of different salinities. ***Osmotic Processes*** can occur if waters of different salinities and/or compositions exist on either side of a particular lithology such as clay, or a lithological boundary that behaves as a semipermeable membrane. At the WIPP, clay layers within the Salado may act as semi permeable membranes across which ***Osmotic Processes*** may occur.

In the absence of a semipermeable membrane, water will move from the more dilute water into the more saline water. However, the migration of dissolved contaminants across an interface

may be restricted depending upon the nature of the membrane. A hydrological gradient across a semi permeable membrane may either enhance or oppose water movement by osmosis depending on the direction and magnitude of the gradient. Dissolved contaminants that cannot pass through a semi-permeable membrane may be moved towards the membrane and concentrated along the interface when advection dominates over osmosis and reverse osmosis occurs. Thus, both osmosis and reverse osmosis can restrict the migration of dissolved contaminants and possibly lead to concentration along interfaces between different water bodies. The effects of ***Osmotic Processes*** have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.7.5.3 FEP Number: W99
FEP Title: ***Alpha Recoil***

SCR-6.7.5.3.1 Screening Decision: SO-C

*The effects of **Alpha-Recoil Processes** on radionuclide transport have been eliminated from PA calculations on the basis of low consequence to performance of the disposal system.*

SCR-6.7.5.3.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.5.3.3 Screening Argument

Alpha particles are emitted with sufficiently high energies that daughter nuclides recoil appreciably to conserve system momentum. For example, ^{238}U decays to ^{234}Th with emission of a 4.1 MeV alpha particle. The law of conservation of momentum requires that the daughter nuclide, ^{234}Th, recoils in the opposite direction with an energy of approximately 0.07 MeV. The energy is great enough to break chemical bonds or cause ^{234}Th to move a short distance through a crystal lattice. If the ^{234}Th is close enough to the surface of the crystal, it will be ejected into the surroundings. ^{234}Th decays to ^{234}Pa which decays to ^{234}U with respective half-lives of 24.1 days and 1.17 minutes. The recoil and decay processes can lead to the apparent preferential dissolution or leaching of ^{234}U relative to ^{238}U from crystal structures and amorphous or adsorbed phases. Preferential leaching may be enhanced due to radiation damage to the host phase resulting from earlier radioactive decay events. Consequently, ^{234}U sometimes exhibits enhanced transport behavior relative to ^{238}U.

The influence of ***Alpha-Recoil*** processes on radionuclide transport through natural geologic media is dependent on many site-specific factors, such as mineralogy, geometry, and microstructure of the rocks, as well as geometrical constraints on the type of groundwater flow, e.g., porous or fracture flow. Studies of natural radionuclide-bearing groundwater systems often fail to discern a measurable effect of alpha-recoil processes on radionuclide transport above the background uncertainty introduced by the spatial heterogeneity of the geological system. Consequently, the effects of the ***Alpha-Recoil*** processes that occur on radionuclide transport are thought to be minor. These effects have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.5.4 FEP Number: W100
FEP Title: ***Enhanced Diffusion***

SCR-6.7.5.4.1 Screening Decision: SO-C

Enhanced Diffusion *is a possible consequence of* ***Chemical Gradients*** *that occur at material boundaries. However, the distances over which* ***Enhanced Diffusion*** *could occur will be small in comparison to the size of the disposal system. Therefore, the effects of* ***Enhanced Diffusion*** *across* ***Chemical Gradients*** *at material boundaries have been eliminated from PAs on the basis of low consequence to the performance of the disposal system.*

SCR-6.7.5.4.2 Summary of New Information

Enhanced *Diffusion* only occurs where there are higher than average chemical gradients. The spatial extent of chemical gradients should be quite limited and as enhanced diffusion occurs, it will tend to reduce the chemical gradient. Thus, the driving force for the enhanced diffusion will be reduced and eventually eliminated as the system approaches steady state or equilibrium conditions. Due to the limited spatial extent of enhanced diffusion, its effect on radionuclide transport should be small.

The effects of ***Enhanced Diffusion*** across ***Chemical Gradients*** at material boundaries have been eliminated from PAs on the basis of low consequence to the performance of the disposal system. Changes have been made to the FEP discussion for clarity and editorial purposes.

SCR-6.7.5.4.3 Screening Argument

Processes that may be induced by ***Chemical Gradients*** at material boundaries include the formation or destabilization of colloids. For example, cementitious materials, emplaced in the WIPP as part of the waste and the seals, contain colloidal-sized phases such as calcium-silicate-hydrate gels, and alkaline pore fluids. ***Chemical Gradients*** will exist between the pore fluids in the cementitious materials and the less alkaline surroundings. Chemical interactions at these interfaces may lead to the generation of colloids of the inorganic, mineral fragment type. Colloidal compositions may include calcium and MgOr, calcium hydroxide, calcium-aluminum silicates, calcium-silicate-hydrate gels, and silica. Concentrations of colloidal suspensions originating from concrete within the repository are considered in PA calculations even though expected to be extremely low.

Distinct interfaces between waters of different salinities and different densities may limit mixing of the water bodies and affect flow and contaminant transport. Such effects have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.8 Ecological Features, Events, and Processes

SCR-6.8.1 Plant, Animal, and Soil Uptake

SCR-6.8.1.1 FEP Number: W101, W102, and W103
FEP Title: ***Plant Uptake*** (W101)

Animal Uptake (W102)
Accumulation in Soils (W103)

SCR-6.8.1.1.1 Screening Decision: SO-R
SO-C for 40 CFR 191.15

Plant Uptake, Animal Uptake*, and* ***Accumulation in Soils*** *have been eliminated from compliance assessment calculations for 40 CFR § 191.15 on the basis of low consequence.* ***Plant Uptake*** *and* ***Animal Uptake*** *in the accessible environment have been eliminated from PA calculations for 40 CFR § 191.13 on regulatory grounds.* ***Accumulation in Soils*** *within the controlled area has been eliminated from PA calculations for 40 CFR § 191.13 on the basis of beneficial consequences.*

SCR-6.8.1.1.2 Summary of New Information

DOE has stated that FEPs related to ***Plant Uptake, Animal Uptake***, and ***Accumulation in Soils*** have been eliminated from the compliance assessment calculations on the basis of low consequence. DOE indicated that the screening of these FEPs is justified based upon the results of PA calculations, which show that releases to the accessible environment under undisturbed conditions are restricted to lateral migration through anhydrite beds within the Salado Formation. PAs for evaluating compliance with the EPA's cumulative release requirements in 40 CFR § 191.13 need not consider radionuclide migration in the accessible environment. Therefore, FEPs that relate to ***Plant Uptake*** and ***Animal Uptake*** in the accessible environment have been eliminated from PA calculations on regulatory grounds.

SCR-6.8.1.1.3 Screening Argument

The results of the calculations presented in Section 6.5 show that releases to the accessible environment under undisturbed conditions are restricted to lateral releases through the DRZ at repository depth. Thus, for evaluating compliance with the EPA's individual protection requirements in 40 CFR § 191.15, FEPs that relate to ***Plant Uptake***, ***Animal Uptake***, and ***Accumulation in Soils*** have been eliminated from compliance assessment calculations on the basis of low consequence.

Performance assessments for evaluating compliance with the EPA's cumulative release requirements in 40 CFR § 191.13 need not consider radionuclide migration in the accessible environment. Therefore, FEPs that relate to ***plant uptake*** and ***animal uptake*** in the accessible environment have been eliminated from PA calculations on regulatory grounds. ***Accumulation in Soils*** that may occur within the controlled area would reduce releases to the accessible environment and can, therefore, be eliminated from PA calculations on the basis of beneficial consequence.

SCR-6.8.2 Human Uptake

SCR-6.8.2.1 FEP Number(s): W104, W105, W106, W107, and W108
FEP Title(s): ***Ingestion*** (W104)
Inhalation (W105)
Irradiation (W106)

Dermal Sorption (W107)
Injection (W108)

SCR-6.8.2.1.1 Screening Decision: SO-R
SO-C for 40 CFR § 191.15

Ingestion, Inhalation, Irradiation, Dermal Sorption*, and* ***Injection*** *have been eliminated from compliance assessment calculations for 40 CFR § 191.15 and Subpart C of 40 CFR Part 191 on the basis of low consequence. FEPs that relate to human uptake in the accessible environment have been eliminated from PA calculations for 40 CFR § 191.13 on regulatory grounds.*

SCR-6.8.2.1.2 Summary of New Information

The DOE stated in the CCA that the results of the PA calculations indicate that releases to the accessible environment under undisturbed conditions are restricted to lateral migration through anhydrite beds within the Salado Formation. The DOE further stated that based upon the bounding approach taken for evaluating compliance with EPA's individual protection requirements in 40 CFR § 191.15 and the groundwater protection requirements in Subpart C of 40 CFR § 191, these abovementioned exposure pathways were found to be of low consequence. However, the analysis did not include analysis of doses from other potential exposure pathways such as stock consumption or irrigation. These weaknesses were remedied by DOE's submittal of a more detailed dose analysis, which included all of the appropriate additional pathways (DOE 1997c).

In both the PAVT and the CCA calculations (DOE 1997a, 1997b, 1997c) a very conservative bounding-analysis approach was used to estimate potential doses. Using this approach, the calculated maximum potential dose (millirems) to any internal organ due to beta particle and photon radioactivity from man-made radionuclides in drinking water was 2.9×10^{-4} in the PAVT and 4.2×10^{-3} for the CCA. Further, the annual effective dose equivalent to the total body due to beta particle and photon radioactivity is 1.5×10^{-5} in the CCA and 2.3×10^{-4} for the CCA. All of these values are well below the acceptable standard of 4 millirems per year as specified in 40 CFR § 141.16(a). Finally, the calculated maximum potential doses (millirems) to an individual due to meat consumption, vegetable consumption, and inhalation of resuspended irrigated soil are 2.7×10^{-7}, 0.031, and 2.1×10^{-5}, respectively, in the PAVT and 3.3×10^{-8}, 0.46, 3.1×10^{-4}, respectively, in the CCA. All of these values are well below the individual protection standard, an annual committed effective dose of 15 millirems as specified in 40 CFR § 191.15(a). Therefore, the original screening decisions remain valid, and no changes have been made to the FEP screening arguments or decisions.

SCR-6.8.2.1.3 Screening Argument

As described in Section 8.1.1, releases to the accessible environment under undisturbed conditions are restricted to lateral migration through anhydrite interbeds within the Salado. Because of the bounding approach taken for evaluating compliance with the EPA's individual protection requirements in 40 CFR § 191.15 and the groundwater protection requirements in Subpart C of 40 CFR Part 191 (see Sections 8.1.2.2 and 8.2.3), FEPs that relate to human uptake

by ***Ingestion, Inhalation, Irradiation, Dermal Sorption,*** and ***Injection*** have been eliminated from compliance assessment calculations on the basis of low consequence.

Performance assessments for evaluating compliance with the EPA's cumulative release requirements in 40 CFR § 191.13 need not consider radionuclide migration in the accessible environment. Therefore, FEPs that relate to human uptake in the accessible environment have been eliminated from PA calculations on regulatory grounds.

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Appendix PA

Attachment SOTERM

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ACRONYMS AND ABBREVIATIONS

An	actinide(s)
atm	atmosphere (a unit of pressure)
aq	aqueous
ASTP	Actinide Source Term Program
BNL	Brookhaven National Laboratory
brucite	$Mg(OH)_2$
calcite	$CaCO_3$
CFR	Code of Federal Regulations
CPR	cellulosics, plastics, and rubber
DOE	(U.S.) Department of Energy
DRZ	disturbed rock zone
EDTA	ethylenediaminetetra acetate
EPA	(U.S.) Environmental Protection Agency
eq	equivalent(s)
ERDA	(U.S.) Energy Research and Development Administration
FA-Suw	fulvic acid isolated from the Suwannee River acquired from the International Humic Substances Society, Golden, Colorado
FMT	Fracture-Matrix Transport
f_{CO_2}	the fugacity of a gaseous species, f_i (similar to the partial pressures of that species, p_i)
g	gaseous or gram(s)
gal	gallon(s)
GWB	Generic Weep Brine
HAal-Ald	aliphatic humic acid purchased from Aldrich Chemical Co., purified by Florida State University
HAal-LBr	aliphatic humic acid isolated from sediments collected from Lake Bradford, Florida, prepared by Florida State University
HAar-Gor	aromatic humic acid isolated from groundwaters near Gorleben, Germany, obtained from Professor J.-I. Kim, Institut für Radiochemie, München
HAar-Suw	aromatic humic acid isolated from the Suwannee River acquired from the International Humic Substances Society, Golden, Colorado
HMW/FW	Harvie-Møller-Weare/Felmy and Weare
hydromagnesite	$Mg_4(CO_3)_3(OH)_2{\cdot}3H_2O$ or $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$
L	Liter(s)
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
m	molal
M	molar
meq	milliequivalent(s)
mL	milliliter(s)
mol	mole(s)
PA	performance assessment
periclase	MgO
pH	the negative logarithm of the activity of hydrogen ion (H^+)

redox	oxidation-reduction
s	second
SIT	Specific-Ion Interaction Theory
SPC	Salado Primary Constituent
STTP	(WIPP) Actinide Source Term Waste Test Program
SWCF	Sandia National Laboratories WIPP Central File
TRU	transuranic
TWBIR	Transuranic Waste Baseline Inventory Report
UV	ultraviolet
WIPP	Waste Isolation Pilot Plant

SOTERM-1.0 INTRODUCTION

The actinide source term used in the performance assessment (PA) calculations for the Waste Isolation Pilot Plant (WIPP) represents the aqueous concentrations of thorium (Th), uranium (U), plutonium (Pu), and americium (Am) in the repository. The source term is the sum of the dissolved species (solubilities) and the mobile suspended (colloidal) species of these radioelements. The actinide source term establishes the mobile concentrations of Th, U, Pu, and Am that may be released from the repository in brine. Brine releases to the accessible environment may occur through the sealed shafts, up possible intrusion boreholes, and/or out laterally through Salado Formation interbeds. (For a discussion of release scenarios and pathways, see Chapter 6.0, Section 6.3). Quantification of the impact of these releases contributes directly to assessing compliance with Title 40 Code of Federal Regulations (CFR) Part 191. Direct releases of particulate actinides to the surface associated with solid waste resulting from drilling (cuttings, cavings, and spallings) are not included in the actinide source term.

The actinide source term is limited to those radionuclides that could significantly impact the long-term performance of the WIPP. These radionuclides are all isotopes of Th, U, Pu, and Am. From the standpoint of their potential effects on the long-term performance of the repository, the order of importance of these actinides is Pu ≈ Am >> U > Th (Helton et al. 1998). Other actinides, especially neptunium (Np), have been included in the laboratory and modeling studies used to develop the actinide source term because it was not known at the outset which actinides could significantly affect the long-term performance of the repository. Other radioelements, such as strontium (Sr), cesium (Cs), and radium (Ra), are not included in the actinide source term because of their relatively short half-lives or limited waste inventory.

Attachment SOTERM (SOurce TERM) focuses on the development of actinide-source-term parameter values and the implementation of these parameters in PA calculations. In Section 2.0, an overview of near-field chemical processes and conditions is presented. Sections 3.0 and 4.0 focus on the development of the dissolved-actinide solubility parameters and oxidation-state distribution, respectively. Section 5.0 focuses on the impact of organic ligands on dissolved actinide concentrations. The colloidal actinide source term is described in Section 6.0. In Section 7.0 the PA implementation of the dissolved and colloidal components of the source term is described.

This attachment is a supplement to information presented in Chapter 6, Sections 6.4.3.3, 6.4.3.4, 6.4.3.5, and 6.4.3.6 of this application.

SOTERM-2.0 OVERVIEW OF NEAR-FIELD PROCESSES AND CONDITIONS

This section presents an overview of near-field processes and conditions that will affect actinide solubilities in the WIPP. Ambient geochemical conditions are described first. The effects of human intrusion and waste are then described. Emphasis is placed on how various components and processes within the repository will affect the dissolution and colloidal suspension of actinides. Excess magnesium oxide (MgO) will be added to the repository for assurance

purposes, so the effect of MgO is included in this discussion. Simplifications and assumptions used to model the components and processes are discussed in each section.

SOTERM-2.1 Ambient Geochemical Conditions

The Salado is predominantly nearly pure halite (NaCl), with interbeds ("marker beds") consisting mainly of anhydrite ($CaSO_4$). The nearly pure halite contains accessory evaporite minerals such as anhydrite ($CaSo_4$), gypsum ($CaSO_4 \bullet 2H_2O$), polyhalite ($K_2MgCa_2(SO_4)_4 \bullet 2H_2O$), magnesite ($MgCO_3$), and clays. Small quantities of intergranular (grain-boundary) brines and intragranular brines (fluid inclusions) are associated with the salt at the repository horizon. These brines are highly concentrated solutions (up to 8 M) of predominantly sodium (Na^+), Mg^{2+}, potassium (K^+), chloride (Cl^-), and sulfate (SO_4^{2-}) with smaller amounts of Ca^{2+}, CO_3^{2-}, and B. These brines have been in contact with the Salado evaporite minerals for about 250 million years and are saturated with respect to these minerals.

Underlying the Salado is the Castile Formation, composed of alternating units of interlaminated carbonate and anhydrite, and nearly pure halite. The Castile in the vicinity of the WIPP site is known to contain localized brine reservoirs under sufficient pressure to force brine to the land surface if penetrated by a borehole. Castile brines are predominantly saturated NaCl solutions containing Ca^{2+} and SO_4^{2-}, and small concentrations of other elements, and are about eight times more concentrated than seawater. Overlying the Salado in the vicinity of the WIPP site is the Culebra Member of the Rustler Formation, a fractured dolomite ($CaMg(CO_3)_2$) layer. It is significant because it is expected to be the most transmissive geologic pathway to the accessible environment. Culebra brines are generally more dilute than the Salado and Castile brines, and are predominantly NaCl with K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, and CO_3^{2-}. (See Chapter 2.0, Section 2.4.2.1 of this application for information on the distribution of Culebra brine salinity.)

SOTERM-2.2 Repository Chemical Conditions

Three aspects of the repository chemical environment can have a major impact on the dissolution and colloidal suspension of actinides. These are:

- brine composition;
- microbial consumption of cellulosic, plastic, and rubber (CPR) materials and concomitant production of carbon dioxide (CO_2); and
- anoxic corrosion of steels and other iron-base (Fe-base) alloys in the waste containers and the waste and concomitant production of hydrogen (H_2).

For each of these, the effect, the range of possible behavior, and the simplifications used in modeling are discussed below.

SOTERM-2.2.1 Brine

The compositions of brines required for mobilization of actinides will affect the quantities of actinidies that may be dissolved or suspended. For example, high-ionic-strength brines have

been shown to increase the solubilities of actinides and to increase the coagulation and settling rate of mineral-fragment colloids.

In human-intrusion scenarios, Salado and/or Castile brine will enter the repository, depending on whether the intrusion penetrates a brine reservoir in the Castile. However, in addition to Salado and Castile brines, brines from the Rustler and Dewey Lake Formation could flow down the borehole to the repository, mix with the waste, and then be forced back up a borehole. Rustler and Dewey-Lake brines are considerably less concentrated than Salado and Castile brines. If the Rustler and Dewey-Lake brines flow into the repository, they would dissolve Salado halite until they attain compositions between those of Salado and Castile brines (see Section 7.1.2). Under any intrusion scenario, therefore, the brine dissolving actinides would have the composition of Salado, Castile, or a mixture of Salado and Castile brines.

The Salado and Castile brine compositions bracket the range of possibilities within the repository, so experimental and modeling studies of repository and actinide chemistry have been performed using the end-member brines only. Inclusion of brine mixing in PA has been considered and rejected because it would not be sufficiently accurate to reduce the uncertainty associated with brine mixing and related brine chemistry compared to bracketing this uncertainty with end-member brines. Brine mixing is addressed in Section 7.1.2.

The two synthetic solutions that best represent the end-member brines that could be present in the repository are: (1) Generic Weep Brine (GWB), which simulates intergranular (grain-boundary) brines from the Salado at or near the stratigraphic horizon of the repository (Snider 2003a); and (2) Energy Research and Development Administration-6 (ERDA-6), typical of fluids in Castile brine reservoirs (Popielak et al. 1983). Through the time of the CCA, Brine A (Molecke 1983) and Salado Primary Constituents (SPC) Brine, a version of Brine A from which trace elements had been removed, were used to simulate Salado brines for laboratory and modeling studies. Since the CCA, however, GWB has been shown to be more representative of intergranular Salado brines than either Brine A or SPC Brine (Brush and Xiong 2003a; Snider 2003a). In particular, the Mg^{2+} concentration of GWB (1.0 M) simulates the average concentration of this element in Salado brines more closely than Brine A (1.44 M). Table SOTERM-1 provides the compositions of GWB and ERDA-6.

In addition to using the end-member brines, other simplifying assumptions have been made, including the following:

- Any brine present in the repository is well-mixed with waste.
- Equilibria with halite and anhydrite, the most abundant Salado minerals at or near the stratigraphic horizon of the repository, are established. Oxidation-reduction (redox) equilibria with waste materials have not been assumed.
- For modeling purposes, brine compositions attained after equilibration of GWB or ERDA-6 with the MgO engineered barrier are assumed for the entire 10,000-year regulatory period.

Table SOTERM-1. Compositions of GWB and ERDA-6 Prior to Equilibration with MgO

Element or Property	GWB[2]	ERDA-6[3]
$B(OH)_3$	155 mM	63 mM
Na^+	3.48 M	4.87 M
Mg^{2+}	1.00 M	19 mM
K^+	458 mM	97 mM
Ca^{2+}	14 mM	12 mM
SO_4^{2-}	175 mM	170 mM
Cl^-	5.51 M	4.8 M
Br^-	26 mM	11 mM
Total inorganic C (as HCO_3^-)	Not reported	16 mM
pH	Not reported	6.17
Specific gravity	1.2	1.216
TDS	Not reported	330,000 mg/l

[1] From Molecke (1983).
[2] From Snider (2003a).
[3] From Popielak et al. (1983).
[4] Reported by Molecke (1983) as BO_3^{3-}.

SOTERM-2.2.2 Microbial Consumption of Cellulosic, Plastic, and Rubber Materials

A large quantity of CPR materials will be emplaced in the WIPP, and could be consumed by microorganisms. There are large uncertainties as to whether significant microbial consumption of CPR materials will occur during the 10,000-year WIPP regulatory period. Therefore, it is assumed that significant microbial consumption of CPR materials is possible, but by no means certain. To incorporate these uncertainties in PA, Wang and Brush (1996a, 1996b) developed a conceptual model for microbial activity in the repository. According to this model, there is a probability of 0.50 for significant microbial activity. In the event of significant microbial activity, microbes would consume 100 percent of the cellulosic materials in the repository. Furthermore, there is a conditional probability of 0.50 that microbes would consume all of the plastic and rubber materials after consumption of all of the cellulosic materials. Thus, there is microbial consumption of all of the cellulosic materials, but no plastic or rubber materials, in about 25 percent of the PA realizations (vectors); microbial consumption of all of the CPR materials in 25 percent of the vectors; and no microbial activity in the remaining 50 percent of the vectors.

Microbial consumption of CPR materials could affect the actinide source term in four ways:

- production of significant quantities of CO_2, which could acidify any brine present and increase the solubilities of actinide elements;
- reduction of oxidized actinide species, which in most cases are more soluble;
- consumption of solubilizing organic ligands; and

- production of humic and microbial colloids, thereby increasing the amount of actinide sorbed on colloidal surfaces.

The effect of CO_2 production is discussed in this section. The remaining three effects are considered in the analyses that have studied the oxidation-state distributions (Section 4.0), the effects of organic ligands (Section 5.0), and the effects of colloids (Section 6.0). The simplifications used in PA calculations for all four of these effects are discussed at the end of this section.

Microbial activity, if it occurs to a significant extent in the WIPP, would consume CPR materials by the following sequential reactions (Brush 1990; Francis and Gillow 1994; Brush 1995; Wang and Brush1996a; Francis and Gillow 1997):

$$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow 7.4H_2O + 6CO_2 + 2.4N_2; \quad (1)$$

$$C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S; \quad (2)$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2. \quad (3)$$

An analysis by Snider (2003b) based on the estimated quantities of CPR materials, nitrate (NO_3^-), and SO_4^{2-} (see Appendix Data, Attachment F) implies that, in the event all of the CPR materials are consumed, denitrification (Reaction (1)) would account for 4.72 mol percent, sulfate reduction (Reaction (2)) would account for 0.82 mol percent, and methanogenesis (Reaction (3)) would account for 94.46 percent of the consumption of CPR materials. (Appendix BARRIERS, Section BARRIERS-2.5, describes these calculations in detail.) Therefore, methanogenesis would be the primary microbial respiratory pathway in the repository.

Microbial consumption of CPR materials could produce significant quantities of CO_2, which could in turn acidify any brine present in the repository and increase the solubilities of the actinides relative to those predicted for neutral and mildly basic conditions. Therefore, the DOE is emplacing MgO in the repository to decrease actinide solubilities by consuming essentially all of the CO_2 that could be produced by microbial consumption of CPR materials,

and by buffering (controlling) the f_{CO_2} and pH within ranges that are favorable from the standpoint of actinide speciation and solubility (see Appendix BARRIERS, Section BARRIERS-2.0).

Laboratory and modeling studies described in Appendix BARRIERS, Section BARRIERS-2.3 have shown that, in the event of significant microbial activity in the WIPP, the carbonation reaction

$$5Mg(OH)_2 + 4CO_2(\text{aq or g}) \square Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O \quad (4)$$

will buffer f_{CO_2} at a value of $10^{-5.50}$ atm in both GWB and ERDA-6. In this reaction, $Mg(OH)_2$ is the mineral brucite (the main hydration product of the mineral periclase (MgO) expected in the WIPP); $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ is the form of the mineral hydromagnesite expected in the

repository; and "aq" and "g" are the abbreviations for "aqueous" and "gaseous," respectively. Furthermore, the brucite-dissolution reaction

$$Mg(OH)_2 \quad Mg^{2+} + 2OH^- \tag{5}$$

will buffer pH in the WIPP at a value of 8.69 in GWB and 9.02 in ERDA-6. These values of f_{CO_2} and pH were used for the actinide speciation and solubility calculations for the CRA-2004 PA vectors with significant microbial activity (see Section 3.5 below).

In the absence of significant microbial activity in the WIPP, the carbonation reaction

$$Mg(OH)_2 + Ca^{2+} + CO_2(aq \text{ or } g) \square CaCO_3 + Mg^{2+} + H_2O(aq \text{ or } g) \tag{6}$$

will buffer f_{CO_2} at a value of $10^{-5.48}$ atm in GWB and $10^{-6.15}$ atm in ERDA-6, and the brucite-dissolution reaction (Reaction (5)) will buffer pH at a value of 8.69 in GWB and 8.99 in ERDA-6 (see Appendix BARRIERS, Section BARRIERS 2.3). In this reaction, $CaCO_3$ is the mineral calcite. These values of f_{CO_2} and pH were used for the actinide speciation and solubility calculations for the CRA-2004 PA vectors without microbial activity (see Section 3.0 below).

Four effects of microbial consumption of CPR materials are recognized in modeling system performance. A simplification has been made that the effects will be time independent after 100 years. The effects are

- CO_2 production. With the addition of excess MgO, the effects of CO_2 production are minimized, and it is assumed that the system may be modeled using the brucite-hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) buffer.

- Redox effects. After 100 years, the repository will have a reducing environment. Even though significant microbial action is only 50 percent likely, the corrosion of steel will also produce a reducing environment (Section 2.2.3).

- Possible consumption of organic ligands. While some microbes are known to consume some organic ligands, there is uncertainty as to the presence or viability of these particular microbes within the repository environment. Therefore, no credit has been taken for the microbial consumption of organic ligands. Other mechanisms for reducing the effect of organic ligands are discussed in Section 5.0.

- Production of humic and microbial colloids.

SOTERM-2.2.3 Anoxic Corrosion of Steels and Other Iron-Base Alloys

The corrosion of steels, other Fe-base alloys, and other metals in the repository will have several effects on the actinide source term. Corrosion is expected to:

- reduce the oxidation states of some actinides, especially Pu, from relatively mobile oxidation states, such as Pu(V) and Pu(VI), to relatively immobile oxidation states, such as Pu(III) and Pu(IV) (Section 4.0);

- produce colloidal corrosion products on which actinides may sorb (see Section 6.0).

It is expected that oxic corrosion of steels and aerobic microbial consumption of CPR materials will quickly consume the limited amount of oxygen (O_2) trapped within the repository at the time of closure. After O_2 is consumed, anoxic corrosion of metals will occur (Brush 1990; Brush 1995; Wang and Brush 1996a. In all of the vectors for the CRA-2004 PA, the EPA's 1997 Performance Assessment Verification Test (PAVT), and the CCA PA, there were significant amounts of uncorroded steels and other Fe-base alloys in the repository throughout the 10,000-year regulatory period. WIPP-specific experiments (Telander and Westerman, 1993; 1997) showed that steels and other Fe-base alloys will corrode by the following reactions:

$$Fe + (x + 2)H_2O \Leftrightarrow Fe(OH)_2 \cdot xH_2O + H_2; \quad (7)$$

$$3Fe + 4H_2O \Leftrightarrow Fe_3O_4 + 4H_2; \quad (8)$$

$$Fe + H_2O + CO_2 \Leftrightarrow FeCO_3 + H_2; \text{ and} \quad (9)$$

$$Fe + H_2S \Leftrightarrow FeS + H_2. \quad (10)$$

Metal hydroxides such as Fe(II) hydroxide ($Fe(OH)_2 \cdot xH_2O$) are more soluble in the WIPP high-ionic-strength brines than in dilute solutions, and significant amounts of Fe(II) may dissolve. Refait and Genin (1994) estimated Fe(II) solubilities between 10^{-4} and 10^{-6} M for pH between 8.5 and 10.5 under redox conditions expected for the repository. Sagoe-Crentsil and Glasser (1993) observed even higher solubilities at pH 13 with electrolytic dissolution of Fe.

Corrosion of metals will produce reducing conditions in the repository, but redox conditions have not been predicted quantitatively. The repository is not described using Eh, because in low-temperature geochemical systems, equilibria among the many redox couples are generally not attained, and Eh is generally poorly defined. For this reason, the oxidation states of the actinides have been determined experimentally, as described in Section 4.0.

SOTERM-2.2.4 Other Effects

High pressure in the repository after closure will have an insignificant effect on actinide solubilities and the association of actinides with colloids and, therefore, its effect is not included in PA. Temperature within the repository is not expected to change by more than a few degrees from ambient (28 ºC) (Munson et al. 1987; Sanchez and Trellue 1996; Wang and Brush 1996a). Because the effect on solubilities of a few degrees Celsius is insignificant compared to uncertainty of the measurements and modeling of solubilities, temperature effects were also discounted (Section 3.3).

Radiolysis of brine may affect redox conditions in the repository. When energy from radioactive decay is absorbed by H_2O, the H_2O molecule is broken into energetic fragments that reassemble

into oxidized and reduced species. Depending on the chemical reactivity of these species, the system may be effectively more oxidizing or more reducing as a result of the radiolysis. For example, radiolysis often occurs by the following reaction:

$$2H_2O + \text{radiation} = H_2(g) + H_2O_2 \quad (11)$$

Hydrogen peroxide (H_2O_2) is more reactive than hydrogen (H_2) (g) at low temperature, and peroxide redox reactions will affect the system more than the slow H_2 reactions. If the system is initially very oxidized, H_2O_2 will cause a reduction in the effective redox state, but if the system is initially very reduced, the peroxide will cause oxidation. In the WIPP, it is expected that the repository will be quite reducing due to the large amount of metallic Fe and dissolved Fe(II) species. Any oxidized species such as H_2O_2 generated from radiolysis are expected to quickly react with the metallic Fe and Fe(II), thus negating any oxidizing effect of radiolysis. Therefore, radiolysis is not expected to affect the redox state of the repository significantly.

Other components of the waste may influence the concentration of dissolved actinides within the repository. These include, for example, organic ligands (Section 5.0); other salts such as calcium chloride ($CaCl_2$), which may raise the ionic strength of the brine; vermiculite, which may sorb actinides; and phosphate (PO_4^{3-}), which may precipitate insoluble actinide phosphates. The effects of most of these components are assumed beneficial and would be difficult to quantify, so they were not included in PA.

SOTERM-2.2.5 Summary

Chemical conditions in the repository will be affected by whether brine is present (humid or inundated conditions) and the type of brine (Salado or Castile); microbial consumption of CPR materials, which will produce mainly methane (CH_4) and CO_2, and colloidal particles; MgO , which will control f_{CO_2} and pH; and corrosion of steels, other Fe-base alloys, and other metals in the repository, which will create reducing conditions.

SOTERM-3.0 PREDICTION OF DISSOLVED ACTINIDE SOLUBILITIES

This section describes the basic approach used to predictactinide solubilities for the CRA-2004 PA. Surveys of different possible conceptual and mathematical descriptions of the system are presented, followed by a more detailed discussion of the method selected.

The material in this section is intended to provide an overview of the modeling methods. More detailed descriptions can be found in the references.

SOTERM-3.1 Previous Approaches to Estimating Actinide Solubilities in the WIPP

Brine flow through the repository was not considered early in the WIPP Project because brine was not expected to enter the repository (see CCA Appendix MASS, Section MASS.2). When it was realized that brines from a variety of sources might enter the repository, scenarios involving brine flow were developed. These scenarios necessitated the investigation of potential

mobilization mechanisms, including dissolution of actinides in high-ionic-strength aqueous solutions applicable to WIPP brines.

The solubilities of actinides in WIPP brines were initially estimated by an expert panel that reviewed the existing literature on actinide solubilities (Trauth et al. 1992). The range of solubilities obtained was about 14 orders of magnitude because the chemical conditions surveyed included extremes of acidity and other conditions. With the addition of MgO and the demonstration of reducing conditions, it was realized that these extreme conditions would not occur in the WIPP. The expert panel also estimated the effect of high CO_3^{2-} concentrations, which are known to increase actinide solubilities significantly, despite the paucity of data for CO_3^{2-}-bearing solutions. Median solubilities developed by the panel were Th: 10^{-10} M; U: 10^{-3} M; Np: 10^{-7} M; Pu: 10^{-9} M; and Am and Cm: 10^{-9} M (Trauth et al. 1992, p. 4-5; Hobart et al. 1996). Published studies of actinides under environmental conditions have focused on actinides in surface waters and groundwaters that are considerably more dilute than WIPP brines, which contributed to the wide range of solubility estimates because more pertinent data were unavailable.

Experimental investigations for other radioactive waste projects (for example, Nitsche 1987) have measured the solubilities of actinides directly. Although this is possible for well-characterized and homogeneous waste and groundwaters, the waste intended for the WIPP is heterogeneous, and a relatively wide range of chemical conditions would be possible in the repository without MgO. Measuring solubilities directly in experiments using transuranic (TRU) waste and ensuring that the measurements reflect steady-state WIPP conditions would entail an extremely large number of measurements and considerable uncertainty. This approach was determined to be neither practical nor feasible. The DOE therefore decided to estimate actinide solubilities by using a thermodynamic model based on experimental parameterization.

SOTERM-3.2 Selection of the Pitzer Activity-Coefficient Model

The thermodynamic activity of a dissolved species is the product of its actual concentration and an activity coefficient. In dilute aqueous solutions, the activity coefficient is close to unity, but in high-ionic-strength solutions such as WIPP brines, the activity coefficient may deviate significantly from unity.

The calculation of activity coefficients is the central feature of thermodynamic models in concentrated electrolyte systems. Activity coefficients represent the deviation from the nearly ideal behavior observed or assumed in dilute solutions. Aqueous-electrolyte activity-coefficient models generally include the Debye-Hückel limiting law (see, for example, Pitzer 1991, 59 et seq.) to describe behavior in the dilute region (<0.1 m), and often include one or more adjustable parameters to reproduce measured behavior in more concentrated solutions.

Numerous activity-coefficient models for concentrated electrolytes have been proposed, including the Pitzer model (Pitzer 1991, Chapter 3), Harned's Rule (Wood 1975), and the Specific-Ion Interaction Theory (SIT) (Grenthe and Wanner 1992), given in order of approximately decreasing mathematical complexity. The Pitzer activity-coefficient model contains parameters that explicitly represent the contributions to the excess free energy from every two-moiety and three-moiety interaction, where a moiety is a cationic, anionic, or neutral

aqueous species. The Harned's-Rule model asserts that the "logarithm of the activity coefficient of one electrolyte in a mixture of constant total molality is directly proportional to the molality of the other component" (Robinson and Stokes 1959, 438), and thus by extension to multicomponent systems containing parameters for two-moiety interactions. The SIT model contains parameters for two-moiety cation-anion interactions.

A primary consideration for selecting an activity-coefficient model to predict actinide solubilities in the WIPP was the demonstrated applicability of existing models and databases to the brines and evaporite minerals at WIPP. The Pitzer model, especially as parameterized by Harvie et al. (1980a), Harvie et al. (1984), and Felmy and Weare (1986), includes an established database describing solubilities in the hydrogen-ion- (H^+)-B-Na^+-Mg^{2+}-K^+-Ca^{2+}-OH^--bicarbonate-(HCO_3^-) CO_3^{2-}-SO_4^{2-}-Cl^--H_2O-CO_2 system. This system includes the significant nonradioactive constituents of WIPP brines. The Harned's-Rule model has been parameterized for the Na^+-Mg^{2+}-K^+-Ca^{2+}-Cl^- and Na^+-Mg^{2+}-$SO_4^{2-}$$Cl^-$ systems (Wood 1975), but does not include CO_3^{2-}, one of the most important actinide complexants in aqueous systems. The SIT model (Grenthe and Wanner 1992) is most commonly used for extrapolating apparent stability constants to zero ionic strength. No demonstrations that the SIT model has been applied to multicomponent, concentrated electrolytes such as brine-evaporite-mineral systems have been identified in the literature.

The chemical behavior of the concentrated brines that occur in evaporites like those at WIPP has been extensively studied and documented. The applications of the Harvie et al. (1980a), Harvie et al. (1984), and Felmy and Weare (1986) parameterization of the Pitzer model include: prediction of the mineral-precipitation sequence accompanying seawater evaporation (Eugster et al. 1980; Harvie et al. 1980b); the formation of borate minerals in Searles Lake, CA (Felmy and Weare 1986); and an analysis of Permian seawater composition based in part on fluid-inclusion data from the Salado (Horita et al. 1991). Additional applications are given in Pitzer (1991, Chapters 6 and 7).

WIPP brines range from about 0.8 m to 8 m in ionic strength. The Pitzer model is developed for and has been shown to work for electrolytes as concentrated as those at WIPP, and has been applied successfully to brines with concentrations greater than 10 m (Felmy and Weare 1986). Rather than develop a new description of the chemical behavior of the nonradioactive constituents of WIPP brines, it was decided to use the Harvie et al. (1984)/Felmy and Weare (1986) (HMW/FW) parameterization of the Pitzer model as the reference activity-coefficient model and thermodynamic database for the WIPP actinide source term. Additional research for the WIPP focused on extending the database to include the actinides that could affect the long-term performance of the WIPP and the organic ligands that could affect the solubilities of these actinides (see Section 5.0).

SOTERM-3.3 The Fracture-Matrix Transport Computer Code

The solubility and speciation code Fracture-Matrix Transport (FMT) (Babb and Nowak 1997 and addenda) uses the Pitzer activity-coefficient model to calculate the solubilities of the actinide elements in equilibrium with the appropriate solubility-controlling solids in WIPP brines by minimizing the Gibbs free energy of the system. Where appropriate parameters already existed in the HMW/FW database, they have been used in FMT calculations for the WIPP. Additional

parameters, most notably those for dissolved actinide species, have been obtained from the literature or determined from experimental data (see Section 3.4) using the NONLIN code (Novak 1995; WIPP Performance Assessment Department 1996). NONLIN calculates the Pitzer parameters using a nonlinear least-squares fitting program.

The FMT calculations were done for three actinides: Am(III), Th(IV), and Np(V) that are oxidation-state analogs for actinides in the +III, +IV, and +V oxidation states, respectively. Because actinides in the same oxidation state exhibit similar chemical behavior, these FMT model calculations apply to all actinides in the same oxidation state; for example, the Am(III) speciation and solubility model applies to Pu(III); the Th(IV) model applies to U(IV), Np(IV), and Pu(IV); and the Np(V) model applies to Pu(V). However, Pu will not persist to a significant extent in the +V oxidation state (or the +VI oxidation state) in the WIPP (see Section 4.6.)

The dissolved concentrations of the actinides Th, U, Np, Pu, and Am will be limited by solubility-controlling solid for each of these actinides in WIPP brines. The important ions in WIPP brines are H^+, Na^+, Mg^{2+}, K^+, Ca^{2+}, OH^-, CO_3^{2-}, SO_4^{2-}, and Cl^-. Other ions, for example, fluoride (F^-), aluminum (Al^{3+}), PO_4^{3-}, Fe^{2+}, and Fe^{3+}, may affect actinide solubilities significantly. Pitzer parameters for these other ions are not included in the dissolved species and source term model, but enhance understanding of the chemical environment. For example, phosphates are known to precipitate actinides (Cotton and Wilkinson 1988), but this effect has conservatively been ignored due to the uncertainty of the phosphate inventory in the WIPP and the lack of a complete set of Pitzer parameters for its inclusion. The existence of Fe(II) from the anoxic corrosion of steels and other Fe-base alloys is accounted for in the oxidation state distribution (see Section 4.0), but is expected to have an insignificant effect on the solubilities of individual actinide oxidation state and distribution.

The expected temperature of the WIPP disposal rooms during the 10,000-year regulatory period is not expected to change by more than a few degrees from ambient (28 ºC) (Munson et al. 1987; Sanchez and Trellue 1996; Wang and Brush 1996). The small differences in thermodynamic properties caused by these changes are well within acceptable uncertainty for the WIPP system. For these reasons, the small differences in properties over this temperature range are not significant for the WIPP, and all information was developed for 25°C. Literature information taken at approximately 20°C was deemed acceptable for model parameterization as well.

The development of the +III, +IV, and +V actinide solubility models consisted largely of the development of a database that includes the standard chemical potentials of the aqueous and solid actinide-bearing species, and the ion-interaction parameters required to describe the interactions between these species and other constituents of WIPP brines. The following sections describe briefly how this database was built and how the needed parameters were obtained. The development of the oxidation-state distributions reflected in these sections is discussed in Section 4.0.

Section 3.4 provides a guide to the information that is needed to predict actinide solubilities. The FMT database currently used to predict the solubilities of the +III, +IV, and +V actinides is documented in Giambalvo (2002a, 2002b, 2002c, 2002d, 2002e, 2003).

SOTERM-3.4 Overview of the Experimental Data

Studies of the solubilities and speciation of actinides, especially Pu, are often conducted by employing the oxidation-state analogy, which states that lanthanides and actinides in the same oxidation state have similar chemical behavior. There are several important advantageous aspects of the use of oxidation-state analogs, such as Th(IV) for Pu(IV). Redox-inert analogs can considerably simplify experimental design and consequently improve reliability of experimental data, in contrast to Pu, which can be a very labile experimental component. Additionally, the lanthanide and actinide analogs possess physical and chemical characteristics that allow them to be used as probes in examination of the chemical behavior of Pu. For example, the luminescence lifetime of europium(III) (Eu(III)) can be directly correlated to the number of H_2O molecules in the inner coordination sphere, which allows interpretation of the nature of complexation of the trivalent lanthanides and actinides with ligands.

The 4f orbitals of the lanthanides and 5f orbitals of the actinides constitute the valence shells of the cations. The f orbitals are more diffuse than the p and d orbitals, and, upon ionization of the atom, become lower in energy than the 5d, 6s, and 6p orbitals in the case of the lanthanides, and comparable or slightly lower than the 6d, 7s, and 7p orbitals in the case of the actinides. The contraction of the radial component of the wave function of the f orbitals upon ionization of the element usually causes these orbitals to be unavailable for overlap with orbitals on other atoms, one of the conditions necessary for the formation of molecular orbitals. As a result, the lanthanide and actinide ions exhibit very little tendency to form covalent bonds.

Formation of complexes of most ligands with f elements is due to the electrostatic attraction between the metal cation and the electron-donating functionality of the ligand molecule. The effect of polarizability and Lewis acidity or basicity on formation of Lewis-acid or Lewis-base pairs has been described by Pearson (1963). Lanthanide and actinide cations, which have high charge density and low polarizability, are classified as hard cations. Similarly, ligands featuring O-donor atoms, such as citrate and oxalate, exhibit low polarizability and strong Lewis basicity, and are referred to as hard bases. Hard-acid metals interact with hard bases through electrostatic attraction. The stability of f-element complexes with many ligands is a function of the charge density on the donor atom. For example, progressively weaker Brönsted-Lowry acids (in order of increasing pKa: trichloroacetic < dichloroacetic < monochloroacetic < acetic acids) have progressively stronger conjugate bases due to increased electron density located on the carboxylic O's. As a result, the electrostatic attraction between the O and protons increases, resulting in weaker acidic behavior and corresponding increases in pKa values. Likewise, the force of electrostatic attraction between the carboxylate group and a metal ion increases with increasing basicity of the ligand.

The magnitude of electrostatic attraction between the f-element cations and ligands is dependent upon the local effective dielectric constant of the solution, the charge on the metal ion, and the distance of separation between the metal atom and the ligating atoms on the complexing agent. The magnitude of the local dielectric constant of the solution depends upon the ordering effect created by the electric-field gradient established by the cation. The charge densities of lanthanides and actinides with the same charge are similar enough that the responses of solvent molecules are similar, yielding local dielectric constants that are nearly constant for lanthanide

and actinide cations with the same charge. The local dielectric constant is primarily dependent upon the charge of the ion; the variation due to the effect of different-magnitude electric-field gradients that result from the differences in ionic radii are small enough to be overlooked to a first approximation in the oxidation-state-analogy approach.

The factors that exert a much more pronounced influence are the ionic radii, charge on the metal ion, and, to a lesser extent, degree of solvation of the metal ion. The Gibbs free energy of complex formation is inversely proportional to the distance between the metal and ligand, and directly proportional to the product of the numerical value of the electrostatic charges on the cation and anion. There are variations in the ionic radii of lanthanide and actinide ions that have the same charge, with decreasing ionic radii corresponding to increasing atomic number within the 4f and 5f series. However, the ionic radii of some of the metal ions are very similar. For example, neodymium ion (Nd^{3+}) and Am^{3+} have nearly identical ionic radii. As a result, the behavior of Nd(III) and Am(III) are very similar, with small differences attributable to the fact that the 5f orbitals of Am are closer in energy to the 6d, 7s, and 7p orbitals than the 4f orbitals of Nd are to the 5d, 6s, and 6p orbitals. Discussions of applications to the +III, +IV, +V, and +VI actinide oxidation states follow.

SOTERM-3.4.1 The +III Lanthanides and Actinides

The actinides most likely to occur in the +III oxidation state in the WIPP are Pu, Am, and Cu. Nd(III), Eu(III), Pu(III), Am(III), and Cu(III) have been widely used in studies of trivalent f-element chemical behavior in brines. The respective ionic radii for coordination number (CN) = 8 are 111, 17, 100, 109, and 97 pm (Shannon 1976). Due to the similarity of ionic radii, the magnitude of the electrostatic attraction between the metal ions and corresponding ligands is similar, yielding comparable thermodynamic stabilities. Each of the analog elements offers noteworthy advantages in probing various aspects of trivalent f-element solution behavior. For example, Nd(III) features hypersensitive absorption bands that respond to changes in the complexation environment, allowing examination of the nature of the metal-ligand interaction. The luminescence lifetime of Eu(III) can be used to measure the number of residual waters of hydration associated with the metal ion after formation of a complex. ^{241}Am, which has a 433-year half-life, undergoes α decay that is accompanied by 59.5-keV γ ray with a 35.9-percent yield. As a result, ^{241}Am may be used at tracer concentrations by well-developed radiochemical techniques, such as solvent extraction and ion exchange, as a means to study the thermodynamic behavior of trivalent actinides. Study of the solution behavior of Am(III) is uncomplicated by redox ability, unlike the situation for Pu(III), which requires Eh and pH controls of the solution to maintain a single oxidation state. Like Nd and Eu, Cu luminescence studies are useful to examine the coordination environment of the metal ion. Pu(III) does not have useful luminescence properties, making it impossible to study its complexation behavior by methods that are effective with the analogs.

The thermodynamic database for the +III actinides currently used in FMT was described by Giambalvo (2002a). Due to the redox ability of Pu, much of the experimental work carried out to develop an understanding of the chemical behavior of the +III actinides, particularly Pu, has been performed with Nd, Am, and Cm due to the stability of the trivalent oxidation states of these three elements. Speciation and solubility data for the +III actinides were parameterized for

use in the Pitzer activity-coefficient model by Felmy et al. (1989) for the Na^+- Pu^{3+}-Cl^--H_2O system; by Felmy et al. (1990) for the Na^+-Am^{3+}-OH^--HCO_3^--H_2O system; by Rai et al. (1995) for the Na^+-Am^{3+}-PO_4^{3-}-SO_4^{2-}-H_2O system; and by Rao et al. (1996) for the Na^+-Nd^{3+}-CO_3^{2-}-HCO_3^--H_2O system. The inorganic aqueous and solubility-limiting species featured in the model for Am(III) are:

$$Am^{3+} + CO_3^{2-} \square AmCO_3^+; \quad (12)$$

$$Am^{3+} + 2CO_3^{2-} \square Am(CO_3)_2^-; \quad (13)$$

$$Am^{3+} + 3CO_3^{2-} \square Am(CO_3)_3^{3-}; \quad (14)$$

$$Am^{3+} + 4CO_3^{2-} \square Am(CO_3)_4^{5-}; \quad (15)$$

$$Am^{3+} + OH^- \square AmOH^{2+}; \quad (16)$$

$$Am^{3+} + 2OH^- \square Am(OH)_2^+; \quad (17)$$

$$Am^{3+} + 3OH^- \square Am(OH)_3(aq); \quad (18)$$

$$Am^{3+} + Cl^- \square AmCl^{2+}; \quad (19)$$

$$Am^{3+} + 2Cl^- \square AmCl_2^+; \quad (20)$$

$$Am^{3+} + SO_4^{2-} \square Am(SO_4)^-; \quad (21)$$

$$Am^{3+} + 2SO_4^{2-} \square Am(SO_4)_2^+; \quad (22)$$

$$Am^{3+} + OH^- + CO_3^{2-} \square AmOHCO_3(s); \quad (23)$$

$$Na^+ + Am^{3+} + 2CO_3^{2-} + 6H_2O \square NaAm(CO_3)_2 \bullet 6H_2O(s); \text{ and} \quad (24)$$

$$Am^{3+} + PO_4^{3-} \square AmPO_4(cryst). \quad (25)$$

In these equations, “aq,” “cryst,” and “s” are the abbreviations for “aqueous,” crystalline,” and “solid,” respectively. The actinide(III) database was extended to mixed Na^+-CO_3^{2-}-Cl^-- media, and was shown to reproduce the independently measured solubility of $NaAm(CO_3)_2(s)$ in 5.6 M NaCl (Runde and Kim 1994) and Nd(III) solubility in WIPP brines.

SOTERM-3.4.2 The +IV Actinides

The tetravalent actinides important to WIPP performance are Th(IV), U(IV), and Pu(IV). Np is not included in the WIPP actinide source term, but has been included in the WIPP Actinide Source Term Program (ASTP). The +IV oxidation state is the only stable one in aqueous solution for Th, whereas U(IV) and Np(IV) are both readily oxidized. As a result, Th is often used to represent the behavior of the +IV actinides. Th(IV) does not have spectroscopic characteristics that are valuable in its study, but does have both long-lived (^{232}Th, $t_{1/2}$ = 1.41×10^{10} year) and shorter-lived (^{228}Th and ^{230}Th $t_{1/2}$ = 1.913 and 7540 year, respectively)

isotopes that are useful in thermodynamic studies. The 105-pm ionic radius of the Th(IV) cation (C. N. = 8) is greater than the 96 pm Pu(IV) cation (Shannon 1976), resulting in complexation properties that vary in a systematic and predictable manner. The larger ionic radius of Th(IV) causes it to have complexes with stability constants lower than the corresponding complexes with Pu(IV). For example, the Pu(IV) complexes with OH^-, resulting from hydrolysis, have higher stability constants than Th(IV)-OH^- complexes. The actinide(IV) hydrolysis products are sufficiently stable that organic ligands present within the WIPP, (see Section 5.0) will be unable to effectively compete with OH^-. The net effect is that actinide(IV) complexation is dominated by OH^-, which forms very insoluble tetrahydroxide ($An(OH)_4$) precipitates. Pu has a pronounced tendency to form insoluble hydrolysis products that are less soluble than the corresponding Th(IV) oxides and hydroxides. The greater solubility of Th(IV) makes it a very good analog for Pu(IV) in the context of modeling the behavior of tetravalent actinides in the WIPP because the solubility of Th(IV) establishes an upper limit for the solubility of Pu(IV). Due to the experimental difficulty working with Pu(IV), it is more straightforward and defensible to establish upper limits rather than attempting to measure the solubility of Pu(IV) directly.

The thermodynamic database for the +IV actinides currently used in FMT was described by Giambalvo (2002c). Speciation and solubility data for Th(IV) were parameterized for the Pitzer activity-coefficient model for the Na^+-K^+-Mg^{2+}-Cl^-- SO_4^{2-}-CO_3^{2-}-HCO_3^- -OH^--H_2O system. The inorganic aqueous and solubility-limiting species featured in the model are:

$$ThO_2(am) + 2H_2O \square Th(OH)_4(aq); \quad (26)$$

$$Th^{4+} + 4OH^- \square Th(OH)_4(aq); \quad (27)$$

$$Th^{4+} + 3OH^- + CO_3^{2-} \square Th(OH)_3CO_3^-; \quad (28)$$

$$Th^{4+} + 5CO_3^{2-} \square Th(CO_3)_5^{6-}; \quad (29)$$

$$Th^{4+} + 2SO_4^{2-} \square Th(SO_4)_2(aq); \quad (30)$$

$$Th^{4+} + 3SO_4^{2-} \square Th(SO_4)_3^{2-}; \quad (31)$$

$$Th^{4+} + 2SO_4^{2-} + 9H_2O \square Th(SO_4)_2 \bullet 9H_2O(s); \quad (32)$$

$$Th^{4+} + 2SO_4^{2-} + 8H_2O \square Th(SO_4)_2 \bullet 8H_2O(s); \quad (33)$$

$$Th^{4+} + 2Na^+ + 3SO_4^{2-} + 6H_2O \square Th(SO_4)_2 \bullet Na_2SO_4 \bullet 6H_2O(s); \quad (34)$$

$$Th^{4+} + 2K^+ + 3SO_4^{2-} + 4H_2O \square Th(SO_4)_2 \bullet K_2SO_4 \bullet 4H_2O(s); \quad (35)$$

$$Th^{4+} + 4K^+ + 4SO_4^{2-} + 6H_2O \square Th(SO_4)_2 \bullet 2K_2SO_4 \bullet 2H_2O\ (s); \text{ and} \quad (36)$$

$$Th^{4+} + 7K^+ + 5.5SO_4^{2-} \square Th(SO_4)_2 \bullet 3.5K_2SO_4(s). \quad (37)$$

SOTERM-3.4.3 The +V Actinides

Both Np and Pu have accessible +V oxidation states; however, Pu(V) is not expected to persist in significant quantities in the WIPP. The model for Np(V) was developed for the German repository program (Fanghänel et al. 1995). The speciation and solubility of Np(V) were parameterized for the Na^+-Cl^--CO_3^{2-}-ClO_4^--H_2O system.

The thermodynamic database for the +V actinides currently used in FMT is described by Giambalvo (2002d). Np(V) speciation and solubility were parameterized in the Pitzer activity-coefficient model for the Na^+-K^+-Mg^{2+}-Cl^-- SO_4^{2-}-CO_3^{2-}-HCO_3^- -OH^--H_2O system. The inorganic aqueous and solubility limiting species used are:

$$NpO_2^+ + OH^- \square NpO_2OH(aq); \quad (38)$$

$$NpO_2^+ + OH^- \square NpO_2OH(s, am); \quad (39)$$

$$NpO_2^+ + OH^- \square NpO_2OH(s, aged); \quad (40)$$

$$NpO_2^+ + 2OH^- \square NpO_2(OH)_2^-; \quad (41)$$

$$NpO_2^+ + CO_3^{2-} \square NpO_2CO_3^-; \quad (42)$$

$$NpO_2^+ + 2CO_3^{2-} \square NpO_2(CO_3)_2^{3-}; \quad (43)$$

$$NpO_2^+ + 3CO_3^{2-} \square NpO_2(CO_3)_3^{5-}; \quad (44)$$

$$Na^+ + NpO_2^+ + CO_3^{2-} + 3.5H_2O \square NaNpO_2CO_3 \bullet 3.5H_2O(s); \quad (45)$$

$$3Na^+ + NpO_2^+ + 2CO_3^{2-} \square Na_3NpO_2(CO_3)_2(s); \quad (46)$$

$$K^+ + NpO_2^+ + CO_3^{2-} \square KNpO_2CO_3(s); \text{ and} \quad (47)$$

$$3K^+ + NpO_2^+ + 2CO_3^{2-} + 0.5H_2O \square K_3NpO_2(CO_3)_2 \bullet 0.5H_2O(s). \quad (48)$$

SOTERM-3.4.4 The +VI Actinides

The actinide(VI) speciation and solubility model for brines under basic conditions has not been developed sufficiently for use in FMT. The hydrolysis behavior of U(VI) is quite complicated and no satisfactory predictive models applicable to WIPP conditions are available. As documented in Hobart and Moore (1996), the solubility of U(VI) at pH 10, in the absence of CO_3^{2-}, was estimated to be 8.8×10^{-5} m.

SOTERM-3.5 Calculations of Actinide Solubilities Using the Fracture-Matrix Transport Computer Code

Details of the solubility calculations for the +III, +IV, and +V actinides and the estimation of the solubility of +VI actinides for the CRA-2004 PA are given in Brush and Xiong (2003a, 2003b, 2003c) and Downes (2003a, 2003b).

The FMT calculations of actinide solubilities for the CRA-2004 PA featured the establishment of equilibrium of Salado brine (GWB) or Castile brine (ERDA-6) with halite, and anhydrite, minerals present in large quantities in the Salado at the repository horizon. The effects of MgO included equilibration of Salado brine or Castile brine with brucite and hydromagnestie ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) in the PA vectors with microbial activity, and with brucite and calcite in the vectors without microbial activity (see Reactions (4), (5), and (6) above; and Appendix BARRIERS, Section BARRIERS-2.3). For the CCA, it was assumed that Salado brine (Brine A) or Castile brine (ERDA-6) would be in equilibrium with brucite and magnesite ($MgCO_3$) in all of the PA vectors (both with and without microbial activity) (ERDA-6). For the 1997 PAVT, equilibria among Salado brine (Brine A) or Castile brine (CCA Appendix SOTERM; CCA Appendix BACK) and brucite and hydromagnesite ($Mg_5(CO_3)4(O4)_2 \bullet 4H_2O$) was assumed (EPA 1998a, 1998b).

The FMT calculations for the CRA-2004 PA also included the effects of acetate, citrate, EDTA, and oxalate on the speciation and solubilities of the +III, +IV, and +V actinides (see Section 5.0 below).

Table SOTERM-2 provides the solubilities calculated for the +III, +IV, and +V actinides and estimated for the +VI oxidation state for the CRA-2004 PA, and compares them to the solubilities calculated or estimated for the CCA PA and the 1997 PAVT.

SOTERM-3.6 Use of Fracture-Matrix Transport Results in Performance Assessment

Table SOTERM-2. Actinide Solubilities (M) Calculated (+III, +IV, and +V) or Estimated (+VI) for the CRA-2004 PA, the 1997 PAVT, and the CCA PA

Actinide Oxidation State and Brine	CRA Solubilities, Microbial Vectors[1]	CRA Solubilities, Nonmicrobial Vectors[1]	PAVT Solubilities[2]	CCA Solubilities[3]
+III, Salado brine	3.07×10^{-7}	3.07×10^{-7}	1.2×10^{-7}	5.82×10^{-7}
+III, Castile brine	1.69×10^{-7}	1.77×10^{-7}	1.3×10^{-8}	1.3×10^{-8}
+IV, Salado brine	1.19×10^{-8}	1.24×10^{-8}	1.3×10^{-8}	4.4×10^{-6}
+IV, Castile brine	2.47×10^{-8}	5.84×10^{-9}	4.1×10^{-8}	6.0×10^{-9}
+V, Salado brine	1.02×10^{-6}	9.72×10^{-7}	2.4×10^{-7}	2.3×10^{-6}
+V, Castile brine	5.08×10^{-6}	2.13×10^{-5}	4.8×10^{-7}	2.2×10^{-6}
+VI, Salado brine[4]	8.7×10^{-6}	8.7×10^{-6}	8.7×10^{-6}	8.7×10^{-6}
+VI, Castile brine[4]	8.8×10^{-6}	8.8×10^{-6}	8.8×10^{-6}	8.8×10^{-6}

1 Brush and Xiong (2003a, 2003b) and Downes (2003a, 2003b).
2 Trovato (1997, Attachment 2), EPA (1998a, Table 5), EPA (1998b, Subsection 4.10.4, Tables 4.10-1, 4.10-3 and 4.10-4; and Subsection 12.4, Table 12.4-1), and EPA (1998c, Subsections 5.26–5.32 and Section 6.0, Table 6.4).
3 CCA Appendix SOTERM, Table SOTERM-2; based on Novak et al. (1996, Table 1, columns entitled "@Mg"), except that Novak et al. (1996) used molal instead of molar units.
4 Hobart and Moore (1996).

Uncertainties in the solubility data and the NONLIN least squares refinement result in uncertainties in the model predictions. This is evident when the data of Runde and Kim (1994) are compared with FMT model results. A measure of these uncertainties was obtained by Bynum (1996) by examining the differences between the modeled solubilities for each oxidation-state analog and comparing these to the experimental data used to generate the respective Pitzer parameters. The results of Bynum's analysis are given in Figure SOTERM-1. These results were combined as shown in Figure SOTERM-2 for entry into the parameter database as a cumulative distribution. This distribution was sampled in PA, as discussed in Section 7.1.3. Note that the median of this distribution is -0.09 and not zero, indicating that slightly more experimental values were below the model predictions than above.

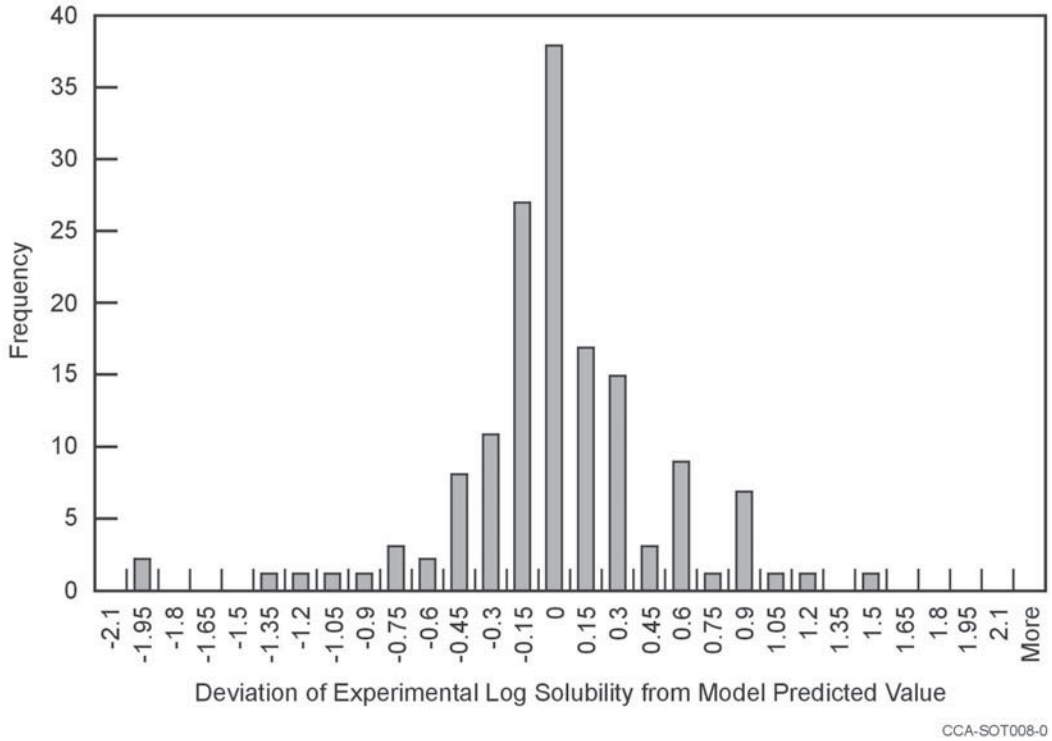

Figure SOTERM-1. Deviation of the log of 150 Experimental Solubilities from the Values Predicted by the Model.

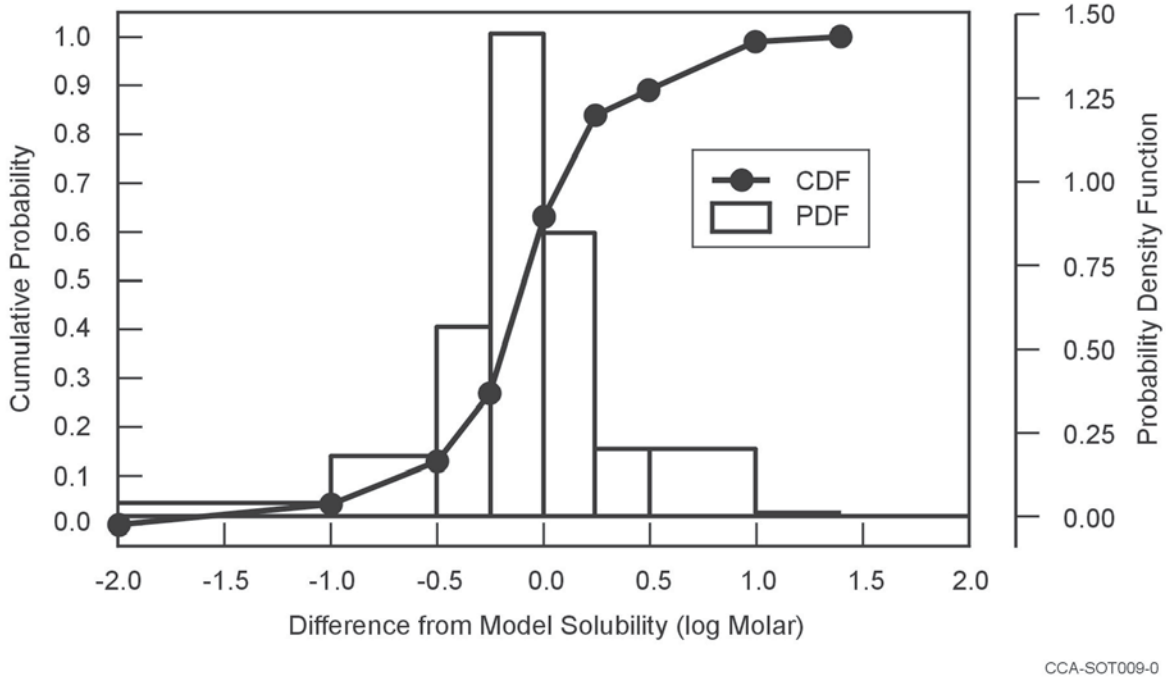

Figure SOTERM-2. Distribution of Actinide-Solubility Uncertainty Utilized in the CRA-2004 Performance Assessment.

SOTERM-4.0 OXIDATION-STATE DISTRIBUTION OF DISSOLVED ACTINIDES

This section describes the literature investigation and experimental program that identified the actinide oxidation states most likely to be stable under expected WIPP conditions.

SOTERM-4.1 Thorium

Th is a very electropositive metal, and Th(IV) is the only stable oxidation state in aqueous solutions and in the natural environment (Hobart 1990; Katz et al. 1986). Conditions in the WIPP cannot produce any other oxidation state of Th.

SOTERM-4.2 Uranium

U can exist in aqueous solution in the +III, +IV, +V, and +VI oxidation states (Hobart 1990; Keller 1971; Clark et al. 1995). The predominant oxidation states for U in the natural environment are +IV and +VI. U(III) may be prepared in aqueous solution but is easily oxidized to U(IV) (Katz et al. 1986, 1139 and following).

The standard reduction potential of U favors reduction of U(V) to U(IV) in aqueous solution, and the pentavalent oxidation state is the least stable oxidation state in solution. U(V) disproportionates in acidic aqueous solution by the reaction:

$$2UO_2^{+} + 4H^{+} \rightarrow UO_2^{2+} + U^{4+} + 2H_2. \quad (49)$$

However, the U(VI) species UO_2^{2+} is the most stable in low concentrations in the pH 2 to 4 range (Katz et al. 1986).

It is the disproportionation reaction of U(V) that limits it to trace level concentrations. U(VI) is a stable oxidation state, even under mildly reducing conditions, but may be reduced to U(IV) by a variety of reducing agents. In the chemically reducing environment expected in the WIPP, U(VI) will be reduced to U(IV). However, Reed et al. (1996) found that at pH 10 under anoxic conditions, U(VI) is stable as a CO_3^{2-} complex in simulated WIPP brines. U(IV) is the predominant oxidation state in half of the PA vectors, and U(VI) in the other half, due to uncertainty predicting the more stable oxidation state of U under WIPP conditions.

SOTERM-4.3 Neptunium

In the natural environment, Np may exist in the +IV, +V, and +VI oxidation states (Hobart 1990; Keller 1971; Clark et al. 1995). In the WIPP, Np(IV) is expected to be present (Rai and Strickert 1980; Rai et al. 1982; Kim et al. 1985; Pryke and Rees 1986). Np(V) appears to be the dominant oxidation state in natural groundwater (Hobart 1990). Nitsche and Edelstein (1985) observed that Np(V) is the most stable oxidation state in Yucca Mountain well water. Studies of the solubility of NpO_2OH in 1 M and 5 M NaCl at pH 6.5 suggest that Np(V) may be reduced to Np(IV) under these conditions (Kim et al. 1985; Neck et al. 1992). Np(VI) may be introduced into the WIPP or be produced by radiolysis, but it will not be stable in WIPP brines that contain or are in contact with reducing agents, such as metallic Fe or Fe(II) oxides and hydroxides. The reduction potential for the Np(VI)-Np(V) couple is +1.24 V in neutral solutions (Martinot and Fuger 1985, 651 et seq.) and +0.6 V in basic solutions (Katz et al. 1986, 470), suggesting that the potential for reduction of Np(VI) to Np(V) at a pH of about 9 will be about 1 V. Reed et al. (1996) found spectroscopic evidence for reduction of Np(VI) to Np(V) in ERDA-6 brine at pH 10, and observed total reduction of Np(VI) to Np(V) in G-Seep brine at pH 7. In the presence of organic ligands (see Section 5.0), Reed et al. (1996) observed rapid and complete reduction of Np(VI) to Np(V). Neck et al. (1995) showed Np(V)-CO_3^{2-} complexes to be stable in 5 M NaCl.

In order to capture the uncertainty in the redox speciation of Np, Np(IV) would be the dominant oxidation state in half of the PA vectors and Np(V) in the other half. However, Np is not transported in PA.

SOTERM-4.4 Plutonium

Pu can exist in the +III, +IV, +V, +VI, and +VII oxidation states (Katz et al. 1986, 781). Pu(III) is the favored oxidation state in acidic solutions, but oxidation of Pu(III) to Pu(IV) becomes progressively easier with increasing pH. This occurs because Pu(IV) features a very strong tendency to undergo hydrolysis, which has the effect of reducing the solution concentration of the free Pu(IV) ion Pu^{4+}. As the pH of a Pu solution is raised from acidic to neutral, Pu(IV) begins to precipitate, resulting in a shift of equilibrium concentrations of Pu(III) to Pu(IV). Consequently, Pu(III) is not a thermodynamically stable oxidation state in the basic environment that will be established by MgO in the WIPP (see Reaction (5) above). Although Pu(III) is unstable under expected WIPP conditions, Felmy et al. (1989) observed Pu(III) in PBB1 and PBB3 brines at neutral and slightly basic conditions.

Pu(V) and Pu(VI) can be produced from Pu(IV) under oxidizing conditions. It is not possible to produce Pu(V) by direct oxidation of Pu(IV) because the oxidation potential that must be applied exceeds the potential required for the oxidation of Pu(V) to Pu(VI). Therefore, in a solution with oxidizing conditions, any Pu(V) that arises from the oxidation of Pu(IV) will be immediately oxidized to Pu(VI). Pu(V) can be produced in solution only by first producing Pu(VI), followed by a carefully controlled reduction of Pu(VI) to Pu(V). Pu(V) may persist in neutral to basic solutions even when it is not the thermodynamically stable oxidation state, due to the reduction reaction's inverse fourth power dependence on the concentration of H^+, which can make the reduction of Pu(V) to Pu(IV) kinetically slow. Neither Pu(V) nor Pu(VI) will persist in significant quantities in the repository, since oxidizing conditions are required to produce them. Pu(VI) was shown to form complexes with Cl^- under oxic conditions in high-ionic-strength NaCl solutions (Clark and Tait 1996). Clark and Tait (1996) and Reed et al. (1996) showed the reduction of Pu(VI) to Pu(IV) by Fe and other reductants under expected WIPP repository conditions. Metallic Fe and Fe^{2+} reduce Pu(VI) in WIPP brines to either Pu(IV) or Pu(III). Clark and Tait (1996) and Felmy et al. (1996) experimentally observed the reduction of Pu(VI)-CO_3^{2-} complexes to Pu(IV) by either metallic Fe or Fe^{2+}. Reduction of Pu(VI) was also observed in the absence of CO_3^{2-}, but the oxidation state of the resulting species was not determined because the concentration was below the analytical detection limit, ca. 10^{-9} M. Neretnieks (1982) showed that dissolved actinides are reduced to a less soluble oxidation state and precipitated from moving groundwater upon coming in contact with Fe(II).

Pu(VII) can be produced in concentrated OH^- solutions that are also highly oxidizing. Pu(VII) will not be formed in the WIPP.

The DOE determined (Weiner 1996) that Pu(IV) will be the dominant oxidation state under WIPP conditions, but the possibility of the existence of Pu(III) cannot be excluded. As a result, Pu is modeled as Pu(III) in half of the PA vectors, and as Pu(IV) in half of the vectors.

SOTERM-4.5 Americium

Am(III) is the most stable aqueous oxidation state of Am (Katz et al. 1986, 912), and will be the only oxidation state of Am in the WIPP. Am(III) is not easily oxidized in aqueous solution (Hobart et al. 1982); however, Am(V) and Am(VI) are accessible at high pH under highly oxidizing conditions. Am(V) and Am(VI) are not stable in natural waters and are readily reduced. Am(V) and Am(VI) can oxidize H_2O, and as a result, they are thermodynamically unstable in aqueous solutions. Am(V) may be formed by oxidation of Am(III) by radiolysis products in NaCl solutions (Runde and Kim 1994), which may occur in microenvironments within WIPP disposal rooms, but Am(V) would not be stable in the homogeneous mixture of waste and brine. Solubility studies carried out by Pryke and Rees (1986) and Felmy et al. (1990) indicated that Am(V) is unstable in brine above pH 9 and reduces to Am(III). These studies also showed significant instability of Am(V) at pH 7. Due to the thermodynamic instability of Am(V) and Am(VI) in aqueous solution, and the lack of a credible mechanism for maintaining the highly oxidizing conditions necessary for persistence of these two oxidation states, Am(III) is the only oxidation state that is used in modeling the speciation and solubility of this element in the repository.

SOTERM-4.6 Curium

Cm is distinguished by the relatively great stability of the +III oxidation state with respect to oxidation or reduction (Katz et al. 1986, 970). The oxidation of Cm(III) is achieved only with the strongest oxidizing agents; one report claims evidence for an oxidation state higher than +IV (Korpusov et al. 1975). The Cm(III)-to-Cm(IV) transition has not been successfully induced by ozone or electrochemically, and the Cm(IV) phosphotungstate produced by oxidizing with peroxysulfate is considerably less stable than the Am(IV) analog (Katz et al. 1986, 971). Cm(III) is the only oxidation state expected to be stable in the WIPP. However, Cm is not transported in PA.

SOTERM-4.7 Summary of Oxidation-State Distributions

Table SOTERM-3 presents the oxidation-state distributions used in the CRA-2004 PA, the CCA PA, and the 1997 PAVT. Np would speciate entirely as Np(IV) in half of the PA vectors and as Np(V) in the other half, but Np is not transported in PA. Cm would speciate identically to Am, but Cm is not transported in PA.

Table SOTERM-3. Actinide Oxidation States Used for the CRA-2004 PA, the 1997 PAVT, and the CCA PA

Actinide Element	Oxidation States			
Th		+IV		
U		+IV		+VI
Pu	+III	+IV		
Am	+III			

SOTERM-4.8 Implications of the Source-Term Waste Test Program for Oxidation-State Distributions of Dissolved Actinides

The Actinide Source Term Waste Test Program (STTP) was an experimental program carried out at Los Alamos National Laboratory (LANL). The objective of the STTP was to examine the behavior of actinides in TRU wastes that will be present in the WIPP. The STTP was conducted by placing samples of various types of wastes from LANL in liter-scale (3-L) and drum-scale (65-gal) titanium (Ti) containers (Scherer and Villarreal 2000, 2001; Scherer et al. 2001a, 2001b, 2001c; Villarreal et al 2000; Villarreal et al. 2001a, 2001b, 2001c, 2001d; Villarreal et al. undated). This discussion focuses on the results from the liter-scale tests.

The samples were composed of process wastes solidified with Portland cement or Envirostone, and pyrochemical salts that resulted from Pu-refining processes. Metallic Fe and Nd, Th, U, Np, and Am were also added. Each waste sample was inundated with about 2 L of either Brine A or ERDA-6.

Pu(V) was identified in two of the liter-scale containers, and Pu(VI) was identified in three of these containers. The DOE's position is that the presence of Fe and other metals within the

WIPP will create and sustain a chemically reducing environment in the event of brine intrusion into the waste-disposal areas. The DOE further concludes that Pu will be maintained in the +III or +IV oxidation state due to the reducing conditions. The observance of Pu(V) and Pu(VI) in the STTP tests was noted by the EPA and the New Mexico Environmental Evaluation Group, which led to reexamination of the DOE position that Pu(V) and Pu(VI) are not expected to persist. The LANL reports on the STTP project consist primarily of process descriptions and extensive compilations of experimental data. The reports do not include extensive discussion of the meaning of the data, or explanations based on thermodynamic or kinetic principles.

Oxidized Pu was never observed in 34 of 39 liter-scale containers or in any of the 15 drum-scale containers, strongly supporting the DOE position that Pu will exist in the +III or the +IV oxidation state under the range of conditions that will exist within the repository. The data tables in the STTP final report are useful for plotting results on a container-by-container basis, to illustrate that in every case in which oxidized Pu was observed, the contents of the containers had not reached either a steady-state behavior or thermodynamic equilibrium. In many cases, first-order kinetic behavior was exhibited for both the solubilization and precipitation of solution components, including Pu. Solubilization of Pu due to oxidation as a consequence of build-up of radiolysis products is not supported by the data. A steady increase in radiolysis products, such as hypochlorite (OCl^-), would result in a steady-state condition of increased Pu(VI) concentrations. The presence of Pu(V) in two containers suggests that a reducing mechanism was available, which led to the reduction of Pu(VI) to Pu(V), followed by a kinetically slow reduction of Pu(V) to Pu(IV). LS-28 and LS-29 were the only two containers that exhibited Pu(VI) in large concentrations that did not decrease over time. However, LS-28 and LS-29 were pressurized with 60 bars of CO_2, and had pcH values about 5 (pH ≈ 4), conditions significantly different from those that will exist in the WIPP.

The STTP containers that were more nearly representative of WIPP conditions support the DOE position that oxidized Pu will not persist in the WIPP. The behavior of Nd, Th, U, Np, and Am in the STTP experiments also supports the DOE position that the solubilities of the actinides will be low in the event of brine influx into the repository.

SOTERM-5.0 THE ROLE OF ORGANIC LIGANDS

Organic ligands are present in the waste to be disposed of in the WIPP. Because organic ligands form dissolved complexes with the actinides, they could increase actinide solubilities. Therefore, the effects of these ligands have been included in the FMT calculations of actinide solubilities for the CRA-2004 PA. Organic ligands also form complexes with dissolved, cationic species of several metals that will be present in the repository, and thus metals compete with the actinides for the binding sites on these ligands. Therefore, the competitive effects of dissolved Mg^{2+} and Ca^{2+} have also been included in the solubility calculations for the CRA-2004 PA.

A number of organic ligands are capable of forming strong complexes with actinide ions, thereby increasing actinide solubilities . In general, the reactions that take place for one-to-one complexes are

$$An^{n+} + L^{m-} \rightleftharpoons AnL^{(n+m)}, \qquad (50)$$

where An is a general symbol for an actinide, with charge n, and L is a general symbol for an organic ligand with charge m. The apparent stability constant for this reaction is

$$\beta = [AnL^{(n+m)}]/[An^{n+}][L^{m-}] . \quad (51)$$

The square brackets indicate concentrations. The constant β is referred to as astoichiometric stability constant. If activities are used instead of concentrations, β is referred to as the thermodynamic stability constant.

Four organic ligands are included in FMT calculations of actinide solubilities: acetate ($CH_3CO_2^-$), citrate ($((CH_2CO_2)_2C(OH)(CO_2))^{3-}$, ethylenediaminetetraacetate (EDTA, $(CH_2CO_2)_2N(CH_2)_2N(CH_2CO_2)_2^{4-}$), and oxalate ($C_2O_4^{2-}$). These ligands are included in the solubility calculations because: (1) approximately 60 organic compounds were identified among the nonradioactive constituents of the TRU waste to be emplaced in the WIPP (Brush 1990; Drez 1991; DOE 1996a, Appendix B); (2) 10 of these 60 organic compounds could, if present in the WIPP, increase actinide solubilities because they are soluble in aqueous solutions such as WIPP brines, and because they form complexes with dissolved actinides (Choppin 1988); and (3) of these 10 H_2O-soluble organic ligands that form complexes with actinides (acetate, citrate, EDTA, and oxalate) were identified in the WIPP inventory (DOE 1996a).

Brush and Xiong (2003d) calculated the current concentrations of acetate, citrate, EDTA, and oxalate in WIPP brines that could be present in the repository after filling and sealing. Brush and Xiong (2003d) obtained the total masses of acetic acid, Na-acetate, citric acid, Na-citrate, Na-EDTA, oxalic acid, and Na-oxalate in the WIPP inventory (see Appendix Data, Attachment F). Brush and Xiong (2003d) then converted the total masses of each of these organic ligands to total moles, assumed that all these ligands will dissolve in any brine present in the repository after filling and sealing, and divided the total moles of each ligand by 29,841 m^3, "the smallest quantity of brine required to be in the repository [for] transport away from the repository" (Larson 1996). These calculations were carried out identically to those by Brush and Xiong (2003b) for the FMT calculations of actinide solubilities for the CRA-2004 PA, except that Brush and Xiong (2003b) used the masses of ligands reported by Crawford (2003, Table 2, column labeled "Scaled mass (kg)"), not the masses in Appendix Data, Attachment F.

Actinide solubilities were not recalculated using the corrected concentrations of organic ligands from Brush and Xiong (2003d) because the corrections decreased the ligand concentrations slightly. Because the concentrations of these ligands decreased, the actinide solubilities calculated using the uncorrected ligand concentrations of Brush and Xiong (2003b) are slightly higher than they would be if recalculated using the corrected ligand concentrations of Brush and Xiong (2003d).

Table SOTERM-4 provides: (1) the current, corrected concentrations of organic ligands calculated by Brush and Xiong (2003d) based on the masses in Appendix Data, Attachment F; (2) the ligand concentrations calculated by Brush and Xiong (2003b) based on the masses provided by Crawford (2003) (these concentrations were used for the actinide-solubility calculations for the CRA-2004 PA); and (3) the ligand concentrations calculated for the CCA

(CCA Appendix SOTERM, Table SOTERM-4) based on the masses of organic ligands provided by DOE (1996a). Mistakes were apparently made in the calculation of the ligand concentrations for the CCA, the most significant of which was the likely transposition of citrate and oxalate in CCA Appendix SOTERM, Table SOTERM-4.

Table SOTERM-4. Concentrations of Organic Ligands in WIPP Brines That Could Be Present in the Repository after Closure

Organic Ligand	Concentrations Based on Corrected CRA Inventory[1]	Concentrations Used in FMT for the CRA-2004 PA[2]	CCA[3]
Acetate	3.56×10^{-3} M	5.05×10^{-3} M	1.1×10^{-3} m
Citrate	2.71×10^{-4} M	3.83×10^{-4} M	7.4×10^{-3} m
EDTA	2.73×10^{-6} M	3.87×10^{-6} M	4.2×10^{-6} m
Oxalate	1.53×10^{-2} M	2.16×10^{-2} M	4.7×10^{-4} m

[1] Concentrations calculated by Brush and Xiong (2003d) based on the masses of organic ligands in Appendix Data, Attachment F.
[2] Concentrations calculated by Brush and Xiong (2003b) based on the masses of organic ligands provided by Crawford (2003).
[3] Concentrations calculated for the CCA (CCA Appendix SOTERM, Table SOTERM-4) based on the masses of organic ligands provided by DOE (1996a).

Stability constants for complexes between acetate, citrate, EDTA, lactate, and oxalate and the +III, +IV, +V, and +VI actinides (or oxidation-state analogs of these actinides) were determined to incorporate these complexes in the actinide-speciation-and-solubility models described above (see Section 3.4). Stability constants for complexes between these ligands and Mg^{2+} were also determined to include competition between Mg^{2+} and the actinides for the binding sites on these ligands. Choppin et al. (2001) provided the results of all of these experiments. Giambalvo (2002b, 2002e) incorporated these results in the FMT database used for the calculation of actinide solubilities for the CRA-2004 PA. Giambalvo (2003) described this database in detail.

Brush and Xiong (2003a) used FMT, the thermodynamic database described by Giambalvo (2003), and the concentrations of acetate, citrate, EDTA, and oxalate calculated by Brush and Xiong (2003b) to calculate the solubilities of the +III, +IV, and +V actinides for the CRA-2004 PA. (No lactate has ever been identified in the TRU waste to be emplaced in the WIPP.) In the FMT calculations with ligands, all four ligands (acetate, citrate, EDTA, and oxalate) were present simultaneously in Salado or Castile brine at the concentrations calculated by Brush and Xiong (2003b). In these calculations, the stability constants for the complexes formed by these ligands and Ca^{2+} were assigned the same values as the stability complexes formed by these ligands and Mg^{2+} (Giambalvo 2003). However, these calculations did not include competition from dissolved metals such as vanadium (V), chromium (Cr), nickel (Ni), copper (Cu), and lead (Pb), all of which could be present at significant concentrations due to dissolution of steels and other metallic constituents of TRU waste (CCA Appendix SOTERM, SOTERM.5). The results of the FMT calculations for the CRA-2004 PA demonstrate that acetate, citrate, EDTA, and oxalate will not form complexes with the +III and +IV actinides to a significant extent under expected WIPP conditions, and thus will not affect the +III and +IV actinide solubilities significantly (Brush and Xiong 2003d; Downes 2003a, 2003b).

SOTERM-6.0 MOBILE COLLOIDAL ACTINIDE SOURCE TERM

Colloidal particles will be generated in the repository as a result of microbial consumption of cellulosics, and corrosion of steel waste containers and waste constituents, by the hydrodynamic entrainment of colloidal-sized mineral fragments and several other mechanisms. Those colloidal particles may sorb dissolved actinides or the dissolved actinides themselves may form colloidal particles. In an intrusion scenario, actinide-bearing colloidal particles, together with dissolved actinides, may be transported to the Culebra by Castile or Salado brines present in the repository. Additional colloidal particles may be present in natural Culebra groundwater and could form additional actinide-bearing colloidal particles. After introduction to the Culebra, the dissolved actinides and actinide-bearing colloidal particles are transported by Culebra groundwaters. Colloidal actinides may also be transported through the fractured anhydrite interbeds of the Salado.

The actinide source term at the WIPP is defined as the sum of contributions from dissolved actinide species and mobile colloidal actinide species. Colloidal actinides that are not suspended in the aqueous phase (that is, not mobile) are not included in the colloidal actinide source term. Sorption of colloidal actinides onto fixed substrates will also reduce the mobile colloidal actinide source term, but no credit is currently being taken for reduction by that means.

In this section, the quantification of the mobile actinide-bearing colloid component of the actinide source term is described. The quantification of colloid-facilitated transport of actinides in the overlying Culebra, in the event of an intrusion into the repository, is described in Chapter 6.0 (Section 6.4.6.2.2) and Appendix PA, Attachment MASS, Section MASS-15.3.

SOTERM-6.1 Introduction

Colloidal particles are generally defined as particles with at least one dimension between 1 nm and 1 μm, suspended in a liquid, and maintained in suspension for very long periods of time by Brownian (random thermal) motion (Hiemenz 1986; Buddemeier and Hunt 1988; Stumm 1992, 1993). Those size boundaries are approximately defined on the basis of physical phenomena. Particles larger than about 1 μm are too large for Brownian motion to overcome gravitational forces, and the particles will rather quickly settle by gravity. An exception is the case of microbes, which are considered to be colloidal, but may exceed 1 μm. The specific gravities of microbes are typically quite close to that of the dispersant, and so they may not settle by gravitational forces. Generally, particles smaller than approximately 1 nm behave in transport like dissolved ionic species.

SOTERM-6.1.1 Formation and Behavior of Colloidal Particles

Inorganic colloidal particles have been reported to form by a variety of processes. Colloidal particles may form by condensation or homogenous nucleation from dissolved species when a mineral phase is supersaturated or as hydrolyzed precipitates of mixed metal ions (Kim 1992). Colloidal particles may also form by release of particles from bulk material due to disruption of fragile aggregates by changes in ionic strength or hydrodynamic forces, dissolution of a more soluble surrounding matrix (Buddemeier and Hunt 1988; Kim 1994), mechanical grinding of

mineral surfaces, or mechanical disruption of secondary minerals present at mineral surfaces (McCarthy and Zachara 1989).

Organic colloidal particles may form from microbial consumption of CPR materials, condensation reactions of organic molecules to form humic substances, or microbial activity. A variety of naturally occurring organic materials, such as viruses, microbes, and pollen, are colloidal-sized particles (McCarthy and Zachara 1989; Stumm 1992, 243).

Colloidal particles may interact with actinides to form radiocolloids in two ways (see, for example, Lieser et al. 1986a, 1986b, 1990; Kim et al. 1984a, 1984b; Buddemeier and Hunt 1988; Kim 1992, 1994). First, radiocolloids may form as a result of chemical reactions involving dissolved polyvalent actinide ions. Hydrolysis and condensation reactions have been shown to form actinide macromolecules in which the actinide ions are bridged with hydroxyl ions to form polymers. Those radiocolloids are termed "actinide intrinsic colloids," "true colloids," "real colloids," "Eigenkolloide," or "type I colloids."

A second means to form radiocolloids is by sorption of actinides by ordinarily nonradioactive colloidal particles. In the actinide environmental geochemistry literature, the nonradioactive colloidal particle has been called a "groundwater colloid." Once actinide sorption has occurred, the resulting radiocolloids may be called "pseudo colloids," "carrier colloids," "Fremdkolloide," or "type II colloids." The colloidal substrate for sorption may be a mineral fragment, a microbial cell, or a humic substance. Bates et al. (1992) recently described radiocolloids, which they called "primary colloids," forming in situ at the surfaces of vitrified radioactive waste as it reacts chemically with H_2O. Considering that coprecipitation is a continuum with adsorption (see, for example, Comans and Middleburg 1987; Stumm 1992, 253 et seq.), the "primary colloid" can be included in the carrier-colloid category, and more specifically, a mineral-fragment-type colloidal particle. A similar sort of colloid would form by isomorphous lattice substitution of actinide ions during mineral precipitation (that is, coprecipitation) or precipitation of actinide minerals.

In the traditional colloid-chemistry literature, two types of colloidal particles are defined on the basis of how they interact with the dispersant (see, for example, Alexander and Johnson 1949, 114; Vold and Vold 1983; Hirtzel and Rajagopalan 1985; Hiemenz 1986; Ross and Morrison 1988; Hunter 1991-1992). Hydrophobic colloids are stabilized by electrostatic forces, whereas hydrophilic colloids are stabilized by solvation forces. In light of increased knowledge of aqueous surface chemistry gained over the past two decades, the terms hydrophilic and hydrophobic must be used cautiously, because even hydrophobic surfaces have hydrophilic surface functional groups. It is important, however, to make the distinction between how those two types of colloidal particles behave, because they exhibit different kinetic stability behaviors in electrolytes.

Kinetic stability differs from thermodynamic stability. Thermodynamic stability refers to the chemical equilibrium between the colloidal particles and the dispersant, whereas kinetic stability refers to the rate at which colloidal particles in a colloidal dispersion are removed from suspension due to agglomeration followed by gravitational settling. Thermodynamic stability may be most important for actinide intrinsic colloids, because that type of colloid forms directly from solution by chemical reactions. Kinetic stability is inversely related to the rate of particle aggregation, which is dependent on the frequency and efficiency (the fraction resulting in

permanent joining) of collisions between colloidal particles. The behavior of colloidal particle types as a function of ionic strength is probably the single most important phenomenon affecting the importance of colloid-facilitated actinide transport at the WIPP.

Hydrophobic colloidal particles are kinetically stabilized and destabilized by electrostatic forces. In an aqueous dispersant, hydrophobic colloidal particles are attracted to one another by van der Waals forces. That electrostatic attraction is countered by repulsive forces generated by a cloud of counterions surrounding each particle (Lyklema 1978; Hiemenz 1986). In a kinetically stable colloidal dispersion, colloidal particles are usually repelled from one another before they get close enough to become agglomerated. However, as the ionic strength of the dispersion is increased, the thickness of the cloud of counterions is compressed, allowing closer particle-particle interaction. The net effect is that as colloidal particles come into proximity with one another in the dispersion, a greater chance for sticking exists, and so the rate of agglomeration increases. That phenomenon is very effective at removing colloidal particles from suspension even at fairly low ionic strengths over periods of hours to days. Mineral fragments, which are a hydrophobic colloid type, are affected by ionic strength in this way.

Hydrophilic colloidal particles are stabilized by solvation forces, which are largely independent of the ionic strength of the dispersant (Alexander and Johnson 1949). This type of colloidal particle is essentially a dissolved macromolecule. Humic materials are an example of the traditional hydrophilic colloid type. Two major categories of hydrophilic colloidal particles are recognized. Micelles are aggregates of dissolved monomers, that are in thermodynamic equilibrium with those monomers. Polyelectrolytes are charged polymers that are not in thermodynamic equilibrium with a monomeric species (examples of polyelectrolytes include gum arabic, gelatin, pectin, and proteins). An important distinction, therefore, is that micelles require a minimum threshold concentration of monomers (the critical micellization concentration, or c.m.c.) to form. In contrast, the formation of polyelectrolytes is not dependent on monomer concentration. Polyelectrolytes may act as an association colloid by adsorbing on hydrophobic colloidal particles. The resulting dispersions may be extremely kinetically stable (Hiemenz 1986, 659).

The kinetic stability of hydrophobic colloidal particles may be modified by coatings of steric stabilizing compounds, which themselves are essentially hydrophilic materials (also referred to as protective or association colloids) which modify the surface behavior to inhibit close interaction of particles. Such colloidal systems are rendered kinetically stable. Particles stabilized by organic compounds in seawater are an example of a sterically stabilized colloidal system. Microbes can be considered as stabilized in a similar manner, except that the stability is imparted by molecules (for example, polysaccharides), attached to the surface of the microbe, which have hydrophilic parts extending into the dispersant.

Colloidal particles may have rigid or flexible structures, which may affect the way in which they interact with the host rock during transport. “Hard-sphere” colloidal particles, such as mineral fragments, have discrete well-defined boundaries at the particle-H_2O interface, and are rigid. “Soft-sphere” colloidal particles, such as humic substances, have less distinct boundaries at the particle-H_2O interface, are flexible and may undergo conformational changes in response to environmental variations. “Soft-sphere” colloids are essentially dissolved macromolecules and

are closest in form and behavior to particles referred to as hydrophilic colloids in the traditional colloid-chemistry literature (Lyklema 1978; Hiemenz 1986).

SOTERM-6.1.2 Definition of Colloidal Particle Types

On the basis of the phenomena described in the previous section, several classification schemes have been proposed by various workers, and a large number of descriptive terms have evolved and been propagated in the literature. For actinide environmental geochemistry, most of the classification schemes are based on how the colloidal particle interacts with radionuclides. Colloidal particles are classified into the following four types for evaluation of the impact of colloidal particles at the WIPP site:

1. Mineral fragments are hydrophobic, hard-sphere particles that are kinetically stabilized or destabilized by electrostatic forces, and may consist of crystalline or amorphous solids. Mineral fragments may be made kinetically stable by coatings with steric stabilizers that prevent close contact. Mineral fragments may act as substrates for sorption of actinides or they may consist of precipitated or coprecipitated actinide solids.

2. Actinide intrinsic colloids are macromolecules of actinides that, at least in some cases, may mature into a mineral-fragment-type of colloidal particle. When immature, they are hydrophilic; when mature, they become hydrophobic.

3. Humic substances are hydrophilic, soft-sphere particles that are stabilized by solvation forces. They are often powerful substrates for uptake of metal cations and are relatively small (less than 100,000 atomic mass units).

4. Microbes are relatively large colloidal particles that are stabilized by hydrophilic coatings on their surfaces, which behave as steric stabilizing compounds. They may act as substrates for extracellular actinide sorption or they may actively bioaccumulate actinides intracellularly.

SOTERM-6.2 Performance-Assessment Implementation

Results of the colloidal actinide investigation were used in the CRA-2004 PA, the CCA PA, and the 1997 PAVT in three types of parameter values: (1) constant concentration values; (2) concentration values proportional to the dissolved actinide concentration; and (3) maximum concentration values. The parameter types are summarized below and are described in parameter record packages (Papenguth 1996a, 1996b, 1996c, 1996d).

For actinide intrinsic colloids and mineral-fragment colloids, actinide concentrations associated with them were described as constant values. Table SOTERM-5 summarizes the material and parameter names and descriptions.

Experiments conducted to quantify actinide concentrations associated with humic substances and microbes provided the basis for a more sophisticated representation, in which colloidal actinide concentrations were related to the dissolved actinide concentration by proportionality constants. For microbes, the proportionality relationship was made by element. For humic actinides,

however, the relationship was made by oxidation state rather than by element. For microbes and humic substances, the experiments also provided a basis to define upper limits for the actinide concentration that could be associated with each of those colloid types. For both humic and microbial actinides, the upper-limit parameter was defined by element rather than oxidation state, and is in units of molarity. The use of the two upper-limit parameters is slightly different, and is described in the sections below discussing humic substances and microbes.

SOTERM-6.3 Development of Parameter Values

In this section, the experimental basis for the parameter values is described. For each of the four types of colloids, the characteristics of the colloidal particle type are described, the experimental program is outlined, methods of interpretation are described, and results are summarized.

Table SOTERM-5. Material and Property Names for Colloidal Parameters

Material	Property	Brief Description of Parameter
Th, U, Np, Pu, Am	CONCMIN	Concentration of actinide associated with mobile mineral fragment colloids
Th, U, Np, Pu, Am	CONCINT	Concentration of actinide associated with mobile actinide intrinsic colloids
Th, U, Np, Pu, Am	PROPMIC	Proportionality constant for concentration of actinides associated with mobile microbes.
PHUMOX3 [1] PHUMOX4 PHUMOX5 PHUMOX6	PHUMCIM	Proportionality constant for concentration of actinides associated with mobile humic colloids, in Castile brine, actinide solubilities are inorganic only (complexes with man-made organic ligands are not important), solubilities were calculated assuming equilibrium with Mg-bearing minerals (brucite and magnesite);
PHUMOX3 [1] PHUMOX4 PHUMOX5 PHUMOX6	PHUMSIM	Proportionality constant for concentration of actinides associated with mobile humic colloids, in Salado brine, actinide solubilities are inorganic only (complexes with man-made organic ligands are not important), solubilities were calculated assuming equilibrium with Mg-bearing minerals (brucite and magnesite).
Th, U, Np, Pu , Am	CAPMIC	Maximum (cap) concentration of actinide associated with mobile microbes;
Th, U, Np, Pu, Am	CAPHUM	Maximum (cap) concentration of actinide associated with mobile humic colloids.

[1] Proportionality constant for concentration of actinides associated with mobile humic substances, for PHUMOX3, for actinide elements with oxidation state ***+III*** (that is, Pu(III) and Am(III)); PHUMOX4, oxidation state ***+IV*** (Th(IV), U(IV), Np(IV), and Pu(IV)); PHUMOX5, oxidation state ***+V*** (Np(V)); and PHUMOX6, oxidation state ***+VI*** (U(VI)).

SOTERM-6.3.1 Mineral-Fragment Colloids

Mineral-fragment-type colloidal particles may be present in naturally occurring groundwaters, and they may be released from the host rock due to disruption of fragile aggregates by changes in ionic strength or hydrodynamic forces, dissolution of a more soluble surrounding matrix, mechanical grinding of mineral surfaces, or mechanical disruption of secondary minerals present at mineral surfaces. Under certain conditions, such as extreme changes in ionic strength of the groundwater or by physical disruption due to natural or human-induced events, mineral-

fragment-type colloidal particles could also be produced within the Culebra. In an intrusion scenario at the WIPP, mixing of repository brines with Culebra brines may result in mineral precipitation that may include coprecipitation of actinide-bearing mineral-fragment-type colloidal particles. Within the repository, mineral-fragment-type colloidal particles may form from corrosion of Fe-bearing waste and the steel packaging materials. In addition, Portland-cement-based matrixes will be attacked and will produce mineral-fragment-type colloidal particles. Bentonite, which may be a constituent of drilling mud is itself a potential source of mineral-fragment-type colloidal material that should be considered for actinide transport.

In terms of colloidal actinide transport, mineral-fragment-type colloids act as carriers, in that actinide ions sorb onto the surfaces of the colloids. Because each mineral substrate has a different affinity for actinides, quantification of actinide concentrations associated with the wide range of mineralogies likely to be present at the WIPP is insurmountable. Instead, a bounding approach was used based on residual concentrations of colloidal particles in WIPP-relevant brines coupled with estimates of reasonable maximum concentrations of actinides that could be sorbed onto the colloid surfaces. That approach requires three pieces of information: (1) the number of mineral-fragment-type colloidal particles in the aqueous phase; (2) the geometric surface area of individual colloidal particles; and (3) the site-binding capacity of the mineral surface. In the remainder of this section, descriptions of the determination of items (1) through (3), the interpretation of that information, and the development of parameter values are provided.

SOTERM-6.3.1.1 Description of Experiments

Hydrophobic colloidal particles, such as mineral fragments, are kinetically stabilized and destabilized by electrostatic forces (refer to detailed discussion in Papenguth and Behl 1996, Sections 2.5.1 and 2.6). In an aqueous dispersant, hydrophobic colloidal particles are attracted to one another by van der Waals forces. That electrostatic attraction is countered by repulsive forces generated by a cloud of counterions surrounding each particle. In a kinetically stable colloidal dispersion, colloidal particles are usually repelled from one another before they get close enough to become agglomerated. However, as the ionic strength of the dispersion is increased, the thickness of the cloud of counterions is compressed, allowing closer particle-particle interaction. The net effect is that as colloidal particles come into proximity with one another in the dispersion, a greater chance for sticking exists, and so the rate of agglomeration increases. That phenomenon is very effective at removing colloidal particles from suspension even at fairly low ionic strengths over periods of hours to days.

The kinetic stability of the mineral-fragment-type colloids in WIPP-relevant brines was evaluated in coagulation-series experiments. Colloidal dispersions of mineral fragments were prepared by mechanical disaggregation of representative mineral, rock samples, and other materials or by chemical precipitation from laboratory reagents. Brine simulants were prepared that covered the ranges of ionic strengths observed in WIPP brines. The brines were sequentially diluted with deionized H_2O by factors of 10 and adjusted to acidic, neutral, and basic pH conditions to evaluate the effects of ionic strength and pH on kinetic stability. At the ionic strength referred to as the critical coagulation concentration (c.c.c.), colloidal particles will rapidly coagulate, forming agglomerates large enough to settle by gravitational forces. The

number population of colloidal particles remaining in suspension in the various dispersions was measured over time to assess their stability as a function of solution ionic strength and time.

Colloidal dispersions were prepared for the following minerals or materials: bentonite, kaolinite, montmorillonite, vermiculite, illite, anhydrite, calcium carbonate, magnesite, hematite (mechanically disaggregated), hematite (chemical precipitate), limonite, goethite, magnetite, quartz, siderite, brucite, strontianite, diatomaceous earth, pyrite, and cellulosic materials (Masslinn paper towels and Scott paper towels). The brine solutions used included a Salado-like brine simulant (SPC brine) and a Culebra brine simulant (H-17). For c.c.c. experiments, sequential dilutions of those brines were made that spanned approximately five orders-of-magnitude. Brine simulants consisting of 0.5 M NaCl or $CaCl_2$ were also used. For the residual concentration measurements which were used as the basis for the CRA-2004 PA, the CCA PA, and the 1997 PAVT, the one order-of-magnitude dilution (that is, 10 percent of original strength) of the Salado-like brine and the Culebra brine simulants were used. That reduction in ionic strength provides a degree of conservatism in the results.

The c.c.c. experiments for the various concentrations of WIPP brine simulants were conducted under acidic (observed pH generally ranging from 3 to 4), neutral (pH 6 to 8), and basic (pH 9 to 12) conditions. Following the introduction of an aliquot of dispersed colloidal particles to a series of test tubes containing the sequentially diluted brine, colloidal particle concentrations remaining near the top of the fluid columns (residual concentration) were measured as a function of time. The degree of coagulation and settling was quantified using an inductively coupled argon-plasma atomic emission spectrophotometer, nephelometry, and direct particle counting.

Most of the experiments conducted relating to the kinetic stability of mineral-fragment colloidal particles were qualitative to semiquantitative, and were focused on evaluating whether a c.c.c. existed. For the final experiments, however, a state-of-the-art particle spectrometer was used with significantly greater sensitivity. That device was designed for semiconductor fabrication plants, which require extremely pure processing H_2O, and use a similar instrument to ascertain purity. The final experiments were conducted over an extended period of time using the more sensitive analytical technique to determine the number and size of colloids in the brine suspensions. Those experiments were conducted in a similar fashion to previous experiments for bentonite (supplied by the Aldrich Chemical Co.), goethite, and hematite (mechanically disaggregated), but in a relatively dilute (and therefore conservative) brine simulant consisting of 0.1 M NaCl. Residual particle concentrations made with the particle spectrometer compared favorably with measurements made with spectroscopic techniques made at similar experiment times. Generally after the first day of the c.c.c. experiments, the majority (greater than 99 percent) of the colloidal particles had already settled out of suspension. With the more sensitive particle spectrometer, however, residual concentrations of colloidal particles were observed to continue to decrease. For experiments analyzed by spectroscopic or light-scattering techniques, final residual colloid number populations remaining suspended in the test vessels were determined by multiplying the initial colloid number populations determined at the start of the experiments by the fraction of suspended colloids remaining at the final reading. Using the particle spectrometer, final number populations were measured directly.

SOTERM-6.3.1.2 Interpretation and Discussion

Parameter values (CONCMIN) describing the amount of actinide element bound by mineral-fragment-type colloidal particles were determined from the information described above, combined with estimates of adsorption-site densities.

Actinides sorbed to the surfaces of colloidal particles can be estimated using ranges of values for adsorption-site densities taken from published surface complexation modeling research. The actinide concentration contained by a single mineral-fragment-type colloidal particle is calculated by considering the geometrical surface area of a spherical particle:

$$[An]_p = \frac{\pi D^2 N_s}{N_A} , \qquad (52)$$

where:

$[An]_p$ = concentration of an adsorbed actinide element (mol/particle)
D = spherical colloidal particle diameter (nm)
N_S = adsorption site density (sites/nm^2)
N_A = Avogadro's number.

An adsorption-site density of 1 site/nm^2 was used for N_S in the above equation, a value which is realistic, but probably conservative. With that site density, 1-nm- and 1-μ-diameter particles could have a maximum of about 10^{-24} and 10^{-18} mol actinide per particle, respectively. To obtain an estimate of the maximum actinide concentrations that could be associated with the colloids, the estimates of residual colloid number populations were multiplied by the estimated maximum actinide-transport capacity described by Equation (52). The use of a uniform adsorption-site density is a conservative approach, because the actual sorption on mineral surfaces should be described by some kind of isotherm that will result in less than 100 percent coverage. Further, if multivalent adsorbates are present (for example, U(VI)), multiple adsorption sites may be required for one adsorbate ion, reducing the net adsorption capacity of the surface.

Final residual colloid populations quantified by spectrophotometry or nephelometry showed that mineral-fragment-type colloidal particles are kinetically destabilized by brines similar in composition to those present at the WIPP site. Colloid number population values were, with a few exceptions, reduced to less than 5 percent of the initial values within one day. Conservative estimates of maximum actinide concentrations associated with those residual colloid populations are on the order of 10^{-7} to 10^{-9} moles actinide per liter of dispersion.

The final experiments, which utilized the particle spectrometer to measure the quantity of colloids remaining in suspension offered the most sensitive estimates. Moreover, those experiments were conducted for substantially longer periods of time than the semiquantitative c.c.c. experiments. Those experimental results are shown in Table SOTERM-6.

Table SOTERM-6. Experimental Results for Mineral-Fragment Colloids

Mineral	Time of Final Reading (days)	Estimated Actinide Concentration (moles/liter dispersion)

Hematite	12.8	1.6×10^{-8}
Goethite	12.9	9.5×10^{-10}
Bentonite	12.8	1.6×10^{-10}
Geometric mean		1.3×10^{-9}

The DOE believes that the experimental results using the particle spectrometer with the three distinct colloids (hematite, goethite, and bentonite), are representative of other mineral-fragment-type colloidal particles in terms of their behavior in brine solutions. The geometric mean was assumed to be a more representative average of the final colloid concentrations than the arithmetic mean because of the very small final colloid concentrations (which, for this particular case, is also conservative).

Mineral-fragment-type colloidal particles are unique among the four colloidal particle types addressed for the WIPP, because their concentrations are not generally linked to solubility, as are actinide intrinsic colloids and humic substances, or to a maximum supportable population in the case of microbes. Consequently, in an intrusion scenario at the WIPP, as dissolved actinide elements are introduced to the Culebra, it is possible that those dissolved actinides could sorb onto a separate population of indigenous mineral fragments, producing a supplemental source term. To account for that possibility, the geometric mean value listed above was multiplied by a factor of two, producing a final "most-likely value" of 2.6×10^{-9} moles actinide per liter of dispersion.

To capture uncertainty, mainly stemming from knowledge of the adsorption-site density value, a triangular distribution with "minimum values" and "maximum values" spanning one order of magnitude about the geometric mean was provided for the CRA-2004 PA, CCA PA, and 1997 PAVT calculations. Additional conservatism is incorporated into the mineral-fragment-parameter values in that the total concentration of actinides carried by mineral fragment colloidal particles have essentially been multiplied by a factor of five, because a separate population of colloidal particles has been assumed for each actinide element. No consideration of competition for sorption sites is incorporated into the calculations. The value used for adsorption-site density is conservative, but reasonable. For the PA calculations, however, the triangular distribution was not sampled. Instead, the maximum parameter values were used as constant values, which essentially results in a site density of 10 sites/nm^2. Parameter values for CONCMIN are summarized in Table SOTERM-11. Section 7.0 of this attachment discusses details on PA implementation.

SOTERM-6.3.2 Actinide Intrinsic Colloids

Actinide intrinsic colloids (also known as true colloids, real colloids, type I colloids, and Eigenkolloide) form by condensation reactions of hydrolyzed actinide ions and consist solely of actinide cations linked by anions. There are several stages in the development of actinide intrinsic colloids at which they have significantly different behaviors. When immature, actinide intrinsic colloids display physicochemical properties that are similar to ionized humic substances. With age, they become more similar to mineral fragment-type colloidal particles.

The experimental approach used was strongly influenced by reviews of published literature on actinide intrinsic colloids. Pertinent literature is discussed below (see also Papenguth and Behl 1996).

SOTERM-6.3.2.1 Intrinsic Colloids of Plutonium

The most well-known and well-studied actinide intrinsic colloid is the Pu(IV) intrinsic colloid, which has been used as a basis of comparison for investigating intrinsic colloids of other actinides. Most of the knowledge about the Pu(IV) intrinsic colloid comes from research at high Pu concentrations in highly acidic solutions, which was conducted to help improve the efficiency of processing techniques. The Pu(IV) intrinsic colloid is notorious in its propensity to polymerize to form a gel-like material, which can even plug process lines.

A conclusive demonstration of the mechanisms of formation of the Pu(IV) intrinsic colloid has not yet been made, but there is a preponderance of evidence that suggests that polymerization is strongly linked to hydrolysis, and that the initial polymerization, or condensation, produces a macromolecule that becomes progressively more crystalline with time. The final mature colloid has a composition between $Pu(OH)_4(am)$ and $PuO_2(c)$, although the latter compound may be only partly crystalline and both may include interstitial H_2O molecules.

The most convincing and consistent explanation for the chemistry of the Pu(IV) intrinsic colloid is presented by Johnson and Toth (1978). Those authors developed a conceptual model to explain the solution chemistry of a variety of metal cations and a variety of oxidation states. The conceptual model involves processes referred to as “olation” and “oxolation” in which metal cations become bridged with hydroxyl groups, which in turn undergo irreversible elimination of H_2O and concurrent formation of O bridges. Johnson and Toth demonstrate that the model is consistent with the observed behavior of the Pu(IV) intrinsic colloid.

Hydrolysis reactions for metal cations such as Pu may be written as follows:

first: $$Pu^{4+} + H_2O \rightleftharpoons PuOH^{3+} + H^+ \quad (53)$$

second: $$PuOH^{3+} + H_2O \rightleftharpoons Pu(OH)_2^{2+} + H^+ \quad (54)$$

third: $$Pu(OH)_2^{2+} + H_2O \rightleftharpoons Pu(OH)_3^{+} + H^+ \quad (55)$$

fourth: $$Pu(OH)_3^{+} + H_2O \rightleftharpoons Pu(OH)_4\,(aq) + H^+ \quad (56)$$

Johnson and Toth (1978) point out, however, that in interpreting the formation of the Pu(IV) intrinsic colloid, it makes better sense to include the implied waters of hydration that surround metal cations in solution. Hydrolysis Equations (53) through (56) can be rewritten as follows, where n equals 4:

first: $$[Pu(H_2O)_m]^{n+} \rightleftharpoons [Pu(OH)(H_2O)_{m-1}]^{n-1} + H^+ \quad (57)$$

second: $$[Pu(H_2O)_{m-1}]^{n-1} \rightleftharpoons [Pu(OH)(H_2O)_{m-2}]^{n-2} + H^+ \quad (58)$$

third: $$[Pu(H_2O)_{m-2}]^{n-2} \rightleftharpoons [Pu(OH)(H_2O)_{m-3}]^{n-3} + H^+ \quad (59)$$

fourth: $$[Pu(H_2O)_{m-3}]^{n-3} \rightleftharpoons [Pu(OH)(H_2O)_{m-4}]^{n-4} + H^+ \quad (60)$$

From the literature, it is clear that polymerization occurs nearly immediately after the first hydrolysis (Equation (57)) occurs. Johnson and Toth (1978) suggest the following reaction involving polymerization of two hydrolyzed species by loss of H_2O (oxolation):

$$2\{[(H_2O)_{d-2}Pu(OH)(H_2O)]^{+(y-1)}\} \rightleftharpoons [(H_2O)_{d-2}Pu(OH)(OH)Pu(H_2O)_{d-2}]^{+2(y-1)} + 2H_2O \quad (61)$$

Aging or maturation of polymer then occurs by loss of H_2O (olation) as follows:

$$[Pu(OH)(OH)Pu(OH)(OH)Pu(OH)(OH)...] \rightleftharpoons [Pu(O)Pu(O)Pu(O)...]_n + 3nH_2 \quad (62)$$

Maiti et al. (1989) and Laul et al. (1985) describe similar reactions, but it appears that they believe that the third hydrolysis reaction occurs, because they use the $Pu(OH)_3^+$ion in their proposed polymerization reaction. Use of that ion does not appear to be consistent with observations by many workers that polymerization occurs immediately after the first hydrolysis reaction.

As the actinide polyelectrolytes mature through the olation process to become closer in composition to an actinide-oxide mineral, they will be kinetically destabilized by the high ionic strengths of the WIPP brines and will not be mobile. Further, the solubilities of the mature solid phase cannot be exceeded. In fairly long-term experiments, Nitsche et al. (1992, 1994) showed that the concentration of Pu(IV) intrinsic colloid stabilized at about 10^{-8} M. It is not known whether the form was Pu(IV) polyelectrolyte or Pu(IV) mineral-fragment-type colloid.

SOTERM-6.3.2.2 Intrinsic Colloids of other Actinides

Reference is made to a variety of intrinsic colloids of other actinides, but no systematic investigations of their formation and behaviors appear to have been made. Pu is apparently unique in its propensity to form an intrinsic colloid. No mention is made in the literature of maturation of polyelectrolytes of other actinides to form mineralfragment-type colloidal particles as Pu does.

In general, the tendency of actinides to hydrolyze and to polymerize to form intrinsic colloids follows the order:

$$An^{4+} >> An(VI)O_2^{2+} > An^{3+} > An(V)O_2^+ \quad (63)$$

(Cleveland 1979a, 1979b; Choppin 1983; Kim 1992; Lieser et al. 1991, 119). The order of oxidation states in the equation above results from the ionic-charge-to-ionic-radius ratios. The tendency for hydrolysis of $An(VI)O_2^{2+}$ is greater than for An^{3+} because the effective charge on the central cation on the linear $[O\text{-}An\text{-}O]^{2+}$ ion is 3.3 ± 0.1, slightly greater than 3. This trend generally holds true for the actinide elements, because of the very small changes in ionic radii among the actinide (this is the oxidation-state analogy; refer to Novak et al. 1996). There are

differences in the behaviors of the actinides from element to element that stem from very subtle changes in the charge-to-radius ratio and the nature of the configuration of the f molecular orbital.

Considering Pu as an example, hydrolysis becomes significant for Pu^{4+}, $Pu(VI)O_2^{2+}$, Pu^{3+}, and $Pu(V)O_2^{+}$ at pH values of <1, 4-5, 6-8, and 9-10, respectively (Choppin 1983). On the basis of the hydrolysis trend, it is not likely that An(III) and An(V) species will form actinide intrinsic colloids. There are suggestions in the literature, however, that Am^{3+} may form an intrinsic colloid, which is surprising because it does not undergo hydrolysis until relatively high pH. Th does not follow the trend described by Equation (63) because its large size makes it resistant to hydrolysis (Cotton and Wilkinson 1988). Nevertheless, thermodynamic data suggest that in almost all environments (near neutral or higher pH) Th exists as $Th(OH)_4(aq)$. Moreover, Th has been reported to form a polymer (Kraus 1956; Johnson and Toth 1978), although as discussed below, this species should be referred to as an oligomer.

Examples can be found in the literature of polymeric species of many of the actinides of importance to the WIPP (see, for example, Baes and Mesmer 1976; Kim 1992). It is important, however, to note the sizes of polymers described in the literature. It is well known that as polyvalent metals, the actinides can form polynuclear species, but they are largely lower polymers (that is, oligomers) such as dimers, trimers, tetramers, and hexamers (see, for example, Choppin 1983, 46). However, in terms of physical-transport behavior, lower polymers will behave no differently than dissolved monomeric species. In contrast, the higher polymers, such as the Pu(IV)-polymer, may reach colloidal sizes (1 nm to 1 μm) and will have different hydrodynamic properties than the subcolloidal-sized dissolved species. Johnson and Toth (1978) reported a molecular weight of 4000 for a Th polymer. Assuming that it consisted of $Th(OH)_4$, that polymer would consist of about 13 Th ions (that is, the degree of polymerization number, N). That observation is consistent with Kraus (1956), in which he quotes an N value of about 9 for Th polyelectrolyte.

Empirical evidence published in the literature does not always support the suggestion that Am, as a trivalent cation, will form an intrinsic colloidal particle. Avogadro and de Marsily (1984) suggested that, like Pu, Am is a likely candidate to form an insoluble hydroxide. Buckau et al. (1986) reported the formation of Am(III) intrinsic colloids at near neutral pH conditions, with a particle size greater than 1 nm. In their study of the hydrolysis of Am(III) over a pH range from 3 to 13.5, however, Kim et al. (1984a) found only monomers of Am. Regardless of whether Am(III) intrinsic colloids will form under highly idealized laboratory environments, it would be highly unlikely that they would form in a geologic system, because of the tremendously strong sorption properties of the Am(III) ion.

SOTERM-6.3.2.3 <u>Experimental</u>

The objective of experiments, conducted at Lawrence Livermore National Laboratory (LLNL), was to test phenomena described in the published literature, under WIPP-relevant conditions:

- critical coagulation concentration for mature Pu(IV) mineral-fragment-type colloid (refer to description of experiment AIC-1 in Papenguth and Behl (1996));

- formation of Pu(IV) colloid, from oversaturation and undersaturation in the absence of CO_2 (AIC-8 and AIC-9, respectively);
- inhibition of Pu(IV) polymerization due to organic complexants (AIC-2);
- depolymerization of Pu colloid due to organic complexants (AIC-2b);
- polyelectrolyte chain termination by nonactinide metal cations (AIC-4); and
- sorption effects of WIPP repository substrates on Pu(IV) colloid (AIC-5).

The last four experiments listed above provide evidence that, under some conditions at the WIPP, the Pu(IV) colloid is less likely to form or is sorbed. To parameterize the CRA-2004 PA, CCA PA, and 1997 PAVT, however, the first two experiments listed above were used. Both sets of experiments (AIC-1, AIC-8/9) can essentially be viewed as solubility experiments. The critical coagulation-experiments are solubility experiments conducted from undersaturation conditions, in which the in-growth of free Pu(IV) is observed (and are therefore equivalent to AIC-9). In both sets of experiments (AIC-1, AIC-8/9), the Pu solution concentration is measured as a function of time for as long as five weeks, as steady-state concentration is being reached. The two sets of experiments were anticipated to provide information to resolve the question of kinetic versus thermodynamic stability control on the formation and development of the Pu(IV) colloid. That question was not resolved, but the data still provide the necessary information for parameterizing the PA calculations. The values for the parameters submitted for calculations were derived from the experiments listed in Table SOTERM-7.

Table SOTERM-7. Pu Intrinsic-Colloid Experiments

Number	Experiment	Starting Material	pcH approx.	NaCl (m)	Duration
AIC-1	c.c.c. (equivalent to undersaturation experiment AIC-9)	Pu(IV) colloid: aged 1 month: about 2×10^{-4} M	4 7 10	0.001 0.01 0.1 0.8 3.0 5.0	3 to 5 weeks
AIC-8	Oversaturation	Pu(IV) aquo ion: about 1×10^{-4} M	3 7 10	0.05 0.5 1.0 5.0	4 weeks

The data from those experiments are plotted in Figure SOTERM-3 along with regression lines for data collected by Rai et al. (1980) for $Pu(OH)_4$(am) and PuO_2 and Rai and Swanson (1981) for Pu(IV) polymer under acidic conditions. With MgO, the pH of the

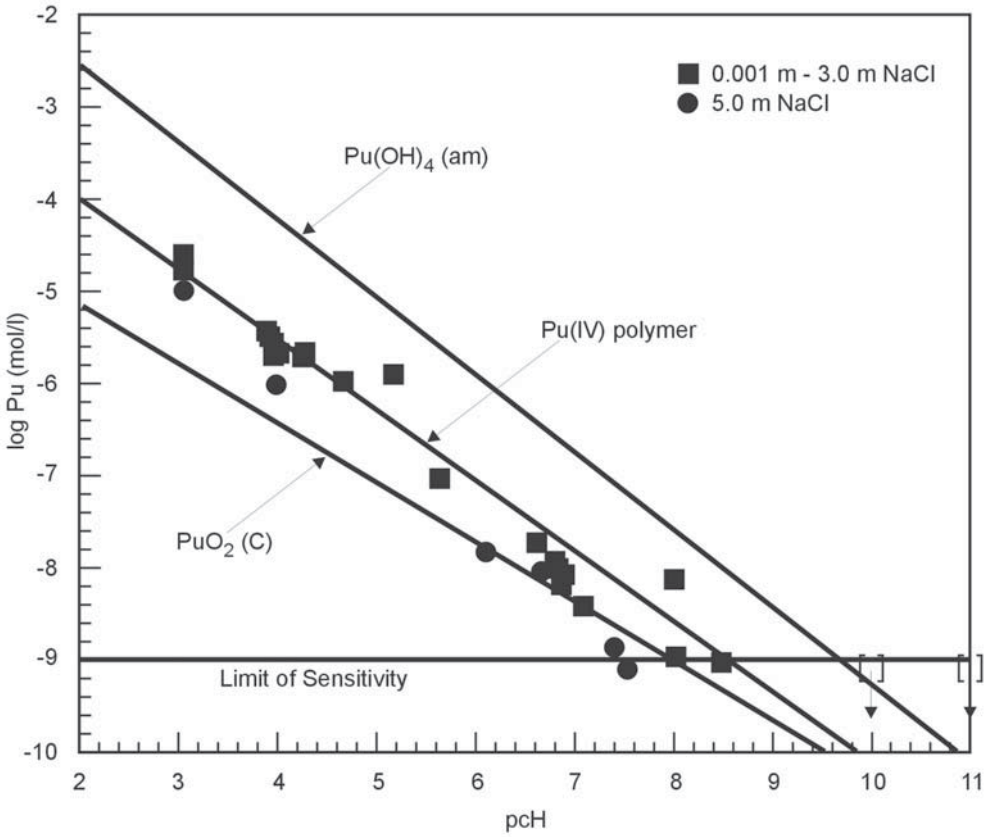

NOTE 1: Open brackets with arrows pointing down indicate Pu concentration is below the minimum analytical detection limit. Solubility lines for $Pu(OH)_{4amorphous}$ and $PuO_{2crystalline}$ are extrapolated from Rai et al. (1980). The solubility line for Pu(IV)-polymer is extrapolated from Rai and Swanson (1981). Plotted values were collected at LLNL as part of the WIPP colloid research program.

NOTE 2: Note that under basic pH conditions fixed by MgO, the solubility of the Pu(IV)-polymer is below the minimum analytical detection limit of 10^{-9} M.

CCA-SOT010-0

Figure SOTERM-3. Solubility of Pu(IV) Polymer in NaCl Media as a Function of pcH.

repository brine is expected to be between 8.69 and 9.02 (see Section 2.0), equivalent to a pcH of 9.40 to 9.72. As shown in Figure SOTERM-3, the regression line calculated from the LLNL data suggests that at a pcH of 9.40 to 9.72, the solubility of Pu(IV)-polymer is less than the minimum analytical detection limit of 1×10^{-9} M. Therefore, the detection limit was selected for use in PA. The LLNL results are consistent with the extrapolated relationships based on published results of Rai et al. (1980) and Rai and Swanson (1981).

SOTERM-6.3.2.4 Interpretation and Discussion

Parameter values (CONCINT) describing the amount of actinide element bound by actinide intrinsic colloidal particles was determined from the information described above. For the Pu(IV) polymer, the minimum analytical detection limit was selected. In the absence of conclusive evidence that intrinsic colloids of other actinides form, or form polymers rather than oligomers, the concentration of Th, U, Np, and Am intrinsic colloids was set to zero.

Geochemical conditions in the Culebra are not conducive to the formation of a new supplementary population of actinide intrinsic colloids. In particular, the concentration of actinide ions is reduced. Therefore, the source term for actinide intrinsic colloids reflects what would form in the WIPP repository, under most favorable conditions for the formation of the Pu(IV) polymer.

Parameter values for CONCINT are summarized in Appendix PA, Attachment SOTERM, Table SOTERM-11.

SOTERM-6.3.3 Humic Substances

Humic substances are defined as high-molecular-weight organic compounds generally present as anions in natural waters. Humic substances may consist of humic acids, which may be aliphatic or aromatic, or fulvic acids. The difference between humic acids and fulvic acids is largely an operational distinction; humic acids can be precipitated at pH values below about 2, whereas fulvic acids are soluble over the entire pH range. Fulvic acids generally have lower molecular weights than humic acids. The dominant functional group that may react with dissolved actinides are carboxyl groups, but phenolic hydroxyl and alcoholic hydroxyl groups also contribute to complexation. At the WIPP, humic substances may be introduced to the repository as a constituent of soil-bearing waste or may be a constituent of the organic-carbon (C) component of Castile, Salado, or Culebra groundwaters. Probably more importantly, humic substances may form from condensation reactions between microbial metabolites (for example, carboxylic acids), byproducts of the consumption of cellulosic materials, and the extracellular polymers associated with microbes. Because of the general lack of knowledge in the scientific community regarding the formation of humic substances, as well as very slow kinetics of formation, a direct attempt has not been made to quantify the amounts of humic substances that would form in situ. Instead, the contribution of humic-bound actinides was bounded through quantification of humic-actinide complexation behavior coupled with quantification of solubilities of humic substances in WIPP-relevant brines. Regardless of the source of humic substances, the total concentration of humic substance available to mobilize actinides is limited by the solubility of humic substances in WIPP brines. The chemical nature of humic substances generated in situ cannot be predicted either, but can be bounded by the three types of humic substances.

To determine the concentration of actinides associated with humic substances, four pieces of information are required: (1) the concentration of reactive humic substance in the aqueous phase (humic solubility); (2) the binding capacity of the humic substance; (3) actinide uptake (that is, actinide complexation constants); and (4) actinide solubilities. The quantification of actinide solubilities is described in Novak and Moore (1996) and results are summarized in Siegel (1996). In the remainder of this document, the focus is on the determination of items 1 through 3, the interpretation of that information, and the development of parameter values suitable for the CRA-2004 PA, CCA PA, and 1997 PAVT calculations.

SOTERM-6.3.3.1 Experimental

In general, humic substances encompass a broad variety of high-molecular-weight organic compounds. The range of their chemical behaviors, however, is covered by consideration of

three types: aliphatic humic acid (generally terrestrial); aromatic humic acid (generally marine); and fulvic acid. The following humic substances were used:

- FA-Suw: fulvic acid isolated from the Suwannee River acquired from the International Humic Substances Society, Golden, Colorado;
- HAal-LBr: aliphatic humic acid isolated from sediments collected from Lake Bradford, Florida, prepared by Florida State University;
- HAal-Ald: aliphatic humic acid purchased from Aldrich Chemical Co., purified by Florida State University;
- HAar-Gor: aromatic humic acid isolated from groundwaters near Gorleben, Germany, obtained from Professor J.-I. Kim, Institute for Radiochemistry, Munich; and
- HAar-Suw: aromatic humic acid isolated from the Suwannee River acquired from the International Humic Substances Society, Golden, Colorado.

Solubilities were measured in experiments conducted over periods of several weeks. The solubilities of humic substances remaining in the fluid column were determined using a scanning fluorometer, C coulometer, and UV/Visible light spectrophotometer, in WIPP-relevant brine simulants with FA-Suw, HAal-LBr, HAal-Ald, and HAar-Suw. In addition to spectroscopic data, visible inspection proved valuable. In oversaturation experiments, humic substances were dissolved in deionized H_2O under basic conditions to enhance dissolution and then added as a spike to a brine . In undersaturation experiments, humic substances were added directly to brines and allowed to dissolve until equilibrium was reached. In either case, equilibrium was reached between dissolved (that is, ionic) and precipitated humic substances. The precipitated humic substances coagulated and settled. The kinetics of precipitation were sufficiently slow that several weeks were required for equilibrium to be reached. Brines consisted of a NaCl matrix with various concentrations of Mg^{2+} and Ca^{2+}. The concentration of Na^{+} in the brine had little effect on solubility except at very high concentrations, but the concentration of the divalent cations had a significant impact on humic-substance solubilities. Consequently, experiments were conducted with a NaCl background electrolyte concentration with concentrations of Mg^{2+} and Ca^{2+} ranging from 10 mM each (representative of natural WIPP brines) to 500 mM each (representative of MgO). At Sandia National Laboratories (SNL), solubilities between approximately 1.5 mg/L and 2.0 mg/L were observed in systems containing 10 mM or greater Mg^{2+} and Ca^{2+}. For the calculations described below, the higher solubility value of 2.0 mg/L was used.

Site-binding-capacity values were determined by titration at Florida State University for two humic substances (HAal-LBr and HAal-Ald). Those values were supplemented with values for a variety of humic substances compiled from published literature. In general, site-binding capacities for humic substances are between 3 and 6 meq OH^{-}/g, but in isolated cases are as low as about 1.5 and as high as about 9.5 meq OH^{-}/g. For the calculations described below, values of 4.65, 5.38, and 5.56 meq OH^{-}/g were used for aliphatic humic acid, aromatic humic acid, and fulvic acid, respectively. The aliphatic humic acid value was determined from HAal-LBr at Florida State University. The aromatic humic acid value was from Gorleben (Gohy-573). The

fulvic acid value represents the mean of 11 published values for fulvic acids collected in Europe (Ephraim et al. 1995).

Actinide complexation factors for U(VI) and Am(III) binding on three humic substances (FA-Suw, HAal-LBr, and HAar-Gor) were measured at Florida State University. Complexation measurements were made at measured pH_{obs} values of approximately 4.8 and 6, conditions at which the humic substances are highly deprotonated, and U and Am have not undergone extensive hydrolysis. Those conditions were chosen to maximize complexation between the humic substances and those actinide elements. Measurements were made in NaCl media with ionic strengths of approximately 3 and 6 m. These experiments were completed prior to the DOE establishing the position that MgO would be emplaced to sequester CO_2 and fix pH at about 9. The experiments conducted at Florida State University represent conservative conditions designed to provide high-end estimates of actinide uptake by humic substances. Actinide complexation by humic substances generally decreases at basic pH values because of the reduction in actinide-complex charges due to hydrolysis. In addition, the high concentrations of Mg^{2+} in solution due to the presence of MgO will compete with actinides for binding sites on humic substances and reduce the actinide uptake. Florida State University reported the first and second stability constants defined as follows (square brackets represent concentration):

$$An + HS \rightleftharpoons AnHS;\ \beta_{1;An} = [AnHS]/[An][HS] \tag{64}$$

$$An + 2(HS) \rightleftharpoons An(HS)_2;\beta_{2;An} = [An(HS)_2]/[An][HS]^2 \tag{65}$$

where:

HS = humic substance (eq OH-/L, that is, site-binding capacity incorporated)
An = actinide element
$\beta_{1;An}$ = first stability constant, for 1:1 An:humic binding
$\beta_{2;An}$ = second stability constant, for 1:2 An:humic binding

For the calculations described below, complexation constants were selected from the most relevant experimental conditions, which were pH_{obs} 6 and 6 m NaCl. The following stability constants reported by Florida State University were used (reported as log values), as shown in Table SOTERM-8.

Table SOTERM-8. Humic Substances Experimental Results

Humic Substance	Am^{3+} : β_1	Am^{3+} : β_2	$U(VI)O_2^{2+}$: β_1	$U(VI)O_2^{2+}$: β_2
HAal-LBr	6.09 +/- 0.05	10.46 +/- 0.12	5.91 +/- 0.16	10.43 +/- 0.19
HAal-Gor	6.02 +/- 0.04	10.40 +/- 0.10	5.35+/- 0.15	8.98 +/- 0.26
FA-Suw	4.6 +/-0.3	8.95 +/- 0.45	Not measured	Not measured

The Florida State University results show that there is little difference in $U(VI)O_2^{2+}$ and Am(III) uptake by aliphatic and aromatic humic acids, but that uptake by fulvic acid is significantly less. The Florida State University results also show that an increase of NaCl ionic strength from 3 to 6 has little effect on actinide uptake. Those observations aid in justifying the use of published stability constants for other actinide elements experimentally determined at lower ionic strengths and for other humic substances. On the basis of the similarities in stability constants for $U(VI)O_2^{2+}$ and Am(III) for the humic acids, SNL has used the Am(III) stability constant for FA-Suw for $U(VI)O_2^{2+}$ on FA-Suw.

Stability constants for Th(IV) with several humic and fulvic acids were reported by Nash and Choppin (1980). In NaCl media at pH values between 3.95 and 5.03, those authors reported log stability constants between 9.7 and 13.2. Under the mildly basic conditions expected in the WIPP repository, it is likely that complexation of Th(IV) will be markedly less, because the dominant Th(IV)-bearing aqueous species will be $Th(OH)_4(aq)$ (Novak and Moore 1996). No reports of direct investigations of Th-complex binding on humic substances were found. For the calculations described herein, the published results from Baskaran et al. (1992) describing the distribution of Th(IV) in seawater were used. From that work, a ratio of dissolved versus colloidal Th(IV) of 6.349 was calculated, assuming that the solubility of colloidal organic material in seawater is equivalent to our measured value of humic substances in WIPP-relevant brines (that is, 2.0 mg/L). The nature of the humic substances is likely to be dominated by aromatic humic acid, but may also contain fulvic acid.

For the calculations described herein, a log stability constant for $Np(V)O_2^{+}$ of 3.67 measured at pH 9 for a Gorleben humic acid (Gohy-573; Kim and Sekine 1991) was used. Results presented in Rao and Choppin (1995) for Lake Bradford humic acid and a Gorleben humic acid (Gohy-573) show little effect of pH on Np(V) stability constants, presumably because of the absence of Np(V) hydrolosis over the pH range studied. The Gorleben humic acid is aromatic in nature.

No published stability constants were found for Pu. For the calculations described herein, an oxidation-state analogy was used for the Pu oxidation species, an approach that is conservative. Allard et al. (1980) have shown that at pH 9, Pu(IV) undergoes hydrolysis to a greater extent than Th(IV), which should result in reduced complexation of Pu(IV).

An oxidation-state analogy was used to develop parameter values for elements expected to have multiple oxidation states in the WIPP repository. Redox speciation of the actinide elements was evaluated as part of the dissolved ASTP. Weiner (1996) concluded that in the WIPP, the following species will be present: Th(IV); U(IV) and U(VI); Np(IV) and Np(V); Pu(III) and Pu(IV); and Am(III). The relative concentrations of the oxidation states of a particular element

are designated by their respective solubility values. The substitutions made following the oxidation-state analogy are summarized in Table SOTERM-9.

Table SOTERM-9. Oxidation State Analogy Substitutions

Required Binding Constant	Substitute	Source of Data
Th(IV)	None required	Baskaran et al. (1992)
U(IV)	Th(IV)	Baskaran et al. (1992)
U(VI)	None required	WIPP-specific data, Florida State University
Np(IV)	Th(IV)	Baskaran et al. (1992)
Np(V)	None required	Kim and Sekine (1991)
Pu(III)	Am(III)	WIPP-specific data, Florida State University
Pu(IV)	Th(IV)	Baskaran et al. (1992)
Am(III)	None required	WIPP-specific data, Florida State University

To compensate for the effects of competition for actinide complexation by the high concentrations of Mg^{2+} and Ca^{2+} in repository brines in the presence of MgO, stability constants for Mg^{2+} and Ca^{2+} were used in simultaneously solved equations (described below). Stability constants for Mg^{2+} and Ca^{2+} at basic pH values are not available, but several published reports provide values in the acidic range. Choppin and Shanbhag (1981) reported log stability constants of 2.25 to 3.32 for Ca^{+} in 0.1 M sodium perchlorate ($NaClO_4$) at pH 3.9 and 5.0 for an aliphatic humic acid (Aldrich humic acid). Schnitzer and Skinner (1967) reported log binding constants ranging from 2.2 to 3.72 for Ca^{2+} in low-ionic strength solutions over a pH range of 3.5 to 5.0 for fulvic acid. For Mg^{2+}, Schnitzer and Skinner (1967) reported log stability constants ranging from 1.23 to approximately 2.0 under the same experimental conditions. For the calculations, a log stability constant of 2.0 for the sum of Mg^{2+} and Ca^{2+} concentrations was used, which is a conservative value.

Binding of Mg^{2+} and Ca^{2+} to humic substances is described in the same way as Equation (64) above:

$$(Mg + Ca) + HS \rightleftharpoons (Mg,Ca)HS;\ \beta_{1;Mg,Ca} = [(Mg,Ca)HS]/[Mg + Ca][HS] \qquad (66)$$

where:

$\beta_{1;Mg,Ca}$ = first stability constant, for 1:1 (Mg + Ca):humic binding (note that no second stability constants exist for divalent-cation binding).

SOTERM-6.3.3.2 <u>Interpretation and Discussion</u>

Proportionality constants (PHUMCIM and PHUMSIM) describing the amount of actinide element bound to humic substances were determined from the data listed above, coupled with dissolved actinide concentrations. In addition, maximum theoretical concentrations of actinides that could be associated with humic substances (CAPHUM) were calculated from the data above.

The concentration of an actinide element of a given oxidation state was calculated by simultaneous solution of Equations (64) and (66), combined with a mass-balance expression:

$$[HS_{tot}] = [AnHS] + [(Mg,Ca)HS] + [HS] \quad (67)$$

where:

$[HS_{tot}]$ = total concentration of humic substance
$[HS]$ = concentration of uncomplexed humic substance
$[AnHS]$ = concentration of humic complexed with an actinide element
$[(CaMg)HS]$ = concentration of humic complexed with divalent cations.

Equation (67) describes the effect of two humic substances binding with one actinide ion was disregarded for these calculations, because its contribution to the total humic-bound actinide concentrations was negligible.

Rearranging Equations (64) and (66) provides:

$$[AnHS] = \beta_{1;An}\,[An]\,[HS]\,, \quad (68)$$

$$[(Mg,Ca)HS] = \beta_{1;Mg,Ca}\,[Mg + Ca]\,[HS]\,. \quad (69)$$

Substituting Equations (68) and (69) into Equation (67) results in:

$$[HS_{tot}] = \beta_{1;An}\,[An]\,[HS] + \beta_{1;\,Mg,Ca}\,[Mg + Ca]\,[HS] + [HS]\,. \quad (70)$$

Rearranging Equation (70) provides:

$$[HS] = \frac{[HS_{tot}]}{\beta_{1;An}[An] + \beta_{1;CaMg}[Ca + Mg] + 1}\,. \quad (71)$$

Equations (68), (69), (70), and (71) were used to calculate humic-bound actinide concentrations ([AnHS]). The resulting AnHS concentration values were then summed for actinide elements with multiple oxidation states, and then divided by the dissolved concentration of the respective actinide element. The final forms of the parameter values PHUMCIM and PHUMSIM are proportionality constants in units of moles humic-bound colloidal actinide per mole of dissolved actinide. The proportionality values may be multiplied by the dissolved actinide concentration expressed in molarity or molality, depending on the desired final unit.

Depending on the intrusion scenario, the WIPP repository may be dominated by Castile brine or by intergranular Salado brine, resulting in different actinide solubilities, but also different solubilities of Mg^{2+} and Ca^{2+}. Under conditions characteristic of equilibrium with MgO, solubility parameters calculated for a system buffered by brucite and magnesite were used (Siegel 1996).

Equations (68), (69), and (71) were used to determine humic-bound actinide concentrations ([AnHS]) for one or more humic substance types for Th(IV), U(VI), Np(V), and Am(III). The oxidation-state analogy is most heavily utilized for Pu, because stability constants for Pu(III) or

Pu(IV) are not available. Concentrations of Mg^{2+} and Ca^{2+} in Salado and Castile brines in equilibrium with MgO were obtained from Novak and Moore (1996). In the PA calculations, the humic-bound actinide concentration in the +III oxidation state in Castile brine was sampled. All other humic-bound actinide concentrations were held constant.

The PHUMCIM and PHUMSIM parameters, used in conjunction with materials (idmtrls) PHUMOX3, PHUMOX4, PHUMOX5, or PHUMOX6, provide the means to calculate actinide-humic concentrations by actinide oxidation state and for intrusion scenarios involving different brines. For example, in an E1 scenario under strongly reducing conditions in the WIPP repository, PHUMCIM would be used with the following materials (idmtrls) to determine actinide-humic concentrations: Th = PHUMOX4; U = PHUMOX4; Np = PHUMOX4; Pu = PHUMOX3; and Am = PHUMOX3. For an E2 scenario under relatively less reducing conditions in the WIPP repository, PHUMSIM would be used with the following idmtrls to determine actinide-humic concentrations: Th = PHUMOX4; U = PHUMOX6; Np = PHUMOX5; Pu = PHUMOX4; and Am = PHUMOX3.

Uncertainties due to analytical precision are small compared to uncertainties in knowledge of the dominant humic substance type, site-binding densities, and actinide solubilities. The proportionality-factor approach coupled with the actinide-solubility-model uncertainty results in an adequate representation of the uncertainty in the concentration of actinides bound by mobile humic substances.

The CAPHUM parameter simply represents the theoretical maximum concentration of actinides that can be bound by a humic substance. Based on a solubility-limit concentration of humic substances of 2.0 mg/L, and the highest site-binding capacity (for fulvic acids) of 5.56 meq OH^-/g, the theoretical maximum is 1.1×10^{-5} eq/L. Assuming the conservative case in which actinide species are monovalent, the maximum theoretical concentration of actinides that can be bound by humic substances is 1.1×10^{-5} M. That number is conservative, because it assumes a pool of humic substances is available for each actinide element, when in reality, actinide elements will compete for the same pool of humic substances. CAPHUM is used in an expression such as the following:

$$[\text{AnHS}] = \text{MIN}(\text{AnHS value calculated with proportionality constant}, 1.1 \times 10^{-5}) \tag{72}$$

in which the calculated concentration of a particular actinide is compared to the upper-limit value. Parameter values for PHUMCIM, PHUMSIM, and CAPHUM are summarized in Table SOTERM-11.

SOTERM-6.3.4 Microbes

Potentially important colloidal-sized microorganisms include bacteria, fungi, yeast, and protozoa. For the WIPP site, the focus is on the halophilic and halotolerant microbes identified at the site (Brush 1990; Francis and Gillow 1994). Microbes are important to consider in PAbecause they may significantly affect the characteristics of the waste stored at the WIPP, and also participate in transport of actinides. Microbes are known to actively bioaccumulate actinides intracellularly as well as act as substrates for passive extracellular sorption.

At the WIPP site, concentrations of naturally occurring microbes are on the order of 10^4 to 10^7 cells per mL (Francis and Gillow 1994, Table 1). In the presence of nutrients provided by WIPP waste constituents, including nitrates, sulfates, and cellulosics such as protective clothing and wood, the population of microbes is likely to increase. Lysis, a natural phenomenon whereby cells die and release their constituents to the solution, also provides a source of nutrients to microbes.

When introduced to nutrients, microbes typically follow a predictable growth curve (defined by the population number of microbes plotted as a function of time), consisting of an initial period of inactivity (very early log phase) ranging up to several days, followed by a sharp increase in growth (early log phase). That level of growth is sustained for one or more days (log phase) during which time microbial metabolites, including carboxylic acids, enzymes, and exocellular polymers, are generated. The growth rate eventually begins to decline (late log phase) due to the effects of those metabolites, limitations in nutrients or substrates, or population dynamics, and reaches a steady-state population (stationary phase). Viable microbes may aggregate to form clusters.

SOTERM-6.3.4.1 Description of Experiments

Several types of experiments were conducted to evaluate the impact of microbes in support of the WIPP colloid research program (refer to descriptions in Papenguth and Behl 1996): (1) evaluation of indigenous concentrations of microbes; (2) quantification of mobile concentrations under nutrient- and substrate-rich conditions; (3) quantification and characterization of actinide bioaccumulation by microbes; and (4) evaluation of toxicity effects of actinide elements on microbe growth.

Experiments were conducted at Brookhaven National Laboratory (BNL) and as a collaborative effort between BNL and LANL. Evaluation of indigenous concentrations was a collaborative effort between BNL and LANL. Quantification of mobile concentrations was conducted at BNL. The bioaccumulation and toxicity work was conducted at BNL or LANL depending on the actinide element. Th and U were investigated at BNL. The other actinide elements of interest, Np, Pu, and Am, were investigated at LANL under the guidance of BNL personnel.

Experiments to determine the mobile concentrations of microbes remaining suspended in the fluid column were conducted similarly to experiments previously conducted in support of the WIPP Gas Generation Program (Brush 1990; Francis and Gillow 1994). Bacterial cultures were introduced to a solution containing nutrient and substrate, and sealed. The bacterial population was monitored over periods of several weeks or more using measurements of optical density or by direct counting of aliquots of fixed cells. An important change in protocol from previous experiments, however, is that instead of filtering the entire contents of the vessels, only the mobile cells remaining suspended in the fluid column were counted. Results of the experiments showed that the mobile concentration of microbes was a couple of orders-of-magnitude less than the total concentration of microbes. The existence of indigenous microbes in Salado groundwaters has been demonstrated in previous work (Francis and Gillow 1994). As part of the WIPP Colloid Research Program, samples of Culebra groundwater were carefully collected from the H-19 hydropad, processed, and characterized for indigenous microbes. Concentrations of

naturally occurring microbes were on the order of 10^5 cells per mL, determined using direct counting methods.

The evaluation of indigenous concentrations of microbes and quantification of mobile concentrations provided important supporting evidence for quantifying the microbial actinide source term and for evaluating microbe-facilitated transport of actinides in the Culebra. However, the basis for developing the actual parameter values used in the CRA-2004 PA, the CCA PA, and the 1997 PAVT calculations was established with bioaccumulation and toxicity experiments, referred to herein as filtration experiments. Those experiments were conducted by combining microbe cultures with various concentrations and complexes of ^{232}Th, ^{238}U, ^{237}Np, ^{239}Pu, or ^{243}Am. The actinide reagents used were Th(IV)-NO_3^-, Th(IV)-EDTA, U(VI)-NO_3^-, U(VI)-citrate, Np(V)-EDTA, Pu(V)-HClO4, Pu(V)-EDTA, and Am(III)-EDTA. For those experiments, a pure bacterial culture (WIPP-1A) and a mixed bacterial culture (BAB) were used. Most of the experiments were conducted with the WIPP-1A culture, because of the fast growth of that pure culture. The WIPP-1A mixed culture typically reaches steady-state concentration within several days, whereas the BAB mixed culture requires several weeks. Because of the rapid response of the WIPP-1A culture, most of the experiments were conducted with that culture to expedite the research program. A complementary set of experiments were repeated with the BAB mixed culture to evaluate the representativeness of the pure culture. Experiments were conducted over periods of 11 to 15 days for the WIPP-1A microbe culture, and up to 21 days for the BAB culture. Each experiment consisted of a subset of two or three replicate test vessels that were sampled during the overall test interval to provide time-sequence data. In addition, replicate test vessels that were not innoculated with microbes were included in each experiment to provide a control. Sequential filtration with 0.03-µm, 0.4-µm, and 10-µm filters was conducted on each vessel. The following size fractions were obtained as shown in Table SOTERM-10.

Table SOTERM-10. Microbe Experimental Results

Fluid Column Sample	Particle Size	Actinide Association with
Not filtered	all	All forms listed below
0.22-µm syringe filter, filtrate	< 0.22 µm	Dissolved; lysed microbes
10-µm filter, filter retentate	> 10 µm	Clumped microbes
10-µm filter, filtrate	< 10 µm	Dissolved; dispersed microbes; lysed microbes
0.4-µm filter, filter retentate	= 0.4 to 10 µm	Dispersed microbes
0.4-µm filter, filtrate	< 0.4 µm	Dissolved; lysed microbes
0.03-µm filter, filter retentate	= 0.03 to 0.4 µm	Lysed microbes
0.03-µm filter, filtrate	< 0.03 µm	Dissolved; lysed microbes

In addition to the potential actinide associations listed above, there was some evidence of the formation of inorganic precipitates in some of the experiments. The nutrient used in many experiments was phosphate PO_4^{3-}(1g/L), which is known to coprecipitate actinide cations. The inoculated control samples provided the means to evaluate the extent of that experimental artifact. The control samples also provided the means to assess the extent of sorption of actinides onto test vessels, sampling, and filtration equipment. All sequential filters were composed of the same material, which simplifies assessment of sorption on the filtration equipment.

The toxicity experiments were conducted as a component of the filtration experiments described above, by varying the actinide concentration, and comparing growth curves measured by optical density and/or by direct cell counting. To increase the total concentration of actinides in solution, EDTA was added in some experiments in a one-to-one molar ratio with the actinide element. That approach was taken for all of the experiments with Th, Np, and Am, and for some of the experiments with Pu.

SOTERM-6.3.4.2 Interpretation and Discussion

Proportionality constants (PROPMIC) describing the amount of actinide element bound to mobile microbes were determined from the data listed above. In addition, maximum concentrations of actinides that could be associated with microbes (CAPMIC) were determined from the experimental data. Those two parameters are suitable for use in the CRA-2004 PA, CCA PA, and 1997 PAVT calculations, when coupled with dissolved actinide solubilities (refer to Section 7.2 for details).

The 0.4-µm-filter retentate and 0.03-µm filtrate (acquired from the inoculated vessels, not the uninoculated control vessels) were selected to represent the microbial actinide and dissolved actinide concentrations, respectively. The ratio between the microbial actinide and dissolved actinide, both expressed in molarity, represents the proportionality constant value used for the PROPMIC parameter. The 0.4-µm-filter retentate was selected to represent the microbial fraction because nearly all of the bacterial biomass was associated with that filter. A small

concentration of actinides was associated with suspected biomass trapped on the 10-µm filter, as clumped microbes, and on the 0.03-µm filter, as lysed microbes. The contribution of actinide-associated biomass consisting of clumped and lysed microbes was typically at least one order-of-magnitude less than the actinide concentration associated with the dispersed microbes collected on the 0.4-µm filter. The concentration of dissolved actinides measured from the 0.03-µm-filter filtrate was used in the ratio because it provides the best indication of final dissolved actinide concentration. Representative values for PROPMIC were developed on an element-by-element basis. Results of experiments using the BAB culture were disregarded, because of their lower uptake of actinides (especially Pu), and because of the limited number of experiments conducted with that culture. For the WIPP-1A culture, the first sampling period (2 to 4 days, but generally 3 days) was disregarded in determining proportionality constants because steady state population had not yet been reached. The remaining values were averaged arithmetically.

The filtration experiments discussed above also provided the basis for determining CAPMIC values. Final cell population numbers in the test vessels were estimated using measurements of optical density at a wavelength of 600 nm or by direct counting with epifluorescent microscopy. The magnitude of the toxicity effects was estimated by comparing final cell numbers obtained from a series of test vessels with varying actinide concentration. The direct-counting technique provided the most dependable measure of cell number and was used where available. The CAPMIC value is defined as the actinide concentration in molarity at which no growth was observed. For cases where growth clearly diminished as actinide concentration increased, but the actinide concentration was not great enough to stop growth, CAPMIC values were determined by linear extrapolation of population numbers, and then adding an order-of-magnitude to account for uncertainty. On the basis of WIPP experimental results (Papenguth 1996b), it appears that the toxicity effects are due to chemical toxicity rather than radiotoxicity. Because of the high radiation levels of Am and safety considerations in the laboratory facility used, the molar concentration could not be increased to the point at which toxicity effects could be observed. Consequently no CAPMIC value is currently available for Am. CAPMIC values are used similarly to the CAPHUM values (see Equation (72)), except that the upper limit for microbe concentration is due to toxicity rather than geometric limitations imposed by the colloid itself. Consequently, for microbes, the total concentration of mobile actinides in a PA realization is used in the comparison, rather than the amount of actinides associated with the microbes.

The experiments conducted do not provide sufficient information to formulate a distribution of values for PROPMIC and CAPMIC. Therefore, single values for PROPMIC and CAPMIC were used in the CRA-2004 PA, the CCA PA, and the 1997 PAVT. Uncertainties due to analytical precision are small compared to uncertainties in knowledge of the microbe culture that might predominate in the WIPP repository or in the Culebra in an intrusion scenario. The proportionality-factor approach coupled with the actinide-solubility-model uncertainty results in an adequate description of the uncertainty in the concentration of actinides bound by mobile microbes.

Parameter values for PROPMIC and CAPMIC are summarized in Table SOTERM-11.

SOTERM-6.3.5 Summary of Parameter Values

Parameter values for CONCMIN, CONCINT, PROPMIC, CAPMIC, PHUMSIM, PHUMCIM, and CAPHUM are summarized in Table SOTERM-11.

SOTERM-6.4 Summary

Results of the colloidal actinide investigation were used in the 1996 PA, the CRA-2004 PA, and the 1997 PAVT in three types of parameter values: (1) constant-concentration values for actinides associated with mineral fragment and actinide intrinsic colloids; (2) concentration values proportional to the dissolved actinide concentration for actinides associated with microbes and humic substances; and (3) maximum concentration values providing an upper limit for actinide concentrations associated with microbes and humic substances. The parameter values are summarized in Table SOTERM-11. Given the actinide solubilities calculated for Salado and Castile brines in equilibrium with MgO, the largest contributors to the mobile colloidal actinide source term are actinides associated with humic substances and microbes. The contribution from mineral fragment and actinide intrinsic colloids is comparatively small. More details can be found in the SNL WIPP Records Center (formerly referred to as the SNL WIPP Central File, SWCF) parameter record packages describing the determination of the mobile colloidal actinide source term (Papenguth 1996a, 1996b, 1996c, 1996d).

Table SOTERM-11. Colloid Concentration Factors

	CONCMIN Concentration on Mineral Fragments [1]	CONCINT Concentration as Intrinsic Colloid [1]	PROPMIC Proportion Sorbed on Microbes [2,3]	CAPMIC Maximum Sorbed on Microbes[4]	Proportion Sorbed on Humics [2]		CAPHUM Maximum Sorbed on Humics [1]
					PHUMSIM Salado	PHUMCIM Castile	
Th(IV)	2.6×10^{-8}	0.0	3.1	0.0019	6.3	6.3	1.1×10^{-5}
U(IV)	2.6×10^{-8}	0.0	0.0021	0.0021	6.3	6.3	1.1×10^{-5}
U(VI)	2.6×10^{-8}	0.0	0.0021	0.0023	0.12	0.51	1.1×10^{-5}
Np(IV)	2.6×10^{-8}	0.0	12.0	0.0027	6.3	6.3	1.1×10^{-5}
Np(V)	2.6×10^{-8}	0.0	12.0	0.0027	9.1×10^{-4}	7.4×10^{-3}	1.1×10^{-5}
Pu(III)	2.6×10^{-8}	0.0	0.3	6.8×10^{-5}	0.19	1.37[e]	1.1×10^{-5}
Pu(IV)	2.6×10^{-8}	1.0×10^{-9}	0.3	6.8×10^{-5}	6.3	6.3	1.1×10^{-5}
Am(III)	2.6×10^{-8}	0.0	3.6	NA	0.19	1.37[d]	1.1×10^{-5}

[1] In units of moles colloidal actinide per liter

[2] In units of moles colloidal actinide per mole dissolved actinide

[3] For the CRA-2004 PA, there were no microbial colloids in nonmicrobial vectors

[4] In units of moles total mobile actinide per liter

[5] A cumulative distribution from 0.065 to 1.60 with a mean value of 1.1 was used

NOTE: The colloidal source term is added to the dissolved source term to arrive at a total source term. Mineral fragments were provided with distributions, but the maximum was used as described in SOTERM-7.1.3. Humic proportionality constants for III, IV, and V were provided with distributions, but only the Castile Am(III) and Pu(III) were sampled.

SOTERM-7.0 USE OF THE ACTINIDE SOURCE TERM IN PERFORMANCE ASSESSMENT

As described in the preceding sections, the s ASTP provided the parameters that were needed to construct maximum dissolved and suspended colloidal actinide concentrations for use in modeling the mobilization and transport of actinides in the disposal system, as modeled by NUTS and PANEL. Prior to these transport calculations, however, some simplifications and manipulations (using PANEL) were required as discussed in the following sections.

SOTERM-7.1 Simplifications

The DOE has concentrated on those processes most likely to have a significant impact on system performance. Therefore, several simplifications were used in the modeling of radionuclide mobilization in the CRA-2004 PA, the CCA PA, and the 1997 PAVT calculations. These include

- using constant solubility and colloid parameters throughout the repository and regulatory period for a given realization,
- limiting the number of isotopes modeled to the ones most important to compliance,
- using the chemistries of Castile and Salado brines — the end member brines — to bracket the behavior of mixtures of these brines within the repository,
- sampling only the uncertain parameters having the most significant effect on repository performance,
- combining dissolved and colloidal species for transport within the disposal system, as modeled by NUTS and PANEL.

SOTERM-7.1.1 Elements and Isotopes Modeled

Selection of isotopes for modeling transport in the disposal system with NUTS and PANEL is described in Appendix TRU WASTE, Section TRU WASTE-2.0. PANEL runs included nearly all isotopes of the six actinides studied in the ASTP: Th, U, Np, Pu, Am, and Cm. NUTS runs included five isotopes: Th, ^{234}U, ^{238}Pu, ^{239}Pu, and ^{241}Am.

SOTERM-7.1.2 Use of Brine End Members

Brine from three sources may enter the repository, depending on the nature of future human intrusion. The general scenarios described in Chapter 6.0 (Section 6.3), and considered in the source-term calculations may be categorized into three groups: (1) undisturbed performance (UP), (2) intrusion through the repository and into the Castile intersecting a pressurized brine reservoir (E1 and E1E2); and (3) intrusion through the repository but not into a pressurized brine reservoir (E2).

Under all scenarios, brine may flow from the surrounding Salado through the disturbed rock zone (DRZ) and into the repository in response to the difference between the hydraulic head in the repository and the surrounding formation. For scenarios in which a borehole is drilled into the repository, brine may flow down the borehole from the Rustler and/or the Dewey Lake. For scenarios in which a pressurized Castile brine reservoir is intercepted, brine from the Castile may flow up the borehole into the repository. As mentioned in Section 2.2.1, the brines in these three formations have different compositions and the solubilities of actinides are somewhat different in each of these end-member compositions. The composition of the more dilute groundwaters from the Rustler and Dewey Lake, however, are expected to change rapidly upon entering the repository due to fast dissolution of host Salado minerals, about 90-95 percent halite and about 1-2 percent each of polyhalite, gypsum, anhydrite, and magnesite (Brush 1990) from the walls and floor of the repository. Calculations titrating Salado rock into dilute brines with the geochemical software package EQ3/6 (Wolery 1992; Wolery and Daveler 1992) show that gypsum, anhydrite and magnesite saturate before halite. When halite saturates, the brine composition is very similar to that of Castile brine. One hundred times as much polyhalite must be added to the system before the resulting brine has a composition similar to Salado brines. These calculations indicate that if dilute brines dissolve away only the surfaces of the repository, they will obtain Castile-like compositions, but if they circulate through the Salado after saturating with halite, they may obtain compositions similar to Salado brine. Similarly, if Castile brine circulates through enough host rock, it may also approach Salado brine composition. In either case, the actual brine within the repository may be described as a mixture of the two concentrated-brine end members — Salado and Castile. This mixture, however, is very hard to quantify, because it is both temporally and spatially variable. Only in the undisturbed scenario is the mixture well defined as 100 percent Salado brine over the 10,000-year regulatory period.

For a panel intersected by a borehole, the BRAGFLO calculations show that in the 10 percent of the repository represented by the BRAGFLO panel computational cells, the ratio of brine inflow that enters by the borehole versus inflow from the repository walls varies through time and depends on the sampled parameter values and scenario being considered. This ratio was the only measure of brine mixing available to the source-term runs in the CRA-2004 PA, CCA PA, and 1997 PAVT calculations. This ratio was quite crude because it (1) did not account for compositional changes that occur when H_2O was consumed by corrosion reactions, (2) did not resolve the details of flow, diffusion and brine interaction with internal pillars and the DRZ, and (3) was an average over one tenth of the repository. It is expected that the fraction of Salado brine will be quite high in areas of the repository distant from the borehole and the fraction will be much lower near the borehole. Because radionuclide travel up the borehole is required for significant release, it is the solubility of radionuclides near the borehole that is most important. Given these uncertainties, the DOE decided to calculate radionuclide solubilities using the Castile end-member composition for scenarios in which a borehole penetrates a brine reservoir and Salado end-member composition for scenarios where it does not.

SOTERM-7.1.3 Sampling of Uncertain Parameters

Distributions of parameter values for up to 30 source-term parameters are available, but many of these are expected to have very limited impact on disposal-system performance. The most

important parameters are expected to be the oxidation-state parameter and the solubilities of Pu(III), Pu(IV), and Am(III) in the two brine end members.

A single distribution (Figures SOTERM-1 and SOTERM-2) was provided for modeling the solubilities of all oxidation states of all actinides in both brines. However, the amount of correlation between the solubilities of the actinides was uncertain. Some factors that cause uncertainty in the solubilities affect all oxidation states of all actinides similarly and some factors will affect only some actinides or some oxidation states. For example, uncertainties in the SO_4^{2-} concentrations will have more effect in the uncertainty of the solubility of the actinides in the +IV oxidation state, while uncertainties in the ionic strength have a more generalized effect of increasing the uncertainty in the stability of any highly charged species. In nature, solubilities show correlation due to redox effects as well as compositional effects. It is therefore expected that solubilities within the WIPP should show some correlation, but not 100 percent correlation.

The use of the end-member brines in the calculations results in a correlation of solubilities due to ionic strength and major-ion effects, and the use of the oxidation-state parameter results in a correlation due to redox effects. The DOE assumes these effects (that is, ionic strength, major ions, and redox state) encompass the major correlations and therefore imposes no further correlations. A better estimate of this correlation would be necessary for more detailed chemical modeling, but for use in PA, this is unnecessary.

The parameters to be sampled were selected based on expectations of their significance of effect on disposal-system performance.

- A 100 percent correlation was made between Am and Cm solubilities. Only the parameters for Am were sampled, and these were copied for Cm.

- Np solubilities were not sampled because Np does not have a very large EPA unit during the 10,000-year regulatory period (see Appendix TRU WASTE, Section TRU WASTE-2.0 for a discussion of EPA units and the relative importance of Np).

- The parameter for actinide concentration on mineral fragments was not sampled because the concentrations of actinides that may be mobilized on mineral fragments were in most cases much lower that the possible concentrations of dissolved actinides.

- Of the humic-acid proportionality constants, only the one for the +III oxidation state in Castile brine was sampled because it was high and it applied to significant elements (Pu and Am).

Parameters not sampled were fixed at a maximum reasonable value during the calculations.

Fourteen parameters were sampled in the CRA-2004 PA for the source term (see Appendix PAR):

Material Name	Parameter Name
SOLAM3	SOLSIM, SOLCIM

SOLPU3	SOLSIM, SOLCIM
SOLPU4	SOLSIM, SOLCIM
SOLU4	SOLSIM, SOLCIM
SOLU6	SOLSIM, SOLCIM
SOLTH4	SOLSIM, SOLCIM
GLOBAL	OXSTAT
PHUMOX3	PHUMCIM

where

SOLAM3 = distribution parameter for SOLubility of AM(III),
SOLSIM = solubility variability in Salado brine,
SOLCIM = solubility variability in Castile brine,
OXSTAT = OXidation-STATe parameter,
PHUMOX3 = the Proportionality constant for HUMic colloids and actinides in the +3 OXidation state,
PHUMCIM = the Proportionality constant for HUMic colloids in Castile brine.

In the CCA PA and the 1997 PAVT, 12 parameters were sampled (all of the 14 parameters listed above except SOLU4, SOLCIM; and SOLTH4, SOLCIM).

SOTERM-7.1.4 Combining the Transport of Dissolved and Colloidal Species in the Salado

Dissolved and colloidal species may transport differently because of different diffusion rates, sorption onto stationary materials, and size exclusion effects (filtration and hydrodynamic chromatography). With maximum molecular diffusion coefficients of about 4×10^{-10} m^2 per s, actinides are estimated to diffuse about 10 m in 10,000 years, a negligible distance. Sorption and filtration have beneficial but unquantifiable effects on performance. Hydrodynamic chromatography may increase colloid transport over dissolved transport by at most a factor of two for theoretically perfect colloidal transport conditions. In real situations, the increase is much less. Given the small or beneficial nature of these effects, they were not included in the CRA-2004 PA, the CCA PA and the 1997 PAVT calculations of radionuclide transport in the repository.

Because there was no modeled mechanism to differentiate dissolved from colloidal species, the DOE combined them for transport within the Salado. In the modeling of transport within the Culebra, however, these simplifications were inappropriate. While transport within the repository is through at most hundreds of meters of poorly defined waste that is undergoing decomposition, transport through the Culebra is over kilometers in a relatively homogeneous (as compared to waste) fractured dolomite. Dissolved and colloidal species could be transported differently through the Culebra. Therefore, the mobilized actinides delivered to the Culebra by Salado transport codes are separated into five components (dissolved, humic, microbial, mineral-fragment, and intrinsic colloids).

SOTERM-7.2 Construction of Source Term

The parameters required for constructing the source term were (1) solubilities for four oxidation states in each brine end member, (2) an uncertainty distribution to be applied to the solubilities, (3) a scheme for assigning sampled oxidation states, (4) colloidal concentrations or proportionality constants for the five actinides or the four oxidation states for each of four types of colloids, and (5) caps on the actinide concentrations that may be applied to two types of colloids. Use of these parameters in the CRA-2004 PA, the CCA PA, and the 1997 PAVT calculations required combining them into a single maximum concentration for each modeled actinide. The term "total mobilized concentration" is used for the combined concentrations due to dissolved and colloidal species. The combined concentrations are not necessarily the actual concentrations, because the concentration may be lower due to inventory limits. Both NUTS and PANEL assume that the concentrations of actinides specified by the total mobilized concentration are attained instantaneously as long as sufficient inventory is available. When the inventory is insufficient, the actual mobilized concentration will be lower and is said to be inventory limited. The calculation of the total mobilized concentration is performed by PANEL, for each of 100 sampled vectors in a replicate,.

All of the source-term parameters and their distributions were entered into the PA parameter database. For each sampled parameter, the LHS code uses the distribution from the PA parameter database to create 100 sampled values. These values are combined with the parameters with constant values and stored in computational databases for each of the 100 vectors, which constitute one replicate. For each realization, PANEL uses both the constant and sampled values for all of the source-term parameters, and constructs the source term for NUTS and PANEL, as shown below. This process is repeated for scenarios using the Salado end-member total mobilized concentration and for scenarios using the Castile end-member total mobilized concentration. (Parameters that are sampled and values derived from them are indicated by italics. Parameters used by PANEL are in bold.)

$$\textit{Dissolved} = \mathbf{Model\ Solubility} * 10^{\textbf{\textit{Sampled from Solubility Distribution}}} \tag{73}$$

$$\textit{Humic} = \textit{Dissolved} * \textbf{\textit{Proportionality Constant}} \tag{74}$$

if *Dissolved* * ***Prop. Const***. < **Humic Cap**, otherwise

$$\text{Humic} = \mathbf{Humic\ Cap} \tag{75}$$

$$\textit{Microbe}\ (\text{microbial vectors only}) = \textit{Dissolved} * \mathbf{Proportionality\ Constant} \tag{76}$$

if the *Total Mobile* < **Microbe Cap**, otherwise

$$\text{Microbe} = \mathbf{Microbe\ Cap} \tag{77}$$

$$\text{Mineral} = \mathbf{Database\ Concentration} \tag{78}$$

$$\text{Intrinsic} = \mathbf{Database\ Concentration} \tag{79}$$

$$\textit{Total Mobile} = \textit{Dissolved} + \textit{Humic} + \textit{Microbe} + \text{Mineral} + \text{Intrinsic} \tag{80}$$

For actinides with more than one oxidation state, the oxidation state is specified by the oxidation-state parameter:

Lower Oxidation State if OXSTAT ≤ 0.5
Higher Oxidation State if OXSTAT > 0.5,

where OXSTAT is the oxidation-state parameter that is sampled uniformly from 0 to 1.

For example, for one realization, in Salado brine, the sampled value for OXSTAT was 0.9 so Pu would be present in the +IV state. The sample of the solubility distribution was 0.8 for the modeled solubility for the +IV state, which has a model solubility of 1.19×10^{-8} M. The humic proportionality constant for the +IV oxidation state in Salado brine is 6.3, the microbe proportionality constant for Pu is 0.3, the humic cap is 1.1×10^{-5} M, the microbe cap for Pu is 2.1×10^{-3} M, the concentration of the actinide on mineral fragments is 2.6×10^{-8} M, and the Pu intrinsic-colloid concentration is 1×10^{-9} M.

For this realization, the maximum mobilized concentration of Pu used by PA would be:

Maximum concentration of dissolved Pu:

$$C_{Pu} = (1.19 \times 10^{-8}) \times (10^{0.8}) = 2.8 \times 10^{-5} \text{ M} \tag{81}$$

(This example has been rounded to two significant figures, although PA would not round at this intermediate point.) C_{Pu} is the maximum concentration of all combined isotopes of Pu.

The maximum humic complexed Pu would be:

$$(2.8 \times 10^{-5} \text{ M})(6.3 \text{ mol adsorbed per mol}) = 1.8 \times 10^{-4} \text{ M} \tag{82}$$

This value, however, exceeds the cap for humic-mobilized Pu, 1.1×10^{-5} M. Therefore, in this case, the cap would be used for the maximum humic mobilized actinide concentration.

The maximum microbial mobilized Pu would be:

$$(2.8 \times 10^{-5} \text{ M})(0.3 \text{ mol bioaccumulated per mol}) = 8.3 \times 10^{-6} \text{ M} \tag{83}$$

which is less than the cap.

The total maximum Pu concentration or total mobilized concentration for this realization would then be the sum of the dissolved and colloidal actinides:

Dissolved + Humic + Microbe + Mineral + Intrinsic

$$2.8 \times 10^{-5} + 1.1 \times 10^{-5} + 8.3 \times 10^{-6} + 2.6 \times 10^{-8} + 1.0 \times 10^{-9} = 4.7 \times 10^{-5} \text{ M} \tag{84}$$

PANEL also calculates the fraction of each actinide mobilized by five different mechanisms, as follows:

$$\text{Fraction dissolved} = \text{Dissolved/Total Mobilized Conc.} \quad (85)$$

$$\text{Fraction on humics} = \text{Humic/Total Mobile} \quad (86)$$

$$\text{Fraction in/on microbes} = \text{Microbe/Total Mobile} \quad (87)$$

$$\text{Fraction on mineral fragments} = \text{Mineral/Total Mobile} \quad (88)$$

$$\text{Fraction as intrinsic colloid} = \text{Intrinsic/Total Mobile} \quad (89)$$

The total mobilized concentration and mobile fractions are then copied from Am to Cm. In addition, PA also combines isotopes (Appendix TRU WASTE, Section TRU WASTE-2.0) for the NUTS and SECOTP2D transport codes. For example, the U solubility is decreased to account for the shared solubility with the low-activity ^{238}U, which is not modeled, enabling NUTS to properly model the effect of the U isotopes on compliance using the single "lumped" isotope ^{234}U.

The output of the PANEL calculations is computational databases that contain the source term and effective inventories. NUTS and PANEL both assume instantaneous dissolution and colloidal mobilization up to the solubility limit when sufficient inventory is present, as discussed in Chapter 6.0 (Section 6.4.13.5). Table SOTERM-12 shows the dissolved and colloidal components of the source term and the total mobile actinide concentrations obtained when median parameter values are used.

Table SOTERM-12. Concentrations (M) of Dissolved, Colloidal, and Total Mobile Actinides Obtained Using Median Parameter Values

Actinide Oxidation State, and Brine	CRA, Microbial Vectors[1]	CRA, Nonmicrobial Vectors	PAVT	CCA
Pu(III), dissolved, Salado brine	2.50×10^{-7}	2.50×10^{-7}	9.75×10^{-8}	4.73×10^{-7}
Pu(III), colloidal, Salado brine	1.49×10^{-7}	7.44×10^{-8}	7.48×10^{-8}	2.59×10^{-7}
Pu(III), total mobile, Salado brine	3.99×10^{-7}	3.24×10^{-7}	1.72×10^{-7}	7.32×10^{-7}
Pu(III), dissolved, Castile brine	1.37×10^{-7}	1.44×10^{-7}	1.06×10^{-8}	1.06×10^{-8}
Pu(III), colloidal, Castile brine	2.56×10^{-7}	2.24×10^{-7}	4.46×10^{-8}	4.46×10^{-8}
Pu(III), total mobile, Castile brine	3.94×10^{-7}	3.68×10^{-7}	5.52×10^{-8}	5.52×10^{-8}
Am(III), dissolved, Salado brine	2.50×10^{-7}	2.50×10^{-7}	9.75×10^{-8}	4.73×10^{-7}
Am(III), colloidal, Salado brine	9.72×10^{-7}	7.34×10^{-8}	3.96×10^{-7}	1.82×10^{-6}
Am(III), total mobile, Salado brine	1.22×10^{-6}	3.23×10^{-7}	4.93×10^{-7}	2.29×10^{-6}
Am(III), dissolved, Castile brine	1.37×10^{-7}	1.44×10^{-7}	1.06×10^{-8}	1.06×10^{-8}
Am(III), colloidal, Castile brine	6.99×10^{-7}	2.13×10^{-7}	7.78×10^{-8}	7.78×10^{-8}
Am(III), total mobile, Castile brine	8.36×10^{-7}	3.57×10^{-7}	8.83×10^{-8}	8.83×10^{-8}
Th(IV), dissolved, Salado brine	9.67×10^{-9}	1.01×10^{-8}	1.06×10^{-8}	3.58×10^{-6}
Th(IV), colloidal, Salado brine	1.17×10^{-7}	8.95×10^{-8}	1.25×10^{-7}	2.21×10^{-5}
Th(IV), total mobile, Salado brine	1.27×10^{-7}	9.96×10^{-8}	1.36×10^{-7}	2.57×10^{-5}
Th(IV), dissolved, Castile brine	2.01×10^{-8}	4.75×10^{-9}	3.33×10^{-8}	4.88×10^{-9}
Th(IV), colloidal, Castile brine	2.15×10^{-7}	5.59×10^{-8}	3.39×10^{-7}	7.18×10^{-8}
Th(IV), total mobile, Castile brine	2.35×10^{-7}	6.07×10^{-8}	3.73×10^{-7}	7.67×10^{-8}
U(IV), dissolved, Salado brine	9.67×10^{-9}	1.01×10^{-8}	1.06×10^{-8}	3.58×10^{-6}

Table SOTERM-12. Concentrations (M) of Dissolved, Colloidal, and Total Mobile Actinides Obtained Using Median Parameter Values — Continued

Actinide Oxidation State, and Brine	CRA, Microbial Vectors[1]	CRA, Nonmicrobial Vectors	PAVT	CCA
U(IV), colloidal, Salado brine	8.70×10^{-8}	8.95×10^{-8}	9.26×10^{-8}	1.10×10^{-5}
U(IV), total mobile, Salado brine	9.66×10^{-8}	9.96×10^{-8}	1.03×10^{-7}	1.46×10^{-5}
U(IV), dissolved, Castile brine	2.01×10^{-8}	4.75×10^{-9}	3.33×10^{-8}	4.88×10^{-9}
U(IV), colloidal, Castile brine	1.53×10^{-7}	5.59×10^{-8}	2.36×10^{-7}	5.67×10^{-8}
U(IV), total mobile, Castile brine	1.73×10^{-7}	6.07×10^{-8}	2.69×10^{-7}	6.16×10^{-8}
Pu(IV), dissolved, Salado brine	9.67×10^{-9}	1.01×10^{-8}	1.06×10^{-8}	3.58×10^{-6}
Pu(IV), colloidal, Salado brine	9.08×10^{-8}	9.05×10^{-8}	9.67×10^{-8}	1.21×10^{-5}
Pu(IV), total mobile, Salado brine	1.01×10^{-7}	1.01×10^{-7}	1.07×10^{-7}	1.57×10^{-5}
Pu(IV), dissolved, Castile brine	2.01×10^{-8}	4.75×10^{-9}	3.33×10^{-8}	4.88×10^{-9}
Pu(IV), colloidal, Castile brine	1.60×10^{-7}	5.69×10^{-8}	2.47×10^{-7}	5.92×10^{-8}
Pu(IV), total mobile, Castile brine	1.80×10^{-7}	6.17×10^{-8}	2.80×10^{-7}	6.41×10^{-8}
U(VI), dissolved, Salado brine	7.07×10^{-6}	7.07×10^{-6}	7.07×10^{-6}	7.07×10^{-6}
U(VI), colloidal, Salado brine	8.89×10^{-7}	8.75×10^{-7}	8.89×10^{-7}	8.89×10^{-7}
U(VI), total mobile, Salado brine	7.96×10^{-6}	7.95×10^{-6}	7.96×10^{-6}	7.96×10^{-6}
U(VI), dissolved, Castile brine	7.15×10^{-6}	7.15×10^{-6}	7.15×10^{-6}	7.15×10^{-6}
U(VI), colloidal, Castile brine	3.69×10^{-6}	3.67×10^{-6}	3.69×10^{-6}	3.69×10^{-6}
U(VI), total mobile, Castile brine	1.08×10^{-5}	1.08×10^{-5}	1.08×10^{-5}	1.08×10^{-5}

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Appendix PA

Attachment TFIELD

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TFIELD-1.0 OVERVIEW OF T-FIELD DEVELOPMENT, CALIBRATION, AND MODIFICATION PROCESS

Modeling the transport of radionuclides through the Culebra Dolomite Member of the Rustler Formation is one component of the Performance Assessment (PA) performed for the Waste Isolation Pilot Plant (WIPP) Compliance Recertification Application (CRA). This transport modeling requires a model of groundwater flow through the Culebra. This Attachment describes the process used to develop and calibrate the transmissivity (T) fields for the Culebra, and then modify them for the possible effects of potash mining for use in flow modeling for the CRA-2004.

The work described in this attachment was performed under two Sandia National Laboratories Analysis Plans (APs): AP-088 (Beauheim 2002a) and AP-100 (Leigh et al. 2003). AP-088 (Analysis Plan for the Evaluation of the Effects of Head Changes on Calibration of Culebra Transmissivity Fields) dealt with the development, calibration, and modification for potash mining of the T fields. AP-100 (Analysis Plan for Calculations of Culebra Flow and Transport: Compliance Recertification Application) included the development of T-field acceptance criteria, as well as radionuclide-transport calculations not described herein.

The starting point in the T-field development process was to assemble information on geologic factors that might affect Culebra T (Section 2.0 of this attachment). These factors include dissolution of the upper Salado Formation, the thickness of overburden above the Culebra, and the spatial distribution of halite in the Rustler Formation above and below the Culebra. Geologic information is available from hundreds of oil and gas wells and potash exploration holes in the vicinity of the WIPP site, while T values are available from only 46 well locations. Details of the geologic data compilation are given in Powers (2002a, 2002b, 2003), and summarized below in Section 2.0 of this attachment.

A two-part “geologically based” approach was then used to generate Culebra base T fields. In the first part (Section 3.0 of this attachment), a conceptual model for geologic controls on Culebra T was formalized, and the hypothesized geologic controls were regressed against Culebra T data to determine linear regression coefficients. The regression includes one continuously varying function, Culebra overburden thickness, and three indicator functions that assume values of 0 or 1 depending on the occurrence of open, interconnected fractures, Salado dissolution, and the presence or absence of halite in units bounding the Culebra.

In the second part (Section 4.0 of this attachment), a method was developed for applying the linear regression model to predict Culebra T across the WIPP area. The regression model was combined with the maps of geologic factors to create 500 stochastically varying Culebra base T fields. Details about the development of the regression model and the creation of the base T fields are given in Holt and Yarbrough (2002, 2003a, 2003b).

By the nature of regression models, the base T fields do not honor the measured T values at the measurement locations. Therefore, before these base T fields could be used in a flow model, they had to be conditioned to the measured T values. This conditioning is described in McKenna and Hart (2003a, 2003b) and summarized in Section 5.0 of this attachment. Section 6.0 of this attachment presents details on the modeling approach used to calibrate the T fields to both

steady-state heads and transient drawdown measurements. Heads measured in late 2000 were used to represent steady-state conditions in the Culebra, and drawdown responses in 40 wells to pumping in 7 wells were used to provide transient calibration data. Details on the heads and drawdown data used are described in Beauheim (2002b; 2003a). Assumptions made in modeling, the definition of an initial head distribution, assignment of boundary conditions, discretization of the spatial and temporal domain, weighting of the observations, and the use of PEST in combination with MODFLOW-2000 to calibrate the T fields using a pilot-point method are described in McKenna and Hart (2003a, 2003b) and summarized in Section 6.0 of this attachment.

Section 7.0 of this attachment addresses the development and application of acceptance criteria for the T fields. Acceptance was based on a combination of objective fit to the calibration data and providing travel time results consistent with the cumulative distribution function (CDF) of travel times from the 23 best-calibrated T fields (Beauheim 2003b). Of the 146 T fields that went through the calibration process, 121 T fields were judged adequate for further use, with the 100 best T fields selected for use in the CRA-2004 transport calculations.

Section 8.0 of this attachment provides summary statistics and other information for the 121 T fields that were judged to be acceptably calibrated. Particle tracks from a point above the center of the WIPP disposal panels to the land withdrawal boundary are shown, along with information on the model fits to steady-state heads, identification of the most sensitive pilot point locations, and characteristics of an ensemble average T field. This information is summarized from McKenna and Hart (2003b).

Section 9.0 of this attachment discusses the modification of the T fields to account for the effects of potash mining both within and outside the WIPP land withdrawal boundary. Mining-affected areas were delineated, random transmissivity multipliers were applied to Ts in those areas, and particle tracks and travel times were determined (Lowry 2003). The flow fields produced by these mining-affected T fields are input to SECOTP2D for the CRA-2004 radionuclide-transport calculations.

Section 10.0 of this attachment provides a brief summary of this attachment.

TFIELD-2.0 DEVELOPMENT OF MAPS OF GEOLOGIC FACTORS

Beauheim and Holt (1990), among others, suggested three geologic factors that might be related to the transmissivity of the Culebra in the vicinity of the WIPP site:

1. thickness (or erosion) of overburden above the Culebra,
2. dissolution of the upper Salado , and
3. spatial distribution of halite in the Rustler Formation below and above the Culebra.

Culebra transmissivity is inversely related to thickness of overburden because stress relief associated with erosion of overburden leads to fracturing and opening of preexisting fractures. Culebra transmissivity is high where dissolution of the upper Salado has occurred and the

Culebra has subsided and fractured. Culebra transmissivity is observed to be low where halite is present in overlying and/or underlying mudstones. Presumably, high Culebra T leads to dissolution of nearby halite (if any). Hence, the presence of halite in mudstones above and/or below the Culebra can be taken as an indicator for low Culebra transmissivity.

Maps were developed for each of these factors using drillhole data of different types. The general area for the geologic study comprised 12 townships, located in townships T21S to T24S, ranges R30-32E (the WIPP site lies in T22S, R31E). The original sources of geologic data for this analysis are mainly Powers and Holt (1995) and Holt and Powers (1988) and new information derived by log interpretation by Powers (2002a, 2003b, 2003). All of the data are either included or summarized in the references cited above, and can be independently checked; basic data reports are available for WIPP drillholes, geophysical logs for oil and gas wells are available commercially or at offices of the Oil Conservation Division (New Mexico) in Artesia and Hobbs, and potash drillhole information is in files that can be accessed for stratigraphic information at the Bureau of Land Management (BLM), Carlsbad, NM. No proprietary data are included.

Factor A is represented by a structure contour map of the elevation of the top of the Culebra (Figure TFIELD-1) that can be digitized and then subtracted from a digital elevation model (DEM) of the land surface to obtain the thickness of overburden. Factor B is represented on a map as an approximate margin of the area beginning to be affected by dissolution of the upper Salado (Figure TFIELD-2). Factor C is delineated on a map by lines that represent as nearly as possible the boundaries of the occurrence of halite in the Los Medaños, Tamarisk, and Forty-niner Members of the Rustler Formation in the study domain (Figure TFIELD-3).

With respect to Factor B, the upper Salado has been dissolved, and presumably is still dissolving, along the eastern margin of Nash Draw. On the basis of limited core information, Holt and Powers (1988) suggested that formations overlying the dissolving upper Salado in Nash Draw are affected in proportion to the amount of Salado dissolution. The most direct way to estimate the spatial distribution of dissolution is to have cores of the upper Salado and basal Rustler and knowledge of the thickness to marker beds (MBs) in the upper Salado. The upper Salado has not been cored frequently, but geophysical logs from oil and gas wells, and descriptive logs of cores or cuttings from potash drillholes, provide a considerable amount of evidence of the thickness of the lower Rustler and upper Salado, even though cores and cuttings are no longer available from potash industry drillholes.

Potash industry geological logs examined at the BLM in Carlsbad, NM are quite variable in the quality of description and the stratigraphic interval described. Drillhole logs from the 1930s and 1950s typically are the most descriptive; recent drillhole logs are commonly useless for this project because no strata are described above portions of the McNutt potash zone of the Salado, near the middle of the formation.

The top of the Culebra and the base of the Vaca Triste Sandstone Member in the upper Salado are the most consistent stratigraphic markers spanning the upper Salado that are recognizable across various types of records. As a guide to the limits or bounds of upper Salado dissolution, a map of the thickness from top of Culebra to base of Vaca Triste was prepared (Powers 2003). In conjunction with previous work by Powers and Holt (1995) and the evidence of the structure of

the top of Culebra (see Figure TFIELD-1), an approximate boundary of dissolution was drawn as shown in Figure TFIELD-2.

With respect to Factor C, the boundaries of where halite is found in the three non-carbonate members of the Rustler have been drawn several times on the basis of different borehole data sets and different data types (e.g., core data and geophysical logs). For the most part, the different versions of the boundaries do not vary significantly. In the map shown in Figure TFIELD-3, the margins are based principally on the work of Powers and Holt (1995), which is a continuation of work reported by Holt and Powers (1988). As discussed in Powers and Holt (1995), the boundaries drawn here vary slightly from those drawn by Snyder (1985) based on core data for two reasons: (1) the Los Medaños Member (Powers and Holt 1999; formerly called the unnamed lower member) is here divided into two separate halite-bearing units (Powers and Holt 2000), and (2) geophysical log signatures are now used to identify halite in areas where cores are not available. Figure TFIELD-3 includes a stratigraphic sketch showing the relationship of halite-bearing strata to other strata in the Rustler. Following the convention established by Holt and Powers (1988), the mudstone/halite (M/H) strata are numbered consecutively starting at the base of the Rustler.

The margins for halite have now been drawn in the area north of the WIPP site around the northeastern arm of Nash Draw based on the descriptions of halite encounters in the Rustler Formation in potash drillholes. In addition, a few areas have been modified (from Powers and Holt 1995) to the south and west of the WIPP based on the records from potash drillholes as well as the records of drilling H-12 and H-17 for the WIPP.

In 12 potash drillholes, halite was reported above the upper contacts of the Culebra or Magenta Dolomite Members. The boundaries for M3/H3 and M4/H4 margins (i.e., the spatial limits of where halite is found in the mudstone intervals) have been drawn north of the WIPP based on these data. The depth below the Culebra at which halite was reported has also been used to draw the boundaries of the lower (M1/H1) or the upper (M2/H2) halite-bearing units of the Los Medaños in this area. Anhydrite A1 divides the M1/H1 (below) and M2/H2 (above) intervals. M2 (no halite) is about 3 m (10 ft) thick. If halite is reported within about 3 m (10 ft) of the base of Culebra or is clearly above A1, H2 is considered to be present. The M1/H1 interval is about 33-37 m (110-120 ft) thick at the WIPP site. In potash drillholes north of the WIPP site, where halite was reported less than 33 m (110 ft) below the Culebra, H1 is present. Within the zone for H1, other drillholes frequently reveal halite less than 33 m (110 ft) below the Culebra.

It should be noted that the report of “top of salt” or first salt in records for potash drillholes does not consistently mean the same thing and is frequently not the uppermost halite. It may instead mean the first halite that is encountered after coring begins or the first unit that is dominantly halite. Detailed inspection of logs sometimes shows halite described from cuttings, with a summary report of “top of salt” much deeper. In some cases, it appears “top of salt” is an estimate of where the Salado-Rustler contact should be.

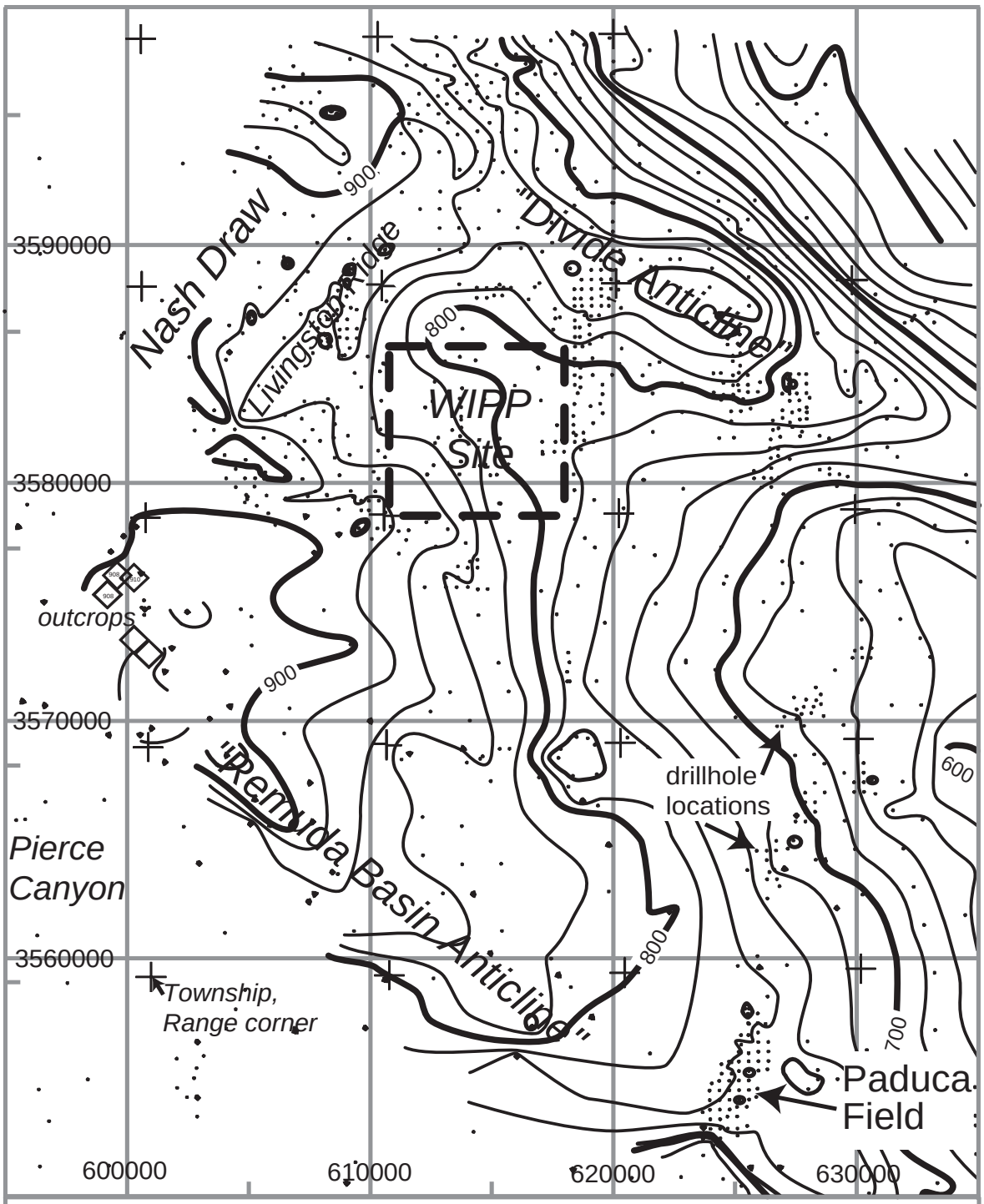

Explanation

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.
The contours for the elevation of the top of the Culebra are in meters (m) above mean sea level (amsl) (after Powers et al. 2003). Contour interval is 20 m.

Figure TFIELD-1. Structure Contour Map for the Top of the Culebra

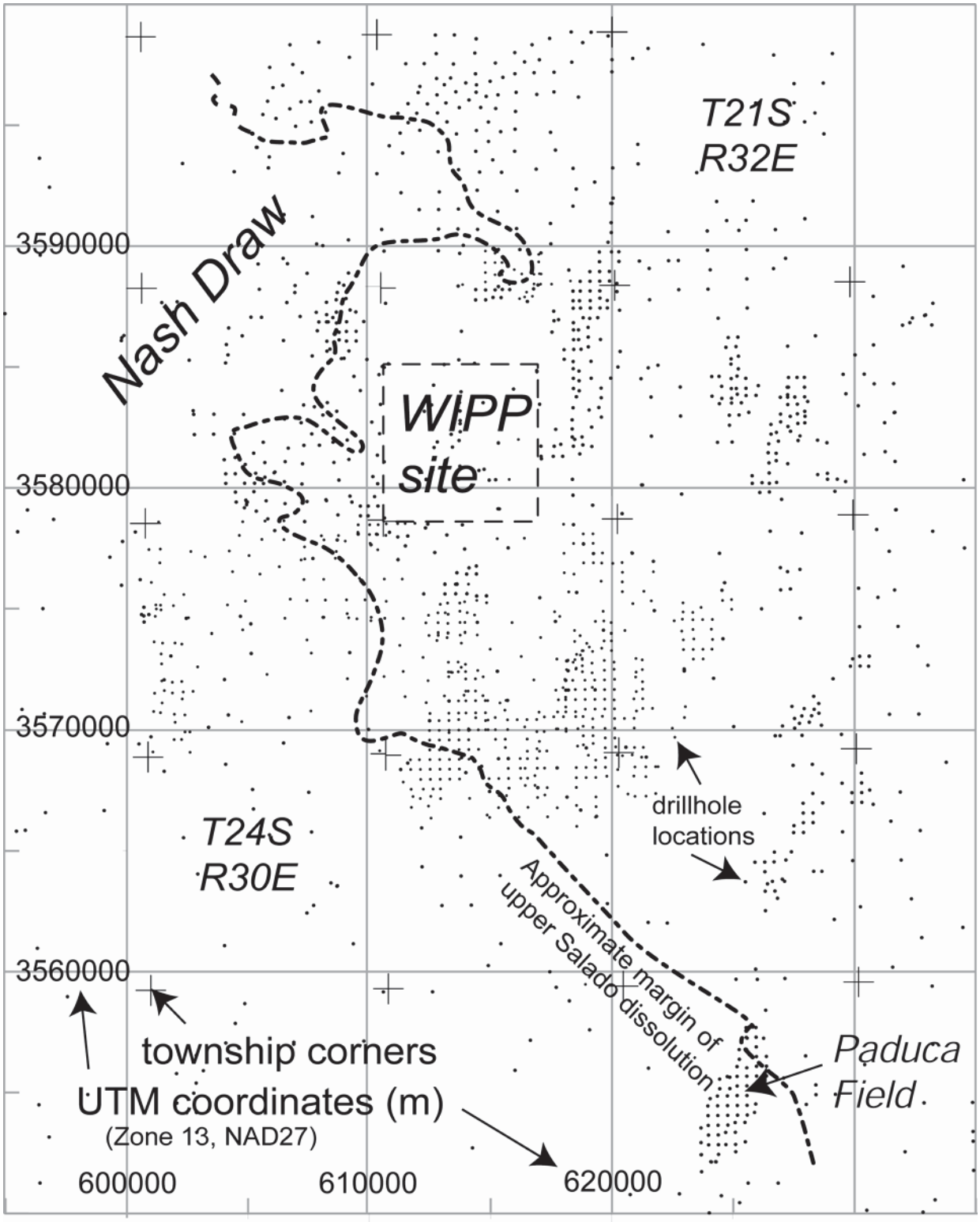

Figure TFIELD-2. Salado Dissolution Margin

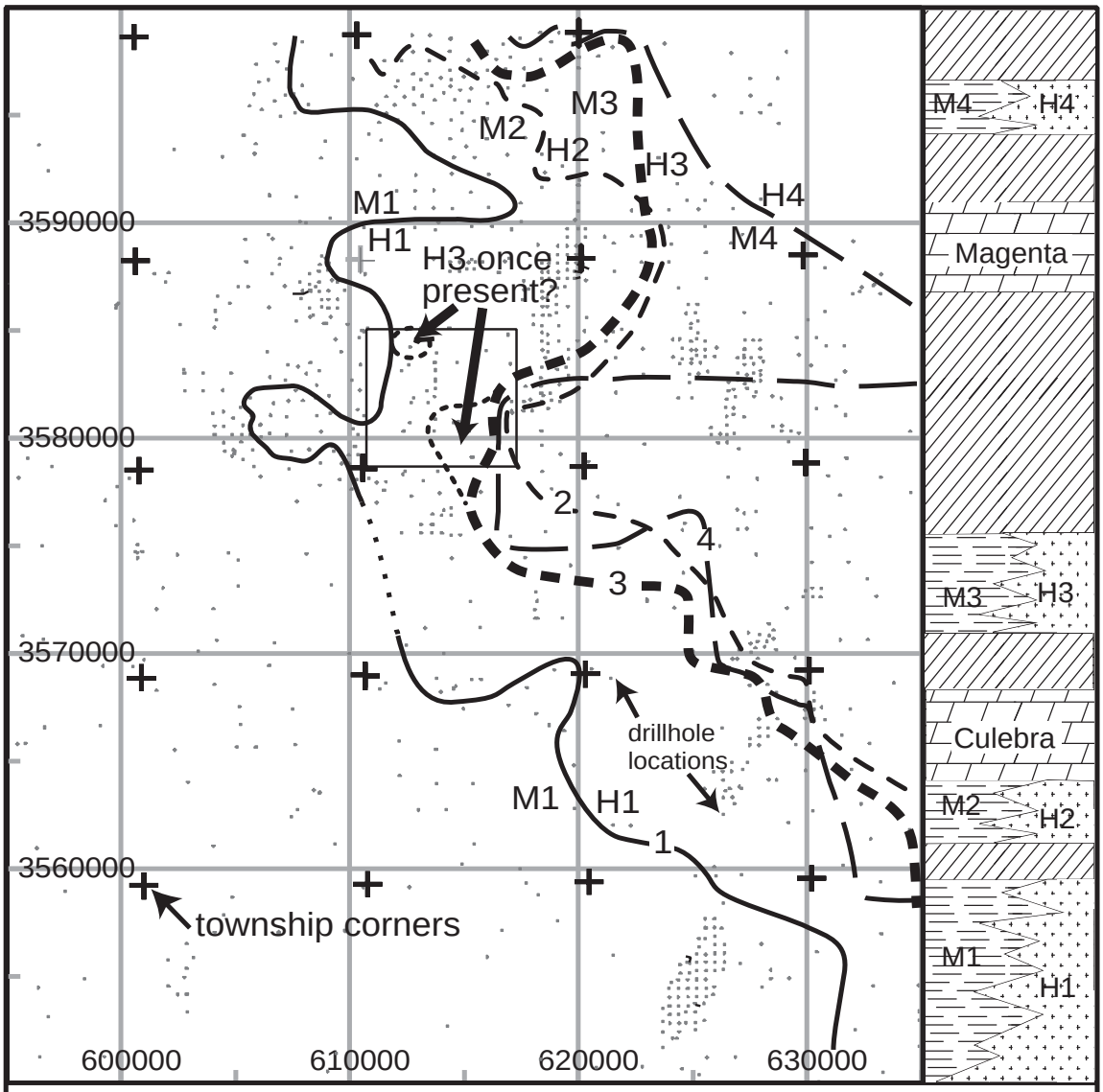

Explanation

M#, H# indicate mudstone and halitic facies on each side of estimated halite margin (numbered line on map) for stratigraphic intervals as indicated in the column to the right (key on Figure TFIELD-4).

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.

Two zones within the WIPP site boundary ("H3 once present?") indicate where halite may have been present west of the current boundary of H3 (marked by ▬ ▬ ▬ ▬ ▪).

Figure TFIELD-3. Rustler Halite Margins. See Figure TFIELD-4 for key to stratigraphic column.

Halite margins in the Rustler Formation are interpreted as mainly due to depositional limits of saltpan environments and syndepositional removal of some halite exposed in saline mud flat deposits (Holt and Powers 1988). The halite margins are expected to be the locus of halite dissolution, if any, since the Rustler was deposited. Facies including halite beds or halite cements are expected to be less permeable than the equivalent mudstone facies. As a consequence, the margin is more likely to be attacked by advection and diffusion at the margin, from the mudstone facies side of the margin. In addition, removing halite along the margin as the saltpan margin fluctuates is likely to introduce some vertical and horizontal discontinuities that persist after lithification and are not created where the saltpan persisted. Water in adjacent units or in the mudstone unit likely has more pathways along these margins, increasing the likelihood that the margins will be the locus of dissolution. Recent findings of a narrow margin along which halite is dissolved from the upper Salado (Powers et al. 2003) are consistent with the expectation that halite margins in the Rustler would be the locus of dissolution.

Two areas have been identified where halite appears to have been dissolved from the M3/H3 interval after deposition of the Rustler. These areas are shown with the annotation “H3 once present?” on Figure TFIELD-3. In the vicinity of drillhole H-19b0 and south (the southern area shown), cores of several WIPP drillholes show brecciation of the upper Tamarisk Member anhydrite in response to dissolution. Another area of dissolution, previously discussed in Holt and Powers (1988), Powers and Holt (1995), and Beauheim and Holt (1990), is around WIPP-13 (the northern area shown), and may represent an outlier of salt left behind during syndepositional removal of halite from the M3 areas west of the WIPP site (Powers and Holt 2000). These areas have not been extended interpretively on Figure TFIELD-3 as was done in Beauheim and Holt (1990), but are limited to the vicinities of the locations at which evidence of dissolution has been directly observed.

Because of the position of M2/H2 directly beneath the Culebra, dissolution of H2 might be expected to have a strong influence on Culebra T. However, the H2 depositional margin is largely east of the WIPP site, barely crossing the southern portion of the eastern WIPP site boundary (Figure TFIELD-3). H2 dissolution does not appear to be a factor affecting Culebra T in any hydrology test well for WIPP, but there are no direct observations along the H2 margin.

TFIELD-3.0 DEVELOPMENT OF MODEL RELATING CULEBRA T TO GEOLOGIC FACTORS

Holt and Powers (1988), Powers and Holt (1990), Beauheim and Holt (1990), and Holt (1997) have described the geology and geologic history of the Culebra. The following model is developed from their work and is consistent with their interpretations. It is important to note that this work follows Holt (1997) and assumes that variability in Culebra T is due strictly to post-depositional processes. Throughout the following discussion, the informal stratigraphic subdivisions of Holt and Powers (1988) are used to identify geologic units within the Rustler Formation (Figure TFIELD-4).

The spatial distribution of Culebra T on a regional scale is a function of a series of deterministic geologic controls, including Culebra overburden thickness, dissolution of the upper Salado Formation, and the occurrence of halite in units above or below the Culebra. Each of these

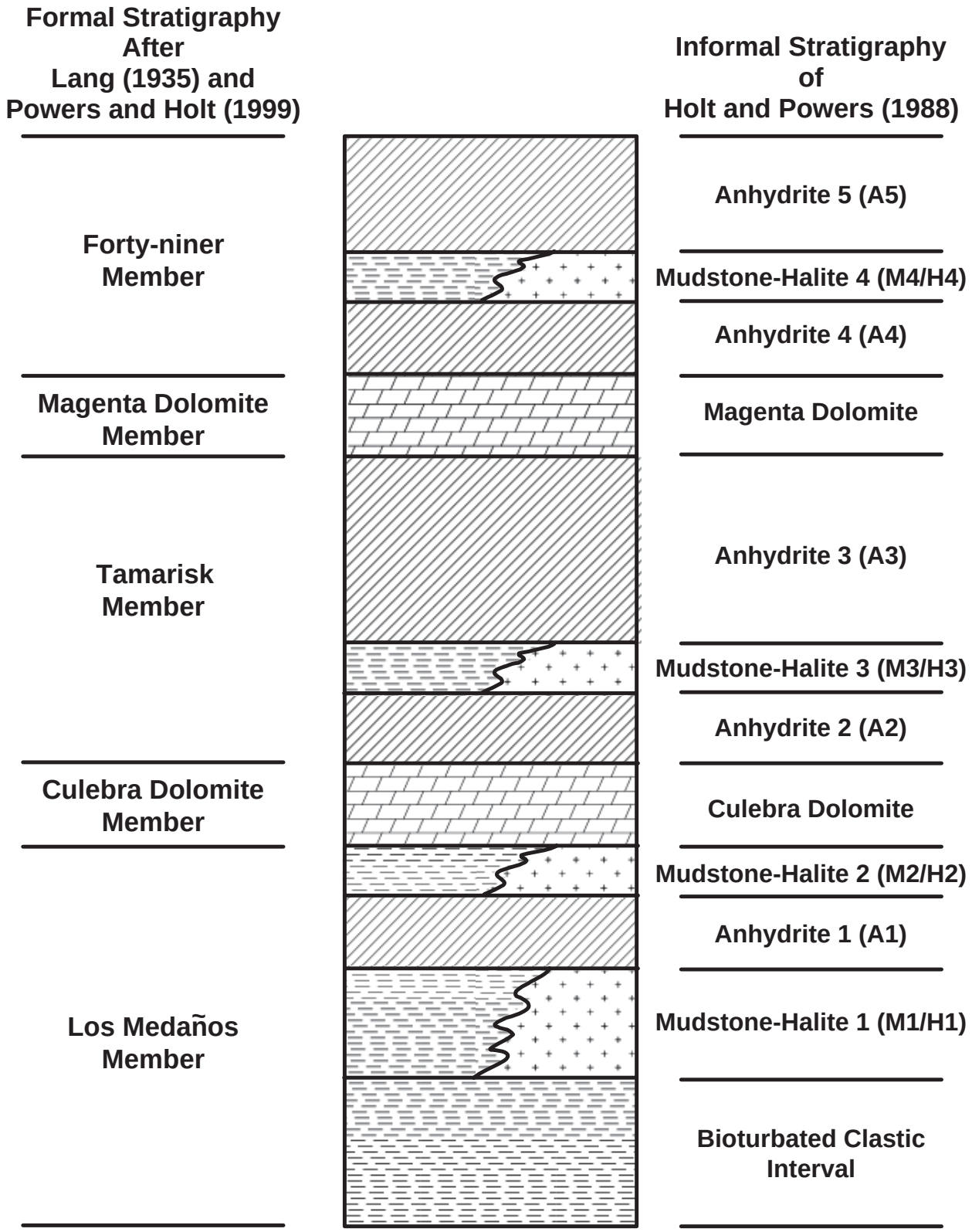

Figure TFIELD-4. Stratigraphic Subdivisions of the Rustler Formation

geologic controls can be determined at any location using geological map data. In the region between the margin of upper Salado dissolution and the margin of halite occurrence above the Culebra, which includes the WIPP site, however, high-T regions occur that cannot be predicted using geologic data. These high-T zones are treated stochastically, using what is termed a fracture-interconnectivity indicator.

In the following paragraphs, the fracture-interconnectivity indicator is defined, and then the specifics of each hypothesized control on Culebra T are outlined. Finally, a linear model relating these controls to Culebra T is presented that provides an excellent fit to the available data, is testable, and is consistent with our understanding of Culebra geology.

TFIELD-3.1 Fracture Interconnection

Culebra T data show a bimodal distribution (Figure TFIELD-5). Interpretations of hydraulic tests (e.g., Beauheim and Ruskauff 1998) and observations of the presence or absence of open fractures in core show the bimodal T distribution to be the result of hydraulically significant fractures. Some degree of fracturing is evident in all Culebra cores, but the fractures tend to be filled with gypsum at locations where the T inferred from hydraulic tests is less than approximately 4×10^{-6} m^2/s ($\log_{10} = -5.4$). Where $\log_{10}$ T (m^2/s) is greater than –5.4, hydraulic tests show double-porosity responses and open fractures are observed in core. Therefore, a fracture-interconnectivity indicator is defined based on a cutoff of $\log_{10}$ T (m^2/s) = -5.4:

$$I_f = \begin{cases} 1 & \log_{10} T(m^2/s) > -5.4 \\ 0 & \log_{10} T(m^2/s) \le -5.4 \end{cases} \tag{1}$$

Open, interconnected fractures and high Ts occur in regions affected by Salado dissolution (e.g., Nash Draw) and in areas west of the M3/H3 margin where gypsum fracture fillings are absent.

TFIELD-3.2 Overburden Thickness

An inverse relationship exists between Culebra overburden thickness and T. At the WIPP wells for which T data are available, the Culebra overburden thickness ranges from 3.7 m (at WIPP-29) to 414.5 m (at H-10) (Mercer 1983), increasing from west to east. Overburden thickness is a metric for two different controls on Culebra T. First, fracture apertures are limited by overburden thickness (e.g., Currie and Nwachukwu 1974), which should lead to lower T where Culebra depths are great (Beauheim and Holt 1990; Holt 1997). Second, erosion of overburden leads to changes in stress fractures, and the amount of Culebra fracturing increases as the overburden thickness decreases (Holt 1997). Holt (1997) estimates that at least 350 m of overburden has been eroded at the center of the WIPP site (where the Culebra is at a depth of approximately 214 m) since the end of the Triassic, with more erosion occurring west of the site center where overburden (chiefly the Dewey Lake) is thinner and less erosion occurring to the east where Triassic deposits are thicker.

TFIELD-3.3 Salado Dissolution

In regions north, south, and west of the WIPP site, Cenozoic dissolution has affected the upper Salado Formation (Figure TFIELD-2). Where this dissolution has occurred, the rocks overlying the Salado, including the Culebra, are strained (leading to larger apertures in existing fractures),

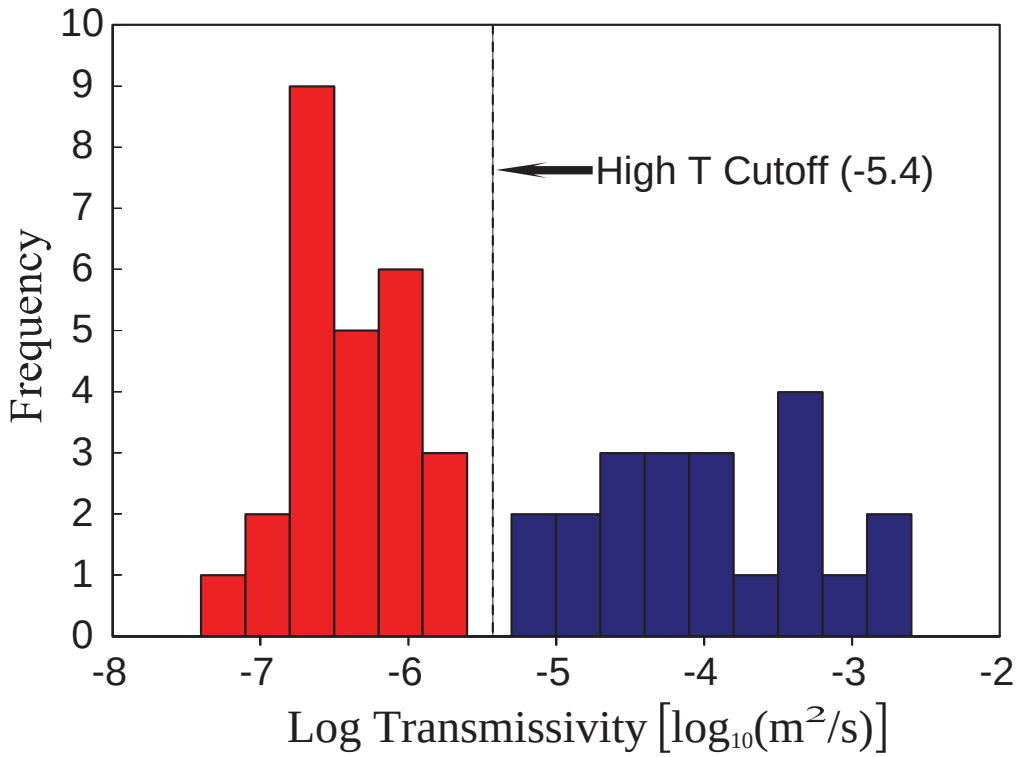

Figure TFIELD-5. Histogram of Log_{10} Culebra T. Data from DOE (1996), Beauheim and Ruskauff (1998), and Beauheim (2002c)

fractured, collapsed, and brecciated (e.g., Beauheim and Holt 1990; Holt 1997). All WIPP wells within the upper-Salado-dissolution zone fall within the high-T population, and all regions affected by Salado dissolution are expected to have well-interconnected fractures and high T.

TFIELD-3.4 Halite Overlying the Culebra

All wells (e.g., H-12 and H-17) located where halite occurs in the M3/H3 interval of the Tamarisk (Figure TFIELD-3) show low T. T data are limited in this region, but it is unlikely that halite would survive in M3/H3, only several meters from the Culebra, in regions of high T where Culebra flow rates are relatively high. High-T zones, therefore, are assumed to not occur in regions where halite is present in the M3/H3 interval.

TFIELD-3.5 Halite Bounding the Culebra

In regions where halite is present in the M2/H2 interval directly below the Culebra, no reliable quantitative estimates of Culebra T are available. Beauheim (1987) estimates T at P-18, the only tested well at which halite is present in the M2/H2 interval, to be less (probably much less) than 4×10^{-9} m^2/s ($\log_{10} = -8.4$). In much of the area where halite is present in the M2/H2 interval (including the P-18 location), halite is also present in the M3/H3 interval. Based upon geologic observations of halite-bound units elsewhere within the WIPP area, Holt (1997) suggests that porosity within the Culebra may contain abundant halite cements in these areas. Beauheim and Holt (1990) and Holt (1997) indicate that Culebra porosity shows increasing amounts of pore-filling cement east of the WIPP site. Consequently, Culebra T is assumed to be much lower in

the region where halite occurs both above (M3/H3 interval) and below (M2/H2 interval) the Culebra. Much lower T is also assumed in the area northeast of the WIPP site where halite is present in the M2/H2 interval but absent in the M3/H3 interval (see Figure TFIELD-3).

TFIELD-3.6 High-T Zones

In addition to the high T that occurs everywhere dissolution of the upper Salado has occurred, high-T zones also occur in the Culebra in the region bounded by the limit of upper Salado dissolution to the west and by the margin of where halite is present in the M2/H2 and M3/H3 intervals to the east (see Figures TFIELD-2 and TFIELD-3). Fracture openness and interconnectivity in these high-T zones are controlled by a complicated history of fracturing with several episodes of cement precipitation and dissolution (Beauheim and Holt 1990; Holt 1997). No geologic metric has yet been defined that allows prediction of where fractures are filled or open, hence our knowledge of this indicator east of the Salado dissolution margin is limited to the test well locations shown in Figure TFIELD-6. Consequently, the spatial location of high-T zones between the Salado dissolution margin and the M2/H2 and M3/H3 margins is treated stochastically.

TFIELD-3.7 Linear Transmissivity Model

Using the hypothesized geologic controls on Culebra T, the following linear model for $Y(\mathbf{x}) = \log_{10} T(\mathbf{x})$ was constructed:

$$Y(\mathbf{x}) = \beta_1 + \beta_2\, d(\mathbf{x}) + \beta_3\, I_f(\mathbf{x}) + \beta_4\, I_D(\mathbf{x}) \qquad (2)$$

where β_i (i = 1, 2, 3, 4) are regression coefficients, $\mathbf{x}$ is a two-dimensional location vector consisting of UTM X and UTM Y coordinates, $d(\mathbf{x})$ is the overburden thickness, $I_f(\mathbf{x})$ is the fracture-interconnectivity indicator given in Equation (1) that assumes the value of 1 if fracturing and high T have been observed at point $\mathbf{x}$ and 0 otherwise, and $I_D(\mathbf{x})$ is a dissolution indicator function that assumes the value of 1 if Salado dissolution has occurred at point $\mathbf{x}$ and 0 otherwise. In this model, regression coefficient β_1 is the intercept value for the linear model. Coefficient β_2 is the slope of $Y(\mathbf{x})/d(\mathbf{x})$. Coefficients β_3 and β_4 represent adjustments to the intercept for the occurrence of interconnected fractures and Salado dissolution, respectively. Although other types of linear models could be developed, this model is consistent with the conceptual model relating T to geologic controls and can be tested using published WIPP geologic and T data. Note that the regression model does not explicitly contain terms relating Culebra T to zones where the Culebra is bounded by halite in both the M2/H2 and M3/H3 intervals because of lack of data from these areas. Therefore, it cannot be used to predict T east of the M2/H2 margin.

TFIELD-3.8 Linear-Regression Analysis

A linear-regression model was written using the Windows-based program Mathcad 7 Professional© specifically for this application. Although other variables are input, this model requires only $\log_{10}$ T data from tested wells, the depth of the Culebra at those wells, and an estimate of whether dissolution of the upper Salado has or has not occurred at each location. The fracture interconnectivity indicator is defined from the $\log_{10}$ T data, and a Salado dissolution indicator is defined using the Salado dissolution data. These data are then used in a standard linear regression algorithm to determine the regression coefficients for Equation (2).

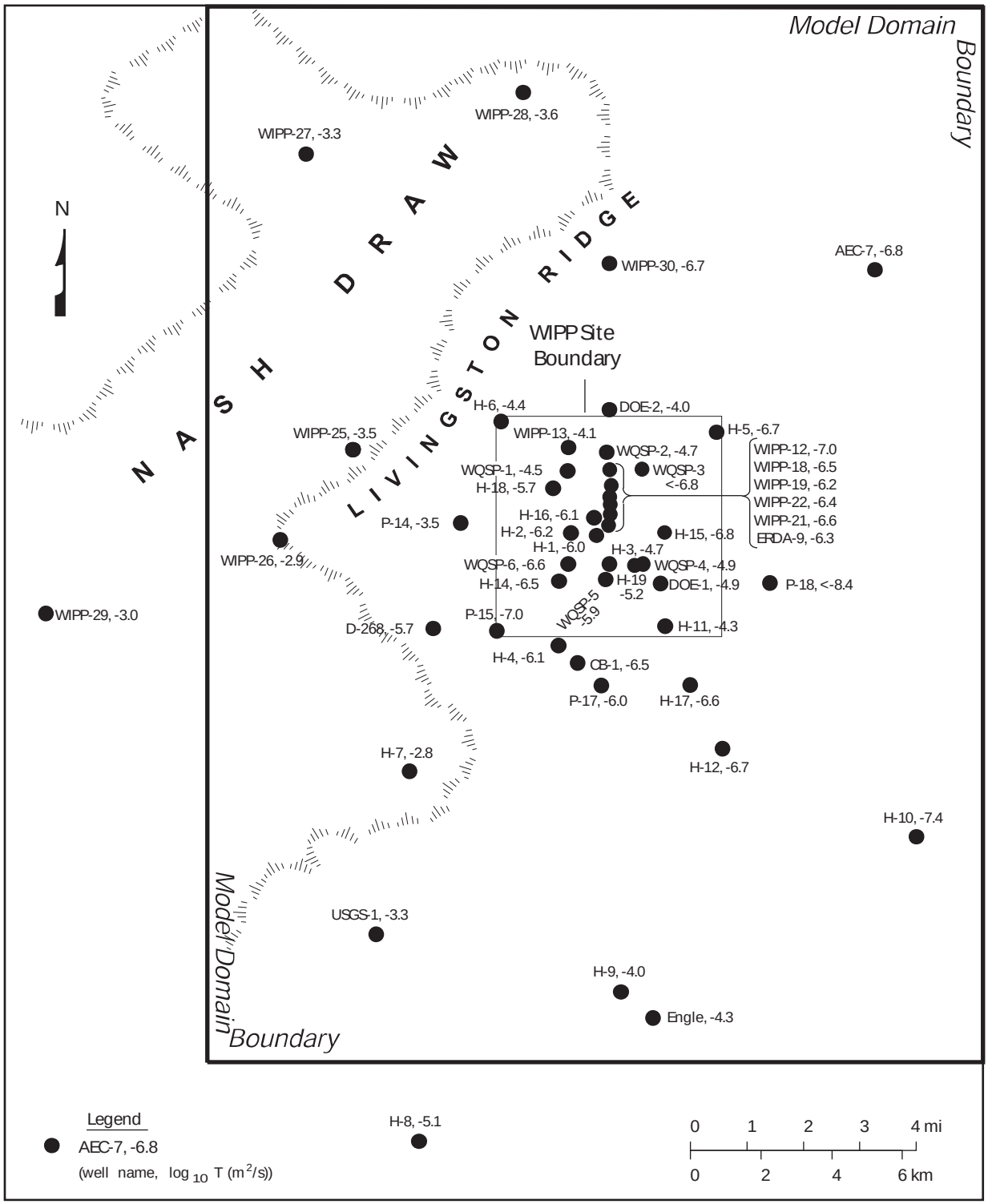

Figure TFIELD-6. Well Locations and Log_{10} Culebra Transmissivities

The regression coefficients for Equation (2) derived from this analysis are presented in Table TFIELD-1. The regression has a multiple correlation coefficient (R^2) of 0.941 and a Regression ANOVA F statistic of 222. The number of degrees of freedom about the regression (n) equals the number of observations (46) minus the number of parameters (4). The number of degrees of freedom due to the regression (m) equals the number of parameters (4) minus 1. With n = 42 and m = 3, the regression is significant above the 0.999 level. Residuals show no anomalous behavior. Accordingly, the regression model provides an accurate and reasonable description of the data. The fit of the regression to the $\log_{10}$ T data is shown in Figure TFIELD-7.

Table TFIELD-1. Regression Coefficients for Equations (2) and (3)

β_1	β_2	β_3	β_4
–5.441	-4.636×10^{-3}	1.926	0.678

The regression model does not predict T in the regions where the Culebra is underlain by halite in the M2/H2 interval because no quantitative data were available from these regions to be used in deriving the regression. In these regions, the following modified version of the regression model of Equation (2) is applied:

$$Y(\mathbf{x}) = \beta_1 + \beta_2\, d(\mathbf{x}) + \beta_3\, I_f(\mathbf{x}) + \beta_4\, I_D(\mathbf{x}) + \beta_5\, I_H(\mathbf{x}) \qquad (3)$$

where $I_H(\mathbf{x})$ is a halite indicator function. This indicator is assigned a value of 1 in locations where halite occurs in the M2/H2 interval and 0 otherwise. The coefficient β_5 is set equal to –1 so that Equation (3) reduces the predicted T values by one order of magnitude where halite occurs in the M2/H2 interval, to accord qualitatively with the expected transmissivity reduction discussed in Section 3.5 of this attachment. With knowledge (or stochastic estimations) of the values of the geologic controls (e.g., Culebra depth, fracture-interconnectivity indicator, dissolution indicator, and halite indicator), Culebra T values can be predicted at unobserved locations in the WIPP Culebra model domain using Equation (3).

TFIELD-4.0 CALCULATION OF BASE T FIELDS

In this section, a method is developed for applying the linear regression model from Section 3.0 of this attachment to predict Culebra T across a model domain encompassing the WIPP area. Culebra overburden thickness, Salado dissolution, and the presence or absence of halite in units bounding the Culebra can be deterministically evaluated across the WIPP region using maps constructed from subsurface data (Section 2.0 of this attachment). The presence of open, interconnected fractures, however, cannot be deterministically assessed across the WIPP area using maps. A geostatistical approach, conditional indicator simulation, is used to generate 500 equiprobable realizations of zones with hydraulically significant fractures in the WIPP region. These simulations are parameterized using the frequency of occurrence of WIPP wells with hydraulically significant fractures and a fit to a variogram constructed using data from those same wells. The regression model is then applied to the entire WIPP area by:

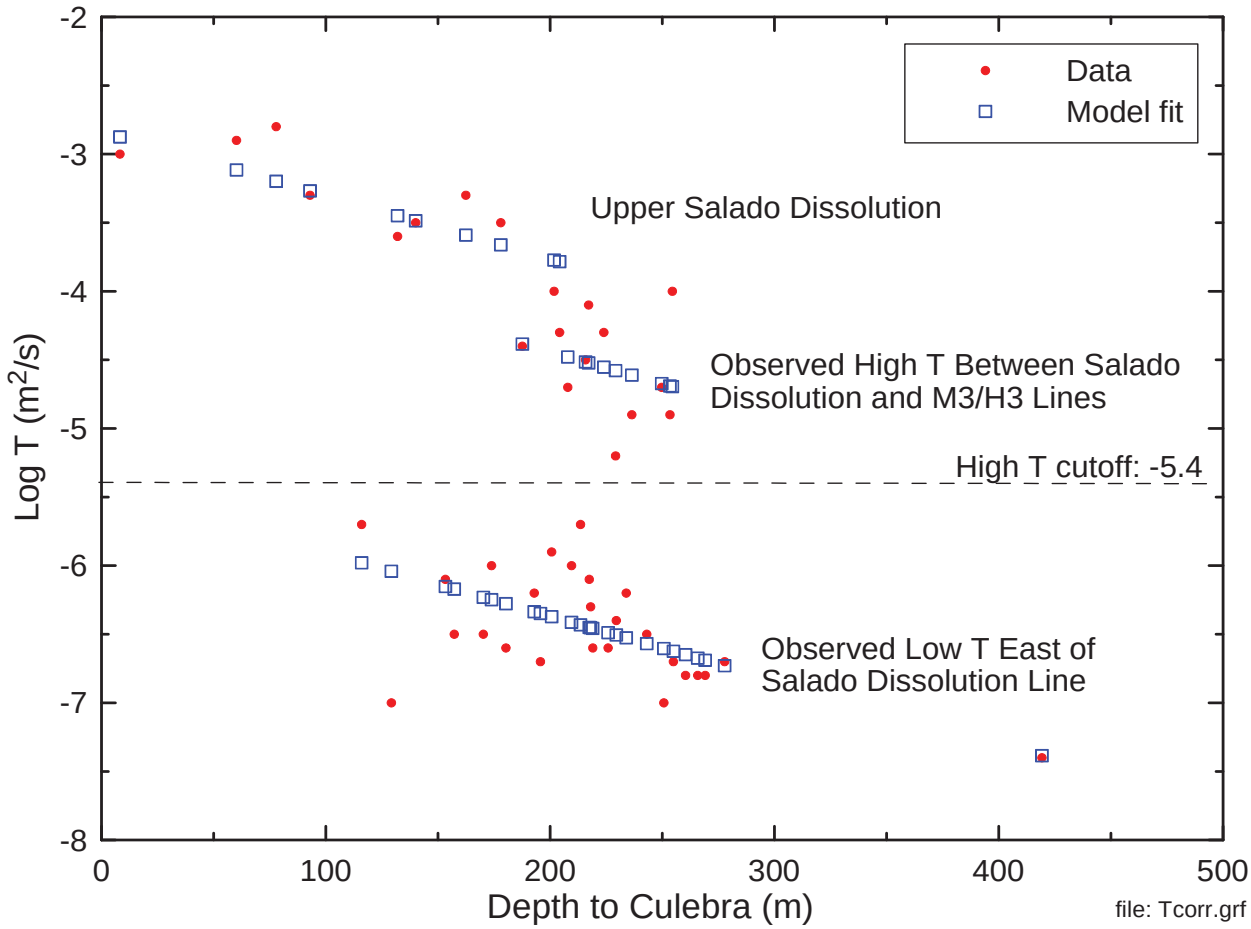

Figure TFIELD-7. Regression Fit to Observed Culebra Log_{10} T Data

1. Overlaying the geologic map data for Culebra overburden thickness, Salado dissolution, and the presence or absence of halite in units bounding the Culebra with each of the 500 equiprobable realizations of zones containing open, interconnected fractures.

2. Sampling each grid point within the model domain to determine the overburden thickness and the indicator values for Salado dissolution, overlying or underlying halite, and fracture interconnectivity.

3. Using the sampled data at each grid point with the regression model coefficients to estimate Culebra T.

When applied to the 500 equiprobable realizations of zones containing open, interconnected fractures, this procedure generates 500 stochastically varying Culebra base T fields. Details about the creation of the base T fields are given in Holt and Yarbrough (2002, 2003a, 2003b).

TFIELD-4.1 Definition of Model Domain

Two principal factors were considered in selecting the boundaries for the Culebra model domain. First, model boundaries should coincide with natural groundwater divides where feasible, or be far enough from the southern portion of the WIPP site, where transport will be modeled, to have

minimal influence in that area. Second, the model domain should encompass known features with the potential to affect Culebra water levels at the WIPP site (e.g., potash tailings ponds). The modeling domain selected is 22.4 km (13.9 mi) east-west by 30.7 km (19.1 mi) north-south, aligned with the compass directions (Figure TFIELD-6). This is the same as the domain used by LaVenue et al. (1990) except that the current domain extends 1 km (0.62 mi) farther to the west than the 1990 domain. The modeling domain is discretized into 68,768 uniform 100-m (328-ft) by 100-m (328-ft) cells. The northern model boundary is slightly north of the northern end of Nash Draw, 12 km (7.5 mi) north of the northern WIPP site boundary and about 1 km (0.62 mi) north of Mississippi Potash Incorporated's east tailings pile. The eastern boundary lies in a low-T region that contributes little flow to the modeling domain. The southern boundary lies 12.2 km (7.6 mi) south of the southern WIPP site boundary, 1.7 km (1.5 mi) south of our southernmost well (H-9) and far enough from the WIPP site to have little effect on transport rates on the site. The western model boundary passes through the IMC tailings pond (Laguna Uno of Hunter [1985]) due west of the WIPP site in Nash Draw. Boundary conditions assigned for the model are discussed in Section 6.2 of this attachment. The coordinates of each corner of the domain are given in Table TFIELD-2**,** in NAD 27 UTM coordinates.

Table TFIELD-2. Coordinates of the Numerical Model Domain Corners

Domain Corner	UTM X Coordinate (m)	UTM Y Coordinate (m)
Northeast	624,050	3,597,150
Northwest	601,650	3,597,150
Southeast	624,050	3,566,450
Southwest	601,650	3,566,450

TFIELD-4.2 Reduction of Geologic Map Data

To create useable data sets for conditional simulation of high-T zones and prediction of Culebra T, the geological maps described above in Section 2.0 of this attachment were imported into a GIS environment and digitized. A uniform 100-m (328-ft) grid was then created over the Culebra model domain. Using the Culebra structure contour map data (Figure TFIELD-1) and surface elevation data obtained from the United States Geological Survey (USGS) National Elevation Dataset (NED) (http://edcnts12.cr.usgs.gov/ned), an isopach map of the Culebra overburden on the 100-m (328-ft) model grid was created.

Using maps showing occurrence of halite in the units above and below the Culebra and well locations, soft data files were created for conditional indicator simulations. T within 120 m (374 ft) of each well is assumed to be from the same population (e.g., high or low T reflecting open, interconnected fractures or filled (poorly interconnected) fractures, respectively), and regions where the Culebra is overlain by halite in M3/H3 or underlain by halite in M2/H2 are assumed to be low-T regions.

Using maps of Salado dissolution and the occurrence of halite in the units above and below the Culebra, 100-m (328-ft) indicator grids were created over the model domain. These indicator grids were created for regions affected by Salado dissolution, regions where the Culebra is

underlain by halite in the M2/H2 interval, and a middle zone in which the Culebra is neither overlain nor underlain by halite where high-T zones occur stochastically (Figure TFIELD-8).

TFIELD-4.3 Indicator Variography

Excluding data where Salado dissolution occurs, Culebra T data are indicator transformed (1 for $\log_{10}$ T (m^2/s) > –5.4, 0 otherwise). A high-T indicator variogram is then constructed for the indicator data in the region not affected by Salado dissolution using the GSLIB program gamv (Deutsch and Journel 1998). The lag spacing for this variogram is selected to maximize variogram resolution. The resulting indicator variogram is then fit with an isotropic spherical variogram model:

$$\gamma(h) = \begin{cases} s[1.5(h/\lambda) - 0.5(h/\lambda)^3] & \text{if } h \le \lambda \\ s & \text{if } h \ge \lambda \end{cases} \tag{4}$$

where $\gamma(h)$ is the variogram as a function of lag spacing h, s is the sill value of the indicator variogram, and λ is the correlation length. This variogram model minimizes the mean squared error between the experimental and modeled variogram. The sill value was determined using:

$$s = P[\log_{10} T\ (\mathrm{m}^2/\mathrm{s}) > -5.4] - \{P[\log_{10} T\ (\mathrm{m}^2/\mathrm{s}) > -5.4]\}^2 \tag{5}$$

For the Culebra data set, excluding wells where dissolution has occurred, s = 0.201. The correlation length λ was estimated to be 1,790 m (5,873 ft). No nugget effect was included in the variogram model (Figure TFIELD-9). Variogram model parameters were then used in conditional indicator simulations of Culebra high-T zones.

TFIELD-4.4 Conditional Indicator Simulation

"Soft" indicator data were created for the indicator simulations. To ensure that no high-T regions develop in areas where halite occurs in M2/H2 or M3/H3, soft data points, indicating low T, were placed on a 200-m (656-ft) grid east of the M2/H2 and M3/H3 salt margins. This 200-m (656-ft) grid used the original 100-m (328-ft) grid excluding every other node to assure the 200-m (656-ft) soft data grid spatially overlay the 100-m (328-ft) grid. Soft data were also specified for every 100-m (328-ft) node along the combined lines of the M2/H2 and M3/H3 salt margins.

Additional soft data were created near well locations establishing a 120-m (394-ft) buffer around each well (Figure TFIELD-10). All 100-m (328-ft) grid nodes lying within the 120-m (394-ft) buffer were selected and assigned the transmissivity attribute of the well. Because all the nodes within 120 m (394 ft) of the well and the node corresponding to the block containing the well were selected as soft data, there was duplication in the input files. Only one data point can occupy a 100-m (328-ft) grid space during a realization. Therefore, the node closest to the well was eliminated from the soft data file.

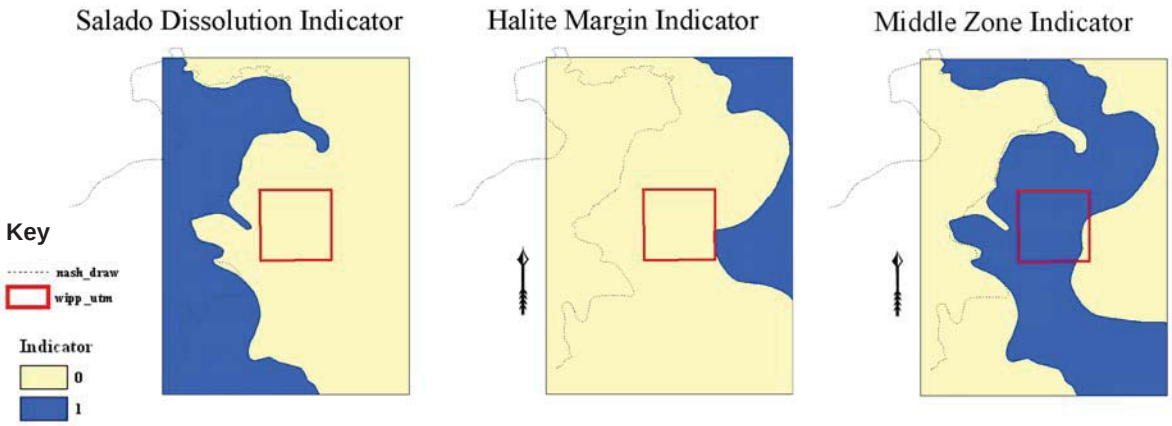

Figure TFIELD-8. Zones for Indicator Grids

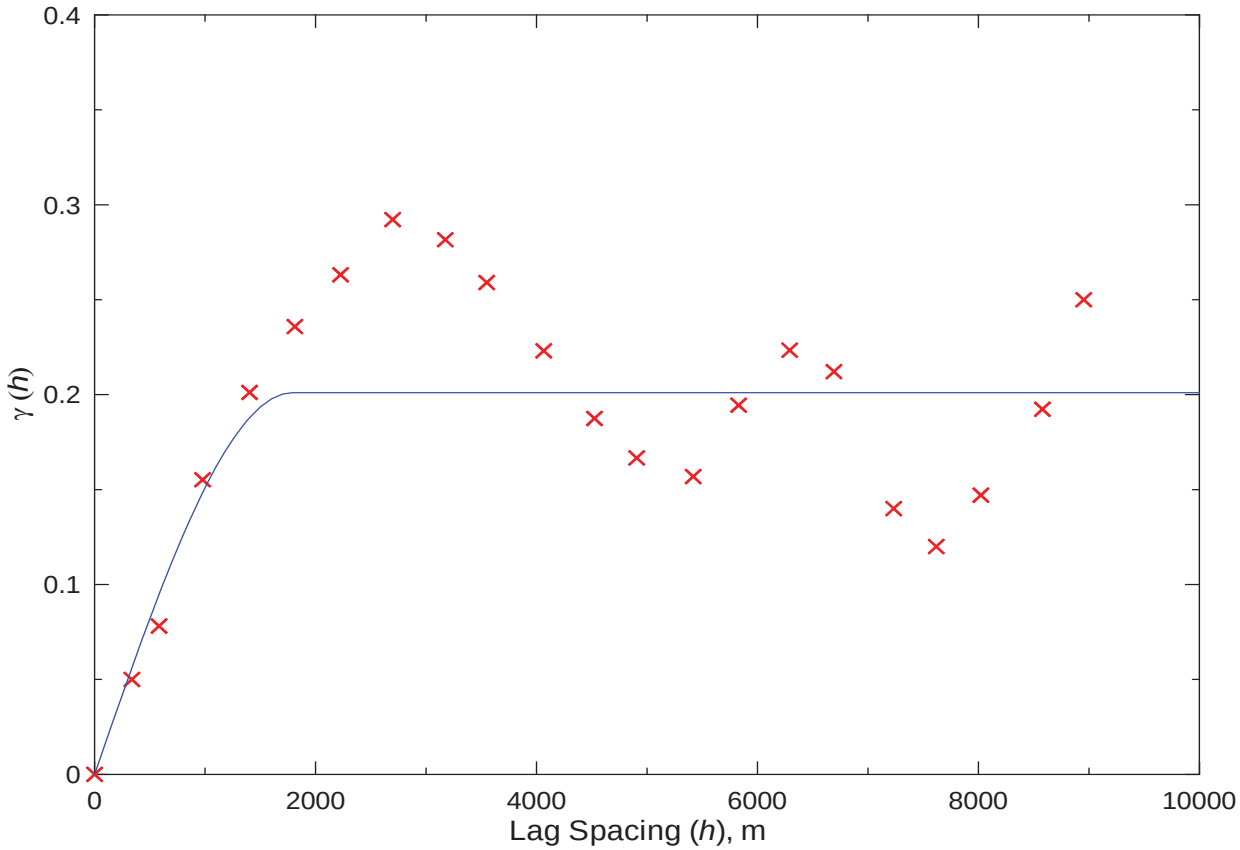

Figure TFIELD-9. High-T Indicator Model and Experimental Variograms

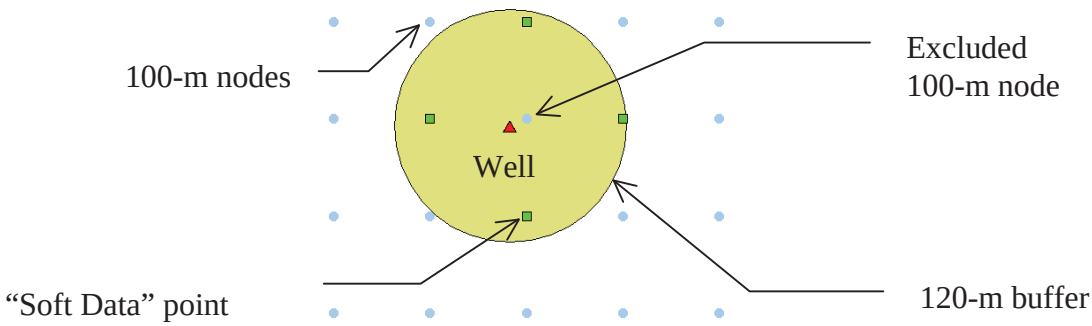

Figure TFIELD-10. Soft Data Around Wells

Five hundred conditional indicator simulations were generated on the 100-m (328-ft) model grid using the GSLIB program sisim (Deutsch and Journel 1998) with Culebra high-T indicator data, soft data for regions around wells and regions where halite underlies and overlies the Culebra, and the variogram parameters. The resulting indicator simulations were used in the construction of base T fields.

TFIELD-4.5 Construction of Base Transmissivity Fields

The linear predictor (Equation (3)) was used to generate 500 equally probable realizations of the T distribution in the Culebra model domain. This calculation required the regression coefficients discussed in Section 3.8 of this attachment, Culebra depth data (Section 3.9 of this attachment), a Salado dissolution indicator function, an indicator for where halite occurs in M2/H2, and the 500 realizations of high-T indicators discussed in Section 4.4 of this attachment.

The 500 base T fields were created in five sets. Each set consists of ten groups of ten realizations given d##r## designations. The "d" counter ranges from 01 to 50, while the "r" counter ranges from 01 to 10. An example base T field is shown in Figure TFIELD-11. Stochastically located patches of relatively high T (yellowish-green) can be clearly seen in the middle zone of the model domain. (Note: On black and white copy, these patches appear as the lightest shade of gray.)

TFIELD-5.0 CONSTRUCTION OF SEED REALIZATIONS

The base T fields described in Section 4.5 of this attachment rely on a regression model to estimate T at every location. By the nature of regression models, the estimated T values will not honor the measured T values at the measurement locations. Therefore, before using these base T fields in a flow model, they must be conditioned to the measured T values. This conditioning is performed with a Gaussian geostatistical simulation algorithm to generate a series of 500 spatially correlated residual fields where each field has a mean value of zero. These fields are conditional such that the residual value at each measurement location, when added to the value provided by the regression model (which is the same for all 500 fields), provides the known T value at that location. The result of adding the simulated residual field to the base T field is the "seed" realization.

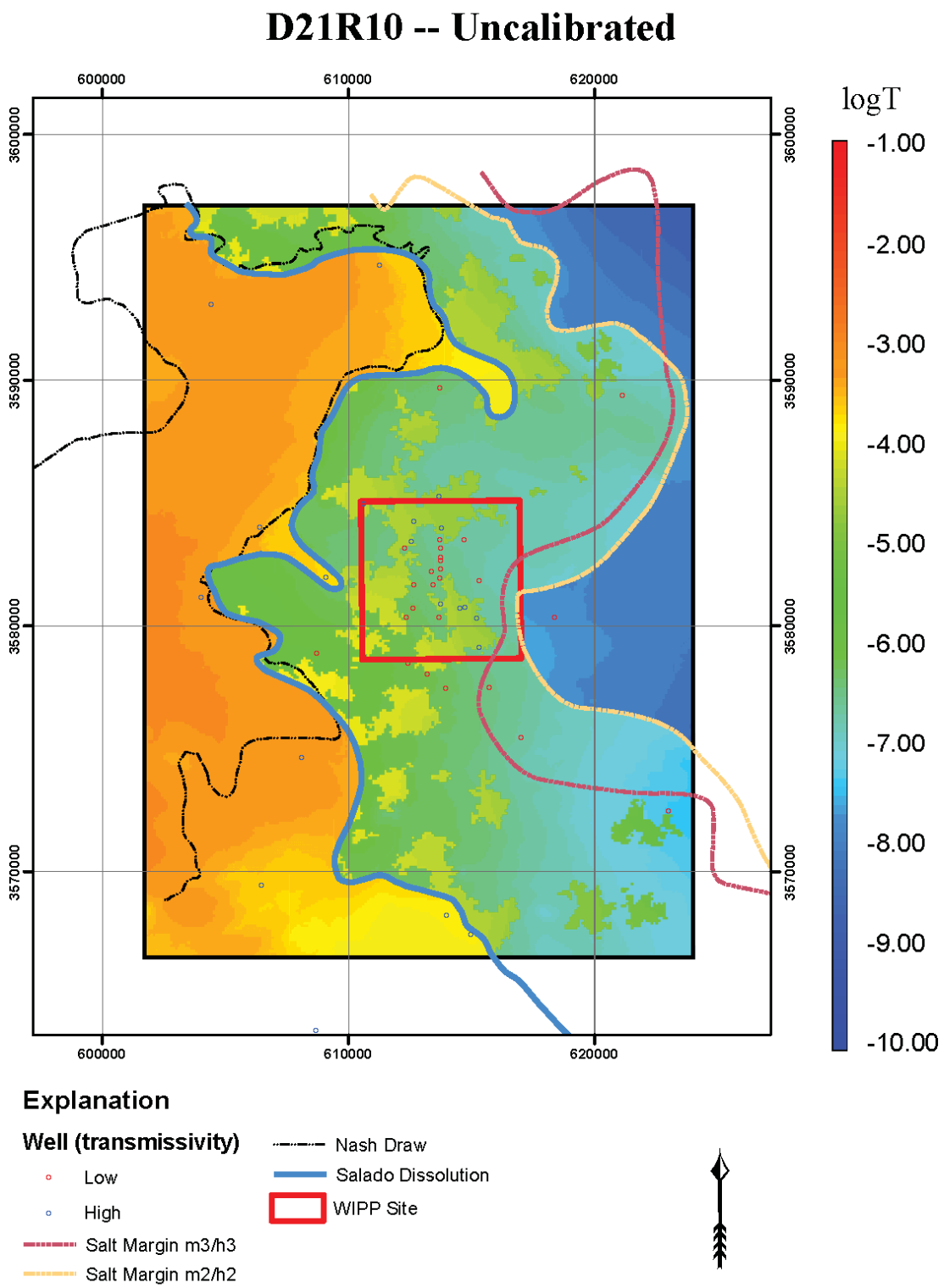

Figure TFIELD-11. Example Base T Field

This process is shown conceptually along a west-to-east cross section of the Culebra in Figure TFIELD-12. The upper image shows the value of the residuals at five T measurement locations across the cross section. These residuals are calculated as the observed (measured) T value minus the base field T value at the same locations. Positive residuals are where the measured T value is greater than that of the base T field. To create a T field from these residuals, there needs to be a way to tie the base field to the measured T values. This tie is accomplished by creating a spatial simulation of the residual values, a "residual field." The middle image of Figure TFIELD-12 is an example residual field as a (red) dashed line along the cross section. This residual field is constructed through geostatistical simulation using a variogram model fit to the residual data. The residual field honors the measured residuals at their measurement locations and returns to a mean value of zero at distances far away from the measurement locations. Finally, this residual field is added to the base T field to create the seed T field. The base T field is represented by the solid (blue) line in the bottom image of Figure TFIELD-12 and the seed T field is shown by the dotted line. The seed T field corresponds to the base T field except at those locations where it must deviate to match the measured T data. The large discontinuity shown in the base T field at the bottom of Figure TFIELD-12 is due to the stochastic simulation of high-T zones within the Culebra.

A total of 46 measured T values and corresponding residual data, both in units of $\log_{10}$ (m^2/s), are available (Table TFIELD-3). For each pair of $\log_{10}$ T and residual data, the well name and the easting (X) and northing (Y) UTM coordinates are also given (for multiwell hydropads, a single well's coordinates were used).

The process of creating the residual fields is to use the residual data to generate variograms in the VarioWin© software package and to then create conditional stochastic Gaussian geostatistical simulations of the residual field within the GSLIB program sgsim (Deutsch and Journel 1998).

To use the data in a Gaussian simulation algorithm, it is first necessary to transform the distribution of the raw residual data to a standard normal distribution. This is accomplished through a process called the "normal-score transform" where each transformed residual value is the "normal-score" of each original datum. The normal-score transform is a relatively simple two-step process. First the cumulative frequency of each original residual value, *cdf(i)*, is determined as:

$$cdf(i) = \frac{R(i) - 0.5}{N} \tag{6}$$

where *R(i)* is the rank (smallest to largest) of the ith residual value and *N* is the total number of data (46 in this case). Then for each cumulative frequency value, the corresponding normal-score value is calculated from the inverse of the standard normal distribution. By definition, the standard normal distribution has a mean of 0.0 and a standard deviation of 1.0. Further details of the normal-score transform process can be found in Deutsch and Journel (1998).

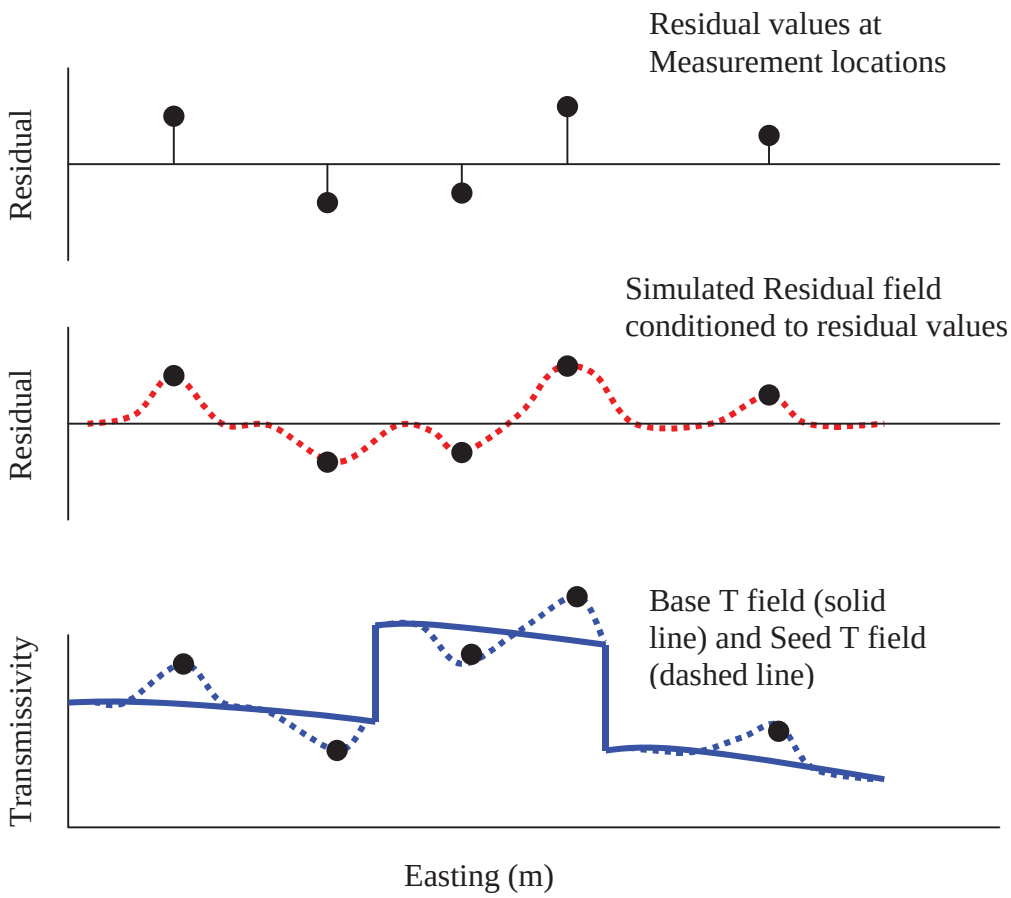

Figure TFIELD-12. Conceptual Cross Section Showing the Updating of the Residual Field and the Base T Field into the Seed T Field

Table TFIELD-3. Log_{10} Transmissivity Data Used in Inverse Calibrations

Well ID	Easting (UTM, m)	Northing (UTM, m)	log_{10} T (m^2/s)	log_{10} T residual (m^2/s)
AEC-7	621126	3589381	–6.8	–0.11078
CB-1	613191	3578049	–6.5	–0.32943
D-268	608702	3578877	–5.7	0.27914
DOE-1	615203	3580333	–4.9	–0.21004
DOE-2	613683	3585294	–4.0	0.69492
Engle	614953	3567454	–4.3	–0.51632
ERDA-9	613696	3581958	–6.3	0.15250
H-1	613423	3581684	–6.0	0.41295
H-2c	612666	3581668	–6.2	0.13594
H-3b1	613729	3580895	–4.7	–0.22131
H-4c	612406	3578499	–6.1	0.05221
H-5c	616903	3584802	–6.7	0.02946

Table TFIELD-3. Log_{10} Transmissivity Data Used in Inverse Calibrations — Continued

Well ID	Easting (UTM, m)	Northing (UTM, m)	log_{10} T (m^2/s)	log_{10} T residual (m^2/s)
H-6c	610610	3584983	–4.4	–0.01524
H-7c	608095	3574640	–2.8	0.39794
H-9c	613974	3568234	–4.0	–0.22763
H-10b	622975	3572473	–7.4	–0.01484
H-11b4	615301	3579131	–4.3	0.25314
H-12	617023	3575452	–6.7	–0.07647
H-14	612341	3580354	–6.5	–0.26934
H-15	615315	3581859	–6.8	–0.12631
H-16	613369	3582212	–6.1	0.34962
H-17	615718	3577513	–6.6	–0.14310
H-18	612264	3583166	–5.7	0.73159
H-19b0	614514	3580716	–5.2	–0.62242
P-14	609084	3581976	–3.5	0.16212
P-15	610624	3578747	–7.0	–0.95938
P-17	613926	3577466	–6.0	0.24762
USGS-1	606462	3569459	–3.3	0.28998
WIPP-12	613710	3583524	–7.0	–0.39627
WIPP-13	612644	3584247	–4.1	0.42180
WIPP-18	613735	3583179	–6.5	0.06840
WIPP-19	613739	3582782	–6.2	0.32598
WIPP-21	613743	3582319	–6.6	–0.11148
WIPP-22	613739	3582653	–6.4	0.10549
WIPP-25	606385	3584028	–3.5	–0.01378
WIPP-26	604014	3581162	–2.9	0.21598
WIPP-27	604426	3593079	–3.3	–0.03209
WIPP-28	611266	3594680	–3.6	–0.15124
WIPP-29	596981	3578694	–3.0	–0.12497
WIPP-30	613721	3589701	–6.7	–0.35131
WQSP-1	612561	3583427	–4.5	0.01540
WQSP-2	613776	3583973	–4.7	–0.02729
WQSP-3	614686	3583518	–6.8	–0.15139
WQSP-4	614728	3580766	–4.9	–0.28895
WQSP-5	613668	3580353	–5.9	0.47178
WQSP-6	612605	3580736	–6.6	–0.32261

The two-step normal-score transformation process is conducted in Microsoft Excel© (see details in McKenna and Hart 2003b). The resulting normal-score values are the distance from the mean as measured in standard deviations. The parameters describing the residual and normal-score transformed distributions are presented in Table TFIELD-4.

Table TFIELD-4. Statistical Parameters Describing the Distributions of the Raw and Normal-score Transformed Residual Data

Parameter	Raw Residual	Normal-Score Transformed Residual Data
Mean	0.000	0.000
Median	–0.015	0.000
Standard Deviation	0.330	0.997
Minimum	–0.959	–2.295
Maximum	0.732	2.295

The omnidirectional variogram is calculated with a 250-m (820-ft) lag spacing. The experimental variogram is shown in Figure TFIELD-13. The model fit to this experimental variogram is Gaussian with a nugget of 0.2, a sill of 0.8, and a range of 1,050 m (3,445 ft). The sum of the nugget and sill values is constrained to equal the theoretical variance of 1.0 by the sgsim software that is used to create the spatially correlated residual fields.

The variogram parameters for the normal-score transformed residuals are used directly in the sgsim program to create 500 conditional realizations of the residual field. Each of these 500 residual fields is used as an initial residual field and each one is assigned to an individual base T field. An example of a realization of the residual field and its combination with a base T field is shown in Figure TFIELD-14. From Figure TFIELD-14, the effect of the residual field on the base T field can be seen. The residual field perturbs the Ts to match the measured Ts at the well locations. The discrete features that are part of the original base T field (e.g., high-T zones in the middle of the domain) are retained when the residual field is added to the base field, although T values within those features may be altered to a degree.

A number of distributed locations within the modeling domain are selected and designated as "pilot points." PEST adjusts the T value at each of these pilot points to achieve a better match between the groundwater flow model results and the observed steady-state and transient head data. The adjustments in T at each pilot point cannot be made independently of surrounding T values and, therefore, these surrounding T values must be updated in a manner consistent with the change made at the pilot point. This updating is done by applying a change at each of the surrounding points that is a weighted fraction of the change made at the pilot point. The weights are calculated from the residual variogram.

These updates are necessary to create a final T field that honors all observed T measurements and matches the observed heads when used as input to a groundwater flow model. Therefore, it is also necessary to calculate and model a variogram on the raw, not normal-score transformed,

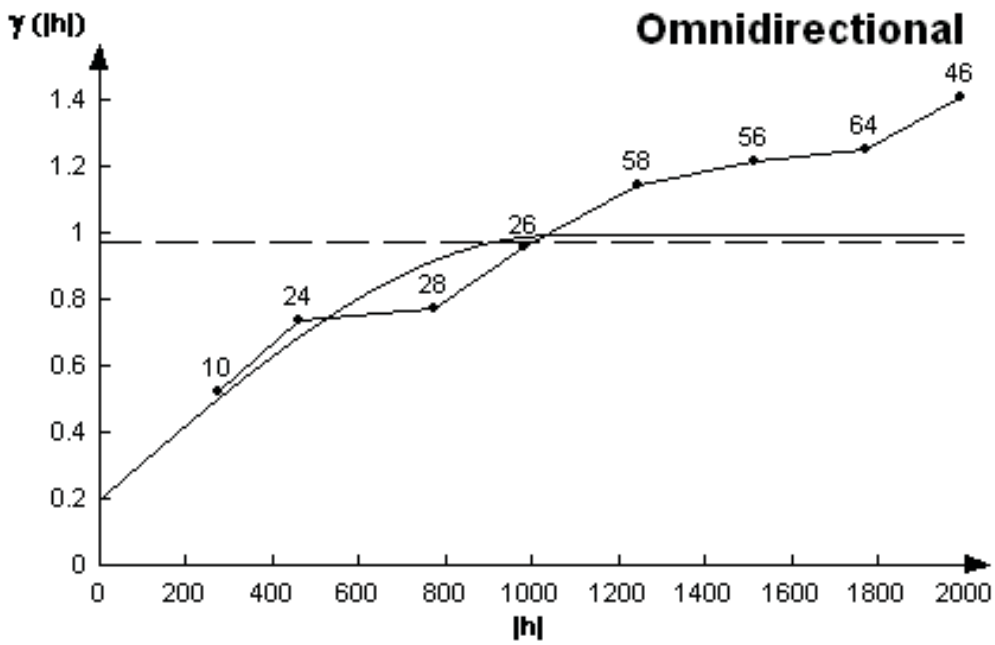

Figure TFIELD-13. Omnidirectional Variogram Model Fit to the Experimental Variogram of the Transmissivity Residuals

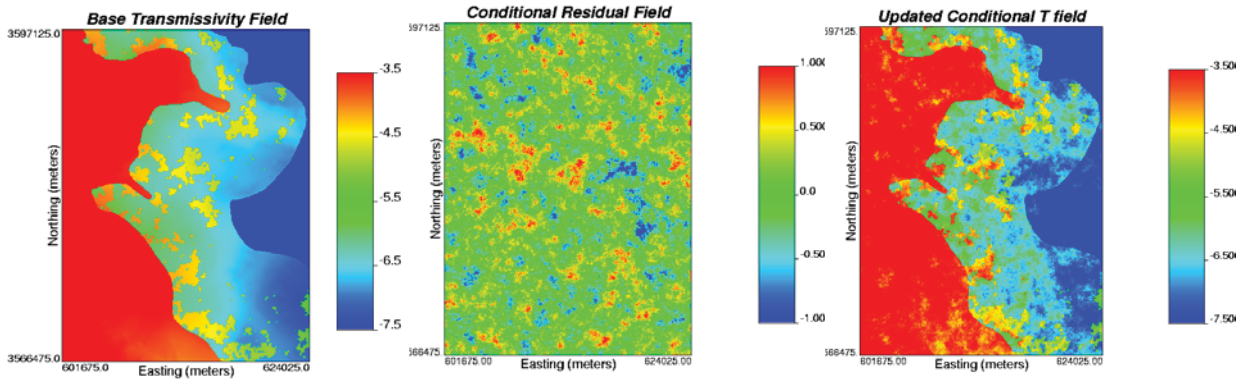

Figure TFIELD-14. An Example of the Creation of a Seed T Field. The base T field (left image) is combined with the initial residual field created through geostatistical simulation (center image) to produce the seed T field (right image). That field is then used as the initial field for the first iteration of the inverse calibration procedure. All three color scales denote the $\log_{10}$ T (m^2/s) value.

residuals for use in this kriging process. This variogram was also calculated with a 250-m (820-ft) lag and is omnidirectional. A doubly nested spherical variogram model was fit to the experimental variogram. The variogram parameters are a nugget of 0.008, a first sill and range of 0.033 and 500 m (1,640 ft), respectively, and a second sill and range of 0.067 and 1,500 m (4,921 ft), respectively (Figure TFIELD-15).

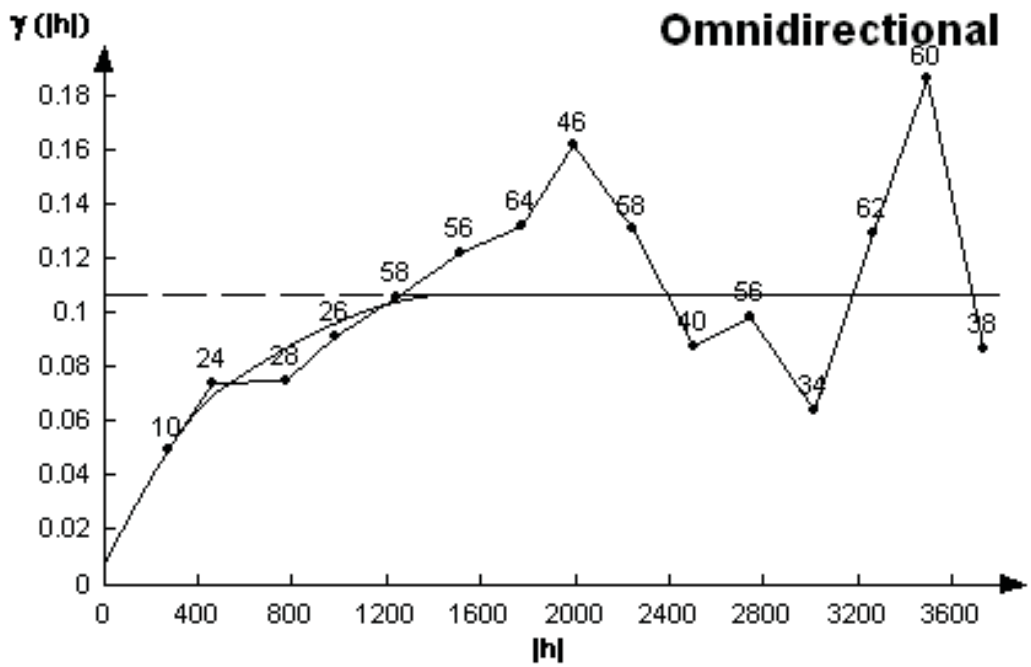

Figure TFIELD-15. Experimental and Model Variograms for the Raw-Space (Not Normal-Score Transformed) Transmissivity Residual Data

TFIELD-6.0 T-FIELD CALIBRATION TO STEADY-STATE AND TRANSIENT HEADS

This section presents details on the modeling approach used to calibrate the T fields to both the 2000 steady-state heads and 1,332 transient drawdown measurements. This section is divided into the following subsections:

1. Assumptions made in the modeling and the implications of these assumptions are provided.

2. The initial heads used for each calibration are estimated at each location in the domain using the heads measured in 2000 using kriging and accounting for the regional trend in the head values.

3. The initial heads are used to assign fixed-head boundaries to three sides of the model. The fourth side, the western edge, is set as a no-flow boundary for the model.

4. The transient head observations for each hydraulic test and each observation well are selected from the database. These heads are shown as a function of time for each hydraulic test.

5. The spatial and temporal discretization of the model domain are presented.

6. The transient head observations are given relative weights based on the inverse of the maximum observed drawdown in each hydraulic test. The relative weights assigned to the steady-state observations are also discussed.

7. The locations of the adjustable pilot points are determined using a combination of approaches.

All of these steps can be considered as preprocessing aspects of the stochastic inverse calibration procedure. The actual calibrations are done using an iterative coupling of the MODFLOW-2000 and PEST codes. The details of this process are covered in McKenna and Hart (2003a, 2003b), and are briefly summarized in this section.

TFIELD-6.1 Modeling Assumptions

The major assumptions that apply to this set of model calculations are:

1. The boundary conditions along the model domain boundary are known and do not change over the time frame of the model. This assumption applies to both the no-flow boundary along the western edge of the domain as well as to the fixed-head boundaries that were created to be consistent with the 2000 head measurements in the model domain. Implicit in this assumption is that the fixed-head boundary conditions do not have a significant impact on the transient tests that were simulated in the interior of the model at times other than the 2000 period.

2. The fracture permeability of the Culebra can be adequately modeled as a continuum at the 100-m (328-ft) × 100-m (328-ft) grid block scale and the measured T values used to condition the model are representative of the T in the 100-m (328-ft) × 100-m (328-ft) grid block in which the well test was performed. Implicit in this assumption is the prior assumption that the hydraulic test interpretations were done correctly and used the correct conceptual model.

3. Variable fluid densities in the Culebra can be adequately represented by casting the numerical solution in terms of freshwater head. Davies (1989) investigated the effects of variable fluid density on the directions of flow calculated in the Culebra using a freshwater-head approach. As the Culebra flow system was conceptualized and modeled by Davies, most of the water flowing in the Culebra in the vicinity of the WIPP site ultimately discharged to the Pecos River southwest of WIPP. When variable fluid density was taken into account, the only locations within the model domain where the flow direction changed by more than 10 degrees were regions 1.1 to 14.3 km (0.7 to 8.9 mi) south of the WIPP site, where the flow direction shifted as much as 70 degrees to the east toward a more downdip direction (but still primarily to the south) (Davies, 1989, Figures 35 and 36). As currently conceptualized, flow in the Culebra in the vicinity of WIPP does not discharge to the Pecos to the southwest, but instead goes to the southsoutheast toward the Paduca oilfield where extensive dissolution of the Salado and collapse of the Culebra has occurred (see Figure TFIELD-1). Hence, taking variable fluid density into account would have little effect on the flow direction.

TFIELD-6.2 Initial Heads

A set of initial head values was estimated across the flow model domain based on water-level measurements made in late 2000 (Beauheim 2002b). The water-level measurements were converted to freshwater heads using fluid-density data collected from pressure-density surveys performed in the wells and/or from water-quality sampling. The head values estimated at the cells in the interior of the domain were used as initial values of the heads and were subsequently updated by the groundwater flow model until the final solution was achieved. The head values estimated for the fixed-head cells along the north, east, and south boundaries of the model domain remained constant for the groundwater flow calculation. The estimation of the initial and boundary heads was done by kriging. Observed heads both within and outside of the flow model domain (Figure TFIELD-16) were used in the kriging process.

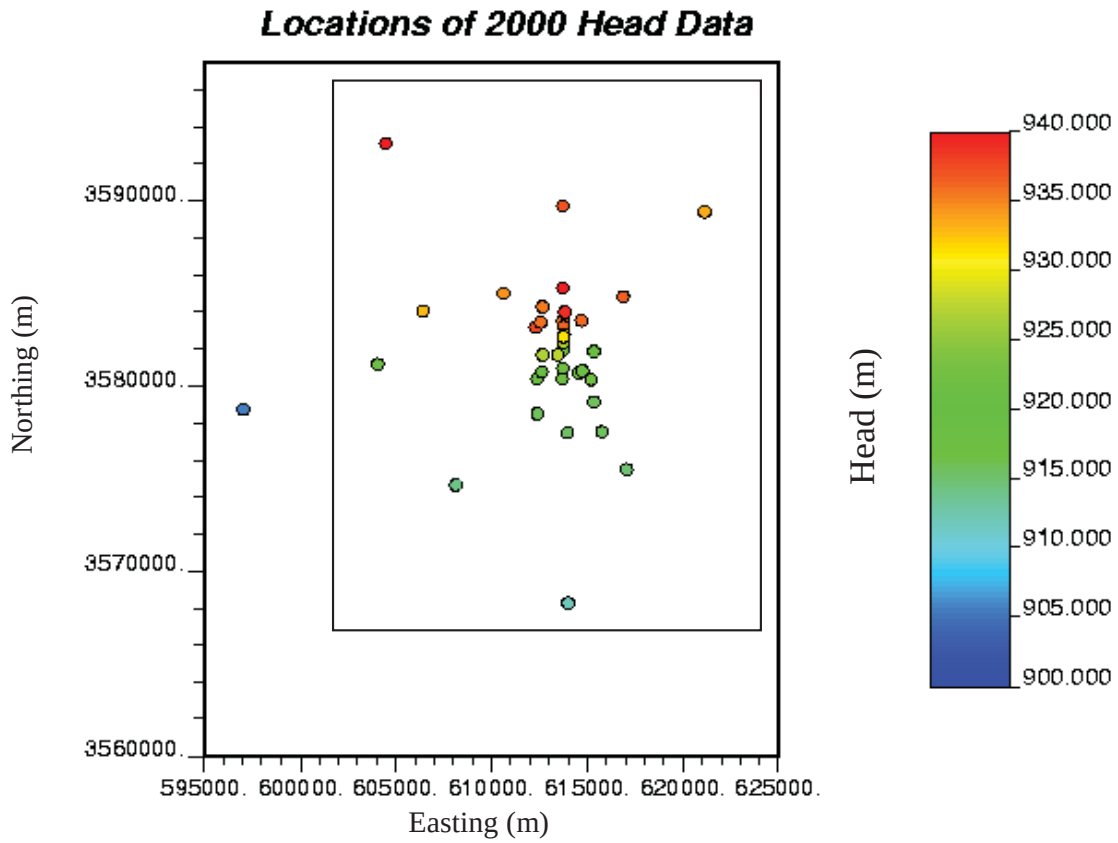

Figure TFIELD-16. Locations and Values of the 2000 Head Measurements Considered in the Steady-State Calibrations. The approximate extent of the numerical model domain is shown by the black rectangle in the image.

Kriging is a geostatistical estimation technique that uses a variogram model to estimate values of a sampled property at unsampled locations. Kriging is designed for the estimation of stationary fields (see Goovaerts 1997); however, the available head data show a significant trend (non-stationary behavior) from high head in the northern part of the domain to low head in the southern part of the domain. This behavior is typical of groundwater head values measured across a large area with a head gradient. To use kriging with this type of non-stationary data, a

Gaussian polynomial function is fit to the data, and the differences between the polynomial and the measured data (the "residuals") are calculated and a variogram of the residuals is constructed. This variogram and a kriging algorithm are then used to estimate the value of the residual at all locations within a domain. The final step in the process is to add the trend from the previously defined polynomial to the estimated residuals to get the final head estimates. This head estimation process is similar to that used in the Culebra calculations done for the CCA (Lavenue 1996).

The available head data from late 2000, comprising 37 measurements, are listed in Table TFIELD-5. In general, these head measurements show a trend from high head in the north to low head in the south. The trend was modeled with a bivariate Gaussian function. The use of this Gaussian function with five estimated parameters allows considerable flexibility in the shape of the trend that can be fit through the observed data. The value of the Gaussian function, *Z*, is:

$$Z = a \exp\left[-\frac{1}{2}\left(\left(\frac{X - X_0}{b} \right)^2 + \left(\frac{Y - Y_0}{c} \right)^2 \right) \right] \tag{7}$$

where X_0 and Y_0 are the coordinates of the center of the function and *b* and *c* are the standard deviations of the function in the *X* (east-west) and *Y* (north-south) directions, respectively. The parameter *a* controls the height of the function. The Gaussian function was fit to the data using the regression wizard tool in the SigmaPlot 2001 graphing software. The parameters estimated for the Gaussian function are presented in Table TFIELD-6. The fit of the Gaussian trend surface to the 2000 heads is shown in Figure TFIELD-17. The locations and values of the residuals (observed value – trend surface estimate) are shown in Figure TFIELD-18.

The next step in estimating the initial head values is to calculate an experimental variogram for each set of residuals and then fit a variogram model to each experimental variogram. Due to the rather limited number of data points, anisotropy in the spatial correlation of the residuals was not examined and an omnidirectional variogram was calculated. These calculations were done using the VarioWin© (version 2.21) software (Pannatier 1996). The Gaussian variogram model is:

$$\gamma(h) = C\left[1 - \exp^{\left(-\frac{3h^2}{a^2} \right)} \right] \text{ for } h > 0 \tag{8}$$

where *C* is the sill of the variogram , *h* is the distance between any two samples, or the lag spacing, and *a* is the practical range of the variogram, or the distance at which the model reaches 95 percent of the value of *C*. In addition to the sill and range, the variogram model may also have a non-zero intercept with the gamma (*Y*) axis of the variogram plot known as the nugget. Due to numerical instabilities in the kriging process associated with the Gaussian model without a nugget value, a small nugget was used in fitting each of the variogram models. The model variogram was fit to the experimental data (Figure TFIELD-19) and the parameters of this model are given in Table TFIELD-7.

Table TFIELD-5. Well Names and Locations of the 37 Head Measurements Obtained in Late 2000 Used to Define Boundary and Initial Heads

Well	UTM X (Easting) (m)	UTM Y (Northing) (m)	2000 Freshwater Head (m amsl)
AEC-7	621126	3589381	933.19
DOE-1	615203	3580333	916.55
DOE-2	613683	3585294	940.03
ERDA-9	613696	3581958	921.59
H-1	613423	3581684	927.19
H-2b2	612661	3581649	926.62
H-3b2	613701	3580906	917.16
H-4b	612380	3578483	915.55
H-5b	616872	3584801	936.26
H-6b	610594	3585008	934.20
H-7b1	608124	3574648	913.86
H-9b	613989	3568261	911.57
H-11b4	615301	3579131	915.47
H-12	617023	3575452	914.66
H-14	612341	3580354	920.24
H-15	615315	3581859	919.87
H-17	615718	3577513	915.37
H-18	612264	3583166	937.22
H-19b0	614514	3580716	917.13
P-17	613926	3577466	915.20
WIPP-12	613710	3583524	935.30
WIPP-13	612644	3584247	935.17
WIPP-18	613735	3583179	936.08
WIPP-19	613739	3582782	932.66
WIPP-21	613743	3582319	927.00
WIPP-22	613739	3582653	930.96
WIPP-25	606385	3584028	932.70
WIPP-26	604014	3581162	921.06
WIPP-27	604426	3593079	941.01
WIPP-29	596981	3578701	905.36
WIPP-30	613721	3589701	936.88
WQSP-1	612561	3583427	935.64
WQSP-2	613776	3583973	938.82
WQSP-3	614686	3583518	935.89
WQSP-4	614728	3580766	917.49
WQSP-5	613668	3580353	917.22
WQSP-6	612605	3580736	920.02

Table TFIELD-6. Parameters for the Gaussian Trend Surface Model Fit to the 2000 Heads

Trend Surface Parameters	Value
X_0	611011.89
Y_0	3780891.50
a	1134.61
b	73559.35
c	313474.40

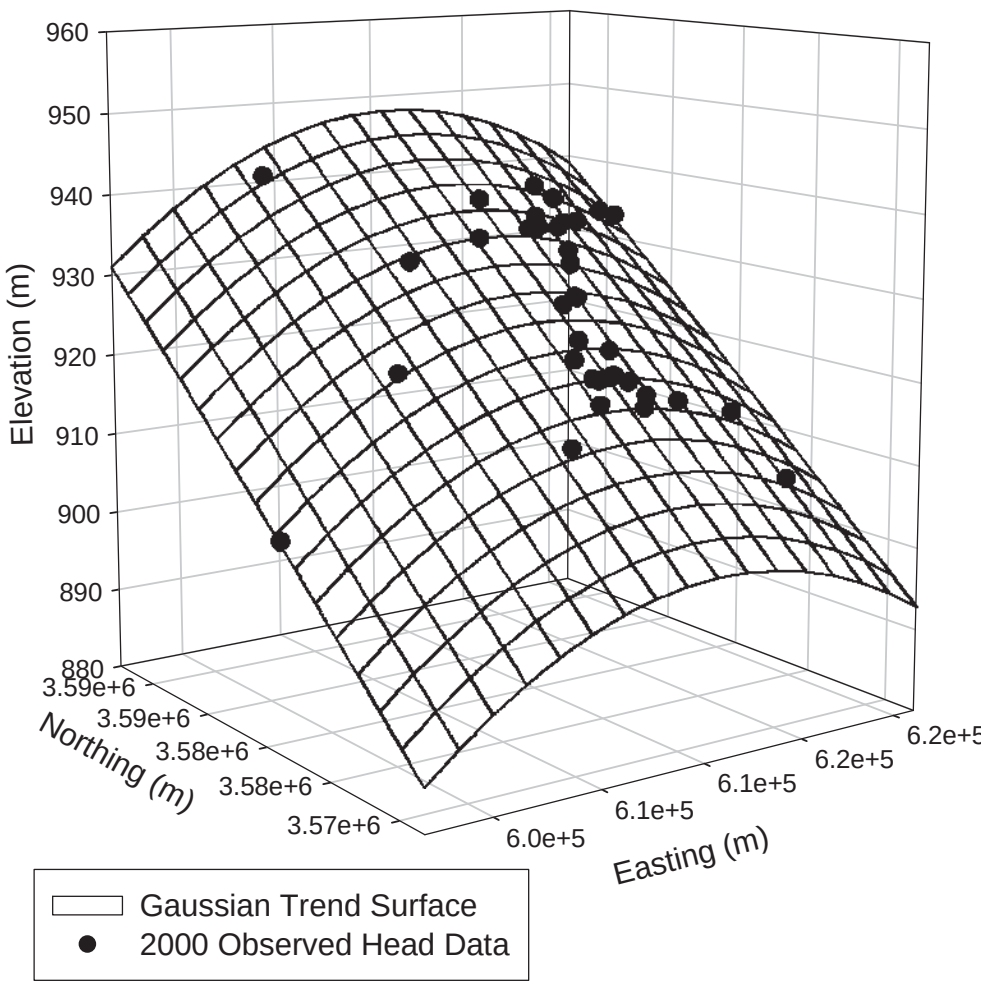

Figure TFIELD-17. Gaussian Trend Surface Fit to the 2000 Observed Heads

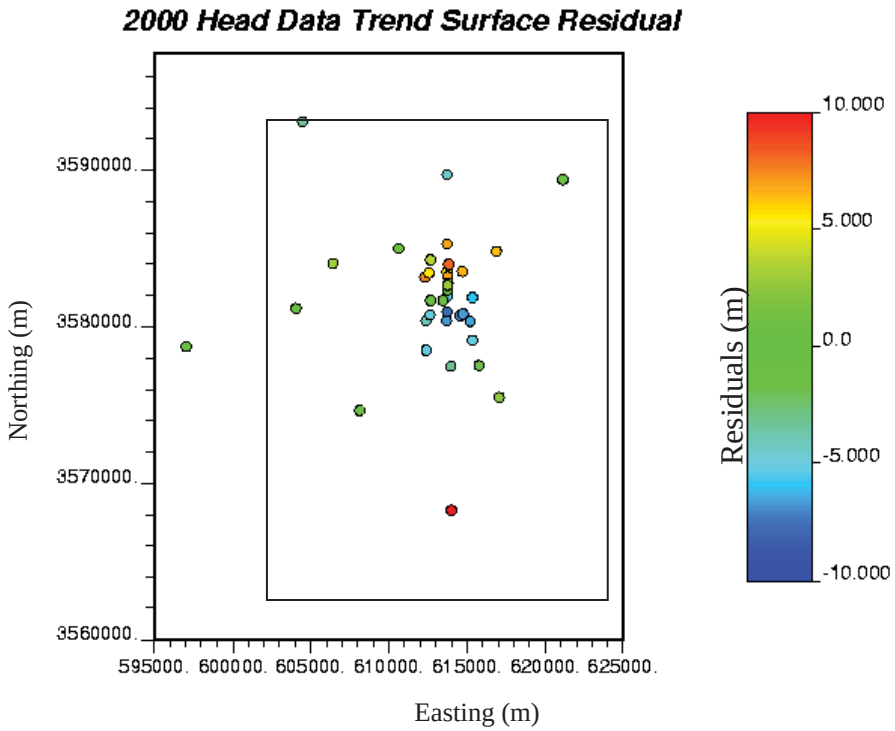

Figure TFIELD-18. Locations and Values of the Residuals Between the Gaussian Trend Surface Model and the Observed Head Data. The approximate boundary of the flow model is shown as a black rectangle in the image.

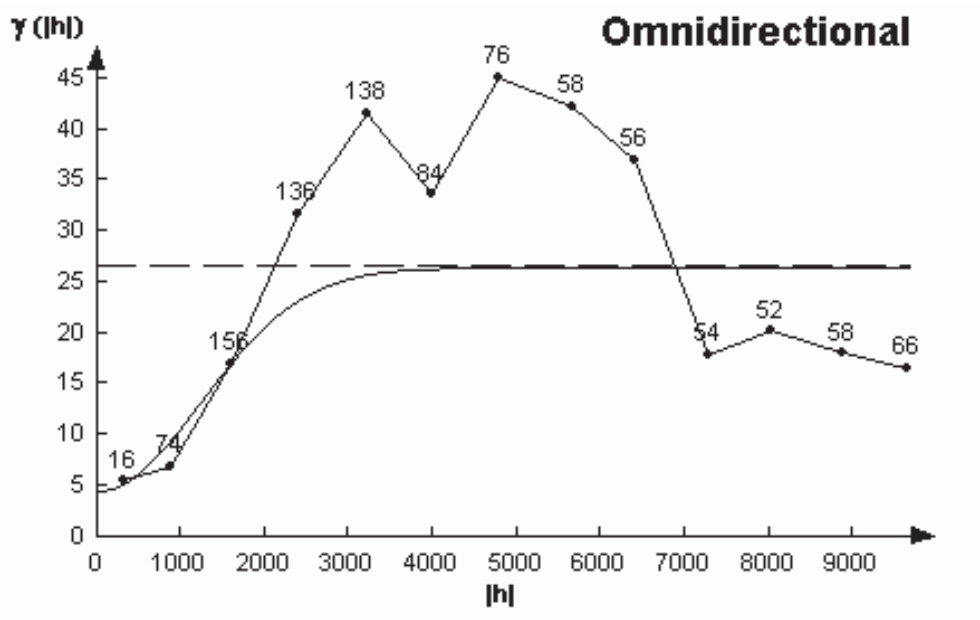

Figure TFIELD-19. Omnidirectional Experimental (Straight-Line Segments) and Model Variograms of the Head Residuals (Curves) for the 2000 Heads. The numbers indicate the number of pairs of values that were used to calculate each point and the horizontal dashed line denotes the variance of the residual data set.

Table TFIELD-7. Model Variogram Parameters for the Head Residuals

Parameter	Value
Sill	22
Range (meters)	3000
Nugget	4.5
Number of Data	37

The experimental variogram calculated on the 2000 data in Figure TFIELD-19 shows a number of points between lags 2,000 and 7,000 m (1.25 and 4.25 mi) that are above the variance of the data set (the horizontal dashed line). This behavior indicates that the Gaussian trend surface model used to calculate the residuals from the measured data did not remove the entire trend inherent in the observed data. A higher order trend surface model could be applied to these data to remove more of the trend, but the Gaussian trend surface model provides a reasonable estimate of the trend in the data.

The GSLIB kriging program kt3d (Deutsch and Journel 1998) was used to estimate the residual values at all points on the grid within the model domain. The Gaussian trend surface was then added to the estimated residual values to produce the final estimates of the initial head field.

TFIELD-6.3 Boundary Conditions

Two types of boundary conditions were specified in MODFLOW-2000: constant-head and no-flow. Constant-head conditions were assigned along the eastern boundary of the model domain, and along the central and eastern portions of the northern and southern boundaries. Values of these heads were obtained from the kriged initial head field. The western model boundary passes through the IMC tailings pond (Laguna Uno) due west of the WIPP site in Nash Draw. A no-flow boundary (a flow line) is specified in the model from this tailings pond up the axis of Nash Draw to the northeast, reflecting the concept that groundwater flows down the axis of Nash Draw, forming a groundwater divide. Similarly, another no-flow boundary is specified from the tailings pond down the axis of the southeastern arm of Nash Draw to the southern model boundary, coinciding with a flow line in the regional modeling of Corbet and Knupp (1996). Thus, the northwestern and southwestern corners of the modeling domain are specified as inactive cells in MODFLOW-2000. The initial (starting) head field is shown in Figure TFIELD-20 and the head values along each boundary of the model domain are shown in Figures TFIELD-21 and TFIELD-22.

TFIELD-6.4 Observed Steady-State and Transient Head Data Used in Model Calibration

In addition to being used to generate an initial head distribution, the water-level measurements made in 35 wells within the model domain during late 2000 were also used in steady-state model calibration. (Note that Table TFIELD-5 includes data from two wells – WIPP-27 and WIPP-29 – that were used to define model boundary conditions but are outside the area of calibration).

The transient observation data used for the transient calibrations were taken from a number of different sources listed in Beauheim (2003a). Responses to seven different hydraulic tests were employed in the transient portion of the calibration (Table TFIELD-8). Hydraulic responses for each of the seven tests were monitored in three to ten different observation wells depending on the hydraulic test.

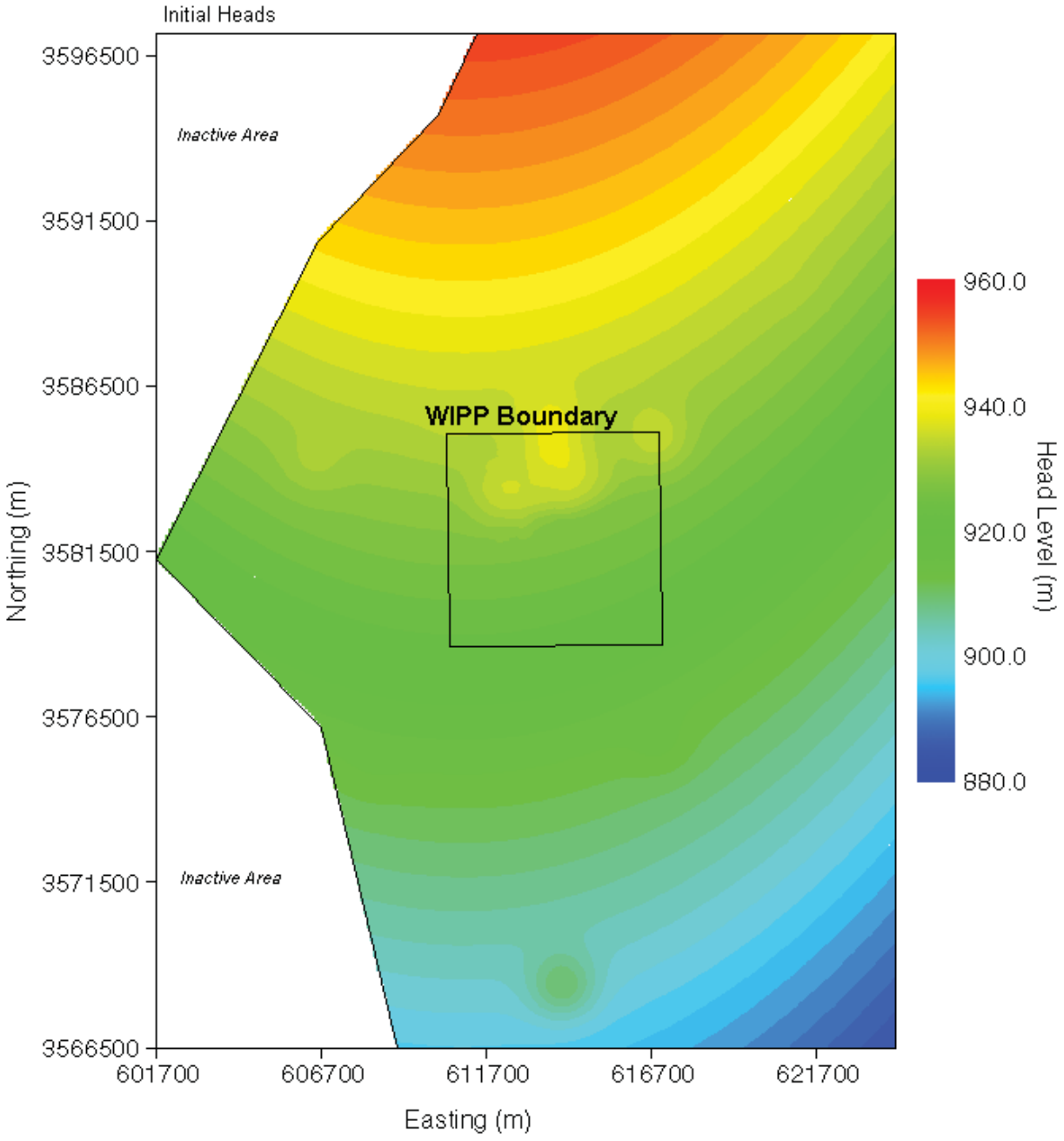

Figure TFIELD-20. Map of Initial Heads Created Through Kriging and Used to Assign Fixed-Head Boundary Conditions

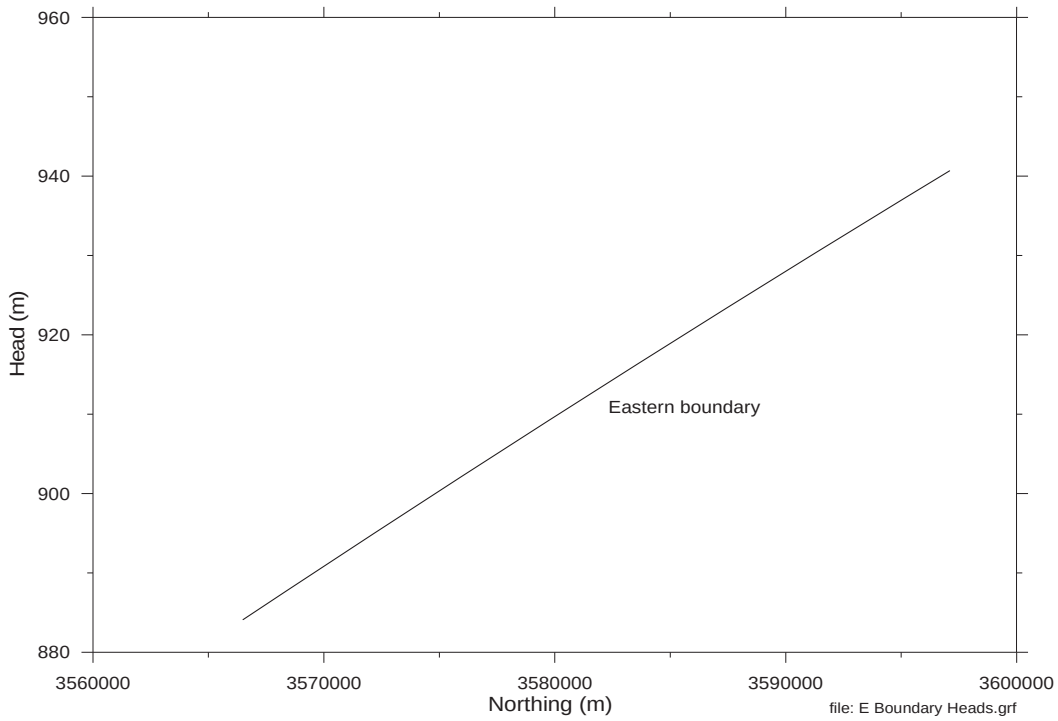

Figure TFIELD-21. Values of Fixed Heads Along the Eastern Boundary of the Model Domain

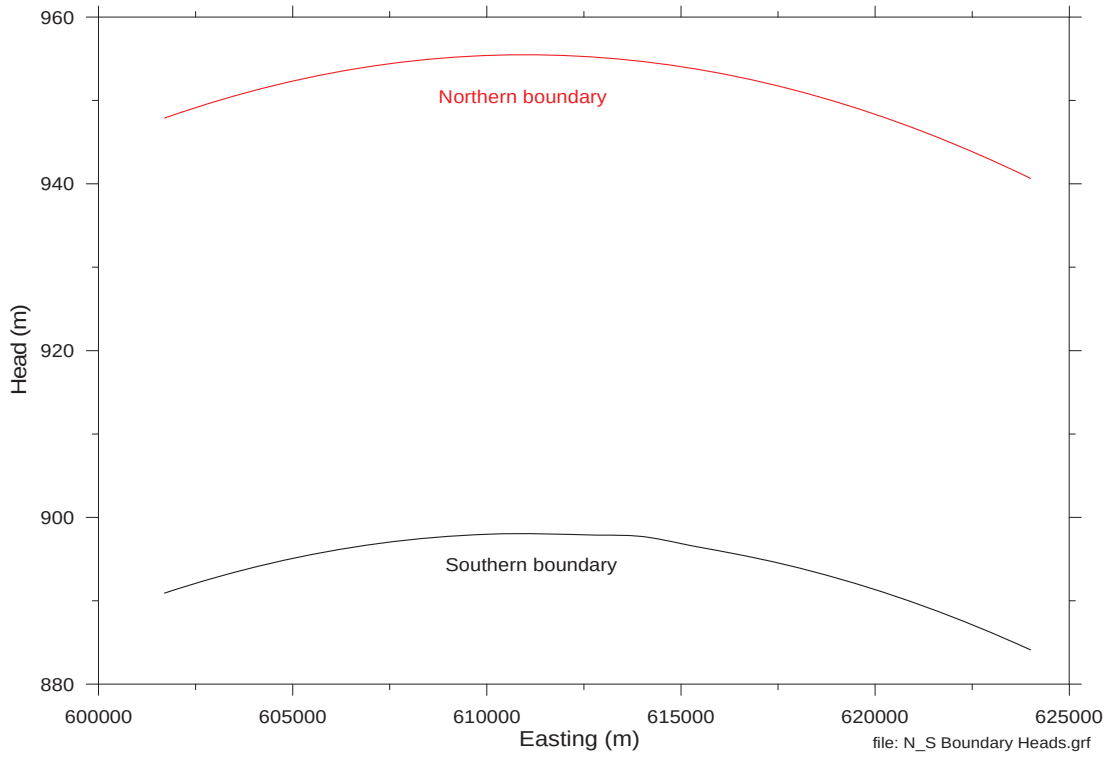

Figure TFIELD-22. Values of Fixed Heads Along the Northern and Southern Boundaries of the Model Domain. Note that not all locations along the boundaries are active cells.

Table TFIELD-8. Transient Hydraulic Test and Observation Wells for the Drawdown Data

Stress Point	Observation Well	Observation Start	Observation End	Observation Type
H-3b2	DOE-1	10/15/1985	3/18/1986	Drawdown
	H-1	10/15/1985	4/14/1986	Drawdown
	H-2b2	10/15/1985	4/2/1986	Drawdown
	H-11b1	10/15/1985	4/21/1986	Drawdown
WIPP-13	DOE-2	1/12/1987	5/15/1987	Drawdown
	H-2b2	1/12/1987	5/15/1987	Drawdown
	H-6b	1/12/1987	5/15/1987	Drawdown
	P-14	1/12/1987	5/15/1987	Drawdown
	WIPP-12	1/12/1987	5/15/1987	Drawdown
	WIPP-18	1/12/1987	5/15/1987	Drawdown
	WIPP-19	1/12/1987	5/15/1987	Drawdown
	WIPP-25	1/12/1987	4/2/1987	Drawdown
	WIPP-30	1/12/1987	5/15/1987	Drawdown
P-14	D-268	2/14/1989	3/7/1989	Drawdown
	H-6b	2/14/1989	3/10/1989	Drawdown
	H-18	2/14/1989	3/10/1989	Drawdown
	WIPP-25	2/14/1989	3/7/1989	Drawdown
	WIPP-26	2/14/1989	3/7/1989	Drawdown
H-11b1	H-4b	2/7/1996	12/11/1996	Drawdown
	H-12	2/6/1996	12/10/1996	Drawdown
	H-17	2/6/1996	12/10/1996	Drawdown
	P-17	2/7/1996	12/10/1996	Drawdown
H-19b0	DOE-1	12/15/1995	12/10/1996	Drawdown
	ERDA-9	12/15/1995	12/10/1996	Drawdown
	H-1	12/15/1995	12/10/1996	Drawdown
	H-14	2/7/1995	12/10/1996	Drawdown
	H-15	12/12/1995	12/10/1996	Drawdown
	H-2b2	2/7/1996	12/10/1996	Drawdown
	H-3b2	12/15/1995	12/10/1996	Drawdown
	WIPP-21	1/18/1996	12/9/1996	Drawdown
	WQSP-4	1/1/1996	12/10/1996	Drawdown
	WQSP-5	1/18/1995	12/10/1996	Drawdown
WQSP-1	H-18	1/25/1996	2/20/1996	Drawdown
	WIPP-13	1/25/1996	2/20/1996	Drawdown
	WQSP-3	1/15/1996	2/20/1996	Zero Response
WQSP-2	DOE-2	2/20/1996	3/28/1996	Drawdown
	H-18	2/20/1996	3/28/1996	Drawdown
	WIPP-13	2/20/1996	3/28/1996	Drawdown
	WQSP-1	2/20/1996	3/24/1996	Drawdown
	WQSP-3	2/20/1996	3/24/1996	Zero Response

A major change in the calibration data set from the CCA calculations is the exclusion of the hydraulic responses to the excavation of the exploratory (now salt) and ventilation (now waste) shafts in the current calibration. The responses to the shaft excavations were excluded because:

1. Only two wells (H-1 and H-3) responded directly to the shaft excavations and the areas between the shafts and these wells are stressed by other hydraulic tests that are included in the calibration data set (H-3b2, WIPP-13, and H-19b0).

2. It was difficult to model both the flux and pressure changes accurately during the excavation of the shafts with MODFLOW-2000. This difficulty is due to both the finite-difference discretization of MODFLOW-2000 that requires each shaft to be modeled as a complete model cell and some limitations of the data set.

3. The long-term effects of the shafts on site-wide water levels were important for the CCA modeling because that modeling sought to replicate heads over time. In the current CRA-2004 calibration effort, shaft effects are not important because drawdowns resulting from specific hydraulic tests are used as the calibration targets and shaft effects can be considered as second-order compared to the effects of the hydraulic tests that are simulated.

A small amount of processing of the observed data was necessary prior to using it in the calibration process. This processing included selecting the data values that would be used in the calibration procedure from the often voluminous measurements of head. These data were chosen to provide an adequate description of the transient observations at each observation well across the response time without making the modeling too computationally burdensome in terms of the temporal discretization necessary to model responses to these observations. Scientific judgment was used in selecting these data points. This selection process resulted in a total of 1,332 observations for use in the transient calibration.

Additionally, the modeling of the pressure data is done here in terms of drawdown. Therefore, the value of drawdown at the start of any transient test must be zero. A separate perl script was written to normalize each set of observed heads to a zero value reference at the start of the test with the exception of the H-3 test that is only preceded by the steady-state simulation. The calculations are such that the resulting drawdown values are positive.

In addition to normalizing the measured head data, some of the tests produced negative drawdown values when normalized. These negative results are due to some of the observations having heads greater than the reference value. This occurs due to some hydraulic tests that were conducted at earlier times in the Culebra but were not included in the numerical model. If the drawdowns from one of these previous tests are still recovering to zero at the start of a simulation, they can cause negative drawdowns in the simulation as the recovery continues. Most of these effects were addressed through trend removal in initial data processing (Beauheim 2003a) but some residual effects remain.

The resultant transient calibration points are shown in Figures TFIELD-23 through TFIELD-36. These sets of figures show the location of each hydraulic test and the locations of the observation wells for that test within the model domain and the time series of drawdown values for each

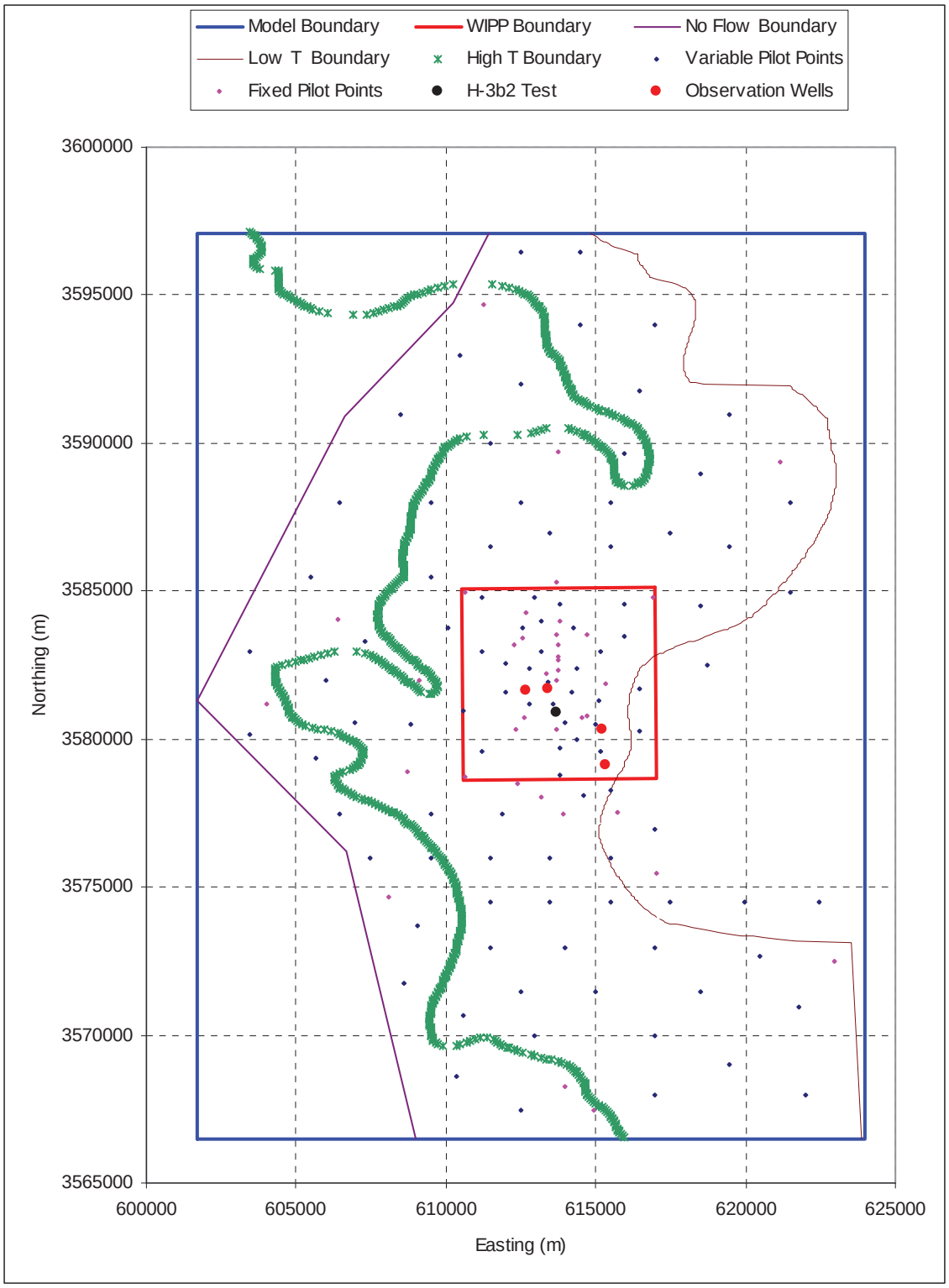

Figure TFIELD-23. Locations of the H-3b2 Hydraulic Test Well and Observation Wells

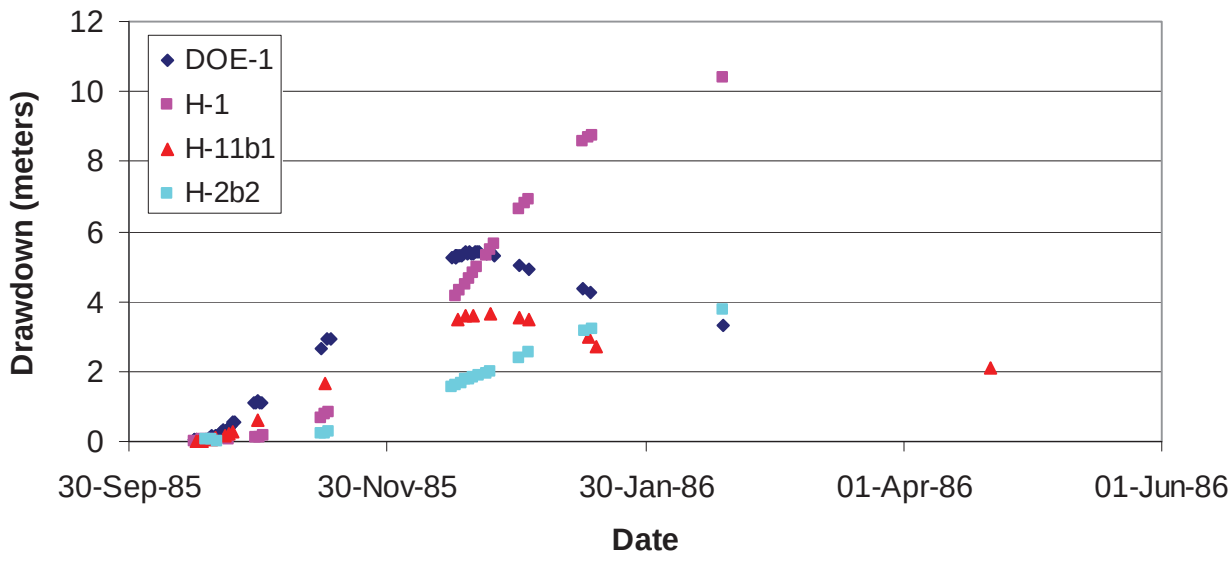

Figure TFIELD-24. Observed Drawdowns for the H-3b2 Hydraulic Test

observation well. The values of drawdown are in meters where a positive drawdown indicates a decrease in the pressure within the well relative to the pressure before the start of the pumping (negative drawdown values indicate rises in the water level). For the WQSP-1 and WQSP-2 tests, well WQSP-3 showed no response. These results are used in the calibration process by setting the observed drawdown values to zero for WQSP-3. The maps in Figures TFIELD-23 through TFIELD-35 also show the locations of the pilot points used in the calibration (these are discussed later).

TFIELD-6.5 Spatial Discretization

The flow model was discretized into 68,768 regular, orthogonal cells each of which is 100 m (328 ft) × 100 m (328 ft). A constant Culebra thickness of 7.75 m (25.4 ft) was used (CCA Appendix TFIELD.4.1.1, Culebra:Thick). The 100-m (328-ft) grid discretization was selected to make the finite-difference grid cell sizes considerably finer, on average, than those used in the CCA calculations, but still computationally tractable. In the CCA calculations, a telescoping finite-difference grid was used with the smallest cell being 100 m (328 ft) × 100 m (328 ft) near the center of the domain. The largest cells in the CCA flow model grid were 800 m (2,625 ft) × 800 m (2,625 ft) near the edges of the domain (Lavenue, 1996).

The cells in the model domain were assigned elevations based on the digitized version of Figure TFIELD-1. Of the 68,768 cells (224 east-west by 307 north-south), 14,999 (21.8 percent) lie to the west of the no-flow boundary, so the total number of active cells in the model is 53,769. This number is nearly a factor of five larger than the 10,800 (108 × 100) cells used in the CCA calculations.

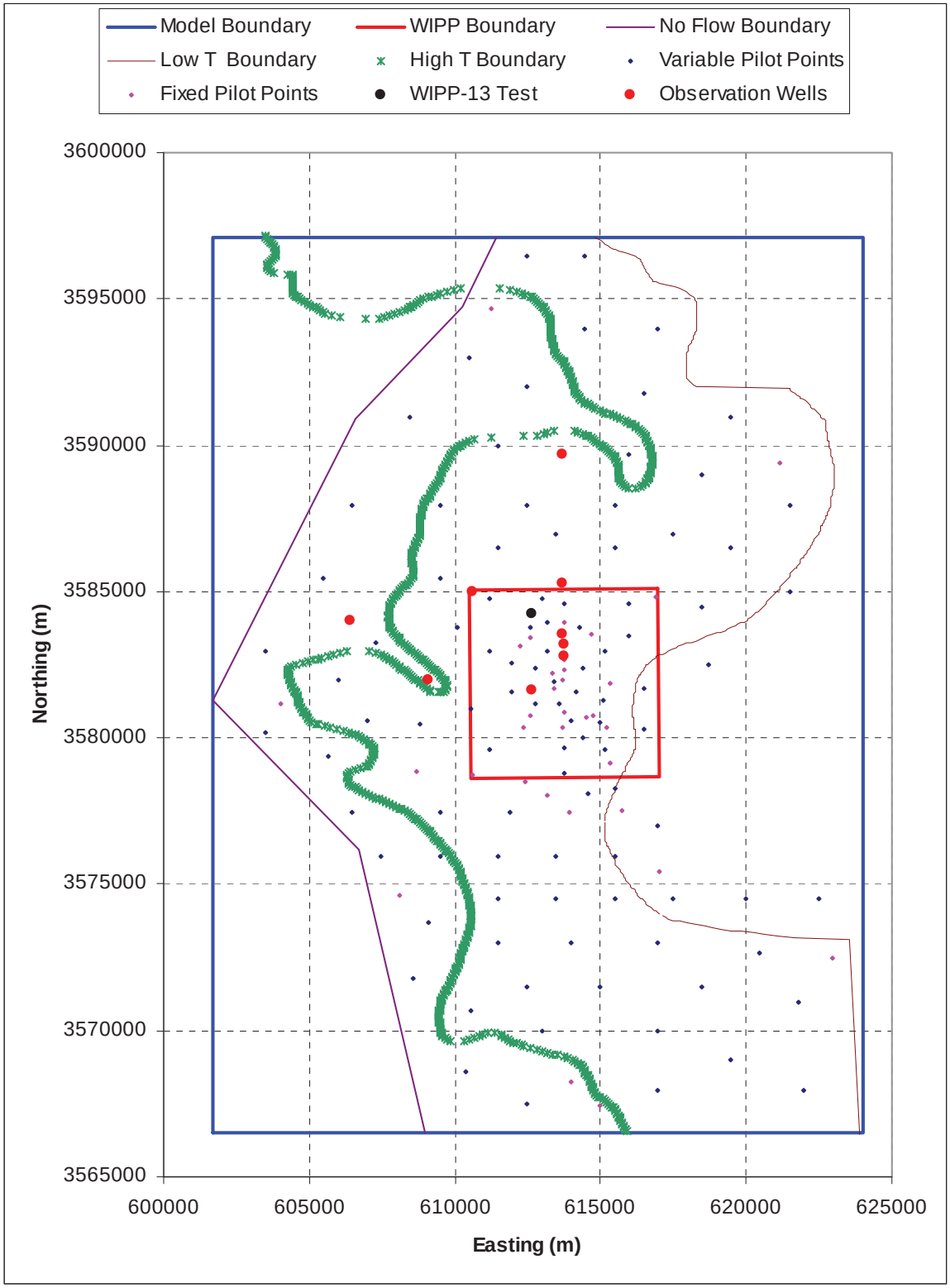

Figure TFIELD-25. Locations of the WIPP-13 Hydraulic Test Well and Observation Wells

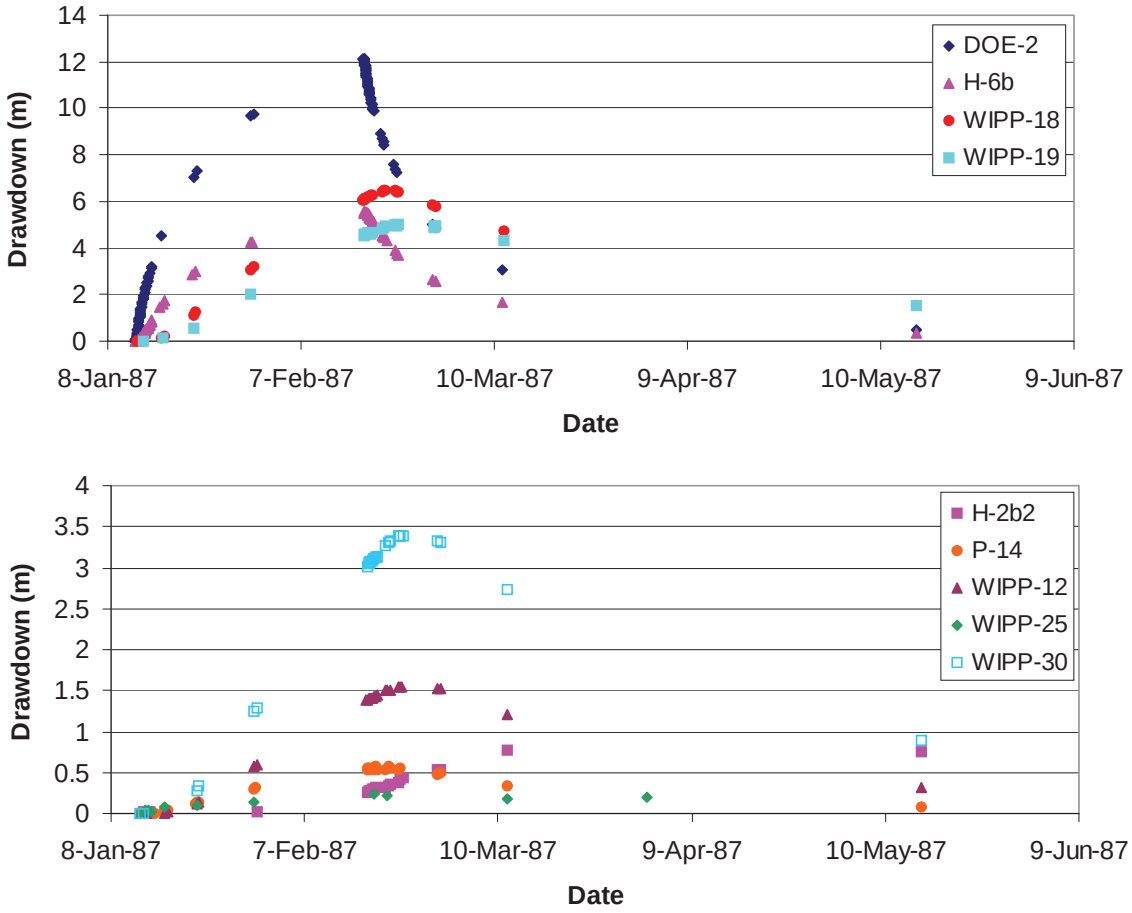

Figure TFIELD-26. Observed Drawdowns for the WIPP-13 Hydraulic Test. Note the change in the scale of the Y-axis from the upper to the lower image.

TFIELD-6.6 Temporal Discretization

The time period of nearly 11 years and 2 months covered by the transient modeling began October 15, 1985 and ended December 11, 1996. Additionally, a single steady-state calculation was run prior to the transient modeling. The length of this steady-state time period and the date at which it occurs were arbitrarily set to one day (86,400 s) occurring from October 14, 1985, to October 15, 1985. These steady-state heads were measured in the year 2000 and were only set to these October dates to provide a steady-state solution prior to the start of any transient hydraulic events. The responses to the transient events were defined by the amount of drawdown relative to the initial steady-state solution. The discretization of this time interval was dictated by the pumping history of the different wells used in the hydraulic testing and consideration of the additional computational burden required for increasingly fine time discretization.

The groundwater flow model, MODFLOW-2000, allows for the discretization of time into both "stress periods" and "time steps." A stress period is a length of time over which the boundary conditions and internal stresses on the system are constant. Even though these stresses are constant, this does not mean that the flow system is necessarily at steady state during the stress

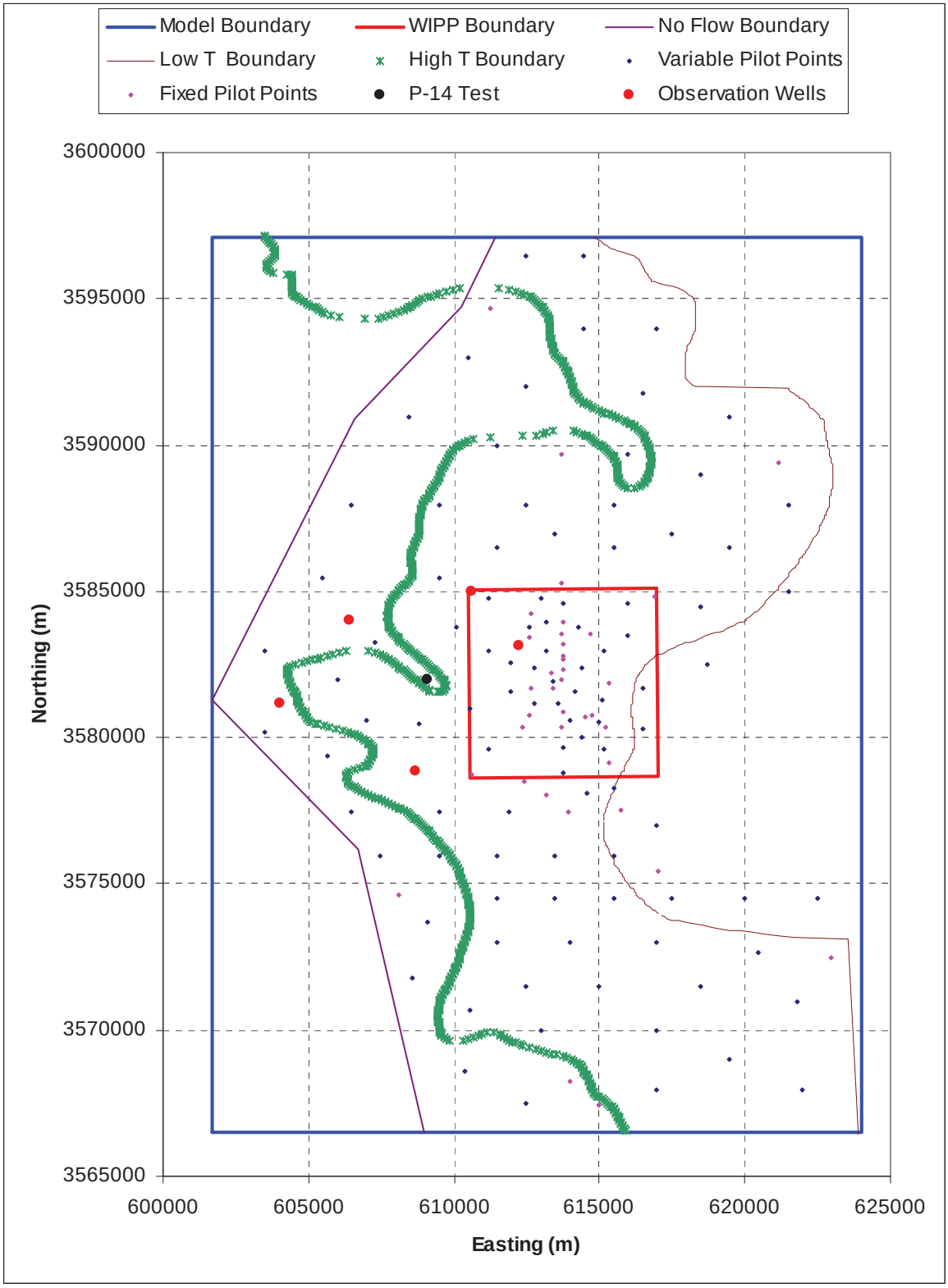

Figure TFIELD-27. Locations of the P-14 Hydraulic Test Well and Observation Wells

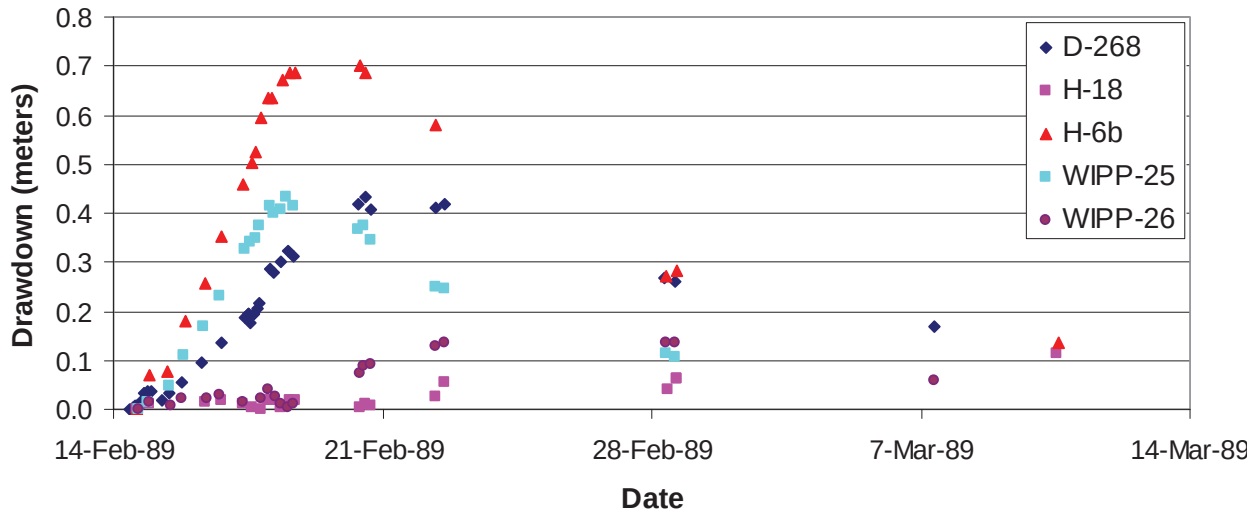

Figure TFIELD-28. Observed Drawdowns for the P-14 Hydraulic Test

period. A time step is a subdivision of a stress period. System information such as the head or drawdown values is only calculated at the specified time steps. Each stress period must contain at least one time step. MODFLOW-2000 allows for the specification of the stress period length, the number of time steps in the stress period, and a time step multiplier. The time step multiplier increases the time between successive time steps geometrically. This geometric progression provides a nearly ideal time discretization for the start of a pumping or recovery period. To save on computational costs associated with calculating head/drawdown at each time step and with writing out the heads/drawdowns, the number of time steps in the model was kept to the minimum number possible that still adequately simulated the hydraulic tests. The time discretization in MODFLOW-2000 resulted in modeled heads calculated at times that sometimes differed from the observation times. For this situation, the PEST utility, mod2obs, was used to interpolate the head, or drawdown, values in time from the simulation times to the observation times.

A summary of the time discretization is given in Table TFIELD-9. There are five separate MODFLOW-2000 simulations for each complete forward simulation of the transient events. Each separate call to MODFLOW-2000 has its own set of input and output files. In Table TFIELD-9, each call to MODFLOW-2000 is separated by a horizontal black line. The first call is the steady-state simulation. The second, third, and fourth calls to MODFLOW-2000 (H-3, WIPP-13, and P-14) are all similar in that a single well was pumped. For the H-3 and WIPP-13 calls, there were a total of three stress periods. In the first stress period, the well was pumping at a constant rate; in the second stress period, the pumped well was inactive and heads were recovering after the cessation of pumping; and the final stress period was simply a long time of no pumping activity used to advance the simulation time to be consistent with the calendar time. The first two stress periods were discretized using eight time steps and the final stress period with no pumping activity was discretized using the minimum possible number of time steps—one.

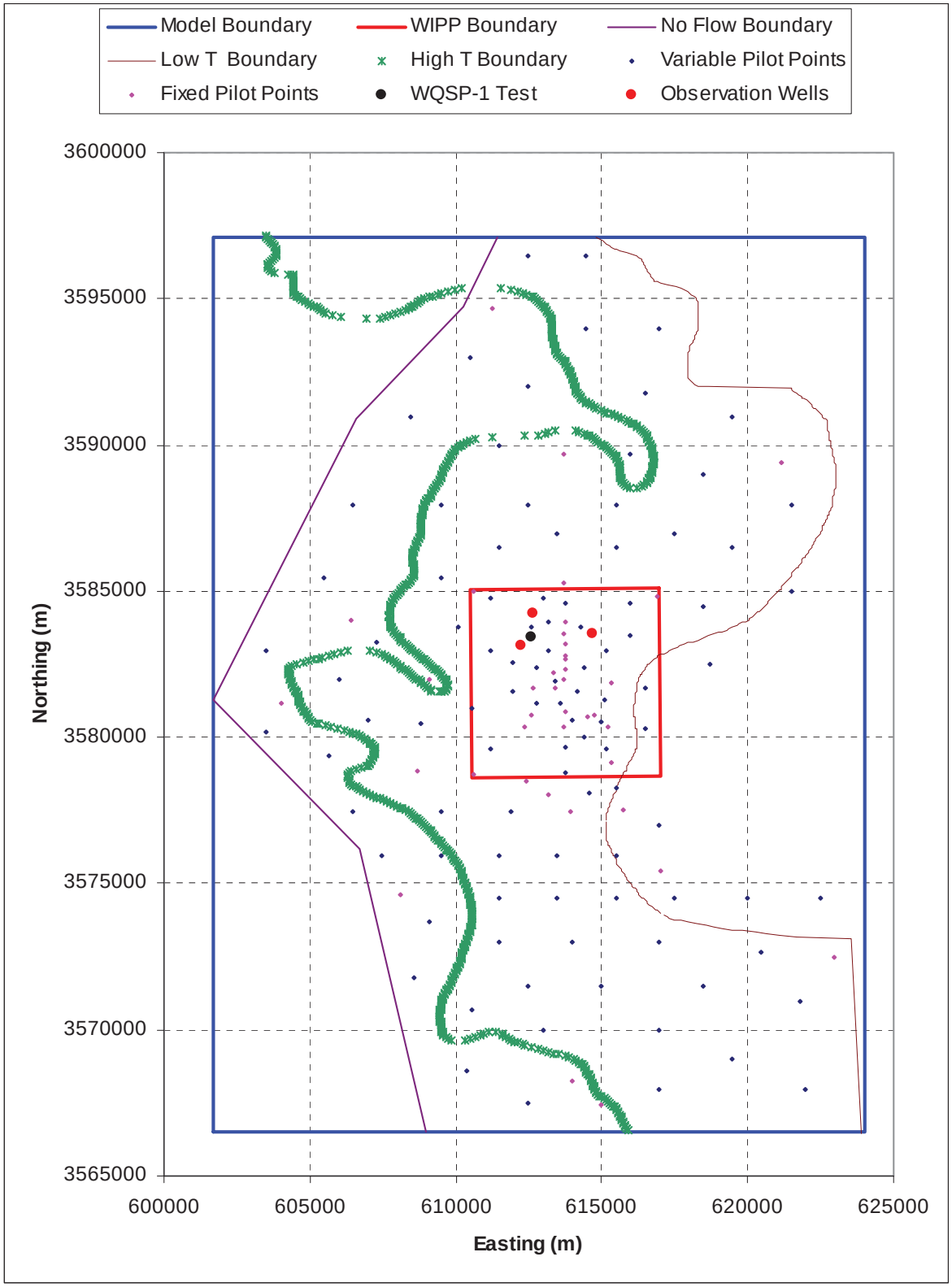

Figure TFIELD-29. Locations of the WQSP-1 Hydraulic Test Well and Observation Wells

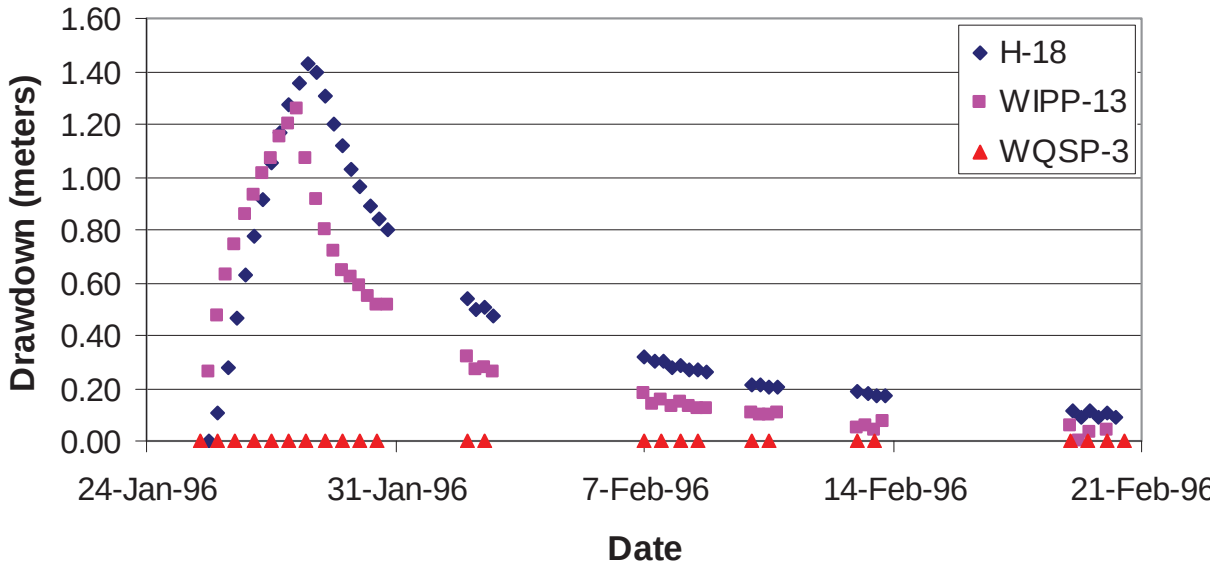

Figure TFIELD-30. Observed Drawdowns for the WQSP-1 Hydraulic Test

The final MODFLOW-2000 call, the H-19 call, was considerably more complicated than the earlier calls to MODFLOW-2000 and simulated the hydraulic conditions during the H-11, H-19, WQSP-1, and WQSP-2 hydraulic tests. This final call contained 17 stress periods with as many as three different wells pumping during any single stress period. The pumping rates of the different wells in this call to MODFLOW-2000 and the stress periods are shown as a function of time in Figure TFIELD-37. The first six stress periods in this call simulated pumping in the H-19 and H-11 wells without any observations (Table TFIELD-9). These pumping periods were added to the model solely to account for the effects of these tests in observations of later hydraulic tests and, therefore, these tests could be modeled with a single time step. The pumping rates shown in Figure TFIELD-37 are given as negative values to indicate the removal of water from the Culebra following the convention used in MODFLOW-2000.

The MODFLOW-2000 simulations could be done using a single call to MODFLOW-2000, but five separate calls were used here. Each of the five calls created separate binary output files of drawdown and head that were much smaller and easier to manage than a single output file would have been. Additionally, the simulated drawdowns at the start of each transient test must be zero (no drawdown prior to pumping). Because MODFLOW-2000 uses the resulting drawdowns and heads from the previous stress period as input to the next stress period, a single simulation would not necessarily start each transient test with zero drawdowns. Calling MODFLOW-2000 five times allowed the initial drawdowns to be reset to zero each time using shell scripts. The heads simulated at the end of the final time step in each MODFLOW-2000 call were used as the initial heads for the next call. The results of all five calls were combined to produce the 1332 model predictions prior to comparing them to the 1332 selected observation data, thus ensuring that all steady-state and transient data were used simultaneously in the inverse calibration procedure.

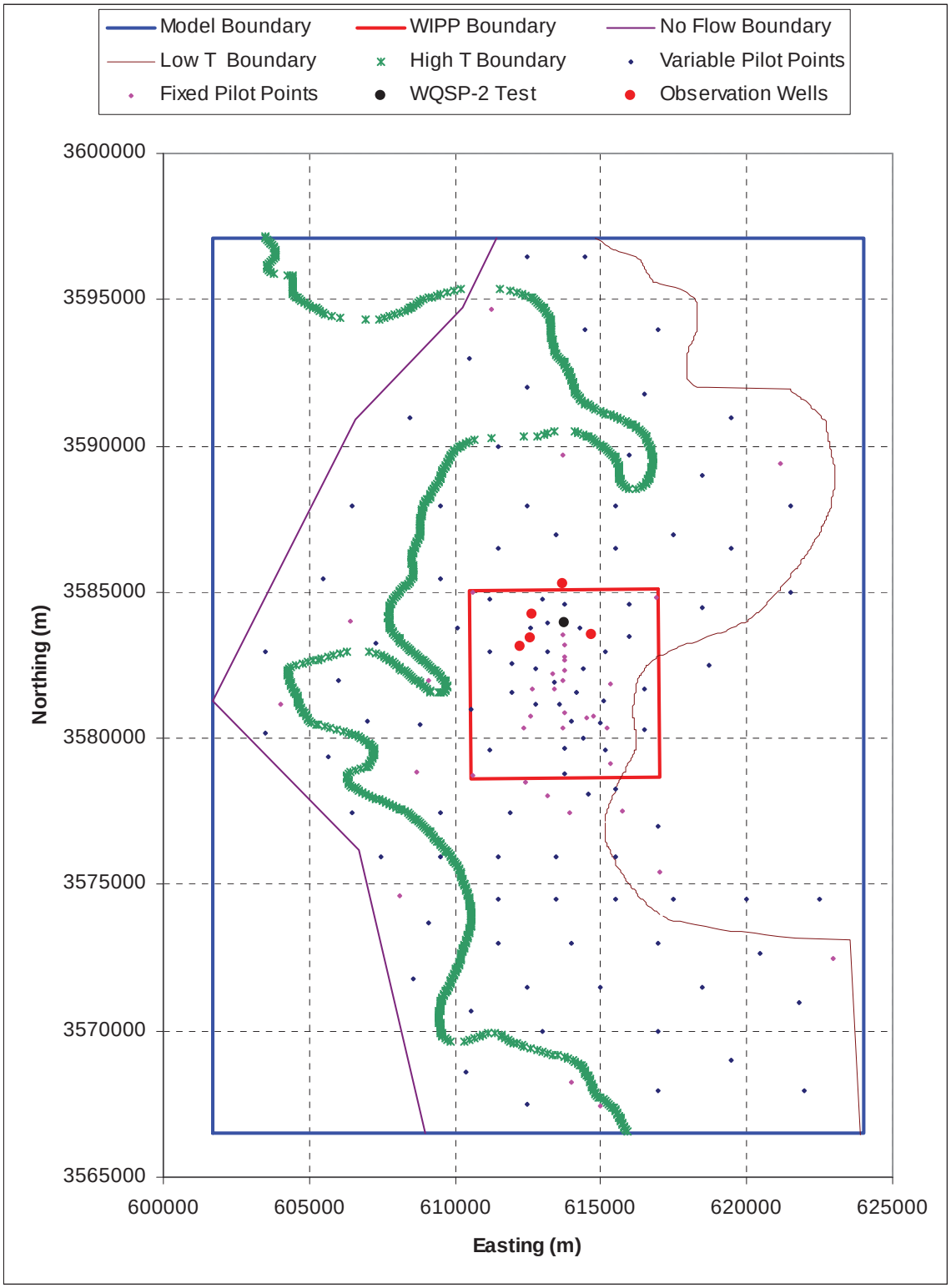

Figure TFIELD-31. Locations of the WQSP-2 Hydraulic Test Well and Observation Wells

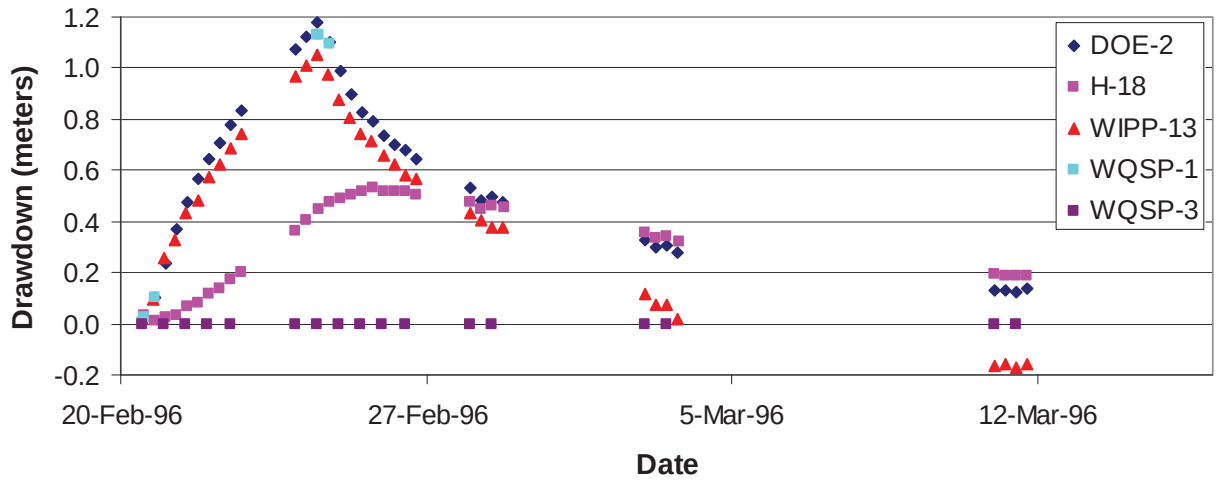

Figure TFIELD-32. Observed Drawdowns from the WQSP-2 Hydraulic Test

TFIELD-6.7 Weighting of Observation Data

The observed data for each response to each transient hydraulic test are weighted to take into account the differences in the responses across the different tests. The weights are calculated as the inverse of the maximum observed drawdown for each hydraulic test. This weighting scheme applies relatively less weight to tests with large drawdowns and relatively more weight to tests with smaller responses. This weighting scheme was used so that the overall calibration was not dominated by trying to reduce the very large residuals that may occur at a few of the observation locations with very large drawdowns. Under this weighting scheme, two tests that are both fit by the model to within 50 percent of the observed drawdown values would be given equal consideration in the calculation of the overall objective function even though one test may have an observed maximum drawdown of 10 m (33 ft) and the other a maximum observed drawdown of 0.10 m (0.33 ft).

The weights assigned in this manner ranged from 0.052 to 20.19. The observed absence of a hydraulic response at WQSP-3 to pumping at WQSP-1 and WQSP-2 was also included in the calibration process by inserting measurements of zero drawdown that were given an arbitrarily high weight of 20. Through trial and error using the root mean squared error criterion of how well the modeled steady-state heads fit the observed steady-state heads, a weight of 2.273 was assigned to the 35 steady-state observations. This weight is near that of the average of all the weights assigned to the transient events and was found to be adequate to provide acceptable steady-state matches. It is noted that the steady-state data provide measurements of head while all of the transient events provide measurements of drawdown. However, the weights were applied to the residuals between the observed and modeled aquifer responses and because both heads and drawdowns are measured in meters, there was no need to adjust the weights to account for different measurement units.

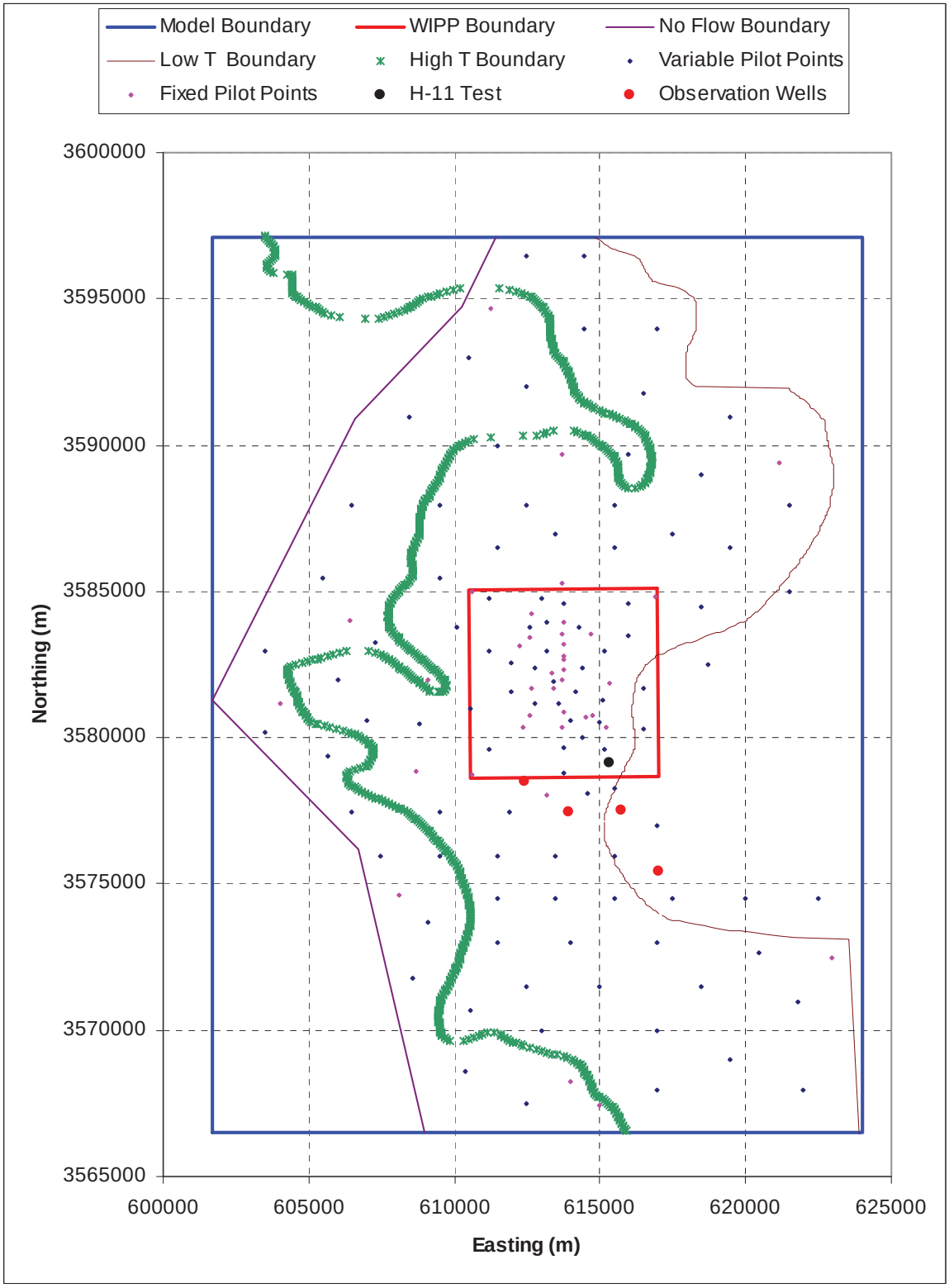

Figure TFIELD-33. Locations of the H-11 Hydraulic Test Well and Observation Wells

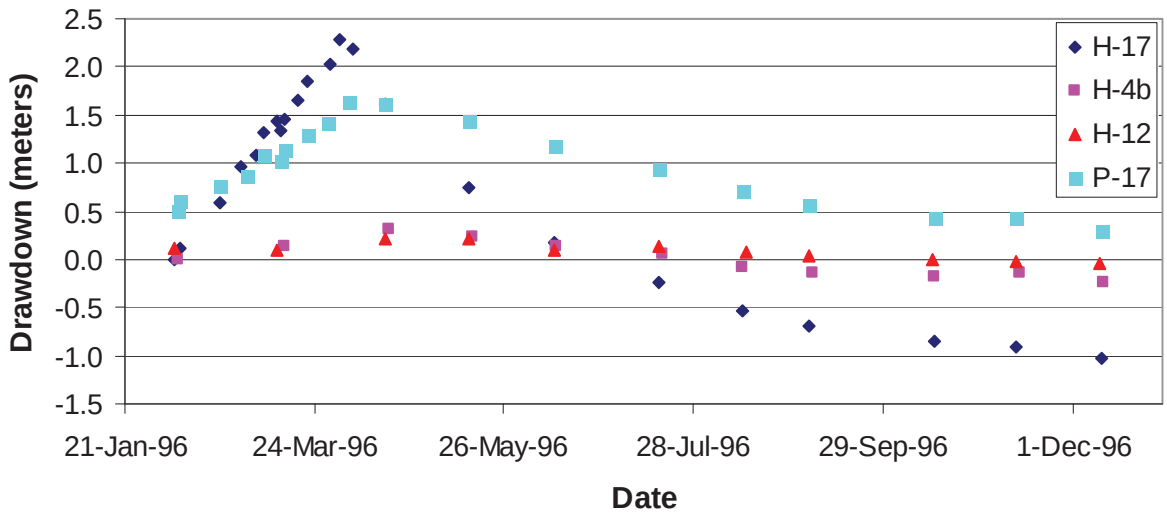

Figure TFIELD-34. Observed Drawdowns for the H-11 Hydraulic Test

The number of measurements used for calibration that were made at individual wells during individual tests ranged from 6 to 104, and the number of measurements used for calibration that were made at all wells during a single test ranged from 64 to 410. This means that different well responses and different tests carried different cumulative weights. The spatially broadest sampling of transient data possible was used in an effort to get transient coverage of as much of the modeling domain as possible. In those areas where no transient data are available, the calibration is dominated by fitting the model to the steady-state measurements. The greatest coverage of transient data is within the boundaries of the WIPP site, which is also the area of most significance for radionuclide transport.

The maximum observed drawdown, the weight assigned to all the observed test values for each test, and the total number of observations for each observation well are given in Table TFIELD-10.

TFIELD-6.8 Assignment of Pilot Point Geometry

A major development in the field of stochastic inverse modeling that has occurred since the T fields were constructed for the CCA in 1996 is that inverse techniques are now capable of simultaneously determining optimal T values at a large number of pilot points. In the T fields constructed for the CCA, pilot points were added one at a time and each point was calibrated prior to the addition of the next pilot point. Furthermore, the total number of pilot points was limited to less than or equal to the total number of T observations to avoid numerical instabilities in the solution of the inverse problem. With the techniques now available and implemented in PEST, it is possible to use many more pilot points than there are T observations and to calibrate these pilot points simultaneously.

The pilot-point locations were chosen using a combination of a regular grid approach and deviations from that grid to accommodate specific pumping- and observation-well locations

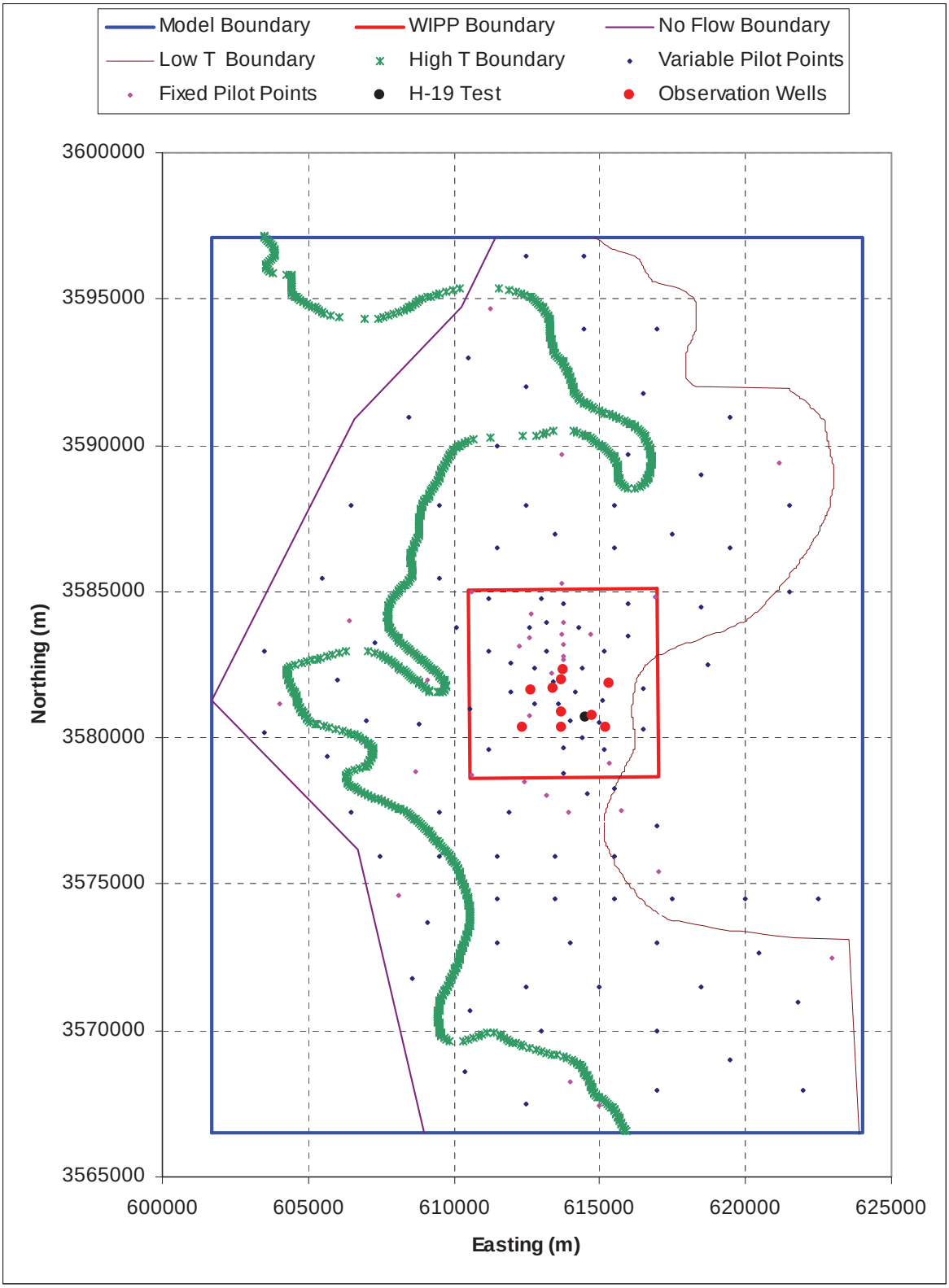

Figure TFIELD-35. Locations of the H-19 Hydraulic Test Well and Observation Wells

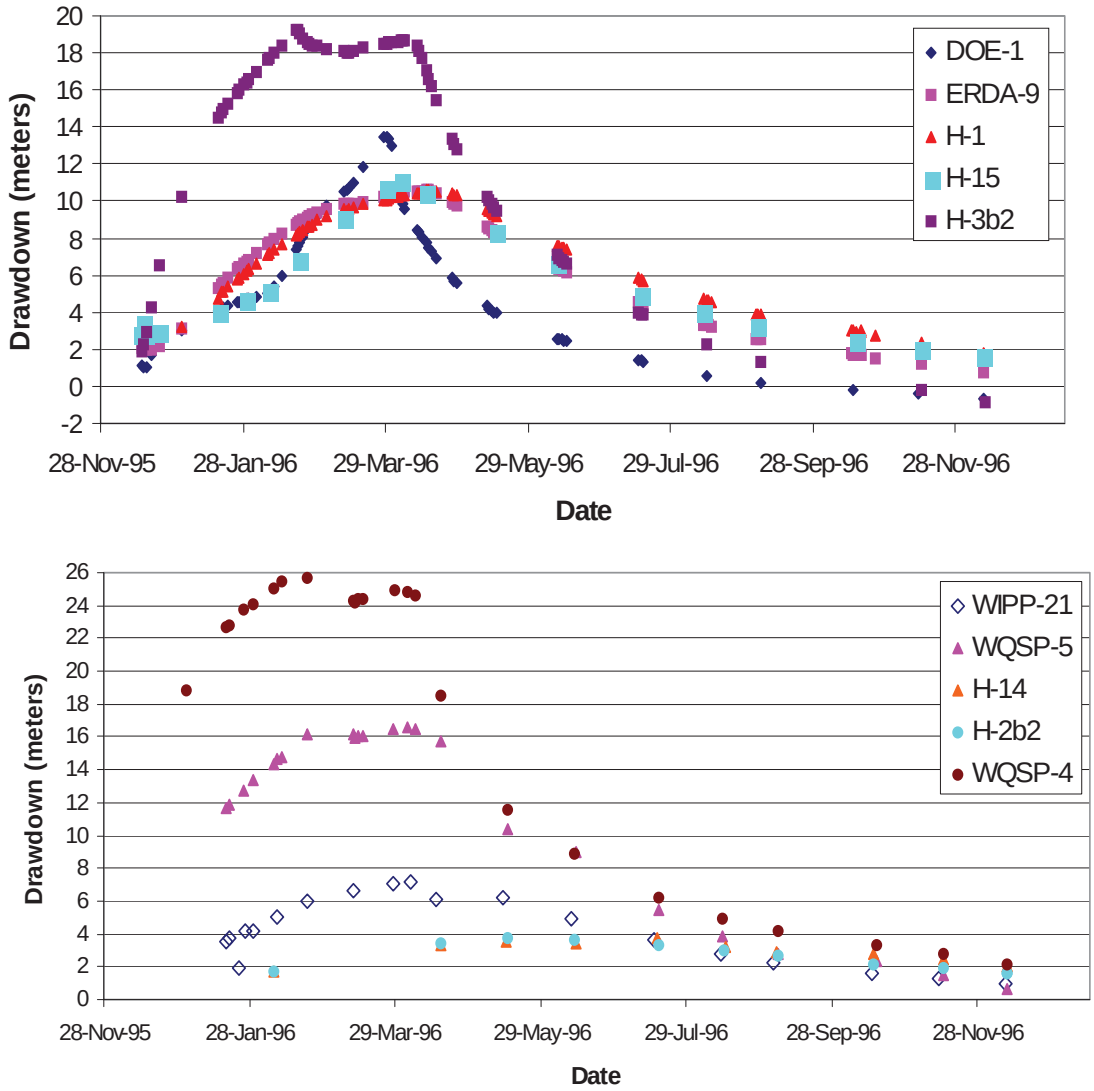

Figure TFIELD-36. Observed Drawdowns From the H-19 Hydraulic Test

(Figure TFIELD-38). The goal in these deviations from the regular grid was to put at least one pilot point between each pumping well and each of its observation wells. Details of the pilot-point locations relative to the pumping and observation wells in the WIPP site area are shown in Figure TFIELD-39. This combined approach of a regular grid with specific deviations from that grid follows the guidelines for pilot-point placement put forth by John Doherty (the author of PEST) as Appendix 1 in the work of McKenna and Hart (2003a). Pilot points located at the T measurement locations were held as fixed values during the optimization (fixed pilot points shown as magenta squares in Figure TFIELD-38). The variable pilot points (dark blue diamonds in Figure TFIELD-38) are those where the T value was adjusted during the calibration procedure. A total of 43 fixed and 100 variable pilot points was used in the T-field calibration process. The zone option in PEST was employed to limit the influence of pilot points in any one zone (e.g., high T or low T) to adjusting only locations that are in the same zone.

Table TFIELD-9. Discretization of Time into 29 Stress Periods and 127 Time Steps with Pumping Well Names and Pumping Rates

Event Name	Global Stress Period No.	Internal Stress Period No.	Stress Period Length (s)	No. of Time Steps	Start Date	Stop Date	Pumping Well(s)	Pumping Rate(s) (m^3/s)
Steady	1	1	86400	1	10/14/859:00	10/15/859:00	0	0
H-3	2	1	5356800	8	10/15/859:00	12/16/859:00	H-3	3.03E-04
	3	2	10892700	8	12/16/859:00	4/21/8610:45	None	0.00E+00
	4	3	22976100	1	4/21/8610:45	1/12/879:00	None	0.00E+00
WIPP-13	5	1	3110400	8	1/12/879:00	2/17/879:00	WIPP-13	1.89E-03
	6	2	7539900	8	2/17/879:00	5/15/8715:25	None	0.00E+00
	7	3	55359360	1	5/15/8715:25	2/14/899:01	None	0.00E+00
P-14	8	1	44928	3	2/14/899:01	2/14/8921:29	P-14	3.92E-03
	9	2	174612	8	2/14/8921:29	2/16/8922:00	P-14	3.64E-03
	10	3	50400	3	2/16/8922:00	2/17/8912:00	P-14	3.37E-03
	11	4	1820396	8	2/17/8912:00	3/10/8913:39	None	0.00E+00
	12	5	193212124	1	3/10/8913:39	4/24/95 19:42	None	0.00E+00
H-19	13	1	148860	1	4/24/9519:42	4/26/95 13:03	H-19b0	2.26E-04
	14	2	4399020	1	4/26/9513:03	6/16/9511:00	None	0.00E+00
	15	3	3614400	1	6/16/9511:00	7/28/95 7:00	H-19b0	2.36E-04
	16	4	1168200	1	7/28/95 7:00	8/10/95 19:30	None	0.00E+00
	17	5	1292700	1	8/10/9519:30	8/25/9518:35	H11	2.44E-04
	18	6	9651300	1	8/25/9518:35	12/15/9511:30	None	0.00E+00
	19	7	2878200	8	12/15/9511:30	1/17/9619:00	H-19b0	2.71 E-04
	20	8	670680	3	1/17/9619:00	1/25/9613:18	H-19b0	2.52E-04
	21	9	238980	3	1/25/9613:18	1/28/96 7:41	H-19b0, WQSP-1	2.52E-04, 4.30E-04
	22	10	872340	3	1/28/96 7:41	2/7/9610:00	H-19b0	2.52E-04
	23	11	1047000	8	2/7/9610:00	2/19/9612:50	H-19b0, H-11	2.52E-04, 2.23E-04
	24	12	81600	3	2/19/9612:50	2/20/9611:30	H-19b0, H-11	1.55E-04, 2.23E-04
	25	13	345600	3	2/20/96 11:30	2/24/9611:30	H-19b0, H-11,WQSP-2	1.55E-04, 2.23E-04, 4.5E-04
	26	14	1395000	8	2/24/96 11:30	3/11/9615:00	H-19b0, H-11	1.55E-04, 2.23E-04
	27	15	1445100	8	3/11/9615:00	3/28/96 8:25	H-19b0, H-11	1.55E-04, 3.76E-04
	28	16	1220700	8	3/28/96 8:25	4/11/9611:30	H-19b0	1.55E-04
	29	17	21074400	8	4/11/9611:30	12/11/969:30	None	0.00E+00

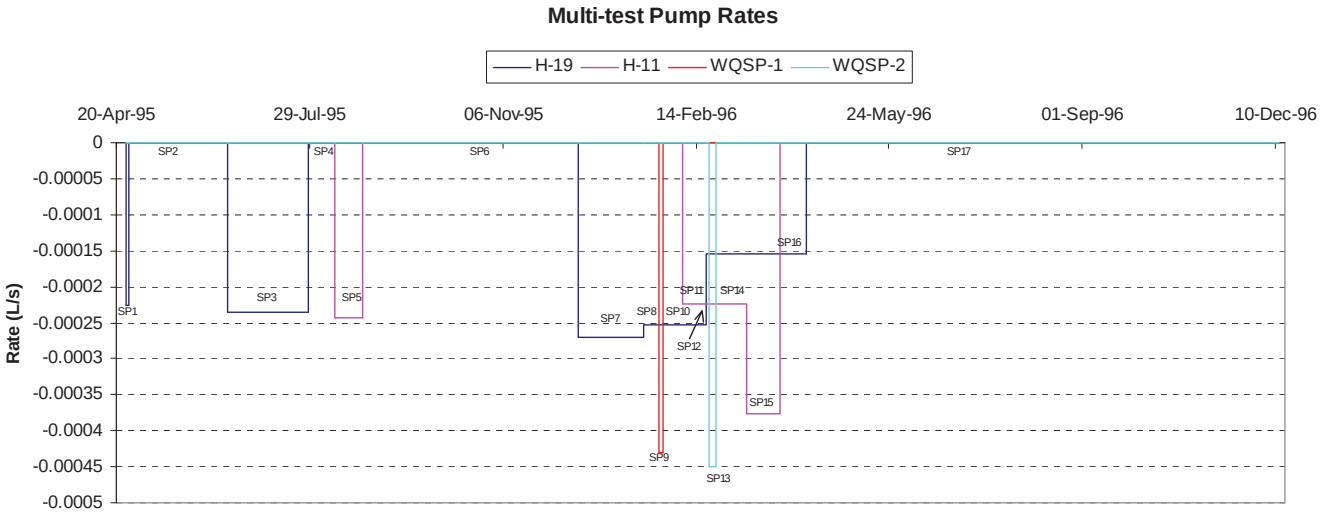

Figure TFIELD-37. Temporal Discretization and Pumping Rates for the Fifth Call to MODFLOW-2000. A total of 17 stress periods (SP*s*) are used to discretize this model call.

Table TFIELD-10. Observation Weights for Each of the Observation Wells

Test Well Observation Well	Maximum Drawdown (m)	Weight	Number of Observations
Steady	NA	2.273	35
H3-DOE1	5.426	0.184	57
H3-H1	10.396	0.096	26
H3-H11b1	3.622	0.276	19
H3-H2b2	3.781	0.265	20
W13-DOE2	12.138	0.082	104
W13-H2b2	0.781	1.281	23
W13-H6	5.545	0.180	93
W13-P14	0.570	1.755	38
W13-W12	1.553	0.644	27
W13-W18	6.481	0.154	26
W13-W19	5.048	0.198	22
W13-W25	0.246	4.062	11
W13-W30	3.391	0.295	24
P14-D268	0.432	2.317	38
P14-H18	0.113	8.850	21
P14-H6b	0.701	1.427	21
P14-W25	0.432	2.315	22
P14-W26	0.137	7.310	20
WQSP1-H18	1.431	0.699	47
WQSP1-W13	1.260	0.794	47
WQSP1-WQSP3	0.000	20.000	25
WQSP2-DOE2	1.178	0.849	34
WQSP2-H18	0.529	1.892	35
WQSP2-W13	1.053	0.949	34
WQSP2-WQSP1	1.132	0.884	6
WQSP2-WQSP3	0.000	20.000	18
H11-H17	1.030	0.971	23
H11-H4b	0.232	4.317	11
H11-H12	0.033	20.190	11
H11-P17	1.628	3.304	19
H19-DOE1	13.463	0.074	70
H19-ERDA9	10.571	0.095	80
H19-H1	10.618	0.094	80
H19-H15	11.110	0.090	22
H19-H3b2	19.283	0.052	69
H19-W21	7.153	0.140	19
H19-WQSP5	16.623	0.060	24
H19-H14	3.759	0.602	11
H19-H2b2	3.794	0.608	11
H19-WQSP4	25.721	0.462	24

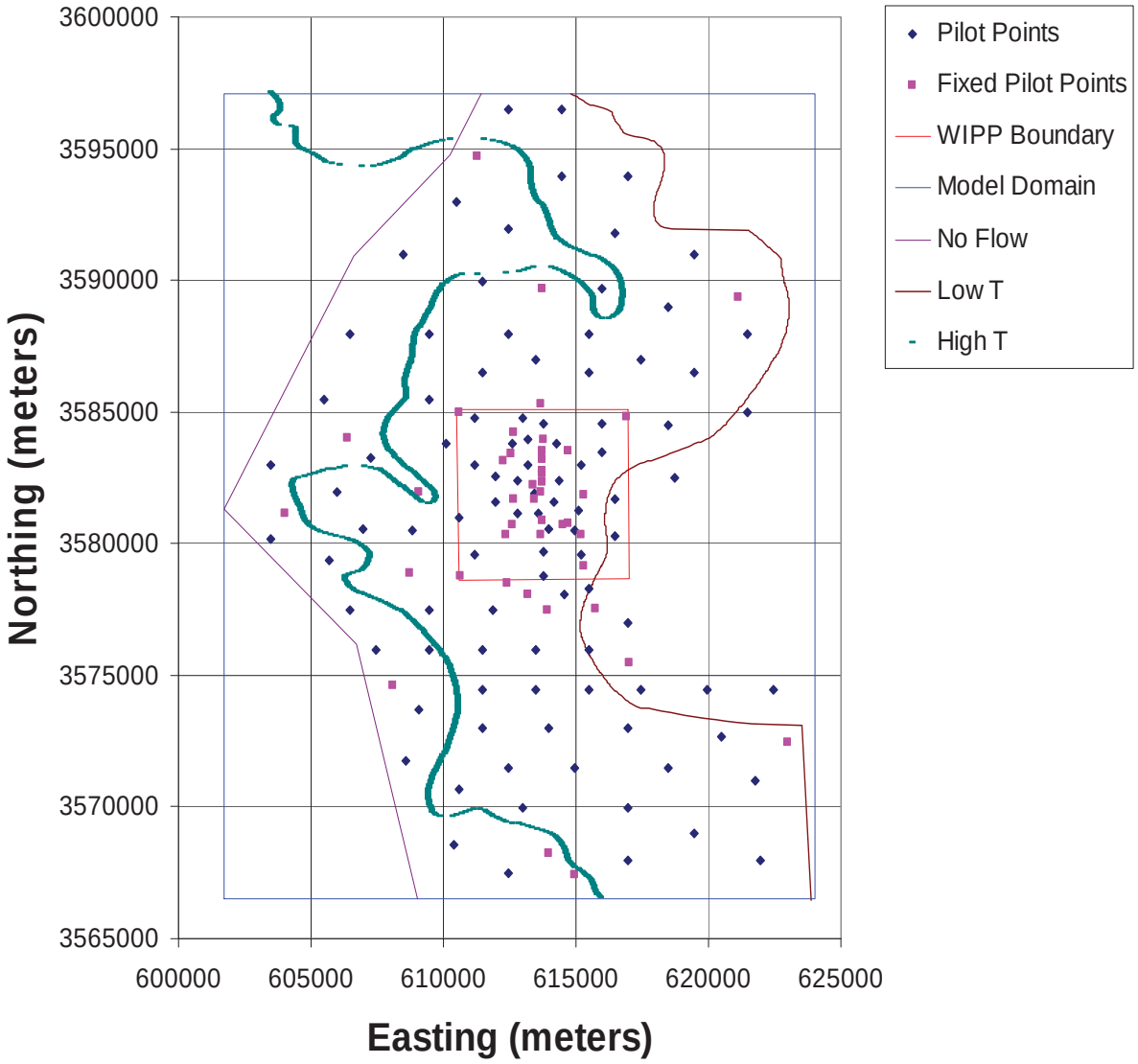

Figure TFIELD-38. Locations of the Adjustable and Fixed Pilot Points Within the Model Domain

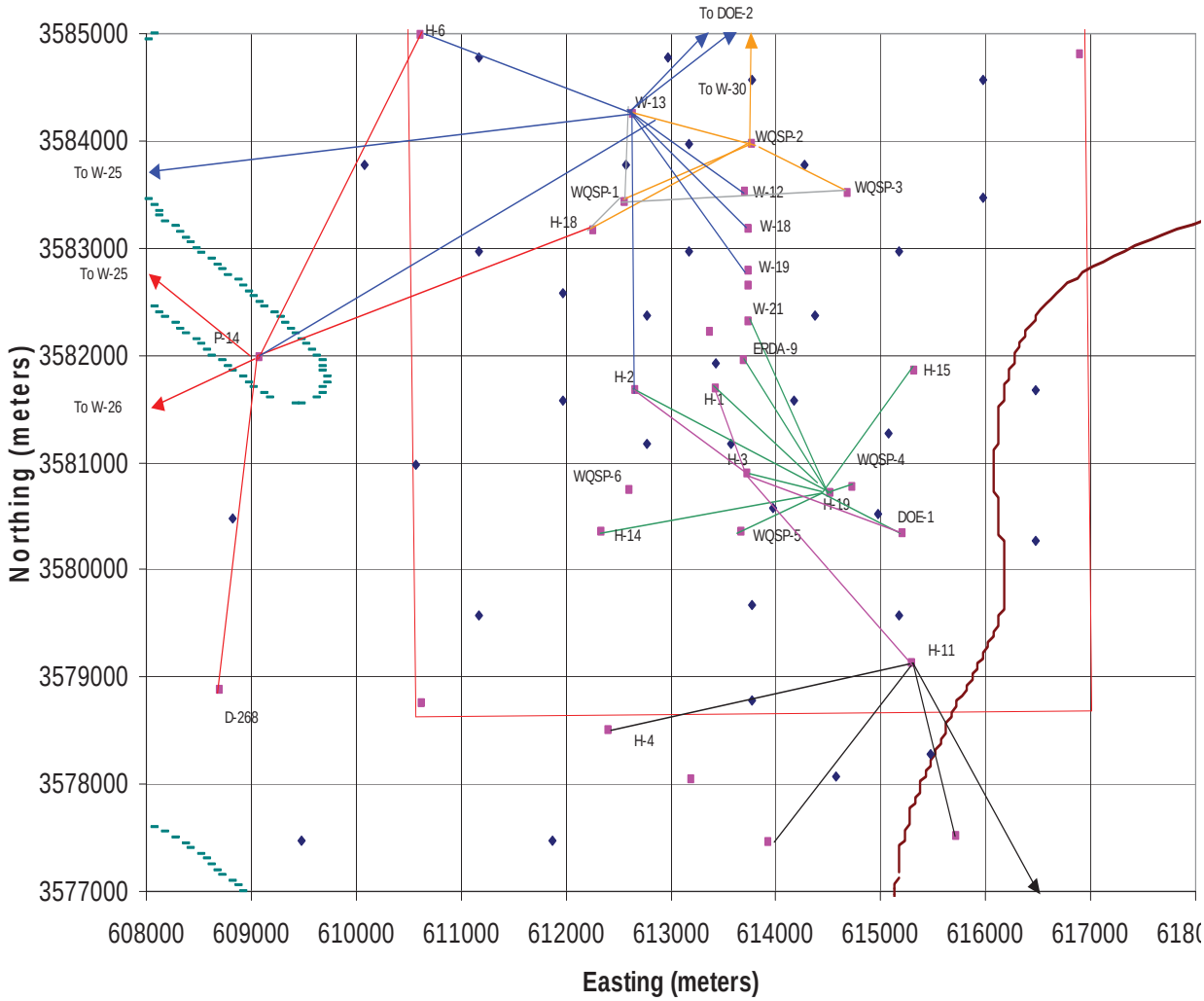

Figure TFIELD-39. Close-Up View of the Pilot-Point Locations in the Area of the WIPP Site. The colored (solid) lines connect the pumping and observation wells. The legend for this figure is the same as that for Figure TFIELD-38.

The variogram model for the residuals between the T measurements and the base field has a range of 1,050 m (3,445 ft). Because the pilot-point approach to calibration uses this range as a radius of influence, locations of the adjustable pilot points were as much as possible set to be at least 1,050 m (3,445 ft) away from other pilot points (adjustable or fixed). For maximum impact, all pilot points should be at least 2,100 m (6,890 ft) away from any other pilot point but, given the existing well geometry, this distance was not always achievable.

TFIELD-6.9 Stochastic Inverse Calibration

The seed realizations are input to the inverse model using the pilot-point method. The seed realizations are calibrated to the steady-state and transient head measurements. The residuals and the T-field calculations are done in $\log_{10}$ space so that a unit change in the residual equates to a one order of magnitude change in the value of T. The initial values of the pilot points are equal

to the value of the initial residual field at each pilot-point location. The pilot points are constrained to have a maximum perturbation of ± 3.0 from the initial value except for those pilot points within the high-T zone in Nash Draw (Figure TFIELD-11) and the low-T zone on the eastern side of the model domain that are limited to perturbations of ± 1.0. These limits are employed to maintain the influence of the geologic conceptual model on the calibrated T fields.

Figure TFIELD-11 is updated as Figure TFIELD-40 to show, conceptually, how the addition of two pilot points along the cross section can modify the residual field and then update the T field. The pilot points are shown as the open circles in Figure TFIELD-40 and are used to modify the residual field before it is added to the base T field. Compare the shape of the dashed red and blue lines in Figure TFIELD-40 to the same lines in Figure TFIELD-11. The values of the residuals at the observation points are held fixed so any adjacent pilot points cannot modify them.

At the heart of the calibration process is the iterative adjustment of the residual field at the pilot points by PEST and the subsequent updates of the residual field at the locations surrounding the pilot points based on the shape of the variogram modeled on the raw residuals. The updated residual field is then combined with the base T field (see Figure TFIELD-18) and then used in MODFLOW-2000 to calculate the current set of modeled heads. These modeled heads are then input to PEST for the next iteration.

The objective function minimized by PEST (phi) is a combination of the weighted sum of the squared residuals between the measured and observed steady-state head data, the weighted sum of the squared residuals between the measured and observed transient drawdown data, and the weighted sum of the squared differences in the estimated T value between pairs of pilot points.

Phi is defined as:

$$\phi = \sum_{i=1}^{n_{obs}^{SS}} (W^{SS}(H_i^{obs-SS} - H_i^{calc-SS}))^2 + \sum_{i=1}^{n_{wells}^{Tr}} \sum_{j=1}^{n_{obs}^{Tr}} (W_i^{Tr}(D_j^{obs-Tr} - D_j^{calc-Tr}))^2 + \sum_{i=1}^{n_{PP}} \sum_{j=j}^{n_{PP}} W_{ij}^{R}(PP_i - PP_j) \quad (9)$$

where n_{obs} is the number of head observations, n_{wells} is the number of wells, n_{PP} is the number of pilot points, W is the weight assigned to a group of measurements, H^{obs} and H^{calc} are the values of the observed and calculated heads, respectively, D^{obs} and D^{calc} are the values of the observed and calculated drawdowns, respectively, PP refers to the $\log_{10}$ T value at a pilot point, and superscripts SS, Tr, and R refer to steady-state measurements, transient measurements, and pilot-point regularization, respectively. For this work, the weights on the head and drawdown observations are as given in Table TFIELD-10. The third weighted sum of squares in the objective function is the regularization portion of the objective function. This weighted sum of squares involves the difference in T values between each pair of pilot points (PP_i - PP_j) and is designed to keep the T field as homogeneous as possible and to provide numerical stability when estimating more parameters than there are data. The pilot-point regularization weights, W_{ij}^{R}, are defined by the kriging factors and are a function of the distance between any two pilot points.

The stochastic inverse calibration process uses multiple pre- and post-processor codes in addition to PEST and MODFLOW-2000. The overall numerical approach to the T-field calibration is shown in Figures TFIELD-41 and TFIELD-42 and the details on this approach are documented

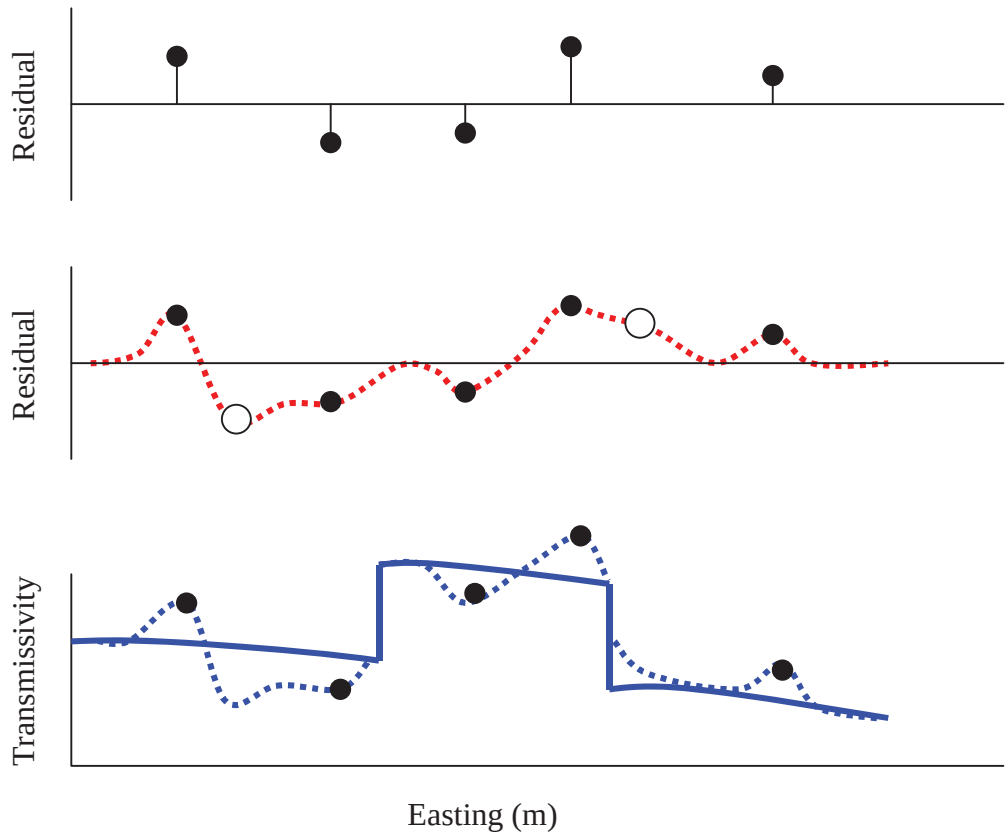

Figure TFIELD-40. Conceptual Cross-Section Showing the Addition of Pilot Points to the Optimization Process

in McKenna and Hart (2003a, 2003b). The top of Figure TFIELD-41 shows the pre-processing steps. The large oval in the middle of the figure contains the link between MODFLOW-2000 and PEST. The "model process" portion of the figure is expanded and the details are shown in Figure TFIELD-42. The output files and the connection to the particle-tracking code are shown in the bottom of Figure TFIELD-41.

The calibration process is run iteratively until at least one of three conditions are met: (1) the number of iterations reaches the maximum allowable number of 15; (2) the objective function reaches a predefined minimum value of 1,000 m^2; or (3) the value of the objective function changes by less than one percent across three consecutive iterations.

At the end of the calibration process, a residual field is created that when added to the base T field reproduces the measured T values at the 43 measurement locations and provides a minimum sum of squared errors (SSE) between the observed and model-predicted heads/drawdowns. An example of the final step in the creation of a calibrated T field is shown in Figure TFIELD-43. The computational cost of calibrating to the multiple transient events is significant. For comparison, a single forward run of MODFLOW-2000 in steady-state takes on the order of 10-15 seconds on a 1.9-GHz Athlon processor, whereas the run time for the combined steady-state and transient events is approximately three minutes (a factor of 12-18 times longer).

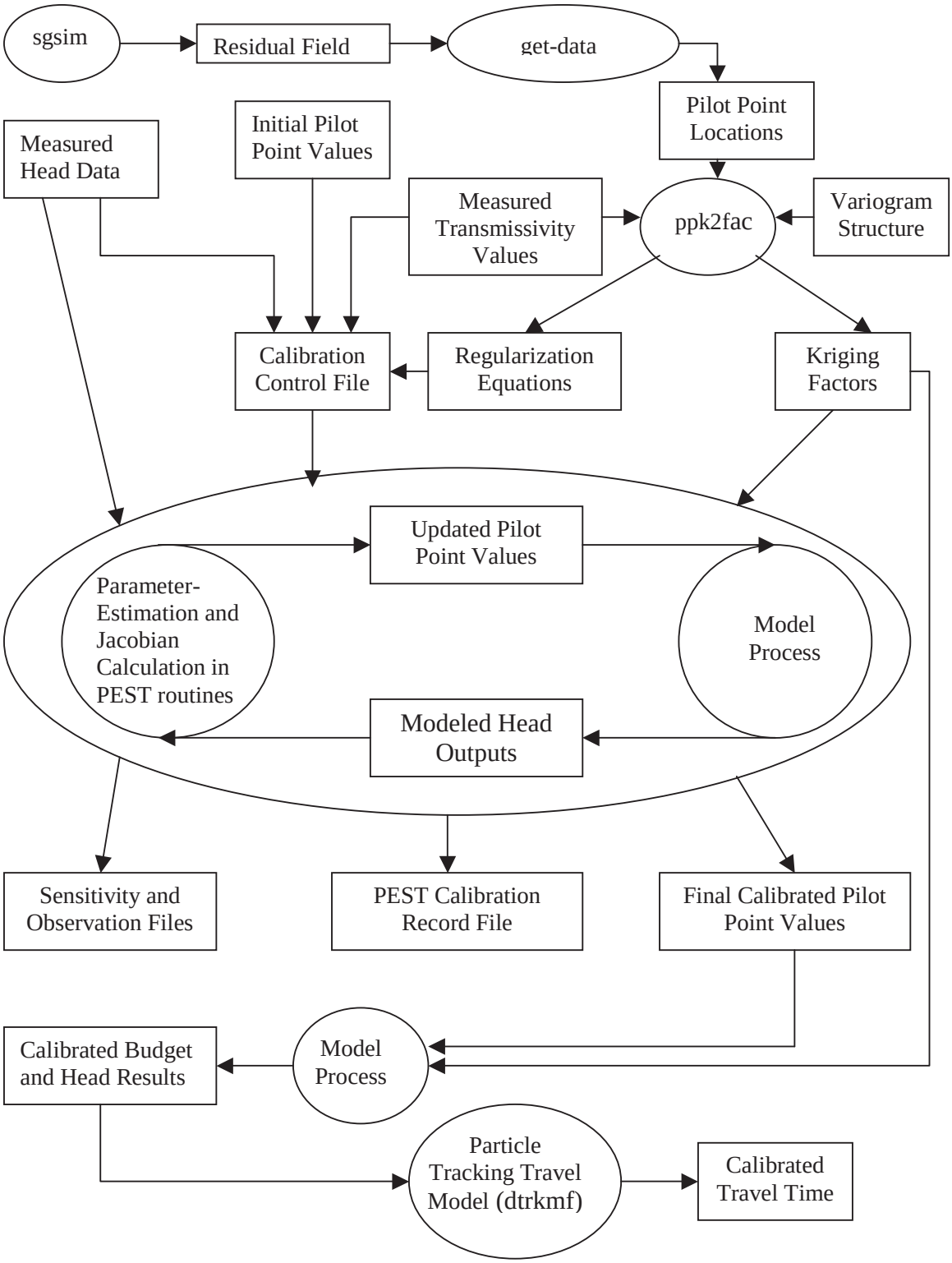

Figure TFIELD-41. Flow Chart of the Stochastic Inverse Calibration Process Used to Create the Final Calibrated Transmissivity Fields

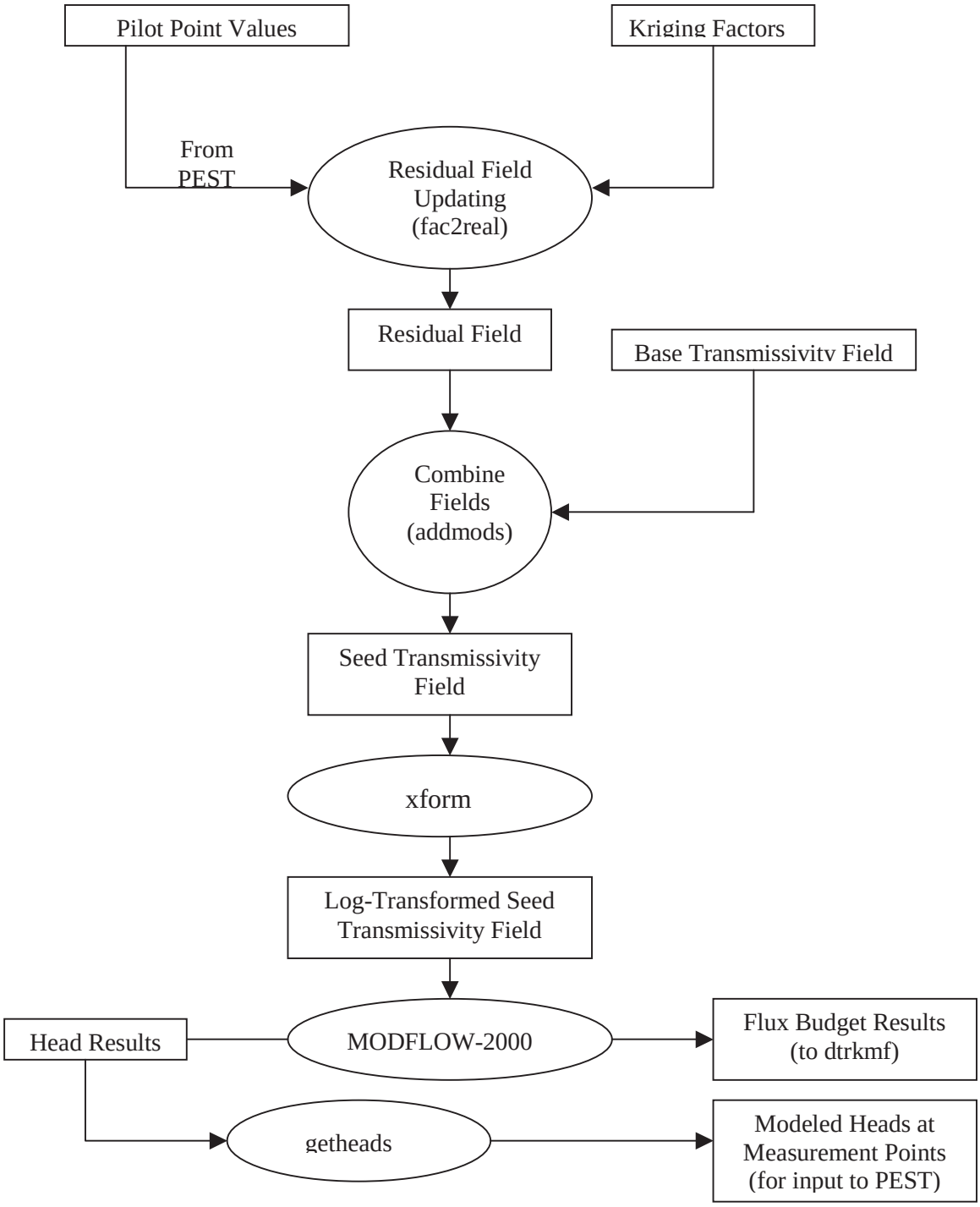

Figure TFIELD-42. Flow Chart of the Core of the Inversion Process Highlighting the Connection Between PEST and MODFLOW-2000

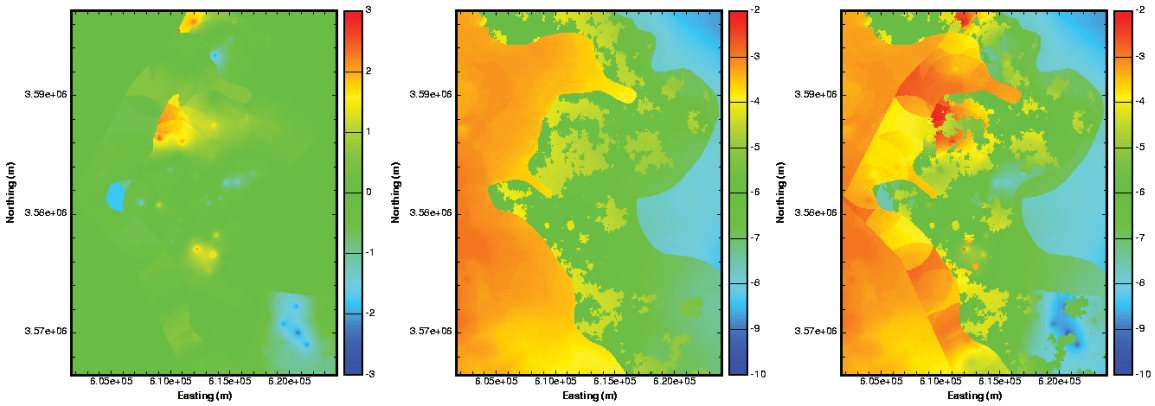

Figure TFIELD-43. Example Final Steps in the Creation of a Calibrated T Field. The calibrated residual field (left image) is added to the base T field (middle image) to get the final calibrated T field (right image). All color scales are in units of $\log_{10}$ T (m^2/s).

Due to these longer run times, two separate parallel PC clusters were employed. Each of these clusters consists of 16 computational nodes running 1.9-GHz Athlon processors with 1 gigabyte of RAM. One cluster is located in Albuquerque, NM and the other is in the Sandia office in Carlsbad, NM. Both clusters use the Linux operating system. The total number of forward runs necessary to complete the calibration process can be estimated as:

Total Runs ≅ (# of parameters) × (#of PEST iterations) × (average runs per iteration) × (# of base T fields).

The maximum number of iterations used in these runs was set to 15, although not all fields went to the maximum number of iterations. Additionally, on average for the first four iterations, PEST used forward derivatives to calculate the entries of the Jacobian matrix and each entry only required a single forward model evaluation. For the remaining 11 iterations, PEST used central derivatives to calculate the Jacobian entries and each calculation required two forward evaluations of the model (22 total). The average number of model evaluations is 1.733 = [(4 + 22)/15]. Therefore an estimate of the maximum possible total number of forward runs is equal to: 100 pilot points × 15 iterations/field × 1.73 runs/iteration × 150 T fields = 390,000 runs. The total time necessary to complete these calculations in serial mode on a single processor would be 813 days, or 2.22 years. PEST allows for parallel calculation of the Jacobian matrix, and this option was used to decrease the total run time significantly relative to the time needed for serial computation.

The model run times, as well as the time necessary to read and write input/output files across the cluster network, were examined to determine the optimal number of client, or slave, nodes for each server, or master, node. The optimal number of clients per server was determined to be eight. More clients per server degraded overall performance due to increased communication between machines and fewer clients per server resulted in underutilization of the system. By combining the client and server activities on a single machine using a virtual server setup, four different base T fields could be calibrated simultaneously on the 32 machines.

TFIELD-7.0 T-FIELD ACCEPTANCE CRITERIA

The calibration procedure described in Section 6.0 of this attachment was applied to 150 of the base T fields (the remaining 350 base fields were held in reserve, to be used only if necessary). Not all base T fields yielded a resulting calibrated T field. Four base T fields (d01r03, d01r09, d02r09, and d08r10) encountered numerical difficulties during the first iteration and did not calibrate at all. For each of the remaining 146 T fields, the calibration procedure stopped for one of three reasons:

1. PEST completed the maximum allowed number of iterations (15);
2. PEST was unable to improve the objective function (sum of squared errors of weighted residuals) for three successive iterations; or
3. the optimization became numerically unstable.

Some of the T fields probably could have been calibrated better with more effort and adjustment of some of the PEST input parameters; however, these parameters were set to work across the largest number of fields possible and no calibration process will necessarily be able to make progress on every base field given the same set of parameters.

Because the T-field calibration procedure did not stop when some objective goodness-of-fit target was achieved, criteria had to be established to define what constitutes an acceptable calibration for use in the WIPP CRA calculations. Because the T fields were to be used for calculation of radionuclide transport, the travel times calculated in the T fields for a conservative particle released above the center of the WIPP waste panels (UTM X = 613,597.5 m and Y = 3,581,385.2 m [Ramsey et al. 1996, p. 9]) to reach the WIPP land-withdrawal boundary (LWB) were used in developing acceptance criteria. That is, the sensitivity of the calculated travel-time distribution to potential acceptance criteria was used to identify those criteria that are important. Once the distribution of travel times showed no (remaining) sensitivity to continued refinement of the criteria applied (e.g., a reduction in some metric below a threshold value), all T fields meeting those criteria were considered to be acceptably calibrated.

The travel times discussed herein were obtained using the streamline particle-tracking algorithm implemented in DTRKMF v. 1.0 (Rudeen 2003) assuming a single-porosity medium with a porosity of 0.16. DTRKMF calculates particle tracks in two or three dimensions for steady-state and time-dependent, variably saturated flow fields. The particles are tracked cell-by-cell using a semi-analytical solution. DTRKMF assumes that the velocities vary linearly between the cell faces as a function of the space coordinate and, for time-dependent cases, that the velocities at the faces vary linearly between time planes. It directly reads the cell-by-cell flow budget file from MODFLOW-2000 and uses those values to calculate the velocity field. For each calibrated T field, a final forward run of MODFLOW-2000 was done and the cell-by-cell fluxes from this run were used as input to DTRKMF to calculate the travel time. For each calibrated T field, only a single particle was tracked, providing a single travel time. The MODFLOW-2000 modeling was performed using a 7.75-m (25.4-ft) thickness for the Culebra, whereas transport calculations assume that all flow is concentrated in the lower 4.0 m (13 ft) of Culebra (Meigs and McCord, 1996). Therefore, the travel times obtained from DTRKMF were scaled by multiplying by the

factor 0.516 (4/7.75). These scaled travel times were then consistent with the travel times calculated and reported by Wallace (1996) for the T fields used in the WIPP CCA (DOE 1996). These travel times do not, however, represent the actual predicted travel times of solutes, conservative or non-conservative, through the Culebra. Culebra transport modeling treats the Culebra as a double-porosity medium with transport through advective porosity (e.g., fractures) retarded by diffusion into diffusive porosity (e.g., matrix porosity) and by sorption. The travel times presented herein are intended only to allow comparison among T fields.

TFIELD-7.1 Candidate Acceptance Criteria

Four factors were evaluated for their potential to provide T-field acceptance criteria: the root mean squared error (RMSE) of the modeled fit to the measured steady-state heads, the agreement between the measured and modeled steady-state gradient/heads, the sum of squared weighted residuals (phi) for the transient data, and the agreement between the measured and modeled transient heads. These factors are not totally independent of one another, but are related in ways discussed below.

TFIELD-7.1.1 RMSE Values

The RMSE is a measure of how close MODFLOW-2000/PEST came to matching the measured steady-state heads for each T field. The RMSE is defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n_{obs}} (H_i^{obs} - H_i^{calc})^2}{n_{obs}}} \tag{10}$$

where n_{obs} is the number of head observations and H^{obs} and H^{calc} are the values of the observed and calculated heads, respectively. Previous Culebra T-field calibration exercises (e.g., LaVenue and RamaRao 1992) achieved RMSEs less than 3 m (9.5 ft) in most cases when calibration was being performed only to steady-state heads. This level of calibration was also achieved by McKenna and Hart (2003a) for four different sets of steady-state head measurements. RMSEs have not previously been reported for steady-state heads in Culebra T fields calibrated to transient heads.

TFIELD-7.1.2 Fit to Steady-State Heads

One measure of how well a T field has matched the steady-state heads can be obtained by simply plotting the measured heads versus the modeled heads. If the measured and modeled heads match exactly, the best-fit straight line through the data will have a slope of one. Exact agreement between measured and modeled heads is not to be expected, so an acceptance criterion on the slope of the best-fit line must be established.

The steady-state heads are important because the transport calculations performed in SECOTP2D rely on the steady-state velocity field provided by MODFLOW-2000. If MODFLOW-2000 has not accurately captured the steady-state heads, steady-state gradients and the associated steady-state velocities will be in error. With measured head plotted as the independent variable (x) and calculated head plotted as the dependent variable (y), a slope of the

best-fit line less than unity implies that the calculated gradient is less than the measured gradient. Low gradients should lead to excessively long travel times. Therefore, it was important to determine if a threshold value of the steady-state-fit slope exists above which the distribution of travel times is insensitive.

TFIELD-7.1.3 Phi Values

As shown in Equation (9), phi values have three components:

- A weighted sum of squared residuals for the steady-state heads,
- A weighted sum of squared residuals for the transient drawdowns, and
- A weighted sum of squared differences between T values for each pair of pilot points.

The steady-state component of phi is a weighted, squared, and summed expression of the RMSE given in Equation (10), above, and is not, therefore, meaningful to consider when RMSE is already being considered. The pilot-point-regularization component of phi relates to the smoothness of the T field, not to the goodness of fit of the measured and modeled responses. Hence, only the transient component of phi is considered in the discussion that follows.

For reasons discussed in Section 6.7 of this attachment, transient phi values do not provide a completely unbiased measure of how well a calibrated T field represents the actual T field. “Measurements” of zero drawdown were given arbitrarily high weights in the calibration process, the number of measurements used from individual wells during individual tests and the number of measurements used from all wells during a single test varied, and some parts of the modeling domain are covered by multiple wells’ responses, while other parts of the domain have no transient response data. Therefore, no simple numerical value can be established that represents an average residual of some meaningful value for each transient measurement, such as the RMSE used to evaluate T-field calibration to steady-state heads alone. Nevertheless, the transient phi values do provide an indication of how well a T field met the calibration targets as defined and could be used qualitatively to define acceptable T fields.

TFIELD-7.1.4 Fit to Transient Heads

Evaluating the model match to transient heads is not as straightforward as for the steady-state heads because the transient match involves both the magnitude and the timing of head changes. The magnitude and timing of a transient response are governed by both the transmissivity and storativity (S) of a system, but S was not included as a calibration parameter during the calibration process. A single S value of 1×10^{-5} ($\log_{10} = -5$) was used during T-field calibration. As reported by Beauheim (2003a), the apparent storativities obtained from independent analyses of the test responses used for the calibration range from 5.1×10^{-6} ($\log_{10} = -5.29$) to 7.3×10^{-5} ($\log_{10} = -4.14$). Because the calibration method only allowed PEST to adjust T to try to match the measured heads, it might actually shift T away from the correct value in trying to compensate for an inappropriate value of S. Thus, some allowance needed to be made for how close PEST could actually come to matching the measured responses.

To establish the bounds of what might be considered acceptable matches to the transient heads, a series of well-test simulations using the code nSIGHTS (Roberts 2002) was performed. For base-case parameter values, a T of 1×10^{-5} m^2/s and an S of 1×10^{-5} were used. Pumping in a well was simulated for 5, 25, and/or 50 days, and the responses that would be observed in observations wells 1, 2, and/or 3 km away were calculated. T and/or S were also varied by approximately a half order of magnitude upward and downward (3×10^{-5} and 3×10^{-6}). The results of these simulations are shown in Appendix A of Beauheim (2003b).

Based on the simulations, a set of guidelines was developed to determine if a modeled response matched a measured response within a half order of magnitude uncertainty in T and/or S. The guidelines were structured around the position of the modeled maximum drawdown relative to the measured maximum drawdown on a linear-linear plot of elapsed time on the x-axis and drawdown (increasing upward) on the y-axis. The guidelines are as follows:

- If the modeled peak occurs early and high (relative to the measured peak), S is too low and the maximum modeled drawdown can be up to three times greater than the maximum measured drawdown.

- If the modeled peak occurs early and low, T is too high and the maximum modeled drawdown can be up to two times lower than the maximum measured drawdown.

- If the modeled peak occurs late and high, T is too low and the maximum modeled drawdown can be up to two times higher than the maximum measured drawdown.

- If the modeled peak occurs late and low, S is too high and the maximum modeled drawdown can be up to three times lower than the maximum measured drawdown.

- If the modeled peak occurs at the same time as the measured peak but is high, the diffusivity (T/S) is correct, but both values are too low and the maximum modeled drawdown can be up to three times greater than the maximum measured drawdown.

- If the modeled peak occurs at the same time as the measured peak but is low, the diffusivity (T/S) is correct, but both values are too high and the maximum modeled drawdown can be up to three times lower than the maximum measured drawdown.

No quantitative criteria were established for how much earlier or later modeled peaks could occur relative to measured peaks because of the wide range observed in the simple scoping calculations (calculated peaks occurring a factor of 5 sooner to a factor of 10 later than the observed peaks) and because of the variability in pumping durations and distances to observation wells associated with the measured responses.

Using these guidelines, plots of each of the 40 transient well responses of each calibrated T field were evaluated visually to determine if the T field represented that response within a half order of magnitude uncertainty in T and/or S. A threshold number of well responses that failed this test was then considered as a possible acceptance criterion for the T fields.

TFIELD-7.2 Application of Criteria to T Fields

The four criteria described above were applied to the calibrated Culebra T fields to determine if they allowed meaningful discrimination among the fields. Given that travel time is the performance measure of most concern, the four criteria were evaluated in terms of their effects on the calculated distribution of travel times from the T fields.

TFIELD-7.2.1 RMSE Values

Steady-state RMSE values for the 146 completed T fields are plotted in Figure TFIELD-44. The data for H-9b, the southernmost well, were excluded from the RMSE calculation because the southern model boundary condition consistently caused the modeled H-9b head to be significantly lower than the measured head, disproportionately affecting the calculation of the RMSE. The exclusion of the H-9b data should provide a better measure of the accuracy of the model in the rest of the model domain.

All nine RMSE values greater than 20 m (66 ft) correspond to T fields that were not considered to have been successfully calibrated by McKenna and Hart (2003b). Figure TFIELD-45 shows the RMSE values plotted against travel time, and shows that the high RMSE values tend to be associated with long travel times. For RMSE values less than approximately 6 m (20 ft), travel times tend to cluster below approximately 50,000 years. Applying an RMSE cutoff value of 6 m (20 ft) would leave 117 T fields, with all but one having travel times less than 102,000 years (Figure TFIELD-46; the outlier with a travel time of ~241,000 years, d01r06, is not shown).

TFIELD-7.2.2 Fit to Steady-State Heads

Figure TFIELD-47 provides an example plot of measured steady-state heads versus modeled steady-state heads for one T field, with a unit-slope line shown as a reference. For each plot of steady-state heads, the slope of the best-fit line through all of the data except for the data for H-9b was calculated using the Excel SLOPE function. The data for H-9b, the southernmost well, were excluded from this calculation because the southern model boundary condition consistently caused the modeled H-9b head to be significantly lower than the measured head. Inasmuch as the gradient in the extreme southern portion of the modeling domain is unimportant with respect to transport across the southern half of the WIPP site, the exclusion of the H-9b data should improve the accuracy of the slope calculation in the area of interest.

The slopes of the best-fit lines through the measured vs. modeled steady-state heads are shown plotted against travel time in Figure TFIELD-48. Steady-state-fit slopes less than 0.5 appear to lead to significantly longer travel times, consistent with the low hydraulic gradients the low slopes imply. Of the 116 T fields with steady-state-fit slopes greater than 0.5, all but nine have travel times less than 50,000 years. Figure TFIELD-49 shows the slopes and travel times for these 116 fields (the outlier with a travel time of ~241,000 years, d01r06, is not shown), and indicates that travel time is not sensitive to steady-state-fit slopes above 0.5.

TFIELD-7.2.3 Phi Values

Transient phi values for all the completed T fields are plotted against travel time in Figure TFIELD-50. As phi values decrease, particularly as they get below approximately 5,000 m^2

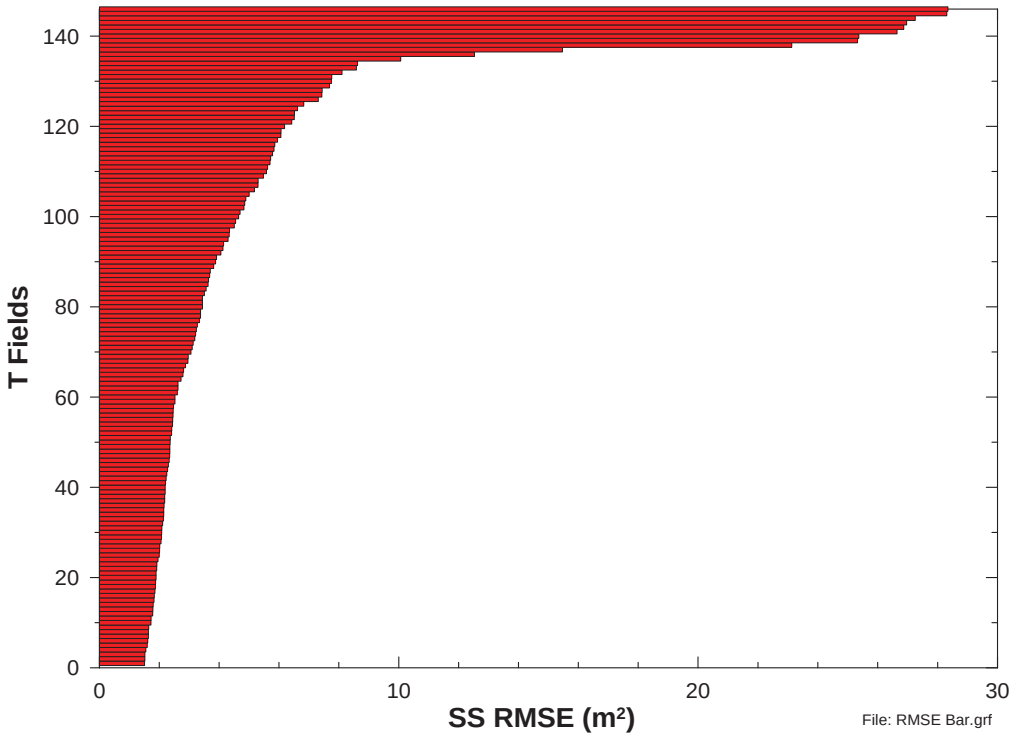

Figure TFIELD-44. Steady-State RMSE Values for 146 T Fields

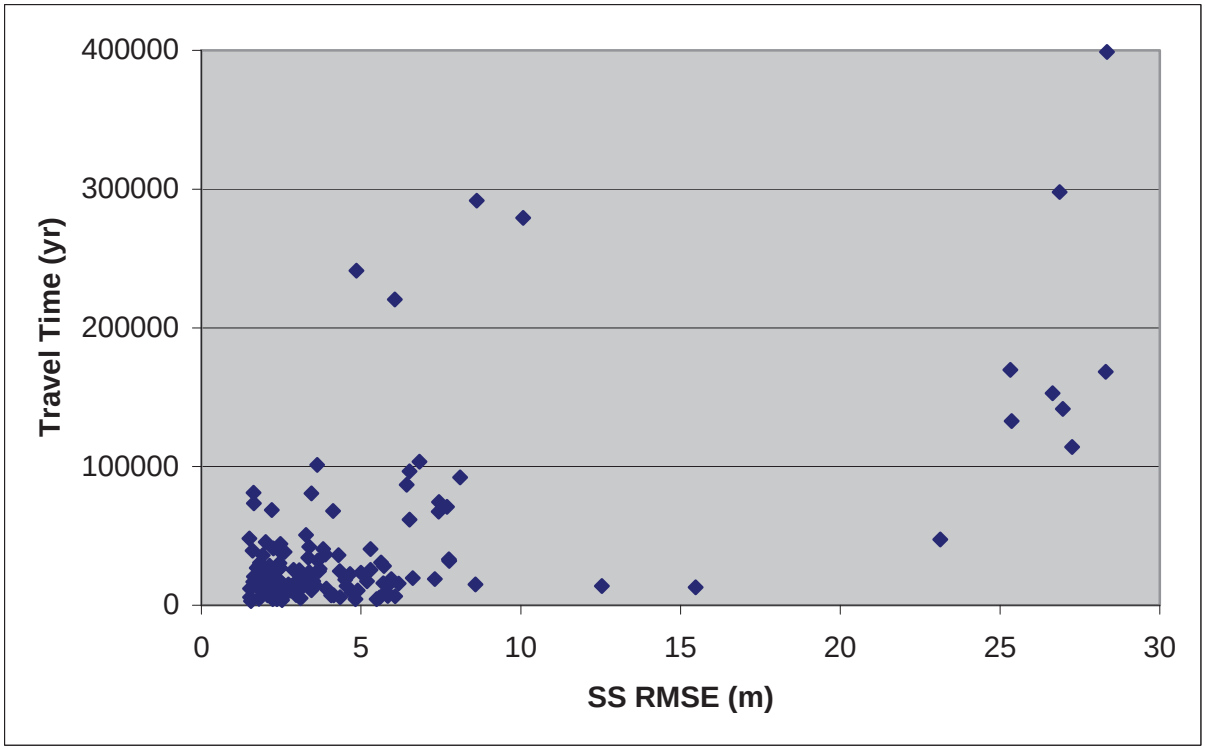

Figure TFIELD-45. Steady-State RMSE Values and Associated Travel Times

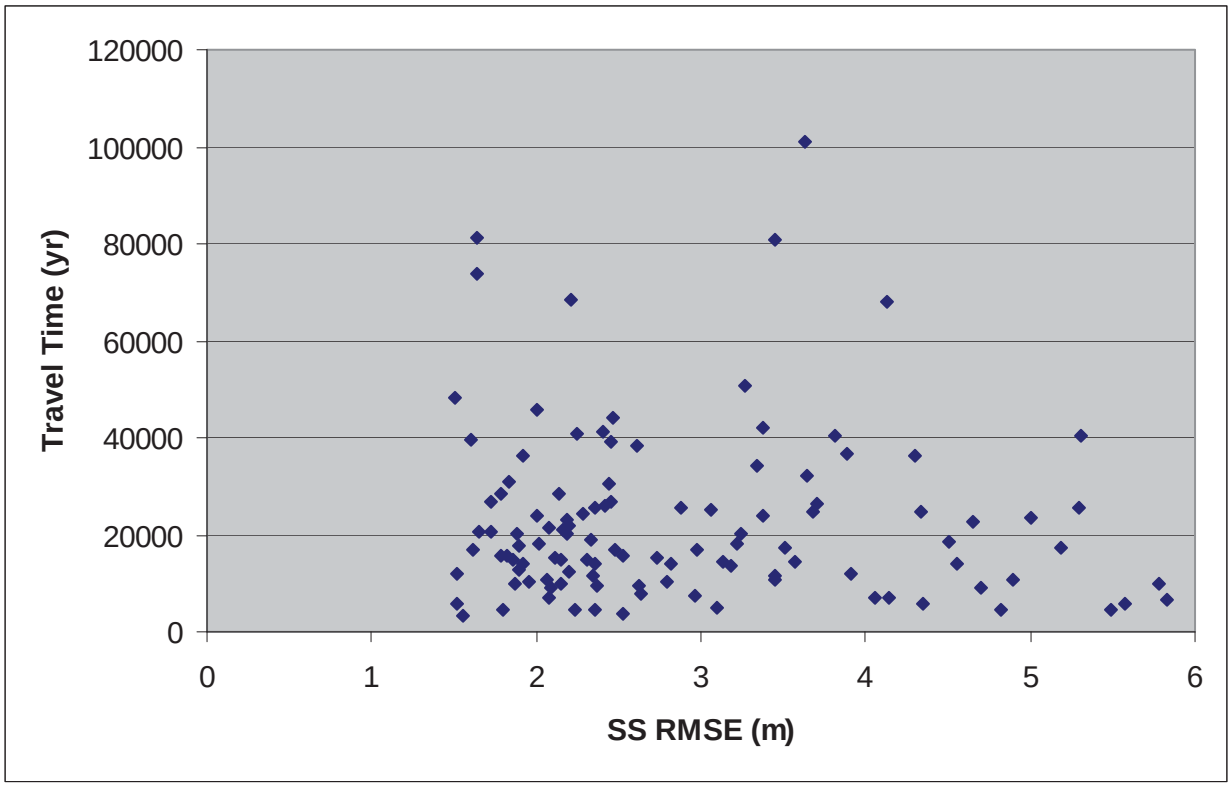

Figure TFIELD-46. Travel Times for Fields with Steady-State RMSE <6 m *(20 ft)*

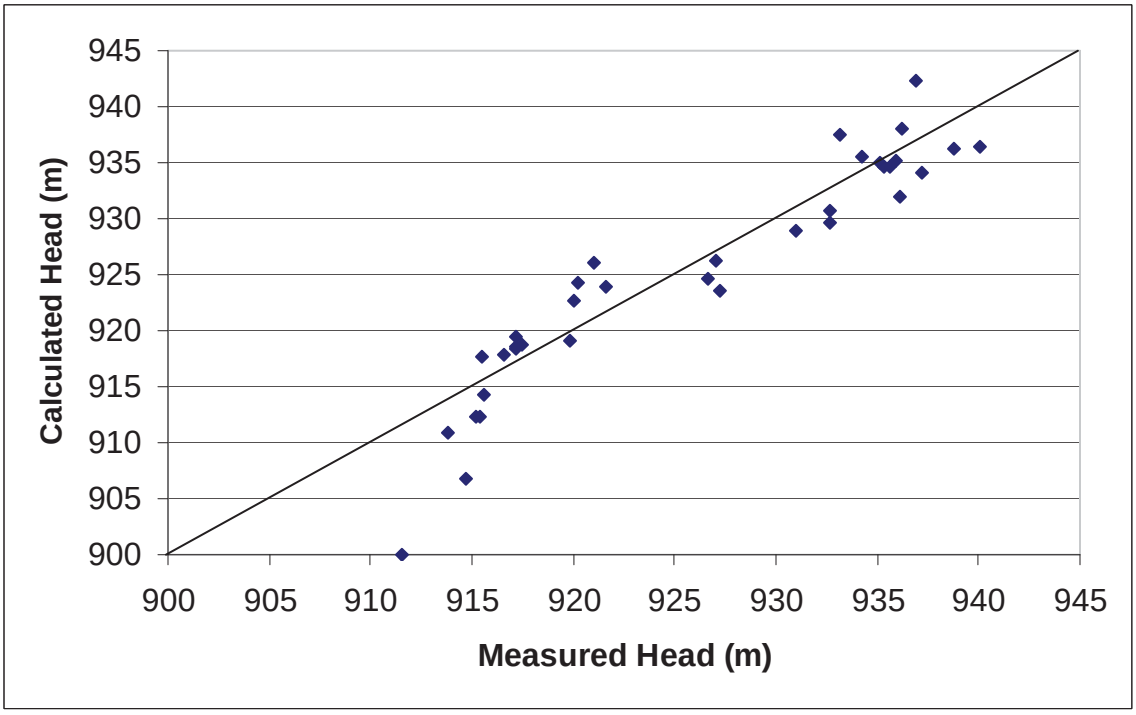

Figure TFIELD-47. Measured Versus Modeled Steady-State Heads for T Field d21r10

(53,800 ft^2), travel times tend to cluster below approximately 50,000 years, but little correlation is seen between transient phi and travel time. Figure TFIELD-51 shows transient phi versus travel time for the 123 fields with transient phi values less than 8,000 m^2 (86,000 ft^2), excluding the five outliers that have travel times greater than 168,000 years. This plot suggests that despite the clustering of travel times below 50,000 years, the overall range of travel times does not decrease significantly as phi decreases. Thus, transient phi does not appear to provide an effective tool for distinguishing among T fields.

TFIELD-7.2.4 Fit to Transient Heads

In applying the tests described in Section 7.1.4 of this attachment to the well responses simulated for each T field, it was found that insufficient data (only six measurements) had been included for the WQSP-1 response to pumping at WQSP-2 to allow any determination of model adequacy. Thus, this response was eliminated from consideration for all T fields. Figures TFIELD-52 and TFIELD-53 provide examples from T field d21r10 of well responses that were judged to PASS and FAIL, respectively, the criteria outlined in Section 7.1.4 of this attachment. The number of responses that failed for each T field is given in Table TFIELD-11. For the WQSP-3 responses to pumping at WQSP-1 and WQSP-2 (for which no clear drawdown was observed and "measured" values of zero were entered), the modeled response was accepted if it showed no more than 0.25 m (0.82 ft) of drawdown.

The number of well responses that fail the tests described in Section 7.1.3 of this attachment should be related to the transient phi for each T field because both are measures of the match between the measured and modeled transient heads. Figure TFIELD-54 shows a plot of transient phi versus the number of failed well responses for all 146 T fields. A definite correlation is evident up to a phi of approximately 8,000 m^2 (86,000 ft^2). Beyond that value, the number of failed well responses simply remains high ($\geq$14).

The number of failed well responses is plotted against travel time in Figure TFIELD-55 for each of the T fields. The scatter in travel time appears to increase with 14 or more failures, but the majority of T fields still have travel times in the same range as the fields with less than 14 failures. Thus, the number of failed well responses alone does not appear to discriminate well among T fields.

TFIELD-7.3 **Final Acceptance Criteria**

Of the criteria discussed above, the two related to the steady-state heads (RMSE and steady-state-fit slope) appear to be more effective at identifying poorly calibrated T fields than the two related to transient heads (transient phi and number of failed well responses). The range and scatter of travel times appears to increase at RMSE values beyond 6 m (20 ft). Applying an RMSE cutoff of 6 m (20 ft) leaves 117 T fields, all with travel times less than 102,000 years except one (d01r06). This cutoff also excludes all T fields with steady-state-fit slopes less than 0.45. Steady-state-fit slopes less than approximately 0.5 appear to lead to significantly longer travel times, consistent with the low hydraulic gradients the low slopes imply. If a simple cutoff of a minimum steady-state-fit slope of 0.5 is applied, 116 T fields are left, again with travel times less than 102,000 years (except d01r06), and also with RMSE values less than 8.6 m (28.2 ft). Five T fields that meet the RMSE less than 6 m (20 ft) criterion fail the steady-state-fit slope

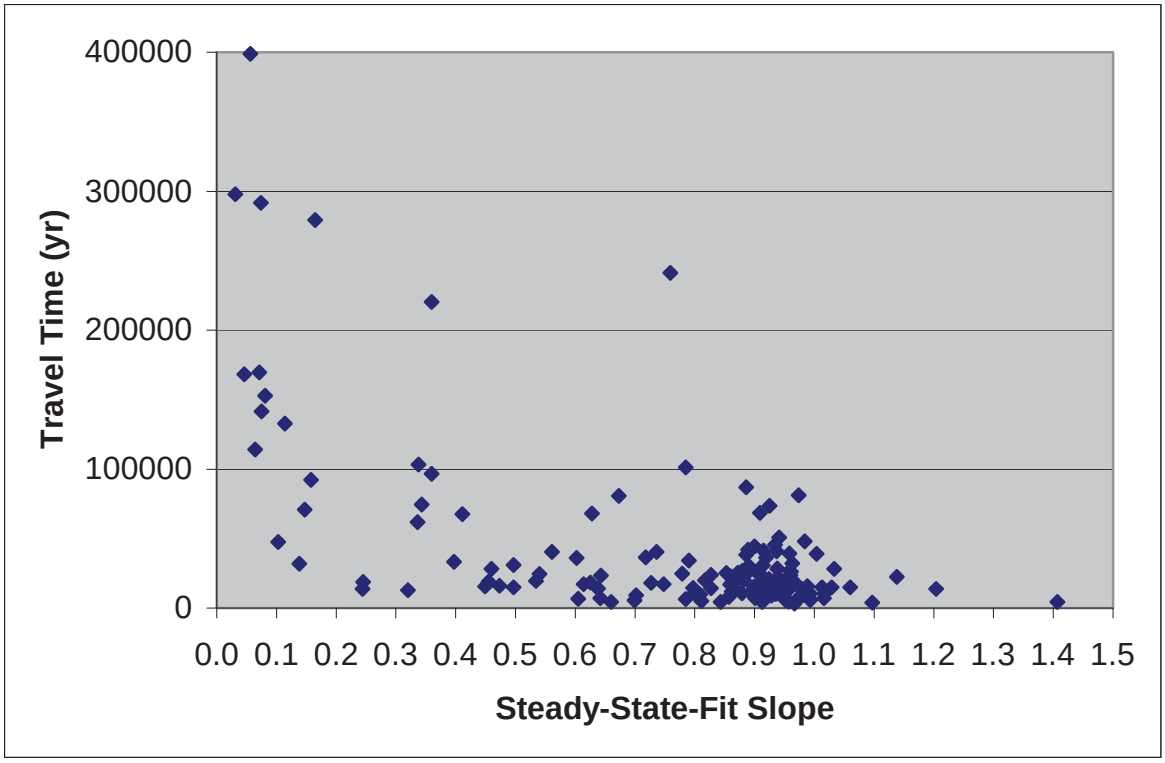

Figure TFIELD-48. Steady-State-Fit Slope Versus Travel Time for All Fields

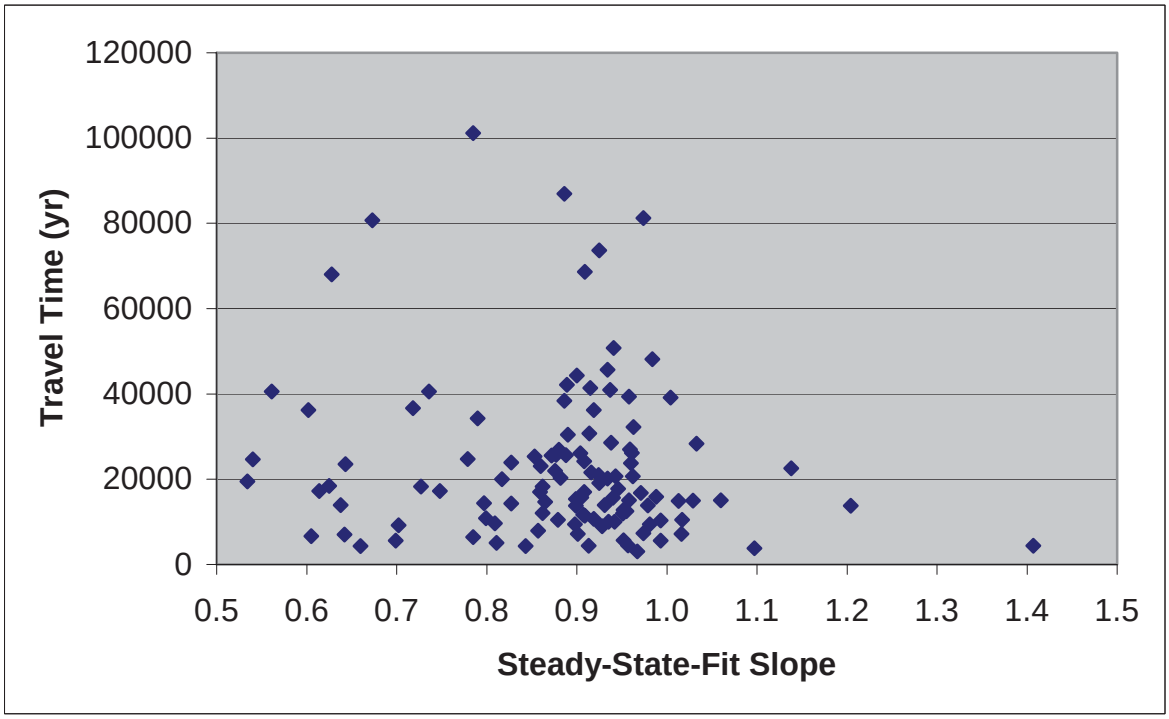

Figure TFIELD-49. Steady-State-Fit Slope Versus Travel Time for Slopes >0.5

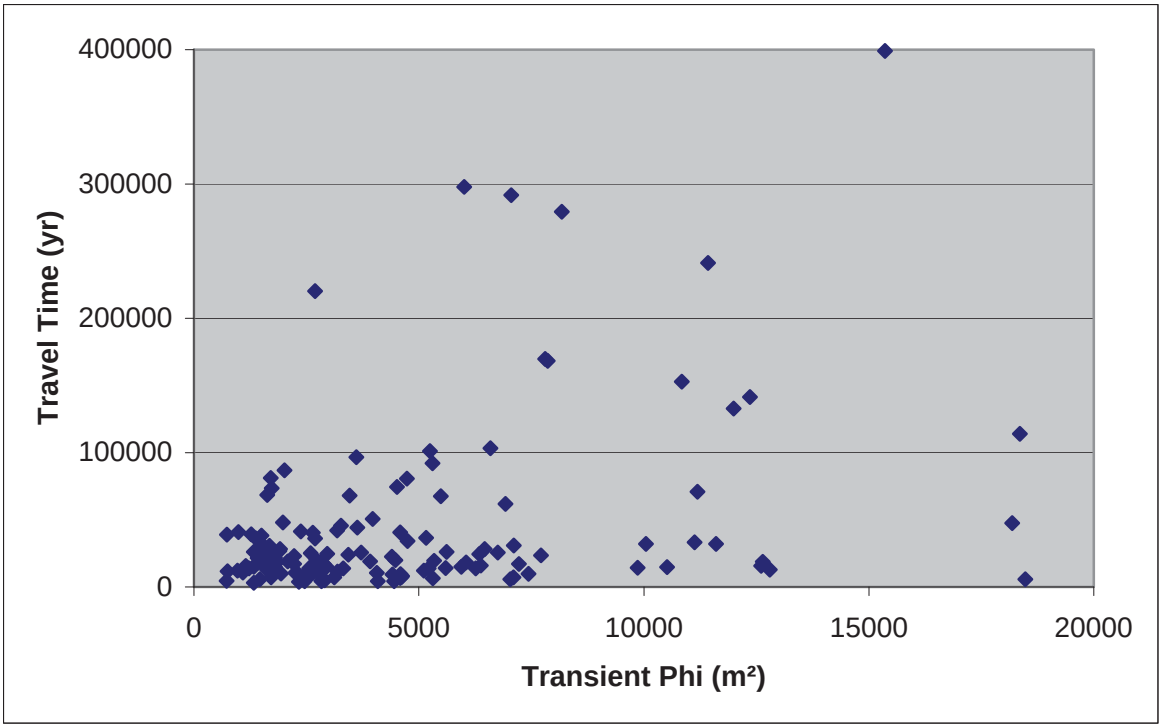

Figure TFIELD-50. Transient Phi Versus Travel Time for All Fields

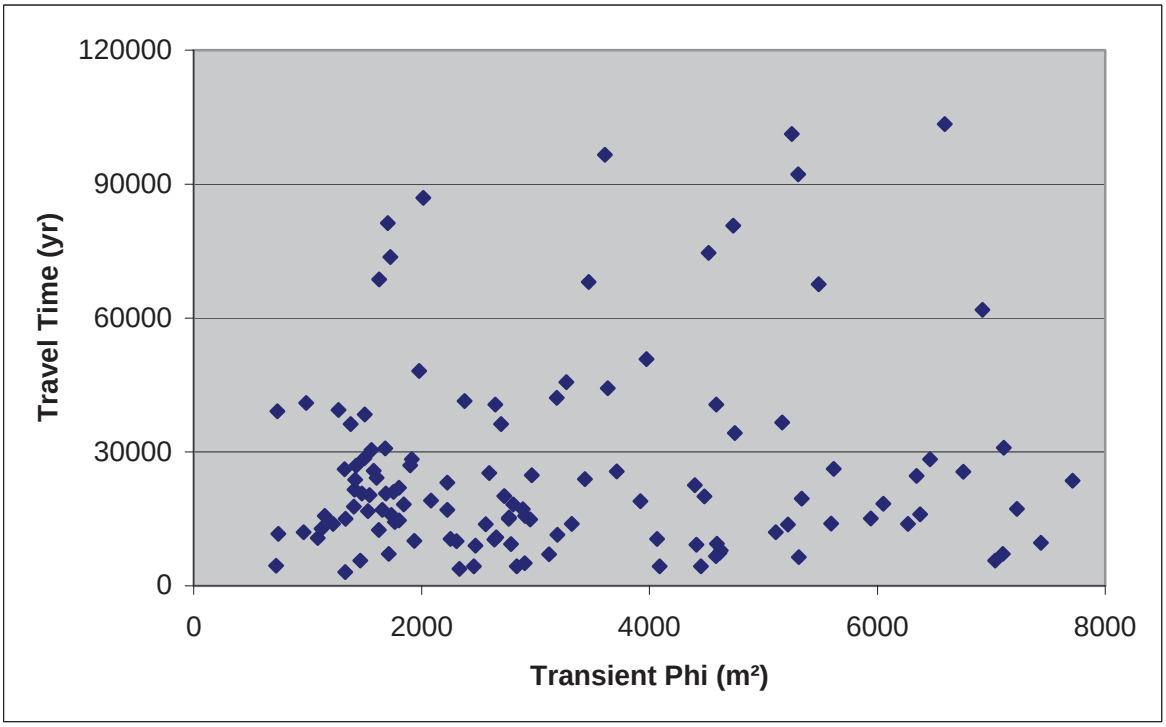

Figure TFIELD-51. Transient Phi Versus Travel Time for Phi <8,000 m^2

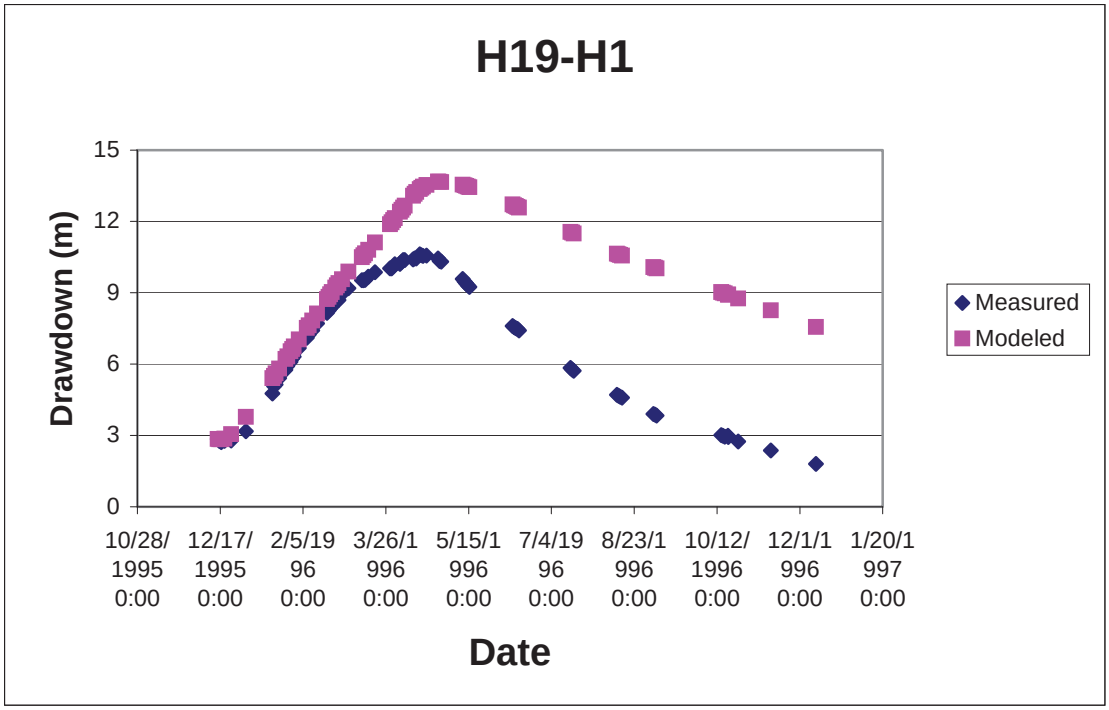

Figure TFIELD-52. Example of Passing Well Response from T Field d21r10

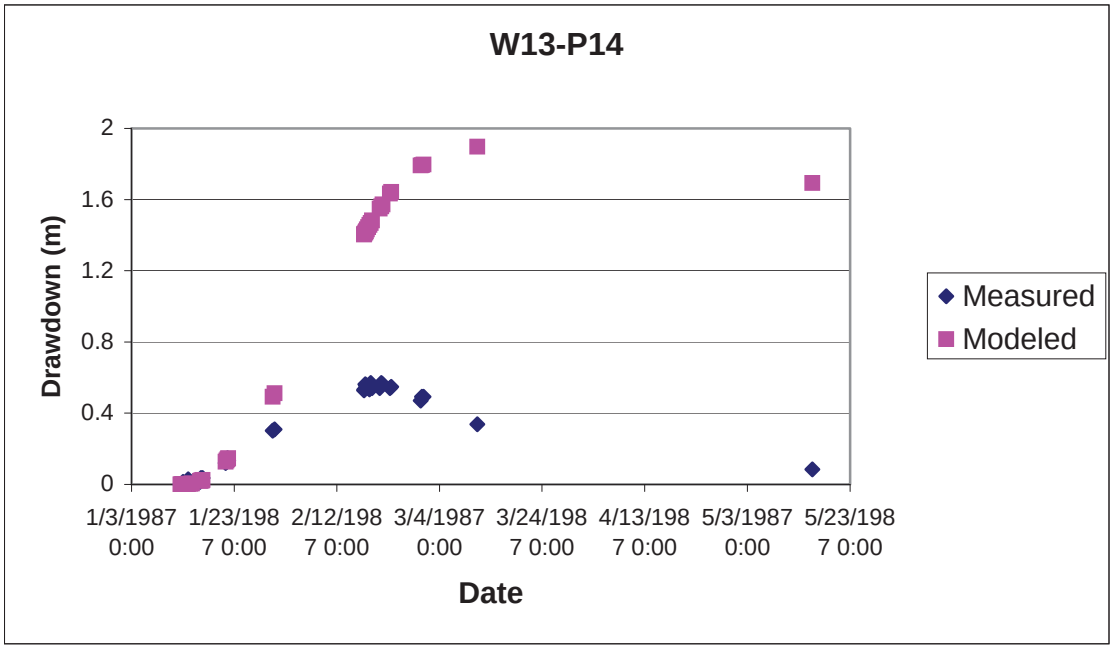

Figure TFIELD-53. Example of Failing Well Response from T Field d21r10

Table TFIELD-11. Summary Information on T Fields

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
[redacted]	7.427	10498	5486	0.411	13	67578
d01r02	3.915	3621	5110	0.862	20	12045
d01r04	2.812	2140	2563	1.204	11	13821
[redacted]	7.313	10245	12643	0.245	16	18886
d01r06	4.856	5006	11426	0.759	15	241211
d01r07	3.377	2851	3187	0.889	9	42123
d01r08	5.484	6122	4091	1.407	14	4399
d01r10	1.646	1094	1476	0.943	9	20685
[redacted]	26.966	128711	12359	0.075	19	141516
d02r02	3.507	2772	2889	0.748	11	17217
[redacted]	10.070	18606	8173	0.165	15	279242
[redacted]	8.104	12482	5305	0.158	12	92235
d02r05	5.184	5577	7224	0.614	17	17255
[redacted]	25.325	113652	7810	0.071	16	169677
d02r07	3.648	3223	10047	0.963	15	32231
d02r08	5.001	5125	7713	0.643	17	23571
d02r10	6.066	6849	5312	0.785	13	6433
d03r01	4.506	4022	6053	0.625	17	18435
[redacted]	28.346	142152	15357	0.056	16	398937
d03r03	4.146	3899	7102	1.016	17	7171
[redacted]	25.367	114006	11991	0.114	14	132833
d03r05	5.836	6873	4585	0.605	13	6638
d03r06	1.729	1208	1899	0.959	13	27006
d03r07	4.655	4740	4399	1.138	13	22599
d03r08	4.550	4250	5593	0.638	17	13942
d03r09	2.352	1574	1580	0.877	7	25757
d03r10	8.584	13811	2766	1.060	13	15054
d04r01	3.447	2370	4736	0.673	17	80690
d04r02	3.818	3175	2647	0.736	12	40593
d04r03	2.352	1659	3317	0.979	12	13888
d04r04	4.298	3692	2697	0.602	13	36245
d04r05	1.507	1059	1980	0.984	9	48168
d04r06	3.705	3146	5618	0.961	16	26199
d04r07	2.183	1397	2226	0.860	10	23105
d04r08	2.444	1759	1560	0.890	11	30470
[redacted]	27.256	131491	18356	0.064	16	114087
d04r10	3.060	2401	2593	0.853	9	25316
d05r01	6.427	8119	2015	0.886	13	86924
d05r02	5.298	5831	6755	0.872	16	25610
d05r03	3.444	2580	2655	0.799	11	10880
d05r04	5.862	6984	10518	0.497	17	14856
d05r05	4.346	4226	18478	0.952	16	5668
[redacted]	6.518	8198	3609	0.360	13	96589
d05r07	3.188	2682	5216	0.899	9	13766
[redacted]	7.686	11242	11194	0.147	16	70896
[redacted]	26.644	125685	10840	0.081	17	152818
d05r10	5.623	6497	7110	0.497	16	30955
[redacted]	6.828	9057	6592	0.338	17	103442
d06r02	1.957	1266	2639	0.993	9	10353
d06r03	1.637	1051	1703	0.974	10	81258
d06r04	3.214	2246	2805	0.727	13	18294

Table TFIELD-11. Summary Information on T Fields — Continued

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
d06r05	3.886	3516	5164	0.718	18	36644
d06r06	2.149	1254	2954	1.013	10	14935
d06r07	1.518	784	965	0.951	7	12035
[redacted]	7.440	10397	4518	0.343	18	74565
[redacted]	28.309	141764	7864	0.046	18	168281
d06r10	2.196	1455	1801	0.876	11	21990
d07r01	3.101	2326	2905	0.811	14	5082
d07r02	2.010	1327	3271	0.934	15	45647
[redacted]	15.470	42986	12795	0.320	19	12919
d07r04	5.579	6230	7033	0.699	18	5638
d07r05	2.727	1705	5942	0.958	10	15097
d07r06	4.334	3927	6345	0.540	12	24641
d07r07	2.477	1737	2225	0.908	9	17038
d07r08	2.232	1097	2836	0.843	9	4355
d07r09	2.207	1239	1628	0.909	8	68629
d07r10	1.782	839	1150	0.940	9	15680
d08r01	2.361	1736	2458	0.913	11	4388
d08r02	2.418	1168	1326	0.904	6	26115
d08r03	2.137	1489	1499	0.938	9	28570
d08r04	3.683	2674	2966	0.779	9	24773
d08r05	2.115	1384	2769	0.899	13	15358
d08r06	1.916	1388	1225	0.931	11	13917
d08r07	1.857	815	1333	1.029	10	15027
[redacted]	12.534	28547	6267	0.244	12	13885
d08r09	5.785	6674	7437	0.809	17	9691
[redacted]	8.621	13909	7050	0.074	11	291623
d09r02	3.243	2418	4482	0.817	12	20048
d09r03	2.252	1337	989	0.937	8	40948
d09r04	1.892	710	1123	0.952	8	12857
d09r05	2.061	954	1088	0.919	8	10726
d09r06	2.794	2313	2253	0.879	16	10509
d09r07	2.629	1676	4591	0.981	10	9472
d09r08	1.895	1030	1406	0.946	9	17741
d09r09	4.826	4945	4453	0.660	14	4359
d09r10	3.273	2790	3976	0.941	19	50791
[redacted]	26.867	127794	6006	0.031	14	297840
d10r02	1.554	589	1330	0.967	8	3111
d10r03	2.201	1474	1626	0.955	9	12533
d10r04	2.527	1788	2334	1.097	9	3799
d10r05	5.722	6646	6463	0.460	18	28390
d10r06	4.702	4644	4412	0.702	13	9210
d10r07	1.870	810	1937	0.935	10	10068
d10r08	2.334	1613	2083	0.925	8	19093
d10r09	4.128	3643	3466	0.628	11	68052
d10r10	1.789	982	1915	1.033	13	28367
d11r01	2.970	2297	1655	0.859	9	17015
d11r02	2.308	1799	1801	0.865	12	14677
d11r03	5.700	6093	6376	0.473	9	16014
[redacted]	6.514	8401	6922	0.336	23	61862
d11r05	5.952	7166	3921	0.455	17	18998
d11r06	2.607	1949	1503	0.886	9	38399

Table TFIELD-11. Summary Information on T Fields — Continued

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
d11r07	1.639	602	1727	0.925	9	73634
d11r08	1.801	1206	723	0.957	6	4520
d11r09	2.073	858	1712	0.901	7	7199
d11r10	3.135	2363	1767	0.827	5	14358
d12r01	3.378	2921	3432	0.827	14	23936
d12r02	2.459	1795	1426	0.880	10	26919
d12r03	1.618	558	1530	0.971	11	16780
[redacted]	6.182	7395	12605	0.449	20	15619
d12r05	1.522	918	1463	0.993	6	5655
d12r06	1.602	539	1271	0.958	13	39399
d12r07	2.016	945	1844	0.862	9	18283
d12r08	2.630	1879	4627	0.857	16	7981
d12r09	2.369	1671	2784	0.898	11	9414
[redacted]	7.762	11431	11606	0.138	18	32059
d13r01	2.163	1061	1753	0.924	11	21032
d13r02	2.881	2054	3715	0.888	14	25639
d13r03	3.444	2580	3192	0.909	11	11493
d13r04	5.302	5856	4588	0.561	13	40601
d13r05	3.343	2671	4750	0.790	12	34247
d13r06	2.410	1441	2377	0.915	10	41400
d13r07	2.280	1395	1606	0.908	10	24211
d13r08	1.879	779	1544	0.882	9	20313
d13r09	1.919	776	1379	0.919	14	36260
[redacted]	6.063	6685	2693	0.360	14	220354
d21r01	2.151	1555	2307	0.942	13	10042
d21r02	2.087	1431	2473	0.928	9	9023
d21r03	2.346	1299	744	0.907	6	11671
d21r04	2.523	1978	2908	0.905	13	15717
d21r05	2.001	932	1417	0.960	10	23750
d21r06	1.721	655	1688	0.962	8	20715
d21r07	2.182	1179	2725	0.934	9	20141
d21r08	6.620	8618	5337	0.534	14	19534
[redacted]	7.750	11501	11124	0.397	19	33308
d21r10	2.959	2226	4615	0.974	13	7384
[redacted]	23.126	94895	18190	0.103	15	47563
d22r02	3.629	3197	5250	0.785	10	101205
d22r03	4.061	3464	3119	0.642	11	7067
d22r04	4.894	5073	4068	1.017	12	10537
d22r05	3.566	3160	9863	0.797	18	14385
d22r06	2.469	1145	3635	0.900	9	44309
d22r07	2.080	999	1413	0.916	9	21589
d22r08	1.837	809	1681	0.914	10	30771
d22r09	1.822	724	1734	0.988	19	15870
d22r10	2.452	1684	735	1.004	5	39116

[redacted] signifies T fields not meeting final acceptance criteria.
Bold italics type signifies 100 final T fields as discussed in Section 7.3 of this attachment.

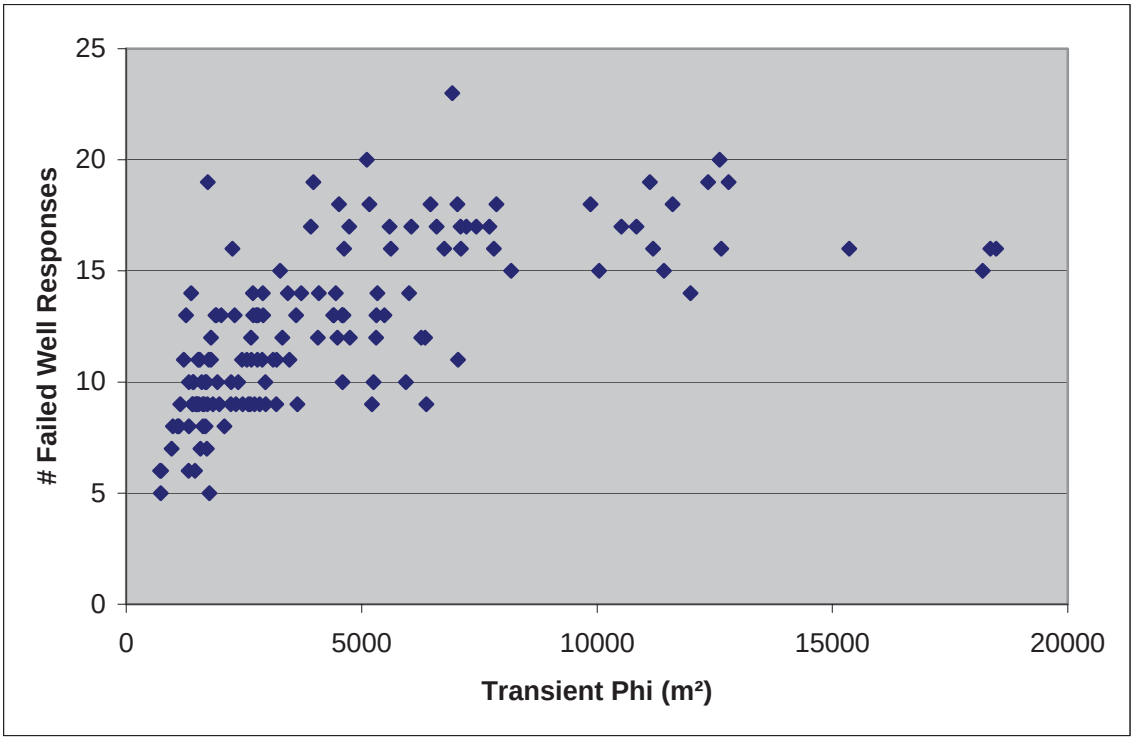

Figure TFIELD-54. Transient Phi Versus Number of Failed Well Responses

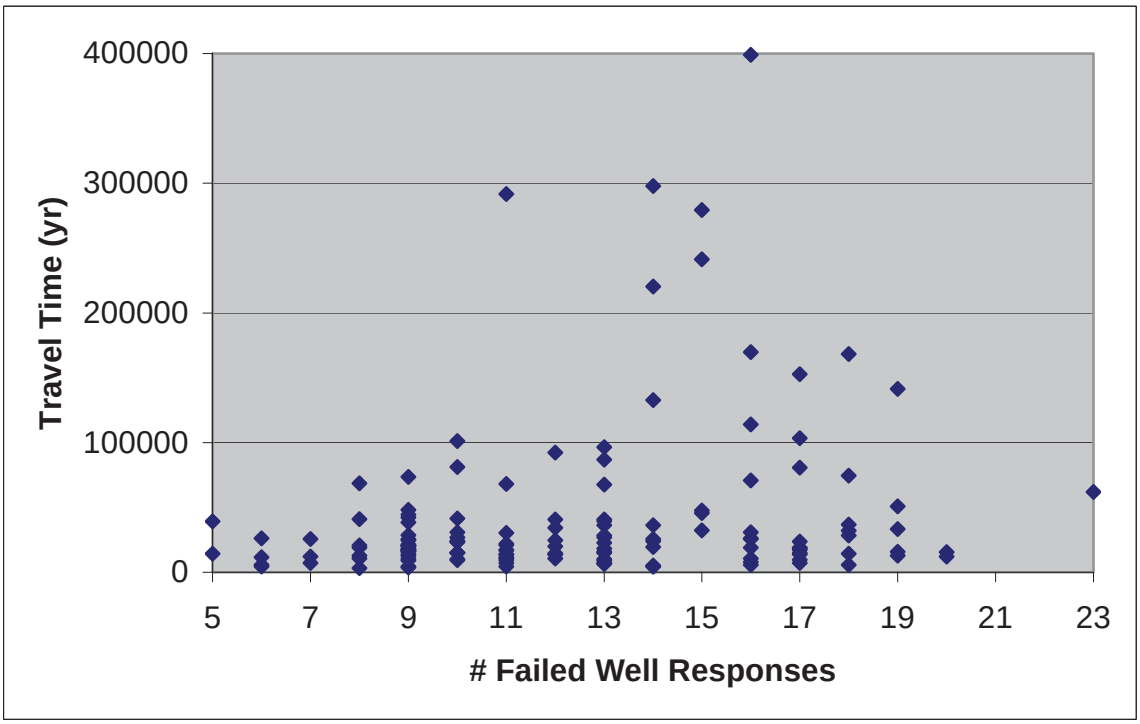

Figure TFIELD-55. Number of Failed Well Responses Versus Travel Time

greater than 0.5 criterion, while four T fields meeting the slope criterion fail the RMSE criterion. Thus, 112 T fields meet both criteria while 121 T fields meet at least one of the criteria.

Figure TFIELD-56 shows a CDF for the 121 T fields meeting the RMSE and/or steady-state-fit slope criteria discussed above. Also shown are curves representing the 100 T fields with RMSE values <5 m (16 ft) and transient phi values <8,000 m^2 (86,111 ft^2), and the 100 T fields with the largest steady-state-fit slopes (>0.72). All three CDFs are very similar, the most significant difference being that imposing a cutoff value on transient phi eliminates the T field with the longest travel time (d01r06). To illustrate the effects of imposing more stringent constraints on T-field acceptance, a fourth CDF is shown in Figure TFIELD-56 that represents the 23 T fields

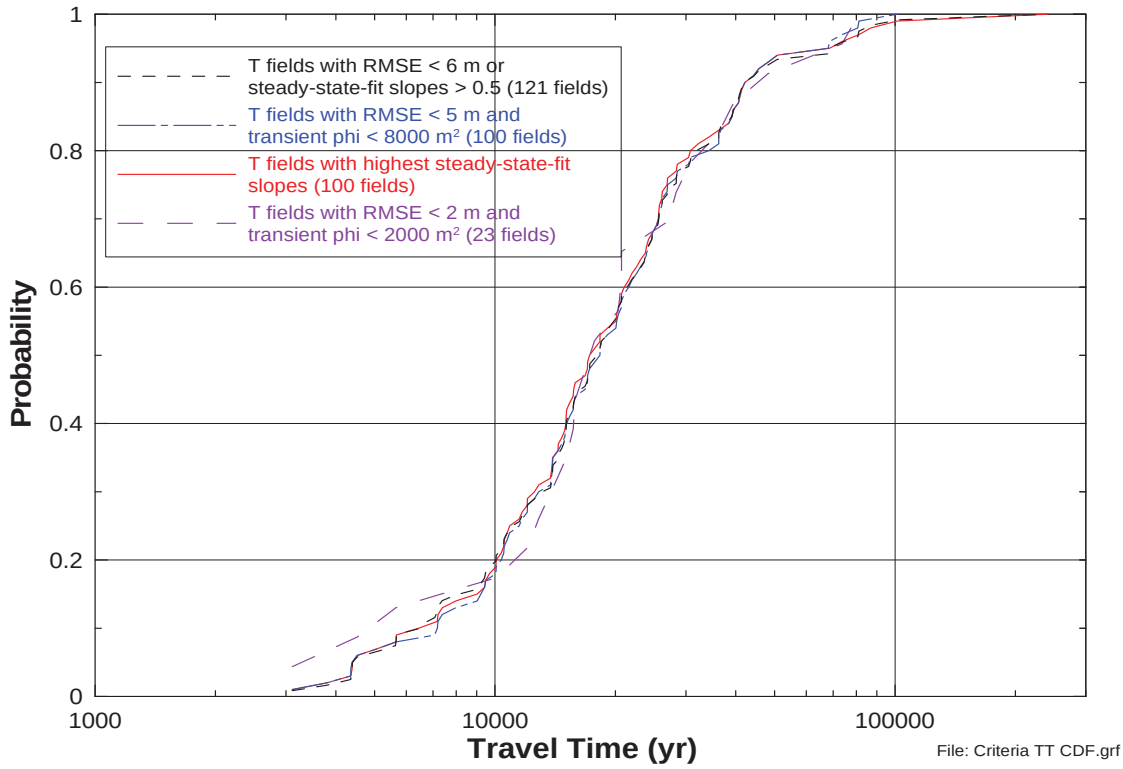

Figure TFIELD-56. Travel-Time CDFs for Different Sets of T Fields

that have RMSE values less than 2 m (7 ft) and transient phi values less than 2,000 m^2 (21,527 ft^2). These 23 T fields all have steady-state-fit slopes greater than 0.88. This CDF generally shows travel times similar to those of the other CDFs, except at the tails of the distribution which are poorly defined because of the relatively small sample size. Thus, because all the CDFs shown are similar, all 121 T fields meeting the steady-state-fit slope or RMSE criteria were considered to be acceptably calibrated. The T fields that have been rejected are shown in reverse type in Table TFIELD-11.

Because only 100 T fields were needed, the criteria were refined to eliminate more T fields. Given that lower travel times provide a conservative (in terms of leading to increased solute transport) way to discriminate among sets of T fields, the 100 T fields with RMSE values <5 m (16 ft) and transient phi values <8,000 m^2 were selected for use in CRA-2004 calculations of

radionuclide transport through the Culebra because that set excluded the calibrated T field with the longest travel time. These T fields are highlighted in ***bold italicized*** type in Table TFIELD-11.

For comparison purposes, the CDF of travel times for these 100 T fields is plotted in Figure TFIELD-57 with the CDF of travel times for the 100 transient-calibrated T fields used in the CCA (Wallace 1996). Generally speaking, travel times are two to three times as long in the CRA-2004 fields as in the CCA fields. Considering the degree of uncertainty involved in characterizing a geologic medium on the scale of the T fields, a factor of two or three difference in travel-time CDFs represents excellent agreement.

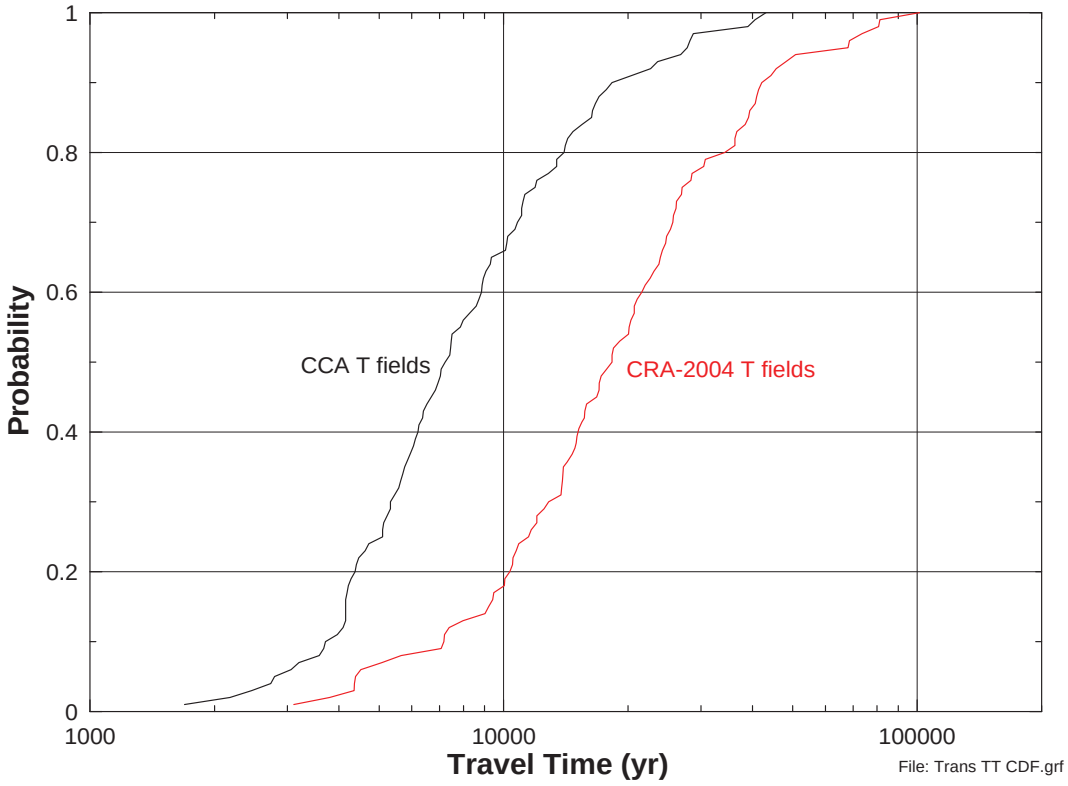

Figure TFIELD-57. Travel-Time CDFs for CCA and CRA-2004 T Fields

TFIELD-8.0 INVERSE MODELING RESULTS

Some fit statistics (phi, RMSE, etc.) for the 121 T fields that were judged to be acceptably calibrated were presented in Section 7.0 of this attachment. Visualizations of the T fields are included in Annex A. Additional properties or characteristics of the T fields are given below.

TFIELD-8.1 Particle Tracking

Particle tracking was performed in the 121 calibrated T fields from a point above the center of the WIPP disposal panels to both the LWB and the boundary of the model domain, as discussed in Section 7.0 of this attachment. The locations of all the particle tracks are show in Figures TFIELD-58 and TFIELD-59. In both figures, the particle tracks are shown using only every 20th

point along the track because of a limitation in the graphing software. This filtering leads to the particle tracks appearing less smooth than they actually are. Figure TFIELD-58 shows a close-up view of the particle tracks within the WIPP LWB. All of the particles exit the southern edge of the LWB and the majority of the particles exit the LWB to the southeast of the release point, although not as far to the east as the particle tracks for the CCA T fields showed (Ramsey et al. 1996, p. 49). Figure TFIELD-59 shows the particle tracks within the entire model domain. The majority of the particles exit the domain nearly due south of the release point. The particles that migrate to the west tend to travel along the boundary of the high-T zone. This result is due to the large amount of groundwater flux within the high-T zone creating a streamline at the high-T zone boundary.

TFIELD-8.2 Fit to Steady-State Heads

Some information about how well the calibrated T fields matched the observed steady-state heads is given in Sections 7.2.1 and 7.2.2 of this attachment. Additional information is shown in

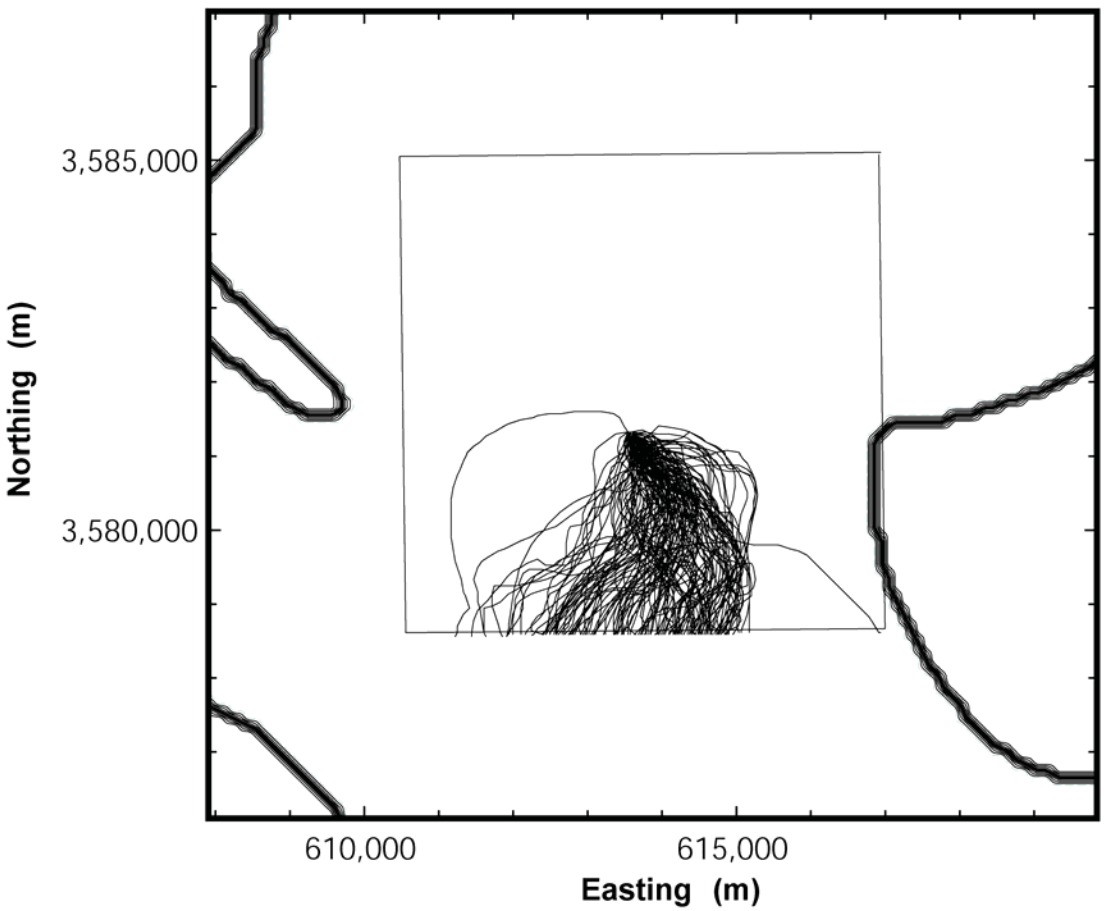

Figure TFIELD-58. All Particle Tracks Within the WIPP LWB. The bold lines show the boundaries of the high-T (left side) and low-T (right side) zones.

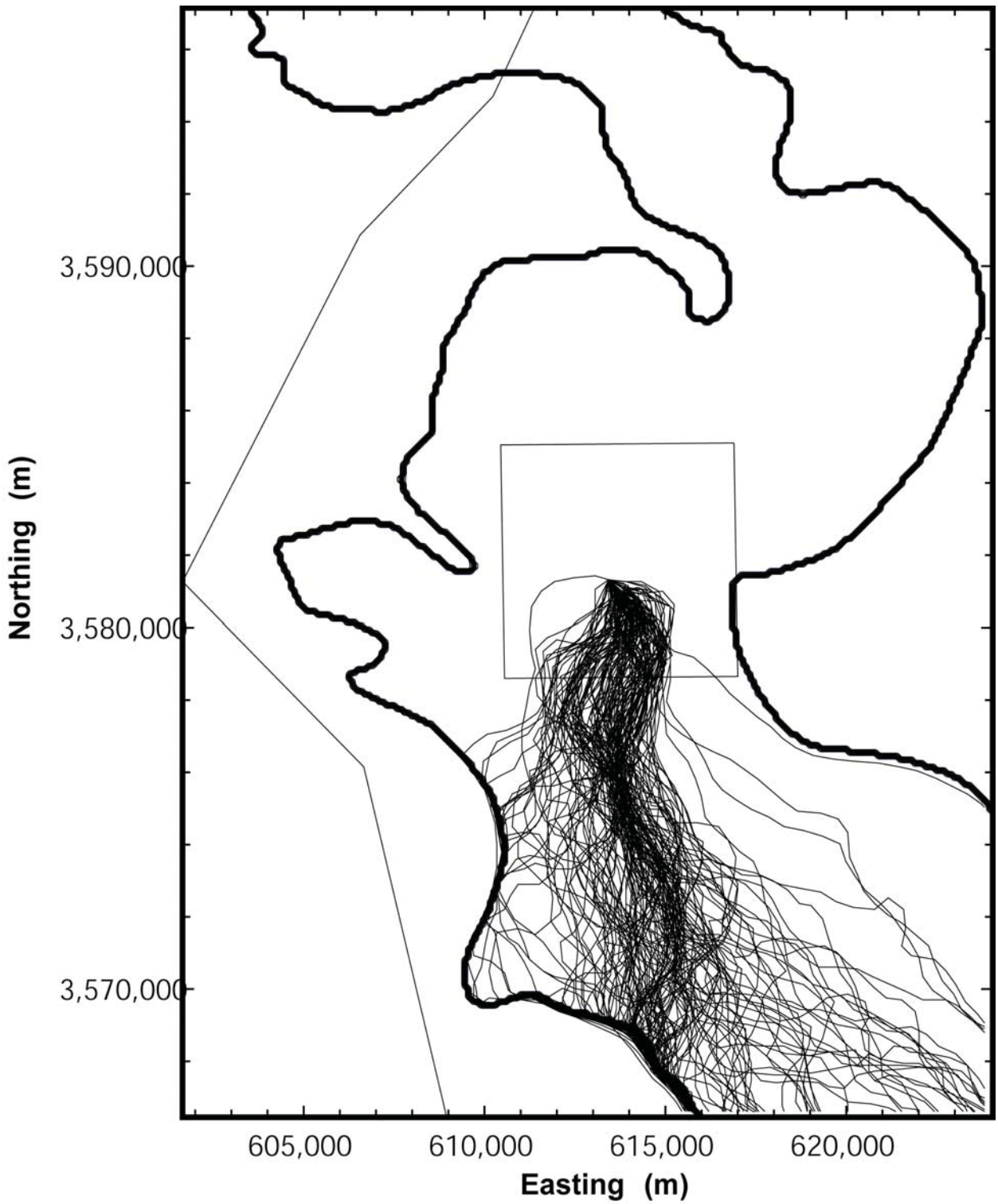

Figure TFIELD-59. All Particle Tracks Within the Model Domain. The bold lines show the boundaries of the high-T (left) and low-T (right) zone boundaries. The no-flow and WIPP site boundaries are also shown.

Figures TFIELD-60 and TFIELD-61. Figure TFIELD-60 shows a scatterplot of the modeled steady-state heads in the 121 calibrated T fields versus the measured heads. Also shown is a unit-slope line representing perfect agreement between the measured and modeled heads, and parallel lines showing a 5-m (16-ft) range on either side. Most modeled head values fall within the ±5 m (16 ft) lines, except for the modeled heads for H-9b, the well with the lowest measured head. As discussed in Section 7.2.1 of this attachment, H-9b is the southernmost well in the model domain and the southern model boundary condition consistently caused the modeled H-9b head to be significantly lower than the measured head.

Figure TFIELD-61 shows a histogram of the differences between the modeled and measured heads. The majority of modeled head values more than 8 m (26 ft) lower than the measured values are associated with H-9b. Excluding the H-9b values, the histogram shows a normal distribution of errors with 48 percent of the modeled heads within 2 m (7 ft) of the measured heads, and 79 percent of the modeled heads within 4 m (13 ft) of the measured heads. The fit between measured and modeled steady-state heads could probably have been improved by allowing PEST to perform more calibration iterations but, as shown in Section 7.3 of this attachment, the travel-time distribution for the T fields would be unlikely to be affected.

TFIELD-8.3 Pilot-Point Sensitivity

Transmissivities at each of the pilot points within the model domain were altered during the calibration process. The maximum allowable change was ± three orders of magnitude in the middle region of the model domain and ± one order of magnitude in the low-T (eastern) and high-T (western) regions of the model domain. Figures TFIELD-62 and TFIELD-63 show the percentage of calibrated T fields in which each pilot point hit the maximum and minimum possible value, respectively. The size of the bubble is proportional to the number of times the value hits one constraint or the other. Figure TFIELD-62 shows that the pilot points south of the western portion of the southern LWB were most likely to reach their maximum allowable values, indicating that the base T fields may have underestimated Ts in this area. Figure TFIELD-63 shows that the pilot point placed in the inferred dissolution reentrant between P-14 and WIPP-25 west of the LWB (see Figure TFIELD-38) was most likely to reach its minimum allowable value, indicating that this reentrant may not be as hydraulically significant as originally assumed.

TFIELD-8.4 Ensemble Average T Field

The 121 T fields that were acceptably calibrated can be combined into an ensemble average T field showing the average properties of the T fields (Figure TFIELD-64). The averaging is performed on a cell-by-cell basis, taking the arithmetic mean of the 121 T values assigned to each cell. Figure TFIELD-65 shows a close-up view of the ensemble average of the 100 T fields used for subsequent calculations in the area surrounding the WIPP site, using a different color scale with T values “binned” by order of magnitude for clarity. This figure does not show a continuous north-south high-T zone exiting the southeastern portion of the WIPP site, as was present in the ensemble average T field provided in CCA Appendix TFIELD (Figure 30). It also shows higher Ts in the southwestern portion of the WIPP site than were present in the CCA ensemble average field. These differences explain why the travel paths in the CRA-2004 T fields (Figure TFIELD-58) take a more westerly course, on average, than those in the CCA T

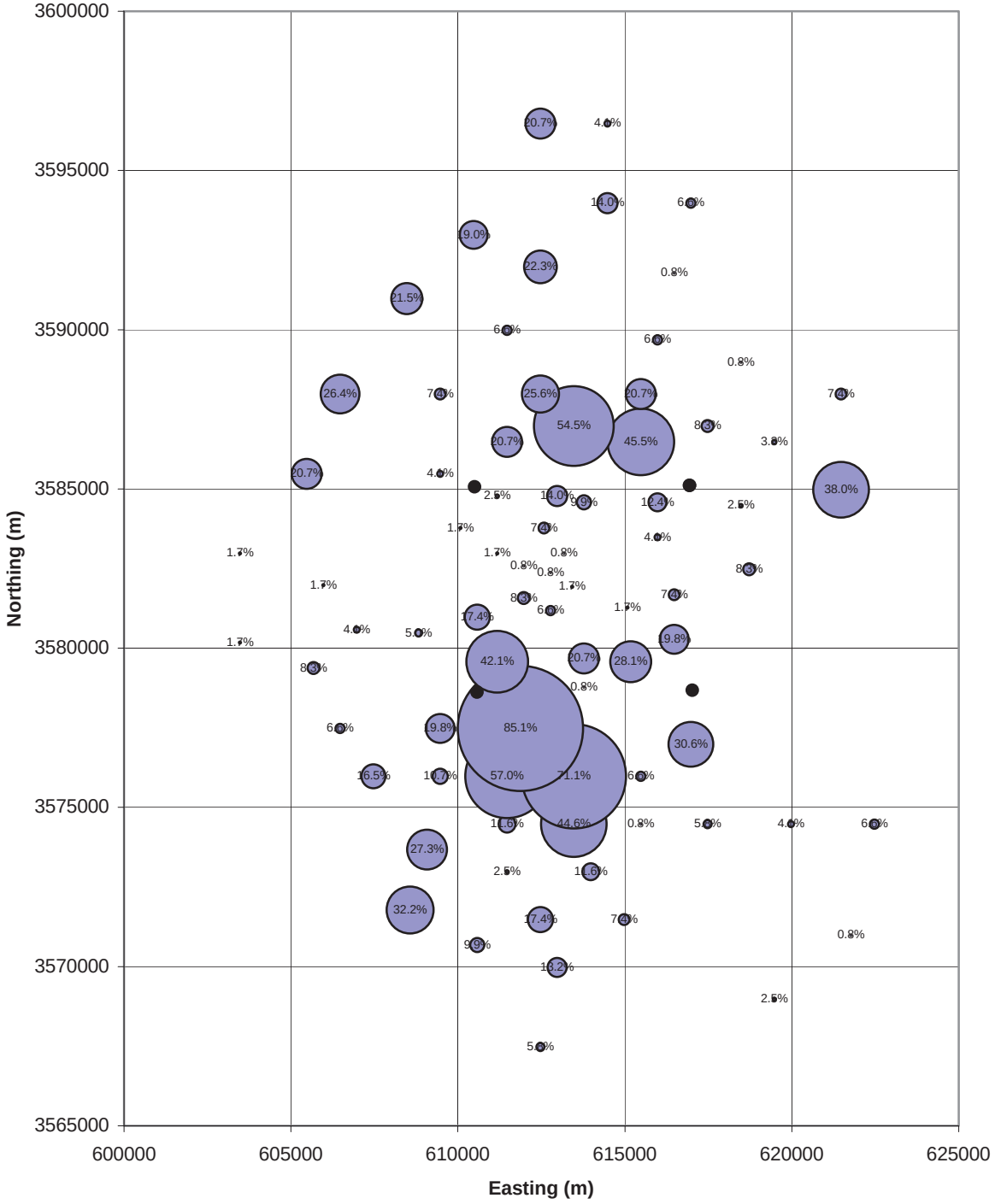

Figure TFIELD-60. Percentage of T Fields in which Pilot Points Hit Maximum Allowable Values. Corners of WIPP LWB are shown by unlabeled black dots.

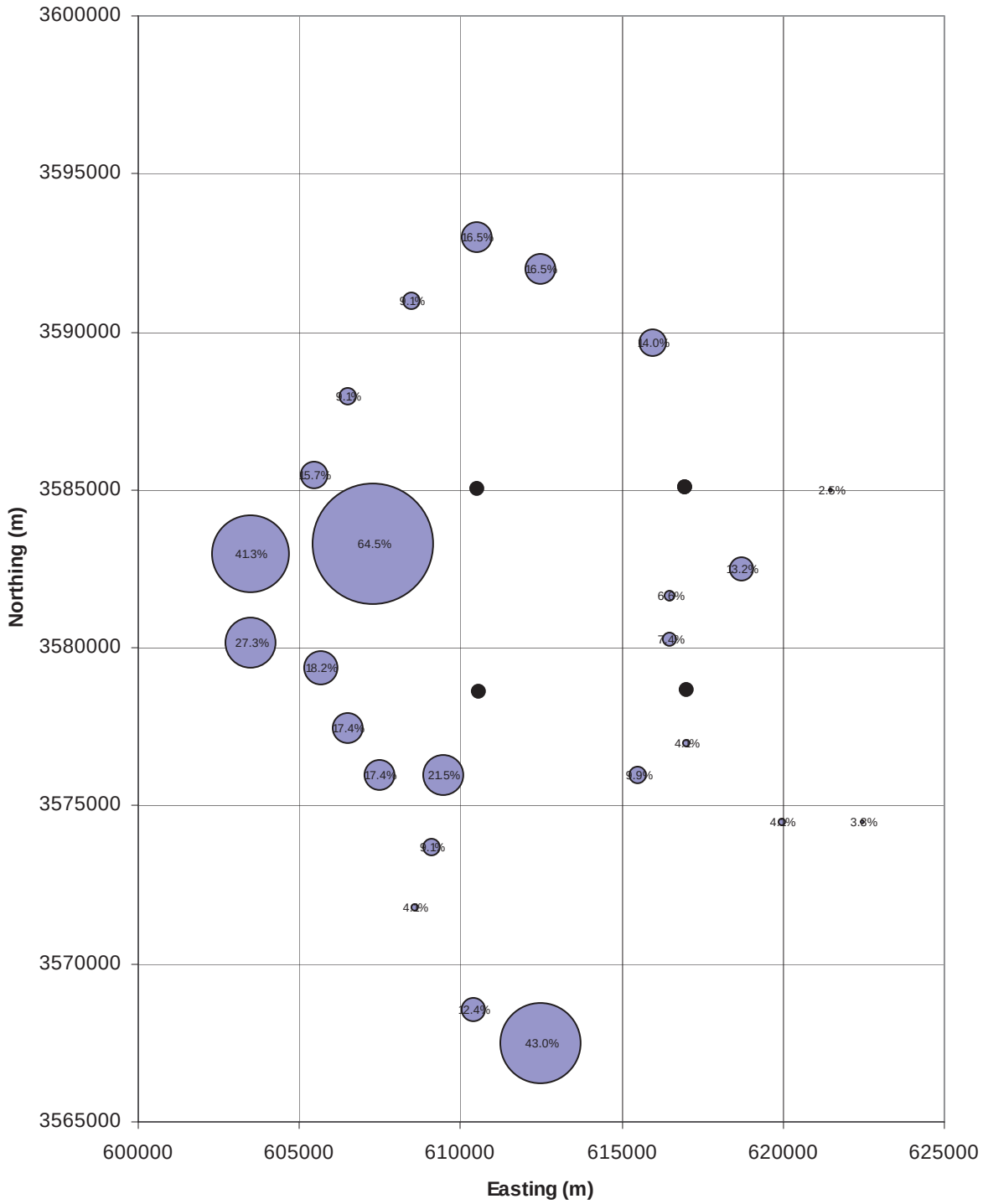

Figure TFIELD-61. Percentage of T Fields in which Pilot Points Hit Minimum Allowable Values. Corners of WIPP LWB are shown by unlabeled black dots.

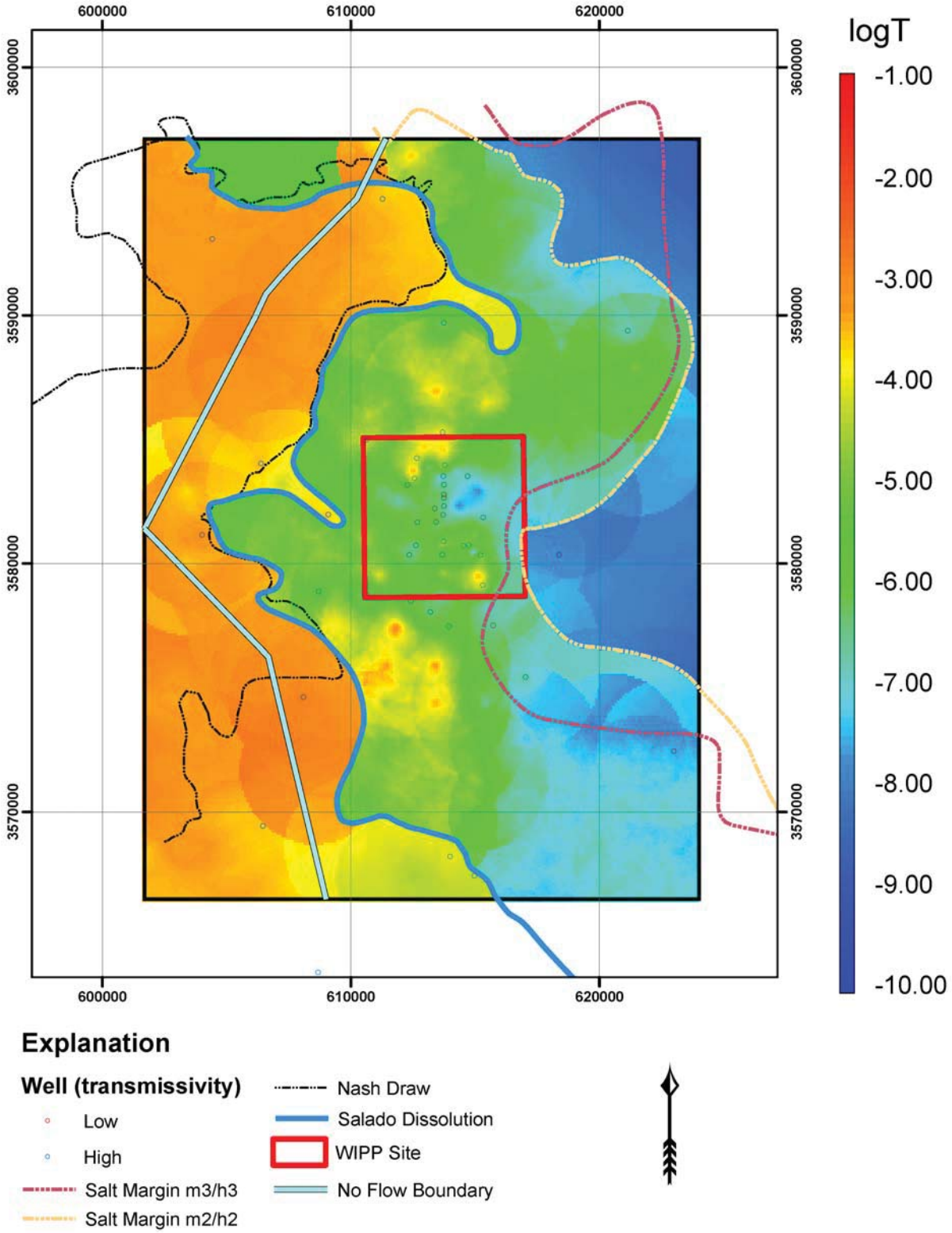

Figure TFIELD-62. Ensemble Average of 121 Calibrated T Fields

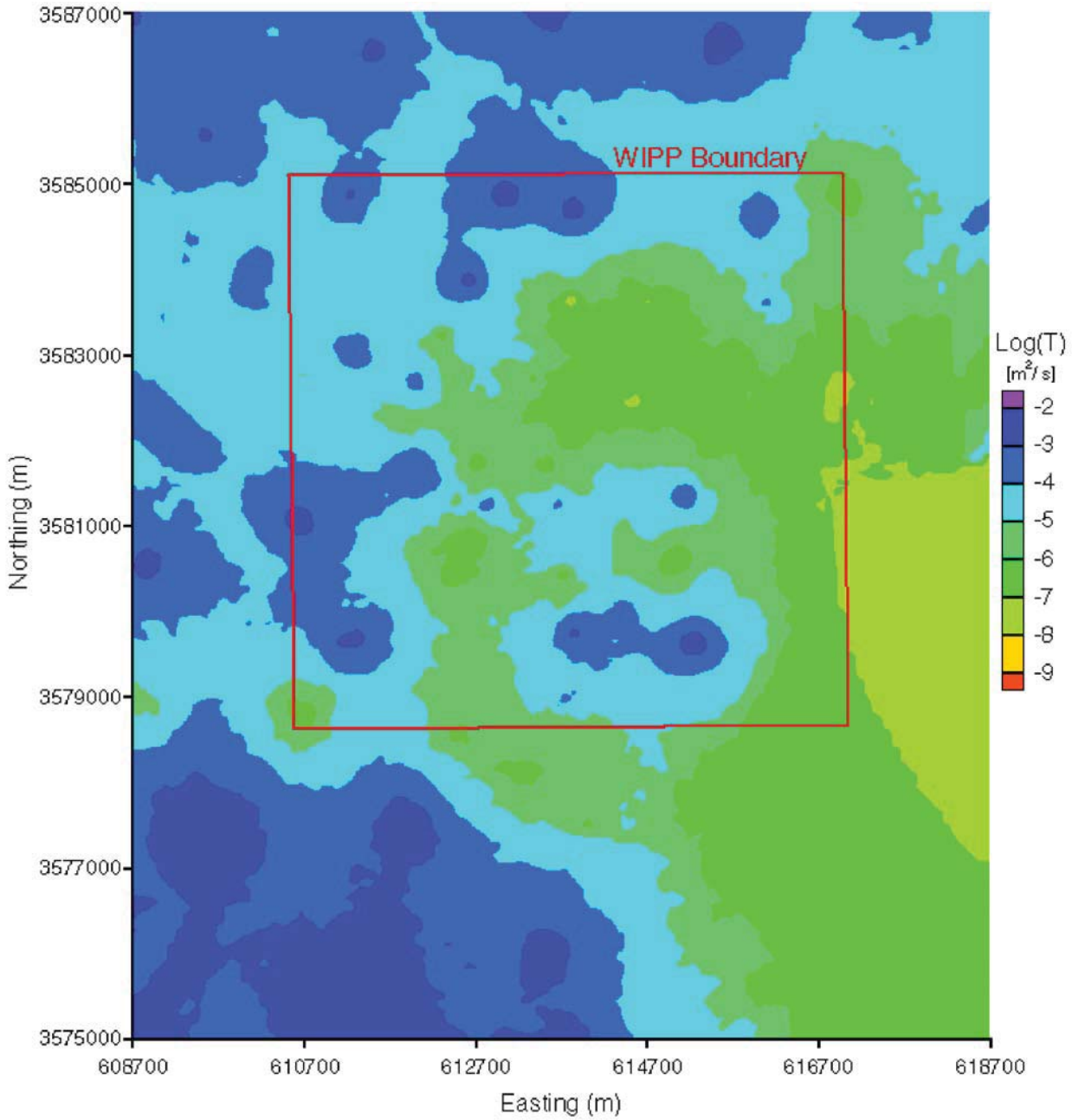

Figure TFIELD-63. Close-Up View of the Ensemble Average T Field Near the WIPP Site. Note the different $\log_{10}$ color scale from Figure TFIELD-62.

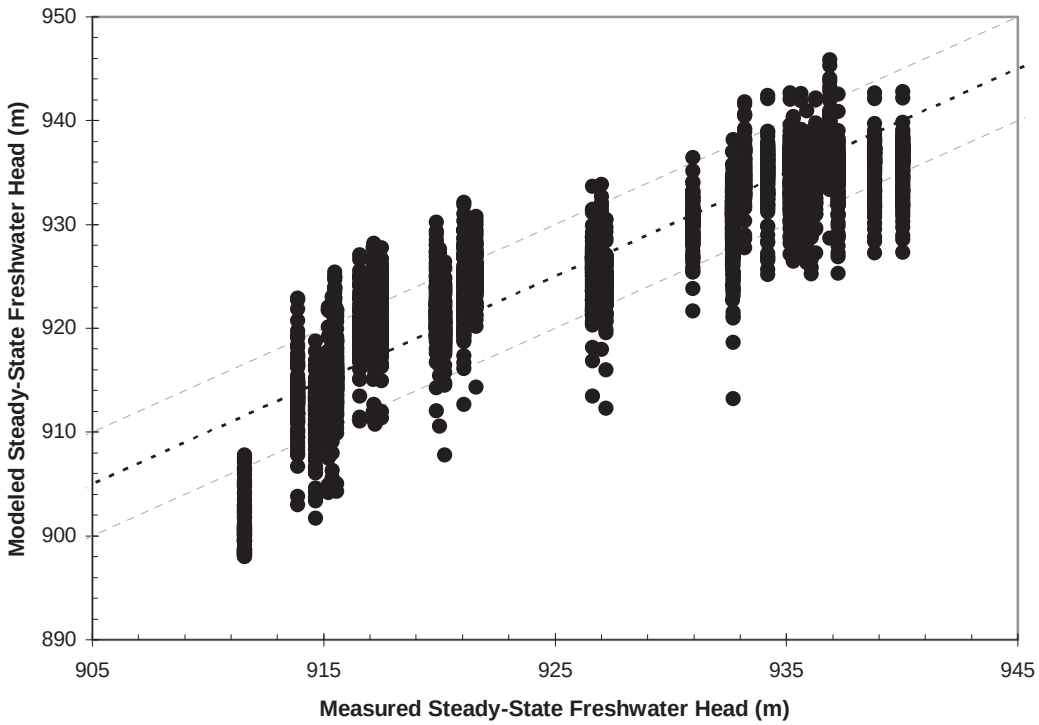

Figure TFIELD-64. Scatterplot of Measured Versus Modeled Steady-State Heads

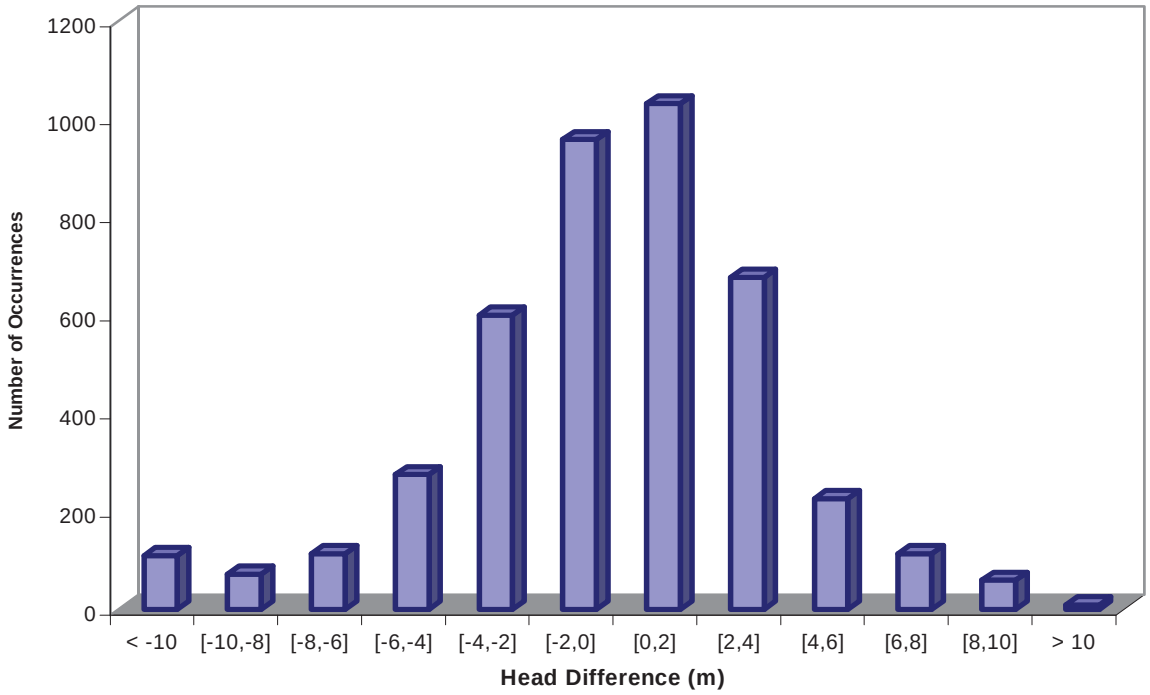

Figure TFIELD-65. Histogram of Differences Between Measured and Modeled Steady-State Heads

fields, and why the CRA-2004 travel times are longer than the CCA travel times (Figure TFIELD-57).

TFIELD-9.0 MODIFICATION OF T FIELDS FOR MINING SCENARIOS

The WIPP site lies within the Carlsbad mining district of southeastern New Mexico. Potash mining in the WIPP area involves resource extraction below the Culebra in the underlying McNutt potash zone of the Salado. In the future, potash mining is expected to occur in all areas where economically extractable ore is present, both outside and inside the WIPP LWB. It is hypothesized that mining of potash leads to subsidence and fracturing of the Culebra, resulting in increased Culebra T. This increase in T may change the regional groundwater flow pattern in the Culebra and affect the transport of any radionuclides entering the Culebra from the WIPP repository.

The EPA (1996, p. 5242) guidance for how the potential effects of future mining should be considered in WIPP PA follows:

> 40 CFR §194.32, Scope of performance assessments.
>
> (a) Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.
>
> (b) Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which suchmining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.
>
> (c) Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can reasonably be expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

The EPA (1996, p. 5229) further states:

> In order to consider the effects of mining in performance assessments, DOE may use the location-specific values of hydraulic conductivity, established for the different spatial locations within the Culebra dolomite, and treat them as sampled parameters with each having a range of values varying between unchanged and increased 1,000-fold relative to the value that would exist in the absence of mining.

Accordingly, for PA purposes, the DOE assumes that all economically extractable potash is mined outside of the WIPP LWB during the 100 years after closure of the WIPP repository during which active institutional control of the site is maintained. Following that 100-year period, the DOE assumes there is a one in 100 probability that the potash within the LWB will be mined during any given century. Therefore, all PA calculations of transport of radionuclides released to the Culebra through inadvertent human intrusion of the repository assume that all potash outside the LWB has already been mined (the “partial-mining” scenario) by the time the

intrusion occurs. The "full-mining" scenario is invoked when the sampled time of human intrusion is coincident with or later than the sampled time of mining within the LWB. Under both scenarios, the hydraulic conductivity (or T) of the Culebra is assumed to be increased by a random factor between one and 1,000 in the areas affected by mining. The process by which the calibrated Culebra T fields were modified to account for the effects of mining, and the characteristics of the resulting modified T fields, are discussed below.

TFIELD-9.1 Determination of Potential Mining Areas

Figure TFIELD-66 shows current potash mines and economically recoverable resources (reserves) in the known potash lease area around the WIPP site, which are the areas where subsidence might occur in the future. The map is based on the BLM (1993) map "Preliminary Map Showing Distribution of Potash Resources, Carlsbad Mining District, Eddy and Lea Counties, New Mexico." Whereas the BLM map shows all reserves, Figure TFIELD-66 shows only reserves that are within existing leases and that are outside the one-quarter to one-half mile (402 to 805 m) exclusion zones around oil and gas wells. Potash reserves outside the current leases will most likely never be mined because active oil and gas exploration is now underway in those areas.

This map is periodically updated as part of the Delaware Basin Drilling Surveillance Program. It also shows the locations of petroleum industry boreholes in the vicinity. The current version of the map differs from the one used for the CCA calculations in that several areas north of the LWB have been ruled out as potential mining areas in the updated version due to recent oil and gas drilling in those areas. Figure TFIELD-67 shows the estimated extent of economically extractable potash within the WIPP LWB.

Because the potash mining horizon is located in the Salado Formation, below the Culebra, the areas in the Culebra that might be disturbed by the mining activities are larger than shown on Figures TFIELD-66 and TFIELD-67 due to angle-of-draw effects associated with subsidence. The rationale for determining the extent of these effects is described in Wallace (1996) with the final conclusion stating that an additional 253-m (830-ft)-wide "collar" was to be added to the mining-impacted areas to approximate a 45-degree angle of draw. For the current T fields, a buffer of three cell widths (300 m [984 ft]) was manually digitized and added to the mining zones. This new delineation was then compared to the CCA model mining zones to make sure there were no significant differences outside of those that can be explained by different gridding of the two model domains and the addition of new data (Figure TFIELD-68). The most notable difference between the two versions is that the area of potential future mining along the northeastern boundary of the LWB is no longer directly connected to the northern boundary of the model domain, which would be expected to decrease flow to the WIPP site.

TFIELD-9.2 Scaling of Transmissivity

For each of the final 100 T fields selected as described in Section 7.4 of this attachment, a random transmissivity multiplier between 1 and 1,000 was assigned using Latin hypercube sampling (LHS) (***Long 2004***). That multiplier was then applied to the modeled T values in the mining-affected areas shown in Figure TFIELD-68 outside of the WIPP LWB to create a partial-mining T field, and to the modeled T values in mining-affected areas both inside and outside the LWB to create a full-mining T field. LHS was performed three times to provide three replicates of 100 full-mining and 100 partial-mining T fields. The purpose of using three replicates is to

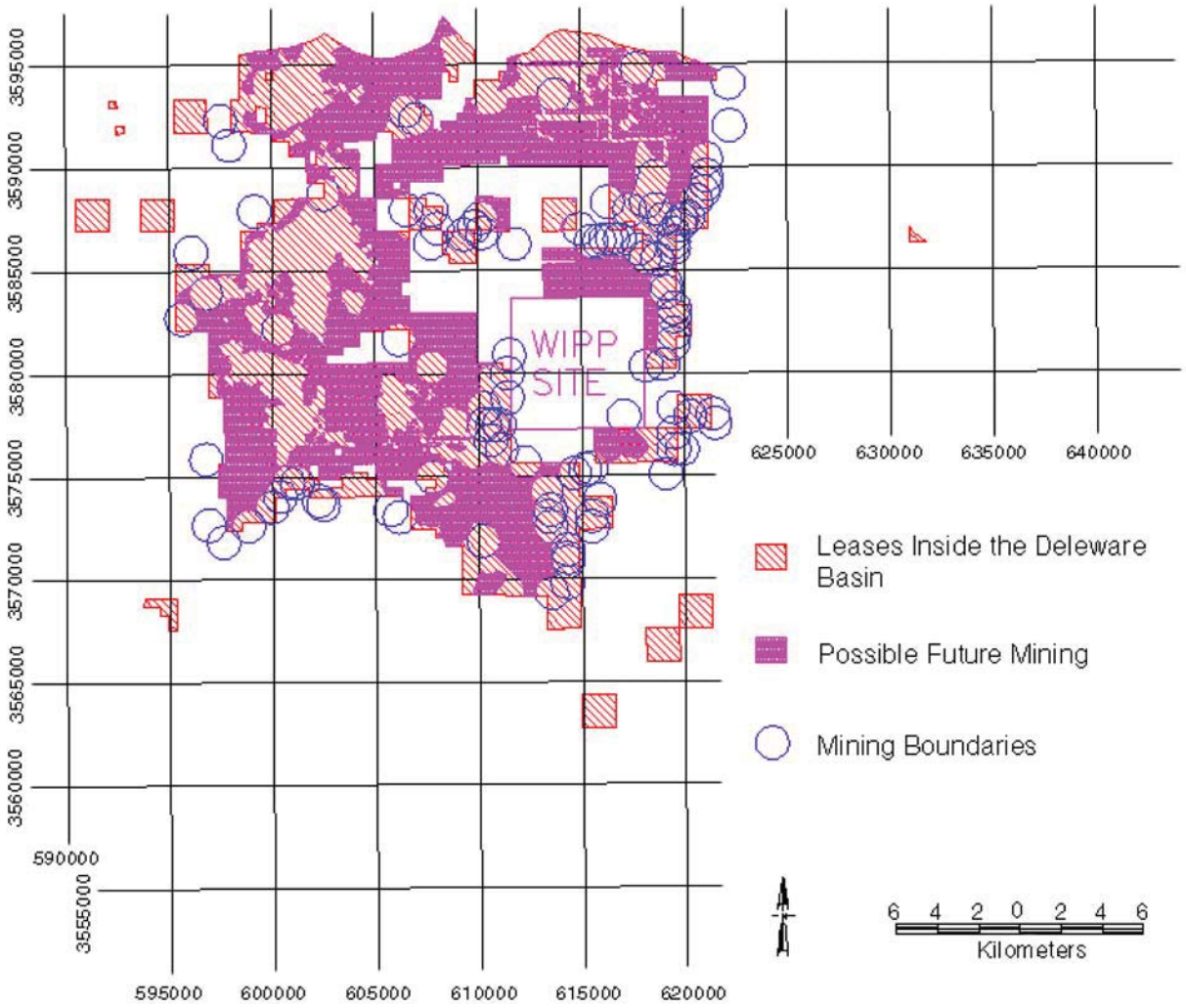

Figure TFIELD-66. Leased Potash Resources Near the WIPP Site

demonstrate that the LHS has adequately captured the uncertainty in the T fields. The transmissivity multipliers applied to each field for the three replicates are shown in Table TFIELD-12.

TFIELD-9.3 Forward Runs

A forward steady-state flow model was run for each of the 100 new T fields under each mining scenario (full and partial) for the three replicates of transmissivity multipliers, resulting in 600 simulations. Particle tracking was performed using DTRKMF on the modified flow fields to determine the flow path and groundwater travel time from a point above the center of the WIPP disposal panels to the LWB. A CDF was produced for each mining scenario (as well as an undisturbed scenario) that describes the probability of a conservative tracer reaching the LWB at a given time.

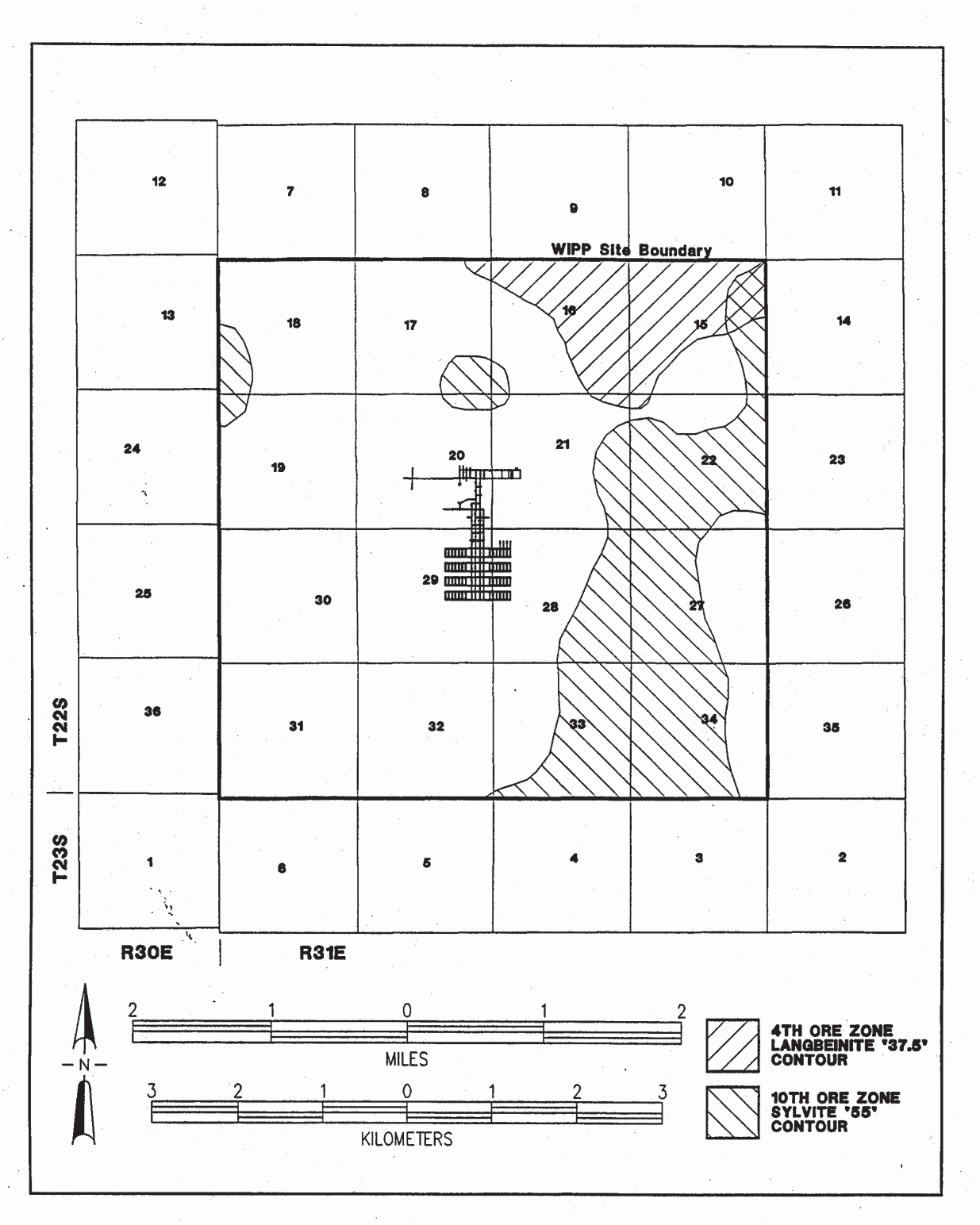

Figure TFIELD-67. Potential Potash Distribution Within the WIPP LWB. The repository excavations are shown in the center.

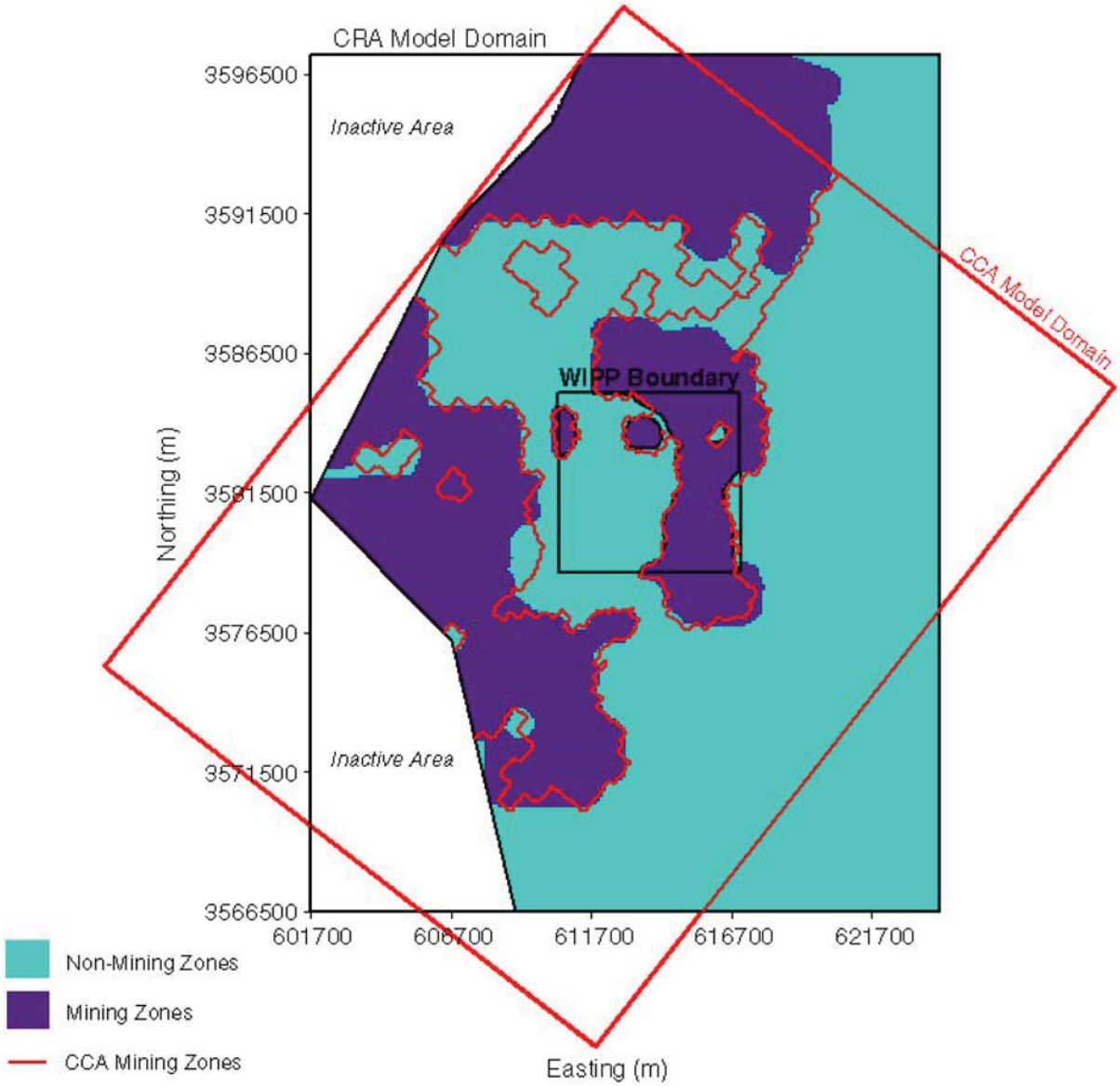

Figure TFIELD-68. Comparison of CRA-2004 and CCA Areas Affected by Mining

As was done for the CCA, it was assumed that mining impacts would not significantly change the boundary conditions used in T-field calibration. Potash mining has already occurred along the northern boundary of the model domain, and the western model boundary is in Nash Draw where subsidence and fracturing of the Culebra are already incorporated in the model.

TFIELD-9.4 Results

TFIELD-9.4.1 Travel Times

Figure TFIELD-69 shows CDFs of travel time for the unmodified T fields and for the Replicate 1 full- and partial-mining T fields. The partial-mining travel times are consistently longer than the no-mining travel times. The distribution of travel times for the full-mining case

Table TFIELD-12. T-Field Transmissivity Multipliers for Mining Scenarios

T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier	T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier
d01r02	905.50	32.85	13.54	d09r08	66.07	339.80	327.30
d01r04	508.40	345.10	202.20	d09r09	375.70	806.30	374.20
d01r07	340.30	996.50	936.30	d09r10	521.10	906.90	24.83
d01r10	615.20	828.20	391.80	d10r02	181.60	274.60	651.90
d02r02	575.30	579.30	306.80	d10r03	298.50	796.60	816.70
d03r01	104.00	760.50	955.80	d10r04	705.30	364.70	518.20
d03r03	94.06	514.90	77.79	d10r06	84.20	819.40	690.80
d03r06	913.30	187.60	238.40	d10r07	627.30	728.60	551.20
d03r07	630.50	567.10	725.20	d10r08	403.20	414.80	670.30
d03r08	208.90	475.90	85.67	d10r09	464.20	649.90	885.40
d03r09	769.30	750.00	647.80	d10r10	821.40	607.80	925.70
d04r01	130.20	630.30	478.70	d11r01	307.60	895.10	492.90
d04r02	351.90	453.30	996.70	d11r02	236.50	918.30	364.50
d04r03	46.87	310.90	123.90	d11r06	249.90	159.70	5.43
d04r04	194.60	487.90	217.30	d11r07	543.50	86.78	966.70
d04r05	806.90	923.80	138.30	d11r08	18.75	16.92	973.80
d04r06	264.40	584.00	835.30	d11r09	215.40	618.30	576.30
d04r07	931.50	733.90	802.00	d11r10	73.60	168.90	403.20
d04r08	897.90	51.08	96.80	d12r01	317.40	683.30	756.20
d04r10	32.56	256.50	34.02	d12r02	958.60	204.90	598.10
d05r03	394.10	108.30	159.00	d12r03	686.00	322.00	333.80
d05r07	998.20	535.90	145.50	d12r05	860.70	637.50	589.70
d06r02	790.00	679.40	826.70	d12r06	363.80	359.00	56.05
d06r03	384.10	171.20	261.20	d12r07	660.40	434.90	463.10
d06r04	258.50	860.00	293.90	d12r08	940.20	708.20	312.10
d06r05	432.50	754.10	257.60	d12r09	132.50	464.10	794.60
d06r06	10.02	653.20	172.50	d13r01	983.00	971.30	901.70
d06r07	514.10	221.50	915.60	d13r02	672.80	144.50	224.80
d06r10	282.90	70.11	861.40	d13r03	643.20	849.00	415.20
d07r01	927.30	694.20	625.20	d13r05	425.80	118.60	688.00
d07r02	691.30	864.90	737.80	d13r06	961.10	785.90	385.40
d07r05	738.40	775.30	241.60	d13r07	346.10	282.90	711.40
d07r06	450.20	591.70	548.70	d13r08	838.60	78.26	64.98
d07r07	609.60	447.20	841.00	d13r09	491.00	8.68	458.00
d07r08	557.70	942.30	349.00	d21r01	755.40	307.30	632.40
d07r09	538.60	98.94	285.00	d21r02	172.60	396.20	614.80
d07r10	713.60	379.60	187.30	d21r03	591.50	422.30	45.61

Table TFIELD-12. T-Field Transmissivity Multipliers for Mining Scenarios (Continued)

T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier	T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier
d08r01	849.30	408.40	194.00	d21r04	322.70	715.50	276.80
d08r02	569.70	989.10	893.90	d21r05	855.70	870.90	105.80
d08r03	419.50	43.16	356.30	d21r06	272.00	501.20	984.40
d08r04	160.00	834.00	857.00	d21r07	652.50	296.70	940.20
d08r05	971.90	881.10	671.60	d21r10	790.50	212.70	562.50
d08r06	118.80	558.90	743.20	d22r02	163.20	527.50	870.60
d08r07	741.30	130.20	706.70	d22r03	812.70	264.30	534.50
d09r02	729.70	497.00	429.30	d22r04	144.70	140.70	526.30
d09r03	483.00	197.30	168.20	d22r06	26.04	962.70	111.70
d09r04	580.60	661.30	766.40	d22r07	870.30	548.10	609.10
d09r05	228.50	240.90	481.90	d22r08	773.60	235.30	771.70
d09r06	474.10	383.50	449.10	d22r09	53.04	937.70	784.10
d09r07	887.20	952.10	503.30	d22r10	460.40	24.35	434.60

is much wider than for the other two cases; some of the full-mining travel times are shorter than the no-mining times, but most are considerably longer. The median travel times across all three replicates for the full- and partial-mining scenarios are approximately 3.6 and 2.6 times greater, respectively, than for the non-mining scenario. Figures TFIELD-70 and TFIELD-71 compare the CDFs of travel time for all three replicates of the partial- and full-mining cases, respectively, to the Replicate 1 results from the CCA T fields (Wallace 1996). These plots show, first, that all three CRA-2004 replicates provided very similar results and, second, that the new travel times are consistently longer than the CCA travel times. The primary reason for this difference is probably the absence in the CRA-2004 T fields of the direct, high-T connection between the WIPP site and the northern model boundary that was present in the CCA T fields and that provided a source of water to the Culebra within the LWB. As discussed in Section 9.1 of this attachment, this difference occurs because recent oil and gas exploratory drilling has precluded potash mining a few kilometers northeast of the LWB (see Figure TFIELD-66).

Given the increase in transmissivity due to mining, the increase in travel time may seem counter-intuitive. However, upon examination of the head contours and flow patterns of the mining cases, the high-T areas corresponding to the mining zones create preferential pathways through the system. Figure TFIELD-72 shows the normalized velocity in each cell for the T field/replicate averaged case for the full-mining scenario. The normalized velocity is the velocity magnitude in each cell divided by the maximum velocity magnitude across the domain. Since the velocity magnitudes are highly skewed, the color bands for Figure TFIELD-72 are nonuniformly scaled at the high end (i.e., a wider range of velocity magnitudes is used to designate the orange and red bands). This allows for a better qualitative comparison of the spatial distribution of high and low velocities. “T field/replicate averaged” means the T value for

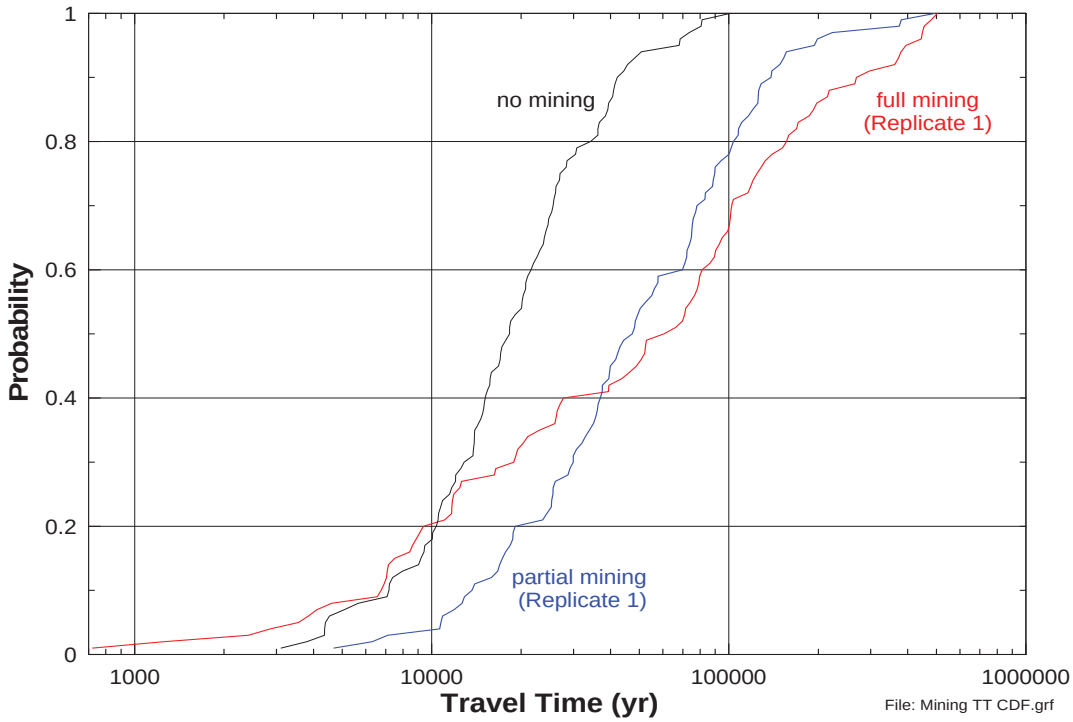

Figure TFIELD-69. CDFs of Travel Times for the Full-, Partial-, and No-Mining Scenarios

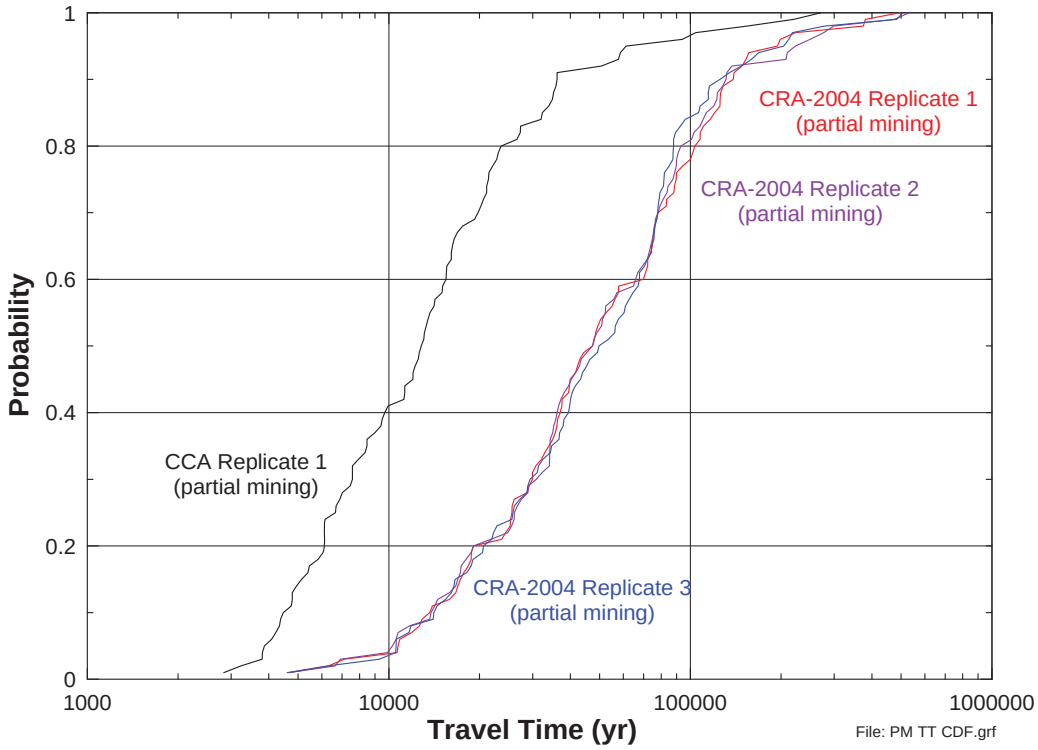

Figure TFIELD-70. CDFs of Partial-Mining Travel Times for Three CRA-2004 Replicates and One CCA Replicate

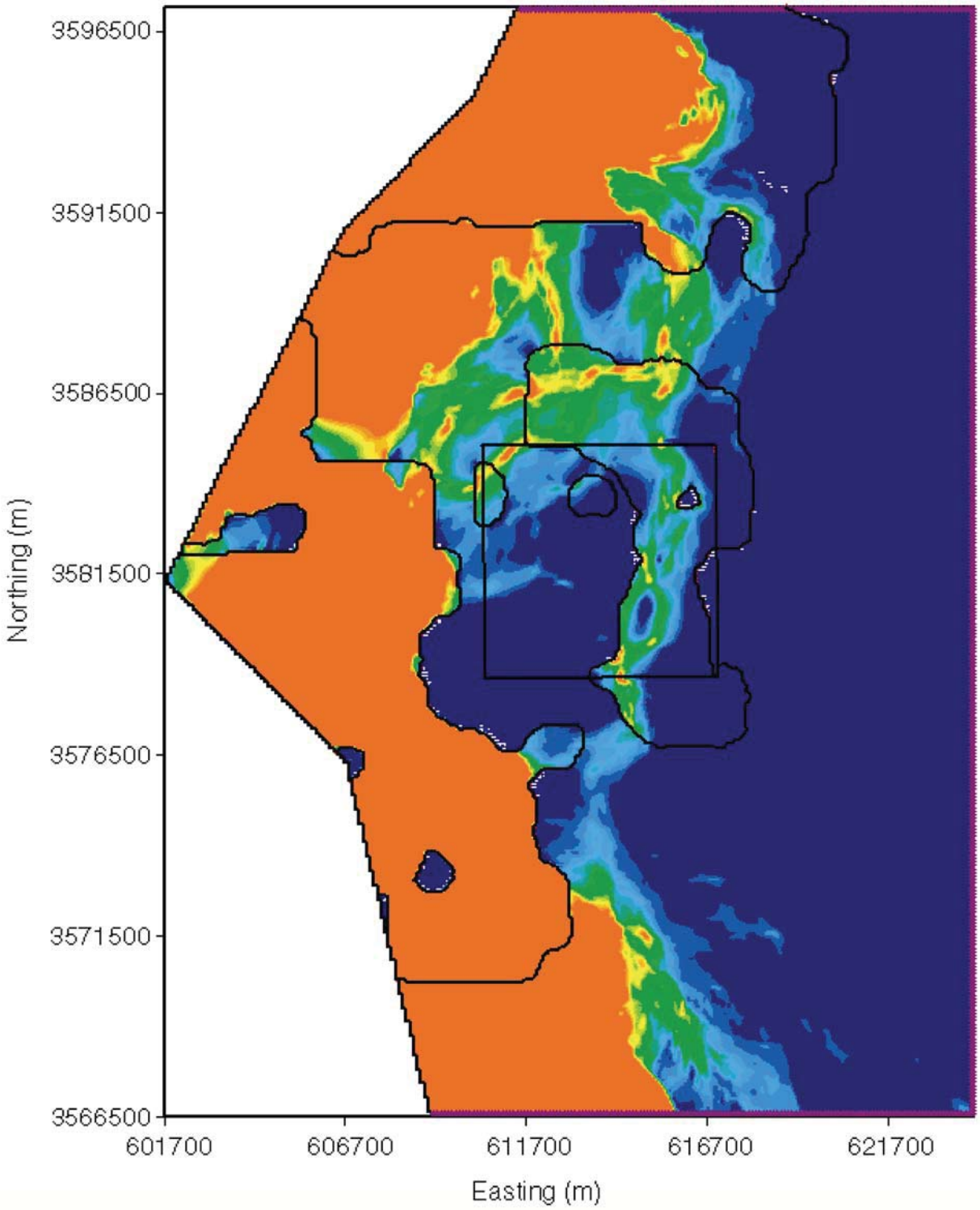

Figure TFIELD-71. Normalized Pore Velocities for the Full-Mining Case. Red indicates zones of high velocity. The black outline shows the full-mining zones and the red box is the WIPP LWB. The T field used to produce the velocity profile is averaged across all T field/replicate combinations for the full-mining scenario (300 T fields in total).

each cell is the average of the Ts across all T field/replicate combinations for the full-mining scenario (300 T fields in total). Not surprisingly, it is clear that the areas of high velocities correspond with the mining zones. The higher velocities and corresponding higher flow rates through the mining zone areas translate to slower velocities in the nonmining zone areas. In most cases, the particles for the mining scenarios stay in the lower velocity zones along the entire pathway to the LWB, which accounts for the higher average travel times. A comparison of the average, maximum, and minimum values for the full-, partial-, and no-mining scenario travel times is presented in Table TFIELD-13.

TFIELD-9.4.2 Travel Directions

The effects of mining also have an impact on the direction of transport, significantly changing where the particles cross the LWB. This is especially true of the full-mining scenario where mining within the LWB creates high head along the eastern boundary of the WIPP resulting in a general flow direction to the westsouthwest. This is in contrast to the partial-mining scenario where the tracking direction is mainly towards the south, similar to the nonmining scenario. The particle-track directions for the partial- and full-mining scenarios are illustrated in Figures TFIELD-73 to TFIELD-78.

There is a strong similarity within each replicate for each scenario. Individual tracks can be recognized from one replicate to the next, with some slight variations. This indicates that track directions are determined more by the spatial variation of the calibrated T field than by the random mining factors. As long as there is some (see below) increase in the mining zone Ts over that of the nonmining areas, the tracks for each T field will be similar from one replicate to the next.

The partial-mining particle tracks in Figures TFIELD-73 through TFIELD-75 follow paths very similar to the partial-mining particle tracks through the CCA T fields (Ramsey et al. 1996, Figure 7.12). The full-mining particle tracks in Figures TFIELD-76 through TFIELD-78 show a more westward component and are generally longer than the full-mining particle tracks through the CCA T fields (Ramsey et al. 1996, Figure 7.13).

The insensitivity of the track directions to the random mining factor also carries over to insensitivity of the travel time. Correlation analysis shows correlations between travel time and the random mining factor for the full and partial-mining scenarios as 0.091 and 0.151, respectively. Thus, like the track directions, travel times are not sensitive to the random mining factor but rather to the spatial structure of the calibrated T field.

This insensitivity to the random mining factor can be explained by recalling that the factor is applied only to zones deemed as probable mining areas. This means that velocity and flow increases are limited to the mining zones, with little change in the nonmining areas (assuming gradients are somewhat constant). Conditions within the nonmining zones are affected most for cases where the mining zone Ts are close to the non-mining zone Ts. However, the mining factor ranges uniformly from 1 to 1,000, meaning 99 percent of the T field/replicate combinations will have multipliers greater than one order of magnitude (for the 300 combinations, only two have multipliers that are less than 10). This translates into small changes within the non-mining zones for relatively large changes in the mining zones. To illustrate this,

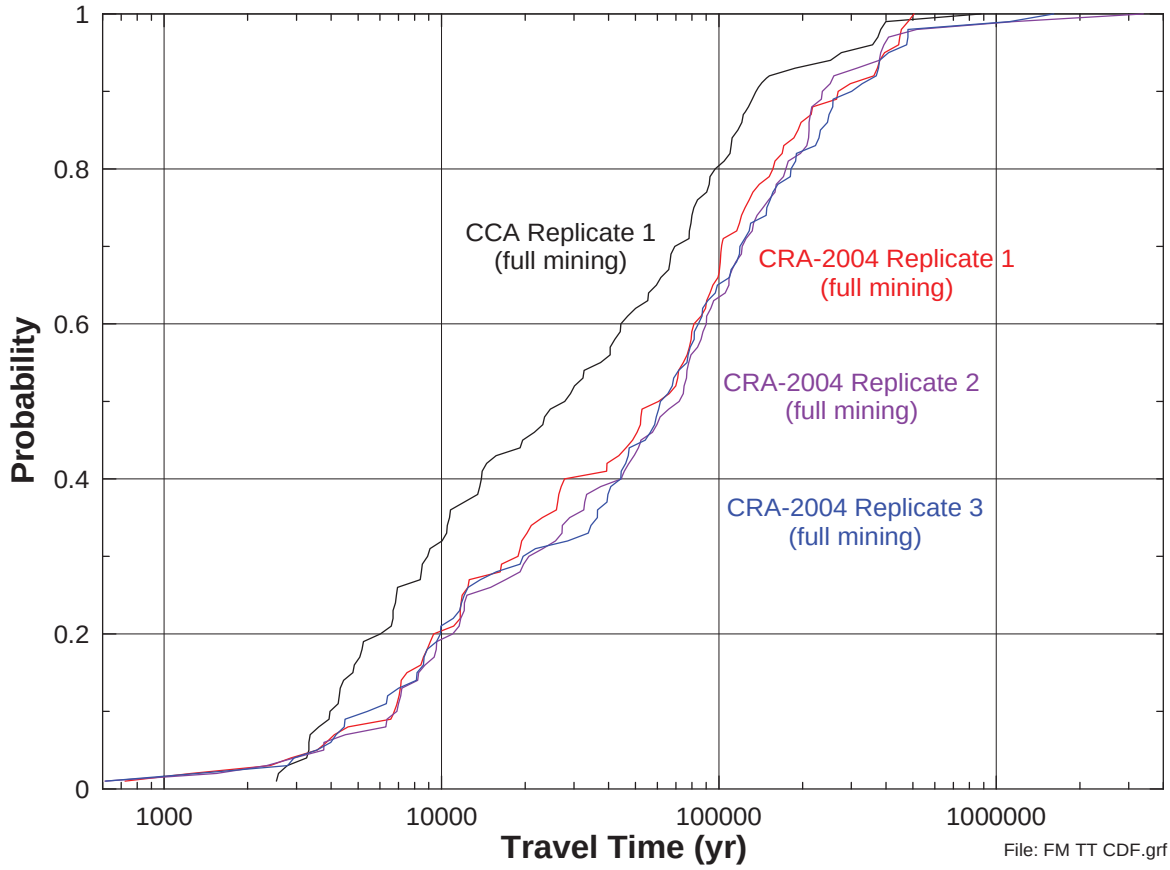

Figure TFIELD-72. CDFs of Full-Mining Travel Times for Three CRA-2004 Replicates and One CCA Replicate

Table TFIELD-13. Travel Time Statistics for the Full- and Partial-Mining Scenarios as Compared to the No-Mining Scenario

Replicate	Statistic	Full-Mining Travel Time (yr)	Partial-Mining Travel Time (yr)	No-Mining Travel Time (yr)
R1	Median	63,370	47,745	
	Maximum	504,174	494,981	
	Minimum	723	4,684	
R2	Median	73,169	47,651	
	Maximum	3,387,185	531,136	
	Minimum	611	4,654	
R3	Median	63,430	51,622	
	Maximum	1,610,979	506,438	
	Minimum	615	4,603	
Global	Median	66,048	48,290	18,289
	Maximum	3,387,185	531,136	101,205
	Minimum	611	4,603	3,111

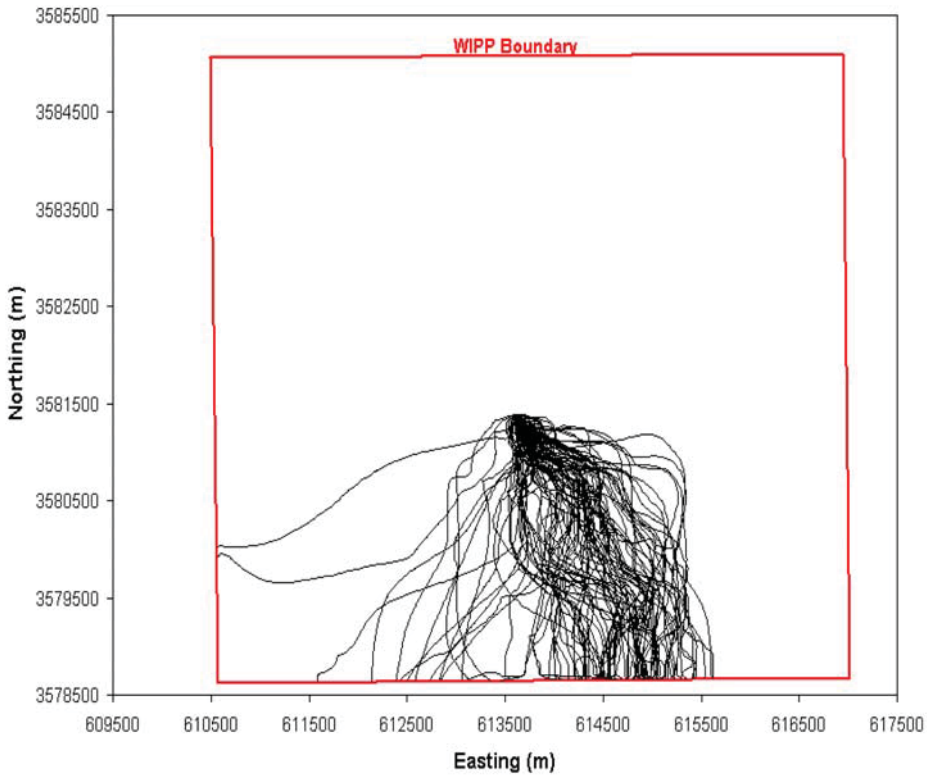

Figure TFIELD-73. Particle Tracks for Replicate 1 for the Partial-Mining Scenario

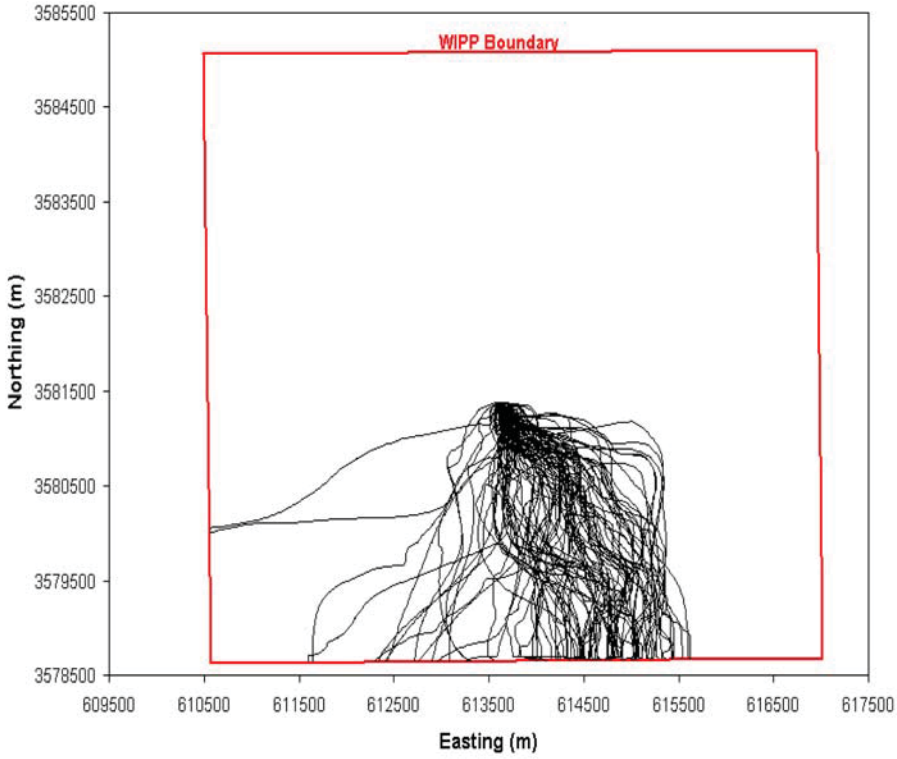

Figure TFIELD-74. Particle Tracks for Replicate 2 for the Partial-Mining Scenario

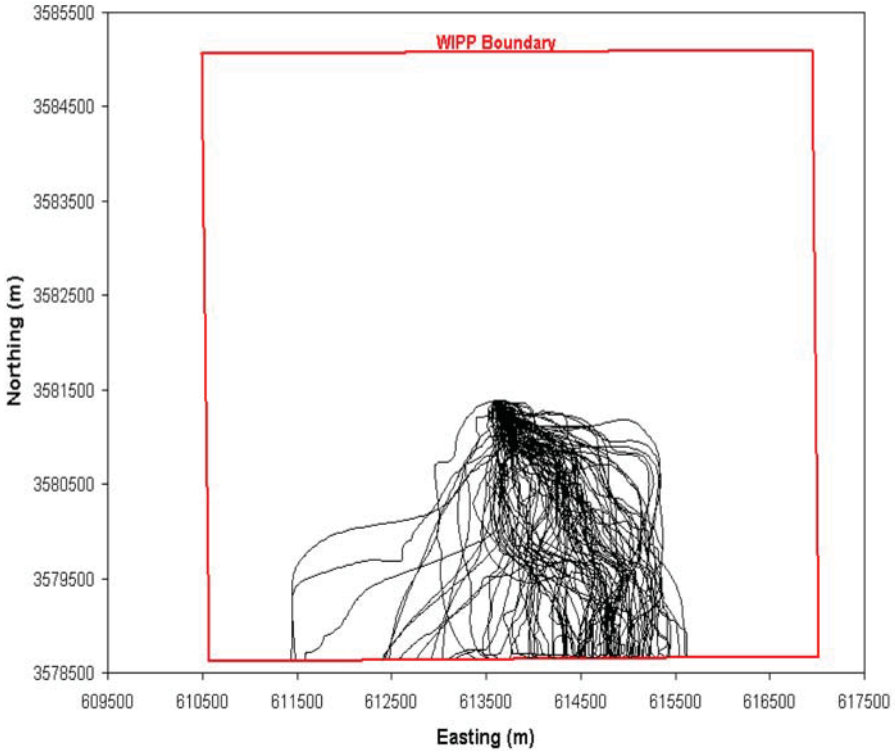

Figure TFIELD-75. Particle Tracks for Replicate 3 for the Partial-Mining Scenario

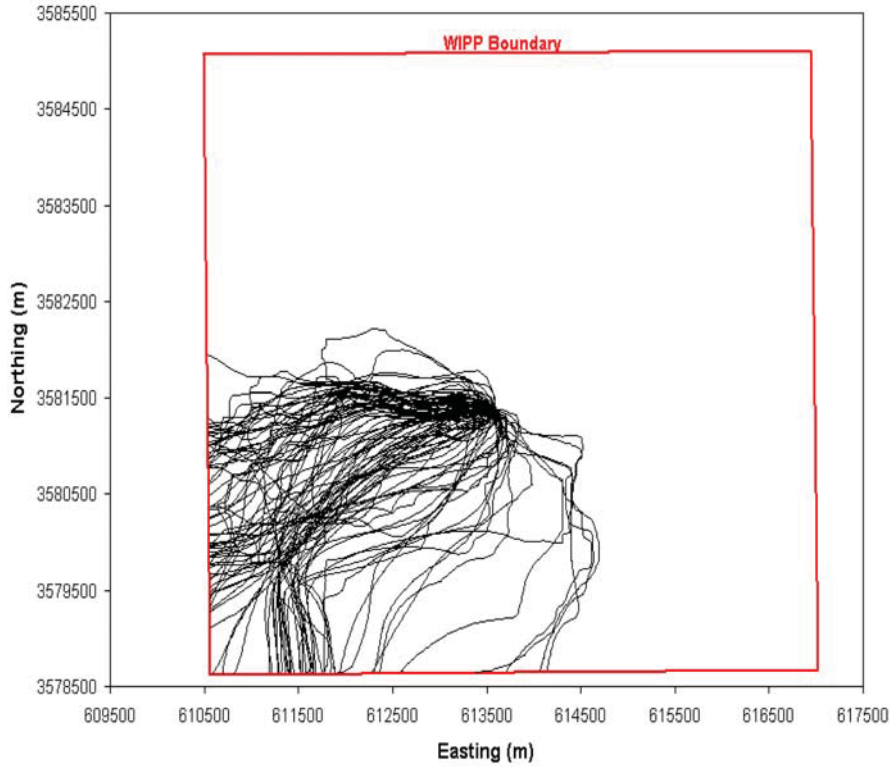

Figure TFIELD-76. Particle Tracks for Replicate 1 for the Full-Mining Scenario

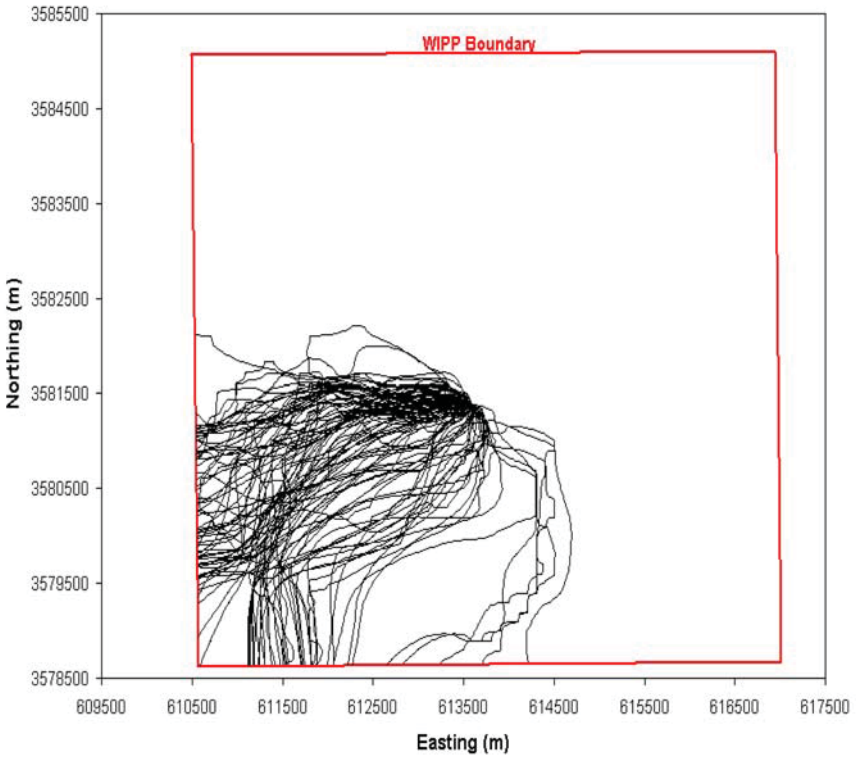

Figure TFIELD-77. Particle Tracks for Replicate 2 for the Full-Mining Scenario

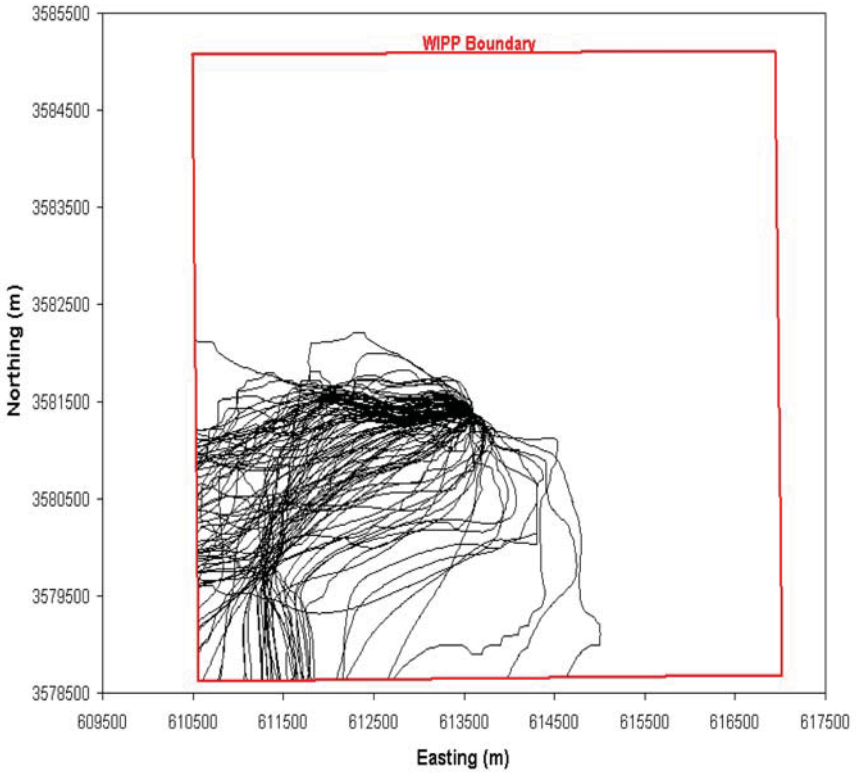

Figure TFIELD-78. Particle Tracks for Replicate 3 for the Full-Mining Scenario

Figure TFIELD-79 shows the $\log_{10}$ travel times versus the random mining factor for the full- and partial-mining scenarios across all replicates. The high scatter in both the plots is due to the independence of travel time with regards to the mining factor. This conclusion supports the mining scenario conceptual model and the use of a random mining factor to model changes in T due to mining activities. It also indicates that the controlling parameters are the spatial distribution of the non-mining scenario T field and the delineation of the mining and nonmining zones.

TFIELD-9.4.3 Extreme Values

Examination of the extreme travel time values and the causes behind those values is useful in quantifying the range of outcomes given the amount of uncertainty incorporated into the models. For the partial-mining scenario, T field d04r01 from Replicate 2 had the longest travel time of 531,136 years. In contrast, T field d08r01 from Replicate 3 had the shortest travel time of 4, 603 years. The median travel time is best represented by T field d01r04 from Replicate 1 with a travel time of 48, 472 years. Figures TFIELD-80 to TFIELD-82 show the head contours for each of these cases along with the corresponding particle tracks. The particle-tracking directions are all fairly similar.

The full-mining cases (Figures TFIELD-83 to TFIELD-85) have similar characteristics to those of the partial-mining cases except that the band of high gradient to the northwest is less pronounced and persistent. For the full-mining scenario, T field d04r01 from Replicate 2 had the longest travel time of 3, 387,185 years. T field d01r07 from Replicate 2 had the shortest travel time of 611 years. The median travel time is best represented by T field d10r09 in Replicate 1 (66, 215 years).

Overall, for both the partial- and full-mining scenarios, those T fields that contain higher and more heterogeneous Ts in the nonmining areas produce the fastest travel times. However, the partial-mining scenario shows a smaller range of values due to the lack of the large mining zone in the WIPP area. This smaller range is clearly visible in Figure TFIELD-79. What distinguishes the plots is the head distribution across the regions. For the slow case (Figure TFIELD-80), the head contours to the west of the repository are spread far apart, indicating a low gradient and thus lower groundwater velocities. The fastest case (Figure TFIELD-81) shows a high-gradient band that originates along the no-flow boundary to the northwest and runs down the western side of the WIPP site. This high gradient corresponds to higher groundwater velocities. The median case (Figure TFIELD-82) also shows this high-gradient band, but it is not as extreme as in the fast case. In all cases, the mining-zone areas look very similar, with widely spaced head contours and higher velocities relative to the nonmining zones.

TFIELD-10.0 SUMMARY

Observed Culebra T has been related to three deterministic factors: the thickness of overburden above the Culebra, the presence or absence of dissolution of the upper Salado, and the presence or absence of halite in units above and below the Culebra. Culebra T is also related to the occurrence of open, interconnected fractures, which cannot be mapped as easily as the other three factors and must be treated stochastically. A linear-regression model for Culebra T has been developed based on these factors that provides an excellent match to the observed data, and

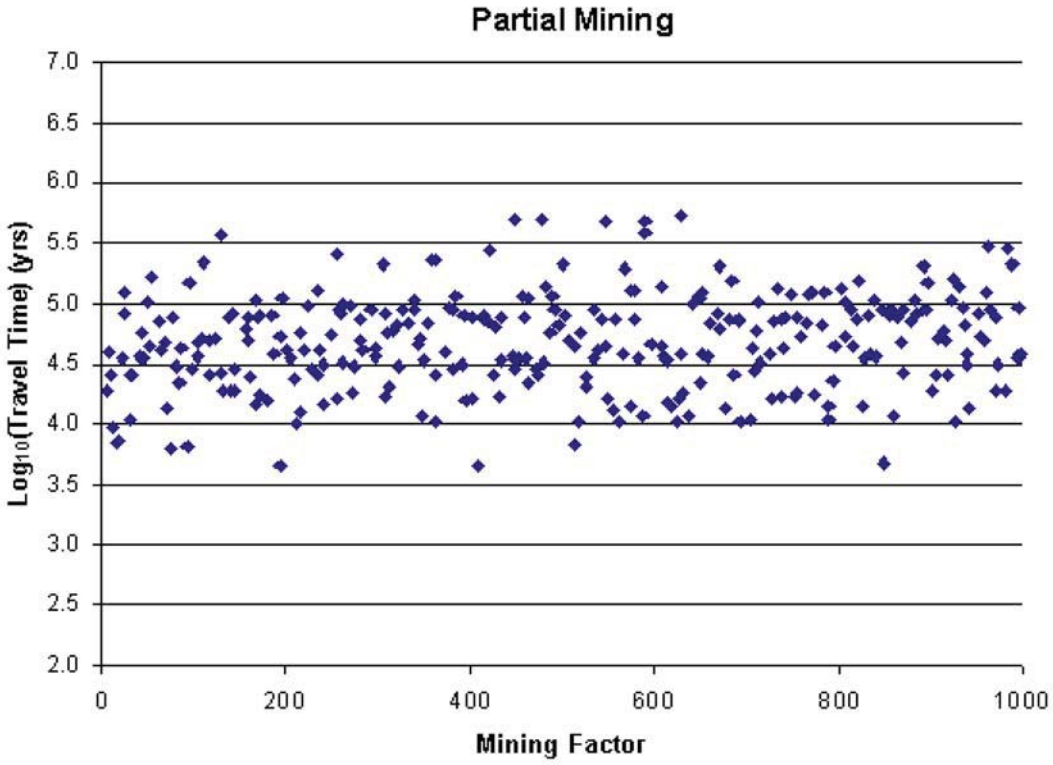

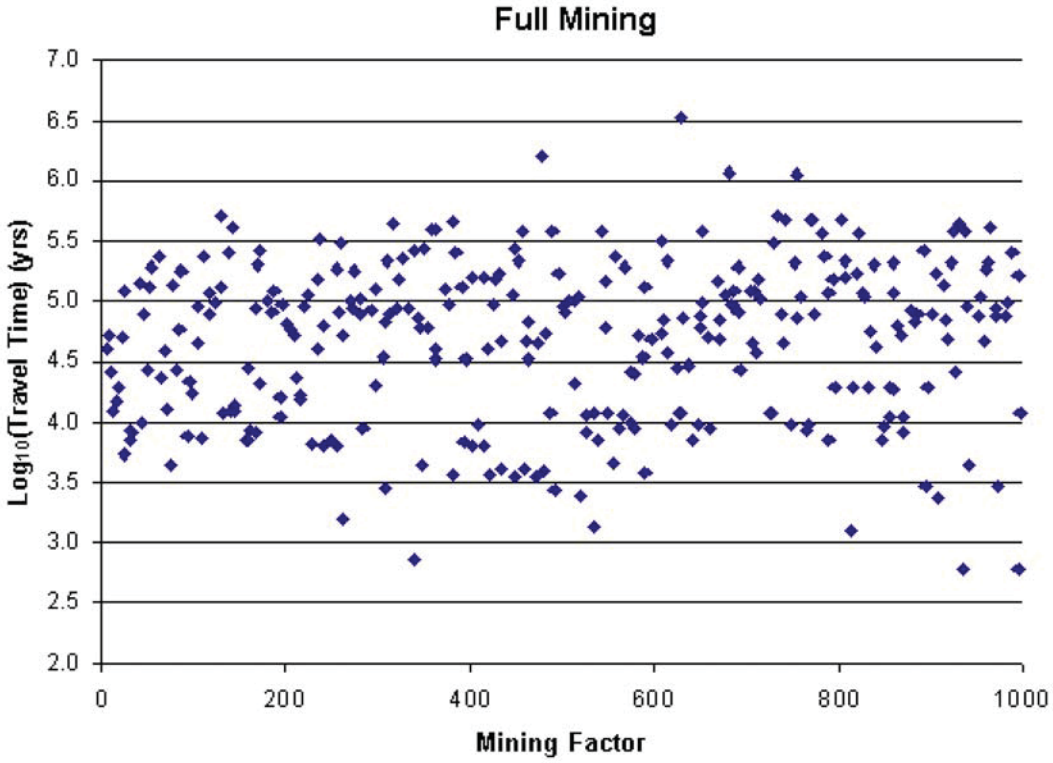

Figure TFIELD-79. Correlation Between the Random Mining Factor and Log_{10} of Travel Time

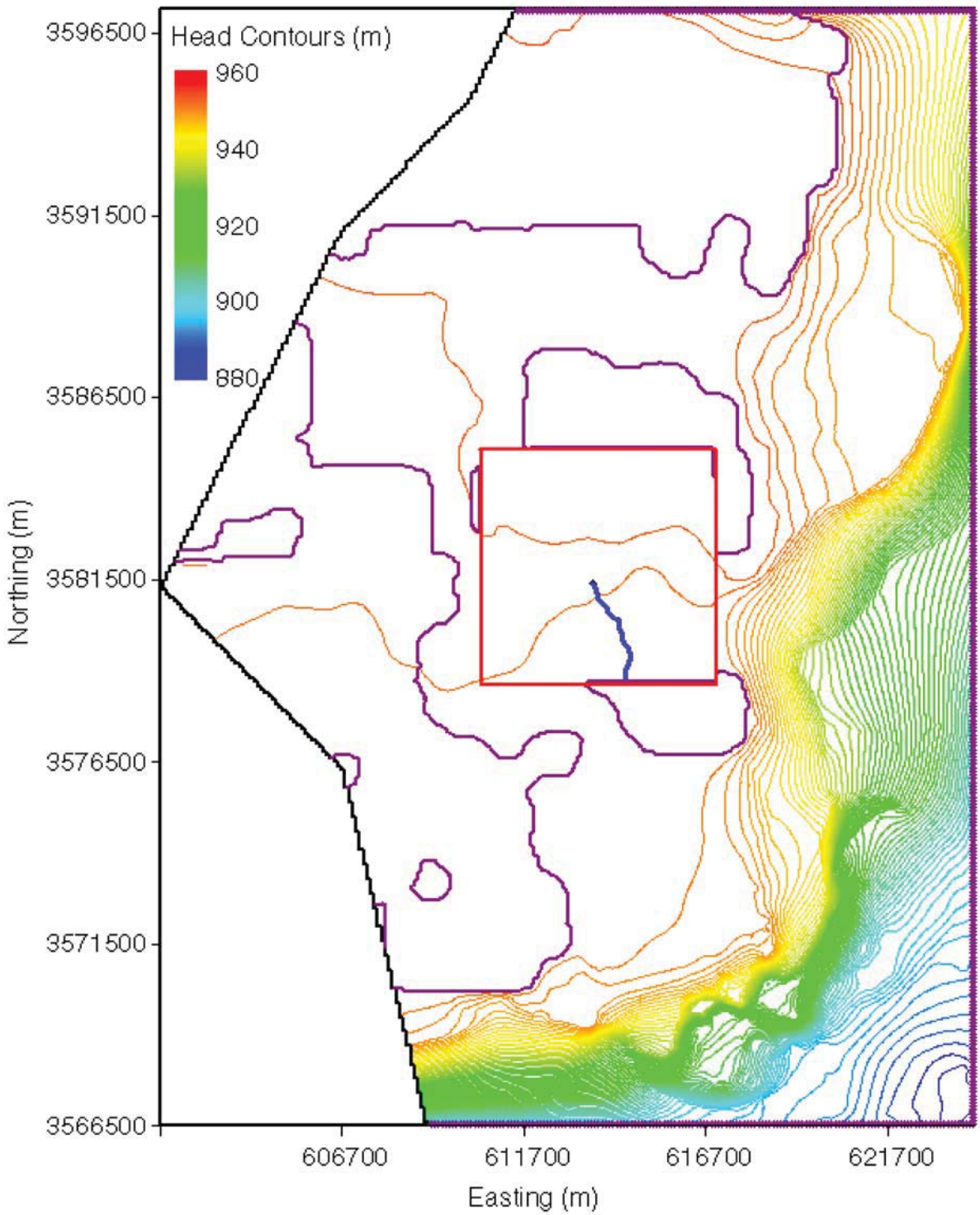

Figure TFIELD-80. Head Contours and Particle Track for the Maximum-Travel-Time T Field (d04r01-R2) for the Partial-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

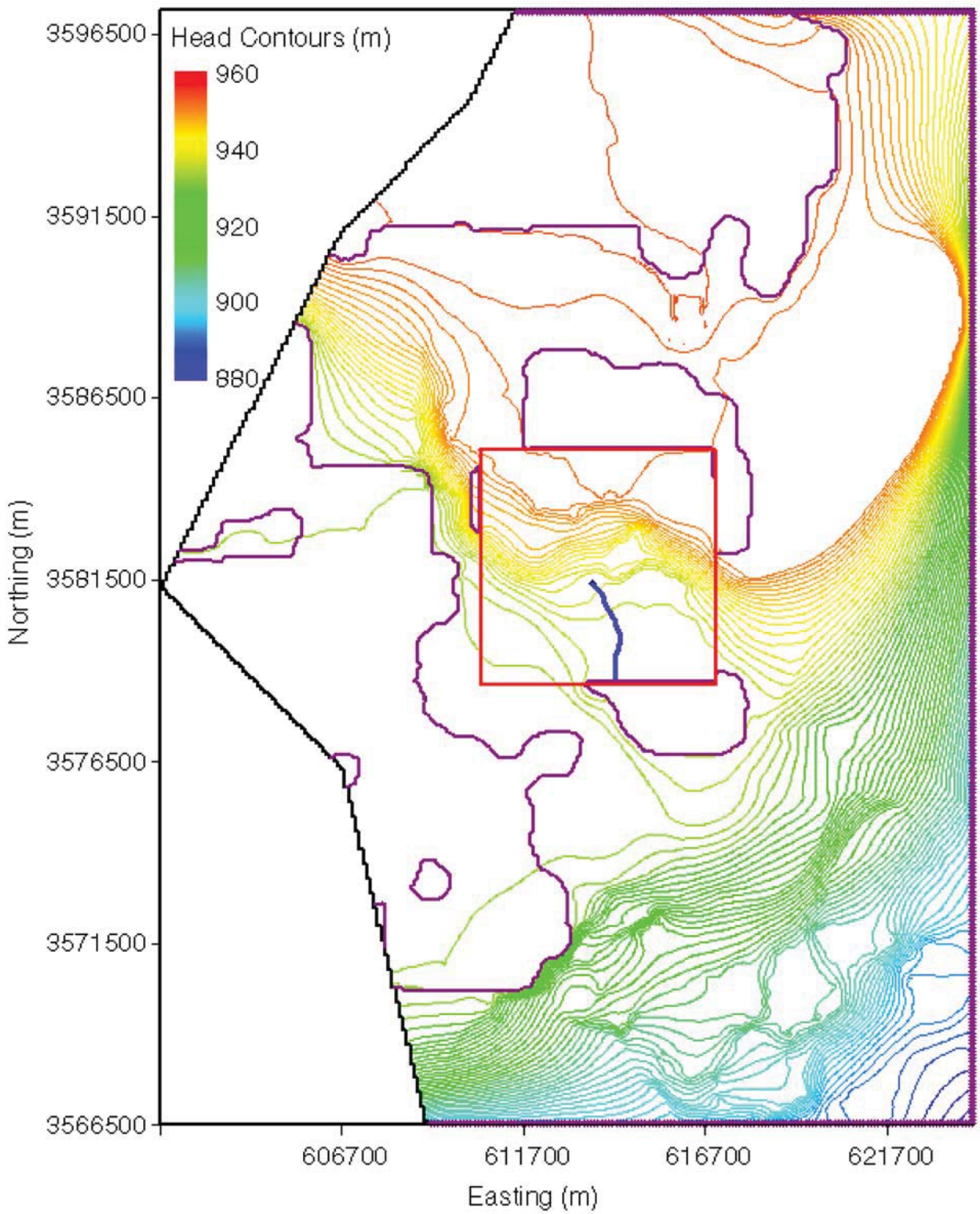

Figure TFIELD-81. Head Contours and Particle Track for the Minimum-Travel-Time T Field (d08r01-R3) for the Partial-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

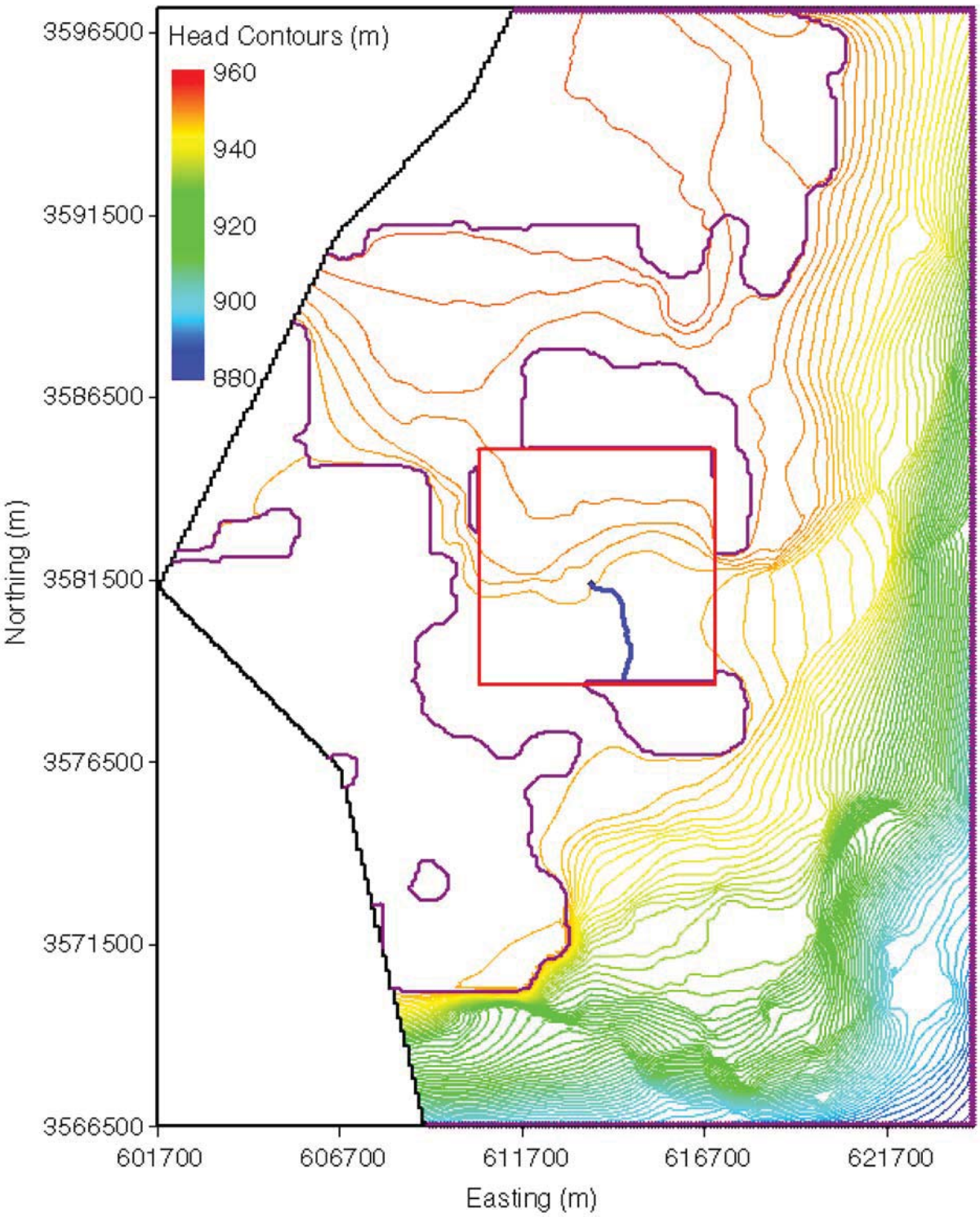

Figure TFIELD-82. Head Contours and Particle Track for the Median-Travel-Time T Field (d01r04-R1) for the Partial-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

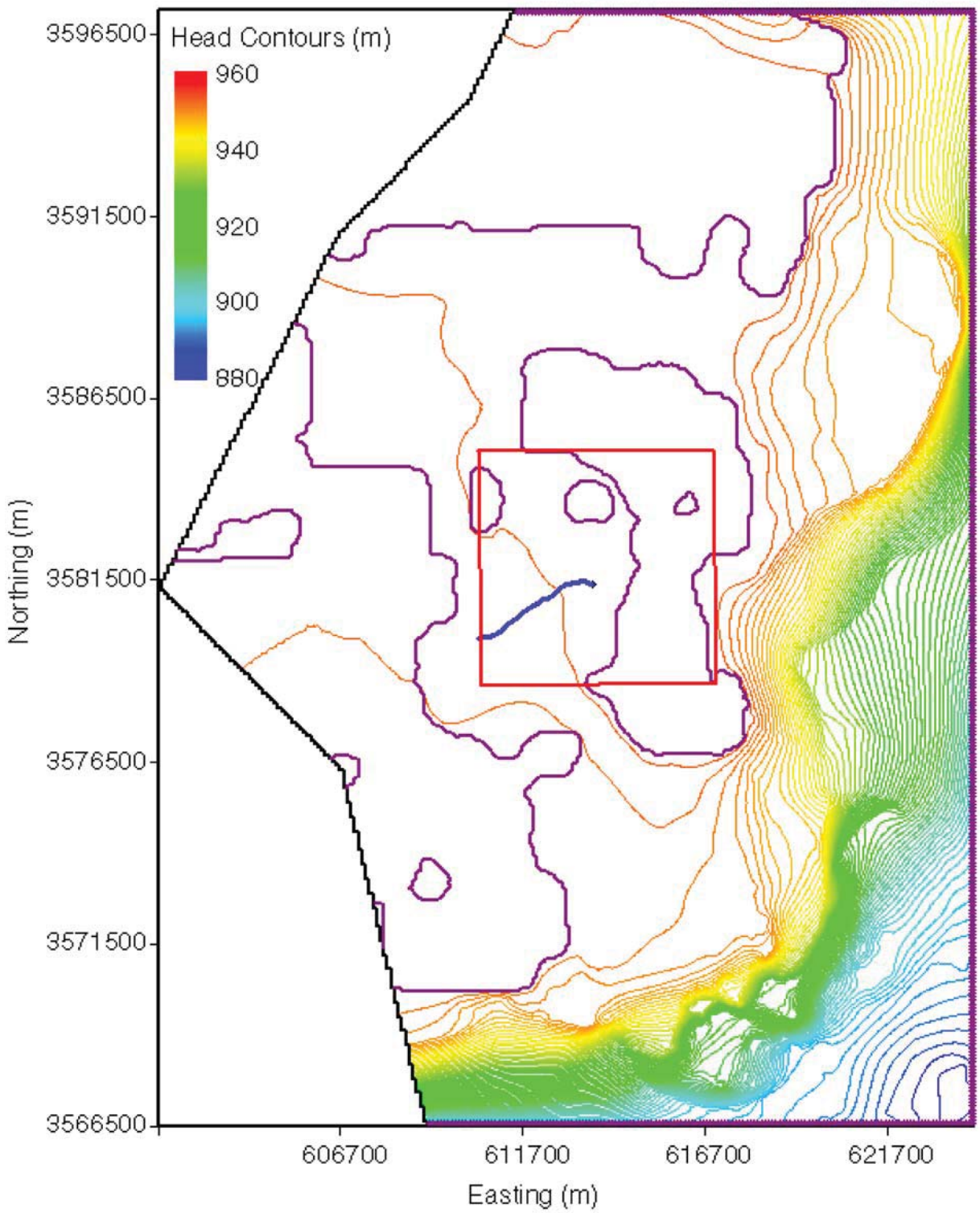

Figure TFIELD-83. Head Contours and Particle Track for the Maximum-Travel-Time T Field (d04r01-R2) for the Full-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

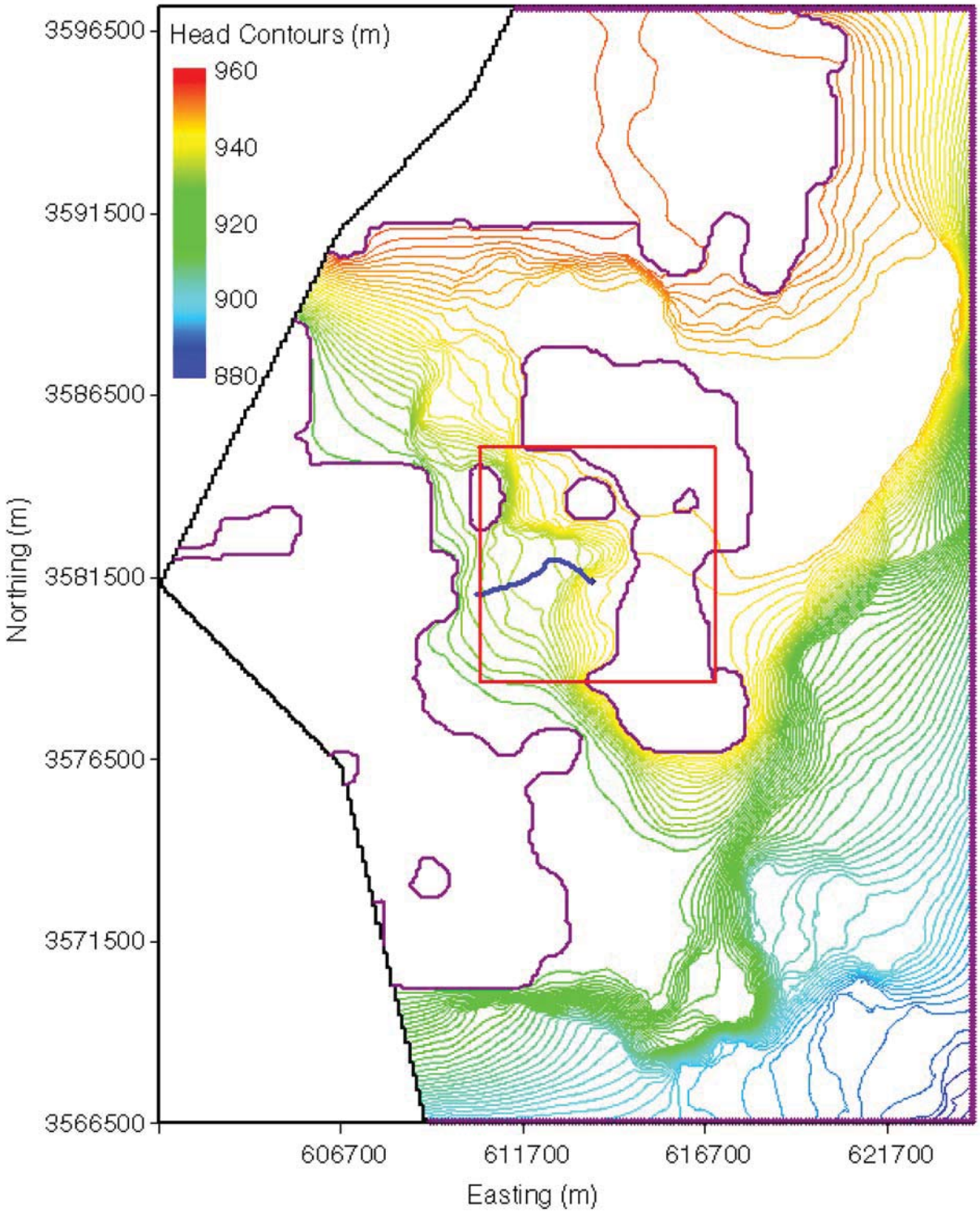

Figure TFIELD-84. Head Contours and Particle Track for the Minimum-Travel-Time T Field (d01r07-R2) for the Full-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

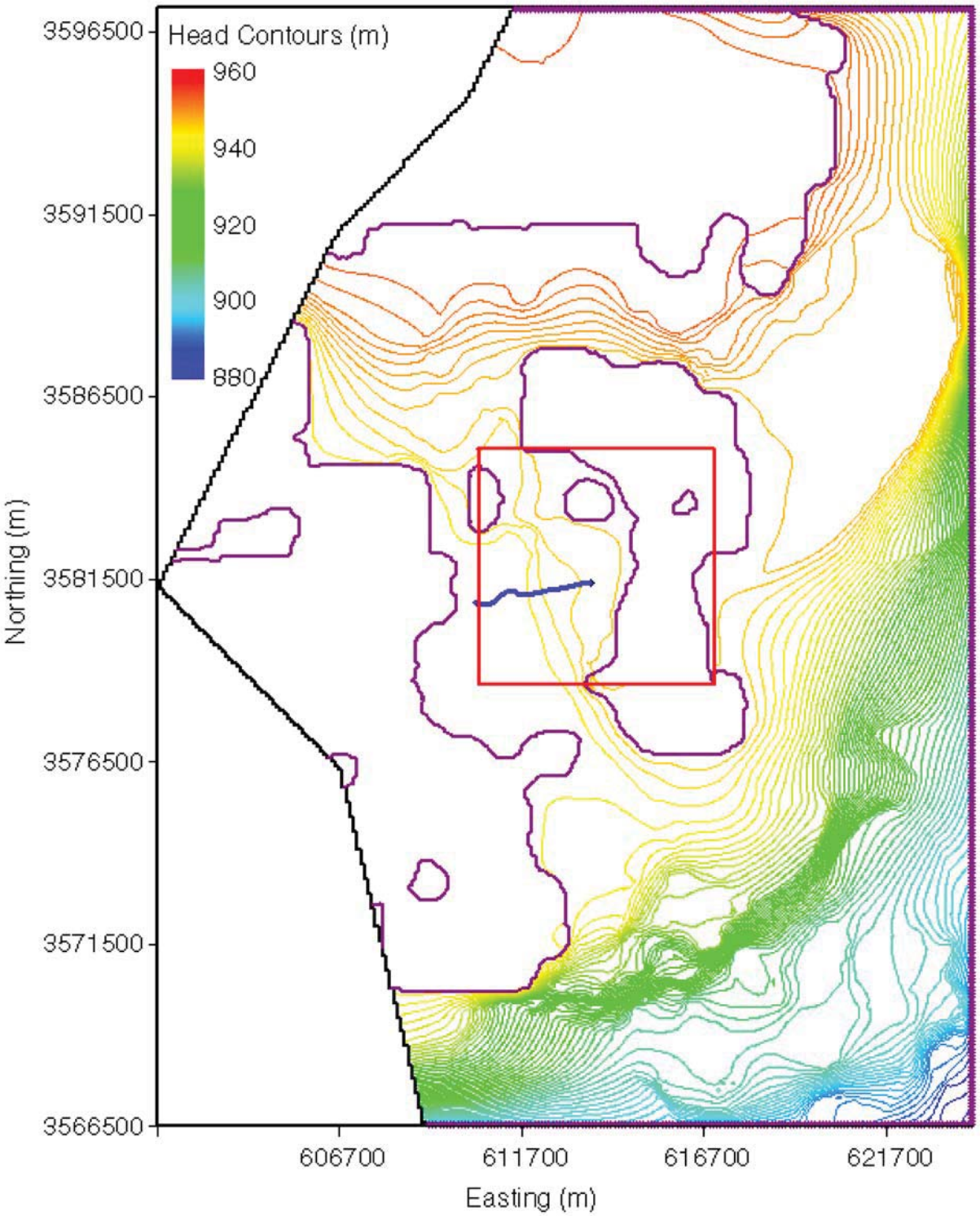

Figure TFIELD-85. Head Contours and Particle Track for the Median-Travel-Time T Field (d10r09-R1) for the Full-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

can be tested through the collection of additional data. This model was used to create 500 stochastic realizations of the distribution of Culebra T ("base" T fields) in the vicinity of the WIPP site.

A MODFLOW-2000 modeling domain was defined extending 30.7 km (19.1 mi) north-south and 22.4 km (13.9 mi) east-west, roughly centered on the WIPP site. This domain was discretized into 68,768 uniform 100-m (328-ft) by 100-m (328-ft) cells. Water-level measurements made in 37 wells in late 2000 were used to define "steady-state" head conditions and constant-head boundary conditions on the northern, eastern, and southern extremes of the model domain. No-flow boundaries down the arms of Nash Draw, representing flow lines, were used on the western side of the model domain, reducing the number of active cells to 53,769.

MODFLOW-2000 and PEST were used to calibrate 146 of the base T fields to steady-state heads and transient drawdown responses to seven large-scale pumping tests. This calibration was done by using 100 pilot points to adjust the T values within the model domain to improve the fit to the observed heads. The pilot points were used to adjust a residual T field that was combined with a previously created base T field to yield the final calibrated T field. Of the 146 T fields, 121 were judged to be adequately calibrated for use in WIPP compliance calculations by virtue of being from a single population with respect to the CDF of travel times from a point above the center of the WIPP disposal panels to the LWB. From these 121 T fields, the 100 having the best objective fit measures were selected for further use.

The EPA requires that the potential effects of future potash mining be taken into account when evaluating the performance of the WIPP disposal system. Accordingly, transmissivities in the areas within the model domain where current or future mining might affect the Culebra were scaled by a random multiplier between 1 and 1,000 obtained from LHS. A single multiplier was used for each T field, applied first to the areas outside the WIPP LWB that might be mined to create a partial-mining T field, and then to the areas both inside and outside the LWB that might be mined to create a full-mining T field. The LHS was performed three times to create three replicates of T fields, leading to a total of 600 T fields. The MODFLOW-2000 water "budget" files from forward runs of these 600 T fields provided the input to radionuclide-transport calculations using SECOTP2D.

In all cases (no mining, partial mining, and full mining), the particle tracks on the T fields show travel times that are longer than those calculated for the T fields used in the CCA. In the case of the T fields unaltered for the effects of mining, the longer travel times are caused by a shift of relatively high Ts from the southeastern to the southwestern portion of the WIPP site relative to the CCA T fields. In the case of the T fields altered for full and partial mining, the longer travel times are the combined result of the westward shift of high Ts discussed above and a change in the definition of the areas to be mined that resulted in less water entering the Culebra on the WIPP site.

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II-G-21: Conceptual Models Second Supplementary Peer Review Report. January 1997

A Peer Review
Conducted By

Charles Wilson, Darrell Porter, John Gibbons,
Eric Oswald, Glen Sjoblom, Florie Caporuscio

for

U.S. Department of Energy
Carlsbad Area Office
Office of Regulatory Compliance

January 1997

EXECUTIVE SUMMARY

This report is a further supplement to a July 1996 report that presented the results of an independent technical peer review of the adequacy of 24 conceptual models representing features, events and processes involved in assessing the long-term performance of the Waste Isolation Pilot Plant. In its December 1996 supplementary report, the Panel stated that it continued to find two of the models not adequate to represent the future states of the repository. For the two models found not adequate, Spallings and Chemical Conditions, the Panel identified its remaining issues.

In this second supplementary report the Panel considers the U.S. Department of Energy's (DOE's) January 1997 responses to these remaining issues. The Panel's evaluation of these responses is presented in Section 3 of this report. Following review of the DOE responses, the Panel continues to find that the Spallings model and the Chemical Conditions model are not adequate to represent future states of the repository.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Conceptual Models Peer Review Panel issued its report in July 1996. The peer review was conducted in accordance with the regulatory requirements of 40 Code of Federal Regulations (CFR) 191 and the implementation of those requirements by 40 CFR 194. The U.S. Department of Energy (DOE) included the Conceptual Models Peer Review Report as part of its Compliance Certification Application (CCA) for WIPP that was submitted to the U.S. Environmental Protection Agency (EPA) in late October 1996.

In the Conceptual Models Peer Review Report of July 1996, 24 conceptual models were

evaluated using the evaluation criteria specified by the EPA, including those of NUREG 1297. The Panel's report identified 13 conceptual models as adequate for implementation in WIPP Performance Assessment and 11 as not adequate for implementation, based on information available to the Panel. The Panel's findings on each of the models judged inadequate were provided in the report. After that report was issued, DOE developed additional information, made changes to some of the conceptual models, and prepared responses to the findings in the Conceptual Models Peer Review Report of July 1996.

The DOE reconvened the Panel in October 1996 to review the changes to the conceptual models, the DOE responses to the findings in the July 1996 Panel report, and information available in the CCA. In December 1996 the Panel issued a report supplementing the July 1996 report, that assessed the changes to the models and the DOE responses. The Panel found that two of the models, Spallings and Chemical Conditions, continued to be not adequate for implementation, and identified its remaining issues.

DOE again reconvened the Panel in January 1997 to review additional information developed in response to the remaining issues of the Panel on these two models. Therefore, this report is a further supplement to the Panel's July 1996 and December 1996 reports.

Section 2 of this report describes the process for this second supplementary review. Section 3 describes the additional information provided by DOE and the Panel assessment of that information.

2.0 SUPPLEMENTARY REVIEW PROCESS

The supplementary review was conducted in accordance with the DOE Quality Assurance requirements at Sandia National Laboratories (SNL) in January 1997. The Panel was provided responses to issues in its December 1996 report during briefings and in written material. This second supplementary review used the same review criteria to judge the acceptability of conceptual models as in the July 1996 report.

3.0 MODEL EVALUATIONS

3.1. Spallings

3.1.1. Model Description

No changes to this model were presented.

3.1.2. Review of Criteria

The review of criteria for the Spallings model remains unchanged.

3.1.3. Review of Responses to Panel Findings of December 1996

3.1.3.1. Summary of Findings

The Panel's December 1996 findings with regard to the Spallings model are summarized in Section 5.0 of that report and reproduced below. A complete statement of these findings is presented in Section 3.14 of the Panel's December 1996 supplementary report.

- An adequate basis for the parameters used in the mathematical expression of the model has not been developed. In particular, ignoring capillary forces and correlating tensile strength with surface erosion have not been adequately supported by either first principles or experiment.

- The principal assumptions on which the mathematical model is based appear to be incomplete. Waste removal by entrainment in gas flow is expected to occur in a highly dynamic sequence principally involving a spalling process driven by gas flow out of the porous waste normal to the eroded surface. Subsequent erosion by gas flow parallel to the eroded surface is not expected to be the primary effect controlling the volume of spall, particularly in early times. In addition, the DOE has not adequately shown that the steady-state assumptions of the model conservatively approximate releases associated with the dynamic process of spall, and the possibility of transonic velocities has apparently not been considered.

- The experiments conducted in support of this model appear to have been designed to reproduce the assumptions on which the model is based, rather than to simulate the dynamic repository system. Although the experiments may support adoption of specific model parameters, they do not demonstrate that the model adequately represents future states of the repository.

3.1.3.2. Summary of DOE Responses to Findings

The DOE responded to the Panel's continued concerns through the SNL Spallings Release Position Paper (Hansen et al., 1997), oral presentations, subsequent discussions, and presentations of additional information. The position paper and initial oral presentations addressed the Panel's concerns by grouping them into the categories of waste characterization, analog comparisons, and conceptual model issues.

The waste characterization information included discussions of the physical condition of the waste that would be capable of release by a spallings process, the waste strength, and expectations of the significance of these results relative to spallings releases. Key points made were that any waste capable of spallings release would be at least partially degraded and have some moisture content, because without the presence of brine the elevated gas pressure that drives the spallings process could not exist. The model assumption that the degraded waste would have the average characteristics of a fine sand were considered by DOE to be highly conservative because not all of the waste would be expected to have degraded to that end state during the 10,000-year regulatory period. The 1 psi cementation strength assumed in the model

was also considered conservative, and experimental results were presented showing that dried samples of sand that had been saturated with WIPP brine had indirectly determined tensile strengths that averaged 49 psi. Higher average tensile strengths ranging up to 114 psi were found when NaCl and MgO were added to the brine. The DOE concluded that waste strength dominates spallings releases, that the assumed waste strength of 1 psi was conservatively low, and that degraded waste will be heterogeneous and cemented, significantly impeding erosion.

Analog comparisons were presented for spallings-type releases induced by pressure surging to stimulate methane production from coal beds, industrial techniques to remove cuttings by air injection during borehole drilling, the downhole pressure gradient requirements for removal of hydrofracture proppants, wellbore stability and sand production as a function of fluid velocities, and the limitations of the borehole as a transport pathway. In addition, the mathematical model used by DOE to calculate spallings releases was compared to models for sediment erosion by moving fluids and to rock mechanics models for time-dependent tensile failure by fluid pressure gradients at the borehole boundary. The DOE believes that the available quantitative data (most notably from the coal bed methane analogs) suggest that the predicted WIPP spallings release volumes were probably larger than would actually occur. The DOE also believes that support was provided for the assumption that the void created by spalling will not continue to grow indefinitely, but will achieve an equilibrium state. Where quantitative data were not available, such as in the air drilling and hydraulic fracture proppant analogs, the comparisons were interpreted to indicate that the phenomenology included in the Spallings model is appropriate and probably conservative. Based on the comparisons with other models, the DOE concluded that the Spallings model has an appropriate functional form and is probably conservative.

The conceptual model and its mathematical expression were reviewed and confirmed by DOE to have an appropriate functional form for properly characterizing the end state of the spallings process in a slightly cohesive material. Experimental and analog evidence were used to support the assumption that the process reaches an equilibrium state, that the equilibrium state establishes the maximum volume of waste released, and that the equilibrium state determined by the erosional forces assumed in the model conservatively predicts the volume of waste released. In summary, the DOE response reiterated that cohesive forces dominate the calculated release, that many key assumptions in the mathematical formulation and parameterization are conservative, and that the releases predicted by the Spallings model are conservative.

In addition to the foregoing, model calculations of pressure transients in the repository were included in an oral presentation but not in the position paper. These analyses showed that depressurization of an isolated waste room is essentially complete within about 1,000 seconds (17 minutes) following borehole penetration of the room. The pressure profiles were interpreted by DOE to illustrate a gradual drawdown of pressure in the room, mitigating a possible spall event.

At the Panel's request, the DOE provided additional information in two areas: (1) a refined estimate of the capacity of the borehole to accommodate spallings releases under WIPP-specific

conditions; and (2) an estimation of the pressure gradients required to cause tensile failure in the waste under WIPP-specific conditions. DOE's responses to these questions are summarized in the following paragraphs. The Panel also requested supplemental information in two additional areas that the DOE was unable to provide within the available schedule. These were (1) information that would further support the assumption that the equilibrium state determined by the model conservatively predicts the total volume of waste released in the spallings process; and (2) correlations between the cohesion of the degraded waste and the maximum cohesion found to exist in natural analogs where spallings releases are observed.

A more detailed analysis of the borehole capacity indicated that the borehole size was adequate to transmit spallings releases to the ground surface at the generation rates predicted by the model in the repository. The borehole was therefore determined to not be a limiting element in spallings releases.

A DOE team made preliminary scoping calculations using an elastic, Mohr-Coulomb model of waste that would be released by tensile failure using the pressure transient data described above and ranges of values for the key waste strength properties. Several cases were run in which assumed waste compressive strength and internal friction were varied. The details of these analyses are presented by Hansen and Knowles (1997). The results indicated that the volume released from a 1-m thick waste horizon (representing the fully compacted state of the waste) ranged from 0.37 to 0.59 m^3, and approached approximately 0.6 m^3 as the waste tensile strength approached zero. The limiting value of the release volume was determined by the fixed volume defined by the zone of tension around the borehole. In responding to additional questions posed by the Panel, the DOE emphasized that although the tensile failure results tended to support the model's conservatism by predicting a lower release volume, the tensile failure model results were considered to be scoping calculations providing order-of-magnitude approximations. The DOE also indicated that there were other factors likely to result in second order effects that were not incorporated into that model. Of particular significance was the consensus of the presenters that the continuing flow of gas through the waste following tensile failure could mobilize additional waste beyond the above quantities, through seepage and erosion processes.

3.1.3.3. Panel Review of Responses

The information presented by DOE in the aforementioned Position Paper and initial oral presentations was not considered by the Panel to adequately support the appropriateness of the Spallings model for use in performance assessment. While it is agreed that degradation of a significant part of the waste must occur to generate enough gas to cause a spallings release, implying that some moisture must be present, the cementation strength information presented to the Panel was determined from oven-dried samples with considerably lower moisture contents than would be expected under repository conditions. The ability of precipitates to cohesively bind a granular material may be significantly lower under partially saturated conditions than when the material is nearly dry. However, strength information for materials with higher degrees of

saturation was not available. Although waste strength may be significant in estimating spallings releases, the assumed strength of 1 psi was not adequately shown by these experiments to be conservatively low under repository conditions. The Panel also agrees that the degraded waste will be heterogeneous and is likely to be at least partially cemented; however, the degree to which this would impede spallings releases was not demonstrated.

The analog comparisons presented appeared to have varying degrees of correlation with WIPP repository conditions, making it difficult for the Panel to directly use the comparisons in making definitive conclusions regarding the degree of conservatism in the model. The coal bed methane analogs were particularly useful in identifying limiting values of cohesion above which spallings-type releases are unlikely to occur and in identifying limiting sizes of artificially induced spallings cavities. However, without waste strength data to use as a basis, conclusions regarding spallings releases under WIPP repository conditions could not be made. Although the Panel agrees that the erosion phenomenon addressed in the Spallings model may occur under repository conditions, it was not adequately demonstrated to be of primary importance in spallings releases. The Panel has come to believe that the erosion process described in the Spallings model may actually be of secondary importance when compared with the waste volumes potentially released by tensile failure and seepage forces under high pressure gradients. Because of the foregoing concerns, the Panel could not conclude, based on the analog information presented, that the Spallings model was conservative. Conversely, the analog information was considered by the Panel to present information suggesting that the Spallings model is not appropriate.

The formulation of the Spallings model as a self-limiting process is based on an analytical statement of the relationships among void volume, gas velocity, and material strength. This formulation appears to be strongly contraindicated by analytical considerations of open completion of coal gas extraction wells. Such wells demonstrate that enlargement of a cavity ceases after a finite number of well pressure surges independent of the number, pressures, or duration of additional surges. The stabilization of cavity size despite the repetition, maintenance of, or increase in gas seepage pressures over time implies that cavity volume stability is related to stress conditions, and in particular to stress geometry and magnitude resulting from arching around the void. The Spallings model does not address the stress state around the wellbore and would not predict the stabilization of cavity volume under progressively increasing surge pressures. There is no mechanism or process in the Spallings model that would predict the cessation of cavity growth if gas seepage pressures were increased. For this reason it appears that the representativeness of the predicted releases due to spalling using the end-state modeling approach of the Spallings model cannot be evaluated because critical processes and local stress conditions are not specifically considered.

The Panel's belief that erosion is of secondary importance in spallings releases, and the lack of a critical comparison between the relative roles of erosional versus tensile and seepage failure mechanisms in such releases, makes it difficult for the Panel to support the credibility of the Spallings model as currently configured. Because the credibility of the basic model assumptions

are being seriously questioned, demonstrations that key aspects of the model and its parameterization are conservative cannot be interpreted to conclude that the present model conservatively predicts the future states of the repository. Although erosion phenomena may be a later mechanism acting for dislodging waste in a spallings release, the early-time tensile failure of waste under high, transient pressure gradients may be capable of removing waste particles that would not have been predicted to be removed under the steady-state assumptions of the Spallings model, leading to underestimating the release volume. Because of these concerns, the Panel does not believe that it has been adequately demonstrated that the equilibrium state determined by the erosional forces assumed in the model conservatively predicts the volume of waste released.

Model calculations of pressure transients were new and helpful to the Panel in determining the time duration over which a spallings release may occur. However, the Panel could not concur with DOE's conclusion that the pressure gradients were sufficiently low to mitigate a spall event because of the results of the tensile failure analysis.

The new tensile failure results presented by the DOE provided insights into a failure mechanism considered by the Panel to be significant to the spallings process. The preliminary nature of the calculations, the possibility that an additional volume of waste would be released by seepage forces from subsequent gas flow in the porous waste, and the lack of information on associated effects (such as waste heterogeneity, stability of the waste cavity, the presence of moisture in the waste, and coupling between the cavity size and the stress and pore pressure fields) did not provide an adequate basis for the Panel to conclude that the spallings release volumes presented in the CCA were conservative. The tensile failure calculations did emphasize, however, the complexity of the spallings process, and are useful because they represent a phenomenologically appealing, more classical approach to such calculations. The tensile failure mechanism is more consistent with the mechanisms observed in the coal bed methane analogs.

In summary, the additional analog, waste strength, model descriptions, and calculational information provided to the Panel were either not adequately correlated with WIPP repository conditions or were not sufficiently complete or supported to provide the Panel with an adequate basis for determining that either the Spallings model or the results obtained from that model were conservative.

3.2. Chemical Conditions

3.2.1. Model Description

No changes to this model were presented.

3.2.2. Review of Criteria

The review of criteria for Chemical Conditions remains unchanged.

3.2.3. Review of Responses to Panel Findings of December 1996

3.2.3.1. Summary of Findings

In summary, the Panel's December 1996 findings were that the ability of the MgO backfill to react completely and rapidly with CO_2 to buffer the chemical system and limit actinide solubilities had not been adequately substantiated by experimental physical results that correctly simulate conditions in the repository. Although the pH buffering assumptions are of considerable importance to many other conceptual models, the conclusion that the MgO will in fact perform as assumed had not been adequately supported.

3.2.3.2. Summary of DOE Responses to Findings

The DOE provided a summary of a calculation of cumulative complimentary distribution functions (CCDFs) intended to show the importance of MgO on repository system performance. The CCDFs without MgO present showed increased releases as compared to those with MgO present. Releases with MgO present predominantly result from cuttings/cavings and spallings, but without MgO present the contribution from direct brine release significantly increases. DOE indicated that the mean CCDF without MgO present still remains lower than the EPA limit. DOE also provided additional results of experiments with MgO from the ongoing test program.

3.2.3.3. Panel Review of Responses

The Panel examined the various assumptions and parameters that were used in computing the CCDFs without MgO present and believes that the differences in CCDFs with and without MgO represent the degree of importance of the chemical getter to repository performance. The Panel believes that adding the MgO getter will positively benefit and not detract from the performance of the repository. However, the Panel identified a few additional factors that would need to be included for such a CCDF calculation to be definitive, including the effect on corrosion rates, gas generation rates, and pressures over time. However, inasmuch as calculations without MgO show that direct brine release would become an important contributor to overall releases, the Chemical Conditions model has been shown to be a significant contributor to the future states of the repository.

Furthermore, the additional results from the ongoing test program, while interesting, are not sufficient to resolve the Panel's concerns with the issue of MgO effectiveness. The results presented to the Panel concerned the effect of CO_2 diffusion into the MgO pellets. Test runs of 4 days followed by dye infusion indicate that in 24 hours the dye will travel through the reaction rims to the center of the pellet. However, the test runs were short, the reaction rims were thin and may not have been fully formed, and there were no transient information or bounding calculations to support a conclusion regarding the role of the reaction rims in impeding CO_2 diffusion. Information was not available on the diffusion rate of CO_2 into the MgO pellets, especially as a function of reaction rim thickening. The Panel believes that the aforementioned

test program has not sufficiently progressed to provide a definitive verification that the MgO will perform as planned under repository conditions. Therefore, as a result of the Panel's review of the added information, the conclusion remains that the Chemical Conditions model is not sufficiently developed to adequately support performance assessment.

3.3. Summary

In summary, the Panel concludes that the Spallings model and the Chemical Conditions model remain inadequate to represent the future states of the repository.

4.0 REFERENCES

Hansen, F.D., M.K. Knowles, and T.W. Thompson, 1997. Spallings Release Position Paper. Prepared for the U.S. Department of Energy Carlsbad Area Office by Sandia National Laboratories, Albuquerque, NM. 17 January 1997.

Hansen, F.D., and M.K. Knowles, 1997. Response to inquiries by CMPRP for spallings. Memorandum to M.S.Y. Chu, Sandia National Laboratories, Albuquerque, NM. 23 January 1997.

ACRONYMS

CCA	Compliance Certification Application
CCDF	cumulative complimentary distribution function
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
SNL	Sandia National Laboratories
WIPP	Waste Isolation Pilot Plant

APPENDIX A - SIGNATURE PAGE

I acknowledge by my signature below that I concur with the findings and conclusions documented in this Conceptual Models Peer Review Second Supplementary Report.

Florie Caporuscio
John Gibbons
Eric Oswald
Darrell Porter
Glen Sjoblom

Charles Wilson

From: Kurt W. Larson
To: malord, pvaughn, msychu
Date: 1/24/96 8:24AM
Subject: Fracture model ideas

A couple of ideas as the frac. model parameters are determined. I will be away next week, so Palmer you will have to see that the memo for Project office to consider gets written.

From brine-outflow meeting 1/23/96:

Wolfgang Wawersik thinks each interbed has a zone about 10cm thick which dilates. Each zone dilates identically. This means a different set of fracture parameters would be applied to each interbed. He and Norm Warpinski think the LEFM model is appropriate analogue. LEFM predicts about 1 cm dilation max with tremendous permeability change for pressures somewhat above lithostatic.

For MB 138 and 139, 1 cm dilation - 1% porosity change over entire thickness
For anh.A+B, 1 cm dilation - 3-5% porosity change over entire thickness (someone who knows modeled thickness can figure out more accurately)

dilation/fracturing begins is a continuous process, so initiation pressure should be low.

Additionally, Norm thinks pressures above 17-18 MPa are not realistic, and indicate too constrictive fracture model conditions. Thus, fracture model must be able to open up better than recent implementations (FEPs) which allowed pressures up to 23 MPa.

This leads me to the following recommendation:

Initiation pressure
about 0.2 MPa above initial pressure of cell
I
Final Pressure, Final Porosity, Final Permeability
I suggest using these as fitting parameters so that the following condition is attained

At about 2.5 MPa above initial pressure in cell, fracture porosity and permeability begin steep rise (commensurate with onset of real fracturing) - below this pressure shallower rises indicate interconnection/dilation of existing fractures

a. At about 3 MPa above initial pressure in cell, fracture porosity reaches 1% for MB 139, MB 138; 3-5% for Anha+b.

b. At about 3 MPa above initial pressure in cell, fracture permabiltiy reaches 87 OM greater than initial.

a+b above make a fracture that is relatively long due to high permeability and narrow due to moderate increase in porosity. condition of a+b is ideal max pressure for model, and commensurate with LEFM model.

Above about 3 MPa increase, fracture porosity and permeabity continue steep rise so that increased pressures have a mechanism for blowing off steam rapidly.

If the model is set so that there is no increased porosity or permeability above about + 3 MPa, then I think some vectors will result in pressures significantly in excess of 20 MPa.

I look forward to hearing what the final values chosen are

Kurt

Date: 1/29/96

To: Margaret Chu, Dept. 6801, MS-1325

From: Michael Lord, Dept. 6749, MS-1328

Subject: **Parameters describing the variable porosity and permeability within anhydrite material.**

I have considered ways of honoring the porosity/permeability response to pressure within the anhydrite marker beds as suggested in the enclosed memo from Kurt Larson of 1/24/96 and discussions with Palmer Vaughn. The following values typical of the performance assessment data were assigned:

pressure at fracture initiation	= 12.7 MPa
pressure at full fracture condition	= 16.5 MPa
porosity at reference condition	= 0.011 (1.1%)
permeability of intact anhydrite	= 2.5E-19 m^2
permeability at full fracture condition	= 1.0E-09 m^2

The porosity at full fracture condition was then adjusted in order to produce a change in porosity of about 1% at 2.5 MPa above fracture initiation pressure or a pressure of 15.2 MPa. This was obtained with a maximum porosity of 0.05(5%). In the attached Fig. 1 the resulting porosity response is shown. The corresponding permeability response is shown in Fig. 2. At 2.5 MPa above fracture initiation pressure, the permeability is between 3 and 4 orders of magnitude larger than the intact value. This would represent the desired response in marker beds 138 and 139. A similar analysis was done for marker bed a+b where the full fracture porosity was taken to be 0.25 (25%). For this value of maximum porosity the porosity at 2.5 MPa above fracture initiation pressure is approximately 3% above the porosity at fracture initiation pressure. This is shown in Fig 3 and the result is in line with the proposed response. Fig. 4 shows the permeability at 2.5 MPa above fracture initiation pressure as approximately 4 orders of magnitude above the intact permeability.

Based on this study I would recommend assigning the fracture parameters as follows. The fracture initiation pressure should be set as done in the FEPs calculations where it is assigned a value of 0.2 MPa above the grid block initial pressure. Therefore, there could be some small variance in the fracture initiation pressure if the reference initial pressure in the Salado is sampled. Also, there will be some small variance due to the dip in the Salado formation. However, the fracture initiation pressures should be near the 12.7 MPa value. The pressure at the full fracture condition should be an increment of 3.8 MPa above the fracture initiation pressure. This would result in a full fracture pressure of approximately 16.5 MPa. The full fracture permeability can be any large sampled or assigned value such as the 1.0E-09 m^2 used in this study. The full fracture porosity for the marker beds 138 and 139 will have value 0.05 and the full fracture

porosity for the marker bed a+b will have value 0.25. With these values the pressure dependent porosity and permeability should closely approximate the LEFM predicted values.

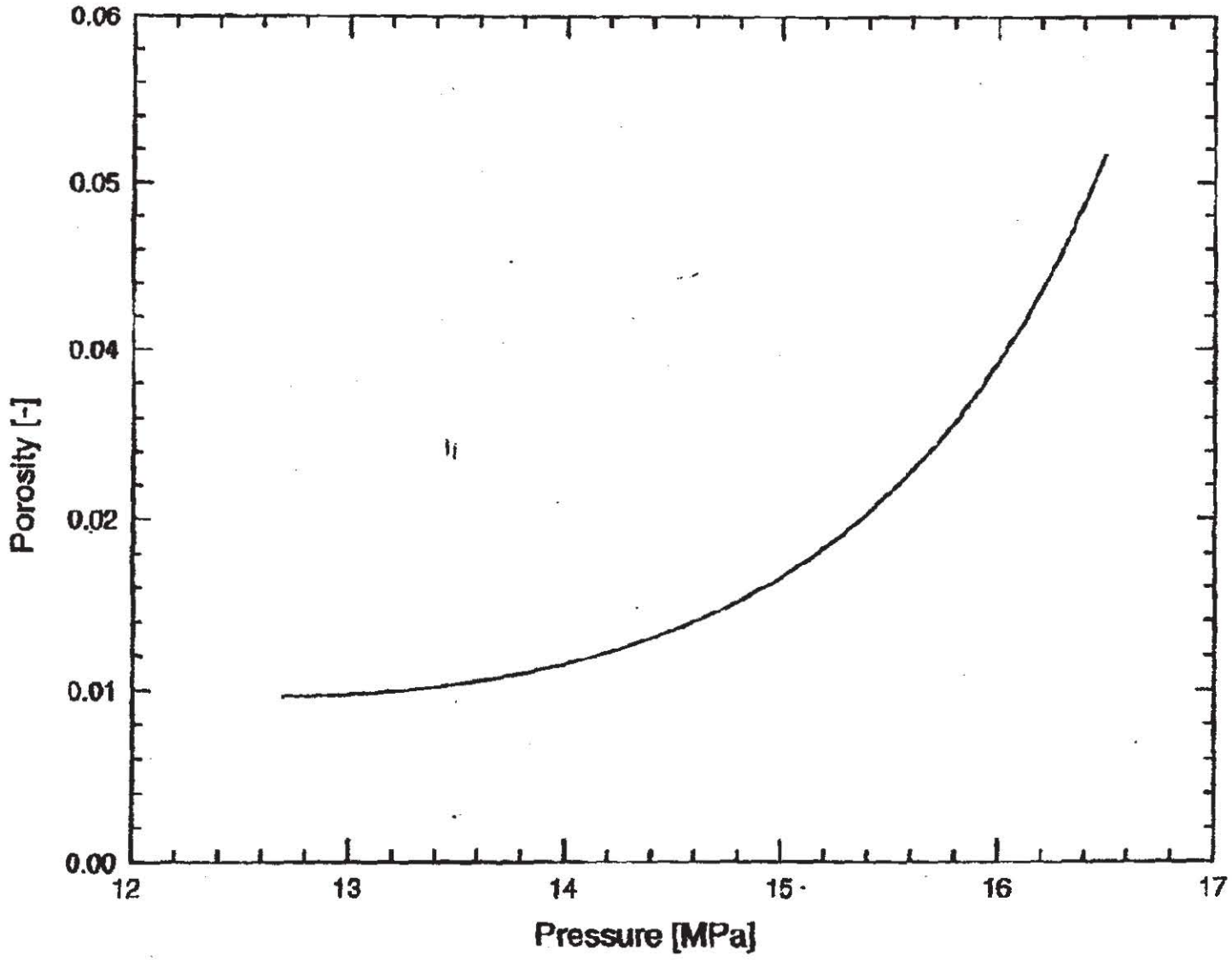

Figure 1: Porosity in Marker Bed 138 & 139 with Fracturing

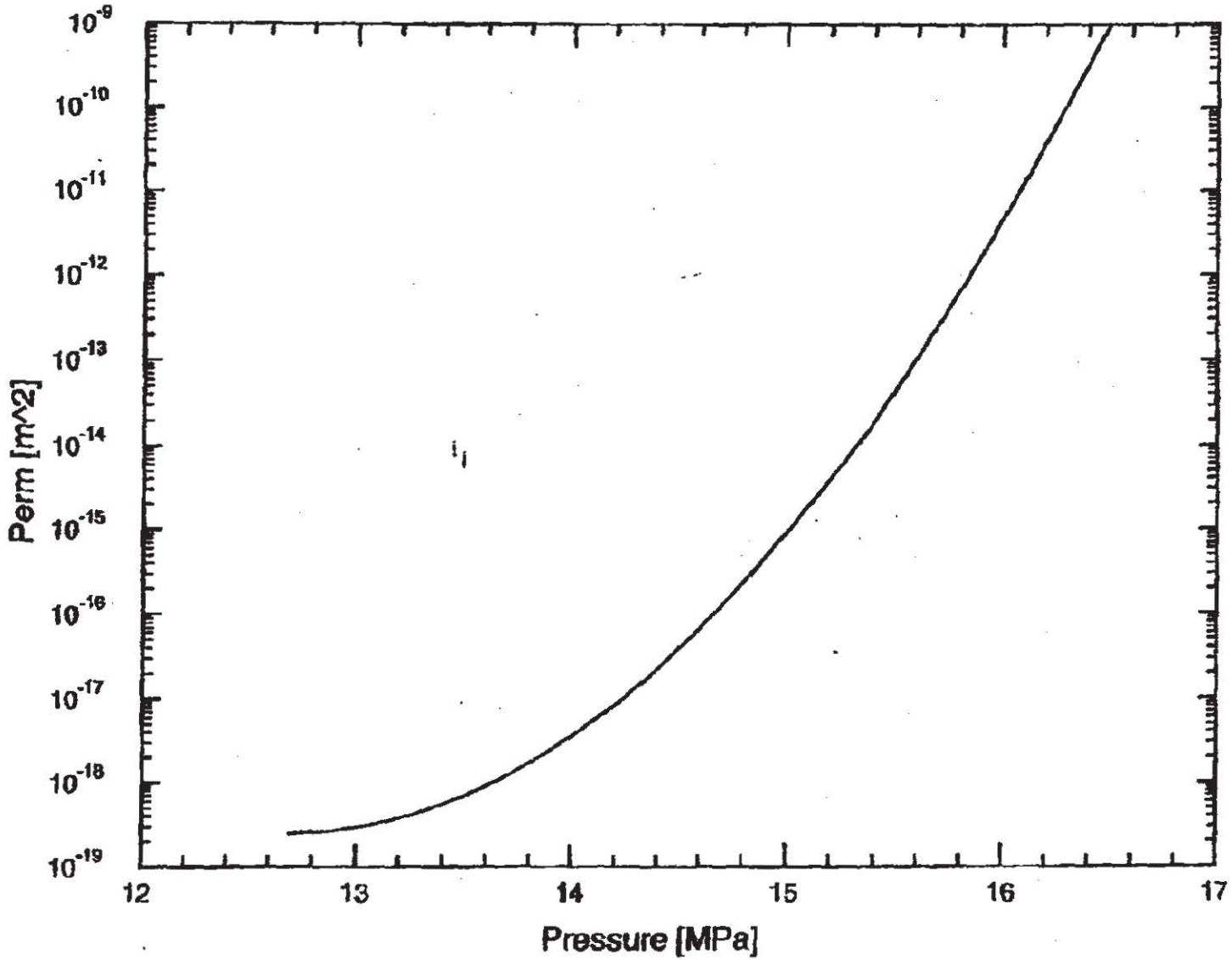

Figure 2: Permeability in Marker Bed 138 & 139 with Fracturing

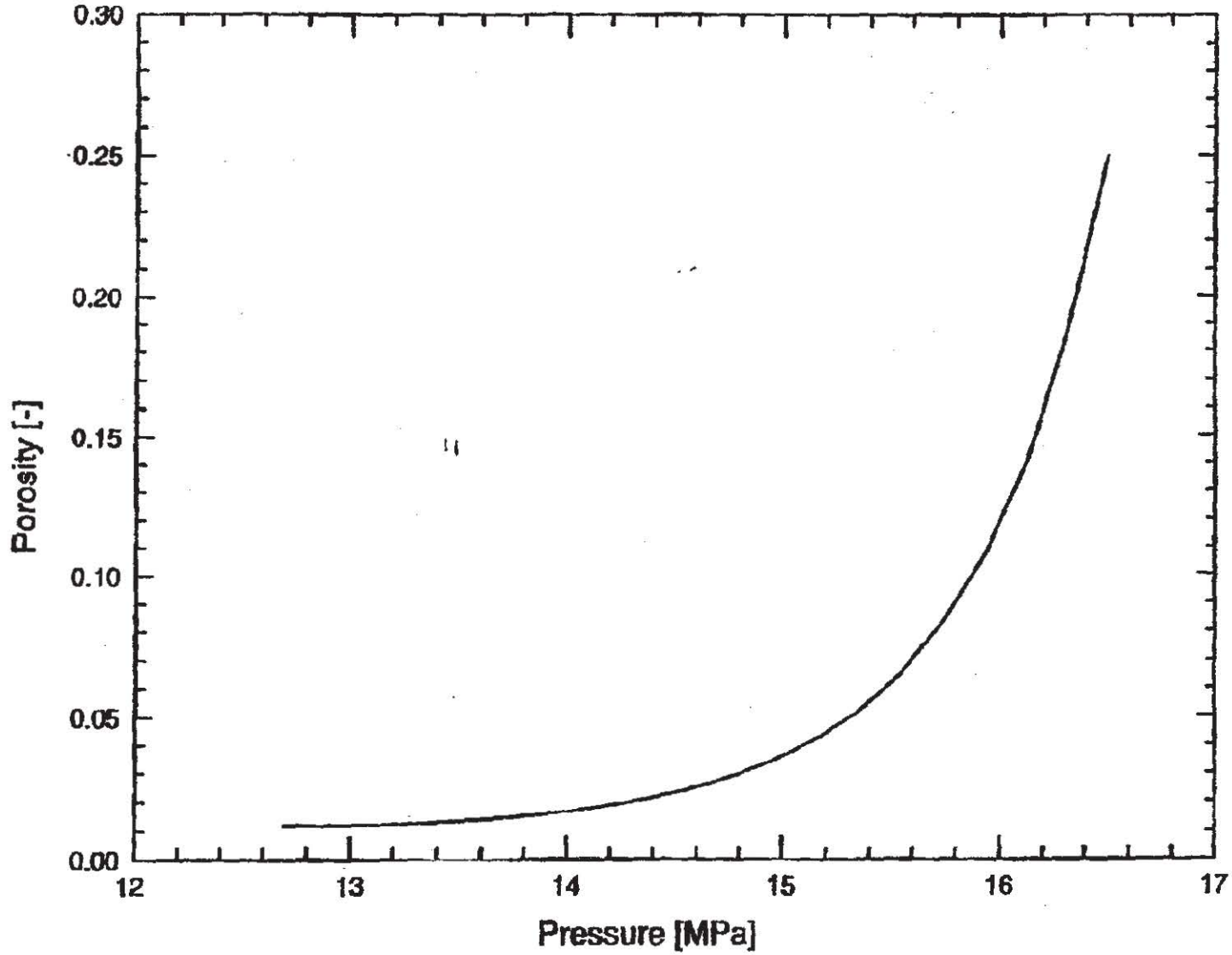

Figure 3: Porosity in Marker Bed A+B with Fracturing

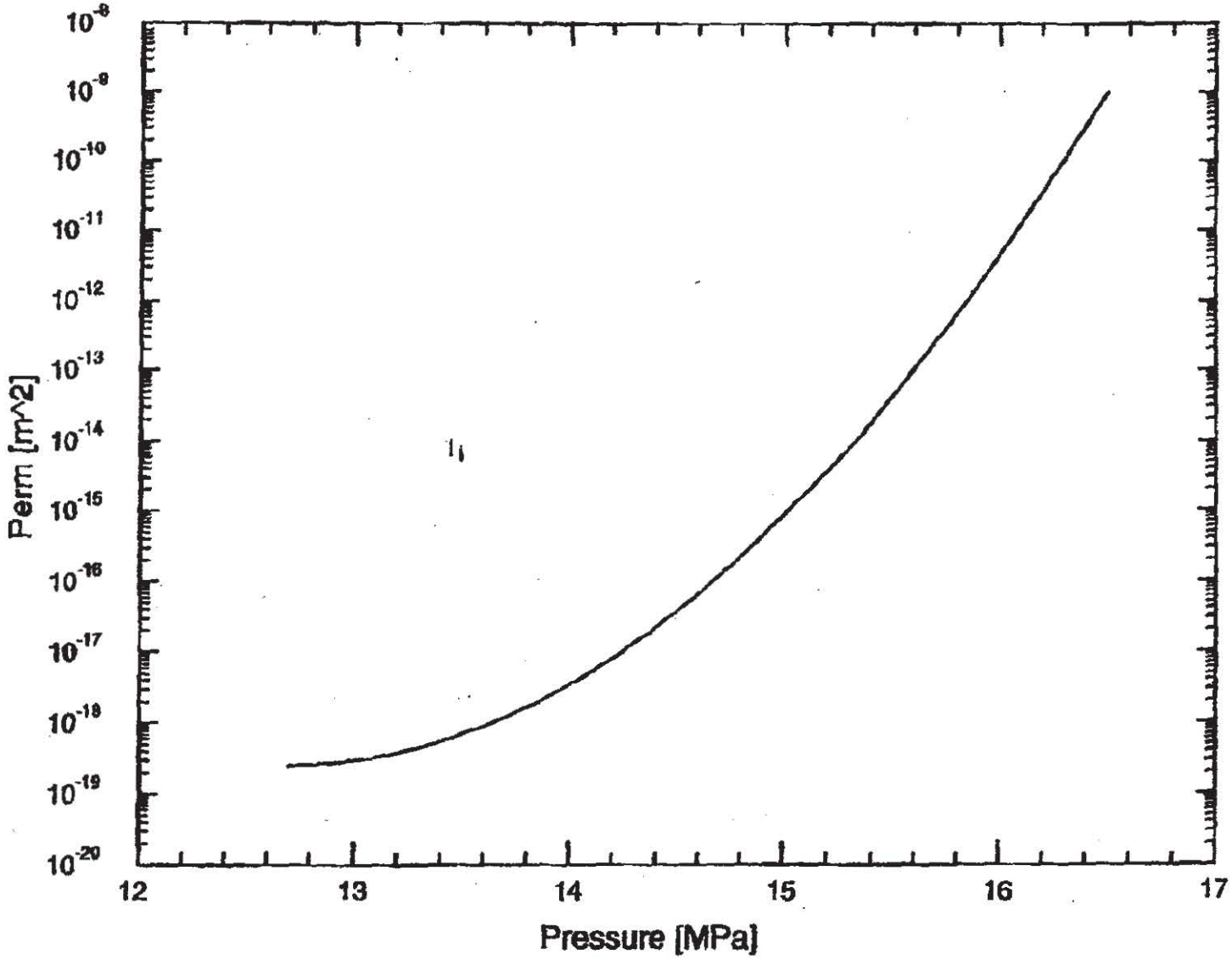

Figure 4: Permeability in Marker Bed A+B with Fracturing

Sandia National Laboratories

Albuquerque, New Mexico 87185-1341

date: August 20, 1996

to: Distribution

pp T.W. Hicks Yifeng Wang T.W. Hicks

from: David Bennett, Yifeng Wang, and Tim Hicks

subject: An Evaluation of Heat Generation Processes for the WIPP

1.0 Introduction

Nuclear criticality, exothermic reactions, and radioactive decay are possible sources of heat in the WIPP repository. Nuclear criticality has been eliminated from performance assessment calculations on the basis of low probability (see SNL Summary Memo of Record RNT-1). This memo discusses possible heat generating processes at the WIPP and the potential magnitude of the temperature increases they might induce. Heat from exothermic reactions is discussed in Section 2 and heat from radioactive decay is discussed in Section 3.

Conclusions are provided in Section 4. In summary, soon after disposal concrete hydration in the panel closures and shaft seals will give rise to temperature increases lasting a few decades. Heat from radioactive decay will generate a maximum temperature increase of less than 2°C above the ambient temperature (about 27°C) within 100 years after disposal. A number of potential exothermic reactions other than concrete hydration have been identified. These reactions are brine limited and will cause only minor perturbations to the temperature distribution within the disposal system. The maximum calculated rate of brine inflow to a waste disposal panel, and thus, the maximum exothermic reaction rates, occur for the S2 scenario involving an E1 drilling event at 350 years after disposal. By the time such a drilling event takes place heat generation from concrete seal hydration and radioactive decay will have decreased substantially, and the temperatures in the disposal rooms will have reduced to close to initial values. Note that active institutional controls are expected to prevent drilling within the controlled area for 100 years after disposal. Thus, exothermic reactions following a drilling intrusion into a waste disposal panel will be the only potentially significant heat generating processes at the time of a drilling intrusion.

The maximum temperature that could be achieved in the panel following a drilling intrusion at 350 years occurs as a result of aluminum corrosion; this reaction could result in a maximum temperature increase of about 6°C two years after the drilling event. This predicted value of temperature increase is based on several conservative assumptions. For example, it is assumed that no aluminum corrosion has occurred prior to the drilling event and that all the brine introduced to the waste panel is available for aluminum corrosion. In reality some aluminum corrosion is likely to have occurred prior to the drilling event, reducing the volume of aluminum available for the reaction, and other reactions with lower reaction enthalpies (such as backfill hydration) or lower reaction rates (such as microbial degradation) will compete with aluminum corrosion to consume brine resulting in a smaller temperature increase. Based on similar conservative assumptions, backfill hydration could result in a maximum temperature increase of less than 5°C. These maximum heat generation rates resulting from aluminum corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability. Thus, the temperature rise of 6°C represents the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously.

2.0 Heat From Exothermic Reactions

Exothermic reactions in the repository will liberate heat resulting in elevated temperatures. The magnitude and duration of this temperature increase will depend on the amount and rate of energy release, the geometry of the heat source, the thermal conductivities of the surrounding rocks, and any influence of groundwater or brine flow on heat transport.

In the WIPP a range of different types of reactions will occur, including corrosion, microbial degradation, waste dissolution, and concrete and backfill hydration, and these will liberate different amounts of heat at different times. The amount of heat liberated by the different reactions will depend on the extent of reaction that occurs (for example, how much gas generation or concrete hydration takes place), and the enthalpy of the reactions. The former will depend on the inventory of materials emplaced in the WIPP, and the subsequent chemical evolution of the repository system. The latter can be assessed by considering typical enthalpies for the reaction types of interest.

Enthalpies of reaction, $\Delta_r H°$, for example reactions representing processes that may take place in the repository are given in Table 1 (from SNL Summary Memo of Record GG-7, SP-7). The reactions shown are based on the chemical conditions expected in the WIPP. Note that negative values for $\Delta_r H°$ indicate that the reactions liberate heat as they progress from left to right.

Table 1. Enthalpies of reaction, $\Delta_r H°$, for the WIPP

Reaction	Example Stoichiometry and Standard Enthalpies of Formation, $\Delta_f H°$ (kJ/mol)	Reaction Enthalpy $\Delta_r H°$ (kJ/mol)	Data Source
Backfill hydration	$MgO_{(s)} + H_2O_{(l)} = Mg(OH)_{2(s)}$ $\Delta_f H°$ -601.7 -285.8 -925.5	-38	Krauskopf, 1982, 561
Backfill carbonation	$Mg(OH)_2 + CO_2(g) = MgCO_3 + H_2O$ $\Delta_f H°$ -925.4 -393.1 -1110.3 -285.8	-77	Drever, 1982, 351-256
Microbial degradation	$C_6H_{10}O_5 + H_2O = 3CH_4 + 3CO_2$ $\Delta_f H°$ -805.5 -285.8 3 x (-74.4) 3x (-393.5)	-312	Lide, 1994, 5-16 to 5-37
Aluminum Corrosion	$Al + 3H_2O = Al(OH)_3 + 1.5H_2$ $\Delta_f H°$ 0 3x(-285.8) 1291.9 0	-434	Drever, 1982, 351-256
Anoxic corrosion of steel	$Fe_{(s)} + 2H_2O_{(l)} = Fe(OH)_{2(s)} + H_{2(g)}$ $\Delta_f H°$ 0 2 x (-285.8) -569.0 0	+2.7	Wagman et al., 1982, Table 41
Waste dissolution	$UO_{2(s,cr)} + 2H_2O_{(l)} = U(OH)_{4(aq)}$ $\Delta_f H°$ -1085.0 2 x (-285.8) -1655.8	+0.9	Grenthe et al., 1992, Table III-1
Concrete hydration	$CaO_{(s)} + H_2O_{(l)} = Ca(OH)_{2(s)}$ $\Delta_f H°$ -635.1 -285.8 -986.1	-65.2	Wagman et al., 1982, 2-26

Even though there is uncertainty surrounding the extent of reactions that will occur, the reaction enthalpies indicate that the thermal effects of anoxic corrosion of steel and the waste dissolution reaction will be endothermic and will be of low consequence to the performance of the disposal system. However, the other reactions shown in Table 1 have the potential to evolve significant amounts of heat. The potential effects of these processes on the temperature within the disposal system are discussed below.

2.1 Backfill Hydration

Potential temperature increases in the repository as a result of exothermic backfill hydration reactions have been evaluated by Wang (1996, attachment to this memo). In his analysis, Wang (1996) made the following assumptions:

- The reaction will proceed rapidly so that the rate of heat generation will be

controlled by brine availability.

- All brine entering a waste disposal panel will contact and react with the backfill in the panel uniformly.

- All of the emplaced backfill will undergo hydration.

The maximum calculated rate of brine inflow into a panel (about 200 m^3/year) occurs for the S2 scenario involving an E1 drilling event at 350 years after disposal. The molar density of water is 5.56×10^4 moles/m^3, and thus, the reaction rate of backfill hydration in the panel will be 1.1×10^7 moles/year. Based on the reaction enthalpy shown in Table 1, backfill hydration will generate a thermal load of about 13 kW. There will be about 2×10^8 moles MgO emplaced per panel and thus the reaction could continue for about 20 years if sufficient brine was available.

Wang (1996) estimated the maximum temperature that could be generated by backfill hydration within a panel. Assuming heat loss will occur by conduction through the salt forming the roof and floor of the panel and that heat losses through the side walls are negligible, Wang (1996) calculated that the maximum temperature rise in a panel, as a consequence of backfill hydration following a borehole intrusion and subsequent brine inflow, would be about 4.5°C.

2.2 Backfill Carbonation

Wang (1996) also estimated the potential temperature rise that could occur as a result of backfill carbonation. Wang (1996) assumed that the reaction will be limited by microbial CO_2 production; the maximum rate of CO_2 production is 2.9×10^5 moles/year. Based on the reaction enthalpy shown in Table 1, backfill carbonation will generate a thermal load of about 0.7 kW. About 3.6×10^7 moles CO_2 could be produced in a single panel (see Wang, 1996) and thus the reaction could continue for about 125 years. Wang (1996) estimated the maximum temperature that could be generated by backfill carbonation within a panel to be about 0.6°C.

2.3 Microbial Degradation

Wang (1996) estimated the maximum reaction rate for microbial degradation in a panel to be about 1×10^5 moles/year and the inventory to be about 1.2×10^7 moles $C_6H_{10}O_5$ per panel. Thus, the reaction could continue for about 120 years. Based on the reaction enthalpy shown in Table 1, microbial degradation will generate a thermal load of about 1 kW. Wang (1996) estimated the maximum temperature that could be generated by microbial degradation within a panel to be about 0.8°C.

2.4 Aluminum Corrosion

Wang (1996) determined that the rate of corrosion of aluminum will be controlled by brine availability. From Table 1, the reaction rate of aluminum corrosion in the panel will be about 0.4×10^7 moles/year, assuming a brine inflow rate of 200 m^3/year (1.1×10^7 moles/year). About 8×10^6 moles of aluminum will be emplaced in each panel and thus aluminum corrosion could continue for 2 years. Based on the reaction enthalpy shown in Table 1, aluminum corrosion will generate a thermal load of about 51 kW. Wang (1996) estimated the maximum temperature that could be generated by aluminum corrosion within a panel to be about 6°C.

2.5 Concrete Hydration

Concrete hydration reactions will occur in the seals and panel closures and in the waste.

2.5.1 Seals and panel closures

Concrete hydration reactions are known to proceed for extended periods (perhaps thousands of years). However, the rates of these reactions decrease with time and, within the WIPP, the greatest evolution of heat will occur during the short periods following emplacement of panel closures during the operational phase and following shaft seal emplacement and repository closure. A quantitative analysis of the thermal effects of emplacing large concrete seals in salt at the WIPP was made by Loken (1994), Loken and Chen (1995). Their analysis showed that the energy released by the hydration of the seal concrete could raise the temperature of the concrete to approximately 53° C and that of the surrounding salt to approximately 38° C one week after seal emplacement.

2.5.2 Waste

WIPP waste contains cement which is used to solidify liquids, particulates and sludges. Storz (1996) estimated that all the waste to be emplaced at the WIPP will contain a total of about 8.5×10^6 kg of cement. This is equivalent to about 1.5×10^7 moles of calcium oxide (CaO) per waste disposal panel, representing the cement as CaO. Although a substantial amount of hydration may occur prior to waste disposal, this process will continue at a slower rate after disposal. Disregarding the hydration that will occur prior to disposal and assuming a brine inflow rate of 200 m^3/year, the reaction rate of concrete hydration in the panel will be about 1.1×10^7 moles/year, and the reaction could continue for about 1.4 years. Based on the reaction enthalpy shown in Table 1, concrete hydration will generate a thermal load of about 23 kW. Thus, using analyses similar to that used by Wang (1996) the maximum temperature that could be generated by concrete hydration of the waste within a panel is about 2°C.

3.0 Heat From Radioactive Decay

Radioactive decay of the contact handled CH and remote handled RH TRU waste emplaced in the repository will generate heat. The importance of heat from radioactive decay depends on the effects that the induced temperature changes would have on mechanics, fluid flow, and geochemical processes. For example, temperature increases could result in thermally induced fracturing, regional uplift, or thermally driven flow of gas and brine in the vicinity of the repository.

According to the Waste Acceptance Criteria (WAC), the design basis for the WIPP requires that the thermal loading does not exceed 10 kilowatts per acre. The WAC also require that the thermal power generated by waste in an RH TRU container shall not exceed 300 watts, but the WAC do not limit the thermal power of CH TRU waste containers.

A numerical study to calculate induced temperature distributions and regional uplift is reported in DOE (1980, pp.9-149–9-150). This study involved estimation of the thermal power of CH TRU waste containers. The DOE (1980) analysis assumed:

- All CH TRU waste drums and boxes contain the maximum permissible quantity of plutonium. According to the WAC, the fissionable radionuclide content for CH TRU waste containers shall be no greater than 200 grams per 0.21 cubic meter drum and 350 grams per 1.8 cubic meter standard waste box (in Pu-239 fissile gram equivalents).

- The plutonium in CH TRU waste containers is weapons grade material producing heat at 0.0024 watts per gram. Thus, the thermal power of a drum is approximately 0.5 watts and that of a box is approximately 0.8 watts.

- Approximately 3.7×10^5 cubic meters of CH TRU waste are distributed within a repository enclosing an area of 7.3×10^5 square meters. This is a conservative assumption in terms of quantity and density of waste within the repository, because the maximum capacity of the WIPP is 1.756×10^5 cubic meters for all waste (as specified by the Land Withdrawal Act [LWA]) to be placed in an enclosed area of approximately 5.1×10^5 square meters.

- Half of the CH TRU waste volume is placed in drums and half in boxes so that the repository will contain approximately 9×10^5 drums and 10^5 boxes. Thus, a calculated thermal power of 2.8 kilowatts per acre (0.7 watts per square meter) of heat is generated by the CH TRU waste.

- Insufficient RH TRU waste is emplaced in the repository to influence the total thermal load.

Thorne and Rudeen (1980) estimated the long-term temperature response of the disposal system to waste emplacement. Calculations assumed a uniform initial power density of 2.8 kilowatts per acre (0.7 watts per square meter) which decreases over time. Thorne and Rudeen (1980) attributed this thermal load to RH TRU waste, but DOE (1980), more appropriately, attributed this thermal load to CH TRU waste based on the assumptions listed above. Thorne and Rudeen (1980) estimated the maximum rise in temperature at the center of a repository to be 1.6°C at 80 years after waste emplacement.

Sanchez and Trellue (1996) estimated the maximum thermal power of an RH TRU waste container. The Sanchez and Trellue (1996) analysis involved inverse shielding calculations to evaluate the thermal power of an RH TRU container corresponding to the maximum permissible surface dose; according to the WAC the maximum allowable surface dose equivalent for RH TRU containers is 1000 rem/hr. The following calculational steps were taken in the Sanchez and Trellue (1996) analysis:

- Calculate the absorbed dose rate for gamma-ray radiation corresponding to the maximum surface dose equivalent rate of 1000 rem/hr. Beta and alpha radiation are not included in this calculation because such particles will not penetrate the waste matrix or the container in significant quantities. Neutrons are not included in the analysis because, according to the WAC, the maximum dose rate from neutrons is 270 mrem/hr, and the corresponding neutron heating rate will be insignificant.

- Calculate the exposure rate for gamma radiation corresponding to the absorbed dose rate for gamma radiation.

- Calculate the gamma flux density at the surface of a RH TRU container corresponding to the exposure rate for gamma radiation. Assuming the gamma energy is 1.0 MeV the maximum allowable gamma flux density at the surface of a RH TRU container is about 5.8×10^8 gamma rays per square centimeter per second.

- Determine the distributed gamma source strength, or gamma activity, in an RH container from the surface gamma flux density. The source is assumed to be shielded such that the gamma flux is attenuated by the container and by absorbing material in the container. The level of shielding depends on the matrix density. Scattering of the gamma flux, with loss of energy, is also accounted for in this calculation through inclusion of a gamma buildup factor.

The distributed gamma source strength is determined assuming a uniform source in a right cylindrical container. The maximum total gamma source (gamma curies) is then calculated for a RH TRU container containing 0.89 cubic meters of waste. For the waste of greatest expected density (about 6,000 kilograms per cubic meter) the gamma source is about $2x10^4$ curies per cubic meter.

- Calculate the total curie load of a RH TRU container (including alpha and beta radiation) from the gamma load. The ratio of the total curie load to the gamma curie load was estimated through examination of the radionuclide inventory presented in the WIPP Baseline Inventory Report (BIR) (DOE, 1995). The gamma curie load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of total curie load to gamma curie load of RH TRU waste was calculated to be 1.01.

- Calculate the thermal load of a RH TRU container from the total curie load. The ratio of thermal load to curie load was estimated through examination of the radionuclide inventory presented in the WIPP BIR (DOE, 1995). The thermal load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of thermal load to curie load of RH TRU waste was calculated to be about 0.0037 watts/curie. For a gamma source of $2x10^4$ curies per cubic meter the maximum permissible thermal load of a RH TRU container is about 70 watts per cubic meter. Thus, the maximum thermal load of a RH TRU container is about 60 watts, and the WAC upper limit of 300 watts will not be achieved.

Note that Sanchez and Trellue (1996) calculated the average thermal load for a RH TRU container to be less than 1 watt. Also, the total RH TRU heat load is less than 10% of the total heat load in the WIPP. Thus, the total thermal load of the RH TRU waste will not significantly affect the average rise in temperature in the repository resulting from decay of CH TRU waste.

Temperature increases will be greater at locations where the thermal power of a RH TRU container is 60 watts, if any such containers are emplaced. Sanchez and Trellue (1996) estimated the temperature increase at the surface of a 60 watt RH TRU waste container. Their analysis involved solution of a steady-state thermal conduction problem with a constant heat source term of 70 watts per cubic meter. These conditions represent conservative assumptions because the thermal load will decrease with time as the radioactive waste decays. The temperature increase at the surface of the container was calculated to be about 3°C.

In summary, analysis has shown that the average temperature increase in the WIPP repository due to radioactive decay of the emplaced CH and RH TRU waste will be about 1.6°C, with a maximum rise occurring at the center of the repository at about 80 years after waste emplacement. Temperature increases of about 3°C may occur in the vicinity of RH TRU containers with the highest allowable thermal load of about 60 watts (based on the maximum allowable surface dose equivalent for RH TRU containers).

4.0 Conclusions

Heat from exothermic reactions and radioactive decay will result in minor temperature increases in the repository. The potential temperature increases caused by these processes are summarized in Table 2.

Table 2. Maximum temperature increases at the WIPP.

Heat Source	Maximum temperature increase	Time of maximum temperature increase
Backfill hydration	4.5°C	20 years after a drilling intrusion
Backfill carbonation	0.6°C	125 years after a drilling intrusion
Microbial degradation	0.8°C	120 years after a drilling intrusion
Aluminum corrosion	6.0°C	2 years after a drilling intrusion
Concrete hydration (seals)	25°C in the shaft seal 10°C in the surrounding salt	1 week after emplacement
Concrete hydration (waste)	2.0°C	1.4 years after a drilling intrusion
Radioactive decay of CH TRU waste	1.6°C	80 years after disposal
Radioactive decay of RH TRU waste	3°C near a few containers	Within 100 years after disposal

During the operational phase and soon after disposal concrete hydration in the panel closures and shaft seals will give rise to temperature increases lasting a few decades. Heat from radioactive decay will generate a maximum temperature increase of less than 2°C within 100 years after disposal. A number of potential exothermic reactions have been identified. These reactions are brine limited and will cause only minor perturbations to the temperature distribution within the disposal system. The maximum calculated rate of brine inflow to a waste disposal panel occurs for the S2 scenario involving an E1 drilling event at 350 years after disposal. The maximum temperature that could be achieved in the panel

occurs as a result of aluminum corrosion; this reaction could result in a maximum temperature increase of about 6°C two years after the drilling event. Similarly, rapid backfill hydration could result in a maximum temperature increase of less than 5°C. These predicted values of temperature increase are based on a number of conservative assumptions. For example, the calculated temperature resulting from aluminum corrosion is based on the assumption that no corrosion has occurred prior to the drilling event and that all the brine introduced to the waste panel is available for aluminum corrosion. In reality some aluminum corrosion is likely to have occurred prior to the drilling event, reducing the volume of aluminum available for the reaction, and other reactions with lower reaction enthalpies or lower reaction rates will consume brine resulting in a smaller temperature increase.

Temperature increases of the magnitude and duration shown in Table 2 will have no significant effects on the performance of the disposal system. The effects of such temperature increases on the performance of the disposal system have been discussed in the SNL Summary Memos of Record RNT-24 (thermochemical effects), S-10 and GG-4 (thermal convection), S-11, SP-6, RM-1 (thermally-induced stress).

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Attachment: memorandum of August 19, 1996, by Yifeng Wang, to Distribution. "Evaluation of the Thermal Effect of Exothermal Chemical Reactions for WIPP Performance Assessment: A revised version," Sandia National Laboratories.

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Albuquerque, New Mexico 87185-1341

date: August 19, 1996

to: Distribution

from: Yifeng Wang (Org. 6832)

subject: Evaluation of the Thermal Effect of Exothermal Chemical Reactions for WIPP Performance Assessment: A revised version

Temperature increases caused by exothermal chemical reactions in the repository have been evaluated in the memo by Wang (1996). This memo is the revised version of the previous memo. Two revisions have been made: (1) anoxic steel corrosion reaction is no longer an exothermal reaction; (2) waste panel number is adjusted from eight to ten. All revisions made here do not change the conclusion that the thermal effect of exothermal chemical reactions in the repository is negligible.

Assumptions:

The following exothermal chemical reactions are considered:

$$MgO + H_2O \rightarrow Mg(OH)_2 \quad (1)$$

$$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 \quad (2)$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2 \quad (3)$$

$$Al + 3H_2O \rightarrow Al(OH)_3 + 1.5\ H_2\ . \quad (4)$$

Anoxic steel corrosion is a major chemical reaction expected to occur in the repository:

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2. \quad (5)$$

However, this reaction is considered here, because it is not an exothermal reaction. The enthalpy change of Reaction (5) is estimated to be 0.64 Kcal/mole Fe.

Considering that the vertical dimension of the repository (~ 1 m, B. M. Butcher, personal comm.) will be much less than the horizontal extension after room closure, we assume that the heat released from the reactions will be dissipated away mainly from the ceiling and ground of the repository and the heat loss from the side walls is negligible. We also assume that all reactions will take place uniformly in a reaction region of interest. We here restrict the reaction region in a single waste panel, for the following reason: Some of the above reactions may be limited by brine inflow. BRAGFLO simulations have shown that, in the human intrusion cases, the rate of brine inflow into a borehole-penetrated waste panel will be significantly higher than that into the rest of the repository. Choosing a panel rather than the whole repository as a reaction region will make heat generation rate per unit of volume higher and the heat dissipating surface area smaller in our calculations, and

therefore it is conservative. However, this choice will not affect the calculations for the reactions that are not limited by brine inflow, as you will see below.

Theory:

Based on these assumptions, the thermal effect of an exothermal chemical reaction can be modeled by a simplified system shown in Figure 1. The temperature distribution (T) can be described by the following equations:

$$C_p \rho \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial X^2} \tag{6}$$

$$T(X,0) = T_0 \tag{7}$$

$$R\Delta H = 2Sk \left. \frac{\partial T}{\partial X} \right|_{X=0} \tag{8}$$

$$T(\infty, t) = T_0 \tag{9}$$

where C_p is the heat capacity of surrounding rocks (J/mole/K); ρ is the molar density of surrounding rocks (moles/m^3); t is time (year); X is the spatial coordinate (m); k is the thermal conductivity of surrounding rocks (J/year/m/K); T_0 is the background temperature (K); R is the reaction rate (moles/year); ΔH is the enthalpy change of the reaction (J/mole); S is the horizontal area of a waste panel (m^2).

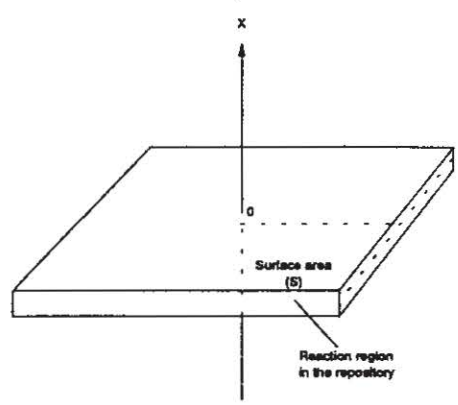

Figure 1. A modeling system for heat production and conduction.

The above equations can be solved for T with a Laplace-transformation method:

$$T - T_0 = -\frac{R\Delta H}{2S\sqrt{C_p\rho k}}\left[2\sqrt{\frac{t}{\pi}}e^{-\frac{C_p\rho X^2}{4Kt}} - \sqrt{\frac{C_p\rho}{k}}X\,erfc\left(\frac{X}{2}\sqrt{\frac{Cp\rho}{kt}}\right)\right]. \tag{10}$$

The temperature increase in the repository (ΔT) is obtained by setting X = 0 in equation (6):

$$\Delta T = T(0,t) - T_0 = -\frac{R\Delta H}{S}\sqrt{\frac{t}{\pi C_p\rho k}}. \tag{11}$$

Equation (7) shows that the repository temperature will increase with t until $t = \frac{M}{R}$, when all the reactant is consumed. Here M is the inventory of the reactant in a waste panel (moles). Therefore, the maximum temperature increase (ΔT_{max}) in the repository due to the exothermal reaction can be calculated by

$$\Delta T_{max} = T(0,t) - T_0 = -\frac{\Delta H}{S}\sqrt{\frac{RM}{\pi C_p\rho k}}. \tag{12}$$

Equation (12) shows that, for the reactions not limited by brine inflow, reducing the reaction region size does not affect ΔT_{max}, because the parameters S, R, and M will be reduced by the same factor, which is canceled out in the equation. This is not true for the brine-limited reactions, the rates of which are no longer dependent on reactant inventory.

Assuming the physical properties of the surrounding rocks can be represented by halite, we then have:

C_p = 50 J/mole/K (Lide, 1994, p. 12-158)

$\rho = 3.7\text{x}10^4$ moles/m^3 (Lide, 1994, p. 4-149)

k = 6 W/m/K = $1.9\text{x}10^8$ J/year/m/K (Lide, 1994, p. 12-165)

S = $1.2\text{x}10^4$ m^2 (Sandia WIPP Project, 1992, p. 3-4).

With these parameter values, we obtain from equation (12):

$$\Delta T_{max} = 2.5x10^{-12} \Delta H \sqrt{RM} \,. \qquad (13)$$

Results:

(1) Reaction: $MgO + H_2O \rightarrow Mg(OH)_2$

We assume that this reaction is instantaneous and thus is limited by brine inflow. Based on BRAGFLO simulations for E1 scenario (Figure 2), the conservative (maximum) estimate of the rate of brine inflow into a borehole penetrated waste panel is about 200 m^3/year, equivalent to the reaction rate of $1.1x10^7$ moles/year. With $\Delta H = -3.9x10^4$ J/mole (Drever, 1982, p. 351-356) and $M = 2x10^8$ moles, we estimate $\Delta T_{max}, \approx 4.5$ K.

(2) Reaction: $Mg(OH)_2 + CO_2(g) = MgCO_3 + H_2O$

We assume that this reaction is limited by microbial CO_2 production. It is estimated that the maximum rate of CO_2 production (R) is $2.9x10^5$ moles/year and the total CO_2 that can be produced (M) is $3.6x10^7$ moles in a single waste panel (Wang & Brush, 1996; DOE/CAO, 1996). With $\Delta H = -0.8x10^5$ J/mole (Drever, 1982, p. 351-256), ΔT_{max}, is estimated to be 0.6 K.

(3) Microbial degradation: $C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2$

The maximum reaction rate and the inventory of $C_6H_{10}O_5$ in a single waste panel are estimated to be $1x10^5$ moles/year and $1.2x10^7$ moles (Wang & Brush, 1996; DOE/CAO, 1996). With $\Delta H = -3.1x10^5$ J/mole (Lide, 1994, p. 5-16 to 5-37), ΔT_{max}, is estimated to be 0.8 K. Because of lack of thermodynamic data for cellulose materials, we here assume that the enthalpy of $C_6H_{10}O_5$ is approximately equal to that of $C_6H_{10}O_4$.

(4) Aluminum corrosion: $Al + 3H_2O \rightarrow Al(OH)_3 + 1.5\ H_2$

The inventory of Al in a single panel is about $8x10^6$ moles (DOE/CAO, 1996). Aluminum are present as foil in the waste and its thickness is estimated to be $2.54x10^{-4}$ cm. The total surface area of Al foil is thus estimated to be ~ $2.6x10^8$ m^2. With this high surface area and the measured corrosion rate (2.9 mole H_2/m^2/year, Telander & Westerman, 1996), Al corrosion reaction is expected to be limited by brine inflow, and the maximum corrosion rate is ~ $0.4x10^7$ moles/year. With $\Delta H = -4.4x10^5$ J/mole (Drever, 1982, p. 351-356), ΔT_{max}, is estimated to be 6 K.

Figure 2. SNL WIPP PA96: BRAGFLO SIMULATIONS (CCA R1 S2)

Cumulative Brine Inflow into Waste Panel

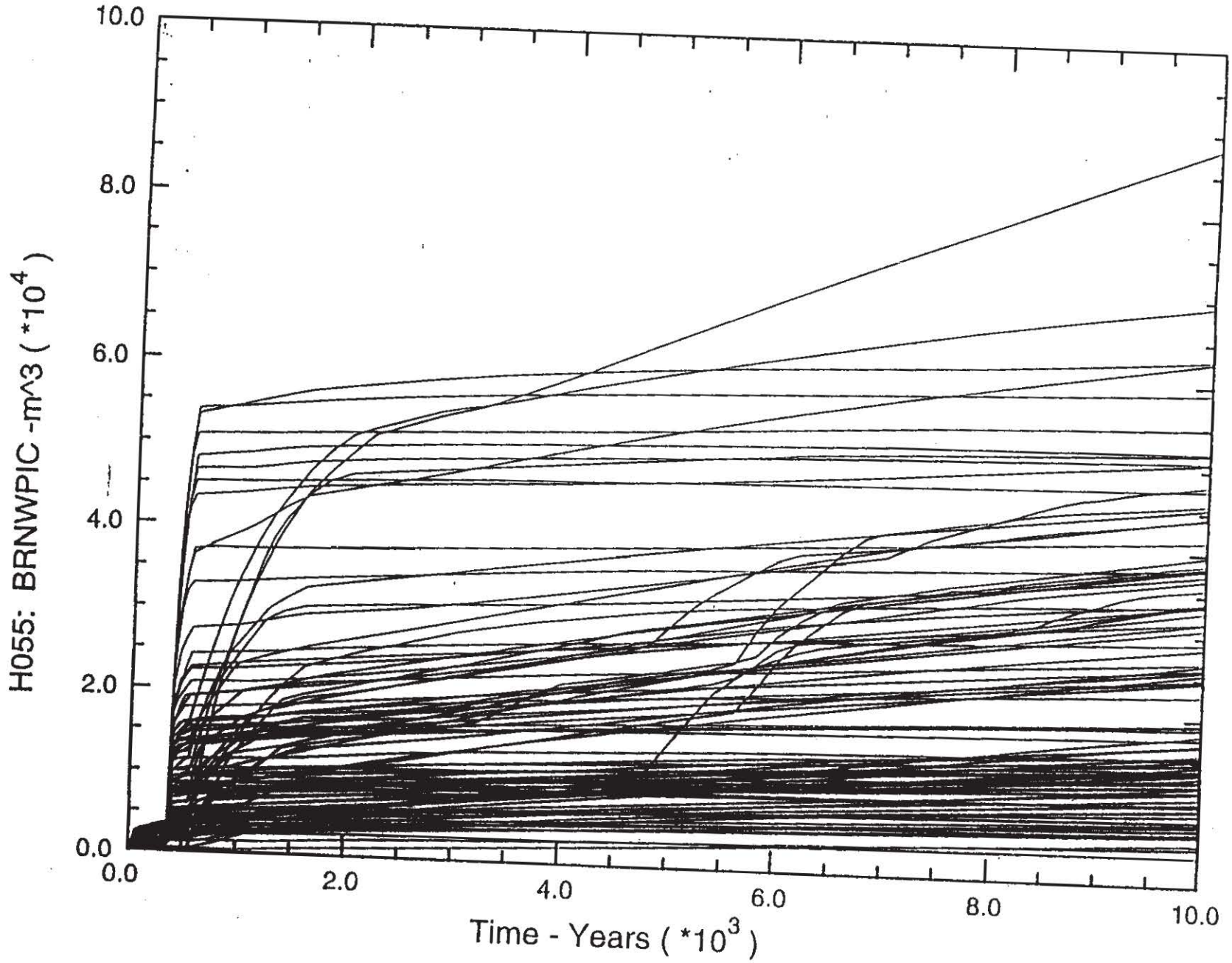

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The two brine-inflow-limited reactions - MgO hydration and Al corrosion - could possibly bring repository temperature up to 6 K. However, this temperature increase will not affect the overall repository performance, for two reasons: (1) The maximum temperature, if it is achieved, will be sustained only over a very short time period. For example, to achieve this temperature, Al has to be corroded completely within 2.5 years. After that, the accumulated heat will be dissipated away quickly. Thus, the maximum temperature, if it is attained, will last perhaps less than a year. (2) More importantly, because the two reactions are brine-limited, they will consume all free brine in the repository until all the reactants are completely consumed. Therefore, the maximum temperature will occur much earlier than enough free brine accumulates in the repository for the release of dissolved actinides. Based on the above calculations, the thermal effect of the other reactions, which are not limited by brine inflow and can last over a significant portion of 10000 year time period, are definitely negligible.

In conclusion, ignoring the thermal effect of chemical reactions (1 - 5) can not affect the overall repository performance assessment.

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SALADO FLOW PEER REVIEW PLAN

1. INTRODUCTION

This Peer Review Plan describes the process and documentation requirements for a peer review of the proposed changes to the Salado flow conceptual models used in the Waste Isolation Pilot Plant (WIPP) performance assessment (PA).

1.1 BACKGROUND

Peer review of conceptual models developed by the Department of Energy (DOE) for the WIPP is required by 40 CFR § 194.27 (EPA, 1996), promulgated by the Environmental Protection Agency (EPA). In accordance with this criterion, the Carlsbad Field Office (CBFO) of the DOE will conduct a peer review of specific conceptual models that are being revised due to changes invoked by the regulator or due to knowledge gained since the original conceptual models were developed. More specifically, a peer review is needed to determine whether revisions to selected Salado flow conceptual models that were developed for the Compliance Certification Application (CCA) (DOE, 1996) reasonably represent future states of the disposal system.

Sandia National Laboratories (SNL) is responsible for the development, maintenance, and conduct of WIPP performance assessments. In the PA for the CCA, SNL determined which processes were significant and developed conceptual models that represent possible future states of the disposal system and subsystems. These conceptual models were approved by the EPA during the original WIPP certification (EPA, 1998). Any proposed changes to the previously approved conceptual models must also be peer reviewed to ensure that future states of the disposal system continue to be adequately represented.

There are 24 conceptual models used in the PA. The proposed changes associated with Salado flow processes are expected to affect the following models:

- Disposal System Geometry
- Repository Fluid Flow
- Disturbed Rock Zone (DRZ)

The requirement for conducting a peer review of conceptual models is specified in 40 CFR § 194.27 (a) (1). The requirements for the peer review process and its documentation are specified in 40 CFR § 194.27(b) and (c). In summary, the peer review process shall be a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. The peer reviewers shall be independent of the work being reviewed;

independence from the work being reviewed means that the peer: a) was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to assure the work is impartially reviewed. Therefore, peer review of the subject matter provides additional assurance to the regulator and the public that the subject matter is reasonable, accurate and valid for its intended use.

1.2 PURPOSE

The purpose of this Plan is to present the plan to perform a peer review of selected Salado flow conceptual models. The process outlined in this plan must result in an independent critical review of the subject matter relevant to the revised conceptual models.

1.3 SCOPE

The Salado Flow Peer Review shall determine if proposed changes to the EPA-approved conceptual models result in revised conceptual models, which reasonably represent possible future states of the disposal system. The peer review shall be performed to meet all the requirements of NUREG-1297 (NRC, 1988), as required by 40 CFR § 194.27(b). The scope of the peer review is limited to assessing the validity of the models that result from these changes.

A peer review is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology and acceptance criteria employed, and of the conclusions drawn in the subject work. This Plan defines the management approach, resources, schedule, and technical requirements for using peer reviews to confirm the adequacy of the revised conceptual models.

2. PEER REVIEW PLANNING AND IMPLEMENTATION

2.1 APPROACH

This Plan documents the approach to conducting the peer review process. The Salado Flow Peer Review will be conducted using a rigorous proceduralized approach in accordance with NUREG-1297 (NRC, 1988). The DOE-CBFO has prepared a procedure, MP 10.5 (DOE, 2001a), for conducting peer reviews in accordance with NUREG-1297. The DOE-CBFO procedure ensures that the peer review will be a documented, critical review performed by qualified peers who are independent of the work being reviewed. Specifically the Salado Flow Peer Review Panel will:

- Follow MP 10.5 requirements. In the event of a conflict between MP 10.5 and NUREG-1297, NUREG-1297 will take precedence over MP 10.5.

- Administer and document the peer review process. Activities include documenting the selection of panel members, assignment of a panel leader, panel member independence documentation and recording and archiving meeting minutes.
- Negotiate schedule for the peer review with the DOE-CBFO Assistant Manager (or designee).
- Conduct and document peer review caucuses.
- Communicate interim peer review findings in hardcopy to the DOE-CBFO Assistant Manager (or designee).
- Produce a formal written report of the peer review findings and conclusions.
- Follow QA requirements for document preparation, control and records archiving.

2.1.1 DESCRIPTION OF CONCEPTUAL MODELS TO BE REVIEWED

Changes have been proposed to three of the conceptual models that represent Salado flow. The conceptual models affected are: Disposal System Geometry, Repository Fluid Flow, and the Disturbed Rock Zone (DRZ). The specific changes to these conceptual models are: 1) change of the shaft model in the BRAGFLO grid, 2) a change to the panel closure dimensions to conform to the Option D panel closure design mandated by the EPA, and 3) changes to the repository layout in the BRAGFLO grid. The changes to the conceptual models are the result of the EPA-mandated choice of the Option D panel closure design and a desire to improve the efficiency of the Salado flow computational model (BRAGFLO). Detailed descriptions of these changes will be provided to the peer review panel through written documentation and oral presentations.

The conceptual models under review were approved by the EPA in their certification of compliance (EPA, 1998). As such, the peer review panel is tasked with reviewing the results of the proposed changes to the conceptual models. The peer review panel shall limit the scope of the review as follows:

Changes within the Scope of the Peer Review

- Reviewing the changes to the conceptual models which include:
  - Removal of the shaft as an explicit region in the BRAGFLO grid
  - Modification of the panel closure representation in the BRAGFLO grid to represent the Option D design mandated by the regulators.
  - Changes to repository layout for the number of panel closures in the BRAGFLO grid and for the flaring of the BRAGFLO grid

These changes are expected to change the conceptual models for Disposal System Geometry, Repository Fluid Flow, and the Disturbed Rock Zone.

Items Outside the Scope of the Peer Review

- Validity of the original conceptual models and conceptual model peer reviews
- Reviewing the codes that implement the conceptual models

2.1.2 COMPOSITION OF PEER REVIEW PANEL

The peer review panel will be composed of a minimum of three individuals who possess the subject matter technical expertise to a degree at least equivalent to that needed for the original work. The panel should include personnel who have demonstrated expertise in geologic disposal systems, rock mechanics, and the numerical modeling of fluid flow.

Each panel member will become familiar with the WIPP containment system and the basis of the conceptual models that describe the containment system by reviewing documents on a required reading list and through a formal orientation process. In addition they will be presented a basic description of how the conceptual models for PA are represented in numerical models, algorithms, and codes. The panel members will become familiar with the parameter inputs to the PA codes and the results of prior PAs, sensitivity analyses, and critical comments from previous reviews. Finally, each panel member will become familiar with the peer review process through formal training in the appropriate peer review procedure(s).

2.1.3 LOGISTICS AND MANAGEMENT

Required reading material necessary to support the Salado Flow Peer Review will be provided to the Peer Review Panel. The first technical meeting will be conducted in early May. It may be necessary to conduct the peer review in a phased manner due to the varied subject matter related to the Salado flow conceptual models. The DOE-CBFO Assistant Manager (or designee) will determine the review sequence based upon the availability of the models, technical staff, panel members, and other logistic factors. Flexibility will be required by all supporting organizations to accommodate potential schedule changes.

2.2 PEER REVIEW PROCESS

The DOE-CBFO Assistant Manager (or designee) is responsible for the peer review. Time Solutions Corp. has been selected as the peer review contractor. Mr. John Thies will serve as the contractor Peer Review Manager pending the approval by the DOE-CBFO Assistant Manager (or designee). This Peer Review Plan is submitted to the DOE-CBFO Assistant Manager (or designee) for approval. This Plan meets the

requirements of MP 10.5. It is understood that MP 10.5 shall supersede any discrepancies between this Plan and MP 10.5.

Mr. Thies will not assign a Peer Review Coordinator (per MP 10.5), but will perform the coordination duties with the help of an administrative assistant since the scope of the Salado Flow Peer Review is not expected to be labor intensive.

Mr. Thies will use a selection committee to select candidates for the peer review panel. Upon verification that the peer review panel members meet the criteria outlined in MP 10.5 Attachment 1, an orientation and training meeting will be scheduled for the peer review panel members. The peer review panel members are expected to complete their review of required reading materials prior to the orientation meeting.

The peer review panel shall perform their review using the evaluation criteria discussed in Section 2.3. Since this peer review is for changes to conceptual models that were peer reviewed previously, many of the adequacy criteria are not applicable because they were determined in the first peer review. It should also be noted that the validity of the results of the previous peer reviews should not be reviewed as part of this peer review. However, the peer review panel is free to comment, as they feel necessary to complete their review.

Throughout the review, the panel is encouraged to engage in clear and frank discussions with the individuals responsible for the work under review. However, the peer review panel must observe all rules for interaction with DOE-CBFO, SNL and stakeholders outlined in MP 10.5. The results of the Panel's review shall be formally documented in a report.

In addition, MP 10.5 states that the DOE-CBFO QA Manager is authorized to conduct independent assessments of the peer review process to ensure that all aspects of the peer review conform to the guidance of NUREG-1297, MP 10.5, and the latest version of the DOE-CBFO Quality Assurance Program Description (DOE, 1999). The DOE-CBFO QA Manager shall inform the Contractor Peer Review Manager (Mr. Thies) of any EPA requests for audits or assessments. The Contractor Peer Review Manager must comply with and resolve all issues arising from such audits or assessments.

2.3 ADEQUACY CRITERIA

Conceptual models that have been selected and developed by the DOE must meet commonly accepted technical and scientific standards based on an in-depth evaluation. The peer review panel shall use the evaluation criteria in NUREG-1297 as the basis for their review. The evaluation criteria in NUREG-1297 are as follows:

- Validity of assumptions;
- Alternate interpretations;
- Uncertainty of results and consequences if wrong;
- Appropriateness and limitations of methodology and procedures;

- Adequacy of application;
- Accuracy of calculations;
  Validity of conclusions; and
  Adequacy of requirements and criteria.

Additional criteria may be defined by the Panel. For example, the first review panel for conceptual models added a criterion for Information Used to Develop the Conceptual Model. Adequacy of the revised conceptual models will be determined based on whether or not they reasonably represent possible future states of the disposal system.

2.4 SCHEDULE

Attachment A presents a preliminary schedule of peer review activities for the process described in Section 2.1.3. This schedule will serve as the baseline schedule from which requested schedule deviations will be evaluated by Mr. Thies if appropriate. Revisions to the baseline schedule will not require revision to this Plan, but must be approved by the DOE-CBFO Assistant Manager (or designee).

2.5 DELIVERABLES

The Contractor Peer Review Manager shall provide weekly status reports addressing peer review progress against the schedule to the DOE-CBFO Assistant Manager (or designee). The DOE-CBFO Assistant Manager (or designee) shall negotiate all deliverables with the Contractor Peer Review Manager such that timely information is delivered to the panel. A final peer review report is scheduled to be delivered to the DOE-CBFO Peer Review Manager by March 9, 2003.

2.5.1 Peer Review Report

The peer review report shall, as a minimum:

- Be signed by each peer review panel member
- Describe the work or issues that were reviewed
- Describe the conclusions reached by the peer review panel (e.g., the peer review panel observation comments and overall conclusions).
- Provide additional statements by the peer review panel members reflecting dissenting views or additional comments as appropriate
- List the peer review panel members and provide acceptability information (i.e technical qualifications and independence) for each member.

3. QUALITY ASSURANCE

The peer review process will be conducted and documented in a controlled manner and in compliance with the DOE-CBFO Quality Assurance Program Description, CAO-94-1012 and other applicable QA procedures. The DOE-CBFO QA Manager may appoint a QA observer to attend the peer review orientation, the peer review training, and peer review meetings. The DOE-CBFO QA Manager may schedule an assessment or audit of the contractor's peer review process and records prior to completion of the review. Upon communication with EPA, the DOE-CBFO QA Manager may schedule any audits or assessments the EPA wishes to perform.

4. RECORDS MANAGEMENT

Records generated as a result of peer review activities defined in this peer review plan and designated as QA records shall be maintained in accordance with DOE-CBFO Management Procedures MP 4.5, Generating, Receiving, Storing, and Controlling Active DOE-CBFO Project Records (DOE, 2001b), and MP 4.9, Quality Assurance Records (DOE, 2001c). Records include items generated by the DOE-CBFO, the peer review Contractor, and SNL and include:

- Salado Flow Peer Review Plan (this document)
- Peer Review Procedure(s)
- Contract documents
- Peer Review Panel Member Verification of Education/Employment Forms
- Determination of Peer Review Panel Member Independence Forms
- Peer Review Panel Selection Justification/Decision Forms
- Peer Review Panel Member Orientation and Training Forms
- Meeting minutes and presentation materials
- Written Materials presented to the Peer Review Panel by DOE-CBFO or investigators
- Written information presented to the Peer Review Panel Members by Observers
- Peer Review Report(s)

QA records shall be maintained by the Contractor Peer Review Manager until completion of the contract with the peer review organization. Duplicate records shall be generated and maintained at separate facilities. Upon completion of the peer review process, the original copy of the QA records (where possible) shall be formally

transferred and delivered to the DOE-CBFO Assistant Manager (or designee) for retention.

5. DOCUMENT CONTROL

All plans, procedures, and other documents that require document control will be processed in accordance with applicable DOE-CBFO controlled document procedures.

6.0 REFERENCES

DOE (U.S. Department of Energy), 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO 1996-2184, October 1996.

DOE (U.S. Department of Energy) 1999. Quality Assurance Program Description (QAPD), DOE-CBFO-94-1012, Revision 4, November 2002.

DOE (U.S. Department of Energy), 2001a. Peer Review, DOE-CBFO Management Procedure MP 10.5, Revision 5, February 1, 2003.

DOE (U.S. Department of Energy), 2001b. Quality Assurance Records, DOE-CBFO Management Procedure MP 4.5. February 16, 2001.

DOE (U.S. Department of Energy), 2001c. Quality Assurance Records, DOE-CBFO Management Procedure MP 4.9, Revision 1, March 4, 2001.

DOE (U.S. Department of Energy), 2001d. Document Preparation and Control, DOE-CBFO Management Procedure MP 4.4, Revision 4, January 5, 2001.

DOE (U.S. Department of Energy), 2001e. Document Review, DOE-CBFO Management Procedure MP 4.2, Interim Change Notice (ICN) #1, June 11, 2002.

EPA (U.S. Environmental Protection Agency). 1996. 40 CFR Part 194: Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations Final Rule. Federal Register, Vol. 61, No. 28, pp.5224-5245, February 9, 1996.

EPA (U.S. Environmental Protection Agency). 1998. 40 CFR Part 194: Criteria for the Certification and Re-certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations: Certification Decision; Final Rule. Federal Register, Vol. 63, No. 95, pp. 27353-27406, May 18, 1998.

NRC (U.S. Nuclear Regulatory Commission), 1988. Peer Review for High-level Nuclear Waste Repositories, General Technical Position, NUREG-1297, February 1988.

Prepared by: John A. Thice

Print name and sign

Approved by: Daryl Mercer

Print name and sign

ATTACHMENT A

SALADO FLOW CONCEPTUAL MODEL PEER REVIEW SCHEDULE

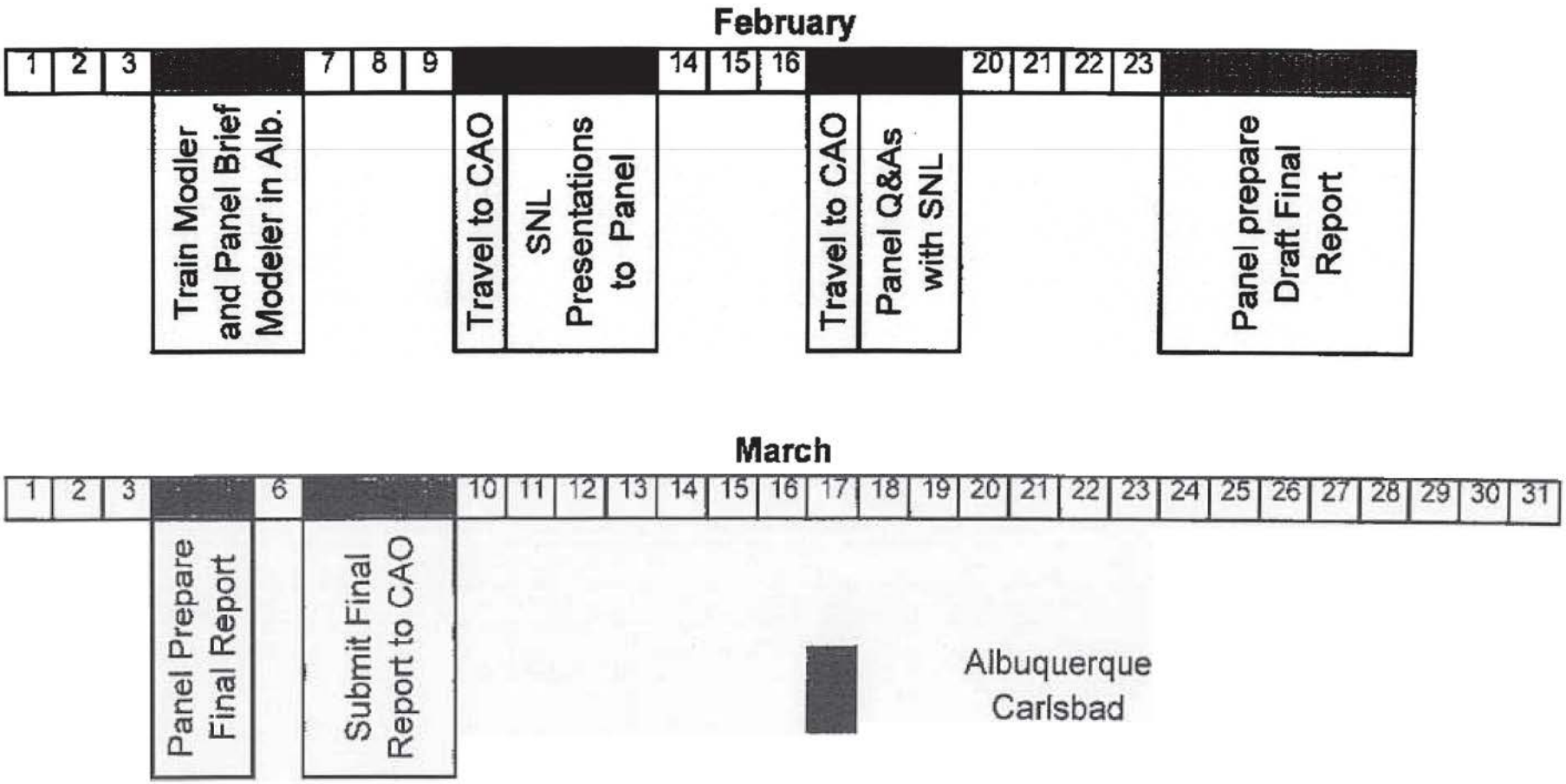

3.2.4 The Post-Penetration Wellbore Flow

In the current SNL model, it is assumed that the gas and spalled waste particles are mixed with drilling mud in the bit cavity forming a slurry; and the slurry is carried up through the wellbore to the surface by the circulating drilling mud. The motion of slurry, which contains mud, gas, salt, and waste particles, in the wellbore is governed by a compressible mixed Navier-Stokes equation. The equations are:

Mass balance equation,

$$\frac{\partial}{\partial t}(\rho V) + \frac{\partial}{\partial z}(\rho V u) = S_{mass},$$

Momentum balance equation,

$$\frac{\partial}{\partial t}(\rho V u) + \frac{\partial}{\partial z}(\rho V u^2) = -V(\frac{\partial p}{\partial z} - \rho g + F) + S_{mom},$$

The equation of state of constituents is:

For the mud, $\rho_m = \rho_{0(m)}[1 + c_m(p - p_0)]$,

For the gas, $\rho_g = \rho_{0(g)} \frac{p}{p_o}$,

and, For the salt and waste particles, $V_{s,w} = \frac{m_{s,w}}{\rho_{0(s,w)}}$.

In the above equations, u is the velocity of flow, ρ is the density of slurry, and V is the volume of slurry, i.e.,

$$V = V_{salt} + V_{waste} + V_{mud} + V_{gas}.$$

The effects of pipe friction, type of flow (laminar or turbulent), and slurry viscosity on the flow property are also taken into consideration in the calculation.

The ideal gas law is used in the formulation, the cavity is assumed to grow with drilling, and there is no momentum transfer between the gas and the mud during mixing. These assumptions are certainly reasonable.

The mass-transport formulation above addresses both the down-going and up-going mud columns in a continuous fashion. Implementation can be likened to a conveyor belt where the

first half of the belt is the down-going column and the second half is the up-going. At post-penetration, gas will be released from the repository and enter the mud-column. If spalling occurs, waste material will also enter the stream. It is important to note here that both the down-going and up-going mud columns are subject to the same boundary conditions within the cavity after post-penetration. This is the correct way to do it.

The model is sufficiently robust to adequately address the ballistic model of waste release as an extreme case. Should the repository gas pressure be sufficiently high, it is conceivable that the down-going flow could be choked off at the bit. Under this condition, there would be no mud supply to mix with the gas and waste entering the stream from the cavity. The up-going mud column would be supported only by a gas-waste column. This condition is sometimes referred to as a blow-out condition in oil field drilling.

The panel's opinion is that the above formulation is indeed proper for describing the release of spalled particles from the repository by the circulating mud during drilling. It is sufficiently robust to address all realistic scenarios.

Signature Page

for

Spallings Conceptual Model Peer Review Report

Revised

Section 3.2.4, The Post-Penetration Wellbore Flow

February 20, 2004

I acknowledge by my signature below that I concur with the attached revised Spallings Conceptual Model Peer Review Report Section 3.2.4, Post-Penetration Wellbore Flow.

Ching Yew 02/21/04

Ching Yew, Ph.D., Chairman Date

Jonathan Hanson, Ph.D. Date

Lawrence Teufel, Ph.D. Date

Signature Page
for
Spallings Conceptual Model Peer Review Report
Revised
Section 3.2.4, The Post-Penetration Wellbore Flow

February 20, 2004

I acknowledge by my signature below that I concur with the attached revised Spallings Conceptual Model Peer Review Report Section 3.2.4, Post-Penetration Wellbore Flow.

Ching Yew, Ph.D., Chairman — Date

Jonathan Hanson, Ph.D. — Date

Lawrence W. Teufel

Lawrence Teufel, Ph.D. — 02/23/04 Date

Signature Page
for
Spallings Conceptual Model Peer Review Report
Revised
Section 3.2.4, The Post-Penetration Wellbore Flow

February 20, 2004

I acknowledge by my signature below that I concur with the attached revised Spallings Conceptual Model Peer Review Report Section 3.2.4, Post-Penetration Wellbore Flow.

Ching Yew, Ph.D., Chairman — Date

Jonathan Hanson, Ph.D. — 2/23/04 Date

Lawrence Teufel, Ph.D. — Date

PEER 1 - Conceptual Models Peer Review

Title: CONCEPTUAL MODELS PEER REVIEW PLAN

(Assistant Manager, Office of Regulatory Compliance, Carlsbad Area Office) Date: 3/28/96

1. INTRODUCTION

This Conceptual Model Peer Review (CMPR) Plan describes the peer review and documentation the WIPP Project will use to ensure that the conceptual models used in performance assessment (PA) reasonably represent possible future states of the disposal system.

1.1 BACKGROUND

In accordance with the regulatory requirements, as specified in 40 CFR Part 191, and the criteria for the implementation of those requirements, as specified in 40 CFR Part 194, the Department of Energy (DOE) will conduct a peer review (PR) of the conceptual models used in the compliance certification application for the WIPP Project. Specifically, a PR will be conducted to determine whether the conceptual models developed and selected by DOE reasonably represent future states of the disposal system. Sandia National Laboratories (SNL) is responsible for the WIPP PA. SNL has determined which processes are significant and have developed conceptual models which represent possible future states of the disposal system and subsystems. To facilitate review of the conceptual models, they have been divided into the following three associated subsystems:

- Natural barriers (Salado and non-Salado flow and transport);
- Engineered barriers (rock mechanics and shaft/borehole seals); and
- Waste form and the disposal room.

SNL has developed a description of the conceptual models, the associated parameters, and parameter values, and is developing and implementing a process for the selection and assembly of data and other information which will be utilized to support PR of the conceptual models.

1.2 PURPOSE

The purpose of the WIPP PR process for conceptual models is to ensure that the conceptual models used in PA reasonably represent possible future states of the disposal system.

The requirement for conducting peer reviews is specified in sections 27 (a)(1) and 22 (b) of 40 CFR Part 194. Specifically, a PR is a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. The PR shall be independent of the work being reviewed; independence from the work being reviewed means that the peer: a) was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to assure the work is impartially reviewed.

1.3 SCOPE

This CMPR Plan describes the peer review process that the DOE Carlsbad Area Office (CAO) will use for review of conceptual models. A PR is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of the conclusions drawn in the original work. This Plan defines the management approach, resources, schedule, and technical requirements for using peer reviews to confirm the adequacy of the conceptual models.

2. PEER REVIEW PLANNING AND IMPLEMENTATION

2.1 APPROACH

The DOE-CAO has prepared this Conceptual Model Peer Review (CMPR) Plan to document the approach to conducting the PR process. The CMPR will be conducted using a rigorous proceduralized approach in accordance with NUREG-1297. The DOE-CAO has prepared a procedure for conducting peer reviews in accordance with sections 27 (a)(1) and 22 (b) of 40 CFR Part 194. The DOE-CAO procedure ensures that each PR will be a documented, critical review performed by qualified peers who are independent of the work being reviewed. SNL has prepared a procedure to provide the information necessary to support peer review of the conceptual models.

2.1.1 DESCRIPTION OF CONCEPTUAL MODELS TO BE REVIEWED

Section 23(a)(3)(v) of 40 CFR Part 194 requires that any compliance certification application shall include documentation that the conceptual models have undergone PR according to 40 CFR Part 194 section 27. SNL will provide a description of the conceptual models and other supporting information to the PR Manager for peer review. The following listed conceptual models have been identified to be reviewed:

CONTAINMENT SUB-SYSTEM	CONCEPTUAL MODELS
Natural Barriers (Flow & Transport)	Disposal System Geometry Culebra Repository Fluid Flow Salado Impure Halite Salado Interbeds Disturbed Rock Zone Actinide Transport (Salado) Units Above the Salado Dissolved Actinides (Culebra) Colloidal Actinides (Culebra) Exploration Boreholes Cutting/Cavings Spallings Blowout Castile & Brine Reservoir Multiple Intrusions Climate Change
Engineered Systems (Shaft Seals & Rock Mechanics)	Disposal Room Geometry Creep Closure Repository Fluid Flow Shafts & Shaft Seals Disturbed Rock Zone
Waste Form & Disposal Room (Disposal Room Closure & Chemistry)	Gas Generation Chemical Conditions Dissolved Actinide Source Term Colloidal Actinides Source Term

2.1.2 COMPOSITION OF PEER REVIEW PANEL

The CMPR Panel will be composed of a minimum of three individuals who possess the subject matter technical expertise to a degree at least equivalent to that needed for the original work. It is currently planned to have panel members who are experts in Natural Barrier System (flow and transport), Engineered Barriers (shaft seals and rock mechanics) and Waste Form and Disposal Room Chemistry.

Through a formal orientation process, each panel member will be made familiar with the WIPP containment system and the basis of the conceptual models which describe the containment system. In addition they will be provided a basic description of how

the conceptual models are represented in numerical models, algorithms, and codes. The peer reviewers will be made familiar with the parameter inputs to the PA codes and the results of prior PAs, sensitivity analyses, and critical comments from previous reviews. Each peer reviewer will be selected, oriented, and trained in accordance with approved procedures.

2.1.3 LOGISTICS AND MANAGEMENT

Not all information necessary to support peer review of conceptual models is currently available. Therefore, it is necessary to conduct the CMPR in a phased manner. The phasing dependens on information availability. The PR Manager, working closely with SNL, has developed a preliminary schedule that provides the necessary information on an "as available" basis. Flexibility is required by all supporting organizations (i.e., DOE-CAO, SNL, and the PR manager, staff and panel members) to accommodate schedule changes due to uncertainty in the timing of information availability.

2.2 SUGGESTED METHODS

The method to be used by the CMPR Panel for the adequacy and reasonableness of the conceptual models will be developed based on SNL requirements for the process of conducting PR. The methods the PR Panel uses to evaluate the subject matter shall include, as applicable, the adequacy criteria identified in section 2.3 below.

2.3 ADEQUACY CRITERIA

Conceptual models which have been selected and developed by the DOE must meet commonly accepted technical and scientific standards based on in-depth evaluation. The peer review panel will evaluate and report on, as applicable:

- Adequacy of requirements and criteria;
- Validity of assumptions;
- Alternate interpretations as appropriate;
- Uncertainty of results and consequences if wrong;
- Appropriateness and limitations of methodology and procedures;
- Adequacy of application;
- Accuracy of calculations; and
- Validity of conclusions.

Adequacy of the conceptual models will be determined based on whether or not they reasonably represent possible future states of the disposal system.

2.4 SCHEDULE

Based on the concept described in section 2.1.3, Attachment A presents a schedule of CMPR activities and milestones. This schedule will serve as the baseline schedule from which requested schedule deviations will be evaluated and approved if appropriate. Revisions to the baseline schedule will not require revision to this Plan, but will be attached to the plan by reference.

2.5 DELIVERABLES

Monthly status reports addressing CMPR progress against schedule and expenditures against budget will be submitted by the CTAC Project Manager and will be incorporated in the CTAC monthly report to the DOE-CAO. Significant variances in progress or spend rates will be explained and will include the cause of the variance, impact to the overall CMPR schedule and recommended corrective actions. A draft and final report of this PR will be submitted to DOE-CAO.

2.6 RESOURCE REQUIREMENTS

To meet the CMPR schedule as outlined in section 2.4 an estimate of the resources which may be required and the allowed manpower support levels are specified in Attachment C.

3. QUALITY ASSURANCE

The CMPR process will be conducted in a controlled manner and in compliance with the CAO Quality Assurance Program Description, CAO-94-1012, and other applicable QA procedures.

4. RECORDS MANAGEMENT

Records generated as a result of PR activities defined in this peer review plan and designated as QA records will be identified in the PR Procedure. Conceptual Models PR records will be assembled and maintained in accordance with the PR Management Procedure and the PR Desk Instruction(s). Ultimately, PR records will be dispositioned in accordance with DOE-CAO records management requirements. SNL records will be managed in accordance with SNL Records Management Procedure, SNL QAP 17-1.

5. DOCUMENT CONTROL

All plans, procedures, and other Documents which require document control will be handled in accordance with applicable DOE-CAO controlled document procedures.

ATTACHMENT A

CONCEPTUAL MODEL PEER REVIEW (CMPR) SCHEDULE

ACTIVITY	DRAFT	FINAL
CMPR Plan	3/8	3/29
PR Panel Assigned	NA	3/29
Information Package to PR Manager	3/15	4/2
Initiate CMPR	NA	4/2
Complete CMPR	NA	6/28
Submit CMPR Report	6/21	7/1

ATTACHMENT B

ESTIMATED PEER REVIEW RESOURCE REQUIREMENTS

Support	Hours
Subject matter experts	1800
Technical Coordinator	300
Clerical Support	300

CONCEPTUAL MODELS

PEER REVIEW REPORT

Final

Waste Isolation Pilot Plant

Conceptual Models Peer Review Report

A Peer Review Conducted By

Charles Wilson
Darrell Porter
John Gibbons
Eric Oswald
Glen Sjoblom
Florie Caporuscio

for

U.S. Department of Energy
Carlsbad Area Office
Office of Regulatory Compliance

July 1996

FOREWORD

The U.S. Environmental Protection Agency promulgated "Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations Final Rule" in Code of Federal Regulations, Title 40, Part 194 (40 CFR Part 194) on February 9, 1996. The 40 CFR Part 194 regulation prescribes three specific peer reviews and also provides the opportunity for the Department of Energy to use peer reviews, conducted in accordance with NUREG 1297, as a means of qualifying data and information for use in the demonstration of compliance.

This report contains the results of a peer review of specific conceptual models to be used in the demonstration of WIPP compliance with 40 CFR Part 194. To ensure the independence of this review, the Department of Energy has directed the assignment of an independent contractor to administratively manage the peer review panel activities. Peer reviewers were selected based on their demonstrated independence from the work being reviewed and their technical expertise in the subject matter to be reviewed. The peer review panel members collectively possess an appropriate spectrum of knowledge and experience in the subject matter reviewed.

This peer review was conducted in full compliance with the quality assurance requirements as defined in 40 CFR Part 194.

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ACRONYMS

WIPP	Waste Isolation Pilot Plant
DOE	U.S. Department of Energy
SNL	Sandia National Laboratories
WID	Waste Isolation Division (Westinghouse)
EPA	U.S. Environmental Protection Agency
EEG	Environmental Evaluation Group
CCA	Compliance Certification Application
CFR	Code of Federal Regulations
TRU	transuranic (waste)
LWA	Land Withdrawal Act
CAO	Carlsbad Area Office
CTAC	Carlsbad Technical Assistance Contractor
ET	evapotranspiration
FEP	features, events, and processes
DRZ	disturbed rock zone
MB	marker bed
MDCF	multimechanism deformation coupled fracture
RM	reduced modules
FMT	fracture-matrix-transport
SIT	specific ion interaction

EXECUTIVE SUMMARY

This report presents the results of an independent technical peer review of the adequacy of 24 conceptual models representing features, processes, and events involved in assessing the long-term performance of the Waste Isolation Pilot Plant (WIPP). These models were identified by the U.S. Department of Energy (DOE) through its scientific advisor, Sandia National Laboratories (SNL). WIPP has been developed at a site near Carlsbad, New Mexico, by the DOE to become the nation's repository for geologic isolation of transuranic radioactive waste resulting from nuclear weapons programs. Westinghouse Electric Corporation, Waste Isolation Division (WID) is the operations contractor for the WIPP. SNL and WID have provided most of the information used in this review. This independent peer review is required by 40 Code of Federal Regulations (CFR) 194.27 as part of the compliance application prepared by the DOE. The U.S. Environmental Protection Agency (EPA) will use the peer review documentation to help ensure that an adequate scientific foundation exists for a national decision on whether to dispose of this waste at WIPP.

The independent review was conducted by a six-member interdisciplinary Review Panel (Panel) having the requisite broad experience and expertise to address the range of issues associated with the ability of WIPP to successfully isolate waste for the 10,000-year regulatory time frame. The peer review was conducted at SNL in Albuquerque, New Mexico, from April through June 1996. The Panel was given access to conceptual model descriptions, scientific reports, briefings, and SNL scientists, and to the SNL Nuclear Waste Management Program Library. During meetings of the Panel, representatives of the EPA, DOE, and New Mexico Environmental Evaluation Group (EEG) observed the Panel's deliberations. The Panel also had access to reports of prior peer reviews and had the full cooperation of the DOE, SNL, and WID throughout the review.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical processes, or intrusion scenarios, are to be represented in performance assessment. To be used in performance assessment, the conceptual model must be successfully translated into analytical statements and mathematical analogs. The Panel reviewed in detail the 24 conceptual models against criteria of the EPA, including the scientific information used to develop the model, the assumptions, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The Panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall performance assessment model. The review process and review criteria are discussed in Section 2.

The Panel has applied the stringent assessment criteria provided in NUREG 1297 and has concluded that thirteen of the models are adequate for implementation. The remaining eleven models were not found to be adequate for use in performance assessment of the WIPP. Models were judged to be inadequate if they failed to convince the Panel of their adequacy in terms of nine criteria. These criteria addressed: adequacy of information; validity of assumptions; alternatives evaluated; uncertainties; adequacy of the model and its application, accuracy, results, and conclusions; and whether the model was ready for implementation in the performance assessment process. Following is a list of the 24 models and a statement of the Panel's conclusion.

Disposal System Geometry	Adequate
Culebra Hydrogeology	Not Adequate (no consequence)*
Repository Fluid Flow	Not Adequate
Salado	Adequate
Impure Halite	Adequate
Salado Interbeds	Not Adequate
Disturbed Rock Zone	Adequate
Actinide Transport in the Salado	Adequate
Units Above the Salado	Not Adequate (no consequence)*
Transport of Dissolved Actinides in the Culebra	Adequate
Transport of Colloidal Actinides in the Culebra	Not Adequate
Exploration Boreholes	Not Adequate
Cuttings/Cavings	Adequate
Spallings	Not Adequate
Direct Brine Release	Not Adequate
Castile and Brine Reservoir	Not Adequate
Multiple Intrusions	Adequate
Climate Change	Adequate
Creep Closure	Adequate
Shafts and Shaft Seals	Adequate
Gas Generation	Not Adequate
Chemical Conditions	Not Adequate
Dissolved Actinide Source Term	Adequate
Colloidal Actinide Source Term	Adequate

*Although the conceptual model was found to be inadequate, no consequence to performance assessment is anticipated.

Several of the issues raised by the Panel could have significant effects on performance assessment. The details of evaluations and issues raised for each model are contained in Section 3 of this report. The relationships among the models are described in Section 4, and a summary of the evaluations is contained in Section 5.

The Panel believes that careful resolution of the issues discussed in Section 3, and any resulting changes to the models, will help to improve the overall quality of the performance assessment and provide a firmer basis for a national decision on whether to emplace waste at WIPP.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Conceptual Models Peer Review is one of several peer reviews being conducted by the U.S. Department of Energy (DOE). The Conceptual Models Peer Review focused on the conceptual models developed and selected by DOE through its scientific advisor, Sandia National Laboratories (SNL), to determine if they adequately and reasonably represent future states of the WIPP disposal system for use in performance assessment. This review was conducted in support of and meets the regulatory requirements of 40 Code of Federal Regulations (CFR) 191 and the implementation of those requirements by 40 CFR 194. In these regulations, this peer review of conceptual models is specifically identified by the U.S. Environmental Protection Agency (EPA) as an activity required to supplement the DOE's Compliance Certification Application (CCA) for the WIPP.

According to 40 CFR 194.27, the peer review is to be conducted in accordance with the Nuclear Regulatory Commission's document NUREG 1297, stipulating requirements for conducting peer reviews. The adequacy criteria set forth in NUREG 1297 were used by the Review Panel (Panel) as a baseline for reviewing DOE's conceptual models. To implement 40 CFR 194, DOE-Carlsbad Area Office (CAO) developed Team Procedure TP-10.5, which stipulates that a peer review is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn in the original work.

This report documents the results of the Conceptual Models Peer Review, as determined in accordance with the aforementioned requirements. Section 2 of this report presents background information relating to the WIPP facility and review methodology. This includes a description of the repository, its geologic and hydrogeologic settings, the scenarios used, review methodology, and evaluation criteria. Section 3 presents the evaluation of each of the 24 models as assessed against a predetermined list of nine evaluation criteria. Section 4 discusses the integration of the 24 models into an overall conceptual model for the waste disposal system. Section 5 provides a summary of the evaluations. These sections are followed by appendices which include administrative information and professional biographies for each of the Panel members.

2.0 BACKGROUND

The DOE was authorized in 1979 (by Public Law 96-164) and funded by the Congress to develop a facility for demonstrating the safe disposal of transuranic (TRU) radioactive wastes generated in national defense activities. The Land Withdrawal Act (LWA) of 1992 (Public Law 102-579) provided additional authorization to continue the project under a stipulated statutory process. This facility, the WIPP, is located in southeastern New Mexico. The WIPP is operationally ready to receive waste and is being proposed by DOE for EPA approval as an operating radioactive waste disposal facility through the CCA process. The purpose of the (Compliance Certification Application (CCA) is to demonstrate through performance assessments the ability of the WIPP to successfully isolate radioactive waste from the accessible environment for the 10,000-year regulatory time frame. If regulatory compliance is demonstrated and a decision to start disposal of waste at the WIPP is made, following the provisions of the LWA, the WIPP will be used for the permanent disposal of TRU wastes, including TRU wastes containing hazardous constituents (TRU mixed waste).

2.1. WIPP Overview

The WIPP facility has been constructed in southeastern New Mexico (Figure 2-1), 26 miles east of Carlsbad, on Federal land. Prior to October 1992, this land was administered by the U.S. Department of the Interior, Bureau of Land Management. In October 1992, Congress transferred jurisdiction of the land through the LWA to the Secretary of Energy. The site encompasses 10,240 acres in a sparsely populated area, with fewer than 30 people living within 10 miles of the WIPP. The immediate surrounding land is used for livestock grazing, potash mining, and oil and gas production.

Surface structures, the planned and partially developed underground repository, and four connecting shafts make up the WIPP facility. The purpose of the surface structures is to provide security and safeguards and to accommodate routine operations, administrative activities, and further scientific studies.

The underground excavation is 655 meters (2150 feet) below the surface in the bedded salt of the Salado Formation. It includes a 12-acre area used for conducting scientific investigations and experiments in which no waste will be placed, an operations area with equipment and maintenance facilities, an area in which the waste will be emplaced for permanent disposal if the disposal site approval decision is made, and four major interconnecting tunnels used for ventilation and traffic. The subsurface waste-disposal area is to cover 100 acres and will contain eight separately excavated panels, each containing

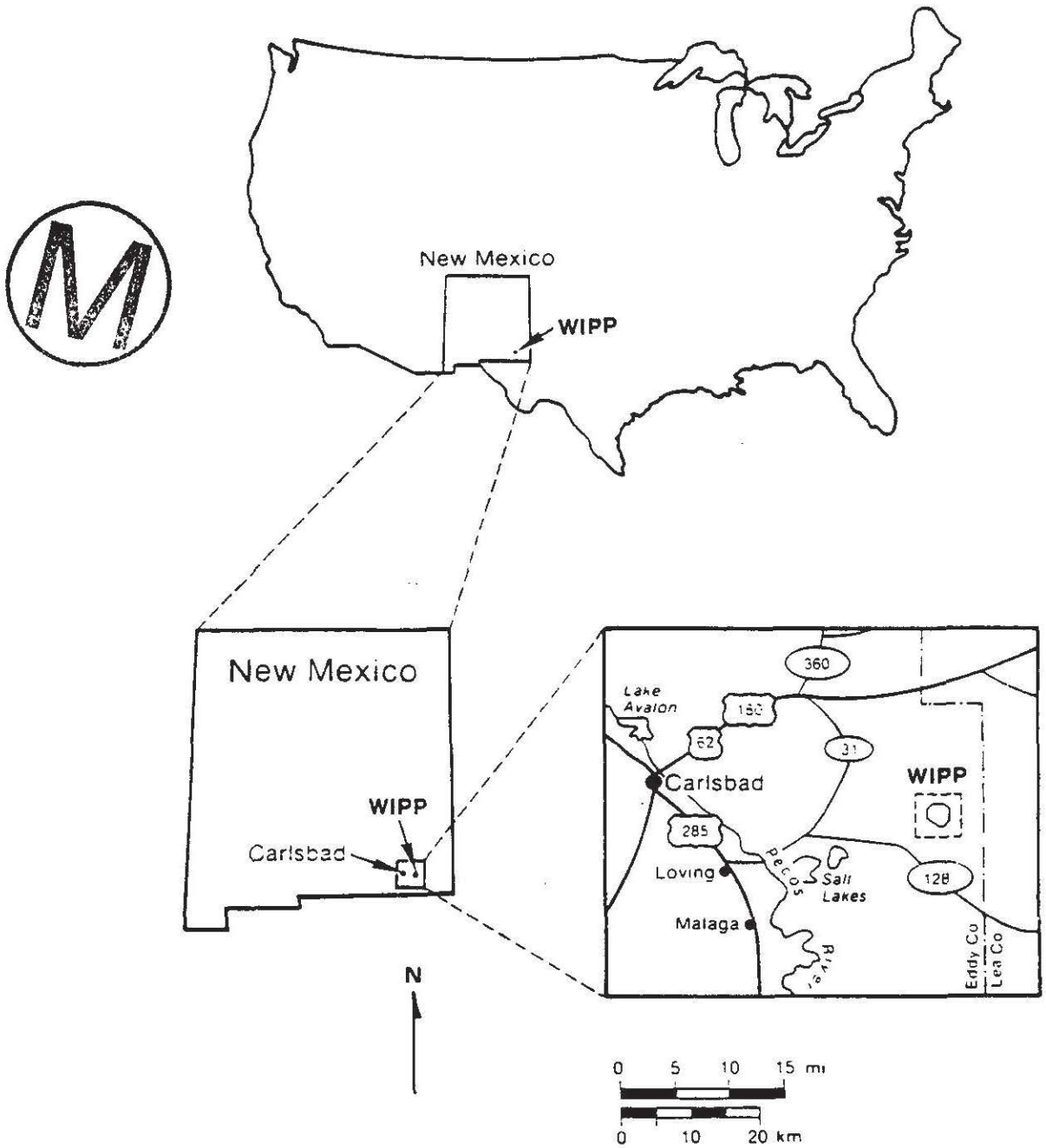

Figure 2-1. WIPP Facility Location

seven disposal rooms, and two additional panels in the area currently containing the drifts accessing the waste disposal area.

2.2. Peer Review Management

The Conceptual Models Peer Review was an independent review supported by the Office of Regulatory Compliance, DOE-CAO and delegated to its technical assistance contractor, known as the Carlsbad Technical Assistance Contractor (CTAC). CTAC commissioned Informatics Corporation, an independent firm, with the task of managing the peer reviews. The Conceptual Models Peer Review is the first of six peer reviews conducted between April 1 and August 15, 1996. The other peer reviews include: Engineered Systems Data Qualification Peer Review; Natural Barriers Data Qualification Peer Review; Waste Form and Disposal Room Data Qualification Peer Review; Passive Institutional Controls Peer Review; and Waste Characterization and Sensitivity Analyses Peer Review. Similar reviews are being conducted on engineered barrier evaluations by the WIPP operations contractor.

Each peer review was administered separately, with its own administrative coordinator and administrative assistant. Early in the review, a technical panel leader was selected from among the peer review members to serve as the focal point for the technical aspects of the review, analysis, and development of a report. The six panels shared access to an administrative document-gathering, recordkeeping, and document processing center comprised of several support staff.

The selection of panel members, training of coordinators and reviewers, and operation of the review process were governed by DOE-CAO's Team Procedure TP-10.5, the Conceptual Model Peer Review Plan, and Informatics' Desk Instruction IDI-1.0. Detailed information regarding the review process is further delineated in these documents and in the records of the Panel's review, both found in the SNL Records Center.

The Panel was requested to review the adequacy of the following 24 conceptual models that are being used by the DOE in assessing the future states of the geologic repository system.

1. Disposal System Geometry
2. Culebra Hydrogeology
3. Repository Fluid Flow
4. Salado
5. Impure Halite

6. Salado Interbeds
7. Disturbed Rock Zone
8. Actinide Transport in the Salado
9. Units Above the Salado
10. Transport of Dissolved Actinides in the Culebra
11. Transport Colloidal Actinides in the Culebra
12. Exploration Boreholes
13. Cuttings/Cavings
14. Spallings
15. Direct Brine Release
16. Castile and Brine Reservoir
17. Multiple Intrusions
18. Climate Change
19. Creep Closure
20. Shafts and Shaft Seals
21. Gas Generation
22. Chemical Conditions
23. Dissolved Actinide Source Term
24. The WIPP Colloidal Actinide Source Term

2.3. System Overview

The WIPP disposal system includes the underground repository and shaft system, the geologic host rocks, and the local and regional hydrologic system. Figure 2-2 shows the WIPP controlled area, the accessible environment, and the disposal unit boundary.

2.3.1. Repository

The WIPP surface facilities, shafts, and underground workings are shown in Figure 2-3. The WIPP repository includes four shafts (exhaust shaft, waste shaft, salt handling shaft, and air intake shaft), an experimental area, an operations area, and a waste disposal area.

Present plans call for mining eight panels of seven rooms each and two equivalent panels in the central drifts. As each panel is filled with waste, the next panel will be mined. Before the repository is closed

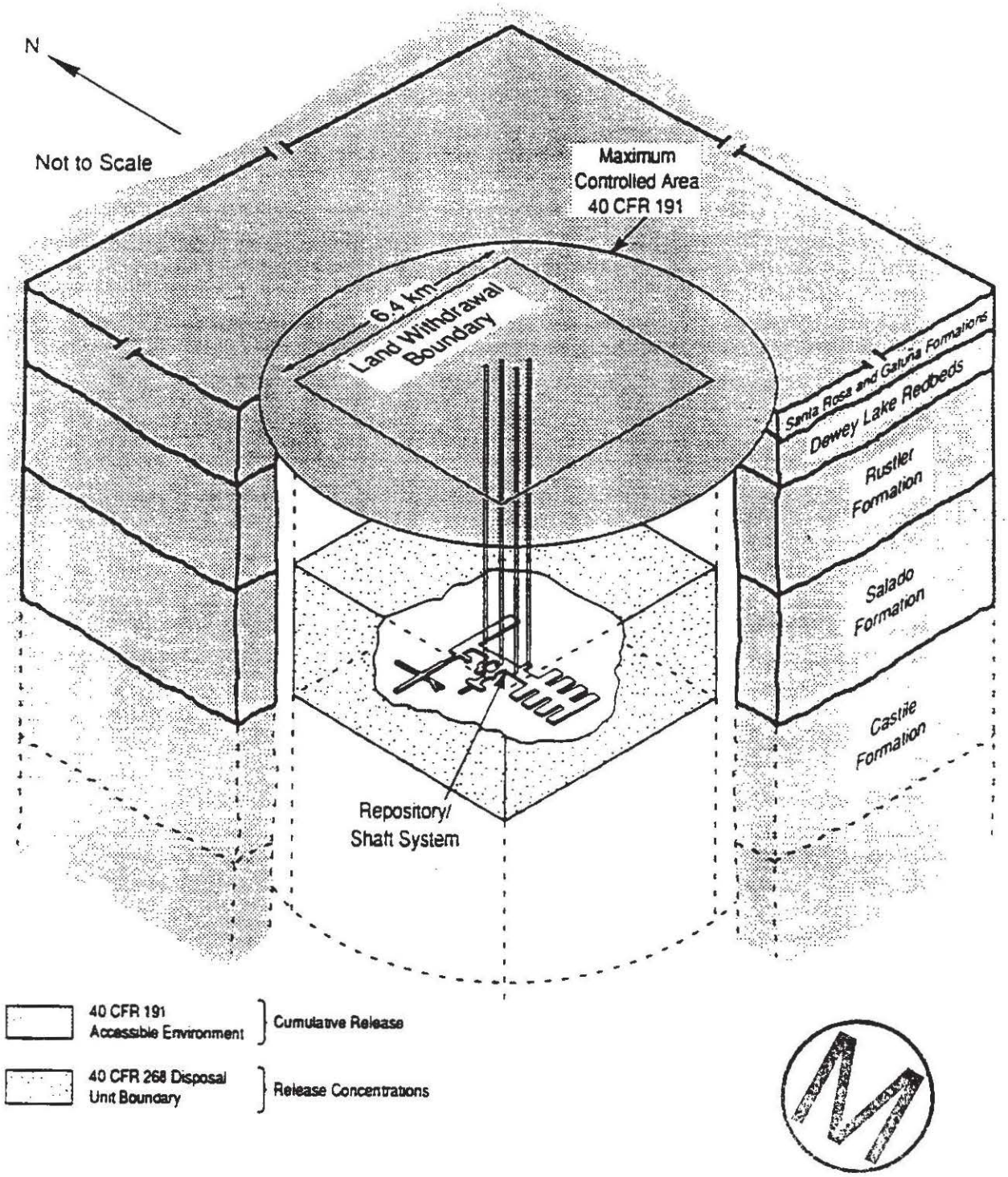

Figure 2-2. WIPP Controlled Area

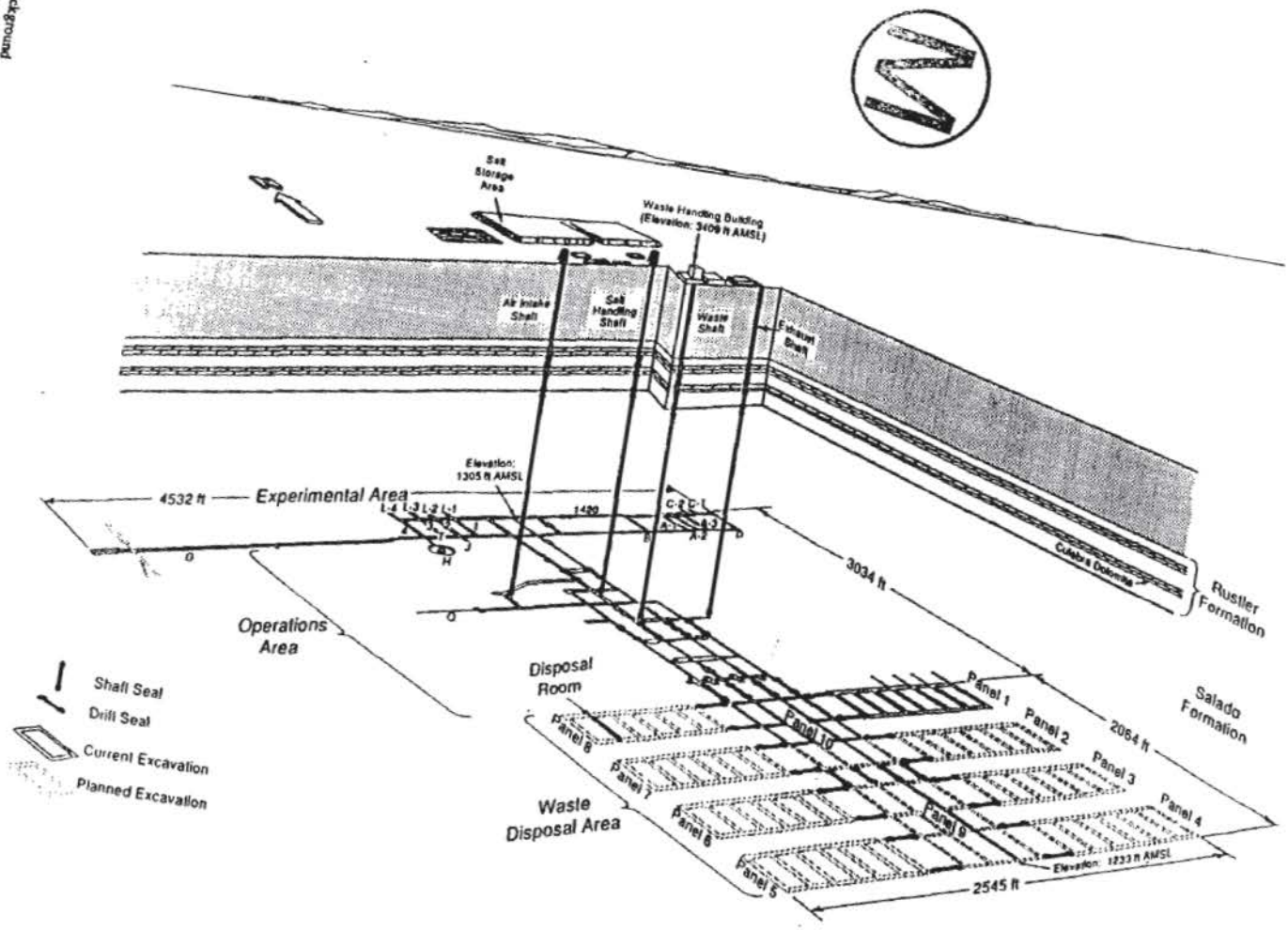

Figure 2-3. WIPP Facilities

permanently, each panel will be sealed, waste will be placed in the drifts between the panels, creating two additional panel volumes, and access ways will be sealed off from the shafts. The shafts will then be sealed to isolate the repository from the ground surface. Final closure of the facility will be facilitated by the creep closure of the salt.

2.3.2. Geologic Setting

The geologic history of southeastern New Mexico and the data collected regarding the subsurface stratigraphy at the WIPP site are important and are discussed extensively in Section 2 of the CCA (DOE 1996) and documents referenced in the CCA. The general stratigraphy at the WIPP site is presented in Figure 2-4. The relevant geologic background setting for the peer review, however, includes specific formations and their lithologies. The Bell Canyon, Castile, Salado, Rustler, Dewey Lakes, Gatuna, and Santa Rosa Formations are the lithologic units within which the conceptual models represent processes and predictions of future states of the proposed disposal system.

The sandstones, siltstones, limestones and shales of the Bell Canyon Formation define the first extensive, continuous, transmissive unit below the WIPP repository and provide a source of groundwater that could migrate vertically into the repository. The halite and anhydrite beds of the Castile Formation separate the Bell Canyon from the Salado and contain pressurized brine reservoirs. Brine reservoirs are a repository performance concern expressed in human intrusion scenarios. The halite-dominated Salado Formation contains the proposed repository and provides the primary natural barrier for containing radionuclides. The laterally extensive Culebra Dolomite Member of the Rustler Formation is the closest stratigraphic unit above the Salado with the potential to transport a radionuclide release to the accessible environment. Studies conclude that transmissivities in the Culebra vary by six orders of magnitude across the WIPP site area. Fracturing and vuggy zones account for much of the variability in the physical/hydraulic properties of the Culebra.

While other stratigraphic members of the Rustler Formation, beds of anhydrite and polyhalite, clays, and other inclusions may be important as each of the conceptual models is reviewed, the four formations and units described above define the most important components of the geologic setting for the WIPP conceptual models review.

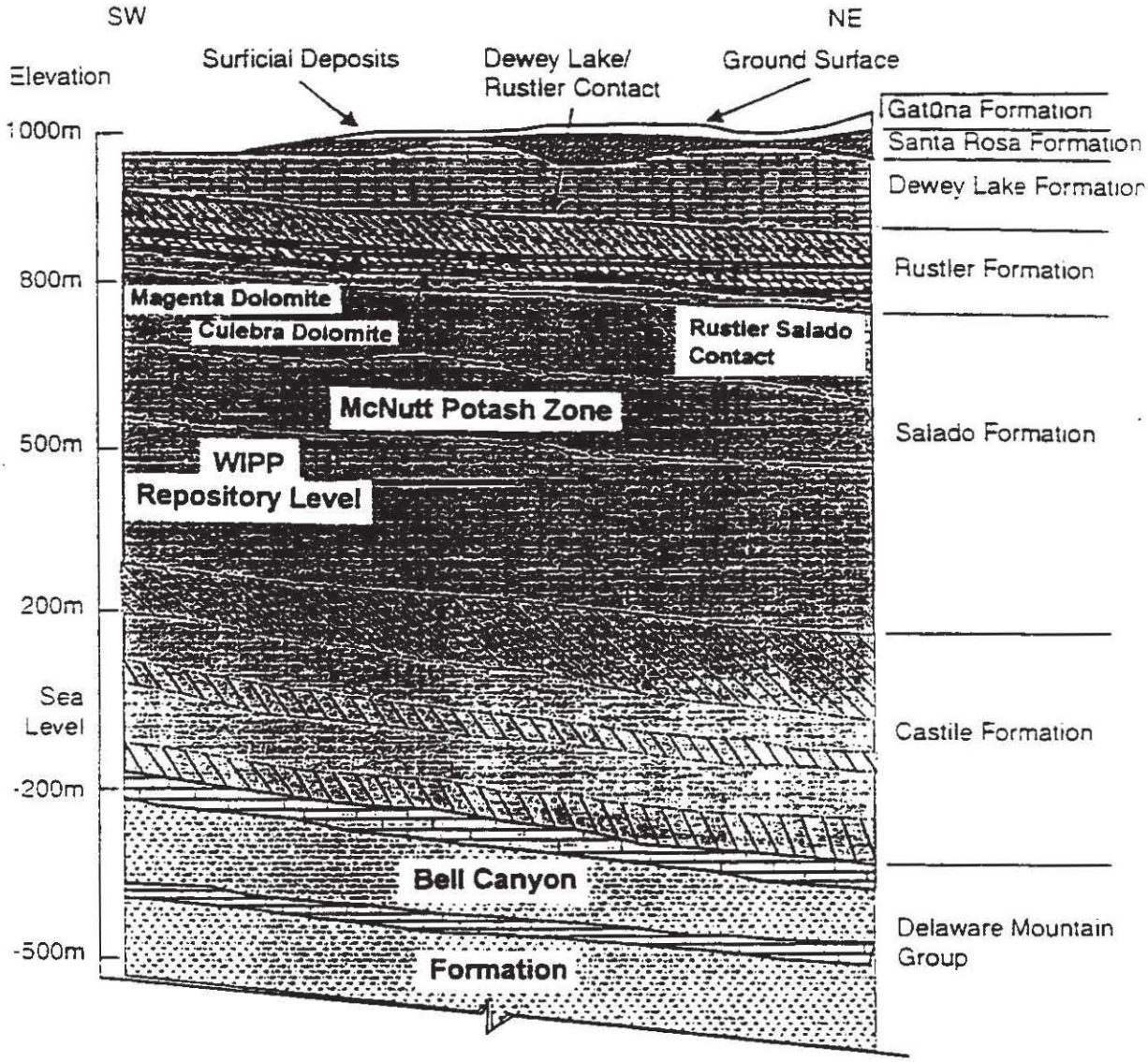

Figure 2-4. General Stratigraphy at the WIPP Site

2.3.3. Hydrologic Setting

2.3.3.1. Surface Water

The WIPP site is located within the Pecos River Basin. At its nearest point, the Pecos River flows approximately 12 miles southwest of the WIPP site boundary. There are no perennial streams at the WIPP site and in this semi-arid region, approximately 75% of annual precipitation results from intense, short-duration events between April and September. More than 90% of the mean annual precipitation is lost through evapotranspiration (ET) and on a mean annual basis, ET potential exceeds expected rainfall. EPA concluded in 1989 (EPA 1990a) that there were "no surface water features near the WIPP that could potentially affect repository performance in such a way as to influence the no-migration demonstration."

2.3.3.2. Groundwater

Extensive coring, logging and testing of boreholes in the vicinity of the WIPP site has provided data for the characterization of the hydrostratigraphy and hydrogeology important to the WIPP site region. While the deep Capitan Limestone, the Rustler-Salado contact zone near Nash Draw, and the shallower Dewey Lakes and Santa Rosa Formations are important in characterizing the WIPP region, the Bell Canyon, Castile, Salado, and Rustler Formations are the units critical to the evaluation of WIPP groundwater issues.

As presented in the geologic setting, the Bell Canyon Formation is the first continuous, transmissive, water-bearing unit beneath the WIPP. This formation provides a source of groundwater below the WIPP repository that could migrate into the repository if a pathway were available. The Bell Canyon Formation exhibits hydraulic conductivities in the range of 10^{-7} to 10^{-12} meters per second and pressures were measured in the range of 12.6 to 13.3 megapascals.

The Castile Formation is of interest to site characterization as a hydrologic barrier between the Salado and Bell Canyon Formations and because it contains isolated pressurized brine reservoirs. The Castile is predominantly low-permeability halite and anhydrite with greater permeabilities in zones of fracture and structural deformation. In the areas of higher permeability, brine pressures exist that are sufficiently above nominal hydrostatic pressure for brine to flow upward through a borehole to the surface.

The halite and anhydrite rocks of the Salado Formation are relatively impermeable and tests have shown that flows range from extremely low to no flow when appreciable pressures are applied. The Salado contains the proposed repository and provides the primary natural barrier for containing radionuclides.

The Magenta and Culebra Dolomite Members of the Rustler Formation are laterally extensive, transmissive, and display hydraulic characteristics sufficient for the lateral transport of radionuclides. Hydraulic conductivities in both members range over five to six orders of magnitude in the WIPP area, but the Magenta is generally less transmissive than the Culebra. The Culebra is the first, most extensive, and most transmissive unit above the Salado at the WIPP site. As such, the Culebra provides the most direct pathway from the WIPP repository to the accessible environment and is the most important component of the hydrogeologic setting for the conceptual models peer review.

2.4. Peer Review Panel Methodology

The review of the conceptual models commenced after a training/orientation period and was conducted in accordance with management plans, the conceptual model peer review plan, desk instructions, and other relevant protocols. Panel member qualifications are detailed in Appendix A of this report.

The work of the Panel began following training/orientation on April 5, 1996 and was scheduled to terminate on June 28, 1996 with the submittal of this final report. The Conceptual Model Peer Review Panel employed six basic approaches in their overall method of conducting and accumulating information for the reviews: 1) extensive review of available, referenced, and "roadmapped" literature relevant to the Panel; 2) attendance at briefings on conceptual models and relevant aspects of the performance assessment process; 3) conduct conceptual model or issue-focused presentations/question-and-answer sessions with DOE scientists and engineers; 4) intensive review of literature/documents discovered through continued research and focused question-and-answer sessions; 5) conduct formal and informal discussions among Panel members; and 6) participate in a tour of WIPP facilities and the local area outside the WIPP site, and in presentations/discussions associated with the tour.

The Panel was provided a list of 24 conceptual models to be independently reviewed with respect to whether or not they represent a reasonable view of future states of the proposed disposal system for the WIPP. For the review, conceptual models are defined as a set of qualitative assumptions used to describe a system or subsystem for a specific purpose. Although such a definition could limit the scope of a review, the Panel evaluated the models in accordance with NUREG 1297 criteria, from conception to their integration with mathematical representations, and paid careful attention to alternative models and approaches. In addition, the Panel recognized that individual models may warrant varying levels of reviews of their mathematical representations, computerized representations, and results.

Individual Panel members were assigned lead responsibility for specific conceptual model reviews and preparation of subsequent sections for the report. The Panel members collectively assumed writing responsibilities for introductory and conclusionary sections in the report.

Early in the review process five Panel members visited the WIPP site to tour surface and subsurface facilities and to view nearby geological features. The purpose of the visit was to view first hand the site-specific features that have potential impact on the long-term behavior of the WIPP. When touring the underground facilities, the Panel members observed the Q Room experiment site, the horizons of the Salado halite visible within the repository, fractures within the repository disturbed rock zone, and collapse features in a room where a roof had fallen. Panel members also visited the WIPP core library and observed selected core samples representative of the geological formations that could not be seen underground. Geological features viewed by the Panel near the WIPP included outcrops of the Culebra and Magenta Dolomites, Dewey Lakes Redbeds, and the Gatuna Formation. Two Panel members visited the Western AG potash mine northwest of the WIPP, where ore zones and anhydrite marker beds not visible at WIPP were seen.

Due to the large volume of project literature required for review, the Panel adopted a process in which each member would work independently in getting pertinent information on a given topic. Group briefings were reserved for the broader topics. All information was freely disseminated for consensus-building among Panel members in the completed analysis. On learning that complete information was not available to complete the Panel's scope of work on time, the Panel requested DOE to provide specific information on an accelerated interim basis. This proved to be highly beneficial to the timeliness of model reviews. It was recognized that much of this input had not been reviewed in accordance with SNL procedures and that some of the information reflected the current status of an ongoing decision process. The Panel members are aware that errors can be made in understanding and accuracy when using information of this type, and used the full access provided by DOE to those personnel necessary to provide guidance and clarification to the answers sought.

In organizing its work, the Panel established limitations on its review and the content of this report. Panel members did not review or offer comments on regulations. The Panel confined its review to the suite of conceptual models identified by DOE (Section 2.2). Finally, to maintain independence, the Panel will not offer recommendations for specific methods and approaches to address its concerns. A cutoff date of June 7, 1996 was established for receiving new information for inclusion in the review. It was

decided that if the Panel could not reach a conclusion due to a lack of information on a particular model, it would be so stated in the Panel's report.

Two additional activities were identified by DOE for the Panel. First, an overview of the Panel's finding would be presented to DOE, SNL, and observers, and the Panel would respond to questions raised to clarify the concerns identified in this report. The presentation is scheduled for July 1 and 2, 1996. Second, the Panel was requested to reconvene in August to review DOE's written responses to the Panel's findings, and prepare an addendum to this report, if necessary, indicating the adequacy with which the Panel's findings and concerns were resolved by SNL.

2.5. Criteria for Conceptual Model Review

The nine criteria used to review each of the 24 conceptual models are listed below along with a brief description of the way in which each was used by the Panel. Examples are provided where appropriate, to provide clarification. The nine criteria are based on the EPA regulation 40 CFR 194.27, NUREG 1297 Section IV.5, the EPA Compliance Application Guidance, and Panel discussions.

Information Used to Develop the Conceptual Model. This is an evaluation of data and information used to develop conceptual models and submodels. It includes attributes of the disposal system learned by DOE during site characterization activities, such as refinements to the room creep closure model or an improved understanding of disturbed rock zone characteristics.

Validity of Model Assumptions. The validity of key assumptions in the model and its application are assessed in terms of how they could affect the usefulness of the conceptual model. The review addresses the comprehensive inclusion of important features, events, processes, and other key assumptions. Examples are the assumption of Darcy flow in the various media, use of the ideal gas law at high pressures, or the method chosen to represent time-dependence of strain.

Evaluation of Alternatives. This section briefly identifies and assesses plausible alternative conceptual models or submodels seriously considered by DOE but not used, and the rationale why such alternative models were not used. Again, important features, events, and processes must be considered. The Panel does not expect the descriptions of alternative models to be as extensive as for the models chosen, but they should adequately document why the alternative models were not used. For example, the choice among matrix, dual porosity, or flow channeling in stratigraphic units, or the use of transmissivity fields versus uniform transmissivity, should be explained.

Uncertainties. This includes an evaluation of the key uncertainties in the selected conceptual models and a discussion of the consequences if aspects of the conceptual model chosen were inappropriate or incompletely constrained for the site or process. For example, if elements of the particular models used to estimate the effect of pH on actinide solubility or the permeability of the disturbed rock zone around the shaft were flawed or incorrect, how significantly would this affect performance? This is not expected to be an exhaustive evaluation, but it should raise the reasonable question, "What if the model were wrong?"

Adequacy of the Conceptual Model. Based primarily on the previous four criteria, this is a simple statement of whether the individual conceptual models and submodels represent a reasonable approximation of the actual disposal system elements.

Adequacy of Application. This is an assessment of whether it appears that the individual conceptual model is being adequately applied into an acceptable overall performance modeling system. This particular assessment does not cover the relationships among conceptual models, but whether the significant components of the individual conceptual models are appropriately implemented in support of performance assessment. For example, are the various geometrical systems and representations of the conceptual models adequately applied within the performance modeling system, or do there appear to be discontinuities between the conceptual model and its application? Also, are there apparently important alterations of key assumptions between the conceptual model and its implementation in performance modeling?

Accuracy of Results. This is a statement of whether the results of performance modeling using the conceptual model within the performance system are sufficiently accurate to adequately simulate the physical and chemical processes represented. This could either be a subjective judgment (if analytical results were not available with any necessary caveats) or a more robust and useful judgment (if results of analyses were available). Review of key results could also improve the basis for the Panel's statements about adequacy of application, overall validity of outcome of analyses, and adequacy for implementation.

Typical results that could be useful in providing a basis for these improved judgments include reports of sensitivity studies among key intermediate parameters, such as: 1) mean and extreme values of expected brine inflows, 2) gas pressurizations, 3) likelihoods of marker bed fracture, 4) directions of brine flow in the undisturbed condition, 5) the effect of mining in the vicinity of waste panels, 6) relative amounts of waste released from intrusion scenario components (direct brine releases, cuttings, cavings and spallings), and 7) initial typical complementary cumulative distribution functions. Similar results from

past performance assessments have provided a basis for improved judgments of models and modeling systems, and numerous improvements have been made in models since the 1992 performance assessment. A review of results is also desirable to facilitate making useful conclusions.

Validity of Conclusions. This is a judgment of the validity of any key conclusions that have been drawn based on results of the implementation of conceptual models in the modeling framework. The key question is whether or not conclusions from model implementations appropriately relate to the expected goal of assessing the long-term performance of the disposal system. Again, a judgment in the absence of some key output information would need to be accompanied by appropriate explanations.

Adequacy for Implementation. This is an overall, bottom-line assessment of whether the conceptual models, as intended for use in the compliance application, represent a reasonable approximation of the actual disposal system based on the eight previous criteria.

3.0 MODEL EVALUATIONS

This section presents the results of the Panel's evaluations of the 24 individual conceptual models that the DOE requested the Panel to review. Each of these models is first described and then evaluated for adequacy in accordance with the nine criteria summarized in Section 2.5. Following each evaluation, space has been provided for dissenting views; however, no dissenting views were forwarded by any Panel member. An evaluation of the integration of these conceptual models into the WIPP performance assessment is provided in Section 4.

3.1. Disposal System Geometry

3.1.1. Model Description

The Disposal System Geometry conceptual model expresses the dimensionality of the engineered system and surrounding geologic/hydrogeologic formations. The parameters of dimensionality are length, width, and height, which are expressed in individual grid blocks and remain constant for all scenarios and realizations. The processes that rely on the geometric assumptions and parameters of dimensionality are represented across the overall performance assessment system through a finite difference mathematical model called BRAGFLO. The principal processes that depend on the conceptual model for disposal system geometry are fluid flow and actinide transport. The flow fields generated by BRAGFLO are based on the geometric representation of the repository and adjacent formations and the finite difference method, and are communicated to the NUTS code that determines the transport of actinides to the accessible environment.

3.1.2. Review of Criteria

3.1.2.1. Information Used To Develop the Conceptual Model

Numerous references accompany the various background, descriptive, and features, events, and processes (FEP) screening write-ups for the repository and disposal system geometries. Except for regulatory and guidance documents, all references are to internal (SNL) reports that characterize various aspects of and inputs to the modeling of the disposal system geometry. The reports present data and information used to develop the conceptual model and background references for specific applications, but no extensive reference list on "conceptual modeling" of disposal system geometry has been compiled by DOE.

Information concerning the effects of detailed stratigraphy and stratigraphic dip on brine and gas flow, and uncertainty and parameter sensitivity analyses for gas and brine migration, is presented in WIPP

(1992a and 1992b) and Christian-Frear and Webb (1996). Other reports (WIPP 1993, Rechard et al. 1990, and Marietta et al. 1989) explain the WIPP performance assessment aspects of characterizing the disposal system geometry, and FEP screening documents present modeling alternatives. Various sections of the Compliance Certification Application (DOE 1996) summarize disposal system, repository, and intrusion event geometries. The Disposal System Geometry conceptual model is the result of integrating other models that describe the physical and chemical conditions and processes expected in the repository into a characterization of the material properties of the repository and surrounding strata. As such, the conceptual model and its application are described in terms of a process that has evolved to its current structure, and has generally been developed after the mathematical models have been defined.

3.1.2.2. Validity of Model Assumptions

The Disposal Systems Geometry conceptual model must have assumptions that are internally consistent and consistent with the assumptions of other models that represent repository processes. Since the geometry by which processes are simulated is so closely tied to the processes themselves, it is difficult to review the conceptual model for disposal system geometry totally separate from other models.

As stated in Part 2.5, the validity of key conceptual modeling assumptions will be assessed in terms of how the assumptions could affect the usefulness of the conceptual model. While the assumptions that describe the repository-process conceptual models that are closely tied to the geometry (Creep Closure, Repository Fluid Flow, Gas Generation, Chemical Conditions, Dissolved and Colloidal Actinide Source Terms) are not reviewed in this section, they are reviewed individually in Section 3, and collectively in Section 4.

Assumptions key to the disposal system geometry conceptual model for undisturbed and disturbed conditions (disposal system, disposal room, adjacent disturbed rock zone (DRZ), and geologic systems) include: 1) the three-dimensional systems can be represented by two-dimensional simplifications; 2) the associations between and relationships across regions with varying material properties can be represented by the discretized grid blocks and by the finite difference method used in the computational model; 3) the four shafts can be represented by one shaft; 4) the entire repository can be represented by the simplified floor plan used in the computation model; 5) the intrusion borehole represents the concerns of the intrusion scenarios; and 6) effects of flow in the DRZ and intact rocks outside of the repository are represented by the divergent grid to the north and south away from the repository.

The representation of relevant systems by two-dimensional simplifications not only affects the usefulness of the conceptual model, it is intended to make the model useful. As stated in Section 3.1.2.1, the geometry followed the definition of the mathematical models. Early three-dimensional mathematical models were unwieldy and computationally inefficient with respect to time, cost, and overall management. The two-dimensional representation is efficient in terms of time, cost, and managing a large number of vectors. The BRAGFLO code, as simplified (BRAGFLO is a three-dimensional code), compared favorably with a three-dimensional alternative (TOUGH 28W) used for verification with respect to the relevant outputs. Two-dimensional simplifications appear to adequately represent the structural system through which fluid flow can be simulated to the shafts or intrusion boreholes. The two-dimensional representation may not be adequate, however, for simulating fluid movement across the repository and waste panel area to the anhydrite interbeds because such flow may be unrealistically impeded by the small depths and potentially low permeabilities assigned to the cells representing the shafts and boreholes in the model. This issue is further discussed in the Repository Fluid Flow conceptual model in Section 3.3.

The conceptual approach of characterizing varying material properties by discretized grid blocks, and using finite differences and partial differential equations to compute a flow field for a series of grid points, is useful and a standard method for hydraulic routing. It is beyond the scope of the conceptual model review to conduct a detailed analysis of the BRAGFLO code, and the finite difference method will be assumed to be of standard computational design. The usefulness of this method is well established in hydrogeology, considered valid for routing liquids, and is a valuable tool for sensitivity analysis.

It appears that the one-degree dip in the Salado, the important cross sectional areas (vertical and horizontal), and distances between key system features and pathways have been retained within modeling simplifications. As these characteristics are retained, the overall geometry conceptual model remains valid. Beyond the conceptual method, the panel makes no comment on the validity of the grid block densities or volumetric variation and whether or not they adequately represent material property maps and changes in properties and their distribution.

The representation of the four shafts by a single shaft of cross sectional area and volume equal to the sum of the four shafts, is a conservative representation and simplifies the mathematical representation of brine and gas flow to and in the shaft. The single shaft is located, geometrically, in the position of the waste handling shaft, which is the closest of all four shafts to the waste disposal regions. The Panel foresees no

reasonable situation where such an assumption could compromise model usefulness and render the assumption invalid, but the presence of four sealed shafts presents four times the risk of failure of one shaft, and this may not have been taken into account. The four-shaft simplification assumption stimulates questions of reality, accuracy, and scientific credibility. While apparent conservatism, at least in the context of the scope of this review, answers most operational and performance questions, it would have been more credible, from a modeling perspective, to model the actual system.

The simplified repository floor plan represents a conservative view, and clearly provides fewer obstacles to flow in the repository than would actually be encountered by fluids. The simplifications and assigned high permeabilities answer operational and performance questions, since the conservatism and validity of the assumption was not refutable within the scope of this review. While the Panel is not satisfied that the simplifications for the sake of conservatism replace credible models of the actual systems, the assumptions remain valid.

The intrusion scenarios require assumptions about the intrusion borehole in terms of location, size, and how the brine and gas are conveyed to the borehole. The intrusion borehole is assumed to penetrate the repository and brine reservoir as appropriate to the scenario. During the intrusion scenario the represented waste panel is discretized to simulate radial flow of waste fluids to the borehole.

3.1.2.3. Evaluation of Alternatives

During the conceptual models review, information that indicated or described alternative conceptual models that were considered but not used was limited to FEP S-1 documents and unpublished informative write-ups provided by DOE (Larson 1996). Many grid configurations were experimented with in previous performance assessments, and sensitivity and uncertainty analyses (WIPP 1992a, 1992b) were conducted relative to the geometry model. Analyses that examined how detailed stratigraphy and stratigraphic dip affected brine and gas migration were reported in Christian-Frear and Webb (1996) and Webb and Larson (1996). Through all of the analyses and experiments the basic concept of the grid as the geometric framework has not changed. The specific geometric framework suitable for modeling disposal system processes and interactions was developed after the mathematical/computational system was defined. Three-dimensional and two-dimensional models were evaluated, with the three-dimensional model described as computationally inefficient for the large number of vectors required for the WIPP performance assessment, and was considered costly in terms of time and resources.

With the selection of the two-dimensional approach and the simplified BRAGFLO code, FEP S-1 screening verified (justified) the two-dimensional WIPP grid with a three-dimensional model (TOUGH 28 W). Based on the favorable comparison of outputs from the models, the DOE selected the two-dimensional model for use in the WIPP performance assessment.

Intrusion scenarios are limited to those that penetrate the repository waste panels or repository and brine reservoir. No alternative borehole intrusion scenarios are considered that miss the repository but penetrate the adjacent DRZ or strata and impact the physical properties of the DRZ or strata.

3.1.2.4. Uncertainties

The key uncertainties associated with the disposal system geometry conceptual model are associated with the simplifications made for the sake of conservatism (as opposed to, for example, operational efficiency, cost, and resource constraints) and with the question of whether the computational mesh is representative of the geometry of the system. While the two-dimensional simplifications embody assumptions key to the conceptual model, verification screening illustrates that these simplifications result in outputs of sufficient quality for use in the WIPP performance assessment (FEP S-1 1992 and 1993).

As stated in Section 3.1.2.2, the Panel concludes that there is little uncertainty or confusion with the fundamental geometric framework of discretized grid blocks or the use of the finite difference method to compute flow fields over a series of grid points. The uncertainty that exists relates to the definition of the processes by the mathematical representations and the representativeness of the computational mesh.

3.1.2.5. Adequacy of the Conceptual Model

The conceptual/geometric framework and computational method selected to characterize the material properties of the disposal system and relevant physical and chemical processes is adequate. As stated in previous sections, the implementation of the conceptual model has not been evaluated within the scope of this review and cannot be commented on.

The two-dimensional simplifications, considered part of the conceptualization of the disposal system geometry, have been subjected to verification and are considered adequate for use in characterizing releases for the WIPP performance assessment.

3.1.2.6. Adequacy of Application

The Disposal System Geometry conceptual model provides an adequate framework, method, and set of assumptions, and appears to be applied as an acceptable performance element. There are no apparent compatibility problems between the geometry and process-related conceptual models in terms of assumptions or application method that would create misrepresentations. The overall adequacy of the application should be measured by how well material properties are represented and physical and chemical processes are simulated. These measures, in turn, depend on the relevant conceptual models and data relevant to those processes being modeled. Therefore, a more definitive assessment of the adequacy of application of the Disposal System Geometry conceptual model could be determined from analyses, outputs, and results generated by the relevant process-related conceptual models, which were not available to the Panel at the time of review.

3.1.2.7. Accuracy of Results

For evaluating the accuracy of the results of the Disposal System Geometry conceptual modeling activity, model formulation results, as well as model evaluation/application results, must be reviewed. Model formulation results are the description or descriptive write-up that presents the conceptual model. Model evaluation/application results are those that indicate the performance of the conceptual model through sensitivity analyses, verification studies, or results of performance modeling of all or intermediate parameters.

The conceptual model, as defined by the geometric framework, the proposed use of a finite difference method, two-dimensional computational simplifications, and disposal system simplifications, is accurately presented as formulated. The Panel was required to consult numerous documents to acquire a comprehensive view of the conceptual model and the formulation process, but the description of the conceptual model is complete and accurate.

As presented in Section 3.1.2.6, the Disposal System Geometry model evaluation results, or results of model applications, should be measured for accuracy within the models that have conceptualized the physical and chemical processes. While the simplifications of this conceptual model have been verified as to comparability of outputs with other models (FEP S-1 1992 and 1993), the Disposal System Geometry model itself only produces results, as it represents material properties and processes conceptualized in other models. Therefore, the Panel cannot attest to the overall accuracy of the model.

3.1.2.8. Validity of Conclusions

The Panel is not aware of any results of the implementation of the Disposal System Geometry conceptual model (see Section 3.1.2.7) and therefore, there are no conclusions to validate.

3.1.2.9. Adequacy for Implementation

The conceptual model for the Disposal System Geometry provides a suitable framework for modeling the important processes and their interactions in the disposal system. The mathematical representation of the conceptual model within the BRAGFLO code has not been reviewed and, as a result, the panel offers no conclusions on the representativeness of applications using the code. The concept that the spatial effects of processes and interactions can be represented in two dimensions is defensible. The simplification in the system representation and computational method to simulate the two dimensions are defensible and adequate for implementation. The basic grid framework for representing the material properties of the disposal system, adjacent DRZ, geologic formations, and intrusion scenarios is adequate, and the proposed use of a finite difference method to connect the nodes and generate flow fields is also defensible and adequate for implementation.

3.1.2.10. Dissenting Views

There were no dissenting views for this model.

3.2. Culebra Hydrogeology

3.2.1. Model Description

The Culebra is identified as a principal potential pathway for radionuclide release to the environment. The conceptual model should support the results of hydrologic testing and provide bases for population of the model in regions lacking data. The conceptual model should correlate the regional and site scale hydrogeology with the model boundaries and help shape hydrologic gradients and local field boundaries.

The Culebra hydrogeologic characterization framework has evolved from two fundamentally different regional flow models, several formulations explaining local flow conditions represented by hydrologic testing, and several hypotheses explaining the distribution of permeability regions in the Culebra. The regional flow models include the "confinement" model and the "groundwater basin" model. The confinement model depicts the Rustler Formation (of which the Culebra is a member) as a series of perfectly isolated layers which are hydrogeologically independent. The groundwater basin model depicts

the Culebra as a layer within a series of interacting hydrologic units of varying properties which include all the hydrologic units between the ground surface and the Salado Formation. In the groundwater basin model, hydrologic gradients are thought to be vertical in the low permeability layers (Tamarisk, Forty-Niner, Unnamed Lower Member) and horizontal in the Culebra and Magenta Dolomites.

Observations in the field and shaft openings indicate that the Culebra is a dolomite averaging approximately 7 meters in thickness. Generally fine-grained, red brown in color, occasionally vuggy and fractured, the crudely layered dolomite appears to be typical of evaporite dolomites. The fractures tend to be disorderly in orientation and in some places polygonal, and the vugs are occasionally open. The MgO content of the dolomite varies greatly vertically and areally within the Culebra member. These lithologic characteristics and the sedimentological setting imply that the Culebra is a reflux dolomite, deposited originally as a calcite sediment and subsequently altered by infiltration of MgO-rich evaporite brine. The variability of MgO content, texture, and fracture distribution are most probably due to variability in volume changes due to timing, rate, and degree of dolomitization of the original calcite sediment.

Hydrologic testing of the Culebra has indicated that the hydrologic properties of the unit (principally permeability and porosity) vary strongly both vertically and areally. At some localities, the test flow rates and interactions between wells have led to hypotheses that relatively low permeabilities resulting from flow through the rock matrix dominates the hydrogeology of the Culebra over regions many tens of meters in extent. Similar tests in other localities have implied high permeabilities over distances of several kilometers, which are hypothesized to be the result of the dominance of fracture permeability along interconnected fracture zones. Other localities show intermediate flow characteristics, which may be the result of combined effects of flow-through fractures and matrix. Multiple models that hypothesize the combined and singular effects of hydrologic sample intervals across regions of vertically varying modes and rates of flow have been proposed to explain some of the variability of test results. These models have been tested by varying sample intervals and pumping rates several times in the same stratigraphic interval. It appears that sample interval does not entirely explain the composite flows observed and that dual porosity flow models are appropriate. There are regional variations in hydrologic properties in the Culebra that are too large in magnitude to be explained by variation in sample interval or proportionality of flow mechanism, and that appear to be areally distributed within and around the repository area. These areal variations in the hydrogeologic nature of the Culebra have not been clearly associated with a conceptual model of the geology of the dolomite or of the Rustler Formation as a whole. The Culebra is the most extensively tested hydrogeologic unit in the WIPP region.

Jones (1974, 1975, 1978) and Snyder and Gard (1982) postulated that the hydrology of the Culebra was primarily related to the dissolution of halite within the Rustler Formation. Jones postulated the existence of dissolution "fronts," partly the consequence of Pleistocene climatological history, which are presently active at reduced rates based on halite distribution within the Rustler and at the Rustler-Salado contact. Subsidence of the Rustler related to dissolution was the postulated mechanism for locally increased aperture of preexisting fractures. Although dissolution is certainly a strong influence on the geology of the Rustler Formation in Nash Draw and isopac maps of the Rustler Formation members show erratic thickness changes in the soluble members (Brinster 1991), workers in the region remain divided about the role of dissolution in the hydrogeology of the Rustler Formation and of the included Culebra Member. Holt and Powers (1988) argue that variations in stratigraphic thickness within the Rustler are the result of depositional processes and that changes in overburden pressure due to erosion explain the variability of hydrologic properties. Bachman (1987) and Lambert (1987) argue that solution has been inactive since mid to late Pleistocene time. Chapman (1986) contends that Culebra waters contain significant amounts of meteoric water, while Lambert argues against the presence of any meteoric water. Corbet and Wallace (1993) argues that the filling of fractures and the removal of fracture fillings by dissolution explains gross regional variations in transmissivity.

Hydrologic testing has not resolved the questions raised by arguments about the origin of variability of hydraulic properties by simple correlation with geologic features. Some fundamental geologic variables, such as fracture distribution, aperture, and orientation, as well as patterns of variation in matrix permeability and porosity, have not been sufficiently characterized to make such correlations possible. Such characterization would require a large investment in angle hole nests and extensive three-dimensional modeling. The uncertainties in the hydrogeologic character of the Culebra has led to the abandonment of attempts to formulate a detailed hydrogeologic conceptual model and there have been several attempts to generate an acceptably predictive numerical hydrologic model exclusively from testing data. These attempts are summarized in Figure 3-1 and in Table 3.1. Recent multiwell tracer tests are presently being evaluated to more fully support transport modeling.

Chapman (1986), LaVenue (1990), Siegel (1991), and Beauheim (1989) have not been able to relate detailed hydrogeologic features, hydrogeochemical facies, radiogenic ages, flow constraints, or hydrologic testing results to a consistent, detailed hydrogeological conceptual model. Neither have they been able to uniquely explain water level changes observed in monitoring of the WIPP region over the last several decades. Groundwater flow directions in the Culebra member over the Los Medanos region,

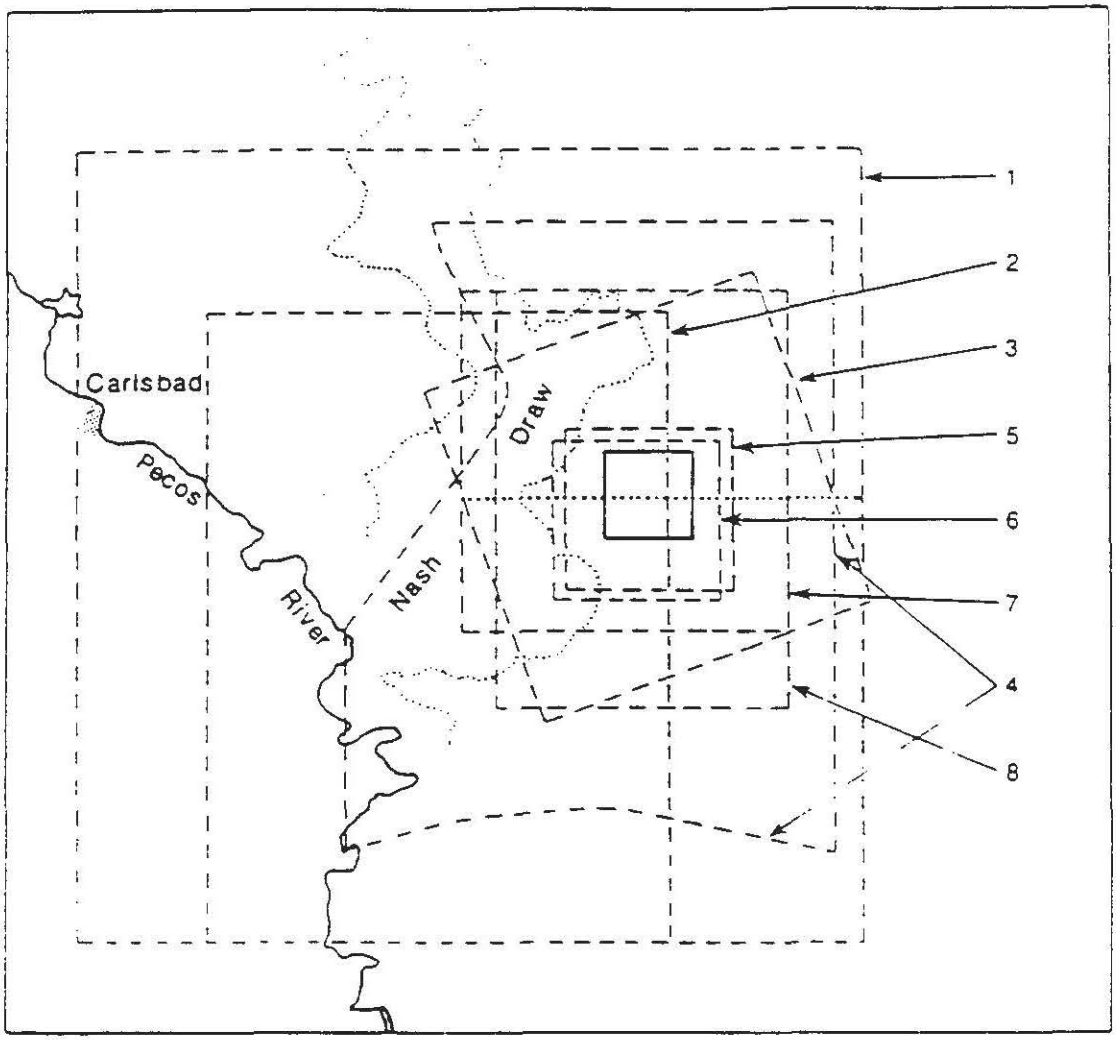

0 5 10 15 Kilometers

1 5 10 Miles

1 U.S. Department of Energy (1980a,1980b); Cole and Bond (1980)
2 D'Appolonia Consulting Engineers (1981)
3 Barr et al. (1983)
4 Davies (1989)
5 Niou and Pietz (1987)
6 Haug et al. (1987)
7 LaVenue et al. (1988)
8 Present Study

INTERA Technologies

Figure 3.1. Approximate Boundaries of Groundwater Flow Models in the WIPP (after Lappin and Hunter 1989)

Table 3.1. Summary of Modeling Investigations of the Rustler Formation or Culebra Dolomite Member in the WIPP Site Region

Investigation	Hydrogeologic Unit Modeled	Head Calibration
DOE 1980	Rustler	Steady State
D'Appolonia 1981	Rustler	Steady State
Cole and Bond 1980	Rustler	Steady State
Barr et al. 1983	Culebra	Steady State
Davies 1989	Culebra	Steady State
Niou and Pietz 1987	Culebra	Transient
Haug et al. 1988	Culebra	Steady State
LaVenue et al. 1988	Culebra	Steady State
Present Study	Culebra	Combined Steady State/Transient

as well as in other members of the Rustler Formation, are reasonably well defined. The work synthesized by LaVenue (1990) and Brinster (1991) and the intervening single and multiwell and tracer testing in the Culebra, are an attempt to characterize the hydrology of the Culebra in a well-constrained area around the WIPP on the basis of a relatively large body of hydrologic test data by numerical modeling alone. If this effort is ultimately successful, perhaps a comparison of model results with the existing hydrogeologic characterization of the Culebra will allow the formulation of a hydrogeologic conceptual model that explains transmissivity variation at the site scale. None exists at this time. The large number of hydrologic tests within the repository area and in the Los Medanos region around the repository, the variety of types of testing, and the long period of monitoring suggest that a numerical flow model may be sufficient to answer most of the performance-related questions about the Culebra at the repository.

3.2.2. Review of Criteria

3.2.2.1. Information Used to Develop the Conceptual Model

Information used to develop the conceptual model included field geologic observations, logging of cores from borings, observations from shaft mapping, petrographic and mineralogic study, subsurface mapping, groundwater geochemistry and geochronology, and hydrologic testing and monitoring including multiwell pumping and tracer tests. Several hypotheses correlating detailed variations in the hydrologic properties and results of monitoring of the Culebra with groundwater geochemistry and geohydrological aspects of the formation were proposed and tested against existing information or information acquired

specifically to test the hypotheses. All hypotheses failed to correlate the detailed hydrogeology of the Culebra with its tested hydrologic character. The information used to develop the conceptual model was insufficient to permit the formulation of the model at a sufficient scale.

The Culebra is a red-brown, fine grained dolomite, continuous over the WIPP area, which displays vugs and fractures that may be the primary sources of permeability and porosity. The lithologic aspect of the Culebra and the variability of its magnesium content suggest that it is a reflux dolomite formed by the gravity-driven infiltration of a calcite sediment by magnesium rich fluids, shortly after deposition in an evaporite sedimentological setting. The Culebra is bounded by two very low permeability anhydrite units. The hydrologic gradient in the Culebra is horizontal and generally southward over the repository area and the gradients in the adjacent beds are vertical. Some water-pressure measurements imply that the Culebra is underpressured. The transmissivity and gradient of the Culebra are capable of discharging more water than the formation is receiving in recharge, at least locally. There is more hydrologic test data for the Culebra than for any other hydrogeologic unit in the repository region. The model boundaries are defined by regional hydrogeologic features mapped and modeled by Corbett (1993). The information is inadequate to develop a conceptual model that explains hydraulic process and property variation at the site scale.

3.2.2.2. Validity of Model Assumptions

Since all detailed conceptual hydrogeologic hypotheses correlating the Culebra hydrogeology and geochemistry to the described hydrologic properties and the results of hydrogeologic testing and monitoring failed, no conceptual model was formed that could be linked to the computational flow model. No model assumptions, which have their origin in the conceptual model and impact performance assessment, exist for testing.

3.2.2.3. Evaluation of Alternatives

Alternative hydrogeologic models, which relied on apportioning fracture and matrix porosity and permeability within the Culebra as a result of: 1) solution of halite within the Rustler Formation; 2) solution of halite at the Rustler Salado interface; 3) variability of superincumbent load due to topography; and 4) dissolution due to gravity driven flow of brines of different density, were considered and discarded.

3.2.2.4. Uncertainties

Model uncertainties as a result of the conceptual model do not exist in this instance because of the absence of an accepted conceptual model at the appropriate level of detail. An alternative approach has been adopted which depends on the modeling of the hydrology of the Culebra entirely on the basis of the results of hydrologic testing. A detailed assessment of this numerical modeling effort is beyond the scope of this review.

Two sources of uncertainty are related to the absence of a conceptual model in this case. A conceptual model helps to explain the sources of variability observed in a data base derived from hydrologic testing and provides rational bases for populating the data-less areas in the model grid. Values are smoothed and gradients between varying clusters of data are shaped on the basis of hydrogeologic character. Absence of this influence on grid population reduces confidence in numerical model representativeness.

The second uncertainty is the absence of hydrogeologic bases for ruling out significant patterns of variance in the flow patterns and hydrologic properties in the Culebra hidden within data-less areas or areas of apparently incoherent variation in the testing area. The Culebra test results have exhibited relatively large, spatially dependent variations in hydraulic conductivity. The relatively dense testing data base and the ongoing multiwell and tracer testing are attempts to resolve this issue. Zones of relatively rapid fracture flow, without significant retardation of radionuclides by physical or geochemical processes, could cause accelerated transport in the Culebra. The existing transmissivity field models seem to cover the regions of greatest concern to site performance with what appears to be an adequate testing data distribution to rule out local variations in flow significant to performance of the site. The density of field testing data seems to be adequate.

The impact of ground subsidence due to repository closure on the hydrogeology of the Culebra is a source of uncertainty. Subsidence of nearby potash mines and an analysis by Westinghouse suggest a lowering of the ground surface of about .5 m and a small horizontal extensional strain in the Culebra (.007%). It has been asserted that the transmissivities represented by the two-dimensional flow model proposed for performance assessment are conservative enough to contain any enhancement of flow caused by subsidence of this scale. No conceptual arguments specific to Culebra hydrogeology or numerical analysis supporting the probable magnitude of enhancement of transmissivity or the sensitivity of the proposed model to that change have been presented.

3.2.2.5. Adequacy of the Conceptual Model

The conceptual model is not adequate to define variations in the transmissivity of the Culebra at the site scale. Its function has been replaced by an extensive hydrologic testing and modeling effort.

3.2.2.6. Adequacy of Application

See Section 3.2.2.5.

3.2.2.7. Accuracy of Results

No conceptual model is employed in performance assessment-related modeling. Assessment of the accuracy of the numerical flow modeling used in performance assessment is beyond the scope of this review.

3.2.2.8. Validity of Conclusions

The validity of the conclusions of numerical flow modeling is not impacted by the conceptual model in this case. Data distribution and density and geostatistical methods used to populate the model appear to be valid. The results make sense in a qualitative way.

3.2.2.9. Adequacy for Implementation

The conceptual model was not adequate for implementation. A numerical model based on an extensive hydrologic testing data base was substituted. The numerical model appears to meet the needs of the performance assessment, although the computational validity and accuracy of that model were not reviewed.

3.2.2.10. Dissenting Views

There were no dissenting views for this model.

3.3. Repository Fluid Flow

3.3.1. Model Description

The Repository Fluid Flow conceptual model addresses (1) fluid distribution in the waste, (2) long-term fluid flow to and from the Salado Formation and shafts, and (3) long-term fluid flow between the repository and intrusion boreholes. Related conceptual models include Disposal System Geometry, Disturbed Rock Zone, Creep Closure, Shafts and Shaft Seals, Gas Generation, Impure Halite, Salado, and Salado Interbeds, Castile and Brine Reservoirs, Exploration Boreholes, and Multiple Intrusions.

The Repository Fluid Flow conceptual model is a complex description of simultaneous, interacting hydrologic, chemical, geomechanical, engineering design, and human intrusion scenarios whose effects can be described separately, but require numerical modeling to identify the combined, integrated outcome. The conditions controlling repository fluid flow include brine inflow rates, halite creep rates, and gas generation from waste corrosion and degradation, which are themselves the objects of related but separately described conceptual models. The Repository Fluid Flow model accepts inputs from these related models and provides descriptions of pressures, flow rates, and flow directions for brine and gas within the excavated areas of the repository. A detailed description of the coupled processes in the conceptual model is presented in Freeze et al. (1995).

The layout of the waste repository is described in Section 2.3.1. The key elements of this layout pertaining to the Repository Fluid Flow conceptual model are the waste disposal area (the waste panels and access drifts), the panel seals, the operational area, the experimental area, the shafts, the WIPP site characterization boreholes in the vicinity of the repository, and any future exploration boreholes that are randomly determined to penetrate the repository. The waste panels in the disposal area will be sequentially filled to capacity with waste and isolated from the rest of the repository by 40-m long closure seals consisting of concrete plugs and crushed salt. The operations area is north of the disposal area and consists of four shafts and a network of interconnecting access drifts. Two additional sets of 40-m seals will be placed in the operations area between the waste and the shafts. The experimental area is north of the operations area and consists of a series of experimental rooms and access drifts.

In the current plan, waste will be placed in steel drums and waste boxes stacked to achieve efficient use of space. Magnesium oxide will be placed around the containers to absorb carbon dioxide gas generated during microbial decay of cellulosics in the waste. No structural backfill is planned for the repository. Analyses have indicated that decay and degradation of the waste are expected to generate little heat and the maximum repository-wide temperature excursion is expected to be about 5°C. The changes in density and viscosity for brine and gas at this temperature rise are small, and are not considered to be significant in performance assessment. Plans for shaft and borehole sealing are discussed in Sections 3.12 and 3.20. On repository closure, the Salado halite is expected to creep into the excavated rooms and crush the waste; however, some porosity will remain, resulting from the strength of the waste materials and from pressurized brine and gas in the waste. A discussion of the Creep Closure model is presented in Section 3.19.

In undisturbed scenarios, brine is expected to flow into the excavated entries of the repository at a slow rate both during and after closure. Brine will flow directly from the Salado halite, from higher conductivity anhydrite interbeds intersected by the excavations, from formations above the Salado by seepage through a DRZ around the shaft, and from brine squeezed from storage in clays in the impure halite. Flow into the repository through the halite is expected to be enhanced by a disturbed rock zone of higher permeability in the walls, floor, and back of the underground entries (see Section 3.7), from a series of 50-foot long site characterization boreholes drilled vertically upward and downward from the repository, and from rock bolt holes penetrating the back and walls of most entries. During the operational period, this inflow is expected to be removed by evaporation into the repository ventilation air. Under undisturbed conditions following closure, inflow is expected to continue at a low rate from the first three of these sources but not from the clay, which is expected to have been fully consolidated. The brine is expected to pool in low spots on the repository floor and to be wicked into the waste and magnesium oxide by capillary forces. Under disturbed conditions, additional inflows of brine may rapidly occur following closure if a borehole penetrating the repository also encounters pressurized brine in the underlying Castile Formation.

Both gas and brine will behave as fluids, filling pore volume in the repository. Gas and brine will be generated at the same time that the repository void spaces are being closed by halite creep, eventually reaching a state of equilibrium where the pressure of the gas and brine is balanced by the pressure of the halite on the remaining void spaces. Brine inflow into the remaining voids is expected to stop when the pressure of brine in the repository is the same as the pressure of brine in the halite. If gas production continues, the pressure of the gas will continue to rise, driving the brine back into the halite.

If the gas pressure exceeds the threshold pressure for its entry into the surrounding geologic media, the gas will enter the geologic media, increasing the available void volume. As the gas pressure approaches the lithostatic pressure, gas is expected to enter the anhydrite interbeds in the vicinity of the repository, increase the porosity in those interbeds by enlarging existing fractures along planes of weakness, and migrate laterally in the interbed away from the repository, until the increased pore volume sufficiently reduces gas pressure that the phenomenon stops (see Section 3.6). The lateral extent of such fracturing will depend on the rate of gas generation and the pressure and volume of gas present in the repository. Microfracturing of the intact halite from gas pressure buildup is expected to occur around the repository, but at a rate that is sufficiently slow that stress redistribution from halite creep will keep these fractures

from developing into a size that would be of concern to performance assessment. More extensive fracturing is expected in anhydrite, which is more brittle and does not have the creep characteristics of halite.

The volume of gas produced will be limited primarily by the volume of source material (primarily steel and cellulosics) in the repository, and the rate of gas production will be limited primarily by the volume of brine present and in contact with the waste. Gas pressure can be relieved if the repository is penetrated by an exploration borehole, in which case releases of gas, contaminated brine, and repository waste materials could occur at the ground surface (see Sections 3.12 and 3.17). The void volume in the repository can also increase when the gas pressure exceeds the lithostatic pressure by reversing the creep process.

The conceptual model for repository fluid flow is implemented for performance assessment using two separate models developed from the BRAGFLO code. The first model, which for purposes of this review will be called BRAGFLO, is used for analyzing long-term flow through the repository under both disturbed and undisturbed conditions. The second model is used for calculating short-term, direct brine releases when the repository is penetrated by one or more boreholes, and will be called BRAGFLO-DBR. This second model is discussed under the Direct Brine Release conceptual model in Section 3.15.

The repository is represented in BRAGFLO in two-dimensional vertical section as a series of volumes, each with homogeneous, isotropic material properties and behaviors, and each representing a major repository feature. The slight 1° southerly dip of the bedding is incorporated into the model. The effective depth of each modeled feature (the third dimension normal to the plane of the model) is addressed through adjusting the cross section areas of the cells representing the feature. The model material numbers and the dimensions of each feature are summarized in Table 3.2. Ranges of depths are given for features with variable depths that are represented by multiple columns of model cells. The heights of the intrusion borehole and shaft are not given because they extend to the ground surface, have varying material properties and behaviors, and heights that are greater than the height of the repository excavations.

The effective depths of the model cells were varied to simulate the increasing hydraulic gradients that would occur into the repository, intrusion borehole, and shaft under radial flow conditions. The model depths used for the borehole and shaft approximate the effective diameters of these features. The model depth for the borehole is held constant whether or not an intrusion borehole is assumed to have been

Table 3.2. Model Material Numbers and Feature Dimensions

Feature	Material Number	Length (m)	Height (m)	Depth (m)
Single waste panel	23	112	4	4.8 to 126.2
Intrusion borehole	1	0.27	- -	0.27
Single panel closure	25	40	4	10
Rest of repository	24	695	4	141.6
Multiple panel closure	25	80	4	18.9
Operations area	26	333	4	18.9
Shaft	2 to 11	10	- -	9.5
Experimental area	27	560	4	20.5 to 53.1

drilled. BRAGFLO is configured assuming a single shaft with a vertical permeability of the four shafts (and their disturbed rock zones) combined, and assuming a single exploratory borehole that penetrates the center of one of the downdip waste panels. The borehole cells are assigned the properties of the undisturbed media until a borehole is randomly assumed to have been drilled. The borehole can be either an E1 type (penetrates a waste panel in the repository and encounters pressurized brine in the underlying Castile Formation) or an E2 type (penetrates a waste panel but does not encounter pressurized brine). Penetration of a waste panel by more than one borehole is also addressed by this version of BRAGFLO and is discussed in Section 3.17. The presence of existing site characterization borehole ERDA-9, very near the repository, is not addressed by BRAGFLO.

The waste is simulated in BRAGFLO in two areas: Material 23, which represents a single waste panel, and Material 24, which represents the rest of the repository. The waste itself is assumed to be distributed uniformly throughout the two areas. Between the waste materials, BRAGFLO simulates a 40-m long panel closure seal (Material 25) representing the seals in the two panel access drifts. In addition, an 80-m long panel closure seal (also Material 25) separates the rest of the repository from the operations area and represents the two groups of 40-m long seals that will be placed in the operations area. The remaining cells (Materials 26 and 27) represent the operations and experimental areas, respectively, and are located on either side of the shaft. Each of these material areas is three cells high in vertical dimension, allowing vertical variations in brine and gas saturations and the resulting varying rates of corrosion and waste decomposition to be simulated.

Gas production rates are estimated as a function of brine availability. Wicking of brine into the waste will increase gas production rates and is modeled by arbitrarily adding a randomly selected value,

varying from zero to 1.0, to the brine saturation value in disposal area model cells containing brine (not to exceed a total brine saturation of 1.0). This value is called the wicking saturation. The additional brine is only used for chemical reaction purposes. The approach increases the volume of brine available for chemical reactions and increases the rate of corrosion and gas production. To simplify analysis of the mechanical effects of gas production and pressure buildup, all gases produced are assumed to have the properties of hydrogen and behave as ideal gases. Although this assumption would lead to underestimating the viscosity and overestimating the compressibility of the hydrogen-carbon dioxide mixture actually expected to be present, the error would be of no significance in view of the considerably larger uncertainties in other parameters in the model and the expected efficiency of the magnesium oxide in removing carbon dioxide from the system.

Repository closure through halite creep is modeled using the porosity surface approach discussed in Section 3.19. The waste disposal rooms are assumed to maintain a relatively high constant permeability, but a varying porosity during the creep closure process. The panel closure seals and the operations and experimental areas of the repository are assumed to have a constant permeability and porosity. BRAGFLO models the repository assuming two-phase Darcy porous medium flow throughout the closure process.

Material 22, representing disturbed halite, lies above and below the repository excavations and interconnects the repository with Marker Beds 138 and 139, and with Anhydrite Layers A and B. No disturbed halite is modeled in the walls of the excavations. The lateral outer boundaries of the model are over 2,000 m from the repository. All outer boundaries below the Rustler are assigned no-flow conditions.

3.3.2. Review of Criteria

3.3.2.1. Information Used to Develop the Conceptual Model

The conceptual model has relied greatly on the general Darcy model for flow in porous media, as amended for gas by considering the Klinkenberg effect, and for two-phase flow using a modified Brooks-Corey model that includes threshold pressures for gas entry into a brine-saturated medium. Brine salinity, density, compressibility, and viscosity are addressed in the model. Gas properties are given by the Redlich-Kwong-Soave equation of state, assuming behavior to be that of pure hydrogen. The principal basis for the conceptual model is not specific to WIPP, but was developed from the general state of knowledge of two-phase, isothermal flow of liquids and gases in porous media. This general

behavioral information was supplemented by site-specific studies that included measurements of the coupled hydromechanical properties of brine, intact salt, crushed salt, gas, and sealing materials. Although site-specific parameters for two-phase flow in the waste are lacking in the data base, representative values for these parameters would be difficult to obtain because of the expected heterogeneity of the waste. Surrogate parameters from other media are instead used for two-phase flow, and the uncertainties are compensated for by random sampling over ranges of values. Detailed modeling sensitivity studies of repository fluid flow and other coupled phenomena are summarized in Freeze et al. (1995) and Christian-Frear and Webb (1996). The information and concepts used were appropriate for developing the conceptual model.

3.3.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.3.1 and are critically reviewed here. Most assumptions are reasonable and appropriate and include the assumption of isothermal conditions for fluid flow calculations, the assumption of Darcy flow, the incorporation of two-phase flow, the treatment of wicking, and the phase stratification from gravity effects. The assumed lack of a DRZ in the walls of the modeled repository rooms is not expected to significantly affect the Repository Fluid Flow model, but would change the frequency of borehole penetration by increasing the target area. This issue is further addressed in Section 3.15. Certain aspects of the principal model assumptions were reviewed more closely and are addressed in the following paragraphs.

The two-dimensional representation of the repository in BRAGFLO is necessary to feasibly perform the many repeated model runs needed for probabilistic analysis. The effect of more explicitly representing the detailed stratigraphy was evaluated in Christian-Frear and Webb (1996), and the sensitivity of a more rigorous evaluation of coupled repository processes was reviewed in Freeze et al. (1995). The results of these studies identified key parameters and processes and support the two-dimensional approach used in BRAGFLO.

BRAGFLO uses the Brooks-Corey relative permeability model for two-phase flow within all media except the anhydrite interbeds. Although site-specific parameters are not available to support this model, the use of surrogate media and the practice of incorporating uncertainty through random sampling from a range of values is considered appropriate. The sensitivity of pressure buildup to the alternative van Genuchten-Parker two-phase model was documented in Christian-Frear and Webb (1996) and found to be relatively low. Although the Brooks-Corey model calculates slightly higher repository fluid pressures

than the van Genuchten-Parker model because of the reduced fluid mobility, the impact of this assumption was found to be small in the repository, where the porosities are high and the threshold pressures are low.

The depth of the model cells increases in a stepwise manner away from the repository to simulate radial flow into the repository, shaft, and borehole. While this is appropriate for flow to or from the shaft or borehole, it creates narrow constrictions in the two-dimensional flow field when considering flow across the shaft or borehole within the repository. The significant decrease in model depth in the vicinity of the borehole and shaft creates artificial constrictions for horizontal flow across the model. Model results were reviewed and have shown that the pressure drop across these constrictions is negligible under an undisturbed flow condition and that fluid movement is not unduly restricted. The lack of a significant pressure drop is expected to be related to the very low rates of flow and the relative mobility of the gas phase. However, this model configuration may restrict the rate of equilibration of brine saturation within the repository following an E1 borehole intrusion and the movement of brine from the "rest of the repository" to the anhydrite beds to the south.

Site characterization boreholes drilled by WIPP in the vicinity of the site are not addressed in BRAGFLO. ERDA-9, for example, penetrates the repository horizon within several meters of a drift wall in the operations area, but does not penetrate the repository excavation. The disposition of these boreholes is not addressed by DOE in the documents provided to the Panel. Unless properly sealed with a low permeability material such as a continuous concrete plug, such boreholes represent potential release pathways.

The permeabilities used in BRAGFLO for the waste materials and the panel closure seals are constants, but in reality are expected to change over time due to repository room closure. These parameters are important to repository fluid flow. The values chosen for permeability are in the high end of the range, and while they are conservative for late times, they underestimate permeabilities for early times. Both the closure seals and the waste may be highly permeable at early times, when the ability of the closure seals to effectively isolate waste panels may be in question. While the operations and experimental areas also are assigned constant permeabilities, the assigned value of 1×10^{-11} m^2 is considered conservatively high and therefore adequate for performance assessment purposes.

The permeability used in BRAGFLO for the DRZ is constant, but in reality is expected to change over time due to repository creep closure and to ultimately approach that of undisturbed halite as the fractures

in that zone heal. The actual permeability will be determined not only by the stress-induced fracturing, but also by the roof falls expected after closure and by the numerous test, characterization, and rock bolt boreholes that penetrate the zone from inside the repository and may not be sealed before closure. The permeability of 1×10^{-15} m^2 assigned to the DRZ has apparently been selected to not impede fluid flow from the repository to the anhydrite interbeds, but has not been based on an analysis to determine what the actual permeability would be. The value chosen for permeability is expected to be in the high end of the range, and while it would be conservative for late times, it may underestimate the permeability at early times.

The evaluation of the panel closure seals in restricting the effects of borehole intrusions to the penetrated waste panels suggests that the design, placement, and performance of these seals is important. The assigned constant permeability of 1×10^{-15} m^2 is equal to that of the disturbed rock zone, yet the crushed salt and concrete to be used in the seal will have considerably different and time-variant properties, depending on the seal design, methods of emplacement, and creep closure rates and pressures. The permeability of the concrete will increase over time due to degradation, while that of the crushed salt will decrease due to consolidation. The panel closures do not appear to have been formally designed and an engineering evaluation of their performance over time does not appear to have been performed.

3.3.2.3. Evaluation of Alternatives

The overall conceptual model for repository fluid flow has evolved over time and has been the subject of detailed review in which alternatives were evaluated and led to refinements in the numerical representation of the model in BRAGFLO (see, for example, Christian-Frear and Webb [1996] and Freeze et al. [1995]). The alternatives evaluated included three-dimensional versus two-dimensional representation, including and excluding gravity effects, and varying configurations of the two-dimensional representation. Based on these studies, the overall conceptual model, as configured for use in performance assessment, has been shown to be adequate; however, the validity of certain assumptions regarding components of this model has been questioned, as described in Section 3.3.2.2. These assumptions include alternative depths for model cells in BRAGFLO, committing to sealing the ERDA-9 borehole prior to repository closure, providing variable permeabilities for the waste, panel closure materials, and the DRZ, and providing an engineering design and performance evaluation of the panel closures.

3.3.2.4. Uncertainties

The principal uncertainties in the model results are expected to stem from uncertainties in the modeling theory and in the parametric data base. Emphasis in this review has been on identifying uncertainties that would lead to underestimating radionuclide releases. While the theoretical basis for the model may contain inaccuracies, it closely represents the state-of-the-art and with the exceptions noted above, does not appear to bias the results toward underestimating releases. The principal uncertainties in the parametric data base are associated with the hydrologic properties of the repository materials and are addressed in the aforementioned reports Freeze et al. (1995) and Christian-Frear and Webb (1996). Material properties with high degrees of uncertainty are generally treated as distributed variables. The properties of the panel seals, however, are not distributed variables and in the absence of a more thorough analysis of the seal design and its long-term performance, the ability of these seals to successfully isolate waste panels must be considered uncertain. Another uncertainty stems from the lack of a DRZ in the repository walls and the potential for waste releases through exploratory boreholes that penetrate the walls rather than the waste itself. The consequence of uncertainties in the models or data base is ultimately to overestimate or underestimate radionuclide releases; however, many of these parameter values reflect best estimates of future conditions and are considered adequate for performance assessment.

3.3.2.5. Adequacy of the Conceptual Model

The conceptual model for repository fluid flow is fundamentally sound and represents an appropriate effort to simulate the complex, strongly coupled fluid flow processes occurring within the repository during periods of simultaneous gas generation and creep closure. The appropriateness of the model was supported by the results of more detailed modeling reported in Freeze et al. (1995) and Christian-Frear and Webb (1996). The issues raised regarding the validity of the model assumptions (Section 3.3.2.2) are associated with specific, but potentially significant, details of the model. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.3.2.6. Adequacy of Application

With the exception of the issues raised in Section 3.3.2.2 regarding model assumptions, the application of the conceptual model in the numerical model is adequate. Principal concerns are related to the model cell depths, the treatment of material properties that vary over time, the disposition of the ERDA-9 borehole, and a more thorough evaluation of the long-term performance of panel closures as repository seals.

3.3.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. Although many simplifying assumptions are made, they are generally demonstrably conservative and are appropriate in view of the need to make the probabilistic modeling effort tractable, and in view of the relatively high degrees of uncertainty in both input parameters and the occurrence of future events. Selected modeling results were reviewed (specifically, repository pressure differences across borehole and shaft cells and at model boundaries) and were found to be reasonable. Although the accuracy of the BRAGFLO results is expected to be adequate and appropriate for performance assessment modeling, provided that the issues raised in Section 3.3.2.3 are appropriately addressed, a final determination of model accuracy cannot be made in the absence of modeling results.

3.3.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain pending resolution of the issues raised in Section 3.3.2.3. In summary, the following concerns remain.

- The sensitivity of modeling results to the depths of the cells in BRAGFLO representing the borehole and shaft does not appear to have been evaluated for a variety of flow conditions to determine if the model configuration unrealistically restricts brine movement within the waste panel area or to the anhydrite beds at the southern end of the repository. If modeling results are found to be sensitive to this model configuration, alternative configurations might be considered.

- A commitment to effectively seal the ERDA-9 borehole with a continuous concrete plug does not appear to have been made by DOE. Such a commitment is expected to be provided in Chapter 3 of the CCA; however, this chapter was not available to the Panel for review.

- The sensitivity of model results to the constant permeabilities assigned to the waste materials and panel seals does not appear to have been evaluated. Higher permeabilities at early times could lead to underestimating radionuclide releases.

- The basis for the permeability value assigned to the repository DRZ has not been adequately supported, and the sensitivity of model results to the selection of a constant value for this parameter does not appear to have been evaluated for the current performance assessment model. The presence of open, unsealed boreholes within this DRZ and the likelihood of massive fracturing during roof failure suggest that the permeability of this zone may approach that of the waste.

- The waste panel closures do not appear to have been formally designed and their long-term performance does not appear to have been evaluated in the same rigorous manner as shaft and borehole seals.

3.3.2.9. Adequacy for Implementation

The Repository Fluid Flow conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.3.2.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.3.2.10. Dissenting Views

There were no dissenting views for this model.

3.4. Salado

3.4.1. Model Description

The Salado Formation is the principle barrier between the waste and the environment and is the primary source of brine flowing into the repository. The conceptual model supports estimates of hydrologic processes and properties, as well as mechanical behavior of the halite-rich rocks of the Salado Formation. A simplified stratigraphy for hydrologic modeling is proposed and supported. The modeling of the anhydrite interbeds is discussed elsewhere.

The Salado Formation was deposited by cyclical evaporation of marine water in an imperfectly closed sub-basin of the Permian Basin. The sub-basin, called the Delaware Basin, contains the Los Medanos region in which the WIPP site is located. The cyclical nature of deposition is represented by variations in the details of the mineralogy and geochemistry of the halite, by the presence of interbeds composed mostly of anhydrite, and by the presence of clay seams. Individual depositional cycles are a few meters thick. Relatively pure and impure (argillaceous) halite layers are present. Anhydrite interbeds, generally less than a meter or two thick, represent relatively fresh water inflow at the beginning of evaporative cycles. All of these variations represent fluctuations in water chemistry and the influx of windblown and water-borne fine clastic sediments.

The layering and composition of the Salado impact the mechanical processes of room closure and the hydrologic processes (both gas and brine) that accompany room closure. A detailed stratigraphy, which defines the distribution of mechanical properties and processes, has been developed for use with the MD model (Munson et al. 1989). Christian-Frear and Webb (1996) asserts that a simplified model containing only impure halite and interbeds is sufficient for hydrologic considerations.

The presence of a significant fraction of clay (≈5%), primarily as interstitial inclusions, significantly impacts the mechanical behavior of halite rocks. The clay promotes fracture and reduces intergranular cohesion and friction, increasing the rate of creep. Impure halite is also more permeable than its purer analogue. This may be due to the interference of clay particles in intergranular spaces with the processes of pore closure related to creep under natural loads.

The pre-excavation hydrologic environment in the halite rocks of the Salado is one which may be characterized as having very low permeability and porosity due to void-filling by diagenetic processes and creep resulting from the superincumbent load. Although both display very low porosity and permeability, the pure halite rocks display lower (almost impossible to measure) permeability than the impure halite. No significant natural flow occurs in the pre-excavation Salado environment. The anhydrite interbeds are more permeable than the halite rocks and have natural fractures. This is presumed to result from the physical properties of anhydrite, which is stronger and more brittle than halite and resists creep at the repository lithostatic pressure. Beauheim (1987) documented that permeability is greater near the excavations (beyond the secondary DRZ) at distances of several meters and that pore pressures decrease near the excavations, implying that flow resulting from stress imbalance around the excavations is occurring. Brine seeps on excavation walls, collection of brine in boreholes in the repository floor, and the measured contribution of inflowing brine to humidity in the repository, are clear indications that brine inflow is occurring.

Three flow mechanisms have been proposed based on the varied, mostly qualitative data about flow into the repository (Howarth et al. 1995). These are: 1) far-field flow in response to potentiometric gradients resulting from excavation through naturally interconnected pore spaces; 2) redistribution of pore fluids (pores not necessarily originally interconnected) due to fracture and creep around the excavations; and 3) flow due to consolidation of water-bearing clay layers. None of these mechanisms can be eliminated on the basis of the existing evidence, so an inflow model combining the estimated volumes of brine from each mechanism is proposed. No consideration of the role of brine included in halite crystals is mentioned, although fracturing and some intracrystalline creep mechanisms may liberate brine from this source.

Estimates of quantities of brine inflow from each proposed flow mechanism over the repository history (to final closure) were made on the basis of best-estimate values. Although the volume of brine inflow from the far-field mechanism is theoretically unlimited, low permeability and the relatively short time

available limit the probable actual volumes of brine that could reach the repository. The far-field mechanism may deliver between 25 to 110 m^3 of brine to a single disposal room over the life of the repository. Brine from the redistribution mechanism may range from 28 to 150 m^3. The clay compaction mechanism is assumed to have mostly ceased by the end of the disposal phase of work. These estimates depend on the repository gas pressures countervening the fluid potential gradient at a reasonably early time in the repository history. In any case, these mechanisms can supply enough brine to fully corrode the waste, between 100 and 150 m^3 per disposal room (Howarth et al. 1995). Flow out of the repository, due to elevated gas pressure by matrix flow or in fractures, is likely to be multiphase and will be less efficient than brine inflow. Specific data on Salado capillary pressures are not available.

Brine inflow and outflow have been simulated using the BRAGFLO model, and some specific enhancements to tie in specific conceptual model components have been proposed. These are: (1) Stratigraphy, (2) Salt Creep, (3) Fluid Flow, (4) Transport, (5) Thermally Driven Fluid Flow (insignificant), (6) Model Initial Conditions, (7) Disturbed Rock Zone, and (8) Interbed Fracturing. The model results were compared with the small scale brine inflow and Room Q experiments. McTigue (1993) evaluated the experimental results, using an exact analytical solution based on simple Darcy flow, for three flow histories for two flow mechanisms. This analysis provided an acceptable comparison between model and experimental results.

The INTERVAL program (Howarth et al. 1995) provided partial review of the model/experimental comparison and concluded that the Darcy-based version of BRAGFLO could replicate the Room Q results consistently with refinements of the inflow models to better simulate the pore pressure field around the excavations.

Electrogeophysical experiments were performed to evaluate the extent of the interconnected pore-space field around the repository and were found to support the far-field flow model (Borns et al. 1990). That is, the extent of saturated and interconnected pore spaces was seen to be infinite in the horizontal direction in the Salado.

3.4.2. Review of Criteria

The Salado is the primary barrier to radionuclide transport out of the repository. Its mechanical properties dictate the most important aspects of room closure and its hydrologic properties control brine inflow and gas and brine outflow. The objective of the Salado model is to provide a set of process and

property descriptions unified to define the original state of Salado equilibrium with its natural environment and its responses to excavation of the WIPP facility. The mechanical aspects of the Salado model support the Creep Closure model. The hydrologic aspects of the Salado model define the framework for consideration of brine inflow and brine and gas outflow from the repository. Detailed consideration of the anhydrite interbed and impure halite behavior are presented in other conceptual model reviews. The Salado conceptual model is central to the performance assessment because of the general absence of important quantitative measurements of principal parameters describing flow in the very low permeability halite rocks.

3.4.2.1. Information Used to Develop the Conceptual Model

Surface-based hydrologic testing of the Salado was abandoned because of the extremely long times required for testing in the extremely low permeability environment. *In situ* testing in the facility excavations included testing in short boreholes in Room Q, laboratory testing on samples from the excavation, electrogeophysical surveys, and collection of water from wall seeps and openings such as unlined boreholes. Packer tests were performed to specifically examine questions about interbed permeability and critical pressures to activate interbed fractures. Mechanical property measurements include closure rate measurements and laboratory tests. Mechanical models are discussed in the Creep Closure and DRZ model reviews.

Inflow and outflow models are based on best estimates, since only indirect measurements of flow and pore pressures in the low permeability Salado in disturbed areas near the repository are available, and no actual data are available for the hydrologic properties of the undisturbed or far-field natural state of the halite rocks. Only one, yet to be qualified, hydrofract experiment far enough from the repository to imply undisturbed stress conditions, has been done. Models of flow are essentially limiting calculations based on estimated and projected process parameters. Hydrofracture of the repository is not considered in the model since such an event is considered a "conservative" result lowering gas pressure. It is also possible that interbed critical pressures are low enough that halite hydrofract pressures may never be reached. Interbed critical pressures are estimated at a maximum of 5 MPa and Salado critical pressures appear to be between 15 and 20 MPa.

3.4.2.2. Validity of Model Assumptions

The hydrologic model of the Salado assumes that the three proposed flow mechanisms (Section 3.4.1), exclusive of flow in the interbeds, are the only credible flow mechanisms and that the estimated volumes

of brine inflow are credible. The estimated volumes of brine inflow are sufficient to corrode all of the corrodable materials in the projected waste. The key assumptions appear to be valid with respect to inflow processes. The inflow volumes depend on the interaction of inflow with repository gas pressures and on the estimates of the far-field flow response to repository excavation. The assumption of Darcy flow seems valid in the far field, but is difficult to demonstrate in the region near the repository. Inflow volume estimates are difficult to validate. Outflow hydrodynamics depend on two-phase flow models, which depend on capillary pressures in the Salado. No capillary pressure measurements are available. Larger outflow into the Salado beyond the DRZ by matrix flow is a conservative influence since the process would amount to interstitial storage of contaminants. Although likely to some extent, no credit is taken in final performance assessment calculations for this phenomenon. The assumption of cessation of flow from clay compaction before the end of the repository phase is acceptable because of the small brine volumes predicted.

3.4.2.3. Evaluation of Alternatives

No alternative models were evaluated by DOE (see Section 3.4.2.2).

3.4.2.4. Uncertainties

Although somewhat uncertain, the brine inflow model predicts sufficient volumes of brine to corrode all of the corrodable waste. There are, therefore, no consequences of reasonable additional uncertainty in terms of corrosion and gas generation. Brine volumes very much greater than those predicted would have to occur before brine mechanically interferes with room closure, and is unlikely. Brine availability for biogenic waste degradation is assumed. The Room Q and other observations appear to support the general validity of brine inflow estimates and the unlikelihood of very large uncertainties. Only very large underestimations of brine inflow would have significant impact, unless the sudden dissolution of dissolved gases during human intrusion might cause direct discharge of brine in the repository to the surface. The timing of the occurrence of gas pressures sufficient to retard brine inflow is the principle control of brine volume. This timing is addressed in the Gas Generation conceptual model and the porosity surface calculations.

3.4.2.5. Adequacy of the Conceptual Model

Given that the conceptual model predicts that there will be enough brine to corrode the waste and that other assumptions appear conservative, making other impacts unlikely, the model is adequate for its intended use.

3.4.2.6. Adequacy of Application

Assuming that the interaction of the inflow model with the gas generation model and the porosity surface calculation are adequate, the application of this model is adequate.

3.4.2.7. Accuracy of Results

It is unlikely that the results of the application of this model are highly accurate, but in view of the conservative assumptions and the large margin between the assumed impact on waste degradation and other significant impacts, the results appear to be accurate enough for the intended purposes of performance assessment.

3.4.2.8. Validity of Conclusions

The conclusions appear to be valid. Estimates of inflow volumes from the mechanisms proposed in the model appear to be reasonable.

3.4.2.9. Adequacy for Implementation

The model is adequate for implementation.

3.4.2.10. Dissenting Views

There were no dissenting views for this model.

3.5. Impure Halite

3.5.1. Model Description

The Impure Halite conceptual model explains the role of impurities in influencing the mechanical and hydraulic properties of the halite-rich rocks in the Salado. The model supports the treatment of the distribution and stratigraphy of impurities in the Creep Closure and Salado conceptual models.

There are two general classes of halite rocks in the Salado Formation. These are called pure and impure halite, based on the occurrence of significant proportions of mineral phases other than halite in the impure type. Impurities include evaporite minerals such as polyhalite and anhydrite, as well as iron oxide coatings and clay. The most abundant (as much as 5%) and important impurity is clay, with the exception of the anhydrite interbeds, which are discussed elsewhere. Clay occurs as clay seams, which

are treated as mechanical discontinuities in the Creep Closure model and as sources of inflowing brine in the Salado hydrologic model. It is as dispersed, interstitial clay that impurities have the most impact on the behavior of halite-rich rock.

Pure halite is more impermeable (Howarth et al. 1995), more ductile, and stronger (lower creep rate by a factor of four) than impure halite (Munson et al. 1989). Mechanically, the elastic interstitial clay platelets probably act as flaws, concentrating stress and modifying plastic micro-mechanical strain mechanisms. Pure halite is thought to be almost perfectly impermeable because creep under natural lithostatic stress has caused adjacent crystals to conform to each other's shape along their interfaces so completely that there is almost no space for interstitial brine. Such close-fit crystal mosaics, even in the presence of thin brine films on their interfaces, have minimal interconnection between pore spaces and any movement through the interstices would be inhibited by adsorptive and film-strength forces.

Clay particles between halite crystals interfere with the closeness of fit of adjacent crystal faces, concentrate stress, and may promote solubility of pore walls. Clays are phylosillicates, which in many cases are capable of chemically driven adsorption and desorption of water, promoting flow and water storage in pore spaces. The mechanical influence of clay promotes microfracture, which may enhance flow in response to stress imbalance around the repository.

Christian-Frear and Webb (1996) has asserted that a hydrologic model of the Salado that ignores the stratigraphic variation within the halite rich rocks of the Salado leads to an acceptable and conservative flow model result if all the halite-rich rocks are modeled as impure halite. This model conservatively overestimates flow in the halite rocks to an acceptable degree and eliminates the need to consider variation in the degrees of impurity and stratigraphic complexities among pure and impure halite rocks. Conservatively chosen values for impure halite permeability make this an adequate approach to modeling of halite-rich parts of the Salado.

The geometry of flow in the impure halite is convergent/divergent as discussed under the Repository Fluid Flow conceptual model review. The probability of hydrofracture of impure halite is probably larger than for pure halite because of the loss of cohesive strength due to clay in the interstitial spaces. Hydrofracture is not considered because it would lower gas pressures (a conservative influence), and because critical pressures for fracture of impure halite are much higher than for interbed flow. Interbed threshold pressures vary from one to five MPa, while halite critical pressures approach 20 MPa. Also, outflow estimates are based on two-phase flow and are not based on measured capillary pressures.

3.5.2. Review of Criteria

The impure halite conceptual model provides a basis for the evaluation of brine inflow and outflow from the repository within the simplified stratigraphic framework based on work by Christian-Frear and Webb (1996). Although differences in the behavior of pure and impure halite, variable degrees of impurity, and complexities of stratigraphic distribution of zones of impurity exist, the modeling of all halite rocks in the Salado as impure halite is an acceptable model simplification (Christian-Frear and Webb 1996).

3.5.2.1. Information Used to Develop the Model

Measurements of impure halite hydrologic properties (see natural barriers panel review) and assumed flow geometry and mechanisms (see the Salado model review) provide the additional bases for brine inflow estimates. Christian-Frear and Webb (1996) evaluated the acceptability of the simplified stratigraphy using impure halite only for halite-rich rocks for the Salado model. The Impure Halite model lacks precise flow rates and capillary pressures from hydrologic measurements and the flow mechanism process models are based on assumptions which have only theoretical bases, but provide results that acceptably match experimental and observational data.

3.5.2.2. Validity of Model Assumptions

The model assumptions are the process models for flow mechanisms, the Darcy nature of far-field flow, and the conservatism of the simplification of stratigraphy proposed by Christian-Frear and Webb (1996). These assumptions are reasonable and are supported by arguments presented by Howarth et al. (1995), by the comparison of model elements and inflow observations by McTigue (1993), and by review of similar results by INTERVAL (Howarth et al. 1995).

3.5.2.3. Evaluation of Alternatives

Early WIPP models considered all halite-rich rocks to be unsaturated and impermeable. Observation of inflow after excavation forced the development of flow models for halite-rich rocks. All observational and most experimental data are from impure halite. No alternative flow mechanism models have been considered (Howarth et al. 1995).

3.5.2.4. Uncertainties

The impure halite model is almost entirely theoretical and no evaluation of uncertainties is considered. Results match *in situ* brine flow observations fairly well. The result of uncertainty in the case of the simplifying assumptions with regard to stratigraphy are conservative.

3.5.2.5. Adequacy of the Conceptual Model

The model appears to be adequate for the same reasons that the overall Salado model is adequate. Brine inflow sufficient to corrode the waste and to drive biogenic degradation is assumed. For error to be significant, brine inflow would have to be very large, which is unlikely.

3.5.2.6. Adequacy of Application

The impure halite submodel is applied adequately, with the assumption that its application in the Salado model and related other models is conservative.

3.5.2.7. Accuracy of Results

The results of the model are probably not highly accurate, but appear to be adequate in their application.

3.5.2.8. Validity of Conclusions

The conclusions drawn on the basis of the impure halite model are valid for performance assessment purposes.

3.5.2.9. Adequacy For Implementation

The model is adequate for implementation for performance assessment purposes.

3.5.2.10. Dissenting Views

There were no dissenting views for this model.

3.6. Salado Interbeds

3.6.1. Model Description

The three Salado interbeds are modeled in BRAGFLO and are represented by region 20 (Marker Bed [MB] 138), region 21 (anhydrite layers a and b), and region 28 (MB 139). All three interbeds have the same model parameters (see Tables 6-12 and 6-13 in Section 6.4) and initially, the parameters are spatially constant. The only initial model difference concerns bed location and thickness.

Three primary interbeds are identified in the region of the Salado Formation nearest the waste panel: MB 138, anhydrite layers a and b, and MB 139. All three interbeds are primarily composed of anhydrite, with clay seams bounding the lower contacts of MB 138 and MB 139. As discussed below, the interbeds

have differing physical and chemical properties from the halite of the Salado Formation. Anhydrite is much less soluble than halite. The interbeds appear to be one or more orders of magnitude more permeable than the surrounding halite, primarily because of subhorizontal bedding-plane fractures (both healed and open) present in the anhydrites. Under differential stress, the interbeds may fracture while, under the same stress, halite would flow by plastic deformation. Fracturing of the relatively brittle interbeds would enhance the local permeability, allowing this otherwise low-permeability rock to carry groundwater. Furthermore, since the interbeds have a large contact area with the adjacent halites, even very small fluxes from the halite into the interbeds or to the halites from the interbeds can accumulate into a significant brine inventory. In this sense, the interbeds may cause the halite to act as a source or sink for brine in the repository. The three interbeds are explicitly represented in the conceptual model because of their physical properties and their existence in the disturbed rock zone around the repository, within which fluids are able to flow with relative ease compared to surrounding rock types.

Two major conceptual features of the interbed model are represented by, 1) transmission of brines from the impure halite to the repository via the interbeds and, 2) incorporation of fracturing and dilation of the anhydrite to allow porosity and permeability variations.

Feature one allows brine flow laterally along the higher permeability interbeds toward or away from the repository, and vertically between the interbeds and low-permeability halite. Horizontal fractures, dilation, and propping are due to gas pressures exceeding the threshold pressure. Induced vertical fractures in the interbeds are caused by interconnection of branching horizontal fractures over time, or high exceedence of the threshold gas pressure (i.e., greater than lithostatic). Pre-existing vertical fractures were caused by tectonic forces or the alteration from gypsum to anhydrite and subsequent volume reduction.

Feature two, alteration of porosity and permeability, is caused by the creation of new fractures or dilation of pre-existing, partially healed fractures due to high gas pressures. *In situ* hydrofracture tests have created sustained fracture apertures to 0.2 mm. Such pressure-dependent variables have created marked permeability changes. In the BRAGFLO model, a porous medium model simulating interbed fracturing and dilation causes porosity and permeability of a computational cell to increase as the pore pressure exceeds the threshold value. In addition, interbed transmissivity increases with increased anhydrite fracturing or dilation. Fluid is able to easily flow radially outward if adequate threshold pressure is available (1 to 5 MPa) to dilate the anhydrite. The model assigns a fracture initiation pressure at which

local fracturing occurs and changes in permeability and porosity subsequently occur. Above the threshold pressure, the local compressibility of the interbed increases linearly with pressure. This greatly increases the porosity with respect to increasing pore pressure. Additionally, permeability increases as a power function of the ratio of altered porosity to initial porosity.

3.6.2. Review of Criteria

3.6.2.1. Information Used to Develop the Conceptual Model

Three primary sources of information were used to generate the conceptual model for the Salado interbeds. These included FEP documentation, position papers, and *in situ* hydraulic tests. Four FEPs were associated with the Salado Interbed conceptual model: DR-9 (anhydrite threshold displacement pressure); S-1 (verification of 2D radial flaring); S-4 (mechanical effects of gas generation); and S-5 (brine storage in anhydrite and halite). A second source of information was the Salado position paper. The third major source of information for developing the conceptual model was obtained from *in situ* field tests of the anhydrite interbeds. Location of these tests was in the vicinity of Rooms Q and L. These information sources are believed to be adequate for model development.

3.6.2.2. Validity of Model Assumptions

The main assumptions of this conceptual model are considered valid. The chemical assumption, that anhydrite is less soluble than halite in the WIPP environment, is proven by both experimental and crystal chemical factors. The Darcy flow model is also deemed reasonable. The type of fracture propagation and dilation used in the conceptual model has been substantiated by *in situ* tests. Assumptions of increased porosity and permeability due to fracturing (caused by gas generation exceeding threshold pressures) is reasonable. Therefore, the assumptions of this conceptual model that have the largest potential impact are believed to be appropriate.

Three other assumptions of the interbed model have not been well documented. The first of these is the description of the mechanism of vertical crack propagation. This potential effect of gas overpressurization needs to either be fully described or discounted from occurring in the interbeds. Second, there does not seem to be any incorporation of the fact that there are continuous clay seams at the base of MB 138 and MB 139. The physical properties of clay seams (water content, low cohesive structure, aniostropic characteristics) may have a substantial effect on the model of the interbeds. Third, the fluid storage capacity of the interbeds is not well documented.

3.6.2.3. Evaluation of Alternatives

Earlier models of the Salado Formation in the 1980 final environmental impact statement did not differentiate the anhydrite interbeds as a separate model. When the 1989 draft environmental impact statement was produced, anhydrite interbeds were included as a model. This was based on *in situ* tests that determined the interbeds had higher permeability than the remaining Salado Formation. The 1992 performance assessment concluded that the interbeds would then be the dominant fluid pathway. It was not until this factor was recognized and gas pressures were calculated to possibly reach 20 to 25 MPa (in the 1992 performance assessment) that an attempt was made to model fracturing in the anhydrite interbeds.

At the level of a conceptual model, the primary factors of the Salado Interbeds have been addressed properly. This has been accomplished by either using well-established models (Darcy flow) or *in situ* experiments, or by adopting reasonable, conservative assumptions.

The following items do not appear to have been addressed by DOE: (1) Is storage capacity of the anhydrite layers so small that brines would be forced to travel to the Land Withdrawal Act boundary? (2) What would the consequence be if the gas threshold pressure of the clay seams was very low (for example, 0.01 MPa)?

3.6.2.4. Uncertainties

The levels of uncertainty associated with the Salado Interbeds performance at the conceptual model stage appear to be quite small. The following uncertainties may affect the model but the consequences are unknown at present. The determination of consequences would hinge on a sensitivity analysis, which is presently unavailable.

The model assumes that fracture propagation would continue uniformly in a horizontal direction. In Domski et al. (1996), test results for interbeds indicate anisotropy. Assuming that the interbeds act in an isotropic manner would be conservative, especially since *in situ* values were determined for the weakest direction (laterally).

Another assumption is that enhanced porosity and permeability in the interbeds would mitigate each other in terms of gas migration responses. This does not seem plausible since permeability increases as a power function to an increase in porosity. It would seem that permeability factors would dominate and therefore allow longer gas migration distances.

The perturbation to the model that is completely unaccounted for (threshold pressure of bounding clay seams) is included as a secondary factor in Section 3.6.2.3 above.

3.6.2.5. Adequacy of the Conceptual Model

The Salado Interbed conceptual model describes fluid flow through three discrete anhydrite layers in the vicinity of the repository. CCA Section 6.4.5.2 reports flow model objectives in dealing with the anhydrite interbeds: (1) fluid flow through the interbeds, (2) fracture formation and/or dilation of the interbeds, (3) variations in porosity of the interbeds, and (4) variations in permeability of the interbeds within the constraints of the conceptual models. These requirements are thought to be adequate. The uncertainties associated with the model can not be constrained since a sensitivity analysis is not presently available.

3.6.2.6. Adequacy of Application

A much greater uncertainty is perceived when it comes to converting the field results into the mathematical model. In all but the simplest of field observations, one must make assumptions in applying a mathematical model. However, the ability to monitor the assumptions made in developing a numerical code to simulate the physical properties acting within the anhydrite interbeds is extremely difficult. SNL states at one point that parameters in the model are treated as fitting parameters and have little relation to physical behavior, except that they affect the porosity change. At no time was the logic clearly presented whereby one could track the implementation of this conceptual model into the numerical code developed for this portion of BRAGFLO. Therefore, one must state that the discussion of how the anhydrite interbed conceptual model is applied into an overall performance modeling element was not adequate.

3.6.2.7. Accuracy of Results

The results obtained for this conceptual model fall into two categories. The first set of results are those determined from physical tests. Hydraulic tests performed *in situ* near Rooms Q and L, and laboratory tests on core samples have provided results that are deemed adequate. These tests are based on standard procedures and have been qualified as to their accuracy. There is no further question as to the validity of these physical parameter results.

The second category is based on whether the results of performance modeling using the conceptual model within the performance system are sufficiently accurate to adequately represent the physical and

chemical processes modeled. It is not possible to make a judgment on this category of results since no values have been presented to indicate the outcome of this model. The 1992 performance assessment did not incorporate a fracture propagation submodel in the Salado Interbeds model, so results and sensitivity analyses from that performance assessment are not applicable to this review. Results for this section are not meant to be the final performance assessment results, but rather are the results of BRAGFLO during various permutations.

For example, hydrofracture experiments in the anhydrite beds have created sustained fracture apertures to 0.2 mm. If BRAGFLO produced fracture aperture dimensions of 5.0 mm during gas pressurization runs, one would conclude that the results are not accurate. This sort of comparison has not been possible because model runs have not been presented.

The implementation of the fracture modeling was not explained in sufficient detail in any document. The method of how the code represents the physical property is unknown and its accuracy cannot be judged. Results of the calculation could vary significantly, depending on whether the fractures propagate gradually or in a stepwise fashion.

3.6.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Salado Interbed model in the modeling framework are valid. Since the accuracy of results is inconclusive (see Section 3.6.2.7), it is difficult to assess the validity of the conclusions. The results of parameters listed in Table 6-12 of the CCA may be considered valid for the purpose of implementation in the overall performance assessment. The results listed in Table 6-13 of the CCA may not be valid at this point. Questions of validity are addressed below.

Fracture initiation pressure for MB 139 at 0.2 MPa above hydrostatic pressure is concluded to be valid. The percent increment to allow full fracture porosity for MB 138 and 139 (3.9%) is also considered valid. The same parameter for anhydrite beds a and b is 23.9%, and no discussion is presented for the large difference in the value. The increase needed to allow full fracture porosity in these two interbeds would not be expected to differ from MB 138 and 139. Such a difference should have been thoroughly explained. The conclusion of maximum permeability (10^{-9} square meters) is extremely suspect since the storativity of the beds was not calculated. These two factors are closely linked and it is hard to envision that the permeability can increase ten orders of magnitude without a dramatically substantial change in

storativity of the interbeds. Finally, the parameter "increment above fracture initiation pressure to obtain maximum fracture pressure," does not account for the effect of bounding clay seams associated with the interbeds. To assume that an increase of approximately 1.5 MPa above lithostatic pressure is needed for maximum fracturing is probably not valid when clay seams are in close proximity

3.6.2.9. Adequacy of Implementation

The conceptual model for the Salado Interbeds is well thought out and substantiated by *in situ* experiments. However, certain items were not clearly explained or documented in Chapter 6 of the CCA. It would be helpful if the following questions were clarified:

- What is the mechanism for vertical crack propagation?
- What is fluid storage capacity of the interbeds after dilation?
- Enhanced porosity and permeability are presumed to mitigate each other in terms of gas migration responses. How can this happen when permeability is a power function (not linear) of porosity?
- What assumptions and limitations are made to represent the conceptual model by the mathematical code?
- Why is the full fracture porosity increment of 23.9% for anhydrite beds a and b so different from the 3.9% for MB 138 and 139?
- What are the calculations that show that permeability increases by 10 orders of magnitude?

It is believed that this model would be adequate for implementation in the compliance application after the question raised below is fully addressed.

- How do the physical properties of clay seams at the contact of the interbeds affect the fracture propagation and permeability of the model?

3.6.2.10. Dissenting Views

There were no dissenting views for this model.

3.7. Disturbed Rock Zone

3.7.1. Model Description

The Disturbed Rock Zone model consists of a description of a fracture zone surrounding excavations that is created by induced stresses. At the WIPP, the primary DRZ exists in all rocks; the secondary DRZ is

applicable only in viscoelastic rocks such as halite. The DRZ varies in depth away from the excavation and has been reported to be up to 50 m deep for large excavations. It exists in the repository roof, floor, and walls, and around shaft and borehole walls. Because of the distinctly different stress fields in each of these locations, the DRZ can have different properties at each location. For example, it is considered to disappear under appropriate conditions and with time in the borehole seals program, and is variously applied as it relates to the repository rooms and panels. Related models include Creep Closure, Shafts and Shaft Seals, Disposal Room Geometry, Repository Fluid Flow, Salado, and Salado Interbeds.

Induced changes to the stress field occur immediately on the passage of mining equipment during excavation. In halite, as the salt adjusts to these changes through the creep process, further micro- and macro-fracturing progressively occur in the intact rock, adding to a fracture region known as the DRZ. This DRZ was first technically addressed and demonstrated by Borns et al. (1987, 1988, 1989, 1990). Van Sambeek et al. (1993) have referred to the mining-induced fractures as the initial DRZ and the progressive fracturing as the secondary DRZ. In this analysis, the Panel will not distinguish between these except for their applications. The characteristics of the DRZ include increased rock volume and permeability and decreased brine saturation due to drainage and drying, load bearing capacity, and lithostatic pressure. Clearly these properties could lead to the DRZ providing flow paths for fluids and gases from the repository to those zones that might carry them to the accessible environment. Studies by Munson et al. (1994) have characterized the DRZ and found it to be irregular in thickness and fracturing and able to heal with time under an applied confinement. Two versions of a creep model, applicable to room closure and DRZ development, have been formulated during this period. These are a model that includes both transient primary creep and steady state creep (MD model), which has been used in the porosity surface lookup table calculation of repository void space, and the MD model, with added tertiary creep fracture (MDCF), used to confirm DRZ thickness, fracture porosity, and healing characteristics. The MD model is central to the porosity surface calculation (SANTOS), which relates creep, waste compaction, and gas pressure to overall room closure rate. The DRZ is not considered in room closure calculations since all DRZ fracture porosity is assumed to be recovered by healing at final closure. For the waste room, the DRZ model is incorporated by assuming a high permeability and low porosity, with the result that the DRZ is unable to act as a constraint to brine or gas flow from the repository rooms and is unable to store brine. A primary reason for this approach is the uncertain behavior of the rock zone, which is dependent on many uncontrollable factors.

3.7.2. Review of Criteria

3.7.2.1. Information Used to Develop the Conceptual Model

The treatment of the DRZ in both the shafts and the repository rooms is the result of development of an equivalent permeability and porosity for addition to the main room and shaft seal model elements rather than by a specific DRZ input. Analyses were conducted evaluating the reasonableness of this approach, but parameters representing the DRZ over the history of WIPP were not developed. Therefore, the information supporting evaluation criteria for review of this conceptual model is essentially the completeness of the considerations and the reasonableness of the DRZ concepts.

The DRZ has several significant impacts on the performance assessment calculations. These include a) room performance, b) gas pressure calculations, especially near term, and c) permeability of the shaft regions. The DRZ in the salt around the rooms appears to be the toughest to model because of the sizes and shapes of the openings. The shaft DRZs appear to be less difficult to model because of their simpler shape. First, the shafts are smaller than the rooms, second they are stable cylindrical forms, and third, studies show that, given a stiff support against creep, the DRZ fractures will heal in a relatively short time. For example, from analysis of WIPP data, Chan et al. (1995) projects full healing within 25 years after the shaft seals have been placed. Within the healed zone, the induced high permeability drops to a level below that of the placed seals, reducing the concern of a large flow path surrounding the sealed shaft. Contrary to this favorable healing in the shafts, DRZ healing in the waste room will not be as responsive in time or extent. Because of the relatively large room, the necessary rigid backing to support the healing process is delayed, and the DRZ functions as a more open fractured rock mass. Furthermore, only the DRZ in the roof and floor of the repository are modeled; the walls of the room are not included in the Repository Fluid Flow model. Neither the roof nor the floor will receive the support needed to close the open cracks and open boreholes that are assumed to be a part of the roof DRZ. Early healing of the floor would be optimal in order to restrain fluid flow downward, and the roof will continue to develop an open fracture DRZ upward, due to roof spalling, as the room seeks its most stable shape within the stress field. The most notable impact of the open fractures to performance assessment in the near term will be in deterring brine flow to the repository because of brine storage in the fracture zone. This could have significant uncertainty effects on the gas pressure calculations.

It should be noted that no information was found concerning studies of how soon after excavation the DRZ is fully formed. It is reasonable to consider that its formation begins concomitant with excavation

and progresses until the salt creep and the stress field have stabilized. The MDCF model appears to be an excellent tool for conceptualizing the phenomenology of salt creep and its mechanisms resulting in fracture closure and healing. Excellent progress in understanding salt's viscoelastic behavior and adding this capability to the creep flow behavior has made the modeling capability a highly supportive tool critical to understanding the DRZ. Testing of these concepts has produced favorable responses that have specifically aided the shaft seals program in mitigating concerns over seals integrity. Significant among these tests are the Room Q experiments, where identification of the reduced brine flow and increased permeability in the DRZ were measured. Data from the air-intake shaft tests showed the change of permeability as a function of distance from the shaft wall and the changes in permeability with time. Knowles et al. (1996) conducted rigid inclusion tests that confirm the ability to heal the DRZ, restoring it to ambient conditions. The many parameters associated with the DRZ have been well defined to support the BRAGFLO models. The permeability and porosities appear to be the most critical parameters for use in performance assessment. Information examined for the DRZ characterization, including its extent, ability to be restored by salt creep and restraint, and ability to be represented by modeling, was found to be acceptable.

3.7.2.2. Validity of Model Assumptions

The following assumptions are basic to the DRZ model:

- A DRZ surrounds the surfaces of any mined opening.
- A permeability value is selected that assures the DRZ is not the limiting zone for fluid transport between the waste rooms and the marker beds.
- A fixed high-level permeability value should be assigned to the DRZ everywhere.
- Roof bolts or other roof support system penetrations of the halite and boreholes through the halite into the marker beds are included as part of the DRZ, and these penetrating boreholes may not close completely.
- Various other processes may contribute to fracturing in the future.
- The DRZ surrounding the shafts will progressively heal toward near complete restoration following placement of the seals.
- The porosity and permeability are increased by the DRZ, except where a rigid backing is present to support the DRZ against creep; however, a low porosity is assumed in the room DRZ to reduce the storage capacity of that zone for performance assessment.

The basic assumption that a DRZ exists at the surface of any mined opening in the Salado is fundamental to the definition of a DRZ. That the leading boundary of the DRZ will heal, provided support exists to resist the creep, has been substantiated through the WIPP research program. Basically, the outer reaches of the DRZ (microfractures) will heal in the near term, and the DRZ primary fractures will close and heal once seal material is placed in the openings to support the process. This might reliably be achieved via the vertical cylindrical openings, but the healing problem is more complex around the waste room. There it is recognized that a variety of effects may work against the reconsolidation of the DRZ. These effects range from uneven placement and non-characterized waste support against room closure to other processes, such as roof falls, that might contribute to further development of the DRZ. These assumptions concerning the DRZ existence and its behavior appear to be adequate.

Given the shaft seals design, it is assumed that the shaft DRZ heals to the point that its permeability is below the level of seal permeability, thereby reducing its importance. Therefore, flow through the sealed shafts is attributed to the permeability of the shaft seal materials, with an adjustment to account for any DRZ component to the permeability (see Section 3.20). At the waste room, the situation is far more complex and the technology less well defined. Therefore, at the room boundary, it appears that the above assumptions support the assignment of a high permeability that essentially removes the DRZ from a limiting position of flow to and from the room, and a low porosity that will not perturb storage of the brine.

3.7.2.3. Evaluation of Alternatives

Fracture zones in the walls of excavations have always been of concern to the mining and construction industries. In most cases, however, fracturing occurs in brittle materials with elastic behavior, which is largely not the case in the viscoelastic host rock of the WIPP repository. Restoration of the DRZ to the original halite properties, as described in this report, would be applicable within most salt formations. However, at locations other than in the Salado Formation at the WIPP site (such as in the Culebra, Magenta and other members of the Rustler Formation), the DRZ will not obey the concepts forwarded. Because the DRZ in MB 138 and 139, and perhaps the anhydrite interbeds a and b, are different from the DRZ discussed here, they pose a concern for the open fractured DRZ concept and its ability to heal. This concern is discussed and analyzed within the seals design (WIPP 1996). It appears from the information available that numerous alternatives have been processed in the analysis and testing programs leading to present concepts and understandings of the DRZ. The assumptions adopted for the DRZ model are alternatives that appear to appropriately represent the existence and effects of the DRZ.

3.7.2.4. Uncertainties

A DRZ thickness of 0.8 shaft radius appears to be conservative. Munson et al. (1994) state that from the air intake shaft data (Dale and Hurtado 1996), the extent of the DRZ at 6 years is certainly less than 1.0 shaft radius, and probably only 0.7 radius. Using these same data, Chan et al. (1994) show a reasonable correlation between the test data and calculations from the multimechanism deformation coupled fracture (MDCF) model. No data were found to evaluate the effects of time on the relationship between excavation and closure. Relative to the room DRZ, the behavior of the roof DRZ might be the source of additional uncertainties in other models. Except for the shaft seals, no data were found to characterize applications of the DRZ in unique locations, such as the unsupported roof and the floor buckling from unrestrained creep.

3.7.2.5. Adequacy of the Conceptual Model

Recognition of the deleterious conditions produced by the DRZ appears to be positively addressed in studies showing the effects on brine flow in the repository and on the ability to heal under conditions of support in the shaft that makes the shaft seals issue more tangible to resolve. Because the uncertainties of possible unknown future effects of the room DRZ might go beyond the recognized problems caused by the DRZ, the room DRZ is dealt with from a conservative viewpoint. It appears that the model adequately addresses the genesis and existence of the damage zone. The MDCF model provides a realistic tool by which to examine the effects and project possible DRZ performance. Research, including that in the Room Q, the air intake shaft tests, and the rigid inclusion in salt tests (Knowles et al. 1996), has been supportive in calibrating and confirming model results (see Section 3.19). Because the roof DRZ is uniquely different from the other DRZs, the model does not adequately represent flow to the overhead marker beds. This issue is discussed in Section 3.3, Repository Fluid Flow, and in the following section. Except for this caveat, this model has the appropriate elements to support its use in the WIPP performance assessment.

3.7.2.6. Adequacy of Application

Recognition of the DRZ phenomenon around the shafts and measurements of its effects are important contributions to waste containment; in some cases these effects are among the few WIPP conditions that can be dealt with in engineering terms. It was important to find that the DRZ nearly completely heals once there is adequate backing within the shaft or borehole against which the creeping salt will reestablish its original state of stress. Because of the healed state and because tests show conservatively

that the DRZ areas of influence are within 1.0 shaft radius, it is possible to demonstrate that the DRZ permeability will become lower than that of the seals. This appropriately allows the performance assessment calculations to treat the DRZ permeability as an integral part of the seal. It is important to recognize that this healing factor is a function of the shaft seals' mechanical properties and time of placement. It is also important to recognize that because of the overwhelming uncertainties of DRZ performance in the waste rooms, it be dealt with conservatively by assumption, as stated in the model description. The waste room DRZ uncertainties basically apply to specific locations such as the roof, floor, or walls, and its extent in each.

Because of the variability of the geometry and the timing of the healing of the DRZ in the different environments in which it occurs, the DOE has substituted conservative permeabilities to represent the effect of the DRZ on repository rooms and shaft seal flows. These permeabilities are carried through the processes of repository closure and the evolution of shaft seal design, taking into consideration the marked differences in characteristics of these zones. While the shaft DRZ has been carefully studied, the repository room roof and floor DRZs have not had equal attention because of their complexity. To compensate for this, the DOE chose to use a constant, conservative value for the permeability of the repository DRZ that would not be the limiting condition for flow to and from the interbeds. This approach has not been adequately supported, particularly for the roof DRZ, where the fractures may be open, large, and progress to roof collapse. Furthermore, this zone is host to drill holes that may not be plugged and can penetrate beyond the overlying marker beds. This issue has been identified as a concern for the Repository Fluid Flow model in Section 3.3. The DRZ in the room walls is not modeled, and is thought to be of little structural impact because by conservation of pore space, the initial fracture volume of this DRZ is recovered during room closure and healing.

This evaluation recognizes that the disrupted zones near the shafts have been characterized. Also, this evaluation has shown that DOE used this information in several ways, leading the Panel to conclude that the DRZ needs to be separately considered for each of its applicable areas. These areas include the roof, floor, and walls of the waste room, and the walls of the long annular openings such as shafts and boreholes. Except for modeling the roof DRZs, the Panel believes that the work to date adequately addresses the DRZ characterization for application to the performance assessment process.

3.7.2.7. Accuracy of Results

While the Room Q tests produce data that contribute to the understanding of the waste room DRZ, it appears that the value of these results is to provide background concepts and guidance for addressing the DRZ issues. After looking at the numerous unknowns or uncontrolled processes in the waste room, it seems prudent to defer analysis of the DRZ issue in the waste room until further understanding of the waste characterization becomes available, in order to more fully consider the effective resistance the waste provides to room closure by creep.

For the shafts and boreholes, the air intake shaft permeability data (Dale and Hurtado 1996), which show the extent of damage resulting from the shaft excavation to be approximately one shaft radius, has provided good basic information on this issue. Other analyses of related data and observations from the air intake shaft tests (Munson et al. 1995; Chan et al. 1995) show that the extent of the DRZ is related to shaft size, and make phenomenon amenable to incorporation in a mechanistic model. The collaboration of Munson et al. (1989) and Chan et al. (1995) has proposed one such model through coupling the DRZ fracture to the creep model (the MDCF Model). Other calculations include the determination of fracture healing time and projections of the effects of shaft seal mechanical properties on fracture healing. It should be recognized that the MDCF modeling results largely represent an early stage in this technological development and are subject to projected corrections as more time-dependent follow-up data become available. Because of the predicted low impact of the DRZ on sealed shaft permeability a few years after seal placement, it appears totally appropriate to adjust the permeability of the shaft seal components for the small contribution that the DRZ will make to the performance assessment calculations.

The same closing comments for Section 3.7.2.6 apply to this section; therefore, the results obtained are sufficiently accurate for application of the DRZ in the performance assessment process.

3.7.2.8. Validity of Conclusions

All observed considerations of analysis, study, and proposed engineered applications regarding the DRZ and its impacts on effective shaft sealing appear to be valid. The understanding developed of DRZ phenomena and data reveal that it is critical to engineering waste containment overall because of its potential for negative impact on shaft seal permeability and integrity, and fluid flow in the rooms and room seals. It appears that all considerations of this impact and the conclusions discussed here are sound and valid.

Relative to DRZs in the waste room roof and floor, the fractured zones have a high probability to exist and not much can be done to mitigate their effects, such as providing the stiff support needed to foster healing of the DRZ as shown by the Knowles (1996b) report test results. Credits taken for room closure due to creep will be beneficial, but this may not be significant help in later years, when the potential higher gas pressures may reverse the creep. At high gas pressure this problem is exacerbated by an expanding room scenario which could extend the DRZ even further. It appears the concepts of characterization of the DRZ, particularly in the floor, have not been well researched; perhaps an elicitation panel would be constructive on this. The roof DRZ should have less significance than the floor DRZ because brine is more likely to flow through the floor than the roof; however, the roof DRZ does facilitate the access of gas to the release pathways. The Panel concludes that while the conservativeness of the assigned DRZ permeability might overcome the lack of detailed information for the roof DRZ, further analysis of the roof behavior would enhance defendability of the otherwise valid model.

3.7.2.9. Adequacy for Implementation

Given the lack of tangible controls over remedying the room DRZ, but the encouraging test results for mitigating the shaft DRZs, it appears that appropriate considerations are being made for the DRZ conditions in all applications. It is clear that continued studies of the room DRZ would provide a better background to more explicitly model the waste room and to ascertain the variation of DRZ characterization for each of its location sites, such as in the roof, floor, or walls of a room. The Panel concludes that the present DRZ model is adequate to be implemented in performance calculations. However, since the roof is different, some other approach may be appropriate for this area.

3.7.2.10. Dissenting Views.

There were no dissenting views for this model.

3.8. Actinide Transport in the Salado

3.8.1. Model Description

The only transport mechanism that will be used in this conceptual model is advection. The Actinide Transport in the Salado conceptual model previously addressed three mechanisms: 1) advection (transport with bulk flow of liquid); 2 dispersion (liquid velocity differences while moving through pores

or surface irregularities); and 3 diffusion (molecular motion in presence of concentration gradients). These mechanisms are all standard contaminant transport phenomena. DOE assumed that these three transport mechanisms of actinides in brine represented the most important processes of actinide movement in the Salado Formation. All three mechanisms look at the transport of dissolved or colloidal actinides through the anhydrite interbeds (MB 138, MB 139, and anhydrite interbeds a and b).

The advection transport mechanism is implemented by the NUTS computer code in conjunction with the Salado fluid flow portion of BRAGFLO. The NUTS code is described in Section 6.4.11 of the CCA and Appendix NUTS (which were not available for Panel review). The actual inventories of actinides come from the Dissolved and Colloidal Actinide Source Term conceptual models. The actinide source terms incorporate the assumed oxidation states and solubility factors for various actinides and a proportion of all colloids permissible.

Three physical influences that may affect actinide transport in the interbeds have been left out of the conceptual model by DOE to promote a conservative philosophy. These influences are sorption of dissolved actinides on clays, retardation of colloidal actinides by surface features, and mineral precipitation containing trace actinides from brine. Sorption of actinides onto clay surfaces is a known reaction, and DOE is highly confident that it will occur; however, the model conservatively neglects the effect. With regard to retardation of colloidal actinides by surface features, it is assumed that offsetting interactions will occur. The philosophy is that colloids can be retarded by surficial features, but will travel faster than the average velocity of the bulk liquid. Precipitation of minerals as brines move into the interbeds due to chemical gradients is a possibility. Given the concept that the amount of precipitation will be minor, and that actinides will only occur in trace amounts in the crystal structures, DOE has decided to neglect this effect in the performance assessment.

Three other mechanical processes may have a lesser impact on actinide transport in the Salado. These are fracture flow, channeling, and viscous fingering. Fracture flow is accounted for in the Salado Interbed model and takes into account increased porosity and permeability through fracture propagation and dilation. DOE expects that other fracture processes and effects not taken into account in the fracture model will be negligible. One process not incorporated, channeling, has offsetting effects. Channeling is the fluid movement through large apertures of a fracture network (i.e., locally high permeability). DOE believes this mechanism will be negated for two reasons. First, if gas is present in the undisturbed state, it will preferentially occupy areas of high permeability over brine. This will preclude these regions of

fast transport from brines. Second, the incoming brine will be miscible with the interbed brine. Such miscibility will allow diffusion and mixing phenomena to broaden finger fronts (i.e., reduce concentration gradients) until they are indistinguishable from the advancing brine front.

Gases may also penetrate interbed brines as a fingered front. However, such a mechanism will not affect actinide transport because the actinides of interest are only incorporated in the liquid phase. DOE also assumes that a liquid will not displace gases in the high-permeability regions (channels) due to capillary effects.

3.8.2. Review of Criteria

3.8.2.1. Information Used to Develop the Conceptual Model

The Actinide Transport in the Salado Formation model is based primarily on the computer code NUTS, with input from BRAGFLO. Since NUTS relies on BRAGFLO input parameters, all BRAGFLO FEPs became information used in the model development. In a sort of circular logic, NUTS was used to evaluate BRAGFLO FEPs by converting flow measurements to normalized release values. The original NUTS program was extremely intricate and robust, with its basis in classical fluid transport. However, FEP studies and system prioritization events have simplified the code. NUTS now only uses advection as a transport mechanism, tracks only the wastes encountered along the flow paths, and treats downstream fluid and the fraction that came into contact with waste. The transport mechanisms of diffusion and dispersion have been excluded from the code, based on policy decisions associated with the system prioritization analysis. The exclusion of these two transport mechanisms is believed to make this conceptual model more conservative. As stated in the model description (Section 3.8.1) the exclusion of six other processes (clay sorption, surface feature retardation, mineral precipitation, fracture flow, channeling, and viscous fingering) is deemed to allow the conceptual model to be more conservative.

A second source of information critical to the NUTS code is the field of radiochemistry. Concepts dealing with radioactive decay, half-lives, and solubilities allow major assumptions to be implemented in the NUTS program.

The third major source of information folded into the actinide transport of the Salado Formation is physical properties of the anhydrite interbeds. These interbeds are the major pathways for fluid transport in the Salado. Data concerning the physical properties of anhydrite were obtained by *in situ* hydrologic tests. The fracturing properties of the beds were deduced from both field and laboratory experiments. It is deemed that the information used is adequate to develop the model.

3.8.2.2. Validity of Model Assumptions

The following assumptions are critical to the conceptual model being evaluated here. Diffusion, hydrodynamic dispersion, and channeling in discrete fractures, are not included in the model. DOE has taken the stance that by not including these factors, the actinides are not further dispersed and therefore the model is made more conservative. These assumptions are considered valid.

The assumption of lumping radionuclides by similar half lives and solubilities is based on the basic tenets of radiochemistry. If any computer run later indicates a potential to exceed EPA's criteria, such lumping factors can be recalculated using specific data for each radioisotope. Evaluations have not been performed to see if the lumping assumption could, in effect, mask runs from approaching the EPA limits. With this caveat in mind, the assumptions made about lumping can be considered valid.

Actinide source terms (dissolved and colloidal) in the repository are used as the input for NUTS. The assumption that these source terms are the limiting cases may not be valid, however that determination is not within the scope of this model (see Sections 3.23 and 3.24).

Once the total concentrations are calculated for the dissolved and colloidal sources for each run, the final value is then transported as one package at the average flow value. The assumption made is that colloids can be transported at this slower rate and still be adequate since sorption and filtration of colloids are not accounted for. This assumption has not been proven to the Panel's satisfaction.

The final major assumptions of this model are that the grid blocks and time steps from BRAGFLO are proper to use in NUTS. Although this final set of assumptions may be reasonable, numerical results must be examined to determine if this concept (and inherent coarseness) is valid. At present, such results are not available.

3.8.2.3. Evaluation of Alternatives

Earlier versions of the NUTS code were much more comprehensive than the present version. Previous compilations had the capacity to treat virtually all special effects of radionuclide migration. However, system prioritization exercises and FEPs studies indicated that a much more simplified version of NUTS was desirable, in that results were still representative and computer run time was compressed. Hence, the present version of NUTS is streamlined. Factors that have been removed (or zeroed) include diffusion,

dispersion, channeling, chemical sorption for dissolved actinides, physical retardation for colloidal actinides, fracture flow, and viscous fingering. The present version of NUTS is reasonable for its intended use.

3.8.2.4. Uncertainties

There are a multitude of uncertainties associated with this conceptual model and the NUTS code. First, there are all the uncertainties associated with the BRAGFLO conceptual model and its parameterizations (see Section 3.3). Values plugged into NUTS from BRAGFLO contain the inherent uncertainties from BRAGFLO since the input parameters are not screened for rationale values. These uncertainties will then be propagated through the NUTS code to the next step (SECOTP2D). The second group of uncertainties centers around the coarseness of the grid blocks and time steps used in NUTS. Although these parameters may be reasonable for BRAGFLO, it has not been justified that the same applies for the NUTS code.

Since Section 6.4.11 of the CCA and the Appendix NUTS are not presently available for review, many questions are unresolved and remain as potential uncertainties. These issues involve long-term transport of radionuclides in the repository rooms, repository panel seals, DRZ, and undisturbed and fractured interbeds, and input to sealed boreholes and shafts to the Culebra Formation. Advection should allow actinides to be transported directly to the Culebra Formation; however, it is not possible at the present time to evaluate how DOE handles these unknown factors.

There are also uncertainties associated with all the assumptions listed in Section 3.8.2.2. In the cases of all valid assumptions, the associated uncertainties are negligible. Since the soluble actinide source term input parameters are directly fed to NUTS, if the values are incorrect, the consequences could be significant in that the code would transmit such errors directly to the Culebra Member.

3.8.2.5. Adequacy of the Conceptual Model

The Actinide Transport in the Salado conceptual model describes the movement of the actinide source terms by advection, using hydrologic phenomena from the BRAGFLO computer code. The concepts of advection and Darcy flow are well characterized in the geosciences and are the mainstays of this conceptual model. However, the specifics of long-term transport through the components of the repository are poorly defined. Documentation that is not present includes Table 6-15, Section 6.4.11, and Appendix NUTS of the CCA. The section describing this conceptual model (Section 6.4.5.4) does not

document in any way how the "lumped" actinide source terms are transported from the rooms through the panel seals and the DRZ, how transport is performed through undisturbed and/or fractured anhydrite interbeds, and up sealed boreholes and shafts to the Culebra. Since this conceptual model is not yet fully described, the Panel can not determine if the model is adequate.

3.8.2.6. Adequacy of Implementation

The description of how this conceptual model is integrated from one computer code to the next (BRAGFLO to NUTS) is supposedly seamless. It is stated in the ten questions document that "NUTS interface with BRAGFLO is essentially perfect in completeness and validity in that NUTS takes virtually all its flow and flow-related attribute and property data from BRAGFLO and treats them as incontestable. Thus the .. interface is perfectly smooth." Hence, in the sense of transferring flow data into the NUTS code, one would conclude that the implementation is adequate.

Two other aspects of implementation are considered. One aspect involves how dissolved actinide solubility is handled in the "lumping" sense. The second aspect of implementation deals with how colloidal actinides are dealt with in the NUTS code. It seems DOE has provided a very rational way to "lump" all the various solubilities of dissolved actinides and to describe how the four main types of colloids will be "lumped" for transport. Both of these source terms have complex properties that could have been negated by the "lumping" factor. As an example, each actinide in its various oxidation states would have specific solubilities. Therefore the dissolved actinide source term is calculated for Salado and Castile brine compositions in both the low and high oxidation states. These four main permutations would then cover the possibilities for total inventories for dissolved actinides. Colloidal actinide sources are handled in a slightly different manner. Mineral fragment and intrinsic colloid values are held constant through all the runs. Humic and microbe actinide inventories are based on mass balance calculations using inventories from waste materials. These two philosophies of solubility "lumping" have been clearly explained for dissolved and colloidal actinide transport in the NUTS computer code by the Principal Investigator and, by this means, the implementation was determined to be adequate.

3.8.2.7. Accuracy of Results

Conclusions for this section are based on preliminary results provided by the Principal Investigator. The results proved to be accurate. However, without the final parameter listings of Table 6.15 of the CCA, one cannot make a final judgment of actinide transport in the Salado Formation. It would be useful to have the following information for comparison: first, actinide values after transport through the Salado

Formation to a borehole or shaft; second, what are the final values that NUTS would produce at the interface with the Culebra; third, an example of a NUTS transport run ("lumped") that approaches the EPA standard, and then a recalculated run using the individual radionuclides. This information would be very useful in determining whether the finalized results of this conceptual model are accurate. Finally, a complete model run has not been performed that transports dissolved actinides at the median velocity and colloidal actinides at maximum velocity. These results could be critical in deciding the accuracy of the model.

3.8.2.8. Validity of Conclusions

This section presents a judgment on whether the key conclusions that have been drawn based on the results of actinide transport in the Salado Formation in the modeling framework are valid. Although the concept of lumping is shown to be rational, the explanation of transporting colloids at a median velocity may be deficient. The parameter values (Table 6-15) were not available for the Panel to review and may bear on the judgment of validity for this model. Until these two final issues are resolved, it is premature to evaluate the validity of the model conclusions.

3.8.2.9. Adequacy for Implementation

This section is an overall assessment of whether this conceptual model represents a reasonable approximation of the actual phenomena and is adequate for implementation in the compliance application. Due to the lack of information provided (Table 6-15, Section 6.4.11, and the Appendix NUTS of the CCA), and the insufficient documentation of how colloid transport at a median velocity is rationalized, it is premature to say that the full conceptual model is completely adequate for implementation. However, if one assumes that BRAGFLO is a competent model for fluid flow in the repository setting, the next step of inputting hydrologic data into NUTS for actinide transport should be straightforward. Because of this, the model is wholly adequate and reasonable for implementation.

3.8.2.10. Dissenting Views

There were no dissenting views for this method.

3.9. Units Above the Salado

3.9.1. Model Description

The conceptual model of the Units Above the Salado has much in common with the conceptual model of the Culebra. The Culebra Dolomite is a member of the Rustler Formation, which is a prominent part of the supra-Salado stratigraphy. The Culebra is modeled separately (Section 3.2) because of its importance as a potential contaminant flowpath. The model of the Units Above the Salado results from a complex of several approaches to the hydrology and hydrogeology of the region and the WIPP site area. The conceptual model would ideally serve as an integrating set of hydrogeologic processes, properties, and principals that could be used to support assumptions about the potential performance of the site, to interpret regions of low data; and to place in context the results of hydrologic testing. The Units Above the Salado conceptual model provides a geometric characterization of the hydrologic system and a general description of the geometry and processes of flow. As with the Culebra, however, no correlation is provided of variation of hydrologic properties at the site scale with hydrogeologic character. The most important assumption in the model is that the Culebra Member of the Rustler Formation is the only potential pathway for radionuclide release to the environment.

The performance assessment of the Culebra is based on a considerable hydrologic testing data base, which addresses many of the potentially significant questions and issues concerning flow along the Culebra flowpath at and around the site. The significance of the hydrology and hydrogeology of the other members of the Rustler Formation and overlying formations lies partly in their interaction with Culebra hydrology and their influence on the interpretation of flow through that unit. The Culebra is treated as a confined aquifer with a much higher transmissivity than the overlying and underlying stratigraphic units and a horizontal flow gradient generally to the south. Flow in both the enclosing units (Unnamed Lower Member and Tamarisk) is believed to be predominantly vertical and into the Culebra. Water pressure in the Culebra is characterized as low because its transmissivity and gradient are capable of discharging more water than is presently being recharged.

The interpretation of the hydrologic processes for performance assessment purposes in the units above the Salado is based mostly on the results of hydrologic testing. A regional hybrid hydrogeologic/hydrologic process model (Corbet and Wallace 1993) sets model boundaries and

speculates about regional processes contributing to the transmissivity contrasts, but offers no site-scale correlation with the testing data. This model does not address mesoscale hydrogeologic variables such as fracture orientation and distribution and the distribution of matrix permeability.

The performance assessment activity associated with the units above the Salado is the two-dimensional Culebra flow model, based solely on the hydrologic testing results. The variability of transmissivity represented in that model within and around the site area is attributed to the relative proportions of flow through fractures and variably permeable matrix, and to fracture distribution and hydraulic activity. The model does not address those variations of hydrogeologic process and properties relative to petrologic, sedimentologic, or structural features, which are the primary sources of variability. The conceptual model is disconnected from the numerical hydrologic model at the scale at which hydrogeologic information could most usefully condition the numerical model.

The assumption that the Culebra is the only potential pathway for release to the environment is related to the movement of radionuclides up a borehole or up the sealed shaft region. The assumption that radionuclides reaching the Magenta Dolomite member of the Rustler Formation or the Dewey Lakes Redbeds, which overlie the Rustler Formation, are not transported to the accessible environment is based partly on the results of very limited hydrologic testing and assumed retardation in the Dewey Lakes.

Hydrogeologically, the Culebra and Magenta Dolomites bear many similarities. Both are dolomites deposited in the same sedimentary environment. They are comparable in thickness and differ in stratigraphic position by a few tens of meters. Their post-depositional histories are identical from location to location. Their porosities are nearly identical and their ranges of permeabilities overlap. The definition of the hydrologic character of the Magenta is based on modeling of approximately 15 data points constrained to a very small geographic area.

The principle hydrogeologic difference between the Culebra and Magenta is purported to be the absence of hydrologically active fractures in the Magenta. This assertion is based on two slug tests and very limited field observation in shaft excavations. The transmissivity of the Magenta is very low in all of the limited number of tests and its low transmissivity is supported by drawdown during the sinking of the air shaft. The characterization of Magenta hydrology as unfractured is based on a very limited observational and testing data base, and the conclusions that there are no regions of high transmissivity due to fractures and that all flow in the Magenta is matrix flow are weak.

The position of the groundwater table at the level of the Dewey Lakes Redbeds is very unclear. Hydrologic testing has not been done to differentiate between purported perched water zones, to characterize saturated zones with continuity to underlying units, and to identify the general hydrologic character of the Dewey Lakes Redbeds. It is presumed that most of the materials above the Dewey Lakes are unsaturated (Gatuna and Pleistocene alluvium) and that recharge through those materials is minimal.

3.9.2. Review of Criteria

The units above the Salado contain the Culebra Dolomite, which is identified as the principal potential pathway for release of radionuclides to the environment. The conceptual model for these units provides the framework for consideration of the hydrology of the Culebra and contains other hydrostratigraphic units (Magenta and Dewey Lakes) whose potential as pathways must also be evaluated.

3.9.2.1. Information Used to Develop the Conceptual Model

The conceptual model is based on stratigraphic information from site borings and shaft excavations and on the position and nature of regional hydrogeologic features. Corbet (1993) has synthesized those features well and uses them as the basis for suggesting model boundaries and to support general flow gradient direction predictions. The model used for performance assessment purposes is a two-dimensional computational flow model based entirely on hydrologic testing in the Culebra. The conceptual model generally supports the descriptions of the hydrologic roles of the units above the Salado, with reservations about the characterization of flow in the Magenta Dolomite and the universal presence of retardation in the Dewey Lakes Redbeds. Hydrologic test data are sparse or nonexistent in all units above the Salado, except the Culebra.

3.9.2.2. Validity of Model Assumptions

The assumption that the Culebra Dolomite is the only hydrostratigraphic unit within the stratigraphic sequence above the Salado, which has the potential to act as a flowpath to the accessible environment, is the principal assumption affecting this conceptual model. That assumption implies that the Magenta Dolomite and the Dewey Lakes Redbeds are not potential pathways and that flow and transport assessments of those units are unnecessary. Estimates of contaminated brine flow up an intruding borehole in the long term imply very small (0.5 m^3) volumes of brine reaching the interval above the Culebra (personal communication, P. Vaughn). This is the consequence of underpressure hydrologic conditions purported to exist in the Culebra throughout the repository area, which lead to injection of

most of the brine rising up the borehole into the Culebra. The magnitude and distribution of underpressure in the Culebra are based on averages of several measurements and an assumed process model, which explains the underpressure condition. The assumption that the Dewey Lakes and Magenta are not flowpaths is not well supported. The assumption of availability of only small amounts of brine to those units appears to be well supported.

3.9.2.3. Evaluation of Alternatives

The conceptual model has evolved over the entire period of site characterization and performance assessment. Some alternative submodels were considered and rejected (e.g., local halite dissolution and anhydrite hydration, gravitational loading). All of these submodels failed to conclusively account for the variations in transmissivity at a useful scale. The final performance assessment model is almost entirely based on numerical assessment of hydrologic test data, which are very sparse except in the Culebra Dolomite, the most thoroughly tested stratigraphic unit at the site.

3.9.2.4. Uncertainties

The principal uncertainty in the conceptual model of the units above the Salado (excluding the details of Culebra flow, treated elsewhere) is the assumption that the Magenta and Dewey Lakes units do not constitute potential release pathways. The effect of underpressure in the Culebra appears to limit flow up an intruding borehole to the upper units in such a way that there is little consequence associated with the Dewey Lakes and Magenta flowpaths.

3.9.2.5. Adequacy of the Conceptual Model

The conceptual model adequately defines the regional and general stratigraphic geometry of the units above the Salado. It does not provide supporting explanations for the variability of hydrologic parameters and processes at the site scale. If the need to assess transport in the Magenta and Dewey Lakes were shown to exist, the small hydrologic testing data base and the existing conceptual model would not be adequate to such an assessment.

3.9.2.6. Adequacy of Application

There is no application of the conceptual model to the computational flow modeling at the site scale except for the definition of stratigraphic geometry. A thorough demonstration of the potential of the Magenta and Dewey Lakes as flowpaths is absent, and the conceptual model is inadequate to support

such a demonstration. The conceptual model adequately provides geometric and process elements to support the Culebra model.

3.9.2.7. Accuracy of Results

The accuracy of results depends on the adequacy of the testing data base and the computational flow models and are beyond the scope of this review.

3.9.2.8. Validity of Conclusions

See Sections 3.9.2.6 and 3.9.2.7. Conclusions are based on the Culebra numerical flow model and are beyond the scope of this review.

3.9.2.9. Adequacy for Implementation

The conceptual model is not significantly implemented in the computational flow model used for performance assessment (the Culebra two-dimensional flow model). The conceptual model provides adequate peripheral support to the implementation of the Culebra flow model by defining geometry and a general description of flow conditions in adjoining beds. The conceptual model is not adequate to support an assessment of the Magenta and Dewey Lakes hydrostratigraphic units as flowpaths. Assumptions supported by analysis imply that the consequences of transport in the Magenta and Dewey Lakes are low because of insignificant input of contaminants as a result of human intrusion.

3.9.2.10. Dissenting Views

There were no dissenting views for this model.

3.10. Transport of Dissolved Actinides in the Culebra

3.10.1. Model Description

The transport of actinides in the Culebra Dolomite Member of the five-member Rustler Formation was determined by DOE to be a significant pathway for potential releases to the accessible environment. This model describes the transport of soluble actinides once the material has moved into the Culebra, which could occur either under undisturbed conditions by movement up the shafts, or under disturbed conditions through intrusion boreholes, which provide a path by which gas or brine can be released up to and above the Culebra. These processes are described in other models. The quantities of actinides transported into the Culebra, as well as their chemical form, are described in the source term models.

The characteristics of the Culebra that relate to flow and transport are described in Section 3.9, and the model for spatial distribution of flow rates in the region and site area is described in Section 3.2. Therefore, this model is related to output from Shaft Seals, Chemical Conditions, and Dissolved Actinide Source Term, as well as Culebra Geometry and Flow, Gas Generation, Fluid Flow in the Salado, Disturbed Rock Zone, and the models related to intrusion, Exploration Borehole, Castile Formation and Brine Reservoir, and Multiple Intrusions.

The model, Transport of Dissolved Actinides in the Culebra, is also related to a parallel model, Transport of Colloidal Actinides in the Culebra, which depends on many of the same processes. Fundamentally, the model describes the horizontal transport of dissolved actinides by water flowing through the porosity of the dolomite, and retardation that may occur along the way. The flows are confined to the lower 4 meters of relatively permeable dolomite of the 7-meter thick Culebra. The model describes advective transport, as well as holdup due to matrix diffusion and chemical retardation. The model assumes that the overall rock porosity is composed of interconnected porosity, which forms the principle paths for advective water flow, and relatively unconnected diffusive porosity, into which species may diffuse under concentration gradients. This model is therefore referred to as a double porosity model.

The advective porosity is envisioned as a web of interconnected horizontal and vertical fractures in the dolomite, with some contribution from flow through interconnected vugs, and comprising less than 1% of the overall rock volume. The diffusive porosity is described as being accessible from advective porosity through small intercrystalline pores of the Culebra rock matrix, and comprising about 15% of the overall rock volume. Physical holdup and chemical retardation are therefore described as predominantly related to the diffusive porosity, with the surface area for chemical adsorption located within the diffusive porosity. This surface area has been measured at about 1 m^2/gm of dolomite.

Diffusion into the rock is described as related to the chemical diffusive properties of dissolved species, the tortuosity of the diffusion paths within the rock, and the surface area for diffusion between advective and diffusive porosity per unit volume of diffusive rock. Chemical retardation is described as chemical adsorption onto the dolomite grains exposed in the diffusive porosity. Although clay is believed to be present in the Culebra dolomite, particularly between horizontal bedding planes, adsorption onto this clay is not specifically assumed because its distribution and quantitative effect have not been demonstrated. Chemical adsorption is further described as a linear isotherm model, with single constants, K_ds, to

describe the equilibrium relationship of the ratio of adsorbed concentrations and dissolved actinide species.

Fifteen years of development of information and models to describe actinide transport in the Culebra has considered two controversial issues. The first is whether a single matrix porosity or a double porosity model is appropriate to describe flow and retardation. The second is whether and how chemical retardation, particularly on corrensite clay, is to be modeled. The project has used a single porosity model and adsorption on clay in the past, but currently uses a dual porosity model with adsorption onto dolomite but not onto clays. This is discussed in more detail later.

3.10.2. Review of Criteria

3.10.2.1. Information Used to Develop the Conceptual Model

The site-related information used to develop the Culebra actinide transport model has included direct observation of the formation in outcrop, borehole cores and wells, and laboratory testing. These site observations have included chemistry measurements, studies of mineralogy, and field hydraulic and tracer testing. The laboratory testing has developed the quantities of actinides in solution in brine, their oxidation states and solubilities in brine, and measured adsorption properties.

Laboratory studies conducted to understand the adsorption process included column tests and the use of intact Culebra cores. Studies of adsorption on dolomite and corrensite clay were conducted, but information on the amount and distribution of clay in advective porosity pathways was judged insufficient to justify assuming adsorption onto clay. Laboratory studies have used four synthetic brine compositions representing the range of actual brines in the Salado, Castile, and Culebra. Information was developed on effects of carbon dioxide on adsorption at partial pressures expected in the Culebra. Adsorption information for plutonium, americium, uranium, thorium, and neptunium at expected oxidation states was developed using laboratory measurements and the oxidation state analogy.

Recently, the H-11 and H-19 tracer testing was completed and the results analyzed and summarized, although no reports of this key work were available to the Panel for review. This additional tracer testing was conducted because the results of earlier tracer testing with soluble dyes did not provide adequate information to convincingly show that the dual porosity model was appropriate for actinide transport purposes. The evaluation of the current work and reevaluation of earlier work has improved the information base. However, much of the work in support of this model is recent and has not yet been

published. Improved correlation with modeling analyses has been achieved for increased ranges of flow rates and other improvements in test conditions. The information base appears generally adequate, although the parameters that relate to this model will need to be carefully chosen. These parameters are the advective and diffusive porosity, the range of block sizes, the soluble species diffusion coefficients, tortuosity, and retardation coefficients.

3.10.2.2. Validity of Model Assumptions

Some of the principal assumptions are that the transport can be described in the dual porosity model, that the oxidation states of actinides in brine transferred into the Culebra do not change during subsequent flow and transport in the Culebra, that dissolved actinides will diffuse into the matrix and be physically retarded, and that dissolved actinides can adsorb on diffusive porosity surfaces.

The basis for the assumption that the transport model should assume both advective transport in principal flow paths and diffusive transport into the rock, is that results of tracer tests along principal flow paths at the WIPP site are only explained using the dual porosity model. This is believed valid in the areas of the site where transmissivity is greater than 1×10^{-6} m^2/sec. In areas of low transmissivity, which have little advective porosity and flow, a matrix diffusion model best explains results, but is not used for the performance assessment because these low transmissivity areas do not contribute significantly to the flows away from the repository. In high transmissivity areas, a single porosity assumption is not consistent with the tracer test results. Therefore, for purposes of transport, the dual porosity assumption appears appropriate.

For purposes of determining appropriate values of adsorption coefficients and solubilities, the project assumes that the oxidation states of actinides generated in the repository do not change when the deep brines are injected into the Culebra brine. Adsorption behavior would be different if oxidation states were different, while concentrations would not be different since precipitation is assumed not to occur in Culebra brine. The assumption of constant oxidation states is based on the repository brines being strongly reducing, the Culebra brine being reducing (though perhaps less so), and the rate of any changes in oxidation state that might occur at low ambient temperatures being slow. This assumption is supported by retardation research program studies involving four different brines, including Castile and Salado brine and two brines representing the Culebra, four different chemical constituents affecting conditions, including sulfides, cellulosics, iron and nitrates, and two different chemical equilibrium data bases. It was stated that 30 of the 32 possible combinations of information indicated reducing conditions,

with only some combinations of nitrates producing slightly oxidizing conditions. Measurements of the redox states of groundwater sampled from over 20 wells around the WIPP site indicated reducing conditions everywhere on and around the site, except for areas a few miles south where recharge was thought to affect redox conditions. Thus, this assumption appears fairly well supported.

The model assumes that the properties of actinides of the same oxidation state generally are similar. This issue is discussed in Section 3.23 and will not be covered here. The most recently conducted tests of adsorption parameters included column tests with crushed dolomite at Lawrence Livermore National Laboratory, and flow-through tests using dolomite cores from the WIPP air intake shaft.

The assumption that batch tests using small particles and flow-through retardation experiments can give valid results for the adsorption parameter needs consideration. In the column tests, not yet published, K_ds were measured using dolomite, with no detectable (<1%) clay, that was crushed and sieved to give particles of about 100 mm diameter. The issue was raised that this might make the internal surface area and the clay that might be present more accessible in the experiment than it is in the intact Culebra. It was noted that measured grains in dolomite are on the order of 2 mm and pore openings are approximately 0.6 mm, and therefore a dolomite particle of 100 mm would have roughly the same surface-to-volume relationships as the rock. Also, the contact times were long enough in the experiment for diffusion transport to reach equilibrium. The issue of diffusion rates into the matrix is determined by other parameters, including porosity and tortuosity, which have been measured in other testing programs.

The flow-through tests used intact horizontal Culebra cores with pressure-induced flow of non-absorbing tracers, as well as five actinides, Pu, Am, Th, Np, and U, in solution. In this case, K_ds were inferred from the overall retardation of the core. The results of these tests are being evaluated and K_ds were determined using the values for the likely oxidation state and the brine type with the lowest values. Without commenting on the specific numerical values, which have not been finalized, this appears to be a reasonable approach. Interpretation of the results of such experiments needs to be made carefully, so that values of K_ds, tortuosity, and porosity can be reliably applied into numerical models. It would also be useful to compare the values thus obtained with other data from past determinations.

One uncertainty in the column tests is that associated with the amount of clay in the tested dolomite. X-ray diffraction studies did not detect clay, with an apparent minimum detectable value of about 1%. There is also clay in the Culebra dolomite, reportedly in the range of 1 to 5%. The intent was to use clay-

free dolomite in the column tests, but it appears this experiment may inherently include the adsorption effects from whatever amount (<1%) of clay was in the dolomite matrix. While it was not shown that this was representative of truly pure dolomite, this appears to be conservative, because the clay was likely at the low end of the range. This is a tentative conclusion however, because the results of this work were not available in published form for review.

3.10.2.3. Evaluation of Alternatives

The principal alternatives considered relate to whether transport is best described by a single porosity fracture only, a single porosity matrix only, or a dual porosity model. Neither of the single porosity models explain the data from tracer tests everywhere on the site, whereas the dual porosity model best explains the data, particularly in the regions on the site where transmissivities are high.

3.10.2.4. Uncertainties

Uncertainties related to oxidation state in the repository source term translate directly into transport-related uncertainties (see Sections 3.23 and 3.24). These uncertainties could have a large effect on the result of performance assessment. However, as discussed in Section 3.10.2.3, there appears to be a reasonable basis to conclude that the oxidation states would not change significantly on entry into the Culebra from the repository. Uncertainties on the extent of adsorption could have a significant effect as well. However, at the conceptual level, the model attempts to proceed in a reasonably conservative manner in light of these uncertainties. This does not mean that particular values of K_ds to be chosen from the conceptual model are all conservative, since numerical values for these parameters have not been evaluated.

3.10.2.5. Adequacy of the Conceptual Model

It is concluded that a dual porosity model is adequate for dissolved actinide transport analyses if ranges of model parameters are chosen properly in light of uncertainties. In that the model is supported largely by evaluation of recently completed but undocumented field and laboratory experiments, this conclusion is necessarily tentative.

3.10.2.6. Adequacy of Application

This model utilizes direct input from only a few other conceptual models: the Actinide Source Term models, and the Culebra Hydrogeology model, as well as output from the flow models under undisturbed

and disturbed conditions. At the conceptual level, these model outputs appear compatible as input to the Culebra Transport model. This does not mean there could not be problems in application through the equations and mathematical formulations in the NUTS code. A more informed judgment could be made from a review of sensitivity among key parameters, such as the relationship of the sensitivity of repository releases on source term concentrations of dissolved actinides, on K_ds, on volumes of brine injected, on effects of climate change, and mine subsidence effects on Culebra transmissivities.

3.10.2.7. Accuracy of Results

A judgment on whether the conceptual model affords sufficiently accurate results for performance assessment depends on the overall importance of various model assumptions. It is judged that the dual porosity model itself is a sufficiently accurate conceptual representation for performance assessment, based primarily on verbal briefings of the results of the latest tracer testing in the Culebra and on visual observations. However, since the results of the latest tracer tests have not been documented, this judgment is tentative. Furthermore, the method of developing parameters of importance to numerical results also have not been supported by written reports of the related recent work. Therefore, these parameters have not been reviewed, although some important uncertainties were identified above. Accuracy of results imply review of results, and none using the current model and parameters were available for review. It would be useful to review results of sensitivity analyses to understand which are the key variables, and then focus on the accuracy of those key variables. Until such information is reviewed, a firm conclusion on their accuracy cannot be properly drawn.

3.10.2.8. Validity of Conclusions

The conclusion that the actinide transport in the Culebra can be adequately modeled in a dual porosity model, with advective transport in the main flow porosity, diffusion into and physical and chemical retardation in the rock matrix porosity, is valid. Other conclusions have not been presented since the model, using the chosen parameters, has not yet been used in the performance assessment.

3.10.2.9. Adequacy for Implementation

The conceptual model appears compatible with other models it intersects with directly. The implementation of the conceptual model is through mathematical formula and computer codes which have not been evaluated. It is concluded that the conceptual model is adequate for implementation. However, the selection of model parameters needs to be critically reviewed when the reports of the laboratory and field tracer tests are available.

3.10.2.10. Dissenting Views

There were no dissenting views for this model.

3.11. Transport of Colloidal Actinides in the Culebra

3.11.1. Model Description

This model is closely related to Transport of Dissolved Actinides in the Culebra (Section 3.10), and shares many aspects and assumptions of that model. This model differs from the Dissolved Actinides model in its application of colloidal properties as opposed to dissolved properties to the transport process. The issue of whether, for transport purposes, a dual porosity approach is appropriate, is not repeated since that issue was covered in Section 3.10. However, differences in how the colloids are transported in this model are covered.

Model adjustments for colloidal transport include the different properties and processes that occur for colloids. For example, colloidal particles travel slightly faster in advective transport than dissolved species due to velocity gradients in flow apertures. Colloids can be trapped along the way, and they can diffuse into the diffusive porosity in the dolomite if they are smaller than the pore throat diameter of the dolomite. Four types of colloids are considered: mineral fragments, microbes, humic and fulvic acids, and actinide intrinsic colloids. These four types are different in size and properties; for example, some are hydrophilic, some are kinetically stable, and others are less so. Colloidal particles that are small enough to enter the dolomite matrix may chemically adsorb on surfaces once inside the diffusive porosity.

The model assumes that the colloidal particles containing actinides originate in the repository and are transferred into the Culebra in the same way as dissolved actinides, as represented in the NUTS code. In this model, it is assumed that soluble actinides do not attach to colloids that may already exist in the Culebra brine when brine containing dissolved actinides is injected into the Culebra and mixes with Culebra brine.

Colloidal transport has not been considered in the earlier assessments of repository performance; therefore the only other model implicitly considered was the null hypothesis. However, experience in other environmental situations at other DOE sites has lead to consideration of colloidal transport to explain greater transport of actinides than had been expected in these other situations, based on models that considered only soluble transport.

3.11.2. *Review of Criteria*

3.11.2.1. Information Used To Develop the Conceptual Model

Information used to develop the colloidal actinide transport model included the amounts and types of colloids thought possible in the source term model, the chemical properties and physical sizes of the particles, and how these would be transported in advective flow. In addition, information was developed on diffusion coefficients, measured pore throat diameter distribution in WIPP dolomite samples, and results of experiments to quantify whether and the extent to which colloids can adsorb onto dolomite matrix surfaces. A growing body of scientific literature and various computerized numerical models have been consulted to develop the conceptual model, and to help guide implementation.

The available information and experience with colloidal actinides is not as robust as for transport of dissolved actinides and, therefore, is likely to be less able to support a completely robust model. This model was conceived to fill a weakness in models considering soluble transport only. The available information appears adequate to formulate a useful conceptual model, but this does not mean that adequate information is yet available to fully implement a conceptional colloid transport model.

3.11.2.2. Validity of Model Assumptions

Some of the key assumptions are that 1) actinide oxidation states do not change when deep brines containing these colloids are mixed in Culebra brines; 2) soluble actinides in brine from the repository do not interact with and become attached to colloidal particles that exist in the Culebra; 3) colloids can be filtered in the advective porosity but not chemically adsorbed there; and 4) colloids which are smaller than a 0.63μm can diffuse into pore throat openings in dolomite and be chemically adsorbed onto surfaces there.

The assumption of oxidation state stability is discussed in Section 3.10.2.2, and no basis has been provided to assume colloid actinides would behave differently from soluble actinides.

The assumption that dissolved actinides do not attach to preexisting Culebra colloids is difficult to justify in principle. This assumption has been made to avoid the complication of the computer code having to simultaneously solve the dissolved species problem and the colloid transport problem. If there were significant transfer of soluble actinides to large colloidal particles in the Culebra flow, the transport of this actinide material could be significantly faster than the current model, due to reduced physical and chemical retardation. If the transfer of soluble actinides to small colloids occurred, it would not increase

the transport as much, since advective transport would be slower and, more importantly, small colloids could diffuse into diffusive porosity in the dolomite matrix and be significantly retarded and perhaps chemically adsorbed. The arguments made to simplify the test plan and model do not consider this effect. Models to predict transport by adsorption onto colloidal particles along the transport path have been developed precisely because models of soluble only transport were inadequate. It is therefore judged that this assumption is unjustified based on the literature and information developed specifically for the WIPP project.

The assumption that colloidal particles can be filtered by entrapment in narrow passages in advective porosity appears viable at the conceptual level, but no information has been presented to demonstrate this occurs significantly in the Culebra, and no information has been presented to confidently quantify the effect. The assumption is implemented as a simple "decay" term for those colloids that are too large to enter diffusive porosity. On the other hand, particles in flowing systems do indeed tend to collect in areas of low flow velocity, so such a filtering process is likely to be useful if parameters are selected carefully to avoid trivializing the overall colloidal transport.

The assumption that colloidal particles smaller than the mean pore throat diameter of 0.63μm can diffuse into the dolomite matrix and be adsorbed onto the interior surface area in the dolomite matrix needs some discussion. Of the four types of colloids being considered, the humic/fulvic acid colloids and the plutonium intrinsic polymer are believed to be smaller than 0.63 μm. Measurements of many different properties of WIPP dolomite were made to develop their ranges and statistically average values, including porosity matrix interior surface area, permeability, grain density, tortuosity and pore throat sizes. Pore size distribution measurements were made on 24 samples using the mercury injection porosimetry technique. These data were interpreted to provide a mean pore throat diameter of 0.63μm. Analysis of the data showed that the accessible internal surface area was a function of pore throat size. For a typical sample with a porosity of 14.8% overall, the data indicated that no internal surface area was accessed for pore throat diameter greater than about 1μm; that about 35% of internal area was accessible at a pore throat diameter of about 0.37μm; and 50% of the internal surface area was accessible at a pore throat diameter of about 0.2μm. Total internal surface area is about 1 m^2/gm of dolomite. Humic acid colloids and the plutonium polymer are thought to be small enough to enter the dolomite. Humic acid colloids are reported to be about 0.1μm or less and single unagglomerated plutonium polymer colloids are on the order of 0.003μm. Intrinsic colloid agglomerates could be as large as 0.04μm. Microbial

colloids are 1 or 2 μm and mineral fragments are on the order of 1μm as well. Based on this information, it appears feasible that the humic/fulvic acid colloids and plutonium intrinsic polymer colloids could diffuse into the matrix, unless surface charge forces prevented this from occurring.

The assumption that colloidal particles could be adsorbed onto the surfaces in matrix porosity is a more complex process to understand because colloidal interactions are less well understood. For example, if the colloids have the same surface charge as the rock, adsorption would be prevented, and if the charges were opposite, adsorption would be relatively strong. To explore this assumption, the project attempted to measure K_ds for actinide colloidal particles of the various types in the same laboratory column tests, and core flow through tests as for soluble actinide measurements. The results showed apparent adsorption in both situations. However, for some of the flow-through experiments, soluble actinides and colloids were mixed and the resulting K_ds were found to be the same as for soluble actinides. Therefore, this experiment did not demonstrate colloidal adsorption so much as perhaps soluble adsorption or filtration, since the experiment did not obviously assure that the actinides were on colloidal particles before being contacted through the dolomite. For microbe colloid experiments, no nitrates were added to keep the microbes growing, so as to prevent changing the oxidation state of the actinides. This may have prevented bioassimilation of actinides in microbe colloids, and again lead to the measurement of K_ds with the same values as for soluble species. Resolution of these and perhaps other uncertainties would add confidence to the assumption that actinide colloids adsorb onto surfaces and the extent to which they adsorb. In the absence of a satisfying resolution, colloidal adsorption onto dolomite matrix porosity may not be a justifiable assumption in the model.

3.11.2.3. Evaluation of Alternatives

Since consideration of transport of colloidal actinide transport has only recently been included in performance assessment, no alternatives were considered.

3.11.2.4. Uncertainties

Uncertainties in the model are associated with the key assumptions discussed in Section 3.11.2.2. The Panel concludes that very large uncertainties exist with the lack of interaction of soluble actinides and Culebra colloids in the model, and with the diffusion into dolomite porosity followed by chemical adsorption. Because of the lack of availability of published reports on the recent testing, a more definite conclusion cannot be drawn.

3.11.2.5. Adequacy of the Conceptual Model

The uncertainties in the validity in some of the key assumptions cast some doubt on the adequacy of this model. Even though the overall performance assessment model is greatly improved by the addition of colloidal actinide consideration, it appears that model predictions will result in negligible transport based on the model and parameters presented to date. If this were the outcome of the fully developed and qualified model, one could have more confidence. However, since significant uncertainties exist in major features of this model, its results could not be trusted, based on the available information. It may be that the issues raised here are readily resolved, but application of colloid science in environmental transport is a new and difficult application, and a cautious approach is believed most appropriate.

3.11.2.6. Adequacy of Application

Soluble actinide interaction with colloidal particles in the Culebra has been assumed not to occur without justification. This represents an issue of integration of this model with the Dissolved Actinide Transport in the Culebra model. Other than this, other system-wide integration issues have not been identified.

3.11.2.7. Accuracy of Results

No actual results have been provided. However, on the basis of the information reviewed, it appears this model, as currently envisioned, would not provide sufficiently accurate results.

3.11.2.8. Validity of Conclusions

Since there is doubt about other criteria, this criterion is also in doubt.

3.11.2.9. Adequacy for Implementation

It does not appear that the information available demonstrates that this model provides a sufficient basis to give confidence in the adequacy of treating colloid transport in performance assessment. It should be noted that, because of the recent undertaking of this work, none of the laboratory test reports or flow-through test reports, on which significant aspects of this model are based, are completed. Further review of the information, when published, could provide a basis to resolve some of the issues raised, after adjustment of some of the assumptions and judicious choice of parameters for a numerical solution. This could lead to an adequate model for implementation.

3.11.2.10. Dissenting Views

There were no dissenting views for this model.

3.12. Exploration Boreholes

3.12.1. Model Description

The Exploration Borehole conceptual model addresses drilling locations, methods, and frequencies within the WIPP controlled area, borehole sealing, and long-term fluid flow through the sealed borehole. Short-term flow through the unsealed borehole is addressed in the Direct Brine Release conceptual model. Associated conceptual models that describe movement of contaminated materials to, within, and from the borehole include Repository Fluid Flow, Castile and Brine Reservoir, Cutting/Cavings, Spallings, Culebra Hydrogeology, and Dissolved and Colloidal Actinide Source Terms. Actinide transport accompanying long-term brine migration is addressed by the Actinide Transport in the Salado conceptual model. The Exploration Borehole conceptual model is limited to a single borehole penetrating the repository. The Multiple Intrusion conceptual model describes conditions when more than one borehole is assumed to penetrate a waste panel. The details of this model were still under development at the time of the peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 22 May 1996 Draft CCA, Section 6.4.7, The Intrusion Borehole (DOE 1996, pp. 6-64 to 6-75), from verbal descriptions, and from the cited references.

An exploration borehole may be drilled on the WIPP site for natural resources investigation and may by chance penetrate a waste panel in the repository. Such boreholes are assumed to be drilled by individuals who have no knowledge of the buried waste, after active institutional control of the site has ceased. The conceptual model for exploration boreholes is based in large part on proscriptive requirements of EPA 40 CFR 194. The EPA requirements are paraphrased as follows:

- The regulatory time frame is the time period beginning at disposal and ending 10,000 years after disposal [40 CFR 194.2].
- Both deep drilling (to or below a depth of 2,150 feet) and shallow drilling (less than a depth of 2,150 feet) that may potentially affect the disposal system during the regulatory time frame are assessed [40 CFR 194.33(a)]. The approximate depth of the repository is 2,150 feet.
- Exploratory drilling is assumed to be inadvertent and intermittent [40 CFR 194.33(b)(1)].

- Exploratory drilling for those resources provided by the waste in the disposal system or the engineered barriers designed to isolate such waste need not be considered [40 CFR 194.33(b)(1)].

- Drilling events in the Delaware Basin are assumed to occur at random intervals in time and space during the regulatory time frame [40 CFR 194.33(b)(2)].

- The frequency of deep drilling within the WIPP controlled area is assumed to be the sum of the rates of deep drilling for each resource in the Delaware Basin over the past 100 years [40 CFR 194.33(b)(3)].

- The total rate of shallow drilling at WIPP is assumed to be the sum of the rates of shallow drilling for each resource in the Delaware Basin over the past 100 years; however, in considering the historical rate of all shallow drilling, the DOE may, if justified, consider only the historical rate of shallow drilling for resources of similar type and quality to those in the controlled area [40 CFR 194.33(b)(4)].

- Future drilling practices and technology are assumed to remain consistent with practices in the Delaware Basin at the time the CCA is prepared, including the types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of boreholes that are sealed [40 CFR 194.33(c)(1)].

- Natural processes are assumed to degrade or otherwise affect the capability of boreholes to transmit fluids over the regulatory time frame [40 CFR 194.33(c)(2)].

- The effects of techniques used for resource recovery following drilling need not be considered [40 CFR 194.33(d)].

In developing a conceptual model that incorporates these assumptions, DOE has considered the following:

- Shallow boreholes will not intercept or affect the integrity of the repository and therefore need not be considered.

- Present drilling practices include the relative economic value of the target resource; on this basis, the objectives of exploration drilling at the WIPP site are assumed to be oil and gas because these are the only commercially viable resources for which exploration drilling would occur to or below the depth of the repository horizon.

- Although commercially viable reserves of potash are known to be within the WIPP controlled area, inadvertent penetration of the repository during exploratory drilling for this resource was not considered because such reserves lie above the repository depth.

- The frequency of deep borehole drilling is estimated based only on historical frequencies of drilling for resources of similar type and quality to those found at the WIPP site.

Exploratory drilling for hydrocarbon resources within the Delaware Basin is assumed by DOE to occur at a rate of 47 holes per square kilometer over the 10,000-year regulatory time frame. Although the timing of intrusions into the waste panels is randomly sampled, based on the 0.125 square kilometer area of the waste panels, the expected average rate of penetration is about 6 boreholes per 10,000 years. Boreholes penetrating the waste panel area but passing through a pillar or wall rather than through the waste are assumed to have no effect on waste releases, but may penetrate and partially deplete brine reservoirs in the Castile. The concept of partial reservoir depletion is discussed further in Section 3.16. Penetration of the operations or experimental areas of the repository by a borehole is assumed to have no significant consequence. All exploratory boreholes are assumed to be drilled in search of hydrocarbon resources and all are therefore assumed to penetrate entirely through the Salado and Castile Formations. Approximately 10% of these are tentatively assumed to encounter pressurized brine in the Castile (E1 scenarios), and the other 90% are assumed to not encounter pressurized brine (E2 scenarios) (see 23 May 1996 Draft CCA, Section 6.4.13.6 (DOE 1996, p. 6-119)).

Drilling is assumed to be conducted by standard rotary methods. At the time of repository penetration, the borehole is assumed to have been cased to the bottom of the Rustler Formation, following current standard practices. After drilling has progressed through the salt section, an intermediate casing is installed to the bottom of the Castile. Below that depth a third, final production casing is installed, which typically extends to the ground surface during production, but is only cemented near the production zones. On abandonment, the production casing is commonly cut above the cemented zone and reclaimed (Thompson et al. 1996, p. 6). Fluid and solids that flow through the open borehole immediately on repository penetration are described in the aforementioned Direct Brine Release, Cuttings/Cavings, and Spallings conceptual models. Long-term fluid flow through the sealed borehole is described in the following paragraphs.

On abandonment, three different scenarios have been adopted by DOE to describe the range of current borehole plugging practices. These are (1) a single, continuous cement plug extending from the top of the Salado to the bottom of the Castile; (2) two 40-m cement plugs, one at the bottom of the Castile (top of the Bell Canyon) and one at the bottom of the Rustler; and (3) three 40-m cement plugs, consisting of the two plugs described above plus an additional plug near the Salado/Castile contact below the repository. In addition, all boreholes have approximately 15-m long concrete surface plugs (Thompson et al. 1996, p. 3).

Degradation of the plugs generally follows the scenarios and rationale presented by Thompson et al. (1996). The continuous plug is not considered to degrade over time because of its structural integrity and the very low brine flow through it. The surface plug is also not considered to degrade over time because of the lack of physical or chemical stresses in the near-surface environment. In the two- and three-plug scenarios the steel casing in the Salado and Castile is expected to be locally pitted and leak within a few decades after abandonment. In these scenarios, within 200 years after abandonment the 40-m concrete plug and remaining casing above the repository and the open casing below the repository are assumed to fail completely from both mechanical and chemical stresses. Simultaneously, with the exception of the concrete plugs below the repository, the entire borehole is assumed to be filled with degraded concrete, corrosion products, and sloughed native materials that are assigned the hydraulic properties of silty sand in accordance with regulatory guidance. Because of increased stresses and halite creep rates below the repository, the borehole filling below the repository is subsequently assumed to be compacted, with a concurrent decrease in permeability. The cement plugs below the repository, however, are assumed to maintain their integrity for the duration of the 10,000-year regulatory time frame because degradation rates will be significantly reduced due to a less aggressive chemical environment (see 23 May 1996 Draft CCA, Section 6.4.7.2.2 (DOE 1996, p. 6-74). Long-term brine flow is expected to occur to or from the repository through the degrading upper borehole plugs as a function of brine availability and repository pressure.

The same version of the BRAGFLO code used to model repository fluid flow is used to implement the Exploration Borehole conceptual model. This model, which portrays a two-dimensional vertical section, is discussed in Section 3.3 of this report and in Section 6.4.2 of the 1 April 1996 Draft CCA (DOE 1996, p. 6-2). The exploration borehole is assumed to penetrate the center of one of the waste disposal panels in the repository. Boreholes penetrating into a waste panel were found in modeling results to not significantly affect brine saturations in neighboring panels, even over the regulatory time frame, because of low hydraulic gradients across the panel closure seals. The borehole is modeled by modifying the material properties of the cells representing the borehole as a function of the type of intrusion (E1 or E2) and the time after intrusion. Short-term brine flow in the open borehole is separately modeled (see Section 3.15).

For long-term flow, the borehole is assumed to be plugged immediately after repository penetration by randomly selecting one of the three plugging scenarios in accordance with its probability of occurrence. The basis for the random selection is discussed in CCA Section 6.4.12, which was not available to the

Panel for review. In an E2 scenario, where the borehole through the Castile is assumed to not encounter pressurized brine, the lower part of the borehole below the repository is given the properties of the surrounding media. In an E1 scenario, where pressurized brine is encountered below the repository, the lower borehole cells are specifically addressed in the model as described in the following paragraph.

The borehole plugs are degraded according to the following assumptions. The continuous plug, the surface plug, and the 40-m plugs below the repository will maintain their initial permeability of 5×10^{-17} m^2 throughout the 10,000-year regulatory time frame. The 40-m plug above the repository maintains its initial permeability of 5×10^{-17} m^2 for 200 years. The borehole between the plugs is assumed to remain open during this period and is assigned a permeability of 1×10^{-9} m^2. The casing is not specifically addressed in the long-term flow model and is assumed to not be present. After 200 years, the upper 40-m plug is assumed to fail and the entire borehole between plugs is assumed to have filled with a material with the properties of silty sand, whose permeability is sampled within the range of 1×10^{-11} m^2 to 1×10^{-14} m^2. Beginning 1,200 years after waste panel penetration, the permeability range of the filling material in the lower borehole below the repository is reduced by one order of magnitude to 1×10^{-12} m^2 to 1×10^{-15} m^2. The porosity of all borehole materials is held at a constant, conservatively high value of 0.32. Pore compressibility is assumed to be zero, giving the medium the approximate compressibility of brine. Two-phase brine and gas flow is modeled using a zero threshold pressure and zero residual brine and gas saturations.

The BRAGFLO model does not explicitly address the continuous plug configuration because the plug permeability is so low that flow is negligible. Under this configuration the borehole cells are given the material properties of the surrounding native materials. BRAGFLO also does not explicitly model the plugs beneath the repository. The plug at the base of the Castile is not modeled because it is considered as part of the impermeable lower boundary. The plug in the upper Castile/lower Salado, which is part of the three plug scenario, is not modeled because it results in conditions essentially equivalent to an E2 scenario in which pressurized brine is assumed to not be encountered in the Castile. If pressurized brine is not encountered in the Castile, the middle plug has negligible function regarding fluid flow in the repository. If pressurized brine is encountered, DOE assumes that the middle plug remains intact and provides an effective seal to brine flow from the Castile reservoir to the repository for the duration of the regulatory time frame. Thus, under either circumstance, the long-term repository fluid flow for the three-plug configuration would be essentially the same as the E2 scenario. Only the two-plug configuration is assumed by DOE to allow long-term releases from a Castile brine reservoir.

BRAGFLO input to performance assessment is accomplished through the use of reference conditions, eliminating the need to run BRAGFLO for each separate set of randomly occurring future intrusion events. Different sets of reference conditions are prepared from BRAGFLO results for each interface with other performance assessment models. For analysis of single exploration borehole penetrations, BRAGFLO is used to calculate cumulative releases over the 10,000-year regulatory time frame for four scenarios: an E1 intrusion at 350 years, an E1 intrusion at 1,000 years, an E2 intrusion at 350 years, and an E2 intrusion at 1,000 years. These calculations are accomplished by running the undisturbed case until the year of the intrusion, and subsequently modifying the properties of the borehole cells in the model over time, according to the degradation rate assumptions described above. The cumulative releases calculated in these runs are used as the reference conditions for analysis of long-term releases.

The reference conditions for long-term releases through exploration boreholes, thus, essentially consist of flow rates over time to the Culebra resulting from borehole intrusions at two specific times (350 and 1,000 years) for each type of intrusion (E1 or E2), and for each set of BRAGFLO parameter input values (that is, for each CCDF). These flow rates are used as input to the NUTS code to calculate cumulative releases to the Culebra. Flow rates (or cumulative releases) resulting from intrusions occurring at other times are determined from the releases computed for these two times by either correlation or interpolation. For intrusions occurring prior to 350 years, the release is assumed to be the same as at 350 years. For intrusions occurring between 350 and 1,000 years, the release is interpolated between the values for 350 and 1,000 years, and for intrusions occurring after 1,000 years, the release is assumed to be the same as at 1,000 years. For long-term release calculations, repository conditions are assumed to not change as a result of short-term releases, thus, repository fluid pressures and volumes are not reduced by the short-term losses.

3.12.2. Review of Criteria

3.12.2.1. Information Used to Develop the Conceptual Model

The principal elements of the conceptual model were developed by DOE in compliance with EPA requirements as summarized in Section 3.12.1 (40 CFR 194.33, Consideration of Drilling Events in Performance Assessments). Pursuant to this regulatory guidance, current borehole drilling, casing, and plugging practices were reviewed by DOE for hydrocarbon exploration boreholes in the Delaware Basin and this information was used as the basis for determining drilling frequencies and methods during the

regulatory time frame. Although documentation of these studies was not reviewed by the Panel, the approach taken appears to have provided a reasonable and appropriate response to the regulatory requirements.

3.12.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.12.1, and are critically reviewed here. Most assumptions are reasonable and appropriate and include the limitation of intrusion to hydrocarbon exploration drilling, use of the BRAGFLO code to simulate release, degradation of the continuous and upper cement plugs, degradation of the casing, permeability reduction in the borehole below the repository due to creep closure, and the assumptions used in modeling the continuous plug configuration. DOE's analysis of current drilling practices in the Delaware Basin, and the drilling frequency and plugging practice information developed from that analysis, are not considered to be conceptual models and were not reviewed by the Panel. An adequate technical basis for estimating the probability of encountering a pressurized brine reservoir in the Castile was not provided to the Panel and is addressed as an issue in Section 3.16 of this report. The method selected by DOE for randomly sampling borehole plugging configurations was also not available for review by the Panel and is not addressed here.

Several simplifying assumptions have been made by DOE that appear to be conservative and therefore acceptable for use in performance assessment. These include neglecting the effects of drilling mud loss into the repository at the time of penetration by an exploration borehole. The drilling mud would likely be a dense, low permeability, water-based brine weighted with bentonite or other additives that may partially fill available repository pore volume, reduce repository permeability, inhibit chemical degradation of the waste by limiting brine availability, and provide additional sorptive capacity for radionuclides. Although the mud could result in other, unforseen chemical reactions with the waste, the overall effect of drilling mud loss into the repository is expected to be beneficial.

The annular space between the borehole plugs is assumed in modeling to be open hole, but according to Thompson et al. (1996, p. C-3), standard practice in the Delaware Basin is to fill this space with a dense plugging mud that provides a platform for setting internal concrete plugs and remains as part of the plugging system. This mud is expected to have a low permeability and may be sufficiently dense to reduce long-term fluid movement through the sealed boreholes between the repository and a partially depressurized Castile brine reservoir. Ignoring this plug in the model may be overly conservative.

The range of permeabilities representative of a silty sand was checked against ranges given in three standard texts, and the results are tabulated below. As can be seen in Table 3.12.1, the values used in performance assessment are neither the highest nor the lowest and are appropriate.

Table 3.12.1. Range of Permeabilities

Source	Medium	High End Value (m^2)	Low End Value (m^2)
Freeze and Cherry 1979, p. 29	Silty Sand	1×10^{-10}	1×10^{-14}
USBR 1987, p. 98	Silty Sand	1×10^{-12}	1×10^{-17}
de Marsily 1986, p. 78	Fine Sand, Silt, Loess	1×10^{-12}	1×10^{-16}
WIPP Performance Assessment 1996	Silty Sand	1×10^{-11}	1×10^{-14}

The frequency of waste panel penetration by exploration boreholes is expected, on the average, to be about 6 penetrations per 10,000 years. This value is based on a waste panel target area of 0.125 square kilometers, which is the approximate area of the disposal rooms themselves and does not include the disturbed rock zone in the walls of the waste panel excavations. This disturbed zone will be fractured by spalling and halite creep and may have sufficient permeability to permit long-term hydraulic communication with the repository. Ignoring this zone in performance assessment reduces the effective area of the waste panels and decreases the frequency of penetration. This issue is discussed further in Section 3.15.

The exploration borehole is assumed by DOE to penetrate the repository within a waste panel. Although such a penetration would be expected to result in the greatest release potential, penetrations could also occur within the operations and experimental areas of the repository, where the greater area of excavations would lead to an increased frequency of penetration. Under long-term flow conditions, pressure is expected to equilibrate quickly throughout a sealed repository by relatively rapid gas movement, and advective brine movement may be small because of the low hydraulic gradients. Penetration of the operations and experimental areas could lower gas pressures throughout the repository, which is expected to be a beneficial result. Diffusive movement of dissolved radionuclides, however, could occur through the panel seals, allowing radionuclides to migrate into the other parts of the repository and be available for release through an exploration borehole. Also, an exploration borehole penetrating the operational area and pressurized brine in the Castile could release Castile brine into the operational, experimental, and waste panel areas and pressurize the entire repository.

Borehole plugs below the Salado are assumed by DOE to not degrade within the 10,000-year regulatory time frame. This lack of degradation is related to suppression of anoxic corrosion reactions, primarily by high hydrostatic pressures in the borehole, and preservation of the concrete plug by the longer term confinement offered by the casing (Thompson et al. 1996, Chapter 3). This approach is based on thermodynamic data and assumes that carbon dioxide and hydrogen disulfide will passivate and reduce the corrosion rate of steel surfaces, and that the buildup of hydrogen fugacity from the corrosion reaction will cause the conversion of iron to $Fe(OH)_2$, to cease at a pressure of about 45 atmospheres (4.5 MPa). Such a pressure is believed to prevent hydrogen bubble nucleation and loss of hydrogen from the chemical system and could be provided by brine inside the casing (Thompson et al. 1996, p. B-21). In the analysis of steel corrosion in the gas generation conceptual model, the DOE indicated that the hydrogen fugacity that would stop corrosion to $Fe(OH)_2$ was 70 atmospheres (7.0 MPa) based on another set of thermodynamic data, but that the corrosion reaction could not be counted on to stop at that pressure because the reaction could convert to Fe_3O_4 and continue until a pressure of perhaps 500 atmospheres (50 MPa) was reached. At these higher pressures, hydrogen bubble formation and loss from the system could occur down to the depths of the plugs below the repository, potentially resulting in their failure during the 10,000-year regulatory time frame. The potential for such failure is also indicated by Thompson et al. (1996, p. 17), where the two lower plugs are given median lives of about 5,000 years and a range of 500 to 50,000 years. The validity of DOE's assumed plug life in excess of 10,000 years is questioned in light of these alternative observations.

If the borehole plugs beneath the repository fail during the 10,000-year regulatory time frame, the role of Bell Canyon groundwater may become important. As previously noted, all exploratory boreholes are assumed to be drilled in search of hydrocarbon resources and all are therefore assumed to penetrate entirely through the Salado and Castile Formations into the Bell Canyon Formation. Although only about 10% of the holes drilled through the waste panels are assumed by DOE to encounter pressurized brine, 100% of the holes will penetrate the Bell Canyon and the plugs below the repository may be significant in isolating the repository from the Bell Canyon. Water pressure in the Bell Canyon is reported in Lappin and Hunter (1989, p. 3-151) to be insufficient to cause water to flow from the Bell Canyon to the Culebra in an uncased or leaky casing borehole if the increase in water density from salt dissolution in the Castile or Salado were considered. However, the potential for water movement to or from the repository horizon was not discussed. If borehole plugs below the Salado cannot be assumed to

have functional lives exceeding 10,000 years with a high degree of certainty, the validity of the assumption that Bell Canyon groundwater can be ignored in the performance assessment analysis may be erroneous.

The assumption in BRAGFLO that the lower plugs need not be explicitly modeled in performance assessment may be valid only if the assumption that they will remain viable during the 10,000-year regulatory time frame is valid. Failure of the lower plugs would provide a low-permeability pathway among the repository, the Bell Canyon, and any pressurized brine that may be encountered in the Castile. If a lifetime in excess of 10,000 years cannot be adequately supported, flow through the lower plugs may have to be explicitly modeled in BRAGFLO.

The three-plug configuration is assumed by DOE to cause an E1 scenario to be equivalent to an E2 scenario by eliminating effects on the repository of encountering pressurized brine in the Castile. The rationale for this assumption, as summarized in Section 3.12.1, does not appear to consider the potential for Castile brine to enter the repository during drilling before the hole is cased through the Salado and Castile. Such an event could increase the brine saturation in the penetrated waste panel, and affect subsequent waste corrosion and gas generation rates. Such a scenario would occur before the plugs were emplaced and thus would be independent of plug degradation rates.

The use of reference conditions, rather than direct model results, as the final input for performance assessment calculations is acknowledged to be a necessary simplification given the thousands of model runs that are necessary to produce stable CCDFs; however, the sensitivity of the current performance assessment inputs to the assumptions inherent in this approach have not been presented to the Panel. The validity of this approach is of concern, particularly when only two release values (those at 350 and 1,000 years) are used to determine releases over a 10,000-year period. Sensitivity studies performed during earlier performance assessments showed this approach to be valid (see, for example, Helton et al. 1992); however, similar studies have not been performed to help assure the validity of this approach for the current performance assessment model.

3.12.2.3. Evaluation of Alternatives

The overall Exploration Borehole conceptual model has evolved over time along with the Repository Fluid Flow model, and has been the subject of extensive sensitivity studies in previous draft performance assessments as noted above. Based on these studies, the overall conceptual model has been shown to be

adequate; however, the validity of certain assumptions regarding components of this model has been questioned as described in Section 3.12.3.2. These include: alternative borehole penetration locations in the repository; allowing for a more rapid degradation of borehole plugs below the repository horizon (including the effects of Bell Canyon groundwater and explicitly including borehole plugs below the repository horizon if adequate longevity of the lower borehole plugs cannot be reasonably assured); reevaluating effects on the repository from an E1 borehole and a three-plug configuration; and assessing the adequacy of the selected reference conditions.

3.12.2.4. Uncertainties

The principal uncertainties in model results are expected to stem from uncertainties in the parametric data base, in the performance of the borehole plugs, and in the accuracy of the reference condition approach to final performance assessment modeling. The principal uncertainties in the parametric data base are associated with the hydrologic properties of the repository materials and are addressed in Section 3.3, Repository Fluid Flow. The hydrologic properties of the seal materials are generally better known and have less uncertainty. Those parameters with the greatest uncertainty, such as the permeability of the silty-sand-like material derived from corrosion products that fill the borehole, are generally sampled from a range of values and their uncertainty is thereby reflected in the overall modeling results. The consequence of uncertainties in these parameters is ultimately to overestimate or underestimate radionuclide releases; however, many of these parameter values reflect best estimates of future conditions and are appropriate for use in performance assessment despite their high degree of uncertainty.

Uncertainty in the performance of the borehole plugs below the repository horizon is discussed in the preceding sections. Plug failure within the regulatory time frame could result in the need to explicitly model the plugs in BRAGFLO, and to consider the effects of a low-permeability pathway to the Bell Canyon Formation on flow into and releases from the repository.

The accuracy of the reference condition approach to final performance assessment modeling has not been demonstrated to the Panel. If sensitivity studies indicate that the present method is inadequate, a denser lookup table may be needed, consequently requiring more computer time to prepare the performance assessment.

3.12.2.5. Adequacy of the Conceptual Model

The conceptual model for exploration boreholes is fundamentally sound, and the issues raised in the validity of model assumptions (Section 3.12.2.2) are associated with specific, but potentially significant, details of the model. The adequacy of the current model is not known because of the unresolved issues identified in Section 3.12.3.3. Further information is required to determine, for example, whether modeling results are sensitive to exploration boreholes that penetrate the operations and experimental areas of the repository, or to the presence of a low permeability pathway to the Bell Canyon Formation. Such changes would affect both the conceptual and numerical models. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.12.2.6. Adequacy of Application

With the exception of the issues raised in Section 3.12.2.2 regarding model assumptions, the application of the conceptual model in the numerical models is adequate. Principal concerns are related to limiting borehole penetrations to the waste panel rooms, assuming no degradation of the lower borehole seals and, therefore, not explicitly modeling them or the Bell Canyon groundwater, and demonstrating the adequacy of the limited reference conditions used to provide input to the performance assessment.

3.12.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. The modeling results were not available for review and could not be checked; however, those areas where the modeling approach is questioned and could lead to inaccurate results have been identified as issues in this report.

3.12.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain pending resolution of the issues raised in Section 3.12.2.3. In summary, the following concerns remain.

- *The potential for releases or changes in repository conditions from borehole penetrations in* the operations and experimental areas of the repository does not appear to have been evaluated. Radionuclides that may have migrated into those areas through the panel closures, by diffusion or other transport mechanisms, could be released to the ground surface, gas pressures could be relieved, and brine could migrate into those areas and then into the waste panels from a borehole penetrating a Castile reservoir or through degraded plugs from the Bell Canyon.

- The assumption that shorter (40-m) borehole plugs beneath the repository horizon will not significantly degrade during the 10,000-year regulatory time frame has not been adequately supported. For the two- and three-plug configurations, degradation of these plugs could result in creation of a low-permeability pathway for fluid migration between the Bell Canyon and the repository. For the three-plug configuration, degradation could result in increased fluid migration from a Castile brine reservoir to the repository.

- The possibility that an effect on the repository could result from Castile brine encountered in an E1 borehole that is assigned a three-plug configuration does not appear to have been considered in the conceptual model. Castile brine could enter the repository during drilling before the borehole is cased and result in increased rates of corrosion, waste degradation, and gas production.

- The sensitivity of the performance assessment to the simplified approach taken to determine reference conditions for BRAGFLO output does not appear to have been evaluated for the current model configuration. If reference conditions are not provided at sufficiently frequent time intervals, the modeling results may be erroneous.

3.12.2.9. Adequacy for Implementation

The Exploration Boreholes conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.12.2.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.12.2.10. Dissenting Views

There were no dissenting views for this model.

3.13. Cuttings/Cavings

3.13.1. Model Description

The Cuttings/Cavings conceptual model describes releases during drilling of exploration boreholes. It is one of several models that address the calculation of direct waste release to the ground surface if an exploration borehole inadvertently penetrates a waste panel, creating a possible pathway for transport of waste to the surface. Other associated models include those describing Exploration Boreholes, Repository Fluid Flow, Multiple Intrusions, and Spalling.

Of the possible pathways for release during the regulatory time frame, one of the most important is that caused by the inadvertent penetration of a waste storage room by an exploratory borehole. Normal oil and gas drilling practices can provide a means for waste to be released to the ground surface in the circulating drilling fluid (mud). From this intrusion, three mechanisms used by WIPP for waste

movement are cuttings, cavings and spallings. Cuttings are waste particles released into the mud from the cutting action of the drill bit itself and from mechanical friction. Cavings are waste particles released by erosion of the borehole walls due to circulating drilling fluids. Spallings are those particulate materials removed and transported by the movement of gases.

The cuttings mechanism is the easiest to address because the volume of waste cuttings is a simple product of the borehole cross sectional area times the room height, and is equal to the waste volume produced by the drill bit moving through the waste. Cavings is somewhat more complicated as it must incorporate the erosional effects of the shearing action of the drilling mud as it moves up the borehole annulus. This shearing may be caused by either turbulent or laminar flow. Repository pressure can have effects on cavings, which is covered by the spalling process. Spallings will be discussed further as a separate model in Section 3.14.

Details of the Cuttings/Cavings model were in a state of flux at the time of this peer review and information describing the model was obtained from various sources, but mainly from the CUTTINGS_S User's Manual, several draft reports, and from numerous contacts, presentations, and discussions.

Releases of cuttings and cavings are calculated using analytical equations governing erosion by flow up through the hole bored in the waste room, based on laminar and turbulent flow (Bergland 1992) as implemented by the CUTTING_S code. This code calculates the final caved diameter of the borehole that passes through the waste by using appropriate input based on assumed physical properties of the waste and drilling parameters. Although DOE is continuing to question whether the flow of the drill mud is laminar or turbulent, and what the parameters should be, the basic model has been generally accepted. However, the amount of material predicted to be released by cavings can be small per penetration and, therefore, its contribution to surface release has not been considered critical relative to other contributions.

The WIPP repository will consist of a number of waste disposal rooms excavated in bedded halite (salt) approximately 650 m below the ground surface. Transuranic waste packed in 55-gallon drums or standard waste boxes will be placed in each room. The waste is expected to be slowly compacted vertically by salt creep, from an original waste room height of 4 m to a compacted height of 0.5 to 2 m in approximately 100 years. In unmodified form, the waste consists of a mixture of, for example, contaminated cloth, wood, rubber, plastics, metals, glass. After placement in the repository, the waste

may become exposed to brine, which is expected to corrode the metals and generate hydrogen gas. Additional gas may be generated by the biodegradation of the organic materials. The gas volumes generated by corrosion and biodegradation are expected to increase continuously for hundreds of years and the pore pressure may become very high, possibly exceeding the lithostatic overburden stress. At some time within the 10,000-year regulatory period, it is probable that one or more exploration boreholes will be drilled into and through the vertically compacted waste and some of the waste will be carried to the surface. The volume of waste removed to the ground surface will depend on the physical properties of the compacted, decomposed wastes, the drilling procedures used, and the pressures encountered. The radioactivity of this waste is determined probabilistically, based on the distribution of waste radioactivity expected in the WIPP repository.

3.13.2. Review of Criteria

3.13.2.1. Information Used to Develop the Conceptual Model

Because the Cuttings/Cavings model is highly dependent on the borehole drilling process, it is important to understand the procedures used in drilling a gas or oil well. The current performance assessment model relies on the regulatory imposed assumption that future drilling techniques will be similar to those used today. When drilling commences, a conductor pipe is set in cement to prevent surface materials from sloughing into the wellbore during later drilling. Drilling is continued to the top of the salt section, using a large-diameter drill bit, where another steel casing is set. This "surface" casing is grouted into the hole and a blowout prevention tree is attached to the casing at the surface level. Drilling in the salt section uses drilling mud mixed in saturated brine to prevent dissolution of the salt.

Drilling mud is pumped from the reserve pit down through the drillpipe and drill bit, and up the annulus formed by the drill string and drilled hole. While drilling in the salt section, no formal attempt is made to monitor the character of the cuttings or the fluid volume of the reserve pit. (In the WIPP intrusion case, this can be an important input.) The drill string generally consists of a drill bit attached to long drill collars (heavy pipe) with a smaller outside diameter than the bit but a larger diameter than the following multiple sections of 4-1/2" diameter drillpipe. Once the drill has passed the salt section (1,375 m), the hole is again cased with cemented pipe. At this point, if the repository had been penetrated, no further contact would occur between the drilling mud and exposed WIPP waste.

Cuttings are a component of the direct brine release model, and cuttings releases are assumed to be the only drilling release to occur for repository pressures less than the hydrostatic pressure of the drilling mud (approximately 8 MPa). Because the volume of cuttings removed and transported to the surface is equal to the product of the drill bit cross sectional area, drill depth and waste porosity, it is only necessary to know these three parameters. The cuttings volume calculated becomes the lower bound to the total quantity of waste removed by drilling. The computation of cuttings release in the CUTTINGS_S code is performed within a module specific to cavings.

For the cavings part of the Cuttings/Cavings model, the erosion process is assumed to be driven solely by the shearing action of the drilling fluid (mud) on the waste as it moves up the borehole annulus between the drill pipe and the waste. For the purpose of the cavings calculations, it is further assumed that the repository is not excessively pressurized by either brine or gas (i.e., the repository pressure is less than the hydrostatic pressure of a brine column to the surface). In the annulus formed by the collars or drill pipe and the borehole wall, the flow of the drilling fluid has both a vertical and rotational component. This helical flow pattern generates shear stresses by the relative motion of adjacent fluid regions and by the action of the fluid on the borehole wall. It is assumed that if the fluid shear stress at the wall exceeds the effective shear resistance to erosion of the wall material (compacted repository wastes), erosion of the wall material will occur, increasing the diameter of the bored hole. The eroded material then will be carried onto the surface, entrained in the flowing drilling fluid. The code probabilistically determines the amount of material removed by the several release mechanisms, and decays the radionuclides release to simulate the source term at the time of intrusion.

3.13.2.2. Validity of Model Assumptions

Many of the principal assumptions used in developing the model are identified in Section 3.13.1. Overall, the assumptions are found to be reasonable and appropriate. Identification of and expansion on the key assumptions are discussed below.

The concept of release due to borehole drilling relies heavily on the assumption that future drilling techniques will be similar to those in use today. The basics of the drilling process are as outlined in Section 3.13.2.1, which comes from a large, well-tested body of experience that can be expected to be reliable.

It is implicitly assumed that the drillhole will encounter waste only as it penetrates the room. This is a simplifying assumption that is realistic but does not have to be absolute. For example, there can be a DRZ over the repository that could contain contaminated brines.

For this model it is assumed that the waste volume is probabilistically determined for each penetration. The Curie calculations are a direct computation from the amount of waste removed.

The cuttings portion of the waste material removed is assumed to be strictly the result of the neat volume of material cut away by action of the drill bit. The cavings portion accounts for the other mechanisms that complement the drilling action, such as frictional drill fluid erosion. These definitions of waste source from this model are inclusive and adequate.

It is assumed by the cavings portion of this model that the fluid shear stress at the waste surface must exceed the effective shear resistance of the waste wall for any release. This is valid since erosion occurs, increasing the diameter of the borehole with the eroded material being carried away by the circulating drilling fluid.

The equations governing waste erosion are based on laminar and turbulent flow, both of which are assumed to occur, depending on the velocity.

Among the basic assumptions made for the fluid flow calculations is that, in the absence of experimental data, the effective shear resistance to erosion of the repository waste is similar to ocean bay mud or montmorillonite clay. In the absence of accurate waste characterization or knowledge of the form this waste is in as the time of intrusion, this assumption appears appropriate because of the low shear strengths of these substances.

3.13.2.3. Evaluation of Alternatives

Only one issue is identified for which an alternative might be considered. It is a possibility that the environment for cuttings and cavings will be saturated with brine. If this becomes the case, this brine might be removed by the drilling action without the benefits of erosion or cuttings. This scenario does not appear to have been incorporated in the Cuttings/Cavings model and its significance is not known.

There are no meaningful alternatives for the cuttings and cavings model, except perhaps to consider using a finite fixed assumed input value, which would be more arbitrary.

3.13.2.4. Uncertainties

Several factors contribute to model uncertainty, principally the undefined nature and complexity of the waste, both in its initial and altered states. Information as basic as granular state, chemical form, decomposed form, density, and waste strength, is unconstrained. To conservatively treat these unknowns, property values of surrogate materials are selected to represent the worse case. As such, the accuracy of the model should be realistic, but on the conservative side. Uncertainty also may arise from inappropriate applications of turbidity resulting from assumptions in turbulent flow, which is a function of the Reynolds Number data on the transition from laminar to turbulence of the fluids. Within the full scope of exposure, however, any reasonable variation from probable waste volume removed would be confined to a restricted, relatively small volume and would not appear to lead to any significant consequences per penetration.

3.13.2.5. Adequacy of the Conceptual Model

This model is fundamentally appropriate. It is based on straightforward analysis, concepts, and technology that is well developed and believed to be adequate for depicting that part of the consequences of a waste room penetration by a borehole drill that is covered by this model.

3.13.2.6. Adequacy of Application

The CUTTINGS_S model contains well thought out and evaluated mathematics, based on researched and established fluid flow technology and science. The FORTRAN computer codes used to simulate the laminar helical flow in an annulus are documented and verified against published results. For turbulent flow, the results are highly dependent on the parameter values. The values given in the CUTTINGS_S User's Manual have resulted from significant research and are believed to provide adequate solutions. The turbulent flow is found to be dependent on absolute surface roughness and the value chosen for the calculation exceeds that of very rough concrete or riveted steel piping. As a result of these considerations, the Panel believes this model is adequate for application.

3.13.2.7. Accuracy of Results

The parameters for calculations were checked as presented in the CUTTINGS_S User's Manual and found to be appropriate. The drilling parameter values were obtained from surveying industry practices and as reported, the values are appropriate for a range of customary industrial size dimensions.

3.13.2.8. Validity of Conclusions

Physically, the conceptual process of this model is simple and valid. Some subjectiveness of validity exists in the questions of turbulent or laminar flow and the state of the waste for determining its resistance to removal by the caving process. The conservative values used in the calculations appear to alleviate these concerns, however. Therefore, the validity of this conceptual model appears to be acceptable within the uncertainties discussed in Section 3.13.2.4.

3.13.2.9. Adequacy for Implementation

This model is sufficiently developed and uncomplicated that no serious concerns were raised. The model appears to be capable of accurately representing the waste that might be removed during a drilling intrusion and is fully adequate for implementation in support of the WIPP performance assessment.

3.13.2.10. Dissenting Views

There were no dissenting views for this model.

3.14. Spallings

3.14.1. Model Description

The Spallings conceptual model is one of several that address the calculation of direct waste release to the ground surface if an exploration borehole penetrates a waste panel. Other associated models include Cuttings and Cavings, Exploration Boreholes, Repository Fluid Flow, and Multiple Intrusions.

Spallings are the particulate materials introduced into drilling mud by the movement of gas from the waste into the borehole annulus. At one time, spallings were conceived to involve three mechanisms: blowout, stuck pipe, and gas-induced spall. Because the latter two were perceived to produce insignificant releases, DOE determined that this model would concentrate on blowout. The repository pressure domain, where spallings are applicable, is above the borehole fluid hydrostatic pressure because it can occur only when the repository gas pressure is capable of countering and reversing the mud-laden drilling fluid during the drilling process. When the drillhole annulus around the drill pipe is cleared of drilling fluid, it becomes a conduit for free release of repository gases.

The principal parameters in the Spallings model are the gas pressure, the volume of gas in the repository when it is penetrated, and properties of the waste such as particle diameters and resistance to erosion.

Because the release associated with spallings is sensitive to gas pressure in the repository, it is strongly coupled to the BRAGFLO-calculated conditions in the repository at the time of penetration. In particular, the spall release may be sensitive to whether the repository has been penetrated previously by another borehole.

3.14.2. Review of Criteria

3.14.2.1. Information Used to Develop the Conceptual Model

This model was based on information on drilling practices, dimensions, and characteristics of drilling equipment parameters, and standard models for gas flow, as well as results of a simple laboratory test to examine some aspects of the conceptual model. Details of the Spallings model were in a state of flux at the time of this peer review. Information describing the model was obtained from various sources, mainly from the CUTTINGS_S Users Manual, several draft reports, presentations, and numerous personal contacts and discussions.

Because this source of release is somewhat dependent on the borehole drilling process, it will be instructive to understand the procedures utilized in drilling an oil or gas well, which the EPA has directed to be the standard for WIPP characterization studies. As described in Section 3.13.2.1, drilling produces a borehole into the repository room by a bit-cutting process that produces rock fragments. The fragments are removed by circulating a mud-laden fluid down through the drill pipe and returning it up the annular space between the pipe and the hole wall. The hydrostatic pressure of this mud column must be kept in balance with the pressure at the drill bit location. When an imbalance from overpressure in the repository occurs unchecked, the mud flow on the return side will be accelerated and ejected from the hole, creating a gas vent to the repository. Until this sudden uncontrolled venting is brought under control, violent escape of gas from the repository is expected to carry with it some of the stored waste, discharging it at the well head on the ground surface. Once gases begin to vent up the drill hole, repository room pressure gradients generated by the penetration of the repository cause a flow of gas toward the borehole that fractures the waste material, permitting the escaping gas to flow within fractures rather than through a porous waste matrix. Consequently, the intrinsic permeability of the matrix does not restrict the gas flow. Gas flow velocity up the borehole is governed by the isothermal flow of gas in a long annular tube of a given cross sectional area, tube roughness, and gas pressure at the borehole entrance. The gas pressure at the borehole entrance to the repository can be assumed to be the initial gas pressure in the repository. The mass-flow rate of gas in the fractured waste at any radial cross section is

equal to the mass-flow rate up the borehole. Radial flow of gas within the fractures in the waste matrix erodes and widens the fractures. Erosion of the waste is assumed to occur if the fracture gas velocity exceeds a threshold velocity related to the terminal velocity of a waste particle at the fracture surface and to the cohesive strength afforded by moisture in the matrix.

A key part of the Spallings model is to determine how much of the waste will be lofted into the gas stream. With the uncertainty of the waste characterization (e.g., its state and chemical form), the premise that the spalling process is self-limiting is based on the assumption that particle movement will cease when the gas velocity, measured radially from the borehole axis, equals the critical entrainment velocity. All material close to the borehole is assumed to be eroded away and removed. A laboratory experiment was modeled to demonstrate a critical lofting velocity for sample materials as a function of particle size distribution. Different terminal velocities were associated with different particle diameters. Confirmative testing of the model was conducted with the standard that if the measured amount of lofted material was less than the predicted amount of erosion, the model was considered confirmed. Confirmation was not obtained because the tests showed the expected uniform gas flow through the waste was not occurring. Instead of a cavity forming around the borehole, flow channels formed that increased in width and length as erosion proceeded in the material. These results forced the latest iteration in the blowout model. The new model (WIPP PA User's Manual for CUTTINGS_S, Appendix A, Section 2.3.1.3), called the channel flow model, is the one used for CCA calculations, although it is the understanding of the Panel that the mechanisms of this model are yet to be confirmed.

A channel-flow mechanism in the model requires either precise definition of the number, geometric configuration, and location of all the channels before they form (which is not technically feasible), or scaling the model results in some manner to reflect the channeling process. The scaling method was adopted, adjusting the predicted releases to agree with experimental release observations in the laboratory test. This laboratory test was a simple, small-scale experiment that yielded useful insights, but it could hardly be an adequate representation of actual degraded waste materials. Although the uniform-flow model was independent of experiments, in the sense that release predictions did not require direct data from the tests, a coupling between experimental results and the model was necessary for scaling. This was accomplished by introducing certain experimentally determined scaling constants into the model (Lenke et al. 1996). Notwithstanding the use of these scaling factors, the model is based on well-defined first order physical principles and is applied to different gases and solid materials by prescribing well-defined material properties, such as particle size and density, viscosity, and cementation tensile

strength. The scaling factors are the only parameters of the model not directly related to geometry or material properties, but they are necessary to represent the way channels for gas flow are likely to develop.

3.14.2.2. Validity of Model Assumptions

It is assumed that the repository pressure domain is above the hydrostatic head of the drill fluid column. This is reasonable because technically, a blowout should not occur at a lower pressure.

A simplifying assumption is that the driller does not have signs of the impending penetration and is unprepared to react. Therefore, the blowout is likely to occur and may be difficult to contain. Because of this, it is assumed that the release will be process-limited rather than operator-dependent.

An implied assumption is that the surface of the cavity will be cylindrical in nature.

The model's limiting characteristic is achieved by the derived equation's function of gas velocity and waste strength. As the velocity declines, the limiting parameter becomes the property of waste strength. The use of this property is valid, but its value is subjective because of the unknowns and uncertainties of the waste itself. In fact, this property is a function of the source of waste strength, such as cohesion, adhesion, or cementation. Cementation from a salt crystallization process in the stored waste is currently being considered as a mechanism that provides a strength value for waste that might be easily validated.

At this writing, it is assumed that the latest CUTTINGS_S model assures that the model relies on channel flow instead of a uniform low porosity flow toward the borehole. It is of concern to the Panel that the mechanisms of this assumption are yet to be confirmed.

3.14.2.3. Evaluation of Alternatives

The Spallings conceptual model has changed several times during its development. Early model development focused on transient, unrestrained outgasing leading to the spall (dynamic fracture) of porous cohesive granular media (Berglund 1992, Section 3.3). An experimental program related to model development focused on almost instantaneous depressurization and was limited to a one-dimensional linear sample configuration. The pore pressures required to cause spall or dynamic fracture could be closely approximated using the tensile strength of the porous soil medium (Berglund and Lenke 1995), but the model was complex and could not be directly related to an intrusion event. In addition, although the experimental observations showed fracturing under instantaneous release of gas pressure,

sample-preparation factors were largely responsible for the locations of the fractures. The fracture patterns also depended on the one-dimensional nature of the experiments, and the model did not adequately explain how the fractured material was removed.

After extensive discussion, the dynamic fracture model was replaced with a more general three-part model based on the premise that the waste could be removed by any one of three mechanisms: blowout, stuck pipe, and gas-flow assisted erosion (as the result of gas-induced spall) (Butcher et al. 1994). Which mechanism will dominate depends on the permeability and pressure drop at the borehole. Well blowout, an uncontrolled gas release from the borehole, was considered the dominant mechanism. The remaining two mechanisms, stuck pipe (waste loosened and moved while attempting to dislodge a stuck drill pipe), and gas-flow assisted erosion, were not thought to be important because they would only occur at waste permeabilities of less than 1×10^{-16} m^2. The gas-flow assisted erosion is now the basis for the channel flow modeling in the Spallings model.

3.14.2.4. Uncertainties

Development of this model is not sufficiently complete to determine uncertainties specific to the channel flow movement of waste to the existing borehole. The lack of adequate waste characterization may also provide a set of uncertainties. Other uncertainties concern the state the waste is in at the time of intrusion, which may not be feasible to ascertain.

3.14.2.5. Adequacy of the Conceptual Model

The Spallings model gives a good conceptual view of how solid waste can be removed by gases that are being rapidly vented. The latest model is most realistic mechanistically because it is predicated on the concepts of moving particles via gas movement. The original model, which relied on instantaneous decrease in gas pressure, was judged by DOE to be unrealistic because of waste permeability and gas flow considerations. The latest model appears to be the most applicable of those that have been considered to date. Notwithstanding the need for establishing two scaling parameters and a waste strength factor, this model is conceptually appropriate, but the Panel could not find sufficient information to determine its adequacy.

3.14.2.6. Adequacy of Application

Integration of the Spallings model into the CUTTINGS_S code is a relatively simple exercise, although the equations governing the waste availability for removal do not appear to be fully developed at this

time. While the concept of scaling parameters, which are intended to address waste strength by providing factors of resistance to erosion or lofting, is appropriate, the proposed parameter value has yet to be validated. Therefore, until these details are resolved, it will not be possible to assess the adequacy of application for this model.

3.14.2.7. Accuracy of Results

On testing the latest modeling efforts for confirmation of principle, additional information was gained that should be pursued before further confirmation is sought. It seems plausible that the performance assessment exercise might use an assumed entrained waste content for a given time period and sample several scenarios for concentration and time domain. Another simplistic approach might be to assume a certain waste volume around the borehole that would be removed. Given the importance to overall performance assessment of results from this model, any laboratory tests could be supplemented by a scaled-up testing demonstration that will more convincingly verify the model. At this time there is not enough information to determine the accuracy of results from the Spallings model.

3.14.2.8. Validity of Conclusions

In the opinion of the Panel, the model development is now on an appropriate path to produce a valid outcome. However, the available information was not sufficient to present a compelling argument that adequate work has been done to confirm that the conclusions would be valid. Additional testing is required to firm up the conceptualization of the channel flow scenario.

3.14.2.9. Adequacy for Implementation

Because of perceived inability to defend a time limit for release, it became necessary to implement a model that provides a self-limiting process for waste removal. It is not reasonable to expect that the entire room would be excavated by the blowout process. If this were possible, a model would not be necessary. *Because of its unconfirmed state of development, this model is not adequate for* implementation at this time.

3.14.2.10. Dissenting Views

There were no dissenting views for this model.

3.15. Direct Brine Release

3.15.1. Model Description

The Direct Brine Release conceptual model describes short-term releases of brine from exploratory boreholes that penetrate waste panels in the repository. The model addresses releases from both single and multiple intrusions. Long-term flow from single intrusions and the assumptions regarding the physical aspects of the boreholes are addressed in the Exploration Borehole conceptual model, and long-term flow from multiple intrusions is addressed in the Multiple Intrusions conceptual model. Other related models include Repository Fluid Flow, Castile and Brine Reservoirs, and Actinide Transport in the Salado. The related Cuttings/Cavings and Spallings models address releases of solid waste materials following borehole intrusions, but do not address brine releases. The details of the Direct Brine Release model were still under development at the time of this peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 22 May 1996 Draft CCA, Sections 6.4.7.1, Releases During Drilling (DOE 1996, pp. 6-65 to 6-70), from verbal descriptions, and from the cited references.

Releases that may occur during and immediately following drilling are modeled in accordance with regulatory guidance, assuming that present standard rotary drilling practices will be used. This assumption was used by DOE to establish borehole geometry during drilling, as well as the drilling, casing, and sealing practices (Thompson et al. 1996). To help prevent blowout, the density of the drilling mud is controlled by drillers based on the fluid pressures expected at the drilling depths. Gas, as well as brine, may enter the borehole from the waste panel if the driller is unable to control the pressure in the borehole. If fluid pressures in the waste panel are sufficiently high, brine or a brine-gas mixture may flow to the ground surface. The boreholes are assumed to be cased from the ground surface to the lower Rustler before entering the Salado; thus, brine flowing up the borehole during drilling would reach the surface, but not enter the Culebra or the other permeable horizons above the Salado. The frequency with which exploration boreholes will penetrate the waste panel area is estimated based on a long-term average of 47 boreholes per square kilometer per 10,000 years, and the size of the waste panel area. This is further discussed in Section 3.12.

Before brine can flow from a waste panel to the ground surface, mobile brine must be present in the waste panel and the pressure of the brine must be greater than the pressure of the drilling mud at the repository depth. Brine is expected to enter the waste panel as seepage from the surrounding halites, anhydrite beds, and through the shaft seals, and will also enter if pressurized brine is encountered in the Castile. Mobile brine will be present in the waste panel if it has not been previously consumed by the corrosion reaction and if there is enough remaining to exceed the residual brine saturation of the waste. The residual brine saturation is the percent saturation below which the brine occurs discontinuously in the porous waste and will no longer move. The residual brine saturation in the waste panel is uncertain and is randomly sampled in performance assessment from the range of zero to 0.552 (DOE 1996, Table 6-6). The drilling mud is assumed to exert a pressure of about 8 MPa at the repository horizon; thus, for brine to be released to the ground surface its pressure in the repository must exceed this value.

In accordance with regulatory guidance, DOE does not assume that a direct brine release would be noticed by the driller, or that the driller is aware of the presence of the repository. The driller is assumed to be exploring for hydrocarbon resources, and after taking normal steps to deal with any brine releases or drilling fluid losses at the repository horizon, would continue drilling to customary depths below the Bell Canyon. Based on a review of current practices in the Delaware Basin, DOE has assumed that direct brine releases to the surface will be stopped by the driller 44 hours after penetrating the repository. Borehole plugs are assumed to be installed in three alternative configurations, and to degrade as discussed in Section 3.12. Because of the assumed degradation rates of the various plugs, only the two-plug and three-plug configurations are of consequence to direct brine releases.

Encountering pressurized brine in the Castile in a borehole is not considered by DOE to result in a direct release of repository waste. The Castile brine will be uncontaminated and, to result in a direct release, would have to be of sufficient pressure to eject the drilling mud from the borehole. Because the repository is likely to have been depressurized a short time before when it was penetrated by the same borehole, the repository pressure is expected to be lower than the Castile brine pressure and initial hydraulic gradients would be from the borehole into the repository. The longer term migration of Castile brines into the repository are addressed in the long-term BRAGFLO calculations and would affect both the long-term releases and the initial conditions (such as waste panel brine saturations and gas pressures) for the next short-term release. Direct release of waste solids by borehole wall erosion from Castile brine moving up the borehole is assumed by DOE to be negligible.

Short-term releases of dissolved or suspended radionuclides contained in brine are modeled using a two-dimensional, two-phase, transient horizontal plane model of the waste panel area, developed using the BRAGFLO code specifically for estimating short-term, direct brine flow. This model has not been specifically named, and for purposes of this report will be called the BRAGFLO-DBR model. Radionuclide transport is calculated using the PANEL code. This code conservatively assumes complete mixing in the waste panels and is further discussed in Section 3.8. BRAGFLO-DBR explicitly models all disposal rooms, pillars, panel closures, and the associated disturbed rock zone within the waste disposal area of the repository.

A one-degree dip in the repository corresponding to the average one-degree dip to the south in Salado bedding is included in the model. Including this dip has been found to be important in modeling results because of the effects of gravity. Gas movement in the anhydrite beds tends to be to the north toward areas of lower pressure, while brine tends to accumulate in the southern or lower end of the waste disposal area. Material properties in BRAGFLO-DBR are generally consistent with those in the standard version of the BRAGFLO model (called BRAGFLO in this report) used to model repository fluid flow (Section 3.3), with the exception that the intact Salado halite is assumed to be impermeable and forms an outer no-flow boundary for the model.

BRAGFLO-DBR takes its initial and boundary conditions from BRAGFLO, CUTTINGS_S, the WIPP data base, and an analytical correlation to simulate flow up the open borehole. Fluid pressures, saturations, permeabilities, porosities, two-phase flow properties, and other repository properties are determined at the time of penetration by the standard version of the BRAGFLO code. The borehole flow model has been developed from a multi-phase vertical pipe flow analysis used in the petroleum industry. Total flux and transport are determined based on a flow duration of 44 hours.

For calculating short-term releases, borehole penetrations are assumed in BRAGFLO-DBR to occur in two reference locations, at an updip location in the center of the waste panel area, and at a downdip location in the southwestern waste panel. Multiple borehole penetrations of the same waste panel are always assumed to occur at the southwestern end of the repository because the reference conditions for multiple intrusions are developed from the standard BRAGFLO model, which conservatively places the single waste panel and intrusion borehole at the downdip end of the waste panel area. Actual intrusion locations are selected randomly, but the boreholes are then assigned standardized reference locations depending on whether they penetrate the waste or a salt column, whether they are updip or downdip,

whether they are E1 or E2, and whether they are the first intrusion or a subsequent intrusion of the same waste panel. Modeling results have indicated that the effects of borehole intrusions on the repository are not significant beyond the waste panel that was penetrated; thus, second and subsequent intrusions into the same waste panel are treated separately in the model.

For the first borehole penetration in a particular waste panel, the initial and boundary conditions are determined by interpolation from reference conditions determined from undisturbed BRAGFLO results at approximately six reference times ranging from 100 to 10,000 years. BRAGFLO-DBR is run for each of these sets of reference conditions to establish a data base for interpolating short-term releases from first penetrations occurring during the regulatory time frame. Conditions for first penetrations are assumed to be the same for E1 or E2 boreholes, because at the time of penetration neither would have been drilled past the repository. Initial conditions for downdip borehole locations are taken from conditions in the single waste panel in BRAGFLO, which is at the downdip end of that model. Initial conditions for updip borehole locations are taken from the "rest of the repository" in BRAGFLO, which is at the updip end of that model.

Conditions for second penetrations are determined based on the date, type, and location of the first penetration, as well as the date, type, and location of the second penetration. Different sets of reference conditions are established for second penetrations depending on whether the first penetration was an E1 or E2, whether the second penetration occurs in the same panel or a different panel, and the lag time between the first and second penetrations. Subsequent penetrations are addressed following similar logic. Reference conditions for second and subsequent penetrations are determined from BRAGFLO calculations for E1 and E2 intrusions occurring at 350 and 1,000 years, as described in Section 3.12.

Changes in repository pressure, fluid saturation, and other repository conditions resulting from the short-term releases are not considered in the long-term flow calculations. Such effects are considered negligible by DOE over the long term because of their transient and local nature.

3.15.2. Review of Criteria

3.15.2.1. *Information Used to Develop the Conceptual Model*

The Direct Brine Release conceptual model was developed based on a combination of conceptual models for repository design and two-phase fluid flow, the physical and hydrologic properties of Castile brine reservoirs, current drilling and borehole sealing practices in the Delaware Basin, fluid flow in open

boreholes, and borehole plug degradation rates. Current practice has provided elements of this model, in accordance with regulatory requirements. This information base is considered reasonable and appropriate.

3.15.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.15.1, and are critically reviewed here. Most assumptions are reasonable and appropriate and include the general approach taken to modeling fluid flow within the boreholes and repository, treatment of borehole sealing practices, and use of reference conditions to address alternative intrusion scenarios. The frequency of drilling and the time required for a driller to control a direct brine release are based on DOE analysis of current practice and are not reviewed here. Reference conditions for direct brine releases are determined at a greater frequency than for the exploration boreholes or multiple intrusions models, and are expected to be adequate for performance assessment. The assumptions related to repository fluid flow, the physical aspects of the boreholes and borehole seals, and the characteristics of Castile brine reservoirs are discussed in Sections 3.3, 3.12, and 3.16, respectively. Changes in these assumptions would affect the approach taken to model direct brine releases. Several assumptions in the Direct Brine Release model that are potentially important to radionuclide containment and are not adequately supported are discussed in the following paragraphs.

No radionuclide release is assumed to occur from direct discharge of Castile reservoir brine in a borehole penetrating a waste panel. The rationale for this assumption does not appear to be supported by an analysis of the potential for brine mixing and borehole wall erosion. This could be more significant for penetrations occurring before complete water panel closure, when waste has not yet been fully compacted. Because the Castile brine would pass directly through a waste panel, the potential consequences of an error in this assumption could be significant.

The potential for entraining waste room brine in rapid gas flow from the waste panel is not considered in the conceptual models for either spallings or direct brine release. The Spallings model considers only the entrainment of solid particles in single-phase gas flow, and the Direct Brine Release model considers only dissolved and colloidal radionuclide transport in brine released to the surface. Brine entrainment in the gas can occur by transport of droplets or, more importantly, by air-lifting brine and waste particulates in a closed-wall pipe (the coffee percolator effect). The air-lift is in fact a method of well completion

where the violent surges from air pumped down a well are used to scour the borehole production zone and remove fine-grained sediments to enhance well production. Depending on the flow velocity in this two-phase brine/gas system, the erosional forces could be greater than for either gas or brine flow alone.

Boreholes penetrating areas of disturbed rock in the walls of the repository excavations do not appear to have been considered in performance assessment modeling. The walls will have a tendency to bow inward under the lithostatic stress, resulting in both micro- and macro-fracturing in the halite. Hydrologic tests in repository walls have shown pore pressure depressurization and reduced permeabilities within 10 m of the workings, most likely in response to halite deformation. Within this zone, pore pressures appear to have dropped to near zero at some locations, and permeabilities nearly three orders of magnitude higher than the high end of the undisturbed halite range have been measured (Lappin and Beauheim 1996). Hydrofracture measurements in horizontal boreholes within the repository have indicated that stress effects from repository excavations may extend on the order of 50 m from the end of a drift (Wawerski and Stone 1986). Boreholes very near the excavation wall could, therefore, encounter open fractures and permeabilities equivalent to those of the waste, while boreholes 10 m or more from the excavation may encounter essentially undisturbed halite. The higher permeabilities encountered in boreholes penetrating the disturbed rock zone in the excavation walls could lead to increased short- and long-term releases.

3.15.2.3. Evaluation of Alternatives

The overall conceptual model for direct brine releases is based on standard hydrogeologic and petroleum industry practices and is appropriate for use in performance assessment. Alternatives to this model may be considered, however, in the details of its application. Three fundamental issues have been identified: waste transport during the direct release of Castile brine, the entrainment of brine and waste solids in two-phase gas/brine flow from the repository, and boreholes penetrating disturbed rock in the excavation walls.

3.15.2.4. Uncertainties

Uncertainty in model results stems from uncertainties in the validity of the underlying fluid flow theory and analysis methods, from uncertainties in the input data, and from the validity of assumptions regarding the conceptual models. The underlying theory is widely used in the petroleum industry for evaluating oil reservoirs and provides a reasonable and appropriate approach to studying direct brine releases. Although the uncertainty in the input data are occasionally high, the parameter values have

generally been appropriately selected for performance assessment. The three additional processes discussed in Section 3.15.2.2 are similar in that they each address processes that were not considered by DOE. The consequence of neglecting these processes is to potentially underestimate radionuclide releases.

3.15.2.5. Adequacy of Conceptual Model

The conceptual model for direct brine releases is fundamentally sound, with the possible exception of the three processes identified in Section 3.15.2.2. These processes were not included in the conceptual model for performance assessment, and if valid, could be important to cumulative radionuclide release. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.15.2.6. Adequacy of Application

With the exception of the issues raised in Section 3.15.2.2 regarding model assumptions, the internal consistency of the conceptual model and its application in BRAGFLO-DBR is logical and is adequate for performance assessment. The simplifications required to model a complex set of conditions in an efficient manner appear to be appropriate.

3.15.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. Although the modeling results were not available for review and could not be checked, the density of reference conditions is expected to provide performance assessment inputs of suitable accuracy.

3.15.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain, pending resolution of the issues raised in Section 3.3.2.3. In summary, the following concerns remain.

- The basis for the assumption that radionuclides do not accompany the direct discharge of Castile brine has not been adequately supported. This assumption could lead to underestimating radionuclide releases if releases do, in fact, occur through this mechanism.

- Radionuclide transport through entrainment of brine and waste solids in rapid gas releases during inadvertent borehole intrusions does not appear to have been evaluated. This transport mechanism may be an important component of the conceptual model.

- Releases resulting from flow into an exploration borehole intersecting a disturbed rock zone in the wall of a waste panel do not appear to have been evaluated. Large, open fractures in the walls could significantly increase the local halite permeability, allowing gas and brine to migrate through the borehole to the ground surface.

3.15.2.9. Adequacy for Implementation

The Direct Brine Release conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.15.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.15.2.10. Dissenting Views

There were no dissenting views for this model.

3.16. Castile Formation and Brine Reservoir

3.16.1. Model Description

The Castile Formation and Brine Reservoir conceptual model addresses the hydrologic characteristics of the Castile Formation and the occurrence, size, hydrologic, and chemical characteristics of brine reservoirs that may underlie the repository within the Castile Formation. Associated models include Exploration Boreholes, Multiple Intrusions, and Repository Fluid Flow. The details of this model were still under development at the time of the peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 23 May 1996 Draft CCA, Section 6.4.8, Castile Formation and Brine Reservoir (DOE 1996, pp. 6-75 to 6-79), from verbal descriptions, and from the cited references.

The Castile Formation consists of a 360-m thick series of halite and anhydrite beds underlying the Salado Formation. Although few tests have been performed, by analogy to the Salado, the Castile is conceptualized as a very low permeability formation whose primary importance to WIPP performance assessment stems from the hydrologic isolation it provides the repository and from the pressurized brine reservoirs that have been encountered during deep drilling.

Deep exploratory boreholes that penetrate both the repository and the underlying Castile Formation may encounter a pressurized, higher-permeability, brine-filled region called a brine reservoir. If encountered, the fluid pressure in such a reservoir would be sufficient to cause brine to flow at potentially high rates

and high pressures through the repository and from the wellbore at the ground surface. The consequences of such flow are addressed in the Exploration Borehole and Multiple Intrusion conceptual models.

The brine reservoir is conceptualized by DOE as a heterogeneous, discontinuously fractured zone of limited extent within the Castile anhydrites. Transmissive pathways for brine and gas movement are provided by interconnected, primarily vertical fractures whose origin may be related to structural deformation. Fluid in the reservoirs is pressurized by the weight of the overlying geologic media and averages about 67% of the lithostatic pressure within the Delaware Basin (Freeze and Larson 1996).

Brine reservoirs are occasionally encountered during deep drilling in the Delaware Basin and, when allowed to flow, may discharge at rates estimated at 1,000 to 2,000 barrels (150 to 300 m^3) per day and last up to 4 to 5 days (Silva 1994). The observation that flows stop by themselves supports the concept that the size of individual brine reservoirs is limited. Brine reservoirs were penetrated by two boreholes (ERDA-6 and WIPP-12) drilled for WIPP site characterization purposes. The pore volumes of these reservoirs were estimated to be about 96,000 m^3 and 2,700,000 m^3, respectively, although the uncertainty in these estimates is large (Popielak et al. 1983). A geophysical survey, using time domain electromagnetic methods, completed over the WIPP-12 brine reservoir and the waste disposal panels, detected a conductor interpreted to be the WIPP-12 brine reservoir, and also indicated that similar brine occurrences may be present within the Castile under a portion of the waste disposal panels (Earth Technology Corporation 1988).

The chemistries of the brines from the ERDA-6 and WIPP-12 reservoirs were studied by Popielak et al. (1983) and found to be distinctly different from each other and from local groundwaters, supporting the concept that the reservoirs are isolated from each other and from local groundwaters. The major and minor element concentration ratios were interpreted by Popielak et al. to indicate that the brines originated from ancient seawater. Based on the geochemical and hydrological information, DOE believes the brine in the Castile reservoirs has not mixed to any significant extent with other waters and has not circulated within the Castile. Further, the brines are nearly saturated with halite and have little potential to dissolve additional halite.

The WIPP performance assessment requires information on the hydrologic characteristics and likelihood of encounter for a brine reservoir beneath the waste disposal area. Many of the characteristics of the reservoir penetrated by WIPP-12 have been used as a basis for modeling the hypothetical reservoir

underlying the waste. The WIPP-12 reservoir is the best characterized, it is relatively large and permeable, and it is the closest identified reservoir to the site. Relatively little gas has been found in the Castile reservoirs and the analyses of WIPP-12 have only considered single-phase brine flow.

The parameters needed to determine the hydrologic characteristics of the hypothetical reservoir beneath WIPP are described in several supporting documents. Reservoir pressure is described in Freeze and Larson (1996) as a distributed parameter with an expected value (12.7 MPa) equal to the estimated pressure of the WIPP-12 reservoir, and a range (11.1 to 17.0 MPa) based on pressures in other reservoirs encountered in the Delaware Basin. Reservoir porosity is described in Freeze (1996a) as a distributed parameter with a mean value (0.009) determined from laboratory measurements of intact anhydrite core from ERDA-6 and WIPP-12. Although the porosity values have not been finalized, they are currently proposed to be treated as a distributed parameter with a range of 0.001 to 0.02. Average fracture porosity in the WIPP-12 reservoir is estimated by Popielak et al. (1983, pp. G-44 to G-48) to range from 0.004 to 0.011, and is similar in magnitude to the intact rock porosity. A fracture porosity of 0.008 was used by DOE in estimating reservoir pore volume.

Bulk rock compressibility is described in Freeze (1996c) as a distributed parameter with a mean of 1×10^{-10} Pa^{-1} and a range of 5×10^{-12} Pa^{-1} to 1×10^{-8} Pa^{-1}. These values were determined as a best estimate considering compressibilities for intact anhydrite computed from elastic theory, compressibilities determined from the results of borehole hydrologic tests in disturbed Salado halites, and literature values for the compressibility range typically associated with fractured rock.

Reservoir permeability is described in Freeze (1996b) as a distributed parameter with an expected value of 1.6×10^{-12} m^2 and a range of 2.0×10^{-15} m^2 to 1.6×10^{-10} m^2. The expected value was derived from a GTFM analysis of Flow Test 3 in WIPP-12 (Reeves et al. 1991, Appendix A). This was a long-term test and the results best represent the average permeability across the volume of the reservoir. Permeability and rock compressibility are strongly coupled in hydrologic test analysis. In a low-porosity medium, their product should be maintained approximately constant for accurately simulating flow from a specific source; however, their ratio should be maintained approximately constant for accurately simulating pressure fluctuations. The most accurate characterization of these parameters is considered to be that which best matches both pressure and flow fluctuations. Because the expected value of rock compressibility used in the GTFM analysis of 1×10^{-9} Pa^{-1} was decreased in the performance assessment to 1×10^{-10} Pa^{-1}, the expected value of permeability used in performance assessment was increased from

1.6×10^{-13} m^2, determined in the GTFM analysis, to 1.6×10^{-12} m^2 to maintain good estimates of fluid flow. The low end of the range of permeabilities was based on the lowest value obtained in flow tests in ERDA-6, and the high end was based on the near-field high permeability zone encountered in WIPP-12.

The pore volume of the WIPP-12 reservoir was estimated using rock compressibility and porosity data and pressure changes measured in response to reservoir flow. The uncertainty in the volume estimate is largely derived from the uncertainty in rock compressibility. Estimates of the WIPP-12 reservoir pore volume are presented by Larson and Freeze (1996) as ranging from 32,000 m^3 to 64,000,000 m^3. This estimate is based on the nearly four order of magnitude range in compressibility used in performance assessment, and an estimated anhydrite reservoir fracture porosity of 0.008. A WIPP-12 reservoir pore volume of 3,200,000 m^3 was estimated for the expected compressibility of 1×10^{-10} Pa^{-1}.

The pore volume of a potential brine reservoir beneath the WIPP disposal panels was estimated by Larson and Freeze (1996) to range from 32,000 m^3 to 160,000 m^3. The lower end of this range was based on the minimum pore volume estimated for the WIPP-12 reservoir. The upper end of this range was based on the size of a reservoir that would extend beyond the perimeter of the WIPP disposal area. Assuming that the anhydrite layer containing the WIPP-12 reservoir is from 7 m to 24 m thick (Reeves et al. 1991, p. 2-10) and is analogous to the hypothetical reservoir beneath the site, the radius of a circular reservoir with a pore volume of 160,000 m^3 would range from about 510 m to 950 m. Larger reservoirs would likely extend beyond the limits of the waste panels, which have a perimeter of about 600 m by 800 m. Based on regulatory guidance, DOE assumes that the waste panels are partially protected from drilling by active and passive institutional controls for 700 years after repository closure. The larger reservoirs would underlie areas that are not protected by such controls and are assumed to be partially depleted by exploratory drilling penetrations before drilling over the waste would occur. In view of this depletion, the larger reservoirs are not considered in performance assessment because a smaller, undepleted reservoir is considered by DOE to be more significant to performance assessment than a larger, partially depleted reservoir.

Exploration boreholes are assumed to occur both in the waste itself and in the surrounding waste panel walls and room pillars. The probability that a borehole will encounter pressurized Castile brine beneath the WIPP disposal area is tentatively assumed in the WIPP performance assessment to be 10%. This probability is primarily based on a geostatistical analysis of the spatial distribution of known Castile brine reservoirs in the Delaware Basin and on the assumption that because of the primarily vertical

orientation of known fractures in the Castile anhydrites, the potential exists that a vertical borehole could penetrate the area of a reservoir without intersecting conductive fractures and, therefore, without encountering significant brine flow. A discussion of the development of this probability is presented in the 23 May 1996 Draft CCA, Section 6.4.12.6, Probability of Intersecting a Brine Reservoir (DOE 1996, pp. 6-109 to 6-110).

Boreholes randomly selected to penetrate the waste panel area and encounter pressurized brine in the Castile are assumed to contribute to the depressurization of that reservoir. Depressurization is currently assumed by DOE to occur to the extent that the reservoir no longer affects the repository after two penetrations for the smallest reservoir size (32,000 m^3), ranging up to ten penetrations for the largest reservoir size (160,000 m^3). Boreholes penetrating the walls and pillars of the waste panel area are assumed to result in no waste release, but will contribute to reservoir depressurization if they are randomly determined to encounter pressurized brine.

Numerical simulations of short-term and long-term flow from a Castile brine reservoir into the repository, to units overlying the Salado, and to the ground surface are handled by the BRAGFLO-DBR and BRAGFLO codes for single or multiple intrusion scenarios. These codes have the capability to model two-phase brine and gas flow, and it is anticipated that this capability will be applied to Castile brine reservoirs. Short-term flow is addressed in the Direct Brine Release conceptual model, and long-term flow is addressed in the Exploration Borehole and Multiple Intrusions models.

3.16.2. Review of Criteria

3.16.2.1. Information Used to Develop the Conceptual Model

The Castile Formation and Brine Reservoir conceptual model draws heavily on the properties of the WIPP-12 brine reservoir in developing characteristics for the hypothetical reservoir that could be encountered beneath the WIPP waste panels. Information is also taken from other brine reservoirs within the Delaware Basin, with emphasis on the ERDA-6 reservoir. Details on the sources and use of this information are presented in Section 3.16.1. Use of Delaware Basin reservoir information and emphasis on the WIPP-12 and ERDA-6 reservoirs are appropriate because of the increased relevance of local information and the relative wealth and accuracy of data from the two specific sources.

3.16.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.16.1 and critically reviewed here. Most assumptions are reasonable and appropriate and include the conceptual hydrologic role of the Castile Formation (exclusive of the brine reservoirs), consideration of the WIPP-12 reservoir as analogous to the hypothetical reservoir beneath the WIPP disposal area, the concept of a brine reservoir as a heterogeneous, discontinuously fractured zone of limited extent within Castile anhydrites, two-phase treatment of reservoir flow, and the selected values for reservoir pressure and porosity.

Bulk rock compressibility data were developed from a variety of sources including elastic modulus values, disturbed Salado surrogates, and literature values. Although the high end of the range (1×10^{-8} Pa^{-1}) is considered appropriate, the low end of the range (5×10^{-12} Pa^{-1}) and the mean value (1×10^{-10} Pa^{-1}) may be unrealistically low. The mean and maximum permeability values used in the performance assessment were adjusted upward by an order of magnitude from the original GTFM analysis of WIPP-12 to compensate for an order of magnitude downward adjustment in the original value of rock compressibility. The result of these adjustments is to decrease the storage capacity, increase the permeability, and increase the maximum size of the potential reservoir underlying the site. The estimated minimum size of the WIPP-12 reservoir directly supports the performance assessment and remains unaffected by the decrease in the mean compressibility. Although the assumption of a lower mean compressibility for the brine reservoir is not fully supported, the effects of this assumption appear to be conservative and therefore acceptable.

The assumption that reservoirs with pore volumes greater than 160,000 m^3 can be ignored is not adequately supported. Although sufficiently large reservoirs would extend beyond the area assumed to be protected by institutional controls for 700 years after closure, and could be intersected and partially depressurized by exploratory boreholes before boreholes are drilled over the waste panels, no supporting studies of the effects of this scenario have been presented to the Panel.

The assumption that reservoirs will be depleted by two to ten penetrations by exploration boreholes is also not adequately supported. Although the concept of depletion is rational, no supporting studies of the effects of this scenario have been presented to the Panel.

The assumed 10% probability of encountering pressurized Castile brine in an exploratory borehole is based on a geostatistical analysis of reported brine encounters, consideration of the relationship of brine

reservoirs to geological features or processes, and on the assumption that not all boreholes penetrating through the area of a reservoir will necessarily encounter brine. The adequacy of the assumption that significant brine releases are routinely documented was checked with Paul Knautz, a geologist with the New Mexico Oil Conservation Division in Hobbs (telephone 505-393-6161). Mr. Knautz indicated his confidence that the reporting requirements for significant releases were met by the operators. He stated that when encountered with a brine reservoir, the operator must report brine volume and pressure by telephone, and must truck the brine to a proper disposal facility.

Although no documentation of the geostatistical analysis was available for Panel review, preliminary results were verbally presented by DOE. The value of the results of this analysis was seriously weakened by a lack of data in the vicinity of the WIPP. The validity of the spatial correlations relied on the assumption that the geologic conditions supporting reservoir development at the WIPP site were similar to those in areas where hydrocarbon exploration boreholes were numerous and where a number of brine reservoirs were encountered. Unfortunately, there is little direct evidence to support or refute this assumption, but regional trends support the hypothesis that the probability of encountering brine decreases to the west. The kriging results on which the estimate of probability of encounter would be based were sensitive to historic brine encounters. The single encounter near WIPP (at WIPP-12) changed the probability over the waste panels from near zero to about 8%. A second encounter could have an equally dramatic effect. Due to the lack of data and the consequent sensitivity of the estimated probability, little credibility can be assigned to either value.

The assumption that not all boreholes penetrating through the area of a reservoir will necessarily encounter brine is reasonable, given that fractures in the anhydrite reservoir rock appear to be predominantly sub-vertical. However, this assumption must be quantified to be of more than conceptual value to performance assessment, and no basis for such quantification, nor of the way in which this concept has been used in developing the final probability value, has been presented to the Panel.

The approach for estimating the probability of a brine encounter apparently does not quantitatively consider the TDEM geophysical results reported in Earth Technology Corporation 1988, which suggest the presence of brine pockets beneath the waste panels and provide an alternative, site-specific approach for estimating the probability of encounter. In considering the reported uncertainty of ±75 m in estimated depth from the geophysical results (Earth Technology Corporation 1988), Borns (1996) estimated the proportion of waste panel area underlain by a potential brine reservoir to range from 10% to 55%, with

an expected value of 25%. A similar study performed on an alternative contouring of the original TDEM data for the 1992 WIPP preliminary performance assessment (WIPP Performance Assessment Department 1992b) identified a maximum proportion of 40%. Although these values may be reduced by evidence that a borehole penetrating the area of a reservoir may not actually encounter pressurized brine, or discarded based on evidence that the geophysical results are quantitatively unreliable, such evidence has not been presented to the Panel.

3.16.2.3. Evaluation of Alternatives

Although the fundamental hydrological behavior of the Castile Formation and its brine reservoirs is conceptually sound, concerns have been identified in Section 3.16.2.2 regarding the manner in which the encounter of pressurized brine is handled in performance assessment. Three fundamental issues are identified for which alternatives may be considered. These are alternative limits on the maximum reservoir volume, alternative concepts for reservoir depletion, and alternative probabilities of encountering pressurized brine.

3.16.2.4. Uncertainties

Uncertainty in model results stems from uncertainties in the validity of the underlying theory and from uncertainties in the input data. Although the underlying theory is widely used in the petroleum industry for evaluating oil and gas reservoirs and provides the best currently available approach, the results must be considered approximate, as illustrated by the high degree of uncertainty in the results presented, for example, by Popielak et al. (1983) and Spiegler (1982). Uncertainties associated with specific input parameters and assumptions are more tractable to address, and the key uncertainties are associated with the three principle issues identified in Section 3.16.2.3. Uncertainty in the two-phase flow parameters used in the analysis cannot be addressed because the values of these parameters had not been selected at the time of this review (see CCA Table 6-yz, draft of 5/23/96).

The uncertainty associated with rock compressibility is approximately one order of magnitude. Although this parameter is coupled with permeability, as previously discussed, the uncertainty in permeability is approximately two orders of magnitude. Uncertainties in compressibility propagate through the calculations and affect the estimates of both the permeability of the hypothetical reservoir at the site and the volume of the WIPP-12 reservoir. Because the uncertainty in permeability is even greater than the uncertainty in compressibility, the consequences of the uncertainty in compressibility may not be significant to the overall performance assessment. Uncertainty in permeability may have a greater

consequence in overestimating or underestimating flow rates from the reservoir if flow rates are controlled by the reservoir rather than by the borehole dimensions or plugging materials. High degrees of uncertainty in the related parameters of compressibility, permeability, and reservoir volume are not readily avoidable and stem from the wide range of values these parameters can have and from limitations in the state-of-the-art in measuring them.

The consequences of assuming a relatively small maximum size for a hypothetical brine reservoir beneath the site are not known because modeling results are not available, but could result in underestimating the volume of brine that could potentially be released. Alternatively, the modeling results may show that the volume of brine released during the 44-hour flow period assumed by DOE is relatively insensitive to reservoir volume if the reservoir volume is significantly greater than the volume of brine released from the reservoir. In this event, larger reservoir sizes may have little effect on performance assessment.

An unrealistically low probability of encountering pressurized brine could lead to underestimating radionuclide releases resulting from flow from Castile brine reservoirs. The consequences of underestimating this probability would be identified in modeling results, which were not available for review by the Panel.

The consequences of overestimating reservoir depletions by boreholes that do not penetrate a waste panel would be to underestimate reservoir and repository releases by boreholes that do penetrate a waste panel. The issue of reservoir depletions is tied to reservoir volumes, compressibility values, reservoir sizes, and the probability of encounter. Changes in any of these parameters would require modifications throughout the conceptual model.

3.16.2.5. Adequacy of the Conceptual Model

The hydrologic aspects of the conceptual model for the Castile Formation and Brine Reservoirs are fundamentally sound, and the issues raised in the validity of model assumptions (Section 3.16.2.2) are associated with the details of its application. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.16.2.6. Adequacy of Application

The internal consistency of the conceptual model is adequate, based on the interdependence of expected or mean values of the parameters as described in Section 3.16.2.1. Although consideration could be given to correlating values during statistical sampling, such as permeability with compressibility, the uncertainties in these values is such that it would be difficult to judge whether any combination were totally unreasonable. The correlation of porosity and reservoir volume in BRAGFLO is considered to be an artifact of the fixed model cell volume and not a true parametric correlation based on conceptual model principles. The integration of the conceptual model with the BRAGFLO and BRAGFLO-DBR codes is addressed under the Exploration Borehole (Section 3.12), Multiple Intrusion (Section 3.17), and Direct Brine Release (Section 3.15) conceptual models.

3.16.2.7. Accuracy of Results

The data base calculations were spot-checked and found to be accurate. The parameter values were also checked against values estimated by other investigators (Popielak et al. 1983; Spiegler 1982; Reeves et al. 1991) and found to be acceptable, given the ranges of uncertainties in the input parameters. The accuracy of integration with the BRAGFLO and BRAGFLO-DBR codes is discussed in Sections 3.12, 3.17, and 3.15.

3.16.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain, pending resolution of the issues raised in Section 3.16.2.3. In summary, the following key assumptions have not been adequately supported in information provided to the Panel, nor do sensitivity studies appear to have been made.

- The basis for excluding larger, potentially depressurized brine reservoirs from performance assessment has not been adequately supported. Larger reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.
- The basis for the concept of reservoir depletion through previous borehole penetrations has not been adequately supported. Non-depleted reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.
- The expected probability of encountering pressurized brine beneath the waste panels has not been adequately supported, nor has the basis for apparently ignoring the quantitative value of site-specific geophysical data been presented. Unrealistically low probabilities of encountering brine may result in underestimating radionuclide releases.

3.16.2.9. Adequacy for Implementation

The Castile Formation and Brine Reservoir conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.16.2.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.16.2.10. Dissenting Views

There were no dissenting views for this model.

3.17. Multiple Intrusions

3.17.1. Model Description

The Multiple Intrusion conceptual model is an extension of the Exploration Borehole model that describes fluid flow between the repository and multiple exploratory boreholes penetrating a single waste panel. The borehole drilling methods and frequencies, borehole plugging, and plug degradation discussed in the Exploration Borehole model in Section 3.12 are the same for multiple intrusion boreholes. Short-term flow through unsealed boreholes is addressed in the Direct Brine Release conceptual model in Section 3.15. Other related conceptual models include Repository Fluid Flow, Castile Formation and Brine Reservoirs, Cuttings/Cavings, Spallings, and Actinide Transport in the Salado. The details of this model were still under development at the time of the peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 23 May 1996 Draft CCA, Sections 6.4.13.6 and 6.4.13.7 (DOE 1996, pp. 6-119 to 6-121), from verbal descriptions, and from the cited references.

The proscriptive requirements of 40 CFR 194 for exploration boreholes also apply to multiple intrusion boreholes. The focal point of the Multiple Intrusion model is the E1-E2 scenario (worst case), wherein more than one exploration borehole penetrates a waste panel and at least one of those boreholes also encounters pressurized brine in the underlying Castile Formation. However, the Multiple Intrusion model also addresses multiple intrusions by other combinations of boreholes.

Multiple intrusions are modeled by the same two-dimensional version of the BRAGFLO code used to model repository fluid flow and single borehole intrusions. Use of this model is supported by preliminary analysis of modeling results, indicating that liquid flow through the panel closure seal

between the isolated, single waste panel in the model and the "rest of the repository" is slow enough that each waste panel is effectively independent from the rest of the repository. Thus, for a multiple intrusion to occur, two or more boreholes must penetrate the same waste panel. Gas flow does occur between panels, and for this reason short-term releases are calculated separately. However, for long-term brine flow from a single waste panel, the BRAGFLO model is considered adequate. Because the panels behave independently, different configurations of boreholes may occur in different panels. The model computes releases from these configurations separately and adds them to estimate a total cumulative release.

To accommodate the limitation in the BRAGFLO model of being configured to represent only one borehole column, the boreholes are assumed to be drilled in a series of specific sequences, with shifts in material properties in the upper and lower parts of the single modeled borehole at specific times. Background information on the development and use of reference conditions and on borehole plug degradation assumptions is presented in Section 3.12. Because 90% of all deep boreholes are assumed by DOE to be of the E2 type (DOE 1996, p. 6-119), it is most probable that the first borehole to penetrate a waste panel will be of this type. The approach taken by DOE in analyzing multiple intrusions has therefore been built around this E2-E1 scenario, which occurs under the following assumptions.

The first borehole is assumed to be an E2 type that penetrates the waste panel 800 years after closure. At 1,000 years after closure the upper seal in this borehole fails and the borehole is filled with a material that has the properties of silty sand. At 2,000 years an E1 borehole penetrates a waste panel and encounters pressurized brine in the Castile. This borehole is assumed to be sealed with the two-plug configuration, the only configuration considered in performance assessment that allows flow to occur between a Castile brine reservoir and the waste panel (Section 3.12). At 2,000 years the properties of the modeled borehole column below the repository are changed to represent an open borehole, while the properties of the borehole column above the repository are unchanged and continue to represent the long-term properties of the earlier E2 borehole for the duration of the modeling. At 2,200 years the upper plug in the E1 borehole fails and the properties of the borehole below the repository are changed to those of silty sand. At 3,200 years the permeability of the borehole below the repository is reduced by one order of magnitude to represent the effects of pore volume reduction due to creep closure. No further changes in material properties occur for the duration of the modeling.

The aforementioned series of assumptions is valid given DOE's plug degradation assumptions, with the exception that after 2,200 years the upper plugs in both the E2 and E1 boreholes have failed and two pathways, rather than one, are available for brine migration to the Culebra. The assumption that only one of these two pathways conducts flow in this scenario is considered by DOE to be consistent with the assumption of complete mixing of brines within the waste panel, which requires that flow from the brine reservoir in the E1 borehole pass through the waste panel and exit through the E2 borehole, rather than through the upper part of the E1 borehole. However, multiple borehole pathways to the Culebra are included in scenarios involving multiple E1 boreholes because flow through the repository and consequent mixing can then occur among multiple boreholes.

The foregoing scenario of an E2, followed by an E1, establishes the basis for determining a standard reference cumulative radionuclide release to the Culebra, assuming an E2 borehole drilled at 800 years is followed by an E1 borehole drilled at 2,000 years. In this drilling sequence the rate of release jumps dramatically at 2,000 years because of pressurized brine flowing from the Castile reservoir. In an actual scenario the randomly selected drilling dates for these two boreholes are likely to be different. In that event, the cumulative release is calculated using the release rate from a single E2 borehole (Section 3.12) up to the date of the E1 penetration, and then applying the reference release rate starting at the time of E1 penetration in the standard E2-E1 scenario to approximate the jump in release rate that would occur at the actual date that the E1 borehole is drilled. In this approach, the brine fluxes after penetration by an E1 borehole are those occurring at the 2,000 year date of penetration assumed in the standard E2-E1 scenario, rather than the fluxes that would have been modeled at the actual date of penetration; however, the radionuclide releases associated with those fluxes are corrected for radionuclide decay and progeny production.

If the first two boreholes are randomly selected to penetrate the waste panel in a different sequence, the following rules for determining reference conditions for long-term flow are applied.

Radionuclide transport is modeled by the NUTS code for single borehole intrusions and by the PANEL code for multiple intrusions (Section 3.8). While the NUTS code is directly coupled to BRAGFLO and uses BRAGFLO's computed velocity field vectors, PANEL is a separate model that conservatively assumes complete mixing in the waste panel. PANEL is used when two or more boreholes penetrate a panel and at least one of those boreholes is an E1 type. In applying the PANEL code, the multiple

intrusions are implicitly assumed to occur in different parts of the waste panel so that cross borehole flow and mixing will occur. The PANEL code is used for transport calculations in the standard E2-E1 scenario, and use of that scenario for multiple borehole intrusions is conservative.

Table 3.17.1. Rules for Determining Reference Conditions for Long-Term Flow

Sequence of First Two Boreholes	Basis for Brine Flux	Basis for Radionuclide Transport
E2 followed by E1	Single E2 flux followed by E2-E1 flux at time of E1 penetration	Single E2 transport followed by E2-E1 transport at time of E1 penetration
E1 followed by E2	Single E1 flux followed by E2-E1 flux at time of E2 penetration	Single E1 transport followed by E2-E1 transport at time of E2 penetration
E1 followed by E1	Single E1 flux plus E2-E1 flux at time of second E1 penetration	Single E1 transport plus E2-E1 transport at time of second E1 penetration
E2 followed by E2	Single E2 flux	Single E2 transport

The first two borehole sequences in the foregoing tabulation (E2 followed by E1 and E1 followed by E2) both assume sequential calculation of flux and transport by jumping from single borehole behavior to E2-E1 behavior at the time of the second penetration. The sequence of two E1s, however, is treated by adding the E2-E1 flux and transport to the single E1 flux and transport, beginning at the time of the second E1 penetration, because flow from two brine reservoir penetrations can circulate and mix within the repository and leave through two boreholes to the Culebra. As previously mentioned, in cases where there is only a single E1 penetration, the brine is considered by DOE to be more likely to circulate within the repository, adequately mix, and then leave only through the E2 borehole to the Culebra. In cases of two E2 penetrations, long-term brine release volume is assumed to be the same as for a single E2 penetration because flow will be controlled by the rate at which brine can be supplied by the Salado halites, rather than the rate at which brine can flow in the borehole. In cases where at least one of the boreholes previously penetrating the panel is an E1 and an additional E1 is added, additional E2-E1 flux and transport values are added to the cumulative release. In cases where none of the boreholes previously penetrating the panel is an E1 and an additional E1 is added, the flux and transport sequentially shift to the E2-E1 values. However, if only E2 boreholes are present, additional E2 boreholes do not increase the flux and transport rates. In all cases, adjustments are made for radioactive decay and progeny generation to account for the times of waste panel penetration in the cumulative releases.

3.17.2. Review of Criteria

3.17.2.1. Information Used to Develop the Conceptual Model

The information used to develop the Multiple Intrusion model is essentially the same as that used to develop the Exploration Borehole and Repository Fluid Flow models. The Multiple Intrusion conceptual model becomes active at the time that two or more boreholes are randomly selected to penetrate a single waste panel. Alternative reference conditions, repository mixing, and transport models are employed for the Multiple Intrusion model, as described in Section 3.17.1. The information used to develop the conceptual model is reasonable and appropriate.

3.17.2.2. Validity of Model Assumptions

The principal assumptions used to develop the Multiple Intrusion model are identified in Section 3.17.1 and are critically reviewed here. Assumptions related to borehole drilling methods and frequencies, borehole plugging, and plug degradation are the same as those reviewed for the Exploration Borehole model in Section 3.12. The principal assumptions specific to the Multiple Intrusion model are reasonable and appropriate for performance assessment applications and include use of the two-dimensional BRAGFLO model for this application, the somewhat gymnastic but conservative assumptions made to accommodate the single borehole column in the model, and the mixing assumptions in the model.

The assumption that only a single borehole conducts brine to the Culebra in an E2-E1 scenario is troublesome; however, the potentially nonconservative nature of this assumption is compensated by the highly conservative assumption of complete mixing of Castile brine with waste panel brine. In reality, the Castile brine would flow through the waste panel to the exit borehole by preferentially following high conductivity flowpaths with relatively little volume compared with the waste panel pore volume, and consequently with relatively little mixing. Even less mixing would occur in brine flowing from the E1 in the bottom of the waste panel and out the same E1 through the top of the waste panel.

The use of reference conditions, rather than direct model results, as the final input has been handled in a relatively conservative manner. The appropriateness of assuming that the flux associated with the E1 penetration at 2,000 years in the standard E2-E1 reference case is representative of the flux into an E1 penetration at other times has not yet been directly supported by sensitivity studies using current performance assessment calculations, but by analogy to the results of such studies performed for the

1991 draft performance assessment, such an assumption is expected to be appropriately conservative (Helton et al. 1992, Chapter 4).

3.17.2.3. Evaluation of Alternatives

The approach taken to address multiple intrusions in performance assessment is reasonable and appropriate considering the complexity of addressing the many possible scenarios in an efficient manner. Further investigation into the approaches taken have indicated that they are adequate and that no alternative approaches are required. However, the validity of the current approach is based on acceptance of DOE's assumptions regarding borehole plug degradation rates. These assumptions were questioned in Section 3.12, and if those assumptions are changed, many of the basic assumptions used in the Multiple Intrusions model should also be changed. For example, if plug degradation allows fluid to flow into the waste panel from the Bell Canyon Formation through an E2 borehole, the significance of the E2 borehole in performance assessment will become more like that of an E1.

3.17.2.4. Uncertainties

The principal uncertainties in model results stem from the same types of issues that were raised for the Exploration Borehole model and are addressed in Section 3.12.2.4. No additional significant uncertainties have been identified that are specific to the Multiple Intrusions model.

3.17.2.5. Adequacy of the Conceptual Model

The conceptual model for multiple intrusions is fundamentally sound and appropriately conservative, given the simplifications that are required to model a complex set of conditions in an efficient manner.

3.17.2.6. Adequacy of Application

The application of the conceptual model to the numerical model is adequate, again given the simplifications that are required to model a complex set of conditions in an efficient manner.

3.17.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. The modeling results were not available for review and could not be checked.

3.17.2.8. Validity of Conclusions

The validity of the conceptual model is expected to be adequate for performance assessment; however, modeling results have not been observed by the Panel and have not been checked through sensitivity studies similar to those used in previous performance assessments. Many of the modeling assumptions were based on borehole plug degradation assumptions whose validity was questioned in Section 3.12. If those assumptions are changed, many of the basic assumptions used in the Multiple Intrusion model would be questioned.

3.17.2.9. Adequacy for Implementation

The Multiple Intrusion conceptual model is adequate for implementation in performance assessment. However, the results of the model have not been checked by the Panel because sensitivity studies similar to those used in previous performance assessments have not yet been performed.

3.17.2.10. Dissenting Views

There were no dissenting views for this model.

3.18. Climate Change

3.18.1. Model Description

The long periods of time over which the isolation of radioactive waste must be considered stimulates concern over climatic cycles and occurrences that may impact the long-term performance of the disposal system. The Climate Change conceptual model provides quantitative consideration about the degree to which future climates may contribute to the uncertainty of estimates of potential radionuclide releases from the WIPP repository. The model does not attempt to predict or simulate a future climate, but intends to implement climate change effects into the performance assessment through a parameter named the Climate Index.

The formulation of the conceptual model for climate change (Climate Index) began with the screening out of the direct effects of climate change that do not involve groundwater. Factors such as wind patterns and thermal effects do not impact the WIPP due to its depth below the ground surface. Additional aspects of climate change were eliminated through the FEP screening process and the conceptualization

of climate change impacts focused on reasonably foreseeable events and the effects of these events on groundwater flow.

A three-dimensional regional groundwater basin model (Corbet and Wallace 1993) was employed to assist in characterizing the natural hydrogeologic processes as they could occur over geologically significant periods of time in the Delaware Basin. The model was bounded on the bottom by "impermeable" rock, on the top by the ground surface, and on the sides by groundwater divides. The upper boundary of the flow domain is the water table and differences in the elevation of the water table across the basin are assumed to be the driving force for groundwater flow. Other notable but standard assumptions are stratigraphic homogeneity and ignoring the unsaturated zone with respect to timing of infiltration (dry to wet periods). The results suggest that flow in the Culebra Dolomite Member of the Rustler Formation is strongly influenced by the water table elevation and the infiltration (recharge) rates associated with that elevation. Infiltration was varied as a step-function of average amounts of moisture reaching the water table. The model results indicated that changes in infiltration rates of tenths of a millimeter per year had significant impacts on flows in the Culebra. The basin modeling and later analyses (Corbet 1996b) approximated recharge rates that maintained the water table at or near the ground surface (maximum recharge situation) and the relationships between the various recharge rates and lateral-flow ratios. The assigned distributions of lateral-flow ratios became the Climate Index. The Climate Index is therefore a factor by which the lateral flow rate in the Culebra is uniformly increased to account for increases in recharge rates.

Two future climate or recharge patterns were evaluated: the step recharge function, with a 0.25 probability of representing the future, and the Holocene recharge function, with a 0.75 probability of occurring. The step recharge function (similar concept to Corbet and Wallace 1993), which represents a steady increase in heads and recharge rates into the future with the lateral-flow ratio reaching its maximum in 10,000 years, is assigned Climate Index values of 1.5 to 2.25. The Holocene pattern of future recharge results in periodic increases and decreases in heads and recharge rates that are assigned Climate Index values of 1.0 to 1.25. These two Climate Index ranges are sampled during each realization of disposal system performance, with each realization representing a different approximation of future climate.

3.18.2. Review of Criteria

3.18.2.1. Information Used to Develop the Conceptual Model

An extensive reference list supports the process of formulating the conceptual model for climate change. Wood (1994) and Campbell (1995) include isotopic quantification of recharge flux, and Corbet and Wallace (1993), Knupp (1995), and Wallace (1994) address groundwater modeling and hydraulic test interpretation. Swift (1992) and Powers (1990) discuss and include additional references on sedimentology, regional geology and geologic history, long-term climate variability, and climatic records. In addition to references used in conceptualizing climatic change at the WIPP, EPA criteria and guidance (EPA 1996), FEP screening references, performance assessment documentation, and evaluation of groundwater flow models developed in support of climate change conceptual model formulation document in detail the data and information used. Documents and reports produced internally to summarize studies and present results of studies relevant to the WIPP performance assessment (e.g., SAND Reports, professional society papers, DOE-WIPP, FEP, memos) were extremely valuable as they summarized data used and explained concepts applied. The information used to develop the conceptual model for climate change is extensive, referenced, available for review, and adequate.

3.18.2.2. Validity of Model Assumptions

The conceptual model for evaluating the effects of future climate change on the long-term performance of the WIPP began with a detailed examination of a great deal of literature, evolved through an understanding of past changes and situations/conditions of future change, and is now implemented through a dimensionless index that is used to change groundwater flow velocity in the Culebra Dolomite. The relationships between climatic extremes and such parameters as temperature, wind, precipitation, evapotranspiration, and vegetation cover have been researched, and the impacts of such factors on recharge have been evaluated. Since recharge impacts groundwater flow and flow characteristics are required by EPA for a compliance application, the Climate Change conceptual model formulation focused on evaluating the effects of climate change on flow characteristics of the Culebra Dolomite and Dewey Lakes Redbeds. After screening was completed (Corbet 1995a), effects evaluations were limited to the Culebra Dolomite. An extensive list of assumptions would be required to cover all of the modeling and evaluations conducted to represent real events and related climatic factors. The conceptual model for climate change assumes to represent ranges of conditions that are not related to specific events or the interactions between climatic factors, but represent reasonable extremes of potential future climates.

In addition to assuming that the climate will change over the next 10,000 years, the conceptual model of climate change assumes that periods of maximum precipitation are also periods of maximum recharge and that during such maximum situations, recharge is sufficient to maintain the water table at the land surface. A supporting (or bounding) assumption is that recharge in the late Pleistocene was sufficient to maintain the water table at the land surface. The conceptual model assumes that the range of recharge rates (0.1 to 5.0 mm/yr) represents the appropriate range of hydrologic conditions and the Climate Index factor distributions represent these conditions appropriately. A key assumption that is not clearly within the conceptual model or its implementation concerns representing three-dimensional flow in the Rustler Formation with a two-dimensional model of the Culebra Dolomite.

To invalidate the assumption that climate change will occur would require an assumption that the climate will remain constant for 10,000 years. This invalidating assumption would be inconsistent with the scientific view of climate. The assumptions of maximum precipitation/maximum recharge and that recharge could be sufficient to maintain the water table at the land surface are defensible, but not unconditionally validated as representative of a future extreme climate. These assumptions are supported by interpretations of sedimentary records (Swift 1992), isotopic analyses (Campbell 1995 and Wood 1994), paleo-environmental records, and other evaluations that estimate the characteristics of groundwater during varying climates. The assumed range of recharge rates is supported by isotopic recharge dating and rate estimation. The support documentation for the two-dimensional assumption is FEP NS-9 (Corbet 1995b).

The Panel members conclude that the main objectives of the conceptual model for climate change at this time are to incorporate uncertainty about the effects of future climates into the performance assessment and meet EPA expectations with regard to the effects of climate change on hydrological conditions and future state assumptions. Since the range of recharge rates represents the reasonable extremes of potential future climates and the climate index carries the representation into the implementation, the assumptions are valid in terms of the usefulness of the conceptual model, as is the Climate Index.

3.18.2.3. Evaluation of Alternatives

The conceptual model for representing the effects of climate change on the WIPP is a result of an evolution of thought requiring the characterization of climatic factors and simulating their effects. While interest in the possible effects of climate change has, historically, been in terms of recharge and groundwater, early interest considered increased rates of salt dissolution, fracture filling in the Culebra

and changes in groundwater flow direction. Early assessments of system performance did not consider that climate change could alter the transport of radionuclides in groundwater. Later performance assessments considered transport effects but as a function of head change. Sensitivity analyses conducted for the 1991 and 1992 preliminary performance assessments determined that cumulative radionuclide releases were not sensitive to head variation as applied, and the boundary-head approach was abandoned.

Alternative approaches to the characterization of climatic effects on groundwater and modeling groundwater flow have been considered and ruled out for conceptual and technical reasons. Alternatives to representing the factors of climate change have also been considered, ruled out during analyses, and screened out through the FEP screening process. In many cases, alternative approaches that attempted to closely relate climatic factors to hydrogeologic effects introduced additional uncertainty, and could have made the overall conceptual approach less defensible. The 1996 EPA guidance presented recommendations for the consideration of future climates in a compliance application. The guidance focuses considerations on natural processes, potential impacts to recharge, and groundwater flow, and indicates that effects on hydrogeologic conditions are expected to be analyzed and demonstrated in compliance and performance assessments. The selection of the Climate Index to implement the effects of climate change through direct scaling of groundwater velocity in the Culebra allows for the uncertainty of effects of future climates to be incorporated into the performance assessment. Multiple realizations provide for a representative range of future climate effects to be included in disposal system performance.

3.18.2.4. Uncertainties

Many obvious uncertainties accompany the interpretation of the magnitude and temporal aspects of historical climatic factors and the representation of such factors at the WIPP site 10,000 years into the future. The uncertainties are less overwhelming when climates are limited to those reasonably foreseeable, and the absolute timing of alternative climates is of less importance than the range of magnitude of the relevant climatic or climate-induced factors.

A primary objective of the Climate Change conceptual model is to incorporate uncertainty about future climates and their potential impacts on radionuclide releases from the disposal system. The conceptual model for climate change is implemented through a single parameter index that scales groundwater flow

in the Culebra Dolomite. Key uncertainties concern whether or not climate will change, if index values represent the appropriate range of changes, and whether or not implementation realizations sample the index in a manner representative of the range of climate change.

The uncertainties related to whether or not climate will change and the representativeness of index values are a result of predictions, analyses that are imprecise, and conclusions about the future based only on the past. While these uncertainties remain, the conservative assumption for performance assessment is that the climate will change, including periods of both drier and wetter conditions. The only relevant uncertainty with respect to the index is whether or not reasonably foreseeable climates are represented by the range of index values. It is the intent of the index to be bounded by the wet extreme of the Pleistocene glaciation and by another climate where there is little or no climatic effect on groundwater flow. Panel members conclude that significant scientific effort has been expended to characterize the periods bounding the index value and relate relevant climatic factors to the index, and that the index is appropriately conceptualized. Uncertainty with respect to implementation of the climate change model cannot be completely addressed by panel members since a detailed analysis of the implementation models and computational scheme is not within the scope of this review. However, even though climate change preliminary calculations resulted in relatively small increases in flow rates, decreased travel times had a large impact on normalized radionuclide releases under certain conditions (calculations performed for the 1992 performance assessment) (Corbet 1995a). Based on the potentially large consequence demonstrated, climate change has been tentatively retained for inclusion in performance assessment calculations.

3.18.2.5. Adequacy of the Conceptual Model

The climate change conceptual model represents a reasonable and defensible range of potential future climate extremes for incorporation into the performance assessment. The conceptual model includes a range of conditions, bounded by reasonably foreseeable future climates and their effects, that are adequate to represent impacts to groundwater flows in the Culebra Dolomite Member of the Rustler Formation. In addition to providing adequate representation of conditions for implementation, the background research and analysis supporting the formulation of the conceptual model for climate change provides adequate information for satisfying EPA guidance.

3.18.2.6. Adequacy of Application

The conceptual model for climate change is implemented through the Climate Index. This index is a dimensionless factor through which direct scaling of specific discharge for the Culebra Dolomite is accomplished in the SECOFL2D code (Section 4.1). The range of sampled index values available for realization of disposal system performance has been verified through modeling to represent the range of recharge impacts that reasonably foreseeable future climates would create. As such, the conceptual model is implemented through an acceptable and adequate performance modeling element.

The conceptual model for climate change is compatible with the closely related model of the steady-state groundwater velocity field for the Culebra, which it directly scales through the index. The relationship is simple and should be adequate for its intended use, assuming that the implementing computational scheme operates as designed.

3.18.2.7. Accuracy of Results

Model formulation results, as well as model application/implementation results, must be reviewed in assessing the overall accuracy of results for the conceptual model for climate change. The accuracy of model formulation results is judged on how well descriptions and descriptive write-ups present the conceptual model. In the case of the climate change model, background research and analysis, history of model development, screening and verification, descriptions of model parameters, assumptions, and an implementation scheme were available. Panel members were required to consult numerous sources for a comprehensive description of the conceptual model but, overall, the model formulation results were judged accurate.

As discussed in Section 3.18.2.6, the application or implementation of the conceptual model for climate change is conducted with the Climate Index. This dimensionless factor is sampled over its distribution and represented by direct scaling of the steady-state groundwater velocity field in SECOFL2D for the Culebra Dolomite. For performance assessment realizations of disposal system performance, each realization represents the effect of a different climate. The model is judged as capable of producing accurate results through implementation if realizations of disposal system performance adequately represent the range of future climates available within the distribution of the index.

While the scope of this conceptual model review did not include verification of realization computations, a single CCDF calculated to address FEP NS-8b had interesting results. The FEP NS-8b, summary

memo of record (SMOR) of 21 September 1995, stated that on the basis of relatively small increases in flow rates expected from including climate change in the performance assessment modeling system, and the associated low consequence of omitting the factor, climate change could be screened out. The SMOR also presented that a single CCDF calculated to address the FEP illustrated that screening out climate change would not be of low consequence. The CCDF illustrated that velocity fields that decreased travel times (increased flow rates) by a factor of 2 resulted in three orders of magnitude increases in releases for release probabilities less than 0.1. The reason for the large impact was not clear, but this quantitative evaluation of the climate change subsystem resulted in the retention of climate change for inclusion in future performance assessment calculations. While the quantitative subsystem evaluation did not prove the accuracy of implementation of the conceptual model, it is indicative and supportive of performance assessment sensitivity.

3.18.2.8. Validity of Conclusions

The results of the implementation of the conceptual model for climate change are the representation of the effects of a reasonably foreseeable range of future climates within realizations of disposal system performance. While Panel members found no documentation of the results of the application of the Climate Index in disposal system-scale performance assessment calculations or conclusions drawn, the FEP screening process (Corbet 1995a) SMOR addressed a quantitative analysis. The SMOR, discussed in Section 3.18.2.7, presents that the results of the quantitative evaluation stimulated the conclusion to retain climate change for inclusion in future performance assessment calculations.

The evaluation presented in the SMOR could not support conclusions to the degree possible from results of disposal system-scale performance assessment calculations and sensitivity analyses. In the absence of results from repository/disposal system-scale realizations and sensitivity analyses, no definitive, valid conclusions can be made. However, the evaluation at the subsystem level did support conceptual model sensitivity and uncertainty assessment and a valid conclusion was drawn on the basis of results of the evaluation.

3.18.2.9. Adequacy for Implementation

The conceptual model for climate change, as discussed in Sections 3.18.2.1 through 3.18.2.8 and defined for implementation by the Climate Index, is adequate for implementation. The Climate Index is capable of representing uncertainty about future climates and their potential impacts on disposal system

performance. While the conceptual model has been judged adequate for implementation, the mathematical representations in the computer code have not been reviewed and no conclusions can be made as to the overall adequacy of the applications/implementations.

3.18.2.10. Dissenting Views

There are no dissenting views for this model.

3.19. Creep Closure

3.19.1. Model Description

The Creep Closure model is part of a complex of submodels that are combined to effect the porosity surface lookup table. This table combines gas pressure, room closure, and waste compaction to pre-calculate repository void space for inclusion in several other performance assessment models. The Creep Closure model is reviewed here and other aspects of the porosity surface are discussed in support of that review. The Creep Closure model has a complex history of development, which extends into the period of review. The generic creep model impacts both the room closure and the development of the DRZ surrounding the repository openings. The DRZ models are discussed elsewhere.

Closure of the repository occurs naturally in the Salado halite as a response to the imbalance of forces created by excavation of the repository rooms and passages. Weak and plastic rock salt begins immediately to flow into the excavated spaces by processes dominated by creep. The rate of closure is the combined result of creep rates inherent to salt, repository temperatures and pressures, and resistance provided by repository contents. The creep rate proceeds to the limits determined by resistance from gas, brine, waste, backfill, or other contents in the repository until the void space is closed to the final porosity dictated by waste and seal material properties, contained fluid pressure, and lithostatic pressure. Roof fall in the disposal rooms, which may have significant impact on flow at least in the short term, is not included in the model.

Both brine and gas content of the repository vary with time. Brine inflow/outflow is partly controlled by gas pressures. The relationship between gas outflow rates and gas generation rates influences pressures within the repository. Gas pressure results from the alteration of waste by biogenic and corrosion-based processes. The rate of the corrosion process is dependent on brine availability. Repository gas and brine pressures are limited by the minimum pressures at which gas or brine would be forced out of the

repository via identified flowpaths through fractured interbeds within the Salado. The threshold pressures for initiation of outflow through these fractured anhydrite interbeds are therefore a key consideration in limiting resistance to closure due to gas and brine pressures. The fractures in the interbeds are essentially horizontal, so the pressures necessary to open the fractures or to initiate new fractures must be greater than the lithostatic load. Further, some resistance to gas release may result from travel through the fractured, rock-bolted halite between the repository and the interbeds. Resistance to gas outflow due to stress cage effects at the repository boundary and gas pressures necessary to maintain very extensive fractures may result in repository pressures larger than interbed threshold pressures. Gas pressures, which are some amount greater than the lithostatic pressure, are therefore possible at some times during the repository gas generation history. Internal gas pressures greater than the stress imbalance that drives creep inflow are conceivable. Internal pressures may contravene stresses in the salt and repository closure may cease, or repository inflation may occur in some scenarios. The stoichiometric treatment of time histories of gas generation and the volumetric model based on creep closure rates and waste compaction are combined in the SANTOS computer code to provide repository void volume estimates through time as part of lookup tables called the "porosity surface."

In the present WIPP performance assessment calculations (using BRAGFLO), the details of the mechanics of disposal room closure and/or eventual expansion are not explicitly calculated. Instead, the room-rock system behavior is obtained from the porosity surface. In this table, the three dimensions are time, total room porosity, and mass of gas in the room. The porosity surface is itself calculated prior to the BRAGFLO runs using the SANTOS code. This procedure is followed to avoid the massive computational effort that would be required to fully calculate (in an iterative sense) the mechanics of room closure for each performance assessment realization. At first, this may seem to be an invalid decoupling of the external environment and the disposal room. However, if the room porosity can be shown to be described with sufficient accuracy as a variable dependent only on time and gas mass (which is itself dependent only on time in the current model), then this approach is quite justified in view of its simplicity and efficiency. Note that brine content of the room is not mentioned at this point, nor are there any brine parameters on the porosity surface parameter list. This is a consequence of the calculation method and interaction with BRAGFLO, and is discussed below.

The porosity surface calculations using SANTOS are described by Stone (1996). The main features of these plane-strain calculations are a simplified stratigraphic model with boundaries at 50 m from the disposal room, the inclusion of the main clean halite and argillaceous halite layers, and the inclusion of

the two anhydrite layers of influence (MB 139 below and anhydrite a above), but no clay seams. The waste drums are lumped into a single rectangular mass, bounded by slip surfaces, that correctly reproduces the initial porosity and density. The simplified geometry used (as compared to the reference stratigraphy) is justified in Stone (1996), with supporting calculations given by Osnes and Lebreche (1995). In justifying the simplification, it is shown that including two types of salt and the anhydrite beds are necessary to provide the model sensitivity needed to support observations, but that the clay seams and additional complexities do not contribute. Thus, only halite and anhydrite properties are included as material properties in the parameters listed for the porosity surface. No roof failure of the room is considered in the porosity surface calculations. The porosity surface and its parameters have also been discussed in Butcher (1996), and Butcher et al. (1995).

The first full explanation of the porosity surface and its justification of use appears in Butcher and Mendenhall (1993). Since the pressure in the room depends on the amount of gas and the room pore volume, and this pressure creates the "back stress" resisting closure, the porosity surface can uniquely represent the room behavior if the relationship between gas volume and time is known. Since that relationship is specified (by corrosion rates and/or intrusion scenarios) the porosity surface can be used as prescribed.

A complication occurs, however, when brine is allowed to flow into or out of the room. Then, the porosity evaluated from the porosity surface must be treated as the gas-filled porosity and added to the brine-filled porosity to become the total porosity required in the performance assessment calculations using BRAGFLO. Furthermore, BRAGFLO, which is a fluid flow code, must be used to provide the brine content of the room for this iterative calculation. This coupling is only valid if the fluid flow is slow, which is a good assumption in the case of WIPP. Also, it must be assumed that the brine pressure is the same as the gas pressure within the room, which is true for high waste permeability.

The resistance to closure resulting from the compaction and consolidation of backfill and waste is based on empirical relationships derived from experimental studies. Some experimental laboratory and *in situ* experiments on crushed salt compaction for shaft sealing studies may provide definitive property assessments for backfill, although the final makeup or certainty of use of backfill materials is not known at this time. Limited experiments involving the compaction of waste-filled drums and simulated waste provide the basis for empirical estimates of waste behavior. The variable nature of waste form and

inventory lends a large uncertainty to the definition of waste physical behavior. The models of waste properties and mechanical behavior are reviewed elsewhere in this document.

The volumetric plasticity model has evolved significantly since it was proposed in its initial form by Kreig (1984). This formulation consisted of a synthesis of published empirical creep constitutive models, the geometry of material distribution, a calculated initial stress condition, and a set of creep constitutive properties derived from laboratory creep tests at SNL. Morgan et al. (1985) applied this initial formulation of the model to closure records from the south drift and found that it significantly under-predicted closure rates. Sjaardema and Kreig (1987) proposed that the characterization of Young's Modulus was the source of error in the initial model. They suggested an empirically derived reduction (division) of Young's Modulus by 12.5, which improved the performance of predictive calculations based on the model to satisfactory levels for use in crushed salt compaction tests for seals and subsequent closure observations. This model has been called the Reduced Modulus (RM) model in subsequent work.

Munson et al. (1989, 1991) undertook to resolve the empirically altered model with a "first principles" model derived from a set of more process-based rock mechanics theories. He demonstrated that a reliance on Von Mise's flow rule was less appropriate than that of Tresca, revised salt property estimates based on elimination of excavation strain from laboratory results, reevaluated creep parameters for argillaceous salt, added a term for primary creep, and improved the micro-mechanical creep models. These modifications enabled the steady-state creep response model (the MD model) to match observed closure rates at WIPP within 10%.

As it is presently formulated, the MD model does not include a treatment of the tertiary creep domain. Tertiary creep may be characterized as an acceleration in creep strain rate, accompanied by extensive microfracture, leading to macrofracture and failure. Chan (1996) has developed an amended version of the model (MDCF model), which includes tertiary creep for prediction of the formation of a DRZ around repository openings. The room closure model does not include tertiary creep on the grounds that all of the acceleration of strain (above the steady state rate) is due to microfracture and is recovered during the final stages of room closure due to DRZ healing. This concept is part of a larger concept called the conservation of void space. Because of void space conservation, no increase of gas pressure in the repository is attributed to this increase of strain rate.

The conservation of void space is only partly proven (experimentally or observationally) and is largely based on theoretical assumptions. In the case of tertiary creep of salt, the primary assumption is that all of the acceleration in strain rate during tertiary creep results from the onset of microfracture generation caused by the accumulation of intracrystalline lattice damage. The accumulation of lattice damage within individual crystals often results in work hardening and the elevated local stress levels may result in the initiation of strain by a "new" mechanism or mechanisms. However, no clear evidence exists that fracture is not accompanied by an undefined intracrystalline micromechanism, which may account for part of the change in the tertiary creep rate. The concept of continuation of unchanged steady state creep by micromechanisms that are unaffected by the damage accumulation to which the onset of fracture is attributed, seems incompatible. A more complex micromechanical model, which might include some acceleration due to non-fracture (plastic) processes, is not ruled out by any of the evidence. None of the closure observations at the WIPP occur over periods of time long enough to encompass the complete creep cycle observed in other salt mines.

Munson et al. (1995) estimates that only about 3% of the total creep strain is attributable to tertiary creep. The MD model matches short-term steady-state creep rates to within approximately 10%. If all or some part of the tertiary creep is not attributable to recoverable microfracture, the MD model may only be able to predict long-term closure rates to about 13% at best. Associated gas pressure changes through the porosity surface calculation are impacted by the inherent uncertainty in closure rates represented by the creep closure model predictions.

3.19.2. Review of Criteria

The room closure model includes the creep closure model (MD), the porosity surface lookup table, and interaction with BRAGFLO to iteratively specify brine inflow volumes. The porosity surface is constructed within the SANTOS model and consists primarily of creep closure, waste compaction, and gas pressure to estimate repository void space versus time. This review concentrates on the adequacy of the creep model (MD) with reference to the other associated models (e.g., BRAGFLO, SANTOS, porosity surface, gas generation) only as necessary to evaluate uncertainties.

3.19.2.1. Information Used to Develop the Conceptual Model

The initial version of the creep closure model was developed from published creep constitutive relationships and rock salt properties from intact rock salt deformation experiments at the SNL Rock

Mechanics Laboratory. The model was revised on the basis of short-term measurement of closure rates when the WIPP experimental rooms were opened. Both empirical revisions of elastic constants, based on closure rates, and revisions to the constitutive model, based on refinement of the understanding of deformation processes and flow rules, contributed to the development of later versions of the model.

Resistance to room closure (backstress) is the result of brine and gas pressure in the repository and of the strength of waste and backfill. Gas pressures used in the model are the result of the interplay between the time history of gas generation, the time history of void volume due to salt creep, and the threshold pressures governing gas outflow along the fractured anhydrite interbeds. Brine inflow is partially controlled by gas pressures. Repository pressure is modeled by an interplay between BRAGFLO and SANTOS, and interactions between gas pressure and creep are presented in the lookup table called porosity surface. Gas generation and brine inflow information are the product of other models. Threshold pressures for gas outflow in the interbeds are taken from packer tests of those horizons (Salado model). Strength of salt backfill is available from extensive experimental work done for the shafts and seals model. Waste strength may be the most uncertain type of information used in modeling room closure. Some experimental waste compaction has been done, but variation in waste form and inventory may make the characterization of waste physical properties highly variable. The creep closure model depends on the waste to resist closure and suppress rockfall and also contributes to the generation of an estimate of final waste porosity for waste dissolution estimates.

3.19.2.2. Validity of Model Assumptions

With the exceptions of the creep model, most of the assumptions in the global room closure conceptual model, as represented by the porosity surface calculation, are discussed in the consideration of other models (e.g., Gas Generation, Repository Fluid Flow). Many of the assumptions in the creep model were modified and tested during the development of the second iteration of the constitutive (MD) model. This redevelopment of the model was driven by the failure of the preliminary model to acceptably predict the short-term rates of closure of WIPP rooms. The redeveloped model contains a new flow rule and refinements of other model elements. The new model predicts short-term, steady-state salt creep rates (room closure rates in the WIPP excavations) acceptably (within 10%) implying that the principal assumptions are correct. No such correlations have been made for the transient (tertiary) creep behavior of the repository because of the limited observation times of room closure behavior. Tertiary creep is neglected in the MD creep closure model because of the assumption that all strain rate acceleration

(above the steady state rate) is due to microfracture and that the porosity caused by microfracture is recoverable during DRZ healing. This assumption is referred to as "the conservation of void space" and is largely unproven.

Because of the complexity of the natural environment and number of parameters evaluated, several assumptions are required to make the process of modeling and mechanical parameter evaluation possible. The most important of these appear to be:

- Thermal effects can be ignored since little waste heat generation is expected. This assumption is reasonable.

- Halite and anhydrite layers can be treated as continuous. This assumption is probably necessary in view of current computer modeling methods. It is also reasonable, in view of program requirements and data accuracy. However, discontinuous surfaces certainly exist within the assumed continuous layers. A good example is given by the few "anomalous" creep results reported by Senseny (1986), which were not included in the final creep parameter determination. Some of these occurred in samples that contained distinct linear clay seams. The effect of ignoring such data and other similar effects by assumption is not severe with regard to the final results, but should not be forgotten.

- Size scale effects can be ignored. Most geologic media exhibit a size scale effect. More often than not, this takes the form (in mechanical properties) of module reduction with size. In the case of WIPP, one might also expect an increase of creep rate with size. A hint of size effect is noted by Munson et al. (1989) but no model changes are proposed. Such effects are frequently attributed to discontinuities, which have differing properties as functions of scale. The assumption of no size scale effects therefore ties in with the continuum assumption discussed previously. Despite these cautions, ignoring scale effects seems reasonable within the realm of available data and accuracy of prediction required for these massive formations.

- The "unknown" long-term creep mechanism can be described by a standard equation and its parameters determined by relatively short-term tests. Virtually all of the halite creep during the lifetime of the repository will occur in response to a mechanism labeled as unknown. Therefore, the equation used for this mechanism, although a standard and acceptable activation equation, must also be labeled as unknown. This may have consequences with respect to long-term predictions. From the viewpoint of repository performance, the consequences are probably not severe since the parameters of the unknown mechanism have been empirically determined with some confidence.

- The presence of water can be ignored as an explicit mechanical properties material parameter. In most geologic media, saturation state strongly affects material properties. Here, with small amounts of water, one can argue that the explicit effects can be ignored. It does not appear that the WIPP project has investigated this, but the results are probably not severe. One area of caution is the possible conversion of anhydrite to gypsum on water absorption. This event,

if it occurs, will make the affected anhydrite zone softer and more plastic than now calculated. However, since the anhydrite beds tend to be zones of weakness to begin with, a severe adverse effect on subsequent modeling is not anticipated.

3.19.2.3. Evaluation of Alternatives

Alternative forms of the creep model were evaluated and compared to repository behavior during the redevelopment of the preliminary (Sjaardema and Kreig 1987) model. The empirical model, which was a version of the preliminary model with elastic modulus modified (RM model) on the basis of observed repository behavior, was used as a stop-gap model to allow the seals and backfill evaluation experiments to move forward. A more process-based model was ultimately developed which utilized a different flow rule and other refinements. This model (MD model) permitted a better understanding of the interaction of individual flow processes and could be more confidently extrapolated to differing initial and environmental conditions than the empirical version. The two models, one empirical (RM) and the other a process-based model (the MD model), agree well and are mutually supportive.

3.19.2.4. Uncertainties

The Creep Closure model contains two of the most important and sensitive variables involved in the potential release of radionuclides. Gas pressure resulting from the compression of gases in the repository from reduction of void volume and gas generation are the principal driving forces capable of pushing brine and dissolved and particulate waste out of the repository toward the accessible environment. Waste consolidation controls the pore space in the waste, which regulates the available surface area across which brine can dissolve radionuclides. Gas pressure is regulated by a complex set of model interactions. Permeability regulates gas outflow via fractured interbeds, and gas generation rates and rate of closure are the primary controls of gas pressure maxima. Gas pressures that exceed lithostatic pressures, sufficient to slow, stop, or reverse repository closure, are credible.

Timing of release relative to a complex interplay of variables controlling gas pressure, void volume, brine volume, residence time, and the reactivity of waste and brine as controlled by brine availability, waste permeability, and porosity are important in determining released brine radionuclide concentration and volume. The assessment of the interplay of timing of multiple processes is controlled by the stochastic manipulation of the processes by SANTOS and is preserved in the porosity surface lookup table. If the latin hypercube sampling strategy adequately addresses the timing issues, as claimed by DOE, consequences of uncertainty in the conceptual models are minimized if the assumed limits of variability in processes are conservative. Only in the case of waste compaction and its influence on the

degree of radionuclide entrainment and solution in brine is the conservatism of assumptions not verifiable. This is because the physical and, to a lesser degree, the chemical character of the waste is essentially unknowable within wide bounds. The consequence of this uncertainty is significant only if release impact is dominated by concentration of released radionuclides rather than by volume of released brine. Those aspects of the consequences of release are considered in other conceptual model reviews. Uncertainty associated with the room closure model (minimum of about 13%) must be evaluated through its sensitivity in the porosity surface calculation, and primarily impacts gas pressures.

3.19.2.5. Adequacy of the Conceptual Model

The adequacy of the Creep Closure conceptual model is demonstrated by its predictiveness of room closure in existing WIPP excavations. The uncertainties inherent in the model must be assessed through the sensitivity of the porosity surface calculation. The model appears to be adequately predictive.

3.19.2.6. Adequacy of Application

Integration of the Creep Closure model with the other component models and submodels to represent repository room closure is contained in the SANTOS code generation of the porosity surface lookup table for a large number of stochastically defined combinations of conditions, and appears to be adequate for performance assessment use.

3.19.2.7. Accuracy of Results

Accuracy of results for the salt creep conceptual model has been demonstrated to be adequate within the sensitivity of the overall room closure model by its ability to predict short-term closure rates in empty WIPP rooms and drifts (10%). The accuracy of the combined model of room closure with, for example, waste, backfill, and gas pressures, cannot be demonstrated at this time. Butcher (1996) claims that the sensitivities to undemonstrated variables in the combined model are low.

3.19.2.8. Validity of Results

The validity of the global room closure model cannot be assessed at this time in the absence of long-term room closure observations of filled and closed rooms, or of analogues or observations of releases from similar structural systems, particularly in the undisturbed scenario. This is ameliorated by the approach adopted in the generation of the porosity surface lookup table, which addresses the complexities of room closure processes and timing among the principal dynamic processes. The Room Closure model appears to be valid as part of the porosity surface calculation for performance assessment purposes.

3.19.2.9. Adequacy For Implementation

Implementation appears to be adequate. The porosity surface calculation appears to address the complex issues of timing among processes and provides a means of choosing representative parameters for individual processes with respect to uncertainty about process results and timing during dynamic process evolution. The creep closure model (MD) appears to be acceptably adequate to the approximation of timing among room closure, gas generation, waste compaction, and brine inflow for performance assessment purposes.

3.19.2.10. Dissenting Views

There were no dissenting views for this model.

3.20. Shafts and Shaft Seals

3.20.1. Model Description

Four existing shafts connecting the repository to the surface, which will be used in the operational phase, are represented in performance assessment by a single shaft with a cross section and volume equal to the total cross section and volume of the four real shafts. This composite shaft is modeled as separated from the waste regions in the model by the distance from the waste to the present waste handling shaft. On closure of the repository, the shafts will be sealed as described below and as represented in performance assessment by nine materials occupying 11 model regions in the shaft, as shown in Figure 3.2. The materials are earthen fill from the surface to the Rustler Formation; a clay region in the Rustler; asphalt at the top of the Salado; three concrete sections within the Salado; an upper clay region within the Salado; a thick section of compacted crushed salt; a lower clay section separated into upper and lower segments; and a concrete monolith at the repository horizon.

Conceptually, the shafts are assumed to be surrounded within the Salado by a DRZ with properties that vary with depth, time, and type of adjacent seal material. The performance assessment calculation grid represents only the cross sectional area of the shafts, and the permeability values for the various seal components at different times have been adjusted to account for the presence of the DRZ. Therefore, the DRZ is not represented explicitly in the BRAGFLO calculation. Thus, the flux that would occur through a shaft and its surrounding DRZ can be modeled equivalently using the shaft cross-sectional area with a higher permeability.

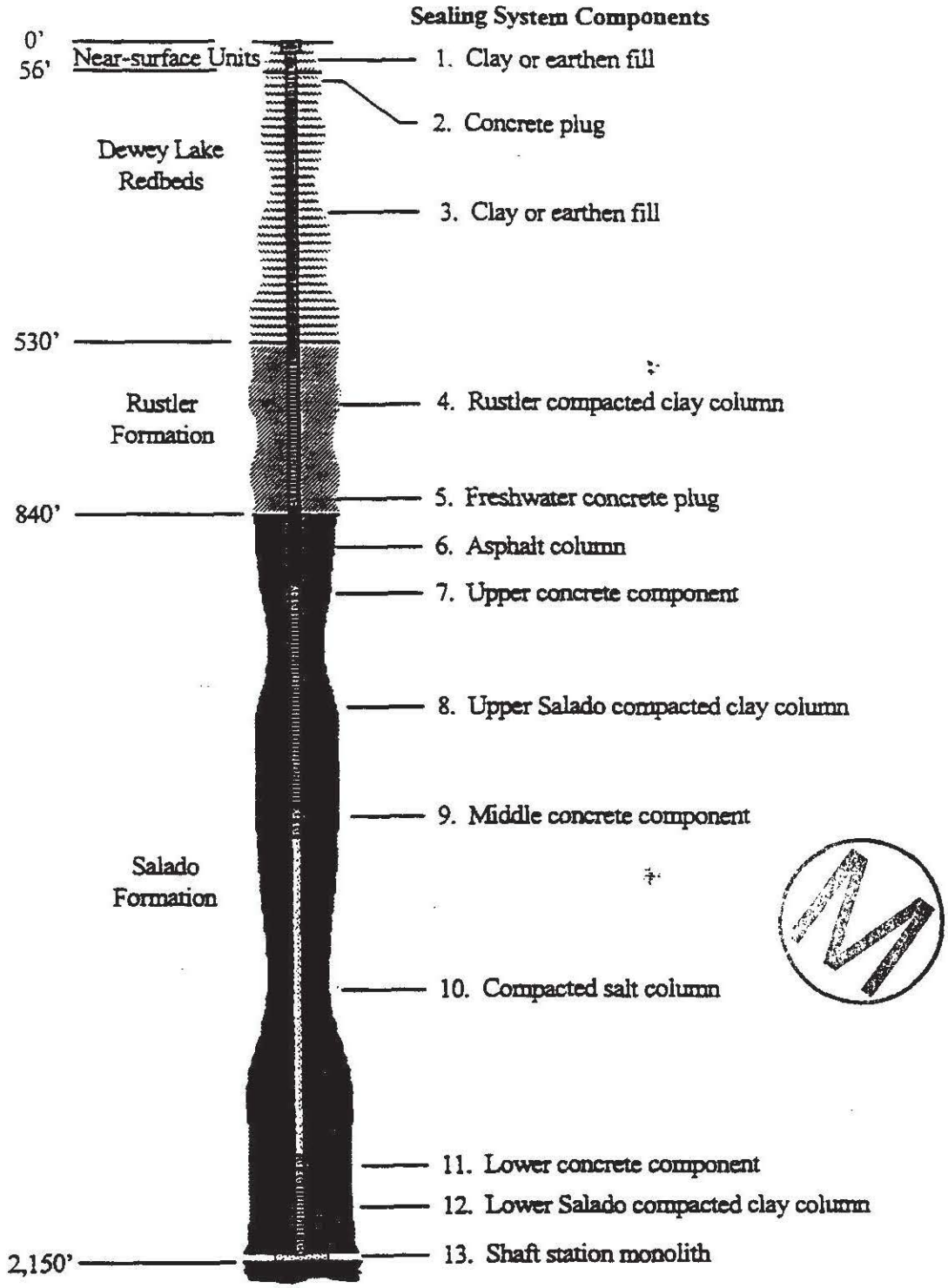

Figure 3.2. Arrangement of the Air Intake Shaft Sealing System

As described by Knowles (1996b), the shaft DRZ permeability is incorporated into the shaft permeabilities by a sampling and calculation process. DOE studies showed that the permeability can vary over an order of magnitude across the DRZ. Test data showed it is greatest near the excavation surface and decreases outward into the rock. To determine the effective permeability of the shaft DRZ, an equation was derived using the assumption that the permeability change is log linear. This equation has as variables a sampled inner DRZ permeability, intact salt permeability, shaft radius, and outer extent DRZ radius. A permeability value is computed for each shaft DRZ. A composite shaft DRZ permeability is then calculated by summing the individual products of the permeabilities and respective areas and dividing by the summed areas. Finally, the adjustment to the shaft zone permeability to account for the DRZ is computed similar to the previous step. The final shaft zone permeability is the sum of the composite permeability times the area of the combined shaft DRZs and the permeability times areas of the summed shaft area divided by the modeled shaft area. The modeled shaft area is assumed to be 95 m^2, which is the computed sum of the areas defined by the shafts' radii. The shaft seal permeability (including the DRZ) is sampled and is temporal in the BRAGFLO calculations.

3.20.2. Review of Criteria

3.20.2.1. Information Used to Develop the Conceptual Model

The conceptual model for the shafts and shaft seals used in the performance assessment has been chosen to provide a reasonable and realistic basis for simulating long-term fluid flow in either direction through the shaft seal system between the repository and brine bearing units and the surface, and to allow evaluation of the effect that uncertainty about the long-term properties of the shaft seal system may have on cumulative radionuclide releases from the disposal system.

Parameters used to characterize the shaft seal system are described in Section 6.4.4 of the CCA and in Appendix PAR. The principal parameters of interest are the permeabilities and porosities of each seal component. For salt, concrete, and clay components, permeabilities are assumed to change with time. Permeabilities are constant for asphalt and earthen fill components. These parameters include the time-dependent properties of the DRZ around the shafts to determine the hydraulic properties of the shaft seal system through time. Other parameters specified for the BRAGFLO model include pore-volume compressibility, two-phase flow parameters, and initial conditions.

The FEPs associated with model development include:

SP-1, Mechanical Effect of Gas Generation.

SP-2, WIPP Shaft Seal Degradation.

SP-4, Other Physical Degradation Mechanisms (Cracking Concrete, Erosion of Seals).

SP-5, Chemical Degradation of Seals (Alkali-Aggregate, Cement Sulfate, Cement Pore Water).

SP-6, Differing Thermal Expansion.

SP-7, Concrete Hydration.

SP-8, Effects of Microbial Growth on Concrete.

SP-9, Effect on Groundwater Chemistry.

SP-10, WIPP Investigation Boreholes.

SP-11, Evaluation of Full Shaft Conceptual Model Seal System.

This information base appears to be adequate for the intended use.

3.20.2.2. Validity of Assumptions

The basic assumptions pertinent to this model concern the applicability of the findings from the test program. Key among these are healing of the DRZ, recompaction of salt (which has application in the shaft sections filled by this material), adequately qualified parametric values for each seal component, a short-term seal to assume appropriate permeability until the salt column is reconsolidated, and implementability of the seal components.

The healing mechanism is discussed in more detail in Section 3.7 of this report. Tests are quite positive in supporting this conclusion, with the most significant of these being the results of testing the zone around a rigid inclusion in salt (Knowles et al. 1996). Recompaction of salt has been demonstrated and concerns are detailed below. Parametric values of components have been scrutinized by a qualification process for adequacy. Implementability of the seal components, as most recently described in the Draft WIPP Shaft Seal System Compliance Submittal Design Report, Appendix B, appears to be readily achievable. All of these assumptions are sufficiently supported to be acceptably valid.

3.20.2.3. Alternatives

The shaft seal system design has evolved over time (Borns and Stormont 1988; Nowak et al. 1992). The Initial Reference Seal System Design proposed a two-phase sealing strategy: short-term concrete and clay

seals and a long-term crushed salt seal. The use of native rock (i.e., crushed salt) as a permanent sealing material is considered the most effective means to eliminate the shafts as a preferred pathway for migration of hazardous constituents. Due to the time necessary for the crushed salt to reconsolidate to sufficiently low permeabilities, short-term seals were incorporated as a means to prevent fluid migration during the interim. Estimates of this interim period ranged from 100 to 200 years.

Results of the scoping calculations (CSDR 1996, Appendix D) showed that low-permeability materials were required for the shaft seals. However, the simplicity of the conceptual model limited the applicability of results to the current detailed seal system design. A comparison of the scoping calculations to the seal system design proposed for the last CCA was found in a memorandum to performance assessment (Knowles 1995a).

The current conceptual model of the WIPP shaft seals is documented in a memorandum to performance assessment (Knowles 1995b). The conceptual model is directly related to the detailed seal design both visually and technically, with all materials and components of the engineered seals being included. Parameters for the materials were developed from field and laboratory testing, literature searches, and numerical modeling. Documentation of the parameter development process is to be published.

3.20.2.4. Uncertainties

The conceptual model of the seals is based on results of detailed numerical models of the shaft seal system design that were developed to evaluate the performance of the shaft system under a range of conditions. Both fluid flow and structural response of the system were evaluated. Principal uncertainties evaluated and incorporated in the model include: 1) reconsolidation of the crushed salt component; 2) construction, permeability, and gas threshold pressure of the clay components; and 3) damage, permeability, healing, and character of the Salado and Rustler disturbed rock zones.

The consequences of uncertainty in seal component performance were a primary motivation in the development of the proposed seal system design. Although there is uncertainty in many of the materials and models, the shaft will be completely filled with high-density, low-permeability materials. The use of multiple materials and components for each sealing function resulted in a robust system. The shaft seal system being evaluated makes no distinction between "short-term" and "long-term" seal components. Instead, time dependency is incorporated directly into the model through temporal variation in seal

properties. On general overview, the uncertainties that emerged in the shaft seals program appear to have been dealt with adequately.

3.20.2.5. Adequacy of the Conceptual Model

Details concerning a description of the sealing materials and why they are expected to function as expected are to be presented in the WIPP Shaft Seal System Compliance Submittal Design Report, currently in draft. The materials include compacted earthen fill, concrete, compacted clay, asphalt, and compacted salt. These different materials are used to reduce uncertainties in performance. All materials are expected to maintain their integrity for very long periods, although for design purposes longevity only is assumed for those materials with strong scientific justification. Concrete plugs with impermeable water stops located in the Salado provide early low permeability, and the rigid support to promote healing of the DRZ. In approximately 100 years (design provides for 100 to 200 years), the compacted salt column will be sufficiently compressed to have a low permeability, thus replacing reliance on the concrete plug. The asphalt is functional as a nonpermeable plug to prevent water flow, and as a water stop within the seals in the Salado Formation. These water stops, backfilled in a one-radius kerf cut surrounding the shaft in the salt, are expected to be highly effective in deterring water flow in the DRZ surrounding the shaft. The Compliance Submittal Design report will describe the processes showing feasibility of achieving adequate placement of these seals (initial drafts appear convincing). Except for confirmation of the compactability performance of salt, this model appears to be fully adequate for implementation.

3.20.2.6. Adequacy of Application

The properties of the designed seals are realistic, achievable, and allow for controllable application. The only relatable issues for application concern the performance of recompacted salt (as discussed in Section 3.20.2.8), and performance of the DRZ. The latter issue regards the accuracy of the assumption that the DRZ will heal and accordingly can be disregarded as an explicit component of performance assessment calculations. This assumption stems from tests showing that with time, the permeability of a DRZ decreases as confirmed by tests when a stiff support is placed in an opening. The property of salt creep forces the fractures to close and original conditions to be re-established (Knowles et al. 1996). As a result of these findings, it can be assumed that following the placement of seals, the DRZ will quickly heal to create a permeability that is lower than the shaft seals provide (Chiesler 1996). Hence, it is argued that by adjusting the permeability of the seal components upward in the model, it will compensate

for the additional low flow in the DRZ, and the DRZ can be removed as an explicit input to the performance assessment calculations. Because of the relatively large extent of the DRZ and its capability of being a potential pathway for releases, this concern bears its rightful recognition in the accuracy of results.

3.20.2.7. Accuracy of Results

The results from development of the shaft sealing system pose questions of achievability, which obviously are subject to incorporating ensured quality in the design and implementation processes. On one hand, a concern may exist that the quality of materials placement might cause performance problems, and on the other hand the system is sufficiently tangible that problems can be resolved provided there is an assurance program that identifies problems in time to be addressed. Only two concerns appear to impact the concepts as discussed relative to accuracy. The first is discussed in Section 3.20.2.8, concerning establishment of a consistent and appropriate permeability value for compacted salt. The second consideration is the reliability of the expected DRZ healing process, which is an assumption of significant proportion, as discussed in Section 3.20.2.6. The results of studies, calculations, test programs, and engineering principles all appear to produce results favorable to achieving the construction of competent seals in the WIPP shafts.

3.20.2.8. Validity of Outcome

A principal conclusion from the studies and design of the WIPP shaft sealing system is that an effective and implementable design has been documented. Existing technology and use of common materials make this engineered barrier system tangible and realistic. This Panel's evaluation confirms that these attributes are fulfilled and the concepts forwarded are believed to be valid.

Two caveats were identified; however, neither threaten the validity of this model but they warrant further investigation to assure the integrity of the system. First, while the tests showing compactability of the halite adequately demonstrate the principle, to date it has not been possible to qualify an established permeability value in this medium. The principle reason lies with problems in interpretation of the test data, believed due to experimental conditions. Furthermore, having recognized that the halite is capable of being recompacted, it appears that the method of compaction by repetitive dropping of a heavy weight could cause an inhomogeneous, nonuniform packed bed. No evidence could be found that addresses this question as a requirement, as a phenomenological process, or experimentally.

The second caveat concerns the shaft monolith placed in the drift at the base of the sealing column. No evidence could be found that any analysis was made concerning whether this monolith could cause a stress condition at the shaft perimeter interface, which might create a shear zone there. The basis for this concern lies with the reality that the dimension of the monolith is sufficiently large that it creates a base platform supporting what appears to be a rigid column in a viscoelastic medium. Its effect will be that the base will be fixed at the floor datum, which might be upward moving, while the salt above in the far field is flowing downward. It appears that an analyses is warranted to assure that this is not a problem.

3.20.2.9. Adequacy for Implementation

Comments concerning two issues from the preceding section are also applicable to the model's adequacy for implementation: 1) further analysis of the salt compaction data base, firmed up with additional data, is important to support parameter permeability values, and 2) an analysis has not been found to assure the shaft monolith does not create a shear zone at the shaft perimeter interface. Aside from these, the foregoing discussions outline an insightful piece of scientific and engineering work. The shafts and seals program is well thought through and the areas of perceived concern have been addressed to various degrees of detail, each believed sufficiently adequate to support qualifying this model as adequate to proceed in supporting performance assessment.

3.20.2.10. Dissenting Views

There were no dissenting views for this model.

3.21. Gas Generation

3.21.1. Model Description

Gas generation within the disposal rooms after closure was identified as an important process to be considered in analyzing both the undisturbed and disturbed performance at WIPP. The principal features of the model are the production of hydrogen from the corrosion of iron in the waste and containers and production of carbon dioxide, methane, nitrogen and hydrogen sulfide from possible microbial degradation of cellulose, rubber, and plastics in the waste. These reactions are assumed to occur under anoxic conditions after the repository is closed and brine enters the disposal rooms and contacts the waste materials. The model also covers the removal of carbon dioxide from the gas phase by absorption and reaction with a chemical getter, magnesium oxide.

Ten to fifteen years ago it was thought that little water would be available in the dry salt to support either significant corrosion or microbial degradation of cellulose in the waste and that any gas that might be produced would be absorbed into the surrounding salt rock. However, observation of water in the underground workings, seeping from clay seams and in drilled holes, and the results of analyses and hydrologic experiments showed that interstitial water can flow into the repository. This lead to the serious consideration of corrosion and microbial action, through assessments that included laboratory analyses, some of which are ongoing. Three conceptual models have been used to describe gas generation: the so-called rates-and-potentials model, the average-stoichiometry model, and the reaction path model. These are further discussed in Section 3.21.2.3.

The amount of gas production in the repository is of considerable interest to assessment of repository disturbed and undisturbed performance. Gas pressure can counteract the brine inflow from salt, relating it to the Fluid Flow in the Salado model. Gas pressure can also drive brine out of the repository, relating it to the Actinide Transport in the Salado model. It can potentially counteract the closure of the salt around the waste, relating it to the Creep Closure model. It includes reactions that relate to the repository Chemical Conditions model and it can, thereby, also affect the Dissolved and Colloidal Actinide Source Term models. It also can affect the integrity of the Shaft Seals model. Under the various intrusion scenarios, gas is a driving force for potential releases, so it inputs to the Direct Brine Release model, as well as to the Cuttings/Cavings and Spallings models, and provides input material to the Culebra Flow and Actinide Transport models.

3.21.2. Review of Criteria

3.21.2.1. Information Used to Develop the Conceptual Model

The information used to develop the model included the quantities and compositions of the transuranic waste, particularly the quantities of radionuclides and corrodable steel and aluminum, and the quantities of water, cellulose material, and plastics, as well as any chemicals and sludges that could provide nutrients for microbial degradation of these materials. Other important information sources were the observation of brine inseepage into the underground salt cavities, and determination of the chemical compositions of brine in the Salado, in the Castile below, and in the Culebra above the repository. Direct observations were made of halophilic microbes in salt lakes in Nash Draw near the site and in repository inseepage water. Information was also obtained on corrosion-induced hydrogen generation experiments at other sites, measurements of radiolytic gas generation from plastics and water, and controlled

measurements of oxic and anoxic corrosion and microbial degradation rates of cellulose using representative brine and cultured microorganisms from the repository brine. These measurements were done for Sandia at Lawrence Livermore National Laboratory and Brookhaven National Laboratory. There is some ongoing experimental work in this latter area at the Idaho National Engineering Laboratory using actual transuranic waste materials. There is little information on the microbial degradation of plastics.

The information on brine compositions, microbe presence and populations, and the controlled experiments of corrosion and microbial processes are very useful. Due to the length of time of the experiments, no evidence for likelihood of self-limiting conditions on corrosion or microbial action were observed, although it is logical that there will be some self-limiting features that would prevent complete reaction of metal, cellulose, and plastics. A determination of whether microbial action on cellulose would have a net production or consumption of water could not be made from the information available. Experiments of potential radiolysis of water do not appear to allow direct differentiation of gas generation from dissolved versus wet particulate alpha-emitting radionuclides. The ongoing longer term experimental work being conducted at the Idaho National Engineering Laboratory could provide improved resolution of some of this information. However, overall there appear to be adequate data to develop a meaningful conceptual model of gas generation.

3.21.2.2. Validity of Model Assumptions

Regarding hydrogen generation by metal corrosion, a key assumption is that hydrogen is generated by corrosion of steel in waste drums. This is certainly valid. The model also assumes that carbon dioxide and hydrogen sulfide generated by microbial degradation will not passivate steel, which appears very valid based on the corrosion experiments and the addition of magnesium oxide as a carbon dioxide getter. Rates of steel corrosion are assumed to be higher for waste inundated or wetted in brine at the bottom of the room, and rates are somewhat lower for metals above the brine level resulting from wicking. These assumptions appear reasonable based on the direct experimental evidence. In fact, assumed rates based on the reasonably short-term iron corrosion experiments could be somewhat conservative with regard to the timing of gas generation, but probably valid for the overall amount of gas from corrosion of this source of metal.

The model ignores corrosion of aluminum, steel in rockbolts and steel netting, and other equipment to be left in the underground workings. This seems to represent an implicit assumption that corrosion of these

materials will not contribute to gas generation and is based on the relatively small amounts of these materials. Aluminum is apparently on the order of 10% by mass of the steel, based on the summary data in the 1995 Baseline Inventory Report. Aluminum is quite corrodable in brine, and rockbolts can directly contact water seeping from the anhydrite interbed above the disposal rooms. The molar quantity of hydrogen produced per mole of aluminum corrosion would be 1.5, due to the stoichiometry involved. Therefore, it seems only logical to include these materials in the corrosion model to avoid a bias.

The model also assumes that the chemical reaction representing the stoichiometry of anoxic corrosion of iron is

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H2$$

thereby yielding one mole of hydrogen per mole of iron reacted, and consumption of two moles of water. The model assumes that the corrosion of iron is not represented by the reaction

$$Fe + 4/3H_2O \rightarrow 1/3Fe3O4 + 4/3H2$$

as this reaction is not expected at low temperatures, and the amount of hydrogen generated in experiments was consistent with the first equation. Except for the initial period after repository closure, when oxygen is available, this appears valid and reasonable, especially since the chemistry conditions model predicts reducing conditions in the repository.

Regarding microbially induced gas generation, the model assumes that the probability of degradation of cellulose and plastics/rubber will be 50% and that in the event that biodegradation occurs there is a 50% probability that plastics and rubber will also be degraded. This assumption is shown schematically in the diagram below.

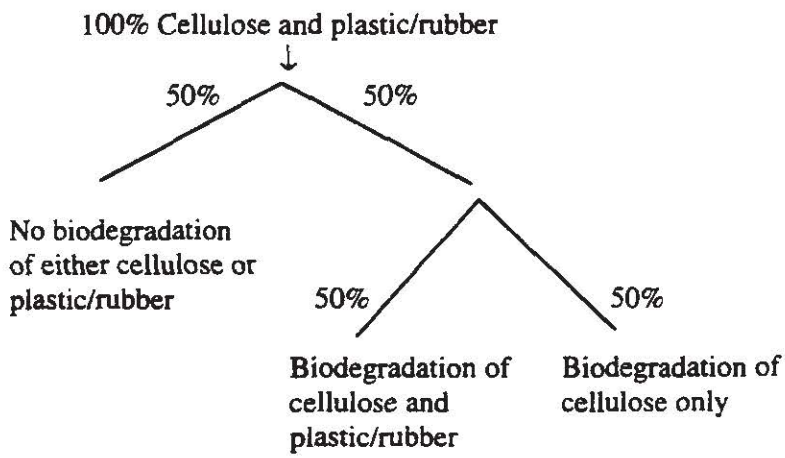

This assumption is based on major uncertainties that are described in Section 3.21.2.4 below, and represents a judgment. For performance assessment purposes, this assumption will result in less gas generation than if one were to assume total consumption of all the organic material. There is apparently no scientific evidence that plastics/rubbers degradation will occur at all with certainty, based on contemporary experience. The possibility that products from microbial degradation of cellulose, and perhaps radiolysis by alpha irradiation, could combine to break down the relatively stable plastics polymers to more consumable fragments suggests the probability should be non-zero. It is difficult to argue for a value higher or more precise than 50%, unless there were more robust long-term data, or experience with plastics degradation in, for example, landfills. Therefore, for performance assessment purposes, the assumption regarding plastics/rubber appears to be adequate.

With regard to the degradation of cellulose, the long list of uncertainties identified in Section 3.21.2.4 below suggests that less than full probability of significant microbial degradation of this more readily consumable material is a reasonably valid assumption. Also, it does not appear scientifically valid to assume that either all or none of the cellulose will be degraded in light of the significant uncertainties that microbial populations would remain viable to the extent of complete cellulose degradation. DOE is not seeking a worst case in performance assessment. Therefore the 50% probability is a reasonable assumption for modeling purposes.

3.21.2.3. Evaluation of Alternatives

The Average Stoichiometry model currently used has been in use since 1991. Its principal features and assumptions have been described in the previous sections. Two alternatives that have been seriously considered are the Rates and Potentials model from about 1989 through 1991, and the Reaction Path model, which was developed between 1992 and 1995, but has not been used.

The Rates and Potentials model used measured rates of gas generation from microbial processes and corrosion and the total potential for gas generation from the available amounts of metal and cellulose. This model assumed no gas generation from plastics, which was controversial. The results of use of this somewhat less involved model demonstrated that gas pressures could have a significant effect on the performance of the repository. This stimulated development of more complex analyses methods involving coupling gas generation with brine flow and incorporating processes of fracturing due to gas

flow into the Salado anhydrite beds. The Rates and Potentials model gave way to the Average Stoichiometry model.

The third model that has been considered is the Reaction Path model in which the reactive gases, carbon dioxide, and hydrogen sulfide produced by microbial action, were assumed to interact with and potentially passivate the surfaces of steel, thereby reducing or potentially stopping the rate of corrosion. Although some passivation was observed in experiments, corrosion films were not judged to be sufficiently adherent. Also, analysis of rates of microbial production of carbon dioxide and hydrogen sulfide showed they would not be present in sufficient quantities to provide passivation. Therefore, the reduced corrosion rates indicated could not be demonstrated reliably and effort on this model was stopped in late 1995. Furthermore, the use of a chemical getter such as magnesium oxide would absorb the carbon dioxide, raise pH and lower actinide solubility, reduce carbon dioxide pressure buildup, and somewhat lower steel corrosion rates at the higher pH.

The alternative models that were seriously considered did not offer sufficient benefits to performance assessment. However, the thermodynamic elements of the more complex Reaction Path model could, in the future, offer improved understanding and more rigorous ability to understand the complex chemical behavior in the repository room. Nevertheless, the purpose of the Gas Generation model to provide input gas generation to other models is adequately met by the Average Stoichiometry model.

3.21.2.4. Uncertainties

There appear to be greater uncertainties in the submodel describing microbial degradation than in the submodel describing metal corrosion. Uncertainties, which have been stated relative to microbial degradation, include the following:

- Will there be adequate populations of microbes capable of surviving for long periods in the disposal environment?
- Will there be adequate nutrients and electron acceptors available from the waste over long periods of time?
- Will sufficient brine enter the room to support the microbes?
- Can chemically toxic metals or radiation destroy or retard otherwise viable microbe populations?

- Will microbial degradation of plastics and rubber occur at all?
- What are the relative amounts of the various gases produced, and will microbes be net producers or consumers of water?

Despite these significant uncertainties, the Gas Generation model will predict significant but not total degradation of cellulose and plastics/rubber. Thus, these uncertainties appear to have been resolved in a conservative manner.

Uncertainties in the submodel describing corrosion-induced hydrogen gas buildup include the amount of metals present; the use of short-term metal rates of corrosion; the potential for oxic corrosion to continue due to radiolysis of water; and the potential for increased amounts of corrosion products from aluminum corrosion or increased rates from iron/aluminum galvanic couples and from corrosion of steel in the repository rock bolts and netting. It is judged that the only one of these that is potentially significant is the amount of added corrosion-induced gases from aluminum in waste and from rock bolts and netting. Another issue is whether some Fe+3 would be produced during the initial period after closure, and later due to continued generation of oxygen from radiolysis, thereby effecting actinide oxidation states.

The radiolysis of water in the waste and in brine, as well as radiolysis of plastics and rubbers, have separately been judged to have an insignificant effect on gas generation compared to the other gas generation mechanisms, and are not included in the gas generation model. For alpha particle irradiation of plastics and rubber, the measured G values (molecules of gas per 100 electron volts) were quite variable over time, leading researchers to conclude that depletion of available hydrogen atoms in plastic/rubber polymers around radioactive particles would stop the generation of such gases. However, over the long term, this conclusion is questionable since the radioactivity and waste can move around and be deformed by salt creep and gas and brine movement. Furthermore, the reported experiments involving radiolysis of brine have used soluble alpha emitters. In this situation the approximately 5 Mev per disintegration would all be dissipated in water. Depending on the solubilities, much of the actinides could remain undissolved. The review of this issue did not cover radiolysis by wetted particulate radioactive materials. This omission could be rather significant. If a significant portion of actinides are not dissolved but remain in small particulate materials that become wetted, a significant portion of the alpha energy could still be deposited in water and generate hydrogen and reactive oxygen species.

A project decision was recently made to add magnesium oxide to buffer the brine pH (in the range of approximately 10) to limit actinide solubility. The model assumes that all carbon dioxide is quickly

dissolved in brine and precipitated as magnesium carbonate, thereby also reducing gas pressure and buffering the pH at 10, rather than about 4 to 5. While this appears clearly desirable, there are significant uncertainties as to whether these benefits will be completely realized. No results have been presented of any consideration of phenomena that could limit the effectiveness of the magnesium oxide. Likewise, there have been no laboratory or pilot scale tests to demonstrate effectiveness. Some potential adverse scenarios that might be considered are as follows:

1. Brine, which slowly enters the room, bypasses the getter and penetrates the drums from below. The current design has no getter beneath the drums.

2. Carbon dioxide, which initially reacts directly in the gas phase with the magnesium oxide getter, creates an insoluble crust around the outer surfaces of the getter, thereby limiting further access of brine and carbon dioxide to the getter. Such a crust might also occur at the water level in the bags of getter stacked around the periphery of the waste rooms.

Thus, the assumption of complete and rapid removal of carbon dioxide appears quite uncertain and, for modeling purposes, seems unjustified in light of such uncertainties. The benefits being counted on in the Chemical Conditions model are extremely significant, which carries with it a very significant obligation to demonstrate the validity of this assumption.

Another uncertainty is whether the heats of the corrosion reactions, and the microbial degradation of the cellulose, will result in elevated temperatures. Analyses of thermal effects of radiogenic heat in contact-handled transuranic waste have shown this source of thermal energy is small. Likewise, analyses of radiogenic heat in remote-handled transuranic waste can result in 38-65°C in the area of canisters but only about 4°C in the repository overall. However, no thermodynamic analysis has been provided to support the single-statement conclusion in the FEP screening document that corrosion and biodegradation do not affect repository temperature due to low enthalpies of the reactions. Heat generated in contact-handled transuranic waste could not dissipate as readily as in remote-handled waste, because of the large mass and dimensions of these relatively low-conductivity wastes. Significant temperature increases could accelerate corrosion rates in the presence of brine and potentially affect other processes, such as creep closure and brine flows. This uncertainty could be resolved readily through a numerical evaluation.

3.21.2.5. Adequacy of the Conceptual Model

The Gas Generation model would represent a reasonable approximation of the most significant processes represented at the conceptual level, were it not for the four potentially significant uncertainties described above. Some modest effort to resolve these uncertainties is needed, as discussed in Section 3.21.2.8.

3.21.2.6. Adequacy of Application

The gas generation model results are applied to the overall performance modeling system known as BRAGFLO, as well as to the Chemical Conditions model. Gas pressures are calculated from molecules of gas produced and assume a reasonable equation of state. As indicated earlier, the assumption that all carbon dioxide is rapidly removed from the gas phase appears somewhat unreasonable in the absence of better chemical and engineering justification for this important assumption. Therefore, this currently represents a discontinuity in the modeling system. The processes not included in the model, including gas generation from aluminum and rock bolts and from radiolysis, represent potential changes in the model but do not affect the modeling application per se. However, if greater thermal effects due to heat generation from corrosion and biodegradation were found through analysis, this could in turn affect other system parameters and processes outside the Gas Generation model.

3.21.2.7. Accuracy of Results

In the absence of key results of the model, it is difficult to draw definite conclusions about what the accuracy of the results will be when implementing a conceptual model. If one were to properly represent the conceptual model in equations, and then properly implement the equations in a numerical system using appropriate data on parameters, the accuracy of results would presumably be that associated with the uncertainties and biases in the conceptual model above, as well as any introduced during implementation, to get numerical results.

The uncertainties and potential biases that have been identified for this model are judged to have a potentially significant effect on its accuracy in predicting gas pressures and other parameters, such as pH and actinide solubilities. However, this judgment could be tempered somewhat if key results of analyses and sensitivity studies were to indicate that the identified uncertainties and biases taken collectively were to show that the effects on waste systems releases under disturbed and undisturbed conditions were small. If this were not the case, changes to the model to account for such effects would be needed. Therefore, it is suggested that results of implementing the Gas Generation model would be useful,

including sensitivities among Gas Generation model variables and brine inflow calculations, and resulting pressure buildup over time. Also, the sensitivity of gas generation to the amounts released from human intrusion scenarios would provide useful information. Such information is believed necessary to make a more useful and informed judgment on accuracy.

3.21.2.8. Validity of Conclusions

There are two issues of concern here, first, whether the predicted outcomes in terms of inputs to other models are valid, and second, whether the outcome of larger issues on disposal system releases are valid in light of remaining issues with the Gas Generation model. A definite conclusion on either point would be somewhat speculative, at least without resolution of several of the issues raised and possibly of the results of sensitivity studies identified. One would also not want to speculate on the validity of conclusions without seeing what the conclusions might be. The following issues have not been adequately resolved:

- Analysis of hydrogen generation by corrosion of metals other than the steel in the waste is inadequate. Ignoring gases generated by corrosion of other metals could result in underestimating the gas pressure in the repository.
- Temperature increases in the repository due to corrosion and microbial degradation are not sufficiently analyzed or characterized. Higher ambient repository temperatures could increase the rates of chemical reactions, fluid flow, and halite creep.
- Due to uncertainties about the effectiveness of the magnesium oxide getter to completely remove CO_2, significant uncertainties exist regarding pH, CO_2 pressure, and actinide solubilities. The chemical conditions in the repository would significantly change if the MgO did not function as planned, and could result in underestimating radionuclide releases.
- Hydrogen and oxygen gas generation from radiolysis of dissolved and wetted particulate actinides have not been adequately evaluated. Radiolysis of cellulose and plastics without assuming local hydrogen depletion has also not been adequately evaluated. Ignoring the gases generated by these effects could result in underestimating the gas pressure in the repository.

3.21.2.9. Adequacy for Implementation

At the conceptual level, without consideration of the integration, accuracy, and conclusions criteria, the conceptual model would be adequate if the significant issues raised above are resolved. However, a bottom line assessment on whether the Gas Generation model, as used in the compliance application, represents a complete reasonable approximation of the actual disposal system, is premature unless the significant issues raised above are resolved and some key results and conclusions are available.

3.21.2.10. Dissenting Views

There were no dissenting views for this model.

3.22. Chemical Conditions

3.22.1. Model Description

This conceptual model has been developed to standardize the chemical conditions of the repository. As such, the data generated by this model are used as input parameters to other conceptual models.

The chemical conditions of the repository are a major influence on actinide solubility. It has been estimated that under specific chemical conditions (low pH), the actinide solubility may increase over expected values by up to five orders of magnitude. This model has used engineering systems to limit such variability. DOE has assumed that equilibrium has been established between the brine in the repository (Castile or Salado), waste forms, and primary minerals. In addition to this basic chemical assumption, a series of other assumptions were made to help facilitate computer code calculations. The assumptions are discussed in further detail below. The defense of model assumptions is presented in Appendix SOTERM, which was not available for the peer review.

Major variables in this conceptual model include brine compositions (fixed chemistry Salado and Castile brines), ligand concentrations, pH, fCO_2, oxidation conditions, mineral stabilities, cement inventories, actinide inventories, and MgO backfill. Of these variables, some can be held constant because of the MgO backfill. The reaction of MgO and CO_2 acts to buffer the pH of the repository and allows other variables to be fixed. The two major variables that will now be constrained are fCO_2 (low fugacity) and pH (between 9 and 10, depending on brine composition).

Certain assumptions are critical to this model. Brine and waste are modeled as a uniform mix of dissolved and solid phases. Thermodynamic equilibrium is assumed for dissolved actinides but not for redox reactions amongst the actinides. Further, chemical homogeneity and solubility equilibrium are assumed. This allows for the assumption of instantaneous reactions. Chemical microenvironments are not believed to persist for this reason. DOE assumes there will not be conditions whereby supersaturation can exist for long periods of time. Temperatures will increase a total of approximately 5.4°C (radioactive decay and exothermic reactions), and it is assumed that there will be negligible effects due to this increase.

DOE believes that calculating mixing of brine from different sources is not amenable to performance assessment. Therefore brine compositions are fixed by performance scenarios. Undisturbed performance and E2 scenarios dictate the use of Salado brine. This is because the Castile Formation is not penetrated. Scenarios E1 and E1-E2 use Castile brine as the solvent for chemical conditions.

Oxidation states of the repository are believed to be reduced. This judgment is based on the thought that available oxygen will be consumed early by oxic corrosion or aerobic microbes. Furthermore, large quantities of iron from 55-gallon drums are consumed by anoxic corrosion, producing hydrogen gas and ferrous iron. Although reducing conditions are expected, redox reactions between dissolved actinides in possible oxidation states are not addressed. DOE assumes this will produce conservative results and increase the total dissolved actinide source term.

Experimental data have shown that acidic conditions greatly enhance the solubility of actinides. Although cement materials in the waste will hydrate to $Ca(OH)_2$, CO_2 produced by microbial degradation of cellulosics will overwhelm this component and force the brine to low pH values. To reduce the potential for highly accelerated actinide dissolution, DOE decided to add MgO to the repository as backfill. The simplified reactions of concern are:

$$MgO + H_2O = Mg(OH)_2$$

$$Mg(OH)_2 + CO_2 = MgCO_3 + H_2O$$

In large enough quantities, the backfill will act as a getter of CO_2 and thereby buffer the liquid, produce low CO_2 fugacities, and provide alkaline conditions in the repository.

Because the addition of MgO will buffer the CO_2 fugacity, many processes that create time-dependent changes in the repository have been negated. The other assumptions imparted on the chemical conditions model, such as fixed ligand inventory, mineral equilibrium (halite, anhydrite, brucite), fixed brine compositions, and fixed actinide inventories have produced a fairly simple system. There is no need for a large computer code to replicate the conditions of the repository. Rather, fixed or calculated (EQ3/6) parameters (pH, fCO_2, phase equilibria, buffering equilibria) from this model are used as input to other, more complex conceptual models.

3.22.2. *Review of Criteria*

3.22.2.1. Information Used to Develop the Conceptual Model

Information used to define the Chemical Conditions conceptual model fall into four main categories: thermodynamic considerations, experimental results, numerical simulations, and results of literature reviews. The first major consideration of this model, equilibrium conditions, is a cornerstone of physical chemistry. The model uses equilibrium conditions between brine and minerals as a given; however, it dismisses the concept of redox equilibrium conditions between dissolved actinide species. The second category, experiments used in the WIPP project (especially gas generation and actinide source terms), have identified significant factors affecting the room chemistry. A clear example is that of WIPP-specific microbes generating large amounts of CO_2 gas. The third major information source is supplied by numerical modeling. Two of these examples are listed. Mineral precipitation sequences were developed from EQ3/6 computational runs. Cement inventories were produced by simple algebraic formulas. The fourth information source came from peer reviewed journal articles. An example would be that of mineral equilibria, such as Felmy and Weare (1986).

The nine FEPs were also used in the development of this conceptual model are:

1. DRG-13, Effects of chemical changes due to gas generation and corrosion.
2. Heat from exothermic reactions and concrete hydration.
3. SP-7, Heat from concrete hydration.
4. Effect of thermal gradient.
5. DR-15, Electrochemical effects.
6. DR-16, Other second-order FEPs similar to electrochemical effects.
7. RNT-25, Electrochemical effects in the repository.
8. SP-5, Chemical degradation of seals.
9. SP-8, Effects of microbial growth on concrete.

It has been decided that this gathering of information is adequate.

3.22.2.2. *Validity of Model Assumptions*

The major assumptions of the Chemical Conditions conceptual model have been listed in the model description above. To summarize, the assumptions are as follows:

1. Brine and waste are modeled as a uniform mix of dissolved and solid phases.

2. Thermodynamic equilibrium is assumed for dissolved actinides but not for redox reactions among the actinides.

3. Chemical homogeneity and solubility equilibrium are assumed. This allows for the assumption of instantaneous reactions.

4. DOE assumes there will not be conditions whereby supersaturation can exist for long periods of time.

5. It is assumed that there will be negligible effects due to the temperature increase (by radioactive decay and exothermic reactions) of approximately 5.4°C.

6. Brine compositions are fixed by performance scenarios.

7. Oxidation states of the repository are assumed to be reduced.

8. All CO_2 will be fixed by available $Mg(OH)_2$, thereby buffering the pH of the repository.

9. Actinide and ligand inventories are fixed.

Assumption (1) is reasonable when one considers the time frame involved for mixing and the difficulty of trying to numerically represent heterogeneous waste forms. Thermodynamics relies on the principal of equilibrium and, therefore, assumption (2) provides a mixed interpretation. Assuming equilibrium for dissolved actinides is valid; however, DOE claims conservatism by not assuming redox equilibrium. This cannot be considered valid without further explanation and demonstration of the conservatism. Equilibrium of solubilites and chemical homogeneity are a simplifying assumption (3) that should be wholly valid over the time frame involved. The corollary of this assumption, that reactions are instantaneous, is wrong. The effect of kinetics was never taken into account in the model.

Assumption (4) is valid as a simplifying assumption. The trade-off between long-term saturation versus supersaturation and precipitation is valid for modeling. Although assumption (5) may be valid, verification calculations that prove negligible differences have not been provided. Assumption (6) is valid for the scenarios described. In effect, these two brines provide end-member compositions for a

complete solution series. Assumption (7) is valid after approximately 100 years beyond closure. In the short term, oxidizing conditions would prevail. The limits allowed for total waste to be entombed at WIPP provide for assumption (9) to be valid.

Assumption (8) is probably the only assumption in this conceptual model that is physically unfounded and very problematic. From a thermodynamic viewpoint, the reactions are proper and the buffering capability is valid. However, there is no physical evidence that the MgO pellets will be allowed to completely react with the CO_2 generated by microbes. Reaction rims forming on the extremity of the MgO packages may not allow the majority of the backfill to be available for interaction. Such a chemical system would then not be buffered and the brine would become acidic. Studies have not been performed to demonstrate that the present engineering design will in fact work and allow all the MgO to react with CO_2 until the gas is exhausted. This is also discussed in Section 3.21, the Gas Generation conceptual model.

3.22.2.3. Evaluation of Alternatives

The majority of the chemical alternatives are described in Section 3.23.2.3 (Dissolved Actinide Source Term). By fixing many of the chemical parameters at reasonable values for repository conditions, the need for alternative models was not required. The primary alternative that is discussed in this section is whether a chemically reactive backfill is required.

In the early 1990s, no backfill was anticipated for emplacement in the repository rooms. When the test plan for soluble actinides was initiated, a large range of CO_2 pressures and pH values was anticipated. High CO_2 generation would produce sufficient carbonic acid to lower the brine pH to approximately 4 or 5. The basic conditions of the natural Salado Formation brine (9.4) would only allow restricted dissolution of the actinides. Under acidic conditions (pH 4) in experiments, actinide solubility was found to increase by approximately 5 orders of magnitude over that of the natural Salado brine. Such a solubility increase could conceivably present problems to the overall project.

It was then decided to buffer the chemistry of the repository and brines by addition of a reactive backfill. The addition of copious amounts of MgO as backfill is designed to react with the microbially generated CO_2 and buffer the overall chemical conditions of the repository. This would, in effect, fix both the pH and fCO_2 of the brine.

3.22.2.4. Uncertainties

Uncertainties associated with this conceptual model fall into three categories. General uncertainties associated with dissolved or colloidal actinides are discussed in Sections 3.23.2.4 and 3.24.2.4, respectively. This section is restricted itself to uncertainties associated with assumptions presented in Section 3.22.2.2 and the uncertainty of whether phase stability has been adequately characterized. In Section 3.22.2.2.. four of the assumptions presented (1, 4, 6, and 9) were deemed to be valid.

The five remaining assumptions presented by DOE were not clearly shown to be valid. The point to keep in mind is what magnitude of uncertainty is associated with each assumption. Although DOE has not validated the assumption of redox disequilibrium (assumption 2), the partitioning of oxidation states into lower and higher oxidation states for model runs has effectively addressed this uncertainty. Assumption 3, that chemical reactions are instantaneous, is not valid. The impact this assumption creates on the conceptual model may be significant. Reactions that are relatively fast present no problem at all. Reactions that take a couple thousand years probably introduce very little uncertainty to the model. It is those chemical reactions that never go to full completion that may invalidate the model. This uncertainty with regard to assumption # 8 is dealt with in detail below.

Assumption #5, that a 5°C increase over STP conditions is negligible, is probably correct. Any uncertainty with this assumption could be clarified with a few verification calculations. The other assumption that contains only a small uncertainty (#7) deals with anoxic conditions in the repository. Even if oxic conditions prevail for the first 1% of the regulatory time frame, only a very small amount of iron would be tied up as oxidized iron oxides (hematite, goethite, leucophane). Although these mineral phases do not react back to reduced phases due to kinetic effects, this is not expected to have any significant effects.

The assumption that $Mg(OH)_2$ will absorb all available CO_2 generated in the repository (assumption #8) contains a very large uncertainty. As mentioned above, there is no uncertainty that the chemical reaction pathway is indeed correct. The uncertainty is whether the engineering design will be effective. If a large portion of the MgO never reacts with CO_2, then the carbonic acid will remain unbuffered and the dissolved actinide source term may increase (depending on model scenario) by up to 5 orders of magnitude. This could be considered a significant uncertainty.

The final uncertainty to be commented on is that of mineral phase stability in the repository. Although the EQ3/6 computer code has been used to qualify which phases will precipitate from solution, no formal phase-stability study has been conducted. There may be phases present that have been overlooked and the consequences of that oversight would impart an unneeded uncertainty. Schreinemakers diagrams have not been calculated to determine the phase-stability fields present in the repository.

3.22.2.5. Adequacy of the Conceptual Model

The present section addresses whether the conceptual model is adequate based on the four criteria above. Since this model strictly consists of a number of chemical condition parameters, it should be easy to evaluate whether the model is valid. It is concluded that the majority of parameters for this model are both reasonable and adequate. For the present model, the uncertainties of the previous section must be dealt with to prove that the model is adequate. Even when one considers the potential uncertainties listed in Section 3.22.2.4, only two could severely impact the adequacy of the Chemical Conditions conceptual model. These are the rigorous treatment of phase stability (Schreinemakers analysis) and the ability for the backfill to sequester the CO_2. For phase-stability analysis, only the omission of a major phase from the stability fields could jeopardize the validity of the conceptual model.

Conversely, the backfill parameter is so key to the model that without test validation that the $Mg(OH)_2$ will work as a getter, the model will not be adequate. The reason is that too many other parameters of this model hinge on the pH and fCO_2 values being fixed.

3.22.2.6. Adequacy of Application

This conceptual model does not flow as total input to a single computer code, rather it functions to set the parameters and boundaries for other conceptual models. As such, the conceptual model does not integrate to larger computer models (e.g., BRAGFLO) in the typical way. Any chemical values or constraints that the model generates should be readily integrated into other conceptual models. If the model provides a specific chemical parameter, that quantity could plug directly into performance assessment codes.

3.22.2.7. Accuracy of Results

This section discusses whether the results of performance modeling using the conceptual model within the performance system are sufficiently accurate to adequately represent the chemical processes occurring. In essence, this question is not applicable to the model in review. There should be no

opportunity to corrupt or distort parameter values from the chemical conditions conceptual model to the performance assessment model. However, this idea has not yet been confirmed by test runs of the performance assessment.

The other manner by which the performance assessment could derive inaccurate results from this conceptual model is to portray thermodynamic assumptions incorrectly. There is no way to judge whether this has happened without viewing the results of the performance assessment runs.

One would assume that the WIPP project can transfer chemical parameter values correctly from the conceptual model to the performance assessment, and that thermodynamic assumptions can be accurately implemented in the same fashion.

3.22.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Chemical Conditions conceptual model in the modeling framework are valid. The conclusions presented here rely heavily on the assumption that $Mg(OH)_2$ buffers the chemistry of the repository and that all stable equilibrium phases have been identified and appropriately considered. If the MgO backfill works as proposed, and all stable phases have been appropriately considered, then it is reasonable to state that the conclusions of this model, as they apply to the full system, are valid.

3.22.2.9. Adequacy for Implementation

The Chemical Conditions conceptual model utilizes a strategy common to the physical sciences, fixing well defined parameters to allow the study of unknowns. For the most part, the model has done a very adequate job of simulating certain physical characteristics of the repository and then determining a reasonable median value. This value has become the fixed parameter (e.g., Salado brine composition) that is then passed on to other models.

To better document that a slight temperature increase in the repository beyond standard temperature and pressure (STP) conditions does not affect the repository chemical conditions, it would be reasonable to validate the assumption with a series of appropriate thermodynamic calculations.

The assumption that chemical reactions are instantaneous led to the belief that all CO_2 released to the brine would be consumed in the repository by MgO. However, this critical chemical process (MgO backfill as buffer) has not been field tested sufficiently to be confident it will work. If the technique does

not perform correctly, then the total model would fail. At a less critical level of model completeness, there is no documentation that a phase-stability review (Schreinemakers analysis) has been performed for the chemical system in question. For these two reasons, and especially that MgO has not been tested as a buffer under WIPP-like conditions, the conceptual model is not yet adequate for implementation.

3.22.2.10. Dissenting Views

There were no dissenting views for this model.

3.23. Dissolved Actinide Source Term

3.23.1. Model Description

This model is based on thermodynamic laws to predict chemical phenomena affecting dissolved actinide concentrations in the presence of actinide-bearing solids. The actinides deemed important to the performance assessment of WIPP are thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), and curium (Cm). The dissolved actinide source term determines the concentration of each actinide in solution by combining the oxidation state distribution of each actinide with the modeled solubility of that oxidation state at repository conditions and the appropriate scenario brine composition (Salado or Castile).

Several oxidation states can be screened out or substantially constrained. Oxidation states initially screened out are Np (+6), Pu (+5), Pu (+6), and Am (+5). The screening rationale are described in Appendix SOTERM (not provided to the Panel for review). Actinides limited to a single oxidation state are Th (+4), Am (+3), and Cm (+3). The model then assumes that the remaining three actinides will exist in only one oxidation state, but is unsure which of two possible states it will be. Therefore, the modeling assumes half the realizations will be in the reduced state (U +4, Np +4, and Pu +3) and half in the more oxidized state (U +6, Np +5, and Pu +4).

The factors controlling dissolved actinide concentrations are equilibrium with anhydrite, halite, MgO, actinide-bearing solid phases, appropriate brine, and water-soluble ligands.

The ligand concentrations used in the calculations are based on the Baseline Inventory Report and are reported to be acetate, citrate, oxalate and EDTA. The concentrations used represent dissolution of the entire ligand inventory. DOE believes this is a conservative approximation for the following two

reasons: (1) it does not reduce the ligand inventory by destruction mechanisms, and (2) although all ligands will dissolve in the first brine volume, the ligand concentration will stay constant for the full simulation.

Folded within the dissolved actinide conceptual model are several conceptual submodels. The solubility submodel is the Fracture-Matrix-Transport (FMT) model, which is based on the Pitzer activity coefficient model of the thermodynamics of highly concentrated electrolytes. This model uses an adaptation of the Harvie-Moller-Weare/Felmy-Weare (HMW/FW) data base. FTM parameters are fitted using the code NONLIN, which calculates the Pitzer parameters. No redox equations are used in FMT; instead, an oxidation state analogy and oxidation distribution state submodel are used.

Soluble actinide concentrations are based on solubility limits (maximum concentrations), or when a cell is partially depleted, by inventory limits. The actinide inventory is depleted on a cell-by-cell basis for the undisturbed, E1, and E2 scenarios. Processes affecting dissolved actinide concentrations in a computational cell are: dissolution of actinide solids, advection of dissolved actinides by brine flow from neighboring cells, diffusion or dispersion from neighboring cells, and interaction with colloidal particles. The E1-E2 scenario assumes homogeneous mixing within the panel for dissolved actinides moving up the borehole.

As mentioned above, the dissolved actinide source term model incorporates a very critical assumption, that of oxidation state analogy. It assumes that all actinides in the same oxidation state (ex. +III) will form the same aqueous species and isostructural solid phases. There is said to be a large data set confirming this for the 3+ oxidation state, but fewer data exist for the 5+ and 6+ oxidation states. It is also noted that such an analogy may not hold to be strictly true for the 4+ oxidation state. The rationale for using the oxidation state analogy is to allow a great reduction in the number of experiments that must be conducted.

A second assumption is that actinide precipitates formed in laboratory experiments will allow the crystallinity to mature with time. Since solids are typically less soluble than amorphous precipitates, laboratory solubility studies can then provide an upper concentration limit. The exception may be that radiolysis could cause certain solids to become more soluble.

A third assumption in the dissolved species model is that no adsorption will occur with immobile substrates in the disposal rooms. DOE however may take credit for adsorption of dissolved actinides to mineral phases in the Culebra Formation, via the Transport of Dissolved Actinides in the Culebra model.

A fourth assumption considers that dissolved actinide concentrations are also coupled to brine compositions in the disposal rooms. DOE expects this capability to greatly enhance their ability to look at site-specific solubilities based on disposal room brines and the effect of engineering modifications on dissolved actinide concentrations.

A fifth assumption centers on the presence of anoxic conditions in the repository setting. Actinide oxidation state distributions are presently unknown, since redox couples are not in equilibrium in low temperature systems. Although it is believed reasonable to expect the actinides to exist in their most reduced state because of anoxic conditions, alpha radiolysis oxidizes Am (III) to Am (V), and Pu (VI) is stabilized in the presence of carbonate. Another potential problem with the assumption is that the repository is actually under oxic conditions for the first few tens of years, due to relict atmosphere and nitrate reactions, and oxidized actinides may encounter kinetic effect problems in attaining their final reduced oxidation state.

3.23.2. Review of Criteria

3.23.2.1. Information Used to Develop the Conceptual Model

The main sources of information used are classical thermodynamics, information gleaned from appropriate journal articles, and experimental programs. The discipline of thermodynamics as a portion of the chemical sciences is well founded. A major assumption of this science is one of equilibrium conditions. The conceptual model has made liberal use of research published in the journals. Items transferred to the dissolved actinide conceptual model from journal articles range from algorithms (Harvie et al. 1987) to phase equilibria fields (Felmy and Weare 1986) to individual thermodynamic parameters (Pitzer 1991). Experimental work on actinide solubility was performed at a number of laboratories, including Sandia, Los Alamos, Argonne National Laboratories, Lawrence Berkeley Laboratory, Pacific Northwest Laboratory, and Florida State University.

Nine FEPs are used in the development of this conceptual model. These FEPs are: effects of chemical changes due to gas generation and corrosion (DR-13), electrochemical effects (DR-15), second order FEPs similar to electrochemical effects (DR-16), effect of thermal gradient (GG-4), heat from exothermic

reactions (GG-7), chemical degradation of seals (SP-5), heat from concrete hydration (SP-7), effects of microbial growth on concrete (SP-8), and electrochemical effects in the repository (RNT-25). Information gleaned from the FEPs was instrumental in both model conceptualization and test plan development.

3.23.2.2. Validity of Model Assumptions

The dissolved actinide source term model is extremely detailed, complex, and contains many implicit and explicit assumptions. One of the most significant of these assumptions is that equilibrium is maintained. Such an assumption is a basic part of thermodynamics and is considered valid only if firmly held to. However, this model picks and chooses when the concept of equilibrium is used. An example is that dissolved actinides are assumed to be in equilibrium with solids; however, redox reactions among actinides and supersaturation are not assumed to be in equilibrium. Such a philosophy may be correct for this model (it builds in conservatism) but each variance must be defended and justified adequately.

The ten other major assumptions are: (1) lack of adsorption onto immobile substrates; (2) anoxic conditions will dominate; (3) dissolved actinide concentrations are based on repository room brine compositions; (4) metastable phases in laboratory experiments become more stable with time; (5) all actinides in the same oxidation state will form the same aqueous species and isostructural solid phases; (6) the oxidation state analogy holds true; (7) experimental runs reached equilibrium; (8) fluids obtained in 1-liter experiments are representative of the tests; (9) all stable phases have been identified; and (10) the hydrogen fugacity system is completely buffered by $Mg(OH)_2$ - $MgCO_3$.

Assumption 1 is probably not valid, but by assuming so in the Salado, DOE has built a conservative estimate. Anoxic conditions in the repository (assumption 2) are valid in the long term, however short term oxidation phases were not considered. This is because activation energies needed to reduce certain oxidized phases may not occur in the repository, and the effect would be to isolate certain phases in an oxidized state. Assumptions 3 and 7 are considered valid. Assumption 4 (metastable phases become stable with time) is not a valid assumption. Time is not the only constraint on the stability of a phase, and there is no documentation that other criteria have been considered. Assumptions 5 and 9 are intimately tied together. The information provided does not confirm that an exhaustive phase equilibria stability study has been performed for this chemical system. In essence, DOE has not proved that the actinides will form the same aqueous species or solid phases, or that all phases have been identified. Regarding assumption 6, the oxidation state analogy is not truly valid. However, the assumption is oft

times conservative. This is the case for the +4 oxidation state that assumes Th solubility values. In the +3 oxidation state, however, values were obtained from another oxidation state (+5) and were not proven to be correct. The test runs for +6 phase (U) could not generate Pitzer parameters or characterize the associated solid phase. In an overall sense, it is probably inaccurate to assume the oxidation state analogy holds true. Assumption 8 (whether final liquids of 1 liter experiments are representative) is not valid due to microdomains and the absence of equilibrium conditions. However, it is not clear that these results were used in the final lookup tables. Finally, assumption 10 is only valid if the CO_2 gas is able to react completely with the $Mg(OH)_2$ backfill. As yet, no discussion exists that sufficiently assures that the reaction will go to completion. There is an equal chance that reaction rims will occur early in the process, isolate a large proportion of the backfill, and not allow the system to be buffered (see also Section 3.21.2.4).

3.23.2.3. Evaluation of Alternatives

The Dissolved Actinide Source Term conceptual model describes the quantity of actinides that would be mobilized as dissolved species in WIPP brine, and would migrate with the brines away from the repository. At one time or another over 18 years, six alternative models were proposed: (1) Expert Panel, (2) Inventory Limits, (3) Inventory Limits with Realistically Conservative Maximum Concentrations, (4) Fresh Water Estimates, (5) Chemical Model for Mobile Actinide Concentrations, and (6) Inventory Limits with Sorption. Of the six models, numbers 1, 4 and 6 were not defensible. As of December 1994, the Expert Panel model was questioned as to its credibility and technical suitability, the Fresh Water Estimate model was essentially undeveloped, and sorptive values for the Inventory with Sorption model were unavailable. Of the remaining three models presented, the Inventory Limits model was complete and defensible but highly conservative. The model that until recently was used as the baseline was the Inventory Limits with Realistically Conservative Maximum Concentrations model. Essentially, this was a combination of the Inventory Limits and Expert Panel models and was intended to be more judiciously conservative than the Inventory Limits model. The Chemical equilibrium model is based on thermodynamics and is robust but was only recently fully developed. The final model for the performance assessment (Chemical Equilibrium Model) will contain submodels that investigate the source terms for both dissolved and colloidal actinide species.

The other realm where a series of alternatives were considered was that of thermodynamic models for activity coefficients. Four modeling approaches were considered by DOE: the Pitzer model, Harned's

Rule (ion pairing), a hybrid of ion pairing and Pitzer formalism, and specific ion interaction (SIT) ion-pairing approach. Harned's Rule was only used for dilute solutions and not for brine more concentrated than 2 molal. Therefore the model was rejected. The SIT model assumes only species with opposite charges interact, and is limited to concentrations up to 3.5 molal. This model was also rejected because of its limitations. The Pitzer-SIT hybrid model did not compare the calculated lanthinide solubilities with data, so the hybrid model was dismissed. The Pitzer formalism has been applied frequently to concentrated electrolyte solutions and is backed by considerable peer reviewed journal articles. This model was therefore judged the most applicable format for characterizing the actinide solubilities in WIPP brines.

3.23.2.4. Uncertainties

There are five groups of relative uncertainty associated with the dissolved actinide source term conceptual model. The first uncertainty involves the experimental results produced by the Actinide Source Term (AST) program, while the other four uncertainties relate to how the experimental results are applied to the conceptual model.

The results of the experimental program exhibit a relatively small uncertainty (Novak 1995; Novak and Roberts 1994). When the solubility data and Pitzer coefficients from the experiments are implemented in FMT, the model results predict an uncertainty of an order of magnitude or less for the chemical conditions tested. The results of FMT modeling also compare favorably with the data of Kim et al. (1985).

The four uncertainties arising from FMT applications to the conceptual model are as follows: (1) is dissolution/precipitation steady state obtained, (2) can FMT data be extrapolated outside the realm of test parameters, (3) is the oxidation state analogy valid, and (4) are WIPP chemical conditions adequately defined? These uncertainties are much more difficult to quantify, therefore, a short discussion of each is given below.

Because of constraints imposed on the time involved in the performance assessment, the uncertainties of dissolution/precipitation steady state are fairly simple. The model assumes a long period of time in which brine will be in contact with waste and this would allow both dissolution and precipitation to equilibrate. Other assumptions that lower the uncertainty of this issue are reduced conditions, lack of

supersaturation, ample solid materials for nucleation and sorption, and brine homogeneity due to long-term mixing. All these assumptions reduce the uncertainties of achieving steady state conditions to a low level.

The second uncertainty, that of extrapolation beyond the realm of test results, has been significantly reduced by the use of MgO backfill. Originally, the experimental tests were carried out over a range of fCO_2 values, but did not entirely cover the conditions expected in WIPP. The use of MgO backfill to provide an $Mg(OH)_2$-$MgCO_3$ buffer has negated this uncertainty. The only potential problem would be if the buffer in effect did not work (see Section 3.23.2.3).

The uncertainties associated with the oxidation state analogy are more ambiguous. Actinides in the +3 state do show the same limited set of solubilities. The +5 (Np) and +6 (U) oxidation state analogies are based on experiments using those specific actinides. The remaining uncertainties all center on the +4 oxidation state analogy. Thorium was used as the test analog and it was determined that Pu and U were slightly less soluble under similar chemical conditions. The analogy of Np to Th in the +4 state was not discussed. The use of Th solubility values is still probably conservative and may raise the total +4 concentration by an order of magnitude.

The last major uncertainty concerns the chemical conditions in the repository of the Salado. The most important parameters are pH, fCO_2, brine major ion concentrations, waste material reducing capability, and organic ligand concentrations. The first two parameters (pH and fCO_2) are well controlled by the addition of MgO backfill. Such a buffering effect allows this uncertainty to be negated. Major ion concentration ranges are well constrained for Salado and Castile brines. They are not so well defined for intrusion of Culebra brine into the repository. DOE believes that the Culebra composition, after mixing with halite or anhydrite, is bounded by the Salado or Castile brines. For two of the four oxidation states, Culebra brines would be within an order of magnitude of other end-member solubilities. The uncertainties for the +4 and +6 oxidation state solubilities is larger than an order of magnitude but undefined. Reduction capabilities of waste are taken care of in a conservative sense by assigning a 50% probability to both the lower and higher oxidation states. The uncertainty concerning organic ligands is resolved by assigning an inventory value that is twice that calculated in the BIR, then incorporating the increased solubility effect of organic ligands on actinides.

In conclusion, the only outstanding large uncertainty (other than assumption validity) is that of the Culebra +4 and +6 oxidation state solubilites.

3.23.2.5. Adequacy of the Conceptual Model

The present section addresses whether the conceptual model is adequate based on the four criteria above. The outstanding issues that must be dealt with are the six unvalidated assumptions stated in Section 3.23.2.2 and the one uncertainty still unresolved in Section 3.23.2.4. When one considers the magnitude and complexity of this conceptual model, and the fact that so many issues are well addressed, these items are not overwhelming. A further nagging problem is that two major appendices of the CCA, NUTS and SOTERM, are not available. If the discussions entailed in the appendices are reasonable and logical, the assumptions are found to be valid, and the uncertainty is resolved properly, then the conceptual model would be wholly adequate.

3.23.2.6. Adequacy of Application

The issue here is whether the individual conceptual model is applied in an acceptable overall performance modeling element. As mentioned above, this is a very complex model with many variables. There is a well-documented data base for thermodynamic modeling of high concentration brines. Such data have served well as a foundation for the model. As an input to the mathematical code NUTS, this conceptual model would present its results in a lookup table. The table takes into account brine compositions, ligand availability, and oxidation state potentials, all of which allow a very robust model to be adequately applied to the performance assessment modeling elements. The true unknowns are to be found in the assumptions that the chemistry rapidly approaches equilibrium and that the waste has uniform characteristics and inventory. These fundamental assumptions are a basis of the conceptual model and are most probably adequate and reasonable.

3.23.2.7. Accuracy of Results

Preliminary results of the lookup tables have been provided to the Panel by a Principal Investigator for the conceptual model. If one assumes that the oxidation state analogy holds true, that the brine stays buffered at a pH of 9 to 10, and that the other assumptions mentioned are valid, then the results of the conceptual model are sufficiently accurate. The only qualification to this opinion is that the results may be too conservative. The solubilities calculated (and determined from experiments) are quite well

defined. To allow an order of magnitude variation on either side of the solubility parameter mean value is probably extreme and not truly representative of the chemical system involved.

The one remaining piece of information needed to thoroughly qualify the accuracy of the results would be a series of sensitivity analyses. These results are not currently available.

3.23.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Dissolved Actinide Source Term conceptual model in the modeling framework are valid. This decision is made more difficult by the fact that the appropriate tables and appendices of the CCA have not been supplied as of this date. If the information not yet available is reasonable and adequate in content, then it is reasonable to state that the conclusions of this model, as they apply to the full system, are valid.

3.23.2.9. Adequacy for Implementation

This model has turned out to be a very strong representation of how actinides would dissolve in the two major brines (Salado and Castile) of the repository and is adequate to support performance assessment. However, this model is closely linked to the Chemical Conditions model discussed in Section 3.22, and to the successful use of MgO to buffer pH conditions in the repository.

For the sake of completeness and accuracy, the remaining concerns listed in Sections 3.23.2.2 and 3.23.2.4 have not been thoroughly documented. These concerns are summarized below:

- What impact does the initial (approximately 100-year) oxygen-rich domain of the repository have on corrosion?
- What were the metastable phases in the laboratory experiments, and what stable phases did they transform to?
- Can a phase equilibria stability determination be performed for this chemical system (same as described in Section 3.22)?
- Is the oxidation state analogy valid for the +4 and +6 oxidation states?
- Did the AST 1-liter liquids reach equilibrium with the solids? If not, were the solubility results still used?
- Does the Culebra brine chemistry affect actinide solubility?

3.23.2.10. Dissenting Views

There were no dissenting views for this model.

3.24. Colloidal Actinide Source Term

3.24.1. Model Description

The Colloidal Actinide Source Term conceptual model describes the concentration of actinides sorbed to or contained in mobile colloidal particles in the disposal rooms and also describes the stable colloids that must be quantified for transport in the Culebra. The actinides addressed with this model are thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), and curium (Cm). Presently, transport of colloids in the Culebra have not been rigorously modeled because of the complexities of coupling hydrogeology, geochemistry, and colloid chemistry. Because of the chemical complexities of the integrated system and high ionic strength brines present, an attempt has been made to characterize the major colloid types believed to be present in the repository.

The four types described are "hard sphere" carrier colloids (mineral fragments), microbes, soft sphere carrier colloids or hydrophilic colloids (humic and fulvic acids) , and intrinsic colloids (true colloids). These particles develop from a variety of processes in the repository, including waste degradation, microbial activity, rock decomposition, and chemical condensation. Intrinsic colloids form by condensation of dissolved actinides in the disposal rooms. Mineral fragments and humic substances provide surfaces that dissolved actinides may sorb to. Microbes actively bioaccumulate actinides intracellularly and also act as substrates for surficially extracellular sorption (Francis 1985).

Four major decisions have been made that greatly simplify this conceptual model. First, DOE has elected to disregard the effects of competition associated with the equilibrium between dissolved actinides and actinides associated with colloidal particles. Therefore, the two source terms are not inexorably linked, resulting in an overestimation of the total concentration of mobile actinides that may leave the repository. Second, in the event that the sum of the concentrations of the dissolved actinide and colloidal actinide source terms for a particular element exceed the inventory limited concentration of that element, then a partitioning scheme is utilized. Instead of basing the partitioning on an equilibrium approach, DOE has decided to use an approach based on conservatism. The concentration of a particular actinide in the inventory is first made available to the most efficient transport mode. If the inventory is not used up, then the next most efficient transport mechanism is filled. This rationale is continued until the inventory

is exhausted by assignment to the five groups of transport vehicles (four colloidal and dissolved actinide source terms). Third, thermodynamic equilibrium is achieved by actinide intrinsic and humic colloids. And fourth, DOE has assumed that microbes and mineral fragments are present in constant quantities in the aqueous phase. This allows a steady state quantity on which the actinides can sorb.

Because of the effect of high ionic strength brines on mineral fragment colloids, which collapses the electric double layer surrounding the colloid, Van der Waals forces can cause agglomeration and settling of such colloids. Laboratory experiments using WIPP brines indicate that this settling effect largely negates mineral fragments as an effective transport mechanism. Thus, DOE has conservatively assigned a mineral fragment concentration for each actinide to be 10^{-9} m/L, one order of magnitude higher than the detection limit of the experiments.

Microbes have a large study base at WIPP, primarily to provide data for the gas generation program. This information has also been helpful in the Colloidal Actinide Source Term model. The source term concentrations associated with microbes are based on actinide uptake experimentally determined from experiments with relevant bacteria cultures. Source term values range from 10^{-5} to 10^{-11} m/L.

Humic and fulvic acids are of particular concern because of their well known capability to complex metal cations, including actinides. These soft sphere carrier colloids are not affected by high ionic strength brines, so they may be important in the transport of actinides at WIPP. To determine humic substance concentrations, actinide complexation constants from WIPP experiments or from literature are coupled with site binding densities and solubilities of humic substances in WIPP brines. Source term values range from 10^{-5} to 10^{-9} m/L.

Intrinsic colloids are well represented by the Pu(IV) polymer. The mechanism of formation of this polymer has not yet been identified; however, it is known to be stable in high concentrations in highly acidic environments. There is some evidence that the polymerization is strongly linked to hydrolysis, and that it produces an amorphous macromolecule that becomes crystalline with time. This polymer is typically on the order of nanometer size range. Hence, it is assumed to act like a hard sphere carrier colloid. Experiments were conducted by over- and undersaturation at a range of pH values to determine concentrations of Pu intrinsic colloids. The source term value of this polymer is 10^{-9} m/L. Other actinide intrinsic colloids (especially Am) were found to have negligible importance.

The computer code that will describe the transport of the Actinide Source Term model is called NUTS. NUTS is dependent on BRAGFLO (chemical conditions in waste rooms) to provide brine volumes and a lookup table to provide actinide concentrations. The actinides that will be tracked in Salado and Culebra Brines by this table are thorium (Th), uranium (U), plutonium (Pu), neptunium (Np), and americium (Am). Other chemical factors originally believed to impact colloidal source terms were pH, pCO_2, major brine constituents, ionic strength, oxidation speciation and organic ligand concentrations. Fixing the brine compositions and the addition of MgO backfill has significantly reduced the number of variables in the lookup table.

3.24.2. Review of Criteria

3.24.2.1. Information Used to Develop the Conceptual Model

The main sources of information used are journal articles, experimental programs, and classical thermodynamics. The conceptual model has made liberal use of research published in the journals. Items transferred to the Colloidal Actinide Source Term conceptual model from the journal articles are voluminous and are the basis of the experimental test program. Experimental work on actinide solubility was performed at a number of laboratories, including Sandia, Los Alamos, Lawrence Livermore, and Brookhaven National Laboratories, and Florida State University. The discipline of thermodynamics as a portion the chemical sciences is well founded. A major assumption of this science is one of equilibrium conditions.

No FEPs were included in the development of this conceptual model. In fact, colloids were not considered as a conceptual model until after the 1992 performance assessment was completed. The study of Ibaraki and Sudicky (1995) is very similar to the conceptual model developed here.

3.24.2.2. Validity of Model Assumptions

The majority of the assumptions used in the colloidal actinide source term are valid, in that they are either accurate scientific extrapolations or based on conservative measures. Four major assumptions made by DOE and discussed in the model description above are most probably valid in the context of this model. To assume that Dissolved and Colloidal Actinides Source Term models do not compete for actinides is certainly conservative and will overestimate the total actinide source term. The partitioning scheme used when the inventory is exceeded is reasonable and again conservative. The assumption that

thermodynamic equilibrium is attained for intrinsic colloids and humic colloids is valid. The assumption that there is a steady state source of mineral fragments and microbes allows for conservatism, in that it provides an abundance of sorbing material.

Two other assumptions in the conceptual model concern the use of bounding calculations. Concentrations of actinides in both intrinsic colloids (Pu+4) and mineral fragments were below the detection limits of the experiments. Therefore, the actual detection limit was used as the bounding value for the intrinsic colloid, and an order of magnitude higher bounding value than the detection limit for mineral fragments. These are probably adequate, possibly overly conservative estimates for concentrations in both cases and can be considered adequate.

3.24.2.3. Evaluation of Alternatives

The Colloidal Actinide Source Term conceptual model describes the quantity of actinides that would be mobilized as colloid species in WIPP brine, and would migrate with the brines away from the repository. At one time or another over the last four years, six alternative models were proposed for the Actinide Source term. The model names are as follows: (1) Expert Panel, (2) Inventory Limits, (3) Inventory Limits with realistically conservative Maximum Concentrations, (4) Fresh Water Estimates, (5) Chemical Model for Mobile Actinide Concentrations, and (6) Inventory Limits with Sorption. Of the six models, numbers 1, 4, and 6 were not defensible. As of December 1994, the Expert Panel model was questioned as to its credibility and technical suitability, and the Fresh Water Estimate model was essentially undeveloped. Sorptive values for the Inventory with Sorption model were unavailable. Of the remaining three models presented, the Inventory model was complete and defensible but highly conservative. The model that, until recently, was used as the baseline was the Inventory Limits with Realistically Conservative Maximum Concentrations model. Essentially, this was a combination of the Inventory Limits and Expert Panel models and was intended to be more judiciously conservative than the Inventory Limits model. The Chemical equilibrium model is based on thermodynamics and is robust but was only recently fully developed. The final model for the performance assessment (Chemical Equilibrium model) will contain submodels that investigate the source terms for both dissolved and colloidal actinide species.

The actinide inventory is originally determined by projections in the Baseline Inventory Report (BIR). A series of chemical reactions that will have a major impact on the colloidal actinide source terms are as follows:

1. Actinide dissolution reactions.
2. Reactions between brines and organic waste.
3. Reactions between brines and backfill materials.
4. Reactions between actinides and dissolved ligands (organic and inorganic).
5. Reactions that produce carrier colloids.
6. Reactions among actinides to produce actinide-intrinsic colloids.
7. Reactions between actinides and carrier colloids to produce radioactive mobile substrates.
8. Actinide sorption onto immobile substrates.

Of the eight reactions listed above, the first seven have been used in developing the current model. DOE has discarded reaction number 8. This decision is thought to be conservative and allows the possibility of more actinides being transported by colloids.

3.24.2.4. Uncertainties

The only uncertainty listed by DOE for this model involves the inventory limited concentration of the actinides. If the sum of the dissolved and colloidal actinides exceeds the inventory total, the actinide concentrations will then be proportioned between the two actinide groups (dissolved and colloidal). This philosophy appears reasonable.

Three lesser uncertainties that would add clarity to the model have not been resolved. First, it has been theorized that the Pu intrinsic colloid would act as a mineral fragment with time. Studies have not proved this theory. The mechanistic operation of this intrinsic colloid has not been determined. A second uncertainty concerns site densities available on microbes for actinides. This parameter has not been determined. Third, it is assumed that humic colloids behave like dissolved actinides. This assumption has not been adequately supported.

3.24.2.5. Adequacy of the Conceptual Model

The present section addresses whether the conceptual model is adequate based on the four criteria above. The conservative bounding values for intrinsic and mineral fragment concentrations should (in a perfect world) be discarded and real measurements taken to obtain scientifically valid results. However, when one considers the magnitude and complexity of this conceptual model, and the fact that so many issues are well addressed, these items appear almost insignificant.

The outstanding issues that must be dealt with are the three unresolved uncertainties in Section 3.24.2.4. A further nagging problem exists in that two major appendices of the CCA are not available (MASS and PAR). If the discussions entailed in the appendices are reasonable and logical, and the uncertainties are qualified, then the conceptual model would be wholly adequate and much more accurate from a scientific viewpoint.

3.24.2.6. Adequacy of Application

This section assesses whether the colloidal actinide source term conceptual model is applied into an acceptable overall performance modeling element. As discussed previously, this complex model has many variables concerning the four colloid types that are merged in. There is a well-documented data base for colloids both from the laboratory experiments specific to WIPP and journal articles. Such a series of articles has served well as a foundation for the model. As an input to the mathematical code NUTS, this conceptual model would present its results in a lookup table. The table takes into account brine compositions, proportionality constants, and oxidation state potentials, all of which allow a very robust model to be applied to the performance assessment modeling elements. The true unknowns are to be found in the assumptions that the chemistry rapidly approaches equilibrium, that the microbe culture is well known, and that the waste has uniform characteristics and inventory. These fundamental assumptions are a basis of the conceptual model and are most probably adequate and reasonable.

3.24.2.7. Accuracy of Results

Draft portions of the lookup tables were provided to the Panel by a Principal Investigator for the conceptual model. If one assumes that the dissolved actinide concentration values are accurate, that the brine stays buffered at a pH of 9-10 due to the addition of MgO, and that the other assumptions mentioned are valid, then the results of the colloidal actinide conceptual model are felt to be reasonably accurate.

The only qualification to this opinion is that the results may be too conservative. To assume concentrations no greater than detection limits of analytical equipment is deemed reasonable by regulatory agencies. However, this method may easily produce inflated values (as applied to intrinsic colloids and mineral fragments). To allow an order of magnitude increase greater than the experimental detection limit for mineral fragments is probably extreme and not truly representative of the chemical system involved.

The one remaining piece of information needed to thoroughly qualify the accuracy of the results would be a series of sensitivity analyses. These results are not currently available.

3.24.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Colloidal Actinide Source Term conceptual model in the modeling framework are valid. Since this model is inexorably linked to the solubility concentrations of the dissolved actinide source term, one may conclude that this model is valid contingent on the validity of the other model (which was determined to be valid, with minor caveats). The overall decision of outcome validity is made slightly more difficult by the fact that the final complete table (6-10) and appendices (PAR and MASS) of the CCA have not been supplied as of this date. If those pieces of information not yet available are reasonable and adequate in their content, then it is sufficient to determine that the conclusions of this model as they apply to the full system, are valid.

3.24.2.9. Adequacy for Implementation

The Colloidal Actinide Source Term model is a reasonable, if somewhat overly conservative representation of how actinides would sorb onto colloids in the two major brines (Salado and Castile) available for the repository. This conceptual model is adequate to support performance assessment. However, this model is closely linked to the Chemical Conditions model (see discussion in Section 3.22 on MgO backfill).

For the sake of completeness and accuracy, the uncertainties listed in Section 3.24.2.4 that would benefit from more supporting evidence are:

- Pu intrinsic colloids are presumed to act like mineral fragments with time, but this assumption is not adequately supported.
- Colloid site densities on microbes have not been thoroughly characterized.
- Humic acid colloids are presumed to behave like dissolved actinides, but this assumption is not adequately documented.

3.24.2.10. Dissenting Views

There were no dissenting views for this model.

4.0 INTEGRATION OF CONCEPTUAL MODELS IN PERFORMANCE ASSESSMENT

For the 24 conceptual models evaluated in Section 3.0 to be collectively useful, they must be integrated into a performance assessment model that adequately represents repository performance. The following paragraphs present a structure (reminiscent of the CCA, performance assessment code sequence) within which conceptual model integration can be illustrated and discussed. The discussion addresses criteria used for the individual conceptual model evaluations in Section 3.0. Since conceptual models are not directly used in the performance assessment, the integration of these models is, in itself, a concept equal in significance to the 24 conceptual component models.

Conceptual models provide the definition of the scope and limits of the issue addressed, define processes, enumerate variables, and provide a framework for consideration of sensitivities within an integrated system definition. The conceptual model specifies the analytical formulations to be used in numerical modeling and their relationships. Process linkages and parameter sensitivities provide a basis for data base planning and data sufficiency assessment. The conceptual model supports judgments used in generalizing data distributions for populating numerical models and supports qualitative judgments like those in the FEP process. A well established and clearly validated conceptual model for each issue is a strong element in the global integration of the overall performance assessment of a site and facility. A robust set of conceptual models for an integrated set of valid issues is the best possible control of site characterization work scope and costs.

The degree of development of conceptual models and their integration within the investigation of issues varied strongly among the models reviewed. In some cases the conceptual model and estimates based on theoretical constructs suggested by the model provided most of the information on which the review was based (for example, the Salado flow model). In some cases no conceptual model relating processes and properties to test results at a useful scale could be propounded. Robust numerical models, based on well developed testing data bases and geostatistical treatments, were successfully substituted for conceptually constrained investigations in some cases (for example, Culebra flow model). The degree to which an unquestionably valid, accurate, and precise modeling result is necessary depends on the consequence of uncertainty in any model system. Some elements of the performance model system could be adequately dealt with by assigning an unquestionably conservative result or by sampling between wide limits, based on credible analytical assessment (for example, the model). Generally, the assessment of consequences and the choice of assigned alternatives depend on strong conceptual model formulations. Where conceptual models failed or were not acceptably replaced, the formulation of a clearly defined and

systematic assessment of the relationship between the issue, processes, and data seemed to be missing. The result was sometimes the overanalysis of inadequate or low quality data or the omission of the consideration of key processes, events, or features.

4.1. Model Integration

Figure 4-1 is an illustration of where the various conceptual models represent their system or subsystem within the CCA performance assessment code sequence. BRAGFLO DBR, as illustrated, is a special, short-term application of BRAGFLO related to a drilling intrusion and includes all conceptual model system representations listed under BRAGFLO plus the Direct Brine Release model. The direct brine release element illustrates that the calculated brine volume removed from the repository by a drilling intrusion is input directly to the CCDFGF. The diamond-shaped element illustrated in the figure that receives input from NUTS and directs that input to SECO TP or CCDFGF is a decision point. If a release into the Salado has occurred, the input is directly to the CCDFGF. If the release involves transport to the Culebra, the input is directed to SECO TP. It is possible for a release scenario where NUTS output is directed to both the CCDFGF and SECO TP.

Figure 4-1 illustrates the primary associations among the conceptual models and the key WIPP performance assessment codes. One conceptual model, Chemical Conditions, is shown twice because it provides primary support to both the BRAGFLO and NUTS codes. As shown in the figure, the conceptual models do not all represent their system or subsystem in the same place in the code sequence. The figure illustrates that the conceptual models, as interpreted through the various codes, are ultimately integrated at the CCDFGF where results are prepared. The figure ignores many preparatory and post-process codes and relationships between codes that are not linear and in one direction. For example, while SANTOS is illustrated as related to BRAGFLO and receiving system representation from the conceptual model for Creep Closure, creep closure results from an iterative relationship between gas pressure, compaction, and brine characterizations from BRAGFLO and the porosity surface in SANTOS.

The integration of the conceptual models, therefore, identifies the overall performance assessment model as a complex structure that represents the 24 conceptual models through preparatory, process, flow and transport, presentation, and enabling codes.

4.2. Review of Criteria

Applying evaluation criteria to the integration of conceptual models as a concept in itself, focuses the discussion on summations of the 24 individual conceptual model evaluations. For example,

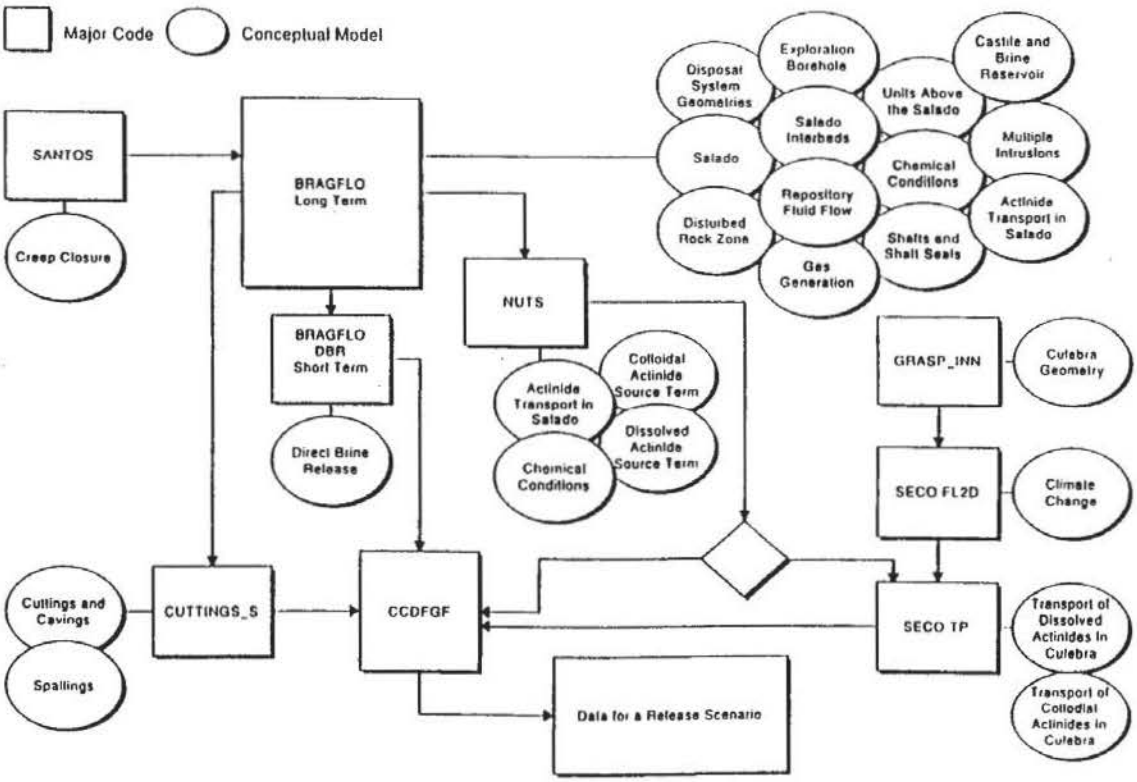

Figure 4.1. Illustration of Conceptual Model Integration

evaluations of information used in the integration, assumptions, uncertainties, adequacies, accuracy, and validity are all based on the individual conceptual models or the implementing mathematical representations or codes. The criteria have already been discussed in Section 3 for the conceptual models and without results of realizations, sensitivity analyses, and uncertainty analyses for the overall system or subsystem, conclusions cannot be made with respect to the implementing mathematics or codes.

Because the overall performance assessment modeling results were not available for Panel review, the overall adequacy for implementation of the integrated conceptual models (PA model) can only be judged at this time through the adequacy of the individual conceptual models. Some of the conceptual models are adequate but there is insufficient information (e.g., results, analysis) for the implementing structure (mathematical representations, codes, code sequence) to be judged adequate or inadequate.

5.0 SUMMARY OF EVALUATIONS

This section presents a summary of the evaluations of the WIPP Conceptual Models Peer Review Panel performed between April 2, 1996 and June 28, 1996. Over 20 years of scientific effort have been expended on the WIPP characterization project and it is beyond the scope of this report to summarize all of the positive factors and scientific evidence compiled. This section is not intended to be a reiteration of comments and discussions on the 24 individual conceptual models, but instead to provide an overview of conclusions from the evaluations. For those models found to be inadequate, the key concerns of the Panel are summarized. With the acceptable resolution of those concerns, the Panel may find most of the models to be adequate. The Culebra Hydrogeology and Units Above the Salado models are exceptions, as discussed below. The Panel's evaluations were made as a best effort over a short period of time when some models were in final development and supporting information was in flux, and therefore it is possible that some key information was available but overlooked.

Of the 24 models reviewed, 13 were found to be adequate for implementation in performance assessment for the WIPP. For most of the adequate models, minor Panel concerns remain and are identified in Section 3. These concerns primarily address issues of documentation gaps and issues with features, events, or processes that were not considered sufficiently important to find the model inadequate. The thirteen models found to be adequate are listed below.

1. Disposal System Geometry
2. Salado
3. Impure Halite
4. Disturbed Rock Zone
5. Actinide Transport in the Salado
6. Transport of Dissolved Actinides in the Culebra
7. Cuttings/Cavings
8. Multiple Intrusions
9. Climate Change
10. Creep Closure
11. Shafts and Shaft Seals
12. Dissolved Actinide Source Term
13. Colloidal Actinide Source Term

The 11 models found to be inadequate are presented in the following paragraphs with a brief discussion of the key concerns identified by the Panel. Comprehensive discussions of each of these models are presented in Section 3.

Culebra Hydrogeology

- No conceptual model was developed that explains the variability of hydrologic properties and processes in the Culebra at a scale that is useful in correlating those properties in the numerical hydrologic flow model.

- An extensive hydrologic testing data base and an apparently adequate numerical flow model were developed as a substitute for performance assessment purposes.

Although the Culebra Hydrogeology conceptual model was found to be inadequate to support numerical modeling, this inadequacy was inconsequential for performance assessment because an extensive hydrologic data base was developed and serves as an adequate substitute to support numerical modeling.

Repository Fluid Flow.

- The conceptual model and its two-dimensional numerical implementation may unrealistically restrict brine movement within the repository to the anhydrite interbeds because of the shallow depths of the borehole and shaft model cells. These restrictions could result in underestimating brine migration in the interbeds toward the accessible environment.

- The conceptual model and its two-dimensional numerical implementation do not include the presence of the unplugged ERDA-9 borehole within the wall of the operations area. This borehole could provide a pathway for gas and possibly brine to the ground surface, and no description of the plugging plan for this hole was seen in the documentation provided to the Panel.

- The sensitivity of model results to the selection of constant permeability values for the waste, panel seals, and repository DRZ has not been evaluated for the current performance assessment. Early time permeabilities may be significantly greater than the model parameter for each of these media, and could lead to underestimating radionuclide releases.

- The long-term performance of the panel closure seals has not been subjected to a detailed engineering evaluation of the type performed for the shaft seals. The role of the panel seals in restricting brine flow among the waste panels and into other parts of the repository is an important element of the conceptual model and its implementation in performance assessment.

Salado Interbeds.

- The conceptual model does not consider how the physical properties of the bounding clay seams affect model fracture propagation and permeability. Ignoring the characteristics of the

clay seams may significantly overestimate the threshold pressure at which repository gases may be released.

Units Above the Salado.

- The conceptual models and the testing data base are inadequate to exclude the Dewey Lakes Redbeds and the Magenta Dolomites as potential transport pathways for radionuclides in the event of an intrusion.

- The analysis of brine flow in the intrusion scenarios limits the quantity of radionuclides reaching the region above the Culebra to such small amounts that transport in the Dewey Lakes and Magenta have negligible consequences.

The Units Above the Salado conceptual model was found to be inadequate to support the assumption that the Culebra is the only horizon above the Salado capable of significant radionuclide transport. This inadequacy was inconsequential for performance assessment because of modeling results indicating that long-term fluid flow in exploration boreholes above the Culebra was negligible because of relatively high permeability and low pressure in the Culebra.

Transport of Colloidal Actinides in the Culebra.

- The conceptual model does not adequately support the assumption that dissolved actinides will not interact with Culebra colloids. Ignoring this phenomenon could overestimate the travel time calculated for radionuclides to reach the accessible environment.

- The experimental K_ds determined for this model are not fully defensible. Such values may overestimate the retardation of actinides in the Culebra.

- Recent experimental work to support assumptions and data for this model has not yet been published and was not available for Panel review.

Exploration Boreholes.

- The potential for releases or changes in repository conditions from borehole penetrations in the operations and experimental areas of the repository does not appear to have been evaluated. Radionuclides that may have migrated into those areas through the panel closures by diffusion or other transport mechanisms could be released to the ground surface, and gas pressures could be relieved by such boreholes. Also, brine could migrate into those areas from a borehole and then into the waste panels.

- The assumption that shorter (40 m) borehole plugs beneath the repository horizon will not significantly degrade during the 10,000-year regulatory time frame has not been adequately supported. For the two- and three-plug configurations, degradation of these plugs could result in creation of a low permeability pathway for fluid migration between the Bell Canyon and the repository. For the three-plug configuration, degradation could result in increased fluid migration from a Castile brine reservoir to the repository.

- The possibility that an effect on the repository could result from Castile brine encountered in an E1 borehole that is assigned a three-plug configuration does not appear to have been considered in the conceptual model. Castile brine could enter the repository during drilling before the borehole is cased and result in increased rates of corrosion, waste degradation, and gas production.

- The sensitivity of the performance assessment to the simplified approach taken to determine reference conditions for BRAGFLO output does not appear to have been evaluated for the current model configuration. If reference conditions are not provided at sufficiently frequent time intervals, the modeling results may be erroneous.

Spallings.

- The conceptual model for channel flow of gases toward an exploratory borehole appears to be valid but has not been adequately evaluated. Spallings is a potentially important mechanism for direct waste release to the ground surface.

- The conceptual model for waste erosion by flowing gases has not been adequately defined. The model describing the source(s) of waste erosion resistance and the parameter(s) characterizing that resistance have not been adequately evaluated. Errors in this conceptual model could lead to overestimating or underestimating the volume of waste released in the spallings process.

- The waste has not been adequately characterized and the understanding of its physical properties in its decayed state has not been adequately developed to support the Spallings model. An adequate understanding of waste erosion processes requires an adequate understanding of the properties of the waste.

Direct Brine Release.

- The basis for the assumption that radionuclides do not accompany the direct discharge of Castile brine has not been adequately supported. This assumption could lead to underestimating radionuclide releases.

- Radionuclide transport through entrainment of brine and waste solids in rapid, two-phase liquid/gas releases during inadvertent borehole intrusions does not appear to have been evaluated. This transport mechanism may be an important component of the conceptual model.

- Releases resulting from flow into an exploration borehole intersecting a disturbed rock zone in the wall of a waste panel do not appear to have been evaluated. Large, open fractures in the walls could significantly increase the local halite permeability, allowing gas and brine to migrate through the borehole to the ground surface.

Castile and Brine Reservoir.

- The basis for excluding larger, potentially depressurized brine reservoirs from performance assessment has not been adequately supported. Larger reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

- The basis for the concept of reservoir depletion through previous borehole penetrations has not been adequately supported. Non-depleted reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

- The expected probability of encountering pressurized brine beneath the waste panels has not been adequately supported, nor has the basis for apparently ignoring the quantitative value of site-specific geophysical data been presented. Unrealistically low probabilities of encountering brine may result in underestimating radionuclide releases.

Gas Generation.

- The conceptual model does not consider aluminum in the waste, steel in the rock bolts and netting, radiolysis of water by undissolved alpha emitters, and radiolysis of plastics and cellulose as sources of additional hydrogen, oxygen, and other gases. Ignoring gases generated by these effects could result in underestimating the gas pressure in the repository.

- An adequate basis has not been presented for the assumption of complete and rapid carbon dioxide removal by magnesium oxide in the waste panels. The chemical conditions in the repository would significantly change if the magnesium oxide did not function as planned, and could result in higher radionuclide releases than the model would estimate.

- An adequate basis has not been presented for ignoring the effects of heat generation from corrosion and microbial action. Higher ambient repository temperatures could increase the rates of chemical reactions, fluid flow, and halite creep.

Chemical Conditions.

- The combined temperature increase (due to radioactive decay and exothermic reactions) and its effect on repository conditions has not been adequately addressed. Significantly higher repository temperatures could accelerate chemical reactions, fluid flow, and halite creep rates.

- Phase equilibria have not been critically assessed within the chemical parameters of the conceptual model. A major element stable phase that was overlooked could significantly alter the chemical conditions of the repository and vary the actinide source terms.

- The MgO backfill has not been demonstrated to be able to react completely with CO_2 generated by microbial action. If the MgO backfill did not react as planned, the pH-buffering capability of the repository would be significantly compromised, and could result in underestimating the actinide source terms.

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APPENDIX A - PANEL MEMBER INFORMATION

John Gibbons, Panel Member, is an independent geosciences consultant residing in Albuquerque, New Mexico. Dr. Gibbons has a Ph.D. in Geology from Syracuse University and Bachelors and Masters Degrees in Geology from the University of Arkansas. Dr. Gibbons has over 25 years of experience consulting to the nuclear industry and regulators. He has been involved since 1965 in several research and field studies of the behavior and geology of bedded salt deposits. He presently is a principal consultant to the Illinois Department of Nuclear Safety in its effort to license a low level nuclear waste disposal facility. His duties include the review of and contribution to work by world class contractors, national laboratories, and state scientific surveys in all aspects of site selection, characterization, and performance assessment. Dr. Gibbons has been a principal investigator for hydrogeology in many low level nuclear waste and uranium mine and mill tailings projects in the southwestern United States since 1976.

Darrell D. Porter, Panel Member, is a Senior Scientist and Manager with Science Applications International Corporation (SAIC). He has a Ph.D. in Mineral Engineering with a specialty in rock mechanics from the University of Minnesota. His M.S. degree from the Colorado School of Mines focused on experimental work in dynamic aspects of rock mechanics. He has 34 years of experience. Much of Dr. Porter's work has been in the field of blasting with high explosives and analyzing effects from a rock mechanics perspective. He has held technical management positions with the Rio Blanco Oil Shale Company where significant testing results paved the way for an effective process development resulting in four patents for Dr. Porter. During the past 13 years, Dr. Porter has supported the U.S. Geological Survey in their site characterization program for the Yucca Mountain Project. The work there included technical reviews, preparation of technical procedures, geological mapping programs, oversight of numerous contributing scientists involved in geologic sampling, mapping, modeling, technical data management, and preparation and implementation of quality assurance programs. He has collaborated with scientists from many of the National Laboratories and Universities on rock fracture and fragmentation issues.

Florie Caporuscio, Panel Member, is a Senior Scientist for Informatics Corporation. He received his Ph.D. in Geology from the University of Colorado, a Masters degree in Geology from Arizona State University, and a Bachelors degree in Geology from the University of Massachusetts. Dr. Caporuscio has 10 years of experience as a geochemist working on issues relating to high level and transuranic waste disposal.

Eric B. Oswald, Panel Member, is a Senior Scientist/Hydrologist-Water Resources Planning Specialist with the Morrison-Maierle Environmental Corporation in Tucson, Arizona. Dr. Oswald has a Ph.D. in Hydrology and Water Resources Administration and a Bachelors degree in Agricultural Economics, both from the University of Arizona. Dr. Oswald has over 25 years of experience relating to mine permitting, hazardous material contamination, flood control and flood plain design, resource damage and conservation, power generation, salinity, solid waste management, and water management. Dr. Oswald has managed many environmental programs for federal and state agencies, and municipalities.

Charles R. Wilson, Panel Technical Coordinator, has 26 years of experience managing a broad range of projects involving hydrogeology and geotechnical engineering, water resources planning, and environmental contamination. Dr. Wilson is a private consultant residing in New Mexico. He has a Ph.D. in Civil Engineering-Groundwater and a Masters degree in Geotechnical Engineering from the University of California at Berkeley. He received his Bachelors degree in Engineering from the University of California at Los Angeles. Dr. Wilson's work has included designing and conducting large scale hydrologic tests in very low permeability, fractured rock; design and regulatory permitting of large mixed radioactive/hazardous waste landfills; development of a national water resources planning agency for the Republic of the Philippines; and design of a site-wide groundwater monitoring system for the U.S. Department of Energy's Idaho National Engineering Laboratory.

Glen Sjoblom, Panel Member, is an independent consultant in the areas of nuclear waste management and safety management, residing in Great Falls, Virginia. He has a Master of Science in Chemical Engineering from University of California, Berkeley, a Bachelors of Science in Chemical Engineering from University of Minnesota, a Certificate in Nuclear Engineering from Bettis Atomic Power School, Pittsburgh, and a Certificate from the Course for Senior Managers in Government, JFK School, Harvard University. His graduate thesis dealt with two phase flow for heat and mass transfer; his undergraduate research dealt with solid liquid state chemical reaction kinetics. He was an officer in the United States Navy. He has held senior technical management positions in four different Federal Agencies over a thirty-year period, in Washington, D.C. He was responsible for the environmental controls aspects of the Naval Nuclear Propulsion Program, while on active Naval Service, including radiation protection, waste management, and environmental monitoring. He was Director of the Office of Radiation Programs at the Environmental Protection Agency, and directed development and promulgation of environmental standards for high level and transuranic waste, uranium mill tailings, Presidential Guidance to Federal Agencies on Occupational Radiation, and improved emergency response capability. He directed improvements in safety regulation and enforcement over nuclear fuel cycle facilities, industrial and

medical uses of radioactive materials, promoted improved cleanup of deactive nuclear facilities, and improved interagency coordination on chemical safety, while a Deputy Division Director at the Nuclear Regulatory Commission. He directed formation of an Environmental Management Advisory Board, and focused on improved public involvement and the use of risk assessment science in environmental restoration and waste management programs, while a Special Assistant Secretary for Environmental Management, Department of Energy. Throughout his career he has utilized risk assessment modeling and methods to promote sound decisions in the public interest.

DETERMINATIONS OF PEER REVIEW MEMBER INDEPENDENCE

C.R. Wilson

Determination of Peer Review Member Independence Form

___ Currently employed by DOE or DOE Contractor? Yes/No

X Employed by DOE or DOE Contractor previously? (Yes)/No

If yes, give dates, location, company, position type work performed.

1978 - 1983 U. of California Lawrence Berkeley Laboratory - Performed field hydrology study of Hanford Site

1983 - 1985 Hydrotechnique Inc, Berkeley CA - Performed consulting services to Hanford Site

1986 - 1996 Golder Associates Inc - Albuquerque NM - Performed consulting services to Hanford, INEL, Los Alamos Sites

___ Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Charles R Wilson

Date: 3/29/96

Peer Review Manager Approval: John A. Thies 4/8/96 Date

Darrell Porter

Determination of Peer Review Member Independence Form

Yes — Currently employed by DOE or DOE Contractor? Yes/No
yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

SRIC, my employer, has been active as a DOE Contractor for many years. To date I have had no work or other relationship to work on the DOE WIPP Programs.

NO — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Darrell Porter

Date: March 29, 1996

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

E.B. Oswald

Determination of Peer Review Member Independence Form

No — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

April through August, 1995. Albuquerque, N.M. S.M. Stoller Corporation. Served as Independent Review Team member assisting WIPP WTAC in the review of data record packages.

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

N/A

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: E.B. Oswald

Date: 3/30/96

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

Florie Caporuscio

Determination of Peer Review Member Independence Form

Yes — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

4/96 Informatics, Albuquerque NM, staff consultant Peer Review of WIPP

8/95 – 3/96 Advanced Sciences Inc, Los Alamos Office, Project Manager and Senior technical Lead, Environmental Restoration Project

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical. I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Florie A. Caporuscio

Date: 4/1/96

Peer Review Manager Approval: John A. Thies — 4-1-96 Date

Glen Sjoblom

Determination of Peer Review Member Independence Form

1. Currently employed by DOE or DOE Contractor? Yes/No
2. Employed by DOE or DOE Contractor previously? Yes/No

See below

If yes, give dates, location, company, position type work performed.

1. I have a contract with Oak Ridge Institute for Science and Education to provide an assessment of effectiveness of DOE office of Nuclear Energy Program of Assistance of nuclear reactor safety to Former Soviet Countries; this has no bearing on the proposed peer review at WIPP.
2. I was a special assistant to the Asst. Secy for Environmental Management but was not involved with activities at WIPP.

NO. Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Glen L. Sjoblom

Date: 3/29/96

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

John Gibbons

Determination of Peer Review Member Independence Form

NO — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

Battelle Alb., IRT reviewer of WIPP Data Packages 1994-1995
AFA, Alb. Site Characterization Technology Research 1992-1993
SNL Civil Systems Inc., High Level WIPP Experiment Planning
1977-1978

NO — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: [signature]

Date: NOV 29/96

Peer Review Manager Approval: [signature] John A. Thies — 4/8/96 Date

CERTIFICATIONS REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

C.R. Wilson

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer _____

Name of Offeror:_____ Signature Charles R. Wilson

Date Signed: 3/29/96 Typed name CHARLES R. WILSON

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Darrell Porter

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer 3/29/96

Name of Offeror: DARRELL PORTER Signature Darrell Porter

Date Signed: April 2, 1996 Typed name_____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

E.B. Oswald

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer 4/1/96

Name of Offeror:_____ Signature [signature]

Date Signed: _____ Typed name Eric B.Oswald

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Florie Caporuscio

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer 3/25/96

Name of Offeror: Florie A Caporuscio Signature Florie A Caporuscio

Date Signed: 4/1/96 Typed name_____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

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(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

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(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Glen Sjoblom

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No _____ Date of Offer 3/25/96

Name of Offeror: Glen L. Sjoblom Signature Glen L Sjoblom

Date Signed: 3/29/96 Typed name _____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

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(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If 'yes' provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

John Gibbons

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer _____

Name of Offeror: John Gibbons Signature _____

Date Signed: Mar 29/96 Typed Name_____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (✓) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (✓) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (✓) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (✓) No

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(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

APPENDIX B - SIGNATURE PAGE

I acknowledge by my signature below that I concur with the findings and conclusions documented in this Conceptual Models Peer Review Report.

Florie Caporuscio

John Gibbons

Eric Oswald

Darrell Porter

Glen Sjoblom

Charles Wilson

II-G-12: Conceptual Models Supplementary Peer Review Report. December 1996

A Peer Review
Conducted By

Charles Wilson, Darrell Porter, John Gibbons,
Eric Oswald, Glen Sjoblom, Florie Caporuscio

for

U.S. Department of Energy
Carlsbad Area Office
Office of Regulatory Compliance

December 1996

EXECUTIVE SUMMARY

This report is a supplement to a July 1996 report that presented the results of an independent technical peer review of the adequacy of 24 conceptual models representing features, events, and processes involved in assessing the long-term performance of the Waste Isolation Pilot Plant (WIPP). WIPP has been developed at a site near Carlsbad, New Mexico, to become the nation's geologic repository for disposal of transuranic waste resulting from nuclear weapons programs. This independent peer review is required by 40 Code of Federal Regulations 194.27 as part of the Compliance Certification Application prepared by the U.S. Department of Energy (DOE). The U.S. Environmental Protection Agency (EPA) will use the peer review to help ensure that an adequate scientific foundation exists for a national decision on whether to dispose of this waste at WIPP.

The peer review was initially conducted from April through June 1996 at the DOE Sandia National Laboratories by a six-member interdisciplinary Review Panel having the requisite broad experience to address the range of issues associated with waste isolation over the 10,000-year regulatory time frame. The Panel selection process and the biographies of the Panel members are included in the July 1996 report.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical processes, or intrusion scenarios, are represented in the performance assessment. The Panel originally reviewed in detail the 24 conceptual models against the criteria of the EPA and NUREG 1297, including the scientific information used to develop the model, the assumptions, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The Panel then determined whether the conceptual model is adequate for

implementation in the overall performance assessment model.

In its July 1996 report, the Panel concluded that of the 24 conceptual models, 13 were adequate for implementation, and 11 were not adequate for implementation based on the Panel review of the available information and the stated EPA criteria.

In this supplementary report, the Panel provides the results of a review of the DOE responses to the Panel findings in the July 1996 report, additional information available since the earlier report (including the Compliance Certification Application) and changes that were made to eleven of the models. Following is a list of the 24 conceptual models and a statement of the Panel's current conclusions.

Disposal System Geometry	Adequate
Culebra Hydrogeology	Adequate*(1)
Repository Fluid Flow	Adequate*(2)
Salado	Adequate
Impure Halite	Adequate
Salado Interbeds	Adequate
Disturbed Rock Zone	Adequate
Actinide Transport in the Salado	Adequate
Units Above the Salado	Adequate*(3)
Transport of Dissolved Actinides in the Culebra	Adequate
Transport of Colloidal Actinides in the Culebra	Adequate
Exploration Boreholes	Adequate*(4)
Cuttings/Cavings	Adequate
Spallings	Not Adequate
Direct Brine Release	Adequate*(5)
Castile and Brine Reservoir	Adequate*(6)
Multiple Intrusions	Adequate
Climate Change	Adequate

Creep Closure	Adequate
Shafts and Shaft Seals	Adequate
Gas Generation	Adequate
Chemical Conditions	Not Adequate
Dissolved Actinide Source Term	Adequate
Colloidal Actinide Source Term	Adequate

The Panel continues to find two of the models to not be adequate, and six additional models to be adequate on the basis that there appears to be little consequence on performance assessment. For the two models found not adequate, Spallings and Chemical Conditions, the remaining issues could have a significant effect on predictions of the future state of the repository. The details of evaluations and responses to previous issues are contained in Section 3 of this supplementary report. Section 4 assesses the integration of the 24 models, and a summary of the remaining issues is contained in Section 5.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Conceptual Models Peer Review Panel issued its report in July 1996. The peer review was conducted in accordance with the regulatory requirements of 40 Code of Federal Regulations (CFR) 191 and the implementation of those requirements by 40 CFR 194. The Department of Energy (DOE) included the Conceptual Models Peer Review Report as part of its Compliance Certification Application (CCA) for WIPP that was submitted to the Environmental Protection Agency (EPA) in late October 1996.

In the Conceptual Models Peer Review Report of July 1996, 24 conceptual models were evaluated using the evaluation criteria specified by the EPA, including those of NUREG 1297. The Panel report identified thirteen conceptual models as adequate for implementation in WIPP Performance Assessment (PA) and eleven as not adequate for implementation, based on information available to the Panel. The Panel findings on each of the models judged inadequate were provided in the report. Since the Panel report was issued, DOE has developed additional information and made changes to some of the conceptual models. The DOE has also prepared responses to the findings in the Conceptual Models Peer Review Report of July 1996.

The DOE reconvened the Panel in October 1996 to review the changes to the conceptual models, the DOE responses to the findings in the July 1996 Panel report, and information available in the CCA. This report therefore supplements the July 1996 report. It is noted that preliminary DOE responses to the Panel findings were informally provided to some of the Panel members, and DOE may have reached some preliminary conclusions based on this informal

process. However, the Panel considers any such DOE conclusions as not dispositive of the Panel findings. This report contains the only definitive Panel review of the DOE responses.

Section 2 of this report describes the process for this supplementary review. For each of the 24 conceptual models, Section 3 describes any identified changes to the models and additional significant results that are important to model evaluation, as well as the DOE responses to the findings and the Panel review of those responses. Section 3 also includes any remaining findings identified, as well as the Panel conclusions on the impact of these findings on the performance assessment. Section 4 of the original report contained a discussion of the integration of the 24 models into an overall conceptual model for the waste disposal system, and Section 4 of this supplementary report provides additional discussion of model integration in the performance assessment based on the additional information now available. Section 5 provides a summary of the supplementary review including any issues remaining to be addressed. Section 5 is followed by administrative information and references. Professional biographies of each of the Panel members are included in the July 1996 report.

2.0 SUPPLEMENTARY REVIEW PROCESS

The supplementary review was conducted in accordance with DOE Quality Assurance requirements at Sandia National Laboratories (SNL) during the period October 1996 to December 1996. The Panel was provided access to written responses to earlier Panel findings, briefings and written material on changes to some of the models, results of sensitivity studies to determine the most important processes and parameters, and the final CCA, including appendices and referenced reports, as well as other information in draft form for work in progress. All this added information supplemented the information available to the Panel at the time of preparation of its July 1996 report.

This supplementary review utilized the same review criteria to judge the acceptability of conceptual models as in the July 1996 report. In the July 1996 report and in this supplementary report, a finding of adequacy was reached if any of the following were valid: (1) the model was judged technically adequate to describe the future states of the disposal system over the 10,000-year regulatory period using the EPA technical criteria; (2) adequately conservative assumptions were made for key input parameters for which a firm technical basis could not be established; or (3) the conceptual model was determined to be inconsequential to the results of performance assessment.

3.0 MODEL EVALUATIONS

3.1. Disposal System Geometry

The manner in which the dimensionality of engineered systems and surrounding geologic/hydrogeologic formations is presented in relevant chapters of the October 1996 CCA

remains substantively unchanged from previous information. Minor changes observed in the October 1996 CCA include discussions of additional intrusion scenarios and editorial inclusions that do not change the conceptual model or its adequacy. The issue raised in Section 3.1.2.2 of the July 1996 Conceptual Models Peer Review Report remains deferred to the Repository Fluid Flow conceptual model discussions in Section 3.3 of this supplementary report.

3.2. Culebra Hydrogeology

3.2.1. Model Description

No changes have been identified to the Culebra Hydrogeology model as compared to the Panel's understanding of it from the original review. An error was identified in the application of the Culebra numerical flow model which consisted of a failure to change a boundary condition from no-flow to flow at the northeast corner of the modeled area during PA calculations. This region is an area of low transmissivity, making the change a very small one. Subsequent PA calculations showed no discernible impact from this small change.

3.2.2. Review of Criteria

The review of criteria of the Culebra Hydrogeology model remains unchanged.

3.2.3. Review of Responses to Panel Findings of July 1996

3.2.3.1. Summary of Findings

The Conceptual Models Peer Review Panel found that the Culebra Hydrogeology conceptual model, though it provided support for regional hydrogeologic interpretations and model boundary conditions, did not explain the variation of hydrologic properties in the Culebra at a scale useful for flow modeling at the site scale. Although the conceptual model could not be implemented to support flow modeling at the site scale, an areally extensive hydrologic testing program at numerous sites over a significant time period had been carried out. This testing program provided the database for apparently adequate numerical flow models of the site and the site region. On the basis of the existence of these flow models, the failure of the conceptual model to provide a basis for the detailed interpretation of the hydrogeology of the Culebra was found to be without consequence to facility performance assessment.

3.2.3.2. Summary of DOE Responses to Findings

The DOE responded to the findings of the Peer Review Panel by providing extensive additional information supporting the validity of the site and site region numerical hydrologic flow models. The additional information was mostly contained in Appendix TFIELD and in results of the performance assessment calculations, which permitted the comparison of head fields based on data supplemented by the generation of pilot points and the GRASP INV code with the original measured data. These documentary sources were supplemented by presentations by and

conversations with SNL project personnel and contractors.

3.2.3.3. Panel Review of Responses

Appendix TFIELD contains an extensive explanation of the integration of regional hydrogeological concepts and the results of hydrologic testing to define general model boundary conditions, regional fields of hydrologic property variation, and preliminary fields of similar transmissivity. The measured data in transmissivity fields were augmented by the development of pilot points and Kriging, and flow model (1996 Culebra model) grids were populated following calibration (PAREST).

Measured and generated transmissivity values within each T field were sampled for PA calculations and maps, and the Panel reviewed 100 PA realizations of the head field maps for the unmined case. These were compared to the original testing measurements and to the United States Geological Survey (USGS) head field maps (Mercer 1983). The PA maps were well behaved, that is, there were no significant differences among the 100 maps reviewed, and they compared well to the original data and to the USGS maps based only on that data. This was despite the fact that the proportion of pilot points to actual data points was fairly high and that the number of adjustment steps to each point was limited. The vertical leakage to the Culebra from the overlying stratigraphic units was ignored because of the under-pressured state of the Culebra. Climatic change might make vertical leakage a significant factor in Culebra hydrology.

Detailed discussions were presented by SNL about the methods of determining the K_ds used in the range of values sampled for performance assessment and the Culebra retardation flow scenarios. The K_d values appear to be reasonable and the definitions of flow mechanisms are reasonable and typical of reflux dolomites. The proportion of flow ascribed to fractures (advection) and that to intercrystalline and intracrystalline matrix porosity (diffusion) appears to be uncertain and incompletely supported. This is in part a result of the lack of a complete hydrogeologic model and in part a function of the narrow range of inter-well distances in the multiwell tests. The scale of fracture length and the anisotropy of the fracture field are important factors in mid-distance transport, but are not likely to affect transport between the panel areas and the site margins.

In summary, it can be said that the Culebra numerical hydrologic flow model produces results that match the results of hydrologic testing well. The methodology used for generalizing the database over the T fields, the conceptual hydrologic support for the model, and the number and distribution of hydrologic tests in space and in time lend mutual support to the reasonableness of the model results. The results of the numerical flow model in performance assessment are reasonable and adequate with respect to their role in assessment of transport of radionuclides through the Culebra.

3.3. Repository Fluid Flow

3.3.1. Model Description

No changes have been identified in the Repository Fluid Flow model, and the description of the model remains unchanged.

3.3.2. Review of Criteria

The review of criteria for the Repository Fluid Flow model remains unchanged.

3.3.3. Review of Responses to Panel Findings of July 1996

3.3.3.1. Summary of Findings

The following key concerns were identified in the July 1996 Panel report for the Repository Fluid Flow model.

- The conceptual model and its two-dimensional numerical implementation may unrealistically restrict brine movement within the repository to the anhydrite interbeds because of the shallow depths of the borehole and shaft model cells. These restrictions could result in underestimating brine migration in the interbeds toward the accessible environment.

- The conceptual model and its two-dimensional numerical implementation do not include the presence of the unplugged ERDA-9 borehole within the wall of the operations area. This borehole could provide a pathway for gas and possibly brine to the ground surface, and no description of the plugging plan for this hole was seen in the documentation provided to the Panel.

- The sensitivity of model results to the selection of constant permeability values for the waste, panel seals, and repository disturbed rock zone (DRZ) has not been evaluated for the current performance assessment. Early time permeabilities may be significantly greater than the model parameter for each of these media, and could lead to underestimating radionuclide releases.

- The long-term performance of the panel closure seals has not been subjected to a detailed engineering evaluation of the type performed for the shaft seals. The role of the panel seals in restricting brine flow among the waste panels and into other parts of the repository is an important element of the conceptual model and its implementation in performance assessment.

3.3.3.2. Summary of DOE Responses to Findings

The initial DOE response to the first concern (potential restrictions to brine flow resulting from shallow cell depths in the two-dimensional BRAGFLO model) cites a similarity in fluid movement between the waste panels and the anhydrite interbeds and between other key macroscopic properties as predicted by the two-dimensional model and its three-dimensional

counterparts (see FEP Screening Analysis S-1: Verification of 2D-Radial Flaring Using 3D Geometry, SWCF-A: 1.2.07.3: PA:QA:TSK:S1, February 19, 1996). In subsequent discussions, additional information was obtained from DOE on cumulative brine flow into the repository under undisturbed conditions.

In responding to the second concern, the DOE indicated that deep, unplugged boreholes within the Land Withdrawal Area, including WIPP 13, WIPP 12, ERDA 9, and DOE 1, will be plugged with a solid concrete plug through the salt section and any water-bearing horizon.

Separate responses were provided by the DOE for each aspect of the third concern (selection of constant permeabilities in the repository). For the waste, the effect of time-varying permeability was studied and found to have an insignificant effect on key waste room conditions (see FEP Screening Analysis DR-7: Permeability Varying with Porosity in Closure Regions, SWCF-A:1.1.6.3:PA:QA:TSK:DR-7, September 28, 1995). A similar study was performed for the DRZ and a similar conclusion was reached (see FEP Screening Analysis S-6: Dynamic Alteration of the DRZ/Transition Zone (TZ), SWCF-A: 1.1.6.3:PA:QA:TSK:S-6, December 21, 1995). For the panel seals, DOE considered that repository performance will not be sensitive to the expected permeability of 1×10^{-15} m^2 or lower because flow would be diverted through the surrounding higher permeability DRZ. In addition, the concrete panel seals were not expected to significantly degrade because of low brine flux through them. This information was supplemented by subsequent information on DRZ healing and panel seal degradation provided by SNL and Carlsbad Technical Assistance Contractor (CTAC) personnel.

The fourth concern, that of the apparent lack of an engineering design for the panel seals, was addressed by presenting seal design and performance information to the Panel. Chemical degradation of the concrete was found to be minimal; however, failure by surface spalling could occur within the regulatory time frame.

3.3.3.3. Panel Review of Responses

In evaluating the response to the first concern (potential restrictions to brine flow resulting from shallow cell depths in the two-dimensional BRAGFLO model), the Panel did not consider the comparison of two- and three-dimensional model results to be adequate because the analyses included an E2 intrusion at 1,000 years which would have caused radial flow, and because the comparison was based on combined inflows in the two-dimensional model into both the single panel and the “rest of the repository.” This comparison, therefore, included flow into the southern half of the single panel that did not cross the narrow constriction created by the borehole cells. Thus, it did not adequately test the ability of brine to cross that constriction and enter the “rest of the repository,” which constitutes approximately 90% of the waste area volume. A more robust test would have been a comparison under undisturbed conditions of flow to and from the “rest of the repository,” which would have evaluated non-radial flow crossing both the constriction at the shaft and that at the borehole. In addition, the constrictions could potentially introduce a significant systematic bias into the modeling results.

In subsequent discussion of the first concern with SNL personnel, it was recognized that the majority of the rapid, early-time brine flow into the undisturbed repository (up to about 20,000 m^3) occurs because of drainage from the DRZ (Figure 3-1), which is considerably larger than the volume (up to about 6,000 m^3) that results from inflow from all anhydrite interbeds (Figure 3-2). Considering only the shaft constriction, the maximum difference in both repository inflow and outflow between the two-dimensional and three-dimensional model results was identified in the aforementioned FEP S-1 study to be about 1 x 10^6 kg of brine, or about 800 m^3 at a brine density of 1,230 kg/ m^3. If both the shaft and borehole constrictions were considered, the difference is unlikely to exceed 2,000 m^3. This volume is small compared with the approximately 20,000 m^3 that can enter by drainage from the DRZ, and its importance would diminish further in any realization involving an intrusion because the two-dimensional model is designed to simulate the radial flow induced by those intrusions. The influence of the constrictions is significantly greater for brine outflow, where FEP S-1 results indicate that the actual outflow may be on the order of twice that predicted by the two-dimensional model. This is considered conservative, however, because the total outflow volume is relatively small (generally less than 2,000 m^3)

Figure 3-1. Cumulative total brine inflow into the undisturbed repository. Not available.(7)

Figure 3-2. Cumulative brine inflow into the undisturbed repository from all anhydrite interbeds. Not available.(8)

and the presence of extra brine in the repository is expected to increase calculated releases. In view of the relatively small fluid volume involved, this first issue is considered to be adequately resolved on the basis of a lack of consequence. However, if subsequent model modifications result in significantly smaller fluid volumes in the repository, the significance of this issue should be reevaluated.

The response to the second concern (plugging of deep, unplugged boreholes) was considered by the Panel to be entirely adequate.

The response to the third concern (selection of constant permeabilities in the repository) was separately addressed by the Panel for each of the three aspects. For the waste, the key Panel concern was underestimating the permeability in early times, and thereby potentially underestimating radionuclide releases at those times. The performance assessment results have shown that the waste is compressed relatively quickly, within the first few hundred years after closure, during a period when very few intrusions occur because exploratory drilling is minimized by active and passive institutional controls. The consequence of underestimating waste permeability during this period is therefore expected to be small. In later years, when exploratory drilling is more frequent, the waste is expected to have been compressed to the extent that the assigned constant permeability will be appropriate. This conclusion is supported by the aforementioned FEP DR-7 screening analysis.

For the DRZ, the situation is more complex. The assignment of constant permeability to the DRZ is one of the more dramatic departures from actual behavior in the performance assessment

assumptions. While simplification may be justified because of the complexity of DRZ behavior, it is important to evaluate whether the assumed constant permeability is appropriate both in early times, when the actual permeability may be several orders of magnitude greater than the assumed permeability because of fracturing associated with expansion of the DRZ into the repository, and in later times, when the actual permeability may be several orders of magnitude less than the assumed value due to healing of the DRZ under lithostatic stress. In early times, the Panel's conclusions regarding the DRZ are similar to that for the waste. Even though the actual permeability may be higher than the modeled value, closure is expected to be fairly rapid and the DRZ permeability is expected to be reduced to the modeled value by the time significant exploratory drilling occurs. In later times, however, the actual permeability may be overestimated by the model and is not adequately addressed by the aforementioned FEP S-6 screening analysis, which focuses on whether the assumed DRZ permeability is high enough to allow relatively unimpeded flow between the repository and the interbeds. The impact of DRZ healing is separately addressed by the Panel for the DRZs adjacent to the roof, floor, walls, and panel seals.

Long-term maintenance of the relatively high-permeability repository DRZ assumed in the BRAGFLO model is important to performance assessment because it has been found to allow relatively unimpeded gas flow within the repository and between the repository and the interbeds. Such gas flow allows pressures within the entire repository to drop following a drilling intrusion in any part. If each waste panel were more effectively isolated, each drilling intrusion into a new panel would encounter higher, essentially undisturbed gas pressures and significantly greater releases would follow. Because of the importance of repository-wide pressure relief to long-term performance, it is necessary to evaluate the impact of the modeling assumption of constant permeability against the likelihood of DRZ healing to permeabilities several orders of magnitude lower than the assumed value.

The roof DRZ is most important to gas flow because brine that could impede such flow will tend to collect on the repository floor. Although the stress-induced fractures in that part of the roof DRZ consisting of halite are expected to heal to permeabilities approaching those of undisturbed halite, the boreholes drilled vertically through the halite for rock bolts and site characterization are not expected to close during the regulatory time frame because of their favorable orientation and circular shape. Boreholes for roof support are expected to be needed in each panel throughout the waste disposal area, and given the high conductance of an open hole, even a few such holes are expected to provide sufficient communication to the overlying anhydrite interbeds to compensate for the general loss of permeability in the halite. Because of their greater strength and reduced plasticity, deformation in the anhydrite interbeds in the roof DRZ is not expected to heal to the same extent as the halite, but rather, the interbeds are expected to retain permeabilities that are several orders of magnitude higher than their initial values. The permeability value of 1×10^{-15} m^2 assumed in performance assessment is an acceptable approximation of this disturbed anhydrite permeability. It may therefore be concluded that despite the general healing of the halite in the roof DRZ, higher conductivity

flowpaths through boreholes and disturbed anhydrites will remain between the individual waste panels and single intrusion boreholes, supporting the adoption of a constant permeability of 1×10^{-15} m^2 for the roof DRZ.

The wall DRZ is not specifically addressed in BRAGFLO and plays no role in the current performance assessment. This assumption is appropriate because in the waste panels the wall DRZ is expected to heal rapidly as soon as a back stress is applied by the laterally expanding waste. This healing is expected to occur within a few hundred years of closure, during the period of active and passive institutional control.

Healing of the floor DRZ is expected to be incomplete because the high degree of brine saturation in that area will act to maintain a higher porosity as stresses resulting from creep closure are applied. The higher porosity is expected to result in a higher permeability, and the capture of that permeability in the model is important in providing a pathway for brine to enter and exit the repository through the underlying anhydrite interbed.

The panel seals will consist of approximately 8-m long concrete plugs within the approximately 40-m long access drifts to each panel. The plug will provide a relatively strong, unyielding surface against which the surrounding DRZ is expected to rapidly heal. The concrete itself is expected to have an initial permeability of about 5×10^{-17} m^2, while the rest of the drift will remain unbackfilled and will eventually be closed by creeping halite. Although the plug and surrounding DRZ are expected to quickly form a lower permeability impediment to fluid movement than is accounted for in the constant permeability of 1×10^{-15} m^2 assigned to both system components in performance assessment, the aforementioned higher permeability pathway afforded by boreholes and disturbed anhydrites in the roof DRZ are expected to continue to allow movement of gas within the repository.

Performance assessment modeling results have shown that at the assumed permeability of 1×10^{-15} m^2 , brine flow between panels is restricted, limiting direct brine releases to the brine within a single panel. Maintenance of the panel seal at or below this assumed permeability is therefore also important to repository performance. If the ends of the concrete plug remain unsupported, it could degrade within about 4,000 to 5,000 years due to progressive spalling of the ends from a combination of applied stresses and formation of expansive minerals within the concrete. The spall would form a fine-grained residue with an initial permeability of less than 1×10^{-14} m^2 , which is similar to that of a sand-clay mixture. Compaction of this material by an applied lithostatic stress, and the closure of the open drift on either side of the plug by halite creep, provide adequate assurance that the permeability of the materials in the access drifts will remain equal to or less than the assumed value of 1×10^{-15} m^2 during the regulatory time frame. In addition, any lateral confinement of the open ends of the plug by the creeping halite is expected to prolong the life of the plug.

The response to the fourth concern (lack of engineering analysis of the panel seals) was considered by the Panel to be adequate. Although the concrete plug used in the seal may degrade within the regulatory time frame, this degradation is not expected to impair repository

performance as discussed above.

In summary, the Panel has found each of the four key concerns identified for the Repository Fluid Flow model in July 1996 to have been resolved.

3.4. Salado

There were no changes to this model and it continues to be acceptable for implementation.

3.5. Impure Halite

There were no changes to this model and it continues to be acceptable for implementation.

3.6. Salado Interbeds

3.6.1. Model Description

No changes have been identified in the Salado Interbeds model, and the description of the model remains unchanged.

3.6.2. Review of Criteria

The review of criteria for the Salado Interbeds model remains unchanged.

3.6.3 Review of Responses to Panel Findings of July 1996

3.6.3.1. Summary of Findings

This model was originally found to be well thought out and substantiated by *in situ* experiments. However, one issue in particular caused the model to be considered not adequate. The issue was:

- How do the physical properties of clay seams at the contact of the interbeds affect the fracture propagation and permeability of the model?

In addition, six other questions were posed by the Panel to enhance the clarity of the model. These are listed below:

- What is the mechanism for vertical crack propagation?
- What is the fluid storage capacity of the interbeds after dilation?
- Enhanced porosity and permeability are presumed to mitigate each other in terms of gas migration responses. How can this happen when permeability is a power function of porosity?
- What assumptions and limitations are made to represent the conceptual model by the

mathematical code?

- Why is the full fracture porosity increment of 23.9% for anhydrite beds a and b so different from the 3.9% for marker bed (MB) 138 and 139?
- What are the calculations that show the permeability increases by 10 orders of magnitude?

3.6.3.2. Summary of DOE Responses to Findings

The question that caused the model to be judged inadequate (clay seams) was specifically addressed by the DOE. The clay seams were noted to be preexisting planes of weakness. Because the *in situ* threshold pressure and permeability tests incorporated the clay seams in the test zones (which was validated by continuous core recovery), the interpreted results were considered to be representative of the combined anhydrite and clay units.

The other six questions posed to clarify the conceptual model were also answered in writing by the DOE. In summary, the abbreviated responses are listed in the same order as the questions above:

1) Fractures will propagate vertically if the least compressive stress is horizontal.

2) Simple calculations indicate storage enhancement by the following: 350% for MB 138 and 139, and 2170% for MB a and b.

3) Both permeability and porosity increase with pressure. Increased porosity provides more gas storage space and shorter migration distances. Increased permeability allows increased fluid mobility. DOE did not mean to imply that the two effects are equivalent and completely counteract each other.

4) DOE responded to this question with a description entailing two pages of the assumptions and limitations needed for the conceptual model to be represented by a mathematical code.

5) Fracture dilation is assumed to be confined to a 10 cm thickness, regardless of the thickness of the MB. Therefore, the percentage differences are based on the proportionality of the thickness differences of the interbeds (i.e., MB 138 and 139 are 5 times thicker).

6) The full fracture permeability is used as a fitting parameter so that the appropriate response is obtained. DOE believes that a ten order of magnitude permeability increase is unlikely to ever be achieved in the model.

3.6.3.3. Panel Review of Responses

The Panel has reviewed the responses by DOE on the above listed questions and finds that the model is now fully adequate for implementation.

3.7. Disturbed Rock Zone

3.7.1. Model Description

The Panel concluded that this conceptual model was adequate in its July 1996 report; however, the Panel expressed some concern for modeling the DRZ in the same manner for each of its location sites, particularly the roof and floor. The floor provides a principal repository access for brine and the roof provides a principal pathway for gas.

The DOE identified the following change. In the final CCA, the DRZ porosity was modeled as 0.29% greater than the sampled porosity of Salado impure halite, based on Room Q experimental results. At the time of the previous panel review, the DRZ porosity was not specifically linked to the halite porosity. DOE indicated that the increased porosity would increase the volume available for fluid storage in the DRZ and further delay the flow of brine into the repository. To compensate for this, the DOE assumed that the DRZ was initially saturated with brine, and concluded that the net effect of these assumptions was small.

3.7.2. Review of Criteria

The Panel agrees this change is not significant, and that this model remains adequate for implementation.

3.8. Actinide Transport in the Salado

3.8.1. Model Description

New information has been developed on this model since the Panel's July 1996 report. NUTS model runs are now performed initially in a fast tracer mode to identify BRAGFLO realizations and associated contaminated brine that never reach the top of the salt or the accessible environment in the Salado. If a tracer run indicates the possibility of a consequential release, a complete calculation of the full transport of each radionuclide is performed.

The tracer runs are performed in the following manner. The simulation considers an infinitely soluble, nondecaying, nondispersive, and nonsorbing species as a tracer element. The tracer is given a unit concentration (1 kg/m^3) in the waste disposal area. If the tracer does not reach the top of the Salado or the land withdrawal boundary in the Salado in a cumulative mass greater than or equal to 10^{-7} kg (1×10^{-6} EPA units) within 10,000 years, it is assumed that there is no consequential release to the boundary. If a mass greater than 10^{-7} kg is achieved in the tracer run, then a complete transport analysis is performed.

3.8.2. Review of Criteria

The use of NUTS as a tracer to identify which runs are capable of transporting consequential releases to the boundary is satisfactory and an efficient use of computing time. It does not

detract from the model, and therefore this conceptual model is still found to be adequate.

3.8.3. Review of Responses to Panel Findings of July 1996

3.8.3.1. Summary of Findings

In the original Conceptual Models Peer Review Report of July 1996 this model was found to be adequate. However, questions were raised in the original review of the model concerning information that was not available. These questions are listed below:

1) Validity of model assumptions - Colloids are transported at the same rate as dissolved actinides. This assumption was made because sorption and filtration of colloids are not accounted for. The assumption was not validated.

2) Validity of model assumptions - Grid blocks and time steps of BRAGFLO are proper for use in NUTS. The assumption was not validated.

3) Uncertainties - Appendix NUTS, Section 6.4.11 of CCA, and Table 6-15 were not available for review.

4) Uncertainties - Transport of radionuclides in the waste panel, panel seals, DRZ, and undisturbed and fractured interbeds was not described.

5) Uncertainties - Radionuclide input to sealed boreholes and shafts to the Culebra were not discussed.

3.8.3.2. Summary of DOE Responses to Findings

Model runs were discussed in Panel briefings by DOE and indicate that the philosophy of transporting colloidal actinides with dissolved actinides is a reasonable assumption. This assumption was also borne out in the cumulative complimentary distribution function (CCDF) runs. One preliminary NUTS model run indicated that an E2 release to the Culebra would in fact transport 18 EPA units to this boundary interface with the Culebra. Appendix SA also indicated that the CCDF runs most likely to impact the assessment are the human intrusion events involving cuttings or spallings.

BRAGFLO grid blocks and time steps have been found to be reasonable and not excessively coarse.

Appendix NUTS and Sections 6.4.10-12 are now available and have adequate explanations of the numerical codes. Table 6-15 was not used in final CCA.

Questions involving long-term transport in the repository rooms, repository panel seals, DRZ, and undisturbed and fractured interbeds have been resolved to the satisfaction of the Panel.

Sealed boreholes and shafts to the Culebra will be treated as filled with sandy material when the plug degrades.

3.8.3.3. Panel Review of Responses

The Actinide Transport in the Salado conceptual model has not changed in an adverse manner and is considered adequate.

3.9. Units Above the Salado

3.9.1. Model Description

No changes have been identified to the model of the Units Above the Salado.

3.9.2. Review of Criteria

The review of the criteria of the model of the Units Above the Salado remains unchanged.

3.9.3. Review of Responses to Panel Findings of July 1996

3.9.3.1. Summary of Findings

The Conceptual Model Peer Review Panel found that the conceptual model of the Units Above the Salado was not adequate to explain the distribution of hydrologic properties in the Magenta Dolomite or the Dewey Lake Redbeds on the site or over the site region for the purpose of the assessment of transport of radionuclides to the accessible environment. Further, the hydrologic testing database in those units is not adequate to support a numerical hydrologic flow model of the kind developed for the Culebra. The Magenta Dolomite and the Dewey Lake Redbeds are the only stratigraphic units above the Salado having significant transmissivity with respect to potential releases of radionuclides.

The Magenta Dolomite appears to be less transmissive than the Culebra, on the basis of very limited hydrologic testing. The Dewey Lake Redbeds appears to have gypsum-filled fractures throughout its lower part (raising the elevation to which brine would have to rise to enter the formation) and contains ferrous minerals that might retard radionuclide transport. Despite these possible mitigating factors, the units above the Salado cannot be adequately modeled over the controlled area to permit reliable performance assessment. However, a finding of no consequence of the inadequacy of the model of the Units Above the Salado to the performance of the facility was made based on the failure of significant quantities of brine to rise above the Culebra in the long-term performance assessment of any intrusion scenario. Volumes and rates of brine flow up and down the borehole, Culebra hydrologic pressure, and the transmissivity of the Culebra at the borehole were the principal variables considered in the calculation.

3.9.3.2. Summary of DOE Responses to Findings

The DOE made presentations to support the mitigating aspects of Magenta and Dewey Lake Redbeds hydrogeology. In addition, further PA calculations were presented using minimum values of Culebra permeabilities at the point of penetration of the intrusion borehole (BRAGFLO

code) to supplement the original calculation based on mean Culebra transmissivity.

3.9.3.3. Panel Review of Responses

The presentation by SNL on the hydrogeology of the Magenta and Dewey Lake Redbeds does provide additional reasons why these units may not be foci of concern about radionuclide releases, but does not constitute an adequate conceptual model to support PA transport modeling. The additional calculation of brine flow in the intrusion borehole through the Culebra provided additional assurance that no significant volume of brine reaches the stratigraphic units above the Culebra. The Panel's original finding that the absence of an adequate hydrogeologic conceptual model for the units above the Salado (excepting the Culebra) is of no consequence to the PA calculations is further supported by this response.

3.10. Transport of Dissolved Actinides in the Culebra

3.10.1. Model Description

This model uses a dual porosity calculation to estimate transport of dissolved actinides. DOE indicated that in implementing this conceptual model, a preliminary calculation was performed for a unit source of each of the soluble actinides, using the sampled range of K_ds based on experimental data. The results indicated an attenuation in the Culebra of more than sixteen orders of magnitude. Because of this result, DOE decided not to run the additional calculations needed to construct CCDFs for this transport pathway. DOE also stated there would be less than $1x10^{-6}$ EPA units of any of the actinides transported to the regulatory boundary through the Culebra. Additional interpretive results of hydropad tracer testing and laboratory measurements of K_ds have also become available since the Panel's July 1996 report. DOE has concluded that the Culebra could best be thought of as having several levels of advective and diffusive porosity, as shown in Figure 3-3. DOE believes that most of the flow and transport is through

Figure 3-3. Multiple scales of porosity in the Culebra.

approximately 16% of the dolomite, represented by lenses of interparticle porosity connected by vugs and fractures. The areas for adsorption are contained in these regions, as well as the intercrystalline porosity accessible only by diffusion of soluble species. This interpretation resulted from analysis of the hydropad testing that was completed after the performance assessment and the Panel's July 1996 report were completed. This added understanding was helpful in interpreting the wide range of K_ds measured.

3.10.2. Review of Criteria

The Panel in its July 1996 report concluded this conceptual model was acceptable for implementation, in that the dual porosity mathematical model provided a sufficiently accurate representation for performance assessment. However, the Panel expressed the view that the K_ds to be used needed to be properly chosen in light of uncertainties.

In its supplemental review, the Panel noted that K_ds from flow-through testing in crushed column and intact cores were significantly lower than K_ds from longer term contact testing with crushed dolomite. DOE provided information showing that the flow-through testing does not provide sufficient contact time to actually reach equilibrium values of K_d, and that therefore, the sampled ranges of K_ds provide conservative values for transport calculations.

The performance assessment used the range of K_ds from both batch tests and flow-through tests, whereas the batch test results should provide the better values. The higher K_ds were from the batch tests. However, as before, this Panel makes no conclusion on the acceptability of individual K_d values, per se, since there are other issues associated with those values that are not related to the conceptual model and that this Panel has not evaluated.

The Panel continues to find this model, as revised, adequate for implementation.

3.11. Transport of Colloidal Actinides in the Culebra

3.11.1. Model Description

DOE has identified conceptual changes in how colloids are transported, as a result of further analysis of experimental results since the Panel's July 1996 report was issued. DOE has also determined that explicit calculations of colloid transport are not needed based on this added analysis. DOE has examined the range of possible colloids by examining four specific representative types.

The model had included advective transport of colloids in advective porosity, and for small colloidal particles, diffusion followed by adsorption onto surfaces in diffusive porosity, as well as filtration of colloidal particles in pore throats. As a result of the reexamination, DOE has assigned a value of zero to K_ds for mineral fragments, microbial, and intrinsic colloids, has assigned filtration coefficients only for microbial colloids and mineral fragment colloids, and for humic colloids has assigned K_d values equal to those for soluble actinides since they are destabilized at Culebra pH conditions. The filtration coefficients are a result of the crushed column tests, and filtration was determined to be so effective at removing microbial and mineral fragment colloidal actinides that they are effectively removed in a short distance in the Culebra. The additional information not available to the Panel for its July 1996 report includes written descriptions of the various crushed dolomite column tests and core flow tests, and an improved presentation of the multiple scales of advective and diffusive porosity that are important in Culebra transport.

3.11.2. Review of Criteria

During the initial Panel review, there were some significant uncertainties that precluded a finding of adequacy for this model, particularly for the Validity of Model Assumptions. The more recent information provides the improved understanding needed for drawing conclusions.

3.11.3. Review of Responses to Panel Findings of July 1996

The Panel issues, a summary of the DOE responses, and the Panel review of the responses are provided below.

3.11.3.1. Summary of Findings

- The conceptual model does not adequately support the assumption that dissolved actinides will not interact with Culebra colloids. Ignoring this phenomenon could overestimate the travel time calculated for radionuclides to reach the accessible environment.
- The experimental K_ds determined for this model are not fully defensible. Such values may overestimate the retardation of actinides in the Culebra.
- Recent experimental work to support assumptions and data for this model has not yet been published and was not available for Panel review.

3.11.3.2. Summary of DOE Response to Findings

Regarding the assumption that dissolved actinides would not interact with Culebra colloids, DOE indicates that stable indigenous colloids in the Culebra are not expected, and that any that could be injected into the Culebra would be so rapidly filtered, based on experimental filtration coefficients, that it is conservative to assume they remain for transport only as soluble species.

Regarding the Panel-expressed issue with use of K_ds, DOE noted that values of zero were assigned to K_ds for mineral fragments, microbial colloids, and intrinsic actinides, and that for humic substances, values equal to dissolved K_ds were assigned because they would be destabilized in Culebra pH conditions and be transported as soluble species.

Regarding the lack of published reports on experimental work, published information in the CCA and its appendices responds to this issue.

3.11.3.3. Panel Review of Responses

The Panel has reviewed the changes to this model and the DOE responses to issues on this model, and concludes that these changes and responses adequately address the Panel issues of its July 1996 report. The Panel concludes that the model is adequate for implementation in performance assessment.

3.12. Exploration Boreholes

3.12.1. Model Description

No changes have been identified in the Exploration Boreholes model, and the description of the model remains unchanged.

3.12.2. Review of Criteria

The review of criteria for the Exploration Boreholes model remains unchanged.

3.12.3. Review of Responses to Panel Findings of July 1996

3.12.3.1. Summary of Findings

The following key concerns were identified in the July 1996 Panel report that were related to the Exploration Boreholes model.

- The potential for releases or changes in repository conditions from borehole penetrations in the operations and experimental areas of the repository does not appear to have been evaluated. Radionuclides that may have migrated into those areas through the panel closures by diffusion or other transport mechanisms could be released to the ground surface, and gas pressures could be relieved by such boreholes. Also, brine could migrate into those areas from a borehole and then into the waste panels.

- The assumption that shorter (40m) borehole plugs beneath the repository horizon will not significantly degrade during the 10,000-year regulatory time frame has not been adequately supported. For the two- and three-plug configurations, degradation of these plugs could result in creation of a low permeability pathway for fluid migration between the Bell Canyon and the repository. For the three-plug configuration, degradation could result in increased fluid migration from a Castile brine reservoir to the repository.

- The possibility that an effect on the repository could result from Castile brine encountered in an E1 borehole that is assigned a three-plug configuration does not appear to have been considered in the conceptual model. Castile brine could enter the repository during drilling before the borehole is cased and result in increased rates of corrosion, waste degradation, and gas production.

- The sensitivity of the performance assessment to the simplified approach taken to determine reference conditions for BRAGFLO output does not appear to have been evaluated for the current model configuration. If reference conditions are not provided at sufficiently frequent time intervals, the modeling results may be erroneous.

3.12.3.2. Summary of DOE Responses to Findings

The DOE response to the first concern cites the lack of significant consequence of borehole penetrations in the operations and experimental areas. Intrusion boreholes in those areas would have no associated cuttings, cavings, or spallings releases, and the direct brine release was stated to be negligible because of the relatively low volume of contaminated brine that would migrate through the panel seals into those areas from the waste disposal area, the dilution of radionuclide concentrations in the contaminated brine from mixing with uncontaminated brine in those areas, and the lower importance of direct brine releases to overall performance. In addition, ignoring

the repository-wide gas pressure relief that would follow such intrusions would be conservative because high gas pressures are drivers for spallings and direct brine releases. In considering brine flow in the opposite direction (from the operations and experimental areas into the waste disposal area) DOE stated that the incremental volume of brine entering the waste area would not substantially add to the brine volumes already there, and that more than enough brine was already potentially available in the waste area from other sources to react with all the waste present.

In responding to the second concern, the DOE indicated that degradation of borehole plugs beneath the repository horizon is not expected during the regulatory time frame because the service life range of 500 to 50,000 years and best estimate of about 5,000 years cited by Thompson et al. (1996) is based on overly conservative assumptions that ignore a correlation between concrete porosity and permeability, assume an unrealistically low value for the minimum concrete porosity, and assume a relatively low number of pore flow volumes required for concrete degradation. In addition, a lack of reported failures of plugs at comparable depths was cited.

The response to the third concern (the effect of Castile brine entering the repository during drilling) was provided in the form of an estimate of the volume of such brine that would enter the repository during a three-day period when the borehole is uncased during drilling. Using conservative values for borehole and repository pressures, and the standard assumptions for waste permeability and waste panel geometry used in performance assessment, the inflow volume was estimated to be less than 100 m^3. Relative to the volumes of brine inflow potentially available from other sources, this volume was not considered significant.

The fourth concern (the sensitivity of performance assessment to the use of reference conditions in determining performance assessment results) was addressed by reviewing with the Panel the shapes of the undisturbed repository pressure curves upon which the two release values for intrusions at 350 and 1,000 years were superposed. Although the response included summaries of reference conditions for other models, including Cuttings and Cavings, Spallings, and Direct Brine Release, these are based on more than two values and were correctly identified as being of lesser concern to the Panel.

3.12.3.3. Panel Review of Responses

In evaluating the response to the first concern, the Panel concurs with the DOE that, based on the performance assessment modeling results, the consequences of borehole penetrations in the operations and experimental areas are not expected to be significant. It is agreed that no cuttings, cavings, or spallings releases would occur from such penetrations. DOE's response indicated that with very few exceptions, the maximum brine flow through a panel seal was found in modeling results to be about 12,000 m^3 following an E1 intrusion, and the expected flow would be about 3,000 m^3. Under undisturbed conditions, the cumulative brine inflow into the operations and experimental areas from all sources ranges from near zero to about 10,000 m^3 (see Figures 3-4 and 3-5). This flow would, on the average, be expected to result in approximately a twofold dilution of brine flowing in from the waste area following an E1

intrusion. Under disturbed conditions with intrusion boreholes penetrating the operations and experimental areas, the inflow of uncontaminated brine and the dilution of contaminated brine would be even greater.

In the event that the operations and experimental areas are penetrated by intrusion boreholes, approximately 12,000 m^3 of brine could conceivably flow from these areas into the waste area. Performance assessment results indicate that total cumulative brine flow into the waste area is typically

Figure 3-4. Cumulative brine inflow into operations area under undisturbed conditions. Not available.(9)

Figure 3-5. Cumulative brine inflow into experimental area under undisturbed conditions. Not available.(10)

about 40,000 m^3 following an E1 intrusion at 1,000 years and about 30,000 m^3 following an E2 intrusion at 1,000 years (see Figures 3-6 and 3-7). Given that about six borehole intrusions are expected to occur during the regulatory time frame, the total volume of brine potentially available to flow into the waste area could exceed 100,000 m^3. Although the actual volume of brine inflow will depend on the interrelationships among time of intrusion, repository creep closure, gas generation, repository pressure, and other factors, the modeling results indicate that sufficient brine is potentially available from other sources that an incremental supply of as much as 12,000 m^3 would have no consequential effect on performance assessment results. However, if subsequent model modifications result in significantly smaller fluid volumes in the repository, the significance of this issue should be reevaluated.

The Panel found that DOE's response to the second concern does not support an expected lower plug service life in excess of 10,000 years because it has not been adequately demonstrated that the lower bound of the expected plug life will exceed 10,000 years. While the 500-year lower bound of the range reported by Thompson et al. (1996) may be unrealistically low, it is difficult to disregard because both the permeability (5×10^{-17} m^2) and the porosity (2%) used to compute this lower bound were reported to have been determined from field tests of an actual Bell Canyon borehole plug. The consequence of plug failure would be to open a low-permeability pathway for brine movement between the repository and the underlying Bell Canyon Formation that is not considered in performance assessment. Brine could flow along this pathway in either direction depending on pressure conditions in the repository. The volume of upward flowing Bell Canyon brine moving into the repository is not expected to be significant compared with the aforementioned volumes potentially available from other sources. Similarly, the volume of Castile Brine that would move upward into the repository following failure of the middle plug in a three-plug scenario would also have insignificant consequences.

Brine flowing downward from the repository to the Bell Canyon would only be significant if it could reach the accessible environment within the regulatory time frame of 10,000 years. A rough estimate of travel time in the Bell Canyon was prepared by the Panel based on hydrologic information provided by the U.S. Geological Survey (Mercer 1983). Primary flowpaths in the

Bell Canyon are identified by the USGS as relatively isolated, permeable channel sandstones separated by siltstones and shales with negligible permeability. Assuming the maximum reported channel hydraulic conductivity of 5 x 10^{-2} ft/day, a hydraulic gradient of 0.0038 underlying the WIPP site (from Mercer 1983, Figure 9), and an effective porosity of 10%, the travel time to the edge of the Land Withdrawal Area 2 miles away is estimated to be 15,200 years. This estimate does not consider the additional effects of chemical retardation, the travel time in the borehole, and the likelihood that a borehole would intersect the negligible permeability siltstones and shales rather than a more permeable sandstone channel. Based on this information, the Panel's second concern is considered to be resolved, based on lack of consequence.

Figure 3-6. Cumulative brine flow into repository following an E1 intrusion at 1000 years. Not available.(11)

Figure 3-7. Cumulative brine flow into repository following an E2 intrusion at 1000 years. Not available.(12)

The response to the third concern (flow of Castile brine into the repository during drilling) was considered by the Panel to be adequate.

The fourth concern (sensitivity of performance assessment to the use of reference conditions) was addressed by DOE with reference to the plot of volume-averaged pressure simulations for an undisturbed waste panel shown in Figure 3-8. As previously stated, the Panel's primary concern was with the use of only two reference conditions (350 and 1,000 years) for evaluating E1 and E2 intrusions. These reference conditions were used by applying conditions at 350 years to intrusions occurring at or before 350 years, applying conditions at 1,000 years to intrusions occurring at or following 1,000 years, and linearly interpolating conditions for intrusions occurring between 350 and 1,000 years.

Both repository pressure and brine saturation results were reviewed by the Panel in addressing this concern.

As shown in Figure 3-8, undisturbed, volume-averaged pressures are steeply climbing in virtually all realizations prior to 350 years, and applying the value at 350 years is conservative. Between 350 and 1,000 years the increase is essentially linear, and the use of linear interpolation is appropriate. After 1,000 years approximately half the curves are reasonably flat; however, the other half of the curves show continuing pressure rises for the duration of the regulatory time frame. Because of this continuing pressure rise, the assumption of constant pressure after 1,000 years is nonconservative for many realizations and may not be appropriate. Undisturbed, volume-averaged brine saturations in the waste panel and rest of the repository are shown in Figure 3-9. Again, the Panel's greatest concern is with the adequacy of assuming constant conditions after 1,000 years. The performance assessment results, however, indicate that the consequences of this concern are expected to be low. The short-term cavings, spallings, and direct brine releases, which are of primary importance to waste isolation, are computed based on a larger number of reference conditions which the Panel expects to be adequate. The two cited reference conditions associated with this concern are used only to determine long-term releases

and to provide a basis for calculating releases for second and subsequent intrusions for the short-term releases.

Figure 3-8. Volume-averaged pressure in undisturbed waste panel. Not available.(13)

Long-term releases occur via the Culebra or the anhydrite interbeds, and releases by these pathways were found in performance assessment modeling to be zero or insignificant. Second and subsequent releases were also found to not be significant because of repository pressure relief following the first penetration. Although the Panel continues to question the accuracy of results based on only two reference conditions, the concern has been adequately addressed on the basis of a lack of consequence.

In summary, the Panel has found each of the four key concerns identified for the Exploration Boreholes model in July 1996 to have been resolved.

3.13. Cuttings/Cavings

3.13.1. Model Description

DOE described a change to this model regarding the method of calculating the actinide concentration of waste that is released during drilling of exploration boreholes. Other aspects of the Cuttings/Cavings model were not changed.

Figure 3-9. Volume-averaged brine saturation in rest of repository and waste panel under undisturbed conditions. Not available.(14)

In the model as previously presented, the concentration of actinides was identified as the mean of all the concentrations of actinides in contact handled transuranic waste. DOE has revised the model to randomly sample concentrations from 569 waste streams for each of three drums assumed to be penetrated by an intrusion borehole. The average concentration from three sampled drums was used to represent the range of concentration of waste removed in Cuttings/Cavings, because the waste will be emplaced three drums high in the WIPP. DOE stated that this provides increased information on the uncertainty in waste activity levels. DOE also used nine reference times, instead of 15 reference times, to provide a basis for interpolating concentration decay curves to the random times used in CCDF construction. DOE indicates that this change does not significantly affect the model accuracy.

3.13.2. Review of Criteria

The Panel considered this model to be adequate in its July 1996 report. During review of the changes, the Panel obtained an evaluation of the significance of drilling through three drums from the same waste stream at the high end of the range of concentrations of contact handled waste, on the basis that this would be a possible, though not likely, event. DOE provided waste concentration distributions, probabilities, and corresponding releases that would result, and showed that this would not have a significant effect on the location of the highest CCDF curves.

In summary, the Panel believes this model to remain adequate, as changed.

3.14. Spallings

3.14.1. Model Description

No changes to the Spallings model have been identified as compared to the Panel's understanding of it from the original review.

3.14.2. Review of Criteria

The review of criteria for the Spallings model remains unchanged.

3.14.3. Review of Responses to Panel Findings of July 1996

3.14.3.1. Summary of Findings

Based on the three following issues, the Panel determined that this model was not adequate for implementation in performance assessment:

- The conceptual model for channel flow of gases toward an exploratory borehole appears to be valid, but has not been adequately evaluated. Spallings is a potentially important mechanism for direct waste release to the ground surface.
- The conceptual model for waste erosion by flowing gases has not been adequately defined. The model describing the source(s) of waste erosion resistance and the parameter(s) characterizing that resistance have not been adequately evaluated. Errors in this conceptual model could lead to overestimating or underestimating the volume of waste released in the spallings process.
- The waste has not been adequately characterized and the understanding of its physical properties in its decayed state has not been adequately developed to support the Spallings model. An adequate understanding of waste erosion processes requires an adequate understanding of the properties of the waste.

3.14.3.2. Summary of DOE Responses to Findings

In responding to the first concern, the DOE notes that their concept of channeling as the source of spallings release is primarily based on results of laboratory experiments conducted on graded, low-moisture silica sands. The tests showed that upon achieving a steady state gas flow rate with no additional material being removed, an irregular void space results. Plaster castings of this void show that some voids are radial channels and others are a series of thin layered lenses or shells. Data from these tests were used to calibrate the model by defining values for "effectiveness factors."

The experiments show channels that extend from the borehole outward as a result of eroding effects of flowing gas within weakened planes which result from local variations in initial porosity

and permeability, or by tensile (or shear) failure resulting from pressure gradients. DOE also describes studies of *in situ* coal fracturing for methane production (Mavor and Logan 1994) by means of rapid drops in gas pressure in the borehole.

The DOE response to the second issue relates the effects of gas movement over a surface to the erosional effects from flow of liquids or gases through a pipe. This erosion is seen to be caused by a combination of shear and tensile stresses which can be related to the force required to dislodge particles from the surface into the fluid stream. This force is seen to be related to the tensile strength and density of the waste. A mathematical model was developed from first principles that relates the particle dislodging forces to the drag forces present from the flowing gas, which are a function of individual particle dimensions and fluid viscosity, density, and velocity. This equation, when "calibrated" by means of experimentally determined effectiveness factors, is believed to be an analogue to the erosional forces described above.

The model is predicated on the assumption that the bonding strength of the particle to the waste surface is related to the macroscopic tensile strength of the degraded waste. One pound per square inch was chosen as an appropriate value for the bonding strength of waste in the calculations. Data were supplied that show this value to be within the range of literature values for strengths of soils, lab mixtures of salt and clay, and various materials mixed with MgO (Bergland et al. 1996).

The third DOE response specifies that the spallings phenomenon occurs only when there is brine inflow and waste decomposition. DOE states that because both of these are unknowable, it is assumed that the decomposed state will be a graded granular material consistent with the granular nature of decomposed geologic materials and corresponding to the end state of the decomposition process.

3.14.3.3. Panel Review of Responses

In reviewing the response to the first issue, the Panel has several basic points of discussion relevant to the DOE's evaluation of the model for adequacy:

- The forces responsible for detaching the waste pieces from their mass do not include the gases exiting the mass into the open gas-filled cavity. The Panel believes this type of gas flow will be largely responsible for the force required to counteract whatever bonding force exists. Such a force might be analogous to the forces (i.e., pressure gradient) on particles or groups of particles at the upper surface of a packed bed nearing the point of fluidization.

- The data on tensile strengths were from static tests and were not shown to be applicable in this dynamic situation. It is noted that in the Cuttings/Cavings model, static shear strengths were modified to be applicable to the dynamic situation.

- There is no evidence found in the record that time effect considerations were evaluated in

either the development of the equations or in the conduct of the experimental tests.

- The bounding equation as presented is not solidly verified, not only because of the lack of consideration for the former comments, but also because the testing results do not support the assumptions used in equation development. For example, the dropped g term dealt with cohesive forces such as water, while the only positive test results achieved were those with moisture-laden sand.

- The effect of cementation was added when formulating the final equations describing the Spallings model and the experimental work did not evaluate these effects.

- Evaluations of the models did not include analogues from other industrial or scientific disciplines to determine a basis for reasonableness. The DOE was apparently not as successful in conducting such an evaluation as it was for the Cuttings/Cavings model. The coal mining methane gas stimulation example is good; however, several others are expected to be applicable, such as chemical engineering processes (for example, fluidized beds) and the work over the years on particulate transport in volcanology. There may be existing correlations to these processes that are directly applicable.

- The experiments were basically quasi steady state, rather than demonstrating the dynamic situation. Uniform particle distribution was used, rather than a more realistic range of particle sizes. No control was maintained over the moisture content of the sand. All these issues would seem to impact the relationship between the experimental system and the repository.

- The experimental results should be subject to scaling, which was not found by the Panel to be addressed. Also, the data did not include measurements of pressure drops at various locations throughout the system (for example, at the cavity-waste interface). Both of these issues might be reanalyzed without further experimental work.

Review of the response to the second issue also raised several points for discussion relative to the design of the model.

- While the concept of cementation was included in the model, the process by which this cementation would occur was not addressed in the experimental program.

- Flow velocities that approach transonic or beyond have not been considered and, if velocities are transonic at times during the spallings process, might require a factor addressing increased effects on the pressure across the cavity-waste interface boundary.

- The process as modeled does not have a provision for processes occurring at times of high pressure gradients. It would appear realistic that some volume of the waste dislodged from the matrix would be a spall produced by a process largely unrelated to the gas velocity parallel to a surface.

Relative to the third issue, the DOE responses are acceptable as explanations of the state of the conditions bounding the effects of the Spallings model. It is important to note, however, that the assumption that the waste will be in a fully decomposed state consistent with the granular nature of decomposed materials could be unnecessarily conservative.

Following the Panel description to DOE of the above concerns, DOE provided a further verbal response addressing the conservativeness believed to exist in the Spallings model. DOE listed as conservative model elements use of a small particle diameter, constant pressure during spalling, ignoring capillary forces, tortuosity of the channels and possible plugging, channels too small or narrow to transport all the particles that may be dislodged, and the use of a low end value of the waste strength range found in the literature.

The Panel believes that because of the many unresolved issues of a fundamental nature, it cannot acknowledge that this model provides a conservative method of calculating Spalling releases.

Integration of the Spallings model in performance assessment revealed that this model is one of the major sources of radionuclide release to the surface. While changes might come about in further work relative to this model, it is realistic to expect that the Spallings model will continue to be important to the total release. Therefore, the Panel believes that this model is not adequate for predicting the future states of the repository.

3.15. Direct Brine Release

3.15.1. Model Description

Since the Panel's July 1996 report, the uncontrolled borehole flow period assumed in performance assessment was changed from 44 hours to a minimum of 72 hours (3 days) and a maximum of 11 days, depending on the rate of gas flow as determined in the model from repository pressure and gas volume. The borehole is assumed to remain uncontrolled for as long as the gas flow rate exceeds a threshold value, up to a maximum of 11 days.

3.15.2. Review of Criteria

The change in the conceptual model was based on current drilling practices in the Delaware Basin and is consistent with regulatory guidance. Although the modeling assumptions are conceptually valid, the validity of their implementation depends on current drilling practices, which are beyond the scope of the Panel to review.

3.15.3. Review of Responses to Panel Findings of July 1996

3.15.3.1. Summary of Findings

The following key concerns related to the Direct Brine Release model were identified in the July 1996 Panel report.

- The basis for the assumption that radionuclides do not accompany the direct discharge of

Castile brine has not been adequately supported. This assumption could lead to underestimating radionuclide releases.

- Radionuclide transport through entrainment of brine and waste solids in rapid, two-phase liquid/gas releases during inadvertent borehole intrusions does not appear to have been evaluated. This transport mechanism may be an important component of the conceptual model.

- Releases resulting from flow into an exploration borehole intersecting a disturbed rock zone in the wall of a waste panel do not appear to have been evaluated. Large, open fractures in the walls could significantly increase the local halite permeability, allowing gas and brine to migrate through the borehole to the ground surface.

3.15.3.2. Summary of DOE Responses to Findings

The DOE response to the first concern addressed the small likelihood that Castile brine flowing up an open borehole would circulate significantly within the repository, displacing contaminated repository brine, which would flow up the borehole. This was considered unlikely because of the unlikely set of pressure conditions that would first allow Castile brine to flow into the repository and then, a few hours or days later, would reverse and allow repository brine to flow into the borehole. Also, unless the pressure gradients were large, the volume of such flow would be small (as described in Section 3.12).

The initial response to the second concern (entrainment of solids in two-phase gas/brine flow) was addressed by modifying the fluid density in the spallings model to estimate the entrainment of solids in a fluid with the density of a gas-brine mixture. A second analysis was later provided at the Panel's request that modified both the fluid density and viscosity. This second analysis indicated that the overall effect of this change was to reduce the volume of solids from that released by the gas flow alone.

In responding to the third concern (releases from a borehole intersecting the DRZ within the wall of a waste panel), the DOE indicated that the wall DRZ is expected to heal soon after a backstress is provided by the compacted waste. This is expected to occur much more rapidly than the healing of the roof and floor of the waste panels and will be essentially complete during the period of active and passive institutional controls. Because drilling rates are very low during this period, few boreholes (if any) are expected to intersect the wall before the DRZ is healed, and the consequences of ignoring the wall DRZ are therefore not significant.

3.15.3.3. Panel Review of Responses

The DOE response to the first concern (entrainment of waste in Castile brine discharges during drilling) was considered to be adequate with regard to the circulation of Castile brine within the repository. However, the possibility of a cavings-type release through erosion of waste in the borehole wall by upward-flowing Castile brine was not addressed. In response to an information request submitted by the Panel, a conservative estimate of incremental cuttings and cavings

releases was prepared by DOE. This estimate indicated an increase in releases for an E1 event ranging from 22% to 87%, depending on the assumed waste shear resistance. The average increase was reported to be 38%. If it is conservatively assumed that the repository is typically intersected by 6 boreholes during the regulatory time frame and that from 8% to 30% of these intersect a Castile brine reservoir, the net effect of borehole wall erosion by Castile brine would be to increase the cuttings and cavings releases by from 3 to 13%. While such an increase may be considered significant, in view of the overall uncertainties in the performance assessment model, such an increase is not expected to have a strong impact on the final CCDFs and the Panel considers this concern to have been adequately addressed.

The quantitative response to the second concern (entrainment of solids in a two-phase gas/brine mixture) was appreciated by the Panel, and the conceptual approach (that of employing the Spallings model to address the issue) was considered appropriate for scoping purposes, although adjustments were not made to the model for two-phase rather than single-phase flow and for liquid rather than gas flow. However, the appropriateness of the Spallings model itself is of concern to the Panel, as discussed in Section 3.14. Until the Spallings model is found to be adequate, the results obtained from the model in addressing this concern cannot be considered valid. The Panel has chosen to find the DOE response to this concern adequate on the basis that application of the Spallings model to this concern is conceptually appropriate in a scoping sense, rather than to determine that both the Direct Brine Release and Spallings models are inadequate on the same basis. However, the Panel believes that this concern should be reevaluated when an adequate Spallings model is developed.

The response to the third concern (releases from a borehole intersecting the DRZ within the wall of a waste panel) was considered by the Panel to be adequate.

In summary, the Panel has found each of the three key concerns identified for the Direct Brine Release model in July 1996 to have been resolved.

3.16. Castile and Brine Reservoir

3.16.1. Model Description

The 10% probability of encountering a brine reservoir provisionally assumed in the early performance assessment documents was changed in the final performance assessment to 8%.

3.16.2. Review of Criteria

The change in the conceptual model was based on results obtained from a geostatistical analysis of brine encounters in boreholes drilled near the WIPP site. The basis used by DOE for estimating this probability was identified as a key concern of the Panel in its July 1996 report and is discussed below.

3.16.3. Review of Responses to Panel Findings of July 1996

3.16.3.1. Summary of Findings

The following key concerns related to the Castile and Brine Reservoir model were identified in the July 1996 Panel report.

- The basis for excluding larger, potentially depressurized brine reservoirs from performance assessment has not been adequately supported. Larger reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.
- The basis for the concept of reservoir depletion through previous borehole penetrations has not been adequately supported. Non-depleted reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.
- The expected probability of encountering pressurized brine beneath the waste panels has not been adequately supported, nor has the basis for apparently ignoring the quantitative value of site-specific geophysical data been presented. Unrealistically low probabilities of encountering brine may result in underestimating radionuclide releases.

3.16.3.2. Summary of DOE Responses to Findings

The DOE response to the first concern (the exclusion of larger reservoirs from performance assessment) indicated that brine flow up the borehole was correlated to the product of reservoir volume and pore compressibility, rather than to the reservoir volume alone. DOE also acknowledged that its range of bulk rock compressibility values may be too large, and if the smaller range of 2×10^{-11} to 1×10^{-10} Pa^{-1} recommended by Popielak et al. (1983) were used, the maximum pore volume x compressibility, product used in performance assessment (6×10^{-2} m^3/Pa) would be equivalent to a reservoir pore volume of 5.5×10^6 m^3, assuming a porosity of 0.0087. This value is considerably larger than those identified in performance assessment, and is of the same order of magnitude as the pore volumes estimated for the reservoir encountered by WIPP-12.

The response to the second concern (basis for reservoir depletion assumptions from prior drilling) was addressed for reservoirs larger than the waste panel area. Because of their size, the areas of the larger reservoirs are predicted to be penetrated more than 1,000 times over a 10,000-year period under the assumptions presented in regulatory guidance. The initial DOE response to this concern was based on the assumption that all deep boreholes would penetrate and partially deplete such reservoirs. A revised response was provided to the Panel during oral briefings in which the assumption that only 8% of the drilled boreholes will actually encounter brine was included. With this revision, depletion of the larger reservoirs was less rapid and led DOE to conclude that the analysis did not strongly support the depletion concept. The DOE response did not address the assumptions presented in the CCA for depletion of reservoirs smaller than the waste panel area, and in subsequent oral presentations it was learned that those assumptions were made without quantitative basis.

In responding to the third concern (the probability of encountering pressurized brine beneath the

repository), the DOE provided a summary of the geostatistical methods applied, as well as information indicating that the consequence of the assigned probability on performance assessment results was small. The small consequence was demonstrated by comparing the long-term effects of Castile brine flows on the key performance assessment parameters of net brine inflow, brine saturation, porosity, and gas generation in a penetrated waste panel, and total spallings releases.

3.16.3.3. Panel Review of Responses

The DOE response to the first concern (the exclusion of larger reservoirs from performance assessment) was considered by the Panel to be adequate. The compressibility range of Popielak et al. (1983) lies within the range used in performance assessment, and reservoir volume is estimated based on such compressibility data. Reservoir compressibility is acknowledged to be highly uncertain, and although the range proposed by Popielak et al. (1983) may be somewhat restrictive on the high end, minor increases in that range would not substantially alter the conclusion that if the smaller range of compressibilities were considered, the DOE *de facto* included consideration of reservoir volumes extending into the millions of cubic meters. Correlary to this issue is the likelihood that the incremental volume of brine flowing to the repository from a larger Castile reservoir would be small in comparison to the volumes potentially determined to be available in the current performance assessment (see Section 3.12) and would have no consequential effect on releases.

The response to the Panel's second concern (basis for reservoir depletion assumptions from prior drilling) was separately reviewed for reservoirs both larger and smaller than the WIPP waste area. Because their analysis did not support the assumption of depletion for the larger reservoirs, the Panel assumes that this aspect of the conceptual model will be withdrawn by DOE. The issue of depletion of these reservoirs is moot, however, because of the Panel's aforementioned conclusion that *defacto* consideration of larger reservoirs was included in the performance assessment model.

The smaller reservoirs explicitly assumed to exist beneath the waste area are assumed by DOE to range in volume from 32,000 m^3 to 160,000 m^3. Such reservoirs are assumed to be depleted to the point of no consequence by from 2 to 6 prior penetrations, which may occur from boreholes penetrating either the waste panels or the unexcavated halite within the waste area. Depletion of a 32,000 m^3 reservoir was included in the aforementioned DOE analysis. The results indicate that less than one borehole is expected to encounter brine in a reservoir of this size during the regulatory time frame because of the small surface area. Assuming the reservoir is 67 m thick, the average maximum total brine flow would be only about 400 m^3 to the surface during drilling and 1,200 m^3 to the Culebra during the following 10,000 years. Results for a 160,000 m^3 reservoir of the same thickness indicated a total brine flow of about 2,100 m^3 to the surface and 6,000 m^3 to the Culebra during the following 10,000 years. Because of the larger surface area of this reservoir, an average of 14.1 brine encounters were expected in that period. After about 6 brine encounters, the brine flow from this larger reservoir to the Culebra totaled 5,200 m^3, or

about 87% of the total.

Based on these results, the Panel concurs that the DOE response to the second concern is adequate. The larger reservoirs are considered to have been included in the performance assessment by virtue of the selection of a narrower range of compressibilities, and the depletion assumptions for the smaller reservoirs are appropriate.

A related concern is the method used to determine the probabilities that the reservoir assumed to underlie the repository would be a certain size. The selected probabilities range from 1/32 for the largest reservoir (160,000 m^3) to 10/32 for intermediate size reservoirs (64,000 and 96,000 m^3). The basis for these assignments was an event tree approach in which the repository, including the operations and experimental areas, was divided into five sections, each with a 50% probability of having an underlying reservoir. This gave 32 possible combinations. Probabilities were then assigned based on reservoir area, with the lowest probability being assigned the largest reservoir (which would have to simultaneously underlie all five sections). The Panel considers this approach to be geologically unrealistic. However, because the brine volume that would be released from even the largest of these reservoirs is low compared with the total volume of brine available to the repository (see Section 3.12), the consequence of the assigned probabilities is considered to be low. However, if subsequent model modifications result in significantly smaller fluid volumes in the repository, the significance of this issue should be reevaluated.

The Panel considers the DOE response to the third concern (the probability of encountering pressurized brine beneath the repository) to have an inadequate technical basis, but finds the concern resolved due to a lack of consequence. The following technical concerns remain: (1) there is a lack of data on brine encounters and non-encounters in the vicinity of the WIPP Site to support the geostatistical analysis, and the adopted probability of 8% appears to be quite sensitive to this lack; (2) the Panel is not confident that non-reported brine can be assumed to be a “no hit”; (3) the concept that a borehole can miss an underlying brine reservoir because of vertical fracturing is conceptually reasonable but lacks quantitative support, yet it apparently provides the primary basis for discounting the quantitative value of the TDEM data; (4) the correlation between reservoir occurrence and geologic structure is conceptually reasonable but ignores other potential correlations; and (5) not enough geological information exists at the site to support such correlations.

A lack of consequence was demonstrated by DOE for the third concern by comparing the long-term effects on the repository and on spallings releases of E1 and E2 intrusions. These comparisons are intended to show that the differences between a reservoir hit and no-hit are not highly significant. Noting that the total number of boreholes penetrating the site is unchanged by this issue, by inference the differences created by increasing the number of hits and decreasing the number of no-hits should also not be significant. The differences between E1 and E2 intrusions are illustrated in Figures 3-10 through 3-18. The net brine inflow into the waste panel for E1 and E2 penetrations at 350 years is shown in Figures 3-10and 3-11. While the early-time results differ, the longer-term results are similar, although the net inflow is on the average about

1,000 m^3 higher for an E1 than an E2. The volume-averaged brine saturation in the waste panel for E1 and E2 penetrations at 350 years is shown Figures 3-12 and 3-13. Here the results are similar for both the short- and long-term, although the number of lower saturation, outlying curves is smaller for the E1 than the E2 intrusions. Cumulative brine flow up the borehole at the bottom of the waste panel for an E1 penetration at 350 years is shown in Figure 3-14. Because the E2 borehole does not encounter a brine pocket, the corresponding E2 flow would be zero and the figure shows the incremental brine available to the repository from an E1 intrusion. Although the maximum volume in excess of 50,000 m^3 is significant, the volume is more typically less than 10,000 m^3 and is not significant in comparison with the overall volume of brine potentially available to the repository (see Section 3.12). The volume-averaged porosity in the waste panel for E1 and E2 intrusions at 350 years is shown in Figures 3-15 and 3-16. The difference between the curves is negligible. The total gas generated in the entire repository is shown for E1 and E2 intrusions at 350 years in Figures 3-17 and 3-18. Again, the difference is negligible. Spallings releases were also reviewed by the Panel for second E1 and E2 intrusions (note that spallings releases for first intrusions would be identical for E1s and E2s).

Figure 3-10. Net brine inflow into waste panel for E1 penetration at 350 years. Not available.(15)

Figure 3-11. Net brine inflow into waste panel for E2 penetration at 350 years. Not available.(16)

Figure 3-12. Volume-averaged brine saturation in waste panel for E1 penetration at 350 years. Not available.(17)

Figure 3-13. Volume-averaged brine saturation in waste panel for E2 penetration at 350 years. Not available.(18)

Figure 3-14. Cumulative brine flow up borehole at bottom of waste panel for E1 penetration at 350 years. Not available.(19)

Figure 3-15. Volume-averaged porosity in waste panel for E1 intrusion at 350 years. Not available.(20)

Figure 3-16. Volume-averaged porosity in waste panel for E2 intrusion at 350 years. Not available.(21)

Figure 3-17. Total gas generated for E1 intrusion at 350 years. Not available.(22)

Figure 3-18. Total gas generated for E2 intrusion at 350 years. Not available.(23)

Because of the moderating effect of gas pressure reduction following the first intrusions, the differences between spallings releases for the second intrusions are not significant. In summary, the Panel agrees that the differences between E1 and E2 intrusions for key repository conditions and performance criteria are small and finds the DOE response to be acceptable on the basis of a lack of significant consequence. However, if subsequent model modifications result in significantly smaller fluid volumes in the repository, the significance of this issue should be reevaluated.

In summary, the Panel finds that each of the three key concerns identified for the Castile and Brine Reservoir model in July 1996 has been resolved.

3.17. Multiple Intrusions

No key concerns were identified for the Multiple Intrusions model in the Panel's July 1996 report.

3.17.1. Model Description

The number of reference conditions for determining releases to the Culebra was reduced from 14 to seven since the July 1996 Panel report was issued.

3.17.2. Review of Criteria

The Panel does not expect the reduction in the number of reference conditions to significantly affect modeling results, and finds the change acceptable.

3.18. Climate Change

3.18.1. Model Description

The description of the Climate Change conceptual model and use of the climate index remains substantively unchanged from the July 1996 review. The model continues to be adequate.

3.18.2. Review of Criteria

The review of criteria for the Climate Change model remains unchanged; however, two issues previously identified for this model were reviewed based on new information received.

3.18.2.1. Summary of Issues

The following two issues related to climate change were reviewed.

1) The absence of a consideration of vertical leakage in the Culebra, which might be considerably enhanced by future, more humid climatic conditions, may overlook significant effects on Culebra flow.

2) The potential change in flow directions in the Culebra associated with future wet climates may impact releases through the Culebra.

3.18.2.2. Summary of New Information

Several conversations with SNL personnel confirmed that the vertical leakage issue has not been specifically addressed. New discussions in the CCA documents address changes in flow direction noted in three-dimensional simulations associated with future wet climates. These changes were excluded from PA modeling for computational efficiency and because the changes in direction were toward regions of lower conductivities.

3.18.2.3. Panel Review of New Information

The FEP NS-9, SMOR of September 21, 1995, included in the recent materials provided to the Panel as CCA Appendix MASS, Attachment 15-7, states that vertical leakage into the Culebra is ignored in flow and transport calculations. The SMOR also states that the basis for the assumption that the two-dimensional model and its boundary conditions adequately represent flow-conditions in the Culebra has not been "systematically investigated or documented." The principles of regional groundwater flow in layered sediments suggest that vertical leakage may make a significant contribution to total inflow to the Culebra within the site area boundaries. While there is limited information describing the leakage, ignoring substantial leakage could introduce error into calibrated T fields, and the resulting two-dimensional flow fields may be erroneous.

While the FEP was reviewed by the Panel earlier, prior to preparing the Conceptual Model Peer Review Report of July 1996, the fact that the Culebra conceptual model was found to be inadequate (but inconsequential since the hydrologic data base supported numerical modeling) precluded further serious inquiry. The Panel's stated lack of suitability of the two-dimensional model for determining boundary conditions and estimating changes in the boundary conditions over time, and the absence of calculations supporting the assumed conditions, re-emphasize this source of uncertainty in the Culebra flow and transport calculations.

Additional calculations with GRASP-INV that would evaluate the sensitivity of T fields, release paths, and travel times to vertical leakage are planned, but are not complete at this time. Preliminary, one-dimensional calculations (not QA[d]) indicate that T field impacts would be less than 10%, although no inverse solution of the T fields has been completed. There are neither preliminary calculations nor reasoned arguments of sufficient strength to judge the impact of the issue with respect to flow fields. In summary, the Panel concludes that there are no appropriate supporting calculations or sufficient reasoned arguments to exclude vertical recharge from flow and transport modeling in the Culebra.

New discussions in CCA documents and additional documents made available to the Panel since the July 1996 Conceptual Model Peer Review Report emphasize potential changes in flow directions in the Culebra associated with future wet climates. The CCA (October 1996, Chapter 6, Section 6.4.9) states that changes in flow direction were noted in three-dimensional simulations associated with future wet climates. It also states that such changes were excluded from modeling for computational efficiency. The only support of the exclusion is the conclusion that the flow direction change is in the direction of lower conductivities and considering only the most conductive portion of the Culebra is conservative. The CCA Appendix MASS 14.2 and 17.1 also discuss changes in flow direction in the Culebra associated with future wet climates and state that the changes are not considered in modeling.

While the new discussions and additional documents mentioned above emphasize the potential for flow direction change, there are no new, reasoned arguments or PA calculations to support the conclusions that the impacts of flow direction change are insignificant. SAND96-2133 is a recent (since the July 1996 Panel report) publication that summarizes the role of the regional

groundwater flow model in characterizing Culebra groundwater flow under various climatic conditions. It describes how the three-dimensional (3-D) regional model simulates changes in flow direction (flow paths) resulting from increased recharge during a future wet climate. The two-dimensional (2-D) model implements the increase through a spatially invariant surface function that does not require the precise definition of recharge points and locational inflows to the system. The resolution of the 3-D model includes only nine nodes within the site/regulatory boundary and therefore, the 2-D model, using numerous nodes, is employed to display the flow paths. The 2-D model is forced to display the flow paths simulated by the 3-D model by using boundary conditions and T fields from that model. As presented in Appendix MASS Attachment 15-7, the 2-D model is, at this point, well suited for the analysis of flow and transport, given the boundary conditions specified to produce the appropriate flow paths. The 2-D model is not suited to determining boundary conditions for climatic events and recharge conditions because those conditions might change over time.

The decision not to include flow direction change as a component of the Climate Change conceptual model is based on the reasoned argument that as the flow direction changes from a southeasterly to a southwesterly or westerly direction, the flow encounters lower permeability zones. With this illustration, it is considered conservative to allow the increased flow velocities associated with future wet climate scenarios to occur in the more permeable zones (more transmissive parts of the T fields). In addition, since performance assessment calculations include no realization where there is a release at the regulatory boundary under the conservative conditions, there is no consequence to excluding flow direction change from the simulations.

In the absence of specific PA calculations addressing the two remaining issues pertinent to this model, the reasoned arguments that the effect of both issues is small and that the PA calculations would not be sensitive to potential flow changes of the magnitude caused by these climatic responses at the regulatory boundary are accepted.

3.19. Creep Closure

There were no changes to this model and it continues to be acceptable for implementation.

3.20. Shafts and Shaft Seals

There were no changes identified for this model and it remains adequate for implementation.

3.21. Gas Generation

3.21.1. Model Description

There were no identified changes for this model. Additional information available since the Panel's July 1996 report is provided by performance assessment results and includes families of CCDFs, sensitivity studies among key parameters, and results related to gas generation. In particular, the results indicate that over 10,000 years, on the average less than 50% of the iron in

the repository is corroded. This means that hydrogen generation is not limited by the amount of iron present but by other parameters, such as the amount of brine available. Also, the gas generated is sufficient to reach 12 MPa in many realizations, which is the value that would open and sequester additional gas in marker beds. Additional results depict the pressure after an initial borehole intrusion, indicating that even with introduction of Castile brine into the repository, subsequent pressures are substantially vented up the initial borehole. This information is useful in putting the output of the Gas Generation model in perspective with the results of the other linked models.

3.21.2. Review of Criteria

During the initial review, significant uncertainties precluded definite conclusions on some of the evaluation criteria, particularly Adequacy of Application, Accuracy of Results, and Validity of Conclusions. Four significant issues were raised, and the Panel concluded that without resolution of these issues, a conclusion on model adequacy and validity of conclusions would be speculative. The Panel therefore stated that the Gas Generation model was not adequate for implementation. The additional information now available, coupled with the responses to the Panel's specific findings, assisted the Panel in drawing conclusions on these criteria.

3.21.3. Review of Responses to Panel Findings of July 1996

The Panel issues, a summary of the DOE response, and the Panel assessment of the responses are provided below.

3.21.3.1. Panel Findings

- Analysis of hydrogen generation by corrosion of metals other than the steel in the waste is inadequate. Ignoring gases generated by corrosion of other metals could result in underestimating the gas pressure in the repository.
- Temperature increases in the repository due to corrosion and microbial degradation are not sufficiently analyzed or characterized. Higher ambient repository temperatures could increase the rates of chemical reactions, fluid flow, and halite creep.
- Due to uncertainties about the effectiveness of the magnesium oxide getter to completely remove CO_2, significant uncertainties exist regarding pH, CO_2 pressure, and actinide solubilities. The chemical conditions in the repository would significantly change if the MgO did not function as planned, and could result in underestimating radionuclide releases.
- Hydrogen and oxygen gas generation from radiolysis of dissolved and wetted particulate actinides have not been adequately evaluated. Radiolysis of cellulose and plastics without assuming local hydrogen depletion has also not been adequately evaluated. Ignoring the gases generated by these effects could result in underestimating the gas pressure in the

repository.

3.21.3.2. Summary of DOE Responses to Findings

In Section 9 of the CCA and Appendices PEER and MASS, DOE responded to the Panel findings. Relative to the first finding, DOE provided additional information that the aluminum in the waste and steel in the rock bolts would add about 10 to 15% to corrodable metals which could potentially generate hydrogen. However, DOE showed results of the CCA calculations indicating that in all realizations over 10,000 years, the total available corrodable metals in the repository are not consumed due to an insufficient volume of brine inflow into the waste panels. Therefore, the amount of corrosion-produced hydrogen is not affected by not specifically accounting for corrosion of aluminum and rockbolts. Only in the event of borehole intrusions through a panel would gas generation become inventory limited, and only in that panel. However, due to the long-term gas flow out of the borehole, the added gas generation would be vented and not adversely affect repository performance.

Relative to the issue on potential for temperature increases due to exothermic reactions, DOE provided a conservative bounding analysis of corrosion heat generation and microbial heat generation in which water reaction was assumed to all be by corrosion of aluminum, which provides the most exothermic reaction. For this reaction, DOE stated that the maximum short-term temperature rise was estimated to be 5 to 7°K, and this is too small to have any significant effect on repository corrosion processes.

In response to the issue of uncertainties in the effectiveness of the MgO to effectively remove CO_2, DOE stated that the method of MgO emplacement within the waste room would ensure there are no brine flow paths that can bypass the backfill. DOE stated that twice as much MgO would be emplaced to react with the CO_2 produced if all the cellulosics, rubber, and plastics were consumed by microbial degradation. DOE stated that the rate of dissolution of MgO in brine is much faster than required to react with the maximum expected CO_2 generation rate.

In response to the issue regarding added gas generation due to radiolysis of water by undissolved but wetted actinide-containing particles, and due to radiolysis of cellulose and plastics, DOE did a bounding analysis based on the stoichiometry of the various possible reactions. DOE stated that if all the brine consumed by corrosion was instead consumed by radiolysis, twice as much gas would be available from this source. DOE also stated that if radiolysis of cellulose and plastics occurred instead of microbial degradation, twice as much gas would also be available from this source. Any CO_2 produced is assumed to be consumed by MgO. DOE states that the combined effect would result, at most, in a two- to threefold increase in total gas generation. DOE then stated that because at gas pressures above 12.7 MPa, gas would be vented into the interbeds, the maximum repository pressure would not exceed the values previously calculated for performance assessment (16.5 MPa). DOE states that radiolysis could result in pressures sufficient to cause spallings releases (above 8 MPa) in a greater number of realizations. However, DOE asserts this would not cause an increase in direct release because

the data from performance assessment indicate no correlation between spallings releases and repository pressure, no correlation between moles of gas generated and repository pressure, and no correlation between direct brine release volume and repository pressure.

3.21.3.3. Panel Review of Responses

The Panel agrees with the DOE responses to the two Panel issues regarding added metal for corrosion, and the effect of exothermic reactions. The Panel did not accept that no correlation exists between repository pressure and the other parameters but accepts that these relationships do not adversely affect performance assessment. The Panel does not believe that the issue of total and rapid consumption of CO_2 by the MgO getter has been fully resolved, but it has been sufficiently resolved for purposes of the Gas Generation model because all that is needed is to substantially remove CO_2 as a pressure source and not remove all of the CO_2. The Panel believes that DOE has not ruled out the possibility that initial brine contact with the surface of MgO granules could somewhat reduce accessibility to the remaining MgO due to formation of phases having lower density and lower permeability to brine and CO_2, but the Panel believes sufficient access will be present to effectively remove most of the CO_2 produced. The Panel believes that since this is important to overall performance of the repository, not just for CO_2 pressure control, the DOE-planned pilot and engineering scale testing of the MgO backfill can provide the necessary assurance that the system will function as intended.

Regarding the DOE response to the issue of added gas generation if radiolysis were to occur, the Panel believes the DOE response is adequate because radiolysis is not likely to fully replace the other gas-producing mechanisms. The Panel also notes that the DOE has not fully accounted for sequestration of water by MgO, which could reduce the availability of brine needed for corrosion of iron, microbial action, or radiolysis.

In summary, the Panel believes the Gas Generation model is adequate based on the responses provided.

3.22. Chemical Conditions

3.22.1. Model Description

This conceptual model was listed as inadequate in the July 1996 Peer Review Report. Three major issues were identified; the most critical of these was the reliability of MgO as a backfill component. The DOE responses to the issues are discussed in Section 3.22.3. Subsequent to the July 1996 findings, two new pieces of information have been identified that are pertinent to the Chemical Conditions conceptual model: 1) a laboratory scoping study has been performed to identify if MgO mixed with CO_2 in a high ionic strength brine would produce carbonate, and 2) a series of CCDFs were prepared in June 1996 to illustrate repository performance with and without MgO backfill.

3.22.2. Review of Criteria

The first new piece of information provided to the Panel (the results of a scoping MgO experimental study) is reviewed under the criterion of "Validity of Model Assumptions." This experiment was performed to ascertain whether magnesium carbonates could be generated under the most optimum conditions. This same study was described as a precursor to future experiments laid out in a recently approved Test Plan (TP 97-01) intended to provide data needed to characterize the performance issues related to MgO. The scoping study looked for maximum results in a very limited time frame. In essence, MgO pellets were placed in applicable brine solutions (Salado or Castile) in a beaker, and then CO_2 gas was bubbled through the mixture to determine the effect of backfill on pH reduction and what magnesium carbonate phases would be produced.

This preliminary experiment showed some promising results. Two metastable magnesium carbonate phases (dipingite and nesquehonite) were produced under slightly varying initial chemical environments. Furthermore, the studies indicated that over a 13-day period the chemical systems increased in pH by approximately 2 orders of magnitude. Unfortunately, the scoping experiment did not reflect the conditions present in the repository with regard to either chemical parameters (especially fCO_2 and interaction with iron oxides), time (diffusion rates), or physical constraints (orientation of backfill containers, pathways for gaseous reaction). Therefore this scoping experiment does not provide a sufficient basis to conclude that the MgO backfill will perform as indicated by thermodynamic equations, or as assumed in performance assessment.

The second new piece of information was a series of CCDFs produced with and without the addition of MgO backfill. This issue was reviewed under the criterion "Accuracy of Results." Of particular interest are two CCDFs that predict "blowout" releases with and without MgO backfill. The Panel was not provided with the assumptions used in preparing these CCDFs and is not aware how other factors (chemical conditions, gas generation, actinide source terms, transport in Salado or Culebra) were varied in preparing these calculations. Because of this lack of information, the CCDFs did not provide an adequate basis for the Panel to conclude that the addition of MgO backfill was of no consequence to repository performance.

3.22.3. Review of Responses to Panel Findings of July 1996

3.22.3.1. Summary of Findings

Three issues were involved in the determination that this conceptual model was not adequate for implementation. Two of the issues were of relatively minor importance to the acceptability of the model, and are summarized as follows.

- The combined temperature increase (due to radioactive decay and exothermic reactions) and its effect on repository conditions has not been adequately addressed. Significantly higher repository temperatures could accelerate chemical reactions, fluid flow, and halite

creep rates.

- Phase equilibria have not been critically assessed within the chemical parameters of the conceptual model. A major element stable phase that was overlooked could significantly alter the chemical conditions of the repository and vary the actinide source terms.

- The third issue was the concern raised over the use of MgO backfill. As discussed in the original peer review report, the thermodynamic equilibrium equations calculated for MgO reacting with CO_2 to produce magnesium carbonates (magnesite) and thereby buffer the chemical conditions, are reasonable and proper. However, the MgO backfill has not been demonstrated to be able to react completely with CO_2 generated by microbial action. If the MgO backfill did not react as planned, the pH-buffering capability of the repository would be significantly compromised, and could result in underestimating the actinide source term.

3.22.3.2. Summary of DOE Responses to Findings

The responses to this conceptual model that DOE presented to the panel were combined with responses to issues raised in the Gas Generation model. This was unfortunate, in that there are subtle differences in the questions raised. The first two concerns of this model were sufficiently similar to those of the Gas Generation model that the responses were not critically affected. However, the third issue, that of the effectiveness of the backfill, was not fully addressed. The actual DOE responses are summarized below.

DOE responded to the first concern with a series of calculations that centered on exothermic reactions and radioactive decay. The presentation was both thoughtful and appropriate. The final resolution was that there may be a 7° C increase in temperature if all the metal in the repository was aluminum, but that the increase would not affect the outcome of the conceptual model.

The second concern was that of phase stability and equilibria conditions in the repository. This information was thought necessary due to the large amount of MgO that would be emplaced in the waste cells. The phase diagram that was presented was limited to the system MgO-CO_2 (with excess H_2O) and only portrayed stable phases (Figure 3-19).

Figure 3-19. Phase diagram for the MgO - CO_2 system. Not available.(24)

The DOE response to the Panel's concern about MgO was based on two factors: thermodynamic equilibrium and calculations of Mg dissolution rates of the pellets. The theory that MgO would react with water to form $Mg(OH)_2$ and then react with CO_2 gas to create $MgCO_3$ was reviewed, along with the thermodynamic basis for the model. The DOE modeling calculations indicated that the MgO pellets would react completely with CO_2. Equations were developed to calculate the particle radius needed to accommodate the maximum CO_2 generation rate.

3.22.3.3. Panel Review of Responses

The first issue (temperature increases) was reasonably discussed by DOE and an appropriate resolution was obtained.

The second issue (phase equilibria) was not addressed in a vigorous manner. The DOE response on this issue was not exhaustive nor completely representative of the system. A more thorough representation would have been the system MgO-FeO-CaO-NaO-CO_2-Cl_2-SO_4 (with excess H_2O). The phase diagrams did not chart the existence of metastable phases in the system, which would have provided a clear visual representation of solid phases most likely to be formed (such as dipingite and nesquehonite) in low temperature systems. A more exhaustive series of phase diagrams would be extremely informative because metastable phases can exist for extremely long periods of time (millions of years) due to kinetics problems and lack of sufficient energy for transition to stable phases. To summarize, the phase stability discussion presented by DOE was only minimally adequate for the chemical system involved, and would lead to many instances where metastable phases (not discussed) would dominate the reactions. Therefore, the second issue (phase equilibria) was addressed in its most restrictive sense and, although not completely satisfying, the response provided sufficient information to resolve this concern.

The third, and by far most critical concern of the Panel centered around the fact that MgO had not been tested to ascertain its ability to effectively react with CO_2 in the repository system. The ability for the backfill to react properly and completely has ramifications to a multitude of other parameters. The buffering capacity of the backfill would theoretically fix many of the other chemical components such as the actinide source terms and gas generation rates. Such a critical interplay of the effect of MgO backfill on other conceptual models is further discussed in Section 4.

A possible shortcoming was identified in the equation developed to calculate MgO particle radius for dissolution. The value used for the density term was that of periclase (3.53 g/cm^3) when in fact it, would have been much more reasonable to use the density of brucite (2.39 g/cm^3). This difference would have increased the assumed particle radius to 0.55 cm, 1.5 times the radius used in the DOE calculation.

Much more important is the fact that DOE has not investigated diffusion rates into the MgO pellets instead of dissolution rates. This was clearly indicated by the fact that reaction rims were created on the exterior of the pellets used in the scoping experiment described in Section 3.22.2. Although dissolution may be the manner in which reactions could start, as soon as magnesium carbonates are formed on the exterior of the pellets, the dominant process to react the remaining $Mg(OH)_2$ would be diffusion of CO_2 into the interior of the pellets. This diffusion phenomenon has not been quantified by experiments.

The final factor that was not sufficiently investigated was whether the reaction to carbonate could seal off large percentages of the backfill, due to the engineering geometry involved, and render

the unreacted MgO inert. No experiments to date have tried to duplicate the placement of the backfill in the repository and understand the effects of the expected volume increase due to the transition from oxide to carbonate. Such a volume increase may effectively block pathways for the CO_2 to reach the backfill. Once again, this emphasizes the need to understand and quantify the diffusion rates of CO_2 gas through the carbonate and into the pristine backfill material.

Many of the above stated issues are identified as factors to be quantified in the DOE Test Plan discussed in Section 3.22.2. The Panel has performed a cursory review of this Test Plan and believes that sufficient data can be extracted from the experimental results to determine if MgO will completely react with the CO_2 and therefore buffer the chemical conditions of the repository.

The critical issue, whether the backfill will react sufficiently with CO_2 to buffer the chemical system, has not yet been substantiated by experimental physical results that correctly simulate the repository. Because the backfill issue has so many ramifications to other conceptual models, it is critical to demonstrate that this material will in fact work properly. Therefore, the Chemical Conditions conceptual model is still not considered by the Panel to be adequate for its intended use in the performance assessment.

3.23. Dissolved Actinide Source Term

3.23.1. Model Description

In the time period between the Conceptual Models Peer Review Panel's July 1996 report and this supplementary review, the CCA and its Appendix SOTERM were produced. An addition to the original conceptual model is now described in Section SOTERM.5, Role of Organic Ligands. In essence, the model now takes credit for an abundance of dissolved transition metals (Fe, Ni, Cr, Mn) from waste drums and from backfill (Mg) in the repository brine. These cations would compete for binding sites on organic ligands and significantly reduce the ability of the ligands to complex with actinides. The conclusion of this section in Appendix SOTERM is that the organic ligands would not be available to complex with actinides and thus will not be a component of the dissolved actinide source term model.

3.23.2. Review of Criteria

Although it might be questioned how completely cations such as Ni prevent complexation of actinides by organic ligands such as EDTA, the Panel believes that this change to the conceptual model has only a slight bearing on the overall prediction of source term concentrations and is not unduly impacted by the backfill component because most of the cations involved with the ligands are transition metals. Therefore, this is viewed as a minor change that only impacts the model in a conservative manner. The Panel has concluded that this is not a significant change to the conceptual model and therefore the model remains adequate.

3.24. Colloidal Actinide Source Term

3.24.1. Model Description

A change to the conceptual model was indicated in Appendix SOTERM in Section SOTERM 6.3.3.1 where it is stated " …the high concentrations of Mg^{2+} in solution due to the presence of MgO backfill will compete with actinides for binding sites on humic substances and reduce the actinide uptake." This statement seems to imply that the source term value used is conservative and in essence overestimates the true humic component source term.

3.24.2. Review of Criteria

This model was originally determined to be adequate for implementation. Although there is now a statement that magnesium in solution will compete for humic acid binding sites, DOE did not take credit for this effect and therefore the model is still deemed adequate.

4.0 INTERRELATIONSHIPS AMONG CONCEPTUAL MODELS AND THEIR SENSITIVITY IN THE PERFORMANCE ASSESSMENT

4.1. Introduction

Most of the models reviewed by the Panel can be organized into a few interrelated groupings based on critical performance issues. Some of those groupings contain some of the same models as others, and some overlapping of issues is necessary. Gas pressures are the source of the driving energy for movement of radionuclides out of the repository, in most cases. The porosity surface look-up table integrates numerous and diverse parameters which interrelate repository volume and the gas pressure history in the repository. The porosity surface calculation, illustrated in Table 4.1, was reviewed and approved by the Engineering Systems Peer Panel Review. This table provides an organizing structure for the consideration of its component parameters.

Table 4.1. Porosity Surface Calculation — Gas Generation and Repository Gas Pressure History

Gas Generation Model	→	**Porosity Surface Calculation** →		**Performance Assessment Gas Pressure History**
Parameters		**Parameters and Models**		**Calculations**
Waste Composition Brine Inflow Volumes Brine Composition Corrosion/Degradation Reactions MgO Effects		Room Closure Model Room Initial Dimensions Waste Initial Dimensions SANTOS Computational Configuration Halite Elastic Properties Halite Creep Properties Argillaceous Halite Creep Properties Anhydrite Properties Waste Composition Waste Solid Densities Waste Volume Fractions Waste Mechanical Properties Waste Pressure - Volume Relation Gas Generation - Constant Saturation Variant		BRAGFLO Code
Most of the parameters listed were reviewed by other panels.				

Gas pressure is also a critical element in the inflow of brine into the repository. High gas pressures retard the flow of brine from the surrounding Salado Formation through the disturbed rock zone, the Salado interbeds, and the matrix permeability of the impure halite. Brine is necessary to the reaction of the waste to generate gas. The coupling of gas pressure and brine inflow to the performance of the repository is illustrated in Table 4.2. The result of performance assessment calculations (100 realizations, using sampled values) is that the fraction of waste steel reacted may range from 0% to 100%. Waste steel is an important element in the gas generation model. It is a sensitive indicator of the overall waste reaction and the physical state of the waste. The great variance in this sensitive performance result is caused by the complex variability of the long chain of component models and the uncertainty in predicting the gas pressure history of the repository.

Table 4.2. Model Chain — Brine Inflow

Brine Availability	Processes	PA Results

The models show that there is enough brine available from the Salado Formation by flow through interbeds due to the permeability of the impure halite and by drainage of the DRZ to react all waste.	Gas pressure (limited by initiation pressure of interbeds) resists brine inflow → ← Inflow through DRZ, interbeds, from halite, and due to intrusion (long-term)	Wide variation in degree of brine consumption by chemical reactions in waste (Figures 4-1 and 4-2)
Models	**Models, Parameters, and Calculations**	**Calculations**
Salado Impure Halite Disturbed Rock Zone Salado Interbeds Repository Fluid Flow	Porosity Surface Calculations Salado Interbeds Gas Generation *Chemical Conditions Creep Closure DRZ Repository Fluid Flow Multiple Intrusions Exploration Boreholes SECO Code BRAGFLO Code	BRAGFLO code
*Model found inadequate for implementation and to have consequence in PA calculations.		

It is the opinion of the Panel that the structure of the conceptual model integration used in performance assessment is reasonable. The source of uncertainty lies primarily in the individual models and is partly mitigated by the use of sampling techniques and by the interrelationships of model sensitivities within the performance assessment calculations in the cases of the conceptual models which are adequate for implementation.

There are four principal conceptual pathways for release of radionuclides to the accessible environment. Release through the Salado interbeds beneath the repository due to the transport of repository brine to the edge of the land withdrawal boundary is considered unlikely due to the very large storage volume available in the interbeds. All other credible release scenarios are the result of human intrusion by drilling through the repository. Release to the surface as a consequence of drilling (Table 4.3), release through the Culebra Dolomite due to long-term flow up an intrusion borehole (Table 4.4), and release through units above the Culebra (Magenta Dolomite and Dewey Lake Redbeds, Table 4.5) are the remaining credible pathways.

Table 4.3. Model Chain — Surface Releases During Drilling

PA Calculations:	Processes	Potential Impact
Source and Volume of Waste		

1. Solid Waste Carried to Surface 2. Dissolved Radionuclides Carried To Surface	Transport of solid, dissolved, and colloidal waste and waste products up borehole annulus during intrusion.	PA calculations predict that releases of waste are probable

Models and Calculations

Cuttings and Cavings
*Spallings
Porosity Surface Calculation
Gas Generation
Direct Brine Release
Multiple Intrusions
Repository Fluid Flow
Exploration Borehole
Castile and Brine Reservoir
*Chemical Conditions
Dissolved Actinide Source Term
Colloidal Actinide Source Term
Creep Closure

* Model found inadequate for implementation and to have consequences for PA calculations.

Table 4.4. Model Chain — Release Through Culebra

PA Calculations: Volume of Brine at Culebra in Borehole →	**PA Calculations: Brine Intrusion Into Culebra** →	**PA Calculations: Radionuclide Content of Brine** →	**PA Calculations: Transport in Culebra**
Models and Parameters	**Models and Parameters**	**Models and Parameters**	**Models and Parameters**
BRAGFLO Code Repository Fluid Flow Exploration Borehole Castile Brine Reservoirs Porosity Surface Calculations Gas Generation Exploration Boreholes Multiple Intrusions Creep Closure *Chemical Conditions	Culebra Hydrologic Model BRAGFLO-SECO Interface PA Calculations of Uphole and Downhole Flow Rates Climate Change	Dissolved Actinide Source Term PA Calculations of Uphole and Downhole Flow Rates	SECO Code Sorption Flow Scenario 1. Advection 2. Diffusion Culebra Hydrologic Model K_ds

*Model found inadequate for implementation and to have consequences for PA calculations

Table 4.5. Model Chain — Releases to Units Above Culebra

Issue	Additional Considerations
Performance assessment calculations show insignificant brine available above Culebra.	Intrusion into Magenta and Dewey Lake Redbeds may be inhibited by low permeability (Magenta) and filling of fractures (Dewey Lake Redbeds). Transport in the Dewey Lake Redbeds maybe inhibited by large hypothetical retardation on ferrous minerals.
Models and Parameters	
BRAGFLO Code Porosity Surface Calculation Repository Fluid Flow Exploration Boreholes Multiple Intrusions Gas Generation *Chemical Conditions PA Calculations (BRAGFLO) Brine Down Hole Brine Up Hole Injection of Brine into Culebra Room Closure Culebra Hydrologic Model	
* Model found inadequate for implementation and to have consequences for PA calculations.	

Sensitivities, variability, and adequacy of individual conceptual models are discussed in Section 3. The sensitivity of the performance of the repository to gas pressure history, brine availability, and the models impacting the three intrusion-related release scenarios are discussed here.

4.2. Gas Pressure History — Porosity Surface Calculations and the Gas Generation Model

The porosity surface calculation is made with the SANTOS code prior to the performance assessment computations done with the BRAGFLO code. The porosity surface calculation describes the changes in repository volume with time for 13 instances of gas generation rate versus room closure resulting from halite creep. Room initial dimensions, waste dimensions, halite elastic and creep properties, waste densities, mechanical properties, and pressure/volume relations and gas generation rates form the Gas Generation model assuming complete and

constant saturation are included as parameters. Brine inflow is not included in the porosity surface but is an important part of the Gas Generation model.

The porosity surface permits the calculation of repository volumes for gas pressures at thirteen times (SANTOS code). The integration of repository volume with gas generation history is accomplished in the performance assessment calculation (BRAGFLO code) by matching gas generation with the appropriate time steps generated in the porosity surface calculation.

The Gas Generation model combines the generation of gas through corrosion of metals and microbial degradation of organic constituents. Both processes are directly dependent on the volumes and compositions of brine entering the repository. During the first round of reviews, the Gas Generation model was found to be inadequate for implementation; however, subsequent review of additional information has shown that the conceptual model is adequate. The addition of MgO backfill is expected to reduce gas generation. The interaction between gas generation and brine inflow is difficult to define with respect to gas pressure. This is because of the absence of clearly defined capillary pressures for Salado halite and the multivariate nature of the repository volume/gas pressure interrelationships within the porosity surface calculation. This wide range of uncertainty is reflected in the wide range of degrees of probable waste degradation recognized in the performance assessment calculations (Figures 4-1 and 4-2).

In the undisturbed scenario, the variation of gas pressure due to brine inflow history has no effect on any probable release. In the release scenarios related to human intrusion, the gas pressure history is related to the potential impact of releases in both the short and long terms.

4.3. Release Through the Culebra

The transport of contaminated brine up an intrusion borehole in the long term is the primary source of radionuclides to be transported in the Culebra. Brine transport up the borehole (and down from units above the Culebra) is calculated in the performance assessment process using the BRAGFLO code. Transport evaluation is supported by SECO code calculations of transport within the Culebra, which neglect the brine volume injected into the Culebra. SNL asserts that this computational method has no effect on transport over the distance from the waste panels to the site boundary.

Vertical leakage from units overlying the Culebra may, especially if enhanced by water wells, raise the pressure in the Culebra. The Culebra is at present underpressured with respect to all other stratigraphic units above the Salado. This underpressure enhances the injection of brine into the Culebra and also helps to explain the insignificance of brine from the borehole in the overall flow in the Culebra. No significant volume of brine rises above the Culebra in the intrusion scenarios based on contemporary conditions. Extensive water well development and climate change are future events that may impact this aspect of Culebra hydrology.

Figure 4-1. Fraction of steel remaining in waste panel for undisturbed conditions. Not available.(25)

Figure 4-2. Fraction of steel remaining in waste panel for an E1 intrusion at 1000 years into the waste

panel. Not available.(26)

There are four general sets of model interactions that impact transport of radionuclides in the Culebra. These are: 1) models contributing to brine volumes, gas pressures, and long-term flow up the borehole to the Culebra, 2) injection of brine from the borehole into the Culebra (entirely performance assessment calculations), 3) the Culebra hydrologic flow model and influences on that model such as climate change, and 4) flow scenarios and K_d values for retardation in the Culebra. There are significant uncertainties in each of these areas such as the influence of MgO backfill on gas generation, climate change, brine flows resulting from penetration of brine reservoirs below the repository, local impacts of brine injection from the borehole, and the proportioning of flow processes on retardation. In general, however, these uncertainties are either small in comparison to the transport distance from the waste panel to the site boundary or, as in the case of the MgO backfill, may have only beneficial impacts. SNL asserts that retardation in the Culebra is sufficient to prevent release even in the case of maximum brine flow and injection into the Culebra. Changes in flow direction resulting from climate change, related increases in recharge, changes in vertical leakage due to water well development to the Culebra, and the impact of brine injection on flow in the Culebra have not been specifically evaluated. Qualitative arguments that these sources of uncertainty are insignificant to a release through the Culebra from the waste panel area to the site boundary have been presented by SNL.

4.4. Release To Units Above The Culebra

The only two stratigraphic units above the Culebra that are permeable enough to cause concern about releases are the Magenta Dolomite and the Dewey Lake Redbeds. The primary reason for a finding of no consequence of release from these units is the performance assessment finding that no significant volume of brine rises past the Culebra in the intrusion borehole. The calculations used median and minimum Culebra permeabilities from the Culebra hydrologic model (T fields). The principal sources of uncertainty in the performance assessment calculation are those associated with models impacting brine volumes and gas pressures in the repository, which are listed in Table 4.2. Low permeabilities measured in the site region in the Magenta and gypsum-filled fractures in the lower Dewey Lake Redbeds are possible additional sources of protection against releases through these units.

4.5. Surface Releases

Four areas of model interactions are sources of uncertainty in the surface releases of radionuclides: 1) gas pressure and brine volumes in the repository, discussed elsewhere; 2) effectiveness of entrainment and transport of solid waste in brine or gas flowing up the borehole annulus; 3) solubility of radionuclides and the formation of actinide-bearing colloids in the brine in the repository; and 4) the effectiveness of the cutting/cavings and spallings processes to provide solid waste particles of an appropriate size for uphole transport.

The effectiveness of transport of both the solid and dissolved fractions of the radionuclides

depends primarily on the velocity of gas or brine flow up the borehole annulus after the drilling mud has been blown out of the hole by repository gas. This set of scenarios has been treated in the performance assessment calculation and the Direct Brine Release model and gets its uncertainty mostly from the uncertainties in gas and brine pressure and volume.

The solubility of radionuclides and the formation of colloids have been adequately treated in the source term models, although the impacts on these models of MgO backfill have not been fully assessed in the Chemical Conditions model. The volumes of particulate waste generated by drilling are adequately addressed by the Cuttings/Cavings model. The volume of solid waste particles generated by spalling is not adequately resolved by the model at this time.

Spalling is sensitive to gas pressure, the moisture content of the waste, and the physical state of the degraded waste. The physical state of the waste, particularly grain size, cementation, and cohesion, are difficult to characterize. SNL has attempted to limit these parameters and to calculate waste release due to spalling through a model which relies on the erosion of channel-shaped voids in the waste by gas overflow. The Panel has found the model inadequate for implementation. The spalling process is also sensitive to the uncertainties contained in the gas pressure history of the repository. SNL is planning further laboratory experiments to support the modeling effort and has stated that the cementing of waste by the reaction with the MgO backfill may have beneficial effects on waste spalling.

Spalling is an important component of the release to the surface. The Panel believes that the development and testing of the Spallings model is currently inadequate to support its use in performance assessment.

4.6. Sensitivity of Performance Assessment to Conceptual Model Acceptability

Three classes of model acceptability result from the peer review process:

1) Model Acceptable. Some issues may be noted, but they are not important to the final application of the model.

2) Model Unacceptable and Has Performance Assessment Consequences. Two models were found unacceptable. The Spallings model appears to be incomplete and is not confirmed by experimental evidence or numerical analysis. Several issues and sub-issues remain to be addressed with respect to this model. This model has significant impact on release of radionuclides to the surface, the most significant release issue at WIPP.

   The Chemical Conditions model is unacceptable because it does not address the impact of MgO backfill on chemical conditions in the repository. Chemical conditions are a critical factor in the results of the application of several other models. These include: Gas Generation, Repository Fluid Flow, Actinide Source Terms, Direct Brine Release, and others. Chemical conditions indirectly impact the transport models and the other models

related to surface release.

3) Model Unacceptable With No Performance Assessment Consequence. The Culebra Hydrogeology model was found unacceptable, but regional elements of the model, combined with an empirical site and site region hydrologic flow model based on testing data, have adequately replaced the missing elements of the conceptual model. The numerical hydrologic flow model and selected PA results were reviewed during this phase of review and found to be adequate.

   The Castile and Brine Reservoir model was unacceptable because the characterization of probability of reservoir interception was not adequately supported. However, the sensitivity of the performance assessment calculations to that probability were so small that the use of either the maximum or minimum conceptually defensible numbers for the probability of an intercept did not affect the computed brine volumes entering the repository. Such findings of no consequence are based on the insensitivity of the performance assessment model to the results of the conceptual model implementation within conceptually defensible limits.

   Some models, as in the case of the Exploration Borehole model, were shown to be of no consequence on the basis of conceptual elimination of the impact of specific issues. In this case, the lower borehole plug could not be shown to persist over the life of the repository. The potential consequence in this case is flow down the borehole to the Bell Canyon Formation and through this formation to the boundary of the accessible environment. A side calculation was made which shows that transport in the Bell Canyon is low enough that no radionuclides would be expected to be transported to the accessible environment if the lower borehole plug fails.

   Additionally, models were found to be acceptable based on no consequence due to low drilling rates in early repository time (for example, the assumption of constant permeability for repository waste), and models were found to be acceptable based on no consequence due to the relatively low additional brine volumes they would provide to the repository (for example, the assumption that borehole penetrations in the operations and experimental areas can be ignored).

In general, when a model is found to be inadequate it affects a chain of models bearing on a release scenario. Tables 4.2 through 4.5(27) are intended to show the associations that lead to these shared impacts for the release scenarios or parts of release scenarios that the Panel believes are the most important. No attempt has been made to propagate the resulting uncertainties through the performance assessment calculations. Such an evaluation is beyond the scope of the Panel's responsibilities. However, two generalities can be drawn with respect to overall model integration. First, the structure of model interactions used in the PA calculations seems reasonable. Second, the variability of sampled parameters in the PA plots appears to capture the distribution of those parameters, as suggested by an inspection of model uncertainties and the complexity of sequences of uncertain models. An example is the wide

distribution of waste consumption completeness represented in Figures 4-1 and 4-2. This result is related to uncertainties in the supporting models, which themselves have wide distributions of uncertain parameters. The wide variability of waste consumption results (0% to 100% consumed) appears to adequately reflect the accumulation of conceptually implied uncertainties in the supporting database.

4.7. Summary

In general, the structure of model interactions seems reasonable. The mitigating effect of sampling of uncertain variables and the sensitivity structure of the PA model may have made the compound uncertainties of complex chains of models manageable in the final performance assessment result. It is important that the effects of all future model changes be evaluated in the context of the integration of all models. This is especially important in the cases of models that were found to be inadequate but of no consequence to performance assessment. Shifts in the results of adequate models may change the sensitivity of performance assessment to models presently thought to be inconsequential.

5.0 SUMMARY OF REMAINING ISSUES

This section presents a summary of the supplementary evaluations of the WIPP Conceptual Models Peer Review Panel performed between October and December 1996. As stated in the Panel's July 1996 report, over 20 years of scientific effort have been expended on the WIPP characterization project and it is beyond the scope of the Panel to summarize all of the positive work that has been performed. This section is not intended to be a reiteration of comments and discussions on the 24 individual conceptual models, but instead to provide an overview of conclusions from the supplemental evaluations. For those models found to remain inadequate, the key concerns of the Panel are summarized. Of the remaining models, those that were found to have important technical concerns, but were nevertheless found to be adequate on the basis of a lack of consequence in modeling results, are also identified and discussed. The Panel believes that the opportunity to reconvene and review the final conceptual models, as developed by the DOE and implemented in the October 1996 Compliance Certification Application for the WIPP, has been beneficial. The DOE responses to the Panel's initial concerns, the changes that were made to the models since the Panel's July 1996 report was prepared, and the results obtained from implementing the models in performance assessment have enabled the Panel to resolve its concerns regarding all but two of the 11 models that were previously identified as inadequate. In addition, the new information obtained during this supplemental evaluation did not change the Panel's previous conclusions for the 13 models that were found to be adequate.

New information relative to the conceptual models was reviewed by the Panel and the adequacy of each model was again evaluated using the same criteria as applied in the initial review. Of the 24 models, 22 were found to be adequate for implementation in performance assessment for the WIPP. For most of the adequate models, minor Panel concerns still remain and are identified in

Section 3 of this report and of the July 1996 Panel report. These concerns primarily address issues of documentation gaps and issues with features, events, or processes that were not considered sufficiently important to find the model inadequate. The 22 models found to be adequate are listed below, and those that have important residual technical concerns but were found adequate based on a lack of consequence are identified.

1. Disposal System Geometry
2. Culebra Hydrogeology*
3. Repository Fluid Flow*
4. Salado
5. Impure Halite
6. Salado Interbeds
7. Disturbed Rock Zone
8. Actinide Transport in the Salado
9. Units above the Salado*
10. Transport of Dissolved Actinides in the Culebra
11. Transport of Colloidal Actinides in the Culebra
12. Exploration Boreholes*
13. Cuttings/Cavings
14. Direct Brine Release*
15. Castile and Brine Reservoir*
16. Multiple Intrusions
17. Climate Change
18. Creep Closure
19. Shafts and Shaft Seals
20. Gas Generation
21. Dissolved Actinide Source Term
22. Colloidal Actinide Source Term

Models identified with an asterisk (*) in the foregoing list had important technical concerns but were found to be adequate on the basis of lack of significant consequence to performance

assessment. A brief statement of the basis for approving each of these models is provided below.

Culebra Hydrogeology. No conceptual model was developed that explains the variability of hydrologic properties and processes in the Culebra at a scale that is useful in correlating those properties in the numerical hydrologic flow model. This model was found adequate because an extensive hydrologic testing data base and an adequate numerical flow model were developed as a substitute to the conceptual model for performance assessment purposes.

Repository Fluid Flow. The two-dimensional numerical implementation of the conceptual model may unrealistically restrict brine movement between the waste panels and the anhydrite interbeds in undisturbed scenarios because of the shallow depths of the borehole and shaft model cells. This model was found adequate because the error in computed flow volumes appears to be small in relation to the total volume of brine available to the undisturbed repository from early-time drainage of the DRZ.

Units above the Salado. The conceptual model and the testing data base are inadequate to exclude the Dewey Lake Redbeds and the Magenta Dolomites as potential transport pathways for radionuclides in the event of an intrusion. This model was found adequate because performance assessment results indicate that the quantity of radionuclides reaching the region above the Culebra is negligible even under low transmissivity assumptions for the Culebra, and the hydrologic characteristics of the Dewey Lake Redbeds and Magenta units are therefore of no consequence to performance assessment.

Exploration Boreholes. The assumption that shorter (40 m) borehole plugs beneath the repository horizon will have a useful life of at least 10,000 years has not been adequately supported. This model was found adequate based on an estimated groundwater travel time in the Bell Canyon to the accessible environment in excess of 10,000 years, and leakage of small amounts of repository brine into that formation would therefore be of no consequence to performance assessment.

Direct Brine Release. The direct discharge of waste materials to the ground surface through enhanced cavings-type borehole wall erosion accompanying discharge of Castile reservoir brine during drilling has not been included in performance assessment. This model was found adequate based on DOE calculations showing that the incremental waste volume released over the regulatory period is small compared with the volumes currently estimated in performance assessment modeling.

Radionuclide transport through entrainment of waste solids in rapid, two-phase liquid/gas releases during drilling was evaluated by DOE using the Spallings model. DOE concluded it was of lower consequence than entrainment of solids in gas releases. Although the approach taken and results obtained support a conclusion of no consequence, the technical adequacy of the Spallings model itself has been questioned by the Panel and this transport concern should be reevaluated at the time the Spallings model is determined to be appropriate for performance

assessment.

Castile and Brine Reservoir. The expected probability of 8% of encountering pressurized brine beneath the waste panels has not been adequately supported. DOE suggested that analyzing the differences between E1 and E2 borehole intrusions provides a basis for estimating the consequences of assuming larger probabilities. This model was found adequate based on a review of such differences, which showed that effects on key repository conditions and surface releases were small and of low consequence to performance assessment modeling.

The Panel wishes to emphasize that models were necessarily found adequate because of lack of consequence on an essentially independent basis. Determining the cumulative effect of a series of low consequence events on overall performance assessment results requires additional performance assessment modeling because of the complex interrelationships among the models and stochastic processes. Although many of the technical concerns for models found adequate on the basis of a lack of significant consequence could each result in increasing releases by a small amount, the Panel believes that unless changes are made in the modeling assumptions that significantly affect key model elements, such as repository pressure or brine saturation histories, the applied institutional controls, or the role of the Culebra as a transport pathway, the cumulative effect of these concerns with models found adequate would not significantly affect the overall performance assessment results.

The two models found to be inadequate are presented in the following paragraphs with brief discussions of the key concerns identified by the Panel. Although the consequences of the Panel's technical concerns for these two models are not known, they are believed by the Panel to be consequential because they significantly impact the release processes found in modeling results to be most significant to overall system performance. Comprehensive discussions of the specific issues on these models that were not adequately addressed are presented in Section 3.

Spallings. The number of remaining concerns for the Spallings model is extensive. Although these concerns have been generalized below for purposes of this summary, they should not be considered the Panel's formal statements of the Spallings issues. Such statements are presented in Section 3.

- An adequate basis for the parameters used in the mathematical expression of the model has not been developed. In particular, ignoring capillary forces and correlating tensile strength with surface erosion have not been adequately supported by either first principles or experiment.

- The principal assumptions upon which the mathematical model is based appear to be incomplete. Waste removal by entrainment in gas flow is expected to occur in a highly dynamic sequence principally involving a spalling process driven by gas flow out of the porous waste normal to the eroded surface. Subsequent erosion by gas flow parallel to the eroded surface in pathways that are not expected to be the primary effect controlling the volume of spall, particularly in early times. In addition, the DOE has not adequately

shown that the steady-state assumptions of the model conservatively approximate releases associated with the dynamic process of spall, and the possibility of transonic velocities has apparently not been considered.

- The experiments conducted in support of this model appear to have been designed to reproduce the assumptions upon which the model is based, rather than to simulate the dynamic repository system. Although the experiments may support adoption of specific model parameters, they do not demonstrate that the model adequately represents future states of the repository.

Chemical Conditions. The ability of the MgO backfill to perform as assumed in performance assessment remains a Panel concern, as described below.

- The ability of the MgO backfill to react completely and rapidly with CO_2 to buffer the chemical system and limit actinide solubilities has not been adequately substantiated by experimental physical results that correctly simulate conditions in the repository. Although the pH buffering assumptions are of considerable importance to many other conceptual models, the conclusion that the MgO will in fact perform as assumed has not been adequately supported.

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ACRONYMS

CCA	Compliance Certification Application
CCDF	cumulative complimentary distribution function
CFR	Code of Federal Regulations
CTAC	Carlsbad Technical Assistance Contractor
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
EPA	U.S. Environmental Protection Agency
ERDA	Energy Research and Development Administration
FEP	features, events, and processes
MB	marker bed
PA	performance assessment
SNL	Sandia National Laboratories
TP	test plan
TZ	Transition Zone
USGS	United States Geological Survey
WIPP	Waste Isolation Pilot Plant

II-G-22: Conceptual Models Third Supplementary Peer Review Report, April 1997.

A Peer Review
Conducted By

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for

U.S. Department of Energy
Carlsbad Area Office
Office of Regulatory Compliance

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EXECUTIVE SUMMARY

This report is a third supplement to a July 1996 report that presented the results of an independent technical peer review of the adequacy of 24 conceptual models representing features, events and processes involved in assessing the long-term performance of the Waste Isolation Pilot Plant (WIPP). The peer review was initially conducted from April through June 1996 at the U.S. Department of Energy's (DOE's) Sandia National Laboratories by a six-member interdisciplinary Review Panel having the requisite broad experience to address the range of issues associated with waste isolation over the 10,000-year regulatory time frame. The Panel selection process and the biographies of the Panel members are included in the July 1996 report.

In its January 1997 second supplementary report, the Panel stated that it continued to find two of the models not adequate to represent the future states of the repository. For the two models found not adequate, Spallings and Chemical Conditions, the Panel identified its remaining issues. In this third supplementary report the Panel considers the DOE's April 1997 responses to these remaining issues. The Panel's evaluation of these responses is presented in Section 3 of this report. For the Spallings Model, the Panel concluded that the predicted volumes of spalled materials presented in the WIPP Compliance Certification Application (CCA) are reasonable based on additional consideration of processes that could lead to spalled releases. The Panel also concluded that the MgO backfill component of the Chemical Conditions Model will function as assumed in the CCA and that this model is adequate to represent the future states of the repository.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Conceptual Models Peer Review Panel (Panel) issued its report in July 1996. The peer review was conducted in accordance with the regulatory requirements of 40 Code of Federal Regulations (CFR) 191 and the implementation of those requirements by 40 CFR 194. The U.S. Department of Energy (DOE) included the Conceptual Models Peer Review Report as part of its Compliance Certification Application (CCA) for WIPP that was submitted to the U.S. Environmental Protection Agency (EPA) in late October 1996.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical systems, or intrusion scenarios, are represented in the performance assessment. In the Conceptual Models Peer Review Report of July 1996, 24 conceptual models were evaluated using the evaluation criteria specified by the EPA, including those of NUREG 1297. The Panel's report identified 13 conceptual models as adequate for implementation in WIPP Performance Assessment and 11 as not adequate for implementation, based on information available to the Panel. The Panel's findings on each of the models judged inadequate were provided in the report. After that report was issued, DOE developed additional information, made changes to some of the conceptual models, and prepared responses to the findings in the Conceptual Models Peer Review Report of July 1996.

The DOE reconvened the Panel in October 1996 to review the changes to the conceptual models, the DOE responses to the findings in the July 1996 Panel report, and information available in the CCA. In December 1996 the Panel issued a report supplementing the July 1996 report, that assessed the changes to the models and the DOE responses. The Panel found that two of the models, Spallings and Chemical Conditions, continued to be not adequate for implementation, and identified the remaining issues with these models. DOE again reconvened the Panel in January 1997 to review additional information developed in response to the remaining issues of the Panel on these two models. The Panel issued a second supplementary report which continued to conclude that these two models were not adequate for implementation and reiterated the remaining issues.

The Panel subsequently communicated by teleconference from February through April to review action plans and monitor progress toward resolving the issues. In meetings held during the week of April 20, 1997, the Panel reviewed information detailing additional DOE work relative to Spallings and Chemical Conditions. This report documents the Panel's April 1997 findings and is a third supplement to the Panel's July 1996 report.

For the Spallings Model, DOE has not requested the Panel to reconsider its conclusion that the original model was not shown to be adequate to represent the future states of the repository, and has not asked the Panel to review a new model against the criteria of 40 CFR 194. For the present review, the Panel was instead requested to determine if the predicted volumes of spalled materials presented in the WIPP CCA are reasonable, based on additional consideration of

processes that could lead to spalled releases. Additionally, for the Chemical Conditions Model, DOE has requested the Panel to determine whether the MgO backfill will function according to the conceptual model, as used in the CCA, with respect to reaction with generated CO_2 gas.

Section 2 of this report describes the process for this third supplementary review. Section 3 describes the additional information provided by DOE and the Panel's assessment of that information. Section 4 contains a summary of the Panel's assessments and conclusions.

2.0 SUPPLEMENTARY REVIEW PROCESS

This supplementary review was conducted at Sandia National Laboratories (SNL) in accordance with the DOE Quality Assurance requirements as modified in January 1997. The Panel was provided information relative to issues in its earlier reports during briefings and in written materials. The same review criteria were used to judge the acceptability of conceptual models as in the July 1996 report.

3.0 MODEL EVALUATIONS

Section 3.1 discusses the additional considerations of the Panel relative to the Spallings calculations and Section 3.2 discusses additional considerations relative to the use of MgO as part of the Chemical Conditions Model.

3.1. Spallings

3.1.1. Model Description

No changes were presented for the Spallings Model used in performance assessment.

3.1.2.Review of Criteria

The review of criteria for the Spallings Model remains unchanged.

3.1.3.Review of Responses to Panel Findings of January 1997

3.1.3.1. Summary of Findings

In its January 1997 report, the Panel found that additional information available on analogs, waste strength, other new model descriptions and calculations of tensile failure were either not adequately correlated with WIPP repository conditions or were not sufficiently complete or supported to provide the Panel with an adequate basis for determining that either the Spallings Model or the results obtained from that model were conservative.

3.1.3.2. Summary of DOE Responses to Findings

Surrogate Waste Materials

In response to the Panel's concern about the properties of the waste that would influence the spalling process, the DOE developed analogs for waste based on ranges of waste contents, corrosion and biodegradation that would perhaps be present following extended exposure to WIPP conditions. The surrogate samples contained varying amounts of corroded and uncorroded iron metal, including addition of goetite, crushed glass and soil, salt and concrete, and MgO in some cases. Physically degraded paper, plastic and peat were added to represent chemically degraded organics in the waste. These surrogate waste materials were mixed with brine, and consolidated to either 5 or 15 MPa to simulate repository conditions. Some of the samples were subsequently dried. Standard testing procedures were used, including Brazilian and hollow cylinder tensile tests, unconfined and triaxial compression tests, and permeability tests. Various parameters, including permeability, porosity, cohesion, tensile strength, compressive strength, Young's modulus, and Poisson's ratio were determined from the results of those tests. These parameters were then used in the various analytical calculations. DOE asserted that these parameters adequately represent the degraded waste expected in WIPP.

Analogs

The Panel was presented with documentation of analogs to the spalling process at WIPP, mostly rooted in petroleum production technology. Exceptions to the oil and gas analogs, such as seepage and earthquake-induced liquefaction and kimberlite pipe genesis, were quickly dismissed because of only tenuous similarity of phenomena. Drillhole blowouts, wellbore stability, sand production, hydrofrac proppant flowback, and cold production of low gravity viscous crude oil all were discussed in more detail and, although they were of qualitative value in understanding the spalling phenomenon, they were not found to be directly applicable as credible quantitative analogs. However, the dynamic cavitation of wellbores, specifically those through coal beds, was found to have notable attributes analogous to the spalling process at WIPP.

Dynamic cavitation has many similarities to the spalling process at WIPP, such as a pressure pulse phenomenon, gas-driven particulate removal, and a highly similar physical configuration. The ability to apply established computational codes, and the available database of results from this remarkably close analog help to corroborate testing and/or computational results. The DOE's draft Spallings Release Position Paper (SNL/CTAC, 1997) presents many of the pertinent similarities with instructive comments in Table 5-3, "Properties of a Characteristic Coalbed Methane Reservoir Used in Single Cycle Surge Modeling."

Computational Methods

In response to Panel findings that the existing model used to estimate spalling inadequately represented critical components of the spalling process, DOE initiated a new, mechanistically based computational approach. This approach is composed of three new computational methods which were used to develop additional information on the spalling process. These are called the cavity growth, the quasi-static, and the numerical computation methods. This approach represents the first time that borehole hydrodynamics and cavity growth have been

linked.

The cavity growth method is presented as the primary method for estimating spall volumes. The method simulates the entire response period of the system to an intrusion event, not just the end point. Assuming initial gas pressures and waste strength, the method accounts for the progressive mechanical response of the waste to a transient solution of gas flow in the waste and includes the hydrodynamics of mud and waste ejection through the borehole. The cavity growth method predicts small spall volumes for assumed initial gas pressures below lithostatic (14.8 MPa) and a maximum spall volume of 0.25 m^3.

The quasi-static method is presented as the simplest of the three methods and, as such, is primarily used to examine sensitivities and verify complex calculations rather than estimate spall volumes. The method is applied to estimate gas volumes, gas pressure distributions and flow rates for comparison to those predicted by the cavity growth and numerical methods. Graphic comparisons of gas flows and pressures predicted by the cavity growth and quasi-static methods illustrate close agreement. The gas pressure distributions and flow-rates predicted by these two methods are higher than those predicted by the numerical solution for the important early time steps.

The numerical method is presented as a tool for evaluating complexities not clearly represented by the other methods. The numerical method couples fluid pressure to the stress response in the waste following a drilling intrusion. Numerical calculations implemented through various computer codes were used to investigate solids mass transport, sensitivity of waste panel geometry and effects of waste heterogeneity, in addition to predictions of gas pressures and flow rates.

Numerical calculations were applied to predict gas pressures and flow rates for comparison to semi-analytic results. The numerical calculations consistently predict lower pressure gradients and lower gas flow rates than the other methods. The gradients and rates predicted by the numerical method are significantly lower than those of the other methods at early time steps. Investigations of layered and random configurations of heterogeneous waste using numerical calculations resulted in a reduction in key parameters that determine spall volume. Solids mass transport was investigated and determined to be limited prior to mud ejection. Tensile strength was determined to govern the system response, thereby minimizing the overall effects of waste panel geometry and flow properties.

3.1.3.3. Panel Review of Responses

Liquefaction, Plastic Deformation, and Cavity Stability

In the seminal paper by Vaziri and Byrne (1990), the detailed discussion providing the groundwork for the consideration of the mechanical stability of deep wells cites liquefaction as the strain mechanism responsible for cavity formation. Subsequent work has developed a more complete picture of stress-strain relationships around an unstable wellbore. Stabilization of a cavity in a wellbore that is in transient instability depends, in part, on the formation of a “stress

arch" around the cavity whose extent and geometry depend on the shear strength of the geologic materials. Shear strain controls the formation of the stabilizing zone, which is in a compressive state around the cavity and is characterized by plastic deformation.

In rocks having sufficient tensile strength and cohesion, the primary strain mode leading to cavity formation may be tensile failure due to differences in pore pressures around the cavity. Models used to predict cavity formation by air pressure pulsing in coal gas recovery wells have been developed and tested against bench models and field observations. In this useful analog of cavity formation caused by the release of gas due to an intrusion by drilling into the WIPP repository, a tensile failure of the cleated coal creates the cavity, and a broad plastic zone (tens of meters wide) forms around the cavity. Even after many repeated pressure pulses the cavity in the coal eventually stabilizes and cannot be made larger. This ultimate stabilization is due to the formation of the broad zone of plastic yield and the resultant concentric compressive stress zone (arch) around the cavity following repeated perturbations.

The WIPP surrogate waste exhibits cohesion and tensile strength as well as a significant tendency to ductile (plastic) deformation under experimental conditions. This has led the DOE to characterize the cavitation process as the result of a tensile failure zone surrounding the cavity at some short distance at any moment during the single short and rapid period of failure. The details of disaggregation and fragmentation of the spalled material moved into the cavity by tensile failure around the periphery of the cavity are not considered. Liquefaction may play a role in spall fragmentation, but all stress states leading to failure at the periphery of the cavity and beyond are characterized by non-zero states of effective stress. No liquefaction is predicted at or beyond the cavity margin.

The representation of cavity formation presented by the DOE is reasonable within the range of tensile strengths and cohesions proposed on the basis of surrogate waste experiments, the proposed stress environment, and the proposed strain processes. Although strain leading to cavity formation takes place over a very short period of time, the absolute magnitudes of continuous strain are relatively small. The rapid strain rates at the time of failure tend to enhance brittle behavior, but the small strain magnitudes and the large ductilities exhibited by the surrogate waste imply that the formation of a plastic zone and a stabilizing compressive shear arch is reasonable.

Distribution of stress and subfailure strain domains in the waste may be spatially complex and subtle. The principle driving mechanism for stress in the waste is pore pressure contrast distributed around the point of repository penetration as relatively symmetrical hemispherical gradients. Formation of the plastic zone and other complexities are secondary features which are kinematic responses to cavity development and relaxation of the waste due to degassing. Small magnitude tensile stress regions outside the compressive plastic zone and stress regions of incomplete symmetry are predicted by some published models and by closed-form numerical calculations presented by the DOE. These stress regions are limited by the small predicted dimensions of the cavity formed in the waste relative to the entire volume of waste in the room

and by the inefficient transfer of small elastic strains by very porous and relatively weak media during second order kinematic adjustments. No loss of strength outside of the tensile zone in the immediate vicinity of the intruded borehole is reasonably expected.

Strength and other properties of the waste are thought to be modified by several aspects of the repository environment. Some of these aspects of waste character are speculative and are not demonstrable so that no representation of their effects is included in the spall volume calculations. Waste heterogeneity and layering, the cementing effect of MgO, and other proposed strengthening effects of degradation are examples of possible but undemonstrated factors in waste physical behavior. Halite cementation of completely dry waste is apparently demonstrated by the increased strength of surrogate waste specimens prepared with added salt, wetted with brine, compacted, dried and tested. Some specimens were tested wet and some were tested after drying. Dried specimens of similar composition were about twice as strong under tensile testing as similar saturated specimens, using two types of tensile tests. Degradation of waste reduces mean grain size and implies the presence of brine to facilitate the degradation processes. Degraded and dry waste may be considerably stronger than undegraded or wet waste.

The DOE suggests that in cases in which high gas pressures occur in the waste, brine consumption during degradation depletes moisture in the waste so that the waste encountered in the top of the repository is likely to be dry. This justifies the assumption in the DOE model that the tests exhibiting the weakest (lowest tensile strengths) surrogate material strengths are highly improbable representations of waste strength at high repository gas pressures. The combined low probabilities of high gas pressure and the presence of saturated, degraded waste during a first intrusion late in the repository history seem to support this premise.

Method Validation

The Panel raised the issue of experimental validation of the new calculational methods, particularly those used to calculate flow and pressure drop through the porous media under highly transient conditions, because these calculations are very critical to the determination of waste stress conditions. The Panel was provided with verification and validation information that generally supports the use of the series of calculational methods, although the Panel did not review all of the available material in detail. DOE stated that the flow equations use Darcy's law, which is applicable except for extremely transient conditions and higher Reynold's numbers in the waste, when gas phase inertial effects could become important. The Panel noted that these calculational methods are used in many applications in situations involving flows in geologic settings and believes they are useful and appropriate for the calculations presented to the Panel, although the literature available apparently did not contain experimental validation under highly transient conditions. The Panel did note that if the calculational flow methods were later proffered for use as part of a new Spallings Conceptual Model, it would be prudent to ensure that the flow calculational methods were fully verified and validated against experimental data for the specific range of conditions of use.

Review of Analogs

The Panel agrees with the conclusion of the DOE analog presentations that the gas pressure gradient and waste cohesion, not the magnitude of the reservoir pressure, controls failure and that the WIPP gas pressure gradients are likely to be less steep than those gradients found effective in coalbed methane production practice. This less steep WIPP gradient is further supported because the WIPP borehole size is approximately a quarter of the cross section area of that used in coalbed treatments, and there will always be a further net borehole area reduction in the WIPP case due to the presence of the downhole drill string.

In the coalbed analog, the volume of solids released increases when the well is pulsed. While pulsing is not a requirement for the cavitation, this fact is important in that the mechanism is a repetitive event and WIPP is only a single cycle, or pulse. Cohesion is also observed to be a factor in the spalling process. Based on the work of Palmer and Vaziri (1994), the DOE's Spallings Release Position Paper (SNL/CTAC, 1997) suggests that because the WIPP waste cohesion is expected to be more than 25% higher than that of the coal tested, cavitation is unlikely. The Palmer and Vaziri modeling, which simulates failure initiation and progressive cavity evacuation by explicitly coupling flow, deformation, and failure, clearly represents events that can be expected of the WIPP waste panel at a time of intrusion.

The Panel concludes that coal methane gas stimulation by cavitation is a highly plausible analog for depicting the spalling process. Its advantages over other analogs considered by DOE are its physical similarities, as well as its relationships to situations and configurations that can be further studied, tested, and defended by well established computer codes, theory, and available corroborative data. However, this analog does not necessarily cover all aspects of the spalling and release process, such as gas erosional effects, liquefactions, and borehole transport mechanisms. The cavity growth calculations presented to the Panel by DOE are based on the same physical and theoretical principles as the Palmer and Vaziri coal gas cavity completion model.

Adequacy of Surrogate Waste Strength

The Panel considered the adequacy of the values of waste tensile strength used in the tensile failure calculations. The Panel concluded that there is some uncertainty in the degree to which the values measured on waste surrogates truly represent the actual waste following extended exposure in WIPP, but that generally, the selected values are reasonable for the intended purposes. The Panel considered the magnitude of spall volume that could result if the actual waste tensile strength were as low as one half of the lower value chosen by DOE for dry waste. In this case, the calculated spall volume at 14.8 MPa initial pressure was roughly estimated by the Panel to increase from 0.25 m^3 to 0.9 m^3. DOE strongly believed that it was not correct to assume such low waste strength values because it introduced unreasonable conservatism into the calculations, and indicated that additional failure criteria would need to be considered if waste strength were significantly lower than the selected values. The Panel agreed with this belief. The Panel notes that the higher spall volume, though perhaps overly conservative, is still lower than

most of the values used in the CCA, which ranged from 0.5 m^3 to 4.0 m^3.

Occurrence of Maximum Pressure Gradient

The DOE calculations presented indicated that the maximum pressure gradients, and therefore tensile stresses within the waste adjacent to an intrusion borehole, occurred within two seconds of the drill penetration into the top of a waste panel, prior to expelling the drilling mud. The Panel questioned whether the gradients and stresses in the few seconds after the drilling mud expulsion might actually be higher. The DOE presented information which showed that this second transient was not expected to be quite as rapid as the first transient, would be at much lower pressure, and would therefore not cause additional spalling volume. The Panel accepted this explanation.

Pressure Bleedoff through the Disturbed Rock Zone

The Panel questioned whether the high gas pressures would bleed off through the disturbed rock zone and Marker Bed 138 before the drill penetrated the top of a waste panel. DOE indicated that, based on the permeability and storativity of these regions, there would not be sufficient time during drilling for such bleedoff to significantly affect waste panel pressures at the time of penetration or to stop drilling operations as a result of interruption of drilling mud flow. The Panel accepted this explanation.

Entrainment of Contaminated Brine Flow During Spallings Events and Release of Radionuclides From Beyond the Tensile Failure Zone

In its earlier reports, the Panel raised the issue of entrainment of contaminated brine in rapid gas flow during a spalling event (p. 98 of the July 1996 report and p. 32 of the December 1996 report). The Panel concluded in the December report that use of the inadequate Spallings Model could not be the basis for an adequate resolution of this issue. The Panel has revisited this issue, which questions whether, in addition to spall of solid waste material due to tensile failure and cavity formation, there would be additional releases of waste particulates and dissolved actinides in liquid brine entrained in rapid gas flow through the waste. This has not been included in spallings calculations. DOE reviewed the calculations methodology in the Direct Brine Release Model and reminded the Panel that full two-phase flow of gas and brine are included for all intrusions, thereby resolving this issue. The Panel also raised the issue of whether solid waste in localized areas of low waste strength would be preferentially released, even from beyond the zone of tensile failure. DOE indicated that these materials would have to penetrate through the other materials and this was highly unlikely. DOE also provided information showing that if channels were to form, this would greatly decrease the pressure gradients and retard the growth of the tensile failure zone. The Panel accepted this as reasonable resolution of these issues.

Effect of Repository Gas Composition

The Panel raised the issue of the effect that the actual repository gas composition would have on the spallings process, since the calculations of spallings volume were performed using gas

viscosity and density for hydrogen. Actual gas composition would be approximately one half methane, which is eight times as dense and 10 percent more viscous than hydrogen. DOE presented calculations addressing the effect of methane, which compared pressures and flows of methane and hydrogen separately. DOE indicated that the most significant effect would be to slightly slow the velocity of flow due to the higher viscosity and density. DOE concluded this would have about a 10 to 20 percent effect on the bottom hole pressure and no significant effect on the waste cavity growth.

The Panel has considered the implications of the use of viscosity and density of a mixture of hydrogen and methane, coupled with the issue of the appropriateness of Darcy flow for the highly transient conditions. It was noted that waste exit velocities are clearly well below the transonic range where further considerations would become highly important. DOE indicated that under somewhat less but still highly transient conditions, where inertial effects may be more important, a rigorous treatment would involve a more complete solution to the Navier-Stokes equation. However, as a first estimate, DOE felt that the increased pressure gradients would probably be commensurate with the steeper stress gradients calculated by the quasi-static method, as opposed to the cavity growth method, as shown in the Spallings Release Position Paper (SNL/CTAC, 1997, pp. 3-32, 33). For this reason, spallings volumes might be more in line with the values of the quasi-static method in Table 3-3 on p. 3-29 of the Spallings Release Position Paper, which represents an approximately threefold increase to a maximum of about 0.7 m^3. These higher values would still be lower than most of the values in the CCA, which ranged from 0.5 m^3 to 4 m^3. Again, the Panel believes that if a new conceptual model were proffered, the combined effects would need to be addressed more rigorously.

Waste Permeability Effects

It was noted by the Panel that the waste permeability values used in the modeling were the same as those used in performance assessment (1.7×10^{-13} m^2), rather than the lower value of about 4×10^{-15} m^2 experimentally determined for the surrogate waste. While the importance of maintaining consistency with performance assessment is understandable, in view of the analog information relating lower permeabilities with higher pressure gradients and therefore larger cavity volumes, the Panel requested the DOE to further discuss the consequences of assuming a higher waste permeability in the analyses than may actually exist in the degraded state. In responding, the DOE referred to sensitivity studies on waste permeability that had been performed with the quasi-static method in which the waste permeability was reduced to 1×10^{-15} m^2. The results indicated that although the pressure gradients did increase at these lower permeabilities, the volumetric flow rate of gas issuing from the waste was insufficient to eject the mud from the borehole, and therefore no spall event could occur. The Panel noted that this conclusion was similar to that reached from modeling studies presented by DOE in January 1997, where it was determined that partial depressurization of the waste panels would not be expected during borehole penetration of the overlying disturbed rock zone because its assigned permeability of 1×10^{-15} m^2 was too low to allow sufficient gas flow to occur. On this basis, the Panel concurred that the higher permeability values used in performance assessment were reasonable for this

application.

Concluding Statements

Upon reviewing the DOE's written materials, oral presentations, and responses to specific issues raised by the Panel, the Panel concluded that no significant issues remained regarding the reasonableness of the spallings volumes used by DOE in its CCA for the WIPP. Although the additional waste strength, analog information, and calculational results that were presented to the Panel could be further refined, the Panel determined that this information was sufficiently accurate and complete to support a conclusion that the spallings volumes used in the CCA are reasonable, and in fact appear to overestimate the actual waste volumes that would be expected to be released by the spallings process.

3.2. Chemical Conditions

3.2.1. Model Description

No changes to this model were presented.

3.2.2. Review of Criteria

The review of criteria for the Chemical Conditions Model remains unchanged.

3.2.3. Review of Responses to Panel Findings of January 1997

3.2.3.1. Summary of Findings

With regard to the Chemical Conditions Model, the Panel concluded that the ongoing test program had not sufficiently progressed to provide a definitive verification that the MgO will perform as planned under repository conditions. The Panel was particularly concerned about whether the results of early tests indicated that reaction rims would inhibit the ability of the MgO to react completely and rapidly with CO_2 to buffer the chemical system and limit actinide solubility.

3.2.3.2. Summary of DOE Responses to Findings

The DOE provided a draft report(1) to the Panel, "Chemical Conditions Model: Results of the MgO Backfill Efficacy Investigation," dated April 23, 1997, along with oral briefings on this report. This report summarizes the currently available data and analyses developed from SNL Test Plan TP-97-01.

Based on current information, DOE indicates that of the various phases formed from the contact of brine with MgO pellets, the initial phase, brucite, will crystallize to nesquehonite and hydromagnesite during short to intermediate times and, over long periods, will dehydrate to magnesite. DOE states that the brine pH and CO_2 fugacity are controlled at levels throughout the process which effectively lead to low actinide solubilities.

Earlier short-term experiments at high CO_2 contact rates indicated the formation of reaction rims. Current results for longer periods with high CO_2 contact rates indicate the growth of brucite films, followed by increasing density of nesquehonite needles projecting from the pellets. Shortly thereafter, hydromagnesite forms among the nesquehonite needles, as well as farther from the pellets. DOE concludes that while there is considerable retardation of CO_2 access to the pellets, accessibility for transfer is maintained. DOE further indicates that the predominant chemical diffusing species are $MgOH^+$ diffusing from the pellets and HCO_3^- diffusing toward the pellets. This gives rise to the precipitation of hydrous magnesium carbonates outside the pellets. DOE further indicates that, in contrast to the experiments, where relatively high CO_2 fluxes occur, the brine at WIPP will become saturated with magnesium compounds before significant introduction of CO_2 species occurs. The reactions will occur at nucleation sites still farther from the pellets, further improving the contact between the reacting species and reducing the formation of reaction rims. This supports the conceptual model assumption that the CO_2 will rapidly and completely react with the MgO. The DOE also reiterated that four times the amount of MgO needed to react with the total quantity of CO_2 generated will be emplaced in the repository.

DOE reviewed the effect of MgO control of pH and CO_2fugacity in actinide solubility, with hydromagnesite being the predominant intermediate carbonate phase. DOE concluded that most solubilities would be lower with hydromagnesite than if the transition to magnesite occurred, as had been assumed earlier. DOE also concluded that the results of the test program and analyses demonstrate that MgO will function in the WIPP according to the Chemical Conditions Model in the CCA.

3.2.3.3. Panel Review of Responses

Reaction Rim Isolation Potential

The fundamental issue that concerned the Panel was whether there would be an inability of the CO_2 to react with the interior of MgO pellets, especially as a function of carbonate reaction rim thickening. The present DOE report has efficiently dealt with this issue. A combination of experimental results, petrographic analyses (both optical and scanning electron microscopy [SEM]), modeling predictions, analog comparisons, and phase equilibria information have satisfied the Panel that reaction rims will not hinder the ability of CO_2 to react with various forms of hydrated MgO pellets. The most compelling evidence that was presented hinged on two factors: 1) the experimental results indicating that hydrous magnesium carbonate phases could nucleate away from the pellet surface and in the saturated brine, and 2) SEM photographs showing partially dissolved cores remaining within reaction rims.

Results of experimental runs were conveyed in carbon uptake curves that plot mole percent conversions versus time. An unusual S-shape to the curves (schematically shown in Figure 4-1 of the draft Chemical Conditions Report [SNL, 1997]) indicated that a substantial amount of magnesium was going into solution in the brine. During the experiments, which were accelerated

due to high CO_2 concentrations, the magnesium saturated brines would combine with CO_2 to form hydrous magnesium carbonates at the most convenient nucleation sites. These sites included pellet surfaces, interstices between pellets, and free grains in the brine (the so-called milky appearance). In Figure 5-1 of the Chemical Conditions Report, precipitation fronts were indicated for carbonate minerals in both the experimental situation and for WIPP conditions. These two diagrams indicated that for WIPP conditions in particular, magnesium would dissolve from the pellets and go into solution. Therefore, the CO_2 would not be required to react with the pellet outer surface to form hydrous magnesium carbonates. This was compelling evidence that any coating that forms on the pellets is a secondary influence of carbonate nucleation.

It was also shown by the carbon uptake curves that the materials deposited on the pellets (nesquehonite and hydromagnesite) form a porous mantling (previously thought to be reaction rims) that allows magnesium to continue dissolving out of the pellets and go into solution in the brine at a somewhat reduced rate. This factor was strongly substantiated by SEM photomicrographs (Figure 4-5 of the Chemical Conditions Report) which show various states of pellet dissolution within concentric shells of mixed nesquehonite and hydromagnesite.

Metastable Hydrous Phases

In both the written presentation (Chemical Conditions Report [SNL, 1997]) and the oral presentation (on April 25, 1997), mention was made that the predominant hydrous magnesium carbonate phases formed in the experiments were nesquehonite and hydromagnesite. That is not surprising since Christ and Hostetler (1970) state " no carbonate mineral has proven more difficult to investigate experimentally than magnesite." These hydrous phases were produced easily in the experiments because of the elevated CO_2 concentrations used. The five order of magnitude higher CO_2 concentration in the experiments relative to predicted WIPP values was used to facilitate carbonate growth in a restricted time frame. Both phases were reported to be metastable, and would dehydrate (mature) with time to magnesite. The predicted time frame for dehydration reactions ranges from approximately 100 to 1000 years, depending on exact chemical conditions in the repository. This hypothesis was well supported by the following information: 1)natural analogs, 2) phase equilibria, and 3) Arrhenius plots.

The most pertinent natural analog study is that of Usdowski (1994), which observed that hydromagnesite would undergo a phase transformation to magnesite in a natural setting in Australia. The chemical conditions of that setting (ionic concentrations relative to ionic proportion and magnesium to calcium ratios) would encompass those of the Salado and Castile brines within the WIPP, as seen in Figure 5-2 of the Chemical Conditions Report. Phase equilibria determinations by Langmuir (1965) and especially Lippman (1973), as represented by Figure 4-3, have indicated that the metastable phases nesquehonite and hydromagnesite would transform to magnesite with sufficient time. The reaction pathway is easily seen in Figure 5-5, which predicts that the two hydrous phases of interest would dehydrate (mature) with time to produce magnesite. The way in which the accelerated experiments provided by DOE could be scaled to the conditions found at WIPP are by Arrhenius plots. This is a well documented and

commonly used technique in experimental petrology to scale experimental results to field conditions that are not conducive to laboratory parameters and time frames. The Arrhenius plot presented to the Panel (Figure 5-4) indicates that magnesite would form in place of the hydrous magnesium carbonate in several hundred years. This supporting information is taken by the Panel as satisfactory evidence that the laboratory phases produced by DOE will in fact transform to magnesite well within the time constraints needed for the Chemical Conditions Model.

Water Sequestration

In the process of forming magnesian minerals in the repository, free water will be sequestered by the first step in the reaction series, the formation of brucite. Some of that water is later returned to the repository by the progressively less hydrous minerals generated in the transformations from brucite through hydromagnesite to magnesite. Since there will be excess MgO in the repository above that necessary to convert all the generated CO_2, most of this sequestered water will remain in brucite, permanently unavailable to react with the waste. The water that is returned will not change the volume of water assumed in performance assessment to be available to react with the waste. However, the reaction with that part of the water will be delayed while it is held by the metastable hydrous magnesium carbonate mineral phases. The process of carbonate hydroxide generation and the eventual dehydration of the anhydrous mineral phases which returns some free water to the system is expected to end after about 2000 years. This is during the period of most rapid brine inflow into the repository, and the return of that water to the waste is not expected to significantly change waste degradation rates at that time or later. The net overall effect of MgO hydration to brucite is to make the repository nominally drier.

Competition of Anions and Cations

The Panel asked whether other anions or cations that would be present in the waste or repository environment would inhibit the desired reaction between magnesium cation species and carbonate anion species. DOE indicated that anion species such as nitrate, sulphates, and chlorides do not significantly precipitate magnesium due to their solubility, and therefore would not prevent magnesium from being available to react with carbonate anions. Similarly, DOE indicated that other cations, such as calcium and iron would, if anything, also precipitate additional carbonate anions, and the resulting compounds are chemically compatible with magnesium carbonate species. Thus, other anions and cations would not interfere with the reactions between magnesium and carbonate species.

Conclusion

Based on the information presented to the Panel in the written material and in oral discussion, the Panel concludes that the results available provide an adequate basis to determine that the MgO backfill will function according to the Chemical Conditions Conceptual Model, as used in the CCA, with respect to reaction with generated CO_2 gas.

4.0 SUMMARY

This third supplementary report documents the Panel's evaluation of additional information regarding the two conceptual models that were not previously determined to be adequate, the Spallings Model and the Chemical Conditions Model.

The additional information on the spallings process included strength data for surrogate waste materials, analog information, and results from computational methods developed since the Panel's January 1997 report. The new information was not presented to the Panel as a new conceptual model, but rather to support DOE's belief that the spallings volumes used in the CCA were reasonable. In reviewing this additional information, the Panel was requested by DOE to determine if the predicted volumes of spalled materials presented in the WIPP CCA are reasonable, based on additional consideration of processes that could lead to spalled releases.

The written materials and oral presentations on the spallings process prepared by the DOE, and the DOE's responses to specific issues raised by the Panel, were based on a detailed evaluation of the conditions, events, and processes at the WIPP that could lead to a spallings release, and on mathematical representations describing the sequence of physical events that could occur. Although further refinement in understanding and predictive capability for spallings events would be desirable as part of a new conceptual model, the Panel has determined that the additional information presented by the DOE is sufficiently complete at this time to support a conclusion that the spallings volumes used in the CCA are reasonable, and may actually overestimate the actual waste volumes that would be expected to be released by the spallings process at the WIPP.

The significance of possible entrainment of brine by expanding gases upon intrusion of a waste panel by a borehole was raised as an issue by the Panel in its July and December 1996 reports. DOE's initial response to this issue was not accepted by the Panel because it was based on computations using the inadequate Spallings Model. In further discussion of this issue during the April 1997 meetings, it was determined that the BRAGFLO-DBR model used to calculate direct brine releases computes two-phase flow effects in both the repository and the intrusion borehole, and accounts for the driving effects of gas expansion. This issue is therefore considered by the Panel to be satisfactorily resolved.

The additional information for the Chemical Conditions Model included further data from the MgO test program regarding hydration of MgO and transition toward magnesite, reaction rates with carbonate species, control of pH, and effect on actinide solubility. The Panel's only remaining concern for this model related to the lack of a demonstrated ability of the MgO backfill to function according to the assumptions in the conceptual model as used in the CCA with respect to reaction with the generated CO_2gas. The results of the information and analysis are sufficiently complete at this time for the Panel to conclude that the MgO backfill will function as assumed in the CCA and that this model is adequate to represent the future states of the

repository.

With the exception of the Spallings Model presented in the CCA, which the Panel continues to find inadequate, all remaining conceptual models have been determined to be adequate and all significant issues regarding their adequacy have been resolved.

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ACRONYMS

CCA	Compliance Certification Application
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
SEM	Scanning Electron Microscopy
SNL	Sandia National Laboratories
WIPP	Waste Isolation Pilot Plant

DETERMINATIONS OF PEER REVIEW MEMBER INDEPENDENCE

C.R. Wilson

Determination of Peer Review Member Independence Form

___ Currently employed by DOE or DOE Contractor? Yes/No

X Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

1978 - 1983 U. of California Lawrence Berkeley Laboratory - Performed field hydrology study of Hanford Site

1983 - 1985 Hydrotechnique Inc, Berkeley CA - Performed consulting Services to Hanford Site

1986 - 1996 Golder Associates Inc - Albuquerque NM - Performed consulting Services to Hanford, INEL, Los Alamos Sites

___ Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Charles R Wilson

Date: 3/29/96

Peer Review Manager Approval: John A. Thies 4/8/96 Date

Darrell Porter

Determination of Peer Review Member Independence Form

Yes — Currently employed by DOE or DOE Contractor? Yes/No
yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

SRIC, my employer, has been active as a DOE Contractor for many years. To date I have had no work or other relationship to work on the DOE WIPP Program.

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Darrell Porter

Date: March 29, 1996

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

E.B. Oswald

Determination of Peer Review Member Independence Form

No — Currently employed by DOE or DOE Contractor? Yes/No
Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

April through August, 1995. Albuquerque, NM, S.M. Stallar Corporation Served as Independent Review Team member assisting WIPP WTAC in the review of data record packages.

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: E.B. Oswald

Date: 3/30/96

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

Florie Caporuscio

Determination of Peer Review Member Independence Form

Yes — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

4/96 Informatics, Albuquerque NM, staff consultant Peer Review of WIPP

8/93 – 3/96 Advanced Sciences Inc, Los Alamos Office, Project Manager and Senior technical Lead, Environmental Restoration Project

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer. or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Florie A Caporuscio

Date: 4/1/96

Peer Review Manager Approval: John A. Thies — 4-1-96 Date

Glen Sjoblom

Determination of Peer Review Member Independence Form

1. Currently employed by DOE or DOE Contractor? Yes No
2. Employed by DOE or DOE Contractor previously? Yes No

See below

If yes, give dates, location, company, position type work performed.

1. I have a contract with Oak Ridge Institute for Science and Education, to provide an assessment of effectiveness of DOE office of Nuclear Energy Program of Assistance of nuclear reactor safety to Former Soviet Countries; this has no bearing on the proposed peer review at WIPP.
2. I was a special assistant to the Asst. Secy for Environmental Management but was not involved with activities at WIPP.

NO

Do you or have you had any direct involvement or financial interest in the work under review? Yes No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Glen L. Sjoblom

Date: 3/29/96

Peer Review Manager Approval: John A. Thies 4/8/96 Date

John Gibbons

Determination of Peer Review Member Independence Form

NO — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

Battelle Alb., IPT reviewer of WIPP DATA packages 1994-1995
ARA, Alb. Site Characterization Technology Research 1992-1993
SNL Civil Systems Inc., High Level WIPP Experiment Planning 1977-1978

NO — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: [signature]

Date: NOV 29/96

Peer Review Manager Approval: [signature] John A. Thies — 4/8/96 Date

CERTIFICATIONS REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

C.R. Wilson

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer _____

Name of Offeror:_____ Signature Charles R Wilson

Date Signed: 3/29/96 Typed name CHARLES R. WILSON

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

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(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Darrell Porter

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer 3/29/96

Name of Offeror: DARRELL PORTER Signature Darrell D Porter

Date Signed: April 2, 1996 Typed name_____

3. SUPPLEMENTAL INFORMATION

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E.B. Oswald

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

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Solicitation No._____ Date of Offer 4/1/96

Name of Offeror:_____ Signature _____

Date Signed: _____ Typed name: Eric B.Oswald

3. SUPPLEMENTAL INFORMATION

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Florie Caporuscio

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

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Solicitation No._____ Date of Offer 3/25/96

Name of Offeror: Florie A Caporuscio Signature Florie A Caporuscio

Date Signed: 4/1/96 Typed name_____

3. SUPPLEMENTAL INFORMATION

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Glen Sjoblom

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

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Solicitation No _____ Date of Offer 3/25/96

Name of Offeror: Glen L. Sjoblom Signature Glen L Sjoblom

Date Signed: 3/29/96 Typed name _____

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John Gibbons

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

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Solicitation No._____ Date of Offer_____

Name of Offeror: John Gibbons Signature John J. Gibbons II

Date Signed: Mar 29/96 Typed Name_____

3. SUPPLEMENTAL INFORMATION

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APPENDIX B - SIGNATURE PAGE

I acknowledge by my signature below that I concur with the findings and conclusions documented in this Conceptual Models Peer Review Report.

Florie Caporuscio

John Gibbons

Eric Oswald

Darrell Porter

Glen Sjoblom

Charles Wilson

MEMORANDUM

To: M.G. Marietta

From: T.W. Thompson, F.D. Hansen

Date: July 24, 1996

Subject: Long-term Performance of Panel Closures

---

1. INTRODUCTION

After waste has been emplaced in a panel, closures will be built to restrict flow from the panel during the remainder of the operational phase. These closures will include a length of concrete placed in the panel entries. Although it is not the intent of these closures to restrict flow over the regulatory period of 10,000 years, values for their long-term performance characteristics are required to successfully determine their contribution to overall system performance.

Flow of fluids into or out of the panels will be controlled by the conductance of the panel closure, and of the surrounding disturbed rock zone (DRZ). Performance Assessment (PA) calculations use a constant value for DRZ permeability of 10^{-15} m^2, a value which is substantiated in the records package for the waste rooms (reference). Consideration of the current panel closure designs indicates that they will maintain their structural integrity for the regulatory period. If this is the case, then the concrete element of the closure system will continue to provide resistance to inward deformation of the surrounding salt, and will prohibit the growth of the DRZ from its initial state. Since the DRZ will not increase during the regulatory period, and may decrease, the assumption of a constant DRZ permeability is reasonable.

The panel closures have been designed to limit the flow of brine and gas between panels during the operational phase, and current designs call for these operational closures to include concrete elements (Figure 1). Although these closures are designed for an operational use, it is expected that they will continue to provide fluid flow restriction during the post-closure phase. The remainder of this memorandum establishes the permeability expectations of the closures, with emphasis on the potential for concrete degradation and increase in permeability. For the purposes of these analyses the concrete elements are taken to have a length of nominally 26 ft (7.9 m) (USDOE, 1996a,b), and to be made of a material chosen so as to be compatible with the environment, such as Salado Mass Concrete (SMC: Sandia, 1996) or a similar mix. Degradation of the concrete may occur by interaction with brine flowing through the plug, or with brines flowing along the plug/salt interface or in the DRZ.

2. CONCRETE PROPERTIES

The initial permeability expected for the concrete panel closures are documented in the materials specification appendix of the Compliance Submittal Design Report (CSDR) (Sandia, 1996) developed for the shaft seal system. In addition to conventional engineering properties, the SMC has well documented permeability characteristics, permeabilities having been determined from field tests (Knowles and Howard, 1996) and laboratory studies (Pfeifle et al., 1996). Figure 2, taken from the CSDR, summarizes the available data, and indicates a permeability for as-placed SMC of between 2×10^{-21} and 1.8×10^{-17} m^2. For calculations performed in this memorandum a value of 10^{-17} m^2 is used, this being at the high end of the values used by PA for the shaft concrete components, and consistent with other data. For example, data on generic portland cement pastes shows that the permeability of oil field concrete plugs is on the order of 1×10^{-19} m^2, while data from the Bell Canyon Test indicate permeabilities for borehole concrete plugs of 5×10^{-17} m^2 (Petersen and Christensen, 1980; Christensen and Hunter, 1980).

For the purposes of calculating degradation of the concrete member an assumption of porosity is necessary. The expected value is 5 %, which is higher than the 2% estimated by Petersen and Christensen (1980) for the Bell Canyon Test plugs, but is generally consistent with practical experience of field emplaced concrete structures, and is the value for cast in-place SMC given in the CSDR (Sandia, 1996). An upper limit for porosity is taken as 10%, which is an engineering estimate for concrete.

As noted in the introduction, the concrete closure member is expected to be structurally stable for the regulatory period, and to provide support for the surrounding rock and the DRZ. In this context it can be noted that the unconfined compressive strength of SMC is greater than 4500 psi (30 MPa), and that under the confined state of stress within the closure system the ultimate strength will be greater than this (Pfeifle et al, 1996). This strength is sufficient to preclude structural failure of the concrete member in the panel entries.

3. DEGRADATION OF CONCRETE

The solid matrix that makes up concrete is composed almost entirely of amorphous to cryptocrystalline solid phases. These phases are thermodynamically unstable, and with time and exposure to water they alter into more stable and more crystalline assemblages. Thermodynamic calculations conducted by Alcorn et al (1992) have predicted the alteration phases of portland cement due to exposure to a variety of waters and brines as including tobermorite, quartz, gypsum, calcite, clays and zeolite, produced at the expense of soluble and unstable materials such as portlandite. The theoretical alteration assemblage occupies more volume than the original solids. These calculated results have been verified by subsequent experiments in which waters and cement were reacted (Onofrei et al., 1992).

At free surfaces concrete materials are not physically supported and can spall. Long term leaching experiments report that surface diffusion controlled alteration is dependent on the C_3A content of the cement and the Mg and SO_4 content of leachant (Walton et al., 1990). Creation of an alteration rind weakens the concrete and makes it subject to spalling (Wakeley et al., 1994). The mechanism for spalling is that the alteration phases occupy more volume than the original

solids, volumetric expansion increases internal pore pressures until concrete tensile strengths are exceeded and spalling occurs. Short-term, empirical studies of ordinary concrete in brine report alteration rates in the range of 0.7 to 1 mm/year (Atkinson and Hearne, 1990) - These rates are likely to be overestimates because diffusion distance varies as the square root of time. Further details are given in Appendix C of Thompson et al., 1996.

4. DEGRADATION OF CONCRETE PANEL CLOSURES

The concrete elements of the panel closures may degrade in one of two ways, either by flow of brines through the mass of the concrete element, or by flow of brines along the interface.

4.1 Flow Through the Concrete Element

An estimate of the degradation of a concrete closure element may be made based on data on the progression of concrete chemical alteration reported by Berner (1990) for both fresh water and brine leachants (Figure 3). The progression is charted in terms of the volume of water flow, and indicates that more than 100 pore volumes of leachants must pass through concrete before there is chemical evidence that the matrix is being attacked. Based on these results, it has been assumed (conservatively) that the concrete closure elements will degrade significantly after 100 pore volumes of water have passed through them. A more detailed discussion of these results is given in Thompson et. al. (1996).

This volume can be converted to performance life by using Darcy's Law and considering the flow of fluids though the plug and the surrounding DRZ. If there is a pressure difference between the panel and the rest of the repository, flow will occur through the panel closure and the surrounding DRZ, with the two elements acting as flow resistors in parallel (Figure 4). If the pressure in the panel is P_1 (Pa) and in the rest of repository is P_2 (Pa), then under brine saturated conditions, the steady state flow rate out of the panels will be Q, where:

$$Q = A*(k'/\mu)*(P_1 - P_2)/L \quad m^3/sec, \qquad (1)$$

where: A is the total flow area of the panel closure plus DRZ (m^2)
L is the flow length (m)
μ is the fluid viscosity (Pa.s)
k' is the composite permeability of the panel closure plus DRZ (m^2).

The composite permeability, k', is given by:

$$k' = (k_d A_d + k_c A_c)/(A_d + A_c), \qquad (2)$$

where: k_d, k_c are the permeabilities of the DRZ and plug closure respectively (m^2)
A_d, A_c are the flow cross-sectional areas of the DRZ and plug closure respectively (m^2).

The flow through the panel closure, q_c, will be:

$$q_c/Q = k_c A_c/(k_d A_d + k_c A_c). \quad (3)$$

The pore volume of the panel closure (V_p) is:

$$V_p = A_c L \phi \text{ m}^3,$$

where ϕ is the porosity. The number of pore volumes (N_p) flowing through the closure in unit time will be:

$$N_p = q_c/V_p \text{ pore volumes/sec},$$

and the time for 100 pore volumes to flow through the closure will be:

$$t_{100} = 100/(N_p * 3.154\text{x}10^7) \text{ years}$$

The current design (USDOE, 1996a,b) calls for a length of 7.9 m (26 ft) for the concrete closure, and a cross-sectional area of 39.6 m^2 (10 m wide by 3.96 m high). As noted in Section 2 an undegraded concrete permeability of 10^{-17} m^2, and a porosity ranging from 5% to 10% may be assumed. The DRZ around the closure is assumed to have a permeability of 10^{-15} m^2. Based on the BRAGFLO grid (reference) the DRZ may be assumed to have a height of 11.95 m above the closure and 2.23 m below. It is assumed that the DRZ in the pillars at either side of the closure heals due to creep closure onto the rigid concrete. The DRZ flow area may therefore be taken as 141.8 m^2 (11.95 + 2.23 m high by 10 m wide).

Given these values, the effective permeability of the closure and the DRZ, from equation (2), is $7.84\text{x}10^{-16}$ m^2, with an effective flow area of 181.4 m^2. When brine flows between the panel and the rest of the repository, from equation (3), only 0.28 % will flow through the closure, the remainder (99.72 %) will be through the DRZ.

An analysis of calculations made with BRAGFLO (reference) using a range of parameters, and assuming permeabilities for the closures and DRZ of 10^{-15} m2, indicates that the maximum cumulative flow between the panel and the rest of the repository for any likely E1 or E2 scenario will be of the order of 10^4 m^3 (Figure 5). With these flows, and the slit in flows indicated above, only 28 m^3 of brine will flow through the concrete closure in 10,000 years. For a porosity range of 5 % to 10 % the maximum cumulative flow through the concrete closure in 10,000 years will therefore be between 0.6 and 1.2 pore volumes. The same point is made in Figure 6, which shows the cumulative flow with closure permeabilities of 10^{-15} to 10^{-17} m^2. Degradation will be minimal with these flow volumes.

4.2 Flow Along the Interface

Flow along the interface may be more rapid due to the higher permeabilities in the DRZ. A maximum effect of this flow might be estimated to be equivalent to the free surface spall rate of 0.5 to 1 mm/yr. Such a degradation rate is unrealistically high, since the degradation will be controlled by the rate of fluid flow, and total loss of material will not occur in a physically constrained region. However this rate of spall is much less than the expected closure rates (measured at the order of 0.1 to 0.2 ft/yr. or 30 to 60 mm/yr in Panel 1: USDOE, 1996b) so even such a rapid spall rate would be more than compensated for by creep of the salt on the closure. It is therefore concluded that the effect of flow along the interface will be minimal. At most it will lead to an insignificant increase in the DRZ flow area.

5. CONCLUSIONS

It is concluded that the potential flow through the concrete closure is nearly two orders of magnitude too small to cause any significant degradation. Degradation caused by flow in the DRZ adjacent to the concrete will be taken up by creep closure. It is therefore concluded that the panel closures will retain their initial permeability in the post-closure phase. If this permeability is 10^{-17} m^2, then the effective permeability of the DRZ and the closure together will be about $8x10^{-16}$ m^2. An assumption of a permeability of 10^{-15} m^2 for the closure and the DRZ is reasonable.

It is also concluded that since no significant degradation is expected for the concrete members, these will maintain their structural integrity and will provide a rigid support to prevent growth of the DRZ during the regulatory period.

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BRAGFLO grid (ref)

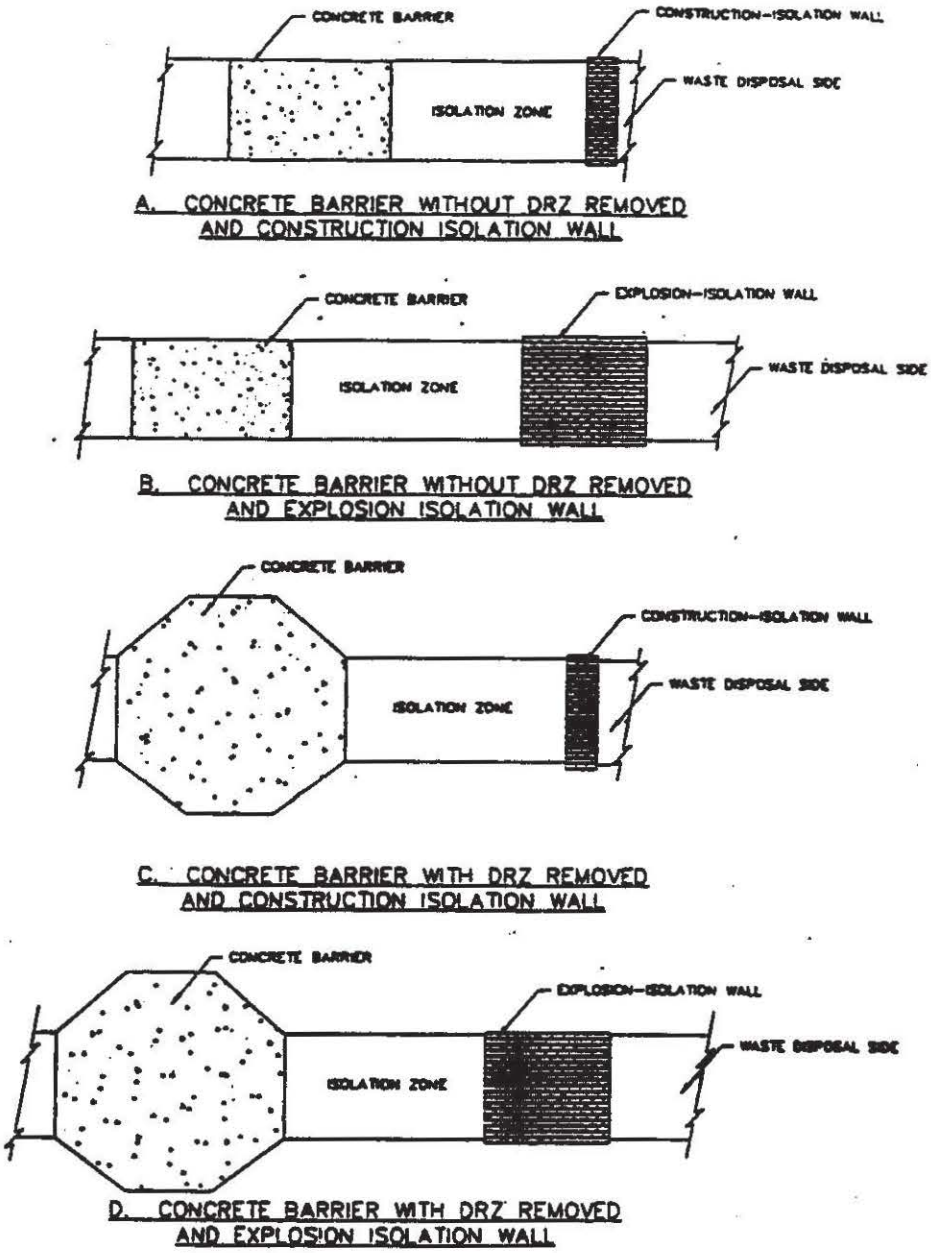

Figure 1: Panel Closure Designs (after USDOE, 1996a)

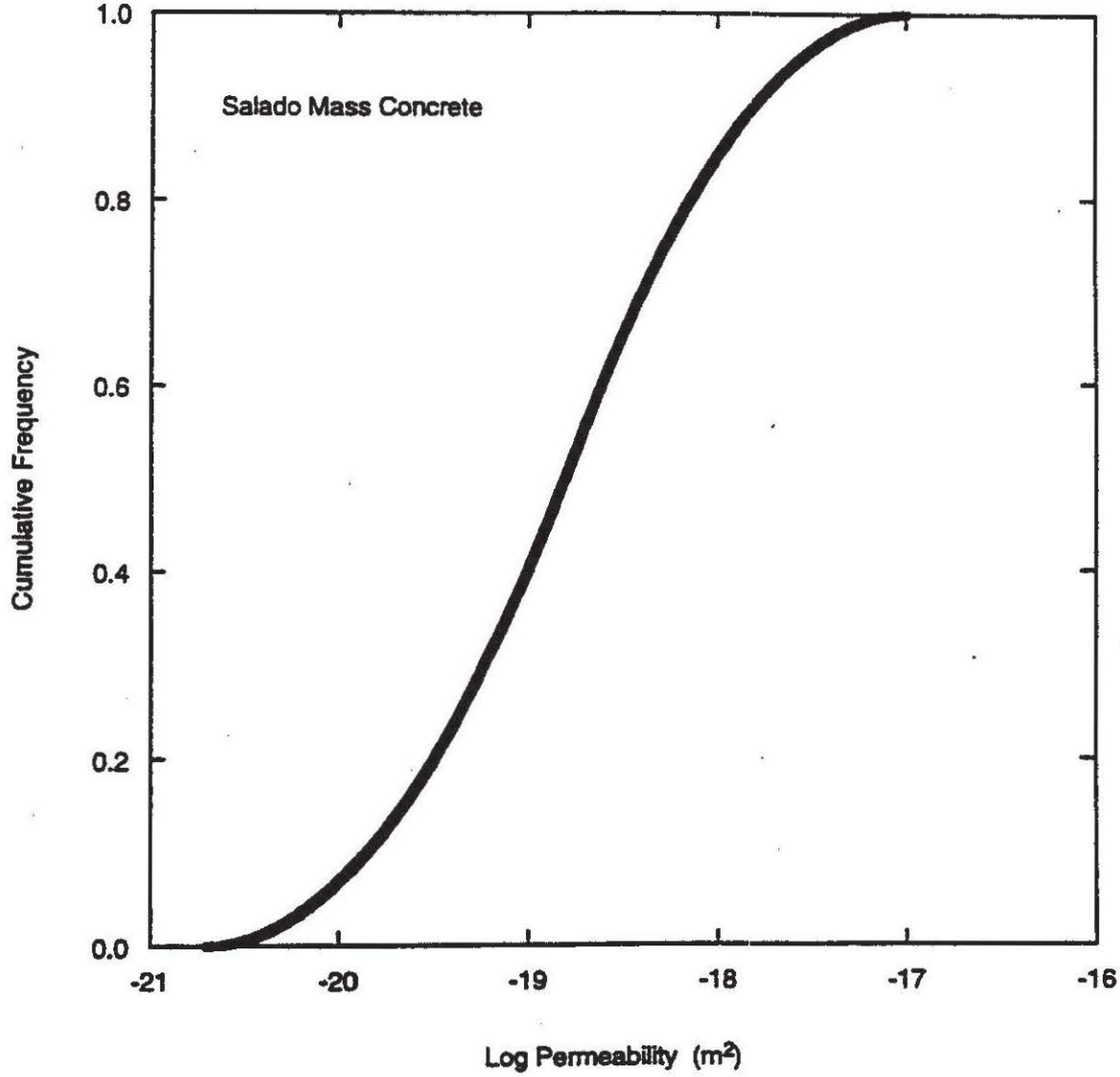

Figure 2: Cumulative Distribution Function for Permeability of SMC (after Sandia, 1996)

Figure c-3 Degradation of "HTS" in standard marl grundwater "MAR". After 6650 cycles calcite is the only solid phase present (T = 25 °C).

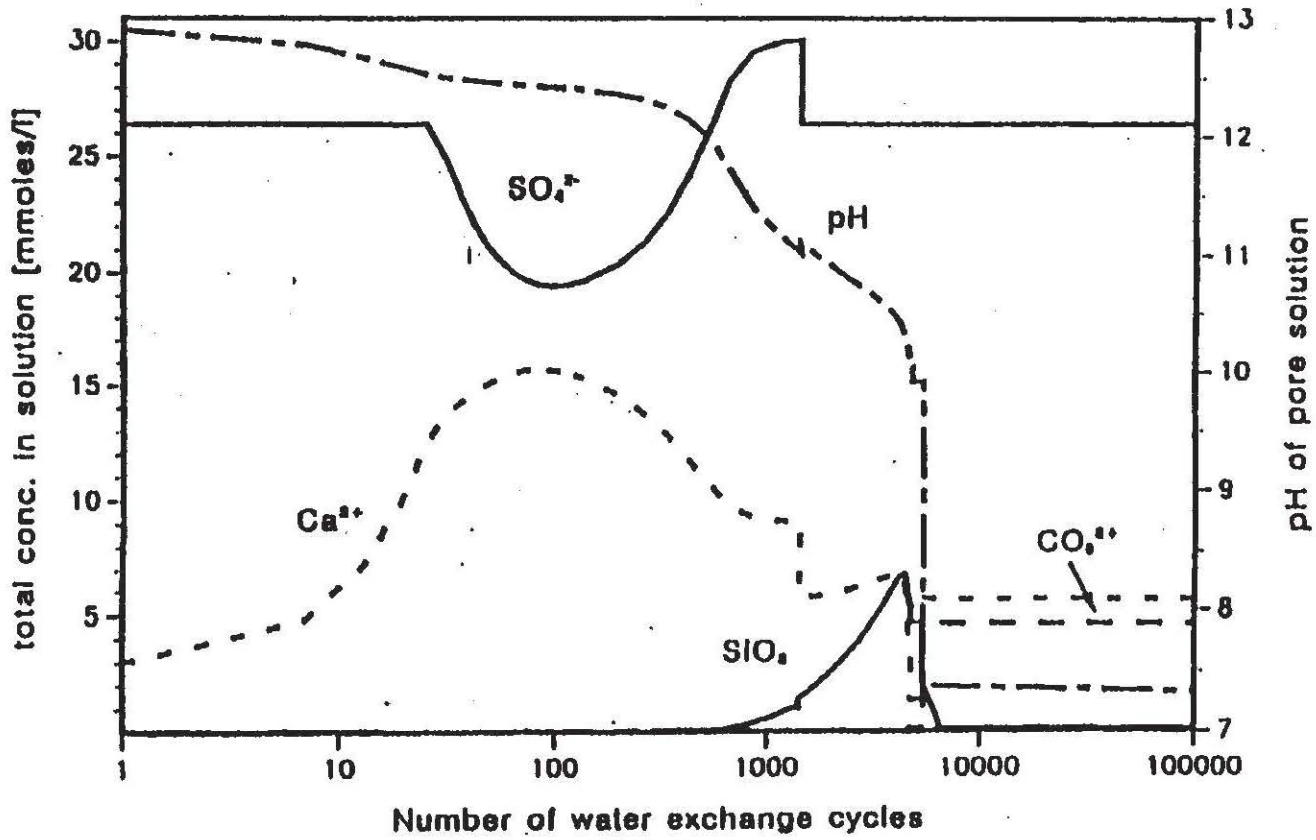

Figure 3: Degradation of Concrete in Brine (after Berner, 1990)

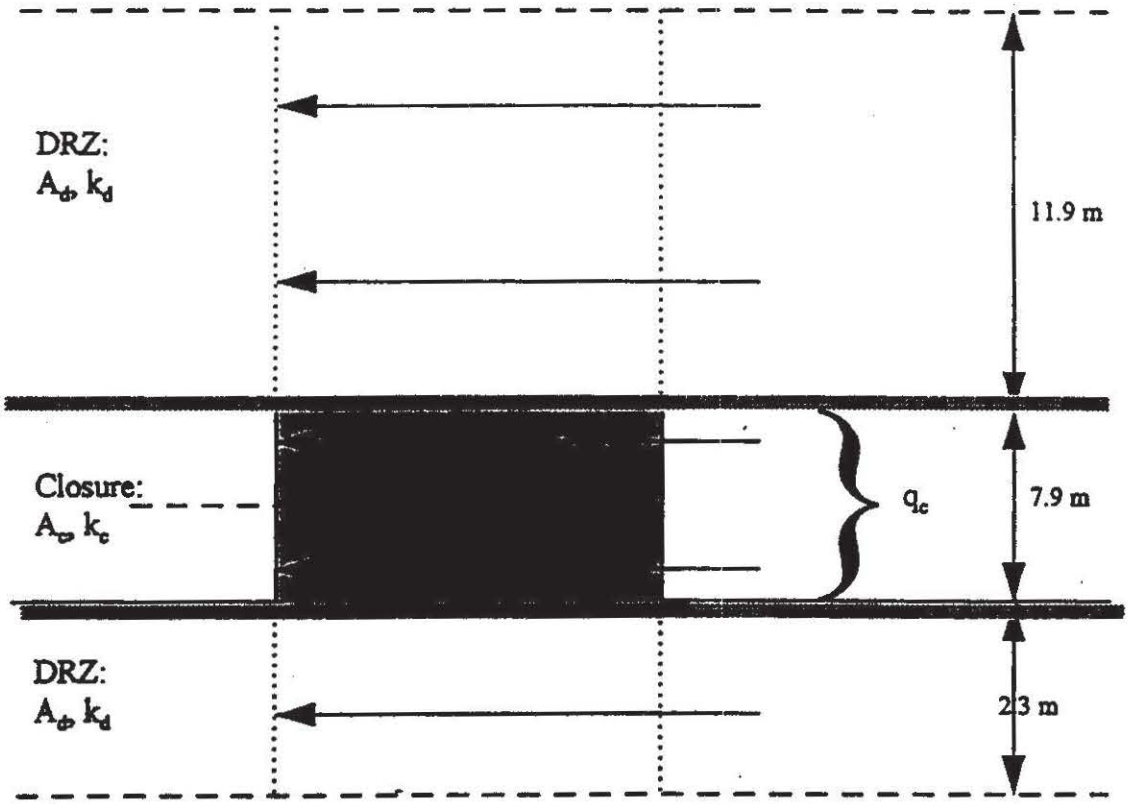

Figure 4: Parallel Flow through the Panel Closure and DRZ

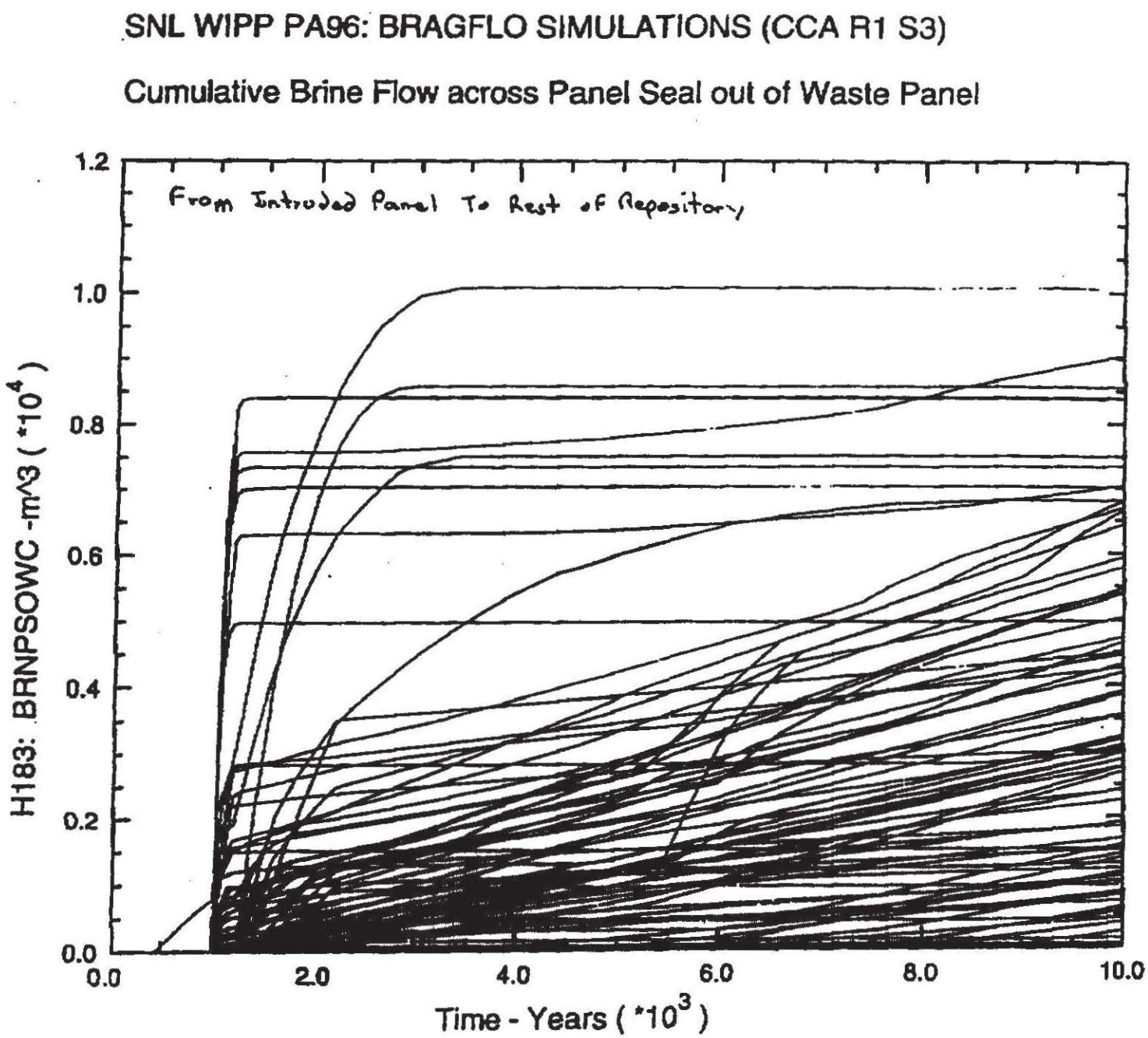

Figure 5: Cumulative flows between a panel and the rest of the repository for an E1 Intrusion at 1000 Years

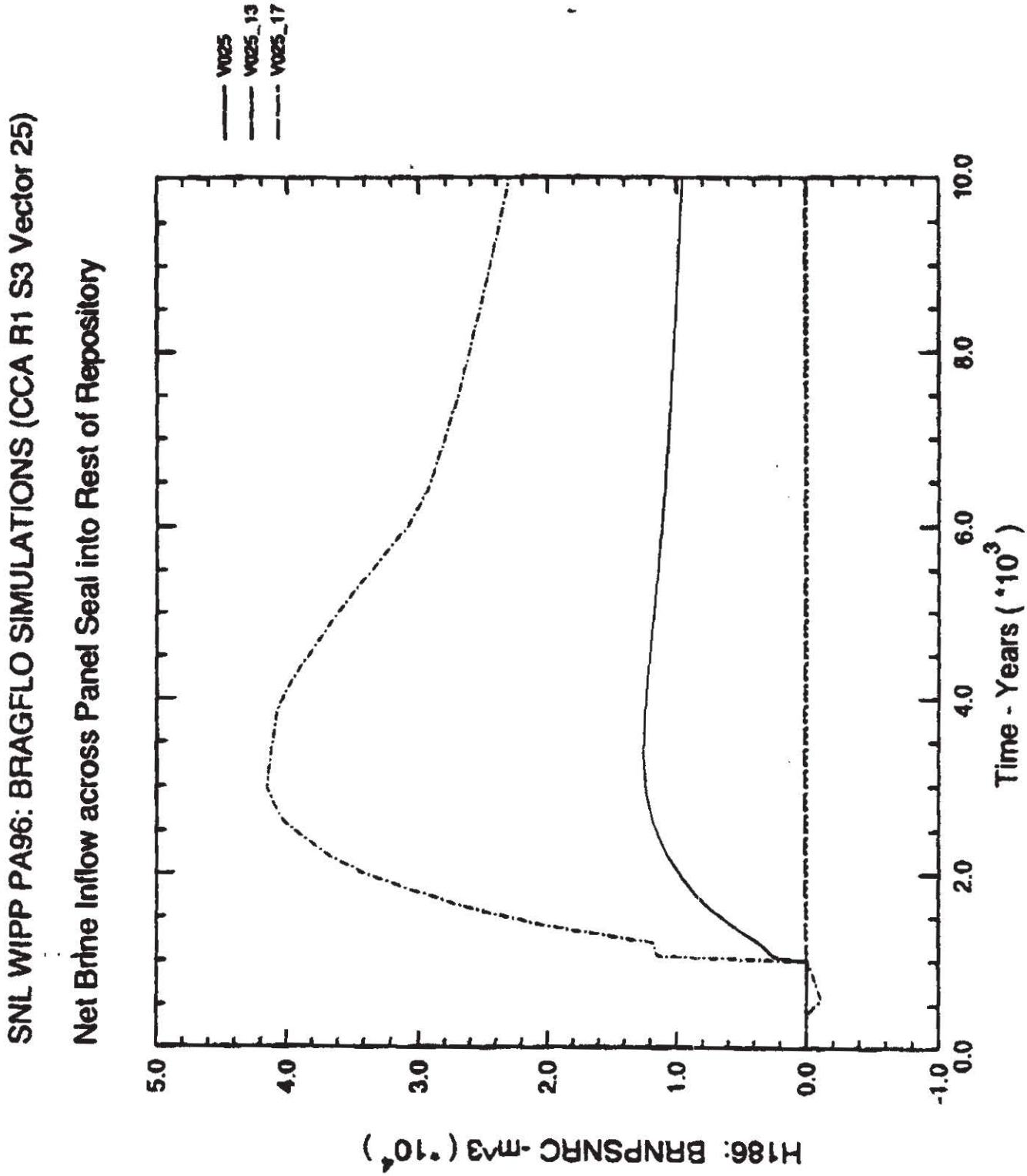

Figure 6: Cumulative flows through the Panel Closures for Permeabilities of 10^{-15} to 10^{-17} m^2. Results shown are for the Maximum Flow Case of Figure 5.

WIPP Colloidal Actinide Retardation Research Program

DOE Consultation with the State of New Mexico

21 May 1996

Carlsbad, NM

Hans W. Papenguth

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Outline of Presentation

Mobile Colloidal Actinide Source Term

- Overview
- Results

Retardation of Colloidal Actinides in the Culebra

- Conceptual models
- Program strategy
- Experiments
- Results by colloidal particle type
- Summary

Several Potential Sources of Colloidal Actinides Exist in the WIPP System

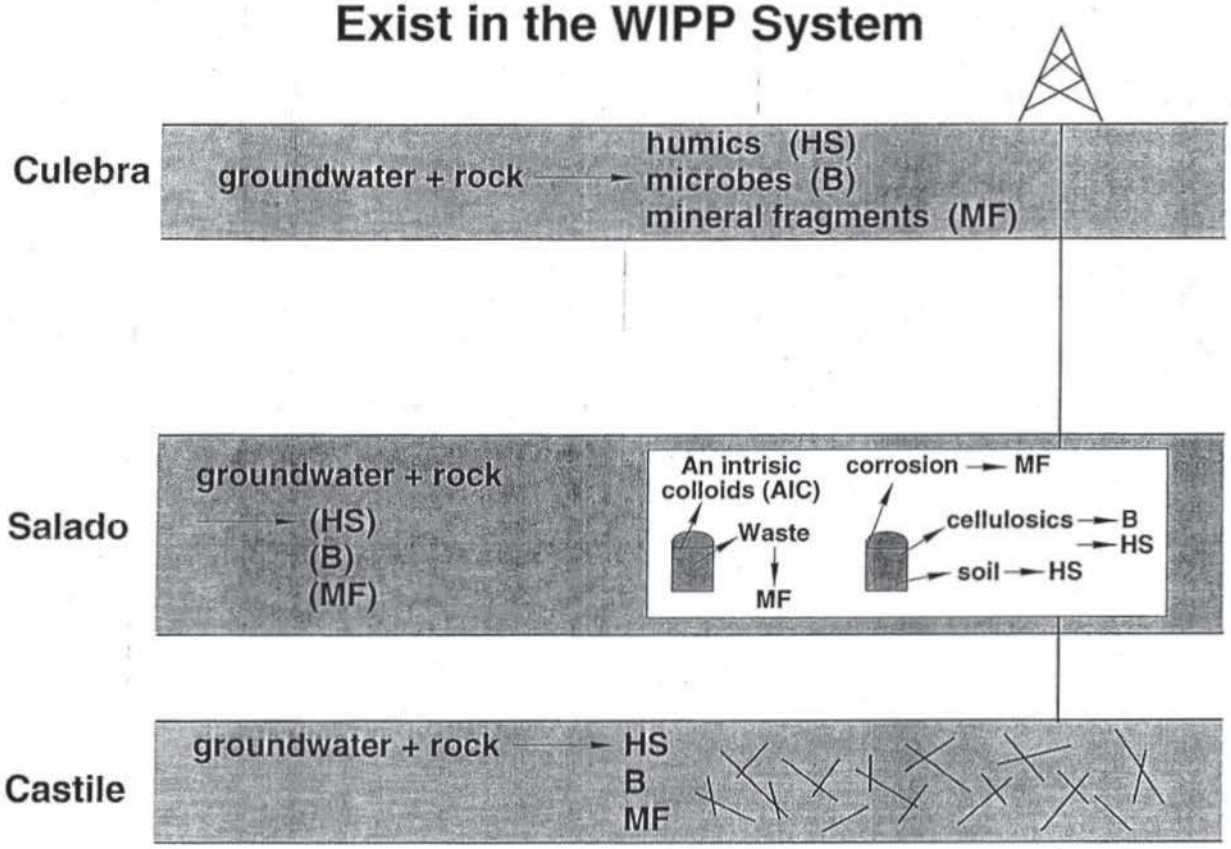

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Colloidal Particle Types Affected Differently by Chemical Conditions

Colloid Type	Stability Behavior in WIPP Brines	Uptake Mechanism for Th, U, Np, Pu, Am
mineral fragments	electrostatically destabilized	sorption
microbes	not affected	passive or active bioaccumulation
actinide intrinsic	solubility reduced; electrostatically destabilized	intrinsic
humic substances	solubility reduced	complexation

Mobile Colloidal Actinide Source Term

Concentrations dependent on repository brine scenario

- Salado brine, lower redox [Th(IV), U(IV), Np(IV), Pu(III), Am(III)]
- Salado brine, higher redox [Th(IV), U(VI), Np(V), Pu(IV), Am(III)]

- Castile brine, lower redox [Th(IV), U(IV), Np(IV), Pu(III), Am(III)]
- Castile brine, higher redox [Th(IV), U(VI), Np(V), Pu(IV), Am(III)]

Summary of ranges

(moles colloidal actinide per Liter of dispersion)

actinide	mineral	intrinsic	microbe*	humic*
Th	10^{-9}	0	10^{-8} to 10^{-5}	10^{-8} to 10^{-5}
U	10^{-9}	0	10^{-11} to 10^{-8}	10^{-8} to 10^{-5}
Np	10^{-9}	0	10^{-7} to 10^{-4}	10^{-9} to 10^{-5}
Pu	10^{-9}	10^{-9}	10^{-9} to 10^{-6}	10^{-8} to 10^{-5}
Am	10^{-9}	0	10^{-7} to 10^{-6}	10^{-7}

* based on mean actinide solubilities reported by Novak and Moore (1996)

Culebra Conceptual Hydrogeological Model

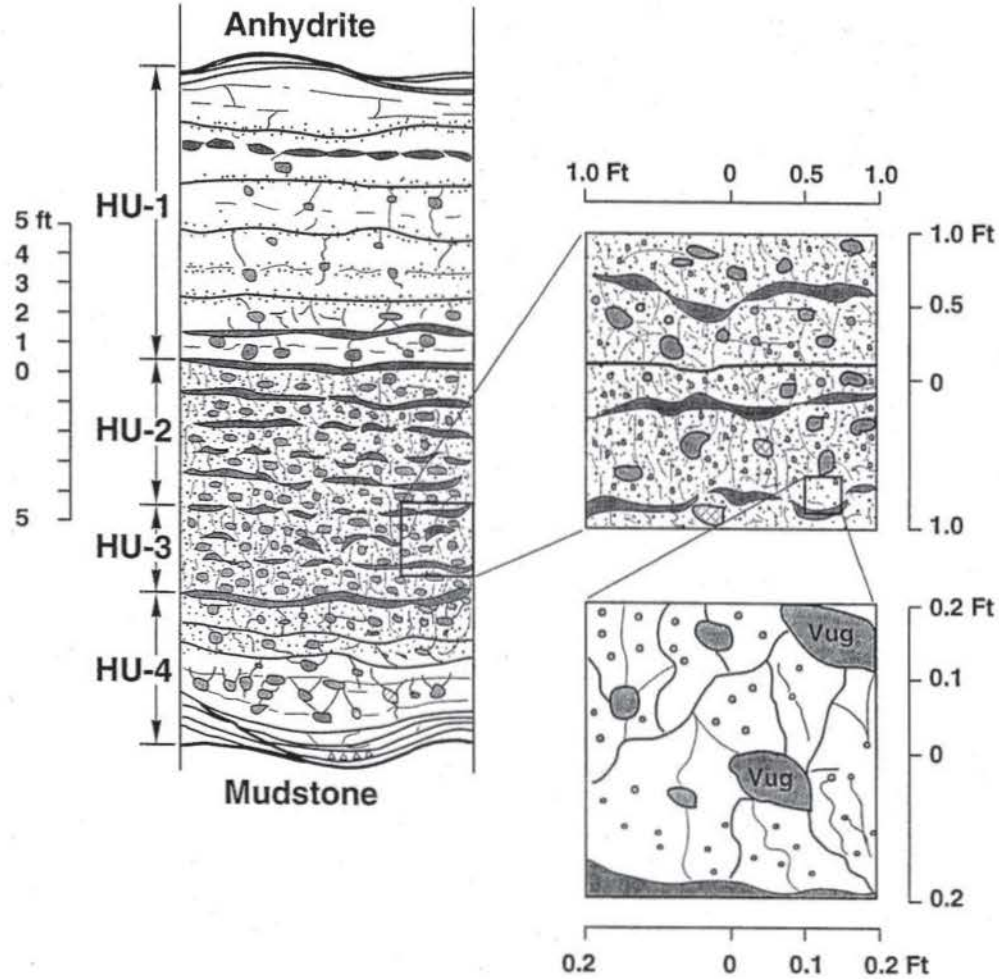

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Transport Behavior Depends on Colloid Type and Culebra Characteristics

Possible interactions between colloidal-actinides and rock:

Colloid Type	Colloid Size Range; Shape	Diffusion ?	Sorption ?	Filtration ?
mineral fragments	1 to 1000 nm; various shapes	smaller colloids only	yes	yes
microbes	250 to 2000 nm; rod shaped	no	yes	yes
actinide intrinsic	1 to 10 nm; dissolved, compact	yes	yes	no
humic substances	1 to 10 nm; dissolved, compact	yes	yes	no

*mean pore throat size in Culebra matrix is 630 nm (Kelley and Saulnier, 1990)

Experimental Approach Tailored to each Colloid Type

Batch sorption experiments (LANL) — K_d
- humic substances (Th, U, Np, Pu, Am)
- actinide intrinsic colloids [Pu(IV)-polymer]

Crushed-rock column flow experiments (SNL, BNL) — R, γ
- humic substances
- preserved microbes
- live microbes
- mineral fragments

Intact-core column flow experiments (SNL, BNL) — R
- humic substances (mixed with U, Pu, Am)
- live microbes (mixed with U, Am)

Diffusion parameter estimation (SNL) — D_{col}, M
- all colloid types

PA Parameter Values for Colloidal Actinide Retardation

Colloid	Actinide	K_d (mL/g)	γ (cm^{-1})
mineral fragments	Th, U, Np, Pu, Am	0.0[a]	0.3
microbes	Th, U, Np, Pu, Am	0.0[a]	0.5
intrinsic	Pu	0.0[b]	
	Th, U, Np, Am	0.0[c]	
humic substances	Am(III)	20 to 500[d]	
	Th(IV), U(IV), Np(IV)	900 to 20,000[d]	
	Np(V)	1 to 200[d]	
	U(VI)	0.03 to 30[d]	

Notes:
[a] chemical retardation observed, but is not included in PA calculations
[b] sorption expected but not quantifiable because of analytical detection limitations
[c] source term is zero for these intrinsic colloids
[d] from Dissolved Actinide Retardation Research Program

Crushed-Rock Column Experiments (SNL)

Packing

- Culebra (AIS; Culebra Bluffs)
- dolomite cleavage rhombohedra (Butte, Montana)
- hand crushed, washed, sieved 125-250 μm; 250-500 μm; 500-1000 μm
- hand crushed, sieved, washed, sieved, dried at low T

Colloidal particles

- humic substances
- preserved and live microbes
- quartz, goethite, hematite
- latex microspheres (non-functional; carboxylated; sulfonated)

Eluent

- H-17 brine simulant; Air intake shaft simulants; 0.001 M NaCl
- CO_2 partial pressure = $10^{-3.5}$ atm
- flow rate 0.1 to 0.5 mL/min

Test configuration

- columns 1 cm diameter; 5 to 100 cm length
- spike injections
- step injections

Crushed-Rock Column Experiments (SNL), cont.

Analytical methods

- in-line laser particle spectrometry
- scanning fluorometry, fixed wavelength fluorometry
- ICP-AES
- epifluorescence microscopy (BNL)

Porosity characterization

- equivalence of advective and measured porosity confirmed with "non-sorbing" tracers (fluoroscein, rhodamine WT, rhodamine B, sulforhodamine B, lithium, bromide)
- gravimetric determinations similar to fluoroscein
- porosity typically 45%

Evaluation of potential artifacts

- varied column lengths
- varied flow rates
- varied injection type
- reversed flow
- varied packing diameter; colloid diameter

Interpretation of Crushed-Rock Column Experiments

Transport and retardation phenomena

- advection (average linear flow velocity; v)
- dispersion and diffusion (D)
- adsorption (R or K_d)
- filtration (γ) includes interception and sieving, sedimentation, irreversible sorption

Advection-dispersion equation with adsorption:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - \frac{v}{R}\frac{\partial C}{\partial x} \qquad (1)$$

Filtration equation:

$$\frac{\partial C}{\partial x} = -\gamma C \qquad (2)$$

Interpretation of Crushed-Rock Column Flow Experiments, cont.

Advection-dispersion equation with adsorption and filtration:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - \frac{v}{R}\left(\frac{\partial C}{\partial x} + \gamma C\right) \qquad (3)$$

Solution of (3) described in Harvey and Garabedian (1991):

[peak concentration obtained from (1)] * exp(-γx) (4)

Conceptualization of the Effect of Filtration on Column Breakthrough

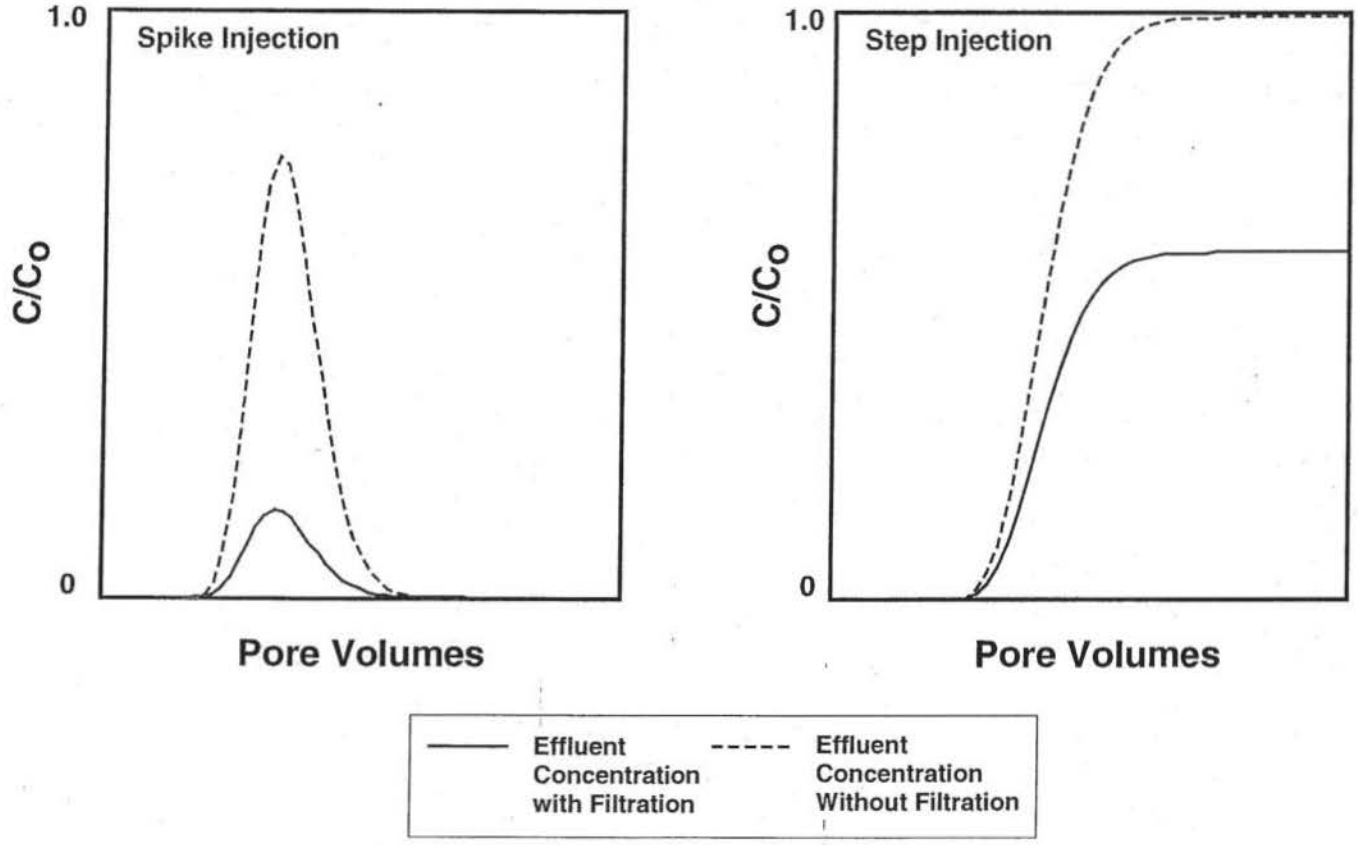

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Interpretation of Crushed-Rock Column Flow Experiments, cont.

Steps in interpretation of elution curves

- R estimated from peak position
- breakthrough curves are often noisy; not suitable for automated curve-fitting procedures
- conservative value of D is established (literature; test with conservative tracer; sensitivity analyses)
- theoretical peak height without filtration calculated with R and D using CXTFIT (Parker and Genuchten, 1984)
- γ calculated (L is column length):

observed peak concentration = theoretical peak concentration * exp($-\gamma L$)

$$\gamma = -\ln\left(\frac{\text{observed peak concentration}}{\text{theoretical peak concentration}}\right) * \frac{1}{L}$$

Batch Sorption Experiments (LANL)

Test design

- rock crushed and wet sieved; 75 to 500 μm fraction used
- rock washed with dilute HCl; rock pretreated in brine
- 1 g rock and 20 mL brine during pretreatment, sorption and desorption experiments
- brines analyzed with ICP-MS or LSC
- K_d determined from difference between initial and final actinide concentration in brine
- controls used to assess whether experimental artifacts occurred, e.g., loss to vessel or coprecipitation

Humic substance mixture consisted of equal parts of:

- purified Lake Bradford, Florida, aliphatic humic acid (FSU)
- Suwannee River aromatic humic acid (International Humic Substances Association; IHSA)
- Suwannee River fulvic acid (IHSA)
- two total concentrations used: 0.01 and 1.0 mg/L

Intact-Core Column Flow Experiments with Colloids (SNL)

Core used

- four Culebra cores extracted from the air intake shaft (AIS) from two stratigraphic horizons (HU-2 and HU-3)
- cores well preserved, intact, horizontally oriented in direction of the current flow path
- colloid test cores approximately 5.7 inches diameter x 4 inches long
- live microbe test with core VPX-27-7A (HU-3)
- humic test with core VPX-25-8A (HU-2)

Test design

- test design consisted of sequential comparison tests
  - without and with live microbes, introduced in eluent
  - without and with humic substances, introduced in eluent
- Am(III), $Pu(V)O_2^+$, $U(VI)O_2^{2+}$, tested in AIS brine
- Am and Pu injected as spikes directly on rock to minimize sorption on apparatus
- U injected as step to provide time for colloid-uranium interaction
- flow rate close to upper flow rate in Culebra (0.1 mL/min)

Microbial Actinide Transport Attenuated by Filtration

Crushed-rock column transport tests

- WIPP-relevant live and preserved microbes supplied by BNL
- experiments with live microbes conducted with and without nutrient
- packing particle size varied
- H-17 brine with or without nutrients
- step injection tests conducted with 10^6 to 10^7 cells/mL; spike injection tests conducted with 10^7 to 10^8 cells/mL

Results

- experiments with 125-250 μm packing resulted in very high filtration
- γ quantified in experiments with 250-500 μm particle size
- step injections resulted in column plugging, pressure build-up
- spike injection of low concentration allowed measurement of γ
- smaller microbes (0.2 to 0.28 μm) less attenuated than larger microbes (0.6 to 1 μm)
- elution curve from smaller microbes used to determine conservative γ
- γ values of about 0.5 cm^{-1} measured for smaller microbes
- R values of about 4 measured

Microbial Actinide Transport Attenuated by Filtration, cont.

Filtration effects confirmed with intact-core column flow tests

- elution of U matched profile of test without microbes
- Am did not elute during the test, consistent with test without microbes
- direct counts (BNL) of microbes showed background concentrations only

Microbe results supported by crushed-rock column flow tests with mineral fragments and latex microspheres

PA Implementation

- represent attenuation with γ
- set R equal to 1 due to complexities of combining R with γ values in SECOTP-2D simulation

Microbe Transport Through a Crushed-Rock Column

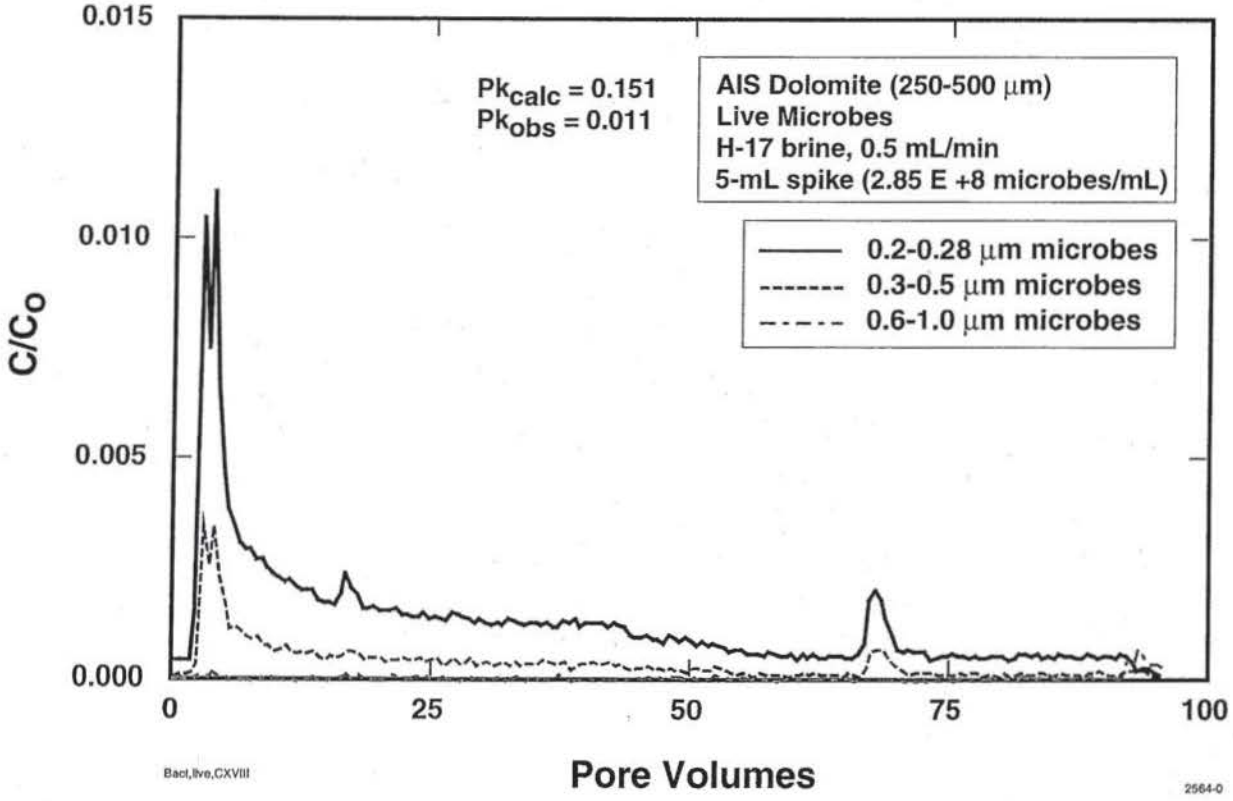

Microbe Transport Through a Crushed-Rock Column

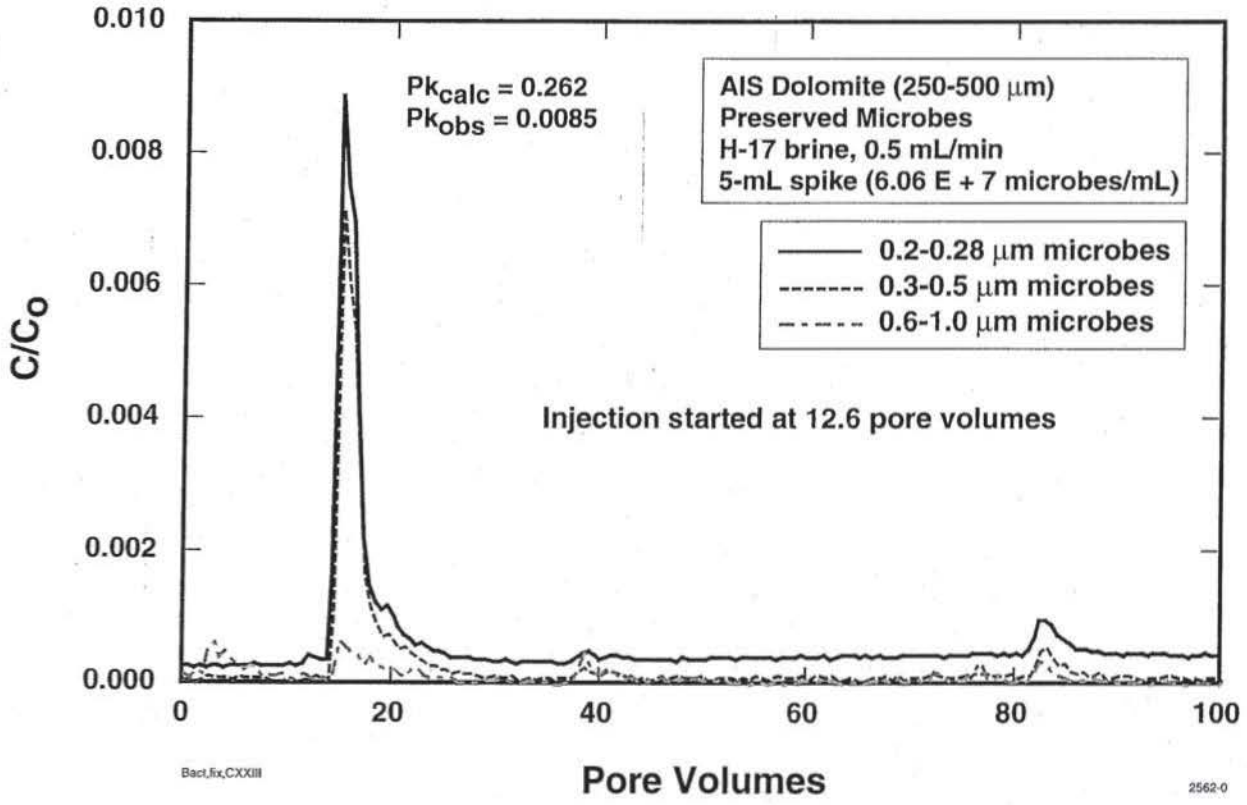

Microbe Transport Through a Crushed-Rock Column

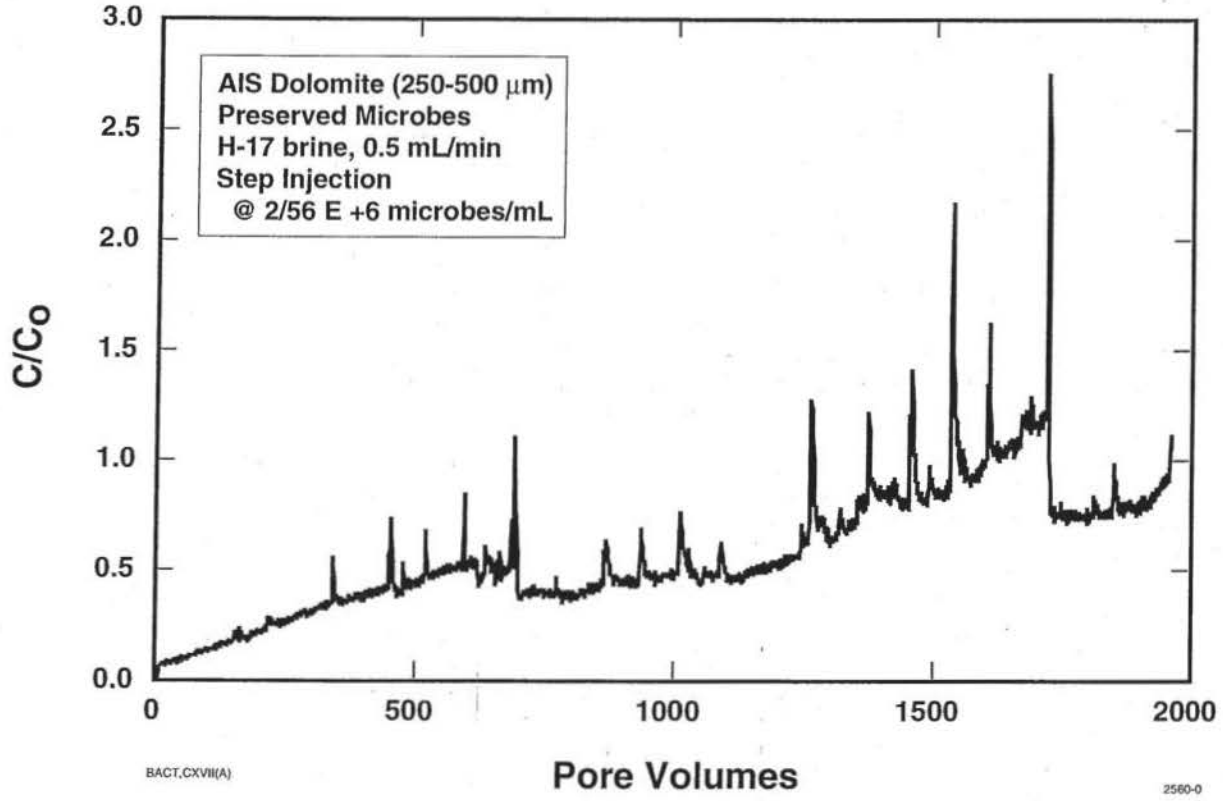

Microbial-Actinide Transport through an Intact Core

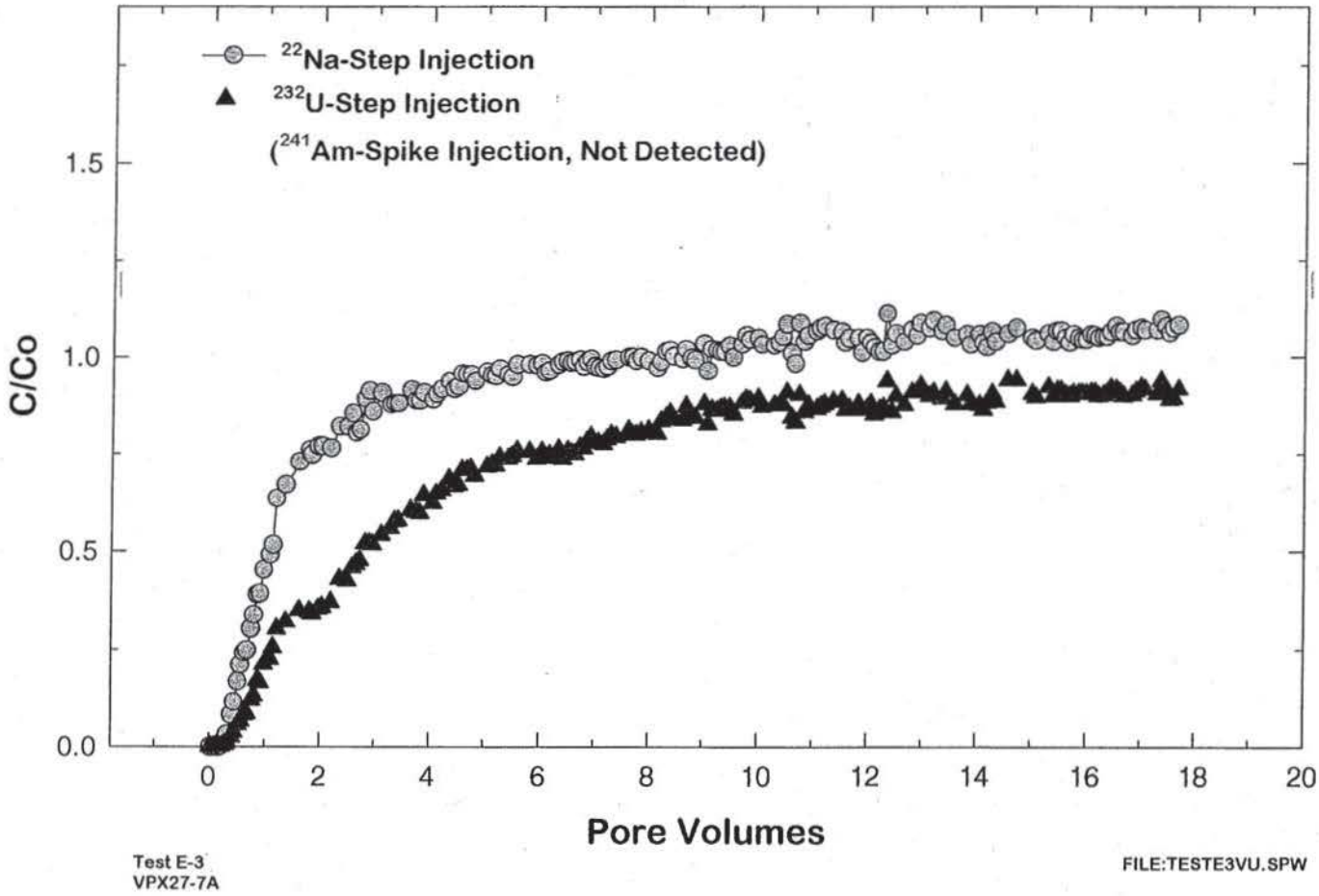

Latex Microsphere Transport Through a Crushed-Rock Column

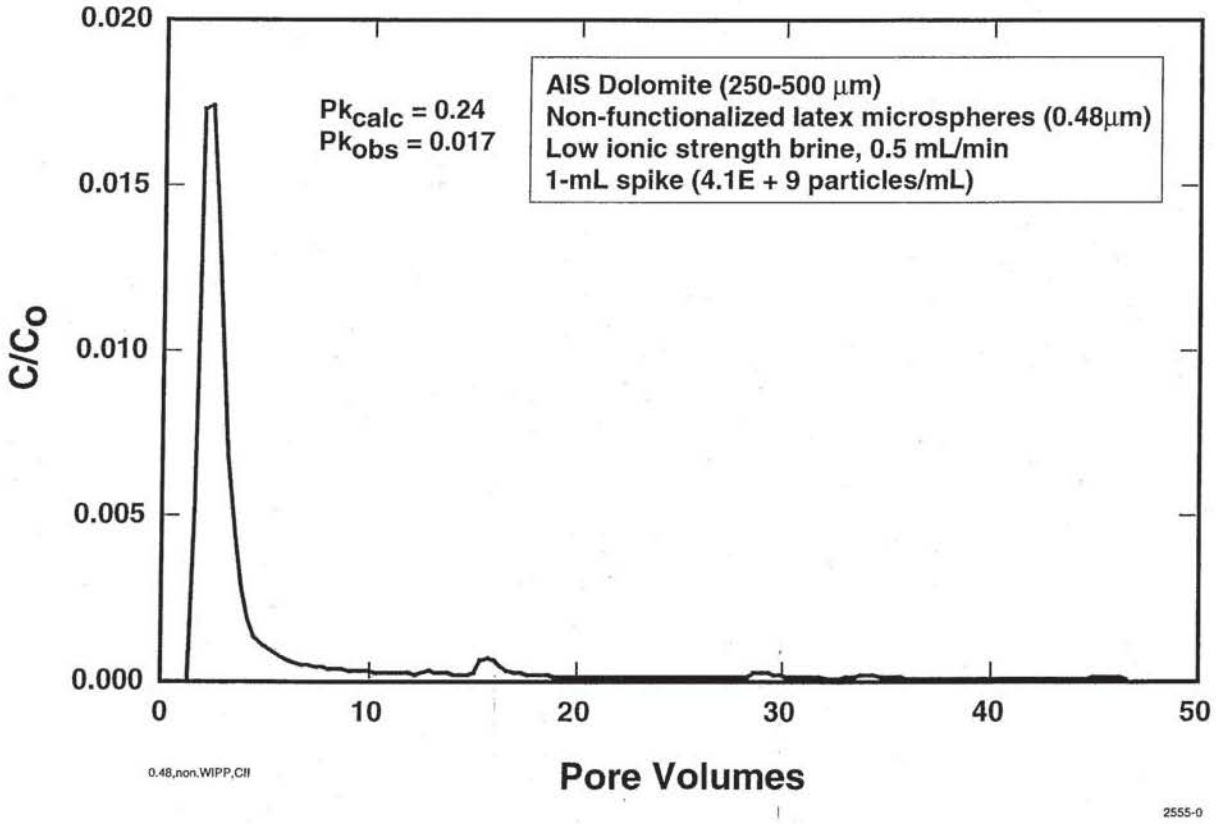

Mineral Fragment Transport Attenuated by Filtration

Crushed-rock column transport tests

- dispersions of mineral fragments prepared by chemical precipitation or mechanical milling
- colloids in spike allowed to coagulate and settle to reach a steady-state population before injection; spike filtered with 1.2 μm filter
- low ionic strength eluent used to isolate filtration effects from kinetic destabilization
- results consistent with microbe tests and latex microsphere tests

Results

- measured R values of 4 to 6 in H-17 brine
- measured γ value of 0.3 to 0.4 cm^{-1}

PA Implementation

- represent attenuation with γ
- set R equal to 1 due to complexities of combining R with γ values in SECOTP-2D simulation
- measured R values may not represent possible range for other colloids

Mineral Fragment Transport Through a Crushed-Rock Column

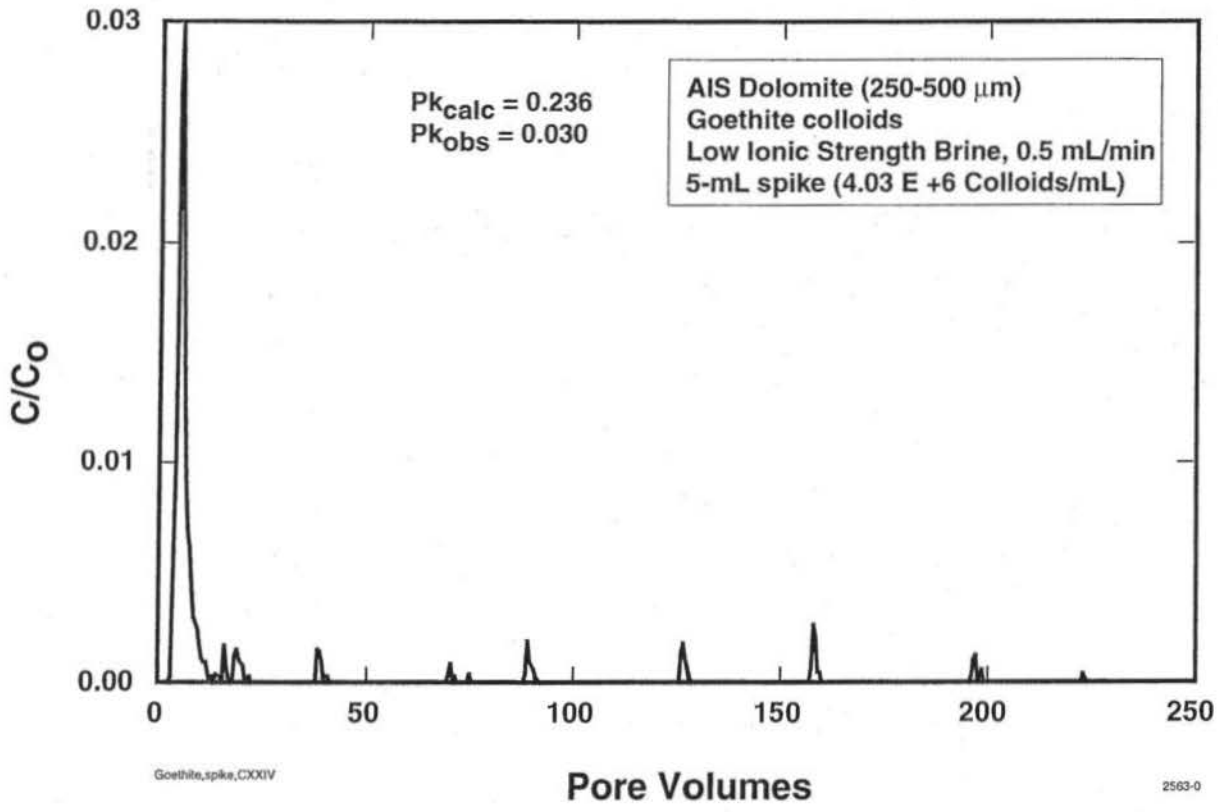

Attenuation of Humic-Actinides Similar to that of Dissolved Actinides

Crushed-rock column flow tests demonstrate no enhanced transport of humic substances (SNL)

- aliphatic humic acid (purified Aldrich; Aldrich Chemical Co.; FSU)
- aliphatic humic acid (Lake Bradford, Florida; FSU)
- aromatic humic acid (Suwannee River; IHSA)
- fulvic acid (Suwannee River; IHSA)

Batch sorption experiments with and without humic substances nearly identical (LANL)

- 1:1:1 mixture of aliphatic + aromatic humic acid + fulvic acid

Intact-core column flow tests demonstrate no difference in elution of U, Pu, Am with and without humics (SNL)

- 1:1:1 mixture of aliphatic + aromatic humic acid + fulvic acid

Retardation can by simulated using values from Dissolved Actinide Retardation Research Program

Humic Acid Transport Through a Crushed-Rock Column

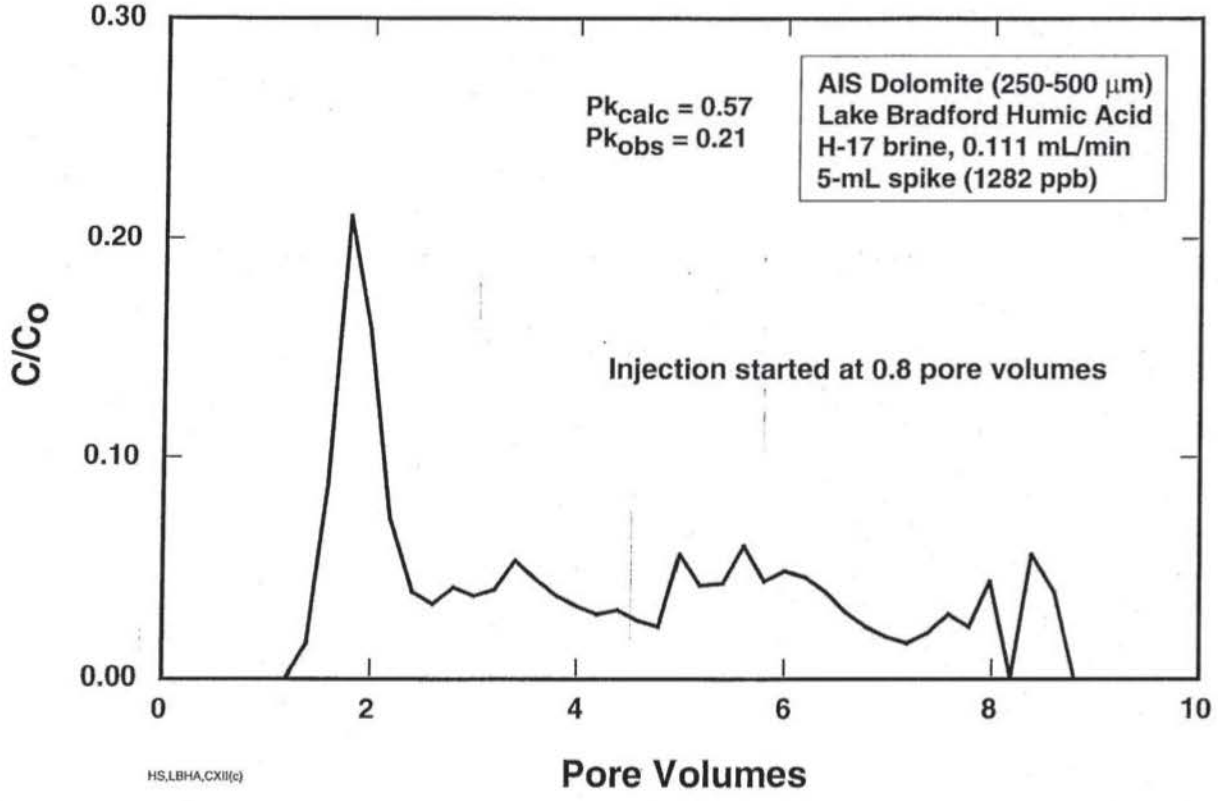

HS,LBHA,CXII(c)

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Fulvic Acid Transport Through a Crushed-Rock Column

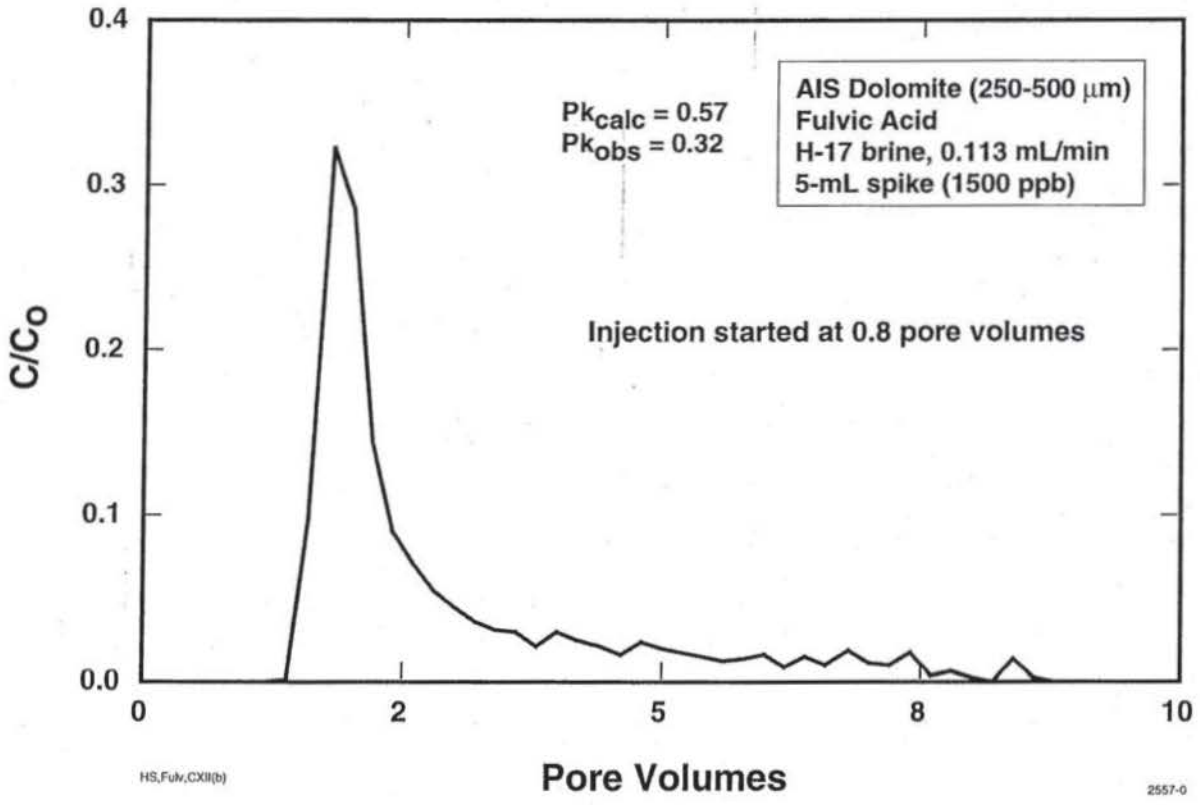

Fluoroscein (Conservative Tracer) Transport Through a Crushed-Rock Column

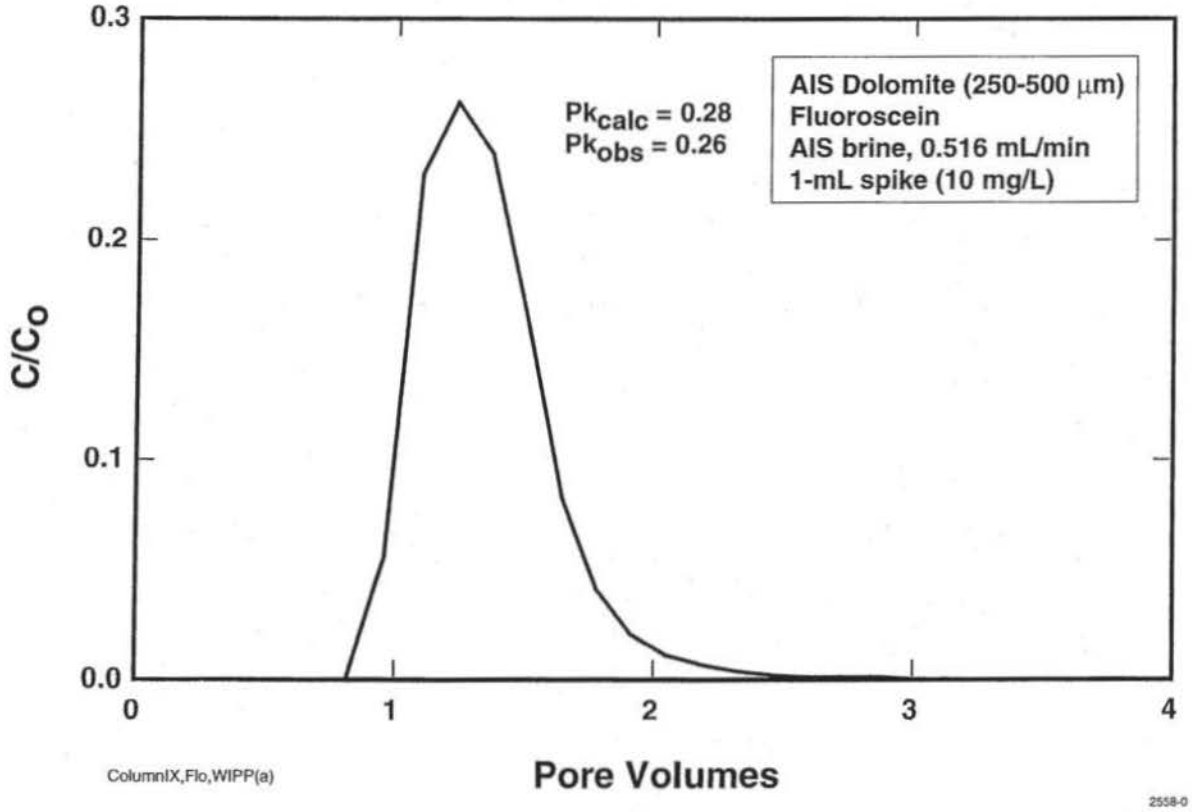

Humic-Actinide Transport through an Intact Core

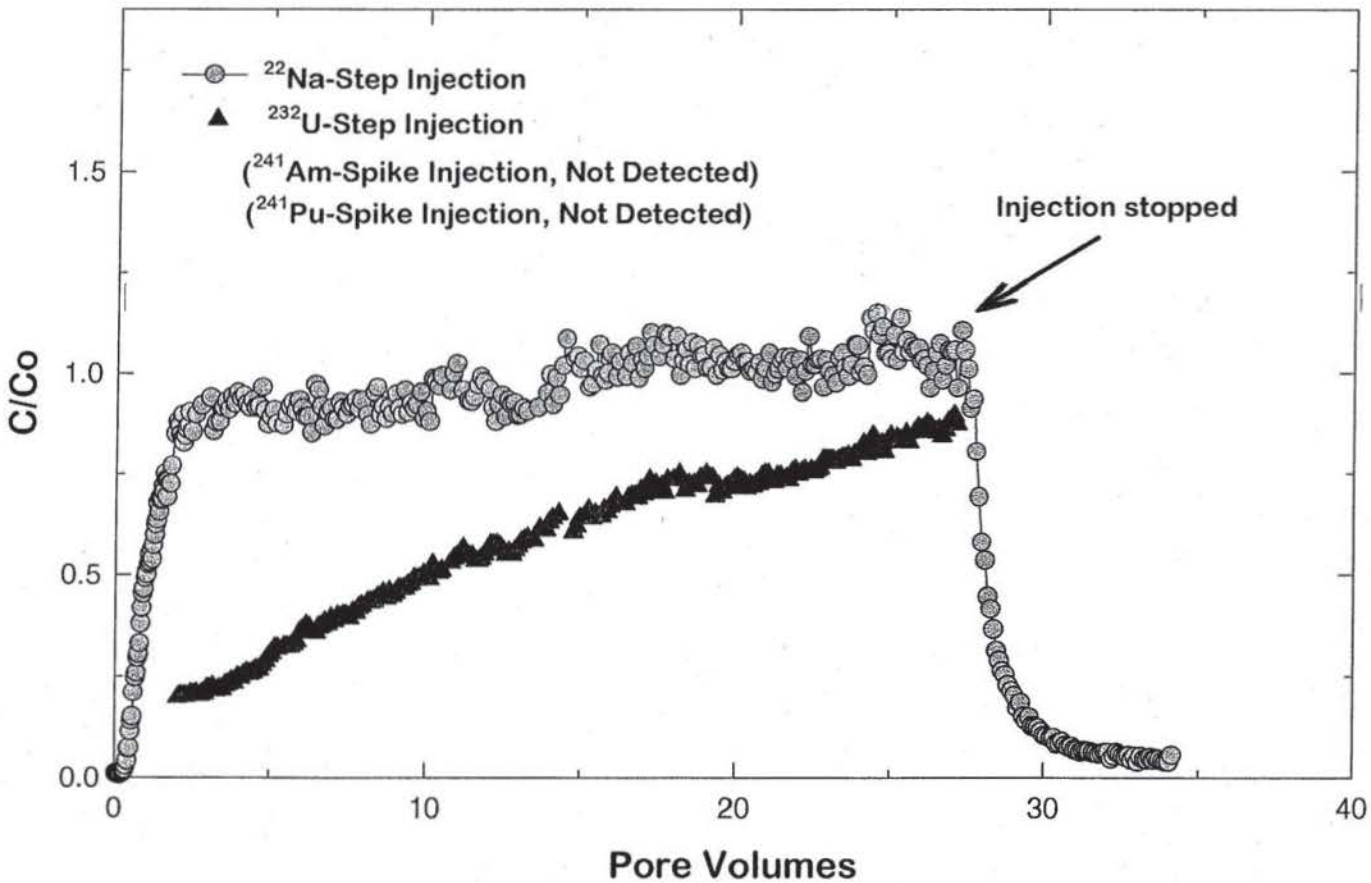

Test D-7
VPX25-8A

FILE:TESTD7VU.SPW

Humic-Actinide Batch-Sorption Results

(K_d values in mL/g)

actinide	[humic] (mg/L)	Culebra H-17; $pCO_2=10^{-3.5}$ atm		Culebra H-17; $pCO_2=10^{-1.5}$ atm		Castile ERDA-6; $pCO_2=10^{-3.5}$ atm		Castile ERDA-6; $pCO_2=10^{-1.5}$ atm	
Th(IV)	none	20	c	10	c	100	c	20	c
	0.01	10	c	10	c	100	c	20	c
	1	20	c	10	c	80	c	20	c
U(VI)	none	-2	b	-1	b	0.04	a	-0.01	a
	0.01	-1	b	-0.8	b	-0.3	a	-0.4	a
	1	-1	b	-0.7	b	0.4	a	-0.03	a
Np(V)	none	5	b	1	b	90	a	100	a
	0.01	5	b	1	b	80	a	100	a
	1	5	b	1	b	70	a	100	a
Pu(V)	none	20	b	9	b	200	a	200	a
	0.01	20	b	7	b	200	a	200	a
	1	20	b	10	b	200	a	200	a
Am(III)	none	500	c	400	c	700	c	3000	c
	0.01	600	c	400	c	1000	c	2000	c
	1	600	c	400	c	2000	c	2000	c

Notes:
reported values are averages of two replicates
LSC analytical error: "a" indicates $\leq 3\sigma$; "b" indicates 3 to 4σ; "c" indicates $> 4\sigma$

Colloid Diffusion Coefficients Required to Simulate Diffusion and Dispersion

Free-solution tracer diffusion coefficients for colloidal particles are required for SECOTP-2D

Estimates made with Einstein's equation for spherical particles (Hiemenz, 1986, p. 83):

$$D_{col} = \frac{k\,T}{3\pi\,\mu\,d_p}$$

where:
- D_{col} = free-solution tracer diffusion coefficient for colloidal particles ($cm^2\ sec^{-1}$)
- k = Boltzman constant
- T = temperature in Kelvin
- μ = brine viscosity
- d_p = colloidal particle diameter

Estimates for D_{col} as much as 1000-times less than Values for Dissolved Actinides

Colloid Type	Colloid Diameter (nm)	D_{col} (cm^2 sec^{-1})
mineral fragments	1000	2.1e-9
microbes	1000	2.1e-9
humics	100	2.1e-8
Pu(IV)-polymer	100	2.1e-8

Notes:

- laboratory measurements of Brine A (Salado-like brine simulant) used as conservative viscosity value ($2.13e10^{-2}$ g $cm^{-1}sec^{-1}$; Gelbard 1993)
- k = 1.38e-16 g cm^2 sec^{-2} $°K^{-1}$
- T = 300 °K
- D_{sol} values reported for dissolved actinides range from 1.53e-6 to 4.26e-6 cm sec^{-1} (Brush, 1996)

Results consistent with published estimations for colloids

- see, e.g., Hiemenz (1986)

Colloid Mass Concentrations Required to Simulate Diffusion

Humic substances

- measured concentration (solubility) = 2×10^{-3} g/L

Actinide intrinsic colloids [Pu(IV)-polymer]

- measured solubility limited to minimum analytical detection limit of LSC
- measured concentration (detection limit) = 1×10^{-9} moles/L = 2.4×10^{-7} g/L

Microbes

- estimate biomass using laboratory measurements and geometry
  - rod shaped with mean dimensions of 0.9 μm diameter x 1.7 μm length
  - density equal to Brine A (1.2 g/cm^3)
  - measured steady-state population of 5×10^6 cells/mL
- estimated concentration = 5×10^{-3} g/L

Mineral fragments

- estimate concentration using laboratory measurements and geometry
  - residual concentration and mean size measured in stability experiments
  - spherical shapes, specific gravity of 3, monodisperse population
- estimated concentration = 1×10^{-3} g/L

PA Parameter Values for Colloidal Actinide Retardation

Colloid	Actinide	K_d (mL/g)	γ (cm^{-1})
mineral fragments	Th, U, Np, Pu, Am	0.0[a]	0.3
microbes	Th, U, Np, Pu, Am	0.0[a]	0.5
intrinsic	Pu	0.0[b]	
	Th, U, Np, Am	0.0[c]	
humic substances	Am(III)	20 to 500[d]	
	Th(IV), U(IV), Np(IV)	900 to 20,000[d]	
	Np(V)	1 to 200[d]	
	U(VI)	0.03 to 30[d]	

Notes:
[a] chemical retardation observed, but is not included in PA calculations
[b] sorption expected but not quantifiable because of analytical detection limitations
[c] source term is zero for these intrinsic colloids
[d] from Dissolved Actinide Retardation Research Program

References

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Comparison of Effects of Brine Pocket Size

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Darien G. O'Brien, PE
Solutions Engineering

July 19, 1996

BACKGROUND

The existence and size of a Castile Brine Pocket below the WIPP repository is uncertain. Brine pockets have been found in the northern Delaware Basin but there is little information on their size. The producibility of brine from these pockets is believed to be related to the interconnectedness of a fracture system. Analysis of WIPP-12 data have led to estimates for the areal extent of several hundred meters (drainage radius as small as 230 m -- dimension smaller than the WIPP waste-area footprint) to several kilometers (drainage radius as large as 19,000 m -- dimension larger than the land withdrawal boundary). DOE does not consider the 19 km radius brine pocket a realistic size, never the less it is included for comparison to other sizes. Because of the interconnectedness of the fracture system, the thickness of the brine pocket has been estimated to be from 7 m to 24 m with a maximum possible of 133.6 m (recent estimate based upon the total thickness of the Castile formation and NOT considered in the 1996 CCA calculations).

Each time a well penetrates the brine pocket, the pressure in the surrounding drainage area depletes. This pressure depletion will extend to those portions of the brine pocket which are interconnected. Passive Institutional Controls shield a region of the Castile from exploratory drilling directly under the waste panels. The 1996 CCA calculations assume that the Castile Brine Pocket under the waste panels is weakly interconnected hydraulically (with vertical and areal extents similar to the lower estimates from WIPP-12, i.e. total brine volume between 32,000 and 160,000 m^3 [Larson & Freeze, 1996]), and is not much affected by penetrations occuring outside the waste-area footprint. Therefore, the pressure underneath the waste panels in the brine pocket is assumed to not deplete until penetrated by a borehole drilled within the panel area. If the brine pocket has an extensive fracture system (and hence is strongly interconnected), the area beneath the waste panels can be depleted by penetrations outside the waste-area footprint.

This study looks at the consequences of assuming that the brine pocket is hydraulically interconnected such that borehole penetration depletion impacts are felt throughout a larger drainage area. The total brine volume which migrates from the Castile Brine Pocket to the Culebra aquifer with depletion impacts (large drainage area) is compared against the brine volume migration without depletion (small drainage area).

THEORETICAL CONSIDERATIONS

For the 1996 CCA calculations, an abnormally pressured Castile Brine Pocket is assumed (i.e. the brine pocket pressure exceeds the anticipated hydrostatic pressure). The brine pocket is assumed to be bounded (i.e. of limited thickness and areal extent) rather than infinite acting (such as the Culebra aquifer). Consistent with DOE regulatory criteria regarding the rate of future drilling activity, it is assumed that 47 boreholes will be drilled per square kilometer over the next 10,000 years (or 0.47/100 yrs/km^2). Each penetration of the abnormally pressured brine pocket will result in flows according to the following time horizons:

1) Time of intrusion to 72 hours - brine flows from the brine pocket, past the Culebra all the way to the surface during active drilling through an open borehole (assuming steady-state flow conditions). A computation to determine the length of time during which steady-state is valid (i.e. infinite acting period when the pressure sink caused by flow into the borehole has reached the extent of the drainage area) as computed by the following [Lee, 1982]:

$$t < \frac{\phi \mu c_t A t_{DA}}{k} \qquad \text{[Equation 1]}$$

where:

- t = Time (for a bounded cylindrical system is infinite acting) (sec)
- ϕ = Porosity (fraction)
- μ = Viscosity (Pa-sec)
- c_t = Total compressibility (Pa^{-1})
- A = Drainage area (defined as the land withdrawal boundary area/avg. no. of boreholes/200 years where 19.5 boreholes is taken as the average in 200 years) (m^2)
- t_{DA} = Dimensionless time (which for a bounded cylindrical system = 0.10, [Lee, 1982])
- k = Brine pocket permeability (m^2)

The solution to Equation 1 is approximately 7 hours. Although the steady-state flow assumption is valid only within 7 hours after penetration, a flow period of 72 hours was used. This is consistent with the 1996 CCA blowout time period to obtain direct brine releases from the WIPP repository. For the purposes of this investigation, pressure depletion during the 72 hour open flow period was not taken into account.

During the 72 hour flow period, flowrate is computed from the following (see nomenclature section for definition of variables):

$$Q_{bp} = \left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{bp} - P_{atm} - \rho g L_{surface} \right) \qquad \text{[Equation 2]}$$

2) 72 hours to 200 years - no brine flows from the brine pocket since the 1996 CCA calculations assume a 200 year time period immediately following intrusion during which the borehole is plugged at the Rustler and Castile formations.

3) From 200 years to 1200 years - cement plugs are no longer active. Flow occurs between the Castile Brine Pocket and the Culebra aquifer via "silty sand" abandoned boreholes with median permeabilities of 3.16E-13 m^2.

4) 1200 years to 10000 years - median abandoned borehole permeabilities are reduced one order of magnitude (3.16E-14 m^2) due to salt creep.

Abandoned Borehole Connection Between Castile Brine Pocket and Culebra Aquifer

Consider the flow rate necessary to achieve flow from the Castile Brine Pocket to the Culebra Aquifer through an abandoned borehole as depicted in Figure 1:

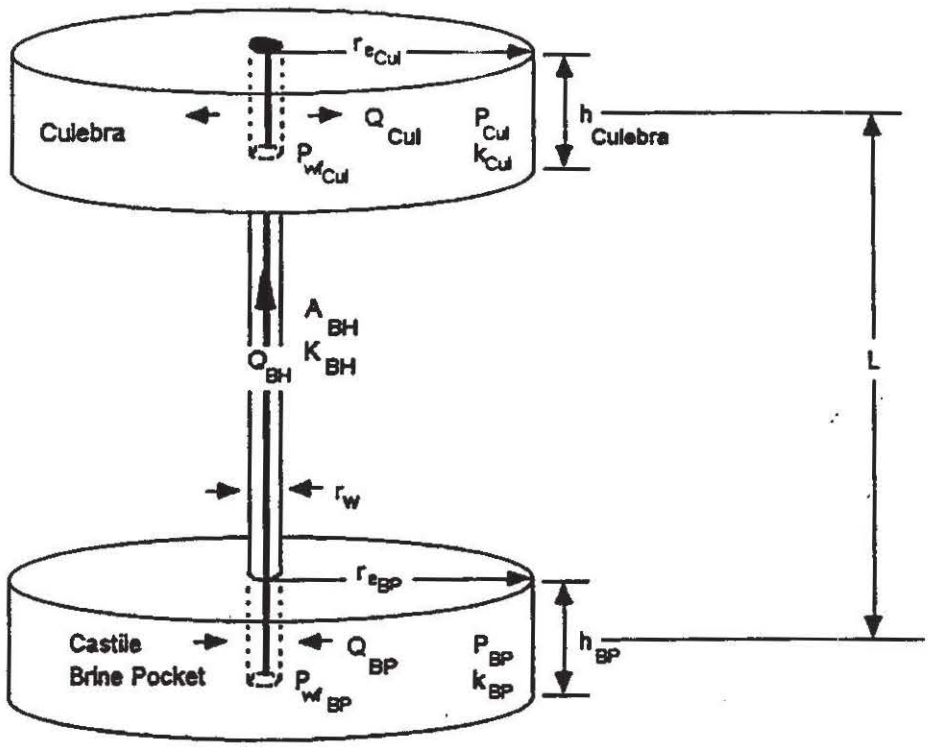

Figure 1: Representation of assumed flow path for Castile Brine Pocket to Culebra Aquifer

NOMENCLATURE

Define the following variables by:

Q = Flowrate (m^3/sec)
k = Permeability (m^2)
h = Thickness (m)
μ = Brine viscosity (Pa-sec)
ρ = Brine density (kg/m^3)
g = Acceleration due to gravity (m/sec^2)
L = Borehole length (m)
r = Radius (m)
A = Cross sectional area (m^2)
P = Pressure (Pa)
$\overline{P}$ = Average pressure between r_e and r_w (Pa)
c = Compressibility (Pa^{-1})
ϕ = Porosity (fraction)
V = Bulk volume (m^3)
ΔN = Brine volume producted between time 1 and 2 (m^3)

Define the following subscripts by:

cul = Culebra
bh = Borehole
bp = Brine pocket
e = External drainage per borehole (brine pocket area divided by number of boreholes)
w = Wellbore
wf = Abandoned wellbore flowing
atm = Atmospheric
b = Rock bulk
f = Pore volume
br = Brine
t = Total
R = Castile Brine Pocket or Culebra Aquifer
1,2 = Time 1, time 2

Refer to Figure 1, assuming steady-state flow is positive between the Castile Brine Pocket and the Culebra Aquifer, the following Darcy Law equations are used to obtain the flowrates out of the brine pocket (Q_{bp}), through the borehole (Q_{bh}) and into the aquifer (Q_{cul}), based upon the pressures, rock and fluid properties and brine pocket/abandoned borehole/aquifer geometries:

$$Q_{cul} = \left\{ \frac{k_{cul} h_{cul}}{\mu \left[\ln\left(\frac{r_{e_{cul}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{wf_{cul}} - P_{cul} \right) \qquad \text{[Equation 3]}$$

$$Q_{bh} = \left[\frac{k_{bh} A_{bh} \left(P_{wf_{bh}} - P_{wf_{cul}} - \rho g L \right)}{\mu L} \right] \qquad \text{[Equation 4]}$$

$$Q_{bp} = \left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{bp} - P_{wf_{bp}} \right) \qquad \text{[Equation 5]}$$

The flowrates through each of these systems are assumed to be equal (i.e. no fluid leaves the system), therefore:

$$Q_{bp} = Q_{bh} = Q_{cul} \qquad \text{[Equation 6]}$$

This results in four equations (Equations 3-6) and two unknowns (P_{wfbp} and P_{wfbp}) which can be algebraically solved for Q_{bp} as follows:

$$Q_{bp} = \frac{\left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{bp} - \rho g L - P_{cul} \right)}{\left[1 + \left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \right] \left\{ \frac{\mu \left[\ln\left(\frac{r_{e_{cul}}}{r_w} \right) - 0.5 \right]}{k_{cul} h_{cul}} + \frac{\mu L}{k_{bh} A_{bh}} \right\}} \qquad \text{[Equation 7]}$$

Equation 7 is the steady-state solution for flow through the brine pocket/abandoned borehole/aquifer system. To account for bounded brine pocket/aquifer sizes, pressure drawdown can be estimated by redefining the brine pocket and aquifer pressures over a series of discrete time intervals by the following:

The pore volume compressibility (c_f) as a function of rock bulk compressibility (c_b) may be defined by:

$$c_f = \frac{c_b}{\phi} \qquad \text{[Equation 8]}$$

The total compressibility (c_t) is the sum of the brine compressibility (c_{br}) and pore volume compressibility (c_f) as follows:

$$c_t = c_{br} + c_f \qquad \text{[Equation 9]}$$

The bulk volume of the bounded brine pocket is a function of the volume of brine removed, average pressure drop, compressibility and porosity as follows:

$$V_R = A_R h = \frac{\Delta N_{1,2}}{\left(\overline{P_1} - \overline{P_2}\right) c_t \phi} \qquad \text{[Equation 10]}$$

Equation 10 can be used to solve for the average pressure at the end of a given time interval by:

$$\overline{P_2} = \overline{P_1} - \frac{\Delta N_{1,2}}{V_R c_t \phi} \qquad \text{[Equation 11]}$$

METHODOLOGY AND RESULTS

Since the size of the brine pocket is unknown, comparisons were made for various areal size and thickness as shown in the following table (consistent with interpreted results from WIPP-12 data [Larson & Freeze, 1996]):

Table 1 - Constant Brine Volumes by Varying Thickness and Areal Extent

Thickness (m)	Areal Extent 1 (m^2)	Areal Extent 2 (m^2)	Areal Extent 3 (m^2)
133.6	6.0E+07	3.0E+06	3.0E+04
66.8	12.0E+07	6.0E+06	6.0E+04
24.0	33.4E+07	16.7E+06	16.7E+04

For the Culebra aquifer, the areal extent was assumed to be 100 times the LWB for all cases (4144 km^2). All other properties were median values obtained from the 1996

CCA database. The combination of three thicknesses and three areas for the Castile Brine Pocket resulted in 9 cases for comparison. Initial brine pocket pressure was assumed to be 12.7 E+07 Pa for all cases.

Table 2 shows an example spreadsheet calculation assuming an area of 6.0 E+07 m^2 and 133.6 m brine pocket thickness.

Table 2 - Example Spreadsheet Calculation

BP area	6.00E+07	m^2
Cut area	4.14E+09	m^2
Pcut (init)	850000	Pa
U	1.80E-09	Pa-s
hCut	7.7	m
L	641.5	m
total L	706.3	m
hBP	133.6	m
Pbp (init)	1.27E+07	Pa
kBH	3.16E-13	m^2
kCUL	2.16E-14	m^2
rw	0.1586	m
Area BH	0.0790922	m^2
kBP	1.58E-12	m^2
rho	220	kg/m^3
g	9.8	
rho*g*l shaft	8.5E+6	Pa
rho*g*l open	11.2E+6	Pa
s/year	3.16E+07	
porosity BP	0.008	
porosity Cut	0.151	
Cr BP	1.00E-10	1/Pa
Cr Cut	1.00E-10	1/Pa
Ct BP	1.36E-09	1/Pa
Ct Cut	6.623E-10	1/Pa
Cbrine	1.00E-09	1/Pa
Cwt BP	1.36E-09	1/Pa
Cwt Cut	1.66E-09	1/Pa
Brine Pocket bulk vol =	8.0E+8	m^3
Cutaway bulk vol =	31.9E+9	m^3
Open BH Dt	2.59E+05	seconds
No. open BH/Dt	2.98E+01	
rc BP	222.96809	
Patm	101300	Pa
drip rate=	0.47	bh/km^2/100years

Time years	Num BH in BP	Number of sand BH	Number of creep BH	BP press Pa	Cut Press Pa	BP radius per ab BH m	Cut radius per well m	Cangl	Cap open BH per well m^3/s	delta flow open m^3
200.0	56.40	0.0	0.0	12.7E+6	850.0E+3	4.37025E+13	4.37E+13	3.58E-09	0.080465874	149.6E+3
400.0	112.80	28.2	0.0	12.5E+6	850.0E+3	822.965098	4.37E+13	1.48E-09	0.017985898	131.2E+3
600.0	169.20	84.6	0.0	12.4E+6	851.3E+3	475.133342	4.37E+13	1.56E-09	0.016578236	113.9E+3
800.0	225.60	141.0	0.0	12.2E+6	852.0E+3	388.036704	4.37E+13	1.61E-09	0.013169822	96.3E+3
1,000.0	282.00	197.4	0.0	12.0E+6	850.9E+3	311.047799	4.37E+13	1.65E-09	0.010789646	78.7E+3
1,200.0	338.40	253.8	0.0	11.9E+6	848.5E+3	274.318988	4.37E+13	1.69E-09	0.008417967	61.5E+3
1,400.0	394.80	310.2	0.0	11.7E+6	877.9E+3	248.130295	4.37E+13	1.71E-09	0.006146544	44.9E+3
1,600.0	451.20	366.6	84.6	11.6E+6	880.3E+3	228.246674	475.1338	1.73E-09	0.003978128	29.1E+3
1,800.0	507.60	366.6	84.6	11.4E+6	900.2E+3	228.246674	475.1338	1.73E-09	0.001891269	13.8E+3
2,000.0	564.00	366.6	141.0	11.3E+6	911.2E+3	228.246674	366.0367	1.73E-09	0.000179623	1.3E+3
2,200.0	620.40	366.6	197.4	11.2E+6	921.7E+3	228.246674	311.0478	1.73E-09	0	000.0E+0
2,400.0	676.80	366.6	253.8	11.1E+6	931.7E+3	228.246674	274.3184	1.73E-09	0	000.0E+0
2,600.0	733.20	366.6	310.2	11.0E+6	941.2E+3	228.246674	248.1303	1.73E-09	0	000.0E+0
2,800.0	789.60	366.6	366.6	10.9E+6	950.3E+3	228.246674	228.2467	1.73E-09	0	000.0E+0
3,000.0	846.00	366.6	423.0	10.8E+6	959.0E+3	228.246674	212.4991	1.73E-09	0	000.0E+0
3,200.0	902.40	366.6	479.4	10.6E+6	967.3E+3	228.246674	199.8969	1.73E-09	0	000.0E+0
3,400.0	958.80	366.6	535.8	10.7E+6	975.2E+3	228.246674	189.7968	1.73E-09	0	000.0E+0
3,600.0	1,015.20	366.6	592.2	10.6E+6	982.6E+3	228.246674	179.5836	1.73E-09	0	000.0E+0
3,800.0	1,071.60	366.6	648.6	10.5E+6	989.7E+3	228.246674	171.589	1.73E-09	0	000.0E+0
4,000.0	1,128.00	366.6	705.0	10.5E+6	996.4E+3	228.246674	164.561	1.73E-09	0	000.0E+0
4,200.0	1,184.40	366.6	761.4	10.5E+6	1.0E+6	228.246674	158.3778	1.73E-09	0	000.0E+0
4,400.0	1,240.80	366.6	817.8	10.4E+6	1.0E+6	228.246674	152.8189	1.73E-09	0	000.0E+0
4,600.0	1,297.20	366.6	874.2	10.3E+6	1.0E+6	228.246674	147.8071	1.73E-09	0	000.0E+0
4,800.0	1,353.60	366.6	930.6	10.3E+6	1.0E+6	228.246674	143.2581	1.73E-09	0	000.0E+0
5,000.0	1,410.00	366.6	987.0	10.3E+6	1.0E+6	228.246674	139.1049	1.73E-09	0	000.0E+0
5,200.0	1,466.40	366.6	1,043.4	10.2E+6	1.0E+6	228.246674	136.299	1.73E-09	0	000.0E+0
5,400.0	1,522.80	366.6	1,099.8	10.2E+6	1.0E+6	228.246674	131.7783	1.73E-09	0	000.0E+0
5,600.0	1,579.20	366.6	1,156.2	10.1E+6	1.0E+6	228.246674	128.524	1.73E-09	0	000.0E+0
5,800.0	1,635.60	366.6	1,212.6	10.1E+6	1.0E+6	228.246674	125.4986	1.73E-09	0	000.0E+0
6,000.0	1,692.00	366.6	1,269.0	10.1E+6	1.0E+6	228.246674	122.6789	1.73E-09	0	000.0E+0
6,200.0	1,748.40	366.6	1,325.4	10.0E+6	1.0E+6	228.246674	120.0403	1.73E-09	0	000.0E+0
6,400.0	1,804.80	366.6	1,381.8	10.0E+6	1.1E+6	228.246674	117.588	1.73E-09	0	000.0E+0
6,600.0	1,861.20	366.6	1,438.2	10.0E+6	1.1E+6	228.246674	115.2368	1.73E-09	0	000.0E+0
6,800.0	1,917.60	366.6	1,494.6	9.9E+6	1.1E+6	228.246674	113.0416	1.73E-09	0	000.0E+0
7,000.0	1,974.00	366.6	1,551.0	9.9E+6	1.1E+6	228.246674	110.9672	1.73E-09	0	000.0E+0
7,200.0	2,030.40	366.6	1,607.4	9.9E+6	1.1E+6	228.246674	109.0031	1.73E-09	0	000.0E+0
7,400.0	2,086.80	366.6	1,663.8	9.9E+6	1.1E+6	228.246674	107.1368	1.73E-09	0	000.0E+0
7,600.0	2,143.20	366.6	1,720.2	9.9E+6	1.1E+6	228.246674	105.3686	1.73E-09	0	000.0E+0
7,800.0	2,199.60	366.6	1,776.6	9.8E+6	1.1E+6	228.246674	103.6828	1.73E-09	0	000.0E+0
8,000.0	2,256.00	366.6	1,833.0	9.8E+6	1.1E+6	228.246674	102.075	1.73E-09	0	000.0E+0
8,200.0	2,312.40	366.6	1,889.4	9.8E+6	1.1E+6	228.246674	100.54	1.73E-09	0	000.0E+0
8,400.0	2,368.80	366.6	1,945.8	9.8E+6	1.1E+6	228.246674	99.07215	1.73E-09	0	000.0E+0
8,600.0	2,425.20	366.6	2,002.2	9.8E+6	1.1E+6	228.246674	97.6966	1.73E-09	0	000.0E+0
8,800.0	2,481.60	366.6	2,058.6	9.8E+6	1.1E+6	228.246674	96.31961	1.73E-09	0	000.0E+0
9,000.0	2,538.00	366.6	2,115.0	9.7E+6	1.1E+6	228.246674	95.02967	1.73E-09	0	000.0E+0
9,200.0	2,594.40	366.6	2,171.4	9.7E+6	1.1E+6	228.246674	93.79444	1.73E-09	0	000.0E+0
9,400.0	2,650.80	366.6	2,227.8	9.7E+6	1.1E+6	228.246674	92.59996	1.73E-09	0	000.0E+0
9,600.0	2,707.20	366.6	2,284.2	9.7E+6	1.1E+6	228.246674	91.43948	1.73E-09	0	000.0E+0
9,800.0	2,763.60	366.6	2,340.6	9.7E+6	1.1E+6	228.246674	90.33108	1.73E-09	0	000.0E+0
10,000.0	2,820.00	366.6	2,397.0	9.7E+6	1.1E+6	228.246674	89.25201	1.73E-09	0	000.0E+0

Figure 2 is a semilog plot comparing the number of borehole penetrations for different brine pocket areal sizes based upon the DOE criterion of 0.47/100 year/km^2 drilling rate. The same number of penetrations apply to each respective areal size regardless of thickness.

Figure 2

Comparison of Drilling Penetrations to Castile Brine Pocket for Different Areas

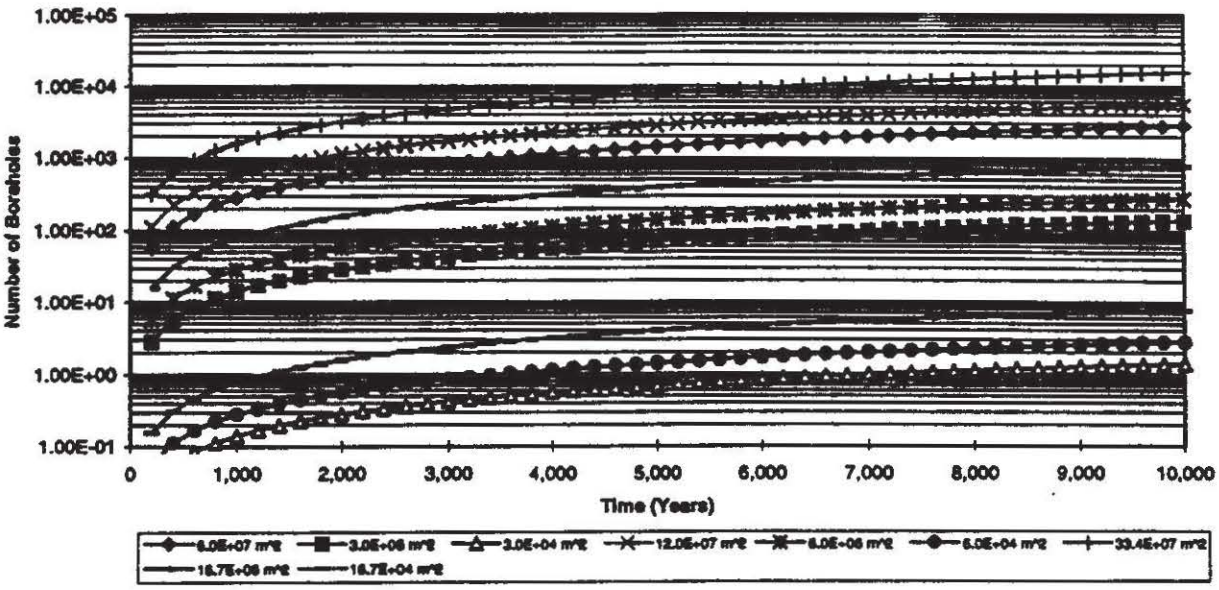

Figure 3 is a semilog plot comparing the amount of Castile brine volume which can be released. This was determined by subtracting the cumulative brine released at a given time from the total cumulative brine released at 10,000 years. The 24 m thickness cases again demonstrate faster depletion than the corresponding 133.6 m thickness cases of equivalent area. For a given thickness, the differences in remaining available flow is caused by differences in the number of depletion boreholes which is a function of the area.

Figure 3

Comparison of Remaining Castile Brine Available for Flow
(Initial Pbp = 12.7 MPa, 72 hour open flow period)

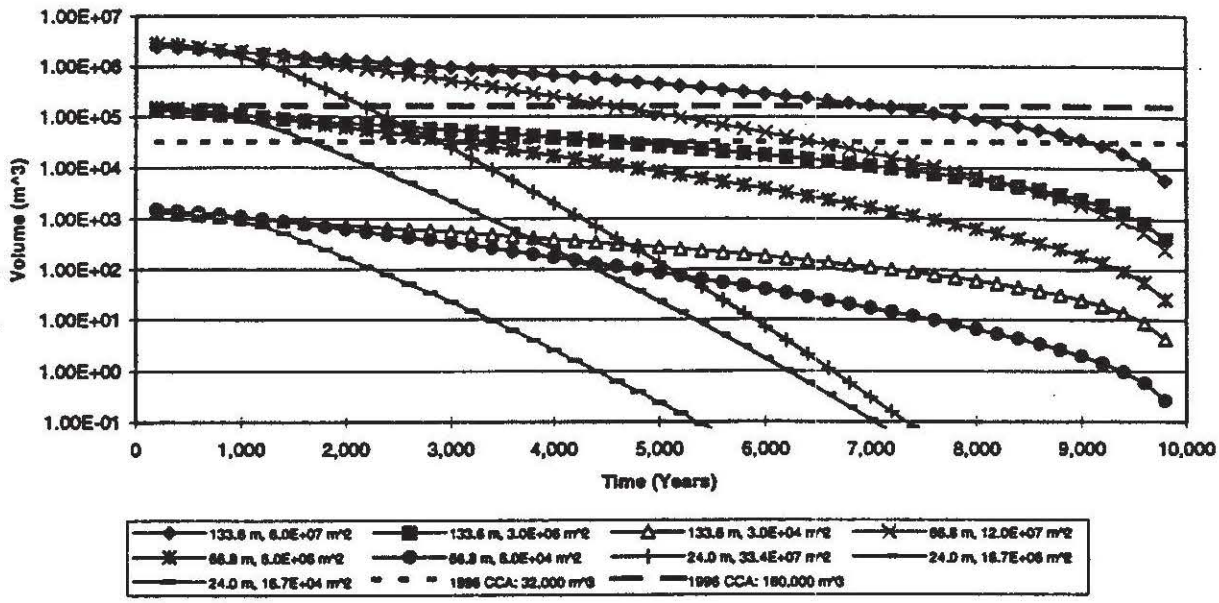

CONCLUSIONS

The 1996 CCA calculations varied the brine pocket volume from 32,000 m^3 to 160,000 m^3. From Figure 3, the only cases which show more brine available for flow for an extended period of time (~2000 to ~7000 years) are the maximum area cases. DOE does not consider the 19 km radius brine pocket to be a realistic estimate of the areal extent, rather an artifact of the unreasonably low rock compressibility ($5X10^{-12}$ pa^{-1}) used for that estimate. In addition, the DOE does not include the depressurization or volume reduction to the brine pocket that would result in numerous borehole penetrations that would statistically "miss" a WIPP panel but penetrate the brine pocket, prior to the first "E1" borehole through a panel. In the CCA calculations for E1 scenarios, the DOE assumes brine pockets of 32,000 m^3 to 160,000 m^3 pore volume at virgin (undepleted) pressures in determining potential releases to the accessible environment, which bounds the range of consequences associated with penetrating a larger but partially depleted brine pocket.

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Date: July 19,1996

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From: J. W. Berglund 6849, NMERI; J. Myers, IT Corp; L.R. Lenke, NMERI

Subject: Estimate of the Tensile Strength of Degraded Waste for use in Solids Blowout

A value of 1 psi (6895 Pa) was chosen to represent the tensile strength of decomposed waste for the purpose of computing blowout spall releases resulting from a drillbit intrusion into a pressurized waste panel. Such spall releases occur only if the gas pressure exceeds the hydrostatic drilling mud pressure of approximately 8 MPa. A chemical reaction between the waste and brine from the surroundings is necessary to generate the gas to raise the waste pore pressure to these levels. Without brine inflow, little gas will be generated and waste decomposition will be negligible. Thus the phenomenon of blowout spall requires both brine inflow and waste decomposition.

The future state of decomposed waste is both time dependent and unknowable. Therefore a decomposed state consisting of graded granular materials is assumed. This is consistent with the granular nature of decomposed geologic materials and corresponds to an end state of the decomposition process. Such materials lack significant composite strength from the interleaving of components and is the state found to be most troublesome in oil production where sand is produced from poorly consolidated sand layers. The value of 1 psi chosen for cementation strength for the decomposed waste can be reasonably expected to be conservative, i.e. lower than those data values found for many weak materials that are naturally occurring or that have been manufactured. Data to support this value can be found in the literature for the strengths of soils, laboratory produced mixtures of salt and clay, and mixtures of various materials with MgO; the latter added as a backfill material to the waste. A discussion of these data sources follows.

Soil Data

Tensile strengths for several compacted, cohesive soils e.g. Vicksburg buckshot clay (CH), Vicksburg lean clay (CL), and a sandy clay mixture from De Gray dam (SC) were measured using hollow cylinder tests and indirect tensile tests in Al-Hussaini (1981). The samples were prepared to optimum water content compacted and tested. Results for the hollow cylinder tests are shown in Table 1. All exceed 1 psi by factors of approximately 3 to 8 times. Similar results were obtained from the indirect tensile tests.

Table 1 Hollow Cylinder Tests

Material type	Tensile Strength (psi)
CL-1	2.95
CL-2	3.90
CL-3	3.93
CH-1	7.93
CH-2	7.41
CH-3	7.99
SC-1	5.90
SC-2	5.38
SC-3	4.49
CH-4	6.46
CH-5	6.12
CH-6	6.52

Direct tensile tests on simulated waste materials were also conducted by Berglund and Lenke, 1995, p13-14. Various mixtures of partially saturated silica sand and kaolin clay were used to represent the waste. The clay represented a natural material that was chosen to be a close surrogate to partially decomposed cellulosics and plastics. The sand represented the particulate structure expected of magnetite or other products of the iron corrosion reaction. The mixture was 85% sand and 15% clay, a ratio similar to the ratio of decomposition products anticipated for some waste conditions. The tensile strength measured in these experiments was 2.9 ± 1.4 psi. A second indirect method of measuring tensile strength in the Berglund, Lenke study implied an even higher tensile strength value of 4.3 ± 1 psi.

The tensile strength of the above materials (Al-Hussaini 1981, Berglund and Lenke 1995) occurred in the absence of any additional cementation process which would tend to increase these measured tensile strengths.

Salt Mixture Data

Some brine is expected to exist within the waste panels after closure of the facility. The most likely source is brine of Permian age that was trapped in the Salado formation at the time of evaporite deposition. Limited brine occurrences in the WIPP underground have been extensively sampled and analyzed, and the composition of Salado brine is well understood. These brines contain approximately 374 grams of dissolved constituents per liter and are in chemical equilibrium with halite (NaCl) anhydrite ($CaSO_4$), and magnesite ($MgCO_3$).

The removal of even a small amount of water from this brine by evaporation or chemical reaction will result in the precipitation of salts which will act as a cementation agent. One such chemical reaction that is anticipated to occur is the anoxic corrosion of iron and ferrous alloys, which constitute a significant percentage of the waste inventory in the form of steel drums and boxes, contaminated tools and sheet metal, etc.

The reaction of brine with metal will consume H_2O and generate hydrogen and some corrosion product. A typical anoxic reaction might be

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2$$

Consumption of H_2O by corrosion reactions will cause the mass of dissolved solids in the brine to precipitate as a series of evaporite minerals in close proximity to the surface of the

corroding metals forming encrustations which tend to cement the waste. Simulation of the removal of H_2O from one kg of Salado brine using the EQ6 code (Wolery T.J., and S.A. Daveler, 1992) yielded 534 grams of precipitates (anhydrite, bischofite, carnallite, halite, kieserite, and magnesite). The mass is greater than the mass of dissolved solids because of the hydrous nature of some of the precipitates.

Evidence for this process in the WIPP underground could be seen at the close of heated brine inflow experiments performed by SNL a number of years ago. In these experiments, a metal canister containing an electrical heater was placed in a vertical hole excavated in the floor of a room in the northern experimental area. The top of the hole was sealed, and anhydrous nitrogen was circulated within the annulus between the canister and the hole. Small amounts of brine flowed toward the hole in response to the pressure and temperature gradients surrounding the heated hole, and evaporated as it approached the canister. The nitrogen acted as a carrier gas for water vapor and was allowed to exit the hole where it flowed into an apparatus where the water vapor was extracted and quantified.

It was found at the close of the experiment that the canister has become firmly cemented in the hole by the precipitation of salts from the evaporating brine within the annulus. A work-over rig had to be employed to extract the canister from the hole. The removal of water from brine by any process, be it evaporation or corrosion reactions, will produce the same cementation effect by the precipitation of minerals at the site of water removal. This cementation will act to increase the strength of the waste.

A number of strength tests were done for consolidated crushed WIPP salt and mixtures of WIPP salt and bentonite (70 and 30% respectively) (Finley, 1996). Finley's memorandum presents estimates of tensile strengths of clay/salt mixtures based on experimental observations of unconfined compressive strengths and the extended Griffith criterion for tensile failure (Jaeger and Cook, 1976). These estimates are for 30/70 percent bentonite/salt mixtures at fractional densities of 0.83 to 0.88. Finley estimates tensile strengths between 10 and 100 psi.

The WIPP waste stream upon creep closure and subsequent brine saturation will consist of approximately 1350 kg of waste solids (assumed average solid density of the waste was taken as 2700 kg/m^3) and 188 kg of precipitated salt (based on dissolved salt solids of 374 gram/liter cited above) per cubic meter of repository. These numbers are based on a typical closure porosity of 0.5 (final room height of 1.2 m). The gravimetric ratio of salt precipitate to solid waste for these conditions is 0.14. This is a factor of 5 less than the ratio cited by Finley. Using this factor, it is not unreasonable to expect tensile strengths between 2 and 20 psi.

Effects of MgO on Strength

An additional process affecting the strength of the waste/backfill composite material is the chemical interactions that will occur between Salado brine and the MgO backfill. These interactions were simulated using the EQ3/6 code (Wolery, 1992; and Wolery T.J., and Daveler, 1992) with the Pitzer activity coefficient option and Harvie-Moller-Weare database. Five moles of MgO were reacted with one kilogram of Salado brine in a series of small steps. The dissolution of the five moles (202 grams) of MgO into the brine resulted in the precipitation of a total of 507 grams of minerals and the incorporation of 20 percent of the original kg of brine as water of hydration within the precipitates. These precipitates include Mg-oxychloride (63% by mass) and brucite (31% by mass), with minor amounts of anhydrite, halite, and magnesite. Similar results were found by Wang, 1996.

The two dominant precipitates (Mg-oxychloride and brucite) are the key phases in Sorel cement. In fact, Sorel cement is commercially prepared by mixing a magnesium-chloride brine (quite similar to Salado brine) with MgO. Sorel cement is known to have uniaxial compressive strengths in the range of 7,000 to 10,000 psi (Sax and Lewis, 1987). This range is equivalent to tensile strengths of from 490 to 700 psi (Dunham C.W., 1966). Thus the use of an MgO backfill will result in the cementation and strengthening of the waste/backfill composite material as long as sufficient brine is available for the chemical reactions to occur.

Conclusions

While tests to actually measure the binding forces between particles of simulated waste have not been performed, there are data available from several independent sources that suggest that the selection of 1 psi is well below the actual value of tensile strength that can be reasonably expected for decomposed waste. The tensile data presented for several soils without chemically generated salt precipitates exceed 1 psi by factors generally greater than 3. Estimated tensile strengths of consolidated halite-bentonite mixtures exceed 1 psi by factors of ten or more. The role of precipitated salts from anoxic reactions of brine with waste metals is expected to be similar though perhaps not as intense. MgO is added to the waste as a backfill material in large volumes. The reaction products of MgO plus brine are the principal components of Sorel cement which attains high compressive strengths and predicted tensile strengths of 490 to 700 psi.

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WASTE ISOLATION PILOT PLANT

SALADO FLOW CONCEPTUAL MODELS PEER REVIEW REPORT

A Peer Review

Conducted By

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for the

U.S. Department of Energy

Carlsbad Area Office

Office of Regulatory Compliance

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Executive Summary

The WIPP site has been developed near Carlsbad, New Mexico, by the Department of Energy (DOE) as the Nation's first underground repository licensed to safely and permanently dispose of transuranic radioactive waste resulting from the research and production of nuclear weapons programs. The first shipment of transuranic waste arrived at WIPP on April 6, 1999.

Peer review of conceptual models developed by the Department of Energy (DOE) for the WIPP is required by 40 CFR § 194.27, which was promulgated by the Environmental Protection Agency (EPA) in 1996. In accordance with this requirement, the Carlsbad Field Office (CBFO) of the DOE has conducted a peer review of three conceptual models that are being revised due to changes invoked by the regulator or due to knowledge gained since the original conceptual models were developed. This peer review addressed revisions to selected Salado flow conceptual models that were developed for the Compliance Certification Application (CCA).

This report presents the results of an independent technical peer review of the adequacy of three of the twenty-four conceptual models representing features, processes, and events involved in assessing the long-term performance of the Waste Isolation Pilot Plant (WIPP). These models were identified by the U.S. Department of Energy (DOE) through its scientific advisor, Sandia National Laboratories (SNL).

This independent peer review was conducted by a three-member interdisciplinary team having the requisite broad experience and expertise to address the range of issues associated with the ability of WIPP to successfully isolate waste for the 10,000-year regulatory time frame. The peer review was conducted primarily in Carlsbad, New Mexico, at the SNL Carlsbad offices. The Peer Review Panel was given access to conceptual model descriptions, scientific reports, briefings, SNL staff, and to the SNL Nuclear Waste Management Program Library. The Panel also had access to reports of prior peer reviews and was given the full cooperation of the DOE and SNL throughout

the review. Representatives of the EPA, DOE, and the New Mexico Environmental Evaluation Group (EEG) observed the SNL technical presentations and the Panel's questions and deliberations.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical processes, or intrusion scenarios are to be represented in performance assessment. To be used in performance assessment, a conceptual model must be successfully translated into analytical statements and mathematical analogs. The Panel reviewed the three conceptual models of interest in detail, including the assumptions and scientific information used to develop the model, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The Panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall performance assessment (PA). The review process and review criteria are discussed in Section 2.

The Panel has applied the stringent assessment criteria provided in NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories,* and has concluded:

> 1) The changes to the three conceptual models appear generally sound in their structure, reasonableness, and relationship to the original models.
>
> 2) The proposed implementation of the three changed models appears reasonable; however impacts of the changes cannot be assessed at this time. Although the data presented depicts selected gas pressure and brine saturation cases, a total system PA is needed to show a complete comparison of the prior CCA results to the new results.
>
> 3) Implementation of the three changed models and their interactions with other models cannot be assessed at this time because determination of "adequacy in application" and "accuracy of calculations" requires a total system PA.

Two review criteria (adequacy of application and accuracy of calculations) require information available only after PA calculations have been performed. Recognizing that a total system PA will not be available for several months, conditional acceptance of the adequacy of the changed models is intended to permit completion of the total system PA.

The changed models should be re-reviewed in the context of the total system PA. The total system PA review may include review of the reasonableness of changes in performance estimates resulting from changes in parameter ranges or in changes to or resulting from single values. The total system PA review should evaluate changes in the conceptual structure of the models and changes in component process models and compare the performance results of the changed models with the results of the earlier models to confirm that the changes in performance estimates are reasonable in sense and magnitude. Changes in computations or in fundamental model aspects, such as gridding, should also be considered. Whatever the methodology chosen, each changed model must be shown to satisfy all of the review criteria after the next iteration of PA calculations. The final review should consider the impacts of the changed models on the implementation of related conceptual models and peripheral issues such as the Option "D" panel closures. The status of the changed models will remain "conditionally adequate" until the final review is completed. The status of any changed model may become "inadequate" if warranted by review in the context of a total system PA.

1.0 Introduction

Peer review of conceptual models developed by the Department of Energy (DOE) for the WIPP is required by 40 CFR § 194.27, which was promulgated by the Environmental Protection Agency (EPA) in 1996. In accordance with this criterion, the Carlsbad Field Office (CBFO) of the DOE has conducted a peer review of three conceptual models that are being revised due to changes invoked by the regulator or due to knowledge gained since the original conceptual models were developed. This peer review has addressed whether revisions to selected Salado flow conceptual models that were developed for the Compliance Certification Application (CCA) continue to reasonably represent the WIPP disposal system.

Sandia National Laboratories (SNL) is responsible for the development, maintenance, and conduct of WIPP performance assessment (PA). As part of the PA methodology included in the CCA, the DOE identified processes important to the WIPP waste isolation system and developed conceptual models that describe the features, events, and processes relevant to the disposal system and subsystems. These conceptual models were peer reviewed and the results were approved by the EPA during the original WIPP certification (EPA, 1998). Any proposed significant changes to the previously approved conceptual models are being peer reviewed to ensure that the disposal system, subsystems, and future state assumptions continue to be adequately represented.

Twenty-four conceptual models are used in the WIPP PA. The proposed changes associated with Salado flow processes are expected to affect the following models:

- Disposal System Geometry,
- Repository Fluid Flow, and
- Disturbed Rock Zone (DRZ).

The peer review process is a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. The peer reviewers are independent of the work being reviewed, i.e., the peer reviewers: a) have not been involved as participants, supervisors, technical reviewers, or advisors

involved with the work being reviewed, and b) to the extent practical, have sufficient freedom from funding considerations to ensure the work is impartially reviewed. Therefore, the peer-reviewed subject matter provides additional assurance to the regulator and the public that the subject matter is reasonable, accurate, and valid for its intended use.

This peer review meets the regulatory requirements of 40 CFR Part 191 and the implementation of those requirements by 40 CFR Part 194. This peer review was conducted in accordance with the Nuclear Regulatory Commission's NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories*. The adequacy criteria set forth in NUREG-1297 were those used by the peer review panel for reviewing the three conceptual models. The Peer Review Panel followed the DOE-CBFO Management Procedure MP-10.5, *Peer Review,* to perform the peer review.

This report documents the results of the subject peer review. Section 2 of this report details background information relating to the WIPP facility and the review methodology. This includes a description of the repository, its geologic and hydrogeologic settings, the review methodology, and the evaluation criteria. Section 3 presents an evaluation of each of the three models. Each model was assessed against the predetermined evaluation criteria. Section 4 discusses the integration of the peer reviewed models with the remainder of the models into an overall conceptual model of the waste disposal system to be used for the WIPP total system PA. Section 5 provides a summary of the evaluations. These sections are followed by appendices that include administrative information and professional biographies for each of the peer review panel members.

2.0 Background

The DOE was authorized in 1979 (Public Law 96-164) and funded by the Congress to develop a facility for demonstrating the safe disposal of transuranic (TRU) radioactive wastes resulting from national defense activities. The Land Withdrawal Act of 1992 (Public Law 102-579) provided additional authorization to continue the project under a stipulated statutory process. With more than 20 years of scientific investigation, public input, and regulatory oversight, the WIPP facility became the first underground repository licensed to safely and permanently dispose of transuranic radioactive waste from the research and production of nuclear weapons. The first shipment of transuranic waste arrived at WIPP on April 6, 1999.

2.1 WIPP Overview

The WIPP facility has been constructed in southeastern New Mexico 26 miles east of Carlsbad, on land owned by the Federal Government. Prior to October 1992, this land was administered by the U.S. Department of the Interior, Bureau of Land Management. In October 1992, Congress transferred jurisdiction of the land through the Land Withdrawal Act to the Secretary of Energy. The site encompasses 10,240 acres in a sparsely populated area, with fewer than 30 people living within 10 miles of the WIPP site. The immediate surrounding land is used for livestock grazing, potash mining, and oil and gas production.

Surface structures and the underground repository make up the WIPP facility. The purpose of the surface structures is to provide security and safeguards and to accommodate routine operations, administrative activities, and support further scientific studies.

The underground excavation is 655 meters (2150 feet) below the surface in the bedded salt of the Salado Formation. It includes a 12-acre area used for conducting scientific investigations and experiments in which no waste will be placed, an operations area with equipment and maintenance facilities, an area in which the waste is emplaced for

permanent disposal, and four major interconnecting tunnels that are used for ventilation and traffic. The subsurface waste-disposal area is planned to cover approximately 100 acres and will contain eight separately excavated panels, each containing seven disposal rooms, and two equivalent panels.

2.2 Peer Review Management

This Salado Flow Conceptual Models Peer Review is an independent review sponsored by the DOE CBFO and delegated to its technical assistance contractor, known as the Carlsbad Technical Assistance Contractor (CTAC). The CTAC appointed Mr. John Thies as the peer review manager.

Early in the peer review process Mr. Thies appointed a technical panel chairperson, John Gibbons, Ph.D., from among the peer review panel members to serve as the technical leader for the peer review and to lead technical development of the peer review report.

The selection and training of the peer review panel members and operation of the review process were governed by DOE CBFO's Management Procedure MP-10.5, *Peer Review,* and the *Conceptual Model Peer Review Plan*. Detailed information regarding the review process is further delineated in this document and in the peer review records.

Twenty-four conceptual models are used in the WIPP PA. This peer review addressed only the proposed changes associated with Salado flow processes expected to affect the following three models:

- Disposal System Geometry,
- Repository Fluid Flow, and
- Disturbed Rock Zone (DRZ).

2.3 System Overview

The WIPP disposal system includes the underground repository and shaft system, the geologic host rock, and the local and regional hydrologic system. Figure 2-1 shows the WIPP controlled area, the accessible environment, and the disposal unit boundary.

Figure 2-1 - WIPP Controlled Area

2.3.1 Repository Setting

The WIPP surface facilities, shafts, and underground workings are shown in Figure 2-2. The WIPP repository includes four shafts (exhaust shaft, waste shaft, salt handling shaft, and air intake shaft), an experimental area, an operations area, and a waste disposal area.

Figure 2-2 - WIPP Facilities

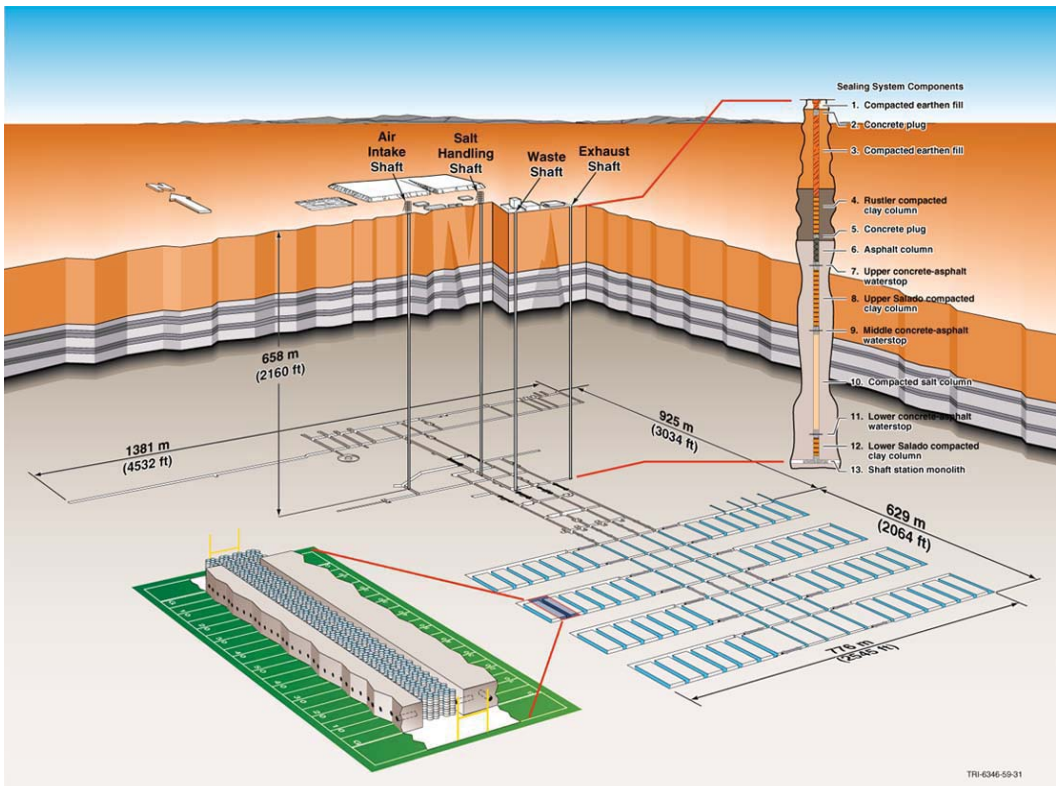

Present plans call for mining eight panels of seven rooms each and two equivalent panels in the central drifts. As each panel is filled with waste, the next panel will be mined. Before the repository is closed permanently, each panel will be closed. Waste will be placed in the drifts between the panels creating two additional panel volumes and access ways will be sealed off from the shafts. The shafts will then be sealed to isolate the repository from the ground surface. Final closure of the facility will be facilitated by creep closure of the salt.

When considering future intrusion scenarios, the DOE used the following EPA assumptions regarding future penetration of the repository:

- The regulatory time frame begins at the beginning of disposal and ends 10,000 years after disposal;
- Exploratory drilling may potentially affect the repository;
- Exploratory drilling is inadvertent and intermittent;
- Drilling events occur at random intervals; and
- Future drilling rates will be the same as the rates of deep drilling in the area over the past 100 years.

2.3.2 Geologic Setting

The geologic history of southeastern New Mexico and the data collected regarding the subsurface stratigraphy at the WIPP site are important and are discussed extensively in Section 2 of the CCA and documents referenced in the CCA. The general stratigraphy at the WIPP site is presented in Figure 2-3.

The sandstones, siltstones, limestones, and shales of the Bell Canyon Formation define the first extensive, continuous, transmissive unit below the WIPP repository and provide a source of groundwater that could migrate vertically into the repository. The halite and anhydrite beds of the Castile Formation separate the Bell Canyon from the Salado and contain pressurized brine reservoirs. The brine reservoirs are a repository performance concern expressed through human intrusion scenarios. The halite-dominated Salado Formation contains the proposed repository and provides the primary natural barrier for containing radionuclides. The laterally extensive Culebra Dolomite Member of the Rustler Formation is the closest stratigraphic unit above the Salado with the potential to transport a radionuclide release to the accessible environment. Studies conclude that transmissivities in the Culebra vary by six orders of magnitude across the WIPP site area. Fracturing and vuggy zones account for much of the variability in the physical hydraulic properties of the Culebra.

Figure 2-3 - *General Stratigraphy at the WIPP Site*

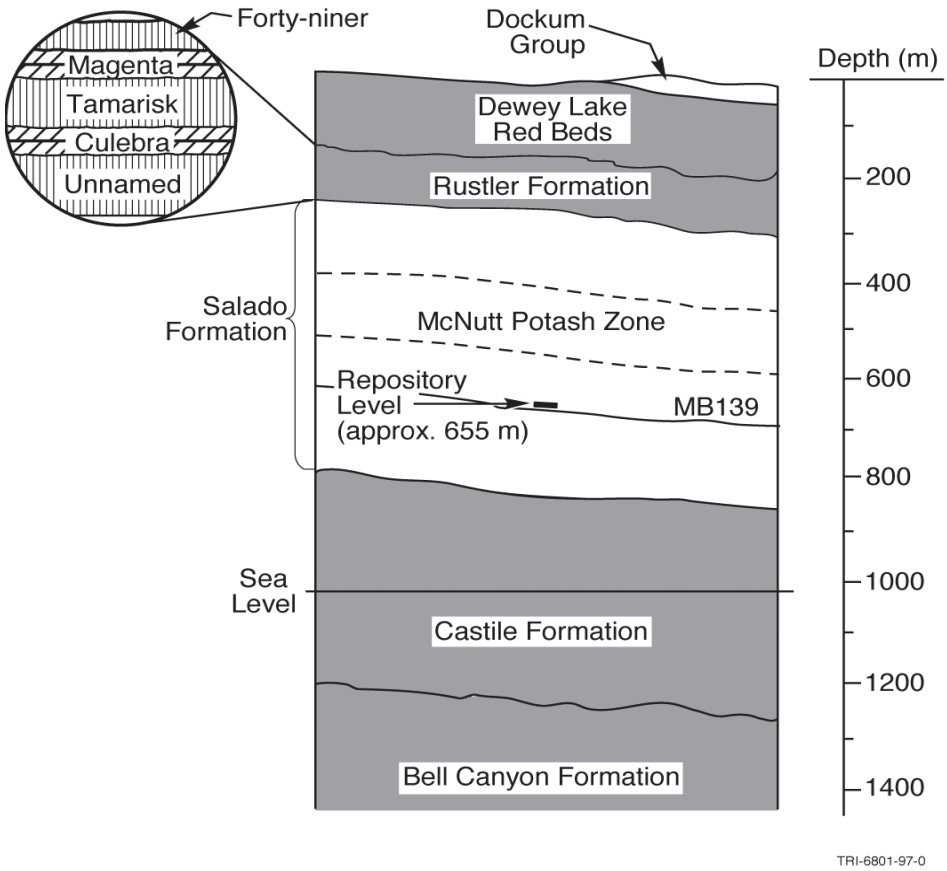

While other stratigraphic members of the Rustler Formation, beds of anhydrite and polyhalite, clays, and other inclusions may be important as each of the conceptual models is reviewed, the Four formations and units described above define the most important components of the geologic setting for the WIPP conceptual models review.

2.3.3 Hydrologic Setting

2.3.3.1 Surface Water

The WIPP site is located within the Pecos River Basin. At its nearest point, the Pecos River flows approximately 12 miles southwest of the WIPP site boundary. There are no perennial streams at the WIPP site and in this semi-arid region, approximately 75 percent of annual precipitation results from intense, short-duration events between April and

September. More than 90 percent of the mean annual precipitation is lost through evapotranspiration and on a mean annual basis, evapotranspiration potential exceeds expected rainfall. The EPA concluded in 1989 that there were "no surface water features near the WIPP that could potentially affect repository performance in such a way as to influence the no-migration demonstration."

2.3.3.2 Groundwater

Extensive coring, logging and testing of boreholes in the vicinity of the WIPP site has provided data for the characterization of the hydrostratigraphy important to the WIPP site region. While the deep Capitan Limestone, the Rustler-Salado contact zone near Nash Draw, and the shallower Dewey Lakes and Santa Rosa Formations are important in characterizing the WIPP region; the Bell Canyon, Castile, Salado, and Rustler Formations are the units critical to the evaluation of WIPP groundwater issues.

As presented in the geologic setting, the Bell Canyon Formation is the first continuous, transmissive water-bearing unit beneath the WIPP. This formation provides a source of non-potable ground water below the WIPP repository that could migrate into the repository if a pathway were available. The Bell Canyon Formation exhibits hydraulic conductivities in the range of 10^{-7} to 10^{-12} meters per second and pressures were measured in the range of 12.6 to 13.3 megapascals.

The Castile Formation is of interest to site characterization as a hydrologic barrier between the Salado and Bell Canyon Formations because it contains isolated pressurized brine reservoirs. The Castile is predominantly low-permeability halite and anhydrite with greater permeabilities in zones of fracture and structural deformation. In the areas of higher permeability brine pressures may exist that are sufficiently above nominal hydrostatic pressure for brine to flow upward through a borehole potentially reaching the surface.

The halite and anhydrite rocks of the Salado Formation are relatively impermeable and tests have shown that flows are extremely low to no flow when appreciable pressure

gradients are applied. The Salado contains the repository and provides the primary natural barrier for containing radionuclides.

The Magenta and Culebra Dolomite Members of the Rustler Formation are laterally extensive, transmissive, and display hydraulic characteristics sufficient for the lateral transport of radionuclides. Hydraulic conductivities in both members range over five to six orders of magnitude in the WIPP area but the Magenta is generally less transmissive than the Culebra. The Culebra is the most extensive and most transmissive unit above the Salado at the WIPP site. As such, the Culebra provides the most direct groundwater pathway from the WIPP repository to the accessible environment and is the most important component of the hydrogeologic setting for the conceptual models peer review.

2.3.4 Implementation of the "Option D" Panel Closure

The option "D" panel closure is a semispherical concrete closure to be emplaced in drifts and panel exits at several positions throughout the repository. The closure will be emplaced in an enlargement of the drift that will remove some material above the drift and all of the halite and the Interbed #139 below the drift floor. It is presumed that the closure will extend into the ribs of the drift a distance sufficient to remove the DRZ in that direction. Back-stress resulting from creep flow in the Salado halite into the repository will immediately begin to heal damage around the closure that may result from construction excavation. It is not expected that the closure will entirely block gas flow in Interbed #139, since flow around the limited footprint of the closure in the anhydrite is not prevented at high gas pressures. Upward gas flow from Interbed #139 into the drift beyond the closure is a possible scenario for the bypassing of the closure by gas from disposal panels. Rapid gas pressure fluctuations, as in the case of an intrusion into a single panel at a time of high overall repository gas pressures, would be significantly damped in adjacent unintruded repository spaces, but not entirely eliminated by the closure. The integrated impacts of the changed DRZ conceptual model and the role of the closure in modeling gas pressure in the waste panels before and during equilibration after intrusion are important interactions with the Repository Fluid Flow conceptual model.

Reduction in the volume of gas available during blowout (single panel isolated by closures) resulting from intrusion may impact the spalling model. Closures between panels imply that a first intrusion may not lower pressure throughout the repository, which may result in several intrusions in several panels having increased spall events. A drop in gas pressure after intrusion into a panel may accelerate brine flow toward the intruded panel. If the panel closure is left unsupported in an open drift, shear and extension stresses related to the creep closure of the spaces on either side of the panel closure may be significant to the mechanical stability of the panel closure. The mechanical stability of the option "D" panel closure in the stress environment represented by creep closure of the drift has not been modeled and should be reviewed following the next WIPP total system PA.

2.4 Peer Review Panel Methodology

The review of the conceptual models commenced after panel member orientation and training in accordance with MP 10.5, the Peer Review Plan, and other relevant information presented in the orientation and training package.

The peer review panel employed the following approaches in their overall method of conducting and accumulating information for the reviews:

- Extensive review of referenced literature relevant to the review;
- Attendance at briefings on conceptual models and relevant aspects of the PA process;
- Issue focused presentations with question-and-answer sessions with SNL scientists and engineers;
- Review of literature and documents referenced during the question-and-answer sessions; and
- Formal and informal discussions among the Panel members.

The Panel was provided several presentations addressing the three conceptual models being reviewed with respect to whether or not they represent a reasonable view of future

states of the proposed disposal system for the WIPP repository. For this review, conceptual models are defined as a set of qualitative assumptions used to describe a system or subsystem for a specific purpose. The Panel evaluated the models in accordance with the NUREG-1297 criteria. In addition, the Panel recognized that individual models may warrant varying levels of reviews of their mathematical representations, computerized representations, and results. Due to the volume and diversity of information to be reviewed, individual Panel members were assigned lead responsibility for specific conceptual model reviews. Dr. Gibbons assigned Dr. Oswald responsibility for review of the Disposal Room Geometry conceptual model; Dr. Caporuscio was assigned responsibility for review of the Repository Fluid Flow conceptual model, and Dr. Gibbons took responsibility for review of the Disturbed Rock Zone conceptual model. The information gathered by individual members during their reviews was freely disseminated among all of the Panel members.

In organizing its work, the Panel established limitations on its review and the content of this report. The Panel members did not review or offer comments on regulations. The Panel confined its review to the three conceptual models identified in the Peer Review Plan. To maintain independence, the Panel did not offer recommendations for specific methods and/or approaches to be employed in future work.

2.5 Criteria for Conceptual Model Review

The nine criteria used by the peer review members are based on the criteria in EPA regulation 40 CFR § 194.27, NUREG-1297, the EPA Compliance Application Guidance, and Peer Panel discussions.

Information Used to Review Changes in Conceptual Model. This is an evaluation of data and information used to review the changes in the conceptual models and sub-models. It includes attributes of the disposal system learned by SNL during site characterization activities, exercising the models, and a review of the science and concepts that the models are based upon. It also includes information gained during the operation of the repository.

Validity of Assumptions. The validity of key assumptions in the model and its application are assessed in terms of how they could affect the usefulness of the conceptual model. The review addresses the comprehensive inclusion of important features, events, processes, and other key assumptions. Examples are the assumption of Darcy flow in the various media, use of the ideal gas law at high pressures, and the mathematical method chosen to develop the model grid.

Alternative Interpretations. This section briefly identifies and assesses plausible alternative conceptual models or sub-models considered by SNL but not used, and the rationale why such alternative models were not used.

Uncertainty of Results and Consequences if Wrong. This includes an evaluation of the key uncertainties in the selected conceptual models and the discussion of the consequences if aspects of the conceptual model chosen were inappropriate or incompletely constrained for the site or process. This is not an exhaustive evaluation, but it does raise the question, "What if the model is wrong?"

Appropriateness and Limitations of Method and Procedures. Based primarily on the previous four criteria, this is a simple statement of whether the individual conceptual models and sub-models represent a reasonable approximation of the actual disposal system elements.

Adequacy of Application. This is an assessment of whether it appears that the individual conceptual model is being adequately applied into an acceptable overall performance assessment system. This particular assessment does not cover the relationships among conceptual models, but rather whether the significant components of the individual conceptual models are appropriately implemented in support of performance assessment. For example, are the various geometrical systems and representations of the conceptual models adequately applied within the performance modeling system, or do there appear to be discontinuities between the conceptual model and its application? Also, are there

alterations of important key assumptions between the conceptual model and its implementation in performance modeling?

Accuracy of Calculations. This is a statement of whether the results of performance modeling using the conceptual model within the performance system are reliable and accurate to adequately simulate the physical and chemical processes represented.

Validity of Conclusions. This is a judgment of the validity of any key conclusions that have been drawn based on results of the implementation of the conceptual models in the modeling framework. The key question is whether or not conclusions from model implementations appropriately relate to the expected goal of assessing the long-term performance of the disposal system. This judgment requires an evaluation of output information from the total system PA.

Adequacy for Implementation. This is an overall assessment of whether the conceptual models as implemented in the PA represent a reasonable approximation of the actual disposal system.

2.6 CONDITIONAL ADEQUACY

Two review criteria (adequacy of application and accuracy of calculations) require information available only after a total system PA has been performed. Recognizing that a total system PA will not be available for several months, conditional acceptance of the adequacy of the changed models is intended to permit completion of the total system PA.

The changed models should be re-reviewed in the context of a total system PA. The total system PA review may include review of accompanying sensitivity analyses appropriate to evaluate the reasonableness of changes in performance estimates resulting from changes in parameter ranges or in changes to or resulting from single values. The total system PA review should evaluate changes in the conceptual structure of the models and changes in component process models and compare the performance results of the changed models with the results of the earlier models to confirm that the changes in

performance estimates are reasonable in sense and magnitude. Changes in computations or in fundamental model aspects such as gridding should also be considered. Whatever the methodology chosen, each changed model must be shown to satisfy all of the review criteria after the next iteration of total system PA calculations. The final review should consider the impacts of the changed models on the implementation of related conceptual models and peripheral issues such as the Option "D" panel closures. The status of the changed models will remain "conditionally adequate" until the final review is completed. If warranted by final review in the context of a total system PA, the status of any changed conceptual model may become "inadequate".

3.0 Model Evaluations

This section presents the results of the Panel's evaluations of the three individual conceptual models that the DOE requested the Panel to review. Each of these models is first described and then evaluated for adequacy in accordance with the criteria summarized in Section 2.5. Following each evaluation, space has been provided for dissenting views. There were no dissenting views by any Panel member resulting from this peer review. An evaluation of the integration of these conceptual models into the WIPP performance assessment is provided in Section 4.

3.1 Disposal System Geometry

3.1.1 Model Description

3.1.1.1 Background

Consistent with the purposes for which the conceptual models were originally developed for the WIPP PA, the Disposal System Geometry conceptual model was developed to express the dimensionality of the engineered system and the surrounding geologic/hydrogeologic formations. The features that rely on the geometric assumptions and parameters of dimensionality for representation are expressed across the overall performance assessment system through a finite difference model called BRAGFLO. The flow fields generated by BRAGFLO, based on the geometric representations and the finite difference calculations, are communicated with the NUTS code that determines the transport of actinides through the anhydrite interbeds and boreholes. The geometry assumed for any model contains important information about the way in which physical processes are thought to act on the system. For WIPP, the model geometry assumed for the disposal system can only be understood in the context of the important processes considered to take place in a particular region during a specific time interval and for a defined purpose.

3.1.1.2 Description

This peer review focused on the changes in a specific group of conceptual models associated with the Technical Baseline Migration (TBM). Changes were evaluated to determine whether or not the models continue to reasonably represent the relevant features, processes, and future states of the disposal system. Changes to the disposal system geometry conceptual model evaluated were: 1) The removal of the shaft seal system from the models, 2) Implementation of Option "D" panel closure design, 3) Dividing the remainder of the repository into two blocks separated by a panel closure, 4) Applying a new method by which flaring is calculated, and 5) Refinement of the grid geometry.

The final certification decision (40 CFR Part 194) requires the implementation of Option "D" panel closure system. The system, characterized by a concrete monolith and an explosion wall, led to the proposed change in grid geometry since the existing grid block discretization was perceived to be too coarse for the representation of the specifics of Option "D" and the interrelated impacts on the DRZ. In general, where flow has been shown to be important, changes to the grid are proposed to add detail. The proposed grid refinement provides for greater segmentation and allows the detail of Option "D" components to be captured. The changes in the grid increased both vertical and horizontal refinement. The number of grid cells representing the repository increased from 51 in the CCA to 69 in the TBM. The total number of grid cells increased from 33 to 68 in the x-dimension and 31 to 33 in the y-dimension. The x-dimension changes in the grid required the recalculation of radial flaring. It is understood by previous peer review panels, and this panel as well, that while flow may not be truly radial, the two-dimensional flared grid is reasonable for estimating releases. The CCA grid had several scales of flaring with each calculation including a series of complicated cell wrapping procedures that are difficult to reproduce and use for characterizing changes. The TBM changes include a new flaring algorithm that uses simplified repository geometry, results in flaring representations that closely approximate those in the CCA grid, and allows for changes to be "more easily" made in the x-dimension.

Changes in the BRAGFLO model considered in this peer review, with respect to the Disposal System Geometry conceptual model, include grid spacing changes, removal of the shaft seal system material properties and replacing them with those representing the surrounding geologic units, and changes in the way flaring is calculated. Implementation of Option "D" panel closure was the stimulus for changing the grid with removal of the shaft seal system being a separate decision represented in the BRAGFLO grid.

3.1.2 Review of Criteria

3.1.2.1 Information Used to Review Changes in Conceptual Model

The 1996 peer review of the Disposal System Geometry conceptual model included review of the screening logic, numerous SNL reports, and many technical presentations and discussion sessions. As stated in the report, (July 1996) the information and background references reviewed at that time were for specific inputs and applications, i.e., a comprehensive list of references addressing the "conceptual modeling" of the Disposal System Geometry was not compiled. Information concerning the effects of detailed stratigraphy and stratigraphic dip on brine and gas flow, and uncertainty and parameter sensitivity analyses for gas and brine migration, is presented in Webb and Larson (1996), WIPP (1992a & 1992b), and Christian-Frear (1996). Other reports (WIPP 1993, Rechard 1990, and Marietta 1989) explain the WIPP performance assessment aspects of characterizing the disposal system geometry, and features, events, and processes (FEPs) screening documents present modeling alternatives. Various sections of the Compliance Certification Application (DOE 1996) summarize disposal system, repository, and intrusion event geometries. The Disposal System Geometry conceptual model, as reviewed in 1996 and as addressed in this peer review, is the result of integrating other models that describe the physical and chemical conditions and processes that are expected in the repository to produce a characterization of the repository and the surrounding strata. The references include the various background, technical descriptions and presentation materials used in conducting the evaluation of the TBM changes in the Disposal System Geometry conceptual model. Previous conceptual model peer review reports, regulatory guidance, and other appropriate documents were provided to the peer review panel early in the process, as required background reading. The key information

sources, with respect to the TBM changes were the technical presentations, supplementary technical and background materials provided by SNL and discussions with SNL scientists.

3.1.2.2 Validity of Assumptions

Along with the assumptions made for the TBM changes, it is important to briefly review the general assumptions made in the original peer review of the Disposal System Geometry conceptual model in 1996. The Disposal System Geometry conceptual model and its assumptions are so closely tied to the processes described by other models that not only is it important that the model have assumptions that are internally consistent, but the assumptions must be consistent with those of the models representing repository processes. The geometry by which processes are simulated is so closely tied to the processes themselves that it is difficult to conduct a review separate from the other models. Fluid flow and actinide transport are principal processes that rely on the geometric assumptions and these processes in turn have interrelationships with other process models. In 1996 the panel recognized the simplifications and assignment of high permeabilities for the sake of conservatism. Although, this panel's view is that it is always more credible to model the actual system, the assumptions supporting the simplifications remain valid.

Assumptions key to the original Disposal System Geometry conceptual model include: 1) the three-dimensional systems can be represented by two-dimensional simplifications, 2) the associations between and relationships across regions with varying material properties can be represented by the discretized grid blocks and by the finite difference method used in the computational model; 3) the four shafts can be represented by one shaft; 4) the entire repository can be represented by the simplified floor plan used in the computation model; 5) the intrusion borehole(s) represent the range of concerns associated with the intrusion scenarios; and 6) effects of flow in the DRZ and intact rocks outside of the repository are represented by the divergent grid to the north and south, away from the repository.

Assumptions key to the proposed TBM changes in the Disposal System Geometry conceptual model include: 1) A more refined grid spacing, generally, provide for more accurate representation of features, events, and processes and do not adversely impact the representation of sources, sinks, and pathways for radionuclide releases; 2) Flow in the shaft is negligible; 3) Removal of the shaft seal system properties and replacement with those of the surrounding geologic units will represent relevant features, processes, and future states of the disposal system; 4) The new flaring algorithm adequately represents horizontal divergent and convergent flows to the north and south of the repository; and 5) The TBM BRAGFLO grid adequately represents the Option "D" panel closure design, the DRZ, anhydrite fracture, repository fluid flow, and other components of the WIPP setting.

During the Salado Flow Peer Review, SNL presented assumptions and justifications for the material property representations proposed for use in the TBM. The panel concludes that the assumptions and justifications are defensible and appear to adequately represent the features and process of concern in TBM changes. The panel also concludes that as a result of previous PA calculations, illustrating that only negligible flows are released up the shaft, removal of the shaft seal properties and replacement of the shaft seal properties with those representing the surrounding geologic units is justified.

The changes in the Disposal System Geometry conceptual model are proposed to be implemented through the same discretized grid block and finite difference computational approach as the CCA, and if key pathways and simplifications are retained, the overall conceptual model remains valid.

3.1.2.3 Alternative Interpretations

During the Salado Flow Peer Review, information presented and considered did not include alternatives or options for changes in the Disposal System Geometry conceptual model. The final certification decision required the implementation of the Option "D" panel closure system and no other panel closure alternative changes are appropriate.

Other changes are proposed to accomplish specific objectives and no alternative approaches have been proposed for those specific changes.

3.1.2.4 Uncertainty of Results and Consequences if Wrong

The key uncertainties associated with the TBM proposed changes to the Disposal System Geometry conceptual model are related to the material property descriptions and the grid simplifications made, for the sake of conservatism, and the representativeness of the computational mesh. Even with the TBM changes the proposed BRAGFLO grid is not sufficiently detailed to describe all flow features and processes and the overall system relies on other conceptual models to reasonably describe such features and processes.

The panel concludes that there is little uncertainty associated with the basic geometric framework and finite difference method used to characterize the changes associated with the proposed TBM. The uncertainty that does exist is related to the grid block densities of the material property representations and the representativeness of the grid block densities/computational mesh. The material property changes appear justified and defensible.

The consequences of the proposed TBM changes in the Disposal System Geometry conceptual model, if they are wrong, can only be addressed in a qualitative way at this time. If the material property representations are wrong and /or the computational mesh is not representative, the consequences depend on the relative magnitude of error(s) and the resulting changes in the total system PA.

3.1.2.5 Appropriateness and Limitations of Method and Procedures

The proposed TBM changes in the Disposal System Geometry conceptual model would be made without changing the fundamental geometric framework of discretized grid blocks and the finite difference method implemented through BRAGFLO. The methodology is considered by the panel to be appropriate for the TBM application. The panel concludes that the conceptual model continues to be an appropriate methodology to

integrate and express the inputs from other conceptual models. The limitations of the methodology and procedures are directly related to validity of assumptions and uncertainties.

3.1.2.6 Adequacy of Application

The methodology employed in the Disposal System Geometry conceptual model is appropriate and adequate for application as a performance element. The proposed TBM changes in the conceptual model would be made through an adequate fundamental framework and implementation method and code. There are no apparent compatibility problems between the geometry and process-related models. Single vector BRAGFLO analyses that focused on saturation and pressure provided comparisons for the Performance Assessment Verification Test (PAVT), Technical Baseline Intermediate (TBI), and TBM. The TBI was intended to isolate Option “D” effects in the BRAGFLO grid. The single vector, time dependent comparisons produced results that were either expected or could be explained. Scatter-plots also provided comparisons where the differences could be explained.

The adequacy of the changes in material properties and their representations in the grid can only be measured by how well overall processes are approximated. These approximations and representations and changes from the previous conceptual model can only be determined through a full system PA.

3.1.2.7 Accuracy of Calculations

It was not within the scope of the Salado Flow Peer Review to evaluate BRAGFLO implementation code changes, related to TBM conceptual model changes, or the resulting representations. Descriptive write-ups and review of uncertainty/sensitivity analyses that compare the relationship between sampled inputs and dependent variables in the PAVT, TBI, and TBM provide no indications that the accuracy of the "baseline" model has been changed. However, the review was limited and the panel cannot conclude as to the overall accuracy of calculations until a total system PA is available for review.

The Disposal System Geometry conceptual model produces results using the material properties, processes, and codes from other models. As such, the results of the Disposal System Geometry conceptual model should be evaluated for accuracy in the context of a total system PA.

3.1.2.8 Validity of Conclusions

Excluding the presentation of intermediate analyses such as illustrations of time dependent vector analyses and horsetail plots, and comparisons using scatter plots that focused on pressure and saturation, the panel is not aware of any results or conclusions as to the impacts of the proposed TBM changes. However, without total system PA results, where the CCDFs and the distribution of results can be compared between the CCA baseline and the TBM changes, there can be no in-depth assessment of the impacts of the proposed changes. No conclusions can be drawn at this time.

3.1.2.9 Adequacy for Implementation

3.1.2.9.1 General

The Disposal System Geometry conceptual model continues to provide an adequate framework for modeling the important processes and their interactions in the disposal system. The concept that the spatial effects of processes and interactions can be represented in two-dimensions is defensible. The simplification in the system representation and computational method to simulate the two dimensions are defensible and adequate for implementation. The basic grid framework for representing the material properties of the disposal system, adjacent DRZ, geologic formations, and intrusion scenarios is adequate. The proposed use of a finite difference method to connect the nodes and generate flow fields is also defensible and adequate for implementation.

3.1.2.9.2 Conditional Adequacy of the Changed Disposal System Geometry Conceptual Model and Requirements for Final Review

Changes to the Disposal System Geometry conceptual model have been evaluated and the only uncertainties are related to the validity of the material property representations and the representativeness of the grid densities and computational mesh. The changed Disposal System Geometry conceptual model is found to be conditionally adequate. The model must satisfy the review criteria adequacy of application and accuracy of calculations for the conditional status to be removed. It also must be demonstrated that the changed model continues to represent relevant features, processes and future states of the disposal system and as such, the changes from the "baseline" conceptual model must be analyzed and understood in light of a total system PA.

3.1.2.10 Dissenting Views

There were no dissenting views for this model.

3.2 Repository Fluid Flow

3.2.1 Model Description

The Repository Fluid Flow conceptual model is a highly complex description of interacting hydrologic, chemical, engineering design, geomechanical, and human intrusion conceptual models whose simultaneous effects can be separately described, but require performance assessment numerical modeling to understand the combined, integrated results. The physical conditions controlling fluid flow in the repository include brine inflow rates, halite creep rates, and gas generation pressures from waste container corrosion and waste degradation. All of these physical conditions are contained in separately described conceptual models (Salado Interbeds, Creep Closure, and Gas Generation conceptual models respectively). The Repository Fluid Flow conceptual model accepts input from these related models and provides descriptions of pressures, flow rates, and flow directions for gas and brine within the disposal cells and other sections of the repository. A formal description of the coupled processes in the original conceptual model was presented in Freeze et al. (1995).

Changes to the original conceptual model are as follows: 1)Brine inflow rates and gas pressures have possibly been altered by the introduction of the Option "D" panel closure model mandated by the regulator, 2) The salt creep rate may be affected due to changes in gas pressure, 3) Gas generation is calculated using a different cellulosic molecular weight that provides approximately 10% greater gas production during microbial degradation, and 4) Flows will be redirected since the Disposal System Geometry conceptual model no longer explicitly represents a shaft in the grid.

3.2.2 Review of Criteria

3.2.2.1 Information Used to Review Changes in Conceptual Model

The Repository Fluid Flow conceptual model relies heavily on Darcy flow in porous media, as revised for gas by taking into account the Klinkenberg effect, and for two-phase flow using a modified Brooks-Corey model that includes threshold pressures for gas entry into a brine saturated environment. Gas properties are given by the Redlich-Kwong-Soave equations of state, assuming that the gas behaves as pure hydrogen. The conceptual model addresses: (1) fluid distribution in the waste, (2) long-term fluid (gas and liquid) flow to and from the Salado Formation, and (3) long-term fluid flow between the repository and the intrusion boreholes. Interactions with other conceptual models include the Disposal Room Geometry, Disturbed Rock Zone, Creep Closure, Gas Generation, Impure Halite, Salado, the Salado Interbeds, Castile and Brine Reservoirs, Exploration Boreholes, and Multiple Intrusions. In the original CCA the Repository Fluid Flow conceptual model was also related to the Shafts and Shaft Seals conceptual model. The Shafts and Shaft Seals model was removed from the present performance assessment because it was determined to have no impact. Therefore, fluid flow will now be modeled as transport exclusively up boreholes (Multiple Intrusions and Exploration).

The conceptual model for repository fluid flow is implemented for performance assessment using the BRAGFLO code. The repository is represented in BRAGFLO in two-dimensional vertical section as a series of volumes, each with homogeneous isotropic material properties and behaviors. Each volume represents a major repository feature.

The slight one degree (1°) dip of the bedding to the south is represented by the code. The effective depth of each feature (the dimension normal to the plane of the model) is accomplished by adjusting the cross sectional areas of the cells representing the feature. The effective depths of the model cells were varied to simulate the increasing hydraulic gradients that would occur in the repository and boreholes under radial flow conditions.

The original conceptual model was validated in the CCA and accepted by the Conceptual Models Peer Review in 1996. Since that time, a PAVT sensitivity study was performed. That PA included 60 parameter changes mandated by the EPA. Sensitivity analysis in the PAVT indicates that changes in the complete PA calculation set were not substantial.

Since the PAVT, there have been minor changes to the fluid pathways in and around the repository. Those changes are the result of modifications to other conceptual models and new EPA mandated parameter values. Those modifications are summarized as follows:

> The Shafts and Shaft Seals conceptual model has been removed from the overall model. With the removal of the Shafts and Shaft Seals conceptual model from the upcoming total system PA, it is estimated that with the enactment of either the Exploration Borehole or the Multiple Intrusions conceptual model, all releases will be channeled up the boreholes. The removal of this conceptual model should provide no significant change to the upcoming PA.
>
> There have been changes to the Disturbed Rock Zone conceptual model. Fluids will no longer transport from one panel to another via Marker Bed #138. Instead, fluids will now migrate along Marker Bed #139 below the floor of the panels. The fluids will not be able to circumvent the Option "D" panel closure by taking the path of least resistance in marker Bed #139. Because of permeability fluctuations now allowed by the DRZ, both gas and liquid phases may be impeded during certain BRAGFLO simulations.

The Option "D" panel closure has been incorporated into the final closure plan and has multiple potential effects on fluid flow. Although the upper DRZ still exists it is not allowed to fracture for the TBM analysis. The lower DRZ is allowed to fracture for the TBM making Marker Bed #139 the preferred pathway. Fluids will more slowly equilibrate throughout the repository after closure, which may result in changes in the output from the next total system PA. Gas pressure in the experimental area will most likely be lower than in the PAVT, since there is no gas generation in that region and no communication with the waste panels. Brine saturation in the waste panel may be lower than in PAVT, since there is less brine communication between panels due to the characteristics of the Option "D" panel closure. Brine saturation in the remainder of the repository will be the same as PAVT calculations because process models for BRAGFLO have not changed.

The parameter value changes include the cellulosic molecular structure change and the EPA mandated parameter value changes. The cellulosic chemical formula ($C_6H_{10}O_5$) provides approximately 10% greater gas production during microbial degradation. The new parameter value changes introduced by the EPA did not seem to introduce significant changes from the CCA to the PAVT CCDFs. Although the TBM CCDF has not been run yet, it is reasonable to believe that no significant changes will occur.

3.2.2.2 Validity of Assumptions

On a larger scale, the original assumptions for the Repository Fluid Flow conceptual model were validated in the original performance assessment (CCA, 1996). The validity of the assumptions hinge in part on the other conceptual models (Disturbed Rock Zone and Disposal System Geometry) currently under review. In so far as the assumptions in the other models are shown to be valid, those same assumptions will propagate through to the Repository Fluid Flow conceptual model. The BRAGFLO computer model was not

significantly changed in its assumption base (creep closure, gas generation, pressure induced fracturing, use of characteristic curves such as Brooks-Corey and van Genuchten), rather cell parameters have been improved and cell dimensions have been better adapted to critical features.

The assumptions addressed are: 1) removal of the Shafts and Shaft Seals, 2) change in representation of cellulosic molecular structure, 3) changes in the DRZ conceptual model, 4) implementation of EPA mandated changes to parameters, 5) implementation of the Option "D" panel closure, and 6) the associated ramifications to other conceptual models and the performance assessment.

The assumption that the removal of the Shafts and Shaft Seals system would affect the overall performance of the PA in a very minor way is reasonable. Maximum brine flow up the Shaft at the top of the DRZ was calculated to be approximately 30 m^3. During borehole intrusions in the upcoming PA this fluid would be directed up the borehole and would still be insignificant.

The larger molecular weight for cellulose is not an assumption, but rather a refinement of a parameter. The recalculation of the molecular weight and the slight increase in gas generation potential (10%) will produce a slightly more conservative value for overall gas generation amounts in certain PA scenarios.

The two major assumptions for the Disturbed Rock Zone conceptual model (permeability and flow geometry) are reasonable.

The 60 parameter changes listed in Table 3-1 (Summary of CCA and PAVT Parameters) and Table 3-1. (Summary of TBM Values and Distributions) appear reasonable and correct. The most notable changes concern actinide solubilities in the fluid. In all cases the solubility values are lower than in the original CCA values. Such values would produce lower value curves in the upcoming CCDFs, if all other variables remain unchanged. Most other changes involve taking a single parameter value and replacing it with a range of values that bracket the original. This is a reasonable and valid

assumption, in that it still focuses most new values near the original value, but allows the CCDF calculations a slightly wider variance.

Table 3-1. Summary of CCA and PAVT Parameters

Parameter	CCA Range and Distribution	PAVT Range and Distribution
Log of Borehole Sand Permeability	-14 to -11 log m^2 Uniform	-16.3 to -11 log m^2 Uniform
Log of Borehole Concrete Permeability	-16.3 log m^2 Constant	-19 to -17 log m^2 Uniform
Log of Disturbed Rock Zone Permeability	-15 log m^2 Constant	-19.4 to -12.5 log m^2 Uniform
Log of Waste Permeability	-12.769 log m^2 Constant	-12.6198 log m^2 Constant
PIC Reduction Factor for 100 – 700 years	0.01 Constant	1.0 Constant
Waste Shear Strength	0.05 to 10 Pa Uniform	0.05 to 77 Pa Loguniform
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Castile Brine	6.52×10^{-8} mol/l constant	1.38×10^{-8} mol/l constant
Coefficient, A, in Equation[(a)] for Solubility for Np+4, Pu(IV), Th(IV) and U(IV) in Castile Brine	6.0×10^{-9} mol/l constant	4.1×10^{-8} mol/l constant
Coefficient, A, in Equation[(a)] for Solubility for Np(V) in Castile Brine	2.2×10^{-6} mol/l constant	4.8×10^{-7} mol/l constant
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Salado Brine	5.82×10^{-7} mol/l constant	1.2×10^{-7} mol/l constant
Coefficient, A, in Equation[(a)] for Solubility for Np(IV), Pu(IV), Th(IV) and U(IV) in Salado Brine	4.4×10^{-6} mol/l constant	1.3×10^{-8} mol/l constant
Coefficient, A, in Equation[(a)] for Solubility for Np(V) in Salado Brine	2.3×10^{-6} mol/l constant	2.4×10^{-7} mol/l constant
Inundated Steel Corrosion Rate	0 to 1.59×10^{-14} m/s Uniform	0 to 3.17×10^{-14} m/s Uniform
K_d in Culebra Dolomite for Am(III) and Pu(III)	0.02 to 0.5 m^3/kg Uniform	0.009 to 0.4 m^3/kg Loguniform
K_d in Culebra Dolomite for Np(IV), Pu(IV), Th(IV), and U(IV)	0.9 to 20 m^3/kg Uniform	0.7 to 10 m^3/kg Loguniform
K_d in Culebra Dolomite for Np(V)	0.001 to 0.2 m^3/kg Uniform	0.001 to 0.2 m^3/kg Loguniform

K_d in Culebra Dolomite for U(VI)	0.00003 to 0.03 m^3/kg Uniform	0.00003 to 0.02 m^3/kg Loguniform
Probability of Hitting a Brine Pocket	0.08 Constant	0.01 to 0.60 Uniform
Drill String Angular Velocity	7.7 radians/s Constant	4.2 to 23.0 radians/s cumulative distribution with mean of 7.77 radians/s
Castile Brine Pocket Rock Compressibility	Min: $5x10^{-12}$ Pa^{-1} Max: $1x10^{-8}$ Pa^{-1} Mode $1x10^{-10}$ Pa^{-1} Triangular	Min: $2x10^{-11}$ Pa^{-1} Max: $1x10^{-10}$ Pa^{-1}; Mode $4x10^{-11}$ Pa^{-1} Triangular
Castile Brine Pocket Porosity	Not used in CCA	Min: 0.1848; Max: 0.9240; Mode 0.3696
Brine Pocket Pore Volume	(3.2, 6.4, 9.6, 12.8, 16) x 10^4 m^3 Discrete	Calculated from Brine Pocket Porosity
Inventory Waste Unit Factor	4.07 Constant	3.44 Constant

[(a)]The equation for solubility is $A \cdot 10^b$ where b is a sampled value. Only the coefficient, A, was changed in the PAVT.

Table 3-2. Summary of TBM Values and Distributions

Parameter	Range	Distribution
Log of Borehole Sand Permeability	-16.3 to -11 log m^2	Uniform
Log of Borehole Concrete Permeability	-19 to -17 log m^2	Uniform
Log of Disturbed Rock Zone Permeability	-19.4 to -12.5 log m^2	Uniform
Log of Waste Permeability	-12.6198 log m^2	Constant
PIC Reduction Factor for 100 – 700 years	1.0	Constant
Waste Shear Strength	0.05 to 77 Pa	Loguniform
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Castile Brine	1.38 x 10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np(IV), Pu(IV), Th(IV) and U(IV) in Castile Brine	4.1 x 10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np(V) in Castile	4.8 x 10^{-7} mol/l	Constant

Brine		
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Salado Brine	1.2×10^{-7} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np(IV), Pu(IV), Th(IV) and U(IV) in Salado Brine	1.3×10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np(V) in Salado Brine	2.4×10^{-7} mol/l	Constant
Inundated Steel Corrosion Rate	0 to 3.17×10^{-14} m/s	Uniform
K_d in Culebra Dolomite for Am(III) and Pu(III)	0.009 to 0.4 m^3/kg	Loguniform
K_d in Culebra Dolomite for Np(IV), Pu(IV), Th(IV), and U(IV)	0.7 to 10 m^3/kg	Loguniform
K_d in Culebra Dolomite for Np(V)	0.001 to 0.2 m^3/kg	Loguniform
K_d in Culebra Dolomite for U(VI)	0.00003 to 0.02 m^3/kg	Loguniform
Probability of Hitting a Brine Pocket	0.01 to 0.60	Uniform
Drill String Angular Velocity	4.2 to 23.0 radians/sec	Cumulative distribution based on range with mean value of 7.77 radians/s
Castile Brine Pocket Rock Compressibility	Min: 2×10^{-11} Pa^{-1} Max: 1×10^{-10} Pa^{-1} Mode 4×10^{-11} Pa^{-1}	Triangular
Castile Brine Pocket Porosity	Min: 0.1848; Max: 0.9240; Mode 0.3696	Triangular
Brine Pocket Pore Volume	Calculated from Brine Pocket Porosity	Not applicable
Inventory Waste Unit Factor	3.59	Constant

[(a)]The equation for solubility is $A \cdot 10^b$ where b is a sampled value. Only the coefficient, A, was changed in the PAVT.

More information is needed to clearly understand how implementation of the Option "D" panel closure will affect fluid flows. At this point, only vectors for three scenarios have been generated and analyzed from PAVT to TBM models, and these were concerned only with brine saturation and gas generation values. First, gas pressure in the experimental area will commonly be lower than in the PAVT, since there is no gas generation in that region and very limited communication with the waste panels. Conversely, TBM

calculations of gas pressures in the waste panels are slightly elevated relative to PAVT values. These two observations were calculated at the 1000-year time frame. At the 10,000 year time frame most TBM gas pressure values converge on the PAVT generated values. Second, brine saturation in waste panels may be lower than in PAVT representations, since there is less brine communication between panels due to the characteristics of the Option "D" panel closure. This calculation proves true for both the 1000 and 10,000 representations. However, Brine saturation in the remainder of the repository (ROR) will be the same as PAVT calculations because ROR grid parameters for BRAGFLO were not changed. Of interest is the fact that the experimental regions of the repository show higher brine saturation in TBM analysis due to the fact that the panel closures don't allow the brine to migrate down dip. Finally, TBM calculations indicate that brine flow up a borehole from a waste panel is slightly elevated relative to PAVT data. In addition, the panel closure now dampens equilibration of gas pressures during multiple borehole intrusion scenarios. During the first intrusion, the panel gas volume will escape up the borehole. However, subsequent waste panels will retain high gas pressure. Secondary or tertiary borehole intrusions may still encounter waste panels with high gas pressures indicating a possibility that spalling events may cumulatively bring more waste to the surface.

The last assumption, that the Repository Fluid Flow conceptual model will have negligible impact on the other conceptual models and the total system PA is unknown. How increased or decreased values of gas pressure and/or brine saturation will impact fluid flow has not been evaluated. Furthermore, the impact that the changes in fluid flow will have on the Spallings and Multiple Intrusions conceptual models, and on the total system PA is unknown.

3.2.2.3 Alternative Interpretations

The changes incorporated into the Repository Fluid Flow conceptual model are based on two earlier cases of the model. The earlier models represent alternative interpretations. The Repository Fluid Flow conceptual model in the CCA was fully peer reviewed and accepted. The second representation of the model was in the PAVT sensitivity study.

The changes incorporated into this rendition of the model are logical improvements based on removal of the Shafts and Shaft Seals and the incorporation of the Option "D" panel closure.

3.2.2.4 Uncertainty of Results and Consequences if Wrong

The uncertainty of results with the changed Repository Fluid Flow conceptual model hinge on the implementation of the Option "D" panel closure. The purpose of the panel closures is to impede flow around the closure between adjoining waste panels. The new Disturbed Rock Zone conceptual model implies that flow will occur in the underlying Interbed #139 at high gas pressure, and in turn, this should allow gas and liquid in the waste panels to equilibrate over time. However, vector analyses of gas pressure and brine saturation in the TBM model show that flow occurs for a limited number of vectors when pressures become high enough to cause significant fracturing. When these factors (pressure and saturation) are allowed to interact with the other conceptual models and are evaluated as part of the total system PA, other outcomes may result. Direct release conceptual models (involving cuttings, cavings, spallings, and direct brine release) provide the most significant release pathways. Since there is evidence that the waste panels do not equilibrate with the ROR nor with the experimental region, the Repository Fluid Flow conceptual model should be evaluated in the context of a total system PA.

If the direct release conceptual models intercept a waste panel with very a high gas pressure (near or above lithostatic pressures), then an increase in direct releases to the surface could occur. Similarly, if a panel with high brine saturation were encountered, it could allow for slightly higher solute transport to the surface. Conversely, if panels with low gas pressure or low brine saturation were intercepted, then the direct release could be much lower. Since specific waste panels and explicit scenarios for direct release have not been specified for the upcoming total system PA, the Peer Review Panel cannot determine the consequences from the Repository Fluid Flow conceptual model.

3.2.2.5 Appropriateness and Limitations of Method and Procedures

The methods and procedures used in the newest rendition of the model are based on refinements of the previous models and should provide representative results in the upcoming total system PA. If representative panels are chosen for the "borehole" models, this new model are expected to provide similar results to the PAVT application.

3.2.2.6 Adequacy of Application

The adequacy of application can not be judged without the total system PA and the associated CCDFs. Once the total system PA is performed, the adequacy of the newest rendition of this model can be compared to previous forms of the model and how it impacts the new CCDFs.

3.2.2.7 Accuracy of Calculations

No new calculations were reviewed by the Panel since the previous two iterations (CCA and PAVT). The accuracy of the calculations already embedded (BRAGFLO) in the Repository Fluid Flow conceptual model should be determined when the next iteration of the total system PA is complete.

3.2.2.8 Validity of Conclusions

The validity of the conclusions cannot be assessed without the total system PA and the associated CCDFs. It is still not known how the implementation of the Option "D" panel closure will affect fluid flow throughout the repository.

3.2.2.9 Adequacy for Implementation

3.2.2.9.1 General

Adequacy for implementation cannot be judged without the total system PA and the CCDFs.

3.2.2.9.2 Conditional Adequacy of the Changed Fluid Flow Model and Requirements for Final Review

The changed Repository Fluid Flow conceptual model is found to be conditionally adequate with the following conditions. The model must satisfy review criteria for adequacy of application, accuracy of calculations, and validity of conclusions for the conditional status to be removed. The information to be judged once the total system PA is available is whether the Repository Fluid Flow conceptual model still correctly couples with the other conceptual models to produce representative results.

3.2.2.10 Dissenting Views

There were no dissenting views for this model.

3.3 Disturbed Rock Zone

3.3.1 Model Description

The DRZ conceptual model, as originally conceptualized in the CCA, was composed of a layer of halite above and below the drift. This layer provided a flowpath between the drift and marker-b
eds. The halite that composed this layer was assigned an arbitrary permeability of $10^{-15}m^2$, considered a conservative value that would permit gas to escape the repository via the fractured interbed and allow gravity-driven drainage of brine from the interbed into the repository ("DRZ rain"). The model was not strongly representative of repository processes; rather it was viewed as a conservative basis for modeling waste degradation and gas generation processes in the repository.

During the PAVT sensitivity study the EPA mandated a range of permeability for the DRZ halite layer which reasonably represents the properties of extensively creep-damaged halite and anhydrite at the high permeability end, and of minimally damaged halite at the low permeability end. This range is unequally distributed around the original single value used for the halite permeability. This range is retained in the changed

conceptual `model under review, and was not previously peer reviewed. The principal change to the hydrologic processes contained in the model presently under review is the flow path through the repository floor, an average of one meter of halite, into Interbed #139 which is composed of about one meter of fractured anhydrite. This flow path represents a considerably more transmissive pathway for the exit of gas and brine from the pressurized repository, into the potential storage medium represented by the fractured anhydrite. The gravity inflow of brine through the halite layer above the repository back is still a factor in modeling brine inflow into the repository, but gas outflow will follow the path of least resistance out through the floor into Interbed #139. The change to the PAVT model under review here is described in some places in the review documents as the addition of a fracture model. The change is actually only a change in flowpath out of the repository and no new fracture model is proposed.

3.3.2 Review of Criteria

3.3.2.1 Information Used to Review Changes in Conceptual Models

The CCA version of the DRZ conceptual model consisted of a 12 meter thick zone above the emplacement panels and drifts that were assigned an assumed permeability of $10^{-15}m^2$ for the entire zone. This conceptual model had no basis in actual repository or site performance, but was rather a conservative representation of the damaged rock zone, conceived to permit brine and gas flow between the repository and the overlying Interbed #138. The PAVT sensitivity study that followed the CCA used a range of permeability values for the zone between the repository and Interbed #138 that were identified by the EPA. The EPA determined the lower bound of the range of permeability from measured gas permeability in anhydrite cores from Interbed #139 (Howarth, 1996, Beauheim, 1996, Howarth and Christian-Frear, 1997). The EPA concluded that a value of $10^{-19.4}m^2$ is an appropriate lower bound for the range of likely values. Based on sensitivity tests, the EPA selected a value of $10^{-12.5}m^2$ as the upper bound of the range of DRZ permeability. Documents held by the WIPP Project office pertaining to DRZ permeability support this range of the PAVT values (Beauheim, 1996). The more permeable limit represents halite and anhydrite heavily damaged by creep strain. The less permeable end of the range assigned to the assumed disturbed zone above the repository is a value conceived to

represent the permeability of halite that has been healed by stresses associated with repository creep closure and is supported by measured permeability values. This value ($10^{-19.5}m^2$) is comparable to the permeability of halite that has been disturbed only by far field stresses caused by creep toward the repository opening beyond the disturbed rock zone (Beauheim, in press). This range of values is an acceptable bound of the permeability of the disturbed rock zone that includes both the Salado halite and the anhydrite of the interbeds.

The change proposed to the DRZ conceptual model for the next total system PA modifies the geometry of flow associated with the DRZ but retains the range of permeability assumed for the DRZ under the PAVT sensitivity study. The changed conceptual model routes flow through the floor of the repository to Interbed #139 whose upper surface is only one meter below the floor over most of the disposal area. This flow routing represents the path of least resistance for the flow of gas out of the repository and provides a reasonable estimation of gas pressures in the repository. The 12 meter thick overhead DRZ has the same range of assumed permeability as that assumed for the floor, but its greater thickness implies that it would be less transmissive than the floor of the drifts and panels. Furthermore, arching stresses over the repository openings are likely to close fractures, reducing permeability while tensile stresses in the repository floor related to floor heave will tend to preserve transmissivity.

The changes to the DRZ conceptual model include the assumptions supporting the range of permeability values and the change in the geometry of flow from the 12 meter overhead DRZ to the 1 to 2 meter long flowpath, through the repository floor and into the fractured anhydrite of Interbed #139.

3.3.2.2 Validity of Assumptions

Assumptions used in developing the proposed changes to the DRZ conceptual model are of two kinds. The values for the permeability of the DRZ have evolved over two iterations of performance assessment. In the first performance assessment (CCA, 1996) the permeability of the thick, overhead DRZ contained in that conceptual model was a

"conservative" value assumed to permit communication between repository openings and the upper Interbed #138. The chosen value was assumed to permit free drainage of brine from the interbed into the repository and to permit gas to escape from the repository to the interbed. The permeability chosen was an intermediate single value between perceived extremes implied by the material properties of the interbed and pure halite. For the PAVT sensitivity study a range of permeability was necessary to permit sampling and development of distributions to better represent flow through this complex zone. The end members of the distribution represent the measured permeability of the fractured anhydrite interbeds and the estimated permeability of "tight" halite. Pure halite, disturbed only by very small and slow strain resulting from creep into the repository beyond the DRZ, is probably a reasonable representation of well-healed halite after the disappearance of the DRZ due to back-stress around seals or after the closure of repository open spaces. As such, these end members are reasonable limits to the permeability of the DRZ. The permeability range used in the PAVT calculations ($10^{-12.4}$m to $10^{-19.5}$m) represent reasonable parameters between the end member conditions.

Changes in the geometry of flow in the DRZ represents the second kind of assumption. The basis of this assumption is that gas flow out of the repository panels will follow the path of least resistance or the path of greatest transmissivity. The short distance (approximately one meter) between the repository floor and Interbed #139 represents a much lower resistance to flow than upward flow through 12 meters of halite that is horizontally compressed by arching stresses over the repository openings. Floor heave implies an extensional stress environment in the floor. This extensional stress and gas pressures may also help to keep the fractures in both the halite in the repository floor and in the anhydrite interbed open. The large storage space represented by the well connected fracture porosity of the interbed may provide for retention of gas and brine expelled from the repository via this flowpath.

The assumptions contained in the changes to the DRZ conceptual model are reasonable to represent repository materials, flow geometry, and system properties. The permeability range used to generate the sampled distributions that will be used in performance

assessment is based on permeability of materials similar to those in the disturbed rock zone in comparable geomechanical environments. The geometry of flow follows principles of hydraulics that are appropriate to the repository structure, stress environment, and material properties.

3.3.2.3 Alternate Interpretations

The proposed changes to the DRZ conceptual model follow two earlier iterations of the model. These earlier iterations include a full performance assessment (CCA) and a sensitivity study (PAVT) that represent alternative models that have received more detailed consideration than is usual in alternative concept evaluation. The CCA iteration was fully peer reviewed. The changes proposed to the model represent reasonable development of the earlier alternatives. The changes to the model are supported in part by recent calculations, geophysical and hydrologic measurements in the repository floor (Bryan, et al, 2001, Beauheim, 2002, Holcomb, 2001). Future alternative models of the disturbed rock zone at the WIPP, based on measured hydrologic and rock mechanical models, may be developed but are not feasible at this time.

3.3.2.4 Uncertainty of Results and Consequences if Wrong

The uncertainty of results in the changed conceptual model lie mostly in the range of porosity used to represent the flow properties of the rock along the flowpath proposed. The geometry of the flowpath is not a great source of uncertainty, in that it is the most reasonable path of least resistance for gas flow and its dimensions and material properties are well known. The range of porosity proposed as bounds of the properties of the rock through which flow will take place are reasonable. The range is supported by measured values and it will be sampled and represented by a CCDF, which is a reasonable analytical approach. Exceeding of the upper limit of the permeability range due to creep damage would allow gas to migrate from the repository more easily and reduce gas pressure. Ultimately, gas pressures depend on permeability in the anhydrite interbed where storage of gas will take place at distances from the repository far enough to be less damaged by creep. The impact of the uncertainty in the conceptual model is that the gas

pressure in the repository might be lower than predicted by modeling, a conservative influence on performance.

3.3.2.5 Appropriateness and Limitations of Methodology and Procedures

The methods and procedures used in the changed model are refinements of the previous models and will generate representative results in PA. Constituative models based on measurement of the influence of creep damage on hydrologic properties may be feasible in the future, but such models are not expected to indicate that the changed model has failed to conservatively bound repository performance. The methods and procedures are appropriate to the present state of information and the needs of PA.

3.3.2.6 Adequacy of Application

Adequacy of application of the changed model cannot be assessed at this time. At the time of the next total system PA, the impact of the changed conceptual model should be considered in comparison with the earlier iterations of the model and in terms of the impact on the overall results of PA.

3.3.2.7 Accuracy of Calculations

No new calculations are contained in the changes to the DRZ conceptual model. Confirmation of the accuracy of calculations that are part of the implementation of the conceptual model in PA should be made following the next total system PA.

3.3.2.8 Validity of Conclusions

Validity of conclusions drawn from the application of the changed DRZ conceptual model in performance assessment is the same as for those drawn from the previous iterations of the model so long as the adequacy of application and the accuracy of calculations are concluded to be appropriate. The general structure of the conceptual model was peer reviewed during the CCA and the changes to the details of flowpath and the definition of porosity appear to be valid. Unless the PA calculation indicates that the

changed model causes unreasonable changes to the predicted performance of the repository, particularly with reference to repository gas pressure, the conclusions drawn using the changed conceptual model should remain valid.

3.3.2.9 Adequacy for Implementation

3.3.2.9.1 General

Adequacy for implementation cannot be judged without the total system PA and the CCDFs.

3.3.2.9.2 Conditional Adequacy of The Changed DRZ Model and Requirements for Final Review

The changes to the DRZ conceptual model consist of the addition of a range of permeability values for the materials along the flowpath through the disturbed rock zone, and a change in the geometry of the flowpath from flow through Interbed #138 above the repository to flow through Interbed #139 below the repository. This latter change was called an "addition of a fracture model" in some of the review documents. This change is a change in flowpath length and routes flow through a different stress environment, but does not constitute a new constituative fracture model. The changed model is reasonable and its conceptual structure implies a useful definition of rock permeability and a realistic flow path in the conceptual modeling of performance of the repository. The changes are reasonable in magnitude and sense. However, because no PA has been performed since the model changes were proposed, adequacy of application and accuracy of calculations cannot be fully assessed.

The changed DRZ conceptual model is found to be conditionally adequate. The model must be shown to satisfy review criteria for adequacy of application and accuracy of calculations for the conditional status to be removed. In addition, the impact of the changed model must be shown to be reasonable on the modeling of repository fluid flow and on the modeling of the performance of the Option "D" panel closure design if that

closure system is chosen. Specifically, the impact of the changed DRZ conceptual model in modeling of pressure equilibration among repository openings in the case of intrusion must be shown to be reasonable and its impact on direct brine release and spallings release scenarios examined.

3.3.2.10 Impact of the Disturbed Rock Zone Model on Closure Performance

The relevance of the Disturbed Rock Zone conceptual model to the modeling of closure performance is limited to the application of disturbed rock zone flow parameters to, through, and from the interbed below the repository floor. It is also related to modeling the equilibration of gas pressure between repository spaces after intrusion. The changed model would be useful in defining flow between Interbed #139 and repository open spaces on either side of the closure. This gas pressure equilibrium conceptual model bears on the spalling and direct brine release scenarios as well as the Repository Fluid Flow conceptual model. These interactions should be evaluated following the next total system PA.

3.3.2.11 Dissenting Views

There were no dissenting views for this model.

4.0 Integration of Conceptual Models in Performance Assessment

4.1 Model Integration

Figure 4-1 is a simplified illustration in which selected conceptual models represent a system or subsystem within the CCA, PA code sequence. BRAGFLO DBR, as illustrated, is a special, short-term application of BRAGFLO related to a drilling intrusion and includes all conceptual model system representations listed under BRAGFLO plus the Direct Brine Release model. The direct brine release element illustrates that the calculated brine volume removed from the repository by a drilling intrusion is input directly to the CCDFGF.

Figure 4-1. Illustration of Conceptual Model Integration

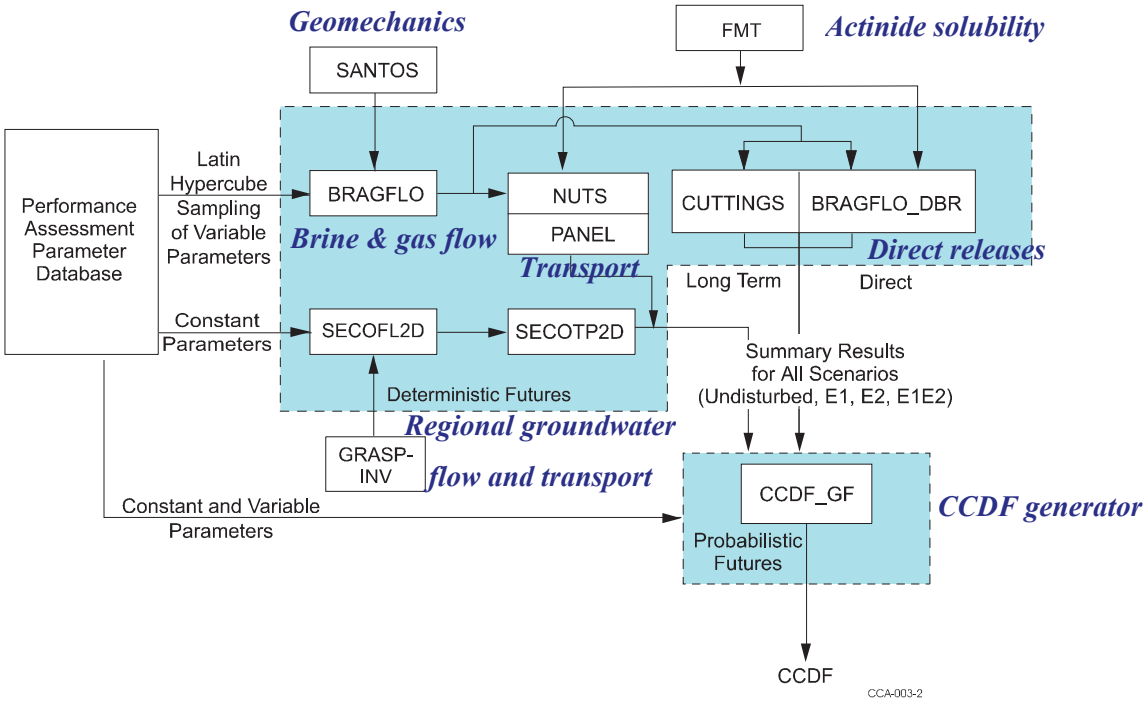

As shown in figure 4-1, the conceptual models do not all represent a system or sub-systems in the same place in the code sequence. Figure 4-1 illustrates that the conceptual models, as interpreted through the various codes, are ultimately integrated at the CCDFGF where results are prepared. The figure ignores many preparatory and post-process codes and relationships between codes that are not linear and in a single direction. For example, while SANTOS is related to BRAGFLO and receives system representation from the Creep Closure conceptual model, creep closure results from an iterative relationship between gas pressure, compaction, and brine characterizations from BRAGFLO and the porosity surface in SANTOS. The integration of the conceptual models, therefore, identifies the overall WIPP PA model as a complex structure that represents 24 conceptual models through preparatory, process, flow, and transport presentation and enabling codes.

4.2 Review of Criteria

Applying evaluation criteria to the integration of conceptual models as a step in the assessment of model adequacy results in most of the discussion being summations of the individual conceptual model evaluations. For example, evaluations of information used in the integration, assumptions, uncertainties, adequacies, accuracy, and validity are all based on the individual conceptual models or the implementing mathematical representations or codes. The criteria have been discussed in Section 3.0 for the three conceptual models reviewed. Without results of realizations, sensitivity analyses, and/or uncertainty analyses for the overall system and sub-systems, conclusions cannot be made with respect to the implementing mathematics or codes.

Because the overall total system PA was not available for Panel review, the overall adequacy for implementation of the integrated conceptual models can only be judged at this time through the adequacy of the three individual conceptual models as discussed in Section 3. There is insufficient information, i.e., total system PA and CCDFs are required, for the implementing structure (model integration, mathematical representations, codes, code sequence) to be judged adequate or inadequate.

5.0 Summary of Evaluations

This section presents a summary of the evaluations of the WIPP Conceptual Models Peer Review Panel performed between April 29, 2002 and May 31, 2002. Over twenty years of scientific effort have been expended on WIPP site characterization and there have been approximately three years of successful operational experience. It is beyond the scope of this report to summarize all of the positive factors and scientific evidence compiled concerning the WIPP site. This section is not intended to be a reiteration of comments and discussions on the individual conceptual models but to provide an overview of conclusions from the evaluations. The Panel's evaluations were made as a best effort without the benefit of the models being exercised as part of a total system PA.

The list of the twenty-four WIPP conceptual models is provided in the Table 4-1 with the three models reviewed during this peer review bolded so as to put them in the context of the total system modeling effort.

Disposal System Geometry

The TBM changes in the Disposal System Geometry conceptual model retain the adequate structure of the original conceptual model and the grid changes appear reasonable and sound. The proposed implementation of the changes appears reasonable, but the impacts of the changes and overall representativeness of the changes in the model cannot be assessed at this time. A total system PA is needed to compare the previous CCA results to the results associated with the TBM changes.

Repository Fluid Flow

The conceptual model itself has been determined to be both reasonable and adequate for its intended purpose. The identified changes (shaft removal, EPA mandated parameters, cellulosic molecular structure) appear reasonable and are expected to have minimal impact on the Repository Fluid Flow conceptual model. However, to understand the interaction of this conceptual model with the Option “D” Panel closure (and subsequent

gas pressure realizations in waste panels); and the influence the model may have when coupled with the other conceptual models requires review of total system PA results.

Disturbed Rock Zone

Two changes to the DRZ conceptual model have the potential to impact PA. These are the adoption of a range of limiting porosity values for the halite and anhydrite layers in which the disturbed rock zone is developed; and the definition of the flow path through the floor of the repository openings into Interbed #139. These appear to be reasonable changes to the model, which make it more representative of the repository processes and are based on measurements of material properties and on measured damaged rock zone processes. The impacts of these changes and the accuracy of model calculations used in their implementation cannot be evaluated until the total system PA can be reviewed.

Table 4-1. WIPP Conceptual Models

Disposal System Geometry	**Addressed During This Peer Review**
Culebra Hydrogeology	Not Addressed During This Peer Review
Repository Fluid Flow	**Addressed During This Peer Review**
Salado	Not Addressed During This Peer Review
Impure Halite	Not Addressed During This Peer Review
Salado Interbeds	Not Addressed During This Peer Review
Disturbed Rock Zone	**Addressed During This Peer Review**
Actinide Transport in the Salado	Not Addressed During This Peer Review
Units Above the Salado	Not Addressed During This Peer Review
Transport of Dissolved Actinides in the Culebra	Not Addressed During This Peer Review
Transport of Colloidal Actinides in the Culebra	Not Addressed During This Peer Review
Exploration Boreholes	Not Addressed During This Peer Review
Cuttings/Cavings	Not Addressed During This Peer Review
Spallings	Not Addressed During This Peer Review
Direct Brine Release	Not Addressed During This Peer Review
Castile and Brine Reservoir	Not Addressed During This Peer Review
Multiple Intrusions	Not Addressed During This Peer Review
Climate Change	Not Addressed During This Peer Review
Creep Closure	Not Addressed During This Peer Review
Shafts and Shaft Seals	Not Addressed During This Peer Review
Gas Generation	Not Addressed During This Peer Review
Chemical Conditions	Not Addressed During This Peer Review
Dissolved Actinide Source Term	Not Addressed During This Peer Review
Colloidal Actinide Source Term	Not Addressed During This Peer Review

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Appendix A - Panel Member Technical Qualifications

Florie Caporuscio

Los Alamos National Laboratory

- Environmental Restoration - developed criteria for and wrote portions of two-site characterization Work Plans (Los Alamos Pueblo Canyon, Canyon Core Document).
- Project Manager to characterize Omega West Reactor leak.
- Developed radiometric survey technique to investigate radionuclide transport (Pu, Cs, Sr) by geomorphic processes in Los Alamos Canyons.
- Investigated Sr transport in aqueous media in Los Alamos Canyon.
- Peer reviews of Performance Assessment of Material Disposal Area (MDA) G at TA-54, Los Alamos National Laboratory.
- Co-author of MDA Performance Assessment Core Document for Environmental Restoration Projects at LANL.

WIPP

- Final Peer Review for License Application Conceptual Models
- Peer Review Member – Natural Barriers

Environmental Protection Agency

- Principal Investigator evaluating effects of U, Th, Ra contamination and transport through geologic media at CERCLA and FUSRAP sites.
- Section Chief of US EPA WIPP Technical Review Program. Supervised review of Test and Retrieval Plan.
- EPA Principal Investigator for Gas Generation and Source Team models at WIPP (ORIA).

Pertinent Research/Other

- Oxidation of Fe oxides - characterization of oxidation state of 24,000 feet of ash flow core on Yucca Mountain.
- Determination of Fe oxidation state for paleomagnetic studies at Yucca Mountain.

- Empirical determination of Hematite-Ilmenite solvus with field samples.
- Crystal chemical studies of radioactive elements in crystal structures of mineral phases.
- Technical reviewer for *American Mineralogist* (1988-1989)

John Gibbons

Over thirty years of experience in the geology and mine mechanics of salt deposits, including New York, New Mexico, Texas, and Kansas bedded salts and domed salts in Louisiana and Texas.

Yucca Mountain Project

Preparation of site suitability documents for presidential consideration, data qualification and integration for the federal high-level nuclear waste disposal site at Nevada

WIPP

Review of conceptual models and engineered barriers models for PA in support of license application. Review of data packages for PA in support of license application.

Illinois Department of Nuclear Safety

As a principal consultant:

- Detailed review of conceptual models (hydrogeologic and site character) and integration with the MODFLOW numerical flow model. Included radionuclide transport models and the site performance assessment model for Martinsville Illinois site.
- Developed site search models for hydrogeology and seismic ground motion for a second site.
- Developed conceptual model for vertical hydrologic flow through overconsolidated, fractured glacial till.
- Developed integration plan for site characterization through performance assessment of new site including applications of STRATAMODEL three-dimensional site model and model-based tests of site hydrologic characterization adequacy.

Applied Research Associates

Principal investigator for a DOE research committee funded study to develop a model-driven site characterization technology, which integrated geophysical (down-hole and surface), cone penetrometer and borehole data acquisition systems.

Senior hydrogeologist in support to Sandia National Laboratory in development of hydrostratigraphy conceptual model of Yucca Mountain High Level Nuclear Waste Repository Site.

Dames and Moore

As a principal investigator, did proposal preparation and was project liaison to the Federal High Level Nuclear Waste Program. Site characterization planning and model integration were principal areas of technical responsibility.

E. B. Oswald

Design of Conceptual Models/Structures

- University of Arizona, Department of Hydrology and Water Resources, Dissertation, 1976. Designed a conceptual model with which to assess the socioeconomic impacts of coal-fueled power generating facilities on Native Americans in the Four Corners region of the Southwest. The conceptual model related critical social, economic and cultural parameters of Native American systems to natural resource use, economic and environmental effects and power plant location and operation phenomenon. The conceptual model was implemented through a mathematical simulation technique.
- Designed conceptual models (assumptions, structures and relationships) for evaluating the impacts of FWPCA, Section 208, non-point pollution control practices on land and surface water quality. As part of a policy analysis project under USDA, Economic Research Service, the models were published in internal, peer-reviewed working papers (1977-1984).
- Assisted in the design of the conceptual models and implementation of the mathematical realizations of a linked system of linear programs and a finite difference representation of the Navajo sandstone aquifer. The linked LPs were designed to evaluate the regional impact of power generation grid distribution and the ground water model was built to estimate the impacts of commercial water withdrawals on local wells. The modeling was done under a contract with the Ford Foundation through the University of Arizona, Department of Hydrology and Water Resources (1976-1977).
- Montana DNRC, 1995. Developed the conceptual model for evaluating the effects of high TDS water from coal mine pit discharges to the Tongue River and reservoir system.
- Montana DNRC and U.S. Bureau of Reclamation, 1994. Designed the conceptual model(s) for evaluating the impacts of increased reservoir depth and area on alluvial ground water quality and storage and shoreline erosion.

- Designed the conceptual model for evaluating water use and disposal systems at remote Missile Launch Control Facilities, Malmstrom AFB, and Montana. The model considered the timing of water use, percolation and infiltration capacities, evapotranspiration and climatic influences and resulting short and long term potential for water balance. This 1995 project was in response to recent EPA guidelines governing remote water systems.
- Montana DEQ. Currently involved in conceptualizing a model or framework for evaluating the utility and stability of post-mining reclamation. The model will involve the characterization of future land use scenarios and the assessment of economic, aesthetic, recreational, surface environmental and alluvial ground water impacts of the scenarios.

Model Operation, Application

- Operated a regional linear program-based model designed to optimize the interplay of agricultural/silvicultural production systems with imposed pollution control practices. Published as part of the USDA, Columbia River Basin Project Report, 1980-1983, Portland, Oregon.
- University of Arizona, Department of Hydrology and Water Resources, 1975. Operated a stochastic, dynamic programming model with an application to a multi-year (50 years) multi-stage water supply reservoir operation system.
- Montana, DNRC, U.S. Bureau of Reclamation, 1994. Application of MODFLOW software to an evaluation of alluvial water withdrawals and the impacts of alternative rates on surface stream flow. At issue was the volume of ground water available for consumptive use without diminishing local stream flows.
- Oregon Department of Environmental Quality, published as USDA Working Paper, ERS Working Paper Series. Design and application of a riparian habitat model to estimate the effects of various agricultural, silvicultural and mining practices on riparian zones and the aquatic and terrestrial habitats included.
- Montana DEQ, U.S. Army Corps of Engineers, 1996. Responsible for review of geochemical, limnological and mixing zone models used to predict water quality in a pit lake, the Blackfoot River and the alluvial ground water resulting from

proposed gold mine operations. The results and interpretations of the model reviews will be presented in an EIS.

- USDA, EPA, Corvallis, Oregon, 1983. Conducted review of alternative models for evaluating chemical and erosional impacts to the ground water and surface streams associated with FWPCA, Section 208 and RCWP practices. The CREAMS model developed by USDA, ARS was adopted for use.
- Reviewed and evaluated various modeling approaches to be applied to the Agricultural/Rural environment system characterized by a project area in Austria. The review and model review was conducted at the IIASA, Laxenburg, Austria during a joint effort by Russian, Austrian and U.S. scientists.
- RCRA, RFI, Malmstrom AFB, Montana. HDR Engineering, 1993. Review and evaluation of proposed deep and shallow aquifer models proposed to characterize potential containment migration.
- Final Peer Review for License Application; Conceptual Models, WIPP, 1996-1997.

Data and Models

- As project operations manager, principal hydrologist and corporate QA manager, I routinely review the raw data and data presented in environmental sampling reports. Included in the reviews are 'cursory' data validation (traceability, achieving QA goals, etc.) as well as how the data can be interpreted, statistically or otherwise.
- Compliance Certification Model Data Review and Certification WIPP, 1995-1996.
- The data reviews and QA reviews routinely lead to conceptual models of contaminant migration route; rate and the conceptual models are used to propose more extensive and/or confirmatory sampling and data collection.
- As applied science manager working on the Rocky Mountain Arsenal and CERCLA projects manager for EPA's TESIV, project data review (QA and statistical) and interpretation of data for intended uses were routine activities. Krieging and other techniques were applied to interpret data spatially, illustrate

data gaps and needs and make decisions on the appropriateness of RFI and RIFS data for proceeding with remedial action.

Appendix B

Determinations of Peer Review Member Independence

Appendix C

Certifications Regarding Organizational Conflicts of Interest

I have reviewed each of the selected peer review panel member's (Florie Caporuscio, John Gibbons, and Eric Oswald) backgrounds and employment histories. I have also interviewed each of them to determine if they have an organizational conflict of interest or a bias for or against the WIPP facility as a nuclear waste repository. Though these background investigations and interviews I have determined that none of the selected peer review panel members has an organizational conflict of interest related to the Salado Flow Conceptual Models Peer Review.

_____

John A. Thies,
Peer Review Manager

WASTE ISOLATION PILOT PLANT

SALADO FLOW CONCEPTUAL MODELS FINAL PEER REVIEW REPORT

A Peer Review

Conducted By

Florie Caporuscio, Ph.D.

John Gibbons, Ph.D.

Chunhong Li, Ph.D.

Eric Oswald, Ph.D.

for the

U.S. Department of Energy

Carlsbad Area Office

Office of Regulatory Compliance

March 2003

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Executive Summary

The Waste Isolation Pilot Plant (WIPP) site has been developed near Carlsbad, New Mexico, by the Department of Energy (DOE) as the United States' first underground repository licensed to safely and permanently dispose of transuranic radioactive waste resulting from the research and production of nuclear weapons programs. The first shipment of transuranic waste arrived at WIPP on April 6, 1999.

Peer review of conceptual models developed by the DOE for the WIPP is required by 40 CFR Part 194.27, which was promulgated by the Environmental Protection Agency (EPA) in 1996. In accordance with this requirement, the Carlsbad Field Office (CBFO) of the DOE has conducted a peer review of three conceptual models that are being revised due to changes invoked by the regulator or due to knowledge gained since the original conceptual models were developed. This peer review addressed revisions to selected salado flow conceptual models that were developed for the Compliance Certification Application (CCA).

This report presents the final results of an independent technical peer review of the adequacy of three of the twenty-four conceptual models representing features, processes, and events involved in assessing the long-term performance of the WIPP. These models were identified by the DOE through its scientific advisor, Sandia National Laboratories (SNL).

This independent peer review was conducted by a four-member interdisciplinary team having the requisite broad experience and expertise to address the range of issues associated with the ability of WIPP to successfully isolate waste for the 10,000-year regulatory time frame. The peer review was conducted primarily in Carlsbad, New Mexico, at the SNL Carlsbad offices. The peer review panel was given access to conceptual model descriptions, scientific reports, briefings, SNL staff, and to the SNL Nuclear Waste Management Program Library. The Panel also had access to reports of prior peer reviews and was given the full cooperation of the DOE and SNL throughout

the review. Representatives of the EPA, DOE, and the New Mexico Environmental Evaluation Group (EEG) observed the SNL technical presentations and the Panel's questions and deliberations.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical processes, or intrusion scenarios are to be represented in performance assessment (PA). To be used in PA, a conceptual model must be successfully translated into analytical statements and mathematical analogs. The Panel reviewed the three conceptual models of interest in detail, including the assumptions and scientific information used to develop the model, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The Panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall WIPP PA. The review process and review criteria are discussed in Section 2.

The changed models were reviewed in the context of the WIPP PA. The review did include an assessment of the reasonableness of changes in performance estimates resulting from changes in parameter ranges and in changes to, or resulting from, single values. The review evaluated changes in the conceptual structure of the models and changes in component process models and compared the performance results of the changed models with the results of the earlier models to confirm that the changes in performance estimates are reasonable in sense and magnitude. Changes in computations or in fundamental model aspects, such as gridding were also considered. The review considered the impacts of the changed models on the other WIPP conceptual models and related issues such as the Option "D" panel closures.

The Panel has applied the stringent assessment criteria provided in NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories*, and has concluded:

- The changes to the three conceptual models appear generally sound in their structure, reasonableness, and relationship to the original models.

- The proposed implementation of the three changed models appears reasonable. Impacts of the changes have been reviewed and the data from selected gas pressure and brine saturation scenarios in performance assessment indicates an acceptable comparison of new results to the prior CCA results.

- Implementation of the three changed models and their interactions with the other models appears reasonable.

1.0 Introduction

Peer review of conceptual models developed by the Department of Energy (DOE) for the Waste Isolation Pilot Plant (WIPP) is required by 40 CFR Part 194.27, which was promulgated by the Environmental Protection Agency (EPA) in 1996. In accordance with this criterion, the Carlsbad Field Office (CBFO) of the DOE has conducted a peer review of three conceptual models that are being revised due to changes invoked by the regulator or due to knowledge gained since the original conceptual models were developed. This peer review has addressed whether revisions to selected salado flow conceptual models that were developed for the Compliance Certification Application (CCA) continue to reasonably represent the WIPP waste disposal system.

Sandia National Laboratories (SNL) is responsible for the development, maintenance, and conduct of WIPP performance assessment (PA). As part of the PA methodology included in the CCA, the DOE identified processes important to the WIPP waste isolation system and developed conceptual models that describe the features, events, and processes relevant to the disposal system and subsystems. These conceptual models were peer reviewed and the results were approved by the EPA during the original WIPP certification (EPA, 1998). Any proposed significant changes to the previously approved conceptual models are being peer reviewed to ensure that the disposal system, subsystems, and future state assumptions continue to be adequately represented.

Twenty-four conceptual models are used in the WIPP PA. The proposed changes associated with Salado flow processes are expected to affect the following models:

- Disposal System Geometry,
- Repository Fluid Flow, and
- Disturbed Rock Zone (DRZ).

The peer review process is a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. The peer reviewers are independent of the work being reviewed, i.e., the peer reviewers: a) have not been involved as participants, supervisors, technical reviewers, or advisors

involved with the work being reviewed, and b) to the extent practical, have sufficient freedom from funding considerations to ensure the work is impartially reviewed. Therefore, the peer-reviewed subject matter provides additional assurance to the regulator and the public that the subject matter is reasonable, accurate, and valid for its intended use.

This peer review meets the regulatory requirements of 40 CFR Part 191 and the implementation of those requirements by 40 CFR Part 194. This peer review was conducted in accordance with the Nuclear Regulatory Commission's NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories*. The adequacy criteria set forth in NUREG-1297 were those used by the peer review panel for reviewing the three conceptual models. The Peer Review Panel followed the DOE CBFO Management Procedure MP-10.5, *Peer Review*, to perform the peer review.

This report documents the results of the subject peer review. Section 2 of this report details background information relating to the WIPP facility and the review methodology which includes a description of the repository, its geologic and hydrogeologic settings, the review methodology, and the evaluation criteria. Section 3 presents an evaluation of each of the three models. Each model was assessed against the predetermined evaluation criteria. Section 4 discusses the integration of the peer reviewed models with the other models used in the overall WIPP waste disposal system PA. Section 5 provides a summary of the evaluations. These sections are followed by appendices that include administrative information and professional biographies for each of the peer review panel members.

2.0 Background

The DOE was authorized in 1979 (Public Law 96-164) and funded by the Congress to develop a facility for demonstrating the safe disposal of transuranic (TRU) radioactive wastes resulting from national defense activities. The Land Withdrawal Act of 1992 (Public Law 102-579) provided additional authorization to continue the project under a stipulated statutory process. With more than 20 years of scientific investigation, public input, and regulatory oversight, the WIPP facility became the first underground repository licensed to safely and permanently dispose of transuranic radioactive waste from the research and production of nuclear weapons. The first shipment of transuranic waste arrived at WIPP on April 6, 1999.

2.1 WIPP Overview

The WIPP facility has been constructed in southeastern New Mexico 26 miles east of Carlsbad, on land owned by the Federal Government. Prior to October 1992, this land was administered by the U.S. Department of the Interior, Bureau of Land Management. In October 1992, Congress transferred jurisdiction of the land through the Land Withdrawal Act to the Secretary of Energy. The site encompasses 10,240 acres in a sparsely populated area, with fewer than 30 people living within 10 miles of the WIPP site. The immediate surrounding land is used for livestock grazing, potash mining, and oil and gas production.

Surface structures and the underground repository make up the WIPP facility. The purpose of the surface structures is to provide security and safeguards and to accommodate routine operations, administrative activities, and support further scientific studies.

The underground excavation is 655 meters (2150 feet) below the surface in the bedded salt of the Salado Formation. The underground excavation includes a 12-acre area used for conducting scientific investigations and experiments in which no waste will be placed, an operations area with equipment and maintenance facilities; an area in which

the waste is emplaced for permanent disposal; and four major interconnecting tunnels that are used for ventilation and traffic. The subsurface waste-disposal area is planned to cover approximately 100 acres and will contain eight separately excavated panels, each containing seven disposal rooms, and two equivalent panels.

2.2 Peer Review Management

This Salado Flow Conceptual Models Peer Review is an independent review sponsored by the DOE CBFO and delegated to its technical assistance contractor, known as the Carlsbad Technical Assistance Contractor (CTAC). The CTAC appointed Mr. John Thies as the peer review manager.

Early in the peer review process Mr. Thies appointed a technical panel chairperson, John Gibbons, Ph.D., from among the peer review panel members to serve as the technical leader for the peer review and to lead technical development of the peer review report.

The selection and training of the peer review panel members and operation of the review process were governed by DOE CBFO's Management Procedure MP-10.5, *Peer Review*, and the salado flow conceptual models peer review plan. Detailed information regarding the review process is further delineated in this document and in the peer review records.

Twenty-four conceptual models are used in the WIPP PA. This peer review addressed only the proposed changes associated with salado flow processes expected to affect the following three models:

- Disposal System Geometry,
- Repository Fluid Flow, and
- Disturbed Rock Zone (DRZ).

2.3 System Overview

The WIPP disposal system includes the underground repository and shaft system, the geologic host rock, and the local and regional hydrologic system. Figure 2-1 shows the WIPP controlled area, the accessible environment, and the disposal unit boundary.

Figure 2-1 - WIPP Controlled Area

2.3.1 Repository Setting

The WIPP surface facilities, shafts, and underground workings are shown in Figure 2-2. The WIPP repository includes four shafts (exhaust shaft, waste shaft, salt handling shaft, and air intake shaft), an experimental area, an operations area, and a waste disposal area.

Figure 2-2 - WIPP Facilities

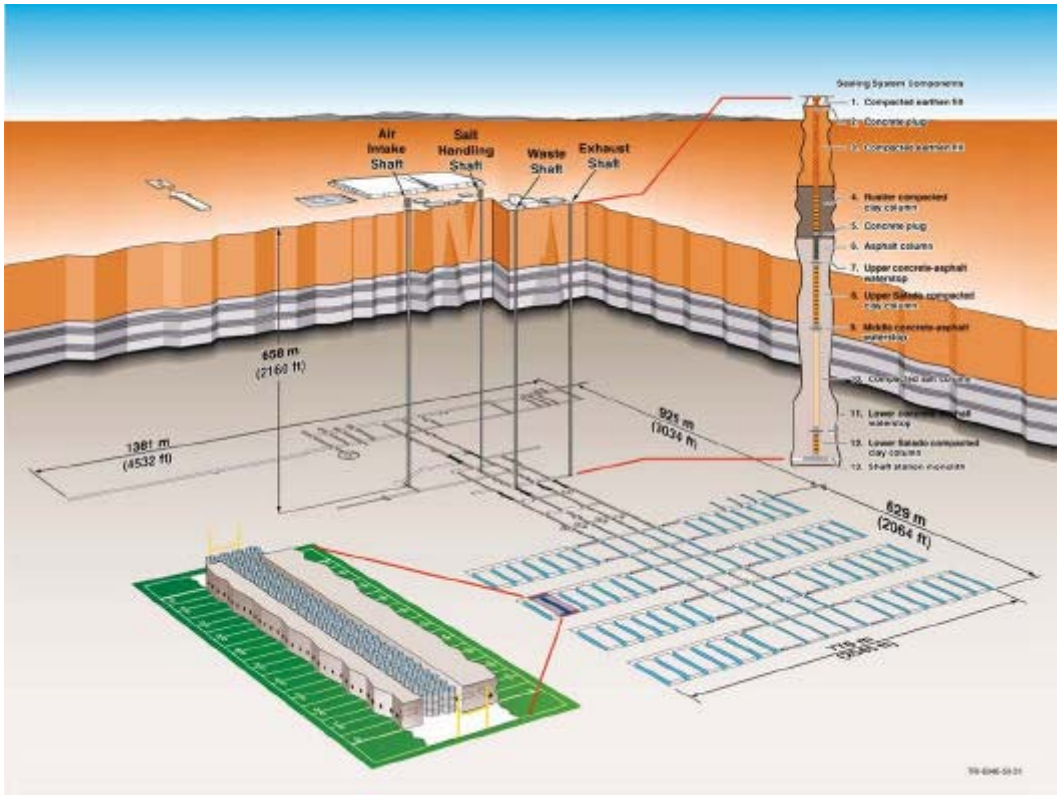

Present plans call for mining eight panels of seven rooms each and two equivalent panels in the central drifts. As each panel is filled with waste, the next panel will be mined. Before the repository is closed permanently, each panel will be closed. Waste will be placed in the drifts between the panels creating two additional panel volumes and access ways will be sealed off from the shafts. The shafts will then be sealed to isolate the repository from the ground surface. Final closure of the facility will be facilitated by creep closure of the salt.

When considering future intrusion scenarios, the DOE used the following EPA assumptions regarding future penetration of the repository:

- The regulatory time frame begins at the beginning of disposal and ends 10,000 years after disposal;
- Exploratory drilling may potentially affect the repository;
- Exploratory drilling is inadvertent and intermittent;
- Drilling events occur at random intervals; and
- Future drilling rates will be the same as the rates of deep drilling in the area over the past 100 years.

2.3.2 Geologic Setting

The geologic history of southeastern New Mexico and the data collected regarding the subsurface stratigraphy at the WIPP site are important and are discussed extensively in Section 2 of the CCA and documents referenced in the CCA. The general stratigraphy at the WIPP site is presented in Figure 2-3.

The sandstones, siltstones, limestones, and shales of the Bell Canyon Formation define the first extensive, continuous, transmissive unit below the WIPP repository and provide a source of groundwater that could migrate vertically into the repository. The halite and anhydrite beds of the Castile Formation separate the Bell Canyon from the Salado and contain pressurized brine reservoirs. The brine reservoirs are a repository performance concern expressed through human intrusion scenarios. The halite-dominated Salado Formation contains the proposed repository and provides the primary natural barrier for containing radionuclides. The laterally extensive Culebra Dolomite Member of the Rustler Formation is the closest stratigraphic unit above the Salado with the potential to transport a radionuclide release to the accessible environment. Studies conclude that transmissivities in the Culebra vary by six orders of magnitude across the WIPP site area. Fracturing and vuggy zones account for much of the variability in the physical hydraulic properties of the Culebra.

Figure 2-3 - *General Stratigraphy at the WIPP Site*

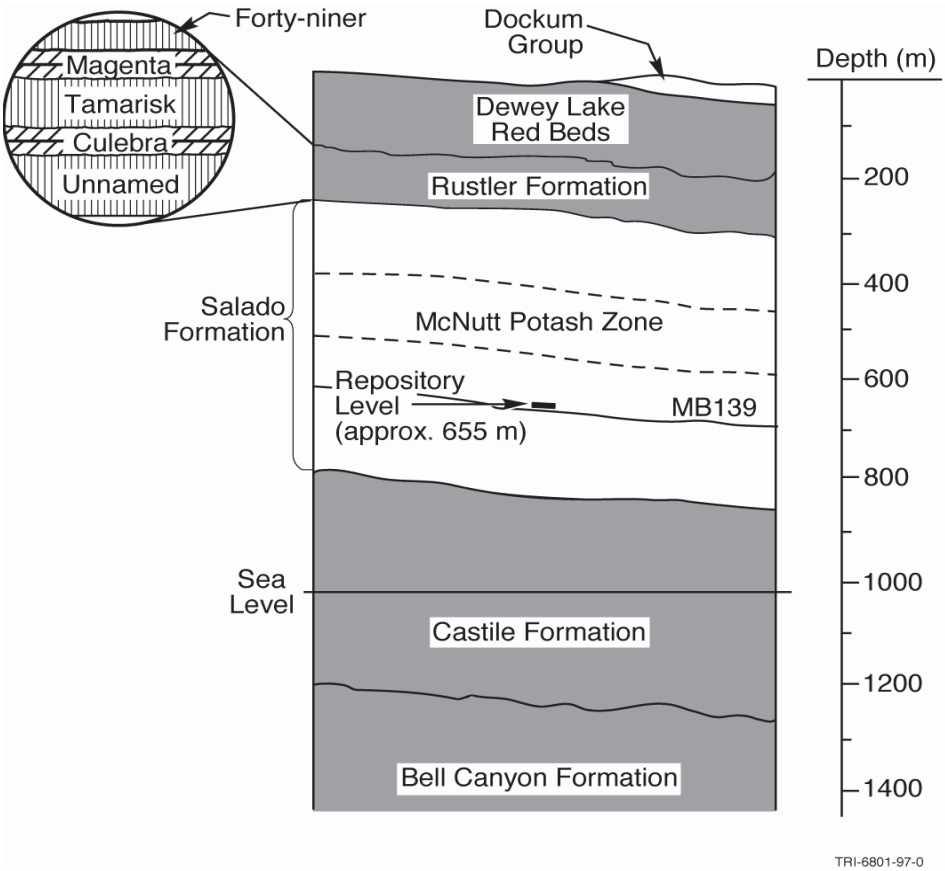

While other stratigraphic members of the Rustler Formation, beds of anhydrite and polyhalite, clays, and other inclusions may be important as each of the conceptual models is reviewed, the four formations and units described above define the most important components of the geologic setting for the WIPP conceptual models review.

2.3.3 Hydrologic Setting

2.3.3.1 Surface Water

The WIPP site is located within the Pecos River Basin. At its nearest point, the Pecos River flows approximately 12 miles southwest of the WIPP site boundary. There are no perennial streams at the WIPP site and in this semi-arid region, approximately 75 percent of annual precipitation results from intense, short-duration events between April and

September. More than 90 percent of the mean annual precipitation is lost through evapotranspiration and on a mean annual basis, evapotranspiration potential exceeds expected rainfall. The EPA concluded in 1989 that there were "no surface water features near the WIPP that could potentially affect repository performance in such a way as to influence the no-migration demonstration."

2.3.3.2 Groundwater

Extensive coring, logging and testing of boreholes in the vicinity of the WIPP site has provided data for the characterization of the hydrostratigraphy important to the WIPP site region. While the deep Capitan Limestone, the Rustler-Salado contact zone near Nash Draw, and the shallower Dewey Lakes and Santa Rosa Formations are important in characterizing the WIPP region; the Bell Canyon, Castile, Salado, and Rustler Formations are the units critical to the evaluation of WIPP groundwater issues.

As presented in the geologic setting, the Bell Canyon Formation is the first continuous, transmissive water-bearing unit beneath the WIPP. This formation provides a source of non-potable ground water below the WIPP repository that could migrate into the repository if a pathway were available. The Bell Canyon Formation exhibits hydraulic conductivities in the range of 10^{-7} to 10^{-12} meters per second and pressures were measured in the range of 12.6 to 13.3 megapascals.

The Castile Formation is of interest to site characterization as a hydrologic barrier between the Salado and Bell Canyon Formations because it contains isolated pressurized brine reservoirs. The Castile is predominantly low-permeability halite and anhydrite with greater permeabilities in zones of fracture and structural deformation. In the areas of higher permeability brine pressures may exist that are sufficiently above nominal hydrostatic pressure for brine to flow upward through a borehole potentially reaching the surface.

The halite and anhydrite rocks of the Salado Formation are relatively impermeable and tests have shown that flows are extremely low to no flow when appreciable pressure

gradients are applied. The Salado contains the repository and provides the primary natural barrier for containing radionuclides.

The Magenta and Culebra Dolomite Members of the Rustler Formation are laterally extensive, transmissive, and display hydraulic characteristics sufficient for the lateral transport of radionuclides. Hydraulic conductivities in both members range over five to six orders of magnitude in the WIPP area but the Magenta is generally less transmissive than the Culebra. The Culebra is the most extensive and most transmissive unit above the Salado at the WIPP site. As such, the Culebra provides the most direct groundwater pathway from the WIPP repository to the accessible environment and is the most important component of the hydrogeologic setting for the conceptual models peer review.

2.3.4 Implementation of the "Option D" Panel Closure

The option "D" panel closure is a semispherical concrete closure to be emplaced in drifts and panel exits at several positions throughout the repository. The closure will be emplaced in an enlargement of the drift that will remove some material above the drift and all of the halite and the Interbed #139 below the drift floor. It is presumed that the closure will extend into the ribs of the drift a distance sufficient to remove most of the DRZ in that direction. Back-stress resulting from creep flow in the Salado halite into the repository will immediately begin to heal damage around the closure that may result from construction excavation. It is not expected that the closure will entirely block gas flow in Interbed #139 or the overlaying interbeds, since flow around the closure is not prevented at high gas pressures. Upward gas flow from Interbed #139 into the drift beyond the closure is a possible scenario for bypassing the closure. Rapid gas pressure fluctuations, as in the case of an intrusion into a single panel at a time of high overall repository gas pressures, would be significantly damped in adjacent unintruded repository spaces, but not entirely eliminated by the closure over long time periods. The integrated impacts of the changed DRZ conceptual model and the role of the closure in modeling gas pressure in the waste panels before and during equilibration after intrusion are important interactions with the Repository Fluid Flow conceptual model.

Reduction in the volume of gas available during blowout (a single panel isolated by closures) resulting from intrusion may impact the spalling model. Closures between panels imply that a first intrusion may not lower pressure throughout the repository, which may result in several intrusions in several panels having increased potential for spall events. A drop in gas pressure after intrusion into a panel may accelerate brine flow toward the intruded panel. If a panel closure is left unsupported in an open drift, shear and extension stresses related to the creep closure of the spaces on either side of the panel closure may impact the mechanical stability of the panel closure.

2.4 Peer Review Panel Methodology

Review of the conceptual models commenced after panel member orientation and training in accordance with MP 10.5, the Peer Review Plan, and other relevant information presented in the orientation and training package.

The peer review panel employed the following approaches in their overall method of conducting and accumulating information for the reviews:

- Extensive review of referenced literature relevant to the review;
- Attendance at briefings on conceptual models and relevant aspects of the PA process;
- Issue focused presentations with question-and-answer sessions with SNL scientists and engineers;
- Review of literature and documents referenced during the question-and-answer sessions; and
- Formal and informal discussions among the Panel members.

The Panel was provided several presentations addressing the three conceptual models being reviewed with respect to whether or not they represent a reasonable view of future states of the proposed disposal system for the WIPP repository. For this review, conceptual models are defined as a set of qualitative assumptions used to describe a system or subsystem for a specific purpose. The Panel evaluated the models in

accordance with the NUREG-1297 criteria. In addition, the Panel recognized that individual models may warrant varying levels of reviews of their mathematical representations, computerized representations, and results. Due to the volume and diversity of information to be reviewed, individual Panel members were assigned lead responsibility for specific conceptual model reviews. Dr. Gibbons made the following assignments. Dr. Oswald was assigned responsibility for review of the Disposal Room Geometry conceptual model; Dr. Caporuscio was assigned responsibility for review of the Repository Fluid Flow conceptual model; Dr. Chunhong Li was assigned responsibility for review of overall mathematical representations and modeling; and Dr. Gibbons took responsibility for review of the Disturbed Rock Zone conceptual model. The information gathered by individual members during their reviews was freely disseminated among all of the Panel members.

In organizing its work, the Panel established limitations on its review and the content of this report. The Panel members did not review or offer comments on regulations. The Panel confined its review to the three conceptual models identified in the Peer Review Plan. To maintain independence, the Panel did not offer recommendations for specific methods and/or approaches to be employed in future work.

2.5 Criteria for Conceptual Model Review

The nine criteria used by the peer review members are based on the criteria in EPA regulation 40 CFR Part 194.27, NUREG-1297, the EPA Compliance Application Guidance, and Peer Panel discussions.

Information Used to Review Changes in Conceptual Model. This is an evaluation of data and information used to review the changes in the conceptual models and sub-models. It includes attributes of the disposal system learned by SNL during site characterization activities, exercising the models, and a review of the science and concepts that the models are based upon. It also includes information gained during the operation of the repository.

Validity of Assumptions. The validity of key assumptions in the model and its application are assessed in terms of how they could affect the usefulness of the conceptual model. The review addresses the comprehensive inclusion of important features, events, processes, and other key assumptions. Examples are the assumption of Darcy flow in the various media, use of the ideal gas law at high pressures, and the mathematical method chosen to develop the model grid.

Alternative Interpretations. This section briefly identifies and assesses plausible alternative conceptual models or sub-models considered by SNL but not used, and the rationale why such alternative models were not used. The panel assessed alternative interpretations in some instances by evaluating elements of the CCA and the PAVT as alternatives.

Uncertainty of Results and Consequences if Wrong. This includes an evaluation of the key uncertainties in the selected conceptual models and the discussion of the consequences if aspects of the conceptual model chosen were inappropriate or incompletely constrained for the site or process. This is not an exhaustive evaluation, but it does raise the question, "What if the model is wrong?"

Appropriateness and Limitations of Method and Procedures. Based primarily on the previous four criteria, this is a simple statement of whether the individual conceptual models, process models, and sub-models represent a reasonable approximation of the actual disposal system elements.

Adequacy of Application. This is an assessment of whether it appears that the individual conceptual model is being adequately applied into an acceptable overall performance assessment system. This particular assessment does not cover the relationships among conceptual models, but rather whether the significant components of the individual conceptual models are appropriately implemented in support of performance assessment. For example, are the various geometrical systems and representations of the conceptual models adequately applied within the performance modeling system, or do there appear

to be discontinuities between the conceptual model and its application? Also, are there alterations of important key assumptions between the conceptual model and its implementation in performance modeling?

Accuracy of Calculations. This is a statement of whether the results of performance modeling using the conceptual model within the performance system are reliable and accurate to adequately simulate the physical and chemical processes represented. Internal consistency among the several iterations of the PA was carefully considered.

Validity of Conclusions. This is a judgment of the validity of any key conclusions that have been drawn based on results of the implementation of the conceptual models in the modeling framework. The key question is whether or not conclusions from model implementations appropriately relate to the expected goal of assessing the long-term performance of the disposal system. This judgment requires an evaluation of output information from the total system PA.

Adequacy for Implementation. This is an overall assessment of whether the conceptual models as implemented in the PA represent a reasonable approximation of the actual disposal system.

2.6 Adequacy

The three conceptual models reviewed were deemed adequate because the changes to the models are sound in their structure, reasonableness, and relationship to the original models. The proposed implementation of the models appears reasonable based on review of selected gas pressure and brine saturation scenarios in performance assessment. Review of the CCDFs for direct brine release and spallings releases which are sensitive to repository pressure and brine volume indicates an acceptable comparison of new results to the prior CCA results. Based on their review, the Panel has judged that the three conceptual models represent a reasonable approximation of the actual WIPP disposal system performance.

3.0 Model Evaluations

This section presents the results of the Panel's review of the three individual conceptual models. Each of these models is first described and then evaluated for adequacy in accordance with the criteria summarized in Section 2.5. Following each evaluation, space has been provided for dissenting views. There were no dissenting views by any Panel member resulting from this peer review. An evaluation of the integration of these conceptual models into the WIPP PA is provided in Section 4.

3.1 Disposal System Geometry

3.1.1 Model Description

3.1.1.1 Background

Consistent with the purposes for which the conceptual models were originally developed for the WIPP PA, the Disposal System Geometry conceptual model was developed to represent the dimensionality of the engineered system and the surrounding geologic and hydrogeologic formations. The features that rely on the geometric assumptions and parameters of dimensionality for representation are expressed across the overall performance assessment system through a finite difference model called BRAGFLO. The flow fields generated by BRAGFLO, based on the geometric representations and the finite difference calculations, are communicated with the NUTS code that determines the transport of actinides through the anhydrite interbeds and boreholes. The geometry assumed for any model contains important information about the way in which physical processes are thought to act on the system. For WIPP, the model geometry assumed for the disposal system can only be understood in the context of the important processes considered to take place in a particular region during a specific time interval and for a defined purpose.

3.1.1.2 Description

This peer review focused on the changes in a specific group of conceptual models associated with the Technical Baseline Migration (TBM). Changes were evaluated to determine whether or not the models continue to reasonably represent the relevant features, processes, and future states of the disposal system. Changes to the disposal system geometry conceptual model evaluated were: 1) The removal of the baseline shaft seal system model and replacement with a simplified model, 2) Implementation of Option "D" panel closure design, 3) Dividing the remainder of the repository into two blocks separated by a panel closure, 4) Applying a new method by which flaring is calculated, 5) Refinement of the grid geometry, and 6) Changing part of the repository horizon vertically approximately 2.4 meters to Clay Seam "G".

The final certification decision (40 CFR Part 194) requires the implementation of Option "D" panel closure system. The system, characterized by a concrete monolith and an explosion wall, led to the proposed change in grid geometry since the existing grid block discretization was perceived to be too coarse for the representation of the specifics of Option "D" and the interrelated impacts on the DRZ. In general, where flow has been shown to be important, changes to the grid are proposed to add detail. The proposed grid refinement provides for greater segmentation and allows the detail of Option "D" components to be captured. The changes in the grid increased both vertical and horizontal refinement with the number of grid cells representing the repository increasing from 51 in the CCA to 69 in the TBM. The total number of grid cells increased from 33 to 68 in the x-dimension and 31 to 33 in the y-dimension. The x-dimension changes in the grid required the recalculation of radial flaring. It is understood by previous peer review panels, and this panel as well, that while flow may not be truly radial, the two-dimensional flared grid is reasonable for estimating releases. The CCA grid had several scales of flaring with each calculation including a series of complicated cell wrapping procedures that are difficult to reproduce and use for characterizing changes. The TBM changes include a new flaring algorithm that uses simplified repository geometry, results in flaring representations that closely approximate those in the CCA grid, and allows for changes to be "more easily" made in the x-dimension.

Changes in the BRAGFLO model considered in this peer review, with respect to the Disposal System Geometry conceptual model, include grid spacing changes, removal of the baseline shaft seal system model and replacement with a simplified model. The peer review panel understands that implementation of the Option "D" panel closure was the stimulus for changing the grid and modification of the shaft seal system was a separate decision represented in the BRAGFLO grid.

3.1.2 Review of Criteria

3.1.2.1 Information Used to Review Changes in Conceptual Model

The 1996 peer review of the Disposal System Geometry conceptual model included review of the screening logic, numerous SNL reports, and many technical presentations and discussion sessions. As stated in the report, (July 1996) the information and background references reviewed at that time were for specific inputs and applications, i.e., a comprehensive list of references addressing the "conceptual modeling" of the Disposal System Geometry was not compiled. Information concerning the effects of detailed stratigraphy and stratigraphic dip on brine and gas flow, and uncertainty and parameter sensitivity analyses for gas and brine migration, is presented in Webb and Larson (1996), WIPP (1992a & 1992b), and Christian-Frear (1996). Other reports (WIPP 1993, Rechard 1990, and Marietta 1989) explain the WIPP PA aspects of characterizing the disposal system geometry, and features, events, and processes (FEPs) screening documents present modeling alternatives. Various sections of the CCA (DOE 1996) summarize disposal system, repository, and intrusion event geometries. The Disposal System Geometry conceptual model, as reviewed in 1996 and as addressed in this peer review, is the result of integrating other models that describe the physical and chemical conditions and processes that are expected in the repository to produce a characterization of the repository and the surrounding strata. The references include the various background, technical descriptions, and presentation materials used in conducting the evaluation of the TBM changes in the Disposal System Geometry conceptual model. Previous conceptual model peer review reports, regulatory guidance, and other appropriate documents were provided to the peer review panel early in the process, as

required background reading. The key information sources addressing the TBM changes were the technical presentations, technical documents, and background materials provided by SNL supplemented by discussions with SNL scientists.

3.1.2.2 Validity of Assumptions

Along with the assumptions made for the TBM changes, it is important to briefly review the general assumptions made in the original peer review of the Disposal System Geometry conceptual model in 1996. The Disposal System Geometry conceptual model and its assumptions are so closely tied to the processes described by other models that not only is it important that the model have assumptions that are internally consistent, but the assumptions must be consistent with those of the models representing repository processes. Disposal system geometry processes are so closely tied to the processes that govern overall repository performance that it is difficult to conduct a review separate from the other models. Fluid flow and actinide transport are principal processes that rely on the geometric assumptions and these processes in turn have interrelationships with other process models. In 1996 the panel recognized the simplifications and assignment of high permeabilities for the sake of conservatism. Although, this panel's view is that it is always more credible to model the actual system, the assumptions supporting the simplifications remain valid.

Assumptions key to the original Disposal System Geometry conceptual model include: 1) the three-dimensional systems can be represented by two-dimensional simplifications, 2) the associations between and relationships across regions with varying material properties can be represented by the discretized grid blocks and by the finite difference method used in the computational model; 3) the four shafts can be represented by one shaft; 4) the entire repository can be represented by the simplified floor plan used in the computation model; 5) the intrusion borehole(s) represent the range of concerns associated with the intrusion scenarios; and 6) effects of flow in the DRZ and intact rocks outside of the repository are represented by the divergent grid to the north and south, away from the repository.

Assumptions key to the proposed TBM changes in the Disposal System Geometry conceptual model include: 1) The more refined grid spacing provides a more accurate representation of features, events, and processes but does not adversely impact the representation of sources, sinks, and pathways for radionuclide releases; 2) Flow in the shaft is negligible; 3) Removal of the baseline shaft seal system model and replacement with a simplified, two layer system conservatively represents the behavior of seal components in the repository system model and accurately represents shaft seal behavior as modeled in the baseline PA; 4) The new flaring algorithm adequately represents horizontal divergent and convergent flows to the north and south of the repository; 5) The TBM BRAGFLO grid adequately represents the Option "D" panel closure design, the DRZ, anhydrite fracture, repository fluid flow, and other components of the WIPP setting; 6) Moving the repository horizon vertically, approximately 2.4 meters, to Clay Seam "G" enhances operational safety and will not significantly impact the long-term performance of the facility in terms of lateral brine flow, creep closure, release pathways and available pore volume.

During the Salado Flow Peer Review, SNL presented assumptions and justifications for the material property representations proposed for use in the TBM. The panel concludes that the assumptions and justifications are defensible and appear to adequately represent the features and process of concern in the TBM changes. The panel also concludes that as a result of previous PA calculations, illustrating that only negligible flows are released up the shaft, removal of the "baseline shaft seal property details" and replacing them with a simplified, equivalent permeability system with fewer time intervals conservatively represents the behavior of seal components and is valid.

Changes in the Disposal System Geometry conceptual model are proposed to be implemented through the same discretized grid block and finite difference computational approach as was done for the CCA. The Panel judges that if key pathways and simplifications are retained, the overall conceptual model remains valid.

3.1.2.3 Alternative Interpretations

During the Salado Flow Peer Review, information presented and considered by the Panel did not include alternatives or options for changes in the Disposal System Geometry conceptual model. The final certification decision required the implementation of the Option "D" panel closure system and no other panel closure alternatives were considered by the peer review panel.

3.1.2.4 Uncertainty of Results and Consequences if Wrong

The key uncertainties associated with the TBM proposed changes to the Disposal System Geometry conceptual model are related to the material property descriptions and the grid simplifications made for the sake of conservatism, and the representativeness of the computational mesh. Even with the TBM changes the proposed BRAGFLO grid is not sufficiently detailed to describe all flow features and processes and the overall system relies on other conceptual models to reasonably describe such features and processes.

The panel concludes that there is little uncertainty associated with the basic geometric framework and finite difference method used to characterize the changes associated with the proposed TBM. The uncertainty that does exist is related to the grid block densities of the material property representations and the representativeness of the grid block densities and computational mesh. The material property changes appear justified and defensible.

The consequences of the proposed TBM changes in the Disposal System Geometry conceptual model, if they are wrong, can only be addressed in a qualitative way at this time. If the material property representations are wrong and or the computational mesh is not representative, the consequences depend on the relative magnitude of error(s) and the resulting changes in the total system PA.

3.1.2.5 Appropriateness and Limitations of Method and Procedures

The proposed TBM changes in the Disposal System Geometry conceptual model have been made without changing the fundamental geometric framework of discretized grid blocks and the finite difference method implemented through BRAGFLO. The methodology is considered by the panel to be appropriate for the TBM application. The panel concludes that the conceptual model continues to be an appropriate methodology to integrate and express the inputs from other conceptual models.

3.1.2.6 Adequacy of Application

The methodology employed in the Disposal System Geometry conceptual model is appropriate and adequate for application as a performance element. There are no apparent compatibility problems between the geometry and process-related models. Single vector BRAGFLO analyses that focused on saturation and pressure provided comparisons for the Performance Assessment Verification Test (PAVT), Technical Baseline Intermediate (TBI), and TBM. The TBI was intended to isolate Option "D" effects in the BRAGFLO grid. The single vector, time dependent comparisons produced results that were either expected or could be explained. Scatter-plots also provided comparisons that were understandable and where differences could be explained.

The adequacy of the changes in material properties and their representations in the grid can only be measured by how well overall processes are approximated. These approximations and representations, and changes from the baseline model have been evaluated through a PA for the TBM. The results of the PA indicate that total releases are nearly identical to the PAVT and direct releases are nearly identical or less that the PAVT. Based on these results, application of the changes, as modeled in the baseline, is deemed adequate.

3.1.2.7 Accuracy of Calculations

It was not within the scope of the Salado Flow Peer Review to evaluate BRAGFLO code changes. Descriptive write-ups and review of uncertainty and sensitivity analyses that compare the relationship between sampled inputs and dependent variables in the PAVT, TBI, and TBM provide no indications that the accuracy of the "baseline" model has been changed. The PA results for the TBM indicate that total releases are nearly identical to the PAVT and direct releases are nearly identical or less than the PAVT. Since the Disposal System Geometry conceptual model produces results using the material properties, processes, and codes from other models, and the TBM PA illustrates that repository performance continues to be represented as it was in the baseline, the relative accuracy of the Disposal System Geometry conceptual model has been demonstrated.

3.1.2.8 Validity of Conclusions

There are no specific conclusions drawn, with respect to the Disposal System Geometry conceptual model, other than its ability to characterize appropriate properties, processes and features. The conclusion derived from the PA is that the conceptual model continues to reasonably represent repository performance.

3.1.2.9 Adequacy for Implementation

The Disposal System Geometry conceptual model continues to provide an adequate framework for modeling the important processes and their interactions in the disposal system. The concept that the spatial effects of processes and interactions can be represented in two-dimensions is defensible. The simplification in the system representation and computational method to simulate the two dimensions are defensible and adequate for implementation. The basic grid framework for representing the material properties of the disposal system, adjacent DRZ, geologic formations, and intrusion scenarios is adequate. The proposed use of a finite difference method to connect the nodes and generate flow fields is also defensible and adequate for implementation.

The results of the PA for the TBM illustrate that the effects of changes to the baseline conceptual models, described in 3.1.1.2 and associated applications are minimal. The Disposal System Geometry conceptual model continues to be adequate for implementation.

3.1.2.10 Dissenting Views

There were no dissenting views for this model.

3.2 REPOSITORY FLUID FLOW

3.2.1 Model Description

The Repository Fluid Flow conceptual model is a highly complex description of interacting hydrologic, chemical, engineering design, geomechanical and human intrusion conceptual models whose simultaneous effects can be separately described, but require a PA to demonstrate the combined, integrated results. The physical conditions controlling fluid flow in the repository include brine and gas inflow and outflow rates, halite creep rates, and gas generation pressures from waste container corrosion and waste degradation. These physical conditions are contained in separately described conceptual models (Salado Interbeds, Creep Closure, and Gas Generation conceptual models respectively). The Repository Fluid Flow model accepts input from these related models and provides descriptions of pressures, flow rates, and flow directions for gas and brine within the disposal cells and other sections of the repository. A formal description of the coupled processes in the original conceptual model was presented in Freeze, et al. (1995).

Changes to the original conceptual model are as follows; 1) Brine inflow and outflow rates and gas pressures have potentially been altered by the introduction of the Option "D" panel closure mandated by the EPA, 2) The Disturbed Rock Zone (DRZ) properties have been altered by the allowance of fracturing both in the anhydrite beds and the salado halite and the "Flow Around" features near plugs at high pressure, 3) The salt creep rate may be affected due to changes in gas pressure, 4) Gas generation is calculated using a

different cellulosic molecular weight that provides approximately 10% greater gas production during microbial degradation, and 5) Flows will be simplified since the Disposal System Geometry conceptual model now has a simplified Shaft component.

3.2.2 Review of Criteria

3.2.2.1 Information Used to Develop Conceptual Model

The Repository Fluid Flow conceptual model relies heavily on Darcy flow in porous media, as revised for gas by taking into account the Klinkenberg effect, and for two-phase flow using a modified Brooks-Corey model that includes threshold pressures for gas entry into a brine saturated environment (Wilson, et al., 1996). Gas properties are given by the Redlich-Kwong-Soave equations of state, assuming that the gas behaves as pure hydrogen. The conceptual model addresses (1) fluid distribution in the waste, (2) long-term fluid (gas and liquid) flow to and from the Salado Formation, and (3) long-term fluid flow between the repository and the intrusion boreholes. Interactions with other conceptual models include the Disposal Room Geometry, Disturbed Rock Zone, Creep Closure, Gas Generation, Impure Halite, Salado, the Salado Interbeds, Castile and Brine Reservoirs, Exploration Boreholes, and Multiple Intrusions. In the original CCA, this model also was related to the Shafts and Shaft Seals model. However, the detailed Shafts and Shaft Seals model was replaced by a simplified Shaft Seals model incorporated into the Disposal Room Geometry conceptual model and flow out of the repository via the shafts is considered insignificant. Fluids will now be transported primarily up boreholes during disruptive events (S3 and S5).

The conceptual model for repository fluid flow is implemented for PA using the BRAGFLO code. The repository is represented in BRAGFLO in two dimensional vertical sections as a series of volumes, each with homogeneous isotropic material properties and behaviors, with each representing a major repository feature. The slight one degree ($1^?$) dip of the bedding to the south is represented by the model. The effective depth of each feature (the dimension normal to the plane of the model) is represented by

adjusting the cross sectional areas of the cells representing the feature. The effective depths of the model cells were varied to simulate the increasing hydraulic gradients that would occur in the repository and boreholes under radial flow conditions.

The original conceptual model was validated in the CCA and accepted by the Conceptual Models Peer Review in 1996. Since that time, a PAVT sensitivity study was performed. That PA included 60 parameter changes mandated by the EPA. Sensitivity analysis in the PAVT indicates that impact on the complete PA calculations were not substantial.

Since the PAVT, there have been minor changes to the fluid pathways in and around the repository. The model packages presented to the peer review panel were the Technical Baseline Migration (TBM) and the CRA (equivalent to AP-106). These changes are the result of modifications to other conceptual models and corrections of parameter values. The Shaft and Shaft Seal model has been removed from the overall performance assessment model in the TBM and replaced with a simplified Shaft Model incorporated into the Disposal Room Geometry. Modification of the Shaft and Shaft Seal model results in fluids being primarily channeled up the boreholes in the event of human intrusion by drilling in to the repository. Addition of a simplified Shaft Model into the Disposal Room Geometry conceptual model should result in no significant change in the PA.

There have been changes to the DRZ conceptual model in the TBM. Fluids would no longer transport from one panel to another via Marker Bed #138. Instead, fluids will now migrate along Marker Bed #139 below the floor of the panels. The fluids will not be able to circumvent the Option "D" panel closure by taking the path of least resistance in marker Bed #139. Because of permeability fluctuations related to gas pressure variation during the repository history, both gas and liquid phases may be impeded in their flow through the DRZ during certain BRAGFLO simulations. In the latest rendition of this conceptual model (CRA), fracturing of the Salado anhydrite beds is a primary storage and transport medium for outflow from the repository. This allows gases to now flow through Marker Bed #138, and liquids to flow preferentially through Marker Bed #139.

Furthermore, at high pressures, a “flow around” parameter has been implemented which would allow fluids to circumvent the Option “D” plug in the “z” dimension. This modification in the CRA now allows gas and liquid phases to be less impeded during some high pressure BRAGFLO simulations.

The Option “D” panel closure has been incorporated into the final closure plan and has multiple potential effects on fluid flow. Although the upper DRZ still exists it is not allowed to fracture for the TBM analysis except at very high pressures (~12 MPA). The lower DRZ is allowed to fracture for the TBM assisted by tensile stresses associated by floor heave making Marker Bed #139 the preferred pathway. Fluids will more slowly equilibrate throughout the repository after closure, which may result in changes in PA. Gas pressure in the experimental area will most likely be lower than in the PAVT, since there is no gas generation in that region and constrained communication with the waste panels. Brine saturation in the southernmost waste panels may be lower than in PAVT, since there is less brine communication between panels due to the characteristics of the Option “D” panel closure which will prevent down-dip flow of brine between repository openings. Brine saturation in the remainder of the repository will be the same as PAVT calculations because the process models for BRAGFLO have not changed. With the addition of the upper DRZ fracturing in the CRA, most of the Option “D” restrictions are less effective at high pressures. Once lithostatic pressure is realized, the anhydrite fractures can open and fluids migrate through both the upper and lower marker beds (#138 and #139, respectively). This will allow for lower maximum gas pressures and relatively increased brine flow in the waste panel. Pressure and saturation will also be affected by higher transmissivities.

The parameter value changes include the cellulosic molecular structure change and the EPA mandated parameter value changes (Table 3-1). The cellulosic chemical formula ($C_6H_{10}O_5$) provides approximately 10% greater gas production during microbial degradation. The new parameter value changes introduced by the EPA did not introduce significant changes from the CCA to the PAVT CCDFs.

3.2.2.2 Validity of Assumptions

On a larger scale, the original assumptions for the Repository Fluid Flow conceptual model were validated in the original performance assessment (CCA, 1996). The validity of the assumptions in the Repository Fluid Flow model depend in part on the other conceptual models (Disturbed Rock Zone and Disposal System Geometry) in so far as the assumptions in the other models are shown to be valid, those same assumptions will propagate through to the Repository Fluid Flow conceptual model. The BRAGFLO model was not significantly changed in its assumption base (creep closure, gas generation, pressure induced fracturing, use of characteristic curves such as Brooks-Corey and van Genuchten), rather, cell parameters have been improved and cell dimensions have been better adapted to critical features.

The assumptions addressed in the TBM are: 1) modification of the representation of the Shafts and Shaft Seals, 2) change in representation of cellulosic molecular structure, 3) changes in the DRZ conceptual model, 4) implementation of EPA mandated changes to parameters, and 5) implementation of the Option "D" panel closure.

The assumption that the modification of the Shafts and Shaft Seals system would affect the overall performance of the PA in a very minor way is reasonable. Maximum brine flow up the Shaft at the top of the DRZ was calculated to be approximately a total of 30 m^3. During borehole intrusions in the upcoming PA this fluid would be directed up the borehole and would still be insignificant. However, the EPA requested that a shaft be reintroduced. Therefore a simplified Shaft model was included in the Disposal System Geometry model. In lieu of the original 22 materials and six time intervals in the CCA, the simplified Shaft model has fewer materials, time intervals, and permeability values. With this simplified shaft most of the brine flow would still be directed up the intrusion boreholes

The larger molecular weight for cellulose is not an assumption, but rather a refinement of a parameter. The recalculation of the molecular weight and the slight increase in gas

generation potential (10%) will produce a slightly more conservative value for overall gas generation amounts in certain PA scenarios.

The two major assumptions for the Disturbed Rock Zone conceptual model (permeability and flow geometry) are reasonable in the TBM model. For the CRA the simplified shaft model is included, fracturing in the upper and lower DRZ is implemented, a high pressure "flow around" concept is extended to permit flow in all anhydrite and Salado beds, and a double concrete panel closure is included at the north end of the repository. These assumptions are reasonable for the CRA and present an acceptable approach to model how fluids would interact with the Option "D" panels.

The 60 parameter changes listed in Table 3-1 (Summary of CCA and PAVT Parameters) and Table 3-2. (Summary of TBM and CRA Values and Distributions) appear appropriate and reasonable. The most notable changes concern actinide solubilities in the fluid. In all cases the solubility values are lower than in the original CCA values. Such values would produce curves with lower values in the CCDF calculations, if all other factors remain unchanged. Most other changes involve taking a single parameter value and replacing it with a range of values that bracket the original. This is an appropriate and reasonable assumption, in that it focuses most new values near the original value, but allows the CCDF calculations a slightly wider variance.

Table 3-1. Summary of CCA and PAVT Parameters

Parameter	CCA Range and Distribution	PAVT Range and Distribution
Log of Borehole Sand Permeability	-14 to -11 log m^2 Uniform	-16.3 to -11 log m^2 Uniform
Log of Borehole Concrete Permeability	-16.3 log m^2 Constant	-19 to -17 log m^2 Uniform
Log of Disturbed Rock Zone Permeability	-15 log m^2 Constant	-19.4 to -12.5 log m^2 Uniform
Log of Waste Permeability	-12.769 log m^2 Constant	-12.6198 log m^2 Constant

PIC Reduction Factor for 100 – 700 years	0.01 Constant	1.0 Constant
Waste Shear Strength	0.05 to 10 Pa Uniform	0.05 to 77 Pa Log uniform
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Castile Brine	6.52×10^{-8} mol/l Constant	1.38×10^{-8} mol/l Constant
Coefficient, A, in Equation[(a)] for Solubility for Np+4, Pu(IV), Th (IV) and U (IV) in Castile Brine	6.0×10^{-9} mol/l Constant	4.1×10^{-8} mol/l Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (V) in Castile Brine	2.2×10^{-6} mol/l Constant	4.8×10^{-7} mol/l Constant
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu (III) in Salado Brine	5.82×10^{-7} mol/l Constant	1.2×10^{-7} mol/l Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (IV), Pu (IV), Th (IV) and U (IV) in Salado Brine	4.4×10^{-6} mol/l Constant	1.3×10^{-8} mol/l Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (V) in Salado Brine	2.3×10^{-6} mol/l Constant	2.4×10^{-7} mol/l Constant
Inundated Steel Corrosion Rate	0 to 1.59×10^{-14} m/s Uniform	0 to 3.17×10^{-14} m/s Uniform
K_d in Culebra Dolomite for Am(III) and Pu(III)	0.02 to 0.5 m^3/kg Uniform	0.009 to 0.4 m^3/kg Log uniform
K_d in Culebra Dolomite for Np (IV), Pu (IV), Th (IV), and U (IV)	0.9 to 20 m^3/kg Uniform	0.7 to 10 m^3/kg Log uniform
K_d in Culebra Dolomite for Np (V)	0.001 to 0.2 m^3/kg Uniform	0.001 to 0.2 m^3/kg Log uniform
K_d in Culebra Dolomite for U (VI)	0.00003 to 0.03 m^3/kg Uniform	0.00003 to 0.02 m^3/kg Log uniform
Probability of Hitting a Brine Pocket	0.08 Constant	0.01to 0.60 Uniform
Drill String Angular Velocity	7.7 radians/s Constant	4.2 to 23.0 radians/s cumulative distribution with mean of 7.77 radians/s
Castile Brine Pocket Rock Compressibility	Min: 5×10^{-12} Pa^{-1} Max: 1×10^{-8} Pa^{-1} Mode 1×10^{-10} Pa^{-1} Triangular	Min: 2×10^{-11} Pa^{-1} Max: 1×10^{-10} Pa^{-1}; Mode 4×10^{-11} Pa^{-1} Triangular
Castile Brine Pocket Porosity	Not used in CCA	Min: 0.1848; Max: 0.9240; Mode 0.3696

Brine Pocket Pore Volume	(3.2, 6.4, 9.6, 12.8, 16) x 10^4 m^3 Discrete	Calculated from Brine Pocket Porosity
Inventory Waste Unit Factor	4.07 Constant	3.44 Constant

[(a)]The equation for solubility is $A \cdot 10^b$ where b is a sampled value. Only the coefficient, A, was changed in the PAVT.

Table 3-2. Summary of TBM and CRA Values and Distributions

Parameter	Range	Distribution
Log of Borehole Sand Permeability	-16.3 to -11 log m^2	Uniform
Log of Borehole Concrete Permeability	-19 to -17 log m^2	Uniform
Log of Disturbed Rock Zone Permeability	-19.4 to -12.5 log m^2	Uniform
Log of Waste Permeability	-12.6198 log m^2	Constant
PIC Reduction Factor for 100 – 700 years	1.0	Constant
Waste Shear Strength	0.05 to 77 Pa	Log uniform
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Castile Brine	1.38 x 10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (IV), Pu (IV), Th (IV) and U (IV) in Castile Brine	4.1 x 10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (V) in Castile Brine	4.8 x 10^{-7} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Salado Brine	1.2 x 10^{-7} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (IV), Pu (IV), Th (IV) and U (IV) in Salado Brine	1.3 x 10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (V) in Salado Brine	2.4 x 10^{-7} mol/l	Constant
Inundated Steel Corrosion Rate	0 to 3.17x10^{-14} m/s	Uniform
K_d in Culebra Dolomite for Am (III) and Pu (III)	0.009 to 0.4 m^3/kg	Log uniform
K_d in Culebra Dolomite for Np (IV), Pu (IV), Th (IV), and U (IV)	0.7 to 10 m^3/kg	Loguniform

K_d in Culebra Dolomite for Np (V)	0.001 to 0.2 m^3/kg	Log uniform
K_d in Culebra Dolomite for U (VI)	0.00003 to 0.02 m^3/kg	Log uniform
Probability of Hitting a Brine Pocket	0.01 to 0.60	Uniform
Drill String Angular Velocity	4.2 to 23.0 radians/sec	Cumulative distribution based on range with mean value of 7.77 radians/s
Castile Brine Pocket Rock Compressibility	Min: $2x10^{-11}$ Pa^{-1} Max: $1x10^{-10}$ Pa^{-1} Mode $4x10^{-11}$ Pa^{-1}	Triangular
Castile Brine Pocket Porosity	Min: 0.1848; Max: 0.9240; Mode 0.3696	Triangular
Brine Pocket Pore Volume	Calculated from Brine Pocket Porosity	Not applicable
Inventory Waste Unit Factor	3.59	Constant

[(a)]The equation for solubility is $A \cdot 10^b$ where b is a sampled value. Only the coefficient, A, was changed in the PAVT.

Scatterplots using the CRA values compare well with those using the TBM assumptions for gas generation. At 1,000 years, waste panel pressures are only slightly elevated versus the TBM. For longer periods of time (10,000 years), the CRA pressures in the waste panel coincide with TBM values. This is most probably caused by gas migration once the upper DRZ opens at high pressure. CRA scatter-plots indicate that the rest of the repository brine saturation is equivalent to TBM values (and therefore are the same as PAVT values). A few of the waste panel saturation values are lower than corresponding TBM values and may be related to slight changes in DRZ parameters related to anhydrite fracture and the double panel seal. The review panel concludes that the proposed impacts of the Option "D" closure and DRZ changes are reasonable assumptions.

The Repository Fluid Flow conceptual model is expected to have negligible impact on the other conceptual models and the total system PA. Presentations by SNL indicate that borehole intrusion scenarios will not change from those in the CCA. Increased and decreased values for gas pressure and/or brine saturation impacts on fluid flow have been evaluated and the impact that the changes in fluid flow will have on the spallings and multiple intrusions scenarios and on the PA are acceptable.

3.2.2.3 Alternative Interpretations

The changes incorporated into the Repository Fluid Flow conceptual model are based on three earlier cases of the model. The earlier models represent alternative interpretations. The Repository Fluid Flow conceptual model in the CCA was fully peer reviewed and accepted. The second representation of the model was in the PAVT sensitivity study. The changes incorporated into the third rendition of the model were logical improvements based on modification of the shafts and shaft seals model and the incorporation of the Option "D" panel closure. Adjustments to include a simplified shaft model for the CRA were requested by the EPA. Upper DRZ fracturing and flow around features now mitigate early concerns with the Option "D" closure panels.

3.2.2.4 Uncertainty of Results and Consequences if Wrong

The uncertainty of results related to the changed Repository Fluid Flow model are primarily related the implementation of the Option "D" panel closure. The purpose of the panel closures is to impede flow around the closure between adjoining waste panels. The new Disturbed Rock Zone conceptual model implies that flow will occur in both Interbed #138 and #139 at high gas pressure, and in turn, this should allow gas and liquid in the waste panels to equilibrate over time. However, vector analyses of gas pressure and brine saturation in the TBM and CRA model show that flow occurs for a limited number of vectors when pressures become high enough to cause significant fracturing. When these factors (pressure and saturation) are allowed to interact with the other conceptual models and are evaluated as part of the full system PA, other outcomes may result. Direct release conceptual models (involving cuttings, cavings, spallings, and direct brine release) provide the most significant release pathways. Since there is evidence that the waste panels do not equilibrate quickly with the rest of the repository or with the experimental region, the Repository Fluid Flow conceptual model may impact direct releases when evaluated in the context of a full system PA. If a postulated intrusion intercepts a waste panel with a high gas pressure (at or above lithostatic pressures), and with high brine saturation, it could allow for slightly higher brine transport to the surface. Conversely, if panels with low gas pressure or low brine saturation were intercepted, then the direct

release could be much lower. Since the last review of this conceptual model specific waste panels and explicit scenarios for direct brine release have been evaluated and TBM CCDF curves presented. The curves suggest that those scenarios do not adversely impact the performance of the repository.

3.2.2.5 Appropriateness and Limitations of Method and Procedures

The methods and procedures used in the Repository Fluid Flow model are based on refinements of previous models and should provide representative results.

3.2.2.6 Adequacy of Application

The adequacy of application of the model to changes in flow in the repository requires that all new definitions, processes, and applications be clearly identified. Parameters have been identified and qualified by the EPA (Table 3-1) for the PAVT. Intrusion scenarios have been defined by SNL and do not differ from the CCA. BRAGFLO calculations are identical to those used in previous applications (CCA and PAVT) of the PA and comparison of the newly generated CCDFs to the PAVT reveal relatively insignificant changes in total releases. The application of the model using redefined flow paths ("flow around" and anhydrite fracturing) and parameters does not require basic changes in the conceptual model itself. The performance of the repository in the TBM and CRA, as viewed by the presented CCDFs, confirms the adequacy of the application of the Repository Fluid Flow conceptual model.

3.2.2.7 Accuracy of Calculations

Scatterplots and CCDFs presented by SNL illustrate the changes made to calculations since the PAVT in this conceptual model and how they impact the performance assessment. No changes have been made to BRAGFLO or the application of BRAGFLO to the process models. Scatterplots presented by SNL allowed observation of how the most important sub-models (gas pressure, brine saturation and volume) respond in the repository performance assessment and variations were logically explained by SNL

personnel. For the CRA, CCDFs were presented for the most pressure sensitive scenario (Spallings) and the most brine sensitive case (DBR). The results of both scenarios were plausible, and did not vary widely from PAVT curves. Importantly, these newly generated curves did not substantially approach the EPA compliance limit. It is concluded that the accuracy of calculations for Repository Fluid Flow conceptual model has been demonstrated.

3.2.2.8 Validity of Conclusions

The conceptual model as reviewed at the time of the CCA was deemed to provide valid conclusions. Present changes to the details of the fluid flow pathway (Anhydrite fracturing, flow around, and repository geometry parameters) are reasonable and appear to be valid. The changes implemented are in the applications of the model and how it relates to other conceptual models in the PA. BRAGFLO has not changed and the conceptual model itself is deemed adequate; the calculations are judged to be accurate; and it is concluded that the changes to the Repository Fluid flow model and how they represent flow in the repository are valid.

3.2.2.9 Adequacy for Implementation

Even though the CCDFs presented were only a partial assessment and not a total system PA, the probability of outliers that would result in non conformance is minimal. The production of Single CCDF curves that represent the most sensitive scenarios (Spallings and direct brine release) in the CRA, along with the full TBM CCDFs, were enough information to judge that the minor modifications made to the Repository Fluid Flow model are reasonable and justifiable. This model is deemed adequate for implementation.

3.2.2.10 Dissenting Views

There were no dissenting views for this model.

3.3 Disturbed Rock Zone

3.3.1 Model Description

The DRZ conceptual model, as originally conceptualized in the CCA, was composed of a layer of halite above and below the drift. This layer provided a flowpath between the drift and the marker beds. The halite that composed this layer was assigned an arbitrary permeability of 10^{-15} m^2, considered a conservative value that would permit gas to escape the repository via the fractured marker bed and allow gravity-driven drainage of brine from the marker bed into the repository ("DRZ rain"). The model was not strongly representative of repository processes; rather it was viewed as a conservative basis for modeling waste degradation and gas generation processes in the repository.

During the PAVT sensitivity study the EPA mandated a range of permeability for the DRZ halite layer which reasonably represents the properties of extensively creep-damaged halite and anhydrite at the high permeability end, and of minimally damaged halite at the low permeability end. This range is unequally distributed around the original single value used for the halite permeability. This range is retained in the changed conceptual model and was not previously peer reviewed. A principal change to the hydrologic processes contained in the model presently under review is the flow path through the repository floor, an average of one or two meters of halite, into Marker Bed #139 which is composed of about one meter of fractured anhydrite. This flow path represents a considerably more transmissive pathway for the exit of gas and brine from the pressurized repository, into the potential storage medium represented by the fractured anhydrite. The gravity inflow of brine through the halite layer above the repository back is still a factor in modeling brine inflow into the repository.

Gas will sometimes, depending on the level of free brine in the repository, flow out through pathways in the repository floor to Marker Bed #139, and , especially at times of high pressure will also flow out through the pathways around the tops of panel seals. This flow will in most cases go to marker beds above and below the repository connected to

the repository by fractures opened by floor heave and by stresses associated with room closure about the rigid panel seals into the void spaces on either side of the seals.

A further change in the potential flow paths out of the repository is represented by a design change applied to several waste panels at the southern end of the repository. The purpose of the design change is to enhance repository construction safety by raising the elevation of the drift to place the back of the excavation at a clay seam (G), mitigating what might have become a parting that could increase the risk of roof fall in those waste panels. This will raise the floor of the repository slightly higher (3.8 meters) above Marker Bed #139.Since the stresses and fracture caused by floor heave in repository drifts extend to considerable depth below the drift floor, and since the role of floor fracture is primarily to connect the repository to Marker Bed #139, this design change is not expected to have any significant impact on the repository floor flowpath.

3.3.2 Review of Criteria

3.3.2.1 Information Used to Review Changes in Conceptual Models

The CCA version of the DRZ conceptual model consisted of a 12 meter thick zone above the emplacement panels and drifts that were assigned an assumed permeability of 10^{-15} m^2 for the entire zone. This conceptual model had no basis in actual repository or site performance, but was rather a conservative representation of the damaged rock zone, conceived to permit brine and gas flow between the repository and the overlying Marker Bed #138. The PAVT sensitivity study that followed the CCA used a range of permeability values for the zone between the repository and Marker Bed #138 that were identified by the EPA. The EPA determined the lower bound of the range of permeability from measured gas permeability in anhydrite cores from Marker Bed #139 (Howarth, 1996, Beauheim, 1996, Howarth and Christian-Frear, 1997). The EPA concluded that a value of $10^{-19.4}$ m^2 is an appropriate lower bound for the range of likely values. Based on sensitivity tests, the EPA selected a value of $10^{-12.5}$ m^2 as the upper bound of the range of DRZ permeability. Documents held by the WIPP Project office pertaining to DRZ permeability support this range of the PAVT values (Beauheim, 1996). The more permeable limit represents halite and anhydrite heavily damaged by creep

strain. The less permeable end of the range assigned to the assumed disturbed zone above the repository is a value conceived to represent the permeability of halite that has been healed by stresses associated with repository creep closure and is supported by measured permeability values. This value ($10^{-19.4}$ m^2) is comparable to the permeability of halite that has been disturbed only by far field stresses caused by creep toward the repository opening beyond the disturbed rock zone (Beauheim, in press). This range of values is an acceptable bound of the permeability of the disturbed rock zone that includes both the Salado halite and the anhydrite of the marker beds.

The changes proposed to the DRZ conceptual model for the next total system PA modifies the geometry of flow associated with the DRZ but retains the range of permeability assumed for the DRZ under the PAVT sensitivity study. The changed conceptual model routes flow through the floor of the repository to Marker Bed #139 whose upper surface is about 4 meters below the drift floor in the raised repository region (south part) and 1 to 2 meters in the north part of the repository. This flow routing represents the path of least resistance for the flow of gas and brine out of the repository and provides a reasonable basis for estimation of gas pressures in the repository.

The potential for flow around the top and bottom of panel seals is a topic whose consideration is made necessary by the addition of the much more restrictive option "D" panel seals. In the case of the bottom footprint of the seal, the concrete monolith is seated at the bottom of Marker Bed #139. The top of the seal is seated against a freshly excavated inset into the halite of the repository roof. At repository pressures that exceed the hydraulic activation pressures of closed fractures in the areas around the seats of the seals, flow is likely around the seals (Figure 68 SNL presentation, Feb. 19, 2003) The cited figure shows flow around the bottom of a panel seal, however, flow around the top of such a seal would differ only in that the top of the seal would be seated in halite and that gas flow only would be predominant around the top of the seal at some times in the repository history. Brine flow would almost always be the dominant flow mode in the lower seat area. This set of flow paths has some potential to impact the pressure histories of the individual spaces in the repository and the model is applied to these consequences

of changes of repository design in a manner similar to that applied to the new scenario of flow through the repository floor.

The changes to the DRZ conceptual model include the assumptions supporting the range of permeability values and the change in the geometry of flow from the 12 meter overhead DRZ (CCA) to the 1 to 3.8 meter long flowpath, through the repository floor and into the fractured anhydrite of Marker Bed #139, and flow at high pressures around the tops and bottoms of panel seals into marker beds above and below the repository (AP 106).

3.3.2.2 Validity of Assumptions

Assumptions used in developing the proposed changes to the DRZ conceptual model are of two kinds. The values for the permeability of the DRZ have evolved over two iterations of PA. In the first PA (CCA, 1996) the permeability of the thick, overhead DRZ contained in that conceptual model was a "conservative" value assumed to permit communication between repository openings and the upper Marker Bed #138. The chosen value was assumed to permit free drainage of brine from the marker bed into the repository and to permit gas to escape from the repository to the marker bed. The permeability chosen was an intermediate single value between perceived extremes implied by the material properties of the marker bed and pure halite. For the PAVT sensitivity study a range of permeability was necessary to permit sampling and development of distributions to better represent flow through this complex zone. The end members of the distribution represent the measured permeability of the fractured anhydrite marker beds and the estimated permeability of "tight" halite. Pure halite, disturbed only by very small and slow strain resulting from creep into the repository beyond the DRZ, is probably a reasonable representation of well-healed halite after the disappearance of the DRZ due to back-stress around seals or after the closure of repository open spaces. As such, these end members are reasonable limits to the permeability of the DRZ. The permeability range used in the PAVT calculations ($10^{-12.5}$ m^2 to $10^{-19.4}$ m^2) represents reasonable parameters between the end member conditions.

Changes in the geometry of flow in the DRZ represent the second kind of assumption. The basis of this assumption is that gas flow out of the repository panels will follow the path of least resistance or the path of greatest transmissivity. The short distance (4 meters in the raised repository region (south part) and 1 to 2 meters in the north part of the repository) between the repository floor and Marker Bed #139 represents a much lower resistance to flow than upward flow through 10 meters (south part) to 12 meters (north part of the repository) of halite that is horizontally compressed by arching stresses over the repository openings. Floor heave implies an extensional stress environment in the floor. This extensional stress and gas pressures may also help to keep the fractures in both the halite in the repository floor and in the anhydrite marker bed open. The large storage space represented by the well connected fracture porosity of the marker bed may provide for retention of gas and brine expelled from the repository via this flowpath.

A further assumption is that at relatively high repository pressures (high enough to activate hydraulic flow through fractures around panel seals) that repository gasses (mostly) will flow out through marker beds above the repository. Flow through these pathways will help to regulate repository pressure at certain times during repository history, but the impact on the cycle of waste decomposition, gas generation, gas pressure, and brine inflow is not expected to be important. Flow around panel seals (both top and bottom) was included in modeling of repository pressure and saturation as shown by SNL in scatterplots for the TBM and AP 106.

The assumptions contained in the changes to the DRZ conceptual model are reasonable to represent repository materials, flow geometry, and system properties. The permeability range used to generate the sampled distributions that will be used in PA is based on permeability of materials similar to those in the disturbed rock zone in comparable geomechanical environments. The geometry of flow follows principles of hydraulics that are appropriate to the repository structure, stress environment, and material properties.

3.3.2.3 Alternate Interpretations

The proposed changes to the DRZ conceptual model follow two earlier iterations of the model. These earlier iterations include a full PA (CCA) and a sensitivity study (PAVT) that represent alternative models that have received more detailed consideration than is usual in alternative concept evaluation. The CCA iteration was fully peer reviewed. The changes proposed to the model represent reasonable development of the earlier alternatives. The changes to the model are supported in part by recent calculations, geophysical and hydrologic measurements in the repository floor (Bryan, et al, 2001, Beauheim, 2002, Holcomb, 2001).

3.3.2.4 Uncertainty of Results and Consequences if Wrong

The uncertainties of results in the changed conceptual model lie mostly in the ranges of permeability used to represent the flow properties of the rock along the flow paths proposed. The geometry of the flow paths is not a great source of uncertainty, in that they are the most reasonable paths of least resistance for gas flow and their dimensions and material properties are easily characterized. The range of permeability proposed as bounds of the properties of the rock through which flow will take place is reasonable. The range is supported by measured values and it will be sampled and represented by a CCDF, which is a reasonable analytical approach. Exceeding the upper limit of the permeability range would allow gas to migrate from the repository more easily and reduce gas pressure. Ultimately, gas pressures depend on permeability in the anhydrite marker bed where storage of gas will take place at distances from the repository far enough to be less damaged by creep. The impact of the uncertainty in the conceptual model is that the gas pressure in the repository might be slightly lower than predicted by modeling at some times in repository history.

3.3.2.5 Appropriateness and Limitations of Methodology and Procedures

The methods and procedures used in the changed model are refinements of the previous models and will generate representative results in PA. Constituative models based on

measurement of the influence of creep damage on hydrologic properties may be feasible in the future, but such models are not expected to indicate that the changed model has failed to conservatively bound repository performance. The methods and procedures are appropriate to the present state of information and the needs of PA.

Changes in the repository design that impact gas and brine flow through the DRZ are clearly defined and present no new problems in characterizing flow processes and flow paths that are different from those that exist in previous PAs. The assessment of any impact on the performance of the repository can be readily accomplished by applying the existing numerical and conceptual models to changes in flow geometry and changes in the geometry and stress/strain states of the DRZ resulting from design changes. The methodologies and procedures of assessment of the repository are therefore fully appropriate

3.3.2.6 Adequacy of Application

Consideration of the adequacy of application of the model to changes in flow in the DRZ due to changes in the repository design, reinterpretation of flow paths or changed definition of properties, requires that the changed processes that impact flow be clearly identified. In the present case, the necessary scenarios have been identified and the new permeability parameters proposed by the EPA for the DRZ are justified in the PAVT. The necessary BRAGFLOW calculations are identical to those used in other iterations of the PA model except that changed (decreased grid cell size) increases resolution of modeling along new flow paths, and two earlier iterations of that model exist for comparison (CCA and PAVT). Application of the model to redefined sets of parameters or to redefined flow paths resulting from changes in the repository design, as in the case of flow over the panel seals, does not require fundamental changes in the conceptual model. The redefinition of a new principal flowpath out of the repository (through Marker Bed #139, through the heaved floor) requires only the application of the flow model to preexisting process models. Application of BRAGFLOW to cases containing new hydrologic definition of flow in the DRZ is straightforward and requires only the recalculation of the pertinent impacts on principal factors such as repository pressure and

brine volume. Those calculations are represented by scatterplots and CCDF plots in the SNL presentations and demonstrate that performance is not significantly impacted. Those representations of the performance of the changed repository are sufficient to demonstrate the adequacy of the application of the model to the changed configuration of flow in the DRZ.

3.3.2.7 Accuracy of Calculations

New calculations since PAVT that impact repository performance assessment are represented in scatterplots and CCDF plots presented by SNL. No changes in BRAGFLOW except the reduction of grid cell size which increases resolution or in the methodology of application of BRAGFLOW to the process models resulting from the changes in DRZ Conceptual Models under review have been made. The plots presented by SNL address the most important sub-models in repository PA (pressure, saturation, and brine volume) and address the variance associated with chosen individual vectors. A CCDF representing the most pressure sensitive release case (spallings) and the most brine volume sensitive case (direct brine release) were presented and the results were seen to be reasonable, lacked large unexplained variance, and did not approach noncompliant releases. It is therefore concluded that the accuracy of calculations which include the calculation of changes in flow due to changes in the DRZ hydrogeological process models is demonstrated.

3.3.2.8 Validity of Conclusions

Validity of conclusions drawn from the application of the changed DRZ conceptual model in PA is the same as for those drawn from the previous iterations of the model so long as the adequacy of application and the accuracy of calculations are concluded to be appropriate. The general structure of the conceptual model was peer reviewed during the CCA and the changes to the details of the flow paths and the definition of permeability appear to be valid. Changes consist entirely of applications of the flow model to process models that either already exist in the PA model (flow through marker beds, inflow through the DRZ,) or are readily defined (flow through fractures connecting the repository

to marker beds) or to application of the flow model to changed results of process models operating on redefined parameters (DRZ permeability). Since BRAGFLOW and the general conceptual model are adequate and the calculations appear to be accurate, the conclusion that the changes more accurately represent flow in the DRZ appears to be valid.

3.3.2.9 Adequacy for Implementation

The changed DRZ model modulates the relationship between repository pressure, waste degradation and brine inflow in a more realistic and conservative way than preexisting models, while integrating the influences of two design changes. Flow of brine and gas into and out of the repository through all of the marker beds within reasonable proximity, both above and below the repository, linked to the repository through its pressure history is more realistic than the previous single flowpath model. Assessment of the impact of the "Option D" panel seals is closely tied to the repository history and flowpath assessment. The impact of the second design change, the small elevation of the southern waste panels for reasons of construction safety, is concluded to be insignificant on conceptual grounds.

The partial PA assessment provided adequately supports the reconfiguration of the model and shows that the impact of the changes on the model is minimal. It is concluded that the changes to the DRZ flow model have not invalidated its adequacy for implementation

3.3.2.10 Impact of the Disturbed Rock Zone Model on Closure Performance

Impact of the changes in the DRZ conceptual model are shown to be small by the limited performance assessment calculations presented by SNL during this review. Although limited, these calculations addressed the most important impacts (gas pressure, brine volume, and saturation) resulting from changes at the process model level, and the release mechanisms (DBR, Spallings) most dependent on pressure and brine volume. These results and the acceptance that the aspects of the model changes leading up to the calculations are adequate indicate that the impacts of the changes to the DRZ model do not negate the compliance of the repository. It must be noted that the Spallings model

used in the calculation of the Spallings release is not the latest iteration of that model, which has yet to be reviewed.

3.3.2.11 Dissenting Views

There were no dissenting views for this model.

4.0 Integration of Conceptual Models in Performance Assessment

4.1 Model Integration

Figure 4-1 is a simplified illustration in which selected conceptual models represent a system or subsystem within the CCA, PA code sequence. BRAGFLO DBR, as illustrated, is a special, short-term application of BRAGFLO related to a drilling intrusion and includes the conceptual model system representations listed under BRAGFLO plus the Direct Brine Release model. The direct brine release element illustrates that the calculated brine volume removed from the repository by a drilling intrusion is input directly to the CCDFGF.

Figure 4-1. Illustration of Conceptual Model Integration

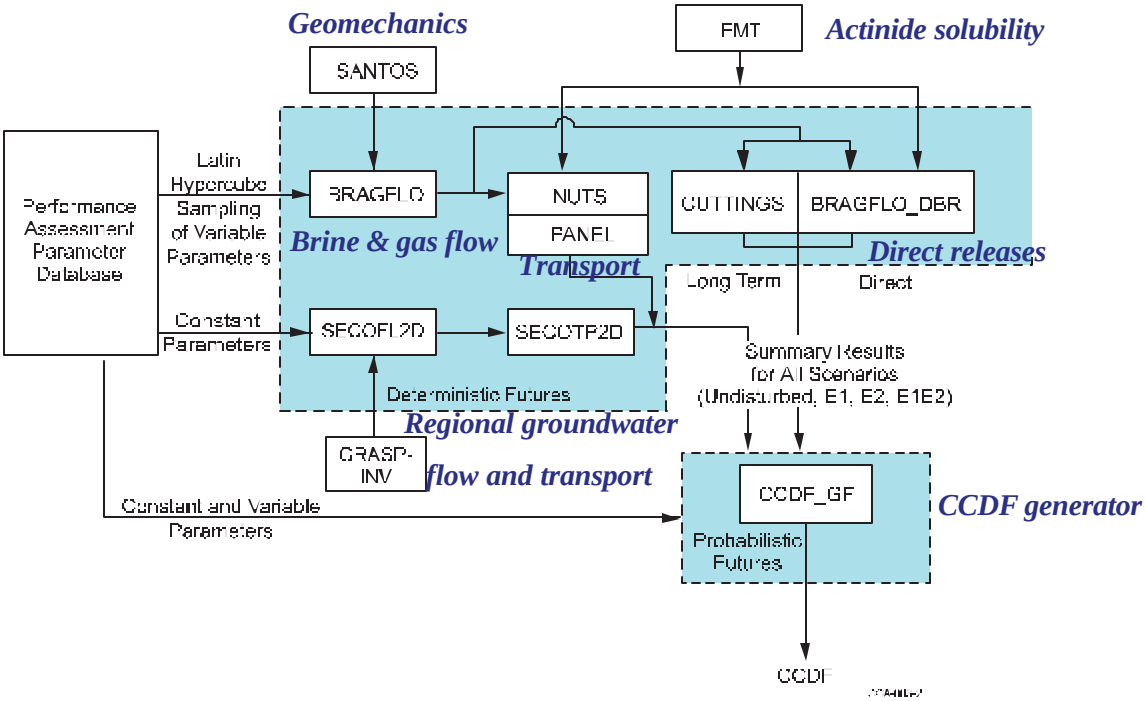

As shown in figure 4-1, the conceptual models do not all represent a system or sub-systems in the same place in the code sequence. Figure 4-1 illustrates that the conceptual models, as interpreted through the various codes, are ultimately integrated at the CCDFGF where results are prepared. The figure ignores many preparatory and post-process codes and relationships between codes that are not linear and in a single direction. For example, while SANTOS is related to BRAGFLO and receives system representation from the Creep Closure conceptual model, creep closure results from an iterative relationship between gas pressure, compaction, and brine characterizations from BRAGFLO and the porosity surface in SANTOS. The integration of the conceptual models, therefore, identifies the overall WIPP PA model as a complex structure that represents 24 conceptual models through preparatory, process, flow and transport, presentation, and enabling codes.

4.2 Review of Criteria

Applying evaluation criteria to the integration of conceptual models, as a step in the assessment of model adequacy, results in most of the discussion being summations of the individual conceptual model evaluations. For example, evaluations of information used in the integration, assumptions, uncertainties, adequacies, accuracy, and validity are all based on the individual conceptual models or the implementing mathematical representations or codes. The criteria have been discussed in Section 3.0 for the three conceptual models reviewed.

Because a total and complete system PA was not available for Peer Review Panel to review, the overall adequacy for implementation of the integrated conceptual models can only be judged at this time through the adequacy of the three individual conceptual models as discussed in Section 3. Based on the review of the individual models, implementation of the integrated conceptual models is expected to be adequate.

5.0 Summary of Evaluations

This section presents a summary of the evaluations of the WIPP Conceptual Models Peer Review Panel performed between April 2002 and March 2003. Over twenty years of scientific effort have been expended on WIPP site characterization and there have been approximately three years of successful operational experience. It is beyond the scope of this report to summarize all of the positive factors and scientific evidence compiled concerning the WIPP site. This section is not intended to be a reiteration of comments and discussions on the individual conceptual models but to provide an overview of conclusions from the evaluations.

The list of the twenty-four WIPP conceptual models is provided in the Table 4-1 with the three models reviewed during this peer review bolded so as to put them in the context of the total WIPP waste disposal system modeling effort.

Disposal System Geometry

The changes in the Disposal System Geometry conceptual model retain the necessary features of the original conceptual model and the grid changes appear reasonable and sound. The Disposal System Geometry conceptual model continues to be adequate. The results of a PA for the TBM illustrated that the effects of changes in the conceptual model are minimal. The Disposal System Geometry conceptual model continues to represent repository performance with no significant change from its representation in the baseline.

Repository Fluid Flow

The Repository Fluid Flow conceptual model has been determined to be both reasonable and adequate for its intended purpose. The identified changes (shaft simplification, EPA mandated parameters, cellulosic molecular structure, and fluid flow paths) appear reasonable and are expected to have minimal impact. The interaction of this conceptual model with the Option "D" Panel closure (with revised anhydrite fracturing and "flow around" features at high pressure), and subsequent gas pressure realizations in waste

panels have been illustrated by a series of TBM CCDF's that show very little resultant change. The influence of the model when coupled with the other conceptual models appears appropriate and adequate.

Disturbed Rock Zone

Four changes to the DRZ conceptual model have the potential to impact PA. These are the adoption of a range of limiting porosity values to replace the original (CCA) single value for the halite and anhydrite layers in which the disturbed rock zone is developed; the definition of a flow path through the floor of the repository openings into Interbed #139; flow paths around the tops and bottoms of panel seals at high pressure; and a change of elevation of the waste panels in the southern end of the repository. Based upon data and analyses presented by SNL, these changes appear to be reasonable. The change of waste panel elevation aides repository operations and is not considered a significant change in concept. The impact of these changes on PA calculations and CCDF plots appears negligible. The impact on releases sensitive to repository pressures, saturation and brine volume, show that changes in the DRZ model do not significantly impact the predicted compliance of the repository.

Table 5-1

WIPP Conceptual Models

Disposal System Geometry	**Addressed During This Peer Review**
Culebra Hydrogeology	Not Addressed During This Peer Review
Repository Fluid Flow	**Addressed During This Peer Review**
Salado	Not Addressed During This Peer Review
Impure Halite	Not Addressed During This Peer Review
Salado Interbeds	Not Addressed During This Peer Review
Disturbed Rock Zone	**Addressed During This Peer Review**
Actinide Transport in the Salado	Not Addressed During This Peer Review
Units Above the Salado	Not Addressed During This Peer Review
Transport of Dissolved Actinides in the Culebra	Not Addressed During This Peer Review
Transport of Colloidal Actinides in the Culebra	Not Addressed During This Peer Review
Exploration Boreholes	Not Addressed During This Peer Review
Cuttings/Cavings	Not Addressed During This Peer Review
Spallings	Not Addressed During This Peer Review
Direct Brine Release	Not Addressed During This Peer Review
Castile and Brine Reservoir	Not Addressed During This Peer Review
Multiple Intrusions	Not Addressed During This Peer Review
Climate Change	Not Addressed During This Peer Review
Creep Closure	Not Addressed During This Peer Review
Shafts and Shaft Seals	Not Addressed During This Peer Review
Gas Generation	Not Addressed During This Peer Review
Chemical Conditions	Not Addressed During This Peer Review
Dissolved Actinide Source Term	Not Addressed During This Peer Review
Colloidal Actinide Source Term	Not Addressed During This Peer Review

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Appendix A - Panel Member Technical Qualifications

Florie Caporuscio

Los Alamos National Laboratory

- Environmental Restoration - developed criteria for and wrote portions of two-site characterization Work Plans (Los Alamos Pueblo Canyon, Canyon Core Document).
- Project Manager to characterize Omega West Reactor leak.
- Developed radiometric survey technique to investigate radionuclide transport (Pu, Cs, Sr) by geomorphic processes in Los Alamos Canyons.
- Investigated Sr transport in aqueous media in Los Alamos Canyon.
- Peer reviews of Performance Assessment of Material Disposal Area (MDA) G at TA-54, Los Alamos National Laboratory.
- Co-author of MDA Performance Assessment Core Document for Environmental Restoration Projects at LANL.

WIPP

- Final Peer Review for License Application Conceptual Models
- Peer Review Member for salado Fluid Flow
- Peer Review Member – Natural Barriers

Environmental Protection Agency

- Principal Investigator evaluating effects of U, Th, Ra contamination and transport through geologic media at CERCLA and FUSRAP sites.
- Section Chief of US EPA WIPP Technical Review Program. Supervised review of Test and Retrieval Plan.
- EPA Principal Investigator for Gas Generation and Source Team models at WIPP (ORIA).

Pertinent Research/Other

- Oxidation of Fe oxides - characterization of oxidation state of 24,000 feet of ash flow core on Yucca Mountain.

- Determination of Fe oxidation state for paleomagnetic studies at Yucca Mountain.
- Empirical determination of Hematite-Ilmenite solvus with field samples.
- Crystal chemical studies of radioactive elements in crystal structures of mineral phases.
- Technical reviewer for *American Mineralogist* (1988-1989, 2002-2003)

John Gibbons

Over thirty years of experience in the geology and mine mechanics of salt deposits, including New York, New Mexico, Texas, and Kansas bedded salts and domed salts in Louisiana and Texas.

Yucca Mountain Project

Preparation of site suitability documents for presidential consideration, data qualification and integration for the federal high-level nuclear waste disposal site at Nevada

WIPP

Review of conceptual models and engineered barriers models for PA in support of license application. Review of data packages for PA in support of license application.

Illinois Department of Nuclear Safety

As a principal consultant:

- Detailed review of conceptual models (hydrogeologic and site character) and integration with the MODFLOW numerical flow model. Included radionuclide transport models and the site performance assessment model for Martinsville Illinois site.
- Developed site search models for hydrogeology and seismic ground motion for a second site.
- Developed conceptual model for vertical hydrologic flow through overconsolidated, fractured glacial till.
- Developed integration plan for site characterization through performance assessment of new site including applications of STRATAMODEL three-dimensional site model and model-based tests of site hydrologic characterization adequacy.

Applied Research Associates

Principal investigator for a DOE research committee funded study to develop a model-driven site characterization technology, which integrated geophysical (down-hole and surface), cone penetrometer and borehole data acquisition systems.

Senior hydrogeologist in support to Sandia National Laboratory in development of hydrostratigraphy conceptual model of Yucca Mountain High Level Nuclear Waste Repository Site.

Dames and Moore

As a principal investigator, did proposal preparation and was project liaison to the Federal High Level Nuclear Waste Program. Site characterization planning and model integration were principal areas of technical responsibility.

Chunhong Li

Numerical Modeling

- Conduct numerical modeling to study groundwater flow and mass transport at the Yucca Mountain site to assist system performance analysis at the proposed high level nuclear waste repository site.
- Carried out numerical simulations to study the influence of matrix diffusion on radionuclide transport in the fractured media at Yucca Mountain site.
- Carried out numerical simulations to investigate the sensitivity of radionuclide transport to variations in transport parameters under different flow conditions in UZ/SZ at Yucca Mountain.
- Worked on scaling related problems in groundwater modeling. Carried out numerical simulations using different scaling schemes for rock permeabilities to reconstruct water imbibition process observed in laboratory experiments in Topopah Spring tuffs at Yucca Mountain site.
- Expanded the Finite Element Heat and Mass transfer code (FEHM) to handle multiple species particle tracking process with spatially distributed transient source terms.
- Developed multiple species radionuclide decay-ingrowth module for FEHM.
- Developed algorithms for use with FEHM particle tracking module to better manage memory for simulating multiple species decay-ingrowth in the unsaturated zone.
- Modified the Finite Element Heat and Mass transfer code (FEHM) for GoldSim-FEHM coupling and supported Total System Performance Assessment (TSPA) work for GoldSim-FEHM simulation runs.
- Developed code SZ_CONVOLUTE V2.2 for calculating saturated zone responsive curves based on unsaturated zone mass flux and generic breakthrough curves for risk assessment at the Yucca Mountain Project.
- Developed a numerical code using the spectral representation theorem and FFT to generate 1-D and 2-D stochastic field with different spatial correlations.
- Developed Lattice Gas Automata (LGA) code to simulate solute transport behavior in fractured porous media.

- Applied harmonic analysis to study the dynamic response of well-aquifer system to earth tides and its application in estimating aquifer parameters, Jilin, China.
- Developed Java, JSP, and Oracle application programs for the Department of Veterans Affairs Data Center at Austin, TX.

Field Investigation

- Involved in designing and setting up a 3-D (multi-level) groundwater flow and transport research site at Sevilleta, New Mexico.
- Conducted field hydrogeological investigations, field pumping tests and tracer tests, and data analysis for a water supply site at Jinan, Shandong, China.

Laboratory Experiment

- Designed and carried out laboratory experiments to investigate solute mixing behavior at fracture junctions. The experimental results were then used to verify the numerical simulation results and good agreement was observed.

E. B. Oswald

Design of Conceptual Models/Structures

- University of Arizona, Department of Hydrology and Water Resources, Dissertation, 1976. Designed a conceptual model with which to assess the socioeconomic impacts of coal-fueled power generating facilities on Native Americans in the Four Corners region of the Southwest. The conceptual model related critical social, economic and cultural parameters of Native American systems to natural resource use, economic and environmental effects and power plant location and operation phenomenon. The conceptual model was implemented through a mathematical simulation technique.
- Designed conceptual models (assumptions, structures and relationships) for evaluating the impacts of FWPCA, Section 208, non-point pollution control practices on land and surface water quality. As part of a policy analysis project under USDA, Economic Research Service, the models were published in internal, peer-reviewed working papers (1977-1984).
- Assisted in the design of the conceptual models and implementation of the mathematical realizations of a linked system of linear programs and a finite difference representation of the Navajo sandstone aquifer. The linked LPs were designed to evaluate the regional impact of power generation grid distribution and the ground water model was built to estimate the impacts of commercial water withdrawals on local wells. The modeling was done under a contract with the Ford Foundation through the University of Arizona, Department of Hydrology and Water Resources (1976-1977).
- Montana DNRC, 1995. Developed the conceptual model for evaluating the effects of high TDS water from coal mine pit discharges to the Tongue River and reservoir system.
- Montana DNRC and U.S. Bureau of Reclamation, 1994. Designed the conceptual model(s) for evaluating the impacts of increased reservoir depth and area on alluvial ground water quality and storage and shoreline erosion.

- Designed the conceptual model for evaluating water use and disposal systems at remote Missile Launch Control Facilities, Malmstrom AFB, and Montana. The model considered the timing of water use, percolation and infiltration capacities, evapotranspiration and climatic influences and resulting short and long term potential for water balance. This 1995 project was in response to recent EPA guidelines governing remote water systems.
- Montana DEQ. Currently involved in conceptualizing a model or framework for evaluating the utility and stability of post-mining reclamation. The model will involve the characterization of future land use scenarios and the assessment of economic, aesthetic, recreational, surface environmental and alluvial ground water impacts of the scenarios.

Model Operation, Application

- Operated a regional linear program-based model designed to optimize the interplay of agricultural/silvicultural production systems with imposed pollution control practices. Published as part of the USDA, Columbia River Basin Project Report, 1980-1983, Portland, Oregon.
- University of Arizona, Department of Hydrology and Water Resources, 1975. Operated a stochastic, dynamic programming model with an application to a multi-year (50 years) multi-stage water supply reservoir operation system.
- Montana, DNRC, U.S. Bureau of Reclamation, 1994. Application of MODFLOW software to an evaluation of alluvial water withdrawals and the impacts of alternative rates on surface stream flow. At issue was the volume of ground water available for consumptive use without diminishing local stream flows.
- Oregon Department of Environmental Quality, published as USDA Working Paper, ERS Working Paper Series. Design and application of a riparian habitat model to estimate the effects of various agricultural, silvicultural and mining practices on riparian zones and the aquatic and terrestrial habitats included.
- Montana DEQ, U.S. Army Corps of Engineers, 1996. Responsible for review of geochemical, limnological and mixing zone models used to predict water quality in a pit lake, the Blackfoot River and the alluvial ground water resulting from

proposed gold mine operations. The results and interpretations of the model reviews will be presented in an EIS.

- USDA, EPA, Corvallis, Oregon, 1983. Conducted review of alternative models for evaluating chemical and erosional impacts to the ground water and surface streams associated with FWPCA, Section 208 and RCWP practices. The CREAMS model developed by USDA, ARS was adopted for use.
- Reviewed and evaluated various modeling approaches to be applied to the Agricultural/Rural environment system characterized by a project area in Austria. The review and model review was conducted at the IIASA, Laxenburg, Austria during a joint effort by Russian, Austrian and U.S. scientists.
- RCRA, RFI, Malmstrom AFB, Montana. HDR Engineering, 1993. Review and evaluation of proposed deep and shallow aquifer models proposed to characterize potential containment migration.
- Final Peer Review for License Application; Conceptual Models, WIPP, 1996-1997.
- WIPP Salado Conceptual Model Peer Review, May 2002

Data and Models

- As project operations manager, principal hydrologist and corporate QA manager, I routinely review the raw data and data presented in environmental sampling reports. Included in the reviews are 'cursory' data validation (traceability, achieving QA goals, etc.) as well as how the data can be interpreted, statistically or otherwise.
- Compliance Certification Model Data Review and Certification WIPP, 1995-1996.
- The data reviews and QA reviews routinely lead to conceptual models of contaminant migration route; rate and the conceptual models are used to propose more extensive and/or confirmatory sampling and data collection.
- As applied science manager working on the Rocky Mountain Arsenal and CERCLA projects manager for EPA's TESIV, project data review (QA and statistical) and interpretation of data for intended uses were routine activities. Krieging and other techniques were applied to interpret data spatially, illustrate

data gaps and needs and make decisions on the appropriateness of RFI and RIFS data for proceeding with remedial action.

Appendix B

Determinations of Peer Review Member Independence

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE ____ or a DOE Contractor X — Yes / No

Were you employed by DOE or a DOE Contractor previously? — Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

1993 – 1996 ASI – ER project at LANL
1996 – 1997 Informatics – WIPP peer Review
1997 – present Eberline Services – Gamma Spectroscopy at LANL, two months writing procedures for TWCP prior to first WIPP shipment.

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Florie A Caporuscio

Print Name: Florie A Caporuscio

Date: 1/24/03

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE or a DOE Contractor — Yes / (No)

Were you employed by DOE or a DOE Contractor previously? — (Yes) / No
(If yes, give dates, location, organization, position, and type of work performed).

YUCCA MOUNTAIN PROJECT
APR 1999 THROUGHOUT 3/2002
DATA REVIEW, SITE SUITABILITY DOCUMENT PREPARATION
PEER REVIEW WIPP 1996-1997-1998

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / (No)
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / (No)
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / (No)
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: John F. Gibbons II

Print Name: JOHN F. GIBBONS

Date: 1/25/03

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE No or a DOE Contractor No — Yes / No

Were you employed by DOE or a DOE Contractor previously? — Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: [signature]

Print Name: CHUNHONG LI

Date: 2/5/2003

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE ____ or a DOE Contractor ___ Yes / No

Were you employed by DOE or a DOE Contractor previously? Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

A previous employer may have been a DOE contractor, at one time, or may be a DOE contractor now, but I was not involved in any aspect of DOE work.

Do you have or have you had any direct involvement or financial interest in the work under review? Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Eric B Oswald

Print Name: Eric B Oswald

Date: 23 January 2003

Appendix C

Certifications Regarding Organizational Conflicts of Interest

I have reviewed each of the selected peer review panel member's (Florie Caporuscio, John Gibbons, Chunhong Li, and Eric Oswald) backgrounds and employment histories. I have also interviewed each of them to determine if they have an organizational conflict of interest or a bias for or against the WIPP facility as a nuclear waste repository. Though these background investigations and interviews I have determined that none of the selected peer review panel members has an organizational conflict of interest related to the Salado Flow Conceptual Models Peer Review.

John A. Thies,
Peer Review Manager

Appendix D – Signature Page

I acknowledge by my signature below that I concur with the findings and conclusions documented in the Salado Flow Conceptual Models Peer Review Report.

Florie Caporuscio — Date: 3/04/03

John Gibbons — Date: March 4/3/03

Chunhong Li — Date: 3/4/03

Eric Oswald — Date: 3/3/03

I have reviewed each of the selected peer review panel member's (Florie Caporuscio, John Gibbons, Eric Oswald, and Chunhong Li) backgrounds and employment histories. I have also interviewed each of them to determine if they have any organizational conflict of interest or a bias for, or against, the WIPP facility as a nuclear waste repository. Through these background investigations and interviews I have determined that none of the selected peer review panel members has a bias or an organizational conflict of interest related to the Salado Flow Conceptual Models Peer Review.

02/07/03

John A. Thies,
Peer Review Manager

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE No or a DOE Contractor No — Yes / No

Were you employed by DOE or a DOE Contractor previously? — Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: [signature]

Print Name CHUNHONG LI

Date 3/5/2005

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE or a DOE Contractor X — Yes / No

Were you employed by DOE or a DOE Contractor previously? — Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

1993 - 1996 ASI - ER project at LANL
1996 - 1997 Informatics - WIPP peer Review
1997 - present Eberline Services - Gamma Spectroscopy at LANL, two months writing procedures for TWCP prior to first WIPP shipment.

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Florie A Caporuscio

Print Name Florie A Caporuscio

Date: 1/24/03

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE ____ or a DOE Contractor ___ Yes / No

Were you employed by DOE or a DOE Contractor previously? Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

A previous employer may have been a DOE contractor, at one time, or may be a DOE contractor now, but I was not involved in any aspect of DOE work

Do you have or have you had any direct involvement or financial interest in the work under review? Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: [signature]

Print Name: Eric B Oswald

Date: 23 January 2003

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE or a DOE Contractor — Yes / (No)

Were you employed by DOE or a DOE Contractor previously? — (Yes) / No
(If yes, give dates, location, organization, position, and type of work performed).

YUCCA MOUNTAIN PROJECT
APR 1999 THROUGH OCT 31 2002
DATA REVIEW, SITE SUITABILITY DOCUMENT PREPARATION
PEER REVIEW WIPP 1996-1997-1998

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / (No)
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / (No)
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / (No)
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: John F. Gibbons II

Print Name: JOHN F. GIBBONS

Date: 1/25/03

WASTE ISOLATION PILOT PLANT

SPALLINGS

PEER REVIEW PLAN

June 20, 2003

Prepared by John A. Thies
Time Solutions Corp

INTRODUCTION

This peer review plan describes the process and documentation requirements for a peer review of the proposed spallings conceptual model to be used in the Waste Isolation Pilot Plant (WIPP) performance assessment (PA). This plan defines the management approach, resources, schedule, and technical requirements for using peer reviews to confirm the adequacy of the new conceptual model for spallings.

1.1 BACKGROUND

Peer review of conceptual models developed by the U.S. Department of Energy (DOE) for the WIPP is required by 40 CFR § 194.27 (EPA, 1996), promulgated by the U.S. Environmental Protection Agency (EPA). In accordance with this criterion, the Carlsbad Field Office (CBFO) of the DOE will have a peer review conducted of specific conceptual models that are being revised due to knowledge gained since the original conceptual models were developed. When approved, the revised conceptual models will be used in the Compliance Recertification Application (CRA) for the WIPP Project.

Sandia National Laboratories (SNL) is responsible for the development, maintenance, and conduct of WIPP PA's. As part of the PA methodology included in the Compliance Certification Application (CCA)(DOE, 1996), the DOE identified and developed conceptual models that describe the features, events, and processes relevant to the WIPP disposal system and its subsystems. These conceptual models were peer reviewed by the Conceptual Model Peer Review Panel (CMPRP) and the Panel's results were approved by the EPA during the original WIPP certification (EPA, 1998a).

The spallings conceptual model is one of 24 conceptual models used in the WIPP PA. The spallings model describes a potential release of degraded solid waste materials when repository gas pressure exceeds the hydrostatic pressure in the drilling fluid at the bottom of an intrusion borehole. The CMPRP found that the spallings conceptual model implemented in the CCA was inadequate to describe the detailed spallings process. However, the CMPRP also concluded that "the spallings volumes used in the CCA are reasonable, and may actually overestimate the actual waste volumes that could potentially be expected to be released by the spallings process at the WIPP" (Wilson et al., 1997, Section 4). The EPA agreed with the CMPRP that the spallings conceptual model was inadequate but the results were acceptable for use in PA (EPA, 1998b, Section 7).

After the CCA and Performance Assessment Verification Test (PAVT) were completed, work continued on the development of a new spallings model that would be more technically defensible than the original model. The major elements of the new spallings

model include consideration of multiphase flow processes in the intrusion borehole, consideration of fluidization and transport of waste particulates from the intact waste mass to the borehole, and a numerical solution for the coupled mechanical/hydrological response of the waste as a porous medium. New software, called DRSPALL, has been prepared to calculate the volume released during a potential spallings event.

1.2 REQUIREMENTS

The requirement for conducting a peer review of conceptual models is specified in 40 CFR § 194.27 (a)(1). The requirements for the peer review process and its documentation are specified in 40 CFR § 194.27(b) and (c). In summary, the peer review process shall be a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. A peer review is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology and acceptance criteria employed, and the conclusions drawn from the original work.

The peer reviewers shall be independent of the work being reviewed; in other words, the peer reviewer a) was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to ensure the work is impartially reviewed. Therefore, the peer-review provides additional assurance to the regulator and the public that the subject matter is reasonable, accurate and valid for its intended use.

1.3 PURPOSE

The purpose of this plan is to describe the scope, approach, and process the peer review panel will use in conducting a peer review of the WIPP spallings conceptual model.

1.4 SCOPE

The Spallings Peer Review panel will determine if the new conceptual model for spallings reasonably represents the failure of solid wastes and their subsequent transport to the surface from a borehole intrusion into a high pressure repository. The scope of this peer review is limited to assessing the new conceptual model for spallings and its implementation in WIPP PA.

PEER REVIEW PLANNING AND IMPLEMENTATION

2.1 APPROACH

This plan documents the approach to conducting the peer review process. The Spallings Peer Review will be conducted using a rigorous proceduralized approach that meets all the requirements of NUREG-1297 (NRC, 1988), in accordance with 40 CFR § 194.27(b). The DOE-CBFO has prepared a management procedure, MP 10.5, Revision 5, February 1, 2003 (DOE, 2002a), for conducting peer reviews in accordance with NUREG-1297. The DOE-CBFO procedure ensures that the peer review will be a documented, critical review performed by qualified peers who are independent of the work being reviewed. Specifically, the Spallings Peer Review Manager will:

- Follow MP 10.5, Revision 5, February 1, 2003 requirements. In the event of a conflict between MP 10.5, Revision 5, February 1, 2003 and NUREG-1297, NUREG-1297 will take precedence over MP 10.5, Revision 5, February 1, 2003.
- Administer and document the peer review process. Activities include documenting the selection of panel members, assignment of a panel leader, panel member independence documentation, and recording and archiving meeting minutes.
- Negotiate a schedule for the peer review with the DOE CBFO Assistant Manager, or designee.
- Conduct and document peer review panel caucuses.
- Communicate interim peer review findings in hardcopy to the DOE CBFO Assistant Manager, or designee.
- Produce a formal written report of the peer review findings and conclusions.
- Implement applicable quality assurance (QA) requirements for document preparation, control and records archiving.

2.1.1 DESCRIPTION OF CONCEPTUAL MODEL TO BE REVIEWED

A new conceptual model for spallings is being proposed. The new conceptual model for spallings includes: (1) the development of numerical techniques to solve the coupled mechanical-hydrologic equations for gas flow and fracture of the waste in the repository, and (2) the use of a conceptual model for multiphase flow in the intrusion borehole.

Detailed descriptions of the model components will be provided to the peer review panel through written documentation and oral presentations.

Peer review of the new conceptual model for spallings will include:

- The conceptual model for the spallings process in the repository and in the intrusion borehole.
- The mathematical representation of the new spallings conceptual model.
- The numerical solution of the mathematical representation through the DRSPALL computer program. The words “computer program” and “code” are used interchangeably in this plan.
- Incorporation of the numerical results from the DRSPALL code into the direct release calculations for PA.

When approved, the new conceptual model for spallings will be used to calculate potential spallings volumes for the Compliance Recertification Application, replacing the original spallings model. *Review of the new conceptual model for spallings will not include consideration of the validity of the original conceptual model peer review.*

2.1.2 COMPOSITION OF PEER REVIEW PANEL

The peer review panel will be composed of a minimum of three individuals who possess the subject matter technical expertise to a degree at least equivalent to that needed for the original work.

Each panel member will become familiar with the WIPP containment system by reviewing documents on a required reading list and through a formal orientation process conducted by the peer review manager. In addition, they will be presented with a basic description of how the conceptual models for PA are represented in numerical models, algorithms, and codes. The panel members will be presented the parameter inputs to the spallings code, results of prior PAs, sensitivity analyses, and critical comments from previous reviews. Finally, each panel member will become familiar with the peer review process through formal training in the appropriate peer review procedure(s).

2.1.3 LOGISTICS AND MANAGEMENT

Required reading material necessary to support the Spallings Peer Review will be provided by the DOE CBFO Assistant Manager, or designee, for distribution to the panel in time to support the first technical meeting which is scheduled for mid July.

2.2 PEER REVIEW PROCESS

The cognizant DOE CBFO Assistant Manager, or designee, is responsible for the peer review. A peer review contractor and Peer Review Manager will be selected by the CBFO Technical Assistance Contractor (CTAC). The responsible DOE CBFO AM, or

designee, shall concur with the peer review manager nominated by the service provider. The Peer Review Manager has prepared this Peer Review Plan and the DOE CBFO Assistant Manager, or designee, has reviewed and approved it. This Plan meets the requirements of MP 10.5, Revision 5, February 1, 2003. MP 10.5 shall supersede any discrepancies between this Plan and MP 10.5.

The Peer Review Manager will use a selection committee to select candidates for the peer review panel. Upon verification that the peer review panel members meet the criteria outlined in MP 10.5, Revision 5, February 1, 2003, Attachment 1, an orientation and training meeting will be scheduled. The peer review panel members shall complete their review of required reading materials prior to the orientation meeting.

Throughout the review, the panel is encouraged to engage in frank discussions with the individuals responsible for the work under review. However, the peer review panel must observe all rules for interaction with DOE CBFO, SNL, and stakeholders, as outlined in MP 10.5, Revision 5, February 1, 2003.

The results of the panel's review shall be formally documented in a report. This report will be prepared independently of the DOE CBFO to ensure the independence of the Panel's conclusions.

MP 10.5, Revision 5, February 1, 2003 states that the DOE CBFO QA Manager is authorized to conduct independent assessments of the peer review process to ensure that all aspects of the peer review conform to the guidance of NUREG-1297, MP 10.5, Revision 5, February 1, 2003, and the latest version of the CBFO Quality Assurance Program Description (DOE, 2002b). The DOE CBFO QA Manager shall inform the Peer Review Manager of any requests for audits or assessments. The Peer Review Manager shall comply with and resolve all issues arising from such audits or assessments.

2.3 ADEQUACY CRITERIA

Conceptual models that have been selected and developed by the DOE must meet commonly accepted technical and scientific standards based on an in-depth evaluation. The peer review panel shall use the evaluation criteria in NUREG-1297 as the basis for their review. The evaluation criteria in NUREG-1297 are as follows:

- Validity of assumptions,
- Alternate interpretations,
- Uncertainty of results and consequences if wrong,
- Appropriateness and limitations of methodology and procedures,
- Adequacy of application,
- Accuracy of calculations,

- Validity of conclusions, and
- Adequacy of requirements and criteria.

Adequacy of the revised conceptual model for spallings will be determined based on whether or not it reasonably represents possible future states of the disposal system.

2.4 SCHEDULE

Attachment A presents the schedule of peer review activities for the process described in Section 2.1.3. This schedule will serve as the baseline schedule from which requested schedule deviations will be evaluated by the Peer Review Manager and the CBFO. Revisions to the baseline schedule will not require revision to this plan, but must be approved by the DOE CBFO Assistant Manager, or designee.

2.5 DELIVERABLES

The Peer Review Manager will provide weekly status reports addressing peer review progress against the schedule to the DOE CBFO Assistant Manager, or designee. The DOE CBFO Assistant Manager, or designee, will work with the Peer Review Manager to ensure that timely information is delivered to the peer review panel. A final report with the panel's findings will be delivered to the cognizant DOE CBFO Assistant Manager, or designee.

2.5.1 Peer Review Report

The peer review report shall, at a minimum:

- Be signed by each peer review panel member
- Describe the work or issues that were reviewed
- Describe the conclusions reached by the peer review panel (e.g., peer review panel observation comments and overall conclusions).
- Provide additional statements by the peer review panel members reflecting dissenting views or additional comments, as appropriate
- List the peer review panel members and provide acceptability information (i.e., technical qualifications and independence) for each member.

QUALITY ASSURANCE

The peer review process shall be conducted and documented in a controlled manner and in compliance with the CBFO Quality Assurance Program Description, DOE/CBFO-94-1012, Revision 5 and other applicable QA procedures. The DOE CBFO QA Manager may appoint a QA observer to attend the orientation, training, and meetings of the peer review panel. The DOE CBFO QA Manager may schedule an assessment or audit of the peer review process and records prior to, or upon completion of the peer review. Communication between the EPA and the DOE CBFO QA Manager may also result in audits or assessments or the peer review process.

RECORDS MANAGEMENT

Records generated as a result of peer review activities defined in this peer review plan and designated as QA records shall be maintained by the Peer Review Manager in accordance with DOE CBFO MP 4.5, Generating, Receiving, Storing, and Controlling Active CBFO Project Records (DOE, 2001a), and MP 4.9, Quality Assurance Records (DOE, 2001b). Records include:

- Spallings Peer Review Plan
- Peer Review Procedure(s)
- Contract documents
- Peer Review Panel Member Verification of Education/Employment Forms
- Determination of Peer Review Panel Member Independence Forms
- Peer Review Panel Selection Justification/Decision Forms
- Peer Review Panel Member Orientation and Training Forms
- Meeting minutes and presentation materials
- Peer review Manager qualification documentation
- Peer Review Panel Member selection documentation
- Peer Review Panel Member contract documents
- Any Observer inquiry forms completed
- Written materials presented to the Peer Review Panel by CBFO or investigators
- Written information presented to the peer review panel members by observers
- Peer Review Report(s)

QA records shall be maintained by the Peer Review Manager until completion of the peer review. Upon completion of the peer review process, the original copy of the QA records (when possible) shall be formally transferred and delivered to the DOE CBFO Assistant Manager, or designee.

DOCUMENT CONTROL

The peer review plans, procedures, and other documents that require document control will be processed in accordance with applicable DOE-CBFO controlled document procedures.

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Wilson, C., Porter, D., Gibbons, J., Oswald, E., Sjoblom, G., and F. Caporuscio. 1997. Conceptual Models Third Supplementary Peer Review Report, April 1997. Prepared for the U.S. Department of Energy, Carlsbad Area Office, Office of Regulatory Compliance, April 1997.

Attachment A

Schedule for Spallings Peer Review

Task Name	Completion Date
1. Identify Peer Review Contractor and Manager	
2. Receive Contract Authorization	
3. Identify Panel Selection Committee	
4. Reserve Meetings Rooms	
5. Identify Panel Members	
6. Justify Selection/Non-Selection	
7. Verify Panel Member Education	
8. Approve Panel Member Travel	
9. Prepare Final Peer Review Plan	
10. Prepare Orientation Notebook	
11. Select Peer Review Panel Chair Person	
12. DOE Delivers Spallings Documentation	
13. Orient Peer Panel	
14. Prepare 1st Meeting Agenda	
15. 1st Peer Panel Meeting	
16. 2nd Peer Panel Meeting	
17. Prepare Final Report	

Prepared by: _____

Approved by: _____

Appendix B

Determinations of Peer Review Member Independence

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE_ or a DOE contractor___? Yes/No

Were you employed by DOE or a DOE Contractor previously? Yes/No

(If yes, give dates, location, organization, position, and type of work performed).

Do you have or have you had any direct involvement or financial interest in the work under review? Yes/No
(If yes, describe the involvement)

Is there any reason why you cannot perform an impartial peer review? Yes/No
If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of bias in the results of your peer review? Yes/No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Ching H. Yew

Print Name: Ching H. Yew

Date: July 7, 2003

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE_ or a DOE contractor___? Yes/No

Were you employed by DOE or a DOE Contractor previously? Yes/No

(If yes, give dates, location, organization, position, and type of work performed).

1978-1982, Livermore, CA
LAWRENCE Livermore National Laboratory
EARTH SCIENCES DIVISION

Do you have or have you had any direct involvement or financial interest in the work under review? Yes/No
(If yes, describe the involvement)

Is there any reason why you cannot perform an impartial peer review? Yes/No
If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of bias in the results of your peer review? Yes/No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Jonathan Hanson

Print Name: JONATHAN HANSON

Date: 7/7/03

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE____ or a DOE contractor___? Yes/No

Were you employed by DOE or a DOE Contractor previously? Yes/No

(If yes, give dates, location, organization, position, and type of work performed).
Sandia National Labs from 1979-1999, Member of Technical Staff
Geomechanics primarily for oil + gas studies

Do you have or have you had any direct involvement or financial interest in the work under review? Yes/No
(If yes, describe the involvement)

Is there any reason why you cannot perform an impartial peer review? Yes/No
If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of bias in the results of your peer review? Yes/No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Lawrence W. Teufel

Print Name: Lawrence W. Teufel

Date: 7/7/02

Statement of Unbiased Peer Review of the Spallings Model by Lawrence W. Teufel

Before accepting my current position in 1994 as the Langdon Taylor Professor of Petroleum Engineering at the New Mexico Institute of Mining and Technology I was a member of the technical staff at Sandia National Laboratories from 1979 to 1999. From 1994 to 1999 I had a joint appointment at Sandia Labs and New Mexico Tech. During my 20 year career at Sandia Labs I was involved with several cooperative DOE/Industry oil and gas projects and worked almost exclusively on petroleum-related rock mechanics studies on hydraulic fracturing, fluid-flow in natural fracture systems, *in situ* stress measurements, and reservoir compaction and subsidence. In my very early career at Sandia Labs I was involved in only one small WIPP related project, which was a rock mechanics study of the mechanical properties of anhydrite in the Salado Formation at WIPP. Colleagues at Sandia were involved with various geotechnical studies at WIPP. Over the years I have had many technical discussions with them on these projects. Since leaving Sandia Labs in 1999 I have had limited technical contact with Sandia staff members and these have been related only to tight gas projects with industry. When I was a member of the U.S. National Committee for Rock Mechanics I was asked and provided unbiased peer review of WIPP and Yucca Mountain geotechnical studies. At that time I was employed by Sandia Labs. I have no vested interest in any of the technical studies at WIPP conducted by Sandia Labs (other than my small anhydrite rock mechanics study, which went through peer review) or by any other group. I can and will provide an unbiased peer review of the Spallings Model.

Lawrence W. Teufel

Lawrence W. Teufel

Appendix C

Certifications Regarding Organizational Conflicts of Interest

I have reviewed each of the selected peer review panel member's (Jonathan M. Hanson, Lawrence W. Teufel, and Ching Hsie Yew) backgrounds and employment histories. I have also interviewed each of them to determine if they have any organizational conflict of interest or a bias for, or against, the WIPP facility as a nuclear waste repository. Through these background investigations and interviews I have determined that none of the selected peer review panel members has a bias or an organizational conflict of interest related to the Spallings Conceptual Model Peer Review. Please note that in the case of Lawrence Teufel having worked for Sandia National Laboratories, I requested a written statement by him attesting to his independence. That signed statement is attached.

John A. Thies,
Peer Review Manager

THE WASTE ISOLATION PILOT PLANT

A Potential Solution for the Disposal of Transuranic Waste

Committee on the Waste Isolation Pilot Plant

Board on Radioactive Waste Management

Commission on Geosciences, Environment, and Resources

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1996

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

Support for this study on the Waste Isolation Pilot Plant was provided by the U.S. Department of Energy, under Grant No. DE-FC01-94EW54069. All opinions, findings, conclusions, and recommendations expressed herein are those of the authors and do not necessarily reflect the views of the Department of Energy.

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Cover: Federal regulations require calculations to show that the Waste Isolation Pilot Plant (WIPP), if certified as a transuranic radioactive waste repository, is expected to isolate waste from the environment for the next ten millennia. Current plans call for the erection on site of permanent markers containing signs and symbols, intended as decipherable messages to warn future generations of the dangers to nature and to human health of digging into a filled and sealed repository below the surface.

Coincidentally, ten millennia is also the approximate age of the earliest known pottery from Asia. One millennium ago, a now-extinct Indian tribe, the Mimbres, lived in Arizona and New Mexico. The cover shows a Mimbres pottery design, perhaps representing the delicate balance of nature, using a man and two animals in a mobile arrangement. The Mimbres design is used by permission from *Art of a Vanished Race: The Mimbres Classic Black-On-White*, by Victor M. Giammattei and Nanci Greer Reichert, Published by Dillon Tyler, Publishers, P.O. Box 645, Calistoga, CA 94515.

The background photograph, provided by the Department of Energy Carlsbad Area Office, shows a close-up of a sample of Permian age salt crystals taken from the WIPP excavations. The permanence of the geologic salt formation (over 200 million years old) is an attractive feature of the WIPP site and illustrates the exceptional time scales of concern in nuclear repository design, time scales that extend well beyond the typical duration of most engineering projects, languages, and civilizations.

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ACKNOWLEDGMENTS

The committee has spent countless hours over the more than ten years since its last full report on WIPP, in discussions with staff from DOE and its contractors, EPA, officials of the State of New Mexico, the Environmental Evaluation Group, community leaders from Carlsbad, and concerned citizens. In open meetings held several times a year for more than a decade, the committee has heard a wide diversity of views on WIPP.

Genuine concerns have been expressed without rancor or polemics, but with conviction and unfailing courtesy. This is a tribute to the community involved in and concerned about WIPP. For the committee, and particularly the chair, it has been a privilege to have participated in these discussions. We sincerely appreciate all of the information and insights gained and hope that our report will be of value in arriving at an appropriate decision on the proposal to establish a TRU waste site at WIPP.

The committee thanks the many anonymous reviewers who painstakingly read and criticized our report, which has benefitted considerably from their efforts.

Finally, we wish to express our appreciation to staff colleagues of the National Research Council's Board on Radioactive Waste Management, both past and present, who have done much to assist the committee in its task. Particular thanks are due to Tom Kiess, Angela Taylor, and Erika Williams, without whose efforts the report would not have been completed.

Charles Fairhurst, *Chair*
October 1996

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Executive Summary

The Waste Isolation Pilot Plant (WIPP) is a network of underground excavations at a depth of approximately 658 m (2,160 ft), in bedded salt formations near Carlsbad, New Mexico, in the southeastern corner of the state (Figure ES.1). WIPP is intended to serve as a permanent repository for transuranic (TRU) waste, which consists of a wide variety of materials (such as protective clothing, laboratory equipment, and machine parts) that have become contaminated with radioactive transuranic elements[1] during use in defense-related activities. These materials, from U.S. Department of Energy (DOE) facilities, currently are stored at several DOE locations around the country and are classified as either CH (contact handled) or RH (remote handled) waste.

DOE has been investigating the suitability of WIPP as a TRU waste repository since the 1970s and plans to submit an application to the U.S. Environmental Protection Agency (EPA) in the fall of 1996 for a certificate of compliance to open and operate the facility. To obtain the certificate of compliance, DOE must demonstrate that the WIPP facility will comply with relevant U.S. federal regulations—chiefly, the EPA's 40 CFR 191 and 40 CFR 194.

The National Research Council (NRC) Committee on the Waste Isolation Pilot Plant was formed in 1978 at the request of DOE to provide scientific and technical evaluations of DOE investigations at WIPP. The committee's statement of task charges it to report on the current state and progress of the scientific and technical issues that form the core of a submission by DOE to EPA for certification of the WIPP facility.

Because DOE's compliance certification application to the EPA consists largely of conclusions drawn from DOE investigations, it is timely to comment on results of committee evaluations and their implications with regard to the overall suitability of WIPP as a repository for TRU waste (Box ES.1). This report presents these findings.

BOX ES.1

Uncertainty in Repository Performance

Assessing the performance of a radioactive waste repository over the long time periods of interest necessarily includes significant uncertainties. This is recognized by EPA in the standards for the disposal of TRU and high-level waste and spent nuclear fuel. Regarding the required degree of proof, EPA notes:

> *Performance assessments need not provide complete assurance that the requirements of Part 191.13(a) [i.e., the containment requirements] will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with Part 191.13(a) will be achieved.* (40 CFR Part 194.13(b))

This review of WIPP should be read with this limitation in mind; the findings and judgments reached in this report could not be achieved with absolute certainty, but instead reflect a reasonable expectation for WIPP performance based on the available evidence.

Several general committee findings regarding TRU waste disposal at WIPP are worth noting. These findings are based on the characteristics of the waste and the salt medium and from scientific and technical studies at WIPP and at potential salt repositories in other countries.

- Although TRU waste contains long-lived radionuclides that require geologic isolation, the overall

[1]Transuranic elements are those elements with atomic number greater than that of uranium. Most are radioactive because of their emission of alpha particles. TRU waste contains those with half-lives greater than 20 years in concentrations exceeding 100 nanocuries per gram.

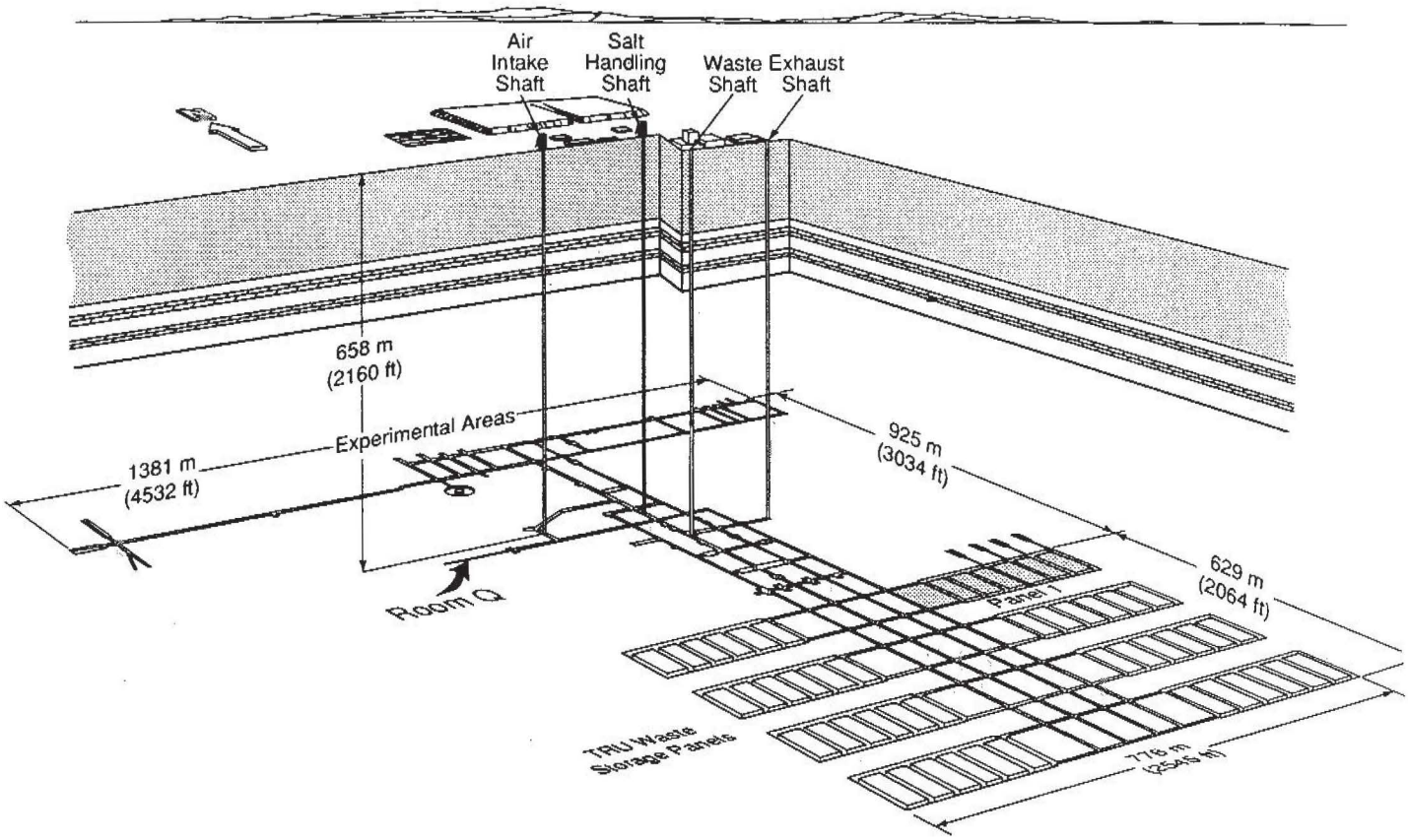

FIGURE ES.1 Three-dimensional view of the Waste Isolation Pilot Plant. The WIPP facility includes surface support buildings, a waste-handling building, four shafts, and the mined underground operations area. The repository is located approximately 658 m (2,160 ft) below the surface, within the Salado Formation, a Permian sequence of bedded salt with minor amounts of anhydrite and clay. The excavations are accessible from the surface by four vertical shafts. Only one of the planned eight panels, labeled Panel 1 in the diagram, has been excavated to date. Each panel consists of seven rectangular rooms, 10 m wide and 91 m long, separated by 30.5-m-wide pillars. Room Q, also labeled, is the site of a series of experiments on brine inflow into a 2.9-m-diameter, 109-m-long bored cylindrical tunnel. (Note: 1 meter [m] is approximately 3.28 feet [ft].) Source: Jensen et al. (1993), modified from their Figure 3-1.

level of radioactivity is much lower than that of high-level radioactive waste.[2]

• The early recognition of salt as an attractive medium for geological isolation (e.g., NRC, 1957) of radioactive waste has been confirmed by subsequent studies.

• Provided it is sealed effectively and remains undisturbed by human activity, the committee finds that the WIPP repository has the ability to isolate TRU waste for more than 10,000 years. The geologic stability and isolation capability of the Salado Formation, which consists of bedded salt, are the primary factors leading to this finding.

• The only known possibilities of serious release of radionuclides appear to be from poor seals or some form of future human activity that results in intrusion into the repository. The committee anticipates that the consequences of such human intrusion can be reduced based on available engineering design options and on improved understanding to be obtained from ongoing scientific studies.

• EPA's regulations (i.e., 40 CFR 191, as specified for WIPP in 40 CFR 194) relating to human intrusion do not take into account that if radionuclide releases to the environment via ground-water pathways at WIPP occur, they will be predominantly in non-potable water. This greatly reduces the risk of human exposure compared to a similar release in potable water.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The combination of general considerations, such as those outlined above, and detailed studies described later in this report, lead to the following conclusions and recommendations.

Based on available scientific evidence, the only probable threat to satisfactory isolation performance of the repository is the possibility of disturbance by human activity, deliberate or unintentional, that could compromise the integrity of the repository. Engineering methods are available, if needed, to reduce the consequences of human intrusion to acceptable levels.

[2]The level of radioactivity per unit volume of WIPP TRU waste is of the order of 0.1 percent of the corresponding level for U.S. spent fuel [see Chapter 1 Table 1.1].

Conclusion: Human exposure to radionuclide releases from transuranic waste disposed in WIPP is likely to be low compared to U.S. and international standards.

Consideration of the consequences of future activities that could violate the natural, or undisturbed, integrity of the repository is valuable for assessing the relative vulnerability of the repository to such activities and in identifying ways to reduce this vulnerability, but assessing human technologies thousands of years hence is highly conjectural and lacks a sound scientific foundation.[3]

Recommendation: Speculative scenarios of human intrusion should not be used as the sole or primary basis on which to judge the acceptability of WIPP (and, by extension, any geological repository).

Findings, Conclusions, and Recommendations on DOE Studies

DOE has concentrated on studies and calculations intended to determine compliance with federal regulations for WIPP in the event of human intrusion. Although the committee has not so restricted its studies, the following comments relate specifically to the DOE compliance activities. Most of the issues discussed below are significant only in the event of human intrusion.

1. *The role of Performance Assessment:* Performance assessment (PA) examines the combined effect of each component of the total system to assess the overall ability of the repository to isolate radionuclides from the biosphere. As used by DOE, PA responds to the question, "Is WIPP in compliance with federal regulations?"

Although PA has made important contributions to the WIPP project, in retrospect, it is clear that the potential of PA is higher, and important opportunities

[3]Federal regulations (40 CFR 191, 40 CFR 194) require stylized calculations on releases due to human intrusion. The level of proof required is a "reasonable expectation." See Box ES.1. The weight to be given to human intrusion possibilities is also discussed in *Technical Basis for Yucca Mountain Standards* (NRC, 1995; see especially, pp. 11, 107-111,115).

to put PA to good use have been missed. PA is valuable at all stages of the repository evaluation process. It can identify the most critical components of the system, assess the significance of engineered supplements to the natural geological barriers, and serve as an aid to planning and management decisions on the most effective allocation of staff and project resources.

2. *Conservatism of performance assessment models:* The PA models currently used by DOE are too conservative in some respects. Such conservatism masks the potential for identifying and assessing the benefits of relatively simple engineering design procedures in reducing the consequences of human intrusion.

The assumption that the Disturbed Rock Zone (DRZ) bordering the room excavations remains a relatively high-permeability region throughout the first 10,000 years of the repository appears overly conservative. This is in marked contrast to the assumption (see Chapter 4) that the DRZ around the shaft will heal, achieving a permeability of between 10^{-16} m^2 and 10^{-18} m^2 within 50 to 100 years and approaching the essentially impermeable condition of intact salt within a small fraction of 10,000 years. Such a conservative assumption with respect to the DRZ in the PA models may prevent a realistic evaluation of the major benefits of compartmentation of the waste by room and panel seals in reducing the consequences of repository disturbance by intrusion.

3. *Complexity of performance assessment models:* DOE's PA modeling of radionuclide releases from WIPP involves complex combinations of many variables such that, to the non-specialist, it is not clear how the predicted releases depend on the component features, events, and processes in the geological isolation system.

The committee recommends that DOE develop, in parallel with the complex PA models, simpler versions that provide a more transparent, traceable path from the model inputs to the predicted releases. The insights gained from the simpler model as to which components of the isolation system are most critical to improved repository performance would serve a very useful role in decision making and in resource allocation for WIPP. It is essential, of course, that the simpler PA models still identify correctly the key features, events, and processes upon which repository performance depends.

To illustrate this recommendation: because plutonium (Pu) is the dominant radioactive element of concern in the WIPP inventory, a simpler model could focus on Pu in the source term to the exclusion of other radioactive elements. However, understanding and predicting the behavior of Pu in the WIPP system is challenging, and experimental work with other actinides is necessary to develop the parameters for Pu required for the PA models, for both the full model and any simpler version. While studies of other actinides are necessary to support the chemical model developed for Pu, a simpler PA of the kind proposed here would consider only Pu isotopes as a source term, and only the dominant pathway(s) for environmental releases, with no more complexity than needed for an adequate representation.

4. *Waste characterization:* The waste characterization program being considered by DOE does not appear to be based on the needs for information important to an assessment of the long-term performance of the facility. Ideally, the PA should be used to determine what characterization is required.

5. *Nonradioactive constituents of TRU waste:* Nonradioactive hazardous constituents of TRU waste are considered to pose negligible long-term hazards compared to the radioactive constituents of WIPP waste (see Box 2.1 and discussion on 40 CFR 268 in Chapter 2).

6. *Behavior of salt at the WIPP site:* Time-dependent deformation of the salt and associated stratigraphic layers at WIPP is now understood well enough to allow reliable long-term calculations of salt deformation behavior as it relates to repository performance.

7. *Salado brine:* Small quantities of brine seep from the disturbed rock zone in the immediate vicinity of any excavation in the Salado Formation. The amount of brine accumulation is not sufficient to be a credible cause for significant escape of radionuclides from the sealed repository.

8. *Non-Salado brine:* Apart from possible effects of deep–well fluid injection in adjacent areas, brine flooding is only likely if, after loss of administrative controls, an intrusion borehole connects the repository with a deeper source of pressurized brine, such as has

been encountered by some deep boreholes in the vicinity of the repository.

9. *Gas generation in the repository*: Gas generation will be minimal in a dry or nearly dry repository such as WIPP because both chemical and biological gas-generating processes (e.g., metal corrosion and bacterial action on organic matter) require a liquid phase for mass transport of the reactants and products that are involved in gas formation.

10. *Treatment of waste:* Sophisticated treatment (e.g., incineration) of the TRU waste to be placed in a well-engineered WIPP repository is unwarranted to further improve repository performance, because gas generation is not a serious concern (see Chapter 3).

11. *Backfilling and compartmentation:* Simple repository engineering measures, such as backfilling of the rooms and tunnels in which the waste is emplaced, can be valuable and cost-effective methods of reducing the consequences of human intrusion and any associated brine flooding. Room and panel seals via backfill are relatively well-defined engineering procedures for improving the isolation process. In this regard, compartmentation is recommended by the committee to provide effective seals to eliminate hydrological communication between the waste-filled rooms.

12. *Non-Salado hydrology*: A more comprehensive understanding of the non-Salado hydrology is needed before a reasonable judgment can be made as to the role of the Rustler and adjacent formations in delaying radionuclide releases *in the event of human intrusion*. To date, studies have been overly focused on a two-dimensional analysis of the Culebra Dolomite. They have not sufficiently considered other possible hydrogeologic release pathways for radionuclides or interconnections between the Culebra and other formations. Potential releases to the Dewey Lake Red Beds, which are less conductive than the Culebra, but contain some potable water, are recommended for further study.

13. *Potash mining:* The consequences to the non-Salado hydrology of subsidence damage due to possible future mining of potash resources above the repository have not yet been evaluated by DOE. If the potential consequences are found to be seriously adverse, it is technically feasible to extract these resources pre-emptively, in a way that avoids subsidence and associated effects and that reduces the potential for human intrusion by drilling.

14. *Deep well fluid injection:* The requirement to consider the effects on the repository of fluid injection activities was a relatively new addition to the final version of EPA criteria for certification (40 CFR part 194.32(c)). Neither the probability nor the effects on the repository from nearby injection of water or brine have been evaluated in detail by the committee, nor has DOE published an analysis of this issue. A comprehensive analysis of the risks and consequences of this scenario should be completed and documented.

15. *Waste solubility and transport:* The PA completed by DOE in 1992, and all subsequent analyses, consistently have identified a set of issues that will have the greatest impact on the compliance of WIPP *in the event of human intrusion* and associated brine flooding of the repository. Prominent among these issues are

- actinide solubilities in brine,
- formation and transport of colloids containing radionuclides, and
- retardation of radionuclides during transport through the Culebra.

The EPA also has identified these issues as critical to its evaluation of the compliance certification application.

At the time of the writing of this report, the data and models to be used to represent these three issues in the next version of the PA (to support the compliance certification application) were not available for review.

16. *Continuation of experiments and analyses:* Continuation of analyses and experiments recently initiated in the WIPP program to address concerns raised in issues 12, 14, and 15 is recommended by the committee, even though the results may not be available in time to be used in the compliance submission. Results of such testing could reduce uncertainties in the long-term performance of WIPP, eliminate concern over other issues, and be useful in judging the cost effectiveness of various waste isolation procedures at WIPP and other repositories.

SUMMARY

- Provided the WIPP repository is sealed effectively and undisturbed by human activity, the committee knows of no credible or probable scenario for release of radionuclides.
- For the WIPP repository disturbed by future human activity, the committee has noted three ways in which confidence in the performance of the repository could be increased:

1. Re-evaluation of the probability and/or consequences assigned to highly speculative scenarios of future human activities may reduce the estimated risk of radionuclide release.
2. Experimental and field programs in progress or planned may show that key parameters (e.g., actinide transport) are well within the range required to reduce the impacts of human activities on radionuclide releases substantially.
3. The implementation of available engineering options (e.g., compartmentation, treated backfill), which have not been considered in published DOE analyses, could reduce the consequences of human intrusion. The cost effectiveness of these options will depend on the outcome of (1) and (2) above.

The committee believes that some combination of the above three considerations will very probably be sufficient to allow DOE to demonstrate that a WIPP repository will keep radionuclide release within acceptable levels for the disturbed case.

Chapter 1

Introduction

The Waste Isolation Pilot Plant (WIPP) is an underground facility in bedded salt approximately 658 m (2,160 ft.) below the surface in a semi-arid region near Carlsbad, New Mexico, in the southeastern corner of the state (see Figure 1.1). A U.S. Department of Energy (DOE) facility, WIPP has been studied intensively to determine its suitability as a permanent repository for disposal of the category of intermediate-level radioactive waste known as defense-related transuranic (TRU) waste.

WIPP is a pioneering effort in the assessment of geological site suitability and design procedures for a waste repository. It is the first geological repository in the nation for which an application to begin permanent geological isolation is being submitted for a regulatory decision. If approved, WIPP will be the first "deep" designed repository in the world. (The low and intermediate-level radioactive waste repository at Olkiluoto, Finland, is located at a shallower depth of 125 m; the German repository near Morsleben is an abandoned salt mine, not designed initially as a repository.)

This report discusses the key technical issues that influence the suitability of WIPP for isolation of TRU waste. This chapter describes the radioactive wastes under consideration for storage at WIPP, the design concept of long-term storage in geological formations, and a brief description of the history of work at the WIPP site. Following chapters address specific technical issues that arise in considering the various pathways or scenarios by which radionuclides could move from the repository and be released to the accessible environment.

TRANSURANIC WASTE: WHAT IT IS, WHERE IT COMES FROM, WHERE IT MUST GO

Transuranic waste results chiefly from the production of nuclear weapons from plutonium and enriched uranium. The term transuranic indicates that the waste contains radionuclides with atomic numbers greater than 92, that is, greater than that of uranium (see Box 1.1). Existing amounts of the principal isotopes of these and other elements and estimates of their projected total quantity in DOE facilities are listed in Table 1.1.

TRU waste consists of a wide variety of contaminated materials from laboratory and production operations, including discarded protective clothing, laboratory test equipment and reagents, machine components, and solidified sludge. This waste has accumulated over the past 50 years as a result of weapons development and production at U.S. defense facilities. Future TRU waste generation is expected to come from cleanup of the contaminated sites and decommissioned facilities of the U.S. weapons complex. Packed in 55-gallon steel drums and wooden boxes, TRU waste currently is being stored at various sites across the nation.

Although not as hazardous as high-level waste (see Table 1.1), TRU waste contains long-lived radionuclides that, if released to the biosphere, pose a risk to humans and the environment for many thousands of years into the future. Of all the actinide isotopes, plutonium-239 (Pu-239) is the one of greatest concerns substantially beyond about 500 years because of its high concentration in the materials to be stored at WIPP (Table 1.1) and its long half-life. Because of its long-lived toxicity, TRU waste, like high-level waste, must be isolated from the biosphere for times greater than 10,000 years. Disposal in deep, stable geological formations, so that very little of its radioactive content will reach the accessible environment by any natural means, has been proposed. The WIPP facility has been designed for the disposal of defense-related TRU waste to meet these conditions.

BOX 1.1 What Is Transuranic Waste?

The Department of Energy, which is responsible for the management and disposal of defense-related TRU waste, uses the following definition: TRU waste is waste that is not high-level waste and that is "contaminated with alpha[1]-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram" (DOE Order 5820.2A). The Land Withdrawal Act of 1992 and the EPA 40 CFR part 191 contain the legal, regulatory definitions that agree with this language. Further details on exclusions and inclusions to WIPP-bound waste are contained in these references.

The most important transuranic elements for judging the suitability of WIPP as a TRU waste repository are plutonium (Pu), the major component; americium (Am), a moderate component; and neptunium (Np), a minor component because of its relatively lower inventory. Common usage of the term TRU waste often includes all elements in the actinide group with atomic number 90 (thorium) or higher. Thorium (Th) and uranium (U) isotopes are minor components of the WIPP inventory (Table 1.1), smaller components than americium. Other radioactive elements are present in the waste but in amounts so small that they have a less significant influence on the determination of the performance of the proposed repository.

Some of the isotopes of the actinide elements are long-lived alpha emitters with half-lives ranging up to billions of years. For many isotopes, however, the concentrations are low. Plutonium-239 (Pu-239), with a half-life of about 24,000 years, is the isotope of greatest abundance beyond about 500 years.

The radioactive constituents of TRU waste pose a radiological health hazard and are regulated by EPA in 40 CFR 191 and 40 CFR 194. Some TRU waste is mixed with chemically hazardous materials (e.g., certain toxic metals and organic compounds); the health consequences of exposure are derived from the chemical effect of these materials on the human body. EPA standards in 40 CFR 268 (also known as the Resource Conservation and Recovery Act of 1976, or RCRA) regulate the chemically hazardous constituents. An amendment (P.L. 104-201) to the WIPP Land Withdrawal Act (P.L. 102-579) exempts WIPP from federal RCRA requirements.

[1]Radionuclides that emit positively charged (alpha) particles in the process of decaying to more stable nuclides. Alpha radiation is the least penetrating of the three common forms (beta and gamma radiation are the other two) and cannot penetrate human skin. However, alpha emitters can be harmful if ingested or inhaled, or if they enter the body through other means, for example, through contact with a cut in the skin.

GEOLOGIC DISPOSAL OF RADIOACTIVE WASTE IN SALT

The objective of the U.S. nuclear waste disposal program is to place the waste in a location where harmful quantities cannot return to the biosphere by any foreseeable processes. The decision to develop a waste disposal facility in salt arose from an assessment by a committee of the National Research Council (NRC) appointed to study the problem of how to dispose of accumulating inventories of high-level radioactive waste. In its report, *The Disposal of Radioactive Waste in Land,* published in 1957, the committee recommended further work to assess the suitability of burying high-level radioactive wastes in stable geological formations at depths on the order of 500-1,000 m below the surface (NRC, 1957). Every other country that must deal with radioactive waste isolation, including Belgium, Canada, China, Finland, France, Germany, Japan, Russia, Sweden, Switzerland, Taiwan, and the United Kingdom, plans to use geological disposal to isolate radioactive waste.

The 1957 committee was particularly attracted to the notion of burying the waste in rock salt, either in salt domes or in thick salt beds It cited the following advantages:

- Salt can be mined easily.
- It is known to flow slowly under the pressure of overlying beds, and so will consolidate around the waste and isolate it in place.
- It is essentially impermeable.

TABLE 1.1 December 1995 Estimates of Inventory of Actinide Waste[a]

	CH-TRU	RH-TRU
Total anticipated activity (Ci), all isotopes	7,880,000	1,020,000
Design capacity of WIPP (m^3)	168,500	7,080
Total anticipated volume of WIPP (m^3)	110,000	27,000
Average activity WIPP TRU waste (Ci/m^3) [b]	46.8	143
Average activity of anticipated volume (Ci/m^3) [c]	71.6	37.8

Isotope	Half-life[e] (years)	Total CH-TRU (Ci)	Total RH-TRU (Ci)
Th-232[d]	1.41×10^{10}	9.11×10^{-1}	9.24×10^{-2}
U-233[d]	1.59×10^{5}	2×10^{3}	3.18×10^{1}
U-234[d]	2.45×10^{5}	5.53×10^{2}	3.93×10^{1}
U-235[d]	7.0×10^{8}	1.28×10^{1}	5.2×10^{0}
U-238[d]	4.47×10^{9}	3.96×10^{1}	1.44×10^{0}
Np-237	2.14×10^{6}	5.49×10^{1}	4.85×10^{-2}
Pu-238	8.77×10^{1}	3.8×10^{6}	1.45×10^{3}
Pu-239	2.4×10^{4}	7.82×10^{5}	1.03×10^{4}
Pu-240	6.5×10^{3}	2.08×10^{5}	5.07×10^{3}
Pu-241[d]	1.44×10^{1}	2.61×10^{6}	1.42×10^{5}
Pu-242	3.7×10^{5}	1.17×10^{3}	1.5×10^{-1}
Am-241	4.33×10^{2}	4.39×10^{5}	5.96×10^{3}

NOTE: CH-TRU = contact-handled transuranic waste; RH-TRU = remote-handled transuranic waste. The design capacity of RH-TRU is legally specified as 250,000 cubic feet (7,080 cubic meters). As the table shows, the anticipated volume specified in (DOE, 1995c) exceeds this quantity. This discrepancy could be resolved by a future change in the numerical estimates of anticipated volumes, or by a future renegotiation to augment the legally specified limit, or by waste processing to reduce the volume of the RH-TRU transported to WIPP to be less than the volume generated. Both DOE documents and EPA standards measure radioactivity in curies, where one curie, 3.7×10^{10} disintegrations per second, is the historical unit representing approximately the radioactivity of one gram of radium 226. The Systeme Internationale (SI) unit for radioactivity is the Becquerel, 1 disintegration per second. U. S. regulations express dose equivalent in roentgen-equivalent-man (rem) units, another historical unit differing from the SI unit, the Sievert (Sv), where one Sv is 100 rem. Because the U. S. work on WIPP uses these older units, they are used in this report.

[a] Not shown are minor concentrations of many other isotopes.

[b] The Ci/m^3 values shown here derive from the total activity (Ci) and the design capacity of the WIPP repository (m^3). By comparison, the average activity of U.S. spent fuel high level waste is 140×10^3 Ci/m^3 (10-year-old waste) and 140×10^2 Ci/m^3 (100-year-old waste). See Roddy et al. (1986).

[c] The Ci/m^3 values shown here indicate the ratio of total activity in curies (Ci) to the total anticipated volume (m^3) of waste to be shipped to WIPP.

[d] Because the half-life of Pu-241 is less than 20 years, it falls outside the EPA 40 CFR 191 definition of TRU waste, although it is a transuranic isotope. The thorium and uranium isoptopes are likewise actinides shown here that are excluded from classification as TRU waste, since they are not transuranic isotopes.

[e] The level of radioactivity decreases exponentially with time, with the half-life denoting the time at which the initial amount of any radionuclide is halved. After ten half lives, approximately 0.1 percent of the initial radioactivity remains. For long times, the WIPP inventory is dominated by Pu-239, ten half lives of which is a quarter of a million years. This time, at which approximately 0.1 percent of the initial amount of Pu-239 remains, is only roughly 0.1 percent of the present age of the geologic formation in which WIPP is excavated.

Source: (DOE, 1995c, Tables ES-3, ES-4, and 3-4).

• Salt that has existed underground for millions of years will almost certainly remain stable for thousands of years into the future.

These advantages, and others also, were noted in a subsequent study (NRC, 1970).

HISTORY OF WIPP

Selection of the present WIPP site came after rejection of a previous candidate site, an abandoned salt mine near Lyons, Kansas. Investigated from the mid-1960s to the early 1970s, the Kansas site was abandoned because of the large number of boreholes penetrating the formation and salt dissolution issues (Powers et al., 1978). Renewed efforts at a nationwide site selection and characterization process resulted in a focus of attention on the New Mexico region of the Delaware Basin (see Appendix A).

Exploratory drilling began in 1974 for a possible deep geologic TRU-waste disposal site in salt beds in New Mexico. The first location selected for study was rejected as the permanent site principally because of irregular subsurface geology (Powers et al., 1978). Recommendation of the present site was made in 1975. In 1976, the name "Waste Isolation Pilot Plant" was given to the project, and ERDA-9, the first exploratory hole located at the present site, was drilled (Powers et al. 1978; NRC, 1984). In 1979, the WIPP site, about 40 km, (25 miles), east of Carlsbad, NM in the southeastern corner of the state (Figure 1.1), was authorized, after preliminary testing, as a "research and development facility for demonstrating safe disposal of radioactive waste from defense activities and programs" (U.S. Congress, 1980). Construction of WIPP, together with studies of its suitability as a TRU repository, proceeded through the 1980s.

THE WIPP UNDERGROUND FACILITY TODAY

The WIPP facility is located approximately 658 m below the surface in the layered salt of the Permian Salado Formation (see Figure ES.1). Four vertical shafts from the surface provide access to the repository horizon and underground excavations. Drifts (underground roadways) link the shafts to the waste disposal area, which is planned to consist of eight panels (the rectangular sections off the main haulage ways in Figure ES.1), each subdivided into seven rectangular rooms excavated between access drifts (corridors that provide passage to the individual disposal rooms, bounded by 30.5-m-wide pillars on each side). To date, only one of these panels has been excavated. Disposal room dimensions are 4 m high by 10 m wide by 91 m long. The drifts are essentially the same height but narrower than the rooms and are of varying lengths. Rooms have been excavated to follow the nonhalite marker beds that occur throughout the Salado, which dip at about 1° (from horizontal) to the south. Thus, the system of excavations is essentially horizontal.

THE DISPOSAL PLAN

The disposal plan involves stacking TRU waste-filled drums in each room until the room is filled. Some material may be packed into the spaces around the drums to fill the void spaces, a process termed "backfilling." Waste-filled rooms could be backfilled with crushed salt (excavated from the repository); crushed salt mixed with bentonite (a water-absorbing clay mineral); other materials combined with the salt (e.g., additives to reduce the solubility of plutonium in brine); or grout (Butcher, 1990; DOE, 1991). The specific plans for backfill have not been revealed in repository designs published prior to 1996.

A separate series of drifts and rooms for underground experiments has been excavated at the north end of the facility, several hundred meters from the disposal area (Figure ES.1). Various underground tests have been performed since the 1980s (see, for example, Butcher and Mendenhall, 1993), but these are now considered complete. The experimental area will not be used for waste disposal.

REGULATION AND LICENSING OF WIPP

In 1992, the WIPP Land Withdrawal Act (LWA; P.L. 102-579) transferred control of land at the WIPP site from the Secretary of the Interior to the Secretary of Energy and granted authority to the Secretary of Energy to close the area and its immediate surroundings to public use. A major provision of the LWA requires

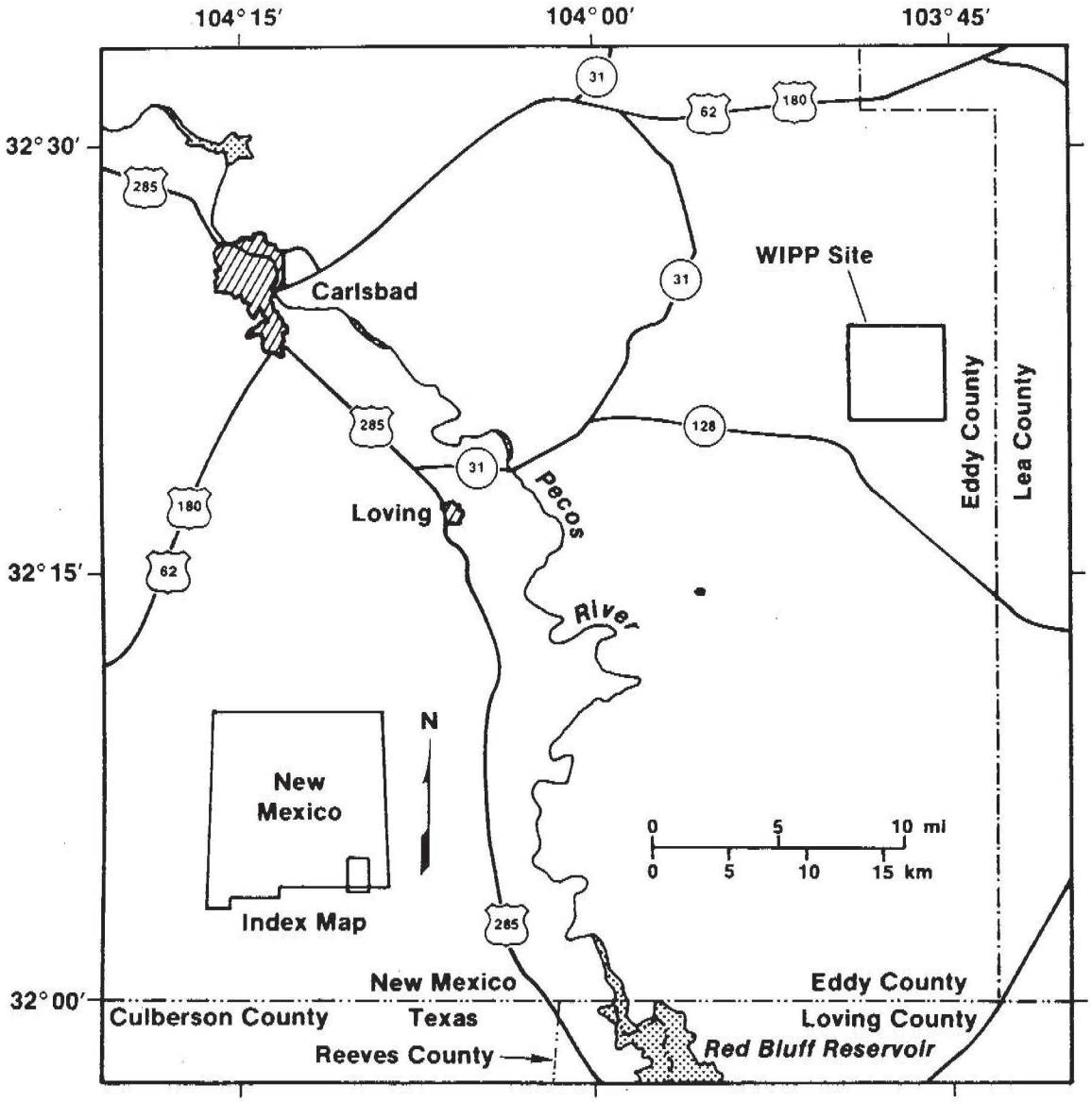

FIGURE 1.1 Location of the Waste Isolation Pilot Plant site. Inset map shows approximate location of map area in the state of New Mexico. Source: Modified slightly from Sewards et al. (1991, Figure III-1).

BOX 1.2 Compliance and Safety

The U.S. Environmental Protection Agency is responsible for ensuring that any U.S. geological repository for radioactive waste does not result in significantly adverse effects on human health and the natural environment. Federal standards have been promulgated to this end, and any proposed repository must be shown to be in compliance with these standards before it can be opened and operated to accept waste. When applied to a particular repository such as WIPP, features not anticipated in formulating the *compliance* standards could affect the overall *safety* of the repository. It is conceivable that a repository could comply with the standard, yet be significantly more or less safe than the measure of safety implicitly understood when the standard was formulated. This distinction could be important, because the federal standard (40 CFR 191) has never been applied to a real repository licensing situation.

The difference between compliance and safety can be illustrated by a simple example from the WIPP repository. EPA has defined the "accessible environment" as the region outside a 5-km-radius vertical cylinder around the center of the WIPP site, extending downward without limit from the surface (see Figure 1.2). DOE has chosen to define the boundary used in the compliance calculations as a smaller region, a 4 mile (N-S) by 4 mile (E-W) square region (6.4 km by 6.4 km square region) placed centrally within the 5-km-radius circle and also extending downwards without limit from the surface. Any migration of radionuclides across this boundary in excess of limits specified in the standard (40 CFR 191) constitutes a violation—that is, a failure to comply. This is independent of the depth at which the migration occurs and without consideration of the pathway by which the radionuclides would reach the surface.

Most of any "escaping" radionuclides would reach the accessible environment by transport in water. At WIPP, the most probable "escape route" to the surface is in the brine of the Culebra Dolomite, but this brine is for the most part undrinkable, even to cattle. This greatly reduces the safety risk compared to transport of the same quantity of radionuclides in fresh water. However, the containment requirement of the EPA standard does not address the potability of water containing the released radionuclides. Releases to salty, unpotable water near the surface thus may pose a *compliance* problem while presenting little *safety* hazard.

The committee found no probable situation for which the WIPP repository could be found to be in compliance with 40 CFR 191 and yet not be safe.

DOE to show that the repository will comply with federal regulations. The LWA designated the Environmental Protection Agency (EPA) as the regulator to determine whether or not compliance with appropriate regulations has been achieved (see Box 1.2). Chief among EPA regulations is the 40 CFR 191 standard, which describes general radiation protection requirements. Two other important regulations are EPA's 40 CFR 194, which describes the specific requirements at the WIPP site for compliance with 40 CFR 191; and EPA's 40 CFR 268 Resource Conservation and Recovery Act (RCRA) requirements on the chemically hazardous constituents of WIPP-bound waste.

Over the past two decades, DOE has conducted an extensive program of investigations to assess the suitability of WIPP as a TRU waste repository—that is, as a site that will adequately isolate the waste from the environment. Sandia National Laboratories has served as chief technical adviser, with help from many sources, including the nearby Los Alamos National Laboratory, several other national laboratories, the U.S. Geological Survey, universities, and private engineering and consulting firms.

FRAMEWORK FOR THE REPORT

Presently, DOE is preparing an application to the EPA for a certification of compliance of the WIPP facility to demonstrate that the proposed repository meets regulatory requirements. Because the compliance certification application consists largely of conclusions drawn from DOE's scientific and technical investigations, it is timely to comment on results of the committee's investigations to date and their implications with regard to the overall performance of WIPP as a repository for TRU waste. Like the previous studies of the WIPP Committee (NRC, 1984), this

report is a review of ongoing activities and should be viewed as a progress report rather than a final evaluation (see also Box 1.3).

Analyses of the performance and regulatory compliance of WIPP are addressed via performance assessment (PA), a process for identifying, for hypothetical future conditions, the potential pathways by which radionuclides could most probably be released to the environment. Chapter 2 reviews the allowable releases of radionuclides in EPA standards, describes the PA methodology used to demonstrate compliance with these release limits, and discusses PA results related to WIPP.

A detailed examination by DOE has been carried out over the past decade to study possible ways in which releases could occur, ranging from inadequate sealing of the repository to meteorite impact, climatic change, glacial erosion of the overlying formations to expose the waste, and many others. These possibilities were reduced by DOE to the 75 most credible features, events, and processes (FEPs), which were then examined in greater detail.

This examination indicated that eight combinations of events, or scenarios, warranted careful scrutiny (see Figure 2.2). From this group, the so-called "E1E2" scenario emerged as potentially the most serious way in which the isolation integrity of the repository could be violated. This scenario, which is discussed in more detail in Chapter 2 (see Figure 2.5), involves the drilling, some time within the next 10,000 years, of two oil or gas wells (either for exploration or for production), both of which intersect the repository. One of the wells also connects into a large reservoir of pressurized brine in the Castile Formation below the repository. It is further assumed that both wells would be "capped" (that is, sealed) near the surface and that the well casings would have corroded so that brine from the Castile could flow under high pressure through the repository, up the second hole, and into the Rustler Formation (principally the Culebra Dolomite), which lies above the Salado Formation. From there, the radionuclide-contaminated brine could flow more or less horizontally in the regional ground-water system, eventually reaching the accessible environment via a well drilled into the Rustler Formation to provide drinking water for cattle.

Detailed investigation of the factors that could influence the radionuclides released by the E1E2 and other scenarios has led to the identification of several issues that could be important in demonstrating the suitability of WIPP as a TRU waste repository. Chapters have been arranged to cover each of these issues. The performance assessment methodology used to calculate compliance integrates information from geological, hydrological, chemical, and repository design influences on radionuclide releases to the environment. The geological and hydrological influences of the salt beds that serve as host rock for the repository are discussed in Chapter 3. The significance of repository design options and waste treatment are discussed in Chapter 4. The chemistry of the radionuclides in brine and mechanisms of radionuclide

BOX 1.3 NRC Committee on WIPP

In March 1978, DOE asked the NRC to review the scientific and technical criteria and guidelines for designing, constructing, and operating the Waste Isolation Pilot Plant to isolate radioactive wastes from the biosphere. The panel (now committee) on the WIPP was established within what is now the NRC's Board on Radioactive Waste Management.

Since 1978, the committee has provided guidance to DOE on the scientific and technical adequacy of DOE programs designed to assess both the capability of the facility to isolate TRU waste and the overall performance of the facility. Two current members (Fred Ernsberger and former Chair Konrad Krauskopf) served on the original 1978 panel; three others (John Blomeke, Rodney Ewing, and Charles Fairhurst) began service in 1984.

The last comprehensive report issued by the committee was in 1984 (NRC, 1984). Eight letter reports on specific issues at WIPP (NRC, 1979a,b, 1987, 1988a, b, 1989, 1991, 1992) also have been produced by the committee.

The committee's current official statement of task is as follows:

> The Waste Isolation Pilot Plant Committee would prepare a report on the current status and progress of the scientific and technical issues that form the core of a submission by DOE to EPA for certification of the WIPP facility as a safe long-term repository for radioactive transuranic waste that complies with relevant regulations.

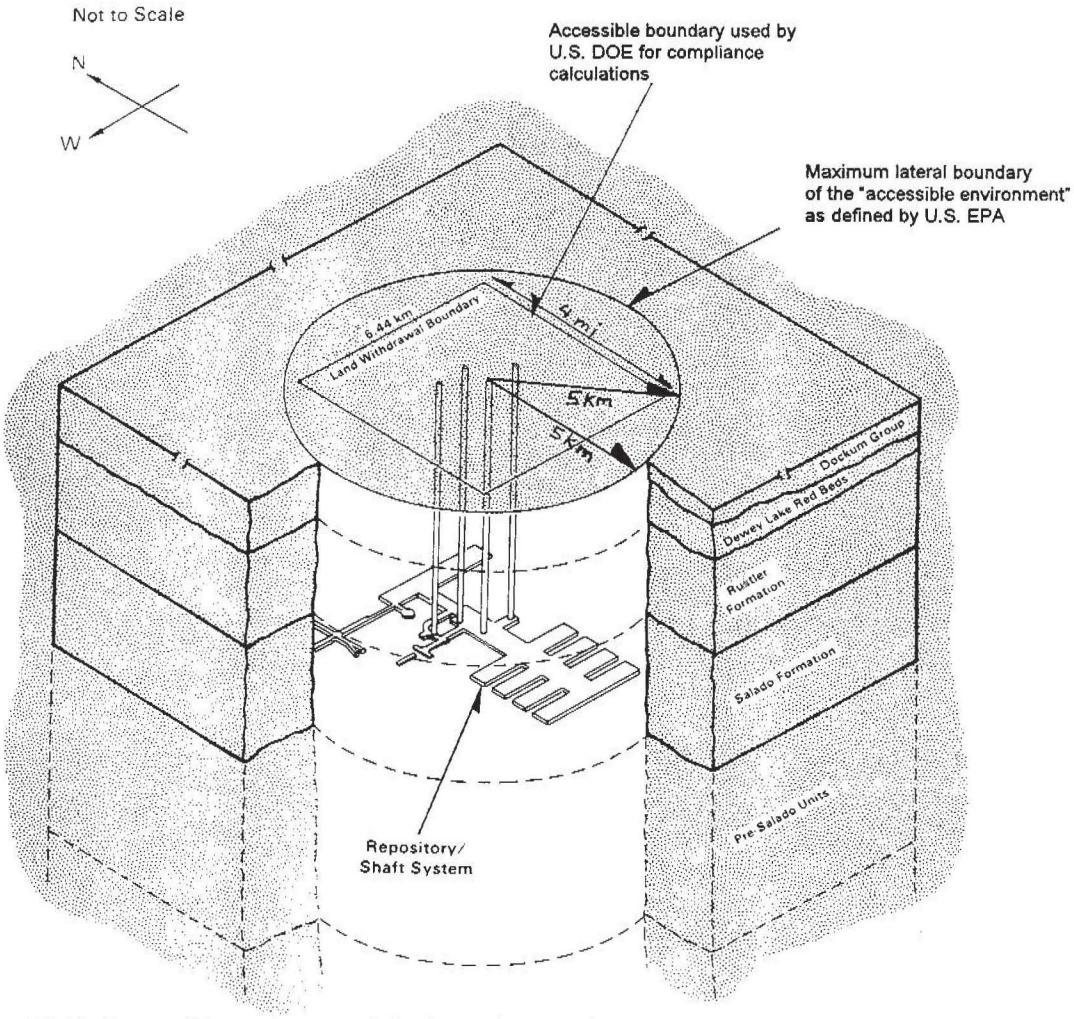

FIGURE 1.2 The EPA's "accessible environment" is shown here as the region outside a vertical cylinder of 5-km radius, centered on the WIPP repository. DOE calculations are aimed at demonstrating compliance within a smaller region, a volume bounded by vertical sides that extend downwards without limit from a 4 mile by 4 mile (6.4 km by 6.4 km) square cross section. Source: Adapted from Marietta et al. (1989, p. II-3).

transport in the subsurface environment are discussed in Chapter 5. Chapter 6 discusses the state of knowledge of the hydrological characteristics of the geological strata above the salt at WIPP, that is, the strata that would serve as a final barrier to releases of radionuclides to the accessible environment. Finally, Chapter 7 provides a summary of the conclusions reached in the committee's investigations. The first seven appendixes to the report provide supplementary information on specific aspects of the chapter discussions. An overview of the WIPP program, intended to assist readers in following the main themes and findings of the report, is presented in Appendix G.

The focus of the committee's review has been on the long-term, post-closure performance of WIPP. The issues associated with the operational phase, both surface and sub-surface, as well as the activities that must occur at other DOE sites, are not included in this evaluation. It is the committee's belief that the scientific basis for these other activities, both by DOE and by the various regulatory agencies involved, has been considered adequately in previous reports, except for a few issues that cut across both the operational phase and the post-closure phase. An example of this type of activity is waste characterization, which is discussed in Chapter 2.

Chapter 2

Regulatory Compliance and Repository Performance

To dispose of transuranic (TRU) wastes in the Waste Isolation Pilot Plant (WIPP), the Department of Energy (DOE) must demonstrate that the repository complies with applicable regulatory standards. These standards address

- transport of TRU wastes to WIPP,
- protection of workers from hazardous materials and mining hazards during operations, and
- the long-term performance of WIPP after wastes have been emplaced and the facility has been closed.

This report focuses on the third issue.

Two general standards of the Environmental Protection Agency (EPA), the first of which is defined in two parts, concern long-term repository performance:

1. a. EPA's *Standard for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Wastes,* 40 CFR Part 191 (or "Part 191"): 40 CFR 191 specifies requirements of geologic disposal systems in the United States.

   b. EPA's *Criteria for the Certification and Determination of the Waste Isolation Pilot Plant's Compliance with Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*, 40 CFR Part 194 (or "Part 194"): 40 CFR 194 addresses the specific application of 40 CFR 191 to WIPP.

2. The Resource Conservation and Recovery Act (RCRA) of 1976, 40 CFR Part 268: This law establishes a procedure to track and control hazardous wastes from the time of generation to the time of disposal.

This chapter is devoted mainly to a discussion of what is and what is not known by the committee about the long-term performance of WIPP in terms of the EPA standards. Compliance issues relating to RCRA are addressed in less detail. Issues associated with operations of the repository and transportation of waste to the repository are not considered. The most likely pathways, or "scenarios," through which radioactive materials could be released to the accessible environment are described, together with the performance assessment (PA) approach used to evaluate those scenarios against the EPA standards and some of the results to date. The chapter concludes with comments on the quality of the performance assessment work for WIPP, a brief discussion of other long-term radiological compliance issues, and some overall conclusions.

EPA STANDARDS FOR RADIOACTIVE WASTE

The EPA standard for long-term isolation of the types of radioactive wastes intended for emplacement in WIPP consists of both (1) the quantitative containment requirements and individual and ground-water protection requirements, and (2) the more qualitative assurance requirements, which are intended to provide confidence that the desired level of protection is achieved. The assurance requirements for waste characterization and monitoring are discussed later in this chapter.

A key aspect of the quantitative standards of 40 CFR Part 191 is the distinction between disturbed and undisturbed performance of the repository.

Undisturbed and Disturbed Repository Performance

Undisturbed performance refers to the case in which any releases of radionuclides to the accessible environment occur as the result of reasonably foreseeable natural processes. Releases due to human intrusion or from unlikely natural events—defined in

Part 191 as events having less than a 1 in 10,000 chance of occurring in 10,000 years—are excluded from the undisturbed case.

Undisturbed performance of the repository is governed by the individual and ground-water protection requirements of 40 CFR Part 191. The individual protection requirements limit the committed effective dose to any individual resulting from releases from the undisturbed repository to 0.15 milliSievert (15 mrem) per year. The ground-water protection requirements set concentration limits for potable sources of ground water that might come in contact with the wastes.

Disturbed performance includes consideration of inadvertent human intrusion into the repository. The EPA standard, Part 191, and supporting guidance require that releases of radionuclides resulting from drilling into the WIPP repository be considered, along with other specified disruptive events, named below, that could affect the performance of the repository. **The containment requirements, reproduced below, apply to the disturbed performance of the repository.**

Part 194 directs DOE to assume that the frequency of boreholes drilled into the WIPP site be based on the rate of drilling observed in the Delaware Basin during the 100 years prior to the time of the compliance application, by taking into account both deep drilling (i.e., boreholes that would reach the depth of the WIPP repository) and shallow drilling (i.e., boreholes that would not reach the depth of the repository). EPA specifies that the assumptions about future drilling practices with regard to borehole diameter and plugging practices should be consistent with practices in the Delaware Basin at the time of the compliance application.

Part 194 also requires that DOE consider the effect that mining of any potash of economic grade (in today's market) would have on the hydraulic conductivity of formations above the repository, and the effect that fluid injection for enhanced oil recovery in nearby oil and gas wells would have on the repository.

Containment Requirements

40 CFR 191.13 requires that

> *disposal systems for . . . transuranic radioactive wastes shall be designed to provide a reasonable expectation, based on performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:*
>
> *1. Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A)*[1]*; and*
> *2. Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).* (40 CFR 191, 1995, p. 11)

The key words in this regulation are "reasonable expectation," in recognition of the uncertainties inherent in making assessments over a 10,000-year time frame.

In paraphrasing 40 CFR 191.12, a performance assessment is defined as an analysis that identifies all significant processes and events that could affect the repository and evaluates the likelihood of each process or event and the effects of each on the release of radionuclides to the environment. To the extent practicable, these estimates are combined into an overall probability distribution displaying the likelihood that the amount of radioactive material released to the environment will exceed the values specified in Table 1, Appendix A to 40 CFR 191 (40 CFR 191, 1995, p. 11).

40 CFR 191 and 40 CFR 194 Radiation Dosage and Containment Requirements

In comparison to the radioactive waste standards adopted by most countries, Part 191 is unique in that, in addition to regulation based on radiation dose, repository compliance also is based on calculations of release fractions of selected radionuclides (Table 2.1). The containment requirement addresses the ability of a

[1]Table 1 of Appendix A of 40 CFR 191 is shown in this report as Table 2.1.

TABLE 2.1 Part 191 Containment Requirements for Selected Isotopes. Source: 40 CFR 191, Appendix A (1995)

Radionuclide	Release Limit (Ci/MTHM)
Thorium-230 or 232	10
Uranium-233, 234, 235, 236, or 238	100
Neptunium-237	100
Plutonium-238, 239, 240, or 242	100
Americium-241 or 243	100

The release limits specified here scale with the quantity of waste in a repository; for this reason, they are specified in terms of curies (Ci) that may be released per 10,000 years per 1,000 metric tons of heavy metal (MTHM). For a repository such as WIPP, which is intended to contain transuranic wastes, EPA has established in 40 CFR 191 that 1,000 MTHM is equivalent to 1,000,000 curies of TRU wastes with greater than 20-year half-lives. Therefore, the limits specified are applicable per million curies of TRU waste.

repository to isolate waste from the environment, without distinguishing releases that would lead to significant doses from those that would not. One advantage of this requirement is that, unlike a dose limit, it does not require assumptions about where people will live, how and where they will grow food, and what water sources will be used. A disadvantage is that the Part 191 containment requirements do not differentiate between transport of radionuclides off-site in a pristine aquifer that is a likely exposure pathway and—in the case of WIPP—transport via the Culebra Dolomite, in which the high content of dissolved solids makes the water unfit for human consumption.

Quantitative Assessment of Human Intrusion

Dealing quantitatively with human intrusion is a difficult issue. Any assessment of releases or risks from human intrusion into a repository is inherently arbitrary because the nature and rate of future intrusion over a 10,000-year time frame cannot be known. One advantage of basing the future human intrusion rate on the historical rate, as EPA does, is that the effect of known resources on past exploration and production activities is considered. However, whether or not this knowledge will predict accurately what may happen in the future—especially when institutional controls preventing intrusion have been lost—is uncertain. The difficulty does not concern specific details of EPA's guidance regarding how to treat intrusion in performance assessment, but rather that such guidance is arbitrary and of unknown validity with respect to how future events actually will occur. The same issue is of concern in Europe and other countries dealing with the regulation of geological repositories. In general, radionuclide releases resulting from human intrusion tend to be treated qualitatively in these countries, for example, as a consideration in site selection.

The way in which human intrusion is handled in regulations 40 CFR 191 and 194 implies that WIPP, or any potential repository, could "pass or fail" on the basis of a human intrusion scenario that is, by necessity, arbitrary, especially in its assumptions concerning future technology. **Indeed, human intrusion rates or scenarios could be devised that would cause *any* geological repository to comply or fail to comply with EPA standards.** This issue of human intrusion has been considered at length in the NRC report *Technical Bases for Yucca Mountain Standards* (NRC, 1995).

40 CFR 268 Hazardous Waste Requirements

Until recently, federal law dictated that WIPP must comply with both the radioactive waste standard (40 CFR 191) and the RCRA standard (40 CFR 268), the latter of which establishes requirements for the disposal of chemically hazardous wastes (see Box 2.1). The 40 CFR 268 standard prohibits the land-based disposal of untreated hazardous wastes under most circumstances. This "land ban" has a "no-migration" provision by which a variance can be granted to permit the disposal

Box 2.1 Chemically Hazardous Waste Issues

Based on information presented by EPA and DOE contractor staff, it appears to the committee that RCRA performance will not be a limiting factor in the long-term performance of WIPP. Nonetheless, the following simple comparison can be made of the quantities and toxicities of the radioactive and chemical constituents of WIPP waste.

Source-term data reported in DOE's 1995 Draft Compliance Certification Application (DCCA) indicate that, in an average cubic meter (m^3) of contact-handled waste, the inventory of radioactive actinides with half-lives greater than 20 years, multiplied by EPA's risk factors for ingestion of these radionuclides, is equal to 8,500.* Thus, the risk from one cubic meter of contact-handled WIPP waste, if ingested, is quite high. By contrast, the inventory of volatile organic chemicals (VOCs) in 1 m^3 of WIPP waste, multiplied by the unit risk factors for inhalation of the VOCs, is reported in the WIPP Draft No-Migration Variance Petition to equal 46.

The EPA unit risk factors are based on daily inhalation of 20 m^3 of air for 70 years. Conversion of the risk factors associated with the inhalation of VOCs in 1 m^3 of waste gives a risk of 9×10^{-5}—that is, 9 chances in 100,000. This suggests that the relative toxicity (i.e., the ratio of the quantity of hazardous material, weighted by its toxicity) of ingested radionuclides to inhaled VOCs is of the order of 10^8. If the risk factors for *inhalation* (rather than for *ingestion*) of radionuclides are used, the toxicity of radionuclides relative to that of VOCs is of the order of 10^{10}.

This simple comparison of the quantity and toxicity of the waste components supports EPA's statement that the hazardous nature of WIPP waste is due to radioactive materials and that provisions for the long-term protection of public health and the environment from radionuclides in WIPP will also offer adequate protection against public health risks from chemical hazards.

* Normally, the product obtained by multiplying a quantity of hazardous material by its unit risk factor is the risk associated with the ingestion or inhalation of that material. However, a risk greater than 1 has no meaning. In such cases, the resultant product should simply be considered a toxicity-weighted inventory of hazardous material.

of untreated waste if the applicant can demonstrate that the waste will not move after disposal. In 1989, DOE submitted a No-Migration Variance Petition for the planned underground test program at WIPP and received approval for a 10-year period. In 1995, a Draft No-Migration Variance Petition was submitted by DOE for full-scale operations at WIPP.

During the 104th Congress, bills (U.S. Congress, House of Representatives, 1995, 1996; U.S. Congress, Senate, 1996) were introduced to amend the WIPP Land Withdrawal Act. Among other features, these bills would exempt WIPP from compliance with long-term RCRA requirements. In hearings on a House bill, EPA indicated that it was not opposed to such a change. An attachment to a letter from Mary Nichols, EPA Assistant Administrator for Air and Radiation, and Elliot Laws, EPA Assistant Administrator for Solid Waste and Emergency Response, to Senators Craig and Kempthorne, stated that

> *. . . the Agency, therefore, believes that in the narrow context of the WIPP, which is subject to comprehensive regulation under the AEA [Atomic Energy Act], the WIPP LWA [Land Withdrawal Act], and RCRA, that a demonstration of no migration of hazardous constituents will not be necessary to adequately protect human health and the environment.* (Nichols and Laws, 1995)

In this letter, EPA indicated that, under current law, it was obligated to continue to enforce RCRA provisions at WIPP. The letter illustrates the degree to which DOE and EPA have worked in a cooperative, constructive manner to address significant issues regarding compliance with RCRA regulations. On September 23, 1996, the President signed into law (P.L. 104-201) an amendment to the WIPP LWA that exempts WIPP from the federal RCRA requirements.

PERFORMANCE ASSESSMENT

Performance assessment (PA) encompasses the overall process of assessing whether or not a waste disposal system meets a set of performance criteria. For the WIPP PA, the system is a deep geologic repository disposal system in bedded salt for DOE TRU waste, and the performance criteria are various

long-term environmental metrics in U.S. government regulations (Rechard, 1995, p. Glos-14).

Methodology

Iterative PAs of WIPP are being performed for DOE by Sandia National Laboratories. The performance assessments are intended to provide interim guidance while final compliance evaluations are being prepared.

The methodology has been developed to calculate a performance measure in the form of a complementary cumulative distribution function (CCDF) that permits comparison with the EPA release limits for radioactive waste disposal. The CCDF, a generally accepted form for depicting risk by a specific performance measure, was popularized by the Reactor Safety Study (U.S. Nuclear Regulatory Commission, 1975) for point estimates and by the Zion/Indian Point risk studies performed by industry (Pickard et al., 1981) for estimates with uncertainty. For WIPP performance assessments, the performance measure takes the form of normalized releases to the accessible environment of the radionuclides listed in Table 2.1. Under a normalized release limit, the estimated release is reported as the fraction of the release limit allowed under Table 1, Appendix A of Part 191. A release estimate equal to the allowable limit would be a normalized release of 1. Figure 2.1 is a hypothetical CCDF illustrating compliance with the 40 CFR 191.13 containment requirements.

The basic framework of the WIPP performance assessment methodology is the Kaplan and Garrick (1981) "triplet" definition of risk. This definition of risk is founded on the principle that to determine risk, the following three basic questions must be answered:

1. What can go wrong?
2. How likely is it to go wrong?
3. What are the consequences?

"What can go wrong" is examined in the form of scenarios that can lead to releases of specific radionuclides to the accessible environment; "how likely," is examined by calculating the probabilities of those scenarios; and the "consequences" are examined in terms of the overall likelihood of various levels of release. The results are then cast into CCDFs of the form illustrated in Figure 2.1. The procedure for developing the CCDFs results in a structured set of scenarios leading to the specific consequences of interest; summing the probabilities of the scenarios for each release set; and plotting the complementary cumulative probabilities as a function of normalized release rates, usually on log-log coordinates (see Appendix B for more details).

A key part of the performance assessment model involves deciding on an appropriate set of scenarios, that is, identifying what can go wrong. The WIPP performance assessment team used the following five-step selection process for human-initiated scenarios (Cranwell et al., 1990):

1. compiling features, events, and processes (FEPs) that could affect the disposal system;
2. classifying events and processes to enhance consistency and completeness;
3. screening individual events and processes;
4. combining events and processes into specific scenarios; and
5. screening scenarios to identify and eliminate those that have little or no effect on the performance assessment.

Final selection of the scenarios in Figure 2.2 was based on screening events and processes according to probability, consequence, and physical reasonableness. The process resulted in the set of eight scenarios illustrated, although calculations were made on the basis of the first four scenarios only. A more detailed discussion of scenarios is presented later in this chapter.

The complexity in the performance assessment results from two main factors:

1. The numerous variables (approximately 50 in all) that represent the hydrological, chemical, mechanical, thermal, and transport processes involved in the transport and physical process models.
2. The effort required to perform sensitivity and uncertainty analyses on the models.

Documentation detailing the WIPP performance assessment effort includes a wide range of source materials documented in various reports and studies—including a 1992 Performance Assessment (the 1992 PA; Sandia National Laboratories, 1992, Vol. 3); the various iterations of the systems prioritization method (SPM; Sandia National Laboratories, 1995); and the Draft Compliance Certification Application (DCCA; DOE, 1995a).

Uncertainties in the knowledge base were propagated through the scenarios, and sensitivity studies were performed so that results of the analysis include a quantification of the uncertainties associated with the calculated release rates.

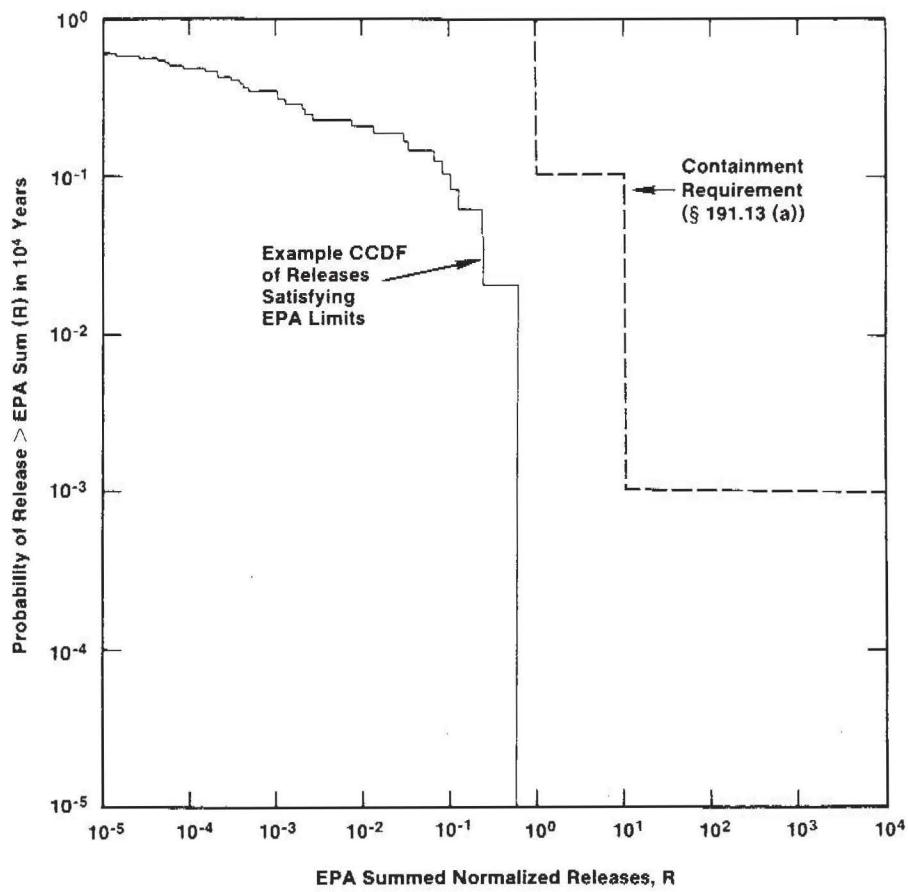

FIGURE 2.1 Hypothetical CCDF illustrating compliance with the containment requirements. Source: Sandia National Laboratories (1992, Vol. 1, Figure 3.3).

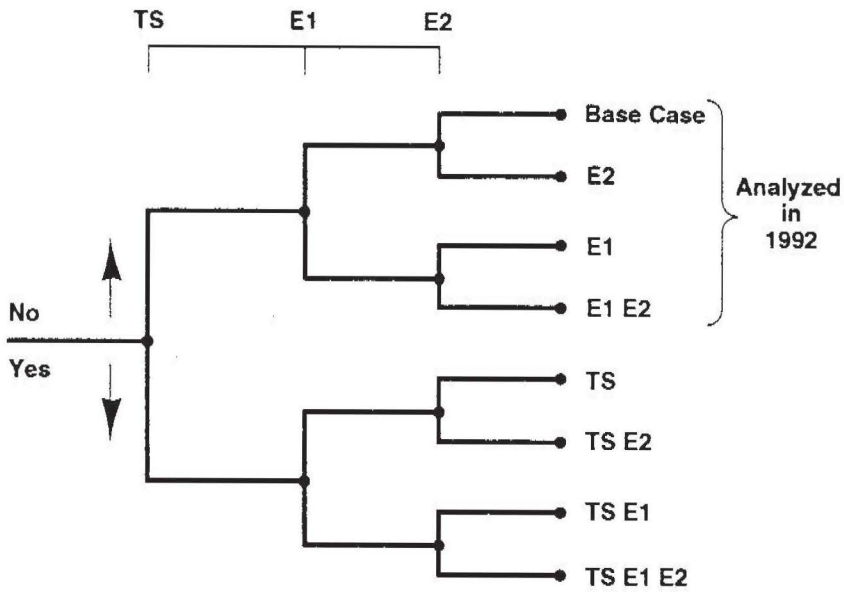

TS Is an Event in which Subsidence Results from Mining of Potash

E1 Is an Event in which One or More Boreholes Pass through Waste Panel and into a Brine Pocket

E2 Is an Event in which One or More Boreholes Pass through Waste Panel without Penetration of a Brine Pocket

FIGURE 2.2 Potential scenarios for the WIPP disposal system. Source: Sandia National Laboratories (1992, Vol. 1, Figure 4.1). NOTE: TS refers to an event in which subsidence results from potash mining; the yes/no decision answers the question of whether potash mining is considered in the scenario. The base case depicted here represents the undisturbed repository. The E1 and E2 scenarios are discussed later in this chapter (see Figures 2.4 and 2.5). For further discussion of potash mining, see Chapter 4.

Results from Containment Requirement Calculations

On March 31, 1995, DOE submitted to EPA a draft analysis of WIPP compliance with 40 CFR 191 for the undisturbed case; this multivolume submission was supplemented in July 1995 with a performance analysis for the disturbed case (i.e., human intrusion; DOE, 1995a). DOE's current schedule calls for new performance assessment calculations for the compliance certification application to be completed and documented by September 1996, for subsequent submission to EPA a month later. Earlier performance results have been published in the 1992 PA (Sandia National Laboratories, 1992) and in the SPM analyses (Sandia National Laboratories, 1995). Compared to these earlier analyses, the DCCA included updates to

the analytical codes and revisions of specific analytical assumptions, where dictated by EPA guidance (although this DOE submission predated the release of the final version of Part 194). The analytical assumptions of the DCCA appear to be largely unchanged from those of the 1992 PA and the SPM.

Although the DCCA indicates compliance with Part 191 containment requirements, the results of this analysis are too aggregated to allow any conclusions to be drawn about which scenarios and pathways contributed to the calculated releases. However, careful study of the 1992 PA does provide some insight into the relative magnitude of release scenarios.

CCDF curves summarizing radionuclide releases to the accessible environment resulting from cuttings removal and ground-water transport fall substantially below release limits promulgated by EPA. Although this is an important result, it must be noted that the rate of intrusion assumed in the 1992 analysis was less than is now required in the final Part 194, issued on February 9, 1996. The two main contributors to radionuclide releases to the accessible environment identified in the 1992 PA were (1) drill cuttings brought to the surface from exploratory drilling and (2) radionuclides transported by ground water flowing through the Culebra following human intrusion.

Some of the results from the 1992 PA with respect to the 10,000-year containment requirements of the EPA standard are as follows:

- Where the intrusion probabilities are based on expert judgment and dual-porosity transport with chemical retardation, the mean CCDF is *more than an order of magnitude below EPA limits.*[2]
- Where an intrusion rate of 30 boreholes per square kilometer per 10,000 years and dual-porosity transport without chemical retardation are assumed, the mean CCDF is *approximately one order of magnitude below EPA limits.*
- Where an intrusion rate of 30 boreholes per square kilometer per 10,000 years and single-porosity, fracture-only transport (with little retardation) are assumed, the mean CCDF is *less than an order of magnitude below EPA limits.*

These three 1992 PA results represent a sample of all the different modeling assumptions and parameter values that were examined to assess their impact on the mean CCDF. The compliance outcome is a common result, with variations on the degree of sensitivity. Of course, individual scenarios can be found to produce CCDF curves that exceed the EPA limits, but for them the important issue is their likelihood, or frequency of occurrence (see Appendix B for more details). This information is used to determine the mean CCDF curve, the one used to assess compliance.

The containment requirement for WIPP (defined by Table 1 of Part 191, shown here as Table 2.1) specifies a release limit of 100 curies of plutonium per million curies of TRU waste, equivalent to a release fraction of about 10^{-4}, at least initially. Although release limits are specified in Part 191 for various isotopes, plutonium appears to be the most significant, in terms of both the inventory and compliance. Based on inventory estimates (DOE, 1995c) adjusted for the estimated date at which the repository would be closed, the WIPP inventory of thorium, uranium, neptunium, plutonium, and americium isotopes with half-lives greater than 20 years (which determine the release limit), is around 6 million curies. The corresponding release limit for plutonium-239 (Pu-239) would be 600 curies, or about 10 kg (approximately 20 pounds).

Figure 2.3, taken from the 1991 PA (Sandia National Laboratories, 1991), describes the radionuclide inventory as a function of time. The inventory is expressed in EPA units used for a single waste panel. An EPA unit is a convenient way to express the inventory, based on release limit definitions in Appendix A of 40 CFR 191. As can be seen, after about 500 years, Pu-239 is the dominant radionuclide of concern at WIPP.

[2]The CCDF results are in the form of mean values as permitted by Appendix C to 40 CFR 191. The means were calculated from a family of curves, each representing different percentiles, and are a direct result of the uncertainty analysis. A CCDF is generated for each "realization," which consists of a particular random choice of value of each of the model parameters (a choice within the range specified for that parameter). A mean CCDF is obtained from a set of CCDF curves generated this way, by averaging the cumulative release quantity for each value of the cumulative probability (see Appendix B).

Results Regarding Individual and Ground Water Protection Requirements

As noted earlier, the EPA standard sets forth two other quantitative requirements in addition to the containment requirements: (1) individual protection requirements; and (2) ground-water protection requirements. The individual protection requirement considers the radiation dose to humans in the accessible environment for 10,000 years of undisturbed performance. Because performance assessment results indicate that for the undisturbed case, brine (the medium for radionuclide transport) in contact with waste will not migrate more than a few "tens of meters" from the waste emplacement panels in 10,000 years, the 1992 PA did not include performance estimates for individual protection requirements. Subsequent assessments (e.g., SPM, DCCA) have also concluded that, under undisturbed conditions, waste would not migrate. The PA work (DOE, 1995a, Section 8.1) uses a bounding calculation to show doses to humans resulting from brine transport to be orders of magnitude below natural background; hence, compliance with the individual protection requirement can be demonstrated easily for the undisturbed scenario at WIPP.

The PA work has noted that the ground-water protection requirement does not apply to WIPP because there is no source of potable ground water as defined in the EPA standard (Sandia National Laboratories, 1992, Vol. 1).

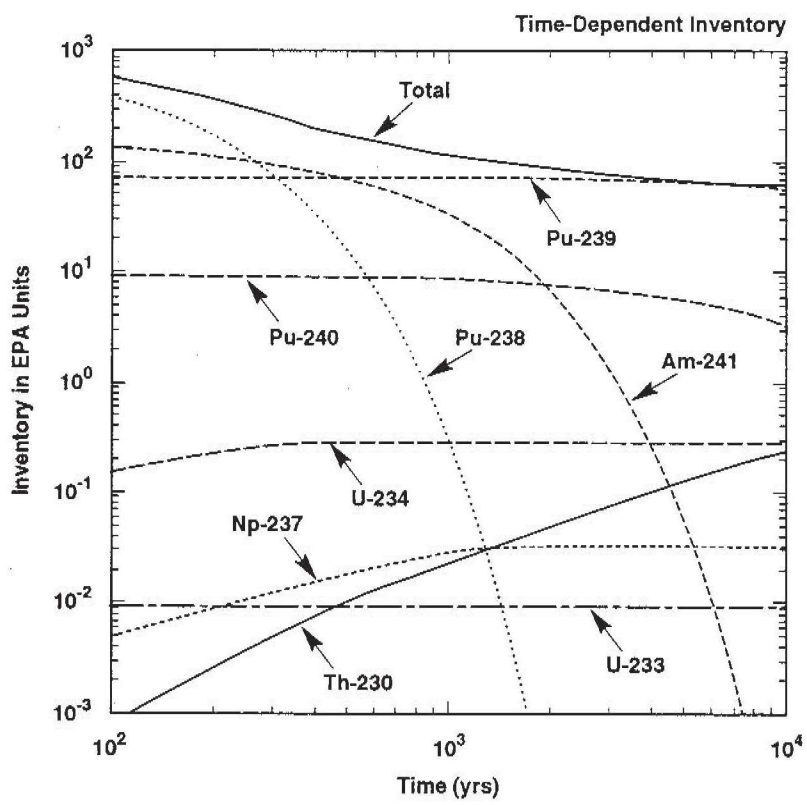

FIGURE 2.3 Time-dependent inventory expressed in EPA units for a single waste panel. Source: Sandia National Laboratories (1991, Vol. 4, Figure 2.4.2). More recent estimates (DOE, 1995c) of the WIPP inventory differ from those used in this figure.

In summary, the sole long-term radiological compliance issue is whether or not the containment requirements are met. Performance calculations indicate that if the shaft seals are effective, there will be little, if any, release or exposure from the undisturbed repository. For the disturbed case, compliance depends directly on the assumptions and analyses made for the frequency and consequences of human intrusion into the repository.

RADIONUCLIDE RELEASE SCENARIOS

Assessment of the likely performance of WIPP begins with the identification of scenarios by which wastes could be released from the repository. The scenarios that have been evaluated in greatest detail are those considered by DOE to represent the major mechanisms and routes for release of radioactive materials.

Undisturbed Case

Scenarios applicable to the undisturbed case considered in WIPP PA work include the following:

1. leakage of brines containing radioactive materials up the shaft and/or through a disturbed rock zone around the shaft up to the Culebra Dolomite and flow to the defined accessible environment via the Culebra; and
2. flow of WIPP brines directly along anhydrite marker beds in the Salado Formation-salt.

These scenarios are mentioned briefly here and represent mechanisms for potential release of radionuclides that underlie the considerations in Chapters 3 and 4.

Under the first scenario, human exposures could occur due to water extraction from the Culebra to add water to stock ponds,[3] and subsequent consumption of beef from cattle that have consumed this water. This scenario, involving flow out of the Culebra, is evaluated against both the containment requirements and the individual protection requirements.

The scenario involving flow along the anhydrite marker beds is evaluated against the containment requirements only, because the marker bed brines are not potable (Davies, 1989; Brinster, 1991; Yaron and Frenkel, 1994; Sexton, 1996), nor do they reach the surface.

Disturbed Case

Scenarios for the disturbed case involve releases resulting from boreholes drilled inadvertently into the waste. One scenario considered is the direct release of waste through drill cuttings brought to the surface. Other disturbed case scenarios include releases that occur through flow up a borehole into the Culebra dolomite, with subsequent transport in the Culebra; the effect of potash mining above the repository; and water flooding from nearby water injection for enhanced oil recovery.

Release of Waste Through Cuttings

The analysis of releases of radionuclides through cuttings brought to the surface in drilling mud includes several factors. In addition to the direct volume of waste displaced by the borehole (i.e., the area of the borehole times the repository height, with the assumption that all such wastes reach the surface), Sandia has made calculations of additional releases due to the erosion of wastes by drilling mud and the movement of wastes in the vicinity of the borehole because of internal gas pressure in the waste.

The quantity of waste intersected directly by a borehole can be determined simply from the frequency and diameter of boreholes assumed to be drilled for the period beginning 100 years after repository closure and continuing until 10,000 years after closure. The previous analyses based on the 1992 PA assumed 30 boreholes per square kilometer per 10,000 years; the current (1996) 40 CFR 194 requirement specifies that the historic record over the past 100 years should be the basis for the borehole rate, which, based on presentations to the committee by EPA and DOE staff,

[3]Without dilution, ground water from the Culebra Dolomite immediately above the WIPP repository site is not potable by livestock or humans. Potable ground water from the Culebra Dolomite in the immediate vicinity is to the southwest, which is not on a projected pathline emanating from any hypothetical release.

Box 2.2 What Fraction of Waste Is Released Through Cuttings from Boreholes?

The degree to which cuttings may contribute to total releases in comparison to the release limits of Part 191 can be illustrated by the following simple calculation. Assume N boreholes per square kilometer per 10,000 years and the surface area of the repository occupied by waste A (m^2). The expected number of boreholes intersecting the waste over a 10,000-year period (I) is then given by

$$I = N\ (\text{boreholes/km}^2) \cdot 10^{-6}\ (\text{km}^2/\text{m}^2) \cdot A\ (\text{m}^2).$$

The volume of waste W (m^3) displaced by these boreholes, by neglecting erosion and spalling and assuming a borehole area B_a (m^2), is

$$W = I \cdot B_a \cdot h,$$

where h is the repository height (m).

The fraction (F) of the repository that is released through these cuttings is simply the volume (W) of cuttings released, divided by the total repository volume (A·h):

$$F = W/A \cdot h.$$

Combining terms yields:

$$F = N \cdot B_a \cdot 10^{-6}.$$

leads to an intrusion rate closer to 45-50 boreholes per square kilometer during a 10,000-year period.

For 50 boreholes per square kilometer per 10,000 years with a 0.073-m^2 cross-sectional area (i.e., 12-inch diameter) borehole, the fraction F of waste released from cuttings (see Box 2.2) is 3.6×10^{-6} (this includes an adjustment to account for no intrusion during the first 100 years after closure). As noted above, the allowable fractional release is about 10^{-4}, initially, and increases with time. Thus, for 12-inch diameter boreholes drilled at a rate of 50 boreholes per square kilometer per 10,000 years, direct cutting releases apparently are less than 4 percent of the allowable limits. Even when allowing for increased release due to waste erosion by drilling mud and spallation, extraction of the waste as cuttings is unlikely to approach the release limits.

This calculation illustrates that the fraction of the Table 2.1 limit released as cuttings is independent of

1. the volume of waste disposed of in WIPP,
2. the geometry of the waste rooms (i.e., the ratio of height to width and length), and
3. the plutonium content of the waste.

To the extent that erosion and spallation are low in comparison to the volume of waste that would be released directly by displacement, the release fraction also does not depend on any waste treatment technology that may be employed. The cuttings release fraction *does* depend on (1) the assumed intrusion frequency, and (2) the assumed diameter of the intrusion borehole.

Therefore, the cuttings calculation is largely independent of the characteristics of the waste and the repository design. Furthermore, it is related to the location of the facility only to the extent that the location affects the assumptions made regarding the frequency and nature of intrusions over the next 10,000 years.

Release of Waste Through Boreholes: The E1 and E1E2 Scenarios

In the "E1" and "E1E2" scenarios, DOE postulates that a borehole through the repository may encounter a pressurized brine pocket in formations below the Salado Formation in which WIPP is located, resulting in the release of radioactive materials. The two specific scenarios analyzed for this type of release are illustrated in Figures 2.4 and 2.5. Figure 2.4 shows the E1 scenario, in which a single borehole penetrates the facility and continues downward into a pressurized brine pocket; Figure 2.5 shows the E1E2 scenario, in which two boreholes penetrate the repository. Because brine is assumed to migrate through the waste in the E1E2 scenario, this scenario is the more significant contributor to total calculated release.

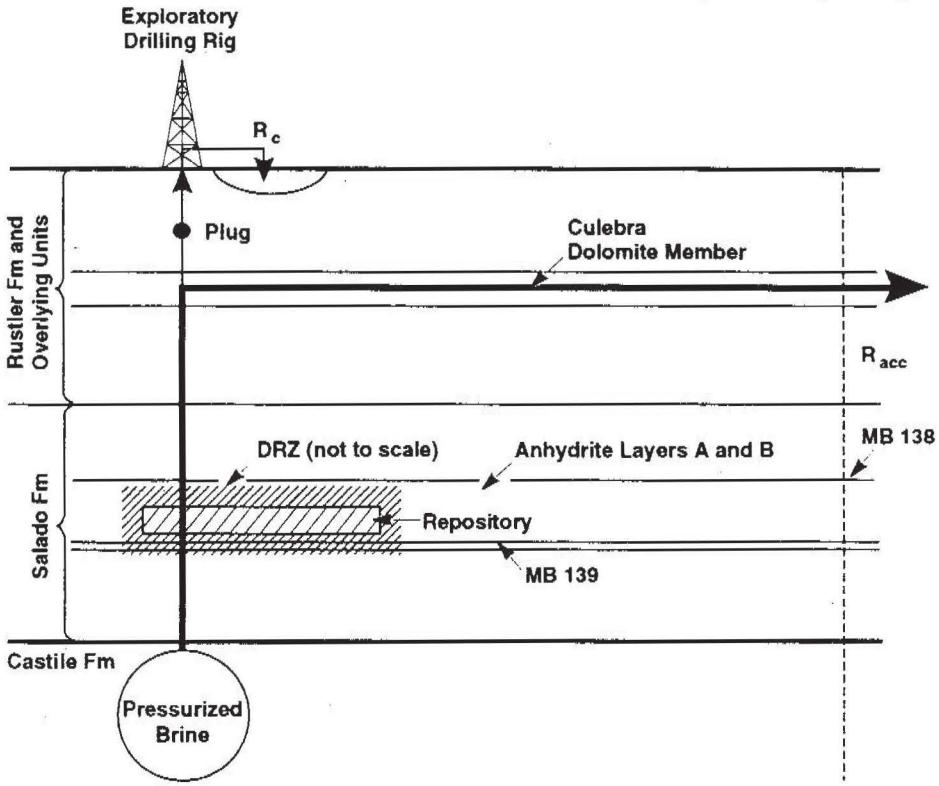

FIGURE 2.4 Conceptual model for the E1 scenario. Source: Sandia National Laboratories (1992, Vol. 1, Figure 4.2).

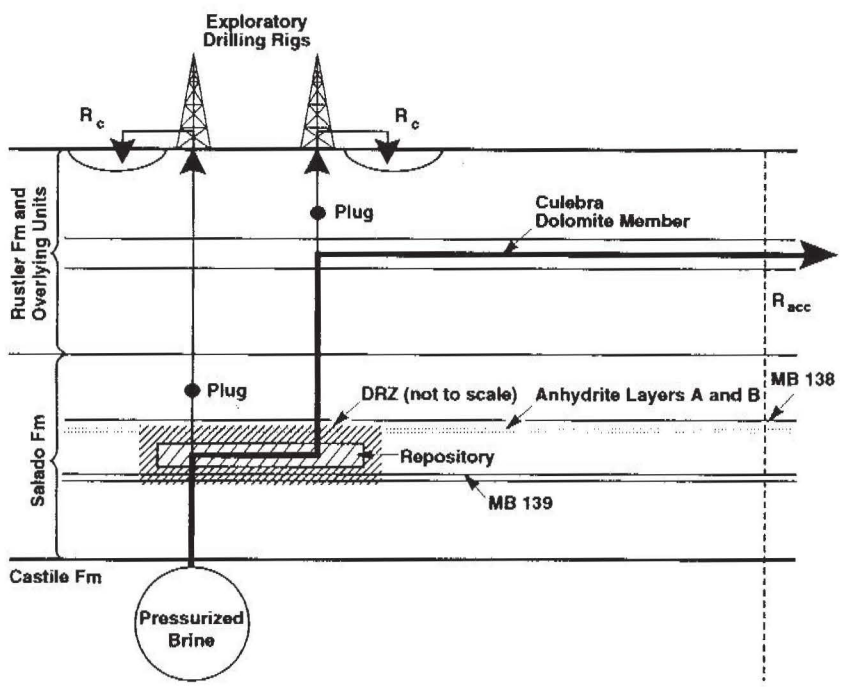

FIGURE 2.5 Conceptual model for the E1E2 scenario. Source: Sandia National Laboratories (1992 Vol. 1, Figure 4.3).

Such brine flow, presumably, would augment the salinity of existing water in the surface and shallow subsurface regions. As noted previously, ground water from the Culebra Dolomite at the WIPP site and in adjacent areas downstream of a hypothetical release already is too high in concentrations of dissolved solids to be potable to livestock or for humans. Regions of potable water from the Culebra are southwest of the site and are not in the direct path of a hypothetical release.

The rate and quantity of plutonium released to the accessible environment through the E1 and E1E2 scenarios depend on a number of factors. In PA sensitivity analyses, the three factors that were found to have a significant effect on calculated releases are

1. the solubility of plutonium in WIPP brines,
2. the potential for retardation of radionuclides in the Culebra, and
3. the potential for movement of actinides in colloids.

As a result of these PA results, expanded work to determine the effects of solubility, colloid formation and retardation on releases has been undertaken (see Chapter 5).

DISCUSSION OF PA MODELING EFFORTS

The committee believes that the PA model assessments of the E1, E1E2, and other scenarios involve technically unrealistic assumptions that have not been probed in past sensitivity analyses. For these scenarios, these technical assumptions also appear to be unreasonably conservative, specifically in the lack of credit given for compartmentation of the waste panels and rooms. These issues are discussed in more detail below.

Assumptions Regarding a Permanent Disturbed Rock Zone

Construction of the repository produces a network of stress-induced cracks that form a disturbed rock zone (DRZ) in the Salado salt bordering the excavated areas. The cracks are expected to close and heal in time due to salt creep. The permeability of the DRZ region, initially higher than that of the undisturbed halite because of these cracks, is restored to a value close to that of the intact salt over time.

The July 1995 update of the DCCA (DOE, 1995a) assumes that the salt around the repository between marker beds 138 and 139 (the anhydrite beds above and below the repository) remains an unconsolidated disturbed rock zone (DRZ) for the full 10,000-year regulatory period, with a permeability of 10^{-15} m^2. For comparison, the undisturbed halite is assumed to have a permeability that ranges between 10^{-24} m^2 (i.e., essentially impermeable) and 10^{-20} m^2. The draft compliance document does note that "although the DRZ is modeled conservatively in this assessment, it is the subject of a modeling study, and assumptions and treatment of this region may be different in the final Compliance Certification Application" (DOE, 1995a, p. 6-76).

The unconsolidated DRZ assumption appears to be inconsistent with the well-established properties of salt. A major feature of salt is that it behaves as a viscous liquid and creeps. The salt around waste rooms will reconsolidate as the pressure on the DRZ exerted by the backfilled rooms rises back to the lithostatic level. Such reconsolidation is estimated to take on the order of a few hundred years at most after repository closure.

A consequence of this conservative assumption is that boreholes that penetrate the salt between waste rooms are assumed to communicate with the waste and serve as release pathways, no matter when the boreholes are drilled. In addition, boreholes that penetrate *different panels* are analyzed as an E1E2 pathway, because under the conditions assumed throughout the entire repository, flow is calculated to occur via the DRZ. Sealing of rooms and panels so that this communication is prevented seems to the committee to be an entirely practical, cost-effective way to reduce the significance of the two-borehole (E1E2) scenario (see Chapter 4).

The more realistic treatment advocated here, of modeling time-dependent DRZ closure, adds complexity to the PA model. This complexity is warranted because it removes the non-physical conservative assumption that the DRZ does not heal. Removing an unrealistic assumption from the PA model has the added benefit of making the sensitivity analyses

derived from the PA more accurate representations of the true dependencies on parameters in the model.

Characterization of Boreholes

It is conservatively assumed in the performance assessment that boreholes retain their initial diameter and have a permeability equivalent to that of a silty sand (10^{-14} m^2) for the entire 10,000-year regulatory period, based on present information of known and defensible natural processes that would fill the hole in time. No credit is given to mechanisms that would cause the boreholes to plug or shrink or that would interrupt the hypothetical flow of radioactively contaminated brine along the greater than 650-m borehole length. However, if further study should identify a natural mechanism that would cause the flow in the boreholes to be restricted, this could result in a significant reduction in calculated releases. Flow through an E1E2 scenario can occur only if both boreholes are open. With boreholes that stay open for times that are short in comparison to the 10,000-year regulatory period (e.g., 1,000 years), some borehole pairs from drilling events at random times will not result in a release because the first borehole will have closed before the second has been drilled. Further study to develop a better understanding of potential borehole closure mechanisms is recommended by the committee to examine an important component of the model calculation of releases.

Apparent Value of Compartmentation

As noted previously, calculations of releases over 10,000 years based on a DRZ that does not reconsolidate close to the value for intact salt are unrealistic (see also Box 4.1 in Chapter 4). This overly conservative assumption prevents the creep and healing behavior of the Salado halite from being properly included in past sensitivity analyses of WIPP performance. With effects such as DRZ reconsolidation excluded from a sensitivity analysis, an opportunity is lost to evaluate the full potential for cost-effective measures to demonstrate compliance. Stated another way, realistic DRZ modeling may lead to a demonstration of compliance using a cost-effective engineering feature such as backfill, which would lessen the dependence of the compliance demonstration on the work addressing each of the three key factors enumerated above. These factors have emerged from the existing PA work and associated sensitivity analysis, and they involve technically complex experimental work. For example, addressing the first factor, that of plutonium solubility, involves completion of ongoing plutonium solubility tests that could be the time-limiting step in determining WIPP compliance, if no more straightforward and cost-effective way to demonstrate compliance were identified. If the DRZ healing behavior were included in the PA sensitivity analysis, confidence in compliance might be increased due to a lesser dependence on results from work in these three more complex areas.

Overly conservative (to the point of being physically unrealistic) analytical assumptions, such as those described above, not only lead to a pessimistic assessment of potential repository releases, but also prevent the identification of design factors that are important to performance. If one assumes, for example, that the salt reconsolidates in times much less than 10,000 years, then compartmentation of WIPP has enormous benefits regarding calculated releases through the E1E2 scenario. The probability of one borehole being drilled into any given area of the repository decreases in direct proportion to the area involved. The probability of two or more such boreholes penetrating the same waste area decreases even more rapidly as the area is reduced. When one also considers that, for flow to occur, boreholes must overlap both in location and in a time window determined by their duration, the great potential value of compartmentation is clear.

A high degree of compartmentation can be obtained at relatively low cost. The current plan calls for waste panels consisting of seven rooms plus access drifts along each end of the rooms in a "ladder" arrangement (Figure ES.1). If, after the rooms are filled with waste, the access drifts are backfilled with compacted salt, then a high degree of isolation would be obtained. Changes in the design layout to ensure improved compartmentation seem entirely feasible, especially if, as is currently estimated (DOE, 1995c), the TRU waste inventory stored in WIPP is significantly less than the original design inventory. This issue is discussed in more detail in Chapter 4.

DISCUSSION OF REPOSITORY PERFORMANCE

The main mechanism through which individuals could be exposed to radioactive materials from WIPP is the migration (through mechanisms discussed below) of material carried by water that is to be used directly or indirectly by humans. Some ground-water sources at WIPP are too saline for consumption by humans or livestock or for irrigation, so therefore, these do not appear to pose a significant risk to humans, even if WIPP radionuclides were to migrate into them. The ground-water pathway that could most directly result in human exposure at WIPP is movement of water containing radionuclides into the Dewey Lake Red Beds (see Appendix A), in which existing ground water is known to be potable, with exposure resulting from direct or indirect human use of this water.

Although many analyses of radionuclide releases from WIPP have been made by Sandia National Laboratory and other DOE contractors, the radiation doses that could result have not been assessed for some reasonably identifiable scenarios and pathways. Most analyses of WIPP performance have focused on regulatory compliance with the EPA containment requirements, that is, calculations to estimate the quantity of radioactive materials that could be released across an arbitrary compliance boundary within 10,000 years. There has been less analysis of individual doses because the individual dose requirements of the EPA standard apply only to an undisturbed repository. For example, because of the high salinity of water in the Culebra, the analyses of releases to the Culebra do not directly translate into an assessment of doses to individuals. However, these analyses do contribute to understanding of how WIPP would perform because they include extensive consideration of processes, mechanisms, and parameters associated with the site and with the transport of radioactive materials from the repository.

Undisturbed Repository Performance

The individual protection requirements (i.e., EPA's 40 CFR 191.15(a)) require that the committed effective dose for the undisturbed repository not exceed 15 mrem/yr for 10,000 years. Because limitation of individual doses under the undisturbed case is a regulatory requirement, DOE has conducted analyses (DOE, 1995a; DOE, 1990; Lappin et al., 1989) of this issue. The process addressed by these analyses is the leakage of radionuclide-containing brines through shaft seals into the Culebra. Human doses are calculated based on the assumption that water from the Culebra dolomite is used in stockponds for cattle, and human exposure occurs through beef consumption (see Box 2.3). The individual doses for the undisturbed repository are estimated to have a peak value of about 10^{-8} mrem/yr, well below the EPA standard of 15 mrem/yr (and below the natural background level of roughly 300 mrem/yr).

Three important features of early analyses are that water in the Culebra appears to be too saline for consumption by cattle, transport by colloids was not considered, and pathways to the Dewey Lake were not included. In addition, the analytical treatment of the behavior of the shaft seals and repository in this analysis appears to be conservative, that is, likely to over-estimate the releases (see Chapter 4).[4] Taking all these considerations together, the committee concludes that the net effect will probably be to lower the already very low concentrations and doses indicated by DOE's analysis of radionuclide releases through shaft seals.

The ground-water protection requirements (i.e., EPA's 40 CFR 191.24(a)) require a calculation of levels of radioactivity in ground water in the accessible environment from an undisturbed repository for 10,000 years. These requirements were not evaluated in the 1992 PA work under the assumption that no relevant potable ground-water sources exist. Recent estimates of radioactivity released from an undisturbed WIPP repository to ground water are 10^{-3} pCi/l, well below not only the EPA standards (ranging from 5 to 15 pCi/l), but also the natural background level of roughly tens of pCi/l (DOE, 1995a).

Thus, for the effectively sealed and undisturbed WIPP repository, the committee has identified no

[4]The seal permeability of $10^{-16}m^2$ results in no releases at 10,000 years (see Figure 4.1). As discussed in Chapter 4, the actual permeability is likely to be even lower than this design value, so that releases beyond 10,000 years are likely to be very small also.

Box 2.3 Human Exposure to Radionuclide Releases from WIPP

Human beings can be exposed to radiation in one of three ways: (1) direct external exposure, (2) exposure from inhaled materials, and (3) exposure from ingested materials. For most WIPP waste release scenarios, plutonium (Pu) is the main radionuclide of concern. Hence, the discussion here is specific to that element. The findings identified below for plutonium apply to other radionuclides in the projected WIPP inventory.

Direct external exposure to WIPP waste (via releases from drill cuttings brought to the surface) would not result in significant doses of radiation (DOE, 1995a), principally because plutonium's hazard is due to alpha radiation, which will not penetrate the skin.

Inhalation exposure occurs when radioactive material is inhaled and subsequently deposited in the respiratory tract or elsewhere in the body. Some low level of inhalation exposure could occur at WIPP if small radioactive particles in the drill cuttings at the surface were picked up and carried by the wind. In such a case, potential exposures to the drillers could be significant, but exposures to individuals off-site would be far less so (Rechard, 1995).

Ingestion exposure occurs when radioactive material that has been released into the accessible environment is ingested by a receptor (a human or some animal, plant, or water that may become part of the human food chain). As discussed in Chapters 5 and 6, the primary release pathway for radioactive material considered for WIPP is through the migration of plutonium in brine. Exposure by ingestion could occur at WIPP if radioactive material were transported underground in brines to a stock well, cattle drank contaminated water from the well, and humans then consumed meat from the contaminated livestock. However, the committee believes that the possibility of ingestion exposure occurring is remote, and that the potential health effects of this type of exposure are of little concern because:

1. Culebra water in the immediate vicinity of WIPP is not potable, even to cattle;
2. even if cattle were to drink the briny water, most of the plutonium would pass through unabsorbed, assuming that the gastrointestinal (GI) tracts of cattle and humans behave similarly (see point 4 below);
3. plutonium absorbed by livestock is deposited preferentially in bone, not meat; and
4. human ingestion is very inefficient in depositing plutonium in the body (a low absorption of Pu occurs in the human GI tract [EPA, 1988]—EPA guidance stipulates that only about one particle in 100,000 entering the GI tract would be absorbed, making ingested plutonium less toxic than inhaled plutonium).

The EPA standard regulates individual doses only for the case in which the repository remains undisturbed. Because the wastes do not appear to migrate under these conditions, DOE studies to date have not addressed specific health consequences of exposure to radiation from WIPP wastes in this case. Some preliminary DOE calculations of possible doses to individuals in the case of human intrusion by drilling suggest that the risk would be very low (see Rechard, 1995).

With the exception of the Dewey Lake aquifer, the major pathways by which plutonium and brine could migrate do not produce potable water. Certain concerns that have been raised by the committee about the possibility of transport of radioactive material to the Dewey Lake aquifer are discussed in Chapter 6. For a discussion of salinity limits appropriate for drinking water of livestock, see Yaron and Frenkel (1994, pp. 32-33, 42).

credible, probable mechanism for release of, or exposure to, radionuclides and concludes that DOE will be able to demonstrate compliance with the EPA standard by a wide margin.

Disturbed Repository Performance

As discussed earlier, DOE's PA showed that cuttings produced by drilling through the repository do not appear likely to cause the release limits to be exceeded. That is, although inhalation exposure from dust containing radionuclides that are brought to the surface as drill cuttings represented the dominant release scenario in the 1992 PA, the releases were within regulatory limits. If this is correct, compliance will depend on the results of other scenarios, such as the E1 and E1E2 scenarios, in which pressurized brine from below the repository horizon flows through the

repository, into the Culebra Dolomite, and then into the defined accessible environment. Releases associated with these scenarios appear to have been calculated by using highly conservative assumptions about the disturbed rock zone around the repository.

Individual exposures that might result from WIPP in the event of human intrusion have not been analyzed extensively because such exposures are not covered by the standard. The scenario thought to represent the dominant exposure pathway is an ingestion exposure assumed to result from the following sequence of events. Two vertical boreholes are inadvertently drilled through the repository in the future, one of which punctures a hypothesized pocket of pressurized brine in the Castile Formation. As a result, brine from the Castile Formation flows through the repository, dissolving and entraining radionuclides that flow up the second drill-hole into the Culebra, which is above the repository but below the surface. These radionuclides would then sorb onto the mineral surfaces of the Culebra (see Appendix A for a more complete discussion of the geologic formations at the WIPP site). Ground water from this formation would then be withdrawn and fed to cattle[5], which subsequently, would be eaten by humans.

This Culebra-to-beef scenario is not the only one that is relevant to an assessment of all possible exposure pathways to humans. That is, using PA calculations of the Culebra pathway as a basis for inferring that minimal exposure would result from a WIPP repository depends on the assumption that there are no other pathways or scenarios worth considering. This is not yet certain. For example, in addition to the postulated main pathway through the Culebra, an alternative (or secondary) pathway exists through the shallower Dewey Lake Red Beds. The committee believes that the potential for individual doses received by drinking water drawn from this formation, located closer to the surface than the Culebra, should be analyzed and documented. That is, the first element of the triplet definition of risk, "what can go wrong," should include the possibility of a borehole release from the repository to the Dewey Lake Red Beds. This is a concern because the Dewey Lake is known to contain potable ground water, and because it is the shallowest water-bearing unit in the area, it is also the easiest subsurface unit to be tapped for water supply by a future society. Thus, the potential for individual doses to be received by individuals (as a consequence of contamination from a breached repository) may be greater than those arising from an equivalent release into the Culebra. Because the Dewey Lake is less transmissive than the Culebra, the relative amount of plutonium reaching the Dewey Lake and the rate of lateral spreading may be less than for the Culebra. A quantitative analysis of this issue has not yet been presented to the committee in documented form for review.

Assessment of the isolation performance of the repository when disturbed by human intrusion is more complicated than in the undisturbed case. Because of gaps in the data available to date and the preliminary nature of the PA work reviewed by the committee to date (i.e., prior to the 1996 PA), it is not possible to make a compelling case that the radionuclide releases will comply with the EPA standard for the disturbed case. However, for the WIPP repository disturbed by future human activity, the committee has noted three ways in which on-going or additional work may lead to a demonstration of compliance. These are:

1. Re-evaluation of the probability and/or consequences assigned to highly speculative scenarios of future human activities may reduce the estimated risk of radionuclide release.
2. Experimental and field programs in progress or planned may show that key parameters (e.g., actinide solubility, sorption, radionuclide travel times, colloidal transport) are well within the range required to reduce the impacts of human activities such that releases fall within the acceptable range.
3. The implementation of available engineering options (e.g., compartmentation, treated backfill), which have not been considered in published DOE PA analyses, can substantially reduce the consequences of human intrusion.

[5]This Culebra-to-beef-to-humans pathway does not seem to account for the fact that the water withdrawn from the Culebra in areas downgradient from a hypothetical leak is too saline to be potable, even for cattle.

Based on the PA analyses published by DOE to date, which the committee believes include some very conservative assumptions (i.e., tending to over-estimate releases), the committee concludes that incorporating the above three considerations very probably will allow DOE to demonstrate that a WIPP repository can comply with the EPA standard for the disturbed case. These topics are treated in the remaining chapters of the report.

GENERAL QUALITY OF WIPP PERFORMANCE ASSESSMENT ACTIVITIES

Development of the WIPP PA has been a pioneering effort: it was the first detailed assessment of an actual radioactive waste repository to be published and has been the model for many subsequent analyses worldwide. The linkage of many computer codes and the capacity to use probability distributions for parameters and to propagate uncertainty through the analysis are major technical achievements. Nonetheless, in several important aspects, the full potential of the PA has not been realized in the WIPP project.

The committee noted several concerns above regarding the analytical treatment of some aspects of WIPP performance, for example, in the failure to consider salt reconsolidation and compartmentation of the waste rooms in the assessment. A more general problem is that the parameter values used in the PA reflect an uneven mixture of conservatism and realism. This is not unusual in risk assessment in which it is accepted practice to use a series of iterative assessments, based initially on conservative bounding values, followed by substitution of more realistic analyses that make a significant difference. A potential problem with this approach in the case of a complex analysis is that sensitivity analyses will fail to identify parameters that are most important to performance when those parameters are represented by a bounding value. A concern also is raised in Chapter 6 that some parameters assumed to be independent are, in fact, interrelated.

The PA identification of actinide solubility in brine and retardation as being among the most important parameters of WIPP performance is probably correct, but to a lesser degree than indicated by the sensitivity analysis. This is because other performance factors, such as DRZ permeability, were not sampled as analytical variables and, thus, their importance was not identified by the sensitivity analysis. As a result, an opportunity may have been missed to demonstrate compliance more quickly and economically than could be done through work on solubility and retardation.

In several iterations (the 1992 PA and SPM efforts), DOE has conducted sensitivity analyses of analytical parameters and used them to identify program research priorities. However, the PA modeling capability does not appear to have been used in a similar way to evaluate design alternatives, despite opportunities to do so. In 1991, DOE published the report of an Engineering Alternatives Task Force (EATF; DOE, 1991), a study conducted at least in part to respond to recommendations from the WIPP Committee (NRC, 1989). A similar study was published in September 1995 (DOE, 1995b) in response to EPA requirements. As described in Chapter 4, both of these reports included very positive comments about the value of sealing waste rooms; however, the current design (DOE, 1995b, p. ii) calls for panel seals but not room seals. Despite these two engineering studies, the PA model has not been used to evaluate what may well be the major potential benefit of such a design modification.

OTHER LONG-TERM RADIOLOGICAL COMPLIANCE ISSUES

Waste Characterization

Waste characterization—the process of identifying and classifying the chemical, physical, and radiological constituents of each drum of waste—is a critical aspect of every waste management project. For a project such as WIPP, many of the waste characterization needs are set by agencies such as the EPA, the New Mexico Environment Department (NMED), the U.S. Nuclear Regulatory Commission, and DOE itself. It is obviously impractical, if not impossible, simply to overlay the requirements of each of these individual agencies. Attempting to do so quickly degenerates into an exercise in a complete analysis of every possible component. Such analysis is costly and time-consuming and would result in the highest potential

health hazard to the employees involved, with no clear need for all of the information collected.

DOE has in view the implementation of "performance-based" waste acceptance criteria for WIPP and extension of that concept to define waste characterization requirements (DOE, 1995a, Section 4.3.2, pp. 4-7). The concept is straightforward and reasonable: the waste characteristics that should receive the most attention in characterization are those that are most important from the viewpoint of the performance measures on which the isolation capability of WIPP is evaluated.

With respect to long-term radiological protection, the requirements proposed by EPA in 40 CFR 194.24(b) are consistent with a performance-based approach. For each performance measure important to isolation capability (e.g., activity, permeability, and porosity), EPA proposes that DOE use performance assessment to establish a range of waste characteristics within which the facility will comply with regulatory standards. For those waste characteristics that are comparatively unimportant to isolation, the ranges will be wide. This approach should help avoid unnecessarily detailed characterization efforts.

The extent to which existing waste drums will have to be opened and characterized is not yet clear, because specific details of the characterization required have not yet been established. In particular, the method by and extent to which a knowledge of historical processes can be used to characterize existing wastes have not been established. Similarly, the requirements for using statistical methods to characterize waste based on measured values from a subset of that waste are not yet defined.

In the committee's view, it is essential that any waste characterization program be established with a clear understanding of potential uses of the characterization information. Measurements of TRU waste characteristics can be expensive and may lead to occupational exposures. The value of information gained by such analysis must exceed the cost and risk of obtaining the information, but these trade-offs can be considered only if the sensitivity of repository performance to different waste characteristics is understood. Where costly waste characterization requirements appear to offer little value in terms of ensuring health protection, DOE should seek to have the requirements reinterpreted.

Existing waste characterization regulations have been developed for surface waste management facilities rather than for a deep repository. These regulations reflect a general bias that more waste characterization is better than less and that the applicant has the burden of explaining why particular requirements should be waived in a particular case. 40 CFR 194 states that "any compliance application shall describe the chemical, radiological and physical composition of all existing waste proposed for disposal . . ." (40 CFR 194.24(a), Federal Register, p. 5240).

This is consistent with a performance-based waste characterization because a description of composition is not the same as a full characterization. The need for descriptive material is recognized. In the committee's opinion, there is no scientific basis for requiring a full characterization.

It appears that the project is concentrating too much on the problem of how to characterize waste and insufficiently on the question of whether to characterize it. The value of extensive characterization of WIPP wastes is questionable on several counts:

1. Whatever the current physical properties of wastes, they are likely to change significantly over the 10,000-year regulatory period of the facility. As the repository consolidates due to salt creep, the waste will be compressed and compacted.

2. The containment requirement of 40 CFR 191 limits the fraction of WIPP wastes that can be released over 10,000 years in terms of a percentage of the initial inventory; the absolute quantities that can be released are not defined. The total amount of radioactivity in WIPP will determine the release limits. For releases as cuttings, inventory information is largely irrelevant (see discussion of human intrusion earlier in this chapter). For releases due to solubility-limited flow, such releases may be largely independent of inventory, but release limits will depend on the total radiological inventory–that is, for the solubility-limited case, the more waste that is placed at WIPP, the easier it will be to comply with 40 CFR 191.

3. Performance assessments to date indicate that little, if any, waste migrates under undisturbed

conditions and that releases from human intrusion—assessed for various stylized scenarios, which include some apparently very conservative assumptions—appear to be small compared to the release limits. If the waste is not going to migrate to locations where humans may come into contact with it later, then the qualitative, common-sense answer to characterization is that it does not matter what the waste contains. A quantitative answer to the degree of characterization required would emerge rigorously from PA calculations, using the release limits specified by EPA standards, which apply irrespective of whether the releases pose a risk to humans.

Monitoring

DOE is required to perform a monitoring study as part of the information to be submitted in the compliance certification documentation. DOE is required to assess the feasibility of monitoring in both pre- and post-closure phases. A key element is that the monitoring techniques cannot impair or degrade the containment of waste.

In the committee's opinion, this DOE monitoring study should distinguish carefully between current technologies and expectations for future technologies. The committee believes that this study should also assess carefully those technologies that must penetrate the integrity of the closed repository to be effective. Simply stated, it may be easy to monitor parameters that will not provide any useful information about the facility and very difficult to monitor parameters that could be informative but almost assuredly require breaching the repository so that probes, cables, and other devices, can be routed to the surface. DOE and EPA must recognize that a monitoring program typical for RCRA facilities may be impossible to implement for the WIPP facility. Although the committee believes that the requirement for DOE to perform this monitoring study is appropriate, both EPA and DOE must be prepared to face a situation in which long-term, postclosure monitoring within the repository may be impractical. EPA, importantly, recognizes that such a monitoring program may be impossible to achieve without impairing the integrity of the repository. However, monitoring of the subsurface environment above the Salado (in particular, with sensors in the Culebra) could provide warning of a breach, probably without compromising the repository.

The 40 CFR 191 regulation require "long-term monitoring" of the closed facility, but without indicating what this implies. How long is long-term? What is to be monitored? The committee believes that long-term monitoring must be done from the surface. Observations that would require instrumentation inside the seals pose a risk of adding potential leakage pathways. The risk from monitoring systems that fail and become part of a leakage circuit could be higher than the risk due to leakage from a reliable unmonitored facility. Considerable advances are being made in remote investigation and monitoring by geophysical methods, but these have not yet matured sufficiently to provide monitoring of a repository. In summary, the committee believes that the EPA, in 40 CFR 194, has proposed monitoring requirements that do not appear feasible today.

The need for a monitoring study nonetheless provides an excellent example of how information from the operational phase at WIPP can be used to deal with compliance issues. It may be feasible, for example, to install probes and conduits into a room or panel that is then sealed. This would provide a direct measure of the ability to perform the monitoring anticipated in the regulations and to assess the reliability and integrity of the monitoring system. Should one of the seals fail because of the monitoring system, the consequences will be relatively slight because the failure could be recognized and repaired easily. A pilot study during the operating period should be informative regarding any early failures of the monitoring systems.

Peer Review and Quality Assurance of the WIPP Project

Two of the most common practices for enhancing the quality of technical work are a process of competent peer review and an appropriate quality assurance program. The WIPP performance assessment activity has been under substantial review, by peer review groups and others, since 1989. With WIPP, the question is not a lack of review, but rather the quality of the review and whether or not the reviews being performed are the ones needed. The reviews fall into three main categories: (1) formal technical reviews, (2)

continuing review and feedback, and (3) miscellaneous review and advisory groups.

The first group of reviews is most likely to have continuity of impact. Reviews that appear to be particularly important are those from the PA Peer Review Panel, the State of New Mexico (both the Environmental Evaluation Group [EEG] and the Attorney General's Office), stakeholder reviews, and the EPA.

Despite the many peer review efforts and the superior technical ability of those performing them, the WIPP PA effort is centered on complex models, making meaningful probes difficult by outside review groups interested in understanding the effects and parameters most important to the outcome and interested in developing a simple, effective way in which these dependencies can be properly viewed. Given the earlier comments about the apparent conservatism in the analysis and the resultant misidentification of sensitivities, it appears that the peer reviews have overlooked these important shortcomings of the WIPP PA and have not resulted in a balanced, realistic assessment of WIPP performance.

One reason for this may be that the technical experts engaged in performance assessment have valued incremental technical innovations over transparency of the process. Understanding of the key aspects of WIPP radionuclide isolation performance need not be buried in a complex computer model. The descriptions of WIPP release scenarios described above are an attempt to indicate that the identified scenarios through which wastes could be released from WIPP are easy to visualize and that the factors contributing to releases can be identified readily. As the WIPP project moves forward in the compliance process, the hope of the committee is that the value of technical transparency and accessibility will be embraced by the project.

The quality assurance (QA) philosophy and procedures covering performance assessment are still under development. This documentation (see Sandia National Laboratories, 1991; 1992) covers QA procedures for (1) parameter selection and use of expert judgment, (2) analyses and report reviews, and (3) computer software supporting PA.

The development and implementation of QA procedures have progressed most visibly in the first of these three activities. Ideally, the QA program is to be implemented fully before final PA results are considered suitable for comparison with 40 CFR 191. However, full implementation alone is not sufficient to guarantee a high-quality result, which can be achieved only through the combination of a competent project team, peer review, and regulatory compliance. The final results have yet to be seen.

CONCLUSIONS

Performance assessment has a major role to play in demonstrating compliance with EPA standards and providing assurance to the public that transuranic waste can be stored without posing a significant health risk to the public in the Waste Isolation Pilot Plant. Although performance assessment did not originate with WIPP, the project has done much to advance the development and applicability of PA to radioactive waste disposal. As with any new development, be it a machine or a thought process such as performance assessment, initial expectations typically are much higher than actually can be achieved. Part of any criticism of the WIPP PA program may reflect these initial expectations.

Federal regulations relating to waste disposal define performance assessment as an assessment of the likelihood that the amount of radioactive material released to the environment will exceed a set of specified values. The analyses required to make such an assessment are capable of much more than merely demonstrating compliance with specific radionuclide release limits; they can be used on a much broader scale to enhance decision making and the overall efficiency of the WIPP project. The committee believes that these opportunities have not been exploited fully by DOE.

The general conclusion is that the WIPP performance assessment program is providing valuable insights on the performance capability of the repository, including the integration of features, events, and processes associated with total repository performance. The program is essential to success in opening the repository and can serve as the primary knowledge base for a meaningful risk management program during the operational phase. The extent to which performance assessment can become a primary monitor of repository

performance clearly depends on the scope and resource base of the PA effort. The committee believes that scope must include performance measures that go beyond radionuclide release rates to the accessible environment. In particular, the WIPP PA, although quite responsive to the letter of the law, is too narrow in scope to serve as a robust basis for risk management—a goal beyond that explicitly required by federal regulations but clearly in the interest of public health and efficient management of public resources.

An example of an opportunity for continued use of PA in the manner recommended here is in waste characterization. PA can provide guidance to waste characterization requirements. The impacts, both in terms of economics and of human exposure to the radioactive materials, can be significant. However, both DOE and EPA seem committed to an extensive waste characterization program that is only minimally defined by the need for information as input to the PA process. EPA is apparently requiring waste characterization efforts well beyond that necessary for assessing performance of the closed repository. The DOE seems intent on fulfilling these requirements with no clear scientific basis for the need for this information.

Remaining issues of concern relate to the timeliness of PA results, the transparency of the PA model, and its limited scope in terms of aiding WIPP program decision making. The complexity of the model and its limited set of performance measures handicap its usefulness in project decision making, because the mechanisms, processes, parameters, and events that contribute to risk are difficult to understand. If a simpler model could be developed that would represent the full model reasonably and adequately, such a simpler model—with expanded performance measures—would benefit the project. Similarly, the results and insights of the performance analysis, as reported in the DCCA, are largely inscrutable. A simplified description of the scenarios and associated processes under which waste from WIPP could be released and people could be exposed to radionuclides would be a valuable complement to the WIPP performance assessment report.

Chapter 3

Salado Hydrogeology, Gas Pressure, and Room Closure

Studies of physical, chemical, and biological processes involving the rock salt environment provide important conclusions about the behavior of waste-filled excavations in the Salado Formation. This information is reviewed briefly in the following four sections. The first discusses the hydrogeological properties of WIPP salt (see also Appendix C). The second draws general conclusions about gas generation. The third section discusses the influence of room closure, with local stratigraphy (Appendix A) and the creep behavior of salt (Appendix D) used as additional inputs. The final section discusses the combined effects of brine inflow, gas generation, and room closure.

SALADO HYDROGEOLOGY

In assessing deep geological disposal as a potential means of isolating radioactive waste from the biosphere and worthy of further research, the National Research Council suggested rock salt as a particularly suitable geological material (NRC, 1957). The fact that water-soluble formations such as the Salado Formation in New Mexico have remained in place for hundreds of millions of years indicates that, except for slow dissolution at the margins, they are hydrologically inactive. Another desirable characteristic of salt is that over time, it will flow around the waste and encapsulate it completely.

The Salado is approximately 600 m thick, extending about 400 m above and 200 m below the horizon selected for the WIPP repository. The Salado contains bedded, continuous layers of relatively pure halite, impure halite with clay and polyhalite constituents, and interbeds of anhydrite, accompanied by underlying clay seams (Freeze et al., 1995a, pp. 1-8).

Some of the interbeds are clearly evident and continuous over many kilometers and have been designated as "marker" beds. They serve as a guide in keeping the excavations within given bedded layers and maintaining a fixed separation from the nearest anhydrite interbeds above and below.

Excavations at WIPP have not revealed any feature that would cause DOE to question the assumption of the very low permeability of the Salado. However, concerns have been raised (Bredehoeft, 1988) that although the Salado appears to be dry, it may still be saturated with brine, that is, the microscopic voids between the crystals that make up the salt beds could be filled with brine and the voids interconnected (see Box 3.1).

In this case, interstitial brine would tend to flow down the pressure gradient and into the excavated repository. Although the porosity of the halite is not high,[1] such a permeable-medium model considers the entire Salado Formation as a brine reservoir, able to flow into and fill the excavations. The brine would corrode the metallic waste containers, generating an underground "slurry" of contaminated brine. Through chemical and bacteriological processes, this brine might generate enough gas to raise the pressure above lithostatic (i.e., the pressure generated by the weight of overlying rock).

Several underground investigations and analyses of the interconnection model have been conducted, and a number of inconsistencies have been noted (Freeze and Christian-Frear, in preparation; Beauheim et al., 1991; McTigue, 1993). These include the following:

- Brine seepage into excavations in the Salado halite occurs in variable small quantities in unpredictable locations.
- Brine composition is quite variable, even among samples separated by distances of only tens of centimeters. Over a period of 230 million years (the

[1]The porosity of the Salado is generally about 1 percent by volume, and the interstitial moisture content is typically less than 0.5 percent by weight.

BOX 3.1 Permeability and Fluid Inclusions of the Salado Formation

The permeability of the Salado Formation salt is an important parameter in evaluating the capability of the WIPP repository to withstand hypothesized future flooding by an external source of water that would flow through any interconnected pores in the salt. Valuable insight into permeability is achieved by examining the composition of fluid inclusions. Fluid inclusions are tiny quantities of liquid or liquid plus gas enclosed in salt crystals of the Salado, which represent samples of the fluid from which the salt crystals formed or were subsequently recrystallized. Compositions of the inclusions show substantial variety, which has led some researchers (e.g., Roedder et al., 1987) to speculate that the salt may have recrystallized in the presence of different fluids that have flooded the salt beds at various times since their formation. However, more recent work (Bein et al., 1991) suggests that variations in chemistry of fluid inclusions is attributable to depositional and recrystallization processes that occurred millions of years ago and indicates that these variations do not require fluid flow through interconnected pores. The most recent work by Jones and Anderholm (1993, 1996) also suggests that the observed variations in fluid inclusion composition can be explained by natural and expected variations in the marine and marine-marginal environmental conditions during Salado deposition in the Permian. This means that the inclusion fluids probably have been isolated since the salt was formed. Thus, the Salado salt probably has remained essentially impermeable since its formation (see also Appendix C).

Salt mines elsewhere in the world have indeed flooded on occasion, but this is typically due to a combination of excessive extraction of salt during mining, presence of fractures in the salt caused by the disturbance of the mining, and close proximity to aquifers or surface water bodies. However, these conditions do not exist for the WIPP repository. The overburden pressure and deformation properties of salt (Appendix D) will close and heal any fractures that might develop in the disturbed rock zone and seal and isolate any residual gas-filled or brine-filled void spaces in the repository horizon. No permeable formations in the vicinity of the repository would serve as a suitable "source" or "sink" of ground water.

age of the Salado), these compositional differences would have been eliminated by diffusion had the pores of the formation been interconnected.

- Rock salt behaves essentially as a viscous fluid, with a zero yield (shear) stress, when the load is applied over a long time (see Appendix D). Such flow behavior would eliminate the possibility of connected pathways between the salt pores. Certainly, rock salt cannot sustain stress concentrations around microfissures over geological time. The inability of salt to sustain a shear stress over a long time is also indicated by the fact that the in-situ state of stress in the salt is isotropic (i.e., equal in all directions).
- Brine pore pressure in both halite and anhydrite marker bed units at WIPP has been found to be approximately 12 MegaPascals (MPa), which is between hydrostatic (6 MPa) and lithostatic (15 MPa). These measurements are consistent with isolated brine.
- In-situ testing (see Appendix C, and Beauheim et al., 1993b) indicates a large variability in intrinsic permeability, ranging from less than 10^{-21} m^2 for pure halite to as high as 10^{-18} m^2 (Freeze et al., 1995a) for anhydrite interbeds. When anhydrite is subjected to internal pressures (e.g., by high gas or brine pressures in the waste rooms) approaching lithostatic, its permeability may increase significantly due to the generation of incipient fractures and eventually open macroscopic fractures. Median values of 10^{-21} m^2 and 2.5×10^{-19} m^2 are used in computations by the Department of Energy (DOE, 1995a, pp. 6-73, 6-75) for halite and anhydrite permeabilities, respectively.
- Stress concentrations around underground boreholes and excavations in the Salado generate a disturbed rock zone (DRZ). The DRZ is a local region of enhanced permeability consisting of microfractures that spread at a slow and exponentially decreasing rate into the salt from any newly generated surface (created, for example, by borehole drilling).

All of these observations support an alternative to the interconnection (Darcy flow) model. In the alternative model, the undisturbed salt is essentially impermeable. Brine seepage comes from isolated domains of porosity containing brine that, in the undisturbed state, will be at lithostatic pressure. These domains become interconnected if they are penetrated by the micro and

macrofissures of the DRZ. If the DRZ should extend to the marker beds, Darcy flow from these beds into the excavations could occur.

Appendix C addresses brine flow into excavations in the Salado and considers the following two possibilities: (1) impermeable salt containing permeable marker beds, from which brine flows into the excavations; and (2) a permeable Salado Formation with Darcy flow into the excavations. In both cases, by using the permeability values considered to be most appropriate on the basis of current data, the total inflow appears to the committee to be too small to result in significant brine accumulation in the rooms. With appropriate design width and sealing of the entrance drifts to the rooms, it should be possible to minimize extension of the DRZ to the marker beds and avoid connection between the beds and the excavation (see discussion of room seals in Chapter 4).

In conclusion, brine inflow to excavations in the Salado is likely to be significantly less than was thought to be the case several years ago—and will occur primarily via anhydrite marker beds. Careful attention to room filling and backfilling could aid in further limiting brine inflow.

GAS PRESSURE

Because the current design of WIPP calls for sealing all shaft communication between the repository horizon and the surface, gas generation could conceivably create a pressurized repository. Three sources of gas generation in the sealed repository have been identified (Lappin and Hunter, 1989):

1. radiolysis;
2. anoxic corrosion, caused by any inflow of brine that might react chemically with the carbon steel waste drums, generating gas (predominantly hydrogen); and
3. bacterial reactions with some of the organic constituents (e.g., cellulose).

The worst case scenario would involve total dissolution of all steel drums in brine, with generation of the equivalent amount of hydrogen, plus bacteriological conversion of all cellulosics, plastics, and rubbers to a mixture of methane, CO, and CO_2. Based on this scenario, by considering gas compressibility but not solubility, reactivity, or the likelihood of interbed fracturing at lithostatic pressure, an early calculation (see Molecke, 1979a, b) indicated that the resulting pressure in the sealed repository could exceed lithostatic.

The generation of such quantities of gas cannot occur under undisturbed conditions because the quantity of brine required in this calculation is not available inside a sealed repository, and an external brine reservoir is sealed off from contact with the waste. However, the E1 and E1E2 scenarios do postulate an unlikely but possible mechanism for the introduction of very large quantities of pressurized brine. Accordingly, theoretical and experimental studies of gas generation have been undertaken (Freeze et al., 1995a) to provide estimates of the amount of gas generation to be expected under any credible set of conditions.

Early in the gas generation studies, DOE-sponsored researchers concluded that the amount of ionizing radiation in the expected WIPP inventory would not be enough to generate significant quantities of gas by radiolysis (see Molecke, 1979a, b). The remaining two sources of gas have been studied in more detail.

Laboratory Studies

Early laboratory experiments at Sandia National Laboratories (Molecke, 1979a, b) designed to permit estimates of chemical and biological gas generation rates were inconclusive because of the small and sometimes inconsistent effects observed. After a hiatus of several years, a larger program (Brush, 1990) was undertaken. This program, performed by recognized specialists, is now approaching completion (Brush, 1994; Beauheim et al., 1995).

The following conclusions about the major corrosion process have been reported:

> *Anoxic corrosion of steels . . . will produce significant quantities of H_2 and consume significant quantities of H_2O if*
>
> *(1) . . . sufficient brine enters the repository after filling and sealing;*

> *(2) significant microbial activity . . . does not occur (microbial activity will produce CO_2 or CO_2 and H_2S, which will passivate steels . . .)* (Brush, 1994, p. 6),

and

> *Under humid conditions (gaseous, but not aqueous, H_2O present), anoxic corrosion of steels and other Fe-base alloys will not occur . . .* (Brush, 1994, p. 7).

With respect to microbial activity, the conclusion announced in the same document is less definite: *". . . although significant microbial gas production is possible, it is by no means certain"* (Brush, 1994, p. 7).

Results of experimental studies (Brush, 1994) show that anaerobic gas generation rates in brine are likely to be quite low—approximately one micron per year rate of dissolution of the steel surface (Brush, 1994, p. E-9) and to be negligible if the waste is exposed only to gaseous phase "brine humid" conditions rather than being immersed in liquid brine.

Time Dependence of Bacterial Activity

Even if the experimental program eventually succeeds in measuring bacterial gas generation rates, a question will remain about extrapolating short-term, laboratory-derived rates to repository compliance time scales. Linear extrapolation may be appropriate for certain physical and chemical processes, but living organisms are more complex. Can bacteria continue to be active metabolically over extremely long periods in a closed system?

Because biologists ordinarily do not deal with long times and closed systems, there seems to be no literature on this subject, especially for the halophilic environment. However, literature does exist on life in extreme environments, and there are basic principles that are true for all forms of life under all conditions.

In the closed WIPP facility, organic and inorganic nutrients must be supplied from the emplaced waste and the enclosing salt. Neither of these can be regarded as a rich source of the complete range of compounds and elements required by the organisms likely to be present. Because extremely halophilic bacteria tend to have unusually complex nutritional requirements, they are not likely to thrive in an environment with a restricted range of substrates (Kushner, 1978). Nevertheless, it is probable that limited amounts of suitable nutrients are present and therefore, that the potential exists for metabolism and cell reproduction.

Unlike the culture medium in a laboratory flask, WIPP waste would not be homogeneous. Bacteria require an aqueous medium to dissolve and transport nutrients and to disperse metabolic products. Unless the repository floods, there is no continuous aqueous medium to give full access to the scattered supply of nutrients.

If a repository room does become flooded (by human intrusion, for example), biological activity will bloom for a time. The activity cannot continue indefinitely because of the bacterial generation of waste products that inhibit further metabolism and the conversion of limiting nutrients to forms that are not available to succeeding generations of bacteria.

Consider a specific example. Phosphorus typically makes up 2-3 percent of the dry weight of a microorganism. Phosphorus is indispensable to life; it is a component of the genetic material (DNA) of every living cell. Some of this phosphorus may be recycled promptly after the death and lysis of a particular cell. However, in a closed environment such as WIPP, a small remainder may be retained in a biologically inactive form for long periods. DNA samples at least 50,000 to 100,000 years old have been isolated from several sources (Williams, 1995). The phosphate deposits of Florida and Tennessee are a striking example of the way a life process can steadily lose a critical material in a "side stream."

Similar arguments can be made concerning other elements and compounds essential for the metabolic activities of bacteria in WIPP. In a closed system, it can be anticipated that at least one of these materials eventually will become limiting, thereby halting reproduction and metabolism.

"Real Waste" Tests

The DOE WIPP program plan of 1990 called for an engineering-scale program of "real" gas evolution tests to be run in parallel with laboratory studies. The plan involved emplacing a large number of drums of actual waste in one or more underground rooms, which would then be sealed and monitored. When this program encountered both practical and political objections, it was redesigned to use specially constructed metal "bins" to be filled with actual waste, placed underground, and monitored. This program also was canceled.

What remains of the real waste concept is the Source Term Test Program set up in 1994 at Los Alamos National Laboratory (LANL; see Chapter 5). As part of this program, gas evolution from selected samples of actual waste under various conditions is to be monitored at both the drum and the liter scale. As discussed in Chapter 5, no results from this program have been reported yet.

Conclusions on Gas Generation and Gas Pressure

The committee thinks that pressurization by gas generated in an undisturbed repository is not a serious concern for three reasons:

1. Laboratory experiments have recently established that hydrogen generation by anaerobic chemical corrosion of steel can occur in WIPP, but only when liquid brine and metal come into physical contact. Gas evolved from such brine-induced corrosion is limited by the contact area of brine with the steel drums. The brine-humid conditions anticipated in the repository restrict the expected gas-generating mechanisms to fewer than the set originally considered.
2. Biological gas generation will be no more than a brief transient because it will be limited by brine availability as well as by nutrient depletion.
3. Although gas sealed in waste-filled rooms can eventually approach lithostatic pressure due to creep closure of the rooms, it will represent a small total volume and a small gas pressure energy.

ROOM CLOSURE

As a result of an extensive rock mechanics research program, prediction of creep closure of repository excavations at WIPP is relatively straightforward. The time-dependent stress-strain behavior of salt is understood sufficiently well to predict closure for most design situations (Freeze et al., 1995b; Freeze and Christian-Frear, in preparation; Munson, in press). Studies to date show agreement between predicted and observed room closure rates within less than 10 percent. Further details are presented in Appendixes C and D.

Marker Bed Considerations

The main source of brine inflow to the repository rooms would be from three adjacent anhydrite layers, two above and one below the rooms. Marker bed (MB) 139, located about 1.5 m below the 4-m-high disposal room, is about 0.9 m thick. Anhydrite "a" and anhydrite "b" (each 0.1-0.2 m thick) are some 2 to 4 m above the 4-m-high disposal room, and MB 138 (approximately 0.2 m thick) is about 11 m above the ceiling (see Figures 3.1, 3.2; and Beauheim et al., 1993a).

The rooms are wide enough (10 m) that the normal rock fracturing and collapse processes around the rooms (i.e., formation of the DRZ) may cause these layers to be brought into hydrological connection with the waste rooms. Over a period of several years from the time of excavation, the DRZ will extend progressively to a distance above and below the repository comparable to the half-width of the room (i.e., about 5 m above and 5 m below the room).

The waste emplacement room dimensions (4 m high × 10 m wide × 91 m long) and the proximity of marker beds suggest that the DRZ formed around each room (including roof sag, floor uplift, and wall fractures) could, after some time, provide hydrologic contact between the waste-filled rooms and one or more marker beds.

Hydrologic contact is a matter of concern because it could create a path for fluid transfer between adjacent rooms. Even when undisturbed, the marker beds are more permeable than the neighboring halite. The

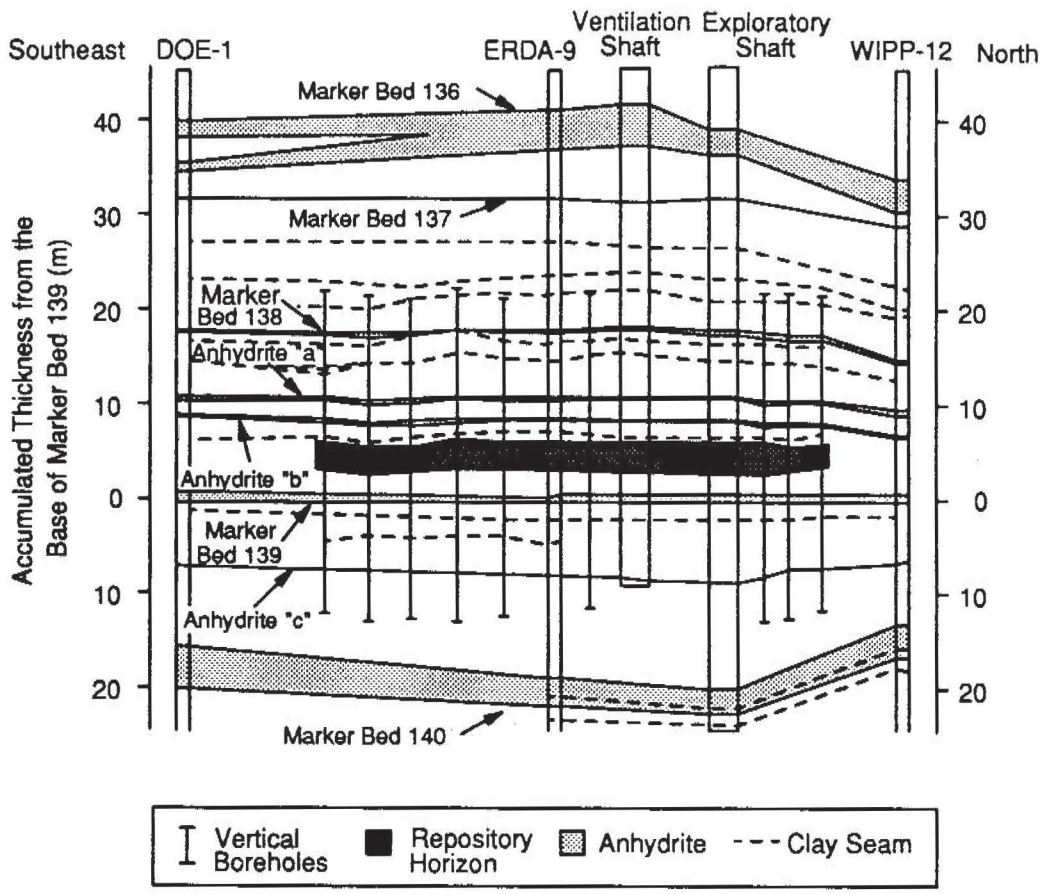

FIGURE 3.1 Stratigraphy of the Salado Formation near the repository horizon, showing adjacent anhydrite layers. Source: Freeze et al.(1995a).

"best-estimate" anhydrite permeability is of the order of 10^{-19} m^2, which is two orders of magnitude greater than the corresponding best estimate permeability for undisturbed halite (Freeze et al., 1995a, b). (See the discussion below on Backfilling and Compartmentation.)

If this interconnection should develop while the gas pressure in the WIPP excavation is below the fluid pressure in the adjacent rock, brine will flow in from the marker beds. The amount of brine available is theoretically large because the MB strata are areally extensive. However, the absolute quantity of Salado Formation brine that can enter an excavation in the repository horizon is limited by the remaining void volume of unconsolidated material during creep closure of the salt (see Appendixes C and D).

Should brine come in contact with the steel drums, gas generation would occur. However, several effects, identified and discussed below, suggest that this gas pressure buildup would be limited.

1. A pressure rise due to gas generation will reduce the rate of flow into the excavations. If the gas pressure reaches lithostatic, it would open fractures in the marker beds, greatly increasing the marker bed permeability to outward flow from the rooms. Gas would tend to flow out of the rooms.

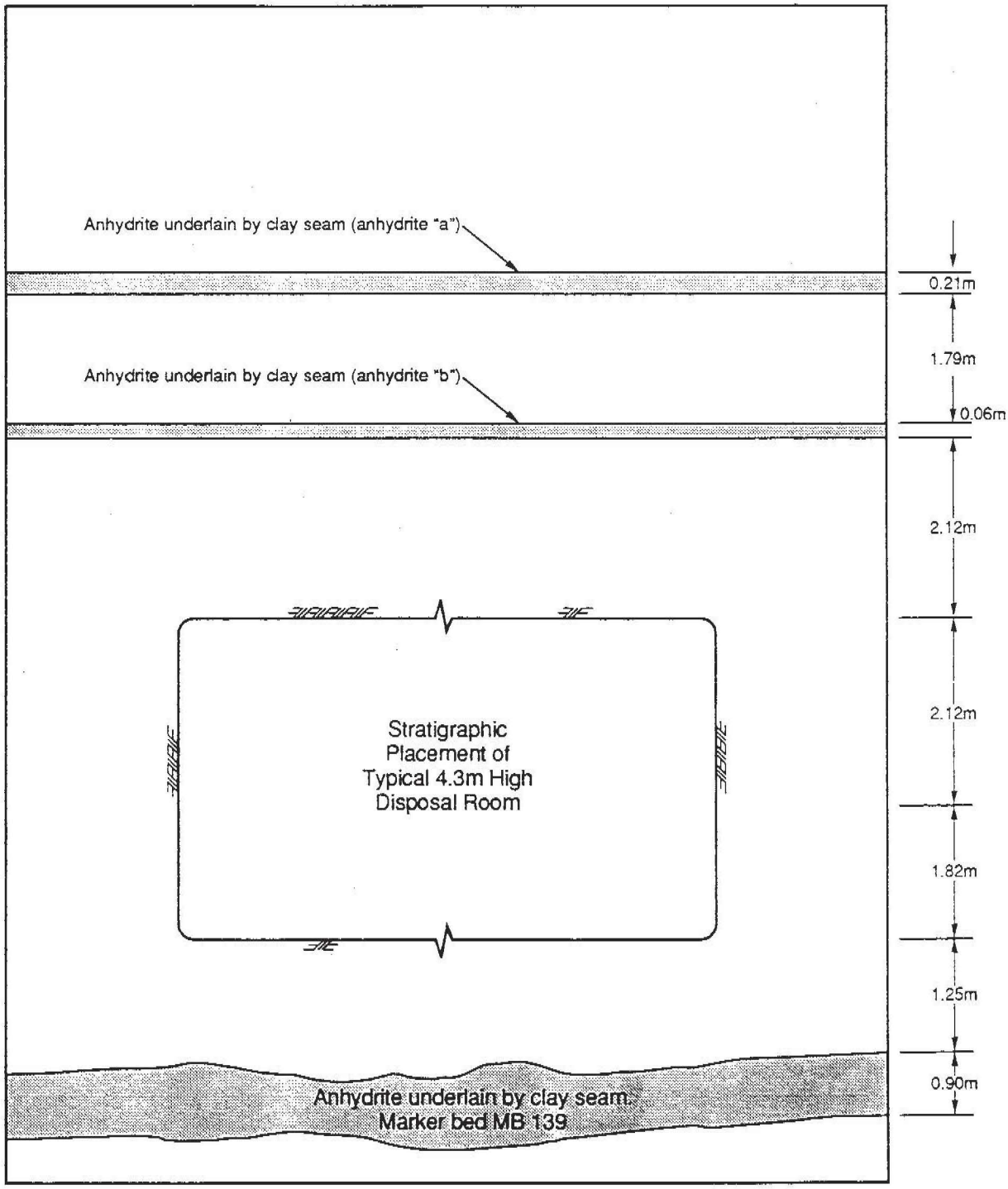

FIGURE 3.2 Close-up of stratigraphy of the Salado Formation at the repository horizon. Source: Department of Energy (1991, Figure 1-4).

Another possible effect of an intersection of the DRZ with the marker beds (particularly those above the repository) is the escape of gas by two-phase flow into the coarser fractures of the marker bed. This becomes appreciable only if the gas-brine pressure approaches lithostatic, when opening of fractures in the anhydrite layers would occur, resulting in a substantial increase in permeability of the marker beds. In this case, as shown by Webb and Larson (1996, Figure 4.9d, p. 37), the 1° inclination of the marker beds results in countercurrent flow (i.e., brine flows into the excavation as gas flows out), increasing the amount of brine inflow. Although variable, the increased inflow is of the same order of magnitude as flow into the unpressurized open excavation.

At gas pressures below lithostatic (i.e., without interbed fracturing), countercurrent flow is not significant. Furthermore, gas pressure acts to reduce brine inflow.

2. During earlier stages of room closure (i.e., 50-100 years), the floor uplift in each waste-filled room would tend to isolate the waste from liquid brine. During this period, the waste drums would be subjected to only a moderately humid environment, in which, as discussed in the previous section, gas generation by drum corrosion is considered negligibly small. However, if the brine remains in communication with the waste-filled drums, the desirability and feasibility of engineered designs to reduce or eliminate return of entrained brine to the waste rooms should be considered.

THE COMBINED EFFECTS OF BRINE INFLOW, GAS GENERATION, AND ROOM CLOSURE

The preceding discussion indicates that the predicted consequences of the combined effects of creep closure of the waste-filled disposal room, formation (and eventual healing) of the disturbed rock zone (DRZ), brine inflow, and gas generation can vary considerably depending on the particular assumptions made with respect to each of these variables (see also Freeze et al., 1995a). From the arguments outlined earlier in this chapter, the committee concludes that the amounts of brine and pressurized gas are likely to be small.

To assess the overall consequences of these issues on radionuclide isolation, it is necessary to incorporate the "room effects" into the entire network of excavations, including the shafts and seals. DOE has made the very conservative assumption that all waste-filled rooms remain permanently interconnected via a relatively high permeability DRZ (see Chapter 2) There is strong evidence, however, that placement of crushed salt seals between rooms and back filling of all other underground excavations with salt from mining operations will result in an overall low permeability within the excavation close to that of the intact salt (of the order of 10^{-20} m^2 or lower) within a few hundred years (see Callahan et al. [1996] and Appendix C). Each waste-filled room will then be an isolated compartment within the essentially impermeable Salado Formation. This compartmentation would greatly reduce the probability and consequences of an E1E2 borehole intrusion (see Chapter 2) and also the potential for brine flow up the sealed shafts.

Backfilling and Compartmentation

The development of hydrological contact between the marker beds and the waste-filled rooms could be inhibited somewhat by the use of well-placed (e.g., pneumatically injected) crushed salt backfill in the waste-filled rooms. Although this probably will not reduce the early development of the DRZ significantly because of the difficulty of packing the fill to a high enough density to obtain a rapid build-up of back pressure in the early stages of room closure, sufficient back pressure eventually will develop to reduce the aperture and hence the permeability of the marker beds.

Hydrological communication between the marker beds and the waste-filled rooms is of little significance provided hydrological communication between rooms is prevented. Careful design of entry rooms and early installation of room and panel seals to ensure that waste-filled rooms are isolated effectively from each other, or compartmented—as discussed in Chapter 4—could greatly reduce the vulnerability of a WIPP repository to human intrusion by drilling (see Chapter 2) or by water injection (see Box 3.2).

BOX 3.2 Potential Consequences of Brine Injection from Petroleum Recovery Operations on Repository Inflow

Although the permeability of halite in the Salado Formation is probably negligible, there remains some concern about flow through marker beds and other impurities in the formation. In oil-producing regions such as southeastern New Mexico, it is common to inject fluids into the deep subsurface, either to stimulate secondary recovery of oil in partly depleted oil reservoirs (e.g., by waterflooding) or to dispose of the large volumes of brine that typically are produced simultaneously with oil. Both types of operations involve high-pressure injection of fluids into a deep rock formation. If there is a failure in the well casing or in the grout or cement outside the casing, fluid can leak into overlying formations and flow laterally along one of the many anhydrite layers in the Salado.

One such recent occurrence, in the Rhodes Yates Field of Lea County in southeastern New Mexico, apparently caused significant flow through the Salado (reported as an unexpected flow of over 1,000 barrels per hour encountered by a well being drilled in 1991; see Silva, 1994, 1996). The unexpected flow through the Salado was attributed to injection into old (1940s-1950s) production wells in the Yates Formation, some 200 m below and 3 km away from the Salado horizon in the well where the flow was encountered. The flow probably was transmitted through anhydrite marker beds.

Because injection wells operate close to the WIPP site now and similar operations can reasonably be anticipated in the future, accidental leaks from such operations might represent a source of fluid that could migrate into the repository. Brine volumes under such conditions would be much greater than those that would seep into the repository from the Salado under undisturbed conditions. The committee believes that the likelihood and consequences of this type of disturbance occurring at the WIPP site should be evaluated by DOE.

There are differences between the petroleum production operations in the vicinity of WIPP and those in the Rhodes Yates Field (see Fig. A.6, Appendix A). Near WIPP, oil is produced below the 500-m-thick Castile anhydrite and salt formation, which underlies the Salado. The main gas-producing horizons are approximately 600 m deeper. Thus, injection for secondary recovery would be 700 m or more below the repository horizon. At Rhodes Yates, the Salado lies unconformably on the oil-producing Guadalupian series. The Castile Formation is absent.

Given the current improved well completion practices and the presence of the Castile into which fugitive brine may flow before reaching the Salado, the probability that fluid injected for enhanced recovery near WIPP would invade the repository horizon would seem to be lower than the Rhodes Yates incident. The potential of such a leak due to the injection of brine for disposal directly into the Castile, closer to the repository, for the period during which petroleum production at WIPP is likely to continue, is of greater concern. The committee recommends that DOE demonstrate how the performance of the repository will be assured against fluid injections.

Conclusion on the Combined Effects of Brine Inflow, Gas Generation, and Room Closure

The initial brine inflow into rooms is likely to be low enough that rates of gas generation will also be very low. Gas pressure will develop slowly (over hundreds of years) and more rapidly if the void volume of the room is reduced by backfill. Eventually, that is, in some hundreds of years, salt creep will close the rooms around the waste containers, with gas isolated in the voids between the waste in individual rooms and pressurized to the order of the lithostatic pressure. The hazard of such "pockets" of pressurized gas is considered by the committee to be negligible because of its small volume and small gas pressure energy. The committee believes that placement of effective room and panel seals will reduce greatly the potential for hydrological communication between the individual rooms.

SUMMARY AND CONCLUSIONS

After some hundreds to perhaps a thousand years, the steady-state condition of the undisturbed repository will be one in which the residual void in each room is a small fraction (10-15 percent) of the original room volume. This residual volume will be occupied by a mixture of deoxygenated gases, mostly hydrogen, probably at a pressure approximating lithostatic. These conditions would be established by Darcy flow of brine along the interbeds, controlled by room gas pressure and interbed permeability. In the absence of adventitious brine, only "brine humid" conditions are

expected. Creep closure and gas pressure buildup will serve to limit liquid brine entry.

Waste-filled rooms would probably be isolated from each other, so that the consequences of human intrusion should be considerably less severe than for the "interconnected rooms" scenario considered in the DOE PA. Chapter 4 discusses the engineering feasibility of compartmentation and other, relatively simple, engineering measures that may be taken to further improve the overall performance of WIPP as a TRU waste repository.

Chapter 4

Engineering to Improve Predicted Repository Performance

As discussed in Chapter 2, the committee judges the probability of radionuclide release from a well-sealed Waste Isolation Pilot Plant (WIPP) repository under undisturbed conditions to be very small. Concern has been raised that corrosion of the steel waste containers exposed to brine could generate gas at substantial pressure in the repository. Although the gas itself would be essentially nonradioactive, it could entrain radioactive material in the process of being released if a drill hole penetrated the repository at some time in the future.

In examining such possibilities, it is useful to consider ways in which the likelihood of potential releases could be reduced by changing the design of the repository or the form of the waste before it is placed underground. It is technically possible, for example, to incinerate the waste at the surface, thereby eliminating the possibility of gas generation underground. However, incineration also poses some risk of radionuclide exposure and would be very costly.

The Department of Energy (DOE) has conducted a number of studies (Lappin and Hunter, 1989; Marietta et al., 1989; Butcher, 1990; DOE, 1991, 1995b)[1] to examine a variety of such options to reduce risks. A short list of engineered alternatives is discussed below.

REPOSITORY DESIGN AND EXCAVATION ALTERNATIVES

Contact of drums with brine could be substantially lower than suggested in Chapter 3 because of both the probable behavior of the excavations (see Box 4.1) and the use of relatively simple engineering design changes, as noted below.

Natural and Engineered Sumps

Closure of the waste storage rooms, which are designed to be 4 m high × 10 m wide, will result from roof sag and floor uplift. Development of the disturbed rock zone (DRZ) and the associated floor uplift will create a "sink" for any brine flowing into the room, while simultaneously raising the waste drums above the brine, thus minimizing any immersion of the drums were liquid brine to be present. Also, because the rooms will follow the 1° inclination (i.e., a dip of 1.8 percent) of the marker beds (MBs), brine will tend to accumulate at the lower end of each storage room, creating the possibility of a drainage sump at this end of the rooms to remove the brine from contact with waste.

Design Considerations to Minimize DRZ Effects

If entrances to each room were to consist of *two* excavations, each 3 m wide, 3 m high, and about 25 m long, separated by a wider pillar, and if the center height of the excavations was located midway between the anhydrite layers, it should be possible to reduce the DRZ for each 3-m-wide excavation to no more than about 1.5 m above and 1.5 m below the roof and floor horizons, respectively (probably considerably less if the rooms are excavated and filled rapidly, within several weeks). In this way, it should be possible to avoid disturbing the anhydrite (brine-bearing) layers or connecting them with the DRZ, thus avoiding any inflow of brine into this section of the excavations. The 25-m section could be sealed with crushed salt or prefabricated compacted salt blocks, thereby isolating each room or panel from its neighbors; these seals (free

[1]DOE (1991) is a comprehensive study of a variety of engineered alternatives by a group of more than 50 engineers and scientists, known as the Engineered Alternatives Task Force (EATF). Results of the EATF study are referred to later in this report. DOE (1995b) is known as the Engineered Alternatives Cost /Benefit Study (EACBS).

BOX 4.1 Creep Closure and the Disturbed Rock Zone

Excavations will creep closed by movement inwards from the entire volume of salt, and eventually by a lowering (subsidence) of the surface, and/or gaps between the salt and overlying more elastic formations. A crude analogy to the viscous behavior of salt is the filling of a cavity of air made in a volume of water. The air cavity will fill by flow of water towards the cavity. The water occupying the volume of the cavity will result in a (slight) lowering of the water surface level.

Measurements at WIPP show that open rooms tend to close at a constant rate of about 1 percent per year. After about a hundred to a thousand years, then, it will be difficult to identify where the original rooms were excavated, because these rooms would be filled in by flow of the entire salt mass.

The Disturbed Rock Zone (DRZ) refers to a region, usually within one diameter or less of the walls of an excavation, in which the difference between the rock stresses prior to and after excavation is sufficient to produce microcracks in the salt. In the immediate vicinity of the walls the microcracks may coalesce to form open fractures. It has been shown, both by laboratory experiment and field observations at WIPP, that the microcracks and fractures can be healed when the deformation of the salt towards the excavation is resisted by a "back-pressure." This back-pressure can be generated by placement of seals or by back-filling the excavations with crushed salt. Calculations (Callahan et al., 1996) indicate that the permeability of a shaft seal of crushed salt that has been dynamically compacted to 90 percent of the density of intact salt (Hansen and Ahrens, 1996; Brodsky et al., 1996) will achieve a value close to that of the intact salt within 50-100 years. The DRZ will disappear over the same time period. Back-filled rooms will require longer to come to equilibrium at lithostatic pressure, but should certainly reach a condition similar to the shaft within a few hundred years.

of brine flow into the DRZ) should close as rapidly and tightly as the shaft seals.

Some redesign of the room and pillar layout may be needed if room compartmentation is introduced. The general principle of designing operations to minimize disturbance of the marker beds prior to room sealing is a useful one to follow. Such seals also should reduce potential impacts of the E1E2 human intrusion scenario substantially (see Chapter 2). Because the projected inventory of transuranic (TRU) waste destined for WIPP may be less than the design capacity of the repository (DOE, 1995c), the separation of individual rooms could be increased and the room seal designs improved.

Room Seals, Panel Seals, and Backfill

Once filled with waste and backfilled, the rooms should close within about 100 years, given the absence of brine in the DRZ (see Appendixes C and D). Although a central "core" of crushed waste materials in the rooms will probably retain significant local permeability, these materials can be isolated from each other by effective room and panel seals. There seems to be no reason why such seals cannot be designed to be as effective as shaft seals. Thus, the room and panel seal permeabilities would decrease progressively (e.g., to 10^{-16} m^2 or lower within 100 years), as assumed for the shaft seals (see discussion below), and, given the essentially viscous long-term behavior of salt, would approach the undisturbed value for salt (i.e., essentially zero) after 500 to 1,000 years. Thus, for at least 9,000 of the 10,000 years for which E1E2 intrusions must be considered, individual waste-filled rooms would be isolated from each other.

The effectiveness of room and panel seals in reducing radionuclide releases has been noted in DOE reports:

> *The concept of sealing individual rooms or portions of rooms, using thick salt 'dikes' which isolate smaller volumes of waste from each other, was considered the most feasible facility design alternative . . . .* (DOE, 1991, p. A-39)

and

> *This alternative was considered for mitigating the effects of the two-borehole* [i.e.,

> the E1E2] *scenario, and to a limited extent, the single borehole drilled into the Castile brine. The EAMP* [Engineered Alternatives Multidisciplinary Panel] *modified this alternative by suggesting that floor to ceiling salt seals could be installed at each end of the waste disposal rooms, as well as at appropriate locations within the rooms. This would decrease the effective permeability of each waste disposal panel, and prevent hydraulic communication between the two boreholes. If this alternative is implemented, it would appear to effectively eliminate the effects of the two-borehole scenario . . . .* (DOE, 1991, p. A-30)

A final report of the Engineered Alternatives Cost/ Benefit Study (EACBS) (DOE, 1995b) considers a wide variety of engineered alternatives, ranging from the use of backfill around the waste drums to reduce the void volume (and, hence, the time required to compact and seal in the waste) to the sealing of individual rooms. The prudence of considering relatively simple measures such as room seals has been recognized in concluding statements such as the following: "Communication between the rooms during an intrusion scenario is significantly reduced (gas, brine, and radionuclides)" (DOE, 1995b, p. B-7).

The committee is disappointed that, as of the time of preparation of this report, these engineered alternatives, despite their appearance in the Engineered Alternatives Task Force (EATF) and EACBS reports and their benefits being noted in Systems Prioritization Method (SPM) efforts (Sandia National Laboratories, 1995), have been neither evaluated by the WIPP program in past compliance documents nor incorporated into the 1995 performance assessment process (DOE, 1995a). The 1995 baseline model used (DOE, 1995b, Introduction) for compliance purposes is a connected repository, a suboptimal design (see Chapter 2). The benefits of using backfill are also supported by recent SPM results (Prindle et al., 1996).

Pre-Emptive Mining of Potash

The McNutt Member of the Salado Formation above the repository horizon contains potash that could be attractive for mining in the future. The field extraction methods currently used in New Mexico potash mines result in substantial ground deformation, both above and below the mined-out horizon, and surface subsidence. The ground deformation and subsidence over the mined-out area involve fracturing of the overlying strata, such as the Culebra Dolomite and the Dewey Lake Red Beds. This, in turn, may increase the hydraulic transmissivity of these layers significantly.

It is not yet clear how important this increased transmissivity might be in compromising the ability of the Culebra and associated strata to delay release of radionuclides from the repository. Studies by DOE are in progress. Should it be determined that the effects are sufficiently adverse to warrant corrective action, it is technically possible, although expensive, to extract the potash "pre-emptively" (i.e., as part of the engineering design of the repository) in such a way as to avoid subsidence and associated damage to the overlying strata.

Extraction of potash would be carried out in two stages, using a room and pillar method with cemented backfill (Brady and Brown, 1987). In the first stage, approximately half of the potash is mined across the entire minable area. The rooms are then filled with cemented backfill. In the second stage, the ore remaining between the cement-filled areas is extracted, and the voids are again filled with cemented fill. In this way, deformation of the overlying formations would be negligible. If desired, special backfill material could serve as a protective cap over the repository and as a deterrent to future drilling.

Waste Form Modification

Concern about potential gas generation in WIPP (Bredehoeft, 1988) arose from the possibility that large quantities of brine might accumulate in the repository during waste storage (see Appendix C). The 1991 EATF (DOE, 1991), a multi-disciplinary group of over fifty scientists and engineers, considered a wide range of waste form alternatives based on existing technologies or on technologies that could be developed within a few years. Such technologies include methods to shred; compact; cement or grout; incinerate; vitrify; melt metal (producing ingots or slag); add pH buffers, salt, or sorbents; decontaminate metals; and use

noncorrosive containers. Changes in facility design also were considered. These options were screened to fourteen combinations that were chosen for detailed evaluation. Although such technologies either were available or probably could improve the waste form, the 1991 EATF report found that

- costs would be higher than if wastes were untreated,
- worker risk would be higher than for untreated waste handling,
- a waste treatment system would take significant time to implement, and
- treatment options would involve more complicated regulatory requirements.

In general, waste treatment options were viewed as properly held in reserve in case a need to supplement more readily implementable alternatives, such as backfill, arose. The 1995 EACBS (DOE, 1995b) chose to evaluate eighteen alternatives and reached similar conclusions and provided a specific ranking of the various alternatives.

In the committee's view, the conclusions of the EATF and EACBS are appropriate. As discussed in Chapter 3, gas generation is not anticipated to be a significant problem at WIPP; therefore, the use of advanced treatments such as incineration is unwarranted.

Findings, Conclusions, and Recommendations on Engineered Features

The committee believes that the WIPP design should incorporate engineered alternative features, and the performance assessment (PA) should reanalyze the human intrusion scenarios, incorporating (1) the existence of effective room/panel seals, and (2) a DRZ permeability that decreases with time, consistent with the known behavior of salt. Further, it is feasible, probably with no major increase in cost, to design the repository so that waste containers avoid contact with brine, thereby essentially eliminating gas generation, and to ensure that waste panels are isolated from each other effectively by seals that are comparable in permeability (10^{-16} m^2) to shaft seals.

The committee thinks that it is prudent to consider such engineering measures as backfilling of the waste rooms to ensure early reconsolidation of the DRZ and minimization of brine inflow. More advanced options, such as incineration or vitrification of TRU waste, are unwarranted.

SEALING OF SHAFTS AND BOREHOLES

In the committee's view, the flow of radionuclide-contaminated brine through inadequately sealed vertical shaft excavations at WIPP is the most probable pathway for release of radionuclides from the repository to the accessible environment under *undisturbed* conditions. Calculations (DOE, 1995d; and Appendix C) indicate that a seal permeability of 10^{-16} m^2 or less, over a minimum seal height of 100 m, is needed over the total (100 m^2) cross-sectional area of the four shafts to limit brine flow sufficiently through the seals to provide adequate isolation of the repository for 10,000 years. Figure 4.1 shows the results of PA calculations on the cumulative flow through the seals in 10,000 years.

In the figure, the net total brine flow through a 100-m-high seal of crushed salt (in each shaft) is plotted for various assumed values of the seal permeability. Each of the different flow values shown for a given seal permeability is the result of one "run" (or CCDF "realization"—see Appendix B) of the repository seal model. This model involves a number of parameters such as salt permeability, brine inflow to the rooms, gas generation, room closure, and gas pressure. Values for each parameter were selected at random from a range of values, and the model was run, computing for the particular combination of parameters selected the mean brine pressure at the bottom of the shaft over 10,000 years. In some cases, this mean pressure over 10,000 years was less than the net flow, or "cumulative release" was negative, that is, brine flowed *into* the repository. In other cases, the reverse was true, that is, the mean pressure below the shaft seal was greater than hydrostatic and so brine flowed *out* of the repository. Thus, Figure 4.1 shows both positive (outflow) and negative (inflow) values at each permeability tested. For permeability of $10^{-16}m^2$ or lower, the flows were negligibly small in all cases tested.

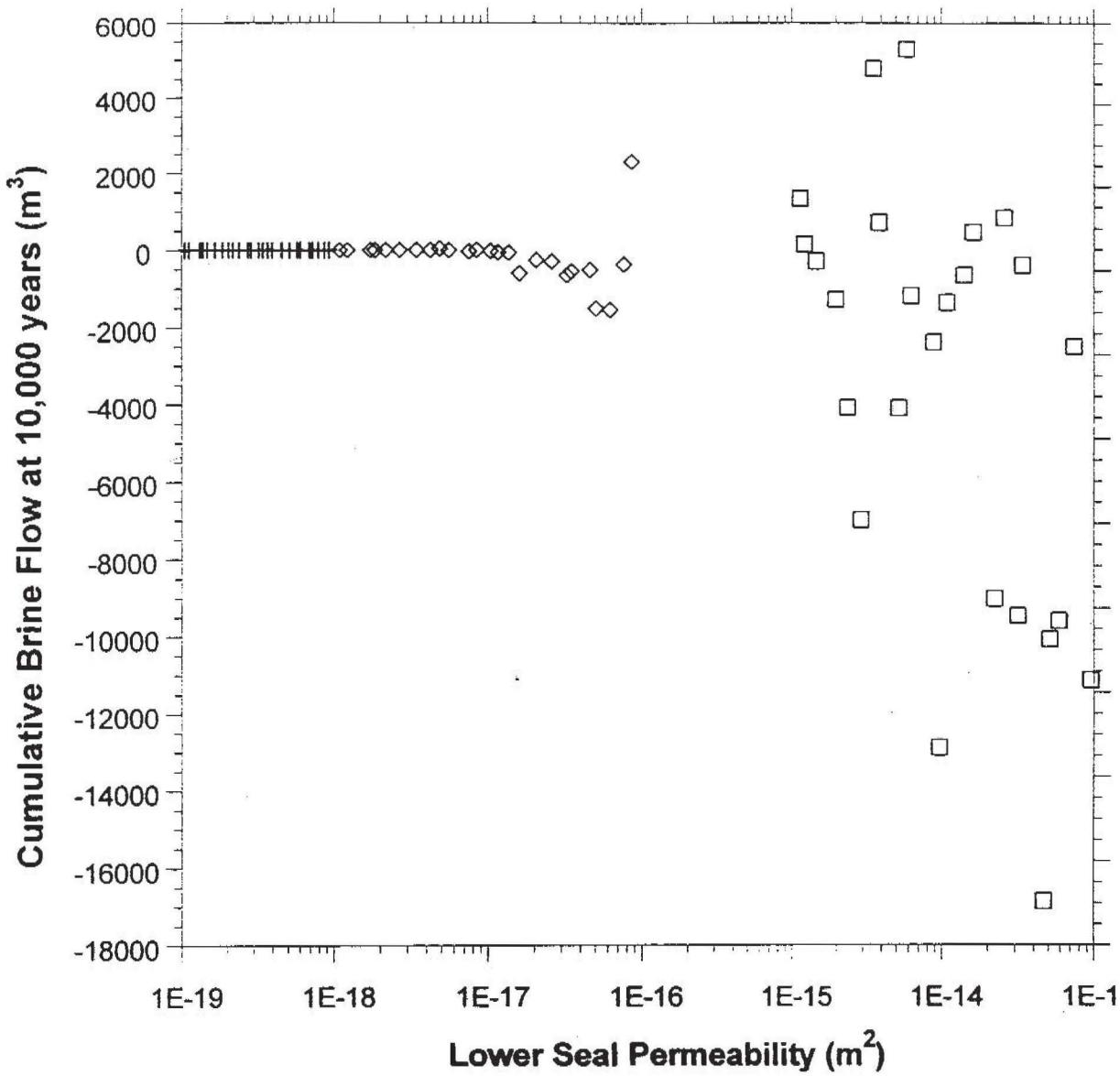

FIGURE 4.1 Predicted cumulative brine flow through (100-m-high) lower seals of the WIPP shaft. Source: Department of Energy (1995d, Figure C-1, p. C-5). This is a compilation of three sets of PA sampling calculations varying the Lower Seal Permeability. Squares indicate the cumulative flow for seal permeabilities in the range 10^{-13} to 10^{-15} m^2; diamonds, in the range 10^{-16} to 10^{-18} m^2; and plus signs, 10^{-18} to 10^{-19} m^2. In the calculation, the rate of brine flow through the seal depends on the *difference* between the pressure below and above the seal and lessens as the seal permeability decreases. The negative results in the figure indicate that the average pressure generated in the repository over the first 10,000 years is less than the pressure (hydrostatic) above the seal—so fluid flows *into* the repository. Thus, the Cumulative Brine (out) Flow is negative (i.e., it is a net inflow). When the permeability is 10^{-16} m^2 or less, there is little flow in or out. These PA calculations are based on the assumption that there are no designed seals in any of the underground excavations. Thus, shaft seals alone are sufficient to prevent radionuclide release for the undisturbed case.

It is seen that a lower seal permeability (abscissa) of 10^{-16} m^2 or less is needed to reduce the cumulative brine flow at 10,000 years (ordinate) to negligible levels for all repository parameter combinations. The accuracy of this result is shown by independent calculations performed by the committee and given in Appendix C. Similarly, a permeability of 10^{-18} m^2 or less is needed to limit gas flow through the seal (DOE, 1995d).[2]

The four shafts at WIPP are each approximately 6.1 m (20 ft) in diameter and approximately 660 m (2,160 ft) deep. The upper 256 m (840 ft) of the shafts passes through relatively permeable water-bearing sediments consisting of evaporites, carbonates, and clastic rocks. The remaining 404 m (1,325 ft) to the bottom of the shaft (and the repository horizon) consists of bedded salt in the Salado Formation. The Salado also extends approximately 200 m below the repository horizon.

Once the repository has been filled with TRU waste, the entire 660-m column of each shaft will be sealed with a variety of seal materials, as shown in Figure 4.2. In designing the seal system, it is necessary to incorporate features that effectively will prevent vertical flow of fluid both within the shaft itself and within an annular region extending about one-half to one shaft radius from the shaft wall into the rock. Within this region, referred to as the DRZ, the initially intact, essentially impermeable salt has been fractured as a consequence of rock stress changes introduced by the process of excavation and by the continuing changes that have occurred over the decade or so since the WIPP shafts were excavated (Figure 4.3). Given the additional 30-40 years needed to fill the repository, these time-dependent effects would be operative for a total of approximately 50 years before shaft sealing could start, creating an annulus of relatively high permeability around the shaft (Figure 4.3). This annular pathway for fluid flow must be eliminated to seal the shafts effectively.

[2]Although concentrations of hazardous gases are not likely to be sufficient to exceed Resource Conservation and Recovery Act regulatory limits on gas leakage to the accessible environment, the gas pressure of the repository is an important design consideration. Any pressurized gas in fractures in the DRZ around the shaft and in the interstices of the crushed salt used to seal the shaft could reduce the rate of salt recompaction significantly, both in the seal and in the DRZ. Brine within the same interstices could have a similarly retarding effect on salt consolidation.

Development and Healing of the Disturbed Rock Zone

The "damage" induced in the DRZ varies progressively from small, isolated microcracks in the regions of low stress change remote from the shaft, through a coalescence of the microcracks, to extensive through-going vertical fractures in the immediate vicinity of the shaft wall. Only in this more extensively fractured region is shaft permeability increased significantly.

Recent gas and brine flow permeability tests (Dale and Hurtado, 1996) around the Air Intake Shaft at the 660-m level and at the top of the Salado (256 m) reveal that there is no measurable change in permeability of the salt at either location, except within an annulus extending approximately 1 m from the shaft wall.[3] Thus, the region of increased permeability is likely to be a small part (10 to 20 percent [maximum] of the shaft radius) of the DRZ around each shaft.

Laboratory studies (Brodsky, 1995) clearly indicate that stress-induced fractures in salt specimens can be eliminated when the damaged region is subjected to sustained moderate confining pressure (approximately 5 MPa [MegaPascals]). The permeability of the cracked specimens is found to approach that of intact salt within a few days.

In the full-scale shaft sealing situation, the rate of reclosing or "healing" of induced (permeable) fracture zones around a shaft in the Salado will depend on the rate of buildup of the confining stress. This depends, in turn, on the compressibility of the shaft seal material and the rate of steady-state creep of salt around the shaft (Figure 4.4).

Numerical simulations by DOE contractors indicate that the width of the DRZ annulus at the time the shaft is filled (i.e., 50 years after excavation) will vary from $0.6R$ (where R [= 6.1 m] is the shaft radius) at a depth of 256 m (i.e., at the top of the Salado, where the lithostatic pressure is 6 MPa) to approximately $0.85R$ at 660-m depth (i.e., at the bottom of the shaft, where

[3]Because the rate of increase in the extent of the DRZ decreases exponentially with time, the 1 m of DRZ developed in about 10 years (the approximate age of the Air Intake Shaft) would grow to no more than about 2 m in 50 years.

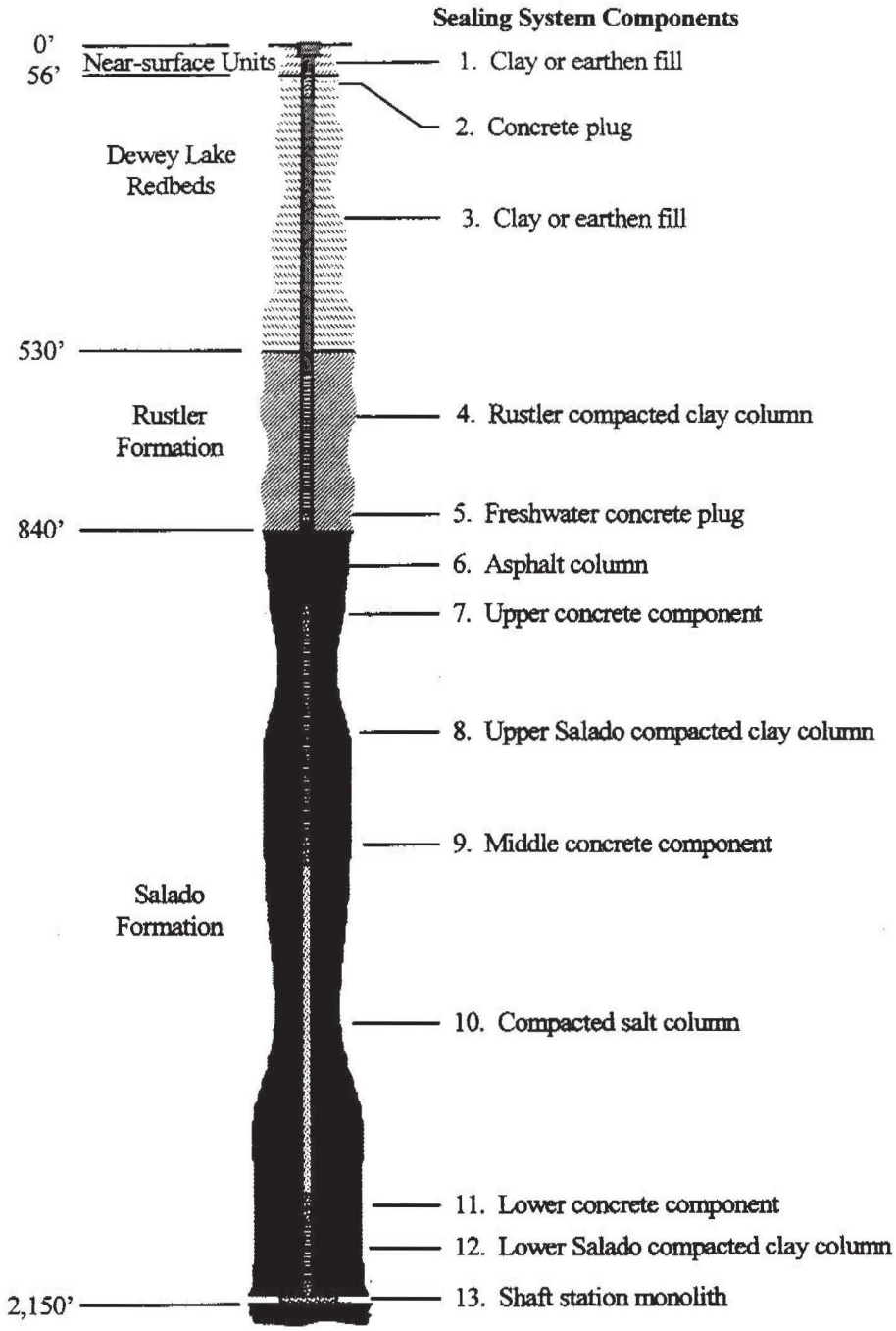

FIGURE 4.2 Arrangement of the WIPP shaft sealing system. Source: Department of Energy (1995d, Figure 2-1, p. 19).

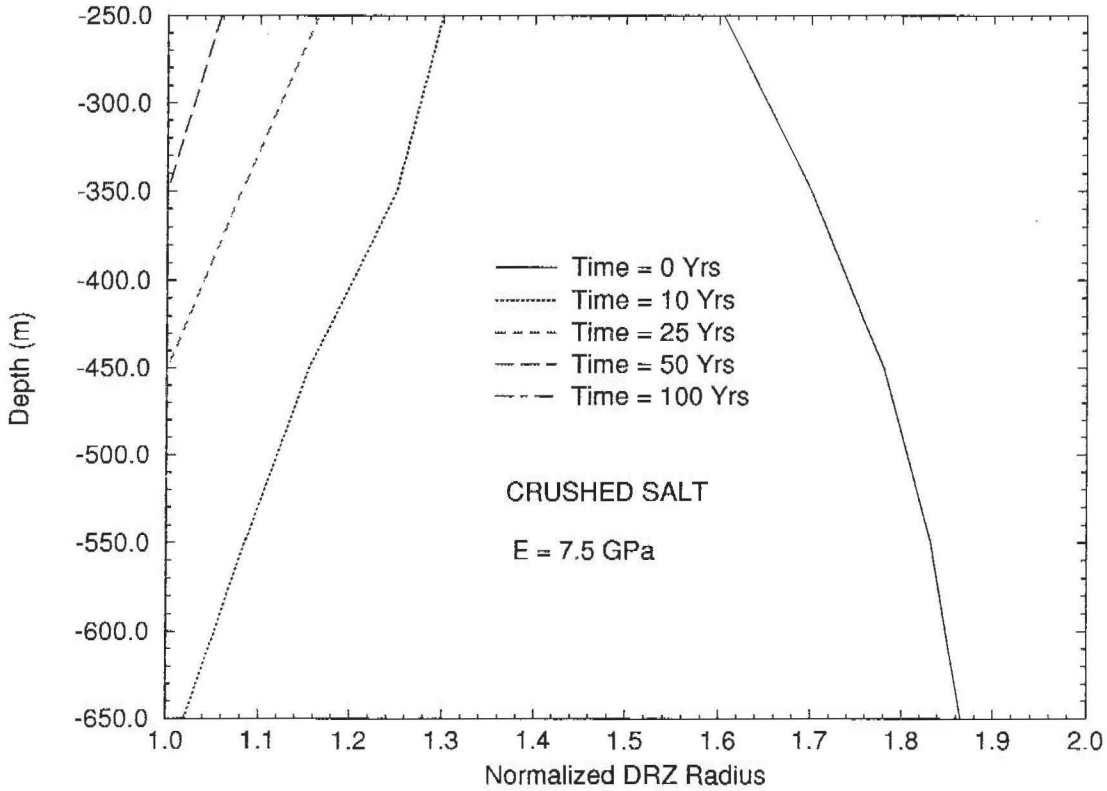

FIGURE 4.3 Calculated radial extent of DRZ annulus around a seal of crushed salt, compacted to 90 percent of the intact salt density. Source: RE/SPEC calculations done under contract to the Sandia WIPP Shaft Sealing Program, in RSI Calculation File 325/11/05.

the lithostatic pressure is 15 MPa). Computations (see Figures 4.3 and 4.4) indicate that with crushed salt that is compacted to 90 percent of the density of intact salt, the DRZ annulus will, 50 years after filling the shaft, have been reduced to $0.05R$ at the top of the Salado and totally eliminated between 350 m and the bottom of the shaft (660 m), that is, over almost 300 m. After 50 more years, the DRZ is eliminated over the entire 400-m Salado section. Because the region of increased permeability in the DRZ is confined to the portion immediately around the shaft wall, it seems probable that the entire 400-m Salado section in the shaft will achieve a permeability close to that of intact salt within 50 years of filling the shaft.

The computations above do not allow for the delaying effect of adventitious brine or high-pressure gases that could be introduced into the DRZ fractures. As mentioned earlier, the presence of these fluids would inhibit closure of both the DRZ and the compacted salt. Eventually, the connected, fluid-filled fractures in the DRZ (and regions in the crushed salt) would probably degenerate into isolated spherical inclusions containing gas or brine at lithostatic pressure within the "healed" salt, but the elimination of permeability may be delayed substantially. It is therefore desirable to ensure that the DRZ fractures and intergranular regions of compacted salt are maintained free of brine or gas during the 50-100 years required for full compaction under dry conditions.

To this end, several strategies have been proposed, including the introduction of supplementary seals above and below the region of the compacted salt seal. Use of the concrete seals, which have a significantly higher initial stiffness than the compacted salt, will result in a

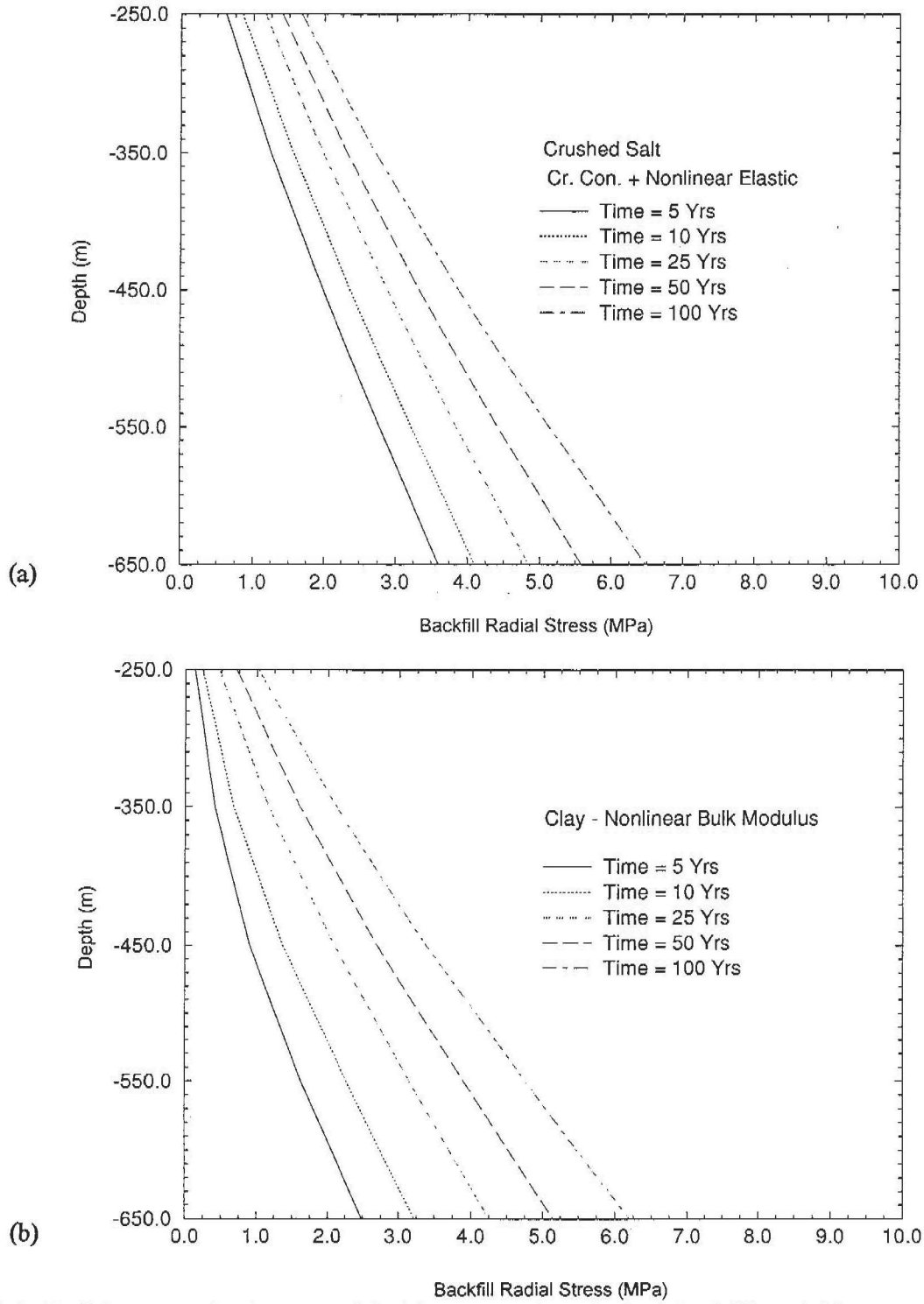

FIGURE 4.4 Radial stresses (back-pressure) in (a) compacted crushed salt backfill, and (b) compacted clay in the WIPP shafts as a function of time and depth. Source: RE/SPEC calculations done under contract to the Sandia WIPP Shaft Sealing Program, in RSI Calculation Files 325/11/03, 325/11/04, and in RE/SPEC External Memorandum RSI(RCO)-325/11/95/23 (November 1995).

more rapid buildup of back-pressure and correspondingly more rapid elimination of any permeability in the DRZ above and below the compacted salt section, thereby sealing this section early against brine inflow. Brine and gas inflow to the compacted salt column can be eliminated effectively by placing a compacted clay column above and below the compacted salt (Figure 4.2). Although probably unnecessary, it is feasible, at the time of sealing, to "ream out" this inner portion (i.e., about 10-20 percent of the shaft radius, as noted earlier) of the DRZ above and below the compacted salt sections where the concrete is to be placed. The reamed-out sections then would be filled with rapid-curing concrete as soon as possible after reaming, ensuring very early protection of the DRZ in the compacted salt section against inflow of brine.

The benefit of retarding release of radionuclides by placing compacted clay columns at various sections in the shaft (Figure 4.2) should be considered fully in the design and PA analysis of the effectiveness of shaft seals. Present PA sensitivity studies model shaft seal permeabilities but not extensive, detailed shaft designs.

No large-scale demonstrations of the effectiveness of proposed shaft-sealing designs have been carried out. However, the reality of salt creep is indisputable; salt around the shaft definitely will flow to seal in the shaft plug and reheal the disturbed rock zone. Because DOE proposes to use compacted crushed salt as the shaft seal material, this too should reconsolidate eventually to a density and impermeability comparable to that of intact salt. The practical feasibility of using temporary seals to eliminate water from the permanent seal sections during closure has to be examined and demonstrated carefully. Because these seals will be required only at the end of the operational phase of WIPP, there is adequate time to address this design problem.

In the proposed multicomponent shaft seal system (illustrated in Figure 4.2), reconsolidated salt is expected to constitute the major long-term seal component. Ahrens and Hansen (1995) demonstrated the feasibility of large-scale dynamic compaction of crushed natural salt in a shaft configuration to achieve 90 percent of its intact density, providing greater confidence in the efficiency of its reconsolidation to produce an effective long-term seal.

As noted previously, major short-term concrete seal components are expected to provide structural support as well as to retard brine or gas flow substantially during the intervening period before the salt seal components are adequately consolidated. This performance of the concrete component has been documented recently by the Department of Energy (1995d) and, in more detail, in individual reports (Stormont, 1984, 1986, 1988; Van Sambeek et al., 1993). The importance of designing concrete to be chemically compatible and durable in the salt-dominated WIPP horizon has been emphasized by several investigators (e.g., Roy et al., 1983, 1985; Wakeley et al., 1993, 1994, 1995). In-place permeabilities of experimental salt-saturated concrete plugs (1-m diameter) in WIPP showed decreased permeabilities with time (less than 4×10^{-19} m^2) after six years (Wakeley et al., 1993). Some remaining concerns exist regarding compatibility of concrete with magnesium-rich brines found at WIPP. Additional confidence in the performance of concrete is provided by field studies of sealing methods in salt or potash mines (Eyermann et al., 1995). The stoppage of major (10 m^3/min) flow of pressurized brine in the Rocanville Potash Mine, Saskatchewan, is a good example of the ability to seal excavations effectively in potash (or salt) using current technology.

The seal design incorporates additional components of shaft seals, planned to perform individual functions (DOE, 1995d). These seals include compacted clays (Meyer and Howard, 1983) for use in both non-Salado and Salado members, asphalt to act as a water-stop between concrete members, and possibly other impermeable chemical seal components to act essentially as an O-ring. Issues of concern about the potential use of asphalt as a seal component have not been resolved fully. As with many organic-based materials, there are issues of potential degradation and gas generation, including microbial attack. Addition of lime to the asphalt mix has been suggested as a possible remedial measure (DOE, 1995d). The influence of the different compressibilities of the seal material (here crushed salt and clay) on the rate of buildup of radial stresses in the seal and the shaft wall is illustrated in Figure 4.4.

The sealing of exploratory and other boreholes, as necessary, is expected to draw on extensive experience

with cementing and plugging technology in the oil and gas industry, much of which has involved bedded salt environments. Impressive early tests of the performance of the borehole plug (cementitious materials) under high well pressure conditions in the specific WIPP environment (Gulick et al., 1980) have been followed by other studies, demonstrations, and plug material development (Finley and Tillerson, 1992; Wakeley et al., 1995).

SEALING OF ROOMS AND PANELS

Sealing sections of horizontal drifts presents essentially the same problems as sealing vertical shafts, except that in this case, gravity acts to accentuate development of the DRZ in the roof and to retard it in the floor. One difference is that during placement, it is difficult to compact crushed salt in a horizontal drift to the same density as in a vertical shaft.

Salt creep should compact horizontal seals eventually to the same high level of impermeability (for both the DRZ and the excavation) as in the shafts. If it is assumed, for example, that 100 m of drift can be packed with crushed salt at 70 percent of the intact salt density (i.e., rather than the 90 percent density for the shafts), 200 or 300 years probably will be required to reach 10^{-16} m^2 seal permeability, rather than the 50-100 years needed for the shaft. Technologies of placing drift seals to isolate radioactive waste have been, or are being, examined elsewhere, for example, in Stripa (Sweden) and Pinawa (Atomic Energy of Canada, Ltd., Canada). Salt has the distinct advantage over most other rocks of exhibiting creep, allowing rehealing of the DRZ, and progressive reduction of seal permeability.

Thus, it seems technically feasible to provide, between the waste storage rooms and panels, drift seals that are sufficiently tight, perhaps 300 years after waste emplacement, to eliminate brine communication between the waste-filled rooms and panels at WIPP. Note that any such communication between rooms via anhydrite marker beds (e.g., MB 138, MB 139) would not be affected by the drift seals. These beds have a low permeability, of median value 2.5×10^{-19} m^2 (DOE, 1995a, p. 6.75) and therefore would contribute negligible brine, with regions near the excavations becoming drained during the period that the rooms are open before waste emplacement. As discussed at the beginning of this chapter, with careful room and panel seal designs, it should be possible to inhibit room-room hydrologic communication.

Whether or not drift seals contribute to the overall isolation capability of the repository depends on the credence given to the human intrusion scenarios that must be examined according to 40 CFR 194. For the undisturbed case, PA studies by DOE in which no drift seals are assumed show that the shaft seals alone are sufficient to prevent radionuclide release. Thus, for the undisturbed case, drift seals are not necessary to demonstrate compliance (see discussion of Figure 4.1).

Currently it is assumed, for example, as part of the E1E2 scenario (see Chapter 2), that brine from a pressurized reservoir will flow through the repository, carrying radionuclide-contaminated brine to the surface via a second borehole. Provision of drift seals would reduce the possibility of establishing such a flow path and hence would considerably reduce the significance of this "two-hole" type of human intrusion.

CONCLUSIONS

The ability of salt to flow under stress is a particularly valuable attribute with respect to sealing excavations in the WIPP repository. While careful attention to good practice during seal construction is very important, it appears to the committee that the design of effective shaft and panel or room seals at WIPP is entirely possible by using currently available technology. The shaft seal design system proposed for WIPP (DOE, 1995d) includes large factors of conservatism and redundancy, which ensure that the requirements of 40 CFR 191 with respect to sealing of excavations at WIPP can be met by a large margin.[4] Although room and panel seals are not essential for adequate waste isolation at WIPP given undisturbed conditions, they would reduce the significance of an E1E2 intrusion event considerably.

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[4]This is a properly conservative design of the engineered seal. There is no contradiction between the conservatism advocated here and the critical remarks against conservatism in Chapter 2. The latter were levied against unrealistic assumptions of salt performance that could lead to a mischaracterization of how WIPP could perform.

Chapter 5

Actinide Source Term

In the performance assessment (PA) of the repository described in Chapter 2, compliance with the Environmental Protection Agency (EPA) requirements is discussed relative to two scenarios, E1 and E1E2 (Figures 2.4 and 2.5), in which pressurized brine from below the Salado Formation flows into the repository and then either directly to the surface or through the Culebra Dolomite to the accessible environment. The amount of radioactive material that might move into the environment obviously will depend on the amounts of the five actinide elements (plutonium [Pu], americium [Am], neptunium [Np], uranium [U], and thorium [Th]) that the flowing brine can transport. This quantity is the actinide source term (AST), defined more specifically by scientists at Sandia National Laboratories as the cumulative amounts, concentrations in solution, and chemical nature of the radioactive materials that conceivably could be moved in solution or suspension from the Waste Isolation Pilot Plant (WIPP) repository into the environment.

Clearly, an estimate of the AST is an important part of any performance assessment. Although the AST program includes an evaluation of five actinides, the most important issue for periods greater than a thousand years is the fate of the more abundant, long-lived isotopes of plutonium (e.g., Pu-239 and Pu-240; see Table 1.1). The study of the other actinides is important because they provide a basis for the oxidation state model in which plutonium may assume a variety of oxidation states. As an example, the following elements may be used to model the behavior of plutonium: Am(III)[1] for Pu(III), Th(IV) for Pu(IV), $Np(V)O_2^+$ for Pu(V), and $U(VI)O_2^{2+}$ for Pu(VI) (Novak, 1995b).

Evaluation of the AST depends principally on the following:

- the total inventory of radioactive material (Table 1.1) and its decrease due to radioactive decay as a function of time;
- conditions within panels of the repository and along the route of transport (e.g., the volume of brine exposed to the waste and transported out of the repository); and
- the timing of potential release events.

The challenge in making a reasonable estimate of the AST is to gain an understanding of the coupling between the chemistry of the system and the boundary conditions and assumptions (e.g., redox potential, flow rate, gas generation, distribution of sorbing clays, presence of ligands) used in the performance assessment.

As noted in Chapter 2, performance assessments to date (e.g., that for 1992) confirm that if the repository, after completion, is left undisturbed by human activity, the presence of brine in contact with waste will not lead to migration and release of appreciable radioactivity beyond the WIPP boundary. The geologic barriers, combined with the planned engineered barriers discussed in Chapter 4, will be sufficient to prevent radionuclide escape. *Thus, for the undisturbed case, the magnitude of the AST is of no consequence for assessing compliance.*

If the repository is disturbed at some time in the future, however, it is possible that some radioactive material might escape. Therefore, estimates of possible amounts of released radioactivity are required for detailed assessment of the performance of the repository under various assumed conditions. In any such assessment, the magnitude of the AST is an important parameter.

In making a performance assessment of the scenarios described in Chapter 2, Department of Energy (DOE) scientists have undertaken an elaborate program of experimental work (Novak, 1995a) to ascertain the

[1]The Roman numerals specify the actinide oxidation state.

possible range of actinide concentrations in the brine as it moves from the panels in the repository to the WIPP boundary. This chapter reviews DOE's proposed experimental program (Novak, 1995b; Papenguth and Behl, 1996a, b) on the AST.

Although the committee has been given a good overview of the work on the AST that has been completed or is still in progress (see Appendix E), much of the research on the source term is not yet complete, and some important results of the program will not be available for review in the immediate future (e.g., experimental studies of Pu speciation in brine). Consequently, this chapter should be viewed as a review of work in progress and cannot serve as an evaluation of the quality or applicability of the final experimental results.

ACTINIDE SOURCE TERM MODEL

Brine that has been in contact with transuranic (TRU) waste (described in Chapter 1) likely will contain actinides as compounds or ions in solution and as colloidal particles. As the brine moves through rock units, the amount of actinide transported will change. Actinide concentrations in brine may be expected to decrease owing to precipitation of actinide-bearing phases or sorption on mineral surfaces; alternatively, actinide concentrations could increase in response to the formation of complexes in solution. To determine the amounts of actinides that might reach the compliance boundary, estimates of the following are required for each element of concern (particularly plutonium):

1. the concentration in solution, as controlled by the solubilities of the actinide-bearing phases and the kinetics of the dissolution process;
2. the amount that could form and be transported as colloidal particles; and
3. the amount that could be removed from solution by sorption on the surfaces of dolomite or other minerals (e.g., the corrensite-lined fractures of the Culebra Dolomite) as the brine moves from the repository into the surrounding rock.

DOE analyses (Sandia National Laboratories, 1992, 1995; DOE, 1995a) consistently have identified these three quantities as important to the long-term performance of WIPP. The same three quantities also have been identified as important by EPA and the Environmental Evaluation Group (EEG; Neill et al., 1996).

Estimates of these quantities can be approached theoretically with models using tabulated chemical data and basic chemical principles, and empirically through either carefully controlled laboratory experiments or measurements under actual field conditions. Each approach has advantages, and all have weaknesses. Although well-controlled experiments using ideal or model systems may provide a fundamental understanding of the chemical processes, conditions of the experiments may be simplified to the point that their direct applicability to the larger-scale, more complex conditions in a waste panel is not clear. Field-scale experiments (e.g., sorbing tracer tests) or experiments with actual waste (e.g., Source Term Test Program [STTP] experiments at the Los Alamos National Laboratory [LANL]) may be difficult to interpret, but they do provide qualitative information on potential chemical interactions and bounding estimates of actinide concentrations in brine. Confidence in the models used in performance assessment will rest inevitably on consistency in the results and the general applicability of the models to all results—experimental, theoretical, and field.

Three principal factors currently being investigated by DOE that determine actinide transport in brine—solubility, colloids, and retardation by sorption—are examined below. Only limited attention is being paid to other factors (e.g., kinetics and redox effects on the reactions) that may also finally influence the transport of actinides to the accessible environment.

Solubility

Estimating actinide solubilities from published data is particularly difficult because the electrolyte concentrations in brines are very high, whereas most existing tabulated data apply to dilute solutions. This means that the thermodynamic formalism related to solubility must incorporate the use of correction factors. Of the numerous such factors that have been proposed, the generally accepted approach has proven to be the parameters developed by Pitzer (Pitzer, 1991). These are the correction factors used by DOE scientists

(see Appendix E for a more detailed discussion of Pitzer parameters).

Difficulties in determining actinide solubilities are compounded by the many gaps in published tables of thermodynamic data. DOE scientists are responsible for filling such gaps through their experimental work. A further complication is the fact that the solubilities of a number of actinide compounds are influenced by the formation of complexes, either with inorganic ions such as Cl^- and CO_3^{2-} or with C-H-O compounds from the organic materials present in much TRU waste. Add the difficulty of knowing or determining the relative proportions of the oxidation states of an actinide element in a given solution, and the complicated nature of the task that DOE researchers have set for themselves becomes apparent.[2]

Based on a review of the AST program, the committee has identified areas of concern that are described in Appendix E. Although the experimental approach chosen to estimate actinide solubilities is acceptable, it will be defensible only when supported by extensive experimental data, which were unavailable at the time of preparation of this report. When compared to published experimental data, current modeling efforts are not capable of conservatively estimating actinide solubilities. For example, Novak and Roberts (1995) found that their model for Np(V) predicted solubilities as much as an order of magnitude less than those determined experimentally. Thus, completing the experimental program in order to generate Pitzer parameters for all oxidation states of the actinides is essential for obtaining credible estimates of dissolved actinide concentrations.

Additionally, the estimate of actinide concentrations in a brine will depend on the solubilities of actinide-bearing phases. In most of the experimental programs, too little attention is being paid to identification of the solubility-limiting phases. These phases may be unusual in composition, and thus difficult to identify, because of the complex composition of the brine and the waste inventory. Many of the thermodynamic data required by geochemical codes to model actinide concentrations in solution are either absent or contradictory. A key factor in the final result will be the "fairly subjective" choice of the solubility-limiting phase (McKinley and Savage, 1993).

Colloids

In the repository environment, many processes can lead to the formation of colloidal suspensions (Laaksoharju et al., 1995), some of which may include actinide elements. In fact, the transport of actinides by colloids greatly can exceed that anticipated from models based solely on the solubility of actinide-bearing phases (Kim, 1994). Recent results (Reed et al., 1994) have demonstrated the important potential role of colloids in retaining plutonium in suspension, with subsequent transport potentially being greater than expected (Ibaraki and Sudicky, 1995).

When a solid actinide compound is precipitated from solution, it may form suspended colloidal particles rather than a crystalline solid, or actinide ions may attach themselves to colloidal particles formed in other ways, either as inorganic particles or as complex compounds derived from organic constituents of the waste. Some of the varieties of bacteria that grow in the waste solution may themselves be particles of colloidal size and may contain sorbed actinides.

Colloid particles (usually in the size range of 10^{-9} to 10^{-5} m) generally have an electric charge, either positive or negative, that helps keep the particles apart and prevents their flocculation as a precipitate. In concentrated electrolyte solutions such as WIPP brines, the charge on particles is neutralized readily and the colloids are generally unstable. This is especially true for colloids of inorganic material (either colloids consisting entirely of actinide molecules or inorganic

[2]Because alpha radiation exists as a continuous source of electron acceptors (reductants), "autooxidation" by alpha bombardment is possible. In some environments this has affected redox-sensitive reactions, because Eh of the fluids is important in solubility determinations. However, the pH and Eh conditions at WIPP are controlled by the geologic environment and by constituents of the waste, particularly the metal of the waste containers and the abundant organic material in the waste. A slight change caused by alpha bombardment is expected to be negligible for both the disturbed and the undisturbed repository. Alpha-radiolysis causing oxidative corrosion is a minor concern in spent fuel storage (Shoesmith et al., 1996). Alpha-radiolysis is expected to be an even more minor concern at WIPP, because a comparison of the U.S. spent fuel inventory to the TRU waste inventory, in an isotope-specific curie comparison of transuranics only, shows spent fuel to be orders of magnitude more radioactive.

compounds with sorbed actinides) and less so for colloids in which the particles consist largely of organic material. The former are called "hard-sphere" or hydrophobic colloids; the latter, "soft-sphere" or hydrophilic colloids. In general, hard-sphere colloids readily flocculate in a strong electrolyte and, hence, are ineffective in mobilizing actinides in the WIPP environment. In contrast, some soft-sphere colloids (including colloidal-size bacteria) remain stable even in concentrated solutions and so can serve as effective transporters of actinides. It is emphasized that colloid stability is a complex function of many other variables, such as acidity and alkalinity, the nature of sorbed ions, and the kinds of organic matter and electrolytes present.

Bacteria may be the most effective vehicle for transport of actinides in the Culebra Dolomite. Their total numbers, sizes, and morphologies in indigenous Culebra brines will be determined, as well as the increase in their numbers if nutrients are added from organic material in the waste. Bacteria can influence the behavior of actinides in several ways:

1. Their metabolic activity will tend to keep conditions slightly acidic, thus helping to determine the oxidation state of actinide elements and so affecting their solubilities.
2. By sorbing ions from solution, bacteria obviously can aid in the transport of actinides.
3. The well-known tendency of microorganisms to adhere to surfaces (Marshal, 1976) may serve to retard actinide transport.
4. If significant quantities of gas are produced as a result of microbial metabolism, this gas also may influence the movement of actinides.

In addition to bacterial activity, any corrosion process will influence the pH and/or the gas content of the brine and thereby influence solubilities and subsequent transport of actinides.

The possibility of substantial transport of actinides in colloidal form has been recognized only fairly recently (Kim, 1994) and has spurred much effort by DOE scientists to investigate the complexities of colloid behavior in strong electrolyte solutions such as WIPP brines (Papenguth and Behl, 1996a). From the proposed experimental program, DOE scientists expect to learn whether there is a serious threat of active transport of actinides by colloidal particles and what measures might be taken to modify conditions in the WIPP repository to reduce this threat.

The DOE study began with a comprehensive review of recent literature on the formation and stability of colloids in electrolyte solutions and now includes detailed plans for experiments designed to answer the many remaining questions about this mode of actinide transport (see Appendix E). This effort is commended by the committee, with the expectation that these results will provide much of the new information needed to gain a deeper understanding of colloids as part of the actinide source term. The experimental work has started and is scheduled for completion soon (see Table E.1), but no results have been presented to the committee.

Retardation

If, as postulated, the dissolved and colloidal actinides that make up most of the source term move with the brine into the accessible environment through the Culebra Dolomite, their transport will be retarded to some extent by sorption on the surfaces of the dolomite and minor amounts of clay minerals (e.g., corrensite) contained in this member. Thus, the amount of radioactive material that might actually reach the accessible environment depends on the effectiveness of this sorption. Accordingly, the amount of sorption is a critical factor in any attempt to estimate whether or not the WIPP project complies with EPA regulations.

As with solubility, the study of retardation by sorption is made difficult by the high concentration of dissolved material in the brine. For dilute solutions, determining the amount of material sorbed is straightforward and experimentally simple. It is commonly expressed in terms of K_ds, or distribution coefficients, which are merely the ratios of amounts sorbed to amounts left in solution. Complexities arise with concentrated solutions, however, because (1) many substances are competing for places on any given sorption site, and (2) the nature of the sorbing substance is influenced by its speciation and the chemical conditions (e.g., acidity and alkalinity) of the solution (see discussion in Appendix E). Additionally, batch K_ds measured in the laboratory rarely have been

used successfully to predict sorption on a larger field scale.

Because simple K_ds are of little use as predictors, amounts of sorption are best determined by direct experiments in which samples of natural or synthetic brine are allowed to flow through samples of the intended sorbent material, and actinide concentrations are measured before and after the passage (see Appendix E). Such experiments have been planned carefully and should give a good indication of the effectiveness of sorption in controlling actinide concentrations; however, no results of the experiments completed to date have been presented to the committee. The experimental results will have to be confirmed by results from actual field experiments. Throughout the history of the WIPP project, such studies ("sorbing tracer tests") have been planned, delayed, and canceled. The status of such tests at present is unclear. It will be difficult for DOE to take credit for sorption in the Culebra (or any other rock unit) in the absence of well-planned and completed field tests.

SCHEDULE

As noted above, the ambitious schedule DOE has set for completion of experimental work for the AST (1996) is unrealistic in that final, definitive values for some of the numbers being sought cannot possibly be obtained and evaluated critically in so short a time. Enough data may be generated to provide a reasonable basis for the proposed compliance application, but important details about the source term and its appropriate use in performance assessment will almost certainly require additional work. Strictly accurate final values are not essential for showing compliance with EPA regulations, but are nevertheless numbers for which DOE will find many uses later. The committee recommends that selected research programs be extended into the operational phase of the repository.

SUMMARY AND DISCUSSION

The actinide source term can be envisioned as the entire mass of actinides destined for disposal at WIPP, partly dissolved and partly in colloidal suspension in a brine similar in composition to Salado Formation or Castile Formation brines (or a mixture of the two). That the entire mass would ever be dissolved or suspended is hardly likely, but a minor fraction could plausibly be mobilized at some time or times in the future. Determining how large this fraction might be requires knowledge of the solubility of each of the actinide elements in brine and its behavior as a colloid, plus data on the sorption of ions and colloidal particles onto mineral surfaces with which the brine may come in contact. Data of this sort, both from the literature and from experimental work, have been and are being accumulated in impressive amounts by DOE scientists and contractors.

Data on the source term, as noted previously, will have no importance if the repository remains undisturbed by human activity for 10,000 years because no appreciable radioactivity will likely escape to the surface. However, for any of the scenarios considered in Chapter 2 describing the results of possible human disturbance of the repository, knowledge about the source term is essential for estimating possible radioactive releases from various assessments of repository performance and, hence, for making a decision on the application for a certificate of compliance to open the WIPP repository.

The ongoing experiments in DOE laboratories and DOE-sponsored universities, if carried to completion, would begin to provide the necessary information. The present schedule will not allow all the work to be finished and evaluated before the Fall of 1996. Nonetheless, enough preliminary data will be obtained to make possible a reasoned judgment of whether WIPP meets the compliance criteria for the disturbed case.

Overall, the scientific program outlined by DOE for study of the source term is adequate, provided that the program is carried to completion. Because the program at this time consists largely of work planned or in progress, it has not been possible to critically review experimental results or to judge whether these results are used appropriately in the PA analysis. Much of the AST work has not been subjected to the type of peer review that is part of publication in scientific journals, and the committee recommends that such review be sought as the work progresses. Interaction between principal investigators in the AST program and modelers in performance assessment has been

disappointingly limited, and the committee recommends that this situation be corrected.

In the opinion of the committee, as soon as substantial results are available from the experiments—provided, of course, that the results show the expected low solubilities, which will permit calculation of low actinide releases based on some of the less improbable variants of the borehole scenario—then DOE will have the information on actinide solubilities needed to prepare the certification of compliance.

Experiments should continue for as long as is needed to obtain reliable values for actinide solubilities, colloidal transport, and nuclide retardation by sorption, a time during which the repository will be in full operation. The new data obtained will be important at the WIPP site as a basis for changes in operational procedures (e.g., use of backfill, improved seals, or reduced waste loading) and, more generally, for providing the fundamental understanding needed to predict actinide behavior in other situations. Actinide chemistry is important, for example, in the disposal of other kinds of radioactive waste and in the nationwide environmental remediation program that DOE has undertaken. Because the experimental work will provide basic data needed for a variety of purposes, the committee recommends that DOE continue this work beyond the scheduled completion dates in mid-1996.

There appears to be no reason that the further required work on the actinide source term cannot be accomplished simultaneously with the disposal of waste in the repository. This additional work will improve the scientific basis of the performance assessment and increase public confidence in the ability of WIPP to isolate TRU waste.

CONCLUSIONS AND RECOMMENDATIONS

The committee offers the following conclusions regarding the actinide source term:

- *For the undisturbed case, the magnitude of the actinide source term is of no consequence to the demonstration that WIPP can isolate waste from the biosphere effectively for many thousands of years.*
- *In the disturbed case, if it is necessary to rely on estimates of actinide concentrations in the brine, colloidal transport, or nuclide retardation by sorption, a well-documented, reviewed, scientific and technical basis for these estimates does not yet exist. With this in mind, the following observations and recommendations are made.*

With the exception of specific scientific issues raised in this chapter (and detailed in Appendix E), the scientific program outlined by DOE is adequate if the proposed program is carried to completion.

Plutonium is the principal radionuclide of interest in any release scenario. Although some aspects of its geochemical behavior can be estimated by studies of other actinides using the oxidation state model, ideally, data for each oxidation state should be followed by experiments with plutonium.

Because the AST program at this time consists mainly of proposed work, the committee has not had the opportunity to review experimental results or to evaluate whether these results were used appropriately in the performance assessment analysis. At present, much of the AST work in support of the WIPP project has not been subjected to the type of peer review that is part of publication in scientific journals. This review process is the essence of quality assurance, and the committee recommends that scientific results of the AST program continue to be published in peer-reviewed journals.

The existing schedule (see Table E.1) will not allow for the timely (i.e., by the Fall of 1996) completion of the proposed experimental work, proper analysis of the results, or publication in peer-reviewed scientific journals. In addition to the STTP, long-term scientifically based experiments are crucial in evaluating the long-term extrapolations that are required by PA analysis. These experiments are not part of the present experimental program; however, they should be an essential aspect of the iterative PA process, which will be required even during the operational phase of the repository. The needs of the AST program are not unique to the WIPP project. DOE inevitably will need a strong program in basic actinide chemistry as part of its nationwide environmental remediation effort. Prudent and efficient planning could consolidate the needs of the WIPP program within a broader program of basic research in actinide chemistry.

The interaction between principal investigators in the AST program and modelers in performance assessment has been disappointingly limited. Thus, it still is not clear how the AST data (experimental or theoretical) will be used in the performance assessment. The PA analysis has not yet provided the type of guidance to the experimental program that is required in order to determine when the work is, in fact, complete.

Concerning the use of performance assessment, there is still no clear distinction between the uncertainty associated with the selection of conceptual models in the AST and the uncertainty that results from the experimental data. This distinction is essential in evaluating the impact of the AST on PA analysis and conclusions.

The use of experimentally determined batch K_ds alone is not sufficient to justify the assumption of retardation of actinides during transport through the Culebra Dolomite. Field confirmation and/or a more fundamental understanding of sorption processes are needed.

Based on the current assessment of the WIPP site, the committee believes that the required work on the actinide source term (actinide concentrations in brine, colloid formation and transport, and nuclide retardation) can be performed simultaneously with the operation of the facility.

Chapter 6

Non-Salado Hydrology

The purpose of this chapter is to review and comment on the state of the U.S. Department of Energy's (DOE's) understanding of hydrology in formations at the WIPP site above the Salado. Studies of these subsurface aquifers ideally should aim to define the flow of ground water as well as possible. Virtually all feasible pathways by which radionuclides can move from the repository to the accessible environment depend on ground-water transport.

Site hydrology considerations are thus relevant to predicting the fate of any radionuclide release from a WIPP repository. Any such release will depend predominantly on three factors:

1. the volume of water (brine) that circulates through the waste-filled rooms and is released;[1]
2. the concentration of radionuclides in this brine; and
3. the rate of transport of the radionuclide-contaminated brine through the permeable sediments above the Salado Formation (e.g., Culebra Dolomite, Dewey Lake Red Beds) to the accessible environment.

WIPP repository design measures that can be taken to reduce the volume of brine release have been discussed in Chapter 4. Detailed studies to determine radionuclide solubilities, and hence concentrations, in brine have been discussed in Chapter 5. This chapter considers the third factor, considerations of ground-water flow and radionuclide transport.

If it can be demonstrated reliably that the concentration of radionuclides in the water and their rate of movement through the repository to the accessible environment together do not cause the release limits specified in 40 CFR 191 to be exceeded, then the repository can be considered to be in compliance with these regulations. Such a demonstration would, in principle, involve a combination of the three factors enumerated above, with their relative importance dictated by the natural site characteristics and any engineered enhancements to the repository design.

REGIONAL HYDROGEOLOGIC MODELING

In the interests of brevity in this overall report, the significant advances in the understanding of the hydrogeologic framework that have been made since the WIPP investigations were started (i.e., since the mid-1970s) are not discussed in detail in this chapter. Appendix A summarizes the regional hydrogeology of the WIPP site.

The latest formal analysis available to the committee and discussed here is the 1992 Performance Assessment (PA). This model assumed a two-dimensional, steady state, horizontal flow of ground water in the Culebra Dolomite, with simple parameterizations of both chemical and physical retardation mechanisms to describe solute transport.

The discussion below outlines the main shortcomings of the 1992 PA models and analysis. Some of the criticisms reflect current limitations of the state of art of ground-water and transport study in general. Some criticisms can be resolved relatively easily, but other criticisms may require considerable effort to address.

The assumptions of the 1992 PA predicted a release of a mass of contaminants under disturbed conditions that, for a compliance demonstration, required a reliance on two features: long ground-water travel times in the Rustler Formation (primarily in the Culebra Dolomite) overlying the Salado Formation, and significant retardation of radionuclides. If this remains true in the PA calculation submitted as part of DOE's compliance certification submission in October 1996, then the committee believes that DOE will have to

[1]For 40 CFR 191 compliance, the total volume over 10,000 years is to be considered.

improve the case presented in the 1992 PA substantially to establish the technical credibility of the assumptions and values used in the analysis.

Most of the critiques in the following discussion of non-Salado hydrology relate to assumptions or numerical methods in the 1992 PA that need to be documented better or evaluated further before a high degree of reliance can be placed in the overall model results. For example, the PA models allow chemical retardation or matrix diffusion to attenuate radionuclides after release to the Culebra. Although it seems likely to the committee that some chemical retardation and matrix diffusion will occur, the documented basis for the assumptions about retardation in the 1992 PA is very weak. It is possible, and in some cases probable, that the final PA models and more recent experimental results—which have not yet been reviewed by the committee, but which will be included in the final compliance submission—will resolve many of these concerns.

Considerable effort has been expended by DOE over the last four years to increase its understanding of the ground-water and transport regimes at WIPP, and informal reports of significant progress have been made. The considerations raised in the following discussions point out shortcomings in past (i.e., 1992) modeling efforts, but the committee has determined that they do not challenge its position that DOE should be able to complete the work required to show that WIPP can comply with 40 CFR 191, and that the repository can probably be shown to present a low risk of human exposure to radionuclides, even in the event of a severe (E1E2) intrusion. However, to the extent that compliance demonstrations may rely on ground-water flow and transport in the non-Salado formations, they will require examination of at least some of the hydrogeology and transport issues discussed below.

FLOW AND TRANSPORT MODELING

A general discussion of ground-water modeling efforts and common difficulties is provided in this section (see Box 6.1 for a summary of key features). Supplemental background discussions of these issues are included in Appendix F. Models that simulate ground-water flow and transport processes are an essential tool in the characterization, analysis, and performance assessment of WIPP. Model predictions also lie at the heart of the PA process for the WIPP site (see Chapter 2). Therefore, it must be demonstrated that a high level of confidence in the PA models is justified.

The accuracy and precision of predictions of transport of radionuclides through a deep regional aquifer system depend on the level of understanding of the processes governing flow and transport through that system, how well the relevant properties of the system are defined, and how accurately the boundary conditions of the system are known. If the assessment of the isolation capability of the site is expected to provide a reasonable level of confidence that the predictions bound the range of plausible values, then the predictions must be based on an appropriate and adequate level of understanding of the processes, properties, and boundaries of the aquifer system and of how these factors may change in the future. If the numerical PA models represent the wrong processes, ignore relevant processes, or incorporate erroneous or biased assumptions or coefficients, then the results may be misleading. These considerations of ground-water modeling efforts as applied to WIPP are discussed below.

Sources of Modeling Error

In applying ground-water models to field problems, there are three primary sources of error, as described by Konikow and Bredehoeft (1993):

1. *Conceptual errors:* theoretical misconceptions about the basic processes that are incorporated in the model.
2. *Numerical errors:* the difference between a true and exact solution to the governing equations and the solution developed by the equation-solving algorithm.
3. *Uncertainties and inadequacies in the input data:* errors arising from the inability to describe actual aquifer properties, stresses, and boundaries. These include measurement errors, interpolation and extrapolation errors, and inaccurate predictions of future conditions.

BOX 6.1 Flow and Transport Modeling

Modeling of transport in this regional flow system requires the following:

1. An adequate conceptual model of the flow system, including
   - water table and potentiometric elevations
   - definition of major hydrostratigraphic units
   - description of potential preferential flow paths, such as fractures
   - evaluation of temporal changes (whether or not system is at steady state)
2. For significant hydrostratigraphic units, descriptions of
   - flow and transport mechanisms
   - flow and transport properties
   - nature and rates of chemical reactions, such as sorption, to estimate chemical retardation
3. Mathematical models that
   - incorporate the relevant processes
   - are not subject to large numerical errors

In most model applications, conceptualization problems and uncertainty concerning the data are the most common sources of error. All three aspects of error are discussed below with reference to the PA models for WIPP.

Conceptual Errors

If the conceptual models upon which the PA models are based are in error, then all of the complementary cumulative distribution functions (CCDFs; see Chapter 2 and Appendix B) and risk assessments derived from the PA also may be in error. Although the tool of PA is designed to account for uncertainties in the parameters, this assessment of uncertainty is necessarily within the context of the PA model used. Factors and processes that are not incorporated into this model are conceptual errors that are not treated by the PA sensitivity analysis.

The 1992 PA for WIPP did not assess adequately the uncertainties in the underlying conceptual model, which might be a more significant effect than the uncertainties in the parameters. For example, because the 1992 PA ground-water model was two dimensional, it cannot be used directly to evaluate the importance of a three-dimensional flow. Errors in a conceptual model are often difficult to detect, and sometimes field measurements can be reproduced by several alternative conceptual models. The alternative models may make little difference over the short duration of a field test but may make a large difference over the life of the repository and predictive horizon. It is therefore critical that the PA conceptual models be rigorously and independently tested.

There also must be consistency among the various conceptual models that describe different elements of the subsurface ground-water system. For example, hydrologic concepts indicate that ground water in the Culebra Dolomite at and near the WIPP site flows generally from north to south. Chapman (1988), among others, notes that there are significant decreases in salinity and changes in water quality in the direction of flow. Siegel and Anderholm (1994, p. 2299) state that "no plausible geochemical process has been identified that would cause this transformation in a hydrologically confined unit." Thus, geochemical interpretations appear to conflict with hydrologic

understanding.[3] Such a discrepancy reflects a lack of comprehensive understanding of the subsurface system, which opens the possibility that some aspects of the overall conceptual model of the Culebra are flawed, and that predictions based on this model are likewise uncertain.

Numerical Errors

The 1992 PA model used the SECO ground-water modeling computer codes to simulate flow and transport. The SECO codes have been developed by recognized experts in numerical methods, and the transport code apparently represents a major advance in controlling and limiting numerical dispersion. However, because the SECO codes are not yet used widely, some "bugs" and other problems in the use of the codes may still remain undetected. Experience with other ground-water model codes indicates that code developers often cannot comprehensively test the code for all possible ranges and combinations of parameter values. Model applications by a variety of users and organizations to a range of problem types and hydrogeologic conditions often will result in the discovery of code deficiencies that were not detected by the model developers, regardless of how comprehensive their testing efforts.

The SECO codes have not yet been subject to extensive benchmarking or international comparisons with other widely accepted codes, such as have been performed for other codes under the recent International Hydrologic Code Intercomparison Project (HYDROCOIN) and the International Project to Study Validation of Geosphere Transport Models (INTRAVAL; Swedish Nuclear Power Inspectorate, 1987, 1990). The committee believes that it is inappropriate to rely exclusively on these relatively new codes before such benchmarking evaluations have been completed in an open, broad-based scientific forum to yield more confidence in the codes.

[3]Possible explanations are that prehistoric flow was in a different direction than current flow, or that geochemical or hydraulic interpretations are flawed, or that vertical components of past or present flows exist that have not been accounted for.

Data Uncertainty

The PA models make predictions based on ranges of values of parameters. The 1992 PA assumed that most of the parameters in the model are "independent random variables even though it is known that some were dependent on others" (Sandia National Laboratories, 1992). It is further stated (Sandia National Laboratories, 1992, p. 1-21) that "the effects of neglecting correlations on the sensitivity/uncertainty analyses are generally unknown." It may be a reasonable first approximation to assume independence of parameters in sampling (i.e., to ignore interactions between variables and their codependence on other factors). However, such an assumption must be carefully tested, and refined if necessary, before a final PA is completed. Independent sampling can yield simulations based on implausible (or contradictory) combinations of parameters. If results of these simulations yield low-risk outcomes, then including the results of such simulations in the generation of CCDFs might skew or bias statistical distributions of the results.

The committee recommends that the assumed independence, ranges, and distributions for the various parameters that are sampled in PA analysis be examined closely for reasonableness and consistency with observed data.

WIPP 1992 PA MODEL ANALYSIS

Regional Ground-Water Flow

As noted previously, the 1992 PA models assumed that ground-water flow through the Culebra Dolomite was two-dimensional, steady-state, and horizontal. Investigations of the larger three-dimensional regional system, of which the Culebra is actually a part, have begun relatively recently but have not yet been completed. These investigations include a new synthesis of all the regional hydrogeologic data and will lead to the development of a three-dimensional numerical flow model. This more comprehensive analysis of the ground-water flow system is very important and relevant to the larger issue of conceptual uncertainty. Among other benefits, this type of analysis may help to resolve existing discrepancies between the

geochemical data and the present conceptual model of the flow system. Until the results of these ongoing studies have been completed and their impact on assumptions about the Culebra has been evaluated, it is too early to determine whether or not many of the simplifying assumptions incorporated into the 1992 PA were reasonable.

Ground-water flow and solute transport are affected strongly by heterogeneity in aquifer properties. Fractures represent an extreme but prevalent type of heterogeneity, so their characterization is important for reliable model development. However, the properties, continuity, and extent of fractures in the Culebra are still highly uncertain. One cost-effective approach to characterize fractures is to complete detailed mapping of any surficial expressions of fracture traces and lineaments at both local and regional scales. This should have been completed in the early stages of site characterization, but there is no written documentation of such analyses having been done.

Fracture and lineament mapping have been applied successfully to several potential fractured-rock repository sites (e.g., for applications in Sweden, see Wikberg et al., 1991; Ahlbom et al., 1992; Swedish Nuclear Fuel and Waste Management Company, 1995). Surface and subsurface features that might represent fracture zones and lineaments were defined by using remote-sensing methods (such as aerial photography and satellite imagery), topographic data (including computer analysis of digital elevation data), and several geophysical surveying techniques (including geomagnetic, electrical, and seismic methods and some recently developed high-resolution, three-dimensional tomographic techniques).

These approaches have helped to clarify the possible existence and spacing of major through-going fracture zones. Although the lithology at WIPP is different from that at the Swedish sites, these approaches have worked in other sedimentary rock basins, and the committee believes that they should be applied in the characterization of the WIPP site. An approach to fracture definition that is potentially more definitive, but also significantly more expensive, would involve drilling of slanted or even horizontal boreholes. However, because this probably would require an extremely expensive and time consuming operation, the possible benefits should be carefully weighed against the likely costs before a decision to undertake such a study is made.

Confidence in PA Analysis of Regional Ground-Water Flow

Significant accomplishments in site characterization have advanced the level of understanding of the regional ground-water flow system at the WIPP site during the past 20 years (see Appendix A for a summary discussion). However, the degree and comprehensiveness of the understanding of some aspects of the local and regional ground-water flow systems are lower than desirable relative to the importance of the repository and to the time and money spent studying the WIPP site and constructing the repository. The following points support this contention:

- There is a disparity (as discussed above) between the regional flow system as determined by geochemical and isotopic interpretations and that indicated by hydrologic analyses. This disparity reflects an inadequate level of understanding of the whole system, and it should be resolved.
- The water table in the region, which represents the top of the saturated zone, has not been defined. This important boundary should be defined, or a reasonable explanation of either why it is not important or why it is technically or economically infeasible to determine should be documented.
- The rates, locations, and mechanisms of natural recharge to and discharge from the Culebra Dolomite are poorly defined (see Brinster, 1991).
- Apparently, there have been no detailed hydrologic studies of the unsaturated zone at the site. Such studies would help to (1) estimate if, why, and how much recharge may exist in the vicinity of the site; (2) define the water-table position; (3) predetermine an appropriate response should there be a spill or accident on the land surface at the WIPP site; and (4) predict how much and where recharge might increase under a scenario of climate change that yields increased precipitation.
- An adequate explanation is lacking for observed changes in water levels in the Culebra, where trends of rising water levels have persisted for several years.

Observed changes in water levels from assumed steady-state conditions were not incorporated into the 1992 PA analysis. However, if the causes of the observed water-level changes during the last several years are unknown, then how is it to be known that even greater changes in the flow field might not occur in the near future? Such changes might invalidate the PA assumptions and predictions.

- These water-level changes are affecting hydraulic gradients, flow directions, and flow velocities and thereby provide some evidence against the assumption that steady-state flow prevails in the aquifer, an assumption that is the basis of many WIPP hydrologic analyses. Small "violations" of this assumption probably would not affect the conclusions to a noticeable degree. However, if the trends observed over the past five or six years persist, recur, or become more widespread, flow systems might change enough to negate the PA analyses based on the assumed steady-state flow field.
- There has been too little accounting for the three-dimensional nature of ground-water flow and consequent leakage through confining layers. If vertical components of flow do materially affect the Culebra, then the ground-water models of the Culebra that were calibrated under the assumption that flow is horizontally two dimensional must include compensating errors to offset ignoring the vertical leakage. Such errors can induce a bias in long-term predictions of flow and transport.

Some necessary and feasible experiments and analyses (of the kind mentioned here), which would lead to a more comprehensive understanding of the ground-water flow system and to more reliable PA models, have either not been undertaken or are not completed yet.

Ideally, the regional system should be understood with sufficient accuracy and precision that professional hydrologists will have confidence in the analyses and predictions, will believe that additional data collection is not critical, and will be convinced that there are no major "surprises" left in the characterization of the system.

Although it is difficult to define precisely when a requisite level of confidence in the hydrogeologic analyses has been achieved, the committee does not believe it has been reached in the 1992 PA. Too many questions remain about the models, assumptions, and data used to analyze the cases in which a significant release of contaminants to the Culebra or other formations is projected to occur.

The potential weaknesses in the ground-water models will be important to a demonstration of compliance only if there are significant releases from WIPP to the stratigraphic units shallower than the Salado. The weaknesses in hydrogeologic modeling discussed in this chapter should be balanced against an examination of the assumptions from which the estimated releases are derived, and assumptions concerning pathways to cattle that drink from stockwells tapping the Culebra. For example, even if contaminants were transported through fast-pathway fractures in the Culebra and were not subject to any retardation processes, the very same conditions that would enable this to occur would assure that the water carrying the contaminants would be far too saline for cattle to consume. This would appear to eliminate the potential for future human exposure, which is an underlying basis for the overall concerns about radionuclide releases.

The non-potable saline character of the ground water in the Culebra will greatly reduce the exposure hazard even though the radionuclides released to the accessible environment may exceed the limits required for compliance in 40 CFR 191. Should the 1996 PA analysis be able to demonstrate convincingly that the releases are sufficiently low to meet compliance standards, then the exposure hazard would be correspondingly lower.

Solute Transport

Transport of radionuclides released into an active ground-water system can and may occur at a rate less than the rate of the ground-water flow, due to physical and chemical interactions with neighboring rock. This radionuclide retardation, where it can be shown to exist, can add important additional assurance with respect to the radionuclide containment capability of the repository. Hence, studies of the radionuclide retardation properties of water-conducting rock formations at WIPP (see Appendix A) are an important complement to the studies of ground-water flow.

Following this discussion of solute transport, the specific retardation mechanisms are treated in turn.

The solute-transport model of the Culebra Dolomite is based on a theoretical understanding of transport and dispersion processes in ground water. However, this underlying theory is itself somewhat weak because the scientific understanding of transport processes in heterogeneous media, particularly in fractured rock systems, is still in a stage of relatively rapid development and evolution. Much remains to be learned, and much ongoing research is devoted to developing a better understanding of the governing processes and parameters at large scales in complex field environments. Recent research indicates that many transport processes and parameters are highly scale dependent. This is one reason why there is often little basis for extrapolation of theory and lab tests to the field environment for predictive purposes.

The 1992 PA separately sampled and independently varied porosity, fracture spacing, and transmissivity. However, it is known that correlations exist among these parameters. Thus, it seems likely that the existing approach may yield unreasonable or unlikely combinations of these parameters in some of the individual simulations. The net impact on the overall PA is uncertain, but the committee believes that the parameter sampling procedure should be examined closely and refined if necessary.

The PA models represent leakage from a borehole into the Culebra as an initial concentration of solute in the transport model for a steady-state flow field. However, transient changes in the flow field, which are induced by the volume of water carrying the radionuclides into the Culebra, are not considered. While the leak is occurring, the velocity away from the well would be greater than the velocity under steady-state conditions, and some of the radionuclides would migrate faster and further than represented in the PA model. The committee recommends that the PA process carefully test and demonstrate that the steady-flow assumption and simplification, which ignore the initial fast advection, are reasonable and do not introduce significant errors.

Confidence in PA Analysis of Solute Transport

The effective porosity (ε) is a critical transport parameter for which few measurements are available. If one assumes that $\varepsilon = 0.001$, which is representative of fracture flow, then travel times to the regulatory boundary would be on the order of hundreds of years. However, if $\varepsilon = 0.16$, which is representative of the rock matrix, travel times would be on the order of many thousands to tens of thousands of years. This could mean the difference between compliance and noncompliance of the site.

The 1992 PA assumed that porosity and transmissivity vary independently. This is a potential weakness in the analysis that needs to be tested, because physically reasonable arguments lead to correlations between the two variables. In this regard, a key issue for the PA flow model is whether the relation between transmissivity and porosity is in fact independent, or if the relation is direct or inverse. Either relation could be conceptualized (or perhaps rationalized), based on present knowledge of the Culebra Dolomite. However, any consistent relation would be contrary to the WIPP Project PA procedure of sampling independently from the populations (or distributions) of transmissivity and porosity. Thus, many simulations would be based on unlikely or contradictory combinations of parameter values. This could bias the PA model-generated statistics on which the CCDFs are based.

The PA sampling approach has yielded some individual outcomes to date that have exceeded the compliance standard. These particular simulations should be examined carefully to highlight and document the combinations of parameter values and boundary conditions that led to prediction of an unacceptable release of radionuclides to the environment. This evaluation would allow analysts and reviewers to focus on an assessment of the reasonableness of those specific and critical conditions, and would serve as a quality assurance check on the statistics generated by the PA analyses.

Some of the 1992 PA simulations of solute transport have allowed physical and/or chemical retardation, as would be derived from matrix diffusion and chemical sorption, respectively. To date, however, no reliable and representative field measurements of the

parameters controlling matrix diffusion and chemical retardation have been carried out at the WIPP site.

Physical Retardation Via Matrix Diffusion

In the 1992 PA model of the Culebra Dolomite, physical retardation may occur in response to matrix diffusion in a dual-porosity system. The magnitude of the retardation is proportional to the effective surface area and volume of the blocks adjacent to the fractures through which advection is occurring. If the contaminant plume spreads through a larger volume of the aquifer, then matrix diffusion will be more effective in removing contaminants from the active flow field. If the transport model artificially spreads the contaminant plume into a larger volume of the aquifer than would actually occur, then the model will overestimate the retardation caused by matrix diffusion, even if the diffusion parameters themselves are estimated accurately.

The artificial spreading of contaminants can arise from errors in the numerical solution, from errors in the initial conditions, and from errors in the conceptual model. All are present to some degree in the WIPP PA model. The committee recommends that PA assumptions and analyses for cases including matrix diffusion be supported by additional model studies to demonstrate that the analyses do not overestimate the magnitude of matrix diffusion because of artificial spreading of the plume. This can be accomplished, for example, by applying a transient ground-water flow model that uses, for a relatively short time period, a much finer spatial grid and smaller time steps near the area close to a human intrusion (HI) borehole. These results can then be compared with those of the coarser PA model for equivalent travel distances and elapsed times.

Confidence in PA Analysis of Physical Retardation

If PA results indicate that repository compliance with EPA standards depends strongly on matrix diffusion, more reliable field evidence to support the assumed range of coefficients should be obtained. In this case, field tests should be completed at several different locations in the vicinity of the WIPP site because of the spatial variability in the properties of the system.

Chemical Retardation Via Reactions

The PA models combine all of the complex chemical reaction processes, such as sorption or exchange, that might retard the movement of a particular chemical species relative to the movement of a nonreactive solute into a single simple parameter—the retardation factor R_f. This factor, in turn, is related to a distribution coefficient K_d. Although the concept of a retardation factor is computationally efficient, it inherently assumes that reaction processes are linear, instantaneous, reversible, and homogeneous.

The concept generally works well in chemical plants where chemical engineers apply it to fluid flow and solute transport through tanks filled with relatively homogeneous, reactive, porous media. However, in a complex regional aquifer system, the reactions rarely are subject to these ideal conditions. The theoretical basis for applying a retardation factor to a field environment is therefore weak, at best, and its application to large-scale hydrogeologic settings, without restrictions or qualifications, has been criticized in the literature (e.g., Reardon, 1981; Miller and Benson, 1983; Valocchi, 1984).

From the perspective of a compliance assessment, use of the simplifying retardation factor may either underestimate or overestimate the overall amount of retardation of a solute relative to the flow of water, depending on the particular chemical species and the types and rates of reactions that affect its fate and transport. To probe this issue, the nature of the expected isotherm for each solute of concern (and within the range of expected concentrations) should be determined experimentally.

Scientists from Sandia National Laboratories recognize the numerous difficulties and weaknesses in applying a linear sorption model for predicting radionuclide transport through the Culebra Dolomite, and many of these concerns have been documented (Novak, 1992). As an example of one of several serious concerns, Novak (1992) points out that available K_d data for uranium sorption in the Culebra are very sensitive to water composition and vary by more than three orders of magnitude for selected representative compositions of Culebra brine. Novak (1992, p. 55) states that "existing radionuclide K_d data are insufficient for predicting radionuclide migration in

the Culebra with a sound scientific basis within reasonable certainty." Ongoing experiments will help to resolve this uncertainty, but results and analyses are not yet available for review.

Confidence in PA Analysis of Chemical Retardation

If performance assessment results indicate that compliance is contingent on the occurrence of chemical retardation, it will be necessary to provide more evidence that the PA approach is reasonable for these conditions. The committee believes that the use of sorbing tracer tests in the field would be highly beneficial for building confidence in the analysis and approach to chemical retardation, in addition to determining whether or not the conceptual model is applicable to the field environment. Because the specific solutes of interest here, such as plutonium and americium, cannot be used in tracer tests, reasonably appropriate surrogate tracers must be used, or field evidence of sorptive behavior must be ascertained from analysis of previous accidental releases elsewhere.

As hypothesized for flow parameters for the Culebra Dolomite, a correlation may also exist between K_d (or R_f) and either transmissivity or porosity. For example, relatively high transmissivity values might coincide with zones of low or zero clay content. Because clay probably yields a higher sorptive capacity per unit volume than dolomite, where transmissivity and flow velocity are the highest, there may be very little chemical retardation. This illustrates one type of predictive error that might be associated with applying one average effective R_f to the entire ground-water system. The greatest risk of release in that case is related to flow through transmissive fractures having a lower than average R_f.

It is unclear whether the PA approach to sampling values of R_f is appropriate if the chemical retardation in critical high-transmissivity channels is not represented accurately by the average R_f assumed for the entire aquifer system. Again, the only way to address this issue in a manner that would instill confidence in the predictive analyses is through a series of in-situ tracer tests or other field-based analyses.

DISCUSSION AND SUMMARY OF FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

This chapter and Appendix F have focused on potential sources of error in the preliminary PA modeling of the Culebra Dolomite. Therefore, the reader should not infer from the tone of this chapter that the WIPP ground-water models are necessarily inaccurate or unacceptable. Rather, the intent is to indicate where the preliminary analyses presented in the 1992 PA need to be revised, strengthened, or better documented. Because there have been four years of additional studies since the 1992 PA, it is possible that recent experimental results and the final PA models, which have not yet been reviewed by the committee, will have resolved many of these questions.

A key question is whether the uncertainties in the properties of the subsurface system above the Salado Formation need to be resolved (or minimized) further to demonstrate adequately the integrity of the WIPP site with respect to containment of radionuclides. Alternatively, is enough information about the subsurface system already available to predict that any potential release from the proposed repository will not cause radionuclides to migrate faster or further than is acceptable from a regulatory standpoint?

These issues are addressed separately for the undisturbed case and the disturbed (i.e., HI) cases described in Chapter 2.

Undisturbed Repository

The committee finds that it is reasonably certain that the WIPP repository will provide an adequate level of long-term isolation of TRU waste under a broad range of natural conditions and stresses for tens of thousands of years into the future. Provided that seals and plugs (as discussed in Chapter 4) are effective, there is no evidence to indicate that any brine that might be contained in the repository after it is closed is likely to leak through the Salado Formation and be released into the regional ground-water flow system in shallower formations. Nor would the committee expect that ground water flowing above or below the Salado might dissolve the salt or in any other way come in contact with the wastes that would be stored in the repository.

For consideration of the undisturbed case, the present state of understanding of the ground-water flow system above the Salado is adequate. The committee finds that the overall permeability and creep properties of the Salado are such that, with effective repository seals and without some form of human intrusion, the flow of radionuclide-contaminated brine from the Salado is very unlikely. Further studies of the hydrogeology of non-Salado units are therefore not necessary to support compliance for the undisturbed case.

Summary of Undisturbed Case

Provided that plugs and seals in the Salado Formation are effective (see Chapter 4), there is high confidence in the conclusion that the WIPP repository will isolate TRU waste adequately from the environment for many thousands of years if it remains undisturbed by future societies. For this undisturbed case, continued studies of non-Salado hydrogeology are not necessary.

Disturbed Repository

In the WIPP PA (see Chapter 2), the HI scenario assumes that future drilling will facilitate upward leakage of brine from the repository through a borehole, thereby permitting radionuclides to be released into an overlying geologic formation through which lateral migration offers a possible pathway for release of radionuclides to the accessible environment. If releases exceed regulatory limits, then a predicted rate of transport in the regional ground-water system above the Salado Formation becomes a critical factor in estimating cumulative releases.

The analysis of the disturbed case hinges on predicting flow and transport through rock formations above the Salado (see Appendix A). The issue of concern to the committee is whether the 1992 PA was based on an adequate conceptual understanding of the regional ground-water flow system near WIPP and whether the relevant parameters had been quantified adequately to support either "realistic" or "bounding" models in the PA.

For example, the 1992 PA assumed that the most likely pathway for a lateral release of radionuclides is through the Culebra Dolomite. However, a release to the shallower Dewey Lake Red Beds also is possible and does not appear to have been considered or evaluated adequately. Releases of saline ground water from leaking deep boreholes directly to the water table are known to have occurred historically in other areas (for example, see Van der Leeden et al., 1975). The Dewey Lake is a plausible exposure pathway because it is known to contain some potable water. Among other concerns, climate changes can increase the recharge rate and raise water levels. In the committee's opinion, releases to the Dewey Lake cannot be discounted summarily; if a borehole to the Salado or to the Castile Formation were to connect these formations to brine at a pressure near lithostatic, then the hydraulic gradient (driving Darcy flow) would be sufficient to enable leakage into both the Culebra and the Dewey Lake if a pathway to either formation were to exist.

Also, the amount and rate of brine release appear to be very sensitive to the assumed permeability of the material that is filling the leaky borehole. In light of the importance of that parameter, values for borehole permeability that are used must be realistic and technically defensible.

If the final analyses of the disturbed-case scenarios yield projected releases of contaminants to formations above the Salado that are less than the release limits of 40 CFR 191 (i.e., for which compliance results even if the releases moved across the regulatory boundary in less than 10,000 years), then no further hydrogeologic characterization work is needed. This means that compliance could be demonstrated even if one assumes that no retardation occurs and that ground-water flow and transport occur through fractures.

Summary of Disturbed Case

For the disturbed case, if the mass of contaminants and brine released is as great as assumed in the 1992 PA, then the ability of the site to isolate waste satisfactorily under such "disturbed" conditions has not yet been demonstrated adequately. However, such a demonstration appears to be a plausible outcome if the following problems, issues, or limitations of present models and data are resolved through further studies.

1. The PA approach must assess the sensitivity of the predictions to uncertainties in the underlying conceptual

models. Alternative conceptual models are feasible, and those that are plausible and that could lead to significant releases should be evaluated. Completion of ongoing three-dimensional analyses of the regional ground-water flow system is critical to this effort and should be given a high priority.

2. The non-Salado site characterization efforts and PA models have been overly focused on a two-dimensional flow analysis of the Culebra Dolomite. The minimal levels of consideration and evaluation of other potential hydrogeologic release pathways (such as the Dewey Lake Red Beds) and of the interconnection between the Culebra and adjacent formations have not been justified adequately.

3. Fractures are a dominant control on the transmissivity of the aquifer system at the WIPP site and represent the highest-velocity channels for migration of contaminants. A better definition and understanding of the nature, density, spacing, length, and interconnectedness of fractures and fracture networks are critically needed. As one step to help achieve this understanding, the committee recommends that modern topographic and geophysical methods of analysis be applied in the site characterization efforts.

4. In general, the types of chemical and geochemical reactions, rates of reactions, and their dependence on spatially heterogeneous mineralogy and changing aqueous geochemical parameters (e.g., salinity, pH, and Eh) are not well characterized for the HI scenario at the WIPP site. Representing all of these sources of variation in the PA model as a single parameter (i.e., an effective retardation factor), as was done in the 1992 PA, has a very weak scientific basis. If the PA assumes that chemical retardation occurs in the Culebra, then supporting evidence from the field environment should be available before any predictions based on that assumption are accepted.

5. Similarly, if matrix diffusion is to be relied upon in the PA models to demonstrate compliance, then additional controlled field experiments must be completed to define rates of diffusion more accurately and to assess spatial variability in the process and parameters. Furthermore, additional testing and documentation are needed to eliminate concern that the net retardation caused by matrix diffusion is being calculated inaccurately in the numerical models.

6. For the disturbed case, if it can be shown that the mass of contaminants and brine released would be significantly less than previously estimated (as might be derived, for example, due to changes in the estimated severity of human intrusion, refinements in estimates of the actinide source term, or in the effects of borehole closure), then further studies of the Culebra would not be necessary. That is, if the total amount of solute entering the non-Salado formations is determined to be sufficiently small to assure compliance, then studies of ground-water transport are not needed for this purpose.

PERSPECTIVE BASED ON INTERNATIONAL REPOSITORY SITING EFFORTS

Insight into the difficulties of hydrogeologic site characterization issues is offered based on examples from and comparisons with international siting efforts. In efforts to site geologic repositories in other countries, a good quantitative understanding of the regional ground-water flow regime and the influence of the geological environment of the repository on radionuclide transport are often the most critical factors needed to determine whether or not a potential repository site can provide adequate long-term isolation of the waste. This is usually true for both the undisturbed and the disturbed cases.

Several countries have opted to site repositories in rock masses of low permeability, such as granites, in regions of low hydraulic gradient, so that flow rates will be very small. Determination of the rock-mass permeability in these cases is often complicated by the presence, on the field scale, of fractures that are not usually present or tested in laboratory specimens. Fractures also complicate larger-scale tests conducted directly in the field, making it difficult to extrapolate to the regional scale. Fractures tend to follow a log-normal distribution in which well-developed, extensive, and often highly conductive fractures are spaced widely apart, with smaller, less extensive fractures becoming progressively more abundant. On the smaller scales, these are not always interconnected and hence may be nonconductive. Definition of rock-mass permeability of fractured systems is difficult, and factors that influence radionuclide transport processes are at least as complex.

Predicting regional ground-water flow and radionuclide transport behavior with the reliability and detail required for repository performance assessment is a complex and formidable challenge. It has been a main focus of international research related to repository siting and design for more than 25 years. Although substantial advances have been made—with project scientists and consultants making notable contributions—significant problems remain. Each potential repository site has unique features. To the extent that long ground-water travel times and significant physical and chemical retardation are necessary to ensure adequate isolation of radionuclides from the accessible environment, characterization of the site is correspondingly necessary to address these problems.

Most repository sites worldwide are located in rock that is part of an active regional ground-water regime. In these cases, except for engineered barriers in the immediate vicinity of the waste, the repository is physically close to circulating ground water. By contrast, locating WIPP centrally within the 400-m-thick, essentially impermeable, Salado bedded salt deposit, some 200 m below the permeable, saturated sedimentary Rustler Formation, which consists of fractured limestones and dolomites, is a major design advantage of this repository. The restrictions to ground-water transport provided by the Salado Formation provide a valuable "buffer zone" between the repository and the non-Salado permeable formations above it, to which the site hydrology considerations of this chapter apply.

Chapter 7

Perspectives

The NRC Committee on the WIPP has followed the WIPP project from its infancy in 1978. There have been some changes in committee membership, but there has been sufficient continuity that the committee has remained aware of the significant scientific and technological issues, as well as the associated policy and budgetary constraints on the WIPP project. This report focuses on the committee's understanding of the specific scientific and technological issues that form the core of DOE's compliance application to the U.S. Environmental Protection Agency and their influence on the perceived ability of WIPP to isolate TRU waste from the biosphere.

During its deliberations, the committee also has arrived at several general conclusions with respect to the overall integrity of WIPP, the difficult problem of human intrusion, and the role of Performance Assessment. Because of their importance to this report and the overall integrity of WIPP, the committee provides a general discussion of these issues in this chapter.

INTEGRITY OF THE WASTE ISOLATION SYSTEM

A previous National Research Council report provides a useful introduction to the topic of geologic isolation at WIPP. The report states that the objective of a geologic waste isolation system is

> *to protect humans now and in the future by isolating the waste from the environment effectively enough and for a period of time long enough that the amount of radioactive material ever reaching the biosphere will present no unacceptable hazard. To achieve this objective, a hierarchy of mechanisms exists to reduce the release of radionuclides to the biosphere and thus have the waste isolation system meet the criterion of overall performance. One or more of the following release control mechanisms must be sufficient to meet the panel's criterion:*
>
> - *delay of ingress of water*
> - *slow dissolution of radionuclides*
> - *slow release from the waste package*
> - *long groundwater travel time*
> - *delay due to sorption in the geologic medium*
> - *dispersion*
> - *dilution*
>
> *The system must guard against an unacceptable release of the radioactive material into groundwater and the transport of this contaminated water to the biosphere—a principal pathway by which some portion of the buried radioactive material may eventually reach humans.* (NRC, 1983, pp. 3-4)

Although the 1983 report gives primary emphasis to geologic isolation for high-level, spent reactor fuel or reprocessed waste (hence the high ranking given above to "slow release from the waste package"), the list of important criteria is essentially the same for a transuranic (TRU) waste repository. The total radioactivity per unit volume of TRU waste planned for WIPP is roughly on the order of one-thousandth of the activity for an equal volume of spent fuel waste, but many of the same long-lived radioactive isotopes are present, and so geologic isolation is necessary.

In the committee's opinion, location of the WIPP repository within the 600-m-thick Salado Formation, some 400 m below the overlying, permeable water-saturated sediments is an exceptionally robust way in which to delay ingress of water to the repository or, equivalently, egress of radionuclides from the repository to the accessible biosphere. Natural salt

creep will result in the encapsulation of waste within what becomes essentially intact salt a few hundred years at most after emplacement. Sealing of the shafts with crushed and compacted salt also should ensure that, by natural salt creep processes, these potential conduits to the biosphere are sealed effectively. Thus, the waste should be sealed, permanently, within the Salado Formation, which has been stable for over 200 million years.

The committee is confident in asserting that, provided the repository is sealed effectively and remains undisturbed by human activity after final closure, WIPP will isolate TRU waste for long enough (i.e., many tens of thousands of years) to ensure that the radioactivity in the waste will have decayed to very low levels.

HUMAN INTRUSION

From the point of view of waste isolation, salt does have one drawback—it is frequently found in association with mineral resources, especially oil and gas. Drilling for these resources could result in one or more holes penetrating the repository and would provide a pathway to bring the waste into direct contact with ground water and the accessible biosphere.

An intrusive drilling event could remove the isolation from ground water provided by the 200-m-thick envelope of salt. Because dispersion and dilution are not significant factors at WIPP, the two remaining mechanisms to control radionuclide releases noted in the NRC (1983) report would be (1) slow dissolution of radionuclides, and (2) delay due to sorption in the geologic medium. Although WIPP does not include a "waste package," the backfill and seals around each waste room and panel serve a similar function. In fact, the salt "package" does not have the limited lifetime of a high-level waste canister. For WIPP, assurance of protection from excessive release of radionuclides due to drilling intrusion relies on (1) engineering efforts to improve repository performance (see Chapter 4); (2) improved understanding of the actinide source term (see Chapter 5); and (3) understanding of non-Salado Hydrology (see Chapter 6)—the same three mechanisms that are identified in the NRC (1983) report.

ROLE OF PERFORMANCE ASSESSMENT

What contribution can be expected from each of these component factors, and how much is needed, to ensure effective long-term isolation of the waste?

Total System Performance Assessment, or PA, is the method that has been used at WIPP to identify and examine all credible pathways by which radionuclides could be released to the biosphere from the repository and to estimate the contribution of each component of the pathway. Although both the undisturbed and disturbed (by drilling) cases have been examined, the DOE PA team has placed appropriate emphasis on the more complex and critical disturbed case.

The latest "complete" performance assessment available to the committee was published in 1992. The 1992 PA identified the same three key factors noted above, and its results suggest that WIPP could comply with the EPA release standards if certain levels of performance were attained from each component.

As noted principally in Chapters 2, 5, and 6, the committee has identified several significant deficiencies in the 1992 PA. These include the following:

1. The assumed permeabilities governing the flow of brine through the underground excavations were much too high. As a result, predicted flow through the repository due to an E1E2 intrusion (see Chapter 2, Figure 2.5) greatly overestimated brine flow, and hence radionuclide release.

In the 1992 PA, no credit was given for the ability of the excavations, especially when back-filled with crushed salt, to close within the order of a few hundred years, or for the potential of room and/or panel engineered seals and various other available engineering techniques to reduce both the consequences and the probability of serious drilling intrusions. For example, if the values for repository permeability used in the assessment are reduced progressively towards the value of intact salt (10^{-23} m^2) over 10,000 years, rather than maintained at a constant 10^{-15} m^2, the total predicted brine flow and radionuclide release would be much lower than indicated in the 1992 PA.

2. There was insufficient experimental justification for the assumptions made with respect to actinide

solubility, colloidal transport, and ground-water flow/radionuclide transport in the Rustler Formation overlying the Salado Formation.

Experimental studies to improve the basis for estimating actinide solubility and Rustler Formation hydrology and transport have now started, but these will require several years of additional work in order to arrive at reliable results. At this stage—with the results of the 1996 PA not yet available, and important experimental studies still in progress—the committee does not know how the results will affect predicted releases and compliance. It does appear to the committee that engineered design features to reduce the adverse consequences of an intrusion are available, but not all of these features may be cost effective or needed if low actinide solubilities and/or sufficiently long travel times and radionuclide retardation can be demonstrated by the PA. Thus, to inform decisions on implementing costly engineering design features, it is important that these experimental studies be continued to completion.

3. The 1992 PA was directed at demonstrating compliance with the radionuclide release limits stipulated in 40 CFR 191. No analyses were made of the health risks associated with these releases. At WIPP, radionuclides would be transported in brine that is considered to be, to a large extent, unpotable even to cattle. Consequently, the health risk will be very much smaller than if the water were potable.

In considering the radionuclide exposure hazard of WIPP to humans (see also Box 1.2), the committee recognizes the unpotable nature of much of the water in the Rustler above the Salado. The committee believes that accounting for the unpotable nature of the water could reduce the health risk by one or more orders of magnitude compared to the same release into a freshwater aquifer that is similar in size and has similar regional flow characteristics.

Taking into account all of the above considerations, the committee is confident in its judgment that DOE should be able to demonstrate that radionuclide releases at WIPP will be within the limits allowed by EPA, for both the undisturbed and disturbed cases, even with the severe criteria defined in 40 CFR 194. The associated health risks are likely to be well below the levels allowed under international standards. The results of the 1996 PA are awaited with interest as a test of this judgment.

The heavy emphasis placed in the 1992 PA on the analysis of compliance with 40 CFR 191 for the "disturbed case"—that is, assessing the consequences of human intrusion—is appropriate in the committee's judgment because of the added complexity of the radionuclide pathways introduced by intrusion. Even so, it is important to recognize the remarkable ability of the salt at WIPP to isolate waste under undisturbed conditions.

THE NATURE AND FREQUENCY OF HUMAN INTRUSION

Although the consequences of some form of human intrusion should be assessed, it is also evident to the committee that there is no scientific justification for estimating the precise nature or frequency of such intrusions over the next 10,000 years. For compliance purposes at WIPP, EPA has decided that the frequency of drilling for oil and gas exploration and production during the past century will continue unchanged for the next 10,000 years, even though it is acknowledged that the oil and gas reserves near WIPP will be practically exhausted within the near future (i.e., in less than 50 to 100 years).

The EPA assumes that today's drilling activities are representative of the type of drilling activities that will occur in the future. Although the resources drilled for today may not resemble those drilled for in the future, the EPA

> *believes it is reasonable for the average rate to be projected over the next 10,000 years, based on the assumption that while oil and natural gas may be depleted, other resources (which are not currently economical to recover, or whose uses are not yet evident) may become more valuable. This assumption leads* [the EPA] *to the conclusions that it is reasonable to project oil and gas drilling rates (based on the historical record) over the regulatory time frame; and second, that since these rates are surrogates for other potential resources, it is inappropriate to include consequences of activities or secondary*

recovery techniques specific to oil drilling. (EPA, 1996, pp. 12-7, 12-8)

In effect, the EPA assumes that resources equivalent to more than 100 oil and gas fields, comparable to those now being exploited, will be explored for and developed at the WIPP site by borehole extraction methods, using the drilling density of the past century over the 10,000-year regulatory time frame. (Note: the mining of potash, using techniques in current use near WIPP, would not involve borehole extraction.)

The EPA prescription in 40 CFR 194 with respect to human intrusion illustrates both the difficulty and the subjective judgment involved in arriving at a regulatory standard for WIPP. Prescribing a future frequency of intrusive drilling based on past and present-day technologies is inherently speculative, highly subjective, and untestable by the scientific method (NRC, 1995). It is disconcerting to the committee that a repository such as WIPP, which appears to be an excellent choice based on geological considerations, could be judged "non-compliant" solely on the basis of a criterion which has a poor scientific basis.

The committee considers the approach proposed in the NRC (1995) report, *Technical Bases for Yucca Mountain Standards* (TYMS), to be a more appropriate way in which to assess the significance of human intrusion. The TYMS report recommends that the consequences of a single or combined drilling intrusion (such as E1E2—see Figure 2.5 of this report) be examined qualitatively, rather than quantitatively as in 40 CFR 191, in order to assess the severity of the consequences and to indicate what repository design measures may be appropriate to reduce the severity.

The incremental risk assumed by accepting human intrusion could also be compared with the long-term risks associated with leaving TRU waste on the surface.

RETROSPECTIVE

The WIPP Compliance Certification Application is the first test of a unique legal framework, which necessarily will not be based on prior experience. Inevitably, such a legal framework will contain controversial and weak elements. DOE and EPA will need to work closely, in the public interest, to ensure that such elements of the complex legal framework are resolved expeditiously, through negotiation based upon scientific understanding.

WIPP also is a pioneering effort in the assessment of geological site suitability and design procedures for a waste repository. It is the first repository in the nation for which an application to begin permanent, deep, geological disposal is being submitted for a decision.

The scientific and technical questions posed, particularly to earth scientists, required unprecedented levels of quantitative assessment of the response of a rock mass over tens of thousands to hundreds of thousands of years. A great deal of original research was necessary to demonstrate the applicability of laboratory data to field-scale conditions and to develop and assess the reliability of computer models to reproduce these complex systems. Teams of specialists were assembled, and scientific programs defined. Total System Performance Assessment was introduced and refined. Inevitably perhaps, the scientific emphases, budget allocations, and the most critical information needs identified by PA were not always in concert. These difficulties notwithstanding, a great deal has been accomplished.

In retrospect, one valuable lesson from WIPP is the importance of establishing site-specific PA early in the repository site characterization and design process, both to identify the critical research needs and to establish the overall goals of the project. Scientific programs, priorities, and budget allocations must be identified and periodically re-examined, all in the context of PA.

Significant uncertainties are implicit in extrapolating from one or two decades of data, at most, to tens or hundreds of thousands of years—but a well coordinated integrated program, using PA effectively, should be able to produce sufficiently credible answers to establish, with "reasonable expectation" and within a finite time and budget, whether or not a proposed repository site and design are appropriate for effective long-term isolation of radioactive waste.

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1. Native yucca in bloom near Carlsbad, New Mexico; the U.S. Department of Energy's Waste Isolation Pilot Plant (WIPP) is in the background.

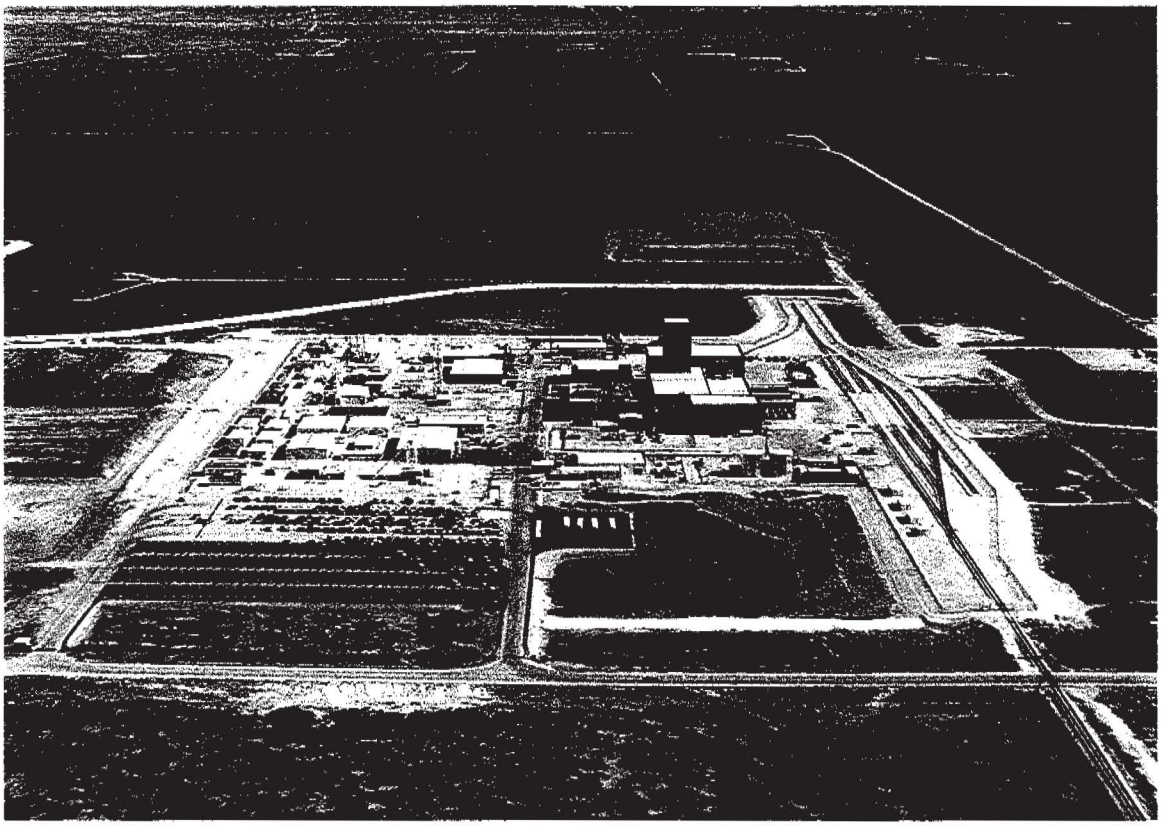

2. Aerial view of WIPP.

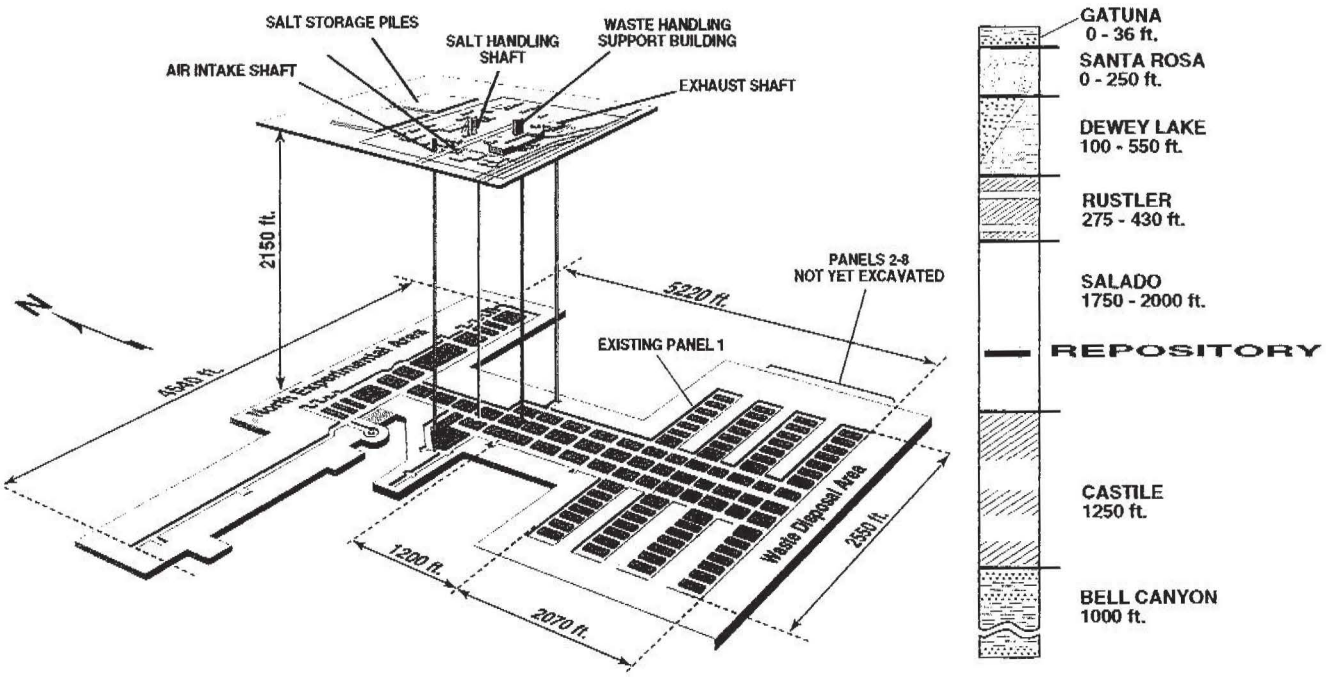

3. Three-dimensional view of the WIPP facility. Panel 1 is the only one of the eight panels shown that has been excavated in the waste disposal area to date. The typical stratigraphy is shown in cross-section on the right of the diagram. WIPP is located in the bedded salt Salado Formation, approximately 660 m below the surface. The Salado is approximately 230 million years old.

4. View of Room 1, Panel 1, underground at WIPP.

5. A tractor-trailer travels to WIPP with U.S. Nuclear Regulatory Commission-certified containers, using the Transuranic Package Transporter (TRUPACT-II) transportation system. The tractor-trailer and containers are designed specially for shipment of radioactive waste for disposal at WIPP. The location of the TRUPACT-II can be pinpointed within 150 m at any time by a satellite tracking system.

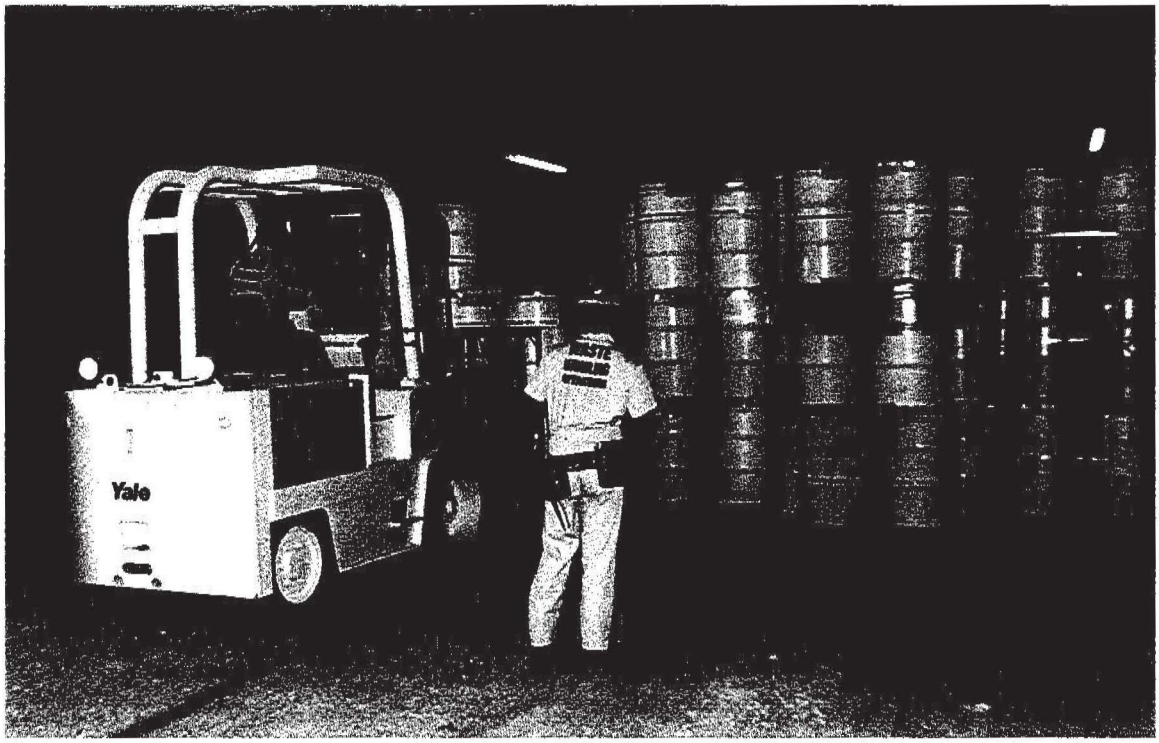

6. Stacking of simulated contact-handled transuranic waste approximately 660 m underground at WIPP.

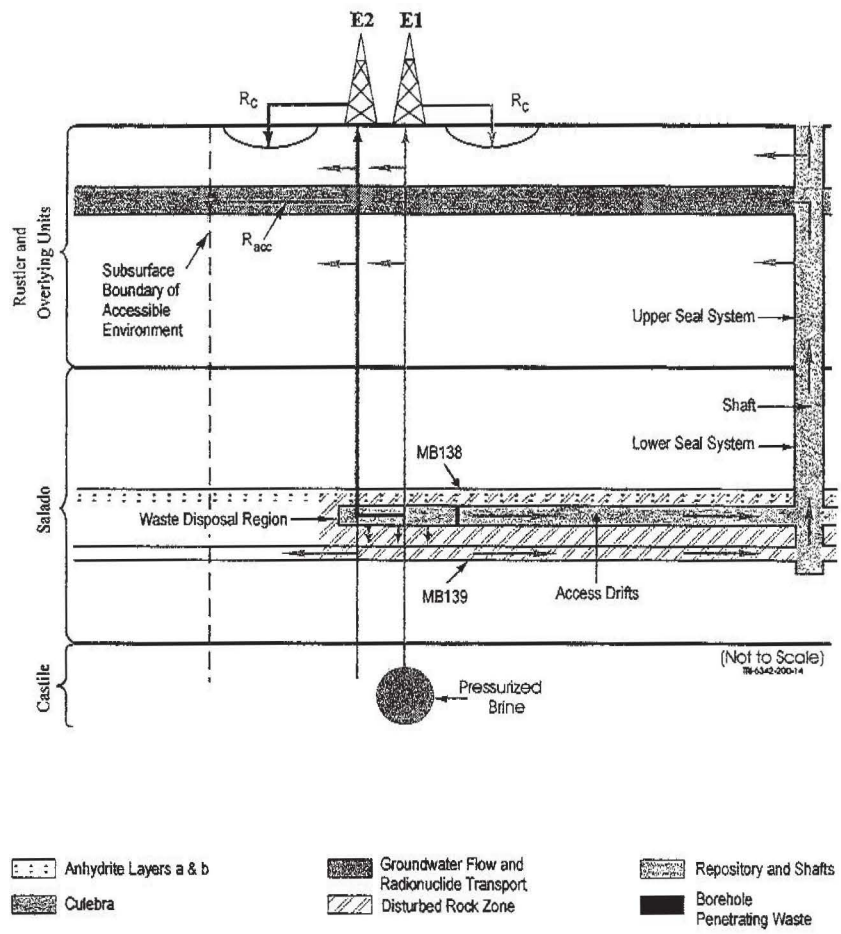

7. Conceptual release pathways for the E1E2 human intrusion event (see Chapter 2). It is assumed that at some time in the next 10,000 years, a borehole penetrates both the waste and a region of pressurized brine in the underlying Castile formation. A second borehole is also assumed to penetrate the waste but not the pressurized brine. Arrows indicate the hypothetical direction of ground water flow and radionuclide transport; R_c indicates material released at the surface directly from the drilling operation; R_{acc} indicates radionuclides released below the surface into a permeable bed of Culebra dolomite. This and other release pathways are considered in calculations made to evaluate whether or not a WIPP repository would comply with U.S. Environmental Protection Agency (EPA) standards.

Source: The figure is taken from the DRAFT-DOE/CAO-2056, p. 6-51 (July 1995 update).

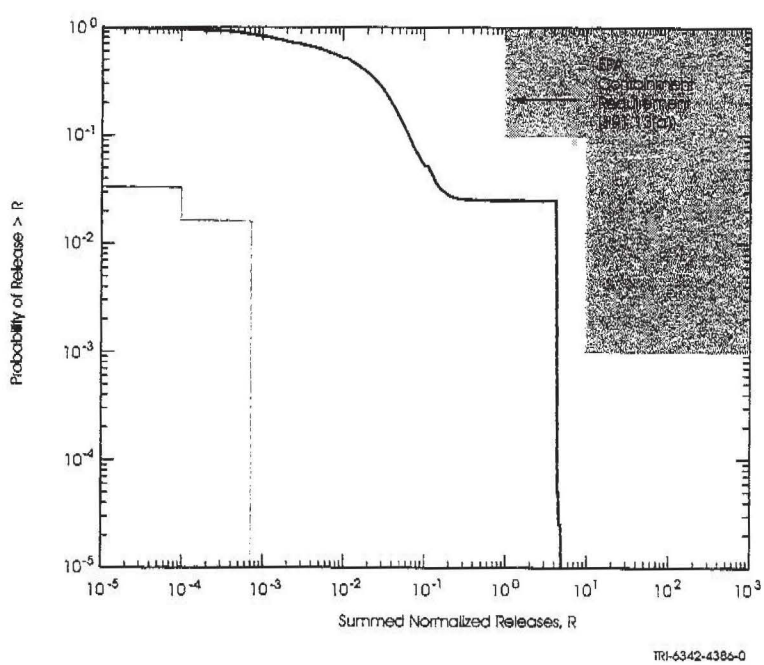

8. Mean Complementary Cumulative Distribution Functions (CCDFs) showing the probability of radionuclide releases from WIPP over 10,000 years for undisturbed conditions (red) and intrusive drilling scenarios (blue). This figure illustrates the dominant influence of intrusion scenarios on the predicted releases. These preliminary CCDFs are based on early models and data and do not address all the requirements of EPA regulations 40 CFR 191 or 40 CFR 194. The EPA release limits are shown as the left-hand-side limits of the region in green. Compliance is achieved if the mean CCDF never enters the green region.

Source: The figure is taken from DRAFT-DOE/CAO-2056, p. 6-59 (Vol. I, March 1995) and p. 6-101 (July 1995 update).

Appendixes

Appendix A

Natural Setting and Resources

As for any deep geologic facility, the natural setting of the Waste Isolation Pilot Plant (WIPP) is important in determining the facility's performance as a repository for radioactive waste. The natural setting consists of the geology, hydrology, geochemistry, climate, and natural resources of the region and local area immediately surrounding WIPP, some of which are discussed below.

GEOLOGIC FRAMEWORK

For a large part of the early geologic history of the North American continent, the land now occupied by southeastern New Mexico was part of an ancient ocean south of the continent. For hundreds of millions of years, this region experienced almost uninterrupted deposition of marine shoreline sediments, primarily beach sands, and shallow water lime and clay muds. In the Pennsylvanian Period and later, coarser continental shelf and slope deposits occasionally slid into deeper basins. The relatively warm, calm seas promoted an abundance of marine life, which, upon death, accumulated in the muds and sands, altered to simple hydrocarbons, and eventually became the oil and gas found in some of these rock layers in recent years.

In pre-Permian periods, the collision of tectonic plates of the earth's mobile crust caused mountains to form to the southeast, north, and west of the WIPP site. The southeastern corner of New Mexico and western Texas remained relatively stable through the Permian Period of earth history (286 million to 245 million years ago [Ma])[1], although some instability caused the earth's crust beneath this region to rise in some places and sink in others, in a belated response to the collision pressures. These fluctuations resulted in shallow areas on the sea floor ("shelves" or "platforms") and deeper areas ("basins") at the beginning of the Permian Period in southeastern New Mexico and western Texas (Figure A.1).

It was in the sediments accumulating in these deep basins that oil was generated, which moved into adjacent shelf environments to form the richest oil pools. One of these deep basins, the Delaware Basin, underlies WIPP and part of southeastern New Mexico. Most of these older rocks beneath WIPP are far too deep to bear on the performance of the repository. However, the presence of oil is considered a possible reason for inadvertent, or even deliberate, human intrusion into the repository in the future.

Late in the Permian, the warm and shallow seas encouraged the formation of reefs, similar to contemporary coral reefs in shallow tropical marine environments. As they grew, the reefs blocked off parts of the sea from time to time. With circulation of seawater restricted by the reef, the seawater began to evaporate, resulting in highly concentrated brines. As the brines continued to evaporate because of the warm temperature and restricted inflow of seawater, crystalline salts began to precipitate and accumulate on the bottom of the restricted basin. The salts varied in chemical composition, depending on the amount of water that had evaporated and on the concentrations of calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), and other components of the common "evaporite" deposits.

As a result of these conditions, the WIPP area is underlain by a total accumulation of hundreds to thousands of meters of reef limestone (calcium carbonate, $CaCO_3$); dolomite [calcium magnesium carbonate—$CaMg(CO_3)_2$]; gypsum [a hydrous (water-bearing) calcium sulfate, $CaSO_4 \cdot 2H_2O$); halite (rock salt, NaCl, the source of common table salt); smaller amounts of anhydrite ($CaSO_4$); and potassium salts (collectively known as "potash," a commercially useful deposit).

[1]Older geologic dating extended the Permian to 225 Ma; more recent methods date the end as 245 Ma.

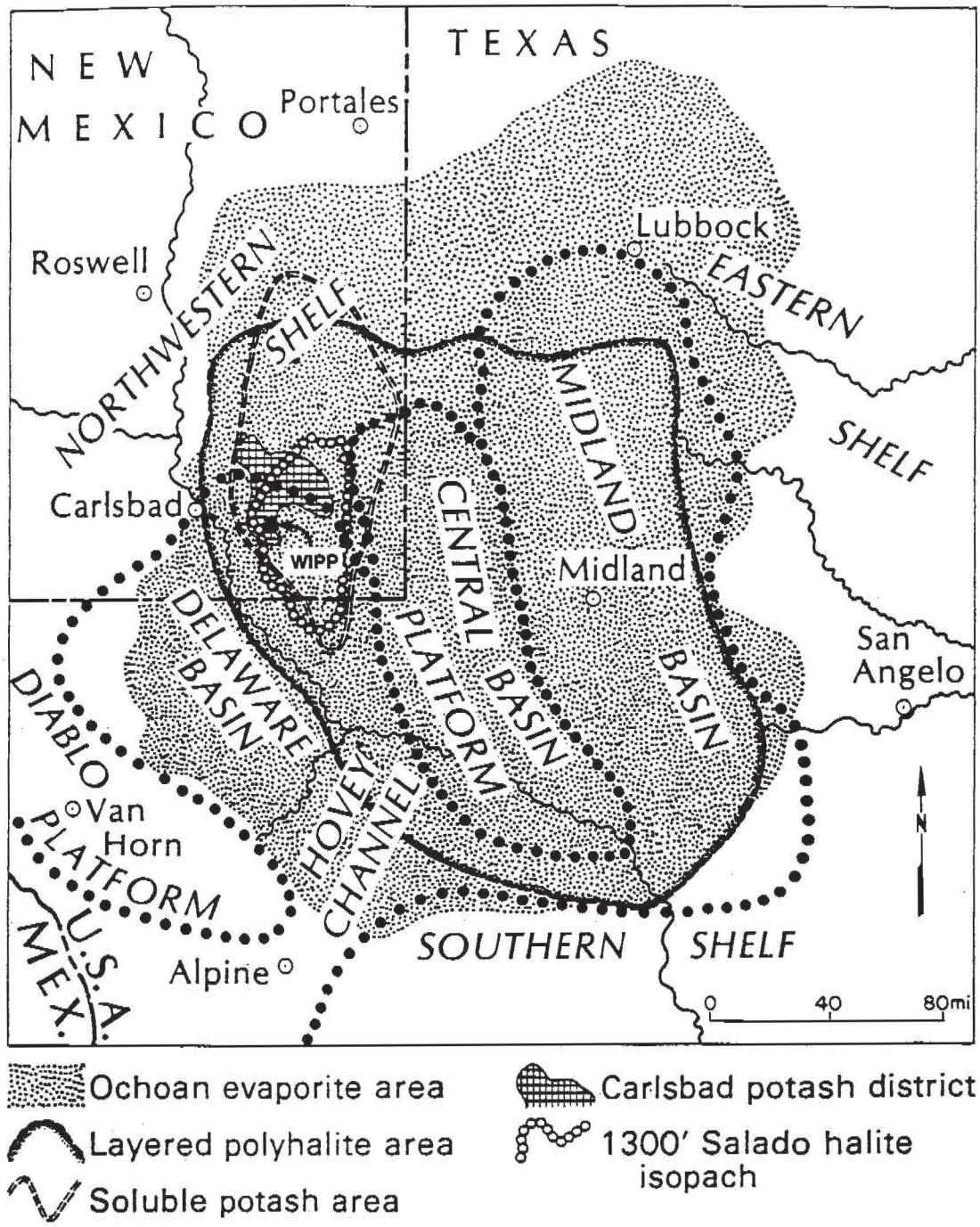

FIGURE A.1 Regional subsurface geology, showing features from before and during the Permian Period. Heavy black dots outline the Pennsylvanian to middle Permian (Guadalupian) shoreline, showing the shallow platforms and shelf areas and the adjoining deeper basins. Superimposed on that background in fine, close-spaced dotted shading is the extent of the late Permian (Ochoan) evaporating sea. A solid black line delineates the extent of layered varied salt deposits. The enclosed form of open circles shows where the Salado Formation salt beds are 396 m (1,300) ft thick. The Carlsbad Potash District is shown in cross-hatch pattern. Source: Barker and Austin (1995).

Within part of the Permian, the Ochoan, during which the sea was blocked intermittently, the following four groups of rocks present at the WIPP site were formed successively:

1. Castile Formation,
2. Salado Formation,
3. Rustler Formation, and
4. Dewey Lake Red Beds.

Castile Formation

The oldest and deepest of these rock units is the Castile Formation. Castile rocks are composed mainly of anhydrite with alternating thin limestone layers and a few thick layers of halite. Anhydrite and/or gypsum begins to precipitate from brines when 75 percent of the original amount of seawater has evaporated, continuing to be deposited until 90 percent has evaporated, at which point halite begins to precipitate (Kay and Colbert, 1965, p. 202). The alternating character of the Castile suggests that limited amounts of fresh seawater were able to enter the basin intermittently.

Salado Formation

The Salado ("salty" in Spanish) Formation, in which the WIPP facility is located at 658 m below the surface, is composed predominantly of layers (beds) of rock salt, 200-400 m thick. It contains very thin layers (typically 0.1-1 m thick) of other materials (such as clay, anhydrite, and potash minerals) intercalated throughout the formation. Because these evaporite beds have been undisturbed by tectonic forces (large-scale movements of the earth's crust) for approximately 240 million years since their original accumulation, they are essentially horizontal and therefore can be traced continuously for great distances. The thin, distinctly identifiable nonhalite interbeds, called "marker beds" (MBs), have been numbered for identification from the lowest, at the top of the formation, to the highest, near the bottom. Marker beds have been used in the construction of the WIPP facility to keep the floor at a specific stratigraphic level, about 660 m below the surface. The floor of the facility is just above anhydrite MB 139 (Figure A.2).

About midway between the bottom and top of the Salado Formation is a notably thick series of beds, known as the McNutt member of the Salado, which contains economically valuable amounts of potash. The McNutt member, stratigraphically above the salt in which WIPP is located (Figure A.2), is about 120 m thick (Griswold, 1995) but is limited in areal extent within the evaporite basin (Figure A.1). The potash minerals, however, are of sufficient quantity for mining and extraction to have been a source of major economic activity in the area for many years.

Rustler Formation

Overlying the Salado Formation is the Rustler Formation, a thinner-bedded series of strata consisting of five distinct subunits (such sequences are called "members" of a formation). At the bottom of the formation are nonevaporite beds derived from clay muds and sands alternating with layers of halite, anhydrite, limestone and dolomite, and gypsum. The total thickness of the Rustler is about 100 m. The presence of nonevaporite materials such as the clay, silt, and sand (called "clastic deposits" or "clastics") indicates that periodic fluctuations in basin water levels and intermittent inflow of river and marine waters carried clastics into the basin material that sometimes formed separate layers without evaporites, such as sandstones and shales, or settled with the evaporites. The Culebra Dolomite Member of the Rustler Formation, which lies directly above the lowest Rustler clastic strata, is only about 7-8 m thick. The chemical, mineral, and hydrogeologic characteristics of the Culebra are important to a ground-water flow model for the WIPP area.

Dewey Lake Red Beds

The youngest (uppermost) Permian strata in the WIPP vicinity are thin, reddish beds of clay, silt, and sandy sediments produced in a restricted marine environment. The red color derives from the oxidized iron dispersed throughout the clay and sand, suggesting semiarid conditions during deposition of the sediments.

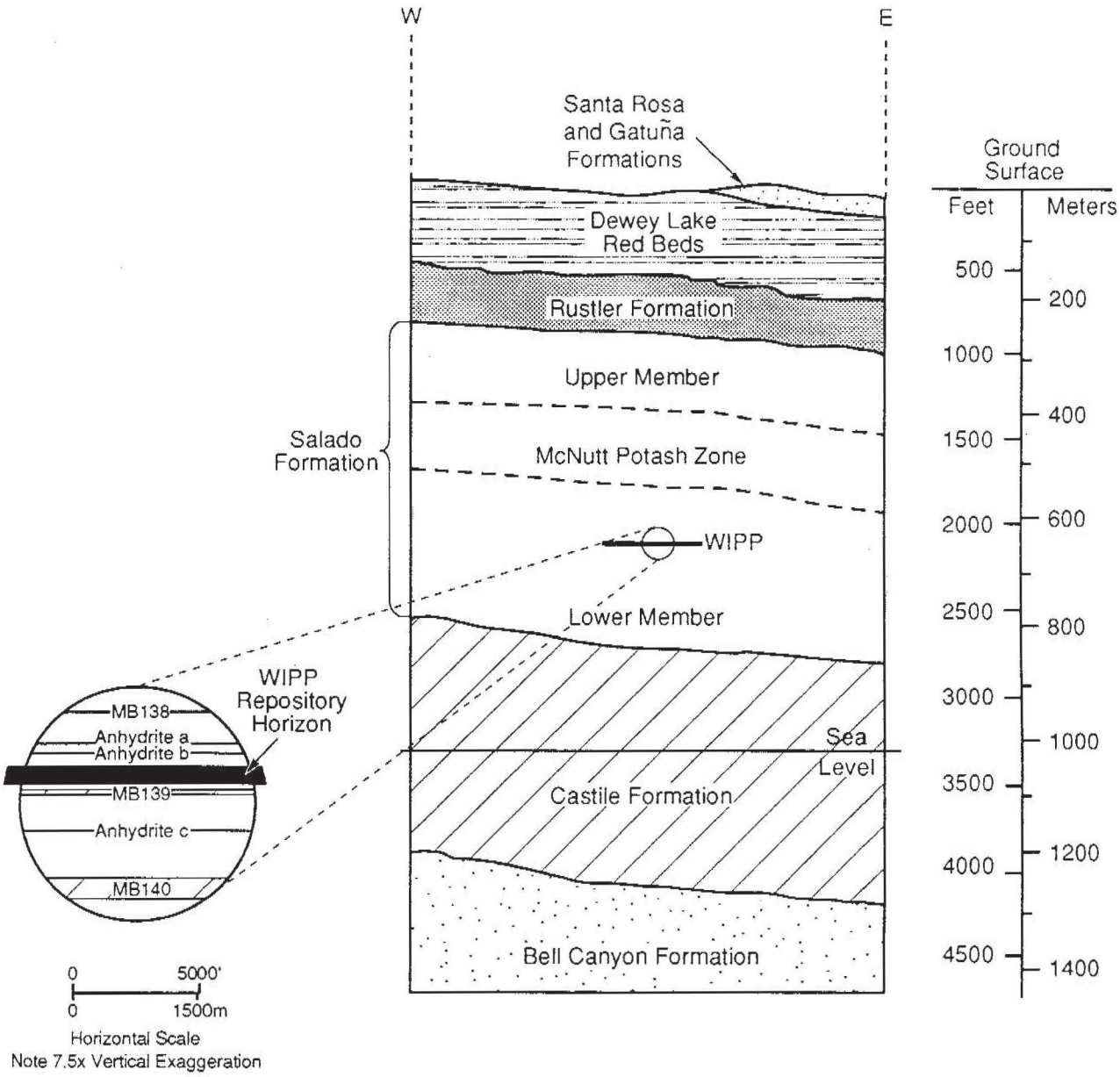

FIGURE A.2 WIPP stratigraphy and depths of four key formations (Castile Formation, Salado Formation, Rustler Formation, and Dewey Lake Red Beds), including the position of the WIPP repository within the Salado. Inset shows finer-scale stratigraphy around the repository horizon, with marker beds and other thin beds. Source: Jensen et al. (1993).

Post-Permian Rocks

An assortment of rock types and ages younger than Permian is present in different locales around the region. Some discontinuous surface deposits were carried by high-energy streams that formed from the melting glaciers to the north during the Ice Age (the Pleistocene, from about 1.6 Ma to 10,000 years ago). One of the Pleistocene stream channels is still present west of the WIPP area as a broad, shallow valley, called Nash Draw, that is wider than 6 km in places (Figure A.3). The valley formed when the high-energy streams eroded down through the rock layers and exposed parts of the Rustler Formation, which are now visible in the walls of the valley. Nash Draw plays a role in determining the regional and local hydrology in the vicinity of WIPP.

HYDROLOGIC SETTING OF WIPP

Because flowing ground water is one of the most likely means by which contaminants could reach the accessible human environment, it is important to understand the hydrogeologic character of the region.

Most of the hydrologic studies of the WIPP site and surrounding region have focused on the Rustler Formation in general, and on the Culebra Dolomite Member in particular. Because the latter is a water-bearing unit that is exposed in Nash Draw, it is a major concern in assessing the capabilities of WIPP to isolate radioactive wastes. However, the other major formations also play a role in WIPP hydrology for varying reasons.

The top of the Castile Formation lies about 200 m below the level of the Salado Formation at which the WIPP facility is located (Figure A.2). Under natural conditions, there is no flow of ground water between the Castile and Salado Formations. However, during exploratory drilling to locate a site for WIPP, project scientists found large, highly permeable zones (pockets) at depths within the Castile, filled with brine under very high pressure (from the weight of hundreds of meters of overlying rocks). This is considered significant in evaluating the WIPP facility because brine in pressurized pockets, once penetrated by drilling, flows out to the surface rapidly and could continue to flow for hours or days, depending on the depth of the pocket, the volume, and pressure of the brine.

Hydrogeology of the Salado Formation

The mechanical behavior of salt, especially massively bedded salt, provides the basis for the inference that water cannot flow continuously through salt along interconnected pathways as it does in many other types of geologic materials. As a weak solid, salt flows under low pressure after a period of time, much as glacial ice flows.

Both are solids, but under pressure such as its own weight or the weight of material above, the crystal structure of the individual minerals that make up the rock salt deforms, causing movement within the minerals (intracrystalline gliding) and movement between crystals (intercrystalline slip) over time. This type of movement, termed "creep," is a very slow process in human terms, in which the actual movement of the salt cannot be seen, although the results of creep are readily observable in room closure and the deformation of boreholes.

The continuous creep of rock salt causes opening and closing of pore spaces that trap droplets of water and prevent the continuous flow of ground water through the interconnected pore spaces in the rock from one location to another. Creep also closes fractures and "heals" them as salt crystals flow into them and interconnect with other salt crystals. For this reason, the permeability of salt (the degree of interconnected pore spaces that allows flow of ground water through the rock matrix or fractures) is generally regarded as extremely low to zero. Pressure tests done on the Salado Formation at various times, both from wells drilled at the surface and from underground tests after the facility was constructed, have indicated that the salt permeabilities are very low, close to the sensitivity limits of the instruments (Mercer, 1987; Beauheim et al., 1991, McTigue, 1993).

During the construction phase of the WIPP facility, brine was observed flowing or seeping into the space created whenever a new opening was made in the salt, whether in a narrow hole or in a large room. These observations led to consideration of the possibility that the disposal rooms could be flooded over the time required for isolation of the long-lived radionuclides

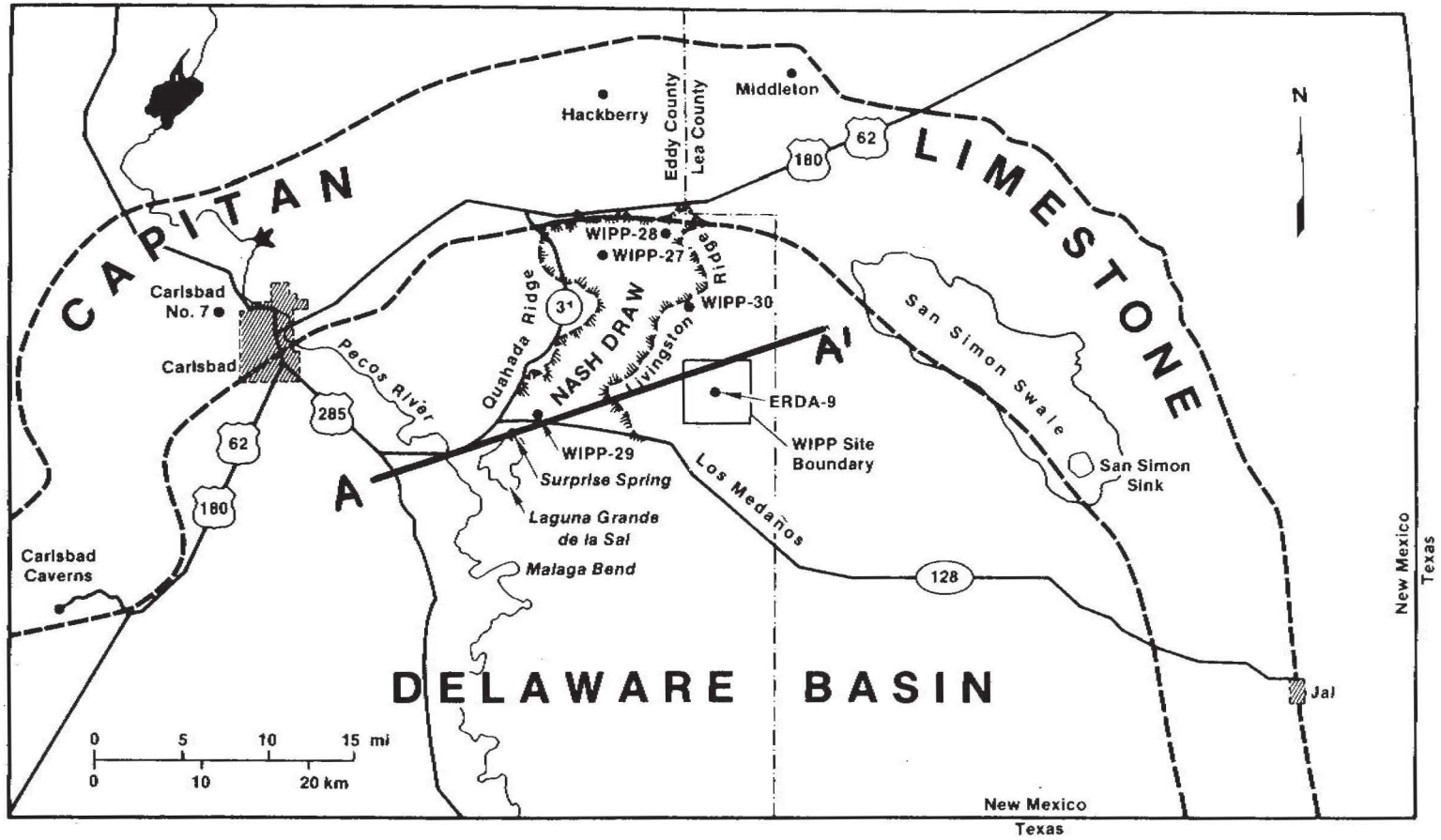

FIGURE A.3 Position of Nash Draw with respect to WIPP. Other features of interest are the location of the Pecos River and the outline of the buried Capitan reef limestone, which encloses the Delaware Basin on the north. Source: Siegal et al. (1991).

and that the consequent chemical reaction of the brine with metal containers would produce large volumes of hydrogen gas (Brush, 1994). These considerations assumed that brine was flowing in from the far field and had a continuous source. However, tests to monitor and measure the inflow of brine over a period of years have shown that the rate of inflow is greatest immediately following the disturbance of the salt to produce a new opening, then declines rapidly, and finally tapers to almost immeasurable amounts (Deal et al., 1991a, b).

These observations have led WIPP project researchers to consider that brine inflow into a newly created opening results when the salt is disturbed by drilling or mining and fracturing occurs in a zone around the new opening (disturbed rock zone, or DRZ), thus releasing brine from entrapped pore spaces (Stormont et al., 1991). Further details and discussion of this issue can be found in Chapter 3 and Appendixes C and D.

The only likely source of measurable Darcy flow in the Salado is the nonhalite interbeds, especially the anhydrite interbeds, which show varying degrees of fracturing. Fracture permeability can provide interconnected pathways for ground water.

Hydrogeology of the Culebra Dolomite

The geological units comprising the Rustler Formation are illustrated in the stratigraphic column shown in Figure A.4. Note that the lithologies represented in this figure are generalized representations for the region and do not necessarily depict the exact distribution of rock types encountered in the Rustler at the WIPP site itself. As illustrated in Figure A.4, the Rustler outcrops are in the Nash Draw area several miles west of the WIPP site, but the formation lies at a depth of about 200 m below the land surface at WIPP.

Ground-water flow in the Rustler Formation is restricted mostly to the Rustler–Salado contact zone, the Culebra Dolomite Member, and the Magenta Dolomite Member (Brinster, 1991). Of these, the Culebra is the most transmissive. Although it is relatively thin (the thickness of the Culebra is generally between 7 and 8 m), it is also extensive in area.

The Rustler Formation, especially the Culebra Dolomite Member, has been the principal focus of hydrogeologic characterization of the WIPP vicinity (Lappin, 1988). The ground-water system in the Rustler is generally characterized by relatively low permeability (or transmissivity) and relatively poor water quality (i.e., too salty to be potable). The Rustler contains a predominance of secondary permeability features, such as fractures, bedding planes, and dissolution features; these may dominate flow in parts of the system, complicate analysis, and render quantitative descriptions difficult. At the very least, these features imply that the ground-water flow system is three-dimensional in a heterogeneous framework that is a challenge to model and understand properly. Both observation and water-supply wells are relatively scarce, contributing to the difficulty and expense of characterization. Although much excellent work has been done during the past 20 years in an attempt to characterize the relatively complex hydrogeology of the area near the WIPP site, some large uncertainties remain in the understanding of the subsurface system above the Salado. The recent state of knowledge has been summarized by Brinster (1991).

A number of water-level measurements and observations of drawdown and/or recovery during hydraulic tests have been used to measure the hydraulic heads and transmissivities in the Culebra. The changes in head over distance determine the hydraulic gradient. Transmissivity, which can vary significantly in value from point to point, is a measure of the ability of the rock to let water flow through it under a given hydraulic gradient.

However, some inconsistencies remain in the interpretation of the long-term flow history of the Culebra based on hydrologic evidence, compared to that inferred on the basis of geochemical and isotopic indicators. These inconsistencies, which reflect some degree of lack of understanding of present or past flow regimes within the Culebra, mean that there is uncertainty in the conceptual model that underlies the performance assessment (PA) model.

Ground-Water Flow Directions

In general, the direction of ground-water flow in the Culebra Dolomite in the WIPP area is from north to

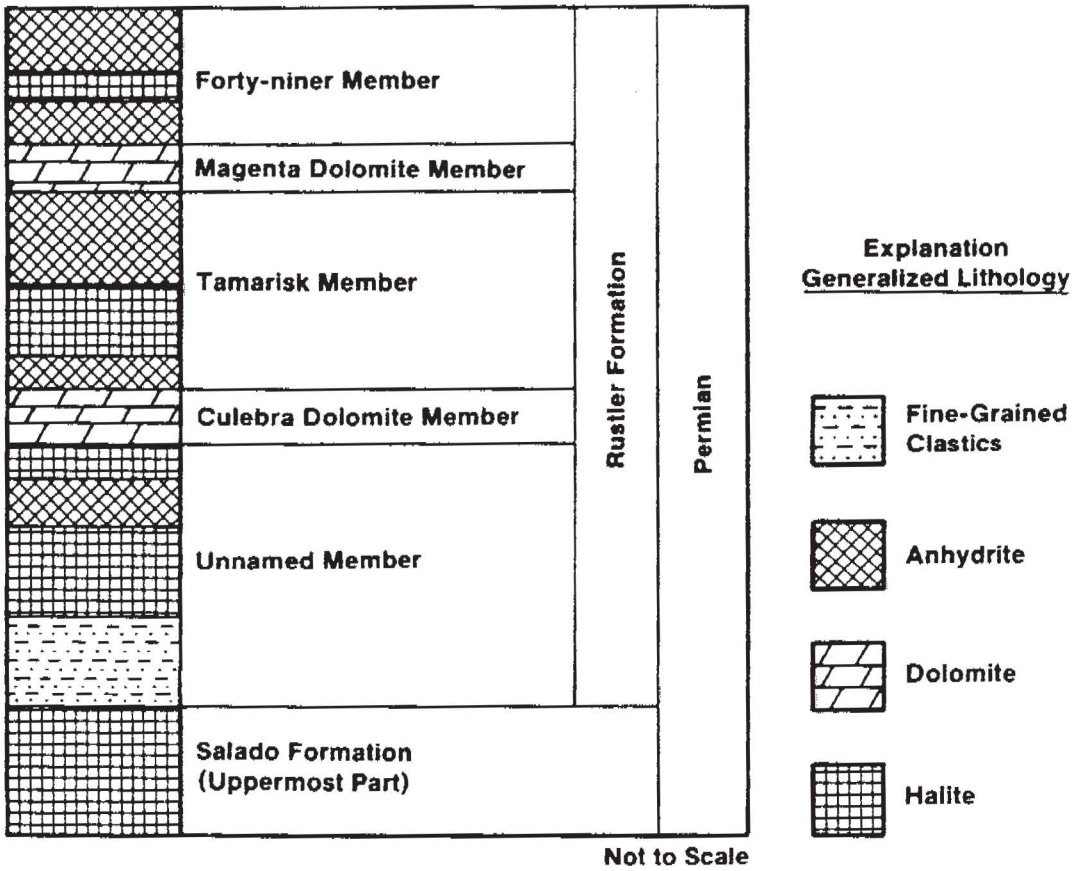

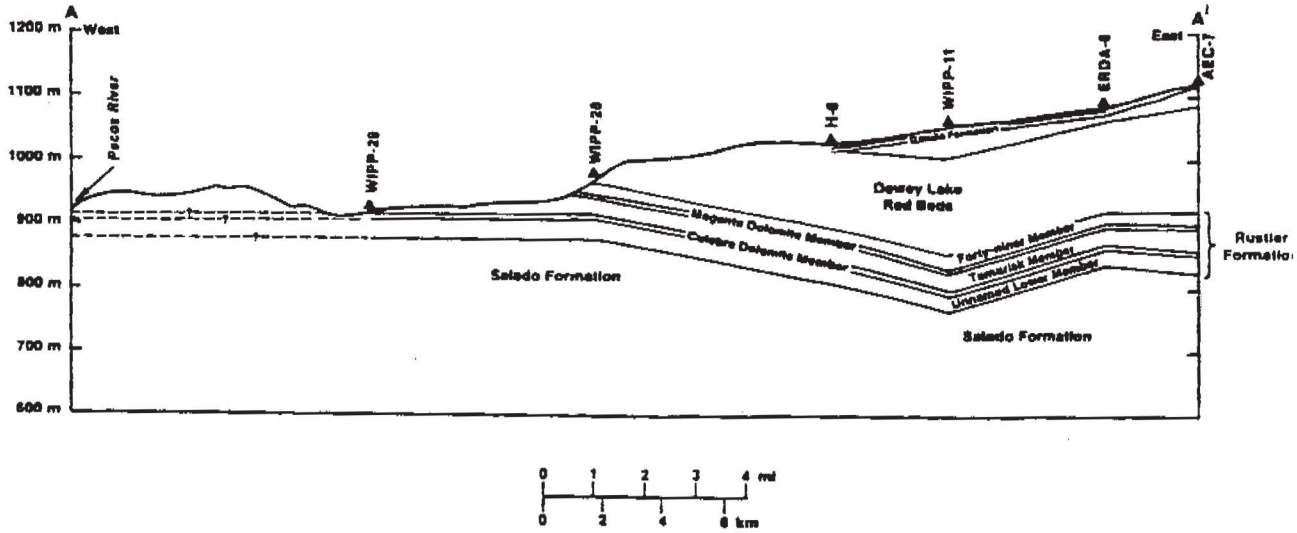

FIGURE A.4 General stratigraphic column showing the five members of the Rustler Formation (top), and cross section from A to A' of Figure A.3 showing Rustler Formation stratigraphy (bottom). Source: Brinster (1991).

south. Because the salinity of the ground water is high and variable, the fluid density also varies significantly. Davies (1989) analyzed variable density flow in the Culebra and concluded that, at least in areas south of WIPP, flow directions can be calculated accurately only if variations in fluid density also are evaluated. Potentiometric data in the Magenta Dolomite indicate that the flow direction is predominantly from east to west. Differences in flow directions within the Rustler Formation reflect the complexity of the hydrogeologic system and may be influenced by vertical components of flow.

A fair degree of uncertainty remains about the amounts and locations of recharge to and discharge from the Culebra. In general, Brinster (1991) notes that recharge occurs north of the WIPP site, although some recharge may also occur east of WIPP because of vertical leakage from the Magenta. Natural discharge is south of WIPP, with some discharge to the Pecos River likely occurring at Malaga Bend.

Transmissivity Estimates

Transmissivity estimates for the Culebra Dolomite in the WIPP area and in Nash Draw range over more than six orders of magnitude. Transmissivity is lowest east of WIPP ($\sim 10^{-10}$ m^2/s) and tends to increase to the west ($\sim 10^{-3}$ m^2/s). However, the transmissivity is highly variable and spatially correlated (e.g., LaVenue et al., 1995). In some areas, the transmissivity is controlled largely by fracture permeability, whereas in other areas it is governed by primary intergranular properties.

Travel Time

The time it takes for a parcel of water in the Culebra Dolomite to travel from the center of the WIPP site to its southern boundary is an important characteristic of the system controlling the transport of any contaminants released into the Culebra. This travel time depends on the transmissivity, hydraulic gradient, and effective porosity. Analyses assuming that the effective porosity governing transport is a value characteristic of the rock matrix (about 0.16) indicate that the mean travel time would be of the order of 14,000 years (LaVenue et al., 1990). However, if one assumes that the effective porosity is characteristic of fracture porosity (~0.0015), then the travel time is reduced to only about 200 years (Davies et al., 1991).

Hydrogeology of the Dewey Lake Red Beds

The Dewey Lake Red Beds are believed to be less permeable than the Culebra Dolomite. However, very few hydraulic tests of this unit have been completed, and few observation wells are available to characterize the flow system. Brinster (1991) reports that although a continuous saturated zone has not been found, some localized zones of relatively high permeability have been identified. Potable water has been reported in some parts of Dewey Lake, perhaps because it is sufficiently shallow to receive direct recharge from precipitation events.

NATURAL RESOURCES

The geologic evolution of this region has resulted in the presence of economically valuable natural resources. The late Permian evaporating basin accumulated a large deposit of potash. The region in earlier Permian time can be characterized as a marine shoreline and some deeper offshore basins accumulating sands and limestone, clastics, and organic debris that resulted in accumulations of economically recoverable oil and gas in rock strata below the evaporites. Thus, the two major activities to extract mineral wealth from the WIPP region are the mining of potash and the drilling and extracting of oil and gas.

Potash Mining

Potash, the commercial name for potassium-bearing minerals, is mined for its potassium, one of the three main plant nutrients in fertilizer. The potassium minerals are concentrated in a middle zone of the Salado Formation, the McNutt Member, which is about 140 m thick (Figure A.2). The Carlsbad Potash District contains the largest potash reserves in the United States (Barker and Austin, 1995; see also Figure A.1). The district is bounded on the west by the dissolution of the shallow Salado strata caused by circulating ground water in the Pecos River drainage area to the west and south of Nash Draw.

Potash mining has been going on in the WIPP vicinity for more than 60 years. Potash was discovered in southeastern New Mexico in 1925. The first mine shaft to the potash 324 m (1,062 ft) below the surface was completed in 1930, and the first commercial shipment took place in 1931. Over the next 30 years, development and production advanced steadily as a large number of companies grew and merged. By the 1940s, New Mexico was the largest domestic potash producer, supplying 85 percent of the country's consumption.

This growth came to a halt and started to decline when potash was discovered, produced, and exported to the United States from Canada in the early 1960s at a lower cost than was economically feasible for U.S. producers. By 1970, Canadian imports exceeded domestic production. The decline continued despite a favorable ruling of dumping against Canadian producers by the International Trade Commission in 1987. Shortly thereafter, the former Soviet Union countries began exporting potash to the United States, further increasing competition and depressing both price and demand. Because of the foregoing and other economic and declining resource factors, the potash industry in the WIPP region is now much depressed, and very few companies are still active (Barker and Austin, 1995).

The mining front is now close to the WIPP site boundary and has reached the edge of the study area on the southwest side of the WIPP site (Figure A.5). In the future, the southwest or north side of the WIPP boundary may be the next target area for mining (Griswold, 1995).

In assessing potential future impacts of potash mining on the WIPP facility, the adoption of solution mining of potash minerals, a technique now being used in Canada, has been mentioned as a possible development. However, of the two dominant potash minerals being mined in the Carlsbad Potash District, sylvite and langbeinite, only sylvite is sufficiently soluble to make this mining process economically and practically feasible. According to specialists familiar with potash mining in this area, the beds containing sylvite are considered too thin for solution mining to be practical, but mine owners have not discounted this process as a future development in the area (Griswold, 1995).

If the potash resources overlying the repository were mined in the future, the resulting subsidence could significantly increase the transmissivity of the Culebra Dolomite, located approximately 200 m above the potash (Figure A.2). This could result in faster release of radionuclides to the environment following a human intrusion event.

Oil and Gas Resources

After the strata below the evaporites of the Delaware Basin had been bypassed for many years as unlikely to be producers of economically recoverable oil resources in the WIPP area, oil was discovered in the late 1980s and early 1990s. Indications in earlier exploration had suggested that mostly water was present in these strata. New techniques in analyzing the geophysical logs led to identification of several commercial oil pools in the Delaware Mountain Group of rocks at and below about 2,500 to 2,700 m in depth.

Major oil drilling activity began in the Delaware Basin following the discovery. This is now one of the most active areas of oil exploration and extraction in the United States (Broadhead et al., 1995, p. XI-10; Figure A.6). In the vicinity of WIPP, four major pools have been discovered, at least one within 1 km of the site boundary.

New technologies in oil drilling have improved recovery, safety, and cost efficiency. Improvements in well productivity result from advances in directional drilling, completion technologies, and stimulation techniques (Hareland, 1995). These advances and projected future oil and gas production were used to calculate the estimated value of oil and gas underneath the WIPP land withdrawal area. The estimated total primary and secondary recovery of probable resources in oil reservoirs under WIPP is about 54 million barrels of oil and gas condensate (Broadhead et al., 1995).

The secondary oil recovery technique known as waterflooding has been used in some areas around WIPP. A concern has been raised that such a process could introduce large amounts of water into the Salado Formation that could find its way to the WIPP facility by flow through marker beds, a process that has been observed in some oil fields in the region. In 1991, a flow of up to 1,200 barrels per hour of brine inflow was encountered in a hole being drilled for petroleum

production. At the time of inflow, the hole was approximately 100 m above the base of the Salado. The inflow was attributed to a waterflooding operation in the Rhodes Yates Field in which a large number of old wells were simultaneously injected. These injections occurred in the Yates Formation some 100 m below the base of the Salado, and 2 miles (3 km) from the well where the inflow occurred. This has raised concerns that similar inflows may occur due to waterflooding operations near WIPP and could compromise the integrity of the repository. This is further discussed in Chapter 3 (Box 3.2). See Figure A.7. A full discussion of waterflooding is presented in Broadhead et al. (1995).

A key issue is whether a future society would be aware of WIPP and its hazardous contents. The presumption that the existence or significance of WIPP would be lost is subjective and unquantifiable and therefore beyond the realm of rigorous scientific prediction. A second issue is whether such a society would elect to drill through it if knowledge of WIPP's existence were retained.

If future societies retain a knowledge of the existence of WIPP, yet still want to explore for or recover petroleum resources below WIPP, then directional drilling is feasible and likely. With present technology, a drilling operation could avoid damage to the repository if it were operated from the surface beyond the WIPP site boundary, and directed to avoid the waste horizon.

Manmade site markers, to be emplaced after closure, are required under the EPA standards. The reason for this requirement is that such markers, if they persist over time and are understood, could reduce the likelihood of inadvertent intrusion. The intent of erecting markers is to lead drillers to reconsider vertical boreholes that would penetrate the repository, and to choose instead alternative methods such as directional drilling techniques.

The assumption that the WIPP area would be drilled by today's methods for the next 10,000 years is also questionable. The recent advances in directional drilling techniques show that technology evolves in time.

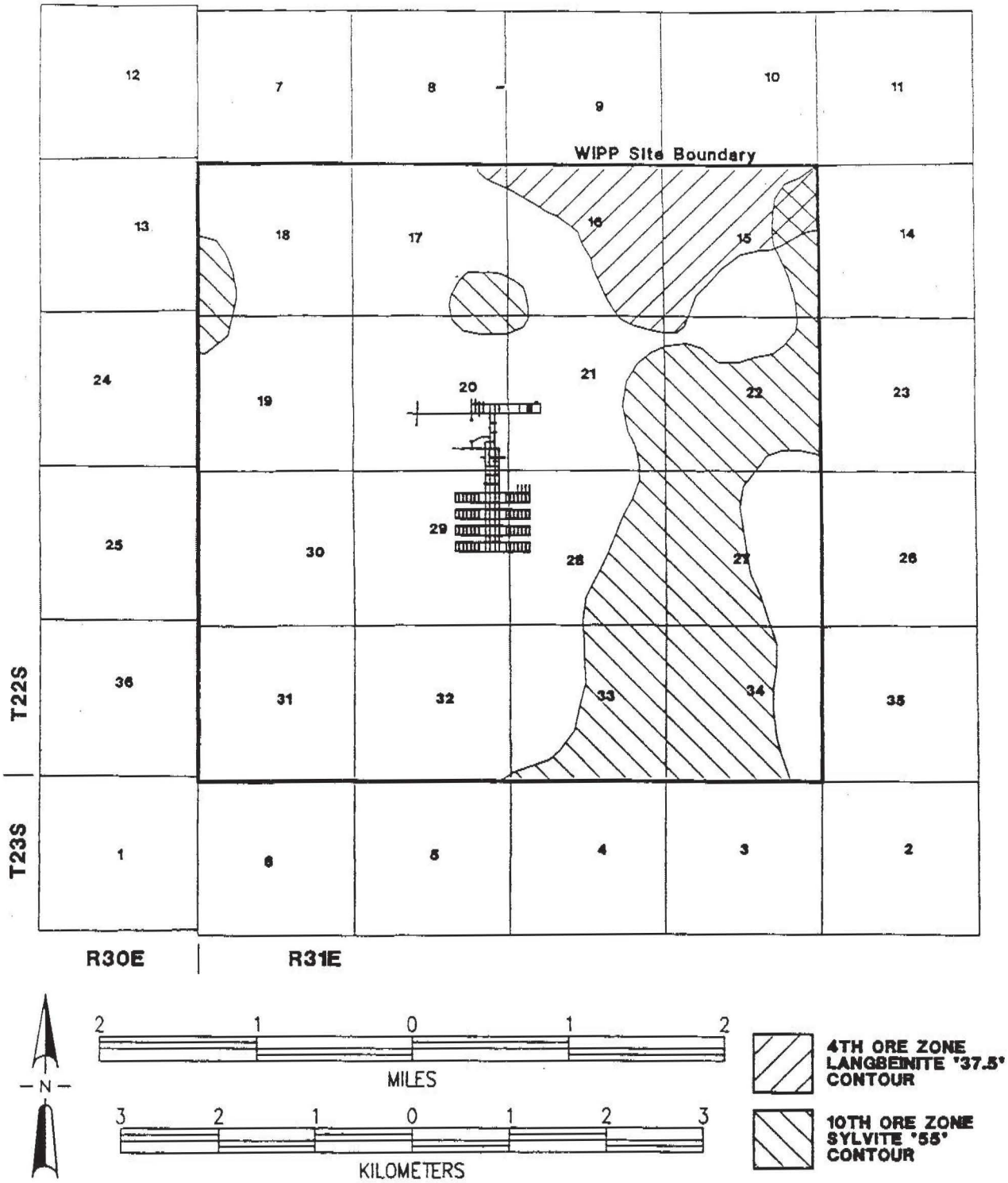

FIGURE A.5 Contours showing potash ores (both langbeinite and sylvite) near WIPP. (The contours are interpolated from figures 4 and 30 of Griswold [1995]). Also shown is the location of the WIPP facility of Figure ES.1.

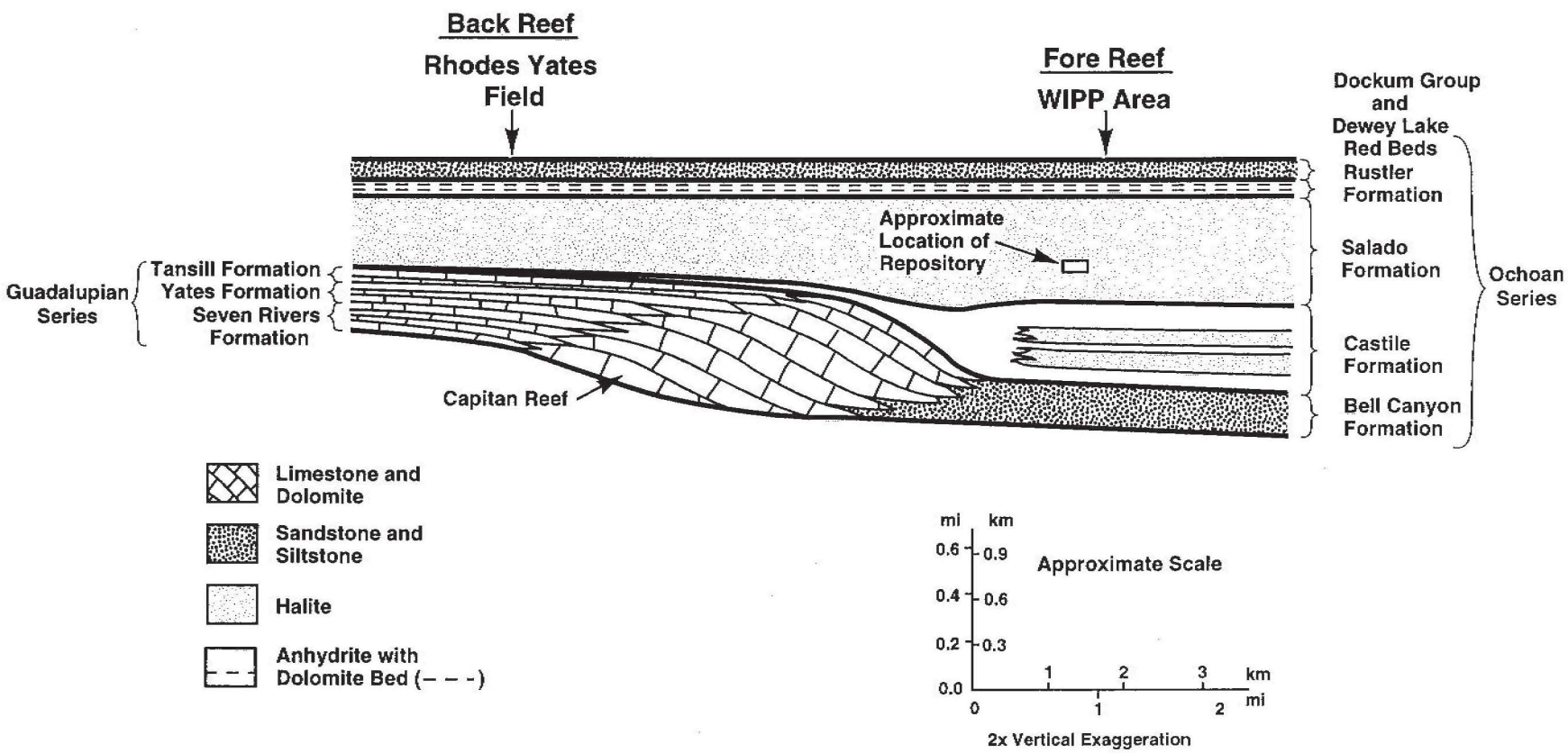

FIGURE A.6 Cross section depicting the relative locations of the Rhodes Yates Field and the WIPP repository. Source: Sandia National Laboratories, unpublished. Data from the State of New Mexico Bureau of Mines.

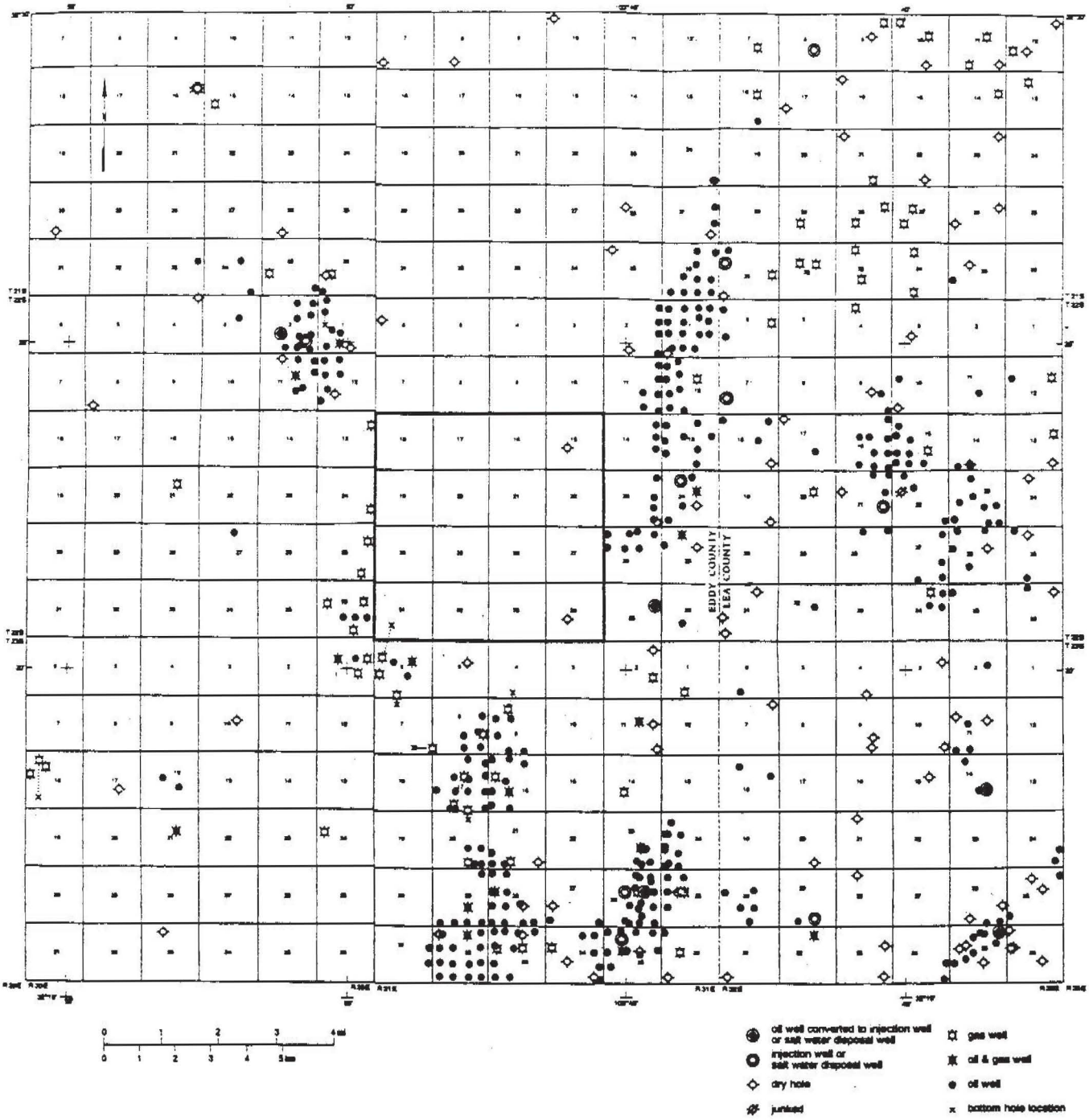

FIGURE A.7(a) Wells drilled for oil and gas in and around the WIPP site, surrounding 1-mile-wide study area, and nine-township project study area. Note that some wells are right at the WIPP boundary. No producing wells are within the WIPP exclusion zone. Source: Adapted from Griswold (1995).

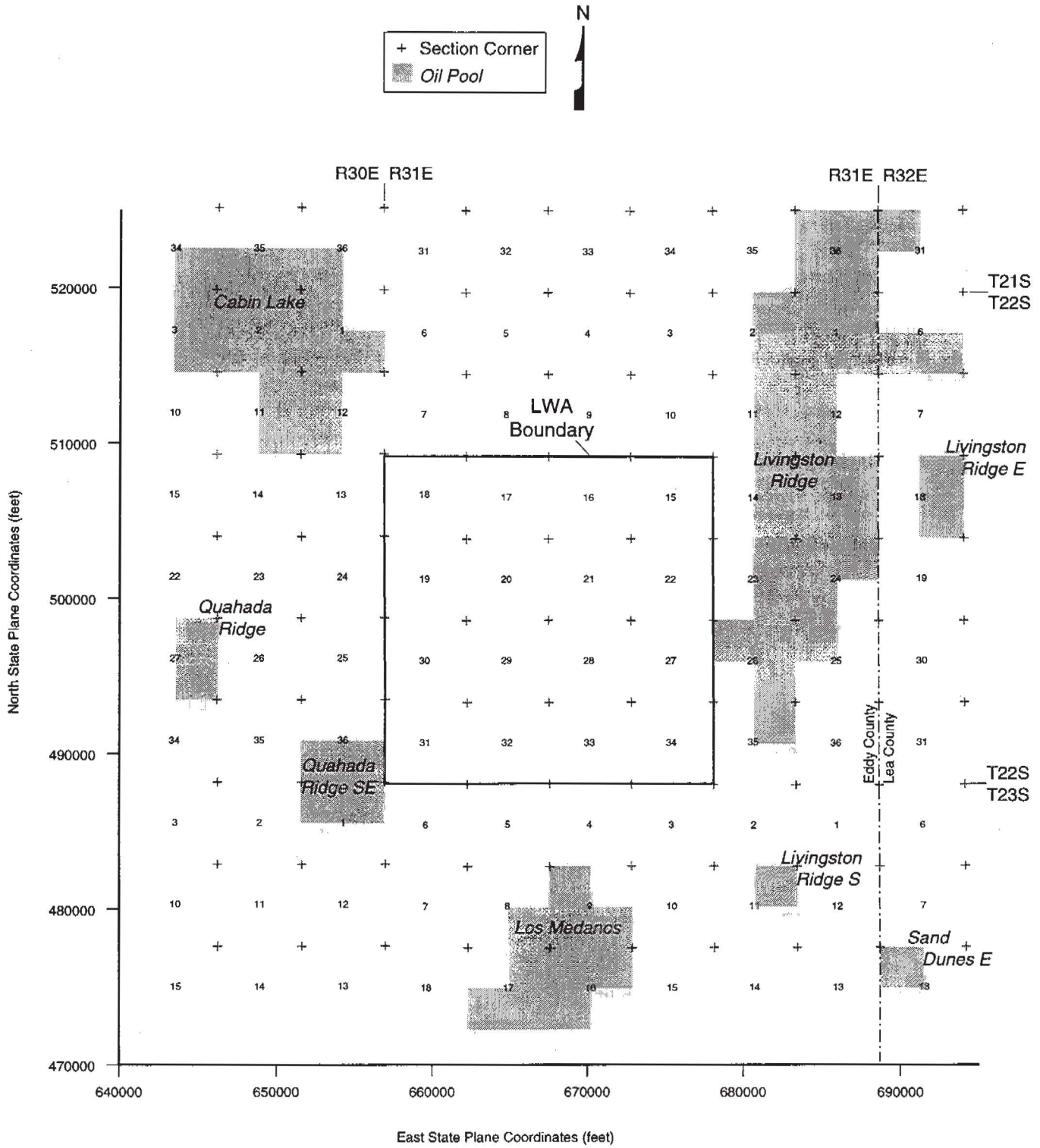

FIGURE A.7(b) Oil pools near the WIPP site, outside of the Land Withdrawal Act boundary, shown on state plane coordinates. Note that two pools abut the LWA boundary. Source: Sandia National Laboratories, unpublished. Data from the Petroleum Institute.

Appendix B

The Complementary Cumulative Distribution Function: The Risk Curve

Risk assessment, including performance assessment, has created the ubiquitous complementary cumulative distribution function (CCDF). Although some advocate a less imposing label such as "the risk curve," CCDF seems to have found its place in the risk literature as the preferred name. As shown below, the words do have mathematical meaning.

What is a CCDF? One answer is that the CCDF is an aggregated response to the triplet definition of risk noted in Chapter 2 of this report. In particular, for the Waste Isolation Pilot Plant (WIPP) performance assessment, the CCDF consists of plots on log-log graph paper of exceedance probability versus consequence. There may be several CCDFs to cover several different consequences of interest. There may also be several CCDFs for a particular consequence to indicate the range of uncertainty involved.

Most people are familiar with the concept of a bell-shaped curve as a way to convey confidence, or probability, in the value of a parameter, such as the number of curies released from an inventory of radionuclides. Such a curve tells how much of the probability is associated with intervals of curies released. This curve, called the probability density function, is the probability per unit interval of curies released. Of course such curves can be discrete, as in a histogram, or smooth, as in a continuous function (see Figure B.1[a]).

A more interesting question than the probability per release interval is referred to in risk assessment as "the exceedance question." This is the probability that the release will exceed a certain value (in the above example, exceed a certain number of curies of a particular radionuclide). This question can be answered by a summing, or integration operation, on the probability density function (Figure B.1[b]). The result of such a summation is called the cumulative distribution function. The complement—that is, one minus the parameter (here, the cumulative probability)—and the log-log scale are the additional steps taken to achieve the desired form (Figures B.1[c] and [d]). These steps result in a compact form for representing parameters that cover an extremely wide range of values.

Suppose, in the spirit of the triplet definition of risk, that a performance assessment has been conducted and a set of scenarios has been developed, each with its own probability density function of the number of curies of a particular radionuclide released. To cast the results in complementary cumulative form, the scenarios are structured in order of increasing release fractions and the probabilities are cumulated from the bottom to the top as a function of the different release fractions. Plotting the results on log-log graph paper generates a curve of the form shown in Figure B.1(d).

Figure B.1(d) does not represent reality, because it suggests that the outcome of a consequence is known with complete certainty. In practice, there are no absolutes; rather, there is significant uncertainty, starting with the uncertainties of the many individual inputs that are used to calculate a CCDF for a typical risk assessment. Thus, it is impossible to specify a single CCDF as the unambiguous outcome of a risk assessment. Instead, there are many possible CCDF curves (Figure B.2), each with its own likelihood of being correct. The spread of these CCDF curves provides a measure of the confidence with which the CCDF, for the consequence under consideration, can be estimated.

The uncertainty that gives rise to the CCDF curves in Figure B.2 is typically characterized by developing a probability distribution for each imprecisely known

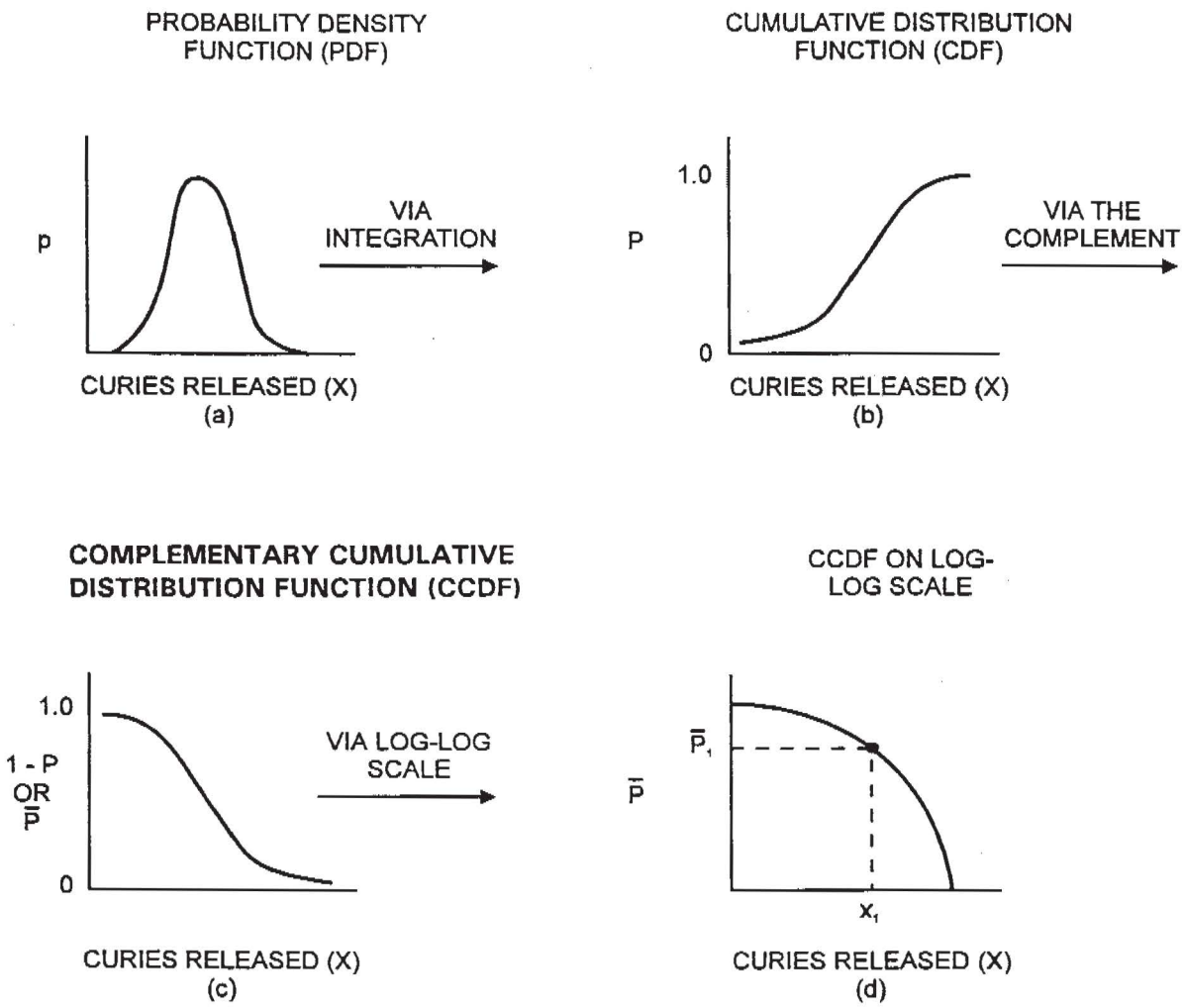

FIGURE B.1 This figure provides an exact interpretation of the parameters $\overline{P}$ and X. In particular, the CCDF representation says that the probability $\overline{P}$ of releasing x_1 curies, or more, does not exceed $\overline{P}_1$.

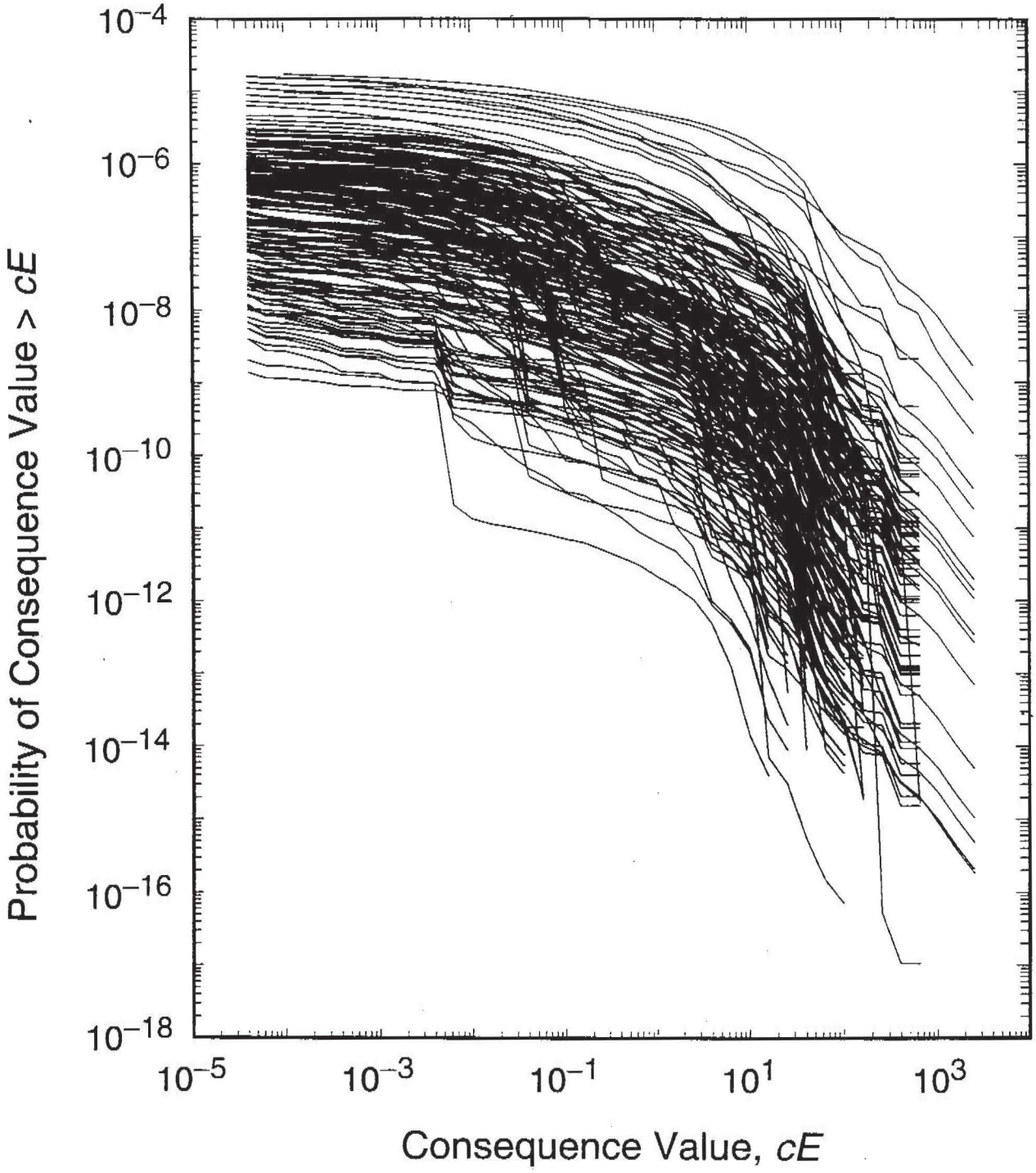

FIGURE B.2 Example distribution of CCDF curves obtained by sampling imprecisely known analysis inputs. Source: Helton et al. (1991).

input used in the analysis. These distributions mathematically describe a degree of belief, based on all the available evidence (e.g., data, background knowledge, analyses, experiments, expert judgment), of the range and weight, in terms of likelihood, of the input values used in the analysis. An example of an input might be a distribution coefficient for a radionuclide transport calculation. Such distribution coefficients cannot be assigned a fixed number because of the uncertainty of what that number should be. Thus, the input has to be in the form of a probability distribution that expresses the analyst's state of knowledge about what the number should be. It tells a much fuller story than would be provided by a single number. The CCDF curves in Figure B.2 arise from the distributions assigned to the individual inputs.

The usual computational procedure is to generate a sample (e.g., random or Latin hypercube[1]) from the uncertain inputs according to their assigned distributions and then to construct one CCDF of the form appearing in Figure B.2 for each element of this sample. With this procedure, each CCDF is constructed from a set of input values (sometimes referred to as a "realization") that is consistent with all available information. Further, the assignment of distributions to individual inputs, and the propagation of these distributions through to the distribution of CCDF curves in Figure B.2, provide a representation of the uncertainty in the final outcome of the risk assessment, where this outcome is a CCDF. Put another way, the distribution of CCDF curves in Figure B.2 provides a measure of the confidence with which the outcome of the risk assessment can be estimated. A tight grouping of CCDF curves in Figure B.2 indicates a high confidence in the estimated location of the CCDF of interest; conversely, a wide spread in the CCDF curves indicates a low confidence in the estimated location of this CCDF.

Although Figure B.2 provides a complete summary of the distribution of CCDF curves obtained by propagating the uncertainty in the individual analysis inputs, it is rather crowded and difficult to read. A less crowded summary can be obtained by plotting the mean value and selected percentiles for each consequence value on the abscissa. For example, the mean plus the 5th, 50th (i.e., median), and 95th percentile values might be used (Figure B.3). The percentile curves then provide a measure of confidence as to the location of the exceedance probabilities for individual consequence values (e.g., there is a degree of belief probability of .9 that the exceedance probability for a particular consequence value is located between the 5th and 95th percentile curves). Further, the mean CCDF, obtained by vertically averaging the individual CCDF curves in Figure B.2, provides a measure of central tendency; the 50th percentile curve provides a related, but different, measure of central tendency. However, it is the distribution of CCDF curves that provides the overall measure of confidence that can be placed in the results of the risk assessment.

The distribution of CCDF curves in Figure B.2, and hence the mean and percentile curves in Figure B.3, are typically obtained by sampling-based techniques and therefore are approximate. However, if a robust sampling procedure is used, these results should show little variation from one sample to the next (Figure B.4). In concept, the mean and percentile curves in Figure B.3 can be specified uniquely by approximately defined integrals; in practice, these integrals have to be approximated by sampling-based techniques.

[1]Latin hypercube sampling is a sampling scheme in which the probability distributions of the input variables are discretized into intervals of equal probability. The advantage of Latin hypercube sampling is claimed to be greater accuracy due to the more detailed sampling of regions of higher probability.

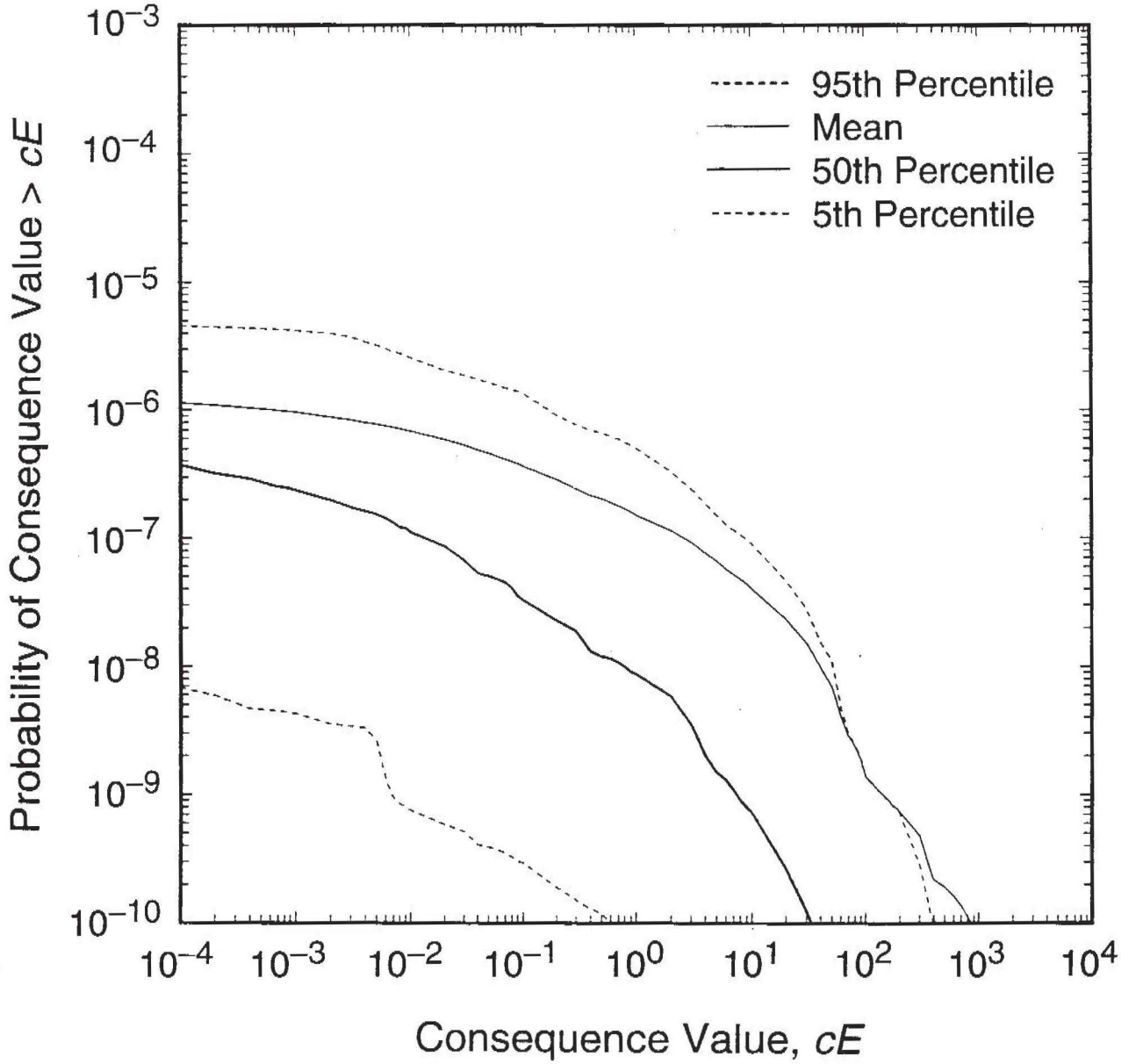

FIGURE B.3 Example summary curves derived from an estimated distribution of CCDF curves. The curves in this figure were obtained by calculating the mean and the indicated percentiles for each consequence value on the abscissa in Figure B.2. Source: Helton et al. (1991).

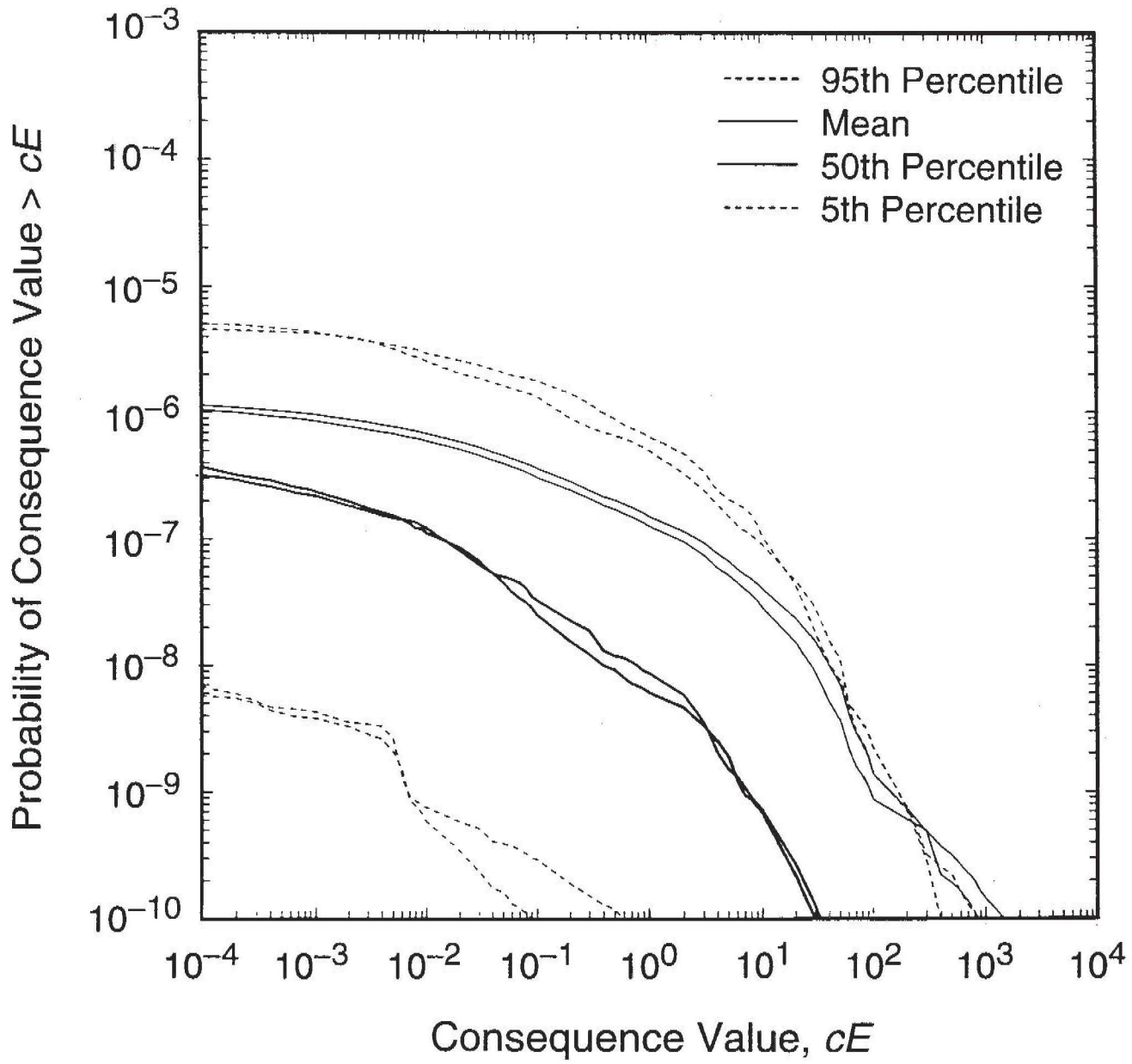

FIGURE B.4 Example of mean and percentile curves obtained with two independently generated samples for the results shown in Figure B.3. Source: Helton et al. (1991).

Appendix C

Brine Inflow to Excavations in the Salado

PERMEABILITY OF WIPP SALT ANHYDRITE AND INTERBEDS

Observation of brine seeps into excavations (both tunnels and boreholes) at the WIPP has led to the assumption that the Salado salt has a finite, but extremely low (~ 10^{-21} – 10^{-23} m^2) permeability in the classical sense of Darcy flow. There are several inconsistencies in this model. An alternative model in which undisturbed salt is assumed to contain brine only in unconnected porosity appears in better agreement with underground observations at WIPP. In this model, "damage" to the salt (i.e., development of the disturbed rock zone, DRZ) resulting from introduction of the excavation, leads to the development of a local zone of interconnected porosity characterized by a finite permeability. It is the release of the brine in the previously unconnected pores by the stress-induced damage that produces the brine seeps—at least in the initial stages (Borns, 1995).

McTigue (1995a,b) has examined this alternative model in detail. he notes:

> *Data for flow to boreholes in WIPP Room D are represented well qualitatively by the classical model. However, the capacitance indicated by fitting model calculations to the field data is orders of magnitude larger than that expected on the basis of the compressibilities of salt and brine. That is, the decay of the brine flux into the boreholes takes place over a time scale that is much too long to be explained in terms of the processes assumed in the development of the classical model. The classical model invokes an unbounded domain of interconnected porosity. This concept is contradicted by both mechanical arguments and geochemical observations. (McTigue 1995b).*

The mechanical arguments from the same reference point out that salt creeps at vanishingly small deviatoric stress (i.e., stress difference). Thus, over long time frames, interconnected porosity can not be sustained. Brine will be confined to local domains of isolated porosity containing fluid at a pressure equal to (minus) the mean [i.e., lithostatic] stress in rock.

Geochemical observations, however, indicate that

> *...brine chemistry is highly variable, even among samples separated by distances of the order of tens of centimeters. If these brines were derived from an interconnected pore network, one would expect that molecular diffusion would have eliminated any significant contrasts in brine composition over the very long existence of the formation....Over a period of 230 Ma the diffusion length, L_a, is...of the order of hundreds of meters. The observation that compositional differences persist in the brines over short length scales and very long time, then, suggests strongly that the brine in undisturbed salt is local, isolated domains. (McTigue, 1995b)*

McTigue (1991) later analyzes brine seepage rates into Room Q and again concludes that this experiment confirms the view that undisturbed salt is impermeable.

Borns (1995) notes that measured changes in the electrical resistivity in the DRZ around Room Q indicate an initial desaturation (as the DRZ develops)

followed by a resaturation over a period of approximately three years. This could suggest that Darcy flow may occur in the salt, but it could also be the result of the progressive development of the DRZ, which eventually connects the anhydrite layers hydrologically to the room excavation.

The McTigue and Borns observations can be reconciled by a model in which classical Darcy flow occurs in the anhydrite marker beds (e.g., MB 139), but the salt between these layers is impermeable.

The following calculations indicate the order of magnitude of brine inflow predicted on the basis of assuming

1. an impermeable salt containing anhydrite interbeds that exhibit Darcy flow;
2. salt with a small, but finite, permeability, allowing classical Darcy flow radially into a circular excavation. (In this case, the permeable interbeds are assumed to be an integral part of the homogeneously permeable salt.)

ONE-DIMENSIONAL FLOW IN ANHYDRITE INTERBEDS IN IMPERMEABLE SALT

The instantaneous rate of fluid inflow q, at some time t, per meter of tunnel length* from a horizontal permeable layer (Figure C-1), thickness d and of infinite extent (one-dimensional flow) can be calculated (Churchill, 1972) from the formula shown in (C-1):

$$q = kd\frac{\phi_0}{\sqrt{\pi ct}} \qquad \text{(C-1)}$$

where $k = \kappa\rho g/\mu$ is the brine conductivity, d is the thickness of the layer, ϕ_0 is the initial head, and $c = k/S_s$ is the diffusivity. (Other symbols are defined in Tables C-1 and C-2.) In the case of a constant head at a finite distance L from the tunnel along the layer, the instantaneous rate of inflow can be written (Churchill and Brown, 1987) in dimensionless form:

$$\bar{q} = 2\sum_{m=0}^{\infty}\exp\left(-m^2\pi^2\tau\right) - 1 \qquad \text{(C-2)}$$

where $\bar{q} = Lq/dk\phi_0$ and $\tau = tc/L^2$. The dimensionless rates of inflow, from an infinite layer and from a layer with a fixed head at the finite distance L, as a function of dimensionless time, are shown in Figure C-2.

The total inflow Q per meter of the tunnel—one side of the tunnel only—from an infinite layer can be obtained by integrating (C-1):

$$Q = \int_0^t q(t)\,dt = 2dk\phi_0\sqrt{\frac{t}{\pi c}} \qquad \text{(C-3)}$$

The curves shown in Figure C-3 are calculated by using the parameters for an anhydrite layer in salt, as shown in Table C-1. Total inflows (C-1) from an infinite layer for the base case mentioned above and two cases used by McTigue (1991) (parameters shown in Table C-2) are compared in Figure C-4.

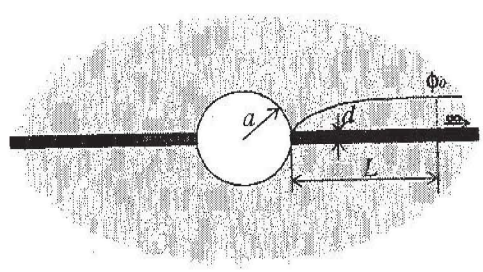

Figure C-1: Model of one-dimensional flow.

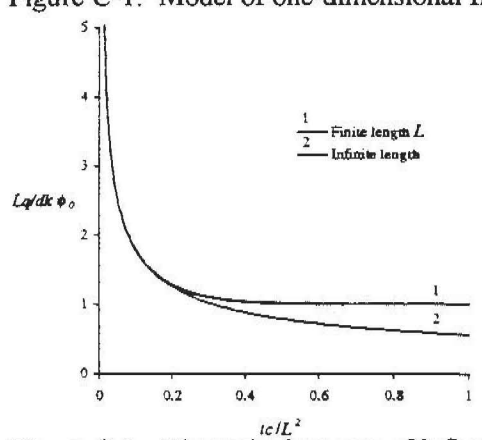

Figure C-2. Dimensionless rate of inflow from one side of a permeable layer.

* Only one side of the tunnel is considered–the total inflow into the tunnel would be double the values shown in equations (C-1), C-2), and (C-3). The remainder of the rock mass is assumed to be impermeable.

permeability	κ	10^{-18}	(m^2)
brine viscosity	μ	$1.8 \cdot 10^{-3}$	(Pa·s)
specific weight	ρ	1230	(kg/m^3)
initial head	ϕ_0	650	(m)
fixed head distance	L	1000	(m)
layer thickness	d	1	(m)
specific storage	S_s	$1.5 \cdot 10^{-7}$	(1/m)
conductivity	k	$6.69 \cdot 10^{-12}$	(m/s)
diffusivity	c	$4.45 \cdot 10^{-5}$	(m^2/s)

Table C-1. Base case values of parameters used to calculate brine inflow into a tunnel from a horizontal anhydrite layer.

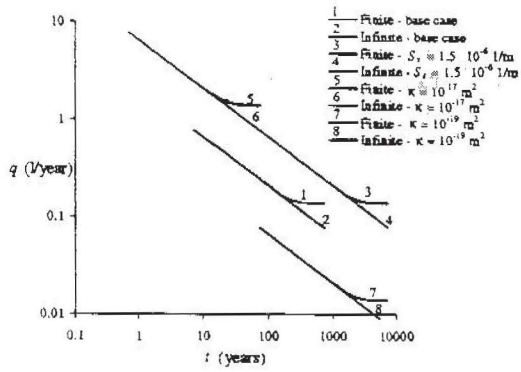

Figure C-3. Rates of inflow from the anhydrite layer (per meter of length along the tunnel). (The rates shown are for one side of the tunnel only, i.e., total inflow rates are double those shown).

	Base case	McTigue case 1	McTigue case 2	
κ	10^{-18}	10^{-21}	10^{-22}	(m^2)
μ	$1.8 \cdot 10^{-3}$	$1.60 \cdot 10^{-3}$	$1.60 \cdot 10^{-3}$	(Pa s)
ρ	1230	1230	1230	(kg/m^3)
ϕ_0	650	815	815	(m)
d	1	1	1	(m)
k	$6.69 \cdot 10^{-12}$	$7.67 \cdot 10^{-15}$	$7.67 \cdot 10^{-16}$	(m/s)
c	$4.45 \cdot 10^{-5}$	$6.20 \cdot 10^{-8}$	10^{-10}	(m^2/s)

Table C-2. Values of parameters used in "base case" and by McTigue to calculate brine inflow from an anhydrite layer into a tunnel.

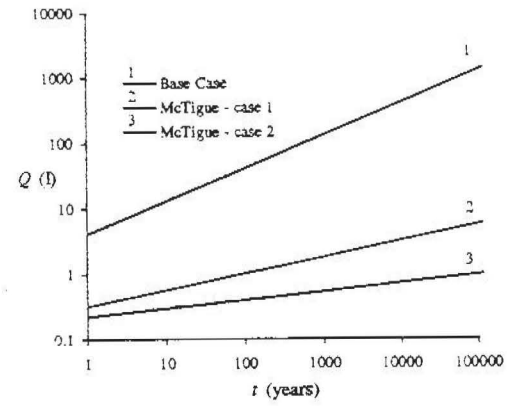

Figure C-4. Total inflow into a tunnel from an anhydrite layer (one side of tunnel only).

RADIAL FLOW INTO EXCAVATIONS IN PERMEABLE SALT

The Laplace transform of the instantaneous rate of inflow $\tilde{q}$ into a circular opening in an infinite, homogeneous, porous medium (Figure C-5) is as follows (Detournay and Cheng, 1988):

$$\tilde{q} = 2\pi a \phi_0 k \frac{K_1(a\sqrt{s/c})}{\sqrt{sc}\, K_0(a\sqrt{s/c})} \qquad \text{(C-4)}$$

where K_0 and K_1 are the modified Bessel functions of the second kind, of order zero and one respectively.

Inversion of (C-4) is performed numerically. The total inflow Q (per meter along the tunnel) for $k = 6.25 \cdot 10^{-14}$ m/s (corresponding to $\kappa = 10^{-20}$ m^2), radius of tunnel $a = 1.524$ m, and an initial hydrostatic pressure $p_0 = 6$ MPa, is shown in Figure C-7.

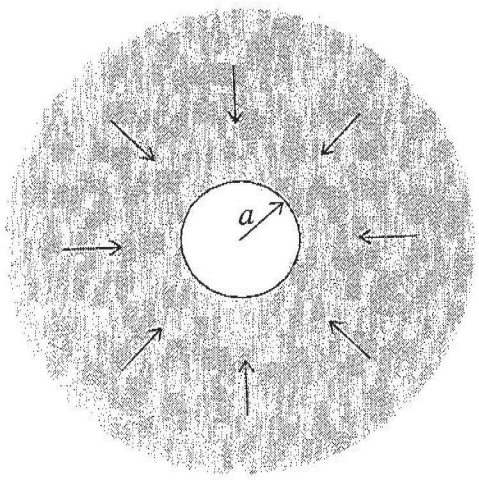

Figure C-5. Model of radial flow into circular tunnel.

BREDEHOEFT CALCULATION (BREDEHOEFT, 1988)

Around 1987, observations of brine inflow into underground excavations at the WIPP led Dr. J.D. Bredehoeft, then a member of the NRC WIPP committee, to suggest that the Salado formation at WIPP could have finite, albeit low, permeability in the classical Darcy sense and that the Salado was possibly saturated with brine. In defining the Salado, he (Bredehoeft, 1988) did not distinguish between the salt and anhydrite interbeds. He calculated, numerically, the daily brine inflow into rectangular excavations for several assumed values of hydraulic conductivity k. [For WIPP brine the intrinsic permeability κ (m^2) = $0.16 \cdot 10^{-6} k$ (m/s). Thus $k = 6.25\ 10^{-14}$ m/s corresponds to $\kappa = 10^{-20}$ m^2, etc.].

Figure C-6 compares Bredehoeft's results (curves 1-4) with those obtained analytically by using (C-4). It is seen that the two sets of results are consistent. The principal difference is due to the higher range of brine conductivities assumed by Bredehoeft. The values used in the current calculations are based on more recent values used by DOE.

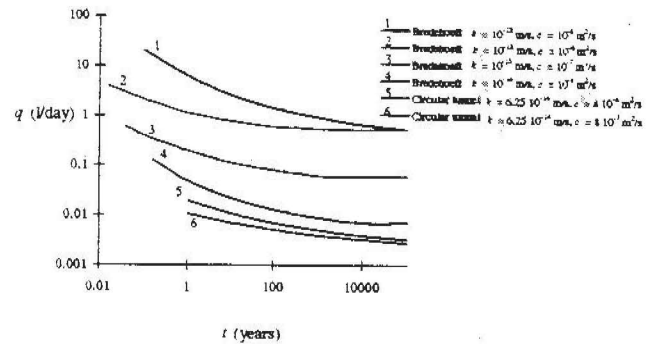

Figure C-6. Rates of inflow into tunnel, as calculated numerically by Bredehoeft (curves 1 to 4) and analytically)(curves 5 and 6).

Using a Darcy flow model to interpret recent in-situ measurements, Beauheim et al., (1993a) conclude that "*the vertically averaged hydraulic conductivities of the tested intervals (primarily anhydrite interbeds) range from about $1 \cdot 10^{-14}$ to $2 \cdot 10^{-12}$ m/s (permeabilities of $2 \cdot 10^{-21}$ to $3 \cdot 10^{-19}$ m^2). Storativities of the tested intervals range from about $1 \cdot 10^{-8}$ to $2 \cdot 10^{-6}$ and values of specific storage range from $9 \cdot 10^{-8}$ to $1 \cdot 10^{-5}$ 1/m. ...*" Anhydrite interbeds appear to be one or more orders of magnitude more permeable than the surrounding halite, primarily because of sub-horizontal bedding-plane fractures present in the anhydrites.

Freeze and Christian-Frear (in preparation) attempting to interpret the brine inflow results for Room Q, indicate that a value of "*far-field permeability of $5 \cdot 10^{-22}$ m^2 with a bulk rock compressibility of $5.4 \cdot 10^{-12}$ 1/Pa*" fits the apparent brine inflow rates from two to five years. Interpretation was complicated by the absence of very early time (0-6 months) brine inflow data—due to malfunctioning of the room seals. Thus, it seems that the hydraulic conductivity of (i) Salado halite (interpreted in terms of Darcy flow model) is of the order of 10^{-13} to 10^{-16} m/s (permeability 10^{-20} to 10^{-23} m^2) and (ii) anhydrite interbeds is 10^{-12} to 10^{-14} m/s (permeability 10^{-19} to 10^{-21} m^2). Since the anhydrite interbeds are relatively thin layers within the halite, an overall value for conductivity (permeability) of the Salado would tend to be at the lower end of the combined anhydrite—halite

range (i.e., say 10^{-14} m/s), resulting in the inflows in the range of curves 4, 5, and 6 in Figure C-6.

Figure C-7 shows the total inflow per meter length of excavation for the lower permeability results (curves 5 and 6) shown in Figure C-6. It is seen that after 100 years, a total of about 200 liters (or 0.3 m^3) of brine has flowed into the excavation. If a 10-m excavation width (or "width" of waste material) is assumed, this amount of brine would occupy a height of 2 cm over the 10-m width. If the compacted waste is assumed to occupy 70% of the original space (i.e., leaving 30% voids), then the height of brine would increase to (2/0.3) cm, or approximately 6 cm of the height of compacted waste. However, since the DRZ would exist for at least a substantial part of the 100 years, then much of this brine would gravitate into the fractured rock in the DRZ underlying the waste. Brine from MB 139, below the excavation, would also flow into the same fractured rock below the floor. It seems probable, therefore, that much of the brine will not come into contact with the waste but instead will flow down-gradient in the DRZ below the waste. This suggests that with appropriate repository design, rooms could be maintained in a "brine humid" condition rather than a "brine-flooded" condition. According to Brush, gas generation caused by corrosion of the steel waste drums in brine humid conditions is negligibly small.

Should there be a more significant rate of gas generation, pressure in the rooms would tend to rise, thereby reducing brine inflow—and the associated gas generation rate. Although it is possible, under some conditions, for gas to flow out of the room [e.g., along the (finite permeability) marker beds] at the same time as brine flows in, a recent DOE study by Webb and Larson (1996) indicates that such "counter-current" flow is unlikely for the 1° dip of the marker beds at the WIPP until the gas pressure in the excavation is close to lithostatic pressure. Any gas at lower pressure will directly reduce the hydraulic pressure differential and, hence, reduce the brine inflow into the excavation as well. This, in turn, will limit corrosion and the associated gas generation. If the gas pressure reaches (and "attempts" to exceed) lithostatic, the permeability of the anhydrite interbeds would increase substantially since fracturing of the interbeds would occur and counter-current flow (gas out, brine in) in the 1° updip section of the anhydrite interbed would result in increased brine inflow into the excavation. From curves presented by Webb and Larson (1996) in inflow appears to be or the order of twice the inflow rate observed for the unpressurized (i.e., open) excavation. With the low brine inflows calculated earlier and the associated low gas generation rates, it seems unlikely that gas pressure could approach lithostatic before the waste-filled excavations had closed to their residual (compacted) volumes.

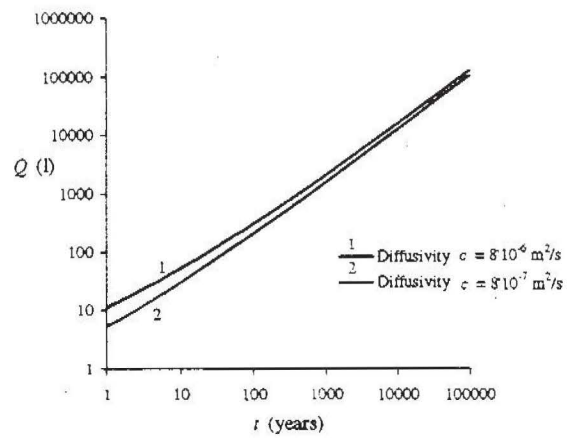

Figure C-7. Total inflow into a tunnel, if radial flow is assumed.

SHAFT SEALS – APPROXIMATE CHECK ON PA FLOW CALCULATIONS

If Darcy flow is assumed,

$$q = -kA\frac{d\phi}{dl} \qquad \text{(C-5)}$$

where q is the volumetric flow rate (m^3/s), k is the hydraulic conductivity of the (porous) seal (m/s), dl is the length (m) across which $d\phi$ (m) is measured, and A is the cross-sectional area (m^2) normal to the flow direction.

The hydraulic conductivity may be determined from the properties of the porous (seal) material and the saturating fluid. Thus,

$$k = \frac{\kappa \rho g}{\mu} \tag{C.6}$$

where κ is the intrinsic permeability of the porous (seal) material (m^2); ρ is the fluid density (kg/m^3); g is the gravitational acceleration (m/s^2); and μ is the fluid viscosity[Pa·s].†

The term "hydraulic conductance" C (m^2/s) is sometimes used, where

$$C = \frac{kA}{L} \tag{C.7}$$

and L is the length of the porous material (i.e., the shaft seal in this case).

$$q = -C \cdot \phi \tag{C.8}$$

where ϕ is the fluid pressure (head) differential (m) over the length L, and

$$v_z = \frac{q}{A} = \frac{C}{A}\phi \tag{C.9}$$

where v_Z is the Darcy velocity‡ or specific discharge (m/s) of the fluid in the porous medium (seal) with a head differential of ϕ (m).

Using PA assumed values (i.e., a shaft seal length L = 100 m; total area of the four shaft seals A = 100 m^2; seal permeability κ of $1 \cdot 10^{-16}$ m^2; brine viscosity of 0.0018 Pa·s; fluid density of 1230 kg/m^3; and gravitational acceleration of 9.792 m/s^2), yields (U.S. Department of Energy, 1995d, p. 5):

$$\begin{aligned} C &= \frac{\kappa A}{L}\frac{\rho g}{\mu} = \frac{10^{-16} \cdot 100}{100}\frac{1.23 \cdot 10^3 \cdot 9.792}{18 \cdot 10^{-4}} \\ &= 6.7 \cdot 10^{-10}\ \mathrm{m^2/s} \text{ or } 211.3\ \mathrm{m^2/10^4\ years} \\ v_z &= 2.1 \cdot \phi\ \mathrm{m/10^4\ years} \\ q &= 211.3 \cdot \phi\ \mathrm{m^3/10^4\ years} \\ & \left[10^4\ \mathrm{years} \simeq 3.15 \cdot 10^{11}\ \mathrm{s}\right] \end{aligned}$$

At the time the seal is first installed, the repository will be essentially dry and fluid flow through the seal initially will be downward—primarily from the Rustler formation overlying the Salado. Flow upward through the seal will begin only when the fluid pressure exerted at the bottom of the shaft seal exceeds the hydrostatic pressure due to the height of water in the shafts.

The predicted change in pressure with time at the shaft bottom will depend on a complex interaction of several repository variables, such as the total amount of void space in the waste-filled rooms and all of the (back-filled or open) excavated space; rate of reduction in void space due to salt creep; rate of inflow of brine into the void space; rate of gas generation and room pressurization; loss in fluid pressure due to fluid flow from the waste-filled rooms to the bottom of the seal, etc. Depending on the particular combination of assumed values of these variables used in a calculation, the brine pressure at the shaft bottom may remain very small for a long time after sealing or may increase after a period of the order of several hundreds of years, when gas generated by brine corrosion of the steel waste containers develops an increasing pressure in the repository.

The relationship between seal permeability and flow through the seal over a given time [Eq. (C.8)] is linear, so the net cumulative flow, over a period of time through a seal of a given permeability can be determined simply from the average driving fluid pressure [i.e., the pressure ϕ above hydrostatic at the bottom of the seal over the same time (This is 650 m for the water-filled shaft.)]. If the pressure ϕ is initially below hydrostatic (i.e., negative), then flow during this period will be negative, that is, downward through the seal.

† Pa·s = $(N/m^2)\cdot s = (kg_{mass}\cdot m/s^2)\cdot s/m^2 = kg_{mass}/m\cdot s$.

‡ See discussion of Darcy velocity.

It is seen from (C-8) that the net cumulative flow over 10,000 years through a shaft seal of assumed permeability 10^{-16} m^2 will be 10,000 m^3, if the average (over 10,000 years) pressure head ϕ at the shaft bottom is $\phi = 10{,}000/211 = 40$ m (above hydrostatic). For a seal of permeability of 10^{-17} m^2, the average pressure head required to produce a cumulative upward flow of 10,000 m^3 over 10,000 years will be $\phi = 470$ m above hydrostatic—(650 m) or a total average brine pressure head of 110 m. Similarly, for a seal permeability of 10^{-18} m^2, a total average pressure head of 1120 m would produce a net cumulative brine outflow of 1,000 m^3 in 10,000 years.

Figure 4.1 in Chapter 4 of this report shows the results of a number of calculations—each for a randomly chosen combination of repository parameter values (closure rate, brine inflow rate, etc.)—of the cumulative brine flow through the seals over 10,000 years, as a function of seal permeability. It is seen that, especially at the higher permeabilities, flow *into* the repository (i.e., the negative values) tends to be more likely. For a permeability of 10^{-16} m^2 or lower, the net flow is essentially zero.

Creep of the salt around the shaft will result in further consolidation of the 100-m-high seal of crushed, compacted salt, so that the permeability of the seal will tend eventually towards the permeability of intact salt. As noted above, intact pure salt likely to be impermeable. Where intact salt is assumed to have a finite permeability, this is usually taken as about 10^{-21} ~ 10^{-23} m^2. Calculations indicate (Callahan et al., 1996) that a seal of crushed salt at a depth between 550 m ~ 650 m, initially compacted to a permeability about 10^{-16} m^2 is likely to achieve a permeability of 10^{-20} m^2 or so within 100 years after placement.

Thus, it appears that seals consisting of 100-m-high layers of compacted crushed salt should provide an effective barrier to release of radionuclide contaminated brine to the accessible environment over 10,000 years or longer.

The height to which the brine would rise above the seals depends on the average porosity of the material in the shaft (see discussion of Darcy flow below). Thus, if the shaft above the seal was left completely open and the (total) cross-sectional area (of the shafts) was assumed to remain constant at 100 m^2, a cumulative brine flow of 10,000 m^3 would create a brine column 100 m high above the seal. If the average porosity of the material in the shaft was 1%, the brine would rise, hypothetically, 100 times higher. In the case of WIPP, the brine would rise to the top of the Salado and then would be able to flow laterally into the Culebra.) In both cases, the *total* volume of brine outflow would be essentially unchanged. For a given concentration of raduonuclides in this same volume of brine, the radionuclide release will also be the same, independent of the porosity of the material through which it flows.

Darcy Velocity

The Darcy velocity (or specific discharge) is the volumetric rate of flow per unit area through which flow occurs. Hence, it has the same dimensions as velocity, but it is not the speed at which the fluid moves. To derive the average fluid velocity in the pore space from the Darcy velocity, it is necessary to divide the latter by the effective porosity of the rock through which flow occurs (i.e., if the effective porosity of the rock is 10% of the total volume of the rock, the average fluid velocity in the pores is ten times the Darcy velocity). The volume of fluid flowing across the cross-section over a given time, which is the relevant quantity for determination of radionuclide flow through the seals (i.e., this is strictly not a "release", since there are additional barriers, such as upper levels of the shaft and the Culebra, between the seals and the accessible environment)—given a known radionuclide concentration in the fluid—is the same for both calculations, that is, with or without porosity.

Conclusion

These approximate calculations confirm the general impression that effective sealing of the repository is achievable using the designs proposed by DOE.

Appendix D

Creep Behavior of WIPP Salt

One of the main attributes of salt as a rock formation in which to isolate radioactive waste is the ability of the salt to creep, that is, to deform continuously over time. Excavations into which the waste-filled drums are placed will close the salt eventually, flowing around the drums and sealing them within the formation. A good understanding of the rate of closure and associated phenomena, such as the development and healing of fractures around the excavations, is essential for the design of an effective repository in salt.

The program of investigations into the mechanics of deformation of salt at the Waste Isolation Pilot Plant (WIPP) has been more extensive and comprehensive than any previous studies world-wide. Carried out over the past decade and a half, it has included theoretical studies coupled with small-scale laboratory tests and full-scale field investigations underground at WIPP.

Initial predictions of the rate of closure of underground excavations—based on deformation parameters derived from laboratory tests—were found to be some three to six times lower than the closure rates observed underground. Continued research to improve fundamental understanding has resulted in a very substantial reduction in this discrepancy. Thus, for the majority of the in situ cases studied, agreement between the closure rates predicted from small-scale laboratory test data and those actually observed is now within approximately 10 percent. Larger discrepancies can be attributed, in some cases, to exclusion of the following from the three-dimensional numerical codes used for the predictions:

- discrete slip surfaces (e.g., between the salt and anhydrite interbeds) in the vicinity of the excavations, and
- separation of interbeds and salt layers in the roof of the excavations.

These limitations are not serious for the assessment of closure performance of the excavations at WIPP since, in both cases, actual closure will somewhat exceed the predicted value. Thus, predictions will be conservative.

Although salt deformation appears to involve a complex interaction of a multiplicity of microscopic mechanisms, these combine to produce a relatively simple, essentially constant rate of room closure (Figures D.1 and D.2).

As shown in Figure D.3, the strain-time behavior of salt can be considered to consist of several regions, namely, ε_E, an elastic strain, which appears immediately upon loading (the amount of elastic strain increases with increase in the applied stress); this is followed by

1. a region of primary or transient creep strain;
2. a region of secondary or "steady-state creep" (where the strain rate $\dot{\varepsilon}_p$ is essentially constant); and
3. a region of tertiary or "accelerating creep" strain.

Accelerating strain indicates a progressive disintegration of the salt structure, leading eventually to collapse.

It is well known that the strain rates involved in salt creep increase in a highly nonlinear manner with increases in temperature and applied stress.

An extensive series of laboratory investigations has led to the definition of a new constitutive model (i.e., relationship between steady-state creep rate and applied load) for WIPP salt. This model is known as the modified Munson-Dawson or multimechanism deformation (M-D) constitutive model.

In the M-D model, the total steady-state creep rate ($\dot{\varepsilon}_s$) is considered to be the sum of three component rates, each dependent on a different fundamental mechanism to creep in the salt: Thus

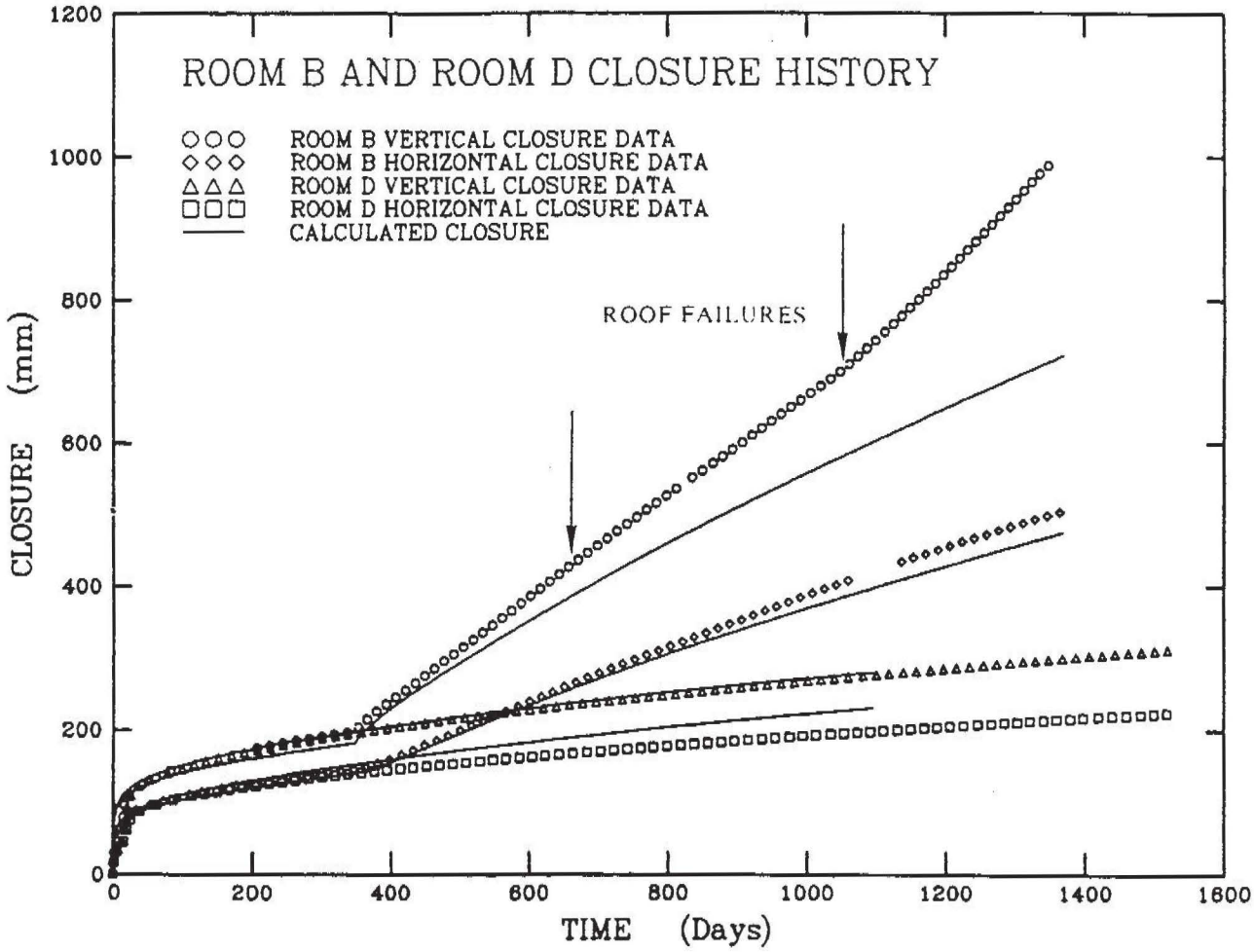

FIGURE D.1 Comparison between predicted and actual room closure rates for Rooms B and D. Note the increase in measured closure compared to calculated closure as roof failures develop. Source: Munson (1996).

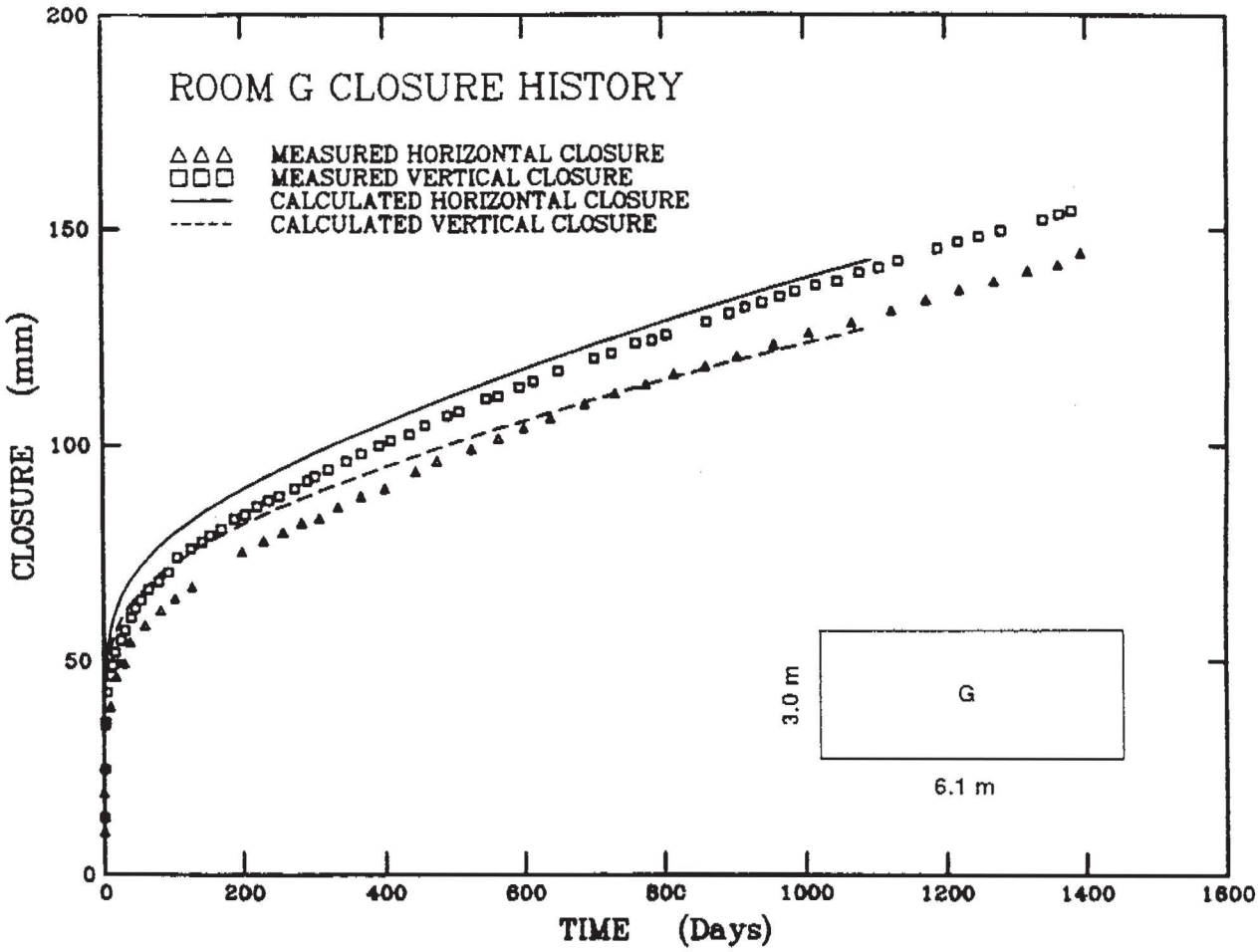

FIGURE D.2 Comparison between predicted and actual room closure rates for Room G. Source: Munson (1996).

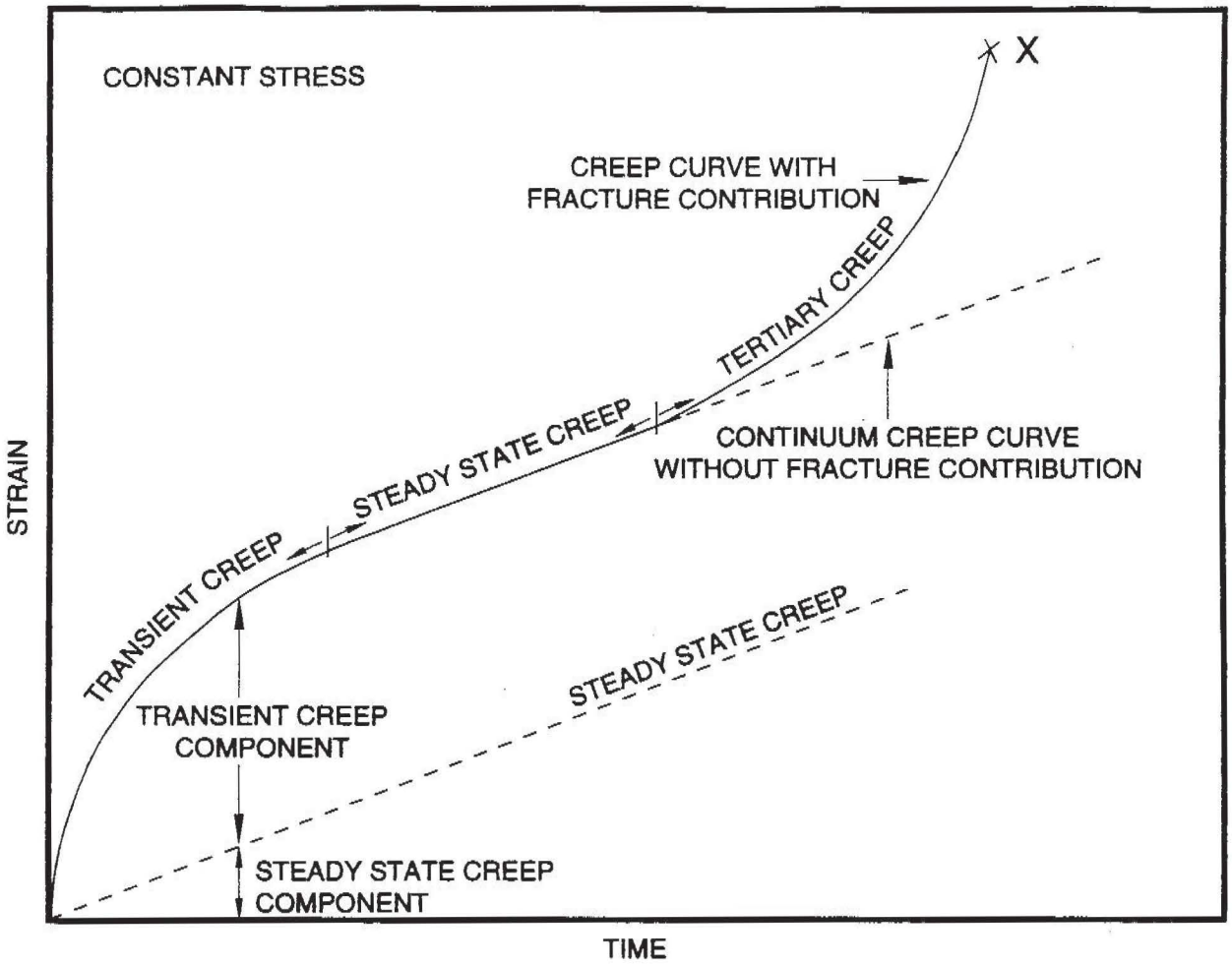

FIGURE D.3 Classical creep-deformation behavior of salt. Source: Munson et al. (1995).

$$\dot{\varepsilon}_s = \sum_{i=1}^{3} \dot{\varepsilon}_{s_i} \tag{1}$$

where the individual steady-state rates of the three relevant mechanisms are given by

$$\dot{\varepsilon}_{s_1} = A_1 e^{-Q_1/RT} \left(\frac{\sigma}{\mu}\right)^{n_1} \tag{2a}$$

$$\dot{\varepsilon}_{s_2} = A_2 e^{-Q_2/RT} \left(\frac{\sigma}{\mu}\right)^{n_2} \tag{2b}$$

$$\dot{\varepsilon}_{s_3} = H(\sigma - \sigma_0)\left[B_1 e^{-Q_1/RT} + B_2 e^{-Q_2/RT}\right] \sinh\left[\frac{q(\sigma - \sigma_0)}{\mu}\right] \tag{2c}$$

where A and B are constants; Q is the activation energy; T is the absolute temperature; R is the universal gas constant; μ is the shear modulus; σ is the generalized stress; n is the stress exponent; g is the stress constant; σ_0 is the lower stress limit of the dislocation slip mechanism; and H is the Heaviside step function with argument $\sigma - \sigma_0$ [i.e., $H(\sigma - \sigma_0) = 0$ for $\sigma < \sigma_0$; 1 for $\sigma > \sigma_0$].

A complete list of the values of the various constants in Equations (2a - c) for WIPP salt is presented in Munson (1996). For the current discussion, it is sufficient to note the following:

1. WIPP underground excavations will not be subject to any significant temperature changes (except for remote—handled transuranic waste locations, where some moderate temperature increases may occur). Thus, temperature dependence on creep closure need not be considered to a first approximation.

2. The value of σ_0 has been determined to be 20.57 MPa (megaPascals). For most of the underground locations at WIPP, since the initial stress state is isotropic (lithostatic pressure in every direction) at approximately 15 MPa, then $H(\sigma - \sigma_0) = 0$, implying that $\dot{\varepsilon}_s = 0$ for these locations.

3. Using the values $n_1 = 5.5$ and $n_2 = 5.0$ for the exponents in Equations (2a) and (2b), the steady-state strain rate $\dot{\varepsilon}_s$ reduces to the expression

$$\dot{\varepsilon}_s = k_1(\sigma)^{5.5} + k_2(\sigma)^{5.0} \tag{3}$$

where the generalized stress $\sigma = (\sigma_1 - \sigma_3)$; σ_1 and σ_3 are the maximum and minimum principal stresses, respectively; and k_1 and k_2 are constants representing combinations of terms in Equations (2a) and (2b), respectively.

For simplicity, it is assumed that both components of Equation (3) have the same exponent (i.e., assuming $n_2 \approx n_1 = 5.5$), so Equation (3) can be written as

$$\dot{\varepsilon}_s = k(\sigma_1 - \sigma_3)^{5.5} \tag{4}$$

where $k = k_1 + k_2$. It is seen that the stress dependence of the creep rate is very strong. For example, if an open borehole in salt closes at the steady-state rate $(\dot{\varepsilon}_p)_{open}$ at some depth h (meters) (i.e., where the lithostatic [driving] stress is $0.023h$ MPa), then a brine-filled borehole (with a hydrostatic pressure

in the hole of $0.01h$ MPa) will close at a rate $(\dot{\varepsilon}_p)_{\text{fluid-filled}}$, where

$$\frac{\dot{\varepsilon}_{\text{fluid-filled}}}{\dot{\varepsilon}_{\text{open}}} = \left(\frac{0.023\text{h} - 0.01\text{h}}{0.023\text{h}}\right)^{5.5} \approx \frac{1}{37}$$

Thus, if an open unlined borehole closes in approximately 100-200 years, an unlined, fluid-filled borehole at the same depth would not close for 3,700-7,400 years. This is a significant change when estimating the consequences of human intrusion events.

Research at WIPP has also confirmed the following:

1. The stress at which inelastic flow of salt occurs is governed by a Tresca or maximum shear stress yield criterion, rather than the more frequently used Von Mises, or maximum octahedral shear stress yield criterion. Given the highly non-linear dependence of the strain and strain rate on stress level, the difference between the two criteria can be very significant. A part of the initial discrepancy between prediction and observation was corrected by making the change to a Tresca criterion.

2. The value of the shear stress at which inelastic strain develops tends toward very low levels at low strain rates. At the very low strain rates associated with geological loading, the yield stress of salt is essentially zero. In other words, at these extremely low loading rates, salt behaves as a (viscous) fluid, unable to maintain a shear stress. This is seen in equation (4) above, which indicates that the salt will have a nonzero strain rate ($\dot{\varepsilon}_s$) as long as $\sigma_1 \neq \sigma_3$. Thus, over long times (especially geological time—here 200 million years) creep will continue until $\sigma_1 = \sigma_3$, (i.e. the in-situ stress state is isotropic).

Hydraulic fracturing measurements of in situ stress conditions of WIPP confirm that the stress state in the salt is isotropic. The isotropic condition and the creep flow characteristic of salt imply that salt in situ should be essentially impermeable, since the connected pathways needed to allow flow of fluid would lead to localized stress concentrations in the vicinity of the connected cracks, etc., that represent the permeability. Such concentrations (stress differences) would produce flow of the salt, leading to closing of the pathway and elimination of the permeability.

3. At the higher strain rates associated with stress redistribution around excavations, salt can behave in a much more brittle manner. Fractures can and do develop progressively in the walls, roof, and floor of the excavation as the result of stress concentrations around the excavations. These fractures produce what is known as the disturbed rock zone (DRZ) around the excavations. The DRZ is important on several counts:

- It could provide a region of connected fractures that allow a high-permeability path around the excavations and brine access to the waste-filled drums. Such fractures (and DRZs) appear around excavations in other rock types, but salt has the attractive feature that fractures in the DRZ in salt can "heal" (i.e., disappear) with the buildup of a "back-stress" (i.e., resistance to closure generated by waste and/or backfill or a shaft lining or seal). This healing can be inhibited by the presence of water in the fractures as back-stress builds up. In the shaft seal designs discussed in Chapter 4, the DOE must take special measures to ensure that the fractures remain "drained" during the period of back-stress buildup. It is worth noting, however, that the fluid pressure required to resist crack closure can develop only if the fluid is sealed in the crack, that is, if it is not part of a permeable connected system of fluid flow.
- Since the DRZ develops in the floor of the excavations as well as the roof and sides, this zone serves as a depository and conduit for any brine flowing into the waste-filled rooms. Because closure of the waste-filled rooms involves floor "heave" as well as roof "sag," the waste drums will tend to be lifted above the brine, especially during the early years after loading of the rooms with waste. This phenomenon has important implications for the question of gas generation due to corrosion of steel waste drums at WIPP.

The practical implications of these deformation properties of salt are discussed in Chapters 3 and 4.

Appendix E

Actinide Source Term

As background for preparing its review of the actinide source term (AST), the AST subcommittee (Clark, Ewing, and Krauskopf) was supplied with abundant literature, including both in-house documents and articles from refereed journals that were considered by the Department of Energy (DOE) to be relevant to the Waste Isolation Pilot Plant (WIPP) program—many of which are listed at the end of Chapter 5. In addition, the subcommittee visited Los Alamos National Laboratory (LANL) in 1994 to view the proposed experiments with real and actinide-spiked waste (these are described as the Source Term Test Program [STTP]). In 1995 and early 1996, DOE scientists and contractors met with the AST subcommittee several times (March 6, April 27-28, and June 29, 1995; and February 14, 1996) to present the rationale for the AST program and some data from experiments completed in the past, and to describe experimental work in progress or still being planned (Novak, 1995a, b).

As late as April 1996, the subcommittee was still receiving revised versions of the proposed test plans, but no results of recent experiments or of the STTP program at LANL were available for review. The subcommittee was given a conceptual outline of the use of actinide source term data in the performance assessment (PA; Ruth Weiner, Sandia National Laboratories, personal communication to S. Clark, January 18, 1996); however, in the absence of experimental data explicitly used in the performance assessment, it was not possible to review this part of the program. Substantive review of AST results must await completion of at least a major part of the proposed work. *To the extent that the actinide source term is an important parameter in the performance assessment and the determination of compliance, it will be necessary to review carefully the final data package, the selection and use of conceptual models, and the final incorporation of data and models into the performance assessment.*

The remainder of this appendix discusses specific issues related to some of the tests planned as part of the DOE experimental program for the AST. The test plans may have changed after they were presented to the subcommittee and even before the experimental program was initiated; thus, these comments are applicable only to those portions of the test plans that have not changed.

The principal laboratories, principal investigators, and status of various components of the AST program are listed in Table E.1. This provides an indication of the materials that were reviewed by the AST subcommittee.

EXPERIMENTAL WORK ON ACTINIDE SOLUBILITIES

Pitzer Parameters

The application of Pitzer parameters (Pitzer, 1973, 1977) specifically to concentrated saline solutions has been described by Harvie et al. (1984) and by Felmy and Weare (1986). The methods of calculating solubilities suggested by these authors have been applied to the WIPP brines by DOE researchers. Particular advantages of using the Pitzer approach, rather than other means of correcting tabulated thermodynamic data to conditions of concentrated electrolytes, include the following:

1. The model is designed specifically for the geochemical conditions anticipated at WIPP and is well described in the peer-reviewed literature.
2. Data are available for many of the constituents in brine, making additional experiments unnecessary.
3. The model provides for complex interactions among more than just two species, reflecting the situation anticipated in highly saline media.

TABLE E.1 Actinide Solubility Work

Program Experimental Component	Principal Investigator (SNL/Subcontractor)	Subcontractor Laboratory	Date Initiated	Experimental Termination Date
Dissolved Concentration Model - Oxidation State Analogy				
An(III) Model Inorganic Interactions	Novak/Felmy, Rai, Rao	PNL	Jul-93	Apr-96
An(IV) Model - Inorganic Interactions	Novak/Felmy, Rai, Rao	PNL	Jul-93	Apr-96
An(V) Model-Part I Inorganic Interactions	Novak/Al Rafai	LBL	Feb-95	Mar-96
An(V) Model-Part II Inorganic Interactions	Novak/Runde	GTS/ITS	Feb-95	Jul-96
An(VI) Model- Inorganic Interactions	Novak/Palmer	LLNL	Jan-95	Mar-96
Organic Interactions An(III, IV, V, VI)	Novak/Moore	FSU	Feb-95	Apr-96
Alternative An(VI) Model-SIT Formalism	Novak/Jenecky	LANL	May-95	Mar-96
SNL Data Interpretation	Novak, Moore, Weiner	SNL	Feb-95	Feb-96
Dissolved Concentration Model - Challenges to the Oxidation State Model				
Tests of Conceptual Model Against Exper. with Actual TRU	Crafts/Villareal	LANL	Liter Scale: Mar-95 Drum Scale:	3-5 yrs. from initiation or steady state
Waste - STTP			Jun-95	
Empirical Solubility for An(IV, V, VI) in WIPP Brines	Moore/Reed	LANL	Jun-95	Sep-96
Further Oxidation State Studies	Weiner/Clark Felmy, Rai	LANL,PNL	Jun-95	?
Oxidation State Studies in STTP Experiments	Weiner/Clark	LANL	June-95	?
Mineral Fragments		SNL	Oct-93	Jan-96
Actinide Intrinsic Colloids		LLNL,LANL	Jul-95	May-96
Humic Substances		SNL, LANL, Gatson	Jul-95	Jul-96
Microbes		BNL, LANL	Jul-95	Feb-96

Source: Papenguth and Behl (1996 a,b); Novak (1995b); Novak et al. (1995).

An additional general cautionary note is in order regarding the estimation of solubilities in concentrated solutions with the use of the Pitzer parameters. The thermodynamic formalism involved in such estimates is based on the assumption that equilibrium exists between material in solution and solids in contact with the solution—in other words, that all reactions leading to formation or dissolution of solids go rapidly to completion. There is no assurance that these assumptions are correct for the experiments or for in situ WIPP conditions. In fact, some of the experimental work has shown that concentrations in a solution, after a solid has precipitated, may change slowly over the course of months or a few years as the solid alters its form, for example, from an amorphous precipitate to a crystalline phase (Nitsche et al., 1994).

Because changes in the solid are generally in the direction of greater and greater stability (Ostwald's step rule), and thus lower and lower solubility, such changes commonly are thought to ensure concentrations of actinides lower than those first measured, and hence not to be important in estimating cautiously conservative values for actinide solubilities. As a general rule this is true; however, for solutions as concentrated, and with compositions as complex as WIPP brines, exceptions can readily be imagined.

Resolving issues such as this will require extending some of the solubility experiments well beyond their scheduled termination dates. These experiments can be conducted at the bench scale under carefully controlled conditions, so that the fundamental aspects of actinide solubility in brine can be determined. Such experiments may be needed for interpretation of the more complex experiments performed as part of the STTP at LANL. These longer-term experiments should not delay compliance of the repository if all else is favorable, but they represent one example of the kinds of research efforts that are recommended to continue after wastes are first brought to the repository.

Concerns

The following are specific concerns about details of the planned experimental work on actinide solubility:

- Most aspects of the experimental program and assumptions in the performance assessment are based on thermodynamic models; however, reaction kinetics may be important in determining the actinide concentrations measured in experiments or modeled in the performance assessment.
- One question is the suitability of the specific-ion interaction theory (SIT), activity coefficient formalism, which has been used in the test plan for the Alternative +6 Actinide Model (Grenthe and Wanner, 1992). This approach for estimating concentrations of actinides in the +VI oxidation state is not scientifically defensible, because SIT theory is designed specifically to extrapolate to zero ionic strength; it is not applicable at ionic strengths higher than 3.5 molal; and it is typically used for applications involving a single dominant electrolyte, rather than the complex brines anticipated at WIPP.
- Another question regards the use of experiments planned in the STTP as direct challenges to the submodel of solubilities. The STTP involves measuring actinide concentrations in solutions formed by allowing waste containers to stand for long periods in contact with brines having compositions similar to those at WIPP; in other words, determining concentrations under laboratory conditions set up to duplicate, as nearly as possible, the conditions expected in the WIPP repository. Such experiments will certainly provide useful qualitative data on actinide concentrations, and this program is applauded. However, the assumption that experimental conditions can be made similar in all respects to repository conditions over time seems tenuous at best. Experiments that challenge the thermodynamic model will require not only careful solution analyses as a function of extended periods of time (more than a year), but the identification of the actinide-bearing solids that are in equilibrium with the solution. This will be difficult, because many of the solids are poorly characterized and may have fairly complex compositions.
- Although the oxidation state model (the assumption that the chemistry of a given oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviations from the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy.

EXPERIMENTS ON COLLOIDS

Although actinide concentrations in WIPP brines are expected to be low, the possibility of transport via colloids must be considered one means by which actinides may reach the accessible environment (Kim, 1994). There are two issues: (1) whether colloids will form in a concentrated brine, and (2) whether these colloids can transport significant quantities of actinides effectively.

In designing their research effort, Papenguth and Behl (1996a, b) distinguish four kinds of colloidal particles:

1. mineral fragments, hard-sphere or hydrophobic particles that may contain actinides or have sorbed actinides on their surfaces;
2. actinide intrinsic colloids, particles consisting of actinide macromolecules that may mature on standing into mineral–fragment type colloids;
3. humic substances, hydrophilic or soft-sphere particles that readily sorb actinide ions from solution; and
4. bacteria, which may themselves be colloidal-sized particles and may contain actinides as part of their structure or sorbed on their surfaces.

All types of colloidal particles are relatively unstable in strong electrolyte solutions, and some of the experiments are designed to show what concentration of electrolyte ("critical coagulation concentration," or c.c.c.) is required to produce destabilization and precipitation.

The procedure is simple: small amounts of a simulated Salado-Castile brine are added to samples of colloid until coagulation is noted. Mineral fragments and mature actinide intrinsic colloids are expected to be the most sensitive to electrolytes (i.e., to have the lowest c.c.c.), whereas humic substances and bacteria will not precipitate as readily. For these latter two types, DOE plans more elaborate experiments to explore the effects of pH and the addition of specific ions and organic solutes.

The simple laboratory experiments on colloids will be supplemented with transport experiments designed to show the extent to which various kinds of colloids may be retarded, by precipitation or sorption, if the solution containing them travels through the dolomite of the Culebra Dolomite. Solutions carrying the colloids will be made up to simulate brine concentrations expected in the Culebra, and samples of the solutions will flow through both crushed dolomite and intact-core columnar dolomite. Transport experiments with bacteria as colloidal particles will be especially important, because microorganisms may serve either to increase radionuclide transport by sorbing abundant actinide ions or to decrease transport because the organisms carrying sorbed actinides are themselves strongly sorbed on rock surfaces (Marshal, 1976).

Again, to the extent that colloid formation and transport remain important issues in the performance assessment, the proposed experimental programs may well extend beyond their planned end dates. Long-term experiments on colloid stability and transport may be required even into the operational phase of the repository.

RETARDATION EXPERIMENTS

During transport, actinide concentrations in brine may be lowered by sorption onto rock and mineral surfaces. Such phenomena can be studied by batch experiments to determine K_d values, column experiments with actual rock units from the relevant geologic horizons, or field-scale tracer tests. The limitations of laboratory-scale tests are discussed briefly in Appendix F as part of the discussion of regional hydrology. The inherent weakness of the concept of a retardation factor determined in laboratory experiments, combined with highly uncertain and variable values for the retardation, requires careful analysis of the laboratory data and some field-scale verification. The proposed suite of DOE experiments has been planned carefully and should give a good indication of the effectiveness of sorption in controlling actinide concentrations; however, no results of the experiments completed to date were available.

Concerning the column experiments, the sorbing materials to be used are cylinders of Culebra Dolomite, 10-50 cm long, cut out of the bed with a drill bit and mounted vertically in metal containers. Various

samples of dolomite will be chosen to ensure adequate representation of different permeabilities, different grain sizes, and different proportions of clay mineral impurities. It is emphasized that the column experiments (plus, hopefully, the field experiments) should be carried on long enough and with sufficient variation in conditions to ensure an adequate replica of the natural situation. In particular, the amount of sorption provided by the corrensite coating on parts of the Culebra dolomite requires careful study, a point on which the State of New Mexico Environmental Evaluation Group (EEG) has expressed considerable skepticism regarding the DOE approach.

Appendix F

Regional Hydrogeology

APPROACHES TO STUDYING REGIONAL AQUIFER SYSTEMS

In the broadest sense, a primary objective of studying a deep regional aquifer system is to improve understanding of the relevant processes and properties. Even after a given study has defined the properties of such a system, there will always remain much uncertainty. A unique definition of the system and its properties is simply not attainable, regardless of the amount of data collected. Data collection is very expensive in deep regional aquifer systems, and the costs of data collection and analysis must be weighed carefully against the benefits of additional data. There is no clear-cut point at which it can be determined objectively or scientifically that additional investments in data collection are either necessary or superfluous. Rather, a subjective assessment must be made on the basis of some type of consensus and in light of the significance of the problem, technical considerations, and economic constraints.

Although it is obvious that the properties of a regional aquifer must be defined with some accuracy in order to permit reliable predictions of ground–water flow and transport, it may be less clear that it is also necessary to define accurately the boundary conditions, recharge, and discharge in order to fully define and calibrate a model of the aquifer system. Studies of regional aquifer systems are most comprehensive when the study area extends to the natural geologic or hydrologic boundaries of the system and includes as much of the natural recharge and discharge areas of the system as possible. In reviewing the relevance of hydraulic analyses to contaminant transport problems, Reilly et al. (1987, p. 9) state that "although the details of the flow system in the immediate vicinity of the contaminant plume are of the utmost importance, an understanding of the regional ground-water flow system is required in order to understand the local system."

Because of the uncertainty and variability (heterogeneity) inherent in deep hydrogeologic systems, data collection in general, and drilling of new test wells in particular, often encounter unanticipated difficulties and frequently lead to some "surprises" in the definition or understanding of the properties of the system. Although experienced hydrogeologists expect this, such surprises unfortunately often lead to delays and tend to confound efforts to keep data collection and analysis to a strict, planned time line or budget.

GROUND-WATER MODELS

Ground-water simulation models help analysts improve their understanding of the subsurface system at the Waste Isolation Pilot Plant (WIPP) site faster than otherwise would be possible by integrating site-specific data with a theoretical understanding of the principles of flow and transport. The models offer a quantitative and objective means of testing hypotheses, evaluating the sensitivity of parameters, and guiding the data collection and experimentation process. Furthermore, if the models are based on reasonable and appropriate concepts, if they are adequately tested and calibrated, and if analysts have high confidence in their reliability, then the models can be used to predict how a particular system will respond to a particular stress or change in boundary conditions. However, even a well-calibrated model is still an approximation of the real system and incorporates many simplifying assumptions.

Sources of Error

In most model applications, conceptualization problems and uncertainty concerning the data are the most common sources of error. All three aspects of error are discussed below with reference to the performance assessment (PA) models for WIPP.

Conceptual Errors

Conceptual errors are derived from theoretical misconceptions about the basic processes, dimensionality, and/or boundary conditions that are incorporated in the model. Conceptual errors include neglecting relevant processes and representing inappropriate ones. Examples of such errors are applying a model based on Darcy's Law to materials or flow regimes for which Darcy's law is inappropriate, or using a two-dimensional model where significant flow or transport occurs in the third dimension.

That the PA models have a number of simplifying assumptions built into them is not, in itself, a problem, but rather reflects the very nature of models. Questions about ground-water models more typically center on whether the assumptions are too simple or too complex and whether they are appropriate for the system and problem at hand. However, there will never be a sure or precise way of measuring this. The reasonableness of the assumptions is perhaps best evaluated by a consensus of experts. If the conceptual models on which the PA models are based are, in fact, judged to be either too simple or inaccurate, then all of the complementary cumulative distribution functions (CCDFs) and risk assessments derived from the PA must be questioned.

The PA models start with the assumption that the primary release of contaminants under the human intrusion (HI) scenario is from leakage into the Culebra Dolomite. This assumption is part of the conceptual model. The risks and consequences of leakage into other formations have not been assessed or documented thoroughly. Release into the Culebra also is constrained by assumptions about the permeability of the material filling the borehole through which leakage occurs. However, in previous PA analyses, the assumed borehole permeability and assumed depths of impermeable plugs appear to be somewhat arbitrary.

Many of the concepts built into PA models may be based on preliminary judgments and assessments that are not well documented. For those ideas that may be critical but are based on minimal evidence, a range of alternative conceptual models should be evaluated in sufficient detail to document their consideration and the basis for their elimination. Examples of alternative conceptual models that should be evaluated further include (but are not limited to)

- contaminant leakage from a HI breach into formations shallower than the Culebra;
- flow and transport through the Culebra as part of a three-dimensional aquifer system;
- impact of changes in the flow field due to transient effects, climate change, or other factors; and
- internal "structure" of the Culebra, including the existence of vertical fracture zones and correlations between transmissivity and other parameters.

More detailed discussions of model testing, model calibration, predictive accuracy of models, and related issues are presented by Anderson and Woessner (1992), Bredehoeft and Konikow (1993), de Marsily et al. (1993), and Konikow and Bredehoeft (1993).

Numerical Errors

The partial differential equations describing ground–water flow and transport can be solved mathematically by using numerical methods. The continuous variables of the governing equations are replaced with discrete variables that are defined at grid blocks (or cells, elements, or nodes). Thus, the continuous differential equation that defines hydraulic head or solute concentration everywhere in the system is replaced by a finite number of algebraic equations that define the hydraulic head or concentration at specific points. This system of

algebraic equations generally is solved by using matrix techniques.

However, numerical methods yield only approximate (rather than exact) solutions to the governing equation (or equations); they require discretization of space and time. The variable internal properties, boundaries, and stresses of the system are approximated within the discretized format. Because numerical methods do not yield exact solutions, *numerical errors* will exist in the solution because of truncation errors, round-off errors, and numerical dispersion. As long as the sources of numerical errors are recognized and the magnitude of the error is controlled, the solution may be sufficiently accurate for use.

The solute-transport equation is in general more difficult to solve accurately using numerical methods than is the ground–water flow equation, largely because the mathematical properties of the transport equation vary depending on which terms in the equation are dominant in a particular situation. Thus, numerical errors often are negligible in solutions to the flow equation but can be significant in numerical solutions to the solute-transport equation.

Where solute transport is dominated by advective transport, as is common in many field problems, the transport equation approximates a hyperbolic type of equation (similar to those describing the propagation of a wave or of a shock front). In contrast, where a system is dominated by dispersive fluxes, such as might occur where fluid velocities are relatively low and aquifer dispersivities are relatively high, the transport equation becomes more parabolic in nature (similar to the transient ground–water flow equation).

In solving advection-dominated transport problems, in which a relatively sharp front (or steep concentration gradient) is moving through a system, it is numerically difficult to preserve the sharpness of the front. Obviously, if the width of the front is narrower than the node spacing, it is inherently impossible to calculate the correct values of concentration in the vicinity of the sharp front without using complex nonlinear mathematical functions or complex nonstandard numerical algorithms. However, even in situations where a front is less sharp, the numerical solution technique can calculate a greater dispersive flux than would occur by physical dispersion alone or would be indicated by an exact solution of the governing equation.

That part of the calculated dispersion introduced solely by the numerical solution algorithm is called *numerical dispersion*. The consequence of numerical dispersion is that the solute is artificially diluted, peak concentrations are lower than they should be, and the solute is distributed throughout a larger than actual area and volume of the aquifer. Although this alone may or may not represent a significant problem, the errors can in fact be magnified and accumulate if the model incorporates a representation of solute retardation processes in which rates or magnitudes are functions of the solute distribution and/or concentration gradients. Because the effectiveness of matrix diffusion and chemical retardation, for example, depends in part on the surface area of aquifer solids that are in contact with ground water containing the solute (or contaminant), numerical dispersion may yield erroneously high rates of matrix diffusion and chemical retardation. Therefore, special care must be taken to assess and minimize numerical errors that artificially would add "numerical" spreading to the calculated spatial distribution of a contaminant.

Data Uncertainty

Data errors arise from uncertainties and inadequacies in the input data. A reasonable way to accommodate such uncertainty is to estimate the mean and the uncertainty in each relevant parameter on the basis of available data, and then use the simulation models to make predictions based on *ranges* of values of the parameters, rather than on single values. Outcomes from the deterministic models can then be presented and assessed in a probabilistic framework. In essence, this is the approach taken by the PA models.

The reliability of site-specific ground-water models typically requires that input data be based on field measurements of critical parameters at a scale appropriate to the size of the model. Unfortunately, very few field measurements are

available for the critical parameters describing the nature of fractures and retardation mechanisms in the Culebra.

Although the probabilistic approach is beneficial and appropriate, it must be cautioned that the results will be affected by assumptions about the statistical distributions and independence of parameters; that is, there is uncertainty in the estimates of uncertainty. The sensitivity of results to assumed frequency distributions should be evaluated.

In addition, the system behavior for some processes is governed essentially by the magnitude of nondimensional parameter groups (or ratios). The rationale for independently sampling the individual parameters comprising such a group is unclear and may result in unlikely parameter ratios.

Hydrologic Performance Assessment Models

Ground-Water Flow

In developing PA models for flow and transport through the Culebra Dolomite, estimates of recharge and transmissivity are keyed into the a priori assumptions that ground-water flow is two dimensional, steady state, and horizontal. In reality, the Culebra is one part of a three-dimensional flow system. Although flow may be predominantly horizontal, some vertical components of flow and transport undoubtedly exist, and they may significantly affect the flow, transport, travel times, and concentration distributions in the Culebra in areas downgradient from a potential release.

Fractures are the high-permeability avenues (or pathways) through which the fastest flow and transport of dissolved contaminants would occur. Fractures thus represent the most likely fatal flaw in site integrity if the HI scenario enables significant leakage of contaminants into the Culebra. In general, where vertical or near-vertical fractures exist, they

1. tend to persist across formation boundaries,
2. often yield some subtle but detectable expression or indication at the land surface, and
3. tend to "channelize" ground-water flow.

Because the presence of a few high-permeability fractures will have a large effect on solute transport, additional efforts to characterize fracture properties are warranted.

Confidence in PA Analysis of Regional Ground-Water Flow

The existence and importance of heterogeneity in the Culebra Dolomite is well recognized. Modern, sophisticated, and complex geostatistical methods have been applied to analyze the statistical properties of the variability in transmissivity and to estimate values of transmissivity in areas where no measurements are available. Accomplished with the assistance and advice of a team of world-class experts, this is a state-of-the-art approach to estimating point values and spatially correlated trends in transmissivity based on existing data, as well as to assessing the reliability of these estimates.

In 1995, a new set of wells was drilled into the Culebra for the purpose of conducting multiwell tracer tests. The site (designated as H-19) was selected in part because it is in the area where the coupling of geostatistical methods and ground-water modeling indicates a relatively high transmissivity zone. If hydraulic testing at this new site confirms prior estimates, it would provide a basis for increased confidence in previous analyses. This new drilling site also would provide a control area in which to apply and test the effectiveness of high-resolution geophysical methods and topographic analyses, in order to better define fracture zones. The result of such analyses could then be correlated with the results of planned tracer tests.

Some concern remains about scale effects on permeability and transmissivity. For example, a comparison of transmissivity values for wells H-14, H-15, and H-17 that were estimated from single-well tests (Beauheim, 1987) with values for the same wells as calculated from data collected during a larger-scale pumping test at H-11 (Beauheim, 1989) shows that the latter are 20 to 60

times greater. Garven (1995) states that fractures in carbonate aquifers tend to increase the hydraulic conductivity at the regional level. He presents a curve indicating that at a regional scale of 1 km or greater, hydraulic conductivity may be a few orders of magnitude higher than estimated from borehole measurements at scales of less than 100 m.

This is relevant to WIPP studies and of some concern to the committee because the assumed transmissivity distributions are keyed to transmissivity values measured in boreholes (see LaVenue et al., 1995, for a detailed discussion of the methodology and its application to the WIPP site). These types of borehole measurements typically sense aquifer properties only in the immediate vicinity (perhaps a few meters) of the borehole. If some of those borehole measurements underestimate the larger-scale effective transmissivity in that area, the regional transmissivity values generated may be too low for purposes of large-scale transport predictions. Although the generated transmissivity fields are calibrated by using observed head measurements from both the assumed steady-state flow field and transient hydraulic tests at a few sites, the heads are less sensitive to transmissivity variations than are seepage velocities.

Geostatistical analysis does not explain why transmissivity varies the way it does. It does not answer the question of whether higher transmissivities are related to increases in fracture density (decrease in fracture spacing), increases in fracture aperture, increases in fracture length (and connectivity), changes in fracture orientation, increases in primary porosity, changes in the amount of evaporite minerals dissolved, and/or changes in mineralogy.

Some might ask whether it is important or necessary to understand the cause of these variations in order to predict ground–water flow and transport. Finding the answers to such questions is not merely an academic exercise; the answers are relevant to the PA models and analyses because whatever is causing the changes in transmissivity will most likely also affect the effective porosity and retardation processes. Developing a better understanding of the causes and controls of transmissivity variations may require improved geological and geophysical mapping of primary and secondary geological properties and characteristics of the Culebra dolomite, particularly fractures.

Franke et al. (1987, p. 2) state that "selection of the boundary surface and boundary conditions is probably the most critical step in conceptualizing and developing a model of a ground-water system." Neither the PA ground-water model of the Culebra nor any of the preceding deterministic models of the system extended to the natural boundaries of the regional aquifer. This makes it difficult to assess the reasonableness of the boundary conditions specified at the outer edges of the PA model, which encompasses only a small part of the entire regional system. It is similarly difficult to calibrate the flux through the Culebra and to distinguish between recharge-discharge in outcrop areas and recharge-discharge from leakage through confining beds. In addition to providing another example of a less than desirable level of understanding of the system of interest, this difficulty also casts doubt on the ability to evaluate and predict the impact of climate change because it is not known how a projected change in climate might interact with the aquifer system in general or with the Culebra in particular.

Future climate change may significantly affect the regional ground–water flow system. The PA assumes that the maximum amount of increased recharge to the Culebra can be represented by increasing assumed boundary heads in the model to the elevation of the land surface. However, because it is well known that heads in confined aquifers can be significantly higher than land surface, it is not clear that this assumption really represents a bounding case. If future climate change induces greater diffuse recharge to the water table, then the saturated thickness of the Dewey Lake Red Beds may increase significantly, resulting in greater transmissivity values and higher flow velocities. Since the recharge would likely retain a relatively low content of dissolved solids, use of the Dewey Lake as a drinking water source might increase significantly in the future. In such circumstances, the Dewey Lake Red Beds could

prove to be a greater long-term environmental risk than the Culebra.

Solute Transport

Solute-transport processes include advection, in which solutes move with the average seepage velocity of the flowing ground water, and hydrodynamic dispersion, which has the net effect of causing the solute distribution to spread about the positions indicated by the mean seepage velocity. Of these two primary processes, advection is the most important to predict accurately, because it controls when the center of mass of a contaminant plume will arrive at the regulatory boundary. Any errors in the solution to the flow equation or in the estimates of effective porosity will affect advection.

The dispersion process in ground-water systems is still the subject of much active research. Although conventional theory holds that the dispersivity coefficients are generally an intrinsic property of the aquifer, in practice they are found to be dependent on and proportional to the scale of the measurement. Recent controlled field experiments and theoretical advances in the study of transport processes indicate that large-scale (macroscopic) dispersion results largely from spatial variations in velocity, caused by spatial variations in hydraulic conductivity and effective porosity (see Gelhar et al., 1992). In that sense, dispersion and advection are interrelated.

Experimental field studies of solute transport at sites that include a dense network of observation wells tend to show that contaminant plumes emanating from known point sources are narrower than expected and that actual dispersion is much less than anticipated by conventional theory (e.g., see Garabedian et al., 1991). The implication for a release of contaminants into the Culebra Dolomite under the HI scenario is that the resulting plume may be longer, narrower, and more sharply bounded than predicted with existing PA models. Overestimating dispersion would have the net effect of diluting the contaminant by spreading its mass through a larger volume of aquifer. In a homogeneous single-porosity medium for a nonreactive solute, this would have no net effect on the center of mass. However, in a heterogeneous system such as the Culebra, overestimating dispersion also forces too much solute into lower-velocity parts of the flow field. This will bias the results toward yielding lower releases during a given time period. Also, if the solute is subject to retardation, overestimating dispersion can lead to a bias of overestimating the magnitude of retardation, as discussed below.

Confidence in PA Analysis of Solute Transport

Because solute-transport processes could be critical to establishing a sufficiently low level of radionuclide releases at WIPP, achieving high confidence in the analyses is important. Although several tracer tests run in the field were valuable steps in this direction, they had to be run under forced-gradient conditions because of time and cost constraints. Running a long-term natural-gradient tracer test should be considered as well, because it would serve as an indicator of true long-term migration paths and velocities under conditions expected after a breach via the HI scenario. However, because such a test might require decades of monitoring, which could be done at very long intervals, it is not recommended that this type of test be performed prior to a compliance decision. Rather, it is suggested that its feasibility be evaluated for possible use as an operational and postclosure monitoring procedure.

Retardation Mechanisms

As solutes migrate through the aquifer, the apparent mean velocity of a particular solute may be retarded relative to the apparent velocity of the water because of several processes that may cause molecules or ions of that particular chemical species to be removed temporarily from the active flow field. Retardation processes thus provide another margin of confidence for the WIPP repository in that retardation will delay (but not prevent) the arrival of a contaminant at the regulatory boundary.

Matrix Diffusion and Physical Retardation

The PA models assume that solute transport through the Culebra Dolomite occurs through continuous sets of horizontal parallel fractures. However, some of the field tests have estimated parameter values for different types of fracture sets and distributions, such as orthogonal sets. The differences in conceptualization must not yield inconsistencies in the effective surface area of fractures per unit volume of aquifer between the field estimates and the PA models, because such inconsistencies might affect the calculated rates of matrix diffusion.

Overestimates of the amount of plume spreading can occur if the assumed dispersion coefficients are too large or if assumed patterns of heterogeneity artificially induce divergence of flow. These effects would be of minor consequence for transport of nonreactive solutes in a single-porosity system. However, if matrix diffusion is a simultaneous process, then the problem is more serious, since the net result would be too much retardation.

Inaccurate or imprecise initial conditions also can lead to significant artificial spreading of the contaminant plume. The HI scenario assumes that the contaminant is introduced into the Culebra by leakage from a borehole (or well) that has a diameter on the order of 0.3 m. In the 1992 PA model, that contaminant source is introduced as an initial condition at the finite-difference cell representing the well. Because that cell has dimensions of 125 m by 125 m, the initial width of the plume at the start of the simulation is perhaps several tens of times greater than it would actually be. The width of the plume then spreads out even more as it is advected and dispersed in a downgradient direction by the regional ground–water flow system.

If the initial width of the plume is much greater than it should be, it has the net effect of giving matrix diffusion an unrealistic "head start" and a growing "advantage" in retarding the movement of the contaminant plume by allowing the plume to be in contact with an erroneously large surface area of the matrix. In a fracture-dominated carbonate aquifer, it is possible that contaminant plumes can migrate long distances with very little lateral spreading, which would minimize any retardation induced by matrix diffusion.

Numerical dispersion also causes artificial plume spreading. The SECO transport code solves the transport equation by using a type of finite-difference scheme. When finite-difference methods are used to solve advection-dominated transport problems, some amount of numerical dispersion is likely to be induced in the solution. Because the numerical code has not been widely available for outside testing and evaluation, it is difficult to know how much numerical dispersion is present. However, any numerical dispersion will necessarily result in overestimates of matrix diffusion.

Confidence in PA Analysis of Matrix Diffusion

The PA models assume that matrix diffusion will be controlled by the intergranular properties of the matrix (including porosity and tortuosity), the free water diffusion coefficient for a particular constituent, and the concentration gradient. *Tortuosity* is a parameter reflecting the fact that the actual tortuous flowpath that a fluid particle would travel through the liquid phase of a saturated porous medium is longer than the length of the porous medium sample. However, tortuosity has been estimated only indirectly in laboratory measurements on a limited number of Culebra samples (Kelley and Saulnier, 1990), where it is shown that the diffusion porosity is usually about two to eight times lower than the porosity measured by other standard methods on the same samples. It is unclear whether these laboratory measurements can be transferred to the field environment.

Field tests by the WIPP project to date have yielded somewhat ambiguous results regarding the occurrence and rates of matrix diffusion. If matrix diffusion must be relied upon to demonstrate compliance, further field studies are necessary to support the model assumptions. Field evidence is needed over moderate distance and time scales and could likely be obtained as part of a series of multiwell tracer tests. Sandia has proposed using single-well injection-recovery tracer tests to

demonstrate the existence of matrix diffusion. However, it is doubtful that such tests could provide either unambiguous results or meaningful measurements of the relevant parameters.

It is also possible that in the field, solute transfer between the fractures and the matrix may be hindered by some type of skin effect or discontinuity at the interface between a fracture and the matrix. Sharp et al. (1995) note that fracture skins are an important and integral part of natural, fractured rock systems and that skin permeabilities and mean pore diameters may be reduced by more than an order of magnitude relative to the matrix. They state that "an extreme case is where the fracture skins have zero permeability and porosity so that no interchange of fluids, colloids and solutes between the fracture and the matrix is possible." Analytical methods are available to interpret the results of tracer tests conducted in fractured aquifers having skin effects (see Moench, 1984; Sharp et al., 1995). The presence of a skin effect would render meaningless any projections of matrix diffusion rates based solely on the physical properties of the matrix. This possibility needs to be given further consideration.

Reactions and Chemical Retardation

As noted in Chapter 6, the appropriateness of predicting the transport of reactive solutes on the basis of a retardation factor (R_f) is questionable. Furthermore, if the use of a retardation factor represents a poor conceptual model, then it is doubtful that the theoretical difficulties can be overcome by simply evaluating a range of values for R_f. For example, if the governing reaction is chemical precipitation of a solid phase, rather than sorption, the species either is less likely to redissolve into the liquid phase in which transport occurs or will do so at a much slower rate. In this case, use of a retardation factor will probably indicate faster and further transport than might occur (but it will still depend on the precipitation rate).

Alternatively, too much retardation could be calculated if the governing process is indeed a type of sorption controlled by surface chemistry. For example, sorption is sometimes characterized by a Langmuir isotherm, which is one type of nonlinear isotherm (although it should not be inferred that a Langmuir isotherm would necessarily be applicable at the WIPP site). In such cases, retardation is greatest at very low concentrations, but at high concentrations the slope of the isotherm approaches zero and the medium will not adsorb additional solute (see Figure F.1). Thus, if sorption is actually governed by a Langmuir isotherm or a similar nonlinear isotherm, applying a retardation factor may lead to a calculation of too much retardation at the high end of the concentration range—the very part of the spectrum at which the greatest toxicity is likely to exist. This illustrates a major weakness of the linear R_f model: it places no upper limit on the amount of the chemical that can be sorbed. However, if it is known that the solute concentration will always remain relatively low, then even if the governing isotherm is nonlinear over the full range of possible concentrations, the sorption behavior within the range of expected conditions will not differ materially from that predicted by a linear isotherm model. If chemical retardation is to be relied on for compliance of WIPP, it must first be demonstrated that the use of a retardation factor is an appropriate representation of reaction processes in the Culebra for the solutes of interest over the transport scales anticipated.

Although most types of reactions tend to retard the transport of a reactive solute, the presence of colloids in the fluid may increase the mobility of solutes that otherwise are retarded or relatively immobile. For example, Ibaraki and Sudicky (1995) cite a case at a liquid waste disposal site at Los Alamos, New Mexico, where both plutonium and americium migrated more than 30 m. They report that predictions based on laboratory results that ignored the role of colloids severely underestimated the migration as just a few millimeters. Colloid-facilitated transport is an issue that warrants additional consideration to justify its exclusion from the PA evaluation.

Confidence in PA Analysis of Chemical Retardation

Not only is the concept of a retardation factor a theoretically weak one for predicting radionuclide transport through the Culebra, but the underlying parameter values for the equivalent K_d are highly uncertain, spatially variable, and based on minimal laboratory experiments that have questionable relevance to the large-scale field environment. Most of the available K_d values obtained by the WIPP project were determined from batch experiments on crushed or powdered samples of rock. There is little evidence that these K_d values are transferable to the field environment, in part because the effective surface areas for water-mineral interactions in crushed samples would be very different from those in situ. For example, Lienert et al. (1994) studied uranium transport in a sand and gravel aquifer and found that the in-situ K_d is much lower than most K_d values obtained from laboratory experiments.

Significant spatial variability in values of K_d may exist and, if so, is probably related to variations in mineralogy. However, in contrast to the consideration of spatial variability in transmissivity, no data are currently available to provide a basis for estimating the magnitude of such variability. A recently published review of transport of reactive contaminants in heterogeneous media concludes that "the transport of reactive solutes appears to be influenced most greatly by subsurface heterogeneity and rate-limited mass transfer interactions" (Brusseau, 1994, p. 306). In discussing the application of theory and laboratory measurements to field-scale systems, the paper further concludes (p. 307): "Of course, true field-scale behavior can be obtained only by performing experiments in the field."

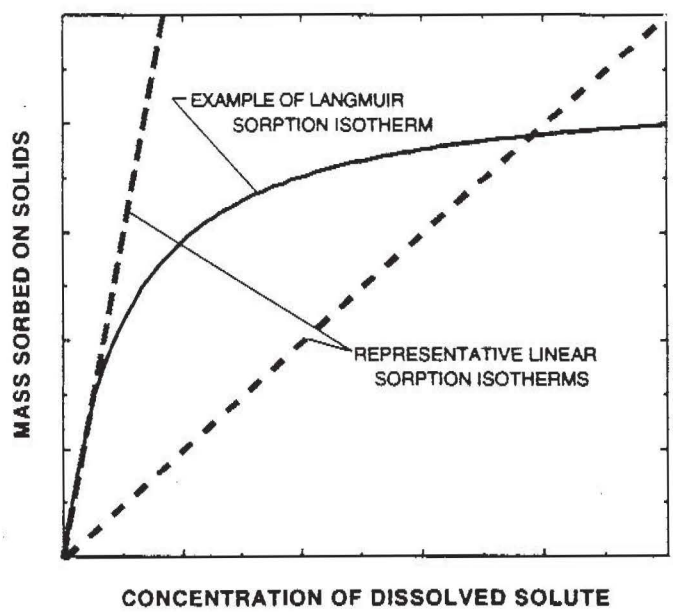

FIGURE F.1. Schematic comparison of representative linear isotherms, describing instantaneous reversible sorption-desorption reactions, with an example of a nonlinear Langmuir isotherm. The distribution coefficient K_d is equal to the slope of the linear isotherm and is directly proportional to the solute retardation factor R_f. Source: Modified from Goode and Konikow (1989).

Appendix G

An Overview of WIPP Compliance Issues

This appendix is a nontechnical synopsis of the major themes and findings of this report. The primary goal of this report is to present a scientific and technical appraisal of DOE activities in connection with the Waste Isolation Pilot Plant (WIPP) radioactive waste isolation program. This entails detailed discussions of complex issues related to engineering measures, biochemical processes, and hydrogeological aspects of the site. Radioactive waste isolation is also a topic of considerable interest and concern to the general public, and it is important that the public understand the basic concepts underlying the design and operation of the WIPP facility.

This appendix aims to describe the WIPP project clearly and concisely by using a "nonspecialist" approach—that is, one that avoids specialized technical terminology as much as possible—to discuss salient issues pertaining to the project. It traces the history of the facility and summarizes the committee's main concerns, conclusions, and recommendations regarding Department of Energy (DOE) activities at WIPP.

DEEP GEOLOGIC DISPOSAL

The objective of the nation's nuclear waste disposal program is to place solid waste in a location where it cannot return to the biosphere by any foreseeable natural process. A generic method has been selected: bury the material deep within the earth's rocky crust. Salt beds are particularly suitable because they are very stable over geological time scales and have the ability to flow and permanently seal the excavations in which the waste is placed. WIPP is located in such a formation.

The plan for waste disposal at WIPP is to excavate a series of underground rooms in the salt deep below the earth's surface. Radioactive waste will be emplaced in the rooms, and then the shafts to the surface will be filled with salt and other materials to close the facility. The weight of the overlying rocks will compress the disturbed salt and reduce its ability to transmit fluids and gases to the very low values of the undisturbed salt, thereby "sealing" the repository.

The worldwide use of salt cavities to store compressed gases attests to the remarkably low permeability of deeply buried salt (Berest and Brouard, 1996). Salt also has a well-known ability to flow under applied stresses. At the depth selected for the repository, crushed salt will reconsolidate to the same low permeability as that of the original formation, and even large cavities eventually will disappear.

Numerical modeling can predict the flow behavior of salt far into the future for any defined situation. The flow is slow enough to allow ample time for underground operations, yet fast enough to be essentially complete in a hundred years or so.

PROJECT ADMINISTRATION AND REGULATION

The WIPP project was begun in the mid-1970s. It has been the responsibility of DOE and its predecessor agencies, but many years passed before it was determined that the U.S. Environmental Protection Agency (EPA) would be responsible for certification. Disposal regulations then had to be developed in parallel with field activities. The "Final Rule" for the Criteria for Certification was published on February 9, 1996, as this report was being prepared.

CERTIFICATION CRITERIA

The long timeline associated with transuranic (TRU) waste poses problems for the regulation of WIPP, just as it does for design and construction. It seems obvious that protection of human health should be fundamental, yet it is impossible to predict what humanity will be doing in the vicinity of WIPP during the next ten

millennia. Given the nature of the EPA standard and the apparent lack of release scenarios for WIPP under undisturbed conditions, it is not necessary to calculate individual doses as part of a compliance analysis. The part of the EPA standard that is relevant to WIPP is a release limit that avoids the necessity of making arbitrary assumptions about population distributions and human activities in the far future. Unfortunately, this release limit fails to account for one of the advantages of the WIPP location—namely, that most of the ground water in the area is so salty (i.e., brine) that it is undrinkable.

The release limit is specified in a rather surprising way: not as an absolute amount, but as a fraction of the waste inventory. The amount is measured conventionally in curies (a measure of radioactivity) rather than mass. This specification can be translated approximately for nonspecialists as follows: the expected waste inventory is of the order of 6 million curies, and the permitted release fraction of plutonium-239, the dominant radioactive isotope of concern, is 0.0001 of that, or 600 curies. This is the same as a mass of Pu-239 of about 20 pounds.

Regulation in terms of release did not entirely relieve EPA from the necessity of making arbitrary decisions. How long a period is implied by the word "permanent"? EPA settled on 10,000 years, although the half-life of plutonium is 24,000 years. How long can one assume "administrative control" of the WIPP area after closure? The EPA chose 100 years. What kind and frequency of human intrusion should be considered? The EPA chose, reconsidered, then chose again. DOE is now required to assume that drilling will continue in the same manner and intensity as today for the next 10,000 years. What credit should be given to the present generation for assuming extra risks that reduce risks to future generations? The EPA is silent on this point.

The simultaneous presence of radioactive and chemically toxic wastes in WIPP presents a "mixed-waste" conundrum. Must EPA enforce Resource Conservation and Recovery Act (RCRA) provisions (relating to disposal of hazardous waste) at WIPP? A recent law (P.L. 104-201) removes this requirement at the federal level, providing DOE with an exemption from the need to demonstrate that volatile organic compounds (VOCs) would not escape from the repository. The justification for this exemption is based on the assessment that the toxicity of the radionuclides in WIPP is far more important than that of the chemicals.

CERTIFICATION OF WIPP

In October 1996, DOE intends to submit to EPA an application for a certificate of compliance. A critical item in the documentation package will be the results of the performance assessment (PA) group at Sandia National Laboratories (SNL). PA is a set of methodologies used to model the long-term behavior of radioactive waste disposal systems.

The purpose of a performance assessment is to answer three questions:

1. What can go wrong?
2. How likely is it to go wrong?
3. What are the consequences?

The first question was answered years ago by inviting interested parties to submit "scenarios" in which human or natural events lead to the release of radionuclides from the repository. After extensive review of a large number of proposed scenarios, eight were selected on the basis of their credibility and significance.

The PA group at SNL is charged with answering the other two questions, using an approach mandated by EPA. The group is developing a large computer model of WIPP. The model interconnects many large special-purpose programs, addressing, for example, site hydrology, geology, and design features. Into this model go descriptions of the eight scenarios, along with data on the many physical and chemical parameters and rate constants required for the computations.

Providing data for this model has been and continues to be a major activity of SNL and its subcontractors. Laboratory and field work play a large part; other approaches include the systematic "elicitation" of expert opinion for matters that are difficult to measure (e.g., the solubility of certain actinides in saturated brine) or impossible to measure (e.g., the best way to communicate to future generations the danger of digging within the WIPP reservation).

In one of the eight scenarios, the repository remains undisturbed by humans after it is closed. For this "undisturbed" case, neither the committee nor DOE's contractors could think of any way in which there is a credible possibility for release of radionuclides.

The other seven scenarios involve human intrusions (HI) of three kinds, alone and in combination, and with various frequencies. A variety of possible circumstances, such as the presence or absence of brine, accompanies each of these "disturbed" scenarios. The existence of many possible scenarios and many kinds of data makes the computations very complex. The computer can handle this complexity, but the computations are nearly inscrutable to all but specialists.

A problem arises for certain data used in the computations: what numerical value should be used when only a broad range of possible values is available? Choosing the "worst case" value (i.e., the least desirable value) of every range maximizes conservatism but introduces an unnatural bias. When faced with such uncertainty, statistical theory provides a means to make predictions on the basis of a defined range in values. This is accomplished by making many simulations for the same scenario, but in each simulation a different value for each uncertain parameter is selected randomly. If implemented carefully and if a large number of such model simulations are made, the average of the numerous predictions can provide a reasonable estimate of the likely outcome for comparison with the compliance criteria.

The output of such simulations is a calculation of hypothetical releases of radionuclides from the repository. Associated with each calculated release is a calculated likelihood (probability) that such a release will occur. Each of these calculations of release and probability of release is called a "realization." The realizations are thus a series of related probabilities and releases that can be plotted on orthogonal axes (e.g., horizontal and vertical, with releases on the horizontal axis and probability on the vertical axis). The releases appear as points, and the curve connecting them would look like a stepped line or a smooth curve, depending on the number of realizations. The analysis of each scenario includes many realizations.

Finally (see Figure 2.1), scenario probabilities are combined for graphical display as complementary cumulative distribution functions (CCDFs). Plotted on the same scale is a single, rather simple graph representing in probability form the EPA maximum-release specifications.

CHEMISTRY, BIOLOGY, AND GEOTECHNOLOGY

It has been the practice of the PA group to be conservative in modeling. This is sensible, except that two or three excessively cautious estimates may combine to produce an unrealistic model result, or a conservative assumption may come to be regarded as a "given." Therefore, it is important that conservative assumptions be confronted constantly with new information as it is developed. This confrontation has not always occurred in the WIPP PA.

For example, the pre-1996 PA efforts used release scenarios that assumed the following:

- all storage rooms were interconnected and able to be flooded with brine;
- brine might dissolve all the steel containers and all the TRU elements within them; and
- gas production by chemical and biological processes might raise the pressure within the sealed repository to and beyond the pressure of the overburden (lithostatic pressure).[1]

These assumptions may be erroneous. The amount of brine that can enter the repository from rock in the immediate vicinity is in fact quite small in the undisturbed case. Brine occurs in the Salado Formation as pockets in "seams" of clay and/or anhydrite (calcium sulfate), and in porous regions that occur irregularly within the otherwise nonporous salt. There appears to have been little or no interconnection within the pockets of brine in the salt for millions of years.

[1]Gas generation is of particular concern because, if excessive, it could lead to a rise in pressure capable of rupturing the repository, with generation of cracks that would provide a pathway for brine to enter and radionuclide-laden brine to migrate out.

Excavation disturbs the brine pockets in the vicinity of the cavity. During excavations, the rock immediately around the excavation becomes fractured, leading to what is called the "disturbed rock zone" (DRZ). Some of the fractures penetrate the brine pockets and cause the brine to drain toward the excavation. The rate of brine collection has been observed to peak within a few years and then drop off as the DRZ ceases to grow.

Hydrogen generation from reaction between the brine and the waste containers also has been overestimated. Laboratory work has established that brine dissolves steel only when there is actual contact between liquid and metal; where there is no contact, only a thin "tarnish" film forms.

Microbiological experiments have not yet given a definitive answer about biological gas generation, but this too requires liquid water. Moreover, there are fundamental reasons for doubting that organisms can continue to be active metabolically for long periods in an isolated environment containing only limited amounts of the many organic and inorganic factors that are required, even when the food (carbohydrate) supply for microorganisms is unlimited.

The committee uses these considerations to judge that there is only a small likelihood that significant amounts of brine will enter the repository and react with the waste to produce hydrogen gas.

On the other hand, brine flooding does occur in scenarios in which a borehole connects the repository with a pressurized brine reservoir in the Castile Formation below the Salado. The possibility of this type of event is given serious consideration, in part because such a reservoir was encountered in a test boring in the 1970s.

THE ACTINIDE SOURCE TERM

Scenarios that assume brine flooding followed by leakage of contaminated brine upward into a near-surface aquifer require data on the possible amount and concentration of radionuclides. The "actinide source term" (AST) refers to the kinds and amounts of dissolved or suspended radionuclides that could be released to the biosphere.

The total quantity of radioactive materials expected to be emplaced in WIPP has been estimated from inventory records of the sites where wastes are currently stored. However, estimates of the proportion of waste that actually would be dissolved in the case of brine flooding are very uncertain. This seems like a straightforward chemistry problem, but few laboratories are equipped to handle plutonium (a large component of the radionuclide inventory at WIPP). There is little useful information about this issue in the published literature.

An experimental study of this problem was begun at Los Alamos National Laboratory (LANL) in 1994, but no data have yet become available. The current suite of experiments is scheduled for completion in May 1996. It is possible that useful data will be available in time to be included in the PA in the October 1996 certification package. Evidence from the German waste isolation program, which is also considering a salt repository, suggests that plutonium solubility in brine is likely to be low, but it is important to ensure that the brine at WIPP, which is different chemically in some respects from the German brine, behaves in a similar fashion with respect to solubility.

HYDROLOGY ABOVE THE SALADO FORMATION

Some scenarios specify that the radionuclide-contaminated brine will be under sufficient pressure to be transported upward into strata above the repository, where it mixes with water of lower salinity, forming a "plume" of contamination.

Much of the radioactivity in the plume may be trapped in the host rock or at least slowed (retarded) by a combination of known effects including precipitation (formation of a solid chemical compound), sorption (chemical reactions with rock surfaces that inhibit transport), and matrix diffusion (egress into fractured rock pores). However, it is difficult to make reliable predictions of these effects. Laboratory experiments with powdered rock are not necessarily good analogues for the natural environment, and even percolation experiments using columns of intact rock cored from the formation are problematical.

Only extensive field experiments can hope to deal directly with the problem of radionuclide transport in the subsurface around WIPP. Unfortunately, the state

of art is such that even this approach is not necessarily definitive.

As used in this report, the term "non-Salado hydrology" refers to ground-water flow that occurs in aquifers within the rock formations that lie above the Salado Formation. The Culebra Dolomite is the major aquifer, and it is the only one considered in the 1992 PA model. The water in this aquifer, however, is too salty for consumption by either humans or livestock, making the Culebra a poor potential route for radionuclides to reach the food chain in the vicinity of WIPP.

A considerable amount of field work has been completed to better define the properties of the Culebra, and significant advances have been made. However, the data base and the level of understanding of this flow system still contain notable gaps. A major gap is the lack of attention to a possible radionuclide contamination route through the Dewey Lake Red Beds, in which the water is known to be potable for both humans and livestock. Although a unique definition of the properties of a deep regional system is neither attainable nor necessary, the committee believes uncertainty about some critical issues could and should be reduced further. Field tests in seven new wells drilled at pad H19 at WIPP are scheduled for completion in April 1996, and the results may provide useful new information on contaminant transport and matrix diffusion for the 1996 PA.

Past PA studies have indicated that releases into the Culebra might be serious enough to disqualify WIPP for certification unless it can be shown that source-term concentrations are lower than the high values now conservatively assumed, or that retardation within the Culebra is much greater than zero. In other words, the combination of high plutonium solubility and low retardation under the assumptions of the 1992 PA have the potential to generate noncompliance. A full description of which combinations of parameter values generate noncompliance is an outcome of the PA analysis, and in particular, of the sensitivity analysis derived from the model. Results from past PA studies are illustrative, but use assumptions (such as the number of future boreholes drilled per unit area per unit time) that differ from the parameter assumptions specified by the recent guidance of 40 CFR 194. The future CCDF results of the 1996 PA, especially the derived sensitivity analysis, would contain the quantitative answer to the dependencies on each parameter of the model.

REPOSITORY DESIGN USING COMPARTMENTATION

Pre-1996 PA calculations were based on a repository design in which separate waste-filled rooms would be connected by the DRZ, which would provide a passage way for gas or liquid. An alternative design would use crushed salt to seal closed each waste-filled room, so that gas or liquid entering one room is prevented from reaching another.

This alternative design provides an approach to demonstrating compliance that the committee expects would lessen the dependencies on (and concerns about) gas generation, the actinide source term, and non-Salado hydrology. Other engineering measures can also be used to improve the repository design. The reconsolidation of salt, discussed earlier, is a powerful design tool, which can be used to create a fully compartmented repository. Access tunnels can be backfilled with some of the salt removed during excavation. Compartmentation and isolation of the waste rooms can be achieved through the use of backfill materials to make effective seals (i.e., barriers to the movement of liquids and gases) to plug all connections made during excavation. Following consolidation of the plugs of backfill material into a tight seal, penetration of any one compartment will have no effect on the rest of the repository.

Such compartmentation would reduce both the probability and the extent of any potential brine flooding associated with human intrusion scenarios. If the rooms were isolated from each other, problems associated with brine entry would be in general reduced, compared with a fully connected repository. By incorporating such a design, the committee believes that the PA model would show that the current state of knowledge about source term and non-Salado hydrology is sufficient to ensure compliance. This expected outcome remains to be demonstrated. However, even should it be possible to certify compliance of WIPP with the available information base, the studies of source term and hydrology should be continued, since these problems are generic to all

concepts of geological waste disposal and could provide considerable additional confidence in the long-term performance of WIPP.

SUMMARY, CONCLUSIONS, AND PERSPECTIVE

The readiness of WIPP to open and operate as a radioactive waste repository is the issue at hand in DOE's efforts to demonstrate compliance with EPA regulations. This appendix presents some of the relevant technical issues. The scientific and engineering work of the past several years will be used for the PA computer model calculations by SNL. These calculations compare the projected, estimated performance of WIPP to EPA requirements. The results, a CCDF curve, contain the quantitative assessment of whether the facility can comply with the regulations.

For the undisturbed repository, compliance depends on the ability of the crushed salt seals in the WIPP shafts to develop a sufficiently low permeability to retard the movement of water into and radionuclides out of the repository. This occurs by natural creep processes in a relatively short time (50-100 years), with the salt seals tending to become impermeable eventually, so that releases should be well below the limits of the EPA standard (see Chapter 4).

For a repository disturbed by human intrusion, when evaluated on the basis of reasonable expectation of intrusive activities and their consequences, and using models that would implement available engineering features and do not make overly conservative assumptions, the consensus of the committee is that the WIPP repository could be shown by DOE to comply with the EPA standard.

Compliance with the EPA standard does not address human exposure for the disturbed case. In some release scenarios, such as releases of radionuclides into water at depth in the Salado, the lack of a credible exposure pathway to humans provides an extra margin of reserve in addition to the compliance requirements.

Appendix H

Biographical Sketches of Committee Members

FAIRHURST, Charles, ***Chair***—T.W. Bennett Professor of Civil Engineering at the University of Minnesota in Minneapolis. He holds a Ph.D. degree in mining engineering from Sheffield University, England. His professional interests are in rock mechanics, mining, and underground construction, and he has consulted widely in this field for private clients and government agencies—foreign and domestic. Prior to joining the University of Minnesota, he worked in underground mining with the Northwestern Division of the National Coal Board in the U.K. Dr. Fairhurst is a member of the National Academy of Engineering and the Royal Swedish Academy of Engineering Sciences, the American Institute of Mining, Metallurgical & Petroleum Engineers, the American Society of Civil Engineers, and the American Underground Construction Association and was former president of the International Society for Rock Mechanics. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1984.

ADLER, Howard I.—Vice President for Research and Development at Oxyrase, Inc. in Knoxville, Tennessee and adjunct Professor of Microbiology, University of Tennessee. He holds B. S., M. S. and Ph. D. degrees in bacteriology from Cornell University. Dr. Adler has conducted work in this and related fields as senior staff member at Oak Ridge National Laboratory and as Director of Microbiology at Oak Ridge Associate Universities. He is a member of the American Society of Microbiology, American Association for the Advancement of Science, and Sigma Xi. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1991.

BLOMEKE, John 0.—Holds B. S. and M. S. degrees in chemical engineering from the University of Texas and a Ph. D. degree in chemical engineering from Georgia Tech. He cultivated his professional interest in chemical engineering while working on the Manhattan Project at the University of Chicago and the Clinton Laboratory in Oak Ridge, Tennessee. Dr. Blomeke has been actively engaged at Oak Ridge National Laboratory in the development and evaluation of commercial nuclear fuel waste management. He has remained very active in this field through his retirement in 1988. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1980.

CLARK, Sue B.—Assistant Professor of Chemistry at Washington State University in Pullman, Washington. She holds a B.S. degree from Lander College and M. S. and Ph.D. degrees in inorganic/radiochemistry from Florida State University. Prior to joining Washington State University, she worked as an assistant research ecologist at the Savannah River Ecology Laboratory at the University of Georgia and a research assistant at Katholieke University te Leuven in Belgium. Dr. Clark has received the Westinghouse Savannah River Company's Total Quality Achievement Award and the National Academy of Science's Young Investigator Award. She is a member of Sigma Xi and the American Chemical Society. She has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1994.

ERNSBERGER, Fred M.—Adjunct Professor of Materials Science at the University of Florida, Gainesville, Florida. He holds an A.B. degree in chemistry from Ohio Northern University and a Ph.D. degree in physical chemistry from Ohio State University. Prior to joining the University of Florida he was Senior Scientist in

the Glass Research Center for PPG Industries, Inc. He has received the George W. Morey Award, the Toledo Glass & Ceramic Award, and the Bleininger Medal of the American Ceramic Society. Dr. Ernsberger is a member of the American Chemical Society and a fellow of the American Ceramic Society. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1978.

EWING, Rodney C.—Regents Professor in the Department of Earth and Planetary Sciences at the University of New Mexico where he has been a member of the faculty for 22 years. He holds a B.S. degree in geology from Texas Christian University (summa cum laude) and M.S. and Ph.D. degrees in geology from Stanford University. His professional interests are in mineralogy and materials science. He has conducted research in Sweden, Germany, Australia, and Japan as well as the United States. Dr. Ewing is a fellow of the Geological Society of America and the Mineralogical Society of America. Presently, he is the vice-president and president-elect of the International Union of Materials Research Societies. He has served on the National Research Council's the Waste Isolation Pilot Plant Committee since 1984.

GARRICK, B. John—Chairman and founder of PLG, Inc., an international engineering, applied science, and management consulting firm in Newport Beach, California. He received his B.S. degree from Brigham Young University and his M.S. and Ph.D. degrees in engineering and applied science from the University of California, Los Angeles. His professional interests involve risk assessment in fields such as nuclear energy, space and defense, chemical and petroleum, and transportation. He received the Society for Risk Analysis Distinguished Achievement Award and was appointed to the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste in 1994, of which he is now Vice Chairman. Dr. Garrick is a member of the National Academy of Engineering and is currently Vice Chairman of the National Research Council's Board on Radioactive Waste Management. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1989.

KONIKOW, Leonard F.—Research Hydrologist with the U.S. Geological Survey in Reston, Virginia. He holds a B.A. degree in geology from Hofstra University and M.S. and Ph.D. degrees from Pennsylvania State University. His research interests include the development and application of solute-transport models to ground-water contamination problems. Previously, he has served on the Editorial Board of *Ground Water* journal, as Associate Editor for *Water Resources Research,* and as Chairman of the Hydrogeology Division of the Geological Society of America. He served on the National Research Council's Committee on Ground Water Modeling Assessment and has been a member of the Committee on the Waste Isolation Pilot Plant since 1989.

KRAUSKOPF, Konrad B.—Professor of Geochemistry Emeritus at Stanford University in California. He holds an undergraduate degree from the University of Wisconsin, and Ph.D. degrees in chemistry from the University of California and in geology from Stanford University. He has received several honors, including Day Medal from the Geological Society of America and the Goldschmidt Medal from the Geochemical Society. He is a member of the National Academy of Sciences and has served as chairman of the National Research Council's Board on Radioactive Waste Management. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1978.

ROY, Della M.—Professor of Materials Science Emerita at the Materials Research Laboratory and Materials Science and Engineering at Pennsylvania State University. She holds a B.S. degree from the University of Oregon and M. S. and Ph.D. degrees from Pennsylvania State University. Her research interests include material synthesis and characterization in inorganic, ceramic, cement, and mineral systems, and nuclear and chemical waste management. She is founding editor and editor-in-chief of *Cement and Concrete Research.*

She is a fellow of the American Ceramic Society, the American Concrete Institute, the Mineralogical Society of America, and the American Association for the Advancement of Science. Dr. Roy is a member of the National Academy of Engineering. She has served on the National Research Council's Committee on the Waste Isolation Pilot Plant since 1995.

WAITE, David A.—Vice President of Health and Safety at Kaiser Hill Co., LLC in Rocky Flats, Colorado. He holds a B.A. degree in physics from Emporia State University, an M.S. degree in radiation physics from Vanderbilt University, and a Ph.D. in general engineering from Oklahoma State University. Prior to joining Kaiser Hill, he conducted work in this and related fields with other companies, including Envirosphere and the Battelle Memorial Institute. Dr. Waite is a member of Lambda Delta Lambda, Sigma Pi Sigma, and the American Board of Health Physics. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1994.

WHIPPLE, Chris G.—Vice President of ICF Kaiser Engineers in Oakland, California. He holds a B.S. degree from Purdue University and a Ph.D. degree in engineering science from the California Institute of Technology. His professional interests are in risk assessment, and he has consulted widely in this field for private clients and government agencies. Prior to joining ICF Kaiser Engineers, he conducted work in this and related fields at the Electric Power Research Institute. He served on the National Research Council's Board on Radioactive Waste Management from 1985 to 1995 and as its Chair from 1992 to March 1995. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1989.

ZORDAN, Thomas A.—President of Zordan Associates, Inc. and concurrently, Senior Project Manager at ICF Kaiser Engineers in Pittsburgh, Pennsylvania. He holds a B.S. degree from Northern Illinois University and a Ph.D. degree in physical chemistry from the University of Louisville. His professional and research interests include environmental management, risk assessment, waste management, software development, and thermochemistry. Prior to joining ICF Kaiser he conducted work in this and related fields with companies such as Science Applications International Corporation, Westinghouse Electric Corporation, and Gulf Research & Development Company. He has served on the National Research Council's Committee on the Waste Isolation Pilot Plant since 1992.

Appendix I

Glossary

absorbed dose—energy imparted to matter in a volume element by ionizing radiation, divided by the mass of irradiated material in that volume element. The SI derived unit of absorbed dose is the gray (Gy); 1 Gy = 100 rad = 1 J per kilogram.

accessible environment—region outside a rectangular block of rock 5 km long on each side placed symmetrically around the Waste Isolation Pilot Plant repository, with vertical sides extending upward to the land surface and indefinitely downward into the earth.

actinide—element with atomic number 90 (thorium) or greater.

actinide source term—cumulative amounts, concentrations in solution, and chemical nature of all radioactive materials to be disposed of at WIPP, which could be moved in solution or suspension (or retarded by sorption on surrounding rock units) from the WIPP repository into the environment.

advection—solute-transport process in which chemical species are carried through an aquifer by the flowing ground water in which they are dissolved.

anhydrite—anhydrous calcium sulfate.

aquifer—formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Becquerel—radiation unit equal to one disintegration per second.

Castile Formation—oldest of the Ochoan sequence of rocks, consisting of alternating layers of anhydrite and thin layers of limestone, with several thick layers of halite. At depth, highly pressurized pockets of brine have been found in this formation.

clastic—term describing rocks or sediments made up of fragments of other rocks. For example, sandstone and shale are clastic rocks.

colloid—particles of size ranging from 10^{-3} to 1 micron (10^{-9} to 10^{-6} m), finer than clay size, and held in suspension in a medium such as water. Because of their fine size, colloids have very large surface areas.

committed effective dose—a measure of human exposure to radioactivity. An ingestion of, inhalation of, or direct contact with radionuclides deposits energy from radioactive decays into bodily tissues. This absorbed dose is multiplied by a weighting factor dependent on the type of radiation to calculate an equivalent dose. The weighted sum of equivalent doses to all bodily tissues and summed over the time of exposure is the committed effective dose, measured in rem. The SI unit, the Sievert (Sv), is equivalent to 100 rem.

compartmentation—filling of tunnels and drifts around rooms and panels, so that the waste is isolated in compartments.

complex—stable association of a metal ion with one or more bulky groups (ligands), resulting in a profound change in the properties of the ion.

corrensite—clay mineral with a structure that represents interstratification of vermiculite and chlorite structures.

creep—slow movement over time of salt as shear stresses cause movement within or between individual crystals.

Culebra Dolomite—second-oldest member of the Rustler Formation ranging from approximately 7-8 m thick at the WIPP site. The Culebra consists of dolomite with some clay minerals. Because it is a water-bearing unit, the Culebra is important to the ground–water flow model for the WIPP site.

curie—measure of the quantity of radioactive material in a sample, equal to 3.7×10^{10} disintegrations per second.

Darcy's law—empirical hydraulic principle stating that the flow rate of a fluid through a porous material is proportional to the hydraulic gradient and the hydraulic conductivity of the material.

Darcy velocity—volumetric flow rate per unit surface area of sample, on the assumption that flow is laminar and that inertia can be neglected. This is more properly called the "specific discharge."

Delaware Basin—sedimentary basin in which the WIPP site is located. The Delaware Basin formed in a Permian sea and was gradually filled with thick, extensive layers of sediments and evaporite deposits.

Dewey Lake Red Beds—youngest of the Ochoan series of rocks, consisting of thin beds of clay, silt, and sandy sediments, red in color.

diffusion length—distance over which chemical species diffuse, or spread out and thoroughly mix, over a period of time, approximated as the square root of the product of diffusivity and time.

distribution coefficient—ratio of the amount of a substance sorbed to the amount in solution when chemical equilibrium exists (also see isotherm); ratio of the concentrations of a substance in two phases at equilibrium.

disturbed repository performance—radionuclide releases from the repository as a result of reasonably foreseeable natural processes as well as inadvertent human intrusion.

disturbed rock zone (DRZ)—localized region of permeability consisting of microfractures in the salt. The DRZ is generated by stress concentrations at a new surface and spreads at a slow and decreasing rate from that surface.

dolomite—a sedimentary rock consisting mostly of the mineral dolomite, calcium magnesium carbonate.

effective porosity—fraction of interconnected void space per unit volume of porous material. It is less than the total porosity because it includes only pores that comprise active flow paths through the medium and excludes voids in isolated or dead-end pores.

Eh—measure of the oxidation-reduction state of a solution.

electrical resistivity—characteristic of a solution depending on the concentration of ions in the solution and measured as the resistance of a centimeter cube of a substance to the passage of a current perpendicular to two parallel faces of the cube.

EPA unit— isotopic-specific unit of measure, used by Sandia National Laboratories, that is equal to the number of curies represented by the release limit of the EPA requirements in 40 CFR part 191.

evaporite—natural deposit of water-soluble salts formed by the evaporation of a body of water.

flocculation—aggregation or clumping together of particles suspended in solution so that they precipitate.

flow path—pathway a particle of ground water would travel, starting from a specified point.

halite—common rock salt, with chemical formula NaCl.

half-life—time required for 50 percent of any amount of a radioactive element to decay.

high-level waste—radioactive waste resulting from the reprocessing of spent fuel rods from nuclear reactors, or of other radioactive materials used for defense purposes.

human intrusion—inadvertent creation of a radiation pathway by human actions.

hydraulic conductivity—capacity for a porous medium to conduct water; defined formally as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow through a porous material. This coefficient incorporates the properties of both the porous medium and the liquid.

hydraulic diffusivity—K/S_s, where K is hydraulic conductivity and S_s is specific storage. It represents the hydraulic conductivity (K) of a saturated porous medium when the unit volume of water diffusing is that involved in changing the head of a unit amount in a unit volume of medium. The time involved for a given head change to occur at a particular point in response to a greater change in head at another point is inversely proportional to the hydraulic diffusivity.

hydraulic gradient—change in static (or hydraulic) head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

hydraulic head—height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point. The hydraulic head is the sum of the elevation head and the pressure head. Under conditions to which Darcy's law may be applied, the velocity of ground-water flow is so low that the velocity head is negligible. Stated more simply, hydraulic head is the height of free surface of water above a given subsurface point.

hydrostatic pressure—pressure exerted in all directions by a body of water at rest.

hydrostratigraphic unit—formation, part of a formation, or group of formations of considerable lateral extent that compose the geologic framework for a reasonably distinct hydrologic system.

ionic strength—half the sum of the products of molality and square of charge for each ion in a solution.

ionization—any process by which an atom, molecule, or ion gains or loses electrons.

ionizing radiation—radiation consisting of directly ionizing particles.

isotherm—line or curve describing the relation between the amount of a substance sorbed and the amount in solution when the chemical system is in equilibrium. The relation is typically very sensitive to temperature changes, so data used to construct such a curve are normally based on experiments conducted at a constant temperature—hence, the name isotherm. The slope of a linear isotherm is often called a distribution coefficient.

isotropic—equal in all directions.

kinetics—general term for rates of reaction.

langbeinite—potash mineral with chemical formula $K_2Mg_2(SO_4)_3$ of economic importance as a source of K_2SO_4.

ligand—compound or molecule in solution that can combine with the ion or molecule of an actinide to form a complex.

lithostatic pressure—pressure exerted by a column of overlying rock at a point in the earth's crust.

Magenta Dolomite Member—second-youngest member of the Rustler Formation, 7-8.5 m thick, consisting of dolomite with gypsum and bearing ground water.

marker bed—horizontally extensive nonhalite interbed in the Salado, numbered from the top of the Salado to the bottom and used to keep the repository at the same level within the Salado.

matrix diffusion—transfer of solute mass by diffusion, driven by a concentration gradient, between an actively flowing part of a ground–water system and low-permeability (often stagnant) parts of the saturated medium. An example is diffusion from a high-permeability fracture into dead-end pores of the adjacent rock matrix.

McNutt Member—a 120-m-thick series of beds midway between the top and bottom of the Salado Formation, which lies stratigraphically above the WIPP repository. The McNutt member contains economically significant potash deposits that have been mined in the area for many years.

molality—number of moles of solute per 1,000 g of solvent in a solution.

Nash Draw—broad shallow valley that developed as a stream channel at the end of the Pleistocene (1.6 million to 10,000 years ago) glaciation. Rocks of the Rustler Formation are exposed in the walls of the Nash Draw.

numerical dispersion—artificial smearing of calculated gradients in a dependent variable (such as concentration) that results from discretization in a numerical solution to the governing partial differential equations (such as the solute-transport equation).

Ochoan—Late Permian stratigraphic series consisting of, from lowermost to uppermost, the Castile, Salado, Rustler, and Dewey Lake Formations.

Ostwald's step rule—rule stating that an unstable phase passes through successive steps of increasing stability as it becomes a final stable phase.

parameter—an algebraic symbol representative of a well defined physical quantity with a numerical value. An adjustable parameter is envisioned to assume any value within its range (between the maximum and minimum numerical bounds). Any particular choice of a value renders a parameter a numerical constant.

Pennsylvanian Period—period of time from 320 million to 286 million years ago.

permeability—capacity of a material to transmit fluids. A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. Permeability depends on the size, shape, and degree of interconnectedness of pores and is generally measured in millidarcies. It is a property of the medium alone and independent of the nature of the liquid.

performance assessment—risk-based assessment of the safety performance of a nuclear waste facility.

Permian Period—period of time from 286 million to 245 million years ago[1].

pH—measure of the acidity of a solution phase; negative logarithm of the hydrogen ion concentration.

[1]Older geologic dating extended the Permian to 225 Ma; more recent methods date the end as 245 Ma.

Pitzer parameters—correction factors for calculating solubilities in strong electrolyte solutions.

potash—group of potassium salts, mined for various uses including plant fertilizers.

potentiometric elevation—elevation that represents the hydraulic head. For an aquifer, it is defined by the level to which water will rise in a tightly cased well. The water table is a particular potentiometric surface.

radiolysis—decomposition brought about by high-energy irradiation.

radionuclide—radioactive nuclide.

recharge—addition of water to the saturated zone; either natural or artificial.

redox potential—number specifying the "oxidation state" of a solution or, alternatively stated, a measure of the ability of a natural environment to control the equilibrium of oxidation-reduction reactions. Redox potential is a synonym for oxidation potential.

retardation factor—in solute-transport analysis, a parameter that describes the ratio of the net apparent velocity of the concentration of a particular chemical species to the velocity of a nonreactive species (or of water). It is proportional to the slope of a sorption isotherm; thus, if the isotherm is nonlinear, the retardation factor is not constant and depends on solute concentration.

risk—probability of a selected set of consequences from the existence of a hazard (e.g., nuclear waste in a repository) or the operation of a facility.

Rustler Formation—second youngest Ochoan formation, overlying the Salado Formation, and consisting of five sequences (members) of thin-bedded strata. The lowermost beds consist of mudstone and sandstone interbedded with evaporites. The upper part of the formation consists of alternating evaporite and dolomite beds. The Culebra Dolomite Member is the second member from the bottom of the formation. The total thickness of the Rustler Formation near the WIPP site is approximately 100 m.

safety—protection against the adverse health effects of hazards (such as radiation and chemicals), regardless of cause.

Salado Formation—second-oldest Ochoan geologic formation consisting of a 230-million year old deposit of rock salt (halite) in near-horizontal beds, in total 200-400 m thick. Very thin layers of clay, anhydrite, and potash minerals are interbedded with the halite beds. Lying at a depth of approximately 660 m (2,160 ft) at the WIPP site, the Salado hosts the WIPP repository.

saturated zone—that part of the water-bearing material in which all voids are filled with water under pressure greater than atmospheric.

sorbing tracer tests—field experiments designed to measure the amount of sorption of a substance.

sorption—chemical reaction processes that result in the accumulation of ions and molecules at a fluid-solid interface. Sorption depends on the balance between the affinity of a substance for a surface and its affinity for an aqueous solution. The term is sometimes used in a general sense to include ion exchange, surface complexation, and surface precipitation.

spalling/spallation—breaking off of very thin sheets from a rock surface.

specific discharge—rate of discharge of ground water per unit area measured at right angles to the direction of flow (see also Darcy velocity).

specific storage—volume of water released from or taken into storage per unit volume of a porous medium per unit change in head. This property is normally considered in problems of three-

dimensional transient flow in a compressible ground–water system.

specific weight—mass per unit volume of a substance.

storativity (or storage coefficient)—volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

sylvite—potash mineral with chemical formula KCl, the principal ore of potassium.

tortuosity—ratio of the length of a fluid particle's path to the length of a straight line between the beginning and ending points of the path. According to this definition, the tortuosity will always have a value greater than one. Note that tortuosity is sometimes defined on the basis of an inverse of this relation; in such cases it will always have a value less than one.

transmissivity—rate at which water of prevailing properties is transmitted through a unit width of an aquifer under a unit hydraulic gradient. For horizontal flow in a homogeneous aquifer, it is equal to the hydraulic conductivity times the saturated thickness. Transmissivity is measured in units of length squared per time (e.g., m^2/s).

transuranic waste—radioactive waste consisting of radionuclides with atomic numbers greater than 92 in excess of agreed limits. A more precise definition, in DOE Order 5820.2A, EPA regulation 40 CFR 191, and the Land Withdrawal Act, is waste that is not high level waste that is "contaminated with alpha-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram." The regulatory definition excludes actinide elements with atomic numbers between 90 and 92 (most significantly, Th and U isotopes), which is in agreement with the literal meaning of "transuranic." However, common usage of "transuranic waste" is often understood to include all actinides.

undisturbed repository performance—radionuclide releases from the repository as a result of reasonably foreseeable natural processes

unsaturated zone—subsurface zone above the water table in which some of the pore spaces are occupied by air and some by water.

waste characterization—process of identifying and classifying the chemical, physical, and radiological constituents of each drum of waste.

waterflooding—technique used in the secondary recovery of petroleum and gas whereby water is injected into a petroleum or gas reservoir so that the pressure of the water expels the petroleum or gas.

water table—surface in an unconfined ground–water system at which the pressure is atmospheric, in the field environment defined by the levels at which water stands in wells that penetrate the saturated zone just far enough to hold standing water.

Appendix J

List of Acronyms and Symbols

ε	effective porosity
AEA	Atomic Energy Act
AEC	Atomic Energy Commission
AST	actinide source term
BRAGFLO	computer code modeling regional hydrology
CAO	U.S. Department of Energy Carlsbad Area Office
c.c.c.	critical coagulation concentration
CCDF	complementary cumulative distribution function
CH	contact handled
Ci	curie
DCCA	Draft Compliance Certification Application
DEIS	Draft Environmental Impact Statement
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
E1	a scenario in which the WIPP repository is breached by one borehole extending down to a Castille brine pocket
E1E2	a scenario in which the WIPP repository is breached by two boreholes, one extending down to a Castille brine pocket and sealed above the repository horizon, and the other providing a flow path above the Salado
EACBS	Engineered Alternatives Cost/Benefit Study
EAMP	Engineered Alternatives Multidisciplinary Panel
EATF	Engineered Alternatives Task Force
EEG	State of New Mexico Environmental Evaluation Group
EPA	U.S. Environmental Protection Agency
ERDA	Energy Research and Development Administration
FEPs	features, events, and processes
GI	gastrointestinal
HI	human intrusion
HYDROCOIN	International Hydrologic Code Intercomparison Project
INTRAVAL	International Project to Study Validation of Geosphere Transport Models
K_d	distribution coefficient
LANL	Los Alamos National Laboratory
LWA	Land Withdrawal Act
Ma	millions of years ago
MB	marker bed
MPa	megapascal
MTHM	metric tons of heavy metal
NAS	National Academy of Sciences
NMED	New Mexico Environment Department
NRC	National Research Council
ONWI	Office of Nuclear Waste Isolation
PA	performance assessment
QA	quality assurance
RCRA	Resource Conservation and Recovery Act
R_f	retardation factor
RH	Remote handled
SECO	computer code used in modeling hydrology
SIT	specific-ion interaction theory
SNL	Sandia National Laboratories
SPM	systems prioritization method
STTP	Source Term Test Program
TRU	literally, transuranic (i.e., with atomic number greater than that of uranium); however, TRU waste is commonly used to refer to all actinide-bearing waste (i.e., containing thorium and uranium isotopes)
VOC	volatile organic compound
WIPP	Waste Isolation Pilot Plant

Appendix K

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Improving Operations AND Long-Term Safety OF THE Waste Isolation Pilot Plant

Final Report

Committee on the Waste Isolation Pilot Plant
Board on Radioactive Waste Management
Division on Earth and Life Studies
National Research Council

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Cover: The four drawings on the left represent the natural process of salt encapsulating transuranic waste drums in the WIPP repository. From top to bottom, the chronological sequence is 0 years, 10-15 years, 50 years, and 1,000 and more years (Hansen et al., 1997). Reproduced with permission. The image in the center shows a sample of Permian age salt crystals, about 225 million years old, taken from the WIPP excavations. The picture on the right shows typical scenery in proximity to the WIPP repository.

Back cover: Picture of three trucks transporting transuranic waste to the WIPP. *Source:* DOE.

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List of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Ray Chamberlain, Parsons Brinckerhoff, Inc.
Darleane C. Hoffman, Lawrence Berkeley National Laboratory
Leonard F. Konikow, U.S. Geological Survey
James O. Leckie, Stanford University
Harry Mandil, MPR Associates, Inc. (retired)
Michael D. Meyer, Georgia Institute of Technology
Michael O. McWilliams, Stanford University
Michael T. Ryan, Medical University of South Carolina
John J. Taylor, Electric Power Research Institute (retired)
Chris G. Whipple, Environ International Corporation

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Frank L. Parker, Vanderbilt University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Preface

This study was sponsored by the U.S. Department of Energy (DOE) Carlsbad Field Office, formerly known as Carlsbad Area Office (CAO). To accomplish this project, the National Research Council (NRC) empanelled a 15-member committee on the Waste Isolation Pilot Plant (WIPP). Committee members were chosen for their expertise in relevant technical disciplines such as nuclear engineering, health physics, chemical and environmental engineering, civil and transportation engineering, performance assessment, analytical chemistry, materials science and engineering, plutonium geochemistry, hydrogeology, rock and fracture mechanics, petroleum engineering, and mining engineering. The committee is operated under the auspices of the Board on Radioactive Waste Management of the NRC.

The first committee on the Waste Isolation Pilot Plant was formed in 1978, at the request of the DOE, to provide scientific and technical evaluations of the investigations at the WIPP. That committee functioned as a standing committee until late 1996 at which time it published its final report (NRC, 1996a), *The Waste Isolation Pilot Plant, A Potential Solution for the Disposal of Transuranic Waste.*[1] This was the last report of the committee prior to certification of the site. The committee concluded that "human exposure to radionuclide releases from transuranic waste disposed in the WIPP is likely to be low compared to U.S. and international standards." The report went on to say, "The only known possibilities of serious release of radionuclides appear to be from poor seals or some form of future human activity that results in intrusion into the repository." The report recommended that "speculative scenarios of human intrusion should not be used as the sole or primary basis on which to judge the acceptability of the WIPP (and, by extension, any geological repository)."

Following the publication of the 1996 report, this WIPP committee was created to carry out the statement of task reported in Sidebar P.1. The committee has produced two reports to cover the statement of task, an interim report published in April 2000 and this final report. The complete interim report has been reproduced as Appendix A1.

[1] Transuranic (TRU) waste is waste contaminated with alpha-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram. For more details see Sidebar 1.2 and the glossary.

Sidebar P.1 Statement of Task

The purpose of this study is to identify the limiting technical components of the WIPP program, with a twofold goal of (i) improving the understanding of long-term performance of the repository and (ii) identifying technical options for improvements to the National Transuranic (TRU) Program (i.e., the engineering system that defines TRU waste handling operations that are needed for these wastes to go from their current storage locations to the final repository destination) without compromising safety.

To accomplish this goal, the study will address two major issues:

1. The first is to identify research activities that would enhance the assessment of long-term repository performance. This study would examine the performance assessment models used to calculate hypothetical long-term releases of radioactivity, and would suggest future scientific and technical work that could reduce uncertainties.

2. The second is to identify areas for improvement in the TRU waste management system that may increase system throughput, efficiency, cost effectiveness, or safety to workers and the public. This study will examine, among other inputs, the current plans for TRU waste handling, characterization, treatment, packaging, and transportation.

In October 2000, the DOE provided a comprehensive response to the recommendations made in the interim report. The response is reported in Appendix A2. The committee is very encouraged by the quality of the responses and the actions the DOE is taking. Although the responses will not have a full impact on this final publication because of the report's tight schedule, the committee has been able to acknowledge a number of them in this report.

As is the normal practice of the National Academies, committee members do not represent the views of their institutions but form an independent body to author the report using the information gathered together with their collective knowledge and experience. The report reflects a consensus of the committee and has been reviewed in accordance with NRC procedures.

B. John Garrick, *Chair*
Committee on the Waste Isolation Pilot Plant
April 2001

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Executive Summary

The Waste Isolation Pilot Plant (WIPP) is a deep underground mined facility for the disposal of transuranic waste resulting from the nation's defense program. Transuranic waste is defined as waste contaminated with transuranic radionuclides with half-life greater than 20 years and activity greater than 100 nanocuries per gram. The waste mainly consists of contaminated protective clothing, rags, old tools and equipment, pieces of dismantled buildings, chemical residues, and scrap materials. The total activity of the waste expected to be disposed at the WIPP is estimated to be approximately 7 million curies, including 12,900 kilograms of plutonium distributed throughout the waste in very dilute form. The WIPP is located near the community of Carlsbad, in southeastern New Mexico. The geological setting is a 600-meter thick, 250 million-year-old saltbed, the Salado Formation, lying 660 meters below the surface.

The National Research Council (NRC) has been providing the U.S. Department of Energy (DOE) scientific and technical evaluations of the WIPP since 1978. This is the first full NRC report issued following the certification of the facility by the U.S. Environmental Protection Agency (EPA) on May 18, 1998. An interim report was issued by the committee in April 2000 and is reproduced in this report as Appendix A1. The main findings and recommendations from the interim report have been incorporated into the body of this report.

The committee's task is twofold: (1) to identify technical issues that can be addressed to enhance confidence in the safe and long-term performance of the repository and (2) to identify opportunities for improving the National Transuranic (TRU) Program for waste management, especially with regard to the safety of workers and the public. The complete statement of task is reported in Sidebar P.1 of the Preface.

The **overarching finding and recommendation** of this report is that the activity that would best enhance confidence in the safe and long-term performance of the repository is to monitor critical performance parameters during the long pre-closure phase of repository operations (35 to possibly 100 years). Indeed, in the first 50 to 100 years the rates of important processes such as salt creep, brine inflow (if any), and microbial activity are predicted to be the highest and will be less significant later. The committee recommends that the results of the on-site monitoring program be used to improve the performance assessment for recertification purposes. These results will determine whether the need for a new performance assessment is warranted. For the National TRU Program, the committee finds that the DOE is

implementing many of the recommendations of its interim report. It is important that the DOE continue its efforts to improve the packaging, characterization, and transportation of the transuranic waste.

The committee's **specific findings and recommendations** have been grouped into three categories: (1) site performance, (2) site characterization, and (3) the National TRU Program.

SITE PERFORMANCE

Every five years, the WIPP must obtain recertification from the EPA by showing that the repository is performing as predicted. Site performance refers to activities, phenomena, or events that occur as a result of repository construction and waste emplacement in the time frame between placement of the waste and final sealing[1] of the repository shaft. Site performance has been evaluated by the DOE in its Compliance Certification Application (CCA) (DOE, 1996). The CCA relies on a model, called a "performance assessment," that calculates the probability and consequence of several scenarios by which radionuclides could be released into the environment. The performance assessment also identifies the major uncertainties and their impact on the overall performance of the system. To reduce some of the uncertainties in the performance assessment and to add confidence in the containment performance of the repository, *the committee recommends taking advantage of the long (35 to possibly 100 years) pre-closure operating period to monitor selected performance indicators,* including those listed below:

1. Brine migration is a key issue because it provides the most realistic mechanism for mobilizing and transporting radionuclides from the waste. The mixing of brine and waste could also result in the generation of gas in the repository. **The committee recommends pre-closure monitoring to gain information on brine migration and moisture access to the repository. Observation should continue at least until the repository shafts are sealed and longer if possible. The committee recommends that the results of the on-site monitoring program be used to improve the performance assessment for recertification purposes.**

2. Gas pressure generation is an important issue in the assessment of human intrusion scenarios. In the committee's opinion, there are uncertainties in some of the assumptions about gas generation used in the performance assessment of the CCA. **The committee recommends pre-closure monitoring of gas generation rates, as well as of the volume of hydrogen, carbon dioxide, and methane produced. Such monitoring could enhance confidence in the performance of the repository, especially if no gas generation is observed. Observation should continue at least until the repository shafts are sealed and longer if possible. The results of the gas generation monitoring program should be used to improve the performance assessment for recertification purposes.**

3. Magnesium oxide (MgO) is used as backfill in WIPP to provide some control of the chemical environment of the waste and, to a lesser extent, to fill voids in the disposal locations, thus enhancing the healing process. The chemical performance of MgO depends on gas generation and brine inflow as well as other chemical processes taking place in the repository. The committee finds that there is uncertainty about the effectiveness of MgO in controlling the chemical environment of the waste. Therefore, **the**

[1] The terms "sealing" and "healing" are both used in this report in relation to the repository. Repository sealing refers to the emplacement of engineered barriers preventing access or leakage to and from the repository. Repository healing indicates a natural process by which the mined salt creeps in around the waste to fill all the void spaces in the repository. See also "salt creep" and "engineered barriers" in the Glossary.

committee recommends that the net benefit of MgO used as backfill be reevaluated. The option to discontinue emplacement of MgO should be considered.

4. Deformation of rock salt and interaction of salt with TRU waste containers are of interest as a part of the pre-closure performance confirmation. The creep of salt is expected to entomb the waste drums in 100 to 150 years; thus, the radionuclide mobility values used in the performance assessment might have been overestimated. This implies less migration of radionuclides from the repository into the environment. **The committee recommends pre-closure monitoring of the status of room deformation and of the disturbed rock zone[2] (DRZ) healing. Seal performance should also be assessed. Observation should continue at least until the repository shafts are sealed and longer if possible. The results of the monitoring of room deformation and DRZ healing should be included in the PA and used for recertification purposes.**

SITE CHARACTERIZATION

The WIPP program has engaged in a comprehensive program of site characterization that, in general, has been adequate to support certification of the facility. *The committee identified four areas in which additional site characterization or monitoring is recommended.* The four site characterization programs are described below:

1. A program for the hydrologic characterization of the Culebra, the most transmissive unit in the Rustler Formation. The Culebra could provide a pathway for the release of radionuclides into the environment in the event of human intrusion. **The committee recommends a monitoring program to characterize the geohydrology of the Culebra Dolomite. Tests and measurements that should be considered include angled boreholes, natural gradient tracer tests, and additional pump or injection tests. These new data should be used to confirm, or modify, the conceptual and numerical models now proposed as reasonable simulation of the actual system.**

2. A program for the detection of deep brine reservoirs below the waste disposal horizon. To improve site characterization and increase confidence in repository performance in view of the recertification application, **the committee recommends the use of seismic survey techniques for detecting large brine reservoirs below the repository.[3] In case a brine reservoir were found beneath the WIPP and its size were larger than what is already taken into account in the PA, then the DOE should conduct an extensive review of the impact of such reservoir on the repository performance. A basis would then exist to take appropriate action to ensure the safety of the repository.**

3. A program for monitoring oil, gas, and mineral production in the area. Oil, gas, and mineral extraction activities in the vicinity of the repository could threaten its integrity. **The committee recommends the development of a database to collect information on drilling, production enhancement,**

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[2] The disturbed rock zone is the zone around an excavation, in the host rock salt, where the stress field has been modified sufficiently to cause the formation of microfractures in the rock salt.

[3] The committee recognizes that small brine reservoirs, including brine occurring as a saturated continuum, could not be detected by seismic surveys, or other noninvasive remote sensing techniques.

mining operations, well abandonments, and unusual events (accidents and natural events) in the vicinity of the WIPP site.

4. A program for establishing the baseline for naturally occurring radioactive material (NORM) in subsurface brines and hydrocarbons in the vicinity of the site. The NRC interim report recommended that the DOE develop and implement a plan to sample oil-field brines, petroleum, and solids associated with current hydrocarbon production to identify the background concentrations of naturally occurring radioactive material in the vicinity of the WIPP site, for baselining purposes. In response to this recommendation, the DOE has started to collect data and is developing a database on NORM. **The committee recommends that the DOE continue the implementation of its plan to sample oil-field brines, petroleum, and solids associated with current and future hydrocarbon production, as necessary to assess the magnitude and variability of NORM in the vicinity of the WIPP site for baselining purposes.**

THE NATIONAL TRU PROGRAM

The National TRU Program, administered by the DOE Carlsbad Field Office, is a program to accommodate all applicable external regulations and internal requirements that are associated with the characterization, certification, packaging, and transportation of TRU waste to the WIPP facility. The committee addressed two main issues pertaining to the National TRU Program: (1) waste characterization and packaging and (2) waste transportation.

Waste Characterization and Packaging

The committee reviewed some of *the waste characterization and packaging requirements* established by the National TRU Program from a safety and cost point of view. This issue was detailed in the committee's interim report. A new issue concerning the *total inventory of organic material allowed in the repository* surfaced after the committee visited the WIPP site.

1. Waste characterization and packaging requirements. A principal finding of the interim report (Appendix A1) was that many requirements and specifications having to do with waste characterization and packaging lacked a safety or legal basis. In fact, the committee concluded that some of the requirements penalized the program by adding unnecessary costs and safety risks. Examples of self-imposed waste characterization requirements are waste repackaging to dilute the hydrogen-producing components and visual examination to verify the content of waste drums and avoid miscertifications. Therefore, the committee recommended in the interim report that the DOE should eliminate self-imposed waste characterization requirements that lack a safety or legal basis. The DOE has responded to this recommendation by initiating a review of all waste characterization and packaging requirements (Appendix A2). **The committee recommends that the DOE's efforts to review waste characterization and packaging requirements continue and that changes be implemented over the entire National TRU Program. The committee recommends that the resources required to complete these improvements be made available by the DOE.**

2. Total inventory of organic materials allowed in the repository. Buried with the waste is a considerable inventory of organic materials, such as plastic film used to stabilize the drums, plastic bags and corrugated cardboard, wooden waste boxes, plastic liners of waste drums, and pressed wood "slip sheets."

The principal concern of the committee is that the DOE does not appear to keep an accurate inventory of such organic material. **The committee recommends a risk-based analysis of the total organic material regulatory limits in WIPP. If accounting for the organic material is important to the safety of the repository, an inventory record system should be implemented as soon as possible to provide a basis for meaningful safety analysis.**

Waste Transportation

The committee has examined various aspects of the WIPP TRU waste transportation system, focusing on system safety and the cost-effectiveness of planned and ongoing activities. In its interim report (Appendix A1), the committee reviewed DOE's TRANSportation Tracking and COMmunication (TRANSCOM) system and its emergency response program. In addition to the *DOE's communication and notification program* and its *emergency response training,* two other issues have been revisited in this report: the potential use of *rail as a transportation option for certain TRU waste,* and *gas generation safety analysis for Transuranic Package Transporter, Model II (TRUPACT-II) containers.*

1. DOE's communication and notification program. The committee's interim report (Appendix A1) reviewed the transportation system for WIPP waste and particularly addressed the issue of the DOE's communication and notification system TRANSCOM and its emergency response program. The committee raised questions about the reliability and ease of use of the TRANSCOM system. Meanwhile, the DOE appears to be moving systematically toward the implementation of an efficient, comprehensive, and state-of-the-art communication and notification system, called TRANSCOM 2000. **The committee recommends that the DOE implement as soon as possible the new TRANCOM 2000 communication and notification system. Moreover, because the human factor is an important element of transportation system quality, TRANSCOM 2000 should include methods to minimize the occurrence and impact of human errors.**

2. DOE's emergency response training. Although the committee is aware of the fact that the DOE is not directly responsible for the emergency response program, DOE should nevertheless identify the resources (e.g., responders, medical facilities, recovery equipment, response teams) that might be necessary to respond to a transportation incident. **The committee recommends that the DOE facilitate the involvement of states in developing and maintaining an up-to-date, practical, and cost-effective spatial information database system to coordinate emergency responses. The DOE should also develop an ongoing assessment program for states' emergency response capabilities and allocate training resources to address deficiencies in coverage along WIPP routes.**

3. Rail as a transportation option for certain TRU waste. Among the generator sites, some have rail-loadings and tracking capabilities that could be used for railway shipping of TRU waste to WIPP. The objective of the following recommendation is to minimize the number of road shipments, and therefore the related risk, and to optimize the waste load for shipments of inner waste packages that are unsuitable for placement in TRUPACT-II overpacks. **The committee recommends that all reasonable transportation options including reduction in the number of shipments, such as rail and road transportation with better-adapted containers, should be part of the decision-making process of transporting TRU waste from generator and storage sites to the WIPP. Future transportation studies should consider railway shipments and their impact on both the safety and the cost of the program. The**

DOE should also continue to pursue the development of packaging alternatives for materials not suitable for TRUPACT-II containers.

4. Gas generation safety analysis for TRUPACT-II containers. Hydrogen gas is generated in the shipping containers by radiolytic decomposition of the organic materials in waste during transportation of TRU waste to the WIPP. The root issue is the interpretation of the U.S. Nuclear Regulatory Commission's (USNRC's) regulations on shipments involving possible flammable gases. The questions of interpretation center around the allowed volume fractions of flammable gases and the definition of the confinement barrier. Depending on interpretation, the regulations can become a severe constraint on TRU waste shipments, with no apparent benefit. In particular, the committee was unable to verify the technical basis for some of the interpretations of the regulations as they relate to the safety of the workers and the public. **The committee recommends a risk-informed analysis of WIPP specific shipment issues to identify core problems related to hydrogen generation and, perhaps, provide a basis for alternative cost-effective criteria while reducing the risk. The committee recommends the use of such risk-informed analysis in the application for revision of the USNRC certificate of compliance concerning hydrogen generation limits for transportation purposes.**

1

Introduction

The Waste Isolation Pilot Plant (WIPP) is the world's first deep underground operational geological repository for the disposal of radioactive waste. The WIPP consists of an underground mined facility located in a 250 million-year-old bedded salt formation (the Salado Formation), which lies 660 meters below the surface in a semiarid desert near the community of Carlsbad, New Mexico. The WIPP repository has been established for the disposal of transuranic (TRU) waste resulting from the nation's defense program. The advantages of the WIPP as a transuranic waste disposal are listed in Sidebar 1.1. Figures 1.1-1.3 show the location, layout, and geologic stratigraphy of the WIPP.

Transuranic waste contains alpha-emitting radionuclides that have atomic numbers greater than 92, the atomic number of uranium, the heaviest natural element. The WIPP Land Withdrawal Act (LWA) (U.S. Congress, 1992) defined TRU waste as waste contaminated with transuranic radionuclides with half-life[1] greater than 20 years and activity greater than 100 nanocuries per gram. It mainly consists of contaminated protective clothing, rags, old tools and equipment, pieces of dismantled buildings, chemical residues, and scrap material. Tables 1.1 and 1.2 provide, respectively, the inventory of major radionuclides in the WIPP and the repository inventory by waste category. More details on transuranic waste are given in Sidebar 1.2. Figure 1.4 shows pictures of typical TRU waste. Even though the backfill magnesium oxide (MgO) appears in the repository inventory, it is not considered to be waste. Water is also not part of the waste inventory. There is only a negligible amount of water in the waste, mostly water vapor and less than 1 volume percent of free liquids as allowed by the Waste Acceptance Criteria (DOE, 1999).

Packed in 55-gallon steel drums and wooden boxes, TRU waste is currently being stored at various sites across the nation. The source of the waste is the manufacture of nuclear warheads and the cleanup of the nuclear weapons sites. The risks associated with transuranic waste are related primarily to plutonium. Plutonium's long half-life (24,000 years for plutonium-239)[2] and toxicity must be considered in assess-

[1] The half-life is the time required for half of the atoms of a radioactive substance to disintegrate.

[2] Plutonium-239 indicates the isotope of mass number 239 of the element plutonium. The same notation is used for other radionuclides throughout this report.

Sidebar 1.1 Why the WIPP?

The rationale for isolating nuclear wastes through deep geologic disposal is based on a large body of U.S. and international research. The National Academy of Sciences observed in 1957 (NRC, 1957): "The best means of long-term disposal . . . is deep geological emplacement. . . ." The Academy reaffirmed and expanded on this view in NRC (1984) and in NRC (1996a). The WIPP repository is carved out of a bedded salt formation, with the following features that make it ideal for transuranic waste disposal:

Dry environment. Large salt beds are found only in geologic regions that lack significant flows of groundwater. This deep, relatively dry underground environment greatly reduces the possibility that wastes could be carried out of a repository by natural processes. The saltbed at the WIPP site has been stable for 225 million years. It can be expected, with high confidence, to remain that way for many thousands of years into the future.

Waste immobilization. Salt tends to "heal" itself after being mined because it gradually creeps under the pressure from overlying earth and fills any openings. After several hundred years, the salt at the WIPP is expected to close in on the waste and lock it deep below the surface.

Since the mid-1970s, the Department of Energy (DOE) and its scientific adviser, Sandia National Laboratories, have studied the WIPP site to make sure it is a safe place to isolate transuranic waste. The WIPP addresses the following two key national needs:

Reducing risk. As long as transuranic waste remains at storage sites, there will be some level of risk to populations near these sites. Also, workers who must maintain current sites and monitor wastes are frequently exposed to low levels of radiation.

Providing disposal. The WIPP is a first-of-its-kind deep geologic disposal facility and will provide a model for radioactive waste disposal. In addition to the existing inventory of stored transuranic waste, estimated at about 2.32 million cubic feet, the WIPP will be the disposal site for more than 3.7 million cubic feet of transuranic waste expected to be generated during the next 35 years as DOE sites are closed. Under current law, the DOE is allowed to store 6.2 million cubic feet of transuranic waste at the WIPP. SOURCE: Citizens' Guide to the Compliance Certification Application (DOE, 1996b).

SOURCE: Citizens' Guide to the Compliance Certification Application (DOE, 1996b).

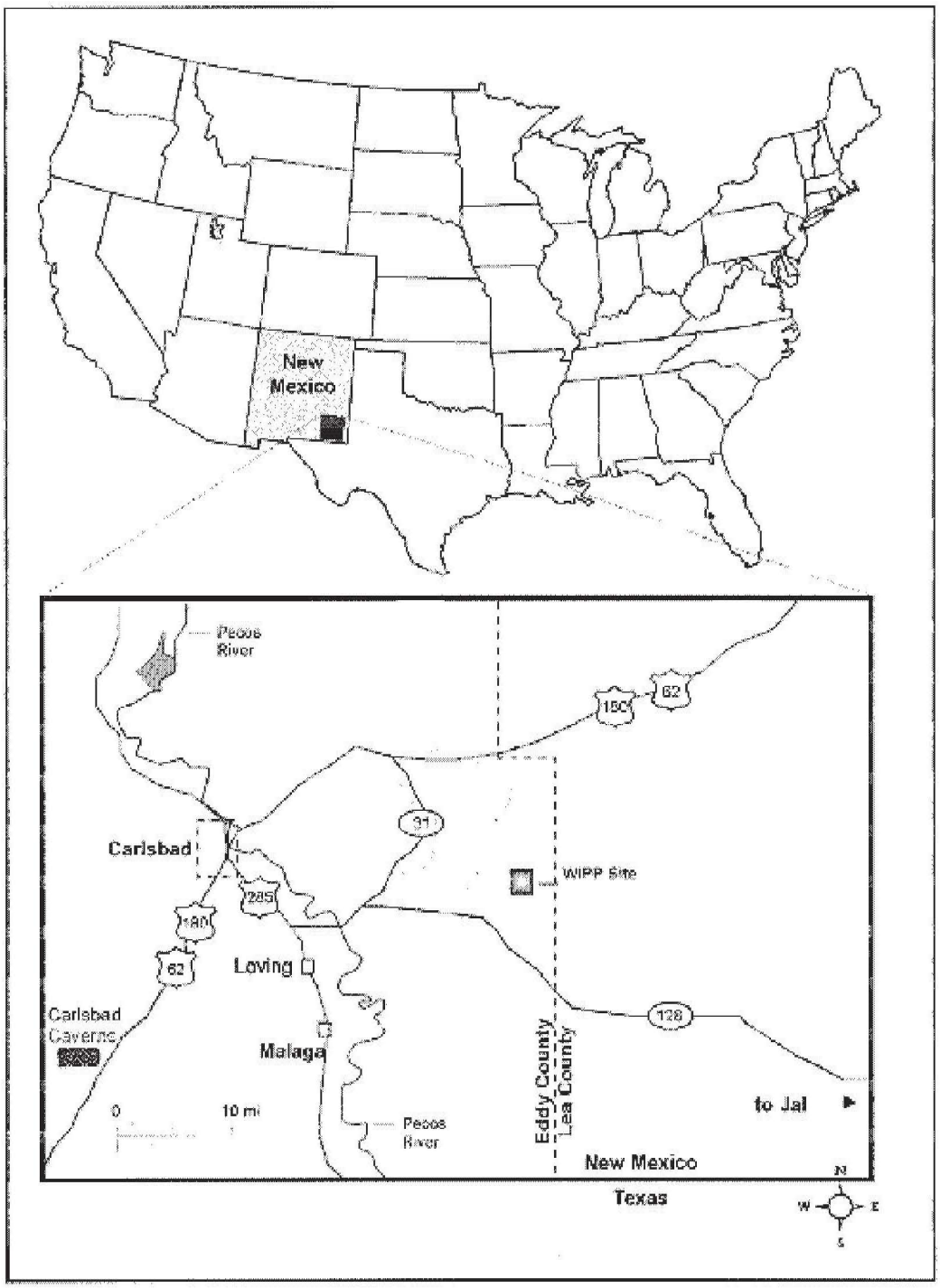

Figure 1.1 Location of the WIPP site. SOURCE: DOE, 2000g.

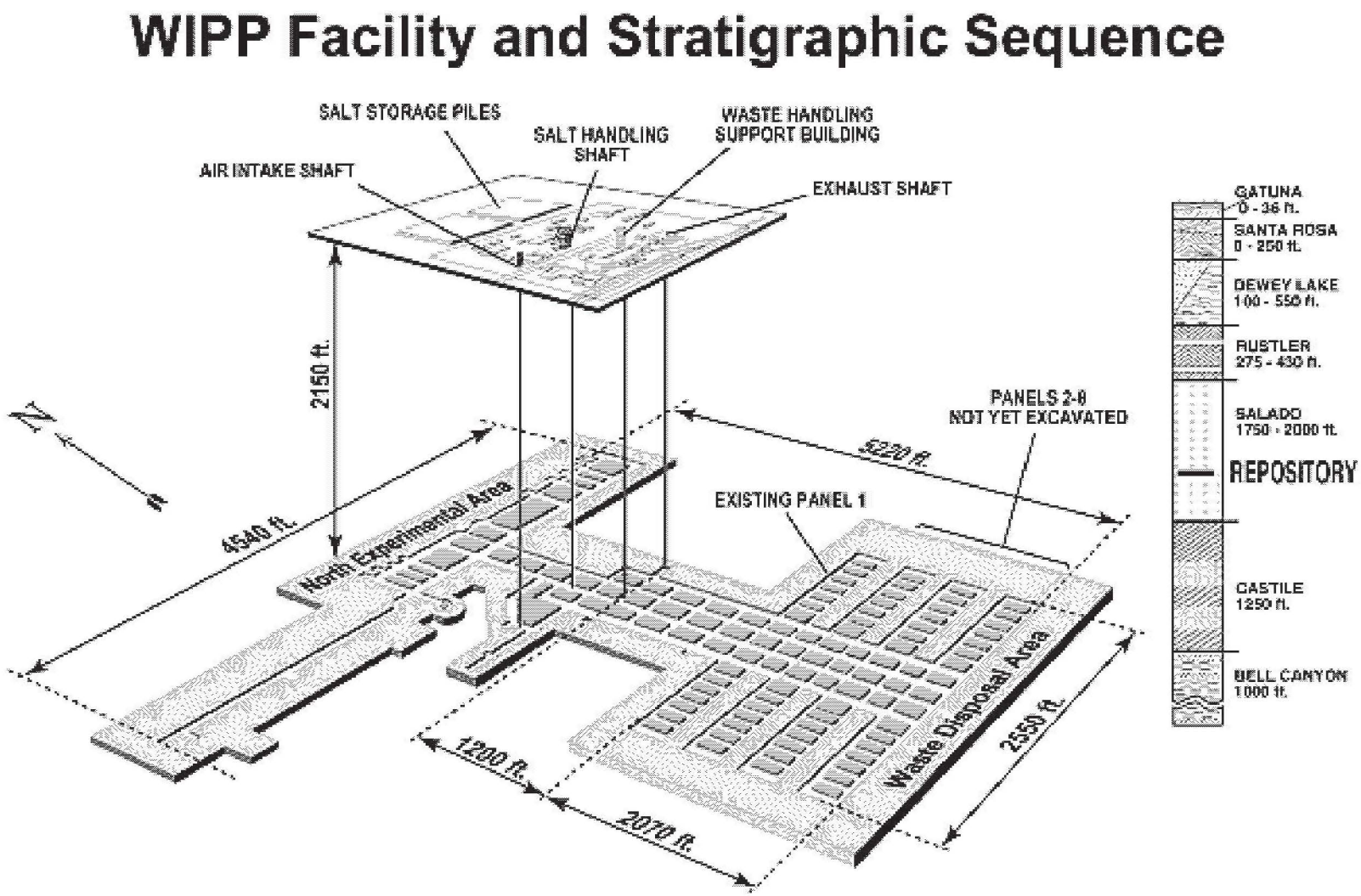

Figure 1.2 The WIPP facility and stratigraphic sequence. Panel 1 is currently in use. The mining of Panel 2 was completed on October 13, 2000. SOURCE: DOE, 2000h.

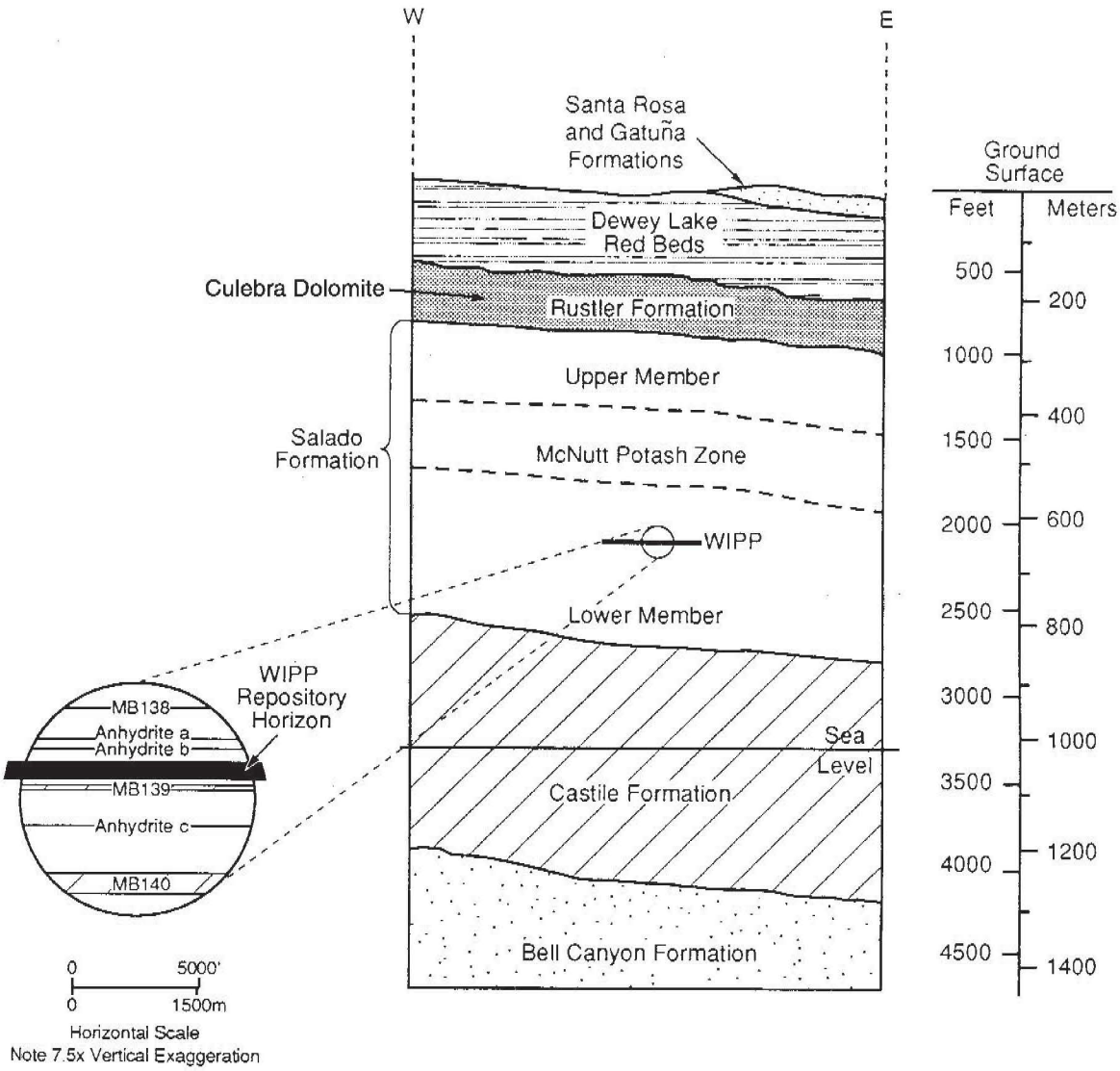

Figure 1.3 WIPP stratigraphy and depths of four key formations (Castile Formation, Salado Formation, Rustler Formation, and Dewey Lake Red Beds) including the position of the WIPP repository within the Salado. The Culebra Dolomite is one of the members of the Rustler Formation. It is approximately 7-8 meters thick at the WIPP site. Because it is a relatively transmissive unit, the Culebra is important to the groundwater flow model for the WIPP site. Inset shows finer-scale stratigraphy around the repository horizon, with marker beds and other thin beds. Adapted from Jensen et al. (1993).

Table 1.1 Inventory of the Most Abundant Radionuclides Expected in the Repository.[a]

Radionuclide	Contact Handled (CH)-Transuranic (TRU) Waste (Ci/m^3)	Remote Handled (RH)-Transuranic (TRU) Waste (Ci/m^3)
Am-241	2.62	0.842
Ba-137m	4.53×10^{-2}	28.9
Cm-244	0.187	4.45×10^{-2}
Co-60	3.83×10^{-4}	1.47
Cs-137	4.78×10^{-2}	30.5
Pu-238	15.5	0.205
Pu-239	4.66	1.45
Pu-240	1.25	0.715
Pu-241	13.7	20.0
Sr-90	4.07×10^{-2}	29.5
Y-90	4.07×10^{-2}	29.5

[a]The expected volumes of CH waste and RH waste are, respectively, 160,000 and 7,079 cubic meters.

SOURCE: DOE, 1996.

Table 1.2 Repository Inventory by Waste Category

Waste Category	Inventory (wt%)
Iron-based metal, alloys	14
Steel container material	12
Aluminum-based metal, alloys	1
Other metal, alloys	6
Other inorganic materials	3
Vitrified	5
Cellulosics	4
Rubber	1
Plastics	3
Plastic container or liner material	2
Solidified inorganic material (including cement)	4
Solidified organic material (not including cement)	0
Solidification cement	4
Soils	4
MgO backfill	37

SOURCE: Knowles et al., 2000.

ing not only the long-term risk of the WIPP, but also the potential radiation exposure of workers who handle, repackage, and transport the waste.

The WIPP has been under study since the mid-1970s, began construction in January 1981, was certified by the U.S. Environmental Protection Agency (EPA) in May 1998, and received its first transuranic waste shipment from the Los Alamos National Laboratory in March 1999. The first out-of-state shipment was received in June 1999 from the Rocky Flats Environmental Technology Site, and in September 2000, the first mixed-waste shipment was received from the Idaho National Engineering and Environmental Laboratory (INEEL). Figure 1.5 shows the main waste generators and the transportation routes to the WIPP.

Sidebar 1.2 What Is TRU Waste And How Is It Classified?

Transuranic waste is waste that contains alpha particle-emitting radionuclides with atomic numbers greater than that of uranium (92), half-lives greater than 20 years, and concentrations greater than 100 nanocuries per gram of waste. TRU waste is classified according to the radiation dose rate at package surface. As defined in the LWA, **contact-handled** (CH) TRU waste has a radiation dose rate at package surface not greater than 200 millirem per hour; this waste can safely be handled directly by personnel. **Remote-handled** (RH) TRU waste has a radiation dose rate at package surface of 200 millirem per hour or greater, but not more than 1,000 rem per hour (U.S. Congress, 1992); this waste must be handled remotely (i.e., with machinery designed to shield the handler from radiation). Alpha radiation is the primary factor in the radiation health hazard associated with TRU waste. Alpha radiation is not energetic enough to penetrate human skin but poses a health hazard if it is taken into the body (e.g., inhaled or ingested). In addition to alpha radiation, TRU waste also emits gamma and/or beta radiation, which can penetrate the human body and requires shielding during transport and handling. RH TRU waste has gamma and/or beta radiation-emitting radionuclides in greater quantities than exist in CH TRU waste (DOE, 2000a).

TRU waste is further classified as TRU waste or **mixed** TRU waste. Mixed TRU waste contains both radioactive materials regulated under the Atomic Energy Act and hazardous chemical compounds regulated under the Resource Conservation and Recovery Act.

The total activity of the waste expected to be disposed at the WIPP is estimated to be approximately 7 million curies (of which 6 million is from CH waste), including 12,900 kilograms of plutonium distributed throughout the waste in very dilute form. According to the Compliance Certification Application (CCA), the volume of CH waste expected in WIPP is 160,000 cubic meters and that of RH waste is 7,079 cubic meters (DOE, 1996).

The WIPP is designed to dispose of approximately 175,000 cubic meters of transuranic waste. Total activity of the waste is estimated to be approximately 7 million curies. The largest fraction of this activity comes from approximately 12,900 kilograms of plutonium distributed throughout the waste in very dilute form. TRU waste is classified as contact-handled (CH) and remote-handled (RH) waste, according to the radioactivity at the container surface [3] (see Sidebar 1.2). According to the National TRU Waste Management Plan, the disposal of RH waste will not begin before early 2002 (DOE, 2000a). Since most of the radioactivity is coming from the plutonium in CH waste (approximately 85 percent of the total curies inventory, see Table 1.1), the disposal of RH waste should not represent a significant added risk to the repository. A further issue concerning RH waste will be discussed in relation with the emplacement of backfill in Chapter 2.

This report presents the results of a National Research Council (NRC) study of operational, technical, and programmatic issues associated with the long-term performance of the WIPP. Previous studies

[3] This type of classification is intended for the protection of workers handling radioactive waste. Public health protection standards have also been taken into account in the design and operation of the WIPP.

Figure 1.4 Radiography of a transuranic waste drum. SOURCE: DOE, 2000i.

by the NRC's committee on the WIPP covered ongoing activities in preparation for the opening of the facility. This study is the first to address the WIPP as an operational repository.

The seeds for this report were planted during the preparation of the 1996 report by the previous WIPP committee (NRC, 1996a). That committee observed that the long operating period of the WIPP (at least 35 years and possibly much longer) provides an opportunity to conduct studies and investigations that would decrease some of the uncertainties about the long-term safety performance of the repository.

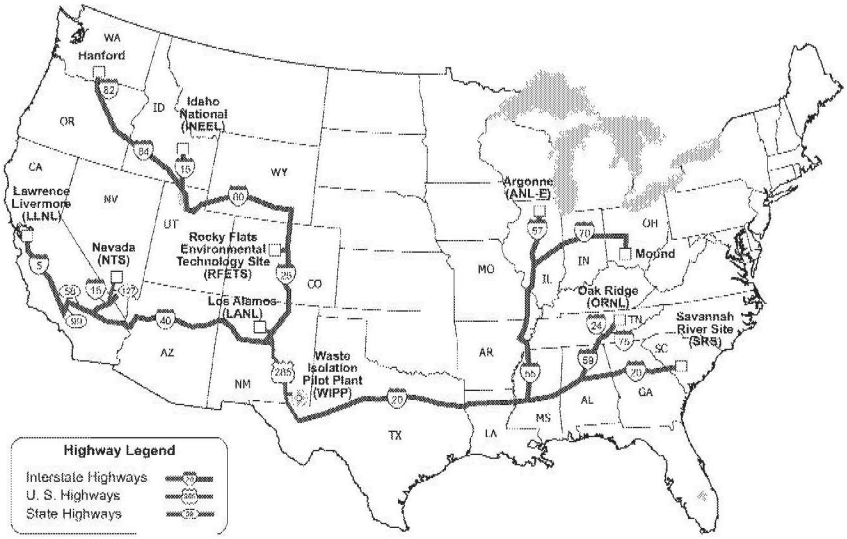

Figure 1.5 Defense transuranic waste generating and storage sites and primary transportation routes. SOURCE: DOE, 2000j.

Thus, this committee has focused on identifying studies and investigations "that would enhance the assessment of long-term repository performance," as noted in the statement of task in the Preface to this report. The second part of this committee's statement of task addresses potential improvements to the National Transuranic Waste Management Plan, also known as the National TRU Program. This program coordinates the management and disposal activities of TRU waste between the WIPP and the 23 generator sites. As written in the statement of task, the committee must "identify areas for improvement in the TRU waste management system that may increase system throughput, efficiency, cost-effectiveness, or safety to workers and the public." The result is the consideration of issues having to do with waste characterization, packaging requirements, waste transportation and handling, and emergency preparedness.

The two-part statement of task required very different skills and approaches: the first part is related to site performance, while the second is programmatic. The committee has chosen to structure this report into two primary sections that can be mapped directly to the two principal requirements of the statement of task. The part of the statement of task relevant to the long-term performance of the repository is addressed in the context of the repository performance confirmation program, in reference to enhancing confidence in the performance assessment models. The task relating to programmatic issues is addressed in the context of the National TRU Program.

SITE PERFORMANCE AND CHARACTERIZATION

To evaluate the long-term performance of the disposal system, the DOE uses a technique developed especially for predicting the behavior of geologic repositories over the thousands of years required for waste isolation. This technique is called "performance assessment." Performance assessment (PA) is a multidisciplinary, iterative, analytical process that begins by using available information that characterizes the waste and the disposal system (the design of the repository, the repository seals, and the natural barriers provided by the host rock and the surrounding formations). To obtain certification for the WIPP,

the DOE used the PA tool to estimate the releases of radionuclides within the first 10,000 years, based on the probabilities of relevant features, events, and processes occurring.

The performance of the repository has been assessed for two main scenarios: the undisturbed repository scenario and the human intrusion scenario. If the repository is left undisturbed, the only release pathway for radionuclide release into the environment is through leakage of brines containing radioactive materials into the environment. Scenarios for the disturbed case involve releases resulting from boreholes drilled inadvertently into the waste. According to the Land Withdrawal Act (U.S. Congress, 1992), the DOE must exercise active institutional controls[4] on a perimeter of land extending up to 5 kilometers from the boundaries of the WIPP site for 100 years after the closure of the repository. During this period, there will be no natural resource extraction activities in the site. Between 100 and 700 years after the closure of the repository, the site will be under passive institutional controls.[5] During this period, drilling activity is expected to resume and to reach its maximum after 700 years, when the land will be released to public use and the WIPP site will be no longer controlled. Uncontrolled extraction activities would increase the probability of drilling directly into the repository.

Sensitivity analyses are used by the DOE to determine which parameters of the disposal system exert the greatest effect on performance (DOE, 1996). Performance assessment calculations show that in the absence of human intrusion, brine inflow and gas generation are the most important parameters affecting the performance of the WIPP (Helton, 2000d). In the case of the disturbed scenario, the most important parameter is the borehole permeability (Helton, 2000e). Sidebar 1.3 describes the main results of the performance assessment and their implication for the long-term performance of the WIPP. For a complete review of the PA for the WIPP see Apostolakis et al. (2000). The containment requirements are set by the regulatory agency, the U.S. Environmental Protection Agency, and are listed in Sidebar 1.4. More information on regulatory compliance can be found in the previous NRC report on the WIPP (NRC, 1996a).

The EPA certified the WIPP on the basis of the performance assessment included in the Compliance Certification Application (CCA). While various mechanisms and scenarios, including their uncertainties, were considered in the performance assessment, the question now is how to enhance the degree of confidence expressed by the performance assessment results. The conceptual structure and the development of scenarios for the WIPP's PA are described respectively in reference Helton et al. (2000a) and Galson et al. (2000).

The uncertainties in the PA for the WIPP are analyzed in Helton et al. (2000b,c). The current committee on the WIPP believes that better knowledge of site performance and better site characterization are important in decreasing the uncertainties, and therefore possibly enhancing the confidence, in the performance assessment of the repository. The committee's approach to examining the PA was to focus on underlying assumptions and results of the performance assessment. Of particular interest to the committee was how the results could be impacted by uncertainties and relied upon EPA's certification for proof of the ability of the computer program to represent the model adequately. The issues and their uncertainties are discussed in Chapter 2 as site performance and site characterization issues.

THE NATIONAL TRANSURANIC PROGRAM

The National Transuranic Waste Management Plan, also known as the National TRU Program, is a plan that organizes the activities concerning storage, characterization, packaging, handling, transporta-

[4] Active institutional controls imply restrictions on land access or use.

[5] Passive institutional controls imply the identification of the controlled area through signs or markers; also, records are kept on the repository and land use.

Sidebar 1.3 Performance Assessment and Regulatory Acceptance

The Environmental Protection Agency's certification of the WIPP facility was based on the performance assessment submitted as a part of the U.S. Department of Energy's Compliance Certification Application. The regulatory basis for the PA for the WIPP is described in Howard et al. (2000). The PA is a computerized, mathematical model that evaluates the performance of the WIPP repository over its lifetime. The main results of this model are shown in Figure A below, and are compared there with the acceptance criterion established by the EPA shown as the line in the upper right corner. These requirements are reported in Sidebar 1.4. The horizontal axis is a measure *C*, of the total radioactivity released from the repository to the biosphere during its nominal 10,000-year lifetime. The vertical axis shows the "probability of release, " that is, at any value of *C*, the probability that the actual release from the repository will exceed that value. Such a curve is called a "complementary cumulative distribution function (CCDF)." It expresses quantitatively the state of knowledge of the analysis team about how much radioactivity will be released from the repository over its lifetime. It is important to observe that the curve is well to the left of the regulatory acceptance boundary set by the EPA, meaning that the repository is in compliance with the regulation.

A variation on this form of presentation is shown in Figure B. In this figure, a family of CCDFs is traced to show the different effects of uncertainties arising from possible human intrusions into the repository (mainly by drilling into it) and the geotechnical uncertainties (e.g., physical and chemical properties of the salt). Again, the important result is that the whole family of curves is well to the left of the EPA acceptance boundary. In addition, the curves bunched close together indicate a reasonable bound on the uncertainties and add confidence that a substantial margin of safety exists.

continued

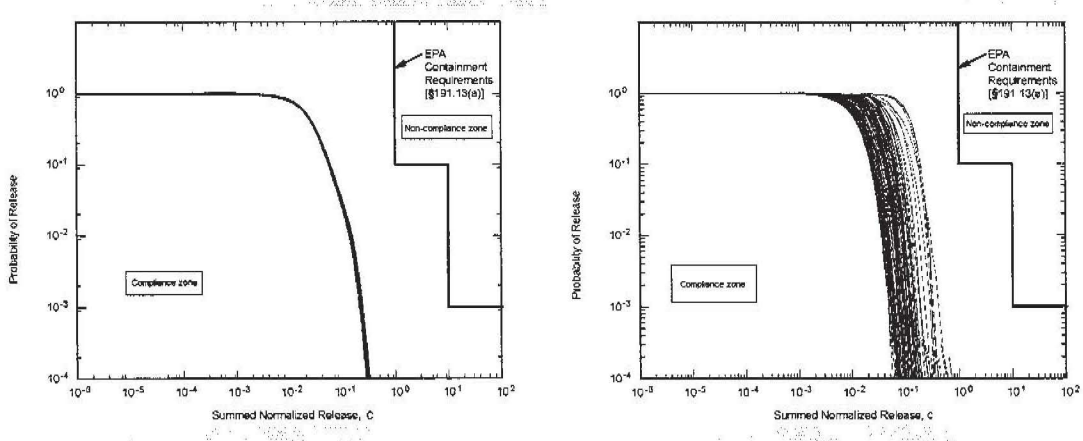

Figures A (*left*) **and B** (*right*) Complementary cumulative distribution functions resulting from the performance assessment. In A, the probability of radionuclide release from the repository is compared to the acceptance criteria. In B, a family of CCDF curves is traced to show the effect of different uncertainties. The "summed normalized release" of radionuclides C, is related to WIPP containment requirements in Sidebar 1.4. The term "normalized" release means that the release *Cj* is divided by the release limit *Lj*. The use of the term "summed" indicates the sum of all *Cj/Lj* over all the radionuclides with half-life greater than 20 years. The summed normalized release represents the total radioactivity released from the repository to the biosphere during its nominal 10,000-year lifetime. More details on CCDFs can be found in NRC (1996a). SOURCE: DOE, 2000k.

Sidebar 1.3 Continued

The committee recognizes that computing the performance of an underground repository over many millennia into the future cannot be done today with the accuracy with which, for example, the performance of an airplane wing can be simulated. Nevertheless, the results of this performance assessment are considered adequate by experts and regulators to support the decision to move waste from its surface storage to the WIPP (EPA, 1998).

Sidebar 1.4 Containment Requirements

Title 40 CFR 191.13 requires that "disposal systems for . . . transuranic radioactive wastes shall be designed to provide a reasonable expectation, based on performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:

1. Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 . . .; and
2. Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1. . .".

To explain how these requirements are applied to the WIPP, let L_j be the limit shown in the above table for radionuclide j. Suppose for the moment that WIPP had only one radionuclide, j, and let C_j be the total release of that radionuclide to the environment, measured in curies per 1000 metric tons of heavy metal (MTHM), during its 10,000 year lifetime. Then the first requirement of 40 CFR 191.13 means that the probability of C_j being greater than L_j should be less than 0.1.

That is: $p(C_j/L_j > 1)$ should be < 0.1

The second requirement then indicates that

$p(C_j/L_j > 10)$ should be < 0.001.

The actual inventory of radionuclides C, is defined as:

$$C = \sum_{j}^{N_j} \frac{C_j}{L_j}$$

with N_j being the total number of radionuclides with a half-life greater than 20 years.
The requirements then become:

$p(C>1)$ should be < 0.1
$p(C>10)$ should be < 0.001

Table 1. Release Limits per 1,000,000 Curies of TRU Waste per 10,000 Years[a]

Radionuclide	Release Limit (curies per 1000 MTHM)
Americium-241 or 243	100
Carbon-14	100
Cesium-137 or 137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, 239, 240, or 242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230 or 232	10
Tin-126	1,000
Uranium-233, 234, 235, 236, or 238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life grater than 20 years that does not emit alpha particles	1,000

[a] Containment requirements for selected isotopes as declared in Title 40 CFR 191, Appendix A (EPA, 1995). The release limits specified here scale with the quantity of waste in a repository; for this reason, they are specified in terms of curies that may be released per 10,000 years per 1,000 metric tons of heavy metal (MTHM). For a repository such as WIPP, which is intended to contain transuranic wastes, EPA has established in 40 CFR 191 that 1,000 MTHM is equivalent to 1,000,000 curies of TRU wastes with greater than 20-year half-lives. Therefore, the limits specified are applicable per million curies of TRU waste.

tion, and disposal of defense-related transuranic waste to the WIPP from the 23 generator sites. The National TRU Program is administered by the DOE's Carlsbad Field Office. The goals of the National TRU Program are the following:

- achieving regulatory compliance among all the sites,
- reducing risk while maximizing rate of TRU waste disposal,
- reducing mortgage costs by closing the generators' sites as soon as possible, and
- using the WIPP effectively by coordinating the shipments with the repository's waste-handling and disposal capabilities.

The issues considered in this report relate primarily to waste characterization and packaging and waste transportation. Because of their importance in the near term for achieving the beginning of operation at the WIPP, the committee focused on these issues in its interim report, reported in Appendix A1. In Chapter 3 of this final report, the committee re-visits the issues related to characterization, packaging, and transportation of the wastes, including communication systems and emergency preparedness. The issue of hydrogen gas generation, as it applies to both waste characterization and transportation, is also discussed in Chapter 3.

2

Repository Performance Confirmation

The performance of geological repositories is evaluated on the basis of their ability to comply with a series of regulatory performance criteria, defined in Title 40 of the Code of Federal Regulations Part 191 (40 CFR 191; EPA, 1985). In the case of the WIPP, the time of compliance with the containment requirements formulated by the U.S. Environmental Protection Agency (EPA) is 10,000 years (see Sidebar 1.4). Of course, the issue does not end at 10,000 years; for example, the risk-controlling radionuclide in the WIPP is plutonium-239, which has a half-life of 24,000 years. The intent of a geological repository is to contain the waste for the indefinite future (e.g., > 10,000 years).

The WIPP was certified by the EPA through a comprehensive process based primarily on a detailed performance assessment (DOE, 1996; see also Sidebar 1.2). Of course, acceptance of the performance assessment (PA) is conditional on several factors that are designed to offset the many uncertainties involved. One of the EPA's requirements is that the DOE must implement a monitoring program designed to provide confidence in the assessed performance of the repository. Furthermore, every five years, the DOE must apply to the EPA for recertification of the WIPP. The recertification application must show evidence that the repository is performing as assessed.

A monitoring program that emphasizes factors contributing mostly to performance uncertainties could provide important evidence of the ability of the repository to perform its intended function. Therefore, the committee has chosen as the theme of this review to be "performance confirmation through monitoring." The strategy of the committee is to focus on safety and monitoring activities that would best enhance confidence in the long-term performance and reduce uncertainties in the performance assessment of the WIPP.

The recommendation to implement an in-situ monitoring program was endorsed by a previous NRC committee on the WIPP in a letter report to the Hon. L. P. Duffy (NRC, 1992). Quoting from that report, "The panel emphasizes that it supports the notion of underground testing with TRU wastes, provided that the underground location does not prevent important tests from being carried out (e.g., the measurement of brine compositions in contact with real waste or progression of gas generation experiments without purging), and that the tests can be continued for sufficient time to provide useful information."

The long operational phase of the WIPP repository (at least 35 years and possibly as long as 100 years) provides an unusual, and perhaps unprecedented, opportunity to implement a monitoring program and reexamine the performance assessment with information based on direct observations of the total system prior to closure of the repository. Although a time frame of 35-100 years is short compared to the 10,000-year period of compliance, the committee believes that it is long enough to develop and implement a monitoring program to observe the development of repository responses. Indeed, the rates of important processes such as salt creep, brine inflow, and microbial activity are predicted to be the highest during the first 50 to 100 years (Knowles and Economy, 2000; NRC, 1996a). If these responses confirm assumptions in the performance assessment, this will reduce uncertainty in the projections of long-term performance of the repository and could improve public confidence in the repository performance.

The ongoing DOE's monitoring program required by the EPA as part of the certification, is described in the next section. The committee strongly supports such a program but believes it could be more focused and risk-informed. The difference in focus between what is planned and what the committee suggests is also discussed.

REGULATORY REQUIREMENTS FOR MONITORING

A monitoring plan for the WIPP was included in 40 CFR 194 under the requirements for the certification of the repository by the EPA. The purpose of the monitoring plan is to confirm that the repository is performing as expected according to the model in the Certificate of Compliance Application. The DOE proposed a monitoring plan, which was accepted by the EPA in 1998 in the certification decision, to address the requirements of the regulations in 40 CFR 194.

The DOE described its monitoring program in the CCA and indicated that it would span 150 years (50 years pre-closure and 100 years post-closure). The DOE program evolved from screening 91 potentially significant parameters down to 10. The 10 parameters were divided among physical measurements in the Salado Formation, hydrological properties in the non-Salado settings, and activity levels of the waste. The four parameters to be measured in the Salado Formation relate to creep closure and stresses, extent of deformation, initiation of brittle deformation, and displacement of deformation features. The program calls for pre-closure monitoring only for the Salado parameters and pre- and post-closure for the non-Salado parameters. Waste activity is to be monitored only during pre-closure. In the DOE program, pre-closure monitoring in waste storage rooms ends with the sealing of individual panels of rooms; hence, pre-closure monitoring of emplaced waste is very limited. The parameters that the DOE is currently monitoring to comply with 40 CFR 194 are shown in Table 2.1.

The committee's proposed performance confirmation monitoring plan is very similar to the DOE's monitoring program. The significant difference between the DOE monitoring program and the committee proposal is that the committee's recommended plan includes monitoring rooms and panels after sealing of the panels and extends until closure of the repository and sealing of the shafts. The committee has put greater emphasis on such issues as brine inflow, gas generation, salt rock deformation following sealing of the panels, auxiliary material inventory in the repository, and radiogenic measurements.

The committee identified important issues relative to the long-term safe performance of the WIPP repository on the basis of the DOE's performance assessment (DOE, 1996), past committee reports, and numerous briefings on the WIPP. The criteria for identifying issues were related principally to the sources of uncertainty in the performance assessment and to the safety of workers and the public. Several of the issues are interrelated but are treated separately to emphasize important points. The following paragraphs describe in detail the issues of consideration in the performance confirmation monitoring program proposed by the committee. The issues have been grouped as *site performance* issues and *site characterization* issues.

Table 2.1 Parameters Currently Monitored by the DOE to Comply with 40 CFR Part 194.42[a]

Parameter Monitored in the WIPP	Pre-closure Monitoring?	Post-closure Monitoring?
Salado physical parameters		
Creep closure and stresses	YES	NO
Extent of deformation	YES	NO
Initiation of brittle deformation	YES	NO
Displacement of deformation features	YES	NO
Non-Salado hydrological properties		
Culebra groundwater composition	YES	YES
Probability of encountering a Castile brine reservoir	YES	YES
Drilling rate	YES	YES
Culebra change in groundwater flow	YES	YES
Subsidence measurements	YES	YES
Waste related parameters		
Waste activity	YES	NO

[a] EPA (1996).

SITE PERFORMANCE ISSUES

The key site issues that should be monitored during the pre-closure period to confirm the performance of the WIPP repository are described below.

Brine Migration and Moisture Access to the Repository

The presence or absence of brine in the WIPP rooms is a key issue in the performance of the repository. Without brine there will be no radionuclide mobilization and transport or any gas generation from corrosion of the steel drums. The brine sources for the undisturbed repository are seepage from brine-filled void spaces in the undisturbed geological setting, the humidity of the repository air, and water used during mining operations. In the long term, after repository closure, additional sources of brine could include accidental fluid injections by inadvertent human intrusions (see section "Oil, Gas, and Mineral Production" and Appendix B). Brine volumes from enhanced recovery fluid injection operations have the potential to be a source of much greater brine inflow than that expected from any other water sources in the undisturbed geological setting. A concern is the possible failure of a well casing or cement outside the casing during an injection operation and fluid leaking into overlying formations and flowing laterally along one of the several anhydrite layers in the Salado Formation.

A previous NRC committee analyzed the brine accumulation issue and concluded that "the formation of an abundant mobile fluid in a repository at the WIPP site . . . is very improbable." Nevertheless, the same committee recommended a "well conceived experimental program at WIPP to reduce remaining uncertainties" (NRC, 1988). The present committee is also in favor of a monitoring program to complement DOE's current program. It would be informative to monitor the brine flow rate into the first panel, or panels, of the WIPP facility that are filled and sealed. Monitoring from inside the face of the seal should be possible for decades after the panel is sealed and would contribute to enhancing confi-

dence in the performance of the repository. Monitoring the humidity and the accumulation of standing brine would indicate the ingress of brine, although salt mines are notoriously dry and probably no standing water will develop. The monitoring of brine inflow and of the humidity in the WIPP should continue at least until the shafts are sealed and longer if feasible.

According to Knowles and Economy (2000), the brine inflow rate will be maximum within the first 50 to 100 years from the mining of the repository and will stabilize progressively after 200 years. The rate of brine inflow depends on the porosity of the medium. The mining of the salt in the repository creates alterations of the stress field of the surrounding rock and forms micro fractures in the salt around the excavation (disturbed rock zone, or DRZ). Compared to the intact salt, the DRZ will have an increased porosity because of all the micro fractures. Over time, the porosity of the DRZ decreases as salt creep continues, thereby decreasing brine inflow. Therefore, the monitoring of brine inflow is particularly important during the pre-closure phase.

At closure, the panel conduits for the instrumentation would be plugged permanently to ensure the sealing of the repository. Maintaining instrumentation at the repository horizon beyond closure of the shafts could be impractical, unless new technologies allow remote monitoring of the repository avoiding instrument conduits through the seals.

***Recommendation:* The committee recommends pre-closure monitoring of the WIPP repository to gain information on brine migration and moisture access to the repository. Observation should continue at least until the repository shafts are sealed and longer if possible. The committee recommends that the results of the on-site monitoring program be used to improve the performance assessment for recertification purposes.**

Gas Generation in the Repository

Gas generation within the WIPP is one of the issues for consideration in the overall performance of the repository. There are two possible effects of gas in the repository. The first is a physical effect due to pressure buildup from any gas. Gas may generate sufficient pressure to eject repository materials during a human intrusion event. Gas pressure could also retard creep closure and brine inflow. Gas pressure in the repository is considered one of the main uncertainties in the PA concerning radionuclide release from the WIPP (Berglund et al., 2000; Helton et al., 2000d; Stoelzel et al., 2000; Vaughn et al., 2000). A performance assessment scenario that could cause violation of the EPA repository release limits involves ejection of waste material through a borehole. In this scenario, it is calculated that the gas pressure at the repository horizon has to be greater than approximately 8 megapascals[1] to result in ejection of cuttings, cavings, and spallings that might contain radionuclides from the repository (Berglund, et al., 2000; DOE, 1996). If the gas pressure approaches the lithostatic pressure, a radionuclide release along open fractures could result.

The second effect of gas generation in the repository is chemical. The main gaseous products potentially formed in the repository are carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4), nitrogen (N_2 or

[1] The value of 8 megapascals is the pressure exerted by a column of brine-saturated drilling fluid at the depth of the repository (Stoelzel and O'Brien, 1996). This threshold in pressure was calculated in the PA on the basis of drilling technologies using mud. The public strongly criticized this assumption because it did not take into account the increasingly popular air drilling technology. However, the EPA analyzed the PA, performed supplementary calculations, and reached the conclusion that the repository would still be in compliance with release limits, even in the event of a human intrusion through air drilling (EPA, 1998).

various nitrous oxides), and hydrogen sulfide (H_2S) (Lappin and Hunter, 1989). Most of concerns come from H_2 and CO_2. Hydrogen is a flammable gas and, in the presence of certain amounts of oxygen or water vapor, could lead to an explosion. In the case of CO_2, its solubility in any brine seeping into the repository could lower the pH of the brine, which would increase actinide solubility (Novak and Moore, 1996) as shown later in this chapter.

The sources of gas generation in the repository are three: radiolysis, metal corrosion, and bacterial action. The PA shows that total gas production is negligible under humid conditions for all substrates.[2] The main uncertainty concerns CO_2 production by microbial degradation reactions; this uncertainty was acknowledged in the PA by assigning a probability of 0.5 to the occurrence of significant microbial activity (DOE, 1996; Larson, 2000). The previous NRC committee on the WIPP (NRC, 1996a) also concluded that gas generation will be minimal, even when microbial degradation of organic material is taken into account. Although this committee concurs with the previous NRC committee and with the DOE that there is "minimal" evidence of gas generation in the WIPP, uncertainties concerning gas generation are still present. The committee is concerned that experimental data were extrapolated from laboratory experiments performed under conditions that are not indicative of the actual environment in the repository.

For instance, in the case of gas generated by radiolysis of brine and organic materials, the majority of experiments were performed with high doses of radiation, which does not apply to TRU waste. Moreover, factors that significantly decrease the rate of radiolysis—matrix depletion, pressure, and inhibition by other chemical compounds—were not taken accurately into account (INEEL, 1998; Molecke, 1979b).

In the case of microbial degradation of cellulosic compounds, rates of gas generation were extrapolated from laboratory experiments performed under humid conditions (70 percent humidity), which are not representative of the intrinsic dryness of salt repositories (Francis et al., 1997). In the case of metal corrosion, gas will not result without brine inflow, an event strongly affected by uncertainties. Furthermore, the nature of the interactions between gas-phase chemicals, the influence of pressure, and of corrosion rates is still not well understood (Telander and Westerman, 1996).

The gas generation rate is expected to be maximum during the pre-closure period because it depends on the brine inflow rate for microbial degradation, corrosion, and radiolysis (NRC, 1996a). As shown in the previous section, the brine inflow rate is expected to be maximum at the beginning of the repository life. Therefore, it is important to monitor gas generation rates and volumes during the first 35 to possibly 100 years. Furthermore, continuous monitoring for gas could lead to the early detection of anomalous behavior of the repository.

Recommendation: **The committee recommends pre-closure monitoring of gas generation rates, as well as of the volume of hydrogen, carbon dioxide, and methane produced. Such monitoring could enhance confidence in the performance of the repository, especially if no gas generation is observed. Observation should continue at least until the repository shafts are sealed and longer if possible. The results of the gas generation monitoring program should be used to improve the performance assessment for recertification purposes.**

[2] A substrate is a generic material, whether it is metal, natural fiber, or plastic, that generates gas via various mechanisms described in this section.

Magnesium Oxide Backfill

In the framework of repository performance confirmation, an issue closely related to brine access and gas generation in the WIPP is the performance of magnesium oxide (MgO) used as backfill. The backfill is introduced in the rooms to fill voids in the disposal locations, thus enhancing the healing process and facilitating the encapsulation of waste in salt. The choice of MgO as backfill is based on its chemical properties in addition to its properties as backfill. If brine is present in the repository, MgO will mix with it to form a compact material that will encapsulate the waste (Berglund et al., 1996). The water uptake of MgO from the brine will result in a volume expansion and in the precipitation of salt from the brine that will heal all pathways for later brine penetration.[3] If brine is not present in the rooms, creep encapsulation of waste would not progress as readily.

The chemical role of MgO is to provide some control of the chemical environment of the waste by reacting with brine and scavenging the CO_2 potentially formed in the repository. In presence of CO_2, brine pH will be decreased by the formation of carbonic acid. In the acid pH range, soluble actinide carbonate complexes can then form, increasing actinide solubility (Novak and Moore, 1996). In presence of MgO scavenging all CO_2, the pH will remain in the alkaline range (9.2 - 9.9), where actinides are less soluble and less likely to be released into the environment. The rationale for this expected action of MgO relies on the following assumptions:

1. There would be significant inflow of brine into the repository's rooms.
2. Microbes would be present and react with organic waste material to form CO_2.
3. CO_2 would dissolve and acidify the brine by forming carbonic acid.
4. MgO would react with water in the brine to precipitate brucite [$Mg(OH)_2$].
5. Brucite would remove carbonic acid from the solution to form magnesite ($MgCO_3$) via intermediate products such as hydromagnesite [$4MgCO_3 \bullet Mg(OH)_2 \bullet 4H_2O$].
6. These reactions with MgO would maintain the pH of brine between 9.2 and 9.9.

As mentioned in the previous section, there are uncertainties concerning assumption 1 about the presence of a significant amount of brine in the rooms. Since assumption 2 relies on microbial generation of CO_2 under repository conditions, it is also affected by uncertainties (see previous section). Moreover, it is unclear whether the rates of reactions in assumptions 4 to 6 are sufficiently high to be effective. The committee has several concerns. How quickly does brucite form at 25°C (Krumhansl et al., 1999; Papenguth et al., 1999)? How quickly does brucite react with carbonate at various carbonate concentrations and brine compositions?[4] When will the water trapped in hydromagnesite be returned to the fluid phase?[5]

There are also uncertainties in other factors related to the chemical environment, including the amount and timing of brine inflow to form the MgO-based chemical buffer and the presence and effectiveness of microbes responsible for the CO_2. On the issue of brine inflow, there is evidence that the salt will creep in the rooms and fill all of the openings in 100 to 150 years (Callahan and DeVries, 1991;

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[3] If the rate of brine inflow is too high, it is uncertain whether MgO can form a compact material around the waste.

[4] The rate to reach the compliance objective (26 mole percent MgO converted) decreases with decreasing CO_2 partial pressure (Krumhansl et al., 1999).

[5] The time to transform hydromagnesite to magnesite was reported to vary between 18-200 (Zhang et al., 1999) and 2.5-1,500 years (Krumhansl et al., 1999), depending on brine composition.

Knowles et al., 2000; Stone, 1997). The absence of void spaces should provide additional protection against extensive chemical reactions between brine and the waste in a short period of time.[6]

The use of MgO in the repository as chemical backfill raises the additional issue of its placement. Because MgO must be in close contact with the drums to better scavenge all CO_2 generated from the waste and because of the way the drums are stacked in the rooms, it is not possible to add MgO mechanically after the room is filled. MgO backfill is as a dry, granular, pelletized material packaged in bags of two different sizes: a smaller bag of about 25 pounds, called the "minisack," and a large bag weighing approximately 4,000 pounds, known as the "supersack." The minisacks are placed manually around and between the drums, and the supersacks are placed with a forklift on the top of each waste stack.

Based on a study by the DOE, it appears that emplacing MgO around the waste adds about 0.726 person-rem per year to the collective dose caused by waste handling. Given that the expected collective dose to waste-handling personnel is 14.6 person-rem per year, this corresponds to about 5 percent of the total dose incurred from waste operations (DOE, 2000b). The committee does not consider this additional dose to be significant. However, once remote-handled (RH) waste and possibly high-specific-activity waste in CH waste such as plutonium-238 or americium-241 are introduced into the repository, the exposures to personnel placing the MgO bags will be considerably increased.

Considering the uncertainties about the chemical performance of the MgO backfill, the committee questions the value of its use in the repository. The same concern was expressed by some of the peer review panels of the CCA (DOE, 1996, Chapter 9.3.2). This is especially true given the small but measurable additional radiation exposure to workers involved in MgO bags emplacement. The committee is not convinced of any major chemical advantages of the MgO backfill and, if its benefits to the long-term performance of the repository cannot be verified, the option to discontinue its use should be considered.

Recommendation: **The committee recommends that the net benefit of MgO used as backfill be reevaluated. The option to discontinue emplacement of MgO should be considered.**

Salt Healing and Disturbed Rock Zone Integrity

The period between placement of waste and closure of the repository provides a window of opportunity to monitor significant deformation of the salt and self-healing of the DRZ. The DRZ is the zone around an excavation in the host rock salt where the stress field has been modified sufficiently to cause the formation of microfractures in the rock salt. Substantial deformation of the salt will occur during the operation phase, which is important in assessing the self-sealing (healing) characteristics of the repository. After an initial period of rapid deformation (a few years to decades), the rooms are expected to deform, crush, and be entirely entombed by salt within 100 to 150 years (Callahan and DeVries, 1991; Knowles et al., 2000; Stone, 1997). Since the waste drums will be immobilized in a relatively short period of time (compared to 10,000 years of compliance), the radionuclide mobility values used in the performance assessment might have been overestimated. This implies less migration of radionuclides from the repository into the environment. In addition to the general deformation and local healing of rooms and panels, an important general healing must take place in the DRZ around rooms, panels, and shafts to achieve complete closure of the disposal region.

The effect of the DRZ around WIPP rooms and panels and around the shaft seal system is important in assessing the safety performance of the repository. A complete analysis of the performance of the

[6] A short period of time compared to the 10,000 years mentioned in the containment requirements (see Sidebar 1.4).

shaft seal system is given in Hansen and Knowles (2000). As with all the factors affecting the performance of the repository and because of the complexity of salt rock behavior, there is uncertainty in the timing and degree of self-healing of the DRZ needed to achieve the expected isolation in the mined regions. In the committee's opinion, there is also uncertainty concerning the behavior of rigid panel seals in the ductile salt surrounding them. Therefore, frequent monitoring during the pre-closure period and assessing the status of room deformation and DRZ healing are the best approaches for reducing the uncertainties associated with closure of the waste disposal area.

Recommendation: **The committee recommends pre-closure monitoring of the status of room deformation and DRZ healing. Seal performance should also be assessed. Observation should continue at least until the repository shafts are sealed and longer if possible. The results of the monitoring of room deformation and DRZ healing should be included in the PA and used for recertification purposes.**

SITE CHARACTERIZATION ISSUES

The committee finds that there are a number of site characterization actions that would decrease uncertainties in the long-term performance of the repository. Among these, site characterization issues related to human activities are particularly important because they constitute the major risk of radionuclide release, according to the performance assessment (NRC, 1996a; Rechard, 2000). Site characterization issues and activities are described in the sections below.

Geohydrological Characterization of the Rustler Formation

The WIPP disposal panels and rooms are located in the Salado Formation, approximately 660 meters from the ground surface, as shown in Figure 1.3. The Rustler Formation, overlying the Salado Formation, consists of five sequences (members) of thin-bedded strata. The Culebra Dolomite member, also called simply Culebra, is the second member from the bottom of the formation and is the most transmissive unit in the Rustler. Thus, the Culebra is important to the groundwater flow model for the WIPP site. The geologic and hydrologic setting of the WIPP have been thoroughly described in Corbet and Swift (2000). A detailed description of radionuclide transport in the Culebra can be found in Ramsey et al. (2000). The Culebra provides pathways for the release of radionuclides into the environment in all main human intrusion scenarios (see Appendix B).

These pathways can conceivably be developed when new wells are drilled through the Culebra. High-pressure fluids are used in the drilling of oil, gas, and injection wells to contain the flow from the high pressure in formations contacted during the drilling process. Formations at shallower depths, which tend to be at low pressure, are protected from the high-pressure drilling fluids by borehole casings. However, if the drilling intersects a pressurized brine reservoir before the borehole casing is placed, and if the pressure in the formation is unexpectedly higher than the pressure exerted by the drilling fluid, the high-pressure formation fluids could flow into the wellbore and cause an underground blowout into the Culebra. Drillers would use a blowout preventer to contain any immediate surface release of brine from the repository horizon. However, release to the Culebra could be synonymous with release to the accessible environment if there were high flow rates and little retardation[7] of radionuclides.

[7] Parameter that describes the ratio of the net apparent velocity of the concentration of a particular chemical species to the velocity of a non-reactive species.

All human intrusion assessment models in the PA require some retardation in the Culebra to meet the EPA's repository performance requirements. Similarly, the PA models require a low flow velocity in the Culebra. Unfortunately, these models are not based on sufficient hydrological characterization of the Culebra. There is uncertainty about flow directions, flow rates, retardation characteristics, and the amounts and location of groundwater recharge and discharge to and from the Culebra. This is due partly to uncertainties about the density, size, and spatial distribution of fractures and potential karstic features. These uncertainties can be reduced through a well-designed monitoring program.

The monitoring program should include angled boreholes to verify assumptions about vertical fractures or karst conduits; monitoring wells to check on conditions of recharge and discharge, water levels, and chemical properties. The program should also include a series of tracer tests to determine spatial flow rates of groundwater and local tracer tests, including the use of new logging technologies. Tracer tests should include suites of conservative tracers injected in differing wells to test the complexities of the flow system over and beyond those withdrawn by the LWA. The tests should span the entire preclosure phase of the repository (35 to 100 years). New data should be implemented continually into scenario models, and PA calculations should be revised as appropriate.

Recommendation: **The committee recommends a monitoring program to characterize the geohydrology of the Culebra Dolomite. Tests and measurements that should be considered include angled boreholes, natural gradient tracer tests, and additional pump or injection tests. These new data should be used to confirm, or modify, the conceptual and numerical models now proposed as reasonable simulation of the actual system.**

Oil, Gas, and Mineral Production

The oil, gas, and mineral reserves in the vicinity of WIPP are considerable. As shown in the interim report (see Appendix A1, Figure 2), there have been multiple drilling operations near the WIPP site and a future increase in production activities is expected. As indicated in the previous section, brine (or any fluid) inflow to the disposal region of the WIPP repository is a serious threat to the containment of radionuclides in the repository. Therefore, it is critical that pathways are not created by human intrusion, either intentionally or unintentionally. Such pathways would allow transport of radioactive materials from the repository to the surface or would bring water or brine in contact with the substances stored in the repository.

No human intrusion should occur during the first 100 years of the repository's life because of the active institutional controls. However, drilling activity will increase progressively during the period of passive institutional controls (100 to 700 years) and will not be controlled beyond that period. Uncontrolled extraction activities would increase the probability of drilling directly into the repository. Extraction activities can be divided into *drilling activities* and *mining activities*.

Drilling Activities

Two scenarios related to drilling activities are of particular interest to the WIPP site: the Hartman scenario and the intersection of a pressurized brine reservoir.

1. The Hartman scenario. In 1993, while drilling in the Rhodes Yates oil field located approximately 45 miles from the WIPP site, Mr. Hartman experienced a well blowout followed by an uncontrollable flow of brine to the surface (Silva, 1996). This event has come to be known as the Hartman scenario

(see additional details in Appendix B, Box B.1). The reason for the blowout has not been fully determined, although there is evidence that it may have been caused by a high-pressure, water-flooding operation approximately 1 mile from the well that blew out. In oil-producing regions such as southeastern New Mexico, it is common to inject high-pressure fluids into the deep rock formations of the subsurface.

The purpose of these fluid injections is to stimulate secondary recovery of oil in partly depleted oil reservoirs (e.g., by water flooding) or to dispose of large volumes of brine produced simultaneously with oil. If there is a failure in the well casing or in the grout or cement outside the casing, fluid can leak into overlying formations and flow laterally along one of the many anhydrite layers in the Salado (NRC, 1996a). Mr. Hartman might have drilled into a hydraulic fracture possibly induced by such water-flooding operation, causing the well to blow out. Bredehoeft and Gerstle (Bredehoeft and Gerstle, 1997; Gerstle and Bredehoeft, 1997) studied the implication of the Hartman scenario for the safety of the WIPP. They argued that if there were an oilfield water-flooding operation in the vicinity of the WIPP, a large amount of brine could flow from a leaky injection well and induce a hydraulic fracture in the anhydrite (or marker bed) directly above or below the WIPP repository (see Appendix B, Box B.2). If, at some later time, another well were drilled through the repository and into this brine-filled fracture, the high-pressure brine in the fracture could flow through the borehole and flood the repository causing a release of radioactive materials. Bredehoeft's analysis was disputed by researchers at Sandia National Laboratories (SNL; Swift et al., 1997; Vaughn et al., 1998). The discussion focused on the size of this potential hydraulically induced fracture and on whether this fracture could reach the anhydride beds directly below or above the repository site.

The committee's opinion is that there are considerable uncertainties concerning both the mechanism of the Hartman scenario and its likelihood to develop at the WIPP site. For instance, if the hypothesis of a hydraulically induced fracture were valid, and the fracture would indeed extend directly below or above the repository, a surge of brine would be expected only when the drillbit penetrates the brine-filled fracture. The volume of brine inflow would not be large enough to damage the repository because hydraulic fractures have small opening widths and high internal flow resistances. Furthermore, a leaky well could not provide sufficient energy and fluid volume to cause a brine inflow into the repository for an extended period of time; also, the energy stored in the room and in the fracture would not be enough to push the waste to the surface.

In addition, the repository is partitioned into isolated rooms, which will be closed progressively by salt creep, so that radionuclides should not be mobilized by the brine inflow. Finally, based on the information gathered and on geotechnical subcommittee's discussions, it appears that the geological setting of the WIPP is different from that of the Rhodes Yates oil field. The geological configuration near the WIPP site is likely to interfere with fluid movement thereby reducing the likelihood of flow from a hydraulic fracture into the repository. Therefore, in the committee's opinion, the Hartman Scenario is not likely to cause a problem in the performance of the repository.

2. *Intersection of a pressurized brine reservoir.* Groundwater containing high levels of dissolved solids (brine) may occur beneath the WIPP site either as discrete pockets (brine pockets) or as a saturated continuum. The committee uses the term "brine reservoir" to refer to both of these occurrences. At present, there is a great deal of uncertainty as to the location and form (i.e., discrete pocket or saturated continuum) of brine reservoirs beneath the WIPP repository. The committee recognizes that direct drilling through the repository into underlying high-pressure brine reservoirs could result in a release of radionuclides.

A survey study of brine reservoirs in the Castile Formation (Popielak et al., 1983) has suggested that the brine reservoirs in the area are not large enough to affect the safety of the WIPP site and that

there is no high-pressure brine reservoir directly underlying the repository. However, this finding is challenged by Silva et al. (1999). Using data from test well WIPP-12, Silva demonstrated that the probability of a large brine reservoir, approximately 260 meters below the repository, is rather high. The issue remains unresolved at the present time. Direct drilling (see Appendix B, Boxes B.1, and B.4) into the WIPP repository would allow circulating drill fluid to bring radioactive materials to the surface through a borehole as cuttings or spallings. In the performance assessment, SNL evaluated different possibilities of drilling into a brine reservoir (see Appendix B).

In the committee's opinion, the upsurging pressure from drilling through a pressurized brine reservoir could be counteracted by the weight of drilling mud. However, the situation could be serious if the brine reservoir were large and contained a significant amount of energy. An intersection with such a reservoir, although extremely rare, could cause the well to blow out and could result in a catastrophic safety problem for the WIPP. In the committee's opinion, when the drillbit penetrates a brine reservoir below the repository, there would be an initial surge of brine flowing through the borehole into the repository, but the rate of brine inflow would decrease rapidly unless this high-pressure brine reservoir had a gas subpocket above it. Because of the low compressibility of brine, without a gas subpocket, the energy stored in the reservoir would not be sufficient to cause a large brine upsurge through the borehole into the repository.

It is therefore important to determine the existence of a brine reservoir directly below the repository. This would be done using seismic techniques, which cannot measure the pressure in the reservoir but can detect its size. The committee recognizes that small brine reservoirs, including brine occurring as a saturated continuum, could not be detected by seismic surveys, or other noninvasive remote sensing techniques. Most seismic surveys are performed from the surface. However, it is possible to perform measurements at a depth, such as in wells or from within the repository. There would be advantages to performing a seismic survey at repository depth (660 meters below the surface) because the unwanted signal from near-earth formations could be eliminated.

The committee is aware of the numerous geophysical surveys that have been performed on the WIPP area in the past (ETC, 1988; Popielak et al., 1983; Silva et al., 1999) and does not suggest repeating what has been already done. However, seismic interpretation technology has improved dramatically in the last decade. These improvements, including but not limited to the almost universal three-dimensional seismic techniques, have greatly enhanced resolution capability and are currently used in the oil industry. Detailed three-dimensional seismic studies results, however, are often highly proprietary because they are performed by the oil industry. The DOE could consider acquiring the results of these studies to obtain new information on possible brine reservoirs in the region.

In case a brine reservoir were found beneath the WIPP site and its size were larger than what is already taken into account in the PA, then the DOE should conduct an extensive review of the impact of such a reservoir on the repository performance. A basis would then exist to take appropriate action to ensure the safety of the repository. If the reservoir is pressurized, the option of drilling a well into it to release the pressure could be considered. In case of drilling, precautionary methods, such as directional drilling, should be taken to prevent brine from entering the repository.

Recommendation: **The committee recommends the utilization of seismic survey techniques to detect the presence of a large brine reservoir below the repository.[8] In case a brine reservoir were**

[8] The committee recognizes that small brine reservoirs, including brine occurring as a saturated continuum, could not be detected by seismic surveys, or other noninvasive remote sensing techniques.

found beneath the WIPP and its size were larger than what is already taken into account in the PA, then the DOE should conduct an extensive review of the impact of such a reservoir on the repository performance. A basis would then exist to take appropriate action to ensure the safety of the repository.

Mining Activities

A further human activity that could threaten the safety of the repository is potash mining in proximity of the WIPP site. Potash mining could impact the performance of the repository by modifying flow pathways in the overlying formations or by creating a path for brine intrusion, if methods such as flood or solution mining are employed. The potential impact of potash mining on WIPP performance is not considered significant, but it is important that the DOE monitor during the operational phase all mining activities in close proximity of the area addressed in the LWA to ensure that the WIPP repository performance is not affected.

After reviewing the analyses performed for the human intrusion scenarios as a part of the performance assessment and given the reasons mentioned above, the committee finds that oil, gas, and mineral activities will not unduly threaten the integrity of the repository. However, there are uncertainties associated with these extraction operations. These uncertainties could be reduced by monitoring and documenting oil, gas, and mineral activities. The DOE could establish a database on oil, gas, and mineral activities in the WIPP area containing information such as:

1. location, depth, and type of each well surrounding the WIPP site;
2. data on accidents or unusual events reported by drilling contractors or operators;
3. data on production-enhancing activities such as water or CO_2 flooding, hydraulic or cryogenic fracturing, and acidizing in surrounding wells;
4. production rates of oil, gas, and brine from nearby wells;
5. data on disposal of drill cuttings and brine from the operators;
6. data from abandoned wells, in particular those relevant to gas leakages; and
7. extent of potash mining in the vicinity of the LWA.

Recommendation: **The committee recommends the development of a database to collect information on drilling, production enhancement, mining operations, well abandonments, and unusual events (accidents and natural events) in the vicinity of the WIPP site.**

Baseline Radiogenic Analysis of Subsurface Fluids

The issue of baseline values for naturally occurring radioactive material (NORM) in the vicinity of the WIPP site is important for future monitoring of any changes in radioactivity levels in and around the site. The reason for concern is that subsurface oil and gas in the vicinity of the site already contains NORM. The potential discovery of radioactive material in oil and gas could mistakenly be assumed to come from the repository and thereby cast a doubt on the performance of the nearby WIPP.

One of the findings of the committee's interim report (Appendix A1) identified an absence of radiological baseline information for subsurface brines and hydrocarbons near the site, even though there has been extensive monitoring of radioactivity in the air, soils, fluvial sediments, surface water, shallow groundwater, and populace. Therefore, the committee recommended that the DOE develop and implement a plan to sample oil-field brines, petroleum, and solids associated with current hydrocarbon production to assess the magnitude and variability of naturally occurring radioactive material in the vicinity

of the WIPP site. The radionuclides of interest include those that contribute to the site's NORM background radioactivity and those present in the TRU waste inventory destined for WIPP. The NORM activity may include contributions from potassium-40, isotopes of uranium and thorium, and daughter products such as isotopes of radium. Radionuclides in TRU waste include isotopes of uranium and TRU elements and, in remote-handled TRU waste, fission and activation products.

Since some TRU inventory radionuclides are not found commonly in nature, sampling to determine whether such radionuclides are present in the environment may be a good way to distinguish radioactivity due to NORM from that due to TRU waste. Further details can be found in Appendix A1. In its interim report, the committee recommended a simple but reliable analysis of the samples that do not include species depending on equilibria that can be shifted by a change in the chemical or physical parameters of the sample.

In response to the interim report, the DOE stated that the New Mexico State University Carlsbad Environmental Monitoring and Research Center (CEMRC) has undertaken a project to carry out the recommended assessment, as part of CEMRC's WIPP environmental monitoring project (Appendix A2). This project will include "completion of a database of active wells and operators, development of sample collection and handling plans, and identification of commercial sample collection services." The CEMRC has also developed analytical methods for NORM in subsurface fluids to complement standard methods. The committee supports and encourages the pursuit of this initiative.

Recommendation: **The committee recommends that the DOE continue the implementation of its plan to sample oil-field brines, petroleum, and solids associated with current and future hydrocarbon production, as necessary to assess the magnitude and variability of NORM in the vicinity of the WIPP site for baselining purposes.[9]**

[9] On March 12, 2001 the DOE-Carlsbad Field Office informed the committee that the efforts to collect data on NORM have received little support from oil companies and that cooperation seems unlikely. The small number of positive responses received would still not provide enough information to constitute a representative baseline of NORM in the region.

3

National Transuranic Waste Management Program

The National Transuranic Waste Management Program, also called the National TRU Program, addresses waste acceptance criteria and requirements for packaging and shipping waste to the WIPP repository. One of the committee's tasks is to identify areas for improvement in the National TRU Program that may increase safety to workers and the public, system throughput, efficiency, or cost-effectiveness. The National TRU Program was reviewed in detail in the committee's interim report (Appendix A1). This chapter gives a status report on the issues discussed in the interim report and reviews other issues that have emerged during the committee's deliberations. The issues addressed in this chapter relate to two areas: (1) *waste characterization and packaging* and (2) *waste transportation.*

WASTE CHARACTERIZATION AND PACKAGING

The committee has identified opportunities for improvement in the TRU waste management system concerning waste characterization and packaging requirements and the total inventory of organic material in the repository.

Waste Characterization and Packaging Requirements

The issues of waste characterization and packaging requirements have been discussed in detail in the interim report (Appendix A1). The principal finding was that many requirements and specifications concerning waste characterization and packaging lacked a safety or legal basis. In addition, many of these same requirements resulted in health and safety risks and added costs. The added safety risks derive from radiation exposure of workers due to the extra handling of waste imposed by some of the requirements. For instance, visual examination of a fraction of waste stream containers to confirm radiography results and information from the history of the container (acceptable knowledge) is a procedure not required by the EPA that increases radiation exposure of workers. The committee recommended in its interim report that the DOE eliminate self-imposed waste characterization requirements that lack a safety or legal basis.

The committee is encouraged by progress made since the interim report to eliminate unnecessary

procedures. In particular, the DOE has initiated a program to review all waste characterization and packaging requirements and to reduce or eliminate those that do not contribute to improved safety or that are not required by law. The DOE may obtained a tenfold reduction of the number of containers to be opened for visual examination by requesting a modification of the WIPP's Hazardous Waste Facility Permit (Appendix A2).

Recommendation: **The committee recommends that the DOE's efforts to review waste characterization and packaging requirements continue and that changes be implemented over the entire National TRU Program. The committee recommends that the resources required to complete these improvements be made available by the DOE.**

Total Inventory of Organic Material in the Repository

A new issue concerning waste characterization has emerged since the committee visited the WIPP site in May 2000. This issue addresses the regulatory limits on the total inventory of organic material allowed in the repository. The performance assessment indicates that there could be significant carbon dioxide generation in the repository due to the decomposition of organic material. Although the committee does not consider gas generation an important safety issue (see Chapter 2), it is concerned whether the current monitoring program will provide the information required to assess compliance with total repository limits of organic material. Title 40 CFR 194.24 states that "the Department [of Energy] shall specify the limiting value ... of the total inventory of such waste proposed for disposal" (EPA, 1996). The DOE has therefore established the limit for organic material in the repository to be 20 million kilograms (DOE, 1996; Table 4-0) on the basis of the average waste composition.

However, the DOE's definition of "waste" includes only what is inside the waste container and does not include either the container itself or any of the auxiliary material buried with the waste. Examples of such auxiliary material are plastic films used to stabilize drums for shipping and handling, plastic bags and corrugated cardboard used as magnesium oxide containers, wooden waste boxes, plastic liners of waste drums, and pressed wood "slip sheets" used between layers of drums and waste boxes. Figure 3.1 shows a picture of waste and auxiliary material in one of the rooms of the repository. Thus, there is a considerable inventory of materials, mostly cellulosics, that are not considered TRU waste but are foreign to the natural setting of the Salado Formation. The principal concern of the committee is that the auxiliary material does not appear to be accurately inventoried. Therefore, it is impossible to know whether the total organic material limit is exceeded.

Recommendation: **The committee recommends a risk-based analysis of the total organic material regulatory limits in the WIPP. If accounting for the organic material is important to the safety of the repository, an inventory record system should be implemented as soon as possible to provide a basis for meaningful safety analysis.**

WASTE TRANSPORTATION

The committee has examined various aspects of the WIPP TRU waste transportation system, focusing on system safety and on cost-effectiveness of planned and ongoing activities. In its interim report (Appendix A1), the committee reviewed the DOE's TRANSportation tracking and COMmunication (TRANSCOM) system and its emergency response program. Two other issues have been revisited in this report: the potential use of rail as a shipping option for a fraction of TRU waste and the gas genera-

Figure 3.1 Standard waste boxes and packs stacked in one room of the WIPP repository. Notice the layers of plastic film around the drums. SOURCE: DOE, 2000d.

tion safety analysis for the Transuranic Package Transporter, Model II (TRUPACT-II) containers. Figure 3.2 shows the internal structure of a TRUPACT-II container. Figure 3.3 shows a truck transporting three TRUPACT-II containers.

DOE's Communication and Notification Program

In its interim report (Appendix A1), the committee recommended that the DOE improve the reliability and ease of use of the TRANSCOM system. On November 21, 2000, a truck hauling waste to WIPP strayed from its designated route as the driver missed the exit from Interstate 25 onto Route 285 toward Carlsbad. The driver proceeded 27 miles before the New Mexico State Police, equipped with a TRANSCOM system, realized the error and turned the truck around. It appears that the TRANSCOM headquarters situated in Oak Ridge, Tennessee, did not notify the driver until a state policeman noticed the error (DOE, 2001). This "strayed truck" episode is an example of the poor reliability of the system, not from a technical point of view since the TRANSCOM was apparently functioning correctly, but from the perspective of the human factor.

The DOE appears to be systematic and expeditious in its development and use of a new, efficient, comprehensive, and state-of-the-art communication and notification system, known as TRANSCOM 2000. The new system will use off-the-shelf, advanced information and communication technologies to track shipments from start to end. Full-scale implementation of TRANSCOM 2000 is scheduled for June 2001. After discussion with transportation management staff and in reaction to the DOE's response to its

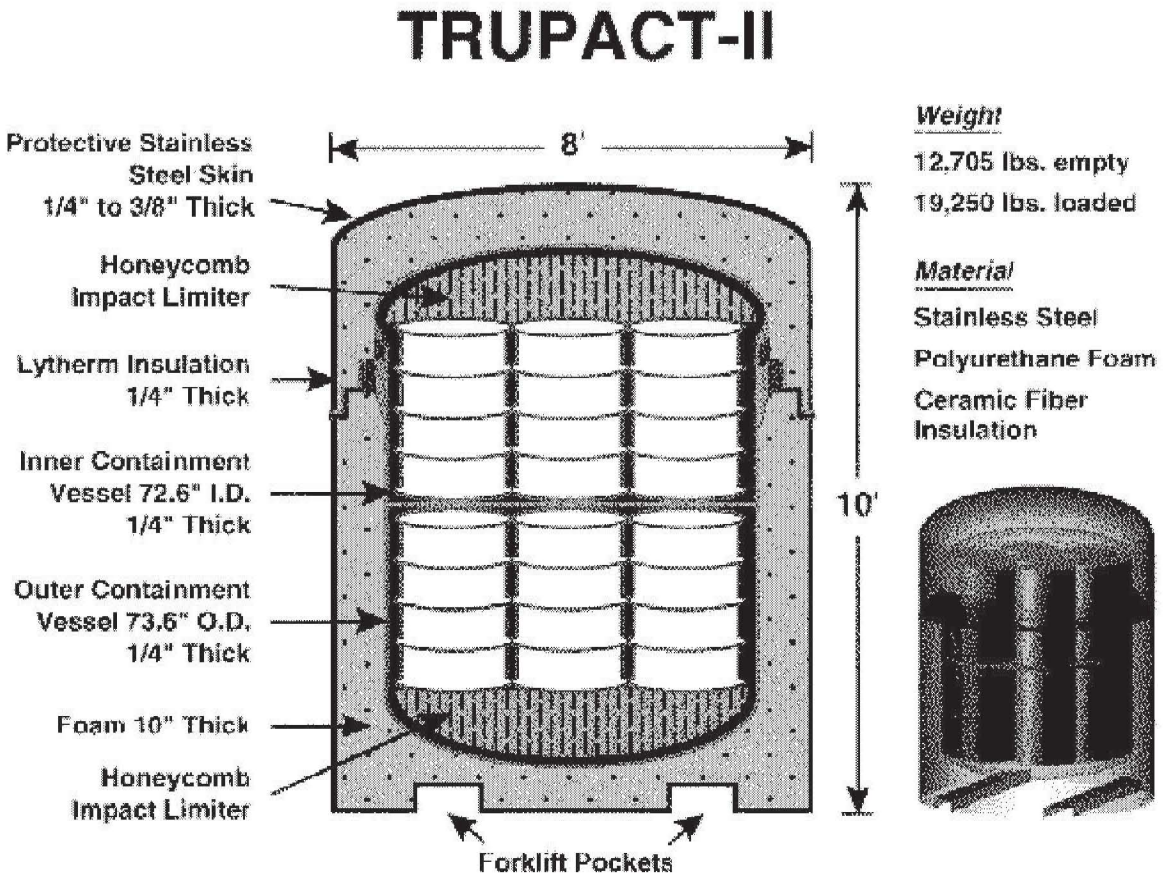

Figure 3.2 Structure of TRUPACT-II container, certified by the USNRC. SOURCE: DOE, 2000l.

Figure 3.3 Truck transporting three TRUPACT-II containers to the WIPP. SOURCE: DOE, 2000m.

interim report (Appendix A2), the committee finds that overall, the DOE has taken active steps to address concerns about the reliability and ease of use of the TRANSCOM system. Moreover, the DOE has integrated new features into TRANSCOM 2000, such as alarms, more frequent satellite and computer tracking, and stronger training for truck drivers to avoid future "strayed truck" episodes. Other suggestions to improve the safety and reliability of TRANSCOM could be the use of checklists, key schedule reporting, and "call-ins" at important route changes.

There may also be further opportunities to improve the performance of the TRANSCOM 2000 system. For instance, integrating TRANSCOM 2000 with other corridor states' information technology programs such as intelligent transportation systems (ITS). More generally, TRANSCOM 2000 must meet performance-monitoring standards similar to those of other advanced systems, such as the air traffic control system, particularly as shipments become routine and drivers and supervisors may become complacent. Investment in tracking and communication systems for the WIPP will also be useful for future radioactive waste transportation systems.

Recommendation: **The committee recommends that the DOE implement as soon as possible the new TRANSCOM 2000 communication and notification system. Moreover, because human factors are an important element of transportation system quality, TRANSCOM 2000 should include methods to minimize the occurrence and impact of human errors.**

DOE's Emergency Response Program

Concerning the emergency response program for the WIPP, the committee recommended, in its interim report (Appendix A1), that the DOE explore with corridor states and other interested parties how to develop processes and tools for maintaining up-to-date spatial information on the location, capabilities, and contact information for the following:

- responders,
- medical facilities,
- recovery equipment,
- regional response teams, and
- other resources that might be needed to support effective emergency response in the event of a transportation incident involving a WIPP shipment.

This recommendation was made in recognition of the fact that, presently, there is no quality control program in existence to evaluate periodically and systematically the extent of training, emergency capabilities, and deficiencies within the states and along WIPP transportation corridors. The committee fully understands and recognizes that the primary responsibility for management and response to hazardous material incidents in transportation rests with state and local authorities and jurisdictions. Although WIPP corridor states actively coordinate in varying degrees with the DOE to ensure the safety of WIPP shipments, the general public may often view this responsibility as ultimately resting with the DOE as the system manager. The public might well expect qualified and trained emergency response coverage along an entire route. In the committee's view, the DOE could face heavy criticism if an event demonstrates weaknesses in the emergency response program, regardless of whether the safety consequences are serious. Any system-level integration necessary to ensure adequate emergency response would have to recognize and coordinate among the jurisdictional boundaries of the various responsible state and local agencies.

To date, the committee is concerned about the progress being made in the emergency response area. For example, only 7 of the 20 states situated along the transportation corridor participated in the last DOE emergency response training class in Carlsbad, New Mexico (DOE, 2000e). The committee acknowledges the challenges faced by the respective states in providing resources to ensure adequate coverage. There continues to be a need for the DOE to facilitate the involvement of states and other interested parties to determine where emergency response capabilities are lacking along transportation routes and to support the states in correcting deficiencies. The committee is encouraged by the new DOE training program, through which DOE trainers have traveled to Indiana, Colorado, Louisiana, and Nevada to teach emergency response professionals what to do in case of an accident involving a WIPP shipment (Westinghouse News, 2001a,b,c,d). A further example for DOE to improve the corridor states' involvement in the emergency response program is to organize training courses through distant learning.

Recommendation: **The committee recommends that the DOE facilitate the involvement of states in developing and maintaining an up-to-date, practical, and cost-effective spatial information database system to coordinate emergency responses. The DOE should also develop an ongoing assessment program for states' emergency response capabilities and allocate training resources to address deficiencies in coverage along WIPP routes.**

Rail as a Transportation Option for Certain TRU Waste

In its interim report (Appendix A1), the committee recommended that DOE reduce the number of truckloads required to transport waste to WIPP, thereby reducing the associated transportation risks.[1] The committee suggested that a way to reduce the number of shipments is to reevaluate the technical and regulatory feasibility of shipping high-wattage TRU waste using a railcar shipping system. The WIPP has access already to rail via a rail spur siding, which runs into the facility.

In response to this recommendation, the DOE (2000c) recently issued a report *CH-TRU Waste Transportation System Rail Study*. This study examined the feasibility of shipping CH-TRU waste from four DOE facilities to WIPP by commercial rail and compared the relative costs of using rail rather than the present use of the highway. The study also examined the feasibility and cost-effectiveness of using several alternative packaging to TRUPACT-II. TRUPACT-II containers, because of their size, shape, or regulatory limits, are not always efficiently utilized during transportation; therefore, an increased number of shipments or repackaging of the waste is sometimes required. The DOE concluded that rail shipment of TRU waste to WIPP might be competitive if certain conditions are satisfied. Those conditions involve negotiation of a more favorable rail rate and development of an alternate type B overpack to TRUPACT-II that would accommodate more packages, thus reducing the number of shipments required.

A recent article (Neill and Neill, 2000) asserts that rail offers considerable advantages, at least with respect to shipments from the Hanford and the Idaho National Engineering and Environmental Laboratory sites. The authors make specific recommendations concerning the use of rail that might enable the DOE to ship TRU waste more efficiently while reducing transportation risk. The committee suggests

[1] On November 2, 2000, a new type of container, called HalfPACT, designed to supplement TRUPACT-II for road transportation, was certified by the U.S. Nuclear Regulatory Commission. The new container is approximately 30 inches shorter than TRUPACT-II and can be utilized more efficiently to transport TRU waste. The DOE estimated that the new HalfPACT container will eliminate about 2,000 projected shipments to the WIPP site.

Sidebar 3.1 The ATMX Railcar System as an Alternative Transportation System?

"ATMX" is an acronym to denote the railcars used by the DOE to ship nuclear weapons components and TRU waste. "AT" stands for Atchison Topeka, the rail carrier. "M" signifies munitions, and "X" on a railcar signifies private ownership (in this case, by the U.S. government), rather than ownership by the railroad company. This system was used by the DOE (and formerly the U.S. Atomic Energy Commission) from about 1968 to 1989 to safely transport more than 1,100 shipments of CH-TRU waste from the Mound Laboratory and Rocky Flats to the Idaho National Engineering Laboratory. The ATMX (600 series) is a specially designed steel railcar with a bolted-on steel cover and an interior compartmentalized by steel frames. Closed steel boxes or bins are positioned and stored in each compartment, and internal packagings are placed in the boxes or bins. Internal packagings need only meet U.S. Department of Transportation (DOT) Type A package test standards and are relieved from Type B (accident-resistant) package test parameters. Each ATMX railcar can accommodate a maximum of 20 crates or 140 55-gallon steel drums. In June 1999, the DOT issued the tenth revision of DOT-E 5948, authorizing the shipment of TRU waste by rail from Miamisburg, Ohio (the Mound Laboratory), to a yet-to-be-designated DOE facility where it will be processed for eventual shipment to the WIPP in TRUPACT-II containers. This option appears to be a very reasonable and cost-effective method of transferring the relatively small amount of TRU waste at Mound to another DOE facility for processing as an alternative to setting up a facility at Mound itself. Since the ATMX system is not certified by the USNRC, its use for rail shipments directly to the WIPP is precluded by the provisions of the Land Withdrawal Act and the Agreement with the State of New Mexico, which require that shipments to the WIPP be in USNRC-certified packages. To obtain USNRC "approval," the DOE would have to support an application to the USNRC for exemption from certain test requirements for the Type B package mentioned in Title 10 CFR Part 71. For certain materials that eventually will not be transportable in TRUPACT-II containers due to high thermal loading, this would appear to be a desirable option for future consideration and possible pursuit by the DOE.

that the DOE develop a strategy to negotiate and reduce the overall rail freight costs and to identify the infrastructure (e.g., costs, emergency preparedness, and schedules) necessary for rail shipments.

In its interim report, the committee recommended the ATMX railcar system as an alternative transportation system for certain materials (see Sidebar 3.1). Specifically, the committee recommended that a risk-informed study should be prepared by the DOE to support an application to the United States Nuclear Regulatory Commission (USNRC) authorizing the use of the ATMX railcar system for shipments of inner waste packages that are unsuitable for placement in TRUPACT-II containers.

Recommendation: **The committee recommends that all reasonable transportation options including reduction in the number of shipments, such as rail and road transportation with better-adapted containers, should be part of the decision-making process of transporting TRU waste from generator and storage sites to the WIPP. Future transportation studies should consider railway shipments and their impact on both the safety and the cost of the program. The DOE should also**

continue to pursue the development of packaging alternatives for materials not suitable for TRUPACT-II containers.

Gas Generation Safety Analysis for TRUPACT-II Containers

The issue of hazardous gas generation in TRUPACT-II shipping containers stems from a U.S. Nuclear Regulatory Commission requirement (USNRC, 1999). The requirement states that, for the shipping container, "hydrogen and other flammable gases comprise less than 5% by volume of the total gas inventory within any confinement volume." The problem is whether a flammable mixture could be generated and trigger an ignition, exothermic reaction, or explosive event with sufficient energy to breach the containment. Excessively restrictive gas generation requirements have severe consequences. The waste is repackaged to redistribute waste in containers to meet the wattage limits derived from gas generation requirements. This repackaging of waste exposes workers to radiation and increases the number of containers, thereby diluting the waste into a greater volume. Transportation-related risks (and costs) are also incurred in repackaging because the extra containers require additional shipping loads and additional truck trips, thereby increasing the likelihood of accidents.

For instance, plutonium-238 found in CH waste is considered a "high-wattage waste" because of its high specific activity (17.3 curies per gram). The USNRC significantly restricts the amount of plutonium-238 that can be transported by TRUPACT-II because of gas generation concerns. The DOE estimates that the repackaging of plutonium-238 in CH waste may involve more than a tenfold increase in the number of shipments of plutonium-238, to as many as 150,000 extra drums (Lechel and Leigh, 1998). The USNRC uses a decay heat limit in watts, originally established by the DOE, based on limiting the volume of hydrogen to less than 50 milliliters per liter of volume in the "innermost confinement barrier." According to waste acceptance criteria for the WIPP, the wattage limit for TRUPACT-II containers is 40 watts (DOE, 1999).

Thus, there is also the matter of what constitutes the innermost confinement barrier in TRUPACT-II, since the containers may consist of separate individual plastic bags of waste (see Figure 3.2). One interpretation is that the requirement applies to these "inner packages." Obviously, there are situations in which such an interpretation would make the flammable gas volume limitation a severe constraint on TRU waste shipments, given the plastic bag packaging practice and the number of different sizes that may occur in a single TRUPACT-II container. Finally, it is the understanding of the committee that the 5 percent volume limitation on hydrogen is intended to preclude the need for a specific safety analysis, which suggests that this limitation is a major source of conservatism and may not be cost-effective or risk-informed.

The committee was unable to verify the technical basis for the several sub-issues that are involved, including a realistic assessment of the conditions that could result in an explosive event in TRUPACT-II containers and a clear definition of what constitutes the innermost barrier. As already recommended in its interim report, the committee reiterates that a risk-informed analysis of WIPP-specific shipments would contribute to a better understanding of the real safety issues and, perhaps, provide a basis for alternative cost-effective criteria while reducing the risk.

In its response to the interim report (Appendix A2), the DOE agreed with the committee's recommendation that a safety analysis be performed to determine the quantity of hydrogen that, upon ignition, could damage the TRUPACT-II shipping container and possibly rupture the seals of the package. The committee is aware of and supports the DOE's initiative of obtaining more realistic G-values[2] for hydro-

[2] The G-value is the measure of radiolytic yield. It is expressed by the number of molecules, in this case of H_2, produced by 100 electronvolts of the ionizing radiation's energy absorbed by the medium, in this case the TRU waste.

gen generation and of exploring the use of hydrogen getters and inerted inner containers as a means of increasing wattage limits for transportation. Moreover, the DOE has applied for a revision of the USNRC's certificate of compliance to authorize the use of lower G-values for hydrogen generation based on matrix depletion, options for mixing of shipping categories, and use more realistic G-values for non-gas generating materials that are present. The committee supports this request.

Recommendation: **The committee recommends a risk-informed analysis of WIPP specific shipment issues to identify core problems related to hydrogen generation and, perhaps, provide a basis for alternative cost-effective criteria while reducing the risk. The committee recommends the use of such risk-informed analysis in the application for revision of the USNRC certificate of compliance concerning hydrogen generation limits for transportation purposes.**

4

Summary

The committee is confident that the WIPP can meet its general performance objectives as requested by the certification process. However, uncertainties remain in the long-term performance of the repository. Some of the recommendations in this report were released in the committee's interim report (Appendix A1) to which the DOE has responded with a number of actions taken (see Appendix A2). The committee encourages implementation of the improvements suggested by the DOE to address its recommendations. In Chapters 2 and 3, the committee addresses some new issues concerning the operation and long-term safety of the WIPP and reiterates for emphasis some of the recommendations of the interim report. This chapter closes the study with an overarching finding and recommendation.

OVERARCHING FINDING

The committee finds that the monitoring of selected performance indicators during the estimated 35-year or longer pre-closure phase of the WIPP is needed to possibly enhance confidence in the long-term safety performance of the repository. Although 35 to possibly 100 years is a short time compared to the 10,000-year period of compliance, the committee believes that it is long enough to reduce the uncertainties in many critical performance parameters. The rates of important processes such as salt creep, brine inflow (if any), and gas generation are predicted to be highest during this period; therefore, monitoring during the pre-closure phase is particularly important. Moreover, the committee finds that there are a number of specific actions that can be taken in the National TRU Program to facilitate operation of the WIPP while increasing safety and reducing costs.

OVERARCHING RECOMMENDATION

The committee recommends that the DOE develop and implement a program during the pre-closure phase to monitor selected performance indicators that specifically relate to the creation of a radionuclide source term and to pathways for radionuclide transport. Monitoring should continue throughout the pre-closure phase and longer, if possible. Emphasis in the monitoring should be on waste mobilization and

transport mechanisms, including brine inflow, gas generation, geochemical reactions, room sealing, and surface and subsurface hydrology. The committee recommends that the results of the on-site monitoring program be used to improve the performance assessment for recertification purposes. These results will determine whether the need for a new performance assessment is warranted. Given the uncertainties, it is impossible to predict if the results of the monitoring program will be different than those modeled by the performance assessment. However, it is important to ensure that, if there are changes, these will be detected.[1] Moreover, actions should be taken to improve and better define the National TRU Program for issues related to waste characterization and packaging requirements, total inventory of organic materials, communication and notification system, emergency response training, and gas generation during transportation.

The committee did not have all of the information necessary to prioritize the issues mentioned in this report. However, it has provided a selected number of recommendations that are believed to improve the operation and long-term safety of the WIPP. The committee recognizes that the recommendations in this report will have some economic impact on the transuranic waste management program. The DOE needs to balance costs against the improved assurance of facility performance in the longer term.

[1] Only measurable changes are important to verify the performance of the repository; for instance, a few drops of brine do not imply that the repository is not in compliance with containment requirements.

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APPENDIXES

Appendix A1

Interim Report

IMPROVING OPERATIONS AND LONG-TERM SAFETY OF THE WASTE ISOLATION PILOT PLANT

INTERIM REPORT

Committee on the Waste Isolation Pilot Plant
Board on Radioactive Waste Management
Commission on Geosciences, Environment, and Resources

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

NOTICE: The project that is the subject of this interim report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council (NRC) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Tom Borak, Colorado State University
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Although the individuals listed above have provided constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by E-an Zen, appointed by the Commission on Geosciences, Environment, and Resources, and Frank Parker, appointed by the Report Review Committee, who were responsible for making certain that an independent examination of this report was carried out in accordance with NRC procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the NRC.

Preface

This report is the product of a National Research Council (NRC) committee study sponsored by the U. S. Department of Energy (DOE). The first NRC Committee on the Waste Isolation Pilot Plant (WIPP) began in 1978, and this committee and its successors issued eight letter reports during 1979-1992 and two full reports in 1984 and 1996. The current WIPP committee study is operating under a revised statement of task (see box) derived from a DOE request (Dials, 1997). This interim report addresses selected issues associated with the task statement, as explained below. The committee will comprehensively address the statement of task in the final report.

The specific approach taken in this interim report was to consider how to assess (1) the performance of WIPP in isolating waste from the environment and (2) the basic, minimal requirements and procedures that should be applied to waste management operations. The committee provides recommendations on several issues that it believes merit immediate consideration and action by DOE. Specifically, these issues include the determination of the natural background radioactivity in the area surrounding WIPP, and improvements in TRU waste operations.

This study is organized within the NRC's Board on Radioactive Waste Management and is being conducted by a 15-member committee. Committee members were chosen for their expertise in relevant technical disciplines such as nuclear engineering, health physics, chemical and environmental engineering, civil and transportation engineering, performance assessment, analytical chemistry, materials science and engineering, plutonium geochemistry, hydrogeology, rock and fracture mechanics, petroleum engineering, and mining engineering. As is normal practice of the National Academies, committee members do not represent the views of their institutions, but form an independent body to author this report.

To conduct the study and prepare this interim report, the committee gathered information principally through meetings and reviews of relevant literature. The committee met several times in open public sessions to hear from DOE and its contractors, as well as from other invited speakers such as regulatory agency personnel and groups with an interest in the WIPP program. Committee members prepared this report

using these inputs together with their collective knowledge and experience. The report reflects a consensus of the committee and has been reviewed in accordance with NRC procedures.

Statement of Task

The purpose of this study is to identify the limiting technical components of the WIPP program, with a two-fold goal of (i) improving the understanding of long-term performance of the repository and (ii) identifying technical options for improvements to the National TRU Program (i.e., the engineering system that defines TRU waste handling operations that are needed for these wastes to go from their current storage locations to the final repository destination) without compromising safety.

To accomplish this goal, the study will address two major issues:

(1) The first is to identify research activities that would enhance the assessment of long-term repository performance. This study would examine the performance assessment models used to calculate hypothetical long-term releases of radioactivity, and would suggest future scientific and technical work that could reduce uncertainties.

(2) The second is to identify areas for improvement in the TRU waste management system that may increase system throughput, efficiency, cost effectiveness, or safety to workers and the public. This study will examine, among other inputs, the current plans for TRU waste handling, characterization, treatment, packaging, and transportation.

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Summary

The National Research Council convened a committee of experts to advise the U.S. Department of Energy (DOE) on the operation of the Waste Isolation Pilot Plant (WIPP), a geologic repository for disposal of defense transuranic (TRU) waste near Carlsbad, New Mexico. The committee was asked to provide recommendations on the following two issues: (1) a research agenda to enhance confidence in the long-term performance of WIPP; and (2) increasing the throughput, efficiency, and cost-benefit without compromising safety of the National TRU Program for characterizing, certifying, packaging, and shipping waste to WIPP.

The committee has written this interim report to provide DOE with recommendations on several issues that the committee believes merit immediate consideration and action. In developing this report, the committee has been guided by the principle of "reasonableness" with respect to risks, costs, and the ALARA (as low as reasonably achievable) principle. In the committee's judgment, implementing the recommendations contained in this report will contribute to the continued safe operation of WIPP. The committee will provide a more comprehensive response to its task statement (see the Preface) in the final report, which is scheduled for completion in the spring of 2001.

Research to Enhance Confidence in Long-Term Repository Performance

There has been extensive monitoring of radioactivity in the air, soils, fluvial sediments, surface water, and shallow groundwater in the area surrounding WIPP. However, the committee has determined that radiological baseline information is not available for subsurface brines and hydrocarbons near the WIPP site. This baseline information is important for environmental monitoring in the operational and post-operational phases of the repository.

Recommendation: The committee recommends that DOE should develop and implement a plan to sample oil-field brines, petroleum, and solids associated with current hydrocarbon production to assess the magnitude and variability of naturally occurring radioactive material

(NORM) in the vicinity of the WIPP site. Samples should be collected and analyzed for the radionuclides that will be present in transuranic waste emplaced at WIPP and the radionuclides common in NORM. These samples should be archived to permit subsequent analysis for constituents that may be of interest in the future. The committee recommends that a sampling plan be implemented prior to the closure of any underground rooms in WIPP that contain TRU waste.

Improvements to the National TRU Program

The National TRU Program is administered by the DOE Carlsbad Area Office and is designed to meet all applicable external regulations and internal requirements associated with the characterization, certification, packaging, and transportation of waste to WIPP. A reasonable goal for the National TRU Program is to send DOE TRU waste to WIPP at a minimum risk (from all sources of risk, including radiological exposure and highway accidents) and cost. The current system for managing TRU wastes does not achieve this goal. **The committee recommends that waste management procedures be reviewed and revised, with reduction of risk and cost as the guiding principles.**

The committee offers recommendations in this interim report to improve the following three aspects of the National TRU Program: (1) waste characterization and packaging requirements, (2) gas generation, and (3) the transportation system.

Waste Characterization and Packaging Requirements

The committee found inadequate legal or safety bases for some of the National TRU Program requirements and specifications. That is, some waste characterization specifications have no basis in law, the safe conduct of operations to emplace waste in WIPP, or long-term performance requirements. The National TRU Program waste characterization procedures involve significant resources (e.g., expenditures of several billion dollars) and potential for exposure of workers to radiation and other hazards. Insofar as some of this waste characterization may be unnecessary, such characterization is inconsistent with economic efficiency or the ALARA principle that guides radiation protection practices.

Recommendation: DOE should eliminate self-imposed waste characterization requirements that lack a legal or safety basis. One way to justify a reduction in waste characterization requirements is through implementation of joint U.S. Nuclear Regulatory Commission–U.S. Environmental Protection Agency guidance (62 Federal Register 62079; see Appendix B), which appears to the committee to provide appropriate guidelines for implementation and integration of Resource Conservation and Recovery Act (RCRA) requirements for mixed TRU waste. Another way to justify a reduction is to identify the origins of all waste characterization requirements and to eliminate those requirements that lack a technical or safety basis. Such reductions may require modifications to exist-

ing permits granted by external regulating authorities such as the Environmental Protection Agency and New Mexico Environment Department.

Gas Generation

The extreme assumptions used in DOE's current gas generation model results in gross overestimates of hydrogen (H_2) concentrations in waste packages to be shipped to WIPP. As a consequence, DOE plans to repackage some of the waste to dilute the hydrogen-producing components. These repackaging operations result in additional risks of radiation exposure to workers and highway accidents, the latter due to the increased number of truckload shipments required to transport waste in diluted form.

Recommendations:

1. DOE should derive a more realistic radiolytic gas generation model, validate it through confirmatory testing, use the results to recalculate gas generation limits, and seek regulatory approval to implement them.
2. DOE should perform a safety analysis to determine the concentration and quantity of hydrogen that, upon ignition, could damage the seals of the TRUPACT-II shipping container. The goal of the safety analysis would be to demonstrate whether such an event could occur inside a waste package, and whether the energy associated with such an event could result in rupturing the containment provided by the TRUPACT-II. This analysis could provide the rationale to obtain relief from the 5 percent hydrogen flammability limit and should form the basis for a future modification to the present TRUPACT-II license.
3. DOE should consider technical approaches for reducing hazards from hydrogen generation, such as filling the headspace of the waste containers or the shipping containers with an inert gas.
4. DOE should reevaluate the technical and regulatory feasibility of shipping high-wattage TRU waste using a railcar shipping system.

The goal of these recommendations is to expedite the transport of TRU waste to WIPP by increasing the amount of waste that can be safely carried in each truckload or trainload, without compromising the level of safety and containment that is provided by the shipping container. These recommended options would reduce the number of truckloads required to transport the waste to WIPP and the associated transportation risks.

Transportation Communication and Notification

DOE bases its system of communication and notification on the TRANSportation tracking and COMmunication (TRANSCOM) system, a satellite-based system initially developed more than a decade ago and used to track all DOE shipments of radioactive materials. Users have found the current level of performance of TRANSCOM to be less than

fully reliable. Although efforts are being made by DOE to keep the system current, it has not kept pace with the rapid development of information technology. As a result, the TRANSCOM system is obsolete when compared to presently available communications systems.

Recommendations: DOE should consider cost-effective ways to improve the reliability and ease of use of the TRANSCOM system, either by improving or replacing it. If DOE decides to replace the current system, the committee strongly encourages the use or adaptation of existing commercial systems. In the near term, the DOE should develop an interim plan for maintaining an adequate communication and notification system until any such alternative system or TRANSCOM upgrade is ready for full-scale implementation. This plan should be driven by a comprehensive assessment of TRANSCOM component performance based on anticipated usage. In the long term, DOE should ensure that the system it employs is designed to meet the needs of WIPP shipment users and other major stakeholders in a timely and cost-effective fashion.

Transportation Emergency Response

The responsibility for emergency response is divided between DOE and the states along WIPP shipment corridors. In the committee's view, a system to maintain up-to-date information on response capability would contribute significantly to the effectiveness of the transportation system. The WIPP emergency response program has not assessed sufficiently whether adequate and timely emergency response coverage for a transportation incident exists along the full extent of each WIPP route. No formal system presently exists to identify areas where coverage may be inadequate.

Recommendations: The committee recommends that DOE explore with states and other interested parties how to develop processes and tools for maintaining up-to-date spatial information on the location, capabilities, and contact information of responders, medical facilities, recovery equipment, regional response teams, and other resources that might be needed to respond to a WIPP transportation incident. This assessment should explore which organization(s) should develop and maintain the capability to generate and maintain such information. DOE should also determine where emergency response capability is currently lacking, identify organization(s) responsible for addressing these deficiencies, and take action to address them.

Introduction

The Waste Isolation Pilot Plant (WIPP)[1] is a series of excavations in a Permian-age bedded salt formation approximately 660 m below the surface near Carlsbad, New Mexico (see Figure 1). Since the mid-1970s, this site has been studied for use as a geologic repository for the disposal of transuranic[2] (TRU) waste resulting from the nation's defense program. This waste contains transuranic isotopes, predominantly plutonium isotopes, which are characteristically long-lived radionuclides and therefore a long-term safety hazard. Removing these wastes from the biosphere, for example, through isolation in geologic repositories, is an appropriate strategy for protection of human health and the environment.

At WIPP, packaged waste is disposed by emplacing it in rooms excavated in the salt. Because salt under pressure flows (or "creeps") and because of the underground pressure exerted on the room ceiling, floor, and walls, over time the salt rock at these surfaces will consolidate around the waste. In time, the salt heals so as to be essentially impermeable, isolating the waste-filled rooms from the rest of the environment.

WIPP is the first deep geological repository that has been designed and engineered for radioactive waste disposal and approved by an external regulatory authority. Operations at WIPP to receive TRU waste and emplace it underground began in 1999, when TRU waste shipments were received from three U.S. Department of Energy (DOE) sites. Drums of TRU waste from the Los Alamos National Laboratory, the Idaho National Engineering and Environmental Laboratory, and the Rocky Flats Environmental Technology Site were first sent to WIPP in March, April, and June 1999, respectively.

The committee has prepared this report to provide findings and recommendations that it considers important for the safe and cost-effective operation of WIPP. The perspective of the committee has been the establishment of "reasonableness" with respect to risks, costs, and the ALARA (as low as reasonably achievable) principle (see footnote 8). The committee believes that the implementation of these recommendations will contribute to the continued safe operation of WIPP.

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[1]A complete list of acronyms used in this report appears in Appendix D.

[2]Transuranic waste contains radionuclides with atomic numbers greater than 92 and half-lives greater than 20 years in concentrations exceeding 100 nanocuries per gram.

As noted in the preface to this report, the first component of the statement of task is "to identify research activities that would enhance the assessment of long-term repository performance" (see Appendix A). The committee considers that data from radiological site characterization measurements would provide a necessary baseline to compare against future measurements, should the integrity of WIPP ever be challenged. This issue is explored in the next section.

The second component of the statement of task pertains to improvements of the DOE TRU waste management system. To address this issue, the committee sought to identify the technical, regulatory, legal, and/or safety bases of waste management activities that significantly impacted the overall system throughput, efficiency, cost, and safety. These issues are addressed in the last section of this report.

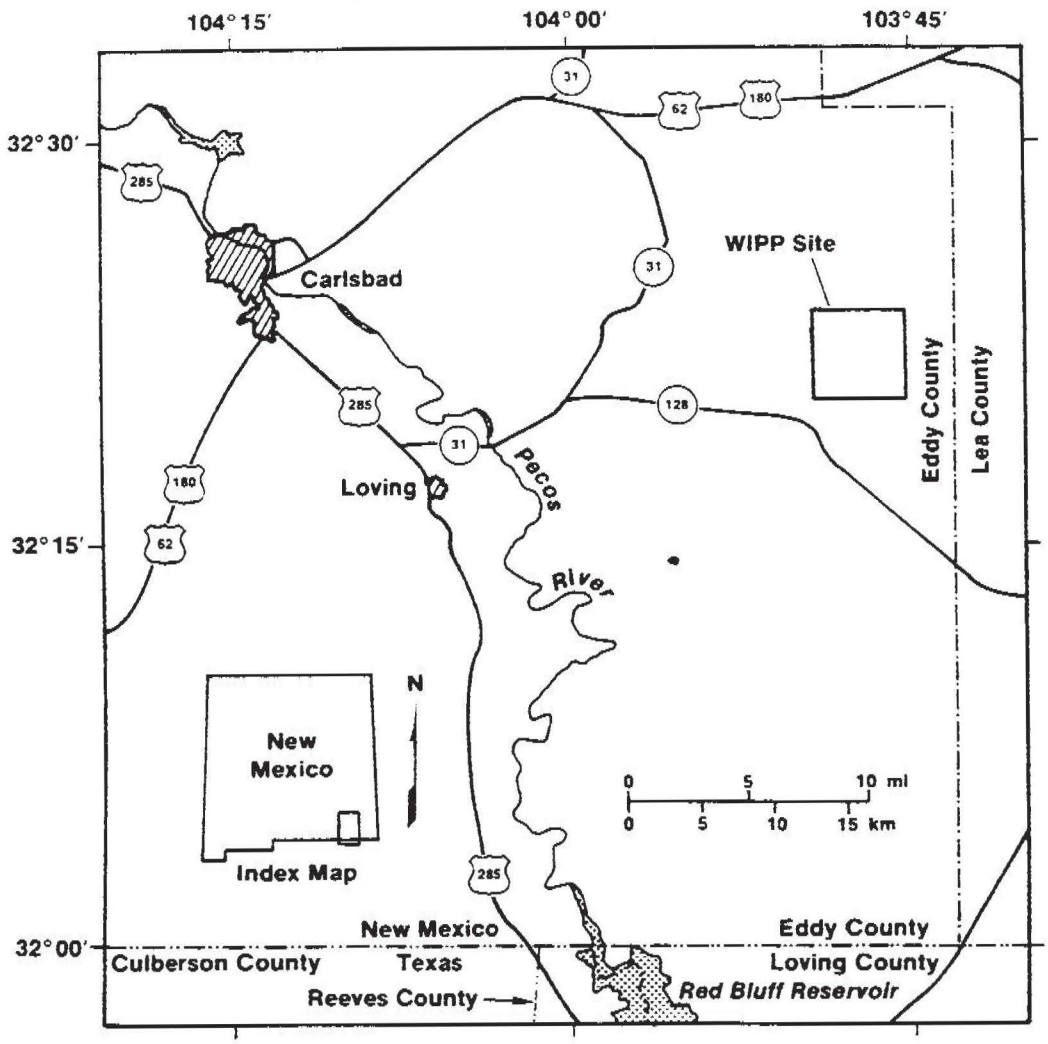

FIGURE 1 Location of the Waste Isolation Pilot Plant. Inset shows the approximate location of the map area in New Mexico. SOURCE: NRC (1996, Figure 1.1.).

Baseline Radiogenic Analysis of Subsurface Fluids

In this section the committee provides recommendations on research activities to enhance confidence in the long-term performance of WIPP. In particular, the committee considered how "baseline" studies undertaken during the early phases of repository operation could be used to support future efforts to assess repository performance.

Finding: There has been extensive monitoring of radioactivity in the air, soils, fluvial sediments, surface water, and shallow groundwater in the area surrounding WIPP.[3] However, the committee has determined that radiological baseline information is not available for subsurface brines and hydrocarbons near the WIPP site. This baseline information is important for environmental monitoring in the operational and post-operational phases of WIPP.

Recommendation: The committee recommends that DOE should develop and implement a plan to sample oil-field brines, petroleum, and solids associated with current hydrocarbon production to assess the magnitude and variability of naturally occurring radioactive material (NORM) in the vicinity of the WIPP site. Samples should be collected and analyzed for the radionuclides that will be present in transuranic waste emplaced at WIPP and the radionuclides common in NORM. These samples should be archived to permit subsequent analysis for constituents that may be of interest in the future.[4,5] The committee recommends that a

[3]See, for example, Conley (1999); DOE (1997c); Herczeg et al. (1988); and Kenney et al. (1999). Additionally, previous Environmental Evaluation Group studies on radiation monitoring of air, surface soil, and biota samples near the WIPP site include Neill et al. (1998); Kenney et al. (1990, 1995, 1998); Kenney and Ballard (1990); and Kenney (1991, 1992, 1994). Ramey (1985) summarizes U.S. Geological Survey data on simple radiological characterization (i.e., gross alpha, gross beta, dissolved radium, and dissolved uranium) of fluids in the Rustler Formation. References to other studies are contained in annual reports of the Carlsbad Environmental Monitoring Research Center (CEMRC, 1999) and on the CEMRC website, http://www.cemrc.org.

[4]A reanalysis of a sample using a different detection method could yield a different value. These detection limitations should be understood and distinguished from true natural differences in background radiation.

sampling plan be implemented prior to the closure of any underground rooms in WIPP that contain TRU waste.

Rationale: Early studies discounted the potential for hydrocarbon production in the vicinity of WIPP, but over the past 20 years this way of thinking has changed dramatically. The site is now surrounded by wells (see Figure 2) for hydrocarbon production (Broadhead et al., 1995), and drilling activities continue. Furthermore, it is relatively common for brines associated with hydrocarbons to be radiogenic (Bloch and Key, 1981; Fisher, 1995). Oil-field brines in the Delaware Basin share this property (Fisher, 1995). The information available on oil-field brines and petroleum resources generally consists of gross radiation measurements (i.e., gross activity), rather than analytical data on the radionuclide constituents. Such analytical data on the radioactivity of oil-field brines and petroleum resources at the WIPP site have not been made available to the committee and may not exist.

If, during or after WIPP operations, increased radioactivity in the vicinity of WIPP is observed, is this the result of a failure of the WIPP to contain its waste, or is it due to NORM? This question cannot be answered easily unless the oil-field brines, petroleum, and solids associated with hydrocarbon production (e.g., suspended solids, precipitated scale, sludges, and formation fragments) are analyzed for their naturally occurring radiation. Analyses for radioactivity and radionuclides will be necessary if disputes arise about potential releases of radionuclides from the repository. An example of the need to obtain adequate NORM background data already has been observed with occurrences of natural surface contamination on the exterior of truck transportation packages while en route to WIPP during the first three months of operation.

"Human intrusion scenarios" involving hydrocarbon exploration and production are now considered processes through which radionuclides might be released from WIPP (Kirkes, 1998). If brines have a measurable NORM content, then human intrusion that results in brine flow through WIPP to the surface is a means by which radioactivity could be carried to the surface that is not due to the TRU waste emplaced in WIPP. If oil-field brine NORM is present, then it is conceivable that NORM releases would be greater than releases from the TRU waste contents of WIPP, even if drilling breaches the repository.

Transport and disposal of oil-field brines that have high NORM contents are also potential mechanisms for localized increases in radiation. Any such increases in radiation in the vicinity of WIPP cannot necessarily be attributed to WIPP operations or the failure of WIPP to contain its waste.

There are data suggesting that oil-field brines near WIPP might contain NORM. Otto (1989, reproduced in Fisher, 1995; see Figure 3)

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[5]The archiving of monitoring data, as well as samples, is also a long-term challenge due to the evolution of information technology and the changes in state-of-the-art storage media that will likely take place over the three decades in which WIPP is projected to be open and operational. Any data records not in paper form would be subject to such challenges.

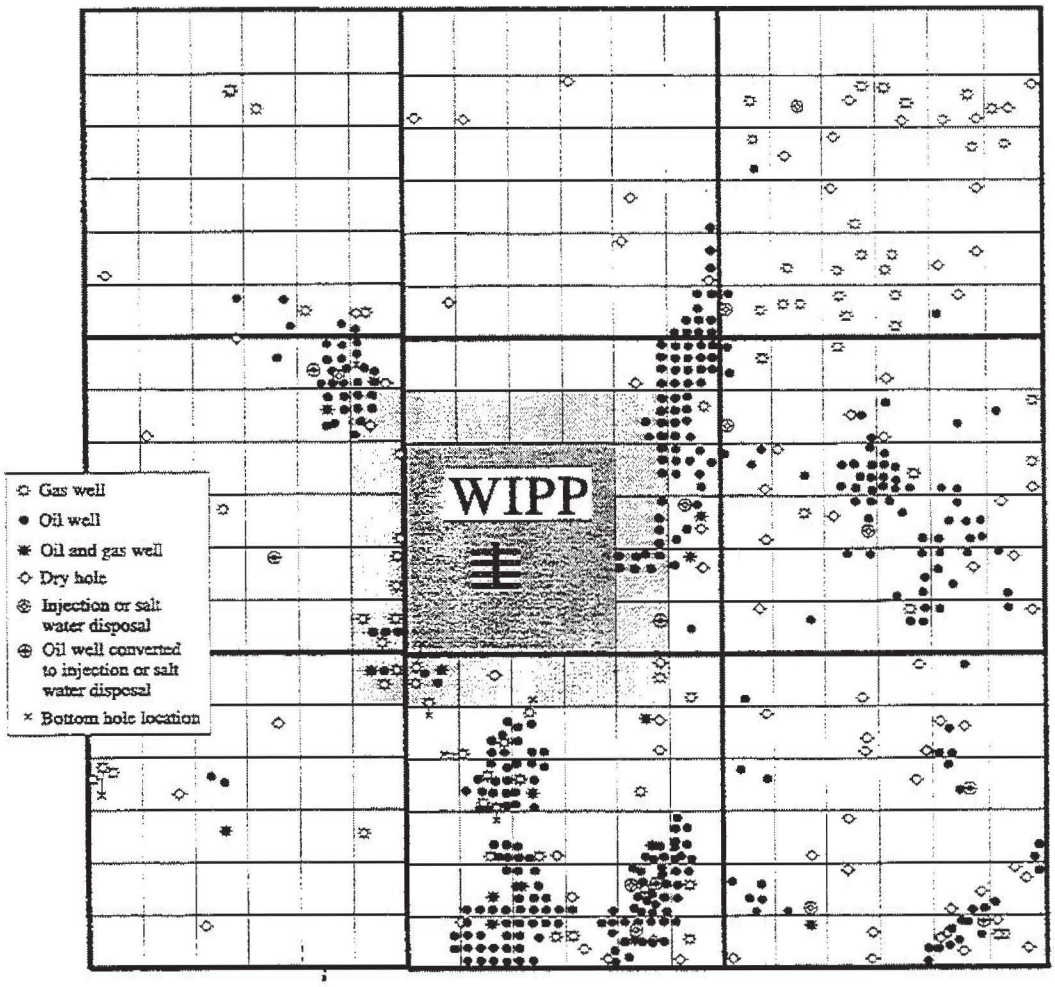

FIGURE 2 Petroleum wells in the vicinity of the WIPP site. See Figure 1 for an inset map showing the WIPP site's approximate location within New Mexico. SOURCE: Silva (1996, p. 24).

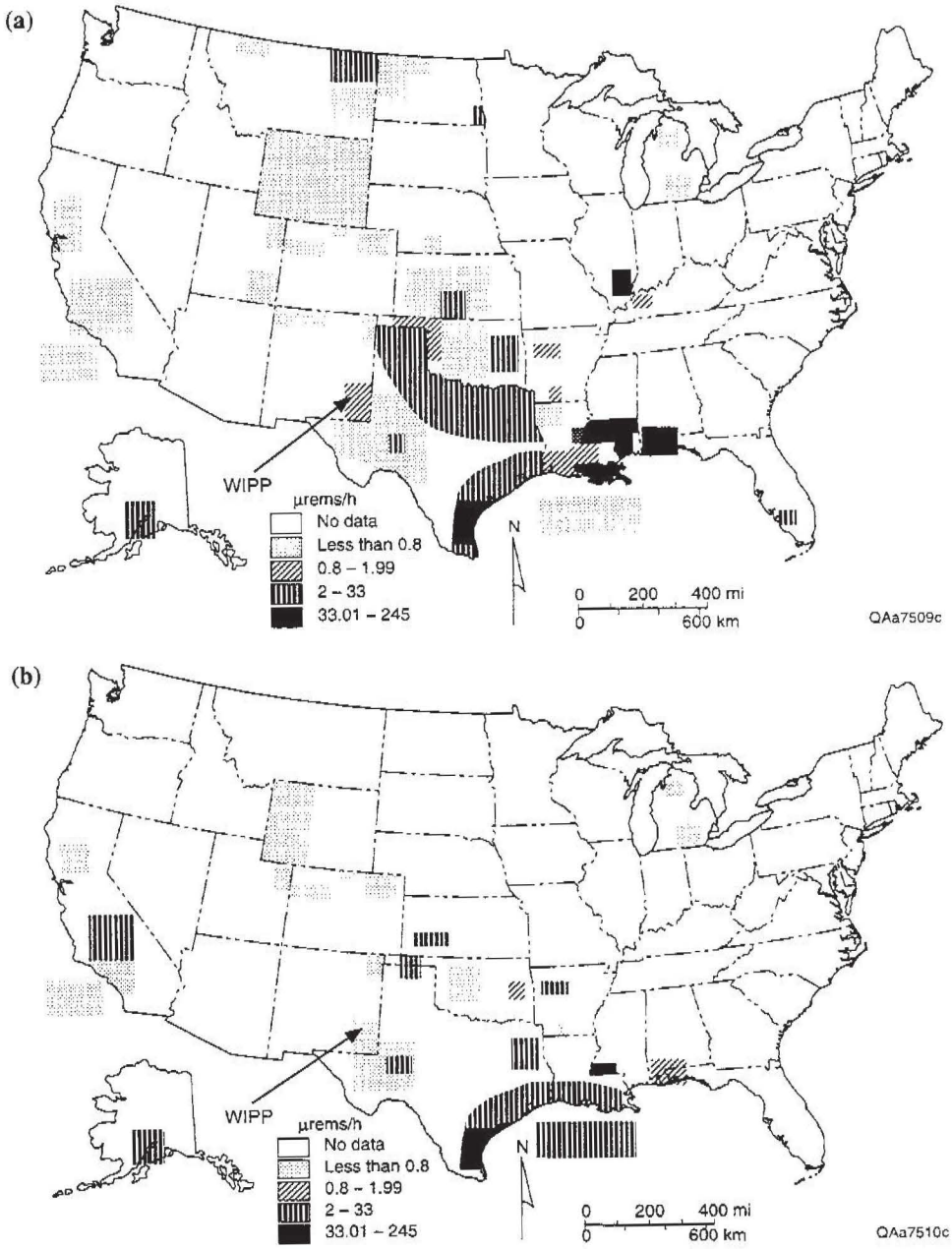

FIGURE 3 Regions of high activity from NORM in the United States from (a) oil-producing facilities and (b) gas-producing facilities. Values are aggregated median differences over background. The legend shows various shadings corresponding to various ranges of dose rates measured in microrems per hour (µrem/h). These dose rates are radioactivity measurements of NORM deposits in piping and in fluids brought to the surface. These measurements describe the concentration of radioactive species, a characteristic of the NORM deposits at any locality that is not directly dependent on the local production rate (of hydrocarbons or brine) or on the amounts of fluid that were extracted to produce the deposits. SOURCE: Fisher (1995), after Otto (1989).

shows the Delaware Basin of southeast New Mexico as a region of NORM activity in oil-and gas-producing facilities. Fisher states that "(1) not every major oil or gas field has associated high NORM levels, and (2) no major hydrocarbon-producing basin in Texas is exempt from high levels of radioactivity." The major hydrocarbon-producing basins in Texas described by Fisher include the Delaware Basin, which contain producing formations near the WIPP site, and the adjacent Central Basin Platform (Hill, 1996, p. 26).

In response to committee requests for information, DOE has answered that no data have been collected on "naturally occurring radionuclides in the underground brines and hydrocarbons near WIPP by DOE. In addition, DOE is unaware of any related information collected by the oil and gas industry" (Mewhinney, 1998b).

The need for these data is clear—no effective monitoring of the WIPP area can be successful without understanding potential sources of radiation in the environment. Air, soils, sediments, ground and surface waters, biota, and people have been analyzed to provide a database (e.g., through CEMRC activities). NORM from local hydrocarbon operations must also be analyzed. The NORM data will

- identify sources of future contamination events that might (wrongly) be attributed to a failure of WIPP;
- place any radioactivity releases from human intrusion scenarios (e.g., from petroleum exploration and production) in perspective; and
- improve the monitoring efforts.

The committee recommends near-term action to collect and analyze these data based on an appropriate sampling plan. The plan must include frequency of sampling and analyses; radionuclides to be analyzed; collection of data to assess NORM radioactivity and to estimate its variability; sampling, analysis, and archiving protocols; and producing formations to be tested. These formations should include both past (if applicable) and present producing zones, new producing zones as they become exploited in the future, and formations from which brine is (or likely will be) extracted.

Samples could come from ongoing well-based operations that generate separator streams of oil, gas, and water. These separators and separator streams are owned by the operators of the leases. The drilling of new wells would be justified if data from separator streams prove to be inadequate.

The radionuclides of interest include both those that contribute to the site's NORM background radioactivity and those in the DOE TRU inventory destined for WIPP. The NORM activity may include contributions from potassium-40, isotopes of uranium and thorium, and daughter products such as isotopes of radium. Radionuclides in TRU waste include isotopes of uranium and TRU elements and, in remote-handled[6] TRU

[6]Remote-handled waste is classified as that with a surface dose rate greater than or equal to 200 mrem per hour. Such waste contains fission products and activation products such as cobalt-60, strontium-90, yttrium-90, ruthenium-106,

waste, fission and activation products. Since some TRU inventory radionuclides are not commonly found in nature, sampling to determine whether such radionuclides are present in the environment may be a good way to distinguish radioactivity due to NORM from that due to TRU waste.

For the reasons given above, the committee supports the collection of NORM data on deep subsurface fluids, even though the isotopic signatures of NORM and TRU waste radioactivity are expected to differ and therefore to be readily distinguishable. In the committee's view, DOE would be better served to possess these NORM data prior to any reported discovery of significant radioactivity in the region; hence, in its recommendation the committee proposes that this survey to sample deep subsurface fluids be conducted in the near term. This survey need not continue once the measurement objectives, as proposed in this recommendation, have been met.

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cesium-137, barium-137, and europium-152. These and other radioisotopes emit penetrating beta and gamma radiation that requires shielding.

Transuranic Waste Management Program

Transuranic waste management operations are performed under the auspices of the DOE National TRU Program administered by the DOE Carlsbad Area Office. This program has been designed and developed, based on initial efforts in the 1980s and subsequent modifications, to accommodate all applicable external regulations and internal requirements that are associated with the characterization, certification, packaging, and transportation of TRU waste to WIPP. These procedures, described briefly in Appendix A, were applied in 1999 for the first contact-handled TRU waste shipments to WIPP from DOE sites that have generated and stored such waste. The remote-handled TRU waste management system is still under development and is not reviewed in this report.

The committee considered three topics associated with TRU waste management: (1) waste characterization and packaging requirements, (2) gas generation, and (3) transportation. These topics are discussed in the following subsections.

Waste Characterization and Packaging Requirements

Finding: The committee found inadequate legal or safety bases for some of the National TRU Program requirements and specifications. That is, some waste characterization specifications have no basis in law, the safe conduct of operations to emplace waste in WIPP, or long-term performance requirements.[7] The National TRU Program waste characterization procedures involve significant resources (e.g., expenditures of several billion dollars) and potential for exposure of workers to radiation and other hazards. Insofar as some of this waste characterization may be unnecessary, such characterization is inconsistent with economic efficiency and the ALARA principle that guides radiation protection practices.[8] The committee regards the 30+ years of waste emplacement op-

[7]A recent study (DOE, 1999c) has also shown that some waste characterization procedures are not prescribed by safety or legal requirements.

[8]ALARA requires that all operations be done with the lowest possible radiation exposure consistent with other requirements of safety and basic programmatic objectives. See, for example, 10 CFR 835, which are requirements for

erations and related worker safety issues at WIPP as posing no significant needs for waste characterization information, because no use of characterization data is made in any handling, shipping, or emplacement operations.

Recommendation: DOE should eliminate self-imposed waste characterization requirements that lack a legal or safety basis. One way to justify a reduction in waste characterization requirements is through implementation of joint U.S. Nuclear Regulatory Commission (USNRC)–U.S. Environmental Protection Agency (EPA) guidance (62 Federal Register 62079; see Appendix B), which appears to the committee to provide appropriate guidelines for implementation and integration of Resource Conservation and Recovery Act (RCRA) requirements for mixed TRU waste. Implementation of this regulatory guidance could significantly reduce the testing protocols and associated radiation exposure of personnel. Another way to justify a reduction is to identify the origins of all waste characterization requirements and to eliminate those requirements that lack a technical or safety basis. Such reductions may require modifications to existing permits granted by external regulating authorities such as the EPA and New Mexico Environment Department.

Rationale: The National TRU Program has developed waste restrictions, as described in the waste acceptance criteria (DOE, 1996a, 1999d), and requirements for waste generating sites presented in the quality assurance program plan (DOE, 1998b). These criteria and plans impose many required procedures on waste-generating sites. EPA and DOE Carlsbad Area Office audits are conducted to certify (i.e., approve for shipment) TRU waste streams. Additionally, each container of waste from a certified waste stream must be characterized, and shipping sites must prepare documentation on characterization data for each waste container. At the Los Alamos National Laboratory, the time to obtain all the requisite documentation and administrative approvals was greater than the time to process a drum of waste through the characterization and packaging protocols that had been developed. At all sites, the assembly, management, and storage of waste characterization information are resource-intensive activities, and drum handling is a major source of worker exposure. Of interest to the committee is the origin of these required procedures, because they increase the cost or risk or decrease the efficacy of operations.

The committee sought to identify the connection between the National TRU Program procedures and the various regulatory, legal, and technical requirements that the procedures should be devised to meet. The committee views these requirements in a hierarchy, at the top of which are legal and safety requirements, with regulatory specifications at the next tier, procedures proposed by DOE to meet regulatory requirements at the third tier, and the DOE protocols for these procedures at the fourth tier.

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worker protection referenced in DOE radioactive waste management practices (specifically, in DOE Order 435.1 [DOE, 1999a]).

The approach used by the committee was to focus on six primary National TRU Program procedures representative of high-level requirements that drive operational activities in waste characterization and repackaging (see Appendix A for an overview of these activities):[9]

1. determination that the TRU waste is of defense origin;
2. sampling and analysis of homogeneous waste;
3. headspace gas sampling and analysis;
4. radioassay of the plutonium content;
5. real-time radiography; and
6. visual examination.

These procedures are incorporated into the terms of the WIPP facility's RCRA "Part B" permit, which was issued in October 1999. The EPA guidelines that are specific to RCRA requirements are presented in Appendix B. However, the committee notes that the permit terms are subject to negotiation in a regulatory permitting process, based on the procedures proposed by DOE that became accepted as meeting regulatory requirements. A recent study (DOE, 1999c) has traced these and other TRU waste characterization requirements to their root origins in either (1) Carlsbad Area Office mandates, (2) regulatory certification and permit terms, (3) regulatory requirements or DOE orders, or (4) legal requirements.

A review of these six procedures revealed that one may be interpreted too strictly by DOE and three are without a technical or legal foundation:

Procedure 1: Determination that the TRU waste is of defense origin. WIPP is limited to defense-related waste as stipulated in the Land Withdrawal Act, with defense activities defined in the Nuclear Waste Policy Act of 1982. The committee notes that this definition includes the words "in whole or in part", which can be interpreted to include mixtures of defense and nondefense waste, although DOE does not appear to take advantage of this (see DOE, 1997a; Nordhaus, 1996). That is, waste such as plutonium-238 (^{238}Pu)-contaminated scrap from a facility used for both defense and nondefense missions at Los Alamos National Laboratory would appear to qualify as defense waste under the definition, without the need for waste segregation restrictions.

Procedure 2: Sampling and analysis of homogeneous waste. DOE has written, "There is no regulatory requirement to conduct homogeneous waste sampling and analysis, however, in an effort to meet the intent of 40 CFR 264.13, WIPP has imposed additional characterization requirements on the waste generators" (Nelson, 1999a, p. 2). No operational decisions are made based on these data; that is, the results of the sampling and analysis do not affect how waste is handled, so it is not clear what justifies the additional radiation exposure risk and cost of this procedure. In the committee's view, this sampling and analysis applied only to homogeneous waste is unnecessary: If acceptable knowledge documentation

[9]A more comprehensive list of TRU waste characterization procedures and their origin is found in DOE (1999c).

(see Appendix A) provides sufficient characterization information for heterogeneous waste, the committee can identify no technical reason why acceptable knowledge should not also be adequate for homogeneous waste.

Procedure 3: Headspace gas sampling and analysis. DOE informed the committee that "there is no regulatory requirement to conduct headspace gas sampling and analysis, however, in an effort to meet the intent of 40 CFR 264.13, WIPP has imposed additional characterization requirements on the waste generators" (Nelson, 1999a, p. 3). The headspace gas sampling and analysis was developed as a means of checking on conformance with USNRC and the U.S. Department of Transportation (DOT) requirements (see Appendix A for relevant sections of these regulations); however, these requirements can be met by other means (see the recommendations that follow on the issue of gas generation).

Procedure 6: Visual examination. Visual examination is done on a fraction of the waste containers to confirm the real-time radiography and acceptable knowledge waste characterization information (Nelson, 1999a, p. 5). However, there is no requirement for verification of real-time radiography results. An alternative way to confirm these results without operator exposure would be to use standardized test drums. The visual examination confirmation is a self-imposed procedure that yields no benefit but results in increased risk of exposure and cost.

A DOE study (1999c) also confirms that procedures 2, 3, and 6 identified above are based on terms negotiated in a permit and not on a required regulation or legal mandate. The committee sees no utility in the information that these procedures provide. Any speculative benefits of acquiring this information must be weighed against the risks and costs. The committee's judgment is that the collection of these data from superfluous procedures increases, rather than decreases, the risk and safety of the overall TRU waste operations.

These superfluous characterization and intrusive procedures also represent a conflict with the ALARA principle. The issue of how to handle conflict between regulatory requirements for waste characterization information and ALARA is beyond the scope of the committee's statement of task. At issue, however, is whether the present TRU waste management program results in significantly more worker radiation exposure than is justified to satisfy safety and nonnegotiable regulatory requirements.

Gas Generation

Finding: The extreme assumptions used in DOE's current gas generation model result in gross overestimates of hydrogen concentrations in waste packages to be shipped to WIPP. As a consequence, DOE's plans to repackage some of the waste to dilute the hydrogen-producing components. These repackaging operations result in additional risks of radiation exposure to workers and highway accidents due to the increased number of truckload shipments required to transport waste in diluted form.

Recommendations:

1. DOE should derive a more realistic radiolytic gas generation model, validate it through confirmatory testing, use the results to recalculate gas generation limits, and seek regulatory approval to implement these limits.
2. DOE should perform a safety analysis to determine the concentration and quantity of hydrogen that, upon ignition, could damage the seals of the TRUPACT-II shipping container. The goal of the safety analysis would be to demonstrate whether such an event could occur inside a waste package, and whether the energy associated with such an event could result in the rupture of containment provided by the TRUPACT-II. This analysis could provide the rationale to obtain relief from the 5 percent hydrogen flammability limit and should form the basis for a future modification to the present TRUPACT-II license.
3. DOE should consider technical approaches for reducing hazards from hydrogen generation, such as filling the headspace of the waste containers or the shipping containers with an inert gas to displace air and thereby reduce the flammability hazard.
4. DOE should reevaluate the technical and regulatory feasibility of shipping high-wattage TRU waste using ATMX[10] railcar shipping system.

The goal of these recommendations is to expedite the transport of TRU waste to WIPP by increasing the amount of waste that can be carried safely in each truckload or trainload, without compromising the level of safety and containment that is provided by the shipping container. These recommended options would reduce the number of truckloads required to transport the waste to WIPP and the associated transportation risks.

Rationale: The amount of TRU waste in each waste drum and truck shipment is limited because of the potential for radiolytic generation of hydrogen gas (H_2). Within TRU waste, radiolytic hydrogen gas generation is due primarily to the co-disposal of alpha emitters with organic materials. The DOE has developed a radiolysis model to calculate hydrogen generation rates and the hydrogen concentration in each headspace[11] inside a waste container. Limiting any H_2 concentration to 5 percent leads to a restriction, expressed as maximum allowable wattage, on alpha activity (i.e., the amount of alpha-emitting radionuclides) within each waste container (e.g., a 55-gallon drum). The value of 5 percent H_2 (as a mole

[10] "ATMX" is an acronym to denote the railcars used by DOE to ship nuclear weapons components and TRU waste. The "AT" stands for Atchison Topeka, the rail carrier. The "M" signifies munitions, and the "X" on a railcar signifies private ownership (in this case, by the U.S. government), rather than ownership by the railroad company. As noted elsewhere in this report, these railcars have been used to ship TRU waste for decades.

[11] In many waste containers, waste is contained in one or more plastic bags that were used for radiological protection against any inadvertent spread of radioactivity. These plastic bags provide resistance to diffusive transport of hydrogen gas, thereby providing multiple headspaces.

fraction) in air as a "flammability limit" can be used in any USNRC license application on a transportation package without the need for further safety analysis because of its conservatism. This allowable wattage is a function of the G value[12] of the solid matrix of the waste materials adjacent to each alpha emitter and the total resistance to the flow of hydrogen gas that the waste and packaging contents provide, due primarily to the layers of plastic bags in the waste.

Wattage limits based on this model determine whether or not a waste container may be transported to WIPP without repackaging. The gas generation model, and the wattage limits derived from it, specify the terms of operation that are contained in the DOE safety analysis report for the TRUPACT-II transportation package. These terms of operation are also specified in DOE's application to the USNRC for regulatory approval of the TRUPACT-II transportation package. The certificate of compliance for TRUPACT-II issued by the USNRC is subject to modifications (and in fact has been amended several times since the original certificate was issued in the late 1980s), provided that DOE can offer sufficient adequate safety assurances and comply with applicable regulations, principally the USNRC's 10 CFR 70-71 and DOT's 49 CFR 171-173.

The current model is based on worst-case scenario of H_2 generation and wattage limits. Because of this worst-case approach and the extreme assumptions used in the model, the calculations often exceed experimental observations by orders of magnitude. The explanations for these large discrepancies are only beginning to be studied (see Idaho Engineering and Environmental Laboratory, 1998; Mewhinney, 1998a). Specific examples follow.

1. A G value of 3.4 is used for the plastic bags in the safety analysis report for the TRUPACT-II (DOE, 1997b). In this analysis, no credit is taken for matrix depletion (i.e., exhaustion of the H_2 source). Therefore, DOE is seeking relief from unrealistically large G values in revisions 17-19 of the safety analysis report and certificate of compliance for the TRUPACT-II (DOE, 1999b).

2. The model assumes that all layers of plastic bags are intact and behave as a new bag (i.e., no credit is taken for changes in permeability with age).

The results of these gas generation model assumptions have severe consequences.[13] Repackaging is carried out to redistribute waste in containers (e.g., 55-gallon drums) in order to meet the wattage limits derived from the gas generation model for each container. This repackaging of waste exposes workers to radiation and increases the number of containers, thereby diluting the waste into a greater volume.

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[12]The G value is the number of electrons (or, equivalently, the number of electron-ion pairs, with H^+ the chief ion produced in materials containing hydrogen compounds) produced in a material per 100 eV of energy that is deposited within it by irradiation.

[13]In general, the use of extreme assumptions that result in overestimating consequences is not a conservative approach, because attending to these overestimated consequences results in unnecessary actions, each of which has its own risks, thus potentially increasing the risks of the overall operations.

Transportation-related risks (and costs) are also incurred in repackaging, because the extra containers require additional shipping loads with many additional truck trips. DOE estimates reveal that this repackaging of ^{238}Pu contact-handled TRU waste may increase the number of ^{238}Pu shipments by more than a factor of ten, to as many as 150,000 extra drums (Lechel and Leigh, 1998).[14] Another consequence of such volume expansions that should be considered is the impact on WIPP's volume limit.[15] Therefore, the maximum allowable wattage imposed by the gas generation model is a major technical restriction of the National TRU Program.

Recent information (DOE, 1999b; Gregory, 1999) suggests that significant progress is being made toward developing technical information to support planned future applications to the USNRC to amend the terms of the TRUPACT-II safety analysis report and certificate of compliance. Research continues to investigate the use of hydrogen getters[16] (Mroz et al., 1997, 1999), methods for puncturing bags, use of vented bags (Gregory, 1999), and relief from the restrictive G values (Idaho Engineering and Environmental Laboratory, 1998).

To provide containment of its radioactive contents, the TRUPACT-II shipping container uses outer O-rings that generate a vacuum seal. In this package design, internally generated gas, such as H_2, builds up to pressurize the internal gas volume. Other transportation package designs are possible that are less sensitive than the TRUPACT-II to the potential for H_2 gas generation. One such system for transport of TRU wastes was the ATMX railcar system, which DOE used for hundreds of shipments over several decades to safely transport TRU waste from the Mound Laboratory in Ohio and from the Rocky Flats Environmental Technology Site in Colorado to the Idaho National Engineering and Environmental Laboratory. Based on the integrity provided by the railcar, this system was exempted (DOT exemption number DOT-E 5948) from the double-containment and vacuum seal requirements for packages used to transport plutonium (classified as "Type B" fissile packages). As a result, this system did not suffer limitations of the kind that are imposed on the TRUPACT-II due to radiolytic gas generated and trapped within the shipping container.

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[14]The actual number of containers to be repackaged and procedures to be used have not yet been determined by DOE but are under active study, as is an analysis of technical options. If each truck carried the maximum number of TRUPACT-II transporters per shipment to WIPP, and each TRUPACT-II carried the maximum number of 55-gallon drums, 150,000 drums would be equivalent to 3,600 additional truck shipments.

[15]The Land Withdrawal Act (P.L. 102-579) specifies a total TRU waste volume limit of 175,600 m^3; if waste were sufficiently diluted, WIPP would be filled to this volume limit without having disposed the total TRU inventory in curies. Therefore, there is a minimum "filling ratio" of curies to volume that must be achieved, on average, for WIPP to contain the total TRU inventory in curies by the time the volume restriction is reached.

[16]A getter is a material designed to absorb gas such as hydrogen.

Transportation

The committee has examined various aspects of the WIPP transportation system, focusing on system safety and the cost-effectiveness of planned and ongoing activities. Based on this review (see DOE, 1999b; Mewhinney, 1998a,b), the committee has identified two issues—DOE's communication and notification system (TRANSCOM[17]) and DOE's emergency response program—that warrant immediate attention.

DOE's Communication and Notification Program

Finding: DOE bases its system of communication and notification on TRANSCOM, a satellite-based system developed more than a decade ago and used to track all DOE shipments of radioactive materials. Users have found the current level of performance of TRANSCOM to be less than fully reliable. Although efforts are being made to keep the system current (Nelson, 1999b), it has not kept pace with the rapid development of information technology. As a result, TRANSCOM is obsolete compared to presently available communications systems (for a summary of recent transportation communication initiatives using information technology, see Allen [1998]).

Recommendations: DOE should consider cost-effective ways to improve the reliability and ease of use of the TRANSCOM system, either by improving or replacing it. If DOE decides to replace the current system, the committee strongly encourages the use or adaptation of existing commercial systems. In the near term, DOE should develop an interim plan for maintaining an adequate communication and notification system until any such alternative system or TRANSCOM upgrade is ready for full-scale implementation. This plan should be driven by a comprehensive assessment of TRANSCOM component performance based on anticipated usage. In the long term, DOE should ensure that the system it employs is designed to meet the needs of WIPP shipment users and other major stakeholders in a timely and cost-effective fashion.

Rationale: Public confidence in a transportation communication and notification system is essential. This will become increasingly important with the growing number of shipments to WIPP. The magnitude of shipping activity and the public interest in WIPP transportation safety dictate the need for a state-of-the-art communications system.

As a means of obtaining information on the current effectiveness of TRANSCOM, the committee contacted 27 users located across the nation, requesting information on their experience with the system. Serious concerns were raised about system reliability and ease of use, giving the impression that key transportation stakeholders have little confidence in TRANSCOM. Comments of the 11 users who responded (from two tech-

[17]The DOE TRANSportation Tracking and COMmunication System, or TRANSCOM, is a satellite-based telecommunications system designed to enable users to track WIPP truck shipments in essentially real time while en route to WIPP on the approved highway routes.

nology companies and various institutions involved in emergency response monitoring in Colorado, Illinois, Pennsylvania, Idaho, Wyoming, Oregon, Arizona, North Carolina, and Utah) to a committee survey are shown below. On a scale of 1 to 5, with 1 = inadequate, 2 = poor, 3 = average, 4 = good, and 5 = excellent, the average scores for TRANSCOM system on five issues were as follows:

Category	Average Score on Scale of 1 to 5
Accuracy	3.5
Cost	3.4
Ease of use	3.2
Communication capability	3.0
Reliability	2.5

Most survey responders also wrote either explicitly or by using examples that the system was (1) unreliable (citing frequent downtime, connection or access problems, or other hardware or software problems), (2) not user friendly (citing features such as slow data rates, the time required to download information, and "old technology"), and (3) not economical because of the high costs for modem connections. Of those survey responders who had experience with at least one other transportation tracking system, each provided written comments attesting to the "unreliable" and/or "not user-friendly" features of TRANSCOM.

The committee concludes from this survey and from other materials received (e.g., presentations at committee meetings in October 1998, May 1999, and July 1999) that the TRANSCOM system has failed to give its users confidence in its reliability, ease of use, and the timeliness with which accurate information can be accessed. The committee regards these features as important for engendering public confidence and trust in WIPP's transportation program, especially for incidents in which some sort of emergency response is required.

The committee considers that given the potential interest in and visibility of WIPP shipments, the tracking system should provide reliable, real-time, and user-friendly access to information for the state users and other interested parties. In principle, this could be accomplished through upgrades to the current TRANSCOM system. However, rather than maintaining and upgrading a technically obsolete system, the committee believes that it would be more prudent for DOE to implement a less expensive, higher-quality system using a currently available commercial communications product (for a summary of transportation communication initiatives using information technology, see Allen [1998]). Careful screening of vendors is necessary to ensure that the desired system can perform to specification and be delivered on schedule and within budget.

Recent DOE efforts (Nelson, 1999b) are aimed at developing upgraded information technology capabilities ("TRANSCOM 2000") for the TRANSCOM system. Specifically, modem connections to access data of interest (e.g., the commercial bill of lading for a shipment) are to be replaced in the near future by internet postings. These plans for improved user interface and data distribution capabilities do not address other parts of the system, such as the speed with which data are acquired and proc-

essed prior to posting. These data acquisition and processing activities appear to introduce time delays that limit system performance; for example, position updates showing the locations of trucks along routes are delayed by several (up to seven) minutes (Nelson, 1999b). An as-yet-unspecified element of these planned upgrades is the extent to which future stakeholder participation will be solicited and used to provide sufficient feedback to ensure that the product ultimately developed addresses user concerns. Moreover, the timetable for off-the-shelf availability of TRANSCOM 2000 appears to the committee to be several years in the future, a problematic scenario for a WIPP shipping activity that is already underway.

One issue relevant to these planned information disclosures in TRANSCOM 2000 is the extent to which such information is needed or useful, by which parties, and to what ends. For example, the terrorist hazard and/or the potential for deliberate sabotage would presumably increase as this information is disseminated more broadly. If restricted access to certain information were important, security firewalls could be used to prevent internet information from being accessed outside of the TRANSCOM user community.

At present, the National TRU Program is one of many DOE users of the TRANSCOM system that is managed by another DOE program unit, the DOE transportation center in Albuquerque, New Mexico; other DOE transportation users include shippers of low-level waste and spent nuclear fuel. If the DOE transportation program that maintains TRANSCOM cannot provide sufficient improvements to fully implement the above recommendations, another approach would be for the National TRU Program to adapt a commercially available tracking system for use on WIPP shipments only. If the tracking system need only meet WIPP shipment requirements, the system specifications would likely be simpler, with a correspondingly greater likelihood that a commercially available product could be adapted for use. For example, WIPP shipments involve unclassified material, which may allow relief from the full suite of TRANSCOM system requirements that have been developed for all of DOE shipping needs.

DOE's Emergency Response Program

Finding: The responsibility for emergency response is divided between DOE and the states along WIPP shipment corridors. In the committee's view, a system to maintain up-to-date information on response capability would contribute significantly to the effectiveness of the transportation system. The WIPP emergency response program has not assessed sufficiently whether adequate and timely emergency response coverage for a transportation incident exists along the full extent of each WIPP route. No formal system presently exists to identify areas where coverage may be inadequate.

Recommendations: The committee recommends that DOE explore with states and other interested parties how to develop processes and tools for maintaining up-to-date spatial information on the location, capabilities, and contact information of responders, medical facilities, re-

covery equipment, regional response teams, and other resources that might be needed to respond to a WIPP transportation incident. This assessment should explore which organization(s) should develop and maintain the capability to generate and maintain such information. DOE should also determine where emergency response capability is currently lacking, identify organization(s) responsible for addressing these deficiencies, and take action to address them.

Rationale: To respond appropriately to any accident or other incident associated with a WIPP shipment, an emergency response system has been developed involving the DOE and state and local governments. Four levels of emergency response teams have been established. The first responders, typically the local police or local fire department, are to alert others. Their "911" call routes the incident to the attention of the second responders, the state emergency management agency, which then involves the state police and any state hazardous material (HAZMAT) or radiological response teams. The third responders are DOE Radiological Assistance Program teams that would be sent from major DOE sites (e.g., Idaho Engineering and Environmental Laboratory or the DOE Carlsbad Area Office) to conduct radiological emergency (medical) response. The fourth level of response is DOE remediation teams who perform measures such as righting a truck and any necessary site cleanup and restoration activities (DOE, 1998a).

Because of the required integrity of the TRUPACT-II shipping container, which is tested and certified to conform to the USNRC's 10 CFR 71 regulatory requirements, the containment offered by this container normally cannot be breached in an accident scenario. Therefore, emergency response procedures in these four levels of response normally would preclude any consideration of releases of materials from the TRUPACT-II. Under normal conditions, the emergency response procedures would still be needed for traffic management and other necessary operations in accident-related situations.

DOE's emergency response program relies heavily on WIPP corridor states to conduct emergency responder training and develop response plans in the event of a transportation incident. DOE also maintains its own specialized response capabilities that can be deployed on an as-needed basis. Although this approach offers certain advantages in terms of state and local involvement, system-level integration is a significant concern.

Maintaining an effective emergency response program necessitates that, if an incident should occur anywhere along a WIPP route, qualified responders can reach the scene in a timely fashion. Emergency preparedness is a formidable challenge given the thousands of miles of highway that comprise WIPP routes.

While WIPP corridor states are coordinating with DOE to ensure the safe transport of WIPP shipments[18] (DOE, 1995, 1999b; Klaus, 1999; Ross, 1999; Wentz, 1999), the public may view this responsibility as ulti-

[18]These activities have included training drills that have been conducted over the past several years to simulate real transportation procedures and accident scenarios.

mately resting with DOE as the system manager. The public might well expect qualified emergency response coverage along the entire length of each WIPP route, and in the committee's view, DOE could be heavily criticized if an event occurs that demonstrates weaknesses in the emergency response program, regardless of whether serious consequences are involved. Hence, although the recommendations in this section are not legal requirements, these assessments of the emergency response capabilities are, in the committee's view, important for providing a well-orchestrated transportation system.

The system-level integration necessary to ensure adequate emergency response would have to manage the jurisdictional boundaries between the various responsible government agencies. For example, under the federal Occupational Safety and Health Act (specifically, 29 CFR 1910.120), an employer is responsible for providing training; consequently, the state has the responsibility to determine the extent and adequacy of training (i.e., who is trained and in what capabilities) for first- and second-level responders. States have, to date, offered free WIPP-related training opportunities. No "quality assurance" program yet exists to evaluate periodically and systematically the extent of training and response capabilities within states. Moreover, the database lists trained personnel by state only, rather than by local region (e.g., county). As required by the Land Withdrawal Act, DOE provides the states with WIPP-specific hazard information, but DOE does not furnish protective, detection, monitoring, or communication equipment to states.

These and other demarcations of responsibilities should be managed to ensure that prompt and effective response capability for any transportation incident exists anywhere along a WIPP route. Although the training and response time associated with the first and second responders are not under DOE's direct control, a system to assess the extent and adequacy of this response coverage would be useful for DOE to properly prepare for and manage WIPP transportation incidents.

Committee Perspective on National TRU Program Requirements

A reasonable goal for the National TRU Program is to send DOE TRU waste to WIPP at a minimum risk (from all sources of risk, including radiological exposure and highway accidents) and cost. The current system for managing TRU wastes does not achieve this goal. The current transportation system cannot be used to ship a large fraction of the TRU waste volume without significant repackaging (Connolly and Kosiewicz, 1997; DOE, 1999b; Mroz et al., 1997). For the waste inventory that does qualify for shipment in this system, risk and cost considerations have not been optimized.

The terms and activities selected by DOE Carlsbad Area Office for submission to its regulatory authorities to satisfy applicable regulations and other concerns do not produce an optimum balance between risk and cost, in the spirit of ALARA. **The committee recommends that waste management procedures be reviewed and revised, with reduction of risk and cost as the guiding principles.**

As experience is gained in the WIPP shipping program, empirical data could be gathered to improve upon the initial estimates of risk and cost that are associated with each operation. The effort to reduce risks and costs necessarily would include some consideration of uncertainty, the procedures needed to adequately bound this uncertainty, and an assessment of which TRU waste program elements are the most important to control.

For example, the current National TRU Program has many procedures to control certain program elements. Over time, the most effective of such controls could be identified and retained. The reduction of risks and costs is possible in a management approach that takes into consideration public preferences for certain restrictions and implements procedures to minimize relevant uncertainties. As empirical data and experience are gathered, estimates of risks and costs of various components of the TRU waste operations can be refined. Such risk and cost estimates are useful to probe the elements of the waste management system that need to be controlled most restrictively, whether to meet legal or technical safety restrictions or to address public preferences for how radioactive waste is to be managed and transported.

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Appendix A

Background Information

The material in this appendix provides background information on the long-term performance of the Waste Isolation Pilot Plant (WIPP) as well as waste characterization and transportation activities associated with the National TRU Program.

Assessment of Long-Term Performance

The ability of WIPP to isolate radioactive waste from the accessible environment has been studied and modeled in a performance assessment calculation. The performance assessment organizes information relevant to long-term (i.e., over a 10,000-year period) repository behavior by assessing the probability and consequence of major scenarios by which radionuclides can be released to the environment surrounding the WIPP site. Important scenarios include those due to human activities, whether deliberate or unintentional, that might occur near the WIPP site and potentially compromise the integrity of the repository. For example, drilling for hydrocarbon resources in formations underlying WIPP is currently practiced in the Delaware Basin on land surrounding the WIPP site; therefore, stylized "human intrusion" scenarios in which future boreholes are drilled through WIPP have been analyzed in the performance assessment model.

Using this performance assessment, the U.S. Department of Energy (DOE) has modeled the long-term performance of the WIPP repository to meet regulatory requirements. As specified by the 1992 Land Withdrawal Act (P.L. 102-579) passed by the U.S. Congress, the U.S. Environmental Protection Agency (EPA) is the external regulatory authority for WIPP, using as a regulatory standard the rule 40 CFR 191.[1] The performance assessment model formed the basis of the 1996 DOE application to the EPA to obtain a certificate of compliance with the 40 CFR 191 standard to open and operate WIPP. The EPA granted this certificate in 1998, and EPA oversight continues in periodic (i.e., every five years)

[1]For compliance with the standard of 40 CFR 191, the EPA issued rule 40 CFR 194 in 1996 to provide a regulatory interpretation of how these requirements would apply to WIPP.

recertifications. Changing some of the repository features (e.g., the design of the engineered seals to close underground rooms once they are filled with waste or the design of the seals to close the vertical shafts to the surface) would require regulatory approval because of their importance to the model of long-term performance.

DOE Management of TRU Waste

Transuranic (TRU) wastes are stored and managed at several DOE sites nationwide. To dispose of these wastes at WIPP, they must be retrieved from storage, characterized, repackaged (if necessary), and transported to WIPP, where they are unloaded from shipping containers and sent underground for emplacement in the disposal rooms.

These activities are conducted under the auspices of the National TRU Program administered by the DOE Carlsbad Area Office. DOE sites sending waste to WIPP must meet the waste characterization and transportation specifications that are contained in the WIPP waste acceptance criteria. The specifications on characterization and transportation operations are designed to meet all applicable regulations that have been promulgated by the EPA (chiefly through the Resource Conservation and Recovery Act, or RCRA), the U.S. Nuclear Regulatory Commission (USNRC), and the U.S. Department of Transportation (DOT). The waste characterization activities and the transportation system are described in more detail below.

Waste Characterization Activities

The characterization program described here has been developed for contact-handled[2] TRU waste and applied to date on non-mixed waste.[3] The methods, equipment, procedures, determination of uncertainty, and other protocols used at DOE sites to perform these characterizations are approved by both the DOE Carlsbad Area Office and the EPA. The major procedures are as described in the following sections:

Determination of the Origin and Composition of the Waste by Acceptable Knowledge. Acceptable knowledge of the origin and composition of the waste must be available in documentation to prove that the waste is of defense origin (by the terms of the Land Withdrawal Act, only defense-related TRU waste may legally be sent to WIPP) and to provide

[2]Contact-handled waste is that for which the maximum radiation dose rate at the surface of the waste container is less than 200 mrem per hour. Essentially no shielding other than the waste container is needed. Much of the DOE TRU waste has radioactivity due primarily to alpha-emitting actinides. Because alpha particles are relatively easy to shield, such waste would have a low surface dose rate and therefore would be classified as contact-handled waste.

[3]Mixed waste is waste with radioactive constituents regulated under the Atomic Energy Act mixed with hazardous chemical materials regulated under RCRA. Non-mixed radioactive waste is waste that can be shown not to contain RCRA-regulated materials.

characterization information on the waste constituents. The DOE Carlsbad Area Office and EPA use the acceptable knowledge documentation to certify each "waste stream" (i.e., waste-generating process), and TRU waste sent to WIPP must come from a certified waste stream.

Sampling and Analysis of Homogeneous Waste for RCRA Constituents. Most of the TRU waste is heterogeneous in nature and requires no further characterization beyond acceptable knowledge to satisfy the regulatory requirements of RCRA. For homogeneous waste, a fraction of the waste containers (e.g., 55-gallon drums or standard waste boxes) are cored to extract representative samples that are analyzed for constituents (e.g., volatile and semi-volatile organic compounds, toxic metals, and other hazardous chemicals) regulated by RCRA. Both the acceptable knowledge procedure (for heterogeneous waste) and the sampling and analysis procedure (for homogeneous waste) were proposed by DOE for the terms of operation that would be specified in its RCRA Part B permit. These terms have been accepted by New Mexico, which has authority delegated by the EPA to regulate RCRA materials and mixed waste and which issued the RCRA Part B permit in October 1999.

Real-Time Radiography. A real-time radiography procedure using x-rays is performed on all waste containers to look for items such as pressurized cans or free-standing liquids that are prohibited from being transported under DOT regulations. If any of these items are present in a waste container, its contents are repackaged, at which time the prohibited materials are removed. Another purpose of the radiography examination is to confirm the acceptable knowledge characterization information.

Visual Examination. A visual examination is performed on a fraction of the waste containers, by spilling the waste contents into a glovebox, to verify the acceptable knowledge and real-time radiography information. The value of this fraction was proposed by DOE to be two percent of the initial population of containers of each waste stream, and if these evaluations resulted in few miscertifications, then the percentage of subsequent waste containers to undergo visual examination would be reduced. In October 1999, New Mexico in its RCRA Part B permit stipulated the initial fraction of containers to undergo visual examination to be 11 percent.

Radioassay and Determination of Fissile Isotope Content. The number of curies of each transuranic isotope is determined by radioassay (e.g., gamma scans) to a specified precision and accuracy. The fissile isotope content is assessed using methods such as passive-active neutron systems. This information is used to ensure criticality safety, a USNRC requirement, which imposes a restriction on the amount (several hundred grams) of each fissile species per container. This restriction is less stringent than the amount derived from the gas generation model, discussed below.

Headspace Gas Sampling. Headspace gas sampling is carried out on all waste containers for flammable gases (specifically, volatile organic compounds, hydrogen, and methane). This procedure has been proposed

as a means of checking on conformity with the DOT regulations (e.g., 40 CFR 173 and 40 CFR 177) and USNRC regulations (e.g., 10 CFR 71) that address the transport of flammable and/or gas-generating substances with radioactive materials (Mewhinney, 1998b). These regulations include the following statements:

- 49 CFR 173.21(g): "Packages which give off a flammable gas or vapor, released from a material not otherwise subject to this subchapter, likely to create a flammable mixture with air in a transport vehicle" are forbidden.
- 49 CFR 173.21(h): "Packages containing materials which will detonate in a fire" are forbidden.
- 49 CFR 173.24(b)(3): "There will be no mixture of gases or vapors in the package which could, through any credible spontaneous increase of heat or pressure, significantly reduce the effectiveness of the packaging."
- 49 CFR 177.848 specifies that flammable gases and radioactive materials "may not be loaded, transported, or stored together in the same transport vehicle or storage facility during the course of transportation unless separated in a manner that, in the event of leakage from packages under conditions normally incident to transportation, commingling of hazardous materials would not occur."
- 10 CFR 71.43(d): "A package must be made of materials and construction that assure that there will be no significant chemical, galvanic, or other reaction among the packaging components, among package contents, or between the packaging components and the package contents, including possible reaction resulting from in leakage of water, to the maximum credible extent. Account must be taken of the behavior of materials under irradiation."

DOE has proposed the headspace gas sampling procedure in its application to the USNRC for a licensing certificate on the transportation package (named the TRansUranic PACkage Transporter, or TRUPACT-II) that is loaded with waste containers for transport by truck to WIPP.

Repackaging of Waste to Meet Wattage Limits Imposed by a Radiolytic Gas Generation Model. Gas generation can occur during the transport of a waste container to WIPP. The radiolytic generation of hydrogen gas in TRU waste comes from the co-disposal of organic materials (containing hydrogen) with alpha-emitting radionuclides, which irradiate the organic matter to produce H^+ ions that combine to form H_2 molecules. The current gas generation model is based on assumptions about the configuration of organic materials and radionuclides. It relates the concentration of hydrogen gas in any headspace to the alpha activity (i.e., activity from alpha-emitting radionuclides) within each waste container. More than one gaseous headspace can exist in a waste container, primarily because TRU waste, when generated and disposed in DOE facilities, was contained within layers of confinement provided by plastic bags that may still be intact and thereby inhibit the flow of hydrogen.

By placing a 5 percent (mole fraction) limit on the maximum H_2 concentration within any headspace, this gas generation model calculates an upper limit, commonly expressed as a maximum thermal wattage, on the alpha activity allowed for the entire waste container. These wattage limits are a function of the waste materials and the number of layers of confinement provided by plastic bags. Because of its conservatism, the value of 5 percent H_2 (as a mole fraction) in air as a "flammability limit" can be used in any USNRC license application for a transportation package without the need for further safety analysis.

For example, for a 55-gallon drum containing a plastic liner and heterogeneous debris with plutonium inside three layers of sealed plastic bags, the wattage limit is approximately 0.028 W (DOE, 1996b, p. 5-6e), which corresponds to a limit of 14 g (0.89 Ci) of plutonium-239 or 0.049 g (0.84 Ci) of plutonium-238. Waste containers containing more wattage than the maximum value allowed by the model have their waste contents repackaged to distribute the TRU waste into configurations that will meet these wattage limits. This is accomplished by spilling these contents into shielded gloveboxes and dividing the waste into several new containers, each filled with a fraction of the contents of the original waste container. At Los Alamos National Laboratory in 1998-1999, gas generation restrictions resulted in the repackaging of 36 drums of plutonium-238 waste from the waste stream "TA-55-43" into approximately 120 drums that were placed inside standard waste boxes.[4]

The output of the characterization program is a set of characterization data for each waste container. If the characterization information is within acceptable limits as determined by the waste acceptance criteria and quality assurance program plan (or waste analysis plan) specifications, the waste container is certified and approved for shipment to WIPP.

Truck Transportation to WIPP

At the DOE sites containing TRU waste, the certified TRU waste containers are loaded inside TRUPACT-II shipping containers that are then sealed with a vacuum-tight seal. The TRUPACT-II is classified and regulated as a "Type B" package for fissile materials.[5] To ensure that the waste contents are safely contained during normal shipment conditions and accident scenarios, this transportation package must meet design features such as double containment (i.e., it must have an inner and outer container) and a vacuum seal. Within the inner container, two standard waste boxes, fourteen 55-gallon drums, or one standard waste box and seven 55-gallon drums can be placed. These waste containers are loaded into the TRUPACT-II using an overhead crane in a bay of a building that a truck can drive into to avoid the need to unfasten the TRUPACT-II from the trailer.

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[4]A 55-gallon drum has a volume of approximately 0.2 m^3, whereas a standard waste box is a 1.9m^3 container that can hold three 55-gallon drums.

[5]This designation is a regulatory term to designate packages used to transport plutonium isotopes, which are contained in TRU waste.

The trucks travel to WIPP on approved highway routes during approved times and maintain communication with a DOE control center. In addition to a cellular telephone and a citizens band radio, each truck contains a satellite transponder that enables it to be tracked en route using DOE's satellite-based telecommunications system, the TRANSportation Tracking and COMmunication (TRANSCOM) System. The TRUPACT-IIs are inspected at the WIPP site and their contents (waste-filled drums or boxes) are unloaded and delivered to an underground elevator for emplacement into rooms excavated in the subsurface salt bed.

Appendix B

Joint USNRC and EPA Guidance on Mixed Waste

A joint U.S. Nuclear Regulatory Commission (USNRC) and U.S. Environmental Protection Agency (EPA) document (62 FR 62079, 1997) provides regulatory guidance outlining the testing requirements for mixed radioactive and hazardous waste. In this dual agency guidance document, the EPA and USNRC position is that a combination of common sense, modified sampling procedures, and cooperation between state and federal regulatory agencies will minimize any hazards associated with sampling and testing mixed waste.

Waste generators may determine whether their waste is a Resource Conservation and Recovery Act (RCRA) hazardous waste based on knowledge of the materials or chemical processes that were used. That is, RCRA regulations do not require testing of the waste.

Therefore, where sufficient knowledge of materials or of the process exists, the generator need not test the waste to determine that it possesses a hazardous characteristic, which would necessitate that RCRA be applied (although generators and subsequent handlers would be in violation of RCRA if they managed hazardous waste erroneously classified as nonhazardous outside the RCRA hazardous waste system). For this reason, facilities wishing to minimize testing often assume that a questionable waste is hazardous and handle it accordingly.

Flexibility exists in the hazardous waste regulations for generators; operators of treatment, storage, and disposal facilities; and mixed waste permit writers to tailor mixed waste sampling and analysis programs to address radiation hazards. For example, upon the request of a generator, a person preparing a RCRA permit for such a facility has the flexibility to minimize the frequency of mixed waste testing by specifying a low testing frequency in a facility's waste analysis plan. The EPA position, as stated in 55 FR 22669 (1990), is that the frequency of testing is best determined on a case-by-case basis by the permit writer.

The joint USNRC-EPA agency guidance document (62 FR 62079, 1997) appears to the committee to provide appropriate guidelines for implementation and integration of RCRA requirements for mixed TRU waste. Implementation of this regulatory guidance could significantly reduce the testing protocols and associated radiation exposure of personnel. At present, the procedures specified in the waste acceptance criteria

and quality assurance program plan documents and in the RCRA Part B permit for the testing of mixed waste seem at odds with the ALARA (as low as reasonably achievable) principle.

Appendix C

Biographical Sketches of Committee Members

B. John Garrick, *Chair*, independent consultant, is a co-founder of PLG, Inc., an international engineering, applied science, and management consulting firm in Newport Beach, California. He received his B.S. degree from Brigham Young University and his M.S. and Ph.D. degrees in engineering and applied science from the University of California, Los Angeles. His professional interests involve risk assessment in applications in fields such as nuclear energy, space, and defense, and in the chemical, petroleum, and transportation industries. He has received numerous awards, including the Society for Risk Analysis Distinguished Achievement Award. He was appointed to the U. S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste in 1994, for which he is now Chairman. Dr. Garrick was elected to the National Academy of Engineering in 1993. He has been a member of the Committee on the Waste Isolation Pilot Plant since 1989.

Mark Abkowitz, professor of civil engineering at Vanderbilt University and director of the Center for Environmental Management Studies, has many years of experience in hazardous materials transport. He has published widely on transportation issues such as the risks of transporting high-level radioactive waste. He is a member and former chairman of the NRC Transportation Research Board standing committee on hazardous materials transport.

Alfred W. Grella, independent nuclear and hazardous materials transportation consultant, retired in 1990 from a career in U.S. government service, first at the Department of Transportation and later at the U.S. Nuclear Regulatory Commission. His distinguished career spans 40 years as a professional in health physics, health protection, transportation, inspection and enforcement, training, and related regulatory activities. Mr. Grella received a Bachelor's degree in chemistry from the University of Connecticut and completed the one-year management program at the National Defense University Industrial College of the Armed Forces. He has authored over 30 published papers. He is a member of the American Nuclear Society and a Fellow of the Health Physics Society. Mr. Grella received the M. Sacid (Sarge) Ozker Award in 1996 for distinguished serv-

ice and eminent achievement in the field of radioactive waste management.

Michael Hardy, president of Agapito Associates, Inc., has experience in numerical modeling and field experimentation in practical, engineering-oriented studies to gather characterization data and to evaluate the merits of design features of proposed high-level waste repositories. Dr. Hardy is a member of the Society of Mining, Metallurgical and Exploration Engineers, Inc., and the American Society of Civil Engineers (ASCE). He is Chairman of the Underground Technical Research Council, a joint ASCE/American Institute of Mining, Metallurgical, and Petroleum Engineers Committee.

Stanley Kaplan, principal of Kaplan & Associates, Inc., is one of the early practitioners of the discipline now known as Quantitative Risk Assessment and a major contributor to its theory, language, philosophy and methodology. Dr. Kaplan is a Fellow of the Society for Risk Analysis and the author of a number of the seminal papers in this field. He is one of the first contributors to the Russian science TRIZ, the Theory of the Solution of Inventive Problems, and currently consults and teaches in this area. He is a founder and board chairman of Bayesian Systems, Inc., a Washington-based company developing diagnostic, decision, simulation, and business management software. Dr. Kaplan is the recipient of several awards and honors, including the Society for Risk Analysis Distinguished Achievement Award in 1996. Dr. Kaplan was elected to the National Academy of Engineering in 1999.

Howard M. 'Skip' Kingston is professor of chemistry in the Department of Chemistry and Biochemistry and in the Center for Environmental Research and Education. Also at Duquesne University, he is director of the Center for Microwave and Analytical Chemistry. His research interests include the development, automation, and standard encapsulation and transfer of analytical analysis methods. For the past several years, he has been actively involved in advancing the area of microwave sample preparation through basic research and the development of procedures that have been adopted by the EPA as standard methods. From 1976 to 1991 he was a supervisory research chemist in the Inorganic Analytical Research Division of the National Institute of Standards and Technology (NIST), where he conceived and managed the Consortium on Automated Analytical Laboratory Systems dedicated to developing automated analytical capability for industry. He has received numerous awards for his pioneering work in several areas, including R&D 100 Awards in 1996 and 1998, the IR 100 Award in 1987, the 1988 "Pioneer in Laboratory Robotics" award, the 1990 NIST Applied Research Award, the Department of Commerce Bronze Medal in 1990, the Award of Merit from the Federal Laboratory Consortium in 1991, and the EPA RCRA Service to Others Award in 1998. He has co-edited and co-authored the American Chemical Society professional reference texts *Introduction to Microwave Sample Preparation: Theory and Practice* (1988) and *Microwave Enhanced Chemistry: Fundamentals, Sample Preparation, and Applications* (1997).

He holds multiple patents in the field of speciation, microwave chemistry, and chelation chromatography.

W. John Lee, Peterson Chair and professor of petroleum engineering at Texas A&M University and formerly executive vice-president of technology at S. A. Holditch & Associates, Inc., has expertise in petroleum reservoir imaging, flow tests in low-permeability formations, and enhanced recovery practices. Professor Lee was elected to the National Academy of Engineering in 1993.

Milton Levenson, independent consultant, is a chemical engineer with over 50 years of experience in nuclear energy and related fields. His technical experience includes work in nuclear safety, fuel cycle, water reactor technology, advanced reactor technology, remote control technology, and sodium reactor technology. His professional experience includes research and operations positions at Oak Ridge National Laboratory, Argonne National Laboratory, the Electric Power Research Institute, and Bechtel. Mr. Levenson is the past president of the American Nuclear Society; a fellow of the American Nuclear Society and the American Institute of Chemical Engineers; and the recipient of the American Institute of Chemical Engineers' Robert E. Wilson Award. He is the author of over 150 publications and presentations and holds three U.S. patents. He received his B.Ch.E. from the University of Minnesota. He was elected to the National Academy of Engineering in 1976.

Werner F. Lutze, professor of chemical and nuclear engineering at the University of New Mexico and director of the UNM Center for Radioactive Waste Management (CeRaM), has over 25 years of research experience in materials science and geochemical issues relevant to the management of radioactive wastes, including selective mineral ion-exchange processes, repository near-field chemistry, waste form development, and trace analyses. He has published widely on weapons plutonium immobilization, waste disposal, and the chemistry of nuclear materials. Professor Lutze is a member of several professional organizations, including the Materials Research Society, the German Nuclear Society, and Sigma Xi.

Kimberly Ogden, associate professor of chemical and environmental engineering at the University of Arizona, has conducted research with Los Alamos National Laboratory collaborators to design treatment methods for remediating hazardous waste sites containing both toxic metals and organics, including plutonium-cellulose mixtures. She is also engaged in collaborations with ECO Compliance Inc. in preparing proposals and reports for the remediation of hazardous waste sites. Professor Ogden has authored or co-authored several book chapters, papers, and presentations in environmental science and technology. She is a member of the American Institute of Chemical Engineers, the American Association for the Advancement of Science, and the American Chemical Society.

Martha Scott, associate professor of oceanography at Texas A&M University, is a researcher in marine radiochemistry and geochemistry. Her

present research involves radionuclide distribution in the Russian Arctic. Her work has dealt with the interaction between oceans and rivers, transport of materials in the marine environment, and chemistry of manganese nodules. The behavior of plutonium isotopes in rivers, estuaries, and marine sediments has been one of her longstanding research interests. She served for two years as an associate program director for chemical oceanography at the National Science Foundation (1992-1993). She received the Ph.D. degree from Rice University and was a National Science Foundation post doctoral fellow at Yale University.

John M. Sharp, Chevron Centennial Professor of Geology at The University of Texas at Austin, leads an active research program in hydrology. Professor Sharp has authored and co-authored over 200 journal articles, books, reports, and presentations. He is a fellow of the Geological Society of America and recipient of its O.E. Meinzer award (1979) and the American Institute of Hydrology's C.V. Theis Award (1996). Dr. Sharp is the current editor of *Environmental and Engineering Geoscience*. He received his B. Geological E. with Distinction from the University of Minnesota and his M.S. and Ph.D. degrees in Geology from the University of Illinois.

Paul G. Shewmon, emeritus professor of materials science and engineering at the Ohio State University, received a B.S. degree in metallurgical engineering from the University of Illinois and M.S. and Ph.D. degrees, also in metallurgical engineering, from the Carnegie Institute of Technology. He recently retired as Humbolt Senior Scientist at the Max Planck Institute Metallforschung in Stuttgart. He has received the ASM deMille Campbell Lecture and Award and the TMS Institute of Metals Lecture & Mehl Medal. He was elected to the National Academy of Engineering in 1979.

James Watson, Jr., professor of environmental sciences and engineering and the Director of the Air, Radiation, and Industrial Hygiene Program at the University of North Carolina at Chapel Hill, holds an M.S. degree in physics from North Carolina State University and a Ph.D in environmental sciences and engineering from the University of North Carolina at Chapel Hill. Professor Watson is accomplished in the fields of environmental radioactivity and radioactive waste management. He has received the Underwood and McGavran Awards for excellence in teaching and the Greenberg Alumni Endowment Award for excellence in teaching, research, and service. He is a past president of the Health Physics Society and a past chairman of the Radiological Health Section of the American Public Health Association. He has served on the Environmental Protection Agency's Radiation Advisory Committee and the executive committee of the agency's Science Advisory Board. He is a past chairman of the North Carolina Radiation Protection Commission and currently chairs the commission's Committee on Low-Level Radioactive Waste Management.

Ching H. Yew, an independent consultant and emeritus professor from The University of Texas at Austin, has specialized in the study of hydraulic fracturing and borehole stability. Dr. Yew is a fellow of the America Society of Mechanical Engineers and a member of the Society of Petroleum

Engineers. Dr. Yew has authored a text and published several articles concerning hydraulic fracturing and borehole stability. The computer code developed by him has been adopted for field use by many oil and gas industries.

Appendix D

Acronyms

ALARA	as low as reasonably achievable
ATMX	Atchison Topeka Munitions private railcar
CFR	Code of the Federal Regulations
CEMRC	Carlsbad Environmental Monitoring Research Center
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
NORM	naturally occurring radioactive material
NRC	National Research Council
RCRA	Resource Conservation and Recovery Act
TRANSCOM	TRANSportation Tracking and COMmunication system
TRU	transuranic
TRUPACT	TRansUranic PACkage Transporter
USNRC	U.S. Nuclear Regulatory Commission
WIPP	Waste Isolation Pilot Plant

Appendix A2

DOE's Response to the Interim Report

Department of Energy
Carlsbad Field Office
P. O. Box 3090
Carlsbad, New Mexico 88221
October 30, 2000

National Research Council
Committee on the Waste Isolation Pilot Plant
Board on Radioactive Waste Management
C/O Kevin D. Crowley, Director
2101 Constitution Avenue, NW
Washington, DC 20418

Dear Committee members:

Thank you for your excellent work on the Waste Isolation Pilot Plant Interim Report. We have read your report with great interest and agree with its principles. I am attaching a response to each of the recommendations which you may wish to consider in developing your Final Report.

To briefly summarize, our responses are as follows:

- Data on NORM is being collected and a database developed.
- We are actively pursuing reduction and elimination of self-imposed waste characterization requirements that lack a technical or safety basis.
- We are working closely with the Nuclear Regulatory Commission to minimize the impact of the 5% hydrogen limit, and to reduce or eliminate unnecessary repackaging of waste.
- TRANSCOM has been completely revised to include requested updates and to incorporate specific WIPP requirements.
- We are working with the states to identify and remedy gaps in emergency response coverage.

In conclusion, your recommendations have been adopted as the cornerstone of our planning to bring WIPP to its full potential as the solution to managing our nation's TRU waste.

Sincerely,

Inés Triay

Dr. Inés Triay, Manager

Attachments
Additional copies of Rail Study
sent under separate cover

cc: Lynne Wade, EM 23
Matthew Silva, EEG

CBFO:OOM:IRT:KJB 00-0467 UFC #5480

Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

I. NORM in the WIPP Vicinity

Recommendation: "DOE should develop and implement a plan to sample oil-field brines, petroleum, and solids associated with current hydrocarbon production to assess the magnitude and variability of naturally occurring radioactive material (NORM) in the vicinity of the WIPP site."

Response: DOE agrees with this recommendation. The New Mexico State University Carlsbad Environmental Monitoring & Research Center (CEMRC) has undertaken a project to carry out the recommended assessment, as part of CEMRC's ongoing WIPP Environment Monitoring project. Although analyses of certain naturally occurring radioactive materials in hydrocarbon and scale matrices are somewhat standardized, the sensitivity of the standard methods will likely not be acceptable for at least a portion of the matrices targeted, resulting in the need for method enhancement research. In addition, no published methods are available for analyses of plutonium, americium and other TRU components of concern in hydrocarbons, so this analytical task will require extensive method development and validation prior to initiation of analyses of actual samples.

NORM is an extremely sensitive topic in the oil and gas production industry in the region of the WIPP. As an example, one major exploration and production company that operates in Lea and Eddy counties recently submitted 48 pages of critique on draft Regulation Guidelines for the Management of NORM in the Oil and Gas Industry in New Mexico, which was issued by the New Mexico Environment Department in 1999. Initial contacts with those familiar with local and regional companies indicate that it is likely that many if not most operators will decline to cooperate. To create the maximum likelihood of obtaining cooperation, an option for anonymity will be offered to the operators, using a form of "double-blind" identification. This system would involve collection of samples by a commercial third-party service company that is acceptable to the operator, submittal of the samples to CEMRC without identification of the operator or well location (formation and production pool only), resulting in CEMRC reporting of results without specific operator or well identification.

Path Forward: CEMRC received approval in August 2000, from DOE to proceed with the project without direct involvement of DOE in contacting affected production operators. A plan for a study entitled "Characterization of radioactive elements in oil and gas production in the vicinity of the WIPP" was developed by CEMRC. The initial phases of the study are in progress, including completion of a database of active wells and operators, development of sample collection and handling plans, and identification of commercial sample collection services currently operating in the area. Initial contacts with operators to solicit participation in the study will occur during November through February 2000. Contingent on cooperation of enough operators to create a representative sampling design, sample collection would be conducted during March through August 2001.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

II. Waste Characterization

Recommendation: "DOE should eliminate self-imposed waste characterization requirements that lack a legal or safety basis."

Response: DOE agrees with this recommendation. DOE has developed and begun the implementation of a strategy to systematically improve the Waste Analysis Plan by reducing the frequency of waste characterization and implementing methods that make characterization simpler, less expensive and, above all, safer.

On August 8, 2000, the New Mexico Environment Department approved two packages of Class 2 modifications to the WIPP's Hazardous Waste Facility Permit. These two packages include three requests submitted on April 5, 2000 and three submitted April 20, 2000.

Approval of these modifications results in significant cost savings associated with waste characterization and will reduce radiation exposures to workers. A summary of the approved modifications follows:

- The "miscertification rate" of TRU waste was revised to apply to the waste summary category group instead of each waste stream. This results in a ten-fold reduction in number of drums that must be opened for visual examination (VE).

- The solids sampling requirements for analysis of VOCs have been revised to allow use of one subsample instead of three subsamples. This will avoid a cost of approximately ten million dollars that INEEL would have had to spend in re-analyzing the samples.

- The number of headspace gas samples required has been reduced for two types of waste streams to a statistically selected number of drums, instead of 100% sampling. The two types of waste streams now eligible for statistical headspace gas sampling are wastes that have been thermally processed and homogeneous wastes with "acceptable knowledge" that demonstrates no volatile organic compounds have been present in the waste.

Several modifications have been prepared and submitted that specifically address safety issues associated with TRU waste handling and disposal. One such modification, submitted in October 2000, will allow generators to remove from consideration for VE any containers that pose a safety concern. For example, if a generator determines that opening a container with a high fissile gram content is a safety hazard, that container can be ruled ineligible for VE and another container selected.

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Path Forward: The next modification request, which will be submitted in November 2000, will provide alternatives to VE as a quality control check on radiography. Should the modification be granted, DOE intends to implement this change across the complex.

The Permit modification requesting authorization for remote handled waste disposal at WIPP (to be submitted in December 2000) presents a performance based waste analysis plan that emphasizes the use of nonintrusive characterization techniques and eliminates the need for headspace gas sampling and analysis, solids sampling and analysis, VE, and other confirmatory measurements.

The DOE also plans to collect data from waste characterization activities that will allow the systematic reduction or elimination of headspace gas sampling, solids sampling, VE, and radiography. These changes will be promptly implemented as suitable supporting data are identified.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

III.A Derive A More Realistic Gas Generation Model

Recommendation: "DOE should derive a more realistic radiolytic gas generation model, validate it through confirmatory testing, use the results to recalculate gas generation limits, and seek regulatory approval to implement these limits."

Response: DOE agrees with this recommendation. An application for Revision 19 of the TRUPACT-II Safety Analysis Report was submitted to the Nuclear Regulatory Commission in April 2000. Among other things, the application includes the following:

- Matrix Depletion – The g-values of organic materials decline as a function of absorbed radiation dose. Testing performed at Los Alamos National Laboratory demonstrated that the g-value of polyethylene declines from an initial g-value of 3.4 to 1.1. The application requests the use of the lower g-value. When approved this new g-value will increase the allowable wattage up to a factor of 3 (depending on the packaging configuration).

- Option for the mixing of shipping categories that will allow the sites to ship payloads with different waste forms and to take credit for the use of dunnage containers (additional void volume and reduced gas concentrations).

- Use of more realistic g-values to take credit for non-gas generating materials present in the waste, based on percentages of moisture or organic material present. The previous model assumed a worst-case, 100% moisture/organic material scenario. (This change has been approved by the Nuclear Regulatory Commission.)

- Use of a new shipping category notation that accurately reflects the packaging configuration of the waste. The previous notation grouped all sites under selected worst-case packaging configurations. (This change has been approved by the Nuclear Regulatory Commission.)

Path Forward: The application for Revision 19 was submitted to the Nuclear Regulatory Commission in April 2000 and is scheduled for approval in January 2001. We believe this to be a very responsive review cycle. Taken as a whole, Revisions 17, 18, and 19 provide an increase of up to 100 times the wattage that was allowed under Revision 16.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

III.B Safety Analysis to Determine the Damaging Concentration of Hydrogen

Recommendation: "DOE should perform a safety analysis to determine the concentration and quantity of hydrogen that, upon ignition, could damage the seals of the TRUPACT-II shipping container. The goal of the safety analysis would be to demonstrate whether such an event could occur inside a waste package, and whether the energy associated with such an event could result in the rupture of containment provided by the TRUPACT-II. This analysis could provide the rationale to obtain relief from the 5 percent hydrogen flammability limit and should form the basis for a future modification to the present TRUPACT-II license."

Response: DOE agrees with the recommendation. Performing the safety analysis, which may include testing, would be the first step toward an application. Preliminary review of the recommendation has raised an issue of handling drums at the WIPP that could have a potentially flammable gas mixture. The safety analysis should be extended to waste handling operations at WIPP. If the safety analysis indicates that there is not a safety concern, then an application would be submitted to the Nuclear Regulatory Commission for their review and approval. One proposed solution is to encapsulate the waste in a manner that would contain any detonation that might occur. It is noted that there is no precedence for Nuclear Regulatory Commission approval of shipment of a flammable gas and radioactive material in the same package. Also, the U.S. Department of Transportation (DOT) prohibition against shipping containers of flammable gas and radioactive material on the same vehicle if they could co-mingle would have to be addressed.

Path Forward: The following steps will be pursued to respond to this recommendation:

- Perform a safety analysis to determine whether WIPP could unload drums of waste that contained flammable gas.
- Assess ArrowPAK™ suitability for macro-encapsulation to contain potential deflagration events.
- Determine the incremental quantity of waste that could benefit from implementation of this recommendation (assuming the current application for Revision 19 to the TRUPACT-II Safety Analysis Report is approved).
- Perform the recommended analysis and/or testing.
- Prepare an application and submit to the Nuclear Regulatory Commission for review.
- Seek DOT concurrence.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

III.C Technical Approaches to Reduce Hazards Such As Inert Gas

Recommendation: "DOE should consider technical approaches for reducing hazards from hydrogen generation, such as filling the headspace of the waste containers or the shipping containers with an inert gas to displace air and thereby reduce the flammability hazard."

Response: DOE agrees with this recommendation and is actively pursuing several alternative technologies such as hydrogen "getters." There are several technical issues associated with this recommendation that would have to be investigated:

- Would a drum containing multiple layers of confinement around the TRU waste benefit from the proposed technology; e.g., inert gas in the drum headspace?
- Does the proposed technology require opening individual payload containers or does it apply to the TRUPACT-II; i.e. inert the TRUPACT-II ICV headspace?
- Does the proposed technology prevent or mitigate detonation/deflagration inside multiple layers of confinement or inside the TRUPACT-II? (See recommendation III.B above.)

A method of measuring the flammable gas concentration in the headspace of a 55-gallon drum has been included in the application for Revision 19 of the TRUPACT-II Safety Analysis Report. This only requires a single measurement that can be made in real-time instead of a lengthy gas generation rate test that requires measuring the rate of change of hydrogen gas over several hours or days.

Path Forward: The following steps will be pursued to respond to this recommendation:

- Alternative technical recommendations such as inert gas or hydrogen getters will be considered and a report prepared.
- Perform analysis and/or testing of those alternative technologies that look promising.
- Submit an application to the NRC for any technologies that can be supported by analysis or test results.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

III.D Reevaluate the Feasibility of Rail

Recommendation: "DOE should reevaluate the technical and regulatory feasibility of shipping high-wattage TRU waste using ATMX railcar shipping system."

Response: DOE agrees with the recommendation to reconsider the use of rail. DOE is currently reviewing a recently commissioned rail study report (included as an attachment). The report concluded that shipment of TRUPACT-II by rail is not cost effective unless significantly reduced rail rates are available. The report also recommended investigation of a new shipping package (TRUPACT-III) for shipping high wattage waste and oversize boxes by rail or truck.

DOE has not made a decision regarding the use of ATMX railcar for shipments to WIPP. Using ATMX would require one of the following to occur:

1. Approval by the NRC – this would require exemption(s) from several of the requirements in 10 CFR 71.

   Or,

2. Revision of the Consultation and Cooperation Agreement between the State of New Mexico and DOE, plus revision to the WIPP Land Withdrawal Act.

Path Forward: The following steps will be pursued to respond to this recommendation:

- Determine the incremental inventory of TRU waste that could benefit from rail shipment (assuming the current application for Revision 19 to the TRUPACT-II Safety Analysis Report is approved).
- Evaluate and compare the benefits and regulatory difficulty of two options – TRUPACT-III vs. ATMX.
- Make a decision based on information obtained.
- Proceed with the chosen option.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

IV. DOE's Communication and Notification Program

Recommendation: DOE should consider cost-effective ways to improve the reliability and ease of use of the TRANSCOM system, either by improving or replacing it utilizing current technologies, and ensure the future system meets the WIPP and other stakeholders needs.

Response: DOE agrees with the recommendations and, in fact, has been working toward this effort since mid-1998. On September 12, 2000 in Albuquerque NM, the DOE National Transportation Program-Albuquerque (NTPA) presented a response to the Interim Report recommendations. Committee members represented were Dr. Mark Abkowitz and Mr. Al Gruella. The presentation included improvements to the present TRANSCOM system and a demonstration of the new web-based TRANSCOM2000 system.

- NTPA has identified the problems and has provided resolution that has increased reliability and stability of the present client server Windows-based system for over 7 months. These problems included difficulty in logging in, extended download times, loss of positional data, and date and time anomalies. Feedback from system users indicates that the system provides consistently reliable and accurate information, is more user friendly, and is meeting the needs of our customers. Customer complaints related to using the client-server version have been reduced to a very rare occurrence.

- In May 1999, NTPA hosted a TRANSCOM user application design session to team with DOE, State and Tribal TRANSCOM users, to develop system requirements for a new Internet-based communications and tracking system. In August 2000, the new application was beta-tested and discrepancies were identified and addressed.

- TRANSCOM2000 uses various commercial state-of-the-art Internet compatible software elements. These include: Object F/X GIS mapping software and engine, QTRACS satellite positional and two-way communications software, Oracle Relational DBMS 8I, Oracle Report and Oracle Forms 6I. The TRANSCOM Communications Center will have up-to-the-minute satellite weather service available.

- Security elements on the new application include native Oracle encryption, operation on the Secure Socket Layer (SSL), and multiple layers of application access security down to the database level. A firewall will also reside between the public and the application server.

- Positional update information will be received via frame-relay between the satellite service provider and the TRANSCOM2000 database. These positional updates will be requested every 2 minutes and should be available to the users on average of 2-5 minute intervals.

Path Forward: The estimated schedule for implementation of the TRANSCOM2000 is mentioned below. Firewall configuration and connectivity to the WIPP has been established. The WIPP Central Monitoring Room operators will be trained during the initial implementation process.

- The Major Application Security and Test Plans are under development. These plans must be approved prior to implementation per DOE Order. Completion date: November 2000.

- DOE/AL Operations configuration: in process. Weather and Qtracs servers being installed, firewall server built and awaiting software installation, Operations Center fully staffed. Completion Date: November/December 2000.

- Demonstration of operational readiness: December 2000.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

V. DOE's Emergency Response Program

Recommendation: The committee recommends that DOE explore with states and other interested parties how to develop processes and tools for maintaining up-to-date spatial information on the location, capabilities, and contact information of responders, medical facilities, recovery equipment, regional response teams, and other resources that might be needed to respond to a WIPP transportation incident. This assessment should explore which organization(s) should develop and maintain the capability to generate and maintain such information. DOE should also determine where emergency response capability is currently lacking, identify organization(s) responsible for addressing these deficiencies, and take action to address them.

Response: The information that needs to be gathered and analyzed must come from the state, tribal, and local governments. According to preliminary telephone calls to the Western Governors' Association and the Federal Emergency Management Agency, there is not a national or state system that currently tracks the information that the Committee recommends the DOE collect and analyze. DOE must determine what level of participation the state, tribal and local governments are willing to have in the collection of this information and the maintaining of a database or reports. Logistically, the DOE will be trying to collect information from 30 states and 12 tribal governments which translates to data on over 100,000 emergency responders, and thousands of fire and police departments, ambulance services, and hospitals.

Path Forward: DOE will send letters to the regional, state, and Indian Tribal governments with whom it has cooperative agreements, asking them to communicate the recommendation of the Committee to all of its affected members. They will be asked to analyze their current data collections systems, and to define their willingness to participate in a regular assessment as recommended by the Committee.

They will further be asked to define their funding and manpower requirements, to submit the required data, and make counter recommendations that may fulfill the intent of the recommendation. This would include their recommendations on where the information is to be maintained and who will have the responsibility to analyze and make recommendations for improvement based on that data.

Appendix B

Human Intrusion Scenarios

Oil, gas and other mineral resources are frequently found in association with salt beds, such as the Salado, where the WIPP is situated. The region around the WIPP has known a high rate of drilling activities in the past and future energy trends indicate that there will be incentives to explore the region again, once institutional controls are removed (starting 100 years after the closure of the repository). The risk of drilling directly into the repository and thus creating pathways for the release of radionuclides into the environment will then increase. Drilling through the repository could transport radioactive materials from the repository to the surface or bring water in contact with substances stored in the repository. The following two scenarios are possible sources of concern about the performance of the repository and have been taken into account in the performance assessment of the WIPP.

1. If there were an oilfield water-flooding operation in the vicinity of WIPP, a large amount of brine could flow from a leaky injection well and induce a hydraulic fracture in the anhydrite (or marker bed) directly above or below the WIPP repository (Box B.1). If, at some later time, another well were drilled through the repository and into this brine-filled fracture, the high-pressure brine in the fracture could flow through the borehole and flood the repository causing a release of radioactive materials. The scenario is known as the Hartman scenario.

2. Direct drilling into the WIPP repository could allow circulating drilling fluid to bring radioactive materials to the surface through a borehole as cuttings or spallings. The situation could be serious if the repository were flooded with high-pressure brines. The Sandia National Laboratories examined three possible flooding scenarios, designated as E1, E2, and E1E2, in their performance assessment. These scenarios are briefly explained in Boxes B.2, B.3, and B.4 and they are described in detail in the Compliance Certification Application (DOE, 1996).

The Hartman Scenario

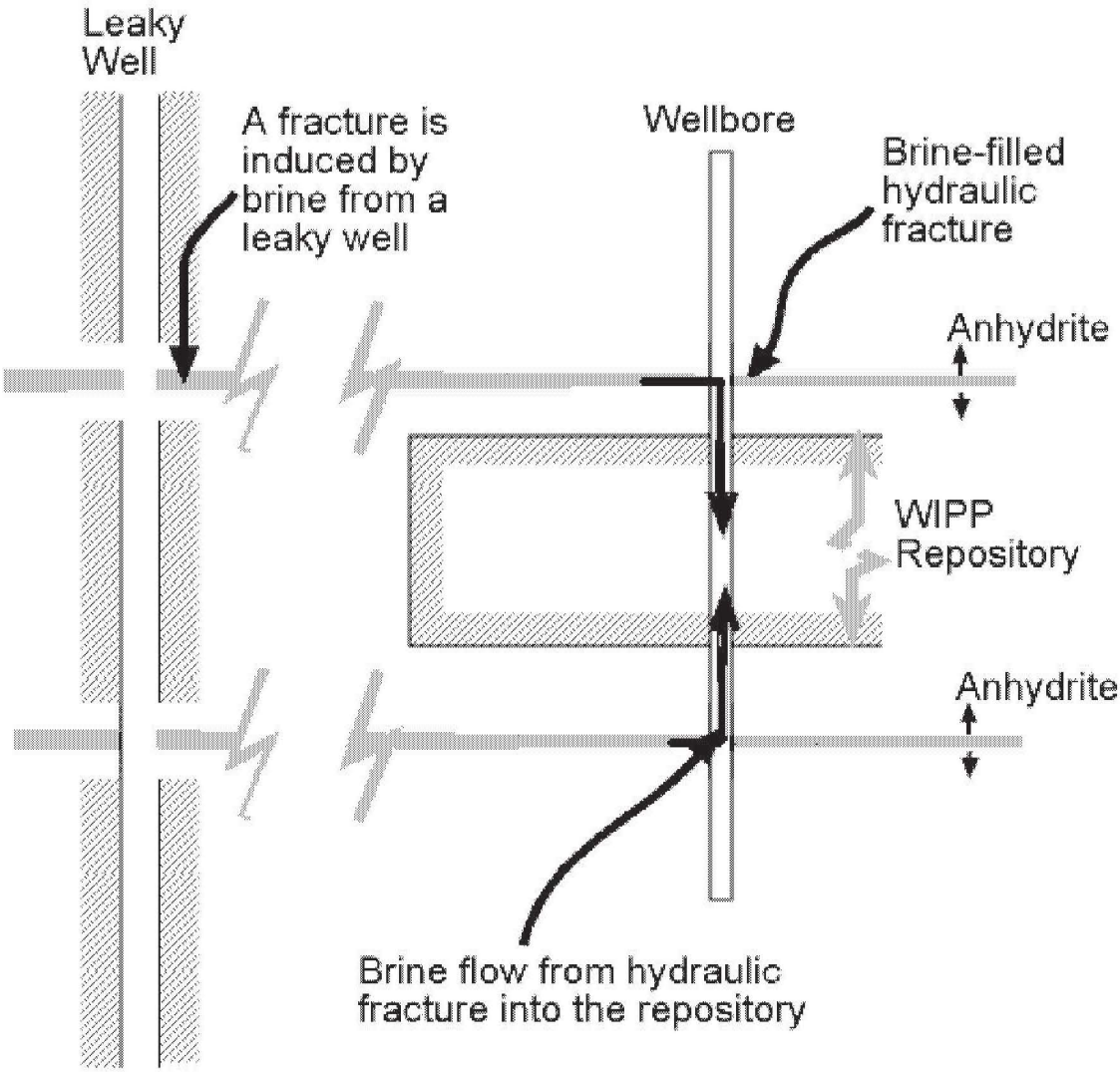

Box B.1: The Hartman Scenario is a scenario in which water from a leaky injection well induces a hydraulic fracture in the anhydrite below or above the repository. If, at some later time, another well is drilled through the repository, the water in the fracture could flow through borehole into the repository.

The E1 Scenario

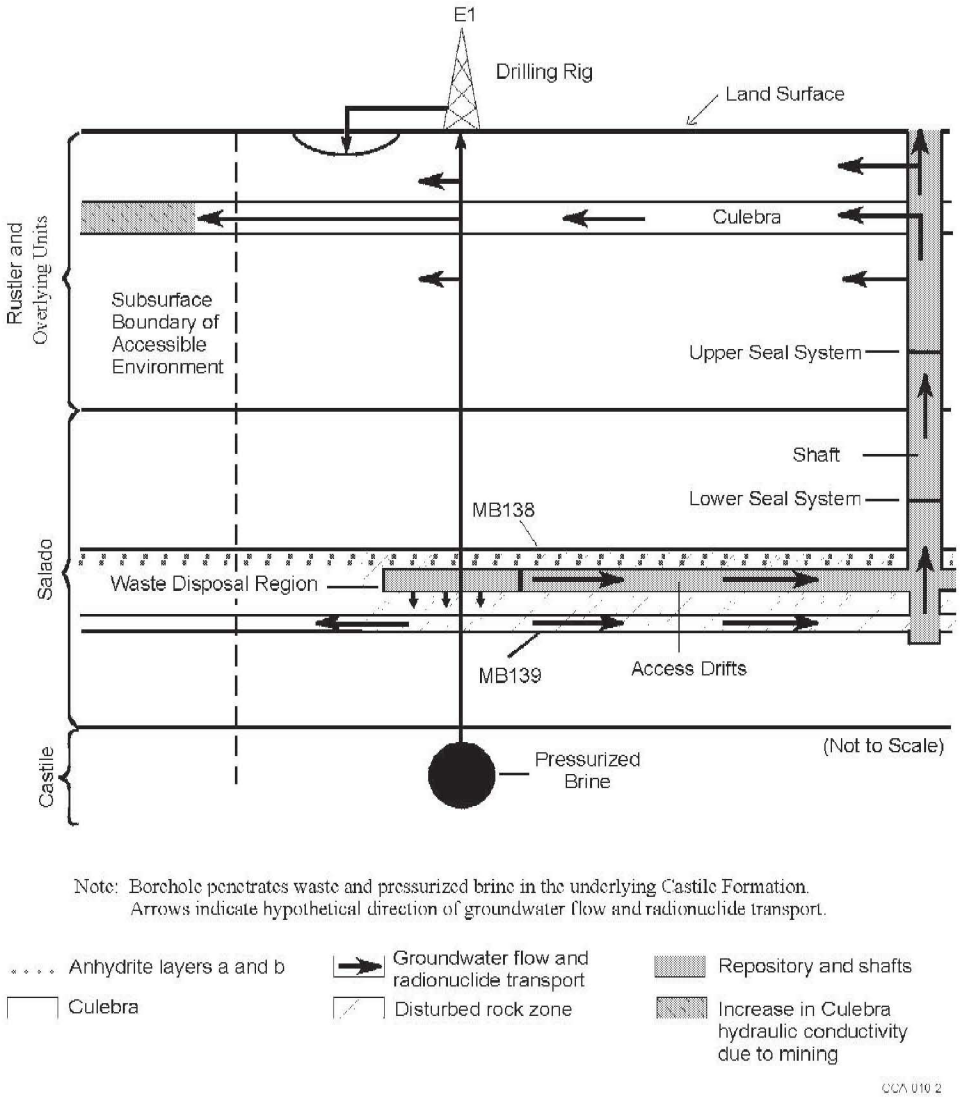

Box B.2: The E1 Scenario is any inadvertent penetration of a waste panel by a borehole that also penetrates a Castile brine reservoir. Sources of brine in the E1 scenario are the brine reservoir, the Salado, and under certain conditions, the units above the Salado.

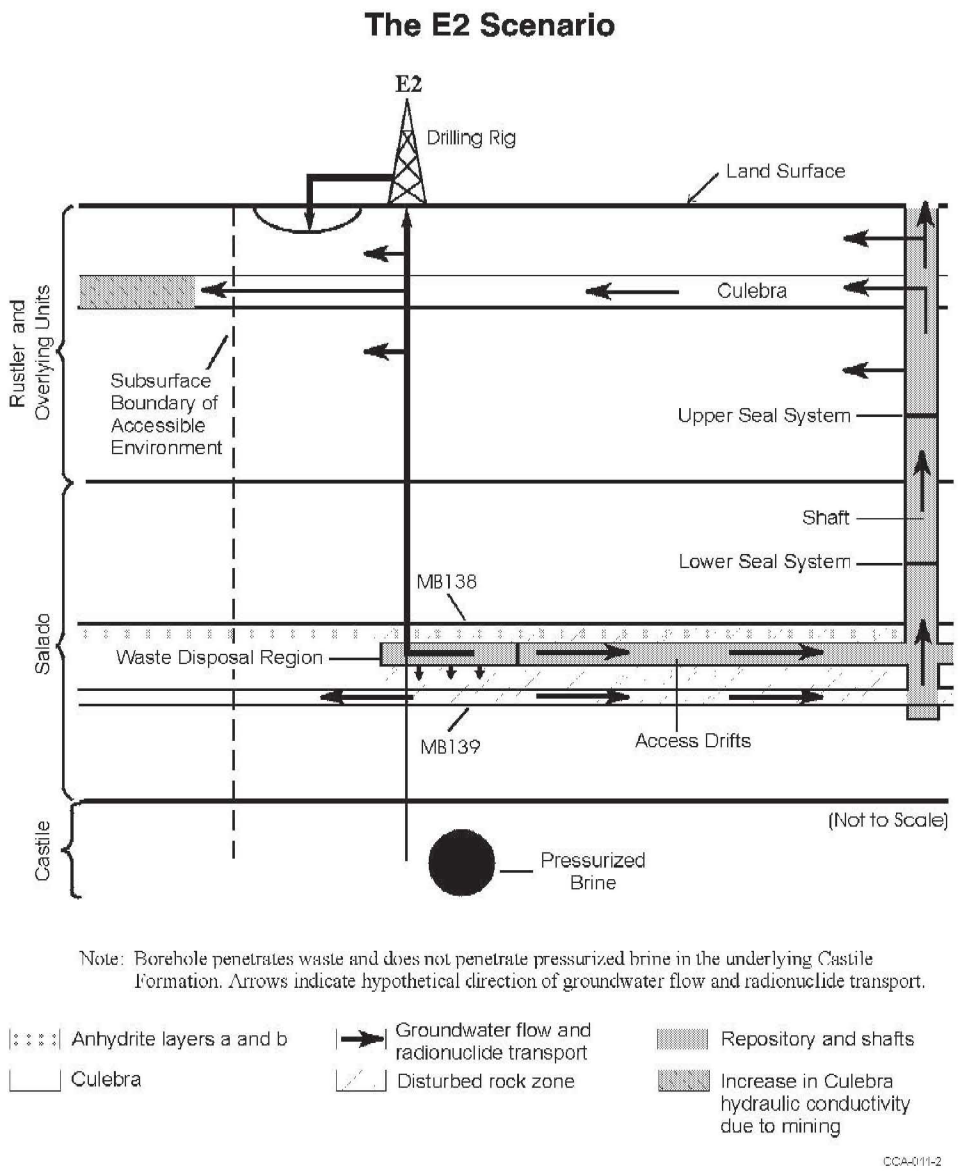

Box B.3: E2 is the simplest scenario for inadvertent human intrusion into a waste disposal panel. In this scenario, a panel is penetrated by a drill bit; cuttings, caving, spallings, and brine flow releases may occur in the borehole after it is plugged and abandoned. Cuttings will be discharged at the surface and may contain waste material if the borehole penetrates waste drums. *Cavings*, which include material eroded from the borehole wall during drilling, may also contain radionuclide waste from the repository horizon. Spallings include solid material carried into the borehole during rapid depressurization of the waste disposal region. The repository horizon could be pressurized by gas generation from degradation of the waste, organic materials and metal corrosion. Brine can be present in the Salado from natural sources or human activities associated with other drilling or production activities. Release to the biosphere is either to the surface or through the Culebra via a leaking *casing.*

The E1E2 Scenario

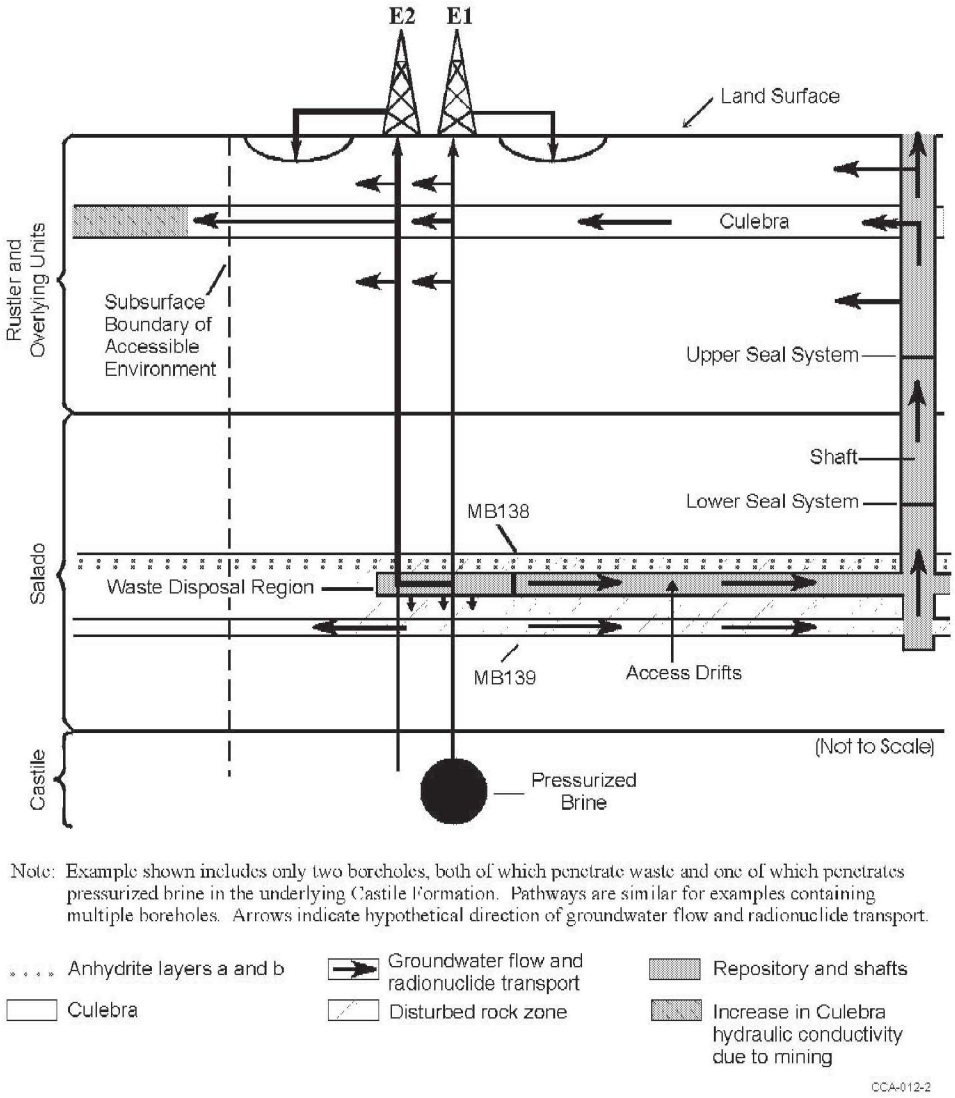

Note: Example shown includes only two boreholes, both of which penetrate waste and one of which penetrates pressurized brine in the underlying Castile Formation. Pathways are similar for examples containing multiple boreholes. Arrows indicate hypothetical direction of groundwater flow and radionuclide transport.

Box B.4: The E1E2 scenario involves multiple well penetrations of a waste panel, with one well penetrating a high-pressure brine panel below. Brine flows from a brine source through well E1 through the repository and is released through well E2. This flow path has the potential to bring large quantities of brine in direct contact with waste in the panel and to bring the contaminated brine to the overlying Salado or Culebra.

Appendix C

Biographical Sketches of Committee Members

Garrick, B. John, ***Chair,*** independent consultant, was a co-founder of PLG, Inc., an international engineering, applied science, and management consulting firm formerly in Newport Beach, California. He retired as president and chief executive officer in 1997. He received his B.S. degree in physics from Brigham Young University and his M.S. and Ph.D. degrees in engineering and applied science from the University of California, Los Angeles, and is a graduate of the Oak Ridge School of Reactor Technology. His professional interests involve risk assessment in fields such as nuclear energy, space and defense, chemical and petroleum and transportation. He is a past president of the Society for Risk Analysis. Dr. Garrick is a fellow of three professional societies and has received numerous awards, including the Society for Risk Analysis' Distinguished Achievement Award. He was appointed to the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste in 1994, of which he is now chairman. Dr. Garrick was elected to the National Academy of Engineering in 1993. He has been a member of the committee on the Waste Isolation Pilot Plant since 1989.

Mark D. Abkowitz, professor of civil engineering at Vanderbilt University and director of the Center for Environmental Management Studies, has an extensive background in environmental risk management, use of advanced information technologies in crisis management, and strategic and operational deployment of intelligent transportation systems. Dr. Abkowitz has been involved in hazardous materials transport education, research, product development, and technology transfer for manufacturers, transporters, regulators, and emergency response personnel. He has authored more than 70 journal publications and study reports, covering issues such as the risks of transporting high-level radioactive waste. Dr. Abkowitz has served on several national and international technical and advisory committees, including as chairman of the NRC Transportation Research Board standing committee on hazardous materials transport.

Alfred W. Grella, independent nuclear and hazardous materials transportation consultant, retired in 1990 from a career in U.S. government service, first at the DOT and later at the USNRC. His distinguished career spans 40 years as a professional in health physics, health protection, transportation, in-

spection and enforcement, training, and related regulatory activities. Mr. Grella received a bachelor's degree in chemistry from the University of Connecticut and completed the one-year management program at the National Defense University Industrial College of the Armed Forces. He has authored more than 30 published papers. He is a member of the American Nuclear Society and a fellow of the Health Physics Society. In 1965, the American Board of Health Physics awarded Mr. Grella certification as a health physicist. Mr. Grella received the M. Sacid (Sarge) Ozker Award in 1996 for distinguished service and eminent achievement in the field of radioactive waste management.

Michael P. Hardy, president of Agapito Associates, Inc., has experience in characterization, numerical modeling, design, and field experimentation for underground mines and high-level nuclear waste repositories at the BWIP site near Hanford, Washington, and Yucca Mountain, Nevada. Dr. Hardy is a member of the Society of Mining, Metallurgical and Exploration Engineers, Inc., and the American Society of Civil Engineers (ASCE). He is a former chairman of the Underground Technical Research Council, a joint ASCE-American Institute of Mining, Metallurgical, and Petroleum Engineers committee. Dr. Hardy received his bachelor of engineering from the University of Adelaide in Australia and his Ph.D. from the University of Minnesota in geoengineering.

Stanley Kaplan is one of the early practitioners of the discipline now known as quantitative risk assessment and a major contributor to its theory, language, philosophy, and methodology. Dr. Kaplan is a fellow of the Society for Risk Analysis and author of a number of seminal papers in this field. He is one of the first American contributors to the Russian science TRIZ, the Theory of the Solution of Inventive Problems, and currently consults and teaches in this area. He is a founder and board chairman of Bayesian Systems, Inc., a Washington-based company developing diagnostic, decision, simulation, and business management software. Dr. Kaplan is the recipient of several awards and honors, including the Society for Risk Analysis' Distinguished Achievement Award in 1996. Dr. Kaplan was elected to the National Academy of Engineering in 1999.

Howard M. Kingston, professor of chemistry and director of the Duquesne Environmental Research and Education Center at Duquesne University, has expertise in analytical chemistry techniques in environmental applications of hazardous waste characterization and remediation. His research interests include the development, automation, and standard encapsulation and transfer of analytical analysis methods. For the past several years, he has been actively involved in advancing the area of microwave sample preparation through basic research and the development of procedures that have been adopted by the EPA as standard methods. He has received numerous awards for his pioneering work and holds multiple patents in the fields of speciation, microwave chemistry, and chelation chromatography. He has co-edited and co-authored two of the American Chemical Society professional reference texts.

W. John Lee, Peterson Chair and professor of petroleum engineering at Texas A&M University, has expertise in petroleum reservoir analysis, pressure transient testing, and enhanced recovery methods. His professional experience includes research, operations, and consulting at Exxon Company U.S.A. and S.A. Holditch & Associates. He has received numerous awards from the Society of Petroleum Engineers, including the Reservoir Engineering Award, the Distinguished Service Award, the John F. Carll Award, Distinguished Membership, Distinguished Faculty Achievement Award, Distinguished Lecturer, and Honorary Membership. He is a member of the Georgia Tech Academy of Distinguished Engineering Alumni and he was elected to the National Academy of Engineering in 1993.

Milton Levenson, independent consultant, is a chemical engineer with more than 50 years of experience in nuclear energy and related fields. His technical experience includes work in nuclear safety, fuel cycle, water reactor technology, advanced reactor technology, remote control technology, and sodium reactor technology. His professional experience includes research and operations positions at the Oak Ridge National Laboratory, the Argonne National Laboratory, the Electric Power Research Institute, and Bechtel. Mr. Levenson is past president of the American Nuclear Society; a fellow of the American Nuclear Society and the American Institute of Chemical Engineers; and recipient of the American Institute of Chemical Engineers' Robert E. Wilson Award. He is the author of more than 150 publications and presentations and holds three U.S. patents. He received his B.Ch.E. from the University of Minnesota. He was elected to the National Academy of Engineering in 1976.

Werner F. Lutze, professor of chemical and nuclear engineering at the University of New Mexico (UNM) and director of the UNM Center for Radioactive Waste Management, has more than 25 years of research experience in materials science and geochemical issues relevant to the management of radioactive wastes, including selective mineral ion-exchange processes, repository near-field chemistry, waste form development, and trace analyses. He has published widely on weapons plutonium immobilization, waste disposal, and the chemistry of nuclear materials. Professor Lutze is a member of several professional organizations, including the Materials Research Society, the German Nuclear Society, and Sigma Xi.

Kimberly Ogden, associate professor of chemical and environmental engineering at the University of Arizona, has conducted research with Los Alamos National Laboratory collaborators to design treatment methods for remediating hazardous waste sites containing both toxic metals and organic materials, including plutonium-cellulose mixtures. She is also engaged in research investigating the merger of the semiconductors and biotechnology. Professor Ogden has authored or co-authored several book chapters, journal articles, and presentations. She is a member of several professional organizations including the American Institute of Chemical Engineers, the American Society of Engineering Education, and the American Chemical Society. She received her B.S.E degree in chemical engineering from the University of Pennsylvania and her M.S. and Ph.D. degrees from the University of Colorado.

Martha Scott, associate professor of oceanography at Texas A&M University, is a researcher in marine radiochemistry and geochemistry. Her present research involves radionuclide distribution in the Russian Arctic. Her work has dealt with the interaction between oceans and rivers, transport of materials in the marine environment, and chemistry of manganese nodules. The behavior of plutonium isotopes in rivers, estuaries, and marine sediments has been one of her longstanding research interests. She served for two years as an associate program director for chemical oceanography at the National Science Foundation (1992-1993). She received her Ph.D. degree from Rice University and was a National Science Foundation postdoctoral fellow at Yale University.

John M. Sharp, Jr., Chevron Centennial Professor of Geology, leads an active program in hydrogeology at The University of Texas at Austin. Professor Sharp has authored and co-authored more than 250 journal articles, books, reports, and presentations. His current research interests include characterization of groundwater flow and transport in fractured and karstic rocks; thermohaline free convection, hydrogeology of semi-arid zones, subsidence, and the effects of man on groundwater systems. He is a fellow of the Geological Society of America and recipient of its O.E. Meinzer Award (1979) and the American Institute of Hydrology's C.V. Theis Award (1996). Dr. Sharp is currently the editor of *Environmental and Engineering Geoscience* and the 2000 AT&T Industrial Ecology Fellow. He received his

bachelor of geological engineering with distinction from the University of Minnesota and his M.S. and Ph.D. degrees in geology from the University of Illinois.

Paul G. Shewmon, emeritus professor of materials science and engineering at the Ohio State University, received a B.S. degree in metallurgical engineering from the University of Illinois and M.S. and Ph.D. degrees, also in metallurgical engineering, from the Carnegie Institute of Technology. He has lead work on fast breeder reactor materials at Argonne National Laboratory and served for 16 years on the USNRC's Advisory Committee on Reactor Safeguards. He has published 130 technical papers and two textbooks generally in the area of physical metallurgy and has received numerous awards for his research. He was elected to the National Academy of Engineering in 1979.

James E. Watson, Jr., professor of environmental sciences and engineering and director of the air, radiation, and industrial hygiene program at the University of North Carolina at Chapel Hill, holds a M.S. degree in physics from North Carolina State University and a Ph.D. in environmental sciences and engineering from the University of North Carolina at Chapel Hill. Professor Watson is accomplished in the fields of environmental radioactivity and radioactive waste management. He has received several awards for excellence in teaching, research, and service. He is a past president of the Health Physics Society and a past chairman of the Radiological Health Section of the American Public Health Association. He has served on the EPA's Radiation Advisory Committee and Executive Committee of the Agency's Science Advisory Board. He is a past chairman of the North Carolina Radiation Protection Commission and currently chairs the commission's Committee on Low-Level Radioactive Waste Management.

Ching H. Yew, an independent consultant and emeritus Halliburton professor of engineering mechanics at the University of Texas at Austin, received a B.S. degree in mechanical engineering from the National Taiwan University and M.S. and Ph.D. degrees in mechanical engineering from Cornell University and the University of California, Berkeley. Dr. Yew has specialized in solid mechanics and experimental mechanics, is a fellow of the American Society of Mechanical Engineers, and is a member of the Society of Petroleum Engineers. Dr. Yew has authored a book on the mechanics of hydraulic fracturing and published many articles concerning hydraulic fracturing and borehole stability.

Appendix D

Glossary

Actinide: Element with atomic number 90 (thorium) or greater.

Anhydrite: Anhydrous calcium sulfate.

Backfill: Earth or other material used to replace material removed during construction or mining. Backfill in excavations may or may not be the material originally removed. In the WIPP, magnesium oxide is the engineered backfill that replaces the mined salt and is placed in the free spaces surrounding the waste containers. Magnesium oxide is intended to chemically stabilize the radionuclides and minimize their solubility.

Borehole: Deep, circular hole of small diameter, such as an oil well or a water well.

Borehole Plugs: Engineered plugs to block the flow of liquid in either direction and to curtail the potential for movement of contaminants to the human environment. Several unplugged boreholes, presently being used to collect information for the WIPP, exist within the WIPP Land Withdrawal Area.

Brine: Water with dissolved salts at levels higher than seawater. Generally, brines are considered to have a total dissolved solids content of more than 100,000 milligrams per liter.

Brine Reservoir: Groundwater containing high levels of dissolved solids (brine) that may occur beneath the WIPP site either as discrete pockets (brine pockets) or as a saturated continuum. The committee uses the term "brine reservoir" to refer to both of these occurrences. At present, there is a great deal of uncertainty as to the location and form (i.e., discrete pocket or saturated continuum) of brine reservoirs beneath the WIPP repository.

Brucite: Magnesium dihydroxide, $Mg(OH)_2$.

Casing: Heavy metal pipe lowered into a borehole during or after drilling and cemented into place. It prevents the sides of the hole from caving and, prevents loss of drilling mud or other fluids into the hole.

Castile Formation: Oldest of the late Permian stratigraphic sequence of rocks, consisting of alternating layers of anhydrite and thin layers of limestone, with several thick layers of halite. See Figure 1.3.

Culebra Dolomite: Second-oldest member of the Rustler Formation ranging from approximately 7-8 meters thick at the WIPP site. The Culebra consists of dolomite with some clay minerals. Because it is a relatively transmissive unit, the Culebra is important to the groundwater flow model for the WIPP site.

Curie: Measure of the quantity of radioactive material in a sample, equal to 3.7×10^{10} disintegrations per second.

Cuttings: Rock chips cut by a bit in the process of well drilling and removed from the hole in the drilling mud in rotary drilling or by the bailer in cable-tool drilling. Well cuttings collected at closely spaced intervals provide a record of the strata penetrated.

Delaware Basin: Sedimentary basin in which the WIPP site is located. The Delaware Basin formed in the Permian sea and was gradually filled with thick, extensive layers of sediments and evaporite deposits.

Disturbed Rock Zone (DRZ): Zone around an excavation, in the host rock salt, where the stress field has been modified sufficiently to cause the formation of microfractures in the rock salt. Compared to the intact rock salt, the DRZ will have increased porosity because of the microfracturing, increased permeability as a result of interconnection of the microfractures, and decreased load-bearing capacity or strength.

Dolomite: Sedimentary rock consisting mostly of the mineral dolomite, calcium magnesium carbonate.

Dose: Energy imparted to matter in a volume element by ionizing radiation, divided by the mass of irradiated material in that volume element. The International System (IS) derived unit of absorbed dose is the gray (Gy); 1 Gy = 100 rad = 1 (Joule) per kilogram.

Drillbit or drill: A tool that cuts with its end by revolving or by a succession of blows.

Engineered Barriers: Man-made waste-isolating features that complement and strengthen natural waste-isolating barriers. These barriers are shaft seals, panel closures, borehole plugs, and backfill.

G-Value: Radiolytic yield unit. It corresponds to the number of molecules produced per 100 electronvolts of energy absorbed in the medium interacting with the ionizing radiation.

Half-Life: Time required for half of the atoms of a radioactive substance present at the beginning to disintegrate.

Hydraulic Fracture: Fracture of a rock in an oil or gas reservoir by pumping in water (or other fluid) and sand under high pressure. The purpose is to produce artificial openings in the rock to increase

permeability. The pressure opens cracks and bedding planes, and sand introduced into these serves to keep them open when the pressure is reduced.

Hydrogen Getter: Material capable of capturing hydrogen gas.

Hydromagnesite: Mixed compound of magnesium carbonate and hydroxide, $4MgCO_3 \cdot Mg(OH)_2 \cdot 4H_2O$.

Injection Well: Well in an oil or gas field through which water, gas, steam, or chemicals are pumped into a reservoir or formation for pressure maintenance or secondary recovery, or for storage or disposal of the injected fluid.

Karst: Type of topography that is formed of limestone, gypsum, and other rocks by dissolution and is characterized by sinkholes, caves, and underground drainage.

Lithostatic Pressure: Pressure exerted by a column of overlying rock at a point in the earth's crust.

Magnesite: Magnesium carbonate, $MgCO_3$.

Marker Bed: Horizontally extensive formation that can be identified readily at different locations. For instance, the nonhalite interbed in the Salado, is numbered from the top of the Salado to the bottom and used to keep the repository at the same level within the Salado.

Panel Closures: Panel closures will limit the interaction of brine and gases among waste disposal panels. These closures will consist of a rigid concrete barrier and an isolation wall made of concrete construction block with an isolation zone between them.

Parameter: Algebraic symbol representative of a well-defined physical quantity with a numerical value. An adjustable parameter is envisioned to assume any value within its range (between the maximum and minimum numerical bounds). Any particular choice of a value renders a parameter a numerical constant.

Performance Assessment: Risk-based assessment of the safety performance of a nuclear waste facility.

Permeability: Capacity of a material to transmit fluids. A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. Permeability depends on the size, shape, and degree of interconnectedness of pores and is generally measured in square meters. It is a property of the medium alone and is independent of the nature of the liquid.

pH: Measure of the acidity of a solution phase; negative logarithm of the hydrogen ion concentration.

Post-closure Period: Period beginning when the shafts of the disposal system are backfilled and sealed and ending 100 years later.

Pre-closure Period: Period between the beginning of operation and the time at which the shafts of the disposal system are backfilled and sealed. The operation period has been set as 35 years.

Radiogenic: Said of a product of a radioactive process.

Radiolysis: Decomposition brought about by ionizing radiation.

Radionuclide: Radioactive atom characterized by its mass and atomic number.

Retardation: Parameter that describes the ratio of the net apparent velocity of the concentration of a particular chemical species to the velocity of a non-reactive species. It is proportional to the slope of a sorption isotherm; thus, if the isotherm is nonlinear, the retardation factor is not constant and depends on solute concentration.

Rustler Formation: Second-youngest Permian Ochoan Formation, overlying the Salado, and consisting of five sequences (members) of thin-bedded strata. The lowermost beds consist of mudstone and sandstone interbedded with evaporites. The upper part of the formation consists of alternating evaporite and dolomite beds. The Culebra Dolomite member is the second member from the bottom of the formation. The total thickness of the Rustler Formation near the WIPP site is approximately 100 meters.

Salado Formation: Second-oldest Ochoan geologic formation consisting of a 230 million-year-old deposit of rock salt (halite) in near-horizontal beds; its total thickness lies between 200 and 400 meters. Very thin layers of clay, anhydrite, and potash minerals are interbedded with the halite beds. Lying at a depth of approximately 660 meters (2,160 feet) at the WIPP site, the Salado hosts the WIPP repository.

Salt Creep: Slow movement of salt over time as shear stresses cause movement within or between individual crystals. Mined salt "heals" as the creep restores its integrity.

Shaft: Vertical or inclined excavation through which a mine is worked.

Shaft Seals: Engineered barrier designed to limit fluid flow through the repository shafts. Once the repository has been filled, the entire column of each shaft will be backfilled with materials that prevent vertical flow of fluid. Materials include concrete, clay, asphalt, compacted salt, grout, and earthen fill.

Spallings: Chipping, fracturing, or fragmentation, and the upward and outward heaving, of rock caused by the interaction of a shock (compressional) wave at a free surface. Spallings in the WIPP can be caused by oil extraction and other human intrusion activities.

Transuranic (TRU) Waste: Radioactive waste consisting of radionuclides with atomic numbers greater than 92 in excess of agreed limits. A more precise definition, in DOE Order 5820.2A, EPA regulation 40 CFR 191, and the Land Withdrawal Act, is waste that is not high-level waste but is "contaminated with alpha-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram." The regulatory definition excludes actinide elements with atomic numbers between 90 and 92 (most significantly, thorium and uranium isotopes), which is in agreement with the literal meaning of "transuranic." However, common usage of the term "transuranic waste" is often understood to include all actinides.

TRUPACT-II: Transuranic Package Transporter, Model II. Container for road transport of contact-handled transuranic waste (see Figure 3.2). The TRUPACT-II container has been certified by the U.S. Nuclear Regulatory Commission.

Waste Characterization: Process of identifying and classifying the chemical, physical, and radiological constituents of each drum of waste.

Water Flooding: Technique used in the secondary recovery of petroleum and gas whereby water is injected into a petroleum or gas reservoir so that the pressure of the water expels the petroleum or gas.

Wattage Limit: In this report, the allowed maximum amount of heat generated by radioactive decay during transportation of TRU waste. The wattage limit for TRUPACT-II containers is 40 watts (40 joules per second).

Appendix E

Acronyms and Symbols

ASCE: American Society of Civil Engineers
CCA: compliance certification application
CCDF: Complementary Cumulative Distribution Function
CEMRC: Carlsbad Environmental Monitoring and Research Center
CH: Contact Handled
CH_4: Methane
CO_2: Carbon dioxide
DOE: U.S. Department of Energy
DOT: U.S. Department of Transportation
DRZ: Disturbed rock zone
EEG: State of New Mexico Environmental Evaluation Group
EPA: U.S. Environmental Protection Agency
H_2: Hydrogen
H_2S: Hydrogen sulfide
INEEL: Idaho Engineering and Environmental Laboratory
ITS: Intelligent transportation system
LWA: Land Withdrawal Act
MgO: Magnesium oxide
MTMH: Metric tons of heavy metal
N_2: Nitrogen
NORM: Naturally occurring radioactive material
NRC: National Research Council
PA: Performance assessment
RCRA: Resource Conservation and Recovery Act
RH: Remote handled
SNL: Sandia National Laboratories
TRANSCOM: Transportation Tracking and Communication

TRIZ: Theory of the Solution of Inventive Problems
TRU: Transuranic
TRUPACT-II: Transuranic Package Transporter, Model II
UNM: University of New Mexico
USNRC: U.S. Nuclear Regulatory Commission
WIPP: Waste Isolation Pilot Plant

Appendix F

Other Relevant Documents

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CHARACTERIZATION
OF REMOTE-HANDLED TRANSURANIC WASTE FOR
THE

WASTE ISOLATION PILOT PLANT

FINAL REPORT

Committee on the Characterization of Remote-Handled Transuranic Waste for the Waste Isolation Pilot Plant

Board on Radioactive Waste Management

Division on Earth and Life Studies

National Research Council

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Cover: Remote-handled transuranic waste re-packaging operations in a ‘‘hot cell’’ at Battelle Columbus Laboratories-West Jefferson North Campus. From top to bottom: a robotic manipulator arm transfers several pool filters into a new container and closes the lid. In the background: picture of sludge at the bottom of the K-Basins at the Hanford Site. The sludge will be removed and pieces larger than 0.25 inches will be separated. The sludge, which is expected to be remote-handled transuranic waste, will be solidified while the larger pieces will be handled as debris waste. The debris could be transuranic or low-level waste.

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Preface

The U.S. Department of Energy (DOE) is seeking authorization to dispose of its remote-handled transuranic (RH-TRU) waste in the Waste Isolation Pilot Plant (WIPP), a geologic repository located in New Mexico. The DOE-Carlsbad Field Office asked the National Research Council to provide an independent review of its proposed characterization plan for RH-TRU waste.

To this end, the National Research Council appointed an ad hoc committee of seven members and one consultant with expertise in the following disciplines: knowledge of the DOE weapons complex, particularly with respect to the generation of RH-TRU waste; TRU waste characterization techniques; health physics; actinide chemistry; environmental policy; public policy; and risk assessment. The committee's statement of task is in Sidebar P.1. The biographical sketches of committee members can be found in Appendix A.

SIDEBAR P.1 Statement of Task

The objective of this study is to review and evaluate the U.S. Department of Energy's (DOE's) plan to characterize remote-handled transuranic (RH-TRU) waste to be disposed of at Waste Isolation Pilot Plant (WIPP). The committee will provide recommendations, as necessary, for improving the plan's technical soundness, protection of worker safety, and compliance with applicable regulatory requirements. This study does not address transportation issues related to RH-TRU waste.

Examples of criteria that could be used by the committee to review DOE's characterization plan for RH-TRU waste are the following: validity of assumptions used for the proposed plan; quality of information available on RH-TRU waste; uncertainties on process knowledge data and consequences if wrong; appropriateness and sensitivity of overall system safety to uncertainties in the waste specifications; limitations of the methodologies and procedures to characterize RH-TRU waste; and validity of DOE's conclusions concerning its characterization plan.

The committee met four times, from June 2001 to May 2002, to complete its review of DOE's characterization plan. The committee interacted with DOE, generator sites, WIPP's primary regulatory agencies (Environmental Protection Agency and the New Mexico Environment Department), the New Mexico Environmental Evaluation Group, and the public to gather information on the status of RH-TRU waste across DOE's complex, characterization requirements, and expectations for this new plan. The diverse mix of participants from DOE (headquarters and the sites), regulatory agencies, and national laboratories contributed to lively discussions and great insights into the committee's task.

The committee gathered information from the following sites: Battelle Columbus Laboratories, Idaho Engineering and Environmental Laboratory, Oak Ridge National Laboratory, Los Alamos National Laboratory, Argonne National Laboratory-West, and

the Hanford Site. These sites were selected because they are the main RH-TRU waste generators or, in the case of Battelle Columbus Laboratories, because this site has begun RH-TRU waste characterization operations. The committee also visited Battelle and the WIPP site. Information-gathering meeting agendas and speakers are listed in Appendix B.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the National Research Council in making the published report technically sound and to ensure that the report meets National Research Council institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Robert M. Bernero, U.S. Nuclear Regulatory Commission (retired)
David C. Camp, Lawrence Livermore National Laboratory
Rodney C. Ewing, University of Michigan
Harry D. Harmon, Harmon Consulting
Darleane C. Hoffman, Lawrence Berkeley Laboratory
Robert H. Neill, Environmental Evaluation Group (retired)
Victoria J. Tschinkel, Victoria J. Tschinkel Environmental Policy and Management
Raymond G. Wymer, Oak Ridge National Laboratory (retired)

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Chris G. Whipple, ENVIRON International, Inc. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

This study could not have been completed without the assistance of many individuals and organizations. The committee thanks many DOE staff members in the Carlsbad Field Office, in the Office of Environmental Management, and at RH-TRU waste generator sites, including contractors, for their active participation in committee meetings and for promptly responding to requests of information. The committee is especially grateful to Roger Nelson, chief scientist at the DOE-Carlsbad Field Office, who served as primary contact for this study and provided outstanding support to committee's activities; Clayton Gist, RH-TRU waste program manager, and Inés Triay, manager of the Carlsbad Field Office. The committee also expresses its deep appreciation to those who organized site tours, especially James Eide at Battelle Columbus Laboratories and Norbert Rempe at the WIPP.

The committee is equally grateful to Steve Zappe of the New Mexico Environment Department and Scott Monroe of the U.S. Environmental Protection Agency for their input on WIPP's regulatory requirements. Matthew Silva, George Anastas, and James Channell of the New Mexico Environmental Evaluation Group also provided the committee with helpful technical and historical perspectives on the characterization of RH-TRU waste.

Finally, the committee thanks the following National Research Council staff members: Kevin Crowley, who provided guidance in separating science from policy; Angela Taylor, who made certain our committee meetings were as pleasant as possible; Darla Thompson who provided strong research support; and Barbara Pastina, whose knowledge, patience, and organizational and writing skills are unparalleled. She anticipated the obstacles and smoothed the way for the committee to deal with issues in the statement of task during this fast-track project. Any success of the project is because of her dedication.

Eula Bingham, *Chair*
Committee on the Characterization of Remote-Handled Transuranic Waste for the WIPP
July 2002

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Executive Summary

The Department of Energy's (DOE's) Carlsbad Field Office asked the National Research Council to review a proposed characterization plan for remote-handled transuranic (RH-TRU)[1] waste and to provide recommendations, as necessary, for improving the plan's technical soundness, protection of worker safety and health, and compliance with regulatory requirements.

There are approximately 3,800 cubic meters of defense-related RH-TRU waste to be removed from DOE's weapons complex. DOE is seeking authorization to dispose of this RH-TRU waste in the Waste Isolation Pilot Plant (WIPP), a geologic repository in southeastern New Mexico. WIPP is regulated by the Environmental Protection Agency (EPA) and the New Mexico Environment Department (NMED).

WIPP is currently certified by the EPA and permitted by the NMED to dispose only of contact-handled (CH) and mixed[2] CH-TRU waste. To obtain authorization to ship RH-TRU waste to WIPP, DOE must submit to the regulatory agencies a characterization plan for RH-TRU waste and request a modification of the EPA Certification and RCRA Permit. The regulatory agencies may accept, reject, or propose modifications to the characterization plan and, eventually, may authorize RH-TRU waste disposal in WIPP.

S.1 Technical and Regulatory Context of RH-TRU Waste Characterization

Remote-handled TRU waste presents a long-term (i.e., 10,000 years) radiological hazard associated with TRU radionuclides (related to the presence of long-lived alpha-emitting isotopes) and a short-term (less than 300 years) radiological hazard associated with short-lived gamma-emitting radionuclides (related to the presence of fission and activation products). Gamma radiation can penetrate through the walls of waste containers and the skin; therefore, RH-TRU waste presents a potential for radiation doses to workers during waste characterization, handling, and emplacement. The associated costs due to the heavy shielding and remote-handling equipment, necessary to protect workers from radiation, are also significant. The long-term radiological hazard of RH-TRU waste is associated with the potential for TRU radionuclide release into the environment once the waste is disposed of in WIPP.

S.1.1 DOE's RH-TRU Waste Inventories

While RH-TRU waste volume represents a small fraction of the allowed TRU waste in WIPP (3,800 cubic meters out of approximately 176,000 cubic meters), it accounts for

[1]Transuranic waste is radioactive waste containing alpha-emitting radionuclides of atomic number greater than 92, half-life greater than 20 years, and activity greater than 100 nanocuries per gram of waste. Transuranic waste is classified as remote-handled or contact-handled depending on the radiation dose rate at the surface of the package. A more detailed definition is given in Sidebar 1.1.

[2]Transuranic waste can be mixed with hazardous components regulated under the Resources Conservation and Recovery Act (RCRA). This type of waste is called mixed TRU waste and is regulated by NMED as hazardous waste.

14 percent of the total curie activity in DOE's TRU inventory. However, the number of TRU (i.e., from alpha-emitting radionuclides with a half-life greater than 20 years) curies in the RH-TRU waste inventory is 2 orders of magnitude lower than that in the CH-TRU waste inventory expected in WIPP. Also, most of the total (CH plus RH) long-term (i.e., TRU) activity expected in WIPP comes from CH-TRU waste, with only a 0.5 percent contribution from RH-TRU waste (see Table 2.3 in Chapter 2).

Remote-handled TRU waste to be emplaced in WIPP is stored or is to be generated as the result of cleanup activities at 13 DOE weapons complex sites (see Chapter 2). Approximately 1,600 cubic meters of projected RH-TRU waste is waste that originates from the dismantlement of hot cells and other facilities used for defense-related purposes, waste that must be recovered and separated from other wastes (such as at the Hanford Site), or waste that must be reprocessed to eliminate hazardous components prohibited in WIPP (such as at Oak Ridge National Laboratory). Already stored at DOE sites are approximately 2,200 cubic meters of RH-TRU waste, but most of this inventory must be characterized and repackaged to meet waste transportation criteria. Only 5 percent of the waste has been characterized and packaged in a form that could be suitable for shipment to WIPP. To obtain authorization to ship RH-TRU waste to WIPP, generator sites must characterize all their RH-TRU waste inventories according to a plan approved by EPA and NMED.

S.1.2 Regulatory Context

Congress designated WIPP as the nation's defense-related transuranic waste repository in the Land Withdrawal Act of 1992. This Act allows the geologic disposal in WIPP of up to 175,564 cubic meters of TRU waste, including 7,080 cubic meters (4 percent of the total volume) of RH-TRU waste. The EPA, under this Act, regulates the radiological release limits for WIPP over a period of 10,000 years. The NMED, under RCRA, regulates the non-radiological risks related to hazardous waste disposal during the operational phase and up to 30 years following repository closure.

The EPA Certification and RCRA Permit establish characterization requirements for all TRU waste (CH and RH) to be emplaced in WIPP. Contact-handled TRU waste is characterized according to a plan that was negotiated for almost two decades among DOE and the regulators prior to the certification of the WIPP facility. This plan consists of 100 percent confirmation of acceptable knowledge (AK)[3] information through visual examination, radioassay, headspace gas sampling, or radiography. A DOE review of the CH-TRU waste characterization procedures revealed that DOE developed self-imposed waste restrictions in the waste acceptance criteria and in the implementation documents used by generator sites to characterize CH-TRU waste. A previous National Research Council committee found that these self-imposed procedures lack technical, safety, or legal basis (see Sidebar 3.1). DOE is now facing the challenge of proposing a characterization plan for RH-TRU waste that meets EPA and NMED requirements but follows a different approach than that used for CH-TRU waste.

[3]According to the EPA's definition, AK consists of historical information on a particular waste stream, which may include administrative, procurement, and quality control documentation associated with the generating process, past sampling and analytical data, information about the process used to generate the waste, material inputs to the process, and the time period during which the waste was generated (see Sidebar 2.1).

S.2 DOE's Proposed Characterization Plan for RH-TRU Waste

The following two documents include DOE's proposed characterization plan for RH-TRU waste:

- Document 1: Notification of Proposed Change to the EPA Title 40 CFR Part 194 Certification of the WIPP.
- Document 2: Request for RCRA Class 3 Permit Modification to the NMED.

On June 28, 2002 DOE submitted Documents 1 and 2 to EPA and NMED, respectively. The committee reviewed two drafts of the above documents prior to their submission. Findings and recommendations in this report apply to the characterization plan as presented in the March 2002 draft.

DOE's goal is to adopt a performance-based approach to meet EPA and NMED requirements for waste characterization. This approach relies on the impact of the RH-TRU waste inventory on the performance of WIPP. The Sandia National Laboratories undertook two performance assessment analyses showing that the characteristics of RH-TRU waste will have a negligible impact on the potential long-term release of radionuclides into the environment. This is due to the characteristics of DOE's RH-TRU waste inventories in terms of volume and radiological composition.

To address the EPA and NMED regulatory requirements, DOE proposes to use the following characterization methods: dose-to-curie conversion, visual examination, radiography, direct assay, counting containers, AK, and characterization at the time of packaging. The dose-to-curie method consists of correlating a surface dose rate measurement with documented waste isotopic distributions through the use of empirically developed conversion factors. Visual examination involves the removal of items from the container (by remote-handled methods) for inspection and identification. Visual examination does not provide information on the isotopic composition of waste. Radiography utilizes penetrating radiation (typically X-rays) to investigate the contents of containers. Direct assay consists of radiochemical analyses using the same methods approved for CH-TRU waste characterization. Counting containers is the method used to determine the amount of metal emplaced in WIPP by an automatic inventory of the number of containers during packaging. Characterization at the time of packaging consists of visual examination and the use of other characterization methods (i.e., AK, radiochemical analysis, or radiography) as waste is generated, packaged, or repackaged in a form suitable for shipment to WIPP. The AK method, which is the primary method of compliance for waste characterization, consists of collecting historical information and new information obtained through the "characterization at the time of packaging" method (see Finding 1B below). Further details are provided in Chapter 4.

Unlike the current CH-TRU waste characterization approach, which requires 100 percent confirmation of the AK information, for RH-TRU waste characterization DOE proposes performing confirmatory measurements only on 10 percent of the waste. This confirmation activity is proposed when AK is insufficient to address a characterization requirement.

S.3 Committee's Assessment of DOE's Proposed Characterization Plan

This report is not meant to be a comprehensive review of the entire RH-TRU waste program, which encompasses RH-TRU waste transportation, storage, waste

certification, operational safety issues, occupational health and safety regulations, waste generator states' regulations, waste acceptance criteria, as well as DOE orders.

The committee used the criteria listed in the statement of task to assess DOE's proposed characterization plan (see Sidebar P.1 in the Preface). Findings and recommendations address: 1) the context of RH-TRU waste characterization, 2) the characterization plan's technical soundness, 3) protection of worker safety and health, and 4) compliance with regulatory requirements. Findings are referenced (in parentheses) according to the order they are presented in Chapter 5. Each finding is followed by the corresponding recommendation (in bold characters). The rationales are provided in Chapter 5.

1) Context of RH-TRU Waste Characterization

The committee did not verify the data provided by DOE on its RH-TRU waste inventories. Acknowledging the past fluctuations of RH-TRU waste inventories, the committee assumes that DOE presented the most up-to-date information available. Even if the information presented in DOE inventories were not accurate, by law the RH-TRU waste emplaced in WIPP cannot exceed 4 percent of the total volume inventory and 5.1 million curies. According to DOE inventories, 95 percent of the RH-TRU waste to be disposed of in WIPP has yet to be generated or needs to be processed, packaged, or repackaged. This waste will be characterized (through visual examination and physical and chemical analyses) at the time of packaging (Finding 1A). **DOE should emphasize the argument that the characterization information collected for most of RH-TRU waste does not need confirmatory measurements because the repackaging or generation of waste will be carried out under a certified quality assurance program.** If the volume of RH-TRU waste represents between 2 and 4 percent of the volume of TRU waste, and the information collected for over 95 percent of RH-TRU waste does not need confirmation, then only the remaining 5 percent of the RH-TRU waste inventory (between 0.1 and 0.2 percent of the total inventory) needs confirmatory activities.

As previously mentioned, DOE uses the term "AK" to indicate both the historical information and the newly generated characterization information collected at the time of waste generation, packaging, or repackaging. However, for 95 percent of the RH-TRU waste inventory, AK refers mostly to the latter (Finding 1B). **The committee recommends that DOE use a different term than "AK" for this newly generated information.** Using AK for both historical and newly generated information is potentially confusing because AK is generally associated with historical information, which requires some type of confirmation.

2) Characterization Plan's Technical Soundness

The committee found that DOE's proposed characterization plan is not completely performance based and that several characterization activities are based on non-technical considerations (Finding 2A). The committee questions the technical basis of some of these characterization activities. The committee acknowledges that non-technical considerations may be important for maintaining effective working relationships among DOE, EPA, and NMED; however, **DOE should propose only characterization activities that have a technical, health and safety, or regulatory basis.**

The committee provides the following examples of activities lacking a technical basis in the context of RH-TRU waste characterization: determination of radiological activity, free water/liquid, ferrous metal, cellulosics, plastic, rubber, and polychlorinated biphenyls

content. According to the Sandia impact analyses, these RH-TRU waste parameters will have only a negligible impact on the performance of the repository. Also, DOE did not provide the technical basis for selecting 10 percent of the waste as a representative waste sample to perform confirmation activities.

In some instances, the plan lacked specificity because most of the operational details are site-specific and were not available at the time of writing (Finding 2B). It is the committee's understanding that, along with Documents 1 and 2, DOE will submit three site-specific documents containing a completed characterization plan for selected RH-TRU generator sites. The committee supports this initiative. **The site-specific documents should present clear and technically defensible data qualification requirements for RH-TRU waste characterization.**

Also, tolerable decision error rates are never clearly defined in Documents 1 and 2 (Finding 2C). Tolerable decision error rates are determined by weighing the consequences of mischaracterization against the costs (including worker risks) of achieving better characterization. Once established, tolerable decision error rates can be used to identify the attendant quality assurance requirements for sampling (i.e., the measurement quality objectives, which DOE calls quality assurance objectives[4]). **DOE's proposed characterization plan should address tolerable decision error rates associated with characterization information. These errors should not be overly stringent so as to negatively impact the sites' ability to implement ALARA.**[5]

For the 5 percent of the RH-TRU waste inventory that does not require packaging or repackaging, it is not clear how visual examination and radiography can confirm AK information for prohibited items (Finding 2D). For example, visual examination and radiography cannot distinguish between corrosive and non-corrosive liquids, whereas AK may provide records of the existence of such liquids in the waste. Historical AK may be a better indicator of some of the currently prohibited items than visual examination and radiography. **The characterization plan should clarify under which conditions confirmation of historical AK is warranted and what are the most effective methods proposed.** The committee could not determine the effectiveness of specific technologies, such as X-ray radiography, in providing confirmatory data for the high-dose-rate fraction of RH-TRU waste containers (Finding 2E). **DOE should provide justification for the technologies proposed for obtaining confirmatory data and provide evidence of their effectiveness across the entire spectrum of dose rates for RH-TRU waste.**

Overall, in the context of RH-TRU waste characterization and from a performance point of view, the committee found that the general approach DOE is proposing is technically sound. However, Documents 1 and 2 do not present a performance-based plan as effectively as they could.

3) Protection of Worker Safety and Health

Potential worker radiation doses and related characterization costs are distinguishing features of RH-TRU waste compared to CH-TRU waste, but estimates of worker doses and characterization costs for RH-TRU waste are limited, site-specific, and not completely reliable (Finding 3A). **DOE could strengthen the rationale of its**

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[4]DOE's "quality assurance objectives" are the accuracy, precision, completeness, comparability, and representativeness of the characterization data.

[5]The ALARA (As Low As is Reasonably Achievable) principle requires that a reasonable effort be made to keep workers radiation exposures as far below the regulatory dose limits as is practical (see Chapter 4).

characterization plan for RH-TRU waste by including a discussion of estimates of worker doses and characterization costs in the three site-specific plans accompanying the submittal documents. Discussion of worker doses and costs is relevant since radiation protection standards and criteria are predicated on the concept of assessing the decrement in risk per increment in cost. It is also important to recognize that tolerable decision error rates associated with characterization methods will have an impact on the implementation of the ALARA principle at generator sites (see Finding 2C).

Documents 1 and 2 provide flexibility to the generator sites in the implementation of the RH-TRU waste characterization plan (Finding 3B). **DOE should continue its effort in ensuring sufficient flexibility to generator sites in the implementation of the characterization plan. However, characterization activities that share common elements across sites should be standardized.** Given the differences among generator sites (for instance, in the composition of waste streams, quality of AK and inventories, and characterization and repackaging facilities), flexibility in a waste characterization plan is important to adapt the sites' implementation programs. A rigid, overly prescriptive characterization plan may lead to unnecessary radiation doses to workers and characterization costs. However, standardization of common elements of the characterization program may facilitate characterization compliance verifications and, possibly, reduce characterization costs.

4) Compliance with Regulatory Requirements

The difficulty of this latter part of the statement of task lies in performing a review of a characterization plan for RH-TRU waste against compliance with existing characterization requirements that currently exclude RH-TRU waste. The task is further complicated by the existence of the characterization approach approved by EPA and NMED that is currently used for CH-TRU waste. It is important to emphasize the difference between regulatory requirements and the approach to meet such requirements. While the regulatory requirements for CH- and RH-TRU waste characterization are the same, the approach to address these requirements can be different. The committee evaluated, from a technical point of view, the approach DOE is proposing to characterize RH-TRU waste and how it addresses regulatory requirements. The committee was not asked to comment on these requirements nor was it asked to determine if the plan complies with the regulatory requirements. The latter is obviously a policy decision belonging to the regulatory agencies.

The committee found that DOE's proposed characterization plan for RH-TRU waste deliberately tracks the characterization plan for CH-TRU waste (Finding 4A). **The committee recommends that DOE evaluate whether existing characterization practices for CH-TRU waste, when applied to the characterization of RH-TRU waste, have an impact on the protection of the environment, health and safety of public and workers, and cost-effectiveness of the characterization program.** Also, like in the CH-TRU waste characterization plan, Documents 1 and 2 include, as basis for characterization objectives, requirements other than those applicable to EPA certification and RCRA permit, for instance transportation requirements or waste acceptance criteria (Finding 4B). **The committee recommends that submittal documents focus on regulatory requirements under the relevant agency's purview and distinguish between these requirements and ancillary information describing the context of RH-TRU waste characterization.** While it is important to provide, in the submittal documents, the full context of the characterization of RH-TRU waste, including material outside the regulatory jurisdiction of EPA and NMED may unnecessarily complicate the

regulatory review process. It would be helpful for both DOE and the regulatory agencies if the submittal documents indicate which requirements are to be reviewed and which are given for information purposes. This would allow the regulator and DOE to keep track of various requirements and to streamline characterization practices as experience is gained.

S.3.1 Overall Assessment of DOE's Characterization Plan

The committee observed a net improvement between the July 2001 and March 2002 drafts of the characterization plan. Concerning the plan's technical soundness, DOE itself recognized that this plan is not completely performance based and that other considerations played a role in its development. The committee identified some characterization activities lacking technical bases in the context of RH-TRU waste and a potential technical problem with radiographic examination of waste. Also, DOE's proposed characterization plan does not adequately address the issue of tolerable decision error rates associated with all characterization information.

In some instances, the plan lacks specificity because most of the operational details are site-specific and were not available at the time of writing. The site-specific accompanying documents should provide useful clarifications. In the context of RH-TRU waste characterization and from a performance point of view, the committee found that the general approach DOE is proposing is technically sound. However, Documents 1 and 2 do not present a performance-based plan as effectively as they could.

Concerning the plan's protection of worker health and safety, the committee recommends that the approved characterization plan not include overly stringent tolerable decision error rates that could negatively impact the sites' ability to manage worker risks. It is important to recognize that the allowable uncertainties in the final characterization plan approved by EPA and NMED may have an impact on generator sites' radiation protection programs.

Concerning compliance with regulatory requirements in the EPA Certification and RCRA Permit, the committee did not observe any requirement that was not addressed in DOE's characterization plan. In fact, the proposed characterization plan for RH-TRU waste addresses some requirements that are not under the relevant agency's purview. Moreover, the characterization plan for RH-TRU waste deliberately tracks that for CH-TRU waste. The committee recommends evaluating whether existing characterization practices for CH-TRU waste, when applied to the characterization of RH-TRU waste, have an impact on the protection of the environment, health and safety of public and workers, and cost-effectiveness of the characterization program.

1

Introduction

The purpose of this report is to provide an independent technical review of the U.S. Department of Energy's (DOE's) proposed characterization plan for defense-related remote-handled (RH) transuranic (TRU) waste. Remote-handled transuranic waste is defined in Sidebar 1.1.

Transuranic waste is classified as remote-handled (RH) or contact-handled (CH) depending on the radiation dose rate measured at the surface of waste containers. While CH-TRU waste can be safely handled by direct contact, RH-TRU waste requires heavy container shielding or remote-handling equipment. Therefore, the main issues with RH-TRU waste characterization are the potential for worker exposure to radiation and the associated costs.

Because of its radiological hazard, TRU waste requires geologic isolation. Congress designated the Waste Isolation Pilot Plant (WIPP), in southeastern New Mexico, as the nation's geologic disposal facility for defense-related transuranic waste (U.S. Congress, 1992). Figures 1.1, 1.2, and Sidebar 1.2 provide a schematic representation and a brief description of the WIPP facility. DOE is seeking authorization to dispose of RH-TRU waste in WIPP as part of its commitment to safely manage and clean up contamination from over 50 years of nuclear materials research and production. About 3,800 cubic meters of defense-related RH-TRU waste (corresponding to approximately 1 million curies) is the current estimated volume of RH-TRU waste to be disposed in WIPP.

The U.S. Environmental Protection Agency (EPA) and the New Mexico Environment Department (NMED) are WIPP's regulatory agencies. In 1998, the EPA, which regulates TRU waste, granted WIPP a Certification of Compliance (referred to as the EPA Certification) with the geologic disposal standards established in Title 40 of the Code of Federal Regulations Part 191 (40 CFR 191). In 1999, the NMED, which regulates hazardous waste disposal under the Resources Conservation and Recovery Act (RCRA), granted WIPP a hazardous waste facility permit (referred to as the RCRA Permit). Regulatory requirements addressing radioactive and hazardous waste will be discussed in Chapter 3.

EPA and NMED authorize only CH- and mixed CH-TRU waste in WIPP. Remote-handled TRU waste is not allowed in this facility because, according to these agencies, DOE does not have an appropriate characterization plan for this type of waste (see Chapter 3).

The EPA Certification and RCRA Permit contain characterization requirements for TRU waste to be emplaced in WIPP. These characterization requirements were negotiated among DOE, EPA, and NMED and they are the basis of the current characterization plan for CH-TRU waste.

SIDEBAR 1.1 Definition of Transuranic Waste and Classification

Transuranic (TRU) waste is radioactive waste containing alpha-emitting radionuclides of atomic number greater than 92, half-life[a] greater than 20 years, and activity greater than 100 nanocuries per gram of waste, except for: high-level radioactive waste; waste that the Department of Energy (DOE) has determined, with the concurrence of the Environmental Protection Agency (EPA), does not need the degree of isolation required by the disposal regulations; or waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with Title 10 of the Code of Federal Regulations Part 61 (U.S. Congress, 1992).

Transuranic waste can consist of sludge or solid material, such as pieces of clothing, tools, and debris. This type of waste was produced during the processing of nuclear materials and continues to be generated in the cleanup of DOE weapons sites. The main alpha-emitting radionuclides in TRU waste (and their respective half-lives indicated in parenthesis) are plutonium-238 (87.7 years), plutonium-239 (24,100 years), plutonium-240 (6,560 years), and americium-241 (433 years). Other long half-life isotopes, such as uranium-233 (159,200 years), uranium-234 (24,600 years), uranium-235 (704 million years), and uranium-238 (4.47 billion years) may also be present in transuranic (TRU) waste.

Transuranic waste is classified as *contact-handled* (CH) or *remote-handled* (RH), according to the dose rate measured at the container surface. According to Land Withdrawal Act, "the term 'contact-handled transuranic waste' means transuranic waste with a surface dose rate not greater than 200 millirem per hour. The term 'remote-handled transuranic waste' means transuranic waste with a surface dose rate of 200 millirem per hour or greater" (U.S. Congress, 1992). The legal definitions of CH-TRU and RH-TRU waste do not clearly address container surface dose rates of exactly 200 mrem per hour. Therefore, waste packages approaching 200 mrem per hour are handled directly or remotely, depending on site-specific practices.

Transuranic waste is further classified as *mixed* or *non-mixed*. Mixed TRU waste contains both radioactive material regulated under the Atomic Energy Act and hazardous waste material regulated under the Resource Conservation and Recovery Act, or RCRA (U.S. Congress, 1976). RCRA is a federal law addressing hazardous waste designed to ensure that the generation, transportation, treatment, storage, and disposal of hazardous wastes are conducted in a manner that protects human health and the environment (EPA, 1994). The statutory definition of hazardous waste is provided in Section 1004(5) of RCRA as follows (EPA, 1994; page 1.3):

> "A solid waste, or combination of solid waste, which because of its quantity, concentration, or physical, chemical, or infectious characteristics may 1) cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or 2) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed."

Examples of hazardous waste material are ignitable, corrosive, reactive, and toxic substances. For an overview of the Atomic Energy Act and major environmental laws, including RCRA, the reader may refer to "The Nuclear Waste Primer" (The League of Women Voters, 1993).

[a]For a definition of half-life see the glossary, Appendix I.

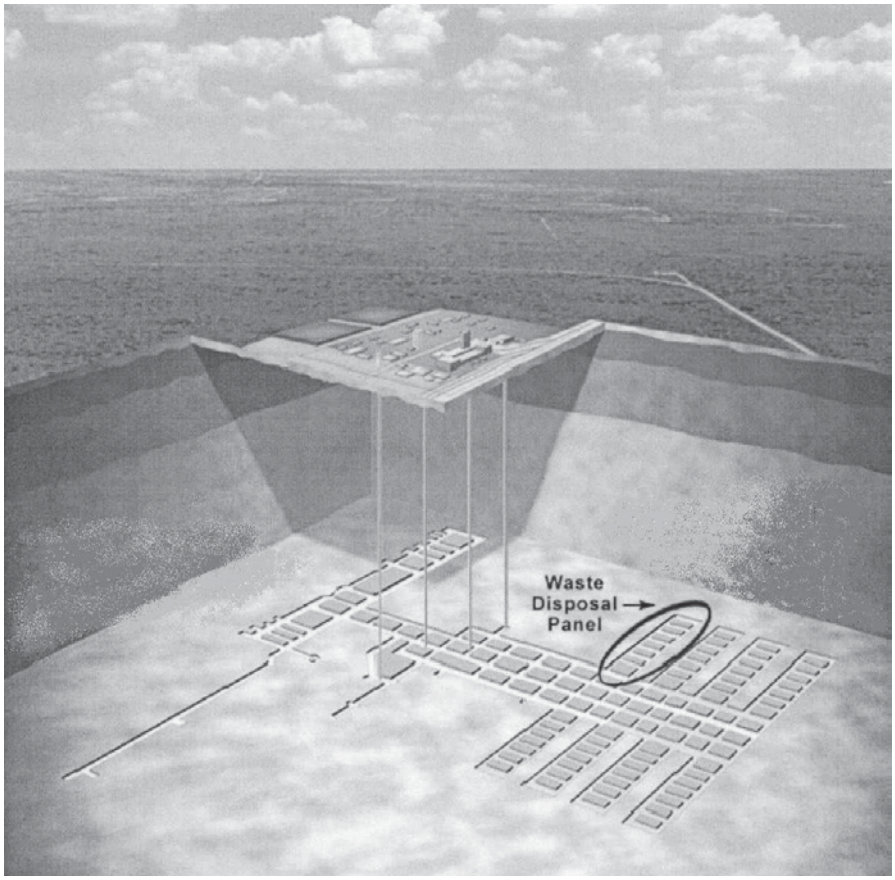

FIGURE 1.1 Schematic representation of the WIPP Facility. The facility will have eight disposal panels, each divided into seven rooms. Only two of the eight panels have been mined to date. SOURCE: DOE (DOE-CBFO, 2000).

To obtain authorization to dispose of RH-TRU waste in WIPP, DOE must request a modification of the EPA Certification and RCRA Permit and present a proposed characterization plan for this type of waste. This proposed characterization plan is the focus of this report.

DOE's proposed characterization plan for RH-TRU waste consists of the following two documents:

- Document 1: Notification of Proposed Change to the EPA Title 40 CFR Part 194 Certification of the WIPP.
- Document 2: Request for RCRA Class 3 Permit Modification[1] to the NMED.

Documents 1 and 2 will often be referred to in this report as the “submittal documents.”

[1]Class 3 permit modifications, as determined by NMED, are considered major changes to the permit. This class of permit modification requires a public notice, a 60-day comment period, and hearings, including testimony and cross-examination of witnesses, before NMED issues the final draft permit language.

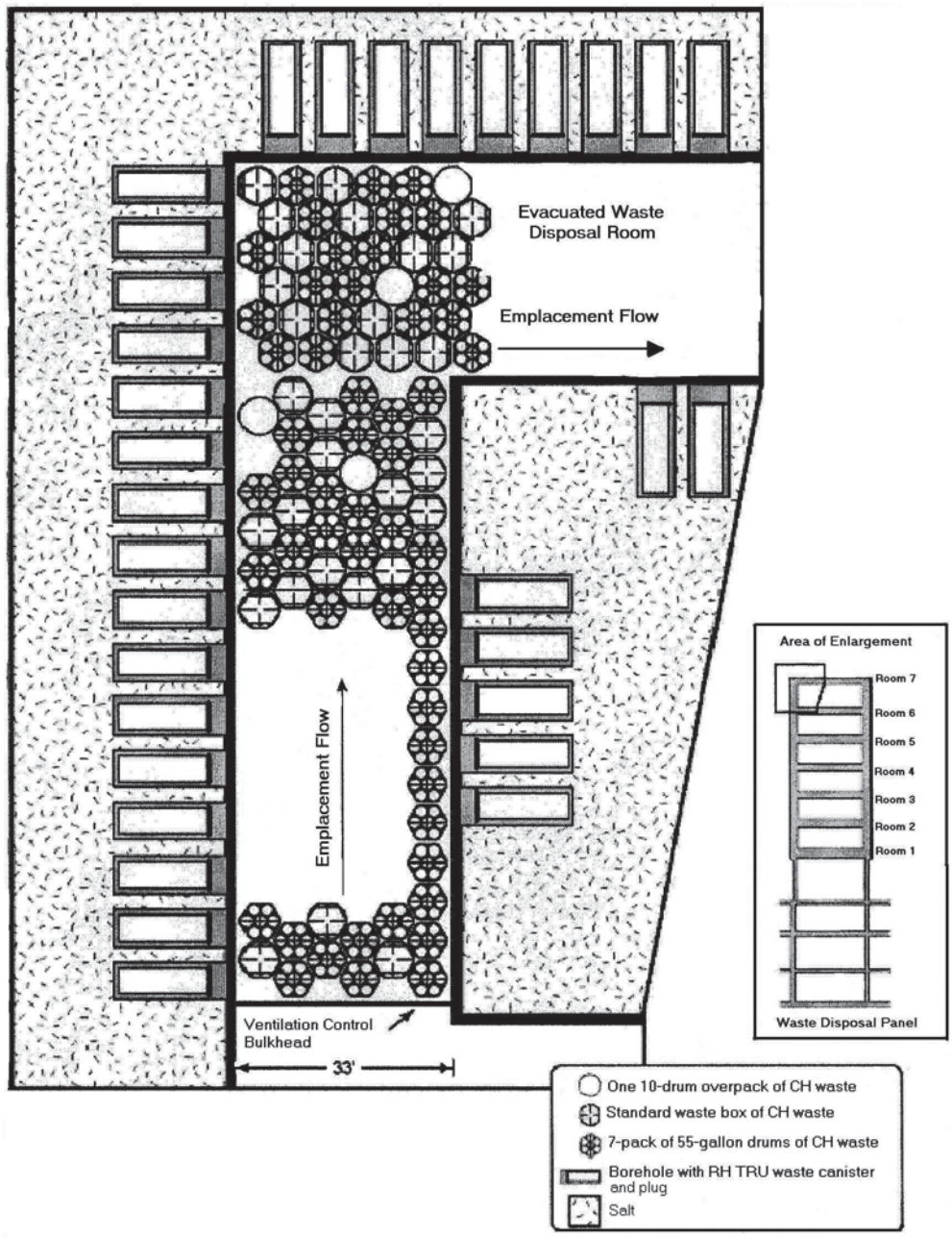

FIGURE 1.2 Plan view of a section of a typical underground disposal area showing CH-TRU and RH-TRU waste emplacement. SOURCE: National Transuranic Waste Management Program, Rev. 2, Figure 3.2.1.1-2 (DOE-CBFO, 2000; page 69).

Document 1 contains EPA regulatory requirements to ensure that the waste emplaced in WIPP falls within the envelope limits required to maintain compliance with radiological disposal standards. Document 2 contains regulatory requirements to ensure that the non-radiological hazardous characteristics of the waste emplaced in WIPP are compatible with RCRA requirements. Documents 1 and 2 also contain additional

information, such as the WIPP's waste acceptance criteria, transportation requirements, description of surface storage and handling facilities, and waste certification process.

DOE's proposed characterization plan must address the characterization requirements in the EPA Certification and RCRA Permit in the context of RH-TRU waste. As shown in Chapter 2, this context is different from that of CH-TRU waste because of the different inventories and radiological properties.

EPA and NMED may accept, reject, or propose modifications to the characterization plan and eventually they may authorize RH-TRU waste disposal in WIPP. Once the characterization methods for RH-TRU waste are finalized, it is the committee's understanding that DOE will produce one document combining all regulatory requirements to help generator sites implement their characterization programs.

SIDEBAR 1.2 The Waste Isolation Pilot Plant

The Waste Isolation Pilot Plant (WIPP), located near Carlsbad in New Mexico, is the nation's defense-related transuranic waste repository, as designated by Congress in the Land Withdrawal Act of 1992. This Act allows the disposal of 175,564 cubic meters of transuranic waste in WIPP, of which 7,080 cubic meters can be remote-handled transuranic (RH-TRU) waste with a maximum radioactivity of 5.1 million curies. Other legal criteria for WIPP related to RH-TRU waste are discussed in Chapter 3.

The WIPP disposal area is located 660 meters below ground in a salt bed, called the Salado Formation (see Figure 1.1). Large salt beds such as this are found only in regions that lack significant flows of groundwater. This deep, relatively dry, underground environment greatly reduces the possibility of waste releases from the repository by natural processes. Moreover, after approximately 200 years, the mined salt will heal and encapsulate the waste, thereby permanently locking it deep beneath the surface (Knowles and Economy, 2000).

The underground waste disposal area in WIPP consists of eight panels, each containing seven rooms. Contact-handled transuranic (CH-TRU) waste drums and boxes are being stacked in three layers in the center of each room. Remote-handled TRU waste is currently not authorized in WIPP. Should the U.S. Environmental Protection Agency (EPA) and the New Mexico Environment Department (NMED) allow disposal of RH-TRU waste in WIPP, it will be emplaced inside horizontal boreholes drilled into the walls of each room. Figure 1.2 shows the CH-TRU and RH-TRU waste emplacement configurations. According to WIPP's design, the diameter of a borehole for RH-TRU waste containers is 76.2 cm and the length is 487.68 cm (DOE-CAO, 1995). A shield plug will cap each RH-TRU waste borehole to provide workers with the necessary protection against radiation.

The WIPP has been under study since the mid-1970s and under construction since January 1981. The facility received the first CH-TRU waste shipment in March 1999 and the first mixed CH-TRU waste shipment in September 2000. To date (July 2002), more than 900 shipments of CH-TRU waste from 26 generator sites have been sent to WIPP.

After three years of operation, the first panel has been almost completely filled with CH-TRU waste. Because CH-TRU waste now blocks the access to the rooms walls, RH-TRU waste cannot be disposed in this first panel. Emplacement of CH-TRU waste in the second panel is currently scheduled to begin in December 2002.

1.1 Committee's Task and its Boundaries

At the request of DOE-Carlsbad Field Office, the National Research Council appointed the Committee on the Characterization of Remote-Handled Transuranic Waste for the Waste Isolation Pilot Plant, referred to as "the committee" in the rest of this report. The committee roster and biographical sketches can be found in Appendix A. The committee's statement of task is reproduced in Sidebar P.1 of the Preface. The committee followed the examples of criteria listed in the statement of task to assess DOE's proposed characterization plan.

The committee was asked to provide recommendations, as necessary, for improving the characterization plan's technical soundness, protection of worker safety and health, and compliance with regulatory requirements. The difficulty of this latter part of the task lies in performing a review of a characterization plan for RH-TRU waste that must show compliance with existing characterization requirements. These requirements exclude RH-TRU waste. Moreover, the approach currently used to characterize CH-TRU waste is different than the approach DOE proposed for RH-TRU waste. It is important to emphasize the distinction between regulatory requirements and the approach to meet such requirements. While the regulatory requirements for the characterization of TRU waste destined for WIPP, established in the EPA Certification and RCRA Permit, apply to both CH- and RH-TRU waste, the waste characterization plans may propose different approaches to address these requirements. The committee evaluated, from a technical point of view, the approach DOE is proposing to characterize RH-TRU waste and how DOE proposes to address regulatory requirements. The committee was not asked to comment on these requirements nor was it asked to determine if the plan complies with the regulatory requirements. The latter is obviously a policy decision belonging to the regulatory agencies.

During this study, the committee reviewed two drafts of Documents 1 and 2, dated July 2001 (DOE-CBFO, 2001a, 2001b) and March 2002 (DOE-CBFO, 2002a, 2002b). The committee provided initial findings and recommendations in an interim report (see excerpt in Appendix C).

The committee did not verify data provided by DOE on RH-TRU waste inventories. Acknowledging the past fluctuations of RH-TRU waste inventory information, the committee assumes that DOE presented the most up-to-date information available. The committee was not asked to identify other potential sources of RH-TRU waste or discuss the origin of RH-TRU waste streams at generator sites.

Also, the committee did not assess the validity of supplementary information supporting the characterization plan, such as the Sandia Inventory Impact Assessment Reports in Document 1 (DOE-CBFO, 2002a; Attachment 2) and Document 2 (DOE-CBFO, 2002b; Supplement 2). The committee did, however, assess how DOE interpreted and used the results of these reports in its characterization plan.

This document is not meant to be a comprehensive review of the entire RH-TRU waste program, which encompasses RH-TRU waste transportation, storage, waste certification, operational safety issues, occupational health and safety regulations, waste generator states' regulations, waste acceptance criteria, as well as DOE orders. The National Research Council is undertaking a more general study on the characterization of TRU waste (including relevant transportation requirements) and its impact on DOE's National Transuranic Waste Management Program.

Documents 1 and 2 were submitted to the regulatory agencies on June 28, 2002. The committee did not review the submittal version of these documents; therefore, findings and recommendations in this report apply to the characterization plan as presented in March 2002.

1.2 Organization of the Report

Following this introduction, Chapter 2 contains updated information on life cycle, status, and inventories of RH-TRU waste at selected generator sites. Chapter 3 describes the regulatory context for the disposal of RH-TRU waste. DOE's proposed characterization plan for RH-TRU waste is described in Chapter 4. Chapter 5 provides the committee's assessment of DOE's proposed characterization plan. In December 2001, the committee released an interim report with initial findings and recommendations relevant to the July 2001 draft. These findings and recommendations can be found in Appendix C. DOE's response to the committee's interim report is reproduced in Appendix D.

2

Remote-Handled Transuranic Waste

This chapter provides the context of RH-TRU waste characterization. The information presented on isotopic composition, life cycle, generator sites, and inventories for RH-TRU waste is provided on the basis of the knowledge gathered during committee meetings and has not been verified. DOE's inventories have been updated since the committee's interim report (released in December 2001).

2.1 Technical Context of Remote-Handled Transuranic Waste Characterization

The radiation-related health hazard associated with TRU waste is due primarily to alpha and gamma radiation. Alpha radiation cannot penetrate human skin but poses a potential health hazard if particles containing alpha-emitting radionuclides are inhaled or ingested. Contact-handled TRU waste typically emits relatively little gamma radiation; therefore, when properly packaged, it can be handled directly by workers.

Remote handled-TRU waste also contains activation and fission products (half-lives are indicated in parenthesis), such as cobalt-60 (5.3 years), plutonium-241 (14.4 years), strontium-90[1] (29 years), cesium-137 (30 years), and their progenies. Some of these products emit gamma radiation, which can penetrate human skin and even the walls of waste containers. Therefore, RH-TRU waste requires heavy shielding and remote-handling equipment. Gamma rays represent the main radiological health hazard to workers during normal RH-TRU waste handling operations.[2] Although alpha-radiation exposure has a greater health risk per unit of energy deposited, the likelihood that workers will be exposed to alpha radiation while handling RH-TRU waste is lower compared to the likelihood for exposure to gamma radiation, because alpha radiation is stopped by the container's walls.

In summary, RH-TRU waste presents a long-term (i.e., 10,000 years) radiological hazard associated with TRU radionuclides (related to the presence of long-lived alpha-emitting isotopes) and a short-term (less than 300 years) radiological hazard associated with short-lived gamma-emitting radionuclides (related to the presence of fission and activation products). Today, most of the radioactivity in DOE's inventory of RH-TRU waste is due to the short-lived non-TRU radionuclides listed above. Nearly all of this activity will decay in 300 years, corresponding to approximately 10 half-lives of the

[1]Strontium-90 and plutonium-241 also emit beta particles (contributing to approximately 35 percent of the curie inventory for RH-TRU waste) but their energy is not high enough to penetrate the walls of RH-TRU waste containers.

[2]Normal waste handling operation implies that the RH-TRU waste container is not breached and workers are not directly exposed to alpha-emitting particles.

gamma-emitting radionuclides. Therefore, the long-term activity of RH-TRU waste is due to the remaining long-lived alpha-emitting (i.e., TRU) radionuclides.

2.2 Life Cycle of Remote-Handled Transuranic Waste

The life cycle of RH-TRU waste, from its generation to its designated final disposal at WIPP, generally consists of the following:

1. waste generation or recovery from its current storage location;
2. processing;
3. characterization;
4. packaging or repackaging;[3]
5. storage on site or off site prior to shipment to WIPP;
6. road transportation to WIPP;
7. receipt, handling, surface interim storage; and
8. underground emplacement at WIPP.

Remote-handled waste is generated during deactivation and decommissioning activities of DOE sites or it is already stored at generator sites and must be recovered for shipment to WIPP. Recovery activities can be complex if containers are difficult to access, if their integrity has been compromised with time, or if storage records are not available. For instance, part of the RH-TRU waste stored at Oak Ridge National Laboratory consists of a sludge that must be processed before shipment to WIPP (see Appendix E).

Waste processing activities consist of converting waste to a form suitable for disposal in WIPP. For instance, wet sludge must be dried because liquids are considered prohibited items (if more than 1 percent by waste volume) in WIPP's RCRA Permit. Waste characterization is necessary prior to waste shipment to WIPP. Waste characterization may be performed at the time of packaging or repackaging of the waste. Packaging is necessary for waste that has not yet been generated. Repackaging is necessary for stored waste that is packaged in a container that does not meet transportation requirements; or for waste that needs processing to remove hazardous material (see Section 2.4). Solid RH-TRU waste will be repackaged in shielded facilities, such as hot cells.[4] During this step, waste can be inspected by visual examination. As the waste is removed from an old container and sorted into new containers, a video camera records the operations on tape while an operator describes the various items. This inspection method requires skilled operators since it is done entirely by remote methods (see Finding 2D in Chapter 5). Volume-reducing operations, such as mechanical waste compacting, are also performed during the repackaging process.

Once a waste stream[5] is characterized and packaged, it must be certified by EPA and NMED and stored on site prior to shipment to WIPP. Selected waste streams may

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[3]For most of the RH-TRU waste inventory, characterization will be performed at the time of packaging or repackaging of waste (see Chapters 4 and 5).

[4]A hot cell is a large chamber for handling highly radioactive materials. It is usually equipped with thick walls with shielding and viewing windows, remote-operated overhead cranes, closed-circuit televisions, and a variety of specialized tools and measuring devices. Throughout DOE complex other shielded facilities may be used with the same purpose as hot cells.

[5]A waste stream is defined as waste material generated from a single process or activity or as waste in multiple containers having similar physical, chemical, or radiological characteristics.

not need certification if they are shipped to other major DOE sites for interim storage. Prior to shipment to WIPP, these interim storage sites will ensure certification of all their waste, including that received from other sites.

Finally, RH-TRU waste must be loaded into transportation casks, transported by road[6] to WIPP, received, temporarily stored at the surface, and finally emplaced underground.

2.3 Generation of Remote-Handled Transuranic Waste

According to DOE's latest inventory, there are approximately 3,800 cubic meters of RH-TRU waste to be removed from DOE sites across the nation. Figure 2.1 shows the geographic locations of the major RH-TRU waste generator sites. These sites are the following:

1. Hanford Site, Washington;
2. Idaho National Engineering and Environment Laboratory;
3. Los Alamos National Laboratory, New Mexico; and
4. Oak Ridge National Laboratory, Tennessee.

There are also nine smaller RH-TRU waste generator sites, not shown in Figure 2.1. Tables 2.1 and 2.2 show DOE's RH-TRU waste inventories in terms of volume and radioactivity. Additional information about the nature and history of RH-TRU waste at selected generator sites is provided in Appendix E.

Tables 2.1 and 2.2 show the substantial variability among generator sites concerning waste volumes and radioactivity contents. These tables show that 60 percent of the stored volume of RH-TRU waste and about 89 percent of the total curie activity is located at Oak Ridge National Laboratory. About two-thirds of the Oak Ridge RH-TRU waste consists of wet sludge, stored in Melton Valley storage tanks, and the rest is debris waste. Debris waste consists of debris from hot cells and glove boxes packaged in shielded concrete casks. This wet sludge and debris waste contains significant sources of neutrons, due to the spontaneous fission of californium-252 and from (alpha, n) reactions (see Appendix E). These reactions involve the capture of highly energetic alpha particles, such as those emitted from curium-244, by nuclei of low-atomic-number elements, such as oxygen and fluorine, and the subsequent emission of neutrons. The neutron emission is primarily a handling, processing, and particularly a characterization issue in the near term for this site. The waste containers that will be used to ship RH-TRU waste from Oak Ridge to WIPP are specially designed to shield neutrons.

To meet the milestones set in the Federal Facility Compliance Act between DOE and the state of Tennessee, the Oak Ridge National Laboratory (through its contractor Foster Wheeler) is building a treatment facility to process, characterize, and package its RH-TRU waste (EPA, 1992). The current plan is to characterize RH-TRU waste following a plan similar to that for CH-TRU waste characterization. Homogeneous samples of wet sludge would be characterized by radiochemical assays performed in a laboratory on site. The sludge would then be dewatered and dried in preparation for shipment. Debris would be characterized by visual and non-destructive examination[7] inside a hot cell

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[6]The U.S. Nuclear Regulatory Commission certifies the design of transportation casks. Currently, these containers are designed for road transportation only.

[7]The definition of non-destructive examination can be found in the glossary, Appendix I.

during repackaging. Debris waste would undergo volume-reduction operations during packaging. Oak Ridge records show that there is considerable historical information available on debris waste (ORNL, 1989).

The processing of RH-TRU waste sludge had been scheduled to begin in December 2002 with shipments to WIPP beginning in January 2003. Debris RH-TRU waste would have been processed and shipped to WIPP between 2004 and 2008. Because of the recent submission of DOE's characterization plan to EPA and NMED (June 28, 2002), the characterization plan will likely not be finalized in time to meet this schedule. Oak Ridge is now organizing waste processing and on-site storage as it waits for authorization to ship RH-TRU waste to WIPP (Forrester et al., 2002).

While most of the stored RH-TRU waste volume is located at Oak Ridge National Laboratory, most of the RH-TRU waste to be emplaced in WIPP has yet to be generated. This waste will come from the Hanford Site cleanup activities. The RH-TRU waste at this site consists mostly of sludge at the bottom of the fuel pools, or equipment inside waste tanks (such as pumps, mixers, and pipelines) or is buried in caissons and drums. Because this waste has yet to be generated and packaged, the Hanford Site has less detailed knowledge of its RH-TRU waste inventory than the other major generator sites.

At the Idaho National Engineering and Environmental Laboratory, the stored RH-TRU waste consists mostly of solids generated during the destructive examination of irradiated experimental fuel pins in a hot cell. The RH-TRU waste stored at this site was generated at Argonne National Laboratory-East from defense-related experiments on nuclear fuel. The destructive examination and testing operations of spent fuel pins involved cutting, grinding, and polishing for subsequent examination.

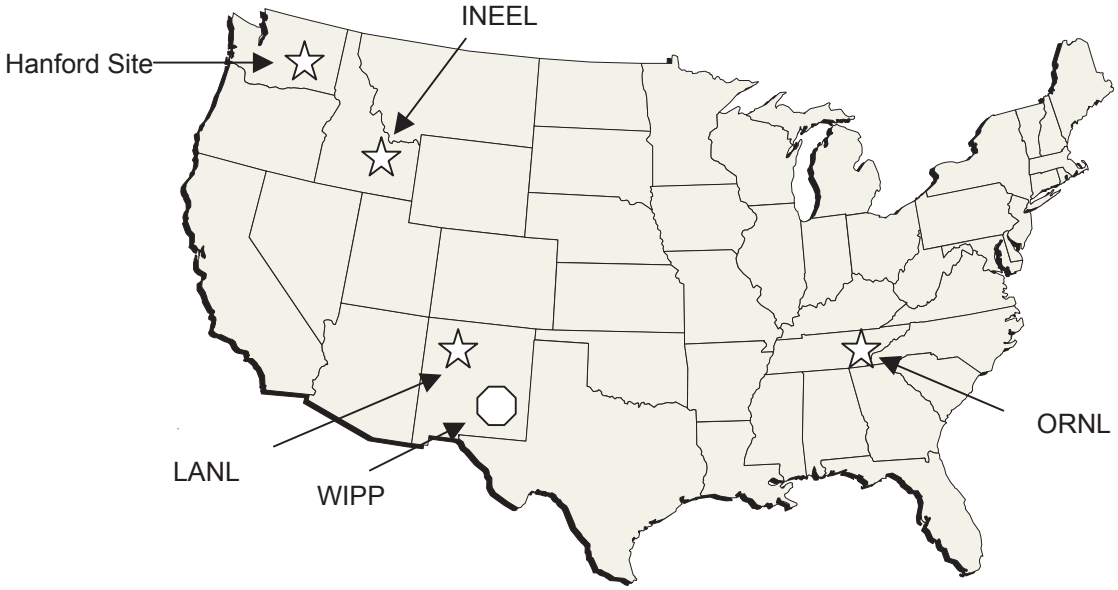

FIGURE 2.1 Geographic locations of the Waste Isolation Pilot Plant (WIPP) and the four major RH-TRU waste sites: Hanford Site, Idaho National Engineering and Environmental Laboratory (INEEL), Oak Ridge National Laboratory (ORNL), and Los Alamos National Laboratory (LANL). There are nine other smaller RH-TRU waste generator sites and several other sites throughout the nation that store CH-TRU waste. SOURCE: DOE (DOE-CBFO, 2001c).

TABLE 2.1 DOE's Inventory of Stored, Projected, Total, and Planned Volumes of RH-TRU Waste

Site Name	RH TRU Waste Volume (cubic meters)				Estimated Range of Concentration of CPR[5] (average kg per cubic meter)	Reported Estimates of Dose Rates[6] (rem per hour)
	Stored[1]	Projected[2]	Total[3]	Planned Disposal[4]		
Hanford Site	207	944	1,151	1,048	0 - 477 (24)	0.2 - 1,000
Idaho National Engineering and Environmental Laboratory[7]	84	52	136	279	0 - 439 (41)	0.2 - 100
Los Alamos National Laboratory	98	24	122	122	0 - 980 (95)	1 - 100
Oak Ridge National Laboratory	1,308	534	1,841	453	0 - 902 (74)	0.2 - 1,000
Total	1,697	1,554	3,250	1,902		
Small-Quantity Sites						
Argonne National Laboratory-East[8]	2	8	10	10	NA	0.2 - 10
Argonne National Laboratory-West	1.1	5	6.1		0 - 1,350 (110)	1 - 100
Battelle Columbus Laboratories[8]	0	20.8	20.8	20.8	0 - 1,430 (117)	0.2 - 150
Bettis Atomic Power Laboratory	2	0	2	2	0 - 1,430 (117)	1 - 100
Energy Technology Engineering Center[8]	8	0	8.7	5.5	0 - 74 (5.2)	0.2 - 1
General Electric-Vallecitos Nuclear Center	11.8	0	11.8	11.8	NA	1 - 100
Knolls Atomic Power Laboratory	3.1	6.8	9.9	10.5	NA	1 - 100
Sandia National Laboratories[8]	1.5	22	23.5		NA	NA
West Valley Demonstration Project[9]	470.5	8.4	478.9		NA	NA
Total Waste Volumes	2,197.7	1,625	3,821.7	1,962.6		

NOTE: The committee did not verify the information in this table.
[1]Stored=waste awaiting treatment or disposal capability, in such a manner as to constitute disposal of the waste.
[2]Projected=the part of the inventory that has not been generated but is currently estimated to be generated at some time in the future.
[3]Total=sum of the stored plus projected volumes.
[4]Planned Disposal=volume expected to be disposed at WIPP. The quantities reflect any volumetric change that would occur during waste processing.
[5]Dose Rate Ranges=the dose rates estimated for as-packaged containers. Dose rates are measured at the container's surface.
[6]CPR=cellulosics, plastics, and rubber. A zero in the average CPR concentration indicates a container including other materials, such as metals or sludge.
[7]It is estimated that about 896 cubic meters of waste will be shipped from Idaho Nuclear Technology and Engineering Center for disposal at WIPP. This waste is expected to be categorized as "Waste Incidental to Reprocessing" and has not yet been approved for disposal at WIPP. Therefore, it is not included in the table.
[8]Current plans are to send the RH-TRU waste at this site to an interim site. Los Alamos National Laboratory's inventory includes Sandia's RH-TRU waste disposal volume. Argonne National Laboratory-East, Battelle Columbus Laboratories, and Energy Technology and Engineering Center are also expected to go to interim sites, but the specific interim sites have not yet been determined. Therefore, the waste volume is included here for completeness.
[9]The West Valley Demonstration Project is not a DOE site, even though it stores some RH-TRU waste. This waste has not yet been determined to be a defense-related waste. It is believed to be commercially derived and therefore not disposable at WIPP in accordance with the Land Withdrawal Act. However, for completeness, this waste is included in the RH-TRU waste inventory.
SOURCE: Document 1, Supplemental Information, Attachment 3, Table 1 (DOE-CBFO, 2002a; page 5).

TABLE 2.2 DOE's Summary Activity Estimates for the RH-TRU Waste Inventory

Site Name	Estimated Stored Activity (total curies)
Hanford Site	36,000
Idaho National Engineering and Environmental Laboratory	6,360
Los Alamos National Laboratory	10,700
Oak Ridge National Laboratory	587,000
Small-Quantity Sites	
Argonne National Laboratory-East	NR
Argonne National Laboratory-West	NR
Battelle Columbus Laboratories	5,800
Bettis Atomic Power Laboratory	16,300
Energy Technology Engineering Center	8
General Electric-Vallecitos Nuclear Center	NR
Knolls Atomic Power Laboratory	118
Sandia National Laboratories	NR
West Valley Demonstration Project	NR
Total Waste Activity	662,286

NOTE: These estimates are for waste currently in storage. They do not take into account "to be generated" RH-TRU waste. The current estimate for stored and future RH-TRU waste is about 1 million curies. NR=Not Reported. NR typically denotes that the site did not report the information for a variety of reasons (e.g., the data are not readily available, the pedigree of the data may be questionable, recent characterization has not been performed, or the site did not respond). The committee did not verify the information in this table.
SOURCE: Document 1, Supplemental Information, Attachment 3, Table 2 (DOE-CBFO, 2002a; page 6).

A fine fuel particulate adhered to the tools required for these operations and contaminated them with TRU elements. These tools (e.g., grinding and cutting wheels, glassware, light bulbs, rags) have been sent to the Idaho National Engineering and Environmental Laboratory. A formal determination of the defense origin for this waste stream will be submitted for approval to DOE prior to disposal at WIPP (Bhatt, 2001). The fuel pin segments, integral fuel pins, and the fuel dust are still stored at Argonne National Laboratory-East, as high level waste or spent nuclear fuel.

Most of the RH-TRU waste stored at Los Alamos National Laboratory was characterized and packaged between 1989 and 1994. The waste was characterized using a similar approach to that approved for CH-TRU waste characterization. Visual examination, non-destructive assay methods, radiography, and radiochemical analyses were used. Characterization operations were performed in a hot cell, except for small quantities of waste analyzed in a laboratory for radiochemical composition.

Among the nine smaller generator sites, the Battelle Columbus Laboratories in Ohio is the only site that is actively characterizing RH-TRU waste. This site is the first originally scheduled to ship RH-TRU waste to WIPP (January 2003). The agreement between Battelle Columbus Laboratories and the state of Ohio requires RH-TRU waste removal from the site by 2002 to meet a 2006 decontamination and decommissioning-completion milestone (Biedscheid et al., 2002).

Battelle Columbus Laboratories began RH-TRU waste characterization activities in October 2001 following a characterization program similar to that used for CH-TRU waste. This characterization program relies on visual examination, performed during

waste repackaging, and previous knowledge of the waste, also called "acceptable knowledge" (AK). Acceptable knowledge is discussed in Sidebar 2.1. The repackaging phase, which occurs in a shielded facility, is necessary because RH-TRU waste containers at this site do not meet transportation requirements. Visual examination is used to estimate physical waste parameters, including weight percentages of metals, cellulosics, plastics, and rubber in the waste, and to determine the absence of prohibited items, including free liquids (see Chapter 3). Acceptable knowledge combined with computer modeling is used to estimate radiological waste parameters, including total activity on a waste container basis (see Appendix G). Acceptable knowledge combined with radiochemical analysis is also used on a fraction of RH-TRU waste for confirmation purposes. For a detailed description of the Battelle Columbus Laboratories' characterization program see Biedscheid et al. (2002).

This site is now seeking interim storage for its RH-TRU waste at the Hanford Site until shipments to WIPP are authorized. Work on a memorandum of agreement among DOE offices in Ohio, Carlsbad, and Richland is in progress (DOE-BCL, 2002) as part of the Hanford Site cleanup acceleration program. One element of this program is a proposal to transform the Hanford Site into a TRU waste-processing center for small generator sites, including Battelle Columbus Laboratories.

2.3.1 Remote-Handled Transuranic Waste Volume Inventory

Table 2.1 shows that the projected total volume inventory of RH-TRU waste in WIPP is 3,821 cubic meters, of which 2,197 cubic meters are currently stored at DOE sites and 1,625 cubic meters are yet to be generated (see the column "Projected"). For reference, the total volume of RH-TRU waste would correspond to approximately 20,000 RH-TRU waste containers (assuming they are all 55-gallon drums). Further volume-reducing[8] operations (mainly at Oak Ridge National Laboratory) may decrease the waste volume to be emplaced in WIPP to 1,963 cubic meters, as shown in the "Planned Disposal" column. According to these data, RH-TRU waste volume inventory represents between 1 and 2 percent of the total TRU (CH-TRU plus RH-TRU) volume allowed in the WIPP facility (175,564 cubic meters). The volume of RH-TRU waste to be emplaced in WIPP is also well below the regulatory limit of 7,080 cubic meters set by the Land Withdrawal Act.

There have been substantial variations in the estimated volumes of RH-TRU waste in DOE weapons complex, as also observed by the New Mexico Environmental Evaluation Group (EEG, 1994). These variations arise mostly from changes in the RH-TRU waste management or treatment plans. For example, DOE's earlier data for the Savannah River Site, in South Carolina, originally indicated a large RH-TRU waste inventory, reflecting disposal of materials stored in the separations canyons as TRU waste. However, the Savannah River Site now plans to send this material to the high-level waste tanks and process it (i.e., transform it into a glass waste form) with other high-level wastes for eventual disposal in a federal high-level waste repository. DOE also indicated that other potential sources of RH-TRU waste at the Idaho National Engineering and Environmental Laboratory are currently being reviewed (DOE-CBFO, 2002b; Supplement 1; page 2). Other potential changes in the RH-TRU waste inventory are noted in Table 2.1. The uncertainties in the estimated volumes can also be significant for the sites that have yet to generate their RH-TRU waste, such as Hanford.

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[8]Packaging of Idaho National Engineering and Environmental Laboratory RH-TRU waste will actually increase its total volume, as indicated in Table 2.1.

SIDEBAR 2.1 Acceptable Knowledge

The Environmental Protection Agency's (EPA's) interpretation of acceptable knowledge (AK) is associated with historical information about the waste. The following is an excerpt of the guidance manual for waste analysis at facilities that generate, treat, store, and dispose of hazardous wastes (EPA, 1994):

> "Wherever feasible, the preferred method to meet the waste analysis requirements is to conduct sampling and laboratory analysis because it is more accurate and defensible than other options. [...] However, generators and TSDFs [treatment, storage, or disposal facilities] also can meet waste analysis requirements by applying AK. Acceptable knowledge can be used to meet all or part of the waste analysis requirements.

Acceptable knowledge can be broadly defined to include:

- 'Process knowledge,' whereby detailed information on the wastes is obtained from existing published or documented waste analysis data or studies conducted on hazardous wastes generated by processes similar to that which generated the waste. […] Therefore, with many listed wastes the application of AK is appropriate because the physical/chemical makeup of the waste is generally well known and consistent from facility to facility.
- Waste analysis data obtained from facilities which send wastes off site for treatment, storage, or disposal (e.g., generators).
- The facility's records of analysis performed before the effective date of RCRA regulations. While seemingly attractive because of the potential savings associated with using existing information (such as published data), the facility must ensure that this information is current and accurate (pages I-11 to I-12). […]

Generators and treatment, storage, or disposal facilities may use AK alone or in conjunction with sampling and laboratory analysis. […] However, there are situations where it may be appropriate to apply AK, including:

- Hazardous constituents in wastes from specific processes are well documented […].
- Wastes are discarded unused commercial chemical products, reagents or chemicals of known physical, and chemical constituents. […]
- Health and safety risks to personnel would not justify sampling and analysis (e.g., radioactive mixed waste).
- Physical nature of the waste does not lend itself to taking a laboratory sample" (Pages I-13 to I-14).

For remote-handled waste characterization, the Department of Energy adopts a broader definition of AK, based on historical and new information, as explained in Chapter 4.

2.3.2 Remote-Handled Transuranic Waste Radioactivity Inventory

Table 2.2 (see above) shows that the activity of RH-TRU waste currently in storage is approximately 660,000 curies. DOE calculated the total activity of the RH-TRU (stored plus projected) waste inventory to be approximately 1 million curies (DOE-CAO, 1996a; Appendix BIR). According to this estimate, the amount of RH-TRU curies to be emplaced in WIPP is about 20 percent of the total amount of curies from RH-TRU waste allowed by the Land Withdrawal Act (5.1 million curies). For comparison, the total activity to be emplaced in WIPP from CH- and RH-TRU waste is estimated to be 7.4 million curies, of which 6.4 million come from CH-TRU waste (DOE-CAO, 1996c; Appendix BIR).

Table 2.3 shows a comparison between the principal TRU and non-TRU radionuclides in CH and RH-TRU waste to be emplaced in WIPP. In 1995, the total activity of RH-TRU waste represented approximately 14 percent of the total activity of the TRU inventory (from CH-TRU and RH-TRU waste). However, the activity due to TRU radionuclides in RH-TRU waste corresponds only to 0.5 percent of the total TRU activity expected in WIPP. Table 2.3 also shows a comparison of the isotopic characteristics of CH- and RH-TRU waste expected inventories in WIPP. The total curie inventory in RH-TRU waste represents roughly 16 percent of the total curie inventory in CH-TRU waste but the number of TRU curies in the latter is two orders of magnitude higher than in RH-TRU waste. Only TRU radionuclides (i.e., radionuclides with a half-life greater than 20 years) have an impact on the long-term[9] performance of WIPP since non-TRU radio-

TABLE 2.3 Principal TRU and Non-TRU Radionuclides in WIPP Disposal Inventory

Radionuclide (half-life)	CH-TRU Waste (total curies)	RH-TRU Waste (total curies)	Ratio RH/CH
Plutonium-238 (87.7 years)	2,610,000	1,000	0.0004
Plutonium-239 (24,100 years)	785,000	10,000	0.013
Plutonium-240 (6,560 years)	210,000	5,000	0.024
Plutonium-241 (14.4 years)	2,310,000	142,000	0.061
Americium-241 (433 years)	442,000	6,000	0.014
Cesium-137 (30.2 years)	8,000	216,000	27
Barium-137m (2.6 minutes)	8,000	204,000	25.5
Cobalt-60 (5.3 years)	0	10,000	N/A
Strontium-90 (29.1 years)	7,000	209,000	30
Yttrium-90 (64 hours)	7,000	209,000	30
Total TRU curies (> 20 years)	4,048,000	22,000	0.005
Total curies (TRU and non-TRU)	6,390,000	1,012,200	0.158

NOTE: Activities for RH- and CH-TRU waste were estimated in 1995, the year of inventory compilation. Activities decrease very rapidly for RH-TRU waste because of the short half-lives of its radionuclides. Total curies calculated assuming a volume of 7,080 cubic meters for RH-TRU waste and 168,500 cubic meters of CH-TRU waste. TRU radionuclides, by definition, have a half-life greater than 20 years.
SOURCE: Appendix BIR, Table 3-1 in TWBIR Rev 3. Supplemental Disposal Inventory Information, June (DOE, 1996c).

[9]Long-term refers to the 10,000 years of regulatory compliance with radionuclide release limits established by the EPA in Title 40 Code of Federal Regulations Part 191 (see Chapter 3).

nuclides will decay away in approximately 300 years.[10]

Therefore, RH-TRU waste has a negligible impact on the long-term performance of WIPP compared to CH-TRU waste because of the small volume to be emplaced in WIPP. However, RH-TRU waste presents a significant short-term potential for radiation exposure to workers during the waste characterization, handling, and emplacement period because of the short-lived gamma-emitting radionuclides.

2.4 Packaging Status of Remote-Handled Transuranic Waste

A different way of sorting the RH-TRU waste inventory (other than the four categories in Table 2.1) is to consider its packaging status. As previously mentioned, before TRU waste is shipped to WIPP, it must be packaged in a suitable form for transport and underground emplacement.

In the March 2002 draft of DOE's characterization plan, the RH-TRU waste inventory is divided into four categories:

- "Packaged - Waste is packaged in a final form suitable for transport to and disposal at WIPP (i.e., the waste is either canisterized [Los Alamos National Laboratory RH-TRU waste] or in a package that may be transported for canisterization at another facility without repackaging).
- To Be Generated - Future waste generation, includes projected generation due to new activities and planned environmental restoration activities (i.e., retrieval from burial grounds, such as the 618 area at Hanford).
- To Be Repackaged - Waste is currently packaged in some form, but is not suitable for transport and disposal as packaged, possibly due to package size, package condition, or knowledge of contents. It will be repackaged into containers suitable for transport and disposal at WIPP. If a decision has already been made to package the waste for disposal at WIPP [i.e., the Oak Ridge National Laboratory RH-TRU waste debris], then this waste volume has been included in the To Be Packaged estimates.
- To Be Packaged - Waste is either not yet packaged (i.e., tank sludges) or the decision has been made to package the current form differently [i.e., RH-TRU waste debris waste at Oak Ridge National Laboratory]" (DOE-CBFO, 2002b; Supplement 1; page 2).

The current RH-TRU inventory of stored and projected waste is distributed among these four categories as shown in Figure 2.2. For comparison with Table 2.1, "Projected Waste" corresponds to the "To Be Generated" column. All other packaging situations correspond to the "Stored" column. The four packaging categories add up to the total number of cubic meters in Table 2.1. In its characterization plan, DOE also indicated that the inclusion of the Idaho Nuclear Technology and Engineering Center waste will further increase the "To Be Packaged" component by increasing the amount of waste in this category by approximately 900 cubic meters.

The committee's interim report discussed the RH-TRU waste inventory using DOE's initial distinction between "Retrievably Stored Waste" and "Newly Generated Waste"

[10]Short-lived radionuclides in RH-TRU waste are included in the calculation of the regulatory release limits. The scenario that would mostly affect release limits from RH-TRU waste is a drilling intrusion in WIPP occurring less than 300 years after closure. This scenario is taken into account in the performance assessment calculation (see Chapter 3, Section 3.2.1).

(NRC, 2001b). Retrievably stored waste is any waste produced after 1970[11] but prior to implementation of an approved RH-TRU waste characterization plan (as of July 2002, no plan has been approved by EPA and NMED). Newly generated waste is waste produced after the development, approval, and implementation of a waste characterization plan and meets the requirements set forth by the regulatory agencies. In this report the committee adopts DOE's new classification system, as shown in Figure 2.2.

Earlier inventory information recorded that 80 percent of the waste was to be repackaged or generated, as cited in the committee's interim report (NRC, 2001b). Updated information in the March 2002 draft indicated that 98 percent of the waste has to be generated or packaged (see Figure 2.2). However, in several other instances, Documents 1 and 2 mention that the fraction of waste to be generated, packaged, or repackaged corresponds to 95 percent of the RH-TRU waste inventory. In this report, the committee uses a conservative estimate of 95 (rather than 98) percent of waste to be packaged. The committee also uses the word "packaged" for waste that has to be packaged for the first time or repackaged.

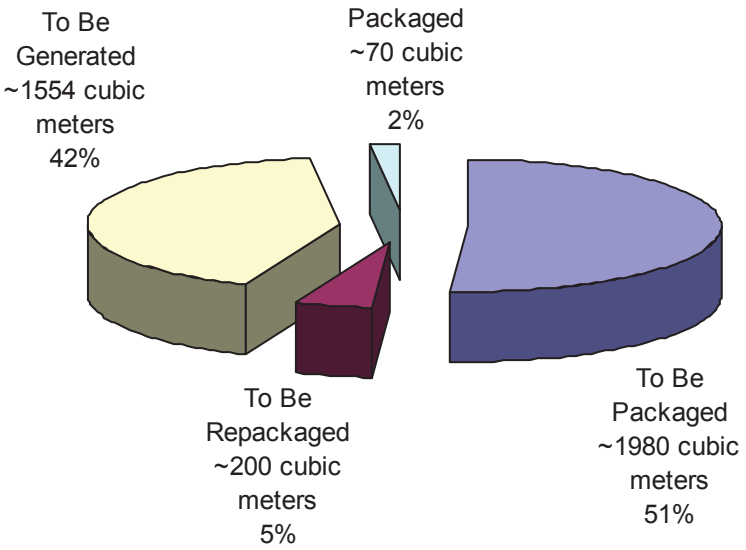

FIGURE 2.2 Packaging status of the RH-TRU inventory. SOURCE: DOE (DOE-CBFO, 2002a).

[11]In 1970, the defense operation division of the U.S. Atomic Energy Commission (predecessor to DOE) first identified TRU waste as a separate category of radioactive waste. That same year the Atomic Energy Commission determined that all TRU waste generated after 1970 must be segregated from low-level waste and placed in retrievable storage pending shipment to, and disposal in, an approved geological repository. Transuranic waste produced in support of the nuclear weapons program from the 1940s through 1970 was disposed of by shallow land burial and other techniques at a number of sites owned and operated by the federal government. This type of waste is referred to as "buried transuranic waste," and most of this waste is considered irretrievable. The characterization plan reviewed by the committee does not address buried TRU waste.

The RH-TRU packaged waste consists of waste from three sites: Hanford, Los Alamos National Laboratory, and Battelle Columbus Laboratories. Waste at Hanford and Battelle is stored in 55-gallon drums. At Los Alamos, waste is stored in 17 canisters, of which 16 were generated during program activities and 1 from hot cell cleanup after the work was completed. Though these canisters are packaged, they are not ready for shipment to WIPP because they have not been characterized in accordance with the current characterization requirements in the EPA Certification and RCRA Permit.[12] Nevertheless, thorough records of process knowledge, visual examination, and prohibited items determination (see Chapter 3, Section 3.3) were kept during the packaging of the 17 canisters stored at Los Alamos.

[12]For instance, when waste was packaged, the records do not demonstrate that the operator was qualified to interpret the videotape, and the headspace gases have not been collected.

3

Regulatory Context for the Disposal of Remote-Handled Transuranic Waste

The Land Withdrawal Act, Public Law 102-579, is the guiding legislation for WIPP (U.S. Congress, 1992). In this Act, Congress established the scope and legal criteria for the facility. The Land Withdrawal Act also assigned EPA regulatory authority over public exposure to radiation from the management and storage of TRU waste at WIPP during the operational period (nominally lasting until 2033) and over radioactivity releases into the environment up to 10,000 years after repository closure. The hazardous non-radioactive component of TRU waste is regulated by the NMED under RCRA (EPA, 1990). The NMED standards for a hazardous waste disposal facility (such as WIPP) seek to minimize releases[1] of non-radiological hazardous constituents during the operational phase and for a nominal 30-year period following repository closure.

The two main regulatory documents for WIPP are the EPA Certification and the RCRA Permit. To continue disposal operations, WIPP must show continued compliance with the EPA Certification and the RCRA Permit. One of the conditions contained in the EPA certification is that EPA and NMED must approve site-specific characterization measures and quality assurance programs before generator sites ship waste to WIPP. Therefore, the EPA Certification and RCRA Permit establish waste characterization requirements for all TRU waste (CH or RH) to be emplaced in WIPP.

The requirements for TRU waste characterization used by EPA and NMED originate from the following standards for owners and operators of hazardous waste treatment, storage, and disposal facilities (40 CFR 264.13):

> "(a)(1) Before an owner treats, stores, or disposes of any hazardous wastes, or nonhazardous wastes if applicable under §264.113(d), he must obtain a detailed chemical and physical analysis of a representative sample of the wastes. At a minimum, the analysis must contain all the information which must be known to treat, store, or dispose of the waste in accordance with this Part and Part 268 of this chapter" (40 CFR 264.13).

EPA indicates in the same document that characterization information can be obtained either by direct measurement or indirectly through AK (see Sidebar 2.1).

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[1]With an exemption from Land Disposal Restriction regulations (40 CFR 268), Congress determined that WIPP waste does not need treatment prior to disposal. As a result, the NMED imposed groundwater and air monitoring requirements to ensure that any detectable releases remain below specific limits that have been established to protect human health and the environment.

The regulatory requirements for the characterization of TRU waste in WIPP originate from the Land Withdrawal Act, the EPA Certification, and the RCRA Permit. These requirements are described below.

3.1 Land Withdrawal Act Requirements for Transuranic Waste in WIPP

The Land Withdrawal Act establishes the five main legal requirements for TRU waste in WIPP, some of which apply specifically to RH-TRU waste. These requirements are the following:

- Nature of waste to be disposed of in WIPP: the WIPP can only receive transuranic waste generated by atomic energy defense activities.
- Total volume of transuranic waste: the WIPP is allowed to contain up to 175,564 cubic meters of transuranic waste.
- Volume of RH-TRU waste: the WIPP is allowed to contain up to 7,080 cubic meters of RH-TRU waste, which represents about 4 percent of the total volume of TRU waste allowed.
- Total activity of RH-TRU waste: RH-TRU waste received at WIPP shall not exceed 23 curies per liter maximum activity level (averaged over the volume of the container). The total curies of RH-TRU waste received at WIPP shall not exceed 5.1 million curies.[2]
- Surface dose rate: no TRU waste received at WIPP may have a surface dose rate exceeding 1,000 rems per hour. No more than 5 percent by volume of RH-TRU waste received at WIPP (354 cubic meters) may have surface dose rates exceeding 100 rems per hour.

Tolerable uncertainties are not specified in the Land Withdrawal Act for the above limits. Laws seldom specify accuracy or precision of limits; it is generally the duty of the implementer to propose tolerable decision errors, such as accuracy or uncertainty, derived from a tradeoff among relevant parameters, such as risk or costs.

3.2 Characterization Requirements in the EPA Certification

In 1998, EPA promulgated the criteria for the certification and recertification of the Waste Isolation Pilot Plant's compliance with the 40 CFR 191, subparts B and C (40 CFR 194). The EPA declared WIPP to be in compliance with its disposal regulations and granted the facility a certification of compliance. The purpose of the EPA characterization requirements is to ensure that WIPP remains in compliance with the EPA disposal regulations and limits set forth in the Land Withdrawal Act. Compliance is ensured if the waste inventory in WIPP stays within the waste envelope limits specified in WIPP's performance assessment. The performance assessment is a tool used to evaluate the safety performance of any nuclear waste facility, as explained below.

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[2]Note that the total activity limits for RH-TRU waste do not distinguish between the activity due to the TRU nuclides and that due to other radionuclides.

3.2.1 WIPP's Performance Assessment

The performance assessment evaluates the ability of a repository to satisfy the release limits (listed in 40 CFR 191, Appendix A) on the release of radionuclides from a repository over a period of 10,000 years. The performance assessment organizes information relevant to long-term repository behavior by assessing the probabilities and consequences of major scenarios by which radionuclides can be released into the environment. Important scenarios include those due to human activities, whether deliberate or unintentional, that might compromise the integrity of the repository. The performance assessment process consists of:

1. compiling features, events, and processes that could affect the disposal system;
2. classifying events and processes to enhance consistency and completeness;
3. screening individual events and processes for likelihood of occurrence and consequences;
4. combining events and processes into specific scenarios;
5. screening scenarios to identify and eliminate those that have little or no effect on the performance assessment;
6. modeling the scenarios;
7. calculating the releases; and
8. comparing the calculated values with the allowable releases.

From the quantitative results of its performance assessment, DOE identified the ten radionuclides most important to the long-term performance of WIPP: americium-241, cesium-137, plutonium-238, plutonium-239, plutonium-240, plutonium-242, strontium-90, uranium-233, uranium-234, and uranium-238. Of these ten, strontium-90, uranium-233, and cesium-137 are important to RH- but not CH-TRU waste streams (due to the gamma and beta emissions).

A sensitivity analysis of the performance assessment also identified the non-radiological waste parameters most important to the performance of the repository (Helton et al., 1998). These parameters are the following:

- Amount of free water: The EPA Certification requirements include a limit on the total amount of water or brine present in the waste. This parameter is important because water is the only means to release radionuclides in the environment and because it controls several other factors, such as corrosion and gas generation.[3] The total limit for free water in WIPP is 1 percent by volume in the entire TRU waste inventory (175,564 cubic meters), which corresponds to 1,756 cubic meters. This limit derives from a transportation requirement forbidding shipment of hazardous waste containing more than 1 percent of free liquids by volume.[4] DOE used this requirement as one of the initial assumptions in the performance assessment calculation, which was part of the compliance certification application. This free water

[3]The main gases potentially generated in WIPP in the presence of brine are carbon dioxide, methane, and hydrogen. These gases are generated by microbial waste degradation inside WIPP. In addition, hydrogen can also be produced by radiolysis or by corrosion of metal containers. An increase in gas pressure inside the repository could affect room closure rates, fracture development, brine inflow, and the possibility of waste entrainment in gas during a drilling event (called spalling).

[4]The committee does not review transportation requirements in this report.

requirement is now integrated as part of the EPA Certification to ensure compliance with release limits.

- Amount of ferrous metals: The EPA Certification requirements include a minimum amount of ferrous metals (20 million kilograms) to ensure a reducing environment inside the WIPP repository. A reducing environment maintains radionuclides in a low oxidation state, which usually corresponds to a minimum solubility. Therefore, waste characterization must ensure that the amount of corrodible metals in the waste is above the minimum.
- Amount of non-ferrous metals: The EPA Certification requirements include a minimum amount (2,000 kilograms) of non-ferrous metals in WIPP. Non-ferrous metals form complexes with organic ligands present in waste (such as EDTA or citric acid[5]). This prevents actinides from binding with these organic ligands and becoming mobile. Therefore, waste characterization must ensure that the amount of non-ferrous metals in the waste is above the minimum.
- Amount of biodegradable cellulosics, plastic, and rubber: The EPA Certification requirements include a maximum amount (20 million kilograms) of cellulosics, plastic, and rubber in the waste to take into account the potential for gas generation from the decomposition of these organic materials. Therefore, waste characterization must ensure that the amount of cellulosics, plastic, and rubber in the waste is below the maximum.

Tolerable uncertainties have not been specified in the compliance certification application for the above limits. In its final certification decision, EPA writes:

> "[T]he EPA confirmed the results of the performance assessment using the same upper and lower limiting values in the performance assessment verification test ("PAVT"). Those upper and lower limiting values apply to contact-handled, remote-handled, and to-be-generated waste from numerous generator sites. Thus, in today's action, EPA certifies that the WIPP will comply with the 40 CFR Part 191 containment requirements to the extent that emplaced waste falls within the waste envelope limits that were shown by the performance assessment, and confirmed by the PAVT, to be compliant with the 40 CFR Part 191 standards" (40 CFR 194).

In summary, the waste characterization requirements appearing in the EPA Certification are aimed to determine:

1. activity and radiological inventory of the waste;
2. surface dose rate;
3. amount of metals (ferrous and non-ferrous);
4. absence of free water; and
5. amount of cellulosics, plastic, and rubber.

Chapter 4 describes the approach DOE proposes to determine these 5 characterization parameters in RH-TRU waste.

[5]EDTA (ethylenediaminetetraacetic acid) and citric acid are common cleaning agents.

3.3 Characterization Requirements in the RCRA Permit

The purpose of the NMED characterization requirements is to ensure that the non-radiological hazardous characteristics of the waste emplaced in WIPP are compatible with the RCRA requirements as codified in Part 20 of the New Mexico Administrative Code. The cornerstone of any RCRA permit is the waste analysis plan, which allows generators and disposal facilities to identify, treat, store, and properly dispose of all hazardous wastes. Waste analysis involves identifying or verifying the chemical and physical characteristics of a waste by performing a detailed chemical and physical analysis of a representative sample of the waste or, in certain cases, by applying AK (EPA, 1994*).*

The characterization plan in the RCRA Permit is aimed at minimizing the possibility of a fire, explosion, or any unplanned sudden or non-sudden release of TRU mixed waste or mixed waste constituents to air, soil, groundwater, or surface water which could threaten human health or the environment (see NMED, 1999a; Module II General Facility Conditions; page II-1).

Currently, the waste characterization requirements in the RCRA Permit are aimed at determining the following information:

1. physical form of waste (homogeneous solids, soil or gravel, debris); and
2. exclusion from waste of the following prohibited items[6]:
   - Liquid waste.
   - Non-radionuclide pyrophorics (addressed by the hazardous waste codes[7]).
   - Hazardous wastes that do not contain TRU waste.
   - Incompatible chemicals (addressed by the hazardous waste codes).
   - Polychlorinated biphenyls greater than or equal to a concentration of 50 ppm.
   - Explosives (addressed by the hazardous waste codes) and compressed gases.
   - Ignitable, corrosive, and reactive wastes (addressed by the hazardous waste codes).
   - Remote-handled transuranic mixed waste.

Prohibited items listed in the RCRA Permit are items that are incompatible (e.g., ignitable, reactive) or inappropriate for the WIPP facility. If combined, incompatible wastes are capable of spontaneous combustion, toxic gas generation, or explosions (EPA, 1994). The selection of waste parameters must include measures to ensure that the waste is appropriate for WIPP's scope and that inappropriate waste is identified and excluded prior to shipment.

The current RCRA Permit excludes RH-TRU mixed waste because:

> "The Applicant [DOE] failed to submit an approvable waste analysis plan describing the procedures for obtaining a detailed chemical and physical analysis of RH [mixed] waste destined for disposal at WIPP. Moreover, there

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[6]Additional prohibited items for WIPP are waste containers that do not have volatile organic compound concentrations reported for the headspace, waste containers that have not undergone radiographic or visual examination, and waste containers that do not have a certified waste stream profile form (see the glossary).

[7]The definition of hazardous waste codes can be found in the glossary, Appendix I.

are substantial questions regarding the applicability of CH waste characterization techniques and the Applicants' capability to characterize RH [mixed] waste" (NMED, 1999b).

To remove the RH-TRU waste prohibition from the RCRA Permit, NMED recommends that DOE build its proposed RH-TRU waste characterization plan upon the requirements in the existing permit and provide justification for any difference between the RH-TRU and the existing CH-TRU characterization plan (Zappe, 2001).

3.4 History of Characterization Requirements at WIPP

When DOE first applied for the EPA certification of WIPP, it proposed the same characterization plan for RH-TRU and CH-TRU waste (DOE-CAO, 1996a). DOE, EPA, and NMED negotiated the characterization requirements for TRU waste during nearly two decades prior to the certification of WIPP. Records of the negotiation process show that DOE proposed to the regulators some waste characterization requirements that lacked a technical, safety, or legal basis (see Sidebar 3.1). These requirements eventually became part of the EPA Certification and RCRA Permit and are now addressed in the CH-TRU waste characterization plan.

Eventually, EPA and NMED declared that DOE did not provide an adequate waste characterization method for RH-TRU waste and prohibited this waste from being shipped to WIPP. Both agencies also stated that DOE did not adequately describe its full RH-TRU waste inventory. DOE is now submitting a new characterization plan for RH-TRU waste to address EPA and NMED characterization requirements. While the regulatory requirements to be addressed are the same for CH- and RH-TRU waste, DOE proposes a different approach to characterize RH-TRU waste than that used for CH-TRU waste, as described in the following chapter.

SIDEBAR 3.1 Findings of the Previous National Research Council's Committee on the Waste Isolation Pilot Plant

A previous National Research Council committee on the Waste Isolation Pilot Plant (WIPP) found that some of the elements in the characterization plan for contact-handled transuranic (CH-TRU) waste are based on terms negotiated in the Resource Conservation and Recovery Act (RCRA) Permit rather than being performance-based characterization requirements (NRC, 2001a; Appendix A1). These requirements concern the sampling and analysis of homogeneous waste, headspace gas sampling and analysis, and visual examination procedures. For instance, the Department of Energy (DOE) proposed to conduct homogeneous waste and headspace gas sampling and analyses on the totality of CH-TRU waste containers to confirm acceptable knowledge (AK) information. Moreover, there appears to be no requirement in the law for the verification of radiography results by visual examination.

These requirements were proposed by DOE during the development of the characterization plan and "have no basis in law, the safe conduct of operations to emplace waste in WIPP, or long-term performance requirements" (NRC, 2001a; page 77). Therefore, the 1998 Committee recommended that DOE "eliminate self-imposed waste characterization requirements" from the CH-TRU waste

characterization plan (NRC, 2001a; page 78). DOE agreed with that committee on the fact that some waste characterization procedures are indeed not prescribed by safety or legal requirements and were introduced to facilitate the WIPP certification process (Kehrman, 2002; DOE-CAO, 1999a). A DOE review of the CH-TRU waste characterization procedures revealed that DOE developed self-imposed waste restrictions in the waste acceptance criteria and in the requirements for waste generating sites presented in the quality assurance program plan. The definitions of waste acceptance criteria (DOE-CAO, 1996b) and quality assurance program plan (DOE-CAO, 1998) can be found in the glossary, Appendix I.

4

Department of Energy's Proposed Characterization Plan

This chapter describes DOE's proposed characterization plan for RH-TRU waste. Because the plan must address EPA and NMED regulatory requirements, the characterization plan consists of two documents: a notification of proposed change to the EPA Certification (Document 1) and a Request for RCRA permit modification (Document 2). On June 28, 2002 DOE submitted Documents 1 and 2 to the respective agencies. This chapter addresses the March 2002 draft characterization plan and the main differences with the July 2001 draft.

It is the committee's understanding that DOE will submit to EPA and NMED, along with Documents 1 and 2, a sample of completed characterization documents for three RH-TRU generator sites (Energy Technology Engineering Center, Battelle Columbus Laboratories, and Oak Ridge National Laboratory). Once Documents 1 and 2 are submitted to the regulatory agencies, and characterization requirements for RH-TRU waste are finalized, DOE will produce one document combining all regulatory requirements to guide generator sites in the development of their characterization programs. Each site-specific RH-TRU waste characterization plan will undergo audits by DOE, EPA, and NMED before the beginning of shipments to WIPP. The new characterization requirements will be combined in a revised version of the waste acceptance criteria incorporating changes to allow RH-TRU waste in WIPP.

4.1 DOE's Considerations in Composing the Characterization Plan

According to the information gathered, several factors played a role in DOE's approach to the characterization of RH-TRU waste, such as: DOE's mission to safely dispose of radioactive waste; WIPP's regulations; federal and state laws and agreements; and DOE's internal drivers to improve the National Transuranic Waste Management Program. The list of considerations, expanded below, is not in hierarchical order and may not be complete.

One of DOE's missions is to safely dispose of radioactive waste, including RH-TRU waste, generated during defense-related activities (DOE-EM, 2002a). To this end, DOE is seeking authorization to dispose of RH-TRU waste stored at 13 sites across the country in WIPP. The proposed characterization plan must meet the requirements in the EPA Certification and RCRA Permit (the latter issued by NMED). Besides strict regulatory requirements, DOE is also taking into account non-technical considerations to maintain an effective working relationship with the regulatory agencies, in particular NMED.

DOE and its RH-TRU waste generator sites must also meet sites' cleanup milestones, set forth by DOE's compliance agreements with EPA and generator states' regulators, such as Federal Facility Compliance Agreements and Tri-Party Agreements.

DOE is also required to comply with Title 10 of the Code of Federal Regulations Part 835, which instructs DOE to apply the ALARA principle to protect workers' health and safety in every DOE facility (10 CFR 835). ALARA (as low as is reasonably achievable), as defined by the Nuclear Regulatory Commission, requires that a reasonable effort be made to keep workers radiation exposures as far below the regulatory dose limit[1] as is practical. Moreover, DOE must ensure that all waste is managed in a manner that is protective of worker and public health and safety, and the environment, as specified in DOE's Order 435.1.

Timeliness and cost of cleanup are two internal DOE drivers. A "Top-to-Bottom" review report on DOE's Office of Environmental Management, which manages the cleanup of all defense-related radioactive waste, recommended adopting an accelerated risk-based cleanup strategy across the DOE complex. The following is an excerpt from this report:

> "National security will be improved through the consolidation of all special nuclear materials in modern safeguarded facilities and through accelerated disposal of transuranic (TRU) waste currently stored at sites around the country (page IV-1) […] [A] limited amount of TRU waste is highly radioactive and must be handled remotely. Efforts to dispose of these materials in WIPP will be accelerated (page IV-2). […] [T]here are thousands of TRU waste drums stored in above-ground EM facilities that require high-priority funding for safety and security. While most of these storage facilities are inexpensive to maintain, there are dozens of them across the complex, so the cumulative annual fixed cost is significant. Certification and disposal of TRU waste are major cost drivers for the EM program. Efforts to expedite shipments to the Waste Isolation Pilot Plant (WIPP) and streamline regulatory procedures would result in obvious cost savings" (page V-13) (DOE-EM, 2002b).

In its WIPP Disposal Phase Final Environmental Impact Statement, DOE estimated the life-cycle cost of the treatment facilities for RH-TRU waste to be $2.94 billion. This corresponds to 15 percent of the total cost of the $19 billion WIPP Project (DOE-CAO, 1997; Volume 5; pages 5-10). DOE also stated in the same reference that the life-cycle cost of the treatment facilities for all the CH- and RH-TRU waste was $11.8 Billion, or 62 percent of the total cost of the WIPP Project. Although these estimates may be outdated, they still demonstrate the magnitude of the characterization costs for TRU waste, in particular for RH-TRU waste.

4.2 DOE's Goal: A Performance-Based Characterization Plan

Given the above considerations, DOE's stated goal is to adopt a "performance-based" approach to characterize RH-TRU waste. Although Documents 1 and 2 do not provide a definition of a "performance-based characterization plan," the committee found the following definition in EPA's Compliance Application Review Document No. 24:

> "DOE must provide waste inventory information for use in the performance assessment, including the radionuclide content of waste and the physical and

[1]The Nuclear Regulatory Commission's limits for radiation doses to workers are established in Title 10 CFR Part 20 (10 CFR 20.1003).

chemical components that may affect disposal system performance" (EPA, 1998; pages 21-1).

EPA defines a "waste characteristic" as "a property of the waste that has an impact on the containment of waste in the disposal system" (40 CFR 194.2). The committee interprets "performance-based characterization plan" as a plan requiring only that information needed to ensure repository integrity, protection of the environment, and health and safety of the public and workers while keeping in consideration tradeoffs between greater characterization accuracy and worker risks.

While the characterization requirements to be addressed are the same, this proposed performance-based approach is quite different from the approach used for CH-TRU waste characterization, as explained later in this chapter. The rationale for this different approach relies on the differences in volume and isotopic inventory of RH-TRU waste compared to CH-TRU waste (see Chapter 2).

To evaluate the impact of RH-TRU waste on the performance of WIPP, the Sandia National Laboratories performed two performance assessment calculations. In these calculations, the effects of the inventories of CH- and RH-TRU waste are decoupled and several bounding scenarios for RH-TRU waste parameters are used. Documents 1 and 2 include two impact assessments: one for the impact of the radiological parameters of RH-TRU waste and one for the non-radiological parameters listed in the EPA Certification.

The Sandia impact analyses showed that radioisotope, free liquids, cellulosics, plastics, rubber, and ferrous metal content in the RH-TRU waste inventory have a negligible impact on repository performance. This is due to the smaller volume and the different radiological composition of the RH-TRU waste inventory compared to the CH-TRU waste inventory projected in WIPP. These performance assessment calculations use the same mathematical models and input parameters used in the compliance certification application (see Chapter 3, Section 3.2.1).

The result of the calculations shows that the characterization of waste material parameter weights (e.g., ferrous metals, cellulosics, plastic, and rubber) and the amount of free liquid for RH-TRU waste can be assumed to be as high as the bounding values and still result in WIPP compliance. The bounding values for RH-TRU waste parameters are the same as those used for EPA Certification. The Sandia impact analyses also show that if all the total (both TRU and non-TRU) activity in RH-TRU waste were due to plutonium-239, there would be only a negligible performance impact on WIPP. Therefore, from a performance point of view, waste characterization activities to quantify the above waste parameters could be unnecessary.

Even though the impact of RH-TRU waste parameters on the performance of WIPP is negligible, DOE is proposing to collect all the waste information requested in the EPA Certification and RCRA Permit using AK as the primary method of compliance. When AK is not complete or not available, additional compliance methods can be applied to a representative portion of the waste. In contrast to the approach used for CH-TRU waste, this plan does not recommend making measurements for the sole purpose of confirming AK or other measurements unless such confirmation is needed to qualify the AK characterization information (DOE-CBFO, 2002a; page 22).

4.2.1. Acceptable Knowledge

The heart of DOE's proposed performance-based characterization plan is the use of AK to collect the necessary information about a waste stream. DOE plans to use two types of AK: one based on historical information of existing waste, which the committee

terms "historical AK" and which is the most widespread interpretation of AK (see Sidebar 2.1), and one based on new information collected during waste generation or packaging.

Historical AK may include administrative, procurement, and quality control documentation associated with the generating process, or past sampling and analytical data. Elements of process knowledge may include information about the process used to generate the waste, material inputs to the process, and the time period during which the waste was generated. Acceptable knowledge is applied on a waste stream basis and may be supplemented with sampling and measurement programs or container-by-container measurements.

DOE also considers AK newly generated characterization information, as described in Document 1:

> "[F]or the RH-TRU waste characterization program, 95 [percent] of the waste will be packaged or repackaged during its preparation for shipment to the WIPP. Information collected under these packaging and repackaging programs is also considered to be AK information. This allows the same AK procedure and guidance to be used in assembling historic AK information or compiling new AK information" (DOE-CBFO, 2002a; Attachment B; page 23).

As shown above, DOE's rationale for proposing AK as the major compliance tool is based on the analysis of the RH-TRU waste inventory. According to the information gathered, 95 percent of RH-TRU waste will either be generated or packaged. This waste will be visually examined during repackaging operations and undergo physical and chemical characterization (for instance, through radiography or radiochemistry) during waste generation and packaging.

Based upon EPA's requirements set forth in 40 CFR 194.22(b), existing information collected before an approved quality assurance program is in place must be qualified for use as AK. Title 40 CFR 194.22(b) lists four methods that may be used individually or in combination to qualify such data: 1) peer review, 2) use of corroborative evidence, 3) confirmation by measurements, or 4) qualification of previous quality assurance programs. DOE is proposing to limit confirmatory measurements only to those cases where historical records are incomplete. DOE proposes not to confirm the newly generated information for 95 percent of the waste since this information will be collected under a certified quality assurance characterization program. The specific needs for waste analysis are described in DOE's proposed characterization plan as data quality objectives and quality assurance objectives.

4.3 Data Quality Objectives and Quality Assurance Objectives

Data quality objectives are proposed by the implementer, in this case DOE, to define what information is necessary to characterize waste. They are qualitative and quantitative statements that clarify program's objectives, define appropriate types of data, and specify tolerable decision error rates that will be used as the basis for establishing the quality and quantity of data needed to support decisions.

The EPA document SW-846 "Test Methods for Evaluating Solid Waste Physical/Chemical Methods" defines data quality objectives as:

> "Data quality objectives … for the data collection activity describe the overall level of uncertainty that a decision-maker is willing to accept in results derived from environmental data" (EPA, 2002; pages 1-2).

Quality assurance objectives establish minimum requirements for the measurement and representation of data. Quality assurance objectives are designed to provide information that will satisfy the data quality objectives. They correspond to EPA's "measurement quality objectives." The elements of the quality assurance objectives are:

- Data accuracy: the degree to which data agree with an accepted reference or true value.
- Data precision: a measure of the mutual agreement between comparable data gathered or developed under similar conditions expressed in terms of a standard deviation.
- Data representativeness: the degree to which data accurately and precisely represent a characteristic of a population, a parameter, variations at a sampling point, or environmental conditions.
- Data completeness: a measure of the amount of valid data obtained compared to the amount that was expected.
- Data comparability: a measure of the confidence with which one data set can be compared to another [40 CFR 194.22(c)].

Documents 1 and 2 describe the data quality objectives and quality assurance objectives to meet the requirements in WIPP's EPA Certification and RCRA Permit, respectively.

4.4 DOE's Proposed Characterization Plan to Address EPA Requirements

The characterization requirements in the EPA Certification, addressing also the requirements in the Land Withdrawal Act, are described in Chapter 3. The data quality objectives, characterization, and implementation methods to address these requirements are provided in Document 1 and summarized in Table 4.1. The characterization methods to meet EPA requirements are the following:

- Acceptable Knowledge: the type of information used to define waste streams is described in Sidebar 2.1. For the RH-TRU waste characterization program, 95 percent of the waste will be packaged or repackaged during its preparation for shipment to the WIPP. Information collected under these packaging and repackaging programs is considered to be AK information along with historical data.
- Dose-to-Curie Conversion: the curie content of waste is based on a dose rate measurement taken with a calibrated field instrument. The dose rate measurement is associated with documented isotopic distributions in the waste through the use of empirically developed conversion factors. Dose-to-curie estimates may also be based on the measurement of an indicator activity (e.g., cesium-137) and correlation of other radionuclides by isotopic conversion factors. This method requires good knowledge of the isotopic distribution in the waste.
- Visual Examination: this method involves the removal of items from the container and their inspection and identification. The examination will be recorded on a signed data form accompanied by visual evidence such as an audio or video tape. Visual examination only provides a visual image of the content of waste containers. It does not provide any information on the isotopic composition of waste.
- Radiography: this method involves the use of penetrating radiation to investigate the contents of containers. The examination will be recorded on a signed data form

accompanied by visual evidence such as an audio or video tape or other media. Radiography only provides an image of the content of waste containers. It does not provide any information on the isotopic composition of waste.

- Characterization at the Time of Packaging: this method involves visual examination and other characterization methods applied as waste is packaged for shipment to WIPP. DOE distinguishes this method from visual examination for the following reasons:

  1. it applies to 100 percent of the waste in the waste stream;
  2. it generally focuses on the development or collection of AK information as opposed to the confirmation of such information;
  3. it applies to waste that is not in its final shipping container; and
  4. it may require the use of other characterization methods (i.e., AK, visual examination, or radiography) to determine the contents of smaller containers that cannot be readily characterized without testing.[2]

- Direct Assay: this method involves using radioassay systems that are qualified for CH-TRU waste characterization.
- Counting containers: this method involves automatically counting containers to maintain the record of the amount of metals introduced in the repository.

4.5 DOE's Proposed Characterization Plan to Address NMED Requirements

The characterization requirements in the current RCRA Permit are described in Chapter 3. The proposed data quality objectives and characterization methods to address these characterization requirements are presented in Document 2 and summarized in Table 4.2.

Characterization methods and the relative quality assurance objectives of precision, accuracy, representativeness, completeness, and comparability are discussed in Attachment R of Document 2. The same characterization methods have been discussed for Document 1 (see above). Radiography, along with other non-destructive examination and non-destructive assay methods, is also briefly described in Appendix G.

[2]The committee observes that "characterization at the time of packaging" may cause a semantic confusion with AK, which is usually associated with historical information. Characterization at the time of packaging generates new information through visual examination, radiography, or other characterization methods; it may also include historical data on a particular waste stream.

TABLE 4.1 DOE's Data Quality Objectives, Characterization and Implementation Methods to Address EPA Requirements

No.	Data Quality Objectives	Characterization Method	Implementation Methods
1	Account for TRU activity. Rationale: This requirement is related to the LWA's definition of TRU waste and to 40 CFR 191. The purpose for this data quality objective is twofold: 1) ensure that waste is TRU (TRU activity equal to or greater than 100 nanocuries per gram of waste); and 2) determine the plutonium-239 content to satisfy the release limits set forth in 40 CFR 191.	1. AK method 2. Dose to curie 3. Direct assay 4. Characterization at the time of packaging[1]	Use AK to determine the relationship of TRU activity to total activity (see no. 6 below) for each waste stream (confirmation unnecessary). AK must include TRU information (sufficient to demonstrate the waste stream concentration exceeds 100 nanocuries per gram), or the waste stream value must be established by sampling and measurement, or the TRU activity must be measured for each container.
2	Ensure that waste is of defense origin. Rationale: The LWA allows only disposal of defense-related transuranic waste in WIPP.	1. AK method	Use AK to determine whether waste was generated in a defense-related activity.
3	Ensure waste is RH (surface dose equal to or greater than 200 mrem per hour). Rationale: operational requirement to determine handling and characterization requirements.	1. Standard industry survey methods 2. Characterization at the time of packaging	Use standard industry survey methods to measure and report surface dose rate. Survey instrument calibrations must be traceable by the National Institute of Standards and Technology.
4	Account for total activity. Rationale: this requirement comes from the LWA limit of 5.1 million curie of total activity for RH-TRU waste.	1. AK method 2. Dose to curie 3. Direct assay 4. Characterization at the time of packaging	Use AK to determine total activity of the waste stream (confirmation unnecessary), or establish a waste stream value by sampling and measurement, or measure the total activity of each container.
5	Limit canister activity to less than 23 curies per liter. Rationale: this requirement comes from the LWA limit on canister activity.	1. AK method 2. Dose to curie 3. Direct assay 4. Characterization at the time of packaging	Use AK to evaluate each waste stream and show that this limit cannot feasibly be approached for that particular waste stream. For the rare exception where AK indicates that 23 curies per liter is hypothetically feasible, measurements of Total Activity should be obtained on few representative containers to establish a waste stream value, or a site may choose to measure the total activity of each container.

6	Limit surface dose rate of each container to less than 1,000 rem per hour. Rationale: This is a LWA requirement.	1. Standard industry survey methods 2. Characterization at the time of packaging	Survey instrument calibrations must be traceable by the National Institute of Standards and Technology.
7	Limit WIPP inventory to 5 percent by volume of canisters with a dose rate greater than 100 rem per hour. Rationale: This is a LWA requirement.	1. Standard industry survey methods 2. Characterization at the time of packaging	Use standard industry survey methods to measure and report Surface Dose Rate. Survey instrument calibrations should be traceable by the National Institute of Standards and Technology.
8	Account for ferrous and non-ferrous metals. Rationale: this is a requirement introduced in the EPA's Certification.	1.Count containers	WWIS [WIPP Waste Information System] electronically counts waste containers. Confirmation unnecessary.
9	Account for cellulosics, plastics, rubber. Rationale: this is a requirement introduced in the EPA Certification	1. AK method 2. Visual examination 3. Characterization at the time of packaging	Use AK to determine Summary Category Group (SCG) of each waste stream. Use generator/storage site SCG designation from site documents. WWIS electronically calculates and assigns for each emplaced container (0 for homogenous solids and soils/gravel, and 50 percent of container weight for debris). Confirmation unnecessary if AK information is complete.
10	Account for free water (up to 1 percent of free water by volume). Rationale: WIPP was certified on the basis of a performance calculation using 1 percent of water by volume in the waste. This limit originates from a transportation requirement.	1. AK method 2. NDE such as Radiography 3. Visual examination 4. Characterization at the time of packaging	If AK documents the use of liquid management procedures (e.g., removal or absorption), or a process that precludes liquids (e.g., material input records or thermal treatment), then assign 0 percent of liquid by volume for each waste stream. Otherwise assign 1 percent volume to the entire waste stream. Confirmation unnecessary. When AK is lacking, use a non- destructive examination, visual examination, or characterization at the time of packaging on a sampling basis to show that a waste stream contains less than one percent residual liquids.

NOTE: AK=acceptable knowledge; LWA=Land Withdrawal Act, NDE=non-destructive examination. Information in this table is presented in Document 1 and supplemented with additional information provided to the committee.

[1]Characterization at the time of packaging is defined in Document 1 as a characterization method. However, this encompasses several activities, such as visual examination, chemical assays, as explained in the description of characterization methods.

SOURCE: DOE (DOE-CBFO, 2002a; 2002c).

TABLE 4.2 DOE's Data Quality Objectives, Characterization and Implementation Methods to Address NMED Requirements

No.	Data Quality Objectives	Characterization Method	Implementation Method
1	Assign hazardous waste codes. Rationale: RCRA requirement as it applies to WIPP.	1. AK method 2. Tests on waste samples	Use AK to delineate waste streams, assign hazardous waste codes and summary category groups (SCG) to waste streams, and assign individual containers to waste streams. Use generator/storage site records of container assignments to the waste stream. Confirmation unnecessary. If AK is insufficient, perform tests on a representative (10 percent) sample of the waste.
2	Identify Physical Form. Rationale: RCRA requirement as it applies to WIPP.	1. AK method 2. Visual examination 3. NDE such as radiography	Summary category groups define the physical form of the waste as solidified solids (SCG=S3000), soil/gravel (SCG=S4000), or debris (SCG=S5000). Confirmation is unnecessary. If AK is insufficient, perform tests such as VE and NDE on a representative (10 percent) sample of the waste.
3	Limit residual liquids to less than 1 percent volume of RH canister (or drum for 160B). Rationale: residual liquids limit arises from transportation and operational safety considerations. Note that the rationale is different from that in Table 4.1 item 10. Residual liquids are a prohibited item in the current RCRA Permit.	1. AK method 2. Visual examination 3. NDE such as radiography	Use AK to demonstrate that the waste stream does not contain residual liquid, or that individual containers contain less than 1 percent by volume of residual liquid (confirmation unnecessary), or sample and NDE/VE to determine the waste stream does not contain residual liquid, or NDE/VE each container in a waste stream. AK must document the use of liquid management procedures (e.g., removal or absorption), or a process that precludes liquids (e.g., material input records or thermal treatment), or there must be a record for each container indicating less than 1 percent by volume of residual liquid, or NDE/VE of a few representative containers (10 percent[1]) from the waste stream can show the absence of residual liquids, or every container must undergo NDE/VE.
4	Limit residual polychlorinated biphenyls to less than 50 ppm. Rationale: polychlorinated biphenyls are a prohibited item in RCRA Permit if present in a concentration greater than or equal to 50 ppm.	1. AK method 2. Visual examination 3. NDE such as radiography	Use AK to determine the absence of possible sources of polychlorinated biphenyls such as transformer oil. If AK is insufficient, perform tests such as VE and NDE on a representative (10 percent) sample of the waste. VE and NDE are used, for instance, to look for parts of or entire transformers.
5	Exclude additional prohibited items	Use EPA hazardous waste	Additional prohibited items listed in the RCRA Permit (see

	(such as pyrophorics, incompatible chemicals, explosives, compressed gases, ignitable, corrosive, and/or reactive wastes). Rationale: these items are prohibited in the current RCRA Permit.	codes	Chapter 3) are addressed by the EPA hazardous waste codes assigned to an RH-TRU waste stream. RH-TRU waste containing any one of these items would have EPA hazardous waste codes that would disqualify it from management, storage, and disposal under the WIPP Part A requirements.
6	Identify and quantify volatile organic compounds. Rationale: any waste container that does not have volatile organic compounds concentrations reported for the headspace is currently a prohibited item in the RCRA Permit.	No volatile organic compounds measurement proposed on RH-TRU waste.	Use bounding analysis for RH-TRU waste contribution to reduce current RCRA Permit Room Limits.

NOTE: AK=acceptable knowledge; NDE/VE=non-destructive and visual examination (see Appendix G); VE=visual examination. Information in this table is presented in Document 2 and supplemented with additional information provided to the committee.

[1]See committee's Finding 2A, Example #6 in Chapter 5. Other elements of this table are also discussed in Chapter 5.

SOURCE: DOE (DOE-CBFO, 2002b; 2002c).

4.6 Major Differences Between the July 2001 and the March 2002 Drafts

As noted in Chapter 1, the committee reviewed two drafts of the proposed characterization plan. This section outlines the five major differences between the two drafts, as follows:

- *Change in the approach to the determination of prohibited items in Document 2.* The determination of the absence of all the prohibited items listed in the RCRA Permit was part of the requirements in the July 2001 draft of Document 2 (DOE-CBFO, 2001b; Item 2; pages 2-27). In the March 2002 draft, the only prohibited items explicitly listed as data quality objectives are residual liquids (if more than 1 percent by volume of waste) and polychlorinated biphenyls (if equal to or greater than 50 ppm). Remaining incompatible prohibited items (ignitable, corrosive, reactive, pyrophoric and incompatible waste, explosives, and compressed gases) will be addressed by excluding from shipment hazardous waste with codes corresponding to ignitable (D001), corrosive (D002), and reactive waste (D003). Pyrophoric materials, explosives and compressed gases fall under the definition of reactive waste (D003). Other waste prohibited in WIPP, such as explosives and compressed gases, can be excluded through hazardous waste code screening because any material whose code does not appear in the list of hazardous waste codes allowed in WIPP cannot be shipped. This drives the determination of the remaining prohibited items from a container-by-container basis to a waste stream level, where hazardous waste code assignment decisions are typically made. The hazardous waste code(s) determination will be accomplished using AK. According to DOE, the 1 percent free liquid criterion was retained as a RCRA operational compliance consideration rather than for performance reasons (see Appendix D).
- *Definition of a representative sample of containers to perform additional tests when AK is insufficient.* The March 2002 draft defines for the first time a representative sample as “at least 10 percent of the samples,” selected by the generator site (DOE-CBFO, 2002a; Attachment B; page 26). The committee discusses the issue of 10 percent representative sample size in Chapter 5, Finding 2A, Example #6.
- *Change of quality assurance objective to determine the total activity of waste by direct assay.* The July 2001 draft of Document 1 read:

> “Track the RH-TRU waste total activity inventory by the quantification of total activity for a unit (waste stream or individual container) within a factor of five of the true value with a confidence level of 95 percent” (DOE-CBFO, 2001a; Attachment A; page 10).

In the March 2002 draft of Document 1, this quality assurance objective was replaced by the quality assurance objective used for CH-TRU waste (DOE-CBFO, 1999b, Appendix A). Moreover, each site will demonstrate the ability of its direct assay measurement system to meet the criteria but will not be subject to the CH-TRU waste performance demonstration program.

- *Distinction between visual examination and characterization at the time of packaging.* Most of the RH-TRU waste will either be generated or repackaged. DOE makes a distinction between the characterization at the time of packaging and visual examination (DOE-CBFO, 2002a; Attachment B; pages 26 and 29). The rationale for the distinction is given above (see also the definition of the method “characterization at the time of packaging” in Section 4.4).

- *More detailed description of characterization requirements and RH-TRU waste inventory in both documents.* The March 2002 draft reports data quality objectives and quality assurance objectives for both EPA and RCRA Permit requirements. The documents also present additional information about generator sites and RH-TRU waste inventories.

While CH- and RH-TRU waste share the same characterization requirements described in WIPP's RCRA Permit and EPA Certification, DOE's approach to meet these requirements for RH-TRU waste is quite different from the way the are met for CH-TRU waste, as explained below.

4.7 Comparison Between the CH- and RH-TRU Waste Characterization Plans

The CH-TRU waste characterization plan approved by EPA and NMED is described in Appendix F. Briefly, the characterization plan for CH-TRU waste is based on a 100 percent confirmation of AK information collected on each waste stream. Confirmation is accomplished by radioassay, headspace gas sampling, radiography, or visual examination. For homogeneous wastes,[3] this includes taking core samples of a fraction of waste containers prior to their shipment to WIPP. For debris wastes, a 100 percent confirmation program (with headspace gas and radiography determinations for RCRA compliance, and non-destructive assay and radiography determinations for EPA's compliance) was negotiated between DOE and NMED. Rather than proposing the same approach as for CH-TRU waste, DOE proposes a "performance-based" approach to characterize RH-TRU waste because of the high radiation fields and the negligible impact of this waste on the performance of the repository.

The most significant difference between the CH- and the proposed RH-TRU waste characterization plans is that the latter does not require confirmatory testing, sampling, or analysis on 100 percent of containers and allows radiography and visual examination only on a representative selection of containers. DOE proposes to use AK whenever possible to accumulate the information on RH-TRU waste and to perform confirmation measurements only when the information collected on the waste stream is not qualified as AK. The rationale provided by DOE in Document 2 relies on the 95 percent of RH-TRU waste volume that is to be generated or repackaged. Instead of confirming AK, generator sites must provide assurances that the waste is adequately characterized at the time of packaging.

On the basis of the Sandia impact analyses, DOE determined that the proposed RH-TRU characterization plan does not require the determination of material parameter category weights and headspace gas analysis, whereas they are required in the CH-TRU waste characterization plan. Instead, DOE proposes to use bounding values for these parameters for RH-TRU waste. Concerning the WIPP's limit on volatile organic compound emissions, the characterization plan for CH-TRU waste requires tracking individual waste container headspace gas concentrations, which are determined by headspace gas sampling and analysis of CH-TRU waste containers.

There is no characterization objective for a direct measurement of the headspace gases in the proposed RH-TRU waste characterization plan because canisters will be located in the walls of the disposal rooms behind shield plugs. Calculations have shown

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[3]Homogeneous waste is one of the "Summary Category Groups" that indicate the final form of the waste. Homogeneous waste is waste consisting of one main constituent (for instance, sludge) as opposed to the other two category groups: soils and gravel, and debris waste.

that it is possible to account for volatile organic compounds emission rates from RH-TRU waste indirectly.[4] This is accomplished by conservatively incorporating the maximum potential volatile organic compounds contribution from RH-TRU waste in the maximum allowable volatile organic compounds emission limits established by the RCRA Permit (Spangler et al., 2002).

[4]To the best of committee's knowledge, experiments on volatile organic compound emissions from RH-TRU waste have not been conducted.

5

Assessment of the Proposed Characterization Plan

This chapter provides the committee's assessment of DOE's proposed plan for the characterization of RH-TRU waste. On June 28, 2002 DOE submitted the characterization plan to EPA and NMED. The committee did not review the plan as submitted; therefore, findings and recommendations in this chapter apply only to the March 2002 draft.[1]

According to the statement of task, findings and recommendations are organized as follows:

1. context of RH-TRU waste characterization;
2. characterization plan's technical soundness;
3. protection of worker safety and health; and
4. compliance with regulatory requirements.

This assessment is based on technical considerations and on the criteria listed in the statement of task (Sidebar P.1).

5.1 Context of Remote-Handled Transuranic Waste Characterization

Below are some general findings about the DOE's RH-TRU waste inventories. According to the information gathered, the RH-TRU waste volume estimated for shipment to WIPP will be about 3,800 cubic meters or 2 percent of the total TRU waste volume allowed in the repository. Even if the information presented in DOE inventories were not accurate, the RH-TRU waste emplaced in WIPP cannot exceed the limits for RH-TRU waste established in the Land Withdrawal Act: 7,080 cubic meters (about 4 percent of the total allowed TRU volume) and 5.1 million curies.

While RH-TRU waste volume represents a small fraction of the allowed TRU waste in WIPP, it accounts for 14 percent of the total curie activity in DOE's TRU inventory. However, the number of TRU curies in the RH-TRU waste inventory is 2 orders of magnitude lower than that in the CH-TRU waste inventory expected in WIPP (see Table 2.3 in Chapter 2). Also, most of the total (CH plus RH) long-term (i.e., TRU) activity expected in WIPP comes from CH-TRU waste, with only a 0.5 percent contribution from RH-TRU waste.

According to the performance assessment calculations by Sandia National Laboratories, the inventory of RH-TRU waste expected in WIPP will have a negligible

[1]The committee also reviewed a previous draft (July 2001), which was the object of its interim report (see excerpt in Appendix C).

impact on the repository's compliance with EPA radiological regulatory standards, compared to CH-TRU waste.

The committee acknowledges that there are uncertainties in DOE's volume and radioactivity inventories of RH-TRU waste. Also, the committee did not assess the validity of the Sandia impact analyses. However, the committee notes that these performance assessment calculations were performed using a peer-reviewed and EPA-approved performance assessment tool, which was the basis for WIPP certification. The committee recognizes that there may be uncertainties associated with the results of these impact analyses and that there may be scenarios that require a new set of performance assessment calculations.[2] In response to the committee's question on uncertainties, Sandia National Laboratories reported that:

> "Uncertainties in Performance Assessment are dominated by those associated with geologic processes, chemical interactions of the waste, and possible human activities in the future. For example, the intrinsic permeability of the proximal host rock can vary over seven orders of magnitude; uncertainties with respect to microbial degradation of organic materials affect several key intermediate variables, such as long-term repository pressure and saturation; assumptions regarding human activities introduce the most notable impacts on repository performance. With these uncertainties in mind, it can be stated that any additional uncertainty associated with waste components within the currently estimated RH-TRU inventory are not significant to long-term repository performance" (Knowles, 2002).

These considerations, as well as the findings and recommendations in this section, set the context for RH-TRU waste characterization. This context is different than that of CH-TRU waste characterization because of the differences in volumes and in isotopic composition, as explained in Chapter 2.

Finding 1A: According to DOE inventories, 95 percent of the RH-TRU waste to be disposed of in WIPP has yet to be generated or needs to be processed, packaged, or repackaged. This waste will be characterized (through visual examination and physical and chemical analyses) at the time of packaging. **Recommendation: DOE should emphasize the argument that the characterization information collected for most of RH-TRU waste does not need confirmatory measurements because the repackaging or generation of waste will be carried out under a certified quality assurance program.**

Rationale: According to the information provided by DOE, over 95 percent of the RH-TRU waste inventory (to be generated, to be packaged or repackaged waste in Figure 2.2) will be characterized using visual examination[3] and physical and chemical methods. This leaves a small fraction of RH-TRU waste with more limited historical, analytical, radioassay, and visual examination information or which was not

[2]An unexpected brine saturation of the repository in less than 300 years, a change in the scope of the WIPP facility, or a change in the configuration of underground disposal are examples of scenarios for which a new set of performance assessment calculations for both CH- and RH-TRU waste would be warranted.

[3]The committee notes that visual examination only provides an image of the content of waste containers. It does not provide any information on the isotopic composition of waste.

characterized under a certified quality assurance program; in this case, AK may require confirmation.

Therefore, for over 95 percent of RH-TRU waste, confirmatory measurements may not be necessary as long as this waste is generated or repackaged using a certified quality assurance program plan. If the volume of RH-TRU waste represents between 2 and 4 percent of the total inventory of TRU waste (176,000 cubic meters), and the information collected for over 95 percent of RH-TRU waste does not need confirmation, then only between 0.1 and 0.2 percent of the total TRU inventory needs confirmatory activities for AK. This is an important observation and it could have a substantial impact on characterization programs proposed for RH-TRU waste.

Finding 1B: For 95 percent of the RH-TRU waste inventory, AK refers to newly generated information acquired during waste generation and packaging. **Recommendation: DOE should utilize a different term than "AK" for this newly generated information.**

Rationale: This newly generated information does not include only historical information on the waste. It can include, for instance, analytical data, radioassay data, and visual examination records obtained during waste generation or repackaging. DOE considers this newly generated information, which may not require confirmation, as AK. The committee believes that this is a potentially confusing terminology because AK is usually associated with historical information, which requires some confirmation (see also Sidebar 2.1).

The committee acknowledges that visual examination during RH-TRU waste generation or repackaging does not provide information on the radiological content or on the presence of corrosive, reactive, or chemically hazardous waste. However, visual examination is not the only characterization method proposed for newly generated or repackaged waste (see description of the "characterization at the time of packaging" method in Chapter 4, Section 4.4).

5.2 Characterization Plan's Technical Soundness

DOE's stated objective is to propose a performance-based characterization plan for RH-TRU waste. The committee interprets "performance-based characterization plan" as a plan ensuring repository integrity, protection of the environment, and health and safety of the public and workers while keeping in consideration tradeoffs between greater characterization accuracy and worker risks (see Chapter 4). This section addresses the characterization activities that DOE proposes to implement the data quality objectives listed in Tables 4.1 and 4.2.

Finding 2A: The committee found that several characterization activities are based on non-technical considerations. Therefore, this characterization plan is not completely performance based. The committee questions the technical basis of some of the characterization activities proposed by DOE with respect to its stated goal of adopting a performance-based approach**. Recommendation: The committee acknowledges that DOE must consider many non-technical factors in composing its characterization plan. However, DOE should propose only characterization activities that have a technical, health and safety, or regulatory basis.**

Rationale: DOE itself recognizes that the characterization plan is based on various considerations other than science and technology. In its response to the findings in the committee's interim report, DOE stated:

> "Nearly all resulting characterization objectives are unrelated to repository performance or to safety/technical considerations" (see Appendix D).

and, during a recent conference on waste management, DOE explains:

> "Based on the results of repository modeling … the DOE believes there are no specific RH TRU waste parameters that need to be measured with precision in order to assure repository integrity and assure protection of human health and the environment. This does not mean that no characterization of RH TRU waste is necessary. To the contrary, in order to meet the requirements of the facility design and the facility waste acceptance criteria, specific needs for waste analysis have been identified" (Gist, et al., 2002; pages 2-3).

The facility design and the waste acceptance criteria address the requirements in the EPA Certification and RCRA Permit. Regulatory drivers are listed in Chapter 3 and other non-technical considerations at the beginning of Chapter 4. Most of the characterization activities proposed by DOE do not have a technical basis but arise from considerations aimed at maintaining an effective working relationship among DOE, EPA, and NMED. The committee acknowledges that maintaining an effective working relationship among DOE and WIPP's regulators is important; however, DOE should propose only characterization activities that correspond to technical, health and safety, or regulatory objectives.

Concerning the technical basis of some of the characterization activities in Documents 1 and 2, the Sandia impact analyses show that radioisotope, free liquids, cellulosics, plastics, rubber, and ferrous metal content in the RH-TRU waste inventory do not have an impact on repository performance (see Chapter 4).

In spite of these impact analyses, Documents 1 and 2 still propose characterization activities to determine the above parameters in RH-TRU waste. The committee provides below examples of characterization activities that do not appear to have a technical basis in the context of RH-TRU waste characterization.

Example #1: DOE justifies the characterization requirement concerning free water or liquid content for both EPA and NMED as a transportation-related requirement or as a requirement present in the WIPP Safety Analysis Report.[5] DOE provides the rationale for this characterization requirement as follows:

> "*[EPA Characterization Objectives] Account for Free Water*, is a regulatory expectation that the RH-TRU Team believes is prudent to meet even though no amount of free water in the RH-TRU waste will impact repository performance. Note that Appendix WCL.5 [of the compliance certification application] states that, 'Consequently, there is no need to monitor water in the waste for

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[4]An unexpected brine saturation of the repository in less than 300 years, a change in the scope of the WIPP facility, or a change in the configuration of underground disposal are examples of scenarios for which a new set of performance assessment calculations for both CH and RH-TRU waste would be warranted.

[5]For a definition of Safety Analysis Report see the glossary, Appendix I.

> compliance with 40 CFR § 194.24(c).' The RH-TRU Team recommends that free water in RH-TRU waste be accounted for by some means.
> *[NMED Characterization Objectives] Limit residual liquids to [less than] 1 [percent] volume of RH canister (or drum for 160B)*, is related to a regulatory requirement to provide secondary containment at the WIPP for potential spills. An analysis justifying the 1 [percent] for CH-TRU waste at the WIPP is part of the HWFP [Hazardous Waste Facility Permit] record, however a similar analysis has not been done for RH-TRU waste. The RH-TRU Team believes it is prudent to include this limit as an RH-TRU waste requirement also" (see Appendix D).

DOE acknowledges that the free water/liquid requirement is an operational concern that does not affect the long-term performance of WIPP. Given the results of the Sandia impact analyses, the committee questions the technical basis of this characterization activity.

Example #2: One of the data quality objectives listed in Document 1 is the determination of TRU activity (expressed as plutonium-239 content) of RH-TRU waste to comply with the EPA radionuclide release limits. The Sandia impact analyses showed that, even if the entire RH-TRU waste radionuclide inventory were composed of plutonium-239, WIPP would still be in compliance with 40 CFR 191 because of the small volume of RH-TRU waste to be emplaced in WIPP. Therefore, the actual measurement of TRU activity does not have a technical basis for RH-TRU waste. The determination of TRU activity could be addressed by assigning a conservative boundary value of plutonium-239 representing the total RH-TRU waste inventory.

Example #3: In the EPA compliance certification application, DOE established limits for ferrous metal content of waste to be emplaced in WIPP. The rationale is the following:

> "Ferrous and ferrous-alloy metals (and their corroded products) provide the reactants that reduce radionuclides to lower and less-soluble oxidation states. As discussed in Appendix WCA [Waste Characterization Analysis in the compliance certification application], the anticipated quantity of these metals to be emplaced in WIPP is two to three orders of magnitude in excess of the quantity required to assure reducing conditions. The waste containers supply more than enough iron to provide adequate reductant. Therefore, no upper or lower limit need be established for the quantity of ferrous and ferrous-alloy metals that may be emplaced, beyond the present projection of containers" (DOE, 1996a; Appendix WCL.2).

According to the information gathered, the minimum amount of ferrous metals will be satisfied by CH-TRU waste containers. The committee was unable to determine the reason for including the implementation of this characterization objective in the RH-TRU waste characterization plan, even though the method (counting containers) is a simple practice performed during waste packaging.

Example #4: The Sandia impact analyses showed that, even if the entire RH-TRU waste inventory were composed of cellulosics, plastics, and rubber, it would only have a negligible impact on the repository performance because of the small volume of RH-TRU waste emplaced. Yet, DOE proposes the implementation of this characterization objective in Document 1. Although this objective is not performance based in the case of RH-TRU waste, the committee acknowledges that DOE does not propose to actually measure cellulosics, plastics, and rubber in the waste but uses a conservative estimate described in Table 4.1.

Example #5: The determination of prohibited items (see Section 3.3, Chapter 3) listed in the RCRA Permit may not be appropriate for RH-TRU waste when the risks associated with hazardous chemical waste are balanced against radiological risks and costs associated with characterization. According to the information gathered, the prohibited items' determination represents one of the major difficulties in the characterization of RH-TRU waste. In DOE's characterization plan, there is no analysis of the health and safety implications of the prohibited items in RH-TRU waste. It is important to analyze these yet-undefined safety implications and balance them against potential radiological risks to workers and associated costs of identifying prohibited items in RH-TRU waste. Such an analysis would be helpful to DOE in comparing workers risks and the associated characterization costs. The results of the analysis could support and strengthen DOE's RH-TRU waste characterization activities with respect to prohibited items.

DOE's proposed characterization plan was significantly modified between July 2001 and March 2002 concerning the determination of prohibited items in RH-TRU waste. In the latter draft, DOE proposes to determine the absence of only free liquids and polychlorinated biphenyls (within their limits). The remaining prohibited items listed in the RCRA Permit (ignitable, corrosive, reactive, pyrophoric and incompatible waste, explosives, and compressed gases) are determined using the EPA hazardous waste codes. This determination is accomplished using AK on a waste stream basis.

This change drives the prohibited items determination (except for residual liquids and polychlorinated biphenyls) from a container-by-container basis to a waste stream basis where hazardous waste code assignment decisions are typically made. The committee supports this change since it streamlines characterization operations but still addresses the prohibited items objective in the RCRA Permit.

The committee could not determine the technical basis for including the determination of polychlorinated biphenyls (over 50 ppm) in the context of RH-TRU waste. DOE provided the following rationale:

> "Polychlorinated biphenyls are subject to EPA regulation under TSCA [Toxic Substances Control Act] and are regulated regardless of whether or not they are included in a RCRA permit as a prohibition" (see Appendix D).

In the case of a change in the polychlorinated biphenyl disposal regulations,[6] DOE must submit a request for a change in the RCRA Permit to remove the 50 ppm provision. This would not be necessary if this provision were not explicitly mentioned in the RCRA permit.

Example #6: The March 2002 draft indicates that, if AK data are not sufficient, then 10 percent of waste should be characterized with alternative methods (see Tables 4.1 and 4.2). The committee could not determine the technical basis for choosing 10 percent of waste as a representative sample of the waste stream. In general, the size of a representative sample is the result of an analysis involving statistical considerations as

[6]The new polychlorinated biphenyls disposal regulations (Disposal of Polychlorinated Biphenyls (PCBs), 63 Federal Register 35384, effective August 28, 1998) allows polychlorinated biphenyl-contaminated radioactive waste to be disposed of without a TSCA permit provided the waste meets the requirements for disposal in a non-hazardous waste landfill or a hazardous waste landfill. This recent regulatory change would allow disposal at WIPP of some polychlorinated biphenyls-contaminated wastes where the polychlorinated biphenyls component exceeds 50 ppm. On March 22, 2002 DOE submitted an "Initial Report" to EPA Region VI requesting authorization to dispose of polychlorinated biphenyls in WIPP.

well as waste stream profile considerations. No such analysis or any other justification was provided in the March 2002 draft. A 10 percent waste sample size may be too big or too small, depending on the waste stream, on the quality of AK available, and on the tolerable decision error rates (see Finding 2C).

Finding 2B: The requirements to qualify information collected on each waste stream, whether by AK or by any other method described in 40 CFR 194.22(b), have not been established with specificity in the submittal documents. **Recommendation: In the site-specific accompanying documents, DOE should present clear and technically defensible data qualification requirements for its RH-TRU waste characterization plan.**

Rationale: The committee recommends that DOE follow a more structured approach in the development of its characterization plan. A structured approach, such as that provided by defining data quality objectives and quality assurance objectives, would clearly define the data needed for characterization, identify the basis for the data need, and then logically determine how to meet those needs. The committee does not expect quantitative quality assurance objectives, especially for AK information. However, it is important to discuss how to determine when or whether AK could meet data quality objectives and under which conditions it would be necessary to supplement AK using other characterization methods (e.g., dose to curie conversion, visual examination, radiography, time of packaging methods, direct assay, surface dose rate). This recommendation is also consistent with the recommendation of a second peer review on DOE's characterization plan.[7]

According to the information gathered, DOE will submit to EPA and NMED along with the draft characterization plan, a sample of completed characterization documents for three RH-TRU waste generator sites (Energy Technology Engineering Center, Battelle Columbus Laboratories, and Oak Ridge National Laboratory). The committee supports this initiative. These companion documents to the characterization plan should be useful in clarifying the intended methods of implementation. The committee could not review these methods, given that these documents were not available at the time this report was written.

Finding 2C: DOE's proposed characterization plan does not adequately address the issue of tolerable decision error rates associated with all characterization information. **Recommendation: DOE's proposed characterization plan should address tolerable decision error rates associated with characterization information. These errors should not be overly stringent so as to negatively impact the sites' ability to implement ALARA.**

Rationale: Tolerable decision error rates are never clearly defined in Document 1 and Document 2. Tolerable decision error rates are determined by weighing the consequences of mischaracterization against the costs (including worker risks) of achieving better characterization. Once established, tolerable decision error rates can be

[7]The Institute for Regulatory Sciences, which reviewed the July 2001 draft of DOE's proposed characterization plan, recommended the following: "A detailed procedure for determining whether there is sufficient AK available on a waste, should be developed as part of the permit application. This procedure should be consistent across all waste generating sites. […] [A] detailed procedure should be provided to go to other characterization methods if AK is found to be insufficient" (Institute for Regulatory Sciences, 2001; page 77).

used to identify the attendant quality assurance requirements for sampling (i.e., the measurement quality objectives, which DOE calls quality assurance objectives). Tolerable decision error rates may not be specified in laws and regulations, but they are a critical judgment that an implementer should propose when interpreting legal or regulatory limits to address the uncertainties inherent in characterization data. As an illustration, Document 1 reads as follows:

> "Tolerable decision error: The limit on residual liquids has been specified with no associated error; therefore, any container that contains more than 1 percent by volume residual liquids cannot be shipped to WIPP" (DOE-CBFO, 2002a; Attachment B; page 7).

The tolerable decision error (and its rate) in the measurement of the liquid volume in a container is never clearly defined. More importantly, the above quote from Document 1 seems to suggest that there is a zero tolerable decision error (and a zero tolerable decision error rate) on the determination of residual liquids. Another example of unclear tolerable decision error rate concerns the quantification of the total activity. The March 2002 draft proposes to use the same quality assurance objective for the total activity of waste as the one used for CH-TRU waste (see Chapter 4, Section 4.6). However, the committee still cannot determine with clarity what is tolerable decision error rate associated with the measurement of the total activity.

It is premature for DOE to develop quality assurance objectives until it has proposed tolerable decision error rates that limit risks related to the waste, and that recognize potential tradeoffs in costs and worker risks. Without setting tolerable decision error rates to create a bridge between the data quality objectives and the characterization methods, it will be impossible to determine whether the waste characterization plan requires too much or too little in terms of the quality of the data needed. The quality assurance objectives should be presented in the site-specific implementation plans and could vary from site to site. The committee supports DOE's plan to submit to EPA and NMED the three site-specific (Energy Technology Engineering Center, Battelle Columbus Laboratories, and Oak Ridge National Laboratory) implementation plans.

It is important to recognize that tolerable decision error rates will have an impact on characterization operations at the generator sites. The ALARA principle must be applied at DOE facilities according to the Code of Federal Regulations (10 CFR 835.101). Therefore, the proposed characterization plan should not set forth overly stringent requirements (such as zero tolerable decision error rates) that could negatively impact the sites' ability to implement ALARA (see also Finding 3A).

Finding 2D: It is not clear how visual examination and radiography can confirm AK information for prohibited items. For example, visual examination and radiography cannot distinguish between corrosive and non-corrosive liquids, whereas AK may provide records of the existence of such liquids in the waste. Historical AK may be a better indicator of some of the currently prohibited items than visual examination and radiography. **Recommendation: The characterization plan should clarify under which conditions confirmation of historical AK is warranted and what are the most effective methods proposed.**

Rationale: This finding applies to the approximately the 5 percent of the RH-TRU waste inventory that does not require packaging or repackaging. The committee observes that the March 2002 draft better explains how AK could be, in some cases, the most suitable method to determine the absence of certain prohibited items. In this draft,

DOE proposes to use AK to identify hazardous waste codes to prevent ignitable, corrosive, and reactive waste from being disposed of in WIPP. However, DOE does not clearly explain under what circumstances AK should be confirmed and what are the results expected from supplementary characterization methods. DOE recognizes that visual examination and radiography are inadequate techniques for addressing the entire list of prohibited items.

From the operational experience acquired with CH-TRU waste, it is possible to obtain some indication of the effectiveness of AK as a characterization method. Most of the information collected for CH-TRU waste characterization consists of historical records about waste streams, which the committee termed "historical AK" (see Sidebar 2.1). Effectiveness of AK for CH-TRU waste is demonstrated by the "AK Information Accuracy Reports" from the various generator or storage sites (DOE-CBFO, 2001c). DOE presented to the committee the results of an analysis of the effectiveness of historical AK for CH-TRU waste. Contact-handled TRU waste generators use radiography or visual examination, headspace gas sampling and analysis, and/or solids sampling and analysis to confirm AK information accuracy.

Results showed a high accuracy of historical AK: above 95 percent for the determination of waste matrix codes at the major CH-TRU waste generator sites and above 93 percent for the determination of hazardous waste codes. The only exception was observed at the Idaho Environmental and Engineering Laboratory, where an accuracy of 80 percent was achieved in the hazardous waste codes determination. This lower accuracy was obtained because this site assigned hazardous waste codes on a waste stream basis, rather than on an individual container basis.

Document 2 provides further feedback on AK confirmation for CH-TRU waste by headspace gas analysis:

> "To date, the headspace gas from over 16,000 CH TRU waste containers has been sampled and analyzed and no hazardous waste numbers have been added to a waste stream. This indicates that the additional benefit from using headspace gas sampling and analysis to confirm the hazardous waste determination are limited" (DOE-CBFO, 2002b; pages 5-21).

The committee emphasizes that these effectiveness analyses provided by DOE are relevant only to AK for CH-TRU waste, which is historical AK. In the case of the 95 percent of RH-TRU waste, most of the information comprising AK will be collected during waste generation or repackaging under a certified quality assurance program and would likely have higher accuracy.

Finding 2E: DOE's characterization plan calls for application of specific technologies, such as X-ray radiography, to provide confirmatory data. The committee could not determine the effectiveness of these technologies in characterizing the high-dose-rate fraction of RH-TRU waste containers. **Recommendation: DOE should provide justification for the technologies proposed for obtaining confirmatory data and provide evidence of their effectiveness across the entire spectrum of dose rates for RH-TRU waste.**

Rationale: Given the importance placed on radiography to determine the presence of prohibited items, the characterization plan should clarify and support the information on the method's effectiveness in high radiation fields expected for a small fraction of RH-TRU waste. The lack of information on the effectiveness of characterization methods for RH-TRU waste was also NMED's main argument to prohibit this type of waste in WIPP

(see Chapter 3). Moreover, this recommendation is consistent with the Institute for Regulatory Sciences' peer review of the July 2001 draft of the characterization plan.[8]

In Documents 1 and 2, the committee did not find adequate justification for the effectiveness of technologies proposed for obtaining confirmatory data, such as radiography, particularly for RH-TRU waste with higher surface dose rates. In its response to the committee's interim report, DOE states:

> "For the minimal use of NDA [non-destructive assay] and RTR [real-time radiography] that will still be required in the overall program, the standard technologies currently being employed in the CH-TRU waste program are more than adequate. The RH Team recommended program […] calls for NDE [non-destructive examination] to be used only to detect 1 [percent] residual liquid and only for a small percentage of the total RH-TRU waste inventory (most RH-TRU waste will be repackaged or newly generated). Resolution of current RTR systems, even in high radiation fields, is adequate for this determination" (see Appendix H).

DOE never addresses the issue of the fraction of waste containers with high surface dose rates. The current DOE inventory in Table 2.1 shows that both the Hanford Site and Oak Ridge National Laboratory have or will generate RH-TRU waste with a surface dose rate as high as 1,000 rem per hour. Moreover, some Oak Ridge National Laboratory RH-TRU waste also emits neutrons, which further complicates non-destructive characterization methods. In Documents 1 and 2, radiography is cited as lead technology to confirm AK, where necessary, or to examine the contents of small containers prior to placing them into the final shipping containers. DOE's proposal to use radiography across the entire spectrum of dose rates warrants an explanation, however small the fraction of high dose-rate containers may be.

The committee was unable to find elsewhere information on whether radiography could be used for RH-TRU waste containers with the highest dose rates. DOE indicated to the committee that:

> "Though DOE collected some data and analysis indicating that there are no fundamental obstacles to radiographing RH TRU wastes, there has not been a systematic demonstration of that capability. As a consequence, there is lingering doubt regarding its feasibility in general. The simplest means to put these doubts to rest is to design and perform a systematic evaluation" (Taggart, 2001).

The committee gathered additional information on non-destructive characterization techniques and there appear to be uncertainties and technical difficulties in high radiation fields (see Appendix G). Under the committee's request for additional information, DOE provided a publication on X-ray radiography applied to RH-TRU waste characterization (Roney and White, 2001). This study, although performed on surrogate waste, showed that X-ray technology could indeed investigate the content of RH-TRU waste drums, although it was discussed for surface dose rates only up to 100 rem per hour. It is unfortunate that this study is not mentioned in DOE's characterization plan. To

[8]The Institute for Regulatory Sciences recommended: "More detail and specificity on WAC [waste acceptance criteria] using AK, VE [visual examination], and [r]adiography (including types of instrumentation to be used) should be provided in the permit application" (Institute for Regulatory Sciences, 2001; page 77).

the best of its knowledge, the committee believes that the application of radiography in the presence of very high radiation fields may be problematic.

Other non-destructive assay and examination techniques are being developed for the characterization of RH-TRU waste (see Appendix G). According to the information gathered, the only example of non-destructive assay characterization performed on actual RH-TRU waste was the characterization of 10 canisters of RH-TRU waste at Los Alamos National Laboratory. This was done using a passive/active neutron assay technique (Estep et al., 1989). Further development and application of non-destructive assay and examination techniques is pending the outcome of the final RH-TRU waste characterization plan.

5.3 Protection of Worker Safety and Health

The main issues concerning the handling of RH-TRU waste are potential radiation worker doses and assorted characterization costs.

Finding 3A: Potential worker radiation doses and related characterization costs are distinguishing features of RH-TRU waste compared to CH-TRU waste. Available estimates of worker doses and characterization costs for RH-TRU waste are limited, site-specific, and not completely reliable**. Recommendation: DOE could strengthen the rationale of its characterization plan for RH-TRU waste by incorporating a discussion of estimates of worker doses and characterization costs in the three site-specific plans accompanying the submittal documents.**

Rationale: The committee observes that the data presented on waste dose rates and characterization cost estimates in the July 2001 draft have been removed from the March 2002 draft. The committee recognizes that, since the characterization plan for RH-TRU waste is not yet finalized, information on worker doses and characterization costs for RH-TRU waste is scarce. The only data available on RH-TRU waste are from Battelle Columbus Laboratory, WIPP, and Argonne National Laboratory-East, and they may not be representative of all RH-TRU waste generator sites (see Appendix H).

The committee also recognizes that the sites are also responsible for applying the ALARA principle to minimize radiation doses to workers during characterization operations. It follows that each site will produce a different implementation plan for waste characterization and worker radiation protection programs based on ALARA will also be different.

However, a risk perspective of worker doses and costs could be illuminating in developing characterization requirements and in adding credibility to the plan. Discussion of worker doses and costs is relevant since radiation protection standards and criteria are predicated on the concept of assessing the decrement in risk per increment in cost as outlined by the International Commission on Radiological Protection (ICRP, 1977). The approach to estimate worker doses would be to structure different scenarios, rank the scenarios on the basis of the supporting evidence, and calculate the worker doses. This type of dose information would add much to the discussion of the differences between CH- and RH-TRU waste characterization plans. An equivalent approach could be adopted to better estimate characterization costs.

The committee recommends that the estimated doses and costs be an integral part of the three implementation plans from representative generator sites that will accompany Documents 1 and 2. Understanding worker doses and underlying characterization costs is important in developing effective radiation protection programs

based on the ALARA principle. The committee provides in Appendix H examples of estimates of worker doses and characterization costs. In Section 5.2, the committee also recommended that DOE's characterization plan should not set forth overly stringent tolerable decision error rates that could negatively impact the sites' ability to implement ALARA (see Finding 2C).

Finding 3B: The submittal documents provide flexibility to the generator sites in the implementation of the RH-TRU waste characterization plan. **Recommendation: DOE should continue its effort in ensuring sufficient flexibility to generator sites in the implementation of the characterization plan. However, characterization activities that share common elements across sites should be standardized.**

Rationale: One of the findings of the committee's interim report is that there is substantial variability among RH-TRU waste generator sites, including:

1. variability in the composition of the waste streams;
2. variability in the extent of AK available;
3. variability in the characterization and repackaging facilities available; and
4. variability and uncertainties in the current and projected inventories of RH-TRU waste.

The committee acknowledges that the March 2002 draft better addresses the substantial RH-TRU waste variability from site to site compared to the earlier draft. DOE's characterization plan allows flexibility to the generator sites in implementing the RH-TRU waste characterization program. In Document 1, DOE directs each TRU waste site to develop standard operating procedures to implement the waste characterization plan at that specific site (DOE-CBFO, 2002a; Section 3.2.2 of Attachment B). DOE also addresses data validation, usability, and reporting at the individual sites in Section 3.5 of Attachment B. Also, Attachment 6 of the application is designated "Site Specific Documentation," but this section has yet to be written. Document 2 requires the sites to develop their own RH-TRU mixed waste characterization programs in compliance with the requirements of the overall waste analysis plan (Document 2, Section R 4.0). These programs are to include characterization strategies, equipment, and health and safety protocols; site-specific characterization methods; quality-assurance plans; and training programs.

Flexibility in a waste characterization plan is important to allow the sites to adapt each characterization requirement to their type of waste inventory and characterization facilities. A rigid, overly prescriptive characterization plan may lead to unnecessary radiation doses to workers and characterization costs. For example, small sites that do not have adequate characterization facilities may find themselves in a difficult situation if the characterization plan mandates specific confirmatory activities, even in the presence of adequate AK. If the site must perform confirmatory measurements or visual examination in a hot cell it would have to ship its waste to a different site[9] equipped with a hot cell or use a mobile hot cell. Therefore, the added costs of such confirmatory measurements could be significant.

The committee reiterates its recommendation that common elements among the sites be standardized to facilitate characterization compliance verifications and, possibly, reduce characterization costs. In the effort of standardizing characterization activities,

[9]Shipments from site to site are allowed before the waste characterization plan is approved because DOE's waste characterization plan applies only to waste shipped to WIPP.

DOE will submit to EPA and NMED a sample of completed characterization documents for three RH-TRU generator sites (Energy Technology Engineering Center, Battelle Columbus Laboratories, and Oak Ridge National Laboratory). The committee supports this initiative.

The committee observes that, in the sites' inventories description, DOE did not differentiate mixed RH-TRU waste from non-mixed RH-TRU waste. DOE indicated that, although some waste streams could be identified as non-mixed RH-TRU waste, all waste is deliberately treated as mixed RH-TRU waste, as a policy decision. In fact, according to the RCRA Permit, all waste emplaced in WIPP (mixed or non-mixed) must be analyzed according to a characterization plan approved by NMED (DOE-CBFO, 2002c). The committee acknowledges DOE's policy decision, although it lacks a technical basis.

5.4 Compliance with Regulatory Requirements

The committee evaluated how DOE proposes to address EPA and NMED requirements from a technical point of view. The committee was not asked to determine if the plan complies with the regulatory requirements. The latter is obviously a policy decision that belongs to the regulatory agencies.

One of the challenges of this characterization plan is to meet characterization requirements specified in the EPA Certification and RCRA Permit that were negotiated with WIPP's regulatory agencies for CH-TRU waste and exclude RH-TRU waste. Moreover, the only TRU waste characterization plan approved by EPA and NMED is that currently used for CH-TRU waste. With this characterization plan DOE proposes to meet EPA and NMED requirements following a different approach than that used for CH-TRU waste.

Finding 4A: The proposed characterization plan for RH-TRU waste deliberately tracks the characterization plan for CH-TRU waste. **Recommendation: DOE should evaluate whether existing characterization practices for CH-TRU waste, when applied to the characterization of RH-TRU waste, have an impact on the protection of the environment, health and safety of public and workers, and cost-effectiveness of the characterization program.**

Rationale: DOE proposes to address regulatory requirements for RH-TRU waste characterization using a performance-based approach, a different approach than that used for CH-TRU waste. The committee observes that the characterization plan for RH-TRU waste has not yet been finalized. The implementation activities for RH-TRU waste to address characterization objectives will be finalized only after negotiations based on the submittal documents take place between DOE and WIPP's regulatory agencies. However, the existence of a characterization plan for CH-TRU waste does not imply that the same approach should be proposed for the characterization of RH-TRU waste.

It is not the committee's intention to say that there are unnecessary regulatory requirements in the current EPA Certification and RCRA Permit. However, there is reason to believe (Kehrman, 2002; NRC, 2001a; DOE, 1999a) that DOE proposed some characterization practices in the CH-TRU waste characterization plan to facilitate negotiations with the regulatory agencies and obtain authorization to operate the WIPP facility. The previous National Research Council committee on WIPP found that some of these self-imposed practices lacked a technical, safety or legal basis (see Sidebar 3.1). The current committee emphasizes that, because of the additional radiological and cost

considerations associated with RH-TRU waste, it is even more important that DOE refrains from proposing characterization requirements that do not have a technical, health and safety, or regulatory basis.

Given the different context of RH-TRU waste characterization described earlier, the committee acknowledges that DOE's efforts to introduce a performance-based approach are technically justified. However, the committee does not find the proposed plan to be completely performance based (see Finding 1A). The committee does not suggest that DOE should do only the "bare minimum" to characterize RH-TRU waste. Rather, the characterization program should ensure repository integrity, protection of the environment and of the health and safety of the public and workers, while keeping in consideration tradeoffs between greater characterization accuracy and worker risks.

Finding 4B: The submittal documents include, as basis for characterization objectives, waste acceptance criteria and other requirements than those applicable to the EPA Certification and RCRA Permit. **Recommendation: Submittal documents should focus on regulatory requirements under the relevant agency's purview and should distinguish between these requirements and ancillary information describing the context of RH-TRU waste characterization.**

Rationale: Document 1 contains the RH-TRU Waste Acceptance Requirements and Criteria. These are the "controlling (i.e., the most restrictive) requirements to be used by the sites in preparing their waste for transportation to and disposal at the WIPP" (DOE-CBFO, 2002a; Section 3.0 of Attachment A). The waste acceptance criteria are drawn from transportation and hazardous waste considerations, as well as repository-performance considerations.

For instance, the waste transportation quality assurance requirements are described in Section 4.3 of Attachment A. Since Document 1 is an application for a change in the EPA Certification, it is not clear why requirements and criteria other than those relating to repository performance are given in the document. Historically, DOE included the waste acceptance criteria in the characterization plan for CH-TRU waste (DOE-CAO, 1996a). This does not need to be the case for the RH-TRU waste characterization plan since, to the best of the committee's knowledge, EPA does not require these criteria to be part of the application. Documents 1 and 2 also contain requirements originating from the Nuclear Regulatory Commission, the Department of Transportation, and the Occupational Health and Safety Administration. While it is important to provide in the submittal documents the full context of the characterization of RH-TRU waste, including material outside the regulatory jurisdiction of EPA and NMED may unnecessarily complicate the regulatory review process.

In the future, DOE may wish to negotiate other requirements with different regulatory agencies than EPA and NMED (for instance, transportation requirements with the Nuclear Regulatory Commission and the Department of Transportation). These negotiations could become more complex if the original requirements had also become a part of a document reviewed and approved by the EPA or NMED. See also the comment on polychlorinated biphenyl limits discussed in Finding 2A, example #5.

The committee believes that it would be helpful for both DOE and the regulatory agencies if the submittal documents indicate which requirements are to be reviewed and which are given for information purposes. This would allow the regulator and the implementer (DOE) to keep track of various requirements, and to streamline characterization practices as experience is gained. This recommendation applies to the submittal documents only. The committee supports the current practice of combining all

regulatory requirements into one document to guide generator sites in the development of their characterization programs.

5.5 Overall Assessment of DOE's Characterization Plan

The committee observed a net improvement between the July 2001 and March 2002 drafts of the characterization plan. Concerning the plan's technical soundness, DOE itself recognized that this plan is not completely performance based and that several other considerations played a role in the development of this plan. The committee identified some characterization activities lacking technical bases in the context of RH-TRU waste and a potential technical problem with radiographic examination of waste. Also, DOE's proposed characterization plan does not adequately address the issue of tolerable decision error rates associated with all characterization information.

In some instances, the plan lacks specificity because most of the operational details are site-specific and were not available at the time of writing. The site-specific accompanying documents should provide useful clarifications. In the context of RH-TRU waste characterization and from a performance point of view, the committee found that the general approach DOE is proposing is technically sound. However, Documents 1 and 2 do not present a performance-based plan as effectively as they could.

Concerning the plan's protection of worker health and safety, the committee recommends that the approved characterization plan not include overly stringent tolerable decision error rates that could negatively impact the sites' ability to manage worker risks. It is important to recognize that the allowable uncertainties in the final characterization plan approved by EPA and NMED may have an impact on generator sites' radiation protection programs.

Concerning compliance with regulatory requirements in the EPA Certification and RCRA Permit, the committee did not observe any requirement that was not addressed in DOE's characterization plan. In fact, the proposed characterization plan for RH-TRU waste addresses some requirements that are not under the relevant agency's purview. Moreover, the characterization plan for RH-TRU waste deliberately tracks as close as possible that for CH-TRU waste. The committee recommends evaluating whether existing characterization practices for CH-TRU waste, when applied to the characterization of RH-TRU waste, have an impact on the protection of the environment, health and safety of public and workers, and cost-effectiveness of the characterization program.

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Appendix A

Biographical Sketches of Committee Members

Eula Bingham, *Chair*, is professor of environmental health at the University of Cincinnati. Dr. Bingham's interests include risk assessment, regulatory toxicology, environmental carcinogenesis, and occupational health surveillance. Previously, she was a volunteer investigator at the National Institute of Environmental Health Sciences and assistant secretary of labor (Occupational Safety and Health Administration). She is the recipient of the Rockefeller Public Service Award from Princeton University (1980) and the first William Lloyd Award for occupational safety. Throughout her career Dr. Bingham has served on numerous national and international advisory groups, including advisory committees of the National Research Council, Food and Drug Administration, Department of Labor, National Institute for Occupational Safety and Health, National Institutes of Health, Natural Resources Defense Council, and the International Agency for Research on Cancer. These committees addressed research needs in health risk assessment and the potential health effects of environmental exposure to chemicals. In 1989, Dr. Bingham was elected to the Institute of Medicine. She earned her M.S. and Ph.D. in physiology from the University of Cincinnati.

Sanford Cohen is founder and president of S. Cohen & Associates (SC&A, Inc.), an energy and environmental consulting firm providing expertise in radiation sciences, management, health and safety analyses, communications services, and information management. He has managed several contracts for agencies of the U.S. government, including the Environmental Protection Agency, Centers for Disease Control and Prevention, Council on Environmental Quality, Congressional Office of Technology Assessment, Department of Energy, and Nuclear Regulatory Commission. Dr. Cohen is involved in regulatory guidance pertaining to environmental management (including Resources Conservation and Recovery Act/Comprehensive Environmental Response, Compensation, and Liability Act requirements), remediation of contaminated sites, safe disposal of hazardous wastes, site characterization in support of decontamination and decommissioning projects, recycling of scrap metal from nuclear facilities, electric and magnetic fields effects, and indoor radon. Prior to founding SC&A in 1981, Dr. Cohen was vice president and manager of Teknekron, Inc. (Washington Operations), and president of Teknekron Research, Inc., a consulting group working with the above government agencies. Dr. Cohen earned his B.S. in science engineering at Northwestern University and his Ph.D. in nuclear engineering at the University of Michigan.

Milton Levenson is an independent consultant and chemical engineer with more than 50 years of experience in nuclear energy and related fields. His technical experience includes work in technologies related to nuclear safety, fuel cycle, water reactors, advanced reactors, and remote control. His professional experience includes research

and operations positions at the Oak Ridge National Laboratory, Argonne National Laboratory, Electric Power Research Institute, and Bechtel. Mr. Levenson is a fellow and past president of the American Nuclear Society, a fellow of the American Institute of Chemical Engineers, and a recipient of the American Institute of Chemical Engineers' Robert E. Wilson Award. He is the author of more than 150 publications and presentations and holds three U.S. patents. Mr. Levenson served as chairman or committee member for several National Research Council studies, including the most recent study on the Waste Isolation Pilot Plant. He was elected to the National Academy of Engineering in 1976. He received his B.Ch.E. from the University of Minnesota.

Kenneth L. Mossman is professor of health physics and director of the Office of Radiation Safety at Arizona State University in Tempe, where he has also served as assistant vice president for research. Prior to his arrival at Arizona State University, Dr. Mossman was a faculty member of the medical and dental schools at Georgetown University in Washington, D.C., and was professor and founding chairman of the Department of Radiation Science of Georgetown's Graduate School. His research interests include radiological health and safety and public policy. Dr. Mossman has authored over 130 publications, including six books and proceedings related to radiation health issues. He has presented testimony before the U.S. House of Representatives and the U.S. Senate. Dr. Mossman served as president of the Health Physics Society and received its prestigious Elda Anderson Award, the Marie Curie Gold Medal, and the Founder's Award. He also served as a Sigma Xi distinguished lecturer. He has been a fellow of the Health Physics Society and the American Association for the Advancement of Science and has served on committees for the National Research Council, National Institutes of Health, Nuclear Regulatory Commission, Nuclear Energy Agency of the Organization for Economic Cooperation and Development (Paris), and the International Atomic Energy Agency (Vienna). Dr. Mossman earned a B.S. in biology from Wayne State University, M.S. and Ph.D. degrees in radiation biology from the University of Tennessee, and an M.Ed. degree in higher education administration from the University of Maryland.

Ernest Nieschmidt is director of the Laser Laboratory and adjunct associate professor of physics at Idaho State University, College of Engineering. His research interests span the development of a neutron activation analysis facility, sonoluminescence, and the destruction of hazardous organic components of mixed waste by free-radical chemistry. He is also involved in the development of the Laser Isotope Separation Laboratory to pursue research into the separation of isotopes using selective excited states induced by laser. For most of his career, Mr. Nieschmidt worked for different contractors at the Idaho National Engineering and Environmental Laboratory on techniques to assay radioactive and transuranic waste material. These included passive and active neutron interrogation, analysis of active gamma rays and gamma rays produced by neutron inelastic scattering, neutron capture, chronoimaging, time correlations, and the application of position-sensitive detectors. He has authored 106 publications related to topics in physical sciences. Mr. Nieschmidt earned his M.S. in physics from San Diego State College.

John Plodinec is director of the Diagnostic Instrumentation and Analysis Laboratory at Mississippi State University. His laboratory specializes in developing instrumentation for unusual environments and in characterizing processes and technologies under real-world conditions. Dr. Plodinec is an internationally recognized expert in waste management and glass science. He has made important contributions in several areas

of radioactive waste management, ranging from waste characterization to glass durability modeling. Prior to joining Mississippi State University, he worked for 22 years at the Department of Energy's Savannah River Site, where he collaborated in building and operating the first remote in-cell melter and served as primary technical lead for the product qualification program. In that capacity he oversaw the remote-handled transuranic waste streams produced by the Savannah River Site. He has authored over 90 publications, primarily on waste vitrification and thermodynamics of waste management. He holds a patent on a device to sample high-level waste and a patent on a slurry-feeding device for glass melters. Dr. Plodinec earned his Ph.D. in physical chemistry from the University of Florida.

Anne E. Smith is a vice president at Charles River Associates, an economics consulting firm. Dr. Smith is an expert in risk management, cost-benefit analysis, economic modeling, and integrated assessment of complex environmental and energy issues. Issues that she has analyzed include contaminated sites, global climate change, air quality, and emissions trading. Dr. Smith has developed and reviewed decision support tools for risk-based ranking of contaminated sites and for making risk tradeoffs in selecting remediation alternatives. She has submitted formal comments on the development of the Environmental Protection Agency Hazard Ranking System for identifying Superfund sites, has served on committees of the National Research Council on assessing contaminated site risk management activities, was a project leader in a review for the U.S. Congress of Superfund and Resources Conservation and Recovery Act concerns about the U.S. nuclear weapons facilities, and her testimony has been sought by committees of the U.S. Senate on air quality issues. Dr. Smith has a Ph.D. in economics from Stanford University, with a minor in engineering-economic systems. Prior to joining Charles River Associates, Dr. Smith was a vice president of Decision Focus Inc. She also served as an economist in the Environmental Protection Agency's Office of Policy Planning and Evaluation.

Appendix B

Information-Gathering Meetings

This appendix describes the three committee's information-gathering sessions throughout the study. The committee held an additional meeting devoted to the writing of this report.

B.1 First Meeting: August 1-2, 2001 (Columbus, Ohio)

Overview of the Battelle Columbus Laboratories: History, Remote-Handled (RH) Waste Inventory, Milestones, Plans for Characterization (James Eide and Craig Jensen, Battelle Columbus Laboratories)

Overview of Characterization Techniques for RH Waste (Greg Becker, Idaho Engineering and Environmental Laboratory)

RH waste at Los Alamos National Laboratory (Larry Field, Los Alamos National Laboratory)

RH Waste at Idaho National Engineering and Environmental Laboratory (Raj Bhatt, Idaho Engineering and Environmental Laboratory)

RH waste at Argonne National Laboratory-West (William Russ, Argonne National Laboratory)

RH Waste at the Hanford Site (Ken Hladek, Waste Management Federal Services of Hanford, Inc.)

RH Waste at Oak Ridge National Laboratory (Gary Riner, Oak Ridge National Laboratory)

Department of Energy (DOE)-Carlsbad Field Office. Introductions. Sponsor's Hopes and Expectations for the Study (Ines Triay, DOE-Carlsbad Field Office)

DOE Strategy for NMED [New Mexico Environment Department] and EPA [Environmental Protection Agency] Submission (Byran Howard, DOE-Carlsbad Field Office)

RH Inventory and Baseline (Joe Harvill, DOE-Carlsbad Field Office)

Repository Performance—RH Impact (Roger Nelson, DOE-Carlsbad Field Office)

Application of Acceptable Knowledge for RH/TRU [Remote-handled transuranic] Waste (Robert Kehrman, DOE-Carlsbad Field Office)

Data Quality Objectives and the State of the Art in Non-Destructive Assay/Non-Destructive Execution Techniques (Dan Taggard, Los Alamos National Laboratory)

The RH Program Audit Process—Emphasis on AK (Marlin Horseman, Carlsbad Field Office Technical Assistance Contractor)

Summary: RH-TRU Small—Volume-Small Impact (Ines Triay, DOE-Carlsbad Field Office)

Environmental Protection Agency Overview of the Regulatory Requirements: Criteria to Evaluate DOE's Characterization Plan (Scott Monroe, U.S. Environmental Protection Agency)

Public Comment Period

Field Trip to the Battelle Columbus Laboratories Site-West Jefferson North Campus

B.2 Second Meeting: October 4, 2001 (Albuquerque, New Mexico)

Introductions and Opening Remarks (Ines Triay, DOE-Carlsbad Field Office)

Updating the RH Inventory—Recent Information on RH Across the Complex (Joe Harvill, DOE-Carlsbad Field Office)

Doses from RH Waste Disposal: From Generator Site to WIPP Emplacement (Chuan Fu Wu, DOE-Carlsbad Field Office)

Transportation Requirements for RH TRU Waste (Brad Day, DOE-Carlsbad Field Office)

Proposed Standardized RH—TRU Characterization Methods for Non-Destructive Assay (Dan Taggart, Los Alamos National Laboratory)

AK Accuracy Analysis—How Well AK Does for CH Waste Characterization (Sean White and Robert Kehrman, DOE-Carlsbad Field Office)

Results of the Battelle Columbus Laboratories Surveillance—Confirming AK with Supplemental Measurements (Wayne Ledford, DOE-Carlsbad Field Office)

Summary and Open Questions and Answers (Ines Triay, DOE-Carlsbad Field Office)

View of the New Mexico Environment Department (Steve Zappe, New Mexico Environment Department)

RCRA [Resources Conservation and Recovery Act] Requirements According to the Environmental Protection Agency (David Neleigh, U.S. Environmental Protection Agency, New Mexico Office)

Views of the Environmental Evaluation Group (Matthew Silva, Environmental Evaluation Group)

The Other Peer Review: Findings and Conclusion (M.C. Kirkland, Institute for Regulatory Sciences)

Public Comment Period

B.3 Third Meeting: February 4-5, 2002 (Carlsbad, New Mexico)

DOE's Presentations on the New Characterization Plan; DOE's expectations from the Committee; How DOE Plans to Use the Committee's Final Report (various speakers, DOE-Carlsbad Field Office)

New Mexico Environment Department's Comments on the Committee's Interim Report (Steve Zappe, New Mexico Environment Department)

Environmental Evaluation Group's Comments on the Committee's Interim Report (George Anastas, Environmental Evaluation Group)

Environmental Protection Agency's Comments on the Committee's Interim Report (Scott Monroe, U.S. Environmental Protection Agency)

Public Comment Period

Field Trip to the WIPP Site

Appendix C

Excerpt from the Committee's Interim Report: Chapter 5

This appendix consists of an excerpt from the committee's interim report (Box C1). This report focuses on the July 2001 draft of DOE's proposed characterization plan (NRC, 2001b).

BOX C1 Excerpt from the Committee's Interim Report: Chapter 5

5
Committee's Preliminary Findings and Recommendations

The following are the committee's preliminary findings and recommendations concerning DOE's proposed characterization plan for RH-TRU waste. The committee also provides observations and issues for further clarification to help DOE in future drafts of the plan's supporting documents. As noted previously, findings and recommendations specific to Document 1 and Document 2 are based on the July 2001 draft.

Finding 1: With this new characterization plan for RH-TRU waste, DOE has an opportunity to introduce a truly performance-based characterization plan containing only requirements relevant to the long-term performance of WIPP and that have a safety, technical, or legal basis. **Recommendation: DOE should not include in its characterization plan unnecessary requirements that do not affect the long-term performance of the repository and that do not have a safety, technical, or legal basis.**

Rationale: The committee observes that characterization requirements for RH-TRU waste do not yet formally exist. Characterization requirements specific to RH-TRU waste will be finalized after DOE submits its characterization plan to EPA and NMED. The only legal requirements applying specifically to RH-TRU waste are those in the Land Withdrawal Act (see Chapter 3).

When DOE first applied for the certification of WIPP in 1996, it proposed a characterization plan for both CH- and RH-TRU waste. To facilitate the certification process, DOE imposed extra characterization requirements in the CH-TRU waste characterization plan, which was accepted by EPA and NMED (National Research Council, 2001, Appendix A1). DOE failed to realize that those characterization requirements would become a burden for the generator sites.[1] Also, DOE did not foresee that characterization requirements for CH-TRU waste would become a standard against which to evaluate the RH-TRU characterization plan. In fact, according to the information gathered by the committee, EPA and NMED intend to compare RH-TRU waste characterization requirements to those in the CH-TRU waste characterization plan, as explained in Chapter 4.

The draft RH-TRU waste characterization plan may be following the same path as the CH-TRU waste characterization plan. That is, by wanting to facilitate the certification process for RH-TRU waste, DOE is failing to ask the most important question about the characterization of RH-TRU waste: what is the purpose of waste characterization for WIPP? The answer is the following: to evaluate the impact of waste components on the long-term performance of the repository. The

committee recommends that existing requirements for CH-TRU waste, when applied to the characterization of RH-TRU waste, should be evaluated on the basis of their impact on the performance of the repository. The existence of regulatory requirements in the CH-TRU waste characterization plan does not imply that the same requirements should be included in the characterization plan for RH-TRU waste.

Finding 2: The committee questions the relevance of some of the requirements in the RH-TRU waste characterization plan to DOE's stated objective. According to the performance-based evaluation of RH-TRU waste by Sandia National Laboratories, presented in the characterization plan, none of the RH-TRU waste components have an effect on the long-term performance of the repository. **Recommendation: DOE should evaluate characterization requirements in the proposed plan against safety, their impact on the performance of the repository, and regulatory compliance.**

Rationale: The committee questions the relevance of some of the requirements proposed in the characterization of RH-TRU waste. For example, the detection of prohibited items, the determination of metal content, and the attribution of waste summary category groups do not seem to be characterization requirements based on the long-term performance of the repository (see examples below). According to the performance-based evaluation of RH-TRU waste by Sandia National Laboratories (Appendix 1 of Document 1 and Attachment B of Document 2), none of the RH-TRU waste components have an effect on the long-term performance of the repository. Many of the requirements in the proposed characterization plan of RH-TRU waste derive from the CH-TRU waste characterization plan described in WIPP's RCRA permit and EPA's certification. Concerning the CH-TRU characterization plan, the 1998 Committee found that "many requirements and specifications concerning waste characterization and packaging lacked a safety or legal basis"[2] (National Research Council, 2001, page 4). The present committee also recognizes that many such requirements were self-imposed and should be removed from the characterization plan of RH-TRU waste. The committee acknowledges that DOE's approach to use mostly AK without requiring 100 percent confirmatory activities is a positive step in this direction. However, the characterization plan's supporting documents should provide an analysis of the legal and safety requirements proposed for RH-TRU waste on the basis of their impact on the performance of the repository. Of course, legal requirements, like those in the Land Withdrawal Act, cannot be changed or removed, but these legal requirements are few and not excessively restrictive. The committee provides the following examples to support this finding and recommendation:

Example 1: The list of prohibited items contained in the RCRA permit for CH-TRU waste may not be appropriate for RH-TRU waste when the risks associated with hazardous chemical waste are balanced against radiological risks and costs. In Documents 1 and 2, there is no analysis of the safety implications of the prohibited items in WIPP. It is important to analyze the yet-undefined safety implications of these prohibited items and balance these implications against potential radiological risks to workers and associated costs of identifying prohibited items in RH-TRU waste. Such an analysis would be helpful to DOE in comparing the risks workers are exposed to and the associated costs of characterizing RH-TRU waste for prohibited items. The results of the analysis will support and strengthen DOE's RH-TRU waste characterization plan or point out deficiencies in it.

Example 2: In the CCA, DOE wrote: "Ferrous and ferrous-alloy metals (and their corroded products) provide the reactants that reduce radionuclides to lower and less-soluble oxidation states. As discussed in Appendix WCA [Waste Characterization Analysis], the anticipated quantity of these metals to be emplaced in WIPP is two to three orders of magnitude in excess of the quantity required to assure reducing conditions. The waste containers supply more than enough iron to provide adequate reductant. Therefore, no upper or lower limit need be established for the quantity of ferrous and ferrous-alloy metals that may be emplaced, beyond the present projection of containers" (DOE, 1996a, Appendix WCL.2). Nonetheless, in the CCA, DOE imposed a lower limit for ferrous material in the repository at 2×10^7 kg. Nowhere else in the CCA is this limit discussed or justified. This self-imposed limit has somewhat severe consequences because it requires DOE to use steel containers throughout the disposal phase. This example of

a self-imposed requirement is acknowledged by DOE-CBFO itself. In fact, DOE informed the committee of its intention to request the elimination of this limit during the re-certification process (DOE-CBFO, 2001f).

Example 3: Waste summary category groups indicate the final form of the waste as it is emplaced in WIPP. These groups are: homogeneous waste, soils and gravel, and debris waste. The CH-TRU waste requirements for NMED direct DOE to attribute a summary category group to each waste container. However, this information does not have any impact on the long-term performance of the repository. According to the information gathered thus far, this information is not used by NMED in any type of decision-making process concerning RH-TRU waste in the repository. Therefore, the committee questions why this requirement is being included in the RH-TRU waste characterization plan. A similar recommendation was made by the Institute for Regulatory Sciences peer review on DOE's characterization plan.[3]

Finding 3: The RH-TRU waste draft characterization plan reviewed by the committee does not clearly present DOE's stated objective of characterizing waste based on its impact on performance of WIPP, while protecting worker safety, reducing costs, eliminating unnecessary self-imposed requirements, and complying with regulatory requirements. In the committee's opinion, the documents reviewed do not put forward a performance-based characterization plan. **Recommendation: In the supporting documents, DOE should clarify the objectives of the characterization plan and how to achieve them.**

Rationale: DOE presented the objectives of its characterization plan for RH-TRU waste during the two information-gathering meetings with the committee. The committee expected these objectives to be clearly presented and pursued in Documents 1 and 2, but this was not the case. Document 2 mentions that DOE's characterization plan adopts a "Performance-Based Measurement System" but the committee struggled to find a clear explanation of this concept and its implementation in the supporting documents. The committee found a clear explanation of a "performance-based characterization plan" in EPA's Compliance Application Review Document No. 24, concerning waste characterization. This document reads: "DOE must provide waste inventory information for use in the performance assessment, including the radionuclide content of waste and the physical and chemical components that may affect disposal system performance" (EPA, 1998, page 21-1). EPA also defines a "waste characteristic" as "a property of the waste that has an impact on the containment of waste in the disposal system" (40 CFR 194.2). DOE's stated objective is in agreement with EPA's statements concerning waste characterization. However, the supporting documents do not explicitly outline the state objectives and the way DOE intends to implement its "performance-based characterization plan." The committee acknowledges that, in Attachment B of Document 1 and in Appendix 1 of Document 2, DOE provides two performance assessment analyses of RH-TRU waste in WIPP. However, these analyses and the performance assessment tool are not fully used to support a performance-based characterization plan. The performance assessment tool played a central role in WIPP's certification process. If the characterization plan were properly built upon performance assessment results, it would be easier for EPA and NMED to assess the plan and it could add credibility to the proposed characterization approach.

Finding 4: From the information gathered during the two committee meetings, it appears that most of the RH-TRU waste to be disposed of at WIPP will be newly generated waste, repackaged waste, or waste that has already been characterized following the CH-TRU waste characterization plan. Therefore, most RH-TRU waste does not need confirmatory measurements because the information collected during repackaging or generation can meet characterization requirements. **Recommendation: In the documents supporting its characterization plan, DOE should discuss the relative volumes of retrievably stored waste and newly generated waste in the context of the different qualities of AK. DOE should also consider the impact of these volumes and AK differences on the characterization plan.**

Rationale: According to DOE, about 80 percent of the RH-TRU waste inventory will be waste to be generated in the future or existing waste that must be repackaged (see Chapter 2). For this

large amount of waste, the information constituting AK will be collected during the generation or the repackaging of the waste. The committee agrees with DOE that AK for newly generated waste can meet the data quality objectives developed under the new RH-TRU waste characterization plan. Therefore, for about 80 percent of RH-TRU waste, confirmatory measurements may not be necessary as long as this waste is generated or repackaged using the approved quality assurance program plan.

Documents 1 and 2 do not mention that over 80 percent of the RH-TRU waste inventory will be newly generated or newly packaged waste. The committee recognizes that DOE made the distinction between the two qualities of AK (Attachment A, Document 1) for newly generated waste and retrievably stored waste. However, the committee suggests that the waste characterization plan distinguish not only AK qualities but also the relative volumes of newly generated waste and retrievably stored waste. This information may help DOE, the regulatory agencies, and the public to frame the context of the characterization plan for RH-TRU waste. If the volume of RH-TRU waste represents between 1 and 4 percent of the volume of TRU waste, and 80 percent of RH-TRU waste will meet AK, then only between 0.2 and 0.8 percent of the waste will need confirmatory activities for AK. This is an important observation, and it could have a substantial impact on characterization requirements proposed for RH-TRU waste.

Finding 5: There is substantial variability among RH-TRU waste generator sites, including:

- variability in the composition of the waste streams,
- variability in the extent of AK available,
- variability in the characterization and repackaging facilities available, and
- variability and uncertainties in the current and projected inventories of RH-TRU waste.

DOE's current characterization plan allows some flexibility to the sites, but it does not account explicitly for the above variability. **Recommendation: The RH-TRU waste characterization plan should recognize the large variabilities from site to site and should ensure sufficient flexibility to accommodate them. However, characterization activities that share common elements across sites should be standardized.**[4]

Rationale: The committee received the information about the RH-TRU waste inventories during its two information-gathering meetings. These data are reported in Tables 1 and 2 in Chapter 2. This information is barely present, as supplemental information, in Document 2. In the supporting documents, the committee expected a discussion about RH-TRU waste inventories at the different generator sites, their characterization plans, and capabilities. Including this discussion in Documents 1 and 2 could help DOE to recognize both the large variances from site to site and common elements across sites. Flexibility is important to adapt each characterization requirement to the site's RH-TRU waste inventory and characterization facilities. A rigid, overly prescriptive characterization plan may lead to unnecessary radiation exposures to workers and characterization costs. For example, small sites that do not have adequate characterization facilities may find themselves in a difficult situation if the characterization plan mandates specific confirmatory activities, even in the presence of adequate AK. If the site must perform confirmatory measurements or visual examination in a hot cell it would have to ship its waste to a different site[5] equipped with a hot cell or use a mobile hot cell. Therefore, the added costs of such confirmatory measurements could be significant. The committee also recommends that common elements among the sites be standardized to facilitate characterization compliance verifications and, possibly, reduce characterization costs.

Finding 6: The requirements to qualify information collected on each waste stream, whether by AK or by any other method described in 40 CFR 194.22(b), have not been established with any specificity in the supporting documents. **Recommendation: DOE should revise the supporting documents by adding clear and technically defensible data qualification requirements for its RH-TRU waste characterization plan. Additionally, each data quality objective should have a safety, technical, or legal basis.**

Rationale: To optimize waste characterization activities, it is important to define how generator sites will use AK, radiography, or visual examination to characterize their RH-TRU waste streams, the data qualification requirements, and the procedures to meet those requirements. This recommendation is also consistent with the recommendation of a second peer review on DOE's characterization plan.[6] The committee provides below an example of a missing or an unclear technical basis for one of the data quality objectives in Document 1.

Example: In Document 1, DOE does not provide a technical basis for the requirement that the quantification of the total activity "must be within a factor of 5 of the true value, with a confidence value of 95 percent." DOE provided an explanation during an information-gathering meeting: "The need to accumulate information regarding the total activity of RH-TRU waste is driven by limits set forth in the Land Withdrawal Act. The Land Withdrawal Act limits are derived from original DOE estimates about the RH-TRU inventory. The Transuranic Waste Baseline Inventory Report indicates that the total RH-TRU inventory to be disposed of at WIPP corresponds to a total activity of approximately one million curies (TWBIR, 1996). This corresponds to approximately one-fifth of the Land Withdrawal Act limit (5.1 million curies), hence the factor of five. Allowing an uncertainty of a factor of five (with a confidence level of 95 percent or greater) ensures that, even if the cumulative measurement of the estimated one million curies of RH-TRU waste activity were offset by a factor of five and biased low, the Land Withdrawal Act limit would not be violated (Nelson, 2001). The committee observes that, just because DOE expects to emplace one-fifth of the curies specified in the Land Withdrawal Act, this does not justify a requirement that the measured activity for a unit be within a factor of five of the "true value."

Finding 7: Available estimates of worker exposure and characterization costs for RH-TRU waste are scarce and may not be representative of all RH-TRU waste generator sites. **Recommendation: To better develop and support its characterization plan, DOE should provide more detailed and site-specific estimates of worker exposure and characterization costs for RH-TRU waste. The characterization plan should clearly demonstrate how it minimizes radiation exposure to workers and associated costs.**

Rationale: Since the characterization plan for RH-TRU waste is not yet finalized, information on worker exposure and characterization costs for RH-TRU waste is scarce. The only data available are from BCL and LANL, and they may not be representative for all RH-TRU waste generator sites (see Chapter 2). However, exposure and cost estimates can be calculated quite well, particularly if the uncertainties become a part of the results. The committee found the risk/cost impact study in Document 2 (Supplemental Information) to be very informative. However, this study only considered three characterization scenarios to estimate exposure risks and costs: the full characterization used for CH-TRU waste (see Appendix A), AK only, and visual or radiographic examination. A detailed risk perspective of worker exposure and costs could be very illuminating in developing characterization requirements and in adding credibility to the plan. The approach to estimate exposures would be to structure different scenarios, rank the scenarios on the basis of the supporting evidence, and calculate the exposures and doses. This type of dose and exposure information would add much to the discussion of the differences between CH- and RH-TRU waste characterization plans. An equivalent approach could be adopted to better estimate characterization costs. A similar recommendation was also provided by Restrepo and Millard.[7]

Finding 8: DOE's characterization plan calls for application of specific technologies, such as X-ray radiography, to provide confirmatory data. The committee could not determine the effectiveness of these technologies in characterizing the high-dose-rate fraction of RH-TRU waste containers. **Recommendation: DOE should provide complete and defensible justification for the technologies proposed for obtaining confirmatory data and provide evidence of their effectiveness.**

Rationale: DOE specifically mentions "X-ray scanning of waste containers to identify and verify waste contents" (Document 1, Attachment A, page 15). Given the importance placed on radiography to determine the presence of prohibited items, the characterization plan should clarify

and support the information on the method's effectiveness in high radiation fields expected for RH-TRU waste. In general, DOE should provide complete and defensible justification for the technologies proposed for obtaining confirmatory data and provide evidence of their effectiveness. This issue was also raised by NMED during the committee's information-gathering meeting (Zappe, 2001). This recommendation is also consistent with a recommendation by the RSI peer review on DOE's characterization plan.[8] DOE also concurs on this matter by stating: "Though DOE collected some data and analysis indicating that there are no fundamental obstacles to radiographing RH-TRU wastes, there has not been a systematic demonstration of that capability. As a consequence, there is lingering doubt regarding its feasibility in general. The simplest means to put these doubts to rest is to design and perform a systematic evaluation" (Taggart, 2001e). The committee supports this suggestion.

Observations and Issues for Further Clarification

To improve understanding, corroborate, and add credibility to its characterization plan, DOE should clarify the following points in its supporting documents:

Observation 1: The committee observes that the information in the supporting documents for the RH-TRU waste characterization plan is sometimes convoluted, difficult to understand, difficult to find, and repetitious. Examples are provided below.

Example 1: DOE presents an analysis that shows that the gamma-emitting radionuclides in RH-TRU waste will have a minimal impact on the long-term performance of the repository. DOE also presents an analysis that shows that RH-TRU waste components (metals, free liquids, cellulosics, plastic, rubber, and hazardous material) will have a minimal impact on the repository performance. These analyses are presented in Attachment B of Document 1 and in Appendix A of Document 2, respectively. The body of the text supporting the characterization plan barely refers to these two key analyses. DOE should give these analyses a more prominent role in Documents 1 and 2 and explicitly refer to these analyses to support its characterization plan.

Example 2: Some aspects of the characterization plan are difficult to evaluate because terms such as "representative selections" and "appropriate samples" are not properly defined.

Example 3: The plan, as described in Documents 1 and 2, lacks specificity. For example, for the CPR and free water, when is AK and when is radiography employed? Are surveys conducted by the same mechanisms for lower and higher surface dose rates? What is the link between the surface dose rates and the total curies by waste stream? How is a waste stream determined to be suitable for disposal at WIPP (i.e., transuranic waste of defense origin)? How are the ten radionuclides important to the long-term performance of WIPP (see Sidebar 2) identified and quantified?

Observation 2: There are conflicting statements and discrepancies between Document 1 and Document 2. The committee acknowledges that the two documents address different agencies and requirements. However, to improve the understanding and add credibility to its characterization plan, the documents could be made consistent with each other and conflicts and discrepancies resolved whenever possible. The committee provides three examples of conflicts or discrepancies between Document 1 and Document 2.

Example 1: Document 1 states that the differences between the RH- and CH-TRU characterization plans are not significant: "Because the RH-TRU waste characterization program does not represent a significant change to the existing certification, the 40 CFR 194 process will be the compliance mechanism for obtaining EPA's approval of each individual TRU waste site for disposal of its RH-TRU waste at WIPP" (Document 1, EPA01 Notice, page 6). However, Document 2 finds the differences significant: "The proposed modification is classified as a Class 3 permit modification per 20.4.1.900 NMAC…As indicated above, the additional provisions being requested in this permit modification, deemed necessary to provide for management, storage, and disposal of RH-TRU wastes, are indeed substantial and therefore meet the criteria and intent of a Class 3 modification" (DOE, 2001b).

Example 2: In Document 2, DOE allows for estimates of CPR, metals, and volatile organic compounds in the characterization of these waste constituents. Yet, DOE requires measurements without any specification of allowable uncertainties of the quantities of free water. This appears to be in conflict with the analysis in Document 1, Appendix A, which concludes that the performance of the repository is insensitive to the water content of the waste.

Example 3: Some of the statements made in Document 2 appear to contradict the approach to waste characterization discussed in Document 1. For example, on page 2-5 of ITEM 2, Document 2, DOE states: "This demonstrates that the waste material parameter weights and amount of free liquid for RH-TRU waste are not needed to ensure the integrity of the repository; therefore, waste characterization activities to identify these parameters are not necessary." Yet in Document 1, DOE lays out a program to measure the amount of free liquid in each waste container. The supporting documents should clearly specify that free liquid limits are necessary to meet transportation requirements and are not directly relevant to repository performance.

Observation 3: It is not clear how visual examination and radiography can differentiate all prohibited from non-prohibited items. For example, visual examination and radiography cannot distinguish between corrosive and non-corrosive liquids, whereas AK may provide records of the existence of such liquids in the waste. Therefore, AK may be a better indicator of some of the currently prohibited items than visual examination and radiography.

Closing Remarks

The statement of task directs the committee to provide recommendations based on scientific and technical considerations. The committee recognizes that some of its recommendations may not be implemented because of regulatory or policy decisions, which may not be based on scientific or safety considerations. These decisions ultimately belong to the regulatory agencies. The committee acknowledges and supports DOE's endeavors to improve worker safety, reduce costs, and eliminate unnecessary self-imposed requirements. However, the documents prepared for EPA and NMED to present the characterization plan for RH-TRU waste do not address these goals as effectively as they could. The committee acknowledges that DOE has been extremely responsive in revising the characterization plan on the basis of discussions during the information-gathering meetings. Also, staff of DOE-CBFO efficiently provided additional information whenever requested. The committee looks forward to future drafts of the characterization plan for RH-TRU waste. The committee will hold two more meetings to discuss the next draft of the characterization plan (if available), further address issues identified in this interim report, and develop its final report, which will be issued in the summer 2002.

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[1]DOE, during the second committee meeting, declared that the "contact-handled TRU waste characterization program is inefficient and costly" (DOE-CBFO, 2001d).

[2]According to the 1998 Committee, the requirements that do not have a technical basis are: sampling and analysis of homogeneous waste, headspace gas sampling and analysis, and visual examination procedures to characterize CH-TRU waste (see Chapter 4).

[3]The RSI peer review recommended: "DOE should evaluate the necessity of identifying waste streams by EPA's Hazardous Waste Numbers or Characteristics. If there is no impact on WIPP performance and integrity, the DOE should work with the regulatory agencies to remove this requirement" (RSI, 2001, page 77).

[4]According to the information provided by DOE, DOE is already amending its characterization plan to standardize as much as possible common elements across the complex.

[5]Shipments from site to site are allowed before the waste characterization plan is approved because DOE's waste characterization plan applies only to waste shipped to WIPP.

[6]The RSI recommended the following: "A detailed procedure for determining whether there is sufficient AK available on a waste should be developed as part of the permit application. This procedure should be consistent across all waste generating sites…[A] detailed procedure should be provided to go to other characterization methods if AK is found to be insufficient" (RSI, 2001,

page 77).

[7]The authors of the risk/cost analysis study in Document 2 recommend that "a detailed risk/cost impact analysis should be performed for individual site generators to quantify waste characterization option costs, potential worker dose rates, worker risks, and overall impact. This would facilitate a more rigorous evaluation of risks and costs for characterization options" (Restrepo and Millard, 2001, page iii).

[8]In its peer review, the RSI recommended: "More detail and specificity on WAC [waste acceptance criteria] using AK, VE [visual examination], and radiography (including types of instrumentation to be used) should be provided in the permit application" (RSI, 2001, page 77).

NOTE: References in this appendix apply to the committee's interim report (NRC, 2001b).

Appendix D

DOE's Response to the Committee's Interim Report

In response to the committee's interim report, the Department of Energy (DOE)-Carlsbad Field Office transmitted a summary of proposed resolutions or action items for the following draft of its characterization plan.

D.1 DOE's Response

DOE's response to the committee's interim report consists of two following two elements: 1) a letter containing DOE's proposed resolution and action items as a result of the committee's findings and recommendations and 2) an attachment to the letter, named Attachment 1. The letter and its attachment are presented in Boxes D.1 and D.2, respectively.

BOX D.1 DOE's Response to the Committee's Interim Report

PROPOSED RESOLUTION/ACTION ITEMS

Concerning NAS Finding and recommendation #1: We have reevaluated the characterization information needs consistent with this recommendation. The process considered long-term repository performance information needs, safety and technical considerations, regulatory requirements, and legal requirements and led to the development of a discreet list of Characterization objectives. Attachment 1 is the result of this effort.
Attachment 1 [see below] is being used to revise the Characterization Implementation Plan in the EPA submittal, as well as the WAP in the RCRA submittal. Attachment 1 also indicates whether or not we believe the characterization objectives require confirmation, and the methods we will propose in the submittal documents to obtain the characterization information.

Concerning NAS Finding and recommendation #2: The aforementioned Attachment 1 is the result of the reevaluation process we conducted as proposed by the NAS WIPP Panel.

Example 1: The list of prohibited items in the draft WAP (July 2001) will not be included as a specific list in the next draft WAP. With the exception of residual liquids, these "items" will be excluded from the list of prohibited items, but will continue to be dealt with by determining the hazardous waste numbers and prohibiting D001, D002, and D003. This effectively drives the decision from the container level to the stream level where hazardous waste code assignment decisions are typically made. The hazardous waste code(s) determination will be accomplished using AK. The 1% free liquid criteria was retained as a RCRA operational compliance consideration rather than for safety or performance reasons. The next draft WAP will be modified consistent with this change.
See Attachment 1 for the rationale and justification for hazardous waste numbers and residual liquids.
Example 2: CBFO may, in the future, choose to remove the metals limits set in the CCA.

Until this change is made, the proposed RH-TRU characterization program must continue to require tracking of metals. Contrary to the NAS statement ("severe consequences") the CBFO believes the "limits" do not impact the program, and the proposed characterization method of counting containers is simple to implement. For other reasons steel is the preferred material for waste containers, but the "limit" does not prohibit the use of other materials. The DOE anticipates that a minor amount of CH-TRU waste and no RH-TRU waste will be shipped in non-metal containers. We therefore do not view the consequences of the limitation as severe.

Example 3: The NAS is correct in pointing out that Summary Category Groups (SCG) have no impact on long-term repository performance. SCG is in the current CH RCRA Permit in order to affect a decision on what kind of waste analysis is required by the Permit (S3000 and S4000 waste streams must be sampled and chemically analyzed). No sampling and analysis is proposed for RH-TRU waste, however the SCG requirement is retained in the program because it allows for an easy method of accounting for cellulosics, plastics, and rubber (CPR), which are related to repository performance. Since SCG determination is relatively easy and is part of the EPA program anyway, it will be included in the RCRA program as an activity complying with 40CFR264.13.

Concerning NAS Finding and recommendation #3: The re-evaluation discussed for Finding #1 considered characterization objectives from a performance driven perspective as well as from regulatory and legal aspects. *Nearly all resulting characterization objectives are unrelated to repository performance or to safety/technical considerations.*
New supporting documentation will clearly show the basis for each characterization objective.

Concerning NAS Finding and recommendation #4: Consistent with this recommendation, DOE is preparing completed characterization documents for three major RH-TRU sites. These documents will be submitted directly to the EPA for its approval through the formal rulemaking process, and they will also be submitted to the NMED as examples along with a new draft request for RCRA Permit modification.

Concerning NAS Finding and recommendation #5: Submittals to both the NMED (RCRA compliance) and the EPA (40CFR194 compliance) are being redrafted to balance flexibility with standardization as appropriate.
The characterization documents discussed for Finding #4 will provide detailed inventory information which will assist in determining what aspects of the program can be standardized and how to allow for flexibility in site programs.

Concerning NAS Finding and recommendation #6: This Finding and Recommendation is also fully addressed by the Resolution discussed for Finding #1.
DOE agrees with the Panel that the former DQO associated with Total Activity is legally based and not technically based. As a result of the re-evaluation process described in the Resolution to Finding #1, it will be removed from the draft regulatory submittal documents.

Concerning NAS Finding and recommendation #7: After re-evaluating the approach to RH-TRU waste characterization, as discussed in Finding #1, DOE continues to believe that nearly all required RH-TRU waste characterization can be accomplished using AK. Therefore worker exposure is no longer a significant issue related to RH-TRU waste, and eliminating most characterization physical activities has minimized program costs.
Characterization activities may still be required on a very small percentage of the RH-TRU waste inventory, but these activities will always be conducted in such a way as to minimize worker exposure.

Concerning NAS Finding and recommendation #8
As suggested by the Panel, DOE will complete the "systematic evaluation" recommended by Taggart to conclusively demonstrate that current RTR technology is adequate for RH-TRU waste characterization use; however, the revised characterization program no longer requires that

confirmatory data be generated. For the minimal use of NDA and RTR that will still be required in the overall program, the standard technologies currently being employed in the CH-TRU waste program are more than adequate.
The RH Team recommended program (see Attachment 1) calls for NDE to be used *only to detect 1% residual liquid and only for a small percentage of the total RH-TRU waste inventory* (most RH-TRU waste will be repackaged or newly generated). Resolution of current RTR systems, even in high radiation fields, is adequate for this determination.

Concerning NAS Observation #1: Example 1: The next draft of the regulatory submittals will clearly reference the supporting analyses, and each characterization objective will have an explicit pointer to its basis.

Example 2: The redrafted documents will be purged of imprecise language and important terms will be properly defined.

Example 3: After the re-evaluation discussed in Finding #1, CPR will not be measured, it will be conservatively assigned a weight (based on the analyses referred to in Observation #1). However, in general, other techniques are to be employed only for the few (and usually small) waste streams for which there are insufficient AK. There is no direct link between surface dose rate and total curies that is used by the proposed program, however in some individual cases for some individual waste streams, if enough is known about the waste stream (AK), surface dose rate measurements can be used to adequately estimate the activity. The Defense Waste determination for RH-TRU waste will follow the acceptable precedent that has been established in the CH-TRU waste characterization program. The modified EPA submittal will provide detail concerning the TRU versus LLW determination. The ten radionuclides *are not important to repository performance* (See RH Impact Assessment included in the EPA submittal). This requirement will therefore not be included in the revised submittal document.

Concerning NAS Observation #2: Example 1: The statement made in Document 1 (the EPA submittal) was made in the context of what is significant relative to 40CFR194 and also allows that the EPA has the final decision regarding significance. The statement made in Document 2 (the RCRA submittal) was made in the context of what is significant relative to 20.4.1.900 NMAC. In addition, the NMED has made it very clear that they consider this to be a Class 3 modification.

Example 2: The modified Documents will no longer require estimates for CPR, metals, or VOCs. Some method of assurance that there is less than 1% residual liquids in a waste container is still required to address RCRA operational requirements, however no statement of allowable uncertainties is derived since there is no technical basis for an uncertainty statement.

Example 3: The redrafted supporting documents will make it clear that the origin of the 1% liquid requirement is from transportation, has no bearing on repository performance, and is only indirectly related to RCRA regulatory requirements.

Concerning NAS Observation #3: *The NAS is correct in the observation that VE and RTR are inadequate techniques for distinguishing the list of prohibited items in the previous draft.*
RTR or VE are suitable techniques for detecting and distinguishing residual liquids, and the re-evaluation requested in Finding #1 has determined that RTR or VE will only be used for that purpose. See also the Resolution to Finding #8.

NOTE: This table has been edited for formatting purposes. The emphasis (italicized text) was added by DOE-Carlsbad Field Office.
SOURCE: DOE (DOE-CBFO, 2002).

BOX D.2 Attachment 1 Accompanying DOE's Letter to the Committee (see Box D.1)

ATTACHMENT 1
RH-TRU WASTE CHARACTERIZATION PROGRAM

Objectives, Characterization Methods, Implementation Standards
RH-TRU Team Rationale and Justification

Introduction

The RH-TRU Team has reached consensus on what the basic elements of an RH-TRU waste characterization program should consist of (i.e., characterization objectives, characterization method, and implementation). This consensus was achieved by taking a "performance based approach" and examining from the "ground up" what the minimum characterization requirements should be to satisfy 40CFR194.24 (EPA) requirements and RCRA (NMED) requirements. Previous recommendations, findings, and observations from RSI and NAS/NRC reviews were heavily considered, and as the re-evaluation process progressed, each potential requirement was examined with respect to its basis; that is safety, repository performance, legal, or regulatory.

Table 1 for EPA requirements and Table 2 for NMED requirements present the RH-TRU Team consensus recommendations of what basic characterization elements should be used to build an EPA and NMED compliant RH-TRU waste characterization program. This paper explains the RH-TRU Team rationale or justification for each entry in the attached Tables. [see Box D.1]

Table Definitions (Columns) and Entry Justification/Rationale

There is a separate Table for the EPA related RH-TRU waste characterization elements and the NMED related RH-TRU waste characterization elements, however the column definitions are identical for both.

Characterization Objectives: This column lists the necessary overall program objective that must be accomplished by collecting waste characterization information. It is the basic question being asked and stems from safety, repository performance, regulatory, or legal considerations.

EPA Characterization Objectives

1. *Account for ferrous and non-ferrous metals*, is related to repository performance in that the CCA Appendix WCL requires a minimum of metals (20 million kilograms of ferrous metals and 2,000 kilograms of non-ferrous metals) be included in the final WIPP repository inventory. Thus it is necessary to account for disposed metals, by some means, in order to ensure that the specified minimums are emplaced. Once the minimum is achieved, no further accounting is necessary.

2. *Account for Cellulosics, Plastics, Rubber (CPR)*, is related to repository performance in that the CCA Appendix WCL limits total WIPP repository disposed inventory of CPR to a maximum of 20 million kilograms. Thus it is necessary to account for disposed CPR inventory, by some means, in order to ensure that the 20 million kilograms is not exceeded.

3. *Account for Free Water*, is a regulatory expectation that the RH-TRU Team believes is prudent to meet even though no amount of free water in the RH-TRU waste will impact repository performance. Note that CCA Appendix WCL.5 states that, "Consequently, there is no need to monitor water in the waste for compliance with 40 CFR § 194.24(c)." The RH-TRU Team recommends that free water in RH-TRU waste be accounted for by some means.

4. *Account for TRU Activity*, is a regulatory expectation that the RH-TRU Team believes is prudent to meet even though, for RH-TRU waste, it is unrelated to repository performance. Note that CCA Appendix WCL.1 states that, "The total activity of the waste is not important for 40CFR194.24(c), because the containment requirements are normalized to the initial inventory." The relationship of TRU activity to total activity is also explained in WCL.1, "The total activity of the waste at emplacement and during the entire 10,000-year performance period is dominated by the activities of four emplaced radionuclides: Am241, Pu238, Pu239, and Pu240." The RH-TRU Team recommends that TRU activity in RH-TRU waste be accounted for by some means.

5. *Ensure waste is TRU (activity ≥100 nCi/gm)*, is a legal requirement from the WIPP Land Withdrawal Act (LWA). The Team is in agreement that it is prudent to include it in the EPA Table, even though some members of the Team do not believe it to be of EPA regulatory concern.

6. *Account for Total Activity*, is related to the LWA legal requirement that WIPP final RH-TRU waste inventory be limited to 5.1 million total curies. Thus it is necessary to account for disposed RH-TRU waste total activity, by some means.

7. *Limit canister activity to <23 curies per liter*, is a LWA invoked legal requirement. This limit is specifically included in 40CFR194 as an EPA regulated Characterization Objective.

8. *Limit Surface Dose Rate of each container to <1000 rem/h*, is a LWA invoked legal requirement. This limit is specifically included in 40CFR194 as an EPA regulated Characterization Objective.

9. *Limit WIPP inventory to <5% by volume for >100 rem/h on a canister basis*, is a LWA invoked legal requirement. Thus canisters with surface dose rate exceeding 100 rem/h must be identified by some means.

10. *Ensure waste is RH (surface dose ≥200 mrem/h)*, is a de facto legal requirement of the LWA. The Team is in agreement that it is prudent to include it in the EPA Table, even though some members of the Team do not believe it to be of EPA regulatory concern.

NMED Characterization Objectives

1. *Assign Hazardous Waste Numbers*, is related to the regulatory requirement to comply with the terms and conditions of the WIPP Hazardous Waste Facility Permit (HWFP). The WIPP HWFP specifically prohibits hazardous wastes with the numbers D001, D002, and D003. Some other hazardous waste numbers have not been applied for and therefore are not allowed by the HWFP.

2. *Identify Physical Form*, is a regulatory requirement that is indirectly related to 40CFR264.13.

3. *Limit residual liquids to <1% volume of RH canister (or drum for 160B)*, is related to a regulatory requirement to provide secondary containment at the WIPP for potential spills. An analysis justifying the 1% for CH-TRU waste at the WIPP is part of the HWFP record, however a similar analysis has not been done for RH-TRU waste. The RH-TRU Team believes it is prudent to include this limit as an RH-TRU waste requirement also.

   Note 1: The current HWFP for CH-TRU waste also includes residual liquid restrictions for internal containers (i.e., "Waste shall contain as little residual liquid as is reasonably achievable by pouring, pumping and/or aspirat-ing, and internal containers shall contain less than 1 inch or 2.5 centimeters of liquid in the

bottom of the container.”). The RH-TRU Team did not retain these requirements for RH-TRU waste since their main purpose was related to eliminating the need to characterize liquids in internal containers (i.e., containers are RCRA “empty”). NMED Characterization Objective Number 1, *Assign Hazardous Waste Numbers*, requires the assignment of appropriate hazardous waste codes to containers, and the driver to further characterize liquids is eliminated.

Note 2: In addition to liquids the September 2001 draft RH-TRU waste WAP included the following “prohibited items:”

- Pyrophoric materials
- Incompatible waste
- Explosives and compressed gases
- PCBs with concentrations greater-than-or-equal-to 50 ppm

The RH-TRU Team concluded that it is unnecessary to specifically identify these “items” in the WAP or as specific Characterization Objectives. Pyrophoric materials, explosives and compressed gases fall under the RCRA definition of reactives (D003) and therefore are precluded by NMED Characterization Objective number 1, *Assign Hazardous Waste Numbers*. All wastes with HWFP acceptable Hazardous Waste Numbers have been demonstrated to be compatible, and therefore NMED Characterization Objective number 1, *Assign Hazardous Waste Numbers*, assures that there are no incompatible wastes. PCBs are subject to EPA regulation under TSCA and are regulated regardless of whether or not they are included in a RCRA permit as a prohibition. Therefore the RH-TRU Team has not included any of these “prohibited items” in the proposed RH-TRU waste characterization program as specific characterization objectives.

4. *Identify and Quantify VOCs*, is related to health and safety considerations derived from other (than RCRA) EPA release and exposure limits imposed by the NMED. The existing VOC conditions in the HWFP (e.g. Room Based Limits for VOCs) are based on an extremely conservative analysis of bounding VOC releases. The RH-TRU Team recommends that a bounding analysis specific to the small volume of RH-TRU waste will obviate the need for generator/storage sites to characterize RH-TRU waste for VOCs. This RH-TRU Team recommended approach for VOCs is exactly that already proposed in the September 2001 draft Class 3 Request for RCRA Permit Modification for RH-TRU waste.

Characterization Method: This column lists the general method to be used (as recommended by the RH-TRU Team) to accomplish the *Characterization Objectives* from the first column.

EPA Characterization Methods

1. *Count containers emplaced in the WIPP*, is a simple administrative accounting using the WIPP Waste Information System (WWIS) that meets the metals Characterization Objective. This method has already been approved by the EPA in the 40CFR191/194 “Final Rule” and is currently employed in the CH-TRU waste program. This is not a generator/storage site characterization requirement; it is a WIPP administrative requirement.

2. *Characterization method—Use AK to determine Summary Category Group (SCG) of each waste stream. WIPP admin requirement—Use WWIS to assign 620 kg/m^3 up to container tare weight for debris waste.* Relative to the CCA total inventory limit of 20 million kilograms of CPR, any practical contribution to the CPR inventory from RH-TRU waste is inconsequential. The *RH-TRU Inventory Impact Assessment Report* (Sandia, June 2001) used 620 kg/m^3 of plastic for a bounding analysis that demonstrated

repository performance is not affected by RH-TRU waste CPR. Out of the three Summary Category Groups, (S3000—homogeneous solids, S4000—soils and gravel, S5000—debris) only S5000—debris contains significant quantities of CPR. Thus a very simple and conservative approach for meeting the CPR Characterization Objective is to use AK to identify S5000—debris waste streams, and use the WWIS to electronically calculate and assign a CPR weight value for every S5000—debris RH-TRU waste container that is emplaced in the repository. Because this assignment is based on a bounding analysis, and because there will always be enough AK to make the simple SCG designation, no confirmation of this designation is required.

3. *Use AK to assign either 0% or 1% by volume for each waste stream.* The *RH-TRU Inventory Impact Assessment Report* (Sandia, June 2001) assumed that the final RH-TRU waste inventory in the WIPP was 50% by volume water. This bounding analysis demonstrated repository performance is not affected by any amount of water in RH-TRU waste. Thus a very simple and conservative approach for meeting this Characterization Objective is to use AK to either assign 0% volume of liquid to a specific RH-TRU waste stream or assign 1% volume. The RH-TRU Team chose 1% rather than 50% because transportation requirements will not allow more than 1% to be transported. Because the Sandia bounding analysis effectively demonstrates that selecting either 0% or 1% makes no difference in repository performance, and because AK will, in some cases, allow a definitive 0% decision to be made for a waste stream (e.g., thermally treated waste) or a default 1% will be assigned, no confirmation of this AK determination is required.

4. *Use AK to determine the relationship of TRU Activity to Total Activity for each waste stream, or establish a waste stream value by sampling and measurement, or measure the TRU Activity of each container.* The *RH-TRU Inventory Impact Assessment Report* (Sandia, June 2001) assumed, for a bounding analysis, that the entire RH-TRU waste curie loading allowed by the LWA (5.1 million curies) was composed of Pu239 and showed that even this impossible condition would still comply with the 40CFR191 containment requirement. Thus any minimal AK information available with which to roughly estimate the ratio of TRU to Total Activity is sufficient to meet this Characterization Objective without the need for confirmation. If this minimal AK information is not available, measurements of Total Activity and TRU Activity should be obtained on a few randomly selected containers from the waste stream to establish a waste stream value. Alternatively a generator/storage site may choose to measure the TRU Activity of each container. Note that the method for meeting this Characterization Objective (EPA number 4) is closely tied to, and interrelated with, the following two methods for EPA Characterization Objectives numbers 5 and 6.

5. The same Characterization Method used for TRU Activity (Characterization Method No. 4) is also used to make the TRU determination. Usually AK can be used to make a determination of TRU (versus LLW) for an entire waste stream if there is loading information (activity or mass) regarding Pu238 or Am241 and Pu239. Since this is a "legal" limit with no safety or repository performance implications, this AK determination need not be confirmed. If the TRU determination cannot be made using AK, a waste stream TRU determination may be made by measuring a few randomly selected containers. A TRU determination may also be made by measuring the value of TRU concentration for each container.

6. *Use AK to determine Total Activity of the waste stream, or establish a waste stream value by sampling and measurement, or measure the Total Activity of each container.* Any minimal AK information available with which to roughly estimate the Total Activity is sufficient to meet this Characterization Objective without the need for confirmation. *Characterization Parameters, Data Quality Objectives, and Methods* (LANL, July 2001) pointed out that the expected (from the TWBIR) RH-TRU waste total activity inventory could be biased low by a factor of five before the LWA limit is challenged. If this minimal

AK information is not available, measurements of Total Activity should be obtained on a few randomly selected containers from the waste stream to establish a waste stream value. Alternatively a generator/storage site may choose to measure the Total Activity of each container.

7. The same Characterization Method used for Total Activity (Characterization Method No. 6) may also be used to meet Characterization Objective number 7. *Characterization Parameters, Data Quality Objectives, and Methods* (LANL, July 2001) showed that for the vast majority of RH-TRU waste streams AK will demonstrate that it is not feasible to load a canister (or any container) to 23 curies per liter. For the rare exception where AK indicates 23 curies per liter is hypothetically feasible, measurements of Total Activity should be obtained on a few randomly selected containers from the waste stream to establish a waste stream value. Alternatively a generator/storage site may choose to measure the Total Activity of each container.

8. *Use standard industry survey methods to measure and report Surface Dose Rate.* This is a standard practice measurement using standard equipment. Any container that has a measured Surface Dose Rate of 1000 rem/h or greater cannot be shipped to the WIPP. This measurement also is used for achieving Characterization Objectives 9 and 10.

9. *Use standard industry survey methods to measure and report Surface Dose Rate.* This is a standard practice measurement using standard equipment. The Surface Dose Rate measured value of each container that is shipped to the WIPP must be reported in the WWIS. The WIPP will use WWIS data to load manage and assure no more than 5% of the containers of RH-TRU waste emplaced in the repository exceed a Surface Dose Rate of 100 rem/h.

10. *Use standard industry survey methods to measure and report Surface Dose Rate.* This is a standard practice measurement using standard equipment. If the Surface Dose Rate measured value of a container is less than 200 mrem/h then that container should be managed as Contact Handled TRU (CH-TRU) waste.

NMED Characterization Methods

1. *Use AK to delineate waste streams, assign Hazardous Waste Numbers and Summary Category Group (SCG) to waste streams, and assign individual containers to waste streams.* Hazardous Waste Numbers and SCG are assigned on a waste stream basis; therefore the population of containers constituting a specific waste stream must be identified. AK must be used for the majority of this information. There are no other reasonable means (i.e., measurement) or confirmation techniques. For example, F codes depend on the generation process and therefore can only be identified by knowledge of the process used (part of AK). Because all allowable hazardous wastes (identified by Hazardous Waste Numbers) are managed identically at the WIPP, Hazardous Waste Numbers, or lack thereof, are not used for any operational management decisions. <u>Confirmation of Hazardous Waste Number assignment is therefore not required.</u>

2. The Characterization Method for establishing SCG is the same as described in the preceding NMED Characterization Method number 1.

3. *Use AK to demonstrate that the waste stream does not contain residual liquid, or that individual containers in a waste stream contain <1% residual liquid, or sample and NDE/VE to determine the waste stream does not contain residual liquid, or NDE/VE each container in a waste stream.* AK may provide definitive information (e.g., all liquids are eliminated by thermal process) to show that the waste stream contains no residual liquids. <u>If so, no confirmation is required.</u> Or AK may provide a record for each container

showing that there is <1% liquid. If so, no confirmation is required. If AK is not definitive, NDE or VE of a few representative containers may show that the waste stream does not contain residual liquids. If AK or sampling indicates that there may be some containers with >1% residual liquid, then NDE or VE of each container should be done.

4. *Use bounding analysis for RH contribution to reduce current HWFP Room Limits.* This is not a Characterization Method. This analysis has already been completed and can be found in Appendix 2 of the September 2001 draft Request for Class 3 Permit Modification (RH-TRU). This analysis bounded the possible contribution of VOCs from RH-TRU waste, and correspondingly lowered the Room Based Headspace VOC Limits set in the current HWFP. Reducing the Room Based VOC concentration limits eliminates the need to characterize RH-TRU waste for VOC concentrations.

Implementation: This column sets the standard of adequacy, sufficiency, or acceptability for the *Characterization Methods* selected in the adjacent column.

EPA Implementation

1. *WWIS electronically counts.* As pointed out in the corresponding Characteriza-tion Method column, this is a WIPP administrative action, not a characterization activity and therefore no adequacy standard is set.

2. *Use generator/storage site SCG designation from site documents.* If a site has previously determined a waste stream(s) to be one of three SCGs (S3000—homogeneous solids, S4000—soils and gravel, S5000—debris), then that determination is acceptable for program use. If the site has not determined the SCG and AK shows the process that generated the waste produces a uniform and homogeneous product, then designate the waste stream as S3000 or S4000 as appropriate, otherwise designate the waste stream as S5000. Current RH-TRU waste inventory information indicates that every retrievable RH-TRU waste stream that is a candidate for WIPP disposal already has a SCG designation. The associated WIPP administrative action is described in the Characterization Method.

3. *AK documents use of liquid management procedures, or a process that precludes liquids; otherwise assign 1%.* To assign 0%, AK is sufficient if it is documented that the waste stream generation procedures included liquid management procedures (e.g., procedures required the removal of liquids or the absorption of liquids), or it is documented that the waste stream generation process precludes liquids (e.g., material balance input records, thermal treatment, etc.). If this AK information is negative or unavailable, a default assignment of 1% is made.

4. *AK must include TRU information (sufficient to demonstrate waste stream concentration exceeds 100 nCi per gram), or the waste stream value must be established by sampling and measurement, or the TRU Activity must be measured for each container.*
    - Because the same AK information is used for both the TRU Activity Characterization Objective and the TRU versus LLW determination, the more stringent TRU/LLW Characterization Objective sets the AK adequacy standard. Generally, AK is sufficient if the predominant TRU isotopes are identified (usually Pu238 or Pu239 and Am241), and there is waste stream activity information regarding those isotopes.
    - If sufficient AK information is not available, TRU Activity for the waste stream can be established by measuring TRU Activity of representative containers. As with AK, only the predominant TRU isotope (usually Pu238 or Pu239 and Am241) need be measured. A sufficient number of containers shall make up the sample size in order to establish that the waste stream value exceeds 100 nCi per gram with 67% certainty.

- If a site elects to measure the TRU Activity of each container, measurement of the predominant TRU isotope is sufficient. If activity of the predominant isotope is marginally below 100 nCi per gram, a site may choose to include additional TRU isotopes in the measurement.

5. See Implementation item number 4 above.

6. *AK must include sufficient information with which to make an estimate of Total Activity for the waste stream, or the waste stream value must be established by sampling and measurement, or the Total Activity must be measured for each container.*
   - AK is sufficient if the predominant high activity isotopes (e.g., Cs137) have been identified for the waste stream and there is a record of a few activity determinations for those isotopes.
   - If sufficient AK information is not available, Total Activity for the waste stream can be established by measuring Total Activity of representative containers. A sample size of two to ten containers, depending on waste stream size, and measurement of only the predominant high activity isotopes, is sufficient to establish a Total Activity value for the waste stream.
   - If a site elects to measure the Total Activity of each container, measurements of the predominant high activity isotopes are sufficient.

7. The analysis from Characterization Method eliminates any need for Implementation.

8. *Industry standard survey instruments.* This is a straightforward, common practice application of standard industry techniques to measure surface dose rate and requires no further explanation.

9. *Industry standard survey instruments.* This is a straightforward, common practice application of standard industry techniques to measure surface dose rate and requires no further explanation.

10. *Industry standard survey instruments.* This is a straightforward, common practice application of standard industry techniques to measure surface dose rate and requires no further explanation.

NMED Implementation

1. *Use generator/storage site waste stream designation, records of container assignments, Hazardous Waste Numbers if mixed waste, and SCG assignment.* Every RH-TRU site planning to ship RH-TRU waste to the WIPP is currently operating under an EPA authorized State RCRA program. Waste streams have previously been designated under these programs, hazardous waste numbers have been assigned when appropriate, and the SCG for each waste stream has been determined.

2. Implementation for Physical Form is included in the above Implementation number 1.

3. *AK must document the use of liquid management procedures, or a process that precludes liquids, or there must be a record for each container indicating <1% residual liquid, or NDE/VE of a few representative containers from the waste stream can show the absence of residual liquids, or every container must undergo NDE/VE.*
   - Liquid management procedures are standard operating procedures used in the waste generation process that eliminate or mitigate the presence of free liquids (e.g., removal or absorption). Examples of processes that preclude liquids are material input records that show no liquids were introduced to the process or a thermal treatment process that removes liquids.
   - If sufficient AK information is not available, the absence of residual liquids in any

container in a waste stream can be demonstrated with a statistical degree of certainty by NDE/VE of representative containers. A sufficient number of containers shall make up the sample size in order to establish that less than 10% of the containers in a waste stream contain more than 1% by volume residual liquids (with 67% certainty).
- A site may elect to NDE/VE every container in order to demonstrate that every container has less than 1% by volume residual liquid.

4. No Implementation is required for VOCs.

DQO: The RH-TRU Team applied the DQO process to each element of the proposed RH-TRU waste characterization program in order to ascertain whether formal DQOs need be developed. The DQO process was designed by the EPA primarily as a decision making tool applied to sampling and analysis studies for contaminated site remediation; however the process remains useful in the RH-TRU waste characterization program as a screening tool to determine if DQOs should apply. The seven-step DQO process is described in "Guidance for the Data Quality Objectives Process, EPA QA/G-4." Essentially DQOs establish what information is needed, and what level of quality the data should have associated with it, in order for a meaningful, risk based or consequence based decision to be made. "Data quality objectives (DQOs) for the data collection activity describe the overall level of uncertainty that a decision-maker is willing to accept in results derived from environmental data" (EPA SW-846). Using this process, the RH-TRU Team determined that there are no DQOs needed for the Characterization Objectives established for the RH-TRU waste characterization program.

EPA and NMED DQOs

- Step 1 of the DQO process is to "State the Problem." The problem statements for each element of the proposed RH-TRU waste characterization program are the Characterization Objectives listed in the first column of the attached Tables.
- Step 2 of the DQO process is to "Identify the Decision."
  - There are no decisions to be made as a result of characterization activities for Table 1 EPA elements 1, 2, 3, 4, 6, and 9. These are all data collection activities to provide information for management, administrative, or load management decisions that may be needed in the future. Thus there are no DQOs for these elements.
  - There are no decisions to be made as a result of characterization activities for Table 2 NMED elements 1, 2 and 4. Elements 1 and 2 are both administrative labeling activities done for the purpose of regulatory compliance that have no safety, repository performance, or technical consequences. NMED element 4 is potentially a data collection activity to enable future load management decisions regarding RCRA Permit *Room Based VOC Limits.* However the approach (Characterization Method from the Tables) taken for RH-TRU waste VOCs has eliminated this element as a RCRA characterization objective. Thus there are no DQOs for NMED elements 1, 2, and 4.
- Step 6 of the DQO process is to "Specify Tolerable Limits on Decision Errors."
  - The decision(s) to be made for EPA elements 5, 7, and 8 are receive-not-receive at the WIPP, and for EPA element 10 the decision is receive as RH-TRU waste or CH-TRU waste. Legal and regulatory limits and/or definitions drive decisions for each of these four elements, and there are no technical, safety, or repository performance consequences. Therefore "Tolerable Limits on Decision Errors" cannot be established for these four elements, and thus there are no DQOs for these elements.
  - The decision to be made for NMED element 3 is receive-not-receive at the WIPP. Regulatory operational compliance drives this decision, and since there are no technical, safety, or repository performance consequences, no "Tolerable Limits on Decision Errors" can be established. Thus there is not a DQO for

NMED element 3.

QAO: The WIPP project has historically listed “accuracy,” “precision,” “representative-ness,” “comparability,” and “completeness” as the elements of QAOs. These are the same elements used in the EPA SW-846 (2.1) definition of DQOs. From an EPA perspective, QAOs are synonymous with DQOs, and thus the RH-Team established no QAOs for either EPA or NMED Characterization Objectives for the same reasons DQOs were not applicable.

NOTE: This copy has been edited for formatting purposes. The emphasis (italicized text) was added by DOE-Carlsbad Field Office. This table is part of the document DOE’s Proposed Resolution and Action Items in Response to the Committee’s Interim Report.
SOURCE: DOE (DOE-CBFO, 2002).

REFERENCE

DOE-CBFO. 2002. This material was submitted to the committee on January 18, 2002. This record is publicly available.

Appendix E

Information About Selected Transuranic Waste Generator Sites

The Department of Energy (DOE) provided this information in the March 2002 draft of both Document 1 (Notification of Proposed Change to the U.S. Environmental Protection Agency (EPA) Title 40 Code of Federal Regulations Part 194 Certification of the Waste Isolation Pilot Plant (WIPP), Attachment 3) and Document 2 (Request for RCRA Class 3 Permit modification to the NMED, Supplement 1). The committee did not verify or review this information. Table E.1 lists the Environmental Protection Agency (EPA) hazardous waste codes relevant to the sites mentioned in this appendix.

E.1 Hanford Site

The Hanford Site is one of the major contributors to the remote-handled transuranic (RH-TRU) waste inventory projected in WIPP (see Chapter 2).

E.1.1 Location and Description

The Hanford Site is located north of the Tri Cities (Richland, Kennewick, and Pasco), in Washington on a 1,450 km^2 area of semiarid land in the Columbia River Basin in the southeastern corner of the State. Normal Columbia River elevations range from 119 m, where the Columbia River enters the Hanford Site near the Priest Rapids Dam, to 104 m where it leaves the Hanford Site near the 300 area. Activities at Hanford are centralized in numerically designated areas. The reactor facilities are located along the Columbia River in what is known as the 100-Area. The reactor fuel processing and waste management facilities are in the 200-Area. The 300-Area, located adjacent to and north of Richland, contains the reactor fuel manufacturing facilities and the research and development laboratories. The 400-Area, 5 miles northwest of the 300-Area, contains the Fast Flux Test Facility, a sodium-cooled fast breeder reactor. The 600-Area covers all locations not specifically given an area designation. Adjacent to and north of Richland, the 1100-Area contains facilities associated with administration, maintenance, transportation, and materials procurement and distribution. The 3000-Area contains engineering and administrative offices. Administrative buildings, including the Federal Building, are located in the 700-Area, which is in downtown Richland. The Hanford Site is administered by the DOE Richland Operations Office.

E.1.2 Mission

The Hanford Site was acquired by the federal government in 1943 for the construction and operation of facilities to produce plutonium for the atomic weapons program during World War II. For more than 30 years, Hanford Site facilities were primarily dedicated to the production of plutonium for national defense and management of the wastes generated by chemical processing operations. In later years, programs at the Hanford Site became increasingly diverse, involving research and development for advanced reactors, renewable energy technologies, waste disposal technologies, and cleanup of contamination from past practices. The DOE has ended the production mission at the Hanford Site and is currently reorienting activities toward waste management and cleanup at the site. The mission now is one of environmental management, demonstration and application of advanced remediation technologies, and restoration of the Hanford Site.

E.1.3 Waste Information

Remote-handled TRU wastes from Hanford are the result of multiple sources. Some of these sources generated waste that now needs to be segregated between the categories of low-level waste, contact-handled transuranic (CH-TRU), and remote-handled transuranic waste. Some RH-TRU waste is currently stored in the 200-W Area in the Central Waste Complex and retrievably stored in the 200-E and 200-W areas in the Low-Level Burial Grounds. Future generation is forecast from activities related to the Hanford cleanup. The mission of the Central Waste Complex is to receive and store solid radioactive waste in a safe and environmentally compliant manner. The Central Waste Complex provides interim storage for mixed low-level waste, transuranic waste, and a small amount of low-level waste, awaiting treatment and final disposal. The design storage capacity is approximately 80,000 55-gallon drum equivalents; the operational capacity is 64,000 drum equivalents. The Central Waste Complex receives waste from both on-site and off-site waste generators.

Receipt of transuranic waste drums retrieved from the Low Level Burial Grounds began in 1999. All newly generated waste must meet acceptance criteria set by the Hanford Site Solid Waste Acceptance Program. Waste is generally packaged in 55-gallon drums unless alternate packages are dictated by size, shape, or other form of waste.

Each drum is handled individually using a hand truck, forklift, or crane. Drums are placed on wooden pallets with a maximum of four drums banded together; the pallets can then be stacked three high, or 12 drums per stack.

The storage buildings or pads have physical features that provide for segregated storage areas to maintain appropriate separation between groups of incompatible waste. Some RH-TRU waste will be segregated from the waste retrieved from the Low-Level Burial Grounds in the 200-Area. The waste to be retrieved from the Low-Level Burial Grounds is believed to primarily be low-level waste, though the waste will be segregated as it is retrieved and characterized. The RH-TRU wastes will be characterized and packaged at the M-91 facility. Another source of RH-TRU waste is the Plutonium Uranium Extraction Plant located in the 200-E Area. Products from this plant were weapons-grade plutonium, fuel-grade plutonium, depleted uranium, slightly enriched uranium, neptunium, and thorium. The plutonium conversion, process solution sampling, laboratory analyses, plant ventilation, and facility ventilation generated waste that was common to all these PUREX operations, including surgical gloves, plastic (polyvinyl

chloride and polyethylene), tape, paper, glass, glovebox gloves, and metal tools and equipment.

The overall PUREX plant process consisted of seven fundamental interfacing processing units: feed preparation; solvent extraction, separation, and purification; solvent recovery and treatment for recycling; back-cycle waste system; acid recovery; waste treatment; off-gas treatment; and conversion of plutonium nitrate to plutonium oxide. Wastes generated were old failed equipment, port covers, replaced windows, brackets and hardware, and acid-soaked rags. Process solution sampling operations extract liquid samples from process control points to be used in system analysis and control. After use, all liquids were drained to the PUREX liquid waste system. Waste generated at this facility included broken glassware and plasticware, wet rags and paper, and piping and valving equipment. Laboratory Analysis Operations were performed on liquid process samples used for system analysis and control. After use, all liquids were drained to the PUREX liquid waste system. Again, wastes generated were broken glassware and plastic-ware, and wet rags and paper.

RH-TRU waste is also being stored in two spent nuclear fuel basins known as the K-Basins in Hanford's 100-K Area. This source consists of approximately 50 cubic meters of layered particulate material, which is generally called sludge. This sludge will be collected and transported to a stable interim storage location away from the Columbia River and eventually sent to a final disposal location. Sludge is found on the K-Basins, floors, in canisters, and in the basin pits. Several different types of sludge exist depending on the basin, canister type, and pit location where the particular sludge is found. Each type of sludge is a unique nonhomogeneous mixture possibly containing corroded fuel (i.e., uranium oxides, hydrates, hydride), cladding pieces, debris such as wind-blown sand or insects, rack and canister corrosion products, ion exchange resin beads, polychlorinated biphenyls, and/or fission products. In addition to the existing sludge material, other particulate materials are expected to be generated in the processing of fuel elements for dry storage. The sludge in the basins is commingled with spent nuclear fuel and is not considered a waste; however, when the sludge is separated from the spent nuclear fuel and removed from the basins, it will be dispositioned as RH-TRU waste.

For the purposes of differentiating spent nuclear fuel and debris from sludge, any material that is less than or equal to 0.64 cm (1/4 in.) in diameter is defined as sludge. Finally, RH-TRU waste will be generated from future activities related to facility stabilization and cleanup, maintenance of process equipment, laboratory operations, and Office of River Protection tank farm cleanup operations. This waste includes miscellaneous debris, equipment, and components and instrumentation trains removed during remediation of the high level waste tanks. The current estimates are that 207 cubic meters of RH-TRU is stored and an additional 944 cubic meters of waste will be generated. No canisterization of this waste has been performed with the majority of this waste to be generated (i.e., packaged) in the future.

The major radionuclides reported are cobalt-60, cesium/barium-137, strontium/yttrium-90, uranium-233, americium-241, plutonium-238, plutonium-239, plutonium-240, and plutonium -241. Based on known information about program activities, the estimated dose rate range is expected to be between 0.2 to 1,000 rem per hour. Due to the variety of processes, the presence of hazardous constituents will need to be ascertained on a stream-by-stream evaluation of the acceptable knowledge available on the generating process. Based on information previously reported in the TRU Waste Baseline Inventory Report, the following hazardous waste codes have been reported for RH-TRU wastes: F001, F002, F003, F004, F005, D001, D002, D005, D006, D007, D008, D009.

E.2 Idaho National Engineering and Environmental Laboratory

The Idaho National Environmental and Engineering Laboratory stores RH-TRU waste generated in national defense programs and research activities from across the country. For volume and radioactive waste inventory information, see Chapter 2.

E.2.1 Location and Description

The Idaho National Environmental and Engineering Laboratory is located in two primary areas: (1) the remote areas known as “the site” along the northern edge of the Snake River Plain in southeastern Idaho and (2) multiple locations southeast of the site in the city of Idaho Falls. Lying at the foot of the Lost River, Lemhi, and Bitterroot-Centennial Mountain ranges, the site covers nearly 2,300 square km (890 mi^2) of dry, cool desert. Most of the land withdrawn from public domain for use by DOE is undeveloped. The facilities located in Idaho Falls include administrative, scientific support, and nonnuclear research laboratories. During World War II, the U.S. Navy and U.S. Army Air Corps used a portion of the present site as a gunnery range. In 1949 the site was formally established as the National Reactor Testing Station, a place where the Atomic Energy Commission could build, test, and operate various types of nuclear reactors. Fifty-two reactors have been built at the Idaho National Engineering and Environmental Laboratory; of these, seven are operating or operable. The Radioactive Waste Management Complex encompasses 144 acres in the southwestern corner of the Idaho National Engineering and Environmental Laboratory. The Radioactive Waste Management Complex was established in 1952 as a controlled area for burial of solid radioactive wastes generated by Idaho National Engineering and Environmental Laboratory operations. In 1954 the burial ground was designated as a solid TRU waste disposal site. Until 1970, all TRU was buried below grade at the Radioactive Waste Management Complex. In November 1970 the Transuranic Storage Area was established for retrievable storage of waste contaminated with greater than 10 nanocuries of TRU alpha activity per gram of waste. In November 1976 the Intermediate Level TRU Storage Facility was established for retrievable storage of RH-TRU contaminated waste (greater than 200 millirem per hour). At the Intermediate Level TRU Storage Facility the radioactive waste is stored in above-grade vaults.

E.2.2 Mission

The Idaho National Engineering and Environmental Laboratory is a multi-program laboratory and has provided innovative technologies, defense-related support, and unique scientific and engineering capabilities to the nation. At present, areas of primary emphasis include nuclear reactor technology research and development, waste management and environmental restoration, advanced energy production and utilization technology development, defense-related support, technology transfer, and nonnuclear research and development projects. Development, transfer, and deployment of technologies to avoid and/or dispose of hazardous and/or radioactive waste and for remediation/restoration of previous disposal sites to protect the public, employees, and environment are also part of the Idaho National Engineering and Environmental Laboratory’s mission.

E.2.3 Waste Information

RH-TRU waste generated in national defense programs and research activities from across the country was buried or stored at the Radioactive Waste Management Complex. The majority of the RH-TRU was generated at off-site facilities and shipped to the Idaho National Engineering and Environmental Laboratory for disposal or storage. These wastes came from Rocky Flats Environmental Technology Site, Argonne National Laboratory-East, Argonne National Laboratory-West, Battelle Columbus Laboratories, and other sites. The physical descriptions for these wastes are therefore consistent with the physical waste descriptions provided for each of these sites in different sections of this appendix, and the reader is directed there for those descriptions. In the case of Rocky Flats Environmental Technology Site, the RH-TRU was only differentiated from the CH-TRU shipped for disposal or storage at the Idaho National Engineering and Environmental Laboratory by its surface dose rate. The physical constituents of this TRU waste were typically the same and included cloth, paper, plastics, metals, rubber, sludge, or concrete. The TRU waste received at the Idaho National Engineering and Environmental Laboratory from November 1970 through July 1980 was placed on asphalt pads with an earthen cover to protect the waste from the environment until it could be permanently disposed of. Waste received after this time frame was placed in air-supported buildings for interim storage. The current estimate is that 84 cubic meters of RH-TRU is stored and that an additional 52 cubic meters of waste will be generated or recovered. No canisterization of this waste has been performed. Storage drums are typically 30 or 55 gallons. Major radionuclides reported include cobalt-60, cesium/barium-137, strontium/yttrium-90, uranium-235, americium-241, plutonium-238, plutonium-239, plutonium-240, and plutonium-241. Due to the wide variety of program activities, the estimated dose rate range is expected to vary from 0.2 to 100 rem per hour. Due to the variety of sources of RH-TRU at the Idaho National Engineering and Environmental Laboratory, the hazardous constituents could be varied, ranging from solvents and degreasers to metals, such as lead or cadmium. The presence of these hazardous wastes will need to be ascertained on a stream-by-stream evaluation of the acceptable knowledge available on the generating process at each generating sites. Based on information previously reported in the TRU Waste Baseline Inventory Report, the following hazardous waste codes have been reported for RH-TRU wastes: D008, D022, D028, D029, F001, F002, F003, and F005.

E.2.4 Supplemental Information

Additional potential sources of RH-TRU waste are being identified during review of Idaho National Engineering and Environmental Laboratory programs. One source is anticipated to be generated at the Idaho National Engineering and Environmental Laboratory from the Idaho Nuclear Technology and Engineering Center. This volume is anticipated to be about 900 cubic meters. The facility was previously known as the Idaho Chemical Processing Plant and was established in the early 1950s. Its original mission was to reprocess spent nuclear fuels by chemically separating out the reusable uranium and subsequently calcining the resultant high-level waste. The current mission is the storage of low-level, mixed low-level, and high-level waste and spent nuclear fuel and the development of treatment methods for high-level waste. Several evaluations are now in process to assess the treatment options for packaging the RH-TRU waste generated during processing of the high-level waste. This waste is expected to be classified as Waste Incidental to Reprocessing and disposed of at WIPP. Evaluations are also under way to examine treatment and packaging options for disposal. Depending on the option

selected, the final packaged volume could be significantly greater than the current estimate of 900 cubic meters.

E.3 Los Alamos National Laboratory

The Los Alamos Scientific Laboratory was established in 1943 by the U.S. Army's Manhattan Engineering District for the purpose of developing the first atomic weapons. Known as the Los Alamos Scientific Laboratory for many years, the name was changed to the Los Alamos National Laboratory in December 1980.

E.3.1 Location and Description

The Los Alamos National Laboratory is located approximately 97 km north of Albuquerque and 40 km west of Santa Fe in Los Alamos County, New Mexico. The laboratory facilities are dispersed among numerous technical areas spread over a 111-km^2 site on the Pajarito Plateau. The plateau consists of several finger-like mesas extending eastward from the Jemez Mountains to the Rio Grande Valley, with steep eroded canyons separating the mesas. The elevation of the mesas ranges from 1,890 to 2,377 m. Some Technical Areas are located in canyons.

E.3.2 Mission

Los Alamos National Laboratory was the research, development, engineering, design, and testing center for the Manhattan Project. The mission was the application of science and technology to problems of national security, including the maintenance of a strong defense, the fulfillment of arms controls commitments, and the guarantee of a secure energy supply for the future. Los Alamos National Laboratory's mission since World War II has included nuclear device design, research, development, testing, stockpile certification, and plutonium storage. Major programs currently include research in nuclear and conventional weapons development; nuclear fission and fusion; nuclear safeguards and security; verification and control technologies; fundamental research in particle physics, mathematics, chemistry, and materials; and waste management technology development and testing. Research on peaceful uses of nuclear energy has included space applications, power reactor programs, magnetic and inertial fusion, radiobiology, and medicine. Other programs include astrophysics, earth sciences, lasers, computer sciences, solar energy, geothermal energy, biomedical and environmental research, and nuclear waste management research.

E.3.3 Waste Information

RH-TRU waste is primarily generated by the Irradiated Materials Examination Group. This waste consists of solid wastes from laboratory and hot cell operations and includes small laboratory and hot cell equipment, materials such as fines resulting from grinding and cuttings, miscellaneous fuel specimens and their containers, and general debris from hot cell cleanup and decontamination. The general debris consists primarily of combustible waste, such as paper, rags, plastic, and rubber, with the plastic component consisting of tape, polyethylene and vinyl gloves, Tygon tubing, polystyrene, plastic vials, Teflon, and plexiglass. The cellulosic portion consists of rags, wood, cardboard, lab coats and coveralls, and paper. Noncombustible wastes that are present include

cans, lids, graphite molds, furnaces, pyrochemical salts and related equipment, and glassware.

Some RH-TRU waste will be received from programmatic activities at the Sandia National Laboratory. The current estimate is that 98 cubic meters of RH-TRU is in storage and that 24 cubic meters of RH-TRU waste will be generated. The Los Alamos National Laboratory is unique in that it is the only site with waste packaged into canisters for handling and disposal at WIPP. Seventeen canisters of waste are currently packaged and stored in the waste storage area at Los Alamos National Laboratory. Other RH-TRU wastes are typically stored in small (1- to 5-gallon containers) and will be canisterized prior to disposal at WIPP. Major radionuclides reported include cesium/barium-137, strontium/yttrium-90, americium-241, plutonium-238, plutonium-239, plutonium-240, and plutonium-241. The estimated dose rate ranges are expected to be 1 to 100 rem per hour. Potential hazardous wastes included various cleaners and degreasers, cadmium, and lead. Based on information previously reported in the TRU Waste Baseline Inventory Report, the following hazardous waste codes have been reported for TRU wastes at Oak Ridge National Laboratory: F001, D006, D008.

E.4 Oak Ridge National Laboratory

The Oak Ridge National Laboratory is the site that stores most of the existing RH-TRU waste in DOE's inventory (see Chapter 2).

E.4.1 Location and Description

The Oak Ridge National Laboratory is located 10 miles southwest of downtown Oak Ridge, Tennessee, and 32 km northwest of Knoxville, Tennessee. The Oak Ridge National Laboratory site occupies about 10,000 acres of the 35,252-acre-Oak Ridge Reservation. The site covers portions of both Melton and Bethel valleys. Approximately 1,100 acres in the Melton and Bethel valleys has been developed. The Oak Ridge National Laboratory is under the auspices of the DOE/Oak Ridge Operations Office, which supports production of nuclear weapon components for national defense programs, production of enriched uranium for defense requirements and for fueling nuclear power plants, processing of uranium feed materials for DOE’s plutonium production reactors, and extensive energy research and development in all DOE program areas.

E.4.2 Mission

The Oak Ridge National Laboratory was established in 1942 in support of the Manhattan Project. The primary mission of the Oak Ridge National Laboratory has been to carry out applied research and engineering development in fission, fusion, and other energy technologies and to conduct scientific research in basic physical and life sciences. Relevant missions include isotope production and processing, research and development, waste management, and decontamination and decommissioning of operating units, and advanced reactor development work. In addition, the Oak Ridge National Laboratory conducts several activities for DOE defense programs. The principal nonweapons-related activities include nuclear power development and magnetic fusion research.

E.4.3 Waste Information

Most of the RH-TRU waste at Oak Ridge National Laboratory has been generated as a result of special isotope separation activities. The Radiochemical Engineering Development Center at Oak Ridge National Laboratory has processed americium-curium targets that were irradiated in the High Flux Isotope Reactor to produce higher actinides such as californium, berkelium, einsteinium, and fermium. The ion exchange processing of these targets generated and consists of two distinct waste streams, a solid stream (debris waste) and a sludge/liquid stream. Solid RH-TRU debris waste consists primarily of miscellaneous hot cell waste (e.g., paper, glass, plastic tubing, shoe covers, wipes), high-efficiency particle activated filters from off-gas cleanup systems, and discarded equipment (e.g., chemical processing racks, vacuum pumps). This waste was contaminated with the original target material and the higher actinides, except for the einsteinium and fermium, which decayed quickly due to their very short half-lives. This solid debris is stored in concrete casks as RH-TRU waste. There is substantial historical process knowledge about the content of each cask (ORNL, 1989). For example, some casks contain a large number of 1 gallon pails of hot cell waste while others may have a single failed piece of equipment. The unshielded individual waste packages in the casks typically have radiation levels that measure 10 to 2,000 rem per hour; the majority are below 100 rem per hour.

Hazardous wastes in RH-TRU solid waste primarily consist of lead that was used as shielding and limited amounts of mercury from discarded mercury vapor lamps. The RH-TRU solid waste is typically contained in cylindrical concrete casks 1.4 m (4.5 ft.) in diameter by 2.3 m (7.5 ft.) high. Wall thickness of the casks are currently either 15.2 or 30.5 cm (6 or 12 in.) thick, depending on the radiation level of the contents.

The majority of RH-TRU sludges at the Oak Ridge National Laboratory are the result of waste accumulation from the past 50 years of liquid waste operations there. These sludges are residuals from sluicing operations conducted in the early 1980s when the majority of the inactive gunite tank contents were removed for hydrofracture disposal at Oak Ridge National Laboratory. This liquid waste is now stored in the Melton Valley Storage Tanks. RH-TRU sludges continue to accumulate due to on going research and development programs, that produce transuranic isotopes for medical, industrial, and government applications.

The surface dose rates of these sludges are generally near 10 rem per hour (unshielded). The current estimate is that 1,308 cubic meters of RH-TRU is stored and that an additional 534 cubic meters of waste will be generated. No canisterization of this waste has yet been performed, but canisterization is scheduled to begin in fiscal year 2003 and will be performed by Foster-Wheeler, the contractor performing the characterization and packaging activities. Major radionuclides reported include cobalt-60, cesium/barium-137, strontium/yttrium-90, europium-152, europium-154, uranium-233, uranium-235, uranium-238, americium-241, plutonium-238, plutonium-239, plutonium-240, plutonium-241, curium-244, and californium-252. The estimated dose rate range is expected to be 0.2 to 1,000 rem per hour. Based on information previously reported in the TRU Waste Baseline Inventory Report, the following hazardous waste codes have been reported for RH-TRU wastes at Oak Ridge National Laboratory: D006, D007, D008, D009, D011.

E.5 Energy Technology Engineering Center

The Energy Technology Engineering Center is a small generator site. This site will serve as model to other small generator sites in the implementation of the RH-TRU waste characterization plan. The site-specific RH-TRU waste characterization implementation plan from this site will be submitted to the regulatory agency along with Documents 1 and 2 (see Chapters 4 and 5).

E.5.1 Location and Description

The Energy Technology Engineering Center occupies 90 of 290 acres of land shared with the Santa Susana Field Laboratory. The Santa Susana site consists of a total of 2,700 acres located in the Simi Hills of Ventura County, California, approximately 48 km northwest of downtown Los Angeles. The facilities include former fuel fabrication facilities, a hot cell, a reactor test building, a storage vault, an on-site transport cask, and other radiologically contaminated support laboratories and areas.

E.5.2 Mission

Energy Technology provides facilities for the testing of equipment, materials, and components for nuclear and other energy programs. Components include steam generators, pumps, valves, instrumentation, and other support elements for power plant design. Various types of testing include reliability, seismic, and performance demonstrations. Current activities include non-nuclear testing and cleanup and environmental restoration from prior nuclear testing programs, such as decontamination and decommissioning of a hot cell licensed by the Nuclear Regulatory Commission that was used for DOE activities.

E.5.3 Waste Information

The RH-TRU waste at Energy Technology Engineering Center was generated during DOE fuel decladding and decontamination and decommissioning operations. The RH-TRU waste consists of two waste streams: (1) hot laboratory drain line residue and (2) a single drum of debris waste from multiple sources. The drain line residue is currently stored in 28 concrete-shielded 55-gallon drums and one 30-gallon drum. An additional amount of about 22 gallons of sludge is estimated to be in a 3,000-gallon drain tank and about 10 gallons of residue in two weir boxes. The total volume of the unpackaged waste is about 0.3 cubic meters. The total volume of the drain line residue material when all of the material is repackaged for on-site storage in concrete-shielded drums is estimated to be forty 55-gallon drums plus one 30-gallon drum, or about 8.5 cubic meters. The single 55-gallon drum from the debris waste has a total volume of 0.21 cubic meters. The total RH-TRU volume is therefore 8.7 cubic meters. There are no plans to canisterize RH-TRU waste at the Energy Technology Engineering Center. The RH-TRU waste will be sent to an intermediate site for final waste disposal characterization and final packaging. It is anticipated that the intermediate site may either be Oak Ridge or Hanford. Major radionuclides expected include cobalt-60, cesium/barium-137, strontium/yttrium-90, americium-241, plutonium-239, plutonium-240, and plutonium-241. Dose rates are relatively low in the range of 0.2 to 10 rem per hour. Based on acceptable knowledge documentation, such as process records, and supplemental analyses, the Energy Technology Engineering Center has assigned waste codes below to these waste streams. Recent tests have also shown that the drain line

residue stream has polychlorinated biphenil levels approaching 100 ppm. The Energy Technology Engineering Center plans to manage its RH-TRU waste as three separate waste streams. Based on information previously reported in the TRU Waste Baseline Inventory Report, the following hazardous waste codes have been reported for RH-TRU wastes at this site: D008 and D009.

E.6 Battelle Columbus Laboratories

This site is the only one actively characterizing its RH-TRU waste inventory. This site is seeking authorization to ship its RH-TRU waste to the Hanford Site for interim storage (see Chapter 2).

E.6.1 Location and Description

The Battelle Columbus Laboratories consists of two research complexes: one at 505 King Avenue in the city of Columbus, Ohio, and the second, the West Jefferson Site in Madison County west of Columbus. The King Avenue facility houses corporate offices and general research laboratories. The West Jefferson site consists of a number of facilities formerly dedicated to nuclear research. The King Avenue facility is located in the western central portion of the city of Columbus. The 10-acre complex accommodates 21 buildings and is bounded on the north by King Avenue, on the east by Battelle Boulevard, on the south by Fifth Avenue, and on the west by the Olentangy River. The Columbus campus of Ohio State University lies immediately north across King Avenue. The remaining contiguous area is a moderately dense residential neighborhood. The West Jefferson Site is located in West Jefferson, Ohio, approximately 24 km west of the King Avenue facility. The 1,000-acre tract accommodates 21 buildings in the Engineering Area, Experimental Ecology Area, and Nuclear Services Area. The site boundary on the north is about 1 mile south of I-70, on the east is Big Darby Creek, on the south are the Conrail tracks, and on the west is the Georgeville-Plain City Road. The land to the north, west, and south for 2 miles is cleared farmland and/or wood lots.

E.6.2 Mission

The mission of Battelle in 1943 was to perform atomic energy research and development activities for the Manhattan Engineering District. Since that time Battelle has continuously performed research and development at these facilities. Past programs have included uranium ore processing and benefaction studies, metallurgical and ceramic process development, corrosion studies, fabrication of weapons components, ballistics experiments, hot cell work, critical assembly and criticality experiments, and an experimental reactor.

E.6.3 Waste Information

The main DOE-sponsored work currently being done at Battelle Columbus Laboratories is decontamination and decommissioning of the contaminated buildings and hot cells at the West Jefferson location. This work is being performed under the direction of the Battelle Columbus Laboratories Decommissioning Project. The decontamination and decommissioning activities involve removing from the hot cells equipment used in the fuel examination process, materials such as fines resulting from grinding and cuttings, miscellaneous fuel specimens and their containers, and general

debris. The current estimate is that a total of 20.8 cubic meters of RH-TRU waste will be generated; some of this waste is currently in the process of being packaged. The proposal is to consolidate this waste at an intermediate facility for disposal characterization and any additional packaging. A memorandum of agreement is currently under development for use of the Hanford Reservation as the intermediate site. None of the RH-TRU waste is canisterized for transport in the RH-72B cask. The current plan is to use the CNS 10-160B to ship the majority of waste; therefore, the RH-TRU waste is being packaged in 55-gallon drums. Major radionuclides reported include cobalt-60, cesium/barium-137, strontium/yttrium-90, americium-241, plutonium-239, plutonium-240, and plutonium-241. Measured dose rates range from 0.2 to 150 rem per hour. Based on acceptable knowledge documentation (e.g., production and process records, analytical lab records), the following hazardous waste codes have been reported for RH-TRU wastes: D005, D007, D009, D011, F001, F002, and F005.

TABLE E.1 EPA Hazardous Waste Codes Relevant to this Appendix

Hazardous Waste Code	Criteria and Characteristics of Hazardous Waste
D001	Ignitability
D002	Corrosivity
D003	Reactivity
D004-D029	Toxicity: A solid waste whose extract under the test procedure specified under 40 Code of Federal Regulations Part 261.24 contains one or more constituents at concentrations greater than those specified in the Maximum Concentration of Contaminants for the Toxicity Characteristic Table. The toxicity characteristics of selected hazardous waste codes together with their maximum concentration of contaminants are listed below (D004-029).
D004	Arsenic > 5 mg/L
D005	Barium > 100 mg/L
D006	Cadmium > 1 mg/L
D007	Chromium > 5 mg/L
D008	Lead > 5 mg/L
D009	Mercury > 0.2 mg/L
D011	Silver, > 5 mg/L
D022	Chloroform > 6 mg/L
D028	Dichloroethane (1,2-) > 0.5 mg/L
D029	Dichloroethylene (1,1-) > 0.7 mg/L
	Hazardous Waste from Non Specific Sources
F001	The following spent halogenated solvents used in degreasing: Tetrachloroethylene, trichloroethylene, methylene chloride, 1,1,1- trichloroethane, carbon tetrachloride, and chlorinated fluorocarbons; all spent solvent mixtures/blends used in degreasing containing, before use, a total of 10% or more (by volume) of one or more of the above-halogenated solvents or those solvents listed in F002, F004, and F005 and still bottoms from the recovery of these spent solvents and spent solvent mixtures.
F002	The following spent halogenated solvents: Tetrachloroethylene, methylene chloride, trichloroethylene,1,1,1-trichloroethane, chlorobenzene, 1,1,2-trichloro-1,2,2-trifluoroethane, ortho-dichlorobenzene, trichlorofluoromethane, and 1,1,2-trichloroethane; all spent solvent mixtures/blends containing, before use, a total of 10% or more (by volume) of one or more of the

	above-halogenated solvents or those listed in F001, F004, or F005 and still bottoms from the recovery of these spent solvents and spent solvent mixtures.
F003	The following spent non halogenated solvents: xylene, acetone, ethyl acetate, ethyl benzene, ethyl ether, methyl isobutyl ketone, N-butyl alcohol, cyclohexanone, and methanol; all spent solvent mixtures/blends containing, before use, only the above spent non halogenated solvents; and all spent solvent mixtures/blends containing, before use, one or more of the above non halogenated solvents, and a total of 10% or more (by volume) of one or more of those solvents listed in F001, F002, F004, and F005; and still bottoms from the recovery of these spent solvents and spent solvent mixtures.
F004	The following spent non halogenated solvents: Cresols and cresylic acid, and nitrobenzene; all spent solvent mixtures/blends containing, before use, a total of 10% or more (by volume) of one or more of the above non halogenated solvents or those solvents listed in F001, F002, and F005; and still bottoms from the recovery of these spent solvents and spent solvent mixtures.
F005	The following spent non halogenated solvents: Toluene, methyl ethyl ketone, carbon disulfide, isobutanol, pyridine, benzene, 2-ethoxyethanol, and 2-nitropropane; all spent solvent mixtures/blends containing, before use, a total of 10% or more (by volume) of one or more of the above non halogenated solvents or those solvents listed in F001, F002, or F004; and still bottoms from the recovery of these spent solvents and spent solvent mixtures.

REFERENCE

ORNL (Oak Ridge National Laboratories). 1989. L. S. Dickerson, Remote-Handled Transuranic Solid Waste Characterization Study: Oak Ridge National Laboratory, ORNL/TM-11050. Oak Ridge National Laboratory. Oak Ridge, Tenn.

Appendix F

Overview of the Contact-Handled Transuranic Waste Characterization Plan

The characterization program described here has been developed for contact-handled transuranic (TRU) waste and applied to date to TRU mixed waste. The methods, equipment, procedures, determination of uncertainty, and other protocols used at DOE sites to perform these characterizations have been approved by the Department of Energy (DOE) Carlsbad Field Office, New Mexico Environment Department (NMED) and EPA. The major procedures are described in the following sections:

F.1 Determination of the Origin and Composition of the Waste by Acceptable Knowledge

Acceptable knowledge (AK) of the origin and composition of the waste must be documented to provide evidence that the waste has a defense origin (by the terms of the Land Withdrawal Act, only defense-related TRU waste may legally be sent to the Waste Isolation Pilot Plant (WIPP) and to provide characterization information on the waste constituents. The DOE Carlsbad Area Office and EPA use the AK documentation to certify each “waste stream” (i.e., waste-generating process), and TRU waste sent to WIPP must come from a certified waste stream.

F.2 Sampling and Analysis of Homogeneous Waste for Resource Conservation Recovery Act Constituents

Most of the TRU waste is heterogeneous in nature and requires no further characterization beyond AK to satisfy the regulatory requirements of Resource Conservation Recovery Act (RCRA). For homogeneous waste a fraction of the waste containers (e.g., 55-gallon drums or standard waste boxes) are cored to extract representative samples that are analyzed for constituents (e.g., volatile and semivolatile organic compounds, toxic metals other hazardous chemicals) regulated by RCRA. Both the AK procedure (for heterogeneous waste) and the sampling and analysis procedure (for homogeneous waste) were proposed by DOE for the terms of operation that would be specified in its RCRA permit. These terms have been accepted by New Mexico, which was delegated authority by EPA to regulate RCRA materials and mixed waste and to issue the RCRA Part B permit in October 1999.

F.3 Radiography

A radiography procedure using X rays, also called real-time radiography, is performed on all waste containers to look for items such as pressurized cans or free-standing liquids that are prohibited from being transported under U.S. Department of Transportation regulations. If any of these items are present in a waste container, the prohibited materials are removed and the contents repackaged. This radiographic examination is also used to confirm the AK characterization information.

F.4 Visual Examination

A visual examination is performed on a fraction of the waste containers by placing the waste contents into a glovebox to verify the AK and real-time radiography information. DOE proposed that 2 percent of the initial population of containers of each waste stream be visually examined, and if these evaluations resulted in few miscertifications, the percentage of subsequent waste containers to undergo visual examination would be reduced. In October 1999, New Mexico in its RCRA permit stipulated the initial fraction of containers to undergo visual examination to be 11 percent.

F.5 Radioassay and Determination of Fissile Isotope Content

The number of curies of each transuranic isotope is determined by radioassay (e.g., gamma scans) to a specified precision and accuracy. The fissile isotope content is assessed using non-destructive assay methods, such as passive-active neutron systems. This information is used to meet the Nuclear Regulatory Commission requirement restricting the amount (several hundred grams) per container of each fissile species to ensure criticality safety.

F.6 Headspace Gas Sampling

Headspace gas sampling is carried out on all waste containers for flammable gases (specifically, volatile organic compounds, hydrogen, and methane). This procedure has been proposed as a means of checking on conformity with the U.S. Department of Transportation regulations, such as Title 40 Code of Federal Regulations (CFR) Part 173 and Title 40 CFR Part 177, and U.S. Nuclear Regulatory Commission regulations, such as Title 10 CFR Part 71, that address the transport of flammable and/or gas-generating substances with radioactive materials. DOE has proposed the headspace gas sampling procedure in its application to the U.S. Nuclear Regulatory Commission for a licensing certificate on the transportation package (named the TRansUranic PACkage Transporter, or TRUPACT-II) that is loaded with waste containers for transport by truck to WIPP.

Appendix G

Non-Destructive Techniques for Remote-Handled Transuranic Waste Characterization

This appendix is based on information gathered by the committee in the time frame allowed by this study. It should not be considered a comprehensive review of all techniques being considered to characterize remote-handled transuranic (RH-TRU) waste.

Non-destructive characterization of RH-TRU waste is challenging because of the high surface dose rate of waste canisters (up to 1,000 rem per hour) resulting from the high background gamma and neutron radiation generated by fission and activation products in the waste. To reduce the risk of worker exposure during characterization of RH-TRU waste, non-destructive examination and assay techniques are needed to avoid performing destructive analysis such as visual examination and radiochemical assays. According to the information gathered from DOE's Transuranic and Mixed Waste Focus Area: "Non-destructive examination and assay techniques to characterize remote-handled wastes must still be developed and demonstrated" (DOE-ID, 2001).

Non-destructive assay (NDA) identifies radioactive components, and non-destructive examination (NDE) determines the physical makeup of the waste. These non-destructive technologies must be capable of accurately identifying the physical and radiological properties of wastes in lead-lined containers as well as correcting for precision or bias problems caused by matrix effects (such as heterogeneity problems and interferences with heavy metals in waste) and by the high radiation background. In particular, the neutron emitting RH-TRU solid debris waste at Oak Ridge National Laboratory is the most challenging to characterize.

The following is a brief overview of the major non-destructive characterization techniques currently under development by various Department of Energy (DOE) generator sites, contractors, and private companies. Further development of these techniques and demonstration on actual RH-TRU waste is pending the outcome of the characterization plan for RH-TRU waste. The major NDA/NDE techniques considered for RH-TRU waste are the following:

G.1 Radiography

This NDE technique is often referred to as X-ray radiography or real-time radiography (RTR). X-rays provide a direct measure of material density and as such can be used to establish the physical form of the waste and identify certain prohibited items. In addition, operators can be trained to look for indicators of prohibited items such as electrical components that could contain polychlorinated biphenyls. This technique consists of an X-ray source combined with a TV camera attached to an X-ray detector.

Roney and White (2001) studied the characterization of RH-TRU and lead-lined drums using X-ray imaging techniques. (Roney and White, 2001). Although no real RH-TRU waste was used in their work, they demonstrated the applicability of radiography to surface dose rates up to 100 rem per hour. TMFA states that: "current real time radiography (RTR) techniques cannot analyze the content of the lead-lined drums. Similarly, RH waste inserts and casks are too thick for conventional RTR analysis and interrogation may be further complicated by high radiation levels and contributed 'white noise' from inside the drum" (DOE-TMFA, 2002a).

To the best of the committee's knowledge, radiography has not been demonstrated on real or surrogated waste with surface dose rates close to 1,000 rem per hour.

G.2 Gamma-Ray Spectroscopy

Gamma-ray spectroscopy uses the gamma emission and transmission properties of radionuclides contained in the waste to obtain qualitative and quantitative information of radionuclide content. Gamma-ray tomography is a variation of gamma spectroscopy and is used to determine the spatial and quantitative information of radionuclide distribution in waste containers. Matrix interferences are corrected by scanning for known gamma-ray sources. For further information on related technologies, see, for example, Meeks and Chapman (1997).

G.3 Gamma-Ray Spectroscopy Combined with Acceptable Knowledge

The GSAK approach is used to determine the quantities and types of radionuclides in waste drums. This technique is based on measurement of the radionuclide distribution in the waste followed by normalizing this distribution to the activity of a gamma-emitter such as cesium-137 or cobalt-60, which can be measured outside the waste drum. Based on the measured surface dose rates for cesium-137 or cobalt-60, the amount of these two radionuclides inside the drum can be estimated. This in turn allows the activity of the other radionuclides in the waste drum to be estimated using their ratio to cesium-137 or cobalt-60. The radionuclide distribution may be determined through gamma spectroscopy methods or other nuclear counting methods for alpha- and beta-emitters. Because alpha- and beta-emitters are often difficult to measure in waste, measurements are sometimes used in conjunction with detailed computer modeling to develop a radionuclide distribution that includes these hard-to-measure radionuclides. This technique requires an accurate knowledge of the waste to be characterized before measurements are integrated with computer modeling.

The Battelle Columbus Laboratories have demonstrated this technique with actual RH-TRU waste (Biedscheid et al., 2002). The Idaho Engineering and Environmental Laboratory is also planning to use this technique for its RH-TRU waste originated in Argonne National Laboratory-East (Bhatt and Clements, 2001). For further information about this technique and its demonstrations see Hartwell et al. (1997, 2000), Jensen (2001), and Klann and Grimm (2000).

G.4 Passive and Active Neutron Measurement

Passive and active neutron measurements are widely used in waste management and safeguard operations for fissile mass measurements (usually plutonium-239,

plutonium-241, or uranium-235) and for determination of alpha contents for disposal sites. This technique is based on the spontaneous fission rate determination of fissile material present in the container in (passive neutron measurement mode) and on the induced fission rate by neutron interrogation (active neutron measurement mode). The technique is sensitive to extraneous neutrons coming from secondary alpha decays and from cosmic background. This technique was used to characterize 10 actual RH-TRU waste containers and over 200 containers of surrogate RH-TRU waste at Los Alamos National Laboratory (Estep et al., 1989; Estep, 2001, 2002). For further information on this technique and its variations see DOE (1998), Ensslin et al. (2000), Royce and Lucero (2001), and Schultz et. al. (1995).

G.5 Multi-Detector Analysis System

The multi-detector analysis system (MDAS) technique is used to obtain a direct isotopic measurement with no prior knowledge of the waste. MDAS interrogates the (unshielded) waste with neutrons, and then collects energy coincidence measurements through multiple detectors for both gamma and neutron data over a small period of time. Coincident neutrons provide information on the quantity of fissile material present, and coincident gamma rays provide information on specific isotopes from fission products. This technique is designed to reduce background measurement interferences so that a direct isotopic measurement is provided. Uncertainties associated with current passive/active neutron measurement techniques are reduced by measuring the coincidence energies fast neutrons. A demonstration of this technique on RH-TRU waste was scheduled for 2001 but did not take place due to problems with the external neutron source. For further information on this technique, see DOE-TMFA (2002b), DOE-ID (2001) and Shelton-Davis (2001).

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Appendix H

Waste Dose Rates and Characterization Cost Estimates

The committee provides the following worker dose and characterization cost estimates as examples of the type of assessments that could be presented in the three implementation plans (from Battelle Columbus Laboratories, Energy Technology Engineering Center, and Oak Ridge National Laboratory) that the U.S. Department of Energy (DOE) is planning to submit to the U.S. Environmental Protection Agency and the New Mexico Environment Department along with its characterization plan for remote-handled transuranic (RH-TRU) waste. The committee's assessment is based on the information gathered during the study. It is not to be considered complete and is not meant to replace DOE's own assessment of worker doses and costs.

The predominant exposure pathways for workers from routine waste handling activities are direct exposure to external penetrating radiation or inhalation from surface contamination, and inhalation of airborne radioactive material generated during characterization and handling activities. The radiogenic health effects associated with TRU waste are due primarily to alpha and gamma radiation. Beta particles and neurons may also pose health concerns for RH-TRU waste if the container is breached or waste is exposed during handling or characterization.

H.1 Committee's Example of Estimate for Waste Dose Rates

Because of the high surface dose rates, all of the handling operations involving RH-TRU waste are performed in hot cells, where available, and/or by remote-handling equipment. Good radiological safety practices require that all radiological activities must maintain worker dose levels ALARA (as low as reasonably achievable). In the absence of appropriate radiological safety measures, the potential for significant radiation exposure is high. The estimated volume-weighted mean RH drum surface dose rate at individual generator sites is 470 mSv per hour (47,000 mrem per hour) (Wu, 2001). Therefore, the cost associated with the handling of RH-TRU waste may be substantial.

Doses from handling RH-TRU waste are expected to be less than contact-handled transuranic (CH-TRU) waste due to requirements for remote handling. For instance, the DOE-Carlsbad Field Office estimated for the period 1999-2001 that the collective dose for handling CH-TRU waste at the Waste Isolation Pilot Plant (WIPP) is approximately 0.08 person-mSv (0.008 person-rem) per transportation cask type TRUPAC-II. According to Wu (2001), this is about two times higher than the estimated collective dose to workers handling a RH72-B type cask of RH-TRU waste.

Doses to workers depends on several factors including the number of drums characterized and handled, types of sampling and measurements conducted, number of workers involved in the characterization and drum handling, worker experience and training, and facilities, equipment and shielding. Table H.1 compares estimated

collective doses to workers at three different sites. Because these data are from different sites they may not be comparable.

TABLE H.1 Committee's Estimates of Worker Doses at Selected Sites

Site	Collective Dose	Comment
Battelle Columbus Laboratories	1.0 person-mSv (100 person-mrem) per container	This dose corresponds to an average of five workers handling the containers and includes waste characterization and handling containers for storage.[1]
Argonne National Laboratory-East	0.22-0.64 person-mSv (22-64 person-mrem) per container	Range of collective doses for four different location and storage scenarios.[2]
Waste Isolation Pilot Plant (WIPP)	0.02 person-mSv (2 person-mrem) per container	Waste is shipped to WIPP in RH72-B waste canisters (assume each canister contains 3 containers of 55 gallons). Waste handlers receive 80 % of the dose.[3]

NOTE: Collective doses may not be representative of all RH-TRU waste generator sites. This table was compiled by the committee as an example of worker dose estimates on the basis of information gathered during the study. It is not intended to be complete and may contain inaccuracies.
[1]Memorandum from Dr. Rigley at Battelle Columbus Laboratories (BCL, 2000).
[2]Radiological risk assessment at Argonne National Laboratory-East (Cheng et al., 2002).
[3]Information presented to the committee during the second meeting (Wu, 2001).

The Battelle Columbus Laboratories in Ohio developed its own RH-TRU waste characterization plan, which involves visual examination of the waste during re-packaging. The re-packaging step, which occurs in a hot cell, is necessary because the this site's RH-TRU waste containers do not meet transportation requirements. At this site, the worker dose per container (100 person-mrem per 5 persons corresponds to 20 mrem) is within the range of worker doses for CH-TRU waste characterization (Wu, 2001). It is unclear how representative Battelle Columbus Laboratories worker exposure data are for other RH-TRU waste generators. However, the Battelle data are informative because this is the only site actively characterizing RH-TRU waste.

A radiological risk assessment for RH-TRU waste has been performed for storage options at Argonne National Laboratory-East (Cheng et al. 2002). Although characterization of RH-TRU waste has not begun at this site, risk assessments have been conducted to analyze potential radiation exposures associated with various on-site storage scenarios. Detailed analyses of container handling activities at the Alpha Gamma Hot Cell Facility show that the major determinants of worker collective dose are manipulation of containers for waste loading and placing and securing container lids. These two activities account for 75 percent of the collective dose to workers (Cheng et al., 2002).

The WIPP facility has estimated worker doses for the handling and emplacement of RH-TRU waste (Wu, 2001). WIPP is currently not authorized to receive RH-TRU waste; estimates of worker doses are based on calculated average container surface dose rates, shielding characteristics of the RH72-B canister, and remote-handling of waste canisters. Worker doses are substantially lower than doses estimated at the generator sites primarily because of RH72-B canister shielding.

As shown in Table H.1, collective dose may vary widely between and within sites. For instance, container handling methods and procedures (the key determinant of worker dose) may differ. Further, the relative importance of worker exposures incurred during the characterization phase compared to that incurred in other handling operations will likely differ at the generator sites. Accordingly, it is important that ALARA programs be site-specific.

H.2 Committee's Example of Cost Estimates

Characterization costs including facilities and instrumentation for RH TRU waste sampling and measurements are significant. According to DOE and the generator sites, the characterization of an RH-TRU waste container under the CH-TRU waste characterization requirements is estimated to cost in the range of $20,000 to $300,000 per container (Restrepo and Millard, 2001). In contrast, the cost of characterizing CH-TRU waste is about $3,800 per container (DOE-EM, 2001). The large range in RH-TRU characterization cost estimates is due to the variability in the waste content and the characterization processes among the sites. In addition, these cost estimates are not site-specific and take into account only a few characterization scenarios. Associated infrastructure costs in support of full characterization of RH-TRU waste have been estimated to be $100,000 per container (Restrepo and Millard, 2001). The Committee has not verified these cost estimates.

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Appendix I

Glossary

20.4.1 (The New Mexico Administrative Code Chapter 20, Section 4, Part 1): New Mexico Environment Department. Establishes the regulations for the management of hazardous waste consistent with the New Mexico Hazardous Waste Act and Federal Resource Conservation and Recovery Act (RCRA) regulations, Titles 40 Code of Federal Regulations (CFR) Parts 260 through 270.

20.4.1.200: New Mexico Environment Department (NMED). This regulation (incorporating Title 40 CFR Parts 261.24, 261.31, and 361.33) requires the US. Department of Energy (DOE) to identify and list hazardous wastes.

20.4.1.500: New Mexico Environment Department. This regulation (incorporating Title 40 CFR 264) requires DOE to conduct a detailed analysis of the hazardous waste components of transuranic mixed waste to obtain all the information on how to treat, store or dispose of the waste. DOE must demonstrate that the design and operation of the facility will minimize the possibility of the release of TRU mixed waste, a fire, or an explosion. NMED prohibits the following at WIPP:

1. liquid waste;
2. pyrophoric materials;
3. non-mixed hazardous wastes;
4. chemically incompatible wastes;
5. explosives and compressed gases;
6. polychlorinated biphenyl concentrations; and
7. ignitable, corrosive, and reactive waste.

20.4.1.900: New Mexico Environment Department. This document contains the hazardous waste permit program requirements issued by the NMED (incorporating 40 CFR 270). These requirements must be met by the DOE to receive NMED approval of the waste analysis plan submitted as Part B of the permit application (see Hazardous Waste Permit) for mixed transuranic waste.

10 CFR 20: (Title 10 Code of Federal Regulations Part 20): United States Nuclear Regulatory Commission. Standards for Protection Against Radiation.

10 CFR 835: U.S. Department of Energy. Occupation Radiation Protection. Establishes the standards, limits, and program requirements for protecting individuals from ionizing radiation resulting from DOE activities.

40 CFR 191: U.S. Environmental Protection Agency (EPA). Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Final Rule. December 20, 1993. Federal Register (FR) 58(242): 66398-66416. This regulation prescribes EPA environmental radiation protection standards that will apply to all sites (except Yucca Mountain) for the deep geologic disposal of highly radioactive waste. Congress required EPA to evaluate whether the WIPP complies with Subparts B and C of the disposal regulations set forth in this document for the management and disposal of transuranic radioactive wastes.

40 CFR 194: U.S. Environmental Protection Agency. Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's compliance with the 40 CFR Part 191 Disposal Regulations, Final Rule. May 18, 1998. Federal Register 63(95): 27353-2740. This regulation stipulates that DOE must provide a list to the EPA that identifies and describes waste characteristics that can impact the WIPP's performance. This list may be derived from methods that include process knowledge and non-destructive assay/examination. On May 18, 1998, the EPA issued a final rule certifying that the WIPP was compliant with applicable EPA TRU waste disposal regulations set forth in 40 CFR 191 and the compliance criteria of 40 CFR 194 (63 FR 27354).

40 CFR 194.22(b): U.S. Environmental Protection Agency. This section includes the quality assurance requirements for waste characterization activities and assumptions. The quality assurance provisions allow the characterization of waste by 1) peer review; 2) corroboration with new data, 3) confirmation by measurement, or 4) qualification of previous QA programs.

40 CFR 261: U.S. Environmental Protection Agency. Identification and Listing of Hazardous Waste. This part identifies those solid wastes that are subject to regulation as hazardous wastes under Parts 262-265, 268, 270, 271, and 124 of Title 40 of the Code of Federal Regulations. Codified in New Mexico as 20 NMAC 4.1, Subpart II.

40 CFR 264: U.S. Environmental Protection Agency. This part consists of "Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities." This subpart establishes minimum national standards, that define the acceptable management of hazardous waste. Codified in New Mexico as 20 NMAC 4.1, Subpart V.

40 CFR 270: U.S. Environmental Protection Agency. This regulation establishes provisions for the Hazardous Waste Permitting Program under Subtitle C of the Resource Conservation and Recovery Act. This regulation and the associated State of New Mexico regulations require the permitting of the WIPP as a hazardous waste management unit. Codified in New Mexico as 20 NMAC 4.1, Subpart IX.

Acceptable Knowledge (AK): a term used by the EPA that encompasses process knowledge and results from previous testing, sampling, and analysis of waste. Acceptable knowledge includes information regarding the raw materials used in a process or operation, process description, products, and associated wastes. Acceptable knowledge documentation includes the site history and mission, site-

specific processes or operations administrative building controls, and all previous and current activities that generate a specific waste.

ALARA (As Low As is Reasonably Achievable): radiation protection program for minimizing personnel exposure to radiation. ALARA means making every reasonable effort to maintain exposures to radiation as far below the dose limits in the DOE guidance as is practical consistent with the purpose for which the activity is undertaken.

Audit: a planned and documented investigative evaluation of an item or process to determine the adequacy and effectiveness as well as compliance with established procedures, instructions, drawings, and other applicable documents.

Buried Transuranic Waste: radioactive waste meeting the current definition of TRU waste, which was disposed of by shallow land burial and other techniques at a number of sites owned and operated by the federal government in support of the nuclear weapons program from the 1940s through 1970. In 1970 the Atomic Energy Commission first identified TRU waste as a separated category of radioactive waste, and all TRU waste generated after 1970 has been segregated from low-level waste and placed in retrievable storage pending shipment to and disposal in an approved geologic repository. Most of this buried waste is considered irretrievable.

Compliance Certification Application (CCA): DOE submits this application (Title 40 CFR Part 191, Compliance Certification Application for the Waste Isolation Pilot) to the EPA in order to request certification from the EPA for the WIPP facility.

Certified Waste: containers of waste that meet the WIPP waste acceptance criteria.

Code of Federal Regulations (CFR): 1) a codification of the general and permanent rules published in the Federal Register by the department and agencies of the federal government. The CFR is divided into 50 titles that represent broad areas subject to federal regulation. It is issued quarterly and revised annually. 2) All federal regulations in force are published annually in codified form in the CFR.

Contact-handled (CH) waste: Transuranic waste that has a measured radiation dose rate at the container surface of 200 millirem per hour or less and can be safely handled without special equipment when in closed containers. [LWA]

Cellulosics, Plastic, Rubber (CPR): the characterization objectives for RH-TRU waste set forth by the EPA in 40 CFR 191 and 40 CFR 194 require that DOE account for the volume of CPR because of the potential gas generation from the decomposition of these organic materials.

Curies (Ci): unit of radioactivity. One curie equals 3.7×10^{10} nuclear transformations per second. This unit reflects the intensity of a radioactive source.

Data Quality Objectives (DQO): qualitative and quantitative statements that clarify program technical and quality objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.

Defense Waste: 1) radioactive waste from any activity performed in whole or in part in support of DOE atomic energy defense activities; excludes waste under purview of the Nuclear Regulatory Commission or generated by the commercial nuclear power industry. 2) Nuclear waste derived mostly from the manufacturing of nuclear weapons, weapons-related research programs, the operation of naval reactors, and the decontamination of weapons production facilities.

Environmental Evaluation Group (EEG): The New Mexico Environmental Evaluation Group conducts an independent technical evaluation of the operations of the Waste Isolation Pilot Plant (WIPP) to ensure the protection of public health and safety, and the environment of New Mexico. The EEG has been serving New Mexico in this capacity since 1978. Public Law 100-456 articulates EEG's role and responsibilities relating to WIPP.

Gray (Gy): the standard unit of absorbed ionizing-radiation dose. One gray is equivalent to one joule of energy absorbed per kilogram of matter. One gray is equal to 100 rad.

Hazardous Constituent: those chemicals identified in Appendix VIII of 20 NMAC 4.1 Subpart II (40 CFR Part 261).

Hazardous Waste: As defined in 40 CFR 261.3, waste that because of its quantity, concentration, or physical, chemical or infectious characteristics, may cause or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible illness, or pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed. Hazardous wastes are listed in 20 NMAC 4.1 Subpart II (40 CFR Part 261) and/or exhibit one of the four characteristics - ignitability, corrosivity, reactivity, and toxicity in 20 NMAC 4.1 Subpart II (40 CFR Part 261).

Hazardous Waste Codes: numbers assigned to identify the EPA category of hazardous waste. Hazardous waste codes' assignment for RH TRU waste ensures that only those wastes that are permitted at the WIPP are disposed of and to ensure waste compatibility during the operational phase at the WIPP.

Headspace Gas: the gas within the free volume at the top of a closed container (between the container lid and the waste inside the container) or containment, such as a drum or bin, containing TRU mixed or simulated waste. The gas may be generated from biological, chemical, or radiolytic processes; this includes contributions from volatile organic compounds (VOC) present in the waste.

Headspace Gas Analysis: headspace gas is sampled using a gas-tight syringe to draw a gas sample from beneath the drum or box lid. The sample is analyzed by gas chromatography and/or mass spectrometry for hydrogen, methane, and volatile organic compounds.

Land Withdrawal Act (LWA): Public law 102-579 withdraws the land at the WIPP site from "entry, appropriation, and disposal." It transfers jurisdiction of the land from the secretary of the interior to the secretary of energy and reserves the land for activities associated with the development and operation of the WIPP. It requires DOE to comply with the EPA's radioactive waste standards and final disposal regulations

and to conduct studies to analyze the impact of RH-TRU wastes on repository performance. It includes many other requirements and provisions pertaining to the protection of public health and the environment. The LWA was signed into law on October 30, 1992.

New Mexico Hazardous Waste Act (HWA): the New Mexico legislation that establishes the state hazardous waste management program.

Newly Generated TRU Waste: waste generated after the development, approval, and implementation of the TRU waste characterization program that meets the requirements outlined in the TRU waste characterization quality assurance program plan. Part of the inventory might not have been generated yet but is estimated to be generated at some time in the future by the TRU waste generator/storage sites.

Non-destructive Assay (NDA): NDA is a general term for a number of techniques, such as gamma spectroscopy and passive/active neutron measurement. These techniques provide information on the radionuclide content of waste and sometimes on its spatial distribution inside containers.

Non-destructive Examination (NDE): NDE is a general term for a number of techniques, such as radiography or computer tomography. Radiography is a non-destructive qualitative and semi-quantitative technique that involves X-ray scanning of waste containers to identify and verify waste container contents. Because of the shielding associated with RH TRU waste, computer tomography, which involves several sources to produce a three-dimensional image may be required rather than the more commonly used radiography.

Packaging: the assembly of components necessary to ensure compliance with packaging requirements, it may consist of one or more receptacles, absorbent material, spacing structures, thermal insulation, radiation shielding, and devices for cooling or absorbing mechanical shocks.

Performance Assessment: risk-based assessment of the safety performance of a nuclear waste facility. The purpose of the performance assessment for WIPP is to evaluate the ability of the repository to isolate radioactive waste from the accessible environment. The performance assessment organizes information relevant to long-term (i.e., over a 10,000-year period) repository behavior by assessing the probabilities and consequences of major scenarios by which radionuclides can be released to the environment surrounding the WIPP site. Important scenarios include those due to human activities, whether deliberate or unintentional, that might occur near the WIPP site and potentially compromise the integrity of the repository.

Pyrophoric: spontaneously ignitable materials.

Process Knowledge: the determination of waste container contents through the study of existing records on the production history of the waste.

Quality Assurance: the planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service.

Quality Assurance Program Plans (QAPP): documents that describe the overall program plans and activities to meet the project's quality assurance goals.

Rad: unit of absorbed dose. It represents 0.01 joules of energy absorbed per kilogram of matter. Rad and rem are important units regarding WIPP because requirements are expressed in rem, a derivative or rad.

Radioassay: a term used to define measurement methods for determining the radionuclide content of waste and includes both non-destructive assay (NDA) and destructive assay (e.g. radiochemistry).

Radiological Survey: Measurements of radioactive contamination levels or dose rates associated with a site together with the appropriate documentation and data evaluation. When AK indicates that some containers may approach 1000 rem/h or that some containers exceed 100 rem/h then radiological surveys of each container may be required. Industry standard survey instruments can be used in this process and are required to discriminate at 100 rem/h and 1000 rem/h.

Radiography: a non-destructive, non-intrusive radiographic examination technique that enables a qualitative (and in some cases quantitative) evaluation of the contents of a waste container. Radiography utilizes X rays to inspect the contents of the waste container in real time. It is used to examine and verify the physical form of the waste for certain waste forms, identify individual waste components, and verify the absence of certain non-compliant items.

RCRA: see Resources Conservation and Recovery Act.

RCRA Part B Permit: issued for the WIPP on October 27, 1999 by the NMED. This permit (incorporating 20.4.1.500 and 20.4.1.900) determines that DOE's disposal plan for mixed TRU waste is acceptable. Also called the Hazardous Waste Facility Permit.

Rem (Roentgen Equivalent Man): unit of absorbed radiation dose used to derive a quantity called equivalent dose. This relates the absorbed dose in human tissue to the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Equivalent dose is often expressed in terms of thousandths of a rem, or mrem. The equivalent dose (rem) is determined by multiplying the absorbed dose (rad) by a quality factor (Q) that accounts for different biological effects caused by different radiations. Dose requirements regarding WIPP are expressed in this unit.

Remote-handled (RH) Waste: transuranic wastes that have a measured radiation dose rate at the container survey of 200 millirem per hour or greater but not more than 1,000 rem per hour. This waste must be handled remotely (i.e., with machinery designed to shield the handler from radiation).

Resource Conservation and Recovery Act (RCRA): established a system for tracking and regulating hazardous wastes from the time of their generation through disposal. The law requires safe and secure procedures to be used by hazardous waste generators in treating, handling, transporting, storing, and disposing of hazardous substances. RCRA is designed to prevent new uncontrolled hazardous waste sites.

The law also regulates the disposal of solid waste that may not be considered hazardous. Note: 20 NMAC 4.1 and 40 CFR Parts 260-281 are the regulations for complying with RCRA with respect to hazardous waste and hazardous waste treatment, storage, and disposal facilities in New Mexico.

Retrievably Stored TRU Waste: waste generated after 1970. In 1970 the Atomic Energy Commission (predecessor to the DOE) first identified TRU waste as a separate category of radioactive waste. The same year, the Atomic Energy Commission determined that all TRU waste generated after 1970 must be segregated from low-level waste and placed in retrievable storage pending shipment to and disposal in an approved geologic repository. Federal facilities in Washington, Idaho, California, Colorado, New Mexico, Nevada, South Carolina, Ohio, Tennessee, and Illinois are currently storing TRU waste. See also Buried Transuranic Waste.

Roentgen: unit used to measure a quantity called exposure. The roentgen is that quantity of X or gamma radiation less than 3 MeV in energy that produces 1 electrostatic unit of charge, 2.58×10^{-4} coulombs, in 1 kilogram of dry air at 0 degree Celsius and at an atmospheric pressure of 760 mmHg. Many radiation measuring instruments measure the roentgen (ionization) directly. It is a measure of the ionizations of the molecules in a mass of air. The main advantage of this unit is that it is easy to measure directly, but it is limited because it is only for deposition in air, and only for gamma and X rays.

Safety Analysis Report (SAR): document representing a statement and commitment by the DOE that the WIPP can be operated safely and at acceptable risk. This document summarizes the safety analyses to ensure the safety of workers, the public, and the environment from the hazards posed by WIPP waste handling and emplacement operations during the disposal phase and hazards associated with the decommissioning and decontamination phase. The WIPP SAR is prepared to satisfy: (1) the commitments in the Working Agreement for Consultation and Cooperation between the State of New Mexico and the U.S. Department of Energy; and (2) to ensure compliance with DOE's 10 CFR 830 about nuclear safety management.

Sievert: unit of measurement of radiation dose equivalent. One sievert is the absorbed dose, expressed in gray, multiplied by a quality factor to account for different biological effects caused by different radiations.

Summary Category Group: categories for each waste stream to facilitate RCRA waste characterization that reflect the final waste forms acceptable for WIPP disposal. The waste summary categories are identified by the generators and are the following:

S3000: Homogeneous solids
S4000: Soils/gravel
S5000: Debris waste

Transuranic Waste: radioactive waste consisting of radionuclides with atomic numbers greater than 92 in excess of agreed limits. A more precise definition, in DOE Order 5820.2A, EPA regulation 40 CFR 191, and the Land Withdrawal Act, is waste that is not high-level waste "contaminated with alpha-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram." The regulatory definition excludes actinide elements with atomic numbers between 90 and 92 (most significantly, Th and U

isotopes), in agreement with the literal meaning of “transuranic.” However, common usage of “transuranic waste” is often understood to include all actinides.

Transuranic mixed waste: transuranic waste contaminated with hazardous constituents as identified in 20 NMAC 4.1 Subpart II (40 CFR 261), Subparts C and D.

Toxic Substances Control Act (TSCA): Act enacted by Congress in 1976 to give EPA the ability to track the 75,000 industrial chemicals currently produced or imported into the United States. EPA repeatedly screens these chemicals and can require reporting or testing of those that may pose an environmental or human-health hazard. EPA can ban the manufacture and import of those chemicals that pose an unreasonable risk.

Visual Examination (VE): process consisting of physically examining TRU waste by removing it from the container it was originally packaged in.

Volatile Organic Compounds (VOC): RCRA regulated organic compounds that readily pass into the vapor state and are present in transuranic mixed waste.

Waste Acceptance Criteria (WAC): set of conditions established for permitting transuranic wastes to be packaged, shipped, managed, and disposed of at the WIPP.

Waste Analysis Plan (WAP): document describing the procedures that will be carried out at a facility to obtain chemical and physical analysis of each waste managed so that all information will be known to treat, store or dispose of the waste in accordance with 40 CFR 264.13.

Waste Characterization: sampling, monitoring, and analysis activities to determine the nature of the waste.

Waste Matrix Code: code assigned by the TRU waste generator/storage sites to categorize mixed and some non-mixed waste streams in the DOE system into a series of five-digit alphanumeric codes (e.g., S5400; Heterogeneous Debris) that represent different physical/chemical matrices. These codes were developed by DOE in response to the Federal Facility Compliance Act of 1992.

Waste Profile Form: form that waste generator must complete to properly identify and document the characterization of any solid, liquid, hazardous, radioactive, or mixed waste. The Waste Profile Form must provide a complete and concise description of the waste, including the details of the generating process. The Waste Profile Form process provides generators with guidance to help make the determination of the waste’s physical, chemical, and radiological characteristics with sufficient accuracy to permit proper segregation, treatment, and disposal according to the final treatment/disposal facility’s waste acceptance criteria.

Waste Stream: waste material generated from a single process or activity or as multiple containers with similar physical, chemical, or radiological characteristics.

Appendix J

Acronyms

AK: acceptable knowledge
ALARA: as low as reasonably achievable
CAO: Carlsbad Area Office
CBFO: Carlsbad Field Office
CH-TRU: contact-handled transuranic
DOE: U.S. Department of Energy
EPA: U.S. Environmental Protection Agency
NMED: New Mexico Environment Department
PUREX: plutonium uranium extraction
RH-TRU: remote-handled transuranic
RCRA: Resource Conservation and Recovery Act
SCG: summary category group
WIPP: Waste Isolation Pilot Plant
WWIS: WIPP Waste Information System

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International Peer Review

of the 1996 Performance Assessment

of the US Waste Isolation Pilot Plant (WIPP)

April 1997

Report of the NEA/IAEA
International Review Group

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OECD/NEA - IAEA JOINT INTERNATIONAL REVIEW OF WASTE ISOLATION PILOT PLANT 1996 PERFORMANCE ASSESSMENT

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Ref. EN/S/5242

Issy-les-Moulineaux, 9 April 1997

Dear Mr. Dials,

Please find enclosed the final report of the international peer review of the 1996 Performance Assessment of the Waste Isolation Pilot Plant (WIPP) as documented in "Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant" (CCA). This technical review was commissioned by the Carlsbad Area Office of the United States Department of Energy (DOE) and jointly organised by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development and the International Atomic Energy Agency as part of their routine services to their member Countries.

The review report is based on the best understanding obtained after several months of deep involvement of the Joint Secretariat and the experts of the International Review Group (IRG) which were especially set up and appointed for this purpose. It represents the combined views of the members of the IRG and is directed to the DOE and thus drafted for a technical audience familiar with contents of the CCA. It contains information which was considered useful and worth bringing to the attention of DOE. This cover letter highlights the main findings of the review in order to place them in a broad perspective, but it does not substitute for a thorough reading and interpretation of the actual report.

The primary focus of the review was on the technical soundness of the analyses and of the DOE approach to post-closure performance assessment, examined from an international perspective. The review report does not formally cover compliance aspects with the national regulations.

Not all parts of the CCA documentation were reviewed at the same level of detail, and specific points were looked at in greater depth according to the technical background, experience and judgement of each member of the IRG. The IRG also took into account additional information provided by the DOE in the course of the review, as well as their knowledge of the WIPP studies gained from previous international contacts. To preserve independence, the IRG did not examine reviews of the WIPP by other groups.

The IRG concluded that the performance assessment methodology is well-founded and has confidence in the majority of judgements and assumptions made in developing the calculational models. The quality of assessment codes and data handling is also generally good. Thus, the analyses reported in the CCA are, in the main, technically sound. The nature of the critical review has tended to identify and emphasise areas where improvements could be made, however, and comments and suggestions are also proposed for consideration by the DOE in future iterations of their assessments of the WIPP, e.g. during the re-certification phase of the facility. These should be considered within the context of the overall positive view of the IRG on the technical soundness and quality of the WIPP performance assessment as documented in the CCA. In particular, two areas are considered as deserving further attention by the DOE: (a) the implications, favourable and unfavourable, of the magnesium oxide backfill, and (b) the assumption of rapidly-reached, homogeneous conditions within the disposal rooms.

From the experience of the review, the IRG believes that, in the case of undisturbed performance, the WIPP facility would meet individual radiation dose standards typical of those used in other countries, even beyond the 10,000 years regulatory period. A judgement could not be reached for the case of disturbed performance, although supplementary analyses by the DOE indicated that a risk target, as internationally accepted, would be met in respect of a direct drilling scenario of the type specified in the regulations.

You will note that the review makes an overall judgement of the 1996 Performance Assessment of the Waste Isolation Pilot Plant rather than emphasizing views on specific aspects, and the report needs to be considered in its entirety. We trust that if the report is read from that perspective, it will prove valuable to the DOE.

On behalf of the IRG and the Joint Secretariat, we would like to take this occasion to thank you and your colleagues for your openness and assistance in the course of the review.

Yours sincerely,

Claudio Pescatore

Dr. Claudio Pescatore
On behalf of the IRG Chairman
and the Joint NEA/IAEA Secretariat

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International Peer Review

of the 1996 Performance Assessment

of the US Waste Isolation Pilot Plant (WIPP)

April 1997

Report of the NEA/IAEA
International Review Group

International Peer Review of the 1996 Performance Assessment of the U.S. Waste Isolation Pilot Plant (WIPP)

Report of the NEA/IAEA International Review Group

Preface

In January 1996, the United States Department of Energy (DOE) requested the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA) and the International Atomic Energy Agency (IAEA) to jointly organise an international peer review of the 1996 post-closure performance assessment of the Waste Isolation Pilot Plant (WIPP). This assessment is described in the DOE document "Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant", issued in October 1996 and referred to as the CCA.

The NEA and the IAEA accepted the invitation and, in June 1996, Terms of Reference for the review were agreed between the DOE, the NEA and the IAEA .

The review was carried out, in the period October 1996 to March 1997, by a team of experts invited by the NEA and the IAEA, referred to as the International Review Group (IRG). The review included an examination of the relevant parts of the CCA, a visit to the WIPP site, and focused discussions between the IRG and DOE staff and contractors.

This report presents the combined, personal views of the members of the IRG, and offers the DOE an independent, international perspective on the 1996 performance assessment of the WIPP. The protocol for the review does not foresee further exchange between the DOE and the IRG and therefore the report is final.

This report has not been checked by the DOE. The IRG has made its best effort to ensure that all information in this report is accurate and takes responsibility for any factual inaccuracies.

International Peer Review of the 1996 Performance Assessment of the U.S. Waste Isolation Pilot Plant (WIPP)

Report of the NEA/IAEA International Review Group

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List of abbreviations

CCA	Title 40 CFR Part 191 Compliance Certification Application for the WIPP
CCDF	complementary, cumulative distribution function
CFR	Code of Federal Regulations
CH	contact-handled (TRU waste)
DOE	United States Department of Energy
DRZ	disturbed rock zone
EPA	United States Environmental Protection Agency
FEPs	features, events and processes
IAEA	International Atomic Energy Agency
IRG	International Review Group
LWA	Land Withdrawal Act
NEA	Nuclear Energy Agency of the Organisation for Economic Co-operation and Development
RH	remote-handled (TRU waste)
TRU	transuranic (waste)
US	United States (of America)
WIPP	Waste Isolation Pilot Plant

1. Introduction

This chapter outlines the background to the review, the composition of the International Review Group, and the process of the review, including the objective and scope. The structure of the report is also outlined.

1.1 Background to the Review

In the United States, the Department of Energy (DOE) is responsible for managing transuranic (TRU[1]) wastes generated by the production of nuclear weapons and other defence-related activities. The Waste Isolation Pilot Plant (WIPP) has been sited and designed to meet the criteria established by the US Environmental Protection Agency (EPA) for the safe, long-term disposal of such wastes. The facility is located near Carlsbad in south-eastern New Mexico and consists of above-ground and below-ground parts. The underground facility (repository) is located at a depth of 650 metres below the surface in a 600-metre-thick, bedded-salt formation.

The EPA regulations require, inter alia, that the DOE demonstrates a reasonable expectation that the WIPP repository will isolate the wastes placed in it from the accessible environment for 10,000 years. The DOE has developed an approach to demonstrating the long-term performance of the WIPP repository based on probabilistic performance assessment. This is designed to estimate how the WIPP disposal system[2] will perform during the 10,000-year regulatory period, taking account of uncertainties in events and processes which could affect the repository in the future.

Beginning in 1980, the DOE has carried out a series of iterative analyses of the long-term performance of the WIPP facility[3]. The latest, the 1996 performance assessment, is described in the DOE document "Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant" [DOE 1996], hereafter referred to as the CCA. The primary purpose of the CCA is to present the information required by the EPA to assess compliance with specific regulations (see Chapter 2). The CCA consists of Volume I plus over 50 appendices.

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[1] TRU waste is defined by the EPA as waste that contains more than 100 nanocuries (3,700 becquerels) of alpha-emitting transuranic isotopes, with half-lives greater than 20 years, per gram of waste, but excluding high-level radioactive waste and certain other wastes, c.f. 40 CFR 191 §191.02(i).

[2] Disposal system means any combination of engineered and natural barriers that isolate the radioactive waste after disposal, c.f. 40 CFR 191 §191.12.

[3] These earlier performance assessment documents have not been examined as part of this review.

1.2 The International Review Group

The International Review Group (IRG) assembled by the NEA and the IAEA included seven members actively involved in national radioactive waste management programmes - from waste management organisations, national regulatory bodies, universities and scientific consultancies. The IRG was completed by two representatives each from the NEA and the IAEA who provided a joint Secretariat and contributed technically to the review.

The names and summaries of experience of members of the IRG are provided in Appendix 1. Mr. Ken Bragg agreed to act as Chairman.

None of the members of the IRG had ever worked directly on the WIPP Project (or worked as a contractor or subcontractor to the DOE). All, however, had participated in international meetings, projects and comparison exercises in which the WIPP project had been represented, and had some prior knowledge of the project and of performance assessment as practised by the DOE. In some cases, this knowledge was extensive and detailed, and gained over many years in bi-lateral or multi-lateral exchanges.

1.3 The Review Process

1.3.1 Objective

The Terms of Reference for the review were negotiated between the DOE, the NEA and the IAEA, based on a first proposal by the DOE. The significant parts of the Terms of Reference are reproduced in Appendix 2. Therein, it is stated that:

> "The objective of the international review is to examine whether the post-closure performance assessment of the WIPP in the CCA is appropriate, technically sound and in conformity with international standards and practices."

The interpretation of this objective was discussed at length within the IRG, especially the phrase "in conformity with international standards and practices".

The IRG decided to conduct its examination to answer the following broad questions stemming from above statement.

Is the WIPP 1996 post-closure performance assessment:

1. appropriate ?

The IRG agreed that this should be interpreted as meaning appropriate in the context of the objective of the CCA, which is to satisfy the EPA regulations. The IRG also agreed that it should not undertake a formal comparison with the EPA regulations since this is the responsibility of the EPA. In this respect, it is emphasised that this review was organised to provide the DOE an independent, international perspective on the 1996 post-closure performance assessment of the WIPP.

2. **technically sound ?**

The IRG agreed that this item should be the primary focus of the review. For example, have adequate data and process information been used, are the conceptual models and their underlying assumptions scientifically-based or reasonable, have adequately tested mathematical and computer tools been applied ?

3. **in conformity with international practices?**

That is, are the scope of the assessment, methods of analysis and quality of application consistent with good practice in other countries ?

4. **in conformity with international guidance and standards?**

That is, are the calculated end-points consistent with international guidance[4] and standards in the manner these are formulated in other countries ?

1.3.2 Scope

The Terms of Reference identify the CCA Volume I as the primary material to be reviewed. After individual examination of this document, and joint discussions, the IRG made the following initial observations and decisions:

- The CCA has been prepared by the DOE to comply with the EPA regulations. These provide detailed guidance on how to demonstrate compliance, and are focused on the evaluation of specific performance indicators.
- The CCA Volume I does not constitute a self-contained or sufficient description of the 1996 performance assessment. Rather, it is necessary to examine many of the CCA appendices in order to find technical information at the level required by the IRG.
- The iterative programme of performance assessment of the WIPP has been the subject of a number of previous independent reviews, notably by the US National Academy of Sciences [NAS 1996]. These other reviews, several of which are summarised in Chapter 9 of the CCA Volume I, would not be examined as part of this review.
- In coming to a view on the four broad questions identified in Section 1.3.1, the IRG considered that it would also be able to examine and comment on other issues indicated by the Terms of Reference, such as the clarity and transparency of the documentation.

1.3.3 Conduct of the review

A summary of the history and conduct of the review is given in Box 1.

The IRG did not review the whole of the CCA at the same level of detail. The focus was on the DOE approach to post-closure performance assessment, technical soundness at a

[4] A list of relevant international documents is annexed to the Terms of Reference, see Appendix 2.

conceptual level, and the performance of the disposal system. Specific points were identified and examined according to the technical background, experience and judgement of each reviewer. During the review, the DOE provided additional information orally, in some cases supported by overheads. This information has been taken into account by the IRG, but has not been formally reviewed.

In their work, the IRG identified technical issues of concern, both general and detailed, made specific comments to define the issues and, in many cases, made suggestions to the DOE on how concerns might be alleviated. It is for the DOE to decide if, or when, any of the suggestions will be implemented in their work[5].

1.4 Structure of the Report

The findings of the review are presented as follows:

- Chapter 2 introduces the EPA regulations which the CCA has been designed to satisfy, identifies and comments on the requirements which have had most influence on the assessment approach adopted in the CCA, and highlights points of interest from an international perspective. The aim of the chapter is to separate observations by the IRG on points related to the EPA regulations from the technical review of work by the DOE.

- Chapter 3 comments on the 1996 performance assessment mainly from a technical perspective. In particular, it examines the technical quality of the stages of post-closure assessment - compilation of data, identification of FEPs and scenarios, treatment of processes and sub-system modelling, system modelling and calculations. Comments are also made on the CCA documentation.

- Chapter 4 summarises the results of the review. This includes observations on the specificity of the WIPP case, the evaluation of the 1996 performance assessment of the WIPP facility against the Terms of Reference, and the overall judgement arising from the experience of the review.

The report assumes that the reader is familiar with the WIPP project and the CCA and presents a minimum of introductory material related to either.

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[5] The Terms of Reference of the review do not ask for recommendations for the future programme of the DOE, and the future programme was not discussed during the review. It is understood, however, that the DOE has already taken action on some of the points raised by the IRG during the discussion meetings, and there are opportunities for further actions to be taken during the WIPP re-certification process.

Box 1: History and Conduct of the International Review

In January 1996, the Manager of the Carlsbad Area Office of the DOE approached the NEA and the IAEA to ascertain their willingness to organise a review of the 1996 performance assessment of the WIPP. In February and March, the NEA and the IAEA agreed, in principle, to carry out such a review, and formal agreement to carry out a jointly organised review was reached in June 1996. The NEA and IAEA formed a joint Secretariat and invited individual experts to participate in the review so that, by July 1996, a team covering the range of relevant expertise was identified - the International Review Group (IRG).

A copy of Volume I of the CCA was supplied to members of the IRG in October 1996. IRG members made a preliminary examination of the document and, in November 1996, met in Vienna to discuss the objectives and approach to conducting the review. The coverage of the various sections of the CCA by the IRG was discussed, and each member was assigned a selection of those CCA appendices and supporting references that he might need to examine. These documents were supplied to individual reviewers by the DOE, mainly by the end of November 1996.

Each reviewer then examined the CCA Volume I, selected appendices and references, and formulated a series of questions arising from the examination. These preliminary questions were compiled and submitted to the DOE in early January 1997 in order to have a more focused meeting between the IRG and DOE later that month. The compiled list included over 100 questions, organised into broad subject headings such as "presentation of safety assessment results", "FEP and scenario identification methods", "radionuclide inventory", etc.. Some of these questions were very specific, referring to particular data items and identified pages of the CCA; others were more general and were requests for clarification about DOE methods as described in the CCA; a few asked for supplementary information not included in the scope of the CCA, e.g. related to radiological consequences. Written answers were not provided, but the questions were used by the DOE to plan a set of focused presentations to the IRG, see below.

The DOE provided an electronic version of the CCA, including its appendices and references, to members of the IRG in early January. The reviewers were not able to take full advantage of these CD-ROMs in their main review work due to the late availability. The CD-ROMs, and the cross-references and search tools which they include, are undoubtedly useful, however, and were used later during the editing of the review report to check specific information in the CCA.

From 26 to 31 January 1997, the IRG met in Carlsbad, New Mexico. In this time, the IRG visited the WIPP facility, received focused presentations from DOE staff and contractors based on the questions previously submitted, and held meetings in closed session to review and confirm individual and joint views on the WIPP post-closure performance assessment. The presentations by the DOE were the starting point for detailed technical discussions which served to answer most of the questions originally raised by the IRG members. The visit to the WIPP facility, and associated discussions with DOE staff, were especially valuable to the reviewers in developing their understanding of the WIPP project and disposal system. During the meetings, information was provided orally, in some cases supported by overheads. This information has been taken into account by the IRG, but has not been formally reviewed.

On the final day of the week, a preliminary oral report was given to DOE representatives by the IRG Chairman.

A first draft report of the review was compiled and circulated to the IRG members for comment in February 1997. These comments were assimilated, and a second draft was produced and discussed at a meeting of the Secretariat, Chairman and consultant in Paris on 12 March 1997. A third draft was prepared and circulated to the IRG members for final comments. After incorporation of final comments, and unanimous approval by the IRG, the final report (this document) was submitted to the DOE on 9 April 1997.

2. The EPA Regulations and their Influence on the CCA

This chapter introduces the EPA regulations which the CCA has been designed to satisfy, identifies and comments on the requirements which have had most influence on the approach to performance assessment adopted in the CCA, and highlights points of interest from an international perspective. The aim of the chapter is to separate observations of the IRG on points related to the EPA regulations, from the technical review of work by the DOE, which is reported in Chapter 3.

In this chapter, factual and neutral observations are given in plain text. Opinions of the IRG are given in italics.

2.1 The EPA Regulations

The DOE was self-regulating until the Land Withdrawal Act (LWA) for the WIPP was promulgated in 1992. Amongst other provisions, the LWA designated the EPA as the regulator for radiological safety of the WIPP facility.

The design and operation of the WIPP are governed by a comprehensive set of US federal and state regulations. The regulations relevant to the post-closure radiological performance of the WIPP, which the CCA is designed to address[6], are contained in two EPA standards:

- **40 CFR Part 191** - Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes - which sets out general requirements for geological disposal systems in the US;
- **40 CFR Part 194** - Criteria for the Certification and Re-certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations - which details the application of 40 CFR Part 191 to the WIPP.

In addition, the EPA has issued guidance on the interpretation of 40 CFR Part 194 in a Compliance Application Guidance document [EPA 1996].

40 CFR 191 was first issued in 1985, remanded in 1987 and re-issued in 1993. The regulation applies to spent nuclear fuel, high-level and transuranic (TRU) radioactive wastes, and sets out environmental standards for management and storage (Subpart A), disposal (Subpart B) and groundwater protection (Subpart C).

40 CFR 194 was issued in February 1996 and became effective two months later. The regulation sets out guidance specific to the WIPP project on the approach to performance assessment that the DOE should adopt and on the structure and content of the CCA. It provides detailed guidance on containment, assurance, and groundwater protection requirements, and includes paragraphs on, for example:

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[6] Compliances with other regulations are dealt with in separate submissions by the DOE.

§194.14 Content of compliance certification application.

§194.22 Quality assurance.

§194.23 Models and computer codes.

§194.25 Future state assumptions.

§194.26 Expert judgement.

§194.27 Peer review.

§194.32 Scope of performance assessments.

§194.33 Consideration of drilling events in performance assessments.

§194.41 Active institutional controls.

§194.43 Passive institutional controls.

§194.45 Consideration of the presence of resources.

Appendix 3 reproduces extracts from 40 CFR 191 and 40 CFR 194 which are most pertinent to this review, including definitions of selected terms. In the following section, where paragraph numbers of 40 CFR 191 and 40 CFR 194 are referred to, the relevant paragraphs, or parts of paragraphs, can be found in Appendix 3.

2.2 The Influence of the EPA Regulations

The DOE designed the CCA to satisfy the requirements of 40 CFR 191 and 40 CFR 194. It is not surprising, therefore, that the structure and contents of the CCA, and the 1996 performance assessment, are strongly influenced by these regulations.

The IRG has not undertaken an analysis of the EPA requirements, nor attempted to systematically check whether the DOE has fulfilled these requirements. In many instances, however, the IRG found that points on which it wished to comment were a result of the requirements of the EPA regulations. This section identifies the more important of these points[7]. This is not intended as criticism of the regulations, nor of the DOE which is obliged to follow them, but to highlight points which are of interest from an international perspective.

2.2.1 Undisturbed and disturbed performance

The EPA regulations set requirements in respect of "undisturbed performance"[8] and "performance taking account of all significant processes" (disturbed performance). The disturbed and undisturbed performance are both judged relative to a "containment

[7] The implications of the the EPA regulations penetrate deeply into the technical details of the 1996 performance assessment. Some of the more detailed implications are perforce mentioned in Chapter 3.

[8] Term defined in 40 CFR §191.12, see Appendix 3. Note that the undisturbed performance includes the effects of human actions, potash mining and deep drilling, that may occur in the future outside the "controlled area".

requirement", based on collective dose considerations, which places a limit on the total release of radionuclides (40 CFR §191.13). The undisturbed performance is also judged relative to an individual dose limit (40 CFR §191.15) and groundwater protection requirements.

This separate consideration of disturbed and undisturbed performance is consistent with regulations in other countries. In several countries, for example, a distinction is made between expected events and processes or a normal scenario, and unexpected events and processes or altered scenarios. In most countries, the criteria applying to the two conditions are derived from the same basis - radiological risk to an individual. The EPA containment requirement, however, is based on collective dose considerations, and cannot be directly related to individual dose and radiological risk standards.

The IRG considers that it is appropriate to assess the undisturbed and disturbed performance separately, and this is in accord with practice in other countries. It is unusual, however, that a different basis for assessment should apply to each.

2.2.2 The 10,000-year regulatory period

The containment, individual dose, and groundwater protection requirements (see above and Appendix 3) all refer to a 10,000-year regulatory period. The EPA does not require any assessment beyond 10,000 years after closure, even in terms of qualitative arguments.

The reliability of performance assessment results declines at times in the far future because of the increasing uncertainty about future conditions, especially of the surface environment and human behaviour. For this reason, in most countries, it is considered that, in respect of performance in the far future, the requirement for quantitative assessments should be less stringent, with more qualitative arguments being allowed [IAEA 1994].

The Canadian, German and French regulations, for example, specify 10,000 years as the maximum time to which quantitative assessment needs be continued, but require qualitative arguments that releases will not increase dramatically beyond this time. In Switzerland, regulatory guidance indicates that calculations should be carried out at least until the estimated maximum of impacts has been reached, even if it is acknowledged that this may be beyond the limits of validity of the models.

The IRG was surprised that it did not find descriptions or arguments in the CCA indicating the possible performance of the WIPP facility beyond the end of the 10,000-year regulatory period. Such descriptions or arguments, including an indication of the mechanisms, likelihood, timing and possible maximum of impacts at longer times, would be an important element of performance assessment in most other countries.

2.2.3 The containment requirement

The major part of the performance assessment work presented in the CCA (Chapter 6 of Volume I) is to demonstrate compliance with the containment requirement (40 CFR §191.13).

The formulation of the containment requirement has several implications not already discussed:

- it is probabilistic and leads to the adoption of a probabilistic methodology to calculate the cumulative release (see also Section 2.2.5);
- it is only concerned with the total cumulative release to 10,000 years, not the timing or rates of release within this period;
- issues of individual dose and risk, as well as the biosphere, are not considered.

Results in the CCA are almost entirely probabilistic because of the focus of the CCA on compliance. The probabilistic systems modelling approach brings important benefits in investigating uncertainties in complex coupled systems and produces integrated measures of impact. Attention must be given, however, to presenting the results of the analysis in an accessible and transparent form. In particular, deterministic analyses may be useful to illustrate the model behaviour and support the probabilistic analyses[9].

Information on the temporal evolution of conditions and releases is important to understanding the physical evolution and performance of the disposal system, and can give confidence in the overall release results which are otherwise opaque. Such information is lacking in the CCA, although supplementary information was presented to the IRG during the meeting in Carlsbad[10]. Whereas the EPA requirements do not seem to exclude the presentation of results as a function of time, the focus of the DOE on compliance may have led to them not being presented.

The EPA containment requirement is based on consideration of collective dose and, moreover, relates to the total activity contained in the repository expressed in terms of EPA units (see 40 CFR 191 Table 1, reproduced in Appendix 3). The IRG found this difficult to relate to safety standards based on individual dose and radiological risk with which they are more familiar. The IRG therefore asked the DOE to provide supplementary information on doses that might be received. These are discussed in Section 3.4.4.

The IRG accepts the probabilistic approach, but found that the focus of the CCA on probabilistic estimates of total cumulative release, and lack of presentation of deterministic calculations or results as a function of time, hampered the understanding of the performance of the disposal system. It would have been helpful to present such results even if they are not required by the EPA.

2.2.4 Treatment of human actions

The EPA regulations give guidance on the assessment of future human actions at the WIPP site. They specify that:

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[9] The relative merits of probabilistic and deterministic methodologies in assessments have been discussed internationally, for example within the NEA Integrated Performance Assessment Group [IPAG 1997].

[10] "Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 CCA for the WIPP", memo by J. Helton, 12/23/96.

- the characteristics of the future (at least in respect of human actions) are assumed to remain as they are at the present day (40 CFR §194.25);
- the assessment shall consider mining, deep drilling and shallow drilling (40 CFR §194.32a);
- in respect of mining, only the effects of changes in hydraulic conductivity of hydrogeologic units should be considered (40 CFR §194.32b);
- inadvertent intrusion by drilling for resources should be assumed to be the most severe scenario, and the method of estimating the future occurrence of drilling is specified, based on the frequency of drilling in the Delaware Basin in the last 100 years (40 CFR §194.33b);
- resource recovery activities, subsequent to drilling of a borehole, need not be considered (40 CFR §194.33d);

It is likely that mining of potash will occur within the controlled area at some time during the regulatory period. The only impact that the EPA asks the DOE to consider, however, is calculated to be beneficial for long-term performance (see Section 3.1.2).

The EPA specification of how to estimate a future drilling rate, plus the assumption of random occurrence in space and time, leaves little uncertainty in the inputs for the assessment of drilling. The actual situation is that there is a very large uncertainty concerning future human actions. Moreover, the case selected for analysis considers an activity that, based on knowledge of the resources in the Delaware Basin (see Section 3.1.2), is not sustainable for more than a few tens of years into the future.

The specification by the EPA on how to assess future human actions leads to a feeling that the performance assessment is arbitrary. The IRG accepts that, given the irreducible uncertainties associated with future human actions, it may be convenient from a regulatory standpoint to define reference events or scenarios that should be the basis of compliance calculations. The IRG, however, would have liked some discussion of the assumptions adopted and, in particular, why other human actions such as resource recovery need not be considered (see Section 3.2.3) and whether the assumptions adopted in representing mining and deep drilling can be considered to be conservative or sufficiently representative.

2.2.5 Results of performance assessment and treatment of uncertainty

The EPA requires that the results of the performance assessment are assembled into complementary, cumulative distribution functions (CCDFs), and that the uncertainty of disposal system parameters should be considered to generate a set of CCDFs (40 CFR §194.34). The regulations also set conditions on the statistical accuracy of results (see Section 3.4.3).

The CCDF is a generally accepted method of depicting uncertain outcomes commonly adopted in reactor safety studies. The DOE has developed the methodology to calculate the

radionuclides releases from the controlled area[11] in the form of CCDFs that can be compared to the EPA containment requirement.

The DOE methodology adopts the Kaplan and Garrick [1981] definition of risk[12] and approach to the treatment of uncertainty. This leads to the generation of a single CCDF where each 'scenario' forms a single-point estimate of consequence and probability on the CCDF. The uncertainty incorporated in this single CCDF, which relates to uncertainty about what might happen in the future, is termed stochastic uncertainty. There is also uncertainty about starting conditions, or values of parameters that must be incorporated in the consequence models. Kaplan and Garrick refer to this as subjective uncertainty on the basis that the parameters do have some "true" or fixed value, but this is imprecisely known. Accounting for this uncertainty in disposal system parameters leads to a family of CCDFs.

The IRG observes that the separation of uncertainty related to disposal system parameters and uncertainty related to future events is presentationally useful and operationally convenient, but is to some extent misleading[13].

The above approach deals with parameter uncertainty. The EPA does not require, and the DOE does not consider, the uncertainty related to choice of features, events and processes, or choice of alternative models[14]. These sources of uncertainty are generally considered to be important internationally [IPAG 1997].

The lack of discussion of other uncertainties, not included through parameter uncertainty, would be considered a serious omission internationally when judging the results of performance assessment, although it is not required by the EPA for compliance calculations.

2.2.6 Institutional controls

The EPA regulations require the DOE to present descriptions of the active and passive institutional controls (defined in 40 CFR §191.12) that are proposed for the site. Further, the EPA allows the DOE to take credit, in terms of a reduced likelihood of human intrusion, for up to a maximum of 100 years after disposal in respect of active controls and "several hundred years"[15] in respect of passive controls (40 CFR §194.41 and 43).

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[11] Term defined in 40 CFR §191.12, see Appendix 3.

[12] According to Kaplan and Garrick, risk is composed of three elements: what can happen, i.e. what scenarios can be identified; how likely is this, i.e. what probability should be assigned to each scenario; what is the consequence, i.e. what is the result, in terms of total release, for each scenario.

[13] It supposes, for example, there is a true long-term rate of drilling applicable to the site, and that the uncertainty in time of occurrence is only a result of statistical variation. This is untrue - the future rate is highly uncertain and may not even be a physically meaningful parameter depending on the model adopted. In addition, the sampling of so-called subjective uncertainty is related, not just to present-day characteristics, but also to what those characteristics might be over the 10,000-year regulatory period.

[14] The EPA does require descriptions of alternative conceptual models that are seriously considered but assumes that one model set, that "accurately portrays the performance of the disposal system", will be used in support of an application (see 40 CFR §194.23, not included in Appendix 3).

[15] The guidance document [EPA 1996] further clarifies this point. It specifies that the EPA will allow up to approximately 700 years of credit (after closure), provided the applicant can support this assumption.

The prevailing international view is that, in the post-closure period, active institutional controls cannot be relied upon to exist for more than a few hundred years[16], which accords with the EPA regulations. Beyond this time, it is accepted that record keeping would be a useful precaution that might reduce the likelihood of future inadvertent human intrusion into the repository but cannot be relied on for long [NEA 1995]. There is no international consensus on the value of passive controls, such as markers, further in the future. Some experts consider that markers could attract unwanted interest in the site [Sumerling et. al. 1996; IAEA 1996], while others consider that markers could be effective in stimulating a search for records and are, overall, useful [SSI 1993].

The IRG observes that the EPA regulations require the applicant to propose a system of passive institutional controls, including site markers, and allow the applicant to take some credit in performance calculations for the effect that these might have. To our knowledge, no other country formally allows credit to be taken for site markers in performance calculations. There is, however, no definitive position on this internationally.

The DOE does take this credit offered by the EPA. The IRG observes that it would be more defensible to demonstrate compliance without attempting to take credit for passive site controls, the effectiveness of which must be uncertain[17].

2.2.7 Terminology

The terminology used in the WIPP performance assessment community, and in some cases formalised by the EPA regulations, is somewhat different from that used in other countries and familiar to the IRG.

The IRG was surprised, for example, that the CCA states that expert judgement is not used, whereas it is clear that the judgements of the project staff have had a very important influence on the performance assessment. This arises because the term 'expert judgement' has a specific meaning in the EPA regulations, indicating formal elicitation of experts independent of the project.

Another example is the DOE use of the term 'scenario' to mean a single simulation of the future (see Section 2.2.5), whereas internationally it is more often used to denote a general description of a possible future [NEA 1992].

The terminology in the CCA did pose some initial problems for the IRG in conducting the review, and also reduces the readability of the documents. The IRG is supportive, however, of the principle of maintaining a well-defined and consistent use of terminology between a regulator and applicant, and recognises that the prime requirement is that the CCA is unambiguous in relation to the EPA.

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[16] The value assumed varies from country to country, usually 100 or 300 years.

[17] The Appendix EPIC, on which the DOE bases its claim to assume a reduced frequency of human intrusion up to 700 years after closure, presents a partial view of the archaeological evidence. The IRG believes that this view would not be generally upheld.

2.3 Discussion

2.3.1 Overall implications for the CCA

The EPA regulations provide detailed guidance and are prescriptive, not only in terms of the quantities that they require an applicant to calculate, but also in terms of the scope of assessment, presentation of results and even fixing of certain key assumptions. The goal of the EPA is to make judging compliance as straightforward as possible by setting out specific requirements. This can simplify the tasks of both the applicant and the regulator. It means, however, that important decisions relating to safety and what is a sufficient method and scope of assessment have already been taken.

Equivalent regulations in most other countries are written in a more general way. Principles and safety targets are set, but the responsibility of preparing a safety case in an appropriate form is left with the applicant. All relevant issues must be addressed, but the applicant has the flexibility to choose a suitable approach. In this case, some communication will usually take place between the applicant and the regulator to explore what might constitute an acceptable approach and scope of assessment.

The location of the WIPP site, in an area rich in mineral resources, requires that the focus of the performance assessment is on human intrusion. This is different from most other geologic environments considered for radioactive waste disposal, where assessments most often focus on an undisturbed case. Any quantitative assessment of future human actions is liable to be arbitrary to a large extent. Attention must therefore focus on the choice of assumptions underlying the analysis, e.g. whether they are reasonable, conservative and acceptable to stakeholders. This is not discussed in the CCA because the EPA specifies the assumptions that should be applied.

The IRG observes that the CCA is precisely designed to satisfy the EPA regulations, and these do not require the applicant to present a comprehensive argument related to safety. Thus, the analysis presented in the CCA appears somewhat arbitrary and does not represent a complete, self-standing, performance assessment as understood in other countries.

2.3.2 Implications for the review

The IRG was initially aware that the CCA is strongly influenced by the EPA regulations, but only became fully aware, during the review process, of the detail to which the regulations specify the technical approach of an applicant.

In preparing this report, the IRG has tried to distinguish between the decisions that have been determined by the EPA regulations (discussed mainly in this chapter), and the decisions made by the DOE, for which the DOE must take technical responsibility (discussed mainly in the next chapter).

3. The 1996 Performance Assessment of the WIPP

This chapter comments the 1996 performance assessment of the WIPP mainly from a technical perspective. In particular, it examines the technical quality of the various stages of post-closure assessment - compilation of data. identification of FEPs and scenarios, treatment of processes and sub-system modelling, system modelling and calculations. Comments are also made on the CCA documentation.

Although the detailed comments are aimed specifically at the CCA, the IRG has built its judgment on the technical soundness of the 1996 performance assessment, not only on its examination of the CCA, but also on the basis of prior knowledge of the WIPP project and work by the DOE and its contractors over a number of years.

In this chapter, factual and neutral observations are given in plain text. The views of the IRG and suggestions to the DOE are given in italics.

3.1 The Compilation of Data

3.1.1 Site geology and hydrogeology

The regional geology of the Delaware Basin is well known, because of the long experience arising from potash mining and hydrocarbon exploration in south-eastern New Mexico. This extensive regional knowledge has been compiled and well assimilated within the DOE programme. The stable focus of the WIPP on the currently selected site, over a period of more than 20 years, has allowed a very thorough investigation of the local and adjacent geology and hydrogeology.

The geological, hydrogeological and tectonic settings provide strong and multiple evidences of the natural long-term stability and isolation capacity of the Salado formation over time scales far in excess of the 10,000-year regulatory time frame. Due to these very favourable geological characteristics, most of the naturally occurring features, events and processes (FEPs) that could be thought of as having the potential to disrupt a geological repository can be screened out. A stronger reference in the CCA to these positive site-specific features could further support the intrinsic containment capacity of the Salado, and thus the safety case.

The existence of natural resources in the region highlights the possibility of human actions aimed at exploiting these resources. Thus, the presence of brine reservoirs in the Castile formation, which have been encountered during drilling for oil and gas mainly at the north-east margin of the Delaware Basin, is of concern. Apparently, no direct or indirect methodology exists to precisely characterise the extension and volume of these brine reservoirs. The lateral extent and volume of the brine reservoir encountered by the WIPP-12 borehole are not well known and the assessment calculations have to rely on a geostatistical approach covering the whole Delaware Basin.

The most recent investigation for the presence of Castile brine reservoirs underlying the facility was done, from the surface, about ten years ago. The possibilities for investigating brine reservoirs beneath, and local to, the WIPP site and, especially, for developing further methods to characterise their extent and volume from the underground, should be borne in mind during the construction phase of the underground facility.

The evidence for the very low permeability of massive salt beds such as the Salado is based on good physical arguments and on extensive measurements. Attention thus focuses on the anhydrite beds within the Salado. These constitute the only possible natural paths for gas, brine and contaminant transport away from the repository, and may also be a route for incoming brines that may react with waste components to produce gas. Hence, their properties are important in determining the pressure evolution of the repository.

A detailed characterisation of these beds has been performed, but it is not clear to the IRG, that the changes that will be induced in these units by repository excavation, subsequent salt creep movements, and gas pressure build-up are as well understood or characterised. The lack of complete understanding is handled by conservative choice of parameter ranges in the BRAGFLO calculations.

In the strata above the Salado most of the water is saline and is not potable, even by livestock, without substantial dilution. This is especially true for the Culebra dolomite, which is the most transmissive unit at the WIPP site, and is considered to be a potential pathway for radionuclide release from the controlled area. Potable water is reported from shallow drilling in the Dewey Lake formation (although not necessarily in the immediate vicinity of the WIPP site).

The IRG considers that, from a dose perspective, greater attention could be given to considering whether any credible scenarios exist in which contaminants might reach these potable or nearly potable resources, under present day and alternative climate conditions[18].

3.1.2 Natural resources

The existence of potash resources at the WIPP site and in the immediate area has been the subject of extensive investigation. This is an unusual situation for a radioactive waste disposal site. Not only is it expected that (unless prevented) mining will occur within a few years, but also, because of the well-understood nature of the potash deposits, it can be estimated which areas of the ore horizons will be mined over the site.

The potential impacts of mining (at the repository horizon and on potential paths for brine and contaminant movement) are not fully discussed in the CCA Volume I, because the EPA has restricted the range of effects to be considered in performance assessment, see Section 2.2.4. The only effect considered, an increase in the hydraulic permeability of the Culebra over the mined areas, turns out to be beneficial: it increases the transport times and hence reduces the calculated release of radionuclides during the 10,000-year regulatory period.

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[18] From a dose perspective, the containment requirement may be conservative where the releases occur in media which man is unlikely to exploit or come into contact with, i.e. saline water in the anhydrite beds or in the Culebra.

It would be preferable to see information on the observed effects of potash mining locally. Reasoned arguments could then be presented on the selection of the processes that are represented in the analysis.

The hydrocarbon resources of the Delaware Basin are well known. They consist of oil and associated gas reservoirs found in the Permian strata, and gas condensate in the Pennsylvanian strata. These strata exist beneath the WIPP site and immediately surrounding areas. The relevant information is presented in Appendix DEL, but is poorly discussed in the CCA Volume I, probably because the EPA specifies the assumptions to be adopted in demonstrating compliance, see Section 2.2.4.

A historical description on the rate of development of oil and gas wells, and discussion of alternative scenarios for future exploitation of oil and gas resources, based on actual practice and the extent of resources in the basin, could set the assumptions used in the analysis in perspective. Depending on the future needs of energy and the current trend towards shallow oil exploitation in the Delaware basin, there is a possibility that the drilling rate in the near future will be greater than the one in the last 100 years, although the rate would not be sustainable over the 10,000-year regulatory period.

3.1.3 The underground facility

The WIPP project has accumulated an impressive database on rock mechanics based on extensive and long-term laboratory and in-situ measurements. This is complemented by detailed and high quality modelling of rock-salt creep, for example, by the SANTOS model. The precise knowledge of the stratigraphy in the salt formation, and salt properties, has facilitated the development of quite detailed repository layouts and designs for various seal elements.

The high quality and extent of the data base, with very specific data relevant to rock mechanical processes and design, provides a high level of confidence in the analyses made on these components.

The DOE gives considerable attention to the design of the multiple-component shaft seals intended to prevent hydraulic connection and movement of brine or contaminants in the shafts after closure. In the long term, the lengths of crushed, compacted rock-salt can be expected to be restored to a low permeability, similar to the host formation, as a consequence of salt creep. The longer-term performance of elements above and below must be less certain since they represent chemical and physical anomalies within the formation. The performance of these elements, however, need only be assured over a period of a few hundreds of years during which the crushed rock salt sections achieve low permeability.

The IRG is content that shaft seals can be constructed to provide the required long-term performance.

Information on the detailed mechanical modelling of the shaft and its associated disturbed rock zone (DRZ) is summarised in Volume I of the CCA and presented in detail in Appendix SEAL. In the BRAGFLO performance calculations, however, a range of time-independent properties are assigned to the shaft and DRZ.

The IRG was not able to fully trace the parameters concerning shaft and DRZ properties given in Appendix PAR to the information in Appendix SEAL. Thus, it is unclear whether the simplified treatment of the shaft and DRZ in performance calculations results from a lack of confidence in estimating time-dependent properties of the shaft seals and DRZ, or a pragmatic finding that the performance of the disposal system is relatively insensitive to a range of shaft and DRZ properties.

Not much data is available on waste compaction, and, due to the variability of the waste, it is difficult to have confidence in the data provided.

The mechanical resistance of the waste is not considered in the modelling of the room closure, and it is not clear whether this approach is conservative, see Section 3.2.4.

A DRZ also forms around the disposal rooms as a consequence of unloading the rock in the vicinity of the excavation. Increased permeability is created by micro-fractures along grain boundaries and by bed separation along lateral seams. Following closure, salt creep will tend to restore low permeabilities within the salt beds, however, some fracturing in non-halitic rock, such as anhydrite, and bed separation on clay seams, may be irreversible.

An area where an improved confidence in the repository evolution might be useful is the understanding of the gas and brine permeability of the DRZ around the disposal rooms. At present, this zone is assumed to release brine to the disposal rooms and to connect the repository-waste void with the anhydrite marker beds above and below the repository horizon. A good understanding of variability of the zone properties and their evolution, especially "healing", might allow a less conservative treatment in assessment models.

3.1.4 The waste inventory

The WIPP facility is designed to receive radioactive and mixed waste, which results mainly from nuclear weapons production and associated activities in the US. By its origin and composition, this is not a waste type which occurs in many other countries. The waste components in the TRU waste are similar to what are internationally called low- and intermediate-level wastes with long-lived radionuclides.

The waste that is expected to be disposed of in WIPP is well documented in appendices of the CCA: the origin, form, characteristics and inventory of the different waste types are described, as well as the characterisation methodologies and controls. Two classes of waste are considered: remote-handled (RH)-TRU-waste and 599 different types of contact-handled (CH)-TRU-waste. Volumes and characteristics are forecast for each class and type.

Only a limited fraction of the wastes to be disposed of is conditioned and packaged already and the characteristics of wastes yet to arise are forecast. As waste processing may change with time, the eventual waste inventory may differ in content and characteristics from those now forecast. This source of uncertainty is not addressed in the CCA.

Repository-based emplacement limits have been imposed by the Land Withdrawal Act (LWA), which specifies a total volume capacity (of RH- and CH-TRU waste) of 6.2 million cubic feet (175,600m^3) and total activity capacity for RH-TRU waste of 5.1 million curies

(1.9×10^5 TBq). Radionuclide inventory limits have been established by the DOE on this basis.

The IRG noted that the inventory of Cs-135 considered in the CCA appears to be inconsistent with that of Cs-137 based on typical fission ratios for these two isotopes. In particular, the Cs-135 inventory appears to be underestimated by three to four orders of magnitude. The implications for the performance calculations were preliminarily checked by the DOE during the IRG visit to the WIPP and found to be insignificant within the EPA regulatory framework. The latter focuses the attention on long-lived alpha emitters, whereas a regulatory context based on dose to the individual would enhance the role of more mobile long-lived radionuclides such as Cs-135. In any event, this inconsistency reveals a weakness in the exchange of information between the waste producers and the performance assessors.

3.2 Identification of Relevant FEPs and Scenarios

3.2.1 General procedure and documentation

According to the CCA, the starting point for the identification of relevant features, events and processes (FEPs) is a compilation of several performance assessment FEP lists made in support of the Swedish SITE-94 study [Stenhouse et al. 1993]. The original purpose of this compilation was to provide a list against which to audit a list of FEPs that were specific to the case of a KBS-3 style repository in Swedish bedrock, where the list of site-specific FEPs was achieved through an independent consideration by yet another study group.

There must be some doubt as to whether a list that was originally intended for one quite specific purpose, related to high-level wastes in a hard rock site in northern Europe, is a sufficiently representative starting point for a catalogue of FEPs related to disposal of transuranic wastes in a bedded salt formation in south-eastern New Mexico.

In the CCA Volume I it is stated: "Finally, to ensure comprehensiveness, other FEPs specific to the WIPP were added based on review of key project documents and broad examination of the preliminary WIPP list by both project participants and stakeholders."

There is no clear indication in Volume I or in Appendix SCR of exactly how this review and examination was managed, or specifically what additions or modifications resulted. The IRG finds this surprising because conversations with WIPP project staff indicated a quite encyclopaedic knowledge of the site and relevant processes. The record shown in the CCA does not indicate that this resource was fully used, although in practice it may have been.

The qualitative and semi-quantitative arguments regarding FEPs that are collected in the Appendix SCR are a key component of the assessment.

This appendix is clear in recording what FEPs are and are not carried forward to further analysis, but does not give a sufficient level of evidence or support for many of the screening decisions. The methodology is satisfactory in principle, but the IRG has difficulties in

understanding the rationale for screening out of individual FEPs[19]. *The IRG suggests that the Appendix SCR should be more critically reviewed with a view to bringing forward more detailed information to support the decisions made.*

Several FEPs were rejected on the basis of regulatory considerations[20].

It would improve the confidence of the reader if the DOE presented the logical or physical arguments for not considering these processes in the assessment, in addition to noting that they are not required in a compliance demonstration. Otherwise, there is an impression that processes that might deserve consideration from a safety perspective have been eliminated.

3.2.2 Climatic and geologic FEPs

The potential for climatic and geological changes within the 10,000-year regulatory period is well documented in the CCA.

The DOE has investigated an appropriate range of future climatic and geological processes, and the possible effects within the 10,000-year regulatory period have been considered. For perspective, it would be helpful to include some qualitative discussion of the possible impact of climatic and geologic FEPs over longer time periods.

3.2.3 Future human actions

The selection of FEPs related to future human actions to be considered in the CCA are closely specified by the EPA (see Section 2.2.4).

Examination of the CCA and conversations with project staff identified a number of events and processes that are not analysed and might deserve consideration from a radiological safety perspective. These are:

- water flooding due to nearby brine injection to aid oil recovery, and possibly other secondary and tertiary recovery methods;
- solution extraction of salt, e.g. for use in drilling muds or other purposes;
- solution mining of underground cavities for storage, e.g. of oil or gas, or for disposal of other wastes;
- disturbance of flow regime due to extraction boreholes just outside the controlled area[21].

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[19] An example of the further documentation on FEPs and screening procedures in project records was provided by the DOE.

[20] The IRG presumes that the EPA decision to constrain and limit the analysis is based on an earlier evaluation of the relative importance of various processes. As far as the IRG is aware, however, this is not documented in the open literature.

[21] A borehole outside the controlled area could affect flow and transport because it would modify the boundary conditions for the flow calculations. In the Salado formation, the dilution effect for the transport of radionuclides along the marker beds, which is observed in the dose calculations, might then be reduced by a more focused flow towards the borehole. This scenario should be included in the undisturbed performance, e.g. assumed to occur with some probability.

All of these, except the last, are ruled out by the EPA regulations.

From a safety perspective, the IRG considers that the documentation and evaluation of FEPs related to future human actions is incomplete. Even if the CCA is focused on regulatory compliance, a demonstration that those processes that must be considered in regulatory compliance are indeed an appropriate and sufficiently representative set, would make the DOE performance assessment more widely acceptable[22].

3.2.4 Waste and repository-related FEPs

The wastes to be disposed of in the WIPP facility are highly heterogeneous. This will lead to a heterogeneity (of initial conditions at least) in the emplaced waste within each waste room both in terms of physical properties, chemical properties and radioactivity. Moreover, as rooms and panels will be filled sequentially over time, and there will be variations in wastes arising, there may be significant variation in physical, chemical and radionuclide inventory between disposal rooms.

The effects of heterogeneity at the room scale are of most concern: in particular, whether the homogenous physical and chemical conditions assumed for the source term and repository modelling will be achieved in reality. This is important because the expected mode of release from the repository involves discrete interceptions of quite small volumes within the total repository volume. The specific conditions at that small volume scale, and immediate vicinity, may be quite different from the averaged mixed conditions of the whole repository. The IRG suggests that (1) additional qualitative thinking is done to identify possible effects of waste heterogeneity and emplacement, and this is supported by (2) quantitative detailed modelling to investigate the possible physical and chemical evolutions within small sections of the repository (of the order of a few square metres).

Flow and transport processes in the repository area depend on the pressure build-up due to the production of gas. The pressure build-up depends on the available void or pore volume in the repository. This volume is reduced by the creep convergence of the salt.

The creep calculations in the CCA account for the pressure build-up itself but not for the mechanical resistance of the waste or for volumetric change of the backfill material (see below). Taking these processes into account could reduce the convergence rate. It is unclear whether neglecting these processes is conservative or not.

The specification of a magnesium oxide (MgO) backfill with the purpose of controlling pH, and hence actinide solubilities, around the wastes is a very late development. Indeed, the most relevant entry of the Appendix SCR - SCR.2.1.5 "Backfill characteristics" - does not say what the backfill material is, referring to it as a "chemical conditioner". The subject is discussed in more detail elsewhere, e.g. Section 6.4.3.4 of Volume I and Appendix BACK. These discussions, however, focus on the desired chemical effects assuming an intimate and instantaneous mixing effect with incoming brine.

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[22] While the EPA regulations allow the DOE not to evaluate the above scenarios, they do not forbid the DOE from presenting ancillary analyses of the scenarios.

The IRG considers that (1) confidence has not been developed that wastes within individual drums, or the brines entering these drums, will undergo the rapid chemical conditioning effect assumed (see comments on heterogeneity above), and (2) insufficient attention has been given to the volumetric expansion and other effects due to MgO reactions[23] *(see Section 3.3.2).*

3.3 Treatment of the Relevant Processes and Sub-system Models

3.3.1 Evolution of the geochemical environment

There is a large amount of mixed organic material contained within the TRU waste which is prone to bio-degradation and CO_2 production in contact with water. This makes the waste packages unstable under the disposal conditions. Therefore, the addition of a backfill material is necessary to stabilise both the pH and partial CO_2 pressure within the repository.

The DOE specifies a MgO backfill, and refers to this as an Assurance Requirement. However, the presumed effect is taken account of in the performance modelling and the IRG considers that a chemical conditioning backfill is required in order to make the performance of the system sufficiently predictable.

The waste panels in the WIPP repository will undergo a complex geochemical evolution that has to be properly addressed in the source term calculations. The processes to be considered in estimating the geochemical evolution include:

- corrosion of the steel waste containers by the contacting fluids;
- degradation of the organic content of the waste with the corresponding generation of both CH_4 and CO_2;
- hydration and subsequent carbonation of the MgO backfill material;
- dissolution of the actinide inventory.

In the CCA, instantaneous equilibrium is assumed in all the processes involved, except for the redox distribution of the actinide species. The result is that the PANEL code calculates radionuclide mobility out of the repository in a well-mixed reactor fashion.

The outcome in terms of actinide releases is non-conservative, as the assumption of full mixing has a beneficial effect on the repository pH and partial CO_2 pressure which is not fully backed up by the experimental evidence reported by the DOE.

The IRG suggests that (1) more detailed modelling is required of the assumed transition from heterogeneous to homogeneous physical and chemical conditions (see Section 3.2.3), and (2)

[23] Appendix SCR entry SCR.2.1.5 states, without further support, that backfill physical properties have been eliminated on the basis of low consequence.

the radionuclide release calculations should include the possibility of failure or insufficient reaction with the backfill and evolving CO_2.[24].

3.3.2 Processes related to the magnesium oxide backfill

The magnesium oxide (MgO) backfill will react with the incoming brines and form magnesium hydroxide ($Mg(OH)_2$). If CO_2 is present, e.g. from waste degradation, magnesite ($MgCO_3$) will be formed after passing through intermediate, thermodynamically meta-stable phases such as dypingite, nesquehonite, and possibly others. This has implications for repository void volume, temperature and water budget as discussed below.

The chemical reaction of the MgO will result in a volumetric expansion of the backfill material. The reactions from MgO into magnesium hydroxide, and then into magnesite, increase the volume by factors of 2.2 and 2.4, respectively. Higher expansion factors can be reached when the intermediate phases between magnesium hydroxide and magnesite are considered.

This volumetric expansion is important and affects, for instance, the void volume that needs to be considered in the analyses of gas pressurisation effects, and may even reduce the pore volume locally to such an extent that uniform chemical mixing of the pore fluids cannot be assumed. Overall, the volumetric expansion of the MgO may entail both positive and negative implications, and a full examination needs to be carried out.

The hydration of MgO is an exothermic process. The heat generated will be deposited locally in each waste panel and it may not be readily dispersed as assumed in the CCA. This is because the waste panel material - mixed waste, backfill, and gas-filled void spaces - will have a relatively low thermal conductivity compared with halite, for example.

The thermal problem warrants a more complete analysis taking into account uncertainties in geometry and other parameters. The implications for the evolution of the underground facility will then need to be examined.

The hydration of MgO requires water, but its carbonation releases the water taken up in the hydration step. Thus water is not consumed in the hydration-carbonation process and will be available for further reaction with the waste and the backfill, and for radionuclide release.

This additional source of water and feedbacks to thermal and volumetric expansion processes are not addressed in the CCA, and warrant fuller consideration.

Overall, the IRG concludes that not all the physical implications of the chemical reactions that the MgO backfill may undergo have been explored in the CCA. This is an important omission. At the very least, the processes have the potential to modify the temporal evolution of the physical environment in the waste panels. The IRG recommends that the DOE give

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[24] There are two issues here: insufficient chemical conditioning at the disposal room scale which would affect releases in the undisturbed case and E1E2 scenario; insufficient chemical conditioning at a smaller scale which may be relevant to the E1 and E2 scenarios.

urgent attention to a fuller examination of the physical implications of the hydration and carbonation of the MgO backfill material.

3.3.3 Calculation of actinide solubilities

The methodology used by the DOE to calculate the actinide solubilities in the repository assumes thermodynamic equilibrium for the main driving geochemical reactions, but excludes the possibility of redox equilibrium for the dissolved actinides.

This probably results in conservative estimates of actinide solubilities, although it is unsatisfactory from a chemical point of view.

The methodology for the derivation of the solubilities as reported in the CCA and Appendix SOTERM does not accord with the procedures used to derive similar parameters in performance assessments in other countries [e.g. SKB 1992; Nagra 1994]. Through discussions with the DOE and contractor staff responsible of this area, and by examining tertiary reports and scientific papers, however, the IRG confirmed that the procedures used in the calculation and derivation of the actinide solubilities were reasonable in terms of the quality of primary laboratory data used and the method of the calculations.

To accord with the methodologies used in other performance assessments, the DOE should include the key thermodynamic data used to derive the actinide solubilities, as well as the procedures used to independently check the validity of the solubility data in a comprehensive and accessible report, either as part of the Appendix SOTERM or as an additional document within the CCA document set.

3.3.4 Two-phase-flow and coupled mechanical and hydraulic modelling

Brine and gas movements in and around the repository and the Salado formation are affected by creep and the production and movement of gas. The coupled processes of brine and gas movement are accounted for by applying the BRAGFLO two-phase-flow model. The modelling also includes other basic features of the disposal system such as the generation of gas by different sources, the change of permeability of the marker beds due to the pressure in the repository, and the creep convergence as a function of the pressure.

The BRAGFLO model is state-of-the-art in two-phase, gas-brine modelling, and its application in performance assessment is in advance of practice in other countries. The model appears to represent all the important coupled hydrologic processes which could take place at repository level and within the marker beds.

The creeping of salt and the pressure build-up in the repository, i.e. the coupling between mechanical and hydraulic processes, is not represented mechanistically. The creeping of salt is modelled in the code SANTOS and the pressure built-up is handled in BRAGFLO. These codes run independently. A porosity surface, which gives the porosity as a function of time and pressure is generated by SANTOS, and the porosity values are picked up by BRAGFLO from this two-dimensional function at each time step.

It is not shown that this method is conservative under all circumstances.

To model brine intrusion into the repository from a Castile reservoir after a future drilling, the brine release to the repository model is estimated by a simple model in which the volume of the brine reservoir and its compressibility are sampled. The parameter range for the volume of the reservoir appears to be an underestimate, whereas the compressibility covers unrealistically high values.

This is a simple approach, but may be sufficient on the basis of currently available data (see, however, comments in Section 3.1.1). The combination of parameter values in the model leads to a very broad range of releases which exceeds the available amount of brine, and probably encompasses a sufficient degree of conservatism.

3.3.5 Modelling of the Culebra hydrology

The Culebra is a fractured and inhomogeneous aquifer system, varying in both horizontal and vertical directions. It is modelled as a horizontal, confined, porous-medium layer with the heterogeneity of the formation represented by statistically generated transmissivity fields. The modelling effort concerning the flow and transport in the Culebra has been considerable in the last few years, and has been the basis for an international intercomparison exercise.

The variability of the hydraulic properties of the Culebra has been treated by a state-of-the-art modelling approach. However, the IRG could not fully trace the incorporation of individual features, such as the instationarity of the flow regime and the density effects to the flow scheme. A more simplified and traceable approach might be preferable in the performance assessment calculations.

An issue of concern for the modelling of the Culebra flow (and especially for the definition of future flow direction on the basis of present head measurements) is the inconsistency between the measured geochemical and isotopic data, and the flow directions inferred from head and transmissivity measurements.

This issue is poorly reported in the CCA and deserves more attention. From the information received during the review, it seems that more recent 3D-modelling of the Culebra[25] could help to correlate flow directions and observed geochemical and isotopic data.

3.3.6 Modelling of radionuclide transport

The modelling of nuclide transport in the Salado formation is based on the time-dependent, advective flow field for the liquid phase from the two-phase-flow modelling. The transport in the Salado formation does not account for diffusion and dispersion terms.

Diffusion is likely to be significant in such a low flow environment, and dispersion may be significant in the anhydrite marker beds. Examination of time-dependent results indicate

[25] The recent study simulates the hydrogeology of the regional basin over the period from 14,000 years in the past to 10,000 years in the future. Infiltration from the overlying beds and the regional transient response to changes in the rate of recharge due to past climatic changes are represented.

that there is significant numerical dispersion, and this may be greater than the true physical effects of diffusion and dispersion. This is unsatisfactory from a modelling point of view and, taking into account the time cut-off of the assessment, the results are not necessarily conservative.

The modelling of nuclide transport in the Culebra formation is based on the steady-state flow fields from the groundwater flow modelling, and modelling of a conservative-tracer. Other processes such as sorption and radioactive decay are then factored in multiplicatively. The chemical retardation of actinide transport is conceptualised by sorption on to the dolomite component of the formation. No credit is given to the existence of clays in the formation, but there is a reliance on matrix diffusion effects as a retardation factor.

The conceptual model used to handle the chemical retardation of actinides through the Culebra appears to be conservative, and the contribution of matrix diffusion is backed up by extensive hydrogeological and tracer tests of the formation. This, however, is not well documented in the CCA. The confidence of the IRG in the experimental basis for the dual-porosity concept applied to the Culebra (and especially the importance of matrix diffusion) comes from prior knowledge of the WIPP programme.

The colloidal transport of radionuclides is considered in detail in the CCA. Different colloidal forms (i.e. humic, microbial, mineral fragment and intrinsic actinide colloids) are distinguished. In the Salado, sorption and filtration processes of dissolved and colloidal forms are neglected. In the Culebra, colloidally transported radionuclides are assumed to remain associated with their colloid carriers. The transport of microbial and mineral-fragment colloids is neglected due to filtration effects. Intrinsic actinide colloids are assumed to occur in insignificant quantities. The sorption of humic colloids is assumed to be the same as the sorption of dissolved radionuclides.

The experimental basis for the above model assumptions is sparse, at least as documented in the CCA. The treatment in the Salado is clearly conservative but the situation is less clear for the modelling of actinide transport in the Culebra.

3.4 System Modelling and Calculations

3.4.1 The system model framework

The WIPP performance assessment is based on a probabilistic analysis using an integrated system model. The major computer codes and the flow of information among them, as they are used to generate radionuclide releases are illustrated, e.g. in Figure 6.25 of Volume I of the CCA, and well documented in Appendix CODELINK.

The limited examination of CCA documents by the IRG, indicates good code configuration and management of data flows. The IRG has confidence that the procedures applied in these areas are consistent with best practice for performance assessment internationally. The IRG is also aware of the long involvement of the WIPP project in international comparison exercises which gives confidence in the performance of several of the component models.

The strategy for connecting submodels is different from that usually adopted in assessment of multi-barrier systems. Usually, an assessment model will consider a linear set of sub-models (e.g. source term, near field, geosphere, biosphere) which may be supported by more detailed models of specific processes (e.g. hydrogeology, geochemistry). In the CCA, a relatively detailed model of hydraulic performance (coupling mechanical and hydraulic pressure, repository gas generation, gas and brine movements) of the whole disposal system - BRAGFLO - is at the core of the analysis.

The codes are not run as a directly coupled system. Rather, for reasons of computing efficiency and convenience, families of simulations are performed with each code (in particular the BRAGFLO, BRAGFLO_DBR and CUTTINGS codes) and outputs held in intermediate files ready to be picked up for uncertainty analysis or input to further calculation (see Section 3.4.3).

Subjective uncertainty in the disposal system parameters (see Section 2.2.5) is represented by latin-hypercube sampling (LHS) of parameters within the BRAGFLO and NUTS models. Parameters which are expected to evolve significantly over time, such as fluid pressure, saturation and porosity, are calculated as a time-evolving function of time-independent parameters. Uncertainty in the models adopted is not addressed directly, although, in some cases, the parameter distributions represent alternative assumptions concerning the possible evolution of the repository.

The overall system-model framework is appropriate, and well suited to the physical and phenomenological characteristics of the disposal system. However, operational factors affect the way the codes are run and linked together (see Section 3.4.3).

3.4.2 Undisturbed performance calculations

Within the 10,000-year period considered, the only pathway by which releases are estimated to occur is through movement of contaminated brine through the marker beds. Movement up the sealed shafts is modelled but no releases occur within the period of regulatory interest. Contamination reaches the site boundary by migration in the marker beds in 9 of 300 calculations.

Although there is no plausible path by which contaminants in the marker beds should then reach the human environment, the EPA requires the DOE to calculate doses corresponding to this release. To effect a calculation, it is assumed that brine from the beds is diluted with fresh water by a factor of about 30 to bring the total dissolved solids of the solution down to about 10,000 mg l^{-1}. This water is then used as a source of human drinking water at a rate of 2 l d^{-1}. This scenario, which must be considered conservative, gives rise to dose estimates in the range zero (for most simulations) to 0.5 mrem y^{-1} (0.005 mSv y^{-1}) compared to a dose limit of 15 mrem y^{-1} specified by the EPA.

The analysis may be sufficient for the EPA requirement. The IRG observes, however, that only two or three of the 300 simulations would contribute to the arithmetic mean of dose, i.e. the result is unlikely to be converged, although so low as to be of no concern.

3.4.3 Disturbed performance calculations

To represent the disturbed case the detailed model - BRAGFLO - is run 300 times for each of six subjectively-selected deterministic scenarios (determined sequences of future drilling penetrating the repository). These results are used to generate a look-up table of estimated conditions of brine and gas pressure, and their evolution after repository penetration, for other times of intrusion. A larger number of calculations by BRAGFLO_DBR and CUTTINGS are required to generate look-up information on radionuclide releases considering radioactive decay. The CCDF-GF code is then used to generate random sequences of future drilling, including times of intrusion. The code automatically picks appropriate results from the previously-generated look-up tables.

This procedure, which is adopted for operational reasons, carries a possibility of introducing bias. It would be prudent to verify the procedure by running the detailed model set for a selected set of time sequences generated by CCDF_GF and to compare outputs (e.g. time history of release and total release) with the results from the interpolation procedure employed in the CCA calculations. The selected sequences should include at least some in which multiple drilling events occur at early times when radioactive decay is most rapid. Satisfactory agreement in respect of total release in a 10,000-year period will be much easier to achieve than satisfactory agreement over time. Therefore, the IRG estimates that the bias is unlikely to be significant for the cumulative estimates of release required by the EPA.

The concentration of radionuclides in solid waste and in brine, calculated by CUTTINGS and BRAGFLO_DBR respectively, is depleted only in respect of radioactive decay, i.e. the inventory of solid wastes is not depleted due to dissolution in brine and the total inventory of the repository is not depleted due to movement of contaminated brine away from the wastes, e.g. into the marker beds.

This is conservative, leading to some "double-counting" of activity in direct brine and cutting releases and, possibly, to an over-estimate of radionuclides in direct releases, especially for more mobile elements.

To investigate the range of model behaviours that can be generated by subjective uncertainty, 300 simulations are carried out for each subjectively selected deterministic scenario (see above).

There is a concern over whether this relatively small sample size is sufficient to adequately explore the range of behaviours of such a complex model. Time-dependent intermediate results[26] *indicate the presence of outlying results, which reinforce this concern. The requirements set by the EPA in respect of statistical meaningfulness of the result are trivial. To meet the EPA containment requirement is a much less demanding condition statistically*[27] *than if the end-point of concern was risk or mean dose. The IRG observes that it is likely that*

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[26] "Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 CCA for the WIPP", memo by J. Helton, 12/23/96.

[27] For example, simulations with a probability of less than 1 in 1,000 are of no concern at all. This is in contrast to assessments of risk in which simulations with a much lower probability than this can contribute significantly to total risk or mean dose.

the behaviour of the models has not been fully explored but that the number of samples may be sufficient for the purpose of demonstrating compliance with EPA regulations.

Overall, the IRG concludes that the analysis of disturbed performance in the CCA is a competent technical analysis and may be sufficient to meet the EPA requirements. The CCDFs are an appropriate method of summary presentation. The case, however, could have been considerably strengthened by presentation of additional intermediate results, especially as a function of time. These would have given better quantitative understanding of the physical processes operating, and hence confidence in the results as expressed in the form of the CCDFs.

3.4.4 Supplementary radiological calculations

The IRG requested the DOE to provide information on the levels of contamination at the surface and radiation doses which might be received as a result of drilling of a borehole into the repository. This information is not required by the EPA and is not available in CCA. The DOE was able to provide this information, informally, for an intrusion at 1,000 years after closure, by extending calculations already made within the analysis of disturbed performance.

The drilling scenario considers the transfer of radionuclides from the repository to the surface environment in the form of drilling cuttings, spallings and brine releases. Radiation doses are estimated to the drill operator from external irradiation due to the handling of drill core samples and due to exposure to radionuclides which accumulate in a mud pit. The dose to the workers during the remediation of the mud pit due to the inhalation of wind-borne material is also evaluated, as are the concentrations of radionuclides that would remain as a potential radioactive anomaly after remediation.

These supplementary calculations have not been formally reviewed by the IRG. They are, however, of value to set the impacts of the drilling scenario in perspective. In particular, they allow the IRG to draw the conclusion that, at least for this scenario, it is likely that the WIPP facility could meet an individual risk-based standard typical of those used in other countries.

3.5 Documentation

The IRG appreciates the very substantial effort that is required to document a performance assessment and its basis at the level of detail that is presented in the CCA. The IRG also appreciates that the documentation was drafted and assembled in a remarkably short period of time, consistent with schedule requirements of the DOE . Cross-referencing, at least between the Volume I and Appendices, is generally good, and is much eased by the use of the electronic version on CD-ROM.

Overall, the IRG finds the CCA difficult to follow and is disappointed with the CCA as a technical description. The main criticisms are that:

- *the documents are repetitious;*
- *many statements concerning the need, or not, to represent processes in the analyses are not sufficiently supported, e.g. by site-specific and experimental evidence, reasoned arguments and reference to natural analogues;*
- *relevant or important information is not always brought forward into Volume I of the CCA, and reviewers had to go deeply into the appendices or referenced documents.*

As a result, it was laborious for the IRG to understand, from the CCA, what was done in the performance assessment: not all the issues of concern could be traced, even using the electronic version of the documentation.

The clarity and general usefulness of the CCA documents to wider audiences have suffered as a result of the guidance from the EPA on content, and possibly also as a result of the limited time available for internal scientific review by the DOE. The IRG suggests that, provided this would not interfere with its prime requirement to achieve approval of the CCA from the EPA, the DOE should consider preparing a more generally-based performance assessment overview document at a level suited to a general technical audience.

4. Conclusions

The results of the review are summarised in the following sections which present:

- observations on the specificity of the WIPP case;
- the evaluation of the CCA against the Terms of Reference specified for the review, in particular, whether the 1996 performance assessment is:
  - appropriate in the context of the EPA requirements,
  - technically sound,
  - in conformity with international practices, and
  - in conformity with international guidance and standards;
- the overall judgement arising from the experience of the review.

4.1 Observations on the Specificity of the WIPP Case

The WIPP project, and the CCA, are different in several respects from geological disposal projects, and assessment documentation, in other countries.

- The WIPP facility is sited in an area in which mineral resources are being actively and extensively exploited.
- The regulator has provided detailed guidance on the assessment approach, documentation and, for the assessment of future human actions, model assumptions.
- The CCA is tightly focused on compliance with the EPA regulations, and does not represent a full safety case as understood in most other countries.

These observations are statements of fact, not criticisms. Such differences, however, have had a strong influence on the performance assessment carried out by the DOE, and have been taken into account by the IRG in formulating its conclusions.

4.2 Evaluation with Respect to the Terms of Reference

4.2.1 Appropriateness

The CCA was specifically designed by the DOE to meet the requirements of the EPA regulations. The IRG has not, during its review, found any indication that the information presented is not appropriate in the context of the EPA requirement. This, however, is a matter for the EPA to judge.

4.2.2 Technical soundness

The analyses contained in the CCA are based on an extensive geological data set resulting from high quality acquisition programmes and compilation of regional data. This has been supplemented by a focused geotechnical and experimental programme that has provided a world-leading understanding of processes relevant to rock-salt behaviour. The uncertainty associated with characterisation of the wastes, processes related to waste and backfill evolution in the repository, and chemical speciation of radionuclides in the repository environment, are less well understood. In particular:

(1) the CCA does not sufficiently explore the possible physical implications of the chemical reactions that the magnesium oxide backfill may undergo. These implications may be both favourable and unfavourable to the performance of the facility;

(2) the CCA does not support the assumption, applied in the performance calculations, that the physically and chemically heterogeneous array of waste, packaging, backfill, reaction products, and void space, will quickly reach well-mixed homogeneous conditions within the disposal rooms. The basis for this assumption and implications of heterogeneities need to be analysed further.

The CCA indicates good code configuration and management of data flows. The IRG has confidence that the procedures applied in these areas are consistent with best practice for computer simulation internationally. The IRG is also aware of the long involvement of WIPP project in international comparison exercises, which gives added confidence in the performance of several of the detailed models.

Thus, the IRG has overall confidence in the majority of judgements and assumptions made in developing calculational models of the disposal system, and concludes that, in the main, the analyses presented in the CCA are based on appropriate studies and are technically sound.

4.2.3 Conformity with international practices

The methods used to assess the performance of the WIPP facility are generally in conformity with practices used in other countries. These include:

- the selection of features, events and processes (FEPs);
- development of scenarios and models representing the evolution of conditions in the repository, and the release of radionuclides;
- quantitative analysis of selected scenarios by means of a linked set of models and comparison of the results to regulatory limits.

The probabilistic analysis methods used by the DOE are comparable to those employed in a number of other countries, and the DOE contractors have contributed substantially to the development of probabilistic methods in the field of repository post-closure assessment.

Specific aspects of the assessment carried out by the DOE do not accord with assessment practices in other countries, and this can be partly traced to the influence of the EPA regulations and the strong focus of the CCA on compliance. For example:

- the probabilistic approach applied by the DOE deals only with parameter-based uncertainty. Conceptual model and scenario uncertainty, are not discussed in the CCA. These are considered to be important internationally;

- results in the CCA focus on the CCDFs of cumulative radionuclide release. Information on the behaviour of intermediate parameters and results of representative deterministic calculations, especially as a function of time, are lacking. Without this, it may not be possible to develop a good understanding of the behaviour of the disposal system;

- the EPA has ruled that the DOE only needs to consider a limited set of future human actions, and has specified the assumptions to make in assessing these actions. Thus, some scenarios that might affect safety have not been evaluated. The lack of a logically-argued explanation for the choice of scenarios analysed, or evaluation of these other scenarios, leads to the impression that the assessment is arbitrary.

4.2.4 Conformity with international guidance and standards

The CCA focuses on a demonstration of compliance with the EPA containment requirement. The latter is based on collective dose considerations, refers to the total activity in the repository, and cannot be related to the standards based on individual dose and risk adopted in most other countries. Moreover, the EPA regulations do not require the applicant to present descriptions or arguments concerning the performance of the disposal system beyond the 10,000-year regulatory period. Thus, for the general case, the CCA does not present calculated end-points that can be compared with international guidance and standards as implemented in other countries.

The CCA does present dose estimates for the undisturbed performance within the 10,000-year regulatory period based on a conservative hypothetical dose pathway. In this case, the results indicate that the WIPP can easily meet typical performance criteria based on dose to the individual. It is likely that, if undisturbed, the facility could meet individual dose criteria over much longer times, due to the long-term stability of the site and the absence of viable fresh water resources locally.

The IRG asked for information, not included in the CCA, on doses that might be received in the disturbed case, as result of drilling of a borehole into the repository. The results provided by the DOE indicated that, for this scenario, the WIPP facility would meet an individual risk-based standard typical of those used in other countries. The CCA does not demonstrate, however, that no other scenarios could contribute significantly to risk.

4.3 Overall Judgement

The WIPP project and the CCA are markedly different from geological disposal projects and assessment documentation in other countries. In particular, important decisions relating to what is a sufficient method and scope of assessment have already been taken, and the CCA is not required to present a complete performance assessment as understood internationally.

The CCA documentation is not transparent and is difficult to follow even from the point of view of experienced performance assessment practitioners. Technical issues are often difficult to trace and some of the choices made and modelling assumptions are not well supported. This, combined with the specificity of the EPA regulations, made it challenging to distinguish between decisions determined by the regulator and those made by the DOE.

Focusing on the decisions for which the DOE must take technical responsibility, the IRG finds that the performance assessment methodology implemented in the CCA is generally acceptable and conforms to practices in other countries. The IRG also has overall confidence in the majority of judgements and assumptions made in developing calculational models, and believes that the quality of assessment codes and data handling is generally good. Thus, in the main, the analyses contained in the CCA are technically sound.

On specific points, the IRG considers that the DOE should give further attention to:

(1) the implications - favourable and unfavourable - that the behaviour of the magnesium oxide backfill may have on the performance of the facility;

(2) the basis for the assumption that homogeneous conditions will be rapidly reached in the disposal rooms, and the potential consequences of heterogeneities in the source term.

The IRG is of the view that, in the case of undisturbed performance, the WIPP facility would meet radiological performance standards typical of those used in other countries. This judgement is based on the analysis presented in the CCA in respect of the 10,000-year regulatory period and, in respect of times beyond 10,000 years, on the geological stability of the site and the absence of viable fresh water resources. The case of disturbed performance is less clear: supplementary analyses by the DOE indicate that a risk target would be met in respect of an exploratory borehole drilling scenario. The CCA does not (and need not) make the case that this is the most important scenario to consider and, therefore, the IRG cannot reach a definite judgement.

Finally, from the experience of the review, the IRG observes that, by commissioning this international peer review the DOE has demonstrated a commendable openness and commitment to improving confidence in the performance assessment of the WIPP facility. The DOE and their contractors were very open in their discussions with the IRG, and were able to provide useful responses, often at short notice, on most issues raised. This was very useful and helpful to the review.

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Appendix 1: The Members of the Review Group

Ken BRAGG (AECB, Canada) - Group Chairman

Ken Bragg graduated from the University of Toronto in 1965 with a Bachelor of Applied Science in Engineering Physics. He has 25 years' experience with industry and several government departments (Mines branch, Environment, and the Atomic Energy Control Board) covering a wide variety of industrial and radioactive wastes, such as uranium and other mine tailings, low-level radioactive waste, spent nuclear fuel, municipal waste and various effluent discharges from industry.

He served as a member of the Secretariat of the OECD/NEA in Paris for three years. He joined the Atomic Energy Control Board (AECB) in 1979 with responsibilities for uranium mine tailings and spent-fuel disposal. His current position is Head of the Nuclear Fuel Wastes & Special Assessments Section.

He has been a member of the Radioactive Waste Management Committee (RWMC) of the OECD/NEA since 1983, and the Chairman of the IAEA Working Group on Principles and Criteria for Radioactive Waste Disposal and of the NEA Working Group on the Regulatory Aspects of Future Human Actions at Radioactive Waste Disposal Sites.

Arnold BONNE (IAEA) - Secretariat

Arnold Bonne graduated from the University of Leuven (Belgium) in geological sciences. He completed a Ph.D. in Natural Sciences (Metallogeny) in 1973, at the same university, and for the following 5 years held a research position at the Belgian National Research Foundation. He joined the National Nuclear Research Establishment SCK/CEN at Mol in Belgium in 1978 and was involved in the Geological Disposal research programme. From 1989 to 1993 he headed the Research Unit on Disposal and Waste. He acquired a broad experience in site investigation, performance assessment and waste characterisation and became acquainted with the international approaches to them through his participation in numerous advisory groups and committees, e.g. he was member of the Steering Committee of the European Commission's PAGIS programme (Performance Assessment of Geological Isolation Systems).

In 1993, he joined the International Atomic Energy Agency (IAEA), Vienna, to lead the unit on disposal of radioactive waste and was appointed Acting Head of the Waste Management Section (now Waste Technology Section) in mid-1995. He is also programme manager of the Waste Management Technical Review Programme (WATRP) at the IAEA.

Jordi BRUNO (QuantiSci, Spain)

Jordi Bruno holds a Master's Degree (M.Sc.) in Analytical and Inorganic Chemistry from the Autonomous University of Barcelona, Spain (1978), and a Ph.D. in Inorganic Chemistry from the Royal Institute of Technology, Stockholm, Sweden (1986). From 1988 to 1990 he was Associate Professor at the same Institute, where he headed the Natural Waters Chemistry Group. He also holds a Master of Business Administration (MBA) from the School of Economics of Stockholm, Sweden (1990). Since 1990, he has been a consultant in the field of environmental issues, and is now Managing Director of QuantiSci SL in Barcelona, Spain. Since 1996, he has been Associate Professor to the Institute of Environmental Sciences of the Autonomous University of Barcelona, Spain.

His areas of professional expertise include spent-fuel dissolution, actinide thermodynamics, radionuclide geochemistry and mobilisation, geochemical modelling, and performance assessment. He performed research work for the SKB (Sweden), and ENRESA (Spain). He has been involved in several international programmes within the European Commission (e.g. MIRAGE) and the OECD/NEA (e.g. GEOVAL, Sorption Modelling Project).

Klaus KÜHN (Technical University of Clausthal, Germany)

Klaus Kühn graduated from the Clausthal School of Mines (now Technical University of Clausthal) with a Dipl. Ing. in Mining Engineering, in 1963. He then worked as an assistant at the Mineralogical-Petrographic Institute of the same University. In 1968, he obtained a Ph.D. (Dr. Ing.) from the Technical University of Clausthal for a thesis on the geochemistry of nickel and cobalt. In 1987, he was appointed Honorary Professor at the same University where he is presently teaching and carrying out research part-time.

His professional activities have concerned all aspects pertaining to the disposal of radioactive waste, notably by substantial involvement in the development of the GSF-Institut für Tieflagerung. In 1973, he was appointed Director of the Institute and Head of its Department of Repository Technology. After the Institute disbanded in 1995, he was appointed Senior Scientist to the Asse Research Mine, where the majority of the in-situ investigations for the German disposal program are performed. He has also been a member of the Reaktor-Sicherheitskommission (RSK) which advises the Ministry of the Environment, Nature Conservation and Reactor Safety (BMU) on all topics related to safety of nuclear installations including the nuclear fuel cycle.

For some ten years he was one of the German representatives to the IAEA's "Technical Review Committee on Underground Disposal of Radioactive Wastes (TRCUD)", and, in 1993, chaired the International Peer Review Team which reviewed the radioactive waste management program of Finland in the WATRP framework. He was the first Chairman of the OECD/NEA "Co-ordinating Group on Geological Disposal" in 1975, and served for about seven years.

Philippe LALIEUX (OECD/NEA) - Secretariat

Philippe Lalieux is a geologist and geophysicist with ten years' professional experience in the field of radioactive waste disposal. He graduated from the University of Brussels (Belgium) in 1983 with a B.Sc. in Geological Sciences and obtained a Master's Degree (M.Sc.) in Geophysical Sciences from the same university in 1984. From 1986 to 1994 he was a staff member of the Belgian Agency for the Radioactive Waste and Enriched Fissile Material (ONDRAF/NIRAS). His responsibilities included the management and supervision of geoscientific characterisation of potential sites for deep and near-surface repositories, and natural analogue studies. He was also in charge of the co-ordination and defence of a Safety Assessment and Feasibility Interim Report (SAFIR).

He joined the OECD/NEA Secretariat in 1995. He is in charge, within the Radiation Protection and Radioactive Waste Management Division, of the programmes on site characterisation and evaluation. In particular he is responsible for the Technical Secretariat of the Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal (SEDE). His current activities also entail involvement in the NEA performance assessment related activities, notably through the launching of the GEOTRAP project on radionuclide transport.

Gordon LINSLEY (IAEA) - Secretariat

Gordon Linsley graduated from the University of Sheffield, in the United Kingdom in 1964 with a B.Sc. in physics. He went on to complete a Ph.D. in solid state physics, awarded in 1969, from the same university. From 1967, he worked in the field of medical physics for the Western Regional Hospital Board, in Glasgow, Scotland before specialising in the area of radiation protection. He was a staff member of the United Kingdom's National Radiological Protection Board (NRPB), Harwell, Oxfordshire, from its inception in 1970 until 1984. During a period as a radiation protection advisor, he acquired a broad experience in relation to the uses of ionising radiations in industry, research and medicine. In 1976, the focus of his work changed to environmental impact assessment and subsequently, he led a section at NRPB, working on this subject.

In 1984, he joined the International Atomic Energy Agency (IAEA), Vienna, Austria, to lead a small group concerned with the environmental aspects of radioactive waste management, safety assessment and radiological criteria for application to waste management. In 1996, he was appointed Head of the newly-formed Waste Safety Section at the IAEA. This section is responsible for establishing international safety standards in the area of waste management.

Sören NORRBY (SKI, Sweden)

Sören Norrby is a chemist with more than twenty-five years' experience in the field of radioactive waste management and disposal. He obtained his M.Sc. in Chemistry at the University of Uppsala, Sweden, in 1970. He worked for five years at the University of Uppsala on research projects mainly in the field of chemical radionuclide separation techniques. He worked for eight years at the Swedish Radiation Protection Institute (SSI) and was engaged in radioactive waste management and disposal matters.

Since 1980 he has worked for the Swedish Nuclear Power Inspectorate (SKI), since 1987 as the Director of the Office of Nuclear Waste. He has been engaged in supervision, regulatory review and licensing of nuclear waste management and disposal facilities in the Swedish nuclear waste programme (e.g. an intermediate storage facility for spent-fuel and a repository for low- and intermediate-level waste). He is also engaged in the review of the Swedish R&D programme on final disposal of spent nuclear fuel. He has served on several governmental committees to review Swedish legislation on nuclear waste. He is active in many aspects of international co-operation in the field of radioactive waste management and disposal.

He is a member of the Radioactive Waste Safety Standards Advisory Committee (WASSAC) at the IAEA and of the Radioactive Waste Management Committee (RWMC) at the OECD/NEA. He is the Chairman of the ACPM for the Community Plan of Action in the Field of Radioactive Waste.

Claudio PESCATORE (OECD/NEA) - Secretariat

Claudio Pescatore obtained a Laurea, *cum laude*, in Applied Physics from the University of Bologna in 1975 and a Ph.D. in Nuclear Engineering from the University of Illinois, Urbana-Champaign (US) in 1982. He has 19 years' experience in research and development, technical assistance to government and industry, university lecturing, and management of international programmes in the field of nuclear waste covering low-level waste, high-level waste, and spent-fuel storage and disposal.

He joined the Brookhaven National Laboratory in 1982 and was involved in: the study of high-level waste and spent-fuel disposal concepts in basalt, salt, and tuff formations; reliability and modelling studies of waste package materials during storage and disposal; analyses of gaseous and aqueous pathways for radionuclide migration; peer reviews of environmental impact assessments studies and site characterisation plans. In 1989 he was nominated Group leader for Radioactive Waste Performance Assessment. Through 1995, he also was adjoint Professor of Marine Environmental Sciences at the University of New York at Stony Brook.

He joined the NEA/OECD Secretariat in 1992 in the Division of Radioactive Waste Management. He is in charge of the Agency's performance assessment programmes, and provides the technical secretariat of the Performance Assessment Advisory Group, the Probabilistic System Assessment Group, the group on validation/confidence building in safety assessments, and the Integrated Performance Assessment Group. He also contributes in the field of site characterisation, and has been at the centre of several international initiatives such as the ASARR and GEOTRAP projects, and the GEOVAL'94 symposium. He was a Secretariat member of the international peer reviews of SKI's Project 90 and of the AECL Postclosure Assessment for the EIS on the Concept for Disposal of Canada's Nuclear Fuel Waste.

Richard STORCK (GRS, Germany)

Richard Storck was educated at the Technical University of Berlin as a nuclear engineer. He graduated from the same university with a thesis on probabilistic risk assessment of technical nuclear facilities (1980). He then worked as a scientific employee of the Technical University of Berlin for four years, on the first German project on the long-term safety of deep underground disposal systems for radioactive waste in salt formations (PSE).

He continued this work as a Group and Project Manager at the GSF research centre in Braunschweig. He was involved in the European performance assessments for high-level (PAGIS) and low-level waste (PACOMA), the long-term safety assessment for the application of the abandoned iron ore mine at the Konrad site for disposal of non-heat-producing radioactive waste, performance assessments for the planned repository at the Gorleben site for all types of waste including spent-fuel (SAM).

In 1995, he joined GRS (Gesellschaft fur Anlagen und Reaktorsicherheit) following the transfer of the repository research area of the GSF research centre to the GRS. Since that time he has been Head of the Long-Term Safety Analyses Department. One of his current main tasks is the long-term safety assessment of the Morsleben repository for low-level waste in the eastern part of the country.

Trevor SUMERLING (Safety Assessment Management Ltd., United Kingdom)

Trevor Sumerling obtained a 1st class honours degree in physics from Lancaster University in 1975. He spent 8 years at the UK National Radiological Protection Board where he gained experience in the fields of in vivo monitoring, internal dosimetry and environmental transfer of radionuclides, and became responsible for the in vivo measurement facilities and various environmental field studies at the NRPB. For the past 10 years he has worked in scientific and engineering consultancies on aspects of radioactive waste disposal assessment and assessment management. In this period, he has contributed significantly to nuclear waste disposal assessment projects in the UK, Switzerland, Sweden, Canada and Japan. He is now Director of Safety Assessment Management Limited, an independent consultancy specialising in radioactive waste disposal assessment.

His more recent experience has included:

- project co-ordination for an independent performance assessment of the Sellafield site and review of the proponent's safety documentation on behalf of the UK regulator, as well as development of assessment procedures and contributions to UK regulatory guidance documentation;
- scenario methodology development and application to both the Kristallin-I (HLW) project and Wellenberg (L/ILW) site, as well as technical work and editing contributing to the Kristallin-I safety assessment report, for the Swiss National Co-operative for Radioactive Waste Disposal;
- carrying out an international comparison of disposal concepts and assessments of nuclear fuel wastes for Atomic Energy of Canada Limited as input to the federal review process in Canada;
- participation in the NEA OECD "FEP Database" and "Integrated Performance Assessment" working groups.

Mr. Sumerling was retained as a consultant to assist the Secretariat in compiling and editing the report of the current review.

Hiroyuki UMEKI (PNC, Japan)

Hiroyuki Umeki is a nuclear-chemical engineer with more than 15 years' experience in the field of radioactive waste management. He obtained his Bachelor's and Master's degrees in Nuclear Engineering from the University of Tokyo in 1977 and 1979 respectively, following which, he worked for 6 years at the University of Tokyo on research and education pertaining to the nuclear fuel cycle, in particular, radioactive waste management.

After he obtained his Ph.D. in 1987, from the University of Tokyo with a thesis on radionuclide transport modelling and uncertainty analysis for the performance assessment of the disposal system, he joined the Power Reactor and Nuclear Fuel Development Corporation (PNC) which is a leading R&D organisation for the Japanese high-level waste disposal programme. His current positions are the Deputy General Manager and Senior Engineer of the Isolation System Research Programme in the Radioactive Waste Management Project. He is responsible for all performance assessment activities in the R&D programme for high-level waste disposal. This includes the H3 project completed in 1992, and the H12 project now on-going. He has been a member of the OECD/NEA Performance Assessment Advisory Group (PAAG) since 1988.

Appendix 2: Terms of Reference for the Review

Terms of Reference for the international review of the Waste Isolation Pilot Plant 1996 performance assessment were negotiated between the DOE, the NEA and the IAEA. Relevant parts of the Terms of Reference, agreed to in June 1997, are reproduced below.

Introduction

A joint international review of the post-closure part of the Compliance Certification Application (CCA) of the US Program for safe disposal of transuranic radioactive waste (TRUW) is to be organized by the Nuclear Energy Agency of the Organisation of Economic Co-operation and Development (NEA) and the International Atomic Energy Agency (IAEA). The review will be conducted by a group of independent experts appointed by the NEA and the IAEA (hereafter referred to as the Expert Group). A joint NEA/IAEA Secretariat will be established for the purpose, and will be managed by the NEA. This Expert Group will examine whether the post-closure performance assessment of the Waste Isolation Pilot Plant (WIPP) disposal system for TRUW is appropriate, technically sound, and in conformity with international standards and practices. 'The results of this international review will be submitted to the US Department of Energy (DOE) in a joint report.

The International Review Process

The international review will be organised jointly by the NEA and the IAEA as part of their international review services programs. The review is at the request of and sponsored by the DOE.

The Expert Group will draw on the experience of the world's leading experts in radioactive waste disposal and safety assessments and their views on the approaches taken by other countries towards the safe disposal of long-lived radioactive waste. As part of the review, the Expert Group may want to meet with scientific and technical groups and government agencies involved in the WIPP.

Objective of the International Review

The objective of the international review is to examine whether the post-closure performance assessment of the WIPP in the CCA is appropriate, technically sound, and in conformity with international standards and practices.

Scope of the International Review

The review should include an assessment of the state of the WIPP *(performance assessment)* technology in comparison to other nations' programs, and should include but not be limited to scenario development, conceptual model and computational model development, data/parameter acquisition and selection, computational model construction, and the results of the probabilistic analysis including tracking of uncertainty. The clarity and transparency of the documentation of the post-closure performance assessment results should also be reviewed. Finally, the Expert Group will review, from an international perspective, the technical soundness and appropriateness of the methodologies used and the arguments presented for the post-closure performance assessment on which the CCA was developed.

In carrying out the review, the Expert Group may consider comparing the post-closure part of the CCA with approaches being taken by other countries on the management and disposal of long lived radioactive waste.

Documentation for this review will primarily consist of the applicable portions of the CCA, the FEIS, the cited references, details of formal past licensing decisions concerning WIPP, and other information as may be requested. All relevant information used by the Expert Group should be listed in the final report resulting from this international review.

The issues which fall outside the scope of the post-closure part of the CCA and which have been dealt with separately or at an earlier stage of the decision-making process, such as repository siting and design, waste form and other pre-closure issues, should not be addressed as such. However, it is recognized that such issues may

have a direct influence on post-closure performance and the Expert Group might wish to comment on how such an influence has been evaluated and taken into account from the point of view of post-closure performance assessment.

The scope of the review should exclude chemical toxicity aspects, socio-economic or political considerations, all aspects of the development of regulations, as well as any issues related to timing and institutional arrangements for the implementation of disposal.

It is anticipated that the international review will be carried out over a 6-month period. The material for the review (see Annex 1) will be made available to the joint NEA/IAEA Secretariat by October 1, 1996. The review will be completed and delivered to the CAO by March 30, 1997.

Deliverable

A report containing the Expert Group's findings will be delivered to the DOE Carlsbad Area Office (CAO). Prior to finalizing report, the Expert Group will present its findings to the CAO to ensure that all pertinent information and data were considered in the review.

Annex 1: US DOE reference documents

Primary Material to be reviewed:

- The CCA's main text, i.e. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, Volume I.

Other Information:

- FEIS Record of Decision.
- Appendices and references cited in the aforementioned documents, as required.
- Other information, as identified by the reviewers themselves.

Annex 2: International reference documents

1. IAEA, The Principles of Radioactive Waste Management, Safety Fundamentals, Safety Series No. 11 I-F (1995)
2. IAEA, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (sponsored by FAO, IAEA, ILO, OECD/NEA, PAHO, WHO), Safety Series No. 115, (1996)
3. ICRP, Radiation Protection Principles for the Disposal of Solid Radioactive Waste, ICRP Publication 46, (1986)
4. OECD/NEA, Disposal of Radioactive Waste: Review of Safety Assessment Methods, (1991)
5. IAEA, Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Wastes, Safety Series No. 99 (1989)
6. IAEA, Safety Indicators in Different Timeframes for the Safety Assessment of Underground Radioactive Waste Repositories, TECDOC-767, (1994)
7. OECD/NEA, Safety Assessments of Radioactive Waste Repositories: Future Human Actions at Disposal Sites, (1995)
8. OECD/NEA, Safety Assessments of Radioactive Waste Repositories: Systematic Approaches to Scenario Development (1992)
9. OECD/NEA, Disposal of Radioactive Waste: Can Long-term Safety be Evaluated ? An International Collective Opinion, jointly sponsored by the NEA, IAEA and CEC (1991).
10. OECD/NEA, The Management of Long-Lived Radioactive Waste: The Environmental and Ethical Basis of Geological Disposal, A collective Opinion of the NEA Radioactive Waste Management Committee (1995).

Appendix 3: Selected Paragraphs From the EPA Regulations

This appendix reproduces selected parts of paragraphs and definitions from 40 CFR 191 and 40 CFR 194 which are referred to in Chapter 2 of the main report. It is emphasised that these have been selected as background to points on which the IRG wished to comment. They are not intended to summarise the EPA regulations.

A3.1 Selected paragraphs from 40 CFR 191

§191.13 Containment requirements.

(a) Disposal systems ... shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment* for 10,000 years after disposal from all significant processes and ... shall:

(1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A)*; and

(2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A)*.

(b) Performance assessments need not provide complete assurance that the requirements of §191.13(a) will be met. ... Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance ... will be achieved.

§191.14 Assurance requirements.

To provide the confidence needed for long-term compliance with the requirements of §191.13, ... :

(a) Active institutional controls* over disposal sites should be maintained for as long a period of time as is practicable ... however, performance assessments ... shall not consider any contributions from active institutional controls for more than 100 years after disposal.

(b) Disposal systems shall be monitored after disposal ...

(c) Disposal sites shall be designated by the most permanent markers, records, and other passive institutional controls* practicable ...

---

* Terms denoted by an asterisk have defined meanings, see Section A3.3.

(d) Disposal systems shall use different types of barriers to isolate the wastes ... engineered and natural barriers ...

(e) Places where there has been mining for resources, or where there is a reasonable expectation of exploration ... should be avoided in selecting disposal sites. Resources to be considered include minerals, petroleum or natural gas ... Such places shall not be ... unless the favorable characteristics of such places compensate for their greater likelihood of being disturbed in the future.

§191.15 Individual protection requirements.

(a) Disposal systems ... shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance* of the disposal system shall not cause the annual committed effective dose, ... to any member of the public ... to exceed 15 millirems (150 microsieverts).

A3.2 Selected paragraphs from 40 CFR 194

Containment Requirements

§194.25 Future State Assumptions

(a) Unless otherwise specified ... performance assessments and compliance assessments conducted pursuant the provisions of this part to demonstrate compliance with § 191.13, § 191.15 ... shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions. ...

§194.32 Scope of performance assessments.

(a) Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.

(b) Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur.

Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.

§194.33 Consideration of drilling events in performance assessments.

(a) Performance assessments shall examine deep drilling and shallow drilling that may potentially affect the disposal system during the regulatory time frame.

(b) The following assumptions and process shall be used... (1) Inadvertent and intermittent intrusion by drilling for resources (other ... the waste ... or engineered barriers ...) is the most severe human intrusion scenario. (2) ... drilling events shall be assumed to occur in the Delaware Basin at random intervals in time and space during the regulatory time frame. (3) The frequency of deep drilling shall be calculated in the following manner: (i) Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years ... (ii) The total rate of deep drilling shall be the sum of the rates of deep drilling for each resource. ...

(c) ... assumed that: (1) Future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. ... The types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of such boreholes that are sealed by humans; ...

(d) ... performance assessments need not analyse the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

§194.34 Results of performance assessments.

(a) The results of performance assessments shall be assembled into "complementary, cumulative distribution functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events.

(b) Probability distributions for uncertain disposal system parameter values used in performance assessments shall be developed ...

(c) Computational techniques, which draw random samples from across the entire range of the probability distributions... shall be used in generating CCDFs ...

(d) The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated

exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability. ...

(e) Any compliance application shall display the full range of CCDFs generated.

(f) ... demonstrates that there is at least a 95 percent level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 ...

Assurance Requirements

§194.41 Active institutional controls.

(a) ... include detailed descriptions of proposed active institutional controls ... Assumptions pertaining to active institutional controls and their effectiveness in terms of preventing or reducing radionuclide releases shall be supported by such descriptions.

(b) Performance assessments shall not consider any contributions from active institutional controls for more than 100 years after disposal.

§194.43 Passive institutional controls.

(a) ... include detailed descriptions of the measures that will be employed to preserve knowledge about the location, design, and contents of the disposal system. ... (1) Identification of the controlled area by markers ... (2) Placement of records in the archives and land record systems of local, State, and Federal governments, and international archives, ... (3) Other passive institutional controls practicable to indicate the dangers of the waste and its location.

(c) The Administrator may allow the Department to assume passive institutional control credit, in the form of reduced likelihood of human intrusion, if the Department demonstrates ... that such credit is justified ... Such credit ... cannot be used for more than several hundred years and may decrease over time. ...

§194.45 Consideration of the presence of resources.

Any compliance application shall include information that demonstrates that the favorable characteristics of the disposal system compensate for the presence of resources in the vicinity of the disposal system and the likelihood of the disposal system being disturbed as a result of the presence of those resources. If performance assessments predict that the disposal system meets the containment requirements of § 191.13 of this chapter, then the

Agency will assume that the requirements of this section and § 191.14(e) of this chapter have been fulfilled.

A3.3 Selected definitions from 40 CFR 191 and 40 CFR 194

§191.02 Definitions.

Transuranic radioactive waste, ... means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years, per gram of waste, except for: (1) High-level radioactive wastes; (2) wastes that the Department has determined, with the concurrence of the Administrator, do not need the degree of isolation required by this part; or (3) wastes that the Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR Part 61.

§191.12 Definitions.

Accessible environment means: (1) The atmosphere; (2) land surfaces; (3) surface waters; (4) oceans; and (5) all of the lithosphere that is beyond the controlled area.

Active institutional control means: (1) Controlling access to a disposal site by any means other than passive institutional controls; (2) performing maintenance operatione or remedial actions at a site, (3) controlling or cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance.

Controlled area means: (1) A surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location.

Disposal system means any combination of engineered and natural barriers that isolate spent nuclear fuel or radioactive waste after disposal.

Passive institutional control means: (1) Permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system.

Performance assessment means an analysis that: (1) Identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties,

caused by all significant processes and events. These estimates shall be incorporated into an overall probability distribution of cumulative release to the extent practicable.

Undisturbed performance means the predicted behaviour of a disposal system, including consideration of the uncertainties in predicted behaviour, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events.

A3.4 Appendix A to 40 CFR 191 - Table for Subpart B

TABLE 1--RELEASE LIMITS FOR CONTAINMENT REQUIREMENTS[Cumulative releases to the accessible environment for 10,000 years after disposal]

Radionuclide	Release limit per 1,000 MTHM or other unit of waste (see notes) (curies)
Americium-241 or -243	100
Carbon-14	100
Cesium-135 or -137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, -239, -240, or -242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230 or -232	10
Tin-126	1,000
Uranium-233, -234, -235, -236, or -238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1,000

Note 1: Units of Waste. The release limits in Table 1 apply to the amount of wastes in anyone of the following:

(e) An amount of transuranic (TRU) wastes containing one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years.

Note 2: To develop Release Limits for a particular disposal system, the quantities in Table 1 shall be adjusted for the amount of waste included in the disposal system. For example:

(b) If a particular disposal system contained three million curies of alpha-emitting transuranic wastes, the Release Limits for that system would be the quantities in Table 1 multiplied by three (three million curies divided by one million curies).

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Technical Peer Review Report

Report of the Review Panel

Requirements for Disposal of Remote-Handled Transuranic Wastes at the Waste Isolation Pilot Plant

ASME International

Institute for Regulatory Science

DISCLAIMER

This report was prepared through the collaborative efforts of the American Society of Mechanical Engineers (ASME) Center for Research and Technology Development and the Institute for Regulatory Science (referred to thereafter with the collaborators as the Society) for the Office of Science and Technology Development of the U.S. Department of Energy (referred to hereafter as the Sponsor).

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Preface

This report contains the results of a peer review performed jointly by the American Society of Mechanical Engineers (ASME) and the Institute for Regulatory Science (RSI). Based on a request from the Carlsbad Operations Office of the U.S. Department of Energy (DOE), a Review Panel was established to review the "Requirements for the Disposal of Remote-Handled Transuranic Wastes at the Waste Isolation Pilot Plant."

Preliminary negotiations between the DOE and New Mexico Environment Department indicated a desire of the New Mexico Environment Department to cosponsor the peer review. Accordingly, there were extensive negotiations between managers of the peer review program and the New Mexico Environment Department (NMED) on the role and responsibilities of cosponsors of the peer review. After considerable discussion within the NMED, based on legal reasons, a decision was made not to cosponsor the peer review. However, the NMED expressly recognized the need for peer review and the credibility of the current peer review program.

Keeping with the ASME Process, the following Review Panel (RP) was appointed by the Peer Review Committee (PRC) of ASME:

Alan S. Corson
Tom A. Hendrickson
M.C. Kirkland
Peter B. Lederman, Chair
James E. Martin
Wade O. Troxell
Richard Wilson

During the period covered by this report, the ASME PRC overseeing the peer review consisted of the following individuals:

Charles O. Velzy, Member of EP, Chair
Ernest L. Daman, Member of EP
Nathan H. Hurt, Member of EP
A. Alan Moghissi, Member of EP, Principal Investigator of the PR Program
Gary A. Benda
Erich W. Bretthauer
Irwin Feller
Robert A. Fjeld

John T. Greeves
William T. Gregory, III
Peter B. Lederman
Jeffrey A. Marqusee
Lawrence C. Mohr, Jr.
Goetz K. Oertel
Glen W. Suter, II

The supporting staff were the following individuals:

Carolyn Davis: Director of Research at the Center for Research and Technology Development of ASME in Washington DC; Administrative Manager of the ASME PRC

Betty R. Love: Executive Vice President, RSI, Columbia, MD; Administrative Manager of the Peer Review Program. During this peer review, Betty Love was also responsible for management of stakeholder participation.

Sorin R. Straja: Vice President for Science and Technology, RSI; Technical Secretary

Sharon D. Jones: Director of Training Programs, RSI; Manager of Review Panel Operations

The biographical summaries of the members of the RP, the PRC, and the technical staff are located at the end of this report.

Extensive written material was provided by the DOE to the Technical Secretary at the beginning of the process. The Technical Secretary extracted a draft summary for inclusion in this report. This summary was provided to DOE for review and was revised accordingly. Based on the information provided to the Technical Secretary, the Summary included in this report is an accurate representation of the project. The written material provided by DOE was made available to the members of the Review Panel in advance of the meeting in Carlsbad, NM. The agenda of the meeting in Carlsbad appears in the Appendix of this section.

The RP considered materials provided by the DOE and presentations during the Carlsbad meeting. The RP benefitted from a site visit to the Waste Isolation Pilot Plant on the morning of Monday, July 30, 2001 immediately prior to the

presentations and from presentations during a workshop convened in conjunction with the peer review meeting. At the end of the meeting, the Review Panel met in an executive session and completed its report. The report of the Review Panel was subsequently copy-edited. Consistent with the procedures established by ASME, this report was provided to DOE for identification of potential errors; misunderstandings; and areas of ambiguity; and was revised accordingly.

The completion of this peer review within the rather short time frame could not have been possible without the support of a number of people. The assistance and cooperation of Bryan Howard, Norbert Rempe, and Phil Gregory are appreciated. The cooperation of Dr. Peter Maggiore, Secretary of the New Mexico Environment Department, and the staff of that Department was most helpful during the peer review.

Charles O. Velzy
A. Alan Moghissi

Appendix

ASME/RSI Peer Review and Workshop
Requirements for Disposal of Remote Handled Transuranic Wastes at the Waste Isolation Pilot Plant
Carlsbad, NM - July 30 - August 3, 2001

AGENDA

Monday, July 30, 2001

Waste Isolation Pilot Plant

8:30 a.m.	Site Visit
11:30 a.m.	Lunch

Pecos River Village Conference Center
Carousel House, Carlsbad, NM

Session 1: Introduction and Regulatory Requirements
Chair: Chuck Wiggins

1:00 p.m.	Welcoming Address	Chuck Wiggins Mayor Pro Tem of Carlsbad
1:10 p.m.	Welcoming Address	Ines Triay Manager, Carlsbad Field Office
1:20 p.m.	Introduction to Panel Workshop	A. Alan Moghissi Institute for Regulatory Science/ASME
2:00 p.m.	NMED Perspective	James Bearzi New Mexico Environment Department
2:30 p.m.	EPA Perspective	Rajani Joglekar U.S. Environmental Protection Agency
3:00 p.m.	Break	

Session 2: DOE Strategy for RH-TRU Waste Disposal
Chair: Betty R. Love

3:15 p.m.	The DOE RH-TRU Waste Characterization Program	Bryan Howard Los Alamos National Laboratory
4:00 p.m.	Discussion Responding to Audience Questions (Bearzi, Joglekar, Howard)	
5:00 p.m.	Adjournment	

ASME/RSI Peer Review and Workshop
Requirements for Disposal of Remote Handled Transuranic Wastes at the Waste Isolation Pilot Plant
Carlsbad, NM - July 30 - August 3, 2001

AGENDA

Tuesday, July 31, 2001

Pecos River Village Conference Center
Carousel House, Carlsbad, NM

Session 3: **Chair:**	**Review of DOE Submission** **Bryan Howard**	
8:00 a.m.	RH Inventory and Compliance Impacts	Joe Harvill Westinghouse TRU Solutions
8:45 a.m.	Repository Performance	M. Kathryn Knowles Sandia National Laboratory
9:45 a.m.	Break	
Session 4: **Chair:**	**Review of DOE Submission (Cont'd)** **Bryan Howard**	
10:00 a.m.	Application of Acceptable Knowledge for RH-TRU Waste	Bob Kehrman Westinghouse TRU Solutions
11:00 a.m.	Characterization Objectives and NDA/NDE Measurement Systems	Dan Taggart Los Alamos National Laboratory
12:00 p.m.	Lunch	
Session 5: **Chair:**	**Placing RH-TRU Waste in Perspective** **Phil Gregory**	
1:00 p.m.	Summary: RH-TRU: Small Volume-Large Impact	Ines Triay, CBFO
2:00 p.m.	Summary: NAS/NRC: WIPP Report	Werner Lutze Center for Radioactive Waste Management
2:30 p.m.	Discussion Responding to Audience Questions (Triay, Lutze)	
3:00 p.m.	Break	

ASME/RSI Peer Review and Workshop
Requirements for Disposal of Remote Handled Transuranic Wastes at the Waste Isolation Pilot Plant
Carlsbad, NM - July 30 - August 3, 2001

AGENDA

Tuesday continued

Session 6:	**Risk Issues**	
Chair:	**Joe Harvill**	
3:15 p.m.	Risk Assessment of Intrusive RH Waste Characterization Methods	Fritz Seiler Sigma Five Associates
4:00 p.m.	Risk/Cost-Impact Analysis for Intrusive RH Waste Characterization Methods	Louis Restrepo OMICRON
4:30 p.m.	Discussion Responding to Audience Questions (Seiler, Restrepo)	
5:00 p.m.	Adjournment	

Wednesday, August 1, 2001

Pecos River Village Conference Center
Carousel House, Carlsbad, NM

Session 7:	**Regulatory Experience**	
Chair:	**M. Kathryn Knowles**	
8:00 a.m.	Application of 40 CFR 260, 262, and 264 to RH-TRU Mixed Waste Characterization	Matt Strauss Clay Associates
9:00 a.m.	Application of 40 CFR 191/194 to RH-TRU Waste Characterization	John Bartlett SC&A
9:45 a.m.	Break	
Session 8:	**Stakeholders**	
Chair:	**A. Alan Moghissi**	
10:00 a.m.	Discussion Responding to Audience Questions and Statements by Stakeholders Addressing Peer Review Criteria	
12:00 p.m.	Lunch	
1:00 p.m.	Discussion Responding to Audience Questions and Statements by Stakeholders Addressing Peer Review Criteria	
4:00 p.m.	Adjournment	

ASME/RSI Peer Review and Workshop
Requirements for Disposal of Remote Handled Transuranic Wastes at the Waste Isolation Pilot Plant
Carlsbad, NM - July 30 - August 3, 2001

AGENDA

Wednesday continued
Lyndam Hotel, Albuqerque, NM

6:00 p.m. Executive Session

Thursday, August 2, 2001

Lyndam Hotel, Albuqerque, NM

Executive Session

8:00 a.m Writing of the Report *(ASME Review Panel Members only)*

5:00 p.m. Adjournment

Friday, August 3, 2001

Lyndam Hotel, Albuqerque, NM

Executive Session

8:00 a.m Writing of the Report *(ASME Review Panel Members only)*

5:00 p.m. Adjournment

Peer Review Process

INTRODUCTION

There is consensus within the technical community on the definition, process, and key criteria for the acceptability of peer review. Peer review consists of a critical evaluation of a topic by individuals who—by virtue of their education, experience, and acquired knowledge—are qualified to be peers of an investigator engaged in a study. A peer is an individual who is able to perform the project, or the segment of the project that is being reviewed, with little or no additional training or learning.

Recognizing that peer review constitutes the core of acceptability of scientific and engineering information, virtually all professional societies of scientists and engineers have instituted formal procedures for peer review for their activities. The American Society of Mechanical Engineers (ASME), also known as ASME International, has over a century of experience in peer review. Consistent with its mission and tradition, ASME recently established a peer review program devoted to the technologies supported by the Office of Science and Technology of the U.S. Department of Energy (DOE). This program is performed in cooperation with the Institute for Regulatory Science (RSI). The reports of the peer reviews resulting from this program have been published (ASME 1997, 1998, 1999, 2000).

PEER REVIEW PROCESS

The structure of the peer review process established by the ASME/RSI team consists of a tiered system. For each specific area of technology, the entire process is overseen by a Peer Review Committee (PRC). The review of specific topics is performed by Review Panels (RPs).

Peer Review Committee

The PRC is a standing committee formed to oversee peer review for one particular program in an agency. Its members are chosen on the basis of their education, experience, and peer recognition. An attempt is made to ensure that all needed technical competencies and diversity of technical views are represented in the PRC. The members of the PRC must be approved by the Board on Research and Technology Development of the Council on Engineering of the ASME. The PRC includes an Executive Panel (EP) that is responsible for the day-to-day operation of the PRC. Except for the EP, membership in the ASME is not required for appointment to the PRC. As the overseer of the entire peer review process, the PRC enforces all relevant ASME policies, including compliance with professional and

ethical requirements. A key function of the PRC is the approval of the appointment of members of RPs for a specific project.

Review Panels

The review of a project, a document, a technology, or a program is performed by a RP consisting of a small group of highly-knowledgeable individuals. Upon the completion of their task, the RPs are disbanded. The selection of reviewers is based on the competencies required for the specific review assignment. The number of individuals in a RP depends upon the complexity of the subject to be reviewed. The selection of a reviewer is based on the totality of that individual's qualifications. However, there are several generally-recognized and fundamental criteria for assessing qualifications of a reviewer. These are as follows:

1. **Education and relevant experience:** A minimum of a B.S. degree and preferably an advanced degree in an engineering or scientific field is required for any peer reviewer. In addition, the reviewer must have significant experience in the area that is being reviewed.

2. **Peer recognition:** Election to an office of a professional society, serving on technical committees of scholarly organizations, and similar activities are considered to be a demonstration of peer recognition.

3. **Contributions to the profession:** Contributions to the profession may be demonstrated by publications in peer-reviewed journals. In addition, patents, presentations at meetings where the papers were peer-reviewed, and similar activities are also considered to be contributions to the profession.

4. **Conflict of Interest:** One of the most complex and contested issues in peer review is a set of subjects collectively called conflict of interest. The ideal reviewer is an individual who is intimately familiar with the subject and yet has no monetary interest in it. Despite this apparent difficulty, the ASME and similar organizations have successfully performed peer review without having a real or an apparent conflict of interest. The guiding principle for conflict of interest is as follows: *An individual who has a personal stake in the outcome of the review may not act as a reviewer or participate in the selection of reviewers.*

Due to the multidisciplinary nature of many projects reviewed by the ASME/RSI team, rapid identification of qualified peer reviewers and their availability to

participate in the review process are key ingredients for a successful program. The process used for the identification of reviewers is multifaceted. The Administrative Manager of the Peer Review Program receives recommendations from sources within ASME; previous members of the RP; sister societies; other organizations and individuals; the DOE; DOE contractors; and others. However, the selection of peer reviewers is entirely based on criteria identified by ASME. The details of various aspects of peer review, including conflict of interest, can be found in ASME *Manual for Peer Review* (ASME 2000) and the *Associated Procedures* (RSI 2000).

COOPERATION WITH OTHER PROFESSIONAL SOCIETIES

The ASME is a large professional engineering society having in excess of 125,000 members. Although the predominant discipline of the members is mechanical engineering, there are members who—by virtue of their education, training, or experience—are competent in other disciplines. The Council on Engineering includes divisions ranging from classical mechanical engineering (design, heat transfer, and power) to solar engineering; environmental engineering; and safety and risk analysis. Despite the diverse competency within the ASME, it is recognized that on occasion it will become necessary to peer review activities which include disciplines that are outside the areas of competency of the ASME and its members. These disciplines may include geology, hydrology, toxicology, and ecology. Consequently, ASME has reached formal and informal agreements with its sister societies to identify qualified reviewers in areas outside of those covered by the membership of ASME.

PERFORMING ORGANIZATIONS

The Center for Research and Technology Development of ASME manages a number of scientific and engineering activities, including peer review for the Office of Science and Technology (OST). Because of ASME's conscious effort to maintain a small in-house staff, it relies upon other organizations to provide detailed project management services in its research, development, and similar activities. Accordingly, ASME and RSI joined forces in a collaborative effort to perform the peer review for OST. While the ASME staff in Washington, DC provides the staff support for the PRC, the detailed management and staff support for the RPs is provided by RSI.

American Society of Mechanical Engineers

As one of the largest professional engineering societies, ASME has a long and distinguished history. Its activities are carried out primarily by members who volunteer their time in support of engineering and scientific advancement. For obvious reasons, ASME also has a paid staff to manage the day-to-day operations of such a large professional society. The ASME has a detailed structure for its operation consisting of councils, boards, divisions, and committees. The Council on Engineering has 38 divisions, including: Environmental Engineering; Solid Waste Processing; Nuclear Engineering; and Safety Engineering and Risk Analysis. The Council on Codes and Standards develops ASME codes and standards that are the backbone of many industries—including power production—worldwide. The Council on Codes and Standards is also responsible for the development of standards for activities such as certification of incinerator operators. The ASME was a founding member of the American Association of Engineering Societies and a founding member of the American National Standards Institute.

Institute for Regulatory Science

RSI is a not-for-profit organization chartered under section 501(c)3 of the Internal Revenue Service. It is dedicated to the idea that societal decisions must be based on the best available scientific and engineering information. According to the RSI mission statement, peer review is the foundation of the best available scientific and engineering information. Consequently, RSI has promoted peer review within government and industry as the single most important measure of reliability of scientific and engineering information. In its activities, RSI seeks the cooperation of scholarly organizations. Historically, a large number of RSI activities have been performed in cooperation with ASME. RSI is located in the Washington, DC, Metropolitan Area.

WIPP Facility

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is the principal facility for the disposal of our nation's transuranic (TRU) radioactive waste generated as a result of over 50 years of nuclear weapons research, development, and production. The selection of the WIPP site followed a lengthy search and extensive studies for the identification of a site for disposal of TRU wastes (NRC 1983, 1984). These efforts led to the selection of a 41 km^2 (16 mi^2) site, 26-miles (42-km) east of Carlsbad, NM. Following studies conducted of geological formations stable enough to contain wastes for thousands of years during the 1950s, the National Research Council (NRC 1957) identified deep geologic isolation in salt as a most desirable disposal mode for radioactive waste. Experiments conducted on salt mines revealed that there were no technical difficulties with waste disposal in salt (NRC 1984). The Carlsbad site was selected by the DOE because the deep salt beds located there are expected to provide the necessary stability for waste disposal. The site and the region surrounding it had been studied for many years, and mineral exploration of both potash and hydrocarbon deposits provided additional knowledge regarding the geology of the region. The U.S. Geological Survey and other agencies assisted DOE in identifying the New Mexico location for the repository. The salt deposit at this site, known as the Salado Formation, is a minimum of 2,000 ft (610 m) thick and located at a depth of 1,000-2,000 ft (305-610 m) (Fig. 1).

Salt allows significant deformation without fracturing. The Salado Formation is regionally extensive, and includes continuous beds of salt without complicated structures. The DOE identified the following four advantages of the site:

1. The salt deposit is in a stable geological area with little seismic activity, assuring the stability of a waste repository for thousands of years.
2. Salt deposits indicate the absence of flowing fresh water which could move waste to the surface. Water, if it had been or were present, would have dissolved the salt beds.
3. Salt is relatively easy to mine.
4. Rock salt exhibits a characteristic mechanical behavior, creep, that makes it an excellent host for waste isolation. In response to excavation-induced stress changes, salt slowly flows (or creeps), to close the mined openings. Creep closure starts immediately and continues until the salt has regained its original density and stress distribution. Salt formations tend to slowly and progressively fill mined areas and safely seal radioactive waste from the environment.

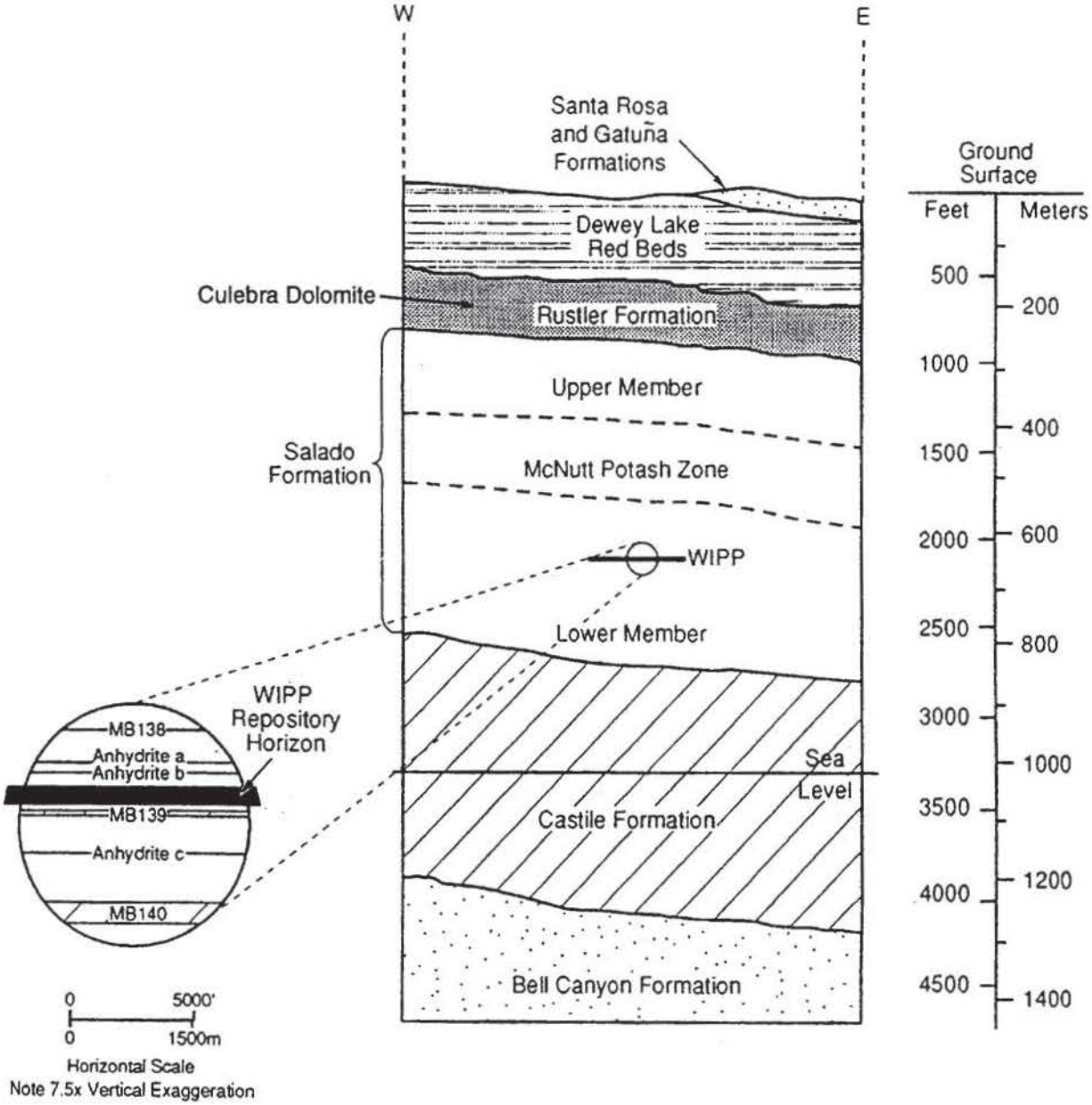

Fig. 1. WIPP Repository and local stratigraphy.

Geological data were collected from the WIPP site and surrounding area to evaluate its suitability as a radioactive waste repository. These data were collected principally by the DOE; the DOE's predecessor agencies; the U.S. Geological Survey; the New Mexico Bureau of Mines and Mineral Resources; and private organizations engaged in natural resource exploration and extraction. The DOE analyzed the data and has stated that the site is suitable for long-term isolation of radioactive waste.

The geology of the WIPP site has specific advantages identified by the DOE against potentially adverse environmental impacts. At the depth of the WIPP repository, the salt will slowly encapsulate the buried waste in the stable rock. Salt rock also shields radioactivity, providing a protection similar to that of concrete. Waste placed in the excavation at the WIPP is expected to be encapsulated and all waste-filled spaces closed over a period of 75-200 years. The waste disposal depth of 2,150 ft (650 m) is close enough to the surface to make access reasonable.

Subsequent to the investigation of the subsurface geology, the DOE selected the Salado Formation as the site of the WIPP repository for the following reasons:

1. The Salado halite units have low permeability to fluid flow, which impedes groundwater flow into and out of the repository;
2. It is regionally widespread;
3. It includes continuous halite beds without complicated structure;
4. It is deep with little potential for dissolution;
5. It is close enough to the surface that access is reasonable; and
6. It is largely free of mobile groundwater, as compared to existing mines and other potential repository sites.

Another of the favorable aspects of subsurface geology at the WIPP site is that the groundwater hydrology in the immediate proximity is characterized by geologic strata with low transmissivity and low hydrologic gradients.

SUBSURFACE GEOLOGY

The WIPP site is located in the northern portion of the Delaware Basin, a structural basin underlying present-day southeastern New Mexico and western Texas, and containing a thick sequence of sandstones, shales, carbonates, and evaporites. At the repository depth of 2,150 ft (650 m), the natural rock is of the Permian age. The

sediments accumulated during the Permian period represent the thickest portion of the sequence in the northern Delaware Basin and are divided into four series. From oldest to youngest, these series are: the Wolfcampian, Leonardian, Guadalupian, and Ochoan. As shown in Fig. 2, the Ochoan series is divided into four formations. From oldest to youngest, these formations are: Castile, Salado, Rustler, and Dewey Lake.

Salado formation

This massive bedded salt formation, predominately halite (sodium chloride), is thick and laterally extensive. The Salado formation is approximately 530 to 610 m (1,740 to 2,000 ft) thick in the WIPP site area, and the repository is located in the thickest part. The Salado formation is comprised of three members. From oldest to youngest, these are: Lower Member, McNutt Potash Member, and Upper Member. The WIPP repository is located in the Lower Member. The Salado formation contains many distinctive and laterally continuous layers composed mostly of anhydrite (a potassium-magnesium-calcium sulfate mineral). These layers have been designated by geologists as "marker beds" and numbered to designate vertical position within the Salado Formation.

Castile formation

This formation directly underlies the Salado Formation and comprises the base of the Ochoan Series (Fig. 2). It is found 244 m (800 ft) below the level of the repository. The Castile Formation near the WIPP typically contains three relatively thick anhydrite/carbonate units and two thick halite units. The thickness of the Castile varies regionally as well as locally beneath the WIPP, and there is considerable evidence from borehole data and geophysical surveys that the units of the Castile are deformed. The more brittle anhydrite units of the Castile are probably fractured, and the fracture zones are relatively permeable and act as zones for accumulation of brine originating in the Castile. The Castile is exposed at the surface over a considerable area along the western side of the Delaware Basin. In the eastern part of the basin, it is approximately 430 to 460 m (1,400 to 1,500 ft) thick. At the northern boundary of the WIPP, the Castile's thickness has been measured at 301 m (989 ft).

Bell Canyon formation

The Bell Canyon Formation underlies the Castle Formation and is the uppermost formation of the Guadalupian Series. Near the WIPP, the Bell Canyon is comprised

SYSTEM	SERIES	GROUP	FORMATION	MEMBER	DEPTH AT WIPP WASTE SHAFT meters (feet)
RECENT	RECENT		SURFICIAL DEPOSITS		
QUATER-NARY	PLEISTO-CENE		MESCALERO CALICHE		
			GATUNA		
TRIASSIC		DOCKUM	SANTA ROSA		30 (97)
PERMIAN	OCHOAN		DEWEY LAKE		164 (538)
			RUSTLER	Forty-niner	182 (596)
				Magenta Dolomite	189 (621)
				Tamarisk	215 (707)
				Culebra Dolomite	222 (729)
				lower unnamed	257 (844)
			SALADO	upper	409 (1,343)
				McNutt Potash	526 (1,727)
				lower WIPP	655 (2,150)
			CASTILE		~810 (2,650)
	GUADALUPIAN	DELAWARE MOUNTAIN	BELL CANYON		~1,200 (4,000)
			CHERRY CANYON		~1,550 (5,100)
			BRUSHY CANYON		~1,900 (6,200)

Fig. 2. Regional geologic column.

of a layered sequence of sandstones, shales, siltstones, and limestones approximately 300 m (1,000 ft) or more in thickness. It is the uppermost target of hydrocarbon exploration in the local area and is known from outcrops on the west side of the Delaware Basin and from oil and gas exploration boreholes.

Rustler formation

The Rustler Formation directly overlies the Salado Formation and contains five members (Fig. 2). From the base of the Rustler, these member are: Los Medanos Member (formerly referred to as the unnamed lower member), Culebra Member, Tamarisk Member, Magenta Member, and Forty-niner Member. The Culebra and Magenta Members are gypsum-bearing dolomites containing numerous cavities, fractures, and silty zones. The other three members contain various amounts of anhydrite, siltstone, claystone and halite. The Rustler is the youngest (uppermost) formation in the Delaware Basin that primarily contains evaporite deposits. In the WIPP region, the Rustler can be 152 m (500 ft) thick, although it ranges from 91 to 107 m (300 to 350 ft) thick within the WIPP boundary.

Dewey Lake formation

This formation overlies the Rustler Formation at the WIPP. Consisting largely of reddish-brown siltstones and claystones with lesser amounts of sandstone, the Dewey Lake Formation is about 30 to 170 m (100 to 560 ft) thick in the vicinity of the WIPP.

Santa Rosa formation

This formation of Triassic Age, also called the Dockum Group, overlies the Dewey Lake Formation. Characterized by the light reddish-brown sandstones and conglomerates, the Santa Rosa Formation is anywhere between thin to absent within the WIPP site boundaries, but is thicker to the east.

Gatuna formation

This formation overlies the Santa Rosa Formation and is somewhat similar in lithology and color, although the Gatuna is characterized by a wide range of

lithologies (coarse conglomerates to gypsum-bearing claystones). The Gatuna is Pleistocene in age, based on the 600,000-year old volcanic ash layer in the Upper Gatuna.

FACILITIES CONSTRUCTED AT THE WIPP

The major construction activities at the WIPP occurred between 1981 and 1990, and the facility accepted its first shipment of Transuranic (TRU) wastes in March 1999. Underground facilities were excavated 655 m (2,150 ft) beneath the surface of the land and include: four shafts; the waste disposal area; an experimental area (now closed); an equipment and maintenance area; and connecting tunnels. The DOE has also excavated the first and second of eight planned panels (designated as Panels 1 and 2) as shown in Fig. 3. Panel 1 has received wastes.

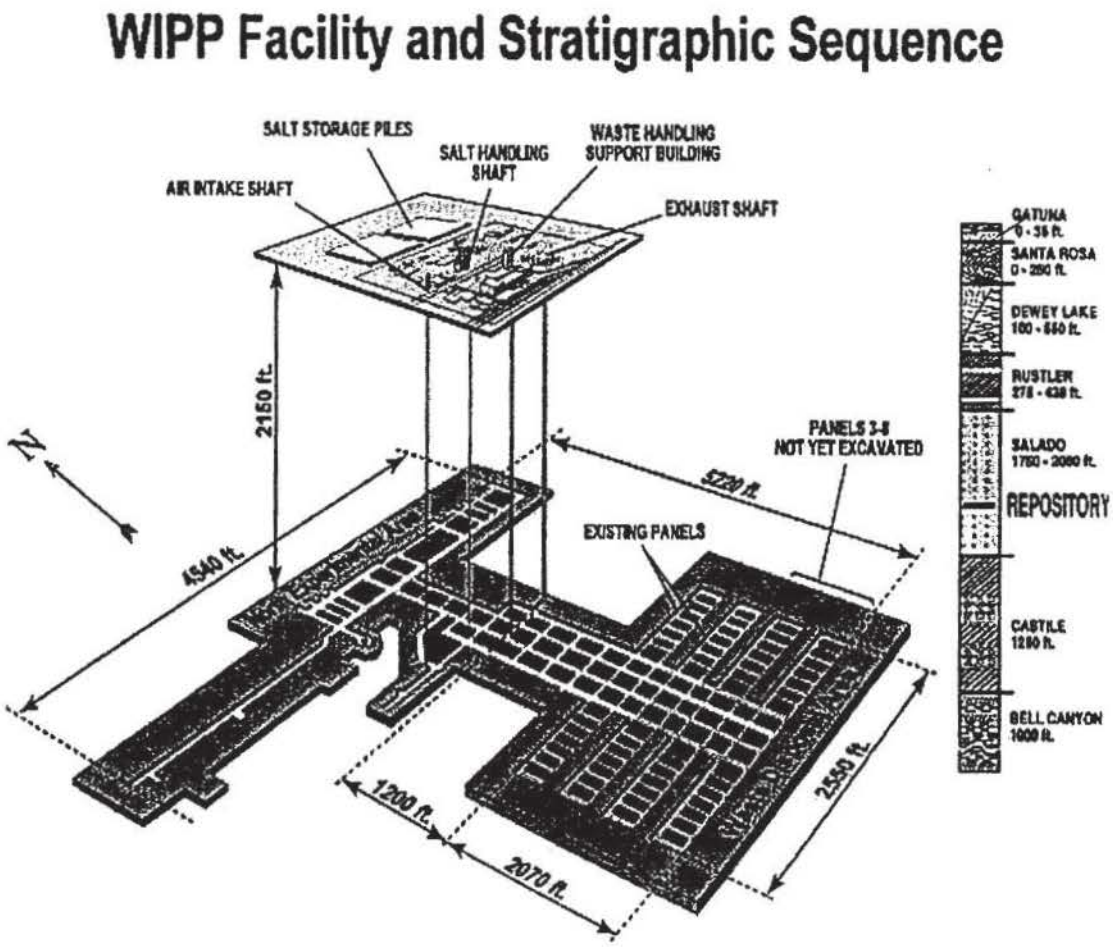

Fig. 3. WIPP facility and stratigraphic sequence.

Each panel is expected to take five years to mine, fill, and close. In addition, panel-equivalents 9 and 10 in Fig. 3 are located in the north-south mine access ways and are calculated to be required to complete the burial of the 1.75×10^5 m^3 (6.2×10^6 ft^3) of TRU waste permissible under the Land Withdrawal Act (LWA). All panels consist of seven waste disposal rooms, each about 91 m (300 ft) long, 10 m (33 ft) wide, and 4 m (13 ft) high. Pillars between rooms are 30 m (100 ft) wide.

A number of surface facilities have been constructed. The principal surface structure at the WIPP is the Waste Handling Building (WHB) where TRU wastes are unloaded from their transportation containers and transferred to the underground disposal area through the Waste Shaft. The WHB contains four functional areas: 1) the Contact Handled (CH) TRU waste handling area; 2) the Remote Handled (RH) TRU waste handling area; 3) the WHB support area; and 4) the Waste Shaft.

Other WIPP surface facilities include the hoist houses; Support Building; Guard and Security Building; Water Pump House; Transuranic Package Transporter, Model 2 (TRUPACT-II) Maintenance Facility; Training Building; office trailers; Exhaust Filter Building; warehouse and shops; Engineering Building; Core Storage Building; and the Safety and Emergency Services Building.

The underground support facilities include those needed to service and maintain equipment for excavation and disposal operations; monitor for contamination; and allow limited decontamination of personnel and equipment, if necessary. All underground facilities are inspected by the Mine Safety and Health Administration.

Waste Handling Building (WHB)–container storage unit

This building is the surface facility where TRU handling activities will take place. The WHB has a total area of approximately 84,000 ft^2 (7,804 m^2), of which 33,175 ft^2 (3,082 m^2) are designated for the waste handling and container storage of CH TRU mixed waste. The concrete floors are sealed with a coating that makes them impervious to the chemicals and facilitates decontamination if necessary.

The vehicles used to transport TRU mixed waste containers will be received through one of three air-lock entries to the CH Bay of the WHB Unit. The WHB heating, ventilation, and air conditioning system maintains the interior of the WHB at a pressure lower than the ambient atmosphere to ensure that air flows into the WHB, preventing the inadvertent release of radioactive constituents as the result of

a contamination event. The doors at each end of the air lock are interlocked to prevent both from opening simultaneously and equalizing CH Bay pressure with outside atmospheric pressure.

The waste containers are visually inspected for physical damage (e.g., severe rusting, apparent structural defects, signs of pressurization) and leakage to ensure that they are in good condition prior to storage. Waste containers are also checked for external surface contamination. If a primary waste container is not in good condition, the DOE will overpack the container.

Parking area container storage unit–parking area unit

The parking area south of the WHB is to be used for storage of waste containers within sealed shipping containers awaiting unloading. The Parking Area Unit provides storage space for 12 loaded containers, corresponding to 1,591 ft^3 (45 m^3) of CH TRU mixed waste. Secondary containment and protection of the waste containers from standing liquid are provided by the transportation containers. Wastes placed in the Parking Area Unit will remain sealed in their TRUPACT-II transportation containers at all times while in this area.

CONTAINER MANAGEMENT PRACTICES

Containers are to be managed in a specified manner that does not result in spills or leaks. Containers are required to be closed at all times, unless waste is being placed in the container or removed. Because containers at the WIPP contain radioactive waste, safety concerns require that containers be continuously vented to obviate the buildup of gases within the container. These gases could result from radiolysis, which is the breakdown of moisture by radiation. The vents are filtered to enable any potential generated gas to escape while particulate matter is retained. Derived waste containers are kept closed at all times unless waste is being added or removed.

Containers with residual liquids

Defense production facilities are prohibited from shipping liquid wastes in the containers sent to the WIPP. In no case is the total residual liquid allowed to equal or exceed 1% (by volume) of the waste container. Consequently, calculations made to determine the secondary containment as required by regulations are based on

10% of 1% of the volume of the containers, or 1% of the largest container, whichever is greater.

Description of containers

Waste containers are to be in good condition prior to shipment from the generator sites, i.e., containers will be of high integrity, intact, and free of surface contamination above established limits. This condition is to be verified upon receipt of the waste at WIPP. Containers are vented through filters, allowing any gases that are generated by radiolytic and microbial processes within a waste container to escape, thereby preventing over-pressurization or development of conditions within the container that would lead to the development of ignitable, corrosive, reactive, or other characteristic wastes.

The volatile organic compounds (VOC) in the headspace of waste containers are limited to maximum allowable VOC room-averaged headspace concentration limits specified in the permit. There are no maximum allowable headspace gas concentration limits for individual containers, as some containers can exceed these values as long as container headspace averages in a disposal room do not.

Containers for CH TRU mixed waste will be either 55-gal (208-L) drums arranged singly in 7-packs; 85-gal (321-L) drums arranged singly in 4-packs; 100-gallon drums, arranged singly or as three-packs; ten-drum overpacks (TDOP) either as overpacks or direct-loaded; or standard waste boxes (SWBs). Following is a summary description for each container type.

Standard 55-gallon drums: These drums meet the requirements for U.S. Department of Transportation (DOT) specification 7A regulations. A standard 55-gal (208-L) drum has a gross internal volume of 7.4 ft^3 (0.208 m^3). One or more filtered vents (as described in Permit Section M1-1d(1)) is to be installed in the drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential for pressurization. Standard 55-gal (208-L) drums are constructed of mild steel and may also contain rigid, molded polyethylene (or other compatible material) liners.

Standard Waste Boxes (SWBs): One or more filtered vents are to be installed in the standard waste box lid or body to prevent the escape of any radioactive

particulate matter and to eliminate any potential of pressurization. SWBs have an internal volume of 66.3 ft^3 (1.88 m^3).

One hundred-gallon drums: A 100-gal (379-L) drum has a gross internal volume of 13.4 ft^3 (0.39 m^3). One or more filtered vents are installed in the drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate potential pressurization. These drums are constructed of mild steel and may also contain rigid, molded polyethylene (or other compatible material) liners. These drums may be used as overpacks or may be direct-loaded.

Ten-Drum Overpack: The TDOP is a metal container, similar to a SWB, and is certified to be noncombustible. It is a welded-steel cylinder, approximately 74 in (1.9 m) high and 71 in. (1.8 m) in diameter with a gross internal capacity of 160 ft^3. The maximum loaded weight of a TDOP is limited to 6,700 lbs (3,040 kg). A bolted lid on one end is removable; sealing is accomplished by clamping a neoprene gasket between the lid and the body. Filter ports are located near the top of the TDOP. One or more filtered vents are installed in the ten-drum overpack lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential for pressurization. A TDOP may contain up to ten standard 55-gal (208-L) drums or one SWB. The TDOPs may be used to overpack drums or SWBs containing CH TRU mixed waste. The TDOP may also be direct-loaded with waste items that are too large to fit into the standard 55-gallon (208-L) drum; the 85-gallon drum; or the SWB.

Eighty-five gallon drums: The 85-gal (321-L) drum overpack is to be used primarily for overpacking contaminated 55-gal (208 L) drums at the WIPP facility. The 85-gal (321-L) drums may be direct-loaded with CH TRU-mixed waste and may be used to collect derived waste. One or more filtered vents are to be installed in the 85-gal (321-L) drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential of pressurization.

Container compatibility: All containers are made of steel, and some will contain rigid, molded polyethylene liners. Requirements to conduct compatibility studies include container materials to assure that containers are compatible with the waste.

WASTE PROCESSING STEPS AT THE WIPP

The handling and disposal of CH TRU wastes at the WIPP involves the following series of steps:

1. A waste shipment arrives at the WIPP by truck. Each truck is capable of carrying up to three TRU Packaging Transport Model IIs (TRUPACT-IIs).
2. After an initial security inspection, a radiological survey, and a shipping documentation review, the truck is parked near the WHB for additional inspection and radiological survey. A forklift is used to transfer each TRUPACT-II from the trailer, through an air lock, and into the WHB, where it is placed in an area called a TRUDOCK, which is used by workers to unload the waste from the TRUPACT IIs.
3. Radiological surveys are conducted to confirm that waste containers have not sustained damage during shipment or waste container removal.
4. At the TRUDOCK, an overhead crane is used to remove the waste containers from the TRUPACT-II and place them on a facility pallet.
5. A forklift moves the loaded facility pallet to the conveyance loading car at the waste handling shaft. The conveyance loading car is used to load the facility pallet onto the waste hoist.
6. The waste hoist descends 2,150 ft (705 m) to the WIPP repository.
7. An underground transporter pulls the loaded facility pallet off the hoist onto the trasporter bed and moves the waste to the appropriate disposal room where a forklift removes the waste containers from the facility pallet and places them in the disposal area. Containers may be stacked three high in the disposal area.
8. Bags of magnesium oxide are placed on top of the stack of containers to serve as backfill. The magnesium oxide will control the solubility of radionuclides and is an added measure of assurance for long-term repository performance.

Legal Requirements

INTRODUCTION

The Waste Isolation Pilot Plant project was authorized in 1979 (PL96-164) as a research and development activity to demonstrate the safe disposal of radioactive waste originating from the U.S. nuclear weapons program. This and several other laws and regulations have resulted in the construction and operation of WIPP as a unique facility for the disposal of transuranic (TRU) waste.

TRU waste is defined as a waste containing alpha-emitting isotopes of transuranic elements which emits more than 100 nCi/g of waste. The half-lives of the isotopes of these elements must be greater than 20 years (LWA 1992; EPA 1993).

Much of the TRU waste contains chemical constituents subject to the regulations of the Resource Conservation and Recovery Act (RCRA) and the New Mexico Hazardous Waste Act. TRU wastes that contain both chemical and radioactive waste are referred to as Mixed TRU. According to RCRA, WIPP is required to have a hazardous waste permit to receive waste containing hazardous waste constituents. The state of New Mexico has adopted the relevant RCRA regulations by reference and thus is authorized to issue hazardous waste permits. WIPP received a permit (NMED 1999) on October 27, 1999 for contact-handled (CH) waste, defined as having a surface radiation dose rate not greater than 200 mrem/h (2 mSv/h). TRU waste with a greater dose rate is defined as Remote Handled (RH) TRU Mixed Waste.

The enactment of the Land Withdrawal Act (LWA 1992) resulted in permanent withdrawal and transfer of the administration of federal land for the site from the U.S. Department of Interior to the DOE. This law mandated that the U.S. Environmental Protection Agency (EPA) certify the DOE's compliance with EPA's relevant, generally applicable environmental standards for radioactive materials. Subsequently, the EPA (1996a) issued the criteria to be used in certifying compliance. In response, the DOE provided the EPA with appropriate documents; models; and evaluations of the geology, hydrology, and climate as well as projected performance of the entire disposal system, including the mined repository, shaft seals, panel closures, borehole plugs, and mine backfill. Finally, the EPA (1998) certified that the WIPP met all of the criteria required for the disposal of TRU waste.

The LWA limited the amount and types of TRU wastes that can be emplaced at WIPP. The limits include the following:

1. The WIPP capacity is limited to 1.75×10^5 m^3 (6.2×10^6 ft^3) total TRU waste by volume.
2. No more than 5% (by volume) of RH-TRU waste may have a surface dose rate in excess of 100 rem/h (1 μSv/h).
3. No RH-TRU waste may have a surface dose rate in excess of 1,000 rem/h (10 Sv/h).
4. RH-TRU waste containers shall not exceed 23 Ci/L (851 GBq/L) maximum activity level averaged over the volume of the container.
5. The total radioactivity of RH-TRU waste shall not exceed 5.1 MCi (188.7 PBq).
6. Of the allowed waste disposal volume of 1.75×10^5 m^3 (6.2×10^6 ft^3), the Consultation and Cooperation Agreement with the State of New Mexico limits the volume of RH-TRU waste to 7,080 m^3 (250,000 ft^3).

The 41 km^2 (16 mi^2) area under DOE's jurisdiction at WIPP is deemed sufficient to ensure that at least 1.6 km (1 mi) of intact salt exists laterally between the waste disposal area and the accessible environment, and also to ensure that no permanent residences will be established in close proximity to the facility.

EPA'S CRITERIA FOR WIPP CERTIFICATION

Criteria for certification and recertification of WIPP were published in final form by the EPA (1996a). These criteria were detailed and contained specific requirements. In its regulations, EPA provided requirements not only for quality assurance and characterization but also specific requirements for expert judgement and peer review. The following are excerpts from EPA's regulations:

"§ 194.22 Quality assurance.

(a)(1) As soon as practicable after April 9, 1996, the Department shall adhere to a quality assurance program that implements the requirements of ASME NQA-1-1989 edition, ASME NQA-2a-1990 addenda, part 2.7, to ASME NQA-2-1989 edition, and ASME NQA-3-1989 edition (excluding Section 2.1 (b) and (c), and Section 17.1). (Incorporation by reference as specified in § 194.5.)
(2) Any compliance application shall include information which demonstrates that the quality assurance program required pursuant to paragraph (a)(1) of this section

has been established and executed for:

(i) Waste characterization activities and assumptions;

(ii) Environmental monitoring, monitoring of the performance of the disposal system, and sampling and analysis activities;

(iii) Field measurements of geologic factors, ground water, meteorologic, and topographic characteristics;

(iv) Computations, computer codes, models and methods used to demonstrate compliance with the disposal regulations in accordance with the provisions of this part;

(v) Procedures for implementation of expert judgment elicitation used to support applications for certification or re-certification of compliance;

(vi) Design of the disposal system and actions taken to ensure compliance with design specifications;

(vii) The collection of data and information used to support compliance application(s); and

(viii) Other systems, structures, components, and activities important to the containment of waste in the disposal system.

(b) Any compliance application shall include information which demonstrates that data and information collected prior to the implementation of the quality assurance program required pursuant to paragraph (a)(1) of this section have been qualified in accordance with an alternate methodology, approved by the Administrator or the Administrator's authorized representative, that employs one or more of the following methods: Peer review, conducted in a manner that is compatible with NUREG–1297, "Peer Review for High-Level Nuclear Waste Repositories," published February 1988 (incorporation by reference as specified in § 194.5); corroborating data; confirmatory testing; or a quality assurance program that is equivalent in effect to ASME NQA-1-1989 edition, ASME NQA-2a-1990 addenda, part 2.7, to ASME NQA-2-1989 edition, and ASME NQA-3-1989 edition (excluding Section 2.1 (b) and (c) and Section 17.1). (Incorporation by reference as specified in § 194.5.)

(c) Any compliance application shall provide, to the extent practicable, information which describes how all data used to support the compliance application have been assessed for their quality characteristics, including:

(1) Data accuracy, i.e., the degree to which data agree with an accepted reference or true value;

(2) Date prevision, i.e., a measure of the mutual agreement between comparable data gathered or developed under similar conditions expressed in terms of a standard deviation;

(3) Data representativeness, i.e., the degree to which data accurately and precisely represent a characteristic of a population, a parameter, variations at a sampling point, or environmental conditions;
(4) Data completeness, i.e., a measure of the amount of valid data obtained compared to the amount that was expected; and
(5) Data comparability, i.e., a measure of the confidence with which one data set can be compared to another.
(d) Any compliance application shall provide information which demonstrates how all data are qualified for use in the demonstration of compliance.
(e) The Administrator will verify appropriate execution of quality assurance programs through inspections, record reviews and record keeping requirements, which may include, but may not be limited to, surveillance, audits and management systems reviews."

"§ 194.24 Waste characterization.

(a) Any compliance application shall describe the chemical, radiological and physical composition of all existing waste proposed for disposal in the disposal system. To the extent practicable, any compliance application shall also describe the chemical, radiological and physical composition of to-be-generated waste proposed for disposal in the disposal system. These descriptions shall include a list of waste components and their approximate quantities in the waste. This list may be derived from process knowledge, current non-destructive examination/assay, or other information and methods.
(b) The Department shall submit in the compliance certification application the results of an analysis which substantiates:
(1) That all waste characteristics influencing containment of waste in the disposal system have been identified and assessed for their impact on disposal system performance. The characteristics to be analyzed shall include, but shall not be limited to: Solubility, formation of colloidal suspensions containing radionuclides; production of gas from the waste; shear strength compactability; and other waste-related inputs into the computer models that are used in the performance assessment.
(2) That all waste components influencing the waste characteristics identified in paragraph (b)(1) of this section have been identified and assessed for their impact on disposal system performance. The components to be analyzed shall include, but shall not be limited to: metals, cellulosics; chelating agents; water and other liquids; and activity in curies of each isotope of the radionuclides present.
(3) Any decision to exclude consideration of any waste characteristic or waste component because such characteristic or component is not expected to

significantly influence the containment of the waste in the disposal system.
(c) For each waste component identified and assessed pursuant to paragraph (b) of this section, the Department shall specify the limiting value (expressed as an upper or lower limit of mass, volume, curies, concentration, etc.), and the associated uncertainty (i.e., margin of error) for each limiting value, of the total inventory of such waste proposed for disposal in the disposal system. Any compliance application shall:
(1) Demonstrate that, for the total inventory of waste proposed for disposal in the disposal system, WIPP complies with the numeric requirements of § 194.34 and § 194.55 for the upper or lower limits (including the associated uncertainties), as appropriate, for each waste component identified in paragraph (b)(2) of this section, and for the plausible combinations of upper and lower limits of such waste components that would result in the greatest estimated release.
(2) Identify and describe the method(s) used to quantify the limits of waste components identified in paragraph (b)(2) of this section.
(3) Provide information which demonstrates that the use of process knowledge to quantify components in waste for disposal conforms with the quality assurance requirements found in § 194.22.
(4) Provide information which demonstrates that a system of controls has been and will continue to be implemented to confirm that the total amount of each waste component that will be emplaced in the disposal system will not exceed the upper limiting value or fall below the lower limiting value described in the introductory text of paragraph (c) of this section. The system of controls shall include, but shall not be limited to: Measurement; sampling; chain of custody records; record keeping systems; waste loading schemes used; and other documentation.
(5) Identify and describe such controls delineated in paragraph (c)(4) of this section and confirm that they are applied in accordance with the quality assurance requirements found in § 194.22.
(d) The Department shall include a waste loading scheme in any compliance application, or else performance assessments conducted pursuant to § 194.32 and compliance assessments conducted pursuant to § 194.54 shall assume random placement of waste in the disposal system.
(e) Waste may be emplaced in the disposal system only if the emplaced components of such waste will not cause:
(1) The total quantity of waste in the disposal system to exceed the upper limiting value, including the associated uncertainty, described in the introductory text to paragraph (c) of this section; or
(2) The total quantity of waste that will have been emplaced in the disposal system, prior to closure, to fall below the lower limiting value, including the associated uncertainty, described in the introductory text to paragraph (c) of this section.

(f) Waste emplacement shall conform to the assumed waste loading conditions, if any, used in performance assessments conducted pursuant to § 194.32 and compliance assessments conducted pursuant to § 194.54.
(g) The Department shall demonstrate in any compliance application that the total inventory of waste emplaced in the disposal system complies with the limitations on transuranic waste disposal described in the WIPP LWA.
(h) The Administrator will use inspections and records reviews, such as audits, to verify compliance with this section."

"§ 194.26 Expert judgment.

(a) Expert judgment, by an individual expert or panel of experts, may be used to support any compliance application, provided that expert judgment does not substitute for information that could reasonably be obtained through data collection or experimentation.
(b) Any compliance application shall:
(1) Identify any expert judgments used to support the application and shall identify experts (by name and employer) involved in any expert judgment elicitation processes used to support the application.
(2) Describe the process of eliciting expert judgment, and document the results of expert judgment elicitation processes and the reasoning behind those results. Documentation of interviews used to elicit judgments from experts, the questions or issues presented for elicitation of expert judgment, background information provided to experts, and deliberations and formal interactions among experts shall be provided. The opinions of all experts involved in each elicitation process shall be provided whether the opinions are used to support compliance applications or not.
(3) Provide documentation that the following restrictions and guidelines have been applied to any selection of individuals used to elicit expert judgments:
(i) Individuals who are members of the team of investigators requesting the judgment or the team of investigators who will use the judgment were not selected; and
(ii) Individuals who maintain, at any organizational level, a supervisory role or who are supervised by those who will utilize the judgment were not selected.
(4) Provide information which demonstrates that:
(i) The expertise of any individual involved in expert judgment elicitation comports with the level of knowledge required by the questions or issues presented to that individual; and
(ii) The expertise of any expert panel, as a whole, involved in expert judgment

elicitation comports with the level and variety of knowledge required by the questions or issues presented to that panel.
(5) Explain the relationship among the information and issues presented to experts prior to the elicitation process, the elicited judgment of any expert panel or individual, and the purpose for which the expert judgment is being used in compliance application(s).
(6) Provide documentation that the initial purpose for which expert judgment was intended, as presented to the expert panel, is consistent with the purpose for which this judgment was used in compliance application(s).
(7) Provide documentation that the following restrictions and guidelines have been applied in eliciting expert judgment:
(i) At least five individuals shall be used in any expert elicitation process, unless there is a lack of unavailability of experts and a documented rationale is provided that explains why fewer than five individuals were selected.
(ii) At least two-thirds of the experts involved in an elicitation shall consist of individuals who are not employed directly by the Department or by the Department's contractors, unless the Department can demonstrate and document that there is a lack or unavailability of qualified independent experts. If so demonstrated, at least one-third of the experts involved in an elicitation shall consist of individuals who are not employed directly by the Department or by the Department's contractors.
(c) The public shall be afforded a reasonable opportunity to present its scientific and technical views to expert panels as input to any expert elicitation process."

"§ 194.27 Peer review.

(a) Any compliance application shall include documentation of peer review that has been conducted, in a manner required by this section, for:
(1) Conceptual models selected and developed by the Department;
(2) Waste characterization analyses as required in § 194.24(b); and
(3) Engineered barrier evaluation as required in § 194.44.
(b) Peer review processes required in paragraph (a) of this section, and conducted subsequent to the promulgation of this part, shall be conducted in a manner that is compatible with NUREG-1297, "Peer Review for High-Level Nuclear Waste Repositories," published February 1988. (Incorporation by reference as specified in § 194.5.)
(c) Any compliance application shall:
(1) Include information that demonstrates that peer review processes required in paragraph (a) of this section, and conducted prior to the implementation of the

promulgation of this part, were conducted in accordance with an alternate process substantially equivalent in effect to NUREG-1297 and approved by the Administrator or the Administrator's authorized representative; and
(2) Document any peer review processes conducted in addition to those required pursuant to paragraph (a) of this section. Such documentation shall include formal requests, from the Department to outside review groups or individuals, to review or comment on any information used to support compliance applications, and the responses from such groups or individuals."

The packaging of waste at the originating sites; transport to the site; transport vehicles; and disposal of heat-generating waste are beyond the scope of this study and are not dealt with in this report.

The health and safety consequences of the postulated repository failure mechanisms appear to be so minimal that simplifications in design may be justified, and cost-effectiveness studies should be carried out to determine whether they would be acceptable. However, the probability and the consequences of potentially rapid flow of brine solutions containing radionuclides, through more permeable formations, have not been completely determined. Once these have been resolved, conventional safety considerations (e.g., number of shafts and packaging of waste for highway transport) might determine the optimum design.

Relaxation of the WIPP waste acceptance criteria (e.g., elimination of the incineration of some of the waste at the Process Experimental Pilot Plant (PREPP) facility and removal of the requirement for the use of steel-case overpack of the wooden boxes) may also have minimal consequences.

EPA'S CERTIFICATION DECISION

Subsequent to the publication of the EPA's regulations on criteria for WIPP certification, DOE undertook a major effort to comply with the EPA's requirements. The result was the decision by the EPA (1998) to certify that WIPP has met the EPA's criteria. However, this certification included certain limitations and requirements. Excerpts of the EPA's certification decision are as follows:

"The EPA finds that DOE has demonstrated that the WIPP will comply with EPA's radioactive waste disposal regulations at Subparts B and C of 40 CFR Part 191.

This decision allows the WIPP to begin accepting transuranic waste for disposal, provided that other applicable environmental regulations have been met and once a 30-day Congressionally-required waiting period has elapsed. EPA's decision is based on a thorough review of information submitted by DOE, independent technical analyses, and public comments. The EPA determined that DOE met all of the applicable requirements of the WIPP compliance criteria at 40 CFR Part 194. However, DOE must meet certain conditions in order to maintain a certification for the WIPP and before shipping waste for disposal at the WIPP."

"The EPA will continue to have a role at the WIPP after this certification becomes effective. As discussed above, DOE must submit periodic reports on any activities or conditions at the WIPP that differ significantly from the information contained in the most recent compliance application. The EPA may also, at any time, request additional information from DOE regarding the WIPP. The Agency will review such information as it is received to determine whether the certification must be modified, suspended, or revoked. Such action might be warranted if, for example, significant information contained in the most recent compliance application were no longer to remain true. The certification could be modified to alter the terms or conditions of certification—for example, to add a new condition, if necessary to address new or changed activities at the WIPP. The certification could be revoked if it becomes evident in the future that the WIPP cannot or will not comply with the disposal regulations. Either modification or revocation must be conducted by rule-making, in accordance with the WIPP compliance criteria (§§ 194.65-66). Suspension may be initiated at the Administrator's discretion, in order to promptly reverse or mitigate a potential threat to public health. For instance, a suspension would take effect if, during emplacement of waste, a release from the WIPP occurred in excess of EPA's containment limits."

"In addition to reviewing annual reports from DOE regarding activities at the WIPP, EPA periodically will evaluate the WIPP's continued compliance with the WIPP compliance criteria and disposal regulations. As directed by Congress, this "recertification" will occur every five years. For recertification, DOE must submit to EPA for review the information described in the WIPP compliance criteria (although, to the extent that information submitted in previous certification applications remains valid, it can be summarized and referenced rather than resubmitted) (§ 194.14). In accordance with the WIPP compliance criteria, documentation of continued compliance will be made available in EPA's dockets, and the public will be provided at least a 30-day period in which to submit comments. The EPA's decision on recertification will be announced in the *Federal Register* (§ 194.64)."

"Notices announcing EPA inspections or audits to evaluate implementation of quality assurance ("QA") and waste characterization requirements at generator facilities will be published in the *Federal Register*. The public will have the opportunity to submit written comments on the waste characterization and QA program plans submitted by DOE. As noted above, EPA's decisions on whether to approve waste generator QA program plans and waste characterization systems of controls—and thus, to allow shipment of specific waste streams for disposal at the WIPP—will be conveyed by a letter from EPA to DOE. A copy of the letter, as well as any EPA inspection or audit reports, will be placed in EPA's docket."

"Finally, the WIPP compliance criteria provide EPA the authority to conduct inspections of activities at the WIPP and at all off-site facilities which provide information included in certification applications. (§ 194.21) The Agency expects to conduct periodic inspections, both announced and unannounced, to verify the adequacy of information relevant to certification applications. The Agency may conduct its own laboratory tests, in parallel with those conducted by DOE. The Agency also may inspect any relevant records kept by DOE, including those records required to be generated in accordance with the compliance criteria. For example, EPA intends to conduct ongoing inspections or audits at the WIPP and at waste generator sites to ensure that approved quality assurance programs are being adequately maintained and documented. The EPA plans to place inspection reports in its docket for public examination."

BRIEF WIPP CHRONOLOGY

1957 National Research Council recommended salt as host rock, Identified areas to investigate, and Identified favorable siting criteria

1974 Atomic Energy Commission selected site near Carlsbad for exploratory work

1979 Congress authorized WIPP for research and development for safe disposal of defense-generated radioactive waste

1980 DOE issued Final Environmental Impact Statement (FEIS)

1981 DOE issued Record of Decision

1981 DOE began construction of WIPP Exploratory Shaft

1985 EPA issued 40 CFR 191--radioactive waste disposal standards applicable to WIPP

1986 EPA stated facilities must comply with Resource Conservation and Recovery Act (RCRA) for disposal of mixed (hazardous and radioactive) waste

1990 New Mexico was authorized by EPA to regulate mixed waste

1990 DOE issued first Supplemental Environmental Impact Statement (SEIS)

1991 DOE submitted Parts A and B of the RCRA Permit Application to New Mexico

1992 WIPP Land Withdrawal Act permanently segregates land for WIPP and gave EPA regulatory authority to certify WIPP compliance to 40 CFR 191.

1995 DOE submitted revised RCRA Permit Application to New Mexico Environment Department

1996 EPA issued 40 CFR 194, compliance criteria in February

1996 DOE submitted 84,000 page Compliance Certification Application to EPA

1998 DOE issued SEIS II in January

1998 EPA certified WIPP ready for disposal

1998 New Mexico Environment Department issued draft hazardous waste facility permit (HWFP) for disposal of transuranic mixed waste

1999 First shipment non-mixed waste in March

1999 New Mexico Environment Department issued Hazardous Waste Facility Permit

2000 First shipment of mixed waste in September

Current Permitted Methodologies for CH TRU Wastes

INTRODUCTION

TRU waste for disposal at the WIPP is characterized to meet RCRA driven requirements; EPA characterization requirements stemming from 40 CFR Parts 191 (EPA 1993) and 194, (EPA 1998) transportation requirements; and WIPP operations and safety requirements. Only the RCRA and 40 CFR 194 requirements are subjects of this review; hence, the transportation and WIPP characterization requirements are not discussed in this report.

RCRA CH TRU WASTE CHARACTERIZATION

Waste characterization for disposal at the WIPP is conducted on a waste stream basis (i.e., waste material generated from a single process or activity that is similar in material, physical form, isotropic make-up, and hazardous constituents) and also on a container basis. Defense production facilities assign the waste stream identifier for each container of waste that is shipped. The waste designation is selected from one of three broad categories of solid wastes: Homogenous Solids, Soil/Gravel, and Debris Wastes (NMED 1999). In addition, a number of sub-categories are assigned to the wastes. Characterization and analysis methods vary for each category and sub-category of waste.

The Waste Analysis Plan (WAP), which is part of the Permit (DOE 1997), describes waste characterization activities that a TRU waste generator/storage site must complete before shipping waste to the WIPP for disposal. These activities include test methods; details of planned waste sampling and analysis processes; a description of the waste shipment screening and verification process; and a description of the quality assurance/quality control program. Before the WIPP manages, stores, or disposes of CH TRU mixed waste from a generator/storage site, the site is required to characterize waste in accordance with WAP requirements. For each container of waste destined for disposal, defense production facilities provide the WIPP operators with a written characterization summary known as a Waste Stream Profile Form (WSPF). A four-page sample is shown in Fig. 4 (NMED 1999).

WIPP WASTE STREAM PROFILE FORM

Waste Stream Profile Number: _____

Generator Site Name: _____ Technical Contact: _____

Generator Site EPA ID: _____ Technical Contact phone number: _____

Date of audit report approval by NMED: _____

Title, version number, and date of documents used for WAP certification: _____

_____

Did your facility generate this waste? ☐ Yes ☐ No

If no, provide the name and EPA ID of the original generator: _____

_____

WIPP ID: _____ Summary Category Group: _____

Waste Matrix Code Group: _____ Waste Stream Name: _____

Description from the WTWBIR: _____

_____

Defense Waste: ☐ Yes ☐ No Check one: ☐ CH ☐ RH

Number of SWBs: _____ Number of Drums: _____ Number of Canisters: _____

Batch Data Report numbers supporting this waste stream characterization: _____

List applicable EPA Hazardous Waste Codes: _____

Applicable TRUCON Content Codes: _____

Acceptable Knowledge Information

[For the following, enter supporting the documentation used (i.e., references and dates)]

Required Program Information

- Map of site: _____
- Facility mission description: _____

Fig. 4. WIPP waste stream profile form.

- Description of operations that generate waste: _____

_____

- Waste identification/categorization schemes: _____
- Types and quantities of waste generated: _____
- Correlation of waste streams generated from the same building and process, as appropriate: _____

_____

- Waste certification procedures: _____

Required Waste Stream Information

- Area(s) and building(s) from which the waste stream was generated: _____
- Waste stream volume and time period of generation: _____
- Waste generating process description for each building: _____
- Process flow diagrams: _____

_____

- Material inputs or other information identifying chemical/radionuclide content and physical waste form: _____

_____

- Which Defense Activity generated the waste: (check one)

  ☐ Weapons activities including defense inertial confinement fusion

  ☐ Naval Reactors development

  ☐ Verification and control technology

  ☐ Defense Research and development

  ☐ Defense nuclear waste and material by products management

  ☐ Defense nuclear materials production

  ☐ Defense nuclear waste and materials security and safeguards and security investigations

Supplemental Documentation

Process design documents: _____

Fig. 4. (cont'd)

Standard operating procedures: _____

Safety Analysis Reports: _____

Waste packaging logs: _____

Test plans/research project reports: _____

Site data bases: _____

Information from site personnel: _____

Standard industry documents: _____

Previous analytical data: _____

Material safety data sheets: _____

Sampling and analysis data from comparable/surrogate waste: _____

Laboratory notebooks: _____

Sampling and Analysis Information

[For the following, when applicable, enter procedure title(s), number(s), and date(s)]

Radiography: _____

Visual examination: _____

Headspace Gas Analysis

VOCs: _____

Flammable: _____

Other gases (specify): _____

Homogeneous Solids/Soils/Gravel Sample Analysis

Total metals: _____

PCBs: _____

VOCs: _____

Nonhalogenated VOCs: _____

Semi-VOCs: _____

Other (specify): _____

Waste Stream Profile Form Certification

I hereby certify that I have reviewed the information in this Waste Stream Profile Form, and it is complete and accurate to the best of my knowledge, I understand that this information will be made available to regulatory agencies and that there are significant penalties for submitting false information, including the possibility of fines and imprisonment for knowing violations.

_____	_____	_____
Signature of Site Project Manager	Printed Name and Title	Date

NOTE: (1) Use back of sheet or continuation sheets, if required.
(2) If radiography, visual examination, headspace gas analysis, and/or homogeneous solids/soils/gravel sample analysis were used to determine EPA Hazardous Waste Codes, attach signed Characterization Information Summary documenting this determination.

Fig. 4. (cont'd)

Waste characterization based on 40 CFR 194

Waste characterization as described in 40 CFR 194 (EPA 1998) requires that a system be in place to track and control the inventory of waste components to assure that limits associated with the components are not exceeded. The waste components to be tracked and controlled, and the associated limits, are set by a Performance Assessment (PA) conducted by the DOE to show that the WIPP complies with the performance criteria of 40 CFR 191(EPA 1993). The waste components and the limits, all of which are total inventory limits at repository closure, are presented in the WIPP Compliance Certification Application (CCA).

The current CH/TRU waste characterization program characterizes each container of TRU waste for each of the limited components. However, characterizing on a waste stream basis, as is done for RCRA waste characterization, is more than adequate to assure adherence to the large limits allowed at repository closure. The Performance Agreement (PA) and the Compliance Certification Application (CCA) specify no corresponding limit associated with radionuclides; however, the current CH/TRU waste characterization program also quantifies a list of specified radionuclides on a container basis.

ORIGIN OF CH TRU WASTE AND ITS ACCEPTANCE CRITERIA AT WIPP

The TRU mixed wastes that are shipped to the WIPP originate at DOE generator/storage sites and contain both radiological and hazardous waste constituents. The DOE and EPA agreed that, of the hundreds of radionuclides present within these wastes, only ten are important for the WIPP performance assessment: ^{241}Am, ^{244}Cm, ^{137}Cs, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{90}Sr, ^{233}U, and ^{234}U. Of these ten, ^{234}Sr, ^{233}U, and ^{137}Cs are important for RH but not for CH waste streams.

Major types of operations generating waste

Examples of the major types of operations that generate this waste include the following:

Production of nuclear products: This category includes reactor operation; radionuclide separation or finishing; and weapons fabrication and manufacturing. The majority of the TRU mixed wastes were generated by weapons fabrication and radionuclide separation or finishing processes. More specifically, wastes resulting from this category consist of residues from chemical processes; air and liquid filtration; casting; machining; cleaning; product quality sampling; analytical activities; and maintenance and refurbishment of equipment and facilities.

Plutonium recovery: These wastes are residues from the recovery of plutonium-contaminated molds; metals; glass; plastics; rags; salts used in electro-refining; precipitates; firebrick; soot; and filters.

Research and development: This group includes a variety of hot-cell or glovebox activities that often simulate full-scale operations described above, producing similar TRU mixed wastes. Other types of R&D projects include metallurgical research; actinide separations; process demonstrations; and chemical and physical properties determinations.

Decontamination and decommissioning: Facilities and equipment that are no longer needed or usable are decontaminated and decommissioned, resulting in TRU mixed wastes consisting of scrap materials; cleaning agents; tools; piping; filters; plexiglass; gloveboxes; concrete rubble; asphalt; cinder blocks; and other building materials. These materials are expected to be the largest category by volume of TRU mixed waste to be generated in the future.

The TRU mixed wastes that are to be shipped to the WIPP facility for disposal have been placed into waste categories based on their physical and chemical properties (Table 1). The waste generating processes can be described in five general categories:

1. Wastes (such as combustible waste) that result from cleaning and decontamination activities in which items such as towels and rags become contaminated both with hazardous waste constituents and radioactivity. In these cases, the hazardous waste and the radioactive constituent are intimately mixed, both on the rag or towel used for cleaning and as residuals on the surface of the object being cleaned. These waste forms are not homogeneous in nature; however, they are generated in a fashion that ensures that the hazardous and radioactive contaminants coexist throughout the waste matrix.
2. Wastes generated when materials which contain metals and metal ions believed to exhibit the toxicity characteristic (EPA 1996b) become contaminated with radioactivity as the result of plutonium operations (leaded rubber, some glass, and metal waste are typical examples). These materials may also become contaminated with solvents during decontamination or plutonium recovery activities.
3. A class of plutonium processes where non-metallic objects are used and become contaminated with radioactive materials. These objects are subsequently cleaned with solvents to recover plutonium. Surfaces of the objects (such as graphite, filters, and glass) are contaminated with both radioactive and hazardous constituents.
4. Waste generating processes involving foundry operations where impurities are removed from plutonium. These impurities may result in the deposition of toxicity characteristic (EPA 1996b) metals and metal ions
5. In all of the process waste categories in the second half of Table 1, the hazardous and radioactive constituents are physically mixed together as a result of the treatment process. In these wastes, the release of any portion of the waste matrix will involve both the hazardous and the radioactive waste components, because the treatment process generates a relatively homogeneous waste form.

Table 1. Summary of waste generation processes and waste forms.

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Combustibles	F001, F002, F003, D008, D019	Cloth and paper wipes are used to clean parts and wash down gloveboxes. Wood and plastic parts are removed from gloveboxes after they are cleaned. Lead may occur as shielding tape or as minor noncombustible waste in this category.	Materials such as metals may retain traces of organics left on surfaces that were cleaned. Waste may remain on the cloth and paper that was used for cleaning or for wiping up spills.
Graphite		Graphite molds, which may contain impurities of metals, are scraped and cleaned with solvents to remove the recoverable plutonium.	Surfaces may retain residual solvents. Lead may be used as shielding or may be an impurity in the graphite.
Filters	F001, F002	Filters are used to capture radioactive particulate in air streams associated with numerous plutonium operations and to filter particulate from aqueous streams.	Filter media may retain organic solvents that were present in the air or liquid streams.
Benelex® and Plexiglas®	F001, F002, D008	Materials are used in gloveboxes as neutron absorbers. The glovebox assembly often includes leaded glass. All surfaces may be wiped down with solvents to remove residual plutonium.	Surfaces may retain residual solvents from wiping operations. Leaded glass may also be present.
Firebrick and Ceramic Crucibles	F001, F002, F005, D006, D007, D008	Firebrick is used to line plutonium processing furnaces. Ceramic crucibles are used in plutonium analytical laboratories. Both may contain metals as surface contaminants.	Metals deposited during plutonium refining or analytical operations could remain as residuals on surfaces. Surfaces may retain residual solvents.
Leaded Rubber	D008	Leaded rubber includes lead oxide impregnated materials such as gloves and aprons.	The leaded rubber could potentially exhibit the toxicity characteristic.

Table 1. (cont'd)

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Metal	F001, F002, D008	Metals range from large pieces removed from equipment and structures to nuts, bolts, wire, and small parts. Many times, metal parts will be cleaned with solvents to remove residual plutonium.	Solvents may exist on the surfaces of metal parts. The metals themselves potentially exhibit the toxicity characteristic.
Glass	F001, F002, D006, D007, D008, D009	Glass includes Raschig rings removed from processing tanks, leaded glass removed from gloveboxes, and miscellaneous laboratory glassware.	Solvents may exist as residuals on glass surfaces and in empty containers. The leaded glass may exhibit the toxicity characteristic.
Inorganic Wastewater Treatment Sludge	F001-F003, D006-D009, P015	Sludge is vacuum filtered and stabilized with cement or other appropriate sorbent prior to packaging.	Traces of solvents and heavy metals may be contained in the treated sludge which is in the form of a solid dry monolith, highly viscous gel-like material, or dry crumbly solid.
Organic Liquid and Sludge	F001, F003	Organic liquids such as oils, solvents, and lathe coolants are immobilized through the use of various solidification agents or sorbent materials.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.
Solidified Liquid	F001, F003, D006, D008	Liquids that are not compatible with the primary treatment processes and have to be batched. Typically these liquids are solidified with portland or magnesium cement.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.
Inorganic Process Solids and Soil	F001, F002, F003, D008	Solids that cannot be reprocessed or process residues from tanks, firebrick fines, ash, grit, salts, metal oxides, and filter sludge. Typically solidified with portland or gypsum-based cements.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.

Table 1. (cont'd)

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Pyrochemical Salts	D007	Molten salt is used to purify plutonium and americium. After the radioactive metals are removed, the salt is discarded.	Residual metals may exist in the salt depending on impurities in the feedstock.
Cation and Anion Exchange Resins	D008	Plutonium is sorbed on resins and is eluted and precipitated.	Feed solutions may contain traces of solvents or metals depending on the preceding process.

Categories of TRU mixed waste

TRU mixed wastes from the above operations are listed by defense production facilities as belonging in one of three broad Summary Category Groups. The characterization is based on the final physical form of the wastes as follows:

Summary category group S3000—homogeneous solids: These wastes include a minimum of 50% (by volume) solid inorganic process residues such as inorganic sludge, salt waste, and pyrochemical salt waste—but exclude soil. Other waste streams are included in this Summary Category Group based on the specific waste stream types and final waste form. This Summary Category Group is expected to contain toxic metals and spent solvents.

Summary Category Group S4000—Soils/Gravel: This Category is assigned to waste streams containing at least 50% (by volume) soil and gravel. This Summary Category Group is expected to contain toxic metals and is also further categorized by the amount of debris included in the matrix.

Summary Category Group S5000—Debris Wastes: These are heterogenous wastes that are at least 50% (by volume) materials that exceed 2.36 inch (60 mm) particle size and that are manufactured objects; plant or animal matter; or natural geologic materials. Smaller particles may be considered debris if they are manufactured objects and if they do not belong to S3000 or S4000. Examples of S5000 waste include gloves; hoses; aprons; floor tile; insulation; plastic; rubber; wood; paper; cloth; and biological materials.

The most common RCRA-regulated hazardous constituents in TRU mixed waste

1. Metals and metal ions: Some of the TRU mixed waste to be emplaced in the WIPP facility contains toxic metals contained in EPA hazardous waste codes D004 through D011 (EPA 2000a). Cadmium, chromium, lead, mercury, selenium, and silver are present in discarded tools and equipment; solidified sludge; cemented

laboratory liquids; and waste from decontamination and decommissioning activities. A large percentage of the waste consists of lead-lined gloveboxes; leaded rubber gloves and aprons; lead bricks and piping; lead tape; and other lead items. Lead, because of its radiation-shielding applications, is the most prevalent toxicity-characteristic metal present.

2. Halogenated volatile organic compounds: Some of the TRU mixed waste to be emplaced in the WIPP facility contains spent halogenated volatile organic compound (VOC) solvents listed as EPA hazardous waste numbers F001 through F005 (EPA 2000a). Tetrachloroethylene; trichloroethylene; methylene chloride; carbon tetrachloride; 1,1,1-trichloroethane; and 1,1,2-trichloro-1,2,2-trifluoroethane (EPA hazardous waste codes F001 and F002) are the most prevalent halogenated organic compounds identified in TRU mixed waste that may be managed at the WIPP facility during the Disposal Phase. These compounds are commonly used to clean metal surfaces prior to plating, polishing, or fabrication; to dissolve other compounds; or as coolants. Because they are highly volatile, only small amounts typically remain on equipment after cleaning or, in the case of treated wastewater, in the sludge after clarification and flocculation. Radiolysis may also generate halogenated volatile organic compounds.

3. Non-halogenated volatile organic compounds: Xylene, methanol, and n-butanol are the most prevalent nonhalogenated VOCs in TRU mixed waste that may be managed at the WIPP facility. Like the halogenated VOCs, they are used as degreasers and solvents and are similarly volatile. The same analytical methods that are used for halogenated VOCs are used to detect the presence of nonhalogenated VOCs.

Prohibited Items

The TRU mixed waste forms describe both radioactive and hazardous characteristics exhibited by the wastes. The Permit Treatment, Storage, and Disposal Facility Waste Acceptance Criteria (TSDF-WAC) places limits on the

waste that can be shipped to the WIPP facility based on the characteristics of the waste form. The following TRU mixed wastes are prohibited at the WIPP facility:

1. Liquid waste. Residual liquid in the container in excess of what is reasonably achievable by pouring, pumping, and/or aspirating; liquid in the internal container in excess of 1 inch (2.5 cm) of liquid in the bottom of the container; or total residual liquid in any payload container (e.g., 55 gallon drum or standard waste box) in excess of 1% (by volume) of that container.
2. Pyrophoric materials, such as elemental potassium.
3. Hazardous wastes not occurring as co-contaminants with TRU wastes.
4. Wastes incompatible with backfill; seal and panel closures materials; container and packaging materials; shipping container materials; or other wastes.
5. Wastes containing explosives or compressed gases.
6. Wastes with polychlorinated biphenyl (PCB) concentration of 50ppm (50 mg/kg) or more.
7. Wastes exhibiting the characteristic of ignitability, corrosivity, or reactivity (EPA Hazardous Waste Numbers D001, D002, or D003).
8. Any waste container that does not have VOC concentration values reported for the headspace.
9. Any waste container which has not undergone either radiographic or visual examination.
10. Any waste container from a waste stream which has not been preceded by an appropriate, certified Waste Stream Profile Form.

Before accepting a container holding TRU mixed waste, WIPP operators audit the radiography or visual examination (VE) data records of the generator/storage sites to verify that the container holds no unvented compressed gas, and that residual liquid does not exceed 1% (volume) in any payload container. Radiography tapes are to be selected randomly for at least 1% of containers received at the WIPP, at which time they are reviewed and compared to radiographic data forms. If waste does not include at least 50% of any given category by volume, characterization shall be performed using the waste characterization process required for the category constituting the greatest volume of waste for that waste stream. To ensure

the integrity of the WIPP facility, waste streams identified as containing incompatible materials or materials incompatible with waste containers are not to be shipped to the WIPP unless they are treated to remove the incompatibility.

Waste generated as a result of waste container handling and processing activities at the WIPP facility are known as "derived" wastes. Because derived wastes can contain only those RCRA-regulated materials present in the waste from which they were derived, no additional characterization of the derived waste is required for disposal purposes. In other words, generator/storage site characterization data as well as knowledge of the processes at the WIPP facility will be used to identify and characterize hazardous waste and hazardous constituents in derived waste.

TRU waste, by definition, must contain 100 nCi or more of transuranic elements per gram of waste, which means that the radioactive component of the waste will always be present within the waste in significant concentrations. The TSDF-WAC limitations and restrictions are provided to ensure that any waste form received at the WIPP facility is stable and can be managed safely. One benefit of waste form restrictions— such as no liquids—is that they limit the kinds of releases that could occur to those that would be readily detectable through visual inspection (i.e., large objects that fall out of ruptured containers) or through the use of radiation monitoring—either locally or within the adjacent area—to detect materials that have escaped from containers.

Releases and spills

Some waste forms only contain radioactive contamination on the surface, because they are not the result of a treatment process or are not porous in form. These include glass, leaded rubber, metals, graphite, ceramics, firebricks, and plastics. In theory, a hazardous waste release could occur if the interiors of these materials became exposed and were involved in a release or spill. Such an occurrence is not likely during operations, because no activities are planned or anticipated that would result in the breaking of these materials to expose fresh surfaces. The WIPP facility will handle only sealed containers of waste and derived waste. The practice of handling sealed containers minimizes the opportunity for releases or spills. For the purposes of safety analysis, it was assumed that releases and spills during operations occur by either of two mechanisms: 1) surface contamination, and 2) accidents.

Regardless of how the release occurs, the nature of the waste and the processes that generated it is such that the radioactive and hazardous components are intimately mixed. A release of one without the other is not likely, except for releases of VOCs from containers. Surface contamination is the only credible source of contamination external to the containers during normal operations. Surface contamination is assumed to be caused by waste management activities at the generator site that result in the contamination of the outside of a waste container. Contamination would most likely consist of particulate matter (dirt or dust) that would be deposited during generator-site handling/loading activities. This contamination may not be detected by visible inspections. Surface contamination is monitored upon arrival at the WIPP facility through the use of swipes and radiation monitoring equipment, as specified in the WIPP Permit (NM Hazardous Waste Regulations, Title 20; NMED 1999). Detection using radioactivity is very sensitive and allows for the detection of contamination that may not be visible on the surface of the container. This exceeds the capability required by the RCRA, which is generally limited to inspections that detect only visible evidence of spills or leaks. Releases can occur from accidents, and those that occur within the waste handling process are assumed to result in the release of radioactive contaminants and VOCs. Radioactive releases are detectable using surface-sampling (swipe) techniques. The most common RCRA-regulated hazardous constituents in TRU mixed waste to be managed at the WIPP facility consist of: metals; halogenated volatile organic compounds; and nonhalogenated volatile organic compounds.

WASTE STREAM IDENTIFICATION

Waste characterization activities at generator/storage sites include the following, although not all of these techniques will be used on each container:

1. Radiography, which is an x-ray technique, to determine physical contents of containers.
2. Visual examination (VE) of opened containers as an alternative way to determine their physical contents or to verify radiography results.
3. Headspace-gas sampling to determine VOC content of gases in the void volume of the containers.
4. Sampling and analysis of waste forms that are homogeneous and can be representatively sampled to determine concentrations of hazardous waste constituents and toxicity-characteristic contaminants of waste in containers.

5. Compilation of acceptable knowledge (AK) documentation into an auditable record, including process knowledge and prior sampling and analysis data.
6. Non-destructive assay, typically segmented gamma scans (SGS) and passive/active neutron interrogation (PAN), to quantify radionuclides for 40 CFR 194 waste characterization compliance.

Auditable records allow DOE operators to conduct a systematic assessment, analysis, and evaluation of generator/storage site compliance with the WAP and the Permit. Waste analysis parameters to be characterized include confirmation of physical form; presence of toxicity characteristic contaminants; and exclusion of prohibited items. The characterization techniques used by generator/storage sites include AK, which incorporates confirmation by headspace-gas sampling and analysis; radiography; and homogeneous waste sampling and analysis. All confirmation and characterization activities are to be performed in accordance with the WAP. The analytical requirements are specified by the analytical method being used (e.g., Fourier Transform Infrared Spectroscopy (FTIRS), Gas Chromatography/Mass Spectrometry (GC/MS)).

Waste analysis parameters characterized for the 40 CFR 194 (EPA 1998) characterization program are quantity of metals; quantities of cellulosics; plastics; and rubber; quantity of free water; and a list of ten radionuclides. The characterization techniques used by generator/storage sites for these parameters also include AK and radiography as well as non-destructive assay (NDA).

Radiography

Radiography techniques have been developed by the DOE to aid in the examination and identification of containerized waste. There are specific requirements that relate to radiography methods used at respective facilities. A radiography system typically consists of: 1) an X-ray-producing device; 2) an imaging system; 3) an enclosure for radiation protection; 4) a waste container handling system; 5) an audio/video recording system; and 6) an operator control and data acquisition station.

Although these six components are required, it is expected that there will be some variation within a given system between sites. The radiography of a waste container is recorded by an audio/videotape or equivalently non-alterable media and is maintained as a non-permanent record. The estimated waste material parameter and weights should be determined by compiling an inventory of waste items, residual materials, and packaging materials. Containers whose contents prevent full examination to the extent expected for the radiography technique and waste form, are subject to visual examination.

Visual examination

As an additional quality control (QC) check on radiography, or in lieu of radiography, the waste container contents are verified directly by visual examination. The visual examination consists of a semi-quantitative and/or qualitative evaluation of the waste container contents, and is recorded on audio/videotape. Visual examination is performed on a statistically determined portion of waste containers to verify the results of radiography. This verification includes use of the Waste Matrix Code; waste material parameter weights; and the ensurance of the absence of prohibited items.

Visual examination includes describing the contents of a waste container, and estimating or measuring the weight of the contents. The description identifies the discernible waste items, residual materials, packaging materials, and waste material parameters. Estimated weights are established through the use of historically derived waste weight tables and an estimation of the waste volumes.

Headspace-gas sampling and analysis

Headspace-gas sampling is performed on waste containers that are in compliance with the container temperature equilibrium requirements (i.e., 72 h at 18°C or higher). Waste containers designated as summary category S5000 (Debris waste) are sampled for headspace gas a minimum of 142 d after packaging. Waste containers designated as Summary Categories S3000 (Homogenous solids) and

S4000 (Soil/gravel) are sampled a minimum of 225 d after packaging. This drumage criteria ensures that the drum contents have reached 90 % of steady state concentration within each layer of confinement to allow a representative sample to be taken (NMED 1999.) Two types of headspace-gas sampling protocols may be employed: 1) the manifold headspace-gas sampling protocol, and 2) the direct canister headspace-gas sampling protocol.

Once the headspace gas sample has been collected in accordance with the HWFP requirements, the sample is taken to a laboratory for analysis. The laboratory analyzes the sample using the allowable methods in the HWFP and reports the concentration of all analytes on the target analyte list. In addition, the presence of any tentatively identified compounds (TICs) observed during the analysis is reported.

Sampling and analysis of homogenous solids and soil/gravel

The methods used to collect samples of TRU mixed waste classified as homogenous solids and soil/gravel from waste containers, are designed to ensure that the samples are representative of the waste from which they are taken. A sufficient number of samples are collected to adequately represent the waste being sampled. For those waste streams defined as Summary Category Groups S3000 or S4000, debris that may also be present within these wastes need not be sampled. Samples of retrievably stored waste containers are collected using appropriate coring equipment or other EPA-approved methods to collect a representative sample. Newly-generated wastes that are sampled from a process as they are generated may be sampled using EPA-approved methods—including scoops and ladles—that are capable of collecting a representative sample.

The QC requirements for sampling homogenous solids and soil/gravel include: collecting co-located samples from cores or other sample types to determine precision; equipment blanks to verify cleanliness of the sampling and coring tools and sampling equipment; and analysis of reagent blanks to ensure that reagents, such as deionized or high pressure liquid chromatography (HPLC) water, are of sufficient quality.

Once the homogeneous solid or soil/gravel sample has been collected in accordance with the HWFP requirements, the sample is taken to a laboratory for analysis. The

laboratory analyzes the sample using the allowable methods in the HWFP and reports the concentration of all analytes on the target analyte list. In addition, the presence of any tentatively-identified compounds (TICs) observed during the analysis is reported.

Acceptable knowledge

This characterization technique incorporates confirmation by headspace-gas sampling and analysis; radiography; and homogeneous waste sampling and analysis. Both RCRA regulations and the New Mexico Hazardous Waste Management Regulations (NMED 1997) authorize the use of AK in appropriate circumstances by waste generators—or treatment, storage, or disposal facilities—to characterize hazardous waste. Acceptable knowledge is described by the EPA (EPA 1994) as an alternative to sampling and analysis; it can be used to meet all or part of the waste characterization requirements under the RCRA. AK includes a number of techniques used to characterize TRU mixed waste, such as process knowledge; records of analysis acquired prior to RCRA; and other supplemental sampling and analysis data (EPA 1994). AK is used in TRU mixed waste characterization activities in three ways:

1. To delineate TRU mixed waste streams
2. To assess if TRU mixed heterogeneous debris wastes exhibit a toxicity characteristic (NMED 1997)
3. To assess if TRU mixed wastes are listed (NMED 1997)

TRU mixed waste streams are evaluated by applicable provisions of the AK process prior to management, storage, or disposal by the Permittees at the WIPP. TRU mixed waste management AK information defines waste categorization schemes and terminology; provides a breakdown of the types and quantities of TRU mixed wastes that are generated and stored at the site; and describes how wastes are tracked and managed at the site—including historical and current operations. Information related to TRU mixed waste certification procedures and the types of documentation (e.g., waste profile forms) used to summarize AK are also provided. The amount and type of supplemental AK information required from

generator/storage sites is site-specific and cannot be mandated, but sites collect information as appropriate to support required AK information.

The AK written record includes a summary that identifies all sources of waste characterization information used to delineate the waste stream. For each TRU mixed waste stream, the generating sites compile all process information and data supporting the AK used to characterize that waste stream. The type and quantity of supporting documentation will vary by waste stream, depending on the process generating the waste and site-specific requirements imposed by the DOE.

Non-destructive assay (NDA)

Radioassay is a term used to define measurement methods for determining the radionuclide content of waste. The isotopic composition of RH-TRU waste is usually determined from documented AK and, in some cases, from measurements taken on the product material during processing at each site. NDA techniques allow an item to be assayed without altering its physical or chemical form. NDA techniques can be classified as active or passive. Passive NDA is based on the observation of spontaneously-emitted radiations created through radioactive decay of the isotopes of interest or their radioactive daughters. Most active NDA is based on the observation of gamma or neutron radiation that is emitted from a target isotope when that isotope undergoes a transformation resulting from an interaction with stimulating radiation provided by an appropriate external source.

STATISTICAL METHODS USED IN SAMPLING AND ANALYSIS

Generator/storage sites use statistical methods to: 1) select waste containers for visual inspection; 2) select retrievably-stored waste containers for totals analysis; 3) set the upper confidence limit; and 4) apply control charting for newly-generated waste stream sampling. Statistical sampling techniques are not currently employed in waste characterization activities employed for 40 CFR 194 (EPA 1999) compliance.

Selecting waste containers for visual examination

As a QC check on the radiographic examination of waste containers, a statistically-selected portion of the certified waste containers is opened and visually examined. The data from visual examination is used to verify the matrix parameter category, waste material parameter weights, and absence of prohibited items, as determined by radiography. The data obtained from the visual examination can also be used to determine— with acceptable confidence—the percentage of miscertified waste containers from the radiographic examination. Miscertified containers are those that radiography indicates meet the WIPP Waste Acceptance Criteria and Transuranic Package Transporter-II Authorized Methods for Payload Control, but visual examination indicates do not meet these criteria. Participating sites initially use an 11% miscertification rate to calculate the number of waste containers that are visually examined until a site-specific miscertification rate has been established.

The site-specific miscertification rate is applied initially to each Summary Category Group to determine the number of containers in that Summary Category Group requiring visual examination. However, a Summary Category Group-specific miscertification rate is determined when either six months have passed since radiographic characterization commenced on a given Summary Category Group or at least 50% of a given Summary Category Group has undergone radiographic characterization, whichever occurs first. The Summary Category Group is then subject to the visual examination requirements of this reevaluated Summary Category Group-specific miscertification rate to ensure that the entire Summary Category Group is appropriately characterized. The site-specific miscertification rate is reassessed annually.

Statistical sampling and analysis of homogeneous solids and soil/gravels for totals

The statistical approach for characterizing retrievably-stored homogeneous solids and soil/gravel waste using sampling and analysis relies on using acceptable knowledge to segregate waste containers into relatively homogeneous waste

streams. Once segregated by waste stream, random selection and sampling of the waste containers followed by analysis of the waste samples are performed to ensure that the resulting mean contaminant concentration provides an unbiased representation of the true mean contaminant concentration for each waste stream.

Preliminary estimates of the mean concentration and variance of each RCRA-regulated contaminant in the waste are used to determine the number of waste containers to select for sampling and analysis. The preliminary estimates are made by obtaining a preliminary number of samples from the waste stream or from previous sampling from the waste stream. Preliminary estimates are based on samples from a minimum of five waste containers. Samples collected to establish preliminary estimates that are selected, sampled, and analyzed in accordance with applicable provisions of the WAP are used as part of the required number of samples to be collected.

The calculated total number of required waste containers can then be randomly sampled and analyzed. Waste container samples from the preliminary mean and variance estimates may be counted as part of the total number of calculated required samples if and only if:

1. There is documented evidence that the waste containers for the preliminary estimate samples were selected in the same random manner as is chosen for the required samples.
2. There is documented evidence that the method of sample collection in the preliminary estimate samples were identical to the methodology to be employed for the required samples.
3. There is documented evidence that the method of sample analysis in the preliminary estimate samples was identical to the analytical methodology employed for the required samples.
4. There is documented evidence that the validation of the sample analyses in the preliminary estimate samples was comparable to the validation employed for the required samples. In addition, the validated samples results should indicate that all sample results were valid according to the analytical methodology.

Upon collection and analysis of the preliminary samples, or at any time after the preliminary samples have been analyzed, the generator/storage site may assign

hazardous waste codes to a waste stream. For waste streams with calculated upper confidence limits below the regulatory threshold, the site must collect the required number of samples if the site intends to establish that the constituent is below the regulatory threshold.

Statistical headspace gas sampling and analysis

If a waste stream meets the conditions for representative headspace gas sampling, then headspace-gas sampling of that waste stream may be done on a randomly-selected portion of containers in the waste stream. The minimum number of containers that are sampled is determined by taking an initial VOC sample from 10 randomly-selected containers. These samples are analyzed for all the target analytes.

Waste container samples from the preliminary mean and variance estimates may be counted as part of the total number of calculated required samples if and only if:

1. There is documented evidence that the waste containers for the preliminary estimate samples were selected in the same random manner as is chosen for the required samples.
2. There is documented evidence that the method of sample collection in the preliminary estimate samples were identical to the methodology to be employed for the required samples.
3. There is documented evidence that the method of sample analysis in the preliminary estimate samples were identical to the analytical methodology employed for the required samples.
4. There is documented evidence that the validation of the sample analyses in the preliminary estimate samples were comparable to the validation employed for the required samples. In addition, the validated samples results should indicate that all sample results were valid according to the analytical methodology.

The mean and standard deviation calculated after sampling n containers is then used to calculate a UCL_{90} for each of the headspace gas VOCs.

Control charting for newly-generated waste stream sampling

Significant process changes and process fluctuations associated with newly-generated waste are determined using statistical process control (SPC) charting techniques; these techniques require historical data for determining limits for indicator species, and subsequent periodic sampling to assess process behavior relative to historical limits. SPC is performed on waste prior to solidification or packaging for ease of sampling. If the limits are exceeded for any toxicity characteristic parameter, the waste stream can be recharacterized, and the characterization can be performed according to procedures required in the WAP.

A Shewhart control chart (Gilbert 1987) is a control chart for statistical means that is used for checking whether current data are consistent with past data and whether shifts or trends in means have occurred. If a current sample mean from the process lies within the limits, the process is said to be "in control," or consistent with historical data. If the current mean exceeds the limits, the process has likely changed from historical periods. Logical sets of historical data to be used for the construction of limits in this application are the data from the initial characterization of the waste stream, if available; from characterization of a different lot of the waste stream, or from a retrievably-stored waste stream of the same type from the same process. At a minimum, the logical set includes ten representative sample values collected and analyzed from the newly-generated waste stream. The data used for construction of the limits is justified. The underlying assumptions for control charts are that the data are independent and normally-distributed with constant mean μ and constant variance σ^2. The statistical tests for normality can be conducted and data transformation to normality performed, if necessary. Transformations should take place prior to any calculations that use the data.

Each limit is constructed such that there is a 90 % confidence that the true mean does not exceed a limit. One-sided control limits are used because once a waste stream has been determined to be RCRA-hazardous and the limit exceedance of interest is on the lower side—that is when the process may become nonhazardous. Likewise, once a waste stream has been determined not to be RCRA-hazardous and the limit exceedance of interest is on the upper side—that is when the process may become RCRA-hazardous. Whether or not exceeding the limit would result in a

change in the RCRA-hazardous nature of the waste stream depends on how close the observed control limits are to RCRA limits.

Current process data are collected and averaged for comparison to the control limit for the mean. The collection period and number of samples included in the average are dependent on the waste stream characteristics. A small number of samples will reflect more of the process variability and there will be more limit exceedances. If two or three samples are collected for the mean in the required annual (or batch) sampling of a relatively homogeneous waste stream, limit exceedances may not occur. If the waste stream is less homogeneous, it will be necessary to collect more samples to meet the required confidence limit. Periodically, it will be necessary to update the control limit for a process. An update that includes all historical data is performed if there is no evidence of a trend in the process or a shift in the mean for the process. If there has been a shift in the mean, only more recent data that reflect the shift are used. Control limits shall be based on at least ten data points that are representative of the process and do not exhibit outliers or a trend with time.

Characterization Approaches Proposed for RH-TRU Wastes

INTRODUCTION

The characterization program proposed by the DOE for RH-TRU wastes is a modified version of what is already approved for CH TRU wastes. The proposed characterization program is a Performance-Based Measurement System (PBMS) approach that focuses on ensuring that sufficient data is collected to meet characterization objectives. The approach allows flexibility in applying the allowable methods to collect the necessary information. This is in contrast to the CH waste characterization approach which requires, for most characterization activities, that a specific method be used to collect data from 100% of the waste.

In order to minimize potentially-large RH-TRU waste characterization costs and also to minimize worker radiation exposure to highly-radioactive RH-TRU waste containers canisters, changes to the characterization approach are necessary. Procedures that rely on AK, which in turn relies largely on process knowledge, are proposed for quantifying and tracking the important RH-TRU waste components. Proposed tracking of the waste components is based on waste stream information. When AK does not provide the necessary waste component information, sampling programs or direct measurement characterization methods (radiography, radioassay, and/or VE) will be used as appropriate. The DOE's approach allows sites to tailor their programs to lower worker exposure, while ensuring that necessary information is collected to meet characterization objectives for safely managing and disposing of the waste.

RH-TRU wastes may contain both radioactive and non-radioactive chemical components. To comply with RCRA requirements, chemical components must be identified. Three chemical constituents have a potential impact on the long-term performance of the repository. These are: 1) the amount of free water; 2) the amount of corrodible metals; and 3) the amount of cellulosics, plastics, and rubber.

The challenges for safely characterizing RH-TRU mixed wastes are substantially greater than for CH TRU wastes. The RH-TRU mixed wastes have the same physical characteristics as the CH TRU wastes (i.e., debris, homogeneous solids, and soils/gravel). However, the distinguishing difference between the two wastes is the radioactivity of relatively short-lived beta and gamma emitters (including the fission and activation products, that can have a surface dose rate of up to 5,000 times more than the largest allowable CH rate) are characteristic of RH-TRU mixed wastes. The higher external dose rates of the RH wastes necessitate additional

precautions be taken in waste management procedures. Whereas CH wastes are stored in unshielded buildings, moved using operators and forklifts, and inspected by physically viewing its condition, RH-TRU mixed wastes are typically stored in heavily shielded vaults or hot cells and managed by indirect management of the waste containers. The proposed RH-TRU mixed waste operations incorporate specially-designed equipment and shielded containers and storage areas to unload, move and store the wastes. The process is intended to minimize operator/technician exposure to the penetrating radiation associated with RH-TRU mixed wastes. The indirect interaction includes inspecting the waste using remote cameras and using specially-designed equipment and shielded containers to move the waste.

Since the volume of RH wastes to be disposed at the WIPP is less than 5% of the total CH wastes, the decision was made to place the RH waste containers in horizontal holes pre-drilled in the walls of the underground rooms where the CH wastes containers are to be stacked. Thus the RH wastes must be placed prior to stacking the CH wastes on the repository floor.

RH CHARACTERIZATION

The proposed RH characterization program (WAP) incorporates a characterization approach that relies on both AK and testing of the waste. The waste characterization proposal is based on EPA guidance published by the EPA's Office of Solid Waste and Emergency Response for a Performance-Based Measurement System (PBMS). The implementing plan (EPA 1994) outlines guiding principles for such a system and states:

"PBMS conveys what needs to be accomplished, but not prescriptively how to do it. Under a performance-based approach, EPA would specify questions to be answered by monitoring, the decisions to be supported by the data, the level of uncertainty acceptable for making the decisions, and the documentation to be generated to support the PBMS approach in the monitoring program."

The EPA further clarified the PBMS approach by stating:

"Regulatory methods are written so that they may be used as quantitative trace analytical methods to demonstrate that a waste does not contain constituents that require it to be managed as a hazardous waste. If particular RCRA applications do

not require this rigor, looser analytical criteria may be applied, provided that they satisfy the data quality requirements for the particular application. Since data quality needs are project-specific in the RCRA Program, in order to successfully perform analyses it is necessary to address data quality issues prior to initiating any analyses. Good science indicates that, at a minimum, the following questions should be asked before beginning any analyses:

1. What is the purpose of this analysis? (Why are we doing this analysis?)
2. How (for what action) is the data generated from this analysis to be used?
3. What are the data quality needs for this project, i.e. how good does the data have to be to be useful for its intended purpose (including regulatory drivers, target analytes, matrices, concentration levels, statistical confidence levels, etc.)?

CHARACTERIZATION METHODS

The characterization methods in the proposed RH WAP are AK, radiography, and VE; site specific methods are selected to ensure quality control. The RH WAP requires that AK be used in making hazardous waste determinations. Under the proposed approach, AK may also be used to determine the physical form of the waste and the absence of prohibited items. Hazardous waste determinations made using AK may be supplemented with applicable information obtained through radiography and/or VE if the AK information alone is insufficient for applying hazardous waste numbers. Testing is required to confirm the characterization that is done using AK as the sole characterization technique; this confirmation utilizes radiography and/or VE. The assignment of hazardous waste numbers by using AK does not have to be confirmed. Due to differences in site-specific AK information and the intense radiation associated with RH-TRU wastes, the process used for confirming the AK must also be site-specific. Each site is to provide confirmation on a representative sample of the waste stream.

The characterization methods in the proposed program for compliance with 40 CFR 94 requirements are AK, radioassay, radiography, and radiological survey. In this program AK is used to identify the physical form of the waste (summary category group), to quantify the important waste components (metals, cellulosics, plastics, rubber, free water)—and where feasible—to quantify the total radioactivity of waste

streams. AK may be supplemented with applicable information obtained through radioassay or radiography if the AK information alone is insufficient to meet characterization objectives.

AK refers to applying knowledge of the wastes based on the materials or processes used to generate the wastes. AK includes documented attributes of waste streams, such as chemical, physical, and radiological properties. This may include process knowledge, which relies on the generators' knowledge of the material properties associated with the waste-generating processes; the fate of those materials during and subsequent to the processes; and associated administrative controls. Process knowledge commonly includes detailed information on the waste obtained from existing waste analysis data; review of waste-generating processes; or detailed information relative to the properties of the wastes that are known due to site-specific and/or process-specific factors (e.g., material accountability and tracking systems or waste management databases may supply information on wasted isotopic composition and/or quantity of radionuclides, among other waste attributes).

Waste characterization using AK involves the compilation and evaluation of information concerning waste-generating processes or activities at a site. AK information may include previous testing data; waste generating procedures; chemical inputs to the processes; time period that the processes took place; the facilities involved; types of waste generated; and past sampling, analytical data, and hazardous waste determinations made to satisfy host state requirements. AK information may contain reference materials; process flow diagrams; personnel interviews; analytical results; hazardous waste determinations under RCRA; and packaging logs and videotapes. AK information may also include administrative controls as a basis for the absence of prohibited items in the waste.

AK is used in program activities to characterize RH-TRU wastes to the extent practicable as determined on a site-by-site basis depending upon the types of wastes being characterized and the types of data required. Hence, AK balances requirements for providing definitive characterization data of waste streams where sampling and analysis are not feasible or necessary (e.g., waste streams for which it is difficult to obtain a representative sample because of physical form and/or heterogeneous composition—including metals, glass, combustibles).

Radiography may be used for determining physical form; the absence of prohibited items; and quantifying non-radioactive waste components. Additionally,

radiography may be used on a limited basis to supplement AK in assuring that appropriate EPA hazardous waste numbers are assigned. Radiography is a nondestructive qualitative and semi-quantitative technique that involves X-ray scanning of waste containers to identify and verify container contents. When radiography data is required, representative selections of containers will be used for these measurements. However, due to the intense radiation and lead shielding associated with RH-TRU wastes, it may not be possible to image all of the waste containers using a site's radiography equipment. Therefore, those sub-populations selected according to the operational constraints associated with the radiography operations (including image quality and operator safety) may be used. To reduce waste characterization worker exposure, the RH WAP does not propose a replicate scan, as is required for radiography of CH TRU wastes. A replicate scan requires removing the container from the radiography system and then replacing it at a later time, resulting in additional exposure. Using VE as a quality control check on radiography also is not proposed in order to reduce waste characterization worker exposure.

The VE is a characterization technique of the proposed RH WAP that may be used for determining physical form and absence of prohibited items, and may be used on a limited basis to supplement AK to ensure that appropriate EPA hazardous waste numbers are assigned. The proposed RH WAP does not make any distinction between newly-generated and retrievably-stored waste for characterization (unlike the CH WAP); therefore, the RH WAP proposes to use VE as a characterization technique for any container. The proposed RH WAP requires that either a videotape (or equivalent) be made of all VE characterizations, or that dual operator signatures be documented in lieu of a tape. Use of existing videotape records (or equivalent) is permitted as it eliminates additional exposure of the waste characterization worker, while ensuring quality control.

Similar to the requirements for radiography in the proposed RH WAP, VE is not required on every container. VE on every container would result in additional exposure to the waste characterization worker and may not be needed to meet quality control supported by VE. Due to the intense radiation associated with RH-TRU waste, it may not be possible to open all of the RH-TRU waste containers for VE due to operational constraints (e.g., hot cell limitations on maximum dose rate). Therefore, subpopulations based on the VE operational constraints may be used. If VE data are being used to meet quality control, containers examined must be representatively selected. Detailed information regarding selection of a

representative container must be included in the site-specific implementation procedures. Because VE operations can produce data that are similar in type and quality to radiography, the procedures parallel those for radiography in the proposed RH WAP.

In addition to the characterization techniques required by the RH WAP, the characterization program for RH waste includes AK and radioassay techniques for determining the radionuclide content of the waste. Radioassay is a term used to define measurement methods for determining the radionuclide content of wastes, and includes both nondestructive assays (NDA) and destructive assays (i.e., radiochemistry). The isotopic composition of RH-TRU wastes is usually determined from documented AK and, in some cases, from measurements taken on the product material during processing at each site. The isotopic composition of the waste need not be determined by direct analysis or measurement of the waste unless AK is not available.

The NDA techniques allow an item to be assayed without altering its physical or chemical form. NDA techniques can be classified as active or passive. Passive NDA is based on the observation of spontaneously-emitted radiations created through radioactive decay of the isotopes of interest or their radioactive daughters. Most active NDA is based on the observation of gamma or neutron radiation that is emitted from a target isotope when that isotope undergoes a transformation resulting from an interaction with stimulating radiation provided by an appropriate, external source.

In the destructive assay technique, a representative sample is collected from the waste and physically and/or chemically processed for subsequent analysis by standard radioactivity counting methods. Radiochemical analyses are to demonstrate that sampling methods and analytical equipment used can produce results with sufficient precision and accuracy to meet disposal requirements.

Dose rate measurements can provide estimates of the radionuclides present in the waste. Measurements are taken of the containerized waste and correlated to a known isotopic inventory to provide estimated curie contents of the container. This process requires knowledge of the isotopic ratios for the waste stream. The isotopic ratios can be determined by AK or by measurement of a sample of the waste. The sample can be a smear taken on the waste or an aliquot of the waste subjected to radiochemistry.

Radiochemistry is a destructive assay technique in which a representative sample is collected from the waste and physically and/or chemically processed for subsequent analysis by standard radioactivity counting methods. Radiochemistry is most commonly used to analyze the radionuclide content of homogeneous waste forms resulting from liquids such as process sludge or other sludge waste forms. (DOE 2001 b)

COMPARISON OF THE RH WAP AND CH WAP

The RH-TRU wastes are currently prohibited at the WIPP because it has not yet been demonstrated that RH-TRU waste could be characterized in the same manner as CH TRU waste. The DOE submits that RH-TRU waste should not be characterized using the same criteria as those used for CH TRU waste; thus, there are differences between the RH WAP and CH WAP. The major differences, which reflect the Performance-based measurement system (PBMS) approach in the RH WAP, are summarized in Tables 2 through 5. In general, the proposed RH WAP requires AK, radiography, and/or VE as characterization methods for RH-TRU waste. The CH WAP requirements for each of the proposed methods has been maintained except where the specific requirement conflicts with the PBMS approach, or could lead to unnecessary additional waste characterization worker exposure. The CH WAP requires sampling and analysis to confirm AK and the application of some characterization techniques on every container. The proposed RH WAP does not require confirmatory testing, sampling, or analysis and allows for representative selection of containers for radiography and VE; thus workers are not unnecessarily exposed to the additional penetrating radiation associated withconducting confirmatory activities.

Any RH-TRU waste container that has not been characterized by AK—supplemented as necessary by radiography and/or VE—is prohibited at the WIPP facility.

Data Quality Objectives		
RH WAP Requirement	**Difference from CH WAP**	**Justification**
Determine the physical form of the waste at the Summary Category Group level • S3000: Homogeneous Solids • S4000: Soil Gravel • S5000: Debris	Only the Summary Category Group is necessary for RH-TRU waste	Evaluation of the repository modeling indicates that the amount of waste in the individual material parameter categories does not affect repository integrity. (See Appendix 1)
Determine the absence of prohibited items • Liquids (Permit Module II, Section II.C.3.a • Pyrophoric materials (Permit Module II, Section II.C.3.b) • Incompatible waste (Module II, Section II.C.3.d) • Explosives and compressed gases (Permit Module II, Section II.C.3.e) • PCBs with concentrations greater-than-or-equal-to 50 ppm (Module II, Section II.C.3.f)	None	N/A
Determine the listed and characteristic hazardous constituents in the waste • Determine if a waste is listed as specified in 20.4.1.200 NMAC (incorporating 40 CFR §261.31 and 33); assign the appropriate US EPA hazardous waste number(s); and ensure that the US EPA hazardous waste number(s) are listed in Permit Attachment O. • Determine if a waste exhibits the toxicity characteristic as specified in 20.4.1.200 NMAC (incorporating 40 CFR §261.24); assign the appropriate US EPA hazardous waste number(s); and ensure that the US EPA hazardous waste number(s) are listed in Permit Attachment 0.	None	N/A

Table 2. (cont'd)

Data Quality Objectives		
RH WAP Requirement	**Difference from CH WAP**	**Justification**
Identification of Appendix VIII constituents	Not required for RH-TRU waste	Identifying the presence of additional Appendix VIII constituents that do not overlap with the hazardous constituents identified for a characteristic or listing does not affect the integrity of the repository and is not necessary to store or dispose of the waste at WIPP.

Table 3. Differences between Proposed RH-TRU Mixed Waste Characterization Acceptable Knowledge Method and the CH TRU Mixed Waste Characterization Acceptable Knowledge Method.

Acceptable Knowledge		
RH Requirement	**Difference from CH**	**Justification**
Administrative controls for prohibited items Sites may rely on administrative controls to ensure absence of prohibited items. Sites must implement a procedure(s) which addresses the following elements associated with administrative controls: • Organization(s) responsible for compliance with administrative controls. • A description of the administrative controls used by the site to ensure that prohibited items are documented and managed in accordance with site-specific certification plans. • The oversight actions, and frequency of actions, to verify compliance with administrative controls. • On-the-job training specific to administrative control procedures. • A statement that personnel may stop work if noncompliance with administrative controls is identified. • The nonconformance and corrective action process	None	N/A
List of information necessary The Permittees shall obtain from each Department of Energy (DOE) RH-TRU waste generator/storage site (site), AK information for meeting the required DQOs in Section R-1c.	The RH WAP requires that only information necessary to meet the applicable DQO(s) be collected and maintained, rather than requiring a prescriptive list of information for all AK.	Based on the PBMS approach, only the data related to the intended purpose need be collected.

Table 3. (cont'd)

Acceptable Knowledge		
RH Requirement	**Difference from CH**	**Justification**
AK auditing The AK process and waste stream documentation must be evaluated through assessments by quality assurance organizations. Audit checklists for AK shall be used to review applicable elements based on the DQOs that are being met using AK data.	Only the information required by the site procedure, which specifies the information necessary to meet the intended DQO(s), will be subject to audit.	Based on the PBMS approach, only the data related to the intended purpose need be collected or evaluated. Each site will establish the requirements that are necessary to meet the intended DQO(s) in their procedure.
AK required for determining listed constituents AK is required to identify toxicity characteristic and listed U.S. EPA hazardous waste numbers pursuant to 20.4.1.200 NMAC (incorporating 40 CFR §§ 261.24,261.31 and 261.33). As allowed by 20.4.1.500 NMAC (incorporating 40 CFR 264.13(a)(2)), the assignment of U.S. EPA hazardous waste numbers in compliance with the generator host-state requirements is considered AK for this RH WAP.	None	N/A
Hazardous waste numbers must be applied conservatively If different sources of information indicate different hazardous wastes are present, then sites shall include all sources of information in its records and conservatively assign all appropriate U.S. EPA hazardous waste numbers.	None	N/A
Use of hazardous waste determinations made in accordance with host-state requirements as AK As allowed by 20.4.1.500 NMAC (incorporating 40 CFR 264.13(a)(2)), the assignment of U.S. EPA hazardous waste numbers in compliance with the generator host-state requirements is considered AK for this RH WAP.	This information is used as AK for CH TRU waste, but was not specifically called out in the CH WAP.	Hazardous waste determinations must be conducted in accordance with the minimum requirements of RCRA, regardless of the state in which they are made. 40 CFR 264.13(a)2 allows for the use of data developed under 40CFR Part 261, which is the process that is used to establish the hazardous waste determination in the host state.

Table 3. (cont'd)

Acceptable Knowledge		
RH Requirement	**Difference from CH**	**Justification**
Use of AK information from similar waste streams • If sites can demonstrate correlations and similarities between the CH and RH-TRU waste operations, characterization information for the CH TRU waste stream may be used to determine the physical form, U.S. EPA hazardous waste number(s), and absence of prohibited items for the RH-TRU waste stream. • If sites can demonstrate correlations and similarities between the RH- TRU waste operations at other sites, characterization information for that RH-TRU waste may be used to determine the physical form, U.S. EPA hazardous waste number(s), and absence of prohibited items for their RH-TRU waste stream.	None	N/A
Training Site personnel responsible for compiling AK, assessing AK, and resolving discrepancies associated with AK shall be qualified and trained in the following areas at a minimum: • RH WAP and the RH TSDF-WAC • State and Federal RCRA regulations associated with solid and hazardous waste characterization • The nonconformance and corrective action process • Site-specific procedures associated with waste characterization using AK	None	N/A

Table 3. (cont'd)

Acceptable Knowledge		
RH Requirement	**Difference from CH**	**Justification**
QAO: Precision The qualitative determinations, such as compiling and assessing AK documentation, do not lend themselves to statistical evaluations of precision. Therefore, precision requirements are not established for AK. However, the acceptable knowledge information is subject to audits as specified in Permit Attachment R3.	None	N/A
QAO: Accuracy The qualitative determinations, such as compiling and assessing AK documentation, do not lend themselves to statistical evaluations of accuracy. Therefore, accuracy requirements are not established for AK. However, AK must be confirmed if it is used as the sole characterization technique to meet a DQO. In addition, the AK process is subject to audits as specified in Permit Attachment R1.	Testing data are required to confirm AK if it is used as the sole characterization technique and the audit process will be used to ensure that the information was accurately collected.	Newly collected data under the WAP should not require additional confirmation. Only information brought into the program through the AK process requires confirmation and only if it is the only information used to meet one or more of the DQOs.
QAO: Completeness The AK record shall contain sufficient information to meet the DQO(s) in Section R-2 that are being supported using AK data or supplemental information must be collected. If additional AK information is part of the identified supplemental information, the additional AK information must be collected and documented to ensure AK completeness.	Only the information that is relevant to the intended DQO(s) must be 100% complete based on the site procedure.	Based on the performance-based approach, only the data related to the intended purpose need be collected.
QAO: Comparability Comparability is ensured through sites meeting the training requirements and minimum standards outlined in this RH WAP. Sites shall ensure appropriate U.S. EPA hazardous waste numbers are assigned in accordance with Permit Attachment R3 and ensure information regarding its waste is available to other sites.	None	N/A
QAO: Representativeness Representativeness will be satisfied by ensuring that the process of obtaining, evaluating, and documenting AK information is performed in accordance with the requirements established in Permit Attachment R3.	None	N/A

Table 3. (cont'd)

Acceptable Knowledge		
RH Requirement	**Difference from CH**	**Justification**
AK Confirmation If AK is used as the sole characterization method to meet a DQO, an AK confirmation program must be developed and implemented by the generator/storage site.	AK must only be confirmed if it is not supported by new testing to meet the DQO. Confirmation must be conducted on a representative sample rather than 100%.	If new testing is conducted, the results of that testing are used in addition to the AK information to meet the DQO providing an implicit confirmation of the AK information used. If no new testing is needed to meet the DQO, the AK information requires explicit confirmation with new testing data. Representative sampling meets the regulatory requirements for sampling.

Table 4. Differences between Proposed RH-TRU Mixed Waste Characterization Radiography Method and the CH TRU Mixed Waste Characterization Radiography Method.

Radiography		
RH Requirement	**Difference from CH**	**Justification**
Material parameter category weight estimation	Not required for RH-TRU waste	Evaluation of the repository modeling indicates that the integrity of the repository is not affected by conservatively bounding the material parameters in RH waste.
Requirement to use other characterization technique if contents cannot be resolved due to interference If a site operates a radiography system that is not capable of X-ray penetration or image quality sufficient to provide information to meet the DQOs, then another suitable waste characterization technique must be used (i.e., AK or VE).	None	N/A
Complete Data Form A radiography data form is also used to document the physical form(s) of the waste and the overall summary category group, the absence of prohibited items and, to a limited extent, hazardous constituents that can be correlated to physical indicators, depending on the DQOs that are being met using radiography data.	None	N/A
Videotape Operation To perform radiography, the operator scans waste container while viewing a video image. A videotape recording (or equivalent) is made of the waste container scan.	None	N/A
Independent Observation Independent observations of the video output of the radiography process shall be performed under uniform conditions and procedures.	None	N/A

Radiography		
RH Requirement	**Difference from CH**	**Justification**
Replicate scan	Not required for RH-TRU waste	Independent observations of radiography are used to meet the accuracy QAO; therefore, any additional worker exposure associated with performing a replicate scan is not necessary.
Contents Test drum is required to contain items common to the waste streams to be generated/stored at the generator/storage site.	None	N/A
Formal and On-the-job Training Although the site-specific training programs will vary to some degree, the Permittees shall require each site's program to contain the following required elements based on the DQOs that are being met using data from radiography: Formal Training 1. Project Requirements 2. State and Federal Regulations 3. Basic Principles of Radiography 4. Radiographic Image Quality 5. Radiographic Scanning Techniques 6. Application Techniques 7. Radiography of Waste Forms 8. Standards, Codes and Procedures for Radiography 9. Site-specific instruction	Training curriculum and drum are only required to contain items that are relevant to the DQO that is being met with radiography data.	Training that is not relevant to the intended purpose of radiography is unnecessary.

Table 4. (cont'd)

Radiography		
RH Requirement	**Difference from CH**	**Justification**
On-the-Job Training 1. System Operation 2. Identification of Summary Category Groups (only required if radiography data are used to support determining the physical waste form) 3. Identification of Prohibited Items (only required if radiography data are used to support determining the absence of prohibited items) 4. Identification of Physical Indicator Parameters Used for Assigning U.S. EPA Hazardous Waste Numbers (only required if radiography data are used as a supplement to AK for ensuring appropriate U.S. EPA hazardous waste numbers are assigned)		
QAO: Precision The precision of the radiography image is verified prior to use of the system through viewing and being able to distinguish an image test pattern.	No change to image test pattern requirement. Relative percent difference (RPD) calculated for CH TRU waste material parameter weights not required.	Material parameter weights are not necessary to ensure the integrity of the repository and are not measured.
QAO: Accuracy An independent observation will be conducted by comparing the contents of a radiography data form to the videotape (or equivalent) of the associated radiography scan by a qualified independent reviewer at the frequency of one per testing batch or once per day, whichever is less frequent.	Use independent observation of radiography rather than VE to ensure accuracy.	Independent observations provide assurance that accuracy is maintained without additional worker exposure during visual examination.
QAO: Completeness A videotape (or equivalent) of the radiography examination and an associated complete data form will be obtained for all waste containers subject to radiography.	None	N/A
QAO: Comparability The comparability of radiography data from different sites shall be enhanced by using standardized radiography operator qualifications that comply with this RH WAP.	None	N/A
QAO: Representativeness Representativeness for waste selected for radiography will be ensured through random container selection.	RH WAP requires radiography of representative waste container selected randomly from the population. There is no CH QAO for representativeness due to the requirement to do 100% radiography	Additional worker exposure from performing 100% radiography is not necessary if a representative waste container is selected.

Table 5. Differences between Proposed RH-TRU Mixed Waste Characterization Visual Examination Method and the CH TRU Mixed Waste Characterization Visual Examination Method.

Visual Examination		
RH Requirement	**Difference from CH**	**Justification**
Material parameter category weight estimation	Not required for RH-TRU waste	Repository modeling demonstrates that the repository integrity is not affected by conservatively bounding the material parameters in RH-TRU waste.
Complete Data Form The results of VE documented on the data form shall clearly identify the physical form(s) and the overall summary category group, the absence of prohibited items and, to a limited extent, hazardous constituents that can be correlated to physical indicators depending on the DQOs that are being met using VE data.	None	N/A
Videotape Operation The VE shall consist of a qualitative evaluation of the waste container contents, and shall be recorded on videotape (or equivalent) or, if two trained operators perform the VE a videotape (or equivalent) is not required.	None	N/A
Independent Observation Oversight functions (i.e., data validation, Permit Attachment R2) include independent review of VE data forms by a qualified VE operator other than the individual who performed the first examination.	Independent observations are required if a single operator conducts the VE.	Independent observation of the VE is necessary to meet the accuracy QAO if two operators are not used.
Representative Sample	Perform VE on representative waste containers selected randomly from the population.	20.4.1.500 NMAC (incorporating 40 CFR 264.13(a)1) requires that a representative sample be taken; any additional worker exposure associated with additional VE is not necessary if a representative waste container is selected.

Table 5. (cont'd)

Visual Examination		
RH Requirement	**Difference from CH**	**Justification**
Training Curriculum Although site-specific training programs will vary to some degree, the Permittees shall require each site's program to contain the following required elements: Form Training 1. Project Requirements 2. State and Federal Regulations 3. Application Techniques 4. Site-Specific Instruction On-the-Job Training 5. Identification of Summary Category Groups (only required if VE data are used to support determining the physical waste form) 6. Identification of Prohibited Items (only required if VE data are used to support determining the absence of prohibited items) 7. Identification of Physical Indicator Parameters Used for Assigning U.S. EPA Hazardous Waste Numbers (only required if VE data are used as	Requires the training curriculum to cover material that is relevant to the DQO that is being met using visual examination data.	Training that is not relevant to the intended purpose of VE is unnecessary.
Training Drum Contents	Training drum is required to contain items that are relevant to the DQO that is being met with visual examination data.	Training that is not relevant to the intended purpose of VE is unnecessary.

Table 5. (cont'd)

Visual Examination		
RH Requirement	**Difference from CH**	**Justification**
Training Examinations Qualification of VE operators shall, at a minimum, encompass the following requirements: 1. Successfully pass a comprehensive exam based upon training enabling objectives. The comprehensive exam will address the VE training requirements and implementation stipulated in this RH WAP. A minimum score of 80% is required to pass the exam. 2. Demonstrate capability in the presence of the appointed site VE expert.	Successfully passing a comprehensive examination is required.	Passing an examination is required because standardized VE operator qualification is used to meet the comparability QAO.
QAO: Precision Precision - The qualitative determinations, such as identifying the summary category group, made during VE do not lend themselves to statistical evaluation of precision because of the qualitative nature of the inspection. Therefore, precision requirements are not established for VE. However, the VE information is subject to the Permittees' Audit and Surveillance Program.	VE provides qualitative data, so a precision is not established. There is no QAO for VE precision in the CH WAP.	N/A
QAO: Accuracy An independent observation will be performed by comparing the contents of a VE data form to the videotape (or equivalent) of the associated examination at the frequency of one per testing batch on once per day, whichever is less frequent. In the case of VE performed by two operators, dual signatures on the data form will verify accuracy in lieu of the independent observation.	Use independent observation or dual signatures for VE to ensure accuracy. There is no QAO for VE accuracy in the CH WAP.	Independent observations or signatures of both operators performing visual examination provide assurance that accuracy is maintained.

Table 5. (cont'd)

Visual Examination		
RH Requirement	**Difference from CH**	**Justification**
QAO: Completeness A videotape (or equivalent) of the VE and an associated complete data form will be obtained for all waste containers subjected to VE. In the case of VE performed by two operators, dual signatures on the data form will verify completeness.	Videotape of the VE of dual signatures on the data form. Data forms must be fully completed. There is no QAO for VE completeness in the CH WAP.	Fully completed data forms and videotapes or dual signatures provide assurance of completeness.
QAO: Comparability The comparability of VE data from different sites shall be enhanced by using standardized VE operator qualifications that comply with this RH WAP.	Standardized training that meets the WAP is required. There is no QAO for VE comparability in the CH WAP.	Using standardized training requirements ensure that comparability is enhanced.
QAO: Representativeness Representativeness for waste selected for VE will be ensured through random container selection.	Require representative sample taken randomly from the population. There is no QAO for VE representativeness in the CH WAP.	Using a representative sample meets the regulatory requirements.

Peer Review Criteria, Findings, and Recommendations of the Review Panel

PEER REVIEW CRITERIA AND FINDINGS

The findings of the RP with respect to the review criteria are as follows:

Criterion 1

Is the draft *RCRA Class 3 Permit Modification* (DOE 2001a) optimized in format and content to facilitate the regulatory review and approval process?

Finding of the RP

The draft *RCRA Class 3 Permit Modification* (DOE 2001a) is optimized in a format to facilitate the regulatory review and approval process. Throughout the document the text has been modified to show the new information added, and there are strike-outs to show the information deleted. The Overview section includes tables showing the regulatory references and their corresponding location in the document. In addition, Table 2 lists all of the sections of the document that have been modified. However, the draft *RCRA Class 3 Permit Modification* (DOE 2001a) is lacking some information that would facilitate the regulatory review and approval process as described in the Findings to several of the Criteria.

Criterion 2

Are the parameters—for which RH-TRU waste will be analyzed—appropriate, and the rationale for the selection of these parameters adequately justified in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a)?

Finding of the RP

The draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) lists the appropriate parameters and attempts to justify the selection of these parameters in the "ITEM 2" section of the document. This section includes the characterization approach, characterization methods, and data reporting and validation requirements. Table 2-1 attempts to justify all of the modifications of CH-TRU parameters to account for RH-TRU. Table 2-2 addresses the differences for Data Quality Objectives (DQOs). Table 2-3 addresses the differences for the Acceptable Knowledge (AK) criteria. Table 2-4 addresses the differences for Radiography, and Table 2-5 addresses the differences for Visual Examination. However, some of the information is presented only as background information and is not referenced in the permit.

Criterion 3

Is the acceptability of relying on AK as the sole analysis tool to meet characterization requirements chosen in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) consistent with relevant regulations as interpreted jointly by the U.S. Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission (USNRC) (1997)?

Finding of the RP

In many cases, reliance on AK as the analysis tool to meet the waste characterization requirements listed in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) as the sole analysis tool can be consistent with the relevant regulations as interpreted by the EPA and the USNRC. There may be cases where AK is not sufficient to meet the regulatory requirements. The WIPP has proposed additional characterization methodologies in a hierarchy of methods to allow for the characterization of all wastes accepted at the WIPP that will meet the DQOs. There will be cases where AK alone is sufficient, but this will be determined on a case-by-case basis depending on the nature of the AK available.

Criterion 4

Is AK alone sufficient to meet the DQOs?

Finding of the RP

In many cases, AK alone will be sufficient to meet the DQOs. Whether or not it is sufficient will be dependent on the nature of the waste and the source and completeness of the data that constitute the AK. For example, AK for waste generated from a chemical conversion process may consist of: 1) material balance and operating data; 2) historical records of the analyses of samples of the waste; and 3) inventory and custody records. Such AK should be sufficient to meet the DQOs. The AK for a drum of scrapped equipment and other waste (not specified) from a decommissioning activity may not provide sufficient information to meet the DQOs.

Criterion 5

Does the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) make a clear distinction between characterization activities using AK versus

supplementary; confirmatory; or verification activities involving physical and other measurements?

Finding of the RP

The draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) makes a distinction between characterization activities using AK versus supplementary, confirmatory, or verification activities involving physical and other measurements. Detailed records exist at the generating sites on many waste forms that will require disposal. Depending on process knowledge and other information sources, AK can be used successfully to fully characterize wastes to meet WIPP acceptance criteria. In some cases the existing information may be insufficient to meet the characterization requirements. When this occurs, supplementary information must be developed by other means. In the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a), several characterization methods—including AK, Radiography, and Visual Examination—are described, as well as their intended use in characterization activities. However, in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a), figures such as R-2 do not provide for the use of other characterization methods should AK be insufficient.

Criterion 6

Is the application of the Performance-Based Measurement System approach consistent with the relevant EPA guidance on performance-based measurement systems?

Finding of the RP

The application of the Performance-Based Measurement System approach meets the EPA's guidance on performance-based measurement systems. The performance-based approach is designed to produce the desired results which eliminate characterization processes that do not produce information used to meet performance requirements. The DOE chose a performance-based approach to meet EPA's guidelines for RH-TRU waste. The characterization objectives for EPA requirements cover metals; residual liquids; cellulosic; plastics and rubber; total radioactivity; and surface dose rate. Baseline calculations for CH-TRU were used for comparisons to determine the relative effects of bounding assumptions regarding characterization data. The performance factors are specified in 40 CFR 191 (EPA 1993) and 40 CFR 194 (EPA 1996a). Section 40 CFR 194.24 (c)(3) of EPA

regulations allows AK and requires the QA standards—as specified in 40 CFR 194.22—to be applied to the process. Furthermore, 40 CFR 194.24 (c)(4) requires a system of controls and packaging of waste components to confirm that the total amount of each waste component falls within the performance limits. It appears that the EPA expects the performance assessment of an RH-TRU package to include uncertainty estimates, and that the actual diverse RH waste steams radionuclide contents be below the estimates.

Criterion 7

Does the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) present an RH-TRU waste characterization program that is consistent with the recommendations of the National Research Council?

Finding of the RP

The draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) presents an RH-TRU waste characterization program that is not consistent in all cases with the recommendations of the National Research Council. The draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) still includes characterization requirements which the National Research Council criticized as being self-imposed and overly conservative. The draft request presents evolutionary steps regarding characterization as site programs evolve.

Criterion 8

Does the *Waste Analysis Plan* (WAP) included in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) meet the requirements for characterizing hazardous waste?

Finding of the RP

The WAP included in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) broadly meets the requirements for characterizing hazardous waste. The RH-TRU waste analysis plan has been prepared for the management, storage, and disposal activities at the WIPP facility, to meet the requirements of the New Mexico Administrative Code (NMED 1997) that incorporates the EPA's 40 CFR 264.13 regulations. However, the WAP, as presented, is not sufficiently detailed and clear on the information that each waste-generating site must supply to the

WIPP—particularly with respect to AK (see also Findings 1 and 2). Guidance concerning the characterization of mixed, hazardous, and radioactive waste has been incorporated into the preparation of the RH WAP. This RH WAP addresses waste stream identification requirements; waste stream parameters; waste characterization and confirmatory methods; data validation; and reporting. Characterization requirements for RH-TRU mixed waste are the same regardless of waste stream designation (i.e., debris, homogeneous solids, soil/gravel) or when the waste was generated (i.e., newly generated versus retrievably stored).

Criterion 9

Does the WAP included in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) contain excessive requirements for characterizing hazardous waste?

Finding of the RP

Although the WAP follows guidance documents for characterizing hazardous waste, DOE has interpreted the requirements quite conservatively such that various proposed characterization methods have no legal or safety basis.

Criterion 10

Is the *Notification of Proposed Change to the EPA 40 CFR Part 194 Certification of the Waste Isolation Pilot Plant* (DOE 2001b) clear and descriptive of the nature and scope of the proposed RH-TRU waste Characterization Program?

Finding of the RP

Section 2.0 "Nature and Scope" of the *Notification of Proposed Change to the EPA 40 CFR Part 194 Certification of the Waste Isolation Pilot Plant* (DOE 2001b) describes the nature and scope of the proposed RH-TRU Waste Characterization Program. Attachment C is a matrix that lists 40 CFR Part 194 requirements and the manner that the RH-TRU program complies with the requirements. Attachment D is a checklist that demonstrates how the RH-TRU program—as compared to the CH-TRU program—complies with the EPA's Compliance Application Guidelines (CAG). All items are completed as suggested by the EPA's CAG. There are no items completed differently than suggested by the CAG, and there are no open items.

Criterion 11

Is the DOE's assessment of the consequences for compliance with EPA disposal regulations clearly and adequately presented in the *Notification of Proposed Change* (DOE 2001b) document?

Finding of the RP

Consistency with EPA disposal regulations is fully demonstrated and documented in resource documents. The performance assessment conducted by Sandia National Laboratory is complete and consistent with EPA regulations in 40 CFR 191 and 40 CFR 194. Also, this conclusion is validated by the recent National Research Council's analysis of disposing RH-TRU at WIPP. The RP fully concurs with the analysis as presented.

Criterion 12

Is the significance of the change in the *Notification of Proposed Change* (DOE 2001b) clearly and adequately addressed?

Finding of the RP

The significance of the change in the *Notification of Proposed Change* (DOE 2001b) is clearly and adequately addressed in section 2.0 "Nature and Scope" and section 3.0 "New Information." Section 2.0 reviews the historical record leading to the need to submit a change to the EPA's WIPP 40 CFR 194 certification to permit the disposal of RH-TRU in the WIPP. It also summarizes the RH-TRU Waste Characterization Program that is discussed in detail in Appendix A "RH-TRU Waste Characterization Implementation Plan." Section 3.0 explains the changes in the DOE's TRU waste characterization program to accommodate RH-TRU.

Criterion 13

Are the consequences for compliance determinations clearly stated in the *Notification of Proposed Change* (DOE 2001b) document and technically justified in the *RH TRU Inventory Impact Assessment Report* (DOE 2001b)?

Finding of the RP

The consequences for compliance determinations are clearly-stated in the *Notification of Proposed Change* (DOE 2001b) document and are technically justified in the *RH TRU Inventory Impact Assessment Report* (DOE 2001b) which is Attachment B of the *Notification of Proposed Change* (DOE 2001b) document. Attachment B demonstrates by analysis that the repository performance of the WIPP would not be compromised even for large deviations from the planned inventories of both radioactive and non-radioactive waste placed in the repository.

Criterion 14

Does the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) present a viable, effective, and efficient performance-based waste characterization program?

Finding of the RP

The *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) presented meets the performance factors of the waste characterization program. Applying knowledge of the characteristics of the waste using available information minimizes additional risk and exposure due to RH-TRU. There is an overall balance in the program activities to characterize RH-TRU waste to the extent possible. The efficiencies are gained by balancing the requirements for providing definitive characterizations data of the waste streams with those circumstances where sampling and analysis are neither feasible nor necessary, given the need for the data. The AK—when used appropriately in combination with NDA/NDE—yields a viable, effective, and efficient performance-based waste characterization program. The *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) provides the sites with considerable latitude in meeting the WIPP-Waste Acceptance Criteria (WAC) requirements; it would be better if WIPP provided definitive requirements for the different sites.

Criterion 15

Does the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) clearly identify and justify the waste components to be characterized?

Finding of the RP

Comprehensive RH-TRU inventory and waste streams were identified, along with a comparison between CH and RH-TRU disposal volume projections. The waste components have been identified and justified in a general sense, but a detailed description of waste streams from the waste-generating sites is lacking. The documents fail to adequately describe the contact and communication among WIPP and the RH-TRU generators.

Criterion 16

Is the associated DQO appropriate for each waste component and consistent with the relevant guidance of the EPA?

Findings of the RP

The documents and the Project Team presentation indicate that the DOE-Carlsbad Field Office has adopted DQOs for metals; liquids; and cellulosic, plastics, and rubber (CPR) materials. The programmatic AK steps outlined in the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) are sufficient to accomplish the DQOs adopted by the DOE-Carlsbad Field Office and can be reasonably relied upon to meet the DQOs for materials received at WIPP. The DQOs are somewhat conservative but they are consistent with the NMED and EPA requirements.

The WIPP-limiting values for radiological components in RH-TRU waste are based on surface-level exposure rates. The methodologies for determining exposure levels are well established, and these levels will be measured and documented for all shipments and disposal containers. These measured values constitute one of the criteria for meeting the DQOs for RH-TRU exposure levels, and therefore, supplement AK.

Criterion 17

Is the reliance on AK as the primary method to meet DQOs and satisfy characterization objectives fully-justified?

Finding of the RP

The acceptability of relying on AK as the primary method in order to: 1) meet the DQOs; and 2) satisfy the characterization objectives, is fully justified for those RH-TRU wastes that have well-documented information regarding their generation and control. The DQOs for the WIPP facility were established using the EPA's Guidance for the DQO's Process (EPA 2000c). Furthermore, the DQOs are identified in the proposed WAP, and they reflect parameters that must be known in order to dispose of waste at the WIPP facility. The DQOs are derived from making a determination of the following waste characteristics: physical form of the waste; absence of prohibited items; and hazardous constituents in the waste. In many cases, the existing documentation would allow these DQOs to be verified with no further characterization efforts required on the part of the waste generator. If the physical form or the absence of prohibited items can not be determined from AK, then other methods (such as radiography) can be used to supplement AK in making a determination that satisfies both the DQOs and the characterization objectives.

Criterion 18

Is the acceptability of relying on AK as the sole method to meet characterization requirements and any DQOs sufficiently explained in relation to the relevant regulations—as interpreted jointly by the EPA and USNRC?

Finding of the RP

The use of AK as a sole method is not sufficiently explained or justified. The AK can be the dominant measure for determining DQOs for RCRA-regulated materials and even for meeting the DQO for radionuclide concentration limits for RH-TRU materials. The explanation of the acceptability of sole reliance on AK represents an apparent inconsistency because as explained in Finding 16 of the RP, meeting the DQOs for RH components at WIPP relies on measured radiation levels for all containers which supplant AK. Therefore, although AK can be a dominant method and sometimes a completely adequate method, it is unlikely to be the sole method.

Criterion 19

Does the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) draw a clear distinction between characterization activities using AK versus supplementary; confirmatory; or verification activities involving physical measurement?

Finding of the RP

The distinction among the characterization activities, AK, supplementary, confirmatory, or verification is inadequate in the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b), and is made particularly confusing by the definitions. All available information about the state of the waste should be used in deciding whether or not the characterization is adequate. It is inefficient to perform additional measurements unnecessarily. The AK is information that has already been obtained (such as process knowledge) before any specific WIPP RH-TRU requirements have been established and sometimes when the waste is already in a container. Supplementary information is used to fill in gaps in the required knowledge. Confirmatory and verification data determine whether the AK is reliable, but the distinction between confirmatory and verification is less clear. There are insufficient examples showing how the required information will be obtained using each of the various methods for each of the major types of waste.

Criterion 20

Does the *Notification of Proposed Change* (DOE 2001b) adequately explain and justify how AK and the WIPP Waste Information System are used to satisfy quantification and control requirements?

Finding of the RP

The *Notification of Proposed Change* (DOE 2001b) adequately explains and justifies how AK and the WIPP Waste Information System (WWIS) are used to satisfy the quantification and control requirements. The WWIS tracking and control system is currently in use in the CH-TRU waste program, and it is operating satisfactorily. To meet additional tracking and control requirements imposed on RH-TRU waste by the Land Withdrawal Act, WWIS will be modified by the addition of data fields. Each waste cannister will be assigned an identification number that will be entered into the WWIS. Characteristics such as curie content and surface dose rates (when the dose equivalent rate exceeds 100 rem/h) will be entered into WWIS to enable tracking and control for that particular container.

Criterion 21

Does the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) adequately describe a Quality Assurance program that meets or exceeds appropriate requirements?

Finding of the RP

In general, the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) describes a Quality Assurance program that addresses the appropriate requirements but lacks sufficient detail. However, to meet the WIPP WAC, the site must develop and implement a quality assurance program that addresses all the applicable requirements specified in the waste analysis plan. Sites may use AK, Radiography, and/or Visual Examination (VE) to assist in the characterization of the waste streams. Qualitative data generated by AK, Radiography, and VE are not amenable to statistical data quality analysis. Rather, these methods provide qualitative data useful for determining the Summary Category Group: EPA Hazardous Waste numbers; and the absence of prohibited items in a waste container. Quality Assurance Objectives (QAOs) complement the DQOs by defining the precision, accuracy, completeness, comparability, and representativeness for each of the characterization methods (AK, Radiography, VE) that may be used. The validation methods are appropriately described and evaluated in Attachment R3 of the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) .

Criterion 22

Does the Plan clearly and adequately explain how the provisions of 40 CFR 194.22 (b) will be utilized in the RH-TRU waste characterization program?

Finding of the RP

Use of the provisions of 40 CFR 194.22 in waste characterization is sufficiently-explained; however, it is important for DOE-CBFO to recognize that additional amplification (similar to that provided to the RP during the peer-review meeting) may be needed. The NMED's earlier limitation of its certification to CH-TRU was clearly based on the information provided which was deemed insufficient for inclusion of RH-TRU in the permit.

Criterion 23

Does the Plan present an RH-TRU waste characterization program that is consistent with recommendations from the National Research Council's Report, *Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant* (2000; 2001)?

Finding of the RP

The RH-TRU waste characterization program is reasonably consistent with the National Research Council's Report, *Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant* (2000; 2001), including its finding of self-imposed requirements that have no legal or safety basis.

Criterion 24

Are the *Request for RCRA Class 3 Permit Modification* (DOE 2001a) and *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) consistent with the ALARA concept?

Finding of the RP

The *Request for RCRA Class 3 Permit Modification* (DOE 2001a) and *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) are consistent with the ALARA concept. However, the reduction of worker exposure—as interpreted by the USNRC Guidance RM-30-2—is by itself not an argument for a modification, nor is it possible to use ALARA to justify repackaging in the interest of repository performance. In the proposed modification, there is no explicit explanation of why the AK-based waste characterization approach is needed to maintain repository integrity and avoid exposures. Reference is made to 40 CFR 194 and a presumption is made that if the requirements of 40 CFR 194 are met, the integrity of the repository will be maintained and such exposures will be ALARA.

Additional Findings of the RP

Finding 25

The AK is the key methodology proposed by the WIPP for characterization of RH-TRU waste. The AK can be most useful. However, its usefulness can be improved by ensuring that the stakeholders achieve a clear understanding of the basis for, and use of AK in a suite of analytical characterization tools.

Finding 26

The communication between the regulated and regulatory communities does not appear to be optimal for the efficient processing of permit modifications. It appears

that there are not sufficient free and full exchanges to keep all parties fully informed of each other's needs and accomplishments. An example of this is the apparent lack of communication regarding the advances in nondestructive testing using radiography to identify the absence of prohibited items.

Finding 27

Although there is a clear statement of the regulatory requirements for the characterization of the waste, there is no statement of the scientific requirements for such characterization upon which the regulatory requirements are based. It would, for example, be useful to know that many safety factors are already included in these requirements before discussing whether or not the requirements can be met. A failure to discuss such matters inevitably results in requirements not justified by safety as decried by the National Research Council's review panel.

Finding 28

Communication between WIPP and the waste-generating sites is not at a level to foster efficient planning and implementation of WIPP WAC.

Finding 29

The draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) has a good basic structure but lacks—in many cases—sufficient details and specificity to facilitate regulatory review.

Finding 30

Audit plans were not provided to the RP.

Finding 31

It is unclear what fraction of the RH-TRU waste has already been containerized or packaged as compared to that which is still to be generated or is stored in bulk.

Finding 32

Significant emphasis is placed on determining EPA's Hazardous Waste Numbers for either listed or characteristic wastes, which in some cases may include organic

compounds. Based on the impact study (Appendix B of the *Notification of Proposed Change* (DOE 2001b), there appears to be no impact on repository performance that depends on this identification.

Finding 33

In keeping with the National Research Council's recommendation to "think smart" good health physics practice and the ALARA philosophy, the efforts to swipe all RH-TRU waste containers is questionable. The containers hold sealed units that have been determined by waste generators and shippers to be "free" of contamination. The commitment to take and analyze six smears—because of the difficulty and complexity of the remote swiping operation—can be a single-point failure in an otherwise straightforward system of waste receipt and emplacement. This approach appears to have evolved from conservative health physics practices used in laboratories and facilities that are relatively clean and quite variable. Records of contamination detected on CH-TRU packages already received could provide a useful baseline of the effectiveness of the waste system in controlling contamination and the degree to which such information has affected WIPP operations. For example, is minimal contamination on one smear (or the absence of a smear result) a basis for not placing an RH-TRU container in the WIPP?

RECOMMENDATIONS

Based on a careful assessment of the information presented to the RP and the findings developed in response to the review criteria, the RP provides the following recommendations:

1. A detailed procedure for determining whether there is sufficient AK available on a waste, should be developed as part of the permit application. This procedure should be consistent across all waste- generating sites.
2. In the final *Request for RCRA Class 3 Permit Modification* (DOE 2001a) a detailed procedure should be provided to go to other characterization methods if AK is found to be insufficient. For example, figures such as Figure R-2 of the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) and the accompanying text, should be reviewed.
3. The DOE should implement the National Research Council's recommendation that review of characterization and packaging requirements continue, especially implementation "... over the entire National TRU Program."

4. The DOE should provide to the EPA a complete inventory of radionuclides and waste forms so that the EPA may verify the repository performance (that WIPP complies with 40 CFR 191 and 40 CFR 194) using its own methods for certification.
5. The DOE should initiate a more appropriate interaction with the EPA and the NMED, not only to determine and meet their respective requirements but also to ensure that the relevant recommendations—such as those by the National Research Council—are evaluated and implemented.
6. Prior to submission, all permit-related documents—in addition to currently planned reviews—should be reviewed in detail for completeness, specificity, and clarity by a team experienced in the permitting process.
7. The *Request for RCRA Class 3 Permit Modification* (DOE 2001a) must be expanded to include more specifics and examples for clarity and completeness.
8. The discussion for Table 1 of the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) should be expanded to justify why sections of the documents require "no action" or "no changes".
9. As part of the permit application, supplemental information should be supplied detailing the waste characterization plans for each waste-generating site and DOE's procedures for determining that these plans meet the WIPP WAC.
10. Detailed audit procedures for WIPP and the waste-generating sites should be provided as part of the permit application.
11. More detail and specificity on WAC using AK, VE, and Radiography (including types of instrumentation to be used) should be provided in the permit application.
12. The DOE should evaluate the necessity of identifying waste streams by the EPA's Hazardous Waste Numbers or Characteristics. If there is no impact on WIPP performance and integrity, the DOE should work with the regulatory agencies to remove this requirement.
13. Whereas it is desirable to preclude contamination and its potential spread, a complete review should be made of what is gained from the remote swiping procedure for "clean" RH-TRU containers and how the information will be used.

Stakeholder Participation

INTRODUCTION

The request for peer review included a consideration for stakeholder participation. Recognizing the significance of the subject, the ASME Peer Review Committee established an ad hoc committee to evaluate possible approaches and procedures for stakeholder participation. The ad hoc committee evaluated a process developed by Love et al. and recommended appropriate revisions. The revised version of that approach was used during this review.

In preparation for stakeholder participation, two guides were prepared: one for the sponsoring agency and the other for stakeholders. In addition, a questionnaire was prepared to evaluate the validity of the approach. After the validity of the process was confirmed in subsequent reviews, Love et al. (2001) published a manual describing the process. One of the key issues advanced by Love et al. was the classification of stakeholders as Personally Impacted, Administratively Impacted, and Generally Concerned Stakeholders. Forms RSI-F-023 and RSI-F-024 in the appendix of this chapter show the guides for the sponsoring agency and the stakeholders respectively. Form RSI-F-025 in the appendix of this chapter is the questionnaire used to seek the views of the stakeholders.

THE PROCESS

Prior to the meeting, the DOE was provided a guidance document (RSI-F-023) containing the definition of stakeholders and certain rules governing participation in a professional society meeting. In addition, the planning of the meeting considered the tradition of all professional societies, indicating that all segments of the meeting—except the executive sessions of the Review Panel—were open to the public. All participants in the peer review meeting were registered and received a name badge. Their registration packets included a summary of the project; peer review criteria; an agenda of the meeting; guidance for stakeholders (RSI-F-024); and a questionnaire (RSI-F-025).

During the introduction, the rules of the stakeholder participation were described. Members of the audience were told that they could ask questions from the speakers

and that they could also make statements during the program designated for that purpose. In every case, the individual who wanted to ask a question or make a statement had to indicate his/her name, affiliation, and the class of stakeholder—if any. Consistent with the peer review process, members of the Review Panel were not introduced to anyone. Review Panel members who wanted to ask questions were instructed to introduce themselves as "I am a panelist". The audience was also asked to fill out the questionnaire (RSI-F-025).

At the end of the meeting, the questionnaires were collected and subsequently evaluated. During the meeting, those who asked questions or made statements appeared to have no difficulties in placing themselves in the correct class.

RESULTS OF THE SURVEY

The respondents overwhelmingly agreed that the definitions of stakeholders as shown in the document provided to them were reasonable. Many respondents complained that the presentations were at a technical level that they could not follow. Even more respondents suggested that the one-to-two weeks notice of the meeting was too short. Most of the other questions were answered positively.

This and similar surveys performed since the initiation of this process suggest that:

1. The classification of stakeholders as Personally Impacted, Administratively Impacted, and Generally Concerned is reasonable.
2. Even those who were opposed to the activity being proposed found the stakeholder participation process as used in the peer review meeting to be fair.
3. Several stakeholders had difficulty assigning their questions or statements to a review criterion and needed help from organizers of the peer review meeting.

Appendix

INSTITUTE FOR REGULATORY SCIENCE STAKEHOLDER PARTICIPATION IN PEER REVIEW MEETINGS

GUIDANCE FOR ORGANIZATIONS REQUESTING STAKEHOLDER PARTICIPATION IN ASME/RSI PEER REVIEW MEETINGS

The American Society of Mechanical Engineers (ASME) and the Institute for Regulatory Science (RSI) have joined forces to provide peer review services to various government agencies. The decision to ask for the participation of stakeholders rests with the agency sponsoring the peer review. When such participation is authorized by the agency, the ASME/RSI team encourages the participation of stakeholders not only as observers, but also as active participants. The details of ASME/RSI peer review may be found at www.NARS.org.

Many federal and state agencies, as well as private industries, desire to include the views of stakeholders in their decision process. This guide is an excerpt from a report which is being prepared by Betty R. Love et al. to assist government agencies and private industry in identifying stakeholders and classifying them in accordance with their respective roles. This guide specifically applies to stakeholder participation in ASME/RSI peer review.

There are three classes of stakeholders as follows:

Personally Impacted Stakeholders: This class consists of individuals whose lives are directly impacted by the action under consideration.

Administratively Impacted Stakeholders: This class consists of elected, appointed, or employed individuals who must ensure that the action under consideration is prepared, reviewed, approved, or implemented in accordance with applicable laws, regulations, permits, licenses, or agreements.

Generally Concerned Stakeholders: This class includes individuals who, by virtue of their personal philosophies, beliefs, or ideologies, are interested in or concerned about the action under consideration.

The participation of stakeholders should be based on the priority placed by the sponsoring organization on the significance of the impact of the decisions to be made on each class of stakeholders. As a general rule, an affirmative outreach is necessary to ensure the participation of personally impacted stakeholders. Experience shows that these stakeholders are reluctant to participate in peer review unless they perceive a significant impact on their daily lives. Accordingly, an affirmative outreach approach is necessary to ensure their participation.

The participation of administratively impacted stakeholders is somewhat less complicated. The mayor of the town; state, federal, and other elected officials representing the locality in which the action under consideration will occur, are desirable stakeholders yet are unlikely to be willing to participate. In contrast, members of agencies responsible for preparation, regulation, and implementation of an action are easier to entice to participate. However, at a minimum, those immediately responsible for the action in these agencies should participate in a well-run program.

The generally concerned stakeholders are normally informed via public media. Their participation is normally determined by the sponsoring agency. As a general rule, they are accommodated after the other two classes are accommodated, and on a first-come first-served basis.

INSTITUTE FOR REGULATORY SCIENCE STAKEHOLDER PARTICIPATION IN PEER REVIEW MEETINGS

GUIDANCE FOR STAKEHOLDERS PARTICIPATING IN ASME/RSI PEER REVIEW MEETINGS

The American Society of Mechanical Engineers (ASME) and the Institute for Regulatory Science (RSI) have joined forces to provide peer review services to various government agencies. The decision to ask for the participation of stakeholders rests with the agency sponsoring the peer review. When such participation is authorized by the agency, the ASME/RSI team encourages the participation of stakeholders not only as observers, but also as active participants. The details of ASME/RSI peer review may be found at www.NARS.org.

The peer review is performed by a Review Panel consisting of individuals whose qualifications for the specific review have been approved by the ASME's Peer Review Committee. All presentations, statements, and discussions are intended to benefit the Review Panel in its deliberations, which result in the *Report of the Review Panel.* There is ample evidence suggesting that participation of stakeholders enhances the outcome of certain activities, notably peer reviews.

All peer review meetings are normally chaired by a representative of the Peer Review Program. All segments of a peer review meeting, except the executive sessions of the Review Panel, are open to the public. Stakeholders can attend these meetings, provided the following criteria are met:

1. Consistent with the tradition of professional societies, all attendees must register. All registered individuals will be provided a name tag, which must be worn while attending the meeting. All registrants will receive a registration package, which includes the list of review criteria provided to the Review Panel. There is no registration fee for these peer review meetings.
2. During the meeting, all attendees may ask questions of the speakers. These questions are limited to clarification of specific issues presented by the speaker.

A segment of the meeting has been slated for comments by stakeholders. Those making statements should be aware that their comments should be directly related to a specific review criterion. General statements that are not related to the review criteria are not considered by the Review Panel and thus, cannot be permitted.

Due to time constraints, lengthy statements should be avoided as there may not be enough time to accommodate all who wish to participate. Therefore, stakeholders designated by the sponsors of the peer review will be provided specific times with a specific duration in the program to state their case. All other stakeholders wishing to make a statement should limit their statements to only a few minutes to allow as many people as possible to make their concerns and questions known during the time allotted for stakeholders' comments.

Members of the Review Panel may ask questions from all speakers, including those asking questions. However, no question may be directed to the members of the Review Panel.

The Chair of the peer review meeting will be responsible for ensuring that the audience adheres to these requirements.

INSTITUTE FOR REGULATORY SCIENCE

ASME Peer Review

Requirements for Disposal of Remote Handled Transuranic Wastes at the Waste Isolation Pilot Plant
July 30 - August 3, 2001 - Carlsbad, NM

QUESTIONNAIRE FOR STAKEHOLDERS

THE PROCESS

1. Was the notification process adequate?
   ❑Yes ❑No Comments_____

2. Were the stakeholders provided sufficient time to identify and describe their concerns?
   ❑Yes ❑No Comments_____

PRESENTATIONS

1. Did presenters explain the sometimes highly technical issues in a language understandable to an audience of knowledgeable non specialists?
   ❑Yes ❑No Comments_____

2. Did presenters explain technical terms in understandable form?
   ❑Yes ❑No Comments_____

3. Did the presentations address the peer review criteria?
   ❑Yes ❑No Comments_____

4. Were the questions from the stakeholders responsive to peer review criteria?
   ❑Yes ❑No Comments_____

5. Were the statements by the stakeholders responsive to peer review criteria?
   ❑Yes ❑No Comments_____

6. Did questions from the Review Panel directly relate to peer review criteria?
❑Yes ❑No Comments_____

_____

_____

LOCAL ARRANGEMENTS:

1. Was registration performed in a professional manner?
❑Yes ❑No Comments_____

_____

_____

2. Was the registration form acceptable?
❑Yes ❑No Comments_____

_____

_____

3. Was the organization of the meeting room acceptable?
❑Yes ❑No Comments_____

_____

_____

4. Were audiovisual arrangements acceptable?
❑Yes ❑No Comments_____

_____

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DEFINITION OF STAKEHOLDERS:

Personally Impacted Stakeholders (PI): This class consists of individuals whose lives are directly impacted by the action under consideration.

Administratively Impacted Stakeholders (AI): This class consists of elected, appointed, or employed individuals who must ensure that the action under consideration is prepared, reviewed, approved, or implemented in accordance with applicable laws, regulations, permits, licenses, or agreements.

Generally Concerned Stakeholders (GC): This class includes individuals who, by virtue of their personal philosophies, beliefs, or ideologies, are interested in or concerned about the action under consideration.

1. Is the definition of various classes of stakeholders as described above reasonable?
❑Yes ❑No Comments_____

_____

_____

_____

2. Please tell us to which class of stakeholders you belong:
❑PI ❑AI ❑GC

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Biographical Summaries

Gary A. Benda* is President of U.S. Energy Corp.—an environmental management firm specializing in radioactive mixed waste management, health physics, decontamination and decommissioning, and technology development. Previously, he was Vice-President, General Manager of the Programs Division for NUKEM Nuclear Technologies, Inc. His responsibilities included developing and maintaining federal programs in North America that specialized in engineering and waste-processing services. Prior to NUKEM, he spent over 17 years with Chem-Nuclear Systems/WMX Technologies in various management roles. He also directed the site investigation, geophysical analysis, site screening, and license application, as well as managed the public hearings and licensing operations associated with local and national regulatory agencies for new low-level waste sites. He has over 20 years of experience in environmental restoration, technology development, and waste management, and has instructed over 20 national and international professional courses on radioactive waste management, mixed waste, and technology development. He is a member of the American Society of Mechanical Engineers (ASME), American Nuclear Society, and Health Physics Society. He has served as Chair of the ASME National Mixed Waste Committee, Environmental Remediation Committee, and Environmental Engineering Division. He has also chaired over 100 technical sessions at numerous national and international conferences on environmental management. He has authored and coauthored various scientific papers, reports, book chapters, and articles on the nuclear environment. Gary Benda is a Certified Health Physicist. He received a B.S. in Health Physics from Oklahoma State University, an M.S. in Applied Nuclear Science from Georgia Institute of Technology, and an M.B.A. from Seattle City University.

Erich W. Bretthauer* is currently President of the Bryce Meadows Development Corporation. He held the position of research professor at the University of Nevada-Las Vegas from January 1993 to March 1995. In that capacity, he served as Executive Director of Nevada Industry, Science Engineering & Technology, a public-private partnership which developed programs to enhance the scientific infrastructure of the state of Nevada. He was Assistant Administrator for Research and Development at the U.S. Environmental Protection Agency (EPA) from March 1990 until January 1993. In that capacity, he managed the Research and Development activities of a large and multi-disciplinary agency. Erich Bretthauer rose through the ranks of the EPA and served in a number of capacities ranging from a bench scientist to policy manager at national and international levels. He directed the EPA's emergency and long-term monitoring program after the accident at Three Mile Island, as well as its bioremediation program in Prince William

Sound after the Valdez oil spill. He also directed the EPA's ecological research program from 1983-1986 and was Director of EPA's Environmental Monitoring Systems Laboratory in Las Vegas from 1986-1990. He is a member of Sigma Xi, the American Chemical Society, the American Association for the Advancement of Science, and the American Water Works Association, and has served on the Federal Advisory Committee to the Civil Engineering Research Foundation. Erich Bretthauer is the author and coauthor of numerous papers, reports, and other publications. He received his B.S. and M.S. in chemistry from the University of Nevada, Reno.

Alan S. Corson is a consultant in hazardous waste issues. He has over 25 years of experience in a number of environmental issues, notably those related to the regulations and management of hazardous waste. Subsequent to his retirement from the U.S. Environmental Protection Agency (EPA), he served in an advisory role to Jacobs Engineering Group and to the Versar Corporation for both government and private sector clients regarding hazardous waste management programs. During his employment at the EPA, he worked at the Office of Solid Waste where he was responsible for regulatory programs and establishing national standards for generators and transporters of hazardous waste; development of sampling and analytic methods for evaluating solid/hazardous waste including the quality assurance/quality control program; and development and management of programs to establish risk assessment of hazardous waste management practices. Alan Corson was instrumental in the development of the original regulatory program defining standards for solid waste and hazardous waste, and setting national standards for recycling hazardous waste. He also initiated, developed, and managed the original program for restricting hazardous wastes from land disposal management options. The framework developed under this program is currently in-place and used for all evaluations in the land-ban program. Alan Corson served as the EPA Office of Solid Waste representative on many intra- and inter-agency workgroups including PCBs, Reportable Quantities, chlorinated solvents, and transportation of hazardous materials. He developed a guide for effective management of infectious wastes—a predecessor to the current regulatory program for medical wastes; characteristics and listings of hazardous waste; and many regulatory options papers for presentation. Alan Corson managed the preparation of numerous regulatory packages for all aspects of the program implementing the Resource Conservation and Recovery Act (RCRA). He has spoken widely and has taught numerous courses on RCRA and its various regulations. He served on numerous national and international panels including review panels of the American

Society of Mechanical Engineers. He received a B.S. in Electrical Engineering and an M.S. in Engineering Management from the Drexel Institute of Technology in Philadelphia, PA.

Ernest L. Daman* is Chairman Emeritus of Foster Wheeler Development Corporation where he previously served as Director of Research and Chairman of the Board. He also held the position of Senior Vice President at the parent company, FWC. He is a Past President of the American Society of Mechanical Engineers (ASME) and was elected to the National Academy of Engineering. Ernest Daman is a Fellow of the Institute of Energy (England) and the American Association for the Advancement of Science, and Past Chairman of the American Association of Engineering Societies. He served on several ASME committees as member or chairman. Ernest Daman is the author of numerous papers and holds 18 patents. He was responsible for the design and development of a combined steam gas turbine plant, fluidized bed combustion, fast breeder reactor components, supercritical steam generators, environmental control processes, and advanced high-efficiency power generation systems. Ernest Daman received his B.M.E. from the Polytechnic Institute of Brooklyn.

Irwin Feller* is Director of the Institute for Policy Research and Evaluation (IPRE) and Professor of Economics at The Pennsylvania State University, where he has been on the faculty since 1963. His current research interests include the economics of academic research, the University's role in technology-based economic development, and the evaluation of federal and state technology programs. He is the author of *Universities and State Governments*: A Study in Policy Analysis, and over 100 refereed journal articles, final research reports, book chapters, reviews, and numerous papers presented to academic, professional, and private organizations. He is former Chair of the Committee on Science, Engineering, and Public Policy, American Association for the Advancement of Science. Irwin Feller was the American Society of Mechanical Engineers Pennsylvania State Fellow in 1996-1997. He has been appointed to the National Academy of Science's Committee on Science, Engineering, and Public Policy, International Benchmarking of U.S. International Competitiveness-Immunology; Transportation Research Board, Research and Technology Coordinating Committee, National Research Council; and National Institute of Standards and Technology-Manufacturing Extension Partnership National Advisory Board. Irwin Feller is Chair of the National Science Foundation's Advisory Committee on Social, Behavioral, and Economic Sciences.

He received a B.B.A. in Economics from the City University of New York and a Ph.D. in Economics from the University of Minnesota.

Robert A. Fjeld* is Dempsey Professor of Environmental Engineering and Science at Clemson University. He coordinates the Department's nuclear environmental focus area, which is concerned with the environmental aspects of nuclear technologies including environmental health physics, radioactive waste management, and risk assessment. Previously, he served as a faculty member in the Nuclear Engineering Department at Texas A&M University. Robert Fjeld is a member of the Health Physics Society, American Nuclear Society, Society for Risk Analysis, and the American Society of Mechanical Engineers, where he serves as newsletter editor for the Mixed Waste Committee. He has served on two National Research Council Committees studying decontamination and decommissioning issues. Robert Fjeld has over 80 technical publications and presentations on topics such as radiation measurements, environmental transport of radionuclides, risk assessment, and aerosol physics. He has active research on actinide transport in soils, instrumentation for measuring radioactivity in environmental samples, and environmental risk assessment. Robert Fjeld received a B.S. from North Carolina State University, and an M.S. and Ph.D. from The Pennsylvania State University. All three degrees are in Nuclear Engineering. He is a registered Professional Engineer.

John T. Greeves* is currently Director of the Division of Waste Management at the U.S. Nuclear Regulatory Commission (USNRC). His experience in the field of nuclear materials management spans 30 years, and includes work in both the private sector and the federal government. Prior to joining the USNRC, he worked for the Bechtel Power Corporation as an engineer responsible for the design and construction of nuclear and conventional power plants. John Greeves has worked for the U.S. government since 1974—with increasing responsibilities in various divisions—including Industrial and Medical Nuclear Safety, and Fuel Cycle Safety and Safeguards. John Greeves has served on a number of national and international panels regarding waste management activities. He is the USNRC's representative to the Waste Safety Standards Advisory Committee of the International Atomic Energy Agency, and has participated extensively in the development of the International Radioactive Waste Management Convention. John Greeves is the recipient of the Presidential Meritorious Rank Award and a member of the

American Society of Civil Engineers. He received a B.S. from the University of Maryland and is a registered Professional Engineer.

William T. Gregory, III* is currently Principal of Vinculum Marketing Solutions. Prior to forming Vinculum, he was Director of Government Programs for Foster Wheeler Environmental Corporation, an engineering and construction firm providing environmental and waste management services to government and private sector clients world-wide. Previously, he held a number of operational and business development positions at equipment manufacturing and service provision firms supporting nuclear utilities, industrial and process industries, and government agencies. His work has involved the management, processing, and disposition of hazardous, radioactive, and mixed wastes. He has also worked on the decontamination and decommissioning of nuclear facilities and on providing a wide range of environmental services in response to regulatory drivers. Prior to entering the private sector, he served with the U.S. Navy on nuclear submarines and at the operational command center for submarine operations in the Atlantic Fleet. William Gregory is actively involved with a number of international, national, and local organizations including: the American Society of Mechanical Engineers (ASME); the American Nuclear Society; and he is a founding member of the Board of Directors for the annual international Waste Management Symposium. William Gregory has served as an elected officer of several ASME divisions. He received a B.S. in Geology from the University of New Mexico, and an M.B.A. from Lamar University. He also attended naval nuclear power, nuclear weapons, and engineering schools as a U.S. Naval officer.

Tom A. Hendrickson is currently an Independent Consultant in the fields of energy, engineering, and technology. His career encompassed service to both government and industry. He was a Senior Executive of Raytheon Federal Engineers & Constructors Company, developing high technology projects which included a privately-financed New Production Reactor; the Accelerator Production of Tritium; and the North Korean nuclear energy program. While working at DOE during the previous Bush Administration, he was Principal Deputy Assistant Secretary of the Office of Nuclear Energy including: Civilian Reactor Development; the Naval Nuclear Propulsion Program; Uranium Enrichment; Space and Defense Power Systems; Isotope Production; and Nuclear Safety Policy. He later became the Director of the New Production Reactors for the DOE, responsible for designing and building new trituim production capacity for nuclear weapons;

research and development; safety and environmental compliance; and construction. Concurrently, he served as acting Under Secretary of Energy responsible for all defense and nuclear energy activities of the department. Early in his career, he served on Admiral H. G. Rickover's staff of the Atomic Energy Commission in Washington, DC. He directed the headquarters staff and contractors involved in submarine nuclear propulsion engineering including: research, development, design, and construction of all new design nuclear powered submarines and land-based prototypes. During this period, he also served as Project Officer for all new submarine developments including the NR-1; the USS Los Angeles SSN-688 class of over 60 attack submarines, and the electric drive submarine. He helped with the development of port-entry safety procedures and sea trials of the United States' first nuclear powered surface ships, the USS Long Beach and the USS Enterprise; as well as the first refueling of the Shippingport Atomic Power Station. He is a member of the following professional organizations: The American Nuclear Society; The American Society of Mechanical Engineers; and The American Physical Society. Tom Hendrickson received a B.A. degree in Physics from Harvard College and an M.S. degree in Physics from Georgetown University. He is a Licensed Professional Engineer.

Nathan H. Hurt* is a consultant in management and engineering with Technical and Management Consulting. He provides services to industrial firms and government agencies involved in environmental clean-up and waste management—both chemical and radioactive. He has extensive experience in the areas of executive management; plant management; engineering management; project management; marketing; and sales. He specializes in the areas of: uranium enrichment/production; engineering; development and marketing; plant management of rubber chemicals; petrochemicals; and thermoplastics. He also specializes in the engineering management of synthetic rubber and lattices; vinyl monomers and copolymers; polyesters; DOE weapons plants; quality assurance management; and operational readiness review. Nathan Hurt has been involved with the decommissioning of nuclear facilities. He was the Corporate Sponsor or Program Manager for seven decommissioning contracts at the DOE Complexes in Oak Ridge, TN; and Pinellas, FL. Previously, Nathan Hurt worked for Sharp and Associates, Inc. as the Director and Project Manager at the Oak Ridge Office. He was Vice President and Director of Oak Ridge Operations for IDM Environmental Corp., where he was responsible for the marketing and sales of decontamination,

decommissioning, and waste management. He served as Project Manager for the laboratory quality assurance program at Westinghouse Hanford; DOE's Rocky Flats Plant—plant-wide identification of electrical equipment. He managed a study for a waste treatment and storage facility at the Portsmouth Area Uranium Enrichment Facility which included incineration and compaction of low-level radioactive wastes. He also worked for The Goodyear Tire and Rubber Company, including Goodyear Atomic, as Director of Research and Development, and President, where he was responsible for the operation of the Portsmouth Area Uranium Enrichment Facility. Nathan Hurt is a past President of, the American Society of Mechanical Engineers. He has been a member of: the American Association of Engineering Societies' Board of Governors; the American Institute of Chemical Engineers; and the Institute of Nuclear Materials Management. He is also a member of Tau Beta Pi Honorary Engineering Society; Pi Tau Sigma Honorary Mechanical Engineering Society; and was a member of The Nuclear Engineering Advisory Board of Worcester Polytechnic Institute. Nathan Hurt received a B.S. degree in Mechanical Engineering from the University of CO and has done Graduate, Technical, and Management course work at Pennsylvania State University. He is a registered professional Engineer in OH.

Michael C. Kirkland is an independent consultant who led a team that performed a Congressionally-mandated External Independent Review of the $1.3 billion Spallation Neutron Source Project at Oak Ridge. He assisted in the planning and review of a management assessment at a U.S. Department of Energy (DOE) Site that involved the restart of a plutonium facility. He participated in planning, procurement, and review activities in the environmental remediation area that included decommissioning activities at a shut down nuclear test reactor; designed and installed a ground water cleanup technology. He also provided design oversight for a new facility related to the DOE weapons complex. During his tenure at Savannah River Site (SRS), Michael Kirkland was a Technical Advisor, Project Manager, and Director of the Project Engineering Division. He evaluated nuclear and mixed waste conditions and aspects of high level wastes and spent nuclear fuel; determined material inventories; performed pollution prevention and environmental health and safety evaluations for a proposed waste treatment facility; served as technical advisor to a study administered by the Savannah River Operations Office; and developed integrated schedules defined for this project. Michael Kirkland was director of the Project Engineering Division and managed the SRS design and construction program. He has been involved with waste management and

environmental projects; cutting edge technology programs; and worked with lasers and magnetic containment. He served as Director of the Waste and Fuel Cycle Technology Office and planned and coordinated the programs of the DOE National High Level Waste Technology Office; the SR Fuel Cycle Technology Program; and the Commercial Interim Spent Fuel Management Program. He planned the initial construction of the Consolidated Incinerator Facility which thermally destroys excess benzene created by the In Tank Precipitation process that was to prepare feed material for the Defense Waste Processing Facility. Michael Kirkland was Director of the Commercial Nuclear Spent Fuel Storage Project Office and managed a contract between DOE and the Barnwell Commercial Nuclear Fuel Reprocessing Facility constructed by Allied General Nuclear Services. Michael Kirkland holds a B.S. in Mechanical Engineering from the University of South Carolina. He is registered as a Professional Engineer in South Carolina.

Peter B. Lederman* is a consultant with over 48 years of experience in all facets of process engineering, environmental management, control, and policy development. This includes hazardous substance management; environmental remediation; environmental audit; pollution prevention; development of air pollution control devices; and reuse of waste products. He recently retired as Executive Director of the Center for Environmental Engineering & Science, Executive Director for Patents and Licensing, and Research Professor of Chemical Engineering and Environmental Policy at the New Jersey Institute of Technology. Peter Lederman managed major programs in industrial waste treatment research and development,and in oil and hazardous material spill control and remediation. Most recently, he was responsible for a study of the Economic Impact of Environmental Regulations. He has been responsible for technology transfer efforts including the maturing and licensing of innovative environmental technologies. He is a Fellow of the American Institute of Chemical Engineers (AIChE); a Diplomat of the American Academy of Environmental Engineers; and a member of the American Society of Mechanical Engineers. He has served on several committees of the National Research Council and is the chair of the NRC Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program. He chaired AIChE's Environmental Division and is currently chair of its Societal Impacts Operating Council. Peter Lederman received a B.S.E., M.S.E., and Ph.D. (All in Chemical Engineering) from the University of Michigan in Ann Arbor, MI and is a registered Professional Engineer.

Betty R. Love is currently Executive Vice President of the Institute for Regulatory Science (RSI). In that capacity, she is responsible for the management of day-to-day operations of RSI, and for administration of several projects with an estimated annual operating budget of $2 million dollars. She is the administrative manager of a large-scale peer review program in collaboration with the American Society of Mechanical Engineers (ASME) for the U.S. Department of Energy (DOE). Her current research activities center around the development and implementation of systematic approach to stakeholder participation, notably in scientific meetings. Previously, Betty Love was Director, Department of Training and Information within Office of Environmental Health and Safety of Temple University in Philadelphia, PA. During that period she was instrumental in the development of a "Handbook of Environmental Health and Safety." She also developed and implemented a large-scale training program not only for the faculty and staff of the University but also for others. Betty Love is currently Managing Editor of *Technology*. She has published several papers in peer-reviewed journals and is the primary author of *Manual for Stakeholder Participation* and *Stakeholder participation in Scientific Meetings*. Betty Love received a B.S. in Business Administration from Virginia State University in Petersburg, VA and an M.S. in Developmental Clinical Psychology from Antioch College in Yellow Springs, OH.

Jeffrey A. Marqusee* is currently the Technical Director of the Strategic Environmental Research and Development Program (SERDP) and the Director of the Environmental Security Technology Certification Program (ESTCP). SERDP is a tri-agency (DoD, DOE and EPA) environmental research and development program managed by the Department of Defense. SERDP supports research and development to solve environmental issues of relevance to DoD in the areas of cleanup, compliance, conservation and pollution prevention. ESTCP is a DoD-wide program designed to demonstrate innovative environmental technologies at DoD facilities. ESTCP provides for rigorous validation of the cost and performance of new environmental technologies in cooperation with the regulatory and end-user communities. Prior to his current position, Jeffrey Marqusee served as a program manager for environmental technology in the Office of the Deputy Under Secretary of Defense for Environmental Security. He was the principal advisor to the Deputy Under Secretary on environmental technology issues. Before joining DoD, he worked at the Institute for Defense Analyses, where he advised both DoD and NASA in the areas of remote sensing, environmental matters and military

surveillance. Jeffrey Marqusee has worked at Stanford University, the University of California and the National Institute of Standards and Technology. He has a Ph.D. from the Massachusetts Institute of Technology in Physical Chemistry.

James E. Martin is currently Associate Professor of Radiological Health at the University of Michigan's Department of Environmental and Industrial Health where he is involved in research and teaching related to radiation protection. His interests include: radiation physics; radiological assessment; radio-analytical measurements; internal radiation dosimetry; radioactive waste management; and radiation protection standards and their regulatory aspects. After a 25-year career with the U.S. Public Health Service and the Environmental Protection Agency, he served as Chief of the Hazardous and Solid Waste Program at the Colorado State Health Department which included consultations with the legislature and EPA. James Martin is Certified in Health Physics by the American Board of Health Physics. He has been involved in numerous scholarly and policy activities including: chair of the Michigan Toxic Substance Control Commission; committee member of the National Research Council on CDC Radiation Studies; member of the EPA's National Advisory Committee on Environmental Protection for Radwaste; member of the Environmental Management Board of the U.S. Department of Energy; Chair of the Committee on Formerly Utilized Sites Remedial Action Program (FUSRAP); member of the Advisory Committee on Nuclear Facility Safety to the Secretary of Energy; and a member of EPA's Science Advisory Board-Radiation Advisory Committee. Professor Martin received the Meritorious Service Award from the U.S. Public Health Service, and has published numerous papers in peer-reviewed journals on radiation measurements, radioactive waste, and radiation protection. He received a B.A. degree in physics from Vanderbilt University in Nashville, TN; an MPH degree in radiological health; and a Ph.D. degree in radiological health from the University of Michigan in Ann Arbor, MI.

A. Alan Moghissi* is currently President of the Institute for Regulatory Science (RSI), a non-profit organization dedicated to the idea that societal decisions must be based on best available scientific information. The activities of the Institute include research, scientific assessment, and science education at all levels—particularly the education of minorities. Previously, Alan Moghissi was Associate Vice President for Environmental Health and Safety at Temple University in Philadelphia, PA and Assistant Vice President for Environmental Health and

Safety the University of Maryland at Baltimore. In both positions, he established an environmental health and safety program and resolved a number of relevant existing problems in those institutions. As a charter member of the U.S. Environmental Protection Agency (EPA), he served in a number of capacities, including Director of the Bioenvironmental/Radiological Research Division; Principal Science Advisor for Radiation and Hazardous Materials; and Manager of the Health and Environmental Risk Analysis Program. Alan Moghissi has been affiliated with a number of universities. He was a visiting professor at Georgia Tech and the University of Virginia, and was also affiliated with the University of Nevada and the Catholic University of America. Alan Moghissi's research has dealt with diverse subjects ranging from measurement of pollutants to biological effects of environmental agents. A major segment of his research has been on scientific information upon which laws, regulations, and judicial decisions are based—notably risk assessment. He has published nearly 400 papers, including several books. He is the Editor-in-Chief of *Technology: A Journal of Science Serving Legislative, Regulatory*, and *Judicial Systems*, which traces its roots to the *Journal of the Franklin Institute*—one of America's oldest continuously published journals of science and technology. Alan Moghissi is a member of the editorial board of several other scientific journals and is active in a number of civic, academic, and scientific organizations. He has served on a number of national and international committees and panels. He is a member of a number of professional societies including the American Society of Mechanical Engineers and is past chair of its Environmental Engineering Division. He is also an academic councilor of the Russian Academy of Engineering. Alan Moghissi received his education at the University of Zurich, Switzerland, and Technical University of Karlsruhe in Germany, where he received a doctorate degree in physical chemistry.

Lawrence C. Mohr, Jr.* is currently Professor of Medicine, Biometry, and Epidemiology; and Director of the Environmental Biosciences Program at the Medical University of South Carolina. His areas of research and special interest include internal medicine and pulmonary disease—specifically diseases of the chest and respiratory system. An area of particular interest to Lawrence Mohr is environmental medicine, including molecular epidemiology and biomarker applications. He has been involved in studies related to environmental lung disease; pathophysiology; prevention and treatment of high altitude illness; high altitude physiology; risk assessment of environmental hazards and clinical epidemiology.

Other areas of considerate interest to Lawrence Mohr are assessment of clinical outcomes; health policy analysis; and international health. This latter area includes: global epidemiology; medical relief operations; and health care in Central and Eastern Europe, as well as medical history—the impact of illness on world leaders. Previously, he held academic appointments as a Teaching Fellow in Medicine at the Uniformed Services University of the Health Sciences in Bethesda, MD. He was Associate Clinical Professor of Medicine and Emergency Medicine at George Washington University, Washington, DC. While in these institutions, he was a staff member of the Medical Support Group for the President of the United States. Lawrence Mohr was on the Medical Staff of Walter Reed Army Medical Center—where he completed his Internship and Residency in Internal Medicine—as well as George Washington University Hospital, both in Washington, DC. He has held Visiting Professorships at various universities. He served as Visiting Chief Resident at Presbyterian Hospital and Visiting Professor at the School of Nursing, both at Columbia University. Additionally, Lawrence Mohr was Visiting Professor of: William Beaumont Army Medical Center, Tulane University, University of Cincinnati, New York University, Brown University, East Carolina University, and the Mayo Clinic. Lawrence Mohr is a Fellow of the American College of Physicians and the American College of Chest Physicians. He is a member of several professional societies including: the American Federation for Medical Research; the Society for Risk Analysis; and the Wilderness Medical Society. Previously, he was on the Scientific Advisory Board for the Consortium in Environmental Risk Evaluation and the Savannah River Health Information System. He has authored or coauthored more than 60 articles, books, or technical publications. He received an A.B. degree in Chemistry as well as an M.D. degree, both from the University of North Carolina, Chapel Hill. Lawrence Mohr, Jr., is certified by the American Board of Internal Medicine.

Goetz K. Oertel* is President Emeritus and former CEO of the Association of Universities for Research in Astronomy, Inc. (AURA). AURA is a $150 Million per year non-profit corporation that operates the Hubble Space Telescope Science Institute and ground-based astronomical observatories around the world and is building international Gemini 8-meter telescopes in Hawaii and in Chile. Previously, he was a Senior Executive in the U.S. Department of Energy. Assignments included Deputy Assistant Secretary for Safety, Health, and Quality Assurance; Deputy Manager of the Albuquerque Operations Office; Deputy and

Acting Manager of the Savannah River Operations Office; and Director of the Office of Byproducts and Waste Management in Defense Programs in Washington. Previously, he was Chief of Solar Physics and manager of several space science programs in NASA Headquarters—and before that—aerospace engineer and group leader at NASA's Langley Research Center. He held career development positions with the President's Science Advisor and in the Office of Management and Budget in the Executive Office of the President. He authored numerous publications in science and engineering and holds patents. He has served on and chaired professional committees in engineering and other sciences—including a committee of the National Research Council. He is the U.S. representative to the Commission on DATA (CODATA) at the International Council of Scientific Unions and serves on several non-profit Boards in Education and science. He is a fellow of the American Association for the Advancement of Science and member of numerous national and international professional organizations. He graduated from the University of Kiel, Germany with major in physics and minors in chemistry and mathematics. As a Fulbright grantee, he earned a Ph.D. in physics from the University of Maryland in College Park.

Sorin R. Straja is currently Vice President for Science and Technology of the Institute for Regulatory Science. He has over 20 years of expertise in mathematical modeling and software development as applied in chemical engineering and risk assessment. Previously he served as Assistant Professor of Biostatistics with Temple University, Philadelphia; as Director of the Department of Occupational Health and Safety of Temple University, Philadelphia; and as a chemist with University of Maryland at Baltimore. Sorin Straja has extensive experience in the chemical industry where he worked as a senior R&D consultant with the Chemical and Biochemical Energetics Institute, and as a plant manager with Chemicals Enterprise Dudesti and Plastics Processing Bucharest from Romania. He was an Assistant/Adjunct Professor of Chemical Engineering with the Polytechnic Institute Bucharest. Sorin Straja is the author of two books and 44 scientific papers published in internationally recognized and peer reviewed journals. He was an editor of *Environment International,* and currently is a contributing editor of *Technology.* Sorin Straja received a Certificate of Appreciation for Teaching from Temple University, the "Nicolae Teclu" Prize of the Romanian Academy, and a Certificate of Appreciation from U.S. Department of Agriculture for significant volunteer contributions. He is a Fellow of the Global Association of Risk Professionals, and a member of the American Chemical Society, American Institute

of Chemical Engineers, Society for Risk Analysis, and New York Academy of Sciences. Sorin Straja holds a M.S. in Industrial Chemistry and a Ph.D. in Chemical Engineering both from Polytechnic Institute Bucharest.

Glenn W. Suter* is currently Science Advisor at the National Center for Environmental Assessment of the U.S. Environmental Protection Agency (EPA) in Cincinnati, OH. Previous to his current position, he was at Oak Ridge National Laboratory, initially as Research Associate and gradually rising to Science Leader at the Environment Science Division of the Laboratory. His interest has focused on Ecotoxicology in general and Ecological Risk Assessment in particular. He is one of the developers of the most widely-used methodology for Ecological Risk Assessment. This method has been applied to the impact of pollutants on fish, contaminated soils, production of synthetic fuels, and various other ecosystems. Glenn Suter has lectured widely, both nationally and internationally on Ecological Risk Assessment. He is currently a member of the U.S. EPA's Risk Assessment Forum. He has been a member of numerous panels and has consulted with various governmental agencies and private organizations, including the Council of Environmental Quality. He was a member of the Scientific Review Panel for Savannah River Ecology Laboratory; the National Science Foundation Panel on Decision Making and Valuation for Environmental Policy; and the U.S. EPA Science Advisory Board and Conservation Foundation, Ecosystem Valuation Forum. In addition, he was a member of the International Institute of Applied Systems Analysis Task Force on Risk and Policy Analysis and the Council on Environmental Quality. He was a member of the Board of Directors, for the Society for Environmental Toxicology and Chemistry. Glenn Suter is presently on the Editorial Board of *Environmental Health Perspectives* and *Human and Ecological Risk Assessment.* Previously, he was on the Editorial Board of *Handbook of Environmental Risk Assessment and Management* and *Environmental Toxicology and Chemistry.* Glenn Suter is the author of three books and is author and coauthor of over 200 publications. He received a B.S. degree in Biology from Virginia Polytechnic Institute and a Ph.D. in Ecology from the University of California, Davis.

Wade O. Troxell is President/Chief Operating Officer and Founder of Sixth Dimension, Inc., a development stage company offering Internet-based products to the electric power industry. He is currently on a leave-of-absence as Associate Professor of Mechanical Engineering at Colorado State University (CSU); and Director of Robotics and Autonomous Machines Laboratory at CSU. His research

interests consist of product realization processes; design support systems; and behavior-based robots (task-structured approach to building robust and reliable autonomous intelligent systems). His research interests also include robot programming and control (high-level formalisms, complexity measures, and verification). His professional experience is extensive and includes his positions as: Executive Director of the U.S. National Institute of Standards and Technology (NIST)/Mid-America Manufacturing Technology Center, Colorado Regional Office; Director of the Manufacturing Excellence Center at CSU; and Assistant Professor of Mechanical Engineering at CSU. He was also a Director of the Manufacturing and Robotic Systems Laboratory, Mechanical Engineering at CSU; Robotic Consultant to the Public Service Company of Colorado, Nuclear Engineering Division (Fort St. Vrain Station on the controller retrofit of the fuel handling robot); and NATO Postdoctoral Fellow at the University of Edinburgh in the Department of Artificial Intelligence. He was a Consultant, specializing in product design and process automation; a Mechanical Engineer for the Eastman Kodak Company; and a Consulting Bioengineer with Staodynamics, Inc. He has provided services as an expert witness related to legal cases involving trade secrets, patent infringements, and product liability. Wade Troxell is currently Advisor to the Senior Vice President of the ASME Council of Member Affairs. He serves on the ASME Inter-Council Committee for Federal R&D; the ASME/NIST Interaction Committee; and is the Chair of the ASME Distinguished Lecturers' Program. In addition, he served as the ASME Vice President for Region XII (Rocky Mountains), and serves as Chair of the Mechanical Engineering MS Program for the National Technological University. He serves on the Board of Directors for Sixth Dimension, Inc, and is Advisor to the Board of Directors for the Boulder Technology Incubator. He is the recipient of the ASME Dedicated Service Award. Wade Troxell is a member of Tau Beta Pi. He is the author or coauthor of over 50 refereed publications, technical reports, and conference proceedings. Wade Troxell received a B.S. degree in Engineering Science, an M.S. degree, and a Ph.D. degree in Mechanical Engineering, all from CSU.

Charles O. Velzy* is a consultant in the field of waste treatment and disposal. Previously, he held increasingly responsible positions with the environmental consulting engineering firm, Charles R. Velzy Associates, Inc., becoming president in 1976. In 1987, when Velzy Associates merged with Roy F. Weston, Inc., Charles Velzy became Vice President of Weston, a position which he held until retiring in 1992. He has over 35 years of experience as an environmental engineering consultant specializing in: the analysis of waste management problems; design of

wastewater treatment and waste disposal systems; and design of new, retrofit of existing, testing, and permitting of waste combustion facilities. He has authored or co-authored over 80 publications—primarily in the field of solid waste management. He has served on the Science Advisory Board of the U.S. Environmental Protection Agency; as President of the American Society of Mechanical Engineers (ASME); and as Treasurer of the American Academy of Environmental Engineers (AAEE). He has served on numerous committees of the ASME, the AAEE, the American National Standards Institute, and the American Society for Testing and Materials. He is a registered professional engineer in New York and eleven other states. Charles Velzy received B.S. degrees in Mechanical and Civil Engineering, and an M.S. in Sanitary Engineering from the University of Illinois at Urbana-Champaign.

Richard Wilson is currently emeritus Mallinckrodt Research Professor of Physics at Harvard University in Cambridge, MA. He is also an affiliate of the Center for Middle Eastern Studies; the Harvard Center for Risk Analysis; and of the Program on Science and International affairs at the Kennedy School of Government. He used the principle of detailed balance to measure the spin of the pi-zero meson and studied nucleon-nucleon scattering at the Harvard Cyclotron Laboratory. He was involved in converting the Harvard University Cyclotron from nuclear physics use to medical treatment. He was the first to analyze elastic scattering data in terms of the electric and magnetic form factors. He studied nucleon structure by electron-proton scattering and muon proton scattering. He was a participant in the Cambridge Electron Accelerator "by-pass" program, which demonstrated an unusually large cross-section for producing hadrons. Richard Wilson closely followed the Russian and Ukrainian radiation accidents at Chernobyl in the Ukraine, and the accidents at the Techa River and the Mayak production complex in the Ural Mountains. He performed research on the risk assessment of chemical carcinogens. Richard Wilson is Chairman of the visiting committee of the radiation medicine department at Massachusetts General Hospital. He is Chairman of an International Advisory Committee to the newly formed Sakharov College of Radioecology in Minsk, Belarus, and serves as a member of the Board of Directors of the Andrey Sakhorov Foundation of New York and Moscow. He was the first Chairman of the Harvard Cyclotron Operating Committee and is still a member. He is a Fellow of the American Physical Society, Chaired its committee to study the radiological consequences of severe nuclear power accidents, and received its

"Forum Award". Richard Wilson chaired an advisory committee for the Minister of Economic Affairs of the Republic of China. He is a founder/member of the Society of Risk Analysis, as well as the recipient of its Distinguished Service Award. He is a member of the American Nuclear Society and the Society of Toxicology. He served as the Director of the NE Regional Center of the National Institute of Global Environmental Change. He has held various positions as a Visiting Professor, Scholar, and Scientist and served on numerous government advisory committees in many different agencies and countries. Richard Wilson is the author or coauthor of more than 800 published papers. He is the editor of the English translation of the Russian Journal, *Radiation and Risk,* which is published by the Russian Medical Research Laboratory in Obninsk and is mainly about the effects of Chernobyl. Richard Wilson holds a B.A. degree; an M.A. degree and a Ph.D. degree; all in Physics and all from Christ Church, Oxford University, Oxford, England.

* Members of ASME Peer Review Committee

List of Acronyms

AK	Acceptable Knowledge
ALARA	As Low As Reasonably Achievable
ASME	American Society of Mechanical Engineers
CAG	Compliance Application Guidelines
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CERCLA	Comprehensive Environmental Response Compensation and Recovery Act
CFR	Code of Federal Regulations
CH	Contact-Handled
CPR	Cellulosic, Plastic, and Rubber
DOE	U. S. Department of Energy
DOT	U. S. Department of Transportation
DQA	Data Quality Objective
EIS	Environmental Impact Statement
EP	Executive Panel
EPA	U. S. Environmental Protection Agency
FEIS	Final Environmental Impact Statement
FTIRS	Fourier Transform Infrared System
GC	Gas Chromathography
HPLC	High Pressure Liquid Chromatography
HWFP	Hazardous Waste Facility Permit
LWA	Land Withdrawal Act
MS	Mass Spectrometry
NDA	Non-Destructive Assay
NDE	Nondestructive Evaluation
NEPA	National Environmental Policy Act
NMAC	New Mexico Administrative Code
NMED	New Mexico Environmental Department
NQA	Nuclear Quality Assurance
NRC	National Research Council
NUREG	Nuclear Regulatory Guidelines
OST	Office of Science and Technology
PA	Performance Assessment
PAN	Passive/Active Neutron
PBMS	Performance-Based Measurement System
PCB	Polychlorinated Biphenyl
PRC	Peer Review Committee (of ASME)
PREPP	Process Experimental Pilot Plant

QA	Quality Assurance
QAO	Quality Assurance Objective
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
RH	Remote-Handled
RP	Review Panel
RSI	Institute for Regulatory Science
SEIS	Supplemental Environmental Impact Statement
SGS	Segmented Gamma Scans
SPC	Statistical Process Control
SWB	Standard Waste Box
TDOP	Ten-Drum Overpack
TIC	Tentatively Identified Compound
TRU	Transuranic
TRUDOCK	Waste handling area of WIPP
TRUPACT-II	Transuranic Package Transporter, Model 2
TSDF	Permit Treatment, Storage and Disposal Facility
TSDF-WAC	Permit Treatment, Storage and Disposal Facility Waste Acceptance Criteria
UCL	Upper Confidence Limit
USNRC	U. S. Nuclear Regulatory Commission
VE	Visual Examination
VOC	Volatile Organic Compound
WAC	Waste Acceptance Criteria
WAP	Waste Analysis Plan
WHB	Waste Handling Building
WIPP	Waste Isolation Pilot Plant
WSPF	Waste Stream Profile Form
WWIS	WIPP Waste Information System

Report of the Review Panel

Desirability of performing certain transuranic waste characterization tests

Institute for Regulatory Science

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Preface

This report contains the results of an independent peer review performed by the Institute for Regulatory Science (RSI). Based on a request from Bob Forrest, Mayor of Carlsbad, NM, a Review Panel (RP) was established to independently review the desirability of eliminating certain tests performed for characterization of hazardous waste constituents of transuranic waste. This request was precipitated by an anticipated action of the U.S. Senate mandating the elimination of these tests.

Most of the activities performed by RSI are in cooperation with certain professional societies. Consequently, detailed policies and procedures have been developed and implemented for performing independent peer review and assessment studies. The process requires the formation of a group consisting of individuals with appropriate education, experience, and peer recognition, that oversees the process. Consistent with these requirements, a Commission on Assessments and Reviews (CAR) has been formed. One of the primary tasks of CAR is to approve the qualifications of members of the RP for a specific peer review or assessment and ensure implementation of policies related to conflict of interest.

The members of the CAR are as follows:

Melvin W. Carter, Chair
Erich W. Bretthauer
Ernest L. Daman
Nathan H. Hurt
Peter Maggiore
Lawrence C. Mohr, Jr.
John E. Moore
Goetz K. Oertel
Harold W. Olsen
Charles O. Velzy
Roger P. Whitfield
Richard Wilson

The Principal Technical Secretary of the Peer Review Program at RSI prepared a list of potential members of the RP and provided it to the CAR for review and approval. This list was modified based on the comments of the CAR. Members of the RP approved by the CAR are as follows:

Goetz K. Oertel, Chair
Bruce M. Thomson, Vice Chair
Alan S. Corson
Robert E. Luna
Fritz A. Seiler

In addition, Peter Maggiore was a consultant to the Panel. The supporting staff of the assessment study for this report are as follows:

Betty R. Love: Executive Vice President, RSI; and Administrative Manager of the Peer Review Program.

Sorin R. Straja: Vice President for Science and Technology, RSI; and Principal Technical Secretary.

Michael C. Kirkland: Vice President Southeast Office, RSI, Aiken, SC.

Wren Prather-Stroud: Manager Western Office, RSI, Carlsbad, NM.

Sharon Jones: Director of Training Programs, RSI; Manager of Review Panel Operations.

The biographical summaries of the members of the RP, the CAR, and the technical staff are located at the end of this report.

The letter from Mayor Forrest (see Appendix 1) included three specific questions (review criteria) which were provided to the RP. The Mayor also asked for the principal conclusions of the RP to be available within a rather short time period. Consistent with RSI policy, the RP was instructed to limit its findings and recommendations to technical issues and avoid social; political; and other non-technical considerations.

In preparation for the review, the RSI staff undertook a concerted effort to gather relevant information from a variety of sources as quickly as possible. Primary sources of information included two reports of the National Research Council (NRC 2001, 2002), the research arm of the National Academy of Sciences; the National Academy of Engineering; and the Institute of Medicine. Dr. Matthew Silva, Director of Environmental Evaluation Group, was asked to provide relevant publications.

Several parts of this *Report of the Review Panel* were prepared by the staff of RSI. The *Process for Independent Peer Review and Independent Technical Assessment* describes various aspects of the process used to produce this report. The two subsequent sections—*Waste Isolation Pilot Plant Facility* and *RCRA Waste Characterization*—were prepared by the staff of RSI from peer-reviewed literature. The two other sections—*Legal Requirements* and the text of *U.S. Senate Report and Bill S. 1424*—are reproduced from official documents. Biographical summaries of participants in this peer review were prepared by the staff of RSI and approved by the relevant individuals.

Based on the desire of Mayor Forrest, the RP provided its principal conclusions in a letter (Appendix 2). Subsequently, the *Report of the Review Panel* was completed by the RP and underwent the customary copy editing.

This peer review was performed as a public service with no external funding. The completion of this report could not have been possible without the support of a number of individuals. We greatly appreciate the contribution of members of the CAR and the RP during various phases of preparation of this report.

Goetz Oertel, Chair of the Review Panel
A. Alan Moghissi, President, RSI

Appendix 1

CARLSBAD

Post Office Box 1569
Carlsbad, NM 88221-1569
(505) 887-1191
1-800-658-2713

BOB FORREST
Mayor

JON R. TULLY
City Administrator

August 12, 2003

A. Alan Moghissi, Ph.D.
President, Institute for Regulatory Science
5457 Twin Knolls Road, Suite 200
Columbia, MD 21045

Dear Dr. Moghissi:

This letter is to confirm our recent discussion of an issue of prime importance to the remediation of the nation's transuranic waste sites. I hereby request that the institute for Regulatory Science perform an independent peer review based on the following criteria:

1. Is the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S.1424 supported by the recommendations of the National Research Council Report "Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant?"

2. Is the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S.1424 supported by various statements and other publications of the New Mexico Environmental Evaluation Group?

3. Based on the information presented to the Review Panel, is the permit modification listed under Section 310 of U.S. Senate Bill 1424 technically defensible?

COUNCILORS

Ward 1	Ward 2	Ward 3	Ward 4
JIMMIE S. CISNEROS	MANUEL C. ANAYA, JR.	H. CALVIN BOWDITCH	LARRY HENDERSON
PAUL C. AGUILAR	JEFF DIAMOND	JUDI WATERS	ROBERT C. MURRAY II

Since time is of the essence, I would appreciate receiving the principal conclusions of the Review Panel no later than August 22, 2003. The full report could follow at a later date.

Sincerely,

Bob Forrest,
Mayor of Carlsbad, New Mexico

Appendix 2

RSI
Institute For Regulatory Science
5457 Twin Knolls Road, Suite 200, Columbia, MD 21045 USA
Phone: 301-596-1700 Fax: 301-596-1707

August 22, 2003

The Honorable Bob Forrest
Mayor of Carlsbad, NM
P.O. Box 1569
Carlsbad, NM 88221

Dear Mayor Forrest:

Thank you for your letter dated August 12, 2003 confirming our verbal agreement on a peer review to be performed by the Institute for Regulatory Science (RSI). In accordance with your request, RSI sought the assistance of the Commission on Assessment and Reviews (CAR) whose membership consists of 12 highly qualified and distinguished individuals. The biographical summaries of the members of the CAR appear in "*Assessment of Desirability of the Formation of a Center of Excellence on Hazardous Materials Management in Carlsbad, New Mexico.*" Through the efforts of the CAR, a Review Panel (RP) was formed consisting of the following individuals:

Goetz K. Oertel, Ph.D., Chair
Bruce M. Thomson, Ph.D., Vice Chair
Alan S. Corson
Robert E. Luna, Ph.D.
Fritz A. Seiler, Ph.D.

Additionally, Peter Maggiore served as a consultant to the RP.

Enclosed are the principal conclusions of the RP. The *Report of the Review Panel* will be made available to you as soon as it is completed.

Enclosed also for your information are the biographical summaries of the members of the RP and the consultant.

Sincerely,

A. Alan Moghissi, Ph.D.
President

AAM:brl

Enclosures

DESIRABILITY OF PERFORMING CERTAIN TRANSURANIC CHARACTERIZATION TESTS

PRINCIPAL CONCLUSIONS OF THE REVIEW PANEL

The Review Panel (RP) was asked to respond to three review criteria identified by the Mayor of Carlsbad, NM. During its deliberations, the RP limited its responses to the review criteria entirely to scientific and engineering issues and specifically avoided political, societal, and other non-technical considerations.

The RP reviewed the report *Improving operations and long-term safety of the Waste Isolation Pilot Plant* of the National Research Council (NRC)—the research arm of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine. In addition, the RP reviewed a number of documents published by the Environmental Evaluation Group (EEG). The RP has concluded its deliberations, and its report is being copyedited. The RP will review the final draft shortly.

The principal conclusions of the RP are as follows:

1. Based on careful evaluation of the NRC report, the RP concludes that the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S.1424 is supported by the NRC.

2. It appears that EEG agrees that the current characterization requirements are excessive. It appears that EEG also agrees that monitoring VOCs in underground disposal rooms is sufficient.

3. Based on the information presented to the RP, the permit modification listed under Section 310 of U.S. Senate Bill 1424 is technically defensible. There is no reason to perform waste confirmation tests that: 1) provide insignificant health and safety benefits to the U.S. population;

and 2) pose serious radiological and occupational health and safety risks for the workers performing these tests.

The RP recommends that the Mayor of Carlsbad make available its report to the U.S. Senate Committee for Energy and Water.

Goetz K. Oertel, Ph.D.
Chair of the Review Panel

8-22-2003
Date

Executive Summary

This report contains the results of an independent peer review performed by the Institute for Regulatory Science (RSI) responding to a request from Bob Forrest, Mayor of Carlsbad, NM to critically review a claim included in a Senate Committee report. The Senate language indicated that the National Academy of Sciences and the Environmental Evaluation Group (EEG) had endorsed the elimination of certain tests currently performed to characterize hazardous waste constituents of transuranic (TRU) waste for disposal at the Waste Isolation Pilot Plant (WIPP). Consistent with the tradition of professional societies, RSI relied upon the Commission on Assessments and Reviews (CAR), a group of individuals with appropriate education, experience, and peer recognition, to oversee the assessment process. The CAR approved the qualifications of members of the Review Panel (RP) to evaluate the desirability of eliminating certain tests performed for characterization of hazardous waste constituents of TRU waste. Consistent with the RSI policy, the RP was instructed to limit its findings and recommendations to technical issues and avoid social, political, and other non-technical considerations.

The RP reviewed two relevant reports of the National Research Council (NRC 2001, 2002)—the research arm of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine. In addition, the RP reviewed a number of documents published by the EEG, an independent group associated with New Mexico Institute of Mining and Technology.

As the principal facility for disposal of the nation's TRU waste generated as a result of nuclear weapons research, development, and production, WIPP must comply with relevant requirements of the U.S. Environmental Protection Agency (EPA) and New Mexico Environmental Department. Whereas the EPA regulates certain aspects of the radioactivity content of TRU waste, the New Mexico Environment Department regulates the hazardous waste constituents of TRU waste. In addition, WIPP must comply with relevant transportation regulations. Compliance with these requirements is based on certain characterization tests. In general, waste characterization activities include the following, although not all of these techniques are used on each container:

1. Radiography, which is an x-ray technique to determine physical contents of containers
2. Visual examination of opened containers as an alternative way to determine their physical contents or to verify radiography results
3. Headspace-gas sampling to determine volatile organic compounds (VOCs) content of gases in the void volume of the containers
4. Sampling and analysis of waste forms that are homogeneous and can be representatively sampled to determine concentrations of hazardous waste constituents and toxicity-characteristic contaminants of waste in containers
5. Compilation of acceptable knowledge (AK) documentation into an auditable record, including process knowledge and prior sampling and analysis data
6. Non-destructive assay, typically segmented gamma scans and passive/active neutron interrogation, to quantify radionuclides.

Confirmation that the waste complies with the requirement that it is not ignitable, corrosive, or reactive is accomplished by AK or appropriate tests.

The U.S. Senate Bill S.1424 states that waste confirmation for all waste received for storage and disposal be limited to:

1. confirmation that the waste contains no ignitable, corrosive, or reactive waste through the use of either radiography or visual examination of a statistically representative subpopulation of the waste; and

2. review of the Waste Stream Profile Form to verify that the waste contains no ignitable, corrosive, or reactive waste and that assigned Environmental Protection Agency hazardous waste numbers are allowed for storage and disposal by the WIPP Hazardous Waste Facility Permit.

Furthermore, the U.S. Senate Bill S.1424 states that compliance with the disposal room performance standards of the Waste Analysis Plan shall be demonstrated exclusively by monitoring airborne volatile organic compounds in underground disposal rooms in which waste has been emplaced until panel closure.

The Review Panel (RP) was asked to respond to three review criteria identified by the Mayor of Carlsbad, NM. During its deliberations, the RP limited its responses to the review criteria entirely to scientific and engineering issues and specifically avoided political, societal, and other non-technical considerations.

After careful review of documents provided to the RP and appropriate deliberations, the RP provided three Findings and one Recommendation. The principal conclusions of the RP are as follows:

1. Based on careful evaluation of the two relevant NRC reports, the RP concludes that the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S.1424 is supported by the NRC.

2. It appears that EEG agrees that the current characterization requirements are excessive. It appears that EEG also agrees that monitoring VOCs in underground disposal rooms is sufficient.

3. Based on the information presented to the RP, the permit modification listed under Section 310 of U.S. Senate Bill 1424 is technically defensible. There is no reason to perform waste confirmation tests that: 1) provide insignificant health and safety benefits to the U.S. population; and 2) pose serious radiological and occupational health and safety risks for the workers performing these tests.

The RP recommends that the Mayor of Carlsbad make available its report to the U.S. Senate Committee for Energy and Water.

Peer Review Process

INTRODUCTION

There is a large degree of consensus within the technical community on basic criteria for acceptability of scientific information. However, the implementation of these criteria requires a reasonably detailed process for identification of the status of scientific information and for the establishment of reliability of the information regardless of its status.

The formation of the Institute for Regulatory Science (RSI) was based on the notion that societal decisions must be based on best available science (BAS). The implementation of the BAS concept required a systematic evaluation of various aspects of scientific information. Consequently, a hierarchy of scientific information and classification of scientific information was developed.

CLASSIFICATION OF SCIENTIFIC INFORMATION

The scientific information was classified into six categories as follows (Moghissi 1996):

Category Ia - Scientific Laws: This class consists of information that is clearly and unambiguously accepted by the scientific and engineering community.

Category Ib - Applied Science: This class consists of application of scientific laws to specific areas. Much of the engineering and many other areas of applied sciences such as industry and commerce fall into this class.

Category IIa - Extrapolated Science: Much of the contested areas of science falls into this class. This category is based on extrapolation of scientific laws beyond their accepted applicability.

Category IIb - Technical Judgement: In many cases, little or no scientific or engineering information is available and the decision maker must rely upon the judgement of qualified individuals.

Category IIIa - Speculation: This class is information that is based on speculation.

Category IIIb - Pseudo Science: Sometimes called "junk" science, this class is clearly based on information which contradicts basic scientific principles.

Similarly, the reliability of scientific information was categorized into four groups as follows:

Group I - Personal Opinion: This group is entirely unreliable unless it is based on the third or fourth group in this grouping system.

Group II - Gray Literature: This group consists of government reports, reports by private organizations, and all other information that has not been subjected to independent peer review. The reliability of this group is questionable.

Group III - Peer-Reviewed Information: This group is the most reliable information. It is based on an assessment of the information by those who are peers to the investigators and are independent of those who have a stake in the outcome of the review.

Group IV - Consensus-Processed Information: This group is particularly applicable to Category IIa and Category IIb of the scientific information. It is based on the notion that information falling into those classes is likely to be contested, and as additional knowledge is gained, the contested area may move to Category Ib or even Category Ia of the classification system. However, the collective wisdom of a profession can be used to reach a conclusion which has a high probability to be correct. For example, in a contested area of mechanical engineering, the collective judgement of the mechanical engineers, as represented by the American Society of Mechanical Engineers (ASME), is the most efficient method to reach a consensus on the likely answer.

PEER REVIEW VS TECHNICAL ASSESSMENT

Peer review consists of a critical evaluation of a product consisting of a document, a study, a program, a technology, a strategy, or any other topic

by a group of individuals who—by virtue of their education, experience, and acquired knowledge—are qualified to be peers to the author of the subject that is being reviewed. In effect, the peers are asked to judge an existing, and partially or entirely completed activity. In its simplest form, peer review responds positively or negatively to the question: Is the claim of the author valid?

In contrast to peer review, a technical assessment guides the requester to a pathway that leads to a decision. In most cases, technical assessments provide detailed information on how an objective can be achieved. Instead of answering a question positively or negatively, an assessment provides a technical judgement on the approach, direction, and implementation of an issue.

PRINCIPLES OF PEER REVIEW AND TECHNICAL ASSESSMENT

Independent peer review, independent technical assessment, and the consensus process are key ingredients of acceptability of scientific information. A peer is an individual who is able to perform the project—or the segment of the project that is being reviewed—with little or no additional training or learning.

Recognizing that peer review constitutes the core of acceptability of scientific and engineering information, virtually all professional societies of scientists and engineers have instituted formal procedures for peer review for their activities. The peer review program of the RSI was developed as a result of its joint efforts with the ASME. The reports of the peer reviews resulting from this program have been published by ASME/RSI (1997, 1998, 1999, 2000, 2001a, 2001b, 2001c, 2002a, 2002b, 2002c, 2002d, 2002e, 2003a, 2003b) and RSI (1998, 2002, 2003).

The most important requirements for independent peer review or independent technical assessment are as follows:

Principle 1: *The selection of members of the review or assessment panel and the outcome of the review or assessment must result from the consensus of a group rather than the decision of an individual.*

This principle implies that all decisions dealing with selection of reviewers and the review must be made collectively by a group of qualified individuals rather than a single individual. Consequently, the RSI process uses the Commission on Assessment and Reviews (CAR) for the appointment of Panels who in turn perform the assessment or the review. Although individuals are involved in the identification of peer reviewers and their nomination, ultimately CAR makes the final decision. Wherever necessary, the CAR decides to change the makeup of the panels, thus demonstrating the necessary oversight.

Principle 2: *Clear and unambiguous policies must be provided to ensure that conflict of interest is avoided.*

The issue of conflict of interest is normally addressed by having each panel member sign a conflict-of-interest form certifying that the individual has no conflict of interest. However, this approach leaves the judgement entirely to the reviewer.

An independent peer review or independent technical assessment process requires clear policies indicating what constitutes a conflict of interest. The CAR relies upon the general conflict-of-interest policies of professional societies resulting in the policy: *Those who have a stake in the outcome of the review or assessment may not act as panel members or participate in the selection of panel members.*

Principle 3: *The findings and recommendations of the review or assessment panel must address unambiguous and clear questions (sometimes called criteria or lines of inquiry) identified by the sponsoring agency.*

Various terms are used in describing review or assessment criteria. These include criteria, questions, and lines of inquiry. During the evolution of the RSI process, much skepticism resulted from the past practice in which panel members had a free reign in addressing any issue. A properly-managed independent peer review or assessment should be based on clearly-identified criteria. These criteria must be technically reasonable and must respond to the needs of the manager.

Principle 4: *The findings and recommendations responding to the assessment or review criteria must be critical, constructive, professional, and collegial rather than adversarial.*

An important and hereto under-emphasized principle is an appreciation of the reason for peer review or assessment. A peer review or an assessment is intended to assist the managers in their decision process. Therefore, the outcome should be helpful to the decision makers rather than being confrontational.

Principle 5: *The participation of appropriately-selected stakeholders significantly enhances the credibility and acceptability of the results of peer review or assessment study.*

The participation of those who are personally impacted by a decision; those who must deal with it during the course of their occupation; and all others who have an interest in the outcome of the peer review or an assessment is desirable. Experience indicates that a properly-managed program of stakeholder participation can avoid the sometimes disorderly and chaotic conditions that can result from such participation. Also, the experience gained during this program indicates that a properly-designed and properly-conducted review or assessment will enhance the acceptance of the decision.

THE PROCESS

The structure of the peer review or technical assessment process established by RSI consists of a tiered system. The process is overseen by the CAR. The review or assessment of specific topics is performed by Review Panels (RPs) or Assessment Panels (APs).

Commission on Assessments and Reviews

The CAR oversees the peer review and assessment studies. Its members are chosen on the basis of their education, experience, and peer recognition. An attempt is made to ensure that all needed technical competencies and diversity of technical views are represented in the CAR.

As the overseer of the entire process, the CAR enforces all relevant policies, including compliance with professional and ethical requirements. A key function of the CAR is the approval of the appointment of members of RPs or APs for a specific project.

Panels

The review of a project, a document, a technology, or a program is performed by a panel consisting of a small group of highly-knowledgeable individuals. Upon the completion of their task, the panel is disbanded. The selection of panel members is based on the competencies required for the specific assignment. The same process is used for the formation and operation of Assessment Panels. The number of individuals in a panel depends upon the complexity of the subject to be reviewed or assessed. The selection of a panel member is based on the totality of that individual's qualifications. However, there are several generally-recognized and fundamental criteria for assessing qualifications of a panel member as follows:

1. **Education:** A minimum of a B.S. degree and preferably an advanced degree in an engineering or scientific field is required for any candidate.

2. **Experience:** In addition to education, the individual must have significant experience in the area that is being evaluated.

3. **Peer recognition:** Election to office of a professional society; serving on technical committees of scholarly organizations; and similar activities are considered to be a demonstration of peer recognition.

4. **Contributions to the profession:** The contributions to the profession may be demonstrated by publications in peer-reviewed journals. In addition, patents, presentations at meetings where the papers were peer-reviewed, and similar activities are also considered to be contributions to the profession.

5. **Conflict of Interest:** One of the most complex and contested issues is a set of subjects collectively called conflict of interest. The ideal panel member is an individual who is intimately familiar with the subject and yet

has no monetary interest in it. The guiding principle for conflict of interest is as follows:

Those who have a stake in the outcome of the review or assessment may not act as a panel member or participate in the selection of panel members.

Institute for Regulatory Science

RSI is a not-for-profit organization chartered under section 501(c)3 of the Internal Revenue Service. It is dedicated to the idea that societal decisions must be based on the best available scientific and engineering information. According to the RSI mission statement, peer review or assessment is the foundation of the best available scientific and engineering information. Consequently, RSI has promoted peer review or assessment within government and industry as the single most important measure of reliability of scientific and engineering information. In its activities, RSI seeks the cooperation of scholarly organizations. Historically, a large number of RSI activities have been performed in cooperation with professional societies. RSI is located in the Washington, D.C. Metropolitan Area with offices in Carlsbad, NM and Aiken, SC.

Project Summary

WASTE ISOLATION PILOT PLANT FACILITY

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is the principal facility for the disposal of the nation's transuranic (TRU) radioactive waste generated as a result of over 50 years of nuclear weapons research, development, and production. The selection of the WIPP site followed a lengthy search and extensive studies for the identification of a site for disposal of TRU wastes (NRC 1983, 1984). These efforts led to the selection of a 41-km^2 (16-mi^2) site, 26 mi (42 km) east of Carlsbad, NM. Following studies conducted during the 1950s of geological formations stable enough to contain wastes for thousands of years, the National Research Council (NRC 1957) identified deep geologic isolation in salt as a most desirable disposal mode for radioactive waste. Experiments conducted on salt mines revealed that there were no technical difficulties with waste disposal in salt (NRC 1984). The Carlsbad site was selected by the U.S. Department of Energy (DOE) because the deep salt beds located there are expected to provide the necessary stability for waste disposal. The site and the region surrounding it had been studied for many years, and mineral exploration of both potash and hydrocarbon deposits provided additional knowledge regarding the geology of the region. The U.S. Geological Survey and other agencies assisted DOE in identifying the New Mexico location for the repository. The salt deposit at this site, known as the Salado Formation, is a minimum of 2,000 ft (610 m) thick and located at a depth of 1,000-2,000 ft (305-610 m).

Salt allows significant deformation without fracturing. The Salado Formation is regionally extensive, and includes continuous beds of salt without complicated structures. The DOE identified the following four advantages of the site:

1. The salt deposit is in a stable geological area with little seismic activity, assuring the stability of a waste repository for thousands of years.
2. Salt deposits indicate the absence of flowing fresh water which could move waste to the surface. Water, if it had been or were present, would have dissolved the salt beds.

3. Salt is relatively easy to mine.
4. Rock salt exhibits a characteristic mechanical behavior (creep) that makes it an excellent host for waste isolation. In response to excavation-induced stress changes, salt slowly flows (or creeps), to close the mined openings. Creep closure starts immediately and continues until the salt has regained its original density and stress distribution. Salt formations tend to slowly and progressively fill mined areas and safely seal radioactive waste from the environment.

Geological data were collected from the WIPP site and surrounding area to evaluate its suitability as a radioactive waste repository. These data were collected principally by the DOE; the DOE's predecessor agencies; the U.S. Geological Survey; the New Mexico Bureau of Mines and Mineral Resources; and private organizations engaged in natural resource exploration and extraction. The DOE analyzed the data and has stated that the site is suitable for long-term isolation of radioactive waste.

The geology of the WIPP site has specific advantages identified by the DOE against potentially adverse environmental impacts. At the depth of the WIPP repository, the salt will slowly encapsulate the buried waste in the stable rock. Salt rock also shields radioactivity, providing a protection similar to that of concrete. Waste placed in the excavation at WIPP is expected to be encapsulated and all waste-filled spaces closed over a period of 75-200 years. The waste disposal depth of 2,150 ft (650 m) is close enough to the surface to make access reasonable.

Subsequent to the investigation of the subsurface geology, the DOE selected the Salado Formation as the site of the WIPP repository for the following reasons:

1. The Salado halite units have low permeability to fluid-flow, which impedes groundwater-flow into and out of the repository.
2. It is regionally widespread.
3. It includes continuous halite beds without complicated structure.
4. It is deep with little potential for dissolution.
5. It is close enough to the surface that access is reasonable.
6. It is largely free of mobile groundwater, as compared to existing mines and other potential repository sites.

Another of the favorable aspects of subsurface geology at the WIPP site is that the groundwater hydrology in the immediate proximity is characterized by geologic strata with low transmissivity and low hydrologic gradients.

WASTE PROCESSING STEPS AT WIPP

The handling and disposal of Contact-Handled (CH) TRU wastes at WIPP involve the following series of steps:

1. A waste shipment arrives at WIPP by truck. Each truck is capable of carrying up to three TRU Packaging Transport Model IIs (TRUPACT-IIs).
2. After an initial security inspection, a radiological survey, and a shipping documentation review, the truck is parked near the Waste Handling Building (WHB) for additional inspection and radiological survey. A forklift is used to transfer each TRUPACT-II from the trailer, through an air lock, and into the WHB, where it is placed in an area called a TRUDOCK, which is used by workers to unload the waste from the TRUPACT-IIs.
3. Radiological surveys are conducted to confirm that waste containers have not sustained damage during shipment or waste container removal.
4. At the TRUDOCK, an overhead crane is used to remove the waste containers from each TRUPACT-II and place them on a facility pallet.
5. A forklift moves the loaded facility pallet to the conveyance loading car at the waste handling shaft. The conveyance loading car is used to load the facility pallet onto the waste hoist.
6. The waste hoist descends 2,150 ft (705 m) to the WIPP repository.
7. An underground transporter pulls the loaded facility pallet off the hoist onto the transporter bed and moves the waste to the appropriate disposal room where a forklift removes the waste containers from the facility pallet and places them in the disposal area. Containers may be stacked three high in the disposal area.
8. Bags of magnesium oxide are placed on top of the stack of containers to serve as backfill. The magnesium oxide will control the solubility of radionuclides and is an added measure of assurance for long-term repository performance.

CONTAINER MANAGEMENT PRACTICES

Containers are to be managed in a specified manner that does not result in spills or leaks. Containers are required to be closed at all times, unless waste is being placed in the container or removed. Because containers at WIPP contain radioactive waste, safety concerns require that containers be continuously vented to obviate the buildup of gases within the container. These gases could result from radiolysis, which is the breakdown of moisture by radiation. The vents are filtered to enable any potential generated gas to escape while particulate matter is retained. Derived waste containers are kept closed at all times unless waste is being added or removed.

Containers with residual liquids

Defense production facilities are prohibited from shipping liquid wastes in the containers sent to the WIPP. In no case is the total residual liquid allowed to equal or exceed 1% (by volume) of the waste container. Consequently, calculations made to determine the secondary containment as required by regulations are based on 10% of 1% of the volume of the containers, or 1% of the largest container, whichever is greater.

Description of containers

Waste containers are to be in good condition prior to shipment from the generator sites, i.e., containers will be of high integrity, intact, and free of surface contamination above established limits. This condition is to be verified upon receipt of the waste at WIPP. Containers are vented through filters, allowing any gases that are generated by radiolytic and microbial processes within a waste container to escape, thereby preventing overpressurization or development of conditions within the container that would lead to the development of ignitable, corrosive, reactive, or other characteristic wastes.

The volatile organic compounds (VOC) in the headspace of waste containers are limited to maximum allowable VOC room-averaged headspace concentration limits specified in the permit. There are no maximum allowable headspace gas concentration limits for individual containers, as some containers can exceed these values as long as container headspace averages in a disposal room do not.

Containers for CH TRU mixed waste will be either 55-gal (208-L) drums arranged singly in 7-packs; 85-gal (321-L) drums arranged singly in 4-packs; 100-gallon drums arranged singly or as three-packs; ten-drum overpacks (TDOP) either as overpacks or direct-loaded; or standard waste boxes (SWBs). Following is a summary description for each container type.

Standard 55-gallon drums: These drums meet the requirements for U.S. Department of Transportation specification 7A regulations. A standard 55-gal (208-L) drum has a gross internal volume of 7.4 ft^3 (0.208 m^3). One or more filtered vents (as described in Permit Section M1-1d(1)) is to be installed in the drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential for pressurization. Standard 55-gal (208-L) drums are constructed of mild steel and may also contain rigid, molded polyethylene (or other compatible material) liners.

Standard Waste Boxes (SWBs): One or more filtered vents are to be installed in the standard waste box lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential of pressurization. SWBs have an internal volume of 66.3 ft^3 (1.88 m^3).

One hundred-gallon drums: A 100-gal (379-L) drum has a gross internal volume of 13.4 ft^3 (0.39 m^3). One or more filtered vents are installed in the drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate potential pressurization. These drums are constructed of mild steel and may also contain rigid, molded polyethylene (or other compatible material) liners. These drums may be used as overpacks or may be direct-loaded.

Ten-Drum Overpack: The TDOP is a metal container, similar to a SWB, and is certified to be noncombustible. It is a welded-steel cylinder, approximately 74 in (1.9 m) high and 71 in (1.8 m) in diameter with a gross internal capacity of 160 ft^3. The maximum loaded weight of a TDOP is limited to 6,700 lbs (3,040 kg). A bolted lid on one end is removable; sealing is accomplished by clamping a neoprene gasket between the lid and the body. Filter ports are located near the top of the TDOP. One or more filtered vents are installed in the ten-drum overpack lid or body to prevent the escape of any radioactive particulate matter

and to eliminate any potential for pressurization. A TDOP may contain up to ten standard 55-gal (208-L) drums or one SWB. The TDOPs may be used to overpack drums or SWBs containing CH TRU mixed waste. The TDOP may also be direct-loaded with waste items that are too large to fit into the standard 55-gallon (208-L) drum; the 85-gallon drum; or the SWB.

Eighty-five gallon drums: The 85-gal (321-L) drum overpack is to be used primarily for overpacking contaminated 55-gal (208-L) drums at the WIPP facility. The 85-gal (321-L) drums may be direct-loaded with CH TRU-mixed waste and may be used to collect derived waste. One or more filtered vents are to be installed in the 85-gal (321-L) drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential of pressurization.

Container compatibility: All containers are made of steel, and some will contain rigid, molded polyethylene liners. Requirements to conduct compatibility studies include container materials to assure that containers are compatible with the waste.

RCRA WASTE CHARACTERIZATION

INTRODUCTION

There are certain waste characterization requirements for the radioactive content of transuranic (TRU) waste mandated by the U.S. Environmental Protection Agency (EPA). Compliance with characterization requirements of TRU waste for disposal at the Waste Isolation Pilot Plant (WIPP) is accomplished on a waste stream basis (i.e., waste material generated from a single process or activity that is similar in material, physical form, isotropic make-up, and hazardous constituents) and also on a container basis. Defense production facilities assign the waste stream identifier for each container of waste that is shipped. The waste designation is selected from one of three broad categories of solid wastes: Homogenous Solids, Soil/Gravel, and Debris Wastes (NMED 1999). In addition, a number of sub-categories are assigned to the wastes. Characterization and analysis methods vary for each category and subcategory of waste.

The Waste Analysis Plan (WAP), which is part of the Permit (DOE 1997b), describes waste characterization activities that a TRU waste generator/storage site must complete before shipping waste to WIPP for disposal. These activities include test methods; details of planned waste sampling and analysis processes; a description of the waste shipment screening and verification process; and a description of the quality assurance/quality control program. Before WIPP manages, stores, or disposes of Contact-Handled (CH) TRU mixed waste from a generator/storage site, the site is required to characterize waste in accordance with WAP requirements. For each container of waste destined for disposal, defense production facilities provide the WIPP operators with a written characterization summary known as a Waste Stream Profile Form (WSPF).

Waste characterization based on 40 CFR 194

Waste characterization, as mandated by the Resource Conservation and Recovery Act (RCRA); and as described in 40 CFR 194 (EPA 1998) requires that a system be in place to track and control the inventory of

waste components to assure that limits associated with the components are not exceeded. The waste components to be tracked and controlled, and the associated limits, are set by a Performance Assessment (PA) conducted by the U.S. Department of Energy (DOE) to show that the WIPP complies with the performance criteria of 40 CFR 191 (EPA 1993). The waste components and the limits, all of which are total inventory limits at repository closure, are presented in the WIPP Compliance Certification Application (CCA).

ORIGIN OF CH TRU WASTE AND ITS ACCEPTANCE CRITERIA AT WIPP

The TRU mixed wastes that are shipped to the WIPP originate at DOE generator/storage sites and contain both radiological and hazardous waste constituents. The DOE and EPA agreed that, of the hundreds of radionuclides present within these wastes, only ten are important for the WIPP performance assessment: ^{241}Am, ^{244}Cm, ^{137}Cs, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{90}Sr, ^{233}U, and ^{234}U. Of these ten, ^{234}Sr, ^{233}U, and ^{137}Cs are important for Remote-Handled (RH) but not for CH waste streams.

Major types of operations generating waste

Examples of the major types of operations that generate this waste include the following:

Production of nuclear products: This category includes reactor operation; radionuclide separation or finishing; and weapons fabrication and manufacturing. The majority of the TRU mixed wastes were generated by weapons fabrication and radionuclide separation or finishing processes. More specifically, wastes resulting from this category consist of residues from chemical processes; air and liquid filtration; casting; machining; cleaning; product quality sampling; analytical activities; and maintenance and refurbishment of equipment and facilities.

Plutonium recovery: These wastes are residues from the recovery of plutonium-contaminated molds; metals; glass; plastics; rags; salts used in electro-refining; precipitates; firebrick; soot; and filters.

Research and development: This group includes a variety of hot-cell or glovebox activities that often simulate full-scale operations described above, producing similar TRU mixed wastes. Other types of R&D projects include metallurgical research; actinide separations; process demonstrations; and chemical and physical properties determinations.

Decontamination and decommissioning: Facilities and equipment that are no longer needed or usable are decontaminated and decommissioned, resulting in TRU mixed wastes consisting of scrap materials; cleaning agents; tools; piping; filters; plexiglass; gloveboxes; concrete rubble; asphalt; cinder blocks; and other building materials. These materials are expected to be the largest category by volume of TRU mixed waste to be generated in the future.

The TRU mixed wastes that are to be shipped to the WIPP facility for disposal have been placed into waste categories based on their physical and chemical properties (Table 1). The waste generating processes can be described in five general categories:

1. Wastes (such as combustible waste) that result from cleaning and decontamination activities in which items such as towels and rags become contaminated both with hazardous waste constituents and radioactivity. In these cases, the hazardous waste and the radioactive constituent are intimately mixed, both on the rag or towel used for cleaning and as residuals on the surface of the object being cleaned. These waste forms are not homogeneous in nature; however, they are generated in a fashion that ensures that the hazardous and radioactive contaminants coexist throughout the waste matrix.

2. Wastes generated when materials which contain metals and metal ions believed to exhibit the toxicity characteristic (EPA 1996b) become contaminated with radioactivity as the result of plutonium operations (leaded rubber, some glass, and metal waste are typical examples). These materials may also become contaminated with solvents during decontamination or plutonium recovery activities.

3. A class of plutonium processes where non-metallic objects are used and become contaminated with radioactive materials. These objects

are subsequently cleaned with solvents to recover plutonium. Surfaces of the objects (such as graphite, filters, and glass) are contaminated with both radioactive and hazardous constituents.

4. Waste-generating processes involving foundry operations where impurities are removed from plutonium. These impurities may result in the deposition of toxicity characteristic (EPA 1996b) metals and metal ions.

5. In all of the process waste categories in the second half of Table 1, the hazardous and radioactive constituents are physically mixed together as a result of the treatment process. In these wastes, the release of any portion of the waste matrix will involve both the hazardous and the radioactive waste components, because the treatment process generates a relatively homogeneous waste form.

Table 1. Summary of waste generation processes and waste forms.

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Combustibles	F001, F002, F003, D008, D019	Cloth and paper wipes are used to clean parts and wash down gloveboxes. Wood and plastic parts are removed from gloveboxes after they are cleaned. Lead may occur as shielding tape or as minor noncombustible waste in this category.	Materials such as metals may retain traces of organics left on surfaces that were cleaned. Waste may remain on the cloth and paper that was used for cleaning or for wiping up spills.
Graphite		Graphite molds, which may contain impurities of metals, are scraped and cleaned with solvents to remove the recoverable plutonium.	Surfaces may retain residual solvents. Lead may be used as shielding or may be an impurity in the graphite.
Filters	F001, F002	Filters are used to capture radioactive particulate in air streams associated with numerous plutonium operations and to filter particulate from aqueous streams.	Filter media may retain organic solvents that were present in the air or liquid streams.

Table 1. (cont'd)

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Benelex® and Plexiglas®	F001, F002, D008	Materials are used in gloveboxes as neutron absorbers. The glovebox assembly often includes leaded glass. All surfaces may be wiped down with solvents to remove residual plutonium.	Surfaces may retain residual solvents from wiping operations. Leaded glass may also be present.
Firebrick and Ceramic Crucibles	F001, F002, F005, D006, D007, D008	Firebrick is used to line plutonium processing furnaces. Ceramic crucibles are used in plutonium analytical laboratories. Both may contain metals as surface contaminants.	Metals deposited during plutonium refining or analytical operations could remain as residuals on surfaces. Surfaces may retain residual solvents.
Leaded Rubber	D008	Leaded rubber includes lead oxide impregnated materials such as gloves and aprons.	The leaded rubber could potentially exhibit the toxicity characteristic.
Metal	F001, F002, D008	Metals range from large pieces removed from equipment and structures to nuts, bolts, wire, and small parts. Many times, metal parts will be cleaned with solvents to remove residual plutonium.	Solvents may exist on the surfaces of metal parts. The metals themselves potentially exhibit the toxicity characteristic.
Glass	F001, F002, D006, D007, D008, D009	Glass includes Raschig rings removed from processing tanks, leaded glass removed from gloveboxes, and miscellaneous laboratory glassware.	Solvents may exist as residuals on glass surfaces and in empty containers. The leaded glass may exhibit the toxicity characteristic.
Inorganic Wastewater Treatment Sludge	F001-F003, D006-D009, P015	Sludge is vacuum filtered and stabilized with cement or other appropriate sorbent prior to packaging.	Traces of solvents and heavy metals may be contained in the treated sludge which is in the form of a solid dry monolith, highly viscous gel-like material, or dry crumbly solid.

Table 1. (cont'd)

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Organic Liquid and Sludge	F001, F003	Organic liquids such as oils, solvents, and lathe coolants are immobilized through the use of various solidification agents or sorbent materials.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.
Solidified Liquid	F001, F003, D006, D008	Liquids that are not compatible with the primary treatment processes and have to be batched. Typically these liquids are solidified with portland or magnesium cement.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.
Inorganic Process Solids and Soil	F001, F002, F003, D008	Solids that cannot be reprocessed or process residues from tanks, firebrick fines, ash, grit, salts, metal oxides, and filter sludge. Typically solidified with portland or gypsum-based cements.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.
Pyrochemical Salts	D007	Molten salt is used to purify plutonium and americium. After the radioactive metals are removed, the salt is discarded.	Residual metals may exist in the salt depending on impurities in the feedstock.
Cation and Anion Exchange Resins	D008	Plutonium is sorbed on resins and is eluted and precipitated.	Feed solutions may contain traces of solvents or metals depending on the preceding process.

Categories of TRU mixed waste

TRU mixed wastes from the above operations are listed by defense production facilities as belonging in one of three broad Summary Category Groups. The characterization is based on the final physical form of the wastes as follows:

Summary category group S3000—homogeneous solids: These wastes include a minimum of 50% (by volume) solid inorganic process residues such as inorganic sludge, salt waste, and pyrochemical salt waste—but exclude soil. Other waste streams are included in this Summary Category Group based on the specific waste stream types and final waste form. This Summary Category Group is expected to contain toxic metals and spent solvents.

Summary Category Group S4000—Soils/Gravel: This Category is assigned to waste streams containing at least 50% (by volume) soil and gravel. This Summary Category Group is expected to contain toxic metals and is also further categorized by the amount of debris included in the matrix.

Summary Category Group S5000—Debris Wastes: These are heterogenous wastes that are at least 50% (by volume) materials that exceed 2.36 inch (60 mm) particle size and that are manufactured objects; plant or animal matter; or natural geologic materials. Smaller particles may be considered debris if they are manufactured objects and if they do not belong to S3000 or S4000. Examples of S5000 waste include gloves; hoses; aprons; floor tile; insulation; plastic; rubber; wood; paper; cloth; and biological materials.

The most common RCRA-regulated hazardous constituents in TRU mixed waste

1. **Metals and metal ions:** Some of the TRU mixed waste to be emplaced in the WIPP facility contains toxic metals contained in EPA hazardous waste codes D004 through D011 (EPA 2000). Cadmium, chromium, lead, mercury, selenium, and silver are present in discarded tools and equipment; solidified sludge; cemented laboratory liquids; and waste from decontamination and decommissioning activities. A large percentage of the waste consists of lead-lined gloveboxes; leaded rubber gloves and aprons; lead bricks and piping; lead tape; and other lead items. Lead, because of its radiation-shielding applications, is the most prevalent toxicity-characteristic metal present.

2. **Halogenated volatile organic compounds:** Some of the TRU mixed waste to be emplaced in the WIPP facility contains spent

halogenated volatile organic compound (VOC) solvents listed as EPA hazardous waste numbers F001 through F005 (EPA 2000). Tetrachloroethylene; trichloroethylene; methylene chloride; carbon tetrachloride; 1,1,1-trichloroethane; and 1,1,2-trichloro-1,2,2-trifluoroethane (EPA hazardous waste codes F001 and F002) are the most prevalent halogenated organic compounds identified in TRU mixed waste that may be managed at the WIPP facility during the Disposal Phase. These compounds are commonly used to clean metal surfaces prior to plating, polishing, or fabrication; to dissolve other compounds; or as coolants. Because they are highly volatile, only small amounts typically remain on equipment after cleaning or, in the case of treated wastewater, in the sludge after clarification and flocculation. Radiolysis may also generate halogenated volatile organic compounds.

3. **Non-halogenated volatile organic compounds:** Xylene, methanol, and n-butanol are the most prevalent nonhalogenated VOCs in TRU mixed waste that may be managed at the WIPP facility. Like the halogenated VOCs, they are used as degreasers and solvents and are similarly volatile. The same analytical methods that are used for halogenated VOCs are used to detect the presence of nonhalogenated VOCs.

Prohibited Items

The TRU mixed waste forms describe both radioactive and hazardous characteristics exhibited by the wastes. The Permit Treatment, Storage, and Disposal Facility Waste Acceptance Criteria (TSDF-WAC) places limits on the waste that can be shipped to the WIPP facility based on the characteristics of the waste form. The following TRU mixed wastes are prohibited at the WIPP facility:

1. Liquid waste which includes residual liquid in the container in excess of what is reasonably achievable by pouring, pumping, and/or aspirating; liquid in the internal container in excess of 1 inch (2.5 cm) of liquid in the bottom of the container; or total residual liquid in any payload container (e.g., 55 gallon drum or standard waste box) in excess of 1% (by volume) of that container
2. Pyrophoric materials, such as elemental potassium
3. Hazardous wastes not occurring as co-contaminants with TRU wastes

4. Wastes incompatible with backfill; seal and panel closures materials; container and packaging materials; shipping container materials; or other wastes
5. Wastes containing explosives or compressed gases
6. Wastes with polychlorinated biphenyl (PCB) concentration of 50ppm (50 mg/kg) or more
7. Wastes exhibiting the characteristic of ignitability, corrosivity, or reactivity (EPA Hazardous Waste Numbers D001, D002, or D003)
8. Any waste container that does not have VOC concentration values reported for the headspace
9. Any waste container which has not undergone either radiographic or visual examination
10. Any waste container from a waste stream which has not been preceded by an appropriate, certified Waste Stream Profile Form

Before accepting a container holding TRU mixed waste, WIPP operators audit the radiography or visual examination (VE) data records of the generator/storage sites to verify that the container holds no unvented compressed gas, and that residual liquid does not exceed 1% (volume) in any payload container. Radiography tapes are to be selected randomly for at least 1% of containers received at the WIPP, at which time they are reviewed and compared to radiographic data forms. If waste does not include at least 50% of any given category by volume, characterization shall be performed using the waste characterization process required for the category constituting the greatest volume of waste for that waste stream. To ensure the integrity of the WIPP facility, waste streams identified as containing incompatible materials or materials incompatible with waste containers are not to be shipped to the WIPP unless they are treated to remove the incompatibility.

Waste generated as a result of waste container handling and processing activities at the WIPP facility are known as “derived” wastes. Because derived wastes can contain only those RCRA-regulated materials present in the waste from which they were derived, no additional characterization of the derived waste is required for disposal purposes. In other words, generator/storage site characterization data as well as knowledge of the processes at the WIPP facility will be used to identify and characterize hazardous waste and hazardous constituents in derived waste.

TRU waste, by definition, must contain 100 nCi/g or more of transuranic elements of waste, which means that the radioactive component of the waste will always be present within the waste in significant concentrations. The TSDF-WAC limitations and restrictions are provided to ensure that any waste form received at the WIPP facility is stable and can be managed safely. One benefit of waste form restrictions—such as no liquids—is that they limit the kinds of releases that could occur to those that would be readily detectable through visual inspection (i.e., large objects that fall out of ruptured containers) or through the use of radiation monitoring—either locally or within the adjacent area—to detect materials that have escaped from containers.

Releases and spills

Some waste forms only contain radioactive contamination on the surface, because they are not the result of a treatment process or are not porous in form. These include glass, leaded rubber, metals, graphite, ceramics, firebricks, and plastics. In theory, a hazardous waste release could occur if the interiors of these materials became exposed and were involved in a release or spill. Such an occurrence is not likely during operations, because no activities are planned or anticipated that would result in the breaking of these materials to expose fresh surfaces. The WIPP facility will handle only sealed containers of waste and derived waste. The practice of handling sealed containers minimizes the opportunity for releases or spills. For the purposes of safety analysis, it was assumed that releases and spills during operations occur by either of two mechanisms: 1) surface contamination; and 2) accidents. Regardless of how the release occurs, the nature of the waste and the processes that generated it is such that the radioactive and hazardous components are intimately mixed. A release of one without the other is not likely, except for releases of VOCs from containers. Surface contamination is the only credible source of contamination external to the containers during normal operations. Surface contamination is assumed to be caused by waste management activities at the generator site that result in the contamination of the outside of a waste container. Contamination would most likely consist of particulate matter (dirt or dust) that would be deposited during generator-site handling/loading activities. This contamination may not be detected by visible inspections. Surface contamination is monitored upon

arrival at the WIPP facility through the use of swipes and radiation monitoring equipment, as specified in the WIPP Permit (NM Hazardous Waste Regulations, Title 20; NMED 1999). Detection using radioactivity is very sensitive and allows for the detection of contamination that may not be visible on the surface of the container. This exceeds the capability required by the RCRA, which is generally limited to inspections that detect only visible evidence of spills or leaks. Releases can occur from accidents, and those that occur within the waste handling process are assumed to result in the release of radioactive contaminants and VOCs. Radioactive releases are detectable using surface-sampling (swipe) techniques. The most common RCRA-regulated hazardous constituents in TRU mixed waste to be managed at the WIPP facility consist of: metals; halogenated volatile organic compounds; and non-halogenated volatile organic compounds.

WASTE STREAM IDENTIFICATION

Waste characterization activities at generator/storage sites include the following, although not all of these techniques will be used on each container:

1. Radiography, which is an x-ray technique to determine physical contents of containers
2. Visual examination (VE) of opened containers as an alternative way to determine their physical contents or to verify radiography results
3. Headspace-gas sampling to determine VOC content of gases in the void volume of the containers
4. Sampling and analysis of waste forms that are homogeneous and can be representatively sampled to determine concentrations of hazardous waste constituents and toxicity-characteristic contaminants of waste in containers
5. Compilation of acceptable knowledge (AK) documentation into an auditable record, including process knowledge and prior sampling and analysis data
6. Non-destructive assay, typically segmented gamma scans and passive/active neutron interrogation, to quantify radionuclides for 40 CFR 194 waste characterization compliance

Auditable records allow DOE operators to conduct a systematic assessment, analysis, and evaluation of generator/storage site compliance with the WAP and the Permit. Waste analysis parameters to be characterized include confirmation of physical form; presence of toxicity characteristic contaminants; and exclusion of prohibited items. The characterization techniques used by generator/storage sites include AK, which incorporates confirmation by headspace-gas sampling and analysis; radiography; and homogeneous waste sampling and analysis. All confirmation and characterization activities are to be performed in accordance with the WAP. The analytical requirements are specified by the analytical method being used such as Fourier Transform Infrared Spectroscopy, and Gas Chromatography/Mass Spectrometry.

Waste analysis parameters characterized for the 40 CFR 194 (EPA 1998) characterization program are quantity of metals; quantities of cellulosics; plastics; and rubber; quantity of free water; and a list of ten radionuclides. The characterization techniques used by generator/storage sites for these parameters also include AK and radiography as well as non-destructive assay.

Radiography

Radiography techniques have been developed by DOE to aid in the examination and identification of containerized waste. There are specific requirements that relate to radiography methods used at respective facilities. A radiography system typically consists of: 1) an X-ray-producing device; 2) an imaging system; 3) an enclosure for radiation protection; 4) a waste container handling system; 5) an audio/video recording system; and 6) an operator control and data acquisition station.

Although these six components are required, it is expected that there will be some variation within a given system between sites. The radiography of a waste container is recorded by an audio/videotape or equivalently non-alterable media and is maintained as a non-permanent record. The estimated waste material parameter and weights should be determined by compiling an inventory of waste items, residual materials, and packaging materials. Containers whose contents prevent full examination to the extent expected for the radiography technique and waste form, are subject to visual examination.

Visual examination

As an additional quality control (QC) check on radiography, or in lieu of radiography, the waste container contents are verified directly by visual examination. The visual examination consists of a semi-quantitative and/or qualitative evaluation of the waste container contents, and is recorded on audio/videotape. Visual examination is performed on a statistically determined portion of waste containers to verify the results of radiography. This verification includes use of the Waste Matrix Code; waste material parameter weights; and the assurance of the absence of prohibited items.

Visual examination includes describing the contents of a waste container, and estimating or measuring the weight of the contents. The description identifies the discernible waste items, residual materials, packaging materials, and waste material parameters. Estimated weights are established through the use of historically-derived waste weight tables and an estimation of the waste volumes.

Headspace-gas sampling and analysis

Headspace-gas sampling is performed on waste containers that are in compliance with the container temperature equilibrium requirements (i.e., 72 h at 18°C or higher). Waste containers designated as summary category S5000 (Debris waste) are sampled for headspace gas a minimum of 142 d after packaging. Waste containers designated as Summary Categories S3000 (Homogenous solids) and S4000 (Soil/gravel) are sampled a minimum of 225 d after packaging. This drum-age criteria ensures that the drum contents have reached 90% of steady state concentration within each layer of confinement to allow a representative sample to be taken (NMED 1999.) Two types of headspace-gas sampling protocols may be employed: 1) the manifold headspace-gas sampling protocol, and 2) the direct canister headspace-gas sampling protocol.

Once the headspace gas sample has been collected in accordance with the Hazardous Waste Facility Permit (HWFP) requirements, the sample is taken to a laboratory for analysis. The laboratory analyzes the sample using the allowable methods in the HWFP and reports the concentration

of all analytes on the target analyte list. In addition, the presence of any tentatively identified compounds (TICs) observed during the analysis is reported.

Sampling and analysis of homogenous solids and soil/gravel

The methods used to collect samples of TRU mixed waste classified as homogenous solids and soil/gravel from waste containers, are designed to ensure that the samples are representative of the waste from which they are taken. A sufficient number of samples are collected to adequately represent the waste being sampled. For those waste streams defined as Summary Category Groups S3000 or S4000, debris that may also be present within these wastes need not be sampled. Samples of retrievably stored waste containers are collected using appropriate coring equipment or other EPA-approved methods to collect a representative sample. Newly-generated wastes that are sampled from a process as they are generated may be sampled using EPA-approved methods—including scoops and ladles—that are capable of collecting a representative sample.

The QC requirements for sampling homogenous solids and soil/gravel include: collecting co-located samples from cores or other sample types to determine precision; equipment blanks to verify cleanliness of the sampling and coring tools and sampling equipment; and analysis of reagent blanks to ensure that reagents, such as deionized or high-pressure liquid chromatography (HPLC) water, are of sufficient quality.

Once the homogeneous solid or soil/gravel sample has been collected in accordance with the HWFP requirements, the sample is taken to a laboratory for analysis. The laboratory analyzes the sample using the allowable methods in the HWFP and reports the concentration of all analytes on the target analyte list. In addition, the presence of any TICs observed during the analysis is reported.

Acceptable knowledge

This characterization technique incorporates confirmation by headspace-gas sampling and analysis; radiography; and homogeneous waste sampling

and analysis. Both RCRA regulations and the New Mexico Hazardous Waste Management Regulations (NMED 1997) authorize the use of AK in appropriate circumstances by waste generators—or treatment, storage, or disposal facilities—to characterize hazardous waste. Acceptable knowledge is described by the EPA (EPA 1994) as an alternative to sampling and analysis; it can be used to meet all or part of the waste characterization requirements under the RCRA. AK includes a number of techniques used to characterize TRU mixed waste, such as process knowledge; records of analysis acquired prior to RCRA; and other supplemental sampling and analysis data (EPA 1994). AK is used in TRU mixed waste characterization activities in three ways:

1. To delineate TRU mixed waste streams
2. To assess if TRU mixed heterogeneous debris wastes exhibit a toxicity characteristic (NMED 1997)
3. To assess if TRU mixed wastes are listed (NMED 1997)

TRU mixed waste streams are evaluated by applicable provisions of the AK process prior to management, storage, or disposal by the Permittees at the WIPP. TRU mixed waste management AK information defines waste categorization schemes and terminology; provides a breakdown of the types and quantities of TRU mixed wastes that are generated and stored at the site; and describes how wastes are tracked and managed at the site—including historical and current operations. Information related to TRU mixed waste certification procedures and the types of documentation (e.g., waste profile forms) used to summarize AK are also provided. The amount and type of supplemental AK information required from generator/storage sites is site-specific and cannot be mandated, but sites collect information as appropriate to support required AK information.

The AK written record includes a summary that identifies all sources of waste characterization information used to delineate the waste stream. For each TRU mixed waste stream, the generating sites compile all process information and data supporting the AK used to characterize that waste stream. The type and quantity of supporting documentation will vary by waste stream, depending on the process generating the waste and site-specific requirements imposed by the DOE.

STATISTICAL METHODS USED IN SAMPLING AND ANALYSIS

Generator/storage sites use statistical methods to: 1) select waste containers for visual inspection; 2) select retrievably-stored waste containers for totals analysis; 3) set the upper confidence limit; and 4) apply control charting for newly-generated waste stream sampling. Statistical sampling techniques are not currently employed in waste characterization activities employed for 40 CFR 194 (EPA 1998) compliance.

Selecting waste containers for visual examination

As a QC check on the radiographic examination of waste containers, a statistically-selected portion of the certified waste containers is opened and visually examined. The data from visual examination is used to verify the matrix parameter category, waste material parameter weights, and absence of prohibited items, as determined by radiography. The data obtained from the visual examination can also be used to determine—with acceptable confidence—the percentage of miscertified waste containers from the radiographic examination. Miscertified containers are those that radiography indicates meet the WIPP Waste Acceptance Criteria and Transuranic Package Transporter-II Authorized Methods for Payload Control, but visual examination indicates do not meet these criteria. Participating sites initially use an 11% miscertification rate to calculate the number of waste containers that are visually examined until a site-specific miscertification rate has been established.

The site-specific miscertification rate is applied initially to each Summary Category Group to determine the number of containers in that Summary Category Group requiring visual examination. However, a Summary Category Group-specific miscertification rate is determined when either six months have passed since radiographic characterization commenced on a given Summary Category Group or at least 50% of a given Summary Category Group has undergone radiographic characterization, whichever occurs first. The Summary Category Group is then subject to the visual examination requirements of this reevaluated Summary Category Group-specific miscertification rate to ensure that the entire Summary Category Group is appropriately characterized. The site-specific miscertification rate is reassessed annually.

Statistical sampling and analysis of homogeneous solids and soil/gravels for totals

The statistical approach for characterizing retrievably-stored homogeneous solids and soil/gravel waste using sampling and analysis relies on using acceptable knowledge to segregate waste containers into relatively homogeneous waste streams. Once segregated by waste stream, random selection and sampling of the waste containers followed by analysis of the waste samples are performed to ensure that the resulting mean contaminant concentration provides an unbiased representation of the true mean contaminant concentration for each waste stream.

Preliminary estimates of the mean concentration and variance of each RCRA-regulated contaminant in the waste are used to determine the number of waste containers to select for sampling and analysis. The preliminary estimates are made by obtaining a preliminary number of samples from the waste stream or from previous sampling from the waste stream. Preliminary estimates are based on samples from a minimum of five waste containers. Samples collected to establish preliminary estimates that are selected, sampled, and analyzed in accordance with applicable provisions of the Waste Analysis Plan (WAP) are used as part of the required number of samples to be collected.

The calculated total number of required waste containers can then be randomly sampled and analyzed. Waste container samples from the preliminary mean and variance estimates may be counted as part of the total number of calculated required samples if and only if:

1. there is documented evidence that the waste containers for the preliminary estimate samples were selected in the same random manner as is chosen for the required samples.
2. there is documented evidence that the method of sample collection in the preliminary estimate samples were identical to the methodology to be employed for the required samples.
3. there is documented evidence that the method of sample analysis in the preliminary estimate samples was identical to the analytical methodology employed for the required samples.
4. there is documented evidence that the validation of the sample analyses in the preliminary estimate samples was comparable to the

validation employed for the required samples. In addition, the validated samples results should indicate that all sample results were valid according to the analytical methodology.

Upon collection and analysis of the preliminary samples, or at any time after the preliminary samples have been analyzed, the generator/storage site may assign hazardous waste codes to a waste stream. For waste streams with calculated upper confidence limits below the regulatory threshold, the site must collect the required number of samples if the site intends to establish that the constituent is below the regulatory threshold.

Statistical headspace gas sampling and analysis

If a waste stream meets the conditions for representative headspace gas sampling, then headspace-gas sampling of that waste stream may be done on a randomly-selected portion of containers in the waste stream. The minimum number of containers that are sampled is determined by taking an initial VOC sample from 10 randomly-selected containers. These samples are analyzed for all the target analytes.

The mean and standard deviation calculated after sampling *n* containers is then used to calculate a UCL_{90} for each of the headspace gas VOCs.

Control charting for newly-generated waste stream sampling

Significant process changes and process fluctuations associated with newly-generated waste are determined using statistical process control (SPC) charting techniques. These techniques require historical data for determining limits for indicator species, and subsequent periodic sampling to assess process behavior relative to historical limits. SPC is performed on waste prior to solidification or packaging for ease of sampling. If the limits are exceeded for any toxicity characteristic parameter, the waste stream can be recharacterized, and the characterization can be performed according to procedures required in the WAP.

A Shewhart control chart (Gilbert 1987) is a control chart for statistical means that is used for checking whether current data are consistent with

past data and whether shifts or trends in means have occurred. If a current sample mean from the process lies within the limits, the process is said to be "in control," or consistent with historical data. If the current mean exceeds the limits, the process has likely changed from historical periods. Logical sets of historical data to be used for the construction of limits in this application are the data from the initial characterization of the waste stream, if available; from characterization of a different lot of the waste stream; or from a retrievably-stored waste stream of the same type from the same process. At a minimum, the logical set includes ten representative sample values collected and analyzed from the newly-generated waste stream. The data used for construction of the limits is justified. The underlying assumptions for control charts are that the data are independent and normally-distributed with constant mean μ and constant variance σ^2. The statistical tests for normality can be conducted and data transformation to normality performed, if necessary. Transformations should take place prior to any calculations that use the data.

Each limit is constructed such that there is a 90% confidence that the true mean does not exceed a limit. One-sided control limits are used because once a waste stream has been determined to be RCRA-hazardous and the limit exceedance of interest is on the lower side—that is when the process may become nonhazardous. Likewise, once a waste stream has been determined not to be RCRA-hazardous and the limit exceedance of interest is on the upper side—that is when the process may become RCRA-hazardous. Whether or not exceeding the limit would result in a change in the RCRA-hazardous nature of the waste stream depends on how close the observed control limits are to RCRA limits.

Current process data are collected and averaged for comparison to the control limit for the mean. The collection period and number of samples included in the average are dependent on the waste stream characteristics. A small number of samples will reflect more of the process variability and there will be more limit exceedances. If two or three samples are collected for the mean in the required annual (or batch) sampling of a relatively homogeneous waste stream, limit exceedances may not occur. If the waste stream is less homogeneous, it will be necessary to collect more samples to meet the required confidence limit. Periodically, it will be

necessary to update the control limit for a process. An update that includes all historical data is performed if there is no evidence of a trend in the process or a shift in the mean for the process. If there has been a shift in the mean, only more recent data that reflect the shift are used. Control limits shall be based on at least ten data points that are representative of the process and do not exhibit outliers or a trend with time.

Legal Requirements

INTRODUCTION

The Waste Isolation Pilot Plant project was authorized in 1979 (PL96-164) as a research and development activity to demonstrate the safe disposal of radioactive waste originating from the U.S. nuclear weapons program. This and several other laws and regulations have resulted in the construction and operation of the Waste Isolation Pilot Plant (WIPP) as a unique facility for the disposal of transuranic (TRU) waste.

TRU waste is defined as a waste containing alpha-emitting isotopes of transuranic elements equal to or in excess of 100 nCi/g of waste. The half-lives of the isotopes of these elements must be greater than 20 years.

Much of the TRU waste contains chemical constituents subject to the regulations of the Resource Conservation and Recovery Act (RCRA) and the New Mexico Hazardous Waste Act. TRU wastes that contain both chemical and radioactive waste are referred to as TRU mixed waste. According to RCRA, WIPP is required to have a hazardous waste permit to receive waste containing hazardous waste constituents. The State of New Mexico has adopted the relevant RCRA regulations by reference and thus is authorized to issue hazardous waste permits. WIPP received a permit (NMED 1999) on October 27, 1999 for contact-handled (CH) waste, defined as having a surface radiation dose rate not greater than 200 mrem/h (2 mSv/h). TRU waste having a greater dose rate than 200 mrem/h (2 mSv/h) is defined as Remote Handled (RH) TRU Waste.

The enactment of the WIPP Land Withdrawal Act (WIPP/LWA 1992) resulted in permanent withdrawal and transfer of the administration of federal land for the site from the U.S. Department of Interior to the DOE. This law mandated that the U.S. Environmental Protection Agency (EPA) certify the DOE's compliance with EPA's relevant, generally applicable environmental standards for radioactive materials. Subsequently, the EPA (1996a) issued the criteria to be used in certifying compliance. In response, the DOE provided the EPA with appropriate documents; model; and evaluations of the geology, hydrology, and climate as well as projected performance of the entire disposal system, including the mined repository, shaft seals, panel closures, borehole plugs, and mine backfill. Finally, the

EPA (1998) certified that the WIPP met all of the criteria required for the disposal of TRU waste.

The WIPP/LWA limited the amount and types of TRU wastes that can be emplaced at WIPP. The limits include the following:

1. The volume WIPP capacity is limited to 1.75 x 10^5 m^3 (6.2 x 10^6 ft^3) total TRU waste.
2. No more than 5% (by volume) of RH-TRU waste may have a surface dose rate in excess of 100 rem/h (1Sv/h).
3. No RH-TRU waste may have a surface dose rate in excess of 1,000 rem/h (10 Sv/h).
4. RH-TRU waste containers shall not exceed 23 Ci/L (851 GBq/L) maximum activity level averaged over the volume of the container.
5. The total radioactivity of RH-TRU waste shall not exceed 5.1 MCi (188.7 Gbq).
6. Of the allowed waste disposal volume of 1.75 x 10^5 m^3 (6.2 x 10^6 ft^3), the Consultation and Cooperation Agreement with the State of New Mexico limits the volume of RH-TRU waste to 7,080 m^3 (250,000 ft^3).

The 41 km^2 (16 mi^2) area under DOE's jurisdiction at WIPP is deemed sufficient to ensure that at least 1 mi. (1.6 km) of intact salt exists laterally between the waste disposal area and the accessible environment, and also to ensure that no permanent residences will be established in close proximity to the facility.

BRIEF WIPP CHRONOLOGY

1957 National Research Council recommended salt as host rock, identified areas to investigate, and identified favorable siting criteria

1974 Atomic Energy Commission selected site near Carlsbad for exploratory work

1979 Congress authorized WIPP for research and development for safe disposal of defense-generated radioactive waste

1980 DOE issued Final Environmental Impact Statement (FEIS)

1981 DOE issued Record of Decision

1981 DOE began construction of WIPP Exploratory Shaft

1985 EPA issued 40 CFR 191—radioactive waste disposal standards applicable to WIPP

1986 EPA stated facilities must comply with Resource Conservation and Recovery Act (RCRA) for disposal of mixed (hazardous and radioactive) waste

1990 New Mexico was authorized by EPA to regulate mixed waste

1990 DOE issued first Supplemental Environmental Impact Statement (SEIS)

1991 DOE submitted Parts A and B of the RCRA Permit Application to New Mexico

1992 WIPP Land Withdrawal Act permanently segregated land for WIPP and gave EPA regulatory authority to certify WIPP compliance to 40 CFR 191.

1995 DOE submitted revised RCRA Permit Application to New Mexico Environment Department

1996 EPA issued 40 CFR 194, compliance criteria in February

1996 DOE submitted 84,000 page Compliance Certification Application to EPA

1998 DOE issued SEIS II in January

1998 EPA certified WIPP ready for disposal

1998 New Mexico Environment Department issued draft hazardous waste facility permit (HWFP) for disposal of transuranic mixed waste

1999 First shipment non-mixed waste in March

1999 New Mexico Environment Department issued Hazardous Waste Facility Permit

2000 First shipment of mixed waste in September

EPA'S CRITERIA FOR WIPP CERTIFICATION

Criteria for certification and re-certification of WIPP were published in final form by the EPA (1996a). These criteria were detailed and contained specific requirements related to the radioactivity content of TRU waste. In its regulations, EPA provided requirements not only for quality assurance and characterization but also specific requirements for expert judgement and peer review. Although EPA's certification and re-certification do not apply to radioactive waste constituents of TRU waste, the description of peer review requirements may be useful as they can be advantageously used also for hazardous waste constituents. The following are excerpts from EPA's regulations:

"§ 194.27 Peer review.

(a) Any compliance application shall include documentation of peer review that has been conducted, in a manner required by this section, for:

(1) Conceptual models selected and developed by the Department;

(2) Waste characterization analyses as required in § 194.24(b); and

(3) Engineered barrier evaluation as required in § 194.44.

(b) Peer review processes required in paragraph (a) of this section, and conducted subsequent to the promulgation of this part, shall be conducted in a manner that is compatible with NUREG-1297, "Peer Review for High-Level Nuclear Waste Repositories," published February 1988. (Incorporation by reference as specified in § 194.5.)

(c) Any compliance application shall:

(1) Include information that demonstrates that peer review processes required in paragraph (a) of this section, and conducted prior to the implementation of the promulgation of this part, were conducted in accordance with an alternate process substantially equivalent in effect to NUREG-1297 and approved by the Administrator or the Administrator's authorized representative; and

(2) Document any peer review processes conducted in addition to those required pursuant to paragraph (a) of this section. Such documentation shall include formal requests, from the Department to outside review groups or individuals, to review or comment on any information used to support compliance applications, and the responses from such groups or individuals."

The packaging of waste at the originating sites; transport to the site; transport vehicles; and disposal of heat-generating waste are beyond the scope of this study and are not dealt with in this report.

The health and safety consequences of the postulated repository failure mechanisms appear to be so minimal that simplifications in design may be justified, and cost-effectiveness studies should be carried out to determine whether they would be acceptable. However, the probability and the consequences of potentially rapid flow of brine solutions containing radionuclides, through more permeable formations, have not been completely determined. Once these have been resolved, conventional safety considerations (e.g., number of shafts and packaging of waste for highway transport) might determine the optimum design.

Relaxation of the WIPP waste acceptance criteria (e.g., elimination of the incineration of some of the waste at the Process Experimental Pilot Plant (PREPP) facility and removal of the requirement for the use of steel-case overpack of the wooden boxes) may also have minimal consequences.

PUBLIC LAW 102-579
THE WASTE ISOLATION PILOT PLANT LAND WITHDRAWAL ACT

as amended by Public Law 104-201
(H.R. 3230, 104th Congress)

SECTION I. SHORT TITLE; TABLE OF CONTENTS.

(a) SHORT TITLE.—This Act may be cited as the "Waste Isolation Pilot Plant Land Withdrawal Act".

(b) TABLE OF CONTENTS.—

Sec. 1. Short title; table of contents.
Sec. 2. Definitions.
Sec. 3. Land withdrawal and reservation for WIPP.
Sec. 4. Establishment of management responsibilities.
Sec. 6. Test phase activities.
Sec. 7. Disposal operations.
Sec. 8. Environmental Protection Agency disposal regulations.
Sec. 9. Compliance with environmental laws and regulations.
Sec. 10. Sense of Congress on commencement of emplacement of transuranic waste.
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Sec. 20. Statement for purposes of Public Law 96-164.
Sec. 21. Consultation and cooperation agreement.
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Sec. 23. Authorization of appropriations.

SEC. 2. DEFINITIONS.

For purposes of this Act:

(1) ADMINISTRATOR.—The term "Administrator" means the Administrator of the Environmental Protection Agency.

(2) AGREEMENT.—The term "Agreement" means the July 1, 1981, Agreement for Consultation and Cooperation, as amended by the November 30, 1984 "First Modification", the August 4, 1987 "Second Modification", and the March 18, 1988 "Third Modification" or as it may be amended after the date of enactment of this Act between the State and the United States Department of Energy as authorized by section 213(b) of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub. L. 96-164; 93 Stat. 1259, 1265).

(3) CONTACT-HANDLED TRANSURANIC WASTE.—The term "contact-handled transuranic waste" means transuranic waste with a surface dose rate not greater than 200 millirem per hour.

(4) DECOMMISSIONING PHASE.—The term "decommissioning phase" means the period of time beginning with the end of the disposal phase and ending when all shafts at the WIPP repository have been back-filled and sealed.

(5) DISPOSAL.—The term "disposal" means permanent isolation of transuranic waste from the accessible environment with no intent of recovery, whether or not such isolation permits the recovery of such waste.

(6) DISPOSAL PHASE.—The term "disposal phase" means the period of time, during which transuranic waste is disposed of at WIPP, beginning with the initial emplacement of transuranic waste underground for disposal and ending when the last container of transuranic waste, as determined by the Secretary, is emplaced underground for disposal.

(7) DISPOSAL REGULATIONS.—The term "disposal regulations" means the environmental regulations for the disposal of spent nuclear fuel, high-level radioactive waste, and transuranic waste under section 8.

(8) EEG.—The term "EEG" means the Environmental Evaluation Group for the Waste Isolation Pilot Plant referred to in section 1433 of the National Defense Authorization Act, Fiscal Year 1989 (Pub. L. 100-456; 102 Stat. 1918, 2073).

(9) ENGINEERED BARRIERS.—The term "engineered barriers" means backfill, room seals, panel seals, and any other manmade barrier components of the disposal system.

(10) HIGH-LEVEL RADIOACTIVE WASTE.—The term "high-level radioactive waste" has the meaning given such term in section 2(12) of the Nuclear Waste Policy Act of 1982 (42 U.S.C. 10101(12)).

(11) NO-MIGRATION DETERMINATION.—The term "No-Migration Determination" means the Final Conditional No-Migration Determination for the Department of Energy Waste Isolation Pilot Plant published by the Environmental Protection Agency on November 14, 1990 (55 Fed. Reg. 47700), and any amendments thereto, pursuant to the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.).

(12) REMOTE-HANDLED TRANSURANIC WASTE.—The term "remote-handled transuranic waste" means transuranic waste with a surface dose rate of 200 millirem per hour or greater.

(13) RETRIEVAL.—The term "retrieval" means the removal of transuranic waste and the container in which it has been retained and any material contaminated by such waste from the underground repository at WIPP.

(14) SECRETARY.—The term "the Secretary" means the Secretary of Energy.

(15) SPENT NUCLEAR FUEL.—The term "spent nuclear fuel" has the meaning given such term in section 2(23) of the Nuclear Waste Policy Act of 1982 (42 U.S.C. 10101(23)).

(16) STATE.—The term "the State" means the State of New Mexico.

(17) SUPPLEMENTAL STIPULATED AGREEMENT.—The term "Supplemental Stipulated Agreement" means the Supplemental Stipulated Agreement Resolving Certain State Off-Site Concerns Over WIPP, dated December 27, 1982, to the Stipulated Agreement Between DOE and the State in *State of New Mexico ex rel. Bingaman v. DOE*, Case No. CA 81-0363 JB (D. N. Mex.), dated July 1, 1981.

(18) TRANSURANIC WASTE.—The term "transuranic waste" means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for—

(A) high-level radioactive waste;

(B) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations; or

(C) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with part 61 of title 10, Code of Federal Regulations.

(19) WIPP.—The term "WIPP" means the Waste Isolation Pilot Plant project authorized under section 213 of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub. L. 96-164; 93 Stat. 1259 1265) to demonstrate the safe disposal of radioactive waste materials generated by atomic energy defense activities.

(20) WITHDRAWAL.—The term "Withdrawal" means the geographical area consisting of the lands described in section 3(c).

SEC. 3. LAND WITHDRAWAL AND RESERVATION FOR WIPP.

(a) LAND WITHDRAWAL, JURISDICTION, AND RESERVATION.—

(1) LAND WITHDRAWAL.—Subject to valid existing rights, and except as otherwise provided in this Act, the lands described in subsection (c) are withdrawn from all forms of entry, appropriation, and disposal under the public land laws, including without limitation the mineral leasing laws, the geothermal leasing laws, the material sale laws (except as provided in section 4(b)(4) of this Act), and the mining laws.

(2) JURISDICTION.—Except as otherwise provided in this Act, jurisdiction over the Withdrawal is transferred from the Secretary of the Interior to the Secretary.

(3) RESERVATION.—Such lands are reserved for the use of the Secretary for the construction, experimentation, operation, repair and maintenance, disposal, shutdown, monitoring, decommissioning, and other authorized activities associated with the purposes of WIPP as set forth in section 213 of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub. L. 96-164; 93 Stat. 1259, 1265), and this Act.

(b) REVOCATION OF PUBLIC LAND ORDERS.—Public Land Order 6403 of June 29, 1983, as modified by Public Land Order 6826 of January 28, 1991, and any memoranda of understanding accompanying such land orders, are revoked.

(c) LAND DESCRIPTION.—

(1) BOUNDARIES.—The boundaries depicted on the map issued by the Bureau of Land Management of the Department of the Interior, entitled "WIPP Withdrawal Site Map," dated October 9, 1990, and on file

with the Bureau of Land Management, New Mexico State Office, are established as the boundaries of the Withdrawal.

(2) LEGAL DESCRIPTION AND MAP.—Within 30 days after the date of the enactment of this Act, the Secretary of the Interior shall—

(A) publish in the Federal Register a notice containing a legal description of the Withdrawal; and

(B) file copies of the map described in paragraph (1) and the legal description of the Withdrawal with the Congress, the Secretary, the Governor of the State, and the Archivist of the United States.

(d) TECHNICAL CORRECTIONS.—The map and legal description referred to in subsection (c) shall have the same force and effect as if they were included in this Act. The Secretary of the Interior may correct clerical and typographical errors in the map and legal description.

(e) WATER RIGHTS.—This Act does not establish, nor may any provision be construed to establish, a reservation to the United States with respect to any water or water rights. Nothing in this Act shall affect any water rights acquired by the United States prior to the date of enactment of this Act. The United States may apply for and obtain water rights for purposes associated with this Act only in accordance with the substantive and procedural requirements of the laws of the State.

SEC. 4. ESTABLISHMENT OF MANAGEMENT RESPONSIBILITIES.

(a) GENERAL AUTHORITY.—The Secretary shall be responsible for the management of the Withdrawal, consistent with the Federal Land Policy and Management Act of 1976 (43 U.S.C. 1701 et seq.), this Act, and other applicable law, and shall consult with the Secretary of the Interior and the State in discharging such responsibility.

(b) MANAGEMENT PLAN.—

(1) DEVELOPMENT.—Within 1 year after the date of the enactment of this Act, the Secretary, in consultation with the Secretary of the Interior and the State, shall develop a management plan for the use of the Withdrawal until the end of the decommissioning phase.

(2) PRIORITY OF WIPP-RELATED USES.—Any use of the Withdrawal for activities not associated with WIPP shall be subject to such conditions and restrictions as may be necessary to permit the conduct of WIPP-related activities.

(3) NON-WIPP RELATED USES.—The management plan developed under paragraph (1) shall provide for the maintenance of wildlife habitat and shall provide that the Secretary may permit such non-WIPP related uses of the Withdrawal as the Secretary determines to be appropriate, including domestic livestock grazing and hunting and trapping in accordance with the following requirements:

(A) GRAZING.—The Secretary may permit grazing to continue where established before the date of the enactment of this Act, subject to such regulations, policies, and practices as the Secretary, in consultation with the Secretary of the Interior, determines to be necessary or appropriate. The management of grazing shall be conducted in accord with applicable grazing laws and policies, including—

(i) the Act entitled "An Act to stop injury to public grazing lands by preventing overgrazing and soil deterioration, to provide for their orderly use, improvement, and development, to stabilize the livestock industry dependent upon the public range, and for other purposes," approved June 28, 1934 (43 U.S.C. 315 et seq., commonly referred to as the "Taylor Grazing Act");

(ii) title IV of the Federal Land Policy and Management Act of 1976 (43 U.S.C. 1751 et seq.); and

(iii) the Public Rangelands Improvement Act of 1978 (43 U.S.C. 1901 et seq.).

(B) HUNTING AND TRAPPING.—The Secretary may permit hunting and trapping within the Withdrawal in accordance with applicable laws and regulations of the United States and the State, except that the Secretary, after consultation with the Secretary of the Interior and the State, may issue regulations designating zones where, and establishing periods when, no hunting or trapping is permitted for reasons of public safety, administration, or public use and enjoyment.

(4) DISPOSAL OF SALT TAILINGS.—The Secretary shall dispose of salt tailings extracted from the Withdrawal that the Secretary determines are not needed for backfill at WIPP. Disposition of such tailings shall be made under sections 2 and 3 of the Act of July 31, 1947, (30 U.S.C. 602, 603; commonly referred to as the "Materials Act of 1947").

(5) MINING.—

(A) IN GENERAL.—Except as provided in subparagraph (B), no surface or subsurface mining or oil or gas production, including slant drilling from outside the boundaries of the Withdrawal, shall be permitted

at any time (including after decommissioning) on lands on or under the Withdrawal.

(B) EXCEPTION.—Existing rights under Federal Oil and Gas Leases No. NMNM 02953 and No. NMNM 02953C shall not be affected unless the Administrator determines, after consultation with the Secretary and the Secretary of the Interior, that the acquisition of such leases by the Secretary is required to comply with the final disposal regulations.

(c) CLOSURE TO PUBLIC.—If during the land withdrawal made by section 3(a) the Secretary determines, in consultation with the Secretary of the Interior, that the health and safety of the public or the common defense and security require the closure to the public use of any road, trail, or other portion of the Withdrawal, the Secretary may take whatever action the Secretary determines to be necessary to effect and maintain the closure and shall provide notice to the public of such closure.

(d) MEMORANDUM OF UNDERSTANDING.—The Secretary and the Secretary of the Interior shall enter into a memorandum of understanding to implement the management plan developed under subsection (b). Such memorandum shall remain in effect until the end of the decommissioning phase.

(e) SUBMISSION OF PLAN.—Within 1 year after the date of the enactment of this Act, the Secretary shall submit the management plan developed under subsection (b) to the Congress and the State. Any amendments to the plan shall be submitted promptly to the Congress and the State.

SEC. 6. TEST PHASE ACTIVITIES.

(a) STUDY—The following study shall be conducted:

(1) IN GENERAL.—Within 3 years after the date of the enactment of this Act, the Secretary shall complete a study on remote-handled transuranic waste in consultation with affected States, the Administrator, and after the solicitation of views of other interested parties.

(2) REQUIREMENTS OF STUDY.—Such study shall include an analysis of the impact of remote-handled transuranic waste on the performance assessment of WIPP and a comparison of remote-handled transuranic waste with contact-handled transuranic waste on such issues

as gas generation, flammability, explosiveness, solubility, and brine and geochemical interactions.

(3) PUBLICATION.—The Secretary shall publish the findings of such study in the Federal Register.

(b) PERFORMANCE ASSESSMENT REPORT.—

(1) IN GENERAL.—The Secretary shall publish a performance assessment report as necessary to demonstrate the long-term performance of WIPP. Each such report shall be provided to the State, the Administrator, the National Academy of Sciences, and the EEG for their review and comment.

(2) RESPONSES BY SECRETARY TO COMMENTS.—If, within 120 days of the publication of a performance assessment report under paragraph (1), the State, the Administrator, the National Academy of Sciences, or the EEG provide written comments on the report, the Secretary shall submit written responses to the comments to the State, the Administrator, the National Academy of Sciences, and the EEG, and to other appropriate entities or persons after consultation with the State, within 120 days of receipt of the comments.

SEC. 7. DISPOSAL OPERATIONS.

(a) TRANSURANIC WASTE LIMITATIONS.—

(1) REM LIMITS FOR REMOTE-HANDLED TRANSURANIC WASTE.—

(A) 1,000 REMS PER HOUR.—No transuranic waste received at WIPP may have a surface dose rate in excess of 1,000 rems per hour.

(B) 100 REMS PER HOUR.—No more than 5 percent by volume of the remote-handled transuranic waste received at WIPP may have a surface dose rate in excess of 100 rems per hour.

(2) CURIE LIMITS FOR REMOTE-HANDED TRANSURANIC WASTE.—

(A) CURIES PER LITER.—Remote-handled transuranic waste received at WIPP shall not exceed 23 curies per liter maximum activity level (averaged over the volume of the canister).

(B) TOTAL CURIES.—The total curies of the remote-handled transuranic waste received at WIPP shall not exceed 5,100,000 curies.

(3) CAPACITY OF WIPP.—The total capacity of WIPP by volume is 6.2 million cubic feet of transuranic waste.

(b) REQUIREMENTS FOR COMMENCEMENT OF DISPOSAL OPERATIONS.—The Secretary may commence emplacement of transuranic waste underground for disposal at WIPP only upon completion of—

(1) the Administrator's certification under section 8(d)(1) that the WIPP facility will comply with the final disposal regulations;

(2) the acquisition by the Secretary (whether by purchase, condemnation, or otherwise) of Federal Oil and Gas Leases No. NMNM 02953 and No. NMNM 02953C, unless the Administrator determines under section 4(b)(5) that such acquisition is not required; and

(3) the 30-day period beginning on the date on which the Secretary notifies Congress that the requirements of section 9(a)(1) have been met.

SEC. 8. ENVIRONMENTAL PROTECTION AGENCY DISPOSAL REGULATIONS.

(a) REINSTATEMENT.—

(1) IN GENERAL.—Except as provided in paragraph (2), the disposal regulations issued by the Administrator on September 19, 1985, and contained in subpart B of part 191 of title 40, Code of Federal Regulations, shall be in effect.

(2) EXCEPTIONS.—Paragraph (1) shall not apply to—

(A) the 3 aspects of sections 191.15 and 191.16 of such regulations that were the subject of the remand ordered in Natural Resources Defense Council, Inc. v. United States Environmental Protection Agency, 824 F.2d 1258 (1st Cir. 1987); and

(B) the characterization, licensing, construction, operation, or closure of any site required to be characterized under section 113(a) of Public Law 97-425.

(b) ISSUANCE OF REGULATIONS.—

(1) IN GENERAL.—Subject to the limitation in paragraph (2), the Administrator shall issue, not later than 6 months after the date of the enactment of this Act, final disposal regulations. Such regulations shall be issued in a rulemaking proceeding conducted under section 553 of title 5, United States Code, except that sections 556 and 557 of such title shall not apply.

(2) LIMITATION.—The regulations required by this subsection shall not be applicable to the characterization, licensing, construction, operation,

or closure of any site required to be characterized under section 113(a) of Public Law 97-425.

(c) ISSUANCE OF CRITERIA FOR CERTIFICATION OF COMPLIANCE WITH DISPOSAL REGULATIONS.—

(1) PROPOSED CRITERIA.—Not later than 1 year after the date of the enactment of this Act, the Administrator shall, by rule pursuant to section 553 of title 5, United States Code, propose criteria for the Administrator's certification of compliance with the final disposal regulations, and sections 556 and 557 of such title shall not apply.

(2) FINAL CRITERIA.—Not later than 2 years after the date of the enactment of this Act, the Administrator shall, by rule pursuant to section 553 of title 5, United States Code, issue final criteria for the Administrator's certification of compliance with the final disposal regulations, and sections 556 and 557 of such title shall not apply.

(d) DISPOSAL REGULATIONS.—

(1) APPLICATION FOR COMPLIANCE.—Within 30 days after the date of the enactment of the Waste Isolation Pilot Plant Land Withdrawal Amendment Act, the Secretary shall provide to Congress a schedule for the incremental submission of chapters of the application to the Administrator beginning no later than 30 days after the date of the submittal of the schedule. The Administrator shall review the submitted chapters and provide requests for additional information from the Secretary as needed for completeness within 45 days of the receipt of each chapter. The Administrator shall notify Congress of such requests. The schedule shall call for the Secretary to submit all chapters to the Administrator no later than October 31, 1996. The Administrator may at any time request additional information from the Secretary as needed to certify, pursuant to paragraph (2), whether the WIPP facility will comply with the final disposal regulations.

(2) CERTIFICATION BY ADMINISTRATOR.—Within 1 year of receipt of the application under paragraph (1), the Administrator shall certify, by rule pursuant to section 553 of title 5, United States Code, whether the WIPP facility will comply with the final disposal regulations, and sections 556 and 557 of such title shall not apply.

(3) JUDICIAL REVIEW.—Judicial review of the certification of the Administrator under paragraph (2) shall not be restricted by the provisions of section 221 c. of the Atomic Energy Act of 1954 (42 U.S.C. 2271(c)).

(4) LIMITATION.—Any certification of the Administrator under paragraph (2) may only be made after the full application has been submitted to the Administrator under paragraph (1).

(e) CONFLICT RESOLUTION.—If the State disagrees with the Secretary's application under subsection (d)(1)(A), the State may invoke the conflict resolution provisions of the Agreement.

(f) PERIODIC RECERTIFICATION.—

(1) BY SECRETARY.—Not later than 5 years after the initial receipt of transuranic waste for disposal at WIPP, and every 5 years thereafter until the end of the decommissioning phase, the Secretary shall submit to the Administrator and the State documentation of continued compliance with the final disposal regulations.

(2) CONCURRENCE BY ADMINISTRATOR.—The Administrator shall, not later than 6 months after receiving a submission under paragraph (1), determine whether or not the WIPP facility continues to be in compliance with the final disposal regulations. A determination under this paragraph shall not be subject to rulemaking or judicial review.

(g) ENGINEERED AND NATURAL BARRIERS, ETC.—The Secretary shall use both engineered and natural barriers and any other measures (including waste form modifications) to the extent necessary at WIPP to comply with the final disposal regulations.

SEC. 9. COMPLIANCE WITH ENVIRONMENTAL LAWS AND REGULATIONS.

(a) IN GENERAL.—

(1) APPLICABILITY.—Beginning on the date of the enactment of this Act, the Secretary shall comply with respect to WIPP, with—

(A) the regulations issued by the Administrator establishing the generally applicable environmental standards for the management and storage of spent nuclear fuel, high-level radioactive waste, and transuranic radioactive waste and contained in subpart A of part 191 of title 40, Code of Federal Regulations;

(B) the Clean Air Act (40 U.S.C. 7401 et seq.);

(C) the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.);

(D) title XIV of the Public Health Service Act (42 U.S.C. 300f et seq.; commonly referred to as the "Safe Drinking Water Act");

(E) the Toxic Substances Control Act (15 U.S.C. 2601 et seq.);

(F) the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (42 U.S.C. 9601 et seq.);

(G) all other applicable Federal laws pertaining to public health and safety or the environment; and

(H) all regulations promulgated, and all permit requirements, under the laws described in subparagraphs (B) through (G).

With respect to transuranic mixed waste designated by the Secretary for disposal at WIPP, such waste is exempt from treatment standards promulgated pursuant to section 3004(m) of the Solid Waste Disposal Act (42 U.S.C. 6924(m)) and shall not be subject to the land disposal prohibitions in section 3004(d), (e), (f), and (g) of the Solid Waste Disposal Act.

(2) PERIODIC OVERSIGHT BY ADMINISTRATOR AND STATE.—The Secretary shall, not later than 2 years after the date of the enactment of this Act, and biennially thereafter, submit documentation of continued compliance with the laws, regulations, and permit requirements described in paragraph (1) to the Administrator, and, with the law described in paragraph (l)(C), to the State.

(3) DETERMINATION BY ADMINISTRATOR OR STATE.—The Administrator or the State, as appropriate, shall determine not later than 6 months after receiving a submission under paragraph (2) whether the Secretary is in compliance with the laws, regulations, and permit requirements described in paragraph (1) with respect to WIPP.

(c) DETERMINATION OF NONCOMPLIANCE DURING DISPOSAL PHASE AND DECOMMISSIONING PHASE.—

(1) DETERMINATION BY THE ADMINISTRATOR.—If the Administrator determines at any time during the disposal phase or decommissioning phase that the WIPP facility does not comply with any law, regulation, or permit requirement described in subsection (a)(1), the Administrator shall request a remedial plan from the Secretary describing actions the Secretary will take to comply with such law, regulation, or permit requirement.

(d) SAVINGS PROVISION.—The authorities provided to the Administrator and to the State pursuant to this section are in addition to the enforcement authorities available to the State pursuant to State law and to the Administrator, the State, and any other person, pursuant to the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.) and the Clean Air Act (40 U.S.C. 7401 et seq.).

SEC. 10. SENSE OF CONGRESS ON COMMENCEMENT OF EMPLACEMENT OF TRANSURANIC WASTE.

It is the sense of Congress that the Secretary should complete all actions required under section 7(b) to commence emplacement of transuranic waste underground for disposal at WIPP not later than November 30, 1997, provided that before that date all applicable health and safety standards have been met and all applicable laws have been complied with.

SEC. 11. MINE SAFETY.

(a) MINE SAFETY AND HEALTH ADMINISTRATION.—The Mine Safety and Health Administration of the Department of Labor shall inspect WIPP not less than 4 times each year and in the same manner as it evaluates mine sites under the Federal Mine Safety and Health Act of 1977 (30 U.S.C. 801 et seq.), and shall provide the results of its inspections to the Secretary. The Secretary shall make the results of such inspections publicly available and shall take necessary actions to ensure the prompt and effective correction of any deficiency, including suspending specific activities as necessary to address identified health and safety deficiencies.

(b) BUREAU OF MINES.—The Bureau of Mines of the Department of the Interior shall prepare an annual evaluation of the safety of WIPP.

SEC. 12. BAN ON HIGH-LEVEL RADIOACTIVE WASTE AND SPENT NUCLEAR FUEL.

The Secretary shall not transport high-level radioactive waste or spent nuclear fuel to WIPP or emplace or dispose of such waste or fuel at WIPP.

SEC. 13. DECOMMISSIONING OF WIPP.

The Secretary shall develop a plan for the management and use of the Withdrawal following the decommissioning of WIPP or the termination of the land withdrawal. The Secretary shall consult with the Secretary of

the Interior and the State in the preparation of such plan and shall submit such plan to the Congress.

SEC. 14. SAVINGS PROVISIONS.

(a) CAA AND SWDA.—Except for the exemption from the land disposal restrictions described in section 9(a)(1), no provision of this Act may be construed to supersede or modify the provisions of the Clean Air Act (42 U.S.C. 7401 et seq.) or the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.).

(b) EXISTING AUTHORITY OF EPA AND STATE.—No provision of this Act may be construed to limit, or in any manner affect, the Administrator's or the State's authority to enforce, or the Secretary's obligation to comply with—

(1) the Clean Air Act (42 U.S.C. 7401 et seq.);

(2) the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.), except that the transuranic mixed waste designated by the Secretary for disposal at WIPP is exempt from the land disposal restrictions described in section 9(a)(1); or

(3) any other applicable clean air or hazardous waste law.

SEC. 15. ECONOMIC ASSISTANCE AND MISCELLANEOUS PAYMENTS.

(a) 14-YEAR AUTHORIZATION.—There are authorized to be appropriated to the Secretary for payments to the State $20,000,000 for each of the 14 fiscal years beginning with fiscal year 1998. The authorization of appropriations for funds for payments to the State under the preceding sentence shall be separate from any authorization of appropriations of funds for WIPP.

(b) SUBSEQUENT AUTHORIZATIONS.—There are authorized to be appropriated to the Secretary, for payments to the State for any fiscal year after the last fiscal year to which subsection (a) applies, such sums as the Congress may, by law, authorize to be appropriated.

(c) INFLATION ADJUSTMENT.—

(1) IN GENERAL.—In the case of any fiscal year after the first fiscal year to which subsection (a) applies, the dollar amount specified in such subsection shall be increased or decreased, as the case may be, by an amount equal to—

(A) such dollar amount; multiplied by

(B) the inflation increase or decrease determined under paragraph (2).

(2) CALCULATION OF INFLATION INCREASE OR DECREASE.—For purposes of paragraph (1), the inflation increase or decrease for any fiscal year is the percentage (if any) by which the inflation index for the preceding fiscal year is greater than or less than, as the case may be, the inflation index for the fiscal year prior to the first fiscal year to which subsection (a) applies.

(3) INFLATION INDEX.—For purposes of paragraph (2), the inflation index for any fiscal year is the average of the Consumer Price Index (as published by the Department of Labor) for the 12 months in such fiscal year.

(d) ELIGIBLE ASSISTANCE.—A portion of the payments under this section—

(1) shall be made available to units of local government in Lea and Eddy counties in the State; and

(2) may also be provided for independent environmental assessment and economic studies associated with WIPP.

SEC. 16. TRANSPORTATION.

(a) SHIPPING CONTAINERS.—No transuranic waste may be transported by or for the Secretary to or from WIPP, except in packages—

(1) the design of which has been certified by the Nuclear Regulatory Commission; and

(2) that have been determined by the Nuclear Regulatory Commission to satisfy its quality assurance requirements. The determination under paragraph (2) shall not be subject to rulemaking or judicial review.

(b) NOTIFICATION.—In addition to activities required pursuant to the Supplemental Stipulated Agreement, prior to any transportation of transuranic waste by or for the Secretary to or from WIPP, the Secretary shall provide advance notification to States and Indian tribes through whose jurisdiction the Secretary plans to transport transuranic waste to or from WIPP.

(c) ACCIDENT PREVENTION AND EMERGENCY PREPAREDNESS.—

(1) TRAINING.—

(A) IN GENERAL.—In addition to activities required pursuant to the Supplemental Stipulated Agreement, the Secretary shall, to the extent provided in appropriation Acts, provide technical assistance and funds for the purpose of training public safety officials, and other emergency responders as described in part 1910.120 of title 29, Code of Federal Regulations, in any State or Indian tribe through whose jurisdiction the Secretary plans to transport transuranic waste to or from WIPP. Within 30 days of the date of the enactment of this Act, the Secretary shall submit a report to the Congress and to the States and Indian tribes through whose jurisdiction the Secretary plans to transport transuranic waste on the training provided through fiscal year 1992.

(B) ONGOING TRAINING.—If determined by the Secretary, in consultation with affected States and Indian tribes, to be necessary and appropriate, training described in subparagraph (A) shall continue after the date of the enactment of this Act until the transuranic waste shipments to or from WIPP have been terminated.

(C) REVIEW OF TRAINING.—The Secretary shall periodically review the training provided pursuant to subparagraph (A) in consultation with affected States and Indian tribes. The training shall also be reviewed by the Occupational Safety and Health Administration, and the National Institute for Occupational Safety and Health, for compliance with part 1910.120 of title 29, Code of Federal Regulations.

(D) COMPONENTS OF TRAINING.—The training shall cover procedures required for the safe routine transportation of transuranic waste, as well as procedures for dealing with emergency response situations, including—

(i) instruction of government officials and public safety officers in procedures for the command and control of the response to any incident involving the waste;

(ii) instruction of emergency response personnel in procedures for the initial response to an incident involving transuranic waste being transported to or from WIPP;

(iii) instruction of radiological protection and emergency medical personnel in procedures for responding to an incident involving transuranic waste being transported to or from WIPP; and

(iv) a program to provide information to the public about the transportation of transuranic waste to or from WIPP.

(2) EQUIPMENT.—The Secretary shall enter into agreements to assist States through monetary grants or contributions in-kind, to the extent provided in appropriation Acts, in acquiring equipment for response to an incident involving transuranic waste transported to or from WIPP.

(d) TRANSPORTATION SAFETY PROGRAMS.—The Secretary shall, to the extent provided in appropriation Acts, provide in-kind, financial, technical, and other appropriate assistance to any State or Indian tribe through whose jurisdiction the Secretary plans to transport transuranic waste to or from WIPP, for the purpose of WIPP-specific transportation safety programs not otherwise addressed in this section. These programs shall be developed with, and monitored by, the Secretary.

(e) SANTA FE BYPASS.—No transuranic waste may be transported from the Los Alamos National Laboratory to WIPP until—

(1) an amount of funds sufficient to construct the Santa Fe bypass has been made available to the State;

(2) the Santa Fe bypass has been completed; or

(3) the Administrator has made the certification required under section 8(d)(1)(B).

(f) STUDY OF TRANSPORTATION ALTERNATIVES.—

(1) IN GENERAL.—The Secretary shall conduct a study comparing the shipment of transuranic waste to the WIPP facility by truck and by rail, including the use of dedicated trains, and shall submit a report on the study in accordance with paragraph (2). Such report shall include—

(A) a consideration of occupational and public risks and exposures, and other environmental impacts;

(B) a consideration of emergency response capabilities; and

(C) an estimation of comparative costs.

(2) REPORT.—The report required in paragraph (1) shall be submitted to the Congress not later than 1 year after the date of the enactment of this Act.

(g) EMERGENCY RESPONSE MEDICAL TRAINING.—

(1) DETERMINATION OF SECRETARY.—If the Secretary determines that emergency response medical training for incidents involving transuranic waste being transported to or from WIPP is inadequate, the Secretary shall take immediate action to correct the inadequacies and, if necessary, suspend transportation of such transuranic waste. If the State disagrees with the Secretary's determination under

this paragraph, the State may invoke the conflict resolution provisions of the Agreement.

(2) STATE ADVISORY GROUP.—The Secretary shall encourage the Governor of the State to appoint, within 30 days after the date of the enactment of this Act, an advisory group of health professionals and other experts in the field to review emergency response medical training programs for incidents involving transuranic waste being transported to or from WIPP. If such advisory group is established—

(A) its purpose shall be to review, within 60 days after its establishment and annually thereafter, the Department of Energy's emergency response medical training programs for incidents involving transuranic waste being transported to or from WIPP, and to report its findings to the State, the Secretary of Labor, acting through the Occupational Safety and Health Administration, and the Secretary; and

(B) the Secretary shall review the findings of the advisory group in consultation with the Secretary of Labor, acting through the Occupational Safety and Health Administration.

SEC. 17. ACCESS TO INFORMATION.

(a) IN GENERAL.—The Secretary shall—

(1) provide the State, the National Academy of Sciences, and the EEG with free and timely access to data relating to health, safety, or environmental issues at WIPP;

(2) provide the State and the EEG with preliminary reports relating to health, safety, or environmental issues at WIPP; and

(3) to the extent practicable, permit the State and the EEG to attend meetings relating to health, safety, or environmental issues at WIPP with expert panels and peer review groups.

(b) EVALUATION AND PUBLICATION.—The State, the National Academy of Sciences, and the EEG may evaluate and publish analyses of the Secretary's plans for test phase activities, monitoring, transportation, operations, decontamination, retrieval, performance assessment, compliance with Environmental Protection Agency regulations, decommissioning, safety analyses, and other activities relating to WIPP.

(c) CONSULTATION AND COOPERATION.—The Secretary shall consult and cooperate with the EEG under the terms of Contract No. DE-AC04-89AL53309 in the performance of its responsibility to conduct

an independent technical review and evaluation of WIPP under section 1433 of the National Defense Authorization Act, Fiscal Year 1989 (102 Stat. 2073).

SEC. 18. JUDICIAL REVIEW OF EPA ACTIONS.

A civil action for judicial review of any final action of the Administrator under this Act may be brought only in the United States Court of Appeals for the Tenth Circuit or for the District of Columbia, and shall be brought not later than the 60th day after the date of such final action.

SEC. 19. TECHNOLOGY STUDY.

Within 3 years after the date of the enactment of this Act, the Secretary shall submit to the Congress a study reviewing the technologies that are available and that are being developed for the processing or reduction of volumes of radioactive wastes. The study shall include an identification of technologies involving the use of chemical, physical, and thermal (including plasma) processing techniques.

SEC. 20. STATEMENT FOR PURPOSES OF PUBLIC LAW 96-164.

For purposes of subsection (c) of section 213 of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub. L. 96-164; 93 Stat. 1265), this Act shall be considered to amend such section.

SEC. 21. CONSULTATION AND COOPERATION AGREEMENT.

Nothing in this Act shall affect the Agreement or the Supplemental Stipulated Agreement between the State and the United States Department of Energy except as explicitly stated herein.

SEC. 22. BUY AMERICAN REQUIREMENTS.

(a) COMPLIANCE WITH BUY AMERICAN ACT.—No funds appropriated or transferred pursuant to this Act may be expended by an

entity unless the entity agrees that in expending the assistance the entity will comply with sections 2 through 4 of the Act of March 3, 1933 (41 U.S.C. 10a-10c, popularly known as the "Buy American Act").

(b) PURCHASE OF AMERICAN-MADE EQUIPMENT AND PRODUCTS.—

(1) IN GENERAL.—In the case of any equipment or product that may be authorized to be purchased with financial assistance provided under this Act, it is the sense of the Congress that entities receiving the assistance should, in expending the assistance, purchase only American-made equipment and products.

(2) NOTICE TO RECIPIENTS OF ASSISTANCE.—In providing financial assistance under this Act, the Secretary shall provide to each recipient of the assistance a notice describing the statement made in paragraph (1) by the Congress.

SEC. 23. AUTHORIZATIONS OF APPROPRIATIONS.

(a) FOR ADMINISTRATOR.—

(1) IN GENERAL.—There are authorized to be appropriated to the Administrator for the purpose of fulfilling the responsibilities of the Administrator under this Act, $10,000,000 for fiscal year 1992, $12,000,000 for fiscal year 1993, $14,000,000 for fiscal year 1994, and such sums as may be necessary for fiscal years 1995 through 2001.

(2) REPORT.—The Administrator shall, not later than September 30, 1993, and annually thereafter, issue a report to the Congress on the status of and resources required for the fulfillment of the Administrator's responsibilities under this Act.

(b) TRANSFERS FROM SECRETARY TO ADMINISTRATOR AND SECRETARY OF LABOR.—The Secretary is authorized to transfer from amounts appropriated for environmental restoration and waste management for fiscal years 1992 and 1993, and (to the extent approved in appropriation Acts) for fiscal years 1994 through 2001, such sums as may be necessary to fulfill the responsibilities of the Administrator under this Act and the Secretary of Labor under, paragraphs (4) and (6) of section 6(b).

(c) ACQUISITION OF LEASEHOLD.—There are authorized to be appropriated to the Secretary such sums as may be necessary to acquire the Federal Oil and Gas Leases No. NMNM 02953 and No. NMNM 02953C.

Approved October 30, 1992.
Amended September 23, 1996.

U.S. NUCLEAR REGULATORY COMMISSION

U.S. ENVIRONMENTAL PROTECTION AGENCY

Joint Guidance on Testing Requirements for Mixed Radioactive and Hazardous Waste

Clarification of RCRA Hazardous Waste Testing Requirements for Low-Level Radioactive Mixed Waste—Final Guidance

Disclaimer: The policies discussed in this document are not final Agency actions, but are intended solely as guidance. They are not intended, nor can they be relied upon, to create any rights enforceable by any party in litigation with the United States. The Environmental Protection Agency and Nuclear Regulatory Commission may follow the guidance, or act at variance with the guidance, based on an analysis of specific site circumstances. The agencies also reserve the right to change the guidance at any time, without public notice.

I. Background

Mixed waste is defined as waste that contains both hazardous waste subject to the requirements of the Resource Conservation and Recovery Act (RCRA) and source, special nuclear, or byproduct material subject to the requirements of the Atomic Energy Act (AEA).[1] This guidance addresses testing activities related to mixed low-level waste (LLW), which is a subset of mixed waste.[2] The term ''mixed waste,'' for the purposes of this document, will refer to mixed LLW. Additional information on the testing of hazardous wastes, which could apply to both mixed LLW and other types of mixed waste (e.g., high-level and transuranic mixed waste), is found in Appendix A. The information below is intended for use by Nuclear Regulatory Commission (NRC) licensees that may not be familiar with the hazardous waste characterization and testing requirements that apply to mixed waste. The guidance assumes that the reader is familiar with the NRC's regulations and regulatory framework for the management of radioactive material and focuses on compliance with the Environmental Protection Agency's (EPA's) requirements for the management of hazardous waste. Although it is written for commercial mixed

waste generators, the guidance may also be useful for Federal facilities that generate mixed waste.

Users of this guidance should have a good understanding of how mixed waste is defined (see above), and what authority, or authorities, regulate mixed waste testing activities. The hazardous component of mixed waste is regulated by EPA in those States where EPA implements the entire RCRA Subtitle C hazardous waste program (i.e., unauthorized States). Currently, EPA regulates mixed waste in Alaska, Hawaii, Iowa, Puerto Rico, the Virgin Islands, and American Samoa. In most instances mixed waste is regulated by State governments. Thirty-nine States and one territory (Guam) have been delegated authority by EPA to implement the base RCRA hazardous waste program and to regulate mixed waste activities (see 51 *FR* 24504, July 3, 1986, and Appendix B). These States are referred to as ''mixed waste authorized States.'' Nine additional States are authorized for the RCRA base hazardous waste program but have not been delegated authority by EPA to regulate mixed waste.[3] In these States mixed waste is not regulated by EPA, but may be regulated by States under the authority of State law. It is important that licensees contact the State hazardous waste agencies in authorized States to determine the specific testing, analysis, and other hazardous waste requirements that may apply to mixed waste managed in their State, because their State may have more stringent requirements than the Federal requirements discussed in this guidance.

This guidance describes:

(1) The current regulatory requirements for determining if a waste is a RCRA hazardous waste;
(2) The role of waste knowledge for hazardous waste determinations;
(3) The waste analysis information necessary for proper treatment, storage, and disposal of mixed waste; and,
(4) The implications of the RCRA land disposal restrictions (LDRs) on the waste characterization and analysis requirements.

This information should be useful for:

(1) radioactive waste generators, who must determine if their waste is a RCRA hazardous waste, and therefore a mixed waste;

(2) for those generators storing mixed waste on-site in tanks, containers or containment buildings for longer than 90 days, that consequently become responsible for complying with RCRA and NRC storage requirements; and
(3) those facilities that accept mixed waste for off-site treatment, storage, or disposal.

Generators and/or treatment, storage, and disposal facilities (TSDFs) handling wastes under RCRA must characterize their waste for several purposes:

(1) To determine if their waste is a hazardous waste (40 CFR 262.11);
(2) To comply with general waste analysis requirements for new or permitted TSDFs, for TSDFs operating under interim status, and for certain generators that treat land disposal prohibited wastes in 40 CFR 264.13, 265.13 and 268.7, respectively. These analysis requirements include:
(a) chemical/physical analysis of a representative sample (and/or, in some cases, use waste knowledge (see below); and,
(b) preparation of a waste analysis plan.
(3) To meet the waste analysis requirements that apply to the specific waste management methods in 40 CFR 264.17, 264.314, 264.341, 264.1034(d), and 268.7;
(4) To ensure, prior to land disposal, that the restricted waste meets the required treatment standard (40 CFR 268.7).[4]

This guidance addresses the need for chemical analysis of mixed wastes to meet these purposes. The guidance also emphasizes ways in which unnecessary testing of mixed waste may be avoided. This is important when handling mixed waste, since each sampling, workup, or analytical event may involve an incremental exposure to radiation. This guidance encourages mixed waste handlers to use waste knowledge, such as process knowledge, where possible, in making RCRA hazardous waste determinations involving mixed waste. It also encourages the elimination of redundant testing by off-site treatment and disposal facilities, where valid generator-supplied, and certified, data are available.

Because mixed waste testing may pose the possibility of increased radiation exposures, this guidance also describes methods by which individuals

who analyze mixed waste samples may reduce their occupational radiation exposure and satisfy the intent of the RCRA testing requirements. Testing to determine whether wastes are hazardous under the RCRA toxicity characteristic may pose special concerns which are examined in Section III of this guidance.

All of the activities described in this guidance are subject to the requirements of both the AEA and RCRA. The focus of this guidance is the RCRA requirements. NRC and NRC Agreement State licensees are authorized to receive, possess, use (which includes storing, sampling, testing, and treating), and dispose of AEA-licensed materials. NRC licensees handling mixed waste should ensure that their RCRA hazardous waste testing activities are consistent with NRC, or Agreement State, regulations and license conditions. Flexibility in the RCRA requirements is emphasized so that the As Low As is Reasonably Achievable (ALARA) concept can be incorporated into the mixed waste testing activities.[5] If other AEA requirements, or RCRA requirements are difficult to meet in a specific mixed waste management situation, licensees should seek resolution by requesting license amendments, approval of modifications to their RCRA permits or interim status Part A applications, or resolution under both authorities.

Section 1006(a) of RCRA states ''Nothing in this Act shall be construed to apply to (or authorize any State, interstate, or local authority to regulate) any activity or substance which is subject to * * * the Atomic Energy Act of 1954 * * * except to the extent that such application (or regulation) is not inconsistent with the requirements of such Acts.'' If a resolution cannot be achieved through the flexibility provided by the two regulatory frameworks, then and only then, should licensees seek resolution under Section 1006(a) of RCRA. Licensees should note that, if an inconsistency exists, relief will be limited to that specific RCRA requirement, and that the determination of an inconsistency would not relieve the licensee from all other RCRA requirements. Section 1006(a) and radiological hazard considerations are addressed more fully in Sections III and IV of this guidance. NRC licensees should also include the necessary flexibility in their RCRA permit waste analysis plans to accommodate the sampling and testing required to meet AEA requirements.

II. Use of Waste Knowledge for Hazardous Waste Determinations

The use of waste knowledge by a generator and/or a TSDF to characterize mixed waste is recommended throughout this document to eliminate unnecessary or redundant waste testing. EPA interprets ‘‘waste knowledge’’ or ‘‘acceptable knowledge’’ of a waste broadly to include, where appropriate:

- ‘‘Process knowledge’’;
- Records of analyses performed by generator or TSDF prior to the effective date of RCRA regulations; or,
- A combination of the above information, supplemented with chemical analysis.

Process knowledge refers to detailed information on processes that generate wastes subject to characterization, or to detailed information (e.g., waste analysis data or studies) on wastes generated from processes similar to that which generated the original waste. Process knowledge includes, for example, waste analysis data obtained by TSDFs from the specific generators that sent the waste off-site, and waste analysis data obtained by generators or TSDFs from other generators, TSDFs or areas within a facility that test chemically identical wastes.[6]

Waste knowledge is allowed by RCRA regulations for the following hazardous waste characterization determinations:

- To determine if a waste is characteristically hazardous (40 CFR 262.11(c)(2)) or matches a RCRA listing in 40 CFR Part 261, Subpart D (40 CFR 262.11(a) and (b));
- To comply with the requirement to obtain a detailed chemical/physical analysis of a representative sample of the waste under 40 CFR 264.13(a);
- To determine whether a hazardous waste is restricted from land disposal (40 CFR 268.7(a)); and,
- To determine if a restricted waste the generator is managing can be land disposed without further treatment (see the generator certification in 40 CFR 268.7(a)(3) and information to support the waste kn/wledge determination in 40 CFR 268.7(a)(6)).

Hazardous waste, including mixed waste, may be characterized by waste knowledge alone, by sampling and laboratory analysis, or a combination of waste knowledge, and sampling and laboratory analysis. The use of waste knowledge alone is appropriate for wastes that have physical properties that are not conducive to taking a laboratory sample or performing laboratory analysis. As such, the use of waste knowledge alone may be the most appropriate method to characterize mixed waste streams where increased radiation exposures are a concern. Mixed waste generators should contact the appropriate EPA regional office to determine whether they possess adequate waste knowledge to characterize their mixed waste.

III. Determinations by Generators That a Waste Is Hazardous

A solid waste is a RCRA hazardous waste if it meets one of two conditions:

(1) the waste is specifically ''listed'' in 40 CFR Part 261, Subpart D, or; (2) the waste exhibits one of the four ''characteristics'' identified in 40 CFR Part 261, Subpart C. These characteristics are:

- Ignitability;
- Corrosivity;
- Reactivity; or,
- Toxicity.

(a) Listed Hazardous Wastes

Generators of waste containing a radioactive and solid waste component must establish whether the solid waste component is a RCRA hazardous waste. Determinations of whether a waste is a listed hazardous waste can be made by comparing information on the waste stream origin with the RCRA listings set forth in 40 CFR Part 261, Subpart D. These listings are separated into three major categories or lists, and are identified by EPA hazardous waste numbers. Most hazardous waste numbers are associated with a specific waste description, specific processes that produce wastes, or certain chemical compounds. For example, K103 waste is defined as ''process residues from aniline extraction from the production of aniline.'' A generator who produces such residues should know,

without any sampling or analysis, that these wastes are ''listed'' RCRA hazardous wastes by examining the K103 hazardous waste description in the hazardous waste lists. Other hazardous waste numbers describe wastes generated from generic processes that are common to various industries and activities. These wastes are referred to as hazardous wastes from nonspecific sources. Radioactively contaminated spent solvents are the most likely mixed wastes to be nonspecific source listed wastes. For example, a generator using one of the F002 halogenated solvents (e.g., tetrachloroethylene, trichloroethylene, and chlorobenzene, etc.) to remove paint from a radiologically contaminated surface, can determine that this waste is a listed RCRA hazardous waste by examining the F002 waste definition for the solvent type, and for a solvent mixture/blend, the percent solvent by volume.

In addition to wastes that are specifically listed as hazardous, the ''derived from'' and ''mixture'' rules state that any solid waste derived from the treatment, storage, or disposal of a listed RCRA hazardous waste, or any solid waste mixed with a listed RCRA hazardous waste, respectively, is itself a listed RCRA hazardous waste until delisted (see 40 CFR 261.3).[7] (Note that soil and debris can be managed as hazardous wastes if they contain listed hazardous wastes or they exhibit one or more hazardous waste characteristics. See hazardous debris definition in 40 CFR 268.2.)

Exceptions to the ''mixture rule'' and ''derived from'' rules exist for certain solid wastes. For example, wastewater discharges subject to Clean Water Act permits, under certain circumstances, are not RCRA hazardous (see 40 CFR 261.3(a)(2)(iv)). Also, hazardous wastes which are listed solely for a characteristic identified in Subpart C of 40 CFR Part 261 (e.g., a F003 spent solvent which is listed only because it is ignitable) are not considered hazardous wastes when they are mixed with a solid waste and the resultant mixture no longer exhibits any characteristic of a hazardous waste (see 40 CFR 261.3(a)(2)(iii)). Likewise, waste pickle liquor sludge ''derived from'' the lime stabilization of spent pickle liquor (e.g., K062) is not a RCRA listed hazardous waste, if the sludge does not exhibit a hazardous waste characteristic (see discussion below on characteristic hazardous wastes). It should be noted, however, that wastes such as F003 and K062 *must* meet LDR treatment standards. Outside of the exceptions mentioned here and in the RCRA regulations, a hazardous

waste that was generated via the ‘‘mixture rule’’ or the ‘‘derived from’’ rule must be delisted through a specific EPA petition process for the listed waste to be considered only a solid waste, and no longer managed as a listed hazardous waste under the RCRA Subtitle C system.

When applying the mixture rule to hazardous wastes, including mixed wastes, generators should be aware that EPA prohibits the dilution (i.e., mixing) of land disposal restricted waste or treatment residuals as a substitute for adequate treatment (see 40 CFR 268.3). An exception to the prohibition is the dilution of purely corrosive, and in some cases, reactive, or ignitable nontoxic wastes to eliminate the characteristic, or the aggregation of characteristic wastes in (pre)treatment systems regulated under the Clean Water Act (55 *FR* 22665).

(b) Characteristic Hazardous Wastes

Hazardous characteristics are based on the physical/chemical properties of wastes. Thus, physical/chemical testing of waste may be appropriate for determining whether a waste is a characteristic hazardous waste. *RCRA regulations, however, do not require testing. Rather, generators must determine whether the waste is a RCRA hazardous waste.* Such a determination may be made based on one’s knowledge of the materials or chemical processes that were used. EPA’s regulations are clear on this point. 40 CFR 262.11(c) states:

‘‘. . . if the waste is not listed [as hazardous waste] in Subpart D [of 40 CFR Part 261], the generator must then determine whether the waste is identified in Subpart C of 40 CFR Part 261 by either:

(1) Testing the waste according to the methods set forth in Subpart C of 40 CFR Part 261, or according to an equivalent method approved by the Administrator under 40 CFR 260.21; or
(2) Applying knowledge (emphasis added) of the hazardous characteristic of the waste in light of the materials or the processes used.’’

Therefore, where sufficient material or process knowledge exists, the generator need not test the waste to make a hazardous characteristic determination, although generators and subsequent handlers would be in

violation of RCRA, if they managed hazardous waste erroneously classified as non-hazardous, outside of the RCRA hazardous waste system. For this reason, facilities wishing to minimize testing often assume a questionable waste is hazardous and handle it accordingly.

A generator must also comply with the land disposal restriction regulations in 40 CFR 268 which require the generator to determine whether the waste is prohibited from land disposal (refer to Section V for a detailed discussion of these requirements).[8] With respect to the hazardous characteristic, and the determination as to whether a waste is restricted from land disposal under 40 CFR 268.7(a), a generator may select the option of using waste knowledge. However, if the waste is determined to be land disposal restricted in 40 CFR 268.7(a), some testing will generally be required prior to land disposal, except where technologies are specified as the treatment standard. For mixed waste, EPA recommends that the frequency of such testing be held to a minimum, in order to avoid duplicative testing and repeated exposure to radiation.

In determining whether a radioactive waste is a RCRA hazardous waste, the generator may test a surrogate material (i.e., a chemically identical material with significantly less or no radioactivity) to determine the RCRA status of the radioactive waste. This substitution of a surrogate material may either partially or completely supplant the testing of the waste. A surrogate material, however, should only be used if the surrogate material faithfully represents the hazardous constituents of the mixed waste.[9] The following example discusses the use of surrogates. A generator is required to determine if a process waste stream containing lead (D008) exceeds the regulatory level of 5.0 milligrams per liter for the toxicity characteristic (40 CFR 261.24). If this determination cannot be made based on material and process knowledge only, the generator would need to test the hazardous material. Rather than testing the radioactive waste stream, the generator may opt to test a surrogate or chemically identical non-radioactive, or lower activity, radioactive waste stream generated by similar maintenance activities in another part of the plant. This substitution of materials is acceptable as long as the surrogate material faithfully represents the characteristics of the actual waste, and testing provides sufficient information for the generator to reasonably determine if the waste is hazardous under RCRA. Non-radioactive or lower activity quality

control samples/species and spiked solutions, for instance, are acceptable to minimize exposure to radiation from duplicative mixed waste testing.

As part of the hazardous waste determination, a generator must document test results or other data and methods that it used. Specifically, 40 CFR 262.40(c) states that "a generator must keep records of any test results, waste analyses, or other determinations made in accordance with 40 CFR 262.11 for at least three years from the date that the waste was last sent to on-site or offsite treatment, storage, or disposal." Section V of this guidance contains information on record keeping requirements for land disposal restricted hazardous (and mixed) wastes.

In summary, testing listed wastes to make the hazardous waste determination is not necessary, because most RCRA hazardous waste codes or listings identify specific waste streams from specific processes or specific categories of wastes. Testing will most often occur to determine if a waste exhibits a hazardous characteristic. However, testing is not required if a generator has sufficient knowledge about the waste and its physical/chemical properties to determine that it is non-hazardous.[10] It is recognized that certain mixed waste streams, such as wastes from remediation activities or wastes produced many years ago, may have to be identified using laboratory analysis, because of a lack of waste or process information on these waste streams. Nonetheless, hazardous waste determinations based on generator knowledge can be used to reduce the sampling of mixed waste and prevent unnecessary exposure to radioactivity. The same principle holds for a generator's determination that a waste is subject to the RCRA land disposal restrictions in 40 CFR 268.7(a).

IV. Testing Protocols for Characteristics

When testing is conducted to determine whether a waste is a RCRA hazardous waste, there are acceptable test protocols or criteria for each of the four characteristics. Testing for characteristics must be done on a representative sample of the waste or using any applicable sampling methods specified in Appendix I of 40 CFR 261.[11]

Ignitability—For liquid wastes, other than aqueous solutions containing by volume less than 24 percent alcohol, the flash point is to be determined by a Pensky-Martens Closed Cup Tester, using the test method specified

in American Society of Testing and Materials (ASTM) Standard D–93–79 or D–93–80, or a Setaflash Closed Cup Tester, using the test method specified in ASTM Standard D–3278–78, or as determined by an equivalent test method approved by the Administrator under procedures set forth in 40 CFR 260.20 and 260.21 (see "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods," 3rd Ed., as amended, EPA, OSWER, SW–846, Methods 1010 and 1020[12]). (Non-liquid wastes, compressed gases, and oxidizers may exhibit the characteristic of ignitability as described in 40 CFR 261.21 (a)(2–4).)

Corrosivity—For aqueous solutions, the pH is to be determined by a pH meter using either an EPA test method (i.e., SW–846, Method 9040 or an equivalent test method approved by the Administrator under procedures set forth in 40 CFR 260.20 and 260.21.) For liquids, steel corrosion is to be determined by the test method specified in National Association of Corrosion Engineers (NACE) Standard TM–01–69 as standardized in "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods," 3rd Ed., as amended (EPA, OSWER, SW–846, Method 1110), or an equivalent test method approved by the Administrator under procedures set forth in 40 CFR 260.20 and 260.21.

Reactivity—There are no specified test protocols for reactivity. 40 CFR 261.23 defines reactive wastes to include wastes that have any of the following properties:

(1) normally unstable and readily undergoes violent change without detonating;
(2) reacts violently with water;
(3) forms potentially explosive mixtures with water;
(4) generates dangerous quantities of toxic fumes, gases, or vapors when mixed with water;
(5) in the case of cyanide- or sulfide-bearing wastes, generates dangerous quantities of toxic fumes, gases, or vapors when exposed to acidic or alkaline conditions;
(6) explodes when subjected to a strong initiating force or if heated under confinement;
(7) explodes at standard temperature and pressure; or
(8) fits within the Department of Transportation's forbidden explosives, Class A explosives, or Class B explosives classifications.[13]

EPA has elected to rely on a descriptive definition for these reactivity properties because of inherent deficiencies associated with available methodologies for measuring such a varied class of effects, with the exception of the properties discussed in No. 5, above. The method used, as guidance but not required, to quantify the reactive cyanide and sulfide bearing wastes is provided in Chapter 7 of ''Test Methods for Evaluating Solid Waste, Physical/Chemical Methods,'' 3rd Ed., as amended, EPA, OSWER, SW–846.

Toxicity Characteristic—The test method that may be used to determine whether a waste exhibits the toxicity characteristic (TC) is the Toxicity Characteristic Leaching Procedure (TCLP), as described in 40 CFR Part 261, Appendix II (SW–846, Method 1311). The TCLP was modified and revised in 55 *FR* 11798, March 29, 1990. Note that this revised TCLP is used (in most cases) for land disposal restriction compliance determinations as well. Differences between the TCLP and the previously required Extraction Procedure (EP) include improved analysis of the leaching of organic compounds, the elimination of constant pH adjustment, the addition of a milling or grinding requirement for solids (waste material solids must be milled to particles less than 9.5 mm in size), and other more detailed alterations.[14] Additionally, the TC rule added 25 organic compounds to the toxicity characteristic. The TCLP (Method 1311) recommends the use of a minimum sample size of 100 grams (solid and liquid phases as described in Section 7.2). *For mixed waste testing, sample sizes of less than 100 grams can be used, if the analyst can demonstrate that the test is still sufficiently sensitive to measure the constituents of interest at the regulatory levels specified in the TCLP and representative of the waste stream being tested*. Other variances to the published testing protocols are permissible (under 40 CFR 260.20–21), but must be approved prior to implementation by EPA. Use of a sample size of less than 100 grams is highly recommended for mixed wastes with concentrations of radionuclides that may present serious radiation exposure hazards. Additionally, Section 1.2 of the TCLP allows the option of performing a ''total constituent analysis'' on a hazardous waste or mixed waste sample, instead of the TCLP. Section 1.2 of Method 1311 states:

If a total analysis of the waste demonstrated that the individual analytes are not present in the waste, or that they are present, but at such low

concentrations that the appropriate regulatory levels could not possibly be exceeded, the TCLP need not be run.

For homogenous samples, the use of total constituent analysis in this manner eliminates the need to grind or mill solid waste samples. The grinding or milling step in the TCLP has raised ALARA concerns for individuals who test mixed waste. The use of total constituent analysis, instead of the TCLP, may also minimize the generation of secondary mixed or radioactive waste through the use of smaller sample sizes and reduction, or elimination, of high dilution volume leaching procedures.

Flexibility in Mixed Waste Testing

Flexibility exists in the hazardous waste regulations for generators, TSDFs, and mixed waste permit writers to tailor mixed waste sampling and analysis programs to address radiation hazards. For example, upon the request of a generator, a person preparing a RCRA permit for a TSDF has the flexibility to minimize the frequency of mixed waste testing by specifying a low testing frequency in a facility's waste analysis plan. EPA believes, as stated in 55 FR 22669, June 1, 1990, that ''the frequency of testing is best determined on a case-by-case basis by the permit writer.''

EPA's hazardous waste regulations also allow a mixed waste facility the latitude to change or replace EPA's test methods (i.e., *Test Methods for Evaluating Solid Waste* (SW–846)) to address radiation exposure concerns. There are only fourteen sections of the hazardous waste regulations that require the use of specific test methods or appropriate methods found in SW–846 which are outlined in Appendix A.[15] However, any person can request EPA for an equivalent testing or analytical method that would replace the required EPA method (see 40 CFR 260.21).

In a recent amendment to the testing requirements, EPA added language to SW–846 that describes fourteen citations in the RCRA program (listed in Appendix A) where the use of SW–846 methods is mandatory (Update II, 60 FR 3089, January 13, 1995). In all other cases, the RCRA program functions under what we call the Performance Based Measurement System (PBMS) approach to monitoring. Language clarifying this approach was included in the final FR Notice which promulgated Update III (62 FR 32542, June 13, 1997) and in appropriate sections

(Disclaimer, Preface and Overview, and Chapter 2) of SW–846. Under PBMS, the regulation and/or permit focus is on the question(s) to be answered by the monitoring, the degree of confidence (otherwise known as the Data Quality Objective (DQO)) or the measurement quality objectives (MQO) that must be achieved by the permittee to have demonstrated compliance, and the specific data that must be gathered and documented by the permittee to demonstrate that the objectives were actually achieved. ''Any reliable method'' may be used to demonstrate that one can see the analytes of concern in the matrix of concern at the levels of concern. Additional reference documents on the characterization and testing methods are listed in Appendix C.

NRC regulations do not describe specific testing requirements for wastes to determine if a waste is radioactive. However, both NRC and Department of Transportation regulations contain requirements applicable to characterizing the radioactive content of the waste before shipment. For example, NRC's regulations in 10 CFR 20.2006 require that the waste manifest include, as completely as practicable, the radionuclide identity and quantity, and the total radioactivity. NRC regulations also require that generators determine the disposal Class of the radioactive waste, and outline waste form requirements that must be met before the waste is suitable for land disposal. These regulations are referenced in 10 CFR 20.2006, and are outlined in detail at 10 CFR 61.55 and 61.56. Mixed waste generators are reminded that both RCRA waste testing and NRC waste form requirements must be satisfied. Generators may also be required to amend their NRC or Agreement State licenses in order to perform the tests required under RCRA. In addition, if an NRC licensee uses an outside laboratory to test his or her waste, that laboratory may be required to possess an NRC or Agreement State license. It is the responsibility of the generator to determine if the outside laboratory possesses the proper license(s) prior to transferring the waste to the laboratory for testing.

Where radioactive wastes (or wastes suspected of being radioactive) are involved in testing, it has been suggested that the testing requirements of RCRA may run counter to the aims of the AEA. The AEA requirements that have raised inconsistency concerns with respect to RCRA testing procedures include ALARA, criticality, and security. Neither EPA nor NRC is aware of any specific instances where RCRA compliance has

been inconsistent with the AEA. However, both agencies acknowledge the potential for an inconsistency to occur.[16] A licensee or applicant who suspects that an inconsistency may exist should contact both the AEA and RCRA regulatory agencies. These regulatory agencies may deliberate and consult on whether there is an unresolvable inconsistency and, if one exists, they may attempt to fashion the necessary relief from the particular RCRA provision that gives rise to the inconsistency. However, all other RCRA regulatory requirements would apply. That is, such a conclusion does not relieve hazardous waste facility owner/operators of the responsibility to ensure that the mixed waste is managed in accordance with all other applicable RCRA regulatory requirements. Owner/operators of mixed waste facilities are encouraged to address and document this potential situation and its resolution in the RCRA facility waste analysis plan which must be submitted with the Part B permit application, or addressed in a permit modification.

Both agencies also believe that the potential for inconsistencies can be reduced significantly by a better understanding of the RCRA requirements, a greater reliance on materials and process knowledge, the use of surrogate materials when possible, and the use of controlled atmosphere apparatuses for mixed waste testing. Where testing is conducted, the use of glove boxes and other controlled atmosphere apparatuses during the testing of the radioactive waste material lessens radiation exposure concerns significantly. These protective measures may also help to reconcile the required testing requirements (including milling) with concerns about maintaining exposures to radiation ALARA and complying with other AEA protective standards. If such protective measures do not exist, or do not adequately reduce individual exposure to radiation or address other factors of concern, relief may be available under Section 1006 of RCRA.

V. Determinations by Treatment, Storage, or Disposal Facility Owner/Operators and Certain Generators to Ensure Proper Waste Management

General Waste Analysis

Owner/operators of facilities that treat, store, or dispose of hazardous wastes must obtain a chemical and physical analysis of a representative

sample of the waste (see 40 CFR 264.13 for permitted facilities, or 40 CFR 265.13 for interim status facilities).[17] The purpose of this analysis is to assure that owner/operators have sufficient information on the properties of the waste to be able to treat, store, or dispose of the waste in a safe and appropriate manner.

The waste analysis may include data developed by the generator, and existing, published, or documented data on the hazardous waste or on hazardous waste generated from similar processes. In some instances, however, information supplied by the generator may not fully satisfy the waste analysis requirement. For example, in order to treat a particular waste, one may need to know not only the chemical composition of the waste, but also its compatibility with the techniques and chemical reagents used at the treatment facility. Where such information is not otherwise available, the owner/operator will be responsible for gathering relevant data on the waste in order to ensure its proper management.

The analysis must be repeated only if the previous analyses are inaccurate or needs updating. EPA regulations at 40 CFR 264.13(a)(3) do require that, at a minimum, a waste must be re-analyzed if:

(1) The owner/operator is notified, or has reason to believe, that the process or operation generating the waste has changed [in a way such that the hazardous property or characteristics of the waste would change]; and (2) For off-site facilities, when the results of the verification analysis indicate that the [composition or characteristics of the] waste does not match the accompanying manifest or shipping paper.

The requirements and frequency of waste analysis for a given facility are described in the facility's waste analysis plan. As required by 40 CFR 264.13(b), the waste analysis plan must specify the parameters for which each hazardous waste will be analyzed; the rationale for selecting these parameters (i.e., how analysis for these parameters will provide sufficient information on the waste's properties); and the test methods that will be used to test for these parameters. The waste analysis plan also must specify the sampling method that will be used to obtain a representative sample of the waste to be analyzed; the frequency with which the initial analysis of the waste will be reviewed or repeated, to ensure that

the analysis is accurate and up to date; and, for off-site facilities, the waste analyses to be supplied by the hazardous waste generators. Finally, the waste analysis plan must note any additional waste analysis requirements specific to the waste management method employed, such as the analysis of the waste feed to be burned in an incinerator.

The appropriate parameters for each waste analysis plan are determined on an individual basis as part of the permit application review process. To reduce the inherent hazards of sampling and analyzing radioactive material, and in particular, the potential risk to workers from exposure to radiation posed by duplicative testing of mixed wastes, redundant testing by the generator and off-site facilities should be avoided. In addition, waste analysis plans must include provisions to keep exposures to radiation ALARA, and incorporate relevant AEA-related requirements and regulations.

Analysis Required to Verify Off-site Shipments

The owner/operator of a facility that receives mixed waste from off-site must inspect and, *if necessary,* analyze each hazardous waste shipment received at the facility to verify that it matches the identity of the waste specified on the accompanying LDR notification or manifest (see 40 CFR 264.13 or 265.13(c)). This testing is known as verification testing. Such inspections and analysis will follow sampling and testing procedures set forth in the facility's waste analysis plan, which is kept at the facility.

It should also be emphasized that, where analysis is necessary, *RCRA regulations do not necessarily require the analysis of every movement of waste received at an off-site facility*. As explained above, the purpose of the waste analysis is to verify that the waste received at off-site facilities is correctly identified, and to provide enough information to ensure that it is properly managed by the facilities.

For example, if a facility receives a shipment of several sealed drums of mixed waste, a representative sample from only one drum may be adequate, if the owner/operator has reason to believe that the chemical composition of the waste is identical in every drum. In such a case, the drum containing the least amount of measurable radioactivity could be sampled to minimize radiation exposures (variations in radioactivity do

not necessarily suggest different chemical composition). This procedure also would apply to a shipment of several types of waste. If the owner/operator has reason to believe that the drums in the shipment contain different wastes, then selecting a representative sample might involve drawing a sample from each drum or drawing a sample from one drum in each ''set'' of drums containing identical wastes. Once this waste analysis requirement has been satisfied, routine retesting of later shipments would not be required if the owner/operator can determine that the properties of the waste he or she manages will not change.

Fingerprint Analysis Versus Full Scale Analysis

Full scale analysis (i.e., detailed physical and chemical analysis) may be used to comply with the waste analysis plan, including verification of off-site shipments. However, for mixed waste, abbreviated analysis or ''fingerprint analysis'' may be more appropriate to meet general waste analysis requirements. The test procedure should be determined on a case-by-case basis.

Fingerprint analysis (which may involve monitoring pH, percent water, and cyanide content) is particularly recommended for mixed waste streams with high radiation levels that are received by an off-site TSDF for RCRA waste manifest verification purposes. It may be appropriate to use full scale analysis, instead of, or after, fingerprint analyses, if the facility suspects that the waste was not accurately characterized by the generator, information provided by a generator is incomplete, waste is received for the first time, or the generator changes a process or processes that produced the waste.

Generators Who Treat LDR Prohibited Waste In Tanks, Containers or Containment Buildings To Meet LDR Treatment Requirements

Hazardous waste generators may treat hazardous wastes in tanks or containers without obtaining a permit if the treatment is done in accordance with the accumulation timeframes and requirements in 40 CFR 262.34. However, generators who treat hazardous waste (including mixed wastes) to meet the EPA treatment standards for land disposal prohibited wastes must also prepare a waste analysis plan similar to that prepared by TSDFs.

The plan must be based on a detailed analysis of a representative sample of the LDR prohibited waste that will be treated. In addition, the plan should include all the information that is necessary to treat the waste, including the testing frequency (See 40 CFR 268.7(a)(5)).

VI. Determinations Under the Land Disposal Restrictions

Generators, as well as treatment facilities and land disposal facilities, that handle mixed waste may have to obtain or amend their radioactive materials licenses if they test or treat mixed waste under the LDRs. The following discussion assumes that generators and treatment and disposal facilities have satisfied the requirement to obtain, or amend, their radioactive materials licenses, as appropriate.

Waste knowledge may also be used to satisfy certain waste characterization requirements imposed by the LDRs for mixed wastes. The Hazardous and Solid Waste Amendments (HSWA) to RCRA (P.L. 98–616), enacted on November 8, 1984, established the LDR program. This Congressionally mandated program set deadlines (RCRA Sections 3004(d)-(g)) for EPA to evaluate all hazardous wastes and required EPA to set levels, or methods, of treatment which would substantially diminish the toxicity of the waste, or minimize the likelihood of migration of hazardous constituents from any RCRA waste. Beyond specified dates, prohibited wastes that do not meet the treatment standards before they are disposed of, are banned from land disposal unless they are disposed of in a so-called ''no-migration'' unit (i.e., a unit where the EPA Administrator has granted a petition which successfully demonstrated to a reasonable degree of certainty that there will be no migration of hazardous constituents from the disposal unit for as long as the wastes remain hazardous) (40 CFR 268.6). Certain categories of prohibited wastes also may be granted extensions of the effective dates of the land disposal prohibitions (i.e., case-by-case and national capacity variances (40 CFR 268.5 and Subpart C, respectively). However, these wastes are still restricted and, if disposed in landfills or surface impoundments, must be disposed of in units meeting the minimum technology requirements.[18]

The requirements of the LDR program apply to generators, transporters, and owner/operators of hazardous waste treatment, storage, and

disposal facilities. Not all hazardous wastes are subject to 40 CFR Part 268. For instance, certain wastes that are identified or listed after November 8, 1984, such as newly identified mineral processing wastes for which land disposal prohibitions or treatment standards have not yet been promulgated, are not regulated under 40 CFR Part 268.[19]

Determinations by Generators

Under 40 CFR 268.7(a), generators must determine whether their waste is restricted from land disposal (or determine if they are subject to an exemption or variance from land disposal (40 CFR 268.1)) by testing their waste (or a leachate of the waste developed using the TCLP or, in certain cases, the Extraction Procedure Toxicity Test (EP), or by using waste or process knowledge). If the waste exhibits the characteristic of ignitability (and is not in the High Total Organic Constituents (TOC) Ignitable Liquids Subcategory or is not treated by the "CMBST" or "RORGS" treatment technology in 40 CFR 268.42, Table 1), corrosivity, reactivity and/or organic toxicity, the generator must also determine the underlying hazardous constituents (UHCs) in the waste. Two exceptions to this requirement are:

(1) if these wastes are treated in wastewater treatment systems subject to the Clean Water Act (CWA) or CWA equivalent; or,
(2) if they are injected into a Class I, nonhazardous Underground Injection Control well. A UHC is any constituent listed in 40 CFR 268.48, Table UTS Universal Treatment Standards, with the exceptions of nickel, zinc and vanadium, which can reasonably be expected to be present at the point of generation of the hazardous waste, at a concentration above the constituent-specific UTS treatment standard. Determining the presence of the UHCs may be made based on testing or knowledge of the waste. The UHCs must meet the UTS before the waste may be land disposed.

If a generator chooses to test the waste rather than use waste or process knowledge for hazardous waste that is not listed and exhibits a characteristic only, the generator must use the TCLP. The only exception is TC metals.

Until the "Phase IV" LDR rule is promulgated in the spring of 1998, generators who characterize their wastes as TC toxic only for metals

may use the EP instead of the TCLP result to determine if their waste is land disposal restricted, because the TC wastes do not have final EPA treatment standards whereas, at this time, the EP metals do. If the EP result is negative, the waste will still be considered hazardous, but is not prohibited from land disposal. The TCLP generally yields similar results as the EP. However, in certain matrices the TCLP yields higher lead and arsenic concentrations than the EP. The rationale for using the EP instead of the TCLP for characteristic wastes is explained in 55 FR 3865, January 31, 1991. For further guidance on using the EP for the land disposal restriction determination, refer to the Figures 1 and 2, of this guidance.

If a waste is found to be land disposal restricted, generators must determine if the waste can be land disposed without further treatment. A prohibited waste may be land disposed if it meets applicable treatment standards (whether through treatment or simply as generated), or is subject to a variance from the applicable standards. As explained above, this determination can be made either based on knowledge of the waste or by testing the waste, or waste leachate using the TCLP.

Generators who determine that their listed waste meets the applicable treatment standards must certify to this determination and notify the treatment, storage, or land disposal facility that receives the waste (40 CFR 268.7(a)(3)). Notification to the receiving facility must be made with the initial shipment of waste and must include the following information:

- EPA Hazardous Waste Number;
- Certification that the waste delivered to a disposal facility meets the treatment standard, and that the information included in the notice is true, accurate, and complete;
- Waste constituents that will be monitored for compliance if monitoring will not include all regulated constituents, for wastes F001-F005, F039, D001, D002, and D012-D043;
- Whether the waste is a non-wastewater or wastewater;
- The subcategory of the waste (e.g., ‘‘D003 reactive cyanide’’), if applicable;
- Manifest number; and,
- Waste analysis data (if available).

If a generator determines that a waste that previously exhibited a characteristic is no longer hazardous, or is subject to an exclusion from the definition of hazardous waste, a onetime notification and certification must be place in the generator's files (40 CFR 268.7(a)(7) or 268.9).

Generators who determine that their waste does not meet the applicable treatment standards must ensure that this waste meets the applicable standards prior to disposal. These generators may treat (or store) their prohibited wastes on-site for 90 days or less in qualified tanks, containers (40 CFR 262.34), or containment buildings (40 CFR 268.50), and/or send their wastes off-site for treatment.[20] When prohibited listed wastes are sent off-site, generators must notify the treatment facility of the appropriate treatment standards (40 CFR 268.7(a)(2)). This notification must be made with the initial shipment of waste and must include the following information:

- EPA Hazardous Waste Number;
- Waste constituents that the treater will monitor if monitoring will not include all regulated constituents, for wastes F001–F005, F039, D001, D002, and D012–D043;
- Whether the waste is a non-wastewater or wastewater;
- The subcategory of the waste (e.g., ''D003 reactive cyanide''), if applicable;
- Manifest number; and,
- Specified information for hazardous debris.

Generators whose wastes are subject to an exemption such as a case-by-case extension under 40 CFR 268.5, an exemption under 40 CFR 268.6 (a no-migration variance), or a nationwide capacity variance under 40 CFR 268, Subpart C must also notify the land disposal facility of the exemption. In addition, records of all notices, certifications, demonstrations, waste analysis data, process knowledge determinations, and other documentation produced pursuant to 40 CFR Part 268 must be maintained by the generator for at least three years from the date when the initial waste shipment was sent to on-site or off-site treatment, storage, or disposal (40 CFR 268.7(a)(8)).

Determinations by Treaters and Disposers

Owner/operators of treatment facilities that receive wastes that do not meet the treatment standards are responsible for treating the wastes to the applicable treatment standards or by the specified technology(ies). In addition, the owner/operators of treatment facilities must determine whether the wastes meet the applicable treatment standards or prohibition levels by testing:

(1) The treatment residues, or an extract of such residues using the TCLP, for wastes with treatment standards expressed as concentrations in the waste extract (40 CFR 268.40); and
(2) The treated residues (not an extract of the treated residues) for wastes with treatment standards expressed as concentrations in the waste extract (40 CFR 268.40).

This testing should be done at the frequency established in the facility's waste analysis plan. Owner/operators of treatment facilities, however, do not need to test the treated residues or an extract of the residues if the treatment standard is a specified-technology (i.e., a technology specified in 40 CFR 268.40 or 268.45, Table 1.—Alternative Treatment Standards for Hazardous Debris).

Owner/operators of land disposal facilities under the LDRs are responsible for ensuring that only waste meeting the treatment standards (i.e., wastes not prohibited from disposal or wastes that are subject to an exemption or variance) is land disposed. Like a treatment facility, a disposal facility must test a treatment residue or an extract of the treatment residue, except where the treatment standard is a specified technology.

Owner/operators must periodically test wastes received at the facility for disposal (i.e., independent corroborative testing) as specified in the waste analysis plan to ensure the treatment has been successful and the waste meets EPA treatment standards, except where the treatment standard is expressed as a technology.[21] The results of any waste analyses are placed in a TSDF's operating records along with a copy of all certifications and notices (40 CFR 264.73 or 40 CFR 265.73).[22]

Mixed Waste Under the LDRs

As clarified in the Land Disposal Restrictions rule published on June 1, 1990 (see EPA's "Third Third rule," 55 FR 22669, June 1, 1990), the frequency of testing, such as corroborative testing for treatment and disposal facilities, should be determined on a case-by-case basis and specified in the RCRA permit. This flexibility is necessary because of the variability of waste types that may be encountered. Mixed waste is unique for its radioactive/hazardous composition and dual management requirements. Each sampling or analytical event involving mixed waste may result in an incremental exposure to radiation, and EPA's responsibility to protect human health and the environment must show due regard for minimizing this unique risk. These are factors which should be considered in implementing the flexible approach to determining testing frequency spelled out in the Third Third Rule language. This flexible approach encourages reduction in testing where there is little or no variation in the process that generates the waste, or in the treatment process that treats the waste, and an initial analysis of the waste is available. Also, the approach may apply to mixed wastes shipped to off-site facilities, where redundant testing is minimized by placing greater reliance on the characterization developed and certified by earlier generators and treatment facilities. On the other hand, where waste composition is not well-known, testing frequency may be increased. Waste analysis plan conditions in the permits of mixed waste facilities should reflect these principles.

Revised Treatment Standards for Solvent Wastes

EPA promulgated revised treatment standards for wastewater and non-wastewater spent solvent wastes (F001–F005) in 57 FR 37194, August 18, 1992. The revision essentially converts the treatment standards for the organic spent solvent waste constituents (F001–F005) from TCLP based to total waste constituent concentration based. This conversion of the spent solvent treatment standards is particularly advantageous to mixed waste generators, since the entire waste stream or treatment residual must be analyzed (instead of a waste or treatment residual extract). This holds true for other mixed waste streams where the hazardous component is measured using a total waste analysis. As discussed in Section IV of this guidance, total constituent analysis has several advantages over the use of the TCLP for high activity waste streams.

EPA and NRC are aware of potential hazards attributable to testing hazardous waste. Moreover, EPA and NRC recognize that the radioactive component of mixed waste may pose additional hazards to laboratory personnel, inspectors, and others who may be exposed during sampling and analysis. All sampling should be conducted in accordance with procedures that minimize exposure to radiation and ensure personnel safety. Further, testing should be conducted in laboratories licensed by NRC or the appropriate NRC Agreement State authority. EPA and NRC believe that a combination of common sense, modified sampling procedures, and cooperation between State and Federal regulatory agencies will minimize any hazards associated with sampling and testing mixed waste.

Note: Section V, ''Determinations under the Land Disposal Restrictions (LDRs)'' and the following flow charts represent a brief summary of the Land Disposal Restriction Regulations. They are not meant to be a complete or detailed description of all applicable LDR regulations. For more information concerning the specific requirements, consult the **Federal Registers** cited in the document and the Code of Federal Regulations, Title 40 Parts 124, and 260 through 271.

FIGURE ONE: TESTING REQUIREMENTS
FOR CHARACTERISTIC LEAD AND ARSENIC NONWASTEWATERS ONLY[a]

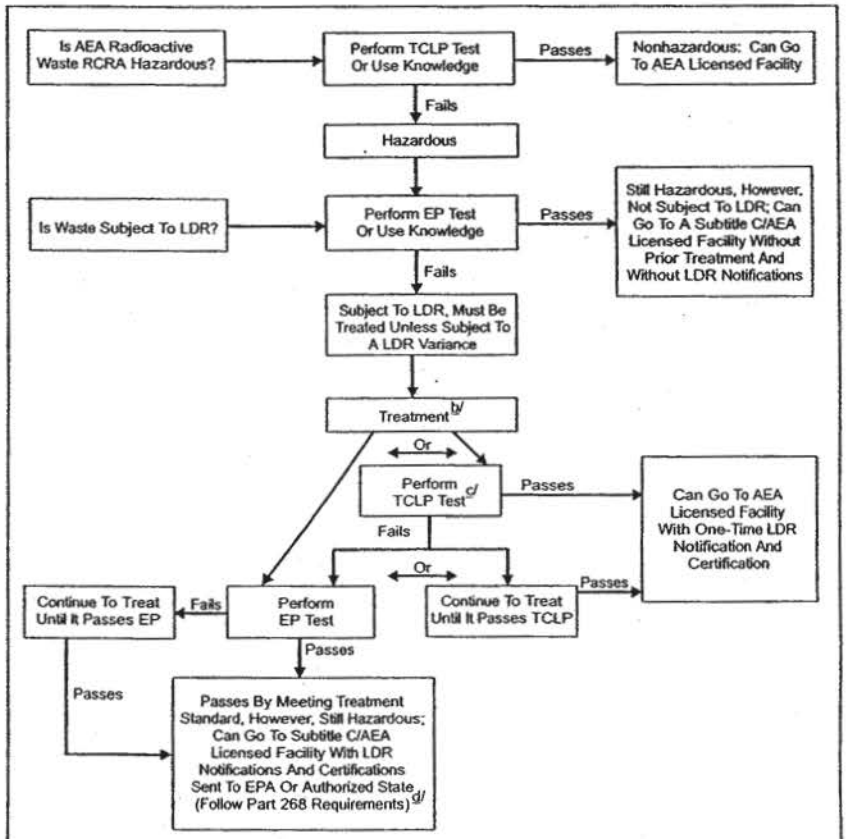

a/ Logic tree assumes the waste also contains AEA regulated radioactive waste.

b/ If the treatment standard is expressed as a specified technology, no further testing is required. However, the mixed waste must go to a Subtitle C/AEA licensed facility with LDR notifications and certifications.

c/ TCLP generally yields higher concentrations than EP for lead and arsenic in certain matrices.

d/ If the waste meets the treatment standard and passes the TCLP, it can go to an AEA licensed facility with one-time LDR notification and certification.

FIGURE TWO: TESTING REQUIREMENTS
FOR ALL OTHER CHARACTERISTIC METALS[a]

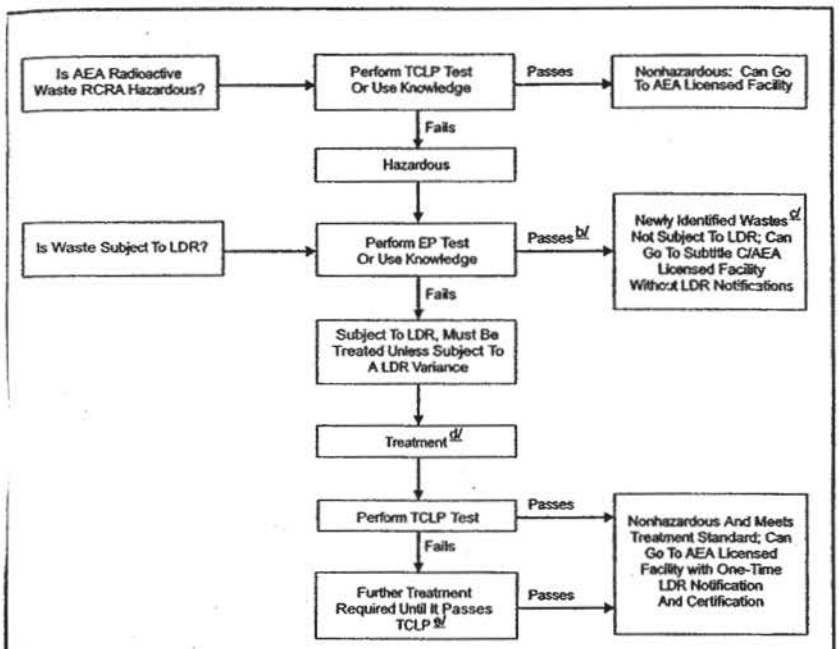

a/ Logic tree assumes the waste also contains AEA regulated radioactive waste.

b/ This should be rare, since the two tests usually yield similar results.

c/ Wastes exhibiting the toxicity characteristic but not the EP are newly identified wastes and, therefore, are not subject to the land disposal restrictions at this time.

d/ If the treatment standard is expressed as a specified technology, no further testing is required. However, the mixed waste must go to a Subtitle C/AEA licensed facility with LDR notifications and certifications.

e/ Selenium is the one exception because it has a treatment standard slightly above the characteristic level.

FIGURE THREE: TESTING REQUIREMENTS
FOR RCRA LISTED HAZARDOUS WASTES ONLY[a]

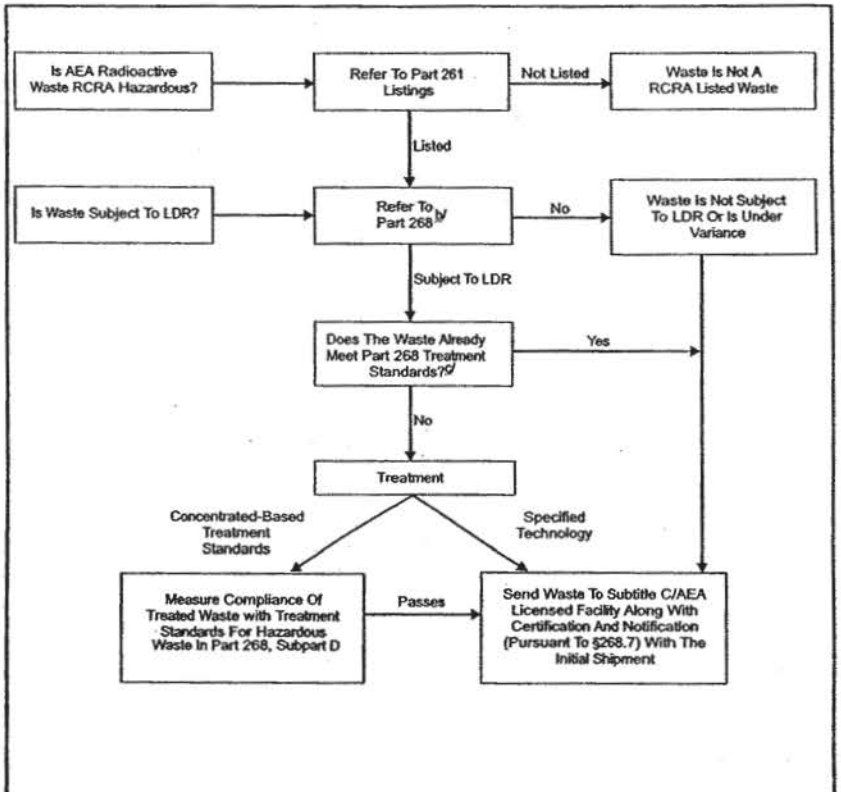

a/ Logic tree assumes the waste also contains AEA regulated radioactive waste.

b/ Refer to §268.1 to determine if LDR is applicable to waste. If so, test using TCLP or use process knowledge to determine if waste is restricted (§268.7).

c/ Test using TCLP or use process knowledge.

FIGURE FOUR: ORGANIC TOXICITY CHARACTERISTIC (TC) WASTES AND PESTICIDE WASTES[a]

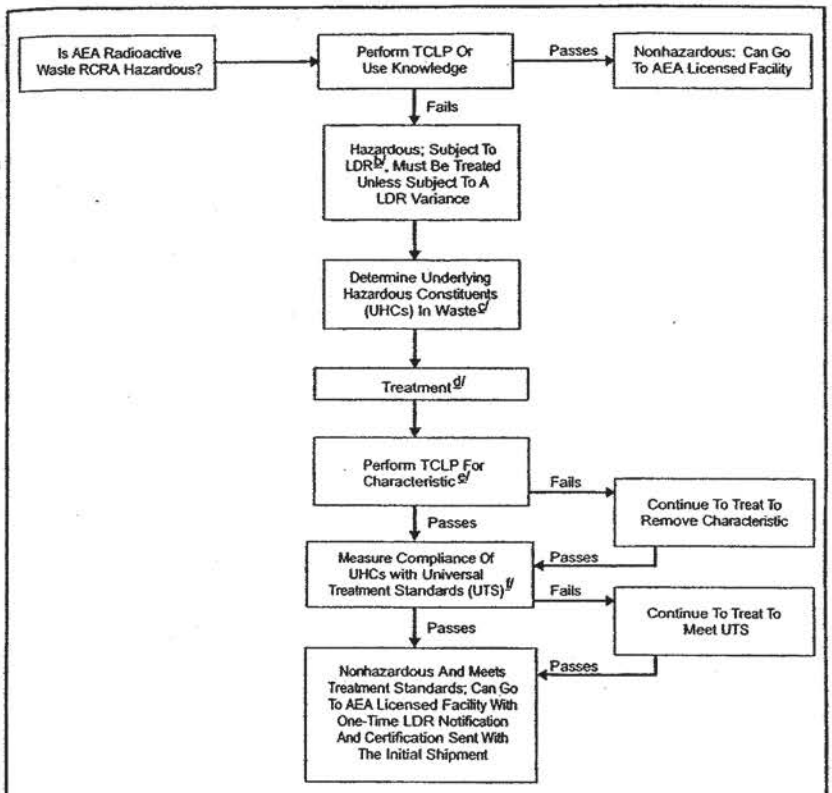

a/ Logic tree assumes the waste also contains AEA regulated radioactive waste.

b/ Restriction applies to TC organic and pesticide wastes managed in non-CWA/non-CWA equivalent/ non-Class I SDWA systems only.

c/ Testing or knowledge of waste may be used. A UHC is any constituent listed in §268.48 Table UTS, except zinc, that can reasonable be expected to be present at the point of generation of the hazardous waste, at a concentration above the constituent-specific UTS treatment standard.

d/ If the treatment standard is expressed as a specified technology, no further testing is required. However, the mixed waste must go to a Subtitle C/AEA facility with LDR notifications and certifications.

e/ Refer to the table "Treatment Standards for Hazardous Wastes" in 40 CFR Part 268, Subpart D.

f/ Compliance should be measured based on the appropriate testing protocols (see SW-846).

Appendix A—RCRA Regulations That Require Specific EPA Test Methods

The use of an SW–846 method is mandatory for the following nine Resource Conservation and Recovery Act (RCRA) applications contained in 40 CFR Parts 260 through 270:

- Section 260.22(d)(1)(I)—Submission of data in support of petitions to exclude a waste produced at a particular facility (i.e., delisting petitions);
- Section 261.22(a)(1) and (2)—Evaluations of waste against the corrosivity characteristic;
- Section 261.24(a)—Leaching procedure for evaluation of waste against the toxicity characteristic;
- Section 261.35(b)(2)(iii)(A)—Evaluation of rinsates from wood preserving cleaning processes;
- Sections 264.190(a), 264.314(c), 265.190(a), and 265.314(d)—Evaluation of waste to determine if free liquid is a component of the waste;
- Sections 264.1034(d)(1)(iii) and 265.1034(d)(1)(iii)—Evaluation of organic emissions from process vents;
- Sections 264.1063(d)(2) and 265.1063(d)(2)—Evaluation of organic emissions from equipment leaks;
- Section 266.106(a)—Evaluation of metals from boilers and furnaces;
- Sections 266.112(b)(1) and (2)(I)—Certain analyses in support of exclusion from the definition of a hazardous waste for a residue which was derived from burning hazardous waste in boilers and industrial furnaces;
- Sections 268.7(a), 268.40(a), (b), and (f), 268.41(a), 268.43(a)—Leaching procedure for evaluation of waste to determine compliance with land disposal treatment standards;
- Sections §270.19(c)(1)(iii) and (iv), and 270.62(b)(2)(I)(C) and (D)—Analysis and approximate quantification of the hazardous constituents identified in the waste prior to conducting a trial burn in support of an application for a hazardous waste incineration permit; and
- Sections 270.22(a)(2)(ii)(B) and 270.66(c)(2)(I) and (ii)—Analysis conducted in support of a destruction and removal efficiency (DRE) trial burn waiver for boilers and industrial furnaces burning low risk wastes, and analysis and approximate quantification conducted for a trial burn in support of an application for a permit to burn hazardous waste in a boiler and industrial furnace.

Appendix B.—States and Territories with Mixed Waste Authorization [As of June 30, 1997].

State/territory	FR date	Effective date	FR cite
Colorado	10/24/86	11/7/86	51 FR 37729.
Tennessee	6/12/87	8/11/87	52 FR 22443.
S. Carolina	7/15/87	9/13/87	52 FR 26476.
Washington	9/22/87	11/23/87	52 FR 35556.
Georgia	7/28/88	9/26/88	53 FR 28383.
Nebraska	10/4/88	12/3/88	53 FR 38950.
Kentucky	10/20/88	12/19/88	53 FR 41164.
Utah	2/21/89	3/7/89	54 FR 7417.
Minnesota	4/24/89	6/23/89	54 FR 16361.
Ohio	6/28/89	6/30/89	54 FR 27170.
Guam	8/11/89	10/10/89	54 FR 32973.
N. Carolina	9/22/89	11/21/89	54 FR 38993.
Michigan	11/24/89	12/26/89	54 FR 48608.
Texas	3/1/90	3/15/90	55 FR 7318.
New York	3/6/90	5/7/90	55 FR 7896.
Idaho	3/26/90	4/9/90	55 FR 11015.
Illinois	3/1/90	4/30/90	55 FR 7320.
Arkansas	3/27/90	5/29/90	55 FR 11192.
Oregon	3/30/90	5/29/90	55 FR 11909.
Kansas	4/24/90	6/25/90	55 FR 17273.
N. Dakota	6/25/90	8/24/90	55 FR 25836.
New Mexico	7/11/90	7/25/90	55 FR 28397.
Oklahoma	9/26/90	11/27/90	55 FR 39274.
Connecticut	12/17/90	12/31/90	55 FR 51707.
Florida	12/14/90	2/12/91	55 FR 51416.
Mississippi	3/29/91	5/28/91	56 FR 13079.
S. Dakota	4/17/91	6/17/91	56 FR 15503.
Indiana	7/30/91	9/30/91	56 FR 41959.
Louisiana	8/26/91	10/26/91	56 FR 41959.
Wisconsin	4/24/92	4/24/92	57 FR 15092.
Nevada	4/29/92	6/29/92	57 FR 18083.
California	7/23/92	8/1/92	57 FR 32725.
Arizona	11/23/92	1/22/93	57 FR 54932.
Missouri	1/11/93	3/12/93	58 FR 3497.
Alabama	3/17/93	5/17/93	58 FR 14319.
Vermont	6/7/93	8/6/93	58 FR 31911.
Montana	1/19/94	3/21/94	59 FR 2752.
New Hampshire	11/14/94	1/13/95	59 FR 56397.
Wyoming	10/04/95	10/18/95	60 FR 51925.
Delaware	8/8/96	10/7/96	61 FR 41345.
Total: 39 States and 1 Territory.			

Appendix C: Testing Reference Documents

The following references provide information on approved methods for testing hazardous waste samples:

American Public Health Association, *Standard Methods for the Examination of Water and Wastewater, 17th Edition.* 1989. Available from the Water Pollution Control Federation, Washington, D.C., #S0037.

U.S. Environmental Protection Agency, *Design and Development of a Hazardous Waste Reactivity Testing Protocol.* EPA Document No. 600/2–84–057, February 1984.

U.S. Environmental Protection Agency, *Methods for Chemical Analysis of Water and Waste.* EPA–6001114–79–020. Washington, D.C., 1983.

U.S. Environmental Protection Agency, *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods.* SW–846. Third Edition (1986) as amended. Available from the Government Printing Office, by subscription, 955–001–00000–1, or from the National Technical Information Service, PB88–239–223. Washington, D.C., January, 1995.

U.S. Environmental Protection Agency, *The New Toxicity Characteristic Rule: Information and Tips for Generators.* Office of Solid Waste, 530/SW–90–028, April, 1990.

U.S. Environmental Protection Agency, ORD, and U.S. Department of Energy, *Characterizing Heterogenous Wastes: Methods and Recommendations.* EPA/600/R-92/033, February 1992.

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. ‘‘Joint EPA/NRC Guidance on the Definition and Identification of Commercial Mixed Low-Level Radioactive and Hazardous Waste,’’ Directive No. 9432–00–2, October 4, 1989.

Appendix D: List of Regulations

Environmental Protection Agency General Regulations for Hazardous Waste Management, 40 CFR Part 260.

Environmental Protection Agency Regulations for Identifying Hazardous Waste, 40 CFR Part 261.

Environmental Protection Agency Regulations for Hazardous Waste Generators, 40 CFR Part 262.

Environmental Protection Agency Standards for Owners and Operators of Hazardous Waste Treatment, Storage and Disposal Facilities, 40 CFR Part 264.

Environmental Protection Agency Interim Status Standards for Owners and Operators of Hazardous Waste Facilities, 40 CFR Part 265.

Environmental Protection Agency Regulations on Land Disposal Restrictions, 40 CFR Part 268.

Nuclear Regulatory Commission Regulations—Standards for Protection Against Radiation, 10 CFR Part 20.

Nuclear Regulatory Commission Regulations—Rules of General Applicability to Domestic Licensing of Byproduct Material, 10 CFR Part 30.

Nuclear Regulatory Commission Regulations—Domestic Licensing of Source Material, 10 CFR Part 40.

Nuclear Regulatory Commission Regulations—Domestic Licensing of Production and Utilization Facilities, 10 CFR Part 50.

Nuclear Regulatory Commission Regulations—Licensing Requirements for Land Disposal of Radioactive Waste, 10 CFR Part 61.

Nuclear Regulatory Commission Regulations—Domestic Licensing of Special Nuclear Material, 10 CFR Part 70.

[FR Doc. 97–30528 Filed 11–19–97; 8:45 am]

FOOTNOTES

[1] See 42 U S.C. §6903 (41), added by the Federal Facility Compliance Act of 1992 (FFCA).

[2] See revised *Guidance on the Definition and Identification of Commercial Low-Level Radioactive and Hazardous Waste and Answers to Anticipated Questions,* October 4, 1989.

[3] The RCRA base hazardous waste program is the RCRA program initially made available for final authorization and includes Federal regulations up to July 26, 1982. However, authorized States have revised their programs to keep pace with Federal program changes that have taken place after 1982 in accordance with EPA regulation.

[4] Refer to Appendix A for specific EPA regulations pertaining to (1)–(4).

[5] ALARA, codified in 10 CFR Part 20, refers to the practice of maintaining all radiation exposures, to workers and the general public, as low as is reasonably achievable.

[6] For a more detailed discussion on process knowledge, see Section 1.5 in ''Waste Analysis at Facilities That Generate, Treat, Store, and Dispose of Hazardous Wastes'' OSWER 9938.4–03, April 1994.

[7] The ''mixture'' and ''derived-from'' rules were vacated and remanded due to EPA's failure to provide adequate notice and opportunity for comment before their 1980 promulgation, in *Shell Oil* v. *EPA,* No. 80–1532 (D.C. Cir. Dec. 6, 1991). At the Court's suggestion, EPA reinstated the ''mixture'' and ''derived-from'' rules as interim final until the rules are revised through new EPA rulemaking. The ''mixture'' and ''derived from'' rules adopted by those States with authorized RCRA programs were not affected by the court case or the subsequent reinstatement by EPA. For further information, see 57 *FR* 49278, October 30, 1992, and 60 *FR* 66344, December 21, 1995.

[8] Generators who also treat their waste are subject to the requirements for treatment facilities unless they treat waste in accumulation tanks,

containers, or containment buildings, for 90 days or less in accordance with 40 CFR 262.34(a). Treatment facilities must periodically test the treated waste residue from prohibited wastes to determine whether it meets the best demonstrated available technology (BDAT) treatment standards and may not rely on materials and process knowledge to make this determination (40 CFR 268.7(b)). This testing must be conducted according to the frequency specified in the facility's waste analysis plan (refer to Section IV of this guidance for a detailed discussion of treatment, storage, and disposal facility requirements).

[9] This definition of surrogate should not be confused with the definition of surrogate for the purposes of sampling and analysis quality control in Section 1.1.8 of "*Evaluating Solid Waste—Volume IA: Laboratory Test Methods Manual Physical/Chemical Methods.*"

[10] Note that characteristic only wastes (which are neither wastewater mixtures or RCRA listed hazardous wastes when generated) may be treated so that they no longer exhibit any of the four characteristics of a hazardous waste. However, these wastes may still be subject to the requirements of 40 CFR Part 268, even if they no longer exhibit a hazardous characteristic at the point of land disposal. After treatment this waste must not exhibit any RCRA hazardous waste characteristic *and* must meet applicable treatment standards before it can be considered a non-hazardous waste (see 57 *FR* 37263, August 18, 1992, and 58 *FR* 29869, May 24, 1993).

[11] Note that hazardous and mixed waste samples analyzed for waste characteristics or composition, and samples undergoing treatability studies may be exempt from all or part of the RCRA regulations if they are managed in accordance with 40 CFR 261.4 (d), (e) or (f).

[12] EPA incorporated by reference into the RCRA regulations (58 *FR* 46040, August 31, 1993), a third edition (and its updates) of "Test Methods for the Evaluation of Solid Waste, Physical/Chemical Methods." The updates can be found in 60 *FR* 3089, January 13, 1995 (update II), 59 *FR* 458, January 4, 1994 (update IIA), 60 *FR* 17001, April 4, 1995 (update IIB), and 62 *FR* 32452, June 13, 1996 (update III). Hazardous and mixed waste

generators and management facilities should verify that the analytical method that they use to analyze hazardous waste has not been superseded in the third edition.

[13] When evaluating test protocols for explosive mixed waste, consideration should be given to the likelihood for dispersing radioactivity during detonation. Using process knowledge or a surrogate material would, in most instances, be appropriate for these wastes.

[14] Note that when using the TCLP, if any liquid fraction of the waste positively determines that hazardous constituents in the waste are above regulatory levels, then it is not necessary to analyze the remaining fractions of the waste. Extraction using the zero headspace extraction vessel (ZHE) is not required, furthermore, if the analysis of an extract obtained using a bottle extractor demonstrates that the concentration of a volatile compound exceeds the specified regulatory levels. The use of a bottle extractor, however, may not be used to demonstrate that the concentration of a volatile compound is below regulatory levels (40 CFR Part 261 Appendix II Sections 1.3 and .4).

[15] With the exception of the fourteen areas (see Appendix D) where test methods are required by hazardous waste regulation, use of EPA's *Test Methods for the Evaluation of Solid Waste* (SW–846) is not required, and should be viewed as guidance on acceptable sampling and analysis methods.

[16] An inconsistency occurs when compliance with one statute or set of regulations would necessarily cause non-compliance with the other. It may stem from a variety of considerations, including those related to occupational exposure, criticality, and other safeguards.

[17] A representative sample is defined in 40 CFR 260.10 as "a sample of a universe or whole (e.g., waste pile, lagoon, ground water) which can be expected to exhibit the average properties of the universe or whole." For further guidance see Chapter 9 of the EPA's testing guidance entitled *Test Methods for Evaluating Solid Waste* or SW–846.

[18] A prohibited waste may not be land disposed unless it meets the treatment standards established by EPA. These standards are usually based on the performance of the BDAT. A waste that is subject to an extension, such as a national capacity variance, does not need to comply with the BDAT treatment standards, but is ''restricted'' and if it is going to be disposed in a landfill or surface impoundment, it can only be disposed of in a unit that meets the minimum technology requirements (MTRs). An exception exists for interim status surface impoundments which may continue receiving newly identified and restricted wastes for four years from the date of promulgation of the listings or characteristics before being retrofitted to meet the MTRs (RCRA Section 3005(j)(6)), so long as the only hazardous wastes in the impoundment are newly identified or listed.

[19] The treatment standards for mineral processing wastes and certain additional newly listed waste streams were proposed in 61 *FR* 2338, January 25, 1996, and a second supplemental proposed rule signed April 18, 1997.

[20] Non-wastewater residues (e.g., slag) that result from high temperature metals recovery that are excluded from the definition of hazardous waste by meeting the conditions of 40 CFR 261.3(c)(2)(ii)(C), and hazardous debris that is excluded from the definition of hazardous waste in 40 CFR 261.3(f) have reduced LDR notification requirements. Specifically, these wastes, and characteristic hazardous wastes that are rendered non-hazardous, do not require a notification and certification accompanying each shipment. Instead, they may be sent to an AEA-licensed facility with a one-time notification and certification sent to the EPA Region or authorized State.

[21] Note that verification testing is a means to verify that the wastes received match the waste description on the manifest, which is required under 40 CFR 264.13 and 40 CFR 265.13(c). The main objective of corroborative testing is to provide an independent verification that a waste meets the LDR treatment standard.

[22] Land disposal facilities must maintain a copy of all LDR notices and certifications transmitted from generators and treaters (40 CFR 268.7(c)).

ACRONYMS/ABBREVIATIONS USED IN THIS GUIDANCE

AEA	Atomic Energy Act.
ALARA	As Low As Is Reasonably Achievable.
BDAT	Best Demonstrated Available Technology.
CFR	Code of Federal Regulations.
EP	Extraction Procedure (toxicity test).
EPA	Environmental Protection Agency.
FR	Federal Register.
HSWA	Hazardous and Solid Waste Amendments.
LDR	Land Disposal Restrictions.
NRC	Nuclear Regulatory Commission.
OSWER	Office of Solid Waste and Emergency Response.
RCRA	Resource Conservation and Recovery Act.
SW–846	Test Methods for Evaluating Solid Wastes, Physical/Chemical Methods.
TC	Toxicity Characteristic.
TCLP	Toxicity Characteristic Leaching Procedure.
TSDF	Treatment, Storage or Disposal Facility.
WAP	Waste Analysis Plan.

Excerpts from U.S. Senate Report 108-105 and Bill S.1424

U.S. Senate Energy & Water Report 108-105

"Waste Analysis Requirements for the Waste Isolation Pilot Plant.—The Committee recognizes that the WIPP facility is central to the cleanup of the nuclear weapons complex and that waste should be emplaced as quickly and safely as possible—for reasons of reducing clean-up costs, public safety, and with the growing threat of radiological terrorism, for national security. Current law and regulation regarding the sampling and analysis of waste destined for WIPP produces substantial health and safety risks to workers with little if any corresponding public benefit. Both the New Mexico Environmental Evaluation Group, an independent WIPP oversight group, and the National Academy of Sciences have strongly suggested that waste destined for disposal at WIPP should not undergo hazardous waste sampling and analysis. To this end, the Committee believes that eliminating dangerous and excessive waste confirmation requirements that offer little if any benefit to the health and safety of the public will serve the national interests inherent in the safe and expeditious cleanup of the nuclear weapons complex. For these reasons, the Committee has included language in section 310 that requires that waste characterization be limited to determining that the waste is not ignitable, corrosive, or reactive. This confirmation will be performed using radiography or visual examination of a representative subpopulation of the waste. The language further directs the Secretary of Energy to seek a modification to the WIPP Hazardous Waste Facility Permit to implement the provisions of this bill by December 31, 2003. The Committee recommendation includes $1,000,000 for regulatory and technical assistance to the State of New Mexico to amend the existing WIPP Hazardous Waste Permit to comply with the provisions of the bill."

U.S. Senate Bill S.1424

Title: An original bill making appropriations for energy and water development for the fiscal year ending September 30, 2004, and for other purposes.
Sponsor: Sen Domenici, Pete V. [NM] (introduced 7/17/2003)
Cosponsors: (none)

"SEC. 310. (a) The Secretary of Energy is directed to file a permit modification to the Waste Analysis Plan (WAP) and associated provisions

contained in the Hazardous Waste Facility Permit for the Waste Isolation Pilot Plant (WIPP). For purposes of determining compliance of the modifications to the WAP with the hazardous waste analysis requirements of the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.), or other applicable laws waste confirmation for all waste received for storage and disposal shall be limited to (1) confirmation that the waste contains no ignitable, corrosive, or reactive waste through the use of either radiography or visual examination of a statistically representative subpopulation of the waste; and (2) review of the Waste Stream Profile Form to verify that the waste contains no ignitable, corrosive, or reactive waste and that assigned Environmental Protection Agency hazardous waste numbers are allowed for storage and disposal by the WIPP Hazardous Waste Facility Permit.

(b) Compliance with the disposal room performance standards of the WAP shall be demonstrated exclusively by monitoring airborne volatile organic compounds in underground disposal rooms in which waste has been emplaced until panel closure."

Peer Review Criteria, Findings, and Recommendation of the Review Panel

The findings of the Review Panel (RP) with respect to the review criteria are as follows:

Criterion 1

Is the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S. 1424 supported by the recommendations of the National Research Council (NRC) report "Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant"?

Finding 1 of the RP

The NRC committee was formed to respond to specific issues identified by the U.S. Department of Energy (DOE) and was disbanded in 2001. Consequently, the RP had no other choice but to rely exclusively upon the text of the NRC (2001) report.

The DOE has been exploring the waste characterization requirements necessary to satisfy the U.S. Environmental Protection Agency (EPA) and the requirements necessary to satisfy the New Mexico Environment Department (NMED). The EPA regulates the long-term repository containment of radionuclides. The following characterization requirements are needed to comply with EPA regulations:

1. Acceptable Knowledge (AK) and Non-Destructive Assay requirements listed in Appendix A of *Contact-Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant*; and

2. Radiography results for ferrous and non-ferrous metals; cellulose; rubber; plastics; and liquids.

The NMED focuses on the containment of materials regulated by Resource Conservation and Recovery Act (RCRA). Characterization requirements of NMED are as follows:

1. AK
2. Headspace gas
3. Solids sampling and analysis

4. Real-Time Radiography/Visual Examination (RTR/VE)
5. Compliance with Waste Acceptance Criteria as described in the Attachments B to the WIPP Hazardous Waste Facility Permit (HWFP)

Characterization requirements in compliance with transportation regulations are:

1. AK
2. RTR/VE
3. Headspace gas flammables analysis
4. Payload container surface dose measurements
5. Fissile material quantity measurements for payload containers
6. Radionuclide description for at least 95% of the activity in each shipment

In complying with transportation regulations, DOE determines when characterization activities beyond the initial AK would need to be used. For some wastes, AK contains sufficient information to comply with transportation regulations.

The U.S. Senate Bill S. 1424 states that waste confirmation for all waste received for storage and disposal shall be limited to:

1. confirmation that the waste contains no ignitable, corrosive, or reactive waste through the use of either radiography or visual examination of a statistically representative sub-population of the waste; and

2. review of the Waste Stream Profile Form to verify that the waste contains no ignitable, corrosive, or reactive waste and that assigned Environmental Protection Agency hazardous waste numbers are allowed for storage and disposal by the WIPP Hazardous Waste Facility Permit.

Reference is made to the 2001 NRC Report under the heading "Waste Characterization and Packaging Requirements",

Pages 77-78:

*"**Finding:** The committee found inadequate legal or safety bases for some of the National TRU Program requirements and specifications.*

That is, some waste characterization specifications have no basis in law, the safe conduct of operations to emplace waste in WIPP, or long-term performance requirements [...]. The National TRU Program waste characterization procedures involve significant resources (e.g., expenditures of several billion dollars) and potential for exposure of workers to radiation and other hazards. Insofar as some of this waste characterization may be unnecessary, such characterization is inconsistent with economic efficiency and the ALARA principle that guides radiation protection practices [...]. The committee regards the 30+ years of waste emplacement operations and related worker safety issues at WIPP as posing no significant needs for waste characterization information, because no use of characterization data is made in any handling, shipping, or emplacement operations."

Page 78:

*"**Recommendation:** DOE should eliminate self-imposed waste characterization requirements that lack a legal or safety basis. One way to justify a reduction in waste characterization requirements is through implementation of joint U.S. Nuclear Regulatory Commission (USNRC)-U.S. Environmental Protection Agency (EPA) guidance (62 Federal Register 62079;[...]), which appears to the committee to provide appropriate guidelines for implementation and integration of Resource Conservation and Recovery Act (RCRA) requirements for mixed TRU waste. Implementation of this regulatory guidance could significantly reduce the testing protocols and associated radiation exposure of personnel. Another way to justify a reduction is to identify the origins of all waste characterization requirements and to eliminate those requirements that lack a technical or safety basis. Such reductions may require modifications to existing permits granted by external regulating authorities such as the EPA and New Mexico Environment Department."*

Pages 78-80:

*"**Rationale:** .... The committee sought to identify the connection between the National TRU Program procedures and the various regulatory, legal, and technical requirements that the procedures*

should be devised to meet. The committee views these requirements in a hierarchy, at the top of which are legal and safety requirements, with regulatory specifications at the next tier, procedures proposed by DOE to meet regulatory requirements at the third tier, and the DOE protocols for these procedures at the fourth tier.

"The approach used by the committee was to focus on six primary National TRU Program procedures representative of high-level requirements that drive operational activities in waste characterization and repackaging [...]:

1. *determination that the TRU waste is of defense origin;*
2. *sampling and analysis of homogeneous waste;*
3. *headspace gas sampling and analysis;*
4. *radioassay of the plutonium content;*
5. *real-time radiography; and*
6. *visual examination.*

".... A review of these six procedures revealed that one may be interpreted too strictly by DOE and three are without a technical or legal foundation:

"Procedure 1: Determination that the TRU waste is of defense origin. WIPP is limited to defense-related waste as stipulated in the Land Withdrawal Act, with defense activities defined in the Nuclear Waste Policy Act of 1982. The committee notes that this definition includes the words 'in whole or in part', which can be interpreted to include mixtures of defense and nondefense waste, although DOE does not appear to take advantage of this (see DOE, 1997a; Nordhaus, 1996). That is, waste such as plutonium-238 (^{238}Pu)-contaminated scrap from a facility used for both defense and nondefense missions at Los Alamos National Laboratory would appear to qualify as defense waste under the definition, without the need for waste segregation restrictions.

"Procedure 2: Sampling and analysis of homogeneous waste. DOE has written, There is no regulatory requirement to conduct homogeneous waste sampling and analysis, however, in an effort to meet the

intent of 40 CFR 264.13, WIPP has imposed additional characterization requirements on the waste generators (Nelson, 1999[...], p. 2). No operational decisions are made based on these data; that is, the results of the sampling and analysis do not affect how waste is handled, so it is not clear what justifies the additional radiation exposure risk and cost of this procedure. In the committee's view, this sampling and analysis applied only to homogeneous waste is unnecessary: If acceptable knowledge documentation [...] provides sufficient characterization information for heterogeneous waste, the committee can identify no technical reason why acceptable knowledge should not also be adequate for homogeneous waste.

"Procedure 3: Headspace gas sampling and analysis. DOE informed the committee that there is no regulatory requirement to conduct headspace gas sampling and analysis, however, in an effort to meet the intent of 40 CFR 264.13, WIPP has imposed additional characterization requirements on the waste generators (Nelson, 1999[...], p. 3). The headspace gas sampling and analysis was developed as a means of checking on conformance with USNRC and the U.S. Department of Transportation (DOT) requirements [...]; however, these requirements can be met by other means [...].

"Procedure 6: Visual examination. Visual examination is done on a fraction of the waste containers to confirm the real-time radiography and acceptable knowledge waste characterization information (Nelson, 1999[...], p. 5). However, there is no requirement for verification of real-time radiography results. An alternative way to confirm these results without operator exposure would be to use standardized test drums. The visual examination confirmation is a self-imposed procedure that yields no benefit but results in increased risk of exposure and cost."

Furthermore the NRC (2001) suggested that a DOE study (1999) confirms that sampling and analysis of homogeneous waste (which frequently requires drilling into a radioactive waste container using a large drill to obtain a core sample), headspace gas sampling and analysis (which requires workers to establish a pathway into a radioactive waste container to attach a sample line, frequently done with a large needle), and

visual examination (which requires workers to open a radioactive waste container and physically sort through its contents), are based on terms negotiated in a permit and not on a required regulation or legal mandate.

Page 80:

"....The committee sees no utility in the information that these procedures provide. Any speculative benefits of acquiring this information must be weighed against the risks and costs. The committee's judgment is that the collection of these data from superfluous procedures increases, rather than decreases, the risk and safety of the overall TRU waste operations." [The RP notes that the second term 'safety' in the quoted phrase conveys the opposite meaning from the first term 'risk'. Upon reading the complete text of the cited report, the RP concludes that the cited phrase should be read 'to reduce risk' rather than 'reduce risk and safety.']

"These superfluous characterization and intrusive procedures also represent a conflict with the ALARA principle. The issue of how to handle conflict between regulatory requirements for waste characterization information and ALARA is beyond the scope of the committee's statement of task. At issue, however, is whether the present TRU waste management program results in significantly more worker radiation exposure than is justified to satisfy safety and nonnegotiabie regulatory requirements."

Based on the careful evaluation of the NRC (2001) report, the RP concludes that the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S. 1424 is supported by the NRC.

Criterion 2

Is the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S. 1424 supported by various statements and other publications of the New Mexico Environmental Evaluation Group?

Finding 2 of the RP

As the Senate language was based on the statements and other publications of Environmental Evaluation Group (EEG), the RP had to rely upon the existing materials prepared by the EEG.

Responding to a question of the NRC (EEG 2003, page 2, #5): "What WIPP waste characterization requirements, if any, has DOE imposed that go beyond EPA, NMED, and transportation requirements?", the EEG response was:

"*None that the EEG is aware of. The DOE established a unique system for waste characterization in order to satisfy the various requirements for opening the WIPP facility and allowing TRU wastes from across the country to be disposed of in New Mexico. These were worked out over several years through various methods with the various agencies and the DOE Generator/Storage Sites, involving give-and-take on both sides. During these negotiations, the DOE wished to deviate from the usual hazardous waste processes for a disposal facility. These deviations were apparently because of the DOE's limited knowledge about the TRU waste, the introduction of RCRA requirements to the DOE holdings, the complications caused by the presence of radionuclides, a desire to have the waste analyzed by those most familiar with them (the generator/storage sites), the uniqueness of the WIPP as a geological repository rather than a landfill, and other considerations. Thus, it is less a condition of whether or not the DOE has imposed requirements that go beyond those of the regulatory agencies than it of whether or not the DOE is going beyond the agreements established with the agencies.*"

Silva (2002b, page 1) provided EEG's views to a committee of NRC by stating:

"*These previous EEG statements reflect our basic criteria regarding waste characterization:*
1. 'We believe overall waste characterization requirements are excessive .... However, any proposed relaxation needs to be evaluated in sufficient detail to convince regulators, EEG, and stakeholders that the modification is justified' ...."

2. "In our October 4, 2001 Statement to the NAS Committee on the Characterization of Remote-Handled Transuranic Wastes for the Waste Isolation Pilot Plant we said, 'The conclusions from EEG-72 were that for routine operations the radiological risk was on the order of 10,000 times the hazardous waste risks, all from Volatile Organic Compounds (VOCs).... The fact that radiological risks are much greater than hazardous waste risks needs to be kept in mind by DOE, regulatory agencies, peer review groups, this Committee, and oversight agencies when addressing possible changes to waste characterization requirements'."

3. "The relaxation of audit requirements and QA/QC is not an appropriate way to reduce the waste characterization burden. These requirements should maintain the current level of stringency. The appropriate way to reduce the waste characterization burden is to eliminate unnecessary requirements, not to reduce the degree of compliance."

Silva (2002b, page 8) has also stated that:

"We see no technical reason why it is necessary to analyze for metals and chemicals at all. [...] Our reasons are: (1) the quantity of these materials to be emplaced in the repository was not important enough to DOE to estimate in the HWFP Application nor for the New Mexico Environment Department to request, (2) the data are not to be used for any regulatory control under the HWFP, and (3) evaluations in EEG-72 concluded that human exposures to hazardous metals and chemicals would only occur from the same type of operational and human intrusion accidents that released radioactive materials. In EEG-72, the calculated radionuclide risk would be $\geq 5x10^5$ times the hazardous metals risk.

"Despite the above statement, we do recognize an advantage of toxic metals sampling; the possible detection of prohibited items, such as PCB concentrations greater than 50 parts per million." [The RP does not understand this statement as it appears inconsistent with the above paragraph.]

"Our concerns about VOC or SVOC sampling are the same as for headspace gas sampling (that room based concentration limit and

transportation requirements be met in some manner). The Committee may wish to explore the need for VOC and SVOC sampling in order to provide additional information on homogenous wastes."

In May 2002, based on the results of an EEG Report (Channell and Neill 1999), Silva (May 2002a, page 5) stated that:

"With respect to waste characterization for non-radiological constituents such as VOCs, the EEG's analyses indicate that the non-radiological risks are substantively less than the radiological risks[...]. The analyses suggest that these constituents do not require the same level of sampling characterization. Furthermore, it has been suggested that additional waste characterization of the non-radiological constituents may increase radiological risks to workers. The EEG recommends that the DOE analyze the efficacy of AK for RH TRU in the absence of confirmatory testing. However, until the data are generated and evaluated, the DOE should not deviate from the characterization process used for CH TRU. The DOE also needs to address the documents identified by the EEG which raise questions about AK at the generator/storage sites."

Furthermore, Channell and Walker (2000 page 60) of EEG concluded that:

"Even if VOC emissions are much higher than expected, the Confirmatory VOC Monitoring Plan at WIPP would detect concentrations that are three orders of magnitude below allowable Permit limits. Any hazardous emissions from pre-Permit wastes would likely be reported and acted on long before Permit limits were reached."

It appears that EEG agrees that the current characterization requirements are excessive. It appears that EEG also agrees that monitoring VOCs in underground disposal rooms is sufficient. The RP was unable to identify more details on views of EEG regarding the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S. 1424.

Criterion 3

Based on the information presented to the Review Panel, is the permit modification listed under Section 310 of U.S. Senate Bill S. 1424 technically defensible?

Finding 3 of the RP

In assessing the need for various characterization tests, the RP first evaluated the regulatory requirements. Regulations promulgated in implementing requirements of RCRA provide guidance on compliance with RCRA. Briefly, each generator is required to perform specific tasks as follows:

1. If the process used by the waste generator does not use or produce any of the classes covered under RCRA, then the waste is not covered under RCRA. Many organizations use the process knowledge to demonstrate exception from RCRA.

2. The generator performs specific tests as provided in the regulations, and can demonstrate a lack of presence of listed waste or passage of specific characteristic wastes.

3. The generator has also the option to request a delisting of the waste even if the process knowledge or the tests indicate coverage under RCRA. The delisting process is intended to remove those waste streams that pose insignificant risks from unnecessary and costly compliance with RCRA requirements.

4. If the process knowledge or various tests demonstrate that the waste is legally covered under RCRA and the waste is not delisted, the generator must treat the waste prior to its disposal. This latter requirement is referred to as Land Disposal Restrictions (LDR) and is intended to ensure the long-term safety of Disposal facilities permitted under RCRA.

For transuranic (TRU) waste, WIPP Managers have chosen to accept the fact that TRU waste includes RCRA constituents. As stated above, the consequence of such a decision is compliance with the requirements of LDR. However, the Waste Isolation Pilot Plant/Land Withdrawal Act

exempts the WIPP from the coverage of LDR. Consequently, it appears that the WIPP managers would have to comply only with those RCRA requirements that are unrelated to LDR. These include those tests that would be required for the safety of operations. The safety-related requirements are those that are also covered by the transportation requirements—notably corrosivity, reactivity, and ignitability/flammability.

Acceptable knowledge can be one way in which compliance with the legal requirements is confirmed. EPA provides guidance in this regard. In particular, EPA (1994) provides guidance regarding waste analysis at facilities that generate, treat, store, and dispose of hazardous waste. Although EPA views representative sampling and laboratory analysis as the preferred method, acceptable knowledge is considered to be a viable alternative to meet waste analysis requirements. EPA (1994, page 1-11) indicates that:

"... generators and TSDFs also can meet waste analysis requirements by applying acceptable knowledge. Acceptable knowledge can be used to meet all or part of the waste analysis requirements."

Moreover, on pages 1-13 to 1-14 of EPA (1994) it is stated that:

"... there are situations where it may be appropriate to apply acceptable knowledge, including:
• Hazardous constituents in wastes from specific processes are well documented, such as with the F-listed and K-listed wastes.
• Wastes are discarded unused commercial chemical products, reagents or chemicals of known physical, and chemical constituents. Several of these fall into the P-listed and U-listed categories...
• Health and safety risks to personnel would not justify sampling and analysis (e.g., radioactive mixed waste).
• Physical nature of the waste does not lend itself to taking a laboratory sample."

The RP finds itself in agreement with the NRC (2001, page 77) that:

"... some waste characterization specifications have no basis in law, the safe conduct of operations to emplace waste in WIPP, or long-term performance requirements."

The NRC (2001, page 80) identifies three tests as having no legal foundation and

"... sees no utility in the information that these procedures provide. Any speculative benefits of acquiring this information must be weighed against the risks and costs. The committee's judgment is that the collection of these data from superfluous procedures increases, rather than decreases, the risk and safety of the overall TRU waste operations." [The RP notes that the second term 'safety' in the quoted phrase conveys the opposite meaning from the first term 'risk'. Upon reading the complete text of the cited report, the RP concludes that the cited phrase should be read 'to reduce risk' rather than 'reduce risk and safety.']

In addition to NRC (2001) report, the RP evaluated a more recent relevant NRC (2002) report. The latter report adopts the conclusions of the NRC (2001) report, and provides the following recommendation (NRC 2002, page 49):

"The committee acknowledges that DOE must consider many non-technical factors in composing its characterization plan. However, DOE should propose only characterization activities that have a technical, health and safety, or regulatory basis."

As no evidence was provided that the views of the EEG—as presented in its statements and reports—had been subjected to independent peer review, the RP used the EEG information cautiously.

DOE has already agreed with the NRC recommendation to eliminate self-imposed waste characterization requirements that lack a legal or safety basis (NRC 2001, page 113). DOE has developed and begun the implementation of a strategy to systematically improve the Waste Analysis Plan by reducing the frequency of waste characterization and implementing methods that make characterization simpler, less expensive—and above all—safer. On August 8, 2000, the New Mexico Environment Department approved two packages of Class 2 modifications to the WIPP's Hazardous Waste Facility Permit that include:

1. The "miscertification rate" of TRU waste was revised to apply to the waste summary category group instead of each waste stream. This could result in a ten-fold reduction in the number of drums that must be opened for VE.

2. The solids sampling requirements for analysis of VOCs have been revised to allow use of one subsample instead of three subsamples. This could avoid a cost of approximately ten million dollars that the Idaho National Engineering and Environmental Laboratory would have had to spend in re-analyzing the samples.

3. The number of headspace gas samples required has been reduced for two types of waste streams to a statistically-selected number of drums, instead of 100% sampling. The two types of waste streams now eligible for statistical headspace gas sampling are: wastes that have been thermally processed; and homogeneous wastes with "acceptable knowledge" that demonstrate no volatile organic compounds have been present in the waste.

Approval of these modifications could result in significant cost savings associated with waste characterization and will reduce radiation exposures to workers.

Additionally, several modifications have been prepared and submitted that specifically address safety issues associated with TRU waste handling and disposal. One such modification, submitted in October 2000, will allow generators to remove from consideration for VE any containers that pose a safety concern. For example, if a generator determines that opening a container with a high fissile gram content is a safety hazard, that container can be ruled ineligible for VE and another container selected.

Based on the information presented to the Review Panel, the permit modification listed under Section 310 of U.S. Senate Bill S. 1424 is technically defensible. There is no reason to perform waste confirmation tests that:

1. provide insignificant health and safety benefits to the U.S. population; and
2. pose serious radiological and occupational health and safety risks for the workers performing these tests.

RECOMMENDATION

The RP recommends that the Mayor of Carlsbad make available this report to the U.S. Senate Committee for Energy and Water.

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Biographical Summaries

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Melvin W. Carter is currently an International Radiation Protection Consultant and Neely Professor Emeritus at Georgia Institute of Technology in Atlanta, GA. His fields of interest include: pollutant pathways in the environment and their kinetics; policy formulation in environmental protection and radiological protection; and procedures and methods for environmental surveillance. His other fields of interest are: the management of radioactive wastes; radiological engineering evaluations for criteria and standards; and the transportation of radioactive materials. He has provided consulting services to a large number of national and international organizations. He served as the Director of the Office of Interdisciplinary Programs at Georgia Tech, which included the Bioengineering Center and Environmental Resources Center. He was also Professor of Nuclear Engineering and Health Physics at Georgia Tech. He developed

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Alan S. Corson is a consultant in hazardous waste issues. He has over 25 years of experience in a number of environmental issues, notably those related to the regulations and management of hazardous waste. Subsequent to his retirement from the U.S. Environmental Protection Agency (EPA), he served in an advisory role to Jacobs Engineering Group and to the Versar Corporation for both government and private sector clients regarding hazardous waste management programs. During his employment at the EPA, he worked at the Office of Solid Waste where he was responsible for regulatory programs and establishing national standards for generators and transporters of hazardous waste; development of sampling and analytic methods for evaluating solid/hazardous waste including the quality assurance/quality control program; and development

and management of programs to establish risk assessment of hazardous waste management practices. Alan Corson was instrumental in the development of the original regulatory program defining standards for solid waste and hazardous waste, and setting national standards for recycling hazardous waste. He also initiated, developed, and managed the original program for restricting hazardous wastes from land disposal management options. The framework developed under this program is currently in-place and used for all evaluations in the land-ban program. Alan Corson served as the EPA Office of Solid Waste representative on many intra- and inter-agency workgroups including PCBs, Reportable Quantities, chlorinated solvents, and transportation of hazardous materials. He developed a guide for effective management of infectious wastes—a predecessor to the current regulatory program for medical wastes; characteristics and listings of hazardous waste; and many regulatory options papers for presentation. Alan Corson managed the preparation of numerous regulatory packages for all aspects of the program implementing the Resource Conservation and Recovery Act (RCRA). He has spoken widely and has taught numerous courses on RCRA and its various regulations. He served on numerous national and international panels including review panels of the American Society of Mechanical Engineers. He received a B.S. in Electrical Engineering and an M.S. in Engineering Management from the Drexel Institute of Technology in Philadelphia, PA.

Ernest L. Daman is Chairman Emeritus of Foster Wheeler Development Corporation where he previously served as Director of Research and Chairman of the Board. He also held the position of Senior Vice President at the parent company, FWC. He is a Past President of American Society of Mechanical Engineers and was elected to the National Academy of Engineering. Ernest Daman is a Fellow of the Institute of Energy (England) and the American Association for the Advancement of Science, and Past Chairman of the American Association of Engineering Societies. He served on several American Society of Mechanical Engineers committees as member or chairman. Ernest Daman is the author of numerous papers and holds 18 patents. He was responsible for the design and development of a combined steam gas turbine plant, fluidized bed combustion, fast breeder reactor components, supercritical steam generators, environmental control processes, and

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Nathan H. Hurt is a consultant in management and engineering with Technical and Management Consulting. He provides services to industrial firms and government agencies involved in environmental clean-up and waste management—both chemical and radioactive. He has extensive experience in the areas of executive management; plant management; engineering management; project management; marketing; and sales. He specializes in the areas of: uranium enrichment/production; engineering; development and marketing; plant management of rubber chemicals; petrochemicals; and thermoplastics. He also specializes in the engineering management of synthetic rubber and lattices; vinyl monomers and copolymers; polyesters; U.S. Department of Energy (DOE) weapons plants; quality assurance management; and operational readiness review. Nathan Hurt has been involved with the decommissioning of nuclear facilities. He was the Corporate Sponsor or Program Manager for seven decommissioning contracts at the DOE Complexes in Oak Ridge, TN; and Pinellas, FL. Previously, Nathan Hurt worked for Sharp and Associates, Inc. as the Director and Project Manager at the Oak Ridge Office. He was Vice President and Director of Oak Ridge Operations for IDM Environmental Corp., where he was responsible for the marketing and sales of decontamination, decommissioning, and waste management. He served as Project Manager for the laboratory quality assurance program at Westinghouse Hanford; DOE's Rocky Flats Plant—plant-wide identification of electrical equipment. He managed a study for a waste treatment and storage facility at the Portsmouth Area Uranium Enrichment Facility which included incineration and compaction of low-level radioactive wastes. He also worked for The Goodyear Tire and Rubber Company, including Goodyear Atomic, as Director of Research and Development, and President, where he was responsible for the operation of the Portsmouth Area Uranium Enrichment Facility. Nathan Hurt is a past President of, the American Society of Mechanical Engineers. He has been a member of: the American Association of Engineering Societies' Board of Governors; the American Institute of Chemical Engineers; and the Institute of Nuclear Materials Management. He is also a member of Tau Beta Pi Honorary Engineering Society; Pi Tau Sigma Honorary Mechanical Engineering Society; and was a

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Michael C. (M.C.) Kirkland is an independent consultant who led a team that performed a Congressionally-mandated External Independent Review of the $1.3 billion Spallation Neutron Source Project at Oak Ridge. He assisted in the planning and review of a management assessment at a U.S. Department of Energy (DOE) Site that involved the restart of a plutonium facility. He participated in planning, procurement, and review activities in the environmental remediation area that included decommissioning activities at a shut down nuclear test reactor; designed and installed a ground water cleanup technology. M.C. Kirkland managed several environmental and construction projects that employed many soil investigative techniques including significant work with cone penetrometers. Additionally, he provided consulting services to a large environmental remediation services company regarding Dense Non-Aqueous Phase Liquid locating and removal techniques. During his tenure at the SRS, M.C. Kirkland was a Technical Advisor, Project Manager, and Director of the Project Engineering Division. He evaluated nuclear and mixed waste conditions and aspects of high level wastes and spent nuclear fuel; determined material inventories; performed pollution prevention and environmental health and safety evaluations for a proposed waste treatment facility; served as technical advisor to a study administered by the Savannah River Operations Office; and developed integrated schedules defined for this project. M.C. Kirkland was director of the Project Engineering Division and managed the SRS design and construction program. He has been involved with waste management and environmental projects; cutting-edge technology programs; and worked with lasers and magnetic containment. He served as Director of the Waste and Fuel Cycle Technology Office, and planned and coordinated the programs of the DOE National High Level Waste Technology Office; the SR Fuel Cycle Technology Program; and the Commercial Interim Spent Fuel Management Program. M.C. Kirkland holds a B.S. in Mechanical Engineering from the University of South Carolina. He is registered as a Professional Engineer in South Carolina.

Betty R. Love is currently Executive Vice President of the Institute for Regulatory Science. In that capacity, she is responsible for the management of day-to-day operations of the Institute, and for administration of several projects. She is the Administrative Manager of a large-scale peer review program in collaboration with the American Society of Mechanical Engineers for a number of organizations including the U.S. Department of Energy. Her current research activities center around the development and implementation of a systematic approach to stakeholder participation, notably in scientific meetings. Previously, Betty Love was Director, Department of Training and Information within the Office of Environmental Health and Safety of Temple University in Philadelphia, PA. During that period she was instrumental in the development of a "Handbook of Environmental Health and Safety". She also developed and implemented a large-scale training program not only for the faculty and staff of the University but also for others. Betty Love is currently Managing Editor of *Technology.* She has published several papers in peer-reviewed journals; has edited a number of compendia; and is the primary author of *Manual for Public and Stakeholder Participation*. Betty Love received a B.S. degree in Business Administration from Virginia State University in Petersburg, VA, and an M.S. degree in Developmental Clinical Psychology from Antioch College in Yellow Springs, OH.

Robert E. Luna is currently a private consultant involved in the packaging and transportation of a wide variety of radioactive materials at national and international levels. His current interests range from risk assessment related to packaging and transportation of radioactive materials, to nuclear weapon accident phenomenology. Previously, he was Senior Manager for the Waste Legacy Program Development Office at Sandia National Laboratory. In that capacity, he was responsible for business development for the mining industry; Department of Defense environmental cleanup needs; U.S. Nuclear Regulatory Commission transportation technology; and application of environmental remediation technology to various U.S. Department of Energy sites. In addition, he was involved in the study of nuclear weapon safety, transportation risk assessment, and cask sabotage source terms. Prior to that position, he managed a number of programs dealing with environmental characterization and monitoring technology, and while at Sandia National

Laboratory, he was involved in the development of the Environmental Impact Statement for the Pantex Plant in Amarillo, TX. For nearly 20 years, Robert Luna was involved with increasing responsibility in various aspects of radioactive and hazardous material package design and transportation, including: package design and testing; structural and thermal analysis; material development; and information management. He led the development of RADTRAN risk assessment code; managed the development of regulatory guide NUREG 0170; and led national efforts related to the risk assessment of packaging and transportation of high level waste/spent nuclear fuel at Sandia. Robert Luna represented the U.S. Department of Energy at the International Atomic Energy Agency in the development of the document regulations for the transportation of radioactive materials and related topics. He managed and contributed to experiments which defined sabotage threat and the potential impact of the sabotage of spent nuclear fuel transportation casks, including: threat evaluation, source-term development, and damage evaluation. He was involved in the development of generation, transport, and the fate of aerosols resulting from nuclear weapons accidents, including mishaps during the stages of assembly, disassembly, deployment, and storage. Robert Luna is a Fellow of the American Society of Mechanical Engineers; a member of the American Nuclear Society; and a member of ANSI N14 Management Committee for Nuclear Material Packaging. He is on the Editorial Board of the *International Journal of Radioactive Material Transportation.* He was past Chair of the Bernalillo County Air Quality Control Board. He received the Department of Energy Award of Excellence for "Significant Contributions to the Nuclear Weapons Program in Plutonium Safety Issues". He is the author or coauthor of more than 100 publications. Robert Luna holds a B.S. degree in Mechanical Engineering from Rutgers University; an M.S. degree in Mechanical Engineering and a Ph.D. in Aerospace and Mechanical Sciences from Princeton University; and Master of Management degree from the Anderson Schools of Management, University of New Mexico. He is a registered Professional Engineer in New Mexico.

Peter Maggiore is currently Principal Scientist with Portage Environmental, in San Antonio, TX. There, he is a corporate resource regarding regulatory analysis, environmental compliance, and scientific matters. In addition, Peter Maggiore has responsibilities in the areas of quality

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Lawrence C. Mohr, Jr., is currently Professor of Medicine, Biometry, and Epidemiology; and Director of the Environmental Biosciences Program at the Medical University of South Carolina. His areas of research and special interest include internal medicine and pulmonary disease—specifically diseases of the chest and respiratory system. An area of particular interest to Lawrence Mohr is environmental medicine, including molecular epidemiology and biomarker applications. He has been involved in studies related to environmental lung disease; pathophysiology; prevention and treatment of high altitude illness; high altitude physiology; risk assessment of environmental hazards and clinical epidemiology. Other areas of considerate interest to Lawrence Mohr are assessment of clinical outcomes; health policy analysis; and international health. This latter area includes: global epidemiology; medical relief operations; and health care in Central and Eastern Europe, as well as medical history—the

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John E. Moore is currently a Hydrogeologist at the Office of Water of the U.S. Environmental Protection Agency in Denver, CO. He is also an Adjunct Professor at Metro State College in Denver, CO, and a consulting hydrologist. His recent activities have included serving as a technical advisor, and planning geologic and hydrogeologic projects nationally and internationally. Prior to his current positions, he was Senior Hydrogeologist at Environmental Strategies Corporation, where he performed site investigations for property transfer, and aquifer remediation. He was a Technical Advisor at the U.S. Environmental Protection Agency in Washington, DC, where he conducted field investigations and prepared data for congressional hearings on the extent of groundwater

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Goetz K. Oertel's career in engineering, physics, chemistry, astronomy, and technical program management spans more than 40 years. He consults for industrial, academic, and governmental organizations in North and South America. As President and CEO of the Association of Universities for Research Astronomy, a nonprofit corporation, he engineered the initiation and completion of two 8-m aperture optical telescopes, and oversaw the Space Telescope Science Institute from before launch, through repair of the "Hubble flaw", to its successful operation. He initiated the conceptional phase of the Next Generation Space Telescope that will succeed Hubble as well as the Advanced Solar Telescope, and he oversaw the completion of ambitious ground-based astronomy facilities. He held technical and management positions in the U.S. Department of Energy, including Director of Defense Waste Management; Acting Manager of the Savannah River Operations Office; Deputy Manager of Albuquerque Operations Office; and Deputy Assistant Secretary for Safety, Health, and Quality Assurance. He had primary responsibility for

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Acronyms

AEA	Atomic Energy Act
AK	Acceptable Knowledge
ALARA	As Low As Reasonably Achievable
ASME	American Society of Mechanical Engineers
BAS	Best Available Science
BDAT	Best Demonstrated Available Technology
CAR	Commission on Assessment and Reviews
CCA	Compliance Certification Application
CFR	Code of Federal Regulations
CH	Contact-Handled
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EEG	Environmental Evaluation Group
EP	Extraction Procedure
EPA	U.S. Environmental Protection Agency
FR	Federal Register
FTIRS	Fourier Transform Infrared System
GC	Gas Chromathography
HPLC	High Pressure Liquid Chromatography
HSWA	Hazardous and Solid Waste Amendments
HWFP	Hazardous Waste Facility Permit
INEEL	Idaho National Engineering and Environmental Laboratory
LDR	Land Disposal Restrictions
MS	Mass Spectrometry
NAS	U.S. National Academy of Sciences
NDA	Non-Destructive Assay
NMED	New Mexico Environmen~~tal~~ Department
NRC	National Research Council
NUREG	Nuclear Regulatory Guidelines
OSWER	Office of Solid Waste and Emergency Response
PA	Performance Assessment
PAN	Passive/Active Neutron
PCB	Polychlorinated Biphenyl
PREPP	Process Experimental Pilot Plant
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
RH	Remote-Handled

RP	Review Panel
RSI	Institute for Regulatory Science
RTR	Real-Time Radiography
SGS	Segmented Gamma Scans
SPC	Statistical Process Control
SVOC	semi-volatile organic compound
SW–846	Test Methods for Evaluating Solid Wastes, Physical/ Chemical Methods
SWB	Standard Waste Box
TC	Toxicity Characteristic
TCLP	Toxicity Characteristic Leaching Procedure
TDOP	Ten-Drum Overpack
TIC	Tentatively Identified Compound
TRU	Transuranic
TRUDOCK	Waste handling area of WIPP
TRUPACT-II	Transuranic Package Transporter, Model 2
TSDF	Permit Treatment, Storage and Disposal Facility
TSDF-WAC	Permit Treatment, Storage and Disposal Facility Waste Acceptance Criteria
UCL	Upper Confidence Limit
USNRC	U.S. Nuclear Regulatory Commission
VE	Visual Examination
VOC	Volatile Organic Compound
WAC	Waste Acceptance Criteria
WAP	Waste Analysis Plan
WHB	Waste Handling Building
WIPP	Waste Isolation Pilot Plant
WIPP/LWA	Waste Isolation Pilot Plant/Land Withdrawal Act
WSPF	Waste Stream Profile Form

EEG-62

FLUID INJECTION FOR SALT WATER DISPOSAL AND ENHANCED OIL RECOVERY AS A POTENTIAL PROBLEM FOR THE WIPP: PROCEEDINGS OF A JUNE 1995 WORKSHOP AND ANALYSIS

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Environmental Evaluation Group
New Mexico

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, is being constructed as a repository for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, continues the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the generator sites' compliance with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP) is a facility of the U.S. Department of Energy (DOE), designed and constructed for the permanent disposal of transuranic (TRU) defense waste. The repository is sited in the New Mexico portion of the Delaware Basin, at a depth of 655 meters, in the salt beds of the Salado Formation. The WIPP is surrounded by reserves and production of potash, crude oil and natural gas.

In selecting a repository site, concerns about extensive oil field development eliminated the Mescalero Plains site in Chaves County (U.S. DOE 1980, 2-10) and concerns about future waterflooding in nearby oil fields helped eliminate the Alternate II site in Lea County (Griswold 1977, 13). Ultimately, the Los Medaños site in Eddy County was selected, relying in part on the conclusion that there were no oil reserves at the site (U.S. DOE 1980, 2-15).

For oil field operations, the problem of water migrating from the injection zone, through other formations such as the Salado, and onto adjacent property has long been recognized (Ramey 1976). In 1980, the DOE intended to prohibit secondary recovery by waterflooding in a one mile buffer surrounding the WIPP Site (U.S. DOE 1980, 8-4). However, the DOE relinquished the right to restrict waterflooding (McGough 1983) based on a natural resources report (Brausch et al. 1982, 30) which maintained that there was a minimal amount of crude oil likely to exist at the WIPP site, hence waterflooding adjacent to the WIPP would be unlikely.

In the early 1990s, the Delaware Basin experienced a drilling boom that included oil field discoveries surrounding and underlying the WIPP Site (Broadhead et al. 1995). Salt water disposal wells are now operating throughout the area (Silva 1994; Broadhead et al. 1995) and waterflooding is just beginning with new oil field pressure maintenance programs underway (Broadhead et al. 1995).

Beginning in 1988, sudden water level rises in the Culebra aquifer to the south of the WIPP site raised questions about the water injection activities of the oil and gas industry (Bailey 1990; LaVenue 1991). LaVenue (1991) cautioned the WIPP Performance Assessment (PA) team about the yet to be determined impact of these activities. However, the WIPP PA team did not include the impact of fluid injection in the calculations citing either "low consequence" arguments for human activities adjacent to the WIPP (SNL 1991, SNL 1992) or "consequences greater than that of exploratory drilling" in the case of human intrusion (SNL 1992). In 1993, the WIPP project was again cautioned about injected oil field water fracturing the Salado Formation and migrating into adjacent properties. An oil and gas producer in southeast New Mexico had suffered a major salt water blowout as a result of a waterflood operation two miles away (Hartman 1993).

The potential impact of brine injection on the long-term performance of the WIPP prompted the Environmental Evaluation Group (EEG) to organize a June 13, 1995, workshop on the issue. This report publishes the workshop presentations (Chapter 2) and presents the author's analysis of the workshop issues (Chapter 3) based on information from the scientific literature, public records, the draft compliance application submitted by the DOE to the U.S. Environmental Protection Agency (EPA), and the WIPP specific compliance Criteria promulgated by the EPA. The workshop included presentations describing the extent of oil and gas resources, the anomalous water level rises in the Culebra Aquifer, the documented effects of water flooding on the Salado Formation, the geology of waterflooded areas in southeast New Mexico, the current petroleum production practices, the treatment of water injection by the performance assessment effort, and the need for a water flooding scenario in the WIPP PA calculations. As was intended, a number of issues were deliberated. On many issues there was no consensus. Nonetheless, the workshop was an excellent example of cooperation and open exchange of information by various federal and state agencies, private industry, the university sector, and other interested parties.

In addition to exploring the potential impact of waterflooding and salt water disposal on the WIPP, Chapter 3 identifies a number of unresolved issues. Some unresolved topics are currently in litigation between oil and gas companies and the federal government for operations adjacent to the WIPP. The issues identified in Chapter 3 include questions about a) the productive life of an oil field in the Delaware Basin, b) the extent of oil and gas reserves in unexplored areas, c) the potential for waterflooding and other secondary recovery methods, d) the volumes of water to be injected, e) the availability of water for waterflooding, f) delays in oil and gas drilling due to the presence of potash g) the true extent of potash reserves, h) evidence of communication between formations above and below the WIPP through vertical pathways possibly created by the improper abandonment of wells, poorly cemented and cased wells, degraded well casings and cement in saline environments, and i) violation of existing regulations.

This report also raises questions about how much credit for protection from out-of-zone injection the WIPP project can justify, based on state regulations unique to the Known Potash Lease Area. The state regulations were never intended to address the needs of WIPP. Rather, the state regulations were promulgated to address the concerns of the potash and oil and gas industries (LeMay et al. 1988). In light of the information presented in this report, it would seem prudent for the WIPP project to analyze the historical effectiveness of the New Mexico regulations specifically intended to address fluid injection, Rule 701, 702, and 703.

The potash companies carefully monitor activities with a potential impact on the Salado Formation. For instance, the New Mexico Oil Conservation Division held a hearing on November 16, 1995, for a proposed oil field pressure maintenance well to be located one mile from the outer boundary of the WIPP and eight miles from IMC's existing potash mine workings. At the hearing IMC expressed concern that injected water could escape or otherwise migrate from the proposed injection interval into potash bearing formations. The DOE was notified of the hearing but did not attend (LeMay 1995b). The injection well was approved to

operate at a pressure that exceeds the lithostatic pressure at the WIPP horizon.

The oil and gas industry is also concerned about the operation of injection wells in close proximity to its hydrocarbon reserves. When Yates Petroleum proposed converting an oil production well to salt water injection, another oil company objected. Mitchell Energy was concerned about excessive injection pressures and the loss of reserves as a result of injection into potential oil producing horizons (Stephenson 1991). An agreement was reached between the two oil companies (Kellahin 1991). The salt water disposal well was approved by the New Mexico Oil Conservation Division (LeMay 1991). The DOE appeared unaware that there was a salt water injection well operating within one mile of the WIPP Site Boundary and continued to list the well as an oil producing well (Arthur 1993a; Arthur 1993b; Silva 1994, 55-56; Kehrman 1995, 254, lines 18-20).

The DOE Draft Compliance Certification Application (DCCA), submitted to EPA in July 1995, did not include fluid injection in the performance assessment calculations. Citing Cranwell et al. (1990), fluid injection within the WIPP site was screened out on the basis of "regulatory guidance" (U.S. DOE 1995, 6-38), but this criterion is not found in Cranwell et al. (1990). Furthermore, DOE's expert elicitation exercise of 1990 identified industrial fluid injection as a potential human intrusion activity for the full 10,000 year regulatory period (Hora et al. 1991, Table IV-16). Fluid injection due to activities on adjacent properties was screened out on the basis of "low consequence" although the DOE draft application had no documentation to support that position (U.S. DOE 1995, SCR-72). With respect to fluid injection adjacent to the WIPP Site, the February 1996 EPA Criteria (40 CFR 194) require performance assessment to include the effects of any near future activities on lands surrounding the WIPP. A credible compliance application should include performance assessment calculations that fully consider the distinct activities of 1) fluid injection for resource recovery and 2) waste disposal activities within the site and adjacent to the site for the regulatory period of 10,000 years.

1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is intended to serve as a repository for the disposal of transuranic (TRU) waste generated by the defense activities of the United States Government. The WIPP is situated in the lower portion of the Salado Formation in a resource rich area in southeastern New Mexico. Natural resources in the immediate vicinity of the WIPP site include economically attractive reserves of potash, crude oil, and natural gas (Foster 1974; Keesey 1976, 1977, and 1979; Griswold 1977; Powers et al. 1978; U.S. DOE 1980; Brausch et al. 1982; Neill et al. 1983; Weart 1983; Silva 1994; Griswold 1995a; Broadhead et al. 1995; U.S. DOE 1995).

1.1 Natural Resources and Water Injection at Other Candidate Sites

The problem of natural resources and the use of water injection in the vicinity of a nuclear waste repository has long been recognized. In 1972, the Lyons, Kansas site for a proposed TRU waste repository was rejected because there were too many drill holes in the area that could not be positively located, and nearby solution mining was experiencing unexplained water losses (U.S. DOE 1980, 2-7; U.S. DOE 1993, 26). Of the three areas in New Mexico chosen for further study, the Mescalero Plains area in Chaves County was disqualified because of extensive oil field development (U.S. DOE 1980, 2-10). In the Carlsbad vicinity, two of eight sites survived the screening criteria, the current Los Medaños site and the Alternate II. However, Alternate II in Lea County was rejected for a variety of reasons including the observation that it lay adjacent to the Double X and Triple X oil fields where waterflooding for secondary recovery could occur (Griswold 1977, 13).

1.2 Oil Field Waterflooding and the Salado

Typical oil field operations include two types of water injection activities - salt water disposal and waterflooding. In a successful salt water disposal operation,

the unwanted brine is injected through a disposal well into an approved zone or zones. The production of oil, particularly in the Delaware Basin, is often accompanied by the production of large volumes of reservoir brine.

Oil production by primary recovery relies on natural reservoir energy to drive oil towards the well bore. These sources of natural energy include fluid and rock expansion, solution gas drive, gravity drainage, and the influx of water from connected aquifers. As oil, gas, and reservoir brine are produced, the natural reservoir energy is expended. Waterflooding aims to enhance crude oil recovery by restoring or supplementing reservoir energy (Willhite 1986). A successful waterflood injects pressurized water through the well bore into the oil bearing zone to force additional oil to flow towards the producing well.

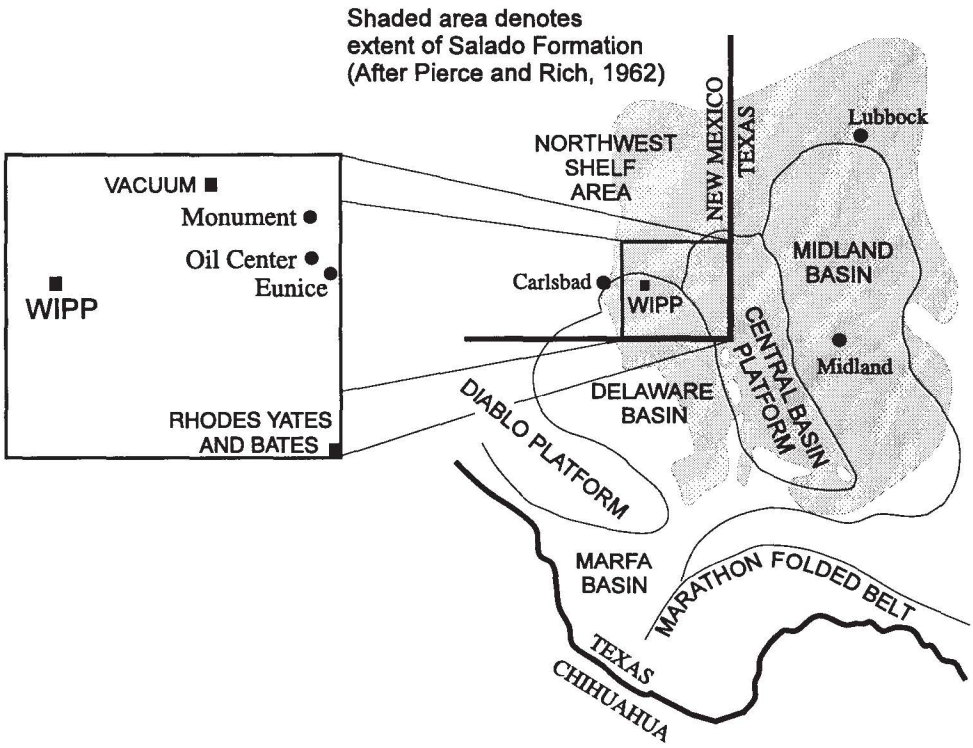

Figure 1-1. Physiographic provinces, extent of the Salado Formation, and oil field locations.

Figure 1-1 shows the locations of the physiographic zone and oil fields mentioned throughout the report. For oil fields underlying the Salado Formation, the problem of water escaping from the injection zone and migrating through the Salado Formation to adjacent properties has long been well known. For example, in a May 5, 1976, letter, Joe D. Ramey, Director of the Oil Conservation Division, advised the Secretary of the New Mexico Energy and Minerals Department (NMEMD), John F. O'Leary, of the situation:

> It has recently come to our attention that there are numerous salt water flows in and around waterfloods in Lea County... Basically the problem is that water injected at around 3600' is escaping from the injection interval, migrating upward to the base of the salt section and then moving horizontally through this section. Waterflows of 5000-6000 barrels per day and recorded surface pressures of 1600 pounds on wells outside waterflood areas are not uncommon. This had resulted in collapsed casing in several wells but the critical aspect in this is the threat of widespread contamination of fresh water.... (Ramey 1976)

In 1980, the U.S. Department of Energy (DOE) intended to prohibit secondary recovery by waterflooding (U.S. DOE 1980, 8-4) in former control zone IV - the area that now forms much of the one mile buffer outside the 4-mile by 4-mile WIPP Land Withdrawal Boundary.[1] The DOE natural resources report (Brausch et al. 1982) maintained there was a minimal amount of crude oil likely to exist at the WIPP site and did not evaluate the potential impact of waterflooding. The DOE subsequently relinquished the right to restrict waterflooding for hydrocarbon recovery in former control zone IV (McGough 1983b).

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[1]See Silva (1994) for a discussion of how previous control zone III was squared off to form the current WIPP site boundary.

FORMATION		DEPTH TO CONTACT AT WIPP (FEET)	PRINCIPAL LITHOLOGY
Surficial Sand			Blanket sand and dune sand, some alluvium included.
		10	
Mescalaro Caliche and Gatuna Fm.			Pale reddish-brown, fine-grained friable sandstone; capped by a 5-10 ft. hard, white crystalline caliche (limestone) crust
		40	
Santa Rosa Sandstone			Pale red to gray, cross-bedded, non-marine, medium to course-grained friable sandstone; pinches out accross site.
		50	
Dewey Lake Redbeds			Uniform dark red-brown marine mudstone and sitlestone with interbedded very fine-grained sandsonte; thins westward.
		540	
Rustler			Anhydrite with siltstone interbeds. Contains two dolomite marker beds: Magenta and Culebra. Thickens eastward due to increasing content of undissolved rock salt.
		850	
Salado	Upper member		Mainly rock salt (85-90%) with minor interbedded anhydrite (43 marker beds), polyhalite and clayey to silty clastics. Potash minerals in McNutt Zone.
	McNutt member		
	Lower member	←	WIPP REPOSITORY
		2825	
Castile	Anh. III-IV		Varved anhydrite-calcite units alternating with thick halite (rock salt).
	Hal. II		
	Anh. II →		
	Hal. I		
	Anh. I		
		4075	
Delaware Mountain Group	Bell Canyon		Mostly fine-grained sandstone with shaly and limy intervals. Bell Canyon is used for salt water disposal. Cherry Canyon and Brushy Canyon contain oil producing zones.
	Cherry Canyon		
	Brushy Canyon	~8000	

Figure 1-2. Stratigraphic cross section at the WIPP Site.

In April 1988, anomalous water level rises in the Culebra Dolomite aquifer were measured in several observation wells to the south of the WIPP site (Beauheim 1990). LaVenue (1991) conducted an investigation that raised serious questions about oil field operations. Bailey (1990), a certified professional geologist and petroleum engineer with the New Mexico State Land Office, described waterflooding problems for the Vacuum Field (an oil field overlain by the Salado and Rustler Formations) in a letter to Marsh LaVenue and suggested that the anomalous water level rises in the WIPP wells may have similar origin:

> Although the Vacuum Field, located in Township 17-18 South, Ranges 34-35 East, is located some distance northeast of the monitor wells in question, I believe the hydrogeologic setting is analogous to the well field you are currently investigating. The Vacuum Field is also overlain with Dewey Lake Red Beds and the Rustler and Salado Formations. Numerous water flows in the Salado were creating oil field casing failures and drilling and cementing problems and many people were concerned that the situation could cause contamination of the Ogallala aquifer.
>
> Discussions at the Vacuum Field Salt Water Flow Committee meetings with the Oil Conservation Division in 1986-1987 indicated that the uppermost water flow occurred at the base of the Rustler and the lowest flow occurred at the top of the Tansill Formation. The most numerous flows were found near the crest of the anticline, but flows were encountered throughout the field. Spot checking of old oil well drilling records indicate water flow drilling problems and numerous casing leak repairs in the Dewey Lake Red Beds, Rustler and Salado formation for many years. These water flows are still occurring in the Vacuum Field although at a lesser rate than during the 1970's and 1980's.

These water flows are characterized as strong, intermittent and spotty. Not all wells have encountered flows, but when they did, the flows were estimated at 1,000 - 2,000 barrels [42,000 - 84,000 gallons] per day. The flows often would last 4-5 days before stopping by themselves. The Oil and Gas Conservation District was greatly concerned about the effects of these flows and the potential for dissolution, vertical fracturing and collapse of the upper beds, and the contamination of the Ogallala aquifer.

After years of study, thousands of pressure tests, installation of pressure monitoring wells, and chemical analyses, the Water Flow Committee, decided that no one knew the origin of the early flows, or specifically where the water was stored. However, individual flows were correlated throughout the field to distinct horizons within the Salado Formation where fluid flow is facilitated along bedding planes at clastic-evaporite interfaces. Chemical dissolution of bounding salts and mechanical fracturing enable large volumes of fluids to be transported over large areas.

Chemical and isotopic analyses of the waterflow brines indicated that the waters were not naturally occurring connate waters produced by the evaporation of Permian seawater. (18)Oxygen/(16)Oxygen ratios and (18)Oxygen/Magnesium ratios indicated injected produced water as a strong candidate as a source of at least some of the water flows in the Salado Formation. Because the Vacuum waterflood project injection zone is at an approximate depth of 4320'-4720', casing leaks through the salt section are the most logical pathways for introduction of fluids into the Salado Formation (Bailey 1990).

The problem of injected water migrating "out of zone" is widespread. Bailey (1990) noted that waterfloods in and around Eunice, Oil Center, and Monument (Fig. 1-1) resulted in water flow problems through the Salado Formation. Nor is this strictly a problem of the past. Water migrating out of zone continues to plague other oil fields underlying the Salado.

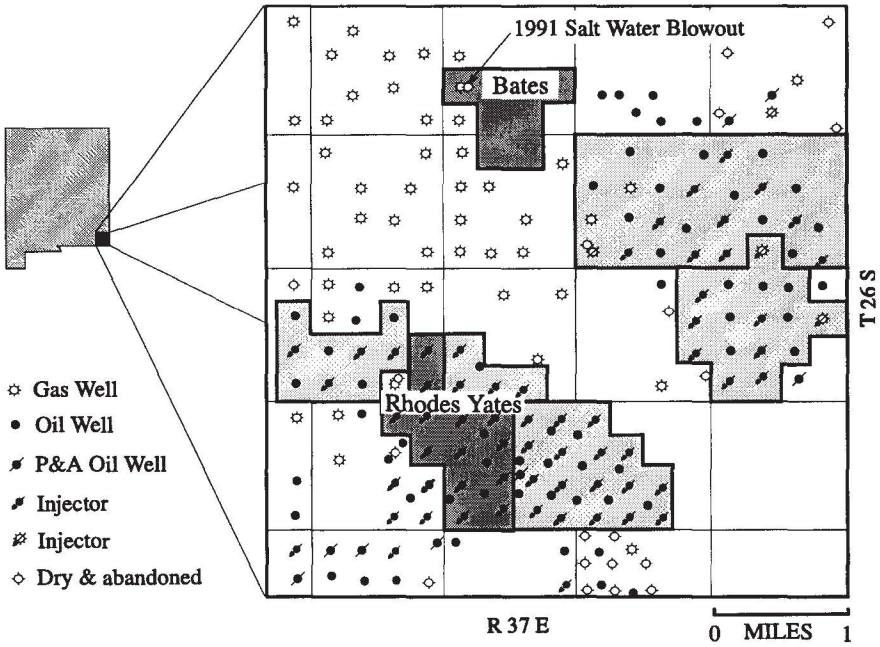

Figure 1-3. Bates Lease (Hartman), Rhodes Yates Waterflood (Texaco) and other nearby leases with injection wells.

1.2.1 Hartman vs. Texaco

On November 22, 1993, Mr. Doyle Hartman (1993) sent Sandia National Laboratories a copy of his November 17, 1993, Complaint (CIV93 1349M) filed in the Federal Court for the District of New Mexico. He stated that he furnished a copy of the complaint to familiarize Sandia "with the Lea County situation so that the proper safety measures will always be taken to preclude the occurrence of such a potentially disastrous event in the close vicinity of the WIPP site in Eddy County, New Mexico." Mr. Hartman claimed that a neighboring waterflood, Texaco's Rhodes Yates, allowed large quantities of injected water to escape out

of the approved injection zone, part and dissolve the Salado Formation, and migrate to Hartman's Bates Lease (Hartman 1993, 13).

On January 15, 1991, while drilling through the Salado Formation, Hartman experienced a salt water blowout, which flowed uncontrolled for five days. The suspected waterflood operation was approximately two miles away. On December 12, 1994, after two weeks of hearing testimony and viewing exhibits, the jury found in favor of Hartman's claim for damages. On January 20, 1995, the court ordered the defendant, Texaco, to compensate Hartman for 5.6 million dollars for damages and for value of the property injured and destroyed due to defendants' trespass (Herrera 1995).[2]

Observations of waterflows during drilling and production in waterflood areas appear to be fairly widespread in time and location. Part of the evidence gathered by Hartman's engineers included a listing of 189 waterflows reported throughout various oil and gas fields in District One[3] of southeast New Mexico for the time period from 1978 to 1993. These may not represent all the water flows encountered in this district because not every waterflow encountered during drilling is reported to the New Mexico Oil Conservation Division (NMOCD) (Lanphere and Sullivan 1994a).

1.2.2 Bass vs. United States of America

The potential impact of water flooding and fluid injection on the WIPP has been cited in the recent denial of a valid lease to directionally drill oil wells under the WIPP site from a surface location immediately adjacent to the WIPP site. In April 1993, Bass Enterprises submitted applications to directionally drill eight

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[2]The Environmental Evaluation Group understands that portions of this judgment may be in the appeal process. The Environmental Evaluation Group has no direct nor implied opinion about the case.

[3]District One of the New Mexico Oil Conservation District consists of Lea, Roosevelt, Curry, and part of Chavez County.

additional oil wells beneath the WIPP Land Withdrawal Area for the production of crude oil from the 320 acre lease (NM 02953C) in the southern half of Section 31, T22S, R31E. Drilling would have initiated on the surface outside the WIPP site Boundary, proceeded downward 6,000 feet, then deviated into the WIPP site Boundary. On August 22, 1994, the BLM denied approval to drill the eight proposed wells "due to the uncertainty of when a final determination will be made, ***and the unknown impacts from injection wells and water flooding***"[4] (Calkins 1994). On January 23, 1995, Bass Enterprises et al. (1995) filed suit against the federal government for a taking.[5]

1.3 Oil Field Salt Water Disposal

Waterflooding to promote oil recovery is not the only oil field water injection practice of concern. In a memo to LaVenue, Bailey (1990) suggested that a salt water disposal well may be the source of the water level rises south of the WIPP site:

> Because a water injection well or salt water disposal well is the most logical source of a long term or continuous increases in fluids in the monitor well (H-9), I investigated locations of such wells in the area, concentrating on any wells located north-northeast. Spot checking of production wells in the section adjacent to the monitor well had not shown a logical production well as the source of a large fluid pressure increase.... In my opinion, the most likely source of increased fluid pressure is the Devon Energy Corp. Todd 26 Federal Well #3 salt water disposal (SWD) well located northeast and upgradient of the monitor well... Since 1971,

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[4]Emphasis added.

[5]The Environmental Evaluation Group understands that this case may be in litigation. The Environmental Evaluation Group has no direct nor implied opinion with respect to this case.

> 2,962,402 barrels of produced water have been injected at a current average pressure of 795 psi. No records of any casing repairs are found in the OCD well files.

This observation invites the following questions. Is there evidence to indicate that the Todd 26 Federal #3 well is the source of the water level rises? How was this well completed? What is the status of this well? If the casing, tubing, and cement of this well are intact, are there other available pathways in the area providing communication? Most importantly, over the next 10,000 years, to what extent will there be salt water disposal in the vicinity of the repository?

The first four questions are explored in the EEG workshop presentations and analysis. As to the last question, salt water disposal in the vicinity of the WIPP is already taking place. As noted by Matthew Silva, Ron Broadhead, and Dan Stoelzel, in their respective presentations (Chapter 2), the Delaware wells surrounding the WIPP site produce a very high fraction of water (water cut), on the order of 50% to 70% by volume, as reflected in production records and tabulated by Broadhead et al. (1995, Table 8). Silva (1994, Figure 13) showed four salt water disposal wells within two miles of the WIPP site Boundary as of 1993. Broadhead et al. (1995, Table 7) tabulates ten salt water disposal wells and two pressure maintenance wells within the nine township area surrounding the WIPP as of 1994.

1.4 Oil Field Brine Disposal and the Potash Industry

The issue of salt water disposal in the Delaware Basin appears to be of concern to members of the potash mining industry, which also operate in the Salado Formation. On November 19, 1993, representatives from Bass Enterprises Production Company, an oil company, met with representatives from Western Ag-Minerals Company, a potash mining company, to discuss the Bass proposal to operate a brine injection well two miles west of the WIPP site. Western Ag was concerned about its substantial potash reserves surrounding the well location.

Rather than rely solely on state regulations to protect their portion of the Salado Formation, Western Ag outlined twelve additional operating provisions that would satisfy their concerns (Heinen 1994). The twelve provisions included notification of any request to increase injection pressure above 765 psi, immediate notification of tubing, casing, or packing failure and cessation of injection until the problem is corrected, an annual chemical analysis of injected brine, an annual test to determine migration of brine into other formations, and specifications for well abandonment.

1.5 Well Abandonment

Concerns about improper abandonment of wells appear to be justified. As discussed by Silva (1994), inadequate practices on U.S. Bureau of Land Management (BLM) properties are documented (U.S. DOI 1989, 1990; Baier 1990). A 1989 evaluation (U.S. DOI 1989) by the Inspector General for the U.S. Department of Interior identified considerable problems on the BLM properties resulting largely from "violations of existing regulations" (U.S. DOI 1989, 4). The report cited problems with wells in BLM's Carlsbad Area (U.S. DOI 1989, 6-7)

In arguing a difference between exploratory and development wells[6], the DOE has also brought the problem of improperly abandoned oil and gas wells to the attention of the EPA. As the DOE Carlsbad Area Office noted:

> Development wells are generally abandoned only after many years of production. Many development wells change ownership several times during their operational lifespan, and may not produce continuously. They may ultimately be abandoned improperly (Dials 1994, Supplemental Information to Options 2, 4 and 3, 12).

---

[6]For other views on well definitions see Neill 1995; Vaughn 1995; Carroll and Bogle 1996; also Gorenflo vs Texaco, 566 F. Supp. 722 (1983); Sun vs. Jackson, 715 S.W. 2D 199 (1986) and 783 S.W. 2d 202 (1989).

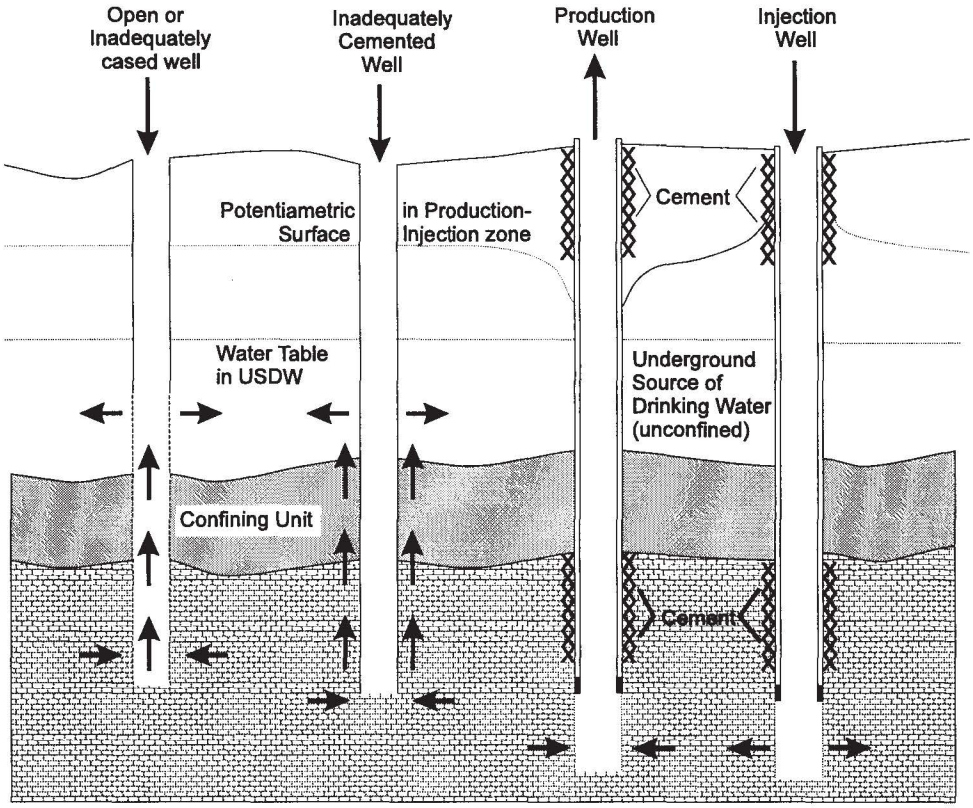

Figure 1-4. Upward flow from underlying hydrocarbon-producing zone to an underground source of drinking water through inadequately plugged wells. After Kreitler et al., 1994.

Improperly abandoned wells, in the vicinity of oil field injection wells, can serve as a pathway for contamination of underground sources of drinking water. The Texas Bureau of Economic Geology, with funding from the American Petroleum Institute, designed a method for use by regulators and operators to identify such areas (Kreitler et al. 1994).

In developing the method, Kreitler et al. (1994 pp. 64, 77) plotted the estimated density and distribution of oil field brine injection wells, as shown in Figure 1-5, and abandoned wells, as shown in Figure 1-6, throughout the greater Permian Basin, which includes the Delaware Basin.

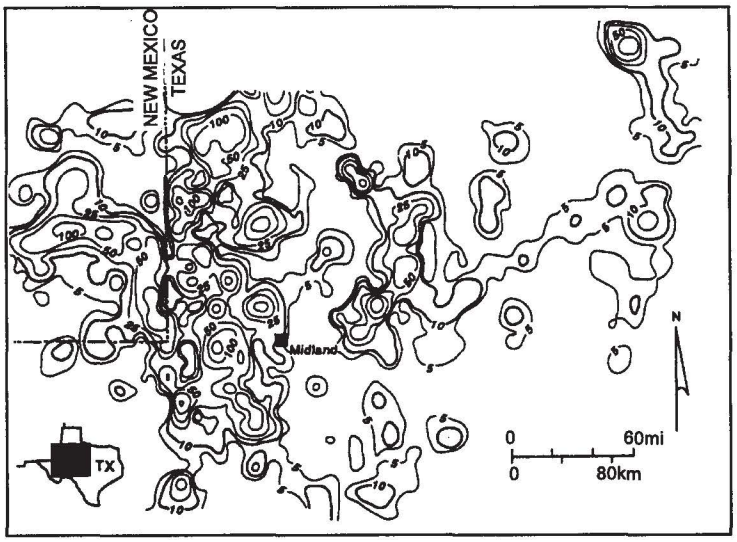

Figure 1-5. Density of Class II injection wells at 0.1°× 0.1° scale. After Kreitler et al. 1994.

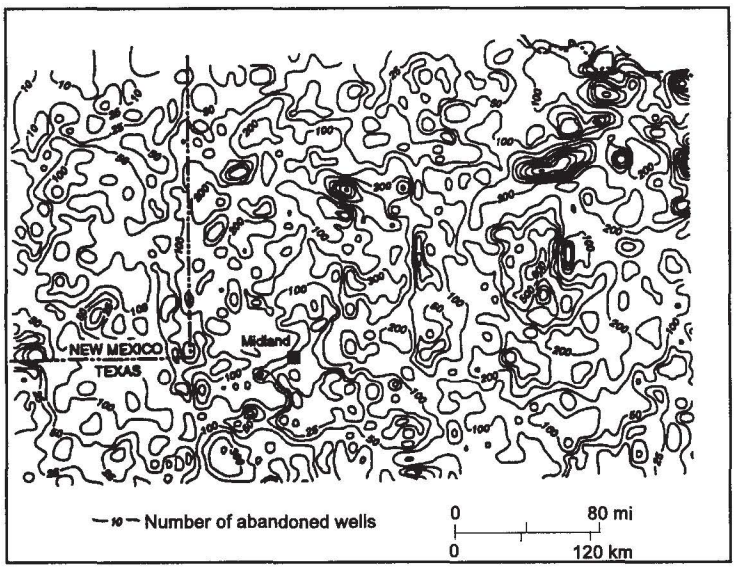

Figure 1-6. Estimated distribution of abandoned wells at 0.1°× 0.1° scale. After Kreitler et al. 1994.

They found that the most extensive area of upward hydraulic gradients occurs in the eastern Delaware Basin, Central Basin Platform, and western Midland Basin. Residual mapping indicates upward gradients with hydraulic head differentials as large as 6,000 ft (1,800 m) (Kreitler, et al. 1994, 73-74).

As part of their study, Kreitler et al. (1994) also offered insight into the problem of abandoned wells completed through salt formations. They note that in addition to less stringent construction and abandonment standards in past decades, the mechanical degradation of older wells may also reflect lengthy periods of exposure to corrosive brines. In the Permian Basin, wells that pass

through a larger number of saline units are of particular concern (Kreitler et al. 1994, 76). LaVenue also commented on 20 to 30 years of exposure to the corrosive saline environment promoting a leak in the casing and/or degrading the grout holding the casing in place (LaVenue 1991, 2). This is consistent with the DOE position that the highly saline environment of some units can promote rapid corrosion of well casings and may result in fluid loss from wellbores (U.S. DOE 1995, SCR-73). All well casings to be abandoned in the WIPP vicinity will be exposed to more than two thousand feet of salt, not only in the Salado Formation, but also in the Castile Formation, a formation unique to the Delaware Basin. It seems prudent to assume saline environments promote rapid corrosion of well casing (Kreitler et al. 1994, 76; LaVenue 1991, 2; U.S. DOE 1995, SCR-73), existing regulations are violated (U.S. DOI 1989), and wells are improperly abandoned (U.S. DOI 1989; Dials 1994). Given these observations, do the existing and yet to be drilled wells in the vicinity of the WIPP represent viable vertical pathways for the upward migration of injected fluids either into the interbeds of the Salado Formation or into overlying aquifers such as the Culebra, the Magenta, and the Dewey Lake Redbeds?

1.6 WIPP and Performance Assessment

To proceed with TRU waste disposal, the WIPP Land Withdrawal Act requires the DOE to receive certification from the EPA that the facility is in compliance with the EPA radioactive waste disposal regulations (U.S. EPA 1985; 1993, 40 CFR 191) including containment and assurance requirements. This requires analyses that the probability and amount of radionuclides released to the accessible environment over the next 10,000 years will not exceed limits specified in the EPA Standards. The performance assessment (PA) calculations published to date have identified future drilling for oil and gas reserves as an event that could disrupt the repository and release radionuclides in excess of the standards (SNL 1992, 4.1.2). The calculations have not addressed the impact on WIPP's performance of the oil and gas industry practices of salt water disposal and

waterflooding for enhanced oil recovery - two expanding activities now underway in the vicinity of the WIPP.

The 1991 DOE PA stated that such fluid injection could be eliminated from consideration in performance assessment on the basis of low consequence:

> The effects of injection wells on groundwater flow in units shallower than the Salado Formation is likely to be negligible. Units selected for injection will be thousands of feet deeper than the Rustler Formation, which is the most likely path for the groundwater transport of radionuclides to the accessible environment. The low permeability Bell Canyon, Castile, and Salado Formations are approximately 4,000 feet (1,220 meters) thick at the WIPP (Powers et al. 1978), and these low-permeability units will isolate flow in the Rustler Formation from the pressure increases in the much deeper units caused by the injection of fluids (SNL 1991, 1:4-36).

This explanation appears to be inconsistent with salt water disposal practices in the Delaware Basin, the observed water level rises in the Culebra, LaVenue's analyses (1991), and Bailey's comments (1990).[7] Records indicate that every salt water disposal well within the nine township area surrounding the WIPP injects into the Bell Canyon Formation (see Broadhead et al. 1995, Table 7). Hence, the Bell Canyon is not serving as an impermeable layer. Further, LaVenue's (1991) analyses indicated that the Bell Canyon Formation, which is below the WIPP horizon, is already in communication with the Rustler Formation, which is above the WIPP horizon. Hence, thousands of feet of vertical separation by

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[7]Despite a January 28, 1991, distribution to the WIPP PA Department, the memos of LaVenue (1991), Bailey (1990), and Ramey (1976) are not referenced in either the December 1991 PA publication or in the December 1992 PA publication.

impermeable layers of salt do not appear to be isolating the Rustler from the fluid injected into the deeper units.

The 1992 PA also did not calculate the effect of adjacent fluid injection on performance assessment, maintaining that injection wells that do not penetrate the repository can be screened out on the basis of low consequence despite the 1976 Ramey memo, 1990 Bailey memo, and the 1991 LaVenue memo, and public records on fluid injection practices in the Delaware Basin.

With respect to any human related activity within the site, including fluid injection, the 1992 PA introduced a new criteria not found in Cranwell et al. (1990) for screening events and processes (SNL 1992, 2:4-3 to 4-4). The 1992 PA stated that the EPA regulations did not require the impact of fluid injection to be evaluated. The WIPP PA Department's interpretation (SNL 1992, 2:4-3) of the non-binding guidance for the disposal of transuranic waste (SNL 1992, 2:4-4) advances the argument that disruptive human activities, such as fluid injection, need not be considered because the consequences are greater than that of exploratory drilling (SNL 1992, 2:4-4). The impact of a future disposal well was limited to drilling and the consequences were assumed to be identical to drilling an exploratory well (SNL 1992, 2:4-4).

1.7 Issue

WIPP is surrounded by new oil producing wells. Many more are planned but have been delayed due to the presence of potash (Woodard 1992; Burski 1994). Oil production is accompanied by salt water injection either for salt water disposal or waterflooding. Forcing large volumes of such brine into the designated formation requires energy in the form of fluid pressure (force per unit area). Brine migration, with energy in the form of pressure, is the same mechanism by which radionuclides can be carried out of the repository and away from the WIPP site.

The potential impact of brine injection on the long-term performance of the WIPP prompted the Environmental Evaluation Group to organize a June 13, 1995, workshop on the issue. The workshop included presentations describing the extent of oil and gas resources, the anomalous water level rises in the Culebra Aquifer, the documented effects of water flooding on the Salado Formation, the geology of waterflooded areas in southeast New Mexico, the current petroleum production practices, the treatment of water injection by the performance assessment effort, and the need for a water flooding scenario in the WIPP PA calculations. As was intended, a number of issues were deliberated. On many issues there was no consensus. The workshop did not address the impact of solution mining of potash surrounding the WIPP or the disposal of potash brine.

2. WORKSHOP PRESENTATIONS

The presentations made at the June 13, 1995, workshop are contained in this chapter. A synopsis of each presentation, distributed by the authors at the workshop, is followed by their presentations. As with any verbal dialogue, some paraphrasing of the presentations was necessary. Nonetheless, every effort was made to preserve the message of the presenters and the thrust of the questions and answers. Also, some figures, most of which were provided by the authors on diskette, required modification from their overhead format into a report format. The cooperation, patience, and understanding of the presenters and participants in addressing these difficult, but important issues, is appreciated.

2.1 R.H. Neill - Opening Statement

All of us are extremely pleased to see this large turnout for this technical workshop. I think it is a good example of the cooperation between the various federal and state authorities with representation from the Department of Energy, the Environmental Protection Agency, the Bureau of Land Management, the National Academy of Sciences, the New Mexico Environment Department, the New Mexico Oil Conservation Division, the New Mexico Bureau of Mines and Mineral Resources, Sandia National Laboratories, Oklahoma University and, of course, the Environmental Evaluation Group.

It is interesting to step back a moment to evaluate our efforts in performance assessment in predicting the behavior of the repository. The focus has been on existing fluids, whether it is the interstitial brine within the Salado or the large brine reservoirs associated with the Castile Formation or the two dolomitic aquifers above the repository horizon and in the perched water aquifer in the Dewey Lake Redbeds. We are now looking at the impact of fluid injection into nearby formations on the long-term behavior of the repository — perhaps from three different standpoints, although we will only be looking at two today. The first is to enhance the recovery of oil. The second is on salt water disposal, which

would be another reason for injecting fluids. The third might well be, in the future, to look at solution mining for potash, although we are not going to address that issue here today.

It might be helpful to mention a few things that we are not going to do today - to put everyone at ease. We are not going to address the legal issues associated with any court cases that have occurred, are pending, or will occur. Specifically, I'm referring to the Hartman vs. Texaco case. There is some very interesting, relevant, technical information associated with that case, but in no way should this workshop be construed as reopening the legal issues associated with that case. I want to make that quite clear.

We also are not going to be able today to determine the consequences of the impact of some of these actions. And although we can get some insights, perhaps, on the probability of events, one is not going to be able to determine the impact.

We look forward to each of us speaking as individuals — no one is being quoted on behalf of their agency. And also none of us have come here with a preconceived position on these issues.

I thought it might be important to those who are familiar with the performance assessment approach to acknowledge the uniqueness of the WIPP in the context that it is the only repository under consideration where there are substantial natural resources - oil, gas, and potash. And for those of you who are not in the business of performance assessment, in order to bring waste to WIPP it is necessary to be able to predict the behavior of these transuranic wastes over 10,000 years and convince EPA of the validity of those calculations and analyses. The way this is done is to come up with scenarios on how this could occur, design a model and then write the equations governing that, whether it is conservation of momentum or mass, conservation of radioactivity, the driving force, solve the equations, and then estimate the amount that arrives at the accessible environment in 10,000

years. You then look up the release limit table of the EPA standard. If the postulated releases are greater than the limits, you have problems. If they are less, you are home free.

On the current schedule, DOE expects to complete all this work by January 1997. We note that the deadline for the models is as early as September 1995, the end of this summer.

If we consider the 4-mile by 4-mile area of the WIPP site, the question comes up regarding the injection of fluids at depths greater than 4,000 feet outside the WIPP site. If by some mechanism, there is vertical movement of the brines or the fluids outside the repository, can this induce hydrofracturing in the Salado for a distance of 2 miles laterally to the repository, which may in turn flood the repository? And the question is, could this have a role in moving radionuclides laterally to the accessible environment, and exceed the EPA limits?

In terms of the location, the injection, and the timing, one can look at it in perhaps four different ways. The first is on the operational consideration of the time period from minus 20 years to t equals zero, and outside of the 4 mile x 4 mile area where this could have some potential effect on the hydrogeological real estate associated with the repository. The second is a period from T=0 to T=100 years where institutional control would prevent anyone from injecting fluids within the 4 mile x 4 mile area. The third might be a period from 100 years to several hundred years; that is not specified in the EPA criteria but it is presumed that one could take steps during that time period to prevent the injection of fluids. And the fourth is when knowledge of the repository is lost at some future date, and one could have brine injection occurring in the 4 mile x 4 mile site. We are not going to focus that much on the fourth one today, because we have some people that are able to contribute in a major way on the first three.

2.2 Evaluation of Oil and Gas Resources at the WIPP Site

Ronald F. Broadhead[1], Fang Luo[1], and Stephen W. Speer[2]

[1]New Mexico Bureau of Mines and Mineral Resources

[2]Independent Geologist, Roswell, New Mexico

2.2.1 Synopsis

Rigorous, quantitative estimates were made of oil, natural gas, and natural gas condensate resources that exist beneath the 16 mi^2 area of the WIPP land withdrawal area and an additional one-mile wide study area around the WIPP site. Calculations were made for resources that are extensions of known, currently producible oil and gas resources thought to extend underneath the WIPP land withdrawal area with reasonable certainty (probable resources). Qualitative estimates were also made of oil and gas that may be present in undiscovered pools and fields beneath the WIPP land withdrawal area (possible resources). Possible resources were not quantified.

Probable resources consist mostly of oil and associated gas in Permian strata and nonassociated gas and gas condensate in Pennsylvanian strata. Currently, most oil and associated gas production in the vicinity of the WIPP site has been obtained from sandstone reservoirs in the Delaware Mountain Group (Permian) at depths of 7,000 to 8,000 ft. Sandstones and carbonates in the Bone Spring Formation (Permian) at depths of 8,000 to 11,000 ft and carbonates in the Wolfcamp Group (Permian) at a depth of approximately 12,000 ft are secondary oil reservoirs. Carbonates in the Strawn Group (Pennsylvanian) at a depth of approximately 13,000 ft are secondary, but important, reservoirs of gas and light oil or condensate. Most nonassociated gas and condensate production in the vicinity of the WIPP site has been obtained from sandstone reservoirs in the Atoka and Morrow Groups (Pennsylvanian) at depths of 13,000 to 14,000 ft.

Probable oil and condensate resources within the boundaries of the WIPP land withdrawal area are 12.3 million bbls of oil and gas condensate recoverable by

primary production methods and an additional 6.4 million bbls of oil potentially recoverable by secondary recovery with waterfloods (Table 1). Probable resources within the one-mile wide additional study area surrounding the WIPP land withdrawal area are 22.9 million bbls oil and gas condensate recoverable by primary production methods and an additional 13.8 million bbls of oil potentially recoverable through waterflooding.

Probable gas resources within the boundaries of the WIPP land withdrawal area are 186 BCF gas (Table 1); 89% of this gas is nonassociated and will be produced from the deep Atoka and Morrow reservoirs. The remainder is associated gas, most of which will be produced from relatively shallow reservoirs in the Delaware Mountain Group. Probable gas resources underneath the one-mile wide additional study area surrounding the WIPP land withdrawal area are 168 BCF gas; 79% of this gas is nonassociated and will be produced from the deep Strawn, Atoka, and Morrow reservoirs.

In addition to probable resources, there are significant possible resources of oil, gas, and gas condensate beneath the WIPP land withdrawal area and the additional study area.

These will be oil and associated gas in untapped sandstones of the Delaware Mountain Group in largely unexplored and unevaluated sandstones and carbonates of the Bone Spring Formation, and in carbonate reservoirs in the Wolfcamp and Strawn Group. Possible resources of nonassociated gas and gas condensate will occur in sandstone reservoirs in the Atoka and Morrow Groups and in the pre-Pennsylvanian section (Siluro-Devonian and Ordovician strata). The elusive nature of possible resources makes their quantification difficult or impossible for an area of limited extent such as WIPP.

2.2.2 Presentation by Ron Broadhead

The New Mexico Bureau of Mines and Mineral Resources (NMBM&MR) contracted to evaluate the resources under the WIPP Site and an adjacent area extending one mile beyond the WIPP Land Withdrawal Area. The evaluation included oil, gas, and other mineral resources.

One purpose of the work was to estimate the total of proven and probable oil and gas resources that could be obtained by primary and secondary recovery. With respect to oil and gas, the WIPP area remains essentially undrilled. Estimating resources is a geological task.

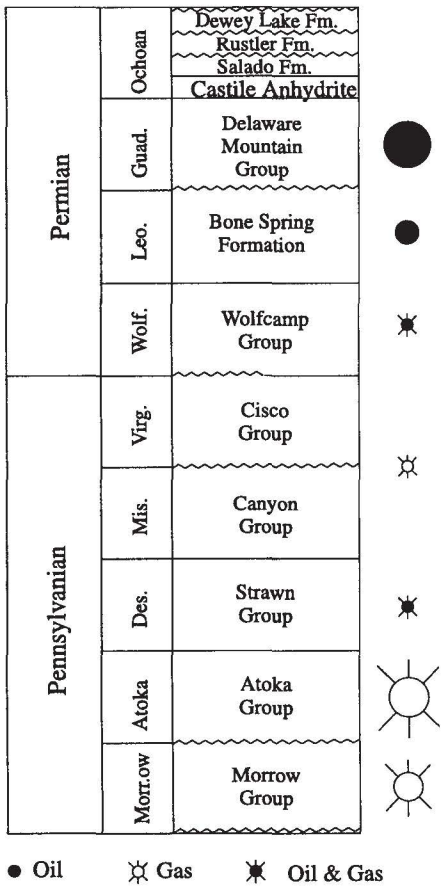

Figure 2.2-1. Productive oil and gas formations in the vicinity of the WIPP Site. Adapted from Broadhead et al. 1995.

The DOE needed a scientific, unbiased, third party estimate of the oil and gas resources. The principal data sources were well records on file at the New Mexico Bureau of Mines and Mineral Resources: Petroleum Information, Midland Oil Scouts Association, the Bureau's Niell Wills Collection, Bureau data gathered through the years, official state data from the New Mexico Oil Conservation Division, data from the U.S. Bureau of Land Management and the U.S. Geological Survey, an extensive collection of electrical logs, and the official production data reported to the State.

2.2.2.1 WIPP Area Description

Figure 2.2-1 shows the principal oil and gas producing formations within the WIPP

Site Area and surrounding areas. The principal oil production is shown by the solid circles and the principle gas production is shown by the open circles with the spikes. The major oil producing group in the area is the Delaware Mountain Group followed by the Bone Spring. There is a some production from the Wolfcamp, Cisco, and Canyon Group. Most of the gas production comes from the Atoka and Morrow Groups.

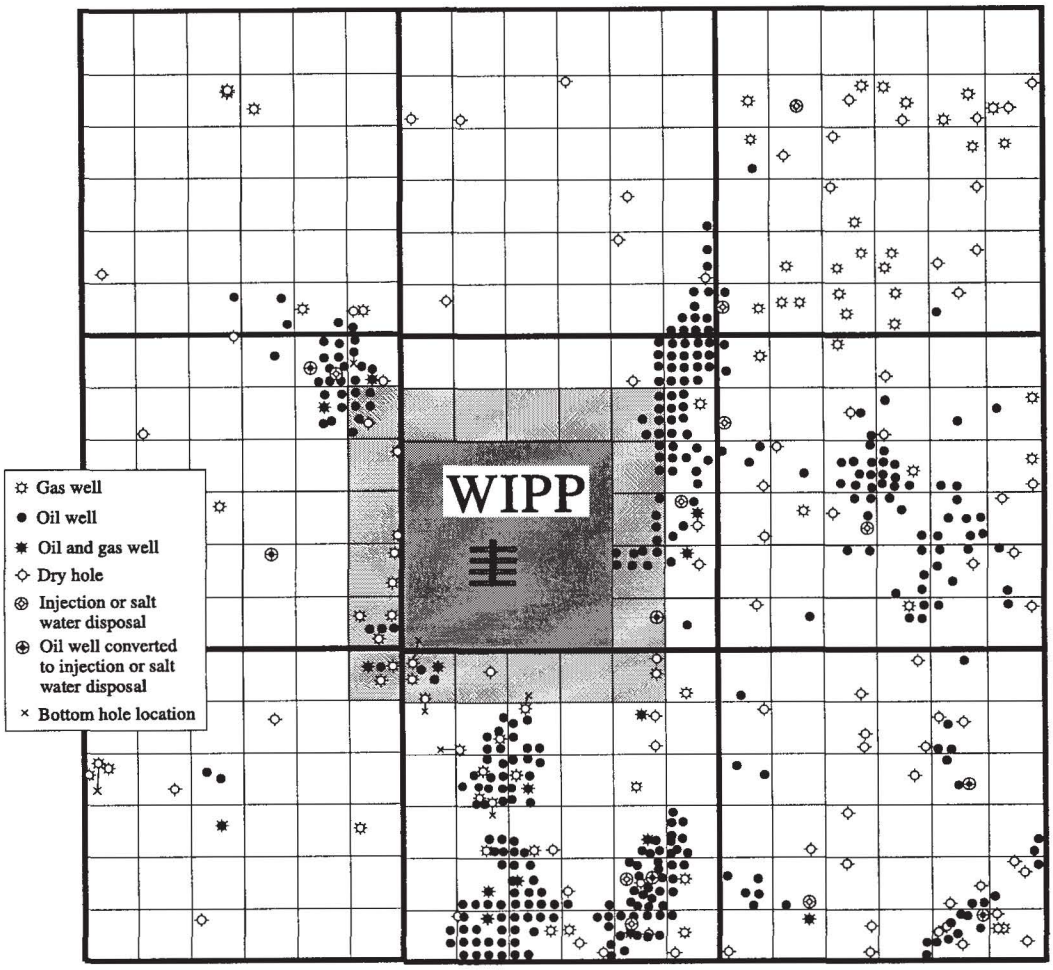

Figure 2.2-2. Oil, gas, and injection wells at WIPP Site, one-mile additional study area, and nine-township project study area.

Figure 2.2-2 shows the four mile by four mile land withdrawal area, the additional one mile wide study area, and the total nine township study area. Solid circles

represent productive oil wells at the close of 1993, or early 1994. The open circles with the eight spikes are productive gas wells. The open circles with (four) spikes are non-productive. There is only one well that produces from under the WIPP Land Withdrawal Area. That is the Bass well in the southwestern part of section 31. That deviated well was directionally drilled under the Land Withdrawal Area. Most of the oil wells produce from the Delaware Mountain Group and most of the gas wells produce from the Atoka and Morrow Groups. A couple of the wells along the western edge of the WIPP produce from the Strawn Group.

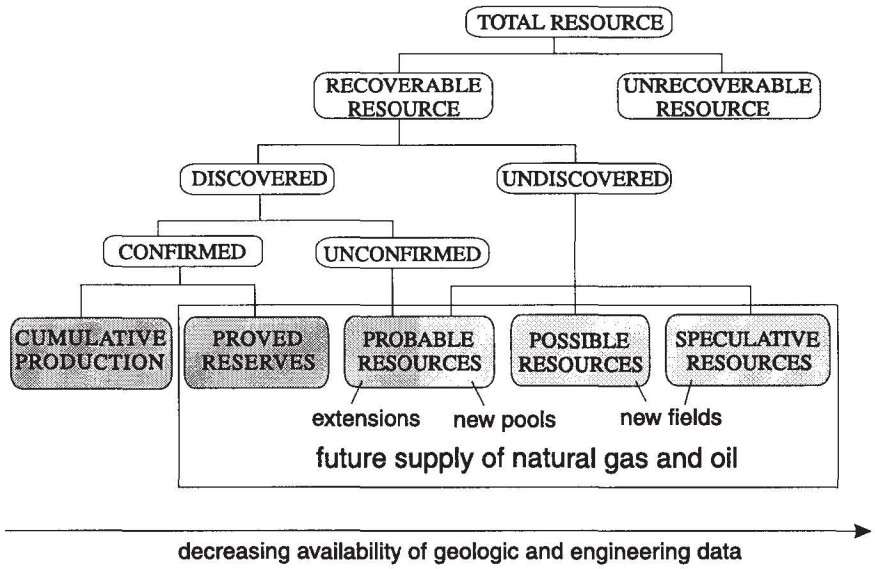

Figure 2.2-3. Oil and natural gas resource categories. From Potential Gas Committee (1993).

2.2.2.2 Method of Assessing Resource Potential

What was estimated and what was not estimated? Figure 2.2-3 illustrates the classification scheme of the Potential Gas Committee of the Potential Gas Agency. This classification can be applied to oil as well as gas. The total resource can be divided into recoverable and unrecoverable resources. The unrecoverable resource represents that which can not be taken from the rock. The recoverable resource

includes the discovered and undiscovered. The numerical estimates are based on that which is discovered. Discovered can be divided between confirmed and unconfirmed. Confirmed is divided between cumulative production and proved reserves. Cumulative production is obviously that which has been produced. Proved reserves are those reserves in known identified traps and accumulations that can be recovered by existing wells. Note there is only one well which produces from within the WIPP Land Withdrawal Area. Hence, there are very little actual proved reserves under the WIPP itself. In the additional study area there are several producing wells.

Most of the estimates included probable reserves. Probable reserves are extensions of known petroleum accumulations that have been discovered. Those are reserves on the flanks of the existing, known accumulations.

Some qualitative assessment of possible reserves was made, but a quantitative assessment of possible reserves was not made. Possible reserves are untested traps, deeper or intermediate pools that have not been drilled, and have not been proven to be productive.

2.2.2.3 History of Drilling

As to the drilling history in this area, Figure 2.2-4 shows that through the 1920s, 30s, 40s, and 50s, drilling bumped along at no wells per year or maybe one well per year. Shallow wells were drilled down to 4,000, 5,000, or 6,000 feet and the wells proved to be non-productive. From the 1960s through the 1980s, there were little spurts of drilling within the nine township area surrounding the WIPP. There were some discoveries of oil but most were discoveries of gas. Around 1990, there was a big increase in drilling - *the Delaware Play*. Delaware Pools were discovered at Livingston Ridge, East Livingston Ridge, Los Medaños, Cabin Lake and a number of other smaller Delaware fields. This occurred throughout the Delaware Basin, not only around the WIPP Site, but throughout southeast New Mexico.

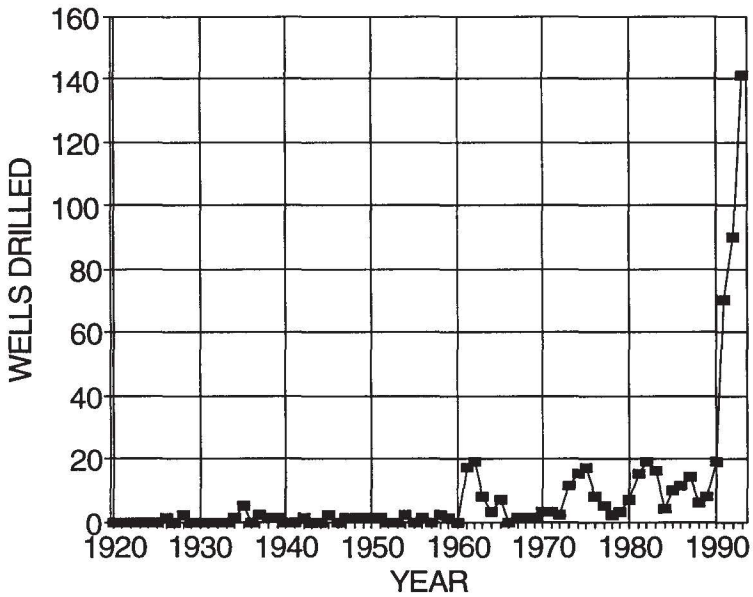

Figure 2.2-4. Annual number of oil and gas wells completed in the nine-township area centered on the WIPP Site.

People had been drilling through the Delaware Mountain Group for decades without realizing that oil could be produced economically. Log analyses and formation testing showed high amounts of water. Operators thought that these formations would produce mostly water and very little oil. With the advent of modern electric log analyses, it became apparent that oil could be economically produced. Oil discoveries were made, mostly in abandoned deep gas wells. As discoveries were made, a flurry of activity followed as the pools were developed.

The following example shows the methodology for estimating the per well resources. Production is obtained from the Brushy Canyon, the lowest formation in the Delaware Mountain Group. The sandstone is primarily interbedded with shales. The production is from stratigraphic traps. The production in the Delaware is oil and associated gas. Reservoir depths near the WIPP are 7,000 to 8,200 feet. Spacing is on forty acres, in other words, one well per forty acres. Production is from deep basin clastics and submarine fans. In order to project

production away from where it presently exists and in order to project into the undrilled areas, we need a geologic model.

The depositional models for the Delaware sands are deep marine sandstones deposited on submarine fans. Closest to the shelf area, in the northern most parts of the Delaware Basin, the sands were deposited in channels. So they are channel like environments. As you get into more distal areas, the sands become unchannelized and become more laterally continuous.

The Livingston Ridge Pool and Lost Tank Pool are administratively separated. But for geologic and engineering purposes, they form the same pool. Figure 2.2-5 shows an isopach map of the main pay at the Livingston Ridge/Lost Tank Pools. The main pay forms a nice channel going from zero feet to a maximum of eighty feet or so in the middle of the channel. The east west cross section of the main pay shows that in the center the pool is fairly thick. It pinches out on the eastern edge. A north-south cross section shows almost constant thickness throughout the pool in that direction. Hence, the variation is

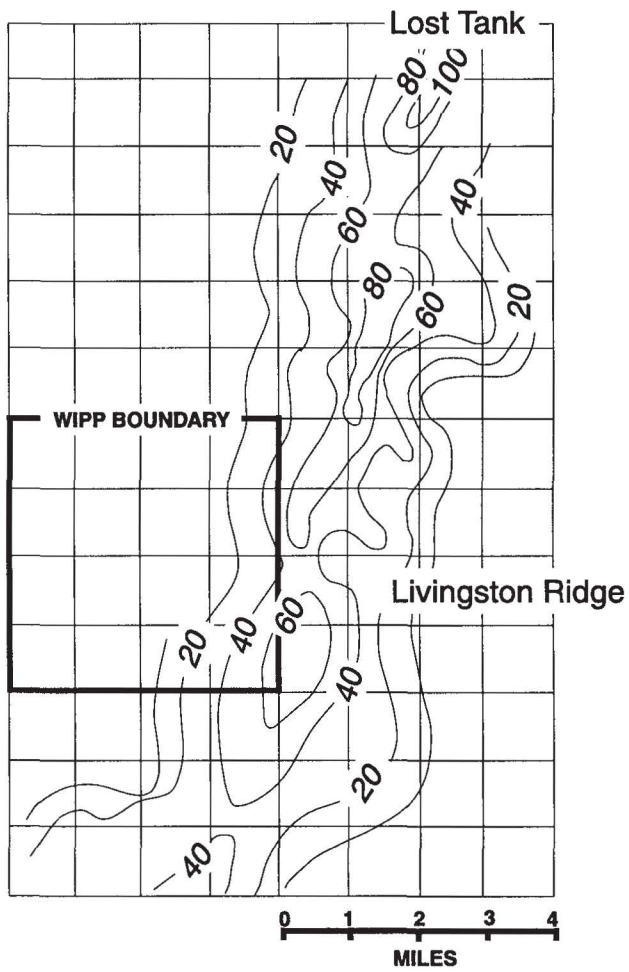

Figure 2.2-5. Isopach of gross channel thickness of Livingston Ridge main pay zone.

in the east-west direction. Economic production takes place where there is forty feet or more of main pay. From this, one can project into undrilled areas[1].

The question then is, are these pools entirely stratigraphic? Most of them seem to be primarily controlled by stratigraphy. The structure map shows that the dip is from the southeast (see Figure 25 of Broadhead et al. 1995). Projecting this channel shows that the WIPP Land Withdrawal Area is either at equal elevation or updip from the present production. Basically, the isopach map and the structural map can be superimposed to determine the areas of probable resources from the projections of known pools.

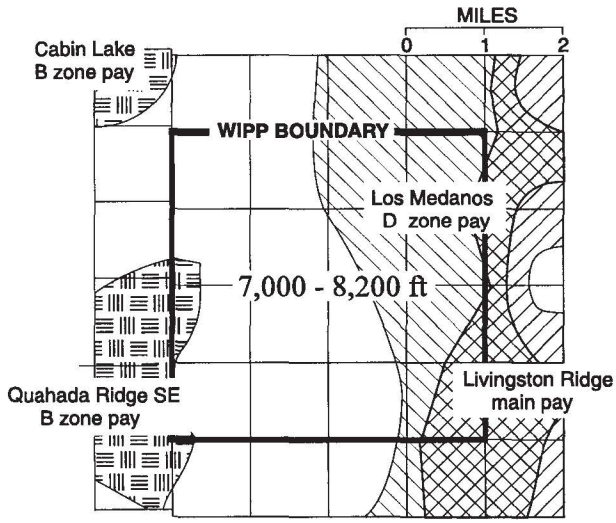

Figure 2.2-6. Areas of known and probable oil and gas resources for Delaware pools.

In Figure 2.2-6, the shaded area along the eastern edge of the WIPP Site shows the projection of the Livingston Ridge Pool. Also shown are other productive pools within the Delaware Mountain Group.

How much oil is each of these forty acre drilling or spacing units going to produce? In the case of the Lost Tank Delaware, a plot of production shows a production decline from roughly 3,500 barrels per month, down after thirty six

[1]Not shown in this report are the control wells and cross sectional diagrams as presented by Broadhead. See Figures 19, 20, and 24 of Broadhead et al., 1995 for the location of the control wells and the cross sectional diagrams.

months, to roughly 1,000 barrels per month. For an exponential curve, there is a high correlation coefficient of 0.87 for this particular well (see Figure 5 of Broadhead et al. 1995).

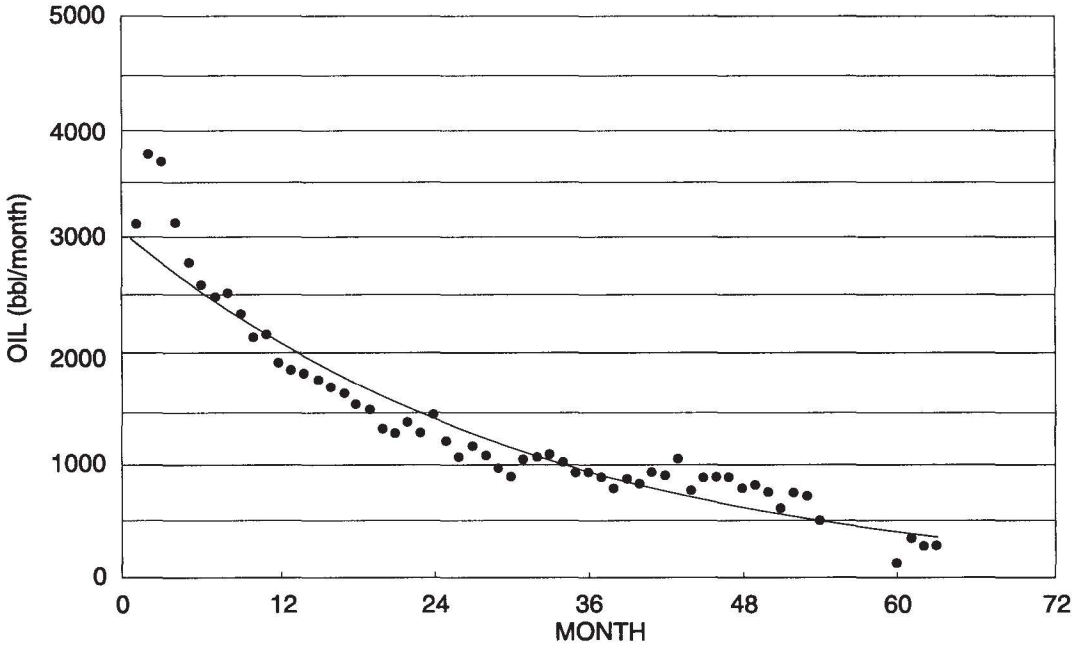

Figure 2.2-7. Average oil production decline curve for Livingston Ridge - Lost Tank Delaware pools, main pay.

As shown in Figure 2.2-7, an average production decline curve was constructed for the Livingston Ridge - Lost Tank pool. Integration of the area underneath that curve yields the resources for an average individual well. In the case of Livingston Ridge, for an assumed economic cutoff of 150 barrels per month, the average well will produce about 89,000 barrels of oil and about 116 million cubic feet of gas. The potentially productive area (calculated in spacing units) is multiplied by the resources for the average well to get an estimate of production for that pool. This was done for each of the Delaware Pools and each of the deeper pools in the area.

Figure 2.2-8 shows an isopach of one of the deep Livingston Ridge zones, the D zone, which produces to the south and the west. The isopach map shows a difference from the Livingston Ridge pay zone and an absence of discrete channels. The result is a blanket type deposit with unchannelized flows containing local thicks and thins and maximums of up to 120 to 140 feet of sand. It never pinches out to zero within the map area.

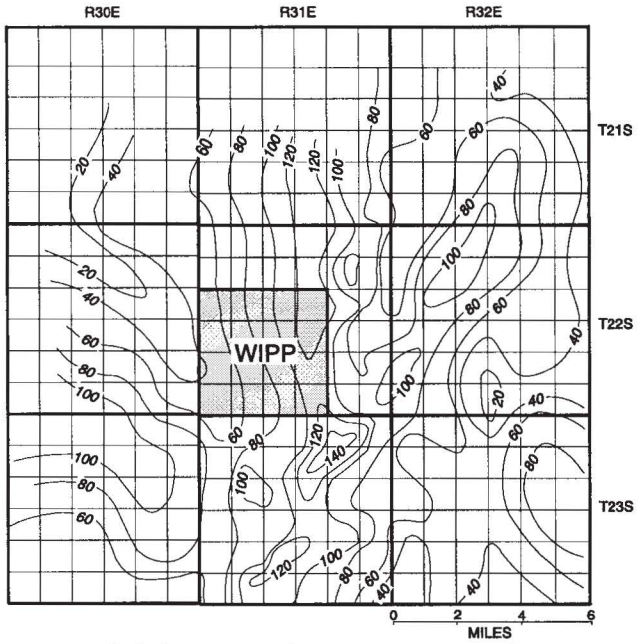

Figure 2.2-8. Isopach of Lower Brushy Canyon Formation zone D.

The deeper sandstones of the 3rd Bone Spring sand produce from stratigraphic or combination traps of deep basin turbidite reservoirs just outside the southwestern boundary of the WIPP Site. Production is oil and associated gas from about 11,000 feet. There are four forty-acre units for probable resources within the WIPP.

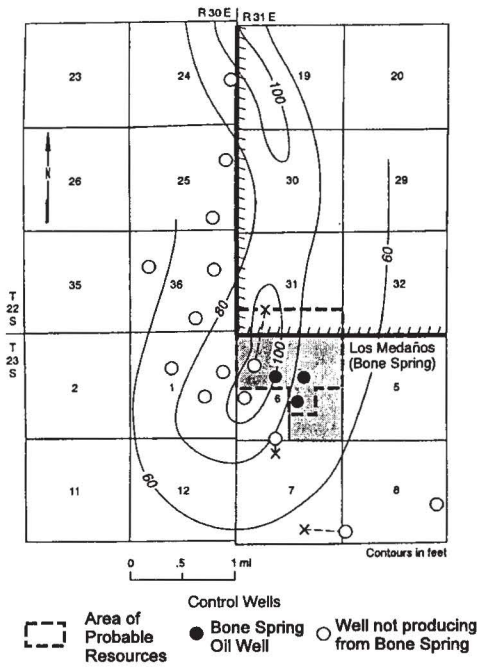

Figure 2.2-9. Isopach of Los Medanos Bone Spring Pool.

For the deeper Strawn Group, production is from limestones interbedded with shales. The reservoirs are bioherms developed on paleogeographic highs. Traps are stratigraphic. Production is gas and liquid condensate at the surface. Reservoir depths are 12,100 to 13,600 feet near the WIPP Site. Spacing is on 320 acres. There are two wells per section. Known and probable resources lie in the northwestern area of the WIPP Land Withdrawal Area.

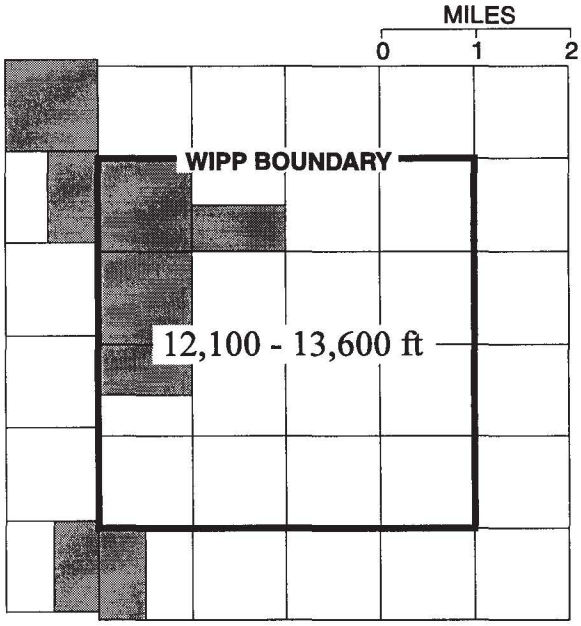

Figure 2.2-10. Areas of known and probable oil and gas resources for Strawn pools projected to extend under WIPP site.

Production of gas and condensate from the Atoka is from sandstones interbedded with shales and limestones. Production is from sandstone channels and a stratigraphic trap near the WIPP. Reservoir depths range from 12,400 to 13,800 feet near WIPP. Well spacing is 320 acres. There are two channels of probable resources that are extensions of existing known discovered traps

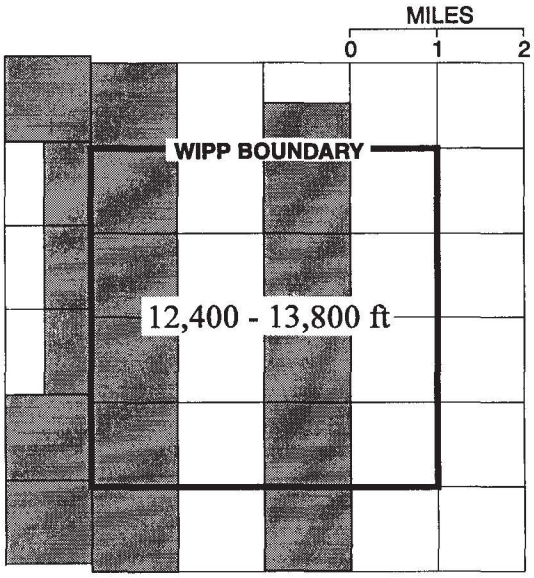

Figure 2.2-11. Areas of known and probable oil and gas resources for Atoka pools projected to extend under the WIPP site.

or pools. There are many sands in the Atoka that are untapped. At this stage of development, it is uncertain whether they are going to be productive or not. The Atoka is the main gas producing zone near WIPP.

The Morrow Group provides the deepest production in the area. Production is from the sandstones of the lower Morrow, interbedded with shales. A whole complex of different geologic models was used to predict production. It produces from stratigraphic, structural, and diagenetic traps. Production is gas and gas condensate. Reservoir depths are 14,300 to 14,800 feet near WIPP. As with the other producing gas zones such as the Atoka and the Strawn, spacing is on 320 acres. Shown are the areas of known and probable oil and gas resources. There is some established production to the south of the WIPP Site. There is no established Morrow production under the Land Withdrawal Area.

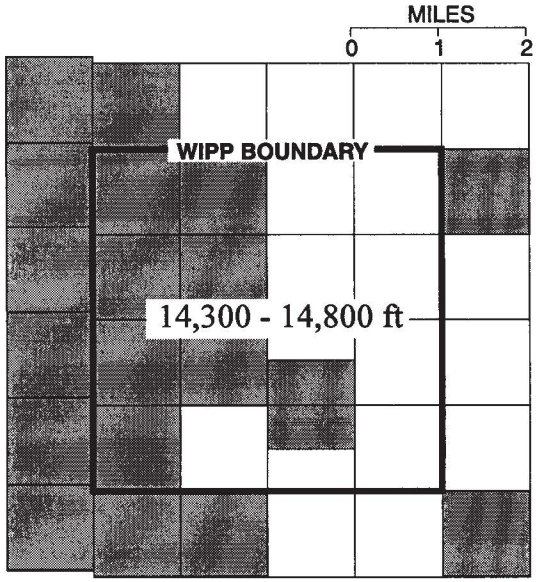

Figure 2.2-12. Areas of known and probable oil and gas resources for Morrow pools projected to extend under the WIPP site.

Table 2.2-1. Probable Resources.

	WIPP LWA	Additional Study Area
Oil and Condensate Primary Recovery (million bbls)	12.3	22.9
Oil Waterflood Recovery (million bbls)	6.4	13.8
Natural Gas (billion ft^3)	186	168

Table 2.2-1 summarizes the probable resources within the WIPP Land Withdrawal Area and the probable resources in the additional one mile wide study area. Under the WIPP Land Withdrawal Area, resources recoverable by primary production are 12.3 million barrels of oil and 186 billion cubic feet of gas. Within the additional one-mile wide study area, resources recoverable by primary production are 22.9 million barrels of oil and 168 billion cubic feet of natural gas.

2.2.2.4 Secondary Recovery Potential

If people decide to waterflood, what could they get if anything? Is it technically possible to waterflood the oil reservoirs, which would be primarily the Delaware under the WIPP Site?

First we looked at the feasibility of waterflooding. Is waterflooding the Delaware technically feasible? Yes, it does appear to be technically feasible although the pools that are under WIPP have not yet been waterflooded. Yes, water has been injected into eight Delaware Pools in southeast New Mexico for secondary recovery. Waterfloods have recently begun in the Avalon and Parkway Pools in the Delaware. One of those is in the Brushy Canyon. If we take a look at the Cabin Lake Pool which produces from the Delaware near the northwestern boundary of the WIPP, there has been some water injection for pressure maintenance purposes and it has showed some good response. There seems to be a chance for technical feasibility for waterflooding.

Feasibility also depends on economics. Obviously, revenues must exceed expenditures. Profits must meet or exceed expected profits from other possible ventures that a company could get into including waterflooding other fields and pools and drilling for primary recovery elsewhere. So even if something is technically feasible, it may not be economically feasible. Our studies show that waterflooding probably is economically feasible. But even if it is economically feasible, it may not be done because there could be a better return on an investment elsewhere.

Within the limited time available, we analyzed two mature waterfloods within the Delaware Mountain Group in southeast New Mexico. We used historical production data to estimate ultimate recovery from each of those mature waterfloods.

One of the mature floods examined was the Paduca Delaware Field. Primary production started in 1961. Projection of the exponential decline curves showed an estimated recovery of 8-1/2 million barrels of oil by primary production and 5-1/4 million barrels by secondary recovery. In the case of Paduca, there was a 61% increase in production by waterflooding the reservoir. Projecting primary and secondary recovery for the Indian Draw (Delaware) Field yields an 81% increase in production by waterflooding. Worthington made an industry estimate of a 100% increase in recovery from Brushy Canyon by waterflooding the East Shugart Delaware field, which has not been waterflooded at this time.

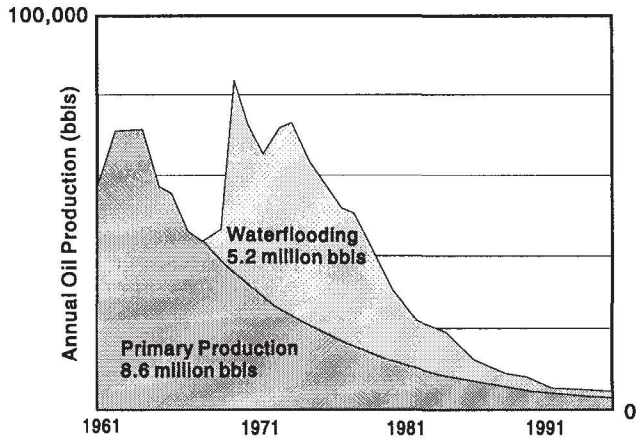

Figure 2.2-13. Production from Paduca Field.

None of the reservoirs under the WIPP Site have been waterflooded yet. Given the three estimates of 61%, 81%, and 100% additional oil recovery by waterflooding, the Bureau used a conservative estimate of 60% additional recovery by waterflooding to project recovery by waterflooding reservoirs in the vicinity of the WIPP Site. Further, there was proprietary information from the oil companies operating in the area indicating that they anticipated 70% to 80% increase in production by waterflooding the Brushy Canyon Formation. To accommodate the uncertainty, the Bureau used a very conservative estimate.

Production from the Cabin Lake Delaware Pool, just outside the northwestern corner of the WIPP Site, was used to provide technical information on the feasibility of waterflooding. Phillips Petroleum is the primary operator of this pool. Figure 2.2-14 shows the initial production at about 4,000 barrels per month for this well and a gradual production decline. The operator completed two wells nearby for pressure maintenance, which is a very early-stage form of waterflooding. The immediate response to water injection is clearly shown. The Delaware sands in the vicinity of the WIPP seem to be amenable to waterflooding. It doesn't mean someone is going to waterflood, it just means that the fields are amenable to waterflooding.

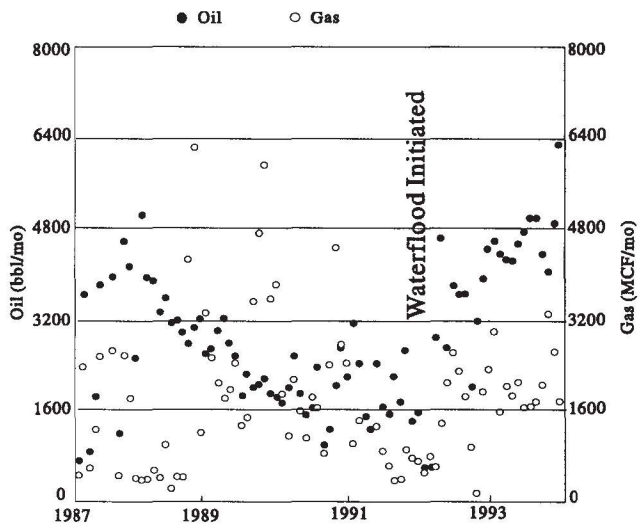

Figure 2.2-14. Monthly production of oil and gas, Phillips Petroleum Company No. 2 James A well, Cabin Lake Delaware pool.

2.2.2.5 Summary

In the Delaware Mountain Group, there is approximately 10 million barrels of oil recoverable by primary production and another 7 million barrels recoverable by secondary recovery. A very conservative estimate shows a little oil recoverable from the Bone Springs Formation and some condensates recoverable from the Strawn, Atoka, and Morrow Formations.

As to gas resources within the WIPP Land Withdrawal Area, approximately 125 billion cubic feet of gas is recoverable from the Atoka Formation, about 30 bcf non-associated gas from the Morrow Formation, and about 20 bcf associated gas

from the Delaware Mountain Group. The Strawn Formation and the Bone Spring Formation would also produce gas.

The above estimates are limited to probable resources. There are probably undiscovered resources under the WIPP Site. But the area has not been drilled. Until then, there is no way of knowing for certain the extent of such resources. For years, operators drilled through the Delaware without knowing of the presence of economically recoverable oil in those formations.

2.2.2.6 Questions:

Wendell Weart: I was wondering if you could provide an average number for the lifetime of a well in this area of the basin, and an average pool lifetime.

Ron Broadhead: Lifetime of the wells. Even though there are some differences from well to well and pool to pool, we can use the average well from the Livingston Ridge to give some idea of a well lifetime. From initial production until about 150 barrels per month, this well is going to produce about 92 months of primary recovery. It is less than ten years for an average Delaware well. Probably production in Delaware pools is going to be in the ten year range, maybe less, because these pools tend to be drilled out and developed very quickly.

Chuck Byrum: What if you add secondary recovery to that? How much would that extend the field life?

Ron Broadhead: Secondary recovery will extend the field life. Secondary recovery will have to start while the primary well is producing. If you wait until the wells are plugged out, secondary recovery is not going to be economically feasible. Secondary recovery is going to have to start when production is around fifty percent, maybe as low as thirty percent of the peak primary production. There are ten years, at the most of secondary recovery, probably less.

Peter Swift: You described the pay zones as about forty feet thick for each pool. Is that all oil saturated or is that just the sand thickness you need in order to have a productive oil zone?

Ron Broadhead: For economic production from Livingston Ridge at present, you need at least forty feet.

Peter Swift: Forty feet of oil or forty feet of sand?

Ron Broadhead: Forty feet of pay, of channel. There is actually less sand. If you get less than forty feet you are going to require a multiple completion. There are a few wells that are completed in multiple zones.

Peter Swift: Is there an oil water contact in that forty feet?

Ron Broadhead: No, there is not.

Chuck Byrum: How much water is being produced during primary recovery per well on average and how much during secondary recovery? Is there a difference?

Ron Broadhead: I don't have an exact number. I can't recall exactly what the water production is from primary. But these wells in the Delaware produce a very high water cut.

Chuck Byrum: Some of the numbers that I have seen, it is like a four to one ratio.

Ron Broadhead: Yes, the water cut is very high. These are fairly unconventional sands. They are pretty fine grained. There is a high water saturation. There is a lot of moveable oil and moveable water. It is not being driven by an oil-water contact. It is water in the actual pore space with the moveable oil.

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2.3 Observations of Water Level Rises in the Culebra Aquifer

2.3.1 Presentation by Rick Beauheim (no synopsis)

The purpose of the presentation was to summarize the observed water level rises since 1988 and offer thoughts on explaining the water level rises, starting with the wells to the south and working northward. The plots start at 1988 because it was in 1988 that water level rises were first noticed in well H-9.

Shown at right are the locations of the Culebra Dolomite Wells in the vicinity of the WIPP Site. Well H-9 is approximately six miles to the south of the WIPP Site. In 1988, a rise in the water levels was first noticed at well H-9. The water level rise propagated north to other wells.

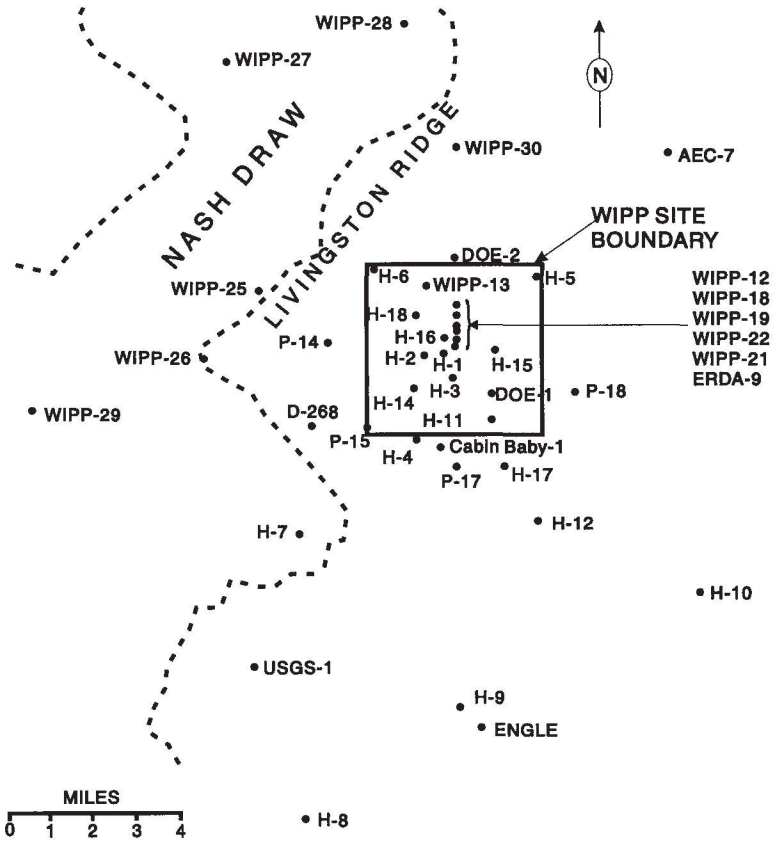

Figure 2.3-1. Locations of Culebra Dolomite Wells in the vicinity of the WIPP Site.

Since that time there have been other Culebra water rises related to other phenomena. To explain the other phenomena, the presentation was divided into three regions around the WIPP Site, starting with each well to the south, covering each well about the center, and finishing with the wells to the north.

2.3.1.1 Southern Region of the WIPP Site

For at least five years prior to 1988, the water level at H-9 was very stable at 431 to 432 feet below the surface. Between March and April of 1988, the water level took an abrupt turn and kept on climbing. In a natural system, that is a system undisturbed by man, you do not expect to see a steady water system and then in the space of one month, the whole thing turn. That is not a natural kind of phenomena. It screams that some event has occurred. Some human induced event has occurred. The rise generally continued from 1988 until about 1993. In 1993, the water level fell off rather abruptly, has been fluctuating, and is now on another rise. The events at H-9 are the result of some phenomena, most likely some well effect.

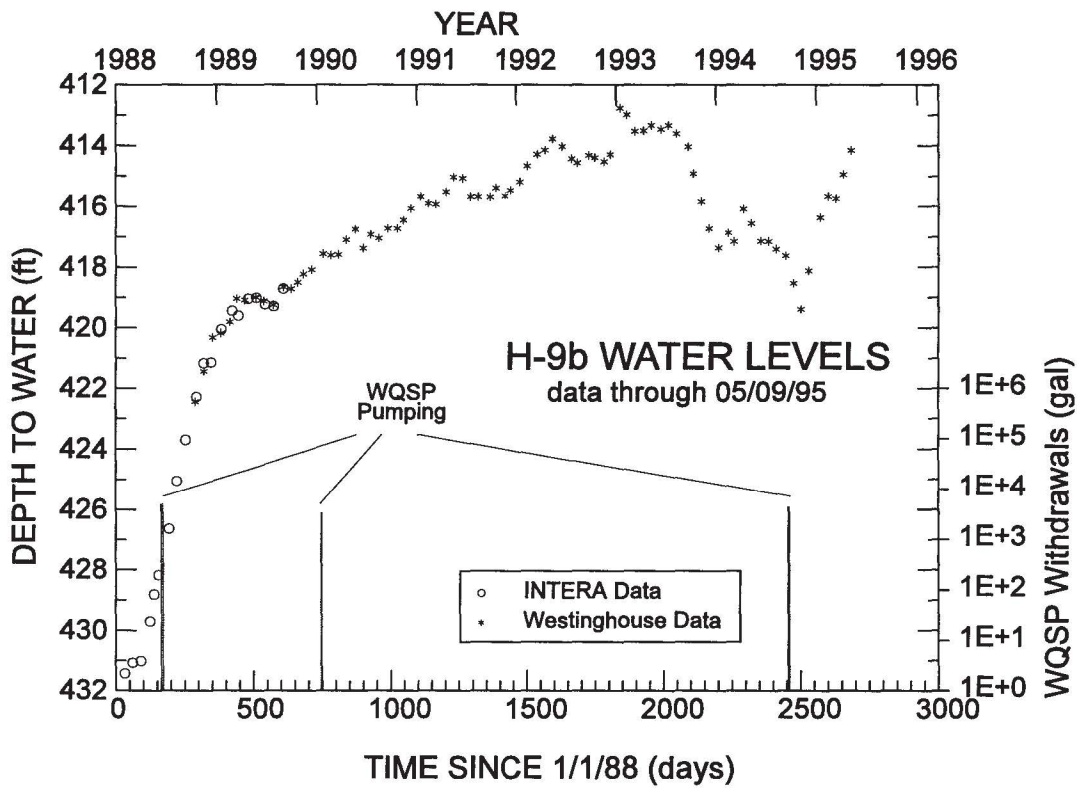

Figure 2.3-2. Well H-9b water levels.

The first well to the north of H-9 is H-12. At the time water levels at H-9 began rising, the water levels at H-12 were controlled by other events. One of those events was the H-11 multipad test. But after the conclusion of the pumping test, the water level was going to clearly recover past the point prior to the pumping test. A water quality sampling test brought the water level down, but at the end of the sampling test the water level continued climbing steadily. The total water level rise at H-12 was on the order of nine feet.

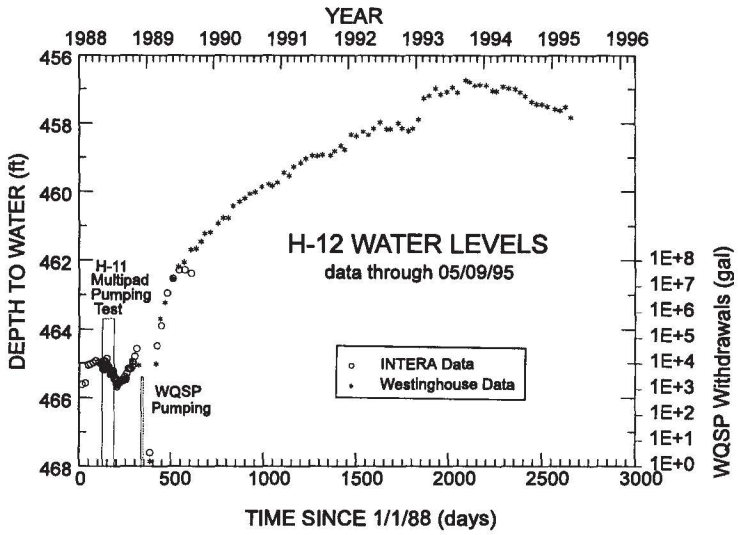

Figure 2.3-3. Well H-12 water levels.

Well H-17 lies a little further to the north of well H-12. Again, after the response to the H-11 multiwell drawdown test, the recovery continued to climb. The water level has fairly well stabilized at the upper end. From 1993, there is not the same kind of detail that is seen in some of the other wells.

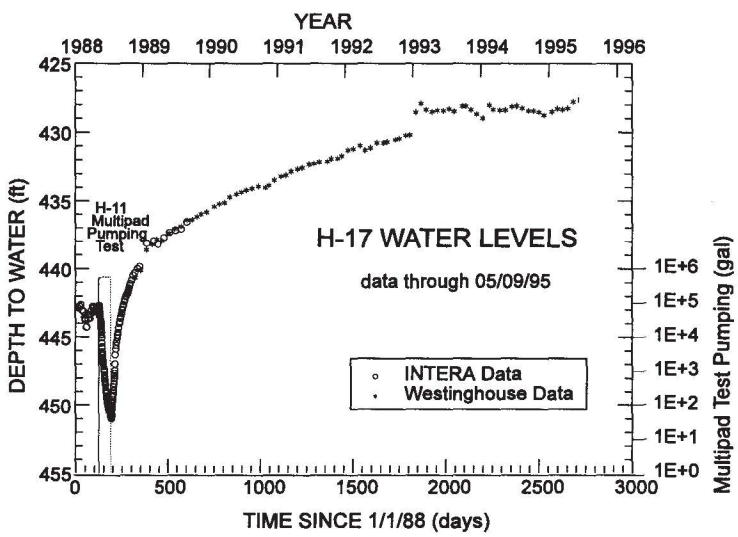

Figure 2.3-4. Well H-17 water levels.

Well P-17, which is due west of H-17, shows the same kind of behavior but it does seem to be a little more in touch with the other fluctuations that have occurred since 1993. There was, again, on the order of nine feet of water level rise.

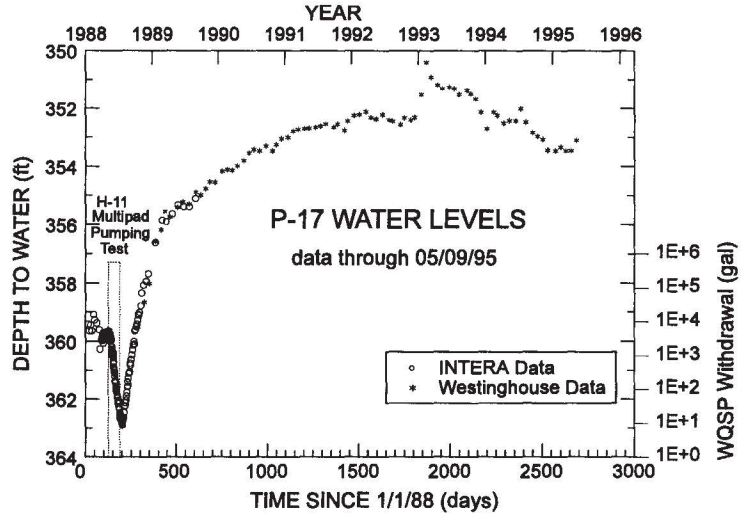

Figure 2.3-5. Well P-17 water levels.

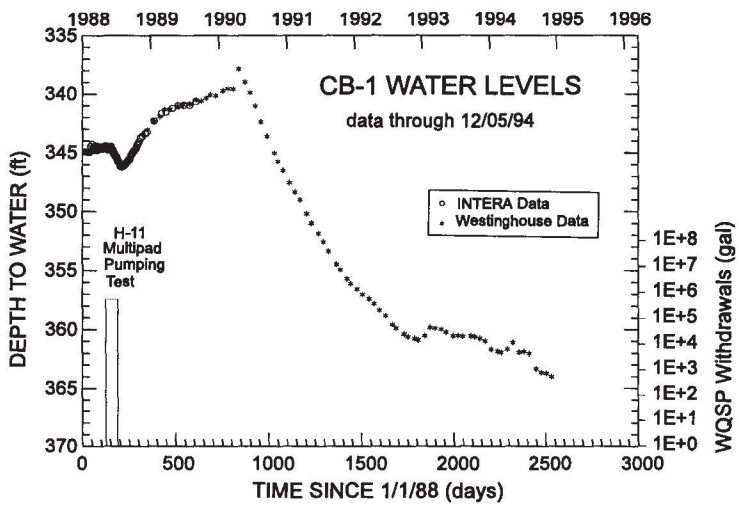

Figure 2.3-6. Well CB-1 water levels.

Cabin Baby [CB-1], which is just to the northwest of P-17, saw the H-11 multipad test response. The water level was continuing to rise and then the packers and bridge plug failed. That drawdown response (after early 1991) has nothing to do with the Culebra. At that time, the Culebra and everything else in that well were interconnected. Late last year we replaced the packers in that well and put in a new bridge at the base of the casing. Westinghouse may not be aware of that and needs to go back to measuring the water levels.

Well H-4b is the next well slightly to the northwest of Cabin Baby, and again you see the same response to the H-11 well and then this rise. Westinghouse takes water samples from time to time resulting in an occasional drawdown, but the well does recover. But they also went into H-4b and a number of other wells. Some of these older wells were caving in and were not providing full access to the Culebra Formation. Some of these wells were cleaned out. The cleaning required Culebra water, but Culebra water was not available from well H-4b. Water from well H-3 was used for all of these 1992 cleaning exercises. The water from H-3 has a different density from the density of the water in the wells that were cleaned out. As a result, upon completion of the cleaning exercise the water level had declined. The foreign water was pumped out and the water level rose sharply as a result of density change more than anything else. The water level has continued to decline. The decline in the H-4b well may reflect the decline in the Cabin Baby well because H-4b and Cabin Baby are very close to each other. The Culebra saw a pressure decline in the Cabin Baby well, which would create the drawdown in well H-4.

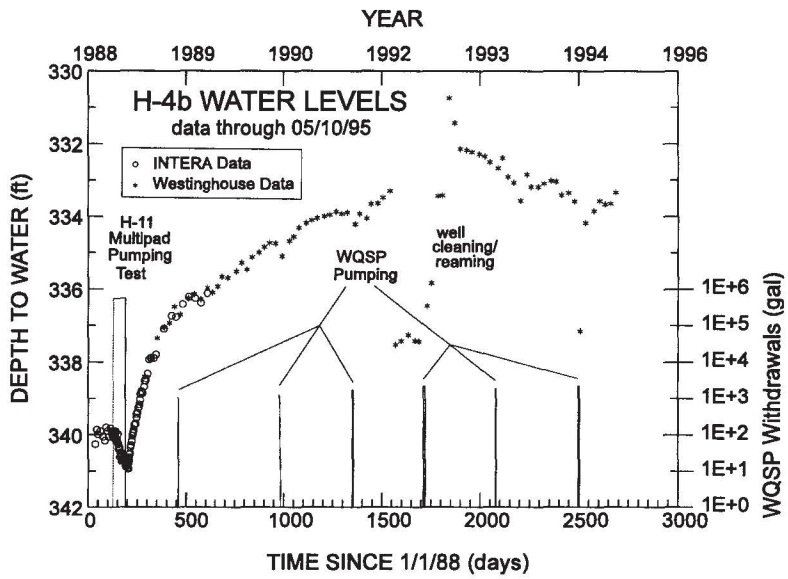

Figure 2.3-7. Well H-4b water levels.

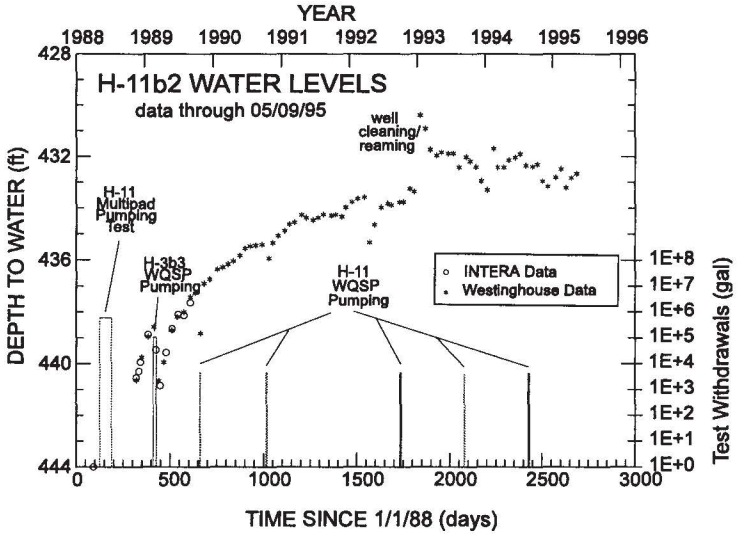

Figure 2.3-8. Well H-11b2 water levels.

After the H-11b2 multipad pumping test, there was pumping at H-3 that effected the water levels at H-11. After the recovery from the H-3 pumping test, the water level continued to rise. The plot shows the response to the cleaning exercise. The water level rose with the density change. The water level has continued to rise since then (with the rest of the response very similar to that at H-4b).

Well P-15 shows the same type of response (as H-11b2).

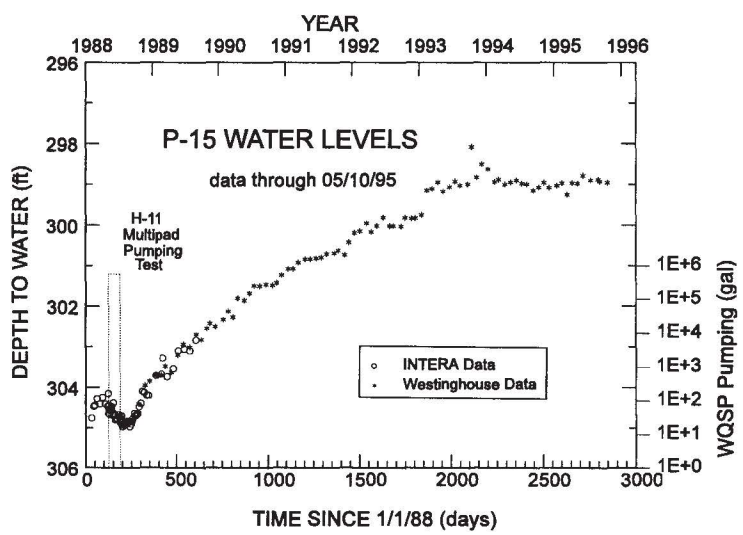

Figure 2.3-9. Well P-15 water levels.

Well H-10 lies northeast of H-9. Well H-10 has quite low transmissivity. It is a very tight well. It appears that whatever happened at H-9 or in the vicinity of H-9 took a number of years to propagate over to H-10 because of the low permeability. It wasn't until the end of 1990 and beginning of 1991 that the water level in H-10 began to take off. The water level has definitely climbed about three feet in the last three or four years.

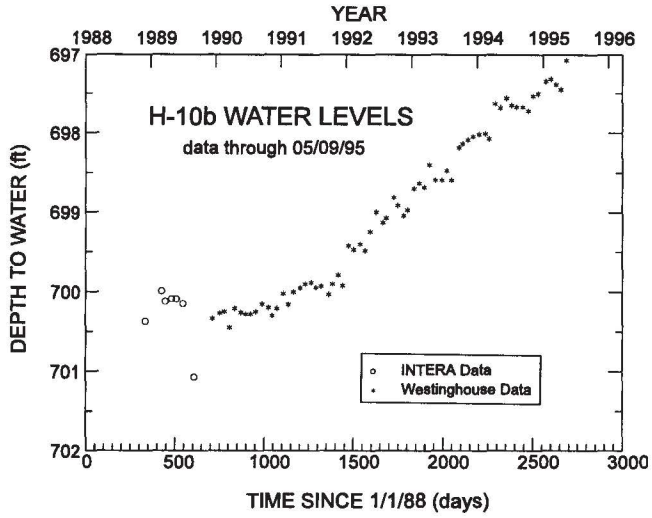

Figure 2.3-10. Well H-10 water levels.

Well H-7 lies off to the west in an extremely high permeability region. H-7 may also be under water table conditions. The scale in the water level plot is on the order of three feet. What appear to be large amplitude fluctuations are actually less than a foot in water level change. Most of these changes are probably due to barometric effects, earth tides, or something of that nature. The changes are just a fraction of a foot. But, one gets the sense that, for

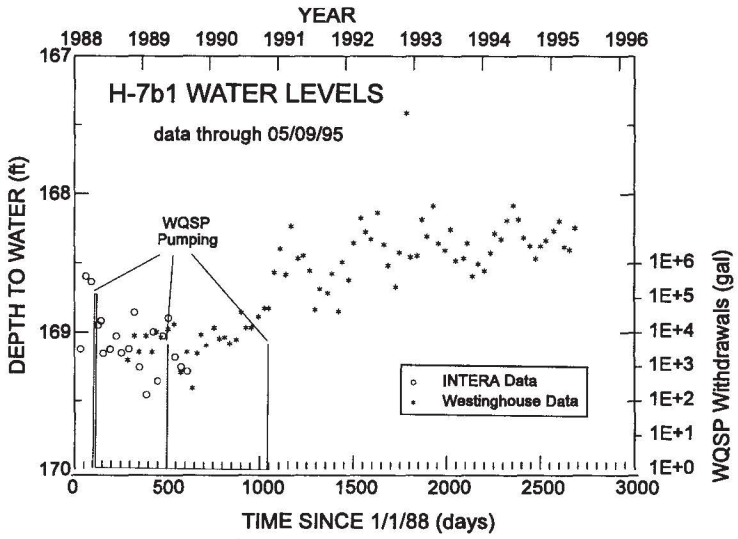

Figure 2.3-11. Well H-7 water levels.

years, the water level seems to be stable at about 169 feet. One does get a sense that the water level is climbing a bit at H-7.

So what might be going on? In 1990, Marsh LaVenue looked at all these rising water levels to the south and went out looking for injection wells in the vicinity of H-9 that might be a cause of this kind of a water level rise. He identified a number of injection wells, some of which the operators thought might be leaking. We really had no evidence that the leakage was specifically going into the Culebra. We were mainly interested in figuring out if that type of a hypothesis, that is a leaking injection well somewhere in the vicinity of H-9, could cause the types of water level rises that we have observed.

LaVenue identified one well not too far from H-9 that was injecting about 12 gallons per minute into a deeper formation. So we decided to play a "what if" game. What if some of the water being injected into this well is actually leaking into the Culebra? Using the existing regional groundwater flow model, LaVenue simulated injection at that well location. LaVenue found that if he put the full 12 gpm, into the Culebra, at that location, he could very nearly match the observed water level rises. Now that is in no way, shape, or form, proof that that [salt water disposal] well is the cause of these water level rises. It merely shows that if something is being injected into the Culebra, in that region, and at about 12 gallons per minute, you can get this kind of a response. It confirms our hypothesis that it really does take some kind of discrete event, turning on a pump, turning on injection, something changing to cause these kinds of water level responses.

From my standpoint, it's really not important what well might be responsible for this. It could be any well out there. The point is, in the future, we won't know. In a hundred years from now we won't know what wells might be leaking. We won't know what casing has failed, what cement jobs have gone bad. The point

is simply that other units can be connected to the Culebra. They can cause changes in the water levels.

So what is the overall implications with respect to compliance? Well, in this particular instance, this well is to the south of the WIPP Site. Rising water levels to the south, that propagate to the north, as they propagate, they diminish in magnitude. What this in effect does, in this instance, is decrease the gradients, the natural gradients, within the Culebra, which are from north to south. So, under ordinary conditions, you have a particular gradient which in the event of a breach of the repository, would drive radionuclides to the south under the existing gradient. Well, what this kind of event does, is it decreases that gradient. So this would actually slow things down a bit. I don't think that is significant because I don't expect this to be a particularly long lived kind of response, probably on the order of tens of years, then it will damp out, reach some new equilibrium. Climate changes in the future could cause similar types of gradient changes, so I really don't think it's important. Let's continue to look at the other water levels and I will show you some other things that are going on.

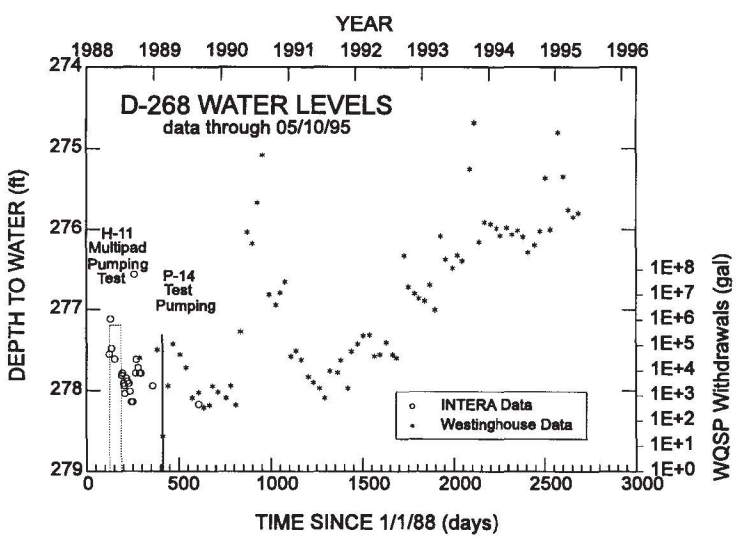

Figure 2.3-12. Well D-268 water levels.

D-268 is off the southwestern corner of the site. We have a troublesome packer in this well. It has to be continually reinflated. It likes to deflate. It sees a lot of water fluctuations as that packer loses its integrity and as

the packer is reinflated and reestablishes its integrity. There may be a slight rise in the water level at D-268.

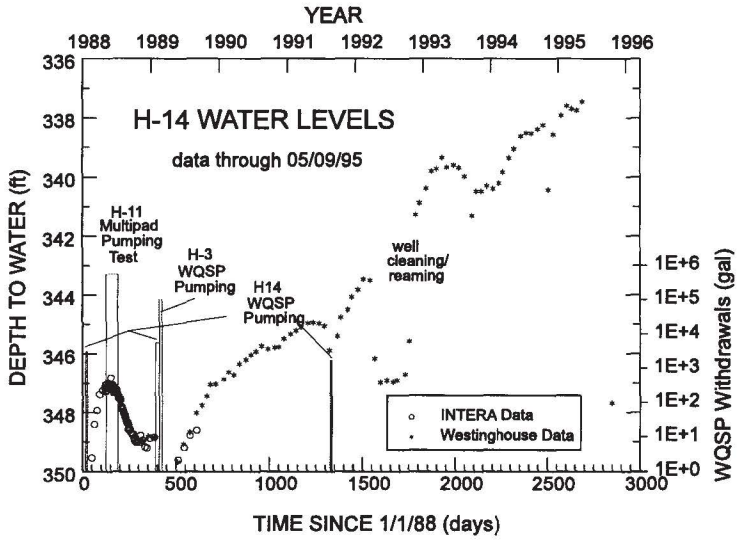

At H-14, there is the same type of response as observed at the other wells - a well cleaning exercise - pumped out - changes in fluid density.

Figure 2.3-13. Well H-14 water levels.

This is a greatly expanded scale, with sixty feet on the vertical scale to capture the response to the H-11 multipad pumping test. The water level continued to rise after the H-11 test. Then there was a packer failure in DOE-1. That packer has since been replaced and the water level is starting to recover from that event.

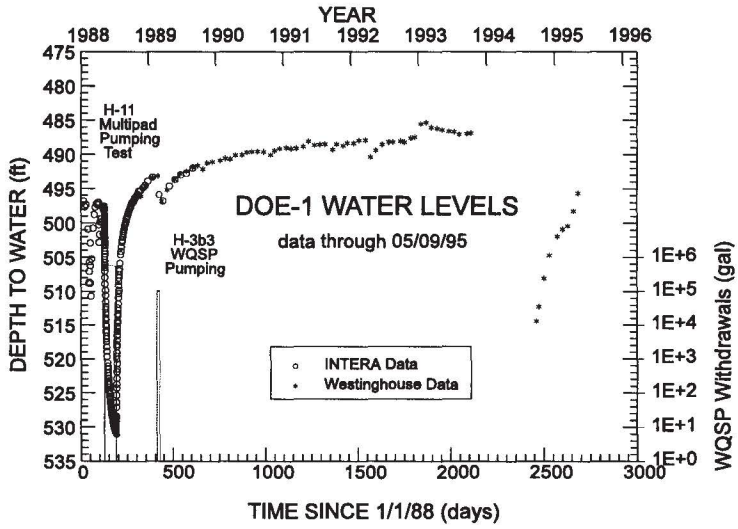

Figure 2.3-14. Well DOE-1 water levels.

Well H-15 shows a type of response similar to that of DOE-1.

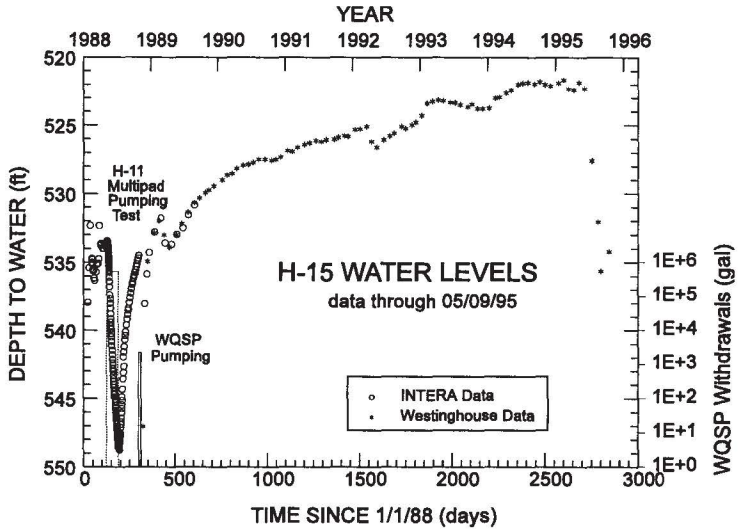

Figure 2.3-15. Well H-15 water levels.

2.3.1.2 Central Region of the WIPP Site

The shafts at WIPP caused a large cone depression in the Culebra. Starting back in 1981, when the exploratory shaft was first drilled, there has been leakage into all the shafts at the WIPP Site and that leakage has brought water levels down, in the Culebra, over the entire site. Over the years, there have been a number of episodes of shaft grouting which have been of varying effectiveness, and sometimes that effectiveness has been limited in time. So, some of the grouting jobs were repeated.

The most recent shaft at WIPP is the air intake shaft. Before the air intake shaft was drilled, we put in an observation well, H-16, fifty feet away to monitor the responses of the Culebra to the construction of the air intake shaft. The pressures that have been measured at H-16 since about August 1987 are shown. The stabilized pressure in the Culebra before the air intake shaft was drilled, was about 128 psig. When the pilot hole for the AIS was drilled, the hole was loaded with drilling mud. Once the drillers hit the Culebra, the pressure at H-16 rose in response to the pressure exerted by the drilling mud. Once the drillers holed through to the underground, the column of drilling mud shot into the underground

resulting in an atmospheric pressure condition in the Culebra. So the pressure in the Culebra at H-16 dropped significantly at H-16. The drillers then upreamed through the Culebra. The pressure again dropped significantly at H-16. The air intact shaft was then lined. The pressure started recovering. Then Fred Gelbard went into the air intake shaft and drilled four horizontal core holes into the Culebra. That caused the pressure to drop at H-16 because of the free drainage into the holes. Those [core holes] were then pressure grouted because the pressure had increased and then the pressure started climbing again. The interesting thing about the pressure grouting is that by simply pressure grouting those four holes, the pressures rise, the buildup was much more than one might have expected. By grouting those holes, the overall leakage into the shaft was greatly reduced.

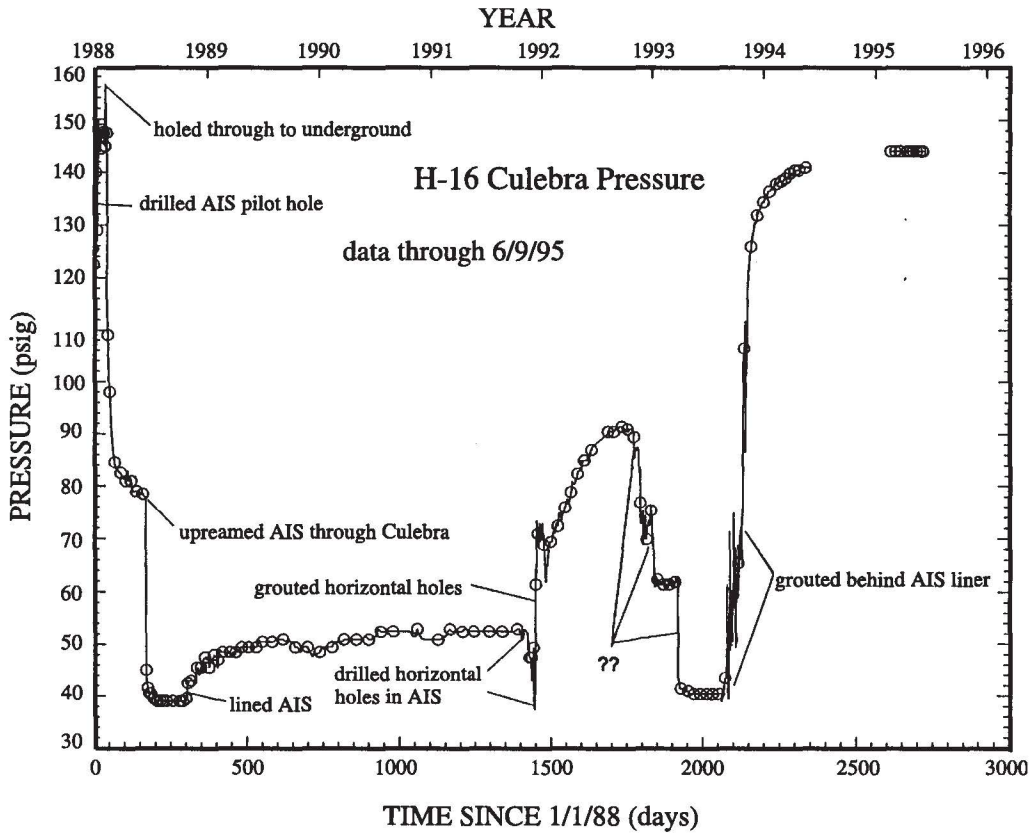

Figure 2.3-16. Well H-16 Culebra Pressures.

There were a number of episodes that I have not been able to pin down. Something happened around the air intake shaft that caused the pressure to drop in at least three distinct steps. I am not quite sure exactly what happened. The pressure stabilized around 40 psig until two summers ago when the project grouted behind the liner. This was a very serious grouting exercise and by far the most effective grouting exercise that has ever been done at WIPP. Sandia was working with the grouting contractor, providing the contractor with pressure data in almost real time. We could show them every single time they drilled a hole into the Culebra to grout. We could see the pressure response at H-16, the immediate drawdown response to drilling that hole. As soon as they did grout that hole, we saw the pressure spike associated with it. So we could track the effectiveness of their grouting program in progress. As soon as the grouting was completed, the pressure at H-16 rose and is now stabilized at 144 psig. Recall that in 1987, the level was stabilized at 128 psig. This grouting job was very effective. The pressure is now higher than it was before the air intake shaft went in. I spent this much time on this well because the other wells exhibit similar behavior. Well H-16 is only fifty feet from the air intake shaft but all of these responses propagated throughout the center of the site. Similar responses are seen for wells ERDA 9, H-1, H-2b2, H-3b2, WIPP-21, WIPP-22, WIPP-18, WIPP-19 and WIPP-12. The responses are more subdued with increased distance from the air intake shaft.

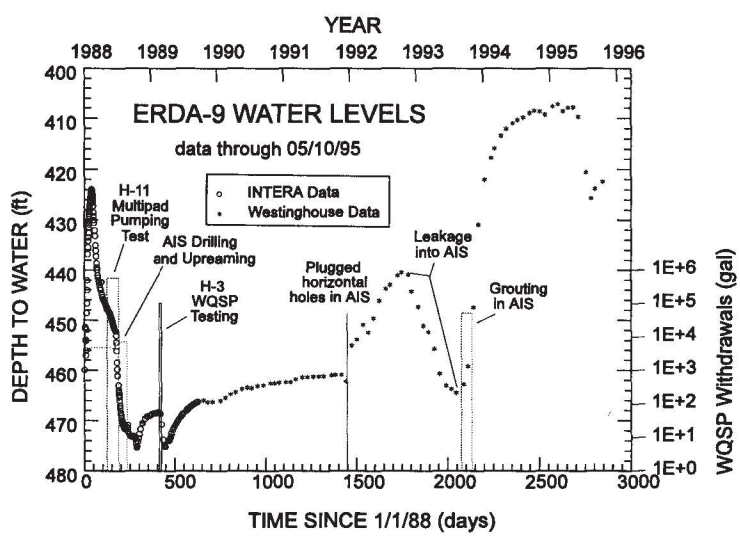

Figure 2.3-17. Well ERDA 9 water levels.

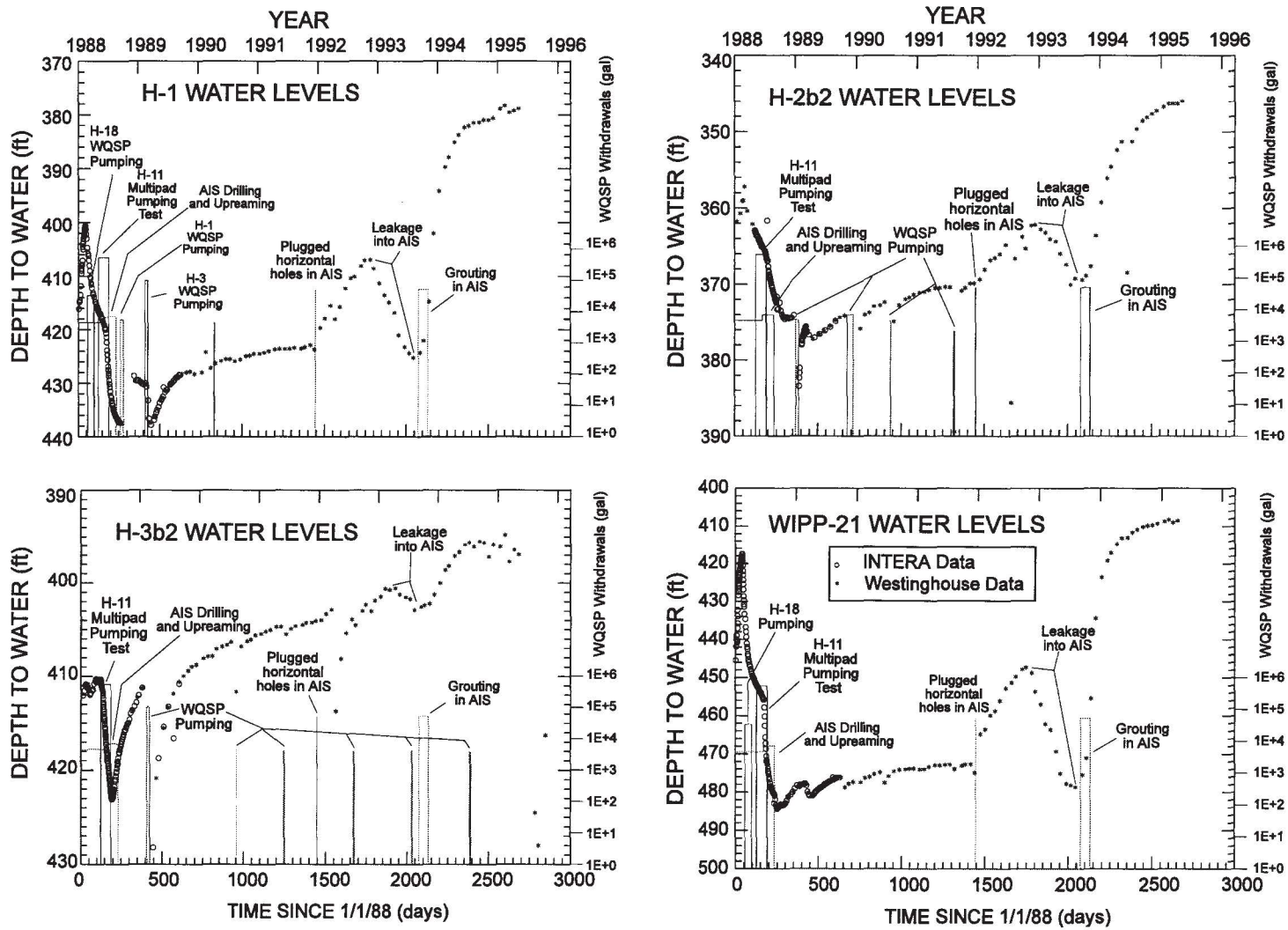

Figure 2.3-18. Wells H-1, H-2b2, H-3b2, and WIPP-21 water levels.

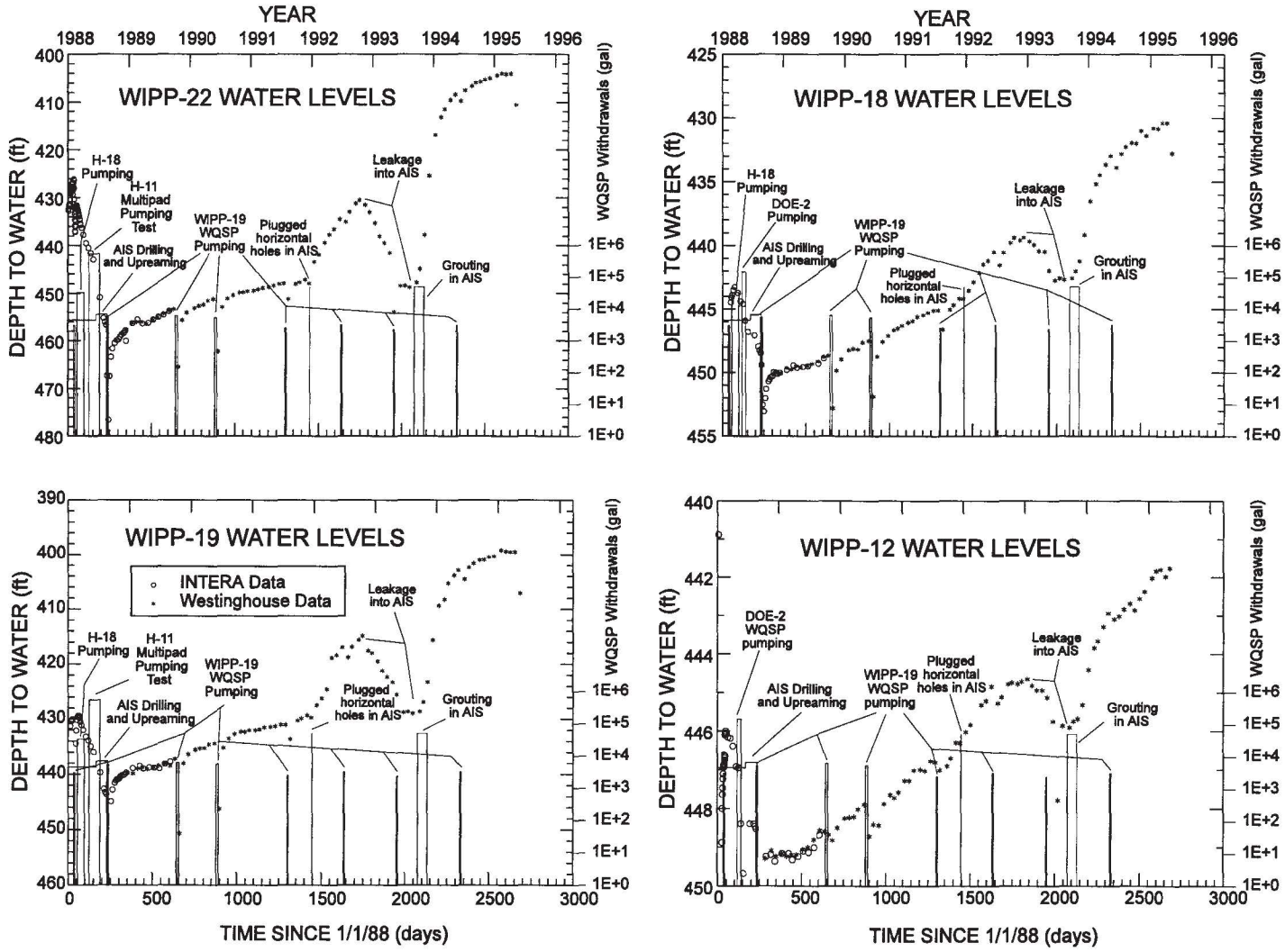

Figure 2.3-19. Wells WIPP-22, WIPP-18, WIPP-19, and WIPP-12 water levels.

Well H-18 shows a general rise in water levels.

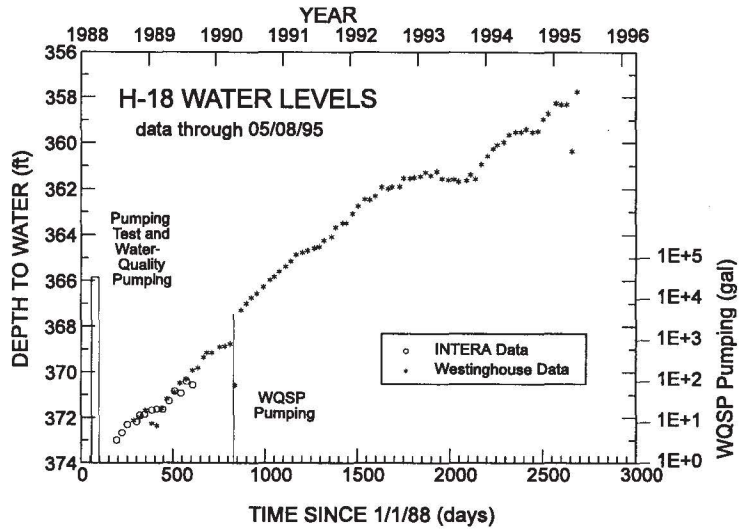

Figure 2.3-20. Well H-18 water levels.

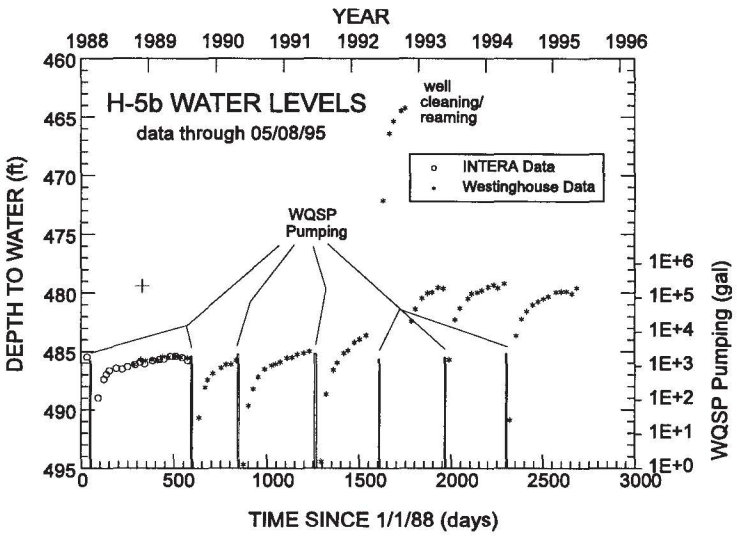

Figure 2.3-21. Well H-5b water levels.

Well H-5b is in the extreme northeast corner of the WIPP Site. It is in a very low permeability zone and it takes a lot to make anything happen at H-5. It is pretty much isolated from other events. It does show that for each water quality sampling, the well takes a time to recover and is still recovering when the next sample is taken. The water level sharply increased, for a while, in response to the well cleaning and reaming. Now the water level is in line with where it should be.

Well DOE-2 shows a water level rise up until mid-1992. Since then the water level has been falling off. This one is pretty anomalous. You don't see this kind

of fall off in any of the surrounding wells. DOE-2 is like DOE-1 and Cabin Baby and some of the other wells. It has a bridge plug in the base of the casing which isolates the Culebra from the Salado and the Castile. There is another deep bridge plug which isolates the Castile from the Bell Canyon. Looking at the water level plot, I would guess that one or both of those bridge plugs have failed and we need to reenter that well and put in a new bridge to isolate the Culebra.

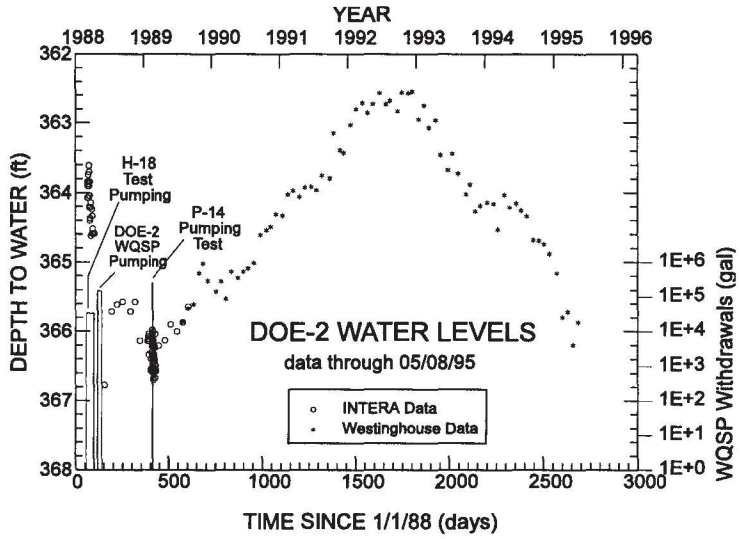

Figure 2.3-22. Well DOE-2 water levels.

WIPP-13 shows a water level rise. As you continue north towards Nash Draw, you see this kind of rise. This rise may be due to a combination of events. The wells are far enough away from the shaft so that they won't see a distinct response to a distinct episode at the air intake shaft. Instead you see a

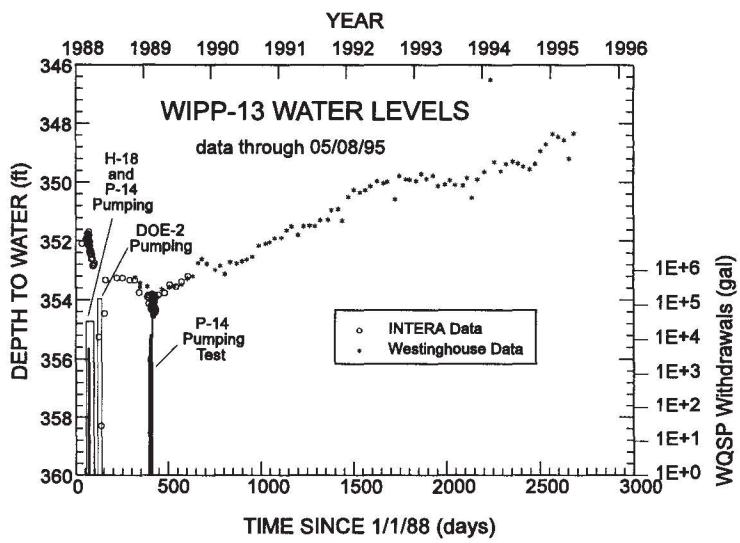

Figure 2.3-23. Well WIPP-13 water levels.

generalized response. In general, leakages into all of the shafts have decreased over the years. The rise in the wells to the north just reflects an overall recovery to the leakage into the WIPP shafts.

H-6 has risen on the order of about 4 or 5 feet since 1989. It is important to remember that H-6 has been there since the late 1970's. Even though it appears that the water level is rising, today's water level does not represent an all time high. Today's water level is approaching the water level of the late 1970's before any of the WIPP shafts were drilled. This appears to be a recovery to the drainage into the WIPP shafts.

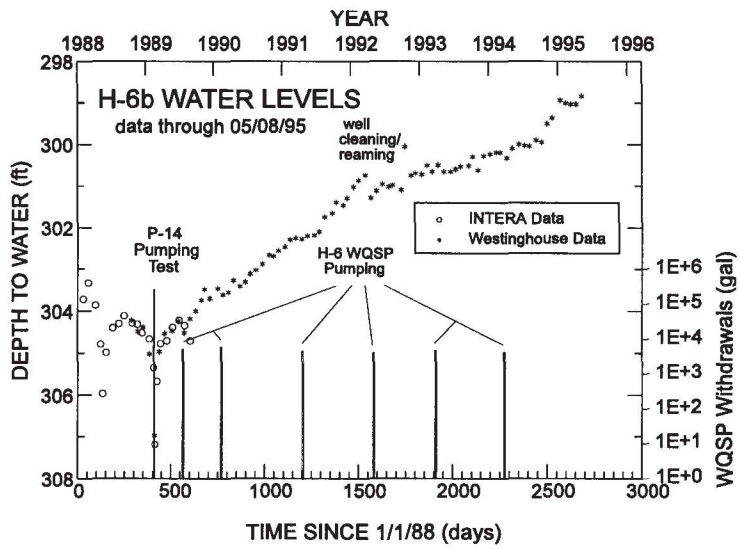

Figure 2.3-24. Well H-6b water levels.

P-14 is in a very high transmissivity region. The water level had been fairly stable. Now it looks like P-14 is going through an historic high.

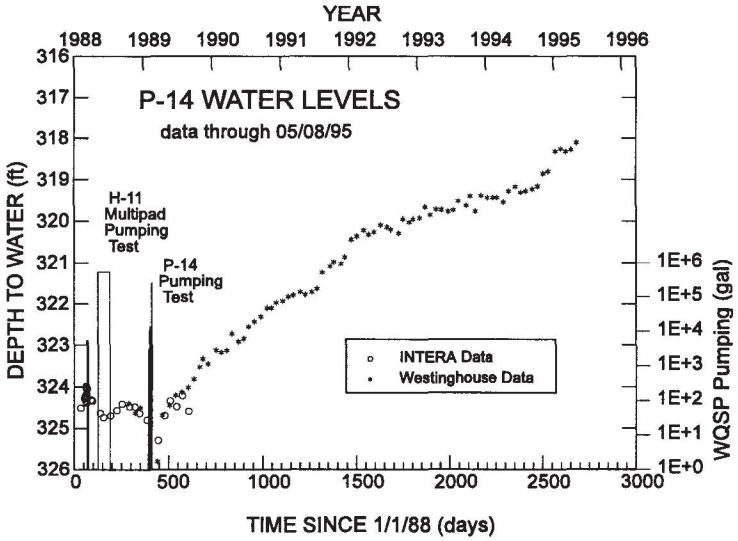

Figure 2.3-25. Well P-14 water levels.

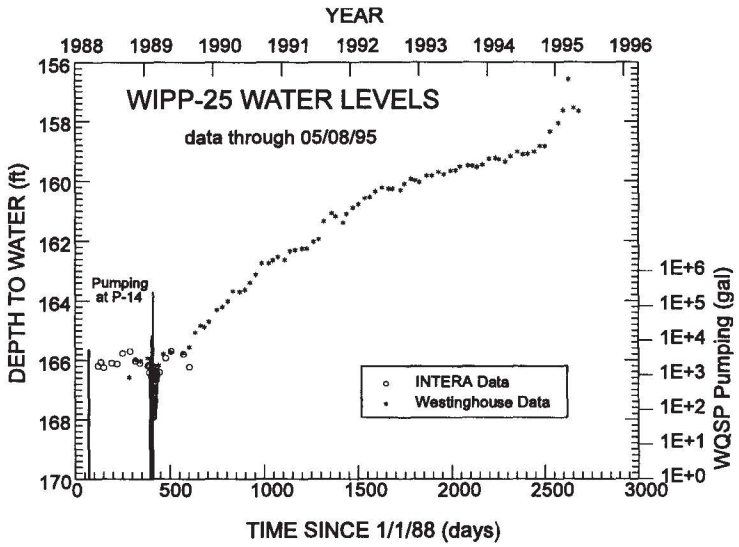

Figure 2.3-26. Well WIPP-25 water levels.

WIPP-25, in Nash Draw, shows a rise. WIPP-25 is in a high permeability region and it takes a fair amount of water to change the water level.

WIPP-26 seemed to be rising, but now it seems to have stopped.

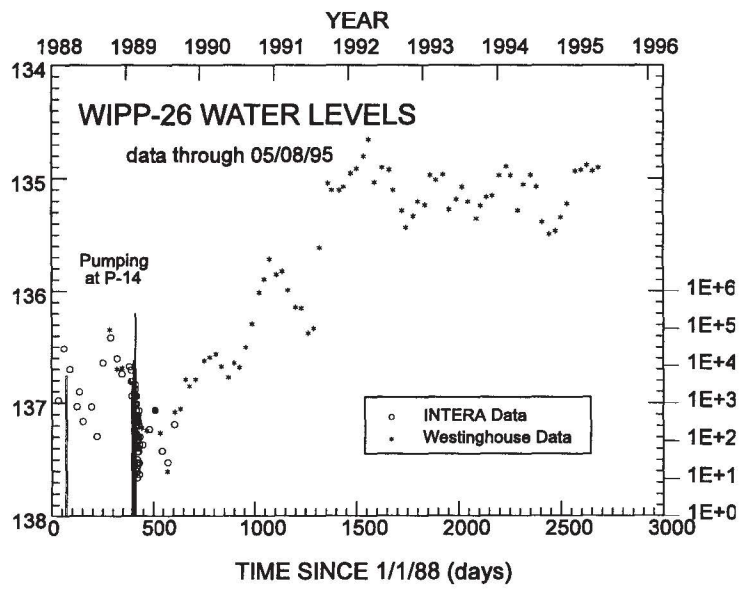

Figure 2.3-27. Well WIPP-26 water levels.

2.3.1.3 Northern Region

WIPP-27 is in the northern part of Nash Draw, very close to one of the potash mines. The potash mines discharge various amounts of effluent into Nash Draw depending on their production. When there is not much production, there is not much discharge into Nash Draw. When there is more mining and more refining, they discharge more. WIPP-27 has a lot of distinct features. The plot of water level rise does not exhibit the noise seen in the plot for WIPP-26. Instead, WIPP-27 is responding to

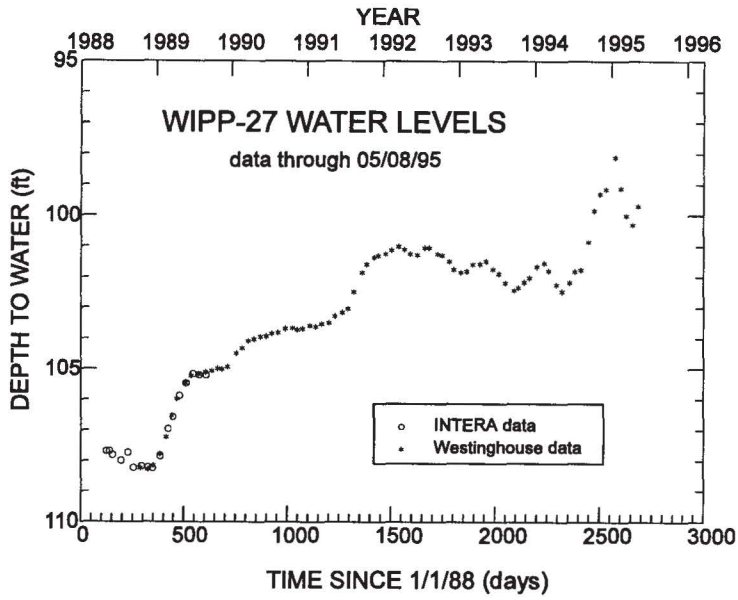

Figure 2.3-28. WIPP-27 water levels.

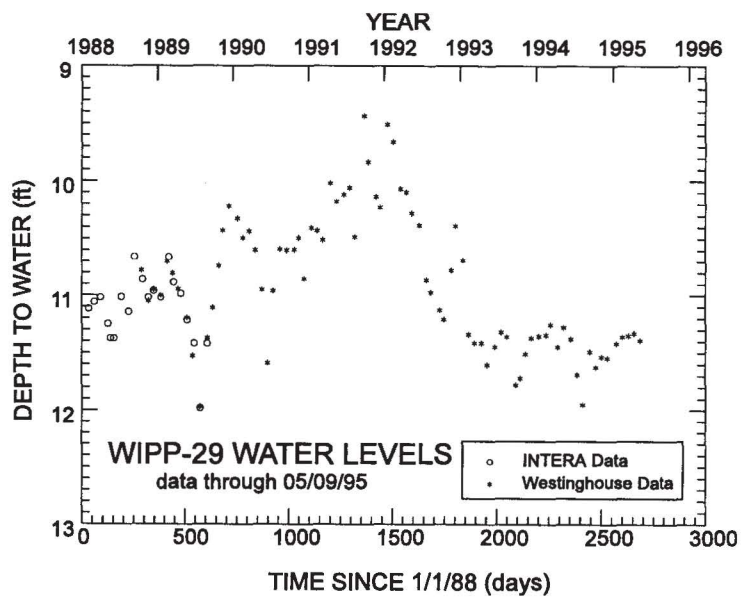

Figure 2.3-29. WIPP-29 water levels.

something fairly distinct. WIPP-27 appears to be providing a good indication of the discharge into Nash Draw. Some of these changes probably propagate through Nash Draw towards the northern part of the WIPP Site. But the changes get more diffuse as they get there.

WIPP-29 is so shallow, 11 feet to water, that it could be responding to almost anything.

WIPP-30 showed a rise, a stabilization for a few years, and now appears to be on another rise.

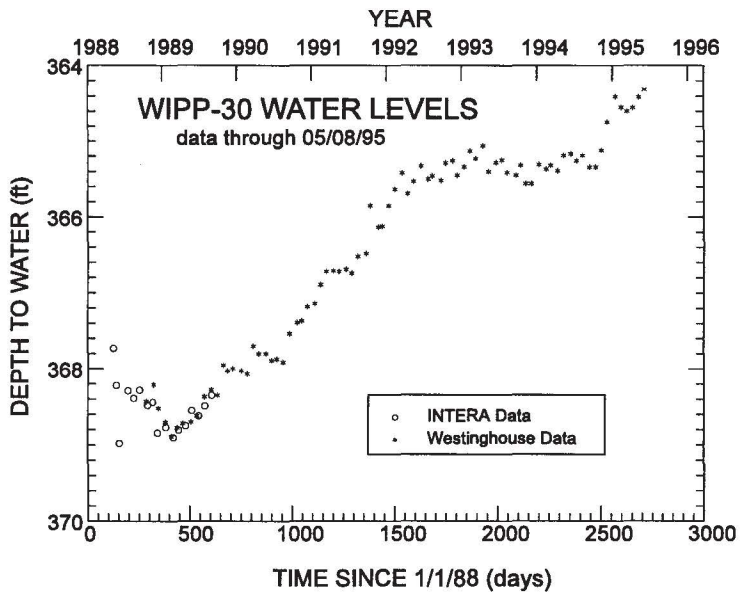

Figure 2.3-30. WIPP-30 water levels.

Well P-18 continues to rise. It is not clear where P-18 is headed. In contrast to all of the other plots, which begin in 1988, this plot begins in 1977. This is the complete water level history on P-18. Until

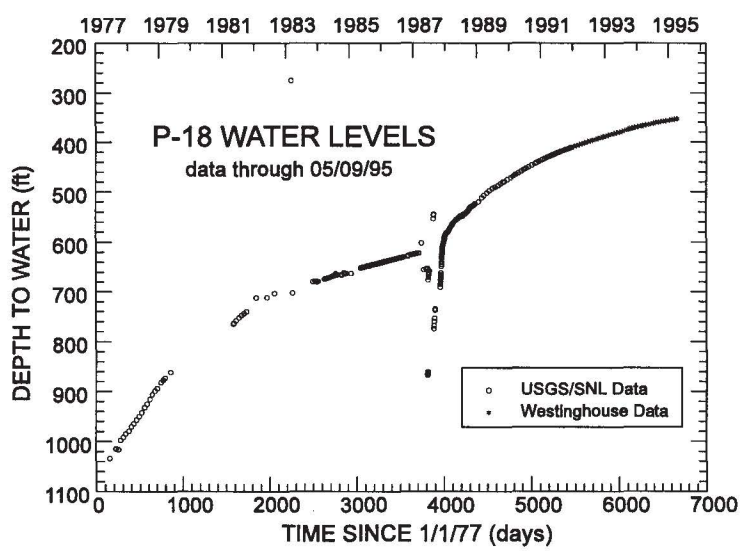

Figure 2.3-31. Well P-18 water levels.

about 1987, the water level was rising in a 4-inch well casing. It never actually stabilized. Then in 1987 we put a pip in the well. So, now the water level is rising in 2-3/8 inch tubing instead of 4 inch casing so it goes up faster because of the smaller diameter. The water level still hasn't stabilized there. A lot of people over the years, including myself, have hypothesized that we may not have the best connection to the Culebra in this well. There may be a problem with the cement bond. This is a cased, cemented, and perforated well. There may be a problem with the bridge plug at the bottom. There may be problem with the cement job. We don't have a lot of confidence that what we are seeing here is the Culebra.

2.3.1.4 Summary

To summarize, I see three different things going on with the water levels at the WIPP Site. To the south, centered around H-9, you see one very distinct water level rise that began abruptly in 1988, reached its peak at H-9 and seemed to propagate to the north, which I think is probably related to some kind of injection from some other well in that region. As you get to the center of the WIPP Site and more or less propagating out from the center of the WIPP Site you see recoveries and drawdowns related to events at the WIPP shafts. Those shafts are pretty well sealed right now, so the overall response you see today is rises in water level. As you move to the North and get into Nash Draw, I think you can probably see responses to the discharge of potash mill effluent into Nash Draw. I'm not sure about the availability of discharge records there. It might be possible to try to reconstruct a discharge history and try to relate that to the water levels we have seen. Again, I'm not sure that it's really relevant to WIPP compliance. The water levels and the flow directions are not from the WIPP Site towards Nash Draw. Any minor changes in gradient, in any event, are not going to effect the results of our performance assessment. We are not on such a hair trigger that a difference of 10% or even 100% is really going to make any difference.

2.3.1.5 Questions:

Dennis Powers: For wells H-7, WIPP-26, and WIPP-27. Are the data precise enough for annual changes?

Rick Beauheim: I have doubts about H-7. H-7 at one time pumped at 80 gpm and the responses we saw at the observation wells on the order of 100 feet away were dominated by earth tides. And the earth tidal responses were almost as great as the pumping test response. It may be of interest to no one but me, but earth tides are changes in water level affected by moon tidal affects and the changes in the configuration in the earth in response to tide. Actually, some of the first work on earth tides was done in Nash Draw, in the Culebra, back in the late 1920s, early 1930s. So H-7 is very close to the location where the very first earth tide research was done. The other ones, Dennis, -- yes I think it is possible that you could try to do that -- I'm not sure what you would turn up, but it might be worth a shot.

Tim Gum: Rick, on your model study where you indicated the 12 gallon per minute increases in fluid level, what was the total volume which had to be injected in order to get the total rise all the way?

Rick Beauheim: The way the modeling was done, the 12 gpm was turned on. I guess I'm not sure exactly when in 1988. In early 1988 this 12 gpm was turned on and was simply allowed to run for the duration of the modeling simulation. At the time that was done, the water levels were all continuing to rise. So the modeling was simply turned on and we watched the hydrograph to see if the simulator hydrograph matched what we observed.

Tim Gum: From 1988 on?

Rick Beauheim: From 1988 on to however long it ran. I honestly don't recall if we just ran a simulation through 1991 at the time or projected further. But we didn't turn it off and then on.

Tom Peake: Yes, do you think this affected your response times, due to rises from the South to the North, up to the Cabin Baby and H-4? Do you think that has any implications for suggesting that there are higher transmissivities in the South Central part of the WIPP site than are currently being modeled?

Rick Beauheim: I think you can look at the pattern of water level responses and learn something about the transmissivities. P-17 and H-17, for instance, lie on an east-west line. Yet their responses were different. I look at those two responses, H-17 and P-17, and what they say to me is there is a high transmissivity feature passing between those two wells. A few responses we observed tell me that the high transmissivity feature is more likely closer to P-17 than it is to H-17. Because the P-17 response seems clearer. It seems to catch the subtleties of the response better than the H-17 response. The propagation on toward Cabin Baby, H-4, P-15, I guess I really could not say whether it holds any surprises. I think it would provide an opportunity to take a closer look with our existing Culebra model to see if our current transmissivity distribution would match the responses that you see that much further away in detail.

Robert Neill: It is an extremely important area. In fact we have a half hour scheduled this afternoon to address this in greater detail. Rick, a quick question. Do you see any merit, at this point, in trying to obtain some water samples from these wells to examine, from a standpoint of chemistry, any change as both a function of location and a function of time?

Rick Beauheim: I really don't think so. We are looking at pressure transient propagation here which can be relatively rapid whereas actual transport of ground water is an extremely slow process. I don't think there is any chance at all of us seeing changes in water chemistry as a result of this.

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2.4. Observations of the Effects of Water Flooding on the Salado Formation

Dennis W. Powers, Consulting Geologist, Anthony, Texas

2.4.1 Synopsis

The Hartman vs. Texaco lawsuit and subsequent discussions with different people focused my attention on a physical condition common to several concerns. The basic physics or hydrology of liquid and gas movement laterally or vertically through the evaporites, especially the Salado, is common to decisions about oil and gas exploration vs. potash mining, deviated or vertical drilling through evaporites outside WIPP boundaries, and the fate of any gas generated by decomposition of waste at WIPP.

Exclusion zones for drilling and potash mining are presumed to be based on two principal concerns: safety and the desired development of resources. Exclusion zones presumably increase as real (or perceived) safety concerns increase; fewer resources are developed in consequence. Among the safety concerns is the possibility of lateral movement of hydrocarbons along evaporite beds from a leaking well into a mine. The same general setting can exist for WIPP from the nearest well to the underground workings. Gas generation at WIPP raised the possibility of movement away from the disposal mine to a boundary or well. And the Hartman Bates well raised the possibility of injected fluids reaching a well at a distance of about 2 miles from the injection field boundary and in a formation overlying the injection horizon.

Perhaps each situation has to be resolved separately (monetary settlement for Hartman, scenario analysis for WIPP, some other means for potash vs. oil and gas exploration). Nonetheless, as similar occasions arise, there will be a continuing need to understand the hydrology of liquid and gas transport parallel to bedding within the Salado or other rock units. There are probably no better investigations yet of these phenomena than for WIPP, and there will be increasing pressure to

understand and apply the results to different versions of the same fundamental problem.

2.4.2 Presentation by Dennis Powers

Today I want to cover a few different topics. The title that is listed for you is a little bit misleading. First, I want to give you a little bit of my impression of some things out of the Hartman vs. Texaco lawsuit that struck me. I also want to talk about some common problems, some underlying principles of physics that are important to several different projects and several different ways of thinking about the Salado.

Today, I am speaking on my own behalf and I am not here representing any organization at WIPP even though, I think most you are aware, I am under contract to one or more organizations to do work at WIPP. I am not a lawyer; this is not a legal analysis of the Hartman vs. Texaco case. I think that the comments that Bob Neill made at the beginning were important. This is not a rehash of that case. But there are some items of technical interest.

2.4.2.1 Background

Let's take a look at the setting for that well and the relationship to the Rhodes/Yates waterflooding unit principally operated by Texaco. In January 1991, Hartman and his company began to drill the Bates #2 well on an acquired lease that had previously been drilled by El Paso Natural Gas and had been producing for about 35 years before plugging and abandoning the Bates #1 well. The Bates lease is located in the southeast corner of New Mexico. It is located in the back reef and not in the Delaware Basin. It was drilled to try to produce Yates gas in the lease that Hartman had obtained. At about 2,240 feet the well begin to produce high volumes of high pressure brine. Drilling operations were stopped at 2,280 feet. The New Mexico Oil Conservation Division was notified. Out of concern that an underground blowout might occur, the driller was not allowed to

shut the well in for any extended period of time. Casing had been cemented back to the surface from about 456 feet in an approved drilling plan.

The flow, at times, was on the order of 1,200 barrels per hour. Nearly 300 truck loads of brine were hauled away and a pipe line was put in to take brine away to the South Leonard Waterflood Unit. It took five days to work out a final solution in consultation with the New Mexico Oil Conservation Division. That solution was to cement the annulus first, to go back in and check the cement job, and then to cement back to the surface, leaving the drill pipe in place. Thus ended Bates #2.

At that point Hartman and his company began to wonder where this had come from. The question that came up - was this a natural flow or was it not natural, that is, brought by some other means such as the water flood unit operated at Rhodes-Yates field? I am giving you some of my impressions and can't speak to the actual thought processes of anyone involved, but late last fall I was contacted. It appeared that there would be a defense during the legal proceedings that this was a natural event, that it was similar to the high pressure brines in the Castile Formation and several wells in the vicinity of WIPP. It bears certain resemblances to the data that had been obtained from underground testing at the WIPP — data that had been obtained by drilling small diameter holes and testing them with rather sophisticated means over a period of time to determine what the pressure buildup was. Hartman called me to see if I would be available to help counter these arguments. I spent some time reviewing the data and decided that the approach that they wanted to take was consistent with what I believed was going on so I joined their team, for a while, to provide consulting services. I was named as a potential rebuttal witness. I did not testify at trial. That gives you a little bit of a background. I thought that was important so you would know where I was coming from and you can judge accordingly whatever is said.

Some notes - the Bates #1 was drilled in 1953 by El Paso Natural Gas. It produced, again, for about 35 years and then was plugged and abandoned. The Bates #2 well is approximately 100 feet away from Bates #1 well on the surface. To my knowledge, there are no directional surveys. I cannot tell you how far apart they might be at the bottom of the hole which is about 2,280 feet.

At the point where the flow began, there is an anhydrite unit. It's on the order of 10-15 feet thick, based on geophysical logs from that well and nearby wells that can be correlated. We are in the Salado Formation. I have not tried to correlate the individual marker beds with those in the Delaware Basin. It's my guess we are somewhere in the range of marker beds 140 to 142, which would put it below the WIPP repository horizon, which is just above marker bed 139. There is, on the natural gamma log signatures for that drill hole and others, a slight gamma kick at the base of that anhydrite, which is consistent with what we see in shafts and drill cores and other logs of boreholes. But there is probably some clay or argillaceous zones besides anhydrite.

The distance from the Bates #2 well to the administrative boundaries of the Rhodes-Yates water flooding operations is approximately two miles. Structurally, the Bates well is generally updip.

2.4.2.2 Observations

The salt water blowout and the subsequent case raised interesting technical issues. One was the unresolved differences in the estimates of the true pressure in the Bates #2 well. The New Mexico Oil Conservation Division was concerned that if the well were shut-in, the high pressure brine would be injected into other formations (an underground blowout). Hence, the well could not be shut-in for an extended period of time to obtain a good bottom hole shut-in pressure. The consultants for Hartman believed that the best shut-in pressure came after the annulus had been cemented and there had been circulation and flow equal to the cementing job which should have relieved any pressure problem, or most of the

pressure brought on by a cementing job. That pressure was on the order of 1,000 psi at the surface. The consultants for Texaco had believed there was a more appropriate pressure that was several hundred psi lower. That would have brought the pressure gradient and the formation pressures down considerably from what the Hartman consultants had estimated. Nonetheless, the pressure measurements were less than desirable 1) because of the condition of the hole and 2) because of the inability to shut the well in and obtain a good shut-in pressure.

It was suggested that the pressure gradients can be used as indicators as to whether the water flows were induced by nature or induced by some other source. For the Rhodes-Yates water flood, the injection pressures at the surface ran 1,200 psi and above. Some injection pressures approached 2,000 psi at the surface. If those are correct, those surface injection pressures begin to produce pressure gradients greater than 1 psi per foot vertical. Typically, the measured pressure gradients from brine reservoirs in either the Castile or the very low flows in the Salado are considerably less than 1 psi per foot, ranging down to 0.8 psi per foot or less. The difference in pressures can be used to distinguish between natural or human induced occurrences.

There was testimony on both sides as to whether or not there were unaccounted injection fluids. The consultant for Hartman estimated that there might be as much as 20 million barrels of fluid that had been injected that was unaccounted for in terms of total production and storage capacity of the formation within the water flood unit. Consultants for Texaco testified that they did not believe, by their analysis, that there were any unaccounted for fluids.

There are differences between the geology at the Bates lease and the geology at the WIPP. The Bates well blowout was a large volume, high pressure flow. The bottom of the borehole was in the Salado Formation. The Castile does not exist in the area of the Bates well.

In the WIPP area there are high pressure, high volume reservoirs within the Castile. One brine reservoir was tapped at WIPP-12, approximately 1 mile north of the site center. Those kinds of brine reservoirs are in the Castile and are generally associated with a zone of relatively high deformation of the Castile, within a few miles of the margin of the Capitan Reef.

At the Bates #2 well, the Salado shows little deformation. It shows a general dip, but nothing of any magnitude comparable to the kinds of deformation observed in the Castile in the area of the Capitan Reef. The WIPP pressures from the Salado testing underground, suggests that the projected pressures will show a gradient on the surface much less than the Castile.

The Hartman-Bates well blowout raised interesting questions about expectations for institutional responses and institutional controls and how they change with time. Presumably they get better, but it is one thing that needs to be looked at.

There is a technical basis for scenario development. In the Hartman case, one has to either accept a natural cause or, if it is not natural, one must believe that fluid was transmitted along a bedding plane to the Bates lease perhaps for a distance of 2 miles. Transport along the bedding plane is the best explanation. For years the (WIPP) project has been concerned about gas, generated by waste degradation, either diffusing, fracing (fracturing), or otherwise moving along bedding planes. It is the same problem but moving in a different direction. With any kind of drilling, including water flood operation, around the boundaries at the site, the same issue comes back again. How are we going to address whether fluids can move along bedding planes or within the formation, a certain distance under different conditions? How will we address that?

BLM is having to try to address the issue, I believe, through litigation of the contrasting desires of oil and gas exploration vs. potash mining. How far away from mining is it safe to drill a hole or mine up to a hole? There are cases where mining has hit petroleum casing underground. That makes people nervous — that

there is an oil or gas well and that you get that gas leaking into a mine. Several things are going to happen. None of them are good. The most benign is that their expenses go up to try to deal with a gassy mine and they go out of business. It is not very benign. People are working with stock holders. That might be one of the more benign consequences, if such a leak did occur. But of course, every time you change that boundary, you say, well, we need to protect the potash and keep the oil and gas away. That just simply magnifies the amount of resources unavailable for both sides. Obviously, if you were going to maximize the resources, what you'd like to be able to say is "It's safe". You can co-exist. Everybody gets their way that way. So those are some issues that have some common problems.

What I see is that everybody will probably attempt to solve it uniquely because nobody likes to try to produce a general solution for all of the world. It is expensive and difficult. If you can produce a simple solution for your problem or concern or issue, whatever it might be, if you can produce that solution for yourself very simply, you'll do it. But it might be good for the different organizations to be thinking about this with a little bit longer term (framework) and to recognize that there may be consequences, even unintended consequences, from one solution to another one's problems. Even if it's a modeling approach that makes certain assumptions that the modeler says don't cause a problem, somebody else might have some difficulty with those assumptions. We need to make sure that those are specific, unique, and identified as being adequate for that problem but not necessarily general assumptions. Those are a couple of the things I wanted to talk about this morning. I believe that the pressure on the WIPP underground data and related data from the WIPP will increase. By pressure I mean there will be a lot more demands for it and a lot more desire to interpret it, to make sense out of the particular application that you have, from BLM trying to resolve oil and gas versus potash mining, to other people. They need to be

aware of that and to think about how best to integrate interactive folks. Thank you, any questions?

2.4.2.3 Questions:

Wendell Weart: Do you know, Dennis, if there is presently a standoff distance, either legal or practical that the industries have used to keep certain separation between potash excavations and petroleum holes?

Dennis Powers: The number I heard was 500 feet but I also know that some of the potash mines have generally, inadvertently drilled into a few, or mined into a few holes, too. Five hundred feet is the number I heard but I haven't seen it written down in some regulatory fashion - it may be there. And there may be somebody that knows that number better than I do.

Dan Stoelzel: You said there has been inadvertent mining into petroleum wells. To your knowledge, is there any record of gas leaking into these mines?

Dennis Powers: I haven't seen any, no. What they did, the records that I saw, indicated that the casings got marked up. Tungsten carbide bits will do that. And then there were various measures to go ahead and protect the drill casing. In one case, I'm trying to remember which mine it was, there was a caisson built and a big cement block support around it.

Dan Stoelzel: What about naturally occurring gas in the potash mines?

Dennis Powers: Well they are not classified as gassy mines with methane residence, but there are occasionally these blowouts of gas which have been trapped, most of which is nitrogen. Lokesh [Chaturvedi] has written, edited, and put together a volume that discusses gases occurring in the Salado Formation. That's one good source and there are other sources within some of the Sandia publications that describe some of the gases. But basically it is nitrogen-dominated and few other minor gases. But potash mining people desperately wish

to avoid the gassy classification because if they ever wind up in a gassy classification, at least at this point, they'll be out of business. And right now I don't see any — there is no particular reason to fear that, as far as I know.

Chuck Byrum: Dennis, do you know why they inadvertently hit some well bores while they were mining?

Dennis Powers: No. It may be known, I just don't know.

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2.5 Geologic Considerations and the Implications for Waterflooding near WIPP

Lori J. Dotson, Sandia National Laboratories

Current Petroleum Practices and their Application to WIPP area Development

Daniel M. Stoelzel, Sandia National Laboratories

2.5.1 Combined Synopsis

A Rhodes Yates/Vacuum Field scenario (where injected water migrated to the overlying salt) is highly unlikely at WIPP because of: differences in geology, changes in oil-well completion practices from the 1940's, and improved reservoir management. In addition, new state regulations are in place to reduce the possibility of a petroleum well leaking into the Salado.

The differences in geology between WIPP and the Vacuum and Rhodes Yates Fields is significant. WIPP is located in a fore reef environment where a thick zone of anhydrite and halite (the Castile Formation) exists. Oil production is from the Brushy Canyon Formation at depths greater than 7,000 feet (5,000 feet below the WIPP repository). By contrast, the Castile Formation is missing at both the Vacuum and Rhodes Yates Fields which are located in reef and fore reef environments, respectively. Oil production at the Vacuum Field is from the San Andres and Grayburg Formations at depths of approximately 4,500 feet and oil production at the Rhodes Yates Field is from the Yates and Seven Rivers Formations at depths of approximately 3,000 feet. At the Rhodes Yates Field, for example, there is only a couple hundred feet of vertical separation between the Salado Formation and the waterflood injection zone. In addition, the oil pools near WIPP are characterized by channel sands with thin net pay zones, low permeabilities, high irreducible water saturations and high residual oil saturations. Therefore, large-scale waterflooding near WIPP is unlikely. The estimated life of the pools near WIPP is less than 10 years for primary production and less than 10 years for secondary production.

The petroleum industry has made many advances since the time when the Vacuum and Rhodes Yates fields were first developed. Improvements in drilling, casing, and cementing technology have greatly reduced the occurrences of leaks in oil wells. An industry-wide effort to reduce formation damage and increase production has led to improvements in completion design and advances in stimulation. Open-hole (non-cased) production/injection wells and nitroglycerin treatments are no longer used. Acid stimulation and hydraulic fracturing techniques have improved considerably in the last ten years. Service industry support has made this technology available to both the large and small operator. The availability of inexpensive software has lead to improved reservoir management, including waterflood design.

State regulations require a salt isolation casing string for all wells drilled in the WIPP area. Injection pressures are not allowed to exceed fracture pressures for all injection/disposal wells. Operators obey these regulations because the State has power to levy fines and/or shut wells in, should they become aware of a violation.

In conclusion, geological differences, modern petroleum development practices, and regulatory oversight will greatly reduce the risk of oil wells leaking to the Salado in the WIPP area.

2.5.2 Geologic Considerations and the Implications for Waterflooding near the Waste Isolation Pilot Plant - Presentation by Lori J. Dotson

There are three main points I'd like to make here.

1) The oil pools near WIPP are relatively small scale when compared to the Vacuum Field and the Rhodes Yates Field.

2) Large scale waterfloods are unlikely. It is not a foregone conclusion that all of the fields will be waterflooded or that any of the fields will be waterflooded.

3) Most importantly, there are a lot of geologic differences between the Rhodes-Yates Field, where the Hartman-Bates well was and WIPP. For one thing there is five thousand feet of vertical separation between the producing interval, at WIPP being the Brushy Canyon Formation of the Delaware Mountain Group and the WIPP repository. It is true that there is salt water disposal in the Bell Canyon Formation, but that is still a vertical separation of about 2,500 feet. In contrast, at the Rhodes-Yates field, you are only looking at a vertical separation of a few hundred feet between where Texaco was water injecting and Hartman encountered the blowout. The Vacuum Field is being produced from the San Andres and Grayburg Formations at approximately 4,500 feet. The Rhodes-Yates is being produced from the Yates and Seven Rivers Formation which is located about 3,000 feet below the ground surface. The producing interval of the Brushy Canyon is located about 3,000 feet below the Bell Canyon. The Castile Formation is present at the WIPP Site but is absent in the backreef at the Rhodes Yates Field.

As to the second point, about generally small pools and thin pay zones, at Livingston Ridge and Lost Tank, you heard Ron Broadhead talk about forty foot of net pay. That's where it is economic to produce oil. There are a lot of wells in the Livingston Ridge area where there is only ten to twenty feet perforated

casing. So there are some pretty small pay zones. In contrast, at the Vacuum Field, one block that I looked at had three hundred feet of gross pay. So we're talking not an order of magnitude difference, but close to it. In the Los Medanos and Sand Dunes there are pay zones that range from less than twenty feet up to one hundred forty feet.

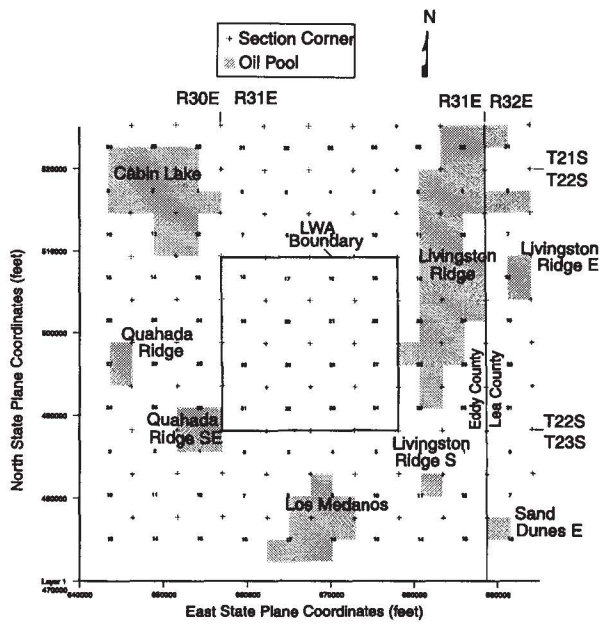

Figure 2.5.2-1. Producing oil field leases surrounding the WIPP.

Another point that Ron made that was really good, the primary production from area around WIPP from the Brushy Canyon is going to be less than ten years and for secondary production, less than ten years of secondary recovery. Production from these fields is going to play out in less than twenty years. Water injection, if water flooding took place, would be less than ten years. Just to give you a reference, the Vacuum Field for instance, over 300 million barrels of oil and 200 BCF of gas have been produced. I will have to get the exact figures from Ron, but we will have to leave that for the discussion. But we are looking at order of magnitudes difference between what is going on at the WIPP area and what we have at some of the larger fields.

This last point, the reservoir characteristics, the 7 to 24 millidarcies is actually a number for the Bell Canyon. The information for Brushy Canyon is actually pretty scarce and the characteristics of the Brushy are such that the permeability

would actually be less. The Brushy Canyon is siltstone and sandstones, but also there is authigenic clays which tend to clog the pores and reduce the permeability somewhat. What this means is that water flooding could occur, but they may have to space the injection wells closer. But then you get into an economic question. There is a technical question and an economics question. It just may not be economical to drill additional wells. The reservoir is also characterized by highly irreducible water saturation and high residual oil saturation. That emphasizes my previous statement. Yes, you can waterflood these fields, you can waterflood those that have better characteristics, but it is an economics issue. If you have to drill additional wells, it may be too costly to get that oil out.

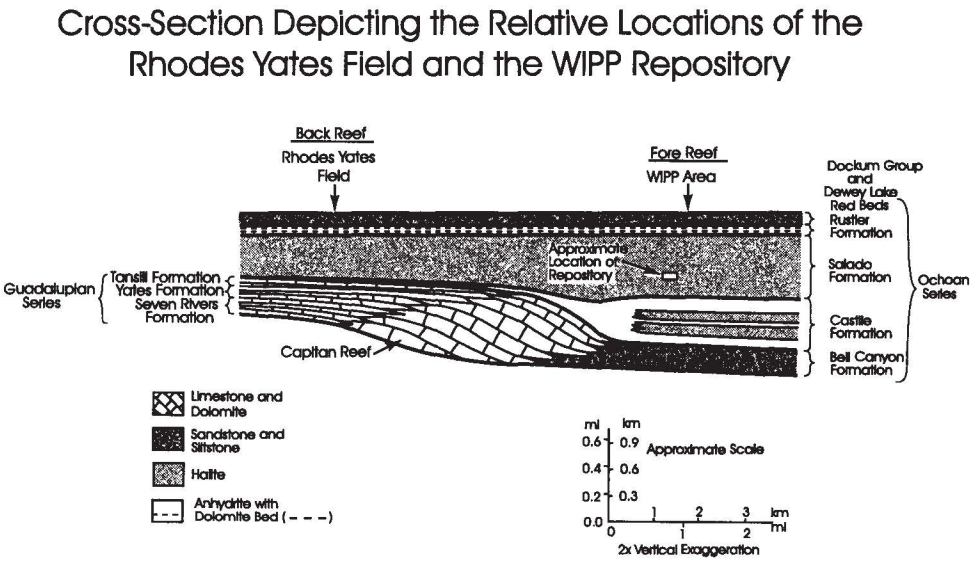

Figure 2.5.2-2. Cross-Section of Rhodes Yates Field and WIPP.

I really wanted to focus on the difference in the vertical separation at WIPP versus Rhodes-Yates which this figure illustrates quite nicely.

At the Vacuum Field, the permeabilities are up to 400 millidarcies. There is an order of magnitude difference. At Vacuum, like I already said, the pay zones are much thicker.

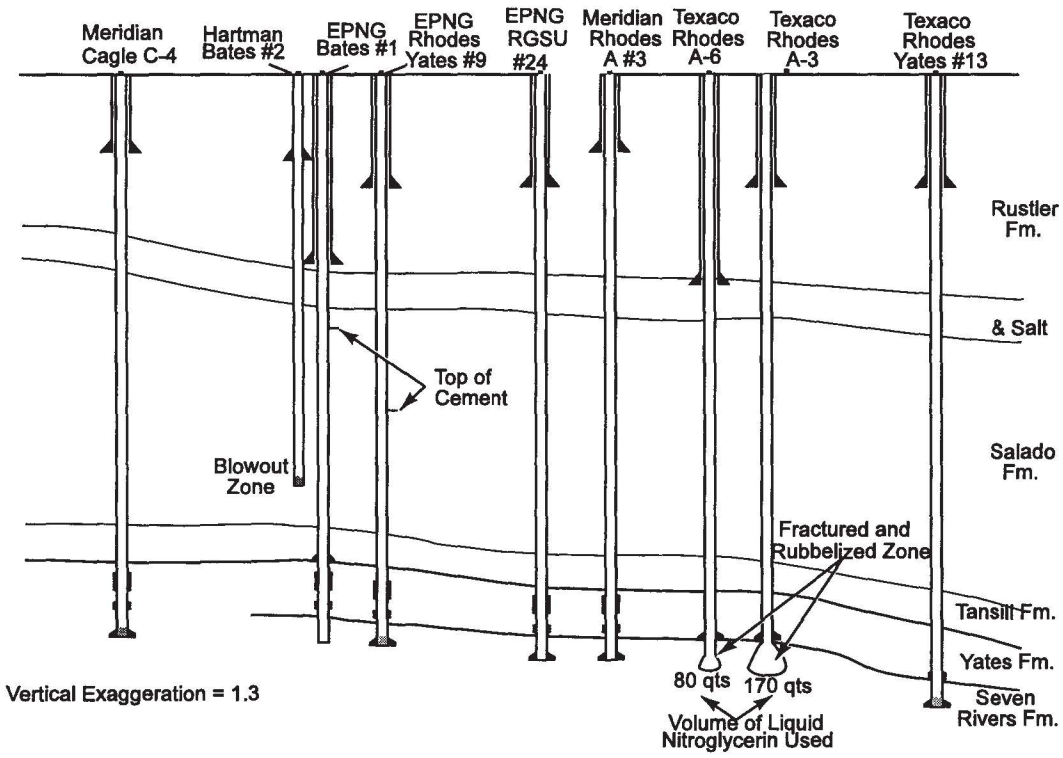

Figure 2.5.2-3. Schematic showing location of Hartman Blowout and Texaco Injection Zones.

This is a schematic showing where the Hartman well blew out and where you have water injection from the Texaco wells. Back in the "old days" a well was made more producible by pouring liquid nitroglycerin down the wells and basically just blow up the formation. So there are rubble and fractured zones. You don't know where your fluid is going at all. Like Dennis Powers stated, I also do not wish to comment on the legal issues of the Hartman-Texaco case. There were clearly practices that occurred back then that are not practiced now. Some of the casing, cementing, and developmental practices will be covered by Dan Stoelzel in his presentation. Between the Hartman blowout zone and the Texaco injection zone, there is hundreds of feet of vertical separation and also the

suspect casing and cementing jobs. The figure shows where the surface casings are set. It is unclear from this figure what they are actually casing off. Some of these don't look like they extend down to the Culebra. There are really strange well constructions there.

Three main points:

1) Potential waterfloods near WIPP would be relatively small scale. I'm not saying that they would or would not waterflood, but it would be small scale if they occurred.

2) The fields will play out in less than twenty years. I think we are all in agreement on that.

3) The interval where they would inject water for a waterflood is 5000 feet beneath the WIPP repository. So you have quite a distance it would have to travel vertically to affect the repository.

2.5.2.1 Questions:

Wendell Weart: When were the injection wells completed - in what time frame?

Lori Dotson: This is something that Dan (Stoelzel) has more information on. In the Vacuum and Rhodes-Yates fields, for example, we are looking at the 30s and 40s and I think some of them in the 50s. But they are older wells, older construction. I hate to keep pushing everything off to Dan, but he has some really nice schematics that show the differences in well construction from the 30s and 40s to the present time. You are looking at wells that are over forty years old.

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2.5.3 Current Petroleum Practices and Their Application to WIPP Area Development - Presentation by Dan Stoelzel

With the older well completion techniques, especially in the Rhodes-Yates Field and Vacuum Field, there has been communication behind pipe caused by situations such as bad cement jobs. In these fields the injection wells were in communication with the overlying strata. In the Vacuum Field, for example, there was concern that some oil field injection wells would contaminate the Ogallala fresh water aquifer. The problems with the Rhodes-Yates waterflood were covered in previous presentations.

The possibility of water injection wells endangering the WIPP is highly unlikely. Neither a Rhodes-Yates nor a Vacuum field scenario will happen at WIPP because of the differences in geology, changes in oil well completion practices from the 1940's, and improved reservoir management. Current industry practices and controls that are in place reduce the risk of injection or disposal wells endangering the WIPP site. There have been changes in the petroleum practices from the 1930s and 1940s and 1950s, even up through the 1970s, versus today. New regulations, mainly statutory regulations, have come into effect. The presentation is divided into the major areas of drilling technology, production and completion technology, and reservoir management. The last 10 or 20 years have seen numerous advances in these areas.

2.5.3.1 Drilling Technology

Since the 1940s and 1950s, there have been considerable improvements in the cement that is used to cement the casing - higher bond strengths, better cement properties, and impermeable cements. Drilling mud technology has improved to limit pole washouts and lost circulation problems. This is especially true when drilling in familiar geology. Lost circulation control becomes a fairly exact science. This is important in the casing stage of a well. If there are lost

circulation problems and washout problems, this could lead to communication or leaks behind pipe. Prudent operators know that any kind of leak behind a pipe is detrimental because it could lead to a loss of production, loss of reserves, and loss of revenue. Compared to drilling operations of the 1970's and early 1980's, drillers have a better understanding of operations such as block control and controlling kicks.

There have been numerous improvements in the last 10 to 20 years in corrosion control. Casing and tubing strings are inspected on the surface prior to running in the ground to eliminate potential leaks before running the casing. There are corrosion inhibitors that are routinely pumped into the tubing and casing to limit corrosion problems. Casing strings are routinely pressure checked. State regulations also mandate pressure testing of the casing. There is a lot of research and development in all these areas.

One point that hasn't been brought out yet is that most of the players in the Delaware Basin area, especially around WIPP, are small time operators. The smaller companies generally don't have the big research and development to support their oil and gas development. However, much research is transferred to the smaller companies through the service industry.

There have been significant advances in directional drilling and horizonal drilling in the last 30 years, but especially in the last 10 years. The costs for directional drilling have come way down. This is important for potential WIPP development because it is feasible to tap into much of the possible and probable reserves by directionally drilling from a surface location outside the land withdrawal area.

2.5.3.2 Completions

Once a well has been drilled and cased, substantial technology is used to develop the pay interval. There have been considerable improvements in perforating technology, tubing packers, gravel packing, well stimulation, fracturing, and acid

stimulation. Open hole completions are rarely used in the industry and are definitely no longer used in the WIPP area. Generally, the production interval is cased and perforated. There have been advances in shape charge perforators, stimulation, and in hydraulic fracing technology, especially in the area of predictive modeling over the last ten years.

There have been substantial developments in fracture height control. Generally, oil companies do not want to hydraulically fracture out of their producing zones. To fracture out of zone could translate to loss of reserves. Operators definitely do not want to exceed fracture pressure in an injection well. The whole purpose for a waterflooding injector is to maintain pressure or inject into a producing horizon. If the operators are injecting out of zone, they are losing reserves.

Acid stimulation has come a long way. Acid stimulation is designed to specific rock types and fluid types.

2.5.3.3 Production

There have been numerous advances in wireline, coiled tubing workovers, and through tubing workovers that greatly reduce cost and could extend the economic lives of wells.

The preferred method of lift in the WIPP area is the sucker rod pump. However, there are alternatives such as gas lift, submersible pump, or plunger lift. Each of these have seen a lot of development in the last 10 to 20 years.

Routinely, coated tubulars are run, especially in injection wells because injection wells are recognized as a highly corrosive environment. Multiple completions are possible. By running dual completion strings, two or more zones can be simultaneously produced. Behind pipe reserves are typically recovered by successively plugging back as the operator comes up the hole.

Leaks are not good. If an operator is aware of a leak, he will generally take remedial action to fix that leak. The state is the regulatory agency that requires frequent pressure checking of tubing and casing. If a leak is detected, the operator must repair the leak.

2.5.3.4 Reservoir Management

One improvement in reservoir management includes the advent of affordable personal computers (PCs) and the availability of inexpensive software. During the last five years there have been significant advances in relatively inexpensive software to run on PCs. Whereas, the small company of the past didn't have the manpower or the money to afford this type of luxury item, now it's fairly routine. Various research firms and universities provide software support. Availability of the software has especially assisted the small time operators to optimize field development and field production.

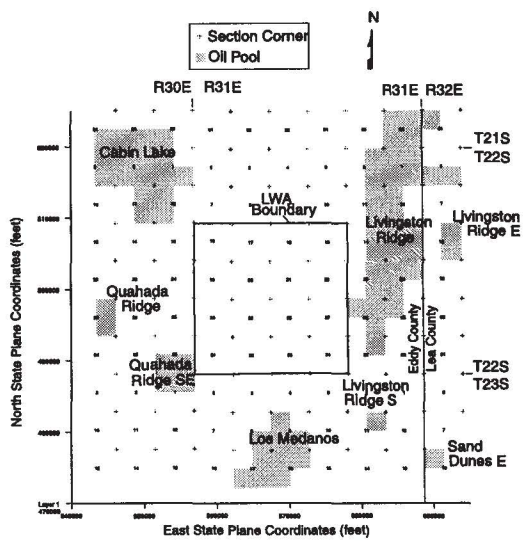

Figure 2.5.3-1. Producing petroleum leases adjacent to the WIPP Site.

The five spot water flood pattern is being used at Rhodes-Yates Field and at the Vacuum Field. However in the WIPP area it is highly unlikely that a five spot pattern would be used, especially with small pools. The decision to convert a well to water injection, in most cases will be more determined from the reservoir geology and geometry. For example, the Livingston Ridge Lost Tank Field is a channel sand. An in-line injection flooding pattern would be more likely. In this case, injectors

would be located in the southern part of the field and drive oil updip to the producers to the north. For these small pools a five spot water flood pattern would be highly unlikely both economically and geologically.

Source water compatibility between the formation rock and the injected fluids is very important. This is relevant to the WIPP area because there has been some speculation that a future driller may decide to use, for example, Culebra fluid as source water for an injection project. This is highly unlikely. The oil bearing formations contain authigenic or interstitial clays. If less saline water was injected into such a formation, it would cause clay swelling and potential plugging of pore spaces. Injecting Culebra water would essentially ruin the well. At this time, none of the injection wells or disposal wells are using the Culebra for source water. And I expect that will be the same forever. Operators will typically find their source water from the same formation as their oil production.

In addition to source availability, economics is the big question. Can small operators afford the surface facilities and the additional costs to drill injection wells or convert producers into injectors? The small oil companies typically have fairly shallow pockets. A water flood requires substantial capital. The return on the investment will be several years down the road in the producing life of the field. Most small companies wouldn't be able to weather that economic return.

The amount of water being pumped into a pool is a direct function of your recoverable reserves. In the WIPP area, the oil is found in small pools. The operators are not going to be injecting large volumes of water, especially in view of the 10-20 year life that most of these pools will last through secondary recovery. In an injection project, operators will stay below the fracture pressure of a formation. Operators don't want to fracture out of zone and pump water into an unknown formation where it is not beneficial to their productive horizon.

2.5.3.5 Wells in the Vicinity of WIPP

The James E #12 well is operated by Phillips and produces from the Cabin Lake Pool. In 1988, the State of New Mexico published regulations on completing oil and gas wells in the potash area, which includes the WIPP area. There was concern about natural gas potentially leaking into potash mines. In the Vacuum Field, the State had seen communication potentially into both the Salado and the Ogallala. The state now requires all the oil and gas operators in the potash area to include a salt isolation casing string in their well design. The surface casing typically runs through the upper stratigraphic units such as the Dewey Lake Redbeds and the Culebra. The intermediate casing, which is required by the state, is cased off below the salt formations, the Salado and the Castile. The state also requires that production casing run to the surface.

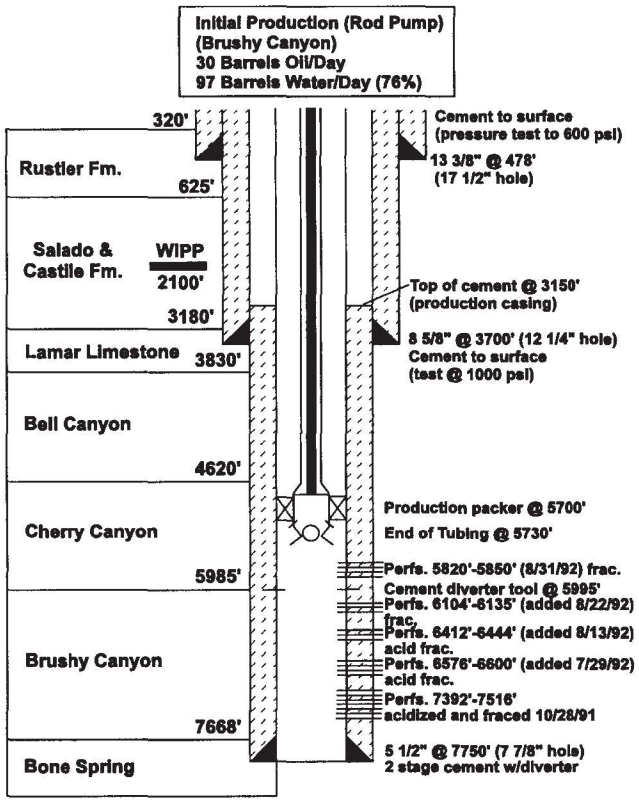

Figure 2.5.3-2. Typical Cabin Lake Pool Completion (James E#12).

The James Ranch Unit #19 well is operated by Enron and produces from the Quahada Ridge Delaware pool. The top of the cement surrounding the 5 1/2 inch production casing is at 2,680 feet. The bottom of the 8 5/8" salt isolation casing is at 3,850 feet. There is about 1,200 feet of cement as well as two sets of casing strings to help isolate the salt. The James Ranch Unit #19 is one of the better producing wells. The initial oil production rate was 213 barrels per day. The initial water production rate was 240 barrels of water per day. Initial production was over 50% water. We also see high water production from the Livingston Ridge. Seventy-six percent of the fluid production was water. These fields have a high water content and produce large volumes of the moveable water.

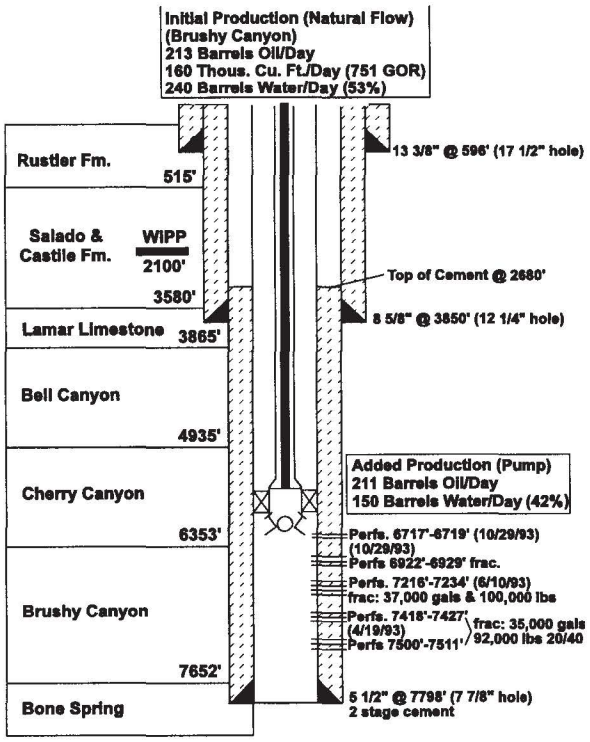

Figure 2.5.3-3. Typical Quahada Ridge Delaware Pool. James Ranch Unit #19.

A typical Livingston Ridge completion and a Morrow gas producer completion are shown. Each schematic shows a salt isolation string. For illustration purposes the WIPP horizon is also shown. The vertical separation between their production perforations and the WIPP horizon is on the order of 5,000 feet or more, which is much greater than that of the Vacuum Field and the Rhodes-Yates Field.

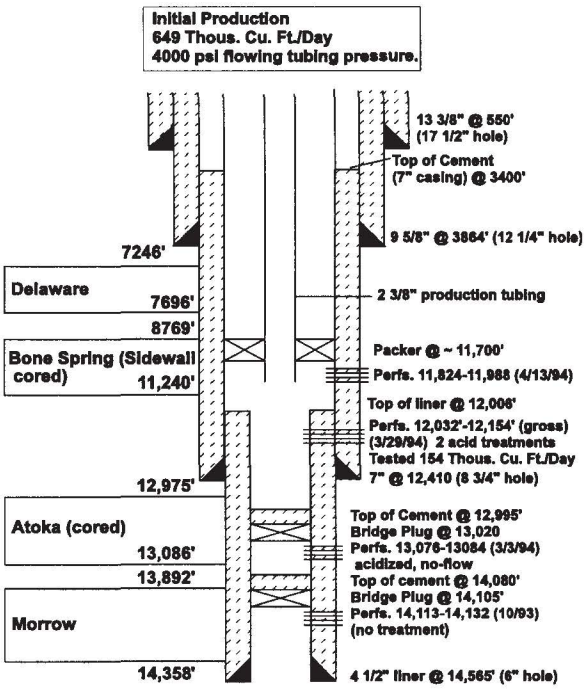

Figure 2.5.3-4. Typical Los Medaños Morrow Pool Apache 25 Federal #2.

The Morrow schematic illustrates the success of the plugback technique used by most operators. Probably the only reason this well is economical is because it has multiple pays. This well was originally perforated in the Morrow gas. It came in at a very high rate for this area, over 600,000 cubic feet a day. It was originally completed in the Morrow Formation in October 1993. By March 1994 this interval had been plugged back and the well completed in the Atoka Formation. In less than a year, this Morrow pay had depleted. The lower Atoka was tested but didn't have sufficient flow rate. The lower Atoka was plugged back and the well was completed in the upper Atoka. The well is apparently producing from the upper Atoka, although this formation may also be plugged back. The information comes from the New Mexico Oil Conservation Division in Santa Fe. There is a six month to one year time delay on the Sundry Reports, so the information on these wells may be outdated.

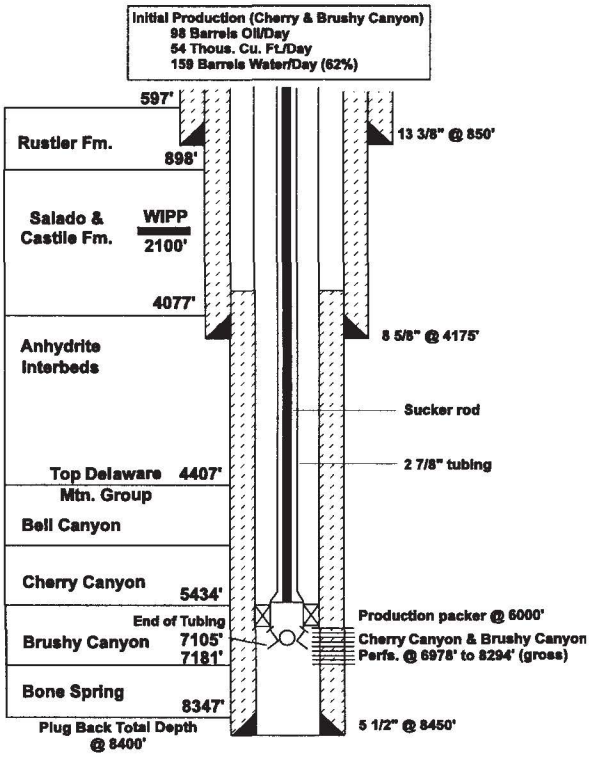

Figure 2.5.3-5. Typical Livingston Ridge/Lost Tank Completion.

2.5.3.6 Early Well Completion Practices

For comparative purposes, the schematics of the Vacuum Field and Rhodes-Yates Field completion are shown here. I didn't have direct well data for these wells. In the case of the Vacuum Field, the discovery well was drilled in 1929 with a cable tool rig. It wasn't developed until the late 1930s and early 1940s. Common practice, during that time, especially in carbonate formations where there is low flow due to tightness, the operator would nitro-frac the completed well. This is a general schematic of their discovery well. It was nitro-frac with 580 quarts of nitroglycerin. I'm not an explosive expert, but I would think that 580 quarts could do considerable damage not only to the formation but to everything else down there.

In the 1930s and 1940s the oil and gas industry was in its infancy. Safety issues, reservoir management issues, and formation damage issues were pretty much nonexistent. Since then, there have been substantial improvements. Similar to the Vacuum Field, the Rhodes-Yates fields were also nitro-fraced. An important thing to note about the typical Rhodes-Yates early completion is the small amount of separation from their open hole productive horizon from here to the Salado, approximately 100 to 200 feet. Furthermore, the wells were nitro-fraced.

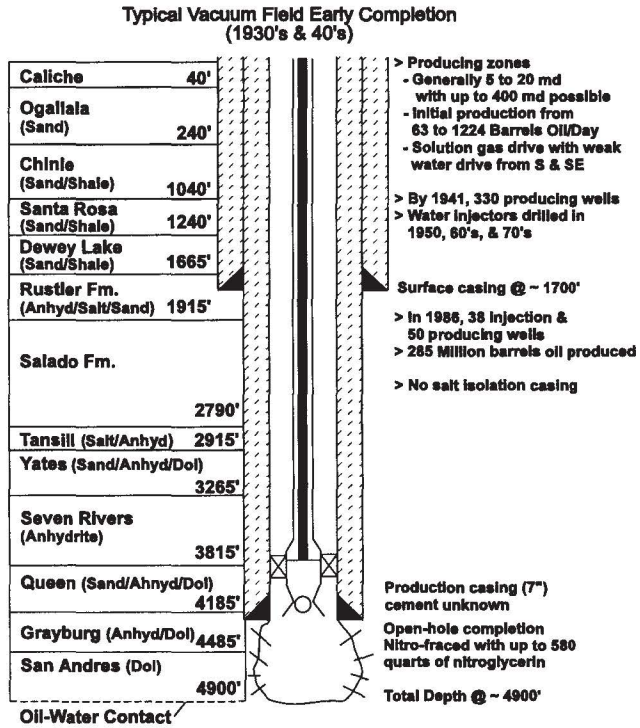

Figure 2.5.3-6. Typical Vacuum Field Completion for 1930s and 1940s.

Originally these early wells were drilled as producers in the 1940s, 1950s, and 1960s. As many of these production wells watered-out, they were reconverted to injection wells. They just pulled sucker rod pumps out and maybe changed out the tubing string. They didn't take any remedial action as far as casing this open hole interval or cement squeezing behind the body to isolate. They just turned it right around and started injecting into this thing. So it is no wonder that there is considerable potential for injection fluid to go anywhere other than where they want it to go. It is going to the path of least resistance.

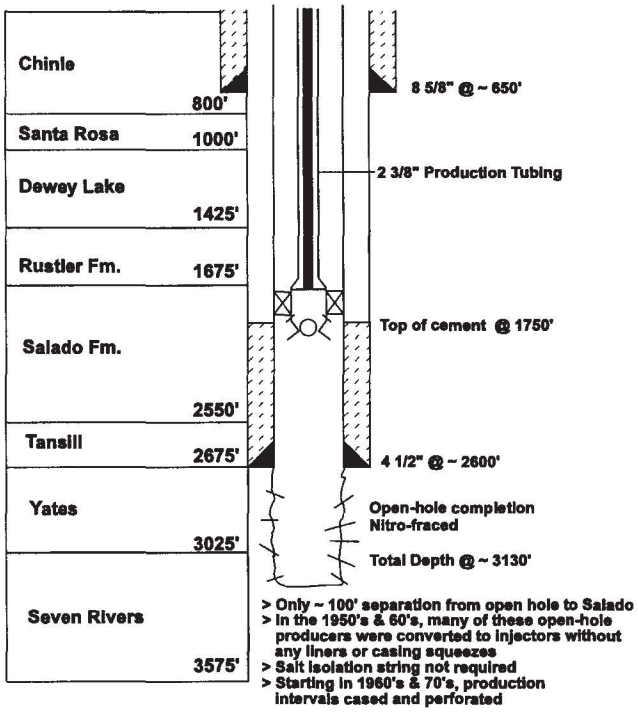

Figure 2.5.3-7. Typical Rhodes Yates-Seven Rivers early completion, 1940s-1950s.

The state rule on the salt isolation casing didn't come into effect until the late 1980s. Both these fields, the Vacuum Field and the Rhodes Yates Field, did not have salt isolation casing. As shown, the Salado is just behind one casing string. Early cementing and completion practices were such that, who knows where the cement went when they pumped it. A lot has improved since the days of these wells.

An older well, Todd 26 Federal #3, is shown. Todd 26 Federal #3 is the suspect well, about one and a half to two miles offset from the H9 WIPP test pad. It was here that Rick Beauheim observed the water table fluctuations. The rises in the Culebra due to potential leaking was attributed to this well. After looking at this schematic, I tend to agree with that. This well was completed in 1971. Originally it was drilled as a Cherry Canyon test well that was probably nonproductive. The well was converted to a disposal well. There was no salt isolation casing and it was an open hole completion somewhat similar to the Rhodes/Yates Field or Vacuum Field situation. This well was a disposal well for about 20 years. It is now plugged and abandoned. I am not sure when that was. I am trying to find out from the New Mexico Oil Conservation Division (NMOCD). There are very few records on this well. However, it is no longer disposing salt water.

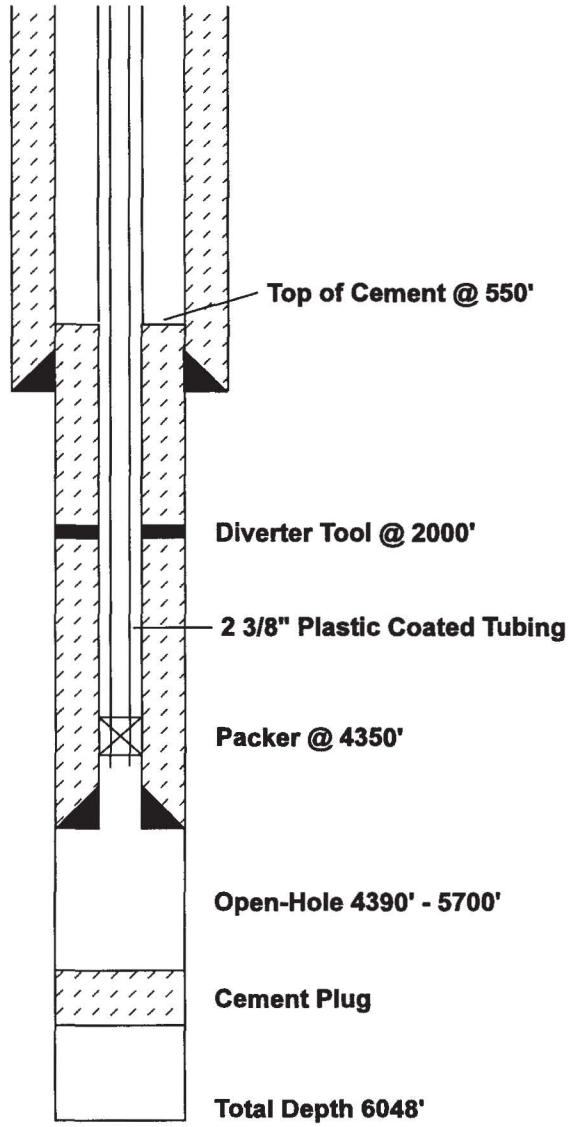

Figure 2.5.3-8. Texas American Oil Corporation Todd 26 Federal No. 3 Water Disposal Well.

A current salt water disposal design planned for the Livingston Ridge Field is shown. The plan shows the salt isolation casing. The production casing is run through the interval and perforated. The well was originally a strong producer. It is not uncommon to convert watered-out or nonproductive production wells to disposal or injection wells, which is the case for this well. The Sundry intent was filed on September 24, 1992. Surface injection pressure for this well is limited to 750 psi which is below fracture pressure. New state regulations require that operators stay below fracture pressures, either below 0.2 psi per foot above the hydrostatic gradient or below the fracture pressure as determined from injectivity tests.

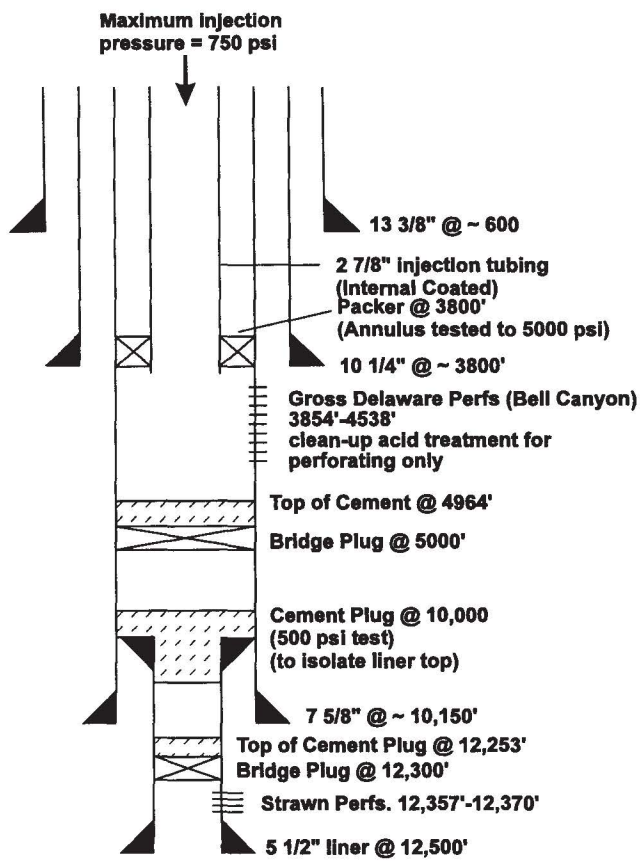

Figure 2.5.3-9. Current Salt Water Disposal Well Livingston Ridge Federal #9. Intent filed September 24, 1992.

2.5.3.7 Questions:

Robert Neill: Dan, you give a very compelling case for some of the current drilling practices and plugging practices. It is a great improvement over what has been done in the past. On the EPA standards, one is talking about what will be the behavior for human intrusion over long time periods. How comfortable do you feel with commitments requiring operators to keep injection pressures less

than fracturing pressures and then going to EPA and arguing that this will continue to be true in the long term future.

Dan Stoelzel: I think it highly likely. Like anything the oil business does, it is driven by economics. Nobody can predict the price of oil in the future which is the governing driver for anything an oil operator does. These regulations are put into effect because of the experiences of the oil companies — the isolation string and the requirement not to exceed fracture pressure. That is not only a regulation but like I said, a common practice with the operators because it is not a good thing to exceed fracture pressure in injection wells. I think it is highly likely that if anything, more constraints and regulations will come into effect or if nothing else, it will remain the same. The industries evolved to this point and because of this we are getting a lot more reserves out of the ground than we did back in the 40s and 50s. You know it is a learning process and I think the oil industry is reaching the top of that curve. They have come a long way.

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2.6 Potential Effects of Oil and Gas Activities on the Salado and Overlying Formations

Matthew Silva

2.6.1 Synopsis

The EPA assurance requirements for the disposal of transuranic waste include the requirement that the site should avoid places where there has been mining for resources, where there is a reasonable expectation of exploration for scarce or easily accessible resources, and where there is a significant concentration of any material that is not widely available from other sources. The WIPP is sited in an area with a 64-year history of commercial mining in a potash enclave which represents 57% of the nation's potash reserves and 80% of the nation's domestic production. Further, there are substantial reserves of oil and gas in the vicinity of the repository.

It has long been recognized that oil fields in southeast New Mexico, overlain by the Salado Formation, have problems with waterfloods. For waterflood projects in Lea County, Ramey (1976) noted that water injected at around 3,600 feet was escaping from the injection interval, migrating upward to the base of the salt section and then moving horizontally through this section. Waterflows of 5,000 to 6,000 barrels per day and a recorded surface pressure of 1,600 pounds on wells outside waterflood areas were not uncommon. Later studies (Bailey 1990) found that in the Vacuum Field, water was indeed flowing along distinct horizons within the Salado. Chemical and isotopic analyses confirmed that the brines were not natural to the Salado. Casing leaks were thought to be the most logical pathway into the Salado. Casing leaks and cement degradation are not uncommon in the highly saline environment (LaVenue 1991).

In the vicinity of WIPP, there are oil and gas resources. Much of the drilling for oil and gas has been delayed by the presence of potash. Nonetheless, there has been drilling for oil and gas in areas known to contain less than economic

quantities of potash. There is no question that waterflooding in the immediate vicinity of WIPP needs to be anticipated. First, the oil reservoirs in the area produce by solution gas drive (Broadhead and Speer 1993). Reservoirs which produce by solution gas drive are usually good candidates for waterflooding (Willhite 1986). Second, there is a waterflood underway in the Cabin Lake Field at the northwest corner of the WIPP Site. A nearby oil well, James A No. 2, has shown a good response with oil production increasing from less that 2,000 barrels per month to more than 4,000 barrels per month for that particular well. Third, there are eight waterfloods underway in the New Mexico portion of the Delaware Basin (Broadhead et al. 1995) and there is a history of waterflooding and enhanced oil recovery in the Texas portion of the Delaware Basin.

2.6.2 Presentation by Matthew Silva

The assurance requirements in the EPA Standards for the disposal of transuranic waste state that one should avoid areas with natural resources. The WIPP is not independent of the potash industry and the oil and gas industry, their schedules for resource recovery, and the problems associated with these industries. In the oil fields overlain by the Salado Formation, where we have experience with waterflooding, there is evidence of water escaping from the injection areas and migrating through the Salado. The Delaware Mountain Group, in the vicinity of the WIPP, is a strong candidate for future waterflooding.

The EPA standards for the disposal of transuranic wastes have assurance requirements. These assurance requirements are intended to accommodate the inherent uncertainty in calculating repository performance over the next 10,000 years. With respect to natural resources, the assurance requirements state that a site should avoid places where there has been mining for resources, where there is a reasonable expectation of exploration for scarce or easily accessible resources, where there is a significant concentration of any material that is not widely available from other sources.

The Known Potash Lease Area, as shown in Figure 2.6-1, is contained in an area roughly 30 miles by 30 miles. The 4 mile by 4 mile WIPP is located within the potash enclave. The first mining and second mining areas are shown. Potash has been commercially mined for 64 years - an area with a long history of mining. Potash in this area represents 57% of the nation's reserves and has consistently represented over 80% of the nation's domestic potash production - a relatively scarce resource. Oil and gas reserves are also found in this area - an easily accessible resource.

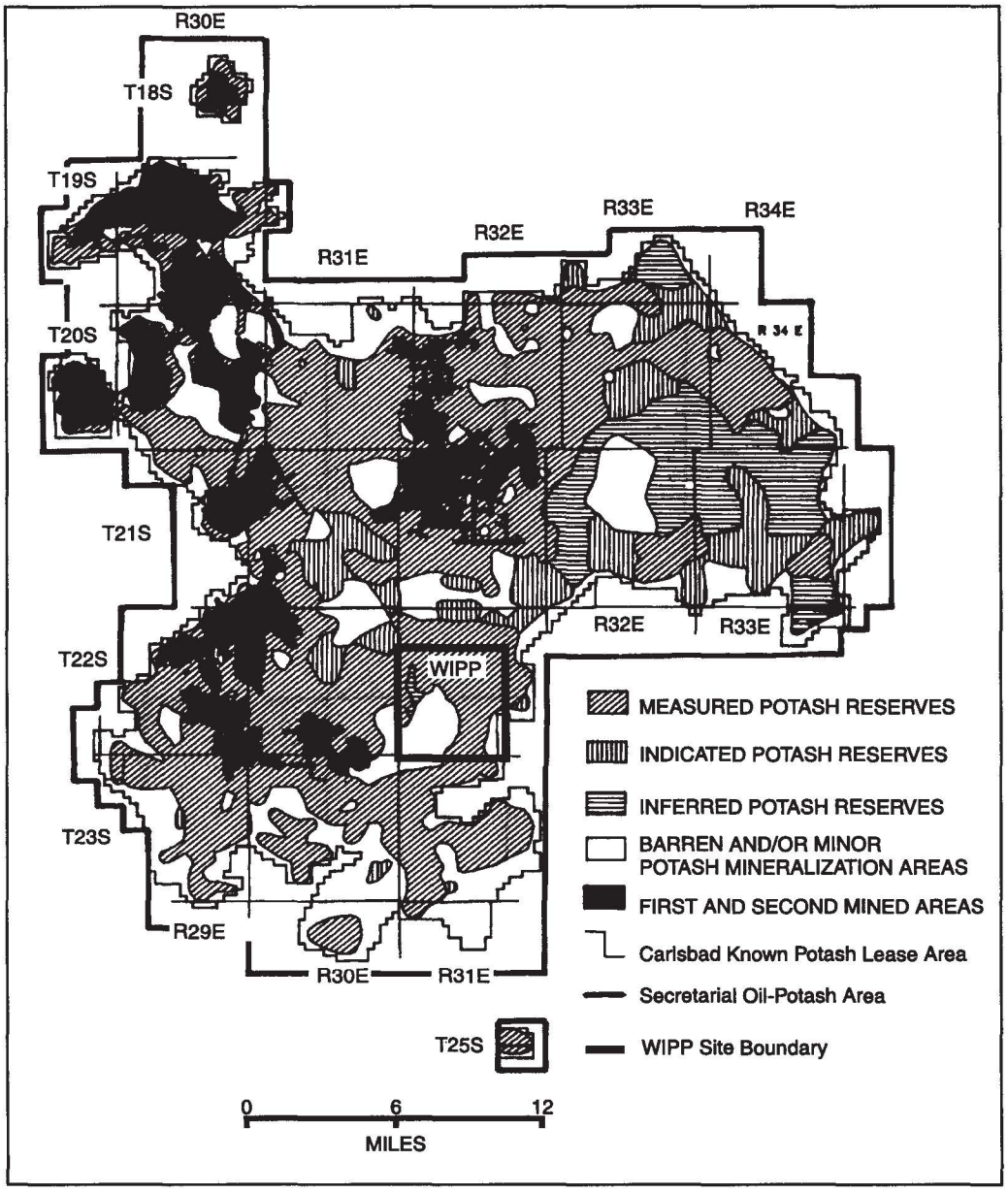

Figure 2.6-1. Potash resources (adapted from Olsen 1993).

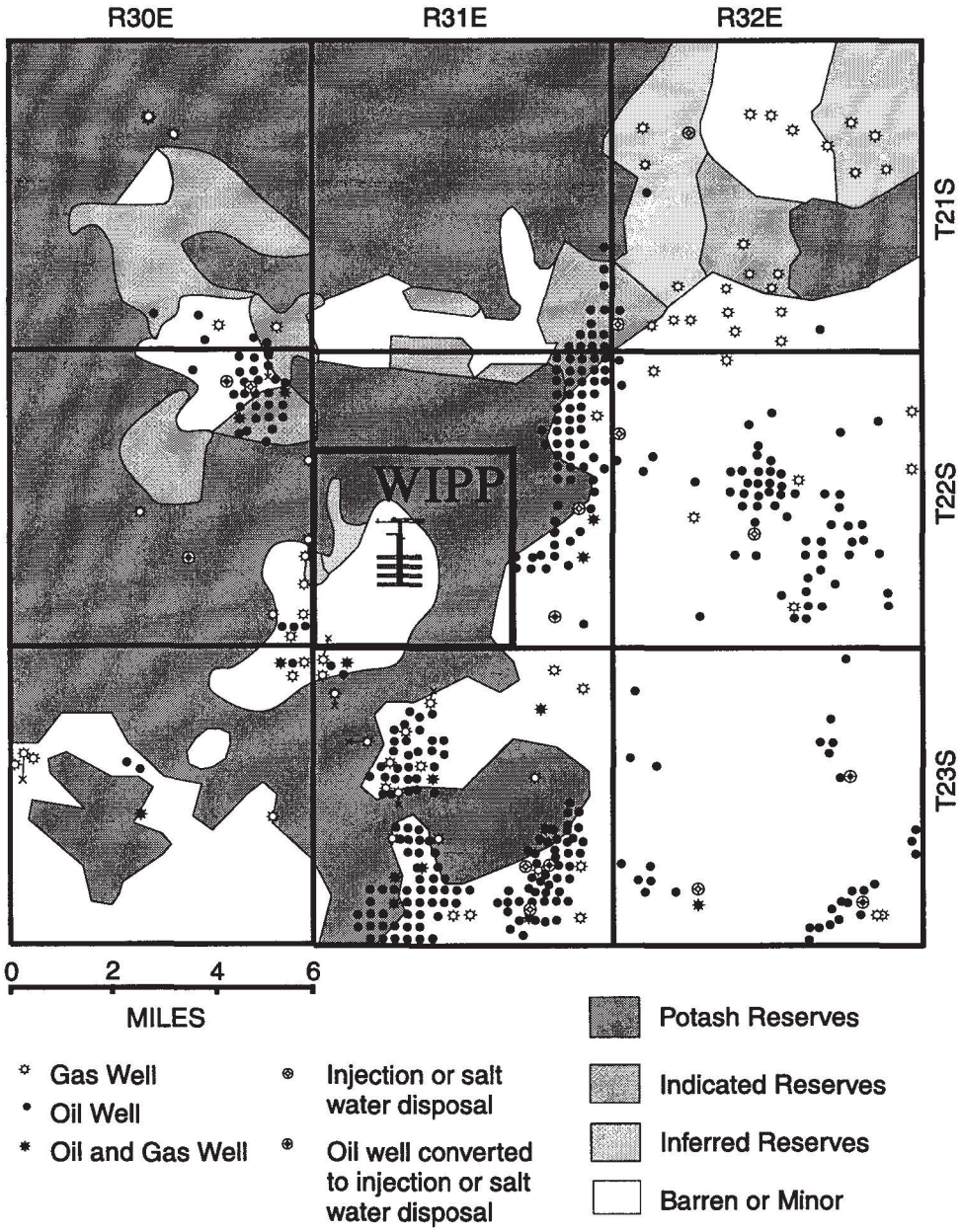

Figure 2.6-2. Oil and gas wells restricted from drilling through potash resources.

For the nine township area surrounding the WIPP, it is important to note that the current areal extent of the oil fields is constrained by the boundary of potash reserves and not the geographic limits of oil and gas.

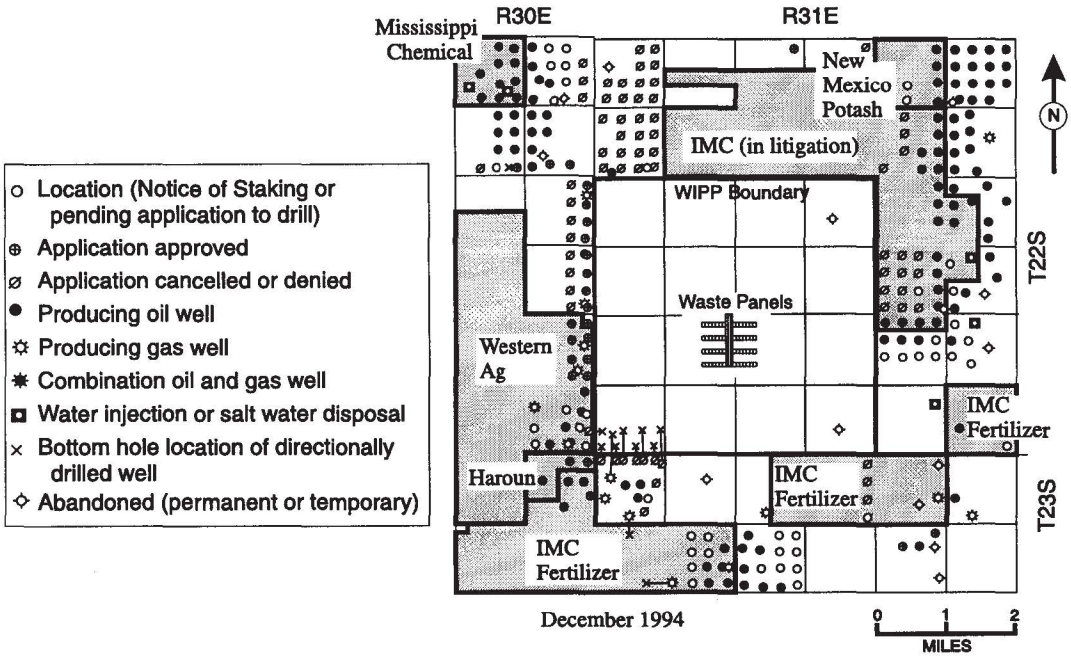

Figure 2.6-3. Resource activity and interest in the immediate vicinity of WIPP.

Will there be any more drilling near the WIPP boundary or is it restricted by the presence of potash reserves? Producing oil and gas wells and applications for permit to drill (APDs) within 2 miles of WIPP are shown in Figure 2.6-3. Applications include those that are pending, that have been cancelled, or that have been approved. Also shown are the active potash leases in the area. Oil and gas resource activities are restricted by the presence of potash. Further, it could be decades before drilling for oil and gas is allowed. Again, the limited number of existing oil and gas wells does not reflect the size of the oil fields, rather it reflects the presence of potash in an active potash leasing area.

Towards the southwest corner of the WIPP Site, the BLM has recently denied applications to slant drill eight wells to be completed within the WIPP Land Withdrawal Area. These applications have been denied for a couple of reasons, including the concerns about the injection of water.

A 1994 map from Midland Map Company indicates that Todd Federal #3 has been

plugged and abandoned. Also Rick Beauheim showed evidence this morning of rising water levels in H-9 up until 1993. The water levels started to decline and are now rising again. Somewhere about that time this well was apparently shut in.

The oil wells producing from the Delaware Mountain Group are very large water producers. That reflects interstitial water, not a large edge water drive. There are a number of salt water disposal wells throughout the area already in operation. The David Ross AIT Federal #1 is an oil well that was converted to a salt water disposal well. It's within a mile of the WIPP site boundary. It injects from 40,000 barrels to 120,000 barrels a month as salt water disposal. Other than state regulations, there are no extra requirements on this particular well.

To the west of the WIPP there is an injection well in the potash area less than a mile from the mining operation of Western Ag. In 1994, when Western Ag learned that this particular well was being proposed as a salt water disposal well for Bass Enterprises, Western Ag proposed 12 stipulations. The stipulations included an annual analysis of the chemical composition of the water and the hydrocarbons and of any hydrosulfide that was being injected into that well. The stipulations also specified maximum injection pressures. Further, Western Ag wished to be notified immediately of any problems with tubing failure. While the David Ross AIT Federal #1 is within a mile of the WIPP site, there are no special provisions for this well. Yet for the well within a mile of potash operations, Western Ag was concerned with water being injected out of zone.

New Mexico has extensive experience with waterfloods in areas overlain by the Salado Formation. Serious problems have been documented for the past 20 years. In 1976, Joe Ramey, as the Director of the New Mexico Oil Conservation Division, identified the problem of "numerous salt water flows in and around waterfloods in Lea County." Basically the water was escaping out of the injection zone, up into the Salado Formation and then moving through the salt section, collapsing oil field well casings. Five thousand to six thousand barrels of water

a day at 1,600 pounds per square inch pressure at the surface were not uncommon.

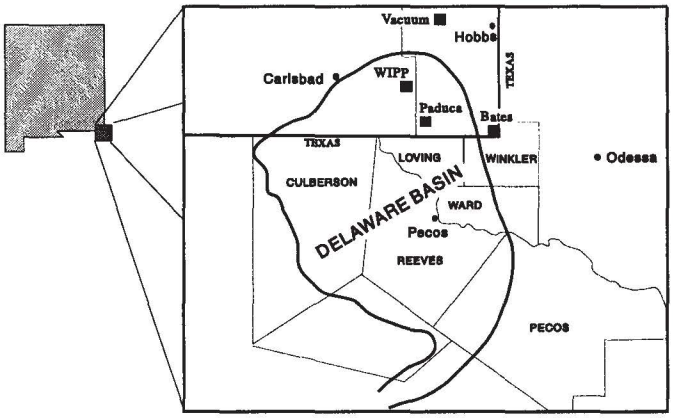

Figure 2.6-4. Delaware Basin.

In 1990, Jamie Bailey, a certified professional geologist and petroleum engineer for the New Mexico State Land Office, sent a memo to Marsh LaVenue on the observed water level rises in the Culebra aquifer during the 1988-1989 time frame. That memo cited the problems in the Vacuum Field waterfloods and the reports prepared by a committee of participating oil companies. The memo noted that waterflows occurred along 48 distinct horizons or interbeds within the Salado. Chemical and isotopic analysis confirmed that the brines were not natural to the Salado and these were injected brines. The memo concluded that failed casing was the most logical pathway into the Salado and observed that there were similar problems in other waterflood areas including the Eunice and Monument areas. Bailey identified a salt water disposal well, the Todd 26 Federal #3, as the most likely source of water to the Culebra aquifer based on the injection pressure history, the age of the particular well, and the location of the well.

There is more recent evidence of problems with waterflooding in New Mexico. The operator of the Bates Lease, Hartman, successfully demonstrated in court that water from the Rhodes/Yates Lease was being injected at high pressures and was migrating more than two miles to his lease. The Bates #1 was drilled in 1953. It was operated until 1988, at which time it was shut in. When it was drilled in 1953, there were no observed waterflows. The Bates #2 was drilled about one hundred feet to the east in January 1991. It experienced a very large salt water blowout. Two-hundred-ninety-eight truckloads of water had to be hauled away

and a pipeline was constructed to the water injection unit at the Leonard Field.

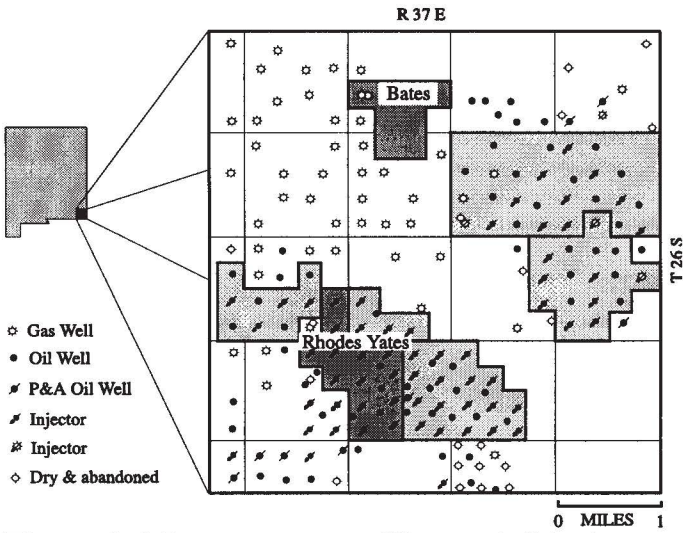

Figure 2.6-5. Bates Lease (Hartman), Rhodes Yates Waterflood (Texaco) and other nearby leases with injection wells.

Hartman argued that the Rhodes/Yates lease was the only water flood with an injection pressure gradient high enough to see the type of water pressure that was seen at the Bates Lease blowout. Hartman also argued that the waters were being injected higher than the rock fracture pressure of the interbeds of the Salado formation.

Are these wells in the area near WIPP waterflood candidates? The major Delaware Mountain Groups produce by solution gas drive (Broadhead and Speer 1993, 299). Solution-gas-drive reservoirs usually are good candidates for waterflooding (Willhite 1986, 3).

Adjacent to the WIPP Site Boundary, the No. 2 James A well responded favorably to waterflooding. This well is operated by Phillips, a major oil company, not a small operator. Initially, this well produced 4,000 barrels per month. As shown, production declined to

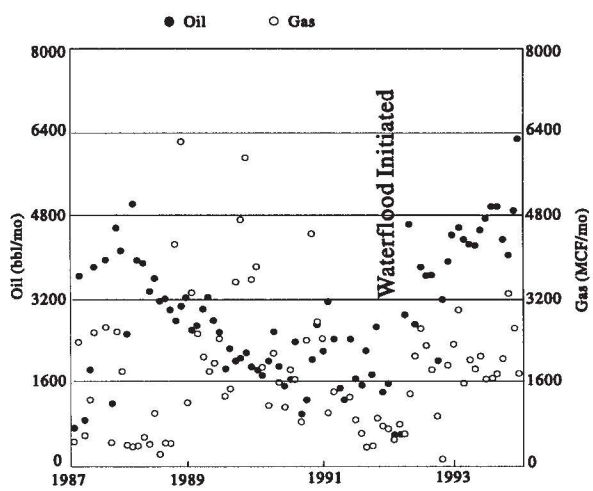

Figure 2.6-6. Response of No. 2 James A to waterflood.

less that 2,000 per month. The pressure maintenance waterflood was initiated with the conversion of one nearby well to waterflooding and later a second injection well. There was an immediate response, even to the one injector well. The oil production rate for the James #2A again exceeded 4,000 barrels per month.

Further, as noted by Broadhead, there are examples of successful waterfloods in the Delaware Basin. For example, the Paduca field which produces from the Delaware Mountain Group responded well to waterflooding as shown. A waterflood was initiated in 1968. Thus far primary production accounts for 8.6 million barrels cumulative production and waterflooding has produced an additional 5.2 million barrels. It is also worth noting that this Delaware Basin field has been in production for over 30 years and is still in production.

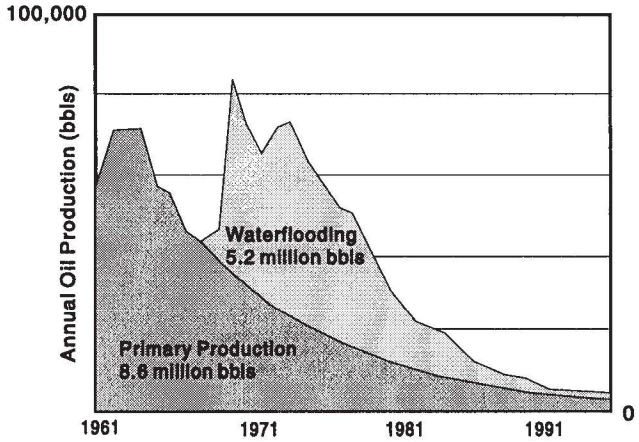

Figure 2.6-7. Paduca Oil Field Production.

2.6.2.1 Conclusions

The WIPP is sited in a mineral rich area and will be subject to the practices of the oil and gas industry and the potash industry. Drilling for oil and gas has been delayed primarily by the remaining presence of potash reserves. There is a history of waterflooding to improve oil recovery from producing fields throughout the Delaware Basin. There is also experience with water migrating out of the injection zone and into adjacent properties in the oil fields of southeast New Mexico. Near WIPP, there are a few new injection wells for the purposes of salt water disposal and waterflooding.

2.6.2.2 Questions:

Dan Stoelzel: Did you find any records of blowouts or casing collapse problems in offset producers. Did you see any of these type of incidences in your research?

Matthew Silva: I did not look in detail at the wells down there.

Dan Stoelzel: That is one thing I planned on doing. I just ran out of time. That would be an indicator that these disposal wells are indeed causing problems, you see it in offset wells both in the drilling phase and later in the production phase.

Matthew Silva: Certainly, part of the problem facing the project is that if you want to look at all of those, you have to look at each well on a case by case basis. It is a massive effort to try to understand that.

Wendell Weart: Something that is not directly related here, but I am curious that we now have such a proliferation of holes around the site which we did not have back around the late 70s and early 80s. Is there any information from those about encounters with brine reservoirs in the Castile?

Matthew Silva: Yes, we do have some information. About 2 years ago I did request from the various oil companies information on their water flows all which were in the Castile Formation around the WIPP site. About one third did respond with detailed records and another third did not respond at all. Some declined to provide that information.

Dan Stoelzel: Are you going to come forth with that information at some point?

Matthew Silva: As soon as I have time to put it together, I will.

Robert Neill: We will certainly share the information for the one third that did respond.[1] *****

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[1]That information was sent to Peter Swift on March 20, 1996.

2.7 Geological Features Across the Oil Fields of Southeast New Mexico and West Texas

Lokesh Chaturvedi

2.7.1 Synopsis

The Waste Isolation Pilot Plant (WIPP) is located in the northern part of the Delaware Basin. The Vacuum Field and the Bates Lease/Rhodes-Yates water flooding areas are situated in the shelf (backreef) areas, about 40 km northeast and 65 km southeast of WIPP respectively. Sratigraphically, the backreef equivalent of the oil producing upper Guadalupian Delaware Mountain Group Formations of Cherry Canyon and Bell Canyon, are the Artesia Group Formations of Grayburg, Queen, Seven Rivers, Yates and Tansill. San Andres limestone of the shelf is the stratigraphic equivalent of the lower Cherry Canyon Formation of the Delaware Basin. The Castile Formation is confined to the Delaware Basin only, but the Salado Formation extends more than 160 km beyond the margin of the Basin to the north and east into west Texas. In the southeast corner of New Mexico in the area of Rhodes-Yates waterflooding, the Salado Formation lies unconformably over the Artesia Group. Thus, a well penetrating through the Salado at the WIPP site would go through the Castile anhydrite and halite beds before entering the Bell Canyon Formation of the Delaware Mountain Group. At the Bates lease area, on the other hand, such a well enters the Tansill and the Yates Formations directly below the Salado. The vertical distance from the oil producing zones in the Cherry Canyon Formation surrounding the WIPP to the WIPP repository is approximately 1,200 to 1,800 m. In the backreef area, the distance between the Yates producing zones and the lower Salado is less, approximately 500 m. However, the Salado interbeds extend through the entire Salado from the Basin to the backreef and once pressurized fluids are injected into them, the Salado interbeds are expected to behave essentially the same way.

2.7.2 Presentation by Lokesh Chaturvedi

The point that Lori Dotson was making is that there is a difference in geology between the situation at the Bates lease and the situation at the WIPP Site. As stated in my synopsis, that difference is mainly in vertical distance. At the WIPP Site, it is the vertical distance between the Lower Salado and the Cherry Canyon or Brushy Canyon oil reservoirs. At the Bates lease it is the vertical distance between the gas producing Yates Formation and the level in the Salado of the salt water blowout in the Bates lease #2 borehole.

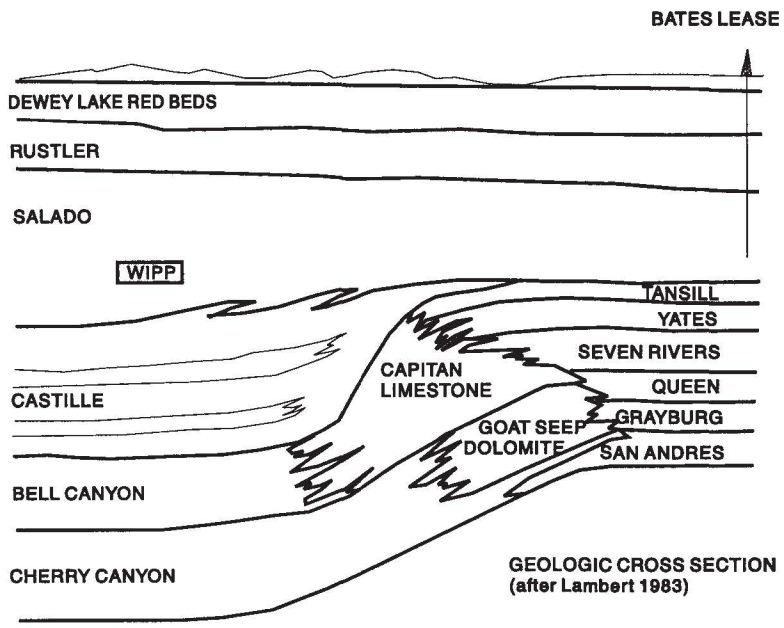

Figure 2.7-1. Geologic cross section at WIPP and Bates Lease (After Lambert 1983).

However, the main point of interest is that the Salado Formation is the formation that remains essentially the same across the reef. The thickness of the Salado decreases somewhat across the reef, but despite the forty mile distance between the WIPP and the Bates lease, the essential characteristics of the Salado, that of the presence of interbeds, remains the same. If the pressures are sufficient and the conditions are appropriate for water to leak out of the casing, water will be

injected into an interbed in the Salado or possibly into the water bearing zones such as the Culebra and Magenta of the Rustler Formation.

There may be a vertical distance but if the pressures are sufficient to cause injection of water into the Salado or Culebra, then it seems to me, that what happened at the Bates lease is quite likely to happen at the WIPP Site. The distance between the Texaco wells and the Bates lease #2 well was about two miles. If we accept, as Dennis Powers described, that there were no likely natural sources of such huge quantities of salt water, then most likely the source of water was the waterflooded area in the Texaco lease. If that is what we believe to be the case, then we know that such an effect can be felt more than two miles away. We know it can be felt two miles away. We don't know if it can be felt more than two miles away. Since the oil wells around the WIPP Site are about two miles away from the repository, regardless of the vertical distance from the Salado to the oil producing zones, I do not see a difference in the essential characteristics of the situation, which is the presence of the Salado Formation and its interbeds.

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2.8 Perspectives from WIPP Performance Assessment

Peter Swift and Rip Anderson
Sandia National Laboratories

2.8.1 Synopsis

Two main EPA regulations address the long-term (10,000-year) performance of the WIPP: 40 CFR 191 sets standards for releases of radioactivity from the disposal system; and 40 CFR 268.6 applies to long-term releases of hazardous constituents (e.g., volatile organic compounds and heavy metals) regulated under RCRA. 40 CFR 191 provides a regulatory definition of performance assessment (PA) that applies to the WIPP. It is "an analysis that: (1) Identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties caused by all significant processes and events." (40 CFR 191.12).

WIPP PA uses computational models to estimate cumulative radionuclide releases for selected scenarios. These scenarios are developed using a methodology which begins with establishing a comprehensive list of features, events, and processes (FEPs) which may affect the disposal system. These FEPs are then screened using four basic criteria: relevance, regulatory requirements, probability of occurrence, and consequence. Scenarios for system level modeling are constructed from those FEPs that remain following screening. To date, screening arguments are documented for approximately 800 of the 900 FEPs initially identified. Screening arguments remain to be developed or documented for many FEPs, including some related to oil and gas activities.

2.8.2 Presentation by Peter Swift

This is a brief overview of performance assessment methodology, more specifically, the development of scenarios for performance assessment. In an effort to address regulatory requirements, performance assessment calculates the long term performance of the repository for the next ten thousand years. There are two regulations of primary interest.

40 CFR Part 191 regulates the release of radioactivity from the site. It was promulgated in 1985, partially vacated by the court in 1987, and repromulgated in 1993. There are essentially three requirements:

- §191.13 limits the cumulative releases of radionuclides to the accessible environment for 10,000 years from essentially all causes.
- §191.15 limits the individual dose for "undisturbed performance" for 10,000 years. (Undisturbed is defined to exclude human intrusion).
- §191.24 requires protection of underground sources of drinking water for "undisturbed performance" for 10,000 years.

The first item, the cumulative release requirement, has been driving the performance assessment calculations.

The second regulation of interest, 40 CFR 268.6, implements RCRA for the long term. It limits the releases of hazardous constituents, such as VOCs, organics, and heavy metals, at the disposal unit boundary for 10,000 years of undisturbed performance.

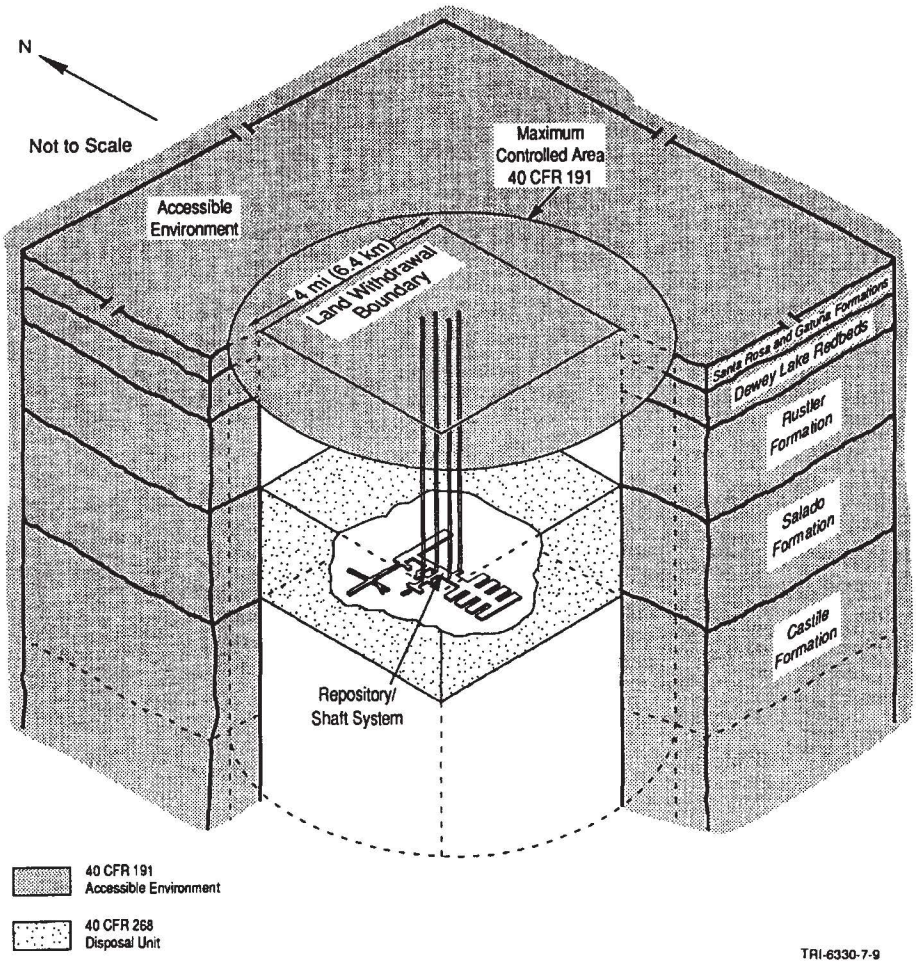

Figure 2.8-1. Accessible Environment and Disposal Unit Boundaries.

Shown here are the regulatory boundaries needed to assess performance measures. The repository is in the Salado Formation. It is underlain by the Castile Formation and the deeper hydrocarbon bearing units. The repository is overlain by the Rustler Formation which contains the Culebra, the formation in which Rick Beauheim observed the water level rises. Above that are the Dewey Lake Redbeds Formation and other relatively thin units such as the Santa Rosa Formation and the Gatuña Formation. The RCRA boundary, the RCRA disposal

unit, is defined to be the Salado Formation inside the four mile area. Releases are of interest at the top of the Salado Formation, at the bottom of the Salado Formation, or laterally to the 4 mile by 4 mile boundary.

For 40 CFR Part 191, the disposing unit is defined a little differently. The boundary of the controlled area is a cylinder extending up to the ground surface and downward as well. Radionuclide releases are of interest if radionuclides reach the ground surface or if they migrate laterally through marker beds in the Salado or through the permeable units in the overlying formations. We estimate the releases and sum the releases over 10,000 years. That is the performance measure that is compared to the EPA standard. The standard is probabilistic and regulates the probability of cumulative releases, not the magnitude of them, but the probability of releases of a certain magnitude.

For the WIPP 40 CFR 191 defines performance assessment. Performance assessment:

- identifies processes and events that might effect the disposal system,
- examines the effects on system performance, and
- estimates cumulative releases, including uncertainties, caused by all significant events and processes.

Performance assessment tries to capture this uncertainty by posing three questions.

1) What are the things that can happen in the future? (Scenarios or S_i)

2) What are the probabilities of those things?

3) What are the consequences of these things, if they should happen?

Risk is represented by an equation which contains an ordered set: 1) scenarios, 2) scenario probabilities, and 3) scenario consequences.

$$Risk = \{(S_i, pS_i, cS_i), i=1...nS\}$$

Performance assessment, for 40 CFR Part 191, is basically an attempt to solve the risk equation.

The flow diagram shows the performance assessment methodology. The process starts by characterizing the system. For the WIPP, there are 3 main parts, the site geology, the engineered facility, and the waste to be emplaced.

Performance assessment needs to develop scenarios. These are the things that might happen. Their probability needs to be estimated and a computational modeling system is needed to simulate these scenarios and estimate the consequences. A Monte Carlo consequence modeling system is used to perform multiple simulations using different sample parameter values, which describe the key parameters of the system. The simulations yield a set of outcomes that describes the uncertainty in the modeling system. The effort calculates the consequences for different scenarios, estimates the scenario probabilities, and gives a result that can be compared to the regulatory standards. If the exercise is a preliminary performance assessment, as has been the case since the late 1980s, then the process executes a sensitivity analysis that iterates through the system. The final iteration leads to the preparation of an application.

The first step to develop scenarios is to establish a comprehensive list of features, events, and processes (FEPs). Events and processes are identified in the regulations. A feature is neither an event nor a process, it simply may exist at the site. The WIPP FEP list was developed from nine independently derived FEP lists from different programs around the world. Some WIPP specific FEPs were added. The "Master List" contained approximately 900 FEPs. Some of these were not particularly relevant to WIPP. But in the interest of completeness they were included on the initial list. That list is in concept, an open list. If someone can think of it, and it has merit of any sort, it should be on that list.

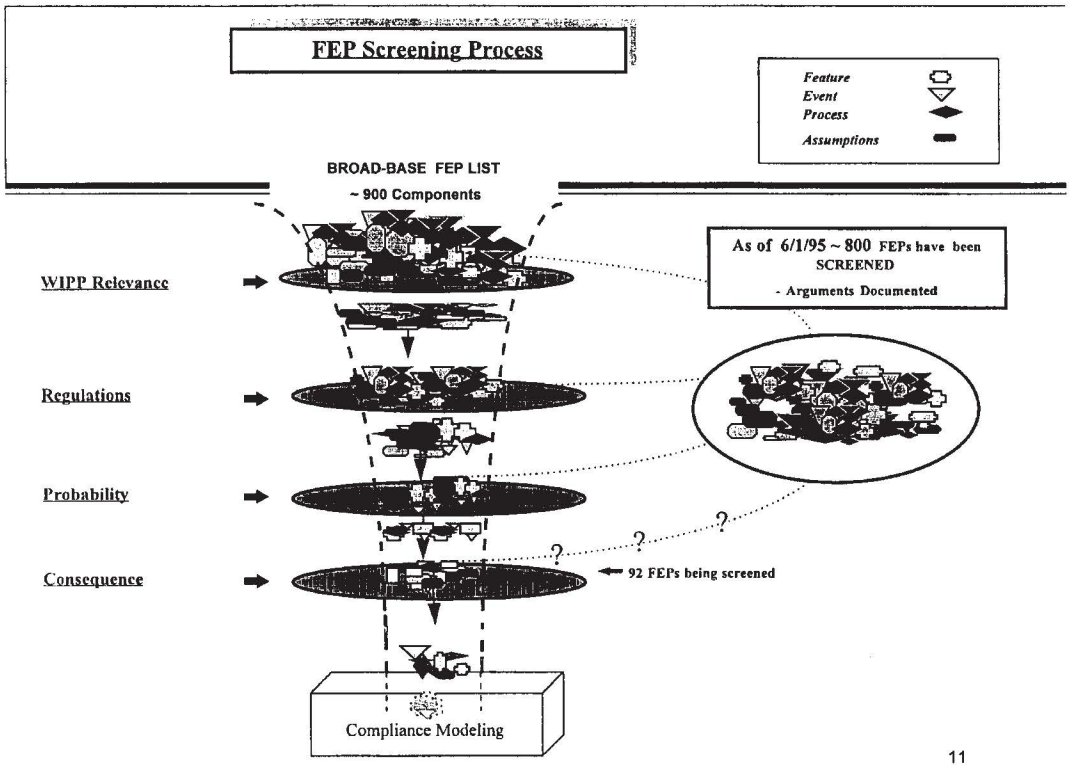

Figure 2.8-2. FEP Screening Process.

Next is the development of a screening argument. Screening does not mean screening out. It means screening either in or out of system level analysis. There are four screening criteria:

1) Relevancy

2) Regulation

3) Probability

4) Consequence

The first one is simply relevancy. For example, FEPs that relate to the disposal of high level waste or spent fuel are not relevant to WIPP.

The second is regulatory criteria. Two are important enough to mention here. First, the American regulatory period is limited to 10,000 years. FEPs beyond 10,000 years are not considered. Second, Appendix C of 40 CFR 191, specifies inadvertent and intermittent exploratory drilling as the most severe human intrusion scenario that should be considered.

The last two screening criteria are probability and consequence, assuming that the remaining FEPs, will be both relevant and included by the regulation. Then the process examines the probability of the FEP occurring and the consequences to the system. Regulation provides guidance for both of these. For probability, if a FEP can be shown to have less than one chance in 10,000 in 10,000 years, it need not be considered further. For consequence, if it can be shown that the performance measure would not be significantly changed by including the FEP in the analysis, then it need not be included. Of course, that presupposes there has been work done to support that consequence argument.

A schematic of the FEP screening process is shown. The order in which the first two screening criteria are applied is done on a case by case basis. At this time of the approximately 900 FEPs, work is ongoing for 92 of the remaining FEPs to determine their status.

2.8.2.1 Conclusions

Oil and gas related activities, e.g. waterflood injection, certainly are on our list along with other FEPs. Screening arguments remain to be developed and documented for several FEPs that are relevant here today, including waterflood injection. In other words, I don't have a screening argument today. I am not going to tell you what we decided to do about waterflood injection in terms of performance assessment modeling. In part, I am eager to hear what we learn here today and it would premature for us to come in with a conclusion already in hand. But I remind you that we will apply the three important criteria, probability, consequence, and the regulatory requirements.

2.8.2.2 Questions:

Robert Neill: In terms of the probabilities for screening, would you say that the probability of salt waterflooding or brine injection to improve oil recovery in the vicinity of WIPP is much, much less than 10^{-4} or much, much greater than 10^{-4}.

Peter Swift: At some locations the probability apparently is one, which is a good high number for a probability. I think it would be pointless of me to make the point any further. It depends on the location.

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2.9 Need for Water Flooding Scenario in WIPP Performance Assessment

William W.-L. Lee

2.9.1 Synopsis

After a series of presentations on the why, where and what-ifs of water-flooding, we come to the question of what does water-flooding mean for WIPP as a geologic repository of nuclear and mixed wastes. The USEPA requires performance assessments to include disruptive events or processes that are estimated to have more than one chance in 10,000 of occurring over 10,000 years. In the 1989, 1990, 1991 and 1992 WIPP performance assessments, the only disruptive event analyzed was human intrusion by drilling. WIPP has not analyzed a scenario specific to water-flooding.

In the most recent position paper on scenarios development, the DOE states:

> Fluid injection.
> Leakage from fluid injection wells associated with enhanced and improved oil and gas production, hydrocarbon storage, and disposal of unwanted liquids is retained for further consideration (p. 7-15).

Among the 124 FEPs being analyzed in side calculations, we find

- Interconnections within the controlled area for disturbed performance (to model effects of existing and future boreholes),
- Interconnections outside the controlled area for disturbed performance (to model effects of existing and future boreholes),
- Leakage from wells (from brine pockets, injection wells, fluids during drilling),
- Effects of mining inside or outside the controlled area,
- Connection to units beneath the repository,
- Current human activities outside the controlled area (e.g. hydrocarbon

extraction, fluid injection. (Anderson 1995).

While SNL/DOE has considered water-flooding, the impacts of water-flooding has not yet been analyzed in the compliance certification application.

2.9.2 Presentation by William W.-L. Lee

What does waterflooding mean and should it be incorporated into WIPP's performance assessment? Features, events, and processes (FEPs) that have a probability greater than 10^{-8} per year have to be considered in performance assessment. However, in the previous iterations of the WIPP performance assessment, the only disruptive event analyzed was human intrusion by drilling. And that is an important qualification.

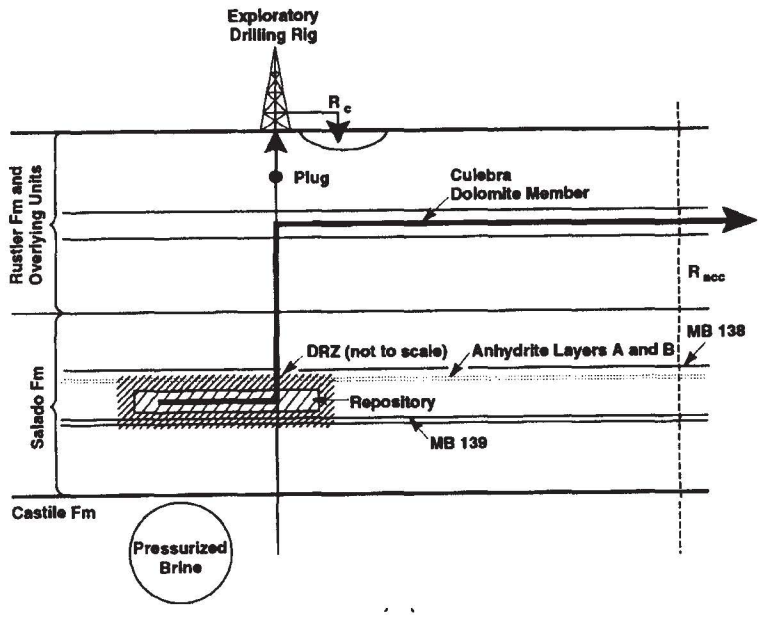

Figure 2.9-1. E2 Scenario

In the spirit of reviewing old work, I will show you the scenarios that were actually analyzed in the 1992 Performance Assessment. There was the E2 scenario in which a repository is pressurized with brine that flowed in from the Salado Formation, a driller hits the repository, and the pressurized waste moves up the well bore. There is a magic plug that diverts the material into the Culebra Dolomite. Compliance is measured at the accessible environment.

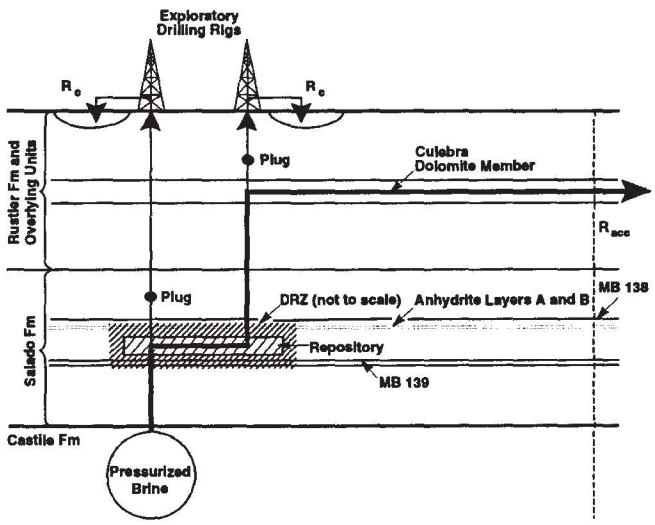

Figure 2.9-2. E1E2 Scenario.

In the E1E2 scenario, a driller first penetrates through the repository into a brine reservoir in the Castile Formation and thus floods the repository. A plug is put in place and there is now a brine pressurized repository. The E1 scenario is then superimposed on the E2 scenario.

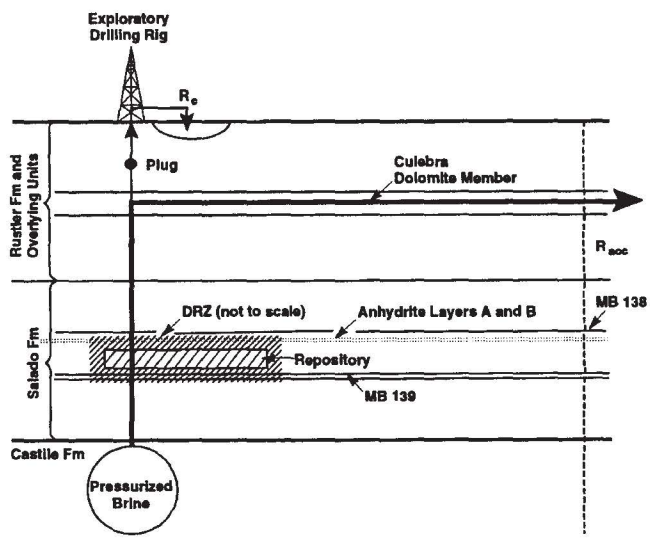

Figure 2.9-3. E1 Scenario.

The other possible scenario that was not analyzed by the 1992 PA was the E1 scenario which is the first half of the E1E2 scenario. The rationale given was that it is dominated by the E1E2 scenario although I believe Sandia has had some second thoughts about it.

Peter Swift just explained the process of screening FEPs. Starting with 900, two months ago there were 124 left. These are the ones related to waterflooding that are left.

- Interconnection within the control zone for disturbed performance and interconnection outside the disturbed performance.
- Leakage from wells including injection wells.
- Effects of mining inside or outside the control area.
- Connection to units below the repository.
- Human activity including fluid injection.

We have been told that Sandia National Laboratories is grinding away on side calculations to provide screening arguments for these FEPs. We await the results of these calculations.

The bottom line is this. Should the impact of potential waterflooding be in the current performance assessments and in particular, the draft application?

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END OF WORKSHOP PRESENTATIONS

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3. ANALYSES OF FLUID INJECTION ISSUES

Potential impact of fluid injection on the WIPP repository is analyzed in this chapter. The analysis uses the information presented at the workshop and that available in the literature and the public record.

As Chuck Byrum (EPA) noted in the afternoon discussion, waterflood and salt water disposal are two different processes regulated in different ways, designed in different ways, and the ultimate effects of each may be quite different. Kreitler et al. (1994, 4) described the difference between these two water injection activities. In waterflood projects, the presence of adjacent producing wells limits the extent of repressurization around the injectors. In contrast, salt water disposal wells are not used to increase oil production. Hence, brine may not always be injected into depressurized producing reservoirs. Initial fluid pressures in the disposal reservoirs may be hydrostatic, leading to overpressured conditions and upward fluid flow potentials. This analysis attempts to preserve the distinction between these two processes.

3.1 Salt Water Disposal

In his presentation, Beauheim showed data which led to his inescapable conclusion that a discreet human activity, most likely an injection well, caused the abrupt 1988 water level rise in wells south of the WIPP Site. Based on his own investigation, LaVenue (1991) also suggested the possibility of leakage from either a producing oil and gas well or a salt water disposal well in the area. Further, LaVenue (1991) speculated on the potential impact of a leaking well on the performance assessment calculations:

> If the recharge source is related to oil and gas wells in the area, it is not difficult to imagine significant increases and/or decreases in the water levels in the future as a result of additional recharge or discharge from oil and gas wells. Fortunately, there are almost no oil and gas wells within the

> WIPP-site boundary. Therefore, if wells are going to leak and have an impact upon the flow field, there is a higher probability that those wells will be located down-gradient or south of the WIPP site. Recharge from oil and gas wells south of the site should flatten the hydraulic gradient which would slightly increase ground-water travel time. If discharges from the Culebra occurs through a leaking oil or gas well south of the site, the hydraulic gradient would be slightly increased and the ground-water travel time would decrease (LaVenue 1991, 10-11).

In his presentation, Beauheim noted that higher potentiometric head in the Culebra in the southern part of the WIPP and south of the WIPP would flatten the hydraulic gradient and increase travel time. But he also emphasized that a change in gradient would not make a difference to the calculated performance assessment because of the relatively short life of such an injection activity. However, could a leaking injection well east, north, or northeast of the WIPP force large volumes of brine into the Culebra and significantly increase the gradient and reduce travel time? There are several new oil wells also producing large quantities of brine from the Delaware Mountain Group. To handle that waste brine, there are new salt water disposal wells operating just east of the WIPP Site. Wells are likely to be drilled to the north of WIPP when the area is open for drilling. The effect of higher heads in the Culebra in the north and east of the WIPP site should be analyzed in performance assessment.

3.1.1 Fluid Injection in the Culebra - *Bounded by Climate Change*

At the EEG workshop, Rip Anderson (SNL) acknowledged that the performance assessment effort, to date, has not specifically addressed fluid injection but that climate change would be in the final calculations. He maintained, however, that climate change assumption would bound any waterflooding scenarios because the climate change scenario takes the water table to the surface and that is the maximum possible water pressure. Anderson also stated that the presence of a

Castile brine pocket for the human intrusion scenario would cover any remaining concerns about waterflooding.

The 1995 DOE draft application to EPA (U.S. DOE 1995, Section 6.4.11) discusses climate change noting that the hydraulic head in the Culebra is raised to the land surface elevation along the northern boundary of the Culebra while the head remains fixed along the domains of the southern boundary. No results were presented. Rather, the draft document notes that the effect of climate change on groundwater flow is the subject of a current study.

3.1.2 Fluid Injection in the Culebra - *Not Bounded by Climate Change*

David Back (SC&A) questioned the DOE position that surface recharge bounded the impact of water level fluctuations in the Culebra. Back noted that the PA modeling assumed that the recharge would occur some miles to the northwest of the WIPP Site at the edge of the regional model. He pointed out that water from this recharge location would not pass through the WIPP site. Modeled this way, the water would flow south, through the higher transmissivity zone, straight to the assumed discharge area in Nash Draw, which is also west of the WIPP Site. However, if recharge occurred along the eastern edge of the WIPP, Back maintained that there would be an increase in the gradient, hence an increase in the flow rate through the Culebra over the WIPP.

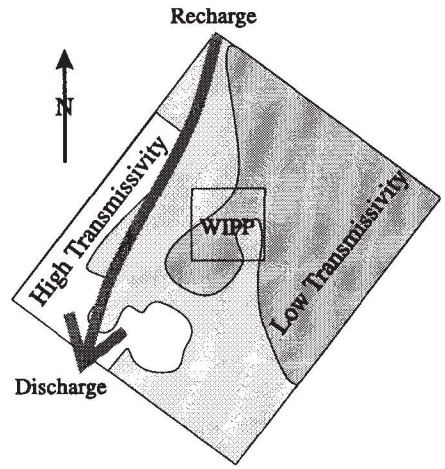

Figure 3-1. WIPP and Regional Flow Model for Culebra. Figure prepared by M.K. Silva.

3.1.3 Culebra Hydraulic Head Limited to Surface

Peter Swift (SNL) maintained that it is unlikely for a failed injection well to cause

pressures in the Culebra that are above the head at the ground surface. Data that support his position include the 181 pressurized water flows logged into the NMOCD Hobbs call-in log (November 1978 to May 1994) for southeastern New Mexico and the eight additional waterflows identified by Van Kirk (1994). Waterflows appear to be largely confined to the Salado and other deeper formations. There does not appear to be any artesian flow from the overlying aquifers such as the Culebra.

The notion of surface limited hydraulic head can not apply to the Salado. In the Vacuum Field, waterfloods exerted sufficient pressure to collapse well casings and pressures as high as 1600 psi were measured at the surface outside of waterflood areas (Ramey 1976). As mentioned by Lokesh Chaturvedi and discussed by Dennis Powers, the 1991 Salado salt water blowout at Hartman's Bates Lease was pressurized far above the surface hydraulic head as Hartman inadvertently discovered.

3.1.4 Brine Flow into Overlying Aquifers

Citing information from Dan Stoelzel, Rip Anderson made the following two points. First, a difference occurs only if water enters the Salado and the repository. Second, water escaping lower injection zones would flow past the Salado and would flow into the more permeable Culebra. Dan Stoelzel also suggested the reason injected water in the Vacuum Field did not come to the surface was because it was potentially going into the Ogallala, which is very permeable near the surface. The mechanism postulated by Anderson and Stoelzel raises interesting questions. At the Vacuum Field, or in other parts of New Mexico, or in other parts of the nation, has there been contamination of overlying aquifers, such as the Ogallala, as a result of oil field waterflooding? Is WIPP relying on contamination of an overlying aquifer by oil field waste brine as an acceptable alternative to flooding the Salado?

Some information supports the notion of water from oil field operations contaminating overlying aquifers. The U.S. Government Accounting Office (GAO) published a 1989 report entitled "Drinking Water Safeguards Are Not Preventing Contamination From Injected Oil and Gas Wastes." Class II injection wells are used to dispose of brine produced with oil and gas or to reinject these fluids to enhance oil recovery. Although the full extent of the problem was unknown in 1989, EPA was aware of 23 cases in which drinking water was contaminated by Class II injection wells. For the 23 confirmed cases of contamination, there were three principal causes. Five cases resulted from leaks in the casing of the injection well, nine resulted from migration through nearby improperly abandoned wells, and nine resulted from injection into the underground drinking water (U.S. GAO 1989).

One case of confirmed contamination occurred in New Mexico. During the 1970s, 20 million gallons of water leaked from a Texaco disposal well in Lea County, New Mexico into portions of the Ogallala aquifer, an underground source of drinking water. Some of the brine migrated into a rancher's irrigation well, damaged his crop and, according to the rancher, ultimately caused the foreclosure of his farm property. On the basis of the results of a pressure test, the rancher successfully sued Texaco in 1977 for damages (U.S. GAO 1989, 25).[9]

In the 1970s, potential contamination of the Ogallala near various waterfloods in Lea County was of concern to the New Mexico Oil Conservation Division (Ramey 1976). After years of study, the Vacuum Field Salt Water Flow Committee [a committee of oil company representatives] indicated flow was confined to the top of the Tansil and the bottom of the Rustler (Bailey 1990), thus isolating the problem of flow largely to the Salado. Bailey's spot checking old oil well drilling

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[9] Texaco has since repaired the well and is now operating in compliance with Underground Injection Control although Texaco was not required to clean up the aquifer (U.S. GAO 1989, 25).

records indicated water flow drilling problems and numerous casing leak repairs in the Dewey Lake Red Beds and the Rustler in addition to the Salado (Bailey 1990).

3.1.5 Pressurized Brine Injection into the Salado

If there was salt water flow into the Ogallala at the Vacuum Field, as suggested by Dan Stoelzel, and into the Dewey Lake Red Beds and Rustler as indicated by Bailey (1990), can the performance assessment assume that overlying aquifers will serve as a relief valve for leaking wells in the WIPP vicinity, thus protecting the Salado, as suggested by Anderson and Stoelzel? It appears not. Despite the presence of overlying aquifers at the Vacuum Field, injected salt water exerted sufficient pressure to collapse well casings at the Salado horizon (Ramey 1976; LaVenue 1991). Similar observations of water flow through the Salado have been made in other oil fields with a history of waterflooding, including the oil fields near Oil Center, Monument, Eunice (Bailey 1990) and Jal (Hartman 1993).

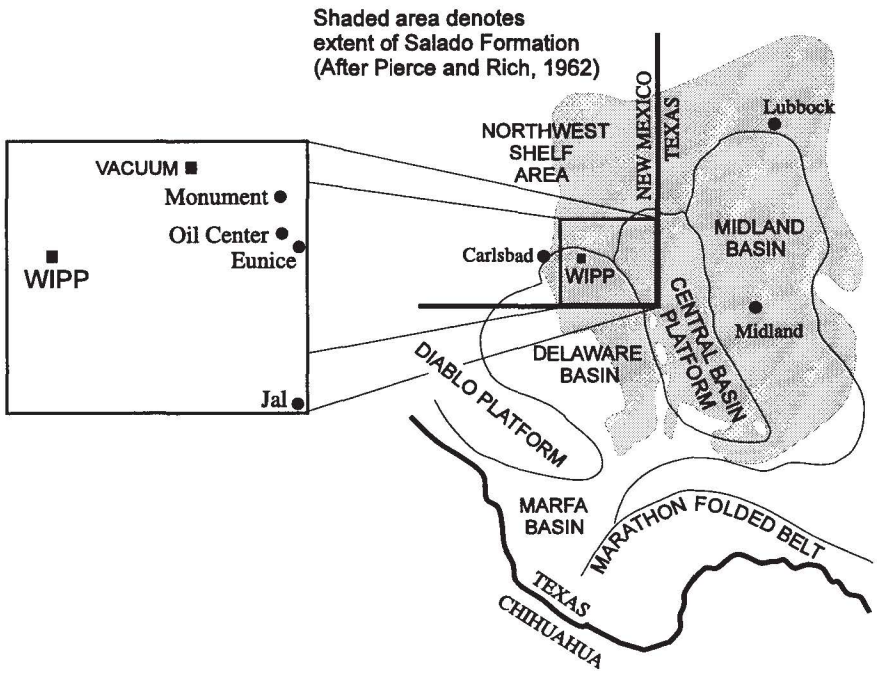

Figure 3-2. Areas overlain by Salado Formation.

Gallegos and Condon (1994) argued that the 189 water flows throughout District One of southeast New Mexico strongly correlated with waterflooding activities. These flows were in the Salado or at depths much greater than the overlying aquifers, strongly suggesting no relief mechanism. In light of this information, can the performance assessment defend the notion that brine escaping from an oil field waterflood or salt water disposal well will preferentially migrate into an overlying aquifer?

3.1.6 Devon Energy's Todd 26 Federal #3

As to the salt water injection well south of the WIPP Site, Dan Stoelzel commented that this well was probably responsible for the water level rises observed in H-9 (see Stoelzel's presentation). His conclusion was based on the schematic of the well completion. The well was originally completed in 1971 as a test well and immediately converted to a salt water disposal well. There is no salt isolation casing and it is an open hole completion similar to that of the Rhodes/Yates Field or the Vacuum Field. He commented that the well is now plugged and abandoned. Matthew Silva's reading of a commercial map also suggested that the well was abandoned.

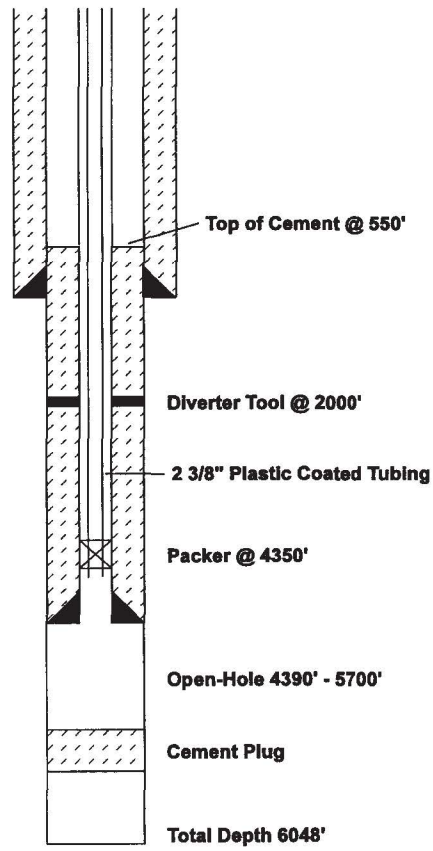

Figure 3-3. Texas Americal Oil Corporation Todd 26 Federal No. 3 Water Disposal Well (After Stoelzel).

It appears that the well was not plugged and abandoned and is still in service (Horsman 1995). The well is injecting into the Bell Canyon Formation, which is below the WIPP horizon. A comparison of the injection history at this well and

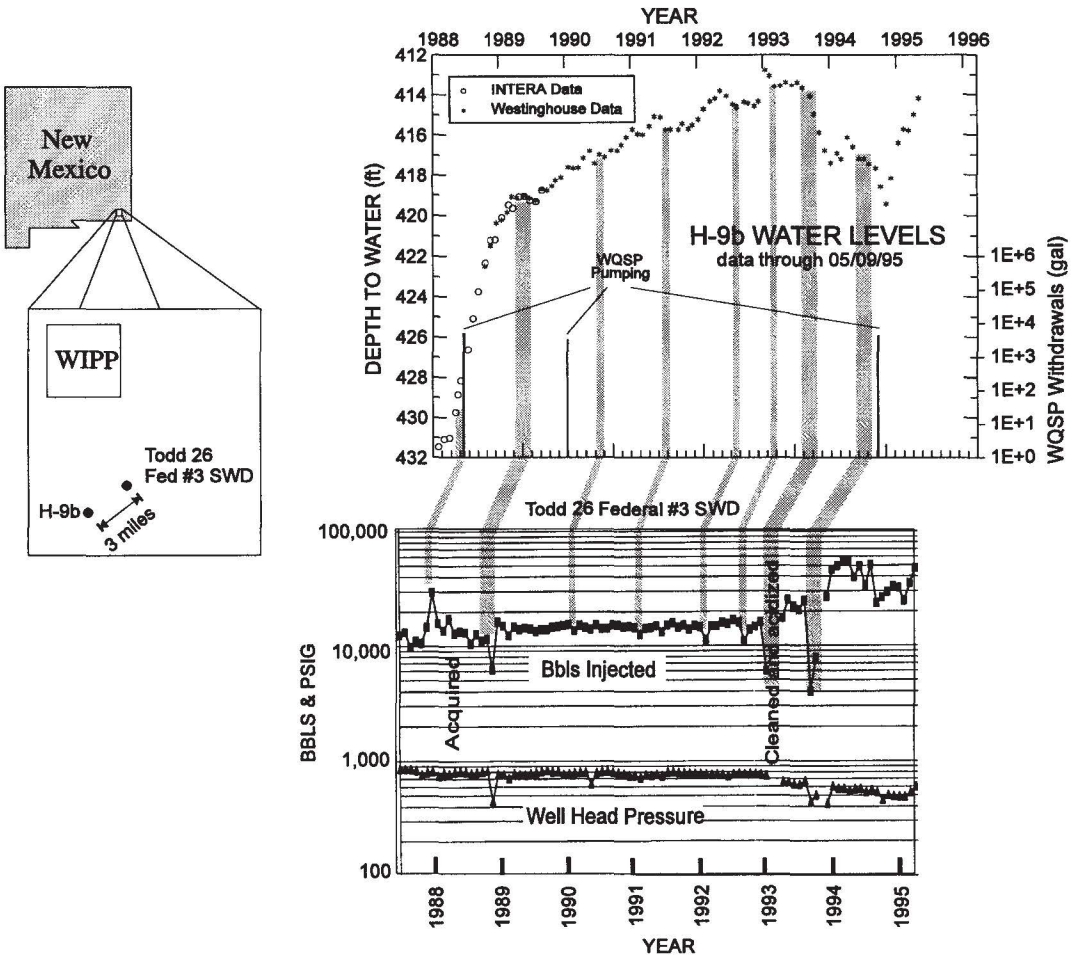

Figure 3-4. Todd 26 Federal #3 well injection data (Horsman 1995) and H-9 water level rises presented by Beauheim.

the water level rises at H-9 strongly suggests communication between the injection horizon, which is below the WIPP horizon, and the Culebra Dolomite, which is an aquifer above the WIPP horizon. There is more than 3,000 feet (980 m) of vertical separation between the horizons and approximately 3 miles (5 km) of horizontal separation between the wells.

Figure 3-4 strongly suggests a delayed response at well H-9 to injection events at the Todd 26 Federal #3. As noted in Richard Beauheim's presentation, the depth to water at well H-9 was essentially constant at 431 to 432 feet (141 m) for five

years prior to April 1988. An increase in the injection rate from 10,000 barrels per month to 30,000 barrels per month in January 1988 corresponds with the observed water level rise at H-9, which began in April 1988. This increase in injection is the event mentioned by LaVenue (1991) as potentially causing a tubing failure. Seven subsequent reductions in injection at the salt water disposal well rate are followed by corresponding water level declines at the monitoring well. In January 1993, injection operation ceased for two months. The water level at H-9 fell to levels not seen since 1990. After 1993, there appears to be either a delay in the response or perhaps a response to other injection wells in the area. It is worth noting that two other salt water injection wells began operating in the same general vicinity as Todd 26 Federal #3; Todd 26 Federal #2 SWD in January 1993 and Todd 36 Federal #1 in September 1994 (Horsman 1995).

The observations invite the obvious question. Are there problems with the Todd 26 Federal #3 well as suggested by Bailey (1990), by LaVenue (1991), and in Stoelzel's discussion of the well completion? Subsequent to the EEG workshop, the well passed a scheduled, routine, mechanical integrity test on August 16, 1995. In response to a request from the U.S. EPA (Catanach 1996a), the New Mexico Oil Conservation Division had the well subjected to a radioactive tracer test on November 13, 1995, to determine if injected fluid is migrating upward through channels in the vicinity of the wellbore (LeMay 1995a).

> The results of the tracer surveys (analysis attached) indicate no channeling behind the production casing and no vertical migration of fluid from the injection interval. It is the opinion of the Division that no further testing of these wells [Todd 26 Federal #3 and David Ross AIT Federal #1] is necessary (Catanach 1996b).

Assuming the tests were conclusive with respect to the integrity of the tubing, the casing, and the cement, the results of the test raise more questions. Are there vertical conduits in the vicinity such as improperly abandoned wells and/or wells

with deficient casing or cementing? Or are there vertical fractures in the vicinity that are not detectable by a radioactive survey of the wellbore area? Is there indeed a correlation between water injected and water level rises as suggested by the injection and water level rise data? If so, how does water injected more than 4,000 feet (1300 m) below the surface get through thousands of feet of two relatively impermeable bedded salt formations, the Castile and the Salado, and end up in an overlying aquifer? Is bedded salt, in the vicinity of water injection activities and abandoned oil and gas wells, truly a geologic barrier?

3.1.7 Yates' David Ross AIT Federal #1

Although there are several salt water injection wells in the area, this is the only salt water injection well operating within one mile of the WIPP Site at this time. During the afternoon deliberations, George Dials (DOE) raised the issue of institutional control noting that DOE has the opportunity to take credit for institutional control for up to 100 years and the DOE intends to maintain institutional control for at least 100 years.

As the only salt water disposal well operating within one mile of the WIPP site, the record on Yates' David Ross AIT Federal #1 provides interesting observations about institutional control.

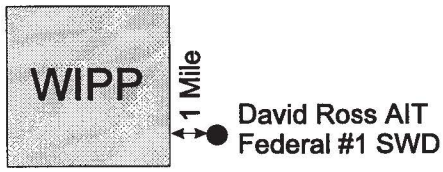

Figure 3-5. Location of David Ross AIT Federal #1 Salt Water Disposal Well.

First, the BLM received an application for permit to drill an oil well on January 17, 1991. The BLM approved the application on January 31, 1991, without obtaining a review from the DOE despite the October 26, 1990, Memorandum of Understanding (MOU) requiring it. The approval of this well completely bypassed "the controls that are crucial to protecting the site from inadvertent exploration" (Arthur 1992; Silva 1994, 46). The policy has been in place since 1983:

> As an additional measure, the BLM will notify the DOE of any requests for resource recovery permits within one mile of the WIPP Site boundary so that the DOE will be aware of resource recovery activities near the Site (McGough 1983).

Second, when the well failed to produce much oil from the perforated zone, the operator proposed to convert it to a salt water disposal well. There was an objection, but it was not raised by the DOE. Mitchell Energy expressed concern about the loss of oil reserves as a result of brine injection into potential oil producing horizons and wished to limit injection pressures (Stephenson 1991). An agreement was reached between the two oil companies (Kellahin 1991) and the conversion to a salt water disposal well was approved on May 22, 1991 (LeMay 1991). The well was to be equipped to operate at a maximum pressure of 900 psi (LeMay 1991). Over the next several months, the well casing was perforated and zones within the approved interval were acidized and fractured until sufficient water could be injected (Goodlett 1991a, 1991b, 1991c, 1991d, 1991e, 1991f).

Third, the DOE continued to list this as an oil and gas well (Arthur 1993a, 1993b) and appeared unaware that this was a salt water disposal well despite the absence of oil production equipment, the presence of a battery of salt water tanks, the presence of a sign labeled "SWD," the "SWD" label on the BLM map, and BLM and NMOCD records clearly stating "salt water disposal well" (Silva 1994, 55-56; Kehrman 1995, 254, lines 18-20).

Fourth, the DOE, the EPA, the BLM, and others rely on the New Mexico Oil Conservation Division to ensure that water is not injected above the approved injection pressure. An examination of the public record (NMOCD 1996) indicates that the David Ross AIT Federal #1 was operated 20 psi above the approved injection pressure of 900 psi (LeMay 1991) during the months of September and October 1995, yet the well had been equipped so that it would not operate above 900 psi.

Government ownership, regulation, and public records are components of institutional control. The observations above raise questions about how much credit can be allowed for institutional control of the resource recovery activities in the vicinity of the WIPP site.

There does not appear to be an identifiable relationship between the injection of brine at the David Ross AIT Federal #1 and the water level rises at the P-18 well. The material presented by Rick Beauheim and the arguments submitted by Fant (1995) strongly suggest that there is insufficient evidence of direct communication between these wells. Fant (1995) makes a compelling argument that the P-18 well, which was originally drilled as a potash corehole, may be providing a connection between the Culebra and Magenta Formations. As noted by Rick Beauheim, there may be a problem in the P-18 well with the bridge plug, the cement job, or the cement bond.

3.2 Water Flooding

The problems with waterflooding in oil fields under the Salado Formation, or more specifically, the migration of injected water through the Salado Formation to adjacent properties, is well documented (Ramey 1976; Bailey 1990; LaVenue 1991; Hartman 1993, Herrera 1995). At the EEG workshop, Dan Stoelzel and Lori Dotson of Sandia National Laboratories maintained that at WIPP, migration of water through the interbeds of the Salado, such as occurred at the Rhodes Yates Field and the Vacuum Field, was highly unlikely for a variety of reasons. These included differences in geology, changes in oil-well completion practices from the 1940's, and improved reservoir management. Stoelzel and Dotson argued greater vertical separation at WIPP will protect the repository. They also argued that large scale water flooding near the WIPP is unlikely because the oil pools near WIPP are characterized by thin net pay zones, low permeabilities, high reducible water saturations and high residual oil saturations. They also maintained that oil

production by primary and secondary recovery would require less than ten years each. These issues are discussed below.

3.2.1 Differences in Geology

With respect to water injection, Dan Stoelzel and Lori Dotson cited vertical separation as an additional protection for the WIPP. Their arguments rely on the observation that oil production near the WIPP occurs at depths greater than 7,000 feet (2300 m) or about 5,000 feet (1640 m) below the repository horizon. Oil production at the Vacuum Field occurs at approximately 4,500 feet (1480 m) and at Rhodes Yates at 3,000 feet (980 m). In their abstract, Dotson and Stoelzel state there was only a couple of hundred feet ~(65 m) of vertical separation between the Salado Formation and the waterflood injection zone at Rhodes-Yates. They also noted that the Castile Formation is missing at the Vacuum Field and the Rhodes Yates Field.

However, as noted by Lokesh Chaturvedi, there is one geologic feature common to the areas on either side of the reef. The Salado interbeds extend through the entire Salado across the Delaware Basin and over the backreef. Lokesh Chaturvedi maintained that once pressurized fluids are injected into the Salado interbeds at WIPP, the interbeds will behave essentially the same way as Salado interbeds at other locations.

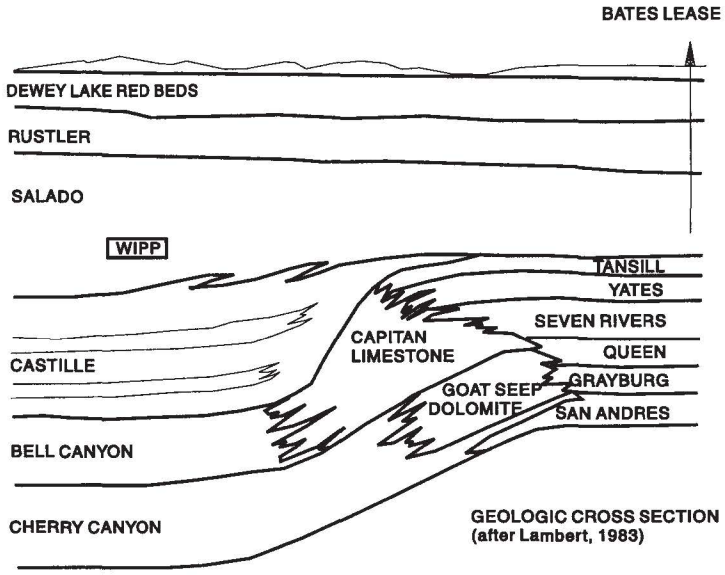

Figure 3-6. Continuity of Salado Formation.

In the afternoon deliberations, Dan Stoelzel and Lori Dotson offered opinions which contradicted the notion that vertical distance would protect the repository from communication with the deeper injection zones. For example, Dan Stoelzel maintained that the most likely source of water level rises in the Culebra at the H-9 well was the Todd 26 Federal #3 salt water disposal well. Matthew Silva observed that the salt water disposal well was injecting fluid in the interval from 4,400 to 5,700 feet (1440 m to 1870 m) below the surface. The water would have to migrate vertically 3,500 feet (1150 m) through the Castile and Salado to the overlying Culebra. That observation undermines Stoelzel and Dotson's position that such water migration would not occur because of about 3,000-5,000 feet (980 to 1640 m) vertical distance between the oil producing Delaware Mountain Group and the WIPP repository, or the overlying aquifers.

Lori Dotson commented that Silva's argument relied on the assumption that the water was leaking upward from the injection interval of 4,400 to 5,700 feet (1440 m to 1870 m). She maintained that the water could have been leaking from anywhere along the casing because that was a poorly designed injection well. Citing Stoelzel's earlier comments, Lori Dotson further commented that even if disposal brine was moving along the casing, it would take the path of least resistance and move into the Culebra. It would be easier for such water to enter the Culebra aquifer and not the Salado Formation. In bypassing the Castile and Salado Formations and flowing into the overlying aquifer, the oil field brine would not have an effect on performance assessment. But this explanation entirely undermines the "greater vertical distance" argument.

3.2.2 Livingston Ridge Delaware Waterflood

Dan Stoelzel maintained that small companies typically have shallow pockets and are unlikely to initiate water injection because of the cost to convert a production well into an injection well. It is worth noting that the active operators within two

miles of the WIPP Site include Phillips, Texaco, Pogo, Yates, Enron, Bass, Mitchell Energy, and Santa Fe Energy.

On October 10, 1995, Pogo Producing submitted an application to begin a pilot pressure maintenance project[10] (Bruce 1995a). Pogo intends to inject water into the Brushy Canyon of the Livingston Ridge-Delaware Pool through a well approximately one mile east of the WIPP Site Boundary. The injection interval is from 7,050 feet to 7,068 feet (2313 m to 2319 m) for a total injection interval of 18 feet (6 m), a relatively narrow zone of perforations. The original spacing of the wells has not been changed. A production well is to be converted into an injection well. Pogo plans to inject 365,000 barrels of water per year. The operator of the pressure maintenance project anticipates that three wells will see increased oil production, Neff Federal #1 and #2 in Section 25 and Neff Federal #1 in Section 26 (LeMay 1995b, 3). The operator also requested an administrative procedure to expand the pressure maintenance project, and at a later date, to include additional lands and/or injection wells (LeMay 1995b, 4). The WIPP can anticipate waterflooding of the Livingston Ridge/Lost Tank Delaware by independent operators on yet to be determined patterns.

3.2.3 Likelihood of Large Scale Waterflooding

Lori Dotson maintained that the oil pools near WIPP are relatively small when compared to the Vacuum Field and the Rhodes Yates Field. Hence, the injection of large volumes of water is unlikely. She suggested that the Livingston Ridge and the Lost Tank Delaware oil fields are unlikely to be waterflooded on a large scale because:

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[10] In a pressure maintenance program, water is injected to supplement declining reservoir energy. Pressure maintenance is a waterflood and often begins while the reservoir is still under primary production to maintain maximum production rates (Willhite 1986, 3, 190).

a) The pay zones are too thin, on the order of forty feet and several wells in the Livingston Ridge area with only ten to twenty feet of casing perforated.

b) The permeability of the Brushy Canyon is less than 7 to 24 millidarcies.

c) For waterflooding to occur, injection wells would have to be spaced closer together, which may be uneconomical.

d) The reservoir has a high irreducible water saturation and a high residual oil saturation.

However, Matthew Silva and Ron Broadhead noted that the Cabin Lake Field, at the northwest corner of the WIPP Site has shown good response to the pilot pressure maintenance project. The reservoirs in the Delaware Mountain Group produce primarily by solution gas drive. Citing the literature, Silva noted that solution gas drive wells are usually good candidates for waterflooding (Willhite 1986). In addition to citing experience and projected performance for the Paduca, Indian Draw, and East Shugart Fields, Broadhead also mentioned there was information, held proprietary by the oil companies operating in the area, indicating that they anticipated 70% to 80% increase in production by waterflooding the Brushy Canyon Formation.

3.2.4 Pay Zone Thickness

Lori Dotson maintained that large scale waterflooding would not occur in the vicinity of the WIPP because the pay zones were too thin. She stated that wells from the Livingston Ridge/Lost Tank portion of the Delaware were perforated for ten or twenty feet and suggested these were indicative of total pay zone potential.

However, a complete assessment of pay zone potential needs to also consider the typical completions for the Quahada Ridge Delaware Pool at the southwest corner

of the WIPP, the typical well completions for the Cabin Lake Delaware Pool at the northwest corner of the WIPP, and the typical multizone well completions for the Livingston Ridge-Lost Tank Delaware.

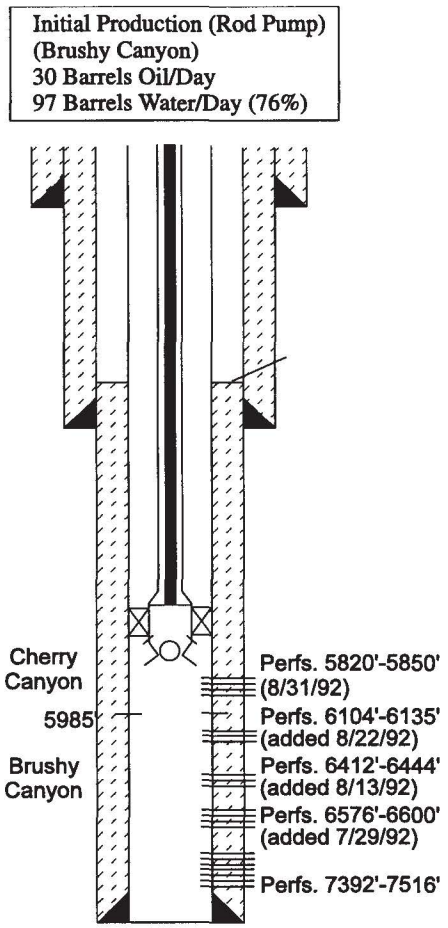

Figure 3-7. James E#12. Typical Cabin Lake Completion. After Dan Stoelzel.

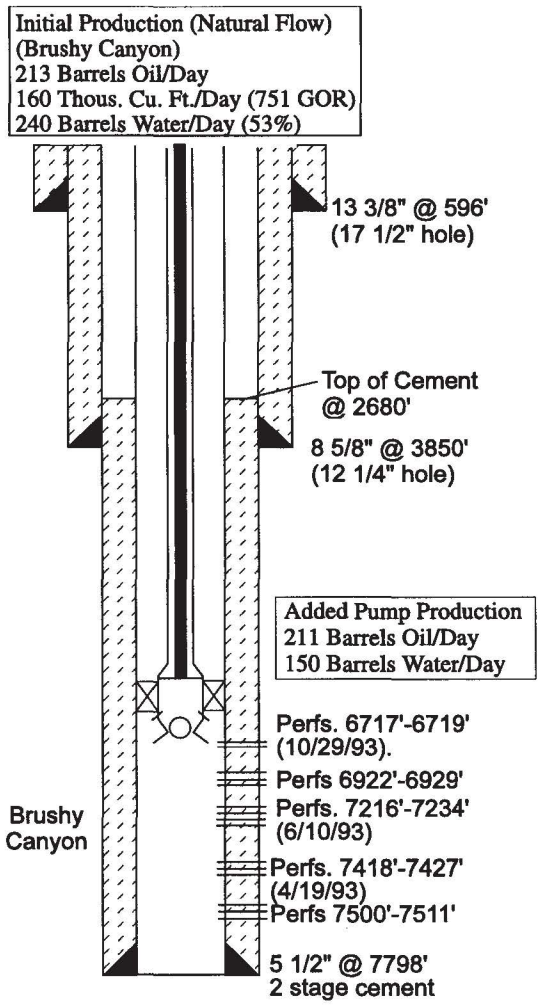

Figure 3-8. James Ranch Unit #19. Typical Quahada Ridge Completion. After Dan Stoelzel.

Stoelzel presented the James E#12 at Cabin Lake as a typical completion with five perforated zones totaling 231 feet (76 m). He presented the James Ranch Unit #19 as a typical Quahada Ridge completion with perforated zones totalling 47 feet (15 m).

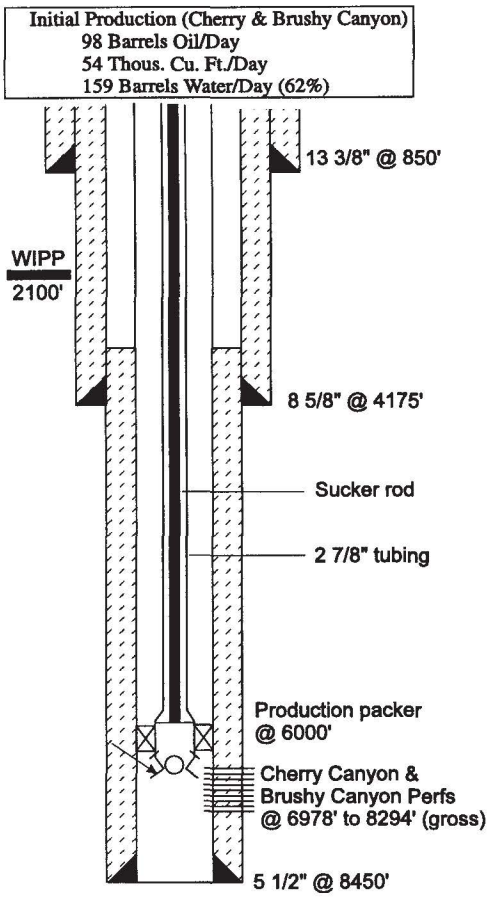

Figure 3-9. Typical Livingston Ridge/Lost Tank Completion. After Dan Stoelzel.

As to the Livingston Ridge/Lost Tank Field, it is true that Pogo Producing's completion records for Federal 23 wells #2, #3, and #5, on the lease immediately adjacent to the WIPP, are completed in the Brushy Canyon main pay zone with perforations ranging from fifteen feet to twenty feet (5 to 7 m). There are, however, other potentially producible zones, such as the B zone and D zone in the Lower Brushy Canyon as shown in Figure 20 of Broadhead et al. (1995). Moreover, the completion record for the Federal 23 Well #1 in that same lease, shows not only 19 feet (6 m) of perforation in the Brushy Canyon main pay, but also shows an additional 91 feet (30 m) of perforations in three other zones that have been temporarily abandoned. Broadhead et al. (1995, XI-16) noted that operators producing only from the main pay zone, at this time, may eventually re-enter their wells and perforate additional zones when the main pay zone ceases to yield economic volumes of oil. The completion records for the twelve additional wells that Pogo wishes to drill on forty acre spacings are not available because the federal government has denied Pogo's application to drill through the potash deposits (Burski 1994).[11]

[11]The EEG understands that this case may be in litigation and the EEG has no implied nor direct opinion in this case.

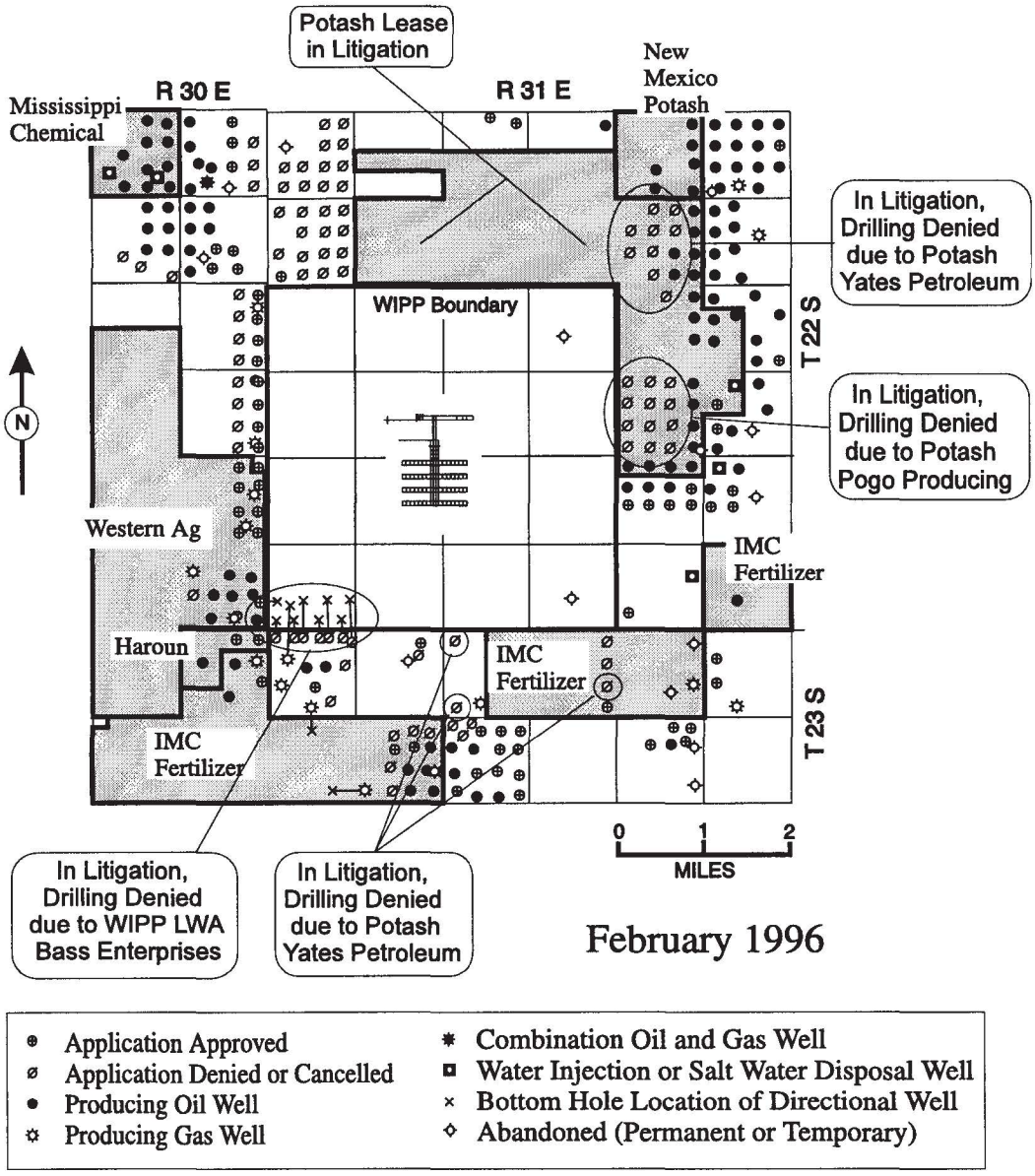

Figure 3-10. Current interest in resources surrounding the WIPP.

In arguing the ten to twenty feet of perforated casing as indicative of no large scale waterflooding, Lori Dotson did not discuss the Yates' wells in the Livingston Ridge. Yates Petroleum has drilled several wells in the west half of the Livingston Ridge but has completed them differently from other operators

(Broadhead et al. 1995, XI-16). All wells are perforated in the main pay and in most cases are also perforated in one to four other sandstones. While some of the completion records provide only the gross interval as shown in Figure 3-9, there is detailed perforation data for the first 3 wells in Section 11, T22S, R31E. Martha AIK Federal Well # 1 was perforated in three zones, 8236'-8308', 7960'-8015', and 7028'-7060', for a total of 159 feet (52 m) of perforations. Well # 2 was perforated in two zones, 6968'-6980' and 7035-7055', for a total of 42 feet (14 m). And Well #3 was also perforated in two zones for a total of 41 feet (13 m). Completion reports for wells #4, #5, and #6 provide only the gross interval of perforations. Wells 7 through 14 are waiting to be drilled. Due to the presence of potash deposits, the federal government has denied Yates' applications for permit to drill wells 7 through 14 (Burski 1994).[12]

3.2.5 Future Decades of Production in Oil Fields Surrounding the WIPP

Three presenters maintained that the oil fields surrounding the WIPP and producing from the Delaware Mountain group will have a maximum production life of less than twenty years. That position contradicts the position of the U.S. Department of Interior's Bureau of Land Management (DOI/BLM) (Woodard 1992, 3).

3.2.5.1 Position of the Department of Interior

The BLM denied Pogo Producing's twelve applications for permit to drill (APDs) in Section 23, T22S, R31E. This lease is immediately adjacent to the eastern boundary of the WIPP site. The APDs were denied because of possible impact on minable potash. Pogo Producing requested a U.S. BLM State Director Review. On March 18, 1992, the State Director of the U.S. BLM listened to a joint oral

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[12]EEG understands that this case may be in litigation and the EEG has no implied nor direct opinion in this case.

presentation by Yates, Pogo, and Texaco. As part of their arguments, Pogo estimated mining operations would not reach the subject area for 20-30 years. During the oral presentation, Pogo's representative and Yates' Engineer maintained that the total projected economic life of the field, including tertiary recovery, would be 15 to 20 years. Therefore, they argued, their oil and gas operation would be completed before potash mining operations reached the area.

However, the BLM noted that the possible deeper gas plays, the current stripper well policy, and the diligence of operations make this estimate of oil field life too short. The BLM maintained that the total economic life could be double the 15 to 20 year estimate (Woodard 1992). In other words, based on its own experience, the BLM anticipates an oil field life of 30 to 40 years.

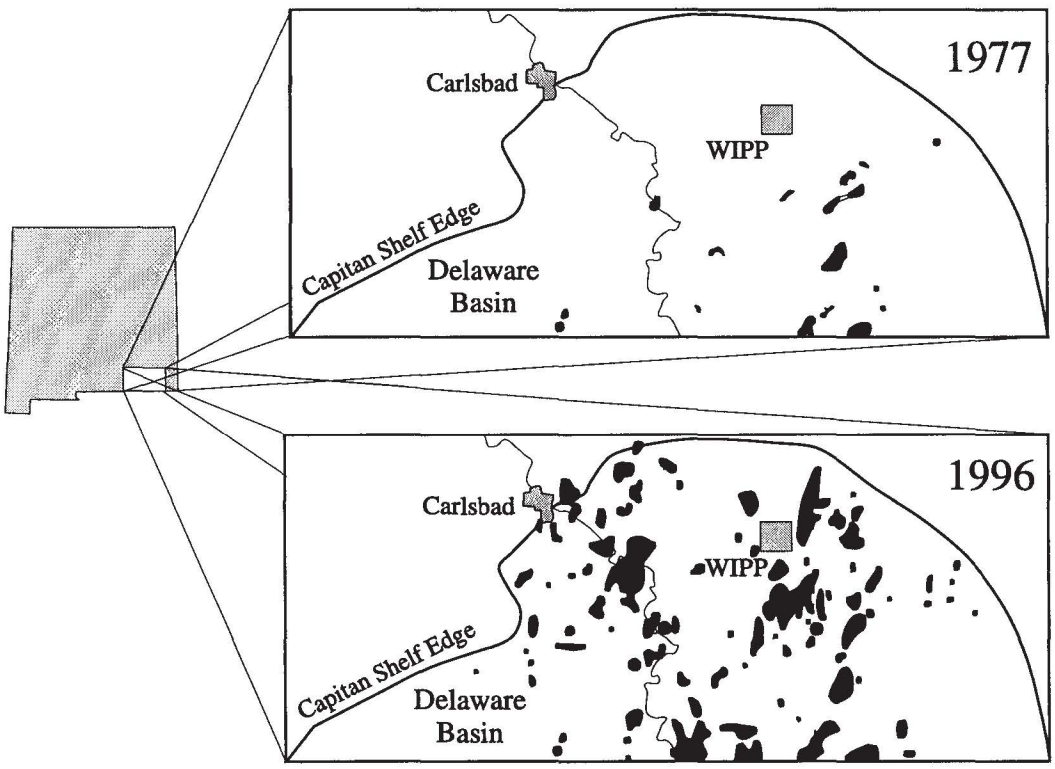

Figure 3-11. Delaware Mountain Group oil fields within the Capitan Shelf Edge of the Delaware Basin. After the Roswell Geological Society (1977) and Broadhead (1996).

Unfortunately, as indicated in Figure 3-11, the oil fields surrounding the WIPP having been only recently drilled, are not yet mature fields and cannot yet provide a direct determination of total field life. However, information in the literature and on public record for mature fields, in other areas of the Delaware Basin, suggest that primary production and waterflooding of the Delaware Mountain Group will generate at least thirty years and as much as fifty years of production after the initial development of a field. This suggests that the longer DOI/BLM estimate of 40 years (Woodard 1992) may be more correct.

Examples of successful waterfloods in the New Mexico portion of the Delaware Basin include Paduca, Indian Draw, and El Mar. The Paduca Field is an example of a successful waterflood that has been in production for over 30 years.

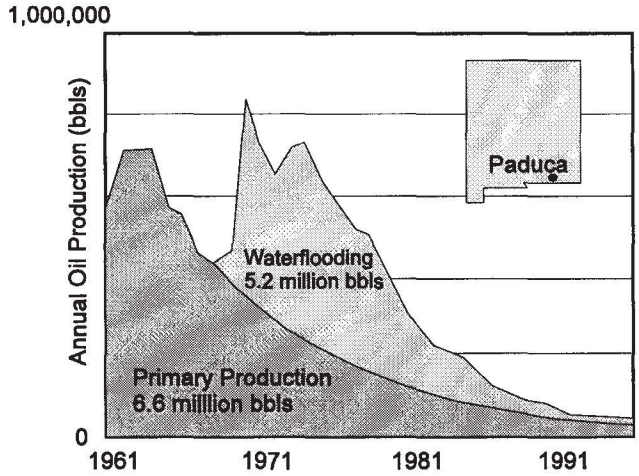

Figure 3-12. Production from Paduca Field. (Broadhead et al. 1995, Figure 38)

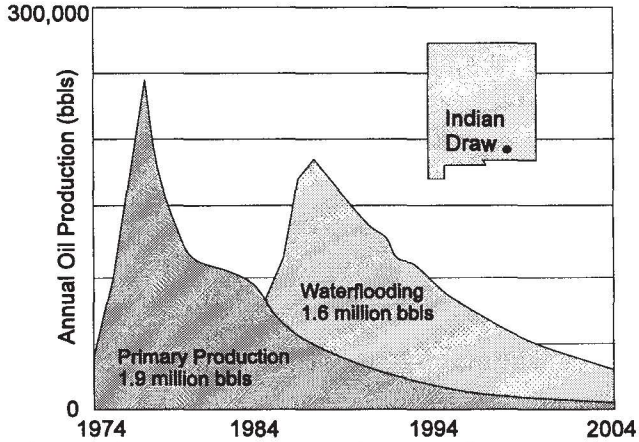

Figure 3-13. Production from Indian Draw. (After Broadhead et al. 1995, Figure 39).

Based on more than twenty years of actual production, including waterflooding initiated in 1980, the projections for the Indian Draw Field also indicate an anticipated oil field well life beyond 30 years.

One company operating in the Livingston Ridge area adjacent to the WIPP has submitted an affidavit which tends to support the position of a maximum of twenty years of operation (Boneau 1992, 2). Yates Petroleum maintains that oil and gas can be produced before any potash mining begins in this area (Boneau 1992, 2; Carroll and Bogle 1995, 33). As Broadhead (1995, XI-16) noted, Yates multiple zone completion practices are different from other operators in the area. Boneau states that Yates can complete primary and secondary development within 12 to 15 years. In the event of tertiary recovery, such as CO_2 flooding, the time would be extended by about five years for a maximum oil field life of twenty years. However, attorneys for Yates maintain that if there is waterflooding, "... the time to produce both primary and secondary oil should be in the range of 30 to 35 years" (Carroll and Bogle 1995, 33).

Comments by the University of Oklahoma Petroleum Engineering Professor Ron Evans at the EEG workshop tend to support oil field lifetimes closer to forty years:

> I will make this statement based on my experience in areas of Oklahoma. I do not believe that you are going to see oil production in the Delaware Basin cease totally in the next 20 years. I don't think that is going to happen. The tendency is like the food chain. You have the little people and you have the big people. Eventually it's the little people that are going to have that area and they'll tend to operate longer than say an Arco or Mobil would. I do not believe, for oil in the Delaware Basin, that production will cease within 20 years. I think it will be there 40 years from now because it will be in the hands of small operators.

3.2.5.2 Avalon Waterflood

Exxon (Bruce 1995c) filed for approval of an enhanced oil recovery project for the proposed Avalon Delaware Unit on May 9, 1995. The Avalon Field is about eight miles west of the potash area, hence the application is not encumbered by

the presence of potash. Specifically, Exxon proposes to inject water into the Cherry Canyon and Brushy Canyon members of the Delaware Mountain Group to promote oil recovery. Cantrell and Kane (1993) describe the geology and history of primary production in detail and note average permeabilities of 1.5 millidarcies (md) for the upper Cherry Canyon Formation and 1.1 md for the lower Cherry Canyon and upper Brushy Canyon Formations.

As noted in the unitization proposal (Bruce 1995b), Exxon projected that a waterflood would extend the producing life of the unitized formation beyond the year 2030. As Exhibit #3, Exxon plotted projected waterflood operations beyond the year 2040 for a field that began oil production in 1983. In terms of total field life, Exxon projects this field will be producing for at least fifty years.

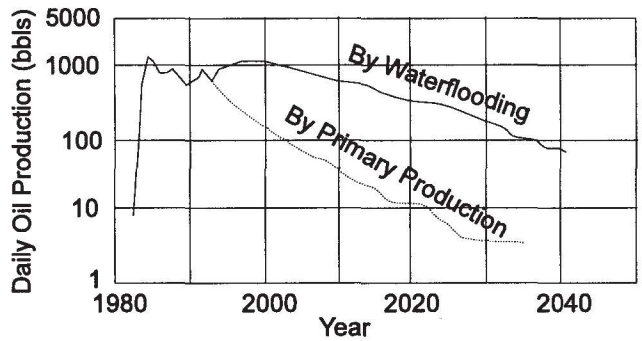

Figure 3-14. Waterflood vs. continued Primary Recovery at the Avalon Field (After Bruce 1995c).

3.2.5.3 Twofreds Waterflood and CO_2 Flood

The Twofreds Field, discovered in 1957 and developed by Mobil, is another example of the sequence of events, problems, and production longevity that might be anticipated for oil fields in the vicinity of the WIPP. The Twofreds is about 3/4 mile wide and is about five miles long with a net thickness averaging about 16 feet (5 m).

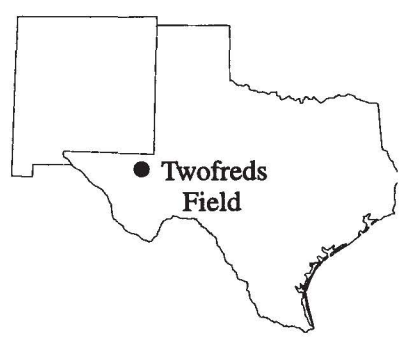

Figure 3-15. Location of Twofreds Field.

The Twofreds Field, like other Delaware fields, has always produced large volumes of water. After six years of primary production, a pilot water injection project with four injection wells was initiated in May 1963. The Twofreds was the first unitized waterflood in the Delaware Basin (Kirkpatrick et al. 1985). Success of the pilot project led to a full scale waterflood with 21 additional injection wells brought on line in January 1966. The waterflood project showed that oil from a Delaware reservoir with a high water cut could be recovered profitably (Jones 1968).

Early estimates anticipated that the Twofreds field would be depleted by 1975. However, carbon dioxide flooding extended the productive life of this field. HNG Fossil Fuel Company acquired the field from Mobil in 1973 for the purpose of initiating a carbon dioxide flood.

At the time of acquisition by HNG, most of the wells were in poor mechanical condition. Only 12 of the 89 wells were producing. Total field production ranged between 150 and 160 bbls oil per day. When the best producing well quit, total field production dropped to 100 bbls oil per day. There was a hole in the casing of the failed well. Many of the other production wells had been abandoned with rods, tubing, and other junk left in the well bores. And although the injection wells had been in waterflood service less than ten years, many had to be reworked to correct channelling problems. In some cases, the water had fingered through some zones, causing channels and leaks around the casing. These had to be repaired to prevent carbon dioxide from leaking out of the productive zone (Wash 1982)

By design, the Twofreds carbon dioxide injection wells were operated very close to the fracture pressure. Surface injection pressures were maintained at 1400 psi which resulted in a downhole bottom pressure of 3,000 psi, only about 100 psi below the fracture pressure. In describing the automatic pressure controls, the field superintendent, W.C. Mason noted:

> We walk a fine line between injection pressures and fracture pressures. If we were to exceed the fracture pressures, the gas would channel up the pipe and get out of zone. Therefore, we'd lose the drive off that well and all the oil that would have been pushed by the CO_2 (Wash 1982).

From 1957 to 1973, primary recovery produced 6.6 million bbls oil. From 1963 to 1973, secondary recovery produced 2 million barrels oil. By 1982, carbon dioxide flooding had produced an additional 2 million barrels of oil (Wash 1982). Carbon dioxide flooding increased oil recovery from 160 bbls oil per day to 1,000 bbls oil per day.

The purpose of the Twofreds carbon dioxide flood was to demonstrate economic feasibility. The field continued to produce based on its economic merit (Kirkpatrick et al. 1985) and demonstrated that carbon dioxide can economically recover tertiary oil from a depleted, waterflooded Delaware sand reservoir (Flanders and DePauw 1993). As of 1993, oil production from the Twofreds was averaging about 500 bbls oil per day (Flanders and DePauw 1993). The Twofreds Field clearly shows that even in a field where the reservoir energy is quickly depleted, fluid injection can improve oil production and add decades to the productive life of a Delaware Basin oil field.

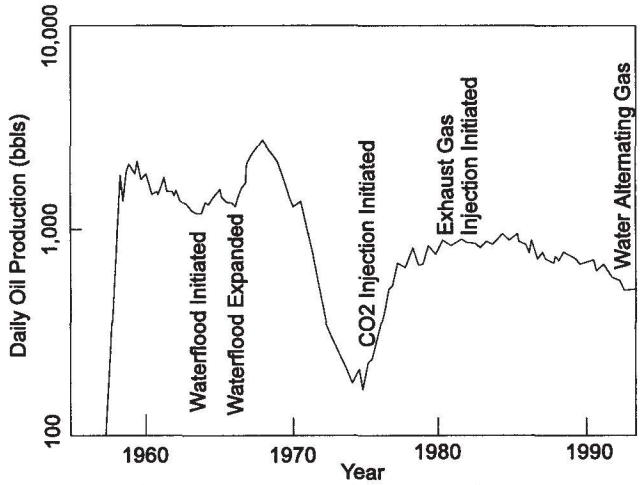

Figure 3-16. Production history of Twofreds (After Flanders and DePauw 1993).

3.2.5.4 El Mar Waterflood and CO_2 Flood

Independent operators continue to explore ways to extend the life of oil field production in the Delaware Basin. The El Mar has been producing from the Bell

Canyon Formation of the Delaware Mountain Group by primary recovery since 1959 (Porter 1966) and by waterflooding since 1968 (Broadhead et al. 1995).

In 1988, Union Royalty purchased the El Mar Unit from Texaco and others. In 1993, the unit was a mature waterflood producing about 140 bbls oil per day. Union Royalty planned to increase production to 2,000 bbls per day using carbon dioxide flooding. In exchange for an interest in the produced oil, Amoco would supply carbon dioxide through a pipeline to be built by Enron from the Dollarhide Field (Moritis 1993). If the success of the Twofreds project is any indication, the El Mar, which has been producing for 37 years can anticipate two or three additional decades of production.

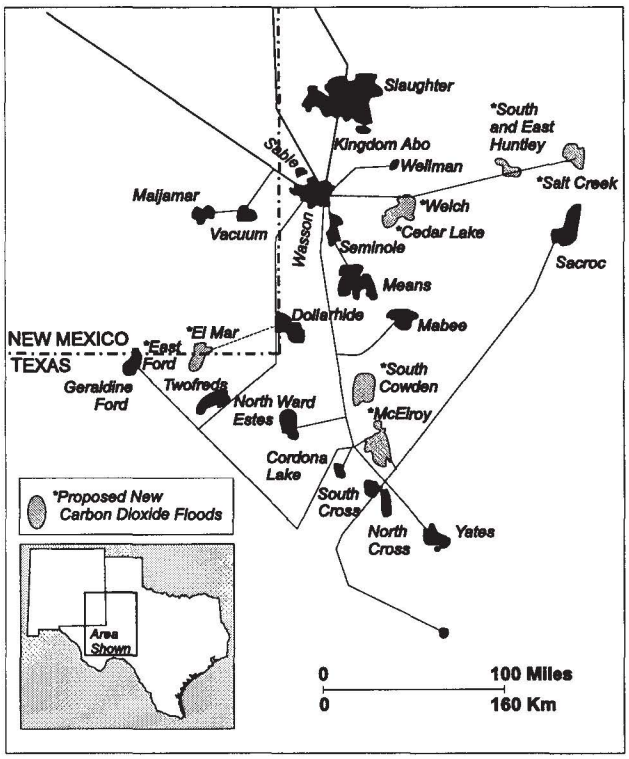

Figure 3-17. Permian Basin main CO_2 pipelines and CO_2 floods (Moritis, 1993).

3.2.6 Waterflood Volumes Around the WIPP

Lori Dotson maintained that waterflooding would not be a problem for the WIPP because such activity, if it occurred, would not be on the same scale as the Rhodes-Yates Field or the Vacuum Field waterfloods. There was disagreement about the amount of water needed to waterflood the oil fields surrounding the WIPP. Matthew Silva suggested that at WIPP, for ten million barrels of oil recoverable by waterflooding, 100 million barrels or more of injected water would

be needed. Stoelzel questioned whether that amount of water would be used for such small pools of oil.

Waterflooding in the vicinity of the WIPP is just beginning and, thus far, experience is limited to pilot pressure maintenance programs. The proposed Avalon Unit provides insight into the anticipated amount of water that is needed to recover oil by waterflooding the Cherry Canyon and Brushy Canyon members of the Delaware Mountain Group. This field lies approximately eight miles west of the potash enclave and is not constrained by the presence of potash. At Avalon, Exxon, has calculated that an additional 8.2 million barrels of oil (Bruce 1995c) will be recovered by injecting 141 million barrels of water through nineteen injection wells. Hence, the anticipated ratio of water injected to oil recovered, for the forty-year life of the project, is 17.2.[13]

For the one mile band surrounding the WIPP Site, Broadhead estimated 13.8 million barrels of the proven and probable crude oil reserves that could be recovered by waterflooding. Assuming the Avalon injection ratio of 17.2, for the life of such a project, one can estimate the volume of injected water will be 237 million barrels of water.

Texaco's Rhodes-Yates Lease was two miles away from Hartman's Bates Lease. Assuming that 29 million barrels of oil can be recovered by waterflooding (0.66 million barrels oil per section) and an injection ratio of 17.2 barrels water per barrel oil, for a two-mile band about WIPP, 500 million barrels of water could be injected over the life of these waterfloods. Of course, this simple estimate of future waterflooding must be viewed with caution. It is based on the estimated performance of an analog and is limited to the extrapolation of only proven and

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[13]The capital cost for the waterflood facilities at Avalon is estimated at $14.4 million and the estimated value of incremental production recovered from this project is estimated at $123 million based on a crude oil price of $15/ barrel (Bruce 1995a, 3).

probable reserves. It does not include possible reserves or undiscovered reserves of oil and gas underneath potash deposits.

Nonetheless, how does an anticipated 500 million barrels of water injected in the vicinity of WIPP compare with the Rhodes-Yates Field? At Rhodes-Yates, from 1964 through 1991, Texaco had injected approximately 41 million barrels of water through eighteen injectors (Hartman 1993, 5). This simple comparison strongly suggests that WIPP will eventually be surrounded by waterflood operations at least on the scale of the Rhodes-Yates Field and demonstrates that the two are comparable.

Actually, the pressure maintenance programs underway in the immediate vicinity of WIPP are already injecting far greater volumes of water than was injected in the pilot pressure maintenance program at Texaco's Rhodes-Yates Unit. Water from the two pilot injection wells at Rhodes-Yates totaled two million barrels from 1964 to 1974 or approximately 100,000 barrels water per well per year for a ten year period. Pogo Producing plans to inject 365,000 bbls of water per year into one well one mile east of the WIPP as part of its pilot pressure maintenance program in the Livingston Ridge Field.

At the Cabin Lake Unit, at the northwest corner of the WIPP Site, Phillips Petroleum has already begun operating two pressure maintenance wells. Water injection for pressure maintenance was initiated at the James A Well No. 12 (Sec 2, T22S, R30E) on February 18, 1992, and the James A Well No. 3 (Sec 2, T22S, R30E) on November 8, 1993 (Telford 1995). The volume of water injected through the James A Well No. 12 was 945,000 bbls for 1992, 1,121,000 bbls for 1993, and 738,000 bbls for 1994. The volume of water injected through the second pressure maintenance well in this area, the James A well No. 3 was 618,000 bbls for 1994. Based on the 1994 figures, these two wells are averaging approximately 1.4 million bbls water injected per year compared with 200,000 bbls water injected per year through the two pilot pressure maintenance wells at

Rhodes Yates. Furthermore, within ***three years*** of the initial operation, these two wells at the northwest corner of the WIPP Site had already injected four million barrels. This is more than twice the amount of water that was injected into the two pilot injection wells at Rhode-Yates in the ***ten year*** period following the initial operation of those wells. These observations strongly suggest that for the WIPP, the large scale waterflooding scenario cannot be ruled out on the basis of insufficient water injection.

In evaluating potential scenarios for the WIPP, the Hartman vs. Texaco case also demonstrates the need to consider the experience of other waterfloods despite any difference in size, in conditions, or in persons involved. Texaco argued to "exclude testimony relative to events or matters occurring in the waterfloods other than the Rhodes Yates waterflood, and to prohibit reference to other waterfloods by counsel for plaintiffs" (Lanphere and Sullivan 1994c; 1994d). Specifically, Texaco's attorneys maintained:

> On the other hand waterflood areas studied with respect to the 1977 hearings were larger waterflood projects than Rhodes Yates....
>
> The events in this case are vastly dissimilar in many respects to the events in the earlier waterfloods. There are fewer wells in the present field than were drilled in the earlier fields (Lanphere and Sullivan 1994d, 3,5)

Hartman's attorneys countered with the following argument:

> Texaco seeks to exclude by its Motion a wealth of data which correlates waterflows in Lea County to waterflood operations. The correlation is based upon public record documents which were generated by, among others, Texaco. The documents indicate that in the mid-1970s the New Mexico Oil Conservation Division determined that waterflood operations were causing waterflows, caused various operators, including Texaco, to establish committees to look into the issue, investigated specific injection

> wells and other aspects of waterflood operations in order to deal with the problem and never investigated naturally occurring sources of water as a potential explanation for waterflows which began to be reported after the start up of waterflood operations. The evidence shows that such waterflows were not randomly distributed, but are strongly correlated to waterflood operations (Gallegos and Condon 1994, 2).

In evaluating potential scenarios, the WIPP project needs to fully consider the experience of other waterfloods, particularly in light of the experience of oil fields overlain by the Salado. Such experience should not be rejected on the basis of difference in size (larger or smaller), differences in conditions, or differences in persons involved. There appears to be a technical basis as well as legal arguments for such consideration.

3.2.7 Availability of Water

Will there continue to be enough water for secondary recovery? Ron Evans commented on the increasing availability of water for oil field operations.

> If you look at water production in the United States, it has been going up significantly faster than overall oil production. We are producing more and more water in the United States than we ever have, in the oil producing regions of the United States.

More specifically, the volumes of water already being injected in the Delaware Basin, either for salt water disposal or pressure maintenance, do not hint at any water shortages for the purposes of oil field waterflooding. For example, the David Ross "AIT" Federal #1 salt water disposal well approximately one mile east of the WIPP Site typically injects between 80,000 and 100,000 barrels of brine per month. Other wells in the vicinity each typically inject volumes ranging between 10,000 and 100,000 barrels per month (Curry 1995; Hunt 1995; Garcia 1995;

Horsman 1995). Presumably, that water could be made available for waterflooding as reservoir pressures decline.

3.2.8 Formation and Well Bore Damage by Nitroglycerin Stimulation

Dan Stoelzel and Lori Dotson suggested that the practice of nitroglycerin blasting caused extensive formation and well bore damage in Rhodes-Yates Field and the Vacuum Field. They further maintained that because such practices are no longer used, there will be no such completion problems in the vicinity of the WIPP. The DOE has also adopted the position that the problems with Texaco's well completions in the Jal area resulted, in part, from the use of nitroglycerin blasting to stimulate the formation (McFadden 1996). However, the comments of Ron Evans tend to contradict the notion of extensive formation damage by nitro-fracing:

> The reason nitro-frac went out of business is because hydraulic fracturing is a superior stimulation technique. Hydraulic fracturing will give you much greater productivity increases than any nitro-frac ever did and that's well documented. Nitro-fracturing, as it was carried out in the late 40s and early 50s, did not destroy the cement shield. You can do the calculations and show, they place that little charge in the center of the formation and the maximum you could get would be of the order of about seven to ten feet zone of change in the radial direction and on the order of 15 feet in the vertical direction. That never even got you out of the Yates formation.

Hartman maintained that the excessive injection pressures in Texaco's Rhodes-Yates waterflood caused the salt water blowout on the Bates Lease. In commenting on the history of waterflood problems in New Mexico, Ramey (1995, XI-2) also states that water probably escaped from the injection zone and into the salt formations as a result of old improperly cemented and plugged wells and excessive injection pressures in oil field waterflood operations. These observations by Evans, Hartman, and Ramey, strongly suggest that stimulation by

nitroglycerin fracturing was not the source of the problem. Rather, it was argued that excessive waterflood injection pressures were the problem (Hartman 1993; Van Kirk 1994).

3.2.9 New Injection Well in Excess of WIPP Lithostatic Pressure

Pogo Producing recently requested and received approval from the New Mexico Oil Conservation Division to operate a pressure maintenance well one mile east of the WIPP site at a maximum surface injection pressure of 1410 psi (9.7 MPa) (LeMay 1995b). Public notice was given and a hearing was held on November 16, 1995. The results of the hearing included the following findings:

> (5) IMC Global Operations, Inc. (IMC), a potash operator in this area, appeared at the hearing and expressed concerns about permitting injection wells in close proximity to potash mining operations. Specifically, IMC is concerned that injected fluid will escape or otherwise migrate from the proposed injection interval into potash bearing formations.
>
> (6) Testimony presented in this case indicates that potash mining operations occur at depths of approximately 1,300 feet to 2,000 feet.
>
> (7) Evidence and testimony present by the applicant indicate that the proposed pilot pressure maintenance project is located:
>
> > a) within the Known Potash Leasing Area as describe within Division Order No. R-111-P;
> >
> > b) directly adjacent to a potash lease which encompasses portions of Section 3 through 5, 8 through 11, 13 through 14, 23 through 24, and 26, Township 22 South, Range 31 East, NMPM. The ownership of this potash lease is undetermined at this time due to ongoing litigation between IMC Global Operations, Inc. and Yates Petroleum Corporation;
> >
> > c) approximately eight miles from IMC's existing potash mine workings; and,

d) one mile from the outer boundary of the Waste Isolation Pilot Project (WIPP)

(8) The applicant notified the Department of Energy (DOE) of its application in this case, however, no representative of that agency appeared at the hearing. (LeMay, 1995b).

The findings also state that injection at an initial surface injection pressure of 1,410 psi should not result in the fracture of the proposed injection interval or confining strata. The well is designed such that the intended horizon for injection is approximately 7,000 feet below the surface.

But in the event of a leak, channeling behind casing, or movement through a vertical fracture, can brine be injected into the Salado Formation? In such an event, under the sustained pressure of a waterflood, what is the fracture pressure of the Salado Formation at the WIPP horizon and what is the hydrostatic pressure of the injected fluid at the WIPP horizon?

The lithostatic pressure at the WIPP horizon is 14.9 MPa (2160 psi). Assuming a brine with a specific gravity of 1.1 and an approved surface injection pressure of 9.7 MPa (1,410 psi), the injected brine can exert a hydrostatic pressure of approximately 16.8 MPa (2440 psi) at the WIPP horizon.

With respect to anhydrite or interbed fracturing, the WIPP conceptual model assumes that repository fracturing or dilation of existing fractures will be less than the lithostatic pressure (Howarth et al. 1995, Section 2.1.2.2). That assumption largely reflects experimental evidence in the excavated areas where the stress fields have been substantially changed. The anhydrite at the injection well bore may or may not be fractured, either naturally or by the drilling activity. Interbeds contain natural fractures which may be partially healed (U.S. DOE 1995, 6-73).

Experimental results indicate the fracture pressure for intact rock to be higher than lithostatic (Beauheim et al. 1993). However, the experiments of Beauheim et al. (1993) were designed to last only a few minutes, hence, they subjected the rock to a very rapid increase in fluid pressure. An injection well operates on the order

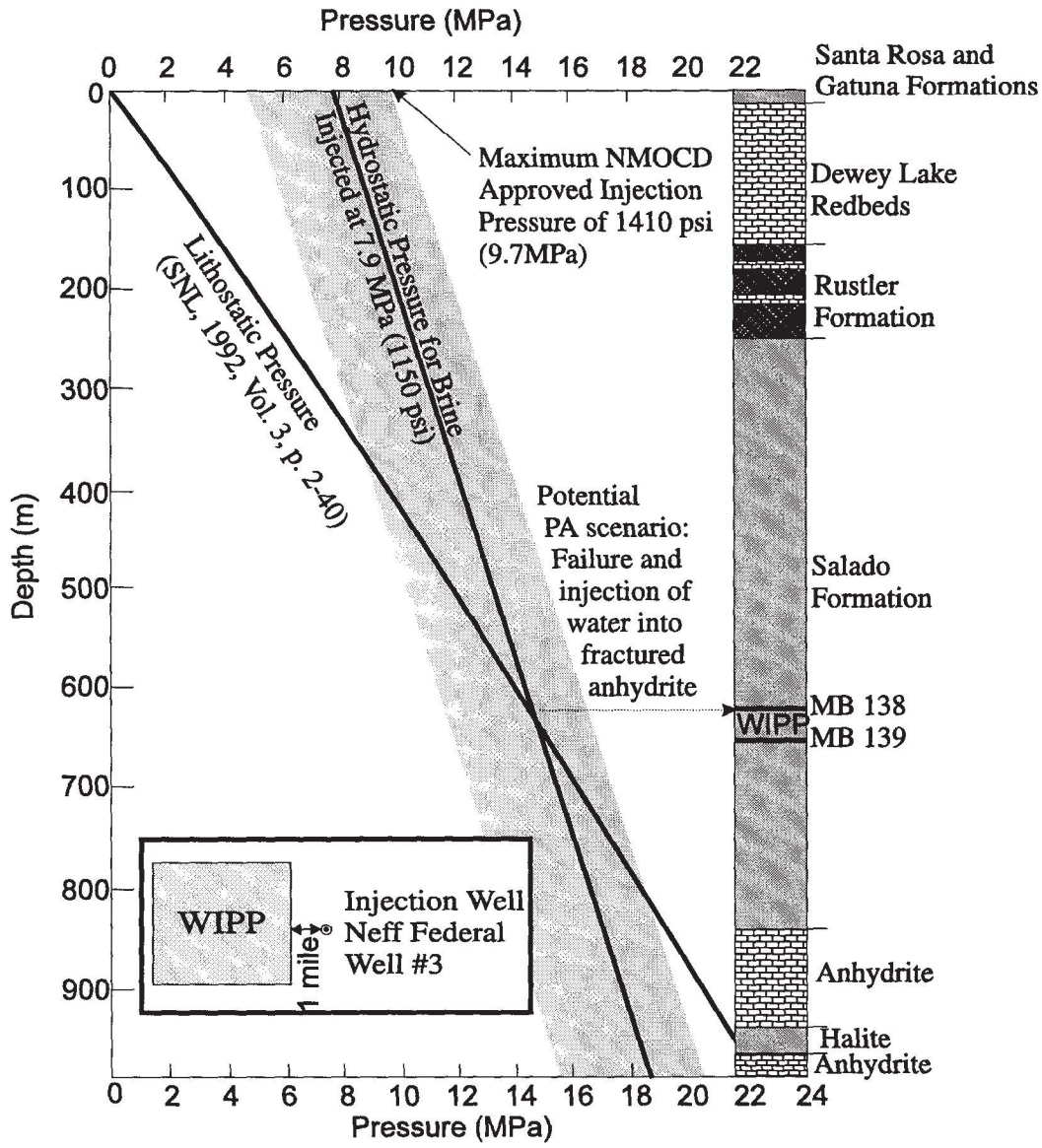

Figure 3-18. Approved Injection Pressure for Neff Federal Well #3 and Potential PA Scenario.

of years or decades. For fracture initiation and vertical fracture propagation, fracture pressures are lower for formations penetrated by an invading fluid (Haimson and Fairhurst 1967, Fairhurst 1968). Atkinson (1987, Chap. 4 and 5) also cautions about subcritical crack growth in the presence of a chemically active environment.

Rather than speculate on the potential for creating a new fracture or propagating an existing fracture in an anhydrite or other marker bed under pressure for a long period of time, this report notes that a pressure maintenance well, approximately one mile from the WIPP, has been approved to operate at an injection pressure 1.9 MPa (280 psi) above the lithostatic pressure at the WIPP horizon. Such a well typically injects brine over a period of several years. The plot of lithostatic pressure and hydrostatic pressure strongly suggests that, in the event of communication, fluid can be potentially injected into the anhydrite beds of the Salado Formation very near the WIPP horizon.

3.3 Regulations and the Salt Isolation Casing String

As noted by Dan Stoelzel, new state regulations require a salt isolation casing string for all wells drilled in the WIPP area. There are no specific oil and gas regulations that apply specifically to WIPP (Ramey 1995). Rather, the WIPP Site is located within the Potash Area near the eastern boundary. As a result of NMOCD Order R-111-P, signed April 21, 1988, all wells completed within the potash area must have a salt isolation string intended to protect the salt section from the intrusion of water and oil and gas (Ramey 1995, IX-1).

At the workshop, Armando Lopez (BLM) noted that a salt isolation string is not required for wells approximately one mile east of the WIPP Site. Exhibit A of R-111-P shows that Sections 26 and 35 (T22S, R31E) lie immediately adjacent to the WIPP site but are not part of the Known Potash Leasing Area. Hence, it appears the salt isolation string may not be required for all oil and gas wells completed in the vicinity of the WIPP.

In 1980, the Department of Energy intended to prohibit waterflooding within former control zone IV (U.S. DOE 1980, 8-4). The DOE surrender of that control was not based on any protective state or federal regulations, but on a report (Brausch et al. 1982) that incorrectly concluded that there would be no waterflooding because there was minimal recoverable oil.

As noted above, the state regulations for completing wells in the potash enclave are not specific to WIPP. In fact, R-111-P (LeMay et al. 1988) addresses only the incompatibilities between the activities of oil and gas production and potash production and does not mention WIPP. With respect to federal regulations, the Secretary of Interior makes it clear that one intent of the order is "to prevent the infiltration of oil, gas, or water into formations containing potash deposits or into mines or workings being utilized in the extraction of such deposits" (U.S. DOI 1986, III.A.4) However, this order is not intended to protect WIPP. Further, despite the salt isolation string requirement, federal and state agencies still restrict drilling for oil and gas through potash reserves or near potash mining operations.

Rather than rely on the intent of new regulations coincidental to the WIPP area, the DOE should fully consider the actual experience and implementation of existing regulations with respect to fluid injection. Such regulations have been in place for decades and provide a measure of the reliability. For example, the enabling orders for the Rhodes Yates waterflood (Campbell et al. 1964; Cargo et al. 1969; Ramey 1977) required operating in accordance with Rules 701, 702, and 703 (Hartman 1993, 4). Rule 702 requires cementing and casing of injection wells to prevent the movement of fluids out of zone. Rule 703 requires operation and maintenance practices to assure no significant fluid movement through vertical channels adjacent to the well bore. Further, the entire operation, including producing wells, must be operated and maintained to confine the injected fluids to approved intervals. The documented problems with the Rhodes Yates waterflood (Hartman 1993; Hererra 1995) and with waterfloods and salt water injection throughout the southeast New Mexico (Ramey; 1976; U.S. GAO 1989; Bailey 1990; Krietler 1994) clearly indicate the limitations of taking credit for state or federal regulations, new or old, for protecting WIPP.

3.4 Safety Analysis Report and Water Injection

Bill Bartlett (EEG) voiced concern at the workshop that waterflooding may need

to be considered in the Safety Analysis Report (SAR) for operations. George Dials noted that waterflooding should be considered in the Final Safety Analysis Report only if data exists which shows a high probability event that could adversely affect the WIPP during the 35 year operating life. George Dials added "there is waterflooding going on in the vicinity of the WIPP as has been discussed today. And we see no great increase in brine inflows and no great increase in moisture or anything else in the facility."

It appears that even small increases in the water inflow into the facility have an impact on the continuous air monitors. WIPP operations rely on continuous air monitors to detect a release of radionuclides. This detection is needed to divert the flow of any contaminated air through the HEPA filters. Water flowing into the exhaust shaft at a depth of approximately 50 to 100 feet (16 to 33 m) was identified as a potential problem for continuous air monitoring. In a report on continuous air monitoring, Bartlett and Walker (1996) commented that air flow through the sampling filter would be reduced as salt aerosol and moisture combine and collect on the filter. Low air flow through the filters at an underground air sampler was observed in 1994 and 1995. Moisture was the likely cause, strongly suggesting that water leakage problems can influence CAM performance (Bartlett and Walker 1996, 39).

Samples collected near the exhaust shaft collar by the DOE have been analyzed (Dials 1996).[14] The samples were analyzed for metals and inorganic compounds, but there was no analyses for hydrocarbons. Although there has been an effort to determine the source of the water (Westinghouse 1995, 1996a, 1996b, 1996c), it appears that the source of this water remains unknown. Hence, questions remain. What is the source of the water? At what rate of water inflow does the intruding

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[14] The inflow of water into the exhaust shaft was not discussed at the EEG workshop.

water create a problem for the air sampling system? And what happens when the water-flooding and brine injection activities become common place around the WIPP?

3.5 1995 DCCA - Features, Events, and Processes

When asked by Don Hancock (SRIC) how Sandia was going to determine the probability of waterflooding, Peter Swift (SNL) clarified that a feature, event, or process can be eliminated on the basis of one screening criterion. The three criteria of probability, consequence, and regulatory, are not all applied to each case. For example, if waterflooding is eliminated on the basis of "regulatory" criteria or "consequence" criteria, then there is no need to assign a probability. There is no need to calculate a consequence for an FEP that has been eliminated on the basis of another criteria. He also commented that he was not prepared to say how the project was going to screen waterflood FEPs. But he felt that an injection well failure at markerbed 139 with fluid migrating towards the WIPP site would be a low probability event that would be difficult to quantify.

On July 31, 1995, six weeks after the EEG workshop on waterflooding and salt water disposal, the DOE submitted a Draft Compliance Certification Application to demonstrate DOE met the requirements of the EPA Standards for the disposal of transuranic waste. As in 1991 and 1992, fluid injection was ***not*** included in the performance assessment calculations. All fluid injection was screened out on the basis of "regulatory guidance" (U.S. DOE 1995, 6-38). Furthermore, some human initiated events such as recent and ongoing fluid injection outside the controlled area were screened out on the basis of low consequence. No supporting documentation was supplied. Supporting documentation would be supplied with the final compliance application (U.S. DOE 1995, SCR-72).

The 1995 DCCA maintains that the screening procedure "is similar to that proposed by Cranwell et al. (1990, 5-10) and used in the 1991 and 1992 WIPP performance assessments" (U.S. DOE 1995, 6-2). However, Cranwell et al.

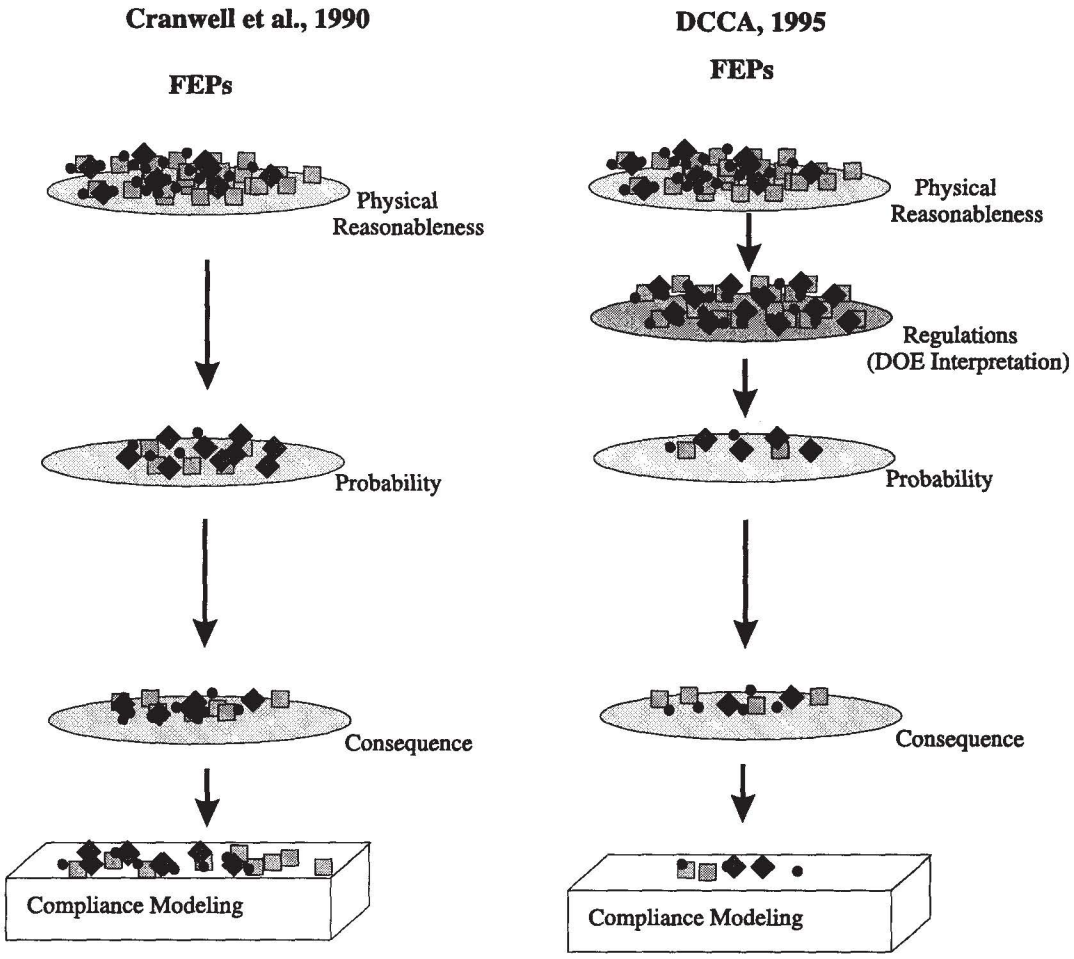

Figure 3-19. "Regulatory" sieve unique to WIPP.

(1990) did not discuss a "regulation" sieve to eliminate otherwise viable scenarios from consideration. This sieve is unique to WIPP (SNL 1992, Vol. 2, 4-3). Further, an inspection of the "regulation" sieve reveals it to be an interpretation of the non-binding guidance by the WIPP Performance Assessment Department which allows the WIPP Performance Assessment Department the latitude to eliminate any inadvertent human activity that could result in a consequence greater than those of exploratory drilling (SNL 1992, 4-4).

3.6 EPA Final Criteria (40 CFR 194) and Compliance Application Guidance

As required by the 1992 WIPP Land Withdrawal Act, the EPA published Criteria,

(U.S. EPA 1996a) for determining if the Waste Isolation Pilot Plant will comply with the EPA's environmental radiation protection standards for the disposal of radioactive waste. The EPA also published the Compliance Application Guidance (U.S. EPA 1996b) as a companion to the final rule.

The EPA Final Criteria for the disposal of transuranic waste requires the DOE performance assessment to address the issue of waterflooding and salt water disposal with the following language:

> Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, ***but shall not be limited to*** [15], existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities (U.S. EPA 1996a, 40 CFR 194.32 (c)).

As stated in the EPA Compliance Application Guidance (U.S. EPA 1996b):

> EPA recommends that the terms "near future" and "soon after disposal" for oil and gas drilling be considered to consist of the expected lives of the oil and gas fields in existing leases that can be reasonably expected to be developed in the vicinity of the WIPP.
>
> For mining, the terms "near future" and "soon after disposal" should be applied to the estimated lives of existing mines and plans for new mines in the vicinity of WIPP. EPA recommends that DOE use minable reserves in estimating mine lives and the extent of potential mining. When establishing the rate of growth for mines, DOE should consider both the

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[15]Emphasis added.

historical growth for mines and the potential for new mines that may be developed in the vicinity of WIPP.

3.6.1 Near Future

For the WIPP project, the DOE has already elicited expert opinion on the definition of *near future* with respect to the recovery of natural resources in the vicinity of a 10,000 year repository.

> For the Boston Team, the near future is 0-300 years after the lapse of institutional controls (100 years after closure). The Southwest Team used a 100-500 year period after closure for the near future while the Washington A Team use the first 200 years after the lapse of active controls. The Washington B Team also adopted a 200-year definition for the near future (Hora et al 1991, V-7).

With respect to current resource development, there appears to be a consensus among this group of experts that the near future includes at least a few centuries; certainly no less than three centuries after closure or at least 3% of the full regulatory period.

3.6.2 Federal and State Plans for Full Resource Recovery

Within two miles of the area withdrawn for the WIPP, the WIPP is surrounded by forty eight sections of federal and state lands. These public lands are managed by either the U.S. Department of Interior or the State of New Mexico. These lands are within the Secretary's Boundary (U.S. DOI 1986) for the potash area. In addition to federal policy (U.S. DOI 1986) for the management of federal lands in the potash area, the management of the federal lands are also subject to the Federal Land Policy and Management Act (FLPMA 1989). The state lands are subject to state regulations protecting natural resources, specifically oil, gas, and potash (LeMay et al. 1988).

With respect to federal lands, it is the stated intent of the Secretary of Interior (U.S. DOI 1986) to "adequately protect the rights of the oil and gas, and potash lessees and operators," (U.S. DOI 1986, 39425). FLPMA intends for "the public lands to be managed in a manner which recognizes the nation's need for domestic sources of minerals, food, timber, and fiber..." (FLPMA 1989, §1702(12)). In addition, FLPMA requires the management of federal lands "be on the basis of multiple use and sustained yield unless otherwise specified by law" (FLPMA 1989, §1701 (7)). "The term multiple use means the management of the public lands and the various resource values so that they are utilized in the combination that will best meet the present and ***future needs*** [emphasis added] of the American people" (FLPMA 1989, §1702(c)). The term multiple use also means "a combination of balanced and diverse resource uses that take into account the ***long-term needs of future generations*** [emphasis added] for renewable and nonrenewable resources...." Sustained yield is defined as "the achievement and management ***in perpetuity*** [emphasis added] of a high-level annual or regular periodic output of the various renewable resources of the public land consistent with multiple use" (FLPMA 1989, §1702(h)). By federal law, human activities in the resource rich areas surrounding the WIPP do not appear to be not limited to the ***near future*** and are not limited to ***the expected use of existing leases***.

The objective of the rules and regulations of the state of New Mexico "is to prevent waste, protect correlative rights, assure maximum conservation of the oil, gas and potash resources of New Mexico, and permit the economic recovery of oil, gas, and potash minerals in the area hereinafter defined" (LeMay et al. 1988).

It is the policy and plans of both federal and state law to promote resource production on these public lands adjacent to the WIPP Land Withdrawal Area. None of the public lands adjacent to the WIPP have been withdrawn from resource development. Hence, the DOE application should assume that potash, crude oil, and natural gas will be allowed to be fully developed, including fluid injection activities necessary for resource recovery.

3.6.3 Oil and Gas Resources

In addition to the oil and gas reserves estimated by Broadhead et al. (1995), the application should also reflect that oil and gas reserves have not yet been quantified on many sections surrounding the WIPP site due to the U.S. Department of Interior and the State of New Mexico restrictions on drilling for petroleum in the potash deposits (U.S. DOI 1986; LeMay et al. 1988). Fifteen sections within the two mile band surrounding the WIPP do not have a single oil and/or gas well drilled into them. Or in terms of forty-acre units, of the 768 forty-acre units within two miles of the WIPP Boundary, 652 of the units do not yet have any oil or gas wells. In other words, 85% of the area immediately surrounding the WIPP has yet to be directly tested for oil and gas. The oil and gas leases in many of these areas have been assigned, but permission to drill has been denied and/or is in litigation (Burski 1994). Similarly, potash reserves are in litigation (Parker 1993) or have yet to be assigned although at least one potash company has stated that it intends to mine these reserves on public land (Morehouse 1995).

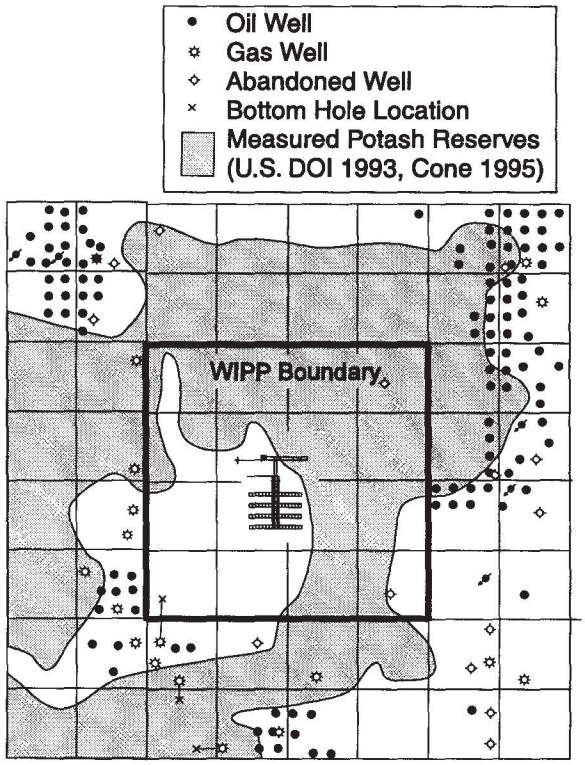

Figure 3-20. Actual oil, gas and injection well boreholes.

The nature of any resource recovery activity, including the oil and gas business, is such that today's non-economical resources often represent tomorrow's producible reserves. The application for a 10,000 year repository should reflect

an understanding of that principle of natural resource economics and can not limit itself to a simple assumption of current economic value. And as emphasized in the executive summary of the 1995 natural resources study (NMBM&MR 1995), the discovery of reserves of oil and gas can hinge simply on a better interpretation of well logs. Hence, current estimates of oil and gas resources reflect, to some extent, the limits of the current interpretation of well logs. Due to the nature of oil and gas production, as practiced throughout southeastern New Mexico, throughout the Delaware Basin, and in the vicinity of the WIPP, the existing federal plans and state plans inherently include salt water disposal and waterflooding throughout each and every federal and state section surrounding the WIPP Site.

3.6.4 Fluid Injection for 10,000 Years

The DOE application may need to consider fluid injection adjacent to the site and within the site for the full 10,000 year period. In the 1991 DOE elicitation of expert opinion on future activities in the vicinity of the WIPP, only one of four teams addressed fluid injection. This team was aware of the need to dispose of waste brine associated with oil production (Gordon et al. 1990, C-29), but was not aware of the extent of drilling for crude oil in the vicinity of the WIPP (Silva 1994, 28-35). Hence, the elicitation panel concluded that the current level of industrial activity in the WIPP area to be low (Hora et al. 1991, IV-10). Nonetheless, three members of the this team assigned probabilities for injection of waste brine associated with other industrial activities for the full 10,000 years. Further, the probability of a larger number of such injection wells was predicted to increase with time for the full 10,000 year period (Hora et al. 1991, Table IV-16).

3.6.5 Areal Extent of Delays in Oil and Gas Production

As to potential delays in oil and gas production and fluid injection due to the presence of minable potash, that issue is still in deliberation (Burski 1994).

Furthermore, there appears to be some disagreement as to what constitutes minable potash. The estimates of potash resources prepared by Griswold (1995a) for the New Mexico Bureau of Mines and Mineral Resources acknowledges federal policy but uses an economic limit which is different from federal policy, resulting in minable areas substantially smaller than federal policy. Cone (1995) later cautioned Griswold about BLM policy and experience. Griswold (1995b) subsequently acknowledges that his interpretation of the estimated extent of potash reserves is "conservative." According to Cone (1995), the federal position for minable potash is 4 feet by 10% for sylvite ("40" contour) and 4 feet 4% for langbeinite ("16" contour). Hence, the federal position on the actual area of minable potash, which could impact the near future activity of oil field production and fluid injection, is significantly larger than that mapped by the "55" contour for sylvite and the "37.5" contour for langbeinite in the natural resources study by the New Mexico Bureau of Mines and Mineral Resources (1995). Drilling for oil and gas may be delayed over a much larger area, thus extending the time for such near future activities.

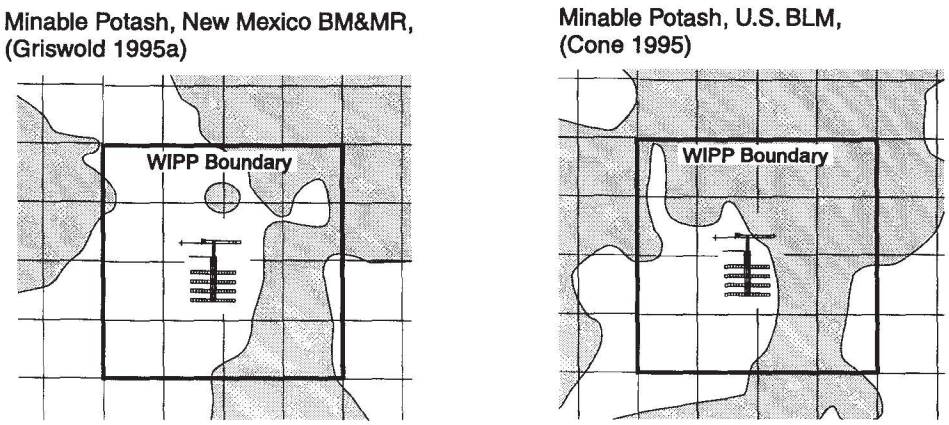

Figure 3-21. Areal extent of minable potash as determined by U.S. BLM and New Mexico Bureau of Mines and Mineral Resources.

3.6.6 Enhanced Oil Recovery by Carbon Dioxide or Gas Injection

The DOE application is sponsoring a new research effort that is exploring the use of pressure maintenance programs and advanced reservoir management to improve oil recovery from fourteen sands in the Brushy Canyon and Cherry Canyon members of the Nash Draw Unit (Strata Production 1996) in the potash enclave. One goal is to transfer the technology to oil and gas producers throughout the Permian Basin. The Department of Energy is sponsoring the project at an annual budget of 1.8 million dollars. The permeabilities in the sands are relatively low, ranging from 0.5 to 18 millidarcies. Although not stated in the progress report (Strata Production 1996), the low permeabilities strongly suggest that it may be necessary to inject a low viscosity fluid such as carbon dioxide or natural gas. Presumably, the Department of Energy is investing in this project, in the Delaware Basin, with the anticipation that such fluid injections will improve oil recovery. The DOE WIPP application should reflect this effort to enhance oil recovery in Delaware sands.

3.6.7 Summary

In summary, the DOE WIPP application to EPA can assume that for crude oil, there will be drilling on a minimum of forty acre spacings in the areas in litigation. There will also be drilling on a minimum of forty acre spacing in areas identified by Broadhead et al., (1995) known to contain proven and probable oil reserves, and there will be drilling into the fifteen yet to be explored sections within two miles of the WIPP. The extent of oil and gas resources remain to be determined. Experience has also shown that additional reserves are often discovered as a result of improvement in well log interpretation (NMBM&MR 1995). The DOE application needs to demonstrate an understanding of the economics of resource recovery and the concept of future reserves, an understanding of federal and state policy and plans regarding resource recovery on public lands, including pressurized fluid injection, an understanding of how

pressurized fluids can transport radionuclides to the accessible environment, and an understanding that the EPA intends that the repository curb the release of radionuclides to the accessible environment for a 10,000 year regulatory period, not just the near future. The application can realistically anticipate that salt water disposal activities and waterflooding, as practiced in the Delaware Basin and in southeast New Mexico, will take place throughout the area surrounding the WIPP. The application needs to consider other fluid injection, such as gas pressure maintenance, and needs to anticipate industrial waste injection over the full 10,000 year life of the repository.

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5. LIST OF ACRONYMS

ANPR	Advance Notice of Proposed Rulemaking
APD	Applications for Permit to Drill
BBL	Barrels
BLM	Bureau of Land Management
CAO	Carlsbad Area Office
CARD	Citizens for Alternatives to Radioactive Dumping
CFR	Code of Federal Regulations
DCCA	Draft Compliance Certification Application
DOE	U.S. Department of Energy
DOI	Department of Interior
EEG	Environmental Evaluation Group
EPA	U.S. Environmental Protection Agency
ERDA	Energy Research and Development Administration
FEP	Features, events, and processes
FLPMA	Federal Land Policy and Management Act
GAO	U.S. Government Accounting Office
GPM	Gallons per minute
MOU	Memorandum of Understanding
MPa	Megapascal
NAS	National Academy of Science
NMBM&MR	New Mexico Bureau of Mines and Mineral Resources
NMEMD	New Mexico Energy and Minerals Department
NMEMNRD	New Mexico Energy, Minerals, & Natural Resources Department
NMOCD	New Mexico Oil Conservation Division
NMPM	New Mexico Principal Meridian
OCD	New Mexico Oil Conservation Division
PA	Performance Assessment
PCs	Personal computers

LIST OF ACRONYMS (continued)

PSI	Pounds per square inch
RCRA	Resource Conservation and Recovery Act
SAR	Safety Analysis Report
SC&A	Sanford Cohen and Associates
SNL	Sandia National Laboratories
SWD	Salt water disposal
SRIC	Southwest Research and Information Center
TA	Temporarily Abandoned
TRU	Transuranic
USCA	United States Code Annotated
U.S. EPA	U.S. Environmental Protection Agency
U.S.G.S	U.S. Geological Survey
U.S. GAO	U.S. Government Accounting Office
VOC	Volatile organic compound
WIPP	Waste Isolation Pilot Plant

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EEG 64

REVIEW OF THE DRAFT SUPPLEMENT TO THE WIPP ENVIRONMENTAL IMPACT STATEMENT DOE/EIS-0026-S-2

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April 1997

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DOE/AL58309-64

REVIEW OF THE DRAFT SUPPLEMENT TO THE WIPP ENVIRONMENTAL IMPACT STATEMENT DOE/EIS-0026-S-2

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, is being constructed as a repository for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, continues the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the generator sites' compliance with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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OUTSTANDING CONCERNS

EEG has published reviews of the previous DOE Environmental Impact Statements (EIS) on WIPP including:

EEG-3 *Radiological Health Review of the Draft Environmental Impact Statement (DOE/EIS-0026-D) Waste Isolation Pilot Plant, U.S. Department of Energy*, August 1979

EEG-10 *Radiological Health Review of the Final Environmental Impact Statement (DOE/EIS-0026) Waste Isolation Pilot Plant, U.S. Department of Energy*, January 1981

EEG-41 *Review of the Draft Supplement Environmental Impact Statement, DOE Waste Isolation Pilot Plant*, July 1989.

Written comments also were provided to DOE on the Final 1990 Supplement to the EIS on WIPP in April 1990. The 1996 Draft Supplement to the EIS (SEIS-II), DOE/EIS-0026-S-2, was received on November 25, 1996, and this review contains our analysis of that document. The 90 day deadline for comments established by DOE was not adequate to do a thorough job since it was necessary to also review the final DOE Compliance Certification Application (CCA) as well as the Safety Analysis Report (SAR) in the same time frame.

Our principal concerns are as follows

- The long-term disposal impact of the Proposed Action is being addressed in much more detail through the DOE Compliance Certification Application (CCA) which provides one year for review. Evaluating alternatives to the Proposed Action outlined in the SEIS cannot be meaningfully addressed in sufficient detail in 90 days.

- Chapter 6 lists all regulatory agencies and the status of permits for WIPP. One regulatory agency is notably absent. It is DOE. The Department has the legal authority to self regulate operational activities at WIPP. The status of WIPP's compliance with DOE Orders or even a list of DOE Orders is conspicuously absent. Indeed, DOE has the authority to self-approve the Draft Supplement to the EIS but fails to describe the internal system to be used. As an example, the DOE long-term disposal calculations in the SEIS are approved by DOE and in the CCA by EPA.

- Parameters and analyses differ in the various DOE WIPP documents such as the SEIS-II, the Compliance Certification Application (CCA) and the Safety Analysis Report (SAR).

- The alternatives are not reasonably viable. As DOE notes, alternative #1 and alternative #3 are in violation of the WIPP Land Withdrawal Act. Alternative #2 exceeds the limits of RH-TRU in the NM/DOE C&C Agreement. The problems of underground stability in leaving the repository open for 150 to 190 years (which would also require new shafts and surface facilities) are not addressed. It would make more sense to complete WIPP and then propose a second repository, tailored to the unique needs of RH-TRU waste emplacement including limits on thermal loading and criticality. The SEIS should address this alternative.

- The alternatives include almost doubling the authorized waste volume, bringing non-defense TRU waste and commercial TRU waste. Increasing the curie inventory would increase the amount of transuranics allowed to be released.

- While several EEG documents are cited, there are a number of relevant EEG publications that the SEIS-II authors have not cited that are directly relevant to the environmental impact of WIPP.

- The text indicates that DOE has a need to dispose of all TRU wastes and does not consistently recognize that only defense TRU wastes can be disposed at WIPP according

to law. Transuranic wastes generated by non-defense activities or civilian nuclear activities of the Department are not eligible for disposal at WIPP. (This point is recognized later by DOE on page 5-7, lines 5 and 6). To avoid confusion, non-authorized waste issues should be clearly identified.

- The document acknowledges that the expected quantity of RH-TRU waste of 35,000 m^3 far exceeds the WIPP design capacity of 7,080 m^3. But the Basic Inventory Table for the Proposed Action shows 35,000 m^3 and the Draft PEIS shows <u>all</u> TRU waste as coming to WIPP. Since RH-TRU waste is not scheduled for shipment for several years, the effective capacity for RH-TRU will only be about 4,300 m^3 with the present design. SEIS-II makes no mention of the need to modify the waste emplacement design in order to accommodate 7,080 m^3 of RH-TRU. Again, footnotes indicate that only the authorized amounts would be disposed at WIPP but it is needlessly confusing.

- EEG is pleased that DOE is seriously considering treatment of radioactive wastes. For years EEG has noted that waste is respirable, soluble and confined by a carbon steel Type A drum. The 20 year longevity requirement for the drum has been deleted by DOE from the WAC as has the 1% limit on respirable particles. In contrast, certain low level wastes are required by NRC to have a 300 year design life for the waste container or the waste form. We believe that modifying the waste form through thermal treatment and shredding and grouting should be vigorously pursued to accommodate the anticipated volume of TRU waste which is twice the capacity of WIPP.

- The inhalation risks to people on the surface from future human intrusion were deemed inconsequential and not calculated in the SEIS-II despite earlier work by both EEG (EEG-11) in January 1982 and DOE (TME 3151) in July 1982 that concluded inhalation is a significant concern.

- Unwarranted claims of conservatism for long-term performance calculations are made in the SEIS-II.

- EEG compared the results of the routine and accidental risks from truck transportation to WIPP with findings in EEG-46 ("Risk Analysis of the Transport of Contact Handled Transuranic (CH-TRU) Wastes to WIPP Along Selected Highway Routes in New Mexico Using RADTRAN IV," Anthony F. Gallegos and James K. Channell, EEG-46, August 1990). Agreement was quite close when allowance was made for differences in miles traveled and other assumptions. Therefore we believe the assessment of transportation risks in SEIS-II is reasonable and adequately conservative.

- For over 20 years, the Department's policy has been to dispose of defense transuranic waste at WIPP rather than leave it at the generator sites indefinitely. The August 1995 DOE Draft Waste Management Programmatic Environmental Impact Statement provides calculations that indicate leaving the waste at the generating sites indefinitely rather than disposal at WIPP would result in fewer cancer fatalities, a smaller collective radiation dose, and a cheaper cost. The SEIS-II needs to explain the reasons why technical objections have not been raised by CAO on these 8/95 DOE conclusions. It is important for credibility that a detailed analysis of the basis of these diametrically opposed conclusions be provided. (SEIS-II, page 3-46 and PEIS, page 8-86).

- Calculations of the long-term consequences should use the analyses submitted in the EPA Application. SEIS-II used methods and data in the Draft Application. EEG had extensive comments on the draft and published them in EEG-61.

SUMMARY

EEG's review of the WIPP Disposal Phase Draft Supplemental Environmental Impact Statement (SEIS-II) concentrated on the radiological aspects of the Proposed Action, including transportation. The alternatives were reviewed in less detail. Some calculations were checked, mostly for the Proposed Action. Because of time constraints, there was little review of Hazardous Chemicals, Economics, or other Environmental Assessments.

SEIS-II was written as a pre-decision document with the Alternatives all plausible and eligible to be selected. Also, the inventory of TRU waste for disposal went well beyond that portion of TRU waste that has been historically considered to be the WIPP inventory. This broadened scope is probably appropriate for an EIS but it is confusing to the reviewer who is aware of the statutory limits of wastes that are allowed to come to WIPP at the present time. EEG has attempted to keep the broadened scope of SEIS-II in mind during our review.

A number of calculations, logic, and perhaps typographical errors were found and are pointed out in the detailed comments. Also, omissions that we believe should be included are mentioned. The more important issues are discussed below.

Alternatives

EEG is bothered by the choice of Alternatives considered. Compared to the Proposed Action, they deal with larger volumes of TRU waste, continue over a much longer period of time and have been evaluated in a more preliminary manner. There is a question of whether these were intended to be viable options. Certainly there is a need for real options to dispose of TRU wastes not included in the WIPP statutory limits.

EEG recommends that short-term, partial solution options be included in the Final SEIS-II and be considered in the Record of Decision (ROD).

Related Documents

SEIS-II recognizes and refers to other important WIPP related documents such as the Compliance Certification Application (CCA), Baseline Inventory Report (BIR - Revisions 2 and 3), and the Safety Analysis Report (SAR). However, SEIS-II, which was published after the CCA and the latest SAR, does not incorporate the latest information or use the same methodology as these documents. The use of different methodology and results in DOE documents published around the same time is inconsistent, confusing and unnecessary. EEG recommends that the Final SEIS-II use methodologies and results from the CCA and the latest SAR because these documents contain more detailed and peer reviewed analyses.

Transportation

EEG checked the transportation calculations in Appendix E and compared these results to those contained in EEG-46. It is concluded that the assessment of transportation risks in SEIS-II is reasonable and adequately conservative.

Analyses in SEIS-II indicated potential advantages to using rail rather than truck transportation for wastes. The rail analyses were not as rigorous as those for truck transportation. However, the findings were consistent with analyses in the FEIS, SEIS-I, and other documents. There appears to have been no serious re-evaluation of WIPP's "truck only" policy in the approximately 12 years since it was established. EEG believes that DOE should take this opportunity to seriously re-evaluate the merits of a "truck/rail mix" or a "maximum rail" policy for WIPP wastes.

Questionable Assumptions

There are a number of questionable assumptions, omissions, or errors in SEIS-II. These are mentioned in the page-by-page comments. The more important ones are given below. The page location in SEIS-II is given in parenthesis.

Human Intrusion at 100 years. The assumption is made that drilling into the repository 100 years after repository closure would lead to maximum consequences. This determination cannot

yet be made. Increased releases from higher pressures in the repository after 100 years may more than offset radionuclide reductions due to radioactive decay. (page 5-45).

Use of 75th Percentile Values. It is argued that the use of 75th percentile parameter values in modeling of long-term releases due to human intrusion will yield consequences that fall in the "upper tail of a full probabilistic analysis." In the actual analysis SEIS-II used median values for most of these parameters and came up with values of radionuclide releases to the surface that were identical to those with median values (Table H-24). We conclude that these are not upper tail releases. (page 5-40).

Family Farm Scenario and Inhalation Doses. The decision was made in SEIS-II that a family farm scenario with inhalation doses from resuspended drilling mud pit material was inappropriate. This is directly contrary with conclusions in SEIS-I as well as EEG and Westinghouse reports. (page 5-41).

Modification of BRAGFLO Volumes. The z distance in a two-dimensional grid was increased by factors of approximately 8 (see Table H-8) in order to accommodate the larger waste volumes in Action Alternatives 1, 2, and 3. This violates the two-dimensional assumption of the BRAGFLO grid. A three-dimensional analysis may be needed to give reliable results. Table H-8 is confusing.

Emplacement of RH-TRU Wastes. Values are given for the volumes of CH-TRU and (especially) RH-TRU wastes that will have to be put into Panels 9 and 10 in order to meet design capacity for the Proposed Action. There is no indication of whether such an increase is possible. (page 3-12).

Conversion Error. Numerous Figures in the Summary Chapter, Chapter 5, and appendix H show the wrong conversion factor from Ci/m^3 to pCi/l. The correct conversion factor is 1 pCi/l= 10^{-9} Ci/m^3. There is uncertainty about which value is used in the plots and this is potentially important. (pages S-51 and 5-43).

RH-TRU Cask. The statement is made that "The Department is currently awaiting NRC certification of the RH-72B cask. DOE had not submitted an application to NRC for certification of the RH-72B cask at the time the SEIS-II was published.

GLOSSARY

Page GL. Line 1.

The definition of backfill as "materials placed in storage panels or drifts" is too ambiguous. CH-TRU waste and RH-TRU waste as well as the drums and containers are placed in storage panels, but they do not qualify as backfill.

Page GL-2. Line 4.

The definition of background radiation does not include global fallout as it exists in the environment. Global fallout is considered to be man made radiation.

Page GL-2. Line 12.

The glossary should include a definition for the Becquerel since it includes a definition for the curie.

Page GL-3. Lines 28-32.

The definition of contact-handled transuranic waste should start with the term "TRU waste" instead of the word "waste".

Page GL-3. Line 13.

The spelling of sievert is incorrect. Also, the sievert is abbreviated as Sv.

Page GL-5. The definition of disposal should use the definition in the WIPP Land Withdrawal Act.

Page GL-5. The definition of disposal phase should use the definition in the WIPP Land Withdrawal Act.

Page GL-5. Lines 33-36.

The definition of absorbed dose should also include the mks unit known as the gray and abbreviated as Gy.

Page GL-5. Lines 37 through 39.

The definition of dose conversion factor should use "resultant dose equivalent" instead of "resultant radiation dose."

Page GL-9. Lines 4 through 7.

The definition of high-level waste should include unreprocessed spent fuel.

Page GL-9. Lines 22 through 26.

The definition of the phrase "immediately dangerous to health" only includes" maximum airborne concentration". The phrase also applies to a dose rate, e.g. 1,000 rem/hour.

Page GL-14. Lines 16 through 20.

The definition of remote-handled transuranic waste should start with the term "TRU waste" instead of the word "waste". Also, while the radiation level at the outer surface of the container is less than 1,000 rem/hour, there is a volume limit of 12,500 cu ft for wastes that have radiation doses that are greater than 100 rem/hr at the outer surface.

Page GL-18. Lines 1 through 4.

The definition of WIPP should be changed. WIPP is no longer an experimental facility.

ACRONYMS

Page AC-1. Line 19.

Only BIR-2 is defined. BIR-3 should also be defined since it is described on page 1-8.

Page AC-1. Line 42.

The AC-section has an acronym for design-basis earthquake, but it does not have an acronym for design-basis criteria.

Page AC-3. Line 46.

PA stands for Performance Assessment. The acronym for Preliminary Performance Assessment would be PPA.

Page AC-4. Line 15.

At present the RH-72B cask is only a proposed RH-TRU shipping container. The design was not submitted by the DOE to the NRC until 12/96.

Page AC-4. Line 33.

The definition of SWIFT-II should indicate that it is computer software.

Page MC-2. Table MC-1.

The table should include other conversion factors such as a conversion factor from Psi to Pa and conversion factors from darcy to other units of permeability.

SUMMARY CHAPTER

Page S-1. Lines 40 and 41.

The statement "DOE subsequently decided to perform the tests in aboveground laboratories instead of at WIPP" is misleading. Most of the tests planned for the test phase (e.g. the alcove tests, which comprised the majority of the wastes in the experiments) are not being performed anywhere.

Page S-2. First Full Paragraph.

The relation of SEIS-II to the Draft WM PEIS is described in this paragraph. DOE apparently believes they need to follow the approach of the WM PEIS and also to consider the disposal of all DOE TRU wastes. This goes beyond the portion of the defense TRU wastes that has historically been considered for disposal at WIPP and includes commercial TRU as well as non-defense TRU. The desire of DOE to consider the universe of TRU waste is understandable and it could probably be argued that NEPA requires it. But it is confusing to the reader who is aware of the statutory limits of wastes that are allowed to come to WIPP at the present time. Also, additional wastes and alternatives have not been evaluated in the detail that the Proposed Action has been. It is realized that a Draft EIS is supposed to be written as a pre-decisional document.

Page S-3. Related Documents.

The major planning and compliance documents that are integrated with SEIS-II that are related to decisions on WIPP are listed and described briefly. A generic comment is that the contents of SEIS-II are not current with the latest DOE documents that were issued before the SEIS (e.g. the CCA and Baseline Inventory Report, Revision 3). Also, SEIS-II developed its own assumptions and methodology rather than using that developed in other official WIPP Project documents (e.g. WIPP Operational Accident modeling was different than that in the Safety Analysis Report). These differences are confusing and unnecessary.

Page S-4. Comprehensive Disposal Recommendations.

The Comprehensive Disposal Recommendations (in preparation, schedule uncertain) document will recommend "disposal options and the time tables for all TRU waste under DOE control." It is unclear how the ROD that is expected with the Final SEIS-II will relate to the Comprehensive Disposal Recommendations. Are these expected before Final SEIS-II? If not, wouldn't the ROD be preempting the Recommendations? Or, is SEIS-II the first step in preparing for the disposition of all TRU wastes under DOE control at WIPP?

Page S-4. List of DOE Decisions.

Although this is mentioned later, it would be helpful to mention here those potential decisions which could be made under current WIPP Authorization and those which would require new Congressional Authorization.

Extensive comments are made later on the truck vs. rail issue. It is hoped that this decision is open and will be seriously re-evaluated.

Page S-9. Emplacement Volumes.

The text and various tables give different values for emplaced volumes of waste in No Action Alternative 2. Table S-3 says 135,000 m^3 CH, 35,000 RH (32,000 being treated). Figures S-2 and S-3 show 143,000 m^3 CH-TRU and 50,000 m^3 RH-TRU (both post-treatment). The text (page S-16) says 170,000 m^3 total. Table 3-16 and the text (on page 3-42) say 135,000 m^3 CH and 35,000 m^3 RH. It is unclear what becomes of the additional 15,000 m^3 of RH-TRU in NAA 2 (which is included in the Proposed Action as excess RH-TRU). This is confusing and needs to be clarified.

Page S-13. Lines 19-20.

The berm is to be constructed around the perimeter of the waste panel footprint (not of the Site).

Pages S-13 to S-19. Alternative Actions.

A general conclusion on the alternatives evaluated is that they are so different from the proposed action as to stretch credibility. The entire TRU waste universe is included. Implementation times of 150-190 years that use present-day technology are mind boggling and there is no indication that the SEIS-II analysis has seriously considered the problem of keeping the underground, shaft, and surface facilities at WIPP open until the latter half of the 22th Century. Nor have the institutional problems that might occur over such long time periods been mentioned.

Three of the Alternatives not considered (deep borehole disposal, greater confinement, and geologic repositories at sites other than WIPP) appear to be as reasonable as the ones chosen.

The concept of making piece meal decisions on solving the TRU waste disposal problem is as reasonable as the Alternatives listed here. For example: (1) make the decision of how to dispose of those wastes that are authorized to come to WIPP; (2) then evaluate how all or a portion of the remaining TRU wastes will be disposed of. It may be better to evaluate these remaining wastes in more than one category (e.g., RH-TRU as one category and buried waste as another).

Page S-14. Text Box.

See comments on this text box (Conservatism of TRU Waste Inventory Estimate) under page 3-6.

Page S-16.

It is noted that No Action Alternative 1, which would have thermally treated wastes, provides for overpacking of waste at 20-year intervals. No Action Alternative 2, which does not have treated wastes, has no plans for repackaging. This is an example of how the alternatives provide different levels of assurance that must be kept in mind when making decisions between alternatives.

Page S-23. Sixth Paragraph.

The value of 0.3 LCF reported for the population dose around the Hanford Site is incorrect. The Hanford Site Environmental Report for Calendar Year 1994 (PNL 10574) reports a total dose of 0.6 person-rem to the population of 380,000 persons. This would be 3×10^{-4} LCF. The values for INEL and NTS also seem to be too high but have not been checked.

Page S-29.

See comments on this text box (Long Disposal Periods and SEIS-II Results) under page 5-49.

Page S-32. Noise.

It would be useful to state the normal non-WIPP truck traffic through Carlsbad as a comparison to the relative noise effect of WIPP traffic.

Page 5-33. Socioeconomics.

The life-cycle cost analyses for Action Alternatives 1, 2, and 3 apparently does not include the cost of exhuming the CH-TRU waste disposed of before 1970.

Page S-34. Table S-5.

It is surprising that No Action Alternative 2 (NAA2) waste treatment costs are only 16% of those for the proposed Action. There is no itemized waste treatment cost in Appendix D for the No Action Alternative 2. However, NAA2 is planning to treat all newly generated waste to WAC standards (73,000 m^3 CH and 32,000 m^3 RH). The proposed action would treat 168,500 m^3 CH and 50,000 m^3 RH. This needs to be explained. The sum of the parts of the proposed action is $18.7B while the total cost is $19.1B. While rounding off is expected, this fails to account for $0.4B or 2.2% of total.

Pages S-42 through S-44.

The analysis for Alternatives 1, 2, and 3 apparently do not include the radiological health impacts from exhuming the pre-1970 disposed TRU waste, which is not considered in the

WM PEIS either, and which in the past was considered important. These radiological health impacts could be important when comparing Alternatives 1, 2, and 3 with the Proposed Action and No-Action Alternatives 1 and 2.

Pages S-51 through S-55.

The conversion factor on Figures S-5 through S-9 relating Ci/m^3 to pCi/l is incorrect. The correct value is 1 pCi/l = 10^{-9} Ci/m^3. This is important. See comment under page 5-43.

Page S-61 to S-68. Table S-7.

This table summarizes all the calculated health and safety effects from transportation, routine treatment and disposal operations, and from accidents. Deaths from transportation and operational accidents, Latent Cancer Fatalities (LCFs) from radiation exposure, cancer incidence from hazardous chemicals, and fatalities from truck pollution are all considered. Presumably, this information will be used in deciding on alternatives. However, SEIS-II does not discuss the relative merits of the alternatives in light of these estimated health and safety effects. Neither is any indication given of how they will be used in decision making. We have several observations.

The estimated cancer incidence from exposure to hazardous chemicals is below 0.05 in all alternatives. This is less than 5% of the expected radiological LCFs in NAA2 and is less than 1% in all other alternatives. The effect of hazardous chemical exposure can be ignored in choosing between alternatives.

EEG Summary of Health and Safety Effects.

EEG has condensed from the Table S-7 tabulation the expected deaths (of all kinds) for each of the Alternatives as shown in Table 1. Also included are the more significant high consequence/low probability accidents (which are not expected to happen) and the consequences of long-term releases.

Table 1

EEG Summary of Expected and Possible Deaths Listed in SEIS-II

Effect	Alternative								
	Proposed	AA1	AA2a	AA2b	AA2c	AA3	NAA1a	NAA1b	NAA2
Routine Radiation (LCFs)									
Truck Transportation	3.3	12	5.4	5.4	6.6	15	0.11	0.57	--
Operations	2.6	3.8	11	8.5	4.3	4.3	11	8.7	1.1
Accidents									
Truck Fatalities	6	19	9	9	12	25	0	1	--
Other Fatalities	6	10	15	13	12	12	1.3	1.1	1.3
Agg. Rad. (LCFs) Truck	0.4	0.8	0.4	0.4	0.7	1.2	.0068	.02	--
TOTAL DEATHS	18	46	41	36	36	58	12	11	2.4
High Consequence Accident Deaths LCFs)	2	300	10	10	2	10	10	10	300
Storage Facilities	4	4	24	24	24	24	--	--	--
WIPP Disposal									
Long Term Releases (LCFs) 10,000 year Aggregate	<0.9	--	--	--	--	--	<2325	<2325	2325
Original Waste Volume(10^3m^3)	218	336	313	313	313	312	313	313	170
Deaths/10^3m^3	.084	0.14	0.13	0.12	0.11	0.18	.040	.036	.014

All values from Table S-7, pages S-62 through S-68, SEIS-II.

If these estimates are assumed to reasonably reflect the differences between the Alternatives one can come to several conclusions:

- The Proposed Action disposes of waste at a lower expected death per volume of waste ratio than any of the Action alternatives. However, all of these ratios are within a factor of about two. The primary variables affecting the deaths/volume ratio are the miles of transportation and amount of treatment required;

- AA1 and NAA2 have very high consequence storage accidents. This is because of long-term above ground storage of waste treated only to WAC standards;

- The aggregate LCFs from long-term release for NAA2 are very high because of assumed loss of institutional control of WAC standard wastes stored above or near the surface. NAA1 LCFs were not calculated but would also be substantial. The thermal treatment of wastes would be expected to provide some reductions during the early part of the 10,000 year period because of greater waste stability.

The Health and Safety aspect of the decision on alternatives would seem to basically reduce to a trade-off between a few expected deaths during the disposal period and a possibility of a much larger number of future LCFs from accidents or environmental releases. A secondary consideration is whether some types of death (e.g. a transportation accident fatality rather than a radiation caused LCF) and the effects on some population groups (workers versus the general public) are more acceptable than others.

In making this decision one needs to keep in mind the uncertainly in these comparative estimates. Also, these various alternatives are not identical and provide different levels of assurance.

CHAPTER 1

Page 1-1. Lines 5 through 16.

The section does not make it clear that only defense TRU can be disposed at WIPP. Instead, the section discusses the need to dispose of all TRU wastes generated by the Department.

Page 1-1. Lines 37 through 39 or Footnote 1.

The footnote indicates that the DOE has sole authority to decide if waste should be disposed of at WIPP. In 1992 Congress reassigned the authority to approve disposal at WIPP from the DOE to the EPA.

Page 1-1. Box entitled TRANSURANIC WASTE.

Since the description of TRU waste includes the maximum dose rate for CH-TRU waste, the description of TRU wastes should also include the maximum dose rate for RH-TRU waste, which is 1,000 rem/hour.

Page 1-1. Box entitled TRANSURANIC WASTE.

The material in the box defines transuranic waste but fails to incorporate the adjective "defense" to modify the noun. The inference is that non-defense DOE TRU waste is eligible for disposal at WIPP.

Page 1-1. Section 1.2 OVERVIEW.

Since the SEIS describes the history to TRU waste disposal, it should include the history of the unilateral decision by the DOE to redefine the threshold of TRU from 10 nCi/g to 100 nCi/g.

Page 1-5. Table 1-2.

The fifth WIPP NEPA document notes that a 1982 deviated gas well at WIPP was discovered by the DOE in 1991.

Page 1-7. Footnote.

Statement: "Overpacking involves placing the 55-gallon drums inside another container and essentially provides double containment of the TRU waste."

The statement is incorrect. Overpacking does not provide "double containment" of a Type A drum in the context of the NRC packaging regulations 10 CFR Part 71.

Page 1-8. Lines 23 through 26.

The purpose of the WIPP/SAR is summarized, but does not do justice to the formal commitment by DOE and the State of New Mexico.

Waste Isolation Pilot Plant Safety Analysis Report, Revision 1 (SAR) Rev. 1 (DOE 1995 i)
"The intent of this document is to demonstrate the safe disposal of CH-TRU waste in compliance with DOE orders."

The Consultation and Cooperation Agreement between NM and DOE states that the SAR"... constitutes the most comprehensive document concerning WIPP both in general and specifically as related to public health and safety as well as other matters." Include this statement as well as a commitment for RH-TRU waste as well.

CHAPTER 2

Page 2-1. Lines 9 through 19.

The Geography of the nuclear weapon complex is described.

States that contain the 10 additional sites are identified in *Identification of Additional TRU Waste Generator Sites*. It appears that the TRU waste generated at the 10 additional sites is not defense TRU waste and is thus not eligible for disposal at the WIPP under the current law.

Page 2-2. Section 2.1.1 Introduction.

The SEIS includes plans to dispose of non-defense TRU waste at WIPP which violates the existing laws. DOE should include a discussion on their plans to modify the law to include commercial and non-defense TRU wastes.

Page 2-2. Section 2.1.1.

The DOE states that the total inventory will now be almost double the amounts authorized for disposal under the WIPP Land Withdrawal Act. The total expected inventory is 312,500 m^3. The authorized volume is 175,000 m^3. Describe the plans for dealing with this excess volume, including amendments to the law.

Page 2-2. Text Box entitled WASTE ACCEPTANCE CRITERIA (WAC). Lines 17 and 18.

Statement: "For the purposes of SEIS-II analyses, all waste would be treated at a minimum to the current planning-basis WAC."

Since the current WAC does not require treatment of most wastes, it is misleading to describe untreated waste as "treated at a minimum to the current planning-basis WAC."

Page 2-2. Text Box entitled WASTE ACCEPTANCE CRITERIA (WAC). Line 1.

It is stated that the WAC was first developed in 1989.

The statement is incorrect. The first set of criteria were issued in 1979. There is no recognition of the work the EEG has done on the WAC (for example, the report EEG-4, Little, Marshall S., *Review Comments on the Report of the Steering Committee on Waste Acceptance Criteria for the Waste Isolation Pilot Plant* dated February 1980).

Page 2-3. Section 2.1.2 TRU Waste.

The section fails to show that there is a volume limit of 12,500 ft^3 for disposal at WIPP of RH-TRU waste between 100 rem/hour and 1,000 rem/hour.

Page 2-3. Text Box entitled *TRU WASTE TRANSPORTATION PACKAGING.*

Lines 10 and 11. Statement: "The Department is currently awaiting NRC certification of the RH-72B cask."

The statement is misleading, since the Department did not submit an application to the NRC for certification until December 1996.

Page 2-3. The text refers to a "specially adapted rail car".

EEG is unaware of an existing rail car nor have we received plans of a design. Please provide them in text.

Page 2-5. 1,800 PE-Ci/Drum.

It is correct that the WAC allows 1,800 PE-Ci CH-TRU drums if the waste is over packed or solidified. EEG has expressed some reservations about this limit. Also, an 1,800 PE-Ci drum could not be shipped in TRUPACT-II because the drum would exceed the 40 watt thermal limit.

Page 2-5. Footnote.

The text cites an August 1995 Draft PEIS which has not been issued in final form and an unidentified undated more recent estimate. Provide specifies.

Page 2-6. Table 2-2.

Statement: "There is uncertainty in the total waste volume figures presented in Table 2-2 and 2-3."

The discussion should include numbers that provide an indication of the uncertainties in the waste volumes of the six alternatives.

Page 2-7. Table 2-3.

Commercial/Non-defense TRU waste is not eligible for disposal at WIPP and should be deleted from the Table.

CHAPTER 3

Page 3-1. Lines 31 through 37.

Statement: "Decisions based on SEIS-II may be a combination of the option presented within alternatives analyzed. This means that portions of two or more of the alternatives analyzed in SEIS-II may be combined and used by the Department for the management or disposal of TRU waste." It would help to clarify this statement if the Final SEIS-II provided hypothetical examples of how the different Alternatives might be combined. The text box on page 5-51 does not provide this clarification.

Proposed Action

Page 3-2.

While there is a clear understanding of the Proposed Action, the description includes activities not in the Proposed Action described in the SEIS. The RH-TRU waste increased considerably, from 7,000 m^3 to 35,000 m^3, and the volume projections show thermal treatment of the waste reduces the volume. These are not included in the Proposed Action submitted by DOE to EPA in the 10/28/96 Compliance Certification Application. Revise this section on the Proposed Action to only include items that are in the Proposed Action.

Page 3-2.

Paragraph 2. The text indicates that the proposed volume of RH-TRU is much less than that allowed by the WIPP Land Withdrawal Act. Not so. While the expected number of curies in RH-TRU are less than the LWA permits, the volume of RH-TRU is considerably greater and the WIPP repository's current design will not accommodate the greater volume.

Page 3-5.

"All waste has been assumed to be treated and packaged to planning basis WAC." There are no requirements in the WAC to treat waste.

Page 3-6. Text Box.

The conservatism of TRU Waste Inventory Estimates text box is limited to the volumes of estimated TRU waste. There is no discussion of the radioactive inventory (in curies or PE-Ci) and its uncertainty. Also, credit is taken for conservatism when the reverse is true. For example:

First bullet. It is more accurate to consider the inventory as uncertain, rather than overestimated. Also, overestimating the TRU waste volume (and of the alpha emitting inventory) permits a larger quantity of plutonium to be released in meeting the EPA 40 CFR 191 Containment Requirements. Update the reference from Rev. 2 to Rev. 3 of the BIR.

Second bullet. The additional Inventory includes TRU waste burial prior to 1970 when the definition of the threshold was 10 nCi/g rather than the current 100 nCi/g. Although DOE indicates that 80,000 m^3 would be excavated from the 141,000 m^3 that was previously disposed, no indication is provided as to whether it is the higher or lower concentration waste. Logically it would be the higher, making the calculation less conservative. No explanation is provided why 80,000 m^3 of buried waste would be exhumed and 60,000 m^3 of other buried waste left in place.

Third bullet. Assuming that 7,000 m^3 of RH-TRU will be emplaced in the repository, when the available capacity may be only 4,300 m^3, may overestimate the amount of actinides allowed to be released.

Fifth bullet. The assumption that 100% of the TRU waste would be treated as TRU mixed waste is no longer true.

Page 3-8.

Since the text cites U.S. DOT regulations (49 CFR Part 391) for driver qualification, also cite the appropriate U.S. DOT regulations for routing (49 CFR 177) and the type A container certification (49 CFR 173).

Page 3-9. 3.1.3.1

"The Department estimates that it would require up to three years to excavate a panel."

Why would it take 3 years to excavate 7 rooms when 4 rooms were excavated in 6 weeks for the SPDV Program? Revise the estimate.

Page 3-9.

"The facility would be inspected a minimum of 4 times a year by the Mine Safety and Health Administration." State that the WIPP Land Withdrawal Act requires this.

Page 3-9.

Shipping Routes. It would be helpful to specify the DOT regulations to change routes including public hearing procedures.

Page 3-12. 3.1.3.4 Emplacement of RH-TRU Waste.

This section states that RH-TRU waste will need to be placed in the access tunnels (Panels 9 and 10). In order to reach design capacity Panels 9 and 10 will each have to be modified to accommodate 944 m^3 of RH-TRU (compared to 649 m^3 in a panel) and 17,500 m^3 of CH-TRU (compared to 16,700 in a panel). Is it physically possible to do this? Please specify the necessary design changes to the repository.

Page 3-12.

Please provide information for a seal that would prevent water from entering the repository and impede gas and brine from migrating out.

Page 3-12.

Closure and decommissioning. Use the definitions of disposal phase and disposal used in the WIPP Land Withdrawal Act. The definitions in the text do not match those in the Act.

Page 3-12.

The projected area above the 10 panel equivalents is said to be 100 acres. It is about 125 acres.

Page 3-12.

Is the proposed fence outside of the 150 acre berm?

Page 3-13.

The commitment to place markers at the site makes no mention that they are required by (PL102-579) and need to be approved by EPA (40 CFR 191).

Page 3-14.

The text states that it is reasonable to examine alternatives that include disposing of all DOE-owned and controlled TRU waste at WIPP. It should also be reasonable to discuss plans to amend the law and explain why DOE did not ask Congress to amend the WIPP LWA at the same time this section was written.

Page 3-14.

Action Alternative 1 would nearly double the repository waste volume. However the SEIS-II does not address the necessary redesign nor operational problems associated with keeping the repository open for 160 years.

Page 3-14.

Problems associated with storage at Consolidation Sites for 160 years are not discussed. DOE has taken the position that such storage would be impracticable and offering this as a viable alternative appears to reverse the Department's position totally.

Page 3-15 and A-14. Tables 3-2 and A-6.

The total volume for column 2, Additional Inventory, should be 139,000 not 136,000.

Page 3-18.

While the text states that the number of panels would be increased from 8 to 68, no specifics are provided on the design to accommodate this. We question whether the current design would be optimum if CH-TRU was not going to be emplaced in the rooms.

Page 3-19.

The surface projection for 68 panels would be about 850 acres rather than the 680 acres estimated if the design is unchanged.

Page 3-19. Text Box, Long Disposal Periods and SEIS Results.

Statement: "The long disposal periods could be shortened by constructing additional shafts, employing additional shifts, or changing the design criteria for thermal loading." The assumptions mentioned in the statement are more reasonable than the assumptions of 160-190 year disposal periods. The analysis of AA1, 2, 3 should contain more detailed and quantitative information about how the periods could be shortened.

Page 3-43.

The SEIS states that alternatives such as transmutation, co-processing with high level waste, and disposal in space were not considered in detail. The desire to use current technology for projects to be completed in 30 or 40 years is understandable. However, it seems unwise for 160-190 year projects. The alternatives that are discussed in the text are also not considered in detail. Problems associated with keeping the mine open for 180 years are not discussed nor are plans to increase the number of panels from 8 to 68.

An alternative not considered at all, which is similar to Action Alternatives 2 and 3, would consist of acid digestion of certain TRU waste followed by volume reduction and solidification. During the 1970s and 1980s the DOE had a research program at Hanford on the acid digestion of TRU waste. The alternative might be preferable to Action alternative 2, which involves a costly thermal treatment process.

Page 3-44. Lines 2 through 8.

Statement: *"While the Storage and Disposition of Weapons-Usable Fissile Materials Programmatic Environmental Impact Statement (DOE 1996b)* considered this process to be a reasonable alternative for analysis the relative large volume of TRU waste (compared to the volume of fissile material) would produce much more waste than the currently planned high-level waste repository could dispose of. This alternative would further delay TRU waste disposal until such a time as sufficient high-level waste

repository space was available. In addition, transportation and safety concerns associated with high level waste would need to be addressed."

The statement is not correct. Because of thermal loading constraints, a high-level repository is mostly empty space that may have to be back-filled. The currently planned high-level waste repository at Yucca Mountain will have over 100 miles of tunnel. However, a high-level waste repository is not expected to be operational for more than 10 years. The transportation and safety concerns associated with high-level waste will be addressed in the licensing of a high-level waste repository. The major difficulty with this alternative is that a high-level waste repository will be licensed by the NRC and Congress does not want the disposal of defense TRU waste to be under the jurisdiction of the NRC.

Page 3-44. Lines 18 and 19.

Statement: "*Underground detonation*. Such detonations would produce a large amount of hazardous fission products."

The statement implies that the underground detonation can only be carried out with nuclear devices. This is not correct and the statement should be clarified.

Page 3-45. Lines 17 through 22.

The following statement is made in the discussion entitled *Alternative Engineered Barriers:* "The Department examined these as alternatives and determined based on the evaluation conducted in the *Engineered Alternatives Cost/Benefit Study Final Report* (DOE 1995c) that they were less effective than the engineered barriers examined in SEIS-II."

There is no discussion of engineered barriers in SEIS-II. However, of the 4 disposal options analyzed, Action Alternatives 2 and 3 include an engineered barrier (waste treatment).

Page 3-45. Lines 11 through 16.

In the discussion entitled *Geologic Repositories at Sites Other than WIPP,* it is implied that salt is a more favorable disposal media than granite, basalt, and tuff. The reference for this conclusion is the 1980 FEIS for WIPP.

Much has been written on the disposal of nuclear waste since 1980. With regards to spent fuel and high level waste, the DOE maintains that the unsaturated zone in tuff is the most favorable medium. Also, Sweden has successfully constructed and is successfully operating a repository in granite for intermediate level waste.

Page 3-46.

"The SEIS-II Proposed Action is similar to the Draft WM PEIS Decentralized Alternative". The Decentralized Alternative described in the WM PEIS is more expensive than the No Action Alternative ($1.7B vs. $7.4B). It also has more worker deaths (4 vs. less than 0.5) and a larger collective dose to workers (1,500 person-rem compared to 20 person-rem). These PEIS findings are similar to those in SEIS-II. The text should clearly explain why these results are totally opposite the DOE conclusion to consolidate the material for disposal at a particular site.

CHAPTER 4

Page 4-1.

The 1996 Amendments to the 1992 WIPP Land Withdrawal Act are not recognized.

Page 4-6.

The text states that backfill is not required for subsidence control or repository performance, but may be placed into the repository for final disposition.

DOE committed to backfill with salt in the 1980 FEIS.

Page 4-9 (Box).

"..... has resulted in confirmation of the Salado's extremely low permeability."

This statement is meaningless. The Salado pure salt has extremely low permeability, impure salt is more permeable, and the fractured anhydrite beds and the clay/anhydrite and clay/halite interfaces are permeable enough to transmit a substantial amount of brine for gas generation.

"...elevated gas pressure may slow down or stop brine inflow, thereby slowing gas-generating processes."

The important point is that sufficient gas is expected to be generated to result in lithostatic pressure in the repository. Once the pressure is dissipated through fractures, brine inflow is expected to resume.

"Geophysical surveys indicate that pressurized brine reservoirs in the Castile Formation occur as three or four discrete pockets." No new geophysical surveys have been conducted to detect Castile brine over the WIPP repository since the publication of SEIS-I. No basis has been provided to alter the previous interpretation of the 1987 TDEM survey over the WIPP site found in SEIS-I, as follows:

"A continuous deep conducting zone underlies the region of the WIPP waste - emplacement panels." (DOE/EIS-0026-FS, Vol. 1, p. 4-71).

and

"In this report, the brines underlying the repository are assumed to be present, as they are at WIPP-12" (DOE/EIS-0026-FS, Vol. 1, p. 4-73).

The EEG position is that, based on the size of the brine reservoir intercepted by the borehole WIPP-12 and the results of the TDEM survey, the WIPP repository is underlain by a continuation of the brine reservoir that was encountered by WIPP-12.

Page 4-10.

"Major tectonic activity (movements of the earth's crust) associated with the development of the Delaware Basin ended over 250 million years ago, and the WIPP site has been geologically stable ever since."

Since its deposition in the Delaware Basin in the late Permian times, the WIPP area has been uplifted, submerged, tilted, intruded by igneous dikes, deformed or dissolved by water, and eroded. In addition, according to Lambert and Canter (1984), Castile brine reservoirs were formed during the past 360,000 years to 800,000 years by an episodic process that "could have resulted from an intermittent hydraulic connection between the Capitan Limestone and Castile anhydrites." (SEIS-I, Vol. 1, p. 4-71).

The WIPP site has not remained geologically stable for 250 million years.

Comments on Page 4-15.

Natural Resource Exploration and Development.

Hydrocarbons

Hydrocarbon resource is a very important issue and merits much more than a cursory overview by three short paragraphs.

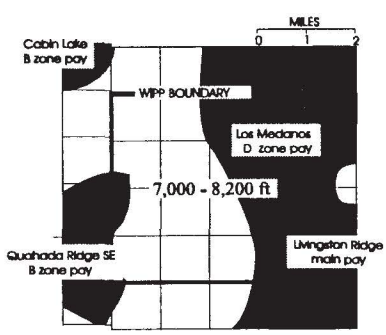

Figure 1. Proven and Probable Hydrocarbon Reserves for Brushy Canyon (after Broadhead et al, 1995, as published in EEG-62).

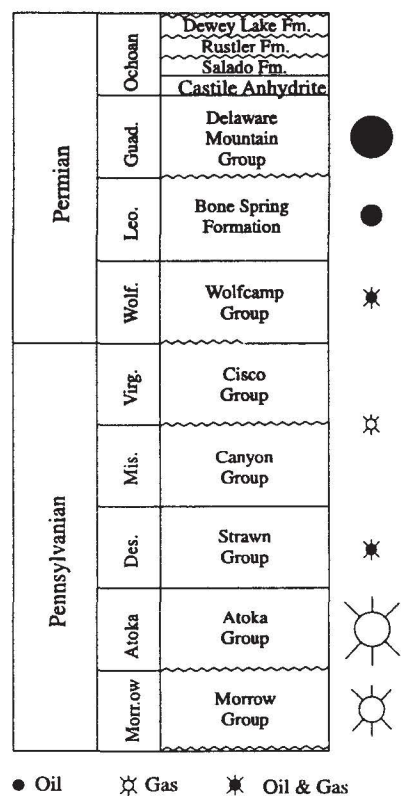

Figure 2. Formation Production (after Broadhead et al, 1995 as published in EEG-62).

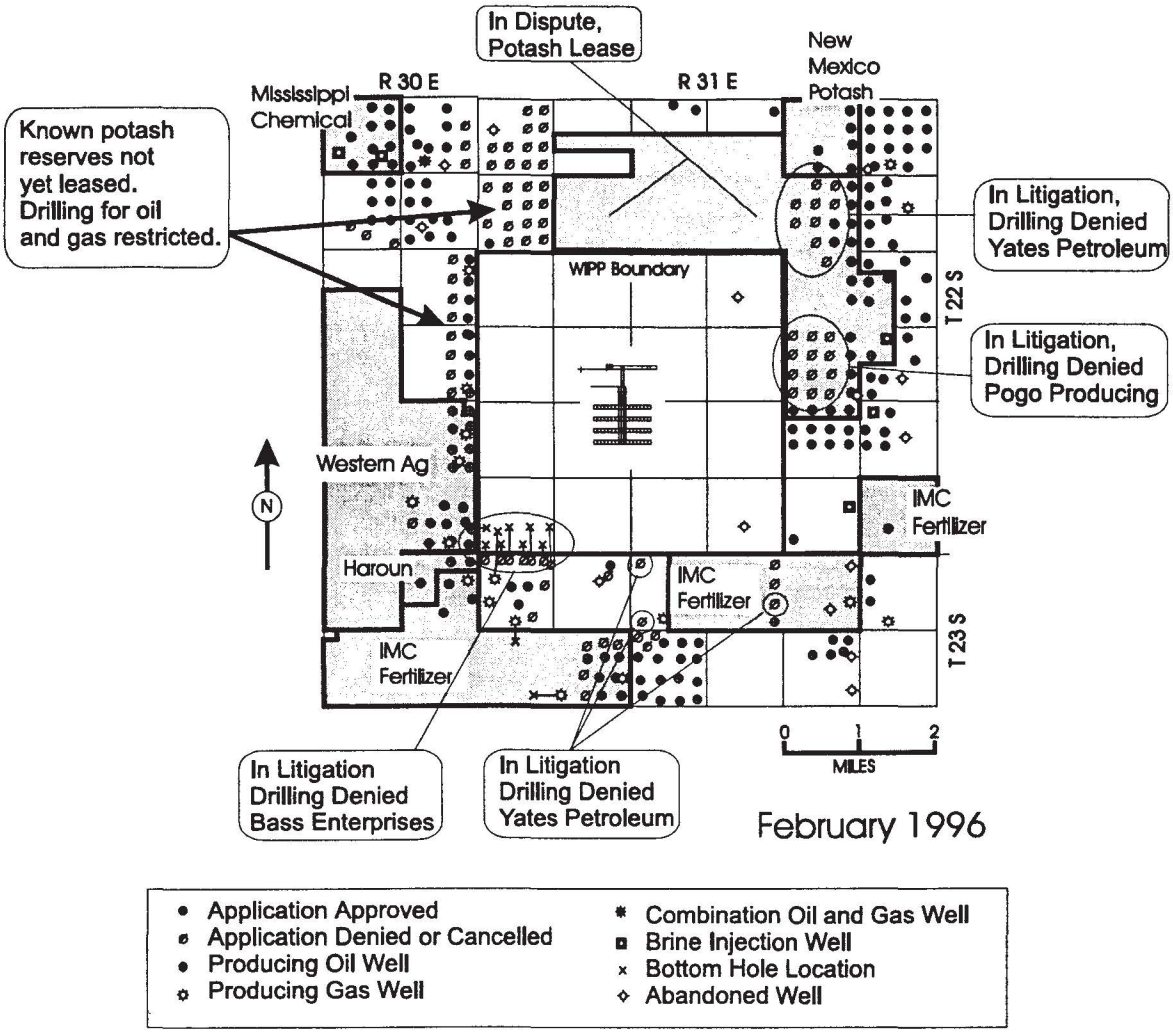

Figure 3. Interest in resources near WIPP (see EEG-62 for more detailed discussions).

The SEIS should have at least a series of maps showing proven and probable reserves at the various reservoir depths (eg. Figure 1), an illustration of the geologic cross section of the area resources and current production (eg. Figure 2), and a current map indicating drilling interest in the area and the extent of drilling delayed due to the presence of potash (eg. Figure 3). See EEG-62 (Silva, 1996) for a discussion of these figures.

Due to the extensive changes from the FEIS, there should also be a detailed discussion of the anticipated resource recovery activities. Topics should include:

- The massive hydrofracturing required by the oil reservoirs surrounding the WIPP.
- Extensive brine injection surrounding the WIPP due to the need for salt water disposal.
- Brine injection for pressure maintenance to enhance oil recovery.

- Documented concerns by the potash industry of the potential impact of fluid injection on the Salado Formation.
- The estimated value of hydrocarbon resources in the area.
- Areas for which there are no estimates due to the lack of drilling and testing as a result of the presence of potash.

Potash

This section should have maps showing the extent of lease grade potash reserves including the extent of potash reserves under the WIPP Site. Further, the SEIS should rely on the official position of the Department of Interior. The text should then discuss the maps and the impact of WIPP on the potash industry and the potential impact of potash mining on the WIPP based on potash reserve estimates by the Department of Interior.

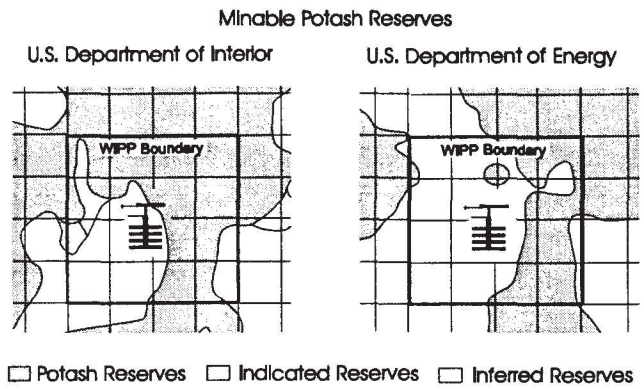

Figure 4. Estimated areal extent of potash reserves.

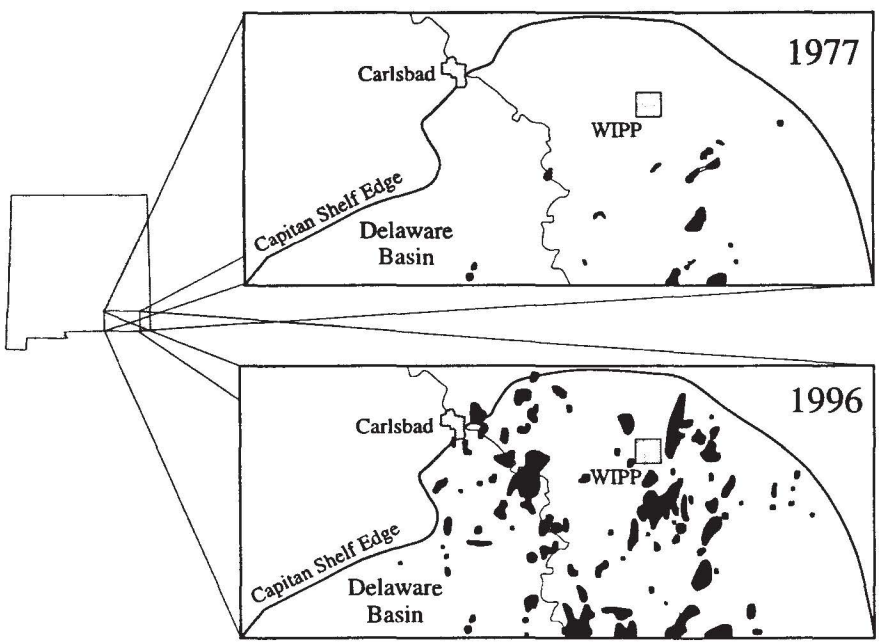

Halite

The increase in oil and gas drilling activities, shown in Figure 5, continues to put demands on the need for brine supplies in the areas of new drilling.

Figure 5. Actual growth of oil production.

There needs to be a section discussing the decades long activity of solution mining of halite, shown in Figure 6, from the Salado Formation to produce brine for drilling oil and gas wells throughout southeast New Mexico.

Pages 4-18, 4-19 Salado Formation Hydrology. This section should describe the higher permeability of the Salado marker beds which act as conduits for flow of water and gas in the Salado.

Also, the assumption of Darcy Flow is not a conservative but a reasonable assumption. According to Beauheim, et al. (SAND 92-0533), "An assumption of Darcy flow through the evaporites is thought to be a reasonable interpretive approach because Darcy-flow models are able to replicate the flow and pressure behavior observed during entire testing sequences involving different types of tests performed with different hydraulic gradients."

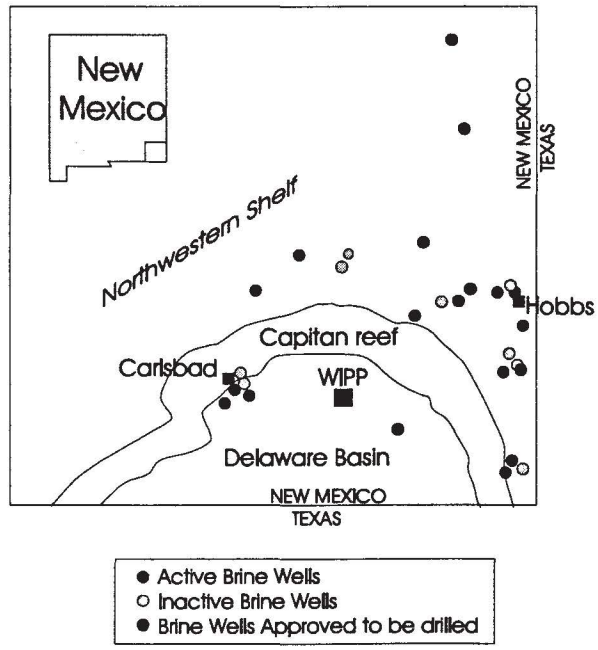

Figure 6. Solution mining of the Salado Formation.

Pages 4-19, 4-20 Castile Formation Hydrology.

The discussion in this section is incorrect in certain aspects and incomplete in others. There are not two but at least thirteen reported boreholes at and near the WIPP site which encountered pressurized brine in the Castile Formation. When the borehole WIPP-12 encountered pressurized brine at the WIPP site in 1981, more than 1.14 million gallons (4.3 million liters) of brine "unavoidably" flowed to the surface and was collected in a large pond on the surface before the well was brought under control (See DOE report on Brine Reservoirs, WIPP/TME 3153, P. H-9). The pore volume of this brine occurrence was estimated by DOE to be 714 million gallons (2.7 million m^3). Accommodation of this volume requires the assumption that the brine reservoir intercepted by WIPP-12 spreads under the repository. The TDEM survey confirmed the existence of brine under the repository. Assumption of four distinct brine reservoirs underlying the repository has no basis. A more justifiable assumption is that the pressurized brine reservoir encountered by WIPP-12 extends under the repository.

Page 4-21.
The discussion of the water level rises in the Culebra Aquifer and the potential impact of salt water disposal wells would be clearer by preparing and presenting a figure such as the one shown here and published in EEG-62.

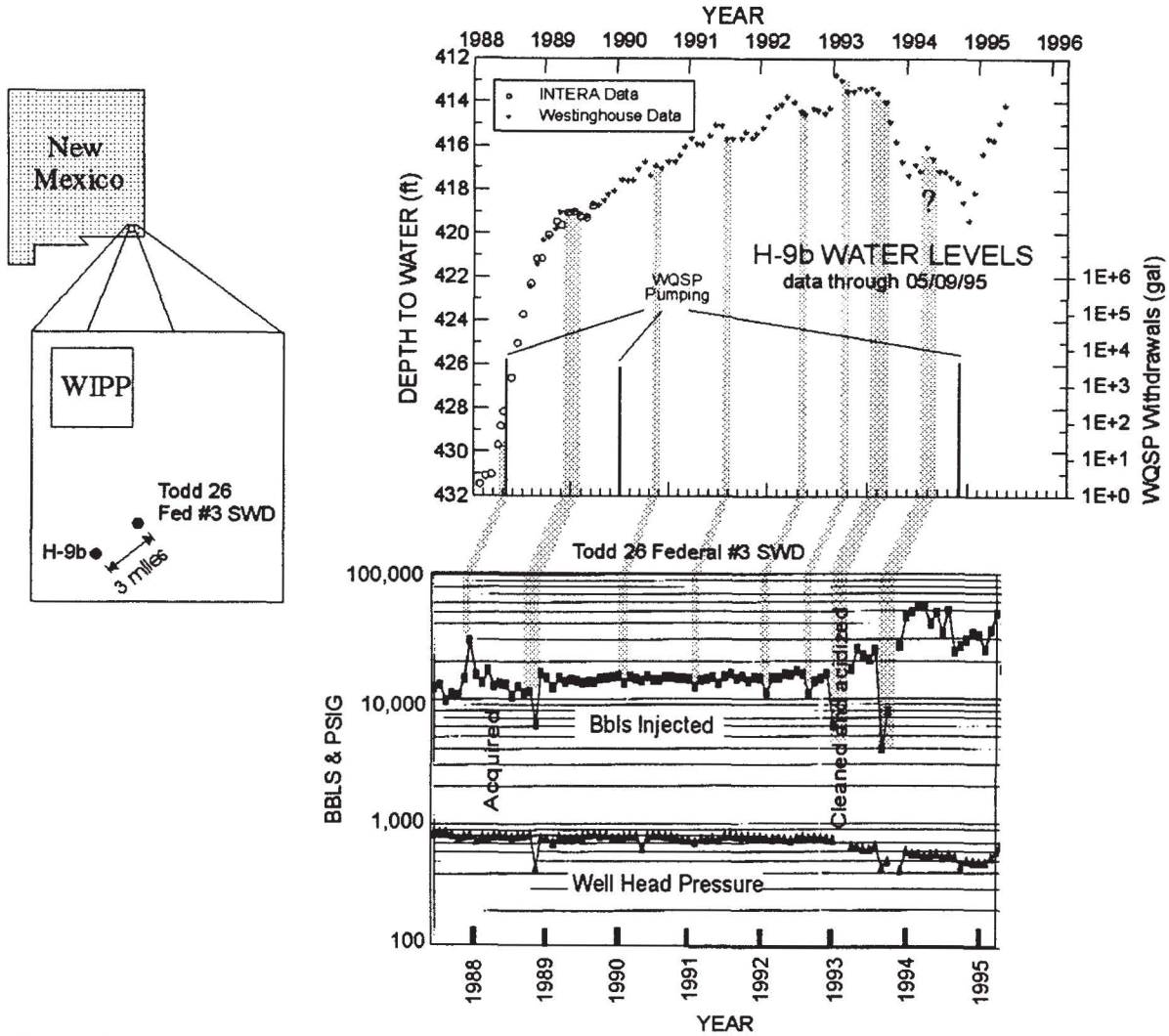

Figure 7. Postulated correlation between oilfield salt water injection and water level rises.

The discussion of potash mining and subsidence would benefit from a more detailed discussion of 40 CFR 194, the CCA, and a map of the extent of potash reserves as determined by the Department of Interior.

CHAPTER 5

Page 5-4.

The statement is made (3 lines above Section 5.1.2) that "No activity is occurring under these leases, and the Department may acquire these leases in the Future." The current status of these leases, including the producing gas wells and the recent court judgement, deserve a more detailed description in the final SEIS.

Page 5-9. Table 5-2.

The total in the second column (Basic Inventory RH-TRU Wastes) should be $4,800 million (not $4,500 million). Estimates should be rounded off using a consistent system.

Page 5-11. Transportation.

Detailed transportation comments are included in the Appendix E comments and are not repeated in these comments. Calculations were checked and compared to the results reported in previous EEG reports. The transportation risks reported in SEIS-II are reasonable and adequately conservative.

Page 5-13.

Highway route-controlled quantities (HRCQ) are discussed in the last paragraph. HRCQs are defined in 49 CFR 173.403(1) and routing is described in 49 CFR Part 177.825. The reference cited is not specific or useful. The statement that a majority of WIPP shipments are not HRCQs is misleading. Any waste shipment containing over 6 Ci of ^{239}Pu or ^{240}Pu, 9 Ci of ^{238}Pu, and 24 Ci of ^{241}Am is a HRCQ. Virtually all WIPP CH-TRU shipments will be HRCQs. Interestingly, the average RH-TRU inventory falls below the HRCQ limits and so the majority of RH-TRU shipments probably are not HRCQs.

Page 5-16.

The Footnote to Table 5-7 states that "shipments would stop at sites chosen, in part, for their lack of population,...." Have such sites been chosen and is their usage required? Unless the answer to both questions is 'yes', this claim should not be made.

Page 5-18. Lines 11 and 12.

The statement is made that, the State inspectors "dose would be limited by administrative rules and the inspector would be rotated to a new position." Unless DOE knows the requirements of the various States they should not take credit for actions by the States.

Table 5-8 is said to indicate that Site and State inspectors would receive the highest probability of health effects. Table 5-8 and Appendix E indicates that the rest stop employee has the highest probability.

Page 5-21. Lines 18 and 19.

The population density should be stated as "3,861 persons per square kilometer"

Page 5-26. Table 5-11.

Footnote d states that the MEI for RH-TRU is located at SRS. There is no RH-TRU at SRS.

Page 5-33. Lines 3 and 4 from bottom.

The assumption that there would be no dose to the maximally exposed involved worker in the T1 and T2 accidents is apparently based on the assumption stated on page G-11 ("The involved workers, positioned outside of the glovebox, were assumed to exit the facility immediately and thus would escape impact"). The assumed geometry and operational procedures need to be described in more detail so that the reasonableness of this assumption could be evaluated.

Page 5-34.

The text box on criticality contains information on the amount of Fissile Gram Equivalents present in the WIPP Waste streams that is inconsistent with Table 1, Appendix B2 of the Baseline Inventory Report Revision 3. This Table shows there are 2,800 m^3 of RFETS residue waste with an average concentration per 0.208 m^3 drum of 13.7 Ci ^{239}Pu and 53.6 Ci of ^{241}Pu. This is an average of 218 FGE per 0.208 m^3 (55-gallon) drum. The permissible limit is 200 FGE/55-gallon drum. Furthermore, Table 1 indicates there are about 151 m^3 of waste at SRS, INEL, and Hanford that have average concentrations that exceed 200 FGE/ 55-gallon drum. This discrepancy needs to be reconciled and the Final SEIS-II should use the values published in the latest BIR. Also, the final disposition of wastes that exceed 200 FGE/drum should be stated.

The RFETS residues deserve more attention in SEIS-II than they have received. On February 20, 1997, the NRC granted DOE Revision 8 to the TRUPACT-II Certificate of Compliance. This Revision allows use of a pipe overpack to transport up to 200 FGE of residues in a pipe that is positioned inside a 55-gallon drum. The volumes of this pipe component would be either about 11 liters or about 45 liters. Up to 2,800 FGE of waste can be placed in a TRUPACT-II containing 14 of these pipe overpacks. The limit for 55-gallon drums or Standard Waste Boxes is only 325 FGE per TRUPACT-II. Some of these residues must be much more concentrated than the average concentration or DOE would not have needed to develop the pipe overpack. So now DOE can ship up to 2,800 FGE in a TRUPACT or 8,400 FGE on a trailer containing 3 TRUPACTs. Eight kilograms of plutonium is considered a significant quantity by IAEA because it is the approximate amount required to manufacture a nuclear explosive device. Such a shipment could be a candidate for a terrorist act of diversion during transportation. the Final SEIS-II should discuss the precautions that will be taken to present diversion of high FGE waste shipments.

Page 5-35.

We were able to approximately reproduce the LCFs for the RH-TRU Waste Storage Accident in Table 5-17 by using the overall release factor for stored CH-TRU waste from Page G-40 (3.125×10^{-6}) rather than the values described on this page for RH-TRU (6.25×10^{-8}). This overall RH-TRU release factor seems unreasonably low. Once again, the SEIS-II calculations are difficult to check because the specific input values are not given. It was necessary to retrieve numbers from two locations in Appendix G and one in Appendix A. We trust these were the values used in the calculation. Please provide more detail to enable the reader to reconstruct the calculation.

Page 5-35 to 37.

WIPP disposal accidents and their consequences are summarized in this section. More detail is provided in Appendix G.4. The WIPP Safety Analysis Report also contains a suite of WIPP disposal accident consequences. The SEIS-II scenarios and SAR Scenarios are not identical. They differ in numbering, description, assumptions, and consequences. A comparison of the consequences of common scenarios is shown in the following table

Table 2

EEG Comparison of SEIS-II and SAR
WIPP Accident Consequences

	Ratio of SEIS-II/SAR Latent Cancer Fatalities		
Scenario	MEI Public	Non-involved Worker	Involved Worker
CH 7 Spont. Ignition, UG	0.72	1.75	—
CH 3 Puncture, Drop in WHB	1.7	0.25	2.7
CH 4 Drop in WHB	2.0	0.29	3.6
CH 5 Waste Hoist	30.	4.0	—
CH 9 Drop in UG	1.0	0.15	15.6
CH 11 Roof Fall	10.	1.9	—

There is no clear pattern to the above ratios. MEI and Involved Worker consequences are mostly greater in SEIS-II, while non-involved worker consequences are mixed. It is unnecessary and confusing to use different scenarios and assumptions in the SEIS-II than were used in the SAR. The scenarios in the SAR evolved over a number of years and influenced by discussions between DOE/Westinghouse and EEG. These SAR scenarios are more specific to WIPP conditions and should be used in the final SEIS-II.

Page 5-36.

As shown in the following Table, the frequency of various accident scenarios are different in SEIS-II than in the 1996 Draft Safety Analysis Report (SAR). An explanation should be provided.

Table 3

EEG Comparison of Accident Scenario Frequencies
in SEIS-II and 1996 SAR

Table 5-18, Disposal	Annual Occurrence Frequency	
Accident Scenarios	Draft SEIS-II	Draft 1996 SAR
W1, WHB Drum Drop	0.1	0.011 (CH4)
W2, WHB Drum Puncture	0.1	0.006 (CH3)
W3, Underground Drum Drop	0.01	0.015 (CH9)
W4, Underground Drum Puncture	0.01	0.015 (CH9)
W5, Underground Container Fire	0.01	No scenario
W6, Hoist Failure	1E-4	1.4E-9
W7, Roof Fall	0.01 Panel 1	4.3E-7 (CH11)
W8, RH-TRU Canister Breach	1E-4 to 1E-6	no scenario

Page 5-39. Long-Term Post-Closure Performance.

The text says that the analysis in Draft SEIS-II are based on results computed for the Draft No-Migration Variance Petition and the Draft Compliance Certification Application (Draft CCA). Also, that "The final SEIS-II will re-examine its long-term performance assessment in light of any changes in methodology adopted for the compliance certification application." This re-examination should be made. It is unfortunate that Draft SEIS-II, even though it was released after the Final CCA was sent to EPA, could not incorporate the same methodology and results for the Proposed Action. We have comments on the current analysis.

Page 5-40 & 41. 75th Percentile Values.

The rationale for using median and 75th percentile parameter values is described: "The 75th percentile parameter values are used to yield model results that should fall in the upper tail of a full probabilistic analysis." But it is then said (lines 1-3 on page 5-41) that there is remarkably little difference between the mean and 75 percentile values. In fact Table H-24 indicates that direct radionuclide releases to the ground surface are identical for the median and 75th percentile values.

This is inconsistent with the CCA (see Figure 6-40) where the median values on the CCDF plot are 67% of the mean value at 0.1 Probability and 40% of the mean value at 0.001 Probability. The reason for this discrepancy is probably because more parameters were sampled over a distribution of values in the CCA than in SEIS-II. For example, the CCA sampled some parameters in the following areas that SEIS-II did not: (1) shaft materials; (2) gas generation, (3) the Culebra aquifer; (4) borehole plugs; and (5) borehole shear resistance. The SEIS-II calculation is, in most cases, using the same parameter values for the 75th percentile as for the median.

The methodology does not yield results that "fall in the upper tail of a full probabilistic analysis."

Page 5-40 & 41. Family Farm Scenario.

The decision was made to not include the family farm scenario (500 meters from drill cuttings) that was used in SEIS-I because the land was poor, little water was available, and water quality is poor. All of these facts are correct but there are ranch houses nearby and the majority of the dose (>99% in SEIS-I, Tables 5.63 and 5.64) is from inhalation. EEG-11[1] calculated CEDE inhalation doses of about 175 mrem/y at 360 m from 13 Ci of TRU radionuclides brought to the surface and deposited in a brine pit. Doses to nearby residents should be included in SEIS-II.

Page 5-41. Third Paragraph.

It is stated that "No population impacts were calculated because only small amounts of radioactive material would be brought to the surface, remain in a wet, relatively nondispersable form, and would

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[1]Channell, James K., "Calculated Radiation Doses from Radionuclides Brought to the Surface if Future Drilling Intercepts the WIPP Repository and Pressurized Brine," NM Environmental Evaluation Group, EEG-11, January 1982.

remain localized." The material brought to the surface will not remain wet. The mud pit will dry, enabling wind erosion to transport the radioactive material over long distances. It is quite possible that the mud pit will be dry prior to dismantling the drill rig and be disturbed by that process, exposing those workers to the risk of inhaling radioactive dust.

The assumption of wet, non-dispersable material in the brine pond is inconsistent with assumptions used in SEIS-I, EEG-11 and TME-3151.[2] Both EEG-11 and TME-3151 calculated inhalation doses to the population within 50 miles from wind erosion. EEG-11 estimated a population dose of 39 person-rem per year (50-year Committed Effective Dose Equivalent) and assumed the exposure would last for many years. TME-3151 projected a population-dose of 76 person-rem CEDE for the one year period before the pond is covered.

Intrusion into the repository would definitely expose the neighboring population to risk. This risk should be calculated.

Page 5-42. 4th line from bottom.

Reference is made to the 5-kilometer subsurface lateral boundary. The appropriate boundary of concern is the WIPP site boundary which is less than 3 km from the waste panels to the south (down gradient in the Culebra aquifer).

Page 5-43. Figure 5-1.

There is a 10^6 conversion error on this Figure (and on lines 18-19 on page 5-42) that is repeated on numerous other Figures in this Chapter and Appendix H. A concentration of 1 pCi/l is equal to $10^{-9}\ Ci/m^3 \left[(1\frac{pCi}{l})(10^{-12}\ \frac{Ci}{pCi})(10^3\frac{l}{m^3}) = 10^{-9}\frac{Ci}{m^3})\right]$ not 10^{-15} Ci/m^3. This mistake raises an uncertainty about which value was used in plotting the extent of migration areas in the various figures. This is important; it must be clarified, corrected, and the areas re-plotted if necessary.

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[2] Radiological Consequence of Brine Release by Human Intrusion into WIPP," US DOE, TME-3151, July 1982.

Page 5-44. Last paragraph.

This paragraph (which concludes on the top of page 5-45) concludes that intrusion at 100 years will have the maximum consequences. This determination cannot be made until calculations are made with an acceptable spallings model. Large spallings releases are possible at higher repository pressures which are expected to increase after 100 years. These increased spallings releases could more than offset the reduction in curies from radioactive decay.

Page 5-46. Fourth Paragraph.

The statement is made here (and elsewhere) that "no radionuclides or hazardous materials would be released into the Culebra within 10,000 years of repository closure for the deep drilling scenario under the proposed action." This is inconsistent with calculations in the CCA which show radionuclide release to the Culebra is a significant fraction of the E1, E2, and E1E2 scenario realizations. Calculations in the Final SEIS-II for the Proposed action need to be consistent with the CCA.

Page 5-48. Section 5.1.12.5.

The statement is made that if all the stored excess RH-TRU waste were released it would cause less than 2 deaths over a 10,000 year period but that if stored it would result in less than 2 worker deaths per 100 years. This suggests that it would be better to release the waste than to store it! This section should go beyond the statement that population may increase around the sites and present a rationale for storing the waste.

Page 5-49. Text Box.

We have several comments about the Long Disposal Periods on SEIS-II results discussed in the text box:

(1) The problems of keeping a facility open for 160 to 190 years are undoubtedly much more complex than SEIS-II suggests. The current shafts and drifts almost certainly can't be maintained for that long and surface facilities would probably also need to be replaced. Institutional problems would also be expected. The discussion also suggests that large work forces would be employed on these long periods and would thus be uneconomical. The concept of committing to any plan for this long a time is unprecedented and probably unwise;

(2) Thermal loading in the repository should not be a major problem. The excavated waste disposal area in the Proposed Plan is about 27 acres (for CH-TRU wastes). This would permit 270 Kw with the present criteria of 10 Kw/acre. The inventory in Appendix A (Tables A-31 and A-33) for Action Alternative 2 would generate less than 170 kilowatts;

(3) We agree that differences in long-term alternatives should be compared in long-term aggregate impacts rather than annual impacts. These comparisons should include the same universe of wastes, regardless of how they are managed.

Page 5-51. Text Box.

The discussion in this text box on Factors to Consider in Combining Alternatives provides useful information. The brief statements on Waste Treatment and Waste Management should be expanded because they contain much of the rationale for choosing the Proposed Action.

Page 5-59. Rail Accident Methodology.

The conclusion that the number of rail accidents using dedicated trains will be 23 times that expected for regular rail service is unrealistic. The methodology used could be used to calculate a wide range of numbers, including zero additional accidents (with the assumption that no new locomotives would ever be used). Some of the potential benefits from dedicated trains (e.g., lower potential accident rate per mile, more control over waste package, and shorter shipment times) should be discussed. It is noted that both regular train and dedicated train shipments have less impacts than truck shipments (Table 5-29 versus Tables 5-25, 5-26, 5-28).

Page 5-60.

Detailed evaluations of rail mileage in the SEIS-I and other earlier documents indicates that rail mileage from the major generating sites to WIPP is 16%-26% greater than truck mileage, not similar as claimed here.

Page 5-67.

The Radiological Impacts storage accidents for Action Alternative 1 in Table 5-34 are from Table G-28. We reproduced the calculation for population and MEI LCFs from the Earthquake Scenario. However,

the maximally exposed non-involved worker should have only 0.4 LCFs and not 0.7 LCFs for a dose of 1,050 person-rem. We calculated only 760 person-rem for this accident.

Page 5-85. 2nd Line Beneath Table.

What is the justification for assuming that thermal treatment of waste reduces the release fraction by a factor of 1,000?

Page 5-104. Section 5.3.

The impacts of disturbed and undisturbed cases of potash mining and brine reservoirs have not been adequately evaluated for the various Action Alternatives.

Page 5-142. Lines 7-9.

The assumption (for No Action Alternative 1) that DOE would indefinitely maintain institutional control at all of the storage sites is inconsistent with regulatory requirements at WIPP. Active institutional control may be allowed by EPA for 100 years at WIPP and credit (or partial credit) for up to 600 additional years of passive institutional control may be allowed. An assumption of perpetual institutional control for a No Action Alternative unfairly biases its comparison with the Proposed Action.

Page 5-145. Table 5-88.

The lifetime waste treatment impacts to involved workers in No Action Alternative 2 are only 0.08 LCFs. Yet for the Proposed Action they are 1.7 LCFs (Table 5-13). NAA 2 would treat 43% of the CH-TRU volume and 64% of the RH-TRU volume as the Proposed Action. Both actions treat waste to the WAC criteria at the generating sites. Why are the human health impacts for the Proposed Action 20 times as great?

Page 5-148. Section 5.6.12.

Detailed comments of intruder scenario modeling for long-term postclosure will be included in the comments on Appendix I.

The discussion of why the Record of Decision (ROD) for the FEIS and SEIS-I came to the conclusion that a No Action Alternative was "unacceptable" is very good.

Page 5-153. First paragraph.

The estimated 2,325 radiological LCFs in 10,000 years from environmental releases at all storage sites is noted. The EPA allowed limit for WIPP amounts to a maximum of 42 LCF's over 10,000 years. If the limit is met, the analysis indicates that disposal at WIPP is clearly more protective than storage at the generating sites.

Page 5-154. Lines 34 through 38.

Statement: "In contaminated areas, currently remote-controlled mining equipment or equipment modified with off-the-shelf systems may be used. Where practical, removal operations would be performed remotely. All support, radiation and air quality monitoring and geotechnical surveying would be performed remotely in the contaminated areas."

The discussion of waste recovery in section 5.7.2 relies almost entirely on remote controlled activities as expressed in the above statement. At present, remote controlled handling of CH-TRU and RH-TRU does not exist. The discussion of radiological impacts in section 5.7.2.1 Operational Impacts of Waste Recovery, has no basis or justification.

Page 5-155. Second complete paragraph.

This discussion mentions the greater external radiation hazard from waste recovery (compared to waste emplacement). However, inhalation exposures from dealing with breached containers and contaminated salt could also be significant and this needs to be recognized in the Final SEIS-II.

Page 5-156. Second complete paragraph.

Was any analysis involved in arriving at the conclusion that health impacts to the public and non-involved workers from recovery operations was 1,000 times that in Action Alternative 3?

Page 5-159. Lines 6 to 9 bottom.

The statement is made that DOE is considering transportation of fissile materials for storage and disposition. Is this being considered for WIPP?

Page 5-161. Lines 5 and 6.

More information is needed on the statement: "Emissions of radionuclides would be 134% of the standards for the alternatives that would involve treatment to the LDRs at LANL;" Page 5-88 mentions a $9x10^{-5}$ chance of an LCF but doesn't mention standards. Is this the 10 millirem/year NESHAPs Standard?

Page 5-162. Last paragraph.

The elimination of former "Control Zone IV" made this land available for oil and gas recovery as well as for potash mining. There are a number of producing wells in this area now. Water flooding is also permitted and is occurring.

Page 5-163. Section 5.11.

The LWA prohibits the extraction of mineral and hydrocarbon resources from the Land Withdrawal Area in perpetuity, not just during the period of disposal operations.

CHAPTER 6

Chapter 6 lists all the regulatory agencies and the status of permits for WIPP. One regulatory agency is notably absent. It is DOE. The Department has the legal authority to self regulate operational activities at WIPP. The status of WIPP's compliance with DOE Orders or even a list of DOE Orders is conspicuously absent. Indeed, DOE has the authority to self-approve the Draft Supplement to the EIS but fails to describe the internal system to be used. For example, the DOE long-term disposal calculations in the SEIS are approved by DOE and in the CCA by EPA.

LIST OF ACRONYMS

BIR:	Baseline Inventory Report
CCA:	Compliance Certification Application
CAO:	Carlsbad Area Office
CCDF:	Complementary Cumulative Distribution Function
CEDE:	Committed Effective Dose Equivalent
CH-TRU:	Contact Handled TRU Waste
DOE:	U.S. Department of Energy
DOT:	U.S. Department of Transportation
EIS:	Environmental Impact Statement
EPA:	U.S. Environmental Protection Agency
FEIS:	Final EIS
FGE:	Fissile Gram Equivalent
HRCQ:	Highway Route-Controlled Quantity
INEL:	Idaho National Engineering Laboratory
IRF:	Impact Release Fractions
LDR:	Land Disposal Regulations
LWA:	Land Withdrawal Act
LCF:	Latent Cancer Fatality
MEI:	Maximum Exposed Individual
NESHAPS:	National Emissions Standards for Hazardous Air Pollutants
NTS:	Nevada Test Site
NRC:	U.S. Nuclear Regulatory Commission
RH-TRU:	Remote Handled Transuranic Waste
ROD:	Record of Decision
RFETS:	Rocky Flats Environmental Technology Site
SAR:	Safety Analysis Report
SEIS:	Supplemental EIS
SRS:	Savannah River Site
TEDE:	Total Effective Dose Equivalent

LIST OF ACRONMYS (CONTINUED)

TRU:	Transuranic
WAC:	Waste Acceptance Criteria
WIPP:	Waste Isolation Pilot Plant
WM PEIS:	Waste Management Programmatic EIS

APPENDIX A
WASTE INVENTORY

Comments on Appendix A are made in the page order they occur. The importance attached to these comments by EEG can be inferred from the text of the comment. Comments related to waste inventory that occur in the Summary or the Chapters will be addressed in those locations.

Page A-2. Lines 19 through 22.

Statement: "The volume of TRU waste for the SEIS-II Basic Inventory is estimated at 135,000 cubic meters (4.7 million cubic feet) for CH-TRU waste and 35,000 cubic meters (1.2 million cubic feet) for RH-TRU waste. These estimates are based on current volumes of stored waste and waste expected to be generated through the year 2033."

The estimates of 135,000 cubic meters for CH-TRU and 35,000 cubic meters for RH-TRU involve significant uncertainties that should be estimated and discussed. A generic weakness of SEIS-II is a lack of discussion of uncertainty in the TRU inventory over the past 18 years.

Page A-6. Lines 22 through 25.

Statement: "Some heat is generated by TRU waste due to the interaction of alpha radiation, emitted in the radioactive decay of plutonium isotopes, with the walls of the waste container."

The heat is not generated in the wall of the waste containers. It is generated in the waste. The alpha particle range is too short to reach the walls of the waste containers.

Page A-7. Lines 2 and 3.

Statement: "The amount of gas generated is a function of the amount of heat produced from radioactive decay and the amount of plastic material present in the TRU waste."

The amount of gas generated is not a function of the amount of heat produced from radioactive decay. The amount of hydrogen gas generated is a function of the amount of energy deposited by ionizing radiation in the hydrogenous material present in the TRU waste and from anoxic corrosion of the drums.

Page A-8. Lines 9 through 14.

The estimated values for V_{site} could also be expressed as: $V_{site} = V_{stored} + (38/28[V_{projected} - V_{stored}])$.

In this form the writing of equation A-1 is consistent with the writing of equation A-7 and A-8. Also, to be consistent V_{stored} should be defined as TRU waste volume stored at the generator storage site through 1995. The use of "in 1995" is ambiguous.

Page A-8. Lines 27 through 33 and Page A-10. Table A-4.

Estimated total volumes of previously disposed TRU waste by site are discussed and presented.

The volumes of previously disposed TRU wastes are based on manifests that were written before 1970. If the waste is excavated and repackaged, the volumes will be significantly different due to compaction and the inclusion of contaminated soils. A discussion of the uncertainty in these volumes should be included.

Page A-12. Lines 5-7.

The statement is made that "only a few waste forms need packaging to meet thermal power limits, provided that plastic wrap is not used when the drums are filled (bagless posting)." Table A-16 indicates that average concentrations in about 19,400 m^3 (about 14%) of stored plus projected wastes do exceed the thermal power limits for bagless posting. Furthermore, our understanding is that the majority of presently stored wastes containers uses bags. Please comment. Does DOE plan to repackage wastes to remove bags? The plans to repackage and treat stored waste in order to meet the WIPP WAC limits should be explicitly addressed in detail in the SEIS-II.

Page A-12. Lines 8 through 17.

The calculation of $V_{Expansion}$ is discussed.

The calculation of $V_{Expansion}$ cannot readily be followed since the input data are contained in other documents such as TRUCON. Tables of adjustment factors similar to those provided in Tables B-2 and B-3 of Appendix B should be provided. See page A-22 to A-28 comment below.

Page A-12. Lines 19 through 24.

The statement is made that some of SRS waste would be processed to become RH-TRU. There is no evidence in the SEIS-II or other documents reviewed that there will be any RH-TRU at SRS.

Page A-13. Lines 21 through 23.

The Statement is made. "A 65-percent reduction in the TRU waste volume to be disposed of was assumed due to LDR thermal treatment of both CH-TRU and RH-TRU."

No justification is presented for the assumption of a 65-percent reduction factor in the TRU waste volume due to LDR thermal treatment. Also, it is questionable whether a 65-percent reduction should be applied to the additional inventory, since it has been compacted and will contain considerable amounts of soil.

Page A-13. Lines 35 through 38.

The statement: "A density change assumption, therefore, is made such that a 55 gallon drum containing the slag would weigh 454 kilograms (1,000 pounds). Waste density values are used in the determination of the number of shipments (Section A.3.9). See Table A-2 for the CH-TRU average drum weights used to determine the number of shipments."

Table A-2 does not provide data for a drum weighing 454 kilograms. It's not clear from Table A-2 whether it is permissible to use any number of waste drums between 11 and 42 as long as the weight of drums plus dunnage does not exceed the payload per shipment.

Page A-16. Table A-8.

The values for INEL and total in the columns labeled Post-Treatment Disposal Volume are in error. The values for INEL should be 10,000, 20,000, 30,000 m^3, instead of 10,000, 31,000, 41,000 m^3. The values for total at the bottom of the page should be 47,000, 49,000, 96,000 m^3 in Tables A-8, A-9, and A-10.

Page A-20. Table A-12.

The values for RFETS Total in the columns labeled Post-Treatment Disposal Volume are in error. The values for RFETS should be 13,000, ---, and 13,000 instead of and 19,000, ---, 19,000, and the values for Total at the bottom of the page should be 162,000, 166,000 and 329,000 m^3.

Page A-22 to A-28.

This section calculates the number of waste shipments for the various alternatives. The methodology is explained about shipping weights (Table A-2) and volume expansion to meet thermal limits (Equation A-2) earlier in the Appendix However, all assumptions were not given (e.g. how volumes were scaled to full repository size and whether the number of drums per shipment is interpolated between values given in Table A-2). For LANL CH-TRU Proposed Action shipments our calculated values were 6% lower than the 5,009 shipments indicated in Table A-15.

Page A-23. Table A-14.

The use of the term "Newly Generated Waste" for waste that doesn't exist is misleading. Use "To be-Generated Waste."

Page A-23. Table A-14.

The values in Table A-14 have not been rounded off, which is unlike Tables A-3 thru 13. Also, the columns labeled Existing Stored Volume should be relabeled Stored (1995) to be consistent with Table A-3.

Page A-28. Table A-17.

The PE-Ci/m^3 values for RFETS residues in Table A-17 are incorrect. From the inventory in Table A-23 it is apparent that the concentration should be about 17.3 PE-Ci per 55-gallon drum or 83.7 PE-Ci/m^3.

Page A-33 to A-40.

The method described here for scaling up radionuclide inventories is said to rely heavily on the Baseline Inventory Report, Revision 2 and the 1995 Integrated Data Base. Yet the results are different from those presented in the CCA and BIR Revision 3 as shown in Table 4. Values are also different for Pu-241, Am-241, Pu-240, Co-137 and Sr-90.

Table A-1

EEG Comparison of Inventories Used in Different DOE Documents

Source	CH-TRU		RH-TRU	
	^{238}Pu CI	^{239}Pu	^{238}Pu	^{239}Pu
CCA at 2033	1.94×10^6	7.85×10^5	1.07×10^3	1.0×10^4
BIR Rev 3,2033	1.93×10^6	7.85×10^5	1.07×10^3	1.0×10^4
Table A-27&28	1.70×10^6	6.82×10^5	6.48×10^2	3.93×10^3

We were not able to reproduce the volume factors reported in Table A-25 for the Proposed Action. Our values were about 3.5% higher for CH-TRU at LANL and SRS when using V_{IDB} values from the 1994 IDB in equation A-8. This Appendix did not specify what volumes were used or how the inventory was scaled to a full repository.

More importantly, we do not see any reason for SEIS-II to derive a different disposal inventory for the Proposed Action. The Final SEIS-II should use the same values as the CCA.

APPENDIX B

SUMMARY OF WM PEIS AND ITS USE IN DETERMINING HUMAN HEALTH IMPACTS

Page B-9. Line 5 or equation B-1.

The equation for site adjustment factors is presented. Equation B-1 is confusing and needs additional brackets and explanations. The subscript $_{site}$ appears inside the square bracket and the subscript $_{keysite}$ appears outside the square bracket. The definition of SF_{site} contains the word site and the phrase key contributing sites. The definition of V_{sites} and $V_{WM\ PEIS}$ contain the word site only. The definition of C_{SEIS} and $C_{WM\ PEIS}$ contain the phrase "site Key" only. It appears that there is a multiplication of data from $_{site}$ tables with data from $_{keysite}$ tables. Finally, the large curved brackets have the subscript $_{alternative,\ subalternative}$ where alternative pertains to the SEIS-II and subalternative pertains to the Draft WM PEIS, which suggests that SF_{site} is a matrix.

Page B-9. Lines 14 through 16.

Statement: "Key contributing sites were determined by ranking the sites by cancer incidence risk for each alternative. The sites with the largest risk were then selected until a contribution of at least 90 percent of the total cancer incidence risk as reported in the Draft WM PEIS was reached."

It is not clear what this paragraph has to do with the calculation of site adjustment factors. Presumably it deals with the evaluation of the ratio of site key radionuclide concentration in SEIS-II/site key radionuclide concentration in the Draft WM PEIS.

Page B-9. Lines 31 through 33.

Statement: "Key radionuclides are those defined in Appendix D of the Draft WM PEIS as the single radionuclide contributing the highest risk cancer fatality at each site under each alternative. Key radionuclides are identified in Appendix D of the Draft WM PEIS."

Equation B-1 deals with "site key radionuclides" and not "key radionuclides."

Page B-11. Line 17 equation B-2.

The equation for adjusting the site-specific cancer incidence values of the WM PEIS is presented.

Equation B-2 is confusing and may contain misplaced subscripts. Again the subscript $_{site}$ appears inside rounded brackets and the subscript $_{keysite}$ appears outside the same rounded brackets. Presumably the subscript $_{keysite}$ should be beneath the summation symbol. Also the large square brackets that enclose R(adj) $_{WM\ PEIS}$ have the subscript $_{alternative,\ subalternative}$ which suggest that R(adj) $_{WM\ PEIS}$ is a matrix. SF_{site}, which is inside the large square brackets also involved the subscript $_{alternative,\ subalternative}$.

Page B-12. Table B-4.

The site adjustment factor for LANL should be 0.13 since this is the value used in the results of the calculations that are presented in Table B-5. The rounded off value of 0.1 is not used in the calculations.

APPENDIX C
AIR QUALITY

No Comments

APPENDIX D

LIFE-CYCLE COSTS AND ECONOMIC IMPACTS

Page D-1. Section D.1. Life-Cycle Cost.

The section does not indicate that life-cycle costs were determined for exhuming the CH-TRU waste disposed before 1970. It does not appear that these costs were analyzed in the draft WM PEIS.

Page D-2. Table D-1.

The bottom part of the table calculated the Volume Adjustment Factor. The volumes in column 5, SEIS-II CH-TRU Waste, column 6, and column 7, SEIS-II RH-TRU Waste, should be rounded off to be consistent with Table A-5. Also, the RH-TRU volumes are quite different in the two tables. The lack of consistency is confusing. It should indicate that the volumes are in cubic meters.

Page D-3. Table D-2.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-6 and A-7.

Page D-4. Table D-3.

Volumes in columns 5, 6, and 7 should be rounded off to be consistent with Tables A-8 and A-11.

Page D-5. Table D-4.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-9 and A-11.

Page D-5. Table D-5.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-10 and A-11.

Page D-6. Table D-6.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-12 and A-13.

Page D-7. Table D-7.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-8 and A-11.

Page D-8. Table D-8.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-9 and A-11.

Page D-10. Line 4.

The discount factor is presented as (1/1+r). There appears to be an error. It is not possible to reproduce the numbers in Table D-10 using the above formula for the discount factor.

Page D-10. Table D-10.

The rounding off of numbers is very crude. The values for Inflation-Adjusted Discount Rate of r=3 percent and r=5 percent in column 3 are the same. It is not possible to come close to the numbers in row 3 using a discount factor of $1/1.05^{35}$. Rounding off to the nearest $0.5 B in column 3 on a value of $3.5B does not build confidence. This amounts to 15%.

APPENDIX E
TRANSPORTATION

The Appendix E, review concentrates on the discussions and calculations relevant to the radiological aspects of the Proposed Action for truck transportation, since this is the most likely final choice for waste shipments to WIPP. Implications of the alternative actions, rail transport, and hazardous chemical impacts were evaluated in less detail.

EEG reviewed various DOE WIPP transportation documents over the years and produced several related reports. None are referenced. One report ("Risk Analysis of the Transport of Contact Handled Transuranic (CH-TRU) wastes to WIPP along Selected Highway routes in New Mexico using RADTRAN IV," Anthony F. Gallegos and James K. Channell, EEG-46, August 1990) is particularly relevant to Appendix E. EEG-46 is a reasonable and adequately conservative evaluation of transportation risks. Our review of Appendix E is a comparison with EEG-46. Consideration was given to the fact that Appendix E is a nationwide assessment and changes in assumptions have occurred since 1990.

Page E-2.

The statement "The SARP application for the RH-72B shipping cask is to be submitted to the NRC in September of 1996 is incorrect." It was submitted in December of 1996.

TRUCK TRANSPORTATION

Routes and Mileage

The proposed waste shipment routes to WIPP agree with our understanding. The distance reported in Table E-5 from LANL to the WIPP site (549 km, with 512 km being rural, 34 suburban and 3 urban) agrees favorably with that used in EEG-46 (548 km, with 509 km rural and 39 km suburban). Distances from the other sites were not checked, but appear reasonable.

Non-radiological Accidents

DOE reported accident, injury, and fatality impacts per roundtrip shipment from each site to WIPP in Table E-8. However, since accident rates per kilometer were not given, the values in Table E-8 could not be checked. The back-calculated accident rates for the LANL to WIPP route (1.62×10^{-6}/km in suburban areas and 3.13×10^{-7}/km for rural areas) are reasonably close to the values used in EEG-46 (3.21×10^{-6}/km rural and 1.78×10^{-6}/km urban and 1.78×10^{-6}/km suburban).

Accident per shipment data from Table E-8 and the number of shipments values from Tables E-1 and E-2 were used to check the total values for the proposed values in Table E-9. Agreement was within 3% and differences were probably due to rounding error. The EEG-46 value of 5.0 accidents (while carrying wastes) in New Mexico extrapolated to 52 CH-TRU roundtrip accidents. This was adequate agreement (-10%) with the SEIS-II value of 58 accidents.

We agree with the value of 0.165 (rounded to 0.2) LCFs from vehicle pollution in urban areas.

Accident Free Radiation Doses

In Table E-10 (RADTRAN INPUT, Etc.) it is not clear why the number of people exposed per stop and the exposure distance is different for CH-TRU and RH-TRU.

The aggregate accident-free dose to occupational and nonoccupational persons is presented in Table E-14. The non-occupational value for CH-TRU (4,200 person-rem) is similar to the value obtained (4,050 person-rem) by scaling up the EEG-46 value of 330 person-rem by a mileage factor of 40.7×10^6 mi/7.8×10^6 = 5.22 and a Transportation index (TI) adjustment of 4.0/1.7 mrem. This is good agreement.

The aggregate occupational dose of 710 person-rem was reproduced within 1% from methodology in SAND 84-0036 (RADTRAN III) and when using the actual average TI value (1.5 mrem/hr.) from Table E-11. This dose was not calculated directly in EEG-46.

Scenarios for calculating doses to the maximum exposed individual (MEI) are described on page E-32 and the doses are shown in Table E-15. The scenario description does not provide all the assumptions necessary to make the calculations. We were able to reproduce the CH-TRU doses for the Departure Inspector, the State Inspector, and the rest stop employee within $\pm$ 12% by using either the TI values reported in Table E-11 or the 4 rem/h value (that the text said was being used). The scenarios are sufficiently conservative so that the MEI doses in Table E-15 adequately represent the doses to members of the public and to occupational workers that do not wear dosimeters.

The calculated risk to these MEIs are not large. However, the doses average several hundred millirem/year for 10 years. This is somewhat greater than the 100 mrem/y value that most national and international agencies believe should not be exceeded from all radiation exposure combined (radiation doses from natural background and medical usage are not included in the 100 mrem/y value). These considerations suggest that the following operational control procedures should be implemented:

(1) persons who routinely inspect vehicles should be classified as radiation workers and required to wear dosimeters;

(2) normal procedures should not allow trucks carrying CH-TRU or RH-TRU wastes to routinely stop for long periods of time at locations where public exposure is likely to occur.

Maximum Transportation Accident Doses

EEG-46 calculated a maximum of 10 LCFs from a category VIII accident in North Carlsbad with an average SRS shipment (1,670 PE-Ci in 3 TRUPACTS). The probability of this event was calculated as 4.7×10^{-8}. SEIS-II calculated a bounding accident value of 16 LCF with a maximum allowable PE-Ci content in a TRUPACT-II (928 PE-Ci) and 3 LCF with an average inventory (191 PE-Ci). There were numerous differences in assumptions and there is an uncertainty about the actual population density used in EEG-46.

Attempts to extrapolate EEG-46 LCFs resulted in only about 60% of the doses reported in SEIS. The SEIS-II bounding values are appropriately conservative and indicate that very low probability accidents could have serious consequences.

It was noted in the PEIS (page E-77) that "waste shipments from LANL were found to result in the highest potential transportation accident doses." SEIS-II did not give highest potential transportation accident doses by site. The WM PEIS (footnote to Table E-26) assumed that all 3 TRUPACTs would fail in an accident. SEIS-II (page E-42) assumed only one would fail.

Aggregate Radiological Impact from Accidents

The aggregate radiological impacts from accidents in Table E-22 present the expected population dose (person-rem) from multiplying the person-rems for each accident by the probability of occurrence. The total dose for the Proposed Action is 850 person-rem (829 from CH-TRU shipments and 15 from RH-TRU. These doses are over two orders of magnitude greater than would be predicted from EEG-46 even after scaling for total system mileage. Most of this difference can be attributed to the higher impact release fractions (IRF) for accident categories V, VI, and VII used in SEIS-II. These IRF values are 100, 40, and 4 times (for categories V, VI, VII) those used in EEG-46. These categories have a much higher probability of occurrence and actually contribute more to the expected doses than category VIII accidents. It is concluded that these aggregate population doses from accidents are appropriately conservative.

Rail Shipments

On page 3-7 the SEIS gives four reasons why truck only transport was chosen: (1) limited interest by rail carriers; (2) higher cost of dedicated trains relative to truck shipments; (3) cost of acquiring additional TRUPACT-IIs; and (4) rail carriers would not assure DOE that transport could occur in less than 60 days. SEIS-II discusses 7 issues (bottom of page E-58 and top of page E-60) that need to be addressed before a decision can be made to use rail transport. The present uncertainties mentioned for these issues are largely true. However, it is unclear whether DOE has seriously re-evaluated this issue since the decision about 12 years ago to have truck

only transport to WIPP. There is no indication in DOE/WIPP 93-050 (Comparative Study of WIPP Transportation Alternatives, February 1994) that the decision was really re-evaluated.

The values reported in Tables E-29 through E-32 were "determined by adjusting the transportation impacts from truck shipments" (page E-58). Examples of questionable assumptions used in this analysis are:

(1) The average speed in all population zones was said to be 55 miles per hour for truck transport. This is inconsistent with Table E-10;

(2) The total miles assumed to be the same for truck and rail. SEIS-I actually developed rail route distances (see Table D.4.2). Distances by rail were 16%-26% greater for all of the major generating sites;

(3) The origin of the 89% rural, 10% suburban, and 1% urban breakdown is not given. The mileage - average for the distances in SEIS-I (weighted for the number of SEIS-II shipments) is 87%, 12%, and 1%;

(4) The basis for the assumption that the number of individuals sharing the transportation corridor is at least two orders of magnitude less is not given;

(5) We cannot reproduce the value in equation E-5 from equation E-4. The value of TI in E-4 should be 0.033 (from the previous page). Also, a value is needed for N (number of rail shipment transfers per shipment). If N were about 3.2 and TI was .033 the dose would be $1.7x60^{-4}$(TI)M;

(6) The logic for assuming that the aggregate radiological consequences of rail accidents were identical to truck accidents (first paragraph under E.7.3, page E-62) is unclear (same miles traveled times less frequency for rail accidents = same as truck). Is this because the release would be double in rail accidents?

A comparison of the Rail Transportation impacts in Tables E-29 (Action Alternative 1) and E-30 (Action Alternative 2) indicates there are less effects from rail transport than from truck transport (Tables E-9 and E-14. This suggests that SEIS-II should provide a better rationale for using truck only transportation or else seriously re-evaluate whether a truck and rail mix might be preferable.

Alternatives

The results of Alternative Impacts from accidents, vehicle pollution, and routine radiation exposure that are presented in various tables were studied to see if the values were reasonable compared to the Proposed Action. In all cases, the values appear to deviate in the expected direction from the Proposed Action and the magnitude of the deviation seemed reasonable. More description in the text explaining these differences would be helpful however. For example, is the lower (relative to the Proposed Action) non-occupational radiation dose total in Table E-14 for CH-TRU waste in Alternatives 2A and 2B due solely to the fact that there are fewer miles travelled (which can be implied from Table E-9)? Does this calculation use the TI values from Table E-11, or does it use a TI of 4 in both cases?

The statement on page E-53 that for thermally treated waste "The release fraction would be reduced by a factor of 1,000, ..." is not referenced or justified. Some reduction would be expected, but a three order-of-magnitude reduction requires justification.

A large number of comparisons are made about the transportation effects between alternatives in Appendix E. These comparisons include expected radiological and non-radiological risks from both incident free and accident conditions. The consequences of severe low probability accidents are also evaluated. Yet there is no discussion in this Appendix of using this information to aid in the selection of the appropriate action. The impression given at this time is that the Proposed Action is the only one being considered.

Page E-43. Equation E-1.

There appears to be a typographical error. Equation E-1 has a parameter named FMPI while the explanatory text has a parameter named FMRPI.

Page E-45. Equation E-2.

There appears to be a typographical error. Equation E-2 has a parameter named FMRT while the explanatory text has a parameter named FMRPT.

Page E-64. Section E.8.2.

There is a conversion error in the first paragraph of this section: 3.4×10^6 cubic meters is equal to 1.2×10^8 cubic feet (not 10^6).

APPENDIX F
HUMAN HEALTH
(from Routine Operations)

Page F-14. Section F.2.3.3 External dose of Involved Workers.

No units are given in Tables F-11 through F-15. This should be corrected in the Final SEIS-II.

Page F-17, last paragraph.

The statement that only a small volume of waste would require packaging is perhaps misleading. "Repackaging" is intended, not "packaging". As mentioned under page A-12 comments, about 14% of wastes exceed thermal limits even with bagless posting and a significant percentage of existing wastes are believed to contain bags. Also note that the Draft SAR Appendix A states that DOE plans to repackage or process 88% of the existing CH-TRU waste.

Page F-18, first paragraph.

Dose rates are said to be reducible by administrative controls but no credit is taken for this. Credit should not be taken because there is no commitment to exercising administrative controls.

Page F-18. Equation F-1.

No reference is provided as to where the input data of D_{id} and C_{ic} can be found. Without these input data, it is not possible to verify independently the average surface dose rate in Table F-17.

Page F-20.

The reason for calculating the worker lifetime dose on a per waste panel basis is not apparent since the exposure assumptions are unrelated to the filling of a panel. All that is needed is the assumption of the hours per year that the worker is present at 1 meter from the drum and the average 1-meter dose rate from Table F-17. The workers should have exposure time limited to 345 hours per year in order to have the annual dose $\leq$ 1 rem for an average 1-meter dose rate of 2.9 mrem/hr. Furthermore the assumption in Table F-18 that the 10 panels will be completed

in 20 years is inconsistent with the rationale described in the last paragraph of page F-20 that would require 23.2 years in order to hold doses to 1 rem/year. These calculations do not appear to address exposures from the installation of MgO around the drums.

Page F-21.

Attempts to reproduce two of the individual dose values for storage site workers for alternative 1 resulted in values that were +12% and -17% of the Table F-22 values. In this effort we started with the average 1-meter dose rate in Table F-17 and decayed screening values from Table F-12 over the 20 to 55 year period to obtain average annual dose rates for the 35 years. Ingrowth of ^{241}Am from decay of ^{241}Pu was also included. It would be helpful to reviewers if SEIS-II gave more details of the calculations so they could be checked without making numerous assumptions.

The SEIS-II chose to evaluate the radiological effects of routine operations involving lag storage and no action alternatives on the 35-year working lifetime of individual workers. These results are presented in Table F-22 and this is an appropriate way to evaluate the risk to an individual worker or a (35-year) generation of workers. However, it does not indicate the cumulative effect over several generations (for the various action alternatives) and perpetually for the No Action Alternatives. The method used makes the human health effects (LCFs) of the alternatives appear better in comparison with the proposed action than it would be if multi-generational effects were included.

Page F-21. Equation F-3.

No reference is provided for the input data of $V_{CH,S}$ and T. The definition of T as a worker throughput rate of one worker per 1,000 cubic meters is confusing. It is not possibly to verify independently the values in Table F-19.

Page F-25.

The involved worker lifetime radiological impacts from routine CH-TRU waste disposal operations in Table F-21 total 720 person-rem for the entire disposal phase. This total is

derived from 36 workers x 20 rem/worker =720. The WIPP Safety Analysis Report (DOE/WIPP-Draft - 2065 Revision 1, Table 7.1-2) used 36.9 rem/year for 38 persons and a 35 year disposal period. This totals 1,292 person-rem and a dose of 34 rem/per person. This is 1.8 times the worker population dose used in SEIS-II. The main difference is in assuming a 35 year disposal phase rather than a 20 year phase. DOE should present consistent methodology and results in its related WIPP documents.

The individual lifetime worker doses in Table F-22 for RFETS are excessively high. Both Action Alternative 1 and No Action Alternative 2 exceed occupational limits (5 rem/y) every year for 35 years. Surely such doses would not be allowed. These doses need to be explained or the text needs to be corrected.

APPENDIX G
FACILITY ACCIDENTS

There is no statement that SEIS-II is in compliance with the report, U.S. Department of Energy, 1993, *Recommendation for the Preparation of Environmental Assessment and Impacts Statement,* Washington, DC: Office of National Environmental Policy Act Oversight nor that it is in compliance with the DOE/New Mexico C & C Agreement. The second statement in the WM PEIS, APPENDIX F, Treatment and Storage Facility Accidents, F.1.1. SUMMARY, indicates compliance with the above cited document.

Page G-1. Lines 31 and 32.

Statement: "The health impacts from acute exposures to radionuclides from accidental releases were calculated as described in Appendix F."

The statement is incorrect. Appendix F deals with human health impacts that may result from exposures to radioactive materials and hazardous chemicals during routine storage operations at waste storage sites and during routine disposal operations at the WIPP.

Page G-2. Lines 3 through 5.

Dose-to-risk conversion factors for a population are given with a unit of /rem.

The unit is incorrect. The unit for dose to risk conversion factor for a population is /(person-rem). The dose-to-risk conversion factors are correctly presented on page F-2.

Page G-8. Table G-4.

If Pu-238 and Pu-240 are considered to be major contributors to dose at ORNL, Pu-239 should also be listed in that category.

Page G-13. Line 40.

Statement: "Because of the serious nature of the accident, the involved workers were assumed to be fatally injured."

There should be an indication of the number of workers involved.

Page G-14. Table G-9.

The text on page G-13 states that thermally treated waste is placed in 5 drums simultaneously. Scenario T4 shows 4.9 drums. The difference is small, but the lack of consistency is confusing.

Page G-17. Line 4.

Q is defined as the radionuclide or hazardous metal inventory of a waste container (from Appendix A). Appendix A provides radionuclide inventories only on a per treatment site basis. Additional calculations are required to convert the data to a per drum basis. It is not possible to independently verify the health impacts data presented in Tables G-13, G-16, and G-19.

Page G-18. Equation G-2 and line 6.

The quantity E/Q is known as the relative concentration (NUREG 1.145 or WIPP/SAR). The quantity is not defined in the Glossary and E/Q cannot be found in Acronyms and Abbreviations. In Table G-12, E/Q is referred to as the atmospheric dispersion factor. There should be consistency and the omission from the Glossary and from the Acronyms and Abbreviation should be corrected. This term has historically been labeled as χ/Q (Chi/Q). The use of the E/Q terminology is unnecessary and confusing.

Page G-18. Table G-11.

Column 3 of Table G-11 presents "population-Weighted E/Q (sec/cubic meter)".

The quantity "Population-Weighted E/Q" is not defined in the Glossary. Presumably, the units of "Population-Weighted E/Q" should be (person-sec)/(cubic meter). The parameter and its correct units should be included in the glossary.

Page G-21. Lines 11 through 15.

Statement: "Acute releases were assumed to be dispersed in one direction, so population impacts were estimated for a single, maximally exposed, 22.5 degree sector (out to 80 kilometers [50 miles]) and not for the entire 80-kilometer (50 mile) region population. Population weighted atmospheric dispersion values were calculated and used to determine the maximally-impacted sector, considering both the change in air concentration over distance and the population impacts in a single 22.5-degree sector."

The description does not make it possible to independently verify the calculations. The discussion should include equations for the calculations of the population-weighted atmospheric dispersion values and for the calculations of the population impacts in a single 22.5 degree sector.

Page G-30. Lines 3 through 5.

Statement: "Intakes of radionuclides could result in a dose of up to 14,800 rem, with a corresponding probability of an LCF of greater than 1."

Numerically, a probability is a dimensionless number with values between 0.0 and 1.0. 0.0 indicates that the event cannot occur and 1.0 indicates that the event will occur with absolute certainty. A probability cannot be greater than 1.0. Also, a TEDE of 14,800 rem may be a lethal dose (rather than an LCF) even for transuranic wastes where internal doses are delivered over many years.

Page G-36. Lines 28 and 29.

Statement: "The fission products contributing the most to external dose rates were Cs-137/Ba-137m and Co-60,...."

Co-60 is an activation product and not a fission product.

G-42. Table G-28.

Insufficient data are provided in the text to verify the dose calculations. The text does not provide a reference for the dose conversion factor, DCF, for PE-Ci, and it is not possible to calculate the source term for accident scenario 3 (earthquake) because there is no reference to the number of waste drums involved.

Page G-46. Table G-31.

See comment page G-42. Table G-28.

Page G-49. Table G-33.

See comment page G-42. Table G-28.

APPENDIX H
LONG-TERM CONSEQUENCE ANALYSIS FOR PROPOSED ACTION AND ACTION ALTERNATIVES

A general comment is that EEG believes that the Final SEIS-II should use methodology, codes, and selected data from the CCA. Any modifications to the October 1996 CCA available prior to writing the Final SEIS-II should also be incorporated.

The EEG has identified a number of concerns on the long-term consequence analysis in our review of the Compliance Certification Application (CCA). A number of plausible scenarios have not been analyzed, many conceptual models of breach are invalid, and many parameter values selected for analysis are wrong. The EEG has submitted detailed comments on the CCA to the EPA and plans to publish a report (EEG-65) outlining these concerns, in the near future. These concerns should be taken into account before a record of decision is developed.

Some of the EEG concerns published in our review of the draft CCA (EEG-61) have been incorporated in Section H-8 of this Appendix. The discussion in this section shows that most of these issues remain unresolved. We recommend, therefore, that no decision on the basis of SEIS-II analysis be made until these concerns are resolved in the process of the CCA review and the EPA's certification rule-making process.

Pages H-7&8. 75th Percentile Values.

There is no justification for the claim that the 75th Percentile Values as used lead to a realization that is "within 1% of the maximum release statistically possible." See comments under Page 5-40 & 41.

Page H-8. Last full paragraph.

The analysis is said to have shown no releases into the Culebra dolomite. This is inconsistent with the CCA, which showed releases in a number of realizations.

Page H-24. Next to last paragraph.

Contrary to the statement in this paragraph, the impacts of chemical retardation are being calculated in the PA for the CCA.

Page H-30. Table H-7.

These solubility values are from the DCCA. They are somewhat higher than those being used in the CCA because of the effect of MgO backfill. Final SEIS-II should use the CCA values.

Page H-34. Lines 1 through 6.

Reference is made to Figure H-7 and to Table H-8.

It is difficult to follow what the relationship is between Figure H-7 and the data in Table H-8. There is no explanation on how the last row of Table H-8, entitled Total Repository Volume, is obtained. It is not clear what the relationship is between Rest of Repository, Separately Modeled Panel Volume, and Total Repository Volume. Some additional clarification should be presented.

Page H-36. Table H-8.

The z distance in a two-dimensional grid was increased by factors of approximately 8 in order to accommodate the larger waste volumes in Action Alternatives 1, 2, and 3. This violates the two- dimensional assumption of the BRAGFLO grid. A three-dimensional analysis may be needed to give reliable results.

Page H-49. Table H-22.

The CCA used much smaller brine reservoir values than the volume estimated for WIPP-12. EEG has reservations about this CCA assumption. Also, the compressibility value shown should be for rock compressibility, not pore compressibility (pore compressibility = rock compressibility ÷ effective porosity).

Page H-52. Lines 1 and 2.

Statement: "The pressure release of the waste panel, as a result of the exploratory drilling event at 100 years post-closure, is clearly evident for Case 2 and 4 in Figure H-8."

In Figure H-8, the pressure release for cases 2 and 4 appears to occur at 400 years post-closure. No explanation is provided in the text for the delay in pressure release from 100 years post-closure (time of drilling event) to 400 years post-closure (time of pressure release). Also, Figure H-8 indicates a significant pressure increase between 700 years and 1,300 year post-closure for cases 2 and 4. Finally, the asymptotic behavior for cases 2 and 4 at 10,000 years post-closure is significantly different. Are the differences in the brine pressure for cases 2 and 4 the result of error propagation in numerical solutions of the differential equations? Some discussion should be provided in the text.

Page H-52, Figure H-9.

The appropriate conversion factor between pCi/1 and Ci/m^3 is 1 pCi/1 = 10^{-9} Ci/m^3 (not 10^{-15} pCi/1). See page 5-43 comment.

Page H-55 and Later. Table H-24.

No attempt was made to check the reasonableness of the assumptions and calculations of releases and doses to the driller. It is noted in Table H-24 that the value for Pu-240 is incorrect. It will be a few percent of the Pu-239 value, not less than 0.01%.

Page H-57. Last paragraph.

Because of the pCi/1 to Ci/m^3 conversion error mentioned, we are unsure whether the 1 pCi/1 value quoted here is correct or whether the value is 10^{-6} pCi/1.

Page H-60. Lines 1 and 2.

Statement: "The pressure release of the waste panel as a result of the exploratory drilling event at 100 years post-closure is clearly evident for case 7 and 9 in this figure."

Figure H-11 indicates a pressure release at almost 500 years post-closure. This is significantly different from 100 years post-closure, which is the time of the drilling event. No explanation is provided in the text for this delay. Are the differences in the asymptotic behavior at 10,000 years post-closure between cases 6 and 8 and cases 7 and 9 the result of error propagation in the numerical solutions of the differential equations? An explanation should be provided in the accompanying text.

Page H-62. Table H-29.

For the radionuclides of Am-241, Cm-244, Pu-238, Pu-239, Pu-240, Pu-241, U-233, and U-234, column 3, CH-TRU and RH-TRU Waste Panel, is the sum of column 1, CH-TRU Waste Panel, and column 2, RH-TRU Waste Panel. For other radionuclides such as Ac-227, Cm-243, Cs-137, Pa-231, Sr-90, and Y-90, column 3 is not the sum of columns 1 and 2. A more detailed explanation for columns 1, 2, and 3 should be provided in the accompanying text.

Page H-66. Lines 25 and 26.

Statement: "The pressure release of the waste panel as a result of the exploratory drilling event at 100 years post-closure is clearly evident for cases 12 and 14 in the figure."

Unlike the spiked brine pressure curves for cases 2 and 4 in Figure H-8 and for cases 7 and 9 in Figures H-11, the brine pressure curves for cases 12 and 14 are smooth and peak close to 1,500 years post closure. No explanation is provided for the difference in behavior of the brine pressure curve for cases 12 and 14 from cases 2, 4, 7, and 9.

Page H-72. Lines 15 and 16.

Statement: "The pressure release of the waste panel as a result of the exploratory drilling event at 100 years post-closure is clearly evident for cases 17 and 19 in this figure."

See comment page H-52, lines 1 and 2. See also comment page H-60, lines 1 and 2.

Page H-74. Table H-39.

See comment Page H-62. Table H-29.

APPENDIX I
LONG-TERM CONSEQUENCES OF NO ACTION ALTERNATIVE 2

This Appendix was reviewed for general approach, assumptions used, and conclusions reached. Little was done to check calculations. The calculations were done in a preliminary manner compared to those for the Proposed Action and (especially) in the CCA. Therefore it is not possible to compare results in more than general terms.

Page I-1. Last paragraph.

The statement is made that both the FEIS and SEIS-I records of decision (ROD) determined that the No Action Alternative was unacceptable "because of the potential impacts of natural, low-probability events and human intrusion at storage facilities after government control of the site is lost." Presumably, this will also be the decision in the SEIS-II ROD. However, this Draft SEIS-II has not addressed the issue of whether it is appropriate to trade-off predictable early fatalities from accidents and routine radiation exposure against the threat of low-probability events far in the future. Nor is there an estimate of the probabilities that these future events will occur.

Page I-3. Section 1.2.1.

The set of assumptions used for inadvertent human intrusion impacts are appropriately conservative.

Page I-6. Equation 1-2.

The convolution integral appears first in equation I-2. All the explanations pertaining to the convolution integral given much later with equation I-7, should be given first with equation I-2.

Page I-9. Equation 1-7.

The symbol for the convolution operation is used twice, the second time inside an integral.

The use of the convolution symbol inside the integral is incorrect. A symbol representing multiplication should be used inside the integral.

Page I-11. Next to last paragraph.

The dimensions given here (66 cm diameter and 91 cm height) for a 55-gallon drum differ from those used in WIPP Performance Assessment (60.2 cm diameter and 89.2 cm height). Use of the PA dimensions gives a surface-area-to-volume ratio of 0.11 cm^{-1}.

Page I-12. Line 3.

The effective lifetime of 500 years for cemented TRU waste forms in this analysis may not be conservative.

Page I-12. Line 9.

Statement: "BIR-2 specifies a waste volume and waste density for each of 10 waste material types (Table I-1). These waste material types were categorized into one of the generated TRU waste-form categories modeled in this analysis."

The reference in parenthesis to Table I-1 belongs at the end of the second sentence.

Page I-12. Lines 23 through 25.

Statement: "These relative quantities were multiplied by the total TRU Waste volumes for the site (see appendix A) to determine final site volumes for each TRU waste form category. Volumes are also reported in Table I-2."

It is not possible to obtain the waste volumes reported in Table I-2 (columns 3 and 4) by multiplying the waste volumes of Table A-14 by the relative quantities given in Table I-2 (columns 1 and 2).

Page I-17. Fourth Paragraph.

Buried wastes are assumed to not release any wastes by surface erosion/dispersion mechanisms. Yet Table I-6 predicts that 6 of the 7 major sites will have enough surface erosion to expose wastes in less than 10,000 years. The assumption used may maximize groundwater contamination. Does it necessarily maximize total population dose?

Page I-27. Table I-7.

Our calculations (for inhalation and soil ingestion only) of driller impacts at LANL and SRS gave values that were 1.6 and 3.1 times as high as the values in this table. We had to make several assumptions that should have been provided.

Page I-31. Twelveth line from bottom.

The maximum dose of 14.5 rem should be per lifetime (not per year).

Page I-31. Figure I-4.

Why are the lifetime doses for MEIs at all sites totalled? These are all different individuals and there is no significance to a total dose.

Pages I-33, 34. Figure I-5 and Table I-11.

The curves in Figure I-5 can be used to approximate the total of 2,325 LCFs over 10,000 years mentioned on page I-31. Our estimate was about 10% higher than this.

It is interesting to compare these estimated LCFs with values that are permitted for geological disposal of TRU wastes in 40 CFR 191. However, in doing so, we realize that these estimates do not have the level of detail and justification required in 40 CFR 191.

The standards in 40 CFR 191 (which apply to WIPP) were based on the assumption that a permissible limit was 10 LCFs per million curies of alpha-emitting transuranic radionuclides with half-lives longer than 20 years. This scales to about 42 LCFs in 10,000 years for the various

inventories listed in Appendix A. The estimate in this Appendix of 2,325 LCFs for NAA 2 is over 50 times higher than would be allowed at WIPP.

A conclusion that long-term storage is much worse is site specific. If one uses the curves in Figure I-5 and the inventories in Tables A-36 and A-38 to determine the amount of activity stored at each site it can be shown that wastes left at SRS, Hanford, and ORNL would be under the 40 CFR 191 limit. Again, there is the caveat that these calculations are less detailed and justified than would be required to show compliance with 40 CFR 191.

EEG-66

INDIVIDUAL RADIATION DOSES FROM TRANSURANIC WASTE BROUGHT TO THE SURFACE BY HUMAN INTRUSION AT THE WIPP

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February 1998

EEG-66
DOE/AL/58309-66

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, is being constructed as a repository for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC04-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, continues the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the generator sites' compliance with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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1. INTRODUCTION

The U.S. Environmental Protection Agency (EPA) standards that are applicable for long-term disposal of radioactive transuranic wastes at the Waste Isolation Pilot Plant (WIPP) facility are codified in 40 CFR Part 191. These standards require the U.S. Department of Energy (DOE) to evaluate the effects of releases from the repository for both undisturbed and disturbed conditions. Undisturbed conditions are those that could occur from natural causes without any human actions. Disturbed conditions are those caused by inadvertent human actions such as drilling through the repository during oil and gas exploration. Deliberate intrusion into the repository does not have to be considered.

Releases from undisturbed events must be evaluated for the radiation dose* to individuals (§191.15) and the effect on groundwater quality (§191.24) as well as for the cumulative release of transuranics to the accessible environment (the Containment Requirement, §191.13). Releases from disturbed events are required to be evaluated only for the Containment Requirements. The Compliance Certification Application (CCA) that DOE submitted to EPA in October 1996 did not evaluate individual doses from disturbed events (U.S. DOE 1996c).

Most other countries with nuclear waste require that radiological risk to an individual (individual radiation doses) be assessed for both undisturbed and disturbed scenarios. An OECD/IAEA International Review Group that evaluated the WIPP Project was concerned that individual doses had not been calculated and Sandia National Laboratories (SNL) provided estimates during the Group's January 1997 Carlsbad meeting (OECD/IAEA 1997).

The National Academy of Science (NAS) WIPP Committee in their review of SNL's 1992 Performance Assessment (PA) also concluded that the scope of the PA effort "must include performance measures that go beyond radionuclide release rates to the accessible environment" (NAS 1996).

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* Radiation doses in 40 CFR 191 and this report are the annual committed effective dose, which EPA defines as the committed effective dose resulting from a one-year intake of radionuclides released plus the annual effective dose caused by direct radiation.

Section 801 of the Energy Policy Act of 1992 (Public Law 102-486) required EPA to set standards to ensure protection of the health of individual members of the public from the proposed Yucca Mountain Project site for high-level radioactive waste. Section 801 also required the NAS to conduct a study providing guidance to EPA. One of the three questions the NAS was charged with addressing was "whether a health-based standard based upon doses to individual members of the public from releases to the accessible environment will provide a reasonable standard for protection of the health and safety of the general public". The NAS Committee on Technical Basis for Yucca Mountain Standards concluded that an individual dose standard was appropriate (NAS 1995). However the Committee did not agree on how the location and lifestyle of this individual should be defined.

Prior to the 1985 promulgation of 40 CFR 191 (which requires probabilistic analyses) WIPP human intrusion scenario calculations by EEG and DOE evaluated the individual dose with deterministic calculations. Several relevant reports were U.S. DOE 1980, Channel1 1982, Woolfolk 1982, and Bard 1982. The latter three reports evaluated the effects of contaminated Castile brine releases to the surface while U.S. DOE 1980 considered only material brought to the surface in cuttings from a drillbit.

The Environmental Evaluation Group (EEG) concluded that it is appropriate to revisit the issue of individual doses from inadvertent human intrusion. The specific purpose of this report is to:

(1) calculate likely individual doses that would result from the same releases predicted by the CCA;
(2) determine whether these calculated doses exceed limits for radiation exposure from other activities;
(3) compare the stringency of an individual dose standard at WIPP with the release limits in 40 CFR Part 191;
(4) discuss the appropriateness and feasibility of reducing potential doses to an individual from human intrusion at WIPP.

Because of the above concerns the deterministic calculations in this report rely primarily on drilling related analyses in the CCA for the determination of source term.[**] Details of the scenarios for workers, individual members of the public and the population within 80 kilometers (50 miles) of the site are adapted from scenarios used in prior WIPP reports. Pathway analyses and dose conversion factors primarily use current methodology from EPA and U.S. Nuclear Regulatory Commission (NRC) reports.

[**]The CCA results were used because one purpose of the individual dose calculation is to compare results with probabilistic cumulative releases and it does not imply that EEG is in complete agreement with the assumptions and methodology used in the CCA. Also, during the summer of 1997 the EPA required DOE to recalculate releases using some different parameter values. The Performance Assessment Validation Tests (PAVT) resulted in calculated waste volume and radioactivity releases that were about twice those in the CCA. These higher values have been used in this report only to determine the magnitude of the 95% upper confidence level release.

2. SCENARIO DESCRIPTION

This section provides an overall description of the drilling scenario, exposed persons, and intrusion times. Some of the major assumptions are also presented. Other assumptions are included in the appendices with the calculation methodology.

2.1 Radionuclide Releases to Surface

Radioactive material will be brought to the surface from all boreholes that penetrate a waste room due to cuttings and cavings. Radioactive material may also be brought to the surface from spallation and/or direct brine release if these processes occur.

Cuttings. Cuttings is the repository material directly intercepted and ground up by the drill bit. This material is brought to the surface in the drilling fluid and settles out in the mud pit before the fluid is recirculated into the borehole. The volume of waste material included in cuttings is equal to the cross sectional area of the drill bit times the initial height of the waste storage room times the fraction of the room contents that is waste.

Cavings. Cavings is the material that is eroded from the borehole wall by the action of the flowing drilling fluid. This eroded material is brought to the surface in the drilling fluid. The amount of cavings depends on the erosion shear resistance of the waste at the time of drilling. The erosion shear resistance parameter is uncertain and is variable. This was a sampled parameter in the CCA and thus the volume of cavings was a variable. The median, mean, and maximum cavings volumes in the CCA were 0.68, 1.0, and 8.7 times the cuttings volume (Helton 1996).

Spallings. Spallings is contaminated material that will be carried to the surface if drilling fluid is expelled from the borehole by high pressure gas flowing into the borehole from the penetrated waste storage room. The gas pressure in the waste room must be greater than the hydrostatic pressure of the drilling fluid in order for spallings to occur. Hydrostatic pressure is about 8 megapascals (MPa) at the repository horizon. DOE sensitivity analysis of the CCA calculations indicated that spallings releases from first intrusions occur less than one-half the time prior to

3,000 years. The frequency and volumes of spallings release from second intrusions into a waste panel are less than for first intrusions.

Direct Brine Release. Direct release of brine containing dissolved radionuclides can occur from a waste room into a borehole if mobile brine (a quantity of brine greater than the residual brine saturation) is present in the waste room and the brine pressure is >8 MPa. In the CCA calculations direct brine releases occur less than 25% of the time for intrusions prior to 10,000 years. The frequency and volume of flows are greater for the E1E2 scenario than for the E1 or E2 scenario.

2.2 Borehole Drilling

The human intrusion scenario is assumed to be the E2 scenario used in the CCA. An exploratory oil or gas drill bit penetrates a repository waste storage room in the Salado formation at a depth of 655 m (2150 feet). Drilling fluid (drilling mud) is continuously circulated during drilling and is the mechanism for transporting cuttings and cavings from the waste room to the surface. This material settles out of the drilling fluid in the mud pit before the drilling fluid is recirculated into the borehole. Contaminated material in the mud pit is the source of radiation doses to drilling crew workers and to the public.

The E1E2 scenario is not explicitly modeled in this report but it is considered by Channell 1982 and the CCA. This scenario involves a first penetration (E1) into a pressurized brine reservoir in the underlying Castile Formation. An E2 borehole penetrates the repository at a later time. This scenario has the potential to result in somewhat greater contaminated brine releases to the surface than from an E2 scenario alone. Also, the E1E2 scenario includes cuttings and cavings releases from two boreholes rather than one.

2.3 Exposure of Drilling Crew Members

Members of the drilling crew are subjected to external exposure as the contaminated drilling fluid flows through the shale shaker to the mud pit. Figure 2-1 shows a diagram of a typical drilling rig

site layout. The contaminated material in the mud pit is assumed to be evenly mixed (horizontally and vertically) with all the cuttings produced in drilling to a depth of 2100 m (the approximate depth of much of the current oil production around the WIPP site). This contaminated material is assumed to deliver an external dose to a worker standing at the edge of the mud pit for a total of 12 hours in the approximate 60-day period needed to complete the well.

The mud pit is assumed to be too moist for resuspension during drilling. However after drilling ceases (about 45 days before well completion) the mud pit will dry out and resuspension will occur. It is assumed that workers will be located at the drilling rig (100 meters from the center of the mud pit) for 80-hours and will inhale resuspended radionuclides during the 37% of the time they are down wind from the dried mud pit. The rational for not assuming that the mud pit would be filled (reclaimed) is discussed in Appendix A.

2.4 Annual Exposure to a Nearby Resident

In Case I the resident farmer is assumed to be living in a ranch house 800 meters from the mud pit in the prevailing downwind direction. This person is present at his residence for 350 days a year and spends 73% of the time indoors. He is exposed to resuspended material from the mud pit and receives a radiation dose from: (1) inhalation; (2) direct radiation from deposited material; (3) ingestion of dirt; and (4) ingestion of beef.

Case II (the resident non-farmer case) is a bounding case. The resident non-farmer is assumed to live at the edge of the mud pit and be in his home 73% of the hours in a year. Radiation dose is received from inhalation, direct radiation, and ingestion of dirt.

Case III (the non-resident farmer case) is another bounding case. The non-resident farmer grows vegetables in the mud pit which has been made fertile with imported top soil. Non-contaminated water from the Dewey Lake formation is assumed to be available for irrigation. This person is assumed to receive a radiation dose only from contaminated vegetables via the soil-to-crop pathway.

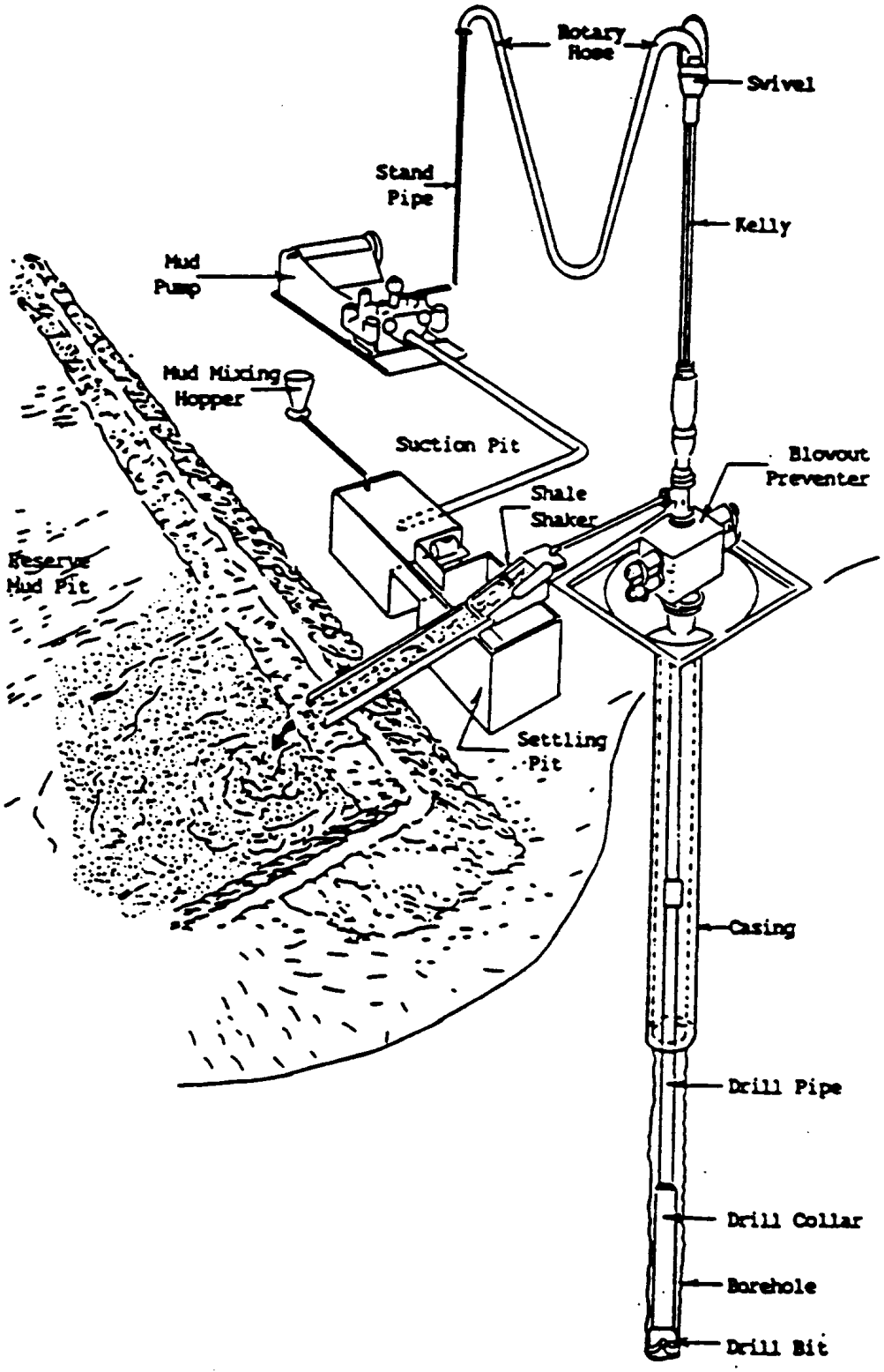

Figure 2-1. Drilling Fluid Circulation Diagram

2.5 Exposure of Population

The annual population dose to the resident population within 80 kilometers (50 miles) of the WIPP site is estimated. This dose is from inhalation of material resuspended from the mud pit. Average annual atmospheric dispersion values are used.

2.6 Times of Intrusion

For contact-handled transuranic (CH-TRU) waste the intrusion times evaluated were 100, 350, 700, 1000, 5,000 and 10,000 years after repository closure for the E2 scenario.

Intrusions into a remote-handled transuranic waste (RH-TRU) canister were evaluated at 100 and 350 years after repository closure for direct radiation. Inhalation doses were evaluated for the 10,000 year period.

3. SOURCE TERM

The source term is defined as the quantity of radionuclides brought to the surface as a result of a drilling event. Contact-Handled Transuranic Waste (CH-TRU) comprises about 96% of the volume of waste expected to be brought to WIPP. The remainder of the waste will be Remote-Handled TRU (RH-TRU) which contains about 10% of the radioactivity at time of closure. This source term will be developed separately for CH-TRU and RH-TRU since they are not placed together in the repository and both would not be expected to be impacted by the same intrusion.

3.1 CH-TRU Waste

3.1.1 Emplacement and Volumes of Waste

The WIPP repository is limited by federal statue to a capacity of 175,600 m^3 of waste. The volume of CH-TRU is expected to be 168,500 m^3. This waste is contained in either 0.208 m^3 (55-gallon) drums or in 1.7 m^3 Standard Waste Boxes. The containers will be stacked 3 high in waste storage rooms that are 90 m long, 10 m wide, and 3.96 m high. Waste containers will also be emplaced in panel drifts and access drifts.

The waste form is not homogeneous but is highly variable, including debris, sludges, metals, and glasses. The radionuclide concentration also varies over several orders of magnitude and there is considerable variation in radionuclide composition. The CCA documents DOE's sampling of 569 waste streams in order to capture the variability in radionuclide concentration and composition.

The amount of cuttings waste intercepted by the drilling bit is 0.301 m^3. This volume is the product of the area of the 0.311 m (12.25 inch) diameter drill bit and the height of the room (3.96 m). The amount of cavings is variable and this leads to a distribution of cuttings plus cavings volumes. In the CCA, the median, mean, and maximum volumes of cuttings plus cavings were 0.51 m^3, 0.60 m^3, and 3 m^3. These volumes need to be multiplied by the fraction of a room volume that contains waste (0.384) to get the volumes of waste brought to the surface. The source term in this report uses the mean and maximum volumes of waste (0.230 m^3 and 1.15 m^3).

Releases from spallings and direct brine release are complex and are related to the amount of pressure and brine in waste rooms at the time of intrusion rather than to the cuttings plus cavings volume. However, for modeling simplicity, the waste volumes brought to the surface by spallings and direct brine release are assumed to be 50% of the value of cuttings and cavings for all intrusion times except at 100 years (because modeling shows that pressures are minimal in the first few hundred years). This additional volume is assumed to have the same radionuclide concentration as the cuttings and cavings. The 50% value is similar to the typical effect on the complementary cumulative distribution function (CCDF) in the CCA from spallings plus direct brine release.

3.1.2 CH-TRU Radionuclide Inventory

The average CH-TRU radionuclide concentrations were obtained from Table 3-1 of U.S. DOE 1996a. The maximum waste stream, taken from Table 1 in Appendix B-2, was the 2800 m^3 of residue wastes at the Rocky Flats Environmental Technology Site (RFETS) and contains high concentrations of ^{239}Pu, ^{240}Pu, and ^{241}Am. The heat source waste from the Savannah River Site (1480 m^3) which contains high ^{238}Pu concentrations was used as the maximum source at 100 years after repository closure.

The curies of the key radionuclides brought to the surface in the mean (0.23 m^3) and in the maximum volumes of cuttings plus cavings (1.15 m^3) for typical 55-gallon drums are shown in Table 3-1. The residue waste is to be packaged in pipe containers positioned within 55-gallon drums. The maximum volume of waste in a pipe container is about 0.0445 m^3 and so the waste volumes brought to the surface are only 0.214 of those from typical drums.

Table 3-1. Curies of CH-TRU Waste Brought to Surface[1]

Nuclide					
Intrusion Time, Years	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Am	Total
Mean Concentration, Mean Volume					
100	1.20	1.07	0.283	0.552	3.11
350	0.249	1.59	0.414	0.555	2.81
700	----	1.58	0.401	0.318	2.30
1,000	----	1.56	0.387	0.197	2.14
5,000	----	1.39	0.253	-----	1.54
10,000	----	1.20	0.149	-----	1.35
Mean Concentration, Maximum Volume					
100	5.99	5.36	1.41	2.76	15.5
350	1.25	7.95	2.07	2.78	14.1
700	----	7.86	2.00	1.59	11.5
1,000	----	7.80	1.94	0.984	10.7
5,000	----	6.95	1.26		8.21
10,000	----	6.02	0.744		6.76
Maximum Concentration, Mean Volume					
100	18.5	1.42	0.180	0.297	20.4
350	0.0101	4.82	1.07	1.97	7.87
700	----	4.75	1.03	1.12	6.90
1,000	----	4.73	0.994	0.693	6.42
5,000	----	4.22	0.655	----	4.88
10,000	----	3.64	0.385	----	4.03
Maximum Concentration, Maximum Volume					
100	92.3	7.10	0.909	1.48	102.
350	0.0499	24.0	5.37	9.87	39.3
700	----	23.8	5.18	5.63	34.6
1,000	----	23.5	4.99	3.47	32.0
5,000	----	21.0	3.27	----	24.3
10,000	----	18.2	1.92	----	20.1

[1] The waste volumes brought to the surface in cuttings and cavings are 0.23m^3 and 1.15 m^3 for mean concentration wastes and for maximum concentration wastes at 100 years. Maximum concentration wastes at later time have volumes of 0.0492 m^3 and 0.246 m^3. Volumes from intrusion at 350 years and later are increased by 50% to approximate typical spallings and direct brine releases.

3.2 RH-TRU Wastes

3.2.1 Volumes of RH-TRU Waste

RH-TRU canisters are to be inserted horizontally into the walls of WIPP waste storage rooms. The cylindrical canisters are about 3.05 m (10 feet) long and have an internal diameter of 0.572 m (1.88 feet). A 0.311 m (12.25 inch) diameter drill bit that encountered the horizontal canister would drill through a maximum effective depth of about 0.542 m. Thus the volume of RH-TRU waste brought up by cuttings alone would be 0.0413 m^3.

Cavings to cuttings volume ratios are assumed to be the same as for CH-TRU waste. Therefore the mean and maximum cavings volumes would be 1.0 and 8.7 times the cuttings volume. The effective depth of waste for cavings is less than for cuttings since the cavings mechanism will not begin until the entire diameter of the drill bit has penetrated the cylindrical canister. This depth is about 0.479 m.

These assumptions lead to a mean cuttings plus cavings volume for RH-TRU of 0.0778 m^3. The maximum volume of waste would be 0.359 m^3, which is about 40% of the contents of a canister.

Releases from spallings and direct brine release are assumed to be zero for RH-TRU canisters. The canisters are isolated from the waste storage rooms and the marker beds so there appears to be little chance of having mobile brine present about and within the canister. Gas generation and some pressurization could occur within an RH-TRU canister but volumes are so limited if the canister maintains its integrity that any spallings effect should be minimal.

3.3.2 RH-TRU Radionuclide Inventories

The RH-TRU radionuclide inventories used in the CCA are derived from Appendix C of the Baseline Inventory Report (BIR) Revision 3 (U.S. DOE 1996a). The Revision 3 inventory, decayed to 1995, is further decayed to the year 2033 for use in the CCA.

The average radionuclide concentration of the Hanford RH-TRU was chosen as the mean concentration. The Hanford RH-TRU has the highest average radioactivity concentrations for most radionuclides and also contains 81% of the volume of all RH-TRU expected to be generated.

The maximum RH-TRU radionuclide concentration was taken from Hanford waste stream RL-W272. Data on this waste stream is presented in Appendix P of U.S. DOE 1996a. This 24 m^3 waste stream had the highest concentrations noted for RH-TRU in Appendix P. However, a number of RH-TRU waste streams did not have any radionuclide information. This waste stream's total radioactivity concentration (7.8 Ci ℓ^{-1}) is 34% of the maximum concentration allowed for an RH-TRU canister (23 Ci ℓ^{-1}) by agreement with the State of New Mexico. The calculated curies of RH-TRU waste brought to the surface are shown in Table 3-2.

Table 3-2. Calculated Curies of RH-TRU Waste Brought to Surface

Nuclide	Hanford Average Concentration				Hanford Max Concern Maximum Volume	
	Mean Volume		Max Volume			
	+100y	+350y.	+100y.	+350y.	+100y.	+350y
^{90}Sr	$9.40x10^{-2}$	$2.40x10^{-4}$	$4.34x10^{-1}$	$1.12x10^{-3}$	$2.39x10^{+1}$	$6.10x10^{-2}$
^{90}Y	$9.40x10^{-2}$	$2.40x10^{-4}$	$4.34x10^{-1}$	$1.12x10^{-3}$	$2.39x10^{+1}$	$6.10x10^{-2}$
^{137}Cs	$1.12x10^{-1}$	$3.40x10^{-4}$	$5.17x10^{-1}$	$1.61x10^{-3}$	$2.82x10^{+1}$	$8.61x10^{-2}$
^{137}Ba	$1.06x10^{-1}$	$3.20x10^{-4}$	$4.89x10^{-1}$	$1.52x10^{-3}$	$2.67x10^{+1}$	$8.15x10^{-2}$
^{238}Pu	$6.10x10^{-3}$	$8.60x10^{-4}$	$2.81x10^{-2}$	$3.95x10^{-3}$	$3.00x10^{-1}$	$4.29x10^{-2}$
^{239}Pu	$1.29x10^{-1}$	$1.29x10^{-1}$	$5.95x10^{-1}$	$5.92x10^{-1}$	$5.59x10^{0}$	$5.51x10^{0}$
^{240}Pu	$6.47x10^{-2}$	$6.32x10^{-2}$	$2.99x10^{-1}$	$2.91x10^{-1}$	$2.76x10^{0}$	$2.68x10^{0}$
^{241}Am	$1.11x10^{-1}$	$7.40x10^{-2}$	$5.10x10^{-1}$	$3.41x10^{-1}$	----	----

4. CALCULATED DOSES TO WORKERS

4.1 Doses from CH-TRU

4.1.1 External Radiation Dose at Shale Shaker

The calculated external radiation dose to a worker at the shale shaker from CH-TRU waste brought to the surface is shown in Table 4-1. Details of the assumptions and methodology used in calculating these doses is in Appendix A.1 and A.2.

Calculated doses are very small because CH-TRU wastes contain very small amounts of non-TRU radionuclides and the TRU radionuclides produce only weak and infrequent gamma radiations. The doses never exceed 0.3 mrem, even for the maximum concentrations and volumes at 100 years. Over 95% of the dose up to 1000 years is due to ^{241}Am, which decays with a 432 year half-life and is not a factor at later times. Doses from the plutonium radioisotopes never contribute as much as 0.1 mrem to the dose.

Table 4-1. External Radiation Dose to Worker at Shale Shaker from CH-TRU Waste (Millirem - Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration		
	Mean Vol	Max Vol	Comment	Mean Vol	Max Vol	Comment
100	1.3×10^{-2}	6.4×10^{-2}	98% ^{241}Am	8.4×10^{-3}	4.2×10^{-2}	80% ^{241}Am, 18% ^{238}Pu
350	1.3×10^{-2}	6.5×10^{-2}	98% ^{241}Am	4.6×10^{-2}	2.3×10^{-1}	98% ^{241}Am
700	7.5×10^{-3}	3.7×10^{-2}	97% ^{241}Am, 3% ^{239}Pu	2.6×10^{-2}	1.3×10^{-1}	98% ^{241}Am, 2% ^{239}Pu
1,000	4.7×10^{-3}	2.4×10^{-2}	95% ^{241}Am, 4% ^{239}Pu	1.6×10^{-2}	8.2×10^{-2}	96% ^{241}Am, 3% ^{239}Pu
5,000	1.9×10^{-4}	9.3×10^{-4}	89% ^{239}Pu, 11% ^{240}Pu	5.6×10^{-4}	2.8×10^{-3}	91% ^{239}Pu, 9% ^{240}Pu
10,000	1.6×10^{-4}	7.8×10^{-4}	92% ^{239}Pu, 8% ^{240}Pu	4.7×10^{-4}	2.3×10^{-3}	94% ^{239}Pu, 6% ^{240}Pu

4.1.2 External Radiation Dose at Mud Pit

The calculated external radiation dose to a worker standing at the edge of the mud pit is shown in Table 4-2. Details of the methodology are included in Appendices A.1 and A.3.

Calculated doses are small and over 95% are due to ^{241}Am from 100 to 1000 years. The maximum concentration - maximum volume dose is only 0.77 mrem at 350 years and this is a low probability event.

Table 4-2. External Radiation Dose to Worker at Mud Pit from CH-TRU Waste (Millirem - Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration		
	Mean Vol	Max Vol	Comment	Mean Vol	Max Vol	Comment
100	4.4×10^{-2}	2.2×10^{-1}	98% ^{241}Am	2.8×10^{-2}	1.4×10^{-1}	80% ^{241}Am, 17% ^{238}Pu
350	4.4×10^{-2}	2.2×10^{-1}	98% ^{241}Am	1.5×10^{-1}	7.7×10^{-1}	99% ^{241}Am
700	2.6×10^{-2}	1.3×10^{-1}	97% ^{241}Am, 3% ^{239}Pu	8.9×10^{-2}	4.4×10^{-1}	98% ^{241}Am, 2% ^{239}Pu
1,000	1.6×10^{-2}	8.0×10^{-2}	95% ^{241}Am, 4% ^{239}Pu	5.6×10^{-2}	2.8×10^{-1}	96% ^{241}Am, 3% ^{239}Pu
5,000	6.3×10^{-4}	3.2×10^{-3}	90% ^{239}Pu, 10% ^{240}Pu	1.9×10^{-3}	9.4×10^{-3}	91% ^{239}Pu, 9% ^{240}Pu
10,000	5.3×10^{-4}	2.7×10^{-3}	93% ^{239}Pu, 7% ^{240}Pu	1.6×10^{-3}	7.9×10^{-3}	94% ^{239}Pu, 6% ^{240}Pu

4.1.3 Inhalation Dose at Drilling Rig

Calculated inhalation doses to a worker at the drilling rig from resuspension of CH-TRU wastes from the mud pit are shown in Table 4-3. The inhalation doses are significant compared to the external doses and since they are due to long-lived transuranic radionuclides they decrease slowly with time (the doses at 10,000 years are 21-30% of those at 100 years after closure).

The probability of intrusions into CH-TRU waste during the 10,000-year regulatory period is high with the drilling rates that DOE is required to use in the CCA (46.8 Boreholes km^{-2} in 10,000 years). There is a >99% probability of at least one intrusion into CH-TRU waste and a >57% probability there will be more than 4 intrusions. Even for the RFETS residues (which would be about 7.2% of the drums in the repository) there is a 31% probability of at least one intrusion.

Also, from the CCA, there is a 10% probability that the volume of cuttings plus cavings released would be ≥ 0.87 m^3.

Table 4-3. Inhalation Dose to Worker at Drilling Rig from CH-TRU Waste
(Millirem - Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration		
	Mean Vol	Max Vol	Comment	Mean Vol	Max Vol	Comment
100	38	190	36% ^{238}Pu, 35% ^{239}Pu	240	1200	90% ^{238}Pu, 8% ^{239}Pu
350	36	180	57% ^{239}Pu, 20% ^{241}Am	100	500	61% ^{239}Pu, 26% ^{241}Am
700	29	150	68% ^{239}Pu, 17% ^{240}Pu	88	440	68% ^{239}Pu, 17% ^{241}Am
1,000	27	140	73% ^{239}Pu, 18% ^{240}Pu	81	410	73% ^{239}Pu, 16% ^{240}Pu
5,000	21	100	85% ^{239}Pu	62	310	87% ^{239} Pu
10,000	17	86	89% ^{239}Pu	51	250	91% ^{239}Pu

4.2 Doses from RH-TRU

4.2.1 Dose at Shale Shaker

Details of the assumptions and methodology necessary to calculate doses to a worker at the shale shaker are in Appendix A.1 and A.2. The results are shown in Table 4-4. Over 99% of the dose at 100 years after closure was due to ^{137m}Ba. At 350 years ^{241}Am comprises 88% of the total dose for the average waste concentration. The maximum concentration waste (which does not contain ^{241}Am) at 350 years is 75% ^{137m}Ba and 19% ^{239}Pu.

These doses are minimal, even for the maximum concentration wastes at 100 years.

4.2.2 Dose at Mud Pit

Details of the calculation of doses to a worker at the edge of the mud pit are in Appendix A.3. The results are shown in Table 4-5. Over 97% of the dose at 100 years for the average concentration wastes was due to ^{137m}Ba. About 2.0% came from ^{241}Am and bremsstrahlung radiation from ^{90}Y contributed about 0.6%. Over 99% of the dose from the maximum concentration waste (which doesn't contain ^{241}Am) was due to ^{137m}Ba at 350 years, while 81% of the dose for the average concentration waste comes from ^{241}Am and 18% from ^{137m}Ba.

The doses at the mud pit are about 15 times those at the shale shaker at 100 years but are negligible except for the maximum concentration, maximum volume case (100 mrem). This dose is equal to the limit for non-radiation workers from all radiation sources (100 mrem y^{-1}). However, the probability of both a maximum concentration and maximum volume event occurring simultaneously at 100 years is low.

Table 4-4. External Radiation Dose to Worker at Shale Shaker from RH-TRU Waste (Millirem - Committed Effective Dose)

Drum Loading	100 years		350 years	
	Dose	Comment	Dose	Comment
Mean Conc. - Mean Vol	2.8×10^{-2}	91% ^{137m}Ba, 9% ^{241}Am	1.9×10^{-3}	88% ^{241}Am, 6% ^{239}Pu
Mean Conc. - Max Vol	1.3×10^{-1}	91% ^{137m}Ba, 9% ^{241}Am	8.9×10^{-3}	88% ^{241}Am, 6% ^{239}Pu
Max Conc. - Max Vol	6.5×10^{0}	99% ^{137m}Ba	2.6×10^{-2}	75% ^{137m}Ba, 19% ^{239}Pu

Table 4-5. External Radiation Dose to Worker at Mud Pit from RH-TRU Waste (Millirem - Committed Effective Dose)

Drum Loading	100 years		350 years	
	Dose	Comment	Dose	Comment
Mean Conc. - Mean Volume	4.2×10^{-1}	97% ^{137m}Ba	7.1×10^{-3}	80% ^{241}Am, 18% ^{137m}Ba
Mean Conc. - Max Volume	1.9×10^{0}	97% ^{137m}Ba	3.3×10^{-2}	80% ^{241}Am, 18% ^{137m}Ba
Max Conc. - Max Volume	1.0×10^{2}	99% ^{137m}Ba	3.2×10^{-1}	98% ^{137m}Ba

4.2.3 Inhalation Doses

Calculated inhalation doses to workers are shown in Table 4-6. Inhalation doses at 100 years are about 9 times the external doses at the mud pit for average concentration RH-TRU wastes and about 5% higher for the maximum concentration. Over 99% of the inhalation dose is due to transuranics and decreases very little with time. For example the calculated dose at 10,000 years is 38% of the 100-year dose for average concentration waste and 60% for the maximum concentration waste. Thus, penetration of an RH-TRU canister will be of concern for the inhalation pathway throughout the regulatory period. Details of the inhalation calculations are presented in Appendix A.4.

The doses for average concentration wastes are less than typical U. S. dose limits for non-occupational workers. There is a reasonable chance of penetrating an RH-TRU canister during 10,000 years. For the 46.8 boreholes km^{-2} drilling rate used in the CCA there is a 50% probability of at least one hit and a 3% probability of 3 or more hits. The doses for the maximum concentration waste stream are significant for non-occupational doses. This waste stream (only 0.34% of the total) has a probability of about 0.002 of being intercepted at least once during the 10,000 year period. Probabilities greater than 0.001 are required by 40 CFR Part 191 to be included in the CCDF.

Table 4-6. Inhalation Dose to Worker at Drilling Rig from RH-TRU Wastes
(Millirem - Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration	
	Mean Vol	Max Vol	Comment	Max Vol	Comment
100	4.0	18.0	41% ^{239}Pu, 36% ^{241}Am	110	64% ^{239}Pu, 32% ^{240}Pu
350	3.4	16.0	48% ^{239}Pu, 28% ^{241}Am	100	67% ^{239}Pu, 33% ^{240}Pu
700	2.9	14.0	55% ^{239}Pu, 26% ^{240}Pu	100	68% ^{239}Pu, 32% ^{240}Pu
1,000	2.7	12.0	59% ^{239}Pu, 28% ^{240}Pu	100	68% ^{239}Pu, 32% ^{240}Pu
5,000	1.9	8.8	74% ^{239}Pu, 26% ^{240}Pu	82	75% ^{239}Pu, 25% ^{240}Pu
10,000	1.5	7.0	81% ^{239}Pu, 19% ^{240}Pu	65	81% ^{239}Pu, 19% ^{240}Pu

5. CALCULATED DOSES TO RESIDENT FARMER

5.1 Doses from CH-TRU

5.1.1 Inhalation Dose

The calculated inhalation radiation dose to a resident farmer located 800 m in the prevailing wind direction from the mud pit is shown in Table 5-1. Radionuclides resuspended from a dried mud pit are the source of this inhalation dose. The long-term resuspension rate, dispersion factor, deposition rate, and annual inhalation rate assumed are discussed in Appendix B.1.

Inhalation doses received by the resident farmer in a year are only 57% of those received by the worker in 80 hours at the drilling rig. This is due to a much higher χ/Q factor and resuspension rate for the worker dose calculations.

These inhalation doses are significant throughout the 10,000 year regulatory period. For a 17-curie release (5% probability of occurring during the regulatory period) the dose is about 120 mrem y^{-1}. The probability of a resident farmer being located 800 m away in the prevailing down wind direction is less than 1.0. Inhalation doses at the WNW Site boundary would be 8.3 mrem y^{-1} and at James Ranch (2.5 miles WSW of the repository and presently occupied) the dose would be about 1.9 mrem y^{-1} for a 17-curie release.

Table 5-1. Inhalation Dose to Resident Farmer from CH-TRU Waste
(Millirem - Annual Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration		
	Mean Vol	Max Vol	Comment	Mean Vol	Max Vol	Comment
100	21.0	110	36% ^{238}Pu, 35% ^{239}Pu	130	670	90% ^{238}Pu, 8% ^{239}Pu
350	20.0	100	57% ^{239}Pu, 20% ^{241}Am	56	280	61% ^{239}Pu, 26% ^{241}Am
700	16.0	82	68% ^{239}Pu, 17% ^{240}Pu	49	250	68% ^{239}Pu, 17% ^{241}Am
1,000	15.0	76	73% ^{239}Pu, 18% ^{240}Pu	46	230	73% ^{239}Pu, 15% ^{240}Pu
5,000	12.0	58	85% ^{239}Pu, 15% ^{240}Pu	34	170	87% ^{239} Pu, 13% ^{240}Pu
10,000	9.6	48	89% ^{239}Pu, 11% ^{240}Pu	28	140	90% ^{239}Pu, 10% ^{240}Pu

5.1.2 External Radiation Dose

The annual external radiation dose to the resident farmer from a one year deposition of CH-TRU radionuclides at the farm was calculated as described in appendix B.2.

Calculated radiation doses at 100 years and 350 years were always less than 0.01 mrem y^{-1}. Since these doses were negligible compared to those from inhalation, they were not calculated for later intrusion times.

Exposure from immersion is also negligible.

5.1.3 Inhalation Dose from Deposited Radionuclides

The annual inhalation dose the resident farmer would receive from resuspension of CH-TRU radionuclides deposited about his residence during the previous year was calculated. The dirt mass loading approach described in Appendix A.4 was used. Key assumptions were: (1) all inhaled dirt was from the top $2x10^{-4}$ m of soil and the deposited radionuclides were in this volume; (2) the average outside air concentration was 65 µg m^{-3} of soil; and (3) the same 5100 m^3 annual effective inhalation rate was used.

These annual doses were found to be about 0.35% of the inhalation doses calculated from resuspension in the mud pit. These doses were greater than 1 mrem y^{-1} only for the maximum concentration-maximum volume case at 100 years.

Doses are not tabulated because they are negligible compared to the direct inhalation dose and would not occur in the same year.

5.1.4 Dose from Ingestion of Contaminated Dirt

Studies have shown that humans ingest a measurable amount of contaminated dirt. A recommended value of 100 mg d^{-1} (0.035 kg y^{-1}) was used (U. S. EPA 1991). The concentration of radionuclides on the dirt was assumed to be the same as that in the top 0.2 mm of soil from deposition.

Calculated doses from CH-TRU ranged from 2.0 mrem y^{-1} at 100 years to 0.43 mrem y^{-1} at 10,000 years for the maximum concentration-maximum volume case. These small doses (only 0.3% of the inhalation dose) were not calculated for all intrusion times and waste quantities.

5.1.5 Dose from Crops

No dose was assumed to occur to the resident farmer in Case I from ingestion of vegetables, fruits, and grains grown in contaminated soil. This is an improbable pathway for a resident near the WIPP Site because the availability of water is limited. No vegetable gardens are known to exist in the ranch houses around WIPP. The potential magnitude of this low probability event is addressed in Case III (the non-resident farmer) which is considered bounding.

5.1.6 Dose from Ingestion of Beef

Cattle graze in land around WIPP and it is reasonable to believe persons living in ranch houses would eat beef that grazes on land contaminated by the Case I scenario. The description of this calculation is in Appendix B.3. WIPP site specific data were used for the amount of feed consumed per day by cattle. However, three other key parameter values (fraction of deposition

retained on crops, weathering rate constant, and the kilograms per meter square of forage) had to be estimated from literature that is not specific to natural, arid rangeland.

Calculated doses from the direct deposition pathway at 100 years for the maximum concentration-maximum volume CH-TRU waste scenario totaled only 0.023 mrem y^{-1}. The dose from the soil to crop pathway is negligible (less than 0.1% of the dose from direct deposition). Doses were not calculated for later times.

5.2 Doses from RH-TRU

5.2.1 Inhalation Dose

The calculated inhalation dose to a resident farmer from RH-TRU wastes is shown in Table 5-2. These doses are only about 10%-25% of those from CH-TRU.

5.2.2 External Radiation Dose

The annual external radiation dose to the resident farmer from one year deposition of RH-TRU radionuclides at the farm was calculated as described in Appendix B.2. Calculated radiation doses at 100 years were only 0.08 mrem y^{-1} for the maximum concentration-maximum volume case. At 350 years the maximum dose was less than 0.001 mrem y^{-1}. These doses are negligible and were not calculated for later times.

Table 5-2. Inhalation Dose to Resident Farmer from RH-TRU Waste
(Millirem - Annual Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration	
	Mean Vol	Max Vol	Comment	Max Vol	Comment
100	2.2	10.0	41% ^{239}Pu, 37% ^{241}Am	62	64% ^{239}Pu, 32% ^{240}Pu
350	1.9	8.8	48% ^{239}Pu, 28% ^{241}Am	58	67% ^{239}Pu, 32% ^{240}Pu
700	1.6	7.6	55% ^{239}Pu, 26% ^{240}Pu	57	68% ^{239}Pu, 32% ^{240}Pu
1,000	1.5	7.0	60% ^{239}Pu, 28% ^{240}Pu	56	68% ^{239}Pu, 32% ^{240}Pu
5,000	1.1	5.0	75% ^{239}Pu, 25% ^{240}Pu	46	75% ^{239}Pu, 25% ^{240}Pu
10,000	0.85	3.9	81% ^{239}Pu, 19% ^{240}Pu	36	81% ^{239}Pu, 19% ^{240}Pu

5.2.3 Inhalation Dose from Deposited Radionuclides

The annual inhalation dose the resident farmer would receive from resuspension of RH-TRU radionuclides deposited on the farm during the previous year was calculated using the dust mass loading approach and the same assumptions as for CH-TRU.

This dose was about 0.2 mrem y^{-1} per year for the maximum concentration-maximum volume case at 100 years (0.3% of the inhalation dose due to resuspension from the mud pit). This dose is negligible and doses were not calculated for later times.

5.2.4 Dose from Ingestion of Contaminated Dirt

Calculated doses from ingestion of RH-TRU contaminated dirt decreased from 0.22 mrem y^{-1} at 100 years to 0.11 $mrem^{-1}$ at 10,000 years (maximum concentration-maximum volume case). These values are negligible and were not tabulated.

5.2.5 Dose from Crops

No dose was assumed to occur from ingestion of contaminated crops.

5.2.6 Dose from Ingestion of Beef

The dose from ingestion of beef in the maximum concentration-maximum volume RH-TRU scenario at 100 years was 0.60 mrem y^{-1}. Approximately 94% of the dose came from ^{137}Cs and 5% from ^{90}Sr. Doses were not calculated for later times.

6. CALCULATED DOSES FOR SCENARIOS II & III

6.1 Scenario II, Resident Non-Farmer

The resident non-farmer in this scenario is assumed to live in a house located at the edge of the mud pit from Scenario I. He receives radiation doses from inhalation, ingestion of dirt and external radiation only during actual residence. Calculation assumptions are given in Appendix C.

This Scenario is considered bounding because it is improbable that a person would be residing at the edge of a radiologically contaminated mud pit shortly after exploratory drilling had taken place. However, higher doses could be calculated by assuming the resident spends some period of time outdoors and also has a vegetable garden as in Scenario III.

6.1.1 Dose from CH-TRU

Calculated inhalation, ingestion, and external doses from CH-TRU releases to the surface for the six intrusion times are given in Table 6-1 for the mean concentration-mean volume and maximum concentration-maximum volume cases. This captures the range of possible doses. The doses are relatively high; in all cases greater than 100 mrem y^{-1} and in the highest case exceeding the limit for occupational workers. However, these doses are not acutely hazardous and unless continued for a number of years would not be expected to significantly increase the incidence of cancer in the resident non-farmer.

6.1.2 Dose From RH-TRU

Doses to the resident-farmer from RH-TRU are shown in Table 6-2 for 100 years, 350 years, and 10,000 years. Calculations were not performed for the other intrusion times because the primary interest in RH-TRU is during the early years. The total calculated dose at 350 years and 10,000 years is only 10% to 25% of that from CH-TRU. The external dose at 100 years for the maximum concentration-maximum volume case (28 rem y^{-1}) is very high. However, the probability of intersecting a maximum concentration RH-TRU canister at about 100 years is low. This external

dose decreases (with the 30-year half-life of ^{137}Cs +^{137m}Ba) to 2.8 rem y^{-1} at 200 years and 0.27 rem y^{-1} at 300 years.

Table 6-1. CH-TRU Dose to Resident Non-Farmer-Scenario II
(Rem - Annual Committed Effective Dose)

Mean Concentration - Mean Volume					Max Concentration - Max Volume			
Year	Inhalation	Ingestion	External	Total	Inhalation	Ingestion	External	Total
100	0.18	0.19	.012	0.38	5.8	6.5	0.038	12.0
350	0.16	0.18	.012	0.35	2.2	2.5	0.21	4.4
700	0.13	0.14	.0068	0.28	2.0	2.2	0.12	4.3
1,000	0.12	0.13	.0042	0.26	1.8	2.0	0.074	3.9
5,000	0.087	0.096	.00016	0.18	1.4	1.5	0.0025	2.9
10,000	0.050	0.084	.00014	0.13	1.1	1.3	0.0021	2.4

Table 6-2. RH-TRU Dose to Resident Non-Farmer - Scenario II
(Rem - Annual Committed Effective Dose)

Year	Mean Concentration - Mean Volume				Max Concentration - Max Volume			
	Inhalation	Ingestion	External	Total	Inhalation	Ingestion	External	Total
100	0.018	0.020	0.11	0.15	0.49	0.63	28.0	29.0
350	0.015	0.017	0.0019	0.034	0.47	0.51	0.084	1.1
10,000	0.0068	0.0076	0.000012	0.014	0.30	0.33	0.00053	0.62

6.2 Scenario III, Non-Resident Farmer

In Scenario III the farmer is assumed to eat 42.7 kg y^{-1} of vegetables that are grown in the mud pit. The 5 cm depth of contaminated material in the mud pit is assumed to be evenly mixed with top soil in order to make the mud pit fertile. The final depth is assumed to be 15 cm. The water used for irrigation is assumed to be uncontaminated. No deposition is occurring on the crops and there is assumed to be no surface contamination from the soil. Therefore the only radionuclides in the food come through the soil-to-crop pathway. The calculation is described in Appendix C.

This scenario is also considered bounding. There is limited ground water of adequate quality in the area and there are no known vegetable gardens. However, if this scenario occurred, doses could be higher than calculated because the non-resident farmer would be subjected to radiation doses from inhalation, dirt ingestion, and external radiation during the time spent farming in the mud pit.

6.2.1 Dose from CH-TRU

Calculated doses from CH-TRU releases to the surface for the six intrusion times are given in Table 6-3 for the mean concentration-mean volume and maximum concentration-maximum volume cases. These doses are significant but are less than the Scenario II doses at all time periods.

Doses received by the non-resident farmer while working in the garden would increase these doses significantly. For example, the inhalation + dirt ingestion + external radiation dose from 100 hours of exposure to the maximum concentration-maximum volume case at 100 years is 53% of the food intake dose.

6.2.2 Dose from RH-TRU

RH-TRU doses at 100, 350, and 10,000 years are shown in Table 6-4. The maximum dose at 100 years is 2.1 times the CH-TRU dose because of the effect of ^{90}Sr and ^{137}Cs. These two fission product radionuclides contribute 96% of the dose. For other times and cases the CH-TRU doses are 3 to 11 times greater than the RH-TRU doses.

The doses received from inhalation, ingestion, and external radiation from 100 hours of exposure were 14% of the maximum food dose at 100 years and 46% at 350 years.

Table 6-3. CH-TRU Dose to Non-Resident Farmer-Scenario III
(Rem - Annual Committed Effective Dose)

Year	Mean Conc - Mean Vol	Max Conc - Max Vol
100	0.14	3.6
350	0.13	1.9
700	0.10	1.5
1,000	0.089	1.4
5,000	0.062	0.91
10,000	0.051	0.76

Table 6-4. RH-TRU Dose to Non-Resident Farmer - Scenario III
(Rem - Annual Committed Effective Dose)

Year	Mean Conc - Mean Vol	Max Conc - Max Vol
100	0.045	7.7
350	0.013	0.33
10,000	0.0046	0.20

7. COLLECTIVE DOSE

Collective dose is the summation of radiation doses received by all persons in an exposed population.

The EPA Containment Requirements (§191.13) limit the cumulative release of transuranic radionuclides to the accessible environment. These limits are based on estimated health effects from a collective dose determined from generic global modeling. There is no regulatory requirement that a collective dose from the actual site be determined from the calculated cumulative releases. DOE has not done collective dose calculations for the releases projected in the CCA.

7.1 Collective Dose from Inhalation

The calculated collective dose from inhalation to the population within 80 km (50 miles) of the WIPP Site is presented in this report. This calculation was made because it is another measure of the health implications of the cumulative releases projected in the CCA. Details of the calculation are in Appendix D.

7.2 Other Collective Doses

Collective doses from pathways other than inhalation (external, resuspension of previously deposited material, ingestion of dirt, and the food pathway) were not calculated because previous calculations for the resident farmer indicate they are much less than inhalation doses for a single year of erosion. However, these doses would persist and there could be a buildup in the environment from continued erosion of mud pits and from subsequent intrusions during the 10,000 years. So, the contribution of non-inhalation doses to the total collective dose from inhalation will not be negligible if the mud pit is not reclaimed and erosion continues for many years.

7.3 Results of Collective Dose Calculation

Results of the annual collective inhalation dose are shows in Table 7-1. A 17 Ci release value was used because this value has about a 5% probability of occurring from an intrusion in 10,000 years (see Appendix E). These values are low because of the low population density within 15 miles of the

repository and the assumption that the future population will be the same as the present. The effect of distance can be seen by noting that the annual collective dose for 100,000 people residing within 50 miles of the site is only 4 times that calculated for two workers at the drilling rig.

Somewhat higher collective doses are theoretically possible for three reasons: (1) doses are assumed to occur only for a one-year period following an intrusion and only 2.3×10^{-3} of the radionuclides in the mudpit are assumed to be depleted by resuspension in a year. If all of the contents were eventually depleted by resuspension the collective dose from this one 17 Ci intrusion increases by a factor of 440; (2) multiple intrusions are expected to occur during the 10,000 year regulatory period; and (3) there would be contributions from non-inhalation pathways and, because of buildup in the environment from multi-year releases, these doses will be much greater than those we have calculated for the resident farmer during the initial year.

Table 7-1. Collective Doses From Inhalation From a 17 Ci Release of Transuranic Radionuclides

Down Wind Sector	Radial Distance (miles)	Collective Dose mrem y^{-1}
SSW	2.5	17.0
NNW	7.5	11.0
SW	15.0	3.1
WSW	15.0	96.0
W	15.0	12.0
WNW	15.0	6.4
W	25.0	640.0
WNW	25.0	340.0
E	35.0	6.4
ESE	35.0	3.6
NW	45.0	490.0
NNE	45.0	24.0
NE	45.0	35.0
ENE	45.0	33.0
	Total	1700.0

8. DISCUSSION AND CONCLUSIONS

The significance of the individual doses calculated in this report are discussed relative to: (1) the potential health effects; (2) a comparison of the health effects from individual doses and the health effects suggested by cumulative releases calculated in the CCA; and (3) the proposed cleanup standards for radiologically contaminated sites.

8.1 Potential Health Effects

The possible somatic health effects of calculated doses to drilling crew members, the resident farmer, and the population can be estimated from dose to excess cancer fatality (ECF) conversion factors in BEIR IV (NAS 1988). BEIR-IV estimates there will be 1.08×10^{-3} to 2.10×10^{-3} ECFs per rad of transuranics taken into the body. This is equivalent to 5.4×10^{-5} to 1.05×10^{-4} ECFs per rem of transuranics taken into the body. Doses from a 17 Ci CH-TRU release are used because there is an estimated 5% probability that an intrusion will bring this amount of radioactive material to the surface in 10,000 years. Results are shown in Table 8-1.

Table 8-1. Risk of Excess Cancer Fatality per Year of Intake[a]

Receptor	Internal Dose (Rem)	Probability of ECF[b]
Drilling Crew	0.22	$1.2\text{-}2.2 \times 10^{-5}$
Resident Farmer(I)	0.12	$0.61\text{-}1.2 \times 10^{-5}$
Resident Non-Farmer (II)	2.0	$1.4\text{-}2.0 \times 10^{-4}$
Non-Resident Farmer (III)	0.68	$3.7\text{-}6.8 \times 10^{-5}$
Collective Dose	1.7	$0.93\text{-}1.7 \times 10^{-4}$

[a] For a 17 Ci release of CH-TRU (Probability of ~ 0.05)

[b] Collective dose risk is to population of 100,000; other risks are to an individual.

These annual risks are low. However, lifetime risks could be much higher. For the 30-year exposure period suggested in U.S. EPA 1991 the cumulative risks to the resident farmer in Scenario I would be greater than 10^{-4}. For Scenarios II and III the cumulative risk would be greater than 10^{-3}. EPA typically sets limits of radiation exposure in its regulations so that lifetime risks would not exceed 10^{-3} to an individual.

The individual doses shown in Table 8-1 for the workers and resident farmers have about a 5% probability of occurring in one of the intrusions during the 10,000 year regulatory period if the projected drilling rate occurs. However, the probability that any one generation will receive similar doses is much lower.

8.2 Comparison of Health Effects

The cumulative release limits in 40 CFR Part 191 were derived from the results of generic, global modeling of the total health effects from a curie of each radionuclide that might be released into the environment. The release limits would result in an estimated 1,000 ECFs in 10,000 years for a full sized repository containing 10^8 Ci of TRU waste.

The WIPP repository is projected to have 3.44×10^6 Ci of TRU waste at the time of repository closure. This would scale to 34.4 ECFs in 10,000 years if the full allowable release occurs. The CCA calculations predicted a release of 6% of the allowable limit at a probability of 0.1. Thus, the implicit number of health effects would be 1.7 deaths in 10,000 years from a release of 17 curies.

The collective dose calculated in Table 7-1 (for a 17 Ci release) would become 1.8 person-rem per year from inhalation when the dose to the resident farmer is added. If it were assumed that all the material deposited in the mud pit was eventually resuspended and transported to the regional population the total dose from primary inhalation would be 810 person-rem. The inhalation doses from resuspension of deposited material and ingestion doses from deposited dirt would also increase by a factor of 440 if all of the contaminated material in the mud pit was eventually resuspended. Also, there would be some food pathway doses incurred.

A conservative integrated collective dose (see Appendix D) was calculated to be 3100 person-rem with calculated health effects of 0.17 to 0.31 excess cancer fatalities. This is reasonable agreement with the implicit value of 1.7 fatalities derived from 40 CFR 191 release limits.

This comparison suggests that the global, generic modeling of health effects conducted by EPA is greater than, but within an order of magnitude of, the very approximate site specific calculation performed here. This is as good agreement as can be expected.

Another implication of this comparison is that at WIPP an individual dose standard that included doses from human intrusion would provide a more stringent limit than the present cumulative release limit. For example, these calculations suggest that a dose limit for the resident farmer of 100 mrem y^{-1} at the 5% probability level would limit the allowable release to 14 Ci for a single intrusion. The cumulative release limit allowed from all intrusions in 40 CFR 191 is 344 Ci at the 0.1 probability level.

8.3 Comparison with Cleanup and Low-Level Radioactive Waste Disposal Standards

8.3.1 Cleanup Standards

Promulgated cleanup standards for contaminated sites do not exist although EPA, DOE, and NRC all have proposed rules. On-going cleanups are being addressed by these agencies on a case by case basis. Cleanup will probably be required to limit doses to an individual to 25 to 100 millirem per year. It is uncertain whether the standards will allow variances to exceed the maximum annual dose for unusual situations.

The methodology and assumptions used to calculate the maximum individual dose need to be known in order to compare with the individual dose calculations in this report. It is likely that EPA cleanup standards will follow the modeling assumptions in U. S. EPA 1989. This methodology determines the reasonable maximum exposure (RME) to an individual that is expected to occur at a site from all environmental media through all reasonable pathways. Both current and future land use is to be considered and this requires professional judgement. The RME is to be calculated at about the 95%

upper confidence level. So, the RME is intended to be a low probability exposure but not a maximum exposure.

The probabilities of the calculated individual doses would include the upper 95% confidence level probability of an RME. For example there is about a 5% probability (using PAVT assumptions) that the release due to cutting + cavings + spallings will be $\geq$17 Ci from a CH-TRU intrusion. The calculated doses from Table 8-1 are 220 mrem y^{-1} for drilling rig workers and 120 mrem y^{-1} for the resident farmer for a 17 Ci release.

This comparison leads to the preliminary conclusion that the predicted doses at WIPP would not meet the expected cleanup standards for contaminated sites. It could be argued that human intrusion should not be considered in a cleanup standard. However, EPA has required that human intrusion at WIPP be considered an expected event. Even if doses to the intruders were excluded (because of their negligence in causing the intrusion) the estimated resident farmer inhalation dose would still exceed any likely clean up standard.

8.3.2 Low-Level Waste Disposal

Dose limits used by NRC in the Final Rulemaking on Land Disposal of Low-Level Radioactive Waste (10 CFR Part 61) could also be compared to these calculated individual doses. These regulations limit doses after closure to 25 mrem to the whole body. NRC also limits concentrations of low level waste so that an inadvertent intruder would not receive a dose greater than 500 mrem y^{-1}. They considered a human intruder-construction scenario (where an intruder builds a house on the disposal site) and intruder-agriculture scenario (where an intruder lives on and consumes food grown on the disposal facility) (U. S. NRC 1981). These scenarios are more comparable to Scenarios II and III than to Scenario I. Doses in Scenarios II and III from a 17 Ci release exceed the 500 mrem y^{-1} dose used by the NRC.

8.3.3 Applicability to WIPP

The results of these comparisons to other standards lead to two questions:

(1) Should WIPP individual doses be less than the maximum allowable doses for remediated sites and/or low-level radioactive waste disposal standards?

(2) If the answer to question one is yes, how can doses be reduced?

The answer to question one should be more of a philosophical and/or societal decision than a technical one. Both the NAS and the EPA have considered this issue. The NAS in their Yucca Mountain high-level waste disposal report on the technical bases for standards recommended that doses to individuals from waste brought to the surface by human intrusion should not be considered (NAS 1995). EPA considered using an individual dose standard in early drafts of the 40 CFR Part 191 rule and concluded that this was not a practical way to regulate high-level and transuranic waste disposal.

Reduction of individual doses could be addressed as an As Low as Reasonably Achievable (ALARA) issue with practical remedial measures being incorporated into a repository design even though not required by standards. ALARA designs, such as waste treatment, would be an assurance requirement as defined in 40 CFR Part 191.14.

In the original CCA submittal to the EPA, DOE assumed that passive institutional controls were 99% effective in deterring human intrusion during the period of 100 to 700 years after repository closure. EPA has, in effect, rejected the efficacy of passive institutional controls (markers, monuments, and records) in their review of the CCA by requiring DOE to assume the full drilling rate after 100 years in the Performance Assessment Verification Test (PAVT) calculations. EPA has allowed 100% credit against human intrusion for active institutional controls during the first 100 years after repository closure.

Waste form modification has the potential to reduce the amount of material brought to the surface from cavings, spallings, and direct brine releases. For example, the amount of cavings is dependent on the shear strength of the waste. If the CH-TRU waste was treated to increase the shear strength so that the present mean volume (0.60 m^3) was never exceeded there would be no intrusion after 154 years where the total release to the surface exceeded 14 Ci (see Table 3-1). This condition would reduce the inhalation dose to the resident farmer to<100 mrem y^{-1}.

8.4 Summary and Conclusions

There are inherent uncertainties in estimating repository conditions, human actions and individual doses at WIPP over a 10,000 year period. With this caveat, the following conclusions are reached:

- Calculated doses to drilling crew members and the resident farmer exceeded annual dose limits for occupational radiation workers only for the low probability Scenarios II and III at the 100 year intrusion time.

- Calculated doses to drilling crew members and the resident farmer exceeded 100 mrem y^{-1} at the 95% probability level. This is greater than the limits allowed in other standards regulating radioactive material, waste disposal and contaminated site cleanup.

- Calculated doses to the resident non-farmer and the non-resident farmer (for the 95% probability release) are greater than the 500 mrem y^{-1} value NRC used for similar scenarios in establishing low-level radioactive waste concentration limits in 10 CFR Part 61.

- Health effects predicted from a very preliminary integrated collective dose calculation are less than but within an order-of-magnitude of the health effects implied from 40 CFR Part 191 for the amounts released in the CCA.

- An individual dose limit of 100 mrem y^{-1} (at the 95% probability level) to the resident farmer at WIPP would be about an order-of-magnitude more restrictive than the cumulative release limit in 40 CFR 191. Releases predicted in the CCA would be less than the 100 mrem y^{-1} limit but releases predicted in the PAVT would be > 100 mrem y^{-1}.

- Since individual doses can be substantial, DOE should use "As Low as Reasonably Achievable" (ALARA) designs (such as treating the Waste) to limit these doses.

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10. ACRONYMS

ALARA	As Low as Reasonably Achievable
BIR	Baseline Inventory Report
CCA	Compliance Certification Application
CCDF	Complementary Cumulative Distribution Function
CH	Contact-Handled
DOE	U. S. Department of Energy
ECF	Excess Cancer Fatality
EEG	Environmental Evaluation Group
EPA	U. S. Environmental Protection Agency
FEIS	Final Environmental Impact Statement
NAS	National Academy of Sciences
NAS/NRC	National Academy of Sciences/National Research Council
NRC	U. S. Nuclear Regulatory Commission
OECD/IAEA	Organization for Economic Cooperation and Development/International Atomic Energy Agency
PA	Performance Assessment
PAVT	Performance Assessment Verification Test
RFETS	Rocky Flats Environmental Technology Site
RH	Remote Handled
RME	Reasonable Maximum Exposure
SNL	Sandia National Laboratories
TRU	Transuranic Waste
WIPP	Waste Isolation Pilot Plant

APPENDIX A
CALCULATION OF DOSES TO DRILLERS

A.1 DRILLING ASSUMPTIONS

The necessary drilling assumptions are taken from values used in the CCA when available. The parameter values necessary for calculations are:

(1) drill bit diameter - 0.311 m (12.25 inch)

(2) drilling fluid flow rate - 0.0309 $m^3 s^{-1}$ (490 gallons per minute)

(3) penetration rate in salt - 0.00254 m s^{-1} (30 feet per hour)

(4) total depth of drilling - 2100 m

(5) size of mud pit - 4300 m^2

The first three parameter values are from the CCA. The depth of drilling is the approximate depth of most oil exploratory holes around WIPP. The mud pit size is the average of those examined around WIPP in a 1984 study (Reith 1984). This sized pit will give a total cuttings plus cavings depth of about 5 or 6 cm in a dried mud pit. Thus, it is reasonable to use external dose coefficients for soil contaminated to a depth of 5 cm (U. S. EPA 1993).

The drilling fluid flow rate and penetration rate in salt are needed to calculate the time that a driller is exposed to contaminated cuttings at the shale shaker and the concentration of radionuclides in the drilling fluid. It is assumed that the contaminated cuttings do not dispense in the drilling fluid as it flows to the surface (i.e. there is "plug" flow) and the radionuclides are evenly mixed in the drilling fluid flow that occurs while the waste is being penetrated.

For an initial CH-TRU room height of 3.96 m, the penetration time would be 1560 seconds and the drilling fluid volume is 48.1 m^3.

For the RH-TRU canister with an assumed effective depth of penetration of 0.7 m, the penetration time would be 275 seconds. The drilling fluid volume during this time would be 8.50 m^3.

A.2 DOSE FROM DRILLING MUD AT THE SHALE SHAKER

A worker is assumed to be standing near the shale shaker during the period of time that contaminated drilling fluid is going through the shale shaker and a one-meter-wide trough to the mud pit. The depth of fluid in the trough is assumed to be 7 cm (equivalent to a soil depth of about 5 cm). The exposure can be treated as a ten-meter-long line source of exposure with the receptor being one meter away. The diagram and equation are shown below:

$$\phi = \frac{S\theta}{4\pi a}$$

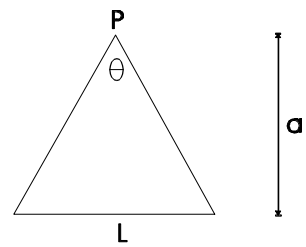

Where S is source of strength in photon s^{-1} cm^{-1} of length (L)

ϕ = flux in photons cm^{-2} s^{-1} at P
a = distance to point of interest from line source (100 cm)
L = length of trough at shale shaker (10 m)
θ = subtended angle in radians (2.75)

The value of S can then be determined from the number of Curies of a radionuclide brought to the surface:

$$S = 7x10^{-4} \frac{m^3 cm^{-1}(Ci)i}{m^3 \ of \ contaminated \ drilling \ fluid}$$

When constant terms are combined the expression for ϕ becomes: $\phi = 6.66x10^3(Ci)_i f_i$ for RH-TRU and $\phi = 1.18x10^3 (Ci)_i f_i$ for CH-TRU, where f_i is the fraction of disintegrations of radionuclide i that emit gamma radiation of a specific energy.

The absorption of gamma radiation in the drilling fluid for the important radionuclides was determined from the ratio of dose coefficients for exposure to contaminated ground surface (Table III.3 in U. S. EPA 1993) to the coefficients for exposure to soil contaminated to a depth of 5 cm (Table III.5). It is necessary to convert the Bq m^{-3} of contaminated soil to Bq m^{-2} of surface area to make this comparison. The dose rate from this calculated flux of a specific energy photon can be obtained from standard curves. (e.g. U. S. DHEW 1970, pg. 132).

A.3 WORKER DOSE AT THE MUD PIT

The radionuclides entering the mud pit are assumed to be evenly mixed in 5 cm of solids that have settled from the drilling mud. The total volume of cuttings was estimated to be about 225 m^3. The concentration (in Bq m^{-3}) of each radionuclide was then calculated and the dose coefficients (in Sv Bq^{-1} s^{-1} m^2) from Table III.3 in U. S. EPA 1993 were used to obtain the effective dose for each radionuclide.

The dose rates for all the radionuclides shown in Tables 3-1 and 3-2 were included in the total dose rate unless it was obvious that their contribution to the total would be negligible. Those radionuclides that contribute more than about 0.2% of the final dose are included in Tables 4-2 and 4-5.

The dose rates in Table III.3 assume the 65 m x 65 m mud pit is an infinite isotropic plane source. A worker standing on the edge of this pit can be assumed to be exposed to one-half of an infinite source and receive one-half of the dose calculated for the center of the mud pit. A residence time of 12 hours was assumed for the duration of the drilling operation.

It is assumed that workers near the drilling rig (100 m from the center of the mud pit) do not receive any direct radiation from the mud pit because (with an assumption that elevation of the mud pit is not lower than the drill rig) a low berm will obstruct the line-of-sight at a point one meter above the surface. This is not the most conservative assumption, since direct radiation could occur.

There will be scattered radiation (skyshine) from the atmosphere and perhaps other objects near the mud pit that will reach workers near the drilling rig. The magnitude of scattered radiation was not calculated.

A.4 INHALATION DOSES TO WORKERS

Workers are assumed to be at the drilling rig for 80 hours after the mud pit has dried. They will be exposed to resuspended material from the dried mud pit during those hours when the drilling rig is downwind. The resuspension factor will be higher initially and the high value of 6.0×10^{-5} m^{-1} from La Plante 1995 was chosen. When coupled with a deposition velocity of 1.8×10^{-3} from Parks 1992 one obtains a resuspension rate of 1.1×10^{-7} s^{-1}. This resuspension rate is applicable primarily to surface contamination and not to the 5 cm depth of contaminated material in the mud pit. An effective depth of 2×10^{-4} m was assumed based on discussions contained in Linsley 1978. This is 4×10^{-3} of the depth of the contaminated material in the mud pit. All resuspended material is assumed to be respirable.

The relative concentration from atmospheric dispersion was calculated from expression (3) in U. S. NRC 1982:

$$\frac{\chi}{Q} = \frac{f}{u\pi\sigma_z\sigma_y}$$

where:

χ/Q = relative concentration in s m^{-3}.
f = frequency that wind blows toward receptor
u = average windspeed, m s^{-1}
σ_z = vertical plume spread in m
σ_y = lateral plume spread in m

The values of σ_y and σ_z are functions of atmospheric stability class and distance from the source. They are obtained from Figures 1, 2, and 3 (for 100 m distance) in U. S. NRC 1982 for Stability Category D. Stability Category D (neutral) was selected because it is more prevalent in daytime hours than the more severe inversion conditions (Categories E and F). Wind direction frequency and mean velocity were determined from Tables H-43 and Appendix H, Annex 1, Table 2 of U. S. DOE 1980. Winds blow from the southeast 37% of the time in July and the mean wind speed was calculated as 3.5 m s^{-1}. It was assumed that the worker inhales 1.4 m^3 h^{-1} during his 40-hour work week.

These combinations of numbers lead to a χ/Q value of 6×10^{-4} s m^{-3} and an inhaled volume of 112 m^3 during the 80 hours of exposure. Radiation doses to workers from inhalation were obtained by multiplying the Becquerels of each radionuclide inhaled by the dose conversion factors (Sv Bq^{-1}) from Eckerman 1988, Table 2.1. The results are shown in Tables 4-3 and 4-6.

A.4.1 Alternate Inhalation Calculation

A common method of estimating inhalation doses for onsite exposure is to assume that the dirt in the air contains the same specific activity as is present in the contaminated soil. Typically, average values for dirt mass loading in the air are used. For example, U. S. EPA 1994 uses 1.5 µg m^{-3} for suburban areas and values as high as 200 µg m^{-3} for rural residential areas. Values for WIPP have been reported as 77.7 µg m^{-3} for 24 hour average and 18.47 µg m^{-3} for annual arithmetic mean (U. S. DOE 1980). This approach was not used in Scenario I for occupational exposure because the contamination was not considered to be onsite. However, it is possible to calculate the concentration of contaminated dirt inhaled from the mud pit as a comparison. For the worker inhalation, this value is about 130 µg m^{-3}. Dirt loadings would typically be higher during the work day when wind speeds are greater and atmospheric stability is less. Therefore, this comparison suggests that the method used gives results that are roughly the same as those obtained using the mass loading approach. The mass loading approach was used to evaluate inhalation from resuspension of deposited contamination at the resident farm and also for inhalation in Scenario II (the resident non-farmer case).

A.4.2 Reclamation of Mud Pits

Mud pits are often reclaimed (i.e. covered with earth) in the area around WIPP. Reith 1984 reports that 70% of the pits surveyed had been reclaimed. There was no definition of what the reclamation criteria was nor any indication of the elapsed time between drilling these wells (an average of 7+ years before the survey) and reclaiming the mud pits. Reclaiming a mud pit is not likely to significantly decrease the dose from resuspension during the first year because the resuspension rate is greatly increased during remediation. For example, Woolfolk 1982 used a resuspension rate 9 times that used in this report for 32 hours during pit remediation. These higher values would have caused several times the worker inhalation dose calculated in this report. Inhalation doses to the resident farmer from a reclaimed mud pit would have been lower in the first year if reclamation occurred within 9 months after drilling.

Reclamation of mud pits was not assumed in this report because: (1) it may not occur at all or soon after drilling; (2) it would lead to higher calculated loses to workers and (3) it might not significantly decrease the dose to the resident farmer in the first year.

APPENDIX B
CALCULATION OF DOSES TO THE RESIDENT FARMER

B.1 INHALATION DOSE

The atmospheric dispersion approach used for the resident farmer inhalation dose was similar to that used to calculate worker inhalation doses. However, an average annual χ/Q value of $5x10^{-5}$ s m^{-3} from WIPP Site data was used.

The median resuspension factor (1×10^{-5} m^{-1}) from La Plante 1995 was used. When coupled with a $1.8x10^{-3}$ m s^{-1} deposition velocity, the resuspension rate becomes $1.8x10^{-8}$ s^{-1} of the top $2x10^{-4}$ m of contaminated soil.

The fraction of resuspended particles remaining in the plume (0.91) at 800 m was taken from Figure 2 in Regulatory Guide 1.111 (U. S. NRC 1977a) and the deposition rate (6.0×10^{-5} m^{-1}) was taken from Figure 6. This value was used in determining the amounts deposited per square meter for external radiation and crop/soil contamination. Inhalation doses from radionuclides deposited at the farm were evaluated. Assumptions that exposure is: (1) 73% indoors at an inhalation rate of 0.63 m^3 h^{-1}; (2) concentration indoors is 0.5 of that outdoors; (3) outdoor breathing rate is 1.4 m^3 h^{-1}; and (4) residence of 350 days per year leads to an annual equivalent inhalation rate of 5,100 m^3 (La Plante 1995).

B.2 EXTERNAL RADIATION DOSE

The deposition rate of radionuclides from the contaminated plume was taken as 6.0×10^{-5} m^{-1} of the 91% remaining in the plume at 800 m. This value, when divided by the arc length of a 22.5° sector (314 m), gives the fraction of the plume depleted per square meter (1.74×10^{-7} m^{-2}).

The amount deposited per square meter in a year is the product of the fraction of each radionuclide in the pit that is eroded per year ($2.3x10^{-3}$), the fraction of the time the wind is blowing toward the resident farm (0.188), the amount remaining in the plume at 800 m, and the fraction deposited per square meter. The amount deposited per square meter is $7.42x10^{-11}$ of the total quantity of radionuclides in the pit. Dose rates for exposure to contaminated ground surface were taken from Table III.3 in U. S. EPA 1993. The dose calculated per year was adjusted by a factor of 0.635 to account for the assumption that the farmer spends 73% of his time indoors, where the exposure rate is 0.5 of that outside.

B.3 CONCENTRATIONS IN CROPS, FEED, MILK AND MEAT

B.3.1 Calculations of Concentrations

The basic equation used for calculating concentrations of radionuclides in forage crops, leafy vegetables, and other produce is equation C-5 in Regulatory Guide 1.109 (U. S. NRC 1977b):

$$C_{iv} = d_i \left[\frac{r[1 - \exp(-\lambda_{Ei} t_e)]}{Y_v \lambda_{Ei}} + \frac{B_{iv}[1 - \exp(-\lambda_i t_b)]}{P \lambda_i} \right] \exp(-\lambda_i t_h) \qquad (B-1)$$

where:

C_{iv} = concentration of radionuclide i in crops, Bq kg^{-1}

d_i = deposition, Bq m^{-2} per year

r = fraction of deposition retained on crops (used 0.2; the median value from La Plante 1995 is 0.4, but about one-half of surface at WIPP is bare ground (U. S. DOE 1981).

λ_{Ei} = effective removal constant, a combination of λ_w, (weathering rate constant) and λ_i (radiological decay). λ_i, is ignored here with long-lived radionuclides. Value used is 6.50 y^{-1}. This is lowest value reported in Till 1983, and appears most logical for an arid area.

Y_v = agricultural productivity in kg (wet weight) m^{-2}, used 0.1 in Case I and 2.0 for all crops in Case III. The Case I value is estimated because no data are available for WIPP. The Case III value is from U. S. NRC 1977b.

t_e = length of time crops are exposed to contamination during growing season. Used 1,440 hours (0.16 year) from U. S. NRC 1977b.

B_{iv} = concentration factor for uptake of radionuclide i from soil by edible portions of crops, in Bq kg^{-1} (wet weight) of crops per Bq kg^{-1} dry soil. Volumes for each element are from La Plante 1995 or U. S. NRC 1977b and are shown in Table B-1.

P = effective surface density of soil for 15 cm deep plow layer. Used 215 kg m^{-2} from Parks 1992.

λ_i = radiological decay constant for radionuclide i.

t_b = build-up time for concentration in soil; used a value of one year.

t_h = hold up time before food is consumed. Ignored here because time is short relative to half-life of these radionuclides.

Table B-1. Soil to Crop and Crop to Milk and Food Concentration Factors

Element	Concentration Ratio		Transfer Coefficient
	Other Vegetables	Grain	Beef
Am	4.7×10^{-4}	2.2×10^{-5}	4.0×10^{-5}
Cs	7.2×10^{-2}	1.0×10^{-2}	5.0×10^{-2}
Pu	2.3×10^{-4}	8.6×10^{-6}	1.0×10^{-5}
Sr	1.7×10^{-2}	1.7×10^{-2}	6.0×10^{-4}

Strontium values from U. S. NRC 1977b. Remaining values from La Plante 1995

The radionuclide concentration in beef is determined by:

$$C_{ib} = F_{ib} C_{iv} Q_f e^{-\lambda t} f \qquad \text{(B-2)}$$

F_{ib} = average fraction of the animals' daily intake for radionuclide i that appears in each kilogram of flesh in days kg^{-1}. Values taken from La Plante 1995 or U. S. NRC 1977b.

Q_f = amount of feed consumed per day. 7.6 kg d^{-1} of air-dry contaminated range was used from U. S. DOE 1981.

t_f = hold up time before beef is consumed by humans. Ignored here because of long half-lives of radionuclides.

B.3.2 Intake and Doses Received by Resident Farmer

The quantity of radionuclides taken into the body of the resident farmer in a year can be obtained by multiplying the calculated concentrations of crops, milk, and meat by reasonable assumptions of the annual intake of locally grown foods. Values for produce are from U. S. EPA 1991. Meat consumption is assumed to be 75% of the value recommended in U. S. NRC 1977b for an average adult (95 kg y^{-1}).

Table B-2. Annual Quantity of Food Ingested by Resident Farmer

Food Item	Kg/y	Comment
all produce	42.7	assumed to be all other vegetables
beef	71.2	75% of total beef intake
soil	0.035	

APPENDIX C
CALCULATION FOR SCENARIOS II & III

C.1 SCENARIO II, RESIDENT-NON FARMER

The resident non-farmer is assumed to live in a house on the edge of the dried mud pit from scenario I and occupies the house 73% of the time (6400 hours y^{-1}). While indoors the resident non-farmer inhales contaminated air, ingests some contaminated dirt and is exposed to external radiation. Time outside the house is minimal and no dose is assumed.

The indoor inhalation rate is assumed to be 0.63 m^3 h^{-1} and the air has a particulate concentration of 32.5 µg m^{-3} (one-half of outdoor air). Only one-half of the airborne particulates come from the mud pit. The amount of mud pit dirt inhaled is 0.0655 g y^{-1}. Dirt ingestion is assumed to occur at a rate of 0.0175 kg y^{-1} (one-half the rate assumed for the resident farmer because of the lack of outside activity). Also, only one-half of the ingested dirt comes from the mud pit. Thus, the amount of mud pit dirt ingested is 0.00875 kg y^{-1}.

External radiation is received for 6400 hours per year at one-half of the unshielded dose rate that exists outdoors at the edge of the mud pit. This is equivalent to 267 times the dose received by a drill crew member in 12 hours.

C.2 SCENARIO III, NON-RESIDENT FARMER

Since only the soil-to-crop pathway is being considered in Scenario III, the first term of the general expression for determining the concentration of radionuclides in crops (the foliage deposition term) shown in Equation B-1 can be deleted. Also, the expression can be further simplified because continuous deposition is not occurring. The term simplifies to:

$$C_{iv} = \frac{dB_{iv}}{\rho}$$

where d is expressed in Bq m^{-2}, B_{iv} is Bq kg^{-1} crops/Bq kg^{-1} soil, and ρ is density of soil (215 kg m^{-2}). When the area of the mud pit and conversion from curies to Becquerels is included this term becomes:

$$C_{iv} = 4.00 \times 10^4 (\text{Curies in mud pit})_t B_{iv}$$

At any time t.

This expression can be multiplied by the 42.7 kg y^{-1} of vegetable consumption to obtain the Bq y^{-1} intake. This value can then be modified by the Sv Bq^{-1} conversion factor to obtain the annual dose.

APPENDIX D
COLLECTIVE DOSE CALCULATION

D.1 ANNUAL COLLECTIVE DOSE FROM INHALATION

The collective dose was calculated only for inhalation of material resuspended from the mud pit.

The same mud pit resuspension rate from the top $2x10^{-4}$ m was assumed ($1.8x10^{-8}$ s^{-1}). The 1990 population distribution in 22.5° sectors at various distances out to 80 km was taken from U. S. DOE 1996b, Table F-10 (see Table D-1). Long-term average χ/Q values were taken from U. S. DOE 1980, Table H-49 (see Table D-2). An equivalent annual breathing intake volume of 5100 m^3 was used. Depletion of the plume at the various distances was also included in the calculation. The dose conversion factor for ^{239}Pu and ^{240}Pu ($1.16x10^{-4}$ Sv Bq^{-1}) was used for all transuranic radionuclides (this overstates the dose calculation from ^{238}Pu by 9% and underestimates the dose from ^{241}Am by 3%).

The combination of these factors leads to a dose for each sector(s) and radial distance (d) of:

$$D_{sd} = 1.58 \; Ci \; (dep_d) \frac{\chi}{Q}_{sd} \; P_{sd}$$

where: D_{sd} is annual collective dose in Sv y^{-1}
Ci is total curies of transuranics in mud pit
χ/Q_{sd} is dispersion expression for given sector and distance, s m^{-3}
dep_d is fraction of transported radionuclides remaining in plume at distance d.
P_{sd} is 1990 population for given sector and distance.

D.2 POSSIBLE INTEGRATED COLLECTIVE DOSE

A conservative, very approximate integrated collective dose can be calculated as follows. Assume that the inhalation doses from deposited radionuclides and ingestion doses from deposited dirt build up to a value of 440 times the initial year values (which were 0.35% and 0.30% of the primary inhalation dose at the end of one year). Also, that there is assumed to be no depletion of these deposited radionuclides and radioactive decay is neglected. The resident population (which is assumed to be stable) is exposed to primary and secondary inhalation and ingestion during the 440

year buildup period. Secondary inhalation plus ingestion will continue for an additional 440 years while the deposited material is being lost from resuspension. These are conservative assumptions because all of the material in the mud pit would not be resuspendable or respirable. However, non conservative assumptions are: (1) neglecting food pathway doses from the >200 km^2 of irrigated agriculture within the 80 km radius; and (2) neglecting doses from all pathways at distances beyond 80 km.

The original dose is 1.8 person-rem per year when the resident-farmer's dose is included. The dose at 440 years is 3.9 times the initial dose (7.1 person-rem per year). For the next 440 years the annual dose drops from 5.3 person-rem per year to zero. With the simplifying assumption that build up and decay of the annual dose rate is linear an integrated collective dose can be calculated. This leads to a total dose of:

$$\textit{Total Collective Dose} = 440 \left[\frac{1.8 + 7.1}{2} + \frac{5.3}{2} \right] = 3{,}100 \ \textit{person rem}$$

This collective dose would result in 0.17 to 0.31 ECFs.

Table D-1. 1990 Population Distribution Within
80 Kilometers (50 Miles) of WIPP

Direction	Distance (miles)										
	0-1	1-2	2-3	3-4	4-5	5-10	10-20	20-30	30-40	40-50	Total
S	0	0	0	0	0	0	3	2	46	20	71
SSW	[a]9	0	0	0	0	0	0	2	43	8	62
SW	0	0	0	0	0	0	37	57	0	5	99
WSW	0	0	0	0	0	0	1,622	191	57	62	1,932
W	0	0	0	0	0	0	138	25,291	197	3	25,629
WNW	0	0	0	0	0	0	38	5,765	242	63	6,108
NW	0	0	0	0	0	0	6	7	14	12,401	12,428
NNW	0	0	0	0	0	9	4	66	104	56	239
N	0	0	0	0	0	0	3	0	63	12	78
NNE	0	0	0	0	0	0	4	3	122	7,353	7,482
NE	0	0	0	0	0	0	0	11	37	9,115	9,163
ENE	0	0	0	0	0	0	0	10	282	30,877	31,169
E	0	0	0	0	0	0	6	5	2,982	19	3,012
ESE	0	0	0	0	0	0	0	16	2,173	97	2,286
SE	0	0	0	0	0	0	0	0	15	20	35
SSE	0	0	0	0	0	1	3	14	5	73	96
TOTAL	9	0	0	0	0	10	1,864	31,440	6,382	60,184	99,889

Source: U. S. DOE 1996b Table F-10

a. Location of these 9 persons is an error. Should be SSW, 2-3 miles.

Table D-2. WIPP Site Long-Term Average X/Q Calculations
(Period of Record, June 1977 through May 1979)

Downwind Sector	X/Q (sec/m^3) at downwind distance (miles)					
	2.5	7.5	15.0	25.0	35.0	45.0
N	$1.0x10^{-6}$	$1.8x10^{-7}$	$3.9x10^{-8}$	$1.7x10^{-8}$	$7.2x10^{-9}$	$8.4x10^{-9}$
NNE	$5.7x10^{-7}$	$9.0x10^{-8}$	$2.0x10^{-8}$	$9.0x10^{-9}$	$3.3x10^{-9}$	2.6x10
NE	$6.8x10^{-7}$	$1.1x10^{-7}$	$3.0x10^{-8}$	$1.2x10^{-8}$	$4.4x10^{-9}$	$3.1x10^{-8}$
ENE	$5.4x10^{-7}$	$5.7x10^{-8}$	$1.5x10^{-8}$	$5.4x10^{-9}$	$1.1x10^{-9}$	$8.6x10^{-10}$
E	$4.8x10^{-7}$	$4.8x10^{-7}$	$1.2x10^{-8}$	$4.2x10^{-9}$	$1.3x10^{-9}$	$1.1x10^{-9}$
ESE	$4.5x10^{-7}$	$4.2x10^{-8}$	$1.1x10^{-9}$	$4.7x10^{-9}$	$1.0x10^{-9}$	$7.3x10^{-10}$
SE	$4.3x10^{-7}$	$5.3x10^{-8}$	$1.6x10^{-8}$	$6.2x10^{-9}$	$1.7x10^{-9}$	$1.5x10^{-9}$
SSE	$5.2x10^{-7}$	$7.7x10^{-8}$	$2.3x10^{-8}$	$3.6x10^{-7}$[a]	$4.0x10^{-9}$	$2.7x10^{-9}$
S	$6.4x10^{-7}$	$1.1x10^{-7}$	$3.0x10^{-8}$	$1.0x10^{-8}$	$6.0x10^{-9}$	$3.2x10^{-9}$
SSW	$8.5x10^{-7}$	$1.4x10^{-7}$	$3.9x10^{-8}$	$1.8x10^{-8}$	$6.8x10^{-9}$	$5.2x10^{-9}$
SW	$9.6x10^{-7}$	$1.6x10^{-7}$	$5.0x10^{-8}$	$1.8x10^{-8}$	$8.8x10^{-9}$	$4.8x10^{-9}$
WSW	$8.5x10^{-7}$	$1.4x10^{-7}$	$3.5x10^{-8}$	$1.2x10^{-8}$	$5.6x10^{-9}$	$3.1x10^{-9}$
W	$1.2x10^{-6}$	$1.9x10^{-7}$	$5.0x10^{-8}$	$1.7x10^{-8}$	$7.8x10^{-9}$	$4.5x10^{-9}$
WNW	$2.5x10^{-6}$	$3.8x10^{-7}$	$1.0x10^{-7}$	$3.9x10^{-8}$	$1.9x10^{-8}$	$9.5x10^{-9}$
NW	$3.2x10^{-6}$	$7.6x10^{-7}$	$2.5x10^{-7}$	$1.1x10^{-7}$	$5.5x10^{-8}$	$3.2x10^{-8}$
NNW	$3.0x10^{-6}$	$5.8x10^{-7}$	$2.5x10^{-7}$	$7.8x10^{-8}$	$4.6x10^{-8}$	$2.6x10^{-8}$

Source: adapted from U. S. DOE 1980, Table H-48

[a] This value appears to be a typographical error

APPENDIX E
DETERMINATION OF 95% UPPER CONFIDENCE LEVEL RELEASE TO SURFACE

The Reasonable Maximum Exposure (RME) used by EPA for cleanup standard calculations is defined as approximately the 95% upper confidence level. This could also be expressed as the dose that is expected to be exceeded only 5% of the time. It is desireable to estimate the approximate number of curies brought to the surface at WIPP at the 95% upper confidence level to cleanup standards.

With all the complicated probabilistic calculations in the CCA it is not easy to arrive at probabilistic values for curies released to the surface. The procedure used here was:

(1) The cumulative probability distribution of curies brought to the surface from 104 intrusions calculated in Futures 1 through 20 of Vector #1 in the CCA was determined. All Vector #1 intrusions had a cuttings and cavings volume of 0.9046 m^3. Similarly, the distribution of curies from 110 intrusions in Futures 1 through 20 in Vector #2 was determined and combined with the distribution from Vector #1. It was necessary to adjust the Vector #2 values (which were for a volume of 0.6164 m^3) by a factor of 1.468 to be consistent with the cuttings & cavings volume of Vector #1. When a constant volume is used the variations in number of curies released is due to the random sampling of radionuclide concentrations in the 569 waste streams, to the time of intrusion, and to the variable releases from spallings and direct brine releases. It is reasonable to assume that this curie distribution which was obtained from 214 data points will be the same for all volumes of cutting and cavings. The values for any intrusion i and cumulative probability, p can be scaled directly by the relationship:

$$Curies_{i,P} = Curies_{.9046P}\left[\frac{Volume\ i}{.9046}\right]$$

(2) Volumes calculated from the PAVT were used rather than the CCA volumes for two reasons: (a) they are believed to be more realistic because of changes in several parameter values; and (b) the distribution of volumes released were more readily available. Thirty six percent of the PAVT volume releases exceeded 1.0 m^3 and 16% exceeded 2.0 m^3.

(3) There are expected to be 5.84 intrusions into the waste repository during the 10,000 year regulatory period. So, the percentile level that has a 5% chance of occurring in one of the intrusions is a value higher than 95% in the curie release distribution. This percentile level can be approximated by the relationship:

$1 - P^n$ = probability that at least one of n occurrences will be $\geq$ the cumulative probability value, P.

For n = 5.84 and the probability of 0.05, the minimum value of P is 0.991 (or 1-P = 0.009)

(4) The volume of each individual intrusion was taken from PAVT 1997 Figure 5.1 beginning from the highest value (3.95 m^3). An estimated curie release limit (e.g. 17 curies) was divided by the volume scaling factor to determine the appropriate curie level on the Vector #1 + #2 cumulative probability plot. This value would be 3.89 Ci for the 3.95 m^3 volume. From this curie level the related probability of the 17 Ci release from the one borehole could be determined. This probability is multiplied by 0.01 because this intrusion volume is only one of 100 volumes. The probabilities are summed for each intrusion volume to determine the total probability that the given release level will occur.

The probability of a 17 Ci release from a single intrusion was found to be 0.00999 or 0.0100. The probability that this large a release would appear in one of the 5.84 expected intrusions in the repository was calculated to be 0.057. So the calculated release is slightly less than the 95% value used for the RME.

The uncertainties in calculating a 95% upper confidence level for WIPP releases are significant and not quantifiable. Similar uncertainties would be expected to occur in calculations at most cleanup sites.

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EVALUATION OF THE WIPP PROJECT'S COMPLIANCE WITH THE EPA RADIATION PROTECTION STANDARDS FOR DISPOSAL OF TRANSURANIC WASTE

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, is being constructed as a repository for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC04-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, continues the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the generator sites' compliance with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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Betsy Kraus prepared the references. The contributions of Jill Shortencarier, Patricia Fairchild, and Susan Stokum who patiently and diligently provided secretarial support through a number of drafts of this multi-authored report are also gratefully acknowledged.

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EXECUTIVE SUMMARY

SCOPE OF THE EEG REPORT

The U.S. Environmental Protection Agency's (EPA) proposed rule to certify that the Waste Isolation Pilot Plant (WIPP) meets compliance with the long-term radiation protection standards for geologic repositories (40CFR191 Subparts B and C), is one of the most significant milestones to date for the WIPP project in particular, and for the nuclear waste issue in general. The Environmental Evaluation Group (EEG) has provided an independent technical oversight for the WIPP project since 1978, and is responsible for many improvements in the location, design, and testing of various aspects of the project, including participation in the development of the EPA standards since the early 1980s. The EEG reviewed the development of documentation for assessing the WIPP's compliance by the Sandia National Laboratories following the 1985 promulgation by EPA, and provided many written and verbal comments on various aspects of this effort, culminating in the overall review of the 1992 performance assessment (Lee, et al., 1994). For the U.S. Department of Energy's (DOE) compliance certification application (CCA), the EEG provided detailed comments on the draft CCA (Neill, et al., 1996) in March, 1996, and additional comments through unpublished letters in 1997 (included as Appendices 8.1 and 8.2 in this report). Since the October 30, 1997, publication of the EPA's proposed rule to certify WIPP, the EEG gave presentations on important issues to the EPA on December 10, 1997, and sent a December 31, 1997, letter with attachments, to clarify those issues (Appendix 8.3). The EEG also presented its views to the DOE and the EPA at a number of meetings during the course of the proposed rule development. Since the publication of the proposed rule, the EEG staff met with the EPA staff on 12/10/97, 1/22/98, and 1/26/98; and with the DOE technical staff and contractors on 1/21/98 (EPA/DOE meeting to which EEG was invited), and on 2/17/98 and 2/20/98.

CONCLUSION

The EEG understands and appreciates the large amount of work that the EPA staff and consultants have accomplished in a very short time, as did the DOE staff and consultants in preparing the CCA. However, the EEG has raised a number of questions that may have an impact on compliance. The impact of these questions on the compliance must be assessed or resolved through additional information, experimentation, or modeling. Unless these issues are satisfactorily resolved, the EPA should conduct another performance assessment calculation using the parameter values and models that are properly justified. EPA should base its compliance certification decision on the results of these new calculations. It is essential that this first repository's predicted behavior instill a high degree of public confidence.

Although the EPA standards require demonstration of compliance only for 10,000 years, some partial calculations performed by the EEG indicate that higher releases may be predicted beyond that period (see Sections 2.9.3 and 2.14.1 of this report). There is no strong justification for stopping the calculation at 10,000 years. The EEG recommends performance of representative calculations to assess the behavior of the repository beyond 10,000 years.

The WIPP repository, as planned, does not have sufficient multi-barrier protection which is a fundamental international design philosophy for a nuclear waste repository. The EEG

recommends EPA require DOE to examine the existing plans for processing and repackaging the waste at its weapons complex, and incorporate in the WIPP design at least those reprocessing and repackaging features which have been planned. This will provide at least some degree of multi-barrier assurance to WIPP.

GENERAL ISSUES

Lack of Feedback From EPA

In spite of the best efforts by the EEG, the EPA reaction to our reviews and suggestions has been slow and apparently driven by legal considerations. This is not a criticism of the EPA, but simply a statement of fact. For example, the EEG and the EPA staff met on June 17, 1997, to discuss the basis for the new parameter values that the EPA had recommended to the DOE for a new set of performance assessment validation test (PAVT) calculations. At this otherwise very productive meeting, the issue of actinide solubility assumptions could not be resolved because the EPA did not have its expert consultant at the meeting and the EPA could not share the technical support document with EEG until it was released as a part of the proposed rule in late October, 1997. When the EEG expressed continued disagreement on this issue with the EPA at the meetings in December, 1997 and January, 1998, the EPA asked EEG to wait until the final rule is promulgated in May, 1998, to get another explanation, rather than discussing the matter at those meetings with its experts. The EPA practice of not identifying the commenters in their responses and combining comments by various individuals and groups makes it further difficult to identify the response to our comments. The net result of this process is that there may be issues included in this report for which the EPA may have valid responses but those will not be available to the EEG until the final rule is promulgated.

Excessive Reliance on DOE

One general impression of the EPA's proposed rule is that the EPA relied heavily on the DOE submissions and rebuttals to reviewers' comments, and sufficient attention does not appear to have been paid to the comments by the reviewers. Serious technical questions with regard to the conceptual models, selected values of input parameters in the calculations, and interpretation of scientific experiments have been raised by the EEG, the National Academy of Sciences Committee on WIPP, the NEA/IAEA International Review Group, and several environmental groups. The proposed rule has, however, accepted the DOE viewpoint on most of the issues, sometimes without any questions, and others after minor clarifications. For example, the EEG has had a longstanding concern about the values used for the chemical retardation parameter, K_d, used in modeling radionuclide transport through the Culebra aquifer overlying the repository. The EEG and the DOE organized a one day meeting in Albuquerque on July 30, 1997, to discuss this issue. The EPA was invited and attended this meeting. Four weeks after the meeting, both the DOE and the EEG submitted letters to the EPA's WIPP docket about this issue. In discussing this issue, the EPA's proposed rule documents extensively discuss and quote from the DOE letter, but do not even acknowledge the existence of the EEG letter in the docket. To provide another example, the NEA/IAEA International Review Group raised a number of questions about the need to more carefully predict the physical and chemical implications of the magnesium oxide backfill. The EEG has questioned a number of assumptions about the repository conditions, which are based on insufficiently justified assumptions on the effect of MgO on the repository. But the EPA has accepted the DOE assumptions without providing sufficient reasons to not

address the NEA/IAEA International Review Group and the EEG questions and recommendations.

Apparent Neglect of Uncertainties

Another disturbing aspect of the EPA's proposed rule is the confidence that has been expressed for assumptions that are clearly based on a number of uncertainties. For example, the EPA has rejected the EEG's suggestion for considering the "stuck pipe" and "gas erosion" scenarios for calculating releases, by the argument that the waste permeability may be as low as 5.3×10^{-15} m^2, but will not be 1×10^{-16} m^2. A value of 1×10^{-16} m^2 is used in the Compliance Certification Application (CCA) as the upper limit for which the stuck pipe/gas erosion process should be considered, but it was based on the rejected spallings code. It is a well established fact that the permeability of the waste is a highly variable and uncertain parameter due to the highly heterogeneous nature of the waste. In fact, the OECD/IAEA International Review Group felt strongly enough about the heterogeneity issue that they included it as one of the two main issues in the cover letter forwarding the report to the DOE.

Increasing Unwarranted Uncertainty Assumptions

On some issues where there is a reasonable data base to make certain straightforward assumptions, the EPA has chosen to widen the margin of uncertainty in the calculations. A case in point is the probability of a future borehole encountering a brine reservoir in the upper Castile Formation underlying the repository. Based on the number of boreholes drilled versus those that reported encountering brine in the northern Delaware Basin, the DOE suggested a probability of 8%in the CCA. The EEG argued that since the borehole WIPP-12 at the WIPP site encountered brine and was extensively tested and was estimated to contain 700 million gallons of brine, any borehole drilled at the repository should be assumed to encounter brine. The EPA argued that the geophysical survey at the site indicates that up to 60% of the area under the repository may be underlain by brine, but then used a range of probability of 1% to 60% in the new PAVT calculations. The EEG sees no justification for this arbitrary spread of the probability range. To argue that this parameter does not make a difference in the calculated releases avoids the question, rather than answer it.

Use of Partial Sensitivity Analyses

It is a known fact that in a probabilistic consequence analysis with a large number of variables, the calculations are sensitive to a large number of parameters. There is doubtless varying degree of sensitivity of calculations to various parameters, but the rational way to get the most reliable results is to determine the value of each parameter as accurately as possible, and then run the calculations. The EPA has, on the other hand, argued that when a parameter value used in the CCA is not otherwise justified, but the compliance is still met with a new value, then the CCA value is "adequate". For example, changing the assumed brine volume of a Castile brine reservoir from 160,000 cubic meters (in the CCA) to 17 million cubic meters (in the PAVT calculation) had a noticeable effect on releases, but the compliance with the standards was still met. However, "EPA believes that the PAVT verifies that the original CCA Castile brine reservoir parameters were adequate for use in PA and comparison against the radioactive waste containment requirements." (U.S. EPA, 1997c, p. 58800). The EEG strongly rejects this argument because there are many other parameter values and conceptual and numerical models that should be

changed unless acceptable justification can be provided for the assumptions in the CCA and the proposed rule; and these changes will change the outcome of calculations. To declare an assumed value that is not otherwise justified "adequate" on the basis of limited changes in other values is, at the least, premature. There is no rational basis for finding an unjustified value to be acceptable unless it is justified based on observations, experiments, or widely known facts.

Faulty Sampling Ranges

The CCA appears to have argued in some cases that if the sampled distribution of a parameter used in the CCA calculations is in error, but includes the likely values of that parameter, then the CCA calculations are acceptable. The EEG disagrees with this approach. Under these conditions, the CCA calculations should be repeated with the best estimate of the parameter distributions available. The use of a faulty distribution of one parameter biases the Complementary Cumulative Distribution Function (CCDF) curves and confuses the assessment of uncertainty. The use of more that one faulty parameter set makes the assessment of uncertainties impossible because of the complex non-linear nature of the performance assessment models. This issue is discussed further in the Section "Faulty Sampling Ranges" in Appendix 8.2 of this report.

Insufficient Scrutiny for DOE Submissions

In many instances, the EPA appears to have accepted the DOE arguments without sufficient independent scrutiny. For example, the EPA agrees with the DOE's assessment that the borehole ERDA-9, which is located in the underground development area and connects the upper Castile Formation with the ground surface, is not significant to the repository's performance assessment and may be "screened out" of consideration. The basis of this concurrence with the DOE is that, "ERDA-9 did not penetrate an area that will become a waste panel and DOE has indicated that abandoned boreholes more than a meter away from the waste can be screened out of PA due to low consequence." (U.S. EPA Proposed Rule, Federal Register, vol. 62, no. 210, p. 58801). The EPA apparently did not investigate that the basis of the 1 meter criterion is the assumed difference in permeability of the disturbed versus the undisturbed rock zone surrounding the excavations, which can be changed by assumptions of less drastic change or an intermediate transition zone. Also, the EEG has not been able to find a reference to the exact location of the ERDA-9 borehole *at the repository horizon.* It is common knowledge that the boreholes are never drilled completely vertical. In fact, a WIPP project borehole, H-19B4, drilled in 1995 to exacting specifications under the guidance of the Sandia National Laboratory hydrologists, deviated 9.5 meters (31 feet) in a vertical depth of 229 meters (752 feet); there was every reason for that test hole to be as vertical as possible. At that rate, a borehole may deviate 27 meters (89 feet) in 655 meters (2150 feet, the depth to the repository) depth. To dismiss the potential impact of ERDA-9 without asking these questions and without requiring any special plugging and sealing in this borehole is difficult to understand.

SPECIFIC ISSUES

The EEG agrees with a number of changes that the EPA required in conducting the PAVT calculations, but believes that another set of calculations needs to be performed with the changes outlined in the following paragraphs.

Solubility
The solubility of actinides is very important to calculating the releases from the repository. The CCA uses a model known as FMT to calculate these solubilities. EEG found that the model predicts differences for actinide sulfate solubilities that cannot be explained by chemistry, thus raising questions about the reliability of this model.

Rather than using an extensive plutonium data base, the FMT predictions relied on thermodynamic data for other elements and an oxidation state analog argument. EEG recommends that the calculations be performed using data for plutonium and the values for solubility and complex ion formation contained in the peer-reviewed data compilation by the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/ NEA).

EEG agrees with EPA's documentation of the shortcomings of the solubility uncertainty ranges advanced by DOE. However, EEG questions EPA's argument that the ranges are adequate. As noted by EPA, there is a lack of data to determine the uncertainty ranges for oxidation states IV and VI. EEG recommends that the uncertainty range needs to be determined with the appropriate plutonium data.

In the solubility calculations, the CCA inappropriately discounts the role of organic ligands on plutonium solubility by arguing that EDTA is the strongest complexing agent and there is not enough amount present in the inventory to make a difference. But citrate forms very strong complexes with actinides in the +4 oxidation state and very weak complexes with other cations. Thus, the solubility of a stable plutonium-citrate complex in individual waste containers needs to be calculated.

There are serious unanswered questions about the impact of magnesium oxide backfill on the solubility of the actinides. It is proposed that magnesium oxide will reduce the solubility of the actinides by controlling the pH. But, it is not known how long the early reaction product, nesquehonite, will persist. The FMT model calculates that the presence of nesquehonite drives the solubility of the +4 actinides, such as plutonium, higher than in the no backfill case. This requires further investigation.

Spallings
The CCA spallings model was rejected by the DOE's peer review after submission of the CCA, but a new coherent model and a computer code that calculates the projected releases has not been developed. The EEG finds the basis of accepting the predicted release volumes due to spallings as determined by the CCA to be both unnecessarily convoluted and faulty. Since this is a mechanism for the largest projected releases from the repository, it is essential that it is treated through defensible conceptual and numerical models.

Air Drilling
The air drilling scenario proposed by Dr. John Bredehoeft was rejected on the basis of regulation, despite records of such drilling in the Delaware Basin. Low probability and low consequence are also discussed in EPA's Air Drilling Analysis (U.S. EPA, 1998), and the scenario was ruled out again. However, the EEG does not believe that the issue has been resolved. Neither EPA nor

DOE examined drilling records in the Texas portion of the Delaware Basin. New developments in underbalanced drilling also inhibit a full understanding of the capabilities of this expanding technology. The EPA's analysis of low consequence, in which a spread sheet model was used, has serious shortcomings.

Fluid Injection

For fluid injection activities adjacent to the site, the EPA has accepted a "low consequence" argument based on a model that has not been verified with oil field water flood data, despite the availability of such data. EPA offers a "low probability" argument based on its expectations of fluid injection practices, although DOE maintains that the probability of future fluid injection practices would be difficult to define. The low probability argument has not been reconciled with the common observation of water flowing through the Salado Formation in water flood operations throughout southeast New Mexico. Neither the DOE nor the EPA have adequately addressed concerns about future CO_2 flooding in the vicinity of WIPP. The basis for dismissing the Rhodes -Yates incident does not reflect a review of the technical information presented in that case. DOE has not explained the anomalous water level rises that have been observed for the last ten years in the Culebra aquifer despite the documented concerns of EEG, EPA and the National Academy of Sciences (NAS) WIPP Committee. EEG recommends additional effort to explain the Rhodes-Yates water flooding incident, if the most obvious explanation of flow of large quntities of water through the Salado interbeds is not acceptable to the EPA and the DOE. The fluid injection scenario cannot be dismissed either on the basis of low consequence or low probability.

Anhydrite Fracturing

The EEG has reviewed the basis of the anhydrite fracture model used in the BRAGFLO code and has a number of questions about its validity. The model is unusual in that the effect of fracturing is treated using an equivalent porous medium. All the relevant literature examined by EEG treat fractures as distinct porosity. Use of an equivalent porous medium is not in itself unreasonable. However, the DOE has not referenced, nor has the EEG been able to find, a description of similar treatment of the dependance of porosity and permeability on pressure as a result of fracturing. The lack of a clear development of the BRAGFLO model from established models makes its review difficult. The EPA should request that the anhydrite fracture model of BRAGFLO be compared to the treatment of fracture development in hydrofracing codes commonly used in the industry. Until the model and its assumptions are properly justified, the EEG finds it difficult to accept the results derived from this model.

Solution Mining

EPA's conclusion that potash solution mining is not likely at WIPP relies on solicited comments that are factually incorrect and inconsistent with the published scientific literature. DOE and EPA maintain that excavation mining captures the effects of solution mining on the hydraulic conductivity of the overlying aquifers. However, based on the scientific literature, the prediction of subsidence above solution mines can be much more complex than the prediction of subsidence due to excavation mining. It appears to be incorrect to calculate a probability of mining based on past potash production, which was inherently dependent on past mineral economics and the availability of high grade ore. Potash is used by the fertilizer industry and is ultimately used for the production of food. It seems reasonable to assume that the demand for food will continue and

low grade potash ores will eventually be mined to meet this demand.

Groundwater Flow and Radionuclide Transport Through the Culebra

A number of questions related to the flow and transport through the Culebra have been identified by the EEG and the National academy of Sciences WIPP Committee that have not been addressed by the EPA. These questions relate to the conceptual models of the origin and flow of water in the Culebra aquifer, modeling of transport through the Culebra, and the justification of the assumed values of the chemical retardation parameter (K_d) in the CCA calculations.

BRAGFLO 2D/3D Modeling

The results of the DOE 's screening analysis for repository processes (FEP S-1) suggest that the two dimensional BRAGFLO model used in the CCA calculations may be misrepresenting repository performance at pressures above the anhydrite fracture pressure. There is the potential of substantially greater brine saturation in the repository at higher pressures than calculated for the CCA. The discrepancy between the 2D and 3D versions of BRAGFLO may have resulted in an underestimate of radionuclide releases to the surface. To resolve this issue, the EEG recommended that several 3D BRAGFLO simulations of the repository should be performed using the parameter values of vectors used in the CCA performance assessment. The 3D BRAGFLO simulations should be used to provide repository conditions for the normal suite of direct brine release calculations. The calculations should also be assessed in terms of impact on spallings calculations.

The DOE and the EEG held a meeting on February 17, 1998, to try to resolve this issue. It was agreed at that meeting that there was sufficient reason to further investigate the potential for greater brine inflow to the repository using 3D modeling compared to the calculated value using the 2D model of the CCA. It was agreed that a simulation corresponding to a parameter vector that led to high pressure and anhydrite fracturing in the CCA calculations will be sufficient to demonstrate the potentially increased brine inflow in comparison to the CCA calculation.

Brine Reservoirs

The EEG raised a number of issues related to the Castile Formation brine reservoirs in commenting on the CCA. The EPA has accepted all of the EEG suggestions except the one related to the assumption of the probability of encounter of brine reservoirs, and we disagree with the EPA on this issue. The CCA assumed 8% probability on the basis of faulty assumptions. The EEG recommended 100% probability on the basis that the WIPP-12 brine reservoir was large enough to most likely extend under the repository, a conclusion also confirmed by geophysical testing directly above the repository. The EPA has sampled on a range of 1 to 60%, but has provided no basis for assuming less than 60%. Based on the arguments that the geophysical (Time-domain electro-magnetic survey) data may be interpreted to indicate the brine to be under 60% of the repository, and that some boreholes adjacent to the brine producing boreholes are known to be dry, the EEG is willing to accept the assumption of a fixed 60% probability of encounter, and recommends that a new performance assessment calculation be run with this fixed value.

Waste Issues

DOE calculations showed that non-random emplacement of radionuclides in the repository led to significantly higher releases from cuttings and cavings and spallings. EEG believes that releases from Direct Brine Releases will also increase. Revised calculations should be incorporated into the CCDF even though partial sensitivity analyses indicate that non-random emplacement would not, by itself, result in non-compliance.

The expected quantity of cellulosics, rubber, and plastics (CRP) in the repository is slightly greater than the waste repository limit. The ability to characterize CRP waste with sufficient accuracy has not been shown. Also, EEG believes the limit should be controlled on a per panel basis rather than for the entire repository.

Assurance Requirements

There are six assurance requirements in the EPA standards (40 CFR 191) which were incorporated to provide additional confidence in the repository, because of the inherent uncertainty in projecting the future behavior of natural systems and inadvertent human action. The EEG agrees with the EPA determination of two of these six requirements, the active and the passive institutional controls, but has questions about the other four. The monitoring plan does not appear to meet the intent of the standards. DOE's retrieval plan and the EPA's determination of its compliance with the requirement appear to give a false sense of security regarding the retrievability of waste. WIPP does not appear to meet the intent of the resource disincentive requirement, and this is an additional reason for EEG to argue that additional engineered barriers should be incorporated in the WIPP design for making the waste less respirable and soluble through treatment and repackaging. Since DOE has plans to treat or repackage 85% of the existing contact handled TRU waste anyway, this recommendation should be easy to implement.

Individual Protection Requirements

Although EEG has minor disagreements about several assumptions used by DOE in evaluating the Individual Dose Requirements, we agree that compliance with these requirements has been demonstrated.

Environmental Standards for Ground-Water Protection

EEG believes there is a very low probability of significant contamination of an Underground Source of Drinking Water (USDW) by an undisturbed release. However, 40 CFR 191.24 specifies that no contamination is permitted if the USDW is initially at or above the radionuclide limits of 40 CFR 141. No documentation of current radionuclide concentrations in the USDWs has been provided. EPA needs to require submission of data showing the USDWs are below allowed limits or that there is a zero probability of any contamination reaching the USDW.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Project is a planned geologic repository for disposal of transuranic (TRU) waste, generated from the nuclear defense programs of the USA since 1970. The repository is located at a depth of 655 meters in the Permian age salt beds of the Salado Formation in southeastern New Mexico, 40 km east of Carlsbad, NM. Since 1978, the Environmental Evaluation Group (EEG) has evaluated various technical aspects of the WIPP project that relate to the impact on the public health and the environment of New Mexico. A list of published reports appears at the end of this report. The U.S. Department of Energy (DOE) is responsible for the management of defense TRU waste as part of the U.S. defense nuclear complex following its predecessor agencies, the U.S. Atomic Energy Commission (AEC) and the Energy Research and Development Authority (ERDA). Before 1970, such waste was buried in shallow pits at several national laboratories. DOE plans to ship only the post-1970 TRU waste to WIPP, that has been stored in above-ground tension-support structures at the national laboratories.

The TRU waste inventory currently in retrievable storage at the DOE sites totals about 104,000 cubic meters including 27,000 m^3 of alpha emitting low level waste scheduled for processing, or the rough equivalent of half a million 55-gallon drums (U.S. DOE, 1995b). The WIPP has been designed to contain up to 168,500 cubic meters (approximately 810,000 drum-equivalent) of contact-handled (CH-TRU), and up to 7100 cubic meters (7500 canisters) of remote-handled (RH-TRU) waste. The CH-TRU waste may have a maximum surface-dose rate of 200 millirem per hour. Ninety-five percent of the RH-TRU canisters disposed at WIPP may have a surface dose-rate of a maximum of 100 rem per hour, and five percent by volume may have a maximum of 1000 rem per hour. The TRU waste generated in the future will come from dismantling and cleanup of the nuclear weapons complex and may be different than the existing waste.

Excavation of the WIPP repository began in 1982 and all the surface facilities, four shafts, and all the basic underground facilities, including 1/8 of the repository “rooms”, had been excavated by 1988,

the year when the DOE had planned to start placing waste in the repository for experiments and operational demonstration. The DOE abandoned this plan in 1993 because there was insufficient justification for conducting the *in situ* experiments with waste and it would have been difficult to ensure retrieval of the waste after several years of emplacement.

The decision to use the WIPP repository for permanent disposal of TRU waste will be made, in large part, on demonstration of the facility's compliance with the long-term disposal standards for TRU waste promulgated by the Environmental Protection Agency (EPA) (U.S. EPA, 1993). These standards require a probabilistic assessment of the integrity of the repository for 10,000 years into the future. Such an assessment requires a detailed knowledge of the geological and hydrological characteristics of the site, physical and chemical characteristics of the waste, formulation of scenarios for breach of the repository and release of radionuclides to the environment, calculation of the probabilities and the amounts of release during the future 10,000 years, and comparison with the releases allowed by the standards. The compliance with the standards is to be judged on the basis of a set of criteria promulgated by the EPA (U.S. EPA, 1996).

EEG has participated in the development of the EPA standards for safe disposal of TRU and High Level Waste (40 CFR 191) beginning in the early 1980's, including reviews of various drafts of the EPA standards, testimony at the EPA Science Advisory Committee Meetings, EPRI workshops, NAS Board on Radioactive Waste Management Workshops, and Congressional Committees. Detailed reviews were provided during the development of the standards, the criteria (40 CFR 194) to implement them, and the Compliance Application Guidance document.

The DOE published a Draft Compliance Certification Application (DCCA) for WIPP in October 1995. The EEG reviewed this document and published detailed comments on it in March 1996 (Neill, et al., 1996). The DOE submitted its Compliance Certification Application (CCA) to the EPA in October 1996 (U.S. DOE, 1996c). The EEG submitted the previously published comments (Neill et al., 1996) on the DCCA to the EPA since the DOE had not provided responses to those and had not indicated how the final application (CCA) had been modified as a result of the EEG comments.

EEG provided additional comments on the specific issues in the CCA as attachments to the EEG letters dated February 7, 1997, and March 14, 1997. Copies of these letters with attachments are included in this report as Appendices 8.1 and 8.2 respectively.

Many meetings were held between the DOE and the EPA to discuss various technical issues both before and after the submission of the CCA in October 1996. The EEG started receiving invitations to these meetings after April 1997.

The EPA issued a Proposed Rule (U.S. EPA, 1997c) in October 1997 proposing to certify that the WIPP meets the EPA standards, and opened a four month period for public comments on the Proposed Rule. At the request of EPA, the EEG staff provided the initial EEG reaction to the EPA decision through technical presentations at a meeting on December 10, 1997, in Albuquerque, and followed with a letter dated December 31, 1997, with attachments. A copy of this letter with the attachments is included in Appendix 8.3. The present report contains the EEG's final comments on the EPA's proposed rule.

This report is organized according to the four "requirements" of the EPA Standards (U.S. EPA, 1993), viz., the containment requirements (40 CFR 191.13), the assurance requirements (40 CFR 191.14), the individual protection requirements (40 CFR 191.15), and the environmental standards for ground-water protection (40 CFR 191 Subpart C). The bulk of the DOE application and the EPA's proposed rule deal with compliance with the containment requirements. The bulk of this report, therefore, also consists of the issues associated with demonstrating compliance with the containment requirements. Rather than providing a critique of the EPA proposed rule chapter by chapter, or page by page, the EEG has adopted the approach of discussing what appear to us to be the most significant issues affecting determination of compliance. The issues relate either to a lack or inadequacy of justification of the conceptual models, parameter values, or computer models, that have been used to compute projected releases of radionuclides to the accessible environment, or insufficient basis for not considering certain scenarios for release. Attempt has been made to describe our concerns as clearly and explicitly as possible with suggestions for ways to resolve the issues.

The Environmental Evaluation Group (EEG) was established by the State of New Mexico in 1978 as an independent scientific group to conduct a scientific evaluation of the WIPP project's impact on the public health and environment of New Mexico. In addition to the reviews of long-term and operational-period safety, EEG has conducted environmental monitoring of air, water and soil at the WIPP site and in the surrounding communities since 1984 to establish a pre-operational environmental baseline against which future suspected contamination episodes may be evaluated. This multi-disciplinary group, with offices in Albuquerque and Carlsbad, is funded totally with federal money by Congressional mandate through the DOE. The EEG continues to influence shaping the project to ensure that the public health and safety of the people of New Mexico is not jeopardized and the environment is not adversely affected. The effect of the EEG's work can be seen, for example, in (1) vastly improved geological and hydrological data base and modeling; (2) relocation of the repository to a more suitable area with respect to long-term integrity; (3) safer operational design and procedures; (4) abandonment of the plans to conduct *in situ* experiments with waste at WIPP; (5) continuation of performance assessment work after the disposal standards were vacated by the court in 1986, thus not losing time when the standards were re-promulgated in 1993; and (6) a much safer and more cost-effective redesigned transport container (TRUPACT-II) for the CH-TRU waste shipment certified by the Nuclear Regulatory Commission.

2.0 CONTAINMENT REQUIREMENTS

2.1 SITE CHARACTERIZATION ISSUES

There are a number of issues concerning the understanding of the geological and hydrological setting and processes at the WIPP site that have been debated since the site characterization at the Los Medanos site began in 1974. Some of these issues, such as the characteristics of the brine reservoirs in the Castile Formation and the probability of their encounter, are directly related to the numerical assessments of compliance and are discussed at length as separate sections in this chapter. Other issues, such as the extent of the effect of Karst processes at the WIPP site and the anomalous water-level rises in a number of boreholes, may have an impact on numerical assessments but the DOE claims that they do not and the EPA has accepted that assertion. There is a third set of site characterization issues which do not appear to have a direct impact on the numerical assessments as framed by the CCA, but relate to the credibility of understanding of the geological and hydrological processes operating at present and how that understanding is used to understand the past evolution and future predictions. In this third category, one may include the issues of recharge and discharge of groundwater, location of water table, the extent and rate of basin-wide dissolution processes, etc. Issues falling in all three categories are discussed in this section. To keep the discussion brief and easy to read, references to previously published reports and papers are frequently made, and only summary statements are provided here.

Chaturvedi (1993) provides the most up to date summary of the EEG's evaluation of these issues, and this paper is included in this report as Appendix 8.5. These issues are discussed by the EPA in the Technical Support Document for Section 194.14 (U.S. EPA, 1997g), CARD 14 (U.S. EPA, 1997b), and the proposed rule itself as published in the Federal Register on October 30, 1997 (U.S. EPA, 1997c).

2.1.1 History of Site Characterization Efforts

Before discussing the specific issues, a brief history of the site characterization efforts for WIPP may be helpful in putting these issues in perspective. Following the abandonment of the Lyons, Kansas site in 1972, a 3.2 km by 2.4 km (2 mile by 1.5 mile) site was selected by the Oak Ridge National Laboratory on behalf of the then Atomic Energy Commission, 11 km northeast of the present 6.4 km by 6.4 km (4 mile by 4 mile) WIPP site. Cores from two boreholes (AEC-7 and AEC-8, Fig. 1) penetrating through the Salado Formation drilled at the northeast and the southwest corners of that site indicated acceptable geology. Sandia National Laboratories (SNL) was given the responsibility for site characterization of WIPP in 1975. A third borehole (ERDA-6; see Fig. 1) drilled by SNL at that site in 1975 encountered a pressurized brine reservoir and intense structural disturbance in the fractured upper anhydrite of the Castile Formation at a depth of 826 m (2709 ft). As a result, the location of the repository was moved to the present site.

The DOE had declared the WIPP site to have been adequately characterized in 1981 on the basis of the Geological Characterization Report (Powers, et al., 1978) and the Environmental Impact Statement (U.S. DOE, 1980). The EEG recommended additional field and laboratory studies to resolve several geological and hydrological questions based on the consensus reached at a scientific conference organized by the EEG in January 1980 and a 3 day field conference at the site in June 1980 (Chaturvedi, 1980). These recommendations were included in a stipulated agreement between the DOE and the State of New Mexico signed in 1981 as part of the settlement of a lawsuit filed by the State Attorney General. One of the EEG recommendations was to deepen the borehole WIPP-12 which had been drilled through the Salado Formation in 1978 to a total depth of 845.6 meters (2773.6 ft), only 14.7 meters (48.3 ft) below the Salado/Castile boundary in to the Castile Formation, but was completed only to the base of the Salado at 834.5 meters (2737.5 ft). Two (N-S and E-W) seismic reflection profiles crossing at the WIPP-12 indicated anticlinal structure at the depth of the Castile Formation at this location, and the EEG suspected the presence of a Castile brine reservoir at this site. The borehole was deepened from its 845.6 meters (2773.6 ft) depth to a total depth of 1197.4 meters (3927.5 ft) in November-December 1981. Pressurized brine associated with hydrogen sulfide gas was encountered at 919.5 meters (93016 ft), only 74 meters (242.4 ft) below the original depth of the

borehole. The EEG recommended relocation of the repository, because according to the plans at that time, the repository was in the northern part of the underground area to be excavated and the edge of the repository would have been only 170 meters (558 ft) south of WIPP-12. The DOE agreed to rotate the repository design so that the experimental area is now located north of the center of the site, and the repository to the south.

The DOE presented the results of the additional studies to the EEG during 1982 and 1983 (EEG, 1983). The EEG published its evaluation of the suitability of the WIPP site in 1983 (Neill et al., 1983) and expressed confidence in the site but also concluded that additional work was needed for assessing compliance with the long-term standards that were in the process of being developed

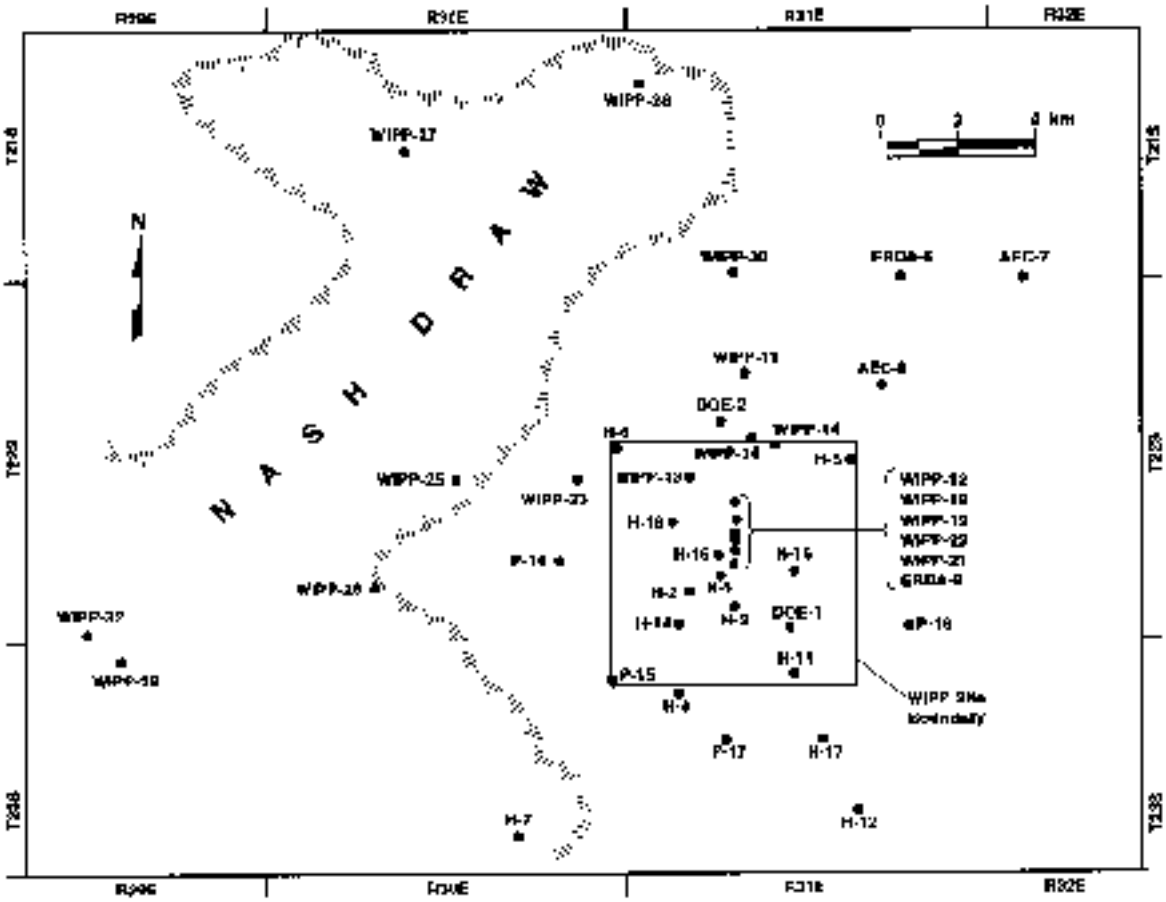

Fig. 1. Location of WIPP Boreholes

by EPA at that time. These additional recommendations related to (a) identifying the extent of the underground brine reservoir in the Castile Formation that had been encountered by the borehole WIPP-12, (b) to address and try to resolve controversial geological issues such as deep dissolution in the Salado Formation and the formation and occurrence of breccia pipes, and (c) to better define the hydrological and radionuclide transport characteristics of the Rustler Formation with its two aquifers. Field and analytical studies conducted since 1983 have answered many of the questions and brought others closer to resolution. Additional specific questions developed as the performance assessment process started in 1986. The EEG has continuously been involved in attempting to resolve these questions.

2.1.2 Deep Dissolution

The EEG agrees with the EPA's conclusion that deep dissolution of the Salado Formation salt is not likely to be a threat to the WIPP repository. A history of the efforts made by the EEG, Sandia National Laboratories, and the DOE to resolve this issue is found under the heading "Dissolution of Salado Salt" in Chaturvedi (1993), Appendix 8.5 of this report.

2.1.3 Karst Processes at the WIPP Site

The WIPP site is located in a karst region and the topography to the west and south of the site is developed in response to the karst processes. However, no sinkholes have been identified at the WIPP site proper and extensive hydrological testing, including several multi-well flow tests at the site, have not encountered karst channels of significantly anomalous transmissivity. Multi-well flow tests have, however, given indications of north-south trending preferential flow paths in the northwestern and the southwestern parts of the WIPP site. The well WIPP-30 (Fig. 1) is located 5.6 km (3.5 miles) NNE of the well WIPP-13, but showed a significant drawdown starting only a few hours after pumping at WIPP-13 began (Beauheim, 1987). This observed drawdown in response to pumping WIPP-13 was higher than at several boreholes closer to WIPP-13, indicating a NNE trending high transmissivity connection between WIPP-13 and WIPP-30. Similarly, the rapid and high magnitude responses observed in wells DOE-1, H-3, and H-15, as a result of pumping in H-11 (Beauheim, 1989) are believed to reflect the presence of a fracture network extending to the north and northwest from

H-11 (see Fig. 1). While these high transmissivity zones are taken into account in the modeling of flow through the Rustler, there are remaining questions that have been raised by Leonard Konikow of the NAS WIPP Committee, and David Snow, regarding the nature of flow and transport through the Culebra, particular in the region directly above the repository, that have not been satisfactorily addressed in the proposed rule.

In summary, with respect to the karst question, while the EEG agrees that karst channels and sinkholes have not been found in the WIPP area east of the sink hole in which WIPP-33 (see Fig. 1) was drilled, we are less certain than the EPA about rejecting the possible effects of this phenomenon now and in the future. The EPA has concluded, "karst is not a problem at WIPP and that geologic evidence of the last approximately 500,000 years and results from DOE's groundwater modeling indicate that future development of karst at the WIPP is not likely." (U.S. EPA, 1997c, p. 58799). The EEG view is that while the effects of karst processes have not been identified at the WIPP site proper, the site is located in a karst region. Therefore, in considering the flow and transport through the Culebra, allowance should be made of this fact and the conceptual models, parameter values, and numerical modeling should be conducted with relatively conservative assumptions. A discussion of the issues of flow and transport through the Culebra is presented in Section 2.9 of this report.

2.1.4 Dewey Lake Redbeds Hydrology

The hydrology of the Dewey Lake Redbeds (DLR) and the overlying Santa Rosa Formation has not been adequately considered in the CCA. The CCA rejected consideration of transport through the DLR on the basis of the DOE assumption that "chemical retardation occurring in the Dewey Lake will prevent release within 10,000 years of any actinides that might enter it." (U.S. DOE, 1996c, p. 6-149). This decision is based on an analysis conducted by Wallace et al. (1995), who assumed the K_d values for the DLR for different radionuclides on the basis of "literature search for sand/sandy soil in saline waters". No K_d values have been obtained on the DLR rock, in situ or in the laboratory, and the reported values from the literature search are meaningless because they were conducted on a variety of soils under a variety of conditions unrelated to the DLR Formation. This fact is obvious from the extremely wide range of reported values; e.g., Table NS1-A3 of Wallace et al. (1995)

reports K_d of 100 to 100,000 mL/g for Plutonium. The EEG therefore rejects the CCA assertion about the contaminant transport through the DLR.

The EPA has advanced an additional argument for not considering DLR as a transport pathway. The proposed rule (U.S. EPA, 1997c, p. 58799) states: "the CCA PA results indicated that no contaminated brine traveled up an intrusion borehole past the Culebra to the Dewey Lake or other units." It is common knowledge that the postulated rise of contaminated brine up an intrusion borehole is based on the assumptions made in conducting the performance assessment rather than any specific inherent property of the system. This EPA assertion for not considering contaminant transport through the DLR is therefore also without basis.

The DOE has conducted hydrological tests in the Dewey Lake Redbeds and the Santa Rosa Formation in 1997 after the submission of the CCA to investigate the source of water leaking in the WIPP exhaust shaft. These tests, conducted at the center part of the site overlying the repository, show that water in the lower Santa Rosa/Upper Dewey Lake Formations is more prolific than believed before (Duke Engineering Services, 1997). The results of these tests and the surprising encounter of water in the DLR in the borehole WQSP 6 and 6a at the site indicates that more surprises may be in store with respect to the hydrology of this Formation. The WQSP 6a produced 12 gallons per minute water of relatively good quality (4,000 mg/L). The EEG recommends a thorough re-examination of the Dewy Lake Redbeds issue.

The NAS WIPP Committee (NRC, 1996) concurs with the EEG view on this issue:

> In the Committee's opinion, releases to the Dewey Lake cannot be discounted summarily; if a borehole to the Salado or to the Castile Formation were to connect these formations to brine at a pressure near lithostatic, then the hydraulic gradient (driving Darcy flow) would be sufficient to enable leakage into both the Culebra and the Dewey Lake if a pathway to either formation were to exist. (NRC, 1996, p. 74).

The NEA/IAEA International Review Group (NEA/IAEA, 1997) also expressed a similar opinion on this subject:

> The IRG considers that, from a dose perspective, greater attention could be given to considering whether any credible scenarios exist in which contaminants might reach these potable or nearly potable resources, under present day and alternative climate conditions.

2.1.5 Rustler Formation Geology and Hydrology

The EEG continues to disagree with several aspects of the CCA conceptualization of the past history of the Rustler Formation, that EPA has accepted without sufficient critical examination of the evidence for alternative conceptual models. These issues are briefly discussed below with references to the EEG reports and papers where more details can be found.

2.1.5.1 Pattern of Rustler Salt

The EEG has shown (Chaturvedi and Channell, 1985; Lowenstein, 1987) that the pattern of occurrence of salt in the Rustler Formation can be more rationally explained by the hypothesis of post-dissolution salt removal as first proposed by Snyder (1985), rather than the Holt and Powers (1988) and Powers and Holt (1990) hypothesis of original deposition. Based on a detailed sedimentological study of the Culebra cores from a number of wells at the WIPP site, Lowenstein (1987) interpreted four distinct dissolution zones in the Rustler Formation.

2.1.5.2 Origin of Rustler Fracturing

The pattern of fracture distribution and corresponding transmissivity values distribution in the Culebra is too complex to be explained away in a simple statement like "density of open fractures in the Culebra decreases to the east", and as expected, has become more complex with additional data acquisition.

The respective thicknesses of the Rustler and the upper Salado (Chaturvedi and Channell, 1985, Fig. 8, p. 23) call into question the Beauheim and Holt (1990) proposition that dissolution of the upper

portion of the Salado Formation may have caused subsidence and fracturing in the Culebra. The Rustler Formation is 137 meters (450 ft) thick four miles east of the center of the WIPP site and only 90 meters (300 ft) thick from the center of the site westward. The upper Salado (from the top of the Salado to Marker Bed 103), on the other hand, maintains a uniform thickness of about 58 meters (190 ft) over the WIPP site and only decreases in thickness west of the Salado dissolution front that coincides with the western margin of the WIPP site. It would be more logical to postulate the gradational removal of salt from the Rustler Formation itself to have caused fracturing in the Culebra over the WIPP site. West of the Salado dissolution front (west of the WIPP site), both the Salado and the Rustler have been affected, grading into total collapse in the Nash Draw.

If the high transmissivity zone in the southeastern part of the WIPP site is related to the dissolution of gypsum fillings in the Culebra fractures, then the high transmissivity zone may extend to the south-central part of the WIPP site.

2.1.5.3 Age of Rustler Water

The EEG has never accepted the bases for the assumption of the Rustler water being "fossil" water, having been recharged under climatic conditions significantly different from the present. Since the EPA has accepted this hypothesis as postulated by the DOE, it is important to state the reasons in detail for the EEG believing that the Rustler water is a mixture of "old" and "new" water, including modern day meteoric recharge.

2.1.5.3.1 Hydrogen and Oxygen Isotopes in Groundwater

The EEG (Chapman, 1986) compiled stable isotope data from throughout southeastern New Mexico and compared them to data from the WIPP area. The stable isotopic compositions of most samples of groundwater from the Rustler Formation were found to be similar to the composition of other, verifiably young, groundwater in the area. Though the stable isotope data cannot indicate ages for water in the various aquifers, neither did the data show any distinction between most Rustler groundwater and verifiably young groundwater. A small number of samples, primarily from the Rustler/Salado contact east of Nash Draw, had isotopic compositions that are not characteristic of

recently recharged meteoric water. These waters' enrichment in heavy isotopes may be due to mixing with deeper groundwater (supported by the stable isotopic composition of Salado fluid inclusions and Castile brine) or to exchange between the groundwater and hydrous minerals.

A comparison of the heavy isotope enrichment observed in evaporating waters and the composition of the water at WIPP-29 and the Surprise Spring showed that the isotopic composition of these Nash Draw waters could be derived by evaporating Rustler groundwater. Based on stable isotopes, both WIPP-29 and Surprise Spring could be discharge areas for Rustler groundwater moving from elsewhere in Nash Draw and the east.

The enrichment in heavy isotopes found in the water from pools in the Carlsbad Caverns was used by Lambert (1987b) as evidence that the relatively depleted Rustler water was recharged during a past, more pluvial, time. However, the uniqueness of the isotopic composition of water in the Caverns' pools suggests that rather than representing the composition of recent recharge, the heavy isotopes are enriched by evaporation and equilibrium isotope exchange in the humid cave environment. Recharge in the extreme karst environment near the cavern may also favor isotopically heavy precipitation. Therefore, the EEG suspects the interpretations from the Lambert (1987b) study regarding the age of Rustler water.

2.1.5.3.2 Radiocarbon Ages of Groundwater

The radiogenic age statement in section 2.2.1.4.1.2 of the CCA is based on Lambert (1987a). This report was reviewed for EEG by Dr. Fred Phillips of the New Mexico Institute of Mining and Technology in 1987 who found the conclusions of the report to be unacceptable for reasons described below.

While it is true that all of the samples (excluding H-5C, which may possibly be contaminated) are probably in the age range 10,000 to 16,500 years B.P., the ages of the water samples vary in a systematic fashion from youngest (10,000 years) in the north to oldest (16,500 years) in the south (with the exception of H-5, which is clearly on a different flow path than the other ^{14}C sampling

wells). This corresponds to the pattern expected from the north-to-south flow direction inferred from the physical hydrology. Thus a more reasonable interpretation of the ^{14}C age distribution is that only a segment has been sampled in the middle of a large-scale flow system. Additional ^{14}C samples to the north and/or east might well yield Holocene ^{14}C ages. Also, well H-5, although it may be contaminated, may also indicate active recharge.

The major conclusion of the report (Lambert, 1987a, p. 5-10 and 81) was, "Because of the questionable validity of the assumptions necessary in applying radiocarbon and radiochlorine dating methods in the evaporite environment of southeastern New Mexico, and because of the previously demonstrated susceptibility of these components to contamination in this groundwater system, these methods will not be pursued beyond this feasibility study." The EEG finds this conclusion to be unnecessary because good results have been obtained from uncontaminated wells. Ground-water systems are fundamentally not amenable to intensive sampling and thus in all ground-water investigations (whether physical or geochemical) assumptions regarding the system are necessary. Useful results can be obtained, even given a wide range in parameters assumed for the ^{14}C dating model. With a properly conducted field study of the system, the parameters could undoubtedly be constrained much more closely and much better refined dates obtained. Because interpreting WIPP site flow patterns by physical hydrology alone is very difficult and uncertain, and because ^{14}C tracing may hold the best hope of elucidating the flow system, the very negative viewpoint expressed by Lambert (1987a) is considered by the EEG to be totally unwarranted.

The contamination issue is even more clear cut. Certainly, it is true that a majority of the wells sampled during this study did not yield useful results due to contamination. One does not need to be an expert in ^{14}C to predict that wells crammed with "shredded paper, cottonseed hulls, peanut shells, and various proprietary organic additives" (Lambert, 1987a, Section 4.2.6) will not yield meaningful ^{14}C dates. There is very little logic in arguing that because wells deliberately injected with organic material were contaminated, all other wells must also be. Contrary to the statement by Lambert (1987a, p. 23), contamination during drilling is not "inescapable". The best evidence of this is that four of the wells drilled without organic circulation-loss additives did not show any sign of

contamination. There is no evidence that this groundwater system is unusually "susceptible" to contamination. Any system is susceptible to inappropriate drilling practices, and appropriate practices should yield acceptable results at the WIPP site.

Based on the data contained in Lambert (1987a), the EEG came to a different conclusion. In all cases, where ^{14}C could reasonably be expected to give useful results, it did so. Although there were only a limited number of uncontaminated samples, the geographic distribution of the resultant ages is hydrogeologically reasonable. The EEG advised the DOE not to abandon this potentially very informative avenue of investigation in 1987 and the EEG recommendation was incorporated in the 1988 modification to the DOE/State of New Mexico Consultation and Cooperation Agreement. However, the DOE did not pursue this investigation.

2.1.5.3.3 Uranium-Isotope Disequilibrium Data

The Lambert and Carter (1987) report was reviewed for the EEG by Dr. John Osmond in 1987. Dr. Osmond is the co-inventor of the Uranium-isotope Disequilibrium technique applied to the study of groundwater flow. Based on Dr. Osmond's review, the EEG provided comments on the Lambert and Carter (1987) report to the DOE through a letter dated 12/2/1987. The following is a summary of those comments.

The limitations of the application of uranium systematics to groundwater interpretations should be kept in mind:

1) one usually cannot deduce from the uranium data alone the **direction** of groundwater flow,
2) one usually cannot determine the **flow rate** of groundwater itself by the use of U-234 decay rates.

The same isotopic data can be used to model water flow in more than one direction. This is because changes in isotopic ratio can be caused either by true ageing (decay or growth of U-234) or by water-

rock or water-water interactions. Researchers in this field usually have independently derived information as to flow directions, which they can use to deduce the possibility of uranium leaching or the mixing of two or more groundwater sources.

Investigators can sometimes determine, in deep confined aquifers, the rate of movement of uranium in the system. The rate of flow of the water itself, however, must be inferred from one's estimate of the retardation factor for uranium in that particular aquifer.

That an aquifer is "confined" is usually an assumption of the modeling of slow-moving systems. Mixing with undefined waters, whether from recharge or other aquifers, negates any evolutionary conclusions. The authors of this report recognize the potential problem, but argue against leakage, perhaps too readily.

Finally, when uranium leaching or adsorption is inferred, it should be remembered that only the grain or fracture surfaces of the host rock are involved. The concentration of uranium on these surfaces can be much different than the concentration values of the whole rock.

Therefore, the principal conclusions of the report must be regarded as possibly overstated: 1) it is possible, but not proven, that the Rustler system can be modelled as a confined aquifer, 2) it is plausible that the flow regime has changed direction, but alternative interpretations based on a more steady-state model are readily visualized, and 3) although the inferred rate of movement of uranium through the aquifer near the site is probably about right, the flow rate of the water itself could be appreciably faster.

The basic pattern of occurrence of uranium isotopes in the Rustler ground water in the western half of the study area, as pointed out by the authors, is consistent with a two-source mixing model. These two end members could be water masses represented by H4 and W29, or by a water with very little U-238, but considerable excess U-234, that has leached to varying degrees uranium from the aquifer rock. The regression line on Fig. 15 implies that these two end members are leached uranium (infinite

concentration) with an atomic ratio of 1.55 and water of zero concentration of U-238 but carrying 13.4 ppb (U-238 equivalent) of U-234.

The authors make use of this pattern to make three different interpretations. Each interpretation is plausible to some degree, but taken together they are somewhat inconsistent.

The most logical has to do with a possible westward flow direction of water from the site toward Nash Draw. Low concentration water (with respect to U) gradually dissolves uranium with lower atomic ratio values. No information regarding flow rate derives from this model.

The least plausible interpretation assumes that the decrease in atomic ratio westward is the result of U-234 decay, which leads to deductions regarding low U movement rates (not necessarily low water flow rates). It is recognized by the investigators that such a model is suspect where uranium concentration values are increasing; leaching, if ignored, produces inferred flow rates which are too low.

The third interpretation is inconsistent with the first, so the authors postulate an earlier flow regime and ask as to why the atomic ratios are so high to the East. Such values depend on fractionation processes that often require time periods commensurate with the half-life of U-234, and therefore are nearly always down-flow. In this case, argue the investigators, the estimates of time are apt to be conservative because leaching would hold the atomic ratio values down.

In all of their modeling, the authors of this report display considerable knowledge and insight; they do not flagrantly misinterpret the data. Their assumptions are made clear. Nevertheless, one aspect of uranium isotope systematics in groundwater is neglected, and could affect their models. In any ancient system, uranium has been moving for much longer than the period of time being modeled. The distribution factor between dissolved and adsorbed uranium (related to retardation) means that any interactions between water and rock are probably independent of whole-rock uranium concentration values. It is the concentration of uranium on adsorption surfaces, rather than that

inside the rock particles, which determines how much fractionation occurs, and how fast relative to water movement. The concept of "reducing barrier" is often cited to explain concomitant decreases in U concentration and increases in atomic ratio over short distances.

The potentiometric contours of the Culebra suggest two flow lines in the study area: to the west, flow is more or less directly south; in the general area of the site, however, there appears to be an easterly flow in the north, a southeasterly flow at the site, and a southerly and westerly flow to the South.

If we postulate a general source area anywhere to the North, with the usual reducing barrier not far from the point of recharge, then all of the water would enter the area with a high atomic ratio and a low concentration. Water flowing southward in the west would dissolve uranium and take on the higher U and lower atomic ratio fingerprint. Water flowing in the east would move slower, dissolve less uranium, and have its atomic ratio altered only gradually with time. When the flow looped west, dissolving and "mixing" with rock-derived uranium would occur.

This scenario combines the three models proposed by Lambert and Carter (1987): mixing in the west and southwest, increasing atomic ratio due to recoil-type fractionation in the north, and decay of excess U-234 in the general area of the site. If this model has merit, we can deduce uranium movement rates in the aquifer near the site which are consistent with those values proposed by the investigators. Because of the retardation factor, the water flow rate could be higher.

All of these remarks concern the Culebra unit of the Rustler. There are not enough data from the other units to do any regional modeling. However, the fact that none of the atomic ratio values from above and below are as high as some from the Culebra suggests that the latter is the "tightest" with respect to uranium mobility.

Apparently the data regarding oxidation potential of the Culebra waters is inconclusive; and the same might be said about the other hydrologic and geochemical information that might be used to

demonstrate that the Culebra is truly confined. Uranium isotopic data has often been used as evidence in such interpretations. Most deep confined aquifer waters carry uranium at very low concentration levels, on the order of .1 to .001 ppb., and with quite high atomic ratio values, anywhere from 2 to 20 or more. The Culebra waters have higher uranium concentration than do truly reducing aquifers suggesting the possibility of leakage from shallower horizons. However, the fact that the isotopic data can be used to model flow in systematic ways suggests that such invasions are not the predominant process. Any such oxidative tendencies would favor interactive models (uranium leaching) over the fractionation and time-related models emphasized by Lambert and Carter (1987).

Regarding flow rates and groundwater residence time, Lambert and Carter (1987) consistently confuse *uranium* residence time with *groundwater* residence time. The data presented in the report do not allow for the calculation of groundwater ages. Even when the appropriate retardation factors and grain and fracture surface characteristics are known, there are still serious questions about applying uranium isotopic data to determine basic groundwater flow characteristics. Davis and Murphy (1987), Simpson et al (1985), and Hussain and Krishnaswami (1980) all express serious reservations about the reliability of uranium-disequilibrium dating because of the many difficult-to-substantiate assumptions involved.

The amount and reliability of the data are also questionable. Outside of Nash Draw, the authors have only four wells on which to base conclusions of changes in flow direction. It is important to consider the dual-porosity nature of the Culebra, indicated by the recent hydrologic testing. The very high activity ratios at H-4 and H-5 may be related to the low-transmissivity, matrix flow found at those wells. Conversely, the lower activity ratios at H-6 may be the result of rapid groundwater flow through fractures. More data east of Livingston Ridge, and from fracture-flow areas such as near H-11 and DOE-1 must be collected before any confidence can be placed in conclusions about flow paths.

Considering the serious questions of groundwater contamination in Nash Draw raised by Lambert

(1987a), there should be an in-depth discussion of the reliability of the presented analyses of a trace constituent like uranium. If contamination with organics is as pervasive in the Nash Draw wells as reported in SAND86-1054, this would very likely alter redox conditions near the wells. Oxidation-reduction potential is an important control on uranium content. Though the authors state on page 6 that the uranium values and isotope ratios have been perturbed at W-29 by wastewater dumping, they then proceed to use this value throughout the report, for instance as an important part of their argument for recharge in southwest Nash Draw.

As previously mentioned, redox conditions are an important factor in modeling uranium behavior. Field evidence (Eh values as reported in Uhland and Randall, 1986 and Uhland et al, 1987) and the relatively high uranium values both argue against reducing conditions in the Culebra. There is no evidence for the "reducing barrier" required by Lambert and Carter's model. The authors should provide some discussion of the physical requirements of the model relative to known aquifer characteristics.

The section on "Implications" for recharge, karst flow, and climate change presents insufficient discussion for reaching the presented conclusions on this broad topic. For instance, if no recharge is supposed to be occurring, there should be some discussion of what happens to rainfall. There is no integrated surface drainage, there are numerous gaps in the Mescalero caliche, and 20 inches of annual rainfall has been common the last few years. The role of southwestern Nash Draw (SWND) is another point requiring additional discussion. The authors present contradictory hypotheses in this section. Lambert and Carter's item number 2 on page 45 says SWND is a recharge area, while item number 4 on page 46 calls for discharge in that area.

Contradictory statements are also made regarding the degree of vertical interconnection in Nash Draw. Item 5 on pages 46 and 47 (Lambert and Carter, 1987) argues that the Magenta and Culebra are freely connected at W-25 and W-27 (as previously discussed in Chaturvedi and Channell, 1985, though overlooked in Lambert and Carter's references). However, item 4 on page 46 argues that recharge to sinkholes in the Tamarisk member cannot be interpreted as providing recharge to the

Magenta or Culebra. Are the authors proposing that the Magenta and Culebra are well-interconnected, but not the intervening Tamarisk? Some discussion of this extraordinary hypothesis is warranted. Likewise, more discussion must also be provided of the author's assertion that the dominant process at W-33 is alluvial infilling. The continued presence of this large depression, even after the springs have ceased to flow, argues against infilling at the surface. We are not aware of any evidence or studies that support the author's statement.

In light of the above comments on the Lambert and Carter (1987) report, all the assumptions arising from the conclusions of that report should be reexamined.

2.1.5.4 Effect of Clays in the Culebra

While the CCA does not assume clay lining in the fractures of the Culebra, the concept of the existence of clays, specifically the clay mineral Corrensite in the Culebra is mentioned in several documents of the proposed rule. Some discussions of this issue refer to the decision to not assume the fracture linings coated with Corrensite to be a conservative decision. It is therefore important to demonstrate that the presence of Corrensite in the Culebra fractures is only a myth without any basis in fact, as described below.

The Corrensite hypothesis is based on the X-Ray Diffraction and Analytical Electron Microscopy analysis of samples collected primarily from clay rich layers of the Rustler Formation from cores of wells drilled primarily in the Nash Draw. Four reports are cited to support this conclusion. These reports are based on the work of Terry Sewards and others at the University of New Mexico under contract to the Sandia National Laboratories.

Sewards, et al. (1991a) contains mineralogical analysis of core samples from a single well, WIPP-19, and presents no claim for clay filled fracture linings in the Culebra.

Sewards (1991) presents data on the "whole rock" as well as the "fracture surface" compositions of samples of cores collected from 6 wells (WIPP-26, 27, 28, 29, 30, 32) in the Nash Draw, one

borehole (WIPP-33) between the Nash Draw and the WIPP site, and three boreholes (WIPP-12, 13, and 34) in the northern part of the WIPP site. Clays are expected to be present in the Nash Draw cores because of extensive dissolution, weathering, and erosion in that area. WIPP-33 is located in a sink hole and processes similar to Nash Draw have operated there as well. Boreholes 12, 13 and 34 are located north of the WIPP repository and upstream from the direction of flow of water in the Culebra. Furthermore, the cores from these wells were selected from known clay seams. For example, the only sample from WIPP-12 (CS-1) came from the zone 838.5 to 838.7 ft below the surface. The Basic Data Report for WIPP-12 (Sandia, 1982) identifies mud seams at 837.7 and 840.7 ft depths.

Three Sandia National Laboratory scientists (Sandia, 1992, pp. A-127 to A- 131) correctly evaluated the Sewards (1991) report and stated the following:

> "Sewards (1991) measured and reported clay abundance for eighteen Culebra samples; thirteen from locations to the north and/or west of the WIPP site, and five from the north end of the WIPP site. None of these samples was from wells along fast transport paths. Because Sewards (1991) was focusing on clay abundance and compositional analyses, it is likely that samples were selected for analysis based on visual appearance of clays. Thus, these data may not be representative of clay abundance on fracture surfaces in the area of interest for transport modeling." (Sandia, 1992, Memo from Craig F. Novak, et al. to Martin S. Tierney, p. A-127 to A-131).

Having made this statement, it is surprising that the authors of the memo, Messrs. Craig F. Novak, Fred Gelbard and Hans Papenguth, nevertheless recommended assuming the probability of the existence of relative thickness of clay linings in the Culebra fractures to be as high as 0.5.

Sewards et al. (1991b) presents mineralogy of 107 samples collected from the cores of 8 wells, 3 of which are located within the WIPP site. However, clay fraction separates (<2 microns) were obtained

for only three samples: "WIPP-12 #3, a clay-poor dolomite; WIPP-12 #16, a clay-rich dolomite; and H6B #3, a shale." X-Ray Diffraction analysis was performed on the clay fractions from these three samples, and one sample (H6B #3) was analyzed under the electron microscope. The electron microscopy on this one sample casts doubt on the accuracy of the X-Ray Diffraction technique used:

> "There is, however, a discrepancy between the results of the quantitative XRD analysis and the results of the AEM investigation of sample H6B #3. In that sample, the XRD results show that the sample contains approximately 50% corrensite. When imaging was attempted on the AEM, it was extremely difficult to find any corrensite at all; the dominant phases appeared to be serpentine, illite, and chlorite." (Sewards et al., 1991b, p. VII-19).

The conclusion of this report, quoted below, clearly demonstrates how very limited information has been used to make important interpretations:

> "The fact that corrensite is the dominant phase in the Culebra samples is important. Corrensite has a high CEC and high surface area, thus it is able to sorb radionuclides very efficiently in the event of a low pressure breach in the WIPP facility. Although the clay minerals of only three samples were investigated, the results of Sewards et al., 1991 show that mixed-layer chlorite/smectite is the dominant clay phase throughout the Rustler Formation, so it is reasonable to suggest that the same is true in the Culebra unit." (Sewards et al., 1991b, p. VII-19).

Sewards et al. (1991) mentioned in the above quotation, is Sewards et al. (1991a) of this review, i.e., "Mineralogy of the Rustler Formation in the WIPP-19 core". As stated earlier, that report makes no claim for clays lining the Culebra fractures. Corrensite is only interpreted to be present in some of the samples, as one mineral among many, when powdered bulk samples were analyzed through X-Ray Diffraction. How can this observation lead to the statement cited above?

The final report by Sewards (Sewards et al., 1992), presents mineralogical analysis from 47 samples. Of these, 17 samples were taken from the Culebra, and of these only 9 are from the WIPP site - 6 from the Air Intake Shaft and 3 from WIPP-12. The report states the following with respect to the existence of clay in the fractures of the Culebra Samples:

> "Only small amounts of clay can be sampled from the Culebra fracture coatings; therefore, initial technique and model development for adsorption studies on WIPP clays (Park et al., in review) were carried out with material from a black shale layer in the unnamed member. This material, so-called CorWIPP, is 94% corrensite and is described as Sample AIS-15 in this report. Corrensite has a high cation exchange capacity and affinity for the uranyl ion in dilute solution (Park et al., in review) and could provide significant radionuclide retardation in fractures in the Culebra." (Sewards et al., 1992).

The above quotation clearly identifies the problem with using Terry Sewards' work to conclude that corrensite clay lined fractures in the Culebra may provide retardation for radionuclide migration through the Culebra. The argument is based on a sample from a "black shale layer" obtained from the lower part of the Rustler Formation, below the Culebra, because not much clay could be sampled from the Culebra fracture coatings! And yet, this information is used to argue that "significant radionuclide retardation in fractures in the Culebra" could be present.

Any reference to the existence of corrensite or other clay minerals lining the fractures in the Culebra Dolomite member of the Rustler Formation at the WIPP site should be deleted from the project documents because there is no basis for this assumption.

2.1.5.5 Culebra Geochemical Facies

The EEG has raised the issue of the inconsistency between the inferred direction of flow in the Culebra aquifer and the chemistry of water since the early 1980s and has published three reports on the subject. The issue was first raised by the EEG in 1983 as follows:

> "The unexplained decrease in TDS and a change in the general chemical nature of the Culebra water from sodium and chloride at the site to magnesium, calcium, and sulfate south of the site indicates that insufficient data are presently available to adequately characterize the flow system south of the site." (Neill, et al., 1983, p. 79).

Ramey (1985, Fig. 7) elaborated on this issue and presented the concept of geochemical zonation of the Culebra water. Chapman (1988) further explored the problem and provided a hypothesis to account for the decreasing total dissolved solids in the direction of flow, as follows:

> "As groundwater moves from north to south across the area, the Total Dissolved Solids (TDS) decrease by an order of magnitude and the major hydrochemical facies change from Na-Cl to Ca-SO_4. The only plausible mechanism to effect this change is the influx of a large quantity of low TDS water. The possibility of recharge in the southern area is enhanced by the presence of solution and fill features such as the gypsum caves in the Forty-Niner Member of the Rustler near the Gnome site. These features could behave as conduits supplying fresher water to deeper Rustler units." (Chapman, 1988, p. iv).

The Siegel et al. (1991) report was prepared following a suggestion by the EEG which was incorporated as a requirement of the DOE/State of New Mexico Agreement for Consultation and Cooperation.

The EPA proposed rule mentions this issue (U.S. EPA, 1997c, p. 58799; U.S. EPA 1997b, CARD 14-28; and U.S. EPA, 1997f; U.S. EPA, 1997g, p. 82), but simply cites the additional information provided by the DOE (Docket Item II-I-31) and the conclusion that “it was sufficient to explain Culebra geochemical facies within the WIPP area” (CARD 14-28). No discussion of the new hypothesis and the EPA conclusion is provided. There is also no discussion of how the new conceptual model may effect any assumptions made in the containment requirement compliance calculations.

2.1.5.6 Rustler/Salado Contact Hydrology

The EPA has accepted the CCA contention that the Rustler/Salado contact groundwater zone does not underlie the WIPP site (U.S. EPA, 1997b, CARD 14-21; U.S. EPA, 1997g, pp. 87-88). As pointed out by Chaturvedi and Channell (1985) and Neill et al. (1996, p. 2-3), this assumption is not correct. Most of the WIPP boreholes have found brine in the Rustler/Salado contact zone (see Mercer and Orr, 1979; pp. 10, 46, 63, 77, 98, 104, and 113) within the WIPP site. In fact, according to Mercer and Orr (1979, p. 120), in at least one borehole (P-18), the water-level recovery rate after pumping from this aquifer was much faster than the Culebra recovery rate.

2.1.5.7 Culebra Water Level Rises

Anomalous rise in water levels has been noted in a number of bore holes completed in the Culebra aquifer at and around the WIPP site. No satisfactory explanation has been provided for this phenomenon. This issue is briefly mentioned by the EPA (CARD14-21 and 14-78 and TSD III-B-3, p. 78 and 82), but has been dismissed from further consideration by the following statement:

> Although some water level changes are not yet explained, EPA believes that these are accounted for in the head uncertainty captured by the PA (CARD 14-78).

The TSD III-B-3, page 82 has a similar statement without further explanation. The EEG has examined the validity of this statement and found it to be incorrect. Additional discussion of this issue can be found in Section 2.6.7 of this report.

See Section 2.9 of this report for response to the proposed rule discussion of the lack of contribution to total releases from the ground-water pathway (U.S. EPA, 1997c, p. 58799).

2.1.6 Brine Reservoirs

See Section 2.11 for a discussion of the Castile brine reservoirs parameters used in the CCA and PAVT.

2.2 SUMMARY OF PA SENSITIVITY ANALYSIS (EEG-69)

The sensitivity of the performance assessment calculations of the CCA was first investigated by Helton (1996) in order to understand the relationship between several key parameters. His analysis used scatter plots and stepwise correlations to determine consistency among repository parameters. One weakness in the sensitivity analysis of Helton (1996) is that the sensitivity to parameters only applies to the actual range and distributions of sampled parameters used in the CCA calculations. Changes to either the range or distribution of one parameter may strongly affect the importance of other parameters, because release estimates vary by orders of magnitude for different combinations of parameter values. A case in point is the brine reservoir compressibility, which has been determined to have insignificant influence on the total release. The brine reservoir pressure and reservoir volume characteristics used in the CCA calculations reduce the importance of the brine reservoir to the calculated releases. It is entirely possible that the brine reservoir would be one of the most important contributors to large releases in calculations using more appropriate characteristics.

The limitations of the sensitivity analysis performed by Helton (1996) prompted the EEG to conduct their own analysis, by changing selected values or the range of selected values that were used in the CCA. This type of sensitivity analysis would truly distinguish the important parameters of repository performance, while testing the robustness of the codes involved. The analysis also allowed for the testing of the limit to which the disposal system would fail under extreme conditions. This is also useful in characterizing the important parameters.

2.2.1 Borehole Intrusion Rate

The consequence of future human intrusion scenarios into the Waste Isolation Pilot Plant was investigated in the CCA (U.S. DOE, 1996c). These scenarios were firmly established by EPA guidelines in 40 CFR Part 194 (U.S. EPA, 1996), and included the possibility of mining and deep and shallow drilling for resources.

The guidelines state in 40 CFR Part 194.33 that the likelihood of a drilling intrusion into the Delaware Basin must be calculated by considering the frequency of drilling over the past 100 years for all resources using a rate to be determined for the entire future of the WIPP. These numbers were calculated in the CCA, Appendix DEL (Tables DEL-3 through DEL-7) and were used to calculate the Complimentary Cumulative Distribution Function (CCDF) curves for the performance assessment calculations of the CCA. A total of 46.8 boreholes per km^2 per 10,000 years were estimated based on past drilling of resources at depths greater than 2150 meters, which equals 10804 boreholes per year in 23,102.1 km^2 (area of Delaware Basin).

The drill intrusion rate for the 10,000 year future of the WIPP was directly implemented in the CCDFGF model, and was calculated to be equal to 0.00468 boreholes/km^2/yr. However, future human activities are uncertain, and the rate was changed to test the effects on the CCA calculations.

The modeling associated with an increased borehole rate shows that a factor of approximately 23 is needed to reach the EPA release limit at a probability of 10^{-1} from values used in the CCA. The overall mean for the highest release tested, 4.68×10^{-1} boreholes/km^2/yr, exceeds the EPA limit of 10 EPA units at a probability of 10^{-3}. This does not seem to be likely, as the number of boreholes drilled in the Basin per 10,000 years would have to exceed one million, or 4,680 boreholes per km^2.

2.2.2 Probability of Brine Encounter at WIPP

The probability of encountering brine at the WIPP from an intrusion into the Castile Reservoir is uncertain. The probability was set to 8% in the CCA, and changed to a range of probabilities from 1% to 60% in the EPA's PAVT. However, the extent of the reservoir beneath the WIPP is unknown, and the influence of this parameter was tested at higher values at 50 and 100%. These values were based on the potential that the Castile reservoir size encountered by WIPP-12 (Chaturvedi et al., 1997) extends below the waste area.

The modeling only compared CCA values to the higher probability of encounter, and found the parameter to be unimportant in the CCA. The increase in releases from the 8% to 100% was only 0.1 EPA units (35 Ci). However, the synergistic affect of changing multiple parameters, especially those that affect the Castile Reservoir directly (pressure, volume, rock compressibility, etc.) may have a more profound result on the calculations, though these changes would have to result in releases of at least 1 EPA unit to significantly impact the CCDFs.

2.2.3 Castile Brine Reservoir Parameters

The pressurized Castile brine reservoir that underlies the Waste Isolation Pilot Plant has been the subject of many controversies on its extent and importance (Neill 2/7/97 and 3/14/97 in Appendices 8.1 and 8.2; Silva, 1994; Dials, 1997c; Beauheim, 1997). The performance assessment calculations of the CCA recognize the fact that the brine could play a significant role in the degradation of wastes and waste container, if an inadvertent drilling intrusion were to pass through the repository to the brine pockets below, by assigning two of the six scenarios to calculate the effects of the breach. However, the characterization of the parameters associated with the reservoir were undermined by associating them to data that clearly lies outside of the domain of the repository. The more realistic parameter values proposed by the EEG could potentially demonstrate higher direct brine releases to the surface, affecting the compliance with the containment requirements in the EPA standards of 40 CFR 191.13. Calculations were performed using more reasonable parameters for the simulation of Castile brine migrating into the repository.

Reservoir parameters used in performance assessment calculations were derived from well information that lies mainly outside the domain of the WIPP repository. The well distances ranged from 6 km (3.75 miles) to over 17.6 km (11 miles) away from the repository center. New values were assigned to several parameters that describe the Castile brine reservoir based on WIPP-12 data that is more closely identified to the conditions at the repository. The WIPP-12 is located 2 km (1.2 miles) north of the repository. The well was originally drilled in 1978 and deepened in 1981 at the request of the EEG, and was the cause for the repository to be moved south after brine was encountered in the well. The well was recorded to have experienced brine

flow when coring reached a depth of 918 meters (3012 feet) (D'Appolonia, 1982). While extending the well to depths greater than 1189 meters (3900 feet), a total of 80,000 barrels (3.36 million gallons) were allowed to flow from the well.

The parameters associated with describing the Castile brine reservoir include reservoir volume, rock compressibility, reservoir pressure, and permeability. The modeling of these parameters began with the two-phase flow code, BRAGFLO, and ended with calculations of solid and liquid waste released due to an inadvertent human intrusion. The outcome showed that there is no significant change in releases for the CCDF due to small changes in the reservoir parameters. However, it is expected that the CCDF curve would move closer to the EPA limit if the solubility of actinides in brine were increased above that assumed in the CCA and PAVT.

2.2.4 Solubility Modeling of Actinides

The solubilities of actinide species at the WIPP in brine solutions are of concern, especially since limited experimental evidence exist (if any at all) on the amount of each species in solution. In some instances, weak analogies are used between species with the same oxidation state to infer a "better" value than would be achieved through actual experiments. Other cases used, in what seemingly appears as a flaw in a model, absurd calculated solubilities. To bound the uncertainty in the values chosen for solubility, the CCA invokes a range from the median value assumed (U.S. DOE, 1996c, Appendix PAR) of 2 orders of magnitude below and 1.4 orders of magnitude above. For example, the solubility for the +3 actinide, which was inferred from Americium data, had a median value of 5.82×10^{-7} M, and ranged from 5.82×10^{-9} to 1.46×10^{-5} M. The distribution to the range was log-cumulative, where most of the values (59%) fall between -1.0 and 0.0 orders of magnitude from the median.

Due to the uncertainties, further modeling by the EEG was conducted on brine movement from the repository under inadvertent human intrusion scenarios. If the actinide species are readily soluble, the brine could be an important mechanism to release a significant portion of actinides to the accessible environment.

For brine to escape the repository and travel upwards through the borehole under blowout conditions, 1) pressures must be significant to overcome the hydrostatic force of the drilling fluid, and 2) sufficient brine must be available for transport. Both conditions have been met in many of the realizations in the performance assessment calculations of the CCA. However, due to the assumed low solubility of actinides in brine, the consequence of a direct release of brine to the surface was minimal. For example, the mean release of radionuclides in the CCA through a direct brine release was 0.04 EPA Units (14 Ci) at the 10^{-3} probability, compared to spallings or cuttings and cavings, each having releases of 0.2 EPA Units (70 Ci).

The physical and chemical aspects of the repository were challenged by the EPA in an evaluation of the CCA, called the Performance Assessment Verification Test (PAVT). The EPA changed several parameters for the disposal system to test the uncertainty associated with the range of uncertainty in the parameter values. The test merely evaluated several parameters that could have significant affect on compliance, changed them to different numbers found to be more reasonable by the EPA, and reran the calculations. Some changes involved the solubility of the actinides in a brine solution by assuming a different speciation of minerals associated with the MgO backfill material, which lowered the median solubility limit for most actinides. The new set of solubility values came from the same flawed code used to establish the original set of numbers, and no new experiments were conducted to verify any of the values.

The results of the PAVT showed a large overall increase in the amount of brine to the surface upon intrusion, yet only nominal increase in release of actinides. This was expected, since the median solubilities were decreased by the EPA to be as much as 2 orders of magnitude for the +4 radionuclides. The effect on compliance from the changes shifted the CCDF for the direct brine release scenario closer to the compliance limit by 0.15 EPA Units. The changes are minimal, since 10 EPA units of release are needed to fail compliance at the 10^{-3} probability.

The problems with both models of the CCA and PAVT prompted the EEG to conduct bounding calculations on solubility. The first set of model experiments assumed that the Plutonium was of the +5 oxidation state, and used +6 values based on the work by Reed et al. (1994), Reed et al.

(1996), and Rao (1996). The values were only nominal increases above the CCA values for Plutonium in the +3 or +4 oxidation state for Salado Brine, but upwards of 10000 times for Castile Brine.

The modeling changes began with input files of the source term for PANEL. The changes were quite easy, and the analyses were complete in a matter of hours. The results showed that increases in solubility with CCA brine release volumes had limited effect on compliance with an overall increase on the mean CCDFs by 0.09 EPA Units. Even when the solubility was pushed to absurdly high values, the maximum release was limited by the availability of the actinide source. At a solubility of $8x10^{-3}$ M (compared to the CCA's $4.4x10^{-6}$ M for Pu+4 in Salado brine), the overall mean for direct brine release was increased from 0.04 to 1.3 EPA Units.

The second set of modeling experiments took the extreme position of assuming the solubilities of all actinides in different mineral species of MgO between the conversion of brucite to magnesite. In particular, calculations by Novak (1997) show values of actinides in the presence of magnesite, nesquehonite, hydromagnesite, and no backfill. CCA calculations assumed the long-term mineral species for MgO to be magnesite, and the PAVT assumed hydromagnesite. Yet, experiments could not prove the existence of either, and only showed hydromagnesite-like or proto hydromagnesite (Sandia, 1997). These other mineral species looked more like nesquehonite, and it seems difficult to justify the presence of either mineral phase assumed by the DOE and EPA.

Bounding calculations were performed on conditions resulting in the highest solubilities in the repository. These included nesquehonite and no backfill. For the nesquehonite simulations, it was assumed that the mineral would persist for the entire proposed history of the repository, and only median values were used. The assumption of the long-lived intermediate species is an overestimate on the expected conditions, to better understand performance of the repository. behavior. Similarly, calculations without the MgO backfill are intended to better understand the repository behavior.

Table 1 shows the solubility factors used to achieve solubility values from Novak (1997). The values have been log transformed for use in the input files to change the values that were established in the CCA. For example, SOLAM3-SOLCIM for nesquehonite increases the solubility of Am+3 in Castile Brine by 1.516 orders of magnitude, whereas SOLAM3-SOLSIM decreases the solubility by .277 orders of magnitude. The changes were made in the source term files, for running of PANEL and NUTS.

In addition to solubility changes from the CCA, the Salado transport files from the PAVT were used for transport calculations of NUTS and PANEL. The PAVT calculations exhibited higher repository pressures, hence larger direct brine releases upon intrusion. The maximum effect would be noticed with both changes together.

One curious observation from Table 1 shows that the solubility of nesquehonite in the +4 oxidation state (Pu+4, U+4, and Th+4) is higher than would be the case without any MgO backfill. Yet, one must keep in mind the context of these number, and remember that they are simply computer generated numbers, which are under much scrutiny. They do however provide a reference point in which compliance can be studied. If it is found that actual experimentation leads to solubility values less than those of Table 1, but slightly higher than the CCA values, one can interpolate compliance releases from existing CCDFs on probabilities and releases.

	Nesquehonite		No Backfill	
	SOLCIM	SOLSIM	SOLCIM	SOLSIM
SOLAM3	1.51616	-.27709	4.48678	3.83714
SOLPU3	1.51616	-.27709	4.48678	3.83714
SOLPU4	5.23242	2.15588	4.06695	2.05552
SOLU4	N/A	2.15588	N/A	2.05552
SOLU6	0.95861	0.96357	0.95861	0.96357
SOLTH4	5.23242	2.15588	4.06695	2.05552

Table 1. Solubility Factors for SOLCIM and SOLSIM

The results of running new solubility values can be seen in Figure 2. The figure shows the overall mean of all processes combined as they relate to compliance. In addition, the PAVT direct brine releases were run with the slightly higher CCA solubilities. The most distinct feature of the figure is the shoulder of the high solubility models that extend below the 10^{-1} probability limit. The "shouldering" is the effect of increased releases due to the direct brine release. Since the Pu+4 and Th+4 (although minor) solubilities increased over 5 orders of magnitude, the release due to this mechanism is expected to increase significantly as well. For example, the CCA median value for +4 actinide solubilities in Castile brine was $6x10^{-9}$ M. If one assumes 100 m^3 of Pu^{239} brine, then it is expected that the release is $2.5x10^{-5}$ EPA units. If the solubility is increased by $10^{5.23}$ as seen in Table 1., then it is expected that 4.24 EPA units are released to the accessible environment. Therefore, the CCDF for higher solubilities would be closer to the EPA limit.

The consequences of higher solubilities, as seen in Figure 2 are quite high. The overall mean

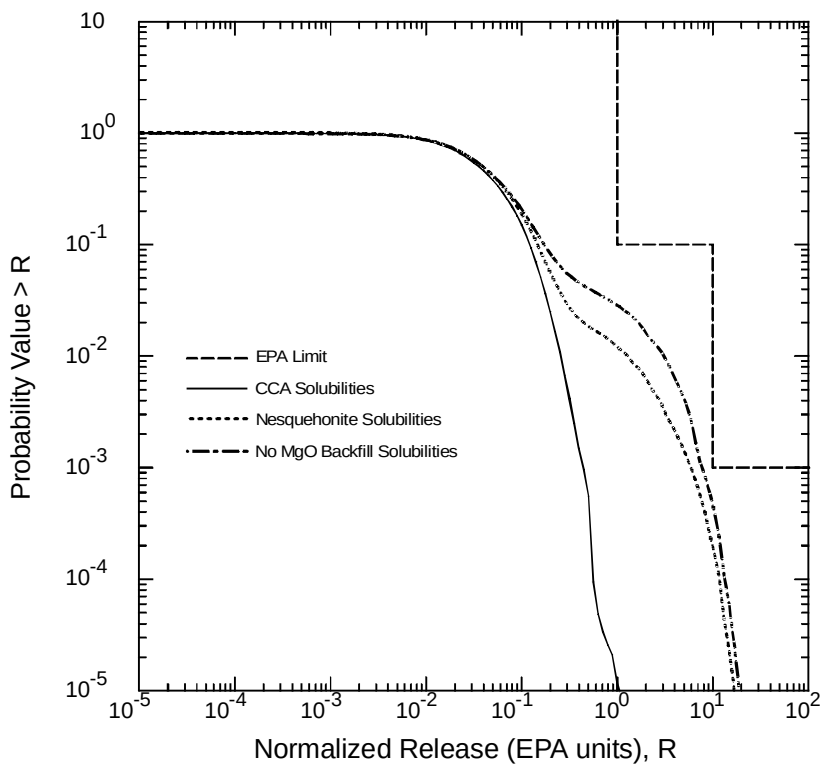

Figure 2. Overall Mean of Normalized Releases for Modeling of increased solubilities using Nesquehonite and 'No Backfill' Values compared to CCA values.

release for the CCA and PAVT were 0.2 and 0.4 EPA u at 10^{-3} probability, respectively. The overall mean for the increased solubilities of nesquehonite and 'no backfill' are 6.0 and 8.0 EPA units at the 10^{-3} probability, respectively. The limit for compliance, according to 40 CFR Part 194 is 10 EPA units. Therefore, it appears that even high solubility values do not cause the disposal to be out of compliance with the EPA regulations. However, there is a deeper issue that one cannot dismiss, that is far less superficial than the previous statement. It deals with the consequences in small changes of solubility and variability in the actual values. Are we so certain that the solubilities of Plutonium or Uranium, in any oxidation state, are less than the values presented in the CCA or the PAVT? How did we arrive at these numbers? Are there experimental evidence to back up the claims made in the CCA that deals with the oxidation state analogy between Am+3 and Pu+3? Once one really delves into the reasoning behind many of the fixed numbers associated with these actinides, many deficiencies appear in the reasoning, and confidence in the values used to show compliance declines.

2.2.5 Flow and Transport Modeling within the Culebra

The transport of radionuclides to the accessible environment can occur in two ways: upwards from the repository through a borehole to the surface into the biosphere, or laterally through the stratigraphy of highly conductive layers across the Land Withdrawal Boundary (LWB). The second method was investigated by modeling the Culebra aquifer of the Rustler. The CCA and PAVT include Culebra modeling and its consequence of transport across the LWB in the CCDF curves. The CCA showed only 1 of 300 realizations to cross the boundary in 10000 years, with the PAVT showing a significantly higher impact on the Culebra. The end result of increased transport across the LWB in the PAVT had little to no effect on the CCDF.

EEG's concern about of the modeling of the Culebra begins with the assumptions used in parameters that describe actinide behavior with the Culebra dolomite. When the actinides are directed along flow paths after a release to the Culebra, the transport will be retarded by the interaction of the actinides with the Culebra matrix. The interaction is known as sorption (either absorption or adsorption, and is usually non-reversible), and different types of sorption, called isotherms, describe the interaction between the two constituents. The Culebra was characterized

as having a linear isotherm with the actinides, and the parameters of the isotherm, known as the partition or distribution coefficient (K_d) were measured in laboratory experiments.

The same oxidation state analogy used to predict similar solubility of actinides was applied to the distribution coefficient. Therefore, many of the actinides' K_ds were not actually measured and it is not clear what the consequence would have been with better values. Though it is well known that high K_d values will retard the actinide species sufficiently to inhibit transport, it is the low K_d values that are of concern. For example, it was shown by Blaine (1997) that K_d values higher than 3 ml/g for most actinides would sufficiently retard transport, and an insignificant portion of the actinides would cross the Land Withdrawal Boundary. Only one actinide in the PAVT, U+6, has K_d values as low as 2 ml/g.

It is also well known that some waste constituents in the WIPP inventory will bind themselves to the actinides to further lower the K_d values. EDTA, for example, is used to bind with Plutonium for cleanup purposes. Other organic ligands in the waste will have similar effect. Furthermore, the lack of measurements decrease the confidence in values used in the CCA and PAVT, and this prompted the EEG to continue with additional calculations, testing the effects of lowered K_ds on the disposal system and compliance.

The interaction between releases from the repository and transport of actinides require a lengthy discussion, and will not be discussed here. It is possible, due to the set up of the codes, to do calculations that assume any percentage of the actinide's mass to completely bind with EDTA and migrate unretarded through the Culebra matrix. Therefore, additional calculations were performed assuming 1% of Pu (+3 and +4) having a K_d=0 ml/g.

The results of the calculations show that the overall mean of the releases through the Culebra was 0.0001 EPA Units at the 10^{-3} probability. Since a large number of realizations crossed the LWB with significant releases, it was reasoned that the mass of radionuclides reaching the Culebra was the limiting factor. This was proved when the models of higher solubility were combined with transport modeling, and the overall mean for release from the Culebra was increased to 0.31 EPA

Units.

Another model was proposed in which the extent of potash mining within the controlled area Land Withdrawal Boundary was extended to include lower grade potash ore. Potash mining occurs in the McNutt Potash Zone of the Salado, which is about 200 meters below the Culebra. The effect of potash mining in the Delaware Basin would cause subsidence to the overlying units, and hence having a possible detrimental consequence from increased transport of radionuclides. The CCA established the criteria for considering the effect of mining by assigning a multiplying factor to the transmissivities of the Culebra, which increased the velocities above the mined region.

The extent of mining is debatable, and depending on which map is used determines the possible economic viability of the resource. In addition, new methods of mining such as solution mining could extract lower grade minerals more readily. Therefore, the EEG included a larger area of mining in a new flow model, yet keeping the same parameter changes that were used in the CCA. It is feasible to change other parameters or include new ones, but due to the limited time available to the project, this was not thoroughly investigated.

The results of extending the areal minable region within the Culebra had little to no effect on the transport of radionuclides across the Land Withdrawal Boundary, though it did change the flow patterns slightly. The limit of transport is sorption, and the PAVT values for K_d were retained for Uranium. The combination of low K_d and larger mining area was studied with Plutonium, again using the 1% K_d=0 ml/g. Again, the amount of initial mass injected to the Culebra crossing the Land Withdrawal Boundary was significantly higher, but limited by the amount reaching the Culebra.

Lastly, the combined effect of extended mining, low K_ds, and high solubilities were combined in an effort to test the synergistic effect of all the previous results. The overall mean for the release

through the Culebra was as high as 1 EPA Unit (or 350 Ci). The addition of the Culebra releases to the overall mean of all combined releases moved the CCDF closer to the EPA compliance limit by 12%.

2.3 ACTINIDE SOLUBILITY

2.3.1 Introduction

Except for the final performance assessment submitted to EPA (U.S. DOE 1996c), actinide solubility had always been identified as one of the key parameters in calculating the 10,000 year performance of the repository. During the early efforts to develop the performance assessment, it was quickly recognized that there was a dearth of actinide solubility data for anticipated conditions of high salinity and high pH for the complex heterogeneous waste chemistry. Moreover, a reliable estimate of the solubility could not be calculated due to the lack of thermodynamic data (Brush and Lappin, 1990). Nonetheless, the development of the PA codes required some estimate for the range and distribution of solubility values for the each of the actinides. In lieu of data, the early PA calculations used a solubility range and distribution recommended by Brush (1990). The solubility of each actinide was assumed to have a log uniform distribution from 10^{-9}M to 10^{-3}M with a median value of 10^{-6}M. However, the PA effort was cautioned about the limited use of these values (Brush, 1990; Brush and Lappin, 1990).

Brush's 1989 estimate of radionuclide solubilities, 10^{-6}M with a range of 10^{-9}M to 10^{-3}M, were a source of concern for another reason. The relatively high values suggested the possibility of significant releases when used in radionuclide-transport calculations (Brush, 1990). There was also concern about the wide range of estimated actinide solubilities. Brush noted that it would be desirable to narrow the range as soon as possible and advocated continuing the ongoing experimental work which would require another two or three years to obtain enough data for comprehensive calculations.

Meanwhile, for the 1991 and 1992 PA, Sandia National Laboratories conducted an elicitation in which four outside scientists collaborated to estimate the median value and range of solubility for each actinide in each oxidation state. However, the results of this exercise did not narrow the range. The estimated range of solubilities expanded from six orders of magnitude to twelve orders of magnitude depending on the actinide and the oxidation state (Sandia, 1991, Vol. 3, pp.

3-62 to 3-66). Moreover, the expected actinide concentrations were much less than those estimated by Brush. For example, the median solubility value for the Pu^{IV} and Pu^{V} decreased by more than three orders of magnitude to 6×10^{-10}M. Not only were the new values lower, this median value was not even in the range recommended by Brush. At the bottom of the range, the solubility for Pu^{V} was estimated to be as low as 2.5×10^{-17}M.

The 1991 and 1992 PA attempted to capture the effects of oxidation on solubility. For these two PA efforts, the amount of each actinide in each oxidation state was estimated from diagrams of actinide oxidation states as a function of Eh and pH (Sandia, 1992, pp. 3-67 to 3-70). Similar methods were used in the 1992 PA with some minor adjustments (Sandia, 1992, Vol. 3, 3-38 to 3-43).

Sandia did not publish an annual performance assessment for the years 1993 and 1994. Rather, the calculation efforts were directed toward the development of a systems prioritization methods (SPM). SPM was advanced as a management decision making tool needed to identify the best use of resources to demonstrate compliance with the EPA Standards.

As a result of the SPM exercise, Novak et al. (1994, p. 7, 29) identified problems with the actinide solubility values used in the 92 PA calculations. The mobile actinide concentration model in the 1992 PA was characterized as the "intuition and impressions of four individual experts." Furthermore, the thought processes used by the members of the panel to generate their predictions had not been documented, making peer review of their reasoning difficult. Hence, Novak et al. maintained that the values used in the 92 PA were indefensible and should not be used in future performance assessment calculations. Novak et al. (1994, p. 29) also argued that any concentration less than 10^{-10}M would not be defensible. Such a low value for concentration could never be confirmed by a measurement because it was below the limits of detection.

Determination of solubilities focused on modeling the solubilities under different repository chemistries. Rather than use a more widely tested model, such as PHREQE or EQ3/6, the project developed its own unique model, FMT. The FMT model would be used by performance

assessment to calculate actinide concentrations in Salado and Castile brines. However, the project still needed data for the development of the model and there was no data forthcoming for review. As noted in the October 1996 NAS/NRC WIPP Committee report:

> Overall, the scientific program outlined by DOE for study of the source term is adequate, provided that the program is carried to completion. Because the program at this time consists largely of work planned or in progress, it has not been possible to critically review experimental results or to judge whether these results are used appropriately in the PA analysis (NRC 1996, p. 62).

The DOE submitted the final Compliance Certification in October 1996. The EPA published its technical review of the actinide source term program and modeling in October 1997. EEG asked Dr. Virginia Oversby to evaluate the DOE modeling efforts and the EPA review. Her evaluations, which are included with this report, identified many of the issues summarized in the EEG letter of December 31, 1997, to EPA (Appendix 8.3). Her reviews of the DOE CCA and other documentation are attached as Appendix 8.4a. On February 20, 1998, EEG met with scientists from Sandia National Laboratories and Dr. Virginia Oversby and Dr. Rodney C. Ewing to discuss the actinide solubility program results. The letters which they prepared subsequent to that meeting are attached as Appendices 8.4b and 8.4c. Dr. Oversby's review of the EPA technical support document is included in Section 2.3.2.

The FMT model is unique to WIPP and is not generally used elsewhere. Calculations using the FMT model result, for example, in a difference of 19 orders of magnitude between the projected solubility of thorium pentacarbonate in the Castile brine versus the Salado brine. This is hard to explain on the basis of differences in the brine compositions. Hence the code becomes suspect. It appears that the EPA verification was limited to an exercise in which EPA used the same computers, codes, and database (after correction of some errors in the database) as DOE, to determine the same numerical values. This is not the standard of verification that one normally applies to chemical modeling codes. Verification would require, at a minimum, an analysis and demonstration that the FMT code correctly solves the simultaneous equations, a thorough

comparison with the results of calculations using a code that is used more widely in the modeling community, and a demonstration that the calculations are consistent with all relevant published data. For example, as a preliminary analysis, it would have been more informative if a widely used code such as EQ3 or PHREEQE had been used with the FMT database and then FMT had been used with a database from some other modeling group.

Plutonium will account for 82% of the WIPP radioactive inventory 100 years after closure. The CCA maintains that the plutonium will exist either as Pu(III) or Pu(IV). However, the plutonium data were not used for developing the FMT model to predict the solubility of Pu(IV). Rather, the CCA relied on data for uranium and thorium as analogs. But there are long recognized concerns about relying entirely on the oxidation state analogy to derive thermodynamic constants for modeling complex electrolyte systems. As stated in the NAS/NRC WIPP Committee report (NRC, 1996, p. 129):

> Although the oxidation state model (the assumption that the chemistry of a given oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviations from the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy.

In its technical support documentation, EPA discusses the shortcomings of the solubility uncertainty ranges advanced by DOE. There is no direct basis for the uncertainty ranges for actinides in oxidations states +4 and +6. Moreover, the uncertainty ranges for oxidation states +3 and +5 are derived primarily from non-actinide data. Nonetheless, EPA has accepted the ranges as adequate, commenting “It is not clear that including more data for the other actinide state would appreciably change this range” (U.S. EPA, 1997c). The argument is weak. It also remains unclear that the range adequately brackets uncertainty for a population for which data have not been examined.

In the solubility calculations, the CCA inappropriately discounts the role of organic ligands on plutonium solubility. The CCA provides information on the amounts and complexing properties of EDTA and then argues that other organic ligands, such as citrate, will be unimportant despite the fact that citrate is the most abundant water-soluble organic constituent. Citrate forms extremely strong complexes with actinides in the +4 oxidation state [e.g. Th(IV)], but very weak complexes with other cations. Moreover, the DOE and EPA have each assumed that the actinides and the brine would be evenly distributed and well mixed throughout the repository. EEG believes that this is an inappropriate assumption. The plutonium and citrate are probably located in the same drums. These waste forms result from chemical separations of Pu and do not fit the classic description by DOE of TRU waste as contaminated tools, rags, gloves, booties, etc. The solubility of the plutonium for these waste forms must also be calculated as a very stable plutonium citrate complex where other cations in the brine diffusing into the drum cannot compete effectively with the complexed actinides (IV).

Perhaps the most important questionable assumption made in projecting the solubility values used in the CCA and the PAVT is the presence of hydromagnesite as the dominant stable mineral species resulting from the MgO backfill. DOE's experimental efforts with MgO predominantly produced nesquehonite, a magnesium carbonate mineral, with the later appearance of an unidentified phase. Hydromagnesite was not formed in the experiments reported by the DOE (Sandia, 1997); a hydromagnesite-like unnamed mineral is reported. The chemical composition of this mineral is in fact more like nesquehonite. The DOE and the EPA believe that "hydromagnesite will be the metastable hydrated magnesium carbonate phase and nesquehonite will be an intermediate phase." (U.S. EPA 1997c). There is no experimental data for the length of time that nesquehonite is expected to exist. The distinction between the projected hydromagnesite-dominated or nesquehonite-dominated chemical environment in the repository is important because the actinide solubilities in the presence of nesquehonite are 3 to 4 orders of magnitude higher than in the presence of hydromagnesite.

The EEG has investigated the effect of actinide solubilities on the mean CCDF plots, using the EPA's PAVT releases, and making no other changes (Neill Letter dated December 31, 1997 –

Appendix 8.3 of this report). The investigation included the “CCA” solubilities, “no backfill” solubilities, and “nesquehonite” solubilities. The overall mean CCDF curve for “nesquehonite” solubility moved one order of magnitude closer to the compliance limit at 10^{-3} probability compared to the CCA solubilities.

The EEG therefore recommends that the EPA reexamine these issues and provide additional justification for the CCA and the PAVT solubility values. If convincing justification is not available, then the "no backfill", or "nesquehonite" solubilities should be used in a new performance assessment calculation. EEG concerns are summarized below.

1. The FMT model is unique to WIPP. EEG found that the model predicts differences for actinide sulfate and carbonate solubilities that can not be explained by chemistry, thus leaving the reliability of the calculations suspect. The unexpected results need to be explained or the model needs to be re-examined for possible problems with the code.

2. Rather than use an extensive plutonium data base, the FMT predictions relied on thermodynamic data for other elements and an oxidation state analogy argument. EEG recommends that the calculations be performed using data for plutonium and the values for solubility and complex ion formation contained in the peer-reviewed data compilation by OECD/NEA.

3. EEG agrees with EPA’s documentation of the shortcomings of the solubility uncertainty ranges advanced by DOE. However, EPA has accepted the ranges as adequate based on a weak argument. EEG recommends that the uncertainty range needs to be determined with the appropriate plutonium data.

4. In the solubility calculations, the CCA inappropriately discounts the role of organic ligands on plutonium solubility by arguing that EDTA is the strongest complexing agent. But citrate forms very strong complexes with actinides in the +4 oxidation state and very weak complexes with

other cations. Thus, the solubility of a stable plutonium-citrate complex in individual waste containers needs to be calculated.

5. There are serious unanswered questions about the impact of magnesium oxide backfill on the solubility of the actinides. It is proposed that magnesium oxide will reduce the solubility of the actinides by controlling the pH. But, it is not known how long the early reaction product, nesquehonite, will persist. The FMT model calculates that the presence of nesquehonite drives the solubility of the +4 actinides, such as plutonium, higher than in the no backfill case. This requires further investigation.

2.3.2 Comments on "Technical Support Document for Section 194.24: EPA's Evaluation of DOE's Actinide Source-Term" - prepared by V. M. Oversby

2.3.2.1 General Comments

The EPA evaluation of expected redox states, solubility, and speciation of actinides under WIPP disposal conditions was very narrow in its scope. In general, only the references cited by DOE and the work done by the DOE contractors was discussed. The evaluation would be considerably strengthened, and might reach different conclusions, if relevant results published in the open literature of studies conducted by other scientists were discussed.

The EPA has limited their review of the DOE solubility calculations to an exercise in which EPA used the Sandia computers, codes, and databases to determine whether they could get the same numerical values for results if they tried to duplicate the work done by DOE. It would have been very surprising if they had failed to find agreement under those conditions. A more reasonable evaluation would require a comparison of the results of calculations using a code that is used more widely in the modeling community with those obtained by the Sandia FMT code.

There has been no evaluation by EPA of the thermodynamic properties data used in the database for the solubility calculations. There has been no attempt by EPA to assess the degree to which the calculations might represent the conditions expected for WIPP disposal. Both of these tasks are needed in order to determine whether the DOE calculations have any validity.

In evaluation of the effect of organic ligands on the mobilization of actinides, EPA considers only the case of homogeneous equilibrium, in which the entire actinide inventory in the repository is well-mixed with a very large volume of brine that inundates the repository. This is an unrealistic and non-conservative model for evaluation of the effect of organics. In addition, EPA bases their evaluation of the ability of organics to mobilize actinides on an analysis that only considers EDTA. While this analysis gives the correct result for the importance of EDTA, it does not speak to the issue of the importance of citrate in the waste and its ability to increase the mobility of Pu.

2.3.2.2 Comments by Section

Section 2 "Solubility and Actinide Oxidation States"

Comments are limited to U(IV), Th(IV), and Pu (all oxidation states).

The EPA document summarizes the discussion of expected actinide oxidation states and concurs with the DOE position. In doing this, the EPA overstates the content of the DOE SOTERM Appendix to the CCA. EPA states on p.5 "DOE provides a summary of the literature and a discussion of experimental results for thorium, uranium, neptunium, americium, curium, and plutonium." Unfortunately, the DOE document limits itself to a discussion of the expected oxidation states for these elements and does not discuss the chemistry sufficiently. For example, after it is concluded that the expected oxidation states for U will be IV and VI, the chemistry of uranium IV is not further discussed. This is unfortunate, because published data on the solubility of UO_2 in concentrated synthetic brines could have been used to evaluate the validity of the claims made for the use of the Th(IV) model for representation of all actinide (IV) species. See discussion of experimental results of DePablo et al. (1995) in Oversby (1997). It is surprising that EPA did not discuss this lack of evaluation of the model against published data, since the necessity for such evaluations had been pointed out by the National Research Council review of the WIPP project as recently as 1996 (NRC, 1996). In their review, the committee states on p.129 that "Although the oxidation state model (the assumption that the chemistry of a given

oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviations from the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy."

The oxidations states expected by DOE for Pu in the WIPP repository are III and IV. Any Pu(V) formed is expected to be rapidly reduced by iron. EPA concurs with this conclusion; however, Pu(V) is observed as a long-lived transient in many laboratory experiments. Pu(V) may be formed as a result of radiolosis reactions in the brines and while its total abundance in the repository is likely to be low, it might be significant as a transient species in some waste containers. The release scenarios considered important for WIPP are those involving human intrusion, with drilling through the repository to a brine-containing formation below the repository. Upwelling of brine from this lower layer through the repository might allow rapid transport of brines containing some Pu(V) to the surface.

The inclusion of Pu(III) for a potential redox state is based on work by Felmy et al. (1989). Their experiments used Pu(III) maintained in that redox state by adding Fe powder to the solutions. The solubility of $Pu(OH)_3$ was measured in dilute solutions and brines. The redox state of Pu was verified by using chemical extraction methods; however, the method used measured Pu(III) + Pu(IV), so there is not positive identification of Pu(III) content. At pH 9 and above, the concentration of Pu was below detection limits (Felmy et al., 1989). This would suggest that Pu(III) needs to be considered only up to pH 9 in modeling calculations if metallic Fe is present, which it will be in the form of WIPP disposal drums. Above pH 9, the upper limit for Pu(III) should be set by the detection limit in the Felmy et al. (1989) experiments as 10^{-9} M.

The EPA claims on p.5 that "The predominance of U(IV) requires extremely reducing conditions, that while possible for the repository, cannot be predicted with certainty." This statement is at odds with the claim that the redox conditions will be controlled by the presence of metallic iron and its oxidation to Fe(II). The redox conditions imposed by the Fe(O)/Fe(II) buffer are much more reducing than those required to stabilize U(IV) as UO_2. This fact was used by Rai et al. (1995), who added Fe powder to their experiments concerning solubility of U in carbonate and

bicarbonate solutions in order to assure the absence of U(VI). Available experimental data for U(IV) are relevant for use in estimating solubility of U under WIPP conditions and also for use in comparison with estimates of solubility for Pu based on the Th(IV) model.

Section 3: "Effects of the Magnesium Carbonates on Predicted Repository Conditions Due to MgO Backfill"

The EPA evaluation claims that DOE described (Sandia, 1997) experiments in which "the reaction of MgO with brines was observed to result in the rapid formation of nesquehonite, which then converted to hydromagnesite within days." EPA concludes "Consequently, nesquehonite cannot be expected to persist in the repository environment."

The Sandia report (Sandia, 1997) does describe results of reaction of MgO with brines. Nesquehonite is found as an early reaction product. Unfortunately, hydromagnesite is never identified in the reaction products, even though sections in the Sandia report claim that a poorly characterized phase tentatively identified to have the composition $MgCO_3 \cdot 3H_2O \cdot MgCl(OH)$ (PDF7-278) (no name given) was hydromagnesite-like or even that it was protohydromagnesite. The chemistry of the phase found is quite different from that of hydromagnesite [$(MgCO_3)_4 \cdot Mg(OH)_2 \cdot 4H_2O$] and contains a major structural unit with the same chemistry as nesquehonite ($MgCO_3 \cdot 3H_2O$). There is no evidence discussed in the Sandia document that shows disappearance of nesquehonite under conditions relevant to WIPP. With the evidence at hand, one must conclude that nesquehonite will, at the very least, be a very long term metastable phase under WIPP repository conditions. So long as CO_2 can be expected to be released into the brines - from any source - and MgO is present in the repository, the reaction to produce nesquehonite will occur. If nesquehonite is present in the phase assemblage in the repository system, it will fix the dissolved carbonate activity at levels higher than those appropriate for hydromagnesite, even though hydromagnesite may also be present. Absence of nesquehonite requires experimental data to show the rate of conversion of nesquehonite to another phase, as well as data to determine the time for an end to the production of new nesquehonite. Appropriate data are currently lacking for both of these items. As noted by EPA (p. 8), the discussion of the correct phase assemblage for

the Mg-Carbonate system under WIPP conditions “may seem academic but is important because of the potential effect on the solution conditions and consequent predictions of actinide solubilities”.

Section 4: “FMT Modeling Results”

This section describes the work done by EPA to evaluate the FTM modeling code and results obtained using that code for prediction of brine chemistry for WIPP conditions.

EPA went to Sandia and used the FMT code and data base there to rerun the same cases as reported in the CCA and subsequent reports on MgO stability. They were able to reproduce the numerical values (after correction of some errors in the data base). EPA considered that this constitutes “verification” of the results. This is not the standard for “verification” that one normally applies to chemical modeling codes.

Normally, verification of a numerical model requires that one determine that the model does what it claims to do. We do not know whether the FMT code correctly solves the system of simultaneous equations - which is what verification would mean in this case. The only thing we know is that it is not so numerically instable as to produce wildly divergent numerical solutions to the same problems using the same data.

There has also not been verification that the thermodynamic data in the database correctly represent what is known about actinide chemistry in brines. The results using the “modified” database that produced lower Th predicted solubilities still seem to have predicted far more Th-pentacarbonate than one would expect based on the experimental studies of Östhols et al. (1994) who did the measurements of ThO_2(am) solubility that provided the basic thermodynamic data for the Th-pentacarbonate association constants. The results are also inconsistent with the measurements of Th solubility in Na-carbonate and Na-bicarbonate solutions (Rai et al., 1995) that showed that a dissolved carbonate concentration of 0.1 mole per liter was needed before a significant increase in Th solubility due to carbonate complexation was seen. The EPA results

reported in tables 4-8 and 4-9 do not show speciation for Th; however, those contained in the Novak (1997) memo do. The following table compares the calculated results for dissolved carbonate, bicarbonate, $Th(CO_3)_5^{6-}$, $Th(OH)_3(CO_3)^-$, and H^+ for nesquehonite and for 5424 hydromagnesite in SPC brine.

Table comparing speciation of Th for different Mg-carbonate phases in SPC brine. Data from Novak (1997). Concentrations in moles/kg of brine.

Solution species	**Nesquehonite**	**5424 Hydromagnesite**
Carbonate	9.9×10^{-4}	2.17×10^{-5}
Bicarbonate	2.15×10^{-3}	4.7×10^{-5}
$Th(CO_3)_5^{6-}$	7.2×10^{-4}	3.6×10^{-12}
$Th(OH)_3(CO_3)^-$	5.7×10^{-7}	1.25×10^{-8}
H^+	4.3×10^{-10}	4.3×10^{-10}

Note the predicted dominance of the Th-pentacarbonate complex for the case of solubility controlled by nesquehonite present, even though the dissolved carbonate and bicarbonate concentrations are about a factor of 50 below where one would expect this complex to begin to become important.

The FMT code was developed at Sandia and has not been generally used in the community that does geochemical modeling, nor by the other groups world-wide that do performance assessment of radioactive waste repositories. Over the years, there have been a number of case studies conducted to compare the results of calculations of the same problem using different modeling codes and databases. It has been found that considerable differences in results have occurred, even when the codes were thought to be using the same solution algorithms and databases. It would be more instructive, from the point of view of verification of the FMT calculations, if a more widely used modeling code, such as EQ3 or PHREEQE had been used with the Sandia

database and then FMT had been used with a database from some other modeling group. It would probably be sufficient to do calculations for each brine with nesquehonite and one of the hydromagnesite phases in sequence controlling the carbonate solution levels.

The subject of validation, which is the degree to which the modeling results can be expected to produce a correct representation of a real, complicated, natural situation is not discussed in the EPA evaluation. Validation of a code is normally considered an essential part of code development prior to use in performance assessment.

Note: There are typographical errors in Table 4-2, Step 4, Novak for Th(IV) concentration (should be E-06, not E-09), and Table 4-3, Total Th, verification (b) column (should be E-06, not E-09).

Section 5: "Review of the Uranium (VI) Solubility"

In this section, EPA critically reviews the assumptions used by DOE in estimating the solubility of U(VI). EPA correctly notes that the assumption by DOE that solubility can be estimated for U(VI) in WIPP by assuming that carbonate is absent is incorrect. EPA provides suggestions for U(VI) speciation and for solubility controlling solids. They also correctly assess the relative importance likely for hydrolysis species of U(VI) as compared to carbonate species. It would be most useful if the critical methodology used by EPA for assessment of Section 5 were used to assess Sections 2, 3, and 4.

Section 6: "Actinide solubility uncertainty range"

EPA describes the method used by DOE to develop the estimate of uncertainties in solubility calculations for the actinides. This is most useful, since the CCA and references therein did not provide this information. Solubilities calculated using FMT were compared with the results of

experimental measurements and the deviations between the calculated and measured values were the basis for the uncertainty distribution.

Not all experimental data were used in this evaluation. First, any solubility data with +6 oxidation state for actinides was eliminated because FMT could not calculate for +6 actinides. Experimental data for +4 actinides were also eliminated because "data available for the +4 model were found to have significant problems in the extrapolated regions and were thus determined to be inadequate for this analysis." EPA notes that this position is inconsistent with the statements in the CCA concerning availability of data for Th(IV) speciation in brines.

Elimination of +4 and +6 oxidation states meant that only +3 and +5 data were used in the uncertainty analysis. The distribution of experimental data used was 69% Nd(III)carbonates (104 measurements), 23% Am(III)carbonates, and 7% Np(V) in carbonated brines. Solubility data for Pu(III) data in brines was not included in the analysis, even though these data were used to obtain parameters for the Pitzer coefficients in the calculations.

EPA correctly notes that the estimation of uncertainties for +3 actinides based mainly on Nd data is somewhat problematical since Nd is not an actinide, even though its chemistry might be expected to be similar to +3 actinides. They also note that it is likely that the uncertainties in the solubilities of +4 and +6 actinides should be expected to be larger than those for +3, since it is for these oxidation states that it was found that insufficient data existed to make an analysis of uncertainty. It is particularly difficult to understand how an assessment of how well the Th(IV) data model the expected solubilities for U(IV) and Pu(IV) can be done if no comparisons are ever made between calculations and experimental results. The large changes in calculated Th solubility when changes were made to Pitzer coefficients after unacceptably high Th solubilities were calculated (see Section 4 in EPA review) suggests that uncertainties in predicted solubilities may be considerably higher than those given in the DOE CCA analysis.

The inconsistencies in speciation for Th in the FMT calculations when compared to the original work that derived the thermodynamic properties data that must be used in the calculations also

points to considerably higher uncertainties than the -2 to +1.4 log units cited in the DOE CCA. The EPA concludes that the range cited by DOE is probably adequate and states "It is not clear that including more data for the other actinide oxidation state would appreciably change this range." It is equally true that it is not clear that the range adequately estimates uncertainty for a population for which data has not been examined.

Section 7: "Influence of Ligands and Complexants on Actinide Migration"

In this section EPA's stated purpose was to "determine whether DOE appropriately characterized organic ligands and humic materials on their potential to increase the mobilities of actinides and to evaluate DOE's approaches for representing such processes." EPA concluded that organic ligands will not increase actinide mobility.

EPA provides a lengthy section of introductory material, which describes complexation chemistry and factors that increase mobility of metals through complex ion formation. They then proceed to assume that brine will be present in the WIPP repository and will commingle with the waste during much of the repository's performance period. In essence, this is equivalent to the assumption made by DOE that the system could be modeled assuming homogeneous equilibria of brine and actinides. In other words, both DOE and EPA assumed that the actinides would be evenly distributed throughout the repository and that the brines would be well-mixed and have a uniform composition throughout the repository. This is unlikely to be the case and is certainly not appropriate for evaluation of the development of dissolved actinides inside a partially destroyed waste container, a scenario that is important with respect to assessment of human intrusion consequences.

In the DOE evaluation of the effects of organics and humic substances, the organics are treated in SOTERM as if they were homogeneously dissolved in 29,841 m^3 of brine. DOE then looked at the values of the complexation constants and concluded that EDTA formed the strongest complexes with actinides, so would be the most important organic ligand. EDTA also forms strong complexes with many other cations, so when DOE evaluated the complexation behavior of

EDTA they found that most of the EDTA would be associated with Ni. EPA disputes this conclusion based on their estimate of Ni solubility in nature, but in their own calculations of EDTA behavior they conclude that EDTA will not increase Th(IV) solubility because the EDTA will be complexed with Ca and Mg under alkaline conditions.

The abundance of EDTA in the wastes intended for WIPP is low; in addition, EDTA forms strong complexes with many cations. For both of these reasons it is reasonable to conclude that the EDTA present in the WIPP repository will not lead to an increase in actinide IV mobility. It is not, however, appropriate to conclude from an analysis of EDTA behavior that organic ligands will be unimportant under WIPP conditions. Citrate is the most abundant water-soluble organic constituent in the waste inventory listed in the SOTERM Appendix to the DOE CCA. Citrate forms an extremely strong complex with Th(IV), but much weaker complexes with other cations. For this reason, even in the presence of very high dissolved Ca and Mg, the citrate will preferentially form complex ions with the +4 actinides.

To model the behavior of Pu with citrate, we must also consider heterogeneous equilibria for organic complexation with the actinides. The main difficulty arises because the Pu in the waste is probably located in the same drums as the citrate, which is the dominant organic ligand. This is because these wastes arise from chemical separations of Pu and are not the type of waste described in the general descriptions of TRU waste as contaminated equipment, clothing, etc. To get an accurate estimate of the effect of organic ligands on Pu solubility, one must calculate the concentration of Pu as citrate complex inside a waste drum that has been breached, but can still provide a hindrance to mixing of the brine inside the drum with a larger pool of brine outside the drum. This will give a high concentration of Pu in solution as the citrate complex. Other ions will not compete with Pu sufficiently to prevent complex formation because the stability for (IV) actinide complexation - as shown by the stability constant for Th(IV) on p. 39 of the SOTERM appendix- is orders of magnitude larger than that for other ion complexes with citrate.

EPA discusses some work by Hummel (1993), who reports the effect of organic ligands under high pH conditions in cement pore waters. The high pH conditions do argue against complex

formation by EDTA and other "conventional" organic ligands; however another possible ligand for increasing Pu(IV) solubility comes from the degradation of cellulose under high pH. Work in England has shown that degradation of cellulose can occur both through chemical processes at high pH and by radiation effects. The degradation products have been shown to increase the solubility of plutonium dramatically (Cross et al., 1989; Greenfield et al., 1992).

The discussion of humic substances in the EPA evaluation is very thorough. EPA concludes that DOE has probably overestimated the effect of humic materials on the mobilization of actinides, but agrees that the approach taken by DOE is conservative. The amount of +4 actinide carried by humic materials is estimated to be 6.3 times the amount actually in solution as dissolved species. This overestimation of the importance of humic substances on Pu mobility may balance, in part, the failure to consider the complexation of Pu by citrate. Some relatively simple calculations should be able to provide sufficient information to evaluate the relative importance of the under and overestimation of Pu speciation on total Pu mobility.

Section 8: "Microbial Effects"

EPA discusses the potential for microbial activity in WIPP and concurs with a DOE contractor assessment that "although significant microbial gas production is possible, it is by no means certain." Other aspects of microbial activity are also discussed and noted to have high levels of uncertainty associated with whether the activities will actual happen and, if so, how will they affect actinide mobility. In general, it is concluded that the effects of microbes are most likely overestimated.

The potential overestimation of CO_2 gas production was the driving force for adding MgO backfill to the repository to control the dissolved carbonate content in any possible brines. The use of MgO backfill is not without its own uncertainties. See discussions above concerning reaction products of MgO with brines containing carbonate and the resulting effects on the solubility of +4 actinides. It might be worth trying to get a more realistic picture of the potential for carbon dioxide production and to re-evaluate the need for the MgO in the repository. Another

possibility would be to follow the NRC (NAS) committee recommendation to evaluate use of compartments in the repository. In this way, use of MgO might be confined to regions that had low Pu inventories, thereby reducing the uncertainties associated with increased solubility of Pu in the presence of metastable MgO-carbonates.

On p. 62, EPA states "For undisturbed repository scenarios cellulose degradation products are unlikely to increase actinide concentrations in the aqueous phase." This statement is in direct conflict with the results of extensive studies in England that showed that Pu solubility was greatly increased by the presence of chemical degradation products of cellulose produced at high pH. See the references cited in the previous section (7) for details.

Section 9: "Conclusions and Key Issues"

This section summarizes positions discussed by EPA in sections 2-8. No specific comments are needed, since the issues have been addressed in the introductory General Comments and in the section-by-section comments above.

2.4 SPALLINGS

The blowout of spalled material reaching the accessible environment through an inadvertent human intrusion through a borehole into the WIPP repository could cause major problems with the compliance of the EPA's limit established in the 40 CFR Part 191 (U.S. EPA, 1996). EEG's Letter to F. Marcinowski, dated December 31, 1997 (Appendix 8.3) has shown that spalled volume, based on 100 realizations which have volumes ranging from 8 m^3 to 64 m^3 can violate these standards. However, the CCA and other DOE published results have shown that a blowout would purge less than 4.0 m^3 of waste from the repository, with 0.27 m^3 being a more typical volume (Hansen et al., 1997). Yet, none of the DOE models accurately calculate spall under varying repository conditions. For example, the main codes used to verify the reasonable volumes predicted in the CCA cannot be used under more appropriate waste permeabilities, gas viscosities, and mud drilling densities (from either mud brine or an underbalanced drilling fluid). The models also ignore potentially important failure mechanisms such as shear failure of waste under compression. It is EEG's belief that the issue has not been addressed fully to determine whether compliance with the containment requirements, 40 CFR Part 191.13 has been met. Therefore, it is recommended that EPA require DOE to develop a new model, which incorporates all the processes involved with spall. This is particularly important since spallings has the potential to returning more waste to the biosphere than any other human intrusion scenario.

2.4.1 Definition

Spall is waste that has been introduced into the drilling fluid due to radially channeled, highly pressurized gas flow from within the repository to a lower pressure borehole. Gas will continue to flow until the system comes to pressure equilibrium between the repository and the borehole. The high flow rates of gas will cause some of the waste material to fail in tension or shear, break off from the borehole cavity, and be introduced into the return stream of the drilling fluid. If gas flow is sufficiently high, it will force all the drilling fluid out of the borehole to the surface. This phenomenon is known as blowout, and is a common occurrence among drilling rigs encountering pressurized pockets of natural gas.

Spall can also occur by the mechanisms of stuck pipe and gas-induced erosion. These phenomena may dominate a spalled event if the gas flows are too low to cause blowout. Stuck pipe is a process of spall that, due to very low permeability and extremely high repository pressures, may cause failed waste to press against the drill string sufficiently hard to prevent normal drilling. The solution for a jammed bit is to pull the drill string up and start drilling again. If the pressures remain high, the driller may have to bring the bit up several times, thus allowing significant quantities of waste to be brought to the surface through the return stream of the drilling mud. Gas erosion is spall that is eroded by the drilling mud due to high repository pressures and low waste permeability. The spall from gas erosion is slower than stuck pipe due to slightly lower pressures in the repository (just above hydrostatic), and may release waste into the drilling mud at a rate undetectable by the driller. Gas erosion would continue until the repository pressure is in equilibrium with the drilling fluid, and may also bring significant quantities of waste to the surface.

When applying the terms of stuck pipe and gas erosion to the disposal system, slightly different definitions may be in order. Stuck pipe and gas erosion releases have been said to occur if the waste permeability is less than $1x10^{-16}$ m^2, as stated in Berglund (1994), and repository pressures are greater than the pressure exerted by the drilling mud (above hydrostatic). The CCA states that the waste permeability can be represented by a constant value of $1.7x10^{-13}$ m^2, which is much greater than the threshold for stuck pipe to occur. Additional studies show that waste surrogates based on current understanding of waste mixtures could have a permeability of $2.1x10^{-15}$ to $5.3x10^{-15}$ m^2 (Hansen et al., 1997), and that the threshold for blowout to cease and stuck pipe / gas erosion to begin is questionable (EEG letter dated Dec. 31, 1997 - Appendix 8.3).

The single representation of waste permeability by DOE was a necessity, based on flow model calculations of brine and gas through the repository in the two-phase flow code, BRAGFLO. The geometry of the disposal system in BRAGFLO only designated 21 cells for the waste area and many of these cells were on the order of 44 meters wide by 1.32 meters high. The spatial variability of the waste permeability could not be accurately implemented in these few large cells, and a constant homogeneous waste was more appropriate. When the scale of modeling reduces

from the entire disposal system to repository room size, or even smaller (a few meters around a borehole intrusion), then the variations in waste permeability should also be on a smaller scale for the local conditions.

2.4.2 Calculation of Spallings

The DOE has calculated the amount of material that will spall through a blowout. The code CUTTINGS_S (U.S. DOE, 1996c-Appendix CUTTINGS_S) incorporates the spallings calculations with calculations of the amount of cuttings and cavings from a drill string drilling through the repository. The calculations showed that a maximum of 4.0 m^3 would spall in the borehole cavity and be transported out of the borehole to the surface. However, an independent peer review found the code to be conceptually flawed. The DOE's Conceptual Model Peer Review Group (U.S. DOE, 1996c-Appendix Peer 1) stated that the "Development of this [spallings] model is not sufficiently complete to determine uncertainties specific to the channel movement of waste to the existing borehole". The threshold for waste permeability and stuck pipe to occur was also based on the findings of this code.

The spallings volume was re-calculated by using a second code, GASOUT (Shatz, 1997), along with several other methods, to assess whether the results of the spalled material calculated in the CCA were reasonable. The GASOUT code was accepted by the Conceptual Model Peer Review Group (Wilson et al., 1997) based only on the conceptual model, without any independent testing or validation. Calculations with the GASOUT yielded a maximum of 0.27 m^3 to reach the accessible environment upon a breach (Hansen et al., 1997). The main assumptions used in the code to derive the calculated volume was a waste permeability of 1.7×10^{-13} m^2, a repository pressure of 14.8 MPa, and a waste tensile strength of 10 psi (0.068 MPa). Despite better understanding of the waste and measured values of the waste permeability, 4.0×10^{-15}, as described in Hansen et al. (1997), the CCA value of permeability (1.7×10^{-13}) was used for this investigation.

GASOUT uses a semi-analytic approach of a mechanistic conceptual model that couples the numerical calculations of a finite difference fluid flow code and a finite element rock mechanics code. This approach has been dubbed "the cavity growth method", because it progressively calculates the region of radial tensile failure within the cavity. Hansen et al. (1997) showed that there is no tensile failure of waste below repository gas pressures of 14 MPa "under realistic but conservative assumptions".

The conceptual model of the code during the blowout process was described as being divided into two stages. The first stage is characterized by the ejection of the drilling mud by high pressure gases, and the response of the waste to the high pressure gradients during blowout. Following the blowout, the second stage is identified by the rapid flow of gas from the repository, including the entrainment of solid waste particles. In the first stage of initial depressurization, gas velocities are small while the mud column is being expelled from the borehole. The velocities will increase during stage two, as the borehole path is clear for rapid gas movement. The larger eroded waste particles will typically be lofted to the surface during this stage. It must be noted that confidence in the GASOUT code can only be placed on the calculations during early times of the first stage. Late times of stage one would involve the decompression of the waste gas, which is not incoporated into the model.

In addition to the analysis using GASOUT, a "quasi-static" and "fully coupled" approach to solve the spallings problem was employed by DOE. The quasi-static used a spread sheet analysis to solve the porous flow equations by a sequence of steady state profiles (Hansen et al., 1997, pg. 3-24), and the conceptual model used in the quasi-static was identical to the cavity growth (GASOUT) method. The major difference in the two models is that the cavity within the quasi-static model does not increase with the calculation of tensile failed waste removal. The results from the GASOUT calculation without failed material removal (removal of failed material is a toggle switch that can be turned on and off in the code), show almost perfect agreement with the quasi-static results under identical initial assumptions. The differences in the two methods are established very early in the conceptual and mathematical model of the system. GASOUT assumes a transient pressure response in the flow calculations, whereas the quasi-static method

assumes a series of steady state calculations. Steady state ignores some very important features of pressure flow with respect to time. Tensile failed material calculations for the quasi-static model showed a 1.17 m^3 of spall with initial pressure conditions of 14.7 MPa and tensile strength of 15 psi (inferred from effective stress calculations). The cavity growth model calculated an equivalent 0.07 m^3 of spall.

The fully coupled approach used a purely numerical code (as opposed to the semi-analytic approach in GASOUT) to calculate the flow of gas within the waste region to the intruded borehole. The mathematical model of the fully coupled approach assumes a one-way coupling of the two-phase pressure decay following an intrusion with a decoupled two-phase pressure response within the simulated waste region. The fluid flow and waste pressure response were solved by the code TOUGH28W with the poromechanical waste response of stress and strain invoked in the code SPECTROM-32.

Though the code did not explicitly calculate failure, it did calculate the effective stresses within the waste. From the results using SPECTROM-32, the normal effective stresses (tensile stresses) shows a semi-hemispherical distribution at very early times. If the initial assumptions are 14.8 MPa, and the waste failure criterion is 10 psi, then the code would indicate a brittle elastic failure radius of 0.8 m (Hansen et al., 1997-Figure 4..4-1.-9, time=0.001 s), or 2.1 m^3 uncompacted volume. The same figure shows a stress distribution extended out to one second, but without considering the possibility of waste removal. The removed waste would have a significant impact on the stresses in the cavity.

2.4.3 The EEG's Concerns on Spallings

2.4.3.1 Waste Permeability and the Stuck Pipe Scenario:

The permeability of waste in the WIPP repository and its effect on stuck pipe and gas erosion were not adequately addressed in the performance assessment calculations of the CCA and PAVT. The constant value of 1.7×10^{-13} m^2 used for waste permeability in the CCA was based on an investigation of waste materials by Luker, Thompson, and Butcher (1991) in which a single value, homogeneous waste was needed for code calculations with BRAGFLO. The calculation of

the permeability assumed that 40% of the waste volume was comprised of combustibles (45% Material 1, 37% Material 2, 9% 1-inch metal parts, 9% dry Portland cement), 40% metals and glass (50% 1-inch metal parts, 50% magnetite), and 20% sludge (assumed to be ordinary Portland cement cured for 130 days). The mean values used for the separate waste types are 1.7×10^{-14} m^2, 5.0×10^{-14} m^2, and 1.2×10^{-16} m^2 for combustibles, metals, and sludges, respectively. The mean values as reported above inherently assume a range of permeability values, and these ranges can be seen in Table 2. Table 2 reports the minimum, median, and maximum from each waste type assumed in the calculation of the permeability value in the CCA as reported in Butcher (1990).

The calculation for the permeability assumed flow parallel to layers of waste. Each waste type was a separate layer in the drum, and the permeability was calculated by:

$$K_{eff} = \frac{1}{V} \sum_{i=1}^{3} V_i k_i ,$$

where V is the total volume, V_i is the volume of the ith component and k_i is the permeability of the ith component. The ith component of k is represented by the median value from Table 1. The volumes of each type of material were also considered in calculating the effective permeability of a drum. For the CCA, 40% combustibles, 40% metals, and 20% sludges were assumed from an average waste drum volume (U.S. DOE, 1996c-Appendix Peer 5). These values also varied from the different drum samples, and from defense site. The Los Alamos National Laboratory volume (by percentage) of combustibles had an averaged value of 20, whereas the Savannah River Plant averaged 70 (Butcher, 1989-Table 2). These variances in volume could cause the expected value of 1.7×10^{-13} to decrease significantly.

A strict calculation of permeability can be a dual-edged sword. The assumption that flow will be parallel to the artificial layers in each drum may be conservative for the calculation of maximum

	Min	Med	Max
Combustibles (m^2)	2.00E-15	1.70E-14	2.00E-13
Metals (m^2)	4.00E-15	5.00E-13	1.20E-12
Sludge (m^2)	1.10E-17	1.20E-16	1.70E-16

Table 2. Permeability Values Used to Calculate Waste Permeability in the CCA.

flow of gas and brine in the repository, yet nonconservative when considering the damaging effects of stuck pipe (and / or gas erosion) from a lower permeability. A lower permeability can be calculated if flow is assumed to be perpendicular to the waste layers. In this assumption, the lowest permeability layer will contribute largely to an effective permeability of the waste. With a perpendicular flow assumption, the effective permeability could be as low as 5.9×10^{-16} m^2. Therefore, the parallel flow is arbitrary, and could be seen as a nonconservative calculation.

In addition to the variability in permeability, the conceptual model review of the CCA (U.S. DOE, 1996c-Appendix Peer 5) agreed that the ranges should be assigned constructed distributions, as opposed to the above mean permeability values, which were mean values of a uniform distribution. Therefore, the new mean values for combustibles, metals, and sludges were given as 5.9×10^{-14}, 5.5×10^{-13}, and 1.05×10^{-16}, resulting in a K_{eff} of 2.4×10^{-13} m^2. This value of permeability was used in the EPA's Performance Assessment Verification Test (PAVT), and was also recommended by the EEG (EEG Letter to F. Marcinowski on March 14, 1997 - Appendix 8.2 of this report) to be more conservative with respect to gas and brine flow in the repository.

To clarify the misunderstanding on apparent conflicting recommendations by the EEG on waste permeability on separate occasions, one must remember the context in which the recommendations were given. The March 14 letter to Frank Marcinowski recommended a value of 2.4×10^{-13} m^2 for the calculation of gas and brine flow within the repository. This value was 1) for use in BRAGFLO, where the spatial variability of heterogeneity is limited to a small number of grid cells and 2) made before the issuance of a new spallings model which showed that stuck pipe and gas erosion could become valid scenarios during a drill intrusion. Therefore, EEG's recommendation (Neill, 1997, Appendix 8.3) given to the EPA that the waste permeability should include variances in all models still remains valid.

Calculations of waste permeability from discrete layers of different waste material in the drums is inherently incorrect. In reality, the waste in the drums emplaced at the WIPP will be heterogeneously mixed, not in distinct layers, and the test specimens from Butcher (1990), and Luker et al. (1991) should have included a mixture of all waste types. A new set of permeability

measurements from Hansen et al. (1997) report that the permeability of waste could be as low as 2.1×10^{-15} m^2 with a typical value of 4×10^{-15} m^2, using heterogeneously mixed waste. These specimens assume 63% metal (iron), 9.6% glass, 6.75% cellulosics, 11.6% crushed rock and cement, 4.8% soil, and 4.5% crushed salt. The permeability was conducted on a specimen containing most types of waste. It cannot be overly stressed that the measurements conducted in Hansen et al. (1997) are actual measurements on waste surrogates. The surrogates were constructed based on a deeper understanding of potentially degraded waste in future repository conditions and included waste forms of 50 and 100% degradation. The measured values are as much as two orders of magnitude lower than the calculated values used in the CCA. Again, calculated values should signal that the values are arbitrary, and do not account for variability in the waste.

In addition to the problems with the waste permeability on the use of measured vs. calculated values, it must also be stated that none of the permeability measurements were on samples that included MgO. The Particle Size Expert Elicitation Panel (U.S. DOE, 1997a) states that corrosion products, dissolved MgO and salt from brine that do not precipitate out as particulates will cement together. Cementation was a major contributor to the projected increase in waste strength to 77 Pa, and MgO is said to occupy 25.5% of the room volume after closure. The panel specifically defined the waste to mean waste plus backfill (U.S. DOE, 1997a).

The permeability of MgO as an additive to Portland cement has been studied by Zheng et al. (1991), and was found to have roughly the same permeability as Portland cement. They noted that higher percentages of MgO would result in higher permeabilities. It therefore follows that the permeability of cemented MgO is at the upper end of Portland cement, approximately 1.05×10^{-16} m^2 for sludges. In addition to lower permeability, the effects of MgO will increase waste strength in some localized areas. Permeability and strength are inversely correlated. Yet, if permeability and strength measurements taken on waste surrogate specimens with MgO are to be ignored based on conservatism, it must be remembered that the waste strength of specimens which varied between 5 to 15 psi in Hansen et al. (1997) also had permeability values on the order of 4×10^{-15} m^2. So, if a permeability, lower than that used in the CCA (and consequently in the

PAVT), is used in a model as more representative repository conditions measured values from Hansen et al. (1997), the waste tensile strength from the same report should also be used.

Keeping in mind that the values used in the calculations were median values from a range of possible permeabilities, the waste permeability could be lower. The median permeability ranged in the CCA from 10^{-12} to 10^{-16} m^2 (U.S. DOE, 1996c). Therefore, the single value of waste permeability used in the CCA does not fully represent the possible range of values that could exist in the repository.

Recommendations for Waste Permeability and Stuck Pipe:

Again, to clarify the EEG's position for waste permeability stated in the March 14, 1997 letter to EPA (Appendix 8.2), it seems as though two contradictory positions were taken. In the position statement on waste permeability used in the direct brine release calculation, EEG suggested a value of 2.4×10^{-13} m^2 be used instead of 1.7×10^{-13} m^2, "if a single value for consolidated waste permeability is to be used for direct brine release". In the position statement on the spallings model, EEG stated that the CCA reported an uncertainty range of 10^{-12} m^2 to 10^{-16} m^2 for compacted repository waste permeability. It is possible that precipitation of magnesium chloride cement and salt would reduce permeability below this range. The EEG recommended that "a more realistic value or range of values should be assumed for the waste permeability parameter and the potential for gas erosion and the stuck pipe processes be included in the spallings scenario with a better defined permeability-pressure threshold".

The spallings investigation documented in Hansen et al., (1997) contains results from permeability measurements of surrogate waste material that provide a much better basis for assigning waste permeability values. The permeability measurements do not include samples that contained magnesium chloride cement and, thus do not represent the lower bound of potential compacted waste permeability.

It is essential that the sensitivity of the Hansen et al., (1997) spallings model to waste permeability be investigated before the EPA can conclude that the spallings model used in the performance

assessment is indeed conservative as stated in the proposed rule. Unless further additional measurements on surrogate waste that includes magnesium chloride cement are available, the range of 10^{-12} to 10^{-16} m^2 is a reasonable range to investigate the sensitivity of the spallings model to permeability variation. If it is found that the model predicts greater spall volumes in this range than calculated in the performance assessment then the measurements of surrogate waste with magnesium chloride cement should be conducted to define the range more closely.

Blowout is not the only mechanism for releases to the surface. Unless it can be shown that entrainment of spall into the drilling mud (gas erosion) or re-drilling by the operator (stuck pipe) will be limited, it should be assumed that all of the calculated spall material will reach the surface.

2.4.3.2 DOE's Model Predictions of Spallings:

It is clear that the prediction of spalled material from the result of a borehole intrusion into the repository is difficult to quantify. The original model used in the CCA, developed by Berglund (1994), oversimplified the process, and therefore was judged as inadequate by the Conceptual Model's Peer Review Panel (U.S. DOE, 1996c, Appendix Peer 1). However, the results of the model were defended as being reasonable for use in the CCA, by presenting additional models which showed lower spalled release upon an intrusion. Therefore, the spallings values calculated in the CCA were considered by the DOE to be the maximum reasonable values that could be brought to the surface during a breach.

The spallings' volumes that were calculated in the CCA ranged from 0.5 m^3 to 4.0 m^3, and were subsequently used in the PAVT. The new prediction, with a more accurate set of models showed the maximum release to be 0.27 m^3. The new model used the lowest measured waste strength and the highest possible repository pressures that could be sustained for long time periods. At higher waste strengths and lower pressures, the analysis predicted much smaller volumes. However, EEG believes that the initial assumptions used in the models simulations do not accurately portray all repository conditions, and that under different circumstances the models can predict higher spalled volumes. EEG also believes that the models are inadequate to quantify the maximum possible releases due to limitations in the conceptual model development and code

implementation. Therefore, the results presented in Hansen et al. (1997) are not actually maximum calculated releases, but only a set of calculated releases under certain repository conditions. The following discussion shows the limitations of the analyses presented in Hansen et al. (1997).

Three methods were used for the analysis of spallings in Hansen et al. (1997): 1) cavity growth method (implemented in the code GASOUT), 2) quasi-static method (implemented in two spread sheet files called P145APC4, and S145APC4), and 3) fully coupled method (used to existing codes, TOUGH28 and SPECTROM32). The results for comparison of the CCA volumes came from the cavity growth method, since this method was the most realistic, physically. The cavity growth allows for material removal during failure calculations, and hence the pore pressures are redistributed at the new boundary. The other two methods strictly calculate the effective stresses in the waste (the difference in the total stress of the overburden rock and pore pressure), and failure is interpolated. These other methods were used to verify the cavity growth model and are explained above in more detail.

The sensitivity of the GASOUT code was studied by EEG, in which permeability, viscosity, and mud density were examined over reasonable repository conditions. For example, the permeability could range between 10^{-12} and 10^{-16} m^2, but was restricted to 10^{-15} m^2 for this analysis. The viscosity of the repository gas could also vary, depending on which gases are produced. This next section presents highlights from a formal sensitivity analysis conducted by the EEG on GASOUT (Rucker, 1998).

Sensitivity to Permeability and Initial Repository Pressure

The GASOUT code was seen to be very insensitive to the initial permeability value chosen in this study. However, the code's use of a narrow range of values kept the sensitivity analysis to a minimum, and true sensitivity could not be established. The range of acceptable permeability values narrowed as the initial repository pressure increased, and waste tensile strength decreased.

Initially, the permeability used in the CCA of $1.7x10^{-13}$ m^2 was assumed in the present study to allow comparisons with the results in Hansen et al. (1997), despite a better understanding of permeability investigated in that report. The single value used in the CCA is under question, as it was calculated from assumed future waste conditions.

The results of spalled material failing in a borehole cavity using GASOUT over a wide range of permeabilities were not meaningful, and the code was simulated using a very narrow range. For the Base Case simulation for example, the waste permeability could only range from $0.8x10^{-13}$ to $4.4x10^{-13}$ m^2. Above and below these permeabilities, the code predicted extremely large failed volumes. The results of the failed volume versus the permeability range that was applicable for a five second simulation can be seen in Figure 3. The figure shows results of varying waste tensile strength, from 10 to 20 psi. The three curves represented in the figure give the upper and lower bounds of the permeability that result in meaningful values.

The reported failed volumes outside the range for the Base Case are extremely high, resulting in as much as 22.5 m^3 for a permeability of $0.5x10^{-13}$ m^2 due to the cascading affect of multiple zone failure. The geometry of the borehole cavity was discretized and solved on a hemispherical coordinate system. The layers of the hemisphere were kept to a minimum (0.01 meters) to avoid instability. When the waste in the borehole fails, it is assumed that the whole layer fails, and peels off like an onion skin. When the code calculates a large failed volume, as in the case with $0.5x10^{-13}$ m^2 permeability, the effect is several layers peeling off in one time step, cascading until an equilibrium is reached with the high pressure gradient that existed at a longer time period. It is assumed that when the cascading effect is exhibited, the results become meaningless.

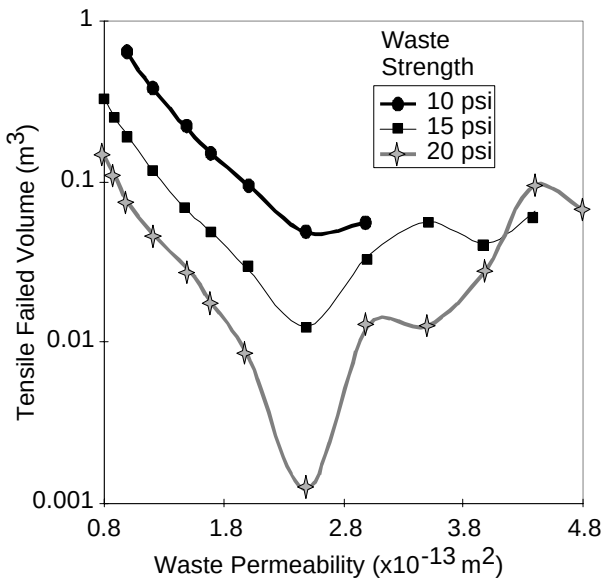

Figure 3. Contiguous Failed Volume as a Function of Increasing Waste Permeability for Different Waste Strengths With Initial Repository Pressure of 14.5 MPa.

Figure 3 shows some interesting results as the waste permeability increases. All the waste strengths tested showed an exponentially decreasing failed volume, up to a permeability of 2.5×10^{-13} m^2. Permeabilities above this value cause larger failed volumes than values below it. The upper limit on permeability shows that the code is reliable to 2.5×10^{-15} m^2 for waste strengths that were measured in the report by Hansen et al. (1997) and initial repository pressure of 14.5 MPa. The lower permeability limit is 1.0×10^{-13} m^2 for 10 psi waste strength, and decreases to 0.8×10^{-13} m^2 for waste strengths of 15 and 20 psi.

When the initial pressure is increased to its maximum of 14.8 MPa, the range is more narrow than discussed above. For all waste strengths investigated, confidence was only in waste permeabilities between 1.7×10^{-13} m^2 and 2.0×10^{-13} m^2. The narrow range that the code is applicable decreases the likelihood that the code can represent the disposal system accurately, and should be modified to allow more representative values to be modeled.

The simulation of the repository with a homogeneous waste in GASOUT is an over simplification of the repository model. It is much more likely that the waste permeability will actually be lower than that assumed in the CCA. The representation of a random permeability was explored in Hansen et al. (1997) using a fully coupled numerical code to solve the flow of gas through the repository. TOUGH28W did not calculate the amount of waste failure, but could calculate the pressure distribution through the waste for varying conditions. The code showed that a lower permeability, with values ranging from $1x10^{-12}$ to $1x10^{-16}$ m^2 would have a much higher pressure gradient near the borehole, than the permeability assumed in the CCA. It also showed that homogeneous waste with lower permeabilities will have higher pressure gradients. Higher gradient will produce lower total stresses of the overburden rock, and lower effective stresses in the waste. This further strengthens the argument for modifying GASOUT to represent the repository more accurately.

Sensitivity of Gas Viscosity

The gas viscosity parameter, along with porosity and permeability, is used to calculate the hydraulic conductivity of gas through porous media, K, by the relationship of

$$K = \frac{\mathrm{k}}{2fm}$$

where k is permeability, ϕ is porosity, and μ is gas viscosity. The original equation for the flow of gas through porous media can be found in Chan et al. (1993) , and is equivalent to the non-linear diffusion equation. The viscosity of in the equation above is indirectly proportional to the gas conductivity, and as viscosity increases, conductivity decreases. The relationship also shows that a constant ratio of permeability to viscosity will yield the same conductivity.

The experiment with permeability demonstrated that values less than $1x10^{-13}$ m^2 for an initial pressure of 14.5 MPa would render the results meaningless. The viscosity used in the experiments was $10x10^{-6}$ Pa*s, and the ratio of permeability to viscosity yields $1x10^{-8}$. Values less than this ratio will cause the code to predict cascading failure of waste. If the original permeability is $1.7x10^{-13}$ m^2, then viscosity values greater than $17x10^{-6}$ Pa*s will cause the code to give erroneous results. The ratio for failure increases to $1.7x10^{-8}$ for initial repository pressure of 14.8 MPa and waste tensile strength of 10 psi. A simulation with the ratio of $1x10^{-8}$ m^2/Pa/s and for an initial pressure of 14.5 MPa and tensile waste strength of 10 psi yields a failed volume of 0.63 m^3.

The possibility of larger viscosity values is not ill conceived. The viscosity value obtained for ydrogen gas was the standard temperature and pressure value (STP), and viscosity will increase moderately as pressure or temperature increases.

The components of the repository gas will also increase the viscosity. Through microbial degradation of plastics, rubbers, and other combustible material in the repository, O_2, CO_2, CH_4, N_2, N_2O and H_2S will be created. Francis et al. (1997) conducted experiments of microbial gas generation under expected WIPP repository conditions and found that the percentage of N_2 varied between 61.9% to 91.4%, CO_2 varied between 0.4% and 34.3%, and H_2 varied between 0% and 12.8%. These other constituents have a much higher viscosity than H_2, with N_2 being as high as $19.2x10^{-6}$ Pa*s (STP), which will undoubtedly increase with an increased repository pressure.

Even though microbial degradation may create higher quantities of CO_2, and N_2 than H_2, the process itself will be limited. It is uncertain if the colonies of microbes will exist under repository conditions, and was assigned a 50% chance in the CCA.

Iron corrosion on the other hand will produce massive quantities of H_2 and it is certain that iron will corrode when brine fills the repository. Approximately $2x10^9$ moles of H_2 (Telander et al., 1996) will be produced from the iron in WIPP. However, the other gaseous constituents could play a small role if microbial degradation does produce gas. In Appendix MASS of the CCA, Figure MASS-1 (U.S. DOE, 1996c, Appendix MASS) shows that at lithostatic pressure, if the mole fraction of H_2 to CO_2 is reduced from 100% to 90%, then the viscosity would increase from $9x10^{-6}$ Pa*s to $16x10^{-6}$ Pa*s. Therefore, it is suggested that the code be modified to allow a larger spectrum of values to be modeled.

Sensitivity to Mud Column Density

The density of the mud column in the borehole is dependent on the type of drilling mud used. For the WIPP, it is most likely that the drilling mud will come from the Salado Formation with additives to increase the average mud density to 10 - 11 lb/gal (1200-1320 kg/m^3). The GASOUT code used a density of 1249.3 kg/m^3 in the Hansen Investigation, and it is possible that this value could vary over the range mentioned above.

Figure 4 shows the results of varying the parameter from 1200 to 1320 kg/m^3 for a 10 second simulation and an initial repository pressure of 14.8 MPa. The figure shows three curves of different waste strength, with all other parameters remaining the same as used in the Base Case simulation. The most outstanding feature of Figure 4 is the disjointed curve of failed waste (left) and mud motion (right) of the 10 psi tensile waste strength simulation. The code had trouble calculating failed waste for mud densities below 1228 kg/m^3, resulting in the cascading affect described above. The code also had trouble at 1240 and 1250 kg/m^3, and if results were plotted for these densities (failed waste and mud motion), sharp spikes would exist in the curve.

For the higher waste strengths (and subsequently lower repository pressures) of 15 and 20 psi, the mud density simulations were able to calculate failed volumes for all density values investigated. However, the results seemed almost as unreliable as the lower waste strength. Though a trend can be seen in the failed volume and mud motion, variances from those trends are high. Both graphs in Figure 4. show trouble with densities between 1230 to 1270 kg/m^3.

Sensitivity to Waste Porosity

Lastly, the code was investigated to test the effect of waste failure with decreasing porosity. If the porosity is lower, then the velocity of the gas moving through the repository to a borehole intrusion is higher. The report by Hansen and coworkers report a porosity of 0.7, which was said to be typical of waste porosity when the pressure reached over 14.8 MPa. However, after investigating the relationship between pressure and porosity, it was found that porosity during the long-term performance of the repository was approximately 0.4 for high pressures, and less for lower pressures. Figure 5 shows the relationship of porosity to pressure for the

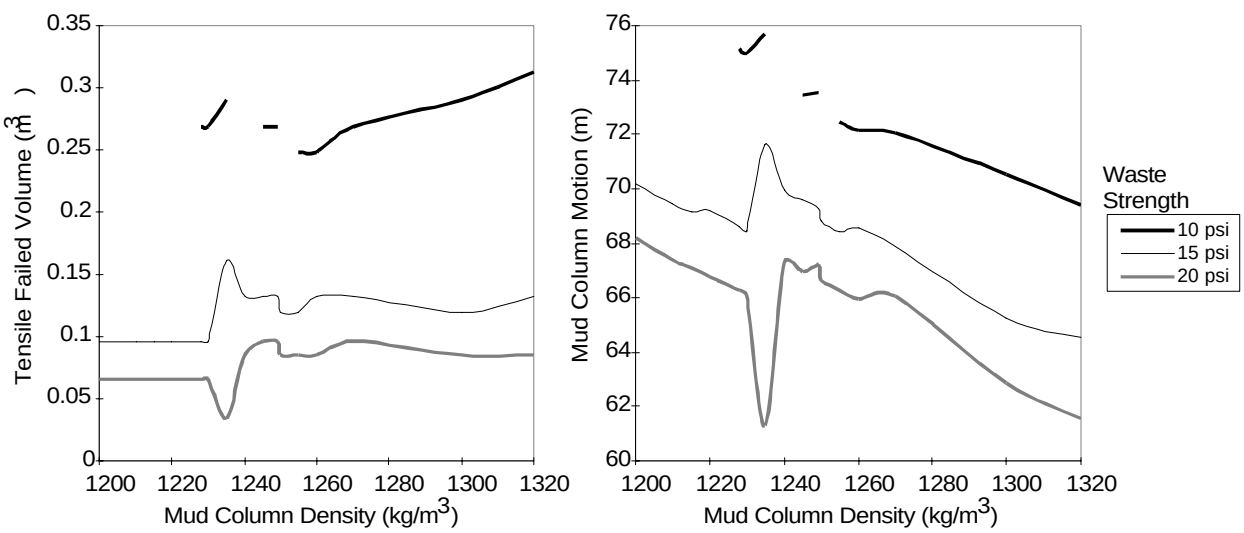

Figure 4. Left) Tensile Failed Volume as a Function of Mud Column Density for Several Waste Strengths. Right) Mud Column Motion as a Function of Mud Column Density. The Discontinuous Curve for the Low Waste Strength of 10 psi Indicates Cascading of Failed Waste at the Values Chosen for the Experiment.

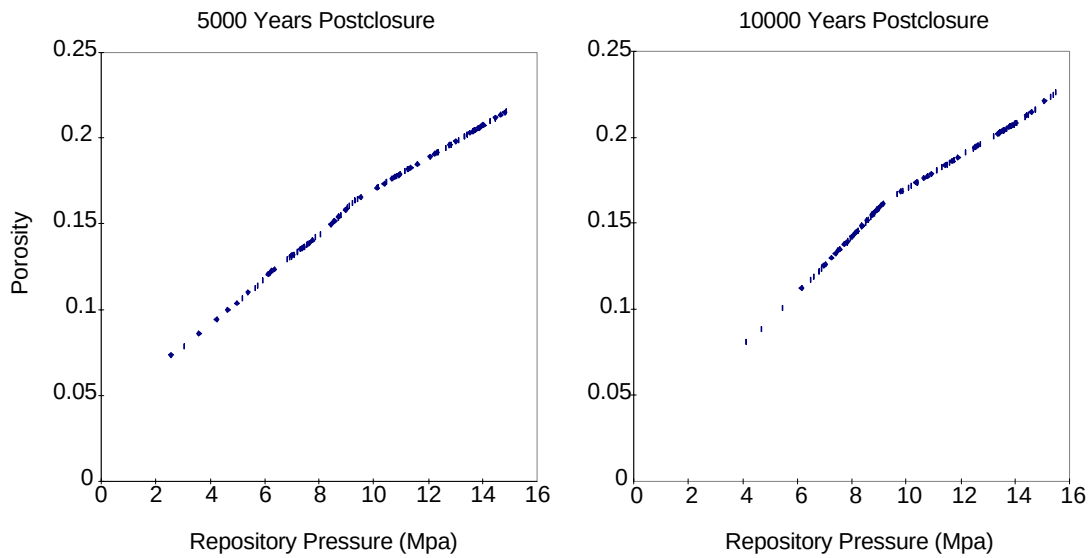

Figure 5. BRAGFLO Porosity Values Versus Pressure Profiles for Undisturbed Scenarios of the CCA.

undisturbed scenario of the performance assessment for the CCA. The figure shows two separate times, at 5000 and 10000 years postclosure using the results of BRAGFLO. The figure reports porosities assuming no compaction of the waste form from consolidation of halite creep. If the room is assumed to shrink by half, then the porosities would double. On this assumption, the actual waste porosities in the repository would be double that of the figure for a given pressure.

Porosity from the two-phase calculations of brine and gas flow through the repository clearly will be lower than anticipated in GASOUT. The response of the code to lower repository porosities shows slightly higher releases. For an extremely low porosity of 0.2, with initial conditions of 14.8 MPa repository pressure, and 10 psi waste strength, the uncompacted spalled volume is 0.47 m^3, and decreases smoothly up to the original porosity of 0.7 and a calculated failed volume of 0.27 m^3. However, porosities above 0.7 and below 0.2 cause the waste to cascade, and results are interpreted as numerical artifacts. Additional experiments using a variety of repository pressures and their expected porosities from Figure 5, does not show any further problems within the code.

-end

In addition to the cavity growth experiments with GASOUT, the option of failed material removal was "turned off", and the affects of decreased permeability was studied again. The surprise result of this new set of calculations shows that the effective stresses in the waste are significantly high to cause radial failure beyond the assumed 0.27 m^3, as presented in Hansen et al. (1997). Figure 6 shows an analogous model for permeability assuming both with and without material failure. The left plot of the figure shows a common scenario with initial repository pressures at 14.5 MPa, permeability equal to 1.7×10^{-13} m^2 and the results from GASOUT with both options of material failure. It shows that material removal produces higher failed volumes than calculations without material removal. The right plot, again with 14.5 MPa initial repository pressure, shows results of GASOUT without material removal for two permeability values. The option for material removal was turned off due to the observations of the above sensitivity analysis. The set of curves on the right-hand-side shows that lower waste permeability produces higher volumes. It therefore can be deduced that if low permeability and waste failure removal calculations are initiated, then the volumes of failed material may be even greater than seen on either plot of Figure 6 It is unknown the exact extent to which material failure will increase. It is plausible that system could attain equilibrium quicker, and the differences are insignificant

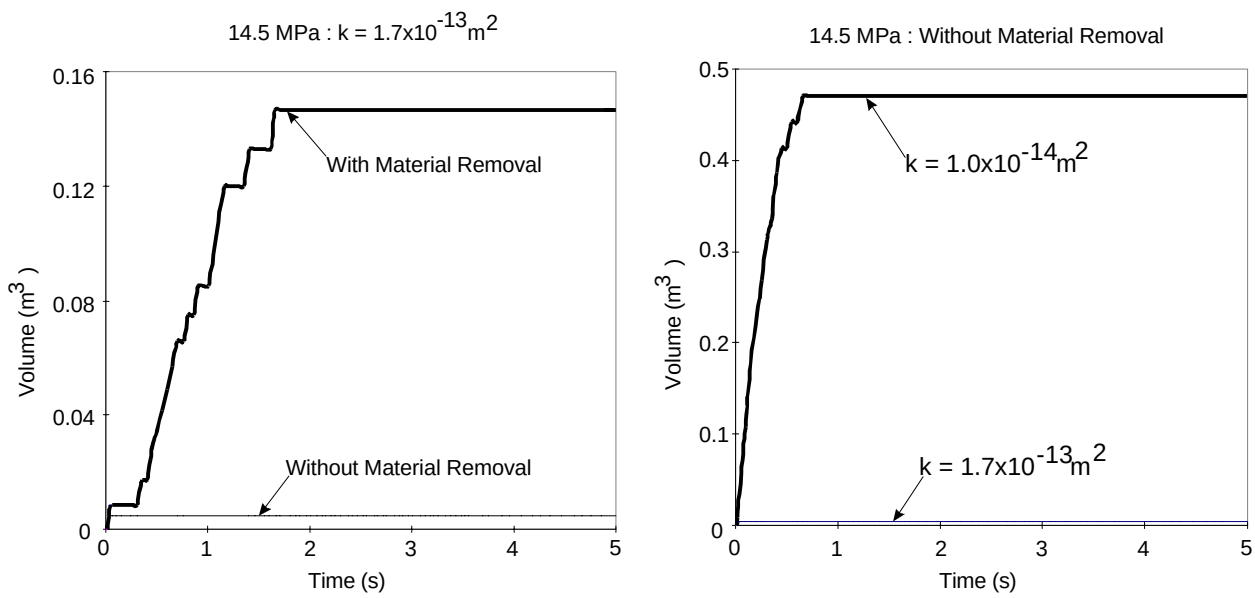

Figure 6. GASOUT Analogy Illustrating The Importance Of Considering Lower Permeabilities. Left) Constant Permeability With And Without Material Removal. Right) Without Material Removal At Two Different Permeabilities.

For an extreme example of the above analogy, Figure 7 shows radial distance of potential failure at permeabilities of 1.7×10^{-13} and 1×10^{-14} m^2 for pressures at 14.8 MPa without material removal. Potential failure was extrapolated from the effective stresses that would exist in non-failed material. The repository pressure was set at 14.8 MPa and waste strength at 10 psi for the experiments in Figure 7.

The figure clearly shows that when permeability is lower than assumed in the CCA then releases will be higher than assumed from the investigation in Hansen et al. (1997). The maximum radial failure at a permeability of 1×10^{-14} m^2 is 1.17 m, equating to an uncompacted spalled volume of 6.6 m^3. It is believed that when permeability is even lower than the lowest value presented in Figure 7, the releases could be higher. However, the code has difficulties with oscillations in pressures at lower permeabilities, and confidence in results is low.

The results of Figure 7 must be kept in context. When material is not removed during the pore pressure calculations (and subsequently total overburden stress), the code does not redistribute values at the new boundary. Instead, the pore pressures decrease in that region, hence lowering the possibility of new failed material. Therefore, Figure 7 actually underestimates the potential effect of failure, and higher volumes will result if the material is removed. These calculations are not possible with GASOUT, with reasons explained from the sensitivity analysis with the code.

Lastly, the issue of shear failure of waste has been eliminated from spall calculations in Hansen et al. (1997) due to its suspected low consequence on overall spall releases. The report by Dr. Frank Hansen and group state that material that fails in shear will not necessarily fragment, and that the region of shear failure is generally less than or equal to the region of tensile failure. The response to the first half of the statement on fragmentation suggests a large degree of uncertainty. The waste will have a residual shear strength component remaining after failure if it does not fragment. Since the nature of the waste already has such a low compressive strength, residual strength after failure will be nominal at best (assuming inelasticity). An average value of 0.75 MPa for shear strength was measured with partially saturated waste surrogates and partially degraded waste forms. After failure, it is assumed that the stresses needed to deform the waste is

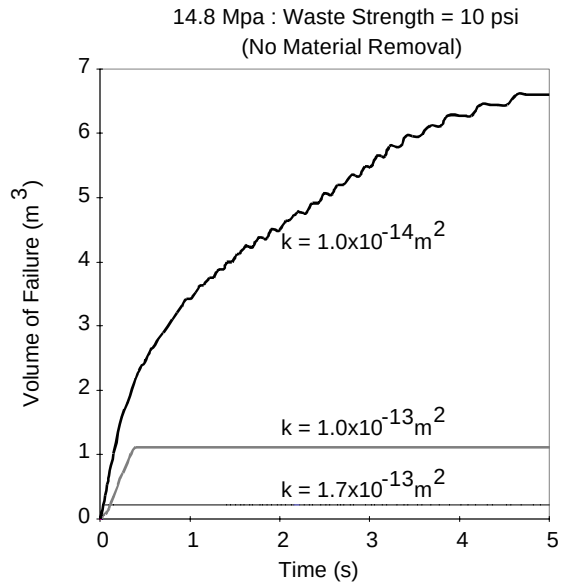

Figure 7. Failure Volume (m^3) vs Time (s) for Different Waste Permeabilities. The results are from GASOUT with the option of 'failed material removal' turned off.

much less, and that the simple act of erosion from the circulating drilling fluid would cause the material to fragment. Therefore, it is conservative to assume that waste failed in shear is totally fragmented.

Considering the region of shear failure, there are some circumstances in which it would be larger than the tensile failed region. Figure 8 shows a calculation by GASOUT without material removal for a typical case of 14.5 MPa repository pressure and permeability of 1.7×10^{-13} m^2. The left plot shows the normal effective stresses in the waste with the tensile strength (dotted line) and the right plot shows shear effective stresses with maximum shear strength. The figure on the left demonstrates that the tensile failed radius will be approximately 0.17 m. The initial borehole radius is 0.1556 m, giving rise to a mere 0.005 m^3 hemispherical volume of failure region. On the right of Figure 8, the shear radius of failure after 5 seconds of simulation shows a value of 0.29 m, equivalent to a hemispherical volume of 0.09 m^3. Though the failed volumes are very slight and may seem inconsequential, the region of shear precedes the region of tensile failure. Furthermore, it is observed that shear failure is an important mechanisms for failure when seepage gradients through the waste are small. For example, when the initial pressure is lowered to 12.0 MPa, no

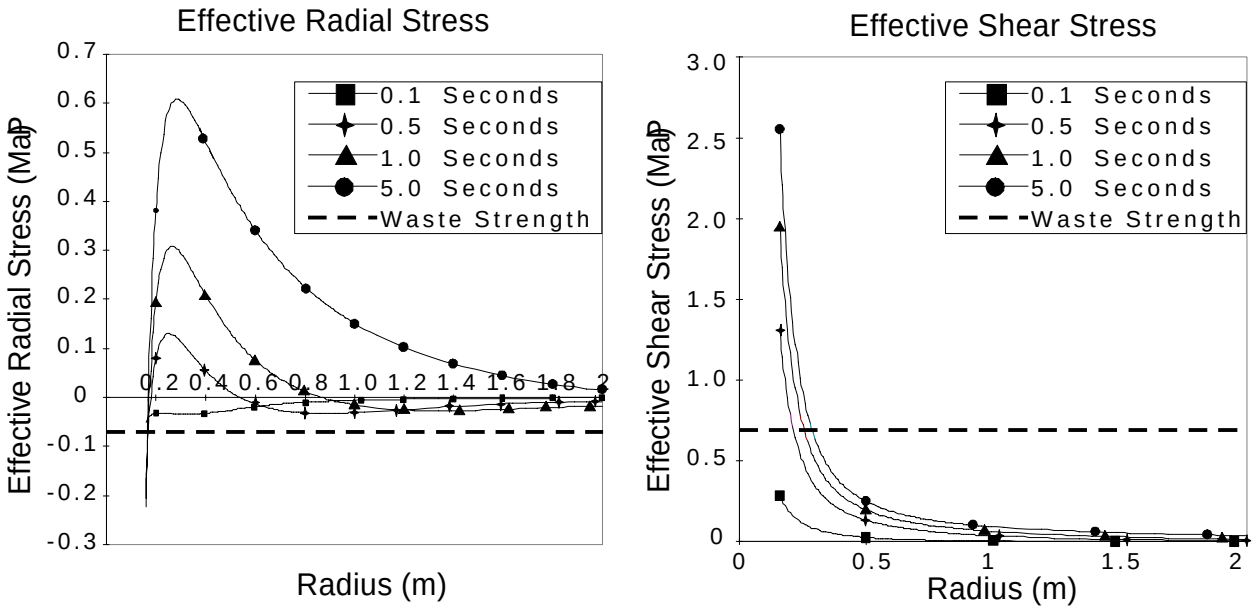

Figure 8. Computed Radial (Normal) And Shear Stresses In A Hemispherical Cavity During Spall From GASOUT, Assuming 14.5 MPa Initial Repository Pressure, 1.7×10^{-13} m^2 Waste Permeability, And No Material Removal From Failure.

tensile failure is observed. Yet, the effective shear stresses in the waste are noticed to increase, and failure for the experiment is seen to occur at approximately 0.3 m from the borehole center. The experiments assume no failed material removal, and it is conceivable that the extent of failure could extend beyond these values. The opposite phenomena is observed when the seepage gradient is high; tensile failure precedes shear failure.

Recommendations for Models:

It is shown that the GASOUT code responds erratically to small changes in the input assumptions, and sometimes gives misleading results. GASOUT was the main code examined, due to its ability to remove material during failure, and for being the major code of spallings verifications for CCA values. EEG recommends that the code be examined more closely, before judging the results of Hansen et al. (1997) as the maximum amount of failed material that will reach the surface, and the spalled volumes calculated in the CCA as reasonable.

It is also recommended that a new spallings code be developed, that incorporates all the aspects of failure correctly. The GASOUT code seems to have difficulty with redistributing the pore pressures once waste has been removed. Also, the code only addressed the concern of tensile

failure. In a hemispherical geometry, tangential forces will cause the material to be in compression, and the material could fail in shear. The GASOUT ignores shear failure as a possible mode of failure, although it is calculated. The strength of the waste is nominal in compression (measured values in Hansen et al., (1997) show a typical value of approximately 100 psi), and the pressures exerted from the overburden rock could cause the material to yield.

2.4.3.3 EPA's Model Prediction of Spallings

The EPA funded a separate investigation of the spallings phenomena that focused on potential limits on spall material reaching the surface because of insufficient lofting capacity of gases vented from the repository. The investigation is described in two reports (U.S. EPA, 1997e and 1997f). The first report assumes that spall occurs prior to penetration of the drill into the repository. It also assumes that the volume of material removed by the spallings process can be ignored. The second report assumes a one to two foot penetration of the drill string into the repository concurrent with formation of a spall cavity. The EPA investigation determined that venting of the repository would not be energetic enough to bring spall material to the surface. The conclusion is valid for evaluating the CCA spallings model but can't be extended to the most recent DOE spallings model. The investigation's focus is on relatively long term transport capability consistent with the CCA spallings model, not immediate transport of material from the formation of an explosive spall cavity, as in the most recent model.

The main emphasis of the EPA investigation is to explore whether there will be sufficient gas velocities in the repository-borehole system to transport particles, created by the spall process, to the surface. The ability of gas to entrain solid material is well understood. Vertical entrainment of larger particles requires greater gas velocities than smaller particles. The calculations predicted the maximum sized particle that could be transported to the surface by comparing calculated velocities to an established relationship of maximum size of entrained particles to hydrogen gas velocity. Three regions were examined to determine the most stringent limit on the size of transported particles. The smallest calculated velocities occurred in assumed void space created by the spall process. Applying the maximum particle size estimate to these velocities results in a prediction of 70 microns as the largest size particle that could be brought to the surface. 70

microns is smaller than the lower limit of particle distribution determined by the "particle size" expert elicitation panel. This leads the EPA investigators to conclude that spallings is a self-limiting process because of the inability of lofting new spall material from the cavity.

The spallings model used in the CCA performance assessment assumed that erosion of waste material would form channels in the repository room. The erosion process could last for days. The EPA investigation adopted an 11 day-long time frame and assumed that the first few seconds were not significant. This allows the adoption of cylindrical , one dimensional, radial flow approximation of flow through the repository to a borehole. The approximation is accurate only when pressure depletion extends far enough into the repository that a region, a few repository thicknesses in size, has a fully developed gradient. A fully developed gradient means, roughly, that little of the flow in the region is derived from local depressurization. Once the fully developed gradient forms, a pseudo skin factor is required to correct the one dimensional model for the two dimensional flow pattern near the borehole. The pseudo skin factor accounts for the fact that the drill was assumed to penetrate the repository only a few feet. The skin factor is applied as a permeability reduction of the repository waste near the borehole. This factor is 0.075 for a one foot penetration and 0.16 for a two foot penetration distance ($2.x10^{-5}$ with no penetration).

Both EPA reports are superceded, however, by the spallings model presented in January 1997 to the conceptual model peer review panel (Hansen et al., 1997). This model predicts that almost all spall would come from the face of the drilling cavity. The spall process would occur in the first few seconds of repository depressurization.

The permeability reduction used in the EPA model is inappropriate to address removal of the initial spall material. The spallings model of Hansen et al. (1997) predicts spalling will stop after a few seconds and that depressurization is negligible beyond roughly 1.5 meters at this time. Figure 5..6 of Hansen et al. (1997) presents the calculated pressure in the repository as a function of distance and time in the region of the borehole. During this initial depressurization the source of

flow is from the region close to the borehole. It is this local depressurization that would cause spalling to progress away from the drilling bit.

The temporal and spatial discretization of the EPA investigation is far too coarse to investigate the potential for evacuation up the borehole of spall material created in the first few seconds. For example, in the case of a two foot penetration with 0.25 m^3 spall cavity, the first element of the EPA analysis is 0.39 m thick. In the Hansen et al. (1997) model, the first element is 0.01 m thick. In the EPA investigation the first time step is 86 seconds compared to 0.001 seconds in the Hansen et al. (1997) model. These differences in both temporal and spatial discretization are an indication that the EPA modeling can not predict gas velocities from local depressurization reliably. Hence, the two EPA reports can't be used to judge the conservatism of the spall model described in Hansen et al. (1997), nor the extension of the Hansen et al. (1997) model to potential spall from air drilling.

Hansen et al. (1997) also considered the issue of maximum particle size that could be transported up the borehole. Figure 6-22 of Hansen et al. (1997) indicates that particles as large as 10,000 microns may be transported to the surface after the mud column has been expelled from the borehole, about 250 seconds after intrusion, and that transport of such large particles could occur for much more than 200 seconds. Two-hundred and fifty seconds is still very early in the EPA investigation (3 time steps). The discritization of the EPA model is too coarse to accurately calculate the flow rates this early in the 11-day period.

The calculated mass flow rate of gas up the borehole does not increase at 250 seconds, in the Hansen et al. (1997) model. Instead, the carrying capacity of the gas jumps because of lower pressure in the borehole due to the removal of the mud column. This confirms the appropriateness of neglecting the mud column in the EPA investigation.

A less important criticism of the EPA investigation is the reliance on velocities calculated in the spall cavity. The velocities are calculated by dividing the flow up the borehole by the area of the entire cavity as if all the flow was vertical. Gas velocities in this region are not spatially constant

and not vertical. Simple mass conservation implies that the velocities must be greater near the drill collar. In addition, particles need not be lofted in this region to be transported, except right at the borehole where the cavity velocities are greatest. Particles may be transported towards the borehole by both collapse of the spall material into the cavity and the drag of the radial velocities of the gas moving toward the drill collar annulus, even if the velocities are too weak to loft the particles. Horizontal transport by gas is known as saltation and should be recognizable to people who have witnessed an aluminum can being bounced along a roadway by the wind. In the case of the can, the wind velocity is rarely large enough to loft the can but the can bounces off the ground as it moves. The blowout experiments conducted for DOE (Lemke et al., 1996) demonstrated that, for material without cohesive strength, particles will be moved radially toward the gas vent. These experiments indicated that the cavity formed by material carried out the vent is filled by material being transported toward the vent along the upper surface of the cohesion-less mass of particles.

For consideration of removal of spall created in the first few seconds of a drilling intrusion into the repository, the calculations of Hansen et al. (1997) are more accurate than those of the EPA investigation because of the use of a one-dimensional cylindrical geometry and coarse discritization in the EPA model. The EPA investigation underestimates velocities during a spallings event. Based on the information supplied by Hansen et al. (1997), large enough gas velocities are likely to occur during a spallings event, for a long enough period, to transport large amounts of the spall material up the borehole. In conclusion, the calculations of Hansen et al. (1997) indicate that transport of spall material up the borehole will <u>not</u> limit the release of spall material to the surface.

2.5. AIR DRILLING

This section is to address the concerns of the EEG on the issue of EPA's Analysis of Air Drilling at WIPP (U.S. EPA, 1998). Based on its own analysis of Air Drilling in the Delaware Basin of New Mexico, the EPA has concluded that the air drilling scenario did not have to be considered in the DOE's Compliance Certification Application.

Dr. John Bredehoeft first proposed air drilling as a plausible scenario at WIPP in 1997 and conducted a modeling experiment (Bredehoeft, 1997a) to quantify the amount of spalled material that would be brought to the surface if the repository was inadvertently breached by a drill intrusion, using air as the drilling fluid. Drilling with air results in lower hydrostatic pressures in the bottom of the borehole, thus the possibility of higher pressure- gradients through the waste repository. Bredehoeft used the code GASOUT for his modeling, admitting that the code was not written for this purpose, but if used with caution, could yield approximate results. Bredehoeft concluded that air drilling could potentially violate the containment requirements of 40 CFR Part 191.13.

The DOE disputed Bredehoeft's modeling analysis, based on incorrect usage of the code. DOE argued that the code was designed for drilling with an incompressible fluid, and for low seepage gradients. When the code was used in Bredehoeft's study, it produced large amounts of waste failure, which were on the order of 500 - 2000 m^3. These high volumes were easily explained, argued DOE, and that the results were highly unlikely to occur at WIPP.

Further analysis by the EEG, which investigated the amount of brine that could be released through an air drilling event, also concluded that large amounts of radionuclides could be brought to the surface. The EEG estimated that the maximum amount of brine that could be blown out of the repository would be approximately 2000 m^3. However, the DOE showed that the EEG analysis contained conceptual errors and the EEG accepted the DOE's criticism.

Finally, the EPA conducted its own analysis and concluded that air drilling scenario of release is not valid on the basis of both low probability and low consequence. The following two sections respond

to the EPA invitation for comments on the EPA analysis.

2.5.1 EEG's Critique of EPA's Air Drilling Analysis

The WIPP is located in a resource rich area and the EPA Standards for the disposal of transuranic waste require that the DOE application address inadvertent human intrusion. However, the DOE Compliance Certification Application did not address the issue of air drilling. In calculating the impact of resource exploitation on the cumulative release of radionuclides from the repository, the CCA performance assessment calculations addressed only the actual drilling event and only drilling methods which use brine as the drilling fluid.

In a report titled *Air Drilling into WIPP*, Bredehoeft (1997a) makes a compelling argument that the application needs to consider other known drilling technologies, such as the use of air rather than brine for the drilling fluid. The repository performance must be determined for the next 10,000 years and Bredehoeft notes that technologies, such as drilling, have changed in the past and will probably change in the future. He suggests that EPA required the DOE to treat the historical drilling rate as representative of the full 10,000 years to accommodate changes in drilling technology and mineral economics including minerals not currently in demand (Bredehoeft, 1997a, p. 1). Indeed, the preamble to the EPA Criteria states:

> In effect, when used for the purpose of determining the future drilling rate, today's drilling activities act as surrogates for the unknown resources that will be drilled for in the future (U.S. EPA 1996, p. 5233).

It is not clear that EPA's assumption of a constant drilling rate was intended to compensate for future changes in technology. Nonetheless, Bredehoeft identifies a problem that needs to be addressed. Bredehoeft attempts to prove, with a known drilling technology, that the assumption of a constant drilling rate for 10,000 years is not adequate to accommodate technological changes and he calculates the release of radionuclides from the repository as the result of a drilling intrusion. His calculations show a much larger release of radionuclides to the surface as a result of using air rather than brine

for the drilling fluid.

2.5.1.1 Scenario Rejected by DOE and EPA on Basis of EPA Regulation

While Bredehoeft is proposing that an air drilling scenario be considered both, U.S. DOE (1998) and U.S. EPA (1998) have reiterated the position that the air drilling scenario can be ruled out on the basis of regulation. Within the confines of considering only the actual drilling event, the EPA Criteria specify a future state assumption for which:

> Performance assessments shall document that in analyzing the consequences of drilling events, the Department assumed that: 1) future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. Such future drilling practices shall include, but shall not be limited to: the types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of such boreholes that are sealed by humans (U.S. EPA, 1996, §194.33(c)(1)).

On October 29, 1996, the DOE submitted the Compliance Certification Application. Appendix DEL states:

> There are a variety of drilling fluids used in Delaware Basin drilling. Most rotary drilling operations use saturated brine (10 to 10.5 pounds per gallon) as a drilling fluid until reaching the Bell Canyon Formation, where intermediate casing is set. (U.S. DOE, 1996c, p. DEL-32).

Hence, the CCA calculations are based on the assumption that all future drilling through the Salado Formation will be done with brine as the drilling fluid and drilling with any other fluid can be ruled out citing regulatory considerations.

The NEA/IAEA International Review Group (IRG) expressed its reservations about scenarios

rejected on the basis of regulatory consideration in the absence of logical or physical arguments for such a scenario rejection (NEA/IAEA, 1997, p. 19). This appears to be an obvious shortcoming.

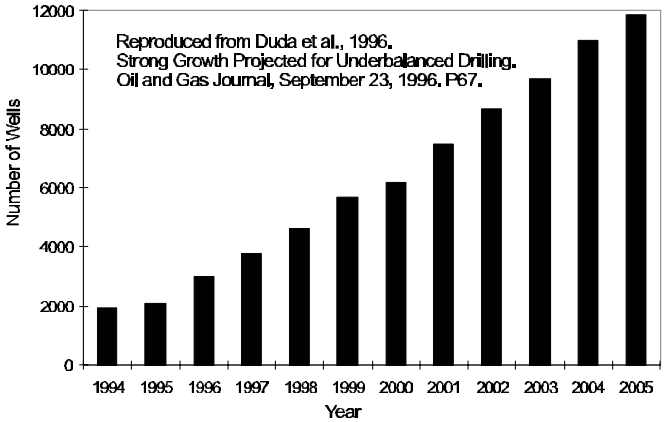

Fig. 9. DOE's projected use of underbalanced drilling in the United States.

Bredehoeft did not limit his consideration of scenarios to a choice of drilling fluid. He observes that air drilling is a proven technology and its frequency of use by the oil and gas industry is increasing as shown in Figure 9. An examination of published materials shows that use of underbalanced drilling, including air drilling, is expanding in the oil and gas industry with the explicit support of the DOE Office of Fossil Energy (Duda et al, 1996) and strongly suggests that the analyses may need to include other methods of underbalanced drilling, including foam, mist, dust, aerated mud and light weight solid additives.

2.5.1.2 Entire Delaware Basin not included in DOE and EPA Review of Records

U.S. DOE (1998) and U.S. EPA (1998) maintain that the drilling fluid used in the PA calculations is limited to current practice in the Delaware Basin which does not include air drilling. They do note a few exceptions in previous years and the more recent use of air drilling on one occasion to address a lost circulation problem.

With respect to current and historical practices, the DOE examined records on file with the New Mexico Oil Conservation Division (U.S. DOE, 1998, p. 5-12). The EPA examined 203 randomly

selected drilling records from the NMOCD files for Eddy County and Lea County (U.S. EPA, 1998). The DOE and EPA each conclude, from information in the New Mexico records, that air drilling has rarely been used in the Delaware Basin.

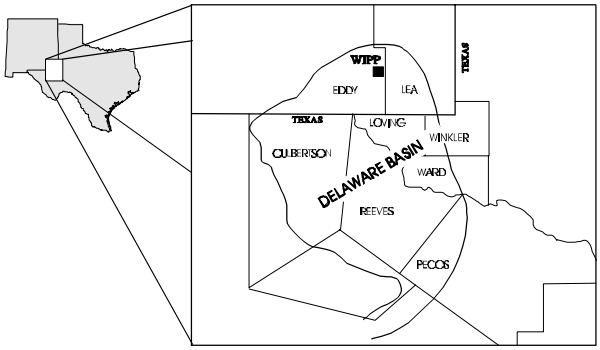

Fig 10. New Mexico and Texas Counties in the Delaware Basin

While, the EPA Criteria requires consideration of practices in the entire Delaware Basin, neither agency reviewed the Texas records although a large portion of the Delaware Basin is located in Texas. EPA documents a conversation with Mark Henkhaus, District Manager of the Texas Railroad Commission in Midland, Texas who indicated that Burlington Resources has done air drilling in Reeves and Pecos Counties, Texas. Although not noted in the EPA document, Reeves County, Texas lies entirely within the Delaware Basin. Compliance with the EPA Criteria requires examination of the appropriate Texas records as well as the appropriate New Mexico records.

2.5.1.3 Potential Inadequacy of Public Records

The EPA survey of drillers, consultants, and state employees found:

> None of the individuals contacted were aware of any oil industry related wells drilled within 20 miles of the WIPP Site using air technology ***for any purpose*** [emphasis added]. In addition, New Mexico Oil Conservation Division (NMOCD) regulatory personnel in Hobbs and Artesia indicated that no wells have been drilled from the ground surface with air in the New Mexico portion of the Delaware Basin because of

> the problems cited above (U.S. EPA, 1998, p. 13).

While the EPA survey did not find a single instance of oil field air drilling within 20 miles, EPA noted (U.S. EPA, 1998, p. 6) that the DOE found some evidence of a well having been partially drilled with air about 8 miles east-northeast of the WIPP Site Boundary. DOE stated:

> The information in the NMOCD and BLM records do not show evidence of air drilling at the Lincoln Federal #1. All information presented below was obtained verbally from representatives at Collins & Ware, Inc., the operator, and McVay Drilling, the driller of the well (U.S. DOE, 1998, p. 7).

The EPA also could not find any direct information documenting the use of air drilling. The use of air drilling was inferred from "statements in the well files that indicate that air was circulated while casing was set to the top of the Delaware Basin" (U.S. EPA, 1998, p. 6).

Neither DOE nor EPA could find documentation in the public record directly stating that this well was partially drilled with air. This raises a very important question about the reliability of the New Mexico records to document air drilling. If air drilling was indeed used in this well and that information is not stated in the public record, how many other wells have been drilled with air (foam, mist, aerated mud, or other underbalanced methods) without documentation? No conclusion can be drawn about the documentation in the Texas records for the Delaware Basin because apparently that search does not appear to have been conducted.

The DOE also conducted a survey of thirty drilling companies. Six were no longer in business, four had been acquired (by companies that did respond to the survey), and five could not be contacted. Fifteen companies responded. It was fortuitous that the company that drilled the Lincoln Federal #1 well was still in business and that the staff responding to the U.S. DOE (1998) inquiry remembered the use of air drilling for this very unusual well.

Although there were no direct statements on file in the public record, there is no question that this well was partially drilled with air. Page four of the actual drilling record clearly states:

4/11/91: Day -10

> Drilling at 2620', made 735' in 19 1/2 hours. Formation Anhydrite and salt. MW 10, Vis 28, Ph 8. Bit #3 12 1/4" HTC, R-1, Jets 3/13's, in at 852', out at 2320', made 1468' in 39 1/4 hours, WOB 15-20,000, RPM 70. Bit #4 12 1/4" HTC, J-33L, Jets 3/13, in at 2320', made 300' in 7 hours, WOB 30,000, RPM 70. Pump #1 SPM 70, GPM 237, PP 700. Deviation survey at 1945' 1/2º, at 2320' 3/4º.
> TIME BREAKDOWN: 2 hours drilling, 1 hour circulate out air pocket and water flow, 1 1/2 hours drilling with water flow, 1/2 hour survey, 9 hours drilling with partial returns, 3 hours trip for new bit and survey, 7 hours drilling with no returns. Hauled 8 loads of formation water to disposal. Will continue to dry drill until air compressors on location and set up to air drill. [Emphasis added].

4/12/91: Day -11

> Drilling at 2984', made 364' in 9 hours. Formation salt and anhydrite. MW brine water. Bit #4 12 1/4" HTC, J-33C, jets 3/13, in at 2320', made 664' in 16 hours, WOB 20-30,000, RPM 76. Pump #1 SPM 90, PP 1100-600 psig. Deviation survey at 2667' 1 1/4º, at 2915' 1 3/4º.
> TIME BREAKDOWN: 2 1/2 hours drilling with no returns, 1/2 hour deviation survey, I hour drilling, 1/2 hour pull 20 stands, 5 hours wait on brine, 1/2 hour trip out of the hole, 4 3/4 hours nipple up rotating head, change flowline and hook up compressors, 1 3/4 hours trip in hole, 1/2 hour install rotating head, 1/2 hour establish circulation, 3/4 hour air drilling, 1/2 hour repair flowline, 4 1/4 hours air drilling, 1/2 hour totco, 1/2 hour air drilling.

Air drilling was used to overcome a lost circulation problem. However, the use of air drilling was not documented in the public record, which raises the concern that there could be other wells that were either fully or partially air drilled without public documentation.

The EPA and DOE report the use of air drilling in areas outside the Delaware Basin, based on discussions with various drillers. Could that information have been discerned from the available public record? There is no indication that either DOE or EPA verified that information obtained from drillers is also contained in the public record.

2.5.1.4 Water Influx

Based on a survey of drillers, the DOE maintains that the potential influx of water is a deterrent to drilling with air. U.S. EPA's (1998) industry survey also found that large water inflow was the most commonly cited reason why air drilling is not conducted in the Delaware Basin, including the area around the WIPP Site. But as noted in the EPA survey of drillers, "air drilling technology is improving at a relatively rapid pace and new larger rigs are capable of handling more water influx than in the past" (U.S. EPA, 1998, p. 9). EPA acknowledges that air drilling technology is capable of handling higher water inflows by using larger air compressors (U.S. EPA, 1998, p. 15) which is consistent with the observation that "new equipment is available" (U.S. EPA, 1998, p. 9). Furthermore, the DOE and industry are also optimistic about the potential market for light-weight fluids not adversely affected by the invasion of other fluids and the use of light weight solid additives to overcome contamination problems associated with fluid influxes (Duda et al.,1996, p. 76) .

The drilling report for the Lincoln Federal #1 includes the following important notation, at the bottom of page four, indicating air drilling moved large volumes of water from 2000 feet up to the zone of lost circulation and the remaining water up to the surface pit.

> **NOTE: Both Air and Brine are being pumped; pit gain with air on hole; pit loss without. We are drilling with air until pits fill up, then dry drilling using brine water that is in the pits. When pits get low we go back to air drilling.

The actual drilling record was used to prepare the following account:

> On April 2, 1991, drilling was initiated for a gas well on Lincoln Federal No. 1 in Section 26, T21S, R32E, NMPM, in Lea County, New Mexico about 8 miles (13 km) east-northeast of the WIPP Site Boundary (Collins & Ware, Inc., 1991 pp. 1-4). On the third day of drilling and upon reaching a depth of 1292 feet, all of the circulating fluid was lost to the formation. The driller began hauling in water to continue drilling. Drilling with water continued for ten additional hours on the fourth day. A survey confirmed 100% circulation loss in the two foot interval from 1290' to 1292'.

> Attempts to seal the formation with cement over the next 5 days largely failed as evidenced by the continued loss of circulating water to the formation. Nonetheless, on the tenth day, drilling continued until an air pocket and brine flow were encountered at 2000 feet. Brine from this formation began filling the surface pit, which is used to contain the circulating fluid. Drilling continued for 1 1/2 hours with brine flowing into the pit. The driller then hauled eight loads of brine to disposal and continued drilling for 9 hours with partial returns of brine to the surface. Apparently, while the brine flowed to the surface, much of the brine continued to flow into the two foot interval between 1290' and 1292'. The drilling report documented an additional 7 hours of drilling with no returns. On the eleventh day, after 3 1/2 hours of drilling with no returns, air drilling was initiated. As drilling continued, the pit filled with formation brine. Once there was sufficient brine in the pit, the brine was used as the circulating fluid for drilling until the pit was nearly depleted. Then air drilling resumed until the pit again filled with brine (Silva, 1994, pp. 63-64).

U.S. EPA (1998, pp. 15-16) presents an argument that water inflow will prevent air drilling in the vicinity of the WIPP. The argument must be viewed with caution. Although EPA alludes to cost limitations, there is no cost analyses for drilling a specified well in the vicinity of WIPP. Instead, referring to information from one industry contact (unnamed) and applying methodology presented by Lyons (1984, p. 109), EPA determined that the reasonable upper bound for water removal under current air drilling practice is in the range of 10 to 20 gallons per minute (gpm). EPA maintains that water inflow into a hole drilled at the WIPP Site would originate primarily from Culebra Dolomite and calculates that wells in the vicinity of WIPP with transmissivities greater than 1×10^{-5} m^2/s identify areas in which water inflow would prohibit air drilling. Furthermore, EPA states “other wells in the area have transmissivities in the 10^{-6} to 10^{-5} m^2/s range, causing much of the WIPP Site to be borderline for feasible air drilling” (U.S. EPA, 1998, p.16).

The wells in the immediate vicinity of the WIPP shafts, H-1, H-16, and ERDA 9, each have transmissivities on the order of 10^{-6} m^2/s. That these would be “borderline for feasible drilling” is

somewhat difficult to understand in view of the measured inflow data for that area, which ranged between 0.3 gpm to 0.9 gpm with an average of about 0.6 gpm (D'Appolinia, 1983, p. 5-2). And that was for the six foot diameter ventilation shaft. An oil and gas well would have a much smaller diameter, hence, an even lower inflow.

With respect to the EPA comment that "the reasonable upper bound for water removal under current air drilling practice is in the range of 10 to 20 gallons per minute," EEG contacted the drilling design engineers of ECD Northwest who confirmed that current air drilling technology could easily handle water inflows on the order of 500 gallons per minute. Moreover, water inflows during drilling can be successfully inhibited by a variety of methods including, for example, reacting a monomer and catalyst in the water producing zone to form a polymer skin. The feasibility of such treatments was a matter of cost. EEG did not ask for the estimated cost of actually air drilling a well at WIPP but simply wanted to know the upper bound for water removal under current air drilling practice.

The DOE concludes that air drilling is not well suited to WIPP based on discussion with fifteen drillers with experience in the area. The DOE report does not include any detailed engineering or economic analysis for the actual cost of underbalanced drilling of a well near WIPP. If DOE and EPA are going to rely on interviews with drillers, than they must also consider the published concerns of others in the industry including drilling fluid manufacturers and suppliers who compete in an industry that must stay at the cutting edge of technological developments. In their recent catalog of supplies, Clearwater, Inc., a company which manufactures and supplies chemicals for underbalanced drilling offers the following thoughts:

> It has been an industry wide misunderstanding that very few wells are suitable candidates for drilling balanced to underbalanced. Through recent technological advancements, many obstacles have been overcome and what was once unthinkable is today "NO PROBLEM". (Capitalized in the original).

In discussing recent technological developments in underbalanced drilling, Clearwater, Inc. also

states:

> Many operators who have attempted air drilling and failed have abandoned the technique. These operators may not have kept abreast of the latest developments. The limited use of air drilling techniques, relative to fluid, is primarily a function of the limited knowledge of new developments and the industry's natural resistance to changing methods. The level of expertise in air drilling technology currently found is comparable to the industry's generally limited knowledge of hydraulic fracturing methods two decades ago.

The EPA should consult with the DOE Office of Fossil Energy. As one DOE sponsored study noted, unfamiliarity with light-weight fluids and the perception of high cost were the two primary reasons operators gave for not using light-weight fluids more often (Duda et al., 1996, p. 76). The DOE Office of Fossil Energy continues to participate in an effort to promote the understanding and use of underbalanced drilling technology.

2.5.1.5 Analysis Conclusions

Bredehoeft (1997a) identified how the drilling rate specified by the EPA Criteria cannot accommodate even a small technological change, such as using air drilling rather than brine drilling for resource recovery in the vicinity of the WIPP.

The DOE and EPA reject the air drilling scenario on the basis of regulatory considerations. Yet the DOE and EPA review of records to determine drilling practices did not include the Texas portion of the Delaware Basin despite verbal information referring to such drilling activities.

DOE and EPA's examination of the New Mexico records raises questions about the adequacy of such records to provide complete information on the use of underbalanced drilling in the New Mexico portion of the Delaware Basin.

The EPA arguments concerning the inability of air drilling to handle water inflow at the WIPP appear to lack merit given the actual measured inflows and the current state of air drilling technology.

The DOE interviews with drillers found that they would not consider using air drilling near the WIPP site. However, written statements by others in the air drilling industry, including the DOE Office of Fossil Energy, identify an industry wide misunderstanding that as led some operators to incorrectly conclude that some wells are not suitable to air drilling. They note that the limited use of air drilling techniques, relative to fluid, is primarily a function of the limited knowledge of new developments and the industry's natural resistance to changing methods.

2.5.2 The Improper Use of the Quasi-Static Method for the Prediction of Spallings

To quantify the consequence of drilling with air as the fluid used for bit lubrication and cuttings removal upon a drill intrusion at the WIPP, the EPA adapted the Quasi-Static spreadsheet model that was described in Hansen et al. (1997) for an air drilling scenario. The results of modeling the air drilling scenario can be found in U.S. EPA (1998). The model was originally designed for drilling with a brine mud medium. The code produced reasonable results for an air drilling model, in that it did not calculate extremely large stresses in the waste near the borehole, considering the large pressure difference between the intruding borehole and the highly pressurized repository. Therefore, it was assumed that the code could be used for the air drilling scenario. However, the model was not developed to predict failure. The code is only capable of calculating stresses in the waste assuming that no material has been removed. Extrapolating a failure from the results of the code misrepresents its design, and may lead to false interpretations.

2.5.2.1 Quasi-Static Model

The Quasi-Static model was developed with three main purposes (or elements): 1) to calculate the motion of the mud column up the borehole, 2) calculate the gas flow within and from the repository, and 3) to calculate stresses in the waste. All three processes are coupled by the pressure at the bottom of the borehole (bottomhole pressure), and are described quite well in Hansen et al. (1997) or Gross and Thompson (1997).

The implementation of the numerical model for the three elements was established by using two spreadsheets. The first spreadsheet calculated the gas flow and pressures within the repository as well as the motion of the drilling mud being expelled from the borehole from a high bottomhole pressure. The second spreadsheet calculated the effective stresses in the waste as a function of radial distance and time from the total stress exerted by the overburden rock and saturated waste and the pore pressure calculations of the first spreadsheet. This was accomplished by numerical integration of the governing equations in Gross and Thompson (1997) by the Runge Kutta method.

The name Quasi-Static refers to the steady state approximations to the analytical solution of the

gas flow equation. The steady state analytical solution differs from a fully transient numerical model, and thus disregards some aspects of flow such as compressibility. The steady state solution assumes that the boundary condition at the borehole is constant. However, since the boundary will change in time during an intrusion at WIPP, the solution undergoes a series of steady state calculations to calculate the pore pressures in the waste and the mud motion up the borehole as a function of time. The solution has been verified by the transient flow calculations of the GASOUT code (Hansen et al., 1997). The results of the two codes show very close agreement.

Once the pore pressures in the waste are known, they can be used to calculate the effective stresses in the waste. If the pore pressures in the waste are greater than the total stresses within the repository and the strength of the waste, then the effective stresses are negative, indicating that the waste could fail. However, the code does not consider the removal of waste in the borehole cavity, and the calculation of pore pressures will decrease as the gas flows from the repository to the borehole. Once pore pressures decrease, the effective stresses increase positively, meaning that the carrying capacity of the waste from the overburden rock must increase. Once this happens, the waste will no longer fail. Since the code was not designed to handle waste removal, the estimation of failure can only be accurate at very early times (most accurate after the first time step). If the code did consider waste removal, the pore pressures would redistribute near the borehole cavity boundary, and the pore pressures in the waste would be higher. Higher pore pressures give rise to more waste failure. The calculation of waste removal was conducted in the code GASOUT (Hansen et al., 1997), and the option can be turned off for comparison with the Quasi-Static model.

2.5.2.2 Application to Air Drilling

The EPA used the Quasi-Static model to calculate spallings from an air drilling scenario (U.S. EPA, 1998) to dispel the scenario from a low consequence point-of-view. The use of the Quasi-Static model on an air drilling scenario to calculate waste failure and blowout is misleading in two ways. First, the calculation of drilling mud motion up the borehole was derived from forces that accelerate the mud upwards. The acceleration of the mud column depends on an incompressible

fluid, i.e., the density is not pressure dependent. The input for the Quasi-Static model uses the density of the boring fluid to calculate the hydrostatic weight of the mud column. Since this is a constant, the weight is a function of the borehole length only. During an air drilling scenario, the air would decompress quickly near the top of the borehole, and the weight of the column would be less. The result would be higher gas flow from the repository, and hence lower total stress and pore pressures near the boundary. The EPA calculated that the blowout of the mud column would take 9.1 seconds. If the air were allowed to decompress, the acceleration of the air column would be greater than that calculated in the Quasi-Static model, and blowout would occur much more quickly than anticipated. The consequence could lead to higher releases of waste in the borehole cavity.

The second misleading interpretation of air drilling model with the Quasi-Static model is the amount of failed material extrapolated from the results of calculated effective stress. The effective stress is calculated from the difference between the total stress of the waste and overburden rock and pore pressures, and is quantified by the equation

$$\sigma' = \sigma - \mu \qquad (2.5\text{-}1)$$

where σ' is effective stress, σ is total stress, and μ is pore pressure (Terzaghi and Peck, 1948).

Effective stress is the stress applied to the grains of material in a saturated medium. Effective stress cannot be measured, and is only a calculated quantity from the other two constituents of the equation. In order for the material to fail in the borehole cavity, the pore pressure must be greater than the total stress of the repository. In normal applications, the total stress is always larger than the pore pressure, and the effective stress is the resultant stress applied to the material on the macroscopic grain level. For this case, where pore pressure is larger, the effective stress is less than zero, and hence cannot sustain the force of the material in contact. In addition to the total stress, the pore pressure must overcome the strength of the material before it will fail. Again, in normal geotechnical applications, the strength of soil in tension is practically zero for cohesionless material (sand and gravel), and nominal in clays. In this application, where cementation of MgO backfill is considered, along with the pressurization and saturation of waste material, the tensile strength was measured to be approximately 10±5 psi (0.07±0.04 MPa).

The results of air drilling from the EPA's analysis at WIPP is reproduced here in Figure 11. The figure shows effective stress versus radial distance within the repository at several times during the simulation. The EPA judged failure in this figure by estimating the point at which the effective stress is less than the strength of the material (indicating high pore pressure). This point is at 1 second from the beginning of the simulation, with a radial failure distance of 0.69 m (1.4 m^3 of uncompacted waste). After 1 second of simulation time, the pore pressure in the waste near the cavity begins to decrease, and the effective stress moves upwards (increases positively) towards the region of higher total stress.

It is stated here again that the code was not designed to calculate failure, and it can only be used to estimate the stresses in the waste assuming that no waste has been removed from failure. If failure of waste is to be assumed from the Quasi-Static model, then it can only be inferred from

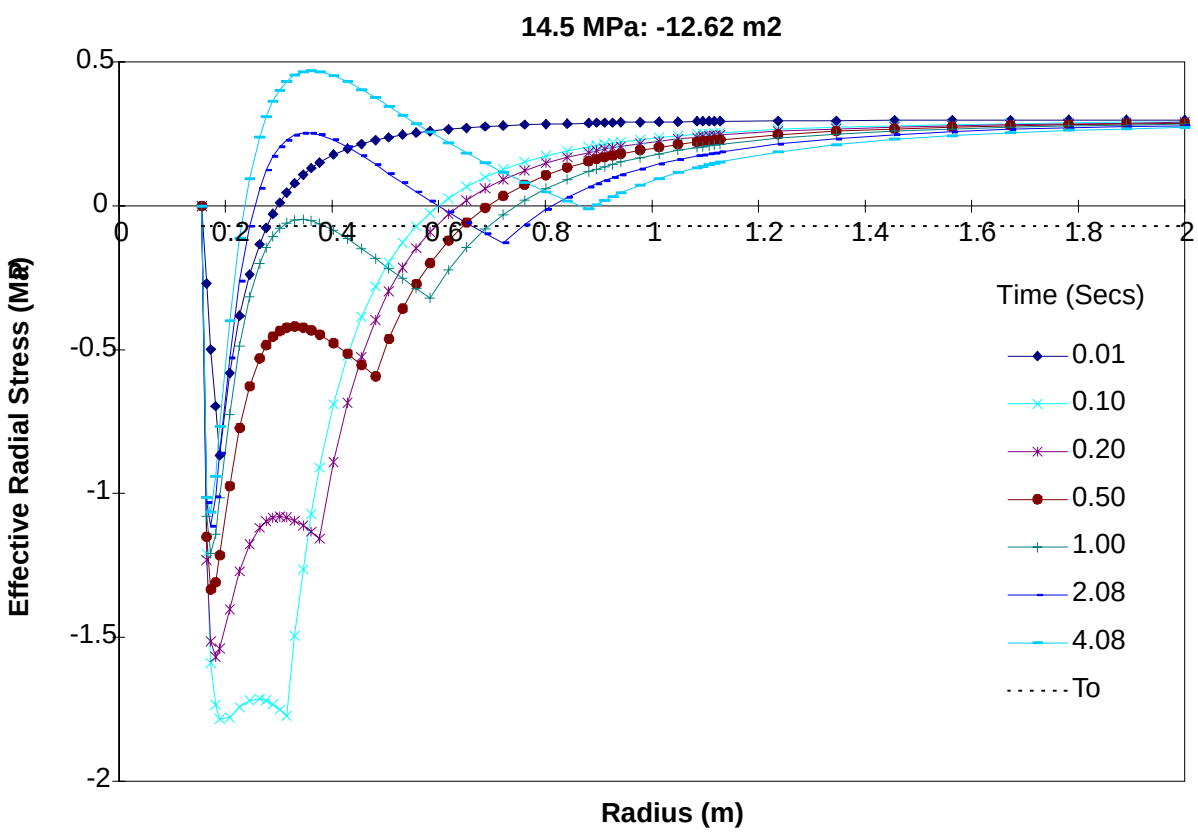

Figure 11. Effective Radial Stress As A Function Of Radial Distance For The EPA's Air Drilling Analysis.

early times during the simulation. To demonstrate the difference in the Quasi-Static model to a model that recalculates stresses after material removal (a.k.a. cavity growth) the results were compared using brine mud as the drilling fluid, since the cavity growth model cannot accurately predict failure with the use of air as a drilling medium. The results show that the Quasi-Static model predicts a failure radius (as estimated from effective stress) of 0.44 m, and the cavity growth model calculates a 0.25 m under the same condition. The same cavity growth model calculates a failure radius of 0.16 m when the option of failed material is turned off. So, the comparison tends to demonstrate that the removal of waste during the stress calculations will predict higher volumes of failed waste.

Intuitively, the results shown in Figure 11 would raise questions about the behavior of the system. Why does the effective stress sharply decrease from 0.01 seconds to 0.1 seconds then gradually rise throughout the remainder of the simulation? Does the system stop predicting failure after 1 second? What is the effect of tangential stresses in the waste? How does the system respond to varying repository parameters? All of these questions are relevant to the understanding of the Quasi-Static model and to the prediction of stresses in the waste from an air drilling event.

The effective stress is simply the difference in the calculated total stress and calculated pore pressure. Figure 12 shows the relationship between these quantities for three separate times for the EPA's analysis of air drilling. The left plot shows the first time step, at 0.01 seconds from time of intrusion. One can see immediately that waste failure occurs due to a slightly higher pore pressure, with the radius of failure being 0.27 m. The relatively large failure at this time is due to the unsmooth function of the pore pressure in the waste, which carries over to the effective stress. The same can be seen the two other plots of 0.1 and 1 second from intrusion time. The effects of the unsmooth pore pressure profile average out as the time from intrusion increases, but is one the reasons for increase in effective stress at later times.

The high radial failure as seen in the effective stress from the unsmooth nature of the pore pressure can be dispelled, once a more accurate code is used to model air drilling. Figure 13 shows the effective stresses as calculated in GASOUT from an air drilling scenario. The code was

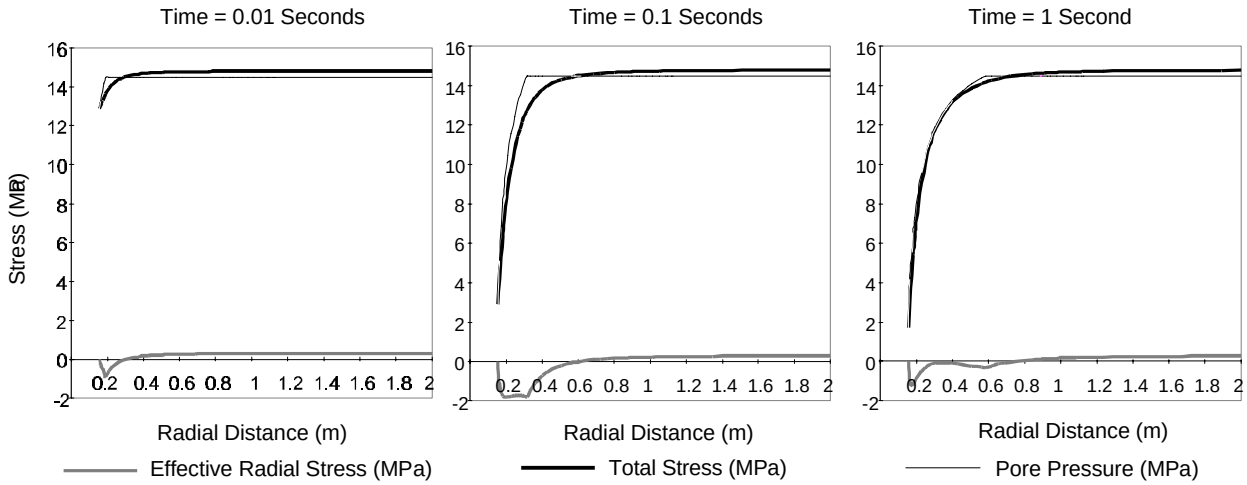

Figure 12. Effective Stress, Total Stress, and Pore Pressure Profiles in the waste at three independent times from the EPA's Analysis of Air Drilling.

run with the cavity growth option turned off and the same input assumptions as used in the Quasi-Static model. Although the code cannot predict failure accurately with the option of failed material removal to be removed (due to multiple layers of cascading waste during a single time step), the code can calculate the pore pressure distribution and effective radial stresses that match quite closely to the Quasi-Static model with the option turned off. Figure 13 shows that at 0.01 seconds from intrusion time, the radial failure is 0.38 m, which is higher than the Quasi-Static model. Although, it must also be noted that the pore pressure eventually decreases after this initial time, at 0.1 and 1 second from the time of intrusion. The conclusion gathered from this analysis is that the pore pressures are smooth through the waste, and subsequently predicts a much higher negative effective stress at earlier times.

Smoothness aside, the major discrepancy between the model and the physicality of the scenario is the fact that material is not being removed during the time that material could fail. This would have a major impact on the results, especially pore pressure, and hence effective stress. If material were allowed to be removed, the pore pressures would stay higher, because the low pore pressure waste would have been removed. The pore pressures would then be recalculated with the remaining waste at higher pressures. This is evident in Figure 13-11 of Hansen et al. (1997). The figure shows the calculations of with and without material removal assuming brine mud is the drilling fluid. The curve showing that material is removed has higher pore pressures in the waste.

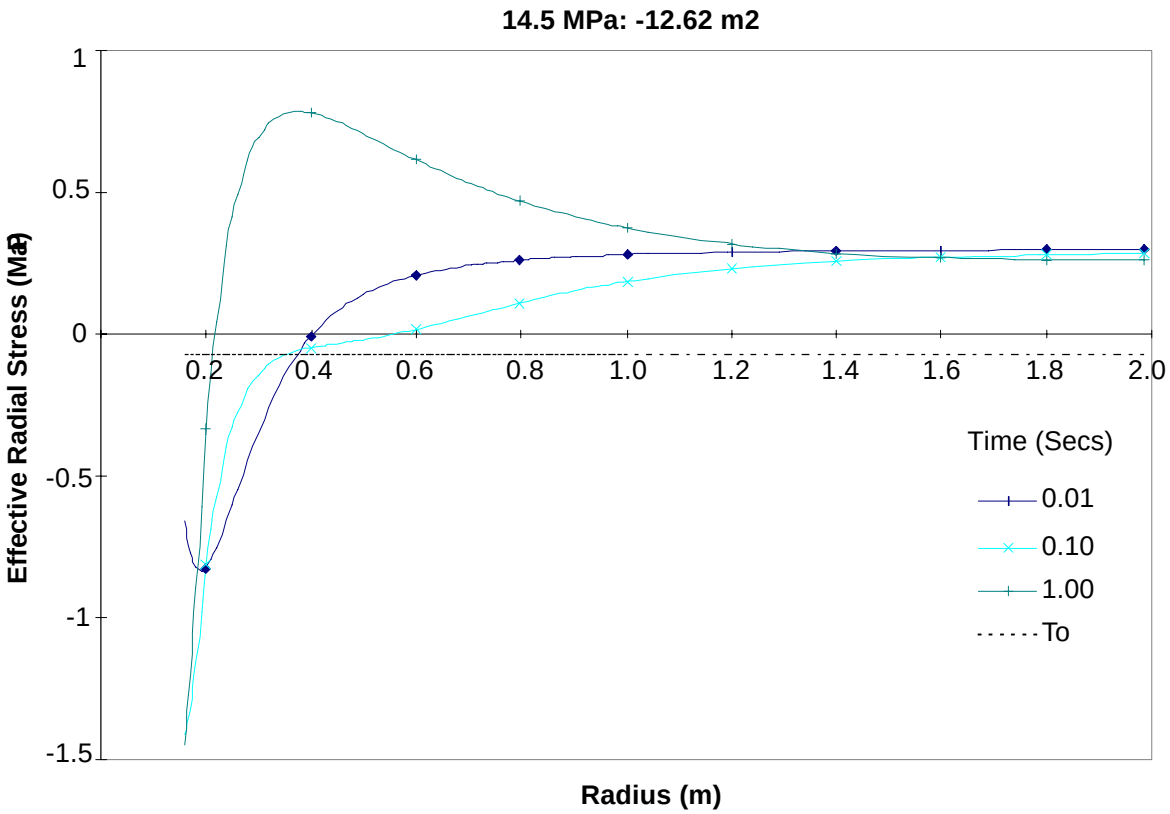

Figure 13. Effective Radial Stress As A Function Of Radial Distance Using GasOut For The Air Drilling Analysis.

Though the difference in pressures between the two curves is slight, it would have a significant impact on the effective stresses and potential releases. For Figures 1 and 3 above, the pore pressures artificially decrease from the flow of gas in material that should have been removed. Therefore, the judgment of waste failure from Figure 11 leads to false confidence by underpredicting waste failure.

Along with the calculated radial stresses, tangential stresses will also exist in the waste. As radial stresses are directed inwards to the borehole center, the tangential stresses are directed along the tangential paths of the hemispherical cavity, and are perpendicular to radial stresses. Essentially, the tangential stresses are compressive stresses acting along the circumference in a spherical geometry, and radial stresses are tensile stresses acting along the radius (or compressive, depending on the nature of the pore pressure and total stresses).

The effective tangential stresses in the waste were calculated much like that of the radial stresses, with effective stress equating to the difference in total stress of the overburden rock and pore pressure. Since the tangential stresses are always in compression, the resultant effective stresses are above zero, and hence no failure occurs from compressive tangential stresses.

The radial and tangential stresses are related by a yield potential, as stated in Jaeger and Cook (1976), which incorporates the compressive strength, internal angle of friction, and cohesion of the waste, by the formula,

$$\sigma_\theta - C_o - \sigma_r \tan^2 \alpha > 0 \qquad (2.5\text{-}2)$$

where σ_θ is the tangential stress (major principal stress), σ_r is the radial stress (minor principal stress), C_o is the compressive strength, and α is equivalent to

$$\alpha = (\pi/4) + \tfrac{1}{2}\,\phi \qquad (2.5\text{-}3)$$

where ϕ is the angle of friction. The left hand side Equation 2 must be greater than zero for yielding to occur.

Figure 14 shows the results of Equation 2.5-2 plotted against radial distance. The first observation is that there is potential for yield out to 2 seconds from the time of intrusion. The yield crosses the axis at approximately 0.8 m, resulting in an uncompacted volume of 2.1 m^3. This is an increase of 33% from the initial estimate stated in the EPA's analysis. The curves also seem to be highly influenced by the discontinuity in pore pressure calculations, and can be seen in Figure 14 by the second peak in the curve as radial distance increases. When compared to the yield potential calculated from GasOut, which calculates a smooth function of pore pressure, the limit for yield is 0.7 m at 0.1 seconds from intrusion (as compared to 0.6 m from the Quasi-Static model). After this time the yield is essentially zero.

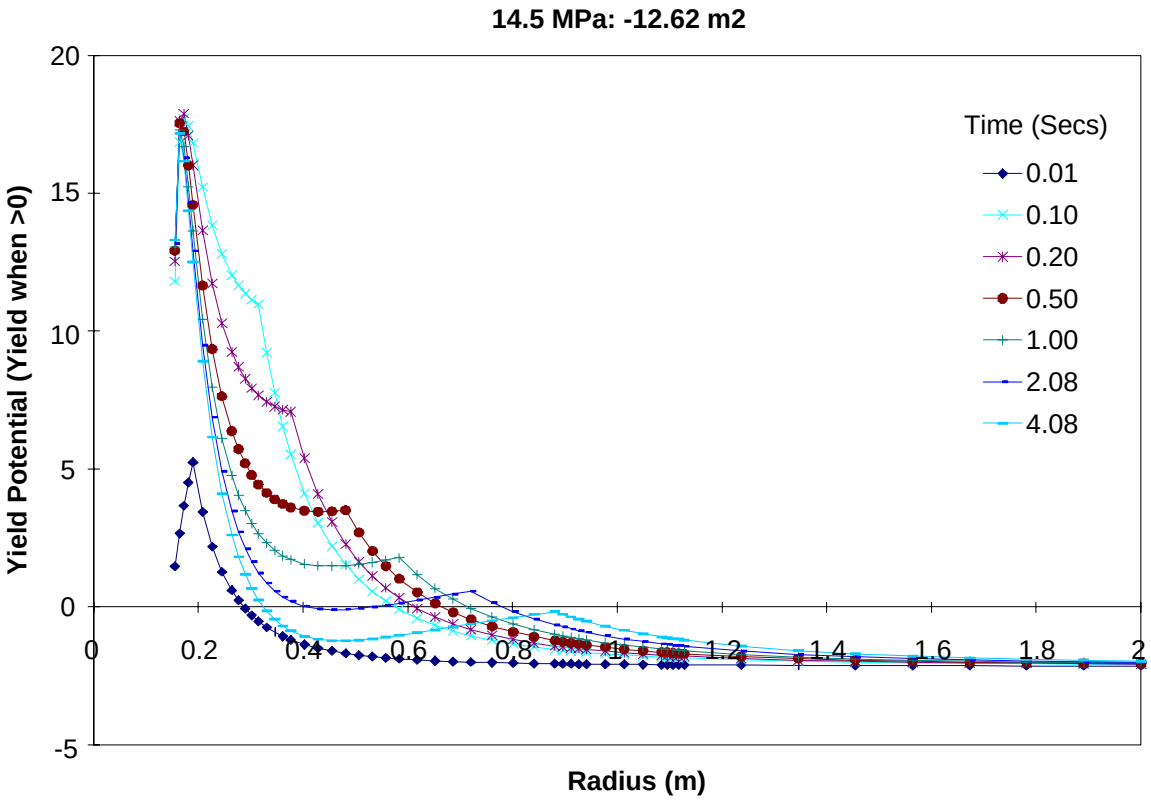

Figure 14. Yield Potential for EPA Air Drilling Analysis. The Figure Represents Equation 2 (above) vs. Radial Distance. Yield Will Occur When the Potential is Greater than Zero.

After the analysis of air drilling using the Quasi-Static model was complete, the EPA dismisses the consequence of air drilling based on the amount of expected failure in the borehole cavity. The volumes, as seen above, do not exceed the 0.5 to 4.0 m^3 of waste, which were calculated in the CCA as being the maximum possible spalled volumes. Therefore, since expected failed volumes are less, they will not affect the CCDF (Complimentary Cumulative Distribution Function) calculations of the CCA, or PAVT. One must keep in mind, however, that the analysis was for only one set of repository assumptions, and that the calculated failures can change drastically when the assumptions are changed.

To demonstrate the response of the model to different input assumptions, Figure 15 shows a simulation in which the repository is increased from the nominal 14.5 MPa that was used in the EPA analysis to 14.8 MPa. The higher pressure is the maximum pressure that the repository will

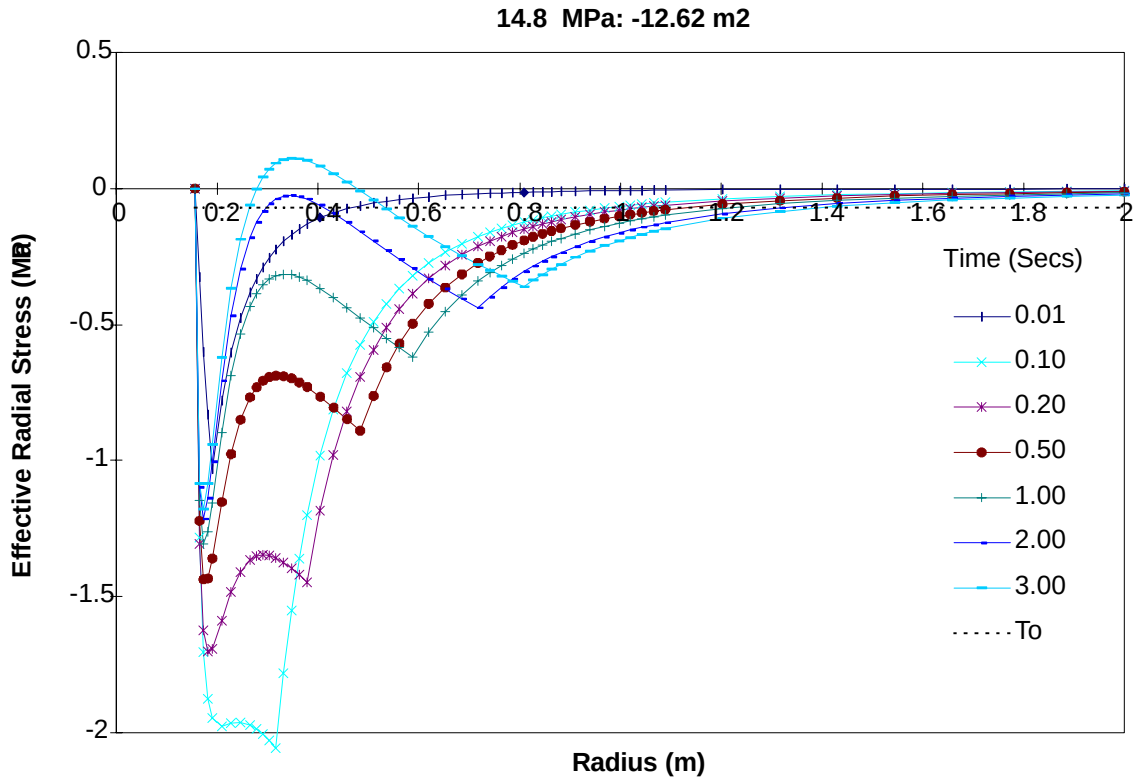

Figure 15. Effective Radial Stress As A Function Of Radial Distance For An Increased Pressure For The Air Drilling Scenario.

sustain for long periods of time, and is the lithostatic pressure of the overburden rock. If gas pressures are above lithostatic, the weak stratigraphic layers will fracture until sufficient energy is released and the pressure returns to the minimum fracturing pressure. The results of Figure 15 are astounding. The figure shows that a nominal increase in pressure will significantly increase potential releases. At 1 second after initial intrusion, the radial distance of failure is 1.22 m (7.58 m^3 of uncompacted waste). Although not shown, the waste will continue to fail during the entire 9 second simulation, in which the radial distance increases to approximately 1.65 m (19.1 m^3 of uncompacted waste). These volumes are greater than the 4.0 m^3 maximum calculated in the CCA, and perhaps would have an impact on the CCDF calculations if air drilling scenarios were considered in the CCA.

The input assumptions for the EPA air drilling analysis also assumed a waste permeability of 2.4×10^{-13} m^2, which is slightly higher than what was used in the CCA, but consistent with the PAVT. It is reasonable to assume that the waste permeability could vary within the repository,

and exhibit much lower values. The investigation by Dr. Frank Hansen and coworkers (Hansen et al., 1997) used a numerical code for gas flow within the repository during an intrusion, which could spatially vary the waste permeability. The results from the analysis showed that the pore pressure gradient will be very high near the borehole cavity. The higher pressure gradients will cause the total stress to decrease and the effective stress to increase negatively, which may lead to higher waste failures.

When the waste permeability was decreased in the Quasi-Static model for air drilling, the code predicted the opposite behavior. Table 3 shows the results of radial failure at various times for different waste permeabilities. The initial repository pressure was 14.5 MPa for these calculations. In the most extreme case, when repository pressure is 14.8 MPa and waste permeability is increased to 10×10^{-13} m^2, the failure at 5.8 seconds (blowout) is approximately 1.9 m (28 m^3 uncompacted volume).

2.5.2.3 Modeling Conclusion

The Quasi-Static model, as introduced in Hansen et al. (1997) was used to model the expected releases during an air drilling scenario into the repository at the WIPP (U.S. EPA, 1998). The investigation was initiated by the EPA to satisfy the contention that if air drilling were to occur, then the consequences would not lead to significant changes in the CCA (or PAVT). The Quasi-Static model uses a Runge-Kutta method for solving the analytical equations for 1-D flow of gas through porous media and the blowout of the drilling fluid. In addition, it solves the analytic expression for radial and tangential stresses in the waste near the wellbore. The model is a simplistic analysis, in that it solves a series of steady state approximations to flow. The model is established on two spread sheets.

Pressure = 14.5 MPa	@ 1 second	@ 1.5 seconds	@ 2 seconds
$2.4 \times 10^{-13} m^2$	1.38 m^3		
1.7×10^{-13} m^2	1.26 m^3	1.43 m^3	
1.0×10^{-13} m^2	1.11 m^3	1.24 m^3	1.35 m^3

Table 3. Estimated Failure Volumes for the Quasi-Static Model Under Varying Waste Permeability

The EPA's analysis showed that under expected repository conditions, the release from an air drilling scenario would not be greater than 1.4 m^3, and hence much less than the predicted releases of the CCA and PAVT. Therefore, their conclusion of the air drilling analysis stated that based on its [the Quasi-Static model] conservatism, air drilling need not be considered in the CCA.

Several conceptual flaws can be seen from the analysis in U.S. EPA (1998). First, the code was not designed for failure. It was only designed to calculate the stresses in the waste, assuming no waste failure and subsequent removal occurs. Waste removal will have significant impact on the actual pore pressures that may exist. Second, the code was not designed to handle a compressible fluid as the drilling medium. The code assumes that water (or some other incompressible fluid) will be ejected from the borehole upon blowout. In reality, the gas from air drilling will expand, causing the weight of the drilling fluid to be over predicted in the model. The over prediction will cause the flow of the gas from the repository to be less, and time for complete blowout to be longer.

The code also only approximates the pore pressures in the repository by assuming steady flow. As seen in Figure 12 (above), the steady flow assumption causes the pore pressure profile to be unsmooth. This characteristic, when combined with total stress of the overburden rock, produces oddly varying effective stresses in the waste. This shows that the code produces unreliable results for an air drilling scenario. When effective stresses are compared to the results of a code that calculates the time-dependent flow and pore pressures (Figure 13, above), the effective stresses are much lower (higher in the negative direction) than the Quasi-Static model at early times. Beyond the first couple of time steps, the code starts to be less accurate, and pore pressures begin to decrease in waste that should have been removed.

The analysis of air drilling by the EPA also only showed one particular view of repository conditions. The uncertainty in repository parameters were not mentioned in the report. The uncertainty in the parameters is presented in this report, and the analysis shown above demonstrates the nonconservative approach of the air drilling scenario. For example, the

repository pressures can be above the assumed 14.5 MPa, and may be as high as 14.8 MPa, which is the lithostatic pressure exerted by the overburden rock at the depth of the repository. When the Quasi-Static model was increased to 14.8 MPa, the code predicted stresses that would lead one to intrepret a failure of 19.1 m^3. This is over ten times the predicted value stated in the EPA analysis. Also, by changing the waste permeability to include the uncertainty of future and existing waste, the code predicted much different results.

In conclusion, the results of the EPA analysis do not reasonably estimate potential spallings releases. The use of a code for air drilling that was developed for an incompressible fluid appears inappropriate. The code cannot accurately predict failure beyond the initial time intrusion due to the assumption that waste will not be removed. The code should only be used to estimate the stresses in the waste when no failure has occurred. The fact that waste is not removed underpredicts the extent of failure, and provides false confidence in that blowout will be less than what may actually occur in field conditions. The results, as stated in the EPA's analysis, is not conservative, and should be re-examined based on a conceptual model that is designed to handle transient flow conditions and compressibility of the repository gas as well as the compressibility of the boring fluid.

2.6 FLUID INJECTION

The petroleum reservoirs surrounding and underlying the WIPP are potential candidates for fluid injection to recover a substantial amount of crude oil reserves (Broadhead et al., 1995; Silva, 1996). For oil field operations in southeastern New Mexico, the problem of water migrating from the intended injection zone, through the Salado Formation, and onto adjacent property has long been recognized (Ramey, 1976; Bailey, 1990; LaVenue, 1991; Silva, 1994; Van Kirk, 1994; Ramey, 1995; Silva, 1996). The observation continues to be of concern for proposed oil field waste disposal into the Salado Formation (Kehoe, 1996; Cone, 1996). Concerns about unexplained water losses due to solution mining (U.S. DOE, 1980, 2-7; U.S. DOE, 1993, 26), potential oil field development (U.S. DOE, 1980, 2-10), or future oil field waterflooding (Griswold, 1977, 13) helped eliminate other sites from consideration for the disposal of transuranic waste (U.S. DOE, 1980; Silva, 1996). Moreover, "... at the time the WIPP site was selected, one of the stated advantages over other locations was that the lack of petroleum development near WIPP was not conducive to secondary recovery techniques" (Weart, 1993).

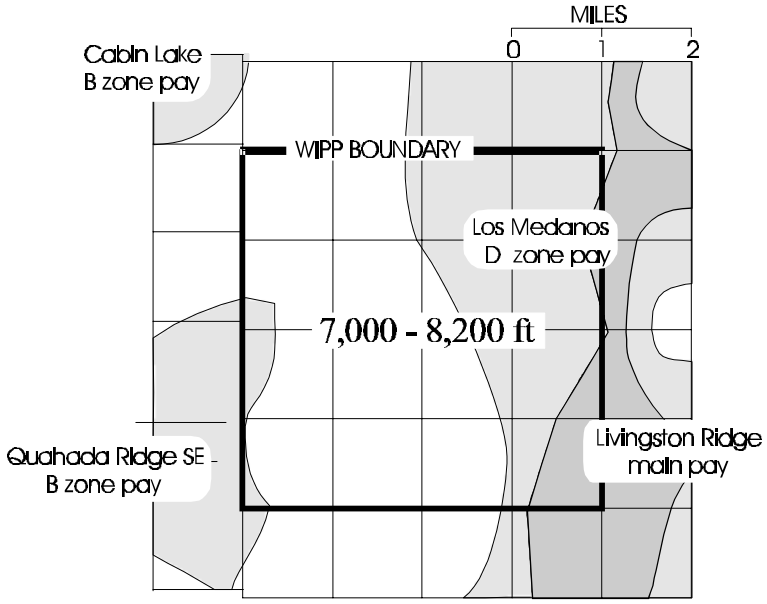

Fig. 16. Areas of Known and Probable Oil And Gas Resources for Delaware Pools. Broadhead et al., 1996.

By now it is well established that the WIPP vicinity is rich in oil and gas resources. The reservoirs are conducive to secondary resource production by waterflooding (Broadhead et al., 1995; Broadhead et al., 1996; Silva, 1996), the use of carbon dioxide flooding adjacent to the WIPP has been postulated (Boneau, 1992, 2) and the use of carbon dioxide flooding throughout the Delaware Basin is being explored with support by the DOE Office of Fossil Energy (Dutton et al., 1996; Dutton el al., 1997; Murphy, 1997) . Nonetheless, the EPA proposes to accept the DOE CCA position that fluid injection can be ruled out as a potential scenario and, hence, need not be considered in the performance assessment calculations. It is essential that the viability of these issues be assessed to ensure confidence in conclusions regarding risks from human intrusions.

2.6.1 Regulatory Argument to Eliminate Actual Resource Recovery Activities

For the recovery of oil and gas resources within the designated four-mile by four-mile boundary, the EPA proposes to accept the DOE argument that the actual recovery method need not be considered in the performance assessment. The DOE need only consider the actual drilling event (U.S. EPA, 1996). The presence of the oil and gas resources are known, the use of fluid injection is a well established oil recovery practice in the Delaware Basin, water injection for salt water disposal and enhanced oil recovery is already underway near the WIPP, and the history of water migrating from leaking injection wells through the Salado Formation in southeast New Mexico is well documented (Silva, 1996). However, the DOE does not need to consider the impact of such recovery methods in the performance assessment calculations. Such scenarios can be rejected for consideration on the basis of regulation (U.S. EPA, 1996).

The concept of rejecting a scenario on the basis of regulation allows the DOE the latitude to eliminate any inadvertent human activity that could result in a consequence greater than that of exploratory drilling (Sandia, 1992, 4-4; Silva, 1996, 158). The other grounds for rejecting scenarios are probability and consequence. These two criteria are potentially quantifiable and are an inherent part of the EPA Standards for the disposal of transuranic waste. However, probability and consequence are not considered if a scenario has already been eliminated on the basis of regulation. The International Review Group expressed reservation about rejecting a scenario solely on the basis of

regulatory considerations. In their review of the WIPP project, they state:

> It would improve the confidence of the reader if the DOE presented the logical or physical arguments for not considering these processes in the assessment, in addition to noting that they are not required in a compliance demonstration. Otherwise, there is an impression that processes that might deserve consideration from a safety perspective have been eliminated (NEA/IAEA, 1997, p. 19).

2.6.2 Low Consequence Argument Relies on Untested Model

For the low consequence argument, the EPA has accepted the modelling results of Stoelzel and O'Brien (1996) and Stoelzel and Swift (1997) and has rejected the modelling results of Bredehoeft (1997b). The DOE maintains that a leaking injection well in the vicinity of WIPP is a low consequence event because the model of Stoelzel and O'Brien does not predict a substantial inflow of brine into WIPP in such an event. But a very fundamental question remains. Can the codes model a documented high consequence event? In other words, can the DOE codes take the injection data and geologic data from the highly visible Hartman case and reproduce what is believed to have happened at the Bates Lease (Hartman, 1993, Van Kirk, 1994, Powers, 1996). At a minimum, the codes must be able to move a substantial amount of water through a single zone of the Salado Formation, two miles in the updip direction, and in a short period of time, about 12 years. If the model, as used by Stoelzel and O'Brien, can not move the water to the Bates Lease, then any low consequence argument based on this model may be meaningless. At this point there is no indication that a verification with actual field events has been conducted and a low consequence argument based on an unverified model could be characterized as speculation.

2.6.3 Low Probability Argument Conceived by EPA contradicted by DOE Observations and Actual Oil Field Experience

The EPA also raised questions regarding DOE's consequence analysis and "concluded that regardless of the consequence argument, the probability of such an injection event that affects WIPP is very low, and so this FEP can be eliminated on the basis of low probability" (U.S. EPA, 1997b, Card 32-42).

But, the DOE chose to examine consequence rather than probability, as noted by Stoelzel and O'Brien, "[b]ecause certain petroleum practices are hard to define in a probabilistic sense (for example, the quality of the cement and/or casing and its ability to withstand leaks over time)..."(Stoelzel and O'Brien, 1996, 8). Nonetheless, EPA assigned probabilities to certain petroleum practices, such as an undetected leak occurring in the annulus, and multiplied the probability of each event and calculated that the *realistic* probability of a injection well impacting the repository was only one in 667 million (U.S. EPA, 1997h, Table Q).

The EPA is relying on an optimistic view of future injection well performance which does not reflect the actual experience of documented waterflows in the Salado Formation in water flood areas throughout southeast New Mexico. As noted in EEG-62, waterflows are not randomly distributed, but are strongly correlated with waterflood operations (Gallegos and Condon, 1994, p. 2). Rules and regulations governing the use of oil field injection wells have been in place for decades and the records of waterflows indicates the level of their effectiveness. For example, the enabling orders for the Rhodes Yates waterflood (Campbell et al., 1964; Cargo et al., 1969; Ramey, 1977) required operating in accordance with Rules 701, 702, and 703 (Hartman, 1993, 4). Rule 702 requires cementing and casing of injection wells to prevent the movement of fluids out of zone. Rule 703 requires operation and maintenance practices to assure no significant fluid movement through vertical channels adjacent to the well bore. Further, the entire operation, including producing wells, must be operated and maintained to confine the injected fluids to approved intervals. The documented problems with the Rhodes Yates waterflood (Hartman, 1993; Hererra, 1995) and with waterfloods and salt water injection throughout the southeast New Mexico (Ramey, 1976; U.S. GAO, 1989; Bailey, 1990; Krietler et al., 1994) clearly indicate the limitations of taking credit for state or federal regulations, new or old, for protecting WIPP. Furthermore, there are literally hundreds of documented waterflows for District 1 and District 2 of southeastern New Mexico. Those records are maintained by the NMOCD. Summaries are included as Appendix 8.9.

To determine its probability, EPA assigns individual probabilities to events such as a leak going undetected and one of those wells leaking into the annulus. However, EPA provides no references

to any field studies to demonstrate that these probabilities have any basis in the actual experience of the oil and gas industry. For example, did EPA actually obtain and review the repair records for oil and gas wells in the Delaware Basin? EPA comments that the Underground Injection Control regulations have proven effective since 1984. Did EPA review well files to determine that all required testing for each injection well had been completed on schedule? For example, DOE sponsored a study in which it was suggested that the Todd 26 Federal #3 was the well most likely responsible for anomalous water level rises observed for the H-9 Culebra observation well (Bailey, 1990; LaVenue, 1991). Did EPA verify that the New Mexico Oil Conservation Division had a record of the mandatory annual Bradenhead test for each year since 1984 and the mandatory mechanical integrity test every fifth year since 1984? The well passed a mechanical integrity test on August 16, 1995 (Silva, 1996, 127). Are there records filed with the NMOCD, which administers the UIC, to show that the well was tested in 1990 and 1985? If not, just how effective are the rules and regulations with respect to underground fluid injection and how did EPA take that observation into consideration in its determination of the probability of a leaking well impacting the performance of the repository? EPA should address all of these issue in the final rule.

There is another issue of concern. 1) If EPA accepts DOE's argument that it is not necessary to examine other criteria once a scenario is rejected on the basis of one criteria (relevance, regulation, probability, or consequence) and 2) if EPA accepts DOE's argument that fluid injection can be rejected on the basis of low consequence, why did EPA feel it was necessary to submit a low probability argument for the fluid injection scenario? By publication of a fluid injection probability calculation, it appears that EPA was not comfortable with rejecting an important scenario such as fluid injection on the basis of one criteria. EPA felt it was necessary to examine another criteria. EPA does not provide any guidance as to which other scenarios would require examination against one, two, three, or all four criteria.

In summary, EPA's rejection of the fluid injection scenario on the basis of low probability is contradicted by the observation that "certain petroleum practices are hard to define in a probabilistic sense" (Stoelzel and O'Brien, 1996, 8). EPA's probability calculation does not coincide with the

observation that there is a history of out of zone water in waterflooded areas despite rules and regulations that have been in existence for decades. (Gallegos and Condon, 1994, p. 2; Silva, 1996, 155). It is not clear that EPA has a defensible basis for assigning probabilities of individual events in calculating a *realistic* probability of a injection well impacting the repository as only one in 667 million (U.S. EPA, 1997h, Table Q). Given EPA's efforts to provide a second basis for rejecting the fluid injection scenario, it is logical to conclude that EPA recognizes that scenario rejection may require meeting two or more criteria. The observation raises questions about each and every other scenario rejection.

2.6.4 EPA Position on CO_2 Injection in Conflict with Literature and Public Record

The potential leakage of injected carbon dioxide into the repository is of concern. Carbon dioxide must be injected into the deep target zone at sufficient pressure to generate a miscible displacement. In the event of leakage into an overlying zone, such injection could propagate a fracture and/or serve as a driving force for moving fluids through various flow paths. In the event carbon dioxide enters the repository, one might anticipate the formation of plutonium carbonates and nesquehonite and a reduction of the repository pH, each of which results in higher plutonium solubilities.

The EPA believes that the potential impact of CO_2 injection on the WIPP Site is very low because the EPA does not anticipate that CO_2 injection for oil recovery will be widespread practice in the future near WIPP (U.S. EPA, 1997b, Card 23-131). The EPA technical support document makes reference to a technical article (Thrash, 1979) suggesting that there may be a remote possibility that CO_2 enhanced oil recovery may also be suitable for some of these types of reservoirs (U.S. EPA, 1997h, 1997i) The EPA also notes DOE's opinion that CO_2 flooding in the vicinity of WIPP is highly unlikely (U.S. EPA, 1997b, Card 23-132).

DOE's position is at odds with the following observations. First, CO_2 flooding has been demonstrated to be quite successful in mature fields in the Delaware Basin such as the TwoFreds (Silva, 1996, pp. 142-145). Second, the DOE continues to sponsor university research on Delaware Basin oilfields, such as the Geraldine Ford and the West Ford, aimed at optimizing infill drilling and

CO_2 flooding throughout the Delaware Basin (Dutton et al., 1996, 1997). Third, oil and gas companies continue to purchase mature fields, such as the El Mar in the Delaware Basin, specifically for carbon dioxide flooding (Moritis, 1993; Silva, 1996). Fourth, the recently drilled reservoirs surrounding the WIPP such as Cabin Lake, Livingston Ridge, Los Medanos, and Lost Tank have oil and reservoir characteristics (Brown, 1995; May, 1995a; White, 1995; May, 1995b) that easily qualify them as potential candidates for future CO_2 flooding using the enhanced oil recovery (EOR) screening criteria described by Taber, Martin, and Seright (1997a, 1997b).

In its supporting documentation (U. S. DOE, 1997d) the DOE cites only one reference from the CO_2 flooding literature, a 1980 preprint of an SPE presentation. The body of literature on oil field carbon dioxide flooding is certainly more extensive and much has been published since 1980, including analyses of the issues raised in that 1980 preprint (Silva and Orr, 1987). Furthermore, the DOE document fails to reference the published proceedings (Silva, 1996) of a workshop on fluid injection which discusses in much more detail evidence of CO_2 flooding activities in the Delaware Basin. The EPA technical support document on fluid injection (U. S. EPA, 1997h) also fails to reference the published proceedings of the EEG workshop, which included participation by EPA staff.

With respect to the EPA documentation, the EPA offers three reasons why it believes that CO_2 will not be a widespread practice in the future near WIPP, but the EPA offers no supporting references for these reasons. (U. S. EPA, 1997b, Card 23-131).

1) EPA maintains that CO_2 injection costs far more than brine injection due to the easily available sources of brine and the injection quantities required.

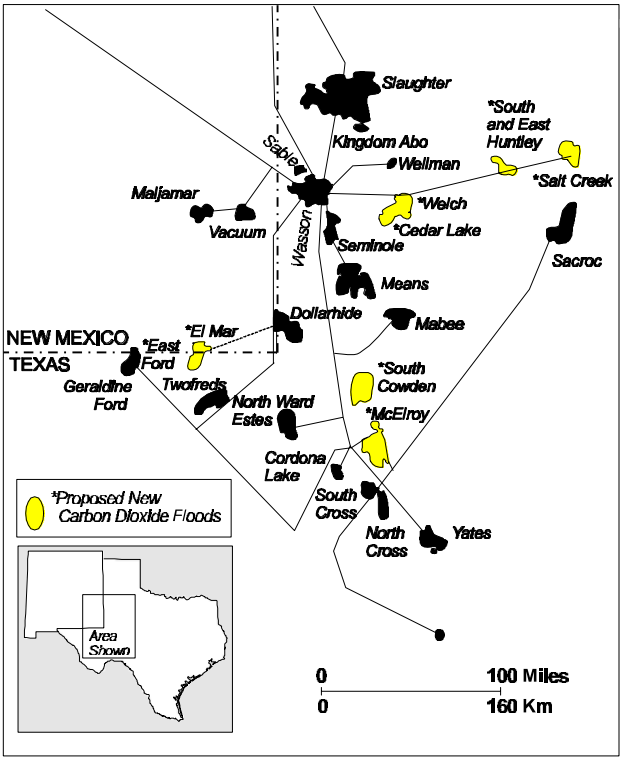

Fig. 17. Permian Basin CO_2 Pipelines and CO_2 Floods (Moritis 1993; Silva 1996)

This statement fails to recognize the availability of carbon dioxide in southeast New Mexico, the practice of conserving water whenever possible, the history of CO_2 flooding in the Permian Basin including parts of the Delaware Basin, the efficiency of a miscible type displacement to increase oil production and extend oil field life, and the willingness of local governments to work with companies to encourage the use of CO_2 flooding. If the EPA statement had any merit there would be no CO_2 flooding used in the Permian Basin or any other oil field for that matter. But as shown here, there is extensive CO_2 flooding in the Permian Basin as a result of a large investment in pipelines across New Mexico to bring carbon dioxide from southeast and southwest Colorado and northeast New Mexico to West Texas. Moreover, the DOE recognizes the potential for enhanced oil recovery in the Delaware Basin and continues to fund research on reservoir characterization and field trials to explore the most feasible use of carbon dioxide throughout the basin (Dutton et al., 1997; Murphy, 1997). In addition to encouragement by federal and state government, county governments in New

Mexico also have the authority to encourage the development of CO_2 flooding operations through tax reduction incentives. For example, under authorities granted by the state, Lea County recently granted Texaco $500,000 in property tax relief to construct a facility to provide CO_2 for injection into the Vacuum Field. In addition to extending the life of the oil field by 20 years, adding 100 construction jobs over the next three years, and providing 15 million dollars in tax revenues, the benefits to Lea County also include:

> Conserving an estimated 130 million barrels of fresh water that, thanks to CO_2, won't be pumped into the field over the next two decades, plus an additional 130 million barrels of saltwater that will be raised from the field (via CO_2 injection) and can then be used for water flooding elsewhere (Jacobs, 1998).

Waterflooding is used to restore energy to a depleted reservoir but displacement efficiency is limited to an immiscible type displacement. The long recognized favorable characteristics of carbon dioxide flooding include the preferential dissolution of CO_2 into the oil rich phase, the reduction of oil viscosity, the swelling of the residual oil droplets, the preferential extraction of lighter hydrocarbons, and the development of a miscible type displacement.

2) The EPA maintains CO_2 injection is more difficult to control, since the rocks are more permeable to gas than to brine, higher injection pressures are required to maintain desired pressure configurations.

It is not clear why EPA believes that the relative permeability of gas and brine in rock has a role in making CO2 injection more difficult to control. Please provide a more detailed explanation and references for the statement.

3) The EPA maintains the presence of gas could inhibit production in that any gas present will be in the nonwetting phase and will occupy the portions of the oil reservoir that have relatively large apertures.

The EPA did not provide any references for this statement. EPA should refer to the results of Monroe et al., (1990) for the effect of dissolved methane on a one dimensional CO_2 flood. Their analysis "indicates that high displacement efficiency is possible even when two-phase flow occurs throughout the displacement and that high recovery is possible even when a live oil is displaced below its bubblepoint pressure (BP), if the pressure is above the minimum miscibility pressure (MMP) for the same oil with all methane removed" (Monroe et al., 1990, p. 423). EPA's third argument for dismissing CO_2 flooding does not appear to be reasonable.

2.6.5 EPA Technical Support Document Inadequate on CO_2 Fluid Injection

The EPA technical support document states "technical articles indicate the remote possibility of CO_2 enhanced oil recovery may also be suitable for some of these types of reservoirs (Thrash, 1979)." EPA references one early article for a reservoir in the Delaware Basin, the Twofreds field. EPA does not reference EEG-62 (Silva, 1996) which discussed the successful Twofreds carbon dioxide flood based on more current literature (Wash, 1982; Kirkpatrick et al., 1985; Flanders and DePauw, 1993).

The EPA Technical Support Document also states "at this time, the only examples of CO_2 injection enhanced recovery techniques are some distance from the WIPP site and under much different geologic conditions (Magruder 1990; Thrash, 1979)." The statement is incorrect. As shown in Figure 17 and in EEG-62, there are many CO_2 enhanced oil recovery injection projects. It is also inaccurate to argue that the field in the Thrash article is under much different geologic conditions. The Twofreds field is in the Delaware Basin and produces from the Bell Canyon Formation, which is found in the upper part of the Delaware Mountain Group. The Cherry Canyon and Brushy Canyon Formations lie further down in the Delaware Mountain Group and are the known oil bearing formations in the vicinity of WIPP. Most importantly, each of these oil bearing formations resulted from saline density currents as the depositional processes (Harms and Williamson, 1988). Hence, the EPA technical support document (U. S. EPA, 1997h, vol. 1, p. 26) is incorrect in stating that the CO_2 flood at Twofreds is under ***much*** different geologic conditions.

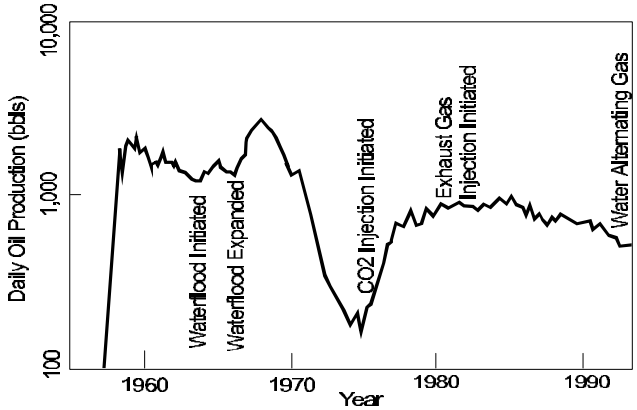

Fig. 18. Production History of Twofreds (After Flanders and DePauw 1993).

EEG-62 (Silva, 1996) discussed the performance of the Twofreds Field. The field is located in the Delaware Basin and produces from the Bell Canyon Formation of the Delaware Mountain Group. The reservoir is about 3/4 mile wide and is about five miles long with a net thickness averaging about 16 feet. The field was discovered in 1957. The Twofreds Field, like other Delaware fields, has always produced large volumes of water. After six years of primary production, a pilot water injection project was initiated in May 1963. A full scale waterflood was brought on line in January 1966. The project showed that oil from a Delaware reservoir with a high water cut could be recovered profitably (Jones, 1968). From 1963 to 1973, waterflooding, an immiscible displacement process, had produced 2 million barrels of oil. But by 1973, the amount of oil produced by waterflooding had dropped down to 160 bbls oil per day. As shown, carbon dioxide flooding, a miscible displacement process, increased oil recovery from 160 bbls oil per day to 1,000 bbls oil per day. By 1982, carbon dioxide flooding had produced an additional 2 million barrels of oil (Wash, 1982). The purpose of the Twofreds carbon dioxide flood to was demonstrate economic feasibility. The field continued to produce based on its economic merit (Kirkpatrick et al., 1985) and demonstrated that carbon dioxide can economically recover tertiary oil from a depleted, waterflooded Delaware sand reservoir (Flanders and DePauw, 1993). As of 1993, oil production from the Twofreds was averaging 500 bbls per day (Flanders and DePauw, 1993; Silva, 1996).

As a practical matter, EPA may not have enough information to conclude whether the oil fields

adjacent to WIPP are conducive to carbon dioxide flooding. As noted by Silva (1996, 162), due to federal and state restrictions on drilling for petroleum in potash deposits, 85% of the area immediately surrounding the WIPP has yet to be drilled and directly tested for its oil and gas reserves. A production history is also needed to gain some understanding about the local geology of the oil producing zones. However, some drilling for oil and gas production adjacent to WIPP has been allowed. Coupling the enhanced oil recovery (EOR) screening criteria described by Taber, Martin, and Seright (1997a, 1997b) with the petroleum and reservoir characteristics (Brown, 1995; May, 1995a; White, 1995; May, 1995b) qualifies these oil and gas fields adjacent to WIPP as potential candidates for future CO_2 flooding. The oil densities for the fields surrounding the WIPP range from 39º to 42º API gravity indicating an abundance of lighter hydrocarbon components for promoting a miscible type displacement. The reservoirs range in depth from 4200 feet to 7100 feet, more than adequate to accommodate the injection pressure required for a CO_2 flood. One obvious limitation is the lack of a local pipeline to bring inexpensive carbon dioxide to these fields. But the major CO_2 pipelines across the state are already in place and recent history has shown that if CO_2 pipelines or facilities are needed, they will be constructed.

The DOE Office of Fossil Energy also recognizes the potential for enhanced oil recovery in the Delaware Basin by carbon dioxide flooding and is sponsoring field research in the Delaware Basin. Specifically, the DOE is funding a study by the Texas Bureau of Economic Geology to couple reservoir characterization with modeling to optimize infill drilling and CO_2 flooding to increase production and prevent the premature abandonment of slope and basin clastic reservoirs (Dutton et al., 1996, 5). The DOE plans to apply the results of studying these two fields to the more than 100 other Delaware Mountain group reservoirs in Texas and New Mexico, which together contain 1.6 billion barrels of remaining oil in place. The compositional simulation of a CO_2 flood in one of the candidate fields has shown that at least 10% of the remaining oil in place can be recovered at breakthrough. The simulation results also show that continuing CO_2 injection beyond breakthrough can result in significant incremental oil recovery, in this case over 30% of the remaining oil in place (Malik, 1998).

Another DOE study of the Brushy Canyon Formation in the Nash Draw fields immediately southwest of the WIPP area also aims to provide information to design enhanced oil recovery operations throughout the Delaware Basin. In addition to obtaining detailed reservoir characterization data for designing an enhanced oil recovery operation, the project also includes the use of a model to "evaluate the technical feasibility and commercial viability of three enhanced recovery processes: waterflooding, lean gas injection, and CO_2 injection" (Murphy, 1997, 26). The investigation is ongoing.

The EPA (U.S. EPA, 1997b, Card 23-132) also relies on the brine injection modeling of Stoelzel and O'Brien (1996) to capture the effects of CO_2 injection. The EPA maintains that the degree of potential anhydrite fracturing by CO_2 "should have been captured by the large volumes of brine and high injection pressures assumed during the brine injection analysis." But as noted above, that analyses is based on an unverified model. Furthermore, the modeling effort is based on the assumption that salt water disposal will potentially cause more problems than fluid injection for enhanced oil recovery because there is less incentive in salt water disposal for the operator to control injection pressures and volumes (U.S. EPA, 1997b, Card 23-132). The assumption invites the obvious question. In New Mexico, why have out of zone waterflows been correlated with waterflood operations and not with salt water disposal wells? For example, in the Hartman vs. Texaco case, it was the Rhodes Yates waterflood operation that was determined to be the culprit and not any of the salt water disposal operations in the vicinity. Hartman produced evidence of very high injection pressures at the waterflood (Van Kirk, 1994; Powers, 1996, 67). In commenting on the history of waterflood problems in New Mexico, Ramey (1995, XI-2) states that water probably escaped from the injection zone and into the salt formations as a result of old improperly cemented and plugged wells and excessive injection pressures in oil field ***waterflood*** operations. There is no mention of salt water disposal operations, the operations that EPA is more concerned about (U.S. EPA, 1997b, Card 23-132). If the concern is excessive injection pressure exerted at the repository horizon in the event of a leak, it seems that waterflood operations would be the most likely concern in the vicinity of the

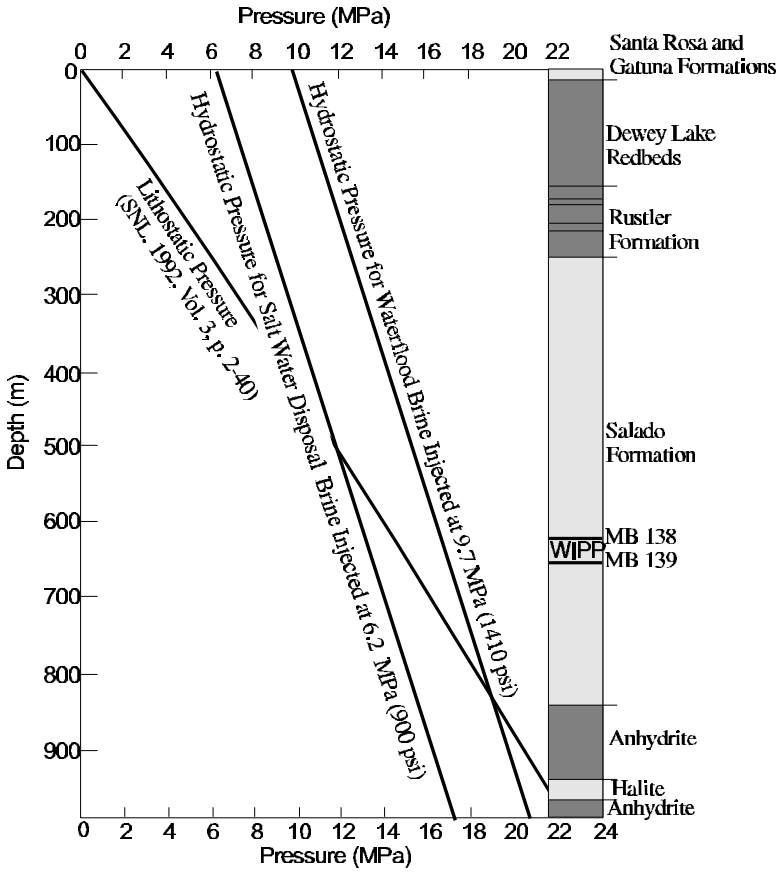

Fig. 19. Comparison of Approved Injection Pressures For Salt Water Disposal Well Versus Oil Field Water Flood Wells Near WIPP.

WIPP. Figure 19 compares the maximum approved disposal pressure for two wells one mile to the east of the WIPP Site. EEG is not suggesting that either of these wells are leaking. But EEG notes that in the event of a leak near WIPP current approved salt water disposal pressures are not sufficient at the repository horizon to exceed the lithostatic pressure. Only the a leak in the waterflood well would be of concern to the repository. This is an inherent result of the greater vertical distance to the oil producing horizons. The DOE and EPA rationale appears to be more appropriate for the more shallow oil and gas reservoirs in the Vacuum Field area and the Rhodes Yates area and not suitable for the WIPP area. Presumably, carbon dioxide for enhanced oil recovery would be injected into the deeper oil producing zones and at sufficient pressures to maintain a miscible displacement. Hence, given the observation above, EPA can not conclude that the salt water disposal well analyses captures the CO_2 flooding scenario.

2.6.6 Rhodes-Yates (Hartman vs. Texaco)

The EPA Technical Support Document acknowledges that the technical evidence related to the case was not reviewed. Rather, the technical support document reviewed a summary of the case. From that summary, the EPA document states:

> Though a jury found the waterflood operator guilty of common law and statutory trespass in the Rhodes-Yates Field, flow paths were not identified with certainty (U.S. EPA, 1997h, vol. 1, p. 31)

But at the EEG fluid injection workshop Powers noted that the flow began at an anhydrite unit on the order of 10 to 15 feet thick. Although he had not tried to correlate it to an individual marker bed, he felt that it was somewhere in the range of marker beds 140 to 142 which are below the WIPP repository horizon (Powers 1996, p. 66). Furthermore, as shown in plaintiff's Exhibit 211 and Van Kirk's testimony (p. 683), the drilling records combined with well logs identified a 36 foot wide zone just above the Cowden Anhydrite Marker as the flow path. If EPA intended to comment on the technical aspects and refer to these comments in the final rule, EPA should have reviewed the technical exhibits and technical testimony of the Rhodes Yates incident.

The EPA discussion on structure can be best described as tentative speculation. The discussion suggests that there might be more flow through possible increased fracturing of the anhydrites ***possibly*** as a result of folding, faulting, or ***perhaps*** salt dissolution which ***might*** be inferred from the varying salt bed thicknesses at the Rhodes Yates Field and the Vacuum Field. The EPA further suggests that water chemistry of the field areas in formations underlying the Salado ***may*** provide evidence of a greater rate of evaporite solution relative to the WIPP Site. But no such evidence is provided. Further, there is no reference to the published literature to support the hypothesis advanced by EPA. In fact, the entire comparison of the geology at the Rhodes Yates, Vacuum, and WIPP areas is filled with statements such as "relatively fresh waters ***may*** have been a contributing factor...", "it is also ***possible*** that fold and dip rates in the vicinity of the other two fields ***may*** contribute to increased fracturing..."(U.S. EPA, 1997h, vol. 1, p. 34). Given the implications of Hartman scenario

at WIPP, it is unclear how EPA's geologic analysis can be considered as adequate to support an EPA conclusion that a repeat of the Hartman scenario is unlikely at WIPP.

2.6.7 Culebra Water Level Rises

EEG remains concerned that there is no explanation for ten years of anomalous water level rises in the Culebra Aquifer. The water level rises began suddenly in April, 1988 (Beauheim, 1990). LaVenue (1991) conducted an investigation that raised serious questions about oil field operations. In a memo to LaVenue, Bailey (1990) identified an old salt water disposal well as the most likely source of the problem. LaVenue also explored the possibility of modelling the change in the aquifer. He found that his model could very nearly match the observed water level rises if he assumed that nearly all of the water from the salt water disposal well was entering into the Culebra (Beauheim, 1996). Beauheim (1996, 40) had also concluded that the water level rises were most likely due to some well effect. EEG-55 (Silva, 1994) had commented on the issue suggesting that leakage of oil, gas, or salt water injection wells in the Delaware Basin may have an impact on the regional hydrology. In response to the EEG report, DOE stated:

> There is currently no credible evidence that the observed water level increases can be directly or indirectly linked to activities in the WIPP area initiated by the petroleum industry. The mechanism that resulted in these water level rises have not been identified, one can only speculate as to their cause (McFadden, 1996, 11).

With respect to this issue, EPA told DOE:

> The statement "they remain unexplained" is insufficient, particularly if the reason for the rise could be interpreted to affect long term hydrologic conditions within the Culebra or be caused by ongoing oil and gas exploration and development activities, such as brine disposal into underlying units (Trovato, 1996).

Silva (1996, 125) found that a comparison of the injection history of the salt water disposal well and

the water level rises at H-9 strongly suggested communication between the injection well and the Culebra Aquifer. The DOE still has not submitted an explanation of the water level rises to the EPA and EPA does not appear to require one for the certification of the repository. In addition to the questions raised in EEG-62, if the modelling results (LaVenue, 1991; Beauheim, 1996) of the water level rises are consistent with a well injecting large quantities of water out of zone and DOE has not been able to find the source of the water, how much credit can DOE or EPA claim for the reliability of the Underground Injection Controls program? The 1996 NRC WIPP Committee report also expressed concern about the unexplained water level rises:

> An adequate explanation is lacking for observed changes in water level in the Culebra, where trends of rising water levels have persisted for several years. Observed changes in water levels from assumed steady-state conditions were not incorporated into the 1992 PA analysis. However, if the causes of the observed water level changes during the last several years are unknown, then how is it to be known that even greater changes in the flow field might not occur in the near future? Such changes might invalidate the PA assumptions and predictions (NRC, 1996, pp. 69-70).

2.6.8 Brine Production

As noted by EPA (U.S. EPA, 1997b, Card 32-10), and identified by EEG at the EPA technical exchange on 10/10/96, the CCA did not address the practice of solution mining of halite for use as brine in the drilling industry. The CCA specifically stated:

> The DOE is not aware of solution mining for potash or other minerals in the Salado within the Delaware Basin at this time (U.S. DOE, 1996c, MASS-87).

The EEG identified seventeen active brine production facilities removing halite from the Salado Formation, three of which were in the Delaware Basin (BW-6, BW-19, and BW-27). EPA notes that Appendix DEL identified a dissolution project approximately 14 miles from the WIPP. Furthermore, EPA notes that DOE submitted additional information which showed that brine production between

1979 and 1991 created a cavity of 3.4 million cubic feet and that it would be longer than 50 years before subsidence would occur.

As shown in Figure 20, there are three solution mining operations for brine production near the city of Carlsbad area and at least 16 miles from the WIPP site. EPA mentions only one about 14 miles from the WIPP Site. Furthermore, EPA does not discuss the trend towards drilling brine production facilities closer to WIPP. Brine well BW-26 has been approved for production from the Salado Formation. The solution mining operation would be located between Jal and Carlsbad to meet the demand for drilling brine. The well was approved to remove salt from the Salado formation which lies between 1500 to 2300 feet deep. The subsidence calculations provided by DOE were for a facility that is 583 feet deep.

Solution mining of the Salado Formation is an important observation. It is important for EPA to

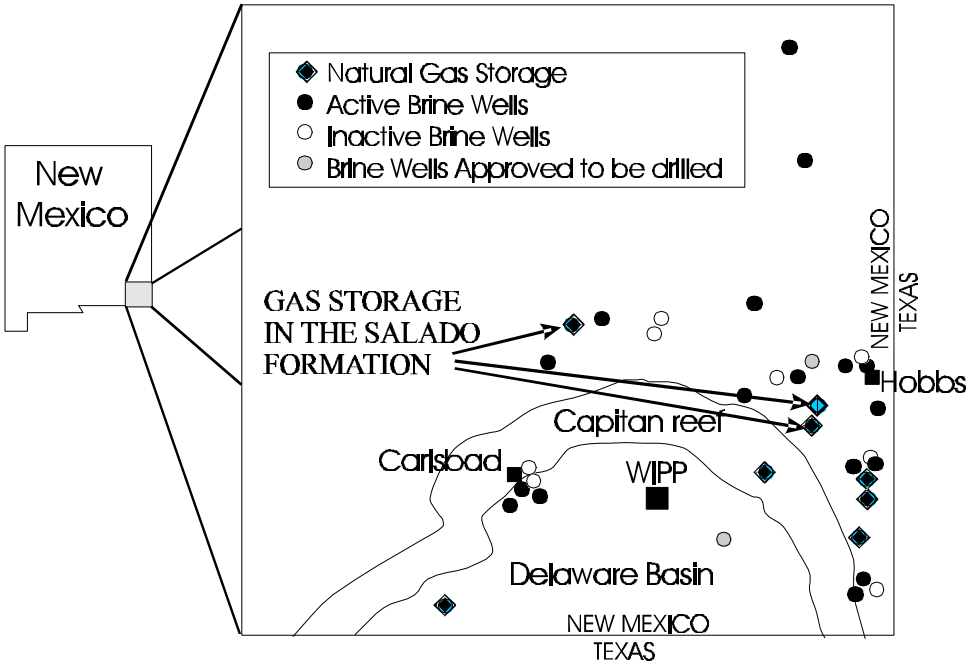

Fig. 20. Solution Mining of Brine and Natural Gas Storage Wells.

demonstrate a very clear understanding of the current situation and the full issue in the final rule.

2.6.9 Natural Gas Storage

EPA maintains that "there are no natural gas storage horizons in the Salado Formation" (U.S. EPA, 1997b, Card 32-71). As shown on a map presented to EPA by EEG on October 10, 1996, there are eight gas storage underground facilities in southeast New Mexico, three of which are in the Salado Formation in which the salt was "washed out to create a cavern." Furthermore, the natural gas storage wells can not be dismissed with a statement that they are not in the Delaware Basin. Successful operation of these three facilities for the last four decades has shown that the Salado Formation is conducive to gas storage facilities and it can be anticipated that oil and gas production will continue to increase in the Delaware Basin.

2.7 ANHYDRITE FRACTURE MODEL

2.7.1 Introduction

Criticisms of the anhydrite fracture model used in the BRAGFLO code have been brought to EPA's attention by Walter Gerstle and John Bredehoeft (Gerstle, 1996, Bredehoeft, 1997c; Bredehoeft and Gerstle, 1997; Gerstle and Bredehoeft, 1997). On March 19, 1997 the EPA requested that the DOE provide additional material describing the development of the anhydrite model beyond that supplied in the CCA documentation. As EEG pointed out during a December 10, 1997, meeting with EPA, this additional documentation indicates that the anhydrite fracture model used in BRAGFLO was intended to mimic the LEFM model developed by Gerstle et al. (Gerstle et al., 1996), but fails to do so.

On September 16, 1997, the DOE sent a letter to the EPA criticizing the LEFM model (Dials, 1997b). The EEG found this letter referred to the opinions of Sandia scientists and contained numerous misleading statements, yet lacked any substantial arguments against the LEFM model.

The EEG has reviewed the basis of the anhydrite fracture model used in the BRAGFLO code and has a number of questions about its validity. The model is unusual in that effect of fracturing is treated using an equivalent porous medium. All the relevant literature that we have examined treat fractures as distinct porosity. Use of an equivalent porous medium is not in itself unreasonable. However, the DOE has not referenced, nor have we been able to find, a description of similar treatment of the dependance of porosity and permeability on pressure as a result of fracturing. The lack of a clear development of the BRAGFLO model from established models makes its review difficult. The EPA should request that the anhydrite fracture model of BRAGFLO be compared to the treatment of fracture development in hydrofracing codes commonly used in the industry.

2.7.2 Questionable Assumptions in the BRAGFLO Model

The BRAGFLO model has been developed using several assumptions that are questionable. The following is a description of each of these questionable assumptions

The first assumption is that anhydrite will fail along planes of weakness that are probably pre-existing fractures. Hydrofracing experiments at WIPP indicated a large permeability increase when the fluid pressure reached the estimated confining stress in some instances (Wawersik et al., 1997). Other hydrofrac experiments at WIPP showed that the anhydrite remained unfractured at pressures which exceeded the confining stress by seven MPa. The BRAGFLO model assumes that hydrofracing will occur at the lower pressures and build up local stresses to cause the other regions to fail as well. While weakness dominated fracture development is probably a reasonable assumption it is not certain. Walter Gerstle believes that the pre-existing anhydrite fractures are healed by salt precipitation (Gerstle, 1998). It is entirely possible that the strength of healed fractures was reduced by local stress changes induced by the proximity of the repository to the fracture tests. This conceptual model uncertainty is not represented in the CCA calculations.

Another major assumption of the BRAGFLO model is that the porosity and permeability will increase at pressures below the lithostatic confining stress. Laboratory investigations of the permeability of fractured rocks support this assumption for existing fractures (Raven and Gale, 1985; Pyrak-Nolte et al., 1987; Cook et al., 1990). Increased permeability of the fracture over intact rock was evident and sensitive to pressure even at the highest confining pressures, 20-40 MPa. Fracture permeability increased 3 to 5 orders of magnitude as the confining stress was reduced to near zero. Note that the BRAGFLO model represents conditions of greater than lithostatic stress, so permeability increases of more than 5 orders of magnitude are possible. At pore pressures greater than lithostatic, confining stress in maintained by deflection of the rocks above the fracture.

The laboratory experiments also support the concept of permeability increasing at a rate greater than implied by the cubic law of parallel plate fractures. The steepest increase reported is an exponent of roughly nine which is considerably less than the exponent used in BRAGFLO. However, the permeability dependance on aperture becomes cubic as the aperture increases. Cook et al. (1990) have fit their experimental data to a simple model that includes the effects of tortuosity on effective permeability. The model indicates that the relationship becomes cubic for apertures in excess of 10^{-4} m. The estimated fracture aperture in the hydrofrac experiments was estimated to be on the order of $5x10^{-3}$ m (Wawersik et al., 1997) and the BRAGFLO model is intended to represent effective apertures up to 10^{-2} m (Larson, 1996).

If one takes 10^{-4} m as the effective aperture for a fracture in contact, then a total permeability increase of nine orders of magnitude is reasonable for an effective aperture of 10^{-2} m, but the greater than cubic law dependance of permeability on porosity is not. Raven and Gale (1985) found fracture permeability became dependent on the cubic of aperture in the laboratory experiments at total confining stresses of less than 1 MPa.

The assumption of multiple anastomosing fractures complicates the comparison of laboratory experiments on single fractures and the BRAGFLO model. The experimental support for multiple fractures comes from examination of core recovered from the hydrofracing experiments (Wawersik et al., 1997). Some of the core showed evidence of multiple flow channels for the tracer dye used in the experiments. This evidence supports the notion of a few channels but not the hundreds to thousands of fractures required to reduce individual fracture apertures below 10^{-4} m. The notion of many fractures of small aperture is also inconsistent with the nine orders of magnitude range of permeability change.

The laboratory experiments also support the concept of reduced fracture stiffness (increased compressibility) with increasing pore pressure. We have not attempted to determine whether a linear change is reasonable. Below lithostatic pore pressures, stiffness may be a combination of stiffness of the fracture contact zones and stiffness of the host rock with respect to both compression and bending. At pore pressures above lithostatic, confining stress is due to

deflection of the fracture faces and resulting bending of the host rock. Given the relatively small deflections of the fracture faces, it seems reasonable to expect that stiffness becomes constant above lithostatic pore pressures.

2.7.3 Summary

In summary, laboratory experiments on individual fractures support the assumptions used to formulate the permeability-porosity relationship of BRAGFLO anhydrite fracture model, but these experiments also strongly indicate that the model is only applicable at pore pressures more than 1 MPa below the lithostatic pressure. Above this pressure threshold the conventional cubic law model applies to the relationship of permeability and porosity. However, the exponent used in the BRAGFLO model is much larger than can be supported using experimental evidence.

The laboratory evidence also supports the concept of increased compressibility with pore pressure. It does not seem reasonable for compressibility to increase with pore pressure above the lithostatic pressure.

2.7.4 Conclusion

Our conclusion is that the conceptual model BRAGFLO for anhydrite fracturing may be a valid description for pore pressures less than 1 MPa below lithostatic but a cubic law formulation of the permeability-porosity relationship is valid above this threshold. As demonstrated by Freeze et al. (1995), the BRAGFLO parameters can not be set to reasonably represent this region. Figure 21 is an updated version of Figure 2 of Freeze et al. (1995). The BRAGFLO model is based on CCA parameters for marker bed 139 and anhydrite layers A and B respectively. The figure shows the permeability-porosity relationship of the BRAGFLO model to a cubic law based model for multiple fractures. Our concern is that the BRAGFLO model under-represents permeability by more than four orders of magnitude for small porosity increases. By setting the model parameters to match a cubic law fracture model at large .porosity, a large error may have been introduced for small porosity changes.

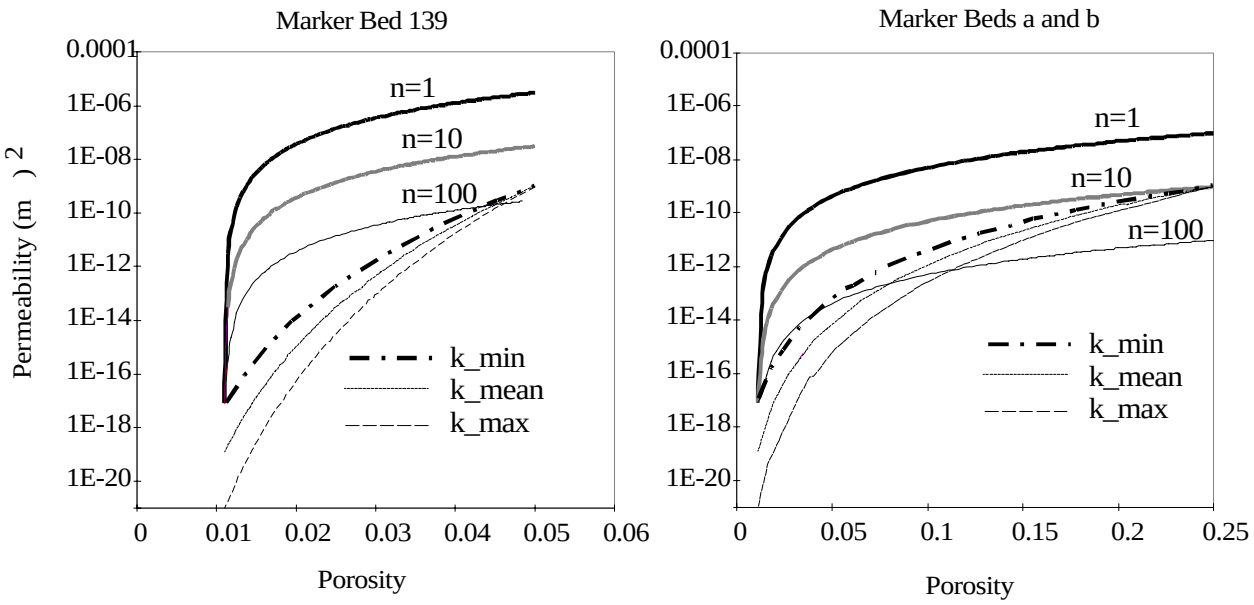

Fig. 21. Permeability vs. Porosity Model With BRAGFLO for Left) Marker Bed 139 and Right) Marker Beds a and b.

The BRAGFLO model has not been tested against either laboratory or hydrofracing experiments or other standard fracture modeling codes. This comparison should be made before the model can be accepted as valid.

A meeting was held pn February 17, 1998 to try to resolve this issue. Participants included scientists from Sandia National Laboratories; EEG; Dr. Charles Fairhurst and Dr. Jim Tracy, DOE consultants; and other DOE consultants. Dr. Walter Gerstle sent a letter to the EEG after the meeting, commenting on some of the presentations. The EEG invited the DOE to allow us to include in this report the viewgraphs used by the SNL presenters and comments on the meeting, but the DOE declined this invitation. Dr. Gerstle's letter is included as Appendix 8.7 to this report.

2.8 SOLUTION MINING AT THE WIPP

The final rule of the EPA for the certification of the WIPP requires the DOE to consider the effects of mining in performance assessments (U.S. EPA, 1996). However, the analyses need only consider the effects of the excavation mining of high grade ores, ores which are currently economical, and which are known to be present near the WIPP site, but which are known not to occur vertically above the repository. The effects of mining for low grade ores, ores which are currently uneconomical, and which could be present below or above the formation containing the high grade ores, need not be considered once the high grade ores have been removed.

The effect of excavation mining is subsidence of the overlying formations and the potential alterations of their hydrologic properties. The most important hydrogeologic unit overlying the repository is the Culebra aquifer. Therefore, in the performance assessments of mining effects, EPA permits the DOE to limit the analysis to changes in the hydraulic conductivity of the Culebra aquifer.

The EPA initially concluded that solution mining of potash is currently not feasible in the Delaware Basin (Peake, 1996). EEG (Neill, 1997a) identified solution mining as a potential scenario that must be considered by the WIPP project. In response to the concerns raised by EEG, Dials (1997d) submitted to EPA materials solicited from Heyn (1997a) and Hicks (1997). Based on the supplemental information provided by DOE, EPA maintains that changes in the hydraulic conductivity as a result of solution mining are captured in the modeled effects of room and pillar mining, that solution mining is not likely in the vicinity of WIPP because fresh water for mining is limited and the overall procedure is cost prohibitive, and that langbeinite is the primary target of extraction and is not readily soluble in water (U.S. EPA, 1997b, CARD 32-55).

The supplemental materials that DOE submitted to EPA are based directly (Heyn 1997a) and indirectly (Hicks 1997) on solicited comments from the Chief Chemist for IMC-Kalium. The comments must be viewed with caution. Heyn (1997a) makes no references to the scientific

literature. With respect to the lack of fresh water for solution mining:

> Solution mining requires access to large quantities of water. As you know, fresh water is a difficult and expensive commodity to come by in this corner of New Mexico. Water rights carry a premium price if they can be obtained at all. I would rather think the agricultural uses would have a far more beneficial use rather than solution mining (Heyn, 1997a).

Records on file with the New Mexico State Engineer indicate that on April 22, 1994, IMC Fertilizer (later IMC-Kalium) purchased 2790 acre feet per annum from Noranda Exploration (Files L-7121, L-7121-S, L-7157, L-7157-S). On November 6, 1996, IMC-Kalium, acquired an additional 2014 acre feet of water per annum to be produced from the Ogallala aquifer and piped to IMC's potash mining and refining operations (Files L-10,580, L-10581, L-10582, L-10583, L-10584, L-10584-S). It appears water rights for mining of potash ore and other related purposes can be obtained in southeast New Mexico, a detail apparently not brought to EPA's attention.

EPA maintains that the overall procedure is cost prohibitive. Heyn argued that the building of any potash mine, refinery and auxiliary facilities would require a capital investment in excess of 100 million dollars and that such an investment would require reserves in excess of 25 years. The argument provides no supporting economic calculations and no estimates of potash reserves. However, in a letter to EPA Heyn acknowledges that he is "not an expert on the extent and grade of ore reserve on the WIPP site" (Heyn, 1997b).

Heyn also suggests that efficient solution mining requires great depths to take advantage of geothermal energy such as at IMC's solution mine at Belle Plains, Saskatchewan. That mine is in excess of 3000 feet deep. Heyn comments that the potash bearing zones are only 650 to 800 feet below the surface at the WIPP site. Actually, the potash bearing zones in the vicinity of WIPP are at depths between 1400 and 1750 feet (Chaturvedi, 1984, Figure 1). Nonetheless, even at a depth of only 1150 feet, Davis and Shock (1970, p. 109) determined that a production operation would

yield 90 pounds of ore for every barrel of water injected for a potash ore zone in the Carlsbad Potash District strongly suggesting that a solution mining operation does not require the depths cited by Heyn (1997a, 1997b).

Heyn (1997a) maintains that solution mines would prefer ore bed depths to be thick, in excess of 10 feet or more to minimize solvating of unwanted minerals and displacement of clay in solubles. Yet Conoco conducted its successful field trial for solution mining of thin bedded potash on an ore zone that was 4 feet thick (Shock and Davis, 1970). In carefully designed two well test, Conoco produced 1600 tons of sylvite (KCl) and 9600 tons of halite (NaCl). And 1500 tons of that halite was produced in a final injection designed to confirm that all of the sylvite ore had been produced. If Conoco had stopped at the previous step, as would be anticipated for actual operating conditions, the total production would have been 1450 tons of sylvite and 8100 tons of halite.

In 1995, the New Mexico Bureau of Mines and Mineral Resources examined future potash mining techniques and concluded that solution mining is the only method that can be reasonably predicted for the Carlsbad District for the far future. The report notes that while no specific plans have yet been formulated, all mines in the Carlsbad area have held open the option of using solution mining once their sylvite deposits are fully mined out (Broadhead et al., 1995, p. IV-5). It is the remaining sylvite pillars, not langbeinite, that would be the primary target for solution mining.

EPA has accepted that changes in the hydraulic conductivity of the overlying Culebra Aquifer as a result of solution mining are captured in the modeled effects of room and pillar mining. The prediction of the subsidence of the ground above solution mines can be a much more complex problem than the prediction of the subsidence of the ground above conventional or excavation mines. There are verified analytical methods and formulae to predict the subsidence of the ground above excavation mines. The subject is treated in great detail in the textbook of Jeremic (Jeremic, 1994). The subsidence of the ground can be illustrated as a crater. The subsidence is uniform over the mined area with gentle slopes over the boundaries of the mined areas. In contrast, the solution mining of sodium chloride has lead to the formation of large caverns, some of which have resulted in the

collapse of the overlying sediments and the appearance of large sink holes. As an example, three spectacular sink holes occurred in 1954 over a solution mine for sodium chloride at Grosse Ile in Michigan (Jeremic, 1994). Non-uniform sinking of the ground has also been observed in Tusla, Bosnia (a former province of Yugoslavia), a town where uncontrolled solution mining of sodium chloride has been practiced for over a century.

2.8.1 Potash Solution Mining

Forty years ago, one could argue that solution mining was not used for potash, therefore it will never be feasible. The solution mining of potash is a young technology. It was started in Canada in the mid 1960's. The solution mining of sodium chloride is a very old technology. There are indications that the solution mining of sodium chloride was practiced as early as 1147AD in the small town of Altaussee, Austria (Gaisbauer, 1997).

The solution mining of potash is significantly different from the solution mining of sodium chloride. For one thing, the size of the literature on the solution mining of potash is small compared to that on the solution mining of sodium chloride, which is very large. The situation was described in 1983 as follows (Diamon, 1985): “There is a scarcity of published material on in situ potash leaching. Only a few studies have been carried out. For competitive reasons, companies involved in solution mining of potash or have an interest in getting involved, generally don’t publish their findings.”

Chemically, the solution mining of potash is significantly different from the solution mining of sodium chloride. The solution mining of potash is complex and carried out with brines. Considerations must be given to the following parameters: 1) the equilibrium system of the solubility of many salts in water; 2) the temperature of the brine in the mine; and 3) the processing of the saturated brine to achieve preferential precipitation at the surface. In contrast, the solution mining of sodium chloride requires only fresh water. Currently, solution mining of sodium chloride is used primarily to create large storage caverns for oil and natural gas.

Some have argued that solution mining of potash more economical than conventional or excavation mining of potash. IMC Kalium is currently expanding the annual production of its solution mining operation at Hersey, Michigan, from 50,000 to 150,000 short tons at a cost of $43 million (IMC, 1996). Such a large investment indicates that production of potash by solution mining in Michigan enjoys strong economic advantages over shipments of potash from Canada or the Carlsbad area. The following statement with regards to economical considerations is made in a publication (Gruschow, 1992): "therefore instead of waiting until an opportunity arises to repair or improve a conventional potash mining operation by conversion to solution mining, potential potash ore mining projects should be designed from the very beginning as solution mining operation."

There are four solution mining operations in North America. Two are in Canada and the other two are in the United States. A large potash solution mine is being operated by IMC Kalium at Belle Plain, Saskatchewan, Canada. The operation was started in the mid 1960's and in 1982 it had an estimated capacity of 940,000 ton per years (Nigbor, 1982). The mine extracts potash from depth where shaft mining is very difficult and hazardous. There are no publications describing all the changes that must have occurred to keep the operation going for about 30 years. The second Canadian solution mining operation is in the Patience Lake area, Saskatchewan, Canada. The mine is currently owned by The Potash Corporation of Saskatchewan, Inc. The mine was started as an excavation mine in the late 1950's, but it had to be converted to a solution mine in 1987 due to large inflow of water. A detailed description of the conversion from an excavation mine to a solution mine has been published (Smith, 1990). In the Canadian mines, potash is precipitated in crystallizers, which is possible because of cold temperatures.

The oldest solution mine operation in the United States is located in Moab, Utah. It is now owned by Potash Corporation of Saskatchewan, Inc. The mine was started as an excavation mine in 1964. The highly folded and distorted nature of the ore zone made mining difficult and largely unprofitable. The mine was converted to a solution mine operation in 1970 and production of potash began in 1972. A detailed description of the conversion from an excavation mine to a solution mine has been published (Jackson, 1973). The Moab mine uses solar energy to precipitate the potash in a 400 acre

evaporation pond. In 1973, the operation was expected to produce 300,000 ton per year for 20 years. Many changes must have occurred since the mining operation is still active. The second solution mine operation in the United States is operated by IMC Kalium at Hersey Michigan. The operation appears to have been started in the mid 1980's (Shock, 1985) and as already indicated, its annual production is currently being expanded to 160,000 short ton per year.

A few research studies have been published. There are two papers on an early solution mining test in the Delaware Basin (Shock and Davis, 1970; Davis and Shock, 1970). The project was not pursued because the price of potash was depressed at that time (Davis and Shock, 1970). Plans for pilot scale testing in the Montana North Dakota area were drawn up in the late 1970's (Nigbor, 1982), but it does not appear that these plans were carried out.

Solution mining of potash has been considered outside of North America. A test facility appears to have been operated at the Potasio Rio Colorado deposits in the Argentine (Colome and Ruse, 1994). Considerations were given once to the solution mining of potash from carnallite in what was East Germany (Duchrow, 1990). It should be mentioned also that Israel and Jordan extract economically about 2.1 million ton of potash from brines of the Dead Sea using large solar evaporation ponds (about 9% of the world production of potash). The KCl of these Brines is only 1% (12g/l), which is considered to be low (Gruschow, 1992).

Solution mining of potash has been successful in the operation of four converted excavation mines in North America. Two mines have operated for about 30 years and the other two for about 10 years. Solution mining is being considered for the Eddy potash mine in the Carlsbad area. The owner ceased excavation mining activities on December 3, 1997 (Davis, 1997) because the mine had been depleted of high grade ores. However, high grade ores, which remain in the pillars of the mine, can only be removed by solution mining. EPA notes that a permit is being sought for a commercial pilot solution mining venture in the Carlsbad area but EPA characterizes the proposed solution mine as speculative because it is not being done and may not take place (U.S. EPA, 1997b, Card 32-55). One might be reminded that a permit is being sought for a federal pilot waste disposal venture in the Carlsbad area,

an activity that is also not being done.

Finally, one must consider that if that extensive oil and gas development continues to expand in the potash portion of the Delaware Basin, the safe and economical production of residual potash may require solution mining.

2.8.2 Probability of Mining for Potash at the WIPP Site.

The EPA derives the mining probability of 1 in 100 in each century of the regulatory time frame using the following assumptions (Peake, 1996): 1) the mining rate in the Carlsbad area in the future will be the same as in the past; 2) the mining of different potash ore zones near Carlsbad has covered an area of 40 square miles in 62 years (1931 to 1993); and 3) future mining of potash can occur in the entire Delaware Basin, which covers an area of 9700 square miles.

The mining rate in percentage per century is

$$(40/9700)*(100/62)*100\% = 0.67\%$$

This value is then rounded upward to 1% and called a mining probability of 1 in 100 in each century of the regulatory time frame.

The assumption that a mining rate can be called a probability is technically incorrect. The EPA should have stated that it is assumed that the mining at a particular site in a century is governed by a Poisson distribution with a rate of 6.7 E-05/yr. The probability of no mining occurring at a particular site in a century is then given by

$$P(\text{no mining in a century}) = e^{-(6.7E-05*100)} = 0.9933$$

and the probability of mining occurring at least once in a century is

$$(\text{Mining at least once in a century}) = 1 - e^{-(6.7E\text{-}05*100)} = 0.0067$$

which can be rounded upward to 0.01 or 1%.

Note that the probability for mining occurring at least once during the regulatory time frame of 100 centuries is given by

$$P(\text{mining at least once in 100 centuries}) = 1 - e^{-(6.7E\text{-}05*10{,}000)} = 0.49$$

for a mining rate of 6.5E-05/yr and

$$P(\text{mining at least once in 100 centuries}) = 1 - e^{-(1.0E\text{-}04*10{,}000)} = 0.63$$

for a mining rate of 1%/century.

It would be shortsighted to assume that the mining of potash in the future will be comparable to the past, which was based on past mineral economics. Modern agriculture depends on nitrogen based fertilizers and almost all the mined potash is mixed with fertilizers. It has been estimated that about 40 percent of the world population is alive because of the use of nitrogen based fertilizers (Smil, 1997). World reserves for high grade ore of potash have been estimated at 8.4 million tons (Searls, 1996). Reserves for Canada and the United States (mostly in the Carlsbad area) have been estimated at 4.4 billion toms and 76 million tons respectively. World production of potash peaked in 1987 at an annual production of 30 million tons of K_2O and then dropped sharply to an annual production of 20 million ton by 1990 (Searls, 1995). Production has fluctuated but increased to 24.3 and 22.9 million tons in 1995 and 1996 (Searls, 1997). Rayrock Yellowknife Resource Inc, a company that mines for potash in the Carlsbad area, reported in 1996 a 6.1% increase in the finished product of langbeinite from 379,100 to 402,400 tons (Rayrock, 1996). Rayrock Yellowknife Resource states also that it has approximately 21 years of remaining reserves in Nash draw. IMC Kalium, a large producer of potash that also operates a mine in the Carlsbad area, indicates that China will have to

increase its potash consumption by the year 2,000 to 7 million tons of K_2O in order to optimize its food production. The 1996 consumption of K_2O in China was 3 million tons (IMC, 1996).

These statistics indicate that the world reserves of high grade potash ores will be depleted in about three centuries, which is very short compared to the regulatory time frame of 100 centuries.

The economic considerations of potash offer two scenarios for consideration:

> 1) low grade potash ores such as occur over the WIPP site will become economical and will be mined. The probability of the mining of potash over the WIPP will be certain or 1.0;
>
> 2) the world population will decrease sharply eliminating the need for large quantities of fertilizer. The probability of the mining of potash at the WIPP site will be much less than 1.0.

The former scenario appears to be far more reasonable.

2.8.3 Conclusions

1. EPA's conclusion that potash solution mining is not likely at WIPP relies on solicited comments that are factually incorrect and inconsistent with the published scientific literature.

2. DOE and EPA maintain that excavation mining captures the effects of solution mining on the hydraulic conductivity of the overlying aquifers. However, based on the scientific literature, the prediction of subsidence above solution mines can be much more complex than the prediction of subsidence due to excavation mining. This issue needs to be reevaluated for the final rule for WIPP.

3. Potash is a resource used for the production of food, therefore it appears to be incorrect to calculate a probability of mining based on past potash production which was inherently dependent on past mineral economics and the availability of high grade ore. It also seems reasonable to assume that low grade potash ores will eventually be mined to meet world demand.

2.9 GROUNDWATER FLOW AND RADIONUCLIDE TRANSPORT THROUGH THE CULEBRA

2.9.1 Introduction

The proposed rule (U.S. EPA, 1997c, p. 58799) discusses the causes for the lack of contributions to the total releases from the ground-water pathway, concludes that this was due to the assumed values for chemical retardation (K_d), and finds the K_d values used in the calculations to be reasonable except the lognormal distribution. As a matter of fact, the very low contribution of the releases from the ground-water pathway is due to a number of assumptions made in the CCA. The amount of radionuclides introduced in the Culebra is low due to the assumptions of actinide solubility, brine reservoir characteristics and the intrusion borehole characteristics. There are other factors in calculating transport through the Culebra besides the assumption of K_d values that result in low releases. These factors are discussed below.

The National Academy of Sciences WIPP Committee (NRC, 1996; Chapter 6 and Appendix F) raised a number of issues regarding the conceptual model and numerical model of transport through the Culebra aquifer. Only some of these issues have been addressed in the proposed rule, and even those in a very cursory fashion. The EPA's Technical Support Document III-B-6, Sections 1.3.18 and 1.3.19, discuss the issues related to Culebra transport, but do not question the DOE assumptions and modeling. The responses to comments on the issue of "Ground-water Flow and Radionuclide Transport in the Culebra" are contained in the CARD 23, pages 127 to 133, but do not discuss most of the issues raised by the NAS WIPP Committee. Several of these issues were also presented by Dr. Leonard Konikow at the EPA/DOE meeting on December 5,6,7, 1995, in Carlsbad NM; and at a meeting of the NAS WIPP Committee's sub panel on Hydrology at the Sandia National Laboratory on February 10 and 11, 1997. Because of the lack of adequate consideration by the EPA, as seen in the "proposed rule" documents, the EEG

requested Dr. Konikow to provide a summary of the issues that he has raised but remain unresolved. The following is based on personal communication from Dr. Konikow (Konikow, 1998).

2.9.2 Transport Calculations

Heterogeneity and Model Discretization: Much recent hydrogeologic research has clarified the importance of heterogeneity in controlling solute transport. What constitutes an adequate scale of definition of formation heterogeneity for a flow model may be inadequate for solving the transport equation in the same formation. Konikow (1997) presented results of numerical experiments indicating that the CCA consistently underpredicted the migration distance of a plume emanating from a human intrusion borehole. In the CCA model of the Culebra, it appears that errors arising from several sources cause an artificial spreading of the calculated width of the plume at the expense of its length. The sources of these errors include: numerical dispersion and spatial truncation errors in the transport code, poor resolution from using a grid that is too coarse for the scale of the problem, and overestimates of the size of the solute source area. The resulting nature of these errors is illustrated in Figure 22, in which plume shapes are simplified to occur as a triangle; also, for simplification, concentrations are assumed to be uniform and equal within the plume, and zero outside of the plume. Then, if the plume spreads out laterally more than would actually occur, for a given mass of contaminant released from a leaky borehole, the wider plume (a) will necessarily move downgradient a shorter distance than the narrower plume (b). Both plumes in Fig. 22 enclose identical surface areas, so they would encompass equal volumes of aquifer and equal masses of contaminants.

The solute-transport model used in the CCA is based on a finite-difference grid having a minimum spacing of 50 m. An alternative analysis was performed using the MOC3D model (Konikow et al., 1996) in which the transmissivity variations are represented on a much smaller scale, using a 2-m grid spacing, rather than the original 50-m grid spacing. This finer-scale representation of the heterogeneity and of the borehole source area results in a much longer, but narrower, plume that would have a significantly shorter travel time to the regulatory boundary for equivalent concentration levels. The 50-m discretization and related approximations, in effect, could bias the

calculations toward demonstrating safety because plumes calculated using the coarser grid would not travel as far towards the regulatory boundary in 10,000 years as they would with a finer grid.

Heterogeneity of Other Transport Parameters and Processes: The CCA model of the Culebra assumes that most properties of the system, except the transmissivity, are homogeneous and uniform within each simulation realization, but that these properties varied from run to run. Field

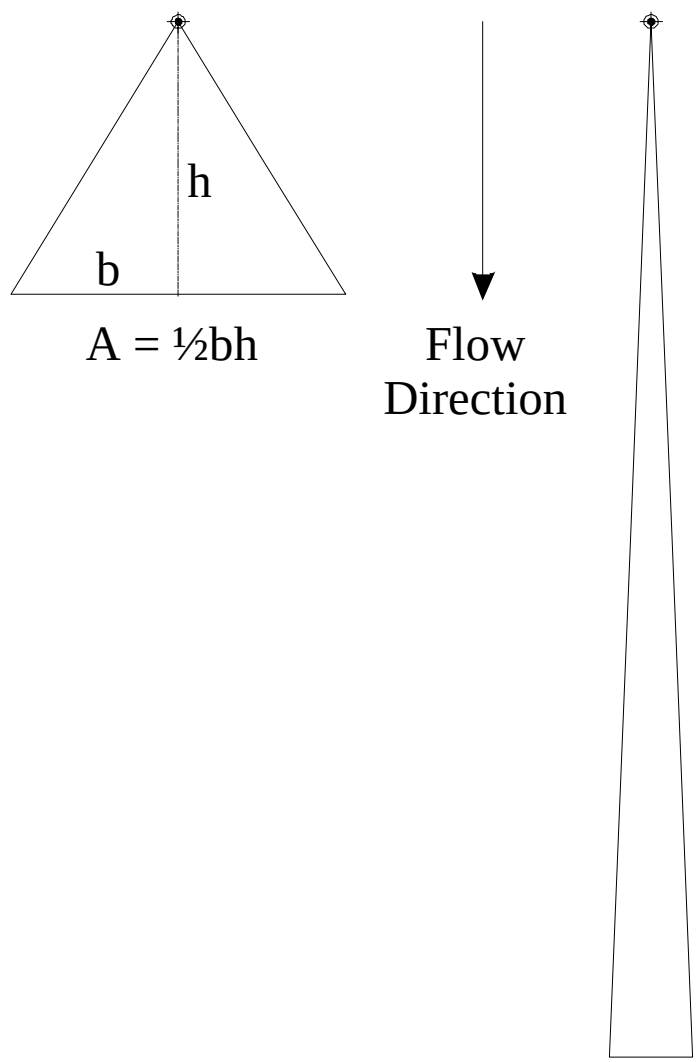

Fig. 22. Conceptual Diagram Of Contaminant Plumes Represented As Simple Triangles, Showing Different Travel Distances For A Relatively Wide Plume Compared To That Of A Relatively Narrow Plume, Where Both Plumes Encompass Equal Volumes Of Fluid And Equal Masses Of Solute.

tests at WIPP, however, indicate significant variability in many of these properties. For example, the effective porosity of the aquifer varies by almost an order of magnitude, even over a distance of only 50 m (the size of one cell of the model grid). Porosity has a strong control on transport velocities and times. Hence, the variability in porosity induces variability in velocity, which means that some parts of the plume may move faster than the local average velocity. This effect cannot be captured by assuming that porosity is uniform in each simulation. One would expect other properties, such as K_d and fracture spacing, to similarly exhibit large spatial variations. The PA procedure inherently assumes that heterogeneity in these variables has no significant impact on transport, or that its effects can be adequately represented by varying uniform properties among all the realizations. Either way, the CCA has not demonstrated that this is indeed the case and that it is reasonable to ignore the spatial variability in all of these critical parameters.

Sampling Procedures for Input Parameters: To generate the statistical distributions from which the risks are calculated, many simulations of hydrogeologic processes are performed to generate an adequate sample size. The approach to varying the values of the many parameters in the multiple realizations can introduce errors into the final analysis. In particular, if hydrogeologic variables that are highly correlated are sampled independently, and if the correlations are ignored, then some of the realizations may be based on unreasonable or very unlikely combinations of parameters; such individual simulations should not be incorporated into the final analysis because they may skew the statistical results. This was the basis for a criticism of the WIPP performance assessment by the NAS WIPP Committee (NRC, 1996, p. 71). For example, the CCA separately sampled and independently varied aquifer transmissivity, fracture spacing, and porosity. Yet there is good reason to suspect that these variables are interrelated.

The significance of this problem can be illustrated with a relatively simple example. Suppose that a strong positive correlation exists between two critical model parameters, as represented in Fig.23a, and that all data points will fall within the indicated bounds. Furthermore, assume that a safety failure for the geologic repository will only occur if the values for both parameters are very high, as represented in Fig. 23a. If the sampling procedure generates values independently for both parameters from uniform distributions for a sample size of 25, for example, then we might

expect the 25 realizations to be based on parameter values distributed uniformly in the sample space, as represented in Figure 23b. That is, we would expect a plot of joint values of the two parameters to yield one point in each of the 25 squares in the grid shown in Figure 23b. Only one of the 25 realizations (representing the value in the upper right corner of the grid) will yield a failure, and the probability of failure on this basis will appear to be 0.04. Twelve of the samples, however, were obtained from outside of the bounds of the feasible set of values. If these are discarded, as they should be, then the failure probability is only one out of 13 (or about 0.077), or nearly twice as great as indicated by independent sampling that ignores the correlation between these two variables. The net effect of the independent sampling approach in this example of correlated parameters is to "pad" the outcome with "safe" cases (or realizations), thereby yielding a biased risk assessment.

Consistency Between Performance Assessment (PA) Models: The PA procedure uses one model to calculate the fluid and solute flux up and out of a Human Intrusion (HI) borehole. This outflow flux should then be equal to the input flux (source term) in the Culebra model that is used to calculate transport distances and times. However, the source term in the Culebra model is apparently not represented as a specified flux, so it is unclear that the flux out of the borehole is equal to the flux into the Culebra for each set of realizations (or even for the mean of all realizations). The PA models should compute mass balances and budgets, to demonstrate that the two boundary conditions are indeed equivalent. Specifically, the total mass of fluid and solute that the borehole model computes to enter the Culebra over 10,000 years should equal the total mass of fluid and solute that is added to the Culebra over 10,000 years in the Culebra model. Is such documentation available? It appears possible that representing the HI borehole solute flux as an initial condition in the transport equation without an accompanying fluid flux could lead to a consistent underestimate of the solute spreading away from the finite-difference cell where the HI borehole is assumed to be located.

Other Concerns about Parameters and Processes: The NAS WIPP Committee report (NRC, 1996) included a number of criticisms of the conceptual models and numerical models of the Culebra, many of which remain unresolved. Please review Chapter 6 and Appendix F of that report for more details. The most critical issues relate to the use of homogeneous and uniform Kds in each realization, and whether the very simple retardation factor concept adequately represents all of the complex reaction chemistry. This has certainly not been adequately demonstrated at the field scale. A related important issue is the accuracy of the definition of matrix diffusion processes and parameters. Another concern is the reliability of the regional

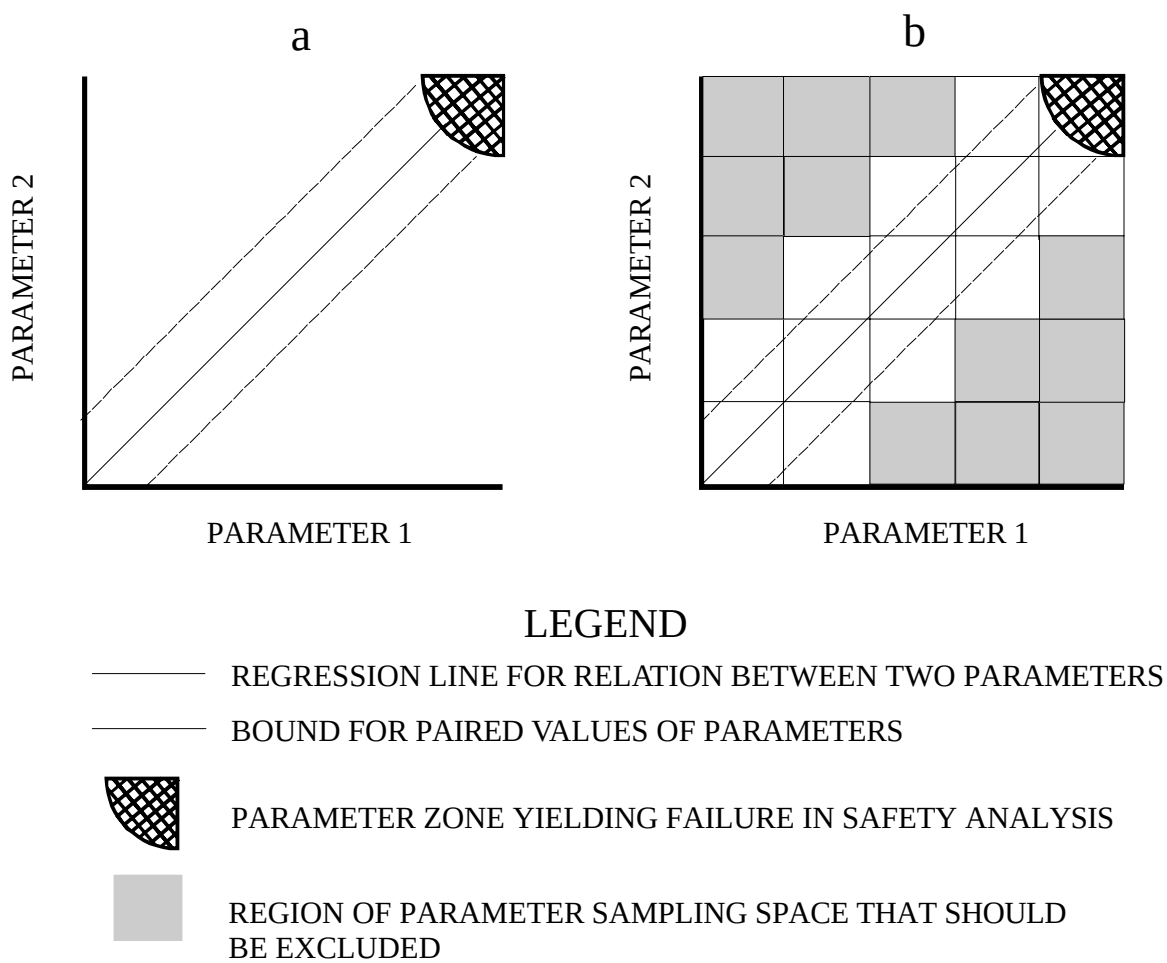

Fig. 23. Example to illustrate effect on calculated risk of independent sampling values of two parameters that are strongly correlated. (a) All data points fall within indicated bounds. (b) Independent sampling can yield paired values that are “out of bounds” and should be excluded from the PA.

transmissivity estimates for the Culebra, which were determined using inverse methods that assumed a non-leaky two-dimensional aquifer. More recent three-dimensional analyses by Sandia clearly indicated that there is significant leakage into the Culebra. A AClimate Index@ has been used as a multiplication factor in the CCA to enhance the magnitude of flow of the Culebra flow field to compensate for the lack of consideration of the additional flux through the system. However, we have not seen any rigorous analysis and documentation of the consequences of such errors, or the sufficiency of corrections applied.

An important overriding consideration is that if the volume of fluid entering the Culebra from HI boreholes is negligible or if the concentration of radionuclides in that fluid is extremely low, then weaknesses and flaws in the Culebra models become a moot point. The reliability of these calculations of fluid and solute fluxes hinges on a number of other assumptions and conceptual models about the high-pressure brine reservoirs underlying WIPP, about the pore-volume and saturation of the sealed repository, about anhydrite marker beds, about solubilities, and about a number of other issues. Some of these assumptions have changed markedly between the time of the 1992 PA and the 1996 CCA. The NAS WIPP Committee (NRC, 1996) examined the assumptions underlying the 1992 performance assessment in moderate detail. Many of the revised assumptions that were made for the CCA models were not subject to rigorous scientific scrutiny by the Committee. Where some of the CCA assumptions were examined and weaknesses in the models detected, it was too late to document the concerns in the 1996 published report of the Committee.

2.9.3 Chemical Retardation

The EEG has submitted the following four documents to the EPA on this issue:

- Copy of November 14, 1996, letter from R.H. Neill to J. Salisbury, with attachments;
- February 7, 1997, letter from R.H. Neill to F. Marcinowski, with attachment “Chemical Retardation”;
- Copy of May 23, 1997, letter from R.H. Neill to J. Salisbury, with attachments; and,

- Copy of August 29, 1997, letter from R.H. Neill to G.E. Dials, with attachments.

The August 29, 1997, letter and the attachments (EPA WIPP Docket # II-D-117) contained the EEG position on this issue based on the July 30, 1997, meeting in Albuquerque, which was organized by the EEG. Copies of this letter with the attachments were mailed to several EPA officials and the EPA WIPP docket. The DOE also sent a copy of their impressions of the July 30 meeting (Dials to Neill 8/25/97 letter with attachments, docket # II-D-115) to the EPA on August 25, 1997, four days before the EEG letter.

The EPA draft rule discusses this issue in the Technical Support Document, "Assessment of K_ds Used in the CCA", docket # III-B-4. This document makes extensive references to the DOE's August 25, 1997, letter, but no mention of the EEG's August 29, 1997, letter. Because the issue was raised by the EEG, and the July 30, 1997, meeting was organized by the EEG, it is difficult to understand why the EPA's analysis makes no mention of the EEG's summary of the July 30 meeting and the recommendations.

As described in the EEG's August 29, 1997, letter, the EEG has recommended conducting both batch and column tests for at least the actinides Pu(III), Pu(IV), and Am(III) in the Culebra brine; setting the lower end of K_d for U(VI) to be zero; conducting sensitivity analysis for potential impact of organic ligands; extending performance assessment calculations beyond 10,000 years to see how long the chemical retardation delays the releases to the environment; investigating the potential impact of nonlinear sorption on radionuclide transport; and, checking the validity of the K_d values derived from the column tests by examining the cores to identify whether the Pu and Am are present in adsorbed or crystalline solid phase.

Before discussing the specific issues and our recommendations, we wish to clarify our philosophy regarding what K_d numbers are needed for showing compliance with the numerical Containment Requirements (40 CFR 191.13) of the EPA Standards. Independent check of the CCA calculations by the EPA and the EEG show that only 3 ml/g value for K_d is sufficient for showing compliance with 40 CFR 191.13. However, that conclusion is based on keeping all the other

parameters and assumptions in the CCA unchanged. It is difficult to accept a particular value or a range of values for any of the input parameters, or to accept conceptual models, on the basis of partial sensitivity analyses. We have communicated this view to the Environmental Protection Agency (EPA) in our comments on the CCA dated February 7, 1997 (Appendix 8.1) and March 14, 1997 (Appendix 8.2). The EEG position is that the values of all input parameters and the validity of all conceptual models be independently verifiable to be robust. The comments below should therefore be read with this philosophy in mind. Letter reports on this question from the EEG consultants, Dr. Don Langmuir, Dr. Leslie Smith, and Dr. Mark Brusseau, are enclosed in Appendix 8.6 of this report.

Transferability of Laboratory K_d Data to Field: Dr. Jim Davis of the U.S. Geological Survey, who attended the July 30, 1997, meeting as a nominee of the NAS WIPP Committee, raised a number of important questions concerning the applicability of the laboratory K_d data for the field conditions. This issue has been debated for many years. The latest report of the National Academy of Sciences WIPP Committee (NRC, 1996), in discussing the chemical retardation issue, states: "...there is often little basis for extrapolation of theory and lab tests to the field environment for predictive purposes". The EEG has, however, accepted the validity of the approach of using the laboratory determined values to get an estimate of the values to be used for modeling contaminant transport in the field, because, as described by Dr. John Bredehoeft at the meeting, groundwater diffusion into the rock matrix will provide opportunities for chemical retardation to occur. But this does not mean that a one-to-one correspondence may be assumed between the laboratory and field values. Dr. Brusseau has recommended additional analyses of the column experiments to help address whether the K_d values obtained under static batch conditions provide an accurate measure for dynamic field conditions. Both Dr. John Bredehoeft and Dr. Leslie Smith emphasized that the K_d range determined from batch tests applies only to the matrix porosity, and not to retardation in the fracture system with advective porosity. This is consistent with the model used in the CCA. There is no discussion of this specific issue in the DOE's August 25, 1997 letter or its attachments, extensively quoted in the EPA's Technical Support Document (U.S. EPA, 1997j).

Limited K_d Data Base: The experimental data base for the K_d values used in the CCA remains insufficient. In the absence of measured K_d values for Plutonium at oxidation states III and IV, and inconclusive results for Am^{III}, the K_d values for these three most important actinides in the WIPP inventory have had to be estimated. These estimations are based on two questionable assumptions. The first is that K_d values for actinide cations of the same charge should roughly be the same. According to Dr. Langmuir, the weakness of this assumption lies in not considering the effect of the speciation behavior of the cations on their adsorption properties. The second assumption is that predictable trends exist for the K_d values of actinide cations of different charge. The DOE used this assumption to argue that Pu^{V} data can be used for Am^{III}. Dr. Langmuir has shown in his letter report to EEG (Appendix 8.6) that this assumption is based on questionable data and interpretations of the experiments conducted with dilute groundwater from the Yucca Mountain site, even though, fortuitously, the same trend has been reported by some other experimenters. Results of the intact core column tests are probably of questionable value as well, because the Am and Pu input concentrations to the cores were so close to saturation with solids that precipitation rather than adsorption may have occurred.

The net result of these assumptions is the use of unjustified K_d values for the three most dominant radionuclides in the WIPP inventory. Pu^{V} data has been used for Pu^{III} through a two step process, both of which are questionable; first, through the predictable trend argument, for Am^{III}, and then, through the oxidation state analogy, for Pu^{III}. Similarly, Th^{IV} data has been used for Pu^{IV}, using the oxidation state analogy. Here too, besides the problems with the oxidation state analogy, there is an additional problem of an inapplicable brine (from ERDA-6 brine reservoir) having been used for the Th^{IV} experiments. As Dr. Clemo showed at the July 30 meeting, the mean K_ds measured in the ERDA-6 brine are greater than the values determined using the other three brines. Thus, the use of Th^{IV} data for Pu^{IV} also has two problems. The EEG has never understood why real data for at least the most dominant components of the WIPP waste has not been obtained. The attachment to the DOE's August 25, 1997, letter (Docket II-D-115, cited in U.S. EPA, 1997j) repeats the previously presented arguments in favor of accepting the data on other actinides at other oxidation states as surrogates for actual data on Pu^{III}, Pu^{IV}, and Am^{III}.

EEG recommends conducting both batch and column tests for at least Pu^{III}, Pu^{IV}, and Am^{III} in the Culebra brine if any credit for retardation of these actinides is to be taken in the WIPP performance assessment.

Uniform Distribution Assumption: Based on the recommendation of our consultants, the EEG now accepts the use of uniform probability distribution to represent the uncertainty in the K_d values for the CCA calculations because the experiments were not designed to provide distribution information. However, Dr. Leslie Smith has taken issue (see page 2 of his letter report, Appendix 8.6) with the CCA values for the lower and upper bounds of the probability distribution, and how these bounds are defined relative to the type of brine used in the batch experiments. The ranges for K_d relative to brine type were selected based on the average value of the sample distribution. For example, the range for Pu^{V} (and by extrapolation, for Pu^{III} and Am^{III}) used in the CCA calculations is 20-500 ml/g, which reflects values from the batch tests using deep brines, while the results with the Culebra brine had a lower range of 9.8, and therefore the assumed range for Pu^{V} should have been 9.8 to 500 ml/g. Dr. Langmuir has asked (see Appendix 8.6) why the lower range of 1-200 ml/g determined for Np^{V} was not used for Am^{III} and Pu^{III} .

Dr. Leslie Smith (in his letter report in Appendix 8.6) has also raised questions about the U^{VI} K_d data. If the negative values are ignored, the low end of the sampling range for U^{VI} is 0.03 ml/g. The zero values assigned to the negative values for the batch tests with the Culebra brine did not get passed into the CCA calculation because of a lower average value of K_d for the batch tests using deep brines. The EEG recommends that the lower end for U^{VI} K_d value be set at zero.

Non-Culebra Dolomite: The issue of the use of Norwegian dolomite K_d data, not a major concern to begin with, may be considered to be resolved because the results of these tests make their way into the final sampling distribution only once, in determining the upper bound for U^{VI} at high pH conditions.

Organic Ligands: The EEG makes the following recommendation, as suggested by Dr. Mark Brusseau (see his letter report in Appendix 8.6):

> The DOE should conduct and publish a formal sensitivity analysis to examine the potential impact of organic ligands on the aqueous concentrations of the radionuclides. The concentrations of the ligand should be varied by several orders of magnitude, and the full list of ligands provided by EEG should be used.

Additional Issues: Dr. Langmuir has questioned the results of the core column tests because of the high concentrations of Pu^{V} and Am^{III} in intake solutions possibly resulting in their precipitation as solids rather than adsorbed in the columns. If precipitation did occur, the concentrations in the rock cannot be used to define K_d values. In order to prove or disprove this concern, it is recommended that the core materials that have been drilled out be examined to identify whether the Pu and Am are present in adsorbed or crystalline solid phase.

Dr. Langmuir has also suggested that it is possible to obtain K_d values for the important actinides in a short period of time from accelerated intact core experiments performed in an ultracentrifuge. Because of the time constraints, the DOE should examine this option.

Dr. Brusseau has recommended investigating the potential impact of nonlinear sorption on radionuclide transport. This could be accomplished by calculating effective K_d values for pertinent C_0 values, using the nonlinear isotherm data available. These values should then be compared to the existing K_d range.

During discussions with our consultants after the July 30 meeting, it was pointed out that if the calculations for release were continued beyond the 10,000 year period, release to the accessible environment will be seen. Rucker (1998) also shows that a significant fraction of actinide mass will cross the LWB beyond the 10,000 regulatory time frame. Figure 24 (reproduced from Rucker, 1998) shows the fractional discharge of Uranium with a retardation coefficient of 2.0

crossing the LWB. The figure demonstrates that very little mass that enters the Culebra crosses the LWB during the initial 10,000 years and almost the entire nuclide mass fraction will cross the LWB by 70,000 years post intrusion. The EEG recommends that the performance assessment calculations be extended beyond 10,000 years to determine long-term system performance.

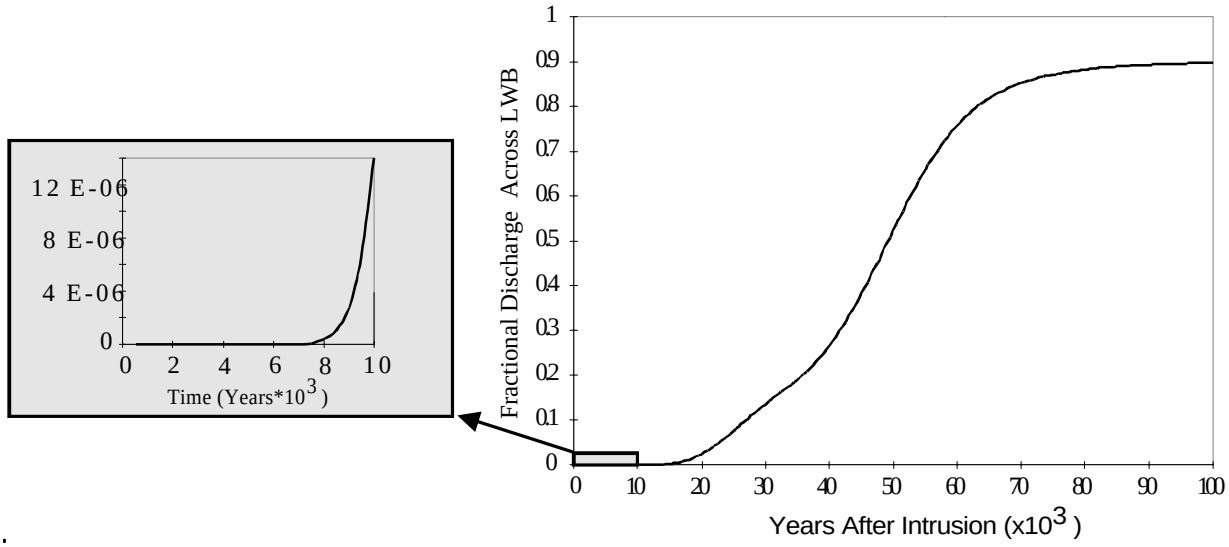

Fig. 24. Fractional Discharge Of Uranium Across The LWB Within 100,000 Years, With Blowout Section Of 10,000 Years. Reproduced from Rucker (1998).

2.10 THREE DIMENSIONAL PROCESSES AND BOUNDARY CONDITIONS

This issue was presented to the EPA staff on December 10, 1997, as "2D/3D Modeling in BRAGFLO". The EEG first brought this issue to the EPA's attention as an attachment titled "Brine Inflow From Salado: 2-D versus 3-D Geometry in BRAGFLO" to the March 14, 1997 Neill to Marcinowski (Neill, 1997b) letter. The DOE submitted a response as an attachment to the June 27, 1997 letter from G.E. Dials to L. Weinstock. The Draft Rule includes this issue as Issue F in CARD #23. The EEG position is summarized by the EPA as Comment #553 on page 115 of CARD #23, and the EPA response is provided on page 116. EEG's detailed response to the DOE and the EPA positions is provided as Enclosure 2 to this letter. DOE once again responded to this issue in attachment 6 of a letter from G. Dials to M. Kruger dated January 26, 1998. On February 17, 1998, EEG met with DOE to discuss this as well as other issues. As an outcome of this meeting, it was agreed that a single 3-D simulation be performed using the parameter values of one vector in the CCA calculations to assess the potential for impact on the CCA release calculations. A summary of the issue, the EEG's response, and the EEG recommendation to resolve the issue, follow.

The results of FEP S-1 screening analysis suggest that the two dimensional BRAGFLO model used in the CCA calculations may be misrepresenting repository performance at pressures above the anhydrite fracture pressure. There is the potential of substantially greater brine saturation in the repository at higher pressures than calculated for the CCA. The discrepancy between the 2D and 3D versions of BRAGFLO may have resulted in an underestimate of radionuclide releases to the surface.

To resolve this issue, the EEG recommended that several 3D BRAGFLO simulations of the repository should be performed using the parameter values of vectors used in the CCA performance assessment. The 3D BRAGFLO simulations should be used to provide repository conditions for the normal suite of direct brine release calculations. The calculations should also be assessed in terms of impact on spallings calculations. Spallings simulations are probably not required to assess the

impact. The following criteria may be used to select the CCA vectors for running the 3D simulations to bound the magnitude of the problem:

- Since the discrepancy occurs above the fracture initiation pressure, the simulations should be limited to parameter vectors that result in pressures above 12.7 MPa at some time during the 10,000 year time frame.

- Direct brine release calculations should be sensitive to increased brine saturations above the waste residual brine saturation. Vectors that had either large brine saturations or a mobile brine component (saturations above the residual saturation) are more likely to be sensitive to increased brine inflow. Figure 5.1.5 of the preliminary sensitivity analysis report (Helton, 1996) indicates one vector with a 10,000 year pressure above 14 MPa and a brine saturation above 0.4. This is a likely candidate.

- The potential for brine consumption by corrosion should be assessed. Vectors with both slow and fast corrosion rates that also meet the above two criteria should be run.

- If the first simulations indicate a large change in saturation, then assess whether the 3D BRAGFLO simulations indicate a much larger number of significant direct brine releases than those calculated in the CCA. Simulations using brine saturations on the order of 0.1 and 0.3 should be performed.

In response to these recommendations, DOE indicated that the conditions used in the FEP S-1 investigation were not representative of CCA conditions and that increased brine inflow should not be expected for CCA conditions. If brine inflow did occur as a consequence of anhydrite fracturing, it was expected that the additional brine would be consumed through metal corrosion and therefor not increase repository saturation. At the February 17, 1998, meeting it was agreed that there was sufficient reason to further investigate the potential for greater brine inflow to the repository using 3D modeling than the calculated in the 2D model of the CCA. It was agreed that a simulation

corresponding to a parameter vector that led to high pressure and anhydrite fracturing in the CCA calculations will be sufficient to demonstrate the potential increased brine inflow in comparison to the CCA calculation.

2.11 BRINE RESERVOIR PARAMETERS

The EEG raised a number of issues related to the Castile Formation brine reservoirs (Neill, 1997a, 1997b) attachments "Brine Reservoir Assumptions", Appendices 8.1 and 8.2 of this report) in commenting on the CCA. The EPA has accepted all of the EEG suggestions except the one related to the assumption of the probability of encounter of brine reservoirs, and we disagree with the EPA on this issue. The CCA assumed 8% probability on the basis of faulty assumptions. The EEG recommended 100% probability on the basis that the WIPP-12 brine reservoir was large enough to most likely extend under the repository, a conclusion also confirmed by geophysical testing directly above the repository. The EPA has sampled on a range of 1 to 60%, but has provided no basis for assuming less than 60%. Based on the arguments that the geophysical (Time-domain electro-magnetic survey) data may be interpreted to indicate the brine to be under 60% of the repository, and that some boreholes adjacent to the brine producing boreholes are known to be dry, the EEG is willing to accept the assumption of a fixed 60% probability of encounter, and recommends that a new performance assessment calculation be run with this fixed value.

According to EPA, changing the assumed brine volume of a Castile brine reservoir from 160,000 cubic meters (in the CCA) to 17 million cubic meters (in the PAVT calculation) had a noticeable effect on releases, but the compliance with the standards was still met. However, "EPA believes that the PAVT verifies that the original CCA Castile brine reservoir parameters were adequate for use in PA and comparison against the radioactive waste containment requirements." (U.S. EPA, 1997c, p. 58800). The EEG strongly rejects this argument because there are many other parameter values and conceptual and numerical models that should be changed, unless acceptable justification can be provided for the assumptions in the CCA and the proposed rule; and these changes will change the outcome of calculations. To declare an assumed value that is not otherwise justified "adequate" on the basis of limited changes in other values is, at the least, premature. There is no rational basis for finding an unjustified value to be acceptable unless it is justified based on observations, experiments, or widely known facts.

2.12 WASTE ISSUES

EEG has two waste issues. One concerns assumptions of random emplacement of radionuclides in the repository and the effect this may have on the final CCDF. The other refers to the determination of quantities of cellulosics, rubber, and plastics in the waste and the control of this waste limit in the repository. These two issues will be addressed separately.

2.12.1 Assumption of random emplacement of radionuclides in repository

The assumption by DOE assumes that the waste inventory will be emplaced in the repository in a purely random manner leads to three further assumptions in the PA:

(1) The 569 CH-TRU waste streams can be sampled randomly to determine the concentrations of radionuclides brought to the surface by cuttings and cavings;

(2) the concentration of radionuclides in the area of the waste room affected by spallings releases can be assumed to be the average of the entire WIPP inventory;

(3) the concentration of dissolved radionuclides in solution in a waste panel that has a Direct Brine Release is also calculated from the average of the entire WIPP inventory.

2.12.1.1 Previous EEG comments

EEG commented on this issue in our March 14, 1997, letter to EPA. The following additional comments are similar to those of 3/14/97, and lead to similar conclusions.

2.12.1.2 EPA response to issue

EPA did not accept DOE's contention in the CCA that emplacement of waste in the repository would be purely random and that a waste loading plan was unnecessary. The EPA requested in a March 19, 1997, letter that DOE provide additional information on the possible effects of non-random loading

on cuttings and cavings, direct brine release, and spallings releases. Upon review of DOE's response (Docket A-93-02 Item II-I-28 Enclosure 1, p. 8-18) "EPA determined that DOE was therefore not required to describe how the planned distribution of radioactive waste (as assumed in the PAs) would be achieved because the random distribution of waste containers in the WIPP resulted in compliance" (i.e., it did not matter to compliance how the drums were placed in the WIPP).

2.12.1.3 EEG evaluation

EEG agrees with EPA's request of DOE for analyses involving non-random loading. However, we have disagreements with several of the DOE assumptions and evaluations as well as the conclusions that were drawn from their results.

Effects on Brine Concentration. The DOE assumes that all brine in a repository would have to travel long distance through large volumes of waste to reach the point of an intruding borehole and concludes that brine concentrations of radionuclides are appropriately determined from the entire repository average.

EEG believes that while the DOE model is possible, it is not the only (and probably not the best) explanation. It certainly is non-conservative. The brine present in an undisturbed waste panel could come, more or less evenly, from all the walls, ceilings, and floors in the panel. If this occurs brine would stay close to the point where it enters the waste room or panel drift. There would be some movement down dip and this would cause water depths at maximum down dip location to be about 25% higher than the average depth (assuming 50% brine saturation). A waste room at 50% brine saturation would contain 270 m^3 of brine. The maximum brine release in PAVT is 100 m^3 and the 90th percentile release is only 15 m^3. It seems unreasonable to assume that most water flowing into the intruding borehole would come from great distances. EEG believes it most reasonable to assume an average concentration of wastes from no larger a volume than one repository room. We have not attempted to estimate how much the concentration in a room would increase the CCDF. However, we note that the plutonium concentration in solution from SRS heat source waste would be at least 6 times the average at 350 years. Also, the RFETS residues are almost 15 times as concentrated in

^{241}Am as is the repository average. Americium-241 has a specific activity that is 56 times that of ^{239}Pu and it will be the dominant radionuclide in solution (in curies) for thousands of years when using either PAVT or CCA median solubilities.

EEG concludes that the amounts of radioactivity in solution from non-random emplacement could be somewhat larger than DOE has calculated and that this issue has not been adequately addressed.

Effect on Cuttings Releases. DOE had previously evaluated effects of non-random loading on cuttings and cavings releases in 1996 when responding to a Peer Review Panel concern. They ran a replicate of 100 realizations of the effect of assuming that all 3 drums in a stack came from the same waste stream (rather than random). The resulting CCDFs are included in DOE's May 2, 1997, response to EPA's March 19, 1997, request for more information. The non-random loading CCDF plots indicated mean values that were 26% higher at 0.1 probability and 22% higher at 0.001 probability than the mean for random loading.

Effect on Spallings Releases. DOE's evaluation of the possible effect of non-random loading on spallings releases considered the number of EPA waste units that would be brought to the surface if 4 m^3 of repository room volume of RFETS residues were brought to the surface. The RFETS residues were considered to be the highest activity waste stream containing more than 810 drum equivalents (0.001 of the total repository volume). The total release of 0.368 EPA units is well below the 10 EPA units allowed at 0.001 probability.

These are reasonable assumptions. However, the total EPA units should include the release from cuttings and cavings into these wastes (mean of 1.0 m^3 in PAVT). Also, the RFETS residues are not the worst waste streams for early intrusion times. There are 810 drum equivalents of heat source waste at SRS that would average 440 ci/m^3 at 100 years after closing and 7,100 drum equivalents that average 130 ci/m^3 at 100 years.

EEG has recommended before that the waste stream activity for spallings release should be a sampled value as it is for cuttings and cavings. An indication of the possible effect can be seen from PAVT volumes and EPA units released. The mean spallings volumes are 1.7 times the mean cuttings and cavings volume for scenario S1 and 1.2 times for scenario S2. Yet the mean CCDF release at .001 percent is 25% greater for cuttings and cavings (with waste stream samplings on random emplacement) than for spallings (assumed average activity).

Summary of EEG Conclusions and Recommendations. EEG believes that releases in brine could be somewhat larger (perhaps more than 100%) than calculated in the CCA or PAVT if non-random loading on a room-size scale was assumed. We agree that the cuttings and cavings releases will be about 25% higher if there is non-random loading on stacks of drums. Also, spallings releases are likely to be 25-50% higher with waste stream sampling on random emplacement and higher yet with sampling on non-random emplacement.

EEG disagrees with the DOE position (and EPA concurrence) that since non-random considerations do not show that these three release mechanisms would lead to non-compliance they are unimportant and can be ignored. The effect of these three mechanisms combined could increase the total mean CCDF at .001 probability by 50% or more. This is still a long way from non-compliance. However, there are other assumptions in PA models and parameter values that EEG does not believe have been shown to be non-conservative, that can also affect the final CCDF curve.

EEG recommends that releases from cuttings and cavings and spallings be determined from waste stream sampling based on non-random emplacement. Direct brine release values should be based on non-random emplacement on a scale no larger than one waste room.

2.12.2 Cellulosics, rubber, and plastics

DOE has concluded that a maximum repository limit of 2×10^7 kg of cellulosics, rubber, and plastic (CRP) is needed in order to prevent production of more CO_2 than can be controlled by the MgO

backfill. EPA has concurred in this recommendation. The expected amount of CRP in the repository is 2.1 x 10^7 kg (U.S. EPA, 1997b, CARD 24-38).

2.12.2.1 Previous EEG comments

EEG commented on this issue in our December 31, 1997, letter to EPA. There were two concerns: (1) whether the quantities of CRP in the waste would be determined with the necessary accuracy in waste characterization; and (2) whether the proposed repository limits on kilograms of CRP would be adequately controlled by the proposed scheme.

2.12.2.2 EPA response to issue

EPA has never expressed a concern about waste characterization of CRP to DOE. They did inquire about the ability of DOE's WIPP Waste Information System (WWIS) to control the repository limits set by DOE. The possible need to control waste repository limits on a scale less than the full repository was not mentioned by EPA.

EPA has not responded verbally or in writing to EEG's concerns mentioned in the December 31, 1997, letter.

2.12.2.3 EEG evaluation

<u>Waste Characterization</u>. EEG is concerned about the ability to measure CRP with enough accuracy to ensure that the 2 x 10^7 kg limit will be met. Visual Examination (VE) is a method that is capable of good precision on those containers measured if all internal containers are emptied and their contents identified and weighed. However, internal containers are not always opened during VE. The preferred method of characterization is real time radiography (RTR) which is only semi quantitative (WMP weights are estimated by determining the void space and weight of waste in the drum which is not very accurate even if there is only one WMP in the container). EEG has not found a reference to the uncertainty in determining the weight of CRP in waste containers in either the DOE or the EPA reports. The EPA needs to point out where this uncertainty has been addressed, if it has been, or address the issue.

Waste Repository Limits. EEG has two concerns about the DOE plan to control CRP waste repository limits on the full repository rather than on a sub-unit (such as a waste panel). There are two concerns that do not appear to have been addressed:

(1) An excess of CRP in a waste panel could overload the MgO in that panel and since no interchange of brine between panels is assumed, it is questionable how much benefit would incur from excess MgO in another panel. Estimated concentrations of CRP do vary significantly between generating sites (e.g. at INEEL the average is 1.8 times the total inventory average);

(2) A management plan that allows emplacement of repository limited parameter quantities that vary significantly from the required average could result in a situation where the required limits could not be met by emplacing the remainder of the inventory. This is a potential problem because the actual content of waste containers will be known only as the individual containers are characterized and may be much different than the current estimates.

EEG believes that waste repository limits for CRP should be controlled on a per panel basis at least until the inventory is known with more certainty.

2.13 QUALITY ASSURANCE

2.13.1 General Comments

The 40 CFR 194.22 criteria for evaluation of the DOE's quality assurance (QA) program provide a clear list of items to be documented by the DOE. In reviewing the EPA's proposed rule for certification of the WIPP's compliance with 40 CFR 191 the EEG's primary concern was to find objective evidence to show that the EPA has examined the DOE's demonstration of compliance with the §194.22 criteria, either in the text of the proposed rule, or by reference to appropriate docket material. Because of a lack of such objective evidence, the EPA's proposed rule, CARD 22, and docket material referenced by CARD 22 do not demonstrate that many of the criteria have been met. The final rule should address these issues.

The July 22, 1996, Neill to Dials letter noted that the proposed QA chapter contained significant omissions and errors, including failure to adequately address many of the criteria in §194.22, and recommended that it be completely rewritten. Only incidental changes were made to the chapter before issuing the October 29, 1996, CCA. The Neill to Kruger August 11, 1997, letter (see Appendix 8.8) contains a later EEG review on the QA chapter of the CCA. Initial portions of this review were provided at a presentation to the EPA by EEG staff on January 21, 1997.

The CCA chapter on QA was neither complete nor accurate, as required by the §194.11. Had the DOE provided the information required by the §194.22 criteria, the EPA's efforts would have been simply to verify the DOE data. However, the EPA has attempted to gather data that shows compliance with §194.22, rather than reviewing the data as presented to them by the DOE. This seems contrary to the intent of the §194.22 criteria, which places the requirement on the applicant; for all but the initial and final criteria, §194.22 states (in §194.22(a)(2), (b), (c), and (d)):

> Any compliance application shall [provide or include] information which [describes or demonstrates] that [statement of criterion].

In the proposed rule, the EPA states that the documentation needed to demonstrate compliance with the criteria was too voluminous to be provided in the CCA. The CCA QA chapter did not, however, provide pointers to the documentation that would provide a demonstration of compliance, nor did it discuss all the programs and activities that should have met the §194.22 criteria.

Some of this voluminous documentation was viewed by the EPA during reviews, audits and inspections of the DOE and its operations, as allowed under §194.21 and §194.22(e). These EPA QA operations provide much of the evidence presented in the proposed rule and CARD-22 to support the argument that the criteria have been met. However, the intent of the audits and inspections as described in §194.22(e) was to verify execution of QA programs, rather than to establish that the §194.22(a)-(d) criteria had been met. The reports from these QA operations (as found in the EPA's WIPP docket) indicate that the EPA did not specifically address many of the §194.22 criteria, nor is there evidence in them that EPA has checked to make sure that the DOE's voluminous documentation contains the descriptions or demonstrations related to each specific criterion.

These EPA documents also do not show an awareness of all the DOE programs and activities that fall under the §194.22 criteria; this is likely related to the failure of the CCA's QA chapter to discuss these programs and activities, even though §194.22 clearly required a demonstration in the application that the NQA standards had been applied to these programs and activities. Since the EEG's day-to-day responsibilities make it familiar with many more of the activities at the WIPP than are a part of the EPA mission, some of the comments below relate to WIPP activities outside of Subpart B. EEG's basic assumption is that QA for any major activity described in the CCA which relates directly to the 194.22 criteria should be addressed in the documentation for the final rule.

The following sections contain a statement of the sense of the individual criteria, a brief summary of EPA's conclusions of compliance in the proposed rule, and the EEG's comments on that documentation. During the December 10, 1998, presentation, the EPA requested that the EEG include recommendations as to how to alleviate concerns raised; these are appended to the section for each criterion.

The term "NQA standards" as used in this review consist of the 1989-1990 Nuclear Quality Assurance (NQA) Standards NQA-1, NQA-2 Part 2.7, and NQA-3 versions as described in §194.22(a)(1).

2.13.2 Specific Comments

§194.22(a)(1): As soon as practicable after April 9, 1996, the DOE will adhere to a QA program that implements the requirements of the NQA standards.

EPA summary: The EPA proposed rule cites the Carlsbad Area Office (CAO) Quality Assurance Program Document (QAPD) included in the CCA as part of Appendix QAPD as addressing the NQA standards, and the flow of requirements from this QAPD to all subsidiary WIPP organizations. The EPA audited the CAO and found the NQA standards were implemented as required in the QAPD. CARD-22 adds that the QAPD is dated April 22, 1996, that the CAO has audited lower-tier programs to enforce the requirements of the QAPD in accordance with the NQA standards, and that these subsidiary organizations conduct their own audits.

EEG comments: The EEG review of the CCA QA chapter (Appendix 8.8) addresses DOE's response of this criterion on page 4.

The EEG agrees that the CAO has established an excellent QA program. The DOE provided the necessary information in the application for this criterion, and the EPA has verified that the WIPP adheres to a program that implements the NQA standards—for the 8 critical areas addressed in §194.22(a)(2).

The beginning of the discussion of §194.22 in the proposed rule interprets both parts of 194.22(a) as a single, interconnected section, so that the NQA standards of the (a)(1) criterion need only apply to the 8 critical areas listed in (a)(2). The language of the two criteria do not necessarily support this interpretation. Had this been the original intent, there would have been no need to divide into two

sections; a single criterion could have been written to cover 194.22(a)(2), and (a)(1) could have been eliminated.

The CAO QAPD Revision 1 included in Appendix QAPD has a rather elegant process for separating QA activities for these 8 areas, and radioactive waste handling and packaging activities, from other WIPP-related processes. Section 1.1.2.3 of the QAPD establishes these areas as responsible for meeting "additional requirements", which are extra to the "general requirements" required for other WIPP activities. The "general requirements" established throughout the QAPD are those related to the requirements of 10 CFR 830.120 and DOE Order 5700.6C, the DOE's normal QA requirements; the "additional requirements" are those found in the NQA standards that are not addressed by §830.120 and 5700.6C. The NQA standards are much more prescriptive than are the normal DOE QA requirements--NQA-1 alone contains over 30 pages of requirements, as opposed to the less than two equivalent pages of requirements found in normal DOE QA standards.

The purpose and scope of the criteria, as found in §194.1, reference both the 1992 Land Withdrawal Act and 40 CFR 191. §191 Subpart A describes management of the waste (placing it in the disposal system), and the intent of §194.22(a)(1) seems to have been to implement the NQA standards for all WIPP activities during the operational phase, as well as for the disposal phase. The EPA's Guidance For The Implementation of EPA's Standards For Management And Storage OF Transuranic Waste (40 CFR Part 191, Subpart A) At The Waste Isolation Pilot Plant (WIPP), EPA 402-R-97-001, Section 2.3, states:

> For Implementing Subpart A at the WIPP, EPA interprets these definitions to mean that all activities at the WIPP up until the point of disposal must be considered in determining compliance. Specifically, this means that all activities in all WIPP facilities, both at above-ground locations and in the underground disposal system, are regulated under the standard.

Recommendation: If the intent of the criterion was that the CAO's QA program only meet the requirements of the NQA standards for the 8 critical areas listed in §194.22(a)(2), then the EEG agrees that the criterion has been met. However, the documentation for the final rule should include a rationale for considering only those areas described in §194.22(a)(2) as falling under the §194.22(a)(1) criterion.

The EPA should also be aware that the revision of the CAO QAPD included in the CCA was to be implemented program-wide for the WIPP by mid-August, 1996, not April 22, 1996, as is implied in CARD 22[1].

§194.22(a)(2) [General Statement]: The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for 8 critical activities.

EEG general comments: The EEG review of the CCA QA chapter (Appendix 8.8) addresses these criteria on page 5, pointing out that the DOE misinterpreted the (a)(2) criteria. In general, the portions of the chapter titled similarly to these criteria do not provide the requisite demonstration of compliance.

The 8 activities are individually addressed below. It is important to note, however, that the EPA's documentation of compliance relies heavily on EPA audits of the CAO, the Waste Isolation Division (WID; the Management and Operating Contractor responsible for conducting most on-site activities), and Sandia National Laboratories (SNL; the WIPP scientific advisory organization). The audit

[1]The QAPD Rev. 1 distribution letter from R. Dennis Brown, CAO QA Manager, to WIPP organizations dated June 13, 1996, requires that the QAPD be properly implemented within 60 days of receipt of the letter. The official sign-offs were on April 22, and the CAO office may have implemented it on that date, but all subsidiary organizations were not required to conform to its dictates until the much-later date.

reports from these EPA activities do not indicate that the specific areas required by each criterion were addressed, but rather show that the overall QA program of the organizations was audited.

The EEG does not agree that verification of the establishment and execution of an overall program provides an adequate demonstration of execution for the specific activities described §194.22(a)(2). The individual (a)(2) criteria would not have been written if establishment and execution of a general QA program was all that was intended. The EPA audits are a snapshot view of QA at these organizations in 1997, but many of the DOE programs and activities that fall under the (a)(2) criteria have been in operation for many years, and the data from these programs was freely used in the compliance application.

To demonstrate establishment and execution of the NQA standards on the programs and activities covered by each criterion, a formal assessment (audit or surveillance) of the process and the resulting records should be cited; the assessment should have been performed by qualified personnel, addressing compliance with QA documents which include the NQA requirements applicable as a part of the assessment. The assessment need not have been entirely devoted to that area, but should have addressed the specific programs and data falling under each criterion. The EPA should verify that the process was performed at a time when the NQA standards were in effect for that program, and that the assessment was conducted according to the requirements of the NQA standards.

Recommendation: If such an assessments are not currently available from the DOE then the EPA should require the DOE to perform and report such assessments. As a last resort, the EPA could assess the program as a part of its verification process (despite the EEG's reservations about using this approach). In any case, the documentation for compliance with the criteria should demonstrate that the NQA standards have been established and executed for the DOE programs that falls under each criterion.

§194.22(a)(2)(i): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for waste characterization activities and assumptions.

EPA summary: The proposed rule notes the current lack of waste characterization at the generator sites and describes how the proposed Appendix A Condition 2 will be used to ensure that these sites will have met the criteria before shipping waste to WIPP. The proposed rule shows evidence that a QA program adhering to the NQA standards have been demonstrated for waste characterization at one generator site (LANL) and for the WIPP Waste Information System (WWIS), a DOE computer system used to ensure that characterization and certification requirements have been met for each waste container before it is shipped. CARD 22 expands on this information, and adds that the CCA QA chapter states that the Transuranic Baseline Inventory Report (TWBIR) was prepared in compliance with the CAO QAPD and its preparation was audited by the CAO in 1995.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on pages 10 and 11.

There are two major components to this criterion: the waste characterization activities at generator sites, and the waste assumptions used to establish parameters for the performance assessment (PA) evaluation.

For waste characterization at generator sites, the EPA has presented adequate evidence that, for LANL and its use of the WWIS, the DOE has demonstrated the establishment and execution of a QA program meeting the NQA standards. The proposed Appendix A Condition 2 seems an adequate compromise method for applying the criterion to other generator sites--the criterion requires a demonstration in the compliance application, but it is obviously not prudent for these generator sites to allocate resources to WIPP waste characterization until there is some certainty that the WIPP will open.

The EPA, however, has apparently accepted DOE's statements concerning QA for the PA component (the TWBIR data) at face value. The TWBIR waste characterization data used in the CCA clearly were not gathered under the NQA standards[2], and "the QAPD" under which the TWBIR was prepared is not the revision that was included in the CCA. The single audit finding was insufficient documentation of the TWBIR process.

The version of the CAO QAPD in effect during the preparation of the TWBIR (and the audit) was Revision 0, which apparently has not been examined by the EPA (it's not a part of the CCA). Table 1-1 of Revision 0 lists NQA-1 as a commitment document, but NQA-2 Part 2.7 and selected parts of NQA-3 are only listed as guidance documents. TWBIR data used in the performance assessment should meet the requirements of NQA-3.

The EEG has often expressed concern over the changes in waste estimates for WIPP found in the various revisions of the TWBIR, and other documents that address the WIPP inventory. For example, the CCA Appendix TWBIR estimated 61787 m^3 of existing CH-TRU waste, yet the 1996 National Transuranic Waste Management Plan (U.S. DOE, 1996a) estimates 102,025 m^3 (Table 1-1) for the same parameter--a 40% increase in the amount of currently existing waste destined for WIPP. These two documents were published only a few months apart. Comparisons for RH-TRU and projected waste volumes show even greater variations. These drastic changes in inventory amounts likely would be reflected (to some unknown extent) in the amounts and types of waste characteristics and components used in developing the PA parameters on waste.

Recommendation: The EPA could examine the audit report of the TWBIR process to ensure that the NQA standards were applied to the gathering and processing of waste characterization

[2]The Waste Characterization Analysis Peer Review Report, DOE/WIPP-96-2012, states (p. 4-3): "Because there had been no prior requirements to gather these types of data under a formal quality assurance (QA) program consistent with NQA-1 requirements, and a very short response time was imposed, the sites compiled their inventories using the best available information." The Panel concluded that, given these constraints, the data submitted are conservative (overstates quantities) and the best that could be obtained within reasonable time and cost". The EEG notes that, for use in the PA, consistency with NQA-3 requirements would also have been necessary.

assumptions used in the PA, despite the Waste Characterization Peer Review's statement to the contrary. Alternately, the Waste Characterization Peer Review accepted TWBIR data even though the panel was aware of the data's QA deficiencies (see footnote). The EPA could consider whether the Peer Review Report can be used as a "qualification of existing data" as allowed by §194.22(b) as a method of meeting the criterion for TWBIR data used in the PA. Documentation of these activities should be included in the final rule or its supporting materials.

§194.22(a)(2)(ii): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for environmental monitoring, monitoring of performance of the disposal system and sampling and analysis activities.

EPA summary: The proposed rules states that the WID developed a WIPP Environmental Monitoring Plan (EMP), which the DOE states is consistent with applicable NQA standards. The EPA audit of the WID determined that the requisite QA program had been established and executed for environmental monitoring, and sampling and analysis activities. CARD 22 adds that EMP was reviewed by the EPA, that sampling and analysis for waste characterization activities was covered under the discussion for 194.22(a)(2)(i), and that "Monitoring of performance of the disposal system has not started, but EPA has no reason to believe that the QA program for this activity will not be similar to the QA program for existing monitoring activities" (p. 22-8; restated on p. 22-9).

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on page 12.

Section 8.1 of Appendix EMP does, indeed state the following (p. 8-1):

> Quality Assurance (QA) practices that cover monitoring activities at the WIPP are consistent with applicable elements of the 10-element [sic] format in ANSI/ASME NQA-1.

NQA-1 consists of 18 basic requirements; the "10-element format" is a usual method of referring to QA requirements found in 10 CFR 830.120, a different set of nuclear QA requirements written for the DOE Management and Operations (M & O) contractors such as the WID. This *faux pas* may indicate how little familiarity writers and reviewers of EMP Section 8, Quality Assurance, have with the NQA standards.

Section 8.1 later states that QA requirements from the EPA's QAMS-005/80 were incorporated into the WID QAPD, and Table 8-1 is an attempt to cross-reference of NQA-1 basic requirements, and requirements from QAMS-005/80, to 10 CFR 830.120. This seems to be an attempt to demonstrate that the 30-odd pages of basic and supplementary requirements from NQA-1 are completely covered by the 2 page of requirements found in 10 CFR 830.120. Section 8.3, which contains the actual QA criteria for environmental monitoring, begins by stating (p. 8-3):

> The specific WIPP QA program elements/criteria that are applicable to the performance of the EMP are listed below by 10 CFR 830.120 criterion.

A comparison of this document to its predecessors may be indicative of the trend in WID QA for environmental monitoring. The 1994 Environmental Monitoring Plan (EMP), DOE/WIPP 94-024, lists the 18 NQA-1 basic requirements (p. 8-1), but follows the 10-element format from DOE Order 5700.6C (which is essentially identical to 10 CFR 830.120) in discussing QA for environmental monitoring. The 1988 "Operational Environmental Monitoring Plan for the Waste Isolation Pilot Plant"(OEMP), DOE/WIPP 88-025, also lists the 18 basic requirements, but also describes how the QA program addresses each of the NQA-1 requirements. The trend seems to be one of moving away from NQA-1. In 1988, WID had an environmental program which clearly attempted to address NQA-1 requirements; in 1994, the NQA-1 requirements were listed, but the DOE's own internal QA requirements were addressed; and Appendix EMP (1996) seems to have completed the transition to the 10-element format.

CCA Appendix EMP Section 8 is clearly directed at compliance with 10 CFR 830.120, not NQA-1. The environmental monitoring program, and the materials in EMP, still may meet the requirements of NQA-1, but Appendix EMP does not provide clear evidence of such compliance.

For the monitoring of the disposal system portion of the criteria, the EPA seems to have been mislead by a DOE statement in the QA chapter of the CCA, that no monitoring of the disposal system had yet occurred. Appendix MON, Table MON-1 lists 11 parameters to be monitored to provide the data required by 40 CFR Parts 191.14(b) and 194.42 for monitoring of the disposal system. The Water Quality Sampling Program (WQSP) wells are specifically listed in Table MON-1 as "Preclosure Monitorable Parameters"; Appendix EMP Section 5.3.8, "Groundwater" states that the WQSP wells have been sampled since 1994. CCA Table 7-7 (p. 1-9) shows that the Culebra wells will also be a part of the postclosure monitored parameters as well.

The WIPP Site Environmental Report for Calendar Years 1994 (Westinghouse, 1995), 1995 (Westinghouse, 1996), and 1996 (Westinghouse, 1997) all contain data directly related to the 3 parameters for Culebra monitoring described in Table MON-1 (See CCA Appendix SER, taken from the 1995 report; Sections 7.1 and 7.2 describe the radiological and Culebra water level monitoring, and the 1996 report contains a section on the third parameter, direction of flow in the Culebra). It is also worth noting that elsewhere in Appendix MON (Section 3.3) the WQSP wells are described as RCRA (40 CFR 264) post-closure monitoring wells, in terms that suggest that they will be continuously monitored until at least 30 years after repository closure.

There are also 4 geomechanical characteristics listed in Table MON-1; CCA Section 7.2.2.4.1 indicates that data is currently being gathered for these, though it is apparently not yet analyzed in terms of preclosure monitoring. Geotechnical Analysis Report for July 1995 - June 1996 (U.S. DOE, 1997b), indicates that measurements of these characteristics have been made for years. Others of the 11 parameters may also have been monitored before the publication of the CCA--CCA Appendices DMP describes the program for monitoring of drilling practices (one of the 11), and DEL describes the state of drilling in the WIPP vicinity at the time the CCA was published.

The CCA QA chapter does not reference CCA Appendices GWMP and GTWP. Appendix GTMP, section 2.0, clearly demonstrates that the NQA-1 standards were established by the 1994 Geotechnical Monitoring Plan; Appendix GWMP (no date given in the CCA), section 4.0, does the same for groundwater monitoring. These documents step through the 18 NQA-1 basic requirements, explaining how the applicable ones are to be implemented. These are clear evidence of establishment of a QA program that meets the requirements of NQA-1, but are not evidence of execution of the program.

For the final part of this criterion, the EPA has misapplied the "sampling and analysis activities" to the waste characterization processes at generating sites. It would seem more logical to assume that sampling and analysis related to the environmental monitoring and monitoring of the disposal system was the intended target, as the phrase was included in the criterion for these activities, not the criterion for waste characterization activities and assumptions.

CCA Appendix AUD does contain a list of WID internal audits, and these may provide a demonstration of establishment and execution of the NQA standards for these areas. Audit I96-03 would seem to cover the WQSP wells and other groundwater monitoring programs; I94-020 covers the 1993 Geotechnical Analysis Report, and could possibly show that the NQA standards had been applied for that year. Several others (I93-03, I93-05, I93-08, I93-048, I93-056) occurred in 1993, before the WID's QA program is said by the DOE to meet the NQA standards, but a case-by-case review may show that at least some of these can be used. The CAO's QA department may also have performed assessments specific to environmental monitoring that considered compliance with the NQA standards.

Recommendations: NQA-1 requires periodic assessment of programs by QA organizations, and the WID Environmental Monitoring Program has been in operation since 1985. The CAO, or the WID, QA departments should have assessed the program by now to ensure that NQA-1 requirements had been properly addressed in the program (that the program is adequate), and that the documentation from the program meets these requirements (that it has been effectively implemented).

The EPA should review reports from these assessments and cite them in the documentation of the final rule as a demonstration of establishment and execution of the NQA standards for environmental monitoring.

The CAO or the WID should also have assessed the WQSP (or the entire Groundwater Monitoring Program), and the Geotechnical Analysis Program. The EPA should review these reports, and cite them as a part of the demonstration of establishment and execution of the NQA standards for this criterion.

Sampling is an integral part of these programs, as are some analysis activities. However, the WQSP samples have been sent to contract laboratories for analysis, and radionuclide determinations from the Environmental Monitoring Program samples have also been performed by contract labs. The EPA should verify that contracts for these analyses include the proper QA requirements.

§194.22(a)(2)(iii): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for field measurements of geologic factors, ground water, meteorologic and topographic characteristics.

EPA summary: EPA's proposed rules states that the EPA audit found the QAPD and WID QA program complies with the NQA standards. CARD-22 indicates that QA of current WID measurements related to subsidence and disposal room monitoring were the field measurements of geologic factors that were considered; that "Groundwater monitoring activities previously conducted at the site also adhere to WID QA documents"' and that the DOE has demonstrated to the EPA that meteorologic information from pp. 2-178 to 2-180 in the PA came from geological data and information rather than from meteorological field measurements. The data generated from topographic characterization were evaluated under the qualification of existing data (QED) process allowed by §194.22(b).

EEG comments: The EEG review of the CCA's QA (Appendix 8.8) chapter addresses elements of this criterion on pages 12 through 15.

Geological factors. EPA was apparently mislead by the CCA QA chapter, which only discussed subsidence and disposal room monitoring in the section that addressed this criterion, citing WID documents. Credit for the current WID QA program does not cover the data from WID's disposal room monitoring program used in the performance assessment, for which MONPAR Sections 3.1 and 3.2 indicates data from pre-1991 was used for disposal room monitoring, and pre-1994 for subsidence.

More importantly, however, SNL was responsible for much of the work related to field measurement of geologic factors used in the CCA, particularly those geological factors used in PA. The CCA QA chapter offers a rationale for considering QA for field measurements of geological factors during site selection and characterization activities as satisfactory (see p. 5-6), but the EPA has not cited that rationale (nor should they; see EEG's review of this rationale, on p. 13 of the CCA QA chapter (Appendix 8.8) review). In addition, the parameters used in PA are based on geological field measurements--pressures at the repository level, strata thicknesses, etc.

The following description of a field measurement is an illustration of the sort of field measurement of geologic factors for which the EPA may want to be able to demonstrate the criterion has been met. The citing of "karst topography"--the possibility that dissolution of the salt beds in which the repository lies may cause a regulatory release of radionuclides--is an argument that refuses to die, despite the DOE evidence that has convinced the EEG, the NAS, and other organizations that such deep dissolution is unlikely. Testimony at recent (January 1998) EPA public hearings on the proposed rule again addressed the topic, and may become a part of lawsuits filed on the WIPP. Proof of adequate QA for measurements that defend against this argument could be an important part of such lawsuits. From CCA Appendix GCR Section 6.3.5:

> Additionally, brines in the sands of the underlying Bell Canyon Formation have been tested. These fluids are under sufficient head to allow them to reach the Salado salt. Because the brines are under saturated, they could dissolve the salt. However, to reach the Salado, these fluids would have to first penetrate the Castile Formation. Permeabilities (or lack of permeability) of the Castile and Salado Formations at the site have been determined by drill-stem tests in two exploratory holes: ERDA No. 9 and AEC No. 8. The tests, summarized by Lambert and Mercer, 1977, Tables 1 and 2, indicate that the two formations are extremely tight.

Appendix GCR, the Geological Characterization Report, contains many examples of field measurements of geologic factors. The term "field measurements" is not defined in §194; a definition that included the laboratory measurements taken from field samples would provide a list of many additional geological factors included in the CCA. Appendix GCR also contains data from these kinds of measurements, on which many of the PA parameters are based.

Groundwater**.** For the groundwater portion of this criterion, CCA Appendix SER (1995 Site Environmental Report) Chapter 7 states:

> The data obtained by the Water Quality Sampling Program (WQSP) in 1995 supported two major programs at the WIPP: Site Characterization and Performance Assessment in compliance with 40 CFR 191...Surveillance of hydrological characteristics in the Culebra provides data which can be used to detect changes in water characterization. It also provides additional data for use in hydrologic models designed to predict long term performance of the repository. Data is gathered from 64 well bores; five of which are equipped with production-inflated packers to allow groundwater level surveillance of more than one producing zone through the same well bore.

> Groundwater Quality data were gathered from ten wells completed in the Culebra member of the Rustler formation and one well completed in the Dewey Lake formation...Seven wells were drilled in the latter part of 1994 constructed for the explicit purpose of gathering water quality data. These wells are constructed with fiberglass casing and screens that will not bias sample collection. In 1995 samples were collected from old as well as new wells.

If data from these wells are used as described, then the requirements of NQA-3, which contains additional requirements for the collection of scientific and technical information to be used for site characterization, should also have been applied to them. The seven wells mention in the second paragraph quoted above are the WQSP wells[3].

CCA Appendix HYDRO contains many statements based on measurements of groundwater--transmissivities, potentiometric-surface maps, ion concentrations, etc. The "Purpose and Scope" section indicates that the USGS performed the activities that resulted in these measurements:

> This report discusses the ground-water systems and the interpretation of test results in the water-bearing zones above and below the proposed facility. Hydrologic data used in these analyses were collected during 7 years beginning in 1975 and were from 39 test holes drilled for, or converted to, hydrologic test holes. The study included: the determination of potential ground-water flow boundaries; potentiometric heads; ground-water chemistry; and hydraulic properties obtained through pumping, slug, pressure-pulse, and tracer tests.

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[3] The WQSP wells not only used special casings and screens, they were also established by air drilling, to ensure that drilling mud did not affect the water sampling process. The DOE has recently stated that it believes that only one borehole in the nine townships surrounding the WIPP used air drilling techniques; see Dials-to-Kruger letter dated January 26, 1998, p. 2.

> The hydrologic investigation is part of a comprehensive study related to site characterization and validation conducted on behalf of the U.S. Department of Energy by Sandia National Laboratories.

Other parts of the CCA contain field measurements of geological factors and groundwater, Chapter 2 in particular. For instance, Table 2-4 shows transmissivity and porosity of the various subunits of the Rustler formation; Section 2.2.1.4.1.1 lists these values for specific boreholes.

No QA for any of these sorts of measurements is described anywhere in the CCA, or in the EPA's proposed rule documentation, that the EEG has been able to identify. The QA for these measurements may have been performed under the SNL Qualification of Existing Data (QED) program (see CCA Table 5-5, p. 5-41) allowed by §194.22(b), but there is no statement in either the CCA or the EPA's proposed rule documentation pointing to QED as covering a portion of this criterion.

Meteorologic Characteristics. QA for field measurements of meteorological characteristics as required by (22(1)(2)(iii)) is not described in the CCA. The EPA asked the DOE for additional information. CARD 22 states (p. 22-11):

> Supplementary information sent by DOE on January 24, 1997 demonstrated to EPA that the measured meteorologic information in pages 2-178 thru 2-180 of the CCA was not used in the performance assessment (PA). DOE demonstrated that the PA instead used meteorological information obtained from geological data and information (Docket A-93-02, Item II-I-03).

This explanation alters greatly the information actually provided by the DOE. Item II-I-03 comments concerning meteorological data are:

> The meteorological data were included in the CCA in response to 194.14(i). The CCA does not contain information on the QA program for meteorological data because this data is not used in the PA.

The EEG also finds nothing in §194 that limits the criteria to consideration of only those data used in the PA. The data used in the CCA on pages 2-178 through 2-191 is from the WID meteorological tower data collected as a part of the WID Environmental Monitoring Program during the years 1990-1994, and there is no demonstration of adherence to a QA program that establishes and executes the requirements of the NQA standards for this data. Note that the dates for these data apparently precede the CCA QA chapter's date for adherence to the NQA standards at WID, which was established as December 1994.

Topographical Characteristics. §194.14(h) requires that the CCA include topographic maps which show contours, WIPP site boundaries, and the location of wells in the vicinity of the disposal system. These would seem to be the topographic characteristics addressed by this criterion.

It is not a demonstration of compliance to simply state that the Qualification of Existing Data (QED) process was executed on topographic characteristics, as is done in both the CCA (p. 5-6) and CARD 22 (p. 22-11, in 22.D.5); the specific instance of QED which qualified the data should be listed and discussed. DOE's QED process used Independent Review Teams (IRT) and Peer Reviews to qualify data; topographical characteristics would not seem to be a part of any of the data packages qualified by IRTs as listed in CCA Table 5-5, nor do the discussions of peer review in the CCA (Chapter 9 and Appendix PEER) mention topographical characteristics. The EEG also could not locate discussions of topographical characteristics in the reports of the peer review panels conducted in 1996 and 1997.

The §194.14(h) requirement for a topographic map that shows the locations of wells in the vicinity of the WIPP seems to have been covered by CCA Appendix DEL, Figure DEL-6[4]. This data was probably gathered as a part of the WID effort to monitor changes in WIPP-area drilling practices, as outlined in CCA Appendix DMP. The legend on this map indicates that locations of well sites were updated after the WID had within 1 mile of the WIPP boundary was updated to 08/06/96--a date well after the WID is said to have a QA program that adheres to the NQA requirements. This portion of the §194.14(h) requirement is likely the most important

Recommendation: The EPA should review the CCA for field measurements of the four areas cited in this criterion to ascertain if the QA processes utilized by the DOE for these field measurements meet the criterion. Measurements of geologic factors and groundwater used in support of the PA were the targets of the IRT reviews listed in Table 5-5 of the CCA. The EPA should correct the support documentation in the final rule to reflect that QA for field measurements of geologic factors and groundwater measurements is covered by §194(b), and cite data for specific parameters examined during the EPA's Audit of the Parameter Traceability and Qualification of Existing Data (II-A-48) as verification of the QED for this criterion. For meteorological and topographical characteristics, the EPA should require that the DOE demonstrate that the measurements presented in the CCA was gathered under QA program that established and executed the NQA standards, or present traceable evidence that these measurements were processed under §194.22(b). Reference to these statements should be a part of the EPA's documentation for the final rule.

§194.22(a)(2)(iv): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for computations, computer codes, models, and methods to demonstrate compliance with the disposal regulations in accordance with the provisions of this part.

[4]Figure DEL-6 is not a topographic map as §194.14(h) specifies, but it does show the locations of the types of wells specified in the criterion.

EPA Summary: The proposed rules states that the requirements of the NQA standards for computations and computer codes are in the DOE QA program, in Section 6 of the CAO QAPD and also in SNL and WID QA documents. Review of the CCA (Section 5.3.20 is included verbatim), and audits of SNL and WID show that the NQA standards have been implemented. CARD-22 also cites a review of procedures and previous assessments (apparently DOE assessments) as evidence that show the requirements have been met, and states that QA for generator sites computer codes were addressed in the waste characterization section.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on pages 15 through 18.

Neither the proposed rule nor CARD 22 address models and methods to demonstrate compliance, and computations (which are not always computer codes) is only lightly touched on. The WID keeps track of huge amounts of information related to other §194 criteria (meteorological data, environmental monitoring data, geotechnical monitoring data, WIPP area drilling activity data, etc.); these data are likely kept in databases, but there is no mention of QA for these areas either in the CCA or in the documentation for the purposed rule.

The meaning of "methods to demonstrate compliance" is not clear, but if the QA chapter of the CCA was a method to demonstrate compliance with the disposal regulations then the adequacy of any QA activities applied must be considered to have failed to meet the criterion.

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Recommendation: The EPA documentation should be more specific in its descriptions of EPA auditing activities for software. A demonstration of execution (an assessment) of the NQA standards for NDA at LANL, the WWIS, and the WID database system(s) should be cited in the documentation for this criterion. The documentation should also reference the DOE's audits the PA process, and of the PA software, as demonstrations of execution of the NQA standards for these computer codes and models.

The EPA will rely on future auditing/inspection activities at generator sites to establish that this criterion is met before these sites ship waste to WIPP; a qualified NQA software auditor should therefore be a part of these audits.

§194.22(a)(2)(v): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for procedures for implementation of expert judgment elicitation used to support applications for certification or re-certification of compliance.

EPA summary: The proposed rule cites CAO's Team Procedure 10.6 and the CTAC Desktop Instruction 1, used for the waste particle size expert judgment elicitation (the only one that has occurred), and cites the discussion of the proposed rule for §194.26. CARD 22 states that the CCA that the CAO QAPD provides for adequate control of any future expert judgments that the DOE may conduct, that he expert judgment of waste particle sizes process was observed and audited by the EPA, and was conducted in compliance with the criterion. CARD-22 references CARD-26; both the proposed rule for §194.26 and CARD 26 discuss QA for the waste particle size expert judgment elicitation in fulsome detail.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on page 18, in a brief paragraph which points out other WIPP activities that might be considered as expert judgment elicitations.

The EPA has presented a demonstration of establishment and execution of the NQA standards for the waste particle size expert elicitation in the documentation for the proposed rule, though it could have been focused more on addressing the §194.22(a)(2)(v) criterion.

However, other panels convened by the DOE would seem to fall under the requirements of this criterion. CCA Appendix PEER_PIC contains the peer review report on passive institutional controls

(PICs); it contains the following statements concerning expert judgment in section 4.1.4, titled "Expert Judgment and Peer Review":

> The use of expert judgment, either by an individual expert or a panel of experts, is permissible under 40 CFR Part 194.26(a) to support the information in the CCA if that information cannot reasonably be obtained through data collection or experimentation...The conceptual design principles presented in the Conceptual Design Report seem to rely heavily on the results of the expert judgment process described in Trauth *et al*. (1992)... The PTF and preparers of the Conceptual Design Report have somewhat blurred the line between reliance on expert judgment and the peer review process by incorporating both processes; their approach is certainly not precluded by the regulations.

Trauth, *et al*. (1993) is "Expert Judgment on Markers to Deter Inadvertent Human Intrusion into the Waste Isolation Pilot Plant". The peer review panel, with full knowledge of the requirements of §194.26, obviously concluded that the Trauth, *et al*. report was generated by an expert judgment elicitation group. The discussion preliminary to the §194 criteria would seem to have addressed the Trauth, *et al.* document straight on (61 FR 5228):

> Typically, expert judgment is used to elicit two types of information: (1) Numerical values for parameters (variables) which are measurable only by experiments that cannot be conducted due to limitations of time, money and physical situation; and (2) essentially unknowable information, such as which features should be incorporated into passive institutional controls that will deter human intrusion into the repository.

CCA Appendix EPIC consists of "Effectiveness of Passive Institutional Controls in Reducing Inadvertent Human Intrusion into the Waste Isolation Pilot Plant for Use in Performance Assessments, June 4, 1996". The second paragraph of this report states

> A task force was formed to estimate the credit for the passive controls for the WIPP repository. The estimate was constrained by the use of existing conceptual designs of these controls, the use of historical analogues for the endurance of materials and structures, the consideration of possible failure modes for each control, and the regulatory assumption of societal "common denominators."

This also seems to be a collection of experts gathered to use their various expertises for determining a value that cannot be obtained by scientific means--in short, an expert judgment.

Recommendation: The EPA should consider whether the Trauth, *et al*. (1993) report is an expert judgment elicitation, and whether other expert judgment elicitations are utilized in the CCA, and analyze the QA applied to any that meet the criteria. Both reports suggested above could be considered to have met this criterion by QED as allowed through §194.22(b), as a peer review of the PICS processes is reported in CCA Appendix PEER_PIC. The final rule for this criterion should describe or reference the process the EPA uses for determining what qualifies as an expert judgment under this criterion, and describe the demonstration of establishment and execution of the NQA standards for any additional expert judgments found.

CARD 22.F.4 contains the following sentence:

> The CCA also indicates that the CAO established and executed a QA program in compliance with NQA requirements for all items and activities important to the containment of waste in the isolation system, including for procedures that may be developed for implementation of future expert judgment elicitation.

The sentence should be revised, as it is a logical impossibility; a QA program cannot be executed on procedures that have yet to be written. The sentence could easily be interpreted as an unwarranted attempt to aid the DOE's efforts at compliance.

§194.22(a)(2)(vi): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for design of the disposal system and actions taken to ensure compliance with the design specifications.

EPA summary: The proposed rule states that the SNL QA program covered seals design, that the seals design was extensively reviewed by other organizations, and verified by a combination of NQA-1 3S-1 methods. The EPA audits show that WID and SNL programs are adequate and properly executed. CARD-22 adds that no QA deficiencies related to design considerations were noted in the EPA audits of SNL or WID, and quotes portions of of the CCA QA chapter (Section 5.1.6) concerning design of the repository.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on pages 19 through 21.

The EEG agrees that the repository seals design program was excellent. Perhaps the best demonstration of establishment and execution of design criteria for seals is not in the CCA QA chapter, or in EPA documentation for the proposed rule, but in CCA Appendix SEAL, Section 1.4, "Sealing System Design Development Process":

> The design team included specialists drawn from the staff of Sandia National Laboratories, Parsons Brinckerhoff Quade and Douglas, Inc. (contract number AG-4909), INTERA, Inc. (contract number AG-4910), and RE/SPEC Inc. (contract number AG-4911), with management by Sandia National Laboratories. The contractors developed a quality assurance program consistent with the Sandia National Laboratories Quality Assurance Program Description for the WIPP project. All three contractors received quality assurance support visits and were audited through the Sandia National Laboratories audit and assessment program. Quality assurance (QA) documentation is maintained in the Sandia National Laboratories

> WIPP Central Files. Access to project files for each contractor can be accomplished using the contract numbers specified above.

The paragraph is an example of the kind of description the EEG expected to find in the CCA for all the DOE programs that fall under the §194.22 criteria.

QA for other portions of the repository design are more problematic. The statements quoted in CARD 22 from the CCA QA chapter do not provide a demonstration of establishment and execution of the NQA standards to the repository design process--the intent of these statements seems related more to establishing that a validation process took place, rather than discussing QA for the design activities. The quoted material addresses only NQA-1 criteria, and CARD 22, Sections 22.G.3 and 22.G.5, indicates that the EPA may used only NQA-1 in consideration of this criterion. Design of the repository as described in the CCA, however, includes site characterization activities, for which NQA-3 also applies.

The criterion seems to be related to §194.14(b), which requires that the compliance application include a description of the design of the disposal system. The CCA contains discussions of repository design in Chapters 2, 3, and 6, as well as CCA Appendix DVR (the Design Validation Report). CCA Section 3.2 gives an indication of the types of information that the §194.22(a)(2)(v) criterion should be applied to:

> A preliminary design of the WIPP repository was presented in the FEIS (DOE 1980). Validation efforts for the WIPP repository preliminary design began in 1981 with the Site and Preliminary Design Validation (SPDV) program. The SPDV program was implemented to further characterize and validate the WIPP site geology and to provide preliminary validation of the underground excavation. The SPDV program involved the excavation of four full-sized disposal rooms, excavated 13 feet (4 meters) high, 33 feet (10 meters) wide, and 300 feet (91 meters) long, and separated by 100-foot (31-meter)-wide pillars. Data obtained from geologic field activities and

> geomechanical instrumentation were analyzed to determine the suitability of the design criteria and design bases and to provide confirmation of the underground opening reference design. Analyses of these preliminary designs performed by the WIPP architect and engineer are included in Appendix DVR. These analyses considered expected creep closure rates in determining disposal room sizes. Information in Appendix DVR (Section DVR.6.4.2) meets the criterion specified in 40 CFR § 194.14(b)(2).

Initial design activities for the repository took place in the 1970s and 1980s, well before any part of the WIPP project had established QA programs which met the requirements of the NQA standards. CCA Appendix DVR, for instance, was published in 1984. QA requirements during these early years were rather loose compared to those of the NQA standards; the following is from WIPP-DOE-71, "Design Criteria Revised Mission Concept - II Waste Isolation Pilot Plant", page 1-16:

> The WIPP Project Office (WPO) and the major project participants will be responsible for the establishment and implementation of adequate quality assurance programs for their respective scopes of work. These programs will be developed, using ANSI N45.2 - 1977 as a guide.
>
> Formal quality assurance programmatic requirements will not be contractually imposed on WIPP construction contractors or suppliers.

On the plus side, ANSI N45.2 -1977 was a precursor to NQA-1, but its obvious that the requirements of the NQA standards was not met by this document.

Design of the repository would also seem to include such relatively recent changes in the design of the repository as the 1996 decision to use magnesium oxide as a backfill material. Earlier design documents mandated completely filling rooms with salt backfill. The criterion seemingly requires demonstrating that the NQA standards have been established and executed for a wide range of

programs over a long period of time, in which multiple changes have occurred. Establishing adequate QA for these changes would enhance confidence that all the potential effects of these changes have been taken into consideration.

Recommendation: The EPA should establish which programs and activities relate to design of the disposal system, and include a demonstration of establishment and execution of the NQA standards for these programs and activities in the documentation for the final rule. Since much of the information predates the use of the NQA standards for WIPP activities, the EPA should consider whether or not a QED process as allowed by §194.22(b) has been applied to these areas, and include that information in documentation of the final rule.

§194.22(a)(2)(vii): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for collection of data and information used to the support compliance application(s).

EPA Summary: The proposed rule states that SNL implemented numerous QA procedures to ensure the quality of data and information, and that EPA's audit of SNL found its QA program to be adequately implemented. CARD 22 notes that DOE audits have also concluded that the SNL QA program has been effectively implemented.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on pages 21 and 22.

The SNL's QA procedures do not address collection of all of the data for even the PA, SNL's foremost contribution to the compliance application. The data from the TWBIR, used to establish parameters for the PA, was not collected under a QA program adhering to the NQA standards (see EEG comments concerning waste characterization above).

The main point of EEG's CCA QA chapter review for this criterion is that all data used in support of the CCA was not collected by SNL, and cites several parts of the CCA for which SNL should not be held responsible. SNL has no procedures which specifically address collection of data and information for the DOE's compliance applications; the EPA apparently accepted the DOE statements from the CCA QA chapter at face value.

This is a "catch-all" criterion, and various descriptions of the huge amount of data and information in the CCA was cited in nearly every media article on the CCA's publication. The data and information was gathered over a 20 year period, for most of which only portions of the NQA standards were in effect. The effort should be to demonstrate that any of this data and information which is important to compliance has been collected under the NQA standards.

Recommendation: The EPA should review the CCA for data and information other than that covered by the other (a)(2) criteria which is important to compliance, and cite the review, and a demonstration of establishment and execution of the NQA standards, for any found not to be a part of the other (a)(2) criteria. The EPA should rewrite section 22.H of CARD 22, and revise the proposed rule, to remove the QA responsibility for all data in the CCA from SNL's shoulders.

§194.22(a)(2)(viii): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for other systems, structures, components, and activities important to the containment of waste in the disposal system.

EPA Summary: The proposed rule states that neither the DOE nor the EPA have identified any activities not already covered which require QA controls, and that the EPA audits have determined that the QA organizations for WIPP have authority, access, and freedom to identify other items affecting the quality of waste isolation. CARD 22 adds nothing of substance.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements related to this criterion on page 22. EEG suggested that QA of the interface between the DOE and the BLM concerning DOE review of proposed mineral resource leases in the WIPP area could be important to waste isolation in the disposal system, referencing a WIPP docket item that pointed out problems in this area in the past.

Recommendation: While not a part of the criterion, it would useful to cite any review activities by the DOE (or the EPA) that demonstrate that this criterion has been addressed.

§194.22(b): The compliance application shall include information which demonstrates that data and information collected prior to the implementation of a QA program adhering to the NQA standards have been qualified in accordance with an alternate methodology approved by EPA, which employs peer review, corroborating data, confirmatory testing, or a QA program equivalent in effect to the NQA standards.

EPA Summary: The proposed rule cites the Independent Review Team (IRT) findings of QA programs equivalent in effect to the NQA standards listed in the CCA QA chapter (Table 5-5), the peer reviews conducted under NUREG-1297 used to qualify existing data for engineered systems, natural barriers, waste form, and disposal room data. The EPA performed two audits tracing new and existing data to their qualifying sources and found that equivalent QA programs and peer reviews were had been properly applied. EPA "concluded that existing data from peer-reviewed technical journals was appropriate since the level of such reviews was likely to provide QA equivalent to NUREG- 1297...". The EPA proposes approval of these three methods--peer review, equivalent QA program to the NQA standards, and peer-reviewed technical journals-- for qualification of existing data. CARD 22 adds that the T=0 process as well as the IRTs were used to determine equivalency of QA programs to the NQA standards, and describes the two audits as having been of SNL data used in the PA.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses this criterion on page 5.

There appears to be environmental monitoring data that was gathered before the NQA standards are said to have been established for the WID; this data is cited and used in the CCA, but it was not addressed by IRTs or the peer reviews, and does not appear to have been published in peer-reviewed technical journals. The CCA Appendix SER (U.S. DOE, 1996c, Chapter 7), states:

> Background water quality data were collected from 1985 through the 1990 sampling period as reported in DOE/WIPP 92-013, Background Water Quality Characterization Report for the Waste Isolation Pilot Plant. This background data will be compared to water quality data collected throughout the operational life of the facility. Pre-operational data gathered in the interim period will be used to strengthen the background data, to evaluate the need to make adjustments to comparison criteria...

The 1985-1990 data was collected as part of the Radiological Baseline Program, as found in CCA Appendix RBP. The RBP program measured air, surface and ground water, and soil. The Executive Summary of this Appendix states:

> This program was designed to provide preoperational measurements of radioactivity in environmental samples that will serve as a basis for evaluating similar data collected during the WIPP Operational Environmental Monitoring Program. The RBP data analyzed in this report cover the period from 1985 through 1989. Sample types included in this report are airborne particulates, soil, surface water, groundwater, sediments, and six types of biotic tissue sample.

This intended use of this data is echoed in Section 1.4. These would seem to be part of the environmental monitoring required as a part of the §194.22(a)(2)(ii) criterion. If this earlier data is

to be used as indicated, then it would seem to need the provisions of §194.22(b), qualification of existing data, applied to it, as it precedes the date established by the CCA QA chapter (December, 1994; U.S. DOE, 1996c, p. 5-52) for adherence to the NQA standards at WID. Appendix RBP Section 1.4 indicates that the Waltz Mill Laboratory performed the sample analyses for this program, and these analyses would seem to fall under the §194.22(a)(2)(ii) criterion also.

There may be other data that should undergo QED cited in the CCA. Groundwater and other site characterization activities have been performed for 20 years; CCA Section 9.4.8 describes the INTRAVAL WIPP2 study used data from sixty wells and also included extensive modeling which apparently has been used in the WIPP considerations. The penultimate sentence of the section states:

> The applied stochastic models have proven to be valuable tools in assessing the effect of uncertainty due to heterogeneity on the performance of a repository.

The EPA's acceptance of existing data from peer-reviewed technical journals conflicts with the NQA standards, at least for site characterization activities. NQA-3 Supplement 3SW-1 Section 9 begins:

> Data to be used which were not collected under the control of a quality assurance program in accordance with this Standard shall be qualified for their intended use. This includes data collected from such sources as professional journals, technical reports, and symposia proceedings.

The claim that such level of review of such articles is likely to provide equivalent QA to NUREG-1297 peer review standards might also need to be reconsidered. For example, review by other DOE personnel is limited in NUREG-1297.

Recommendation: The EPA should reconsider the use of data from peer-reviewed technical journals for site characterization activities as an acceptable method under this criterion. The EPA should review the CCA for data related to the §194.22(a)(2) criteria that precede adherence to the

NQA standards, and determine if the programs cited under this criterion have assessed and qualified that data. The conduct of this review should be recorded in the documentation of the final rule.

§194.22(c): The compliance application shall provide, to the extent practicable, information which describes how all data used to support the compliance application have been assessed for their quality characteristics, including accuracy, precision, representativeness, completeness, and comparability (these characteristics are abbreviated as "the PARCC characteristics" in the discussion below).

EPA Summary: The proposed rule describes the CCA's statement that it was not practicable to document data quality characteristics (DQCs) in most cases. The DOE clarified, but did not substantially alter its approach in response to an EPA request for additional information; while the EPA agreed that the DQCs cannot be appropriately applied to parameter values the measured data on which they were based could have been assessed for them. Because the DOE misinterpreted the requirement, the EPA assessed SNL data records packages and found that for newer data, experimental plans generally addressed DQCs including the PARCC requirements, and for older data laboratory notebooks supplied some information related to DQCs. The EPA also "concluded that the peer review panels considered the use of DQCs in determining that such data were adequate", agreed with the DOE argument that collection of most data under programs equivalent to the NQA standards was adequate evidence of the quality of the data, and concurred with the DOE that uncertainty in data measurements as reflected in DQCs has a minor effect on compliance certainty compared to other PA uncertainties. CARD 22 adds that EPA performed a review of parameters discussed at length in a Technical Support Document for §194.23, and notes that the reviewers specifically looked for evidence of DOE's assessment of the PARCC characteristics. CARD 22 also offers as an example of EPA's assessment of DQCs a discussion of two parameters, for which "instrument calibration, calibration records, acceptance criteria, and procedures for calibration checks" were documented that the EPA considered to be adequate to demonstrate assessment of DQCs.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this topic on page 5, with a more thorough discussion on pages 32-35.

The CCA QA chapter specifically lists waste characterization and environmental data are two areas to which DQCs should be applied, but does not provide a demonstration of how they were applied in these areas for the WIPP--and the EPA proposed rule documentation doesn't, either. For the record, the EEG notes that CCA Appendix EMP, Section 7, describes how environmental monitoring addresses accuracy, precision, an comparisons, as well as other DQCs not a part of the PARCC requirements, and the TRU-Waste QAPP (U.S. DOE, 1994), Section 3.2, describes required validation methods for waste characterization which address precision, accuracy, completeness, and comparability. Appendix MON contains a probably identical discussion to that in EMP.

CCA Appendix GCR, the summary of USGS data used, indicates that accuracy and precision were considered (see sections 7.6.13 and 10.7.6, where concerns are raised due to analysis of accuracy and precision of measurements is discussed). There are other similar, rather minor discussions in many appendices, but there are certainly no indications that a systematic consideration of DQCs, "...for all data..." was a part of the WIPP project.

Both the DOE and the EPA discussions of this topic seem to miss the point of DQCs; the DOE saw them as related to the uncertainty of measurements, the EPA is willing to accept instrument calibration data as evidence that DQCs have been assessed.

DQCs relate to the intended use of the data. In an ideal world, the use to which the data is to be put is known, and the PARCC requirements are established in advance of the taking of measurements to demonstrate the limits of acceptability of the data for these uses. The WIPP studies were not developed along these lines; this criterion was not promulgated until well after most of the basic measurements for disposal considerations at the WIPP had already been taken. The lack of evidence of systematic DQC assessment at WIPP does not invalidate any data, it merely prevents taking credit for additional confidence in the supportive value of the data. The criterion does not require the DOE

to assess DQCs--it only requires that the DOE show in the compliance application how they were assessed, to the extent practicable. The extent practicable for past WIPP activities was obviously near nil.

Recommendation: EPA should consider rewriting the final rule discussion related to this criterion along the lines of the EEG comments above. The EPA may also wish to consider including in the final rule a more specific criterion for the establishment of DQCs for data to be used in support of future applications.

§194.22(d): The compliance application shall provide information which demonstrates how all data are qualified for use in the demonstration of compliance.

EPA Summary: The proposed rule states that the SNL generated a table providing information of how all data in the PA were qualified; the EPA audited existing QA programs and determined that data is qualified for use in accordance with the NQA requirements. CARD 22 adds discussions of the T=0 process, QED, peer review, and the SNL QA program, noting that these were audited by the EPA.

EEG comments: The attached EEG review of the CCA's QA chapter addresses elements of this topic on page 6.

The CCA QA chapter and the EPA's proposed rule and CARD-22 contain adequate descriptions of how data used for PA parameters were qualified--but this is certainly not "all data" used for demonstration of compliance. Many of the CCA Appendices--RBP, GTMP, GWMP, USDW, to name a few--were not a part of the PA process.

Recommendation: The EPA should review the CCA to establish a list of the data for which the application should demonstrate how it was qualified, and ensure that the documentation reflects the elements of this list.

§194.22(e): The EPA will verify appropriate execution of quality assurance programs through inspections, record reviews, and record keeping requirements.

EPA summary: The proposed rule cites the EPA audits already conducted, and proposed reaudits and future waste generator site inspections. CARD 22 lists the specific audits, describes the auditing process used, and notes again that EPA did not expect all necessary QA documentation to be provided in the CCA because of its voluminous nature.

EEG comments: The EPA has met this requirement, in that it has adequately verified that, during the year 1997, the QA programs for CAO, WID, SNL, and LANL adhered to the requirements of the NQA standards. Additional audits verified that QA programs adhering to the NQA standards had been established and executed for the single expert judgment elicitations considered so far, the qualification of existing data programs including the 1996-1997 peer review activities, and parameter traceability.

Recommendation: The EPA should review internal EPA documents relating to the promulgation to ensure that the underlying reasoning behind each §194.22 criterion has been adequately addressed for the information presented in the CCA.

2.14 MISCELLANEOUS CONTAINMENT REQUIREMENT ISSUES

2.14.1 Beyond 10,000 Years

Although the EPA standards require demonstration of compliance only for 10,000 years, some partial calculations performed by the EEG indicate that higher releases may be predicted beyond that period (see Section 2.9.3 of this report). There is no strong justification for stopping the calculation at 10,000 years. The EPA provided the following reason for selecting this time period (U.S. EPA, 1985, p. 38070):

> A period of 10,000 years was considered because that appears to be long enough to distinguish geologic repositories with relatively good capabilities to isolate wastes from those with relatively poor capabilities. On the other hand, this period is short enough so that major geologic changes are unlikely and repository performance might be reasonably projected.

The NEA/IAEA International Review Group (NEA/IAEA, 1997) made the following comment on this subject:

> The IRG was surprised that it did not find descriptions or arguments in the CCA indicating the possible performance of the WIPP facility beyond the end of the 10,000 year regulatory period. Such descriptions or arguments, including an indication of the mechanisms, likelihood, timing and possible maximum of impacts at longer times, would be an important element of performance assessment in most other countries.

While EEG agreed with the 10,000 year cut-off point in the development of the standards, we now recommend performance of representative calculations to assess the behavior of the repository beyond 10,000 years to enable comparison with other countries and conformance with the NAS Committee Conclusions on the High Level Waste Yucca Mountain Program.

2.14.2 Effect Of ERDA-9

The EPA has "screened out" (U.S. EPA, 1997c, p. 58801; 1997b) the potential effect of the existence of borehole ERDA-9, which is located only 28.5 meters (93.5 ft) east of the surface projection of the north-south drift E300 of the WIPP underground. The EPA concludes:

> ERDA-9 did not penetrate an area that will become a waste panel and DOE has indicated that abandoned boreholes more than a meter away from the waste can be screened out of PA due to low consequence. EPA agrees with DOE'S assessment that these boreholes are not significant to performance of the disposal system and can be screened out of PA.

The CCA argument for screening out the potential effect of ERDA-9 on the disposal system is presented in Appendix SCR 3.3.1.42 of the CCA, which refers the reader to an analysis conducted as a part of the WIPP 1991 performance assessment (Sandia, 1991/1, Appendix B, pp.26-27). This analysis was conducted by the DOE in response to a question raised by EEG in 1990 about the extent of the Disturbed Rock Zone (DRZ) and the permeability of Marker Bed 139. The analysis concluded that if permeability value difference of three orders of magnitude is assumed between a DRZ and the adjacent intact rock, then the bore hole flow rates from the two zones are markedly different. This is, of course, something to be expected. The questions to be asked and the issues to be considered before the effect of ERDA-9 can be written off, are:

1. How far is ERDA-9 from the drift E-300 *at the repository level?* Boreholes are seldom vertical; they deviate. For example, the borehole H-19-B-4, drilled under strict specifications for hydrologic and tracer testing of the Culebra aquifer in 1995-96, deviated 9.5 meters (31 ft) in 229 meters (752 ft) depth. At that rate, a borehole drilled to 655 meters (2150 ft) depth of the repository may deviate 27 meters (89 ft). Could ERDA-9 be very close to E-300 at the repository level?

2. How far does the DRZ of E-300 extend?

3. Whether or not there is pressurized brine reservoir underlying ERDA-9 is not definitely known,

although there is good reason to suspect it. ERDA-9 penetrated the Castile Formation for 17 meters (56 ft). The borehole WIPP-12 was drilled in 1978 to penetrate 14.7 meters (48.3 ft) into the Castile, and encountered pressurized brine when drilled an extra 74 meters (242.4 ft) in 1981.

4. How will ERDA-9 be sealed? Appendix SCR, Section 2.3.8.2, of CCA, states:

> WIPP investigation boreholes will be sealed using materials and designs in accord with industry standards for the Delaware Basin. A survey of plugging practice (Appendix DEL) shows that the majority of boreholes have a plug below the water-producing zones in the Rustler and a plug at the top of the Bell Canyon. Drilling and abandonment procedures may lead to additional plugs within the Salado. A few boreholes (2 percent of those surveyed), however, have a continuous plug of salt-saturated cement from the top of the Salado to the top of the Bell Canyon. ERDA-9 will be sealed in a similar manner. Other WIPP investigation boreholes will be plugged according to regulatory requirements and standard industry practice. The DOE has committed to plug with cement the portion of these boreholes that penetrate the Salado.

Why is EPA not requiring at least a special plugging procedure for ERDA-9 and other boreholes that penetrate the repository horizon within the WIPP site?

2.14.3 Brine Seepage into the Shafts

The EPA was concerned about the potential for seepage of brine into the shafts in the Salado Formation zone to be occupied by compacted salt plug. Attachment 1 of TSD III-B-3 (U.S. EPA, 1997g) is a trip report of inspection of the air intake shaft by EPA to verify the DOE statements concerning the lack of observable brine inflow in the lower Salado where the compacted. The inspection report concludes, “The air shaft inspection did not result in observations of any current brine seepage, as no areas appeared to be wet and no brine was observed.” It is common knowledge that the rate of brine inflow from the Salado marker beds is low enough that brine dries up almost instantly due to ventilation in the WIPP mine. This would certainly be expected in the air intake shaft. If the rate of water inflow is large enough, as is being observed in the WIPP exhaust shaft at the level

of Santa Rosa and Dewey Lake Formations for the past several years, then even a large blast of air does not completely dry up water. As far as brine inflow from the Salado Formation is concerned, the presence of salt encrustations (efflorescences) clearly indicates current brine seepage. The inspection team's conclusion therefore simply indicates the absence of understanding of the mechanics of brine drying up in the air intake shaft, rather than the absence of brine inflow.

2.14.4 Iron in the Repository

There is a curious response by the EPA to the question of the amount of additional iron that may be introduced in the WIPP repository through rock bolts and other ground control and roof support system (U.S. EPA, 1997b, CARD14-95). Corrosion of iron in the presence of brine in the repository is expected to produce hydrogen. For at least the past 10 years, the question of gas production in the repository has been a concern and it is common knowledge that reduction of the amount of iron in the repository will help meet compliance with the EPA standards and is therefore a desirable goal. The EPA should therefore explain the following response:

> The amount of iron introduced into the disposal system by rock bolts is inconsequential since there is no upper limit on the amount of iron that can be emplaced in the repository. The DOE did specify a minimum amount of iron that must be emplaced into the repository withine (sic) Appendix WCL, Table WCL-1, which is based on the quantity of iron within the waste containers to be emplaced at the WIPP and does not rely (sic) the amount of iron contained in the roof support system to meet this minimum requirement. (U.S. EPA, 1997b, CARD 14-95).

Does EPA now believe in a *minimum* amount of iron that must be emplaced in the repository?

3.0 ASSURANCE REQUIREMENTS

3.1 INTRODUCTION

The EPA standards (U.S. EPA, 1993) contain a set of assurance requirements to provide the additional confidence needed due to the long period of time of concern and the uncertainties associated with the decision to dispose of waste without practical possibility of retrieval. The philosophy of the Assurance Requirements is clearly stated in the "Overall Approach of the Final Rule" (U.S. EPA, 1985, p. 38072), as follows:

> In contrast to the containment requirements, the assurance requirements were developed from that point of view that there may be major uncertainties and gaps in our knowledge of the expected behavior of disposal systems over many thousands of years. Therefore, no matter how promising the analytical projections of disposal system performance appear to be, these materials should be disposed in a cautious manner that reduces the likelihood of unanticipated types of releases. Because of the inherent uncertainties associated with these long time periods, the Agency believes that the principles embodied in the assurance requirements are important complements to the containment requirements that should insure that the level of protection desired is likely to be achieved.

During the promulgation of the original standards (40 CFR 191) in 1985, the EPA considered an additional assurance requirement that called for releases to be kept as low as reasonably achievable (ALARA) even when the numerical containment requirements have been complied with. This proposed requirement was deleted by EPA from the final rule for two reasons (U.S. EPA, 1985, p. 38072):

> First, NRC's 10 CFR Part 60 implemented the multiple barrier principle by requiring very good performance from two types of engineered components: a 300 to 1000- year lifetime for waste packages during which there would be essentially no expected release of waste, and a subsequent long-term release rate from the waste form of no more than one part in 100,000 per year....(and) Second, the DOE has included a provision in its site selection guidelines (10 CFR 960) that calls for significant emphasis to be placed on selecting sites that demonstrate the lowest releases over 100,000 years compared to the other alternatives available.

Neither of these provisions apply to WIPP and the net result for the TRU waste is that the DOE has argued for the minimum requirements rather than design for ALARA. EPA is proposing to certify WIPP on the basis of a very narrow interpretation of the assurance requirements without acknowledging the history of promulgation and the philosophy behind it.

There are six assurance requirements included in the standards (U.S. EPA, 1993). The following is the EEG assessment of the EPA's proposed rule for each of these.

3.2 ACTIVE INSTITUTIONAL CONTROLS

Title 40 CFR 191.14 (a) requires maintenance of active institutional controls for as long a period of time as is practicable after disposal, but credit in performance assessment may not be taken for more than 100 years. The DOE has proposed controls for 100 years and has assumed no drilling in the repository for that period. The EEG agrees with the EPA's finding for this requirement, but recommends that if in the final rule EPA finds WIPP to be in compliance with the standards and proposes to grant certification, oversight by the federal (other than DOE) and state authorities should be required to ensure vigorous implementation of the active institutional control.

3.3 MONITORING

Title 40 CFR 191.14 (b) requires disposal systems to be monitored both pre- and post-closure to detect any substantial or detrimental variations from expected performance. The monitoring shall be done with techniques that do not jeopardize the isolation of the wastes and should be conducted until there are no significant concerns to be addressed by further monitoring.

Specific criteria to be met are outlined in 40 CFR 194.42 and require any compliance application to document and substantiate the decision not to monitor a disposal system parameter because the parameter is considered to be insignificant to the containment of waste in the disposal system or the verification of predictions about the future performance of the disposal system. The proposed criteria did not contain a mechanism whereby DOE could decide not to monitor a particular disposal system parameter on the basis that DOE considered it to be unimportant to the containment of waste or to verify predictions about future performance of the disposal system. Hence, EEG never had the opportunity to comment on this change that was effected in a meeting between EPA, DOE, and OMB and incorporated in the final criteria.

DOE has chosen to exclude from monitoring all parameters of interest in the repository during the pre-closure phase (excluding stress and deformation measurements and radioactivity in air) by qualitatively evaluating their significance in shifting either the probability or the consequence in calculations for the containment requirements. EPA has accepted the CCA analysis for this assurance requirement.

The reason for including the assurance requirements in the standards was the inherent uncertainty in the calculations of releases for 10,000 years. The benefits from the assurance requirements were never intended to be quantified. It was recognized that there could be no clear yardstick to measure the benefit of a marker or the detriment to confidence in predicting the behavior over 10^4 years if markers were not used. The same logic applied to records maintained by institutions and the benefits

of the ability to retrieve waste. The approach allowed by EPA in the final criteria is to permit DOE to assess the usefulness of monitoring by a qualitative evaluation of the impact of improving our knowledge of the potential behavior of the repository. This is contrary to the intended purpose of the assurance requirements. It does not make sense to exempt DOE from the assurance requirement for monitoring based on a qualitative evaluation that depends on the containment calculations being correct.

Chapter 7.2 of the CCA evaluated various parameters including those listed in 194.42 and concluded that there was little merit in obtaining measurements of changes in various parameters since changes occurring over a short time period may not be representative of the steady state conditions that would exist over long time periods. DOE points out that obtaining data for a 35 year period is of little value in extrapolating results over a 10,000 year regulatory period. For years, DOE pursued the desire to conduct an experimental program with waste at WIPP and argued that obtaining 5 years worth of data would be effective in confirming the predicted behavior of the TRU waste.

DOE identified 10 parameters needing monitoring in the pre-closure period and only 5 of those worthy of monitoring in the post-closure period. EPA concurred. The post-closure monitoring parameters are:

- Culebra groundwater composition
- Culebra change in groundwater flow
- Probability of encountering a Castile brine reservoir
- Drilling rate
- Subsidence measurements

EEG believes there are a number of parameters that can be monitored in both the pre- and post-closure period that could help verify predictions of the future behavior of the disposal system.

1. Drilling practices in the Delaware Basin of air drilling, CO_2 injection and other underbalanced

drilling should be monitored as well as borehole diameters and mining practices such as shaft diameters.

2. Continued investigation of non-invasive techniques to monitor brine migration, gas generation and radionuclide movement. While DOE acknowledges (U.S. DOE, 1996c, page 7-50) these remote techniques to determine characteristics of the earth have been well established in measuring resistivity, acoustic velocity, magnetism, density, temperature, moisture control, and radioactivity, they conclude that changes in the repository will be too small or too slow to be detectable using remote techniques. EEG sees no evidence to warrant this conclusion.

3. Prior to sealing Panel 1, remote sensors could be placed in the rooms of Panel 1 to measure moisture content, CO_2, room closure or other parameters and detectors hooked to cables located outside Room 1. One could obtain 10 years worth of highly detailed data on the actual behavior of the repository.

4. Non-invasive detectors could be located outside the Panel 1 seal to monitor parameters inside Panel 1 rooms. One could obtain 35 years worth of data on the actual behavior of the repository.

5. Groundwater quality of the Dewey Lake and Santa Rosa Formations be monitored.

Note that the U.S. Nuclear Regulatory Commission (U.S. NRC) plans to require DOE to monitor post-closure at the Yucca Mountain High Level Waste Repository {10 CFR 60.51 (a)(1)}. The Performance Confirmation Program outlined in Subpart F, 40 CFR 60.140 through 60.143 establishes detailed programs to monitor the condition of the waste packages as well as subsurface changes during construction and waste emplacement operations. The NRC Subpart F requirements apply to the pre-closure conditions. EEG is unaware that DOE finds such a request unreasonable for the high-level waste repository. EEG believes that DOE should be required to pursue non-invasive long-term monitoring programs during the operational period as a condition for approval, and a major evaluation should be undertaken prior to the first recertification.

3.4 PASSIVE INSTITUTIONAL CONTROLS

Title 40 CFR 191.14 (c) requires designation of the repository site by the most permanent markers, records, and other passive institutional controls (PIC) practicable to indicate the dangers of the wastes and their location. The EPA proposes to require WIPP to implement the system of PICs but proposes to deny taking credit for PICs in the performance assessment for the containment requirements. The EEG agrees with this determination of denying credit for PICs for reasons stated by the EPA in U.S. EPA (1997c), as well as for reasons that EEG has previously submitted to the EPA (see Appendix 8.2-Passive Institutional Controls).

3.5 ENGINEERED BARRIERS

Title 40 CFR 191.14 (d) requires use of both engineered and natural barriers in the repository design. The CCA proposed a chemically-buffering magnesium oxide backfill as the only engineered barrier, and the EPA has accepted in the proposed rule the DOE (U.S. DOE, 1996c) proposal to satisfy this assurance requirement. The EEG view is that while there are still some questions about the efficacy of the chemical buffer aspect of the magnesium oxide (MgO) backfill (see section 2.3 and Appendix 8.4 of this report), this engineered feature has been selected primarily to enable DOE to use numerical values of certain parameters in the containment requirement calculations. The MgO backfill may not therefore be considered to satisfy this assurance requirement in a strict sense of the philosophy of these requirements. Incorporation of backfill in the WIPP design is nevertheless a good idea and the EEG has been recommending a salt/clay mixture as backfill for years. A pure MgO backfill does not have the benefit of the chemical retardation of radionuclides that clays afford, but may help keep the repository chemical environment stable. The EEG would prefer addition of clays such as commercially available bentonite to the backfill, but is willing to accept emplacement of MgO backfill for the sake of operational ease and efficiency.

The EEG disagreement with the EPA on this issue concerns the lack of incorporation of engineered

barriers that would provide additional assurance beyond helping in the calculations to satisfy the containment requirements. With respect to the engineered barriers as an assurance requirement, the "Overall Approach of the Final Rule" (U.S. EPA, 1985, p. 38072) states:

> Designing disposal systems to include multiple types of barriers, both engineered and natural, reduces the risks if one type of barrier performs more poorly than current knowledge indicates.

The CCA (U.S. DOE, 1996c, Sec. 3.3) describes four types of engineered barriers in the design of the WIPP disposal system: (1) Shaft Seals, (2) Panel Closures, (3) Backfill around the waste, and (4) borehole plugs. EEG does not consider any of these to be engineered barriers, for the following reasons:

3.5.1 Shaft Seals

Shaft seals are at best an attempt to undo the damage done to the natural environment when the shafts were excavated, and therefore cannot be considered to be an engineered barrier as distinct and *complementary* to the natural barriers.

Note that the 40 CFR 191.12 definition of a "Barrier" includes the following examples of engineered barriers, but does not include "shaft seals".

> ... A canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around waste, provided that the material or structure substantially delays movement of water or radionuclides.

The repository standards for the high-level nuclear waste repository (10 CFR 60) specifically exclude shaft seals from engineered barrier system. "Engineered Barrier System" is defined in 10 CFR 60.2 as:

Engineered barrier system means the waste packages and the underground facility.

and

Underground facility means the underground structure, including openings and backfill materials, <u>but excluding shafts, boreholes, and their seals</u> (underline added).

3.5.2 Panel Closures

Like the shaft seals, panel closure systems (separation of waste panels by engineered structures) cannot be considered to be engineered barriers because they too can at best be imperfect attempts to restore the original natural system. Panel seal is not included in the examples of engineered barrier in the EPA definition (40 CFR 191.12).

The Marker Bed 139 lies directly below the WIPP repository and is connected to the floor of the waste rooms through extensive fractures, floor upheaval and milling of the floors. Water (with anomalous lead content acting as a tracer) seeping down from the exhaust shaft has moved 400 ft through the marker bed from the base of the air exhaust shaft to the waste handling shaft in a short period of time during 1995-96. This pervasive marker bed would not allow effective separation of the panels unless the entire floor of the repository is dug down 10 ft and grouted.

According to the CCA (U.S. DOE, 1996c, p. 3-27, lines 19-20), "The panel closure system was not designed or intended to support long-term repository performance." How then can it be considered an engineered barrier for the long-term performance?

3.5.3 Backfill Around the Waste

The DOE plans to put sacks of magnesium oxide (MgO) over and around the waste drums to try to control the future chemical conditions in the repository. The expectation is that MgO will react with the carbon dioxide (CO_2) that is produced from microbial action in the repository. Removal of CO_2 will result in alkaline conditions in the repository. Since the experimentally determined solubilities of radionuclides are lower in alkaline (high pH) conditions, the emplacement of MgO and its

postulated effect allows assumption of lower solubility values in the CCA. This assumption results in lower postulated releases to the accessible environment and thus helps in showing compliance with the Containment Requirements (40 CFR 191.13) of the EPA Standards.

Since the publication of the CCA, the DOE has argued that the MgO is not needed for showing compliance with the Containment Requirements because the mean CCDF without MgO, although showing higher releases than "with MgO", still is within the compliance limits. Such an argument is based on a partial calculation without altering other assumptions and input parameters, and therefore appears meaningless. The fact remains that the purpose of including MgO in the WIPP repository is to control the chemical conditions in the WIPP repository to allow assumption of lower actinide solubility values. It may therefore satisfy a need for the Containment Requirement of the Standards, but does not provide *complementary* added assurance visualized by the Assurance Requirements (40 CFR 191.14).

3.5.4 Borehole Plugs

Since the stated requirements for plugging the boreholes (U.S. DOE, 1996c, Section 3.3.4, Figure 3-10) are much less stringent than the shaft seals, the borehole plugs have a lesser claim as engineered barriers than the shaft seals. The EPA Standards (40 CFR 191.12) do not include borehole plugs as an example of engineered barriers. The NRC specifically excludes borehole seal as part of an engineered barrier system (see the quote under Shaft Seals section above). Hence, the borehole plugs should not be considered to be an engineered barrier.

Incidentally, the DOE's CCA - Figure 3-9 (U.S. DOE, 1996c, "Approximate Locations of Unplugged Boreholes") does not include two deep abandoned oil and gas wells that are located within the WIPP site: Badger Unit Federal in Section 15 (between WQSP-3 and H-5 in the northwest part of the WIPP site), and Cotton Baby Federal in Section 34 (east of H-11 in the southeast corner of the WIPP site).

3.5.5 Waste Processing and Repackaging

Additional confidence in predicting the behavior of the waste over 10,000 years can be obtained by

processing the waste. Hence, EPA should encourage the DOE to process the waste before shipment to WIPP. TRU waste is highly heterogeneous and there are no limits on the allowable particle size of the waste. The Nuclear Regulatory Commission (10 CFR 61) requires a 300 year waste-form or container longevity for class B or class C *low-level* waste, whereas there are no requirements for the TRU containers or the waste-form in 40 CFR 191. Moreover, the DOE proposed action in the WIPP 1997 Environmental Impact Statement only commits to meeting the Waste Acceptance Criteria for acceptance of waste at WIPP. The DOE **preferred alternative**, published in the 1997 Final Waste Management Programmatic Environmental Impact Statement for Managing, Treatment, Storage and Disposal of Radioactive and Hazardous Waste, is to **treat** and store at the sites where it is generated prior to shipment to WIPP.

The recommendation to treat the waste before shipping to WIPP should be easier to accomplish because several of the DOE's waste generator sites are planning to process and/or repackage the waste before shipping to WIPP anyway, for other reasons, as described below. The EPA's recommendation will result in an orderly and coordinated decisions on this matter throughout the DOE weapons complex, and will make WIPP safer.

- According to the September 1997 WIPP Final Supplemental Impact Statement (U.S. DOE, 1996d), 27,000 m^3 of alpha emitting low level waste at INEEL will be processed to convert it to TRU waste.

The information for the following processing and repackaging plans is derived from the National TRU Waste Management Plan (U.S. DOE, 1997c).

- INEEL plans to process all the existing and projected TRU waste except for 15,000 drums (3,000 m^3) to meet the INEEL/State of Idaho agreement, which amounts to processing 79,600 m^3 - 3,000 m^3 = 76,600 m^3 of waste.

- ANL-E plans to treat and stabilize all the 203 m^3 existing and newly generated CH-TRU waste.

- Hanford plans on repackaging most of its 16,127 m^3 of CH-TRU waste.

- Rocky Flats Plant will process most of the plutonium residues and all of the scrap alloy since plutonium concentrations exceed the DOE limits. About half the other TRU waste will be processed and repackaged.

- The Plutonium-238 heat source wastes at Savannah River exceed the hydrogen gas limits imposed by NRC and will require treatment or an easing of the regulations for a less stringent flammable limit or the use of hydrogen getters in the transportation containers.

- All the 1097 m^3 CH-TRU waste at ORNL will be processed with a 50% volume reduction.

- SRS plans to process and repackage 9,525 m^3 of the existing 11,725 m^3 of CH-TRU waste.

In summary, of the existing 104,400 m^3 of CH-TRU waste, DOE has plans to treat or repackage 88,900 m^3 or 85%. Of the 15,500 m^3 not being processed, 3,000 m^3 is intended for shipment to meet a scheduled commitment between DOE and the State of Idaho. The EPA should recognize DOE's efforts in stabilizing the waste and encourage DOE to also fix the yet-to-be generated waste.

3.6 RESOURCE DISINCENTIVE REQUIREMENT

Title 40 CFR 191.14 (e) requires that areas with natural resources should be avoided in selecting a site for a TRU waste repository, unless the favorable characteristics of such places compensate for their greater likelihood of being disturbed in the future. The WIPP site is located in the middle of an area with extensive history of exploitation of potash, oil and gas, and is surrounded by hundreds of currently producing oil and gas wells, as well as several currently producing potash mines. It is

expected that the mining and drilling activity will continue around the WIPP site for the foreseeable future. If the WIPP site had not been withdrawn for exclusive use by DOE, almost certainly there would have been a number of exploratory oil and gas wells and potash mines at the site by now. The EPA has proposed to determine that the WIPP meets this compliance requirement on the basis of the results of the calculations for the containment requirements.

The EEG believes that in allowing the resource disincentive requirement of the EPA standards to be satisfied if the numerical containment requirements (40 CFR 191.13) are satisfied (through 40 CFR 194.45), the EPA deviated from the basic philosophy of the multiple barrier "belt-and-suspender" approach inherent in the assurance requirements of the standards. Faced with the *fait accompli* of promulgation of 40 CFR 194, the EEG recommended (Neill et al., 1996) that at least the actual conditions at the site related to the presence of natural resources be fully and conservatively assumed in projecting compliance with the numerical containment requirements. This does not appear to have been done in the CCA, judging from the DOE resistance to consideration of fluid injection, air drilling, and mining scenarios. The other suggestion made by the EEG (Neill et al., 1996) is to compensate for siting the repository in a mineral resource rich area by incorporating robust engineered barriers in the WIPP's design. The DOE has proposed Magnesium Oxide backfill as an engineered barrier, but that is needed for assuming low actinide solubility to show compliance with the containment requirement. The "containment" and the "assurance" requirements of the EPA standards thus have not been kept separate, as was intended by the EPA standards, 40 CFR 191.

The EEG recommends that full consideration of the effects of the presence of natural resources be incorporated as suggested in Sections 2.5, 2.6, and 2.8 of this report, in a new PAVT, and the engineered barriers be incorporated as suggested in Section 3.4 above.

3.7 RETRIEVABILITY

Title 40 CFR 191.14 (f) states, “Disposal systems should be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal.” The EPA explained in the preamble to the originally proposed rule (U.S. EPA, 1985, p. 38082; September 19, 1985) that the recovery of waste does not have to be “easy or cheap”.

In response to this requirement, the CCA (U.S. DOE, 1996c) presented a five phase approach from planning to decontamination and decommissioning of the facility, and the EPA proposes to find WIPP in compliance of this requirement. As a practical matter, however, the EEG believes that attempts to remove the waste from the repository, even 10 years after first emplacement, will be so hazardous and expensive that it is not a reasonable option. The EPA and the DOE should clearly acknowledge that fact.

4.0 GROUNDWATER PROTECTION REQUIREMENTS

Subpart C of 40 CFR 191 contains the Environmental Standards for Groundwater Protection. Section §191.24 specifies that undisturbed performance of the repository shall not cause the limits specified in 40 CFR part 141 to be exceeded during the 10,000 year regulatory period in any underground source of drinking water (USDW). An aquifer must be able to supply sufficient quantity of water to a public water system and to contain less than 10,000 milligrams of total dissolved solids per liter (§191.22).

Compliance with these requirements requires that USDWs about the WIPP Site be identified, that existing concentrations of radionuclides in these USDWs be estimated, and the increased radionuclide concentrations and doses from the undisturbed performance of the repository be determined.

Previous EEG Comments

The DCCA (U.S. DOE, 1995c) did not address groundwater protection requirements and consequently EEG did not make comments in our review of the DCCA (Neill, et al., 1996). EEG has not made any previous written comments to DOE or EPA on Chapter 8 of the CCA (U.S. DOE, 1996c).

EPA Response to Chapter 8

EPA mostly concurred with DOE's evaluation of the location of possible USDWs. However, in a December 19, 1996, letter EPA did specify that "the CCA needs to include appropriate maps of USDWs using Plan views with information such as township, range, and estimated latitude and longitude of the center of the USDW." A map was provided in DOE's February 27, 1997, response to EPA's request for additional information. DOE did not provide a location of the estimated center of the USDWs because of the contention that sufficient data were not available.

EPA accepted DOE's map of USDWs as adequate without location of their centers. Also, EPA concluded that even though DOE calculated a maximum total alpha radioactivity concentration of about 9 pCi/ℓ (compared to the limit of 15 pCi/ℓ) the potentially large uncertainty was not a problem because these concentrations were in anhydrite formations and not USDWs.

EEG Evaluation

EEG has several concerns or questions about DOE calculations or assumptions and about EPA's Compliance Review.

<u>USDW Designation</u>. The assumption by DOE that a 5 gallon per minute pumping rate was necessary to supply 25 persons is non-conservative. Water consumption may average 282 gallons per capita per day in nearby communities where there is a water system that can supply additional water for lawns, gardens, swimming pools, etc. However, in a rural community where nearby water sources are limited, persons can live quite well on 100 gallons per capita per day. Thus, a pumping rate of 2 gpm should be adequate for 25 persons. The pumping rate criterion did not actually affect DOE's designation of USDW areas because pumping rate data were usually not available and the boundaries were selected on the basis of the total dissolved solids criteria.

EEG is satisfied with the boundaries of USDWs for the Culebra, Dewey Lake, and Santa Rosa aquifers that are shown in Figure 1 of DOE's February 27, 1997, submittal.

<u>Radionuclide concentrations in USDWs from undisturbed releases</u>. DOE relied on the analysis performed for the individual protection requirements to show that the maximum concentration of alpha emitting radionuclides and the allowable dose from beta and gamma radiation was not exceeded. The concentration from the maximum realization was 6.61 pCi/ℓ for ^{239}Pu + ^{230}Th + ^{234}U. These concentrations were determined from BRAGFLO flows and the NUTS code for radionuclide transport and are in anhydrite beds and not an USDW. A different calculation scheme was used to estimate the ^{226}Ra concentration. This calculation led to an estimated ^{226}Ra concentrations of 2 pCi/ℓ which is 2 orders of magnitude greater than the maximum concentration of its parent, ^{230}Th in the

BRAGFLO/NUTS calculation. It seems apparent that these two methods of calculation are unrelated.

EEG believes the concentrations of radionuclides due to an undisturbed release from WIPP in any possible USDW will be somewhat less than the Maximum Concentration Limits (MCLs) in 40 CFR 141. This conclusion is based on the belief that while some contamination could occur between anhydrite beds and USDWs the amount of dilution that would be needed in order to maintain a TDS concentration in a USDW aquifer below 10,000 mg/ℓ would more than offset uncertainty in estimating radionuclide concentrations.

Radionuclide concentrations in uncontaminated USDWs. 40 CFR 191.24 states that any release from undisturbed performance shall not cause the levels of radioactivity in USDW to exceed the limits specified in 40 CFR part 141. In other words, the releases from the repository should be added to the existing radionuclide concentrations to determine compliance. This point was contested in comments on the proposed rule and EPA's decision to include both existing and added concentrations was explained in the preamble to the rule. Basically, EPA doesn't want to have any degradation in a USDW that has concentrations at or above MCL values.

The final 40 CFR 194 and the Compliance Application Guidance (CAG) (U.S. EPA, 1996a) are vague about whether existing concentrations of radionuclides need to be determined and added to estimated concentrations from undisturbed releases in order to show compliance. No relevant discussion was found in the preamble to 40 CFR 194 or in the Background Information Document.

The CCA provided no information on existing concentrations of radionuclides in the possible USDWs and EPA did not ask for this information. Natural system compliance with the MCLs should not be assumed. EEG measured radionuclide concentrations in 3 Dewey Lake wells just south of the site in 1989 and 1990 . One of the four samples measured 37 pCi/ℓ gross alpha, 13.6 pCi/ℓ uranium, and 2.4 pCi/ℓ ^{226}Ra + ^{228}Ra (Kenney and Ballard, 1990).

EPA needs to either obtain existing radionuclide concentrations in the possible USDWs in order to show compliance with 40 CFR 191.24 or explain why this requirement is not applicable.

5.0 INDIVIDUAL PROTECTION REQUIREMENTS

Section §191.15 of 40 CFR 191 provides that disposal systems "shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual committed effective dose, received through all potential pathways from the disposal system, to any member of the public in the accessible environment, to exceed 15 millirems (150 microsieverts)." The Individual Protection Requirements were addressed by DOE in Chapter 8 of the CCA.

Previous EEG Comments

The DCCA did not provide dose calculations to determine if the individual protection requirements had been met. Consequently, EEG had no comment on this requirement in our review of the DCCA (Neill et al., 1996). EEG has not made any previous written comments to DOE or EPA on Chapter 8 of the CCA.

EPA Response to Chapter 8

In the CCA DOE concluded that the only mechanism for undisturbed releases and a dose to an individual was from migration of brine from the repository in anhydrite marker beds to the accessible environment. This contaminated brine was pumped to the surface and diluted to decrease total dissolved solids to 10,000 milligrams per liter. The individual was assumed to drink 2 liters per day of this diluted water. The realization with the highest concentration of radionuclides (out of 300 realizations) was used for the dose calculation.

EPA requested that DOE provide analyses of other exposure pathways beside the drinking water pathway evaluated in Chapter 8 of the CCA. DOE provided this analysis in their February 27, 1997 response to EPA's request for additional information. The additional pathways scenarios analyzed were: (1) farm family inhalation; (2) farm family ingestion; and (3) cattle rancher. DOE dose

estimates for the maximum realization were 0.47 mrem for drinking water and 0.46 mrem from ingestion (the other scenario doses were negligible).

EPA also made their own Dose Verification Evaluation and included this Technical Support Document (U.S. EPA, 1997k) with the proposed rule. Pathways evaluated were drinking water; crop, soil, meat and milk ingestion; inhalation; and direct radiation. EPA calculated doses of 0.49 mrem per year from drinking water and 0.16 mrem for all other pathways.

EPA agreed that the DOE scenario assumptions were conservative and actually unlikely. Also, that the CAG (U.S. EPA, 1996a) requirements were fully met. Therefore, they concurred in the adequacy of DOE's Individual Protection Requirement evaluation.

EEG Evaluation

The EEG checked both DOE's and EPA's dose calculations. Agreement was within 5%.

CCA calculations of the concentration and quantity of radionuclides reaching the accessible environment in the anhydrite interbeds were taken as a given by EPA. EEG has not checked these calculations either but they appear reasonable. Also, the limited quantity of contaminated water calculated to reach the accessible environment (a maximum of 216 m^3) was not invoked by DOE or EPA in their calculations. This limited quantity of contaminated water would preclude EPA's calculated 30-year radionuclide buildup in soil (which contributes less than 1% of the other pathways dose).

We consider two inhalation and soil ingestion pathways to be more likely than those considered by DOE and EPA. These are: (1) resuspension of solids from undiluted brine used for dust control about a residence; or (2) resuspension of solids from a mud pit where the contaminated brine has evaporated. The brine could be in the mud pit as a result of an aquifer pump test, an oil or gas borehole, or as a residue from a water treatment process (such as reverse osmosis). However, these

scenarios result in estimated doses that are less that 0.1 mrem/y. So, these scenarios, though perhaps more reasonable, lead to lower doses than calculated by DOE and EPA.

EEG agrees that this requirement has been adequately and conservatively evaluated. We consider this to be a closed issue.

6.0 EVALUATION OF EPA'S RESPONSES TO EEG'S COMMENTS

The EPA has provided responses to some of the EEG comments on the CCA provided to the EPA before the March 17, 1997, deadline. These responses are found at the end of each Compliance Assessment Review Document (U.S. EPA, 1997b). References have been made to these responses in the relevant chapters in this report. For the sake of completeness, the EEG review of these responses are grouped together in this chapter.

Section 194.14 (CARD 14)

Issue 14.T: The probability of encountering a brine reservoir during drilling and the reservoir's potential volume are underestimated.

103. The CCA assumed that the probability of encountering a brine reservoir is a function of reported brine encounters expressed as a percentage of total boreholes drilled. The problem with this assumption is that drillers are not required to report brine encounters; moreover, drillers tend not to report such encounters unless they result in significant delays or cause other problems during operations. Thus, the eight percent brine encounter rate used in the CCA dramatically understates the actual rate, which probably lies somewhere between 50 and 100 percent. (103)

525. The EEG does not find the CCA reservoir volume assumption of 32,000 to 160,000 m^3 to be justified. (525) (II-H-12.4)

EPA response to Issue T:

EPA found that DOE's representation of brine pocket occurrence probability and brine pocket size/volume in the CCA were not consistent with available information. EPA directed DOE in letters dated March 19, 1997 (Docket A-93-02, Item II-I-01, enclosure 3) and April 25, 1997 (Docket A-93-02, Item III-I-27) to conduct new performance assessment modeling that includes modified parameter values. EPA requested that the brine pocket probability be modified to a range from 1 percent to 60 percent, and that this occurrence be sampled rather than a fixed value of 8 percent. In addition, EPA requested that the parameters regarding rock compressibility and porosity (e.g. Castile COMP_RCK), as well as how the brine pocket volume is sampled, be modified in the mandated Performance Assessment Verification Testing (DOE, 1997b and 1997c). This approach effectively modified the sampled brine pocket volume to include more representatively the possibility of higher brine pocket volumes, including that of WIPP-12. As a result of the PAVT, EPA found that the original brine reservoir characteristics were, in fact, acceptable. For more discussion on this topic, also see this CARD, section 14.B.5, EPA's Technical Support Document for Section 194.14: Content of Compliance Certification Application (EPA, 1997a) and the Technical Support Document for Section 194.23: Parameter Justification Report (EPA, 1997e).

EEG assessment of EPA response to Issue 14.T

The Performance Assessment Verification Test has demonstrated that the brine reservoir characteristics have a large effect on predicted repository pressure and brine saturation. The EEG believes that the Performance Assessment Verification Test is a valuable set of calculations that were needed to demonstrate the robustness of the performance assessment calculations.

The characterization of the potential high pressure brine pocket used in the PAVT is much more accurate than the representation used in the CCA calculations. There are two parameters used in the PAVT that are still inaccurate. First, the PAVT uses a sampled

pressure range of 11.1 to 16.5 MPa gage for the Castile brine, based on regional occurrences of brine, rather than the 12.6 MPa gage measured at WIPP-12. WIPP-12 brine almost certainly protrudes under the WIPP repository. However, it was found that the pressure range used in the PAVT leads to prediction of more and larger brine releases than the single value of 12.6 MPa (Rucker, 1998).

Secondly, there is poor justification for the 1% lower end of the EPA range for the probability of encountering a pressurized brine pocket. The 60% upper end is based on an electromagnetic survey of the WIPP site (U.S. DOE, 1996c, 2.2.1.2.2) that indicates brine is likely under about 60% of the repository. Most importantly, the probability of hitting brine under WIPP should be based on local WIPP information and not the entire Delaware basin. The calculated size of the WIPP-12 brine reservoir and the existence of boreholes around WIPP-12 that have not encountered brine in the Castile constrain the WIPP-12 reservoir such that the reservoir must extend under the repository (Neill, 1997d). The brine indicated by the electromagnetic survey must be part of the WIPP-12 reservoir. Hence, the probability of encountering brine should be modeled as 60%. Thus, the PAVT under represents the probability of encountering a brine reservoir while overestimating the effect of the reservoir.

Section 194.23 (CARD 23) Models and Computer Codes

ISSUE 23.A: Cuttings/Cavings and Spallings Model

97. The CCA fails to consider cavings that occur as the drill bit passes through the waste, cavings from particle impact, cavings from helical turbulent flow, and radioactive brine ejected before spallings.

EPA Resolution of comment 97

EPA disagrees with the comments. The cavings submodel rigorously considers the impact of helical laminar flow on cavings release by numerically solving a series of non-linear integral equations. Because of complexities in the turbulent flow regime, similar mathematical treatment is not possible and it is necessary to resort to empirical procedures. DOE accounts for the helical flow component in the turbulent regime by using a rotation factor (F) which increases the erosion as compared to that calculated by uniaxial flow (Docket: A-93-02, II-G-1, Volume V, Appendix CUTTINGS_S, WPO #37765, page 47). For radioactive brine to be ejected from an inadvertent human intrusion borehole which penetrates waste, two conditions must be met (Docket: A-93-02, II-G-1, Volume 1, Chapter 6, Section 6.4.7.1.1, page 6-152):

> *The waste must be under sufficient pressure to drive the drilling mud from the borehole (greater than 8 MPa). Mobile brine contaminated with radionuclides must be present.*

The direct brine release conceptual model as implemented with the BRAGFLO_DBR code addresses this issue of ejection of radioactive brine (Docket: A-93-02, II-G-5). The cavings model does not explicitly consider erosion from particle impact as the drill bit passes through the waste. Any such erosion would be of very short duration (about four minutes for fully compacted waste at a drilling rate of 50 ft/h). Borehole enlargement from particle impact would produce lower flow velocities for the drilling mud and reduce the erosion calculated by the cavings model. Consequently, EPA believes that any impact from this process is included within the range of calculated cavings releases.

EEG Assessment of comment 97.

The EEG concurs with EPA's assessment.

98. The spallings model assumes constant pressure, although blow-out is a phenomenon related to pressure differentials. There are several methodological problems with the experiments (e.g., no dimensional analysis, no vent sensitivity analysis, etc.). The model considers only particle dislodgment, not lifting or lofting. Limited parameters are sampled or calculated (e.g., particle diameter, but not waste permeability, cementation strength, drill bit diameter, or radioactive content of waste).

EPA Resolution on comment 98

EPA agrees that the spallings conceptual model was initially inadequate. However, these inadequacies result in higher releases. Since the Conceptual Model Peer Review Panel found the spallings model implemented in the CCA to be inadequate, DOE conducted a significant computational and experimental program as documented in Docket A-93-02, Item II-G-23. These new computational approaches include consideration of pressure transients. On the basis of this new material, the Peer Review Panel determined that the spallings model used in the CCA resulted in the calculation of release volumes which are reasonable and may actually overestimate expected releases (Docket: A-93-02, II-G-22, Conceptual Models Third Supplementary Peer Review Report, April 1997, page 12).

The new computational approach predicts extremely small spallings volumes for all gas pressures below lithostatic pressure. EPA has concluded that, since the spallings model in the CCA considers only particle dislodgement from the waste and not lifting or lofting of dislodged particles up the borehole, the approach taken by DOE is conservative. Larger particles dislodged from the surfaces of radial fractures in the waste will not be lifted 2150 ft to the land surface. In Docket: A-93-02, II-G-23, page 1-3, the tensile strength of saturated surrogates waste was measured to be 0.074 MPa while that of dry waste was 0.15 MPa. This may be compared to a value of 1 Pa used for the cementation strength in

the spallings model. Thus the tensile strength in the spallings model was conservatively assumed to be several orders of magnitude lower than determined by tensile tests on waste surrogates. As discussed in detail in Section 1.2.3.2.4. of the '194.23 Technical Support Document- Models and Computer Codes, the use of a single value for the drill bit diameter is reasonable.

In the CCA, DOE chose to treat the radioactivity released by spallings as the average radioactivity in the repository (Docket: A-93-02, II-G-1, Volume 1, Chapter 6, Section 6.4.7.1, page 6-151) and based this position on the fact that the spallings model presumed that waste was eroded from fracture channels extending over a large portion of a waste room. In contrast, radioactive releases from cuttings and cavings were based on randomly sampling three of 569 waste streams for each intrusion. In this case the argument was made that cuttings/cavings removed only a localized volume of waste. Thus, the approach taken by DOE is consistent with the conceptual model in each case (ibid., page 6-189). It may further be noted that the CCDFs for waste volume removed by cuttings/cavings and spallings are about the same magnitude (see Figures 4.2.2 and 4.4.3, right frame, mean in Helton and Jow 1996, pages 4-6 and 4-22, Docket: A-93-02, II-G-07). Thus, if waste stream variability were incorporated into spallings releases, the results would be roughly comparable to those for cutting/cavings which as can be seen in Figure 4.2.3 (ibid., right frame, mean, page 4-6) are well below the EPA release limits. Since the average activity of the CH-TRU and the RH-TRU waste is essentially the same (ibid., page 4-1), and since the spallings model considers removal of waste from throughout an entire room, omission of RH-TRU waste from the spallings model will not have a significant impact on calculated releases.

EEG assessment of comment 97

The newer spallings model (Hansen et al., 1997) and subsequent peer review resolves this comment. However, the issue of an adequate spallings model remains. As shown in Section 2.4 of this report, the newer codes fail to model expected repository conditions.

This is still a major concern.

262b. The CCA fails to consider RH-TRU waste in the spallings scenario.

EPA Resolution on comment 262b

EPA agrees [sic]. EPA believes that combining the RH-TRU waste streams into a single volume-averaged stream is a reasonable modeling simplification. This is supported by the fact that the average activity in the RH-TRU and the CH-TRU waste is about the same while the probability of encountering CH-TRU is about seven times greater. Consequently cuttings releases are dominated by CH-TRU (Docket: A-93-02, II-G-07, Helton and Jow 1996, page 4-1).

DOE Response to issue

669 The conceptual models used to characterize the spallings and direct brine release processes were developed to describe the effects of rapid depressurization of large volumes of interconnected, homogeneous, and relatively permeable waste material. The models do not apply to the effects of rapid depressurization on the relatively small and relatively well isolated volumes anticipated for the RH-TRU waste. RH-TRU waste will be emplaced in boreholes in the halite walls of the waste disposal region. . .The volume of pressurized fluid available within a single RH-TRU canister will be far too small to displace the drilling fluid within the borehole, and therefore intrusions directly into an RH-TRU canister are very unlikely to result in a spall or direct brine release event. Intrusions into CH-TRU, waste near an RH-TRU emplacement borehole will draw spalled material and contaminated brine from the more permeable CH-TRU waste, rather than from the RH-TRU waste. It is therefore correct not to apply the spallings and direct brine release models to RH-TRU waste. (II-H-21.26)

670 DOE chose to model cuttings and cavings releases of RH-TRU waste using a single, average activity level for RH-TRU waste based on consideration of information available

in the Baseline Inventory Report (BIR) Rev. 2 (Appendix BIR of the CCA). Individual waste streams are reported for RH-TRU waste. Most of these waste streams represent small volumes of material, however, and the probability assigned to the penetration of many of these individual categories by an intrusion borehole would have been below the regulatory threshold of 10^{-3} in 10^{4} yr. Rather than neglect these low-probability events, the DOE has included them in the analysis by lumping them, and their activity loads, into a single category with the other, more abundant RH-TRU waste that dominates the volume-averaged activity of RH-TRU waste used in the performance assessment. The activity levels that might be calculated by random combinations of large numbers of waste streams plus backfill would closely resemble the overall average activity. (II-H-21.27)

EEG assessment of EPA comment resolution

The EEG is satisfied that neglecting RH-TRU in spallings calculations and using a single waste stream to represent RH-TRU in the cuttings and cavings model are acceptable modeling approximations. The primary reasons for this assessment are that RH-TRU will be less that 1% by volume of the transuranic inventory of the repository and that the high activity levels in the RH-TRU waste are from fission products that will have significantly decayed in the first two hundred years of burial. While the present activity of RH-TRU waste varies many orders of magnitude, the transuranic content of the waste does not.

535 The spallings model is defined as gas driven entrainment of solid particles. The spallings model should include the effects of brine. (II-H-12.14)

EPA Resolution of Comment

EPA disagrees with the comment. Spallings occurs only if the pressure in the intruded waste panel exceeds 8 MPa. As the gas pressure increases, the brine saturation in a waste panel decreases (Docket: A-93-02, II-G-07, Helton and Jow 1996, page 5-1). Thus, at pressures where spallings can occur, less brine is available for release. In addition, the

spallings model uses the average radionuclide concentration in the waste to develop the source term (ibid., page 4-7). If some radionuclides are dissolved in brine which is transported along with solid waste to the surface, this radioactivity will have been accounted for by the solid material since mass must be conserved. The spallings model addresses all the radioactivity as if it remained with the solids rather than partitioned between the solid and the brine. Direct brine releases in which brine flows up the borehole after intrusion are accounted for by the direct brine release model (Docket: A-93- 02, II-G-05). EPA believes that this "double counting" of solid spall releases and waste mobilized by brine overestimates releases from these mechanisms and therefore is adequate for use in PA and is conservative.

EEG assessment of EPA comment 535 resolution

In light of the newer spallings model (Hansen et al., 1997), the inclusion of brine release in the spallings model is a minor concern.

536 With the composition of the waste ranging from large pieces of metal to ash, it is unlikely that the waste will degrade to a uniform grain size. There has been no analysis to show that the releases calculated by sampling for a uniform distribution size bounds the release from a heterogeneous medium. (II-H-12.15)

EPA resolution of comment

EPA agrees that a uniform particle size is not appropriate. The CCA does not assume that waste degrades to a uniform particle size. Waste particle diameters in the spallings model were assumed to be distributed log-uniformly from $4x10^{-5}$ to 0.2 m (Docket: A-93-02, II-G-1, Appendix PAR, page PAR-115). Spallings releases are dominated by transport to the surface of solids of small particle size (see, for example Fig. 4.3.5 in Helton and Jow 1996, page 4-14,Docket A-93-02, II-G-07). Since use of a loguniform distribution biases parameter selection during LHS sampling to smaller (i.e., more conservative) values, releases will be higher with this parameter distribution. In addition, it was deduced from

the findings of the Expert Elicitation Panel on waste particle diameters that the particle range was most probably between 1 mm and 10 cm which would reduce the spallings release (Memorandum entitled "Estimate WIPP Waste Particle Sizes Based on Expert Elicitation Results: Revision 1" from Yifeng Wang to Margaret S. Chu and Mel G. Marietta, Sandia National Laboratories, SNL WPO# 46936, June 27, 1997). The use of the mean particle size in determining the shear strength of the waste is a reasonable approach to characterizing the fact that the waste does not have a uniform particle size.

EEG's assessment of the EPA comment resolution

The EPA missed the point of this comment. The spallings model used for the CCA calculations did assume a uniform particle size. The uniform size was assumed to be uncertain and was therefore sampled from a range. However, the issue is no longer pertinent to the CCA because of the development of the newer spallings model.

537 [DOE argues that] a larger initial spall will be followed by less erosion than a smaller initial spall, resulting in the same final void ration. We find two errors in this argument: 1) The pressure difference between the waste repository and the hydrostatic pressure of the drilling mud can be over 6 MPa, three orders of magnitude above pressure differential need for explosive spall. 2) The second argument presupposes, without justification, that the erosion volume is larger than the initial spall volume and that the cavity caused by the initial spall will be partially filled by the erosion process. (II-H-12.16)

539 The spallings model does not include a sensitivity to scale leading the developers of the spallings model to state extrapolation of release volumes to WIPP, using the parameters evaluated using small scale laboratory models, has the potential for grossly under-predicting such releases. (II-H-12.18)

EPA resolution of comments 537 and 539

The CMPRP was not satisfied with several aspects of the spallings model as implemented in the CCA (see, for example, Docket: A-93-02, II-G-1, Volume XII, Appendix PEER, PEER 1, page 3-88 to 3-93). However, based on additional information subsequently developed by DOE and included in the Spallings Release Position Paper (Docket: A-93-02, II-G-23), the Panel concluded that the model was reasonable and probably conservative (Docket: A-93-02, II-G-22, page 12). EPA agrees with this position and believes this responds to EPA's initial concerns.

538 The model tests the erosion portion of the spallings phenomena for waste with no cohesive strength, but not the initial explosive phase, nor the effect of cohesion. (II-H-12.17)

EPA resolution of comment 538

EPA disagrees with the comment. The spallings model used in the CCA assumed that the cementation strength of the waste was 6,895 Pa or 1 psi (Docket: A-93-02, II-G-10, Appendix PAR, page PAR-190, ID #3245). Testing of surrogate waste mixtures as described in Spallings Release Position Paper (Docket: A-93-02, II-G-23, page 1-6) indicated that the strength of the waste was substantially higher than assumed in the CCA with the average tensile strength of saturated waste being 74,000 ± 40,000 Pa. Thus, the amount of spallings should be reduced as compared to that calculated in the CCA. (see response to comment 537 above.) EPA believes this increased waste strength would mitigate the impact of the "initial explosive phase" and that total releases would be well below the 0.5 to 4.0 m^3 range used in the PAVT calculations.

EEG's assessment of the EPA resolution of comments 537, 538, 539

EPA's assumption that the new spallings model is adequate to answer all spallings'

concerns does not address EEGs' concerns. EEG believes that relying solely on the results from the new spallings model may be underestimating the importance of the issue. For example, the new spallings model cannot simulate all expected repository conditions. Locally varying waste permeability or different gas viscosities cause the code to produce erroneous results. It is therefore suggested that the EPA look more closely at the newer model before dissmissing any comment on spallings.

540 The "gas erosion" and the "stuck pipe", considered by the DOE in earlier performance assessments, have been excluded from the CCA spallings model. These two phenomena could cause releases that are over an order of magnitude larger than the largest releases calculated in the CCA. (II-H-12.19)

EPA Response to comment 540

EPA does not believe it is necessary to include gas erosion and stuck pipe processes in the CCA spallings model. Gas erosion and stuck pipe releases occur only if the waste permeability is less than $1x10^{-16}$ m^2 (Docket: A-93-02, II-G-1, Appendix CUTTINGS_S, page 37). In addition, the gas pressure in the intruded panel must exceed 8 MPa for gas erosion and 10 MPa for stuck pipe processes to occur. Based on earlier experimental work, DOE used a value for waste permeability of $1.7x^{-13}$ m^2 (see discussion in Section 1.3.2.7.4 of the TSD for '194.23 - Models and Computer Codes). More recently, DOE measured the permeability of surrogate waste mixtures based on current understanding of waste mixtures and degraded waste characteristics and determined the permeability of waste surrogates to be $2.1x10^{-15}$ to $5.3x10^{-15}$ m^2 on two samples (Docket: A-93-02, II-G-23, page 2-18). Based on the available waste permeability information, EPA concluded that the gas erosion and stuck pipe processes should not occur because permeabilities will be greater than the $1x10^{-16}$ m^2 threshold.

EEG assessment of EPA comment resolution

EEG still considers “stuck pipe” and “gas erosion” as potentially important processes in the calculation of spallings releases. See Section 2.4 of this report.

ISSUE 23.F: Three Dimensional Processes and Boundary Conditions

553 The EEG concludes that the use of a 2-D geometry in the BRAGFLO may introduce significant non-conservatism into the CCA calculations. The FEP S-1 needs to be reexamined with appropriate consideration of the impact of increased brine saturation on calculated estimates. (II-H-25.4)

EPA response to comment 53

EPA disagrees with the comment. The work that is most relevant to this concern is the FEP Screening Analysis titled S1: Verification of 2D-Radial Flaring Using 3D Geometry, WBS No. 1.1.6.3, SANDIA WIPP CENTRAL FILES-A: 1.2.07.3: PA:QA:TSK:S1, ERRATA - February 19, 1996 (SNL WPO #30840). In this work, a simplified version of the two dimensional CCA PA grid was tested against a corresponding three-dimensional (3-D) model. BRAGFLO was used in both two-dimensional (2-D) and 3-D simulations, and TOUGH28W was used to model the 3-D simulations only. Simulation results were compared for cases with an average repository gas generation rate, and a gas generation rate that was double the average. The results of the second case, in which the gas generation rate was doubled, indicates that a combination of pressure induced fracturing and the 1-degree dip cause flow paths which are different for the 2-D and 3-D grids. Once fracturing of the interbeds occurs, the 3-D model displays an immediate migration of gas primarily out of the west side of the repository into the anhydrite layers, accompanied by brine inflow to the repository. This phenomenon is not seen in the results from the 2-D model, in which the west side of the repository is a no flow boundary, which demonstrates

that the 2-D and 3-D simulations show local variations. However, the results also show that the predictions of brine flow to the accessible environment are similar for both 2-D and 3-D grids. With respect to increased brine saturation, Figures 7 and 12 of the FEP Screening Analysis referenced above (WPO# 30840), shows the average gas saturations calculated with the 3-D simulations of TOUGH28 and both the 2-D and 3-D versions of BRAGFLO. Simulation results are compared for the base case and twice the base case generation rates, respectively. These curves indicate that gas saturations are higher in the 2-D simulations (WPO# 30840, page 27). Since brine and gas saturations are inversely related a similar trend would be observed for the brine saturations. In the Performance Assessment Verification Test (PAVT) , it was determined that the greatest potential releases could be attributed to those associated with spallings and direct brine releases. Furthermore, these releases are pressure controlled and will not occur if repository pressures are below 8 MPa. The fact that the 2-D model may overestimate gas saturation by underestimating brine saturations will lead to the prediction of higher gas pressures than those that would have been predicted with the 3-D configuration and this will result in more conservative estimates of releases. Based on this, EPA believes that the 2-D geometry used in the BRAGFLO CCA PA calculations is a reasonable simplification and that the predicted results are conservative.

EEG assessment of EPA resolution of comment 553

The EEG does not consider this issue to be resolved. See Section 2.10 of this report

Issue 23.W: CCA Parameters and PAVT Parameter Selection

550 The data and rationale for the sampled distribution of the waste-room residual-brine saturation is presented on pages PAR-27 through PAR-31. . .The non-conservative distribution of 0 to 0.560 reduces the estimated releases of direct brine release [sic].

Appropriate ranges for the waste room residual brine saturation are a constructed distribution using values from the eight unconsolidated materials; a uniform distribution from 0.0783 to 0.277, or a uniform distribution from 0 to 0.277. (II-H-25.1)

DOE Response to the Issue

845 The comment about the distribution of 0 to 0.560 for S [residual brine saturation of wr waste] being non-conservative is not correct because one should not be using a value just because it is more conservative. Instead, the use of a particular distribution or value should be based on how closely it represents the processes being modeled and how accurately it reflects realistic expectations of what will occur in the repository. The range of 0 to 0.560 was therefore chosen on the basis of being both reasonable and realistic. (II-H- 45.6)

EPA's Response to Comment 550 and 845

The residual brine saturation is that value at which no more flow will occur even with further decreases with capillary pressure. The range used for the CCA is based on literature values for unconsolidated materials. EPA agrees with DOE's comment, in that DOE has selected a reasonably representative range value for the wastes. This parameter will change with time, as the wastes gradually compacts, the porosity will become lower and the residual brine saturation will increase due to the increased capillary pressure of the smaller pores. Therefore, the low end on the distribution represents coarse material prior to waste compaction and the high end would be representative of fairly compacted waste. EPA's basic philosophy in dealing with such uncertain parameters has been to be reasonably sure that one or more of the following criteria are true : 1) that the values selected for a parameter in question leads to conservative results; 2) that the results are relatively insensitive to that parameter, or 3) that the selective range is representative of the actual parameter values. In the case of brine saturation, the complexity of the problem does not allow a predetermination to be made regarding whether a certain range or

distribution is conservative. A further complicating factor is that the BRAGFLO computer code contains a wicking function that allows gas generation to occur even if the capillary pressures are low (Appendix BRAGFLO). Based on modeling experience EPA believes that residual brine saturation is insensitive and that the selected values does not impact the final results to a significant degree. EPA is confident that the range and distribution placed on the residual brine parameter are reasonably representative of the wastes and are adequate for use in the CCA PA calculations.

EEG assessment of EPA resolution of comment 550

Based on the information presented during the January session of the conceptual model peer review panel and to the particle size expert elicitation panel that some waste may be consolidated, the range of sampled residual brine saturation of the waste in the CCA calculations was appropriate.

551 Even though the parameter ranges recommended by Beauheim are more reasonable than the ones used in the CCA, the EEG disagrees with the recommended values for reservoir volume because the range includes the value derived from testing the ERDA-6 brine reservoir and initial pressure because of the use of data from twelve other brine encounters in the Salado. . . The recommended initial pressure range of 16.5 to 11.0 MPa gage is based on pressure measurements from thirteen Castile brine encounters. At WIPP-12 the measured pressure was 12.6 MPa gage. Therefore, the reservoir pressure should be a constant value of 12.6 MPa gage in the revised CCA calculations. (II-H-25.2)

EPA’s response to comment 551

No response given.

EEG assessment of EPA resolution of comment 551

See resolution to Issue 14.T on page 224.

552 If the samples distributions of parameters used in the CCA calculations are in error, but include the likely values of those parameters, should the CCA calculations be acceptable? The EEG position is that, under the these conditions, the CCA calculations should be repeated with the best estimate of the parameter distributions available. The use of a faulty distribution of one parameter biases the CCDF curves and confuses the assessment of uncertainty. The use of more than one faulty parameter set makes the assessment of uncertainties impossible because of the complex non-linear nature of the performance assessment models. (II-H-25.3)

EPA's general response to Issue 23.W and to comment 552

EPA performed a thorough review of the parameters and the parameter development process (see Section 12.4 on requirement §194.23 (c)(4) above in CARD 23 -- Models and Computer Codes; EPA Technical Support Document for § 194.23: Models and Computer Codes (Docket A-93-02, Item III-B-6); and EPA Technical Support Document for § 194.23: Parameter Justification Report (Docket A-93-02, Item III-B-14)). EPA reviewed parameter packages in general for approximately 1600 parameters used in the CCA Performance Assessment calculations. EPA further reviewed parameters record packages and documentation in detail for more than 400 parameters important to performance of the disposal system. Records reviewed include the Docket: A-93-02, II-G-1, Volume 1, Chapter 6, Tables 6-8 through 6-27, page 101 to page 166, A-93-02, II-G-1, Volume XI, all of Appendix PAR, WIPP parameter entry forms (464 Forms), Parameter Records Packages (PRP), Principal Investigator Records Packages (PIRP), Analysis Packages (AP), and Data Records Packages (DRP). The evaluation included a review of the expectations listed in the "Compliance Review Criteria" for §194.23(c)(4) above in Section 5.4.2. As a result of substantial information gathering at the Sandia Records

Center, EPA was able to uncover on its own substantial necessary documentation supporting most of the parameters used in the CCA PA. EPA first examined the sources of different parametric values used in the computer codes. EPA found that 416 (26.4%) of the 1571 parameters used in the CCA PA calculations are well-established constants found in general literature and general engineering knowledge. EPA discovered that DOE derived 887 (56.6%) of the parameters from experimental data, either from its own experiments or from journal articles. EPA also found that 89 (5.7%) are waste-related parameters derived from the waste inventory report (see docket: A-93-02, II-I-1, Volume III, Appendix BIR). EPA found that DOE selected the values of 149 (5.9%) parameters using professional judgment of its employees. Approximately 194 (12.3%) parameters were "legacy parameters" originally used in DOE's 1992 PA and again incorporated in the CCA PA (see Docket: A-93-02, II-I-31, Comment No. 11).

EPA selected 465 parameters on which to concentrate its analysis. EPA selected parameters to review based on the following criteria:

- parameters that appeared to be important to compliance or seemed to be poorly justified, such as material permeabilities and porosities, particle size, brine reservoir characteristics, pressures, solubilities of actinides, and waste inventory information,

- parameters that control various functions of the CCA PA computer codes that appeared to be important to compliance, such as permeability threshold, and dispersivity characteristics of the Culebra,

- other parameters EPA used to evaluate the overall quality of SNL's documentation traceability, such as reference constants and general reference values.

The purpose of the parameter review was to verify that DOE's documentation includes

adequate information to fulfill the compliance review criteria of section 12.2, for §194.23(c)(4) of this CARD. For greater detail about EPA's examination of the specific parameters in each category, see EPA Technical Support Document for Section 194.23: Parameter Justification Report (Docket A-93-02, Item III-B-14).

EPA strongly believes that EPA-mandated Performance Assessment Verification Test was done with the best estimate of the parameter distributions available. EPA did an exhaustive review of the parameters used in the CCA PA and altered those needed and required DOE to repeat the calculation with the necessary changes. See A-93-02, III-B-5, II-G-26 and II-G-28 for documentation of the changed parameters and their impact on potential releases.

EEG assessment of EPA resolution of comment 552

Though the EPA did a thorough job in evaluating the parameters for the PAVT, the EEG believes that the performance assessment evaluation is still incomplete. For example, the EPA studied the evidence carefully when considering the Castile Brine Reservoir parameters and selected relevant values to assign to the parameter. Yet, the solubility of certain actinides in Salado and Castile brines or the partition coefficient of actinides for sorption onto the Culebra Dolomite and the probability of brine reservoir encounter were inadequately addressed. These few examples play an important role in compliance, as studied by the EEG in sensitivity analyses (Section 2.2 of this report). The synergetic effect off all parameters is unknown, and it is important to characterize each parameter carefully. The EEG believes that this has not been done, and perhaps a new performance assessment should be conducted with parameter values that are more easily justified through experimentation.

554 The sampled parameter for the probability of microbial gas generation determines whether cellulose and plastics and rubber will be degraded by microbial action after

closure of the repository. . . It is the opinion of EEG that the numerical value of this parameter constitutes expert judgment. Given the importance of this parameter to the estimates of radionuclide release, this parameter should be demonstrated to be either solidly based on scientific evidence or be conservative. The justification for this parameter presented in support of the CCA does neither of these. (II-H-25.5)

DOE response (II-H-45)

The interaction of gas generation with other processes in the repository is complex. Because of this, an *a priori* determination of a meaningful, conservative selection from the possible processes of gas generation is difficult. The suggestion of the EEG that microbial degradation should always be specified, i.e., a 100% probability, is not necessarily conservative since this would tend to reduce brine inflow. Therefore, to be consistent with the treatment of uncertainty throughout the performance assessment, the DOE assigned probabilities to gas generation processes to ensure that assessment results reflect the uncertainty associated with the occurrence and extent of these processes, i.e., both possible outcomes be sampled.

The conceptual model for gas generation in the WIPP repository includes two dominant generation processes: metal corrosion and microbial degradation of organic material. The probabilities of occurrence of these processes were established through a procedure that included careful review of uncertainty suggested by experiments conducted specifically for the WIPP, literature review, and consideration of local scale processes in the disposal room. Given the presence of brine, it is reasonable to assign a 100% probability to metal corrosion. However, there are considerable uncertainties associated with the occurrence of significant microbial populations. These are:

(1) Whether micro-organisms present in the waste are capable of carrying out the potentially significant processes that generate gas identified by Brush[6].

(2) Whether these microbes will survive for a significant fraction of the 10,000 year period of performance of the repository.

(3) Whether sufficient electron acceptors (oxidants) will be available to any microbes that survive.

(4) Whether enough nutrients, especially N and P, will be available.

Electron acceptors and nutrients will be present in the repository (see Appendix BIR7). Therefore, points (3) and (4) relate to the uncertainty as to whether these materials will be physically and chemically available to any microbes that survive. Brush[8] discussed these issues in more detail.

In addition to uncertainty over the possibility of microbial activity, there is also uncertainty over the amounts and types of biodegradable waste. It is reasonable to assume that readily biodegradable material such as cellulosics will be consumed if microbes are active. However, plastics and rubber are much less biodegradable than cellulosics and may not contribute to the gas generation process. Two factors may potentially increase the biodegradability of those materials: (1) long time scale; (2) co-metabolism. Over a time scale of 10,000 years, the chemical properties of plastics and rubbers may change, possibly resulting in enhanced biodegradability. Furthermore, micro-organisms may co-metabolize plastics and rubbers with cellulosics and other more biodegradable organic compounds. All of these uncertainties precluded the use of experimental and/or modeling studies to quantify the probability of significant microbial gas generation in WIPP disposal rooms and the probability of significant microbial degradation of plastics and rubbers for the performance assessment calculations to support the CCA.

To incorporate the uncertainty about the dominant processes of gas generation, the DOE assigned a value of 50% to the probability of significant microbial gas generation and 50% to the probability of significant microbial degradation of plastics and rubbers in the case of significant microbial gas generation. In other words, steel corrosion alone occurs in 50% of LHS sample vectors, steel corrosion and microbial degradation of cellulosics occurs in 25% of LHS sample vectors, and steel corrosion and microbial degradation of cellulosics, plastics, and rubbers occur in 25% of LHS vectors. This is consistent with the treatment of uncertainty throughout the PA calculations (see Appendix PAR, page PAR-6, Delta Distribution). As the EEG requests, it is also based on scientific evidence as to the likely gas generation processes and ensures that all the possible complex interactions between gas generation and other processes are accounted for.

The EEG also states that the gas generation probabilities used should be peer reviewed. In fact the Conceptual Model Peer Review Panel have done this (see Appendix PEER, Section 1). With regard to the gas generation model probabilities, the Panel stated (p. 3-144 to 145):

> "Regarding microbially induced gas generation, the model assumes that the probability of degradation of cellulose and plastics/rubber will be 50% and that in the event that biodegradation occurs there is a 50% probability that plastics and rubbers will also be degraded." [Illustration callout and illustration omitted in this quote]
>
> "This assumption is based on major uncertainties that are described in Section 3.21.2.4 below, and represents a judgement. For performance assessment purposes, this assumption will result in less gas generation than if one were to assume total consumption of all the organic material. There is apparently no scientific evidence that plastics/rubbers degradation will occur at all with certainty,

based on contemporary experience. The possibility that products from microbial degradation of cellulose, and perhaps radiolysis by alpha irradiation, could combine to break down the relatively stable plastics polymers to more consumable fragments suggests the probability should be non-zero. It is difficult to argue for a value higher or more precise than 50%, unless there were more robust long-term data, or experience with plastics degradation in, for example, landfills. Therefore, for performance assessment purposes, the assumption regarding plastics/rubbers appears to be adequate.

With regard to the degradation of cellulose, the long list of uncertainties identified in Section 3.21.2.4 below suggests that less than full probability of significant microbial degradation of this more readily consumable material is a reasonably valid assumption. Also, it does not appear scientifically valid to assume that either all or none of the cellulose will be degraded in light of the significant uncertainties that microbial populations would remain viable to the extent of complete cellulose degradation. DOE is not seeking a worst case in performance assessment. Therefore the 50% probability is a reasonable assumption for modeling purposes."

The DOE believes this excerpt shows that the Conceptual Model Peer Review Panel fully understands the goals of performance assessment in general, the purpose of model and parameter selection, and in particular the basis and reasonableness of the DOE gas generation model.

EPA's response to comment 554

EPA has examined information to support these parameters. See EPA Parameter Justification Report (Docket A-93-02, Item III-B-14),

Section 5.25, for detailed discussion of the PU, PROPMIC parameter.

Section 5.33, for detailed discussion of the AM, PROPMIC parameter.

EEG assessment of EPA resolution of comment 552

It appears from the response that EPA did not understand the question. The EPA response in Section 5.25 and Section 5.33 (U.S. EPA, 1997m) addresses concerns of Plutonium and Americium sorption onto microbial colloids and humid colloids.

The sampled parameter for the probability of microbial gas generation determines whether cellulose and plastics and rubber will be degraded by microbial action after closure of the repository. No degradation of cellulose or plastics occurs in the calculations with a 50% probability. Only cellulose degrades in 25% of the sampled vectors. Cellulose, plastics, and rubber degrade with a probability of 25%. The preliminary sensitivity analysis report (Helton, 1996) lists this parameter as the largest influence on the variation of total calculated release from the WIPP repository.

The documentation supporting this parameter does not contain any numerical justification for the probabilities assigned to this parameter. All of the hand calculations performed to calculate the gas generation parameters are included as attachments to the memo of Wang and Brush (1996). Calculations for the degradation probabilities are absent from these attachments. It is the opinion of EEG that the numerical value of this parameter constitutes expert judgment. Given the importance of this parameter to the estimates of radionuclide release, this parameter should be demonstrated to be either solidly based on scientific evidence or to be conservative. The justification for this parameter presented in support of the CCA does neither of these.

The numerical values of the degradation probability parameter should undergo peer review

consistent with expert judgment. Otherwise, the parameter should be conservatively set to always specifying microbial degradation of cellulose, plastics, and rubber.

EEG assessment of DOE's response

The parameter used to set the probability of microbial degradation in the CCA calculations is not derived analytically but instead was a result of interpretations that constitute expert judgment. The EEG suggested that the probability of microbial degradation should undergo peer review as parameter obtained using expert judgment. It was suggested that without this peer review the microbial degradation parameter should be set to always specifying microbial degradation of cellulose, plastics, and rubber. The EEG has been convinced by DOE's arguments that setting the parameter to always specifying microbial degradation of cellulose, plastics, and rubber is not appropriate. The central point remains that the probabilities used in the CCA calculations are a result of expert judgment. As such the parameter is required to be peer reviewed using the procedure outlined in 40 CFR Part 194.26. The conceptual model peer review does not meet the requirements outlined in the section.

557 If a single value for the consolidated waste permeability is to be used for direct brine release, then it should be 2.4×10^{-13} m^2 and not 1.7×10^{-13} m^2 . (II-H-25.8)

DOE's response to comment 557

The [waste permeability] value of 2.4×10^{-13} m^2 is both reasonable and is as technically correct as the 1.7×10^{-13} m^2 value. There has been no technical reason offered which would justify using the higher value instead. (II-H-45.5)

EPA's response to comment 557

EPA has examined information to support this parameter. EPA believes that a single value

instead of a probability distribution is justified for permeability. See EPATechnical Support Document for Section 194.23: Parameter Justification Report (Docket A-93-02, Item III-B-14), Section 5.19, for detailed discussion of the BLOWOUT, APORO parameter.

EEG assessment of EPA resolution of comment 557

Refer to EEG Chapter 2.4 for full explanation of EEG's concerns and responses.

Section 194.27 (CARD 27) Peer Review

ISSUE 27.A: EPA should look carefully at Peer Review conclusions

2 Our impression is that certain panels have performed a thorough and credible review, while others have not. Our recommendation to the EPA is to review the bases of findings of the panels and subject them to your own critical review by the EPA staff, contractors, or formally assembled peer review groups. (522) (II-H-12.1)

EPA's response to Issue A

EPA's audit of DOE's records did not result in any findings that substantially compromised the credibility of the process used to implement the peer reviews required by Section 194.22(b) or Section 194.27(a) (see "EPA Compliance Review" under 194.27(b) above). As stated in EPA's response to comments received on the proposed compliance criteria, "The Agency does not intend for peer review of DOE's activities to supplant or replace the Agency's review of compliance applications. . . Regardless of the recommendations or judgments made by the peer review groups, all decisions on the adequacy of the compliance application will be EPA's and EPA's alone" (Response to Comments Document for 40 CFR Part 194, pp.9-6 to 9-7). In other words, EPA

recognizes that peer review contributes to but does not supplant the Agency's independent review. EPA therefore considered peer review panels' findings in technical areas in conjunction with other information relevant to compliance. EPA's consideration of the scope and findings of the required peer reviews may be found in **CARD 22 – Quality Assurance, CARD 23 -- Models and Computer Codes, CARD 24 -- Waste Characterization, and CARD 44 -- Engineered Barriers**.

EEG assessment to EPA resolution of comment 2

It appears that discussions on several issues dealt by peer review groups may have been made without EPA's own analysis. An example is the new spallings code. The peer review accepted the conceptual model, without an actual testing of the code. The EEG found that after conducting a thorough sensitivity analysis with the codes, variations in several parameters may lead to conclude that the CCA spalled volumes are not conservative. If the EPA had conducted their own analysis, they too would have reached to the same conclusion. The same can be seen with the issue of actinide solubility or actinide partition coefficient (K_d).

Section 194.32 (CARD 32) Scope of Performance Assessment

ISSUE 32.A: The CCA does not adequately address the effect of fluid injection on the repository

12 The DOE has chosen "soon after disposal" to mean 50 years in the context of the fluid injection scenario. However, in the 1991 DOE elicitation of expert opinion on future activities in the vicinity of WIPP, one of the four teams addressed fluid injection and assigned probabilities of waste brine disposal associated with other industrial activities for

the full 10,000 years. Further, the probability of a large number of such injection wells, within the site was predicted to increase with time. (526) (II-H-12.5).

13 The discussion of fluid injection in Appendix SCR of the CCA is incomplete and largely incorrect. For example, Appendix SCR mentions gas injection for natural gas storage in the Morrow Formation but fails to mention natural gas storage in the Salado Formation. It is argued that the differences between the geology at WIPP and the Vacuum Field and Rhodes-Yates Field provide for more potential thief zones below the WIPP horizon in the event of water escaping the injection zone. However, field evidence strongly suggests that brine injection into the Bell Canyon below the WIPP horizon appears to be leaking into the Culebra aquifer above the WIPP horizon. The CCA provides no experimental evidence such as the measurement of water quantities in the anhydrite beds of the Salado Formation to support the CCA speculation. (527)(II-H-12.6)

14 The claim that there will no waterflooding on the scale of Rhodes-Yates is also undermined by field evidence. (528)(II-H-12.7)

15 While the Delaware sands, including those around the WIPP produce large volumes of water, they are nonetheless, technically and economically amenable to waterflooding as well as CO2 flooding. (529)(II-H-12.8).

16 The CCA-SCR notes that state regulations do not allow injection pressures to exceed the rock fracture pressure. However, that portion of the regulation applies to the target injection zone and not any overlying formations. The producing reservoirs near WIPP are greater than 7,000 feet. One consequence of greater vertical distance is that the surface injection pressure is automatically approved for 1,400 psi or 0.2 psi per foot. This corresponds to 2,400 psi at the WIPP horizon which is well in excess of the fracture pressure of the anhydrite beds in the Salado Formation.(531)(II-H-12.10).

17 Stoelzel and O'Brien consider only salt water disposal and assume an injection depth of 260 feet, a surface injection pressure of 850 psi, and a pressure at the WIPP horizon of 1,900 psi. However, pilot water flooding operations near WIPP are underway for reservoirs at 7,000 feet depth and have been approved to inject at a surface pressure of 1,400 psi, which in the event of communication, would exert a pressure of 2,400 psi at the WIPP horizon. Hence, the anhydrite beds in the Salado Formation would fracture, as successfully argued by Hartman and brine would migrate for miles in the inadvertent waterflooding hydro fracture scenario. (532)(II-H-12.11).

EPA's comment to Issue 32.A

DOE evaluated fluid injection in connection with the scope of the performance assessment but rejected the scenario on the grounds of low consequences. EPA evaluated DOE's Hartman Scenario and also performed an independent fluid injection analysis; see EPA Technical Support Document for 194.32: Fluid InjectionAnalysis (EPA 1997b). The results of these studies show that effective permeability in marker beds is probably lower than that used in the PA, and that other factors (such as injection rate, injection interval, etc.) also play a very important role in fluid injection. EPA agrees that under very unrealistic conditions, modeling can show fluid movement toward the WIPP under an injection scenario. These conditions include those modeled by Bredehoeft, such as steady state flow, two well scenarios, and pulsing flow. However, when modeling assumes more realistic but still conservative conditions, fluid movement sufficient to impact disposal performance of the WIPP does not occur.

In addition, EPA believes that geologic and hydrogeologic conditions in the Hartman area are different than in the WIPP area, which also precludes one-to-one comparison of conditions at the WIPP and at the Bates lease. For example, the Castile Formation is not present in the Bates area, but over 1,000 feet of Castile is present in the WIPP area. Also,

the present oil well completion practices in the Delaware Basin are substantially improved. Injection rate, pressure, target and fluid volume related regulations are different and are closely monitored by the state agencies. EPA concludes that the model representation in DOE studies, including two-dimensional analysis, appears to be appropriate for the intended use, because the model uses radial flaring in the z direction to capture compatible volume in the 360 o flow to compensate for 3D simulation.

EPA also requested (see Docket A-93-02, Item II-I-17) that DOE consider different factors in its fluid injection modeling (Stoelzel and Swift, 1997). Refer to the discussion in this CARD under 194.32(c). EPA concluded that DOE's initial modeling studies (Stoelzel and O'Brien, 1996) and supplemental modeling studies (Stoelzel and Swift, 1997 and Docket A-93- 02, Item II-I-36), together with EPA's own fluid injection analysis (EPA 1997b) all indicate that DOE's screening of fluid injection from consideration in PA is appropriate. EPA also notes that DOE considered waterflooding for the undisturbed (historical, ongoing, and near future time frame) and screened it from consideration based upon consequence. In so doing, DOE is not required by the Compliance Criteria to evaluate this FEP for the long-term future.

EEG Assessment to EPA Resolution of Issue 32.A

As discussed in Secion of 2.6 of this report, the EEG disagrees with the EPA on this issue.

ISSUE 32.C: The CCA does not adequately consider solution mining of potash

4 The CCA (Appendix MASS, p. 87) claims that the DOE is not aware of any ongoing solution mining in the Delaware Basin. However, that activity has been ongoing for

several decades in southeast New Mexico, including the Delaware Basin, to provide brine for oil field drilling operations. Furthermore, state records show fluid injection for solution mining of halite is expanding into areas closer to the WIPP to meet the needs of drilling activities in that area. (533)(II-H-12.12)

8 The CCA inappropriately eliminates solution mining for potash. DOE relies on current regulations which do not fully cover all scenarios, nor do they prevent solution mining for potash. (751) (II-H-32.12)

DOE's response to Issue 32.C

It is unlikely that potash mine operators in the vicinity of the WIPP will elect to use solution mining in the future, even once Sylvite deposits are fully mined out by conventional excavation methods, because conditions are economically unfavorable, as noted by Heyn (1997), a potash mine operator within the Delaware Basin. Points raised by Heyn (1997) are summarized below: (1) Solution mining requires heat to increase the ambient temperature of the injected water in order to increase the dissolved salt capacity of the brine. This is usually accomplished by taking advantage of geothermal heat found in deep wells or mines. Most solution mines are at depths in excess of 3,000 feet (910 meters). The potash ore bodies in the vicinity of the WIPP are less than 1,740 feet (530 meters) below the surface. Also, the cost of evaporation equipment to recover the potassium salts may be prohibitive. (2) Solution mining of the Sylvite ore bed in the vicinity of the WIPP would result in excessive solution of unwanted minerals and clays because the ore zone is too thin. Solution mining usually requires an ore bed thickness in excess of 10 feet. (3) Unavailability and cost of fresh water in the area would impede implementation of solution mining. (4) Potash ore reserves in the vicinity of the WIPP are too low in potash grade and the life expectancy of the mines is too low to justify the cost of constructing a solution mining refinery. Thus, it is likely that the potash bearing ore

zones in the vicinity of the WIPP will continue to be extracted using conventional room and pillar methods, rather than solution mining. (724)(II-H-24.19)

EPA's response to Issue 32.C

EPA agrees that the CCA did not appropriately treat solution mining of potash; however, DOE provided supplemental information concerning solution mining in response to public comments e.g., DOE, 1997i, 1997m, and Docket A-93-02, Items II-H-44 and II-H-45). DOE indicated that the target potash intervals for conventional room and pillar mining are Zones 4 and 10, which would also be the target horizons for solution mining. DOE concluded that the effects of solution mining relative to changes in overlying Culebra hydraulic conductivity are included in the modeled effects of room and pillar mining. The increase in hydraulic conductivity is related to the reduction in confining stress. Unless the mean confining stress is reduced to zero, the increase in hydraulic conductivity will be considerably less than what DOE has considered in PA. However, DOE indicated in supplemental information that solution mining is not likely in the vicinity of WIPP because fresh water for mining is limited and the overall procedure is cost prohibitive. Also, langbeinite, which is the primary target of extraction, is not readily soluble in water.

EPA noted that a permit is being sought for a pilot solution mining venture in the Carlsbad area. However, it is not possible to accurately predict the future possible minable zones if mining techniques are refined. Solution mining is presently not being done and may not take place in the future, and solution mining would likely include those horizons already included in the room and pillar mining modeling assumptions. With the supplemental information, EPA concludes that DOE has sufficiently addressed the potential effects of potash solution mining and that they were addressed within the scope of the PA.

EEG assessment of EPA response to Issue 32.C

EEG's responses to EPA are:

- EPA's conclusion that potash solution mining is not likely at WIPP relies on solicited comments that are factually incorrect and inconsistent with the published scientific literature.

- DOE and EPA maintain that excavation mining captures the effects of solution mining on the hydraulic conductivity of the overlying aquifers. However, based on the scientific literature, the prediction of subsidence above solution mines can be much more complex than the prediction of subsidence due to excavation mining. This issue needs to be reevaluated for the final rule for WIPP.

- Potash is a resource used for the production of food, therefore it appears to be incorrect to calculate a probability of mining based on past potash production which was inherently dependent on past mineral economics and the availability of high grade ore. It also seems reasonable to assume that low grade potash ores will eventually be mined to meet world demand.

ISSUE 32.D Potash reserve assumptions are contradictory and/or inadequate

8 The CCA claims credit for addressing the issue of potash mining. However, the CCA underestimates the areal extent of potash reserves and the potential impact of the excavation mining of potash within the site and on adjacent federal and state properties. The use of only existing releases adjacent to the site does not account for the currently economical potash reserves. . . Further, the Department of Interior notes that potash ore

has been and can be economically mined at ore concentrations less than current lease grade. (560) (II-H-25.11)

EPA's response to Issue 32.D

EPA concurs that the DOE and BLM minable footprints do not coincide. Relative to potash, the CCA indicated that only the 4th and 10th horizons are economic reserves, although remaining ore zones are considered resources that would be mined with advances in thin-seam extraction technologies. However, the minable footprint presented in the CCA on Figure 2-38 does not entirely match or coincide with the locations or information presented by Griswold in NMBMMR 1995. DOE provided supplemental information concerning the minable potash footprints, in response to stakeholder questions (Docket A-93-02, Item II-H-45). Although the minable footprints identified by DOE and Department of Interior differ, DOE concluded that this is due to the difference between the definition of "resources" and "reserves." (Reserves are hose resources that are currently economically recoverable with currently available technology, and resources are mineral deposits that are not currently economical or have not been discovered.) That is, DOE contended that their estimates were based on actual minable reserves, which are less pervasive than resources. However, DOE also contended that this approach is consistent with the intent of Section 194.32(b), which states that DOE must consider resources similar in quality and type to those currently extracted.

EEG assessment of EPA response to Issue 32.D

The EEG has conducted a sensitivity analysis pertaining to the extent of potash reserves within the controlled area. The conclusion is that with current models and the implementation of mining in those models (increase in effective transmissivity of the Culebra), the scenario has little effect. However, simply increasing the transmissivity within the Culebra does not account for all processes involved in subsidence due to mining, and other parameters, such as fracture width, or porosity may be significantly

changed. Therefore, the EEG concludes that a more accurate portrayal of mining should be included in the performance assessment, including extent and consequence.

ISSUE 32.I: Justification of FEPs screening

3 Operations involving the screening and other processing of FEPs are inadequately documented. 25% of the original FEPs list was eliminated with no documentation of the process; 70% of the remaining FEPs have essentially no more documentation than what appears in the CCA. The documentation for the other 30% also appears to be incomplete. The rationale for excluding many of the FEPs from the PA is not documented in the CCA. (559) (II-H-25.10)

EPA's response to Issue 32.I

In general, EPA found DOE's screening analyses and justifications for inclusion or exclusion of FEPs to be adequate. However, EPA determined that additional information or justification was necessary regarding certain FEP issues (e.g., dissolution, brine mining, solution mining, and fluid injection). Public comments also identified similar deficiencies in the screening analyses for some FEPs in the CCA. DOE provided supplemental information addressing EPA's questions and public comments (Docket A-93-02, Items: II-I-24, II-I-31, II-I-34, II-I-36, II-I-37). EPA reviewed the information and concluded that DOE's responses have adequately addressed all its concerns regarding FEPs and scenarios.

EEG assessment of EPA response to Issue 32.I

The EEG does not agree that the screening of FEPs in the CCA were adequate. The fluid injection scenario (Section 2.6 of this report), for example, addresses several concerns of the inadequacy by the DOE and EPA in their analysis. Also, arguments can be made on

the Air Drilling Scenario (Section 2.5) and issues surrounding production well ERDA-9 (Section 2.14).

Section 194.33 (CARD 33) Consideration of drilling events in performance assessment

ISSUE 33.B: The Performance should incorporate lower plug permeabilities

555. Borehole lifetime should be a sampled parameter in the CCA calculations or else the DOE should provide demonstration that variations in borehole lifetime do not effect [sic] the release estimates. (555)(II-H-25.6)

EPA response to Issue 33.B:

EPA reviewed natural borehole degradation processes and the subsequent effect of these processes on borehole permeability. Based on available information (e.g., WPO# 41131 and Appendix PAR, p. 192), EPA found that a constant value of permeability 10^{-14} m^2 throughout the regulatory period would not be conservative because of pressure buildup in the repository. The Agency believes that, primarily due to the solidification of drilling muds within the borehole in time, variations in the permeability of borehole plugs will occur and that a lower value of permeability would be more realistic than the constant and relatively high permeability value that DOE used.

EPA agrees that DOE gave little credit to factors that could sustain or enhance the potential effectiveness of plugs. Although DOE provided a combination of site-specific and theoretical justifications in support of plug parameter assignments, the assumed value of the plug permeabilities is subject to uncertainty and EPA determined that a modification of DOE borehole plug permeability values was necessary. EPA required that EPA-mandated PA simulations be conducted using lower permeability values (parameters used

in model- CONC_PLG maximum of 10^{-19} m^2, BH_SAND maximum of 5 x 10^{-17} m^2) to account for possible cases in which complete degradation does not occur throughout a well, or natural materials and mud provide additional layers with sealing properties.

EEG assessment of EPA resolution of Issue 33.B

The EEG suggested the borehole plug lifetime should be a sampled parameter based on two observations. 1) It is likely that the performance assessment calculations are sensitive to the assumed borehole plug lifetime. 2) Borehole plug lifetime is an uncertain parameter. The use of a constant value for borehole plug lifetime in all the calculations is inconsistent with DOE's guidelines for sampled parameters. Contrary to the assertion in the DOE response (II-H-46), the EEG did not argue that the estimate of 200 years is unreasonable.

The DOE (II-H-45) claims that borehole plug lifetime uncertainty is accounted for by assuming that two percent of the plugs are continuous (long-lived) and hence do not degrade (II-H-46). This claim is wrong.

The EEG recognizes that sampling borehole plug lifetimes would be impractical using the present performance assessment design. The DOE should investigate the influence of borehole plug lifetimes on repository conditions and assess the potential impact on CCDF calculations.

The EPA mandated verification test used a range of permeabilities of degraded boreholes that extended lower than the range used in the CCA calculations. The lowest permeability effectively limits flow through the borehole. The effect may have similar consequences to the effect on the repository conditions of long lived borehole plugs. Thus, the EPA mandated verification test may, in conjunction with the CCA calculations, provide a bound

on the influence of variable borehole lifetimes. This, however, is speculation and needs to be confirmed.

Issue 33.D: The estimated probability of intersecting a pressurized brine reservoir is adequately/inadequately justified, and E1 intrusions will not necessarily affect disposal system performance.

219. EEG finds no justification for assuming only eight percent probability of intercepting a pressurized brine reservoir in the Castile Formation, 800 feet below the repository. (219)(A-50 [II-H-12])

EPA response to Issue 33.D:

EPA found that DOE's representation of brine pocket occurrence probability in the CCA was not consistent with available information. EPA requested that the brine pocket probability be modified to range from 1 percent to 60 percent, and that it must be a sampled value rather than a fixed value of 8 percent. These values were used in the PA verification test (PAVT). Results of the PAVT indicated that the modified Castile Brine Pocket parameters increased releases (DOE 1997a, 1997b). However, the resulting PAVT CCDF curves, while closer to the EPA limit than PA CCDF curves, are still well below the EPA limits. EPA agrees that the E1 scenario does not always enhance radioactive releases in all instances. Refer to **CARD 14-- Content of Compliance Application** for further discussion of brine pocket probability.

EEG assessment of EPA resolution to Issue 33.D

There is poor justification for the 1% lower end of the EPA range for the probability of encountering a pressurized brine pocket. The 60% upper end is based on an electromagnetic survey of the WIPP site (US. DOE, 1996c, 2.2.1.2.2) that indicates brine

is likely under about 60% of the repository. Most importantly, the probability of hitting brine under WIPP should be based on WIPP, not the entire Delaware basin. The WIPP-12 brine reservoir is of sufficient size to protrude under the repository. The existence of boreholes around WIPP-12 that have not encountered brine in the Castile constrain the WIPP-12 reservoir so much that it is almost certain that the reservoir extends under the repository (II-H-25). The brine indicated by the electromagnetic survey must be part of the WIPP-12 reservoir. The probability of encountering brine should be modeled as 60%. The PAVT thus underrepresents the probability of encountering a brine reservoir.

Section 194.41 (CARD 41) Active Institutional Controls

ISSUE 41.B: DOE should provide specific commitments preventing human intrusion for 100 years

1 EEG recommends that EPA should require DOE to provide specific commitments on how they will prevent human intrusion for the first 100 years. As part of building a credible argument, the CCA should also take into account the pessimism of its own expert elicitation on the limited effectiveness of active institutional controls. (562) (II-H-25.13)

EPA response to Issue 41.B:

Upon preliminary review of the CCA, EPA requested that DOE provide specific commitments concerning AICs for the WIPP site, including fencing, signs, and site patrols (Docket A-93-02, Item II-I-01). DOE provided the requested information (Docket A-93-02, Item II-I-07, Enclosure 1c). DOE also described legal prohibitions on resource extraction and other activities at the WIPP site that function as AICs, such as the erection and testing of passive institutional controls and the implementation of the site monitoring plan.

DOE did not conduct an expert elicitation for the purpose of determining how long the proposed AICs specifically are expected to be effective. As EEG noted, an expert elicitation conducted prior to the promulgation of the final Compliance Criteria resulted in predictions of AICs' effectiveness generally (see A-93-20, Item II-H-25). However, DOE did not rely on these predictions in proposing that AICs will be completely effective for 100 years. EPA believes that it is fully within DOE's capacity to maintain the proposed controls for 100 years after disposal, is discussed under EPA Compliance Review for Section 194.41(a) above.

EEG assessment of EPA resolution to Issue 41.B

Title 40 CFR 191.14 (a) requires maintenance of active institutional controls for as long a period of time as is practicable after disposal, but the credit in performance assessment may not be taken for more than 100 years. The DOE has proposed controls for 100 years and has assumed no drilling in the repository for that period. The EEG agrees with the EPA's finding for this requirement, but recommends that if in the final rule EPA finds WIPP to be in compliance with the standards and proposes to grant certification, oversight by the federal (other than DOE) and state authorities should be required to ensure vigorous implementation of the active institutional control.

Section 194.43 (CARD 43) Passive Institutional Controls

ISSUE 43.B: DOE's proposal for PICs credit is or is not acceptable

5 Based on DOE's experience with institutional controls in the recent past, a claim of 99% credit for passive institutional controls for 700 years does not appear justifiable. (561) (II-H-25.12)

EPA response to Issue 43.B

EPA proposes to deny DOE's application for PICs credit for two reasons. First, DOE did not employ expert judgment to derive the credit. EPA stated in the preamble to 40 CFR Part 194 that "the degree to which PICs might reduce the future drilling rate can be reliably determined only through expert judgment" (61 FR 5232). Instead, DOE developed a proposal and submitted it to a peer review panel of three experts. EPA does not view peer review as equivalent to expert judgment. The Agency laid out explicit requirements for the conduct of expert judgment in Section 194.26.

Second, EPA found that DOE's analysis does not account persuasively for the uncertainty associated with the forecasting the effectiveness of PICs. EPA does not concur with the conclusion of the PICs peer review panel that DOE's proposed credit is reasonable. Among other issues, EPA considers DOE's assertion that every aspect of the PICs design is virtually certain to endure and be understood for the proposed period to be contrary to EPA's specification in Section 194.43(c) that "[i]n no case. . . shall passive institutional controls be assumed to eliminate the likelihood of human intrusion entirely" (61 FR 5243). This topic is discussed in greater detail in EPA Compliance Review for Section 194.43(c).

EEG assessment of EPA resolution of Issue 43.B

The EEG agrees with this determination of denying credit for PICs for reasons stated by the EPA in U.S. EPA (1997c), as well as for reasons that EEG has previously submitted to the EPA (see Appendix 8.2-Passive Institutional Controls).

Section 194.44 (CARD 44) Engineered Barriers

ISSUE 44.A: Borehole plugs, shaft seals, panel closure, and backfill should/should not be considered engineered barriers.

5 Shaft seals are at best an attempt to undo the damage done to the natural environment when the shafts were excavated, and therefore cannot be an engineered barrier as distinct and complementary to the natural barriers. (545) (II-H-12.24)

6 Like the shaft seals, panel closure systems (separation of waste panels by engineered structures) cannot be considered to be engineered barriers because they too can at best be imperfect attempts to restore the original natural system. Panel seal is not included in the examples of engineered barrier in EPA definition (Section 191.12). (546) (II-H-12.25)

7 The fact remains that the purpose of including MgO in the WIPP repository is to control the chemical conditions in the WIPP repository to allow assumption of lower actinide solubility values. It may therefore satisfy a need for the Containment Requirement of the Standards, but does not provide complementary added assurance visualized by the Assurance Requirements (40 CFR 191.14). (547) (II-H-12.26)

8 Since the stated requirements for plugging the boreholes (Section 3.3.4 and Figure 3-10 of the CCA) are much less stringent than the shaft seals, the borehole plugs have a lesser claim as engineered barriers. The NRC specifically excludes borehole seals as part of an engineered barrier system. Hence, the borehole plugs should not be considered to be an engineered barrier. (548) (II-H-12.27)

EPA response to Issue 44.A

Section 194.14(b)(1) required DOE to include in the description of the disposal system information about engineered barriers, i.e., "any material or structure that prevents or substantially delays movement of water or radionuclides toward the accessible environment," as defined at Section 191.12. The CCA treated panel seals, shaft seals, and borehole plugs as features of the disposal system design, and EPA evaluated them in that context. For a discussion of these features, see Section 194.14(b)(1) and Response to Comments in **CARD 14 – Content of Compliance Certification Application.**

For the purpose of complying with the assurance requirements at Section 194.44, DOE proposed to implement one engineered barrier -- magnesium oxide (MgO) backfill. EPA believes that DOE adequately demonstrated in the CCA and supplementary information that MgO will serve to prevent or substantially delay movement of water or radionuclides toward the accessible environment. For more discussion of the effectiveness of MgO backfill, see Section 194.44(a) above in this CARD, as well as Response to Issue C below.

EEG assessment to EPA resolution to Issue 44.A

Title 40 CFR 191.14 (d) requires use of both engineered and natural barriers in the repository design. The CCA proposed a chemically-buffering magnesium oxide backfill as the only engineered barrier, and the EPA has accepted in the proposed rule the DOE (U.S. DOE, 1996c) proposal to satisfy this assurance requirement. The EEG view is that while there are still some questions about the efficacy of the chemical buffer aspect of the magnesium oxide (MgO) backfill (see Appendix 8.4, section 2.3 of this report), this

engineered feature has been selected primarily to enable DOE to use numerical values of certain parameters in the containment requirement calculations. The MgO backfill may not therefore be considered to satisfy this assurance requirement in a strict sense of the philosophy of these requirements. Incorporation of backfill in the WIPP design is nevertheless a good idea and the EEG has been recommending a salt/clay mixture as backfill for years. A pure MgO backfill does not have the benefit of the chemical retardation of radionuclides that clays afford, but may help keep the repository chemical environment stable. The EEG would prefer addition of clays such as commercially available bentonite to the backfill, but is willing to accept emplacement of MgO backfill for the sake of operational ease and efficiency.

As to the distinction between “engineered barriers and “engineered features”, it is not based on the standard (40 CFR 191), or its criteria (40 CFR 194). The CCA (U.S. DOE, 1996c) included these “features” in the section on “engineered barriers”, hence the EEG comment.

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ACRONYMS

AEC	U.S. Atomic Energy Commission
ALARA	As Low As Reasonably Achievable
BIR	Baseline Inventory Report
CAG	Compliance Application Guidance
CAO	Carlsbad Area Office
CARD	Compliance Assessment Review Document
CCA	Compliance Certification Application
CCDF	Complimentary Cumulative Distribution Function
CH-TRU	Contact-Handled Transuranic
CRP	Cellulosics, Rubber and Plastics
DCCA	Draft Compliance Certification Application
DLR	Dewey Lake Redbeds
DOE	U. S. Department of Energy
DQC	Date Quality Characteristics
DRZ	Disturbed Rock Zone
EEG	Environmental Evaluation Group
EMP	Environmental Monitoring Plan
EOR	Enhanced Oil Recovery
EPA	U. S. Environmental Protection Agency
ERDA	Energy Research and Development Authority
HI	Human Intrusion
INEEL	Idaho National Engineering and Environmental Laboratory
IRG	International Review Group
IRT	Independent Review Teams
LANL	Los Alamos National Laboratory
LWB	Land Withdrawal Boundary

M&O	Management and Operations
MCLs	Maximum Concentration Limits
MMP	Minimum Miscibility Pressure
NAS	National Academy Science
NRC	National Research Council
NMOCD	New Mexico Oil Conservation Division
NEA/IAEA	Nuclear Energy Agency/International Atomic Energy Agency
OECD/IAEA	Organisation for Economic Cooperation and Development/International Atomic Energy Agency
OECD/NEA	Organisation for Economic Cooperation and Development/Nuclear Energy Agency
PA	Performance Assessment
PAVT	Performance Assessment Validation Test
PIC	Passive Institutional Controls
QA	Quality Assurance
QAPD	Quality Assurance Program Document
QED	Qualification of Existing Data
RTR	Real Time Radiography
RH-TRU	Remote-Handled Transuranic
SNL	Sandia National Laboratory
SWND	Southwestern Nash Draw
STP	Standard Temperature Pressure
SPM	System Prioritization Method
TRU	Transuranic
TWBIR	Transuranic Waste Baseline Inventory Report
USDW	Underground Source of Drinking Water
U.S. NRC	United States Nuclear Regulatory Commission
VE	Visual Examination
WID	Waste Isolation Division

WIPP	Waste Isolation Pilot Plant
WQSP	Water Quality Sampling Program
WWIS	WIPP Waste Information System

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U.S. Environmental protection Agency
Office of Radiation and Indoor Air
401 M Street SW
Washington, DC 20460

Dear Mr. Marcinowski:

At our January 21, 1997 meeting, you requested our comments on the WIPP Compliance Certification Application (CCA) now, because the end of the 120 day comment period on March 17 may be too late for you to seriously consider our comments in your deliberations on the CCA. We are therefore submitting our partial comments on the CCA at this time for your consideration.

The EEG has identified many specific issues in its evaluation of the WIPP-CCA. These issues can be grouped in the following broad categories:

- Lack of sufficient justification in disqualifying several features, events, and processes (FEPS) from consideration.

- Insufficient basis for selecting certain conceptual models and rejecting others.

- Incorrect estimation of probabilities of certain events.

- Insufficient justification or erroneous assumptions in assigning values for several input parameters.

The EEG has attended most of the meetings of the WIPP/CCA Peer Review Panels that were organized as required by 40 CFR 194.27. Our impression is that certain panels have performed a thorough and credible review, while others have not. Our recommendation to the EPA is to review the bases of findings of the panels and subject them to your own critical review by the EPA staff, contractors, or formally assembled peer review groups.

In reviewing the CCA, the EEG does not accept the arguments of "no consequence" to delete the otherwise plausible features, events and processes, and to justify incorrect values for certain input parameters. Such arguments, made on the basis of piecemeal, limited sensitivity analyses, may be misleading in projecting the relative importance of scenarios, conceptual models and input parameters for CCDF calculations. We strongly recommend that the EPA reject all such "no consequence" arguments and demand that a fresh set of calculations be performed after the EPA has examined the robustness of all the CCA assumptions regarding FEPs, conceptual models, numerical models, probability assignments, and input parameter values, and has provided alternative models and numbers to the DOE. This comment also applies to the recommendations of the peer review groups. The Conceptual Model Peer Review Group, for example, provides solid technical arguments for not accepting certain conceptual models advocated and used in the CCA, but then has found them acceptable on "no consequence" basis without providing sufficient explanation for such acceptance.

Comments on specific issues are enclosed. These are arranged as brief papers that can be read as stand-alone documents. We plan to submit additional comments to you in this format, as they are developed in the next few weeks.

Sincerely,

Robert H. Neill
Director

RHN:LC:js
Enclosures: EEG Reviews of the WIPP-CCA,
Plutonium Solubility
Chemical Retardation
Spallings Model
Fluid Injection
Brine Reservoir Assumptions
Engineered Barriers

cc: Ms. Jennifer Salisbury, NMEMNRD
Mr. Lindsay Lovejoy, Jr., NMAG
EPA docket for WIPP (A-9302)

CHEMICAL RETARDATION VALUES FOR THE CULEBRA

In the event of a borehole intrusion, the Culebra Aquifer, which lies 400 meters above the WIPP horizon, is one possible groundwater pathway for release of radionuclides to the accessible environment. Chemical retardation is expected to slow the transport of radionuclides through the fractured dolomite of the Culebra Aquifer. However, the DOE application has used values for estimating retardation coefficients that appear to lack justification.

Faced with a lack of field data and limited column test data for WIPP, the DOE CCA used retardation values from crushed rock samples in the laboratory to represent field conditions. Justification by the DOE is based on the following observations.

1) Sorption can occur in pores of various scales.

2) The surface area to volume ratio in crushed rocks sorption tests are similar to in-situ Culebra dolomite.

3) For long flow paths and long flow times radionuclides have sufficient time to diffuse into these pore spaces and sorb.

While EEG agrees that there appears to be a reasonable theoretical basis for using crushed rock, the EEG disagrees with the final data used in the CCA. Empirical sorption tests were done for all permutations of four types of brine; CO_2 levels of 0.033%, 0.24%, 1.4%, or 4.1%; and no, low, intermediate or high levels of organics. Because DOE plans to add M_gO as backfill, the fugacity of CO_2 in the repository is expected to be 10^{-7}. Thus, EEG discarded the results for CO_2 levels of 0.24%, 1.4%, and 4.1%. EEG also discarded results that did not meet DOE's own quality control criteria, and the results from a set of mechanistic sorption experiments because the dolomite was not from the Culebra. The average of the batch results formed the upper end of a uniform distribution.

Results from flow-through experiments using rock cores formed the lower end of the uniform distribution. In some cases, there was no radionuclide breakthrough at 300 days, so a minimum estimated K_d, assuming breakthrough at 300 days was used.

The DOE did not include the influence of organics on K_d values. In batch tests, even low concentrations of organics dramatically reduced K_d values. The impact of organics are included in the Kd values recommended by EEG.

The following tables show the Kd values used in the CCA, and the values suggested by the EEG using the criteria described above.

Table 1. K_ds used by DOE in CCA.

Oxidation State	Am	Pu	U	Th	Np
III	20 - 500	20 - 500			
IV		900 - 20000	900 - 20000	900 - 20000	900 - 20000
V					1 - 200
VI			0.03 - 30		

Table 2. K_ds recommended by EEG.

Oxidation State III, IV, V, VI	Am	Pu	U	Th	Np
	73 - 314	83 - 270	0.35 - 5	0.15 - 1.5	1.0 - 21

PLUTONIUM SOLUBILITY-EXPERIMENTAL MEASUREMENTS VERSUS CCA CALCULATED VALUES

Where brine has dissolved waste in the repository, direct drilling provides a vertical pathway for the long-lived actinides to return to the environment. Plutonium constitutes 87% of the initial radioactivity in the performance assessment calculations. Oxidation state is a factor that has an impact on the plutonium solubility. The DOE CCA assumes that the plutonium in the repository will be either at Pu(III) or Pu(IV), with 50% probability of one or the other. However, the solubilities are not measured for Pu(III) or Pu(IV). Rather, the solubility of Pu(III) is calculated using thermodynamic data for Nd(III) and the solubility of Pu(IV) is calculated using thermodynamic data for Th(IV).

While solubility experiments show that regardless of the initial oxidation state, Pu (VI) dominates at steady state conditions, it is not included in the performance assessment calculations. Pu(VI) has a high solubility in the conditions anticipated for the WIPP repository by the CCA.

The magnesium oxide backfill is anticipated to keep the repository at a pH of 10 and reducing. Reed et al. (1996) reported, that for brine at pH of 8 to 10, and reducing conditions, Pu(VI) is stable with an apparent solubility of 10^{-4} M. While it has been argued that corrosion of the steel drums would result in a reducing environment, Rao (1996) found that it was not possible to reduce Pu(VI) below Pu(V) despite adding more iron per unit mass of plutonium than could be expected in the repository, even assuming complete dissolution of the steel containers. Clark and Tait (1995) also concluded that Pu (VI) is stable in WIPP brines. Table 1. compares the calculated values used in the CCA and the measured values reflective of conditions anticipated in the repository.

Table 1. Solubility of plutonium as determined by calculations and experiments

Source of Brine	CCA calculations	Experiment, Reed et al.
Castile	5.7×10^{-9} M	8×10^{-5} M
Salado	4.4×10^{-6} M	9×10^{-5} M

The experimental evidence leads to the following conclusions:

1) Pu(VI) will be stable in the WIPP repository.

2) There is no support for the assumption that plutonium will stabilize in either oxidation state Pu(III) or Pu(IV).

3) The calculated results used in the DOE CCA are significantly different from experimental results for WIPP brines under anticipated repository conditions.

The EEG therefore recommends using the experimental values determined by Reed et al. (1996) shown in Table 1, for the CCA calculations.

References

1. D. L. Clark and C. D. Tait, 1995. LANL Progress Report. December 12, 1995. CCA Additional References No. 134.

2. L. F. Rao, 1996. PNNL Progress Report, April 1, 1996.

3. D. T. Reed, D. G. Wygmans, M. K. Richmann, 1996. "Stability of Pu(VI), Np(VI), and U(VI) in Simulated WIPP Brine," ANL Interim Report, CCA Additional References No. 539.

SPALLINGS MODEL

1. Critique of the Model Used in the CCA

For the purposes of the WIPP Compliance Certification Application (CCA) calculations, spallings refers to the entrainment of solid waste during the venting of high pressure gas from the repository in the event of a drilling intrusion. Spallings will occur when the roof of a waste room is penetrated by a drill, if the pressure in the room is sufficient to overcome the hydrostatic pressure of the drilling mud, about 8 MPa. Visual inspection of gas pressures calculated by the BRAGFLO code[1] indicates that over 80% of the undisturbed repository calculations predict pressures over 8 MPa after 10,000 years, with roughly 25-30% reaching this level in less than 1,000 years. The highest pressure calculated was nearly 16 MPa. The CCA calculations predict spallings to be a very important release mechanism. Spallings contributes to over 50% of the release estimates for human intrusion and was the largest form of release in over 10% of the calculated histories. The largest calculated release was less than, but within a factor of five, of the EPA normalized release limit for the 10% probability level.

The EEG finds the spallings model as used in the CCA to be inappropriate on three counts; 1) exclusion of brine from the spallings scenario, 2) the conceptual model of the spallings process, and 3) the experimental basis of the model validation. The spallings model is defined as gas driven entrainment of solid particles. The effect of brine in the waste panel is ignored. Brine may effect the spallings process in three ways. Capillary forces from low saturation may provide a binding force that inhibits spall which is conservatively ignored. Brine may also increase the effective driving force of the spall process increasing the amount of spall. In addition, the brine would contain radionuclides in solution. The CCA does include brine release from the penetration of the repository as a separate, longer term, two-phase flow calculation using repository conditions that are unmodified by the spall process. The spallings model should include the effects of brine.

For the spallings calculations, waste is assumed to be composed of uniform sized granules held together by a cohesive strength of 1 psi (0.007 MPa). The grain size is a sampled parameter in the CCA analysis. With the composition of the waste ranging from large pieces of metal to ash, it is unlikely that the waste will degrade to a uniform grain size. There has been no analysis to show that the releases calculated by sampling for a uniform distribution size bounds the releases from a heterogeneous medium.

Spalling can be viewed as a two step process. First, the explosive depressurization of the waste near the drill puncture, lasting a few seconds, followed by the erosion of channels through the waste by gas further from the puncture location, lasting hundreds of seconds. However, the spallings model includes only the second process. Two justifications are presented for ignoring the first process: 1) The pressure drop increase resulting from ejecting the drilling mud from the drill string is a relatively slow process, 2) the erosion process will proceed to a stable void

configuration independent of the initial entrainment. In other words, a larger initial spall will be followed by less erosion than a smaller initial spall, resulting in the same final void ratio. We find two errors in this argument: 1) The pressure difference between the waste repository and the hydrostatic pressure of the drilling mud can be over 6 MPa, three orders of magnitude above the pressure differential needed for explosive spall. 2) The second argument presupposes, without justification, that the erosion volume is larger than the initial spall volume and that the cavity caused by the initial spall will be partially filled by the erosion process.

The spallings model was validated by DOE using a set of bench scale experiments. A four inch high cylindrical cavity of 20 inches in diameter was supplied with high pressure gas through a plenum around the circumference. A vent of variable diameter was placed in the center of the top of the cylinder. The cylinder was filled with silica sand. The experiments were run by stepping the pressure maintained at the plenum. The pressure was held constant until no more material was entrained, then stepped to a higher value. These essentially steady state experiments do not encompass the highly transient spallings phenomena. The model tests the erosion portion of the spallings phenomena for waste with no cohesive strength, but not the initial explosive phase, nor the effect of cohesion. The inclusion of cohesive strength in the spallings model reduces the calculated spall mass by as much as two orders of magnitude. The attached figure shows the sensitivity of the model to waste strength assumptions. The figure presents plots of mass removed by spallings as a function of sampled particle diameter. Each plot represents the mass removed for an assumed waste strength. The waste strength is varied from 0 to 2 psi.

The experiments indicated increasing spall with increasing diameter of the vent. The spallings model does not include a sensitivity to scale leading the developers of the spallings model to state "Extrapolation of release volumes to WIPP, using the parameters evaluated using small scale laboratory models, has the potential for grossly under-predicting such releases[2].

In their initial review, the conceptual model peer review panel deemed the spallings model to be inadequate.[3] Subsequently, the DOE has reconvened the peer review panel twice to reassess the spallings model among others. The DOE presented additional information intended to demonstrate both the validity of the spallings model and the conservatism of the calculations. The peer review panel still considers both the model and the case for conservatism to be inadequate[4,5].

The EEG therefore recommends that further development of the spallings model be pursued. The spallings model should be validated by a set of experiments that adequately simulate the expected processes of spalling in the event of human intrusion into the waste repository. These experiments should include:

a) the effects of varying the brine saturation
b) investigation of the effects of heterogeneity
c) both the rapid depressurization and longer term erosion through channels
d) the effects of varying the waste strength

e) investigation of scale influences

2. Exclusion of Two Processes from the Spallings Model

Two potentially important processes, viz., the "gas erosion" and the "stuck pipe", considered by the DOE in earlier performance assessments[6], have been excluded from the CCA spallings model. These may occur if the gas flows into the drilling mud because the pressure in the repository exceeds the hydrostatic pressure of the drilling mud but the flow rate is insufficient to expel the mud from the drill string. These two phenomena could cause releases that are over an order of magnitude larger than the largest releases calculated in the CCA.

Waste permeability has a strong influence on the gas flow rate through the waste. At lower flow rates, the drilling mud may be able to wash the spall material from the drilling cavity. This is termed gas erosion. In the SPM-2 report[6], releases from 44 to 356 m^3 were considered possible from gas erosion. Compare this to the maximum calculated release of 4 m^3 in the CCA calculations[7]. If the amount of spall is above the carrying capacity of the drilling mud, then the spall will press against the drilling string, slowing the rotation of the drill bit. The normal response of a drilling crew in such circumstances is to raise and then lower the bit in order to clean out the cavity. In the SPM-2 report[6], releases from 43 to 238 m^3 were considered possible from stuck pipe type spall.

Gas erosion and stuck pipe have been excluded from the spallings model because the waste permeability assumptions of the CCA calculations are above the threshold for ejection of the drilling mud from the drill string. The SPM-2 report[6] assumed 10^{-16} m^2 to be the threshold permeability. However, this threshold is not well defined. It certainly is related to the pressure in the repository.

The CCA (Chapter 6, p. 6-100) states that simulated waste compacted under a lithostatic load yielded waste permeability in the range of 10^{-12} m^2 to 10^{-16} m^2. The CCA assigns the waste permeability as a constant at 1.7×10^{-13} m^2, as "representative of the average value of compacted waste." There is no indication that the effects of neglecting the permeability uncertainty on the CCA spallings model were considered[8].

The permeability of the waste is a critical parameter in determining the plausibility of these processes occurring. The value of the permeability should therefore be carefully chosen to reflect, as accurately as possible, the future conditions in the repository. If the potential cementation of the waste by magnesium chloride cement and salt precipitates is considered, the waste permeability may be even lower than the 10^{-16} m^2 lower band assumed in the SPM-2 report[6].

The Engineered Systems Peer Review Panel did not consider these processes or the validity of their deletion from the spallings model. They considered the waste permeability to be adequately determined for the BRAGFLO calculations, but did not consider its potential effect on these

processes, or the effect of MgO backfill in reducing waste permeability.

The EEG recommends that a more realistic value or a range of values should be assumed for the waste permeability parameter and potential for the "gas erosion" and the "stuck pipe" processes be included in the spallings scenario with a better defined permeability-pressure threshold.

References

1. Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, SAND96-2226, Figure 2.3.1, December 1996.

2. L.R. Lenke, J.W. Berglund, and R.A. Cole, Blowout Experiments Using Fine Grained Silica Sand in an Axisymetric Geometry, NMERI 1996/7/32250 - Draft, March 1996.

3. C. Wilson, D. Porter, J. Gibbons, E. Oswald, G. Sjoblom, and F. Caporuscio, Conceptual Model Peer Review Report, DOE, July 1996.

4. C. Wilson, D. Porter, J. Gibbons, E. Oswald, G. Sjoblom, and F. Caporuscio, Supplementary Conceptual Models Peer Review Report, DOE, December 1996.

5. C. Wilson, D. Porter, J. Gibbons, E. Oswald, G. Sjoblom, and F. Caporuscio, Conceptual Models Second Supplementary Peer Review Report, January 1997.

6. B.M. Butcher, S.W. Webb, J.W. Berglund and P.R. Johnson, Systems Prioritization Method — Iteration 2 Baseline Position Paper: Disposal Room and Cuttings Models, Volume 1, March, 1995.

7. J. Helton, Memo: Preliminary Summary of Uncertainty and Sensitivity Analysis Results in Support of the 1996 Compliance Certification Application for the Waste isolation Pilot Plant, December 23, 1996.

8. Form 464 for cuttings waste permeability, WPO 37102, Nov. 28, 1995, and referenced source B.M. Butcher memo to M.S. Tierney, QAP 9-2 Documentation of the Overall Waste Permeability and Flow Property Values for the CCA, January 29, 1996.

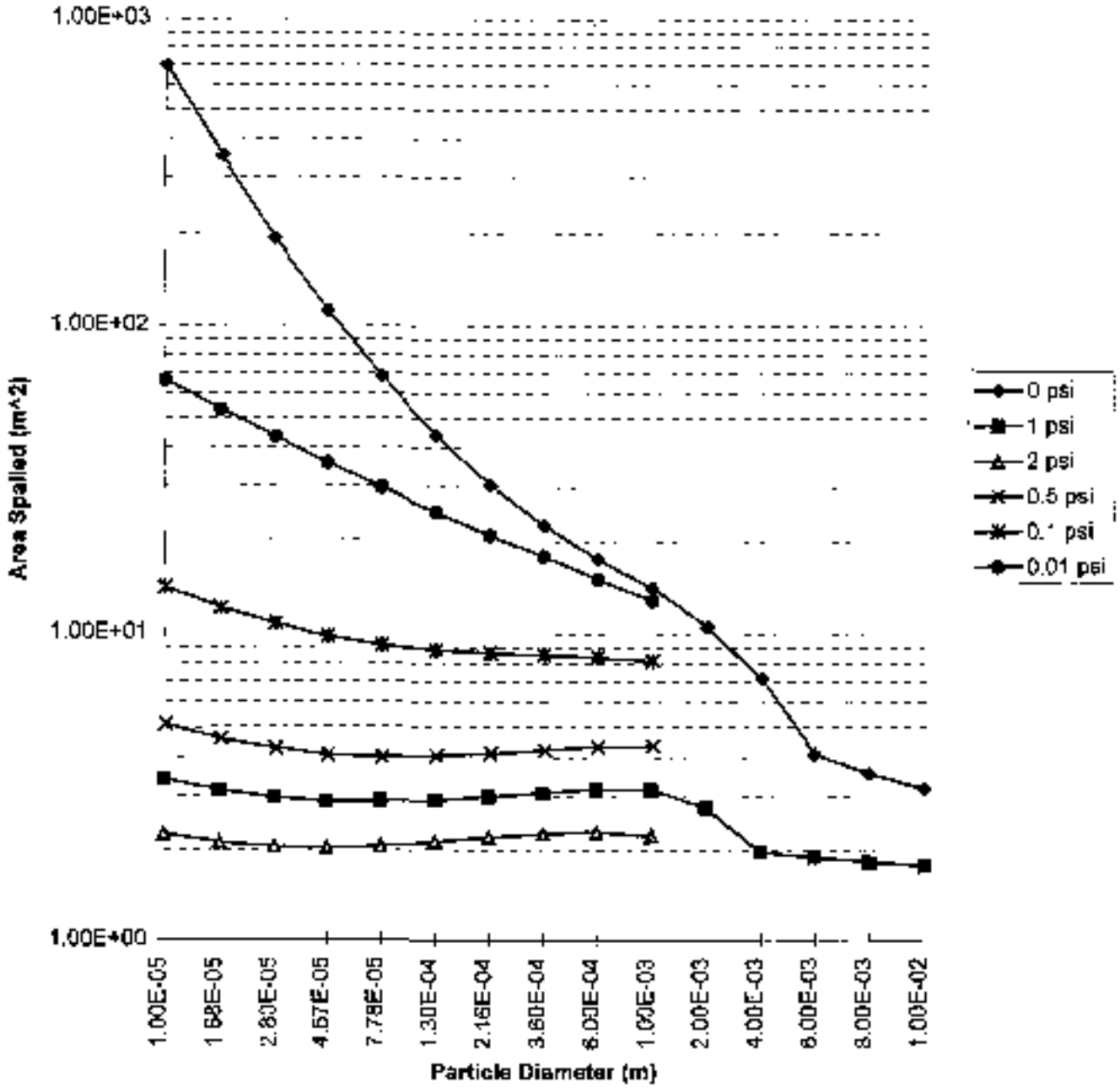

Spall area as a function of particle diameter and cementation strength
(Unpublished EEG Calculations Using CUTTINGS_S; Version PA98)

Environmental Evaluation Group Review of the WIPP-CCA, 2/7/97

BRINE RESERVOIR ASSUMPTIONS IN THE CCA

The EEG sees no justification for assuming only 8% probability of intercepting a pressurized brine reservoir in the Castile Formation 250 meters below the repository. The fatal flow in the CCA argument for 8% is the assumption that the oil and gas wells that did not report encountering brine did in fact not encounter a brine reservoir. The fact is that the drillers are not required to report brine encounters to the state or federal authorities and no mention would be found in the records unless undue delays or hazardous conditions are encountered.

The 8% probability also ignores the data from WIPP-12 and the TDEM survey over the repository. The borehole WIPP-12 is located north of the repository within the WIPP site. It was drilled to the bottom of the Salado Formation in 1978 and deepened in 1981 at the EEG's suggestion. The DOE contractor (Popielak et al., WIPP-TME-3153, 1983) estimated the volume of the reservoir to be 2.7 million m^3 (17 million barrels). For the maximum possible reservoir thickness of 24 meters, the surface footprint of a cylinder containing this volume would have a diameter of more than 3 km. As the attached figure shows, the WIPP repository is most likely underlain by the brine reservoir encountered by WIPP-12. In addition, the TDEM survey (SAND 87-7144) gives an indication of the presence of brine at the upper Castile horizon. To try to assign specific areas of the presence of brine from this geophysical survey would be over-interpretation of the geophysical data. Combination of the WIPP-12 data and the results of the TDEM survey indicate the existence of brine under the repository. Any borehole drilled into Castile under the repository should therefore be assumed to encounter brine.

The EEG does not find the CCA reservoir volume assumption of 32,000 to 160,000 m^3 to be justified. This is based on the assumption of depletion of reservoirs by future drillers - 100% probability of encounter for the depletion assumption, while only 8% for releases!

The attached table shows the comparison between the characteristics of the WIPP-12 brine reservoir and the CCA assumptions.

The WIPP site was moved twice; in 1975 after the borehole ERDA-6 encountered a brine reservoir, and again in 1982, after WIPP-12 encountered brine. The CCA assumptions of probability should be realistically based on the site specific information, and the characteristics should be based on the WIPP-12 experience.

The DOE Conceptual Model Peer Review Panel, in their December 1996 report, essentially agrees with the EEG position, but has accepted the DOE position that there is no significant consequences of the probability and volume assumptions.

The EEG does not accept the "no consequence" argument that is based on piecemeal, partial sensitivity analyses.

Comparison of WIPP-12 Brine Reservoir and the CCA Assumptions

Parameter	WIPP-12 (m^3)	CCA (m^3)
Total Reservoir Volume	2.7×10^6 (a)	32,000 to 160,000 (d)
Projected Max. Artesian Flow	55,821 (b)	5,200 (e)
Flow to Surface During Drilling	4,306 (c)	400 to 2,100 (f)

(a) WIPP/TME-3153, p. H-54
(b) WIPP/TME-3153, p. H-55
(c) WIPP/TME-3153, p. H-9; Actual "unavoidable" flow
(d) DOE/CAO-1996-2184, Table 6-26
(e) CMPRR-Suppl., 12/1996, p. 42; To the Culebra, after 6 encounters
(f) CMPRR-Suppl., 12/1996, p. 42; In 10,000 years

ERDA-6 ●

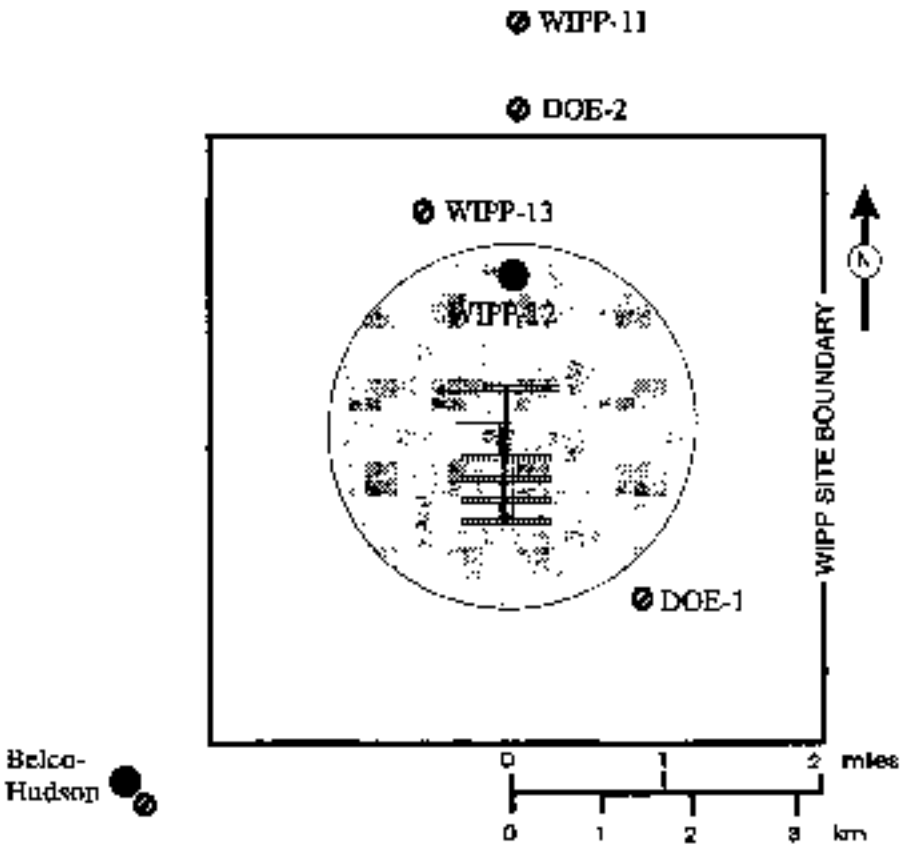

● Record of brine encountered in the Castile

⊘ No record of brine encountered in the Castile

Potential extent of the brine reservoir encountered by WIPP-12

Potential extent of WIPP-12 brine reservoir using WIPP-12 pressure recovery data, rock compressibility of $1x10^{-10}Pa^{-1}$, and reservoir thickness of 24 meters.

ENGINEERED BARRIERS FOR WIPP

The EPA regulations require engineered barriers to be included in the repository design as an Assurance Requirement (40 CFR 191.14d and 40 CFR 194.44). The philosophy of the Assurance Requirements is clearly stated in the "Overall Approach of the Final Rule" (Federal Register v. 50, no. 182, p. 38072), as follows:

> In contrast to the containment requirements, the assurance requirements were developed from that point of view that there may be major uncertainties and gaps in our knowledge of the expected behavior of disposal systems over many thousands of years. Therefore, no matter how promising the analytical projections of disposal system performance appear to be, these materials should be disposed in a cautious manner that reduces the likelihood of unanticipated types of releases. Because of the inherent uncertainties associated with these long time periods, the Agency believes that the principles embodied in the assurance requirements are important complements to the containment requirements that should insure that the level of protection desired is likely to be achieved.

With respect to the engineered barriers as an assurance requirement, the "Overall Approach of the Final Rule" states:

> Designing disposal systems to include multiple types of barriers, both engineered and natural, reduces the risks if one type of barrier performs more poorly than current knowledge indicates.

The CCA (Sec. 3.3) describes four types of engineered barriers in the design of the WIPP disposal system: (1) Shaft Seals, (2) Panel Closures, (3) Backfill around the waste, and (4) borehole plugs. EEG does not consider either of these to be engineered barriers, for the following reasons:

Shaft Seals

Shaft seals are at best an attempt to undo the damage done to the natural environment when the shafts were excavated, and therefore cannot be considered to be an engineered barrier as distinct and *complementary* to the natural barriers.

Note that the 40 CFR 191.12 definition of a "Barrier" includes the following examples of engineered barriers, but does not include "shaft seals".

> ... A canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around waste, provided that the material or structure substantially delays movement of water or radionuclides.

The repository standards for the high-level nuclear waste repository (10 CFR 60) specifically exclude shaft seals from engineered barrier system. "Engineered Barrier System" is defined in 10

CFR 60.2 as:

> *Engineered barrier system* means the waste packages and the underground facility.
>
> and
>
> *Underground facility* means the underground structure, including openings and backfill materials, but excluding shafts, boreholes, and their seals (underline added).

Panel Closures

Like the shaft seals, panel closure systems (separation of waste panels by engineered structures) cannot be considered to be engineered barriers because they too can at best be imperfect attempts to restore the original natural system. Panel seal is not included in the examples of engineered barrier in the EPA definition (40 CFR 191.12).

The Marker Bed 139 lies directly below the WIPP repository and is connected to the floor of the waste rooms through extensive fractures, floor upheaval and milling of the floors. Water (with anomalous lead content acting as a tracer) seeping down from the exhaust shaft has moved 400 ft through the marker bed from the base of the air exhaust shaft to the waste handling shaft in a short period of time during 1995-96. This pervasive marker bed would not allow effective separation of the panels unless the entire floor of the repository is dug down 10 ft and grouted.

According to the CCA (p. 3-27, lines 19-20), "The panel closure system was not designed or intended to support long-term repository performance." How then can it be considered an engineered barrier for the long-term performance?

Backfill Around the Waste

The DOE plans to put sacks of magnesium oxide (MgO) over and around the waste drums to try to control the future chemical conditions in the repository. The expectation is that MgO will react with the carbon dioxide (CO_2) that is produced from microbial action in the repository. Removal of CO_2 will result in alkaline conditions in the repository. Since the experimentally determined solubilities of radionuclides are lower in alkaline (high pH) conditions, the emplacement of MgO and its postulated effect allows assumption of lower solubility values in the CCA. This assumption results in lower postulated releases to the accessible environment and thus helps in showing compliance with the Containment Requirements (40 CFR 191.13) of the EPA Standards.

Since the publication of the CCA, the DOE has argued that the MgO is not needed for showing compliance with the Containment Requirements because the mean CCDF without MgO, although showing higher releases than "with MgO", still is within the compliance limits. Such an argument is based on a partial calculation without altering other assumptions and input parameters, and therefore appears meaningless. The fact remains that the purpose of including MgO in the WIPP

repository is to control the chemical conditions in the WIPP repository to allow assumption of lower actinide solubility values. It may therefore satisfy a need for the Containment Requirement of the Standards, but does not provide *complementary* added assurance visualized by the Assurance Requirements (40 CFR 191.14).

Borehole Plugs

Since the stated requirements for plugging the boreholes (Section 3.3.4 and Figure 3-10 of the CCA) are much less stringent than the shaft seals, the borehole plugs have a lesser claim as engineered barriers than the shaft seals. The EPA Standards (40 CFR 191.12) do not include borehole plugs as an example of engineered barriers. The NRC specifically excludes borehole seal as part of an engineered barrier system (see the quote under Shaft Seals section above). Hence, the borehole plugs should not be considered to be an engineered barrier.

Incidentally, Figure 3-9 ("Approximate Locations of Unplugged Boreholes") does not include two deep abandoned oil and gas wells that are located within the WIPP site: Badger Unit Federal in Section 15 (between WQSP-3 and H-5 in the northwest part of the WIPP site), and Cotton Baby Federal in Section 34 (east of H-11 in the southeast corner of the WIPP site).

Recommendation

The EEG has recommended a multi-barrier approach for WIPP since the beginning of the project. The EPA regulations also require such an approach as "assurance requirements". According to the WIPP Safety Analysis Report (App. A), 88% of the WIPP bound waste is planned to be processed. At the least, the DOE should take credit for such reprocessing in the WIPP performance assessment and the CCA. EPA should encourage DOE to process the waste to make it insoluble.

<u>Enclosure</u>:
Information from the draft 1996 WIPP SAR

Information from the draft 1996 WIPP SAR
Appendix A, page A-4 to A-15
Data is from final row of cumulative values for each waste form

Stored Drum Equivalents

Final Waste Form	**Not Processed**	**To Be Processed**	
Combustible	4194	23570	
Filter	976	72	
Graphite	616	1845	
Heterogeneous	6355	104300	
Inorganic Non-metal	1168	12911	
Lead/Cadmium Metal	83	31	
Salt Waste	34	68	
Soils	95	1862	
Solidified Inorganics	15651	30670	
Solidified Organics	1077	3311	
Uncategorized Metals	3348	48751	
Unknown	129	188	
Various	0	20105	
Subtotal of column	**33726**	**247684**	Total stored **281410**
Percent of Total Stored	**11.98%**	**88.02%**	

Notes from the 1996 draft SAR
Final SAR Expected late Jan. 1997
W.T. Bartlett 1/21/97

Environmental Evaluation Group review of the WIPP-CCA, 2/7/97

FLUID INJECTION AND SOLUTION MINING

The EPA Requirement and the CCA

The EPA criteria (40 CFR 194.32 c) requires an analysis of the effects of fluid injection activities on the disposal system, prior to disposal and soon after disposal. The CCA has screened out the fluid injection scenario within the site on a "regulatory basis" and adjacent to the site on the basis of "no consequence" and has provided a number of arguments why it should not be considered in the performance assessment for WIPP. This paper is a critique of the CCA arguments contained in Chapter 6 and Appendix SCR. The EEG has reviewed the Stoelzel and O'Brien[1] assumptions (discussed in the CCA and later in this paper), and finds the critique by John Bredehoeft[2] (enclosed) to provide additional compelling arguments for not accepting that analysis to be valid. A copy of a consequence analysis by John Bredehoeft[3] is also enclosed. This preliminary analysis clearly establishes the importance of considering the fluid injection scenario in predicting the near-term and long-term integrity of the WIPP repository.

How Long in the Future?

The DOE has chosen "soon after disposal" to mean 50 years in the context of the fluid injection scenario. However, in the 1991 DOE elicitation of expert opinion[4] on future activities in the vicinity of WIPP, one of the four teams addressed fluid injection and assigned probabilities of waste brine disposal associated with other industrial activities for the full 10,000 years. Further, the probability of a larger number of such injection wells, within the site, was predicted to increase with time (Ref.4, Table IV-16).

With respect to natural resource recovery activities surrounding the WIPP, the surrounding public lands are managed by either the Federal Government or the State of New Mexico. In addition to federal law, state and federal agencies know that this is a resource rich area and have developed additional policies for the effective recovery of these resources consistent with federal and state law. The Federal Land Management and Policy Act[5] states that public lands and resources are utilized to "meet the present and future needs of the American people" and take into account the "long term needs of future generations." This federal law does not limit consideration of natural resources on public lands to "near future" nor to "existing leases." On the contrary, federal agencies such as the Bureau of Land Management have explicitly argued that lessees can plan and submit plans for resource recovery activities outside their actual leases[6].

Review of Appendix SCR Arguments

The discussion of fluid injection in Appendix SCR of the CCA is incomplete and largely incorrect. For example, Appendix SCR mentions gas reinjection for natural gas storage in the Morrow Formation but fails to mention natural gas storage in the Salado Formation. It is argued that the differences between the geology at WIPP and the Vacuum Field and Rhodes-

Yates Field provide for more potential thief zones below the WIPP horizon in the event of water escaping the injection zone. However, field evidence strongly suggests that brine injection into the Bell Canyon below the WIPP horizon appears to be leaking into the Culebra aquifer above the WIPP horizon (see the discussion in Ref.7, section 3.1.6). Further, the CCA provides no experimental evidence such as the measurement of water quantities in the anhydrite beds of the Salado Formation to support the CCA speculation.

The claim that there will be no waterflooding on the scale of Rhodes-Yates is also undermined by field evidence. The proposed waterflood at the Avalon Unit will recover 8.2 million barrels of oil by injecting 141 million barrels of water for forty years through nineteen injection wells into the Cherry Canyon and Brushy Canyon members of the Delaware Mountain Group. At Rhodes-Yates, approximately 41 million barrels of water were injected through eighteen injectors over a 26 year period. Further, the pressure maintenance wells at the Cabin Lake Unit, at the northwest corner of the WIPP Site are injecting 1.4 million barrels of water per year compared to 200,000 bbls water that were injected per year through the two pilot pressure maintenance wells at Rhodes-Yates.[7]

The CCA Appendix SCR argues that waterflooding on the same scale as the Vacuum or the Rhodes-Yates Field is unlikely because oil pools in the vicinity of the WIPP are characterized by channel sands with thin pay zones, low permeabilities, high irreducible water saturations, and high residual oil saturations. However thin pay zones tend to maximize vertical sweep efficiency and have a history of successful waterflooding throughout the United States, including the Delaware Basin. "Low" reservoir permeabilities of oil reservoirs near the WIPP area has not detered waterflooding in the mature oilfields of the Delaware Basin. Further, mature oil fields in the Delaware Basin have responded favorably to carbon dioxide flooding. The observation of high irreducible water saturations is irrelevant. A waterflood is not designed to reduce the water saturation. A waterflood designed to reduce the oil saturation and increase water saturation in the reservoir by producing the oil. The CCA comment on high residual oil saturations does not speak to the economics of waterflooding. While the Delaware sands, including those around the WIPP, produce large volumes of water, they are, nonetheless, technically and economically amenable to waterflooding[7,8] as well as CO_2 flooding[7,9,10,11,12].

The CCA-SCR cites New Mexico state regulations as also protecting the WIPP. However, the emplacement of a salt isolation string is not intended to address the needs of a 10,000 year nuclear waste repository. It is required to meet the near term safety concerns of the potash industry[13]. Further, even oil and gas wells equipped with a salt isolation string are restricted from drilling through potash reserves or near potash mining operations. With respect to brine injection wells, the potash companies and oil companies have documented their concerns[14,15,16].

The CCA-SCR notes that state regulations do not allow injection pressures to exceed the rock fracture pressure. However, that portion of the regulation applies to the target injection zone

and not any overlying formations. The producing reservoirs near WIPP are greater than 7000 feet. One consequence of greater vertical distance is that the surface injection pressure is automatically approved for 1400 psi or 0.2 psi per foot. This corresponds to 2400 psi at the WIPP horizon which is well in excess of the fracture pressure of the anhydrite beds in the Salado Formation.

As to state regulations in general, state regulations for fluid injection have been in place for decades. Documented problems with fluid injection projects throughout southeast New Mexico identifies the limitations of state regulations. In the case of waterflood brine migrating through the Salado and damaging another oil company property, there is litigation and monetary compensation[17,18]. In the case of a nuclear waste repository, there are performance assessment calculations. However, the CCA does not include this scenario in the performance assessment calculations.

Stoelzel and O'Brien Model

The fluid injection scenario on adjacent properties for the near future has been screened out by the DOE citing low consequence as determined from calculations by Stoelzel & O'Brien[1]. It should be noted that a two dimensional, vertical model was used. Further, the assumptions used in the calculations (DOE SCR) either underestimate or fail to consider hydraulically fractured Salado anhydrite permeability, permitted surface injection pressures in the vicinity of WIPP, injection pressure gradients, the volume of disposal brine that is typically injected by oilfield operations, and the anticipated time of fluid injection activities.

The model assumes a total of $7x10^5$ cubic meters of brine was injected during a fifty year period. This is equivalent to 4.4 million barrels of brine. The David Ross AIT Federal #1 salt water disposal well, which is less than a mile from WIPP, alone has injected more than 5 million barrels brine in five years of operation. And there is no basis for assuming that industrial fluid injection will not continue for the full 10,000 years.

Stoelzel and O'Brien consider only salt water disposal and assume an injection depth of 4260 feet, a surface injection pressure of 850 psi, and a pressure at the WIPP horizon of 1900 psi. However, pilot waterflooding operations near WIPP are underway for reservoirs at 7000 feet depth and have been approved to inject at a surface pressure of 1400 psi, which in the event of communication, would exert a pressure of 2400 psi at the WIPP horizon. Hence, the anhydrite beds in the Salado Formation would fracture, as successfully argued by Hartman[17] and brine would migrate for miles in the inadvertent waterflooding hydrofracture scenario.

Solution Mining

In 1979 the EEG recommended[19] that the DOE consider solution mining for salt as an intrusion scenario. The CCA (Appendix MASS, p. 87) claims that the DOE is not aware of

any ongoing solution mining in the Delaware Basin. However, that activity has been ongoing for several decades in southeast New Mexico, including the Delaware Basin, to provide brine for oilfield drilling operations. Furthermore, state records show that fluid injection for solution mining of halite is expanding into areas closer to the WIPP to meet the needs of drilling activities in that area.

As to future mining of potash, solution mining is the only method that can be reasonably predicted for the Carlsbad District[20]. In Canada and the United States, solution mining is used for recovery of sylvite. Langbeinite is not readily soluble. So if solution mining is employed in the vicinity of the WIPP Site, it will be to recover only sylvite. While no specific plans have yet been formulated,

all mines in the Carlsbad area have held open the option of using solution mining once their sylvite deposits are fully mined out. The concept would rely on the fact that the open spaces left over from mining would allow ore remaining in pillars to be recovered[20].

How can the CCA reject the solution mining scenario, if private companies surrounding the WIPP site are holding the option of using solution mining?

EEG Recommendations

Based on a technical analysis of available information, the EEG recommends that the CCA include the effect of fluid injection and all other resource recovery activities for future and existing wells drilled within the site and adjacent to the site. These activities should include:

- Waterflooding for enhanced oil recovery.
- Carbon dioxide flooding for enhanced oil recovery.
- Salt water disposal from oil production and other industrial activities.
- Solution mining for halite and sylvite.

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Enclosure:

Bredehoeft Memoranda dated January 10, 1997 and January 14, 1997

The HYDRODYNAMICS Group
studies in mass and energy transport in the earth

JOHN BREDEHOEFT *PhD, NAE*
principal

January 10, 1997

MEMORANDUM

To: **Lindsay Lovejoy, Jr.**

From: **John Bredehoeft**

Subject: **Hartman Scenario**

Hartman Scenario—Introduction

The so-called Hartman Scenario is based upon a law suit in the Delaware Basin. In 1991, Hartman, an independent oil operator, attempted to drill a well on the Bates lease approximately 2 miles from the Rhodes Yates water-flood project operated by Texaco. The Hartman #2 Bates well encountered brine at a depth of 2240 feet; the drilling had to be terminated at 2280 feet. In 1953, the Bates #1 well was drilled without encountering pressurized brine.

Water flooding was started in the Rhodes oil field in 1959. Texaco initiated a pilot water flood in 1964. The water flood was extended in the Rhodes field in 1974. There are several active water flood projects in the Rhodes Yates area.

I reanalyzed the Hartman Scenario. In doing so, I first estimated the transmissivity of the Bates # 2 well that flowed extensively. From the transmissivity, I estimated the permeability. This should be obvious, but we are not totally sure what constituted the permeable zone in the Bates # 2 well. I then: 1) compared this estimate of permeability with those measured at WIPP, and 2) estimated the inflow to WIPP should the permeabilities at the Bates # 2 site apply in the vicinity of WIPP.

Transmissivity & Permeability

The Bates # 2 well flowed 840 gpm, or 1.9 cubic feet per second (cfs). The shut-in pressure at the land surface was 1000 psi—approximately 2000 feet of head at the land surface (Van Kirk, 1994). Knowing both the flow rate and the well-head, shut-in pressure there are several methods that can be used to estimate permeability. I first used the Theim, steady-state solution for radial flow to a well and solved for transmissivity, T. I then compared this result to results from two other estimating procedures.

The difficulty with the Theim approach is that we do not know how far out the cone of depression for the Bates # 2 well extended. (We can define the other boundary of the cone as the point where the drawdown caused by flow to the well is negligible.) I assumed several different radial distances for the extent of the cone (r_2), and make the calculations. The differing radial distances bracket the cone. As we see, the estimates do not vary a great deal—by a factor of only two which is small in estimating transmissivity.

$$T = 2.3\, Q \log (r_2/r_1)/[\, 2\pi (s_2 - s_1)]$$

where T = transmissivity

Q = well production rate

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r_2 and r_1 are selected radial distances from the center line of the well bore. I chose r_1 at the wall of the borehole approximately 0.5 ft (1 foot diameter well bore—slightly larger than the drill bit). I let r_2 be the radial extent of the cone of depression—the distance at which the drawdown is negligible.

(s_2 - s_1) is the total drawdown within the cone of depression caused by the well—1000 psi. (Perhaps I need to amplify this explanation. When the well is flowing the pressure at the well head is atmospheric—which is generally defined as 0. The well head, shut-in pressure gives a us an indication of what the formation pressure would be without the well flowing. The total pressure drop when the well is flowing is 1000 psi. It could be smaller due to friction losses in the well bore —a smaller pressure drop gives a higher estimate of permeability. The total pressure drop across the cone of depression is also 1000 psi.)

I assume the brine produced a pressure of 0.5 psi per foot of brine. (Van Kirk, 1994, reports the normal pressure gradient for saturated salt water as 0.525 psi per foot; I simplified the calculation by rounding to 0.5 psi / ft.)

With r_2 = 1,000 ft.

$T = 2.3 \times 1.9 \times \log(1{,}000.0 / 0.5) / (2\pi \times 2000.0) =$ 0.0011 ft^2/sec

With r_2 = 10,000 ft

$T = 2.3 \times 1.9 \times \log(10{,}000.0 / 0.5) / (2\pi \times 2000.0) =$ 0.0015 ft^2/sec

With r_2 = 100,000 ft

$T = 2.3 \times 1.9 \times \log(100{,}000.0 / 0.5) / (2\pi \times 2000.0) =$ 0.0018 ft^2/sec

With r_2 = 1,000,000 ft

$T = 2.3 \times 1.9 \times \log(1{,}000{,}000.0 / 0.5) / (2\pi \times 2000.0) =$ 0.0022 ft^2/sec

We can also estimate the transmissivity using estimating procedures suggested by Theis et al. (1963) for pumped wells, and by Bredehoeft et al. (1983) for flowing wells. The specific capacity is 0.4 gpm per foot of drawdown, or 0.00095 ft^2 / sec per foot of drawdown. The Theis estimate yields:

T = specific capacity x 2000 (in units of gallons per day per foot)

T = 0.4 x 2000 = 800 gallons per day per foot = 0.0012 ft^2/sec.

Bredehoeft et al (1983) produced a graphical type curve: use of the Bredehoeft et al. method yields:

T = 0.0015 ft^2/sec

The estimates compare favorably; the values vary by only a factor of two. Since transmissivity can vary over 15 orders of magnitude, a factor of two variation (100%) in the estimates is considered quite good.

The permeability is less clear, only because we do not know through what vertical thickness of rock brine flowed. The drilling encountered brine at a depth of 2240 feet, and was stopped by too much flow at 2280. Assuming the entire 40 feet was permeable, the

	k = T/ thickness = 0.001 / 40.0 =	0.000025 ft/sec
or	k =	0.00075 cm/sec
	k =	0.75×10^{-12} m^2

Implications of the Analysis—Comparison to WIPP

It should be remembered that these numbers are estimated by applying a model for radial flow to/from a well. The estimate is some kind of an average permeability that applies to the entire cone of depression for the well. In other words, it is an estimate of the regional permeability within the assumed cone of depression.

The permeability of the Anhydrite marker beds was measured in-situ at WIPP. The range in anhydrite marker bed permeability data used in PA is

k anhydrite– undisturbed	7.94×10^{-18} m^2 to 10^{-21} m^2
k anhydrite—hydro-fracture maximum value (PA)	10^{-9} m^2
Hartman— Bates # 2	7.5×10^{-13} m^2

The permeability encountered in the Bates # 2 well almost surely represents hydro-fractured anhydrite in the Salado Formation. The shut-in pressure of the Bates well was 1000 psi at land surface. There were reports of oil field brine injection activities in the area with 1000 psi land surface pressures and higher (Van Kirk, 1994). Dennis Powers reported: *"For the Rhodes Yates water flood, the injection pressure at the surface ran 1200 psi and above. Some injection pressures approached 2,000 psi at the surface." (Silva, 1994, p. 67)* A pressure of 1000 psi at land surface is approximately lithostatic at a depth of 2000 feet.

The consensus interpretation of what happened in the Rhodes Yates area is that water injection at high pressure caused massive hydraulic fracturing within the Salado Formation. Numerous wells have encountered flows of water in the Salado (Van Kirk, 1994). The hydraulic fracturing has increased the Salado permeability on a regional scale. Hartman won his law suit on the basis of this hypothesis. This interpretation is consistent with our analysis of the permeability encountered in the Bates # 2 well.

Potential Flow to WIPP

It is of interest to calculate the flow to WIPP through the anhydrite marker beds. I will do two calculations with 1) unfractured anhydrite, and 2) hydro-fractured anhydrite. I will use a simplified model for analysis. I make a number of assumptions

1. two-dimensional, areal flow (x, y) in contained marker beds 139, A and B.
2. good connection between the marker beds and WIPP,
3. single-phase, liquid flow only;
4. steady flow (not transient).

5 that fluid is injected with a pressure at a land surface of 1000 psi (68 atmospheres)—pressures like that measured at the surface in the Bates # 2 well; (This is lower than the 1200-2000 psi pressures reported for surface pressures of injection wells in the Texaco Rhodes Yates water flood. As we will see, 1000 psi poses problems.)

6 that the casing of the injection well fails, and 1000 psi surface pressure is imposed on marker beds 139, A and B;

7 in the hydro-fractured case that the marker beds have a regional permeability equal to that at the Bates # 2 site—7.5×10^{-13} m^2; (This assumption deserves more explanation. I suggested above that the hydraulic fracturing in the vicinity of the Texaco Rhodes Yates water flood increseased the permeability on a regional scale. I am assuming that similar, regional scale hydraulic fracturing occurs in the vicinity of WIPP.)

8 the repository is at hydrostatic pressure and remains at hydrostatic pressure; (Early in the history of the repository the pressure could be more nearly atmospheric. As the repository receives significant flow the pressure will increase. For this analysis, I neglect both the early pressure history below hydrostatic, and the later potential pressure build-up above hydrostatic If one examines the pressure histories of WIPP computed by PA, hydrostatic pressure is the dominate mode.)

9. since the region of the model is finite, I assume no flow boundaries at the edge of the modeled region. (These boundaries force the flow to go to WIPP where the head is held hydrostatic. Ideally, we would like no head build-up at the boundaries; as one can see below there is some build-up at the model boundaries. This condition can be relaxed by extending the model outward. In the hydro-fractured case the permeability is increased in a restricted area; therefore the outer, no-flow boundary may not be as bad an assumption as might appear at first glance. The region model is fairly large; and the boundaries are somewhat removed from the area of principal interest.)

The results are summarized in the following table:

Table I Flow to WIPP

	Distance from well to WIPP	Well-head pressure (psi)	Permeability m^2	Flow rate m^3 / sec	Flow rate m^3 / day
Model 1	2 km	1000	10^{-18}	7×10^{-9}	0.0006
Model 2	2 km	1000	7.5×10^{-13}	5×10^{-3}	430.0 (157,000 / yr)

Note: the approximate total pore volume of the repository, after the salt deforms, is 50,000 m^3.

It is of interest to examine the head distribution produced by this model's. The head is the same for each permeability distribution; even though, as Table I shows, the flows are quite different. The attached Figure is an isometric projection of the head. One can picture the flow if you remember that flow is directly down the gradient in head—it is analogous to a marble rolling down hill.

Concluding Remarks

Injection fluid pressures in the vicinity of the Bates lease were high. It seems clear from the data that the pressures were sufficiently high to produce massive hydraulic fracturing over a large area that included the Bates # 2 well. The permeability, as estimated from the well, is five orders of magnitude higher than the highest undisturbed measurements at WIPP. On the other hand, the Bates # 2 well permeability is three orders of magnitude lower than the maximum hydro-fracture permeability used in Performance Assessment.

Fluid injection in the vicinity of WIPP has the potential to quickly fill the repository with brine should the operation be similar to that which occurred in the vicinity of the Bates lease. The Hartman Scenario is not easily dismissed.

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WIPP–Hartman Scenario
(head above hydrostatic)

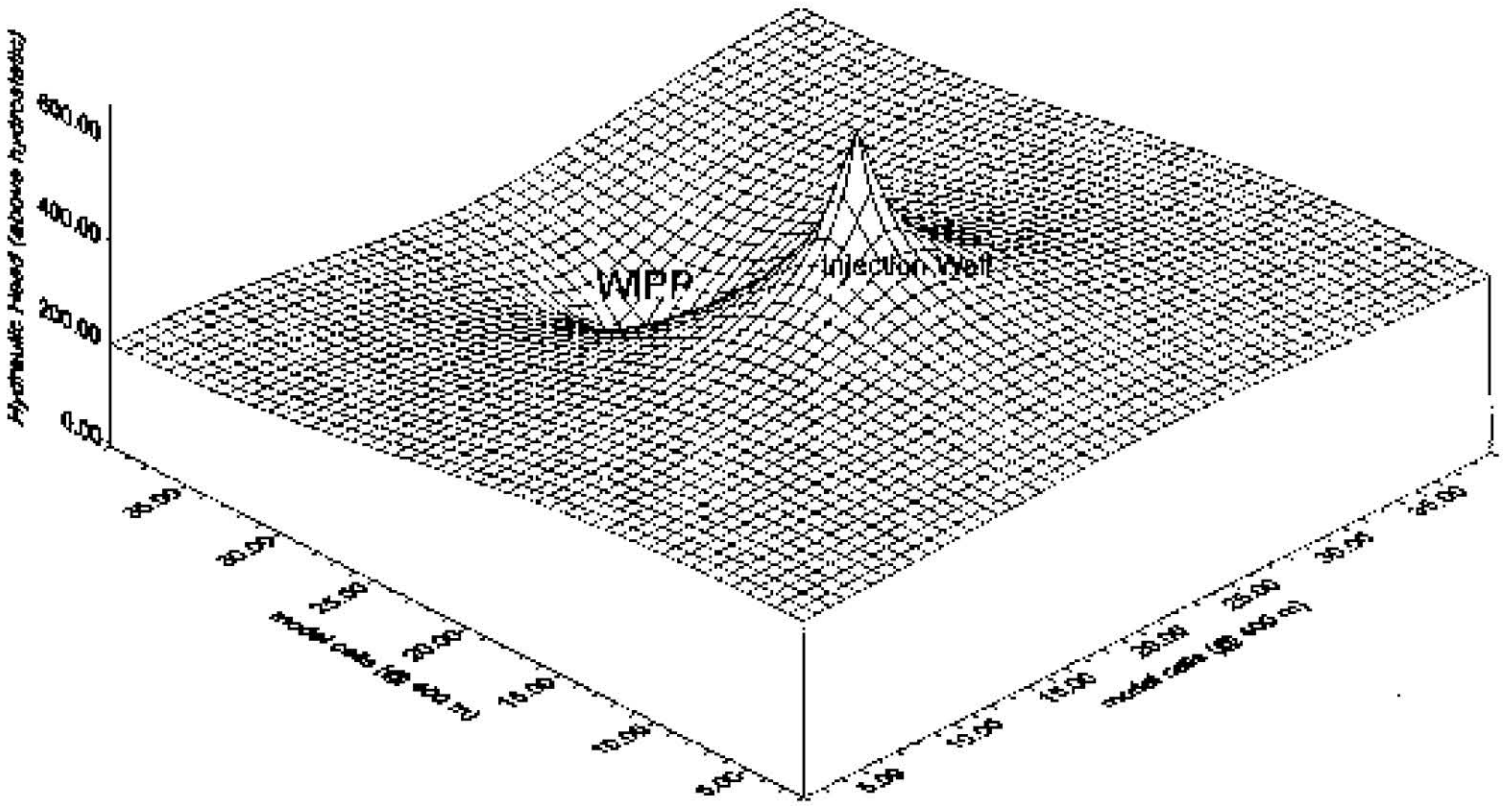

The HYDRODYNAMICS Group
studies in mass and energy transport in the earth

JOHN BREDEHOEFT *PhD, NAE*
principal

January 14, 1997

MEMORANDUM

To: **Lindsay Lovejoy, Jr.**

From: **John Bredehoeft**

Subject: **Hartman Scenario—Stoezel-O'Brien Analysis**

Introduction

Stoezel-O'Brien did a cross-sectional analysis. I modeled a cross-sectional to compare with our areal analysis and show you the difference.

Analysis

I selected a cross-section strip that is two model cells in width—a total width of 800 meters. This is approximately as wide as the smaller dimension of the repository foot print. As before, I placed the injection well 2 km from the repository. I used the permeability estimates from the Hartman # 2 Bates well. I assumed an injection pressure of 1000 psi at land surface; held the repository at hydrostatic head; and did a steady-flow calculation.

This analysis is analogous to our previous analysis except that we now have flow only in the cross-sectional strip. Enclosed is an isometric plot of head for comparison.

Results

The results are summarized in the following table:

Table 1 Flow to WIPP

	Distance from well to WIPP	Well-head pressure (psi)	Permeability m^2	Flow rate m^3 / sec	Flow rate m^3 / day
Model 1 (areal)	2 km	1000	10^{-18}	7×10^{-9}	0.0006
Model 2 (areal)	2 km	1000	7.5×10^{-13}	5×10^{-2}	430.0 (157,000 m^3/yr)
Model 3 (strip)	2 km	1000	7.5×10^{-13}	1×10^{-3}	86.4 (31,600 m^3/yr)

Note—the approximate total pore volume of the repository, after the salt deforms, is 50,000 m^3.

As you can see, restricting the flow to a cross-sectional strip reduces it to approximately 1/5 of the amount in areal model. This is the conceptual difficulty with the Stoezel-O'Brien approach.

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WIPP Analysis

Flow to/from WIPP is three dimensional. Sandia claims, perhaps correctly, that analyzing the full 3D flow problem is much too computer intensive to be practical for PA. For this reason the problem is idealized currently into a plane—a cross-section in the case of WIPP. (Two dimensional analyses, either areal—x, y; or cross-sectional—x ,z; or radial—r, z, are the rule in analyzing flow problems.) Any of 2D geometry is an approximations for the 3D problem. The simplification is a compromise—sometimes good, and sometimes not so good. You can see that the Stoezel-O'Brien cross-section was not very good for analyzing flow to WIPP.

In previous PA analyses a radial formulation was used in which radial distances were measured out ward from the disposal room. This formulation did not handle the connection between the disposal panel and the rest of the repository very well. This was changed to a cross-section in an effort to improve this portion of the modeling. The new cross-section will not do well in handling flow outward in the marker beds, the radial model was better in this instance.

I know that Chuck Byrum is concerned about the 2D approximations used in WIPP PA. EPA has had HydroGeologic looking into these approximations.

My gut reaction is that most of the approximations associated with the cross-sectional analysis used in BRAGFLOW are probably okay—assuming a 2D analysis is the only one practical. As I suggested to Sandia when it was presented, the Stoezel-O'Brien cross-section concept used for analysis was poor, at best.

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Head (m)
Injection Well
WMPd

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March 14, 1997
Director,

Center for the Waste Isolation Pilot Plant Program
U.S. Environmental Protection Agency
Office of Radiation and Indoor Air
401 M. Street S.W.
Washington, D.C. 20460

Dear Mr. Marcinowski:

Enclosed please find the EEG's additional comments on significant issues arising from our review of the WIPP Compliance Certification Application (CCA). This package of 14 papers complements the package of 6 papers submitted to you on February 7, 1997, following the same format.

Please note that as we continue to explore deeper into the assumptions, professional judgements, calculations, conceptual and numerical models, and secondary documentations related to the CCA, we are bound to come up with additional issues to be sesolved. We do not view the March 17, 1997 deadline as a bounding date for communicating additional concerns to the EPA. Given the significance of the decision that the EPA has to make, and the time that the DOE has taken to prepare this application since EPA originally promulgated 40 CFR 191 in 1985, 4 months of review time is not enough. Actually, the review time was much shorter since many of the issues that we have identified required a review of the Sensitivity Analysis Report that was provided to the EEG on January 20, 1997, and additional materials that have only recently been added to the Records Packages at the Sandia National Laboratories.

A detailed review of the July 1995 DOE draft CCA (DCCA) was provided by the EEG to the DOE in February 1996 and later published as the EEG report, "Review of the WIPP Draft Application to Show Compliance with EPA Transuranic Waste Disposal Standards", EEG-61, March 1996. The EEG has not received comments on that review from the DOE to date, and we have found no changes between the draft and the final CCA as a result of the EEG review (EEG-61). In our additional comments on the CCA to be provided in a report that we plan to publish this year, we will analyze our comments on the DCCA and how they have been treated in the CCA. At this time, we are formally submitting a copy of EEG-61 to you and to the Docket as part of our comments on the CCA.

The issues identified in EEG-61, our letter and encloserues date 2/7/97, and this letter and the enclosures, should therefore be considered to be our formal comments on the CCA submitted to you before 3/1797 deadline. As you can see, we have concentrated our efforts so far on reviewing the Containment Requirement related issues of the CCA. We will provide comments on the other parts of the 40 CFR 191 subpart B compliance as we review the compliance with them.

The overall EEG recommendation to the EPA at this point is to require the DOE to include consideration of additional scenarios like water-flooding and solution mining, with corrected conceptual models and parameter values in showing compliance with the Containment Requirements of the EPA Standards, 40 CFR 191. EPA should also require robust engineered barriers as part of the Assurance Requirement of 40 CFR 191.

Sincerely,

Robert H. Neill
Director

RHN:LC:pf
Enclosures: EEG Reviews of the WIPP CCA

Brine Reservior Assumptions in the CCA (Revised)
Faulty Sapling Ranges
Brine Inflow from Salado: 2D versus 3D Geometry in BRAGFLO
Probability of Microbial Degradation
Borehole Plug Lifetime
Inconsistency Between Direct Brine Release and Spallings Geometry
Waste Permeability Values
Random Emplacement of the Waste in the Repository
Residual Brine Saturation of Waste
Compendum of Direct Brine Release Problems
Active Institutional Controls
Passive Institutional Controls
Potash Mining
Documentation of FEPs and Parameters

cc: Ms. Jennifer Salisbury, NMEMNRD
Mr. Lindsay Lovejoy, Jr., NMAG
EPA Docket for WIPP (A-9302)

BRINE RESERVOIR ASSUMPTIONS IN THE CCA (Revised)

This section updates EEG's previous submission of 2/7/97 to the EPA on brine reservoir assumptions. A new section, "Revisions to Parameters" has been added to address issues raised in the January 16, 1997 memo of Rick Beauheim to Palmer Vaughn[1]. No other changes have been made to the original submission.

The EEG sees no justification for assuming only 8% probability of intercepting a pressurized brine reservoir in the Castile Formation 250 meters below the repository. The fatal flaw in the CCA argument for 8% is the assumption that the oil and gas wells that did not report encountering brine did in fact not encounter a brine reservoir. The fact is that the drillers are not required to report brine encounters to the state or federal authorities and no mention would be found in the records unless undue delays or hazardous conditions are encountered.

The 8% probability also ignores the data from WIPP-12 and the TDEM survey over the repository. The borehole WIPP-12 is located north of the repository within the WIPP site. It was drilled to the bottom of the Salado Formation in 1978 and deepened in 1981 at the EEG's suggestion. The DOE contractor (Popielak et al., WIPP-TME-3153, 1983) estimated the volume of the reservoir to be 2.7 million m^3 (17 million barrels). For the maximum possible reservoir thickness of 24 meters, the surface footprint of a cylinder containing this volume would have a diameter of more than 3 km. As the attached figure shows, the WIPP repository is most likely underlain by the brine reservoir encountered by WIPP-12. In addition, the TDEM survey (SAND 87-7144) gives an indication of the presence of brine at the upper Castile horizon. To try to assign specific areas of the presence of brine from this geophysical survey would be over-interpretation of the geophysical data. Combination of the WIPP-12 data and the results of the TDEM survey indicate the existence of brine under the repository. Any borehole drilled into Castile under the repository should therefore be assumed to encounter brine.

The EEG does not find the CCA reservoir volume assumption of 32,000 to 160,000 m^3 to be justified. This is based on the assumption of depletion of reservoirs by future drillers - 100% probability of encounter for the depletion assumption, while only 8% for releases!

The attached table shows the comparison between the characteristics of the WIPP-12 brine reservoir and the CCA assumptions.

The WIPP site was moved twice; in 1975 after the borehole ERDA-6 encountered a brine reservoir, and again in 1982, after WIPP-12 encountered brine. The CCA assumptions of probability should be realistically based on the site specific information, and the characteristics should be based on the WIPP-12 experience.

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[1]Beauheim, R., Revisions to Castile Brine Reservoir Parameter Packages, memo to P. Vaughn, in WPO 31084, Sandia National Laboratory, January 16, 1997.

The DOE Conceptual Model Peer Review Panel, in their December 1996 report, essentially agrees with the EEG position, but has accepted the DOE position that there are no significant consequences of the probability and volume assumptions.

The EEG does not accept the "no consequence" argument that is based on piecemeal, partial sensitivity analyses.

Revisions to Parameters

On January 16, 1997, Rick Beauheim of Sandia National Laboratories recommended revising five parameters describing the Castile brine reservoir conditions[1]. The reasons for these changes are presented in the parameter record packages WPO 31070, 31072, 31082, 31083, and 31084. Even though the parameter ranges recommended by Beauheim are more reasonable than the ones used in the CCA, the EEG disagrees with the recommended values for reservoir volume because the range includes the value derived from testing the ERDA-6 brine reservoir and initial pressure because of the use of data from twelve other brine encounters in the Salado. The combination of the TDEM survey and the estimates of the areal extent of the WIPP-12 brine reservoir provides a strong evidence that the WIPP-12 reservoir and the brine under the repository are one and the same. Therefore, only the WIPP-12 brine reservoir characteristics should be used to define the parameters used in the CCA performance assessment.

Beauheim points out that the parameters should be constrained by what he terms the productivity

$$PR = V\frac{C_r}{f}$$

ratio (PR), given by:
Where V is the sampled reservoir volume, C_r is the rock compressibility and ϕ is the porosity. Beauheim's recommended range for this constraint is $7x10^{-4}$ to $4x10^{-2}$ m^3/Pa, in which the $7x10^{-4}$ m^3/Pa value is from ERDA-6 data and $4x10^{-2}$ m^3/Pa is consistent with the WIPP-12 data. The constraint PR should be fixed at $4x10^{-2}$ m^3/Pa in order to agree with the WIPP-12 data, and the ERDA-6 data should not be used because it is irrelevant to the present WIPP site. Thus, with porosity fixed, the reservoir volume (V) should be inversely correlated with the sampled value of rock compressibility so that PR equals $4x10^{-2}$ m^3/Pa. Attached is a figure from an October 3, 1996 memo from Rick Beauheim to Les Shephard[2] showing PR calculated from the sampled parameters of the CCA calculations. The figure has been modified to point out the $4x10^{-2}$ m^3/Pa value determined for WIPP-12. Only five out of 300 samples were as large as the WIPP-12

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[2]Swift, P.N., K.W. Larson, and R.L. Beauheim, Treatment of Castile Brine Reservoir in the 1996 CCA Performance Assessment, Memo to L.E. Shephard, WPO 41885, Sandia National Laboratory, October 3, 1996.

measurements. This figure clearly demonstrates the inappropriateness of the Castile brine parameters used in the CCA calculations.

The recommended initial pressure range of 16.5 to 11.0 MPa gage is based on pressure measurements from thirteen Castile brine encounters. At WIPP-12 the measured pressure was 12.6 MPa gage. Therefore, the reservoir pressure should be a constant value of 12.6 MPa gage in the revised CCA calculations.

Comparison of WIPP-12 Brine Reservoir and the CCA Assumptions

Parameter	WIPP-12 (m^3)	CCA (m^3)
Total Reservoir Volume	2.7×10^6 (a)	32,000 to 160,000 (d)
Projected Max. Artesian Flow	55,821 (b)	5,200 (e)
Flow to Surface During Drilling	4,306 (c)	400 to 2,100 (f)

(a) WIPP/TME-3153, p. H-54
(b) WIPP/TME-3153, p. H-55
(c) WIPP/TME-3153, p. H-9; Actual "unavoidable" flow
(d) DOE/CAO-1996-2184, Table 6-26; Beauheim (1/16/97 Memo to Vaughn) revised the estimate to 100,000 to 1,700,000 m^3
(e) CMPRR-Suppl., 12/1996, p. 42; To the Culebra, after 6 encounters
(f) CMPRR-Suppl., 12/1996, p. 42; In 10,000 years

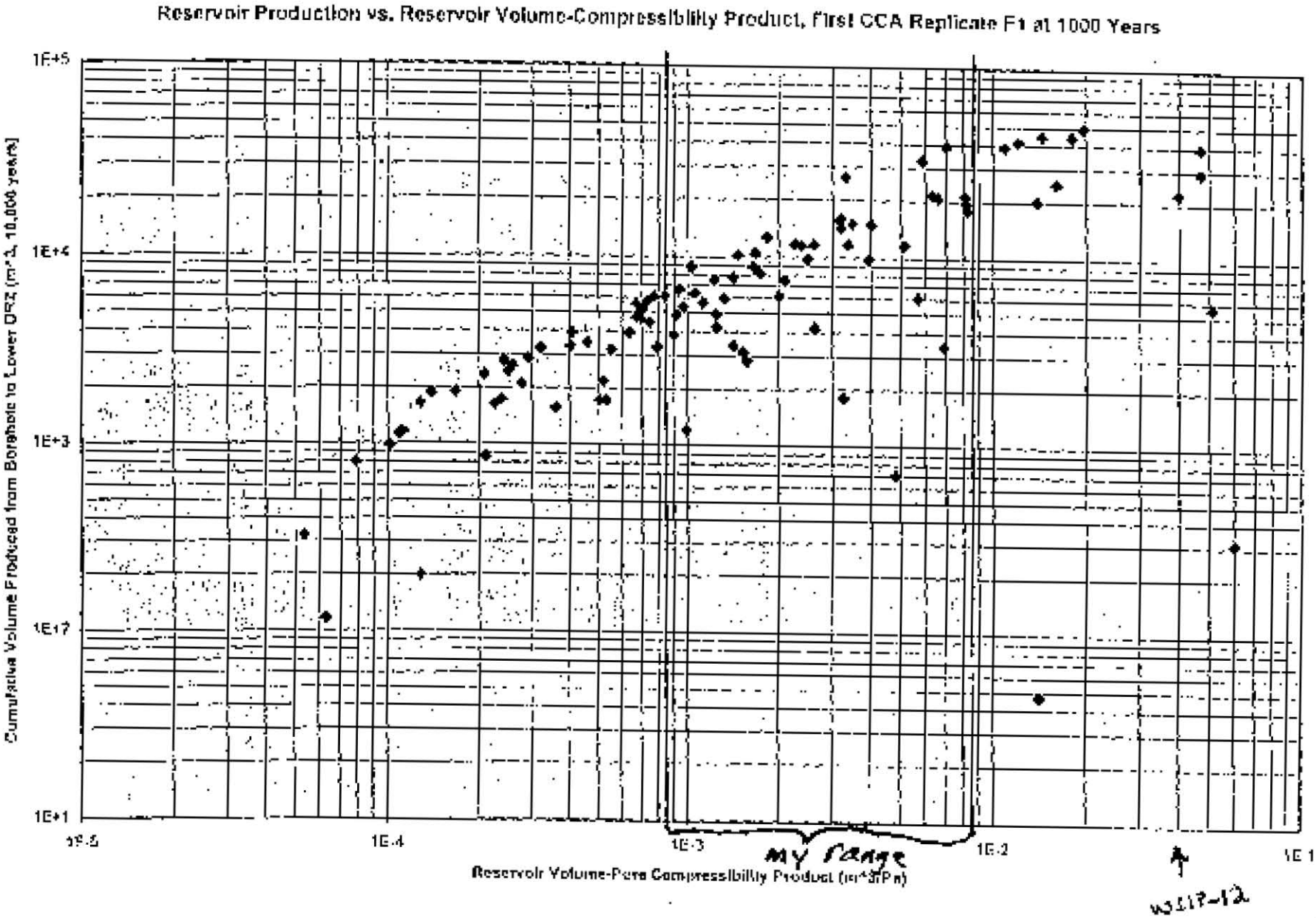

Figure 2

Figure 1 (From Sunkit et al., 1996)

INFORMATION ONLY

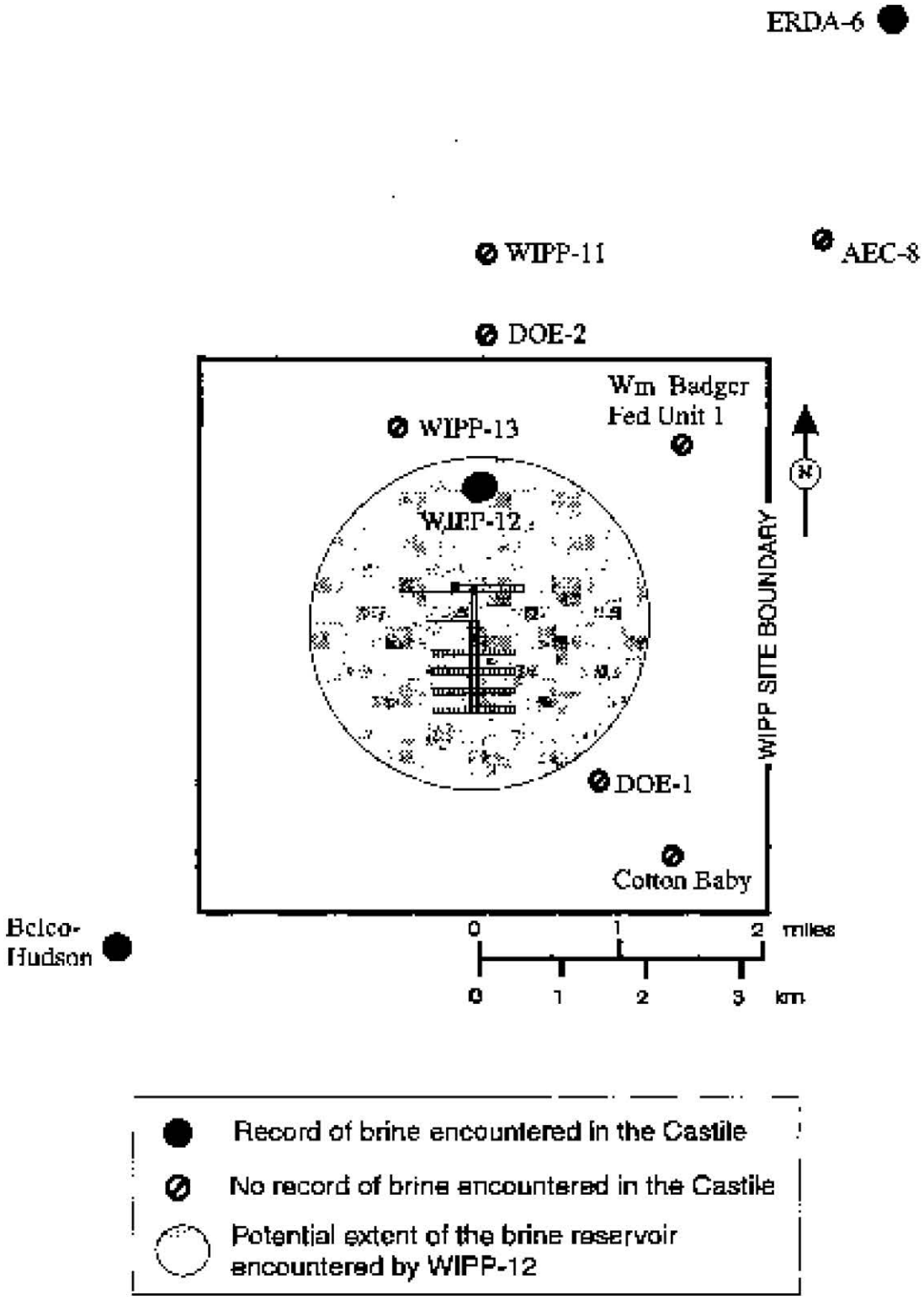

Potential extent of WIPP-12 brine reservoir using WIPP-12 pressure recovery data, rock compressibility of $1 \times 10^{-9} Pa^{-1}$, and reservoir thickness of 24 meters.

FAULTY SAMPLING RANGES

Recently, arguments have been made that if the sampled distributions of parameters used in the CCA calculations are in error, but include the likely values of those parameters, then the CCA calculations are acceptable. We disagree. Under these conditions, the CCA calculations should be repeated with the best estimate of the parameter distributions available. The use of a faulty distribution of one parameter biases the CCDF curves and confuses the assessment of uncertainty. The use of more that one faulty parameter set makes the assessment of uncertainties impossible because of the complex non-linear nature of the performance assessment models.

In this report we state our case in two ways - first by example and then abstractly. The most notable occurrence of a faulty parameter distribution is the Castile brine reservoir volume distribution used in the CCA calculations. The error has been admitted by DOE and considered by the conceptual model peer review panel.

1) The Brine Reservoir Example

This example demonstrates the pitfalls of accepting parameter errors as inconsequential in a piecemeal fashion. The conceptual model peer review panel accepted the argument that the brine reservoir parameters were acceptable because the correct values were effectively included in at least some of the sampled vectors. They also concluded that the brine reservoir interception probability was inconsequentially in error because encounters with a brine reservoir, E1 events, do not have substantially different consequences from intrusions that do not encounter brine, E2 events. They reached this conclusion through inspection of results presented for the entire set of sampled vectors. First, their basic conclusion was flawed because the repository system is too complicated to be evaluated using the data presented. Second, they had no way to evaluate the effect of the biases introduced by the flawed reservoir volume parameter distribution on the data presented.

The EEG understands that the DOE currently considers the parameter distribution for the brine reservoir volume to be from 10^5 to $1.7x10^6$ m^3 rather than the range of $3.2x10^4$ to $1.6x10^5$ m^3 as used in the CCA calculations[3]. In the first supplemental conceptual model peer review report, the panel concludes that the error in volume is of no consequence because the pore compressibility-volume product range of the calculations includes the correct range[4].

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[3]Beauhiem, R., Revisions to Castile Brine Reservoir Package Packages,memo to P. Vaughn, in WPO#31084, Sandia National Laboratories, January 16, 1997.

[4]Wilson C., D. Porter, J. Gibbons, E. Oswald, G. Sjoblom, and F. Caporuscio, Supplementary Conceptual Models Peer Review Report, DOE, Dec. 1996, Page 41.

Later, the peer review panel used the comparison of plots of brine inflow, brine saturation, and gas generation from the both E1 and E2 intrusions to conclude that the intersection of the brine reservoir insignificantly impacted the releases and hence the probability of intersecting a reservoir was unimportant to the CCA calculations. The plots included data from all vectors of replicate 1 with no indication of which data were from vectors with the acceptable pore compressibility-volume product range.

The data the peer review panel used for their decision was inadequate. This conclusion is based on our interpretation of Figures 5.1.6 and 5.1.7 of the preliminary sensitivity analysis report on the CCA Calculations[5]. Figures 5.1.6 and 5.1.7 contradict the panels conclusion. Figure 5.1.6 presents volume and EPA unit releases for the different specified second intrusion times for an initial E1 intrusion at 350 and 1,000 years. Figure 5.1.7 presents similar release data for initial E2 intrusions. For initial intrusions of 350 years, and especially at earlier second intrusion times, Figure 5.1.6 presents substantially larger volumetric and radionuclide releases. The average volumetric release is almost two orders of magnitude higher for a second intrusion at 200 years after the E1 event compared to the E2. Because of assumed solubility differences in Castile and Salado brine, the normalized EPA release is only a factor of 30 higher 200 years after an E1 at 350 years. Since EEG has stated elsewhere that the solubility differences for plutonium are much smaller than assumed for the CCA, the comparison of volumetric releases may be a better indication of the differences. However, such a comparison is biased toward low volumetric releases in the case of an initial E1 event by the use of a flawed distribution of the pore compressibility-volume product.

With a pore-compressibility-volume product equivalent to WIPP-12, the probability of brine reservoir encounter set to 1. and, plutonium solubilities consistent with experimental data, the possibility that direct brine release will violate the compliance criteria can not be ruled out based on our present understanding of the CCA modeling.

2) General Considerations

Construction of CCDF curves to demonstrate compliance with 194 Part B requires estimates of the uncertainty in parameter values. Sampling over the parameter uncertainty ranges incorporates this uncertainty in the CCDF curves. Sampling also provides some assurance that deviations from reality, of best estimates for the repository system, will not have disastrous consequences. Thus, the parameters ranges must capture the true uncertainty in the results, unless compensating conservatism is used.

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[5]J. Helton, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Dec. 23, 1996.

If the parameter ranges are in error then the mean value of the CCDF curves will be biased and the distribution of the curves no longer represent the uncertainty in the understanding of the WIPP site. An error in this context means an incorrect representation of current understanding and should not be confused with an inaccurate understanding. Errors in the analysis are recognizable and correctable. The concern here is the consequence of recognizing an error but failing to correct for it. The basis for such a decision could be that the error does not matter or leads to higher CCDF curves. The decision to not correct a parameter error should only be made if the effects of the parameter are completely understood and the insensitivity or conservatism in the results can be clearly demonstrated.

Demonstrating the consequences of errors in most of the CCA parameter ranges would be difficult. The difficulty is compounded by potential interactions of errors in more than one parameter. Not only the effect on the CCA calculations must be demonstrated but the effect on potential calculations under conditions that may be caused by the other parameters must also be included. The effort could easily be much greater than the effort of a completely new set of CCA calculations and yet still fail to provide an adequate demonstration of the consequences.

The most reliable way to eliminate concerns about parameter errors is to rerun the CCA calculations with the proper values. It makes little sense to do so in a piecemeal fashion. The CCA calculations should be rerun only after a complete evaluation of the current set of calculations. Otherwise it will be nearly impossible to credibly provide reasonable assurance that the compliance criteria are met.

BRINE INFLOW FROM SALADO: 2-D VERSUS 3-D GEOMETRY IN BRAGFLO

The 2-D geometry used in the BRAGFLO appears to have caused an under-prediction of brine inflow to the repository and thus may have resulted in a significant under-prediction of the direct brine release. This assumption may also have effected the amount of releases predicted by the spallings scenario.

The justification for modeling the repository in a pseudo 3-D manner (2-D radial flaring) rather than in a full 3-D geometry has been provided through evaluation of FEP S-1[1]. The summary memo of record for the FEP S-1 screening analysis discusses the impact of the 2-D assumption on 1) brine flow through the anhydrite layers to the 2.4 km boundary, 2) flow to the top of the shaft, 3) brine flow up the borehole, and 4) the repository pressure. That memo[6] does not consider the effects of the 2-D assumption on the inflow of brine to the repository, and on the spallings or direct brine releases.

The amount of projected inflow of brine in the repository directly effects the gas pressure in the repository. Table 5.5.3 of the sensitivity analysis reported[7] lists the residual gas saturation as the parameter with the strongest influence on the projected direct brine releases. This is also shown in Figure 5.1.5 of the sensitivity analysis report (the attached Figure 1). In addition, brine inflow is important to the spallings release estimates through increased gas generation. This dependence is made clear in Table 4.4.3 of the sensitivity analysis report which lists halite porosity, a large source of brine, as the second most important parameter to spallings releases.

The screening analysis compared 2-D simulations of the repository to 3-D simulations of the repository. For computational efficiency, the calculations were performed for half the repository. Two sets of simulations were conducted for the analysis. One set of calculations used a gas generation rate below the level that would cause anhydrite bed fracturing. The second used twice the gas generation rate to ensure anhydrite bed fracturing. In both sets, less brine-inflow occurred in the 2-D case compared to the 3-D geometry. No dependency of gas generation on brine inflow to the repository was included in the calculations; gas generation was prescribed as a function of time, ending after 1,000 years in the screening calculations.

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[6]Vaughn, P., T. Hadgu, D. McArthur, and J. Schreiber, FEP Screening Analysis S1: Verification of 2D-Radial Flaring Using 3D Geometry, Memorandum to D.R. Anderson, January 26, 1996, WPO 30840, Sandia National Laboratory, Attachment 4-1 to Appendix Mass of the Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184, December, 1996.

[7]Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

The largest impact of 2-D geometry occurs with anhydrite bed fracturing. The 3-D model predicts the flow into the repository to significantly increase if the anhydrite beds fracture, while the 2-D model predicts the flow to decrease in relation to calculations without anhydrite fracturing.

Figure 15 of the FEP S-1 analysis (Figure 2) shows the cumulative brine inflow to the repository for the high gas generation calculations. The flows calculated using the 3-D model indicate that once anhydrite bed fracturing occurs, roughly $2x10^6$ kg (1,600 m^3) of brine enters the repository in a period of 200 to 300 years and that this flow rate was continuing unabated at the time of drilling intrusion. Another $4x10^6$ kg (3,200 m^3) flowed into the repository shortly after the drilling intrusion. Figure 2 shows differences of $4x10^6$ to $6x10^6$ kg (3,200 to 6,500 m^3) for much of the 10,000 years. The brine inflow differences listed above should be doubled for the full repository. Virtually no flow enters the repository as a result of anhydrite bed fracturing in the 2-D geometry. In fact, the net flow over the 10,000 year simulation is less with anhydrite fracturing compared with the simulation without the beds fracturing. Figure 2.1.4 of the sensitivity analysis report[2] (Figure 3) indicates very little marker bed inflow with microbial gas generation of plastics and rubber, supporting the findings of the FEPs analysis. Figure 5.1.5 of the sensitivity analysis report reveals the importance to direct brine release of these low brine inflows. The highest pressures are correlated with brine saturations below the residual brine saturation of the waste. The low saturations are due partly to increasing repository pore space with increasing pressure and partly to lower brine inflow.

Table 2.5.13 of the sensitivity analysis report indicates that the potential for anhydrite bed fracturing is high. As a crude approximation, consider the undisturbed scenario of a total fracture-enhanced flow of 20,000 m^3 over a period of 2,000 years. The highest repository pressure in the FEP S-1 calculations was 13 MPa. This corresponds to a repository pore space of 85,000 m^3 (Figure 2.3.5 of the sensitivity analysis report). The increased brine flow would increase the average brine saturation by 0.23. The CCA calculations do not include simulations of both very high pressure and brine saturations above the residual brine saturation of the waste. Inspection of Figure 5.1.5 suggests a significant impact from a 0.23 saturation shift at high pressures.

The simulations without anhydrite fracturing show a decrease of $1x10^6$ to $2x10^6$ kg (800 to 1,600 m^3) in predicted brine inflow in the 2-D simulations compared to the 3-D simulations (Figure 4; Figure 10 of the FEP S-1 memo). These flows are doubled for the full repository. The differences are most likely from differences in marker beds flows to the repository.

To put these brine inflow differences in perspective, note that average brine inflow to the repository in the CCA calculations of the similar S5 scenario was almost 40,000 m^3, with an average 8,000 m^3 from the marker beds[2]. Marker bed brine flows in the S5 scenario are dominated by flows under low pressure conditions. The marker bed flows are a more significant concern in the S1 undisturbed scenario. An average of roughly 3,000 m^3 flowed into the repository from the marker beds in the S1 CCA calculations. To approximate the brine flow error

in the undisturbed calculations for pressures below the anhydrite fracture threshold, we ratio the FEP S-1 differences by 3,000/8,000 - resulting in the range of 600 to 1,200 m^3 less brine inflow to the full repository. If 1,200 m^3 of brine were distributed throughout the entire repository it could increase the average saturations by 0.015 to 0.03 (0.04 to 0.08 in the S5 scenario and 0.16 to 0.32 after anhydrite fracturing in an S5 scenario). It is more likely that much of the additional brine would be consumed through increased gas generation, leading to higher repository pressures.

There are indications in the sensitivity analysis report that the computational grid effects the distribution of brine within the repository in addition to the overall magnitude of brine. One indication is the statement on page 2-26 that "Due to the computational grid in use (Fig. 1.2.1), the lower panel receives more brine inflow from the marker beds relative to its size than the upper waste panels (Fig. 2.1.2)." Another indication may be the importance of the residual gas saturation of the shaft seals to flow through the marker beds (Table 2.1.1 of the sensitivity analysis report). As stated in the report, "its selection may be due to effects related to brine and gas movement across the part of the computational grid that corresponds to the shaft in the repository and DRZ (i.e., regions 10,11 in Fig. 1.2.1)." As a result, the upper waste panels receive roughly one ninth of the brine inflow from the marker beds per panel as the lower waste panel. In a large fraction of the sampled vectors, gas generation stops in the upper panels because of limited brine availability for steel corrosion. Thus, the CCA calculations are under-predicting repository pressure as well as brine saturation.

The EEG concludes that the use of a 2-D geometry in the BRAGFLO may introduce significant non-conservatism into the CCA calculations. The FEP S-1 needs to be re-examined with appropriate consideration of the impact of increased brine saturation on calculated release estimates.

Figure 1

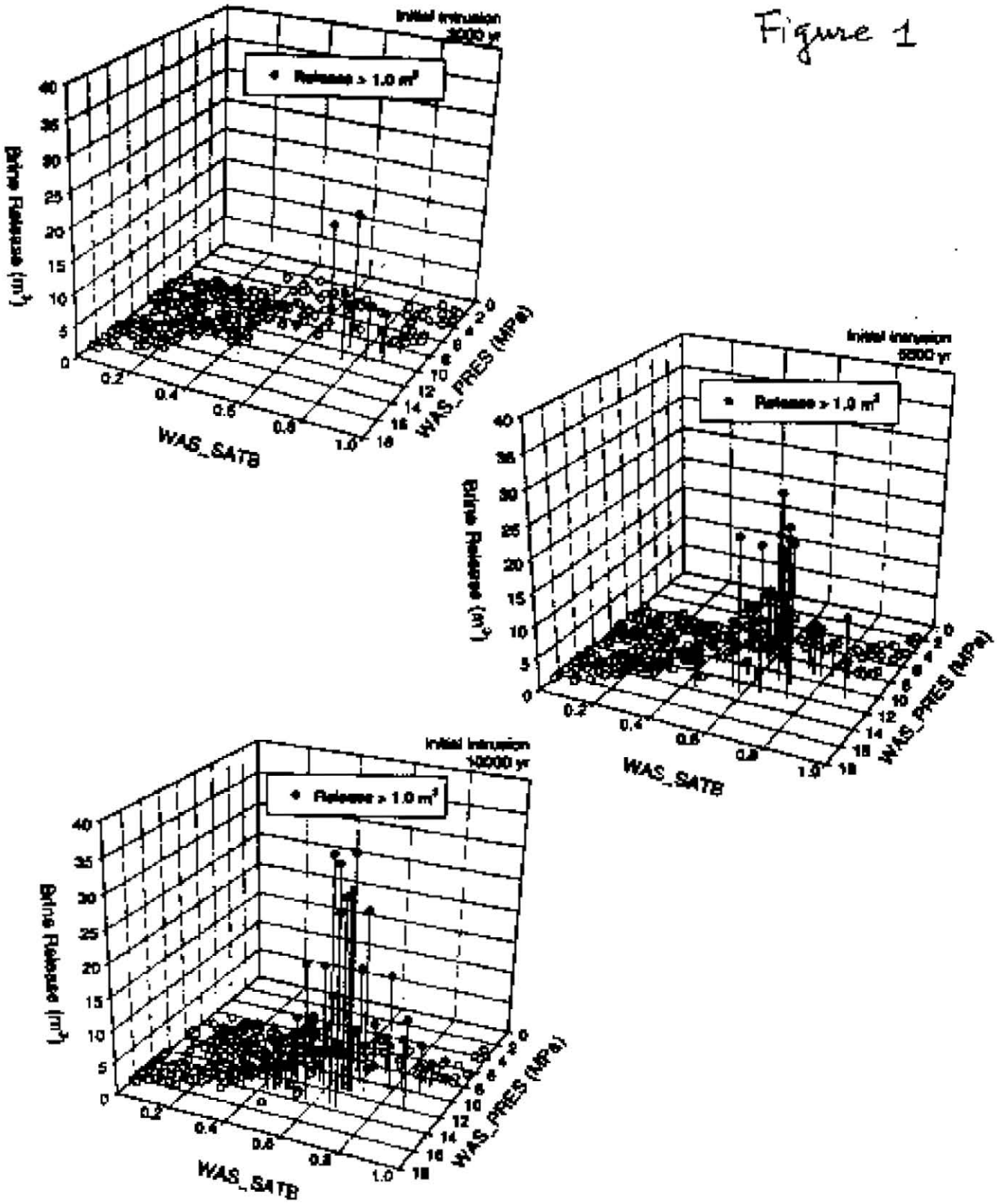

Fig. 5.1.5. Three dimensional scatterplots for volume of brine (m^3) removed due to direct brine release resulting from a single drilling intrusion into a previously unintruded repository that passes through CH-TRU waste in a lower waste panel, brine saturation and pressure (MPa).

From: Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

From: Vaughn, P., T. Hadgu, D. McArther, and J. Schreiber, FEP Screening Analysis S1: Verification of 2D-Radial Flaring Using 3D Geometry, Memorandum to D.R. Anderson, January 26, 1996.

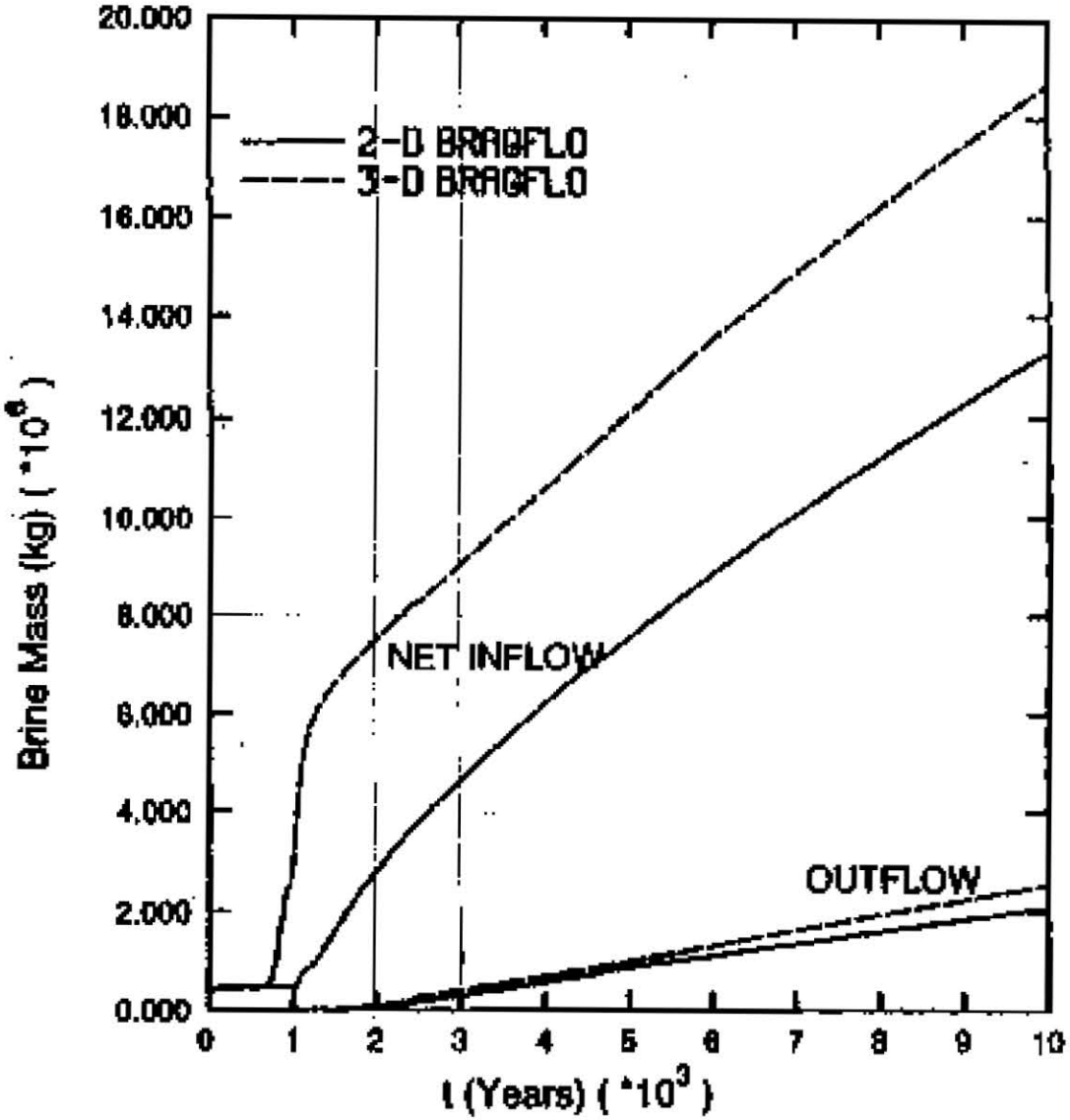

Fig. 15 Cumulative Net Brine in and Outflow at Repo.-Doubled Gas Generation rate

Figure 2

CRRA TA

SWCF-A:1.2.07.3:PA:QA:TSK:S1

Figure 3

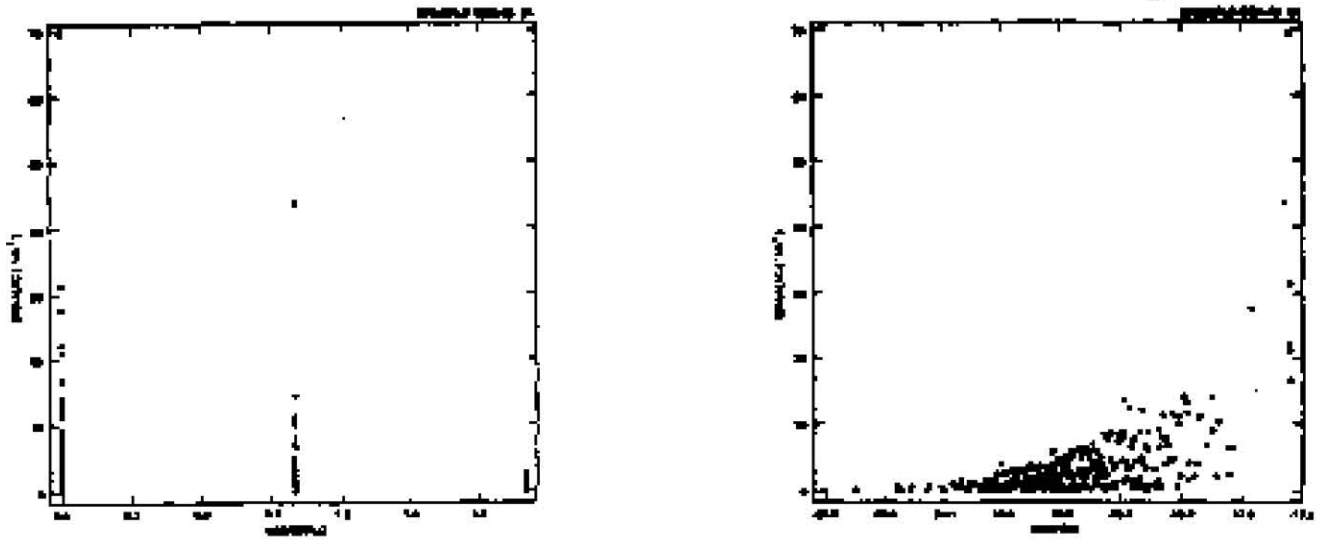

Fig. 2.1.4. Scatterplots for cumulative brine discharge (m^3) from the marker beds over 10000 yr under undisturbed conditions versus microbial gas generation flag (*WMICDFLG*) and marker bed permeability (*ANHPRM*, m^2).

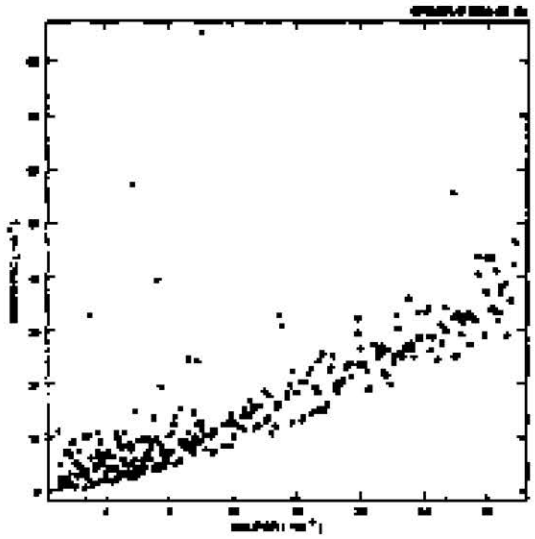

Fig. 2.1.5. Scatterplots for cumulative brine inflow (m^3) to the repository over 10000 yr under undisturbed conditions versus halite porosity (*HALPOR*).

From: Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

From: Vaughn, P., T. Hadgu, D. McArther, and J. Schreiber, FEP Screening Analysis S1: Verification of 2D-Radial Flaring Using 3D Geometry, Memorandum to D.R. Anderson, January 26, 1996.

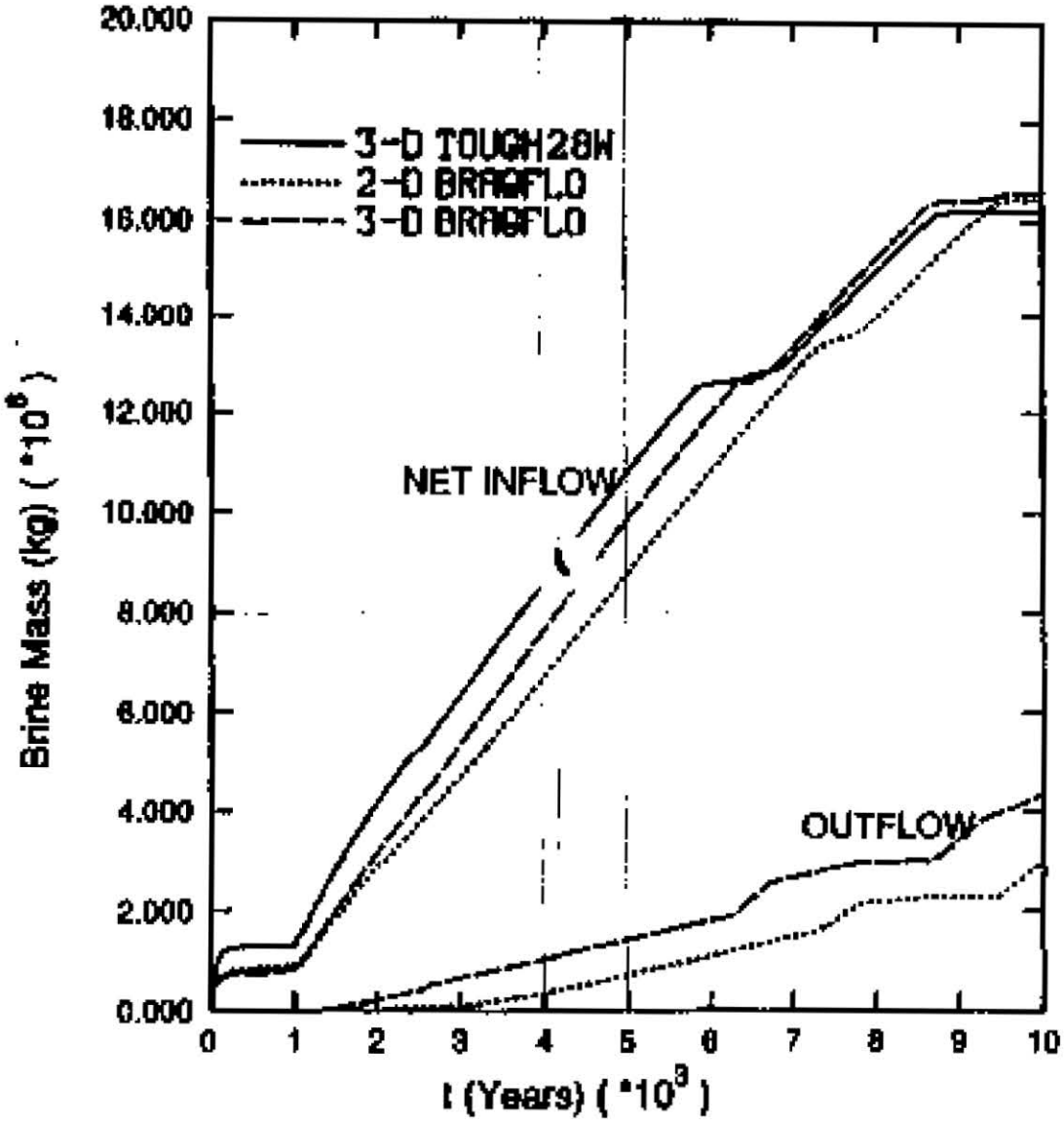

Fig. 10 Cumulative Net Brine In and Outflow at Repo. - Base Gas Generation rate

Figure 4

PROBABILITY OF MICROBIAL DEGRADATION

The sampled parameter for the probability of microbial gas generation determines whether cellulose and plastics and rubber will be degraded by microbial action after closure of the repository. No degradation of cellulose or plastics occurs in the calculations with a 50% probability. Only cellulose degrades in 25% of the sampled vectors. Cellulose, plastics, and rubber degrade with a probability of 25%. The preliminary sensitivity analysis report[8] lists this parameter as the largest influence on the variation of total calculated release from the WIPP repository.

The documentation[9] supporting this parameter does not contain any numerical justification for the probabilities assigned to this parameter. All of the hand calculations performed to calculate the gas generation parameters are included as attachments to the memo of Wang and Brush. Calculations for the degradation probabilities are absent from these attachments. It is the opinion of EEG that the numerical value of this parameter constitutes expert judgement. Given the importance of this parameter to the estimates of radionuclide release, this parameter should be demonstrated to be either solidly based on scientific evidence or be conservative. The justification for this parameter presented in support of the CCA does neither of these.

The numerical values of the degradation probability parameter should undergo peer review consistent with expert judgement. Otherwise, the parameter should be conservatively set to always specifying microbial degradation of cellulose, plastics, and rubber.

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[8]Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

[9]Wang, Y. and L. Brush, Estimates of Gas-generation parameters for the long-term WIPP performance assessment, Memorandum to M. Tierney, WPO 31943, January 26, 1996.

BOREHOLE PLUG LIFETIME

Borehole lifetime should be a sampled parameter in the CCA calculations or else the DOE should provide demonstration that variations in borehole lifetime do not effect the release estimates.

Repository pressure is one of the key factors determining the severity of both spallings and direct brine release. The repository pressure decreases rapidly after the failure of the borehole plug from an initial human intrusion in BRAGFLO calculations of most of the sampled vectors[10]. Thus, the assumed lifetime of the borehole plugs may have a large impact on the final release estimates. The upper borehole lifetime is fixed at two hundred years in all of the BRAGFLO calculations, except for the continuous plug configuration. This conflicts with the data used to calculate the borehole lifetimes[11]. The analysis indicates that the results of investigation on corrosion and borehole lifetimes are expected to vary over an order of magnitude (Thompson, et al. page B1) and are considered to be conservative(Page B-17).

The calculation of upper plug lifetime is not entirely clear. It seems to rely on 1) an assumed corrosion rate of 1- 3 mm/year for steel casing 2) the assumption of sufficient water 3) field observations of casing failures in the Salado and 4) rapid degredation of the concrete plug after casing failure. The assumption of corrosion rate is stated to be "very aggressive" and conservative and about one thousand times faster than the corrosion rate in the repository. Short borehole plug lifetimes could be considered conservative for releases to the Culebra, but not for spallings and direct brine release to the surface. The general assumption of sufficient water is adequately justified in the analysis. However, the point is made that cement outside of the casing may inhibit access to brine(Page B-18). Field observations indicate that casing failures in the Salado are well-known (Page B-20; Bailey memo in La Venue, 1991[12]) at depths less than 1,000 feet. However, the same report(Page B-17) also includes information that casing failures in the Salado are common but not pervasive.

The borehole plug lifetimes are likely to vary by over an order of magnitude. Borehole plug lifetimes should be a sampled parameter.

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[10]Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December 23, 1996.

[11]Thompson, T.W., W.E. Coons, J.L. Krumhansl, and F.D. Hansen. Inadvertent Intrusion Borehole Permeability, Attachment 16-3 in Appendix MASS of the Compliance Certification Application, DOE/CAO-1996-2184, October, 1996.

[12]La Venue, M. Anomalous Culebra water-level rises near the WIPP site, INTERA: Technical Letter Memorandum, January 28, 1991

INCONSISTENCY BETWEEN DIRECT BRINE RELEASE AND SPALLINGS GEOMETRY

The EEG considers the inconsistency in the conceptual models of direct brine release and spallings in the CCA calculations to be unacceptable. The transport of solids and brine to the surface as a consequence of human intrusion is a single process where both brine and solids are entrained in a high velocity gas flow. In our January 21st presentation to EPA, we argued that both brine and gas flow should be modeled as a single process.

The spallings model predicts that channels of void space will be created in a waste room as a result of room depressurization from drill penetration into the room. The channels develop because the velocity of gas is large enough to break the bond of particles from the compacted mass of waste and entrain them in the gas-flow down the channels. This process is aided by the flow of gas perpendicular to the channels. The solid mass calculated to have been released in the spallings model is assumed to evacuate an annular region around the borehole in the direct brine release model. Brine is calculated to be transported to the enlarged borehole region as described by Darcy's Law.

If open channels are created in the spallings process then pressure gradient will drive brine towards these openings. The distance to the open channels would be far less than the distance to the borehole for most of the brine in a waste room and all brine in other rooms of a repository panel. The cumulative release to the surface would, thus, be much larger than calculated by the direct brine release model.

Direct brine release and spallings should be modeled as a single process. If the process is separated into two models, these models must be consistent with each other.

WASTE PERMEABILITY VALUE FOR DIRECT BRINE RELEASE

Issue

The CCA uses a constant waste permeability value of $1.7x10^{-13}$ m^2 in the Direct Brine Release calculations. The method of calculating this value was questioned by a Peer Review Panel and DOE agreed that $2.4x10^{-13}$ m^2 was the appropriate value. The use of this higher value in CCA calculations is considered here.

The rate of radial flow to a well per unit drop in pressure or drawdown is directly related to the permeability of an aquifer. The same relation would apply to flow into a borehole that penetrated a waste storage room.

This discussion will not address other waste permeability related aspects of the Direct Brine Release, Spallings, or BRAGFLO Models such as relative permeability, residual brine saturation, and fracture flow.

Evaluation

SNL arrived at the value of $1.7x10^{-13}$ m^2 for consolidated waste from laboratory data on three major waste components (sludge, combustibles, and metals). The Engineered Systems Data Qualification Peer Review Panel discovered an error in the calculation of the overall permeability and, after discussions with SNL on the appropriate distribution to use on permeability values for each material, agreed with SNL that the appropriate calculated value should be $2.4x10^{-13}$ m^2.

The Peer Review Panel recognized that use of this higher permeability value would increase brine releases in direct proportion to the increase in permeability (41%). Yet they concluded that changing this value is not warranted because "the change does not have any effect on the final outcome," (page 9-191). The panel also opined that the data and assumptions that were used to develop the values were limited and either value was as good as the other.

Clearly there are uncertainties in the actual value of the consolidated waste permeability. There is also the question of whether the current assumption of darcy flow is appropriate or whether the rooms should be modeled as fracture flow. Neither issue is being addressed here.

Changes in the volume fractions of combustibles, metals, and sludges in the waste from the .40, .40, .20 values used in 1991 would also change this permeability calculation. The Final Waste Form volumes shown in Table 4-3 of the CCA are slightly different and result in a calculated permeability of 2.2^{-13} m^2.

Effect on CCA

The use of the higher waste permeability value ($2.4x10^{-13}$ m^2) should cause the CCDF plot of direct brine release to move 41% towards the compliance limit. The CCDF plot in the CCA (Figure 6-41) shows direct brine release to be only 0.05 EPA units at .001 probability. Increasing this by 41% would give a value of only 0.07 units and would have little effect on compliance. However, other questions are being raised about these releases: (1) Castile Brine Reservoir assumptions; (2) appropriate solubility values to use; and (3) details about the Direct Brine Release Model. These other factors could increase the calculated release by more than an order-of-magnitude. If this occurs the 41% increase could become significant.

Recommendation

If a single value for the consolidated waste permeability is to be used for direct brine release, then it should be $2.4x10^{-13}$ m^2 and not $1.7x10^{-13}$ m^2.

RANDOM EMPLACEMENT OF WASTES IN REPOSITORY

Issue

In the CCA, DOE assumes that the waste inventory will be emplaced in the repository in a purely random manner. This assumption leads to three further assumptions in the CCA:

(1) The 569 CH-TRU waste streams can be sampled randomly to determine the concentrations of radionuclides brought to the surface by cuttings and cavings;

(2) the concentration of radionuclides in the area of the waste room affected by spallings releases can be assumed to be the average of the entire WIPP inventory;

(3) the concentration of dissolved radionuclides in solution in a waste panel that has a Direct Brine Release also is calculated from the average of the entire WIPP inventory.

Evaluation

DOE correctly recognizes that the concentrations and radionuclides composition of individual waste containers vary widely and have attempted to account for this in the CCA by sampling on a volume weighted distribution on all 569 CH-TRU waste streams identified in the Baseline Inventory Report, Revision 2. This approach, if done properly, has the potential to fully capture the variability if emplacement is purely random.

EEG believes that actual waste emplacement may deviate substantially from random. This is due to three factors: (a) during the period that a waste room is being filled there is unlikely to be shipment of waste from all Generating Sites on a volume weighted basis. (b) waste being shipped from a Site in a TRUPACT II is unlikely to be representative of the entire site; and (c) wastes arriving on a TRUPACT-II trailer (e.g. 4 to 6 seven-packs of 55-gallon drums) from a site would be emplaced to gather. Its possible that as many as 1/3 of the 7-packs or Standard Waste boxes on a TRUPACT-II trailer would be stacked two-high in a waste room.

Examples of the deviations of average concentrations from individual sites from the total inventory average concentration are: (1) The Savannah River Site (SRS) average is 2.9 times the total average at 100 years; (2) Los Alamos National Laboratory (LANL) averages range from 1.3 to 1.8 times the total average from 100 years to 10,000 years; and (3) Rocky Flats (RFETS) averages range from 3.0 to 4.5 times the total average from 100 years to 10,000 years. Examples of variations within waste streams at a Site are: (1) 2,800 m^3 of residues at RFETS that are 3.3 times the Site average: (2) 60 m^3 of SRS waste that are 42 times the Site average; and (3) 850 m^3 at SRS that are 1.5 times the Site average.

Effect on CCA

In the 1991 Performance Assessment (SAND91-0893/2), Sandia National Labs (SNL) demonstrated that considering the effects of variable radionuclide concentrations in waste containers ("activity loading") resulted in normalized releases from cuttings and cavings to increase by a factor of about ten (at .001 probability) compared to using average activity in containers. SNL has used "activity loading" in PA methodology since that time and in the CCA, the sampling is on 569 waste streams for cuttings and cavings. There is no disputing the fact that sampling on activity levels will increase the calculated releases from cuttings and cavings for probabilities below about 0.5.

The radioactivity concentration and radionuclide composition of waste within a waste room or portion of a panel (i.e. the areas of influence for the spallings and Direct Brine Release calculations) would be expected to vary from the total inventory average. This variation would not be nearly as great as that expected between individual stacks of waste containers, but increases to several hundred percent of the average radioactivity concentration are clearly possible. The calculated releases from spallings at any intrusion time would be directly proportional to the radioactivity concentration.

The calculated radionuclide releases from Direct Brine Releases would depend on the concentrations of each radioactive element in solution. This concentration is dependent on the composition of individual radioisotopes in the waste. For example, in average SRS waste at 350 years the ^{238}Pu radioactivity is 75% of the total plutonium radioactivity compared to 11% of the total plutonium in the total inventory average. Thus, the radioactivity concentration of plutonium in solution would be higher for SRS waste at 350 years. Another example is concentrations of ^{233}U and ^{234}U. Appendix WCA of the CCA states the assumption that only 1% of dissolved uranium would be ^{233}U and ^{234}U, because in the total inventory these radioisotopes comprise less than 1 wt% of total uranium. However, data in the Baseline Inventory Report indicates that the 28,000 m^3 of stored CH-TRU at INEEL contains 20 wt% of ^{233}U.

These concerns of non-uniform emplacement of wastes in the repository touch on the issue of load management. The CCA concludes that load management is not necessary at WIPP (Chapter 4.3.1).

Importance to Compliance

EEG believes that deviations from the assumption of average emplacement has the potential to increase calculated releases at .001 probability from spallings and Direct Brine Release by several fold. Using a more conservative assumption of random emplacement may not result in non-compliance if all other assumptions in the CCA were held constant. However more conservative assumptions could noticeably shift the CCDF curve toward the compliance boundary and, when incorporated with other changes to the 10/96 CCA, calculations could have a significant effect on the final CCDF.

Recommendations

For the Spallings and Direct Brine Release scenarios, determining average waste concentration in one room would be closer to reality compared with using the average for the whole repository as currently used in the CCA. There are several possible approaches to determining justifiable waste room radioactivity concentrations. We recommend the following:

(1) The deviation from average concentrations of radionuclides in waste and brine could be mitigated by load management such that the concentrations in any waste room be limited to (say) 1.5 or 2 times the average at any time during the 10,000 year regulating period;

(2) A reasonable upper bound (not the theoretical maximum) for radionuclide concentration can be obtained by assuming that a room is filled entirely with average concentration waste from the generating site that results in the greatest consequences. For concentrations in the waste this would be RFETS. It is not obvious which site's waste would result in the highest brine concentration.

(3) Allow DOE to show by an appropriate statistical scheme that there is an acceptably low probability that concentrations in wastes and brine will not exceed (say) 1.5 or 2 times the average;

(4) Actually sample on this variability. Sampling might be first on the fraction of waste from each site that is brought into the room (with some deviation above and below the actual fraction of the total repository volume expected from that site). Then the variation of waste composition and concentration from each site (obtained from the 569 waste streams data) could be sampled on.

For the cuttings and cavings calculation DOE should determine an appropriate statistical scheme to evaluate the effect that emplacing wastes from individual sites in clusters will have on the current calculations involving sampling on 569 waste streams. If significant these new values should be incorporated into the CCA.

RESIDUAL BRINE SATURATION OF WASTE

The preliminary sensitivity analysis report[13] indicates (Table 5.3.3) that the calculated releases to the surface from the direct brine release model are most sensitivite to the sampled variation of the waste room residual brine saturation. For various reasons the direct brine release model may be significantly under-predicting releases. See, for example, the EEG position statements on the brine reservoir parameters, solubilities, sampled parameters and probability of microbial degredation. The sampled range of the waste room residual brine saturation is another one of those reasons.

The data and rationale for the sampled distribution of the waste-room residual-brine saturation is presented on pages PAR-27 through PAR-31[14]. The recommended distribution is uniform from 0 to 0.56. It is stated in the data section that the parameter values are based on literature values of unconsolidated materials. Ten materials are listed as the source of the data set. Eight of these data values are from unconsolidated materials with a range of 0.0783 to 0.277. Two of the source materials are consolidated sandstones with values of 0.243 and 0.560. As suggested in Appendix PAR, the sampled range should be based on unconsolidated materials. Use of the single consolidated sandstone value of 0.56 doubles the range of sampled values in a non-conservative direction.

The non-conservative distribution of 0 to 0.560 reduces the estimated releases of direct brine release. Appropriate ranges for the waste room residual brine saturation are a constructed distribution using values from the eight unconsolidated materials; a uniform distribution from 0.0783 to 0.277, or a uniform distribution from 0 to 0.277.

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[13]Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

[14]Appendix PAR of the Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184, December, 1996.

COMPENDIUM OF DIRECT BRINE RELEASE PROBLEMS

We have organized our comments on the CCA in a format so that individual sections tend to focus on single issues. To keep the individual sections brief, we have only occasionally touched on interrelationships between issues. In the case of the direct brine release model, we have found so many interrelated problems that it is worth bringing them together in a separate section. The issues raised in this section are discussed in more detail in their separate sections. The purpose here is to highlight how they have compounding effects on the direct brine release calculations.

We have identified nine separate issues that effect the direct brine release calculations. The issues are:

Probability of microbial degradation
Borehole plug lifetime
Brine inflow from Salado: 2-D versus 3-D geometry in BRAGFLO
Brine reservoir assumptions in the CCA
Inconsistency between direct brine release and spallings geometry
Waste permeability
Residual brine saturation of waste
Random emplacement of wastes in the repository
Plutonium Solubility

Probability of microbial degradation

Direct brine release will only occur if the repository pressure is over 8MPa at the time of drilling intrusion. Above a pressure of 8 MPa, the magnitude of release is more strongly related to waste room saturation. Waste room saturation is dependent on the amount of brine entering the repository and on the repository pressure because the pore space is a function of pressure. The most important sampled parameter effecting repository pressure is microbial degradation. The microbial degradation assumptions are not defensible and may lead to a severe under prediction of the probability of greater than 8 MPa pressure and anhydrite fracturing.

Borehole plug lifetime

Borehole plug lifetimes were not sampled in the CCA analysis, so this parameter does not show up as important in the statistical sensitivity analysis. However, inspection of disturbed scenario pressure histories and the importance of borehole permeability are clear indications of the importance of plug lifetime. Borehole plug lifetimes are uncertain and the description of the development of this parameter in the CCA documentation indicates that the parameter is biased toward short plug lifetimes in an attempt to be conservative. Short plug lifetimes may lead to an under-prediction of the period of high pressures and, hence, may actually be non-conservative.

Brine inflow from Salado: 2-D versus 3-D geometry in BRAGFLO

The importance of anhydrite fracturing to direct brine release is under-represented in the CCA modeling. A full 3-D representation of the repository indicates that substantially more brine will enter the repository if the anhydrite beds open as a result of high pressures compared to brine-inflow under lower pressure conditions. The pseudo 3-D model used in the CCA analysis predicts the opposite. The highest direct brine release predictions occur with repository pressures below the initiation of anhydrite fracturing because of concurrent low brine saturation conditions. This is most likely in error.

Brine reservoir assumptions in the CCA

The DOE has admitted to the conceptual models peer review panel and in post application documents that the Castile brine reservoir parameters are incorrect. The use of these parameters in the CCA calculations severely under-predicts the importance of the Castile brine under the repository. In addition, the likelihood of intercepting Castile brine under the repository is reduced from a certainty to eight percent. Proper incorporation of the Castile brine reservoir in the CCA analysis will lead to higher brine saturations and most likely longer periods of pressures above the 8 MPa threshold.

Inconsistency between direct brine release and spallings geometry

We have identified three flaws in the actual direct brine release model. The most significant of these is the inconsistency of the void geometry of the spallings model to that assumed in the direct brine release model. The spallings model predicts the development of void channels throughout the room penetrated in a drilling intrusion. The direct brine release model assumes that all of the solid material entrained in the room depressurization has come from a annular region about the borehole. The geometric inconsistency could have a very large impact on calculated brine releases.

Waste permeability

The second flaw in the direct brine release model is a calculational error on the part of DOE. The waste room permeability value used in the direct brine release calculation is in error by 41%, based on the data used by DOE. This error leads to a 41% bias to low values in the calculated releases.

Residual brine saturation of waste

The calculated flows are also biased by using a distribution of residual brine saturations that is unrealistic. Brine moves much slower if the saturation is near or falls below the residual saturation level. Residual saturation is twice as high in the CCA calculations than can be supported. This reduces both the frequency and magnitude of the estimated releases to the surface.

Random emplacement of wastes in the repository

The CCA calculations ignore the possibility of higher consequence events due to non-uniform distribution of waste emplacement. In the direct brine release calculations the

actinide content of waste in a room is assumed to be the average of all waste. In practice waste will tend to be grouped by origin and to a degree the waste steams. This would result uncertainty in the radionuclide concentrations in a room's brine content and higher releases in some instances.

Plutonium Solubility

Finally, the importance of brine release to the surface is under-represented in the calculations because of the low assumed values of plutonium solubility, especially in the case of releases subsequent to an interception of Castile brine. The difference in plutonium solubility in the Castile brine become important to calculations that include a proper representation of the Castile brine.

Of these nine problems in the direct brine release calculations, probably only the inconsistency in the direct brine release model geometry has the potential to shift the release calculations to the release criteria values. When considered together, it is clear that radionuclide transport to the surface through brine transport is potentially a much larger threat to safety than predicted in the CCA calculations and could be a much larger concern than the current predictions of release of solids to the surface.

ACTIVE INSTITUTIONAL CONTROL

The DOE conducted an elaborate elicitation exercise in 1990 to address the issue of future inadvertent human intrusion into WIPP (Hora et al., 1991). Members from each of the four "futures teams" expressed reservations about the ability of the project to fully maintain active control for even a very short period of time. Participants in the elicitation exercise were asked to address seven specific issues including the issue of active controls:

> Assuming that the radioactive waste exists and is harmful, what is the likelihood that active controls (continued management of the site) have been maintained to prevent inadvertent intrusions? (Hora et al., 1991, p. G-4).

Three of the four members of the Washington A Team predicted a steep decline in the probability of active controls as a function of time beginning immediately after closure (Hora et al., 1991, Figure IV-10). At 100 years after closure, they predicted the probability of active control for all four postulated future states at less than 30%. The fourth member also predicted an immediate decline, although at a slower rate, in the probability of the effectiveness of active control after closure (Hora et al., 1991, Figure IV-11). In summary, the Washington A Team predicted less than 100% active institutional control for the first 100 years beginning immediately after closure.

The Washington B Team assigned probabilities that the government would continue to maintain prudent and effective control over the WIPP. They defined the near future as 0-200 years after closure (Glickman et al., pp. F-4, F-27; Hora et al., 1991, p. IV-55). This team questioned the effectiveness of active control for the near future and assigned a probability of 80% for prudent and effective control for the near future (Hora et al., 1991, pp. IV-55-56).

Hora stated that the Boston Team allowed for 100 years administrative control (Hora, 1992, p. A-87). However, scrutiny of the Boston Team report (Gordon et al., 1991) and the report by Hora et al. (1991) suggests otherwise. It appears that the input was adjusted to fit the needs of the performance assessment calculations as explained below. This adjustment, and not the Boston Team, allowed for 100 years administrative control.

The Boston Team did not offer direct estimates of the duration of active institutional control. Rather, the Boston Team predicted socio-technical factors at 100 years, 1000 years, and 10,000 years (Gordon et al., 1991, p. C-5); points in time were incompatible with the needs of performance assessment. As noted by Hora et al. (1991, p. IV-3) "...the performance assessment calculations require rates of intrusion during the entire continuum from 100 to 10,000 years after closure." Thus, the use of midpoints on the logarithmic scale was introduced to define time periods. For example, the 100 year point was converted to a period of 0 to 300 years after closure (Hora et al., pp. IV-3 to IV-4). The first 100 years were then dropped and the results of the elicitation for ten tables were presented for time periods from 100-300 years (Hora et al., 1991, Tables IV-2 through IV-11) and not from 0-300 years. However, Table IV-14 (Hora et al., 1991) presents the calculated drilling rate probability for 0-300 years after closure. This table

suggests that the Boston Team did not allow for 100 years administrative control.

Moreover, one member of the Boston Team disputed the existence of administrative control for even a short period of time. In an appendix to the Boston Team report (Gordon et al., 1990), Baram addressed the question "Can memory of WIPP be retained?" Rather than argue in the abstract, he cited examples of the factual loss of history or active control for periods shorter than 50 years. The examples included:

1) the loss of drilling history at Lyons, Kansas that was fortuitously recaptured by opponents to a proposed repository at that location,

2) the loss of information for 45 years on the dumping of barrels of radioactive waste from the Manhattan Project in the late 1940's by the Department of Defense at the Massachusetts Bay site,

3) the unavailability of information until 1986 on the release of radiation and exposure of thousands of people near Hanford beginning in 1944,

4) the use of uranium mill tailings in Colorado to construct homes and other concrete structures despite a prohibition against such activity,

5) the 1982 sewer line construction and inadvertent intrusion into a poison gas container abandoned by the Army when it closed an airfield in 1945.

"The [Southwest] team was fairly pessimistic with respect to society's ability to maintain active controls and effective markers" (Hora et al., 1991, p. IV-31). One member speculated that controls and markers may last as long as 1,000 years, two members felt that loss would likely occur within hundreds of years, and one member thought loss of markers and active control would occur in less than 100 years.

Thus, all four teams in the elicitation exercise on future societies expressed reservations about the project's ability to maintain active control for even a short period of time.

EEG recommends that the EPA should initially assume zero credit for active institutional and ask DOE to cite specific tangible factors as to how much credit can be justified. As part of building a credible argument, the CCA should also take into account the pessimism of its own expert elicitation on the limited effectiveness of active institutional control.

References

1. Hora, S.C., von Winderfeldt, D., and Trauth, K.M., 1991. Expert Judgment on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant. SAND90-3063. Sandia National Laboratories.

2. Glickman, T., Singer, M., Rosenberg, N., Vinovskis, M., 1991. The Report of the Washington Area Second Team on Future Inadvertent Human Intrusion into the WIPP Repository. Appendix F to SAND90-3063. Sandia National Laboratories.

3. Hora, S.C., 1992. Probabilities of Human Intrusion into the WIPP Methodology for the 1992 Preliminary Comparison, August 25, 1992. Appendix to SAND92-0700, pp. A-69 to A-99.

4. Gordon, T.J., Baram, M., Bell, W., Cohen, B., 1990. Inadvertent Intrusion into WIPP: Some Potential Futures. Appendix C to SAND90-3063. Sandia National Laboratories.

PASSIVE INSTITUTIONAL CONTROL

The CCA claims that passive institutional control will be 99% effective in deterring drilling into the repository from 100 years to 700 years after closure. The components of passive institutional control include government ownership, records, and markers. Based on the DOE's experience with institutional controls in the recent past, a claim of 99% credit for passive institutional controls for 700 years does not appear justifiable.

Government Ownership and Regulation

With respect to the government ownership, the DOE maintains that "the controls that are crucial to protect the site from inadvertent exploration are BLM leasing procedures and lease records and the internal procedures of the BLM which require the DOE's review and comment for any permit application to drill within one mile of the WIPP site."[1] On October 26, 1990, the DOE and the DOI/BLM signed a Memorandum of Understanding. With respect to drilling for oil and gas, the MOU specifically required the BLM to notify the DOE of applications for permit to drill for oil and gas within one mile of the WIPP Site Boundary and that "drilling approval will be withheld until comments are received from the DOE."[2] The MOU was revoked on October 30, 1992 with the passage of the 1992 WIPP Land Withdrawal Act[3] (Section 3 (b)). How effective was the MOU for that two year period? The following example is fairly typical of the overall failure of the MOU.

The BLM approved an application to drill Well #4, Section 26, T22S, R31E, on October 15, 1991. Two days later, the BLM[4] sent a letter to the DOE requesting a review of an "Application for Permit to Drill" within one mile of the WIPP Site Boundary. The BLM received DOE's review[5] on October 25, 1991. However, not only had the application already been approved by BLM ten days earlier, but drilling had already commenced the previous day. Thus, the DOE's review was never considered in the application permitting process, the DOE review was not solicited until after the drilling had been approved, and the DOE review was not received by BLM until after drilling had started.

Table 1. Summary of Lapses in Institutional Control

Satisfactory procedure	3
BLM failed to request DOE review.	3
DOE failed to respond to BLM request.	9
BLM approved permits to drill before requesting DOE review.	5
BLM approved permits to drill before receiving DOE review.	5

The MOU failed in twenty-two out of twenty-five applications for an institutional failure rate of 88%. EEG notified DOE of this lapse in institutional control in 1993[6,7]. Fifty-five subsequent applications, processed through July 1994, showed a failure rate of 9%.

Records

A recent example illustrates the failure of records to communicate important information prohibiting drilling in a certain area. In 1978, the DOE purchased leases in the vicinity of the current WIPP site for the explicit purpose of preventing drilling. One area was the N½ NW¼ of Section 6 T23S, R31E (eighty acres) for which the DOE paid Bass Enterprises et al. $207,972 not to drill through the uppermost 6000 feet[8,9].

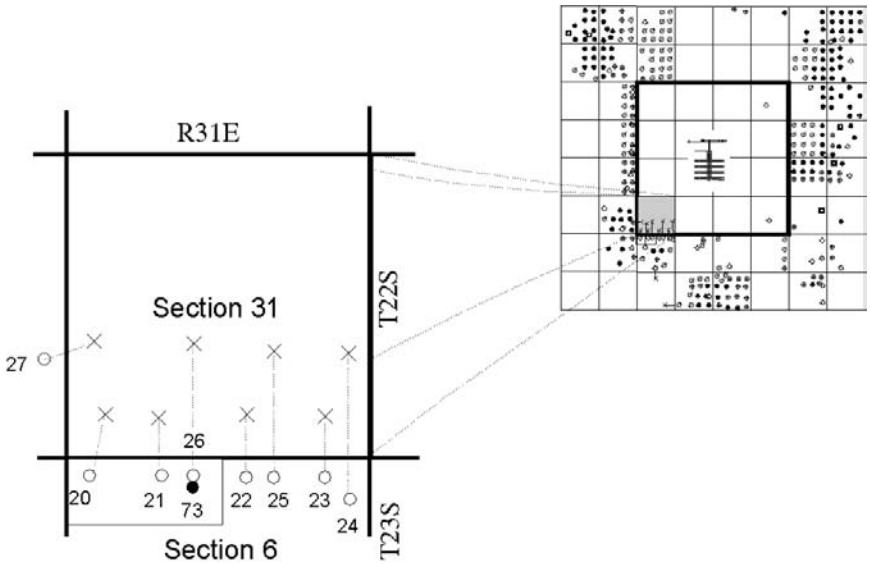

In April 1993, Bass Enterprises et al. applied to the BLM to directionally drill eight wells from Section 6 locations outside the WIPP Site to their oil and gas lease reserves 6000 feet below the WIPP Site. In August 1994, the BLM denied the drilling applications citing the WIPP Land Withdrawal Act.[10] In January 1995, Bass et al. filed a claim in federal court for a takings.[11] In June 1996, the federal court awarded Bass et al. $8.9 million plus interest.[12]

Despite the active involvement of attorneys and officials for the oil companies and four federal agencies (DOE, BLM, EPA, and the Justice Department), the 1978 judgment, forbade drilling wells in Section 6 T23S, R31E, was not discovered until after the June 1996 judgment.[13,14,15] (Refs. 14 and 15 attached). Subsequent appeal by the Justice Department states:

> Among the issues that could be addressed on remand are the implication of the discovery, made after the notice of appeal was entered in this case, that Bass did not have the right to drill from three of the locations from which it proposed to drill — and for which it sought and received compensation — because DOE had

condemned those surface locations in 1977.[13]

Hence, in less than twenty years, records failed to communicate important information concerning the restriction against drilling for oil and gas. Furthermore, a vertical gas well, James Ranch Unit 73, was drilled and completed on the eighty acres in July 1996 prior to the discovery of the lease records by the attorneys for the various federal agencies.

Markers

"Any compliance application shall include the period of time passive institutional controls are expected ***to endure*** and be understood."[16].

On October 26, 1963 a twelve kiloton device was detonated underground at Fourmile Canyon, Nevada. The site was designated as the Shoal Site. In the late 1970's the DOE placed a substantial marker consisting of a brass plaque set in a concrete podium and anchored to a concrete base at ground zero. By 1985, the marker at the Shoal site had been completely destroyed by a massive explosion with pieces of marker scattered to the west. The brass plaque had disappeared. Shown below are the gathered remains of a DOE marker intended to identify an area contaminated by radioactive fission products. This marker lasted less than ten years. This example raises questions on the DOE's commitment to maintain a marker at WIPP.

Recommendation

EEG recommends that the EPA include full consideration of these lapses in the assessment of the DOE's claim of 99% effectiveness of passive institutional controls from 100 to 700 years after closure.

References

1. Arthur, W.J., 1992. November 3 letter from the WIPP Project Director to R.H. Neill, Director of the Environmental Evaluation Group.

2. U.S. Department of Energy/U.S Department of Interior, Bureau of Land Management. October 26, 1990 Memorandum of Understanding cited by the 1991 Administrative Land Withdrawal, 43 CFR Public Lands Order 6826, January 22, 1991.

3. U.S. Congress, 1992. Waste Isolation Pilot Plant Land Withdrawal Act. Public Law 102-579, 102d Congress.

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16. U.S. Environmental Protection Agency, 1996a. 40 CFR Part 194, Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations, Final Rule. Federal Register (9 February) vol. 61, no. 28, 5224-5245.

POTASH MINING

The CCA underestimates the areal extent of potash reserves and the potential impact of the mining of potash within the site and on adjacent federal and state properties. The use of only the existing leases adjacent to the site does not account for the currently economical potash reserves. Figure 1 shows the extent of lease grade potash ore as determined by the Department of Interior. Further, the Department of Interior notes that potash ore has been and can be economically mined at ore concentrations less than current lease grade[1].

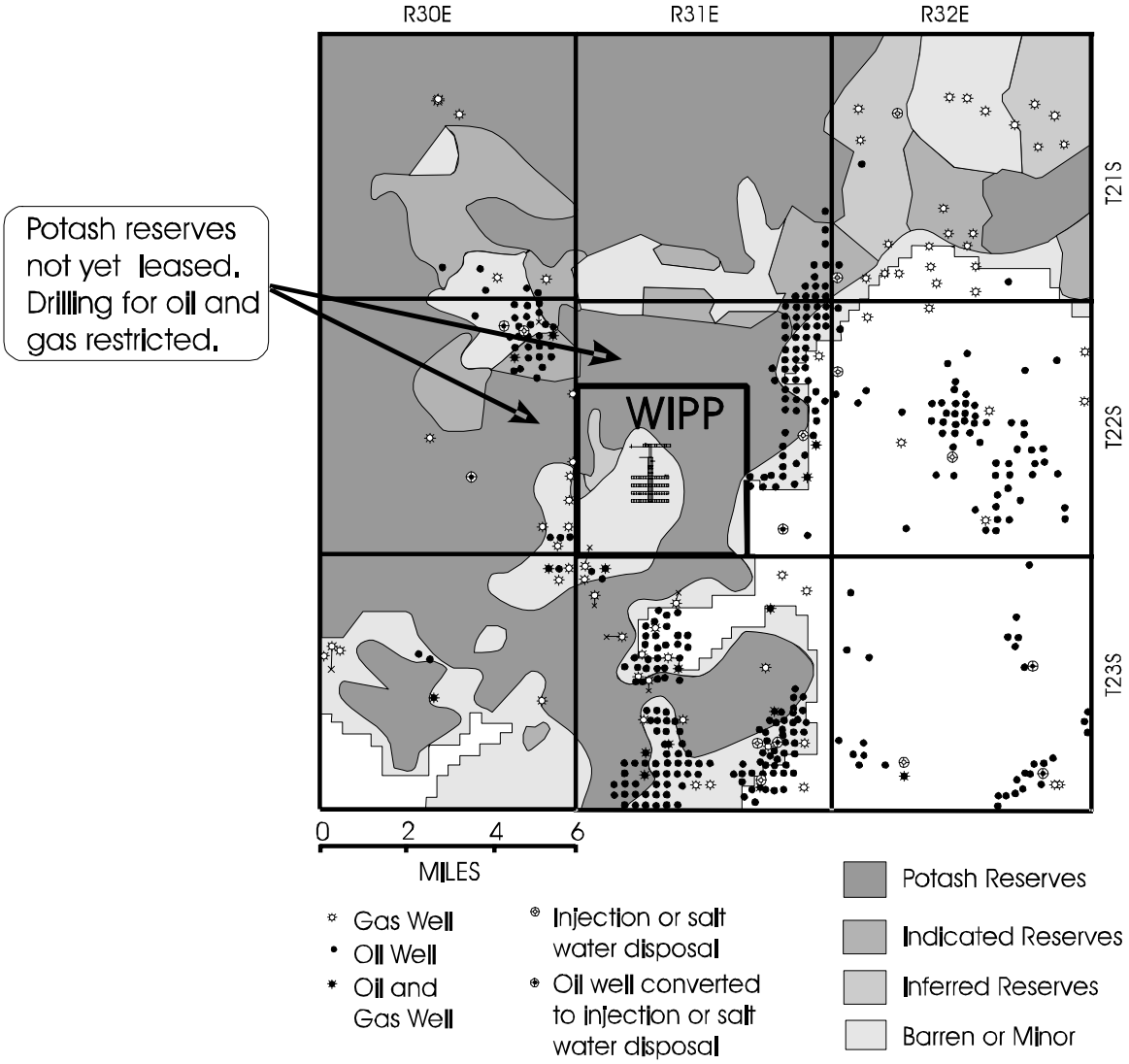

Figure 1. Lease grade potash ore[2] and oil and gas wells.[3]

For illustrative purposes, Figure 1 identifies one area of known potash reserves adjacent to the northwest boundary of the WIPP Site. Figure 2 indicates that these potash reserves have not been leased. Potash operators are allowed to hold, directly or indirectly, no more than 51,200 acres in potash permits and leases in a state (43 CFR 3530.3). An operator may not hold all the potash leases he intends to develop (Ref.4, p. 11).

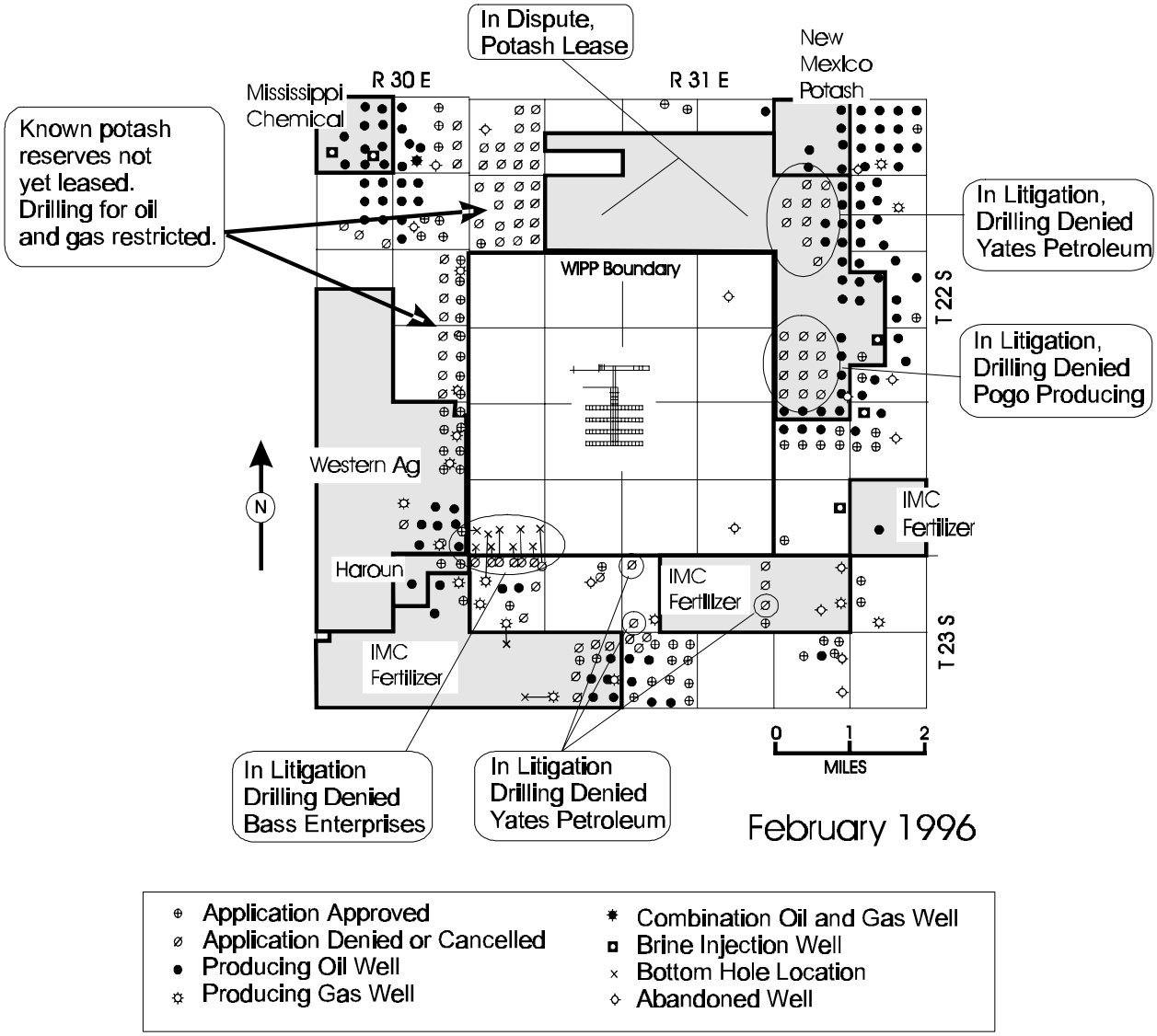

Figure 2. Drilling for oil and gas restricted by BLM due to the presence of potash reserves, leased and unleased.

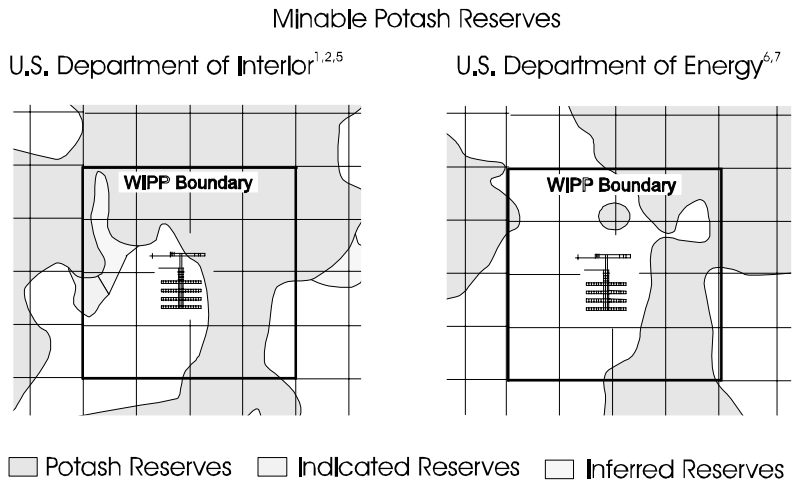

Figure 3. Minable potash.

Figure 3 shows the different estimates by DOE and DOI of the extent of minable potash within the WIPP site.

As shown in Figure 4, the CCA does not include the impact of potash mining in unleased areas which will also affect the regional hydrology. 40 CFR Part 194.32 states:

> Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur.

EPA's Compliance Application Guidance for 40 CFR Part 194 (p. 46) states:

> EPA recommends that DOE use minable reserves in estimating mine linve and the extent of potential mining.

The Use of only the existing potash leases does not therefore satisfy the EPA's intent.

Limiting the CCA to "near future" resource recovery activities appears to be inconsistent with the Federal Land Policy and Management Act[7] and limiting the CCA to "exisiting leases" does not reflect anticipated mining. All federal public lands, including those adjacent to the WIPP Site, are "to be managed in a manner which recognizes the nation's need for domestic sources of minerals, food, timber, and fiber...." (Ref.8, §1702(12)). In addition, FLPMA requires the management of federal lands "be on the basis of multiple use and sustained yield unless otherwise specified by law" (Ref.8, §1701(7)). "The term multiple use means the management of the public land and the various resource values so that they are utilized in the combination that will best meet the present

and ***future needs*** [emphasis added] of the American people" (Ref.8, §1702(c)). The term multiple use also means "a combination of balanced and diverse resource uses that take into account the ***long-term needs of future generations*** [emphasis added] for renewable and nonrenewable resources.... Sustained yield is defined as "the achievement and management ***in perpetuity*** [emphasis added] of a high-level annual or regular periodic output of the various

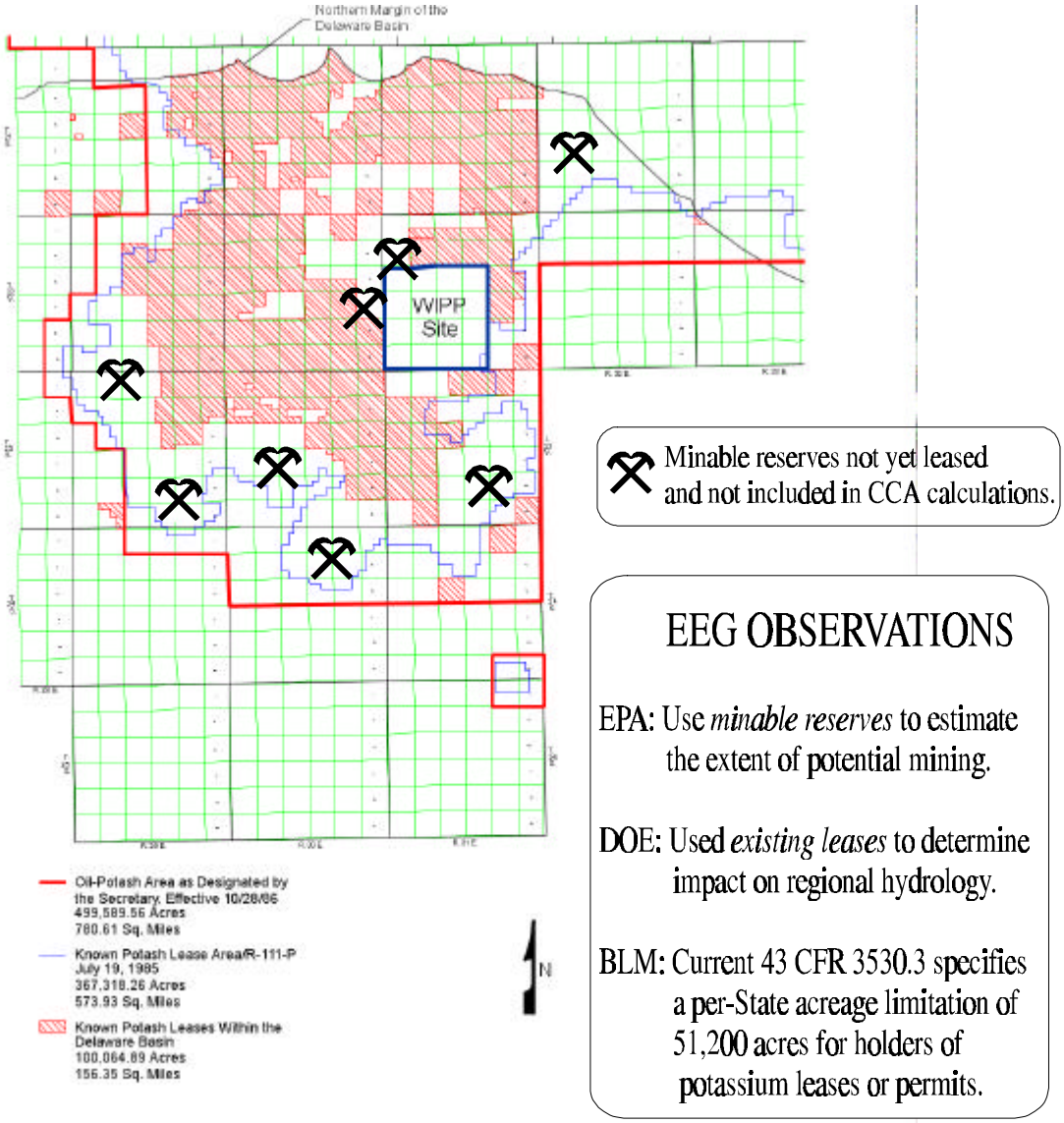

Figure 4. Potash leases within the Delaware Basin and minable potash not yet leased.

renewable resources of the public land consistent with multiple use" (Ref.8, §1702(h)). Human activities in the resource rich areas surrounding the WIPP are not limited to the ***near future*** and are not limited to ***the expected use of existing leases***.

The objectives of the state are also "to prevent waste, protect correlative rights, assure maximum conservation of the oil, gas and potash resources of New Mexico, and permit the economic recovery of oil, gas, and potash minerals..." (LeMay et al. 1988).

Recommendation

EEG recommends that the CCA consider all minable potash resources, as specified by the BLM, in the performance assessment calculations.

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4. Vaughn, G.L., 1995. December 13 Agency Answer to Appellant's Statement of Reasons by U.S. Department of Interior Bureau of Land Management General Counsel. Yates et al., appellants. IBLA 92-612.

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DOCUMENTATION OF FEPs AND PARAMETERS

In reviewing the CCA, assumptions concerning the features, events, and processes (FEPs) used in performance assessment (PA) and parameters used by the computer modeling should be checked to ensure that supporting documentation is valid. Due to limitations in manpower the EEG has not made as extensive effort to investigate the DOE's documentation of its efforts in these areas as has the EPA. However, in conjunction with various EPA efforts at SNL since the publication of the CCA, the EEG has investigated a small sample of both parameters and FEPs. This sample shows that there is cause for concern about the records available for both FEPs and parameters. In brief, three of the four parameters examined showed what seem to be significant problems for CCA documentation; and FEPs screening activities are dominated by what appears to be significant omissions and errors.
The information below may no longer be current, as SNL attempts to improve the documentation as feedback from the EPA is received. The attempt here is to show the types of problems that were in the documentation at the time the CCA was submitted.

CCA Appendix PAR Values Differ from PA Code Values

The parameter database used to construct Appendix PAR is different than the parameter database used by the computer codes at the time PA analysis for the CCA was performed. A later version of the parameter database, in which different values for some of the parameters had been added, was used for Appendix PAR, according to SNL personnel.

Table PAR-12 in the CCA shows Parameter ID # 3148, bulk compressibility (COMP_RCK CONC_PLG), to have a value of 1.2E-09 Pa^{-1}, whereas the value used in the CCA PA calculations was 2.64E-09 Pa^{-1}. Supporting documentation (Form 464s in WPO # 36591) indicates the value was 0 Pa^{-1} from March 14, 1996, to May 2, 1996, when it was changed to the 1.2E-09 Pa^{-1} value. The 264E-09 Pa^{-1} value apparently preceded the March 14, 1996 date. This implies that the parameter database used in the CCA PA may have preceded the March 14, 1996 date.

A June 17-21, 1996, CAO audit of SNL (A-96-03) discovered that many parameters had been entered into the database without following proper procedure, which included not only completion of records but also required reviews and sign-offs before entry into the database. The list of such parameters eventually grew to more than 230 (out of 1500 total parameters). If the CCA PA was using a database established prior to corrective actions for these parameters then the parameters may not have been properly qualified for use.

Documentation of Supporting Information for Parameters

Form 464s are the records that establish and justify values for parameters that are to be entered into the database used by PA analyses. The Form 464s either show justifications directly or provide information which allows tracing of the values to supporting data and analyses. For the

Castile Brine Reservoir Pressure parameter (WPO #31612), successive Form 464s may be used to illustrate the sorts of problems encountered in tracing values used for parameters.

The later of two Form 464s in the data package changes the distribution "Type" of the earlier Form 464 from "cumulative" to "triangular", which changes the method of calculating the uncertainty distribution from the median value to the mode. The use of the median value (cumulative distribution) is supported in 5 pages of information attached to the earlier Form 464, but the later Form 464 merely announces the change to the mode (triangular distribution) without justifying it. The only documentation for the change is the statement under "Interpretation" on the later Form 464:

> The mode is entered into the database in place of the median. The median was calculated and is 13.4E+06 Pa.

Apparently, the mode value was erroneously placed into the database as a median, because the mode value had been erroneously entered on the earlier Form 464 in the median block. On discovery, the solution was to use a new Form 464 to change the type of distribution so that the mode value already in the database would match the Form 464, rather than change the value in the database to the correct median value. The result appears to be that an unsupported value of 2.17E+07 Pa is in the database instead of the supported value of 1.34E+07 Pa.

The support information for the Form 464s shows additional problems. Attached to the 464s is a document entitled "Original Interpretation (1/12/96)", which includes a table of data that:

> ...defines a cumulative (empirical) distribution based on the 8 data points for pressure mentioned in the <u>source</u> <u>document</u> (SWCF-A:1.2.07.1: PDD: NON-SALDO: PKG # ?: Castile Brine Reservoir)
>
> The weights to be given to the 8 values of pressure were specified by author of source document.

The 8 pressure data point values are copied into a second table later on the page, and includes the weighting value for each.

Two other documents in the package (changes suggested by Tierney and Freeze) add two more pressure values, for a total of 10, without documenting the rationale for the addition, or referencing any document which might explain it. These might be in the "source document" cited in the quotation above, but that quote specifies "...the 8 data points...", not "...8 of the data points...".

Further, the weighting assessments are different between the Tierney and Freeze two documents, and both differ from the weighting assessments in the original interpretation. No justification is given for changing these weighting factors.

The Freeze document is apparently one page from a larger document to which there is no reference tie. On the page included, the statement is made:

> The weights are approximately based on distance from the repository. Note that WIPP-12 (inside the site boundary) is assigned a weight of 0.45...The rationale for the weights for the highest pressures (17.4 and 20.0 Mpa [sic]) is described in a later paragraph.

No later paragraph in the included parts of the document describes weighting rationale for the added pressure values, and WIPP-12 is assigned a weighting value of 0.30, not 0.45, in the table just above the quoted statement (WIPP-12 is the 12.7 MPa pressure value).

The last page in the supporting documentation consists of two source document listings, one a SAND document and the other the 1992 PA. The references list specific page numbers; the referenced pages in both documents consist of descriptions of Salado porosity parameters, and would seem to having nothing to do with Castile brine reservoir pressure.

The Form 464 points to another SNL data package (WPO # 31072), which contains a memorandum listing the data that had been sent to the Natural Barriers Peer Review Panel (the Panel was to perform a necessary review for quality assurance purposes). However, there was no documentation of the findings of the Peer Review Panel in the package, or references to the Peer Review Panel Report.

Another parameter data package (Castile Brine Reservoir Permeability; WPO # 31070) which had been sent to the same Peer Review Panel did contain a memorandum that referenced the Panel Report qualifying the parameter.

Castile Reservoir Compressibility/Volume Documentation

Another parameter (Castile Brine Reservoir Rock Compressibility; Parameter # 61) offers an interesting set of memoranda from key SNL personnel. Briefly, in late August, 1996, a SNL scientist sent a memorandum to SNL's upper management in which he stated that

> ...I believe that treatment of brine reservoirs for the CCA was indefensible and non-conservative. I believe we are systematically underestimating the amount of brine that could reach the repository....The low end of the range comes from interpretation of hydraulic tests in Salado anhydrites, not from any direct Castile anhydrite measurements. The high end of the range comes from generic information reported by Freeze and Cherry (1979) for the compressibility of jointed or fractured rock, again not from actual Castile data...

The conclusion quoted above covers both the compressibility and volume of Castile brine reservoirs, which SNL analyses consider to be interdependent.

On October 3, 1996, the same scientist wrote another memorandum in which he concluded that, because the range of values he had calculated fell within the range used in the CCA, and other SNL personnel had told him that sensitivity calculations showed that the change in range would not shift the CCDFs, the treatment of Castile brine reservoirs in the CCA was acceptable.

However, whatever the effect on the CCDFs, the range used for the parameter in the CCA are still "...indefensible and non-conservative." None of the later memoranda contest this statement.

A graph of the data points appended to the October 3, 1996 memorandum shows that the new range lay in the upper end of the range used in the CCA calculations, and the data points that lay below the new range (38% of the total) were a much longer chain, while the ones above the new range (13% of the total) were more closely associated with the new range. Monte Carlo or Latin Hypercube Sampling would seem to result in more emphasis on lower values while using the CCA range than would be the case with the new range shown in the memorandum.

This package also received its QA acceptability from the Natural Barriers Peer Review Report (DOE/WIPP-96*2004). The peer review was held months before the new range was developed, and it would seem that a similar body should pass on the validity of the use of a new range of values for the parameter.

It may be worth noting that the discussion in the Natural Barriers Peer Review Report indicates that the peer review panel viewed Castile data from the WIPP-12 borehole in considering these parameters (see Report, p. 5-18) which the SNL scientist's memorandum stated was not used in the supporting documentation for the parameter.

Documentation of the Culebra Porosity Parameter As A Constant

The CCA (in Appendix PAR) states that:

> Parameters may also be assigned a constant value in the performance assessment parameter database. These parameters are tabulated at the end of the appendix. [PAR.2.1, end of section]

The Culebra porosity parameter (Parameter ID 140, Effective Porosity) is in the Table PAR-30 (Appendix PAR, p. PAR-214) as a constant value of 1.5100E-01. The Form 464 for the parameter (WPO #32769) describes the distribution type as a constant, and states a curious circular logic in the "Interpretation" section:

> The distribution equates a point and that point is equal to the mean. Therefore, that point is a constant.

However, the documentation appended to the Form 464 shows an approximate 30% standard deviation among the 103 data points used to establish the mean. Justification for the change

(from a "student's t" distribution type) is a memorandum entitled "Distributions" (Tierney, March 21, 1996) that describes the use of the various types of distributions (cumulative, delta, normal, triangular, uniform, lognormal, loguniform) but does not a description for "constant" distributions. When SNL personnel were asked for documentation of the rationale for using a constant, a memorandum relating to category 3, physical constant parameters (Pi, Avogadro's number, etc) was the only information available (the porosity parameter is a category 1, derived from experimental data). In short, no justification is provided in the data package or seems to be available for considering this parameter to be a constant.

Documentation of Features, Events, and Processes (FEPs)

Operations involving the screening and other processing of FEPs are inadequately documented. 25% of the original FEPs list was eliminated with no documentation of the process; 70% of the remaining FEPs have essentially no more documentation than what appears in the Compliance Certification Application (CCA). The documentation for the other 30% also appears to be incomplete. The rationale for excluding many of the FEPs from performance assessment (PA) is not documented in the CCA, as required by 40 CFR 194.32(e)(3).

The DOE originally developed a list of nearly 1200 FEPs, and the draft CCA (the DCCA; DOE/WIPP/CAO-2056, March 31, 1995) considered about 900 FEPs. For the CCA, approximately 240 were to be addressed, and about 90 of these are said to be "screened in", or used in the PA process. The DCCA list (≈900) is included as Appendix A to Attachment 1 of Appendix SCR to the CCA; the CCA list (≈240) are in the CCA as three tables, found in Chapter 6 (Tables 6-3, 6-4, and 6-5) and also in Appendix SCR (Tables SCR-1, SCR-2, and SCR-3).

No screening analysis plans were utilized for the reduction of the nearly 1200 FEPs to the approximately 900 included in the CCA, nor is there any documentation of the process used for each FEP. Reduction of the ≈900 was also performed without an analysis plan; this operation was later reviewed, and about 30% of the FEPs were passed on to the "SNL Side Efforts Program". The preliminary decisions on the other 70% of the FEPs seems to have been accepted without documentation of the process for including or excluding them. (The 70%-30% split of FEPs is taken from SNL documents and has not been independently verified by the EEG.)

The 30% that passed to the SNL "Side Efforts" program are required to have packages supporting the screening decision in the Sandia-WIPP Central Files (SWCF); these were to be screened based on the "FEPs Screening Analysis Plan, Version 5.2, for Phase I FEPs", dated 12-20-95 (for FEPs related to numerical and conceptual models), and "FEPs Screening Analysis Plan, Version 5-4, for Phase II FEPs" dated April 29, 1996 (for parameterized FEPs). However, at least 31 of the "Side Efforts" FEPs were only to be documented in the CCA (letter from DOE's McFadden to EEG's Neill dated August 2, 1996).

These 31 FEPs may have been part of a perhaps larger group of Phase II FEPs which were not processed in accordance with the analysis plan due to "resource constraints". The Change

Control Board was utilized to justify incorporating these FEPs into the CCA (see Wilmot, R.D., "Relationship of Side Efforts to the Compliance Certification Application" Galson Sciences Ltd 9507a-6, November 26, 1996, p. 2).

Not all of the 31 FEPs are documented in the CCA. Only "Side Efforts" FEPs were given an alphanumeric designator; the first FEP on the list (from the Neill-to-Dials letter dated July 11, 1996), "DR11, waste degradation", does not appear in the CCA nor did a rationale for its exclusion seem to be included. The Galson Sciences Ltd document cited above was written to document the location within the CCA of side efforts (p. 1); it indicates (Table 2, p. 15) that this FEP is

> ...not included in PA calculations [because]...Changes in mechanical and hydrological properties of the waste caused by corrosion need not be explicitly modeled.

Table 2 also indicates that the FEP is discussed within the CCA in Sections 6.4.3.1, 6.4.3.2, and 9.3.2.2.5. These sections do not provide a rationale for excluding waste degradation--indeed, the discussions in these sections only discuss waste in terms of consolidation (p. 6-97 & 6-98), gas generation (p. 6-100) and compaction (p. 9-138). The sections from Chapter 6 could be better used to show that consideration of waste degradation was included in the PA.

Appendix A, "DCCA Fep List By Category", of Attachment 1 of Appendix SCR to the CCA does list a general category of "1.9 Waste: degradation/corrosion/dissolution" with 12 subcategories (p. 26), but no alphanumeric designators are supplied. This seems to be the closest representation of the "Side Efforts" FEP designated as "DR11, Waste Degradation", in the CCA.

This illustrates a principal concern EEG has about the FEPs documentation process: many FEPs seem to be neither adequately defined nor consistently identified. FEPs would seem to require more than a two or three word designator to adequately delineate what is encompassed and excluded from the concept, but the CCA does not contain such descriptions, nor do such accurate definitions seem to exist.

A second concern is that 40 CFR 194.32(e) requirements for documentation seem to be inadequately met. 40 CFR 194.32(e) requires that the CCA include (1) identification of all FEPs that might affect the disposal system in the regulatory time frame; (2) a list of those used in PA; and (3) documentation of the rationale for excluding those not used. There are abundant lists that show which FEPs were used in PA (Tables 6-3, 6-4, and 6-5 of Chapter 6, which are duplicated in Tables SCR-1, SCR-2, and SCR-3 in Appendix SCR; and Table 4 of Attachment 1 to Appendix SCR), but the original list of ≈1200 FEPs has not been included, and the rationale for not including at least some of the FEPs seems to be missing.

A third concern is that the Change Control Board decision to incorporate FEPs which had not been processed in accordance with analysis plans would seem to have circumvented the WIPP

quality assurance programs.

This leads to a fourth concern: it appears that much of the work on FEPs has not been performed in accordance with the Nuclear Quality Assurance (NQA) standards required by 40 CFR 194.22(a). NQA-1 Basic Requirement 5 states:

> Activities affecting quality shall be prescribed by and performed in accordance with documented instructions, procedures, or drawings of a type appropriate to the circumstances. These documents shall include or reference appropriate quantitative or qualitative acceptance criteria for determining that prescribed activities have been satisfactorily accomplished.

Prescribing instructions or procedures which included acceptance criteria were apparently not developed for much of the FEPs process.

When questioned about QA assessments of the FEPs screening and documentation process, SNL cited CAO surveillance S-96-21 as having covered the 70% FEPs in its assessment of the DCCA. According to the surveillance report, this assessment was conducted by one auditor and a software QA specialist over a five-day period (February 5-9, 1996), and covered training and personnel qualification, procurement control, document reviews, records, and software. The only part of the report that could possibly be considered an assessments of FEPs is in the section concerning technical document reviews (p. 4), which covered not only the entire DCCA, but also the RCRA permit application, No Migration Variance Petition, and an Engineered Alternatives study. There is no documentation that any FEPs were reviewed during this surveillance. Thus, the reduction of FEPs from ≈1200 for the CCA's ≈240 has not been assessed by an independent organization.

FEPs in the "Side Efforts" program were said by SNL to have been assessed during CAO surveillances S-96-04 (December 1995), S-96-32 (April 1996), and CAO audit A-96-03 (June 1996). The program was still in progress during this time period, and the Change Control Board decision may not have been fashioned yet.

FEPs Screening Decision Adequacy

For the CCA, FEPs were eliminated (screened out) from consideration in PA by one of three criteria: regulatory (SO-R), for FEPs excluded by language in 40 CFR 191 or §194; low consequence (SO-C) FEPs; and low probability (SO-P) FEPs, which are defined in §194.32(d) as processes and events with less than one chance in 10,000 of occurring over 10,000 years. For SO-P, the CCA offers a less stringent interpretation (Section 6.2.2.1 lines 20-23, p. 6-39):

> In practice, for most FEPs screened out on the basis of low probability of occurrence, it has not been possible to estimate a meaningful quantitative probability. In the absence of quantitative probability estimates, a qualitative

> argument has been provided.

Some FEPs screening arguments seem inadequately supported. For example, GG-13, electrochemical gradients, is screened out on the basis of probability (Galson Sciences Ltd 9507a-6, p. 25). The argument offered in Appendix SCR (p. SCR-62) is:

> Galvanic coupling could lead to the establishment of potential gradients between metals in the waste form, canisters, and other metals external to the waste form. Such electrochemical effects can potentially influence corrosion processes and therefore gas generation rates and chemical migration...Good physical and electrical contact between the metals involved is critical to the establishment of galvanic cells. Experience with experimental investigations suggests that this requirement is unlikely to be achieved under repository conditions.

None of the experimental investigations are listed in Appendix SCR. However, the Sandia-WIPP Records Center does store supporting documentation for the CCA, and for this FEP the records package is WPO # 31491, "Electrochemical Gradients Qualitative Screening Arguments for Side Effort GG-13". This document echoes Appendix SCR, stating that the FEP is SO-P because:

> Good physical and electrical contact between the metals involved is critical to the establishment of galvanic cells. Experimental investigations suggest that this requirement is unlikely to be achieved under repository conditions (Telander and Westerman, 1993).

The cited document is SAND92-7347, "Hydrogen Generation by Metal Corrosion in Simulated Waste Isolation Pilot Plant Environments: Progress Report for the Period November 1989 through December 1992". The EEG was unable to locate any descriptions of experiments or any data relating to physical or electrical contact between metals, or any references to galvanic cells or coupling in the document. The report covers experimentation on corrosion and consequent H_2 gas generation by low-carbon steel and alternative packaging materials in contact with gases (N_2, CO_2, H_2S) and brine, but offers no indication that interactions between metals was ever a consideration.

For this SO-P FEP there is not only no evidence that the 1 chance in 10,000 over the next 10,000 years criteria is met, there also appears to be no evidence for the less stringent qualitative argument offered.

In discussing this FEP, the DOE has intermingled electrochemical gradients (GG13) with another FEP, galvanic coupling (GG12), and then used an argument based on galvanic coupling to cover electrochemical gradients; this intermingling amounting to a circular argument exemplifies the EEG's concern about inadequate delineation of FEPs. Electrochemical gradients may be formed by means other than galvanic coupling (oxidizing conditions in one part of the repository,

reducing in another, with brine linking them), and the possibility of such gradients should also be addressed.

Given the uncontrolled and intense compression the waste in the repository will undergo, it seems possible that the necessary physical and electrical contact between metals cited in the CCA as necessary for galvanic coupling can occur. The DOE's contention that this will not occur is unsupported by cited documents. A reliable and objectively supported argument should be advanced before rejecting the possibility--for both the GG12 and the GG13 FEPs.

FEPs Excluded on the Basis of Administrative Control

Table C-3 in Appendix C to Attachment 1 of Appendix SCR to the CCA (SCR p. 92 & 93) is titled "FEPs on the DCCA FEP list excluded from the development of the CCA FEP list as issues relating to designs different to that forming the basis of the CCA".

The FEPs in the table are the sorts of events that would seem to require a more serious consideration before excluding them from PA. Among these are the FEPs "Backfill/seal material deficiencies", "inadvertent inclusion of undesirable materials", "poor quality construction", "radioactive waste disposal error", "stray materials left", "Preclosure events", "Faulty seal emplacement", "Inadequate seal or compaction, voidage", and "Seal material deficiencies", all of which would seem to be possible events which could alter the adequacy of the repository for its intended task.

"Abandonment of unsealed repository", another on the list, would certainly seem important enough to require close consideration. Will there be funding and a willingness to continue the WIPP for a full 35 years anticipated by the design presented in the CCA?
A statement in the narrative portion of Appendix C (pp. 11-12) addresses exclusion of these FEPs:

> FEPs relating to constructional, operational and decommissioning errors (classified as RD in the DCCA) have been eliminated from the CCA FEP list. The DOE has administrative and quality control procedures to ensure that the facility will be constructed, operated, and decommissioned as specified in the CCA.

The EEG considers this statement to be inadequate justification for excluding these FEPs. Among other examples, recent administrative and quality controls concerning drilling rights and privileges in the vicinity of WIPP (see recent EEG discussions of active and passive institutional controls) illustrate that such controls are not always effective.

General Considerations: DQC's

1. For sampled distributions, CCA Chapter 5 provides a good description of why simulation values need not be covered by DQC's:

   - Applicable to tasks involving quantification through sampling and analysis of specific constituents in an environmental medium (e.g., pollutants in wast streams waste characterization and environmental monitoring).
   - The performance assessment is estimated using mathematical models rather than being determined by direct measurement.

     1) Parameters are treated as being uncertain variables, rather than precisely determined quantities and are characterized by probability distributions.

     2) Parameter distributions may span several orders of magnitude due to uncertainty introduced in subsequent processing. Many parameters derived from data measurements need be known only within orders of magnitude of their true value. Efforts to reduce the range do not necessarily improve model accuracy.

     3) As an example, data accuracy would be very difficult to assess for geologic site characterization activities because reference or true values do not exist.

     4) In summary, it's not practicable to apply DQC's to most scientific investigations used support a performance assessment, in which there uncertainty in the conceptual models and the resultant ranges of parameters. Instead, controls established by the QA program provide the necessary quality.

2. There are a lot of technical discussions that could be presented to describe why DQC's don't apply to specific data sets The intent here is to provide some general discussion regarding the topic.

3. 194.22(c) itself says "...to the extent practicable, information which describes how all data used to support the compliance application have been assessed for their quality characteristics, including:...[PARCC]".

4. Natural features do not lend themselves to DQC's.

Attachment 1
P. 1

January 16, 1997

CATEGORY	DATA SET	DATA SET DESCRIPTORS	PRECISION, ACCURACY, REPRESENTATIVENESS, COMPLETENESS, COMPARABILITY (PARCC)
Dominant force - relative to releases	Particle Size	• Particle sizes of waste and backfill at the time of human intrusion • What future waste might look like 10,000 years • No physical data collected • interpretative • Sampled distribution	P: No physical data collected by project. Values were selected by smallest size analog materials & largest annular space. Smallest sized values determined from textbooks standard equations. A: No physical data collected by project. Values were selected by smallest size analog materials & largest annular space. Smallest sized values determined from textbooks standard equations. R: The uniform distribution assures that all possible values are fully represented. C: Distribution captures plausible and realistic values. C: N/A. Because there is only one data set. All of the available data were used.
Less important - relative to releases	The Probability of Microbial Degradation	• Interpretative • ~~Some data collected~~ • Estimate of the likelihood of occurrence of gas generation - 50% likelihood	P: Data collected was not used to determine the distribution. Model decision formulated - 50% likelihood (yes/no), if the process will take place. The 50% value reflects a lack of knowledge of the distribution. A: Data collected was not used to determine the distribution. R: 50%, only 2 possibilities. C: Based on ~~non-experimental data and~~ interpretation. C: N/A: ~~Because there is only one data set.~~ For the 50% there are only 2 possibilities.
No Impact - relative to releases	Anhydrite Permeability	• A measure of a porous medium to transmit fluid • Experimental data • Field data • Laboratory data • Sampled distributions	P: A wide range of values doesn't affect release. The laboratory and field data were combined into a single data set. A: Distribution was set up to account for a wide range of data and uncertainty in data points. R: Latin Hyper Cube sampling assures that distribution and values fully represented. C: Latin Hyper Cube sampling assures that distribution and values fully represented. C: N/A: Because all of the available data were used to create the distribution.

Attachment 1, P. 2

CATEGORY	DATA SET	DATA SET DESCRIPTORS	PRECISION, ACCURACY, REPRESENTATIVENESS, COMPLETENESS, COMPARABILITY (PARCC)
Less important - relative to releases	Gas Generation Rates	• Rate of gas generation • Experimental data • Laboratory data • Sampled distributions	P: Variability in values doesn't significantly affect release. Wide variability due to a large range of conditions in ~~field~~/lab data dominates the variability in the individual experiments. Variability scatter of the data collection values is small compared with the much broader spread assumed by the distribution to account for uncertainties in the conditions. A: Variability in values doesn't significantly affect release. Wide variability due to a large range of conditions in ~~field~~/lab data dominates the variability in the individual experiments. Variability scatter of the data collection values is small compared with the much broader spread assumed by the distribution to account for uncertainties in the conditions. R: The Test Plan is designed to explore the range of conditions expected in the repository. The sampling assures that distribution and values are fully represented. C: Latin Hyper Cube sampling assures that distribution and values fully represented. C: N/A: Because there is only one data set.
Less important - relative to releases	Panel Closure	• Bounding argument • No data collected for panel closure	Permeability is larger than what we think the true value would be. Very conservative value. The true distribution of values would all be below the assumed values and is therefore very conservative. R: Bounds all plausible values.

No Impact - relative to releases	Releases through the Culebra: Kd's	• Experimental data
		  • Field data
		  • Laboratory data
		• All distributions
			P: Variability in values doesn't significantly affect release. Wide variability due to a large range of conditions in field/lab data dominates the variability in the individual experiments. Variability scatter of the data collection values is small compared with the much broader spread assumed by the distribution to account for uncertainties in the conditions.
			A: Distributions set-up for variability uncertainty.
			R: Representativeness of collection cannot be known for 100% certainty for natural features. Therefore accounted for by probabilistic method.
			C: Same as for Representativeness.
			C: N/A: Because all of the available data were used to create the distribution.

Attachment 1
P. 3

ENVIRONMENTAL EVALUATION GROUP

AN EQUAL OPPORTUNITY / AFFIRMATIVE ACTION EMPLOYER

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December 31, 1997

Mr. Frank Marcinowski
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U.S. Environmental Protection Agency
401 M Street SW
Washington, DC 20460

Dear Mr. Marcinowski:

At our meeting on December 10, 1997 in Albuquerque, the EPA WIPP project staff asked us to provide a written description of each of the issues related to the EPA's draft rule on WIPP, that we presented that day. This letter is to provide you a summary of each of the issues that we presented, as well as summaries of the issues that we did not have the time to present that day. Where more details are needed, we have enclosed extended descriptions. As requested by your staff, we have made specific suggestions on how to resolve each of these issues. This letter is not a replacement for the material presented to the EPA, but supplements and amplifies it. Also, please note that our presentations at the 12/10/97 meeting, and this letter, constitute our initial reaction to the EPA's draft rule published on 10/30/97. As we continue to review the voluminous materials released with the draft rule, we will provide additional comments to you in the near future.

As we noted on December 10, the issues presented to the EPA were those for which we have additional analyses or arguments. The issues not discussed that day were those for which we have previously provided detailed comments to the EPA, but the EPA has disagreed with our position, as indicated in the Draft Rule. Those issues are also included here with our reasons for continuing to believe in our previously stated positions. We trust that this material will be of use to you in your continuing review of the DOE application.

SUMMARIES OF THE ISSUES PRESENTED ON 12/10/97

Solubility

In reviewing the basis for the selection of actinide solubilities in the CCA and PAVT calculations, the EEG finds that the FMT model is unique to WIPP and is not used elsewhere. Calculations

using the FMT model result, for example, in a difference of 19 orders of magnitude between the projected solubility of thorium pentacarbonate in the Castile brine versus the Salado brine. This is hard to explain on the basis of differences in the brine compositions. Hence the code becomes suspect. It appears that the EPA verification was limited to an exercise in which EPA used the same computers, codes, and database (after correction of some errors in the database) as DOE, to determine the same numerical values. This is not the standard of verification that one normally applies to chemical modeling codes. Verification would require, at a minimum, an analysis and demonstration that the FMT code correctly solves the simultaneous equations, a thorough comparison with the results of calculations using a code that is used more widely in the modeling community, and a demonstration that the calculations are consistent with all relevant published data. For example, as a preliminary analysis, it would have been more informative if a widely used code such as EQ3 or PHREEQE had been used with the FMT database and then FMT had been used with a database from some other modeling group.

Plutonium will account for 82% of the WIPP radioactive inventory 100 years after closure. The CCA maintains that the plutonium will exist either as Pu(III) or Pu(IV). However, the plutonium data were not used for developing the FMT model to predict the solubility of Pu(IV). Rather, the CCA relied on data for uranium and thorium as analogs. But there are long recognized concerns about relying entirely on the oxidation state analogy to derive thermodynamic constants for modeling complex electrolyte systems. As stated in the NAS/NRC WIPP Committee report (Oct. 1996, p. 129):

> Although the oxidation state model (the assumption that the chemistry of a given oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviations from the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy.

In its technical support documentation, EPA discusses the shortcomings of the solubility uncertainty ranges advanced by DOE. There is no direct basis for the uncertainty ranges for actinides in oxidations states +4 and +6. Moreover, the uncertainty ranges for oxidation states +3 and +5 are derived primarily from non-actinide data. Nonetheless, EPA has accepted the ranges as adequate, commenting “It is not clear that including more data for the other actinide state would appreciably change this range” (EPA, III-B-17, p.35). The argument is weak. It also remains unclear that the range adequately brackets uncertainty for a population for which data have not been examined.

In the solubility calculations, the CCA inappropriately discounts the role of organic ligands on plutonium solubility. The CCA provides information on the amounts and complexing properties of EDTA and then argues that other organic ligands, such as citrate, will be unimportant despite

the fact that citrate is the most abundant water-soluble organic constituent. Citrate forms extremely strong complexes with actinides in the +4 oxidation state [e.g. Th(IV)], but very weak complexes with other cations. Moreover, the DOE and EPA have each assumed that the actinides and the brine would be evenly distributed and well mixed throughout the repository. The problem with this assumption is that the plutonium and citrate are located in the same drums. These waste forms result from chemical separations of Pu and do not fit the classic description by DOE of TRU waste as contaminated tools, rags, gloves, booties, etc. The solubility of the plutonium for these waste forms must also be calculated as a very stable plutonium citrate complex where other cations in the brine diffusing into the drum cannot compete effectively with the complexed actinides (IV).

Perhaps the most important questionable assumption made in projecting the solubility values used in the CCA and the PAVT is the presence of hydromagnesite as the dominant stable mineral species resulting from the MgO backfill. DOE's experimental efforts with MgO predominantly produced nesquehonite, a magnesium carbonate mineral, with the later appearance of an unidentified phase. Hydromagnesite was not formed in the experiments reported by the DOE (Van Bynum's 4/23/97 report); a hydromagnesite-like unnamed mineral is reported. The chemical structure of this mineral is in fact more like nesquehonite. The DOE and the EPA believe that "hydromagnesite will be the metastable hydrated magnesium carbonate phase and nesquehonite will be an intermediate phase." (EPA Technical Support Document III-B-17, p.2). There is no experimental data for the length of time that nesquehonite is expected to exist. The distinction between the projected hydromagnesite-dominated or nesquehonite-dominated chemical environment in the repository is important because the actinide solubilities in the presence of nesquehonite are 3 to 4 orders of magnitude higher than in the presence of hydromagnesite.

The EEG therefore recommends that the EPA reexamine these issues and provide additional justification for the CCA and the PAVT solubility values. If convincing justification is not available, then the "no backfill", or "nesquehonite" solubilities should be used in a new performance assessment calculation.

The EEG has investigated the effect of actinide solubilities on the mean CCDF plots, using the EPA's PAVT releases, and making no other changes. The investigation (Enclosure 1) included the "CCA" solubilities, "no backfill" solubilities, and "nesquehonite" solubilities. The overall mean CCDF curve for "nesquehonite" solubility moved one order of magnitude closer to the compliance limit at 10^{-3} probability compared to the CCA solubilities (Enclosure 1, Fig.1).

Three Dimensional Processes and Boundary Conditions

This issue was presented to the EPA staff on December 10, 1997 as "2D/3D Modeling in BRAGFLO". The EEG first brought this issue to the EPA's attention as an attachment titled "Brine Inflow From Salado: 2-D versus 3-D Geometry in BRAGFLO" to the 3/14/97 Neill to

Marcinowski letter. The DOE submitted a response as an attachment to the 6/27/1997 letter from G.E. Dials to L. Weinstock. The Draft Rule includes this issue as Issue F in CARD #23. The EEG position is summarized by the EPA as Comment #553 on page 115 of CARD #23, and the EPA response is provided on page 116. EEG's detailed response to the DOE and the EPA positions is provided as Enclosure 2 to this letter. A summary of the issue, the EEG's response, and the EEG recommendation to resolve the issue, follow.

The results of FEP S-1 screening analysis suggest that the two dimensional BRAGFLO model used in the CCA calculations may be misrepresenting repository performance at pressures above the anhydrite fracture pressure. There is the potential of substantially greater brine saturation in the repository at higher pressures than calculated for the CCA. The discrepancy between the 2D and 3D versions of BRAGFLO may have resulted in an underestimate of radionuclide releases to the surface.

To resolve this issue, the EEG recommends that several 3D BRAGFLO simulations of the repository should be performed using the parameter values of vectors used in the CCA performance assessment. The 3D BRAGFLO simulations should be used to provide repository conditions for the normal suite of direct brine release calculations. The calculations should also be assessed in terms of impact on spallings calculations. Spallings simulations are probably not required to assess the impact. The following criteria may be used to select the CCA vectors for running the 3D simulations to bound the magnitude of the problem:

- Since the discrepancy occurs above the fracture initiation pressure, the simulations should be limited to parameter vectors that result in pressures above 12.7 MPa at some time during the 10,000 year time frame.

- Direct brine release calculations should be sensitive to increased brine saturations above the waste residual brine saturation. Vectors that had either large brine saturations or a mobile brine component (saturations above the residual saturation) are more likely to be sensitive to increased brine inflow. Figure 5.1.5 of the preliminary sensitivity analysis report (Helton, 1996) indicates one vector with a 10,000 year pressure above 14 MPa and a brine saturation above 0.4. This is a likely candidate.

- The potential for brine consumption by corrosion should be assessed. Vectors with both slow and fast corrosion rates that also meet the above two criteria should be run.

- If the first simulations indicate a large change in saturation, then assess whether the 3D BRAGFLO simulations indicate a much larger number of significant direct brine releases than those calculated in the CCA. Simulations using brine saturations on the order of 0.1 and 0.3 should be performed.

Review of the EPA Spallings Investigation

The EPA funded a separate investigation of the spallings phenomena that focused on potential limits on spall material reaching the surface because of insufficient lofting capacity of gases vented from the repository (TSD III-B-10 and TSD III-B-11). The EPA investigation determined that venting of the repository would not be energetic enough to bring spall material to the surface. The conclusion is valid for evaluating the CCA spallings model but cannot be extended to the most recent DOE spallings model. The investigation's focus is on relatively long term transport capability consistent with the CCA spallings model. It should be on the immediate transport of material from the formation of an explosive spall cavity, as in the most recent DOE model.

The EPA modeling is superceded by the new spallings model presented in January 1997 (Hansen et al., 1997) to the DOE's Conceptual Model Peer Review Panel. The Panel rejected the CCA model and accepted this new model. This new model predicts that almost all spall would come from the face of the drilling cavity and that the spall process would occur in the first few seconds of repository depressurization.

The permeability reduction used in the EPA model is inappropriate to address removal of the initial spall material. The spallings model of *Hansen et al.* predicts that spalling will stop after a few seconds and that depressurization is negligible beyond roughly 1.5 meters at this time. During this initial depressurization, the source of flow is from the region close to the borehole. It is this local depressurization that would cause spalling to progress away from the drilling bit.

The temporal and spatial discretization of the EPA investigation is far too coarse to investigate the potential for evacuation up the borehole of spall material created in the first few hundred seconds. For example, in the case of a two foot penetration with 0.25 m^3 spall cavity, the first element of the EPA analysis is 0.39 m thick. In the *Hansen et al.* model, the first element is 0.01 m thick. In the EPA investigation the first time step is 86 seconds compared to 0.001 seconds in the *Hansen et al.* model. These differences in both temporal and spatial discretization are an indication that the EPA modeling cannot predict gas velocities from local depressurization reliably. Hence, the EPA model cannot be used to judge the conservatism of the spall model described *by Hansen et al.*, nor the extension of the *Hansen et al.* model to potential spall from air drilling.

Hansen et al. also considered the issue of maximum particle size that could be transported up the borehole. Their results indicate that particles as large as 10,000 microns may be transported to the surface after the mud column has been expelled from the borehole, about 250 seconds after intrusion, and that transport of such large particles could occur for much more than 200 seconds. Two-hundred and fifty seconds is still very early in the EPA investigation (3 time steps). The discretization of the EPA model is too coarse to accurately calculate the flow rates this early in

the 11-day period. In conclusion, the calculations of *Hansen et al.* indicate that transport of spall material up the borehole will not limit the release of spall material to the surface.

The EEG therefore recommends to the EPA to **not** use the results of simplified modeling contained in the draft rule attachments TSD III-B-10 and III-B-11 to confirm the validity of the CCA spallings model, or to limit the potential releases from air drilling.

Stuck Pipe/Gas Erosion Scenarios

"Stuck pipe" is a scenario that occurs when, due to very low permeability of the waste and extremely high pressures in the repository, the amount of failed waste (spall) is more than the carrying capacity of the drilling mud. The spall then presses against the drill string sufficiently hard to slow down the rotation of the drill bit, preventing normal drilling. To free the jammed bit, the drillers pull the drill string up and start drilling again. If the pressures remain high, the driller may have to bring the bit up several times, thus allowing significant quantities of waste to be brought to the surface. "Gas erosion" refers to the scenario in which the failed waste is slowly eroded by the drilling mud when the repository pressure is just above hydrostatic and the waste permeability is low. Under these conditions, waste may be released into the drilling mud at a rate undetectable by the driller. Gas erosion would continue until the repository pressure is in equilibrium with the drilling fluid, and may bring significant quantities of waste to the surface in the process. Both these scenarios were considered by the DOE in an earlier exercise in the WIPP performance assessment (Systems Prioritization Method, 1995), but were not considered in the CCA because the permeability of the waste was assumed to be higher than the threshold for these processes to occur.

The CCA (Chapter 6, p. 6-100) states that permeability of the waste compacted under a lithostatic load was found to be in the range of 10^{-12} to 10^{-16} m^2, but assigns a constant value of $1.7x10^{-13}$ m^2, which is much greater than the assumed threshold of 10^{-16} m^2 for the "stuck pipe" scenario.

This issue was first raised in my February 7, 1997 letter to you, and has been numbered 540 in the draft rule (CARD 23). The response to Comment 540 states that the phenomena of stuck pipe will not occur because the permeability of the waste in the CCA (DOE, 1996-Chapter 6) was greater than the threshold permeability for stuck pipe stated in the CCA (DOE, 1996-Appendix CUTTINGS_S). The EPA quotes additional studies of permeability made by the DOE, in which the waste permeability was found to be 100 times less than the CCA value (Hansen et al., 1997), but still greater than the threshold permeability. Thus, the EPA does not believe that stuck pipe and gas erosion are processes to be considered in the CCA spallings model.

The EEG continues to believe that the "stuck pipe" is a plausible scenario because the threshold of $1x10^{-16}$ m^2 for stuck pipe and gas erosion may be faulty. This value resulted from the CCA Spallings model (as part of CUTTINGS_S), which was found to be conceptually flawed.

Berglund (1994) states that, for model simplicity, a value of $1x10^{-16}$ m^2 will be used for a cutoff for blowout. The new spallings model, GASOUT (Hansen et al., 1997), shows that blowout will cease when permeability is between 10^{-14} and 10^{-15} m^2. Berglund (1994) has shown that when blowout stops, the stuck pipe and gas erosion mechanisms of spall take over because the failed waste will be introduced into the borehole cavity and will not be blown out. Thus, the permeability threshold for the stuck pipe and the gas erosion scenarios appears to be 10^{-14} to 10^{-15}, rather than 10^{-16}. In any case, because of the stuck pipe and the gas erosion scenarios coming into play when the blowout ceases, release to the surface will occur even when the conditions for blowout of the mud column cease. We therefore recommend that it should be assumed that all of the calculated spall material will reach the surface.

Furthermore, the permeability of the waste in the WIPP repository is quite likely to be lower than that anticipated by the DOE. None of the waste surrogates for permeability testing included MgO as a backfill material. It is suspected that MgO precipitation will decrease the permeability by providing material for interstitial cementation, which has been postulated by the DOE's Particle Size Expert Elicitation Panel to be a major contributor to increased waste strength and lower permeability. Since the permeability of the waste is such a key parameter in assessing compliance with the standards, additional permeability measurements on surrogate waste that includes magnesium chloride cement should be carried out. Until this is done, the calculations may sample on the 10^{-12} to 10^{-16} range.

To get a perspective on the potential magnitude of impact of these scenarios on compliance, the EEG conducted calculations to investigate the amount of spallings release through either the stuck pipe or the gas erosion process that would violate the EPA standard. Enclosure 3 shows that if between 8 m^3 and 64 m^3 of spalled material is assumed to reach the surface, the standard is violated at 10^{-1} probability. The EEG is in the process of computing the releases from the stuck pipe and the gas erosion scenarios, and will transmit the results to the EPA as soon as possible.

Brine Release in Air Drilling

The EEG has investigated the effect of air drilling on direct brine release, and the results are shown in Enclosure 4. The results show that brine releases to the surface could be between 1000 and 2000 m^3, compared to a maximum of 180 m^3 from the EPA's PAVT computations. The CCDF from the EEG's runs show that the overall mean for all types of releases (including brine release from air drilling) comes very close to the EPA limit at 10^{-3} probability for the actinide solubilities assumed in the CCA, and violates the standard at the "no backfill" and "nesquehonite" solubilities.

Fluid Injection Scenario

The petroleum reservoirs surrounding and underlying the WIPP are potential candidates for fluid injection to recover a substantial amount of crude oil reserves. For oil field operations in

southeastern New Mexico, the problem of water migrating from the intended injection zone, through the Salado Formation, and onto adjacent property has long been recognized. In fact, concerns about unexplained water losses due to solution mining, potential oil field development, or future oil field waterflooding has helped eliminate other sites from consideration as documented in an EEG report on fluid injection (Silva 1996; EEG-62). The EPA proposes to accept the DOE position that fluid injection can be ruled out as a potential scenario and, hence, need not be considered in the performance assessment calculations.

For fluid injection activities on leases adjacent to the site, the DOE argues that such events can be eliminated from further consideration on the basis of low consequence. The EPA raised questions regarding DOE's consequence analysis and "concluded that regardless of the consequence argument, the probability of such an injection event that affects WIPP is very low, and so this FEP can be eliminated on the basis of low probability"(CARD 32, p.42). The DOE chose to examine consequence rather than probability, as noted by Stoelzel and O'Brien, "[because certain petroleum practices are hard to define in a probabilistic sense (for example, the quality of the cement and/or casing and its ability to withstand leaks over time)..."(Stoelzel and Obrien 1996, 8). Nonetheless, EPA assigned probabilities to certain petroleum practices, such as an undetected leak occurring in the annulus, and multiplied the probability of each event and calculated that the *realistic* probability of a injection well impacting the repository was only one in 667 million (EPA, III-B-22, Table Q). But this value appears to be based on an optimistic view of future injection well performance and does not reflect the actual experience of documented waterflows in the Salado Formation in water flood areas throughout southeast New Mexico.

In the final analysis, for the low consequence argument, the EPA has accepted the modeling results of Stoelzel and O'Brien (1996) and Stoelzel and Swift (1997) for DOE, and has rejected the modeling results of Bredehoeft (1997) for the New Mexico Attorney General. The DOE maintains that a leaking injection well in the vicinity of WIPP is a low consequence event. But a very fundamental question remains. Can the DOE codes model a documented high consequence event? In other words, can the DOE codes take the injection data and geologic data from the highly visible Hartman case and reproduce what is believed to have happened at the Bates Lease? Can these codes model the migration of substantial amounts of water through a single zone of the Salado Formation, two miles in the up dip direction, in about 12 years? That has yet to be shown. Unless the code is verified with actual field data, the low consequence conclusion will remain a speculation at best.

The EPA does not anticipate that CO_2 injection for oil recovery will be a widespread practice in the future near WIPP (EPA CARD-23, p. 131). However, EPA's reasons do not have supporting references and appear to be at odds with the published literature. The EPA technical support document (III-B-22) states "at this time, the only examples of CO_2 injection enhanced recovery techniques are some distance from the WIPP site and under much different geologic conditions

(Magruder 1990; Trash 1979)". But an examination of the current and relevant literature strongly suggests that the Delaware Mountain Group sands are excellent prospects for future CO_2 flooding. First, CO_2 flooding has been demonstrated to be quite successful in mature fields in the Delaware Basin such as the TwoFreds (Silva, 1996, pp. 142-145). Second, the DOE continues to sponsor university research on Delaware Basin oilfields, such as the Geraldine Ford and the West Ford, aimed at optimizing infill drilling and CO_2 flooding throughout the Delaware Basin. Third, oil and gas companies continue to purchase mature fields, such as the El Mar in the Delaware Basin, specifically for carbon dioxide flooding. Fourth, the recently drilled reservoirs surrounding the WIPP such as Cabin Lake, Livingston Ridge, Los Medanos, and Lost Tank have oil and reservoir characteristics that easily qualify them as potential candidates for future CO_2 flooding using the enhanced oil recovery (EOR) screening criteria.

EPA maintains that "there are no natural gas storage horizons in the Salado Formation" (EPA CARD-32, p.71). As shown on a map presented to EPA by EEG on October 10, 1996, there are eight gas storage underground facilities in southeast New Mexico, three of which are in the Salado Formation in which the salt was "washed out to create a cavern", according to entry in a State document.

There are other fluid injection issues that have either not been fully addressed or in which there appears to be a misunderstanding of the issue including, for example, the yet to be explained water level rises in the Culebra Aquifer, the likely expansion of solution brine wells in the Delaware Basin, and the likely initiation of solution mining activities in maturing potash mines.

SUMMARIES OF THE ISSUES NOT PRESENTED ON 12/10/97

The following are the summaries of the other important issues related to the CCA and the Draft Rule that were not presented to your staff on December 10, but have been previously presented to the EPA.

Waste Issues
EEG has concerns about some EPA conclusions regarding: (1) waste inventory and waste form; (2) waste characterization; and (3) waste repository limits.

Waste Inventory and Waste Form:
The EPA has concurred with the DOE's contention that there is no uncertainty in the waste inventory. EEG's view is that: (1) there is considerable uncertainty in the stored inventory; (2) there is uncertainty in the volume of newly generated waste and the processes at the generating sites have changed significantly since the stored waste was generated; and (3) DOE plans to treat most of the waste at INEEL and the RFETS (residues) and repackage, and treat for size reduction, at other facilities. These plans are not reflected in the CCA inventory.

EPA should recognize this uncertainty and either not accept the DOE inventory and Waste Material Parameter (WMP) values or not permit DOE to bring in waste that differ significantly from the values in the CCA until more accurate inventory data have been developed and used in the PA calculations.

Waste Characterization:
DOE has concluded that a maximum repository limit of $2x10^7$ kg of cellulosics, rubber, and plastic (CRP) should be set in order to prevent production of more CO_2 than can be controlled by the MgO backfill. EPA has concurred in this recommendation. The expected amount of CRP in the repository is $2.1x10^7$ kg (see CARD 24-38).

EEG is concerned about the ability to measure CRP in the waste with enough accuracy to ensure that this limit will be met. Visual Examination (VE) is a method that is capable of good precision on those containers measured if all internal containers are emptied and their contents identified and weighed. However, the preferred method of characterization is real time radiography (RTR) which is only semi quantitative (WMP weights are estimated by determining the void space and weight of waste in the drum which is not very accurate even if there is only one WMP in the container). EEG has not found a reference to the uncertainty in determining the weight of CRP in waste containers in either the DOE or the EPA reports. The EPA needs to point out where this uncertainty has been addressed, if it has been, or address the issue at this time.

Waste Repository Limits:
DOE has concluded that all repository limits need to be controlled only for the full repository. EPA has concurred in this recommendation and concluded that DOE's WIPP Waste Information System (WWIS) is capable of controlling repository limits.

There are two concerns that do not appear to have been addressed:

(1) An excess of CRP in a waste panel could overload the MgO in that panel and since no interchange of brine between panels is assumed, it is questionable how much benefit would incur from excess MgO in another panel. Estimated concentrations of CRP do vary significantly between generating sites (e.g. at INEEL the average is 1.8 times the total inventory average);

(2) A management plan that allows emplacement of repository limited parameter quantities that vary significantly from the required average could result in a situation where the required limits could not be met by emplacing the remainder of the inventory. This is a potential problem because the actual content of waste containers will be known only as the individual containers are characterized and may be much different than the current estimates.

EEG believes that the case for controlling limits on a repository basis has not been justified. We recommend control on a per panel basis, at least, until the inventory is known with more certainty.

Retardation Coefficient
The EEG has submitted the following four documents to the EPA on this issue:

- Copy of November 14, 1996 letter from R.H. Neill to J. Salisbury, with attachments;
- February 7, 1997 letter from R.H. Neill to F. Marcinowski, with attachment "Chemical Retardation";
- Copy of May 23, 1997 letter from R.H. Neill to J. Salisbury, with attachments; and,
- Copy of August 29, 1997 letter from R.H. Neill to G.E. Dials, with attachments.

The August 29, 1997 letter and the attachments (docket # II-D-117) contained the EEG position on this issue based on the July 30, 1997 meeting in Albuquerque, which was organized by the EEG. Copies of this letter with the attachments were mailed to several EPA officials and the EPA WIPP docket. The DOE also sent a copy of their impressions of the July 30 meeting (Dials to Neill 8/25/97 letter with attachments, docket # II-D-115) to the EPA on August 25, 1997, four days before the EEG letter.

The EPA draft rule discusses this issue in the Technical Support Document, "Assessment of K_dS Used in the CCA", docket # III-B-4. This document makes extensive references to the DOE's August 25, 1997 letter, but no mention of the EEG's August 29, 1997 letter. Because the issue was raised by the EEG, and the July 30, 1997 meeting was organized by the EEG, it is difficult to understand why the EPA's analysis makes no mention of the EEG's summary of the July 30 meeting and the recommendations.

As described in the EEG's August 29, 1997 letter, the EEG has recommended conducting both batch and column tests for at least the actinides Pu(III), Pu(IV), and Am(III) in the Culebra brine; setting the lower end of K_d for U(VI) to be zero; conducting sensitivity analysis for potential impact of organic ligands; extending performance assessment calculations beyond 10,000 years to see how long the chemical retardation delays the releases to the environment; investigating the potential impact of nonlinear sorption on radionuclide transport; and, checking the validity of the K_d values derived from the column tests by examining the cores to identify whether the Pu and Am are present in adsorbed or crystalline solid phase.

The EEG recommends that the EPA consider the EEG submissions to the docket before reaching a final conclusion on the issue.

Brine Reservoir Probability
The EEG raised a number of issues related to the Castile Formation brine reservoirs (see R.H. Neill letters to F. Marcinowski, dated 2/7/1997 and 3/14/1997, attachments "Brine Reservoir Assumptions"). The EPA has accepted all of the EEG suggestions except the one related to the assumption of the probability of encounter of brine reservoirs, and we disagree with the EPA on this issue. The CCA assumed 8% probability on the basis of faulty assumptions. The EEG recommended 100% probability on the basis that the WIPP-12 brine reservoir was large enough to most likely extend under the repository, a conclusion also confirmed by geophysical testing directly above the repository. The EPA has sampled on a range of 1 to 60%, but has provided no basis for assuming less than 60%. Based on the arguments that the geophysical (Time-domain electro-magnetic survey) data may be interpreted to indicate the brine to be under 60% of the repository, and that some boreholes adjacent to the brine producing boreholes are known to be dry, the EEG is willing to accept the assumption of a fixed 60% probability of encounter, and recommends that a new performance assessment calculation be run with this fixed value.

Assurance Requirement/Engineered Barriers
The EEG believes that in allowing the resource disincentive requirement of the EPA standards (40 CFR 191.14 e) to be satisfied if the numerical containment requirements (40 CFR 191.13) are satisfied (through 40 CFR 194.45), the EPA deviated from the basic philosophy of the "belt-and-suspender" approach inherent in the assurance requirements of the standards. Faced with the *fait accompli* of promulgation of 40 CFR 194, the EEG recommended (EEG-61, May 1996) that at least the actual conditions at the site related to the presence of natural resources be fully and conservatively assumed in projecting compliance with the numerical containment requirements. This does not appear to have been done in the CCA, judging from the DOE resistance to consideration of fluid injection, air drilling, and mining scenarios. The other suggestion made by the EEG (in EEG-61) is to compensate for siting the repository in a mineral resource rich area by incorporating robust engineered barriers in the WIPP's design. The DOE has proposed Magnesium Oxide backfill as an engineered barrier, but that is needed for assuming low actinide solubility to show compliance with the containment requirement. The "containment" and the "assurance" requirements of the EPA standards thus have not been kept separate, as was intended by the EPA standards, 40 CFR 191.

The EEG recommends that additional confidence in predicting the behavior of the waste over 10,000 years can be obtained by processing the waste. Hence, EPA should encourage the DOE to process the waste before shipment to WIPP. TRU waste is highly heterogeneous and there are no limits on the allowable particle size of the waste. The Nuclear Regulatory Commission requires a 300 year waste-form or container longevity for class B or class C *low-level* waste, whereas there are no requirements for the TRU containers or the waste-form in 40 CFR 191. Moreover, the DOE proposed action in the WIPP 1997 Environmental Impact Statement only commits to meeting the Waste Acceptance Criteria for acceptance of waste at WIPP. The DOE

preferred alternative, published in the 1997 Final Waste Management Programmatic Environmental Impact Statement for Managing, Treatment, Storage and Disposal of Radioactive and Hazardous Waste, is to **treat** and store at the sites where it is generated prior to shipment to WIPP.

The recommendation to treat the waste before shipping to WIPP should be easier to accomplish because several of the DOE's waste generator sites are planning to process and/or repackage the waste before shipping to WIPP anyway, for other reasons, as described below. The EPA's directive will result in an orderly and coordinated decisions on this matter throughout the DOE weapons complex, and will make WIPP safer.

- According to the September 1997 WIPP Final Supplemental Impact Statement (DOE/ES-0026-S-2), 27,000 m^3 of alpha emitting low level waste at INEEL will be processed to convert it to TRU waste.

The information for the following processing and repackaging plans is derived from the National TRU Waste Management Plan, DOE/NTP.-96-1204, Rev.1.

- INEEL plans to process all the existing and projected TRU waste except for 15,000 drums (3,000 m^3) to meet the INEEL/State of Idaho agreement, which amounts to processing 79,600 m^3 - 3,000 m^3 = 76,600 m^3 of waste.

- ANL-E plans to treat and stabilize all the 203 m^3 existing and newly generated CH-TRU waste.

- Hanford plans on repackaging most of its 16,127 m^3 of CH-TRU waste.

- Rocky Flats Plant will process the plutonium residues and the scrap alloy since plutonium concentrations exceed the DOE limits. About half the other TRU waste will be processed and repackaged.

- The Plutonium-238 heat source wastes at Savannah River exceed the hydrogen gas limits imposed by NRC and will require treatment or an easing of the regulations for a less stringent flammable limit or the use of hydrogen getters in the transportation containers.

- All the 1097 m^3 CH-TRU waste at ORNL will be processed with a 50% volume reduction.

- SRS plans to process and repackage 9,525 m^3 of the existing 11,725 m^3 of CH-TRU waste.

In summary, of the existing 104,400 m^3 of CH-TRU waste, DOE has plans to treat or repackage 88,900 m^3 or 85%. Of the 15,500 m^3 not being processed, 3,000 m^3 is intended for shipment to meet a scheduled commitment between DOE and the State of Idaho. The EPA should recognize DOE's efforts in stabilizing the waste and encourage DOE to also fix the yet-to-be generated waste.

We look forward to continuing the dialogue with you to resolve these and other issues.

Sincerely,

Robert H. Neill
Director

RHN:js
Enclosures

cc: Mr. Richard Wilson, EPA
Mr. Larry Weinstock, EPA
Ms. Mary Kruger, EPA
Mr. Chuck Byrum, EPA
Mr. Tom Peake, EPA
Mr. George Dials, DOE
Mr. Chris Wentz, NMEMNRD
Mr. Lindsay Lovejoy, Jr., NMAG
EPA Docket for WIPP (A-93-02)

(Enclosure 1 to the 12/31/97 Letter From R.H. Neill, EEG to F. Marcinowski, EPA)

Issue: Solubility Modeling

The modeling of solubility changes to the PAVT started with the re-running of the 'Source Term' files. The Latin Hypercube Sampling (LHS) generated a range of solubilities in the CCA that were 2.0 and 1.4 orders of magnitude below and above the median values, respectively. For the present model the range of solubilities were reduced to a constant value, based on solubilities of 'No Backfill' from Van Bynum (1997), and Nesquehonite in Novak (1997). The parameters of SOLSIM (solubility factor for Salado) and SOLCIM (solublity factor for Castile) (DOE, 1996-Appendix PAR) were changed for the oxidation states of +3, +4, and +6.

Table 1 shows the values used to replace SOLSIM and SOLCIM for all the actinides for the different mineral types. Again, the range from -2.0 to 1.4 with a cumulative continuous distribution was changed to the values below with a cumulative discrete distribution. One hundred vectors were created for all six scenarios of the first replicate with the new LHS file.

Once Source Term files were created, PANEL was rerun with the new solubilities using BRAGFLO files of the PAVT. The BRAGFLO files supply the velocity information for PANEL to use in the transport equations. The PANEL 'concentration' simulations were ran for 100 vectors of S1 and S2 scenarios. The PANEL 'time' simulations were reran for 100 vectors of S6 for times 100, 350, 1000, 4000, 6000 and 9000 years postclosure.

Lastly, the PANEL files were incorporated into the CCDFGF to create CCDF curves for comparison with 40 CFR Part 194. In addition to the Nesquehonite and No Backfill simulations with PANEL to create the new CCDFs, the CCA PANEL files containing CCA solubilities were used with PAVT releases of direct brine release, cuttings, spallings, and transport through the Culebra. Figure 1 shows the CCDF results of the different solubilities.

The figure shows that none of the curves violate the standard. The CCA solubility model has an estimated release of 0.45 EPA units at the 10^{-3} probability level. This is slightly higher than the 0.37 EPA units of the PAVT model and 0.22 EPA units of the CCA. The releases are shown to increase to 6 EPA units for Nesquehonite solubilities and to 7.5 EPA units for 'No Backfill' solubilities. The EPA compliance limit for the 10^{-3} probability level is 10 EPA units, or 3500 Ci for Plutonium, Uranium, Thorium, and Americium.

References

Bynum, R.V., 1997. Chemical Conditions Model: Results of the MgO Backfill Efficacy Investigation, SAND97-2511. Albuquerque, NM: Sandia National Laboratories.

Novak, C.F., 1997. Memorandum from Craig F. Novak to R. Vann Bynum "Calculation of Actinide Solubilities in WIPP SPC and ERDA6 Brines Under MgO Backfill Scenarios Containing Nesquehonite or Hydromagnesite as the MgO-CO_3 Solubility-limiting Phase". Albuquerque, NM: Sandia National Laboratories. WPO# 46124.

U.S. Department of Energy, 1996. Title 40 CFR 191 Compliance Certification Application. DOE/CAO-1996-2184.

	Nesquehonite		No Backfill	
	SOLCIM	SOLSIM	SOLCIM	SOLSIM
SOLAM3	1.51616	-.27709	4.48678	3.83714
SOLPU3	1.51616	-.27709	4.48678	3.83714
SOLPU4	5.23242	2.15588	4.06695	2.05552
SOLU4	n/a	2.15588	n/a	2.05552
SOLU6	0.95861	0.96357	0.95861	0.96357
SOLTH4	5.23242	2.15588	4.06695	2.05552

Table 1. Solubility Factors for SOLCIM and SOLSIM

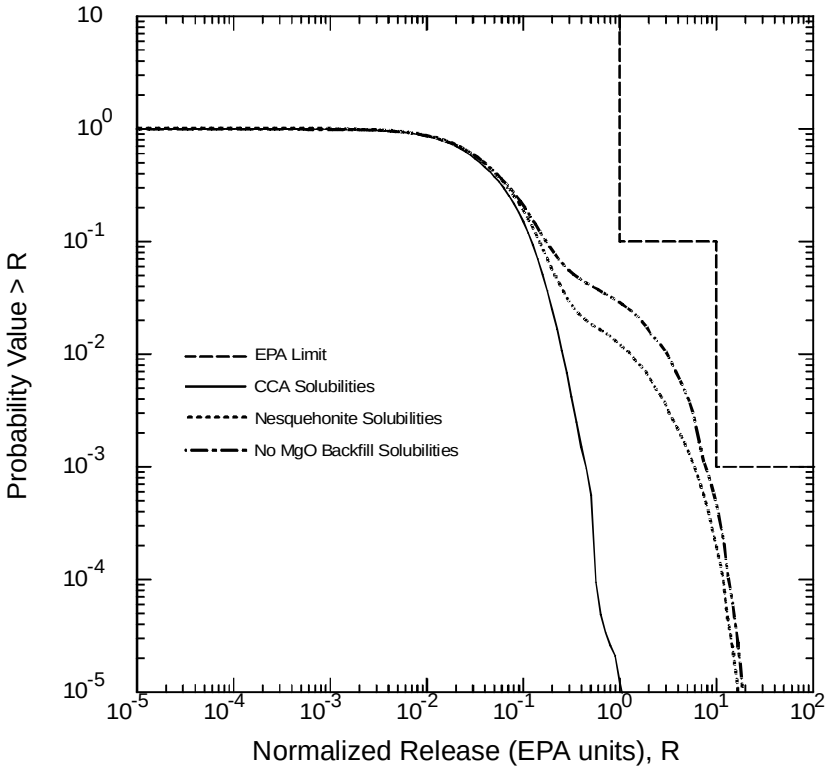

Figure 1. CCDF Overall Mean for Solubility Modeling with the CCA, Nesquehonite, and 'No Backfill' Values.

(Enclosure 2 to the 12/31/97 Letter From R.H. Neill, EEG to F. Marcinowski, EPA)

Issue: Three Dimensional Processes and Boundary Conditions

Problem Description

The EEG first brought this issue to the EPA's attention as an attachment titled ABrine Inflow From Salado: 2-D versus 3-D Geometry in BRAGFLO to the 3/14/97 letter from R.H. Neill to F. Marcinowski. The DOE submitted a response as an attachment to the 6/27/1997 letter from G.E. Dials to L. Weinstock. The Draft Rule includes this issue as Issue F in CARD #23. The EEG position is summarized as Comment #553 on page 115 of CARD #23, and the EPA response is provided on page 116. This issue was presented by the EEG to the EPA on December 10, 1997 as 2D/3D Modeling in BRAGFLO.

The FEP Screening Analysis titled S1: Verification of 2D-Radial Flaring Using 3D Geometry (*Vaughn et al.*, 1996) compared the two dimensional radial flaring model of BRAGFLO used in the CCA performance assessment to a three dimensional BRAGFLO model of the repository. The 3-D model calculated a large flow of brine into the repository after the pressure reached the anhydrite fracturing pressure. The large flow did not occur in the 2-D model. Figure 1 shows the pressure history for the two models. The scenario used for the investigation included a drilling intrusion at 1,000 years, accounting for the large drop in pressure at that time. Our concern is the difference in behavior of the two models after the pressures reach 12.7 MPa but prior to 1,000 years.

Figure 2 depicts the calculated brine inflow and outflow rates. The figure shows a large difference in calculated inflows of the two models during the period of 700 to 1,000 years. Figure 3 reinforces the perception that the brine inflow in the 3-D model is large. As shown in Figure 3, during the 700 to 1,000 years period the 3-D model shows a decrease in gas saturation of 0.05. Our concern is that if the brine inflow calculated in the 3-D model persists for thousands of years then the 2-D model calculations significantly under-predict repository saturation at high pressures.

Greater saturations could lead to much larger direct brine release calculations. Figure 4 (Figure 5.1.5 of *Helton)* is the basis of this contention. Figure 4 depicts the relationship of calculated direct brine releases to repository conditions at three separate times. The average repository brine saturation and repository pressure are plotted for each vector on the horizontal plane. A vertical line connects the plane to a small circle at the level of the vertical axis corresponding to the volume of brine calculated to reach the surface. Calculated releases greater than one cubic meter are highlighted using a filled circle.

Figure 4 indicates that there were few calculated direct brine releases when the calculated repository pressures exceeded 12.7 MPa and almost none when the pressure exceeded 14 MPa. Almost all of the larger calculated direct brine releases occurred when brine saturations were above 0.5, a condition never calculated at pressures above 14 MPa. The FEP S-1 analysis suggests that the potential for many of the vectors with great repository pressure to also have large brine saturations. Thus calculated direct brine releases might have both larger volumes and greater frequency in the performance assessment.

EEG Assessment of DOE Response to Comment # 553

The major concern of the EEG is that the 3-D modeling of the repository system indicates the potential for large brine inflow to the repository at high pressure which leads indirectly to the potential of larger direct brine releases than calculated in the CCA. The DOE has presented three independent lines of reasoning to indicate that the EEG's concern is unwarranted. If convinced that any of these lines of reasoning are correct then the EEG will concur with DOE's assessment that the issue is of little concern.

DOE's three arguments are: 1) Additional brine will be consumed by corrosion and the resultant gas generation will not cause greater repository pressures. 2) The difference in the two dimensional and three dimensional models only occurs at pressures above those calculated during the performance assessment for CCA. 3) The changes in the repository consistent with the three dimensional model are of little consequence to the performance assessment.

At this time, the first two of the lines of reasoning appear to be flawed. The third argument relies on the CCA values of actinide solubility that the EEG is not convinced are correct.

1. *Additional brine will be consumed by corrosion and the resultant gas generation will not cause greater repository pressures.*

That additional brine inflow will lead to more gas generation is not questioned. The flaw in this argument is that the potential brine inflow is too large to be consumed in a short period and could lead to large enough amounts of additional gas to significantly effect the pressure. The result could be both larger brine saturations and higher pressures. Figure 1 indicates that lower pressures are also possible. In the FEP S-1 the rate of gas generation was assumed to be constant. Thus, there was no feedback between brine inflow and gas generation in the FEP S-1 study.

The DOE cites the amount of iron remaining in the repository (Figure 5; *DOE*, 1996 Figure 12-13) as support for the argument that more brine inflow will lead to more gas generation not higher saturations. Figure 6 (Figure 2.2.9 of *Helton*) shows less iron remaining

in the lower (waste) panel, presumably due to relatively more brine inflow to the lower panel (Pg 2-18 of *Helton*, 1996). Figure 7 (Figure 2.2.7 of *Helton*, 1996) shows that at most 30,000 cubic meters of brine are predicted to be consumed through iron corrosion. In most vectors, the calculated brine consumption was less than 15,000 m^3. In many, brine consumption continues though-out the 10,000 year compliance period. Other vectors show a secession of brine consumption after less than 2,000 years, presumably due to exhaustion of available brine (See Section 2.2 of *Helton*). Figure 2 suggests that brine inflow from fracturing may be on the order of 10 m^3 / year or more and continue for hundreds to thousands of years. Drawn on the Figure 7 is a line with a slope of 10 m^3 / year. Comparing the brine consumption with this slope indicates that the potential brine flow is large compared to the rate of brine consumption. The potential brine inflow is greater than 10,000 m^3. Most of this flow would likely be into the lower panel. The maximum amount of brine consumed in the lower panel was 6,000 m^3 (Figure 8, Figure 7.2.1-10 of *Bean et al.*).

2. *The difference in the two dimensional and three dimensional models only occurs at pressures above those calculated during the performance assessment for CCA.*

DOE cites Figure 9 (Figure 2.3.2 of Helton), showing the 10, 50 and 90 percentile pressures for each replicate for the 10,000 years, as demonstration that pressures will not increase greatly above 12.7 MPa. In fact, Figure 10 (Figure 2.3.1 of Helton), which depicts the pressure history of each vector of replicate 1, indicates that many of the calculated pressures were greater than 13 MPa and that for one vector the calculated pressure reached close to 16 MPa. 16 MPa is less than 2 MPa below the 17.5 MPa peak pressure of the 2-D simulation of the FEP S-1 analysis (Figure 1). The DOE has offered no explanation of what happens between 16 and 17.5 MPa to cause such large brine inflow in the 3-D simulation but not the 2-D simulation. A believable explanation is that the change occurs at initiation of anhydrite fracturing not just above 16 MPa.

3. *The changes in the repository behavior consistent with the three dimensional model are of little consequence to the performance assessment*.

There are two obvious potential impacts on the performance assessment calculations from greater pressure and brine saturations in the repository. Greater pressures would lead to larger calculated releases from the spallings model. If the spallings model described in Hansen et al. is correct then it is unlikely that the volumes brought to the surface because of greater pressures would approach those calculated in the CCA.

Either greater pressures or saturations could lead to much larger direct brine release calculations. Figure 4 indicates that there were very few calculated direct brine releases when the calculated repository pressures exceeded 12.7 MPa and almost none when the pressure exceeded 14 MPa. Almost all of the larger calculated direct brine releases occurred when brine saturations were above 0.5, a condition never calculated at pressures above 14 MPa. The FEP S-1 analysis suggests that the potential for many of the vectors with great repository pressure to also have large brine saturations. Thus calculated direct brine releases might have both larger volumes and greater frequency in the performance assessment.

Direct brine release was a minor component of the total calculated radionuclide releases in the CCA (Figure11; Figure 6-41 of the CCA). The volumes of direct brine release would have to be two orders of magnitude greater to have an impact on agreement with the containment requirements which is large in relation to a possible increases in the calculated volumes of brine brought to the surface through direct brine release. However, the radionuclide content of brine brought to the surface may be underestimated in the CCA which would make direct brine release of greater significance to the performance assessment (See EEG comments on solubility).

EEG Response to EPA's Resolution of Comment # 553.

The EPA's resolution of this comment relies on the fact that Abrine and gas saturations are inversely related. This relationship does not necessarily lead to higher brine saturations indicating lower pressures or less gas in the repository. The statement AThe fact that the 2-D model may overestimate gas saturation by underestimating brine saturations will lead to the prediction of higher gas pressures than those that would have been predicted with the 3-D configuration and this will result in more conservative estimates of releases.@ is a conclusion that the 3-D modeling results may indicate is not valid.

Consider Figure 4. This figure provides a plot of calculated brine saturation and pressure conditions in the repository at three separate times for undisturbed performance. This figure shows a correlation of brine saturation with repository pressure. There are at least three mechanisms that may lead to such a correlation:

A) Faster corrosion rates lead to more gas generation, less brine and greater pressures. Table 1 (Table 2.3.1 of *Helton*) lists the parameters most closely correlated with pressure in the lower waste panel. The list results from a step wise rank regression of the sampled parameters with pressure. The parameter that correlates the most pressure is listed first. The table lists the microbial degradation of cellulose and rubber and plastics (WMICDFLG) as the most important factor with halite porosity (HALPOR) next. Table 1 indicates that sampled corrosion rate (WGRCOR) is not a dominant factor in repository pressure. Halite porosity is a reasonable surrogate for brine availability (see Figure 2.1.5 of *Helton*).

Table 2 (Table 2.2.2 of *Helton*) lists halite porosity as by far the most important controlling factor over iron consumption. The second most important factor is the corrosion rate. Other parameters identified as slightly correlated with repository pressure and fraction of steel remaining are: ANHPRM (unfractured anhydrite permeability), SALPRES (Far field pressure in the Salado Formation), SHRGSSAT (residual gas saturation in the shaft seal), and WASTWICK (the parameter describing the tendency of brine to be pulled above the lower part of a room by capillary forces)

Figure 12 (Figure 2.4.3 of *Helton*) provides important supporting evidence. The figure presents the fraction of iron remaining in the lower waste panel (FEREM_W) or in the rest of the repository (FEREM_R) with respect to halite porosity, microbial degradation, steel corrosion rate. The plots of remaining iron and halite porosity suggest that a sufficient supply of brine is needed for iron consumption but other factors also limit corrosion. The main factor is probably corrosion rate. Figure 12 shows that low corrosion rates limit iron consumption, but that predicted iron consumption is not strongly dependent on corrosion rate. The comparison of iron remaining to microbial degradation is important because its strong correlation with repository pressure (Table 1). These plots show that the fraction of iron remaining in the repository is only weakly correlated with microbial degradation and that the correlation is positive e.g. microbial degradation, hence pressure, is inversely correlated with iron consumption. This inverse correlation is probably linked to the availability of brine.

B) Less brine flows into the repository at high pressures, at least in the 2-D BRAGFLO model used for the CCA performance assessment.

C) The repository inflates as the pressure rises (Figure 13; Figure 2.3.5) leading to more void space and lower saturations per unit volume of brine. Figure 13 indicates that the calculated void space in the repository is twice as large at 12 MPa than at 5 MPa and nearly three times at 16 MPa. Thus, the correlation of brine volume to pressure is much weaker than the correlation of saturation to pressure seen in Figure 4.

The FEP S-1 screening analysis concluded that the increased brine inflow to the repository in the 3-D simulation did not increase release to the accessible environment through the marker beds. The EEG agrees with this conclusion. It has not been demonstrated, however, that the increased flow into the repository predicted using the 3-D geometry will not lead to much greater releases from human intrusion. The 3-D modeling indicates that there is a potential for the combination of high pressure and relatively high brine saturation in the repository at the same time. This combination did not occur in the performance assessment modeling for the CCA and thus conclusions of the impact on radionuclide releases due to human intrusion can not be assessed using the CCA performance assessment.

The DOE has not yet demonstrated that the performance assessment modeling for the CCA accurately represents the potential repository conditions. The results of FEP S-1 screening analysis suggest that the two dimensional BRAGFLO model used in the CCA calculations may be misrepresenting repository performance at pressures above the anhydrite fracture pressure.

Recommendations for Resolving the Issue

To resolve this issue, the EEG recommends that a few 3D BRAGFLO simulations of the repository should be performed using the parameter values of vectors used in the CCA performance assessment. The 3D BRAGFLO simulations should be used to provide repository conditions for the normal suite of direct brine release calculations. The calculations should also be assessed in terms of impact on spallings calculations. Spallings simulations are probably not required to assess the impact. The following criteria may be used to select the CCA vectors for running the 3D simulations to bound the magnitude of the problem:

- Since the discrepancy occurs above the fracture initiation pressure, the simulations should be limited to parameter vectors that result in pressures above 12.7 MPa at some time during the 10,000 year time frame.

- Direct brine release calculations should be sensitive to increased brine saturations above the waste residual brine saturation. Vectors that had either large brine saturations or a mobile brine component (saturations above the residual saturation) are more likely to be sensitive to increased brine inflow. Figure 5.1.5 of the preliminary sensitivity analysis report (Helton, 1996) indicates one vector with a 10,000 year pressure above 14 MPa and a brine saturation above 0.4. This is a likely candidate.

- The potential for brine consumption by corrosion should be assessed. Vectors with both slow and fast corrosion rates that also meet the above two criteria should be run.

- If the first simulations indicate a large change in saturation, then assess whether the 3D BRAGFLO simulations indicate a much larger number of significant direct brine releases than those calculated in the CCA. Simulations using brine saturations on the order of 0.1 and 0.3 should be performed.

REFERENCES

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Vaughn, P., T. Hadgu, D. McArthur, and J. Schreiber, FEP Screening Analysis S1: Verification of 2-D Radial Flaring Using 3D Geometry, Memorandum to D.R. Anderson, January 26, 1996, WPO 30840, Sandia National Laboratory, Attachment 4-1 to Appendix Mass of the Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184, December, 1996.

Figures

Figure 1: Average Pressure in Repository, FEP S-1 Analysis
From Vaughn et al, 1996.

Figure 2: Cumulative Net Brine in and outflow at Repository, FEP S-1 Analysis
From Vaughn et al, 1996.

Figure 3: Average Gas Saturation in Repository, FEP S-1 Analysis
From Vaughn et al, 1996.

Figure 4: Three dimensional scatter plots for volume of brine reaching the surface due to direct brine release for a drilling intrusion into the lower panel.
From Helton, 1996.

Figure 5: Fraction of Initial Iron Remaining in Repository
From: DOE, 1996.

Figure 6: Remaining Fraction of Steel Inventory in Waste Panel
Modified from Figure 2.2.9 in Helton, 1996.

Figure 7: Cumulative Volume of Brine Consumed by Corrosion in the Repository
Modified from: Helton, 1996.

Figure 8: Cumulative Volume of Brine Consumed in the Waste Panel
From Bean et al., 1996

Figure 9: Percentile curves for three replicated LHSs for pressure in waste panel
From: Helton, 1996.

Figure 10: Pressure in waste panel
Modified from Figure 2.3.1 of Helton, 1996.

Figure 11: Mean CCDFs for Specific Release Modes, Replicate 1.
From DOE, 1996.

Figure 12: Scatter Plots of the Fraction of Iron Remaining in the Waste Panel (Right Frames) and Rest of the Repository (Left Frames) for Undisturbed Conditions at 10,000 Years.
From Helton, 1996.

Figure 13: Scatter plot of pressure versus total pore volume in the repository.
From Helton, 1996.

Tables

Table 1: Stepwise Regression Analysis with Rank-Transformed Data for Pressure in the Waste panel at 10000 years. From Helton, 1996.

Table 2: Stepwise Regression Analysis with Rank-Transformed Data for Fraction of Steel Remaining and Total Gas Generation in Upper and Lower Waste Panels at 10000 years.
From Helton, 1996.

FULL TEXT OF ORIGINAL EEG COMMENT

Environmental Evaluation Group Review of the WIPP-CCA, 3/14/97

BRINE INFLOW FROM SALADO: 2-D VERSUS 3-D GEOMETRY IN BRAGFLO

The 2-D geometry used in the BRAGFLO appears to have caused an under-prediction of brine inflow to the repository and thus may have resulted in a significant under-prediction of the direct brine release. This assumption may also have effected the amount of releases predicted by the spallings scenario.

The justification for modeling the repository in a pseudo 3-D manner (2-D radial flaring) rather than in a full 3-D geometry has been provided through evaluation of FEP S-1. The summary memo of record for the FEP S-1 screening analysis[1] discusses the impact of the 2-D assumption on 1) brine flow through the anhydrite layers to the 2.4 km boundary, 2) flow to the top of the shaft, 3) brine flow up the borehole, and 4) the repository pressure. This memo does not consider the effects of the 2-D assumption on the inflow of brine to the repository, and on the spallings or direct brine releases.

The amount of projected inflow of brine in the repository directly effects the gas pressure in the repository. Table 5.5.3 of the sensitivity analysis report[2] lists the residual gas saturation as the parameter with the strongest influence on the projected direct brine releases. This is also shown in Figure 5.1.5 of the sensitivity analysis report (the attached Figure 1). In addition, brine inflow is important to the spallings release estimates through increased gas generation. This dependence is made clear in Table 4.4.3 of the sensitivity analysis report which lists halite porosity, a large source of brine, as the second most important parameter to spallings releases.

The screening analysis compared 2-D simulations of the repository to 3-D simulations of the repository. For computational efficiency, the calculations were performed for half the repository. Two sets of simulations were conducted for the analysis. One set of calculations used a gas generation rate below the level that would cause anhydrite bed fracturing. The second used twice the gas generation rate to ensure anhydrite bed fracturing. In both sets, less brine-inflow occurred in the 2-D case compared to the 3-D geometry. No dependency of gas generation on brine inflow to the repository was included in the calculations; gas generation was prescribed as a function of time, ending after 1,000 years in the screening calculations.

The largest impact of 2-D geometry occurs with anhydrite bed fracturing. The 3-D model predicts the flow into the repository to significantly increase if the anhydrite beds fracture, while the 2-D model predicts the flow to decrease in relation to calculations without anhydrite fracturing.

Figure 15 of the FEP S-1 analysis (Figure 2) shows the cumulative brine inflow to the repository for the high gas generation calculations. The flows calculated using the 3-D model indicate that once anhydrite bed fracturing occurs roughly $2x10^6$ kg (1,600 m^3) of brine enters the repository in a period of 200 to 300 years and that this flow rate was continuing unabated at the time of drilling intrusion. Another $4x10^6$ kg (3,200 m^3) flowed into the repository shortly after the drilling intrusion. Figure 2 shows differences of $4x10^6$ to $6x10^6$ kg (3,200 to 6,500 m^3) for much of the 10,000 years. The brine inflow differences listed above should be doubled for the full repository. Virtually no flow enters the repository as a result of anhydrite bed fracturing in the 2-D geometry. In fact, the net flow over the 10,000 year simulation is less with anhydrite fracturing compared the simulation without the beds fracturing. Figure 2.1.4 of the sensitivity analysis report[2] (Figure 3) indicates very little marker bed inflow with microbial gas generation of plastics and

[1]Vaughn, P., T. Hadgu, D. McArthur, and J. Schreiber, FEP Screening Analysis S1: Verification of 2-D-Radial Flaring Using 3D Geometry, Memorandum to D.R. Anderson, January 26, 1996, WPO 30840, Sandia National Laboratory, Attachment 4-1 to Appendix Mass of the Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184, December, 1996.

[2]Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

rubber, supporting the findings of the FEP analysis. Figure 5.1.5 of the sensitivity analysis report reveals the importance to direct brine release of these low brine inflows. The highest pressures are correlated with brine saturations below the residual brine saturation of the waste. The low saturations are due partly to increasing repository pore space with increasing pressure and partly to lower brine inflow.

Table 2.5.13 of the sensitivity analysis report indicates that the potential for anhydrite bed fracturing is high. As a crude approximation, consider the undisturbed scenario of a total fracture-enhanced flow of 20,000 m^3 over a period of 2,000 years. The highest repository pressure in the FEP S-1 calculations was 13 MPa [Correct value is 16.5 MPa]. This corresponds to a repository pore space of 85,000 m^3 (Figure 2.3.5 of the sensitivity analysis report)[at 13 MPa]. The increased brine flow would increase the average brine saturation by 0.23. The CCA calculations do not include simulations of both very high pressure and brine saturations above the residual brine saturation of the waste. Inspection of Figure 5.1.5 suggests a significant impact from a 0.23 saturation shift at high pressures.

The simulations without anhydrite fracturing show a decrease of $1x10^6$ to $2x10^6$ kg (800 to 1,600 m^3) in predicted brine inflow in the 2-D simulations compared to the 3-D simulations(Figure 4; Figure 10 of the FEP S-1 memo). These flows are doubled for the full repository. The differences are most likely from differences in marker beds flows to the repository.

To put these brine inflow differences in perspective, note that average brine inflow to the repository in the CCA calculations of the similar S5 scenario was almost 40,000 m^3, with an average 8,000 m^3 from the marker beds[2]. Marker bed brine flows in the S5 scenario are dominated by flows under low pressure conditions. The marker bed flows are a more significant concern in the S1 undisturbed scenario. An average of roughly 3,000 m^3 flowed into the repository from the marker beds in the S1 CCA calculations. To approximate the brine flow error in the undisturbed calculations for pressures below the anhydrite fracture threshold, we ratio the FEP S-1 differences by 3,000/8,000 - resulting in the range of 600 to 1,200 m^3 less brine inflow to the full repository. If 1,200 m^3 of brine were distributed throughout the entire repository it could increase the average saturations by 0.015 to 0.03 (0.04 to 0.08 in the S5 scenario and 0.16 to 0.32 after anhydrite fracturing in an S5 scenario). It is more likely that much of the additional brine would be consumed through increased gas generation, leading to higher repository pressures.

There are indications in the sensitivity analysis report that the computational grid effects the distribution of brine within the repository in addition to the overall magnitude of brine. One indication is the statement on page 2-26 that "Due to the computational grid in use (Fig. 1.2.1), the lower panel receives more brine inflow from the marker beds relative to its size than the upper waste panels (Fig. 2.1.2)." Another indication may be the importance of the residual gas saturation of the shaft seals to flow through the marker beds (Table 2.1.1 of the sensitivity analysis report). As stated in the report, "its selection may be due to effects related to brine and gas movement across the part of the computational grid that corresponds to the shaft in the repository and DRZ (i.e., regions 10,11 in Fig. 1.2.1)." As a result, the upper waste panels receive roughly one ninth of the brine inflow from the marker beds per panel as the lower waste panel. In a large fraction of the sampled vectors, gas generation stops in the upper panels because of limited brine availability for steel corrosion. Thus, the CCA calculations are under-predicting repository pressure as well as brine saturation.

The EEG concludes that the use of a 2-D geometry in the BRAGFLO may introduce significant non-conservatism into the CCA calculations. The FEP S-1 needs to be re-examined with appropriate consideration of the impact of increased brine saturation on calculated release estimates.

DOE Response to the EEG Comments

Attached to Letter by GE Dials to L. Weinstock, *DOE Response to Comments made to EPA by EEG on the DOE's CCA Dated March 14, 1997.*, June, 27, 1997.

Brine inflow to the repository

Vaughn et al. justified the use of the 2-D radial-flaring BRAGFLO model by comparing the results of the 2-D model with those of a corresponding 3-D model. However, the limits of the analysis exceeded the highest predicted pressures in the repository by approximately 4 to 5 MPa.

The 2-D and 3-D model results show reasonable agreement, except under conditions where fracturing of the anhydrite beds occurs (at pressures above 12.7 MPa). The 3D model predicted a greater flow of brine into the repository than the 2-D model when the pressure in the repository was sufficient to increase porosity in the fractured anhydrite beds. However, the high constant gas generation rate assumed in the *Vaughn et al.* analysis resulted in peak average pressures in the repository of about 17.5 MPa (2-D BRAGFLO) and 16.5 MPa (3-D BRAGFLO) *(Vaughn et al.*, Figure 11) (not 13 MPa as stated by the EEG), which are greater than the highest pressures expected in the repository (see *Helton*, Figure 2.3.2). Thus, the large increases in average anhydrite porosity and associated brine inflow predicted by 3D-BRAGFLO are not likely to occur in the repository.

Vaughn et al. assumed constant gas generation rates with no brine consumption. In reality, any additional brine entering the repository would likely be consumed by gas generation processes, which would limit brine saturation. PA calculations show that significant

amounts (at least 409G of the initial inventory) of uncorroded iron will persist throughout the lO,OOO year regulatory period under conditions of undisturbed performance (CCA Figure 9-10). The extent of corrosion is limited by the amount of brine available, and the iron inventory will not be exhausted as a result of the increase in brine flow to the repository predicted by 3D-BRAGFLO. Subsequent to an intrusion the pressure within the repository is relieved and remains below the fracture initiation pressure.
EEG acknowledges that higher brine saturations would not necessarily occur as a result of increased brine flow to the repository, but that increased brine flow would lead to increased gas generation. Increased volumes of gas generated at high pressures (above 12.7 MPa) would tend to result in increased porosity in the fractured anhydrite rather than significant increases in pressure. *Helton* (Figure 2.3.1) showed that repository pressures do not increase greatly above 12.7 MPa (after fracturing has occurred).

Pressures sufficiently high to cause fracturing (12.7 MPa) tend to occur at low brine saturations (*Helton* Figure 5.1.5) due to the consumption of brine by corrosion. If brine inflow occurs at the high pressures suggested by the 3-D BRAGFLO analysis (in excess of 16.5 MPa), then brine saturation in the repository could increase. The EEG suggests that brine saturation could increase by as much as 23 % at such pressures. However, as discussed above, this value of pressure is unrealistically high given that gas generation processes could consume most of any additional brine entering the repository. Nonetheless, even with the unrealistic assumption that brine saturation increases by 23%, Figure 5.1.5 of Helton shows that the number of simulations in which direct brine release resulting from a drilling intrusion occurs would not increase significantly. Although accounting for higher brine saturations could increase cumulative direct brine releases, the overall CCDFs from all release pathways would be little changed because of the relatively minor contribution of direct brine release to overall releases (CCA Figure 641).

In summary, the set of conditions where the 3D-BRAGFLO and 2D-BRAGFLO do not show good agreement (average pressures above 16 MPa) are not expected to occur in the repository. Even if such pressures did occur, resulting in anhydrite fracturing and porosity increase, the brine inflow predicted by 3D-BRAGFLO would have little effect on direct brine release during a drilling intrusion.

EPA Response to Comment # 553

EPA disagrees with the comment. The work that is most relevant to this concern is the FEP Screening Analysis titled S1: Verification of 2D-Radial Flaring Using 3D Geometry, WBS No. 1.1.6.3, SANDIA WIPP CENTRAL FILES-A: 1.2.07.3: PA:QA:TSK:S1, ERRATA - February 19, 1996 (SNL WPO #30840). In this work, a simplified version of the two dimensional CCA PA grid was tested against a corresponding three-dimensional (3-D) model. BRAGFLO was used in both two-dimensional (2-D) and 3-D simulations, and TOUGH28W was used to model the 3-D simulations only. Simulation results were compared for cases with an average repository gas generation rate, and a gas generation rate that was double the average. The results of the second case, in which the gas generation rate was doubled, indicates that a combination of pressure induced fracturing and the 1-degree dip cause flow paths which are different for the 2-D and 3-D grids. Once fracturing of the interbeds occurs, the 3-D model displays an immediate migration of gas primarily out of the west side of the repository into the anhydrite layers, accompanied by brine inflow to the repository. This phenomenon is not seen in the results from the 2-D model, in which the west side of the repository is a no flow boundary, which demonstrates that the 2-D and 3-D simulations show local variations. However, the results also show that the predictions of brine flow to the accessible environment are similar for both 2-D and 3-D grids. With respect to increased brine saturation, Figures 7 and 12 of the FEPs Screening Analysis referenced above (WPO# 30840), shows the average gas saturations calculated with the 3-D simulations of TOUGH28 and both the 2-D and 3-D versions of BRAGFLO. Simulation results are compared for the base case and twice the base case generation rates, respectively. These curves indicate that gas saturations are higher in the 2-D simulations (WPO# 30840, page 27). Since brine and gas saturations are inversely related a similar trend would be observed for the brine saturations. In the Performance Assessment Verification Test (PAVT) , it was determined that the greatest potential releases could be attributed to those associated with spallings and direct brine releases. Furthermore, these releases are pressure controlled and will not occur if repository pressures are below 8 MPa. The fact that the 2-D model may overestimate gas saturation by underestimating brine saturations will lead to the prediction of higher gas pressures than those that would have been predicted with the 3-D configuration and this will result in more conservative estimates of releases. Based on this, EPA believes that the 2-D geometry used in the BRAGFLO CCA PA calculations is a reasonable simplification and that the predicted results are conservative.

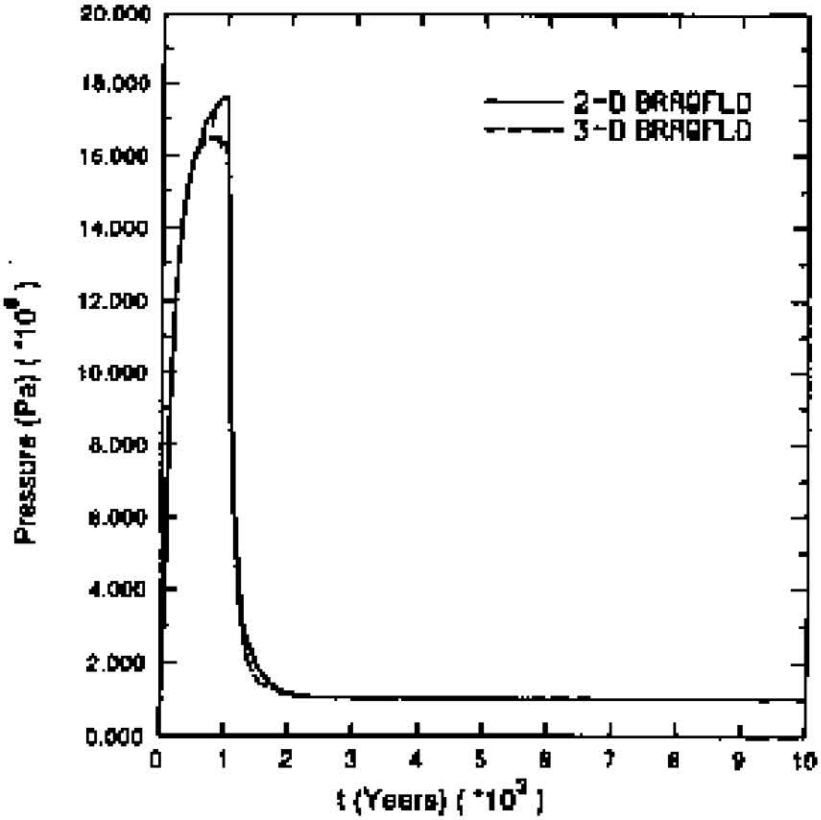

Figure 1: Average Pressure in Repository, FEP S-1 Analysis From Vaughn et al, 1996.

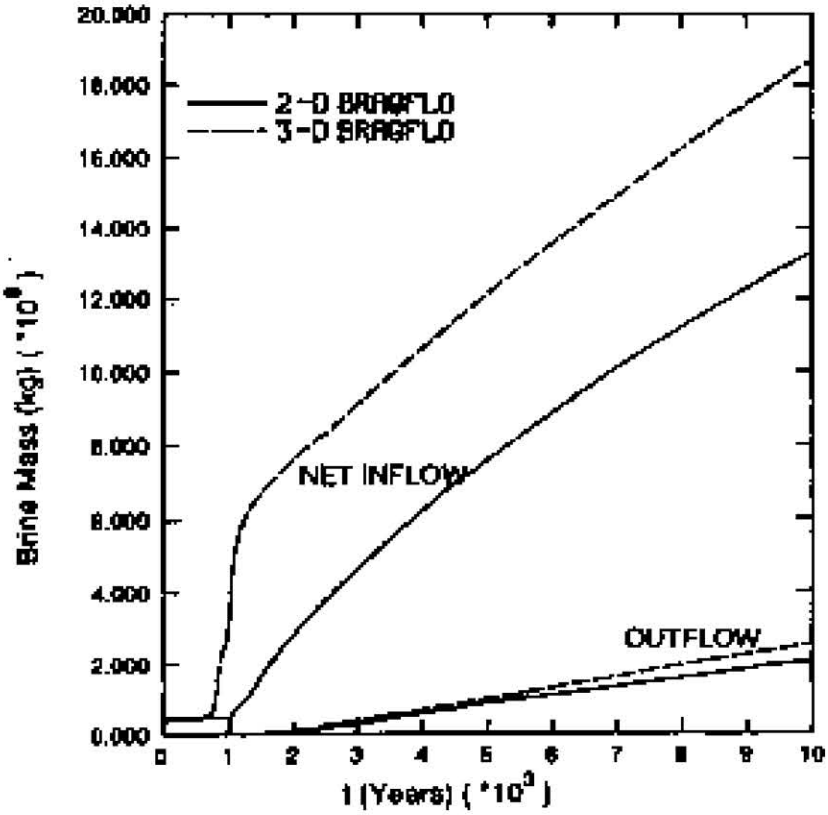

Figure 2: Cumulative Net Brine in and outflow at Repository, FEP S-1 Analysis From Vaughn et al, 1996.

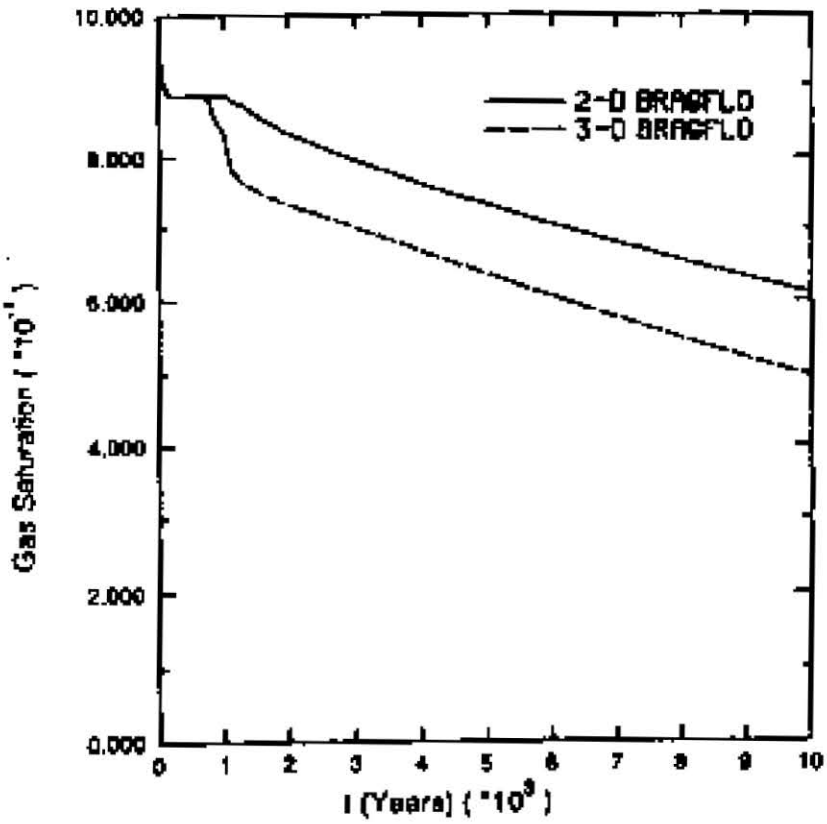

Figure 3: Average Gas Saturation in Repository, FEP S-1 Analysis
From Vaughn et al, 1996

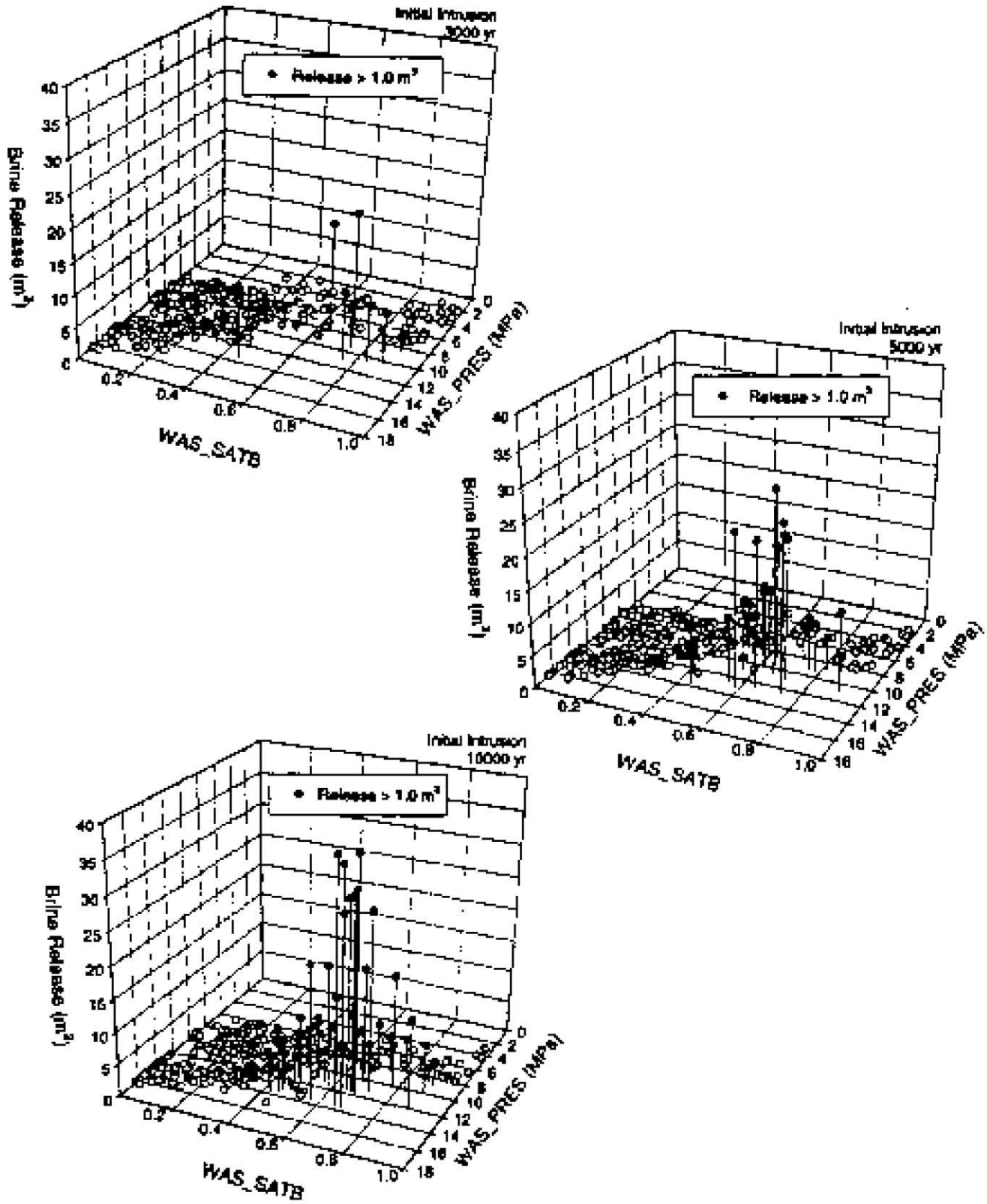

Figure 4: Three dimensional scatter plots for volume of brine reaching the surface due to direct brine release for a drilling intrusion into the lower panel.
From Helton, 1996.

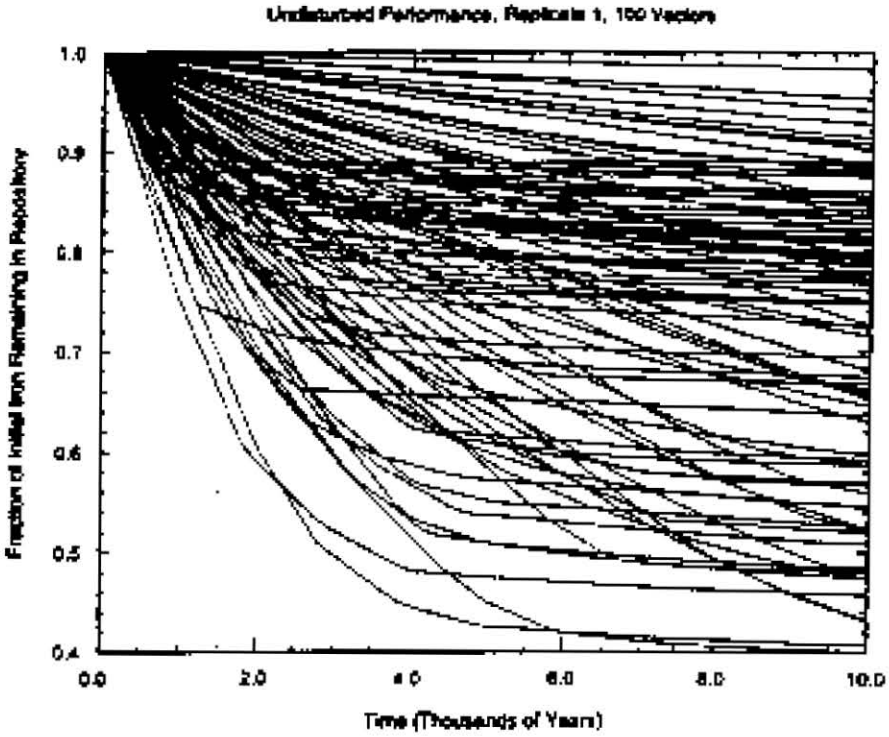

Figure 5: Fraction of Initial Iron Remaining in Repository
From: DOE, 1996.

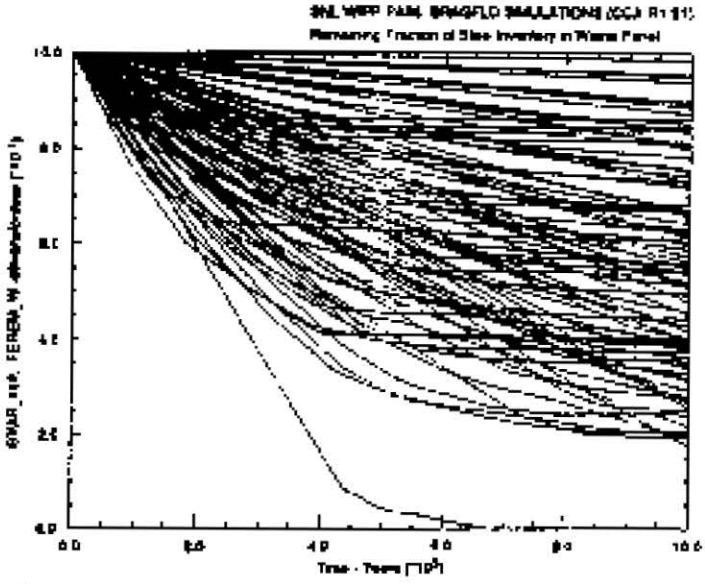

Figure 6: Remaining Fraction of Steel Inventory in Waste Panel
Modified from Figure 2.2.9 in Helton, 1996.

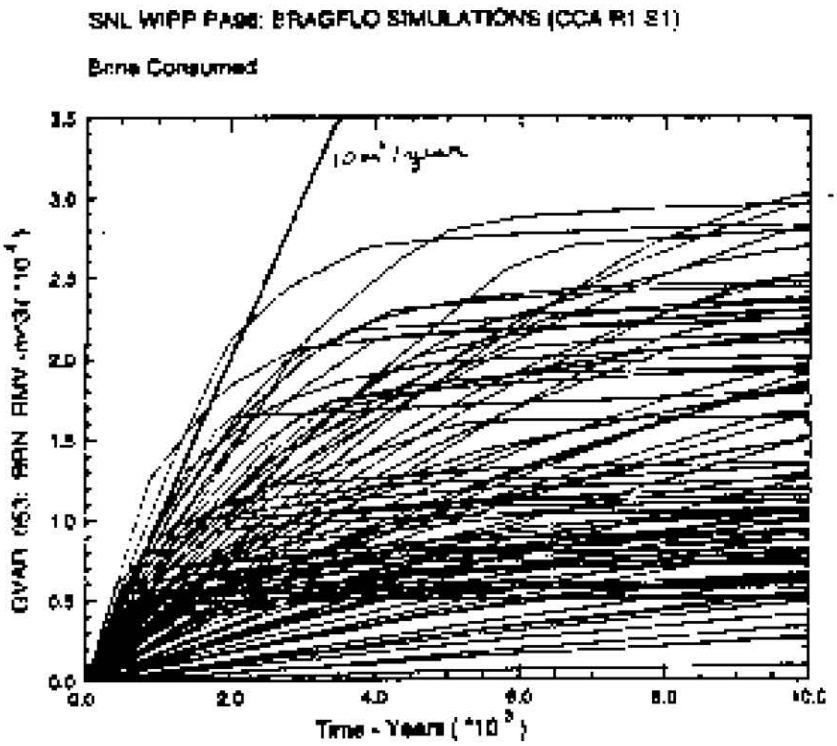

Figure 7: Cumulative Volume of Brine Consumed by Corrosion in the Repository
Modified from: Helton, 1996.

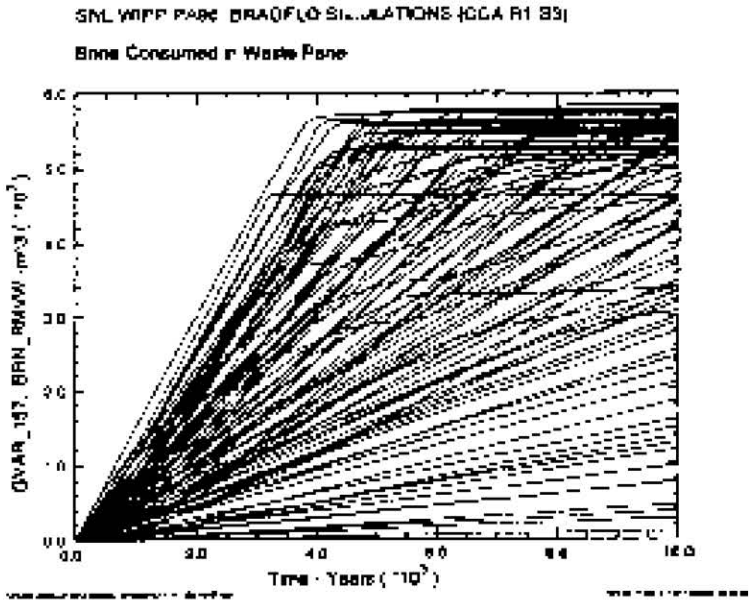

Figure 8: Cumulative Volume of Brine Consumed in the Waste Panel
From Bean et al., 1996

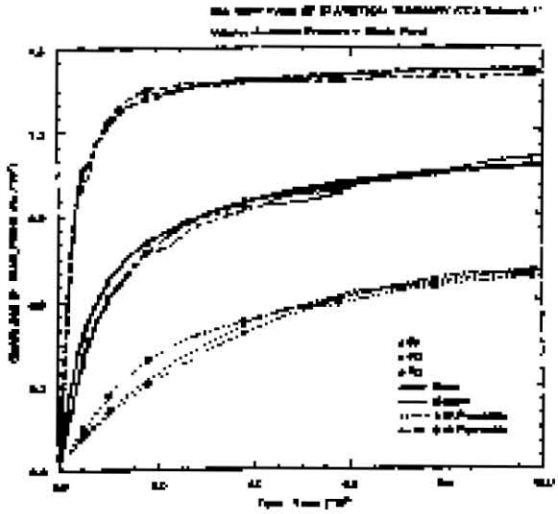

Figure 9: Percentile curves for three replicated LHSs for pressure in waste panel
From: Helton, 1996.

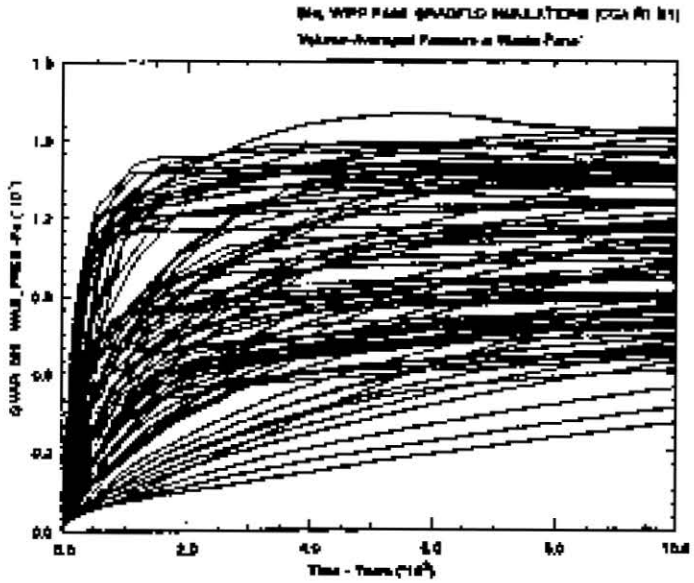

Figure 10: Pressure in waste panel
Modified from Figure 2.3.1 of Helton, 1996.

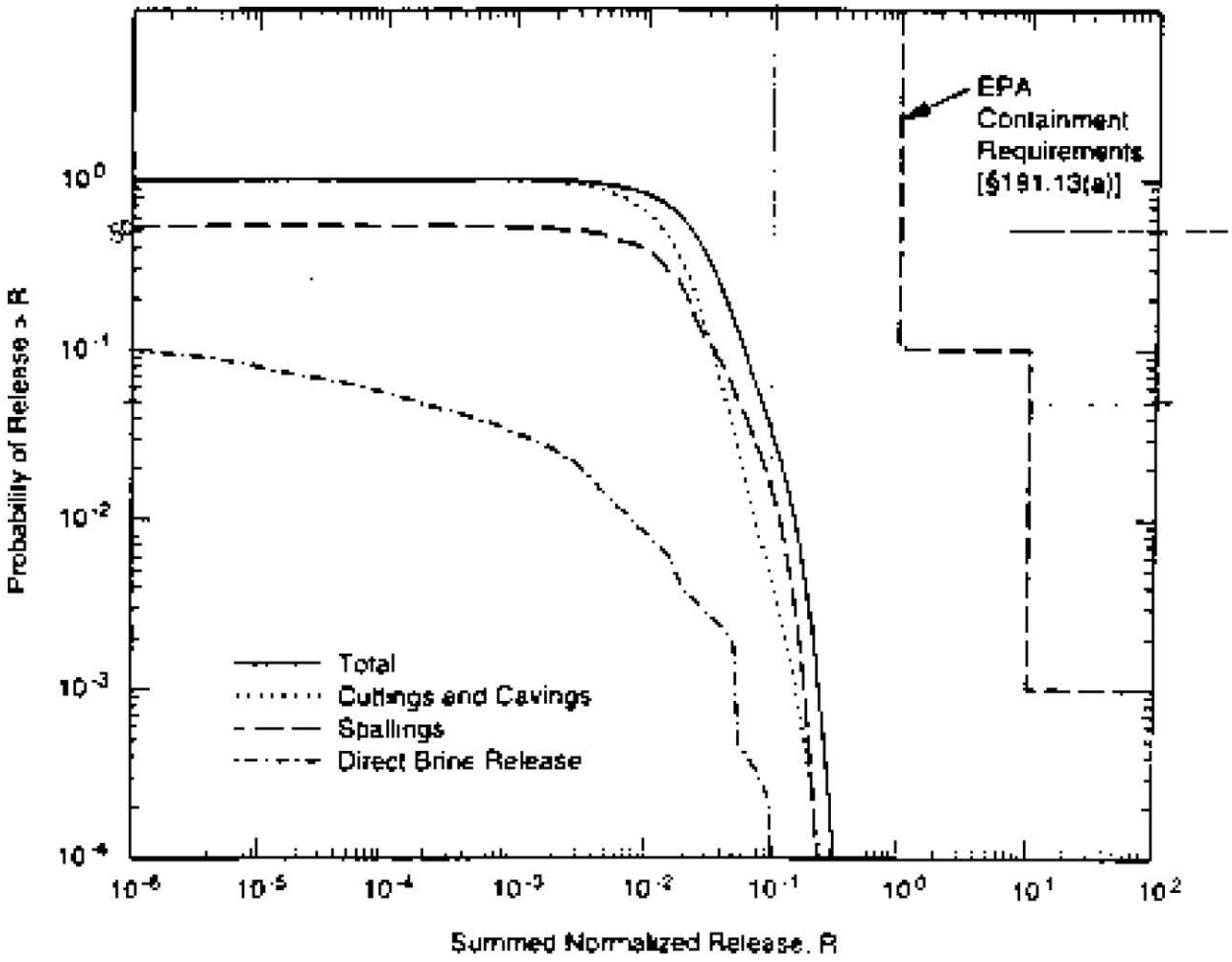

Note: Mean CCDFs are shown for the total normalized release (this curve is also shown in Figure 6-40 and is the mean of the family shown in Figure 6-35) and for the normalized releases resulting from cuttings and cavings, spallings, and direct brine release. The mean CCDF for subsurface releases resulting from groundwater transport is not shown because those releases were less than 10-6 EPA units and the CCDF cannot be shown at the scale of this figure.

Figure 11: Mean CCDFs for Specific Release Modes, Replicate 1.
From DOE, 1996.

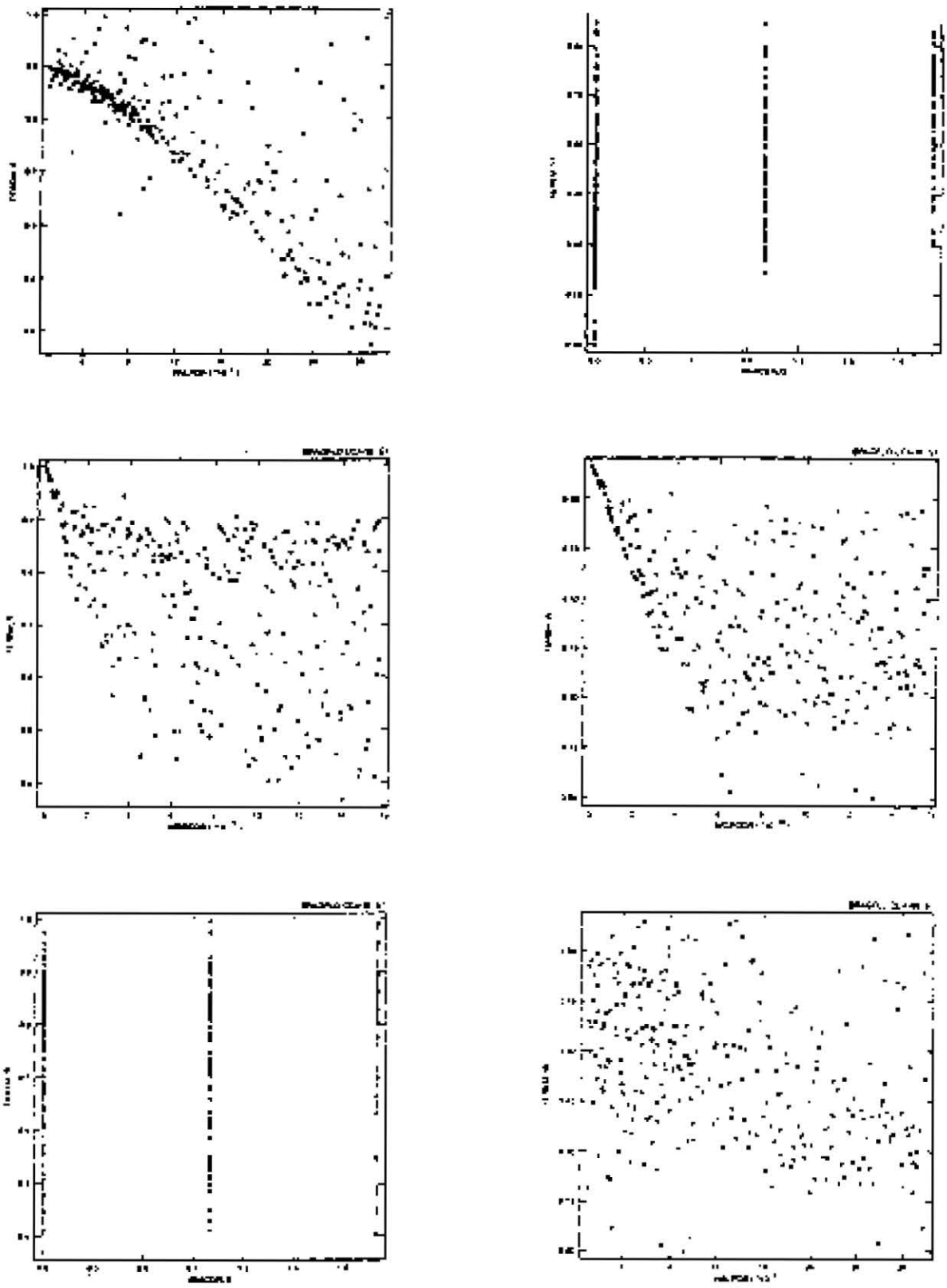

Figure 12: Scatter Plots of the Fraction of Iron Remaining in the Waste Panel (Right Frames) and Rest of the Repository (Left Frames) for Undisturbed Conditions at 10,000 Years.
From Helton, 1996.

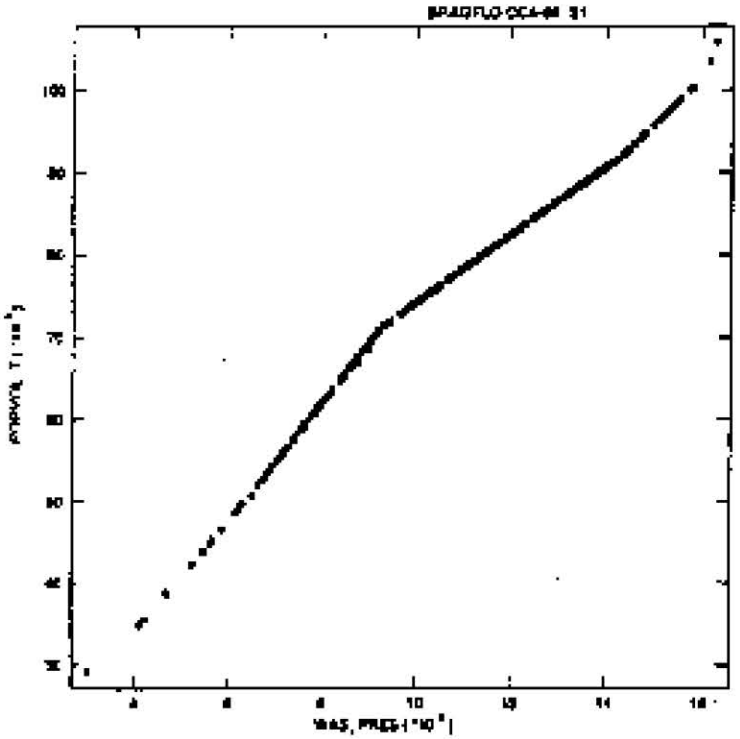

Figure 13: Scatter plot of pressure versus total pore volume in the repository. From Helton, 1996.

Table 1: Stepwise Regression Analysis with Rank-Transformed Data for Pressure in the Waste panel at 10000 years. From Helton, 1996.

Step[a]	Variable[b]	SRRC[c]	R^{2d}
1	*WMICDFLG*	0.71	0.52
2	*HALPOR*	0.45	0.73
3	*WGRCOR*	0.23	0.79
4	*ANHPRM*	0.11	.080
5	*SALPRES*	0.07	0.80
6	*SHRGSSAT*	0.06	0.81

[a] Steps in stepwise regression analysis.

[b] Variables listed in order of selection in regression analysis with *ANHCOMP* and *HALCOMP* excluded from entry into regression model.

[c] Standardized regression coefficients in final regression model.

[d] Cumulative R^2 value with entry of each variable into regression model.

Table 2: Stepwise Regression Analysis with Rank-Transformed Data for Fraction of Steel Remaining and Total Gas Generation in Upper and Lower Waste Panels at 10000 years. From Helton, 1996.

	Fraction Steel Remaining Upper Waste Panels			Fraction Steel Remaining Lower Waste Panels			Total Gas Generation Upper Waste Panels			Total Gas Generation Lower Waste Panels		
Step[a]	Variable[b]	SRRC[c]	R^{2d}	Variable	SRRC	R^2	Variable	SRRC	R^2	Variable	SRRC	R^2
1	*HALPOR*	−0.70	0.63	*WMICDFLG*	0.46	0.20	*WMICDFLG*	0.65	0.43	*WGRCOR*	0.47	0.23
2	*WGRCOR*	−0.35	0.75	*WGRCOR*	−0.45	0.41	*HALPOR*	0.58	0.77	*HALPOR*	0.45	0.44
3	*WMICDFLG*	0.12	0.76	*HALPOR*	−0.38	0.56	*WGRCOR*	0.24	0.83	*ANHPRM*	0.33	0.55
4	*WASTWICK*	−0.10	0.77	*ANHPRM*	−0.25	0.63	*WASTWICK*	0.07	0.83	*WMICDFLG*	0.17	0.58
5	*SHRGSSAT*	−0.08	0.78	*HALPRM*	−0.09	0.67	*SHRGSSAT*	0.06	0.83	*HALPRM*	0.12	0.59
6	*RPINTPRS*	−0.06	0.78	*SHRGSSAT*	−0.09	0.64				*SHRGSSAT*	0.08	0.60

[a] Steps in stepwise regression analysis.

[b] Variables listed in order of selection in regression analysis with *ANHCOMP* and *HALCOMP* excluded from entry into regression model.

[c] Standardized regression coefficients in final regression model.

[d] Cumulative R^2 value with entry of each variable into regression model

(Enclosure 3 to the 12/31/97 Letter From R.H. Neill, EEG to F. Marcinowski, EPA)

Issue: Compliance Failure as a Result of Spalled Material Reaching the Accessible Environment

Introduction

The issue of spalled material reaching the accessible environment at the WIPP has undergone much research within the past few years (Berglund, 1994; DOE, 1996; Hansen et al., 1997). Spall is the mechanical failure of waste due to high repository gas pressures that could be induced by a drop in pressure from a drilling intrusion. This process of waste removal has been included in the Performance Assessment calculations of the CCA. Yet, the amount that will actually reach the surface it is still unclear. Spallings are very important to the compliance of the disposal system, because the large release of radionuclides in the spalled material may prove the repository to be unsafe to future generations.

The three mechanisms of spall include blowout, stuck pipe and gas erosion, with the latter two being eliminated from calculations at the WIPP. It has been estimated that stuck pipe and gas erosion could bring more waste to the surface than blowout (Berglund (1994)). Blowout is the removal of the drilling fluid from the wellbore from a high influx of gas into the spalled cavity. The gas will cause some of the waste material on the cavity walls to fail in tension and be transported to the surface. High repository pressures and high waste permeability are general repository conditions for blowout.

Stuck pipe is a process of spall that, due to relatively low permeability and high repository pressures, may cause failed waste to press against the drill string sufficiently hard to prevent normal drilling. The solution of a jammed bit is to pull the drill string up and start drilling again. If the pressures remain high, the driller may have to bring the bit up several times, thus allowing significant quantities of waste to be brought to the surface. Gas erosion describes spall that is eroded by the drilling mud and may occur due to high repository pressures and low waste permeability. The rate of spall is slower than stuck pipe due to slightly lower pressures than stuck pipe (just above hydrostatic), and may release waste into the drilling mud at a rate undetectable by the driller. Gas erosion could continue until the repository pressure is in equilibrium with the drilling fluid, and may also bring significant quantities of waste to the surface. Stuck pipe and gas erosion releases would occur if the waste permeability is less than 10^{-16} m^2, a permeability threshold defined in Berglund (1994) that is currently under question, and repository pressures are greater than the pressure exerted by the drilling mud.

As part of the performance assessment, blowout calculations were performed, and volumes of failed waste material were estimated for the CCA, which ranged from 0.5 m^3 to 4 m^3. However, these calculations were found to be faulty by the DOE's Conceptual Model Peer Review Group (Wilson et al., 1997), and a new model for blowout was developed (Hansen et al., 1997). The new model showed that the CCA predicted blowout releases were conservative, by estimating a maximum release of only 0.27 m^3 at the worst conditions of repository behavior.

Through an investigation of permeability of the new spallings model, it is questionable whether the calculations of blowout is sufficient in estimating releases to the surface. The model was run with a range of permeability values consistent with Hansen et al., (1997), and was found to have high volumes of failed material in the repository cavity when gas influx was insufficiently large to cause blowout. Though blowout had not occurred, the failed waste in the borehole cavity would be introduced into the drilling mud and be carried to the surface with other cuttings and cavings from borehole drilling activity. This defines gas erosion and was not considered in Hansen et al., (1997).

More important to the question of the amount of waste released to the surface that will be expelled from the pressurized repository, is the amount of spalled material that will cause the repository to fail compliance. The performance assessment calculations of the CCA (DOE, 1996) and PAVT (DOE, 1997) demonstrated that any combination of spalled releases from blowout from 0.5 m^3 to 4 m^3 will demonstrate compliance. However, no one, as of yet, looked at the issue of failure. This report investigates the amount of spalled material that would result in failure to meet the EPA compliance standards.

Discussion

For the performance assessment calculations of the PAVT, the EPA decided to sample blowout releases on a range from 0.5 m^3 to 4.0 m^3 with a uniform distribution assigned to that range. The result was an increase in the overall mean of releases for spallings in the CCDF from 0.04 EPA units at the 10^{-1} probability in the CCA to 0.08 EPA Units in the PAVT. The increase was also due to the number of vectors that exhibited pressures above hydrostatic. The spallings and cuttings portions of the CCDF contribute equally to the overall mean of the CCDF.

For a more complete view of spallings and its contribution to the overall mean of the CCDF, the values of 0.5 to 4 m^3 used in the PAVT calculations were increased by a factor until it was shown that there was failure of compliance. The factor ranged from 2 to 16, and was a very simple adjustment to the PAVT values.

The results of increased spall reaching the surface can be seen in Figure 1. The increase in spall was accomplished by multiplying the PAVT generated releases by a factor of 2, 4, 8, and 16. These curves are seen in Figure 1, and are compared to the CCA releases. The figure suggests that a maximum of 16 times the amount of spallings will cause the repository to fail at the 10^{-1} probability, which corresponds to spallings releases between 8 m^3 and 64 m^3.

Conclusion

The questions raised on the amount of spalled material that will cause the disposal system to fail compliance is addressed here. The concern of additional spalled material that may reach the surface, by either a stuck pipe / gas erosion process, or through air drilling can be seen in Figure 1. The figure shows that a maximum of 16 times the PAVT spalled release can be brought to the surface before compliance of the disposal system is compromised if other modes of releases are held constant.

References

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Wilson, C., Porter, D., Gibbons, J., Oswald, R., Sjoblom, G., 1997. Waste Isolation Pilot Plant Conceptual Models Peer Review: Final Report. DOE/CAO-1996-1985. Carlsbad, NM:U.S. Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

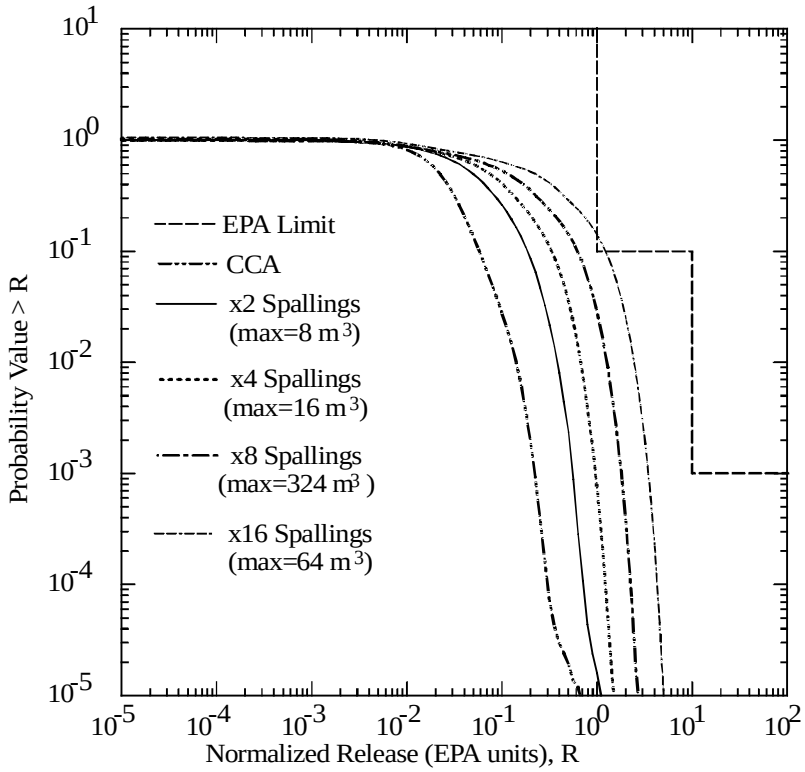

Figure 1: Overall Mean For PAVT Increased Spallings

(Enclosure 4 to the 12/31/97 Letter From R.H. Neill, EEG to F. Marcinowski, EPA)

Issue: Modeling the Air Drilling Scenario through a Direct Brine Release at the WIPP

Introduction

The practice of drilling with air as the circulation fluid in wells has been established in the Delaware Basin. On April 2, 1991 the Lincoln Federal Well No. 1 in Section 26, T21S, R32E, NMPM, in Lea County, New Mexico was drilled with air after 11 days of drilling with mud brine (Silva, 1994; EEG-55 p.63-64). The CCA did not consider the practice of drilling with air as a possible method for well development.

The modeling of air drilling was first raised by Bredehoeft (1997). Bredehoeft addressed the concern of spalled (solid) material that would reach the accessible environment through an air drilling scenario. His results show that a large amount of material could reach the surface, thus breaking the compliance standards set in 40 CFR Part 194 (EPA, 1997). This is the first report to address the issue of contaminated brine released after drilling with air. The issue is studied here, by applying a model to the release of brine through an inadvertent drill intrusion into the WIPP repository.

Discussion

An air drilling scenario is investigated using the Sandia developed code for a brine release through an intruding borehole. The code, BRAGFLO_DBR, is used along with the same assumptions as the Performance Assessment Verification Test (PAVT), including the BRAGFLO output files, and CUTTINGS_S files, but changing the boring fluid from a brine mud to air. The change in boring fluid would decrease the pressure at the bottom of the borehole, thus allowing a higher release of brine to escape to the surface.

For blowout to occur, the pressure of the repository must be higher than the borehole pressure at the repository depth. For brine mud, the pressure is assumed to be hydrostatic, or 8 MPa. For the air column, the air pressure will be very low, and was assumed to be approximately 2 MPa for this model, thus allowing higher and more frequent blowout occurrences than higher pressures. The 2 MPa is assumed to approximate the pressure exerted by a foam/air mixture at the depth of the WIPP repository. Air alone would exert pressures far below that of foam/air combination. However, this cutoff is reasonable due to the extremely low number of vectors that are expected to fall below the 2 MPa cutoff. One additional change from the PAVT for modeling with air includes the density of the drilling fluid from 1215 kg/m^3 for brine to 1.161 kg/m^3 for air.

The model was run for an initial E1 intrusion at 350 and 1000 years, and subsequent E2 intrusions at 550, 750, 1200, 1400, 2000, 3000, 4000, 5000, and 10000 years post closure (S2 and S3 scenarios). The results, shown in Figure 1, demonstrates the danger of drilling with air into the repository. The figure shows the results of 100 vectors for time 1200 years for S3, Replicate 1 using air as the drilling fluid. A single realization is shown to release as much as 2400 m^3 of brine to the surface at a second intrusion time of 1200 years. This is the highest brine release seen for all vectors at all times. The mean value for all releases at 1200 years is 436 m^3. The PAVT results show a maximum of 76 m^3 at 1200 years postclosure (DOE, 1997), and the CCA predicted a maximum release of 15 m^3 (DOE, 1997).

The high volumes of release seen in Figure 1 can be attributed to the high pressures of the repository. At 1200 years postclosure, the repository pressure of vector 51, which has the highest releases, exceeds most other vectors at 13.3 MPa, and is ranked 4th out of 100 vectors for highest repository pressure. Also contributing to its high release is the waste saturation. Vector 51 has a saturation of 0.67, which has been seen in past sensitivity analyses (See Figure 5.1.5. of Helton, 1996) to be an ideal saturation for release.

Inherently, there are problems with using the BRAGFLO_DBR code this way. The model assumed an incompressible fluid in the wellbore. Air is compressible, and the effects of incompressibility on the releases are not known. There are also some questions of whether the drilling fluid density change affected the whole repository or just the wellbore. This was a quick experiment, and these questions will be investigated further by the EEG. However, the results seen in Figure 1 are believed to provide an indication of the magnitude of potential releases.

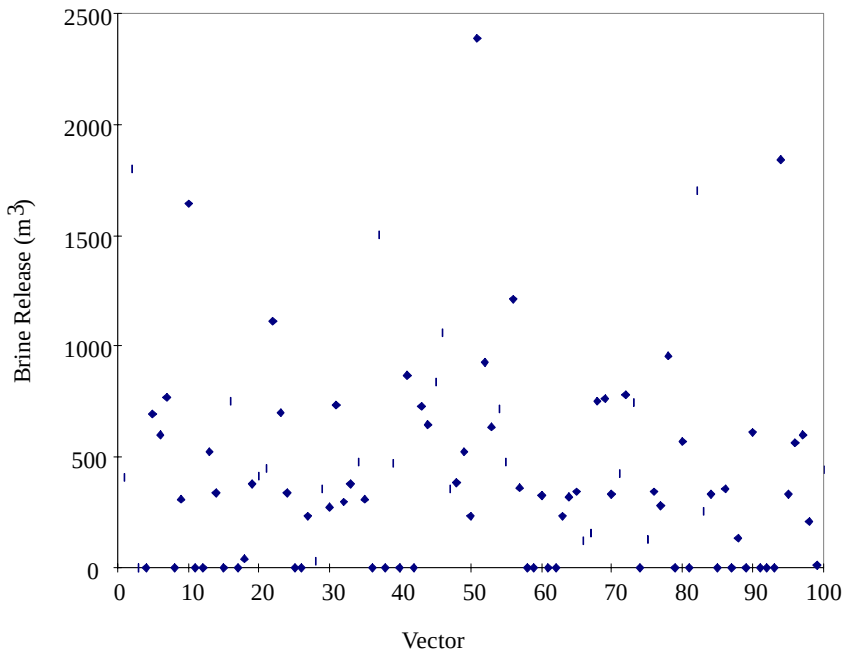

Figure 1. Air Drilling Results for 100 vectors of an S3 scenario at 1200 years postclosur

The carrying capacity of the brine to transport radionuclides to the surface depends on the solubility of the actinides in solution. The CCA's median value of solubility for a +4 actinide (Plutonium (IV), Uranium (IV), or Thorium (IV)) in Salado brine is approximately 4e-6 M. Thus, calculating the number of grams of Plutonium-239 (IV) for 2400 m^3 of brine is 2300 g. The grams can be converted to activity, and the 2400 m^3 of brine can be calculated to carry 140 Ci, or 0.4 EPA units. Higher solubility values will result in higher releases to the surface.

The CCDF curves, using the results of air drilling, can be seen in Figure 2. The code, which produced the curves, used the releases from PAVT and solubilities from the CCA. The direct brine release results of air drilling were then substituted for the results of the PAVT. Again, it should be noted that the CCDF results use spallings releases calculated in the PAVT. Spallings releases due to an air drilling event were not incorporated into the results. These curves assume a worst case scenario, in which all the drilling from an E1E2 drilling event would be using air as the drilling fluid.

In addition to the CCA solubilities, actinide solubilities with different mineral species were included. The solubilities were from median values using Nesquehonite, a mineral phase of the magnesium carbonate system, and from no MgO backfill. The 'No Backfill' case does not suggest that MgO should not be present in the repository, but gives an upper bound on solubility and how it affects compliance to the EPA standards. Table 1 shows the values used for each actinide oxidation state.

The CCDF curves for CCA solubility values do not exceed the EPA standard at the 10^{-1} or 10^{-3} probability level. Yet, the issue should not be readily dismissed. The problem was run on the scenarios of S2 and S3 only. The other three scenarios assumed brine mud as the drilling fluid. Furthermore, solubility values are shown to be greater in other mineral species of the magnesium carbonate system, and if the repository is breached during a time when these minerals will dominate the repository, then there may be sufficient releases to the accessible environment to cause the repository to fail compliance. This example can be seen in the curve for the Nesquehonite solubility. Again, this is a worst-case scenario in which all vectors for the simulation of air drilling uses the median values for Nesquehonite solubility, which can be seen in Table 1. The curve for Nesquehonite crosses the EPA compliance limit at the 0.02 probability level. This relates to a 1 in 50 chance of releasing more than 3500 Ci to the surface. The curve drops to a 1 in 500 chance of releasing more than 35000 Ci to the surface.

Salado	**+3 (M)**	**+4 (M)**	**+6 (M)**
Nesquehonite	3.17e-7	6.3e-4	NA (used No Backfill)
No Backfill	4e-3	5e-4	8e-5
Castile			
Nesquehonite	2.4e-6	1.04e-3	NA (used No Backfill)
No Backfill	2e-3	7e-5	8e-5

Table 1. Solubility values used in PANEL for generation of CCDF curves.

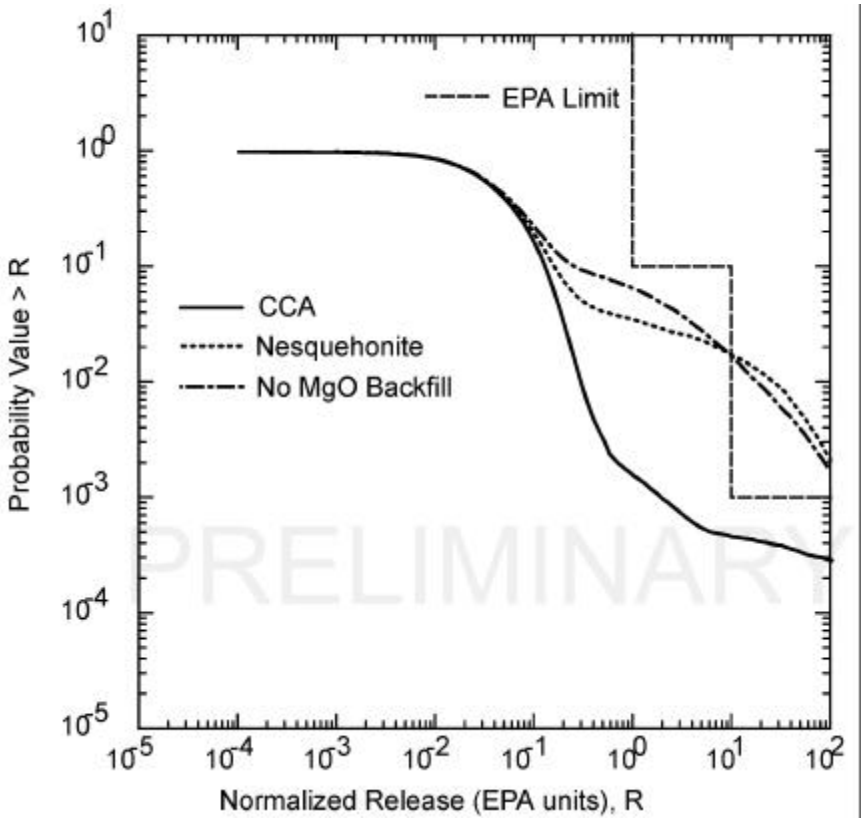

Figure 2. CCDF for Air Drilling with different solubilities. Air Drilling Modeling only included Direct Brine Releases for S2 and S3. Cuttings, spallings, and transport through the Culebra results are from PAVT, with actinide solubility values from the CCA, formation with Nesquehonite, and no MgO backfill.

The third curve on the CCDF plot shows the response of the disposal system for solubility values from 'No MgO Backfill'. The releases for probabilities greater than 1 in 50 are much higher than the other two curves. However, at lower probabilities the 'No MgO Backfill' has lower releases than the solubilities with Nesquehonite. This is due to the difference in solubility values at the +4 oxidation state for both Salado and Castile brine. In conclusion, the CCDF curves are shown to cross the EPA Release limits for higher solubility values, and the issue of air drilling must be taken more seriously than previous evaluations.

Recommendations

1) The EPA should look more closely at the issue of air drilling to determine the probability of such an event occurring in the 10000 year projected history of the disposal system.
2) EPA needs to asses the appropriateness of using the BRAGFLO direct brine release model for air drilling.
3) Depending on EPA's resolution of the solubility issue, the EPA may need to calculate CCDFs for air drilling.

Reproducibility

To reproduce the results of this experiments, the summarized files (*.TBL) of CUTTINGS_S, BRAGFLO_DBR, and SECOTP2D from PAVT, and the summarized files of NUTS, PANEL, and ST (Source Term) from the CCA are needed for the input for CCDFGF. In addition, the BRAGFLO_DBR files from an air drilling scenario will replace some of the BRAGFLO_DBR of the PAVT. Attachment 1 shows the input for the preprocessor of CCDFGF. The Direct Brine Release summarized files begin with: 'SUM_BF4_CCGF_AIR'.

The simulation of drilling with air with BRAGFLO_DBR was accomplished by changing the inputs to the preprocessor of the model. The ALGEBRA file 'ALG_BF4_CCA_PRE_DIR_REL_S3_DIST.INP' was modified to allow a lower threshold of pressure from the drilling fluid for time stepping. The file sets the time step for the BRAGFLO_DBR to 0 if the flowing bottomhole pressure (FBHP) is less than the pressure of the drilling fluid column, and to a maximum 1000 time steps if the pressure is greater. The FBHP was established in the preprocessor by a 3D curve fit from the Poettmann-Carpenter correlation (DOE, 1996). The ALGEBRA file was also modified for drilling fluid density. Attachment 2 lists the file and highlights the areas of change. The original ALGEBRA file used 8 MPa as the cutoff for timestep configuration. The new model sets the cutoff at 2 MPa.

References

Bredehoeft, J., 1997. Air Drilling Spallings Report. Draft Report of The Hydrodynamics Group. La Honda, CA.

Helton, 1996. Preliminary Summary Of Uncertainty And Sensitivity Analysis Results Obtained In Support Of The 1996 Compliance Certification Application For The Waste Isolation Pilot Plant. Memo, Dec. 23, 1996. Sandia National Laboratories, Albuquerque, NM. SAND 96-2226.

Silva, M.K., 1994. Implications of the Presence of Petroleum Resources on the Integrity of the WIPP. Albuquerque, NM: Environmental Evaluation Group, EEG-55.

U.S. Department of Energy, 1996. Analysis Package for the BRAGFLO Direct Release Calculations (Task 4) of the Performance Assessment Analyses Supporting the Compliance Certification Application. Sandia National Laboratories, Albuquerque, NM. WPO#40520.

U.S. Department of Energy, 1997. Summary of the EPA-Mandated Performance Assessment Verification Test (Replicate 1) and Comparison with the Compliance Certification Application Calculations. EPA Docket A-93-02, II-G-26.

U.S. Environmental Protection Agency, 1997. Title 40 CFR Part 194 Criteria for the Certification and Recertification of the waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations; Proposed Rule.

Attachment 1: Input for CCDFGF Preprocessor Mode for Air Drilling

```
$! .
$! MODULE:     PREPRO.COM
$! PURPOSE:    RUN PREPROCESSOR CODE TO CREATE CUTTINGS, SPALLINGS
$!            BLOWOUT, NUTS, AND SECOTF INPUT TABLES FOR USE BY
$            CCDFGF PREPROCESSOR OPTION
$! ---
$! AUTHOR:     JAY D. JOHNSON
$! DATE:       11/22/96
$!
$! Date        Changes
$! 11/10/97    Solubility     -D. Rucker
$!              CCA denotes CCA Solubilities
$!              EEG2 denotes Nesquehonite Solubilities
$!              EEG1 denotes No Backfill Solubilities
$!
$! 12/3/97     Air Drilling    -D. Rucker
$!              Direct Brine Release  'SUM_bf4_ccgf_air'.tbf
$! ---
$! Setup to run
$  SET NOON
$  REP := "R2"
$!
$  Testdir1 := "t4:[d1rucke.ccdfgf]"
$  Testdir2 := "t4:[d1rucke.ccdfgf.input_'REP']"
$  Testdir2a:= "t4:[d1rucke.pavl]"
$  Testdir3 := "t4:[d1rucke.ccdfgf.input_'REP']"
$  Testdir3a:= "t4:[d1rucke.pavl]"
$  Testdir4 := "t4:[d1rucke.ccdfgf.input_'REP']"
$  Testdir5 := "t4:[d1rucke.ccdfgf.input_'REP']"
$  Testdir6 := "t4:[d1rucke.panel.com]"
$  Testdir6a := "t4:[d1rucke.panel.time]"
$  Testdir7 := "t4:[d1rucke.cusp]"
$  Testdir8 := "t4:[d1rucke.dbr]"
$  testdir9 := "t4:[d1rucke.ruts]"
$  testdir0 := "t4:[d1rucke.st]"
$  Curdir   := "t4:[d1rucke.ccdfgf]"
$! ---
$! Define CUTTINGS file names
$! ---
$  DEFINE/NOLOG HT_FRACSINP                    'TESTDIR1'CCGF_CCA_HT_FRAC.DAT
$  DEFINE/NOLOG EPAUNI_CCH$INP                 'TESTDIR1'EPU_CCGF_CCA_CCH.DAT
$  DEFINE/NOLOG EPAUNI_CRH$INP                 'TESTDIR1'EPU_CCGF_CCA_CRH.DAT
$  DEFINE/NOLOG SUM_CUSP_CCGF_CCA$INP          'TESTDIR2a'SUM_CUSP_C97_'rep'_S1_L_T5000.TBL
$  DEFINE/NOLOG CCGF_CUTTINGS$OUT              'OUTDIR'CUTTING.TRN
$! ---
$! Define SPALLINGS file names
$! ---
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$! ---
$  DEFINE/NOLOG CUSP_S1_L_T100$INP             'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_L_T100.TBL
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$ DEFINE/NOLOG BF4_S3_L_T1400$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_L_T1400.TBL
$ DEFINE/NOLOG BF4_S3_L_T3000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_L_T3000.TBL
$ DEFINE/NOLOG BF4_S3_L_T5000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_L_T5000.TBL
$ DEFINE/NOLOG BF4_S3_L_T10000$INP         'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_L_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S3_U_T1200$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_U_T1200.TBL
$ DEFINE/NOLOG BF4_S3_U_T1400$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_U_T1400.TBL
$ DEFINE/NOLOG BF4_S3_U_T3000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_U_T3000.TBL
$ DEFINE/NOLOG BF4_S3_U_T5000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_U_T5000.TBL
$ DEFINE/NOLOG BF4_S3_U_T10000$INP         'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_U_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S4_L_T550$INP           'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Lower_T550.TBL
$ DEFINE/NOLOG BF4_S4_L_T750$INP           'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Lower_T750.TBL
$ DEFINE/NOLOG BF4_S4_L_T2000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Lower_T2000.TBL
$ DEFINE/NOLOG BF4_S4_L_T4000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Lower_T4000.TBL
$ DEFINE/NOLOG BF4_S4_L_T10000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Lower_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S4_U_T550$INP           'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Up_T550.TBL
$ DEFINE/NOLOG BF4_S4_U_T750$INP           'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Up_T750.TBL
$ DEFINE/NOLOG BF4_S4_U_T2000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Up_T2000.TBL
$ DEFINE/NOLOG BF4_S4_U_T4000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Up_T4000.TBL
$ DEFINE/NOLOG BF4_S4_U_T10000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Up_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S5_L_T1200$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Lower_T1200.TBL
$ DEFINE/NOLOG BF4_S5_L_T1400$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Lower_T1400.TBL
$ DEFINE/NOLOG BF4_S5_L_T3000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Lower_T3000.TBL
$ DEFINE/NOLOG BF4_S5_L_T5000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Lower_T5000.TBL
$ DEFINE/NOLOG BF4_S5_L_T10000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Lower_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S5_U_T1200$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Up_T1200.TBL
$ DEFINE/NOLOG BF4_S5_U_T1400$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Up_T1400.TBL
$ DEFINE/NOLOG BF4_S5_U_T3000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Up_T3000.TBL
$ DEFINE/NOLOG BF4_S5_U_T5000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Up_T5000.TBL
$ DEFINE/NOLOG BF4_S5_U_T10000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Up_T10000.TBL
$! ---
$ DEFINE/NOLOG CCGF_BLOWOUTSOUT            'OUTDIR'BLOWOUT.TRN
$! ---
$! Define NUTS file names
$! ---
$ DEFINE/NOLOG ALG_ST_CCGF_CCA_S1$INP      'TESTDIR0'SUM_ST_CCGF_aeg1_'REP'_S1.TBL
$ DEFINE/NOLOG ALG_ST_CCGF_CCA_S2$INP      'TESTDIR0'SUM_ST_CCGF_aeg1_'REP'_S2.TBL
$! ---
$ DEFINE/NOLOG SUM_NUTS_S1$INP             'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S1.TBL
$! ---
$ DEFINE/NOLOG SUM_NUTS_S2_100$INP         'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S2_T100.TBL
$ DEFINE/NOLOG SUM_NUTS_S2_350$INP         'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S2_T350.TBL
$ DEFINE/NOLOG SUM_NUTS_S3_1000$INP        'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S3_T1000.TBL
$ DEFINE/NOLOG SUM_NUTS_S3_3000$INP        'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S3_T3000.TBL
$ DEFINE/NOLOG SUM_NUTS_S3_5000$INP        'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S3_T5000.TBL
$ DEFINE/NOLOG SUM_NUTS_S3_7000$INP        'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S3_T7000.TBL
$ DEFINE/NOLOG SUM_NUTS_S3_9000$INP        'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S3_T9000.TBL
$! ---
$ DEFINE/NOLOG SUM_NUTS_S4_100$INP         'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S4_T100.TBL
$ DEFINE/NOLOG SUM_NUTS_S4_350$INP         'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S4_T350.TBL
$ DEFINE/NOLOG SUM_NUTS_S5_1000$INP        'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S5_T1000.TBL
$ DEFINE/NOLOG SUM_NUTS_S5_3000$INP        'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S5_T3000.TBL
$ DEFINE/NOLOG SUM_NUTS_S5_5000$INP        'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S5_T5000.TBL
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$ DEFINE/NOLOG SUM_NUTS_S5_7000$INP          'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S5_T7000.TBL
$ DEFINE/NOLOG SUM_NUTS_S5_9000$INP          'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S5_T9000.TBL
$! ---
$ DEFINE/NOLOG SUM_PNL_S6_100$INP            'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_100.TBL
$ DEFINE/NOLOG SUM_PNL_S6_350$INP            'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_350.TBL
$ DEFINE/NOLOG SUM_PNL_S6_1000$INP           'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_1000.TBL
$ DEFINE/NOLOG SUM_PNL_S6_4000$INP           'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_4000.TBL
$ DEFINE/NOLOG SUM_PNL_S6_6000$INP           'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_6000.TBL
$ DEFINE/NOLOG SUM_PNL_S6_9000$INP           'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_9000.TBL
$! DEFINE/NOLOG SUM_PNL_S6_100$INP           'TESTDIR4'SUM_PANEL_CCDfgf_'REP'_S6_100.TBL
$! DEFINE/NOLOG SUM_PNL_S6_350$INP           'TESTDIR4'SUM_PANEL_CCDFgf_'REP'_S6_350.TBL
$! DEFINE/NOLOG SUM_PNL_S6_1000$INP          'TESTDIR4'SUM_PANEL_CCDFgf_'REP'_S6_1000.TBL
$ DEFINE/NOLOG SUM_PNL_S6_2000$INP           'TESTDIR4'SUM_PANEL_CCDFGF_'REP'_S6_2000.TBL
$! DEFINE/NOLOG SUM_PNL_S6_4000$INP          'TESTDIR4'SUM_PANEL_CCDFgf_'REP'_S6_4000.TBL
$! DEFINE/NOLOG SUM_PNL_S6_6000$INP          'TESTDIR4'SUM_PANEL_CCDFgf_'REP'_S6_6000.TBL
$! DEFINE/NOLOG SUM_PNL_S6_9000$INP          'TESTDIR4'SUM_PANEL_CCDFgf_'REP'_S6_9000.TBL
$! ---
$ DEFINE/NOLOG SUM_CCDFGF_CCA_CAVGE0D$INP    'TESTDIR5'SUM_PANEL_eeg1_CON_'REP'_S1.tbl
$ DEFINE/NOLOG SUM_CCDFGF_CCA_CAVGE1D$INP    'TESTDIR5'SUM_PANEL_eeg1_CON_'REP'_S2.tbl
$! ---
$ DEFINE/NOLOG CCGF_NUTS$OUT                 'OUTDIR'NUTS.TRN
$! ---
$! Define SECOTP file names
$! ---
$ DEFINE/NOLOG ST2D3_CCA_PM$INP              'TESTDIR2a'SUM_ST2D3_c97_R1_PM.TBL
$ DEFINE/NOLOG ST2D3_CCA_FM$INP              'TESTDIR2a'SUM_ST2D3_c97_R1_FM.TBL
$ DEFINE/NOLOG CCGF_SECOTP$OUT               'OUTDIR'SECOTP.TRN
$! ---
$ DEFINE/NOLOG CCGF_MISC$INP                 'TESTDIR1'CCGF_MISC_PRE_CCA.INP
$ DEFINE/NOLOG CCGF_SDB$INP                  'TESTDIR1'CCDFGF.SDB
$ DEFINE/NOLOG CCGF_PRT$OUT                  'OUTDIR'CCGF_CCDFGF_CCA_'REP'.OUT
$ DEFINE/NOLOG CCGF$OUT                      'OUTDIR'CCGF_cca_'REP'.OUT
$! ---
$! Define release summary tables file name
$! ---
$ DEFINE/NOLOG CCGF_RELEASE$OUT              'OUTDIR'eeg1_reltab_eeg1_'REP'.DAT
$! ---
$! Execute CCDFGF with preprocessor option
$! ---
$ CCDFGF
$! ---
$ EXIT
$! ---
```

Attachment 2: ALGEBRA file for Air Drilling Scenario

```
!-----------------------------------------------------------------------
!
!TITLE:BRAGFLO 1996 DCA CALCULATIONS: REPOSITORY SCALE BLOWOUT
!ANAYLST: Dan Stoelzel, SNL
!CREATED: NOV 2, 1995
!PURPOSE: ALGEBRA file computes properties that can not be obtained
!       from CAMDAT and/or assigns properties to element blocks.
!            THIS FILE PREPARES A .CDB FILE FOR PREBRAG TO READ
!IMPORTANT: This file originates from J.E. Bean's algebra file for his FEP
!       model. The methodologies to calculate dip were copied from his
!       file, with minor changes
!       made to account for the differences in the meshes.
!       ALGEBRA TO CALC. DIP IN REPOSITORY - SCALE BLOWOUT MODEL.
!       new version of bragflo
!
!          MODIFIED:
!                    MARCH 26, 1996
!                    BLOWOUT MODEL STRUGGLING IN PANEL SEAL REGION. TURNED OFF
!                    CAP PRESSURE IN PANEL SEAL AND HALITE BY SETTING EQUAL TO
!                    CAP PRESSURE IN WASTE REGION
!
!                    MAY 17, 1996
!                    ADDED BOUNDARY CONDITION WELL CALCULATION FOR E1-E2 SCEN
!                    NEW CHANGES FOR LATEST DCA ANALYSIS
!
!                    MAY 20, 1996
!                    WELL 2 INPUT FILE TO ACCOUNT FOR E1-E2 SAME PANEL BOUNDARY
!                    COND.
!
!                    MAY 30,1996
!                    ADDED LOGIC TO ACCOUNT FOR CHANGES IN ABANDONED WELLBORE PERM
!                    FOR BOUNDARY CONDITION WELL.
!                    SCENARIO 2 AND 4 FILE  FIRST INTRUSION AT 350 YEARS
!
!                    December 1, 1997
!                    Changed Cutoff for pressure in the repository to allow Air Drilling
!                    Dave Rucker, EEG
!=====================================================================
!
!CHAPTER 0:  DEFINE NEW VARIABLE NAMES AND SOME NEEDED CONSTANTS
!
!---------------------------------------------------------------------
!
!
! SET CONSTANTS AND PUT IN WASTE REGION
LIMIT BLOCK 1
THETA1  = MAKEPROP(DIP_DEG[B:8]*2.0*PI[B:8]/360.0;
THETA2  = MAKEPROP(0.0)
!
!
PERM_X  = 10**PRMX_LOG
PERM_Y  = 10**PRMY_LOG
PERM_Z  = 10**PRMZ_LOG
SB_MIN  = SAT_RBRN * 1.05
POR_COMP = COMP_RCK/POROSITY
! CALCULATE PROPERTIES FOR DRZ & HALITE
LIMIT BLOCK 2 3
PERM_X  = 10**PRMX_LOG
PERM_Y  = 10**PRMY_LOG
PERM_Z  = 10**PRMZ_LOG
SB_MIN  = SAT_RBRN * 1.05
! NOW ADJUST POROSITY AND PORE COMPRESSIBILITY TO EQ. PORE VOL WITH CRUSHED
! ROOM HEIGHT
POROSITY = HEIGHT * POROSITY / HEIGHT[ID:1]
POR_COMP = COMP_RCK/POROSITY
! CAP PRESSURE MODEL CHANGES HERE:
```

```
CAP_MOD = CAP_MOD[ID:1]
PCT_A   = PCT_A[ID:1]
PCT_EXP = PCT_EXP[ID:1]
! CALC PROPERTIES FOR PANEL SEALS
LIMIT BLOCK 4
PERM_X  = 10**PRMX_LOG
PERM_Y  = 10**PRMY_LOG
PERM_Z  = 10**PRMZ_LOG
SB_MIN  = SAT_RBRN * 1.05
! NOW ADJUST POROSITY AND PORE COMPRESSIBILITY TO EQ. PORE VOL WITH CRUSHED
! ROOM HEIGHT
POROSITY = HEIGHT * POROSITY / HEIGHT[ID:1]
POR_COMP = COMP_ROK/POROSITY
! CAP PRESSURE MODEL CHANGES HERE:
CAP_MOD = CAP_MOD[ID:1]
PCT_A   = PCT_A[ID:1]
PCT_EXP = PCT_EXP[ID:1]
!==========================================================================
[redacted]
!==========================================================================
! SET WELLBORE PROPS
LIMIT BLOCK 7
SEBRINE1 = MAKEPROP(0.0)
SEGAS1   = MAKEPROP(0.0)
KRW1     = MAKEPROP(0.0)
KRG1     = MAKEPROP(0.0)
SEBRINE2 = MAKEPROP(0.0)
SEGAS2   = MAKEPROP(0.0)
KRW2     = MAKEPROP(0.0)
KRG2     = MAKEPROP(0.0)
SEBRINE3 = MAKEPROP(0.0)
SEGAS3   = MAKEPROP(0.0)
KRW3     = MAKEPROP(0.0)
KRG3     = MAKEPROP(0.0)
SEBRINE4 = MAKEPROP(0.0)
SEGAS4   = MAKEPROP(0.0)
KRW4     = MAKEPROP(0.0)
KRG4     = MAKEPROP(0.0)
! DEFINE CONSTANTS FOR THE THREE EQUATIONS TO BE USED TO CALCULATE FBHP
! EQUATION 1: (FOR BRINE FLOW ONLY, KRG = 0)
! FBHP = (A+BX+CY)/(1+DX+EY)
!   X = LOG10(BRINE CONST) LOG M^3/μA-S
!   Y = PANEL PRESSURE (Pa)
! 8,002,373 Pa < FBHP < 8,036,090 Pa
EQ1_A = MAKEPROP(8002577.4)
EQ1_B = MAKEPROP(62.1375 75)
EQ1_C = MAKEPROP(0.024916098)
EQ1_D = MAKEPROP(0.10254807)
EQ1_E = MAKEPROP(5.1235777E-9)
! EQUATION 2: (FOR LOG10(KRG/KRW) < 0 BRINE DOMINATED FLOW)
! FBHP = (A+BX+CX^2+DX^3+EY)/(1+FX+GX^2+HY)
!   X = LOG10(KRG/KRB)
!   Y = PANEL PRESSURE (Pa)
! 225,453 Pa < FBHP < 8,028,643 Pa
EQ2_A = MAKEPROP(947082.65)
EQ2_B = MAKEPROP(2788147.8)
EQ2_C = MAKEPROP(3451058.3)
EQ2_D = MAKEPROP(-54884.388)
EQ2_E = MAKEPROP(-0.017079483)
EQ2_F = MAKEPROP(0.8953587)
EQ2_G = MAKEPROP(0.54041537)
EQ2_H = MAKEPROP(-4.9369107E-9)
! EQUATION 3: (FOR LOG10(KRG/KRW) > 0 GAS DOMINATED FLOW)
! FBHP = EXP(A+BX+CX^0.5+DE^-X+EY^0.5)
!   X = LOG10(KRG/KRB)
!   Y = PANEL PRESSURE (Pa)
```

```
! 153,271 Pa < FBHP < 385,493 pA
EQ3_A = MAKEPROP(8.9214835)
EQ3_B = MAKEPROP(-0.2274279)
EQ3_C = MAKEPROP(1.3680586)
EQ3_D = MAKEPROP(1.8350386)
EQ3_E = MAKEPROP(0.00045726223)
!
  CALCULATE SKIN FROM SPALL REMOVED, & WELL PRODUCTIVITY INDEX
  ELEMENT 59 IS LOCATION OF WELL 2 (2ND INTRUSION DOWN DIP)
WELLRAD = BITSIZE/2
DRAINRAD = SQRT(DEL_X[E:59]*DEL_Y[E:59]/PI[B:B])
SKIN    = -1.0*LOG(SQRT(AREA_TOT/PI[B:B])/WELLRAD)
SKIN    = IFLT0(SKIN,SKIN,0)
! CHECK TO BE SURE WELLPI IS NOT 0 OR NEG. & SET TO 1.0 IF IT IS
! WELLPI  = PERM_X[ID:1] * HEIGHT[ID:1] / (LOG(DRAINRAD/WELLRAD) + SKIN - 0.5)
WELLPI  = IFGT0(LOG(DRAINRAD/WELLRAD) + SKIN - 0.5,PERM_X[ID:1]*HEIGHT[ID:1] &
     / (LOG(DRAINRAD/WELLRAD) + SKIN - 0.5),1.0)
! CALCULATE CONSTANTS NEEDED FOR WELLBORE MODEL:
! CALCULATE EFFECTIVE SATURATION USING KRP = 4 (BROOKS - COREY MODIFIED,
! WITH LAMBDA (PORE_DIS) = 2.89, NO CAP PRESSURE). DO FOR 4 COUPLED REGIONS
! REGION NO 1 (PANELS 1 & 8)
BRINE1  = IFLT0((BSATPAN1[ID:1]-SAT_RBRN[ID:1]),SAT_RBRN[ID:1],BSATPAN1[ID:1])
SEBRINE1 = (BRINE1 - SAT_RBRN[ID:1])/(1.0 - SAT_RBRN[ID:1])
SEGAS1  = (BRINE1 - SAT_RBRN[ID:1])/(1.0-SAT_RBRN[ID:1]-SAT_RGAS[ID:1])
SEGAS1  = IFLT0(1.0 - SEGAS1,1.0,SEGAS1)
KRW1    = SEBRINE1**((2+3*PORE_DIS[ID:1])/PORE_DIS[ID:1])
KRG1    = (1.0-SEGAS1)**2*(1.0-SEGAS1**((2 + PORE_DIS[ID:1])/PORE_DIS[ID:1]))
! NOW CALCULATE CONSTANT FOR BRINE AND GAS
CONBR1  = WELLPI * KRW1 / VISCO[ID:5]
CONGAS1 = WELLPI * KRG1 / VISCO[ID:6]
! NOW TAKE LOG BASE 10 OF PARAMETERS NEEDED FOR FBHP EQUATIONS
LOG_B1  = IFEQ0(KRW1,-10,LOG10(CONBR1+1E-24))
LOG_KR1 = IFEQ0(KRW1,10,LOG10((KRG1+1E-24)/(KRW1+1E-24)))
! CALCULATE FBHP's AND SET WITHIN LIMITS
PR1_EQ1 = (EQ1_A+EQ1_B*LOG_B1+EQ1_C*PRESPAN1[ID:1])/ &
      (1.0+EQ1_D*LOG_B1+EQ1_E*PRESPAN1[ID:1])
PR1_EQ1 = IFLT0(8002373.0 - PR1_EQ1,IFLT0(8036090.0 - PR1_EQ1,8036090.0, &
      PR1_EQ1),8002373.0)
PR1_EQ2 = (EQ2_A+EQ2_B*LOG_KR1+EQ2_C*LOG_KR1**2+EQ2_D*LOG_KR1**3+ &
      EQ2_E*PRESPAN1[ID:1])/(1.0+EQ2_F*LOG_KR1+EQ2_G*LOG_KR1**2+ &
      EQ2_H*PRESPAN1[ID:1])
PR1_EQ2 = IFLT0(225453.0 - PR1_EQ2,IFLT0(8028643.0 - PR1_EQ2,8028643.0, &
      PR1_EQ2),225453.0)
PR1_EQ3 = EXP(EQ3_A+EQ3_B*LOG_KR1+EQ3_C*ABS(LOG_KR1)**0.5+ &
      EQ3_D*EXP(-1.0*ABS(LOG_KR1))+EQ3_E*PRESPAN1[ID:1]**0.5)
PR1_EQ3 = IFLT0(153271.0 - PR1_EQ3,IFLT0(385493.0 - PR1_EQ3,385493.0, &
      PR1_EQ3),153271.0)
! RESET FBHP TO 0 IF NO BRINE BLOWOUT (KRW = 0 OR PRESSURE < 2 MPa (300 psi))
[redacted]
! IF NO BLOWOUT, SET NUMBER OF BRAGFLO STEPS TO 1, ELSE 1000
NUMSTEP1 = MAKEPROP(IFEQ0(FBHP1,1,1000))
! REGION NO 2 (PANELS 2 & 7)
BRINE2  = IFLT0((BSATPAN2[ID:1]-SAT_RBRN[ID:1]),SAT_RBRN[ID:1],BSATPAN2[ID:1])
SEBRINE2 = (BRINE2 - SAT_RBRN[ID:1])/(1.0 - SAT_RBRN[ID:1])
SEGAS2  = (BRINE2 - SAT_RBRN[ID:1])/(1.0-SAT_RBRN[ID:1]-SAT_RGAS[ID:1])
SEGAS2  = IFLT0(1.0 - SEGAS2),1.0,SEGAS2)
KRW2    = SEBRINE2**((2+3*PORE_DIS[ID:1])/PORE_DIS[ID:1])
KRG2    = (1.0-SEGAS2)**2*(1.0-SEGAS2**((2 + PORE_DIS[ID:1])/PORE_DIS[ID:1]))
! NOW CALCULATE CONSTANT FOR BRINE AND GAS
CONBR2  = WELLPI * KRW2 / VISCO[ID:5]
CONGAS2 = WELLPI * KRG2 / VISCO[ID:6]
! NOW TAKE LOG BASE 10 OF PARAMETERS NEEDED FOR FBHP EQUATIONS
LOG_B2  = IFEQ0(KRW2,-10,LOG10(CONBR2+1E-24))
LOG_KR2 = IFEQ0(KRW2,10,LOG10((KRG2+1E-24)/(KRW2+1E-24)))
! CALCULATE FBHP's AND SET WITHIN LIMITS
PR2_EQ1 = (EQ1_A+EQ1_B*LOG_B2+EQ1_C*PRESPAN2[ID:1])/ &
      (1.0+EQ1_D*LOG_B2+EQ1_E*PRESPAN2[ID:1])
PR2_EQ1 = IFLT0(8002373.0 - PR2_EQ1,IFLT0(8036090.0 - PR2_EQ1,8036090.0, &
```

```
        PR2_EQ1,8002373.0)
PR2_EQ2 = (EQ2_A+EQ2_B*LOG_KR2+EQ2_C*LOG_KR2**2+EQ2_D*LOG_KR2**3+ &
        EQ2_E*PRESPAN2[ID:1])/(1.0+EQ2_F*LOG_KR2+EQ2_G*LOG_KR2**2+ &
        EQ2_H*PRESPAN2[ID:1])
PR2_EQ2 = IFLT0(225453.0 - PR2_EQ2,IFLT0(8028643.0 - PR2_EQ2,8028643.0, &
        PR2_EQ2),225453.0)
PR2_EQ3 = EXP(EQ3_A+EQ3_B*LOG_KR2+EQ3_C*ABS(LOG_KR2)**0.5+ &
        EQ3_D*EXP(-1.0*ABS(LOG_KR2))+EQ3_E*PRESPAN2[ID:1]**0.5)
PR2_EQ3 = IFLT0(153271.0 - PR2_EQ3,IFLT0(385493.0 - PR2_EQ3,385493.0, &
        PR2_EQ3),153271.0)
! RESET FBHP TO 0 IF NO BRINE BLOWOUT (KRW = 0 OR PRESSURE < 2 MPa)
[redacted]
! IF NO BLOWOUT, SET NUMBER OF BRAGFLO STEPS TO 1, ELSE 1000
NUMSTEP2 = MAKEPROP(IFEQ0(FBHP2,1,1000))
! REGION NO 3 (PANELS 3 & 6)
BRINE3  = IFLT0(BSATPAN3[ID:1]-SAT_RBRN[ID:1],SAT_RBRN[ID:1],BSATPAN3[ID:1])
SEBRINE3 = (BRINE3 - SAT_RBRN[ID:1])/(1.0 - SAT_RBRN[ID:1])
SEGAS3  = (BRINE3 - SAT_RBRN[ID:1])/(1.0-SAT_RBRN[ID:1]-SAT_RGAS[ID:1])
SEGAS3  = IFLT0((1.0 - SEGAS3),1.0,SEGAS3)
KRW3    = SEBRINE3**((2+3*PORE_DIS[ID:1])/PORE_DIS[ID:1])
KRG3    = (1.0-SEGAS3)**2*(1.0-SEGAS3**((2 + PORE_DIS[ID:1])/PORE_DIS[ID:1]))
! NOW CALCULATE CONSTANT FOR BRINE AND GAS
CONBR3  = WELLPI * KRW3 / VISCO[ID:5]
CONGAS3 = WELLPI * KRG3 / VISCO[ID:6]
! NOW TAKE LOG BASE 10 OF PARAMETERS NEEDED FOR FBHP EQUATIONS
LOG_B3  = IFEQ0(KRW3,-10,LOG10((CONBR3+1E-24))
LOG_KR3 = IFEQ0(KRW3,10,LOG10((KRG3+1E-24)/(KRW3+1E-24)))
! CALCULATE FBHP's AND SET WITHIN LIMITS
PR3_EQ1 = (EQ1_A+EQ1_B*LOG_B3+EQ1_C*PRESPAN3[ID:1])/ &
        (1.0+EQ1_D*LOG_B3+EQ1_E*PRESPAN3[ID:1])
PR3_EQ1 = IFLT0(8002373.0 - PR3_EQ1,IFLT0(8036090.0 - PR3_EQ1,8036090.0, &
        PR3_EQ1),8002373.0)
PR3_EQ2 = (EQ2_A+EQ2_B*LOG_KR3+EQ2_C*LOG_KR3**2+EQ2_D*LOG_KR3**3+ &
        EQ2_E*PRESPAN3[ID:1])/(1.0+EQ2_F*LOG_KR3+EQ2_G*LOG_KR3**2+ &
        EQ2_H*PRESPAN3[ID:1])
PR3_EQ2 = IFLT0(225453.0 - PR3_EQ2,IFLT0(8028643.0 - PR3_EQ2,8028643.0, &
        PR3_EQ2),225453.0)
PR3_EQ3 = EXP(EQ3_A+EQ3_B*LOG_KR3+EQ3_C*ABS(LOG_KR3)**0.5+ &
        EQ3_D*EXP(-1.0*ABS(LOG_KR3))+EQ3_E*PRESPAN3[ID:1]**0.5)
PR3_EQ3 = IFLT0(153271.0 - PR3_EQ3,IFLT0(385493.0 - PR3_EQ3,385493.0, &
        PR3_EQ3),153271.0)
! RESET FBHP TO 0 IF NO BRINE BLOWOUT (KRW = 0 OR PRESSURE < 2 MPa)
[redacted]
! IF NO BLOWOUT, SET NUMBER OF BRAGFLO STEPS TO 1, ELSE 1000
NUMSTEP3 = MAKEPROP(IFEQ0(FBHP3,1,1000))
! REGION NO 4 (PANELS 4 & 5)
BRINE4  = IFLT0((BSATPAN4[ID:1]-SAT_RBRN[ID:1]),SAT_RBRN[ID:1],BSATPAN4[ID:1])
SEBRINE4 = (BRINE4 - SAT_RBRN[ID:1])/(1.0 - SAT_RBRN[ID:1])
SEGAS4  = (BRINE4 - SAT_RBRN[ID:1])/(1.0-SAT_RBRN[ID:1]-SAT_RGAS[ID:1])
SEGAS4  = IFLT0((1.0 - SEGAS4),1.0,SEGAS4)
KRW4    = SEBRINE4**((2+3*PORE_DIS[ID:1])/PORE_DIS[ID:1])
KRG4    = (1.0-SEGAS4)**2*(1.0-SEGAS4**((2 + PORE_DIS[ID:1])/PORE_DIS[ID:1]))
! NOW CALCULATE CONSTANT FOR BRINE AND GAS
CONBR4  = WELLPI * KRW4 / VISCO[ID:5]
CONGAS4 = WELLPI * KRG4 / VISCO[ID:6]
! NOW TAKE LOG BASE 10 OF PARAMETERS NEEDED FOR FBHP EQUATIONS
LOG_B4  = IFEQ0(KRW4,-10,LOG10(CONBR4+1E-24))
LOG_KR4 = IFEQ0(KRW4,10,LOG10((KRG4+1E-24)/(KRW4+1E-24)))
! CALCULATE FBHP's AND SET WITHIN LIMITS
PR4_EQ1 = (EQ1_A+EQ1_B*LOG_B4+EQ1_C*PRESPAN4[ID:1])/ &
        (1.0+EQ1_D*LOG_B4+EQ1_E*PRESPAN4[ID:1])
PR4_EQ1 = IFLT0(8002373.0 - PR4_EQ1,IFLT0(8036090.0 - PR4_EQ1,8036090.0, &
        PR4_EQ1),8002373.0)
PR4_EQ2 = (EQ2_A+EQ2_B*LOG_KR4+EQ2_C*LOG_KR4**2+EQ2_D*LOG_KR4**3+ &
        EQ2_E*PRESPAN4[ID:1])/(1.0+EQ2_F*LOG_KR4+EQ2_G*LOG_KR4**2+ &
        EQ2_H*PRESPAN4[ID:1])
PR4_EQ2 = IFLT0(225453.0 - PR4_EQ2,IFLT0(8028643.0 - PR4_EQ2,8028643.0, &
```

```
        PR4_EQ3),225453.0)
PR4_EQ3 = EXP(EQ3_A+EQ3_B*LOG_KR4+EQ3_C*ABS(LOG_KR4)**0.5+ &
        EQ3_D*EXP(-1.0*ABS(LOG_KR4))-EQ3_E*PRESPAN4[ID:*]**0.5)
PR4_EQ3 = IFLT0(153271.0 - PR4_EQ3,IFLT0(385493.0 - PR4_EQ3,385493.0, &
        PR4_EQ3),153271.0)
!RESET FBHP TO 0 IF NO BRINE BLOWOUT (KRW = 0 OR PRESSURE < 2 MPa)
[illegible]
!IF NO BLOWOUT, SET NUMBER OF BRAGFLO STEPS TO 1, ELSE 1000
NUMSTEP4 = MAKEPROP(IFEQ0(FBHP4,1.1000))
DELETE BRINE1, BRINE2, BRINE3, BRINE4
!==========================================================================
!--------------------------------------------------------------------------
!SET UP BOUNDARY CONDITIONS FOR PREVIOUS INTRUSIONS HERE
!--------------------------------------------------------------------------
! SET UP NEEDED CONSTANTS (NOTE: BOREHOLE LENGTH FROM PANEL TO CASTILE B.P.
! IS 247 METERS -- USED IN CON_SAND & CON_CREP)
! MODIFICATIONS MADE 5/30/96
LEN_BC   = MAKEPROP(247.0)
DRAIN_BC = MAKEPROP(SQRT(DEL_X[E:15]*DEL_Y[E:15]/PI[E:8]))
WELPI_BC = PERM_X[ID:*] * HEIGHT[ID:1] / (LOG(DRAIN_BC/WELLRAD) + 0.0 - 0.5)
RHO_G_H  = MAKEPROP(DNSFLUID[ID:5]*GRAVACC[ID:5]*LEN_BC)
CON_OPEN = MAKEPROP(PRM_CAST*THCK_CAS[ID:5]*(LOG(DRAIN_BC/WELLRAD)-0.5)) &
        / (PERM_X[ID:1]*HEIGHT[ID:1]*(LOG(RE_CAST[ID:5]/WELLRAD)-0.5))
CON_SAND = MAKEPROP((PRM_SAND*PI[ID:8]*WELLRAD*WELLRAD* &
        (LOG(DRAIN_BC/WELLRAD)-0.5)) / (PERM_X[ID:*]*HEIGHT[ID:1]*LEN_BC))
CON_CREP = MAKEPROP((PRM_CREP*PI[ID:8]*WELLRAD*WELLRAD* &
        (LOG(DRAIN_BC/WELLRAD)-0.5)) / (PERM_X[ID:1]*HEIGHT[ID:1]*LEN_BC))
! SOLVE FOR OPEN BOREHOLE TO CASTILE B.C. (WITHIN 200 YEARS AFTER FIRST INTR.)
! USE FBHP4 SINCE BOUNDARY CONDITION WELL IS ASSUMED TO BE IN PANEL 5 (DOWN-
! DIP) FOR ALL SUBSEQUENT INTRUSIONS
BHP_OPEN = (FBHP4+CON_OPEN*(CAST_RE-RHO_G_H))/(1.0+CON_OPEN)
! SOLVE FOR SAND-FILLED BH CONDITION (200 TO 1200 YEARS AFTER 1ST INTRUSION)
BHP_SAND = (FBHP4+CON_SAND*(CAST_WB-RHO_G_H))/(1.0+CON_SAND)
! SOLVE FOR CREEP CLOSED BH CONDITION (> 200 YEARS AFTER 1ST INTRUSION)
BHP_CREP = (FBHP4+CON_CREP*(CAST_WB-RHO_G_H))/(1.0+CON_CREP)
ASSIGN ABANDONED BH PRESSURE BASED ON INTRUSION TIME
PREV_TME = MAKEPROP(1000.0)
DELT_TME = INTR_TME/YRSEC[ID:8] - PREV_TME
BHP_ABAN = IFGT0(DELT_TME - 200.1,IFGT0(DELT_TME - 1200.1,BHP_CREP,BHP_SAND), &
        BHP_OPEN)
--------------------------------------------------------------------------
==========================================================================
--------------------------------------------------------------------------
!--------------------------------------------------------------------------
!CHAPTER 3.  COMPUTE DIP IN REPOSITORY
!--------------------------------------------------------------------------
!--------------------------------------------------------------------------
!--------------------------------------------------------------------------
!==========================================================================
LIMIT ELEMENT OFF
!COMPUTE THE GRID BLOCK ELEVATIONS ACCOUNTING FOR 1 DEGREE DIP IN SALADO
!DEFINE GRID BLOCK ELEVATIONS DUE TO DIP
! USE ELEVATION OF SHAFT AT MID-REPOSITORY
ZORIGIN  = 382.671
YORIGIN  = 1000.0
ELEVN    = MAKENODE(COS(THETA1[ID:1])*(Z-ZORIGIN) &
        - SIN(THETA1[ID:1])*(Y-YORIGIN))
ELEVE    = NODEELE(ELEVN) + ZORIGIN
COMPUTE GRID BLOCK POTENTIAL ASSUMING BRINE IS INCOMPRESSIBLE (APPROXIMATELY)
POTE     = PRESEL(DNSFLUID[ID:5]*GRAVACC[ID:5]) + ELEVE
!
! NOW SET GRID THICKNESS FOR ALL ELEMENTS TO CRUSHED PANEL HEIGHT
THICK    = MAKEATTR(HEIGHT[ID:1])
!
DELETE ELEVN, YORIGIN, ZORIGIN
EXIT
```

8.4a. Solubility of Plutonium as Expected Under Conditions in the WIPP Repository (V.M. Oversby, 1997)

THE SOLUBILITY OF PLUTONIUM UNDER CONDITIONS EXPECTED IN THE WIPP REPOSITORY

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October 31, 1997

This report was prepared for the Environmental Evaluation Group, Albuquerque, New Mexico. Every attempt has been made to make the report as complete as possible within the time available for its preparation; however, the author cannot guarantee that all relevant work is included in the discussion. The author is not responsible for the subsequent use of information and opinions contained in this report.

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Appendix A: Review of Chemical Conditions Model

Appendix B: Review of Novak and Moore solubility calculations

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Appendix D: Summary of relevant articles used in preparation of this report

Introduction

The Waste Isolation Pilot Plant (WIPP) is located in southeastern New Mexico. It is designed to be a final disposal site for transuranic wastes (TRU) produced from defense-related activities in the USA. The repository site is 655 meter below ground surface in a bedded salt formation (Salado Fm.) of Permian age. The planned inventory of wastes includes 850,000 canisters of relatively low activity, contact-handled, TRU, and about 7500 canisters of higher activity, remote-handled, TRU (Chaturvedi et al., 1997). The remote handled TRU canisters will contain about 15% of the total activity in the repository and, thus, can be expected to contain the highest concentrations of Pu and Am, the main actinide constituents in the waste.

The Environmental Evaluation Group (EEG) conducts independent technical evaluations of the impact of the WIPP project on public health and on the environment. In October, 1996, the US Department of Energy submitted their Compliance Certification Application (CCA) to the US Environmental Protection Agency. During their independent review of the CCA, EEG identified a number of concerns (Chaturvedi et al., 1997). They determined that an additional review of the factors that influence the solubility of plutonium under the conditions that will pertain at WIPP would assist them in their evaluation of the CCA. The work covered by this report was initiated in response to EEG's request. Some specific questions were proposed as important to their evaluation:

Is there enough experimental evidence to rigorously conclude that plutonium will be in the Pu(III) and Pu(IV) states in the repository environment, rather than the potentially more soluble Pu(V) state?

Is there something that has not been considered in the CCA that might result in higher Pu solubility?

What is the effect on the solubility of Pu of the compounds formed by the MgO backfill interactions with brine?

What, specifically, are the scientific shortcomings of the DOE arguments in the CCA and what needs to be done to address these shortcomings in terms of calculations and experimental work?

This report attempts to answer those questions by discussing the most likely redox state for Pu based on published experimental work, the effect of brine composition on solubility of actinides in the (IV) valence state, the influence of solution species formed by reaction of the MgO backfill on An(IV) solubility, and the influence of other potential ligands present in the waste itself on actinide solubility. An analysis of the calculational path used as a result of the scenario adopted for the calculations suggests that there are means of forming significant

amounts of soluble Pu as citrate complexes or as complexes with the chemical degradation products of cellulose. A new scenario for calculations to test the sensitivity of the results to pathway is proposed. In addition, some inconsistencies in the calculated results reported in the CCA are discussed and issues are identified that need resolution.

Factors controlling solubility

There are four major factors that will determine the effective solubility of plutonium in the WIPP environment. These are (1) the redox conditions, (2) the brine composition, (3) the availability of ligands through degradation of the waste, and (4) the effects of slow kinetics of reaction due to lack of lability of species (i.e., persistence of metastable species). The brine composition, itself, will be affected by the persistence of metastable reaction products, especially those formed by the MgO backfill. Each of these factors is discussed in the sections that follow.

Redox state

Plutonium can exist in several oxidation states in natural waters depending on the availabilty of oxygen and complexing agents. Under normal atmospheric carbon dioxide pressure (p_{CO_2}= 3.2 x10^{-4} atm), but in the absence of other complexing ligands, the expected oxidation states of Pu are PuO_2^{2+}, PuO_2^{+}, and Pu^{4+} under oxic conditions and Pu^{4+} and Pu^{3+} under reducing conditions. PuO_2^{+} disproportionates into PuO_2^{2+} and Pu^{4+}, but the rate of the reaction depends on the 4th power of the H^{+} concentration and on the square of the PuO_2^{+} concentration so that at low concentrations of Pu in neutral solutions the reaction rate is negligible (Choppin, 1990). This suggests that PuO_2^{+}, once present, may persist outside of its stability field because of slow reaction kinetics.

During the operational period of the WIPP repository, oxygen will be present in the storage rooms. This oxygen will be trapped in the salt formation after repository closure and will be available to react with the waste materials and their containers. Void space in the repository will be reduced by salt creep, and the encroaching salt will eventually crush the waste drums. The residual oxygen can react with the drum material or with the waste itself, producing soluble corrosion products, such as Fe^{2+}, and possibly PuO_2^{+}. Radiolysis of water inside the waste drums can also result in oxidation of plutonium to produce PuO_2^{+}. If there are organic complexing agents present, the PuO_2^{+} will be rapidly reduced to Pu(IV) and stabilized in solution as soluble complex ions (AlMahamid et al., 1996). It is reasonable to conclude that PuO_2^{+} will not be able to coexist with organic ligands for any significant period of time, and that solubility calculations should consider either transient presence of PuO_2^{+} or presence of Pu(IV) with or without organic ligands.

Weiner et al. (1996) discuss the possible oxidation states of Pu under WIPP conditions. They conclude that Pu(IV) is expected to be the stable state, but include Pu(III) based on observations by Felmy et al. (1989). These experiments used Pu(III) maintained in that redox state by adding Fe powder to the solutions. The solubility of $Pu(OH)_3$ was measured in dilute solutions and brines. The redox state of Pu was verified by using chemical extraction methods; however, the method used measured Pu(III) + Pu(IV), so there is not positive identification of Pu(III) content. At pH 9 and above, the concentration of Pu was below detection limits (Felmy et al., 1989). This would suggest that Pu(III) needs to be considered up to pH 9 in modelling calculations if metallic Fe is present, which it will be in the form of WIPP disposal drums. Above pH 9, the upper limit for Pu(III) is set by the detection limit in the Felmy et al. (1989) experiments as 10^{-9} M.

Pu(V) has been observed in a number of experiments conducted in brines. Weiner et al. (1996) discuss some of these results in Appendix A to their report and conclude that Pu(V) will not be important because it disappears with time. This conclusion would be perfectly valid for cases where release from the repository is assumed to occur through flow mechanisms that take long periods of time to reach the accessible environment; however, for human intrusion scenarios where the brine may reach the surface directly via a borehole, it is probably more valid to include transient species that have been shown to have long lifetimes. Since any Pu(V) is likely to react with dissolved Fe(II), the steady-state amount of Pu(V) should be small and not lead to a large increase in calculated total mobile Pu species in the repository.

Brine composition

Brine composition can affect solubility in two principal ways. The first is through the effect of ionic strength, which will generally lead to higher actinide solubilities for high ionic strength. Most of the effect of ionic strength increase is seen by the time a solution concentration of 2M NaCl is reached, with little change in effective activity coefficients expected as ionic strength increases further. The second means of affecting solubility is through the formation of complex ions. Carbonate ion and hydroxyl ion are the main inorganic ligands that will cause increased solubility of Pu in the WIPP brines. Novak and Moore (1996) calculated that sulfate complexes are important for some cases; see Appendix B for discussion.

In this section we will consider experimental evidence that can be used to evaluate the expected effects of brine composition on the solubility of Pu. The conclusions that can be drawn from the experimental evidence will be useful in assessing the validity of model calculations. Most measurements using Pu have

been done with oxygen present in the system, either with normal atmospheric composition together with carbon dioxide, or under argon glove box conditions with 18 to 30 ppm oxygen in the gas. While the latter amount may seem very small, it is enough to provide for oxidation of Pu from Pu(IV) to Pu(V) in solution. Once Pu(V) is formed, it may be long-lived if there is not an active reductant present.

DePablo et al. (1995) conducted experiments using unirradiated crystalline UO_2 (s) in synthetic brines. Both oxidizing and reducing conditions were studied; reducing conditions were maintained using a hydrogen flux and a Pd catalyst. Carbon dioxide was not present in the experiments. Brine compositions (molal concentrations) were

Species	NaCl-brine	$MgCl_2$-brine
Na+	6.036	0.48
K+	0.037	0.57
Mg^{2+}	0.018	4.21
Ca^{2+}	0.021	0
Cl-	6.036	8.84
$SO_4^{=}$	0.058	0.32
Ionic Str.	6.25	14.00
pH	7.7	4.7

The UO_2 (s) had an initial surface condition that was very oxidized, $UO_{2.7}$ as measured by XPS. This led to an initial rapid dissolution of the oxidized surface even when the solution was maintained with reducing conditions. The solution concentrations in both brines gradually decreased and settled after 20 to 25 days at steady-state values of 2.8×10^{-7} mol/kg in the NaCl brine and 3.1×10^{-7} mol/kg in the $MgCl_2$-brine. At the end of the experiments the Eh was measured to be 0 to 60 mV (compatible with the stability of UO_2) and the surface of the dissolving solid was measured to have a composition of $UO_{2.1}$ as measured by XPS. A model calculation was done using the PHRQPITZ code (the PHREEQE equilibrium code with Pitzer parameters added) and gave quite good agreement of the concentrations predicted by the calculations with those measured in the experiments. The calculated concentrations for zero ionic strength solutions were about a factor of 3 lower than those calculated for the brines.

The experiments of DePablo et al. (1995) show that for UO_2 (s), there is very little variation in solubility that can be attributed to the combined effects of increasing the brine ionic strength by a factor of more than 2 and simultaneously increasing sulfate by a factor of 5. In addition, changing the dominant cation from Na+ to Mg^{2+} did not seem to have a large effect. From the modelling calculations, the effect of high ionic strength on solubility of the UO_2 (s) was limited to an increase of a factor of 3.

The effect of carbonate ion on the solubility of Th was measured in solubility and speciation experiments by Östhols et al. (1994). They measured the solubility of a freshly precipitated thorium oxide/hydroxide with low crystallinity as a function of pH with an atmosphere of 10% carbon dioxide. They analyzed the data and deduced speciation with $Th(OH)_3CO_3^-$ as the dominant species from pH 5 to slightly greater than 7 and with $Th(CO_3)_5^{6-}$ beginning to occur at pH just under 7 and taking over from the hydroxycarbonate complex after pH7.4. The total solubility of Th(IV) at pH 7 was 10^{-5} M. Östhols et al. (1994) also calculated stability constants for these species and the solubility product for amorphous ThO_2 for their experimental solution conditions of 0.5 M $NaClO_4$ and for the extrapolated values at zero ionic strength.

Rai et al. (1995) measured the solubility of U(IV) and Th(IV) freshly precipitated oxides under inert atmosphere conditions as a function of carbonate/bicarbonate concentration in solution. For the U experiments, Fe powder was added to the solutions to ensure that no U(VI) formed. At low carbonate concentration, the uranium solubility was about 10^{-8} M. (This is about a factor of 10 lower than the value calculated by DePablo et al. (1995) for low ionic strength and no carbonate. See above). Two data points at a carbonate content of 0.1 molal also had a solubility of 10^{-8} M for Th(IV). The Th solubility increased to be 10^{-5} M at a sodium carbonate content of about 0.3 m, which is similar to the carbonate content that one would expect with a partial pressure of CO_2 of 0.1 atmosphere. For U, a carbonate concentration about a factor of 4 higher was needed to achieve the same solubility of 10^{-5} M. It should be noted that for both U and Th, the concentration of carbonate had to exceed 0.1 molal before a dramatic increase in solubility was observed.

From the results presented above, we may derive two important conclusions concerning the effect of brine composition on Pu(IV) solubility.

(1) The detailed composition of the brine will probably not be important in determining Pu(IV) solubility in the absence of organic ligands and at low carbonate concentrations.

(2) Carbonate ion concentrations will only have a large effect on Pu(IV) solubility if they are above 0.1 molal.

These conclusions should be valuable in assessing the reliability of modelling calculations for WIPP long-term performance predictions.

Experimental studies of Th and Pu solubility were supported by the WIPP Project in FY 1997 to determine what the effects of the MgO backfill would be on solubility and to validate the model assumption that Th data could be used to model Pu behavior. Preliminary results are available in the annual report for

FY97 (Rai et al., 1997). All experiments were done with nitrogen atmosphere. The concentrations of Th in the presence of MgO after 5 days exposure in two brines was between $10^{-7.3}$ and 10^{-8} M, while with hydromagnesite present the solubility was much higher (10^{-5} and $10^{-6.5}$ M). The solubility of amorphous plutonium dioxide in the brines in the presence of Fe powder was measured to be $10^{-6.5}$ M at pH 7.5 and $10^{-7.5}$ M at pH 8. Solubility changes when hydromagnesite was present were +/- a factor of 10 with increase in pH of 0.5 units in both brines. The presence of $Na_2S_2O_4$, a strong reducing agent, resulted in higher Pu solubility in all cases. This was interpreted to indicate the possible presence of Pu(III) species that were more soluble than the Pu(IV) species. Pu(V) was also considered as a possible species to explain some of the higher-than-expected concentrations found.

The solubilities for Pu in the absence of carbonate found by Rai et al. (1997) are quite similar to those found by DePablo et al. (1995) for UO_2. Solubilities for Pu and Th depend to a large degree on the "age" of the solid and its degree of crystallinity. This factor is less important for UO_2. Since the preliminary results for Pu in brines seem to be consistent with those for UO_2 solubility in brines, the UO_2 solubility data measured in brines would seem to represent a sounder basis for performance prediction than those calculated from a model based on Th with Pitzer parameters. This conclusion is strengthened by the fact that the solubilities of Th measured by Rai et al. (1997) in the presence of hydromagnesite are much higher than those calculated by Novak (1997 - see discussion in the next section and in Appendix A).

Phases controlling brine composition

The brine compositions assumed for the WIPP performance assessment conditions are either the Salado brine or the Castile brine or a mixture of these brines. To assess the solubility of actinides in the brines, Novak and Moore (1996) further assumed that the brines became saturated with halite and anhydrite, the major minerals in the associated salt formations. The effective pH of the brines under these conditions was about 5.6 to 5.8, which was thought to be lower than desirable. Actinide solubility goes down with increasing pH, at least until pH of 11 or 12 is reached; for this reason, addition of a backfill material was considered to buffer the pH at about 10 and to absorb CO_2 gas that might be generated by microbial action. (See Appendix A for a more detailed discussion of this issue.)

The MgO from the backfill was thought to produce brucite and magnesite as its stable reaction products and that these materials would be those responsible for conditioning the brine chemistry. During experiments with alteration of MgO with the brines, it was found that other phases formed. These phases are (or, at least, may be) metastable with respect to magnesite and brucite; however, they

may persist for extended periods of time under the WIPP disposal conditions. The draft report on the MgO alteration shows evidence for the formation of reaction products that are predominantly nesquehonite ($MgCO_3 \cdot 3H_2O$) with the later appearance of a phase that could not be positively identified, but was tentatively identified as $MgCO_3 \cdot 3H_2O \cdot MgCl(OH)$ (PDF7-278) (no name given). The chemistry of this phase is quite different from that of hydromagnesite [$(MgCO_3)_4 \cdot Mg(OH)_2 \cdot 4H_2O$]. Despite this, the draft report claims on page 30 that "we observed that hydromagnesite, with a loose platy habit, is the favored metastable phase in our experiments, rather than nesquehonite" (Sandia, 1997).

The identity of the Mg-carbonate phase that forms with alteration of MgO is important because this phase will control the carbonate and bicarbonate concentrations in the brines. High concentrations of carbonate in the brines can increase the solubility of Pu via complex ion formation with carbonate. Calculations in the Sandia, 1997, draft manuscript reported only the effect of hydromagnesite on expected actinide solubility. Hydromagnesite, however, was never identified in the experiments described in the draft manuscript. In other materials available from Sandia, it was seen that calculations were also done with nesquehonite (C. F. Novak memo to R. Vann Bynum dated 21 April 1997, "Calculation of actinide solubilities in WIPP SPC and ERDA6 brines under MgO backfill scenarios containing either nesquehonite or hydromagnesite as the Mg-CO_3 solubility-limiting phase.") Since the results with nesquehonite were quite different for the (IV) actinides, they are reproduced here together with the results reported in the draft manuscript.

Conditions	+4 act., molar Salado (SPC)	+4 act., molar Castile	log fugacity (CO_2)
CCA calc.	4 E-6	6 E-9	-6.9
No backfill	5 E-4	7 E-5	0 to 2
5424 hydromag.	1 E-8	4 E-8	-5.5
4323 hydromag.	2 E-8	5 E-8	-5.39
Nesquehonite	6.3 E-4	1.0 E-3	-3.8

Note that with nesquehonite present, the solubility of the +4 actinides is calculated to be higher than it is with no backfill present. pcH for Salado conditions is calculated to be 9.4 and for Castile, 9.9.

The predictions of solubility in the presence of hydromagnesite are lower than the experimental results for Th discussed above, but are similar to the results found for Pu in the presence of hydromagnesite and Fe. No experimental data on the solubility of Th or Pu in the presence of nesquehonite is yet available.

Complex ion formation

Discussions in the previous sections have shown that the inorganic anions most likely to affect actinide (IV) solubility through complex ion formation under WIPP brine conditions are hydroxide and carbonate ions. Sulfate ion has been shown in experiments with U(IV) to have no significant effect on overall solubility over the range of variation in sulfate content expected for the WIPP.

The remaining possibility for complex ion formation comes from the waste materials, themselves. Citrate, which forms a very stable complex ion with Th, is present in large amounts in the waste inventory. The solubility calculations for the actinides in brines with and without MgO are discussed in Appendix B. These calculations assume homogeneous equilibria, which for actinides in the absence of complexing ligands from the waste is probably an adequate estimate. For the case where organics are present, the organics are also treated by SOTERM as if they were homogeneously dissolved in 29,841 m^3 of brine.

To model the behavior of Pu with citrate, we must consider heterogeneous equilibria for organic complexation with the actinides. The main difficulty arises because the Pu in the waste is probably located in the same drums as the citrate, which is the dominant organic ligand. This is because these wastes arise from chemical separations of Pu and are not the type of waste described in the general descriptions of TRU waste as contaminated equipment, clothing, etc. To get an accurate estimate of the effect of organic ligands on Pu solubility, one must calculate the concentration of Pu as citrate complex inside a waste drum that has been breached, but can still provide a hindrance to mixing of the brine inside the drum with a larger pool of brine outside the drum. This will give a high concentration of Pu in solution as the citrate complex. Other ions will not compete with Pu sufficiently to prevent complex formation because the stability for (IV) actinide complexation - as shown by the stability constant for Th(IV) on p. 39 of the SOTERM appendix- is orders of magnitude larger than that for other ion complexes with citrate.

Another possible ligand for increasing Pu(IV) solubility comes from the degradation of cellulose. Work in England has shown that degradation of cellulose can occur both through chemical processes at high pH and by radiation effects. The degradation products have been shown to increase the solubility of plutonium dramatically (Cross et al., 1989; Greenfield et al., 1992).

To obtain a more accurate estimate of the effect of citrate and cellulose degradation products on Pu solubility in the event of human intrusion, calculations that use Pu complexes formed inside a waste drum and model the mixing of that relatively concentrated brine with the average repository brines must be done, taking into account the time scales for mixing and the possibility that the intrusion event may release some brine from waste drums that has not

had an opportunity to mix with the average repository brines. The development of an appropriate scenario is discussed further in the next section.

The conclusion given in the CCA SOTERM appendix that EDTA complexes will not increase actinide solubility is probably correct, since the amount of EDTA is small and the Ni and Fe complexes have stability constants that are similar to those for the actinides. It is not shown, and is probably not true, that the more abundant citrate inventory will not increase actinide solubility, especially for Pu.

Scenarios for dissolution of plutonium

Analyses of the long-term performance of the WIPP repository have shown that the only likely cause for significant releases of radioactivity would come as the result of human intrusion into the repository. One pathway for release involves drilling into the repository level, flooding of the repository with brine, and then flow of the brine through the overlying Culebra dolomite aquifer. This pathway would require considerable time before radionuclides would reach the accessible environment and, in this case, the model of homogeneous brine compositions averaged over the whole repository at the time of the release is probably appropriate. For this scenario, the large volume of brine (29,841 m^3) discussed in the SOTERM calculations is probably needed.

Another human intrusion release scenario involves drilling through the repository and reaching the underlying Castile formation, in which there are pockets of pressurized brine. If a pocket of pressurized brine were to be encountered during drilling, it is possible that it might rise up the drill hole, through the repository, and up to the surface very rapidly. The only waste encountered in this case might be that in a few drums that were in the immediate path of the drill hole. These drums might contain low Pu concentrations and little or no citrate ions or cellulose degradation products, or they might contain the maximum allowed Pu concentration and sufficient citrate or cellulose degradation products to fully complex the Pu. The brine composition would be determined by the local, internal environment in the waste drum, rather than by the grand average of the repository.

As an illustration, the volume of brine that would be associated with this release scenario may be estimated by assuming a small diameter exploratory drill hole of about 0.01 m^2 area (a bit over 10 cm diameter drill core) and a hole depth of about 900 m. The volume to fill this hole would be 9 m^3. A reasonable volume for the release of brine before it was capped off would be about 100 m^3, or about 10,000 liters of brine. This brine could be assumed to contain the contents of two waste drums, each containing 10g Pu and 10 moles of citrate. The brine inside a crushed waste drum with these inventory amounts could be modelled assuming the drum material was actively corroding to provide Fe(II) at equilibium

concentration with appropriate citrate complexation as well as the Pu(IV) citrate complex. The amount of such brine could be quite small (< 1 L) or moderate (10-30 L). This assumed concentrated brine could then be intercepted by the drill hole and the brine rising from the Castile formation, providing dilution of the concentrated brine, but probably not a major change in speciation. The appropriately diluted brine would then be the material that would be assumed to reach the surface.

The construction of the CCDF for assessment of compliance with 40 CFR 191 would then involve a selection of model realizations with the release from a pressurized brine and a probability distribution of whether the drums that might be intersected by the drill hole were those with high Pu or with low Pu. This method for handling heterogeneous waste distributions and heterogeneous equilibria in the respository would be rather simple to implement, at least on the level of exploratory calculations.

Suggestions for future work

Experimental work

Performance predictions for WIPP are currently done using equilibrium thermodynamic modelling of brine chemistry and with Th as the representative of the (IV) actinides. The calculated Th concentrations have internal inconsistencies (described in Appendix B) with respect to both the total solubility and the speciation of Th under conditions with similar brine composition. Experimental work on systems that contain Pu itself, rather than Th as a surrogate, have been started and should be continued. Results from these and future experiments should be compared with existing experimental results on U(IV) compounds.

If MgO will be used in the repository to control pH and to attempt to control carbon dioxide fugacity, experiments using brines with nesquehonite and brines with hydromagnesite should be conducted. Carbon speciation should be measured in these experiments as a function of reaction progress, as well as the evolution of the brine chemistry. These parameters will be needed if the longer term solubility of Pu in these systems is to be modelled. Redox state of Pu in solutions should be measured; methods that might be used are direct spectroscopy at relatively high concentrations and valence-specific solution extraction methods at low concentrations.

The stability constant for formation of citrate complex ions with Pu(IV) should be determined. The sensitivity, if any, of the value of the stability constant on brine composition should be evaluated. Experiments in systems that contain abundant citrate and Pu together with metallic iron and iron corrosion products formed under WIPP-relevant conditions should be done to evaluate the ability of

Fe(II) in solution to compete for citrate ion in complexes. Sequential dilution of brine with Pu-citrate complexes in solution by adding samples of that brine to solutions containing brine with metal and corrosion products should be conducted to provide validation of the calculations suggested below.

Thermodynamic properties and models

Use of Th to model the behavior of all actinide (IV) elements requires that (1) the chemistry of all actinide (IV) elements in brines is closely similar and (2) that the data base for species formation and solubility as well as for activity coefficients of Th(IV) species in brines is sufficiently well known. The differences found between Th concentrations calculated by Novak and Moore (1996) and those measured by Rai et al. (1997), and the differences between the calculations for Th and the experimental data for U(IV) indicate that one or both of those requirements is not met.

Several work areas need to be undertaken in order to improve the reliability of the calculations. First, the calculations should be done using data for Pu and the values for solubility and complex ion formation contained in the peer-reviewed data compilation prepared by OECD/NEA. This work has been underway for about 10 years and has had many man-years of effort from the members of the specialist review committee. Even though small changes may be made between the current draft document and its final publication, it is likely that a significant improvement in the consistency of the calculated results and the findings in solubility and speciation experiments could be found if this source were used for the basic thermodynamic data.

DePablo et al. (1995) reported calculations of U(IV) solubility in brines using an equilibrium thermodynamic modelling code developed by the US Geological Survey. It would be instructive to compare the results of calculations of Th solubility using the same code and data base to the reported results of Novak and Moore (1996). In particular, a comparison of the calculated activity coefficients for dissolved species using each code would be useful. For highly charged species such as $Th(CO_3)_5^{6-}$ it is extremely difficult to estimate the activity coefficient using calculational methods. Comparison of the species included in the calculations as well as the results of speciation and solubility predictions for Th would be interesting and might give an insight into the uncertainties that exist in the calculation of solubilties for these systems.

A sensitivity analysis should be conducted to determine the effects of uncertainties in both the solubility measurements and stability constant determinations as well as the estimation of Pitzer parameters on the final calculated solubility. This would involve a “Monte Carlo” type of sampling procedure that selects a value within the range of +/- appropriate to the solubility

product for a given compound and then values for each of the complex ion stability constants within their range of data uncertainties. A similar process would be used for the calculation of the Pitzer coefficients. Results of 30 to 40 calculations using this type of sampling method should give a reasonable indication of the real range of combined uncertainty in the calculations.

Release scenario calculation

A scenario for release via human intrusion that involves release of brine with concentrated Pu-citrate content via mixing with a larger volume of brine and transport through the Culebra aquifer should be done. This calculation can be done as a simple, sequential dilution model in which 10 liters of initial Pu-citrate-containing brine is mixed with 10 liters of Salado brine equilibrated with appropriate minerals and Fe(II) corrosion products. The second calculation would then mix this 20 liter volume of brine with another 20 liters of Salado brine. Ten steps of mixing would give a brine volume of 10,000 liters. The pattern of speciation changes in Pu and the overall Pu solubility calculated could then be compared to the sequential dilution experiments discussed above. If the results agree, a level of validation is achieved for the calculations. If the results disagree, insight into requirements to improve the data base and calculational methods should be gained.

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Appendix A

Review of "Chemical Conditions Model: Results of the MgO Backfill Efficacy Investigations", Sandia National Laboratories (no author names), April 23, 1997, Draft.

This paper describes some experiments in which MgO in the form of small pellets (2 to 4 mm in size) or MgO "fines" (0.5 to 1.0 mm) were reacted with Castile and Salado brines (presumably synthetic, but the text does not address this point).

The experiments produced reaction products that are predominantly nesquehonite ($MgCO_3 \cdot 3H_2O$) with the later appearance of a phase that could not be positively identified, but was tentatively identified as $MgCO_3 \cdot 3H_2O \cdot MgCl(OH)$ (PDF7-278) (no name given). The chemistry of this phase is quite different from that of hydromagnesite [$(MgCO_3)_4 \cdot Mg(OH)_2 \cdot 4H_2O$]. Despite this, the paper claims on page 30 that "we observed that hydromagnesite, with a loose platy habit, is the favored metastable phase in our experiments, rather than nesquehonite." (See comment 4 below for a more detailed discussion.)

The concentration of an element in solution is the sum of all of the species concentrations in which that element is present. Usually, one species predominates as the most soluble for a given element under a given set of conditions, and the concentration of that species is determined by the solubility of the most soluble solid phase that results in that species being formed. That phase will continue to control the solubility so long as it is present in the system, even if other, more stable, phases are also present. For the set of possible conditions with MgO backfill present, and assuming the absence of ligands for the actinides that result in even higher solubility species, the phase that results in highest (IV) actinide solubility is nesquehonite. So long as nesquehonite may be present in the WIPP repository, the solubility of (IV) actinides must be modelled using calculations that include it as a member of the phase assemblage. Since the production of CO_2 is assumed to persist over periods of thousands of years, and since nesquehonite is observed to be formed early in the sequence of phases formed when carbon dioxide reacts with MgO in the backfill, we must assume that nequehonite will be present over thousands of years, even if it can be shown that the conversion of a particular amount of nesquehonite to a less soluble phase occurs over a time scale of a few hundred years.

As shown in item 7 of the detailed comments, the solubility of (IV) actinides with nesquehonite present is even higher than that calculated for the case with no MgO present. If nesquehonite must be considered as present for most of the performance period of the repository, it would seem that the addition of MgO does not enhance the performance of the repository, but rather adds to the uncertainties to be considered, if our attention is limited to the case of the (IV) actinides. For the (III) and (V) actinides, the MgO does seem to reduce the solubility considerably, even with nesquehonite present (data in Novak,

21 April 1997 memo). Since Pu is the dominant actinide, and since (IV) is the most likely oxidation state for Pu under WIPP conditions, there might be good cause to reconsider the inclusion of MgO as backfill in the repository.

Detailed comments:

1. p. 5, bottom. "There is evidence in the literature that MgO can exhibit a bactericidal characteristic. However, there [*sic*] studies supporting this assertion were performed under conditions far removed from those expected in the WIPP and no direct correlation could be drawn from the literature conditions to those expected at WIPP. Therefore, no beneficial credit was taken for the potential bactericidal effect of MgO and the microbial gas generation rates were left unchanged."

> The microbes are assumed to decompose cellulose to CO_2 and methane. If the microbes are not present, chemical degradation of cellulose at high pH is likely to result in compounds that can form complexes with actinide elements and increase their solubility. See, for example, the paper by J. E. Cross, F. T. Ewart, and B. F. Greenfield in Mat. Res. Soc. Symp. Proc. Vol. 127, W. Lutze and R. Ewing, eds., pp. 715-722, 1989. Absence of microbes may provide negative as well as positive contributions to the potential performance of the repository.

2. p.2, middle. "Arrhenius plots assembled with laboratory synthesis of magnesite at 60°C for 7 years and at higher temperatures suggest that magnesite will form within several hundred years in the WIPP." And, p. 19, "Nesquehonite is also temperature sensitive, but is stable well within the temperature range anticipated at the WIPP; it will convert to hydromagnesite above about 60°C (Lippmann, 1973)." The extrapolations using Arrhenius plots are discussed in more detail on pages 35-6.

> The use of data obtained outside of the field of temperature stability of a phase to estimate kinetics of converstion of that phase to another phase is invalid. In addition, the phase into which nesquehonite converts is stated on p. 19 to be hydromagnesite, not magnesite.

3. p. 13. The pH curves vs reaction time show Salado brine with both the "coarse" and "fine" MgO with pH about 6, and the Castile samples to have pH about 6.8. In the figure caption, it is claimed that "The difference between the Salado and Castile curves reflects differences in the mineralogy of the coatings formed in these two brines."

> This statement seems to conflict with the reaction product discussion in the manuscript on page 20 ff.

4. p. 30. "As describe [*sic*] in Section 4, we observed that hydromagnesite, with a loose platy habit, is the favored metastable phase in our experiments, rather than nesquehonite."

> This statement conflicts with the content of section 4. Hydromagnesite was never identified in any of the experiments. Nesquehonite was described as the abundant and identifiable phase in most of the experiments.
>
> The reaction sequence observed is decribed on p. 20 ff. in the draft manuscript. There is no clear difference in the phase assemblage claimed in the two brine

systems, only in the morphology of the phases; see p. 27 top in the draft manuscript. From what can be seen in the text, nesquehonite, once formed, persists in the system even if a new, unidentified phase also forms later.

The first phase observed (at point c in the model of reaction progress) is stated to contain C, O, and Mg, with very little Cl. It is interpreted to be protohydromagnesite on p. 21, top. Note: protohydromagnesite is not the same phase as hydromagnesite.

"For the coarse fraction samples, nesquehonite formation had become the dominant alteration process by day two for the Salado fraction and day three for the Castile fraction." (p. 21)

For the fines, at day four there was no nesquehonite observed in either brine, but the original alteration product (noted above as point c) was thicker and is now referred to as "hydromagnesite-like". At day ten, the Salado brine sample with MgO fines showed nesquehonite as a mat over a Cl-rich version of the "hydromagnesite-like" material. (p. 21, middle and Fig. 4-5).

At stage f in the reaction progress model, the samples (not stated whether it is coarse fraction, fine fraction, or both) develop an interlocking mesh of fine, platy crystals, which is interpreted to be protohydromagnesite containing a detectable amount of Cl.

On p. 27, the appearance of the new phase is claimed to be related to the presence of a high Mg concentration. The phase identification was tentative. "Although the SEM photographs show the material to be crystalline, the small crystal size has made it very difficult to get positive identification by x-ray diffraction. The best, though still highly tentative, identification arises from the comparison of the fines recovered from a 10-day treatment. In the case of the Castile coarse sample, a very clean pattern for pure nesquehonite was obtained. The dominant peaks in the Salado coarse sample were also nesquehonite, but a comparison with the Castile pattern showed that a few very small new peaks were present. These could be indexed to the material $MgCO_3 \cdot 3H_2O \cdot MgCl(OH)$ (PDF7-278)." Six lines later, the manuscript claims "The parallel between this new material and hydromagnesite is quite evident. Both this phase and hydromagnesite $[(MgCO_3)_4 \cdot Mg(OH)_2 \cdot 4H_2O]$ consist of mixtures of magnesium carbonate, magnesium hydroxide, and waters of hydration." This analogy would imply that most of the other phases listed on page 18 would also be equally closely related to the new material. The presence of Cl in the new material is, apparently, not considered to be important.

On. p. 29, the results of the "tea-bag" experiments are discussed. The samples with longest reaction times were for 19 days. "In the 19-day samples, masses of nesquehonite needles are readily observable in the pore spaces between the grains."

5. p.32. "Given the extremely slow precipitation rate detailed by the low pCO_2 in the repository, we expect that nesquehonite will not form. The favored metastable phase is hydromagnesite."

It is difficult to reconcile this claim with the experimental evidence presented in Section 4 of the manuscript, especially since hydromagnesite has not been seen to form in any of the experiments described in that section.

6. In the figure caption for Fig. 5-5, it is stated "In our experiments, nesquehonite, [*sic*] is initially formed but converts to hydromagnesite, probably through the protohydromagnesite intermediary."

This statement misrepresents the experimental results. The only phase that was positively identified was nesquehonite, which was found in abundance in nearly all of the experiments discussed in the draft manuscript. The reaction path described at the top of page 37 as "possible" is just that - possible, not definitive.

7. p. 38. "As shown previously, hydromagnesite has been observed and predicted to be the metastable phase possibly formed in the repository which then ages to form magnesite. Model predictions were performed to predict the actinide solubilities which could occur during these transient periods. To perform the model predictions, hydromagnesite had to be added to the actinide solubility database."

As stated above, hydromagnesite was never identified in the experiments described in the draft manuscript. In other materials available from Sandia, it was seen that calculations were also done with nesquehonite (C. F. Novak memo to R. Vann Bynum dated 21 April 1997, "Calculation of actinide solubilities in WIPP SPC and ERDA6 brines under MgO backfill scenarios containing either nesquehonite or hydromagnesite as the Mg-CO_3 solubility-limiting phase.") Since the results with nesquehonite were quite different for the (IV) actinides, they are reproduced here together with the results reported in the draft manuscript.

Conditions	+4 act., molar Salado (SPC)	+4 act., molar Castile	log fugacity (CO_2)
CCA calc.	4 E-6	6 E-9	-6.9
No backfill	5 E-4	7 E-5	0 to 2
5424 hydromag.	1 E-8	4 E-8	-5.5
4323 hydromag.	2 E-8	5 E-8	-5.39
Nesquehonite	6.3 E-4	1.0 E-3	-3.8

pcH for Salado conditions is calculated to be 9.4 and for Castile, 9.9.

Note that with nesquehonite present, the solubility of the +4 actinides is higher than it is with no backfill present. This suggests that the addition of MgO backfill may

not provide clear improvement in performance, but may add significant uncertainty in performance predictions.

Appendix B

Comments on SNL Tech Memo by C. F. Novak and R. C. Moore dated March 28, 1996, "Estimates of Dissolved Concentrations for +III, +IV, +V, and +VI Actinides in a Salado and a Castile Brine under Anticipated Repository Conditions." (Referenced in US DOE Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, Appendix SOTERM, October 1996. Stated to be on file in Sandia WIPP Central File A: WBS 1.2.0.7.1; WBS 1.1.10.1.1: WPO 36207.)

This memo describes the general method used to calculate the solubilities of actinides for use in the CCA and gives the results for several sets of calculations. The database used is cited, but not included in the memo.

Solubilities were calculated using an equilibrium thermodynamic speciation code "FMT", which employs Pitzer-type interaction parameters to obtain activity coefficients for dissolved species.

Equilibrium thermodynamics for solution chemistry requires the use of the activity, a, of species in equations that describe solubility or complex ion formation. The activity of a species is related to its concentration in solution by the relationship

$a = \gamma m$ where γ is the activity coefficient and m is the concentration of the species in moles per kg of solution.

The solubility product, K_{eq}, of the salt AB in an aqueous solution can then be written as

$$K_{eq} = a_{A+}a_{B-}/a_{AB} = (\gamma_{A+}m_{A+})(\gamma_{B-}m_{B-})$$

The term a_{AB} is eliminated because the activity of a pure solid is unity. The terms such as γ_{A+} are the activity coefficients of the dissolved ionic species. For an ideal solution, which generally means solutions near infinite dilution (very little solute), these terms approach unity and the solubility may be approximated by the product of the molal concentrations. At low total dissolved solids for aqueous solutions, molal concentration (m) approaches molar concentration (M = moles/liter).

When solubilities are calculated for systems with many components, a group of equilibrium solubility equations must be solved simultaneously with a group of association relationships that describe formation of complex ions in solutions. The association relationships generally are limited to the attachment of an anionic ligand, L, to a cation, A+.

$\beta_{1,1} = a_{AL} / a_{L-}a_{A+}$ where the subscript 1,1 indicates that the complex consists of 1 cation and 1 ligand.

To solve the system of equations, data are needed for the equilibrium solubility constants, the association constants for ligands with cations, and the activity coefficients for all solution species.

What is available from direct measurements is the equilibrium solubility of compounds under various conditions at a fixed ionic strength in some noncomplexing electrolyte such as 0.5M $NaClO_4$ and similar data for association reactions for ligands and cations. These data must first be extrapolated back to zero ionic strength to get true equilibrium values for infinite dilution and then extrapolated up to the ionic strength of the actual solution. For dilute natural groundwaters, the zero ionic strength data are generally used directly. For brines, the use of some scheme such as Pitzer parameters is needed to provide the activity coefficients for the calculations.

Chemical solutions with many components are routinely modelled using computer codes such as EQ3, or, in the case of the WIPP project, FMT. These codes use a database of equilibrium, zero ionic strength data for solubility and complex ion formation, a method to calculate activity coefficients as a function of solution chemistry and solution ionic strength, and a numerical method to solve a large number of simultaneous equations. Errors and uncertainties can enter the calculations from any and all of these areas. In addition, since the codes are for equilibrium conditions, when systems occur with long-lived metastable species the code user must select which species will be surpressed in the calculations. This means that the surpressed species are eliminated from the calculations so that less stable species can control solution concentrations. For example, if hydromagnesite is to be allowed to be present, the more stable magnesite phase must not be included in the calculations. The user of the code must select the phases that will not be allowed to form.

The types of difficulties that can be encountered in using computer modelling of solution chemistry are

(1) Data for solubility or complex ion formation are not available for the species needed or are incorrect.

(2) Insufficient data exist to allow accurate estimation of ion interactions at high ionic strength. (Activity coefficients cannot be accurately estimated.)

(3) Data for solubility or for complex formation are known, but are not included in the data base used by the code in question.

(4) Incompatible thermodynamic properties data are included in the data base. (This can cause erratic results in calculations.)

(5) Calculational problems related to the algorithms used to solve the simultaneous equations. (This can result in errors from accumulation of rounding errors in calculations or from multiplication of uncertainties through use of a convoluted calculational path.)

It is rare that the accuracy of computer calculations of thermodynamic equilibria for complex systems can be determined directly. In most cases, one must examine the results of calculations for consistency with experiments on related, but not identical, systems. It is also important to examine the results of calculations for internal consistency, i.e., when large changes occur in the calculated concentration of a solution species, are these accompanied by other changes in the solution species that would be expected.

When I examined the calculational results in the memo by Novak and Moore, I found inconsistencies both internally and with respect to relevant published work. These are discussed below.

Novak and Moore did a series of calculations in which they stepwise equilibrated a brine composition with selected solids, actinides, more selected solids, and organics in the solution phase. The sequence of calculations was

(1) Brine alone
(2) Brine plus halite and anhydrite
(3) Brine from step 2 plus Am(III) + Th(IV) + Np(V) until an actinide solid phase precipitated for each actinide
(4) Brine from step 3 plus brucite and magnesite
(5) Brine from step 4 plus organic ligands.

In addition, steps 4 and 5 were done with saturation with portlandite and calcite instead of with brucite and magnesite.

Selected calculation results are presented in Table 1 as element concentrations and in Table 2 as species concentrations in mol/kg. The changes in major solutions chemistry in going from step 1 to step 3, which is the first result shown in Tables 1 and 2, were

ERDA brine: sodium increased from 5.63 m to 6.22 m, and pmH decreased from 6.74 to 5.84, accompanied by changes in carbon dioxide and carbonate species related to pH and compex ion formation.

Salado brine: sodium increased from 2.06 m to 2.9 m, and pmH increased from 4.11 to 5.63, again with changes in carbon dioxide and carbonate species.

We will discuss only the calculations for Th solubility and speciation here. For the case with actinides plus brine plus saturation with halite and anhydrite, two sulfate complexes with thorium appear as the sole reason for high solubility in the Salado brine case and are significant contributors to high solubility in the ERDA brine case. The abundance of these

calculated species does not appear to be strongly affected by the factor of 4 difference in sulfate ion concentration in the two brines. When calculations are then done for addition of brucite and magnesite, the sulfate ion concentrations in solution remain about the same, but the Th sulfate complexes become insignificant. This occurs together with a calculated decrease in total Th solubility. Since the only major change in brine chemistry for the ERDA case is an increase in pH and accompanying changes in carbonate equilibria, the Th sulfate solution complexes should remain dominant. Their absence in the speciation results for the step 4 cases suggests that there are major calculational problems with the FMT code and its data base.

Experimental data for the solubility of UO_2 in brines of NaCl with similar ionic strength (pH = 7.7) and $MgCl_2$ with higher ionic strength (pH = 4.7) under reducing conditions in the absence of carbon dioxide gave U^{4+} concentrations of 2.8×10^{-7} m and 3.1×10^{-7} m, respectively (DePablo et al., 1995). These results are compared to calculations for thorium by Novak and Moore in the following table. (See Tables 1 and 2 at the end of this appendix for detailed results.)

Table B-1: Comparison of experimental determination of solubility for U with calculated solubility for Th.

Brine type	Experimental value UO_2, DePablo et al.	Calculated value ThO_2, Novak and Moore
NaCl/ERDA	2.8×10^{-7} m	3.9×10^{-3} m
$MgCl_2$/Salado	3.1×10^{-7} m	4.4×10^{-4} m

The Th solubility in the ERDA brine was calculated to be dominated by the pentacarbonate complex; however, the amount of soluble Th sulfate complexes was calculated to be 7×10^{-4} m. For the Salado brine, the calculated Th solubility was due almost completely to the soluble sulfate complexes. Since DePablo et al. had no carbon dioxide in their system, the soluble species should be present as hydroxy or sulfate complexes only. The experimental results are three and four orders of magnitude lower than those calculated by Novak and Moore for Th. Since the WIPP project bases their model for (IV) actinide solubility on the assumption that all (IV) actinide solubilities can be calculated using Th as the model, this discrepancy between calculations and experiments under similar conditions is significant.

The Th sulfate complexes used in the calculations were proposed by Felmy and Rai (1992) when they reinterpreted data published originally in 1963; they do not consider the monosulfate complex. Data for sulfate complexes of Pu being considered for use in the international compendium of thermodynamic data for Pu and Np under preparation by OECD/NEA contains recommended values for a mono-sulfate, $Pu(SO_4)^{2+}$, and a di-

sulfate, $Pu(SO_4)_2$, complex, rather than the di- and tri-sulfate complexes, $Th(SO_4)_2$ and $Th(SO_4)_3^{=}$, used in the Novak and Moore calculations (K. Spahiu, personal communication). This suggests that either (1) the complexes used to model Th were incorrect, or (2) that Th is not a good surrogate for Pu in its behavior with respect to sulfate complexes. In either case, the calculations done for Th would not be valid for use in estimating Pu solubility.

Another problem that is evident in the Novak and Moore calculations concerns the carbonate species calculations. At low pH in the Castile brine, the dominant soluble Th species is calculated to be $Th(CO_3)_5^{6-}$ with very minor amounts of $Th(OH)_3CO_3$. At higher pH (9.9), the two species are calculated to be about equal in importance in Castile brine, but with the solubilities in the 2 to 4 x 10^{-9} range. In Salado brine, the pentacarbonate complex is absent at pH 5.6 (nearly the same pH as for the equivalent Castile calculation, which shows this complex present at 3 x 10^{-3}m), but appears at 3 orders of magnitude higher than Castile calculated concentrations at pH 9.4, with similar total dissolved carbonate species in the two cases. These internal inconsistencies in calculated results point to problems in the calculational methods used and/or the data base parameters selected. In addition, the species predominance at low pH should be the opposite of that calculated for the Castile brine. The stabilitiy constants for these species were determined by Östhols et al. (1994); a graphic display of the progression of species as a function of pH is given in their paper. The pentacarbonate complex is dominant at high pH, while the hydroxycarbonate species is important at lower pH.

An additional problem with the calculated carbonate species for Th is that the pentacarbonate complex is predicted to exist in solutions with only micromolal carbonate concentrations. In general, this species is not important until carbonate concentrations are above 0.1 molal. See, for example, Rai et al. (1995). Discussion with K. Spahiu confirmed that behavior of Pu carbonate complexes could be expected to be similar to Th and to require concentrations in the > 0.1 m carbonate range.

It should be noted that conclusions drawn by Novak and Moore concerning the lack of importance of organic complexation in the determination of Th solubilities are invalidated since their basic calculations for Th solution species appear to contain a number of significant errors.

References

J. DePablo, J. Giménez, M. E. Torrero, and I. Casa (1995) Mechanism of unirradiated UO_2 (s) dissolution in NaCl and $MgCl_2$ brines at 25°C, Mat. Res. Soc. Symp. Proc. 353, T. Murakami and R. C. Ewing, eds., 609-615.

E. Östhols, J. Bruno, and I. Grenthe (1994) On the influence of carbonate on mineral dissolution: III. The solubility of microcrystalline ThO_2 in CO_2-H_2O media, Geochim. Cosmochim. Acta 58, 613-623.

A. R. Felmy and D. Rai (1992), An aqueous thermodynamic model for a high valence 4:2 electrolyte Th^{4+}-SO_4^{2-} in the system Na^+- K^+- Li^+-NH_4^+- Th^{4+}- SO_4^{2-} - HSO_4^- - H_2O to high concnetrations, J. Soln. Chem. 21, 407-423.

D. Rai, A. Felmy, D. A. Moore, and M. J. Mason (1995) The solubility of Th(IV) and U(IV) hydrous oxides in concentrated $NaHCO_3$ and Na_2CO_3 solutions, in Mat. Res. Soc. Symp. Proc. 353, T. Murakami and R. C. Ewing, eds., 1143-1150.

Table 1: Results of model calculations by Novak and Moore(1996) in concentrations of moles/kg brine. Equilibrations of Castile-like brine (ERDA) and Salado-like brine with anhydrite and halite plus actinides with and without MgO or CaO.

Element	ERDA-HA-An		Salado-HA-An		
	no MgO	with MgO	no MgO	with MgO	with CaO
Hydrogen	111	111	111	111	111
Oxygen	56.5	56.5	55.8	55.9	55.6
Sodium	6.22	6.2	2.9	4.69	3.5
Potassium	0.11	0.11	0.865	1.05	1.06
Magnesium	0.0214	0.0443	1.62	0.51	6.0 E-6
Calcium	0.0112	0.0133	0.0305	0.0331	1.31
Chlorine	5.98	5.97	6.95	6.67	7.12
Sulfur	0.189	0.191	0.0529	0.06	0.002
Carbon	1.86 E-2	3.15 E-5	1.15 E-2	4.08 E-5	5.87 E-6
Boron	0.0709	0.0708	0.0225	0.0272	0.0244
Bromine	0.0124	0.0124	0.0112	0.0136	0.0122
Th(IV)	3.88 E-3	6.78 E-9	4.37 E-4	4.98 E-6	1.16 E-9
Am(III)	4.49 E-4	4.12 E-7	2.57 E-4	4.39 E-6	1.25 E-9
Np(V)	1.74 E-4	7.53 E-6	1.78 E-5	7.64 E-6	4.85 E-6
pmH	5.843	9.893	5.63	9.366	12.124
Solid phases	halite anhydrite	halite anhydrite brucite magnesite glauberite	halite anhydrite	halite anhydrite brucite magnesite Mg-oxychloride	halite anhydrite brucite portlandite calcite Ca-oxychloride
	AmOHCO3(s) ThO2(am) KNpO2CO3.2H2O(s)	AmOHCO3(s) ThO2(am) KNpO2CO3.2H2O(s)	AmOHCO3(s) ThO2(am) KNpO2CO3.2H2O(s)	Am(OH)3 ThO2(am) KNpO2CO3.2H2O(s)	Am(OH)3(s) ThO2 (am) NpO2(OH)(aged)

Table 2: Solution species concentrations in brines (from Novak and Moore, 1996) in moles/kg
Only species involving major ions, sulfate, carbonate, and actinides are given.

Species	Castile ERDA6-HA-An	ERDA-HA-An-Mg	Salado SPC-HA-An	SPCHA-An-Mg	SPC-HA-An-Ca
Na+	6.22	6.2	2.9	4.69	3.5
K+	0.11	0.11	0.865	1.05	1.06
Ca++	0.011	0.011	0.03	0.032	1.29
Mg++	0.071	0.039	1.67	0.496	3.6 E-6
MgOH+	2.1 E-8	4.2 E-4	1 E-6	1.7 E-3	4.4 E-6
H+	1.4 E-6	1.3 E-10	2.3 E-6	4.3 E-10	7.5 E-13
Cl-	5.98	5.97	6.95	6.67	7.12
SO4=	0.187	0.191	5.16 E-2	6.02 E-2	1.97 E-3
HSO4-	4 E-6	3.6 E-10	8 E-7	3 E-10	1 E-14
HCO3-	8.1 E-4	7.1 E-6	2.39 E-3	1.78 E-6	1.4 E-10
CO3=	8.0 E-8	8.0 E-6	6.4 E-7	8.3 E-7	3.1 E-7
CO2(aq)	1.4 E-3	1.2 E-9	9.1 E-3	1.2 E-9	6 E-16
NpO2+	1.7 E-4	1.7 E-6	1.7 E-5	2.4 E-6	7.3 E-8
NpO2OH(aq)	1.9 E-9	2.1 E-7	1.5 E-10	1.2 E-7	2.4 E-6
NpO2(OH)=	NEGL.	1.0 E-9	NEGL.	1.8 E-10	2.4 E-6
NpO2CO3-	6.6 E-7	6.3 E-7	4.2 E-7	1.2 E-7	1 E-9
Am+++	3.4 E-4	7.8 E-11	1.94 E-4	3.2 E-9	1.4 E-17
AmOH++	1.1 E-4	2.7 E-7	5.6 E-5	3.8 E-6	1.2 E-11
Am(OH)2+	5.0 E-9	1.4 E-7	1.8 E-9	5.7 E-7	1.1 E-9
AmCO3+	3.2 E-6	7.2 E-11	7.3 E-6	2.9 E-10	3 E-19
Th(SO4)2(aq)	1.35 E-5	9 E-22	1.4 E-5	1 E-20	0
Th(SO4)3=	5.9 E-4	4 E-20	4.2 E-4	8 E-20	0
[Th(CO3)5]6-	3.27 E-3	3.7 E-9	0	5 E-6	0
Th(OH)3CO3-	2.0 E-7	1.8 E-9	6.9 E-7	5 E-10	1 E-13
Th(OH)4(aq)	1.3 E-9	1.3 E-9	1.1 E-9	1.2 E-9	1.2 E-9

APPENDIX C

Comments on Appendix SOTERM to the Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant dated October 1996.

Comments will be confined to those sections of the Appendix that deal with estimation of the dissolved actinide portion of the source term as it applies to plutonium. Most attention will be focused on Pu(IV), which is the most probable oxidation state under WIPP conditions. The section concerning the potential for colloidal transport (6) is quite thorough and, if anything, overestimates the amount of actinide that might be transported as the result of the presence of colloids in the brine.

The solubility calculations for the actinides in brines with and without MgO are discussed in Appendix B. These calculations assume homogeneous equilibria, which for actinides in the absence of complexing ligands from the waste is probably an adequate estimate. For the case where organics are present, the organics are also treated by SOTERM as if they were homogeneously dissolved in 29,841 m^3 of brine. There are some inconsistencies in the table of inventories and molal concentrations (see item 8 below); however, this problem is small when compared to the failure to consider heterogeneous equilibria for organic complexation with the actinides.

The main difficulty arises because the Pu in the waste is probably located in the same drums as the citrate, which is the dominant organic ligand. This is because these wastes arise from chemical separations of Pu and are not the type of waste described in the general descriptions of TRU waste as contaminated equipment, clothing, etc. To get an accurate estimate of the effect of organic ligands on Pu solubility, one must calculate the concentration of Pu as citrate complex inside a waste drum that has been breached, but can still provide an hindrance to mixing of the brine inside the drum with a larger pool of brine outside the drum. This will give a high concentration of Pu in solution as the citrate complex. Other ions will not compete with Pu sufficiently to prevent complex formation because the stability for (IV) actinide complexation - as shown by the stability constant for Th(IV) on p. 39 - is orders of magnitude larger than that for other ion complexes with citrate.

To obtain a more accurate estimate of the effect of citrate on Pu solubility in the event of human intrusion, calculations that use the Pu citrate formed inside a waste drum and model the mixing of that relatively concentrated brine with the average repository brines must be done, taking into account the time scales for mixing and the possibility that the intrusion event may release some brine from waste drums that has not had an opportunity to mix with the average repository brines.

The conclusion that EDTA complexes will not increase actinide solubility is probably correct, since the amount of EDTA is small and the Ni and Fe complexes have stability constants that are similar to those for the actinides. It is not shown, and is probably not

true, that the more abundant citrate inventory will not increase actinide solubility, especially for Pu.

Specific comments:

(1) p.2 and later discussions of the same topic. The authors appear to believe that degradation of organic waste can only occur by microbial action and that the most detrimental product will be carbon dioxide gas. Work in England has shown that degradation of cellulose can occur both through chemical processes at high pH and by radiation effects. The degradation products have been shown to increase the solubility of plutonium dramatically (Cross et al., 1989; Greenfield et al., 1992).

(2) p. 17 Figure caption seems to be incorrect. This should be the Castile Brine.

(3) p. 19 The corrosion equation at the bottom of the page is not balanced. If the corrosion is envisaged to occur through the action of water, rather than dissolved oxygen, it should be written as

$$Fe + 2H_2O = Fe(OH)_2 + H_2$$

(4) p. 20, near bottom "Therefore, radiolysis is not expected to affect the reduction-oxidation state of the repository." This is probably true on the scale of the entire repository, averaged over time; however, radiation effects within a waste canister that contains up to 10 g of ^{239}Pu could be quite significant on the local scale.

(5) p. 26 The selection of species for Th solubility includes $Th(SO_4)_2$ (aq.) and $Th(SO_4)_3^{=}$. The data base being prepared by OECD/NEA for recommended thermodynamic properties for Pu and Np includes sulfate complexes for Pu with one and two sulfate ligands and none with 3 sulfate ligands. In addition, the calculations of speciation with sulfate complexes for Th appear to give erratic results. See appendix B for further discussion.

(6) P. 29 The small range in uncertainties estimated for the calculation of solubilities seems to be at odds with the differences in calculated results for brines with rather similar chemistry and the difference between the calculated results and those measured for solubility of uranium dioxide in brines. See Appendix B for details.

(7) p. 35 bottom and 36 top. "Neretnieks (1982) has shown that when dissolved actinides in moving groundwater came in contact with Fe(II), the actinides were reduced to a much less soluble state and precipitated." Actually, Neretnieks did not <u>show</u> that reduction occurred; he did a model calculation that predicted the process should occur. His calculations, of course, have the same limitations concerning the adequacy of the data base used as do those done by Novak and Moore.

(8) p. 37, Table SOTERM-4. This table gives organic ligand inventories and calculated molal concentrations in a brine that is stated to be 29,841 m^3, being the smallest volume of brine that could escape from the repository. Converting to kg of brine using a density of 1.125 kg/L gives a total of 3.35×10^7 kg of brine. Using the inventory amounts in grams and converting to moles, one finds

Ligand	Mol. Wt.,g	Inventory, g	Inventory, moles
Acetate	60	1.3×10^6	2.2×10^4
Oxalate	126	1.6×10^6	1.3×10^4
Citrate	192	1.4×10^8	7.3×10^5
EDTA	372	2.3×10^4	62
(Mwt. as Versenate)			

Dividing the inventory in moles by the brine amount in kilograms gives the molal concentration of the organics. The table below compares the results of my calculation with the values given in Table SOTERM-4

Ligand	Molal conc. from Inventory calc. above	Molal conc. from SOTERM
Acetate	6.6×10^{-4}	5.2×10^{-4}
Oxalate	3.9×10^{-4}	2.3×10^{-4}
Citrate	2.2×10^{-2}	3.6×10^{-3}
EDTA	1.8×10^{-6}	2.0×10^{-6}

The differences in calculated concentrations range from 10% for EDTA to a factor of 6 for citrate.

References

J. E. Cross, F. T. Ewart, and B. F. Greenfield (1989) Modelling the behaviour of organic degradation products, Mat. Res. Soc. Symp. Proc. 127, W. Lutze and R. C. Ewing, eds., 715-722.

B. F. Greenfield, A. D. Moreton, M. W. Spindler, S. J. Williams, and D. R. Woodwar (1992) The effects of the degradation of organic materials in the near field of a radioactive waste repository, in Mat. Res. Soc. Symp. Proc. 257, C. G. Sombret ed., 299-306.

Appendix D: Summary of relevant articles used in preparation of this report

D. Rai, A. Felmy, D. A. Moore, and M. J. Mason (1995) The solubility of Th(IV) and U(IV) hydrous oxides in concentrated $NaHCO_3$ and Na_2CO_3 solutions, in Mat. Res. Soc. Symp. Proc. 353, T. Murakami and R. C. Ewing, eds., 1143-1150.

Measurements of the solubility of U(IV) and Th(IV) in carbonate and bicarbonate solutions of various concentrations, in some cases with added NaOH. Both solubilites increase dramatically as carbonate concentrations increase beyond 0.1 M. In general, Th(IV) hydrous oxide was about 1000 times more soluble at a given carbonate concentration than U(IV). Solubilites of Th in Na_2CO_3 solutions decreased with added hydroxide ion at fixed carbonate concentration (1M).

U(IV) experiments were conducted in inert atmosphere (Ar chamber) and with Fe powder present in the experiments to ensure absence of U(VI). Th(IV) experiments were also conducted in an Ar atmosphere, but without Fe powder present. Solubility limits were approached from undersaturation by suspending freshly precipitated amorphous hydrous oxides in the appropriate solutions.

Th(IV) solubility increases from 10 E-8 M at 0.1 M Na_2CO_3 concentration to > 10 E-3 M at 1 M Na_2CO_3. U(IV) shows the same behaviour, but the steep increase starts at 1 M Na_2CO_3 and finishes at 6 M. Species responsible for this increase is most likely $An(CO_3)_5^{6-}$. Similar behavior is observed in bicarbonate solutions, but the increase in solubility begins at lower concentrations - 0.01 M for Th and about 0.08 M for U.

G. R. Choppin (1990) Actinide Speciation in Spent Fuel Leaching Studies, in Mat. Res. Soc. Symp. Proc. 176, V. M. Oversby and P. W. Brown, eds., 449-456.

Results from SKB's spent fuel testing program, in which LWR fuel is leached at room temperature in deionized water or in dilute sodium bicarbonate (synthetic) groundwater were used as the basis for deciding the expected speciation of U and Pu in these liquids under oxic conditions.

Figure 2 (p. 452) is a Pourbaix diagram for plutonium redox states under atmospheric CO_2 pressure and including carbonate complexes and hydrolysis reactions. The stable conditions shown are PuO_2^{2+}, PuO_2^{+}, and Pu^{4+} for oxic conditions and Pu^{4+} and Pu^{3+} for reducing conditions. It is noted that PuO_2^{+} disproportionates into PuO_2^{2+} and Pu^{4+} but that the rate of the reactions depends on the 4th power of the H^+ concentration and on the square of the PuO_2^{+} concentrations so that at low concentrations of Pu in neutral solutions the reaction rate is negligible. As an example of this lack of disproportionation, a table is given listing the redox state of Pu in natural waters and showing more than 50% Pu(V) in most cases. (Note that at high pH this would also be expected. This may explain the relative long life of Pu(V) in some of the speciation experiments done in brines.) Choppin concludes that in oxic conditions with Pu concentrations of 10^{-6} M and lower, the dominant species may be PuO_2^{+}.

The relative strengths of complexation for plutonium cations is $Pu^{4+} > PuO_2^{2+} > Pu^{3+} > PuO_2^{+}$, which is the same order of relative stability as for U cations. (Complexes of Pu(IV) are not discussed, since the paper limits itself to oxic conditons.)

Under oxic conditions, the spent fuel leaching studies showed apparent solubility for Pu of 5-10 ppb in DIW and 0.3 to 1 ppb in synthetic groundwater (0.002 M carbonate). The redox states present are interpreted to be Pu(V) as PuO_2^{+} and Pu(IV) as precipitated $Pu(OH)_4$ or $PuO_2 \cdot xH_2O$ present as the solid phase that limits total Pu solubility. The ratio of Pu(V) to Pu(IV) in the solution phase is predicted to be extremely large: 10^{23} in DIW and $10^{26.6}$ in the synthetic groundwater at pH 8.2. (Note: There is no reason to believe that this mechanism for solubility control under oxic conditions would not also work in brines.)

H. Nitsche (1991) Basic research for assessment of geologic nuclear waste repositories: what solubility and speciation studies of transuranium elements can tell us. Mat. Res. Soc. Symp. Proc. 212, T. Abrajano, jr. and L. H. Johnson, eds., 517-528.

Discusses experimental results for NpO_2^+, Pu^{4+}, and Am^{3+}/Nd^{3+} in J-13 well water, a natural dilute sodium bicarbonate groundwater, at pH 6, 7, and 8.5 and at T = 25, 60, and 90°C. The experimental results are compared to modelling calculations using EQ3/6. Tables of stability constants for solution species used in the calculations are given and may be useful for comparison with those used in calculations for WIPP.

Plutonium was added to the groundwater as Pu(IV). The solubility controlling species were found to be polymeric plutonium(IV) and lesser amounts of plutonium carbonates. At pH 7 and 8.5, Pu solubility at 25°C was about 5×10^{-7} M. The Pu used was Pu-239 isotope. Calculations that assumed crystalline PuO_2 predicted solubility at 25°C of 10^{-12} M. Use of amorphous $Pu(OH)_4$ in the calculations overestimated the solubility limit to be 10^{-4} M at 25°C. The oxidation state distribution found in the pH 8.5 experiments for species in solution was about 70% Pu(V) and 25% Pu(VI) with minor amounts of Pu(IV) and Pu(III)+polymer. (Note, this agrees with Choppin's predictions that the solid phase under oxic conditions contains Pu(IV), while the solution species would be Pu(V).)

J. E. Cross, F. T. Ewart, and B. F. Greenfield (1989) Modelling the behaviour of organic degradation products, Mat. Res. Soc. Symp. Proc. 127, W. Lutze and R. C. Ewing, eds., 715-722.

Research into the effect of alkaline degradation of organic materials that might be found in low and intermediate level radioactive wastes showed that the degradation of cellulose produced products that greatly increased the solubility of Pu. The details of the experimental results can be found in a report by J. D. Wilkins, UKAEA Report AERE R 12719 (1987).

The specific ligands responsible for the enhanced solubility could not be identified. Also, attempts to reproduce the effect using possible ligands with Pu did not produce as high a solubility. This shows the importance of examining actual waste mixtures to ensure that symbiotic effects are included.

Experiments were conducted with cement equilibrated with water with and without organic materials and with Pu added as a separate acid solution. The precipitated Pu was separated and the solution concentrations were measured. The results were

Cement alone + Pu	[Pu] = 5×10^{-10} M
Cellulose chemical degradation	[Pu] = 7×10^{-6} M
Cellulose, radiation degradation	[Pu] = 5×10^{-6} M

The effect of other organics was much less.

New experiments were done with separated organic acids. The closest results were found with D-saccharic acid HOOC · $(CHOH)_4$ · COOH, which at pH 12 gave Pu solubility of 7.2×10^{-6} M at 10^{-5} organic acid concentration, 7.3×10^{-6} M at 10^{-4} M organic acid, 8.2×10^{-6} M at 10^{-3} M organic acid, and 9.3×10^{-6} M at 10^{-2} M organic acid. This behaviour pattern, with little change in Pu solubility even though large changes were made in organic acid concentration, was successfully described so long as one considered complexation involving hydroxyl groups as well as carboxylic acid groups.

Both experiments and modelling were done for conditions at a redox potential of + 200 mV.

B. F. Greenfield, A. D. Moreton, M. W. Spindler, S. J. Williams, and D. R. Woodwar (1992) The effects of the degradation of organic materials in the near field of a radioactive waste repository, in Mat. Res. Soc. Symp. Proc. 257, C. G. Sombret ed., 299-306.

A number of different solid organic materials were degraded in the presence of Portland cement and blast furnace slag (representing the concrete components in the proposed UK Nirex low and intermediate level radioactive waste repository) at 80°C under anaerobic conditions. Generally the experiments contained 10% organic and 90% cement. Samples of liquid were taken periodically, cooled to room temperature, pH adjusted to 12 (if necessary), and then spiked with a small volume of radioactive elements in acid solution to measure their solubility in the leachates. After 2 days samples were taken and filtered, and then the radioelement concentrations were measured.

Results found for Pu(IV) solubility in leachates produced from 500 days of degradation of the organics were

Cellulose or wood fiber	10 E-3 M
Cotton wool	10 E-5 M
Bakelite	6 x 10 E-6 M
PVC	10 E-9 M
Polystyrene	5 x 10 E-10 M
Nylon, Polythene, and Pure cement leachate	10 E-10 M

Degradation of cellulose under aerobic conditions resulted in a lower solubility for Pu(IV), namely 10 E-4 M, and solubilities of 10 E-5 M for Th(IV) and U(IV). Am(III) and Np(IV) in these leachates had apparent solubilities of 10 E-6 M.

The effect of varying cellulose to cement ratio was tested under anaerobic degradation conditions. The Pu (IV) solubilites found were 4 x 10 E-10 M at 0.1% cellulose, 4 x 10 E-9 M at 0.5% cellulose, but 1 x 10 E-6 M at 1% cellulose.

The product of cellulose degradation that is most likely to explain the enhanced Pu solubility is isosaccharinic acid (ISA); other possible degradation products are produced in lesser amounts and have less effect on Pu solubility than ISA. If ISA is exposed to cement, it will sorb onto the cement surface, thus diminishing its effect on Pu solubility. This is thought to explain the results found at low cellulose loadings in cement.

Modelling calculations were able to reproduce the effects seen in the experiments. It was concluded that the solubility enhancement for Pu was achieved through complexation that involved 4 deprotonated hydroxyl groups in the bonding.
I. AlMahamid, K. A. Becraft, N. L. Hakem, R. C. Gatti, and H. Nitsche (1996) Stability of various plutonium valence states in the presence of NTA and EDTA, Radiochimica Acta 74, 129-134.

Experiments were conducted using solutions of nitrilotriacetic acid (NTA) and ethylenediaminetetraacetic acid (EDTA) with all four soluble plutonium oxidation states - III, IV, V, and VI - at macroscopic (10^{-3}M) and microscopic (10^{-7}M) concentrations. Experiments were performed at room temperature in an argon atmosphere. Pu was prepared by dissolving PuO_2 electrochemically in 1 M $HClO_4$ and then adjusting to produce the desired oxidation states.

NTA was added to an acidic solution of Pu and the pH adjusted to 5 with NaOH. Final ionic strength of the solutions was about 0.01 M. At the higher Pu concentrations, the final species is a Pu(IV)-NTA complex, regardless of the initial oxidation state of the Pu, at NTA/Pu ratios of 6. At higher NTA amounts, the Pu(IV) polymeric form can even be dissolved. With EDTA, only Pu(III) was studied. This oxidized to produce an EDTA-Pu(IV) complex.

Studies with the lower Pu concentrations with NTA resulted in mainly Pu(IV) if the starting valence was III or IV. For initial Pu(V), about 65% of the Pu persisted as V, with a little becoming VI and most of the rest present as IV. For initial Pu(VI) at NTA/Pu of 100, 48% of the Pu was IV after 10 days and 31% was V, with 21% remaining as VI. Very high NTA/Pu ratios reduced essentially all of the Pu(VI), producing 38% Pu(IV) and 61% Pu(V). Experiments with EDTA at ligand to Pu ratios of 100 and of 1 also showed persistance of Pu(V) if the starting materials were VI or V, but little or no Pu(VI). It is expected that the Pu(V) will reduce to Pu(IV) with time. These solutions had low ionic strength (as low as 10^{-5} M) and no active reducing agents other than the organic ligands themselves.

J. DePablo, J. Giménez, M. E. Torrero, and I. Casa (1995) Mechanism of unirradiated UO_2 (s) dissolution in NaCl and $MgCl_2$ brines at 25°C, Mat. Res. Soc. Symp. Proc. 353, T. Murakami and R. C. Ewing, eds., 609-615.

Experiments using unirradiated crystalline UO_2 (s) with 1 mm particle size and BET surface area of 0.0016 m^2/g were done in synthetic brines. Both oxidizing and reducing conditions were studied. Reducing conditions were maintained using a hydrogen flux and a Pd catalyst.

Brine compositions: molal concentrations

Species	NaCl-brine	$MgCl_2$-brine
Na+	6.036	0.48
K+	0.037	0.57
Mg^{2+}	0.018	4.21
Ca^{2+}	0.021	0
Cl-	6.036	8.84
$SO_4^{=}$	0.058	0.32
Ionic Str.	6.25	14.00
pH	7.7	4.7

The UO_2 (s) had an initial surface condition that was very oxidized, $UO_{2.7}$ as measured by XPS. This led to an initial rapid dissolution of the oxidized surface even when the solution was maintained with reducing conditions. The solution concentrations in both brines gradually decreased and settled after 20 to 25 days at steady-state values of 2.8×10^{-7} mol/kg in the NaCl brine and 3.1×10^{-7} mol/kg in the $MgCl_2$-brine. At the end of the experiments the Eh was measured to be 0 to 60 mV (compatible with the stability of UO_2) and the surface of the dissolving solid was measured to have a composition of $UO_{2.1}$ as measured by XPS. A model calculation was made using the PHRQPITZ code (the PHREEQ equilibrium code with Pitzer parameters added) and gave quite good agreement of the predicted concentrations with those measured in the experiments. The predicted concentrations at zero ionic strength were about a factor of 3 lower than those predicted for the brines.

Under oxidizing conditions, the final uranium concentration in the $MgCl_2$-brine was about 10 E-5.7, and still slowly rising, while that in NaCl brine was considerably lower (10 E-6.4) and was constant. Modeling calculations for oxidizing conditions overestimated the solubility of U in the Mg-brine by about a factor of 1000, while modeling of the NaCl brines was able to produce compatible results by using a schoepite solubility of 6.2×10^{-7} mol/kg as the solid controlling the final solution concentrations.

E. Östhols, J. Bruno, and I. Grenthe (1994) On the influence of carbonate on mineral dissolution: III. The solubility of microcrystalline ThO_2 in CO_2-H_2O media, Geochim. Cosmochim. Acta 58, 613-623.

The solubility of microcrystalline ThO_2 was measured in 0.5M $NaClO_4$ at 25°C and 1 atm. as a function of pH and partial pressure of CO_2 to determine the stability of carbonate complexes of Th^{4+}. The following species and stability constants were proposed to explain the results:

For 0.5 M $NaClO_4$ conditions,

(1) $ThO_2(act) + 4H^+ \leftrightarrow Th^{4+} + 2\ H_2O$ $\log K_s = 9.37 \pm 0.13$

(2) $ThO_2(act) + H^+ + H_2O + CO_3^{2-} \leftrightarrow Th(OH)_3CO_3^-$ $\log \beta_{1,3,1} = 6.11 \pm 0.19$

(3) $ThO_2(act) + 4H^+ + 5CO_3^{2-} \leftrightarrow Th(CO_3)_5^{6-}$ $\log \beta_{1,0,5} = 42.12 \pm 0.32$

Note: For mass balance, equation (3) should have 2 H_2O added to the right hand side. This will not affect the calculated $\log \beta_{1,0,5}$.

Extrapolation of these constants to zero ionic strength gave

(1) $\log K_s = 7.31 \pm 0.3$

(2) $\log \beta_{1,3,1} = 6.78 \pm 0.3$

(3) $\log \beta_{1,0,5} = 39.64 \pm 0.4$

The solid used in these experiments was a freshly prepared precipitate of thorium oxide/hydroxide, which was of low crystallinity, and the atmospheres were mixtures of 97% CO_2 in N_2, 10% CO_2 in N_2, and pure N_2.

For the experiments at 0.1 atm carbon dioxide, the crossover between the Th-hydroxycarbonate and Th-pentacarbonate species as dominant in solution occurred at pH = 7.5. Above pH 8, essentially all of the dissolved Th was present as the pentacarbonate complex.

F. L. Sayles and W. S. Fyfe (1973) The crystallization of magnesite from aqueous solution, Geochim. Cosmochim. Acta 37, 87-99.

In the introduction section of this paper, evidence is presented to show that the oceans are supersaturated with respect to magnesite and dolomite, and that their formation is controlled by kinetic rather than thermodynamic considerations. Natural occurences of magnesite are generally in hypersaline environments, with salinity much greater than seawater.

Reagent grade basic magnesium carbonate (hydromagnesite) was reacted with saline solutions that had been equilibrated with atmospheric pressure carbon dioxide at 25°C. The solid and solutions were sealed into Pyrex ampules and reacted at 126°C to produce magnesite, which was detected using X-ray diffraction. The experiments showed that there was a long induction period prior to the production of any detectable magnesite. After crystallization of magnesite started, conversion to pure product proceeded fairly rapidly. The conversion rate increased with ionic strength and partial pressure of carbon dioxide, but decreased with Mg concentration. Nucleation of magnesite occurred on hydromagnesite surfaces (seen in SEM images).

M. P. Neu, D. C. Hoffman, K. E. Roberts, H. Nitsche, and R. J. Silva (1994) Comparison of chemical extractions and laser photoacoustic spectroscopy for the determination of plutonium species in near-neutral carbonate solutions, Radiochimica Acta 66/67, 251-8.

Experiments were conducted to investigate the solubility and speciation of ^{242}Pu in a 1.93 mM total carbonate solution of 0.100M $NaClO_4$ at pH = 6.0 and 30°C. The isotope ^{242}Pu was chosen to minimize the radiolysis effects that occur. The experiments were conducted in a controlled atmosphere argon glove box in which the oxygen concentration was typically 18 to 30 ppm. The Pu solution was added to a 0.100M $NaClO_4$ solution that had been pre-equilibrated with 5.71% CO_2 in Ar gas together with an amount of base needed to neutralize the acid from the Pu stock solution.

Experiments with a starting solution of Pu(V) with an initial concentration of 2.51×10^{-5} M had a soluble Pu concentration of $2.1 \pm 1 \times 10^{-5}$ M after 53 days. The speciation was determined by spectroscopy to be PuO_2^+ at the level of 95 ± 5%. When the Pu solution was initially Pu(VI) as PuO_2^{2+} at $2.4 \pm 1 \times 10^{-4}$ M, the concentration of soluble Pu after 120 days was $3.1 \pm 5 \times 10^{-6}$ M, or only 1.3% of the initial concentration. This was also 7 times lower than the final concentration when Pu(V) was the initial valence state for the Pu, even though it is Pu(V) as PuO_2^+ that represents the soluble Pu after 28 days of the experiment. If Pu(VI) disproportionates to produce Pu(IV) at pH =6, polymeric Pu-hydroxide will precipitate. This may explain the lower final concentrations found when Pu(VI) was the starting valence.

Speciation inferred from chemical extraction agreed with that measured directly from spectroscopy.

H. Nitsche, K. Roberts, R. Xi, T. Prussin, K. Becraft, I. Al Mahamid, H. B. Silber, S. A. Carpenter, R. C. Gatti, and C. F. Novak (1994) Long term plutonium solubility and speciation studies in a synthetic brine, Radiochimica Acta 66/67, 3-8.

This paper describes solubility studies of ^{239}Pu in a synthetic brine (H-17) conducted with a gas phase overpressure of 0.26% CO_2 and 20.75% O_2 in argon. Five separate experiments were conducted using initial species of Pu as Pu^{3+}, Pu^{4+}, PuO_2^{+}, PuO_2^{2+}, and Pu(IV) polymer at concentrations high enough to ensure supersaturation. The brine composition was

Ca^{2+}	0.029 M/L	Cl^-	2.482 M/L
Mg^{2+}	0.074	$SO_4^=$	0.075
Na^+	2.397	Br^-	0.00095
K^+	0.031	TIC	0.00082 (Total inorganic C as HCO_3)
B^{3+}	0.004		

pH = 7.0, $pCO_{2(g)}$ = 10 E-2.56 ATM
Ionic strength = 3.0 molal
Density = 1.10 g/cm^3

This brine is similar chemically to the Castile simulant brine ERDA-6 diluted by a factor of 2.

Solids that precipitated from the samples that originally contained Pu(III), Pu(IV) or Pu(IV) polymer appeared to be identical and consist of Pu(IV) polymer. Solids recovered from the experiments that initially contained Pu(V) and Pu(VI) effervesced when dissolved in HCl, indicating that they contained carbonate. Similarities of the x-ray patterns for these solids with those of $KPuO_2CO_3$(s) suggested that the solid was $NaPuO_2CO_3$(s), for which no reference powder pattern was found, since there is so much more Na than K in the brine.

Steady state concentrations found range from 2 x 10^{-7} M for solutions that originally contained soluble Pu(III) and Pu(IV), to 3.6 ± 0.8 x 10^{-7} M for Pu(V) solution, and 7.6 ± 2.3 x 10^{-7} M for initial Pu(VI). The predominant oxidation state of the solution species at the end of the experiments was (VI) with lesser amounts of (V), found mainly in those experiments that began with Pu as VI and V. Eh measured in solution at the end of the experiments was +400 to +500 mV vs. the normal hydrogen electrode.

D. T. Reed, S. Okajima, and M. K. Richmann (1994) Stability of plutonium (VI) in selected WIPP brines, Radiochimica Acta 66/67, 105-111.

States that the predominant actinide in TRU waste will be plutonium-239 at the level of up to 10 grams per waste drum.

Studies were done in two synthetic brines - brine A (similar to Salado conditions) and ERDA-6, which represents expected conditions in the Castile formation brines - and in two brines collected from the WIPP site. The natural brines had a composition that was between those of the synthetic brines with the exception of sulfate, which was a factor of two higher than ERDA brine for one of the natural brines. The pH was about 6 in all cases.

Pu(VI) was stable in Brine A, which contained carbonate. In the ERDA brine, which had no intrinsic carbonate (other than that which would dissolve from contact with normal air), the predominant species was a Pu(VI) hydrolytic form, with the possibility of some Pu(V) forming over time. In the natural brines, the Pu(VI) species disappeared from spectra after 6 days and no peak attributable to Pu(V) was observed. Final concentrations in these brines for Pu were about 5×10^{-5}M, which would make direct observation of Pu(V) doubtful; however, the authors conclude that the Pu has been reduced further to an unidentified species, possibly polymeric plutonium.

8.4b Solubility Issues Raised by Dr. Rodney C. Ewing After the February 20, 1998 Meeting Between the EEG and Sandia.

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Rodney C. Ewing

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ENVIRONMENTAL EVALUATION GROUP

February 22, 1998

Robert H. Neill, Director
Environmental Evaluation Group
Suite F-2, 7007 Wyoming Boulevard, NE
Albuquerque, New Mexico 87109

Dear Bob,

Thank you for inviting me to attend the technical exchange meeting between DOE contractors and the EEG on the subject of the actinide source term (AST) held this past February 20th. Since the time of the last meeting of the National Research Council's Committee on the Waste Isolation Pilot Plant (May, 1997), I have not had the opportunity to follow the progress of the AST program. I should also emphasize that I am no longer on the NRC WIPP Committee, and these brief comments represent my own views. I am not a representative or consultant for any committee or agency regarding the WIPP.

I want to emphasize my view of the importance of the actinide source term work. Although the NAS (1996) report on WIPP arrived at a positive evaluation of the potential for the WIPP as a repository for transuranic waste, the same report clearly identified outstanding technical issues, prominent among them was the issue of actinide solubilities in brine (page 5). Unfortunately, there was little of substance to review concerning the AST program at the time the WIPP committee completed its report in October of 1996. We concluded (page 62):

> "Overall, the scientific program outlined by DOE for study of the source term is adequate, provided that the program is carried to completion. Because the program at this time consists largely of work planned or in progress, it has not been possible to critically review experimental results or to judge whether these results are used appropriately in the PA analysis."

Thus, I believe the review of this topic by EEG and EPA is essential to establishing confidence in the data and models used for the AST in the performance assessment. I note that the most recent PA analysis suggests that the actinide solubilities in brine are of lesser importance; however, this conclusion is based on the new and revised view of transport in the Culebra and the introduction of the MgO backfill. In the event, either or both of these issues

change with further analysis or experimental results, then the role of actinide solubilities may again become important.

My general observations and comments include:

1. The oxidation state analogy and the FMT calculations appear to predict trends in actinide solubilities; however, this work still requires important experimental verification. The NAS (1996) report concluded (page 63),

   "Although some aspects of its geochemical behavior can be estimated by studies of other actinides using the oxidation state model, ideally, data for each oxidation state should be followed by experiments with plutonium."

   The presentations this past week only emphasized and confirmed the need for such experiments. Particularly important were the points made by the EEG consultant, Dr. Virginia Oversby, which were based on a critical review and use of data in the published scientific literature. It seems to me that the credibility of the project would be greatly enhanced by the comparison of FMT results to experimental results obtained outside of the project, as an example, studies of actinide solubilities in spent fuel or UO_2 corrosion experiments.

2. It certainly appears to be an opportune time to review the results and analysis of the source term test program (STTP) at LANL. The limited results presented, were used to conclude that the predicted actinide concentrations in brine are "conservative". In my view, the data only suggest that there are processes (not identified) that affect the actinide concentrations, and these processes, in general, lower the actinide concentrations.

   There was some mention of discontinuing some of these tests; however, considering the time, effort and expense required to begin and sustain these experiments, such a decision should be made only after careful review and analysis of the data from the STTP experiments. Although some of the experiments may have no present applicability to the WIPP project, DOE may want to consider the experiments in a wider context, as an example the interaction of actinides and clays may be important to other DOE projects; thus, there may be value to continuing even those experiments which are not now considered to be relevant to WIPP.

3. The project still is not in a position to present and discuss models of the longer term evolution of the chemistry of the WIPP system. In this regard, well constrained, simple, experiments with relevant actinides (e.g., Pu) that are designed to run for years are still much needed. I see no reason that such experiments cannot be initiated and run through the operational phase of the repository, and their results may be utilized in the recertification process. This is consistent with the recommendations of the NAS (1996) study (page 64). Similar experiments to study retardation in the Culebra would also be of value.

4. Concerning the report and comments by the EEG consultant, Dr. V. Oversby, I believe that some of the issues she raised can be rather directly addressed by the exchange of recent and relevant results, straightforward calculations, and/or limited additional experimental work. However, her approach to the review of the CCA, particularly in the areas of verification and validation, merit careful attention. I believe that she very commendably demonstrated the real meaning of a *critical* review by:

   i.) comparison of project results to the published literature (e.g., use of the NEA data base; UO_2 and spent fuel corrosion studies);

   ii.) comparison of results from project codes and models to more generally used and accepted geochemical code results.

I hope that these brief comments are of use to the project. You may give copies to this letter to DOE and EPA.

Sincerely,

Rod Ewing

cc: John Garrick, chair, NRC WIPP Committee
Thomas Kiess, staff officer, NRC WIPP Committee

8.4c Solubility Issues Raised by Dr. Virginia Oversby After the February 20, 1998 Meeting Between the EEG and Sandia.

Issues related to solubility of Pu at WIPP

1) Heterogeneous vs homogeneous equilibria

Calculations of solubility of actinides under WIPP conditions have been done assuming that before any release the repository will contain 29,841 cubic meters of brine that is well equilibrated. This assumption is doubtful and other models should be investigated to determine the effects of local variations in brine compositions and actinide speciation and concentration. After closure, the repository salt formation will creep and close up void spaces. Subsequent intrusion of brine, either as drilling fluid during an intrusion event or as intrusion of pressurized brine following penetration to layers below the repository, will add concentrated - if not saturated - brine solutions to the repository horizon. After fluid is added, the resulting physical state of the repository should still be one of rather low total porosity and have a high proportion of solids relative to fluids. In that case, equilibration of fluid compositions over large distances is unlikely, since the mechanism of mixing would be diffusion rather than advection. Local pockets of solutions with chemical compositions representative of the range of potential waste container soluble actinide inventory should be considered, rather than the grand average of the actinide inventory and brine compositions. This is particularly important for issues such as the complexation of Pu by citrate and/or cellulose degradation products, as well as the changes in solubility that may accompany presence of different alteration products of MgO.

2) MgO alteration products

The CCA calculations of solubility of actinides assumed that MgO backfill would alter to produce an equilibrium assemblage of brucite and magnesite. Later investigations indicated that the first phase formed from reaction of MgO with aqueous carbon dioxide dissolved in the brine would be nesquehonite. Calculations of actinide solubility in the presence of nesquehonite resulted in estimates of Th solubility (and, thus, other actinide (IV) elements) that were in the range of those calculated for the case without backfill. While it was argued that the longer-term phase would be hydromagnesite, nesquehonite might persist for rather long times.

At the meeting between WIPP staff and EEG on February 20, 1998, it was stated that the reason nesqhehonite had been found in the previously reported experiments was that a high pressure of carbon dioxide had been used. New experiments, with lower carbon dioxide pressure, produced an unidentified phase, persistent over at least 200 days, that was thought to be hydromagnesite.

Two issues remain to be resolved: 1) what is the identity of the phase in the new experiments, and 2) what is the effect of heterogeneous repository conditions on the pressure of carbon dioxide in local regions of the repository. Gas generation rates will depend on the local abundance of bacteria and microbes as well as the local abundance of materials that can degrade to produce carbon dioxide. An analysis of maximum gas generation rates in local areas is needed before it can be assumed that nesquehonite can not form.

3) Relative solubility of Th versus other actinides

As part of the rationale for using Th as an analog to estimate the solubility of other actinides in the (IV) oxidation state, the WIPP staff claim that Th always shows higher solubility than U(IV) and Pu(IV). While this has been shown to be the case for freshly precipitated Th and U hydroxides, it is not the case for the vast majority of materials that contain U and Th in natural settings - i.e., minerals containing U and Th. A vast body of geochemical data pertaining to the U-238 decay series shows that U leaches from minerals in preference to Th.

Th (and Pu) forms an amorphous solid when freshly prepared from solution by precipitation of the hydrous oxide. The solubility of this amorphous hydrous oxide can be quite high. With time, Th and Pu precipitates of hydrous oxides age into materials that have increasing degrees of crystallinity. As crystallinity increases, the measured solubility of the materials decreases. This is the major reason for the very large range of reported solubility data for Th and Pu oxides in the literature.

4) Solution speciation in solubility calculations

In order to evaluate the potential validity of calculated actinide solubilities one must closely inspect the identity of the solid phases assumed to control the brine composition and the speciation of the actinides in solution. As conditions change (e.g., identity of solids assumed to be present, or chemistry of the brine), the speciation of the actinides should change in a manner consistent with the changes in assumed solids and fluid compositions. Changes in speciation between two successive calculation that cannot be explained by rational chemical arguments are symptomatic of problems in the chemical data base or the calculational methods. An example of this type of problem was seen in the CCA calculations, where Th solubility was dominated by di- and tri-sulfate complexes in the no backfill case, but these species were calculated to be insignificant in the case where Mg was added. Detailed examination of the solution speciation did not indicate any reason for this drastic change in calculated speciation.

5) Calculations and measurements for pyrochemical salts

Tests underway at LANL using actual waste samples have produced conditions for which the calculated solution concentrations for Pu were greater than 0.001 M. The details of these calculations have not been presented. If the pH of the brines in contact with the pyrochemical salts is near neutral or higher, the high calculated solubility should not be greatly affected by the assumption of adding MgO to the system. Measurements of Pu-239 in these tests gave concentrations of about 1 E-5, which is higher than the concentration used in the CCA for demonstration of compliance with release limits. These high calculated and measured solubilities need to be investigated, particularly in light of the fact that inventories of Pu contained in chloride salts at Rocky Flats exceed 1 ton.

6) Direct estimates of solubility for U(IV) and Pu(IV)

The Nuclear Energy Agency (NEA) of the OECD has published a compendium of recommended values for the thermodynamic properties of U. Data from this volume (I. Grenthe, ed.) should be used to provide a direct estimate of the solubility of U(IV) in brines similar to those expected at WIPP. Also, data on U solubility in brines published in the open literature should be used as a means to estimate solubilities for U(IV) under WIPP conditions.

The NEA is also preparing a compendium of recommended values for the thermodynamic properties of Np and Pu (R. Lemire, ed.). This volume is in the final stages of preparation, so that any changes in the recommended data between the present draft and the final issued volume should be small. This volume could provide a sound basis for estimation of Pu solubility in WIPP brines.

7) Needs for additional experimental work

Direct measurements of solubilities of actinides under conditions that are assumed to be relevant for WIPP are needed. Some examples of the types of experiments needed are measurements of the solubility of Pu in brines in the presence of Fe, direct measurement of Pu speciation in brines, and solubility of actinides in the presence of the alteration phases of MgO, both at low and high carbon dioxide concentrations.

8.5 WIPP Related Geological Issues (Chaturvedi, 1993)

WIPP-RELATED GEOLOGICAL ISSUES

LOKESH CHATURVEDI
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Abstract — The Waste Isolation Pilot Plant (WIPP) is a proposed repository for disposal of defense transuranic (TRU) radioactive waste. Located in southeastern New Mexico, 25 mi (40 km) east of Carlsbad, the repository has been excavated in the Salado Formation bedded salt at a depth of 2150 ft (656 m) below the surface. The concept of geologic isolation of radioactive waste, with the half-life of the radionuclides measured in tens of thousands of years, is to primarily rely on the geologic barriers to keep the radionuclides from leaking to the biosphere. Several geologic features and processes have been identified during the site characterization of the WIPP site that could impact the performance of the repository for the 10,000 year regulatory period. These include salt dissolution breccia chimneys, brine reservoirs, Salado Formation hydrology, hydrology of the overlying Rustler Formation water-bearing units, disturbed rock behavior and natural resources. These geologic factors are being considered in the analysis of breach scenarios from the WIPP repository for the next 10,000-year period.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is being excavated and constructed to be a geologic repository for permanent disposal of defense transuranic (TRU) waste. It is located 25 mi (40 km) east of Carlsbad, New Mexico. In addition to support facilities on the surface to provide office space to workers and to receive and handle radioactive waste (Fig. 1), there are four shafts (waste handling, construction and salt hoisting, air intake and air exhaust shafts) that connect the surface to the underground facilities. The project is being administered by the U.S. Department of Energy (DOE), with Sandia National Laboratories

FIGURE 1. An aerial view of the WIPP (courtesy U.S. Department of Energy)

in charge of site characterization and most of the experiments and Westinghouse Electric Corporation as the managing contractors.

The repository is excavated at a depth of 2150 ft (655 m) below the surface and consists of an experimental area to the north and the main repository to the south of the shafts (Fig. 2). The experiments carried out in the northern part of the facility include mechanics of closure of excavations; effect of heat on closure and brine migration; development of plugs and seals to be used to plug the excavations, shafts and bore holes; and the effect of salt creep on the waste drums. The repository itself will consist of 56 "rooms," each 300 ft long, 33 ft wide and 13 ft high (91.5 m × 10 m × 4 m), divided in eight panels of seven rooms each. The seven rooms of the first panel were excavated between 1986 and 1988. Since the DOE had planned to start shipping radioactive waste to WIPP in 1988 for an "operational demonstration," Excavation for the other seven panels of the repository has not yet begun.

Transuranic waste consists of various kinds of trash including paper, rubber, wood, metals and sludges, contaminated with radionuclides heavier than uranium with half-lives greater than 20 years and a level of contamination exceeding 100 nanocuries per gram. The waste has resulted as a by product of nuclear weapons production in the United States during the past 50 years. Only waste retrievably stored since 1970 is presently planned to be shipped to WIPP. Two-thirds of the planned capacity of waste for WIPP is yet to be produced. Two categories of the TRU waste are currently stored at DOE-managed national laboratories and will be disposed at WIPP. The contact-handled (CH-TRU) waste is contained in 55 gallon (0.21 m³) mild carbon-steel drums that have a maximum surface-dose rate of 200 millirem per hour. The remote-handled (RH-TRU) waste will be disposed of in 0.85 m³ capacity cylindrical canisters with unshielded surface dose rate higher than 200 millirem per hour and up to a maximum of 1000 rem per hour. The 50 hectare WIPP repository has been designed to hold 850,000 drums (176,000 m³) of CH-TRU waste containing 9 million curies of radioactivity and 7,500 canisters (7100 m³) of RH-TRU waste containing 5 million curies. The CH-TRU waste drums will be stacked three high in 56 "rooms" to be excavated in salt. The RH-TRU canisters will be disposed in 36 in. (0.91 m) diameter and 10 ft (3 m) deep horizontal holes.

The TRU waste to be disposed at WIPP consists of both hazardous chemical waste and radionuclides. Its disposal should therefore be according to the requirements of the Environmental Protection Agency (EPA) Standards for the handling and permanent disposal of transuranic radioactive materials (U.S. CFR, 1985), as well as the requirements of the Resource Conservation and Recovery Act (RCRA) (U.S. CFR, 1991). The idea of permanent disposal of the radioactive waste is to isolate it from the environment for a very long period of time. The EPA Standards for radiation protection specify a time of 10,000 years for containment of the waste and require probabilistic risk analyses to assure that potential releases to the environment will have a low probability and not allow more than a specified amount of various radionuclides. The RCRA regulations require assurance of no releases of hazardous materials beyond a specified "unit boundary," which in the case of WIPP has been accepted to be the 2.5 mi by 2.5 mi (4 km × 4 km) WIPP site laterally and up to the top of the Salado Formation vertically.

A geological repository relies primarily on the geology of the site to provide containment of waste for thousands of years. This is especially true for the WIPP project, because there is no commitment to use critical engineered barriers for disposal of the TRU waste. Ninety seven percent (by volume) of the waste to be disposed at WIPP will be contained in ordinary mild carbon steel 55 gallon drums with an expected life of only 20 years, or in Standard Waste Boxes made of plywood or metal. The containers are expected to get crushed and corroded in a few years in the corrosive briny environment of a repository in salt beds and salt creep is expected to close the openings and form a cocoon around the waste. Geologic integrity and the absence of geologic and geohydrologic conditions or processes that may breach the integrity of the repository are, therefore, critical issues in assessing the suitability of the WIPP site for use as a permanent geologic repository for radioactive waste.

The purpose of this paper is to describe and discuss the geological features and processes that potentially may have an impact on the integrity of the WIPP site. Most of the geologic and hydrogeologic investigations pertinent to the WIPP have been performed by the scientists of the U.S. Geological Survey, Sandia National Laboratories, other contractors of the DOE and university researchers. The Environmental Evaluation Group (EEG) has analyzed the importance of various geologic issues and controversies as they have come to light from time to time and has proposed mechanisms and further investigations to resolve them. The EEG is affiliated with the New Mexico Institute of Mining and Technology and has offices in Albuquerque and Carlsbad. It was established in 1978 as an interdisciplinary group of scientists and engineers to provide an independent technical evaluation of various aspects of the WIPP project to protect the health and safety of the people of New Mexico. The group is funded 100% by the DOE.

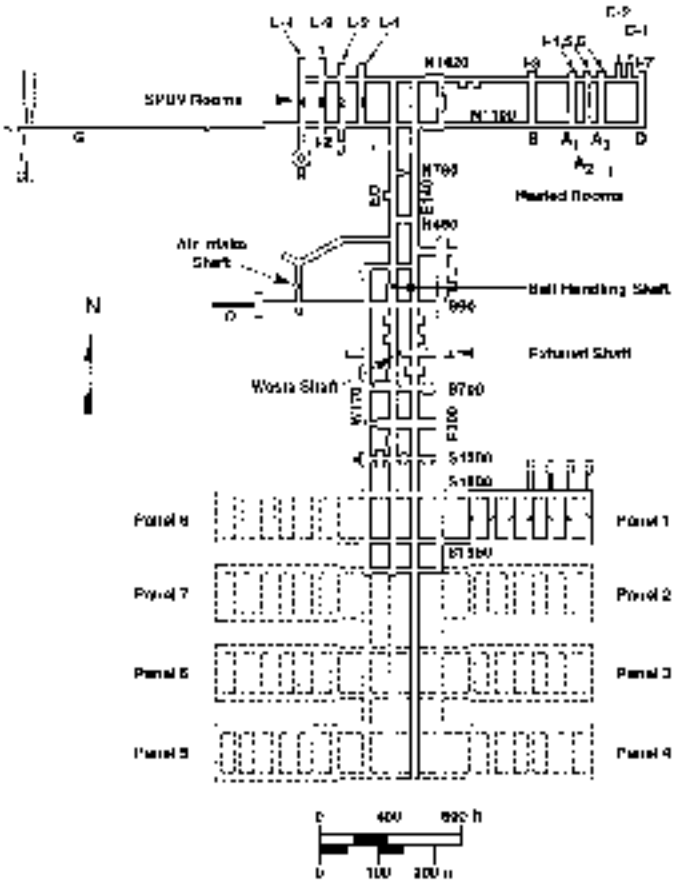

FIGURE 2. Underground layout of the WIPP repository.

GEOLOGICAL SETTING OF WIPP

The WIPP site is situated in the northern part of the Permian Delaware Basin. The repository is located at a depth of 2150 ft (655 m) from the surface in the Salado Formation of the Permian Ochoan Series. The Salado Formation is about 1975 ft (602 m) thick at the center of the WIPP site and the repository is situated at a depth of 1300 ft (396 m) from the top of the formation (Fig. 3). The Delaware Basin is bounded by the Permian Capitan Reef (Fig. 4). The basin contains about 15,000 ft (4575 m) of Paleozoic sedimentary rocks overlying the Precambrian basement. The formations of interest with respect to the WIPP project, from the oldest to the youngest, are the Bell Canyon Formation of the Delaware Mountain Group, the Castile, Salado, Rustler and Dewey Lake Formations of the Permian Ochoan Series, the Upper Triassic Santa Rosa Sandstone Formation that tapers from the east to the west across the WIPP site and the Pleistocene Gatuña Formation. A caliche layer known as the Mescalero caliche is consistently encountered underlying the surficial sands at the WIPP site.

The site lies on a generally flat plain covered with sand, caliche and

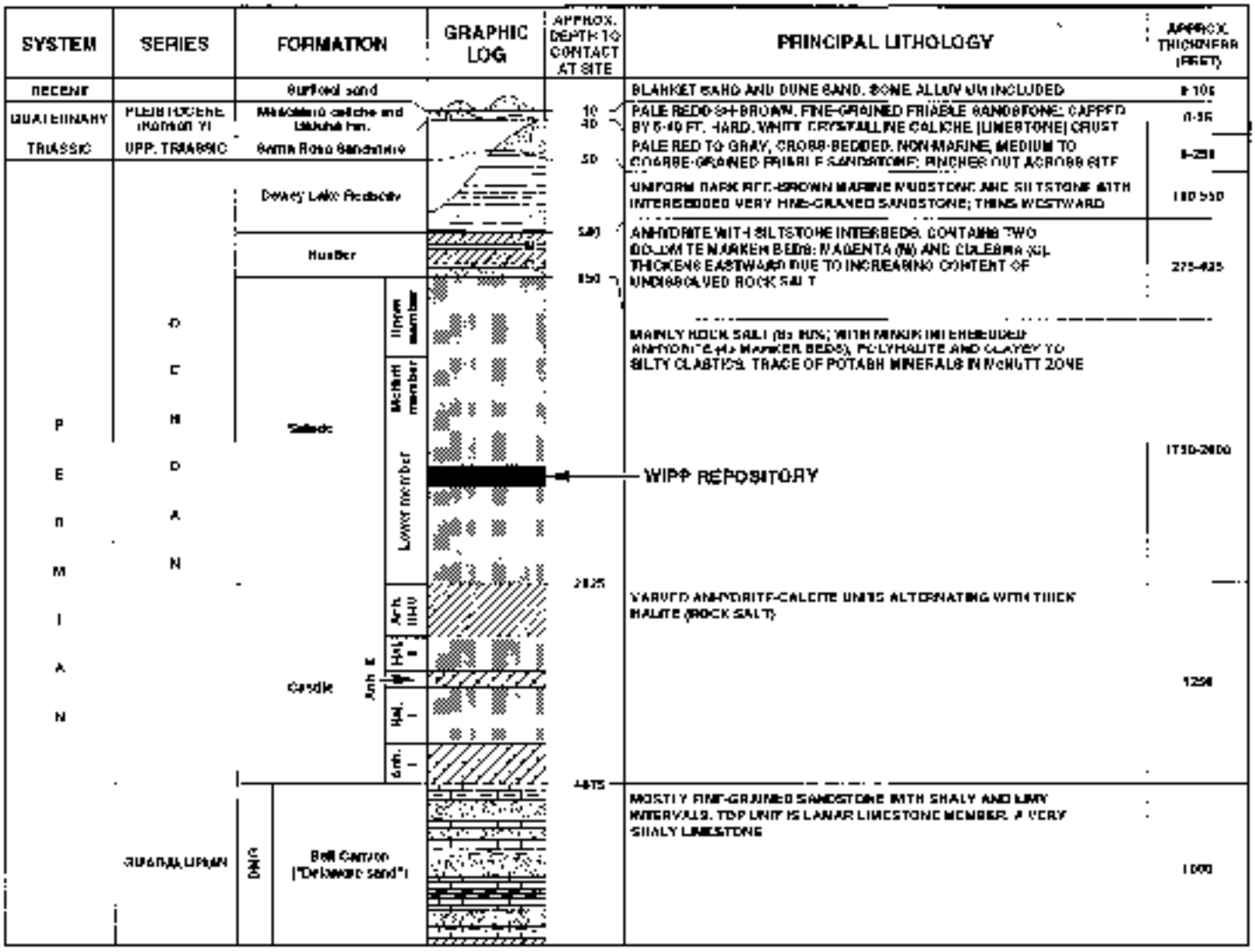

FIGURE 3 General stratigraphy at the WIPP site, including the complete Ochoan section and overlying strata, plus underlying Guadalupian Bell Canyon Formation (adapted from Fig. 4.2-2 of Powers et al., 1978)

desert bushes. It is located in a gypsum karst region. A subsidence landform feature called Nash Draw lies about 3 mi (5 km) west of the WIPP site. It is 6–7 mi (10–12 km) wide in the east-west direction, about 18 mi (30 km) long in the north-south direction and has resulted from erosion by solution and fill (Lee, 1925) of soluble rocks, a process that has occurred in the past and which is also presently active. The Pecos River flows from northwest to southeast, about 12 mi (20 km) west of the WIPP. Based on the presence of saline seeps along the Malaga Bend of the Pecos River (14 mi southwest of WIPP repository), a marked increase in the salinity of the river south of the bend and the general flow direction of the water bearing beds of the Rustler Formation, the Malaga Bend has been identified as an area of discharge of the Rustler water from Nash Draw and perhaps even from the WIPP site.

All the formations shown on Fig. 3 are geohydrologically significant. Ground water occurs in the upper part of the Bell Canyon Formation in poorly cemented sandstone stringers (Hiss, 1976). The Castile Formation is about 1500 ft (450 m) thick at the WIPP site and overlies the Bell Canyon. It consists of alternating layers of anhydrite and halite, with four anhydrite and three halite members. The uppermost anhydrite member contains pressurized brine reservoirs that have been encountered by two of the boreholes drilled for the WIPP project and by several oil and gas exploratory wells. The Salado Formation overlies the Castile Formation and the repository is located in its lower part (Fig. 3). The Salado consists primarily of halite with a zone of potassium- and magnesium-bearing minerals (sylvite, langbeinite) and thin (<3 ft) seams of clay, anhydrite and polyhalite. Before 1986, thick salt beds, as in the Salado Formation, were considered essentially dry and impermeable. Observations from the WIPP excavations, however, indicate that the salt beds may be saturated with brine and the salt may exhibit Darcian flow, albeit at very low permeability.

The Rustler Formation overlies the Salado and contains the most important geohydrologic units in the region. The thickness of the Rustler varies between 275 ft to 425 ft (84 m to 130 m) in the northern Delaware Basin and is approximately 310 ft (95 m) at the WIPP site. Sedimentology of the Rustler Formation was described by Lowenstein (1987) and Powers and Holt (1990). The formation contains three recognized fluid-bearing zones: in ascending order the Rustler-Salado contact residuum, the Culebra dolomite and the Magenta dolomite. The transmissivity of the Culebra is the highest, followed by the Magenta and the Rustler-Salado contact. The water quality is highly variable within each unit. The total dissolved solids concentration is lowest in the Magenta and highest in the Rustler-Salado contact zone. Nearly all the water in the Rustler Formation at the WIPP site has total dissolved solid (TDS) concentrations greater than 10,000 mg/l.

All three Rustler hydrologic units probably discharge into the Pecos River, 14 mi (22 km) to the southwest near the Malaga Bend. The recharge areas are identified rather imprecisely as being upgradient of

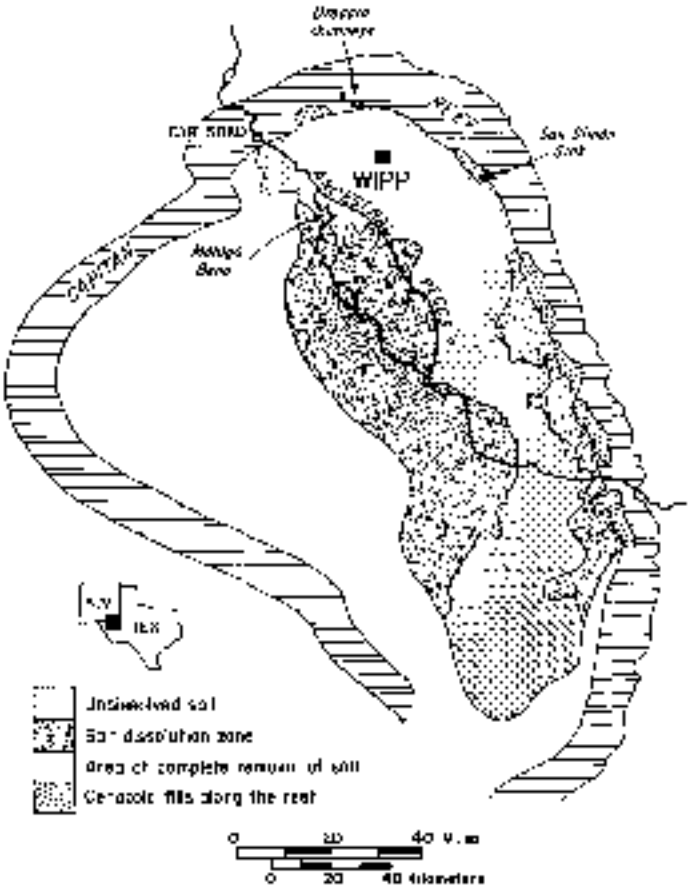

FIGURE 3. Regional extent of removal of salt from the Salado Formation.

the measured hydraulic heads, about 10 to 15 mi (16–24 km) north of the WIPP site. At the WIPP site, the three units are separated but are probably interconnected in Nash Draw, west and southwest of the site. Of the three Rustler units, the Magenta and the Culebra are of prime concern because they extend over the WIPP site, whereas the Rustler–Salado contact zone mainly produces water west of the WIPP site (Mercer, 1983). The majority of testing in the Rustler has concentrated on the Culebra because it is more transmissive than the Magenta and therefore better suited for analyzing boundary breach scenarios.

Results of several single hole and multiple flow tests (Rappin, 1988) at the site indicate that the transmissivities of the Culebra aquifer at and near the WIPP site range from 2000 ft²/day (10^{-3} m²/s) in Nash Draw to 10^{-2} ft²/day (10^{-7} m²/s) east of the WIPP site. Generally, transmissivity increases from east to west across the WIPP site. High transmissivity zones occur in the southeastern part of the site, in the area of boreholes DOE-1 and H-11 and in the north central and northwestern parts in the vicinity of boreholes WIPP-13, DOE-2 and H-6 (Fig. 5).

Chemical composition of ground water from the Culebra aquifer varies widely within short distances at and near the WIPP site (Chapman, 1988). Three miles south of the WIPP site, the Culebra water typically contains 3000 mg/l of total dissolved solids (TDS). At the site itself, TDS varies from 12,500 mg/l at H-2 (Fig. 5) to 130,500 mg/l at H-5. Extreme variation in the chemistry of the Culebra water within short distances is illustrated by the TDS at H-2 (12,500 mg/l), H-3 (134,500 mg/l) and DOE-1 (118,000 mg/l), within a distance of less than 2 mi.

The WIPP is situated in a mineral-rich area. Potash minerals are mined around the WIPP site from the McNutt potash zone in the upper part of the Salado Formation, approximately 1500 ft (450 m) below the surface. Oil and gas are produced around the WIPP site from the Permian Delaware Mountain Group and Pennsylvanian Atokan and Morrowan strata.

STATUS OF WIPP-RELATED GEOLOGICAL ISSUES

History of WIPP site characterization

The geological site characterization for the WIPP began in 1974, following the abandonment of the Lyons, Kansas site in 1972. A 2 mi by 1.5 mi (3.2 km × 2.4 km) rectangular site was selected by the Oak Ridge National Laboratory (ORNL) about 7 mi (11.2 km) northeast of the present site. Cores from two boreholes (AEC 7 and AEC 8, Fig. 5) penetrating through the Salado Formation drilled at the northeast and the southwest corners of that site indicated acceptable geology. Sandia National Laboratories (SNL) was given the responsibility for site characterization for WIPP in 1975. A third borehole (ERDA 6), drilled by SNL in the northwest corner of that original site in 1975, encountered a pressurized brine reservoir and intense structural disturbance in the fractured upper anhydrite of the Castile Formation at a depth of 2709 ft (826 m). The present site was selected by the SNL and the U.S. Geological Survey (USGS) and a stratigraphic borehole (ERDA-9) was drilled in 1976 through the Salado Formation at the center of the new 2.5 mi by 2.5 mi (4 km × 4 km) WIPP site.

Early site characterization activities focused on obtaining basic data on the stratigraphy, hydrology and mineral resources at the WIPP site. As these studies progressed, several geologic features or processes that were potentially deleterious to a radioactive waste repository were identified. The EEG organized a meeting of geoscientists in January 1980, and a field trip in June 1980, to discuss these geologic issues (EEG, 1980; Chaturvedi, 1980). Based on the recommendations from these meetings and independent analyses by the EEG scientists, the EEG proposed preparation of a number of topical reports to address the geological issues that had surfaced at that time. These recommendations were accepted by the DOE and a Stipulated Agreement between the State and the DOE was signed on 1 July 1981, that included the DOE commitment to prepare eleven "topical reports" and six "additional investigations." As a part of additional investigations, the DOE deepened the borehole WIPP-12, located 1 mi north of the center of the WIPP site, from its 1978 completed depth of 2737.5 ft (834.5 m) at the top of the Castile, to a total depth of 3921.5 ft (1197.4 m). Pressurized brine associated with hydrogen sulfide gas was encountered at a depth of 3146 ft (959.5 m). As a result, the DOE, following the EEG recommendation, again relocated the repository about 1.25 mi (2 km) south of the planned location that would have brought the repository within a few hundred feet of the WIPP-12 borehole.

The WIPP topical studies were published in 1983 and the DOE claimed that the geologic site characterization issues were resolved. The EEG reviewed the reports and concluded (Neill et al., 1983) that the site characterization work completed until then warranted confidence in the site, but work still remained to be done to answer the remaining questions. Underground excavation began in 1982 and additional issues came to light from the observations underground.

The more important geologic issues relevant to WIPP are described below and the status of their resolution is discussed.

Dissolution of Salado salt

There is indisputable evidence that the Ochoan evaporite deposits (Castile, Salado, Rustler and Dewey Lake formations) have undergone erosion and blanket dissolution in the Delaware Basin. The edges of the Castile and the Salado halite can be traced west of the Pecos River essentially running parallel to it in a northwest southeast direction (Anderson, 1981).

Based on a 600,000 year dating of the Pearlette O ash layer exposed at the ridge on the 200 ft (61 m) deep Nash Draw margin, Buchanan (1980, 1981) calculated an average rate of 150 ft (100 m) per million years for the vertical dissolution. Assuming that the edge of the Salado salt has moved from the Capitan Reef front to its present location during the past 7 to 8 Ma (since Ogallala time), Bachman and Johnson (1973) concluded that the horizontal rate of movement of the blanket dissolution front is about 6 to 8 miles per million years. These are, of course, very rough average rates of movement; the front itself may have moved faster under less arid climatic conditions. Also, an advancing "tongue" of the front may reach a point faster than the front itself. Using the

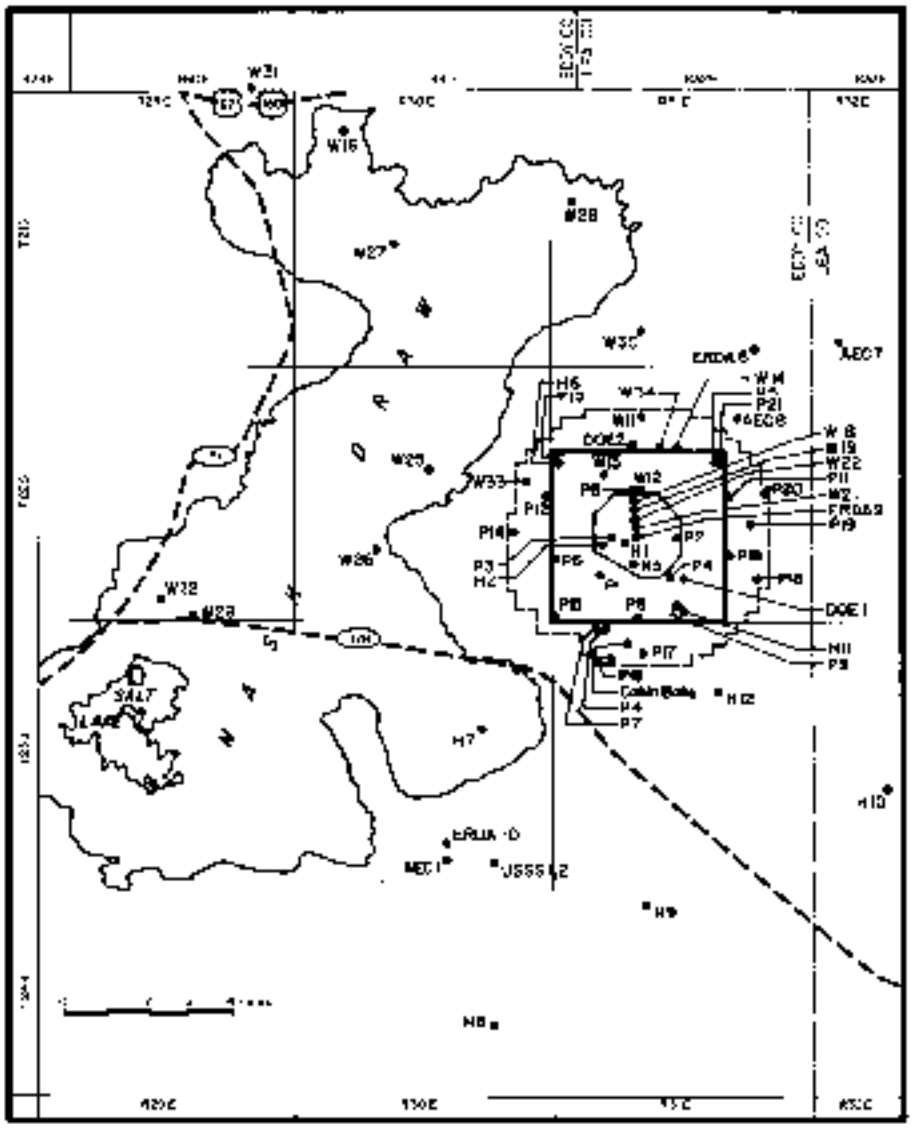

FIGURE 5 The location of boreholes drilled in connection with the WIPP project

above rates for horizontal and vertical dissolution, it would take approximately 225,000 years for the front to travel approximately 2 mi to reach the western edge of the WIPP site and start dissolving salt from the upper Salado, about 1500 ft (457 m) above the repository horizon. It would then require at least 2 to 3 Ma for the removal of 1500 ft (457 m) of salt by dissolution, at the rate of 330 to 500 ft (100 to 150 m) per million years. In spite of the very approximate nature of the estimated rates of advance of the dissolution front and the possibility of a more rapid advance of a segment of the front, these calculated rates provide sufficient safety from an advancing front of blanket shallow dissolution of salt toward the WIPP site.

In addition to the blanket dissolution of salt described above, Anderson et al. (1972) raised the possibility of a different kind of dissolution process acting at depth from the margins of the basin by noting that large quantities of bedded salt were missing from the middle of the evaporite sequence near the center of the basin. Using the correlation of acoustic logs across several lines in the Delaware Basin, Anderson (1978) concluded that (1) the preferred horizons from which salt has been removed by dissolution occur between the Halite III salt of the Castile Formation and the 136 marker bed of the Salado Formation and (2) the large depressions in the basin, first identified by Maley and Huffington (1953), were the result of selective dissolution of lower Salado salt beds. Anderson (1981) further developed the idea of deep-seated dissolution and concluded that such dissolution has occurred around the margin of the basin where the Capitan aquifer is in contact with the Permian evaporites, and within the basin where selective dissolution in the lower Salado has undercut the overlying salt beds. He calculated that more than 70% of the original salt has already been removed from the lower Salado horizon in the basin.

As requested by the DOE, Lambert (1983) prepared a topical report on the dissolution issue for the WIPP project. Another WIPP project report (Wood et al., 1982) examined the viability of the Delaware Mountain Group aquifer removing the dissolved salt, as hypothesized by Anderson (1981). The EEG (Chaturvedi, 1982; Neill et al., 1983; Chaturvedi and Rehfeldt, 1984) examined the deep-dissolution hypothesis and concluded that although the timing and the mechanism were not fully explained by the hypothesis, the evidence from geophysical well logs did indicate that a large amount of salt from the lower Salado units was missing. However, there were eight WIPP project boreholes (AEC-7 and AEC-8 to the northeast, ERDA-10 to the southwest, WIPP-11 to the north and WIPP-9, 12, 13 and DOE-1 within the WIPP site, see Fig. 5), which had obtained cores of the Salado Formation but did not show any evidence of extensive dissolution. From this, the EEG concluded (Chaturvedi and Rehfeldt, 1984) that the Salado Formation does not appear to have been affected in and around the WIPP site by past regional dissolution at depth, although an area located 2 mi (3.2 km) north of the center of the WIPP site was suspected as a potential area of point-source dissolution. At the urging

of the EEG, the DOE drilled a 4325 ft (1319 m) deep corehole (DOE-2, Fig. 5) to investigate the origin of this feature, which was identified as a structural depression on the basis of observed depression in the anhydrite/clay marker-beds in the potash industry boreholes.

The core from the DOE-2 borehole confirmed the existence of the structural depression but showed no indication of this being due to dissolution at depth. The absence of any dissolution residue and a thickened halite section can best be interpreted as due to gravity-driven salt flow in the area (Borns, 1987). The WIPP repository is no longer considered to be threatened by the effects of the Salado salt dissolution at depth.

Breccia chimneys

A breccia chimney is a solution-subsidence structure formed by dissolution of an evaporite layer at depth that results in collapse of the overlying layers, thus forming a brecciated chimney up to several thousand feet in diameter with its base in the collapsed cavity. These features are found in many evaporite basins of the world. With respect to the WIPP, the concern was that a breccia chimney may form under the WIPP repository sometime in the future, thereby providing a potential pathway for breach of the repository.

Vine (1960) identified as possible breccia chimneys several domal structures in the Delaware Basin that have been explored during the investigations for WIPP. After extensive investigation, the existence of only two chimneys (Hills A and C) was confirmed. Geophysical and geological studies show that two others (Hills B and Wills-Weaver) are also likely breccia chimneys, although they were not cored. All of these features appear to be situated over the Capitan Reef limestone, which is a prolific aquifer in the area. Davies (1983) pointed out that the Hill "C" breccia pipe is located at the southern edge of the buried Capitan Reef and since the borehole WIPP-16, drilled to explore this chimney, was drilled only to the level of the McNutt potash zone of the Salado formation, it is not clear whether the Hill "C" breccia chimney roots in the Capitan aquifer.

Besides boreholes WIPP 31 and WIPP 16, which were drilled at Hills A and C, respectively, to investigate the breccia chimneys, three other boreholes were drilled at suspected breccia chimney locations in the basin. Borehole WIPP-32 was drilled in a small topographic high in Nash Draw, which had been described by Vine (1963) as a domal karst feature. These features (domal karst) have been extensively studied by Bachman (1980, 1984). Boreholes WIPP 12 and WIPP 33 were also drilled to explore for possible breccia chimneys. There is a marked electrical resistivity anomaly at WIPP 12 and a prominent topographic depression exists at the location where WIPP-33 was drilled. Collapsed breccia was not found at either of the wells.

Anderson and Kirkland (1980) described the occurrence of collapse breccia in a borehole in Culberson County, Texas, about 55 mi south of the WIPP site. Anderson (in Chaturvedi, 1980) described occurrences of "castiles," which are mounds of brecciated rock that crop out a few miles south of the New Mexico–Texas border, south of the WIPP site. Both occurrences are in the exhumed western part of the Delaware Basin, which has already undergone extensive dissolution.

Snyder and Gard (1982) studied the known occurrences of breccia chimneys in the Delaware Basin. They studied in detail the Hill "C" breccia chimney, which is also encountered at the McNutt potash zone of the Salado Formation in the Mississippi Chemical Company potash mine, 1200 feet (366 m) below the surface. From study of this exposure, the core of WIPP-16 drilled in this chimney and the core of WIPP-31 drilled in the Hill "A" breccia chimney, Snyder and Gard (1982) concluded that the breccia chimneys are formed by collapse of the overlying rocks in solution cavities in the Capitan Reef aquifer. Bachman (1980) hypothesized that the location of all the known breccia pipes in a small area over the reef is due to the presence of an old submarine canyon in the reef in this area. On the basis of the presence of Miocene caliche over the breccia pipes, Bachman (1980) also concluded that the collapse occurred prior to the deposition of this caliche layer, i.e., more than 0.5 Ma.

Davies (1984) also studied chimneys A and C and concluded that they were produced by salt dissolution at the base and within the lowermost portion of the Salado Formation, through incremental subsidence rather than catastrophic collapse of the overlying strata. The EEG concluded (Neill et al., 1983) that the probability of a breccia chimney forming under the WIPP site was fairly remote and that this phenomenon did not appear to pose a threat to the WIPP repository.

Brine reservoirs

Within a few miles of the WIPP site there are at least sixteen reported encounters of pressurized brine in the upper anhydrite layer of the Castile Formation (Fig. 6). Two of these encounters (ERDA 6 and WIPP 12, Fig. 5) were in the WIPP project boreholes and the rest have been reported by oil and gas drilling companies. When borehole WIPP 12, located 1 mi (1.6 km) north of the center of the WIPP site, hit brine at a depth of 3016 ft (919.5 m), brine started flowing out of the well at a rate of 350 gallons per minute (22 liters/sec) and more than 1.14 million gallons (4.3 million liters) of brine flowed out before the well was controlled. Based on an extensive series of flow tests, the brine reservoirs penetrated by the WIPP-12 and ERDA-6 boreholes were estimated to contain 17 million barrels (2.7 billion liters) and 630,000 barrels (100 million liters) of brine, respectively (Popielak et al., 1983). The different pressure potentials and geochemical data from the two encounters suggested a lack of communication between the ERDA-6 and WIPP-12 brine reservoirs. There was no consensus on the origin and the age of the brine reservoirs.

The planned configuration of the WIPP repository and the WIPP experimental areas would have brought the waste within 460 ft (140 m) south of the WIPP-12 borehole. The EEG recommended moving the repository in 1982 and the DOE rotated the repository configuration to relocate the nonwaste experimental area to the north and the repository 1.2 mi (2 km) south of WIPP-12. In 1983, EEG formally proposed geophysical investigations to delineate the extent of pressurized brine in the Castile Formation underlying the WIPP site and particularly under the new location of the repository. The work was performed in 1987, and the results gave a clear indication of the presence of brine under parts of the WIPP repository (Earth Tech. Corp., 1988).

The presence of brine reservoirs in the Castile Formation is a major geological issue affecting the anticipated performance of the repository. Since there are good geophysical indications of the presence of brine in the Castile Formation, 800 ft (244 m) or so below the repository, the inadvertent drilling to a brine reservoir through the repository is a scenario that the WIPP project has to evaluate. Such a drilling sometime during the next 10,000 years would allow pressurized brine to flow into the repository. Several pathways for injection of such contaminated brine into the Rustler Formation or directly to the surface have been postulated.

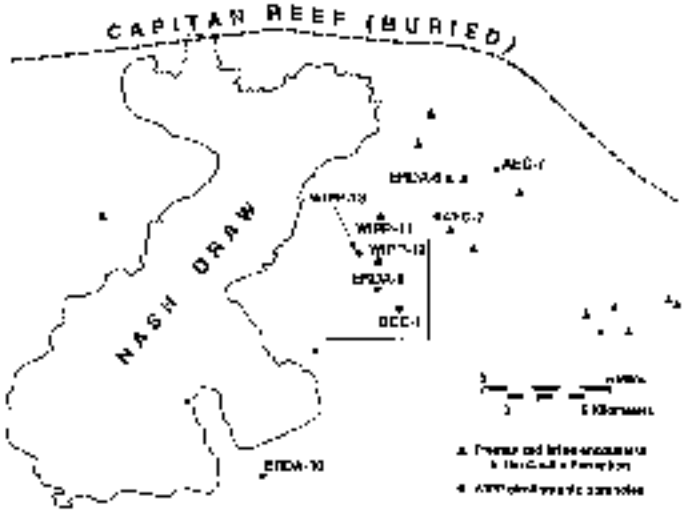

FIGURE 6. Pressurized brine encounters in the Castile Formation in the vicinity of the WIPP site.

Salado brine

A reason for selecting bedded salt deposits for isolating radioactive waste was the assumption that salt would be essentially dry. One of the surprises encountered by in situ underground studies at the WIPP is that the Salado salt yields a fair amount of water. A large percentage of boreholes drilled down from the WIPP excavations fill up with brine and the walls are covered with efflorescences and encrustations resulting from brine inflow from salt into the excavation and drying up by ventilated air. Several boreholes completed in the Salado Formation indicate fluid pressure buildup (Mercer, 1987). In situ Salado salt has low (10^{-21} m^2), but measurable, permeability.

Bredehoeft (1988) proposed that the Salado salt is saturated with brine and exhibits Darcian flow. Nowak et al. (1988) calculated that for salt permeabilities of 10^{-21} to 10^{-19} m^2 (1 to 100 nanodarcies), between 4 m^3 to 44 m^3 of brine would accumulate in a typical WIPP repository room with dimensions of 300 ft × 33 ft × 13 ft (91.5 m × 10 m × 4 m). Since the WIPP CH TRU containers are ordinary 55-gallon mild carbon steel drums that are not expected to last much beyond their 20-year design life, the brine would mix with the TRU waste and may form a slurry. Sandia National Laboratories (1987) calculated that if someone drills into such brine slurry and inadvertently brings a part of it to the surface, EPA Standards may be violated.

Corrosion of the metal containers and metal in the waste would produce hydrogen. Microbiological degradation of the organic material in the waste would produce carbon dioxide and methane. These processes require water to produce gas and the Salado brine inflow will satisfy that need. The rate of brine inflow in the repository is therefore a very important parameter for assessing breach scenarios. DOE has been monitoring and sampling the Salado brine from 13 boreholes in the WIPP underground since 1984 (Deal et al., 1991). After five years of observation, five 50 ft (15 m) deep holes have remained steady producers of brine, one showing increased brine production and five showing decreasing rates. One step in the floor has produced between 0.15 to 0.2 gallons (0.5 to 0.75 liters) of brine per day for five years. Several holes in the roof and in the walls also have been producing brine.

Hydraulic testing of the Salado Formation at the WIPP repository horizon (Beauheim et al., 1993) shows the brine flow in the Salado salt to be Darcian in nature because the Darcy flow models are able to replicate the flow and the pressure behavior observed during the entire testing sequences involving different types of tests. The estimation of brine inflow by Nowak et al. (1988) appears to be on sound theoretical basis. Estimation based on actual inflow observation for a long time, under progress now, would provide confirmatory evidence of this calculation.

Rustler Formation hydrology

The Culebra dolomite member of the Rustler Formation, being the most prolific of the three water-bearing zones overlying the WIPP repository, is the most likely pathway for transport of radionuclides after a breach of the repository. Based on three multiwell flow tests, several single-well flow tests and nonsorbing tracer tests at four hydropads, LaVenue et al. (1990) performed ground water flow modeling of the Culebra at the WIPP site. The flow model suggests that if radionuclides are injected into the Culebra directly above the repository panels near the center of the WIPP site, the fastest flow path out of the WIPP area would be to the south-southeast past the boreholes H-3 and H-11 (Fig. 5).

The calculated travel time for contaminant transport along this pathway, however, is very sensitive to assumptions of fracturing in the Culebra dolomite and distribution of contributing porosity between the rock matrix and the fractures. If double-porosity flow is assumed, with diffusion of contaminants in the rock matrix, the shortest travel time from the center of the WIPP site to the southern boundary is 14,000 years. If, on the other hand, transport is assumed through fractures only (single porosity), then the travel time would be less than 100 years. Additional multiwell flow tests are required to better define the transmissivity field at the WIPP site. Additional tracer tests designed to better define the fracture vs. matrix porosity flow are also needed. The breach scenario calculations have identified radionuclide retardation during contaminant transport through the Culebra as one of the sensitive parameters that control the magnitude and timing of the postulated releases of radioactivity to the environment. Field and laboratory experiments are required to provide reliable and justifiable numbers for physical and chemical retardation. Laboratory experiments are being set up and initial results are expected in 1993 or 1994.

The WIPP site is situated in a gypsum karst area. The subsidence feature called Nash Draw has been formed by the karstic process of solution and fill (Lee, 1925; Bachman, 1980, 1984). The depression in which borehole WIPP-33 (Fig. 5) was drilled is a karst sink. No positively identified karst feature has been encountered east of WIPP-23 in the WIPP area, nor have hydrologic tests in the area detected any channelized flow. Breach scenario calculations have not considered potential releases through channelized flow or through narrow transmissive layers due to vertical heterogeneity. Such conceptual models would result in greater releases, as shown by Chaturvedi and Channell (1985).

Beauheim and Davies (1992) have proposed a sever-well flow and tracer test to be fielded between H-9 and DOE-1. This test is designed to address the questions of vertical heterogeneity and matrix diffusion and would provide data to better characterize the flow mechanism. It is also intended to use the instruments for a field nonsorbing tracer test for providing data on chemical retardation processes and properties within the Culebra. This test is planned to begin in 1993.

Disturbed rock behavior

Before underground excavation at WIPP began in 1982, DOE scientists performed calculations to predict the closure history of the excavations. These calculations used the geomechanical properties of the rock strata at the selected WIPP repository horizon obtained from testing of the rock cores from boreholes. The calculations predicted that a WIPP room would "close slowly in a stable manner as the salt creeps" and "relative closure values of 0.21 m (8.25 in.) in the vertical direction and 0.28 m (11 in.) total in the horizontal direction are seen for the isothermal room after 10 years" (Miller et al., 1982). The WIPP excavations have behaved very differently than predicted. Vertical closure in the WIPP test rooms has varied between 3 in. (75 mm) and 4 in. (100 mm) *per year* and horizontal closure has ranged between 2 in. (50 mm) and 3 in. (75 mm) *per year*. A "disturbed rock zone" consisting of fractured rock surrounds all the excavations. In less than eight years after excavation, the roof of the first of the four test rooms fell in February 1991, due to fractures propagating above the roof and creating an up to 7 ft (2 m) wide unstable trapezoidal beam between the roof and a thin layer of anhydrite above the roof.

The difference between the predicted and measured closure rates has been explained on the basis of use of the wrong geomechanical models and not taking into account the details of the stratigraphy (Munson et al., 1989). While the faster closure rate will help entomb the waste sooner, it creates problems during operations. The WIPP repository rooms should be excavated just before they are needed for waste emplacement and backfilled soon thereafter. It will also create problems in maintaining retrievability of the waste. Due to its interaction with brine inflow and gas pressure from gases produced by the waste, the room closure rate also affects long-term performance of the repository.

Natural resources

The WIPP site is located in a region that contains substantial amounts of potash, natural gas and petroleum resources. Therefore, breach scenarios involving inadvertent drilling by future generations must be considered. The EPA Standards 40 CFR 191 (EPA, 1985, App. B) prescribed a limit of assuming 30 boreholes/km^2/10,000 years, which was based on the drilling frequency in the WIPP site vicinity in 1970s. Judging by the number of producing wells, drilling activity around the WIPP site in 1992 and the number of applications to the U.S. Bureau of Land Management for new drilling permits, the oil and gas resources in the WIPP area are much more prolific than previously considered. This fact must be taken into account in the assessment of the WIPP's compliance with the EPA Standards.

CONCLUSIONS

Since the WIPP repository is designed to rely on geologic isolation for 10,000 years, consideration of the various geologic features and processes are very important to assess the capability of the site to keep the waste isolated from the environment. The impact of the potentially deleterious geologic factors on the repository will be judged on the results of consequence analyses of potential breach scenarios.

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8.6 Letter Reports of EEG Consultants on the K_d Issue

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ENVIRONMENTAL EVALUATION GROUP

August 5, 1997

Dr. Robert H. Neill
Director, Environmental Evaluation Group
7007 Boulevard, N.E., Suite F-2
Albuquerque, NM 87109

Dear Bob:

Following are some thoughts based on my attendance at the DOE/EEG Meeting on Chemical Retardation in Albuquerque on July 30, 1997, and on related reading. I have ordered the discussion topics as they were set forth by Dr. Lokesh Chaturvedi of EEG in his introductory presentation.

Transferability of Lab K_d Data to Field

Transferability has always been an issue of concern. My understanding is that a consensus now exists that groundwater flow in the Culebra is slow enough to guarantee that important diffusion of the groundwater into rock matrix will occur. If this is the case then the radionuclides in groundwater will have ample opportunity to access mineral surfaces in pores in the dolomite, making laboratory measured batch K_d values applicable to the field.

The Limited K_d Data Base

The limited K_d data base remains a serious problem. We can all agree that K_d values for the important actinides Pu, Am and U, regardless of oxidation state, probably equal or exceed 1 ml/g in Culebra groundwaters, which is necessary for compliance. However, the hydrologic model for the Culebra and associated groundwater flow mechanisms and travel times in the formation have non-zero uncertainties. It is unclear how much these hydrologic uncertainties contribute to the uncertainty of assigning a minimum compliance K_d value of 1 ml/g. Given this additional hydrologic uncertainty, if I were a regulator, I would be much more confident that the site was in compliance if the DOE's recommended K_d's for the important actinides were at least 10 to 100 times greater than 1 ml/g. As discussed below, the approach used by the DOE for estimating unmeasured K_d values involves questionable assumptions.

K_d Estimation Methods used by the DOE

The DOE proposes that K_d values for actinide cations of the same charge should be roughly the same. This approach has been used by many others. (See discussion below). Its weakness lies in the fact that such approximations assume that differences in the speciation behavior of the cations does not affect their adsorption and can be neglected.

The second assumption used by the DOE to estimate K_d values, is that predictable trends exist among the K_d's of actinide cations of different charge. The DOE assumed that such trends

identified by Canepa (1992)[1] in dilute, J-13 groundwaters at Yucca Mountain would apply to WIPP brines. Canepa (1992) proposed that K_d values for actinides in J-13 groundwater should decrease in the same order as their solubilities increased in the same groundwater. The reported solubility data for U(VI), Np(V), Pu(IV)[2] and Am(III) plotted linearly, seeming to support her contention. This led to the proposal that K_d values should decrease in the order Am(III)>Pu(IV)?>Np(V)>U(VI). The DOE has suggested that the same order of K_d values should apply in groundwaters at the WIPP site. However, recent solubility measurements performed at LANL indicate that Np(V) solubility is about 10 times lower than assumed by Canepa (1992). The computed solubility of Np in J-13 groundwater is in fact as low as 10^{-7} mol/L (Langmuir, 1997, p. 534)[3], about 10^{1} less than suggested by Canepa (1992). Similarly, the solubility of U(VI) in J-13 groundwater may also be about 10^{-7} mol/L, 10^{1} to 10^{3} times lower than proposed by Canepa (cf. Langmuir, 1997, p. 533). Assuming as did Canepa (1992), that the actinide solubilities in J-13 groundwater should be inversely proportional to their K_d values, these changes suggest that the order of decreasing K_d's in J-13 and in WIPP groundwaters should be Am(III)>U(VI)>Pu(IV)>Np(V).

In fact, in general K_d values are probably not inversely proportional to the solubilities of the actinides. Thus, in a summary of adsorption trends among the actinides, Langmuir (ibid, p. 536) reports that K_d's decrease in the order Th(IV)>Am(III)>Np(V) for the adsorption of these actinides by Al_2O_3 as evidenced by respective pH values of 2.4, 5.8, 7.3 at 50% of each species adsorbed. Similarly, as pH is increased, goethite has adsorbed 50% of Pu(IV), U(VI) and Np(V) at pH values of 3.2, 4.2 and 7.0, respectively. This is therefore also the order of their decreasing K_d's (Langmuir, ibid, p. 537). Also, based on a literature survey, Silva and Nitsche (1996)[4] propose a general order of decreasing K_d's for the adsorption of actinides (An elements) by the same sorbents, of An(IV)>An(III)>An(VI)>An(V), in general agreement with the abbreviated adsorption series listed previously. Based on the plot of Canepa (1992), the DOE argues in the CCA, that estimated K_d values for Am(III) and Pu(III) should be greater than the measured K_d for Pu(V). Although their conclusion is based on the questionable data and assumptions in Canepa (1992), the same trend of K_d values for these species is fortuitously observed within the adsorption trends for the actinides reported by Langmuir, (1997) and Silva and Nitsche, (1996).

Availability and Reliability of Measured K_d Values

At the July 30, 1997 meeting in Albuquerque, the DOE presented the results of adsorption measurements performed in both column and batch tests. Results of the intact core column tests are probably of questionable value for determining Am(III) and Pu (V) (Pu(IV)?) adsorption K_d's , in that the Am and Pu input concentrations to the cores were high and so close

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[1]Los Alamos National Laboratory

[2]The oxidation state of Pu may have been a mixture of IV, V, and VI.

[3]Aqueous Environmental Geochemistry. Prentice Hall, Upper Saddle River, NJ, 600 pp.

[4]Actinide Environmental Chemistry. Radiochim. Acta, in press.

to saturation with solids, that precipitation rather than adsorption may have occurred. The Th(IV) column adsorption experiments and their results were not discussed at the meeting.

Useful batch adsorption results have been reported for Pu(V), U(VI), Th(IV) and Np(V). Performance assessment indicates that the important actinides at WIPP are Pu and Am, with U of tertiary importance. Based on oxidation state predictions, Pu(III) and Pu(IV) are the dominant Pu oxidation states in WIPP brines. Unfortunately, Am(III) batch adsorption experiments have given inconclusive results, and batch adsorption of Pu(III) and Pu(IV) has not been measured. Thus, the K_d values for the most important actinides in WIPP brines have had to be estimated.

K_d Values Chosen for the CCA

In the CCA, it was conservatively assumed that the lowest K_d values measured in the Culebra Dolomite or deeper Castile or Salado brines would be assumed for performance assessment (PA). Ranges of K_d values for the actinide cations proposed in the CCA are given in Table 1.

Table 1. K_d values used by DOE in the WIPP 1996 Compliance Certification Application (CCA) (assumes uniform distribution). Bold values are based chiefly on batch adsorption measurements discussed by L.H. Brush in his June 10, 1996 memo to M.S. Tierney of Sandia Natl. Laboratories. The probable order of decreasing K_d's in column 7 is based on earlier discussion in the text.

Oxidation State	Am	Pu	U	Th	Np	Probable Order of Decreasing K_d's
III	20-500 (no data)	20-500 (no data)				2
IV		900-20,000 (no data)	900-20,000 (no data)	**900-20,000**	900-20,000 (no data)	1
V		**20-500**			**1-200**	4
VI			**0.03-30**			3

The DOE reported a measured batch K_d of 20-500 ml/g for Pu(V), a species not expected in WIPP brines. Based on adsorption trends, the K_d for Am(III) and Pu(III) should be greater than its value for Pu(V). Given this assumption, the DOE conservatively assumes the K_d for Am(III) and Pu(III) equals the range measured for Pu(V). One could as well argue that the lower measured K_d range of 1-200 ml/g for Np(V) adsorption could instead have been assumed conservatively for Am(III) and Pu(III).

In summary, the most important actinides in WIPP brines are Pu(III), Pu(IV) and Am(III). The DOE has used the Canepa (1992) report and limited batch adsorption data to estimate K_d values for these actinides in WIPP brines. Although the estimated K_d values used in the CCA are probably conservative, it is most unfortunate that Am(III), Pu(III) and Pu(IV) adsorption has not

been measured. I understand that batch adsorption experiments designed to obtain K_d values for these actinides would not be particularly difficult to perform, and might be completed in a few months. It is also possible that accelerated intact column tests could be run in a few months using an ultracentrifuge. Admittedly, resultant K_d's can be predicted to exceed 1-3 ml/g. However, having measured instead of estimated values for the key actinide species would greatly improve confidence that K_d values for the most important actinides are in compliance with regulations.

Solubility Controls on Am, Pu, U and Np Concentrations in WIPP Brines

According to an unpublished July 6, 1996 Sandia report by Stockman and Stockman, titled "Constraints on Actinide Oxidation State in the Culebra: Reaction Path Mixing Calculations", the Culebra Dolomite contains an average of 0.17% FeO. These authors also note that 20 polished sections of the Culebra from 9 WIPP-area boreholes contained pyrite (FeS_2) in every section. The redox state of the rock will ultimately control redox conditions in the WIPP brines. In the absence of a source of free oxygen, reducing conditions are likely to dominate groundwaters away from the waste. Ferric iron staining is common in the Culebra. Eh values in the brines are thus likely to be poised by reactions between either ferroan dolomite and the Fe(III) oxyhydroxides, or pyrite and the Fe(III) oxyhydroxides.

In the vicinity of the waste, iron and nickel metal and organic matter will also tend to deplete any oxygen introduced with the waste. Reduced Fe, S and C in the waste and the rock are likely to cause reduction not only of Pu(V) to Pu(IV) and Pu(III), but may also lead to reduction of U(VI) to U(IV) and Np(V) to Np(IV). If these reductions take place, then maximum concentrations of Pu, U and Np may be limited by the solubilities of their quadrivalent oxides or hydroxides to values of 10^{-8} mol/L or less. If maximum concentrations of Pu and U are so limited, then the adsorption behavior of higher oxidation states may be irrelevant to performance assessment.

In carbonate-rich groundwaters, the concentration of Am(III) is limited by the solubility of Am(III) hydroxy-carbonate to values below 10^{-4} mol/L between about pH 7.5 and 9 (Langmuir, ibid). In WIPP brines at high pH's in the presence of MgO to scavenge the carbonate, $Am(OH)_3$ solubility may limit Am(III) concentrations at similarly low concentrations.

Limited solubility data for these actinides in WIPP brines is available. However, those of Am(IV) species in particular are likely to be well below 10^{-8} mol/L in the presence of MgO and in the absence of carbonate. It would be useful for the DOE to evaluate and report on the available solubility data for these actinides measured in WIPP brines and in similar brines. The brine solubilities of analog rare earth cations and analog actinides such as Th(IV) would also shed light on the probable behavior of Am(III), Pu(III) and Pu(IV) in WIPP brines.

Non-Culebra Dolomite

The Kd's for U(VI) adsorption by Norwegian dolomite are within the range of values for U(VI) adsorption by Culebra Dolomite. This is reasonable. That this pure dolomite adsorbed more U(VI) than some Culebra Dolomites that contain other sorbing minerals, does not strike me as an issue of concern.

Effect of Organic Ligands on Actinide Complexing and Adsorption

It seems probable as argued by Vann Bynum, that organic complexing of actinides does not significantly increase their solubilities or adsorption behavior in the vicinity of the waste. This reflects the competition of more abundant cations such as Ni^{2+}, Ca^{2+} and Mg^{2+} for organic ligands such as EDTA. Also important is the fact that actinides such as Th(IV), Pu(IV) and Np(IV) form strong OH complexes at neutral to alkaline pH's so that their free ion concentrations are many orders of magnitude lower than the free ion concentrations of Ni^{+1}, for example. Van Bynum made his calculations ignoring hydrolysis of the actinide cations, and still found less than 1% of Th(IV) complexed with EDTA, the strongest organic complexer. If he had corrected for Th-OH complexing, orders of magnitude less Th would have been complexed by EDTA.

It would be most convincing if the actinide complexation reaction calculations were rerun, but including OH and other inorganic actinide complexing, and varying (increasing) the amount of EDTA in the waste within possible ranges, to more rigorously disprove the importance of actinide-organic complexing near the WIPP waste.

Kd's Based on the Intact Column Test Results

As noted earlier, the Pu(V) and Am(III) column test results are of dubious value for determining K_d values for these actinides. Because of the high concentrations of Pu(V) and Am(III) in intake solutions, they could have been precipitated as solids rather than been adsorbed in the columns. If so, their concentrations in the rock cannot be used to define K_d values. In order to prove or disprove this concern, if possible, it is recommended that the core materials that have been drilled out be examined to identify whether the Pu and Am are present in adsorbed or 3-D solid phase form. It is also unclear whether the Pu is adsorbed as Pu(V) or as a lower oxidation state such as Pu(IV). The similar K_d values for Pu(V) and Th(IV) found in batch tests with ERDA-6 brines (about 10^5 and $10^{5.4}$ ml/g) suggest that the Pu may be adsorbing as Pu(IV). We were never shown tomographic results of the Th(IV) column tests and resultant K_d values. If these tests were run at Th(IV) concentrations below saturation with Th(IV) solids, the test results could be used to estimate the K_d for Pu(IV) adsorption. Finally, as noted earlier, it is possible that K_d values for the important actinides could be obtained in a few months from accelerated intact core experiments performed in an ultracentrifuge.

I hope my comments and suggestions have been useful to you.

Yours truly,

Don Langmuir

Donald Langmuir, PhD

RMN
8/19

REPORT ON CHEMICAL RETARDATION DATA FOR CULEBRA AQUIFER

To: Environmental Evaluation Group (EEG)
7007 Wyoming Blvd, NE
Albuquerque, NM

From: Mark L. Brussean

Date: 11 August 1997

I have reviewed the documents supplied to me before and during the July 30 meeting, and have considered the presentations and comments provided during the meeting. My comments and recommendations are presented below.

I. Analysis of Original EEG Concerns

1. Use of batch K_d data: EEG originally expressed concern with the use of K_d values determined from batch experiments for the field-scale modeling. The major question was the representativeness of batch K_d values for the field scale. It appears that at least some (the more recent) batch experiments were conducted under well defined and controlled conditions. The results obtained from these experiments may thus provide an accurate data set for evaluating the "sorptivity" of the specific radionuclides used in the experiments.

   However, there remains the basic question of whether or not K_d values obtained under static batch conditions are an accurate measure for dynamic field conditions. I do not believe that this question has been answered for the Culebra system. To help address this issue, I recommend that additional analyses be made of the column experiments (to be discussed in greater detail below).

2. Use of Oxidation State Analogy: EEG expressed concern with the use of the oxidation state analogy for estimating K_d values. This approach appears to have merit in some cases (when it is definitively conservative), but appears to have large uncertainty for other cases. It is not clear why batch experiments were not conducted for the most critical radionuclides. An opinion was expressed by a DOE employee that the K_d values for at least some of the unmeasured radionuclides could be measured relatively easily. I recommend that such experiments be conducted for as many of the critical radionuclides as is feasible.

3. Use of Uniform Distribution: EEG expressed concern with the use of an uniform distribution for representing the K_d data. The reasoning provided by DOE for the use of an uniform distribution appears to be valid. As they noted, the experiments were not designed to provide a statistically representative sample of all possible field conditions. Thus, the uniform distribution should be the one to use. I recommend that this approach be accepted.

4. Organic Ligands and Facilitated Transport: EEG expressed concern regarding the potential of organic ligands to complex the radionuclides and thereby facilitate their transport. There were three subconcerns associated with this topic--

A) There was concern regarding the varied sources of complexation-coefficient data used in the original DOE analyses. The DOE mentioned new data at the meeting that may negate this concern. The DOE now appears to have a consistent set of measured complexation-coefficient data specific to the Culebra/WIPP system.

B) There was concern regarding the amount of EDTA DOE assumed would be present in the waste. I agree that there is great uncertainty in the concentration of EDTA that may be present in the WIPP system, and that the value used by DOE may be too small.

C) There was concern regarding the potential for other organic ligands, which were not included in the DOE analysis, to facilitate the transport of radionuclides. I agree with this concern.

To help resolve both B and C, I recommend that the DOE conduct a formal sensitivity analysis of the potential impact of organic ligands on the aqueous concentrations of the radionuclides. The concentrations of the ligand should be varied by several orders of magnitude, and the full list of ligands provided by EEG should be used. Based on the preliminary analysis presented by DOE personnel at the meeting, it is quite possible that the results from this study will indicate that complexation by the organic ligands may have minimal impact on radionuclide behavior. A formal sensitivity analysis will provide greater confidence in the results.

5. Other Concerns of EEG: EEG expressed concern with the application of the Norwegian dolomite study results to the Culebra system, and with the use of different CO_2 concentrations in the batch experiments. After the meeting, EEG commented that these were of minor concern, and I concur.

II. Additional Concerns

1. Potential Nonlinear Sorption: The data I reviewed indicates that the sorption of many of the radionuclides is most likely nonlinear. This is to be expected given the sorption mechanism stated by DOE (exchange reaction). As is well known, nonlinear sorption can cause retardation to vary as a function of solute concentration. In addition, it is possible that the initial representative retardation factor operative during field-scale transport may not be the same as that calculated using the batch K_d data. Thus, not accounting for nonlinear sorption may under or over predict retardation, depending on the initial solute concentrations used in the analyses. It is not clear if the range of K_d values reported by DOE take into account the concentration dependency of sorption. I recommend that the potential impact of nonlinear sorption be addressed.

2. Use of a K_d Approach versus a more Complex Approach: The transport model used by DOE is based on the simple K_d approach, which is based on linear, instantaneous sorption. It is clear that the fluid-solid interactions influencing radionuclide transport at the WIPP site are more complex, potentially involving inorganic/organic complexation, precipitation/dissolution, competitive sorption, and varying pH and ionic strength effects. The simplicity of the K_d approach makes its use understandable. However, some analysis of the potential impacts of more complex fluid-solid interactions on radionuclide transport would be useful.

3. Spatial Variability of Sorption: The current modelling analysis is based on a homogeneous K_d field. It is highly likely, however, that sorption is spatially variable at the site. The potential impact of spatially variable sorption on radionuclide transport should be evaluated.

III. Conclusions and Recommendations

Several questions and concerns were addressed satisfactorily at the meeting. However, some issues remained unresolved. The majority of these could potentially be resolved with relatively minimal additional effort. Recommendations for additional activities are as follows:

1. It is recommended that additional analyses be made of the column experiments. This includes additional analysis of the completed experiments and additional analysis of the ongoing experiments. The latter should involve an attempt to determine if precipitation is occurring during the column experiments, which appears to be a major uncertainty influencing the applicability of the column results. Would it be possible to sample the column material at the completion of the experiment and analyze for precipitated forms of the radionuclides?

2. I recommend that additional batch experiments be conducted to measured K_d values for the critical radionuclides, at least Pu^{III} and Pu^{IV}.

3. I recommend that a formal sensitivity analysis be conducted to examine the potential impact of organic ligands on the aqueous concentrations of the radionuclides. The concentrations of the ligand should be varied by several orders of magnitude, and the full list of ligands provided by EEG should be used.

4. If the potential impact of nonlinear sorption is not incorporated in the range of K_d values used by DOE, I recommend that the potential impact of nonlinear sorption on radionuclide transport be addressed. This could be accomplished by calculating effective K_d values for pertinent C_0 values, using the nonlinear isotherm data available. These values could then be compared to the existing K_d range.

5. I recommend that the potential impact of spatially variable sorption on radionuclide transport be evaluated. This could be done by conducting a series of model simulations using spatial distributions of K_ds based on the conceptual site models.

Leslie Smith
Hydrogeological Analysis • Groundwater Contamination Studies

August 12, 1997

Dr. Robert Neill
Director
Environmental Evaluation Group
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Dear Bob,

In this letter I provide my viewpoint on chemical retardation in the Culebra dolomite. The opinions expressed reflect my consideration of the reports and correspondence supplied to me prior to the meeting, the material presented by EEG and DOE at our meeting on July 31, and the ensuing discussions that day. I will not comment directly on the issues concerning the amount of EDTA in the waste inventory, the potential for EDTA to facilitate transport of thorium, or the data presented by DOE to justify their application of the oxidation state analogy.

The Probability Distribution for Kd

I accept the DOE position that it is appropriate to adopt a uniform probability distribution to represent the uncertainty in the Kd values for the CCA calculations. The use of a log-uniform distribution, as required of DOE in the EPA verification tests, has the primary benefit of placing considerably more weight on the lower end of the proposed range for Kd. The EPA verification test suggests that the conclusions drawn from the CCA calculations with respect to transport in the Culebra are not sensitive to this marked change in the form of the distribution.

The probability distribution for Kd can be interpreted in terms of the likelihood that a value sampled from the distribution will correspond to an effective Kd value for sorption in the matrix blocks. This value must be applicable for transport times greater than 100 years, and transport distances of approximately 3 km. I see the attempt to quantify this likelihood as an issue related to, but distinct from, the distribution of Kd values obtained in the replicate batch tests. It is not feasible to obtain a set of field data, applicable at the scale of the transport predictions, that would allow one to equate the distribution of measurements with an appropriate sampling distribution in the CCA. One is forced to adopt a more subjective viewpoint in representing the uncertainty in the Kd value, with the consequence that the distribution of the data from the batch tests need not correspond to the distribution describing the likelihood for the effective Kd value. This approach is the most reasonable way to account for the spatial variability in Kd, and the influences of brine type and pH conditions inside a plume migrating through the Culebra.

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The position taken by DOE that the sorption experiments (batch, mechanistic, and column tests) should be used to define a range for the Kd parameters, rather than its distribution in probability space, is reasonable.

I have used decision models that adopt uniform distributions to characterize the uncertainty in the key model parameters (eg. Bugai, Smith, Beckie; Environmental and Engineering Geoscience, 1996). We took this approach because we were faced with a sparse data base, and there were confounding uncertainties in future system behavior. A uniform distribution is appropriate when there is no strong basis for deciding if one value in the range is more likely than any other. It is my opinion that this is the case we face when selecting an effective Kd value for radionuclide transport in the Culebra. This is a slightly different spin on the DOE statement that "the uniform distribution is appropriate when all that is known about a parameter is its range".

In more recent work, I have adopted truncated exponential distributions to represent uncertainty in model parameters (Smith and Gaganis, Environmental and Engineering Geoscience, submitted). This latter model for representing parameter likelihood includes the uniform distribution as a special case, if the prior estimate of the mean is midway between the specified lower and upper bounds of the distribution. There is a sound basis in theory for choosing a truncated exponential distribution to represent parameter uncertainty, when the data base is sparse. Qualitatively, the log-uniform distribution is similar to the truncated exponential distribution, when the estimate of the mean is closer to the lower bound than the upper bound.

The more important issue to debate, in my opinion, is the values that DOE has selected for the lower and upper bounds of the probability distribution, and how these bounds are defined relative to the type of brine used in the batch experiments. I agree with the approach taken by DOE in choosing a range for Kd relative to brine type that will give a conservative estimate of retardation. I was somewhat bothered by DOE's decision to select this range based on the average value of the sample distribution. It is possible to criticize the sampling range for Pu^{V} in this regard (and by their extrapolation, the sampling ranges for Pu^{III} and Am^{III}). The recommended range used in the CCA calculations was 20 - 500 ml/g, which reflects values from the batch tests using deep brines. Batch tests for Pu^{V} with Culebra brines had a higher mean value for Kd, but the lower bound was smaller (9.8 ml/g). Therefore, the sampling distribution in the CCA does not encompass all the measured values from the batch tests for a Culebra brine, at the low end of possible values. A more conservative sampling distribution would have ranged from 10 - 500 ml/g. However, because I would not expect the lowest value from a set of small-scale batch tests to equal the lower bound for a single, effective Kd value along a 3 km flow path, the consequence of their approximation is not likely to have a significant impact on the reliability of the CCA calculations. The analogy here is that the smallest value of hydraulic conductivity measured in a set of slug tests is not a reasonable lower bound on the estimate of a larger-scale effective hydraulic conductivity. A similar approximation did not emerge in selecting the sampling range for Th^{IV} because data are only available for the deep brine.

The DOE data base indicates U^{VI} will be the most mobile radionuclide of concern in the Culebra. The low end of the sampling range for U^{VI} is 0.03 ml/g, if we ignore the negative Kd values. This lower bound is obtained from the observed breakthrough of U^{VI} in the column tests. If we accept the interpretation of Bob Holt that the column test for U^{VI} measures retardation tied to the advective porosity, then this lower bound should be a conservative value for the compliance calculations when matrix diffusion plays a major role in retardation. The value from the column test is lower than any of the values in the batch tests (Tables D-1 through D-4 of the Brush memo, June 10, 1996). This sampling range for U^{VI} introduces the possibility that the EPA standard could be violated in an undetermined number of observations in the CCA calculations, if alternate scenarios were considered for the release of the uranium inventory from a disposal panel (ie. a Kd less than 1 ml/g, using the DOE benchmark for Pu^{III} and Am^{III}). We do not know how robust the CCA calculations are to a violation of the assumptions on the uranium release to the Culebra. Several factors need to be considered. A lower bound for Kd more reflective of matrix sorption than the value obtained in the column tests is not well-defined because of uncertainties in the batch tests (eg. the negative values). The zero values assigned to the negative Kd values for the batch tests with the Culebra brine did not get passed into the CCA calculation because of a lower average value of Kd for the batch tests using deep brines. This issue may be worth pursuing if BEG has concerns about the scenario assumed in characterizing the release of uranium to the Culebra.

An alternate interpretation in adopting the log-uniform distribution is that it de-emphasizes the importance of the Kd value that defines the upper bound of the distribution. Given the results of the EPA verification test, I have concluded that the questions regarding the relevance of the mechanistic Kd tests on pure dolomite from Norway are not a significant issue. These tests only make their way into the final sampling distributions once, in determining the upper bound for U^{VI} at high pH conditions.

The Sparse Kd Data Base

I disagree with the characterization made by M. McFadden in his opening presentation that Kd values used in the CCA are well-founded on experimental data. This simply is not the case, given the lack of experimental data for some radionuclides. The real issue is whether there is an adequate data base, and evidence to support the application of the oxidation state analogy, in assigning conservative bounds for radionuclides where measurement are not available from batch or column experiments. While I found the arguments presented by DOE to be compelling, they are not based on experimental data specific to the Culebra. It is still reasonable to ask if it would be more expedient, in a project of this magnitude and duration, and given the importance to DOE of a public demonstration of their commitment to ensuring the safe disposal of radioactive wastes, to complete a set of batch experiments on Pu^{III}, Am^{III}, and Pu^{IV}. DOE could then avoid the arguments and indirect support that must be linked to the oxidation state analogy. I understand for informal comments made at our meeting that these experiments could be carried out without great technical difficulty. My expectation from all that I have

heard is that these tests would serve to confirm that DOE has used a suitable range of values in the CCA calculations.

Batch Tests

BEG has accepted the viewpoint that the batch tests have relevance in determining Kd values for the CCA calculations. After considering the geologic and hydrologic descriptions in the report by Bob Holt on a conceptual model for multi-rate transport in the Culebra, I am persuaded the batch tests can provide a basis for defining Kd values that characterize matrix sorption. The approach is subject to uncertainty (which should be balanced by conservative approximation), and I would not necessarily expect a one-to-one correspondence between a batch test and a long-term column test in a core from the same sample location (and interpreted with a dual porosity model). However, I am now of the opinion that the batch tests can be used to identify the sampling range in the CCA calculations. This sampling range applies only to the matrix porosity. It is inappropriate to use these batch test values to characterize retardation in the fracture system (advective porosity).

Column Tests

It is my impression that the latest analyses of the column tests do not move us much further along in reducing the uncertainty in the appropriate sampling range of Kd for Pu^{III} and Am^{III}. The attempt was worthwhile, but we now see there are limitations in the experimental design, because of issues tied to solubility. I agree that if it is technically feasible, it would be worthwhile to request that DOE try to determine if a mineral phase is present, that would confirm if the migration distance cannot be interpreted strictly in terms of a Kd estimate. It is not apparent to me what else could be done with the column experiments to gain further insight to the magnitude of Kd for Pu^{III} and Am^{III}.

Tom Clemo has raised the important issue that the only batch test data available for Th^{IV} (and, by DOE extrapolation U^{IV} and Pu^{IV}) are for the ERDA-6 brine. His statistical analysis suggests that the mean Kd's measured in ERDA-6 brine are greater than the values determined using the other 3 brines. It is my understanding that the column tests on the B core were carried out using Culebra brine. The estimated Kd value from tomographic analysis on the B-core is reported to be approximately 400 ml/g. Although this value is lower than the sampling range from batch tests that was used in the CCA calculations (900-20,000 ml/g), the value is sufficiently beyond 1-3 ml/g (the DOE benchmark) to suggest that Th^{IV} will not be of concern. Whether this same conclusion can be drawn for Pu^{IV} and U^{IV} depends upon the acceptability of the oxidation state analogy in setting conservative bounding values for their sampling distributions.

Beyond 10,000 Years

In our discussion after the meeting with DOE, we considered whether the CCA calculations should be extended beyond the mandated 10,000 year time frame. This topic

is akin to an issue of full disclosure. There has been considerable informed debate on the regulatory time frame, and the advantages / limitations of looking beyond 10,000 years. My personal bias, influenced by reviewing projects under Canadian regulations, is to base siting decisions on a 10,000 year time frame, but to examine system behavior from a more qualitative perspective over a longer time horizon. Perhaps there is a role to be played here by EEG, in representing the interests of the State of New Mexico. It could be informative to look at the probability of radionuclide release along the pathway through the Culebra for time frames of 20,000 or 30,000 years, using the sampling distributions adopted by DOE.

Closure

EEG should continue to press DOE to refine and verify their calculations and modeling assumptions used in the CCA. Comments made by Sandia and LANL staff at the meeting suggest that this process is ongoing, if informal. For example, Vann Bynum described his latest calculations on the effects of the amounts of organic ligands on transport, and we heard that measurements of the EDTA β for nickel under WIPP conditions have recently been completed. Efforts to update the performance assessment should continue as time and computational tools become available.

Sincerely,

Leslie Smith

Leslie Smith

8.7 Walter Gerstles' Responses to Anhydrite Fracturing Issues Raised on February 17, 1998

Memo

Feb. 24, 1998

To: Lokesh Chaturvedi
Environmental Evaluation Group
Albuquerque, NM
Fax: (505) 828-1062
Phone: (505) 828-1003

From: Walter Gerstle
Dept. of Civil Engineering
University of New Mexico
Albuquerque, NM 87131

I have had a few days to digest Norm Warpinski's presentation at our meeting last week. I make the following observations.

I. Estimate of Crack Opening Displacements in Bragflo Model.

The Bragflo model "smears" cracks in the anhydrite layers, using the porosity model. Assuming 200,00 m^3 of gas is stored in these cracks, and assuming n layered cracks, with radius R=1000 m, it is possible to calculate the average crack opening displacement, w. Figure 1 shows the situation.

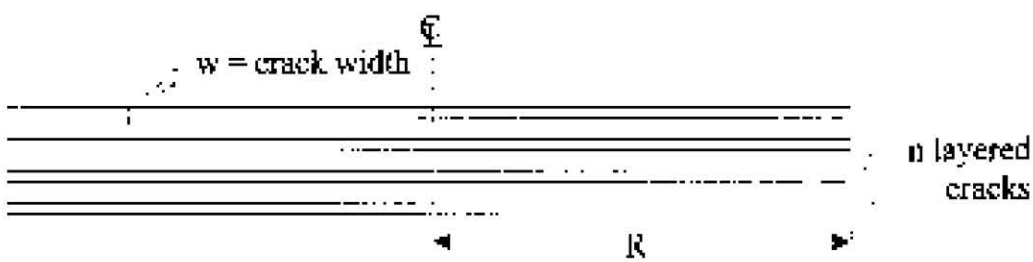

Figure 1. Cross Section Along Crack Diameter

The area, A, of each crack is $A = \pi R^2 = \pi(1000\ m)^2 = 3.14 \times 10^6\ m^2$.

$$olume = V = nwA;\ w = \frac{V}{nA} = \frac{200{,}000m^3}{n(3.14\times10^6 m^2)} = \frac{6.37cm}{n}$$

So the average crack opening displacement is 6.37 cm divided by the number of layered cracks.

The following table shows the average crack width for various numbers of cracks.

n	w, cm.
1	6.37
5	1.27
10	0.64
20	0.32

So the consequence of the Bragflo porosity model is many cracks with wide openings. However, anhydrite is relatively fine grained, and certainly cannot transmit stresses across crack openings of larger than approximately 0.001 cm. Consequently, it is reasonable to assume that all but one of the cracks would close up, but that single crack would extend in radius, as both the Gerstle and Bredehoeft 1997 and the Geertsma and Deklerk 1969 models assume.

II. Geertsma and Deklerk 1969 "Industry" Model

Warpinski made reference to the Geertsma and Deklerk 1969 model as being both an industry standard model and as being more consistent with the Bragflo model than with the LEFM model. In fact, the Geertsma and Deklerk model is an LEFM model, with fracture toughness assumed to be negligible, and it predicts even longer crack radii than the Gerstle and Bredehoeft 1997 model, contrary to Warpinski's assertions. I agree with Warpinski that the Geertsma and Deklerk model is basically reasonable, in that it assumes a single, localized, discrete crack.

A quote from Geertsma and Deklerk 1969 illustrates the fundamental difference between this model and the Bragflo model: "it is found that p_w (pressure at the well bore) decreases with increasing fracture length and approaches S (overburden stress) for large values of L (crack length). Such pressure behavior is in agreement with reported field observations." It is noted that the Gerstle and Bredehoeft 1997 model also demonstrates this pressure behavior, while the Bragflo model demonstrates the opposite pressure - crack length behavior. The decreasing pressure vs increasing crack length behavior also is indicative of a single, localized hydrofracture, which is in contrast with Bragflo's assumption of widely dispersed cracks forming simultaneously in multiple anhydrite layers.

Warpinski in his presentation predicted a crack radius of R = 366 m using Geertsma and Deklerk's formula:

$$R = \frac{1}{\pi}\left[\frac{Q^2 t}{C^2}\right]^{1/4} \qquad (24)$$

Where R = fracture radius
Q = rate of flow into hydrofracture
t = time
C = fracturing fluid coefficient, $C = u\sqrt{\Delta t}$
U = rate of filtration loss per unit of exposed surface of the fracture.

I do not know what numbers Warpinski used, but I used the following numbers and arrived at a much larger predicted radius, R.

$$u = \frac{4499 m^3}{2\pi(750m)^2(1000yrs)} = 1.27\times10^{-6}\ \frac{m^3}{m^2-yr}.$$

$$C = u\sqrt{\Delta t} = 1.26\times10^{-6}\frac{m^3}{m^2-yr} \times \sqrt{1000yr} = 4\times10^{-5}\frac{m^3}{m^2-\sqrt{yr}}$$

$$Q = \frac{200{,}000m^3}{1000yrs} = 200m^3/yr.$$

$$So\quad R = \frac{1}{\pi}\left[\frac{(200m^3/yr)^2(1000yr)}{(4\times10^{-5}\ m^3/m^2-\sqrt{yr})^2}\right]^{1/4} = 4003\ m.$$

Obviously, there is room for debate upon precisely what values of C, Q, and t are reasonable, but Sandia has not performed any calculations using the Geertsma and Deklerk model or any other standard hydrofracture model. This should be done.

III. Warpinski's claim that Gerstle and Bredehoeft model is incorrect.

Warpinski claimed that Gerstle and Bredehoeft's 1997 model is incorrect because it contained no explicit flow equation and no leakoff equation. In fact, calculations in (Gerstle, Mendenhall, and Waweisik 1996) show that leakoff is negligible - and therefore does not need to be explicitly included in the LEFM model. Warpinski also claimed that our model would require flow rates of $Q = 1.85 \times 10^6$ m^3/yr, using the equation

$$Q = \frac{\pi}{6\mu} \frac{w^4 \Delta P}{\ln [R/r]}$$

In fact, use of this equation is inappropriate because we assumed identical pressure ($\Delta P=0$) everywhere within the crack, and thus flow Q would be negligible. Our LEFM model neither assumes nor requires high flow rates.

IV. Conclusions

It is essential for the WIPP facility that a credible gas-driven hydrofracture model be used. I believe that the (Gerstle and Bredehoeft 1997) model is essentially correct despite Warpinski's observations about it. Warpinski's comments appear to be spurious.

I would suggest that Sandia present calculations of hydrofracture extent using Geertsma and Deklerk 1969 model, fully documenting all inputs to the model. I believe they will arrive at conclusions similar to those I have presented.

8.8 Neill to Kruger letter dated 8/11/97 with attachment, "EEG comments on CCA Chapter 5"

ENVIRONMENTAL EVALUATION GROUP

COPY

AN EQUAL OPPORTUNITY / AFFIRMATIVE ACTION EMPLOYER

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August 11, 1997

Mary Kruger
U.S. Environmental Protection Agency
Office of Radiation and Indoor Air
401 M Street SW (6602J)
Washington, DC 20460

Dear Ms. Kruger:

Enclosed please find the *EEG Review of the WIPP/CCA (DOE/CAO-1996-2184), Chapter 5 (Quality Assurance).*

Sincerely,

Robert H. Neill
Director

RHN:js

cc: EPA Docket

EEG REVIEW OF WIPP/CCA (DOE/CAO-1996-2184)
CHAPTER 5 (QUALITY ASSURANCE)

The DOE's Carlsbad Area Office (CAO) has successfully focused on developing a quality assurance (QA) program which implements the Nuclear Quality Assurance (NQA) standards required by 40 CFR 194 over the last few years. Chapter 5, Quality Assurance (QA), in the DOE's Compliance Certification Application (CCA), is, however, of lesser quality than the QA program it attempts to describe. The chapter fails to show compliance with most of the requirements of 40 CFR 194.22, Quality Assurance, and ignores most of the expectations for QA published in EPA 402-R-95-014, Compliance Application Guidance for 40 CFR 194 (the CAG).

In a chapter which should provide specific responses to clearly delineated requirements and expectations Chapter 5 offers a diffuse scattering of relevant information, provides generalized information without examples or details, and references other documents which are no more specific (and were not intended to address the QA requirements for the CCA). The chapter contains what seems to be extraneous information (some of which is found elsewhere in the CCA), glosses over past QA problems rather than explaining how they were resolved, and fails to include information explicitly required by 40 CFR 194.22. In many cases the CAO QA program and process has adequately covered the area, yet the chapter fails to fulfill the responsibility of describing how it was done.

Parts of Chapter 5 are also misleading. For example, "the CAO QAPD" is referenced throughout much of the chapter and is initially identified as appearing in CCA Appendix QAPD. The version in the Appendix QAPD is Revision 1, dated April 22, 1996, though it was not officially transmitted to, or required to be implemented by, subsidiary organizations until after June 13, 1996--when essentially all QA-related activities for the CCA had already been completed. Revision 1 is a substantial rewrite of Revision 0, among other things establishing the CAO QAPD as a requirements document for all CAO subsidiary programs for the first time, and adding elements of NQA standards previously not included. To state that

> The TWBIR was prepared in compliance with the CAO QAPD...

(p. 5-3) implies that the data from the TWBIR used in the CCA (first published in December 1995) was prepared according to the requirements in Revision 1. It wasn't, and the distinction should have been clearly made. Similar statements are found elsewhere Chapter 5:

> The WAC was written and reviewed in compliance with the CAO QAPD [p. 5-3]...The TRU QAPP was written and reviewed in compliance with the CAO QAPD requirements [p. 5-4]...NDA software is controlled in accordance with the requirements of the CAO QAPD [p. 5-9]...

Versions of the WAC and TRU QAPP current at the time the CCA was submitted were written under Revision 0; the NDA (Non-Destructive Assay) software is, of course, currently controlled under Revision 1, but any NDA data used in the CCA would clearly predate the issuance of Revision 1.

The chapter contains an important misinterpretation of the intent of 40 CFR 194.22(a)(2). This paragraph requires the compliance application to demonstrate that a QA program adhering to the 1989 edition of the Nuclear Quality Assurance (NQA) standards has been established and executed for eight specific areas considered by the EPA to be critical to the compliance application. In Chapter 5, this is interpreted (p. 5-3, line 28) as:

> 40 CFR Part 194 stipulates that the DOE apply QA controls to eight areas.

Under this interpretation Chapter 5 fails to clearly demonstrate that the requirements of the NQA standards have been executed for any of the eight areas, though discussions under specific headings for each of the eight areas immediately follows. In some of these discussions virtually no QA information is supplied at all.

The EEG, in a preliminary commentary (Neill-to-Dials letter dated July 22, 1996; see Attachment I) on what now must be considered a draft of the final Chapter 5, pointed out several clearly erroneous statements in the text. Most of these have been removed from this October version, but the chapter still includes a curious concept that since the EPA had reviewed site selection and site characterization QA programs during examination of the 1989 No-Migration Variance Petition (NMVP), the QA for site selection and characterization is considered satisfactory by the DOE (p. 5-8). The EEG's comment pointed out that the argument was untenable, in that (among other reasons) compliance with NQA standards was not a part of the 1989 NMVP. The DOE response (enclosure to undated Dials-to-Neill letter received August 9, 1996; see Attachment II, enclosure p. 4) stated that the DOE agreed with the comment, and "We have updated this portion of Chapter 5". The updating is not apparent--the argument is still the same, and still an obvious error (see line-by-line review of p. 5-6, lines 6-13 for more discussion).

The EEG's July 1996 letter concerning Chapter 5 (see Attachment I) recommended that the DOE rewrite the chapter to meet the published EPA requirements and expectations for QA. The DOE has not substantially rewritten the document (though material was added and removed), and this final CCA Chapter 5 and associated materials arguably fails to demonstrate fulfillment of the requirements in 40 CFR 194.22, Quality Assurance.

The following sections consist of 1) a comparison of Chapter 5 to the CAG expectations; 2) a comparison of Chapter 5 to the requirements for QA in 40 CFR 194.22; and 3) a line-by-line review of the document.

OCTOBER '96 CCA CHAPTER 5 (QA) AND THE CAG

The DOE has previously (see Attachment II, letter p. 2, and enclosure p. 7) informed the EEG that, as a guidance document, the Compliance Application Guidance (CAG) expectations need not necessarily be included in the CCA. However, the CCA begins with the statement that:

> This application has been developed to be fully responsive to the requirements of 40 CFR Part 191, the criteria in 40 CFR Part 194, and the guidance in the *Compliance Application Guidance for 40 CFR Part 194*, EPA 402-R-95-014. [p. EXEC-1;

emphasis in the original]

Chapter 5 is not fully responsive to the CAG expectations. The chapter seems to address the CAG requirements for QA only occasionally, and by accident, rather than design. Below are listed some of the CAG expectations for §194.22, Quality Assurance, and the results of EEG's attempts to find the data in Chapter 5. This is not an exhaustive list, as it is intended only to show that the CAG expectations for QA were not addressed by the DOE.

CAG §194.22(a)(1) Expectations (p. 18 of CAG):

1. *DOE top tier QA documents will be included in the CCA.*

   The DOE included only the CAO QAPD. The TRU Waste Characterization Quality Assurance Program Plan, Revision 0 (QAPP; CAO-94-1010) would also seem to be a DOE top-tier document, and much of it would enhance the DOE's claim to having implemented a QA program in accordance with the NQA statutes. The TRU-Waste Characterization QAPP (Section 1.0, p. 1.1) does contain an important statement that the CAO QAPD Revision 1 lacks:

   > This QAPP addresses all of the basic requirements, and their supplements, of ASME NQA-1.

   Section 1.9.3, Computer Hardware and Software, of the Waste Characterization QAPP also supplies a clear statement requiring the use of the successor document to the 1989 NQA-2 Subpart 2.7, "Quality Assurance Requirements of Computer Software for Nuclear Facility Applications", which would seem to address the specifications for software QA as required by 40 CFR 194.22(a)(1). The CAO QAPD Revision 1 contains no comparable direct statement of compliance with the requirements found in §194.22(a)(1)--that is, adherence to a QA program which implements the requirements of NQA-1, NQA-2 Part 2.7, and NQA-3.

   Nor, in fact, does Chapter 5 contain a direct statement of compliance to the requirements of NQA-1, NQA-2 Part 2.7, or NQA-3.

2. *DOE principal contractor top tier QA documents, and a list of all non-principal contractor or sub-contractor top tier QA documents will be included in the CCA.*

   SNL QA top-tier documents were not included, nor any listing of QA documents for non-principal contractors or subcontractors for WID or SNL.

CAG §194.22(a)(2) expectations are that, for each of 8 defined critical areas, the CCA will (among many other expectations):

1. *Provide a list of quality affecting activities and items important to a demonstration of compliance.*

   Lists seem to be incomplete. For instance, the bulk of field measurements of geological factors

were performed by SNL, yet SNL activities are described as "None" in the section concerning measurement of geological factors (5.1.3; p. 5-6, line 26). Other examples: Section 5.1.1 identifies the WIPP Waste Information System (WWIS; p. 5-4, lines 2-3) and the Performance Demonstration Program PDP (p. 5-4, lines 22-23) as elements of the waste characterization system, but doesn't show them as activity for any of the organizations involved. Section 5.1.2 doesn't include a discussion of QA on the current WID environmental monitoring program; Section 5.1.3 doesn't mention QA of the current WID meteorological monitoring program, or past SNL meteorological programs. These two sections have "environmental monitoring" and "meteorological" in their titles.

2. *Describe the selection of applicable NQA requirements for each of the areas.*

   No descriptions are included.

3. *Provide dates of QA implementation conforming to NQA for each item or activity, and the nature and location of objective evidence which supports this determination.*

   No dates are provided.

CAG §194.22(b) expectation (other expectations were also not met, though some were met in part):

1. *Provide the QED governing documents that include procedures and management plans for independent review, peer review...*

   QED governing documents were not included in the CCA (CAO MP 10.5, SNL QAP 20-3).

OCTOBER '96 CCA CHAPTER 5 (QA) AND §194.22 REQUIREMENTS

§194.22(a)(1) Requirement: *As soon as practicable after April 9, 1996, the DOE will adhere to a program that implements the requirements of the NQA standards.*

The CAO QAPD Revision 1 (in CCA Appendix QAPD) does not require full implementation of NQA standards for all activities, but only for those listed in §194.22(a)(2), other radioactive materials handling, and processes related to transportation containers. This is established in the CAO QAPD in section 1.1.2.3, Applicability of QAPD Requirements, where the difference between general requirements and additional requirements is introduced, and subsections A through J list the areas that fall under the additional requirements. The additional requirements generally seem to be those which are found in the NQA standards, but not in DOE Order 5700.6C, the DOE's internal QA requirements document (which follows 10 CFR 830.120). For compliance with 40 CFR 194.22(a)(1), the NQA standards may need to be the primary criteria.

There is no indication in §194.22(a)(1), or anywhere else in the criteria, that some WIPP activities can be granted a variance from the requirements of the NQA standards.

§194.22(a)(2) Requirement: *The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for the following activities: waste (i) characterization activities and assumptions; (ii) environmental monitoring, monitoring of the disposal system performance, and sampling and analysis activities; (iii) field measurements of geologic factors, ground water, meteorologic, and topographic characteristics; (iv) computations, computer codes, models and methods used to demonstrate compliance; (v) expert elicitation procedures used to support compliance; (vi) design of the disposal system and actions taken to ensure compliance with design specifications; (vii) collection of data used to support the compliance application; (vii) other systems structures, components, and activities important to containment of waste .*

The requirement is misinterpreted in Chapter 5 as "40 CFR 194 stipulates that the DOE apply QA controls to eight areas" (p. 5-3, line 28). The misinterpretation is essentially an echo of page 5-2, lines 6 and 7. This statement is far from presenting evidence that the program has been established and executed. Demonstration of execution would presumably be by citing independent assessments (audits and surveillances) for the different areas.

The chapter does provide separate sections for each of the eight activities, but demonstration of establishment and execution of adherence to the NQA standard requirements is weak or nonexistent in these sections and references from these sections (see line-by-line review below).

§194.22(b) Requirement: *The compliance application shall include information which demonstrates that data collected prior to establishment of adherence to the NQA standards has been qualified by a methodology approved by the EPA.*

Chapter 5 offers no demonstration of EPA approval of any of the methods used. While the EEG understands that the EPA has not provided approval/disapproval to the DOE for the various methods the DOE has utilized, §194.22(b) clearly requires information demonstrating approval to be in the CCA. The CCA should at least contain a statement concerning qualification of the methodology by the EPA.

§194.22(c) Requirement: *The compliance application shall provide, to the extent practicable, information which describes how data in support of the application have been assessed for data quality characteristics, including precision, accuracy, representativeness, completeness, and comparability (PARCC).*

The application provides an argument that it is not practicable to apply the PARCC characteristics to "most scientific investigations used to support performance assessment in which there is uncertainty in conceptual models and the resultant ranges of parameters" (section 5.21.1, lines 40-42). The characteristics are not provided as required. While it may be that evaluation of these characteristics did not take place at the sampling level, some assessment should have been made to establish how much uncertainty in models and parameters would be not only practicable, but necessary. Note also that apparently some of the scientific investigations are not covered by the argument, and information which

describes how PARCC was assessed for these, at least, should have been included. For example, the argument states specifically that the PARCC requirements would apply to waste characterization and environmental monitoring activities, yet provides no information as to how data from these areas were assessed for PARCC.

§194.22(d) Requirement: *The application shall provide information which demonstrates how all data are qualified for use in the demonstration of compliance.*

Section 5.4.2.1 of the CCA does provide a description of the programs for qualifying data.

LINE-BY-LINE REVIEW OF CHAPTER 5

Introductory Material

Page 5-1, Lines 17-18: *...see Table 1-5 in Chapter 1.0 for a list of appendices that provide additional information supporting this chapter...*

Table 1-5 lists only Appendices QAPP and AUD, but other appendices are referenced in Chapter 5 (MON, p. 5-5 line 38; EMP, p. 5-6 line 20); SEAL, p. 5-12 line 24)

These additional appendices should have been included in Table 1-5.

Page 5-1, Lines 29-31: *A comprehensive series of assessments has determined that the DOE, SNL, and WID QA programs are adequate and effectively implemented.*

The overall CAO assessment of SNL QA (May 1996) and WID QA (June 1997) previous to the publishing of the CCA found the SNL program to be marginal both for adequacy and implementation, and the WID program marginally effective (see CCA p. 5-39, lines 6-13 for definitions of these terms.). It is the later resolution of issues raised during the assessment by which the CAO determined SNL and WID QA to be adequate and effectively implemented (see Section 5.4.2, p. 5-45 ff, and section 5.4.3, lines 24-29). The text of this portion of Chapter 5 should reflect that the resolution of concerns raised by the assessments were performed before the SNL and WID QA programs was determined to be adequate and effectively implemented.

5.1. Applicability

Page 5-2, Line 6: *These NQA requirements form the basis of the CAO QAPD.*

Revision 1 of the CAO QAPD may incorporate the requirements in the NQA standards, but they are split between general requirements (for all activities) and additional requirements (applied to activities in which radioactive materials, shipping packages, or the eight compliance activities specified by §194.22(a)(2) are involved). This division indicates that DOE Order 5700.6C is the basis of the CAO QAPD rather than the NQA requirements, as DOE Order 5700.6C is covered by the general requirements, and the additional requirements are those NQA requirements not covered in the DOE Order.

There is no variance granted in §194.22(a)(1) for activities in the QA program, and Chapter 5 presents no evidence of any agreement for such a variance. The intent of the regulation seems to be that the WIPP will adhere to NQA standards for at least all disposal-related activities, and arguably for the entire QA program.

This statement is, however, as close as Chapter 5 gets to a clear statement of compliance with §194.22(a)(1), which requires that the DOE

> ...shall adhere to a quality assurance program that implements the requirements of [the NQA standards].

Page 5-2, Lines 6-7: *Additionally, 40 CFR § 194.22 requires that QA programs be applied to the following eight items or activities:...*

§194.22(a)(2) does not require the application of QA programs to the areas described in its eight subparagraphs. The requirement is for the compliance application: the CCA must demonstrate that the requirements of the NQA standards have been applied for each of the eight subparagraphs. The regulation is:

> Any compliance application shall include information which demonstrates that the quality assurance program required pursuant to paragraph (a)(1) of this section has been established and executed for [the eight activities].

Demonstration of execution of the requirements of the NQA standards would presumably be by describing QA assessments which confirm adherence to the NQA standards for each of the areas.

The difference in approach to the requirement is critical. Chapter 5 describes the general QA program which includes the eight critical area specified by §194.22(a)(2), but is ineffective in demonstrating that the QA program has been established and executed for each of them.

This misinterpretation of the regulatory requirement is repeated on page 5-3, line 28 (see below). The chapter should address the requirements as stated.

Page 5-2, lines 33-39: *The CAO QAPD establishes two primary categories of requirements, identified as general requirements and additional requirements. The sections of the CAO QAPD that do not identify specific applications are general requirements that apply to all items, activities, and processes under the cognizance of the DOE. The requirements of the CAO QAPD sections identified as additional requirements apply to the eight key areas identified above.*

See comment for page 5-2, line 6. These statements imply that the NQA standards in the CAO QAPD Rev. 1 additional requirements are to be applied only to the eight key areas, omitting the radioactive materials handling and NRC packaging included in Revision 1 of the CAO QAPD (sections 1.1.2.3.A and 1.1.2.3.J; pp. 1-10 and 1-11).

Page 5-2, line 41, to page 5-3, line 8: *Additionally, the use of a graded approach supports the proper implementation of QA program requirements...*

The discussion of the graded approach offers no tie of the graded approach to the compliance application requirements. A statement that NQA-1 does allow the graded approach (with reference) would seem appropriate, and perhaps necessary.

40 CFR 194.22(a)(1) specifically excludes those portions of NQA-3 (which addresses QA for site characterization data collection activities), that refer to the graded approach. Having raised the "graded approach" issue, Chapter 5 should provide evidence (even a single statement) that the site characterization data was not collected or processed using a graded approach to QA.

Page 5-3, lines 11-14: *The CAO QAPD requirements are further supported and amplified by the next tier of QA program documents which include the DOE TRU Waste Characterization Quality Assurance Program Plan (TRU QAPP), the SNL Implementing Procedures, and the WID Quality Assurance Program Description.*

The first CAG expectation (p. 18) is that the DOE top tier QA documents be included in the application; the second is that the top tier QA documents of principle contractors also be included in the application. This first mention of these documents should also state where they can be found. CCA Appendix QAPP contains the CAO QAPD Rev. 1 and the WID QAPD Rev. 16, but the TRU QAPP, SNL's procedures, and QAPjPs from the generator sites are not included.

It is important to note that the CAO QAPD Revision 1 became the sole "top tier" DOE QA document after June 13, 1996 (the CAO transmittal letter dated June 13, 1996 requires it to be implemented within 60 days after receipt). There was no requisite condition previously that programs other than the CAO itself adhere to the CAO QAPD. Revision 0 states that the QA programs of WIPP participants are expected to be "guided" by the CAO QAPD only (p. 1-1), and the DOE has informed the EEG that guidance documents need not be followed (Neill-to-Dials letter received August 9, 1996).

Revision 0 also did not place an emphasis on the NQA standards as requirements for WIPP QA programs, instead stating that (p. 1-1):

> WIPP participants develop, implement, maintain, and document their quality assurance programs either in accordance with DOE Order 5700.6C or 10 CFR Part 830.

Page 5-3, line 28: *40 CFR Part 194 stipulates that the DOE apply QA controls to eight areas.*

The requirement (§194.22(a)(2) is that the compliance application demonstrate that a QA program adhering to the NQA standards has been established and executed for the eight areas (see comment for page 5-2, lines 6-7).

Section 5.1.1, Waste Characterization Activities and Assumptions

Page 5-3, lines 34-39: *The Transuranic Waste Baseline Inventory Report (TWBIR) (see Appendix BIR) is the inventory source document that provided the waste data used in the performance assessment and is presented in tabular form in Chapter 4.0...*

Chapter 5 is titled "Quality Assurance", but is noticeably incomplete in discussing QA for the TWBIR.

The TWBIR has been published separately as Revision 0 (June 1994), Revision 1 (February 1995), and Revision 2 (December 1995), and some of the radionuclide data varies widely between the different versions. CCA Appendix BIR data is from Revision 2, with additional material requested by the EPA after Revision 2 was published (included in TWBIR Revision 3, according to the Executive Summary).

None of the data in any of the TWBIR versions seems to have been gathered under the NQA standards as required by §194.22(a)(2)(i). Sources of information included extrapolations from, among other sources, safety documentation and interviews with workers (TWBIR 2 p. 1-21; DOE/CAO-95-1121). EEG-61, Review of the WIPP Draft Application To Show Compliance with EPA Transuranic Waste Disposal Standards (EEG, March, 1996) on page 4-5 quotes a 1995 ORNL report that "TRU waste streams at ORNL are not as yet fully characterized...waste sludge...physical data such as particle size, hardness, viscosity and particle distribution are unknown".

The bulk of the source data may be more reliable, but is based primarily on acceptable knowledge (TWBIR 2, p. 1-20), which is in turn predominantly process knowledge. Use of process knowledge to quantify components in waste, which is how the TWBIR data is used in the CCA, is required by §194.24(c)(3) to conform to the NQA standards, also. There is no evidence in the CCA that any of the process knowledge activities were conducted under the requirements of the NQA standards.

The Waste Characterization Analysis Peer Review Report (p. 4-3) mentions both cost and time restraints as justification for the lack of QA on the TWBIR. The NQA standards contain no variances for cost and time considerations.

Page 5-3, lines 36-38. *The TWBIR was prepared in compliance with the CAO QAPD and this activity was audited by the DOE QA Program on September 5 and 6, 1995.*

Chapter 5 is offering incomplete and misleading data here. Note that the data (taken from Revision 2) used for the CCA was published months after the single assessment (a surveillance by one auditor, not an audit) cited, and QA of the additional data requested by the EPA (in 1996) included in CCA TWBIR was certainly not assessed during the surveillance. The surveillance issued one significant finding, which essentially stated that there was no analysis or data collection plan to assess the TWBIR against, as is required by the NQA standards.

The implication is that the waste characterization data used in the CCA has not undergone sufficient QA assessment. Given that both §194.22(a)(2) and §194.24(c)(3) required a demonstration in the CCA that QA has been performed on the TWBIR data, it would seem that a QA assessment should have been conducted of the TWBIR data used in the CCA.

Page 5-3, lines 38-39: *Quality assurance of the use of these waste data (by SNL) for performance assessment is addressed in Sections 5.1.4 and 5.1.7.*

The referenced sections are brief generalized statements which include no specific discussion of waste characterization data from the TWBIR. The data in section 5.1.4 is, in fact, misleading when applied to TWBIR data--it does contain a brief paragraph on the use of NDA (non-destructive assay) QA, which in part states that:

> NDA software is controlled in accordance with the requirements of the CAO QAPD.

NDA software used to gather data in the TWBIR, Revision 2, was not controlled by the requirements of the CAO QAPD (see earlier discussion).

Page 5-3, line 41 - page 5-4, line 12: *The Waste Acceptance Criteria (WAC) serve as the primary directive for ensuring that only waste that can be transported, handled, and disposed of in the WIPP are shipped and or ensuring that these wastes are certified by the generator and storage sites....The TRU QAPP describes the QA and quality control requirements for characterization....*

The requirement from §194.22(a)(2) is for a demonstration that a QA program in conformance with the NQA standards has not only been established, but also executed for waste characterization activities. Presumably, demonstration of execution would be accomplished by citing QA assessment reports on the generator sites. The EEG is unaware of any demonstration that compliance with the WAC criteria has been officially met for any waste container, so it seems unlikely that the NQA requirements can be said to have been "executed".

It may be argued that establishing the QA of the WAC, the TRU QAPP, and site QAPjPs and procedures as documents shows that the NQA standards have been "executed". One counter to this argument is provided on page 4-9 of EEG-61 (cited above): 58% of a WAC-certified population of 80 drums at INEL were miscertified according to a 1993 DOE report (DOE/WIPP 93-062).

The DOE now has a strict program for certification of generator sites before waste characterization can take place. Information on a demonstration of a full execution of the requirements of the NQA standards at the generator sites, including the certification audits, should have been provided in the CCA.

Page 5-4 line 14-16: *The DOE verifies program implementation at participating sites through audits and assessments to ensure that WIPP waste characterization activities comply with*

applicable QAPjPs and standard operating procedures.

The first three sites to ship waste to WIPP will be INEEL, Rocky Flats, and LANL. The three CAO formal assessments of waste characterization QA at these sites previous to CCA publication found that at INEEL (August 1995; INEL at the time), that ANL-W QA was inadequate; at Rocky Flats (September 1995), that the program was marginal; at LANL (August 1996), that software QA had only just begun. LANL waste characterization has not yet been formally audited by CAO to the NQA standards, though several surveillance-type activities have taken place. None of these would qualify as a demonstration that a QA program adhering to the requirements of the NQA standards had been established and executed for waste characterization activities and assumptions.

Page 5-4 Lines 25-42: *The following identifies the applicable quality-affecting activities, QA documents, and examples of subcontractors for the principal participants. DOE Activities: ...DOE QA Documents: ...*

The list of documents does not include some that would seem to be applicable. For instance, documentation used in design of the TWBIR (which should have addressed QA), the TRU Waste Characterization QAPP, the WWIS Software Quality Assurance Plan, and Performance Demonstration Program documentation should be listed, as these activities are all mentioned in the preceding text.

The "examples of subcontractors for the principal participants" does not include the subcontractor that assembled the TWBIR, which is the principal waste characterization activity that had taken place at the time the CCA was published.

Page 5-5 Lines 3-25: *Generator Site Activities: 1. Characterize TRU waste. Generator Site QA Documents: The following sites have Generator Site QAPjPs that have been approved by the DOE...*

The DOE should show that the QAPjPs were in force for the collection of data for the TWBIR. It is likely that the approval of at least some of the QAPjPs by CAO post-dates the accumulation of the TWBIR data.

The CAG (Compliance Application Guidance for 40 CFR Part 194; EPA 402-R-95-014) states (p. 18-19) that the EPA expects much more information on waste characterization activities and assumptions than is included in this section. Among these expectations are several that relate to objective evidence for various QA activities; a listing of dates when conformation to the NQA standards for each activity became effective; a description of not only DOE but principal contractor QA assessment activities; and the schedules for these activities. None of these are supplied in the CCA, though Appendix AUD lists by title (which is not a description) and date a general list of assessments that includes CAO's waste characterization assessments. The list does not however, show assessments by "principal contractors", which for waste characterization would be the generator site QA programs.

Section 5.1.2 Environmental Monitoring, Monitoring of the Performance of the Disposal System, and Sampling and Analysis Activities.

Page 5-5, Lines 30-38: *The monitoring plans required by 40 CFR § 194.42 detail the disposal system monitoring program that will be implemented during pre-and postclosure of the WIPP. This program will be implemented by the WID under the QA program described in this chapter. SNL Activities: None. WID Activities: Conduct performance monitoring. WID Documents: Reference Appendices MON and EMP.*

Lines 30-38 are the complete section. The section offers no demonstration that the "monitoring plans" have been established in accordance with the NQA standards; the "monitoring plans" are not even identified, though one can infer that the appendices may contain them. The section itself offers no demonstration that a QA program adhering to the requirements of the NQA standards has been established and executed for the titular areas--no QA documents specific to the activities are listed, no procedures that would demonstrate QA requirements at the working level.

Environmental monitoring activities, and associated sampling and analyses activities, have been conducted for years by the WID but no mention is made of QA for this effort.

The referenced appendices do not contain information which demonstrates execution of the NQA standards, even for the pre-closure activities that have been in operation for years. The QA section in CCA Appendix MON simply states (p. MON-62) that future work will be controlled by the CAO QAPD Rev. 1, and that the DOE has "agreed to adopt QA and quality control guidance" from the NQA standards (the DOE opinion is that guidance for QA is not a requirement, and therefore need not be addressed). CCA Appendix EMP describes in general terms the QA program for environmental monitoring but does not demonstrate that it has been executed. The description is in terms of 10 CFR 830.120 (from which DOE Order 5700.6C was derived), not the NQA standards, though a table (Table 8-1 on p. 8-2) attempts a cross-reference to NQA-1 requirements.

The mapping of 10 CFR 830.120 or DOE Order 5700.6C requirements to the NQA standards is not a satisfactory process--nor a quality one. NQA-1 alone contains about 30 pages of basic and supplemental requirements (not counting definitions or suggested practices); the §830.120 requirements cover about 2 pages. To find 30 pages of requirements in 2 pages of information would seem to require an exceedingly imaginative approach.

It appears that 40 CFR 194.22(a)(2)(ii) requirement for demonstration in the CCA that a quality assurance program in conformance with the NQA standards has been established and executed for monitoring has at best only been partially met.

The CAG expectations seem to have been ignored completely, unless "conduct performance monitoring" can be considered a "list" of quality affecting activities.

Section 5.1.3 Field Measurements of Geological Factors, Groundwater, Meteorologic, and

Topographic Characteristics

Page 5-5, Lines 43 to page 5-6, line 4: *The current WIPP activities related to field measurements are conducted by the WID and include several areas. Measurements of geologic factors include...*

> No statements related to QA are attached to the description of measurement of geological factors.

Page 5-6, lines 6-13: *In 1989, the EPA reviewed and commented on much of the data collected by the DOE during the site selection and site characterization program. After this review by EPA geologists, hydrologists, and other scientists, the EPA reached conclusions regarding the adequacy of the DOE's site characterization program and the reasonableness of the site characterization activities. The EPA's independent reviews and conclusions regarding the adequacy of the data were supplemented by the independent reviews conducted by the National Academy of Sciences. Therefore, the DOE considers the adequacy of the QA program and the data collected during site selection and characterization to be satisfactory.*

> Substantially the same argument was included in the earlier version of Chapter 5 that EEG commented on (Neill to Dials letter dated July 13, 1996). The EEG comment (p. 3 of the enclosure) noted that:
>
> > This is untenable on several grounds, not the least of which is that the NMVP is for compliance with 40 CFR 268.6, which has no requirement that QA programs must comply with the 1989 versions of NQA-1, NQA-2 Part 2.7, and NQA-3, as is found in 40 CFR 194.
>
> The DOE's response (p. 4 of the enclosure to Dials-to-Neill letter received August 9, 1996) was as follows:
>
> > We agree with the comment on the No Migration Variance Petition (NMVP) and had already noted this. We have updated this portion of Chapter 5.
>
> The only substantive differences between the two presentations of the argument is that 1) in the most recent version, a statement that the EEG also conducted an independent review and was in agreement with the EPA and NAS conclusions has been dropped; and 2) references to the source document were dropped.
>
> The argument is ludicrous in a document written to show compliance with 40 CFR 194. A large part of site characterization data included in the CCA has been performed since 1989; the NMVP is concerned with disposal of chemical wastes, not the radiological component that is the §194 concern, and the major concern at WIPP (plutonium is not on the list of 40 CFR 268 hazardous components); QA approaches and philosophies have changed in the intervening years; the regulation to be complied with is different for the CCA (40 CFR 191 and 194) than it was for the NMVP (40 CFR 268); and a demonstration of establishment

and execution of a QA program that adheres to the NQA standards was not a requirement for the 1989 NMVP.

Neither the "References" nor the "Bibliography" at the end of Chapter 5 contain an entry for either an EPA document, or an NAS document, concerning the 1989 NMVP. The accuracy of the DOE interpretation cannot be verified without proper referencing of the source documents.

The May 31, 1996 draft of Chapter 5 (p. 5-6) included the statement that:

> These conclusions were issued in a document titled Background Document for the U.S. Environmental Protection Agency's Proposed Decision on the No-Migration Variance for the U.S. Department of Energy's Waste Isolation Pilot Plant.

No further information on this document was provided in the bibliography of the May 31, 1996 draft Chapter 5. One of the EEG's comments on this draft was that documents were not referenced in a manner which allowed traceability.

Page 5-6, lines 15 and 17: *Topographic characteristics were characterized early in the site characterization phase of the WIPP project, and the QA of data from that period is addressed in detail in Section 5.4.2.2.*

Section 5.4.2.2 discusses in very generalized terms the Qualification of Existing Data (QED) process (for data that was not collected under an NQA program) and includes no commentary specific to measurements of topographic characteristics. Reference to this section implies that a demonstration of adherence to NQA standards for topographic characteristics as required by §194.22(a)(2) cannot be performed.

Page 5-6, lines 20-21: *See Appendix EMP for QA controls applied to monitoring activities of groundwater well levels.*

The section of Appendix EMP concerning groundwater (Section 5.4.3, p. 5-12) does not include any QA information; the QA section of Appendix EMP does not discuss establishment and execution of NQA requirements (see comments to p. 5-5, lines 30-38 above for additional data on the QA section of Appendix EMP).

Page 5-6, lines 23-35: *The following identifies the applicable quality-affecting activities, QA documents, and examples of subcontractors for the principal participants. SNL Activities: None.*

SNL was responsible for most of the measurements of geologic factors, including the "site selection and characterization program" mentioned in this section. To state that there were no SNL activities, QA documents, or subcontractors is ludicrous.

WID Activities:

No mention is made of the WID meteorological measurements or associated QA efforts.

The WID has measured meteorologic characteristics at the WIPP for many years; Section 2.5.2 (p. 2-178 ff) of the CCA indicates that data was used in the CCA from WID environmental monitoring reports from 1991-1995. This section of Chapter 5 should demonstrate that a QA program adhering to the requirements of the NQA standards was established and executed for these data and reports.

Appendix EMP also contains a section on meteorological monitoring (section 5.4.1, p. 5-11) which states that:

> A Quality Assurance Project Plan (QAPjP) is being developed for the collection of meteorological data use [sic] for regulatory purposes.

This QAPjP may be necessary before demonstration of establishment and execution of a quality assurance program that adheres to the NQA requirements can be made.

Appendix EMP section 5.4.1 lists the requirements documents for the QAPjP. Those listed do not include 40 CFR 194, the NQA standards, or the CAO QAPD Revision 1.

Page 5-6, lines 36-39: *WID QA Documents...WP 02-1 WIPP Groundwater Monitoring Quality Assurance Plan*

The title of this document since March 3, 1996 (eight months before the CCA was published) has been "Groundwater Surveillance Program Plan, Revision 3"; it is not a "Quality Assurance Plan", but five of the 25 pages (pp. 5-9) have brief sections addressing each of the 18 NQA-1 Basic Requirements.

The QAPjP for collecting meteorological data described in Appendix EMP is not listed among the WID QA documents.

5.14 Computations, Computer Codes, Models, and Methods to Demonstrate Compliance

Page 5-7, lines 9-10: *Computations and computer codes used to demonstrate compliance with 40 CFR Parts 191 and 194 are controlled as described in Section 5.3.20.*

Section 5.3.20 is a general description of computer software QA for the WIPP. It does not address computations (which are not always performed on a computer) and does not demonstrate the establishment and execution of a QA program which adheres to the requirements of the NQA standards for computer codes. It also does not describe the process for controlling the most important of computer codes for the CCA, those related to performance assessment (PA).

None of these PA codes were properly qualified (as prescribed by NQA-2 Part 2.7) for use at the time the PA calculations used in the CCA were performed (see p. 1 in Attachment 1 of the EEG July 11, 1996 Walker-to-Neill memorandum, "CAO Audit of SNL PA June 17-

21, 1996", included here as Attachment III, for a more complete discussion). Some of the important documentation for perhaps the most important computer code, BRAGFLO, had still not been completed in December, 1996—two months after the CCA was submitted, and several more months after the PA for the CCA was ran.

Page 5-7, lines 11-16: *Software supporting compliance fall into one of three categories...Table 5-1 lists the compliance software according to category.*

It is unclear why the three categories are described, as no information on the differences in QA among the various categories is supplied. Were these three categories graded differently for QA purposes?

The statement implies that all software supporting compliance is to be found in Table 5-1 (which lists only SNL's PA-related software). Other software (data acquisition, WWIS, facility design, NDA) are discussed later in this section (p. 5-9, lines 14-30), but these are not identified in Table 5-1, which is titled "Computer Software and Codes".

Page 5-7, lines 19-37: *SNL QAP 9-2, Quality Assurance Requirements for the Selection and Documentation of Parameter Values Used in WIPP Performance Assessment...The four parameter categories that are used in current compliance calculations are...1. parameters derived from experimental data...2. parameters representing inventory of the waste...3. parameters representing physical constants...4. parameters that are model configuration parameters or that are assigned based on assumed correlation of properties between similar materials.*

It is unclear why the description of the four categories of parameters is included in a section that should be discussing QA for computations, computer codes, models, and methods. Discussion of parameter categories are not a part of the requirements of either 40 CFR 191, §194, the CAG, or the NQA standards. The categories are more properly described in Appendix PAR (p. PAR.1).

Since SNL's QAP 9-2 and parameter categorization is mentioned, however, it should be pointed out that parameters of the 4th type are divided into type 4a and 4b in the version of QAP 9-2 current at the time of publication of the CCA (Revision 2, effective 09-12-96; see p. 3).

It should also be pointed that various groups of parameters are not required to comply with the complete QAP 9-2. None of the parameters entered into the PA database before 11-28-95 are required to comply with the quality-affecting portions of 9-2 according to Revision 2 (see p. 3), which was current when the CCA was published. Revision 1 did not require any of the type 4 parameters to comply with QAP 9-2, though 9-2 could be used at the discretion of the Parameters Task Leader (Rev 1, p. 3). Type 4b in the current Revision 2 are the "model configuration parameters", and are excluded from the requirements of QAP 9-2 (p. 3 of Revision 2).

> ...as they are not used in current compliance calculations and therefore are not

subject to this procedure.

QAP 9-2 requires, among other things, that the need and intended use of a parameter be documented; that the rationale for the parameter choice (the value range) be documented; and that documentation of the parameter development be referenced or attached to the Form 464 (which is a form essential to tracing of parameters). These requirements are unique to QAP 9-2, and should be required of all parameters used. Assuming that the PA is considered a scientific investigation, the CAO QAPD Rev. 1 would seem to require use of QAP 9-2 for all but the excluded type 4b parameters under the dictates of Section 5.1.B, 5.1.C, 5.1.D, 5.1.E, and 5.1.H (other sections may also apply).

Finally, it seems useful to note that parameter data in the CCA (in Appendix PAR) is not necessarily the same values as was used in the running of the PA codes for the CCA. For example, Parameter # 3148, a concrete compressibility parameter, is listed in Appendix PAR as having a value of 1.2e-9/Pa, but is shown in the code listings for the CCA (not in the CCA; at SNL) as 2.64e-9/Pa. This difference is apparently due to Appendix PAR being taken from a later database than the one used by the PA codes for the CCA. The information and data in the CCA should be the same data that was used to demonstrate compliance.

Page 5-7, line 39, to page 5-9, line 2: *A set of screening efforts, comprised of calculations and reasoned arguments, has been identified to help define and build confidence in assumptions, data sets, and conceptual and numerical models on which the performance assessment in this application is based. Assessing the effects of features, events, and processes (FEPs) on system performance is a primary component in conceptual model development...*

No explanation as to the definition or purpose of "screening efforts" is supplied, and the terminology is rather obscure. The calculations and reasoned arguments are used to determine whether or not to include consideration of a FEP in a model, but this is not explained in the text.

The connection between screening efforts and the requirements of 40 CFR 194.22 or the NQA standards is not made clear in this section. As with the parameter categorizations, this is not a QA description but a description of an operational process.

No screening efforts other than those for FEPs are identified.

Page 5-9, lines 4-10: *FEP screening is phased. Phase I FEPs are those that could potentially affect conceptual and/or numerical models. Phase II FEPs are those that could impact parameter input to the numerical models. FEP screening analysis plans for Phase I and Phase II FEPs were developed and controlled in accordance with SNL QAP 9-1...*

Phase I and II screening were only performed separately so that SNL could meet deadlines, and under SNL QAP 9-1 could have easily been written as a single analysis plan. The necessity for describing them in the CCA chapter on QA is not apparent.

FEPs screening is an area of controversy all its own, as 40 CFR 194.32(e) requires that the CCA include documentation of the reason for excluding any identified processes or events that may affect the disposal system during the regulatory time frame. The DOE originally developed a list of nearly 1200 FEPs; the draft CCA (DOE/WIPP/CAO-2056, March 31, 1995) considered about 900 FEPs; of the 900, about 30% were addressed by Phase I and II screening plans for the CCA, and 89 of these were "screened in" to the CCA. No documentation, or screening analysis plans, were developed for the reduction of the vast majority of the nearly 1200 FEPs to the approximately 240 included in the CCA.

The FEPs which were to be addressed by Phase I and II analysis plans were not all adequately documented. The EEG asked for information on 31 of these FEPs (Neill-to-Dials letter dated July 11, 1996) and the response (McFadden-to-Dials letter dated August 2, 1996) was that screening information would be supplied only in the CCA--though the analysis plans indicate screening decision packages were to be kept for each FEP. All FEP screening decisions should have been performed according to a reviewed plan, and be adequately documented. §194.32(e) requires the CCA to include documentation of why those screened out were not included in the PA results. This was not done.

Page 5-9, lines 10-11: *Additionally the DOE and SNL have provided oversight of the FEPs screening process in the form of detailed audits and surveillances.*

Failure of the DOE and SNL detailed audits and surveillances to discover and require resolution to the FEP screening problems described above does not establish confidence in the application of the quality assurance process to FEPs.

Page 5-10, lines 20-23: *WID Documents...WP 16-117 WIPP Computer Software Quality Assurance*

This document was replaced by WP16-IT3117, Revision 0, which has the same title, on 9/26/96 (a month before publication of the CCA).

5.1.5 Expert Judgment Elicitation

This section simply states "No expert judgment activities have been identified" (p. 5-10, line 31). There have been many expert judgment activities; the question is whether or not any of these should have been performed under the formal elicitation process regulated by 40 CFR §194.26.

Some examples of expert judgment activities used in the CCA follow. Expert judgment is a part of the passive institutional control development process according to the WIPP Passive Institutional Control Peer Review Report (p. 4-3 and 4-4). Numerous parameters used in the performance assessment are justified by "investigator judgment" or "professional judgment". A November 14, 1995 RE/SPEC Inc. memorandum (RE/SPEC's Pfeifle to SNL's Diane Hurtado) outlines as part of a task plan "solicitation of expert opinion" for establishing seals parameter values, and execution of this task plan would seem to fall directly under the §194.26, Expert Judgment requirements.

5.1.6 Design of Disposal System and Actions Taken to Ensure Compliance with Design Specifications

5.1.6.1 WIPP Facility

Page 5-11, lines 6-11: *Disposal system items and processes were designed using sound engineering practices, scientific principles, and applicable industry and government standards. System design descriptions, conceptual design reports, performance requirements, and regulatory requirements are included in new designs. Designs are initiated using a classification system that ensures that the proper level of design and QA requirements is employed to meet design and testing requirements.*

The EEG and the EPA have both commented that many assertive statements in previous drafts of Chapter 5 were not substantiated. These are examples of such statements. The requirement is that the application should demonstrate that the design was established and executed under a QA program that adhered to the requirements of the NQA standards, not to merely restate those requirements. Chapter 5 contains many other such unsubstantiated statements (see, for example, most of section 3.1), so many that the EEG will desist from pointing them out--but the practice adds no substantive value to the application.

Note that the initial sentence alone covers past development of designs. NQA-1 Basic Requirement 3, Design Control, begins:

> The design shall be defined, controlled, and verified. Applicable design inputs shall be appropriately specified on a timely basis and correctly translated into design documents. Design interfaces shall be identified and controlled. Design adequacy shall be verified by persons other than those who designed the item.

The final sentences of the Chapter 5 statement is in the present tense. What QA documents show that the WIPP facility was initially designed according to the NQA standards? The documents should be properly referenced.

Page 5-11, lines 13-22: *NQA-1 Supplement 3S-1 requires that design verification be performed...Design verification was accomplished by a combination of Supplement 3S-1 methods.*

Again, this is an assertive statement which is unsupported by evidence. A reference to the document which shows that Supplement 3S-1 methods were used to verify the WIPP facility design should be referenced.

5.1.6.2 Original Repository Design

Page 5-11, lines 26-31: *After Bechtel turned systems over to the DOE, an extensive and comprehensive program of start-up testing was initiated by the DOE. The program tested systems and components against the requirements specified in design documents. This testing*

meets the requirements of Supplement 35-1 for design verification.

The design documents and start-up testing documents should be referenced. The §194 requirement is to demonstrate that the activities described in these statements were performed, not to describe them.

Page 5-11, lines 33-38: *Brookhaven National Laboratory performed independent calculations of important design parameters...This task was documented in a report commissioned by the Office of Environmental Safety and Health (EH-30) titled, "Waste Isolation Pilot Plant Safety Evaluation Report" dated August 1989, including two subsequent addenda, the last of which closed all action items, concluding the Brookhaven effort.*

The report (referred to hereafter as the 1989 SER) is not listed in either the "References" or "Bibliography" sections at the end of the chapter, though a memorandum which apparently describes the report is. The document is dated July 27, 1989, not August. The document and addenda (Supplements) should have been properly referenced in the bibliography.

The purpose of the report was to independently document the completeness and adequacy of the Final Safety Analysis Report (FSAR) on WIPP that was current at that time (December 1988 version). The 1989 SER was only for the now-discarded "test phase" which had a 5-year lifespan rather than the 10,000 year requirements in §194, and notes that the 1989 FSAR did not include remote-handled waste (RH-TRU) in its considerations. The 1989 SER does, however, state that the review addresses the adequacy of design for the lifetime of ground structures and site characterization.

The 1989 SER also contains the following statement (p. 11-3 and 11-4):

> A Quality Assurance issue...was the failure to adequately transfer knowledge of facility design bases (Ref 13) to either DOE or the operating contractor. DOE and operating contractor staff engineer(s) were not fully knowledgeable of the details of the WIPP designs, the design calculations, specifications and drawings (as-built, ship, etc.). It is therefore unlikely that issues pertaining to the design bases, design calculations, structures, etc., and related quality control can be adequately addressed.

This is related to a concern expressed in an EH-30 Request for Additional Information, which stated that

> The FSAR states that construction management documents...are available at the WIPP Facility. Based on our efforts to collect information from the site, this is a gross misstatement of the facts. Documents are not generally available nor are they organized in any fashion which lends itself to review and/or audit...Any attempt to assess as-built conditions are clearly frustrated by such a situation. [SER Appendix B, Response to DOE/EH Request for Additional Information: Chapter 3, May 3, 1989, p. 22; the DOE's response was to simply note

that these were program management documents, not construction records]

Supplement 1 to the 1989 SER ("Supplement 1 to Safety Evaluation Report for Waste Isolation Plant" dated 01/16/90, p. II-3) notes that the WIPP committed to completing the "as-built" drawings for critical systems in the facility on a schedule provided. A memorandum from M. R. Brown, Manager of Westinghouse Engineering & Repository Technology Support, to Richard J. Figlik, WIPP Project Office, dated May 5, 1989 (see Attachment IV), illustrates the extent of the process necessary for developing the "as-built" drawings: Attachment 1 to the memorandum is a list of prioritized "as-builts" to be reconstituted, which, among other items, includes the electrical system for both the surface and underground, the environmental monitoring system, the radiation monitoring system, the underground ventilation system, the confinement facilities, the shaft hoist systems, communication systems, fire protection systems, waste handling equipment, the central monitoring system, security systems, water systems, underground testing and testing equipment, and "General Civil and Standard Systems" (which would seem to be the non-specialized items such as the site support buildings).

In short, the original QA records for design were not collected, stored, or maintained as required by NQA-1 Supplement 3S-1.7, and had to be redone. Chapter 5 should reflect the true history of QA for the facility design.

Page 5-12, line 4: *See Section 5.3.1.8 for the location of applicable QA records [for WID design].*

Section 5.3.18 (p. 5-37) contains QA records location information (there is no section 5.3.1.8).

Page 5-12, lines 24-34: *The repository sealing system design....report [Appendix Seal] was extensively reviewed...audits and surveillances were performed on each of the primary contractors...The DOE performed oversight activities...of the SNL QA program as it relates to the SNL Sealing Systems Program...*

References to the specific audits and surveillances should have been included.

5.1.7 Collection of Data and Information to Support Compliance Application(s)

Page 5-14, line 17: *WID Activities: None.*

Data and information collected by WID is used throughout the CCA. Several chapters in the CCA reference the Site Environmental Reports for 1990 and 1992-1995, for example. Many of the appendices to the CCA are totally based on WID or WID subcontractor data. These include the Annual Site Environmental Report (Appendix SER); Appendix RPB, Statistical Summary of the Radiological Baseline Program for the WIPP, March, 1992; the Engineered Alternatives Cost/Benefit Study (Appendix EBS); Appendix EMP, the Environmental Monitoring Program (which wasn't mentioned as part of Environmental

Monitoring, section 5.1.2); Appendix GTMP, the geotechnical surveillance program; and Appendix GWMP, the groundwater monitoring program.

Organizations other than the DOE, SNL and WID are referenced in the CCA; for instance, Appendix HYDRO is written from US Geological Survey reports. The introduction to the Appendices (in the computerized version of the CCA) states that:

> Significant portions of the hydrological data in Chapter 2.0 are derived from this report.

Chapter 2 is Site Characterization, a major component of the CCA; and hydrological considerations are of major importance to compliance. This, too, is data and information used to support compliance, and demonstration of establishment and execution of a QA program that adheres to the NQA standards for the USGS data would seem to be a requirement of §194.22(a)(2)(vii)--though processing through the QED process allowed by §194.22(b) would seem to be a viable alternative.

5.1.8 Other Systems, Structures, Components, and Activities to the Containment of Waste in the Disposal System

Page 5-14, Lines 24-26: *At this time, the DOE has not identified any other systems, structures, components, or activities important to the waste isolation in the disposal system that require controls to be applied as described in the CAO QAPD.*

The process utilized for controlling drilling activities in the WIPP vicinity is an important activity for containment of waste with which the DOE has had problems in the past (see the "Passive Institutional Controls" section of EEG's March 14, 1997 letter to the EPA, in the WIPP docket for a pertinent example). QA oversight of this process could enhance the WIPP disposal system.

5.2 Program History

Page 5-15, Lines 1-19: *A QA program was established in late 1977 that was based on 10 CFR Part 50, Appendix B...By late 1978, DOE policy refinements had expanded the QA program to incorporate the requirements of...(ANSI)/ASME N45.2, and had extended the applicability...to all earth science activities furnishing information on the possibility of radionuclide release into the biosphere...in late 1979...The WIPP QA program was revised to meet the DOE/Albuquerque Operations Manual (Chapter WIPP), which was equivalent to the requirements of ANSI/ASME NQA-1-1979...Over the next 12 years, the WIPP QA program was revised to reflect the ...changes in upper tier QA program documents NQA-1-1979 to NQA-1-1989...*

The principle documents for the QA program(s) described, and the documents showing the changes, should be referenced. The DOE/AL Operations Manual should be included in the References/Bibliography at the end of the chapter.

The 1989 SER (FSAR review by DOE Headquarters EH-30; referenced above in comments

on p. 5-11, lines 33-38) found in late 1988 (p. II-2):

> (1) A lack of sufficient independence for the QA organization, (2) a lack of adherence to the intent of the ANSI/ASME NQA-1 Supplements, (3) a lack of an adequate design control program, (4) an inconsistent approach for the evaluation of "Important to Safety" items and services, (5) a lack of training, qualification and certification of audit, inspection, and test personnel and (6) no training and indoctrination programs.

The first attempts to address these were also woefully inadequate, indicating that basic knowledge of NQA-1 was not highly developed. The 1989 SER comments on WIPP's first response (from the 1989 SER, p. II-3):

> The requirements of ANSI/ASME NQA-1 were quoted but no description of how they would be implemented was provided. Although there was improvement in most areas, the Quality Assurance Program still lacked: (1) identification of the responsible Quality Assurance authority and its place in the WIPP Organization Structure, (2) interface requirement between the three major participants [DOE, SNL, WID], (3) responsible authority and commitment for a Training and Indoctrination Program, (4) specific commitments for review and approval of procurement documents, (5) a requirement for receipt inspection and the option of using source inspection to accept procured items or services, (6) the specifics for waste material receipt inspection at the site, (7) responsibilities for the processing and storage of radioactive materials, (8) test procedure requirements, (9) handling and storage requirements for radioactive waste materials, (10) responsibilities for nonconformance control, and (11) qualification and certification of audit personnel.

Given that these items reflect language from many NQA-1 requirements it seems likely that the application of NQA-1 was not a significant part of the WIPP QA program before the EH-30 evaluation took place. 10 CFR 50 Appendix B, cited as the basis for the 1977 origin of WIPP QA, contains similar requirements.

A June 1, 1989 memorandum from James P. Knight, Director of the DOE's Office of Safety Appraisals, to Richard W. Starostecki, on the subject "EH Oversight of the Waste Isolation Pilot Plant Project (WIPP)" (see App. V), adds other failures in the WIPP QA program to address NQA requirements (p.2):

> A fundamental management issue also remains at this time; the adequacy of the DOE Quality Assurance (QA) program for the WIPP project. As presently structured, neither the dedicated QA staff, one person designated as the QA Manager, nor the low reporting level of the QA program meet the ANSI/ASME, NQA requirements espoused by DOE orders.

The "one person designated as the QA Manager" was the entire WIPP Project Office QA staff at the time (Westinghouse apparently had the "dedicated QA staff" mentioned). Indirect evidence also points to a lack of QA during the period up to 1989. The "as-built" design problems addressed above (see comment to page 5-11, line 33-38) were apparently never addressed by the WIPP QA organizations. Jack B. Tillman, DOE's WIPP Project Manager in 1989, testified during the June 12, 1989 hearings of the U.S. House of Representatives Environment, Energy, and Natural Resources Subcommittee of the Committee on Government Operations that:

> The as-builts have been known as a deficiency since the Corps of Engineers left the site...

(Page 171 of the printed hearings; U.S. Government Printing Office, 1990.) However, there is no evidence that responsible QA organizations pursued remediation of that deficiency in the years after the Corps of Engineers left. Any auditing activity seeking objective evidence that NQA-1 Basic Requirement 3 had been met, in virtually any area at WIPP site during this time, would have rediscovered the deficiency. Chairman Synar of the subcommittee later indicated his view of the QA program (p. 333 of the printed hearings):

> ...without an adequate quality assurance program, Mr. Tillman, I think it is very unlikely that you are going to be able to ensure that the experiments are going to be run properly, that the appropriate data is collected, and that it is applied properly.

In 1989, it appears that reviewers did not find a WIPP QA program which met the requirements of the NQA standards. Chapter 5 should reflect a more accurate history of WIPP QA.

5.3. Adequacy

"Adequacy" is later defined (p. 5-39) as the flowdown of requirements contained in upper-tier documents into implementing procedures. The subsections under this heading seem to be arranged in accordance with the Basic Requirements of NQA-1, with NQA-2 Part 2.7 and those portions of NQA-3 not already covered added at the end. This format and intent should have been made explicit in the text.

Though arranged according to the NQA standards, the subsections do not describe how all of the requirements described in the Basic Requirements and Supplements are met. The matrices mentioned on page 5-1, which link NQA requirements to the principal QA documents for the major WIPP organizations, would seem to have been more effective (and concise) in demonstrating that the WIPP QA program documents contain the requirements of the NQA standards.

In several subsections implementing documents for SNL are described as "None", even though these are requirements of the NQA standards which are applicable to SNL operations. These

appear to reflect a lack of research in writing Chapter 5, rather than an absence of adequacy in the SNL QA program.

Page 5-16, lines 12-18: *From May 1993 to March 1994, DOE Headquarters...(EM-342) assessed the quality of the WIPP data acquisition process for performance assessment...The team concluded that the DOE needed to reevaluate all experimental program data used to support performance assessment.*

The EM-342 documents describing the assessment and its conclusions should be referenced.

Page 5-16, lines 20-42: *The adequacy of the current DOE QA program is ensured by passing down requirements...with the directive that applicable requirements then be passed down to lower tier organizations...Adequacy of QA program requirements are initially verified by the DOE through the review of lower-tier QA program documents prior to their implementation...Formal document review forms are used...*

QA documents that demonstrate this is being done should be referenced (the CAO QAPD in Appendix QAPD, Section 1.1.2.1 covers the majority of these requirements).

Page 5-21, Lines 1-8: *The DOE has also prepared matrices tracing the applicable NQA requirements referenced in Section 5.1 to the CAO QAPD. WID and SNL likewise are required to prepare and maintain matrices...the matrices are designated [sic] to demonstrate that the DOE, SNL, and WID QA programs are adequate and address all applicable requirements.*

Including the matrices could have been a major step in demonstrating adherence to a QA program that implements the requirements of the NQA standards, as required by 40 CFR 194.22(a)(1). These matrices would also provide substantiation for many of the assertive statements that currently lack substantiation (see comment addressing page 5-11, lines 6-11).

Page 5-21, lines 10-11: *The DOE, SNL, and WID perform assessments that include the review of implementing documents for adequacy.*

The source document(s) for this requirement should be properly referenced.

5.3.3.1 Grading

Page 5-25, line 19-21: *WID Implementing Document: WP13-QA3501 Graded Approach*

The EEG controlled copy of the WID QA procedures shows that this document was removed from the WID Quality Assurance Manual on September 27, 1996, a month before the CCA was issued. The controlled copy change notice does not indicate any replacement document. At the EPA audit of WID in February, 1997, WP13.03 Revision 0, Quality and Regulatory Assurance Department Assessment Program, effective August 26, 1996, was identified as the current implementation of the WID grading process (Section 7.3.1,

"Activity Grading Process").

5.3.3.2 QA Program Documents (p. 5-25)

This section does not include SNL QA program documents. The CAG expectation (p. 18) is that DOE principle contractor top tier QA documents would be included in the CCA, not merely listed.

5.3.3.3 Qualification and Training

Page 5-26, line 2: *Personnel performing work are qualified and capable of performing their assigned tasks.*

Personnel are required to be qualified and capable—that does not mean personnel will always be so. It hasn't been in the past. for example, an SNL surveillance in November, 1995 discovered that only 2 of 30 personnel in the FEPs program had fulfilled the training requirements.

Similar overstatements, wherein a QA program requirement is described as if absolute compliance with the requirement is a certainty, are made throughout Section 5.3 subsections. These are logical fallacies for which countering examples can nearly always be found (see comment to the following section, 5.3.3.4, for another example). Such statements are usually so self-evidently overdone that most are only a minor distraction, and will not be individually pointed out.

Many of these statements also should provide a specific reference to the section(s) of WIPP QA document(s) that establishes the requirement. These will also not be individually pointed out--but assertions should always be backed by objective evidence or a path to the objective evidence.

5.3.3.4 Management Assessments

Page 5-26, lines 28-30: *Management personnel...perform assessments of the portions of the program for which they are responsible to assist in ensuring effective implementation of QA requirements.*

The CAO Manager had yet to perform an assessment of CAO at the time the CCA was published (one is scheduled for February 24-28, 1997). The NQA-1 requirement (Basic Requirement 2, last paragraph) is that management "...shall regularly assess the adequacy of the program for which they are responsible...". SNL's last WIPP Project Management Assessment (previous to the October 1996 publication of the CCA) was June 12, 1995. Corrective Action Reports on management assessments have been initiated at both CAO and SNL.

Pages 5-17 to 5-32, Sections 5.3.4 Design Control...5.3.5 Procurement Document Control...5.3.6 Instructions, Procedures and Drawings...5.3.7 Document Control...5.3.8

control of Purchased Items and Services...5.3.9 Identification and Control of Items...5.3.10 Control of Processes... No significant additional comments, though these sections do not necessarily address all the NQA-1 requirements for the area specified. For instance, section 5.3.4, Design Control, does not show how design inputs are identified, documented, reviewed, and approved, as required by NQA-1 Supplement 3S-1.2. Editorial note: page 5-30, line 31, "WP 13-QA10003" should be "WP 13-QA 1003".

5.3.11 Inspection

Page 5-32, lines 6-22: *Inspections determine acceptance or rejection of a process, product, or service. Inspection documentation for DOE participants includes the following: approved implementing procedures...DOE Implementing Documents: None SNL Implementing Documents: None*

> The CAO QAPD, Rev. 1 requires that inspections be performed in accordance with approved implementing procedures (Section 2.4.1). This section implies that SNL does not have the procedure required by the CAO QAPD for conducting inspections. It further implies that there are no documents controlling SNL's inspection activities at all.

5.3.12 Test Control

Page 5-32 line 32 to Page 5-33 line 16: *...Test included as part of scientific investigations are conducted in accordance with the QA methods described in Section 5.3.21...SNL Implementing Documents: None*

> Apparently all SNL tests are considered to be scientific investigations, covered by the procedures listed in Section 5.3.21. This should have been made explicit in the text, as the sense of the text in this section is that SNL has no implementing documents for control of testing.

Page 5-33 line 20: *WID Implementing Documents: WP 03-001 Preparation, Release, and Cancellation of Start-up Test Procedures*

> While this is not particularly a CCA concern, the document has not been changed since August 21, 1992, and the last periodic review noted in EEG's controlled copy was August 12, 1993. Page 4-5 of the document requires control and startup QA records to be processed in accordance with WP 13-6, a procedure removed from service before September 27, 1996.

5.3.14 Handling, Storage, and Shipping

Page 5-34, lines 21-37: *Items...are handled, stored, and shipped using approved and documented methods...SNL Implementing Documents: None*

> NQA-1 Supplement 13S-1.2 requires that these processes are to be "...conducted in accordance with established work and inspection instructions...or other pertinent documents

or procedures specified for use in conducting the activity." This section implies that SNL has no such documents or procedures.

5.3.15 Inspection, Test, and Operating Status

Page 5-35, lines 5-7: *The specific status indicators, their use, and the authority to apply or remove them are delineated in applicable QA plans or implementing procedures...SNL Implementing Documents: None*

The implication is that SNL has no internal documents requiring compliance with NQA-1 Basic Requirement 14, Inspection, Test, and Operating Status.

5.3.16 Control of Nonconforming Items

Page 5-35, line 30 to page 36, line 13: *...When appropriate, further work on the item is halted by senior management until the appropriate actions have been taken and verified. The nonconformance control process is documented in applicable QA plans or implementing procedures...WID Implementing Document: WP13-007, Hold Tag Issuance*

In this section, neither SNL or DOE implementing documents are specified. SNL does have at least one procedure that would seem to apply to the discussion in this section (QAP 2-5, "Issuing and Lifting Stop Work Orders"); WID, too, has a "Stop Work" procedure that would also seem to apply (WP13-008).

The CAO QAPD, Rev. 1, Section 1.3.2.3.D. requires that disposition of nonconforming items, and the responsibility and authority for evaluation and disposition, be defined in QA documents (plans or procedures). The NQA-1 requirement (Supplement 15-S1.4.1) is:

> Nonconforming characteristics shall be reviewed and recommended dispositions of nonconforming items shall be proposed and approved in accordance with documented procedures.

Procedures covering the discussion of nonconforming items should have been listed.

5.3.17 Corrective Actions

Page 5-36, lines 21-23: *A significant condition adverse to quality is defined as a condition that, if not corrected, could have a serious effect on compliance with 40 CFR Parts 191 and 194.*

A statement that compliance with the EPA disposal regulations is the only defining factor for a significant condition adverse to quality is exceptionally disconcerting. This definition is simply unacceptable--A WIPP QA program utilizing such a definition would likely be unacceptable. Fortunately, the CAO QAPD, Rev 1, offers an infinitely better definition which is in use by WIPP QA (Section 1.3.2.1, p. 1-16):

> Significant conditions adverse to quality are conditions that if not corrected,

could have a serious effect on safety, operability, waste isolation, compliance, or the reliability of the QA program.

The difference between chapter 5 and the QAPD definitions of what constitutes a significant condition adverse to quality is evidence both of poor writing and inadequate review of chapter 5.

Page 5-37, lines 8-9: *Minor software problems are documented by software problem reports or other resolution mechanisms as discussed in Section 5.3.20.*

No specific mention is made of software problem reports or other resolution mechanisms in Section 5.3.20; the closest statement is (p. 5-41, lines 25-26):

> For released versions, software problems are documented, evaluated, and, if appropriate, corrected.

This seems far short of the "discussion" indicated.

Page 5-37, lines 9-10: *If a software problem is determined to be a condition adverse to quality, it is documented and resolved as described in this section.*

The difference between a minor software problem, which may or may not be corrected, and a condition adverse to quality in software, for which the corrective action process must be followed, is not explained. The term "condition adverse to quality" is not defined, though "significant conditions adverse to quality" is.

5.3.18 QA Records

Page 5-37, line 36, to Page 5-38, line 6: *The records management process includes provisions for...classifying QA records as either lifetime, nonpermanent, or postclosure...*

Classification of the many unique records generated by the WIPP has yet to be accomplished, as the DOE must submit suggestions to NARA (National Archives and Records Administration) on classification of WIPP records and await NARA's guidance. The NARA positions could take some years to obtain. The provisions are in place, but many of the QA records have not been classified yet. This should have been explained in the CCA.

Page 5-38, lines 17-22: *These [QA] records are maintained by the proper organization for approved disposition. DOE QA records are retained in the document services storage facility in Carlsbad, New Mexico. SNL QA records are retained in the SNL WIPP Central Files located in Albuquerque, New Mexico, and Carlsbad. WID QA records are retained in the WID WIPP Files located in Carlsbad. Generator site QA records are retained in NQA-1 storage facilities at each site.*

Essential records are still at several subcontractor sites other than those mentioned. For

instance, records related to microbial degradation of the waste were at Brookhaven National Laboratories in early February, 1997, four months after the CCA was published.

5.3.19 Audits and Surveillances

Page 5-39, lines 15-16: *The management and control of audits and surveillances are documented in QA plans or implementing procedures.*

The "implementing documents" sections for this section list procedures, but no QA plans are cited.

5.3.20 Computer Software QA

Page 5-40, lines 10-12: *Plans are prepared at the start of the software life cycle to document the software basis and objectives of the software to meet its intended use.*

This description (however it may be interpreted) falls short of describing the necessary "requirements phase" documentation specified by NQA-2 Part 2.7 sections 3.1 and 6.2. These sections require that in the requirements phase that software functionality, performance, design constraints, attributes, and external interfaces shall be specified documented, and reviewed, that the software response to anticipated classes of input data shall be defined. Section 3.1 also requires that verification and validation plans are to be written. The CAO QAPD Revision 1 (in Appendix QAPD) does contain what seems to be an adequate description of the process, and could have easily been referenced.

Page 5-40, lines 15-17: *Any software errors and failures are reported to the sponsoring organization for analysis and then forwarded to the supplier, if applicable.*

NQA-2 Part 2.7 Section 10.1 states that not only will the supplier report software errors or failures to the purchaser, but "...the purchaser shall report software errors to the supplier." No mention of determination of applicability by the purchaser is to be found in NQA-2 Part 2.7--the reporting of software errors and failures to the supplier must always be performed.

Page 5-41, lines 25-26: *For released versions, software problems are documented, evaluated, and, if appropriate, corrected.*

When would correction of software problems not be appropriate? NQA-2 Part 2.7 Section 8 does, however, have similar language:

> Corrective action by the responsible organization shall assure that: (a) problems are identified, evaluated, documented, and, if required, corrected...

Software problems that do not require correction should not be considered problems.

Page 5-41, lines 39-42: *WID Implementing Documents... WP 16-117, WIPP Computer Software*

The comment to Page 5-10, lines 20-23 was that this document was replaced by WP16-IT3117, Revision 0, same title, on 9/26/96, a month before publication of the CCA.

5.3.21 Scientific Investigations

Page 5-42 line 4-6: *Process variables affecting scientific investigations are measured and controlled as described in Section 5.3.13.*

The section referenced is "Control of Measuring and Test Equipment". Process variables other than equipment can affect scientific investigations.

Page 5-42, lines 31-32: *Scientific investigations are performed according to requirements documented in scientific notebooks or technical implementation documents or both.*

The statement reverses the order found in Section 5.2.A of the CAO QAPD Rev 1 (p. 5-2):

> Scientific investigations shall be performed in accordance with requirements documented in test plans, procedures, and scientific notebooks.

Test plans and procedures go through a series of required reviews, a comment resolution process, and approvals before promulgation; it is hard to imagine that requirements listed in scientific notebooks would undergo anywhere near the same scrutiny.

The problem of using scientific notebooks as a requirements document has cropped up at SNL in the past, when scientific investigations were in process (sometimes completed) before test plans or procedures governing the operation had finished the review and comment process. When QA assessments uncovered the deficiency the response has been that daily communications documented by entries in scientific notebooks were thought to be sufficient. If comments have yet to be resolved and approvals haven't been granted, how can the daily communications recorded in the notebooks reflect the yet-to-be-determined requirements?

If the result of the CAO QAPD statement quoted above is to allow scientific notebooks to be used as described at SNL, the CAO QAPD may have failed to fulfill Basic Requirement 2 of NQA-1. This requirement states in part that the documented quality assurance program

> ...shall provide for the planning and accomplishment of activities affecting quality under suitably controlled conditions. Controlled conditions include the use of appropriate equipment, suitable environmental conditions for accomplishing the activity, and assurance that prerequisites for the given activity have been satisfied. [emphasis added]

Scientific notebooks are a record of thoughts, processes, data, and results from within a scientific investigation. Planning documents establishing requirements for the investigation should be completed before the work begins. Use of scientific notebooks should not be a circumvention of the responsibility to plan, review, and authorize requirement documents for scientific investigations.

Since SNL is responsible for the bulk of scientific investigations for WIPP matters, it is worth noting that SNL QA Procedure (QAP) 20-2, Preparing, Reviewing, and Approving Scientific Notebooks, requires as the first step in the process (Section 4.1, Step 1, p. 5) that the principal investigator

> Ensure that planning is documented in an approved Test Plan according to QAP 20-1 or an approved TOP [Technical Operating Procedure]...

QAP 20-1, Preparing Reviewing, and Approving Test Plans, dictates that requirements are to be addressed in test plans (Appendix A, p. 11).

Page 5-43, lines 1-2: *Uncertainty limits are assigned to the data prior to their use.*

Uncertainty limits should be derived from statistical interpretation of the data, rather than assigned (this may be simply poor word choice).

Page 5-43, line 34: *WID Implementing Documents: None*

WID performs scientific investigations (under any rational definition of the term WID's environmental monitoring program qualifies), and undoubtedly has implementing documents in the form of plans and procedures which should have been listed here.

<u>5.3.21.1 Data Quality Characteristics</u>

Page 5-43, line 38-40: *40 CFR § 194.22(c) states that to the extent practicable, data used to support compliance will be assessed according to their accuracy, precision, representativeness, completeness, and comparability.*

This is a misinterpretation of 40 CFR 194.22(c)]. The requirement is as follows:

> Any compliance application shall provide, to the extent practicable, information which describes how all data used to support the compliance application have been assessed for their quality characteristics, including...[the PARCC characteristics (precision, accuracy, representativeness, completeness, and comparability)]

The requirement does not state that the data must be assessed the PARCC characteristics, only that the CCA include a description of how the assessment was performed. It is also important to note that the requirement does not limit the DOE to only considering the PARCC characteristics--the DOE could also take the opportunity to describe how other

quality characteristics of the data were assessed.

Page 5-43, line 39 to page 5-44, line 2: *The DOE believes that these data quality characteristics are applicable to tasks involving the quantification through sampling and analysis of specific constituents of an environmental medium. The DOE also believes that these requirements are intended to address activities such as the determination of the presence or absence of pollutants in waste streams. Waste characterization and environmental monitoring are examples of the types of activities at the WIPP in which data quality characteristics apply. In these cases the performance measurement is the concentration of the constituent of interest.*

The DOE agrees that waste characterization and environmental monitoring activities could be assessed using the PARCC characteristics, but no description of how data from these areas were assessed is included in this section, chapter 5, or elsewhere in the CCA.

Page 5-44, lines 4-12: *In performance assessments...the performance measure is cumulative release of radionuclides to the accessible environment over the next 10,000 years. This measure is estimated using mathematical models rather than being determined by direct measurement. The performance assessment process requires the use of mathematical models for the repository, which, in general, require that numbers (here called parameters) be assigned to geologic formation and waste properties. Since many of these parameters are not amenable to direct measurement, they must be treated as uncertain variables, rather than precisely determined quantities, and characterized by probability distributions.*

There seems to be a logical jump at the beginning of this paragraph that is not warranted. The ultimate performance measurement for PA is compared with an interim performance measurement for environmental monitoring. The ultimate performance measure for environmental monitoring is determination that radionuclides have, or have not, been released, just as it is for PA; concentration values are an interim step to that measurement, just as many parameter values are for PA (the difference is, of course, that environmental monitoring results are real, while PA is a projection). Other parameter values, those "not amenable to direct measurement", should be based on data measurements to which PARCC characteristics could be applied. Finally, the PARCC characteristics do not need to be applied only to "precisely determined quantities"; for example, the completeness figure for a difficult process could be 10%, and the accuracy set to 300%. The requirement is to show how the values were assessed, not to require that narrow limits be put on the measurements.

The PARCC characteristics are a method for establishing the validity of the measurement—but that is a scientific usage, not a QA function. The §194.22(c) QA requirement is that the CCA should contain information which describes how the PARCC characteristics were assessed.

Page 5-44, lines 14-21: *Data are used to develop conceptual models for disposal system performance that are implemented as computational models in the performance assessment. Data are also used to support distributions for parameter values used in computational models. Between the point of data collection and the final computational model, uncertainty is introduced*

(for example, experimental design, extrapolation of the experimental results to spatial or temporal scales, etc.). These parameter distributions may span several orders of magnitude, and many parameters derived from data measurements need be known only within orders of magnitude of their true value. Efforts to reduce the range do not necessarily improve the model accuracy.

The requirement is for the data, not for the computational modeling use of it. If the low-level data, based on measurements, have not been assessed for their quality, how much assurance can there be that the parameter distributions based on it are a measure of reality? An original measurement that represents a sample three orders of magnitude from the mean of the population is not much improved by establishing a three orders of magnitude range. The last sentence implies again that the PARCC characteristics are a requirement to reduce the range; they aren't. The PARCC characteristics help establish what sort of range should be used. This relates to the confidence which can be placed on the model accuracy, not the accuracy itself.

Page 5-44, lines 31-26: *Uncertainty and sensitivity analyses respectively assess the uncertainty in system performance measures and identify modeling areas and parameters in which reductions in uncertainty can increase confidence. If the uncertainty of a parameter is of significant importance to the performance of the WIPP, more data could possibly be collected to reduce uncertainty.*

This paragraph doesn't address the requirement at all. PARCC characteristics are not intended to reduce uncertainty, but to establish the quality of whatever uncertainties are used. The requirement is to ensure that an attempt has been made to address the uncertainty at the experimental data level. Uncertainty and sensitivity analyses at SNL determine the most important parameters, but it is the level of confidence in the underlying data for parameters that the application of quality characteristics is meant to establish.

Page 5-44, lines 33-38: *Instead of the above quality characteristics, other steps ensure that data are of adequate quality. Upper-tier quality requirements documents specifically define QA requirements for the collection of scientific and technical information. Section 5 of the CAO QAPD, Scientific Investigation Requirements, identifies the current requirements for data collection. For inclusion in compliance calculations, the data must be collected under an approved QA plan or otherwise be qualified.*

§194.22(a) covers the requirement for the QA program described; §194.22(c) seems clearly to be a requirement independent, and additional, to that established for the overall QA program.

Page 5-44, lines 40-43: *In summary, it is not practicable to apply data quality characteristics to most scientific investigations used to support a performance assessment in which there is uncertainty in the conceptual models and the resultant ranges of parameters. Instead, controls established by the QA program provide the necessary quality.*

The section fails to supply the required PARCC information for those scientific

investigations which this summary admits are not covered by the arguments.

It is likely that some, if not most, of the underlying scientific investigations used in PA had some sort of evaluation related to quality characteristics applied to it. The PARCC characteristics in particular have been established scientific quality attributes for many years. Some of evaluations may have even been clearly prescribed and documented. Retrieval of this data would be an enormous task, and even when retrieved would not be likely to show a consistent method of application. It may be that it is not practicable to supply information in the CCA as to how the PARCC characteristics were applied to all the data used in the CCA--but the arguments used in this section of Chapter 5 are not persuasive.

The arguments presented in this section are concerned solely with the PARCC characteristics. The DOE has provided no information as to how any quality characteristics were assessed for data, at any level. It may not be practicable to always assess the PARCC characteristics, but different quality characteristics for data used in the CCA could have been defined and assessed, and information concerning these assessments could have been included in the CCA.

5.4 Implementation

This section is for the most part a well-written and accurate description of the proactive and effective WIPP QA program the EEG has observed in recent years. Many of the comments that follow are editorial in nature--but there are still significant deviations from easily discoverable facts.

5.4.1 DOE QA Program Implementation

Page 5-45, lines 26-31: *The most recent audit of DOE/CAO...concluded that the DOE/CAO QA Program was adequate and effective, but not completely implemented. They cited nonimplementation of two DOE procedures...These procedures are now fully implemented and the overall DOE QA Program is effectively implemented.*

Reference to the documentation of the acceptance by the auditors that the program is now considered to be effectively implemented should be included.

5.4.2 SNL QA Program Implementation

5.4.2.1 Data Qualification

Page 5-48 line 41 to page 5-49 line 6: *An SNL audit Internal Audit [IA] 95-03...was conducted in August 1995 to verify the adequacy and effective implementation of QA requirements...All the resulting corrective actions have been completed and verified...The audit concluded that...SNL QA controls were in place and that they were adequate and effectively implemented.*

This paragraph begins the section on data qualification, and appears as a *non sequitur* in

that it doesn't seem to relate to the title. It is not until the succeeding paragraphs define what "data qualification" is that a possible clue to the applicability of the paragraph may be deduced: this audit may have established the time after which SNL's data can be said to have been developed under the NQA standards. This interpretation can only be tentatively made. The reason for including the paragraph should have been made explicit.

Page 5-49, lines 8-16: *Data can be qualified for use by one of five methods...(2) existing data collected before the implementation of a qualified QA program are qualified by showing that the data were obtained under a QA program that is equivalent to one satisfying the NQA requirements referenced in Section 5.1...*

In the Independent Review Team (IRT) process, the entire QA program did not need to be equivalent to one which satisfied the NQA requirements. Only those portions applicable to the data being qualified needed to be equivalent to NQA requirements. The difference is important, in that none of the data qualified by IRT processes was collected under a fully NQA equivalent program.

Page 5-50, lines 1-2: *...collected after August 1, 1995 when SNL QA program was qualified by the DOE (Method 1).*

The DOE document establishing the qualification should be referenced.

5.4.2.2 Qualification of Existing Data

Page 5-51, lines 13-14: *All data sets not qualified by IRT or collected under a qualified QA program were qualified by the peer review process.*

Only those data sets used in the CCA were qualified. About 30 data packages failed the IRT process but were not sent to peer review.

5.4.2.3 T=0 Process

Page 5-51, Lines 30-31: *The process [T=0 for subcontractors to SNL] is documented in SNL procedure QAP 20-7.* Establishing T=0 for Internal and External Experiment Activity QA Programs, *and includes the following key elements...*

Revision 0 of QAP 20-7 has an effective date of November 20, 1996, nearly a month after the CCA was published. The process used may be documented in the procedure, but an approved version of QAP 20-7 was obviously not available at the time the T=0 determinations for the subcontractors listed in Table 5-6 were made. The process of determining T=0 is a quality-affecting one, and should have been controlled by procedures or instructions as required by NQA-1, Basic Requirement 9 and Supplement 9S-1.2, and the CAO QAPD Section 2.1.A--that is, the SNL document(s) that controlled and authorized the process at the time the subcontractor T=0 determinations were made should have been cited, not QAP 20-7.

5.4.3 WID QA Program Implementation

Page 5-52, lines 36-40: *WID determines the adequacy of the implementation of QA requirements for both internal WID customers and external contractors. Internal determinations of adequacy of QA implementation are generally based on adherence to the WID QAPD requirements. The process includes a review of the contractor's QA program with regard to the applicable element of the WID QAPD, nationally recognized codes and standards, and regulations.*

The term "internal customer" is not a commonly understood term, and should have been defined.

The transition from internal QA to external contractor QA between the second and third sentences is not explicit.

Page 5-52, lines 40-43: *The WID has performed audits and surveillances to determine the dates when each of its supplier's and subcontractor's QA programs were considered adequate and effectively implemented. These dates and the basis for determination are shown in Table 5-10.*

This is the "T=0" process which was more carefully described for SNL in Section 5.4.2.3. The controlling instructions or procedures for this process required by NQA-1, Basic Requirement 9 and Supplement 9S-1.2, and the CAO QAPD Section 2.1.A, should have been cited.

List of Attachments

I. July 22, 1996 letter from R. H. Neill, EEG, to George Dials, DOE (Referenced on page 2 of this review.

II. Undated letter (received by the EEG on August 9, 1996), from G. Dials, DOE, to R. H. Neill, EEG (Referenced on page 2 of this review).

III. August 20, 1996 memorandum from B. Walker, EEG, to R. H. Neill, EEG (Referenced on page 16 of this review).

IV. May 5, 1989 memorandum from M. R. Brown, WID, to R. J. Figlik, WPO/DOE (Referenced on page 21 of this review).

V. June 1, 1989 memorandum from J. P. Knight, DOE, to R. W. Starostecki, DOE (Referenced on page 23 of this review).

Attachment I to EEG Review
of CCA, Chapter 5

ENVIRONMENTAL EVALUATION GROUP

AN EQUAL OPPORTUNITY / AFFIRMATIVE ACTION EMPLOYER

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July 22, 1996

Mr. George Dials, Manager
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P. O. Box 3090
Carlsbad, NM 88221-3090

Dear Mr. Dials:

Attached is the EEG review of Chapter 5, "Quality Assurance," from the WIPP Compliance Certification Application (CCA), published as DOE/CAO-96-2056 on May 31, 1996. Chapter 5 contains significant omissions and errors, and does not appear to meet the QA requirements listed in 40 CFR 194 or the expectations for QA as listed in the Compliance Application Guidance (CAG; EPA 402-R-95-014).

While the EPA has agreed to review the CCA a chapter at a time, the expectation was that each chapter would be a final version that would illustrate the DOE's best explanation of how the regulatory requirements for the areas covered by that chapter have been met. Chapter 5 contains many "placeholders", which are apparently to be replaced by data and analyses which have yet to be generated. Two appendices are referenced which were not included; the included Appendix RE-5 is apparently not referenced by the chapter, and is either incomplete or unnecessary. The EEG cannot provide a complete review until the additional information is added to the chapter package.

Chapter 5 also fails to meet the QA expectations listed in the CAG under the heading "§194.22 Quality Assurance" (page 18). The EPA clearly states on page 1 of the CAG that these expectations will be the criteria by which the completeness of the application will be judged, and that no further actions will be taken until the expectations are included. EEG could only verify that one of the first five expectations was included in Chapter 5. Unless it is the DOE's intention to meet the CAG QA expectations elsewhere in the CCA then Chapter 5 is also deficient in this regard.

For the most part Chapter 5 also fails to respond to the EPA comments on the Draft Compliance Certification Application (DCCA), as transmitted to your office on October 31, 1995 and January 30, 1996, and to some extent fails to address the comments published in

EEG-61, "Review of the WIPP Draft Application to Show Compliance with the EPA Transuranic Waste Disposal Standards" (March, 1996) concerning the DCCA QA Chapter. Chapter 5 contains editorial and technical difficulties which could delay the EEG and the EPA review of the complete application. A listing of some of these, as well as additional commentary on the "placeholders", CAG expectations, and other issues, can be found attached to this letter.

There is no indication in Chapter 5 that objective criteria are applied when audit teams determine the effectiveness of QA program adequacy and implementation. The process by which program effectiveness is determined should be described in Chapter 5.

Chapter 5 appears to be substantially incomplete. EEG recommends that the DOE withdraw the Chapter 5 submission, and resubmit it after (1) data to be included has been collected and analyzed, (2) the document has been rewritten to conform to CAG and other EPA expectations, and (3) full editorial and technical reviews of the contents by cognizant personnel have been performed.

Sincerely,

Robert H. Neill
Director

RHN:BAW:ss
Enclosure

ENVIRONMENTAL EVALUATION GROUP REVIEW OF CHAPTER 5 OF WIPP COMPLIANCE APPLICATION (DOE/CAO-96-2056)

Chapter 5 of the CCA, "Quality Assurance", published as DOE/CAO-96-2056, is an incomplete document which fails to adequately support compliance with the 40 CFR 194.22 QA requirements and the expectations for QA in the Compliance Application Guidance (CAG). This issuance of Chapter 5 appears to have been premature; material is missing, adequate technical and editorial review were apparently not performed, and there seems to have been no attempt to compare its contents against the EPA's criteria for completeness, or comments on the DCCA version of the chapter.

The following commentary is not a line-by-line review of Chapter 5, as the document is incomplete, and more general concerns should be addressed before such a review could be considered useful. Examples are randomly selected, to show the types of corrections necessary rather than a complete list of them.

Chapter 5 is an incomplete draft.

Chapter 5 as received by EEG on June 6, 1996, is a draft that would have been more appropriate in the DCCA. The document must be considered a draft, rather than a submittable document for compliance, as information has been replaced by "placeholders". The first page (5-1) has the following statement in the middle of a paragraph:

> This program of audits and surveillances assesses the adequacy and effectiveness of implementation of the individual QA programs. **[Placeholder for conclusions concerning the adequacy and effectiveness of implementation of the CAO and SNL QA programs].** (Emphasis in the original)

There are many such placeholder statements to be found in the document. Page 5-16 has one, page 5-42 has two, page 5-43 has one, 5-44 has two, 5-46 has two, 5-47 one, 5-50 three, and there may be others. The apparent reason for many of the placeholder statements is that QA activities necessary for production of a QA chapter in the CCA have not yet been completed and adequately analyzed. The placeholder quoted above, for instance, probably is due to external audits which had been scheduled, but not completed, of SNL (performed in May and June 1996) and CAO (scheduled for July 15-19, 1996) prior to the writing of Chapter 5. Other placeholders (on p. 5-46 and 5-47) are related to peer review qualification of data; these peer reviews are still in progress.

The results of these QA activities may not always support the conclusions already drawn in Chapter 5. The effectiveness of SNL's QA program was recently adjudged as "marginal" by a CAO-contracted audit, and if the DOE intends to use the results of the audit in the CCA

then some sort of updating activity should be performed to show that the program is adequate.

Note that neither WID nor any of the generator sites were included in the placeholder statement quoted above. Adequacy and effectiveness of QA at these sites, too, was yet to be established at the time of publication of the document, though major audits of INEL (effective, except for ineffective ANL-West) and Rocky Flats (marginal) were performed in late 1995.

In addition to "placeholder" statements, other information to be used for compliance is yet to be obtained. For example (from p. 5-3 and 5-4, Section 5.1.1):

> The TWBIR was prepared in compliance with the CAO QAPD and was audited by CAO QA on September 5 and 6, 1996.

Since the EEG is reviewing Chapter 5 in June, 1996, it is not meaningful to take credit for an audit in September, 1996. The version of the TWBIR to be audited hasn't been published yet, either; and the version of the CAO QAPD with which it apparently is to comply was not officially transmitted to TRU-waste personnel (or EEG) until after Chapter 5 was received (distribution memo dated June 13, 1996, from CAO's QA Manager).

Until the evidence to be used in Chapter 5 has been appropriately gathered and properly analyzed, the chapter can only be considered an incomplete draft.

Chapter 5 was not adequately reviewed by the DOE.

In the above quotation, the applicable version of the CAO QAPD is not listed, nor is the version number of the TWBIR. Document version numbers are not to be found for most (if not all) documents in the chapter, which makes verification of many statements impossible.

Other editorial and technical review mistakes exist. Descriptions of the "graded approach" appear in two different places (p. 5-2 and 5-23); these provide different (though partially overlapping) sets of criteria for grading activities. Section 5.1.2 "Environmental Monitoring, Monitoring of the Performance of the Disposal System and Analysis Activities" (p. 5-6) indicates that no monitoring need take place prior to closure, in direct contrast to the §194.42(c) requirement that monitoring of critical parameters commence before waste emplacement begins. The section concerning software (5.1.4, p. 5-77 ff) considers only PA software as necessary for compliance activities, though software used in waste characterization and for site activities carried out by WID are also used for compliance with 40 CFR 194. In Section 5.3.7, Document Control (p. 5-28), WID's principal procedures for document control are not listed--and WID has been tasked with the ultimate storage of all pertinent documents to the project. Section 5.3.9 (p. 5-29) offers no objective evidence (in the form of governing procedures) to show that identification and control of items is required to be performed, though all the other sections of Section 5.3 have such references.

In Section 5.1.3,(p. 5-6), it is asserted that since the EPA had reviewed site selection and site characterization QA programs during examination of the 1989 No-Migration Variance Petition (NMVP) that the QA for site selection and characterization should be considered satisfactory. This is untenable on several grounds, not the least of which is that the NMVP is for compliance with 40 CFR 268.6, which has no requirement that QA programs must comply with the 1989 versions of NQA-1, NQA-2 Part 2.7, and NQA-3, as is found in 40 CFR 194.

Section 5.4.2 (Page 5-44) illustrates several potential deficiencies. The initial paragraph contains a statement which includes placeholders, as follows:

> A primary result of the qualification of the SNL QA audit and surveillance programs **[Placeholder]** the determination of which performance assessment data provided by SNL subcontractors **[Placeholder]** collected under an approved QA program and which data requires additional qualification.

Unfortunately, without the placeholders, the statement has effectively no useful semantic content, and cannot be analyzed in relation to the requirements of 40 CFR 194.

The next paragraph describes the change from the SNL QAPD revision P to revision R. Some mention of revision Q would prevent possible confusion.

Under the heading "Scientific Investigation" (still Section 5.4.2, p. 5-44), the statement is made that

> QAP 20-2 was added to address scientific notebooks. Previously, scientific notebooks were rarely used...

Notebooks are usually considered the basic documentation of scientific work, and the DOE may want to reconsider the phrasing of the second part of the statement.

The results of SNL Audit IA 95-03 (August, 1995) are reported in Section 5.4.2.1, Data Qualification (pp. 5-44, 45):

> The audit resulted in 14 findings in the areas of calibration, procedures, training, experimental planning, test records, and equipment and data acquisition...The audit concluded that, with the exception of the Corrective Action Requests, there was evidence that SNL QA controls were in place and that they were adequate and effectively implemented.

Given the breadth of the Corrective Action Requests(CARs), what areas were left to show adequate and effective implementation of the QA controls? In this presentation, it seems as if the program was considered adequate and effective regardless of the audit findings. Chapter 5 also lacks discussion of the process used by audit teams for determining the effectiveness of QA programs; if adequacy and implementation effectiveness statements are

included in the CCA, then the process by which these statements are generated should be described.

Almost no document in Chapter 5 is properly referenced. QA documents are listed without version numbers; published government documents are listed without document numbers (p. 5-6, "Background Document..."; p. 5-14, "DOE/Albuquerque Operations Manual"), or without even a title (p. 5-11, "This task was documented in a DOE Headquarters report..."). None of these documents appear in the bibliography for the chapter, either.

Anything more than a rudimentary review by personnel familiar with the overall WIPP project and QA would have uncovered at least some of these deficiencies. In a QA chapter, the DOE has failed to adequately perform one of the basic principles of QA--review of documents. Such an omission creates an erroneous impression of the quality of QA activities that CAO has developed in the last few years.

Chapter 5 does not address CAG expectations.

While it is not a compliance requirement for DOE to fulfill the expectations in the Compliance Application Guidance (CAG EPA 402-R-95-014), the guidance was developed to assist the EPA in determining if the CCA is complete (CAG, page 1). The document goes on to state (also page 1):

> A completeness determination is a threshold determination that the application warrants further scrutiny, so that EPA, DOE, and the public do not invest major resources in a rulemaking proceeding for an incomplete document will likely (and justifiably) consider the CCA incomplete until these expectations are met.

There is no evidence in Chapter 5 that the expectations in the CAG were considered during the development of the chapter. The DOE sent out Chapter 5 with a matrix which matches the requirements of 40 CFR 194 QA requirements with the chapter, but makes no reference to the CAG expectations. There are no statements, references, or sections within Chapter 5 that echo language or structure unique to the CAG. An attempt to verify that the five expectations on page 18 of the CAG were met in Chapter 5 produced febrile results--only one of the five could be considered to be completely met. These five expectations, and the result of the EEG's verification attempt, are as follows:

1. That DOE top tier QA documents demonstrating commitment to NQA-1 (1989), NQA-2 Part 2.7 (1990), and NQA-3 (1989) be included in the CCA. Revision 1 of the CAO QAPD (if Revision 1 will be the version used for the CCA--see expectation 3) could be said to meet this requirement by itself, and evidence in Chapter 5 is that this document will be included in Appendix QAPD.

   This expectation is also the heart of the 40 CFR 194 QA requirements, and it is not likely that it was included as a CAG consideration.

2. That DOE principal contractor top tier QA documents, and a list of all top tier documents of subcontractors performing quality affecting activities as listed in §194.22(a)(2), be in the application. Appendix QAPD will apparently include the SNL and WID QAPDs, but Chapter 5 includes no listing of subcontractor documents as specified, nor the top-tier documents for generator sites, and even the TRU-QAPD may not be included in Appendix QAPD (it is not so referenced in Chapter 5).

3. That the effective dates the documents from expectation 2 were in conformance with the NQA requirements be listed in the application. No effective dates were listed for QA documents in Chapter 5; version numbers were not even given.
4. That a list of quality affecting activities and items important to demonstration of compliance be included in the CCA. No such list is in Chapter 5.

5. That the rationale used in developing the list for expectation 4 be given. No list, no explanation.

Chapter 5 is manifestly not complete according to the criteria in the CAG, nor, it seems, has DOE made an attempt to meet the completeness for QA as identified in the CAG.

The included appendix was poorly presented.

In its mailing of Chapter 5, the DOE included a separate bound document, "Appendix RE5", dated May 10, 1996. The letter of transmittal indicates that

> This appendix contains excerpts and summaries of specific references used to support CCA conclusions within the chapter. It will allow reviewers to quickly find the specific portions of referenced documents when tracing the logic of the CCA's conclusions.

EEG could find no specific references in Chapter 5 to Appendix RE5, nor was the rationale for the contents of Appendix RE5 apparent. The appendix consists of brief abstracts from the NQA standards and two NUREG position papers (1297, Peer Review, and 1298, Qualification of Existing Data). The bibliographic references for the documents duplicate the bibliography in Chapter 5. All five documents are readily available as published documents. The abstracts, when pertinent, are not so lengthy that they could not have been quoted directly in Chapter 5.

Appendix RE-5 appears to either be an unnecessary addition to the CCA, or perhaps another "placeholder" into which filler material was inadvertently placed. In any case, it is apparent that the Appendix as it exists is not a well-thought-out addition to the CCA.

Two referenced appendices were not included.

In contrast to Appendix RE-5, two other appendices are referenced in Chapter 5, but neither of these were sent with the document. "Appendix QAPD" is referenced throughout much of

the chapter, and would seem to include the current QAPDs for CAO, SNL, and WID, but no complete listing of the contents is included. These documents are expectations in the CAG, along with other top-tier documents (see discussion of CAG requirements above).

"Appendix AUDIT" is said to contain results of internal audits and surveillances of the WID QA program, and lists of both internal and external audits and surveillances of the CAO, WID, and SNL (Section 5.4.4); whether generator site assessments are included as a part of "CAO" is indeterminate.

All references to Appendix AUDIT appear on the last page of Chapter 5 (p. 5-51). For such an Appendix to have real meaning, specific audits contained in it should be referenced by Chapter 5 as objective evidence that requirements have been met.

Without these appendices, the effectiveness of Chapter 5 cannot be completely assessed. Appendices QAPD and AUDIT should have been transmitted with the chapter.

Chapter 5 fails to address EEG's comments on the DCCA.

The EEG's comments on the DCCA QA chapter as published in EEG-61 (March, 1996) are also only partially addressed in Chapter 5. EEG (EEG-61 p. 5-2) suggested that the QA chapter should have addressed the requirements of 40 CFR 194.22, and Section 5.1 of Chapter 5 does address the requirements from 40 CFR 194.22(a), including the overriding requirement for conformance with the applicable NQA standards (NQA-1, NQA-2 Part 2.7, and NQA-3). However, 40 CFR 194.22(b) requires that:

> Any compliance application shall include information which demonstrates that data and information collected prior to the implementation of the quality assurance program required pursuant to paragraph (a)(1) [the requirement for the NQA standards] of this section have been qualified in accordance with an alternate methodology, approved by the Administrator or the Administrator's authorized representative, that employs one or more of the following methods: peer review...; corroborating data; confirmatory testing; or a quality assurance program that is equivalent in effect to...[the NQA standards].

Chapter 5 describes the processes used for data qualification by SNL (Section 5.4.2.1 and following sections, beginning on p. 5-44), but does not include information which demonstrates that the Administrator has approved of these methods.

As in the DCCA QA chapter, Chapter 5 emphasizes the QA program as it exists in 1996 over QA of the data gathering and processing activities which make up a major part of 40 CFR 194 requirements; this was another principal concern expressed in EEG-61. The CCA QA chapter should provide objective evidence that information utilized by the other sections of the CCA fulfills the quality requirements in 40 CFR 194. In places this is partially achieved; Table 5-4 contains a list of data packages qualified by the Independent Review Teams in the Qualification of Existing Data process under SNL's Quality Assurance

Procedure 20-3, but does not explain where and how these packages are used, and their importance to compliance, nor are any references or guidances provided that would allow confirmation of the table of contents.

Chapter 5 fails to adequately address EPA's comments on the DCCA.

The DOE has failed to completely address the EPA general comments on the QA chapter as provided in the enclosure from EPA's Larry Weinstock to CAO's George Dials dated October 31, 1995 (pp. 3 & 4). The EPA stated that:

> A number of assertive statements intended to describe the current status of the program are made without substantiation, including statements regarding training records, calibration records, and document and record control procedures. Objective evidence should be presented which demonstrates the successful implementation of these and other aspects of a quality assurance program for the WIPP. Examples of the evidence of implementation may include approved governing documents, implementing procedures, implementing plans and timetables, audits, surveillance, and verification reports, history of corrective actions, and the effective dates of program implementation.

Some of the governing documents, some of the procedures, and some of the effective dates of program implementation can be found in Chapter 5. However, many more assertive statements are to be found in Chapter 5 than were in the DCCA QA chapter, and objective evidence for them is not presented. A few examples follow: Section 5.1.6.2 (p. 5-11), "Original Repository Design", states that "All changes are approved by technically qualified individuals", but no evidence is supplied for the statement. Section 5.3.8 (p. 5-28), "Control of Purchased Items and Services", states that "Prospective suppliers are evaluated and selected on the basis of documented criteria", and eight bullets list other procurement controls said to be in place. However, only WID implementing documents are provided as evidences for the section, and these are for "Receipt Inspections" and "Source Inspections" (which may cover two of the eight bullets). The section does not reference the missing appendices, which might possibly include more objective evidence.

The DOE also seems to have made only a cursory attempt to address the more specific comments the EPA provided on the QA Chapter of the DCCA (transmitted as pp. 39-42 of the January 30, 1996 letter from Weinstock to Dials). For example, the first specific comment states in part, "The DCCA should have specified the roles of EM-1, EM-20, and EM-30". While Chapter 5's "Organizational Interfaces" chart (Figure 5-3, p. 5-21) shows EM-1 and EM-30, EM-20 is still not listed. The same EPA comment also implies that the organizations that conduct QA audits of contractors and waste generator sites should be listed; they aren't. Another EPA comment indicates that evidence substantiating that all workers were properly trained should be included; it wasn't.

The inclusion of the "Organization Interfaces" figure, which was not in the DCCA, implies

that the EPA's comments were considered on some level. However, it also seems obvious that no line-by-line check to make sure that concerns raised by EPA comments were addressed was made. A search for a random sample of three other EPA comments--lack of objective evidence for control and maintenance of QA records, missing data quality indicators for the waste characterization program, and a need to address software reporting, correction, and implementation of requirements--shows that only the last of these is included in Chapter 5.

Chapter 5 apparently circumvents CAO's own QA program.

The weaknesses described above, in a chapter concerning QA, are apparently due to circumvention of the DOE's own QA program. CAO Management Procedure (MP) 4.4, Revision 0, dated April 19, 1996, states (Section 3.1.1) that

> Before a document is produced, the requestor should evaluate the need, end use, cost-effectiveness, intended audience, duplication of effort, regulatory and technical requirements, and any external organization's requirements or agreements related to the document.

MP 4.4 also establishes review processes, which are to be in performed in accordance with MP 4.2.

Recommendation

The DOE should consider developing not only Chapter 5 but all of the CCA under the requirements of the CAO QAPD, Revision 1. A solid quality assurance program is of little utility unless work is performed under its control.

Department of Energy
Carlsbad Area Office
P.O. Box 3090
Carlsbad, New Mexico 88221

RECEIVED
AUG 9 - 1996
ENVIRONMENTAL EVALUATION GROUP

Mr. Robert H. Neill, Director
Environmental Evaluation Group
7007 Wyoming Blvd. NE, Suite F-2
Albuquerque, N.M. 87109

Dear Mr. Neill:

We were quite surprised by your July 22, 1996 letter that expressed your concerns with Chapter 5, "Quality Assurance", of the Waste Isolation Pilot Plant (WIPP) Compliance Certification Application (CCA). Your letter implied that there are deficiencies in the Carlsbad Area Office (CAO) Quality Assurance (QA) program based upon your analysis of the Chapter 5. Contrary to this, we have shown time and again, through surveillance and audit, that the CAO QA program is effective. Let me remind you that the Carlsbad Area Office has just been audited by the Department of Energy-Headquarters (EM-30), led by an NQA-1 certified QA auditor, during which some of your staff attended, along with the Environmental Protection Agency (EPA). The report concluded that the CAO QA program was adequate and effective.

We feel that many of your comments are incorrect, exaggerated, and in some cases they reflect a basic lack of understanding of the intended requirements, expectations, and subject material. Your analysis brings to mind that we are not aware of any Environmental Evaluation Group (EEG) employee who is a certified QA auditor or has the relevant QA experience to make the judgments of a QA program as contained in your letter. Please reconsider your conclusions based upon the following:

General Comments

The following general responses are provided to express our overall disagreement and disappointment with your response. Specific responses to each of your concerns are addressed in the enclosure to this letter.

1. Your letter indicates that Chapter 5 contained significant omissions and errors. We totally disagree with this statement Specific responses provided herein should convince you that Chapter 5 contains neither significant omissions nor significant errors.

2. With respect to the "placeholders" identified in Chapter 5: the placeholders were planned and incorporated in the May 31, 1996 revision, to flag events that had not yet occurred, but would take place at a later time The placeholders represented assessment dates or conclusions that had not been fully completed by the May 31, 1996, Chapter 5 submittal date. The placeholders do not represent "data and analyses" as alluded to in your letter. The missing appendices referred to are not critical to the review of Chapter 5. EEG

currently has copies of the information in the appendices:

> Appendix QAPD is comprised of the CAO, SNL, and WID QAPDs. EEG has copies of these documents.
>
> Appendix SCHED is an example of a typical assessment schedule. EEG is on distribution for the quarterly issue of the CAO Assessment Schedule and the biweekly draft updates.
>
> Appendix AUDIT identifies in tabular form audits and surveillances performed by CAO, SNL, and WID, which are only indirectly related to supporting conclusions made in the Chapter. This information has also been provided to EEG in the form of the CAO Assessment Schedule.

Appendix RE-5 is a compilation of reference material from Chapter 5 and is intended to be a source of references or portions of references to make it easier for the reader. A similar appendix is included for each Chapter of the CCA.

3. Throughout your comments you refer to the "QA expectations" listed in "Section 194.22 Quality Assurance" of the Compliance Application Guidance (CAG).

   The Preamble to the CAG clearly indicates that the CAG is to be used as guidance:

> "The CAG summarizes and explains the February 9, 1996 final rule. The United States Environmental Protection Agency (EPA) developed this guidance to assist the United States Department of Energy (DOE) with the preparation of any Compliance Certification Application (CCA) for the WIPP and, in turn, to assist in EPA's review for completeness and generally to enhance the readability and accessibility of the CCA for EPA and public scrutiny. It is EPA's intent that this guidance will facilitate the understanding that DOE and public have of the specific information that is expected to be included in a complete application for certification of compliance. Examples used for clarification in this guidance should not be considered exhaustive or definitive, since they are provided merely to facilitate DOE's understanding of the types of information EPA is expecting."

   The EPA staff clearly supports the position that the CAG is for guidance only. The CAG is only guidance and therefore should not be used by EEG to make an argument that Chapter 5 is deficient, nor that expectations have not been met.

4. We disagree with your statement that the May 31, 1996 revision of Chapter 5 fails to respond to EPA comments. Specific responses to the EPA Draft Compliance Certification Application (DCCA) comments were provided to EPA on January 23, 1996. In addition, the current revision of Chapter 5 has been specifically revised in format and content to address EPA DCCA comments.

5. Your comment relative to the lack of objective criteria used by audit teams "to determine the effectiveness of QA program adequacy and implementation" reflects a basic misunderstanding of QA audit processes, audit scopes, and audit terminology. Quality Assurance auditors and lead auditors are qualified and trained; lead auditors are certified. As part of their training, the three components of the audit conclusion are clearly presented. While it may appear that the process is subjective to casual observers, the process is well understood by qualified QA audit personnel. We feel that a discussion of basic auditing practices should not be included in Chapter 5.

The enclosure to this letter will further address the specific points included in your enclosure "CCA Ch. 5 (DOE/CAO-96-2056) Review."

In summary, your letter does not provide an accurate assessment of the condition, content, or quality of Chapter 5. Again, we feel that many of your comments are incorrect, exagerrated, and in some cases they reflect a basic lack of understanding of the intended requirements, expectations, and subject material.

We are, however, currently updating the placeholders and other information contained in Chapter 5 and will consider the specific comments you have made. If it is appropriate that they be addressed in Chapter 5, we will do so.

Sincerely,

George E. Dials
Manager

Enclosure

cc w/enclosure:
R. Brown, CAO
M. McFadden, CAO
J. Mewhinney, CAO
J. Maes, CAO

Enclosure

This enclosure addresses the specific comments provided by EEG in the enclosure to the "Robert H. Neill letter to George Dials, dated July 22, 1996."

Introductory Paragraphs

Chapter 5 of the CCA, "Quality Assurance", published as DOE/CAO-96-2056, is an incomplete document which fails to adequately support compliance with the 40 CFR 194.22 QA requirements and the expectations for QA in the Compliance Application Guidance (CAG). This issuance of Chapter 5 appears to have been premature; material is missing adequate technical and editorial review were apparently not performed, and there seems to have been no attempt to compare its contents against the EPA's criteria for completeness, or comments on the DCCA version of the chapter.

1. We disagree. The document is complete (with the inclusion of placeholders for ongoing activities).
2. We disagree. Chapter 5 does adequately support compliance with the 40 CFR 194.22 QA requirements.
3. We disagree. The CAG is a guidance document and does not contain requirements.
4. We disagree. The Chapter went through extensive technical and editorial revision. Over 80 pages of Document Review Records that include comments and resolutions are maintained as CAO QA records.
5. We disagree. Responses to EPA comments were provided to EPA on January 23, 1996. Additionally, the current format and content of Chapter 5 are a direct result of the EPA comments made concerning the DCCA.

"Chapter 5 is an incomplete draft."

Chapter 5 as received by EEG on June 6, 1996, is a draft that would have been more appropriate in the DCCA. The document must be considered a draft, rather than a submittable document for compliance, as information has been replaced by "placeholders". The first page (5-1) has the following statement in the middle of a paragraph:

> ***This program of audits and surveillances assesses the adequacy and effectiveness of implementation of the individual QA programs. [Placeholder for conclusions concerning the adequacy and effectiveness of implementation of the CAO and SNL QA programs]. (Emphasis in the original)***

We disagree with the comment that it "would have been more appropriate in the DCCA." The Chapter is complete (with the inclusion of the placeholders). The use of placeholders was a planned feature that permits a review of the content with the knowledge that specific information will be updated as it becomes available.

There are many such placeholder statements to be found in the document. Page 5-16 has one, page 5-42 has two, page 5-48 has one, 5-44 has two, 5-46 has two, 5-47 one, 5-50 three, and there may be others. The apparent reason for many of the placeholder statements is that QA activities necessary for production of a QA chapter in the CCA have not yet been completed and adequately analyzed. The placeholder quoted above, for instance, probably is due to external audits which had been scheduled, but not completed, of SNL (performed in May and June 1996) and CAO (scheduled for July 15-19, 1996) prior to the writing of Chapter 5. Other placeholders (on p. 5-46 and 5-47) are related to peer review qualification of data; these peer reviews are still in progress.

> We agree with your description of the reasons for the placeholders used in Chapter 5. Further classification includes: Of the 21 placeholders identified in Chapter 5, 15 are for dates to be supplied as activities occur (e.g. audit dates); three are for a description of audit conclusions (when they are reached); two are to identify the past tense; and one is a table of the packages qualified through the Peer Review process.

The results of these QA activities may not always support the conclusions already drawn in Chapter 5. The effectiveness of SNL's QA program was recently adjudged as "marginal" by a CAO-contracted audit, and if the DOE intends to use the results of the audit in the CCA then some sort of updating activity should be performed to show that the program is adequate.

> With respect to the SNL audit conducted by CAO in May 1996, the SNL QA program was determined to be "marginal." CAO had already invited EEG and EPA to attend a review of the corrective actions for those areas that contributed to the marginal conclusion. This review is currently scheduled to be held during the last week of August. This evaluation will also include a review of the status and effectiveness of critical corrective actions identified during previous assessments.

Note that neither WID nor any of the generator sites were included in the placeholder statement quoted above. Adequacy and effectiveness of QA at these sites, too, was yet to be established at the time of publication of the document, though major audits of INEL (effective, except for ineffective ANL-West) and Rocky Flats (marginal) were performed in late 1995.

> We agree, WID will be included as appropriate. However, since none of the generator sites will be certified by 10/31/96, generator sites will not be included. QA program assessment conclusions will be prepared for the generator sites at the appropriate time.

In addition to "placeholder" statements, other information to be used for compliance is yet to be obtained. For example (from p. 5-3 and 5-4, Section 5.1.1):

> ***The TWBIR was prepared in compliance with the CAO QAPD and was audited by CAO QA on September 5 and 6, 1996.***

Since the EEG is reviewing Chapter 5 in June, 1996, it is not meaningful to take credit for an audit in September, 1996. The version of the TWBIR to be audited hasn't been published yet, either; and the version of the CAO QAPD with which it apparently is to comply was not officially transmitted to TRU-waste personnel (or EEG) until after Chapter 5 was received (distribution memo dated June 13, 1996, from CAO's QA Manager).

In the above question, the applicable version of the CAO QAPD is not listed, nor is the version number of the TWBIR.

We agree. We had also identified the typo reflecting the incorrect TWBIR audit date. The correct date was September 5 and 6, 1995. This has been changed. The audit was conducted in accordance with implementing procedures and CAO QAPD, Revision 0.

"Chapter 5 was not adequately reviewed by the DOE"

We disagree with the basic premise. Chapter 5 went through a rigorous and comprehensive review process conducted in accordance with CAO MP 4.2. Over 80 pages of review comments were identified, resolved, and, where appropriate, incorporated into the document. In addition, Chapter 5 went through extensive editing for grammar, format and consistency, by professional document editors.

Document version numbers are not to be found for most (if not all) documents in the chapter, which makes verification of many statements impossible.

We disagree with your comment relative to indicating the version, (or more correctly, the revision) of the CAO QAPD and other document referenced in the Chapter. Documents in any complex, regulated program will change over a given period of time and should always be verified for each application. Omission of the revisions for these documents is appropriate and reflects the basics of information controls.

Other editorial and technical review mistakes may be found also. Descriptions of the "graded approach" appear in two different places (p.5-2 and 5-23); these provide different (though partially overlapping) sets of criteria for grading activities. Section 5.1.2 "Environmental Monitoring, Monitoring of the Performance of the Disposal System and Analysis Activities" (p. 5-6) indicates that no monitoring need take place prior to closure, in direct contrast to the §194.42(c) requirement that monitoring of critical parameters commence before waste emplacement begins. The section concerning software (5.1.4, p. 5-77 ff) considers only PA software as necessary for compliance activities, though software used in waste characterization and for site activities carried out by WID are also used for compliance with 40 CFR 194. In Section 5.3.7, Document Control (p. 5-28), WID's principal procedures for document control are not listed—and WID has been tasked with the ultimate storage of all pertinent documents to the project. Section 4.3.9 (p. 5-29) offers no objective evidence (in the form of governing procedures) to show that identification and control of items is required to be performed, though all the other sections of Section 5.3 have such references.

1. We agree with some of the specific comments here. For example the comment relative to the grading paragraphs in the two locations. While they are included in the two separate locations for different reasons, the amount of detail in the "Applicability", Section 5.1, is not required. The description will be kept, but the details (bullets) will be deleted.

2. We agree with the comment regarding monitoring of the performance of the disposal system. Monitoring will commence prior to waste emplacement. Appendix I.TM to CCA Chapter 7 will be referenced as the document describing the WID performance monitoring.

3. We agree with your comment relative to additional software that should be referenced. In our current update we have already added words to describe the application of software to data acquisition activities, WID design activities, and nondestructive assay activities.

4. We agree that one additional WID document control procedure is appropriate for reference (WID WP15-PS3103). However, we do not agree that document control and QA records are related in the manner that you indicate. The document control procedures are not intended to address "... the ultimate storage of all pertinent documents to the project." Record storage requirements are different than document control requirements. In addition we are adding one WID implementing document that addresses the identification and control of items (WP 15-PM3517).

In Section 5.1.3 (p. 5-6) the theory is advanced that since the EPA had reviewed site selection and site characterization QA programs during examination of the 1989 No-Migration Variance Petition (NMVP) that the QA for site selection and characterization should be considered satisfactory. This is untenable on several grounds, not the least of which is that the NMVP is for compliance with 40 CFR 268.6, which has no requirement that QA programs must comply with the 1989 versions of NQA-1, NQA-2 Part 2.7, and NQA-3, as is found in 40 CFR 194.

We agree with the comment on the No Migration Variance Petition (NMVP) and had already noted this. We have updated this portion of Chapter 5.

Sections 5.4.2 (Page 5-44) illustrates several potential deficiencies. The initial paragraph contains a statement which includes placeholders, as follows:

> ***A primary result of the qualification of the SNL QA audit and surveillance programs [Placeholder] the determination of which performance assessment data provided by SNL subcontractors [Placeholder] collected under an approved QA program and which data requires additional qualification.***

Unfortunately, without the placeholders, the statement has effectively no useful semantic content, and cannot be analyzed in relation to the requirements of 40 CFR 194.

We disagree with the comment on the "semantic content" without the placeholders being included. The placeholders are intended to be replaced by the word "was" at the appropriate time to indicate that the activity has already occurred.

The next paragraph describes the change from the SNL QAPD revision P to revision R. Some mention of revision Q would prevent possible confusion.

We disagree with the need to discuss revision "Q" of the SNL QAPD. Since EEG has observed CAO audits and surveillances of SNL starting in August of 1995, you should be aware that there is no revision "Q" of the SNL QAPD. The alpha designators "O" and "Q" are often intentionally not used due to the potential for mistaking one for the other. This was the case here.

Under the heading "Scientific Investigation" (still Section 5.4.2, p. 5-44), the statement is made that

> ***QAP 20-2 was added to address scientific notebooks. Previously, scientific notebooks were rarely used...***

Notebooks are usually considered the basic documentation of scientific work, and the DOE may want to reconsider the phrasing of the second part of the statement.

We agree with the poorly phrased statement relative to the "previous use of scientific notebooks". This sentence will be deleted.

The results of SNL Audit IA 95-03 (August, 1995) are reported in Section 5.4.2.1, Data Qualification (pp. 5-44, 45):

> ***The audit resulted in 14 findings in the areas of calibration, procedures training, experimental planning, test records, and equipment and data acquisition...The audit concluded that, with the exception of the Corrective Action Requests, there was evidence that SNL QA controls were in place and that they were adequate and effectively implemented.***

Given the breadth of the CARs, what areas were left show adequate and effective implementation of the QA controls? In this presentation, it seems as if the program was considered adequate and effective regardless of the audit findings.

We disagree with your overall conclusion regarding the SNL internal audit (IA-95-03). The executive summary indicated:

"Within the scope of this audit it was determined that, with the exception of the identified CARs, there was evidence that SNL QA controls were in place and that they were adequately and effectively being implemented for those experimental programs addressed in Phases 1, 2, and 3."

There were 14 criteria evaluated over 11 experimental programs. The 14 CARs were distributed over the 11 experimental programs and were not concentrated in one particular area or in one particular program. Thus, neither the criteria nor the programs were compromised to the extent that the audit team would conclude that implementation was not effective.

Chapter 5 also lacks discussion of the process used by audit teams for determining the effectiveness of QA programs; if adequacy and implementation effectiveness statements are included in the CCA, then the process by which these statements are generated should be described.

We disagree with the need to include a discussion of basic auditing conclusions (adequacy, implementation and effectiveness). The CCA is not intended to be a primer on "how to audit".

Almost no document in Chapter 5 is properly referenced. QA documents are listed without version numbers; published government documents are listed without document numbers (p. 5-6, "Background Document.."; p. 5-14, "DOE/Albuquerque Operations Manual"), or without even a title (p. 5-11, "This task was documented in a DOE Headquarters report.."). None of these documents appear in the bibliography for the chapter, either.

1. We disagree with the need to include document versions, revisions, or other designators in the CCA. As previously indicated, Chapter 5 describes the QA program that is directed to the control of important WIPP activities. This program will constantly be changing as requirements, expectations, or the need for improvements arise.

2. We agree that the DOE Headquarters report should be identified. We had already researched the document title and date and have included it in the Chapter.

Anything more than a rudimentary review by personnel familiar with the overall WIPP project and QA would have uncovered at least some of these deficiencies. In a QA chapter, the DOE has failed to adequately perform one of the basic principles of QA--review of documents. Such an omission creates an erroneous impression of the quality of QA activities that CAO has developed in the last few years.

1. We disagree with the comment concerning "A rudimentary review by personnel familiar with the overall WIPP project and QA would have uncovered at least some of these deficiencies." As previously indicated Chapter 5 received extensive QA and editorial reviews. Likewise, we disagree with the use of the word "deficiencies".

Most of the EEG comments relate to areas that have been planned to be upgraded during the current review or comments relative to alternate ways to approach the Chapter.

2. We disagree with the statement that "DOE has failed to adequately perform one of the basic principles of QA -- review of documents. Such an omission creates an erroneous impression of the quality of QA activities that CAO has developed in the last few years." Review is not one of basic principles of QA, rather it is an activity that supports QA principles. The type of generalization indicated in this comment without any idea of the process that was used, is unprofessional and unnecessary.

"Chapter 5 does not address CAG expectations."

While it is not a compliance requirement for DOE to fulfill the expectations in the CAG, the guidance was developed to assist the EPA in determining if the CCA is complete (CAG, page 1). The document goes on to state (also page 1):

> ***A completeness determination is a threshold determination that the application warrants further scrutiny, so the EPA, DOE, and the public do not invest major resources in a rulemaking proceeding for an incomplete document will likely (and justifiably) consider the CCA incomplete until these expectations are met.***

There is no evidence in Chapter 5 that the expectations in the CAG were considered during the development of the chapter. The DOE sent out Chapter 5 with a matrix which matches the requirements of 40 CFR 194 QA requirements with the chapter, but makes no reference to the CAG expectations. There are no statements, references, or sections within Chapter 5 that echo language or structure unique to the CAG. An attempt to verify that the five expectations on page 18 of the CAG were met in Chapter 5 produced febrile results--only one of the five could be considered to be completely met. These five expectations, and the result of the EEG's verification attempt, are as follows:

> We agree that Chapter 5 is not complete with respect to the CAG, however, we disagree with your conclusion that it must be. The Preamble of the CAG, clearly indicates that the CAG is to be used as guidance. The EPA staff clearly supports the position that the CAG is for guidance only.
>
> The CAG is only guidance and, therefore, should not be used by EEG to make an argument that Chapter 5 is deficient nor that expectations have not been met.

"The included appendix was poorly presented."

In its mailing of Chapter 5, the DOE included a separate bound document, "Appendix RE5", dated May 10, 1996. The letter of transmittal indicates that

This appendix contains excerpts and summaries of specific references used to support CCA conclusions within the chapter. It will allow reviewers to quickly find the specific portions of referenced documents when tracing the logic of the CCA's conclusions.

EEG could find no specific references in Chapter 5 to Appendix RE5, nor was the rationale for the contents of Appendix RE5 apparent. The appendix consists of brief abstracts from the NQA standards and two NUREG position papers (1297, Peer Review, and 1298, Qualification of Existing Data). The bibliographic references for the documents duplicate the bibliography in Chapter 5. All five documents are readily available as published documents. The abstracts, when pertinent, are not so lengthy that they could not have been quoted directly in Chapter 5.

Appendix RE5 appears to either be an unnecessary addition to the CCA, or perhaps another "placeholder" into which filler material was inadvertently placed. In any case, it is apparent that the Appendix as it exists is not a well-though-out addition to the CCA.

We disagree. The Appendix RE5 is a compilation of reference material from Chapter 5. Appendix RE5 is intended to be a source of references or portions of references in context to make it easier for the reader. A similar Appendix is included at the end of each CCA Chapter.

"Two referenced appendices were not included."

In contrast to Appendix RE5, two other appendices are referenced in Chapter 5, but neither of these were sent with the document. "Appendix QAPD" is referenced throughout much of the chapter, and would seem to include the current QAPDs for CAO, SNL, and WID, but no complete listing of the contents is included. These documents are expectations in the CAG, along with other top-tier documents (see discussion of CAG requirements above).

"Appendix AUDIT" is said to contain results of internal audits and surveillances of the WID QA program, and lists of both internal and external audits and surveillances of the CAO, WID, and SNL (Section 5.4.4); whether generator site assessments are included as a part of "CAO" is indeterminate.

Without these appendices, the effectiveness of Chapter 5 cannot be completely assessed. Appendices QAPD and AUDIT should have been transmitted with the Chapter.

The missing appendices are not critical to the review of the chapter, but are now included.

Appendix QAPD is comprised of the CAO, SNL, and WID QAPDs. EEG has copies of all three documents.

Appendix SCHEDULE is an example of a typical assessment schedule. EEG is on distribution for the quarterly issue of the CAO Assessment Schedule and the weekly draft updates.

Appendix AUDIT is a list of audit and surveillances that were conducted by CAO, SNL, and WID, which are only indirectly related to supporting the conclusions made in this Chapter. EEG is on distribution for the quarterly issue of the CAO Assessment Schedule and the weekly draft updates.

Since none of the generator sites will be certified by 10/31/96, generator site assessments are not included as a part of Appendix AUDIT.

"Chapter 5 fails to address EEG's comments on the DCCA."

The EEG's comments on the DCCA QA chapter as published in EEG-61 (March, 1996) are also only partially addressed in Chapter 5. EEG (EEG-61 p. 5-2) suggested that the QA chapter should have addressed the requirements of 40 CFR 194.22, and Section 5.1 of Chapter 5 does address the requirements from 40 CFR 194.22(a), including the overriding requirement for conformance with the applicable NQA standards (NQA-1, NQA-2, Part 2.7, and NQA-3). However, 40 CFR 194.22(b) requires that:

> ***"Any compliance application shall include information which demonstrates that data and information collected prior to the implementation of the quality assurance program required pursuant to paragraph (a)(1) [the requirement for the NQA standards] of this section have been qualified in accordance with an alternate methodology, approved by the Administrator or the Administrator's authorized representative, that employs one or more of the following methods; peer review...; corroborating data; confirmatory testing; or a quality assurance program that is equivalent in effect to...[the NQA standards]."***

We disagree that the purpose of Chapter 5 includes addressing EEG comments. EEG comments were addressed and included in the January document that addressed all comments on the DCCA. You were provided a copy of this document by letter dated January 23, 1996.

Chapter 5 describes the processes used for data qualification by SNL (Section 5.4.2.1 and following Sections, beginning on p. 5-44), but does not include information which demonstrates that the Administrator has approved of these methods.

We disagree with your interpretation of when the Administrator has to approve methods for qualifying data and information collected prior to the implementation of the quality assurance program. It is our opinion that the EPA Administrator's authority in this area begins with the submittal of the CCA.

Table 5-4 contains a list of data packages qualified by the Independent Review Teams in the Qualification of Existing Data process under SNL's Quality Assurance Procedure 20-3, but does not explain where an dhow these packages are used, and their importance to compliance, nor are any references or guidance provided that would allow confirmation of the Table contents.

We disagree with the need to explain where and how QED packages are used and their importance to compliance in Chapter 5. This technical information is not appropriate to this chapter and is discussed in other CCA Chapters.

"Chapter 5 fails to adequately address EPA's comments on the DCCA."

Chapter 5 fails to adequately address EPA's comments on the DCCA.
The DOE has failed to completely address the EPA general comments on the QA chapter as provided in the enclosure from EPA's Larry Weinstock to CAO's George Dials dated October 31, 1995 (pp. 3&4). The EPA stated that:

> ***"A number of assertive statements intended to describe the current status of the program are made without substantiation, including statements regarding training records, calibration records, and document and record control procedures. Objective evidence should be presented which demonstrates the successful implementation of these and other aspects of a quality assurance program for the WIPP. Examples of the evidence of implementation may include approved governing documents, implementing procedures, implementing plans and timetables, audits, surveillance, and verification reports, history of corrective actions, and the effective dates of program implementation."***

Some of the governing documents, some of the procedures, and some of the effective dates of program implementation can be found in Chapter 5. However, many more assertive statements are to be found in Chapter 5 than were in the DCCA QA chapter, and objective evidence for them is not presented.

We disagree with your statement that the May 31, 1996 revision of Chapter 5 fails to respond to EPA comments. Specific responses to the EPA DCCA comments were provided to EPA on January 23, 1996. In addition, the current revision of Chapter 5 has been specifically revised in format and content to address EPA DCCA comments.

A couple of examples: Section 5.1.6.2 (p. 5-11), "Original Repository Design", states that "All changes are approved by technically qualified individuals", but no evidence is supplied for the statement. Section 5.3.8 (p. 5-28), "control of Purchased Items and Services", states that "Prospective suppliers are evaluated and selected on the basis of documented criteria", and eight bullets list other procurement controls said to be in place. However, only WID implementing documents are provided as evidences for the section, and these are for "Receipt Inspections" and "Source Inspections" (which may cover two of the eight bullets). This section does not reference the missing appendices, which might possibly include more objective evidence.

We disagree. Because WID is responsible for design, only WID implementing documents are appropriately provided Sections 5.3.8.

We disagree that the comment concerning qualifications and training of workers is not addressed. Section 5.1.6.2 (p 5-11) does state that changes are approved by "technically qualified individuals." Chapter 5 describes the CAO QA program that is used to train and qualify personnel. These records are subject to the audit process. Individual qualification and training records are maintained as QA records. We do not believe that the thousands of records for all WIPP personnel performing quality affecting activities are appropriate to be included in the CCA. These records are subject to the audit process.

The DOE also seems to have made only a cursory attempt to address the more specific comments the EPA provided on the QA Chapter of the DCCA (transmitted as pp. 39-42 of the January 30, 1996 letter from Weinstock to Dials). For example, the first specific comments states in part, "The DCCA should have specified the roles of EM-1, EM-20, and EM-30". While Chapter 5's "Organizational Interfaces" chart (Figure 5-3, p. 5-21) shows EM-1 and EM-30, EM-20 is still not listed. The same EPA comment also implies that the organizations that conduct QA audits of contractors and waste generator sites should be listed; they aren't. Another EPA comment indicates that evidence substantiating that all workers were properly trained should be included; it wasn't.

We disagree. Chapter 5's "Organizational Interfaces" chart is correct in not identifying EM-20. The EM-20 responsibility for QA oversight of WIPP has been re-assigned to EM-30. EM-30 recently performed an independent assessment of the CAO QA Program.

The inclusion of the "Organization Interfaces" figure, which was not in the DCCA, implies that the EPA's comments were considered on some level. however, it also seems obvious that no line-by-line check to make sure that concerns raised by EPA comments were addressed was made. A search for a random sample of three other EPA comments—lack of objective evidence for control and maintenance of QA records, missing data quality indicators for the waste characterization program, and a need to address software reporting, correction, and implementation of requirements—shows that only the last of these is included in Chapter 5.

We disagree that the EPA comments have not been addressed as identified by the random sample of three EPA comments - lack of objective evidence for control and maintenance of QA records, missing data quality indicators, and a need to address software reporting, correction, and implementation of requirements. The comments are addressed within the discussion of the appropriate implementing procedures and overall controls established by the QA Program. We do not consider it necessary to supply more detail in Chapter 5.

"Chapter 5 apparently circumvents CAO's own QA program."

The weaknesses described above, in a chapter concerning QA, are apparently due to circumvention of the DOE's own QA program. CAO Management Procedure (MP) 4.4, Revision 0, dated April 19, 1996, states (Section 3.1.1) that

Before a document is produced, the requestor should evaluate the need, end use, cost-effectiveness, intended audience, duplication of effort, regulatory and technical requirements, and any external organizations's requirements or agreements related to the document.

MP 4.4 also establishes review processes, which are to be in performed in accordance with MP 4.2.

1. We disagree with this topic in its entirety. The review process was conducted in accordance with MP 4.2. Results of the reviews, for this revision of CCA Chapter 5, including comment resolution documentation, were completed and are maintained as QA records.

2. We disagree that the CAO QA Program was circumvented in any respect and believe this EEG determination was based on a lack of facts and a lack of understanding of the CAO Quality Assurance Program.

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MEMORANDUM

DATE: August 20, 1996

TO: Robert H. Neill, Director

FROM: Ben Walker, QA Specialist

SUBJECT: CAO Audit of SNL PA June 17-21, 1996

Tom Clemo and I observed the CAO audit of SNL's PA program during the week of June 17-21, 1996. Seven auditors were involved; other observers were Mario Italiano and George Basabilvaso from CAO, and Patrick Kelley, James Channell, David Back, and William Sublette for the EPA.

The audit team judged the PA program implementation of QA to be "marginal", and the software development and qualification was judged "marginally effective". Five draft Corrective Action Reports (CARs) were generated, and eight draft observations. Attachment 2 is a listing of these draft CARs and observations, and other material presented by the lead auditor at the closeout meeting.

Two items would seem to be of particular concern to QA for the PA effort: software codes were still not qualified, and some parameter values used by PA codes had been entered into the parameter database without formal processing. The software codes had incomplete baseline documentation but were nevertheless being utilized in Compliance Certification Application (CCA) calculations. The SNL QA Manager had agreed to this usage. The parameter value changes were a different sort of problem, in that the well-established parameters data entry formalism at SNL had been circumvented for the entry of some 25 parameter changes. These two events do not increase confidence in SNL's commitment to established quality for PA calculations.

A more complete description of these findings, and other events that took place during the audit, can be found in Appendix 1. The audit also found several laudatory practices at SNL; these include ease of retrieval of documents from the Sandia WIPP Central Files (SWCF), extensive error checking of inputs, software test scripting, and documentation and archiving of

software production runs. As always, SNL personnel were for the most part easily accessible and very helpful.

The auditors were well prepared, and those I observed stayed on task. Their knowledge and experience with SNL's PA efforts were readily apparent; and as is usual with CAO's auditors, they were persistent and thorough. This was a conscientious audit.

BAW:TC:sz
Enclosures

ATTACHMENT 1 to SNL PA Audit

Attachment 1 of the memorandum on the SNL QA audit (Walker to Neill, May 24, 1996) stated that:

> There still seems to be a sense at SNL that QA is secondary to scientific pursuit rather than an integral, and, for this project, essential part of it, and this attitude may have its effects even on QA personnel and their activities.

This hypothesis receives additional support from the sections that follow.

Software Qualification

Evidence of considerable effort to get the PA codes into QA conformance has been demonstrated in other software assessments in the recent past, and the documentation viewed in this audit was of good quality. However, SNL has decided to run calculations for the CCA using codes that are not yet in accordance with the dictates of NQA-2 Part 2.7, the 40 CFR 194 standard cited for software QA.

None of the PA codes were found to be fully qualified during the audit. Memoranda dated May 23, 1996 from the PA Manager in charge of software to the SNL QA Manager list the "current QA status" of each of the codes, all of whom contained incomplete items, and then request permission from the QA Manager to proceed with the CCA calculations. The QA Manager signed approval of the requests, without so much as initiating a CAR or requiring a schedule for completions.

A copy of the memorandum for NUTS is attached (Attachment 3); the distribution list shows that no copies were provided to the CAC. Nearly all aspects of the QA process are said to be "in progress"--i.e., none were completed. This includes the Requirements Document (RD) and the Verification and Validation Plan (VVP), which make up the first step in the NQA-2 Part 2.7 life cycle for software (§ 3.1; Requirements Phase), and define the requirements for the design of the testing phase and test cases. The memorandum later states that "Test cases #1 through #9 have been run" (though the requirements are still in draft) and that "...the testing is far along...."

The memorandum for CUTTING_S listed similar deficiencies (for all developmental parts of the software life cycle) in similar language. The other memoranda were probably similarly organized, though completion of parts of the life cycle may have occurred. NQA-2 Part 2.7 § 1 states:

> Software development shall proceed in a traceable, planned, and orderly manner...Software development may be performed in an interactive or sequential manner.

While "interactive" might be interpreted to indicate that test results can be used to change code requirements in an iterative fashion, it does not imply that all parts of the life cycle can be developed in parallel. Operational use of the software is the penultimate (6th) step in the software life cycle (followed only by the "retirement phase"), and NQA-2 Part 2.7 clearly states that for the "Operations and Maintenance Phase" (§ 3.6):

> Prior to this phase the software has been approved for operational use.

The memoranda also contain the statement that "The remaining testing and QA documentation will be completed expeditiously", and (for NUTS) that "If this testing uncovers any problems with NUTS then the impact on the CCA calculations would be assessed at that time". It seems likely that the purpose of the memoranda is to remove the pressure to complete QA work expeditiously; and the cost and effort to completely trace errors through a submitted CCA could be extensive.

The process to be followed as described in these memoranda are clearly at odds with the 40 CFR 194 requirements concerning software.

Parameter Entry Control

SNL-WIPP Form 464, WIPP Parameter Entry Form, is required for entry of any parameter values or changes in these values to the database for use by PA. Form 464s are initiated by the Parameter Task Leader, who enters information on the parameter, the change to be made, and justification for the change, attains signatures of the change requestor and an approval signature (others are sometimes required), then submits the Form 464 and supporting information to the Database Administrator as a Parameters Records Package (PRP). Data entry personnel are trained to use the Form 464s for input; the data entry person's signature is added to the 464, as is the signature of the person who checks the entry. The PRP, including the Form 464, is then filed in the Sandia Wipp Central Files (SWCF).

At the February 16, 1996, closeout of a CAO surveillance of parameters the lead auditor complimented SNL on the rigor with which use of Form 464s was enforced for database entry.

An auditor uncovered three or four parameters in the database for which no Form 464s could be found. In pursuit of this problem, the auditors were eventually shown a list of 25 parameters titled, "CHANGES NOT COVERED BY 464's". According to notes took while viewing this list, the first change entered was on February

16, 1996 (date of the closeout compliment mentioned above). That these entries had circumvented the established requirements was uncovered about a week later by a PI (while researching a parameter request from EEG). The compiling of the list began at that time.

It is one sort of error to fail to follow practices that have yet to be firmly established; it's another to fail in follow those that are established. During the audit we suggested that the audit team should find out the details of how these entries were made. We were informed that SNL would have to perform that activity and report it to CAO as part of the CAR resolution. It is hoped that the entries are the result of a preoccupied PI submitting changes directly to an improperly trained data entry person, but the problem is likely more serious.

In defense of SNL, this has all the appearances of being a single lapse in which all 25 parameters were changed in a matter of days, and SNL personnel were attempting to establish proper documentation. On the other hand, no internal CARs were generated by SNL's discovery of the problem.

Procedure Problems I: Data qualified by audit

During the audit, I had reason to read the versions of SNL QAPs 9-1 and 9-2 used by the auditors, and discovered lapses in each.

QAP 9-1 version 1 contained the statement (Section 4.3, Step 2):

> When data sets are used to support the analysis, document the source of the data and whether the data have been qualified through collection under an approved SNL QA program, the application of QAP 20-3, or *by SNL WIPP audit* (emphasis added).

Audits do not qualify data. When I questioned this statement it was explained to me that the phrase was more a slang term, and what was meant was that the program under which the data was developed had been audited by SNL to confirm that the program conformed to SNL's QA standards.

I was told SNL was in the process of revising the procedure, and indeed they were. EEG now has a copy of Revision 2 of the procedure, which became effective April 11, 1996, (a copy was received at EEG on April 18, 1996) and the statement quoted above has been removed. I remain confused, however. The audit was two full months after the effective date of the revision; why were auditors using the older one? And, why wasn't I simply shown that the newer version did not contain the item in question?

Analysis Plan AP-016, version 00, "Groundwater Modeling Analysis Plan for the Generation of Transmissivity Fields for the Culebra

Flow and Transport Calculations", dated May 2, 1996, Section 3.1, contained a similar statement:

> Only data that has been qualified through collection under an approved SNL QA program, through application of QAP 20-3, or *by SNL WIPP* audit will be used for this analysis [emphasis added].

I suspect this document was written with QAP 9-1 in hand; other analysis plans may have similar statements. This is an example of why the writing and reviewing of QA documentation is so important.

Procedures Problems II: Parameter "Category" Definitions

QAP 9-2, "Quality Assurance Requirements for the Selection and Documentation of Parameter Values Used in WIPP Performance Assessment" presented a more serious problem. The definition of parameter categories indicates that adequate control over parameters may not be adequately performed. Section 2.0 of the procedure offers a list of five categories, and states that Category 1, 2, and 3 parameters are subject to the requirements of the procedure, but 4 and 5 are not. The QAP 9-2 Revision 1 Category table:

Category	Description
5	Parameters not used in current compliance calculations;
4	Parameters that are model configuration parameters or that are assigned based on an assumed correlation of properties between similar materials;
3	Parameters representing physical constants...
2	Parameters representing the inventory of the waste to be emplaced at WIPP...
1	Parameters that do not fall into Categories 2 through 5, but are necessary to WIPP PA calculations.

The audit team failed to see why Category 4 parameters were deemed to be excludable from the QA requirements, and that the process for categorization of parameters was not adequate; a draft observation to that effect was made (draft Observation No. 3; in Attachment 2, p. 5).

I thought it should have been a CAR (and inappropriately said so at an audit team caucus). The table is unnecessarily confusing for the purpose of the procedure (establishing QA for

parameters). The procedure should have been written to require documentation for all parameters used in PA considerations, and should also require a documented rationale for parameters that are dropped from use in PA.

BEG's controlled copy version of SNL QAP 9-2 still shows Revision 1 as the current process to follow (August 9, 1996). The draft observation apparently had no effect on SNL, and parameters can still be included in PA calculations without necessarily being adequately documented.

Dating on Documents

Many kinds of SNL documents have inconsistencies in the dates listed in them. I have noticed several during previous audits and surveillances, but since the dates are always reasonably close I've not documented them.

Most pernicious are reviews or approvals of documents with dates that post-dated the issuance of the documents. For example, six Form 464s were found which were started on April 23, 1996, and entered into the database on April 22, 1996. The approvals for the change were all dated April 23, 1996.

Analysis plans I viewed had similar inconsistencies. "Analysis Plan for ORIGEN2 Inventory Calculations for First Phase Determination of the Initial Radionuclide Inventory for Performance Assessment Analysis Supporting the Compliance Certification Application", dated April 4, 1996, had all its signatures on or after April 9, 1996. "Analysis Plan for the Salado Flow Calculations (Task 1) of the Performance Assessment Analyses Supporting the Compliance Certification Application" was effective March 8, 1996, yet the author and reviewer signatures were dated March 12, 1996.

An internal SNL surveillance (96-08) of software was conducted on April 9-11, 1996. The surveillance report contains the following statement:

> One item of concern was the inconsistency of document dates. As this has been identified by CAO CAR 96-016, the inconsistencies will be listed in this report for correction without an additional CAR being issued.

The report has nine pages of documentation of violations which fall under CAO CARs for document dates and comment resolution. The report itself has an inconsistent date: the date on the memorandum transmitting it is April 3, 1996, 6 days before the surveillance took place.

Resolution of Previous CARs

A part of the scope of this audit was to verify the effectiveness of corrective actions for previous CAO CARs. None of the corrective actions were found by the auditors to be effectively implemented during this audit. Some, but not all, of the "observations" (a category for findings that could potentially generate CARs in the future if not corrected) for which CAO required responses were found to be adequately addressed.

Project Technical Baseline Updating

The FEPs plan suggested that the Project Technical Baseline (PTB) be updated. Discussions with SNL employees indicated that although significant changes in nearly all portions of the baseline have been instituted, SPM-2 (established in 1994) was still the PTB of record. "The CCA itself will be the new baseline" one employee stated, and suggested that the FEPs plan would be changed rather than establishing a pre-CCA update of the baseline.

U.S. Congress H.R. Hrg. 101-6/12

Attachment IV to EEG Review of CCA, Chapter 5

REVIEW OF THE STATUS OF THE WASTE ISOLATION PILOT PLANT PROJECT

pg. 163

HEARING

BEFORE THE

ENVIRONMENT, ENERGY, AND NATURAL RESOURCES SUBCOMMITTEE

OF THE

COMMITTEE ON GOVERNMENT OPERATIONS HOUSE OF REPRESENTATIVES

ONE HUNDRED FIRST CONGRESS

FIRST SESSION

JUNE 12, 1989

Printed for the use of the Committee on Government Operations

RECEIVED FEB 6 1991 ENVIRONMENTAL EVALUATION GROUP

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Westinghouse Electric Corporation

Government Operations

[illegible]

Box 7078
Cincinnati, OH 45227

May 5, 1989
WD:89:00514

Mr. Richard J. Figlik, Manager
Management Support Staff
U. S. Department of Energy
WIPP Project Office
P. O. Box 3090
Carlsbad, NM 88221-3090

DRAFT PLAN FOR AS-BUILTS

Dear Mr. Figlik:

Four different completion times have been looked at for completion of as-builts. The completion times looked at are 15 months, 12 months, 9 months and less than 9 months. The data provided in the previous correspondence, HA:89:4057 dated 4/26/89, was used as a basis for the plan development, the system breakout, and the system priority. Currently, there are no funds within Westinghouse or people to support an as-built program. Past progress in this area has been made with people or funds diverted from other work. To get a quality product, a dedicated effort is needed. In order to obtain the necessary field data, there will be plant power outages and other impacts. Cables will have to be traced or rung out. It was assumed that the work would be conducted on any shift that the systems were available. Hourly rates and per diem costs are actual costs from PEAK. Where possible to prevent wasted time, activities would be worked in parallel. Due to problems scheduling outages, each team could be working on 5 or 6 systems at a time.

This document does not identify resources to correct any deficiencies discovered during the as-built program.

Sincerely,

M. R. Brown, Manager
Engineering & Repository
Technology Support

MRB/dc:3

HA:89:4064

Attachments (1): System Priority List
(2): Plan for Less than 9 Months
(3): Plan for 9 Months
(4): Plan for 12 Months
(5): Plan for 15 Months

U.S. Congress H.R. Hrg. 101-6/12

Attachment V of EEG Review of CCA, Chapter 5

REVIEW OF THE STATUS OF THE WASTE ISOLATION PILOT PLANT PROJECT

pgs. 330-332

HEARING

BEFORE THE

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U.S. GOVERNMENT PRINTING OFFICE

United States Government — Department of Energy

memorandum

DATE: JUN 1 1989

REPLY TO ATTN OF: EH-331

SUBJECT: EH Oversight of the Waste Isolation Pilot Project (WIPP)

TO: Richard W. Starostecki, EH-90

This Office has completed two major efforts related to the oversight of WIPP. On April 28, 1989, we completed a one-week, onsite review of the WIPP Final Safety Analysis Report (FSAR). On May 15, 1989, we completed a Readiness Review Inspection (RRI). The EH staff trip report summarizing the FSAR review, dated May 4, 1989, and the RRI report are attached to this memorandum. Your approval of the RRI report by signature on the cover page is requested.

During the FSAR review a team of EH staff and consultants interacted with DOE WIPP Project Office (DOE/WPO), Westinghouse, and Bechtel representatives to close out requests for information flowing from our review of the FSAR and supporting documents. This effort also included resolution of questions that arose from independent calculations performed for EH by Brookhaven National Laboratory (BNL).

Most of the information required to close EH concerns related to the FSAR was developed during the onsite FSAR review. The task was hampered by almost total reliance on a single Bechtel representative to provide information related to the design or technical basis for selection of the structures, systems, and components that comprise the WIPP facility. This absence of knowledge on the part of operating staff indicates a significant deficiency in the transfer of the technical basis for the facility from the constructor (Bechtel) to the operating contractor (Westinghouse). Efforts are now underway to correct these deficiencies through such efforts as developing as-built drawings and the conduct of air flow tests to explore the rationale for the placement of monitors for airborne radioactive material.

Residual issues from the FSAR review have continued to be closed through review of later material provided by Bechtel and by onsite verification during the RRI. However, the accident analysis section of the FSAR contains issues that remain open and will be so noted in the EH Safety Evaluation Report. The seismic issues cited in the May 4, 1989, EH report are closed based on EH consultant review of analysis at the San Francisco offices of Bechtel.

The remaining design issue, documented adequacy of the concrete waste shaft key, is being addressed through new analyses by Bechtel to replace and update earlier analysis that were apparently destroyed and confirmatory analysis by BNL for EH. In our view, those retrospective analyses will likely have to be

supported by measurement of in situ stress in the inner surface of the concrete and monitoring of the key inside diameter for several years until its performance is sufficiently well understood for long-term acceptance. The likelihood of acceptable resolution appears good.

A fundamental management issue also remains open at this time; the adequacy of the DOE Quality Assurance (QA) program for the WIPP project. As presently structured, neither the dedicated QA staff, one person designated as the QA Manager, nor the low reporting level of the QA program meet the ANSI/ASME, NQA requirements espoused by DOE Orders. I believe that the adequacy of the DOE QA function at WIPP, particularly during the initial five-year experimental program will be a pivotal element in the successful demonstration of long-term isolation. Useful models for both DOE and the experimental program manager, Sandia National Laboratory, can be found in the evolving quality assurance programs associated with the high level waste program being conducted by the Office of Civilian Radioactive Waste Management. This issue deserves close and very high level attention.

The conduct of the RRI was based on 15 modules designed to sample a broad range of requirements based on commitments made in the FSAR, DOE Orders, the Design Validation Final Report (DVFR), and TSA criteria. The inspection was conducted by a twelve-member team of EH staff and consultants over a period of eight days. The team members reviewed the key technical documents that translated requirements into day-to-day operations, interviewed WIPP personnel, and inspected the facility buildings and systems.

As a result of the RRI, we have concluded that the physical plant at WIPP is very close to being ready for operation. The small number of exceptions appear to be addressed through satisfactory programs.

We have also concluded, however, that significant additional effort in ongoing staffing, training, procedure development, and documentation is necessary before EH could support a recommendation for startup. The areas most affected by these additional efforts are support functions such as radiological protection, maintenance, and quality assurance although additional training and qualification remain in operational areas as well.

Substantial efforts are underway in many of the areas needing improvement. For example, reorganization of the Radiation Protection Division was implemented during the week of our RRI, and we saw evidence of active recruitment efforts to staff this new organization. Although the as-built drawing effort noted above has not started, Westinghouse proposals for conduct of the program have been received and DOE/WPO has informed EH of its intent to make the availability of as-built electrical drawings to facilitate viable lockout and tagout procedures a first priority.

We have also briefly reviewed DOE/WIPP 89-011, Draft Plan For The Waste Isolation Pilot Plant Test Phase: Performance Assessment and Operations Demonstration, April 1989. This report summarizes the five year experimental program that will develop the data necessary to demonstrate the ability of the WIPP facility to meet applicable regulations and agreements for long term isolation. A complete internal review of DOE/WIPP 89-011 will require strong expertise in the geoservices and related geo-engineering disciplines that is not presently represented by cognizant DOE staff in the field or at headquarters.

James P. Knight
Director
Office of Safety Appraisals

cc: w/o attachment
W. Kornack, ACNFS
W. Kranz, RL
J. Tillman, WIPP
A. Follett, DP-122

8.9 Summaries of Waterflows for the New Mexico Oil Conservation Division Districts 1 and 2

SUMMARY OF WATERFLOWS IN NMOCD DISTRICT 1 (NOVEMBER, 1978 TO PRESENT)

(SORTED BY LOCATION)

UNIT NO.	DATE	OPERATOR	LEASE NAME/ WELL NO.	UNIT	T-R-SEC	OCD REF	REPORTED	DEPTH	DRILL OR MOD	FPM	PRESSURE	COMMENTS
1	[illegible]	[illegible]	[illegible]	K	04-17-33			[illegible]				HIT 5" WATERFLOW ON [illegible] WELL AT 3000'.
2	[illegible]	[illegible]	[illegible]	[illegible]	04-10-32			3002		4		DECREASED TO 2 BPM ON [illegible].
3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]		60		DRILLED TO 4187' @ 8[illegible] PM Dec. w/160# SI. STILL HAD SOME FLOW ON INTERMEDIATE.
4	1/7/81	[illegible]	[illegible]	C	18-16-35			2470		100		[illegible] DO NOT REPORT DRILLING [illegible] HIT WF 2470'. DEPLETED & DRILLED AHEAD. [illegible]
5	[illegible]	[illegible]	[illegible]	L	15-16-35			3710'		8700		
6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	CLOSED		[illegible]				WATER FLOW OUT SURFACE. NEW 1/4/78. [illegible]
7	[illegible]	Monsanto	Ventura [illegible]	F	14-16-19			6300'				HIT WF @ 6300'. OPTED TO CONTINUE.
8	6/7/80	[illegible]	[illegible]	M	16-17-37	CLEMENTS						PLUGGED WELL. IN 3 DAYS [illegible] AROUND MARKER. [illegible]
9	5/29/79	Arco	[illegible]	E	17-32-29							1 STREAM FROM CSG THAT HAD [illegible] AT SURVEY TIME. [illegible]
10	12/27/79	Arco	[illegible]	J	17-33-29	BECKNER		3400'				@ STREAM [illegible] PM W/ SOME GAS [illegible] AT 3400'.
11	11/1/79	Arco	[illegible]	H	17-33-29							BETWEEN [illegible] & 7-CSG. WATERFLOW ON [illegible].
12	[illegible]	Conoco	[illegible]	G	17-33-29							
13	1/1/80	Conoco	[illegible]	B	17-33-29							
14	3/10/80	Abandoned Corp	[illegible]	C	17-33-30			3700'				HIT WATERFLOW ON DRILLING WELL.
15	[illegible]	Duval Exploration	[illegible]	M	17-33-30	CLEGG		[illegible]				LARGE WATER FLOW FROM SALT.
16	3/13/81	Jameland		K	17-33-30			[illegible]				HIT @ [illegible]
17	3/3/81	[illegible]	[illegible]	G	17-33-30			4400'				
18	No date	Crown Central	[illegible]	M	17-33-30							
19	[illegible]	Phillips	[illegible]	[illegible]	17-33-31			4300'				HIT WF @ 4300' @ 5 MM. [illegible]
20	[illegible]	Phillips	[illegible]	E	17-33-31			3794'	DRLG			60 GAL PER MM.
21	No date	Phillips	[illegible]	F	17-33-31							
22	[illegible]	Phillips	[illegible]	H	17-33-31			3450'		31		
23	[illegible]	Phillips	[illegible]	[illegible]	17-33-31					30		
24	[illegible]	Phillips	[illegible]	H	17-33-31			4000'	[illegible]	31		
25	[illegible]	Phillips	[illegible]	G	17-33-31			4300'		68		WELL LOCATIONS FROM INTERIOR WELL. WILL HAVE AROUND [illegible] INJECTION WELL [illegible]
26	[illegible]	Phillips	[illegible]	D	17-33-31			3400'		30		VAC AREA.
27	No date	Mobil	[illegible]	A	17-34-32			3500'				REPAIR JOB WATER ENTERING CSG AT 3500'.
28	[illegible]	Mobil	[illegible]	G	17-34-34							TRG/TOR LEAK REPORTED. WILL REPAIR [illegible].
29	[illegible]	Phillips	[illegible]	L	17-34-30			4017'		60		HIT WF @ 4017' @ 60 BPM.
30	[illegible]	Phillips	[illegible]	L	17-34-30			3073'				
31	[illegible]	Phillips	[illegible]	M	17-34-30			3027'		400	150	
32	[illegible]	Phillips	[illegible]	F	17-34-30			3000'				CASING COLLAPSED @ 3000' WAVE OUT SURVEYED [illegible] WELL P.A.
33	[illegible]	Texaco	[illegible]	O	17-34-31	CLOSED		1167		91	450	WATERFLOW @ 1167' @ 90 BPM. [illegible]
34	[illegible]	Texaco	[illegible]	I	17-34-31	CLEMENTS		1167	DRLG	12		WATERFLOW @ 1167' @ 10 BPM.
35	[illegible]	Texaco	[illegible]	K	17-34-31	CLEMENTS		1167	DRLG	78		WATERFLOW @ 1167' @ 15 BPM. RAN CSG. AND CEMENTED OFF.
36	[illegible]	Texaco	[illegible]	L	17-34-31	BLINEBRY		3920'	DRLG	78		WATERFLOW @ 1920' @ 76 BPM.
37	[illegible]	Texaco	[illegible]	M	17-34-31	BLINEBRY		3700'		60	640	WATERFLOW @ 1700' @ 60 BPM. [illegible]
38	[illegible]	Texaco	[illegible]	H	17-34-31			1700'	DRLG	60		WATERFLOW @ 1700', 1777', 1800', 1850', 1930', 2900'. TOTAL FLOW [illegible]
39	[illegible]	Texaco	[illegible]	H	17-34-31			1700'	DRLG	1000		WATERFLOW @ 1700' @ 1000 BPM. AT 1850' INCREASED TO 2000 BPM.
40	[illegible]	Texaco	[illegible]	H	17-34-31			1850'	DRLG			WATERFLOW @ 1850' @ 40 BPM. [illegible]
41	[illegible]	Texaco	[illegible]	H	17-34-31				DRLG			RUNNING THE APPROXIMATELY 70 JOINTS OF 8 5/8. NO OTHER INFO AVAILABLE - [illegible]
42	[illegible]	Texaco	[illegible]	O	17-34-31				DRLG	800		WATERFLOW WHILE CEMENTING. [illegible]
43	[illegible]	Texaco	[illegible]	F	17-34-31	CLEMENTS		1000'		60	300	WATERFLOW @ 1000', 2510', 2510', 3P = 700 PSI.
44	[illegible]	Texaco	[illegible]	F	17-34-31	CLEMENTS		3700'		100		WATERFLOW @ 3700'. [illegible]
45	[illegible]	Texaco	[illegible]	F	17-34-31			1700'	DRLG	3000	450	WATERFLOW @ 1700' [illegible]
46	[illegible]	Phillips	[illegible]	F	17-33-31				PROD	9		SEE FLOW OUTSIDE [illegible] CSG. [illegible]
47	[illegible]	Phillips	[illegible]	I	17-33-31			1800'	[illegible]			300 GAL OIL PER MINUTE
48	No date	Phillips	[illegible]	J	17-33-31							
49	[illegible]	Texaco	[illegible]	H	17-33-31			1771'	DRLG	2500	940	12 HOUR AIR BLOW. CHANGE VALVE TO 60 INTO FLOW LINE. NOW 2500-3000 BPM AT [illegible]
50	No date	Phillips	[illegible]	K	17-33-31							
51	[illegible]	Phillips	[illegible]	M	17-33-31							REVERSED WATERFLOW FROM SURFACE CSG.

SUMMARY OF WATERFLOWS IN NMOCD DISTRICT 1 (NOVEMBER, 1978 TO PRESENT)

(SORTED BY LOCATION)

DIST NO.	DATE	OPERATOR	LEASE NAME/ WELL NO.	UNIT	T-R-SEC	OCD REP	REPORTED	DEPTH	DRLG OR PROD	BPH	PRESSURE	ADDITIONAL REMARKS
32	8/7/83	Arco	State B 1576 #6	N	17-35-33					40		WATER BROKE INTO CELLAR. FLOWED 40 BBLS & APPEARED TO BE FLOWING ABOUT 4 BPH FROM AROUND SURFACE
33	8/7/83	Amoco	CHGBAU Tr 3229 #1 P	N	17-35-33							
34	5/3/78	Phillips	Fed Vacuum Unit	N	17-35-33	CLEMENTS		2507'		20		
35	4/2/91	Texaco	NMA St #1L	A	18-34-01			1760'	DRLG	60		4/3/91 @ 1760'. CROSSFLOWED THEN FLOWED 4 BWPH @ 2990' @ 30 BPH.
36	11/29/78	Texaco	Vac GBSA Ut #5P	B	18-34-01			3184'	PROD	8-10	Flow	CASING LEAK AT 2284' IN COLLAR. WATERFLOW @ 8-10 BPH. SIP=1105 PSI.
37	4/18/91	Texaco	VGSAU A Ut #1M	B	18-34-01			1447'	DRLG	48		WATERFLOW @ 1400' @ 40 BPH
38	4/22/91	Texaco	NM L St #40	B	18-34-01			1711'	DRLG	16		WATERFLOW @ 1600' & M @ 1711' @ 16 BPH
39	No date	Texaco	VGSAU #57	B	18-34-01				PROD			
40	7/3/90	Texaco	VGSAU A Ut #107	C	18-34-01			1777	DRLG	108		WATERFLOW @ 1777' @ 108 BPH.
41	3/91	Texaco	VGSAU 30	E	18-34-01							SOME WATERFLOW ON INTERMEDIATE. DAMPED TO 40-60 PPM
42	No date	Texaco	VGSAU Ut #140	H	18-34-01							
43	4/7/91	Texaco	NM B NCT-3 #4	H	18-34-01			1900'	DRLG	99		WATERFLOW @ 1900' @ 99 BPH. NO OTHER INFORMATION AVAILABLE
44	7/7/87	Texaco	NM B St NCT-3 #24	P	18-34-01			2419'	DRLG	144		VAC POOL
45	7/16/87	Texaco	NM B St NCT-3 #24	P	18-34-01				DRLG			WATERFLOW @ 1870', 2070', 2560'. TOTAL FLOW=2200 BWPH.
46	5/16/92	Texaco	West Vac Ut #44	C	18-34-03				PROD		Flow	WATERFLOW TEST ON 8 5/8. WILL REPAIR.
47	6/4/84	Amoco	ETH Q #4	L	18-34-04			3000'		99		1ST WATER FLOW ON DRLG. WELL AT 2987 - 3000'.
48	No date	Phillips	Evi Fed U 1987 #16	I	18-35-05							SIGNIFICANT FLOW AT 3400' OR 4 5/8 ON REPLUGGING
49	9/24/90	Texaco	Central Vac Unit #144	A	18-36-06			1840'	DRLG	30		WATERFLOW @ 1840' @ 30 BPH.
50	2/25/91	Texaco	NM B St NCT-1 #12	K	18-36-06			2040'	DRLG	30		WATERFLOW @ 2040' @ 30 BPH. AT 2440' FELL 30 BPH. IN INTERMEDIATE CSG
51	10/15/78	Texaco	Central Vac Unit #127	D	18-36-06	CLEMENTS		2000'	DRLG	1000		WATERFLOW DRILLING @ 2000' 1000 BWPH.
52	11/27/80	Texaco	Central Vac Unit #Wn. 11	D	18-36-06			1800'	DRLG	60	Flow	WATERFLOW @ 1010', 2100', 2510'. MAX FLOW=600 BPH. MAX SIP=900 PSI.
53	10/27/78	Texaco	Central Vac Unit #134	E	18-36-06	CLEMENTS		1840'	DRLG			WATERFLOW @ 1840' & 2241' @ 100 BPH.
54	3/79	Texaco	Central Vac Unit #105	E	18-36-06	CLEMENTS			PROD			WE BELIEVED TO HAVE PRESS. FLOWING FROM 2000'-2100'. DV 3000' @ 1500'.
55	4/79	Texaco	Central Vac Unit #100	F	18-36-06	CLEMENTS		1450'	DRLG	25	Hot	WATERFLOW @ 1450' AND 1560'. EVER-PRES. WILL RETCSG. @ 2040'.
56	9/18/78	Texaco	Central Vac Unit #109	G	18-36-06	MORROW		2017	DRLG		Hot	WATERFLOW @ 2017 @ 10 BPH. INC. TO 15 BPH. SIP=800. P @ 2147.
57	8/30/79	Texaco	Central Vac Unit #108	G	18-36-06			3140	DRLG	15		WATERFLOW @ 3140' AND 3560'. TOTAL=15 BPH. 10 MIN SIP=300#
58	No date	Texaco	Central Vac Unit #107	G	18-36-06	CLEMENTS		1977		30		
59	9/25/87	Texaco	Central Vac Unit #90	H	18-36-06				DRLG			WATERFLOW @ 400 A.M. RAN=400 BPH. SIP=200#.
60	2/20/88	Texaco	NMO St NCT-1 #28	H	18-36-06			1740'	DRLG	1800		WATERFLOW @ 1740' @ 1800 BPH.
61	8/27/79	Texaco	Central Vac Unit #116	J	18-36-06			2300'	DRLG	15		WATERFLOW ON DRILLING WELL @ 2300'. FLOWING 15 BPH. DRILLING AHEAD WITH NO INCREASE IN VOLUME. WILL RETCSG
62	12/1/81	Texaco	Wasson A/B 4	K	18-36-06			3900'	PROD	400		1ST WATER FLOW ON WORKOVER JOB. VOLUME CALCULATED AT 2200'. FLOWED AT 400 BPH
63	4/19/90	Texaco	Central Vac Unit #134	L	18-36-06			1840'	DRLG	40		WATERFLOW @ 1840' @ 40 BPH. INC. TO 70 BPH @ 2000'. @ 60 @ 2200'.
64	9/3/81	Texaco	Central Vac Unit #114	L	18-36-06	CLEMENTS		1960	DRLG			WATERFLOW @ 1960'. 2340'. TOTAL FLOW=600 BPH. SIP=1000'. @ 60 @ 2160'. DV1 @ 1900'.
65	4/29/80	Texaco	Central Vac Unit #114	M	18-36-06				PROD			WATERFLOW AFTER BOTTOM WAS PLUGGED OFF ON P.L.
66	2/18/79	Texaco	Central Vac Unit #131	N	18-36-06			2030	DRLG	40-60	1000	WATERFLOW ON DRILLING WELL @ 2030' FLOWING 40-60 BPH. SIP=1000#. 500' 8/18/79.
67	8/14/79	Texaco	Central Vac Unit #132	O	18-36-06			2194	PROD	10	1100	WATERFLOW @ 2194' @ 10 BPH. SIP=1100#
68	10/1/79	Texaco	Central Vac Unit #139	O	18-36-06			2340'	DRLG	15		WATERFLOW @ 2340' @ 15 BPH. SIP=1000#. RAN 7" @ 2000'.
69	5/21/80	Energy Reserves	TP State #1	J	18-36-08			3340'				POOR LY PLUGGED.
70	No date	Amoco	Amoco St M #1	L	18-36-14							
71	12/11/84	Bonds Energy	Aco State #1	O	18-36-14			2000		400-600		4 HR FLOW @ 1000 BPH @ 300#. ASSUMED TO BE OR RETDISPOSAL WELL.
72	8/24/87	Bass Enterprises	Forest St #1	P	18-36-21				DRLG	1440		
73	1/11/90	Glenn Energy	Hobbs St	B	18-36-27				DRLG			1ST WATER, DRLG DEPTH UNKNOWN. 30 BPH. COMPLETED AT 4567'. INTEND TO P.A. (DRY).
74	3/27/91	Bonds	Barron St	D	18-36-27			2900'	DRLG	1000	900	
75	12/11/81	Union Oil	Mexico Ut D	F	18-36-33	CLEMENTS		3450'		800		
76	No date	Arco	Hawkins Fed (MD) #3	G	18-36-33							
77	12/80	Amerada	Gil Lanier #3	B	18-37-21			1000'				
78	5/30/81	Amerada	Gil Lanier #7	C	18-37-33	CLEMENTS		1530'				
79	6/9/79	Gulf	State H Com	K	18-37-33			3200'				LOCATED WATERFLOW AT 2200'. REPAIRED.
100	No date	Amoco	Mid Vacuum	B	18-38-08							
101	5/81	Anadarko	Bass Com Unit	P	20-33-19			3700'		600		
102	1/11/80	Anadarko	Tom Kuykendall St #1	G	20-33-34			3511'		900		

SUMMARY OF WATERFLOWS IN NMOCD DISTRICT 1 (NOVEMBER, 1976 TO PRESENT)

(SORTED BY LOCATION)

UNIT NO.	DATE	OPERATOR	LEASE NAME/ WELL NO.	UNIT	T-R-N-C	OCCURRENCE	REPORTED	DEPTH	DRLG OR PROD	BPH	PRESSURE	ADDITIONAL REMARKS
[illegible]	[illegible]	[illegible]	[illegible]	E	[illegible]			[illegible]				DRILLING.
[illegible]	[illegible]	[illegible]	[illegible]	G	[illegible]			[illegible]				[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]					[illegible]		APPROXIMATELY [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	I	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	F	[illegible]				[illegible]			[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	G	[illegible]				[illegible]			[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	G	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	K	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	D	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]	[illegible]		[illegible]		[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	P	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	B	[illegible]			[illegible]	[illegible]			[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]		[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	M	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	K	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]						[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	E	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	D	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	E	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	M	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	I	[illegible]			[illegible]			[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]	[illegible]						
[illegible]	[illegible]	[illegible]	[illegible]	E	[illegible]			[illegible]				[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	F	[illegible]					[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]			[illegible]		[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	K	[illegible]			[illegible]	[illegible]			[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]	[illegible]		[illegible]				[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	D	[illegible]			[illegible]		[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]		[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]		[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	F	[illegible]			[illegible]		[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	I	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]			[illegible]		[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]		[illegible]		[illegible]

SUMMARY OF WATERFLOWS IN NMOCD DISTRICT I (NOVEMBER, 1978 TO PRESENT)

(SORTED BY LOCATION)

SITE NO.	DATE	OPERATOR	LEASE NAME / WELL NO.	UNIT	LOCATION	OCD NOTIFIED	REPORTED	DEPTH	DRILL OR PROD	BPH	PRESSURE	ADDITIONAL REMARKS
154	8/27/82	Texaco	Jal Brantley Fed NCT-3#4	C	23-26-37			3005	DRLG	40	650	WATERFLOW @ 3000' @ 60 BPH. PRESS=400#.
155	10/18/84	Amoco	A.A. Brantley Fed NCT-3#3	D	23-26-37			3055'	DRLG	1000		WATERFLOW @ 3100' @ 1000 BPH OR MORE. TY TUBING PLUGGED DOWN ENOUGH TO DRILL AHEAD
156	5/10/79	Amoco	SNC #1	E	23-26-37							
157	3/4/83	Sun	Brantley Ring NW #3	C	23-26-37							CASING COLLAPSED APPROX 600-700' MONITOR OFF. WILL MOVE RIG TO COMPLETE PA
158	3/24/80	Amoco	SNC #1	C	23-26-37							RF. REPAIR CASING. PUNCHED LOC.
159	8/14/79	A. Crosby	Brantley Fed #3	D	23-26-37							PROBLEM OF SALT WATER COMING OUT SURFACE. WILL PERFORATE @ 1200' & SQUEEZE.
160	[illegible]	[illegible]	[illegible]	M	23-27-01			1500'	DRLG	400		SHUT IN PRESSURE 1000 CSP VIA [illegible].
161	10/10/81	Mewbourne	Gulf St #1	F	23-27-03			2600'		6000		DOG HOUSED TO 300 BPH IN 1.5 HOURS
162	4/9/83	Texaco	Elan State #2	N	23-27-03			3047'	DRLG	400	625	WATERFLOW ON AIR @ 3047' & 3417' @ 400 BPH. ANOTHER @ 3700'. CEMENTED OFF DRLG ON INTERMEDIATE.
163	1/10/85	Texaco	Shelly Ranch A #37	J	23-27-05			1600'		750		WATERFLOW @ 1/2/86 @ 2415' @ 300 BPH. 1/22/86 RETIPPED AND DRILLED AHEAD
164	3/1/84	Texaco	Shelly Ranch A #47	N	23-27-05				DRLG			WATERFLOW @ 2700' @ 65 BPH.
165	4/2/83	Texaco	State #2	N	23-27-04			2600'	DRLG			NO FLOW 3000'. INCREASED TO 315 BPH AT 3800 @ 600 PSI 20 BPH H2S. FLOW STABILIZED AT 120 BPH. SHUT IN PRESSURE
166	No date	Texaco	RK State #3	H	23-27-04			3047	DRLG	80		SHUT IN 1100-600 PSI.
167	11/24/83	Texaco	GW State #3	B	23-27-07			1444	DRLG	1200		WATERFLOW @ 1444' @ 1200 BPH. PRESS=300 PSI
168	8/23/84	Texaco	B Hanson #425	G	23-27-09			3067	DRLG	600		WATERFLOW @ 3067' @ 600 BPH. SP=[illegible]
169	8/3/81	Texaco	B Hanson #4	D	23-27-09			1307	DRLG	65	850	WATERFLOW @ 1307' @ 65 BPH. SEEMS TO INTERMEDIATE THROUGH FLOW.
170	3/13/84	Texaco	B Hanson #3	K	23-27-09			1317	DRLG	100		WATERFLOW @ 1317' @ 100 BPH. WATERFLOW @ 3700' @ 1200 BPH.
171	7/24/84	Texaco	B Hanson #1	L	23-27-09			1327'	DRLG	85		WATERFLOW @ 1327' @ 85 BPH
172	No date	Texaco	B Hanson #2	L	23-27-09			1327'	DRLG	1000	650	WATERFLOW @ 1327' @ 1000 BPH. [illegible]
173	11/1/84	[illegible]	Gomez #1	K	23-27-13			1500		100		
174	4/16/81	Texaco	Elvin #NCT-2 #1	P	24-27-33	CLOSED						WATERFLOW. [illegible] TO REPAIR [illegible].
175	5/13/84	Texaco	WTSU #14	C	24-28-33				TPLG			FLOW [illegible] BPH.
176	5/1/80	Gulf	WTSU #119	P	24-28-32							SHUT IN TO REPAIR TO REMOVE CIBP. PA'D.
177	5/11/84	Texaco	WTSU #131	P	24-28-32			1400	DRLG			WATERFLOW @ 1400' @ 7 BPH. WATERFLOW @ 2000' @ 20 BPH.
178	8/27/80	Gulf	SWU #178	I	25-27-15							CASING FLOWED TO SURFACE DUE TO PERFORATE.
179	5/24/81	D. Hardman	Gl Ranch #3	L	26-27-15			2997'	DRLG	Avg. 1200		SALT WATER.
180	8/24/83	Mewbourne	Dragoon NP Federal #3	A	26-27-15					Avg.		
181	10/27/83	Texaco	Brantley Yates Unit #14	C	26-27-27					7		WATERFLOW @ 7 BWPH. (NO REPORT TO OCD).
182	3/22/84	Texaco	Brantley Yates Unit #3	F	26-27-27			1311'	PROD		400	WATERFLOW ON BACKHEAD (NO REPORT TO OCD)
183	10/31/83	Texaco	Brantley Yates Unit #4	A	26-27-27					900		WATERFLOW ON BACKHEAD @ 43 BWPH. (NO REPORT TO OCD).
184	1/84	Texaco	Brantley "B" #1	G	26-27-27			1335'				WATERFLOW ON BACKHEAD @ [illegible]. (NO REPORT TO OCD).
185	10/11/84	Texaco	WTSU Producer #4	H	26-27-27					650		REPORTED TO OCD ON 10/1/84. REPORTED 10/10/79
186	3/84	Texaco	Brantley "B" #4	H	26-27-27					450		WATERFLOW ON BACKHEAD @ 35 BPH. (NO REPORT TO OCD)
187	11/13/87	Texaco	Brantley "B" #20	I	26-27-27					1000		WATERFLOW ON BACKHEAD @ 40 BWPH. (NO REPORT TO OCD)
188	11/20/87	Texaco	Brantley "B" #21	I	26-27-27					75		WATERFLOW @ 15 BWPH. (NO REPORT TO OCD).
189	11/2/87	Texaco	Brantley Yates Unit #46	K	26-27-27					1000		WATERFLOW @ 15 BWPH. (NO REPORT TO OCD).

WATERFLOW INFORMATION

1. Pogo Producing Co. 9/30/92 ; Federal Red Tank 34 #1-34-22-32 Drilling 3000' Flowed 800 bbls - High in H_2S, - Don Riggs 713-297-5045 10/23/92

2. Texaco Expl & Prod. 4-7-93; NMR NCT-3 #5- Drilling @ 1864' 90 BPH No other information available.

3. Texaco Expl & Prod. 4-9-93; Ellen Sims #9-3-23-37 Drilling @ 3049' Flowing 660 BPH @ 825# 4:00 AM -5-10-93 down to 440; 5/11/93 James Elliott down to approx. 70 BPH since 5-10-93 PM - setting 8 5/8" intermediate @ 3750'.

4 Texaco Expl & Prod. ; BF Harrison B #9 9-23-37 Drilling @ 1571' Flowed 1000 BPH Shut in Pressure 600#

5. Samedan; Sarah B #3-M 1-23-37 Drilling @ 1590' 600 BPH +-; Shut In Pressure 1000 Est. Vol 92000 +-.

6. Texaco Expl & Prod; R. R. Sims A #3 - 4-23-37; Drilling @ 2240' ; Flowed 80 BPH, Shut In Pressure 600 psi.

7. Texaco Expl & Prod: 11/24/93 - 9:00 AM; G. W. Sims #3- B - 9-23-37; Drilling @ 1444' Flowed 1200 BPH; Pressure 500 psi; Flowed down in 6 hours - 12-1-93 Drilling @ 5600', no further problems.

8. Texaco Expl & Prod; 5/17/94; WDDU #131 -32-24-38; Drilling @ 1420' ; Flowed 7 BPH @ 2000' 20 BPH.

9. Texaco Expl & Prod; 5/13/94; WDDU #146 - C 32-24-38; Drilling @ ?; Flowed 70 BPH.

10. Texaco Expl & Prod; 5/25/94; B F Harrison B #25 - C - 9-23-37; Drilling @ 2065'; Flowed 600 BPH; Shut In Pressure 875 down to 400 BPH @ 2:35 puff H_2S down to 1 PPM @ 2:35 Drilling ahead.

11. Texaco Expl & Prod; 5-1-95; R.R. Sims B #1 - 4-23-37; Drilling @ 1709'; Flowed 390 BPH; Pressure not recorded 5/1/94 up to 800-1000 BPH - Flow heavy for approx 1 hour then slacks off - Drilling not delayed and drilling at 3282' approx. 7:45 AM 5/1/95.

12. Phillips Petro. Co.; 7/1/96; Hale 25 25-17-34; Drilling @ approx. 4800' - Poss hit earlier no pressure - 10 BPH up to 20 BPH and back to 10 BPH - com. Drilling set production casing 7/2/96.

13 Nearburg Prod. Co.; 10/6/97; Madura Federal #5 - E- 28-19-33; Drilling @ 8549 10-6-97; No record of pressure or volumes 100 BPH per Jack - Hit @ 1300' swedge and squeezed hit again 1900#.

14. Texaco Expl & Prod.; 10/25/97; State AN #12 ; Drilling @ 2985; No pressure recorded

60 BPH - down to 45 BPH @ 11 am - 10/27/97 Depth 3380' will set intermediate @ 3506.

15. John H. Hendrix 12/2/97; Boyd #7 - 23-22-37 Drilling; No pressure recorded 700 BPH.

TOWN	RANGE	SEC	UNIT/LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	PRM TOPS
1	2	26	E	Petrosaic Co	Summer 36	1		294'	
1	28	6	H	Diamondback Petro. Inc.	Cave St.	2	1289'-1408WPD		
5	26	18	D	Yates Petro. Corp.	Paulsen PV ST	5			
5	26	34	E	Meridourne Oil Co.	Pecos Slope 34	1			
8	26	20	D	Yates Petro. Corp.	Hancock AHC Com.	3	28-30 bbls Hrs 5# Pump Flash		
8	26	33	D	Yates Petro. Corp.	Tamarack DF St.	1		597'	
8	26	33	E	Yates Petro. Corp.	Tamarack DF St.	2			
8	26	33	E	Yates Petro. Corp.	Tamarack DF	3		718'	
7	22	1	P	Mesa Petro. Corp.	Haley Com.	2			
7	22	2	F	Exxon Corp.	New Mexico CS St.	1		95'	
7	22	12	A	Yates Petro. Corp.	Haley Com.	3			
7	23	3	M	Yates Petro. Corp.	Barnett SN St.	1		318'	
7	23	8	M	Mesa Petro. Corp.	W.E.C. Com.	1			
7	23	10	L	Mesa Petro. Corp.	Round Top St.	5		460'	
7	23	20	O	Mesa Petro. Corp.	McKnight Com.	1		175'	
7	23	32	A	Yates Petro. Corp.	Rambler AGU St.	1			
7	24	8	J	Yates Petro. Corp.	Salmon Draw NR	1			
7	24	11	P	Yates Petro. Corp.	Red Bluff St.	1			
7	24	27	E	Yates Petro. Corp.	West Dixon NK St.	1			
7	24	35	P	Yates Petro. Corp.	Snakeweed SO St.	1			
7	25	2	P	Yates Petro. Corp.	Canelo BH St.	1			
7	25	7	C	YATES PETRO. CORP.	HILLTOP NO ST	1			
7	25	11	A	Mesa Petro. Corp.	Burns Com.	2			
7	25	11	I	Mesa Petro. Corp.	Burns Com.	1			
7	25	17	P	Yates Petro. Corp.	Cockburn RD	1			
7	25	23	A	Yates Petro. Corp.	Red AN$	1			
7	25	27	I	Yates Petro. Corp.	Pegasus OI ST Com.	5			
7	25	30	F	Yates Petro. Corp.	Saint SK St.	4			
7	25	5	F	Mesa Petro. Corp.	Neal Com.	1			
7	26	6	B	Yates Petro. Corp.	Crandel UD	2			
7	26	16	K	Sanders Petro. Corp.	McKay Samedan	2	1850'-20 BPM		
8	23	33	D	Yates Petro. Corp.	Middle Creek St.	1		75'	
9	23	5	K	Mesa Petro. Corp.	Ned St.	1			
9	23	5	O	Mesa Petro. Corp.	Ned St.	2		300'	
9	23	8	L	Mesa Petro. Corp.	Ned St.	3			
9	23	11	H	Yates Petro. Corp.	Whipple ZH St.	1			
10	25	2	H	Yates Petro. Corp.	Erickson KY	1		320'	
10	25	8	H	Yates Petro. Corp.	Hargrove AIH	1			
10	25	16	M	Yates Petro. Corp.	Bluer Lake FX St.	1			
10	25	17	C	Yates Petro. Corp.	Eakin AKB Com.	1			
10	25	17	H	Union Inc.	Cannon Fed.	3			
10	25	17	H	Yates Petro. Corp.	Cannon XF	1		402'	
10	25	27	B	Yates Petro. Corp.	Unruh AFF	1	612'-15-20 BWPM Gyp/Wtr 0000 ppm/cl		

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TOWN	RANGE	SEC	UNIT/LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	FRM TOPS
11	24	18	J	Wallace Oil & Gas Inc.	Hain	1			
11	25	3	M	Wallace Oil & Gas	Britt	1			
11	25	3	M	Wallace Oil & Gas	Britt	2	830' Fresh Water		Hondo SA Perf. 858'-88'
11	25	4	F	Fred Pool Drlg co.	Hondo River Farm	1			
11	25	8	J	Wallace oil & Gas Co.	Payton	1			
11	25	10	D	Wallace oil & Gas Co.	Marshall & Winston	1	W.F. @ 870' 5800Gal./Min. 2300ppmCl.		
11	25	20	F	Wallace oil & gas Inc.	Perrine	1		800'	
11	25	29	F	William R. Mason	Stanell Com.	1			
11	26	14	L	YATES PETRO. CORP.	Mccaw bt	7	0	750	
12	23	28	E	Philips Petro. Corp.	N.M. 28 St.	1		1032'	
12	26	3	L	Meinetz Oil Co.	Bogle	1	W.F. @ 30' .0626 Stream No Pst.		
12	26	3	L	Meinetz Oil co.	Bogle	1	1/16" Stream No PSI @ 30' Closed off		
12	26	8	N	Patroit Corp.	Capt Johnson	1			Top S.A. 680'
13	26	35	J	Clemente Energy Inc.	New, Mex. 35 St.	2			
14	24	9	I	The Superior Oil Co.	Ivy League Fee	1			
14	26	20	J	Clemente Energy Inc.	Bird	1y			
14	26	22	K	Southland Royalty Co.	Hagerman West 22	1			
14	26	23	M	Shenandoah Oil Co.	Rhodes	1			
14	26	33	E	Lynx Petro. Corp.	Drumm Com.	1			
14	26	33	G	Clemente Energy Corp.	Drumm Com.	1			
14	26	36	J	Clemente Energy Corp.	King 36 Com.	1			
15	25	28	F	Yates Petro. Corp.	Carol Jackson RD	1		900'	Top S.A. 802'.
15	26	32	F	Mesa Petro. Corp.	Mesa State Com.	2	1187'-800BPH Brine FLOW SI PSI 650#		
15	26	32	K	Mesa Petro. Corp.	Mesa State Com.	4	468' 180 BWPH		
16	17	6		J. Cleo Thompson	State A	6		AirDil	
16	30	5	J	Petro. Devel. Corp.	Marcello Fed.	1	2350' 8" Stream.		
16	30	9	C	Yates Petro. Corp.	Sidey PY Fed.	1	2737' 10BPM		
16	30	11	I	Yates Petro. Corp.	Strange "PZ" Fed.	1	2950' 3BWPM SI PSI 1350J.		
17	17	3	F	J. Cleo Thompson	State A-3	1		412'	Open. LC @ 1210' Cag Was Set In Orig Brack.
17	26	13	I	Yates Petro. Corp.	Aichen Fray DM	2			
17	26	14	H	Yates Petro. Corp.	McCaw BT	2		750'	
17	26	14	M	Yates Petro. Corp.	Morris Estate DG	6		723'	
17	26	14	P	Yates Petro. Corp.	Winters DN	4		740'	
17	25	15	P	Yates Petro. Corp.	Morris Estate DC	7		715'	
17	25	16	P	Yates Petro. Corp.	Morris Estate CC	7		715'	
17	26	22	H	Yates Petro. Corp.	J Lary J	1			
17	25	23	I	Yates Petro. Corp.	Michell Jo	6			
17	25	23	K	Yates Petro. Corp.	Giesler AV	6			
17	25	23	M	Yates Petro. Corp.	Giesler AV	30			
17	25	27	A	Yates Petro. Corp.	Ingram Jackson BV	10			
17	26	35	O	Yates petro. Corp.	Pearl DG				
17	26	36	I	Yates Petro. Corp.	Avon ES St.	2			
17	26	10	P	Marbourne Oil Co.	Sullivan	1			

TOWN	RANGE	SEC	UNIT/LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	FMN TOPS
17	28	14	E	Mewbourne Oil CO.	Haldermas	1			
17	28	14	M	Mewbourne oil Co.	Vogel	1			
17	28	15	J	Texas Petro. Corp.	Cyfiell Fed. FD	2			
17	28	19	K	Medallion Prod.Co.	Levels 19	1			
17	28	36	N	Balbala Forkin	State 36	1			
17	28	27	J	Mabuh Energy Corp.	NG Phillips St.	25	494:88'1.50GaWtr.		
17	28	35	O	Mewbourne Oil CO.	State BX	1	870' 516 BWPD		
17	28	12	P	Marbob Energy Corp.	Burch Keely Ut.	1	2430		
17	30	1	A	Ray Westall	Artesia Paso.Fed.	4	2385' 8000BPD oil psi-950#		
17	30	2	B	J.Cleo Thompson	Hayes ST.	9	2530' 3" Stream		
17	30	16	I	Pinnler Oil & Gas Co.	Dale H. Parke "D"	2	2317' 1100BWPD		
17	30	34	G	Anadarko Petro. Corp.	Arnold Fed. Com.	1	6185'284 BWPD		Glorieta 4700'-6000'
17	31	3	G	Devon Energy Corp.	H.E. West A	32	2549' 1 BPH		
17	31	3	J	Devon Energy Corp.	H.E. West "B"	76	33 BWPH @ 2550'		
17	31	3	L	Devon Energy Corp.	H.E. West B	33	3227' 14 BPH		
17	31	3	O	Devon Energy Corp.	H.E. West "B"	86	18 BWPD @ 2637'		
17	31	4	E	Devon Energy Corp.	H.E. West B	73	3225' 7.50 BPH		
17	31	5	O	Devon Energy Corp.	J.L. Keel B	69	2800'-3000' 14 BPH		
17	31	5	N	Devon Energy Corp.	J.L. KEEL B	64	2510' 2.3 BPH		
17	31	8	B	Sosemo Petro. Co.	J.L. Keel "B"	93	2500'-320BPH		
17	31	7	A	Devon Energy Corp.	J.L. Keel A	23	3000'-3100' 38 BPH		
17	31	7	H	Devon Energy Corp.	J.L. Keel A	33	3800' 50 BPH		
17	31	7	J	Devon Energy Corp.	J.L. Keel A	137	730' 10 15 BPH		
17	31	8	F	Devon Energy Corp.	J.L. Keel B	90	3800' 23 BPH		
17	31	8	I	Devon Energy Corp.	J.L. Keel B	57	1297' 48 BPH		
17	31	8	J	Devon Energy Corp.	J.L. Keel B	78	3400' 17 BPH		
17	31	8	M	Devon Energy Corp.	J.L. Keel B	93	1400' 3.8 BPH		
17	31	9	G	Devon Energy Corp.	H.E. West B	61	2568' 43 BPH		
17	31	9	O	Devon Energy Corp.	H.E. West B	81	3502' 2 BPH		
17	31	9	P	Devon Energy Corp.	H.E. West B	72	3300' 118 BPH		
17	31	10	D	Devon Energy Corp.	H.E. West B	66	3800'-4190' 33 BPH		
17	31	10	E	Devon Energy Corp.	H.E. West B	81	3598' 5 BPH		
17	31	10	F	Devon Energy Corp.	H.E. West B	60	3877' 16 BPH		
17	31	10	G	Devon Energy Corp.	H.E. West B	67	3313' 1.5 BPH		
17	31	10	I	Devon Energy Corp.	H. E. West "B"	70	4010' 1.50 BPH		
17	31	17	E	Devon Energy Corp.	Hudson Fed.	A	20-147 BPH @ 590'		T.Rustler @ 367'T.Salado @ 500'B.Salado @ 1325'
17	31	17	M	DEVON ENERGY CORP.	TURNER B	116	2798'-60 BPH		
17	31	18	E	Devon Energy Corp.	C.A. Russell	15	4 BWPD @ 738'		
17	31	18	I	Devon Energy Corp.	Turner "A"	52	47 BWPD @ 1003'		
17	31	18	L	Devon Energy Corp.	Turner A	38	17 BWPD @ 2625'		
17	31	18	N	Devon Energy Corp.	Turner A.	33	18 BWPD @ 2842'		
17	31	18	P	Devon Energy Corp.	Turner "A"	40	47 BWPD @ 1003'		
17	31	19	A	Devon Energy Corp.	Hudson Fed.	11	7 BPH @ 3080'		

TOWN	RANGE	SEC	UNIT/LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	RIM TOPS
17	31	18	A	Devon Energy Corp.	Hudson Fed.	7	0 BPH @ 1905'		
17	31	18	A	Devon Energy Corp.	C.A. Russell	17	778'-809' 142 BWPH		
17	31	18	I	DEVON ENERGY CORP	TURNER A	55	22 BPD @ 3061'		
17	31	18	M	DEVON ENERGY CORP.	TURNER A	41	2579'-43 BPH		
17	31	18	N	DEVON ENERGY CORP	TURNER A	59	27 BPD @ 2611'		
17	31	18	O	Devon Energy Corp.	Turner A	42	2265' 21 BWPD		
17	31	18	O	DEVON ENERGY CORP	TURNER A	58	80 BPD @ 2696'		
17	31	18	P	DEVON ENERGY CORP.	TURNER A	44	752'-20 BPH		
17	31	18	P	DEVON ENERGY CORP.	TURNER A	43	803'-88 BPH		
17	31	19	H	Devon Energy Corp.	Turner "A"	50	482'90BWPD, 1188'200BWPD, 1388'240BPD		
17	31	19	I	Devon Energy Corp.	Fern Oil Co.	24	14 BWPD @ 1440'		
17	31	19	G	Devon Energy Corp.	Turner A	46	61 BWPH @ 1575'		
17	31	19	G	Devon Energy Corp.	Turner A	45	34 BPH @ 1320'		
17	31	19	G	DEVON ENERGY CORP	TURNER A	67	11 BPD @ 1614'		
17	31	19	F	Devon Energy Corp.	Turner A	48	42.6 BWH @ 1326'		
17	31	19	G	Devon Energy Corp.	Turner A	49	800' 143 BWPD		
17	31	19	H	Devon Energy Corp.	Turner A	47	3.0 BPH @ 1050'		
17	31	19	J	Devon Energy Oper. Corp.	Turner A	51	1402'-1408' 71 BWPH		
17	31	19	J	DEVON ENERGY CORP	FRESS FED	4	172 BPD @ 718'		
17	31	20	M	DEVON ENERGY CORP	TURNER A	118	57 BPD @ 882'		
18	25	10	I	Yates Petro. Corp.	Thistle AKF	1		693'	
18	25	34	K	Yates Petro. Corp.	Rio Penasco RT	2		770'	
18	26	1	D	Barrera Falkon	Higgins Trust "1"	1			
18	26	18	N	Yates Petro. Corp.	West Dayton AJR	1		765'	
18	26	18	A	Yates Petro. Corp.	Vandiver Oil Com.	2		894	
18	26	22	H	Yates Petro. Corp.	Lawrence ADZ	2			
18	26	22	M	Yates Petro. Corp.	Paybuck Fz	2		60'	
18	26	26	C	Yates Petro. Corp.	Dayton FN	2			
18	26	34	C	Yates Petro. Corp.	Allied Lee ABH	2			
18	26	34	C	Yates Petro. Corp.	Allied Lee ABH	2			
18	26	34	C	Yates Petro. Corp.	Allied Lee ABH	2			
18	27	7	K	Devon Energy Corp.	West Red Lake Ut.	65			
18	27	7	D	Devon Energy Corp.	West red Lake Ut	39			
18	27	7	F	Devon Energy Corp.	West Red Lake UT	37			
18	27	7	F	Devon Energy Corp.	West Red Lake Ut	52			
18	27	7	I	Devon Energy Corp.	West Red Lake Ut	38			
18	27	7	O	Devon Energy Corp.	West Red Lake UT	42			
18	27	26	H	SDX Resources Inc.	Allegia Mesa	84			
18	28	8	A	Anderto Petro. Corp.	Mallard 08 AU TR. 5	15	1385' 214 BPH SI PSI 180#		
18	28	22	G	Primier Oil & Gas Co.	Yates Primier Fed.	3	1566' 10# Brine		
18	29	22	K	B&W Inc.	Empire 22 Fed. Com.	1	960'28000 BWPD		
18	29	22	K	Pay Weight	Dayton Fed.	6	938' 5000 BPD		
18	29	22	O	Premier	Yates Premier Fed.	1	1543' 10 GM (Min.		

TOWN	RANGE	SEC	UNIT	LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	FRM TOPS
18	30	2	N		MEWBOURNE OIL CO.	LOCO HILLS ST.	4	1615 38PM 450 SI PSI MACKISM WTR		
18	30	2	O		Mewbourne Oil Co.	Cedar Breaks St. 2	3	838 40 BWPH SI PSI 350# 10.6 Brine		Salt Section 720'-1500'
18	24	4	N		Yates Petro. Corp.	Rancherie AMH St. Com.	1		79'	
19	24	33	E		Yates Petro. Corp.	Agave AAJ St.	3		80'	
19	25	4	O		Yates petro. Corp.	Brainhaw	2			
19	25	4	O		Anadarko Petro. Corp.	Brainhaw	2			
19	25	8	I		Yates Petro. Corp.	THOMAS AJJ	4		470'	
19	25	8	I		Yates Petro. Corp.	Thomas AJJ	6			
19	25	8	J		Yates Petro. Corp.	Thomas AJJ	3			
19	25	8	P		Yates Petro. Corp.	Roy AET	5			
19	25	8	E		Yates Petro. Corp.	Marshall Aph	1			
18	25	8	F		Yates Petro. Corp.	Marshall APH	1			
18	25	8	F		Yates Petro. Corp.	Marshall APH	1			
18	25	8	G		Yates Petro. Corp.	Patrick AFI	2			
19	25	16	G		YATES PETRO. CORP.	APARIJO AFA ST COM.	6		80'	
19	25	15	D		Yates Petro. Corp.	Apache AMP	1			
19	25	16	K		Yates Petro. Corp.	Anole Amm St. Com.	2			
19	25	17	K		Conoco Inc.	Bairain 17	17			
19	26	20	H		Yates petro. Corp.	Hooper AMP	3			
19	20	20	M		Yates Petro. Corp.	Fairole Alt Com.	1			
18	25	21	E		Yates Petro. Corp.	Hooper AMP	2			
18	25	21	H		Yates Petro. Corp.	Parch AIZ	10		384	
18	26	24	E		Newburg Prod. Co.	Ferrel 24	1		55'	1" from 100' to 55' Pres. vold 400' 100'.Quer. wil
18	25	27	E		Newburg Prod. Co.	South Boyd 27	3			
18	26	27	L		Newburg Prod. Co.	South Boyd 27	4			
19	25	28	B		Yates Petro Corp.	Hinkle AUD	2		400'	
18	25	28	G		Yates Petro. Corp.	Hinkle AIB	1		53'	
18	26	28	J		Yates Petro. Corp.	Tackett AQT	1		247'	
18	20	28	J		Newburg Prod. Co.	State K	2		190'	
19	25	28	O		Yates Petro. Corp.	Tackett AQT	3			
18	26	29	D		Yates Petro. Corp.	Wright AJD Com.	1			
19	25	32	A		Conoco Inc.	Savannah St.	1			
19	25	32	A		Conoco Inc.	Savannah State	1		960'	
19	25	33	A		MEWBOURNE OIL CO	STATE B	2			
19	26	18	I		Newburg Prod. Co.	Lakewood Farms 18	1			
19	26	1	B		Bass Enterprises Production Co.	Merchant Bass	3	1390' 146 BWPH 10# Brine 200#S PSI		
19	30	14	K		Texaco Explo. & Prod. Co.	Renuida Basin St.	2			Top Salt 837' Base Salt 2870'
20	24	1	A		Yates Petro. Corp.	Foster AN	3			
20	24	1	A		Yates Petro. Corp.	Foster AN	1		825'	
20	24	1	G		Yates Petro. Corp.	Mobil AOB	1		247'	
20	24	2	M		Yates Petro. Corp.	Candelilla AKD	2			
20	24	11	F		Yates Petro. Corp.	Sara AHA Com.	6		308'	
20	24	14	M		Yates Petro. Corp.	John AGU	5			

TOWN	RANGE	SEC	UNIT LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	RIM TOPS
20	24	21	A	Yates Petro. Corp.	Albert AJH	1		62'	
20	24	22	C	Yates Petro. Corp.	Carl TP	3			
20	24	24	D	Nearburg Prod. Co.	Mayer 24	2		171'	
20	24	25	E	Yates Petro. Corp.	Chandler McKay Com.	4		185'	
20	24	25	L	Yates Petro. Corp.	Kirin ALA	1		172'	
20	24	26	A	Yates Petro. Corp.	Conoco AKG FED.	4		171'	
20	24	36	M	Marathon Oil Co.	Indian Hills St.	8		86'	
20	24	36	K	Marathon Oil Co.	Indian Hills St.	1		45'	
20	28	6	O	Chi Oper. Inc.	savage	1			Pro stiff section 260-1000 No capitan reef sec. 8
20	28	30	F	Exxon Corp.	Avalon Delaware UT	232			
20	28	32	E	EXXON CORP.	AVALON DELAWARE UT.	2220			
20	28	32	L	Exxon Corp.	Avalon Dela. Ut.	2420		1700'	
21	22	32	O	Premier Oper. Co.	Fanning Draw St.	1		Air Dr	Water 1330'-1490' bailed full of water,Fluid level 80'
21	23	2	J	Marathon Oil Co.	N. Indian basin Ut.	10		Airdrl	
21	23	2	M	Marathon Oil Co.	N. Indian Basin Ut.	12		airdrl	Fresh Water @ 218', Brackish Water @ 710'
21	23	2	O	Marathon Oil Co.	N.Indian Basin Ut.	11		800	
21	23	16	A	Marathon Oil Co.	North Indian Basin Ut.	8		148	
21	24	36	M	Mitchell Energy Corp.	Indian Hills 36	1		117'	
21	26	9	E	Chi Oper. Inc.	Winer St.	3		420	
21	26	9	F	Chi Oper. Inc.	OXY St.	2		1148	
21	26	9	K	Chi Oper. Inc.	OXY St.	1		850	B. Capitan-3130
21	26	8	N	Chi Oper. Inc.	Winer Com.	5		848	
21	26	16	F	Devon Energy Corp.	Cactus State	8			
21	26	16	I	Devon Energy Corp.	Cactus State	10		1220'	
21	26	16	O	Devon Energy Corp.	Cactus St.	4			
21	26	16	O	Devon Energy Corp.	Cactus State	5			
21	26	16	A	Devon Energy Corp.	Cactus St.	12		770'	
21	26	16	B	Devon Energy Corp.	Cactus State	7		890'	
21	26	16	C	Devon Energy Corp.	Cactus St.	1		650	
21	26	16	D	Devon Energy Corp.	Cactus State	5			
21	26	16	E	Devon Energy Corp.	Cactus State	8			
21	26	16	G	Devon Energy Corp.	Cactus St.	3		78'	
21	26	16	G	Devon Energy Corp.	Cactus ST.	3		443'	LC-78'
21	26	16	J	Devon Energy Corp.	Cactus Samp.	5			
21	26	16	K	Devon Energy Corp.	Cactus St.	4			
21	27	9	D	Ray Westall	Myrtle Myra	5			Capitan Reef 1348-1719
21	27	16	A	Ray Westall	Myrtle Myra	8			
21	27	17	F	Yates Petro. Corp.	Glider AG St.	1		1264	
21	28	3	K	Energex Oil Co.	Teodoro St.	1			Capitan Reef 1350 2106
21	28	3	M	Pogo Prod. Co.	State	1		1359	
21	31	36	P	Pogo Prod. Co.	State 2	1			
21	31	36	P	Pogo Prod. Co.	State 2	1			
22	23	3	M	Oryx Energy Corp.	Conoco St. Gas Com.	2		542'	

TOWN	RANGE	SEC	UNIT	LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	FRM TOPS
22	23	18	D		Chevron USA Inc.	Bogle Flats UT	18			
22	23	21	G		Yates Petro. Corp.	Wagon Ut.	1		835'	
22	24	2	K		Nearburg Prod. Co.	Big Walk 2 St.	3			
22	28	32		A	Louis Dreyfus Nat. Gas.	E.V. State	1			
22	30	34	A		Exxon Oil & Gas Co.	James Ranch Ut.	71			Base Salt 3588'
22	30	35	K		Basa Enterprises Prod. Co.	James Ranch Unit	29			Base Salt - 3808'
22	30	36	N		BASS ENTERPRISES Prod. Co.	James Ranch Ut.	41			Base Salt-3664'
22	31	17	A		Yates Petro. Corp.	Graham AKB St.	1			B. salt 4073'
22	31	20	H		Yates Petro. Corp.	Graham AKB St.	2			
22	31	29			Pogo Prod. Co.	Stace 2	3			Base Salt-4100'
22	31	29	U		Pogo Prod. Co.	Stace 2 #4	4			Base Rustler @ 700'.Top Salt @ 800'.
22	31	2	K		Yates Petro. Corp.	Flora AKF State	2			Base Salt 4020'
22	31	2	N		Yates Petro.Corp.	Flora AKF St.	1	2032' Flowed 35.30 MMFr w/H2S Sm.		
22	31	2	O		Pogo Prod. Co.	State 2	2	1208PH @ 3087' flowed to 0 10 Hrs.		
23	28	24	A		B.K. Oper. Corp.	Remuda Basin St.	2			Base Salt 3001'.
23	30	19	C		Texaco Expl. & Prod. Inc.	Remuda Basin 19 Fee	1			Base Salt 3328'
23	31	16	C		Yates Petro. Corp.	Medano VA St.	10			Base Salt-3913
23	31	22	E		Enron Oil & Gas Co.	Poker Lake 32 St.	9			Base Salt 3840'
24	25	8	C		W.A. Moncrief Jr.	Jurnegan St.	1			
24	25	8	K		W.A. Moncrief Jr.	Jurnegan St.	2		1005'	Top Delaware-2784'
24	26	9	B		Santa Fe Energy	Mosley Canyon 9 St.	1		1070'	Base Capitan Reef-2484
24	26	10	C		HNG Oil Co.	S. Horseshoe Bend 10	1		1272'	
24	26	17	C		R.E. Hebert	Ridge St	1		939'	
24	26	17	D		Santa Fe Energy	Lonbshop 17 St. Com.	1		1539	Base Capitan Reef 2279'
24	25	20	B		Santa Fe Energy	Lonbshop 20 Fed.Com.	1		2090	Top Capitan Reef 845',Base Capitan Reef 2385'

EEG-69
DOE/AL58309-69

SENSITIVITY ANALYSIS OF PERFORMANCE PARAMETERS USED IN MODELING THE WIPP

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independant technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, is being constructed as a repository for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC04-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, continues authorization.

EEG performs independent technical analyses of the suitability of the proposed site, the design of the repository, its planned operation, and its long-term integrity, suitability and safety of the transportation systems, suitability of the Waste Acceptance Criteria and the generator sites' compliance with them, and related subjects. These analyses include assessments of reports issued by the DOE and its contractors and other federal agencies and organizations as they relate to the potential health, safety, and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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EXECUTIVE SUMMARY

Introduction

The sensitivity of the performance assessment calculations in the Department of Energy's (DOE) Waste Isolation Pilot Plant (WIPP) Compliance Certification Application (CCA) (U.S. DOE 1996) was first investigated by Helton (1996) in order to understand the impact of several key parameters. His analysis used scatter plots and stepwise correlations to determine consistency among repository parameters. However, his analysis only applied to the actual range and distributions of sampled parameters used in the CCA calculations. Changes to either the range or distribution of one parameter may strongly affect the importance of other parameters, because estimates of releases vary by orders of magnitude for different combinations of parameter values. A case in point is the brine reservoir compressibility, which has been determined to have insignificant influence on the total release. The values chosen for brine reservoir pressure and volume used in the CCA calculations reduced the importance of the brine reservoir on the calculated releases, therefore eliminating the compressibility. It is entirely possible that this brine reservoir parameter would be one of the most important contributors to large releases in calculations using more appropriate brine reservoir parameter values of pressure and volume.

The scope of the sensitivity analysis performed by Helton (1996) prompted the Environmental Evaluation Group (EEG) to conduct an independent analysis, by changing selected values or the range of selected values that were used in the CCA. This type of sensitivity analysis would distinguish the important parameters of repository performance, while testing the robustness of the codes involved. The analysis also allowed for the testing of the limit to which the disposal system would fail under extreme conditions. This is also useful in characterizing the important parameters.

Borehole Intrusion Rate

The consequence of future human intrusion scenarios into the WIPP was investigated in the CCA, as required by EPA in 40 CFR Part 194 (U.S. EPA 1996b), and included the possibility of mining and deep and shallow drilling for resources.

The 40 CFR Part 194.33 criteria state that the likelihood of a drilling intrusion into the Delaware Basin be calculated by considering the frequency of drilling over the past 100 years for all resources and that rate be used for the 10,000 year future of the WIPP. A total of 46.8 boreholes per km^2 per 10,000 years were estimated based on past drilling of resources at depths greater than 655 meters (2150 feet), which equal 10,804 boreholes per century in 23,102.1 km^2 (area of Delaware Basin).

The above drill intrusion rate for the 10,000 year future of the WIPP was used by DOE in the CCDFGF model. Due to the uncertainty in predicting future human activities, the effect of altering this rate on the CCA calculations has been assessed in this report.

The modeling associated with an increased borehole rate shows that a factor of approximately 23 is needed to reach the U.S. Environmental Protection Agency (EPA) release limit at a probability of 10^{-1} from values used in the CCA. The overall mean for the highest release tested at 0.468 boreholes/km^2/yr exceeds 10 EPA Unit limit at the 10^{-3} probability on the CCDF curve. This high rate of bore hole intrusion, however, does not seem to be likely, as the number of boreholes drilled in the Basin in 10,000 years would have to exceed one million per century, or 4,680 boreholes per km^2 per 10^4 years.

Probability of Brine Encounter at WIPP

The probability of encountering brine at the WIPP from an intrusion into a Castile brine reservoir is uncertain. The parameter describing the probability was set to 8% in the CCA, and changed to a range of probabilities from 1% to 60% in the EPA's Performance Assessment Verification Test (PAVT). Since the extent of the reservoir beneath the WIPP is unknown, the influence of this parameter was tested at higher values at 50% and 100%. These values were based on the potential that the Castile brine reservoir encountered by WIPP-12 (Chaturvedi et al. 1997) extends below the waste area.

The modeling presented in this report only compared CCA release values to the proposed higher probability of encounter, and found the parameter to be unimportant in the CCA. The increase in releases from the 8% to 100% was only 0.1 EPA units (35 Ci). However, the synergistic effect of changing multiple parameters, especially those that affect a Castile brine reservoir directly (pressure, volume, rock compressibility, etc.) may have a more profound result on the calculations, though these changes would have to result in releases of at least 1 EPA unit to significantly impact the CCDFs.

Castile Brine Reservoir Parameters

A pressurized Castile brine reservoir that may underly the WIPP has been the subject of many controversies on its extent and importance (EEG 1997b; EEG 1997d; Silva 1994; U.S. DOE 1997a; Beauheim 1997). The scientists who conducted the performance assessment calculations of the CCA recognized the fact that the brine could play a significant role in the degradation of wastes and waste containers, if an inadvertent drilling intrusion were to pass through the repository to the brine pockets below, by assigning two of the six scenarios to

calculate the effects of the breach. However, reservoir parameters used in the CCA were derived from borehole information that are mainly outside the domain of the WIPP repository. The borehole distances ranged from 3.75 miles to over 11 miles from the repository center. New values were assigned to several parameters that describe a Castile brine reservoir based on WIPP-12 data that is more closely identified to the conditions at the repository. The WIPP-12 borehole was originally drilled in 1978 and deepened in 1981. After brine was encountered at WIPP-12, EEG recommended that the site be relocated to the south and DOE concurred. Brine flow occurred when coring reached a depth of 3012 feet (D'Appolonia 1982). While extending the borehole to depths greater than 3900 feet, a total of 80,000 barrels were allowed to flow from the borehole.

The parameters associated with describing a Castile brine reservoir include reservoir volume, rock compressibility, reservoir pressure, and permeability. Assuming an inadvertant human intrusion, modeling of these parameters began with the two-phase flow code, BRAGFLO, and ended with calculations of solid and liquid waste released to the accessible environment. The outcome showed that there is no significant change in releases for the CCDF due to small changes in the reservoir parameters. However, it is expected that the CCDF curve would move closer to the EPA limit if the solubility of actinides in brine were increased above that assumed in the CCA and PAVT.

Solubility Modeling of Actinides

For brine to escape the repository and travel upwards through the borehole under blowout conditions, 1) pressures must be significant to overcome the hydrostatic force of the drilling fluid, and 2) sufficient brine must be available for transport. Both conditions have been met in many of the realizations in the performance assessment calculations of the CCA. However, due to the proposed low solubility of actinides in brine, the consequence of a direct release of brine to the surface was minimal. For example, the mean release of radionuclides in the CCA through a direct brine release was 0.04 EPA Units (14 Ci) at the 10^{-3} probability, compared to spallings or cuttings and cavings, each having releases of 0.2 EPA Units (70 Ci).

The physical and chemical characteristics of the repository used in the CCA were questioned by the EPA. The EPA changed several disposal system parameters to test their range of uncertainty. Using EPA's values, DOE reran the calculations for the Performance Assessment Verification Test (PAVT). Some of the changes involved the solubility of the actinides in a brine solution assuming a different speciation of minerals associated with the MgO backfill material, which lowered the median solubility limit for most actinides. The new set of solubility values came from the same FMT code used to establish the original set of numbers. No new

experiments were conducted to verify any of the values.

The results of the PAVT showed a large overall increase in the amount of brine brought to the surface upon intrusion, yet only nominal increase in release of actinides. This was expected, since the median solubilities decreased by as much as 2 orders of magnitude for the +4 radionuclides. The effect on compliance from the changes shifted the CCDF for the direct brine release scenario closer to the compliance limit by 0.15 EPA Units. The changes in consequence are minimal, since 10 EPA Units of release are needed to fail compliance at the 10^{-3} probability.

Based on the observations of Reed et al. (1994; 1996) and Rao (1996), EEG questioned the CCA assumption that plutonium would exist only in +3 and +4 oxidation states. Hence, EEG conducted bounding calculations on solubility. The solubility values were only nominal increases above the CCA values for plutonium in the +3 or +4 oxidation state for Salado Brine, but upwards of 10000 for Castile Brine.

The results of the EEG modeling showed that increases in solubility using CCA brine release volumes had limited effect on compliance with an overall increase on the mean CCDFs by 0.09 EPA Units. Even when the solubility was increased to absurdly high values, the maximum release was limited by the availability of the actinide source. At a solubility of 8×10^{-3} M (compared to the CCA's 4.4×10^{-6} M for Pu+4 in Salado Brine), the overall mean for direct brine release was increased from 0.04 to 1.3 EPA Units.

The second set of EEG modeling experiments changed the solubilities of actinides in several mineral species of MgO between the conversion of brucite to magnesite. Calculations by Novak (1997) estimated solubility values for the major oxidation states (III, IV, V, and VI) at WIPP in the presence of magnesite, nesquehonite, hydromagnesite, and no backfill. The release calculations of the CCA assumed the long-term mineral species for MgO to be magnesite, and the PAVT assumed hydromagnesite. Yet, laboratory experiments could not prove the existence of either, and only showed hydromagnesite-like or proto hydromagnesite (Papenguth et al. 1997). These other mineral species looked more like nesquehonite (Neill et al. 1998), making it arduous to justify either mineral phase assumed by the DOE and EPA.

Bounding calculations were performed on conditions resulting in the highest solubilities in the repository. These included nesquehonite and no backfill. For the nesquehonite simulations, it was assumed that the mineral would persist for the entire proposed history of the repository. Only median solubility values were used, as opposed to the CCA, which generated a set of expected values from a range of -2 to +1.4 orders of magnitude from the median to capture the

uncertainty. The assumption that the intermediate species being long-lived is an overestimate on the expected conditions, and the EEG does not suggest that MgO not be used as a backfill material. The models were established to better understand the performance of the repository.

Table Ex-1 shows the solubility factors used to achieve solubility values from Novak (1997). The values have been log transformed for use in the input files to change the values that were established in the CCA. For example, SOLAM3-SOLCIM for nesquehonite increases the solubility of Am+3 in Castile Brine by 1.516 orders of magnitude, whereas SOLAM3-SOLSIM decreases the solubility by 0.277 orders of magnitude. The changes were made in the source term files, for the running of PANEL and NUTS.

In addition to solubility changes from the CCA, the Salado flow files from the PAVT were used for transport calculations of NUTS and PANEL. The PAVT calculations exhibited higher repository pressures, hence larger direct brine releases upon intrusion. The maximum effect would be noticed with both changes together.

Table Ex-1 shows that the solubility of the +4 actinides (Pu+4, U+4, and Th+4) in the presence of nesquehonite is higher than without any MgO backfill. This would suggest that the scenario with backfill has larger releases than without.

Figure Ex-1 shows the overall mean of all processes combined as they relate to compliance. In addition, the PAVT direct brine releases were run with the slightly higher CCA solubilities. The most distinct feature of the figure is the shoulder of the high solubility models that extend below the 10^{-1} probability limit. The “shouldering” is the effect of increased releases due to the direct brine release. Since the Pu+4 and Th+4 (although minor) solubilities increased over 5 orders of magnitude, the release due to this mechanism is expected to increase significantly as well. For example, the CCA median value for +4 actinide solubilities in Castile brine was $6x10^{-9}$ M. If one assumes 100 m^3 of Pu^{239} contaminated brine, then it is expected that the release is $2.5x10^{-5}$ EPA Units. If the solubility is increased by $10^{5.23}$ as seen in Table Ex-1, then it is expected that 4.24

	nesquehonite		No Backfill	
	SOLCIM	SOLSIM	SOLCIM	SOLSIM
SOLAM3	1.51616	-.27709	4.48678	3.83714
SOLPU3	1.51616	-.27709	4.48678	3.83714
SOLPU4	5.23242	2.15588	4.06695	2.05552
SOLU4	N/A	2.15588	N/A	2.05552
SOLU6	0.95861	0.96357	0.95861	0.96357
SOLTH4	5.23242	2.15588	4.06695	2.05552

Table Ex-1. Solubility Factors for SOLCIM and SOLSIM

EPA Units are released to the accessible environment. Therefore, the CCDF for higher solubilities would be closer to the EPA limit.

The consequences of higher solubilities, as seen in Figure Ex-1 are quite high. The overall mean release for the CCA and PAVT were 0.2 and 0.4 EPA Units at 10^{-3} probability, respectively. The overall mean for the increased solubilities of nesquehonite and 'no backfill' are 6.0 and 8.0 EPA Units at the 10^{-3} probability, respectively. The limit for compliance, according to 40 CFR Part 194 is 10 EPA Units. While these calculations, based on DOE's own solubility values, do not violate the containment requirements, they show that there is little margin for error.

Flow and Transport Modeling within the Culebra

The transport of radionuclides to the accessible environment can happen two ways: upwards from the repository through a borehole to the surface into the biosphere, or laterally through the stratigraphy of highly conductive layers across the Land Withdrawal Boundary (LWB). The second method was investigated by modeling the Culebra aquifer. The CCA and PAVT include Culebra modeling and its consequence of transport across the LWB in the CCDF curves. The CCA showed only 1 of 300 realizations to cross the boundary in 10000 years with the PAVT showing a significantly higher impact on the Culebra. The end result of increased transport across the LWB in the PAVT had little to no overall effect on the CCDF.

The EEG's concern in the Culebra modeling began with the parameter assumptions that describe actinide behavior with the Culebra Dolomite. When the actinides migrate along flow paths after a release to the Culebra, the transport will be retarded by the interaction of the actinides with the Culebra dolomite matrix. The interaction is known as sorption. The Culebra was characterized as having a linear isotherm with the actinides, and the parameters of the isotherm, known as the partition or distribution coefficient (K_d) were measured or inferred from laboratory experiments.

The same oxidation state analogy used for solubility was applied to the distribution coefficient; same oxidation states would exhibit similar values. Therefore, many of the actinides' K_ds were not actually measured and it is not clear what the consequence would have been with directly measured values. Though it is well known that high K_d values will retard the actinide species sufficiently to inhibit transport, it is the low K_d values that are of concern. For example, it was shown in Blaine (1997) that K_d values higher than 3 ml/g for most actinides would sufficiently retard transport. Only one actinide in the PAVT, U+6, has K_d values as low as 2 ml/g.

Some waste constituents in the inventory at WIPP may bind to the actinides and further lower

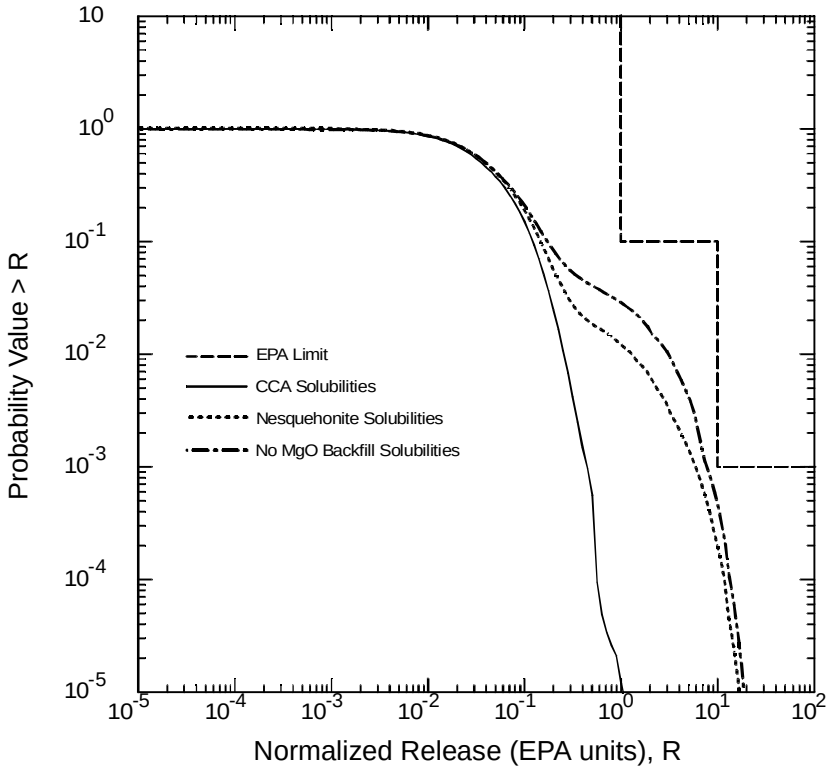

Figure Ex-1. Overall Mean of Normalized Releases for Modeling of Increased Solubilities using Nesquehonite and 'No Backfill' Values Compared to CCA Values

the K_d values. EDTA, for example, is used in industry for chelation with plutonium for quick cleanup. Other organic ligands in the waste will have similar effect. Furthermore, the lack of K_d measurements decrease the confidence in values used in the CCA and PAVT, and this prompted the EEG to continue with additional calculations, testing the effects of lowered K_ds on the disposal system and compliance.

The interaction between releases from the repository and transport of actinides require a lengthy discussion, and will not be discussed here. It is possible, due to the set up of the codes, to do calculations that assume any percentage of the actinide's mass to completely bind with EDTA and migrate unretarded through the Culebra matrix. Therefore, additional calculations were performed assuming 1% of Pu (+3 and +4) having a K_d=0 ml/g.

The results of the calculations show that the overall mean of the releases through the Culebra was 0.0001 EPA Units at the 10^{-3} probability. Since a large number of realizations crossed the LWB with significant releases, it was reasoned that the mass of radionuclides reaching the Culebra was the limiting factor. This was proved when the models of higher solubility were combined with transport modeling, and the overall mean for release from the Culebra was

increased to 0.31 EPA Units.

Another model was proposed by EEG in which the extent of potash mining within the controlled area (or Land Withdrawal Area-LWA) was extended to include lower grade potash ore. Potash mining occurs in the McNutt Potash Zone of the Salado, and is several hundred feet below the Culebra. The effect of potash mining in the Delaware Basin would cause subsidence to the overlying units, and hence have a possible detrimental consequence from increased transport of radionuclides. The EPA established the criteria for the mining by assigning a multiplying factor to the transmissivities of the Culebra, which increased the velocities in the mined region.

The extent of mining in the long-term future is debatable, depending on assumed future economic viability of the resource. New methods such as solution mining could extract lower grade minerals more readily. Therefore, the EEG included a larger area of potential mining in a new flow model, yet keeping the same parameter changes that were used in the CCA. It is feasible to change other parameters or include new ones, but due to the limited time available, was not thoroughly investigated.

The results of extending the areal minable region below the Culebra had little to no effect on the transport of radionuclides across the LWB, though it did change the flow patterns slightly. The limit of transport is sorption, and the PAVT values for K_d were retained for uranium. The combination of low K_d and larger mining area was studied with plutonium, again using the 1% K_d=0 ml/g. Again, the amount of initial mass injected to the Culebra crossing the LWB was significantly higher, but limited by the amount reaching the Culebra.

Lastly, the effects of extended mining, low K_ds, and high solubilities were combined in an effort to test the synergistic effect of all the previous results. The overall mean for the release through the Culebra was as high as 1 EPA Unit (or 344 Ci) at a 10^{-3} probability of release. The addition of the Culebra releases to the overall mean of all combined releases moved the CCDF closer to the EPA compliance limit by 12%, but did not show non-compliance.

SENSITIVITY ANALYSIS OF PERFORMANCE PARAMETERS USED IN MODELING THE WIPP

1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is intended to be the first repository for the permanent disposal of defense generated transuranic (TRU) wastes. The WIPP is located in southeastern New Mexico, 655 meters below the surface in the Salado Formation. The containment of transuranic wastes in the ancient salt beds of the Salado *"will result in extremely effective isolation of the radioactive waste"* if the repository is to remain undisturbed for 10,000 years (U.S. DOE 1996). Modeling of this undisturbed scenario encompasses the natural processes such as the salt creep closure of the excavated repository and disturbed rock zones (DRZ) which surround the repository, brine flow into the repository from under- and over-lying formations, and gas generated through degradation of waste and waste containers. The performance assessment of the repository was also required by 40 CFR Part 191 Subpart B (U.S. EPA 1996a) to consider disturbed scenarios by which a breach may occur through inadvertent drilling for resources. The release of radionuclides to the accessible environment during the 10,000 year future of the repository must be quantified to ensure compliance with the requirements stated in 40 CFR Part 191.13 (Containment Requirements). The accessible environment refers to everywhere beyond the controlled boundary, including land, air, and water. The cumulative radionuclide release through a probabilistic performance assessment must fall below specified limits within the time frame designed for containment. The estimate of probabilistic releases through these scenarios was calculated using computer codes designed specifically for the flow and transport of radionuclides through the formations that overlie the WIPP, as well as direct releases to the surface.

1.1. Performance Assessment

The estimated releases from the performance assessment for WIPP were incorporated into probability distributions. One of the requirements used to judge satisfactory performance of the repository is to demonstrate that the calculated releases have a likelihood of less than 1 in 10 to exceed the quantities listed in Table 1.1 (U.S. EPA 1996a), and less than 1 in 1,000 to exceed ten times the quantities in Table 1.1. A performance assessment refers to an analysis that *(1) identifies the process and events that might affect the disposal system, (2) examines the effects of the processes and events on the performance of the system, and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant process and events* (U.S. EPA 1996). In addition to the performance assessment of the disposal

Radionuclide	Release (curies) per million curies of alpha-emmiting radionuclides
Americium-241, -243	100
Carbon-14	100
Cesium-135, -137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, -239, -240, -242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230, -232	10
Tin-126	1,000
Uranium-233, -234, -235, -236, -238	100
Other α-emitting radionuclides, half-life > 20 years	100
Other α-emitting radionuclides, half-life < 20 years	1,000

Table 1.1. Release Limits as Stated in 40 CFR Part 191, Subpart B

system, certain assurance requirements were necessary to provide confidence that the containment of TRU wastes will be maintained for 10,000 years as stated in CFR 40 Part 191.13. For example, active institutional controls (AICs) should be exercised for as long as possible after disposal. Active institutional control simply means the maintenance of the site, remediation or cleanup of a release, and monitoring after closure of the repository. These controls can be assessed up to 100 years after disposal, after which passive institutional controls (PICs) will proceed that include markers, public records, and other methods to preserve the knowledge of the dangers of the wastes contained below. Although AICs and PICs are considered part of the assurance requirements, they were included in the containment calculations.

The performance assessment calculations were submitted to the EPA in October 1996 in the form of a Compliance Certification Application (CCA). The CCA was compiled from many years of scientific and engineering investigations, and consists of nine chapters with 58 supporting appendices that reference over 600 professional publications. The CCA also describes the DOE Quality Assurance Program and the results of independent peer reviews.

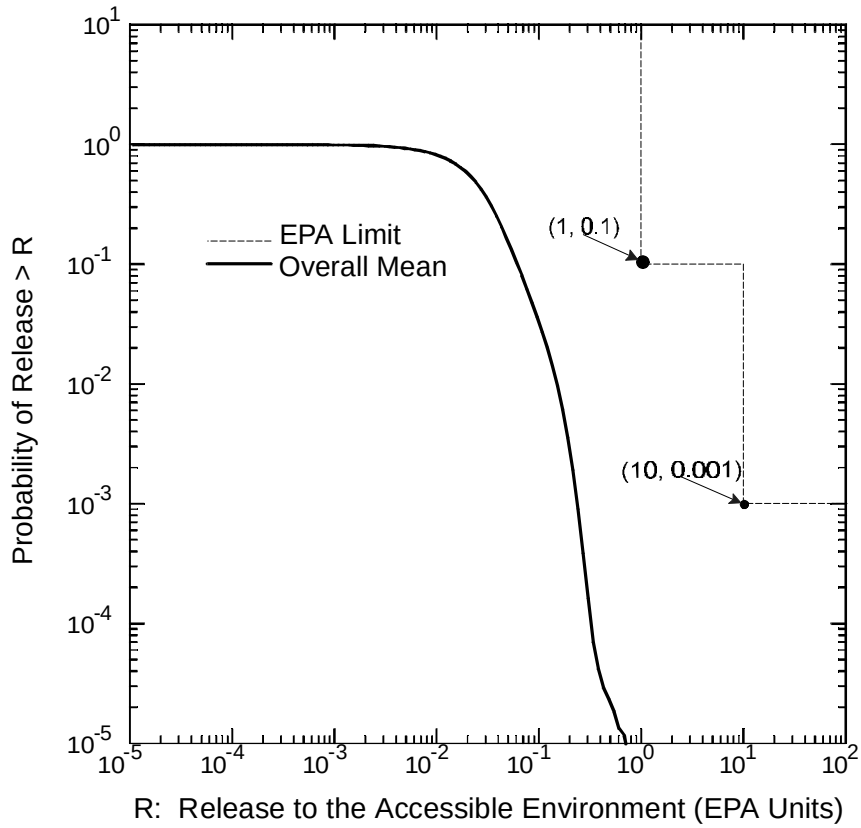

Figure 1.1. DOE's CCDF of Normalized Releases, Showing Overall Mean for all Release Types

The quantitative results from the performance assessment, shown in the CCA, are presented as complementary cumulative distribution functions (CCDFs). To facilitate comparison with 40 CFR Part 191.13, the CCDFs are plotted on a log scale with a probability-of-releases greater than the abscissa value on the ordinate axis, and release to the accessible environment in EPA units on the abscissa. Figure 1.1. shows an example of a constructed CCDF from the performance assessment of the CCA. The curve is an overall mean for all types of releases to the accessible boundary that can occur. A list of these release types are mentioned in the subsequent chapters. The EPA requirements for release, as stated in 40 CFR Part 191, are shown as points.,which are the allowable cumulative releases for two probabilities.

The term 'EPA Unit' is used to describe the amount of release compared to the total allowable release limit from Table 1.1. multiplied by a waste unit factor. The waste unit factor is defined as the number of α-emitting TRU radionuclides with half-lives larger than 20 years in millions of curies (U.S. DOE 1996). An estimated 3.44 million curies of waste will be disposed at the WIPP, equating to a waste unit factor of 3.44. The total number of curies allowed to be released for any

one radionuclide is 3.44 multiplied by 100. Therefore, the total number of EPA units of amercium-241 is 1420, assuming an inventory of 4.88 x 10^5 curies postclosure. The sum of releases in EPA units is expressed by

$$R_j = \left(\frac{1}{f_w} \right) \sum_{i=1}^{n} \frac{Q_{ij}}{L_i}$$

where R_j is the release under scenario j, f_w is the waste unit factor, Q_{ij} is the cumulative release for radionuclide i under scenario j for n scenarios, and L_i is the EPA release limits from Table 1.1.

1.2. Repository Design and Site Characterization

The repository was designed to limit the quatity of TRU wastes from being released to the accessible environment. Long term disposal requires many barriers between the repository and environment, including both natural and engineered. The placement of the repository in the Salado Formation halite is one barrier that is very crucial to containment. The halite beds are stable and exhibit many desirable qualities for encapsulating the buried waste.

The Salado Formation is bound by the Rustler Formation above, and the Castile Formation below. The stratigraphical cross section of the area can be seen in Figure 1.2. The figure is a southwest to northeast cut through the geologic profile and shows the formations associated with the Ochoan series. The Castile is bound on the bottom by the Bell Canyon Formation, which is the first laterally transmissive unit underlying the WIPP. However, for performance assessment calculations, the Bell Canyon was omitted.

1.2.1. Castile Formation

The Castile Formation is 425 to 490 meters thick consisting of alternating beds of anhydrite and halite. Pressurized brine occurs in discrete pockets of the upper anhydrite layer. Several exploratory boreholes in the vicinity of the WIPP site have encountered these pressurized brine reservoirs. More than 12720 m^3 of brine flowed out during deepening of the WIPP-12 borehole 1 km north of the WIPP in 1981 (D'Applonnia 1983). Hydrologic tests estimated the size of the reservoir to be 2.7x10^6 m^3. Using a rock compressibility of 10^{-10} Pa^{-1} , porosity of 0.008, and a reservoir thickness of 24 meters, the diameter of an assumed cylindrical reservoir encountered by WIPP-12 would be 4 km.

1.2.2. Salado Formation

The Salado is the most important geological unit in the disposal system, since the repository is in this formation, and represents the primary natural barriers needed to contain the waste. The Salado is divided into three informal members: the upper, the McNutt Potash Zone and the lower. The thickness of the Salado ranges from a few meters in the eastern part of the Delaware Basin to over 600 meters at the WIPP site. Though the Salado deposits are mainly halite, sulfate minerals form many interbeds in the formation, with the most common being anhydrite, polyhalite, and gypsum. The anhydrite layers are commonly referred to as markerbeds and are numbered sequentially from top to bottom 101 through 144 (MB101 - MB 144). The repository is

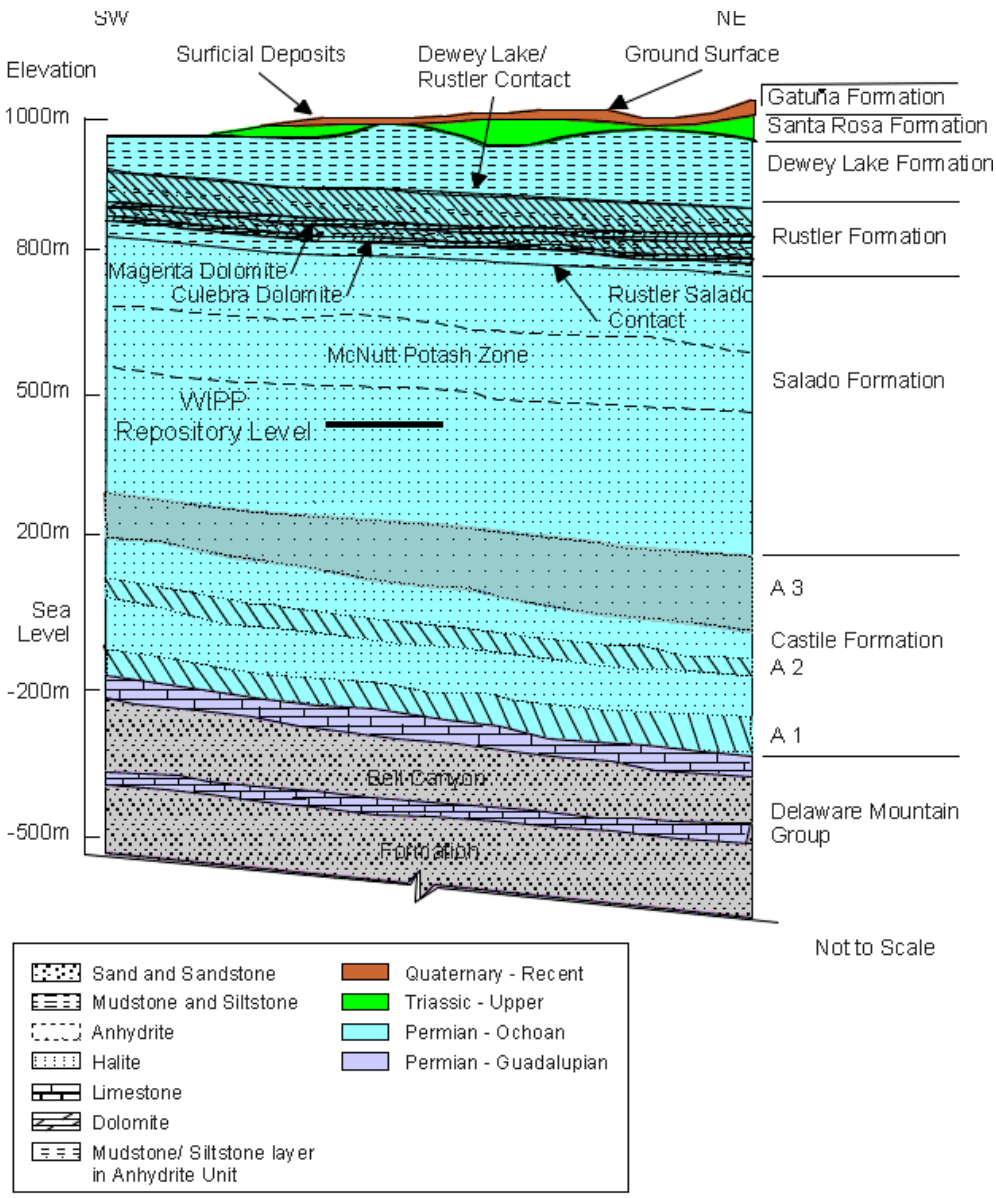

Figure 1.2. Stratigraphic Cross Section of Geologic Region around WIPP (U.S.DOE 1996)

located between MB138 and MB139.

1.2.3. Rustler Formation

The Rustler Formation contains a wide variety of different types of deposits, including anhydrite, halite, carbonate, dolomite, mudstone, and sandstone. Though not as thick as the members below, the Rustler Formation is far more extensive in area. Its thickness ranges between 90 to 107 meters at the WIPP site.

Within the Rustler lies the Culebra Dolomite member, the most hydrologically transmissive unit. It is believed that this member can transport a radionuclide release to the accessible environment in a relatively short period of time upon breaching the repository. The fractured Culebra dolomite aquifer is approximately 11 meters thick at its maximum with a transmissivity up to 10^{-3} m^2/s. The minimum values for thickness and transmissivity are 4 meters and 10^{-9} m^2/s, respectively. The hydraulic head in the aquifer ranges from approximately 950 m in the north to less than 900 m in the south, showing a general north to south flow. Tracer tests show that solute travel is mainly through fractures and interconnected vugs, but can also diffuse into the dolomite matrix (U.S. DOE 1996).

Above the Culebra Dolomite lies the Tamarisk, Magenta Dolomite, and Forty-niner Members of the Rustler Formation. The Tamarisk and Forty-niner members vary significantly in composition and are much thicker than the Culebra, ranging from 26 to 56 meters and 13 to 24 meters, respectively (LaVenue et al. 1990). The Magenta Dolomite varies from 7 to 8.5 meters in thickness, is primarily composed of gyspiferous dolomite, and is also an aquifer, but less transmissive than the Culebra.

1.2.4. Dewey Lake Redbeds, Santa Rosa, and Gatuna Formations

Moving upward in stratigraphic sequence at WIPP, the Dewey Lake Redbeds lie directly above the Rustler. The Dewey Lake Formation is mainly sandstone, siltstone, and claystone. Analysis of the Dewey Lake shows that it is not hydrologically connected to the Rustler, but may actually have lateral water movement (U.S. DOE 1996).

The Santa Rosa and Gutuna Formations lie directly above the Dewey Lake, and are the closest formations to the surface at the WIPP site.

1.2.5. The Repository

The repository was designed to dispose approximately 176,000 m^3 ($6.2x10^6$ ft^3) of CH-TRU (contact handled) waste and RH-TRU (remote handled), of which no more than 7080 m^3 ($2.5x10^5$ ft^3) can be of RH-TRU waste (U.S. Congress 1992; Silva 1994; U.S. DOE 1990). The waste contains organics such as rubber, plastic, and cloth; metals; and waste sludge. The CH-TRU waste is stored in 55-gallon drums and will be stacked three-high in rooms that are 300 feet long, 33 feet wide, and 13 feet high. The RH-TRU waste containers are 26 inches in diameter and 121 inches long, and will be placed in horizontal holes in the walls of the waste panel rooms.

The rooms are separated by 100 foot thick pillars. The repository consists of eight waste panels with seven rooms in each panel. The waste panels are separated by 60 meters (200 feet) of intact rock. Each room will contain approximately 6000 drums of CH-TRU waste and 50 canisters of RH-TRU waste.

Figure 1.3. shows the configuration of the three main area of the repository: experimental area, operations region, and waste disposal region. The experimental region was used as an area to perform geotechnical evaluations, which consisted of rock mechanics tests, waste package experiments, and brine migration tests. The operations region contains the passages to connect the surface to the waste disposal area. There are four shafts in this area: the waste handling shaft for the transport of personnel and waste to the subsurface, the air intake and exhaust shafts allowing fresh air to the underground and exhaust to leave, and the salt handling shaft for the removal of mined salt.

The waste disposal area contains the eight panels for waste storage. The main north-south and east-west access drifts in this area will also house waste after the main panels are filled and are called panels 9 and 10. The disposal area will be sealed after all panels are filled.

1.2.5.1. Room Collapse and Post Closure

Once eachpanel has been filled, they will be sealed to prevent the escape of actinides when the drums begin to fail from the pressures exerted by salt creep from the ceiling, floor and walls. The salt creep will consolidate the drums, producing stress fractures that will ultimately cause the waste to spill out. However, one of the main reasons for chosing salt for disposal was its mechanical response to the overpressures of the rock above. The salt will encapsulate the waste, creating a natural barrier.

The closure process of the salt begins as soon as the rooms are excavated and continues until an equilibrium state of the rock and the waste are reached (Butcher 1997). At equilibrium, the salt deformation ceases, and the waste in the room has undergone all possible compaction. The measure of compaction in the repository is the amount of change in pore volume of the waste, which continues to decrease under pressure. However, it is not likely that the salt surrounding the repository will ever come to a pure equilibrium with the waste. The waste changes form continuously throughout most of the initial time history of the repository and gases are progressively generated from degrading waste. During the time of degrading waste, the repository is expected to make minor readjustments. Waste rooms will continue to deform until all stress gradients vanish.

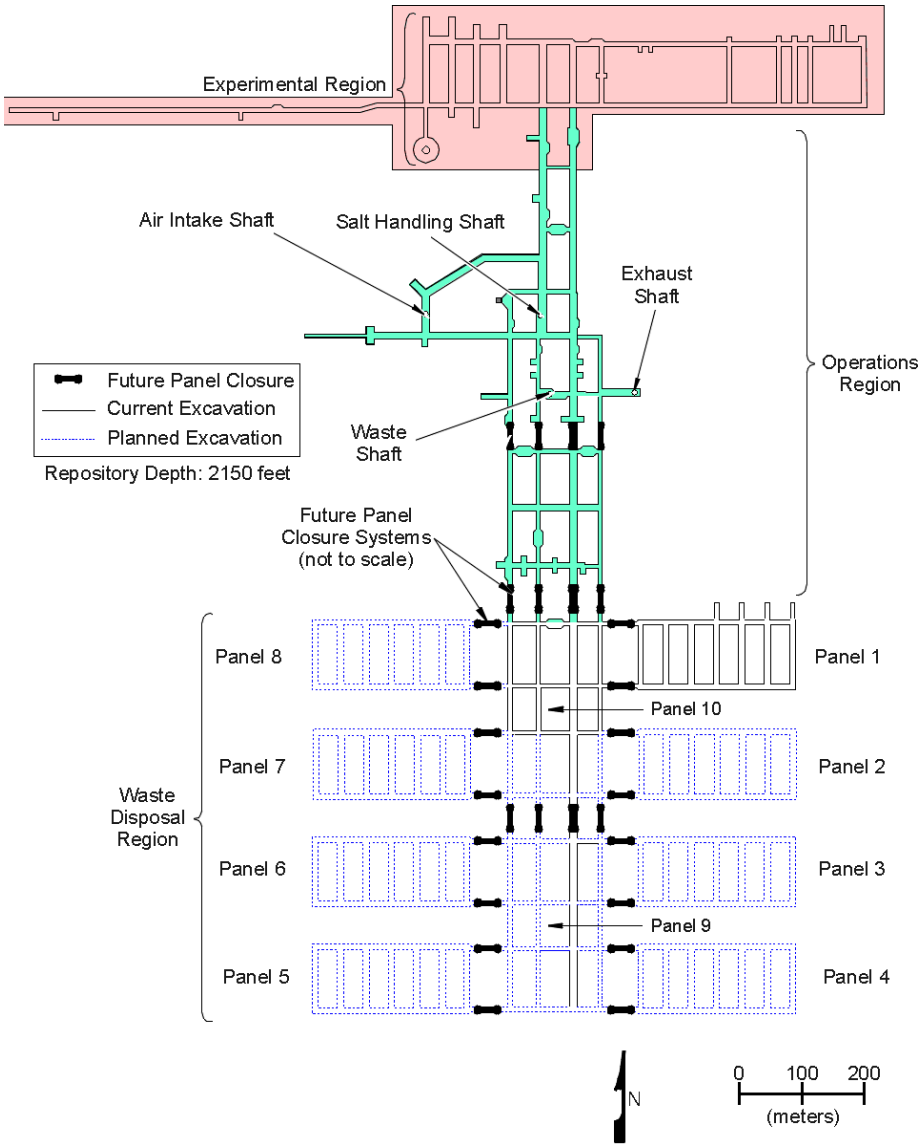

Figure 1.3. Areal View of the Underground WIPP Facility (U.S. DOE 1996)

A computer model was developed (Butcher 1997) to estimate the compaction and decrease in the pore volume of the compacted waste. The initial room height is approxiamtely 4 meters. The drums, stacked three high will be approximately 2.7 meters, leaving 1.3 meters of air space above for the placement of backfill. After consolidation, the room heights will be compacted to roughly 2 meters, and porosity of the waste will decrease from an average of 0.7 to ~0.25.

1.2.5.2. Gas Generation and Waste Backfill

Before sealing, the panel rooms will be backfilled with a buffer to reduce the amount of gas generated from degrading organic material. Several backfill materials have been considered, including bentonite clay, CaO, and MgO. MgO was selected as the backfill material based on its postulated benefits to increase the pH of the repository, which decreases the solubility of the actinides in brine. The cemented MgO, called Sorel cement, will also strengthen the repository waste.

The generation of gases in the repository, if produced in significant quantities, may affect the performance of the WIPP. An increase in CO_2, for example, will decrease pH and increase the solubility of the actinides in brine. The corrosion of metals and microbial activity are seen as the major contributors of gas generation in the disposal system. A minor source of gas is the radiolysis of water, but is much less a contributor than corrosion or degradation.

The oxic corrosion of metals (iron, aluminum, aluminum-based alloys, and lead) will deplete the rooms of O_2 and water, thus allowing anoxic corrosion to produce large amounts of H_2. The anoxic corrosion process will consume a large amount of water, depleting brine availability for other processes, such as chemical degradation or physical blowout. The rate of corrosion for metals is dependent on the pressures and quantities of CO_2, H_2S, N_2, and other gases (Telander and Westerman 1996) and is said to vary from 0 to 1.587×10^{-14} m of steel per second in the CCA. The values assume no CO_2 present.

Microbial activity from the degradation of cellulosics, plastics, and rubbers will consume O_2 and produce CO_2, N_2O, N_2, H_2S, H_2, and CH_4 (Brush 1995). The generation of H_2S is important to corrosion, and experiments have found that steel corrosion will almost cease in H_2S overpressures, and that Al corrosion was relatively high (Telander and Westerman 1996). The formation of CO_2 from microbial denitrification, sulfate reduction, and methogenesis will decrease the pH, increasing the solubility of the actinides in brine solution. A low pH, with values <6, has been shown to have the highest solubilities, decreasing as pH increases until the pH

reaches 10. When pH is greater than 10, the solubilities are anticipated to increase (U.S. DOE 1996).

The MgO backfill will react with the brine to produce brucite ($Mg(OH)_2$). Brucite will then react with the CO_2 to produce magnesite ($Mg(CO_3)$), or any mineral species of magnesite (nesquehonite and hydromagnesite). One mole of MgO will react with one mole of water and one mole of carbon dioxide to produce one mole of magnesite. Thus, the one-to-one relationship of carbon dioxide and MgO consumption is important in respect to the amount of MgO needed as backfill to consume the CO_2. The CCA estimates that a maximum 1.4×10^9 moles of gas will be generated and the DOE has therefore planned to emplace 1.875×10^9 moles of MgO (83,150 tons) in the repository.

The effectiveness of the MgO to mix completely with the CO_2 has invited much debate, and even DOE's own Peer Review Group reassembled on three separate occasions to examine further evidence. Their final report on the subject can be found in Wilson et al. (1997). The EEG also outlined a number of concerns (Neill et al. 1998), including the exact mineral phases of the MgO species that will persist as it forms complex minerals with carbonate.

1.2.5.3. Panel Closure

Figure 1.3. shows the location of plugs for each panel access drifts. The intent of the barriers was not to aid in long term repository performance, but to prevent potentially high levels of unacceptable volatile organic waste from seeping into the operations area (U.S. DOE 1996). The closure system design allows for a two layer protection scheme, which consists of an explosion- (or construction-) isolation wall and a concrete barrier. These barriers are separated by 20 feet of space called the isolation zone.

1.2.5.4. Shaft Seals

The four shafts in the operations region of the repository will be sealed after the decommissioning of the WIPP repository. The sealing allows for additional barriers of isolation from the accessible environment, and are not technically "engineered barriers", since they represent an effort to fix the damage to the natural barriers. The seal will consist of 13 elements, layered throughout the shaft length with the purpose to limit fluid flow in the column with high density/low permeability materials (Sandia 1996). Figure 1.4. shows the layout of the shaft seal system. Some materials that will fill the shaft include: concrete, clay, salt, asphalt, earthen fill, and cementitious grout. The performance assessment calculations included degradation of the materials in the shaft over time.

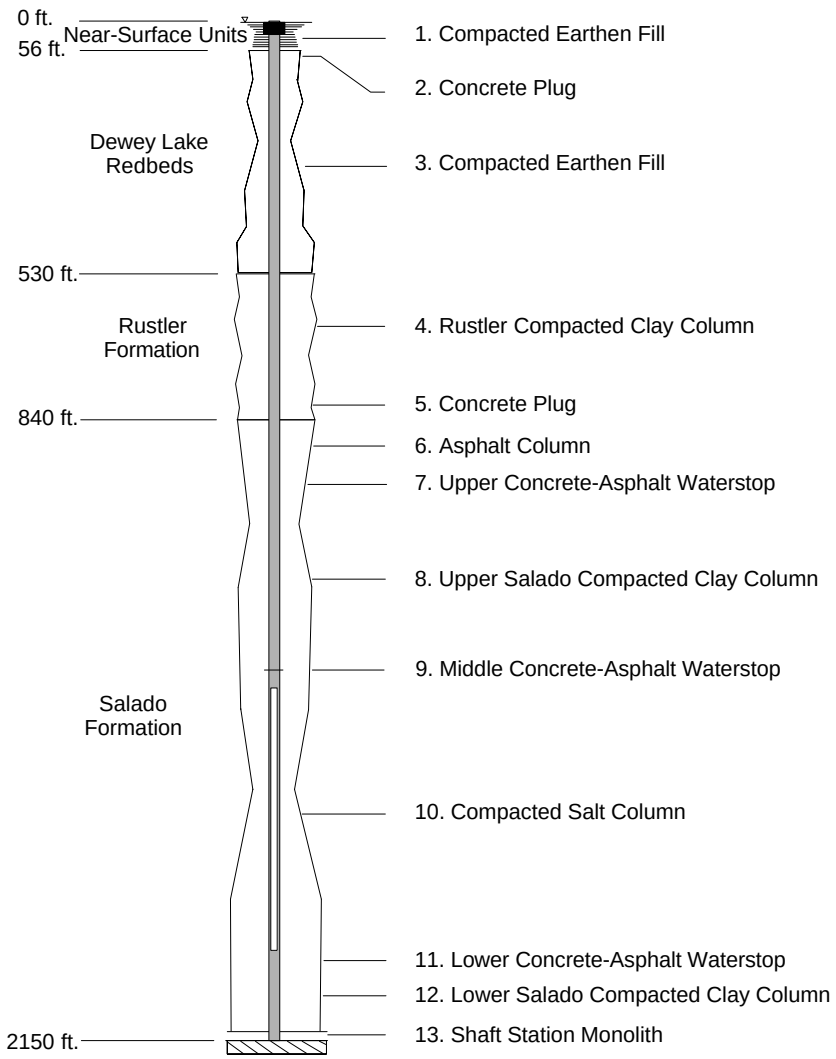

Figure 1.4. Shaft Seal System at the WIPP (Modeled after Figure 4.1 of Sandia 1996)

1.2.5.5. Borehole Plugs

The last barrier to be implemented in the repository is the plugging of boreholes, which play a role in projected future human intrusion scenarios. The borehole plugs are expected to reduce the amount of water from overlying formations from entering the repository, and the contaminated brine from escaping to the surface. The DOE plans to use mainly cement or grout with mud and clay, compacted to closely match the physical properties of the surrounding rock. The plug will fill the entire length of the borehole casing.

There are several designs being considered for the borehole plug. These consist of a one-, two-, and three-plug configuration. Based on a survey of current plugging practice, the DOE has assigned probabilities for usage to each configuration and these are incorporated into the

probabilistic modeling of future events. The two-plug configuration is the most common type, with the three-plug being less likely, and the single concrete plug being the least likely to be used.

1.2.6. Potential Pathways for Release

Though there are several safeguards to reduce the possibility of release of radionuclides to the accessible environment, it is not totally improbable that the waste may escape from the disposal system. In undisturbed performance, the radionuclides could be transported through fissures and fractures of the weaker anhydrite units above and below the repository. Marker beds 138 and 139 provide potential pathways for escape, especially when the pressures in the repository reach a level, above lithostatic, that will induce further fracturing. Fluid injection in nearby oil/gas wells for the secondary and tertiary recovery of resources may also induce fracturing at WIPP levels, and possibly leak into the repository (Silva 1996; Bredehoeft 1997a,1997b). However, the probability and consequence of fluid injection has yet to be determined as a possible mechanism for release.

Disturbed performance of the disposal system allows several pathways of release upon breach of the repository. If the repository is sufficiently pressurized, then the blowout of solid waste material may entrain radionuclides, and be brought to the surface via the intruding borehole. Also, a breach of the pressurized repository may bring radionuclides dissolved in contaminated brine up to the hydrologically transmissive units above the repository and possibly to the surface. If contaminated brine reaches the Culebra aquifer, radionuclides may be transported to the accessible environment with the groundwater.

1.3 Scope

A basic understanding of the performance assessment (PA) calculations of the CCA is needed to understand much of the work in this report. The report starts with an overview of the PA, repository design, and site characterization of the WIPP disposal system.

Background is provided to allow the reader to move into a detailed description of the PA presented in Chapter 2. The chapter explains the organization of the PA and how the different mechanisms of flow and transport for release scenarios are split into the computer codes. A discussion of the parameters will be followed by an uncertainty analysis description of the PA.

Chapter 3 discusses EEG's outstanding concerns of the calculations performed in the CCA and the parameters used in modeling. The remaining chapters adress the sensitivity of the different parameters. The modeling started simply, investigating less complicated parameters and

models and then moved to more complex scenarios. A summary and conclusion for each model study are presented in the modeling chapters.

2. PERFORMANCE ASSESSMENT REVIEW

To understand the long term behavior characteristics of the disposal system, the probabilities and future occurrences must be determined. A set of scenarios have been analyzed for the potential effect of the repository on the accessible environment. These scenarios have undergone a formal screening by DOE to eliminate features, events, and processes (FEPs) that are unimportant to the performance of the disposal system. The scenarios are based on the FEPs that are predicted to be both potentially likely and have significant consequence, and categorized as having an influence on either the undisturbed or disturbed performance of the repository.

The purpose of FEPs screening is to identify those FEPs that need not be included in the PA calculations based on either low probability, or low consequence, or regulations. A FEP was screened out of inclusion based on probability when it is expected that there is less than one chance in 10,000 that the event or processes will occur in 10,000 years. A FEP may also be excluded if the consequence to the overall calculations of the CCDFs are less than 10^{-4} EPA units. In addition EPA promulgated criteria to allow for certain human initiated events to be eliminated from consideration (tunneling, excavation, deliberate drilling, fluid injection for resource recovery, etc.).

2.1. Scenarios of the Performance Assessment

2.1.1. Undisturbed Performance

Undisturbed performance, as stated in the 40 CFR 191.12, is defined as *"the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events".* The undisturbed scenario forms the base case for PA calculations and includes only natural events and human influences that do not affect the repository directly. Some low probability FEPs that were screened out are regional tectonics, fault movement, seismic activity, and volcanic activity.

2.1.2. Disturbed Performance - Human Intrusion

The disturbed performance of the repository must include human initiated events as stated in the 40 CFR Part 194. However, there are only two disturbed events that were considered for the long term performance of the repository: deep drilling (E), and mining (M) with all others being screened out. The drilling events were subcategorized into two scenarios, one for drilling only into the repository waste panels (E2), and the other for drilling through the waste panel into the

underlying pressurized brine reservoir of the Castile formation (E1). A combination of the two drilling scenarios were also considered, noted as an E1E2 scenario. A third type of drilling, shallow drilling for underground sources of drinking water (E3), was eliminated from the performance assessment calculations based on low probability due to the groundwater being nonpotable in the Culebra Dolomite aquifer.

Mining at the WIPP may occur in combination with drilling (ME1, ME2, ME1E2), potentially producing a more rapid transport to the accessible environment through the Culebra aquifer than drilling alone. The mining for resources, such as potash in the McNutt Potash Zone of the Salado Formation for example, can cause subsidence in layers above the Salado. The subsidence could result in greater fracturing of the Culebra possibly causing faster transport of radionuclides to the accessible environment.

Although the drilling intrusion scenarios were narrowed down to two types, the time at which they can occur during the repository future are too numerous to simulate directly. Over one thousand future drilling times could occur during the life of the repository, requiring unachievable computer time and storage requirements. Therefore, the intrusion times were reduced to two separate times for each of the E1 and E2 intrusion type, and a single, two-time drill intrusion of E1E2 scenario. A total of six scenarios (S1 through S6), including one undisturbed scenario, were created for the performance assessment calculations.

S1 - undisturbed
S2 - E1 at 350 years postclosure
S3 - E1 at 1000 years postclosure
S4 - E2 at 350 years postclosure
S5 - E2 at 1000 years postclosure
S6 - E2 at 800 years followed by an E1 at 2000 years postclosure

The times at which these scenarios occur are mainly used as reference times for additional calculations. The computer models use these reference times to calculate an intermediate step for determining individual futures. The individual futures are then scaled to the 10,000 possible futures during the construction of the CCDFs assuming a linear interpolation between calculated times. However, these interpolations become more complicated as radioactive decay and ingrowth are incorporated into the CCDF. A more detailed description of how the computer models interact and the calculated times for the construction of the CCDFs is described below.

2.1.3. Probabilistic Performance Assessment

The performance of the disposal system was quantified in a probabilistic analysis, in which key parameters for model input were stochastically varied over a wide range of values. The ranges were intended to accomodate the uncertainty in the disposal system and was modeled using codes designed to simulate the transport of radionuclides through the system. The simulations (or realizations) were incorporated into a probabilistic process that determined the average behavior of the repostiory. Monte Carlo analysis is the general name for the technique used for probabilistic analysis of the WIPP.

A Monte Carlo analysis uses a probabilistic approach on the selection of values from parameter ranges for the input to the models for performance assessment. The chosen values represent one of many in a set of separate calculations (vectors) that are used for the probabilistic assessment. For example, the halite permeability of the Salado Formation around the WIPP was found to vary from $1x10^{-24}$ m^2 to $1x10^{-21}$ m^2 (U.S. DOE 1996-Appendix PAR). This parameter was assigned a uniform distribution and a set of vectors were created by sampling from the distribution. The vectors were then used as input to the two phase brine and gas flow code, BRAGFLO, to create a set of outputs for the calculation of a distribution function that would best describe the performance of the disposal system. The halite permeability is one of 57 parameters used in the Monte Carlo analysis of the CCA.

2.2. Computer Models

In order to accomplish the numerical modeling of the WIPP repository, several computer codes were written to quantify the long term behavior of the waste disposal. These codes can be broken into several categories with each major code having smaller supporting codes to pre- and post-process data. The major codes include:

(1) BRAGFLO - Salado Flow
(2) NUTS and PANEL - Salado Transport
(3) CUTTINGS - Borehole calculations of cuttings, cavings, and spall
(4) BRAGFLO_DBR - Direct brine release from the repository
(5) SECOFL2D - Culebra Flow
(6) SECOTP2D - Culebra Transport
(7) CCDFGF - Probabilistic modeling of the 10000 year future

Figure 2.1. shows the relationships between the codes.

2.2.1. BRAGFLO

BRAGFLO (BRine And Gas FLOw) models the processes occurring in the repository and the surrounding rock, including two-phase fluid flow, anhydrite fracturing, and gas generation. These processes are simulated on a simplified two-dimensional, north-south cross-section of the disposal system from the overlying units above the Dewey Lake down to the Castile formation. The geometry of BRAGFLO's irregular grid spans 46,629.88 m in the north-south direction and 939.06 m vertically. The code was used to calculate brine pressure, saturation, and flow over the entire 10,000 year future of the repository for each of the six scenarios.

2.2.2. NUTS

NUTS (NUclide Transport System) models the migration rate, distance, concentration, and level of radioactivity of radionuclides transported from the repository to the surrounding formations. The equations are solved on the same grid as used in BRAGFLO using BRAGFLOs' brine flow rates, porosities, pressures, and saturation. The NUTS code was used to calculate transport times at 100, 3000, 5000, 7000, and 9000 years postclosure for scenarios S1 through S5.

Of the 33 assumed radionuclides that will be in the WIPP waste, only five lumped isotopes were simulated using NUTS to reduce computer time and memory requirements. The lumped isotopes are assumed to have equivalent decay and transport characteristics of the remaining isotopes, and account for approximately 99% of the activity of radionuclides in the repository. The five lumped isotopes are: ^{241}Am, ^{239}Pu, ^{238}Pu, ^{234}U, ^{230}Th.

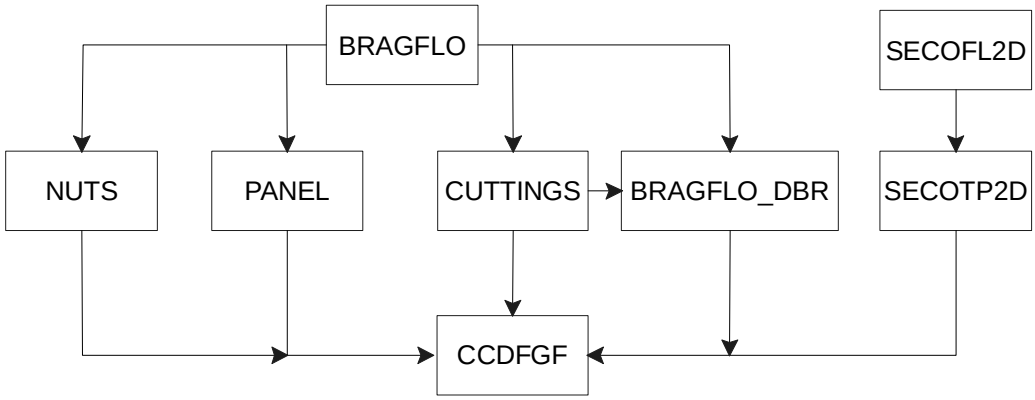

Figure 2.1. Major Codes with Linkages

Computationally, NUTS is a very slow code to run. Therefore, it was first used to simulate a nonreactive passive tracer to test which BRAGFLO flow velocity calculations would transport radioactive isotopes to the accessible environment. Several BRAGFLO simulations were screened out and no longer needed for the calculations. The simulations exhibiting a tracer release and having a mass in excess of 10^{-7} kgs across the accessible environment underwent a complete transport analysis. For the CCA, repilcate 1, only one vector was not screened out of the complete analysis for Scenario 1, 23 for S2, 21 for S3, 6 for S4, and 6 for S5. Thus, only 57 out of 500 vectors were needed for running the NUTS simulations.

The complete analysis included an 'isotope' simulation and a 'time shifted' simulation on the unscreened vectors. The isotope simulation establishes the transport of an undisturbed performance. The isotope simulation results are then used as input for the time shifted calculations at 100, 3000, 5000, 7000, and 9000 years post closure.

2.2.3. PANEL

PANEL calculates the "*mobilized radioactive load in the brine phase of the brine/gas mixture that seeps or flows through the repository's decommissioned waste panels"* (U.S. DOE 1996-Appendix PANEL). Simply, PANEL was used to model the release of radionuclides in a direct brine release scenario to the surface and to model the upper bound of long term releases to the Culebra in the S6 scenario. The times at which PANEL was calculated were 100, 350, 1,000, 4,000, 6,000, and 9,000 years post closure.

PANEL uses BRAGFLO's information, much like NUTS, on a more simplified scale. PANEL represents each waste room as a well mixed grid cell, and solves integrated analytical equations with 50 year time stepping. PANEL simulated the release of 21 of the 33 isotopes from the repository in less time than the NUTS simulation of 5 isotopes.

2.2.4. CUTTINGS_S

CUTTINGS_S calculates the cuttings, cavings, and spallings from an intrusion borehole through the disposal system. CUTTINGS_S receives its initial and boundary conditions from BRAGFLO and can simulate the effects of multiple boreholes. BRAGFLO also provides repository pore pressures, saturations, and porosities for solid removal calculations.

The cuttings and cavings portion of the code models the direct removal of wastes brought to the surface by the drilling cooling liquid (usually a mud brine) and is the sum of the material cut by the drill bit and eroded material. The eroded material is a function of fluid shear stress acting on

the borehole wall and the strength of the waste.

The third type of removal of wastes calculated by CUTTINGS_S is through the process of spall. If the repository is significantly pressurized (above hydrostatic), then a portion of the solid waste could be forced to separate from the bulk mass of waste inward toward the borehole by high pressures in the repository. The amount of spallings removed is dependent upon the waste shear strength and permeability. If the permeability is too low, then it is assumed that the flow of gas to the borehole is too slow to cause a waste blowout up the borehole. Berglund (1994) indentified the "threshold" permeability at 10^{-16} m^2, below which the blowout would cease. The CCA used a value of $1.7x10^{-13}$ m^2 for waste permeability in the repository after compaction. For a comparison of the significance of spallings, the maximum release due to spalling calculated in the performance assessment was 4.0 m^3 with a maximum release of 3.0 m^3 for cuttings and cavings combined.

The scenarios of S1 through S5 were used to calculate borehole times other than those specified in Section 2.1.2. The results of pressures and saturations from the undisturbed scenario (S1) were used as the initial conditions for a first time borehole intrusion at 100, 350, 1000, 3000, 5000, and 10000 years. The CUTTINGS_S simulations for scenarios S2 through S5 were like the S6 scenario (E1E2), and the initial intrusion at either 350 or 1000 years in the BRAGFLO calculations was used to calculate conditions at 550, 750, 1200, 1400, 2000, 3000, 4000, 5000, and 10000 years.

The spallings portion of the CUTTINGS_S was deemed inadequate by the Conceptual Models Peer Review Committee. The peer review (U.S. DOE 1996-Appendix Peer1) reported on the uncertainty in the conceptual model and its inadequacy to calculate the channel flow of waste to the borehole. However, with additional calculations of another spallings code, the spalled releases of the CCA were considered reasonable by the Peer Review Committee (Wilson et al. 1997). Based on a sami-analytical model of spall (Hansen et al. 1997) which calculated a maximum release of 0.25 m^3 at repository pressures of 14.8 MPa, the CCA values of 0.5 to 4.0 m^3 were accepted by the committee. Chapter 9 of this reports explains this new model and some problems associated with the analysis.

2.2.5 BRAGFLO_DBR

BRAGFLO_DBR (BRine And Gas FLOw, Direct Brine Release) calculates the brine released from an intrusion borehole through the repository. The released brine was not assessed in the CUTTINGS code, as that code only calculated the solids removed during drilling. For a direct

brine release to occur, certain conditions must exist in the repository. The repository pressure must be above 8 MPa. This pressure is the hydrostatic pressure at the depth of the repository, which accounts for the column of mud in the borehole that the waste brine must overcome and the frictional forces in the borehole. There must also be enough mobile brine present in the waste panels to flow up the borehole to the surface.

The BRAGFLO_DBR uses the BRAGFLO code, converted to a repository scale model. The model is set up on an areal, two-dimensional grid. The direct brine release can occur at any time during the 10000 year period of the repository, and the saturation and pressure history from the S1 to S5 BRAGFLO calculations are used as initial and boundary conditions. The code calculates a brine release that lasts between 3 and 11 days.

Intrusion times, other than that specified for the different scenarios, were calculated in the same way that CUTTINGS_S intrusion times were calculated. The BRAGFLO intrusion times at 350 or 1000 years postclosure for either an E1 or E2 intrusion were used to establish initial conditions for a direct brine release of a subsequent E2 intrusion at later times. These times correspond with the intrusion times of CUTTINGS_S.

2.2.6. SECOFL2D

SECOFL2D simulates the single-phase flow of groundwater through the Culebra Dolomite member of the Rustler formation. The Culebra member is of particular importance, since this is the most transmissive unit in the disposal system. Radionuclides released from the repository can be transported up an intrusion borehole into the aquifer and be transported to the accessible environment in a short period of time, relative to other units within the subsurficial disposal system.

The Culebra is considered to be a confined aquifer in steady-state. The equations are solved on two grids, regional and local. The regional domain is solved first for the discrete hydraulic head to be used as boundary conditions on a much smaller, finer local grid. Figure 8.1 of this report shows the regional grid in relation to the Land Withdrawal Boundary (LWB) of the WIPP site.

The effects of potash mining in the McNutt member of the Salado formation is considered in modeling of the Culebra aquifer. The subsidence of the mined area may adversely effect the fractured dolomite, creating even more fractures. To simulate the additional fractures, a scaling factor was used to increase transmissivity in a full and partial mining scenario. The scenarios are based on the extent of allowable mining in the region of the Land Withdrawal Boundary. The

scaling factor was sampled from a uniform distribution for a range of 1 to 1000.

2.2.7. SECOTP2D

The transport of radionuclides through the Culebra Dolomite was accomplished with the code, SECOTP2D. The transport code used the local grid velocities of SECOFL2D to calculate the concentration of the actinide species on a nonuniform grid. SECOTP2D reported the mass of simulated actinides that crossed the Land Withdrawal Boundary through time.

The transport calculations of the radionuclides used in the performance assessment first assumes that the initial mass to be injected into the Culebra will be 1 kg. This is a unit mass, that is coupled with predicted mass that reaches the Culebra through a NUTS calculation. The transport of the same five lumped isotopes of NUTS was also transported in SECOTP2D.

2.2.8. CCDFGF

The results of the numerical simulation from NUTS, PANEL, CUTTINGS_S, BRAGFLO_DBR, and SECOTP2D were summarized into tabular form for input to CCDFGF. The NUTS information includes the time integrated discharge of ^{241}Am, ^{239}Pu, ^{234}U, and ^{230}Th up the borehole to the Culebra. The information from PANEL includes the time integrated discharge of ^{241}Am, ^{239}Pu, ^{234}U, and ^{230}Th from the waste panels. The tables from CUTTINGS_S include the volume of cuttings, cavings, and spallings. The flow of brine up the borehole after intrusion is summed in the tables of BRAGFLO_DBR, and the time integration of mass across the accessible environment is located in the tables from SECOTP2D. All together, they represent the possible discrete calculations from a breach into the repository, on a purely deterministic basis.

As a final step to the modeling of the disposal system, complementary cumulative distribution functions (CCDFs) were created to represent the probabilistic future of the repository and to calculate the potential cumulative releases. The CCDF is used to compare release limits specified in 40 CFR Part 191. For the CCA performance assessment, there were only three modes that produced nonzero releases to the accessible environment: cuttings and cavings, spallings, and direct brine release. The calculated amount of radionuclides released through the Culebra was considered negligible.

The sequence of future events simulated for the disposal system was generated by the random sampling of eight individual “events” that could occur at the WIPP. Each sequence is given equal weight in the 10,000 possible futures, and are combined with the results of the numerical

simulations. The individual events are (1) the interval time between drilling intrusion, (2) the location of the drilling intrusions, (3) the drill bit diameter used for drilling intrusion, (4) range of borehole permeabilities, (5) the activity of the waste penetrated by a drill intrusion, (6) the borehole plug configuration, (7) penetration of the Castile brine reservoir, and (8) the occurrence of mining.

Each sampled future requires the determination of a normalized release to the accessible environment. The releases were calculated from the deterministic calculations of the above computer codes. The releases were then scaled and ordered from lowest to highest according to normalized releases. The CCDF is then plotted by summing the probabilities of all futures at a given EPA release limit, with the probabilities of all futures exceeding the summed value. Figure 2.2 shows the individual releases summed to a total release for all pathways, with cuttings and cavings showing the highest releases, spallings, then direct brine release with the least. CCA calculated releases to the accessible environment from transport modeling within the Culebra Dolomite were always less than 10^{-6} EPA Units.

2.3. Parameters

The complexity of the disposal system required the use of computational models to quantify the effects of scenarios in the performance assessment calculations. The computer codes required specific information about the initial and boundary conditions and the parameters needed to quantify the physical system. The parameters were obtained from data surveyed through various experiments or observations. However, when no data were available, expert judgement was employed.

A careful distinction is needed between parameters and data. Parameters are based on the supporting data and are values used in the model calculations. Data are commonly spread over a range for a particular observation/experiment, and statistical quantities are used to summarize that range (minimum, maximum, mean, and mode). A distribution type is assigned to the parameter range, and can be either uniform, loguniform, normal, lognormal, cumulative (delta or otherwise specified), student's-T, or triangular.

There are approximately 3500 parameters used in the performance assessment modeling of the WIPP disposal system, 57 of which are not constants. The constants represent one value, whereas nonconstants have an assigned range and distribution type. Of the 57 ranged parameters, 24 have uniform distributions, which suggests the lack of information about the data.

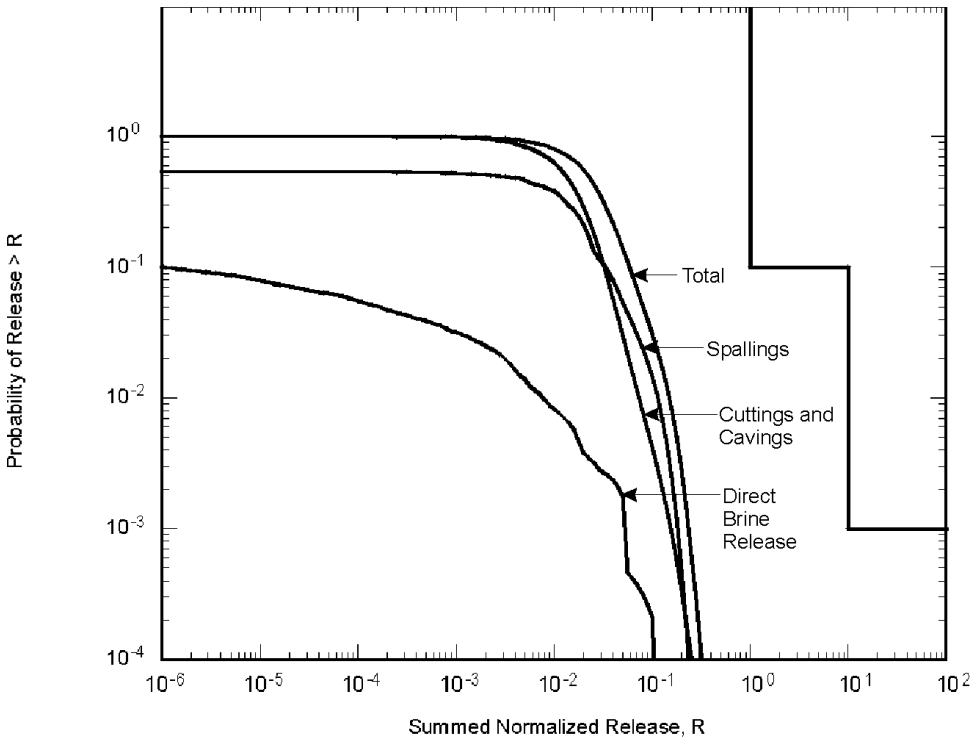

Figure 2.2. Mean CCDFs for Specific Release Modes (U.S. DOE 1996)

A uniform distribution is assigned to a parameter if nothing is known other than its range. However, if the range spanned several orders of magnitude, a loguniform distribution was assigned. This is also equivalent to a uniform distribution applied to a log-scaled parameter.

A range that is representative of a parameter cannot be directly implemented into the computational models. Instead, that range is broken up into several sampled values that fall within the probable range of data, based on the distribution type assigned to that range. For the performance assessment calculations 100 samples were created for each parameter to cover the likelihood of that value existing in the disposal system.

The 5700 total samples were represented by 100 vectors, each with 57 parameters. The vectors were created through the Latin-Hypercube Sampling (LHS) technique. The LHS allows sampling from the outer wings of a distribution with relatively small sample sets, as opposed to other procedures like a strict Monte Carlo method, where sampling is biased more towards higher probability-of-occurrence segments of the distribution. Although the parameters are selected individually through sampling, user-specified correlations are permitted between parameters.

The creation of the LHS sampled vectors uses a random number generated from a seed value

from which the random number generator begins and is specified by the user. The seed value allows duplication of sampled results if the same number is used again for quality assurance measures. For CCA calculations, three separate seed numbers were used to generate three sets of sampled vectors. These are referred to as replicates, and are numbered R1 through R3.

Results of the performance assessment calculations are sensitive to the sampled parameter values. As seen in Figure 2.2, the parameters chosen for the CCA demonstrated compliance of the disposal system. The figure, however, only shows the mean for all individual vectors. Individual CCDF vectors are averaged based on the probability of the parameter occurring during the future of the repository. If only a single vector, for example, were to have parameter values that were to show noncompliance with 40 CFR 191, then that vector could have been averaged out by vectors that show smaller releases. The parameters underwent analyses to test the system and to fully understand the behavior of the repository.

2.4. Sensitivity and Uncertainty Analysis of Performance Assessment Parameters

The sampling of parameters in the CCA calculations is intended to capture the uncertainty in the understanding of the repository environment and those processes that may occur in the event of human intrusion. The purpose of sensitivity analysis is to determine which of the sampled parameters have the greatest influence on the uncertainty of the calculated release to the accessible environment. The sensitivity analysis is based on the use of statistical manipulations to discover the key dependencies in the CCA calculations. This overview summarizes the major conclusions drawn from the DOE's sensitivity analysis report (Helton 1996).

The sensitivity analysis used stepwise correlations and scatter plots. Stepwise correlation is a powerful tool to rank the relative influence of the various parameters. If only a few parameters are important, and the effect of these parameters is consistent, then the correlations work well. Often, however, the effects of some parameters are not consistent. An example is the influence of corrosion rate on spallings. Pressure tends to increase with corrosion rate. Spallings increases with pressure above 8 MPa, but is insensitive to pressure below 8 MPa. Thus, spallings is only weakly correlated with corrosion rate. Scatter plots are very useful for spotting inconsistent correlations and for revealing large changes in system behavior. Scatter plots, however, can be unreliable in determining relative importance because they are qualitative rather than quantitative. Scatter plots are two or three dimensional plots of points defined by measures of interest and one or two parameters. These allow a visual determination of sensitivities.

One inherent limitation in the sensitivity analysis presented by Helton is that the sensitivity to parameters only applies to the actual range and distributions of sampled parameters used in the CCA calculations. Changes to either the range or distribution of one parameter may strongly effect the importance of other parameters, because release estimates vary by orders of magnitude for different combinations of parameter values. A case in point is the brine reservoir compressibility, which has been determined to have insignificant influence on the total release. The brine reservoir pressure and reservoir volume characteristics used in the CCA calculations reduce the importance of the brine reservoir to the calculated releases. It is entirely possible that the brine reservoir would be one of the most important contributors to large releases in calculations using more appropriate characteristics.

The description that follows refers to sampled vectors and histories. A sampled vector is a single random selection of parameter values used to define the physical characteristics of both the repository and relevant human intrusion processes such as spallings. One hundred vectors were used for one replicate of the calculations. Three replicates were used to demonstrate the stability of the averaged results to different sets of vectors. Describing the results in terms of vectors refers to the six scenario calculations performed at fixed intrusion times for each vector. A time history describes the timing of events such as potash mining and drilling intrusions. Ten thousand time histories were generated and applied to each sample vector. Describing the results in terms of time histories refers to probabilities averaged over either a single replicate or all three replicates. The abscissa of the CCDF curves is the probability of a release magnitude for a single history. The lowest cumulative release probability in any CCDF calculated for the CCA is 10^{-4} , one over 10,000. The mean and percentile cumulative release probabilities can be less than 10^{-4} because of averaging over 100 or 300 sampled vectors.

2.4.1. Repository Conditions

2.4.1.1. Repository Pressure

Repository pressure at the time of intrusion is a critical condition that influences spallings release, direct brine release, and flow to the Culebra. The factors controlling repository pressure are complex and change over time. Prior to an intrusion, the pressure uncertainty is almost entirely controlled by gas generation. After an intrusion, gas flow up the borehole can keep the repository near atmospheric pressure. At high borehole permeability, brine flows down the borehole from the Culebra causing the pressure to eventually reach hydrostatic equilibrium with the Culebra.

By far the most important influence on gas pressure prior to an intrusion is the switch for microbial degradation of cellulose and plastics. Fifty percent of the vectors assume no microbial degradation, twenty-five percent have degradation of cellulose only and twenty-five percent include both cellulose and plastics. Microbial degradation is so fast that it tends to exhaust supplies in less than 1,000 years. Hence, the rate hardly matters and the switch parameter becomes the most important indicator of large releases. The numerical values for this parameter are set to capture a lack of understanding of the possibility of microbial degradation.

Microbial generation produces either 0, 1.5×10^6, or 4.6×10^6 moles of gas in the first 1,000 years depending on the microbial generation switch. Steel corrosion generates up to 7.5×10^6 moles averaging roughly 3×10^6 moles after 10,000 years. If microbial degradation produces gas then the steel corrosion rate is increased by a factor of 13. Steel corrosion is rate-controlled throughout the 10,000 years for slow corrosion rates, but only at early times, first 2,000 to 4,000 years, for microbial enhanced fast rates. This makes the steel corrosion rate the second most important parameter in controlling repository pressure and the third most important parameter in determining overall releases to the accessible environment. The rate of steel corrosion is effected by the height of the capillary rise of brine from the repository floor, which is approximated by a sampled parameter known as “waste wicking”. The waste wicking parameter value is important at early times but less so than the base corrosion rate.

Steel corrosion is dependent on the availability of its two ingredients, steel and brine. Brine is readily available through the 10,000 years with slow corrosion rates. At faster rates the lack of brine inhibits corrosion. The mechanisms controlling brine availability are described later, in order to keep the focus here on gas generation. In one of the undisturbed vectors, and in some 30% of the disturbed cases, steel is exhausted in the lower panel but never in the upper panel. Steel consumption does not appear to be greater as a result of interception of the brine reservoir.

After an intrusion, the borehole permeability effects the flow of gas up the borehole which depressurizes the repository. Only about 10% of the vectors have repository pressures above the critical 8 MPa threshold for more than 2,000 years after a drilling intrusion. Very high permeability almost completely determines the repository pressure at 10,000 years. If the permeability is greater than 2.5×10^{-12} m^2 then the repository fills with brine and the pressure reaches hydrostatic equilibrium with the Culebra within a few thousand years of the intrusion. If the permeability is slightly less, down to roughly 2×10^{-12} m^2, then gas vents to the surface as fast as it is generated, inhibiting brine flow down the borehole and thus holding the repository pressure to near atmospheric. The influence of borehole permeability on post intrusion

pressures causes this parameter to rank sixth in importance to total releases. Even the diminished brine reservoirs of the CCA analysis have a strong effect on repository pressure in the case of a brine reservoir interception.

2.4.1.2. Brine Saturation

Brine saturation in the repository is important to the direct brine release calculation and to repository pressure through steel corrosion. Unlike pressure, saturation predictions are different between the upper and lower panels of the BRAGFLO model. Brine saturation depends on brine inflow and the consumption of brine by steel corrosion. The brine inflow is less per panel for the upper panels compared to the lower panel. Because the lower panel is down dip it is expected that it would receive more brine inflow. Saturation also depends on gas pressure because the repository swells in response to pressure increases. The upper panel is much less likely to have a saturation that exceeds the sampled residual gas saturation of the waste. Most vectors show brine saturation going to zero in the upper panel over the 10,000 years because of steel corrosion.

2.4.1.3. Brine Flow

As mentioned earlier, the availability of brine becomes important if the steel corrosion rates are fast. The largest source of brine in early times is the disturbed rock zone (DRZ). This flow averages about 13,000 m^3, most of which enters the repository in the first thousand years. The DRZ porosity is a function of halite porosity which is a sampled parameter. Halite porosity has the fifth largest correlation with total releases of the 57 sampled parameters. The marker beds contribute an average of 3,000 m^3. Although one vector produces 70,000 m^3 from the marker beds, less than 10% of the vectors are above 10,000 m^3. The anhydrite permeability and repository pressures have the greatest impact on brine flow through the marker beds. Anhydrite permeability ranks ninth in importance to total releases.

2.4.2. Cuttings and Cavings

Cuttings and cavings are the largest releases in most of the generated drilling intrusion histories. Only cavings, not cuttings, is effected by sampled parameters. Cuttings release varies due to the sampling of 569 CH-TRU waste streams or the average RH-TRU radionuclide concentration. Waste stream sampling creates about a three order of magnitude variation in cuttings release per intrusion. Cavings is dependent on the sampled value of waste shear resistance. The volume of cuttings, 0.3 m^3, plus cavings varies between 0.4 and 3. m^3.

2.4.3. Spallings

Repository conditions necessary to produce spallings occurs for 80% of the sampled vectors, but spallings only occurs in just over half the time histories. However, spallings along with cavings contribute to the largest release estimates in the CCA. The release estimates from the two mechanisms are roughly equivalent at the critical 10% probability level, as seen in Figure 2.2. The conceptual model uncertainty in the spallings model is enormous. The calculations for a given set of repository conditions could be low by an order of magnitude or more. In addition, the potential influence of repository pressure uncertainty is also enormous. At this time, uncertainty in the spallings conceptual model makes it difficult to assess the CCA calculations in terms of compliance.

2.4.4. Direct Brine Release

Direct brine release contributes only marginally to the overall release estimates and to only 48% of the sampled vectors. Considering the vector average, the direct brine release is larger than the median combined cuttings, cavings and spallings releases in less than 0.4 percent of the time histories. The largest calculated direct brine release was 0.2 normalized EPA Units, i.e. 20% of the release limit.

The releases strongly depend on several factors, including brine saturation and repository pressure. These two conditions are not independent. Large gas pressures usually mean low brine saturation and vice versa. The largest releases are associated with the larger pressures and higher saturations. However, the parameter that correlates best with the direct brine release is the residual brine saturation for the waste area. This parameter describes the minimum amount of brine that is necessary for brine movement through the waste. Direct brine release will occur only if the brine saturation is above the minimum value and the hydraulic conductivity of the waste will be small for saturations near the residual which inhibits brine flow into the waste.

2.4.5. Culebra Transport

Releases to the accessible environment through the Culebra were negligible in the CCA calculations. Large amounts of radionuclides reached the Culebra from the intrusion borehole, but only for a few vectors. More than one EPA Unit of radionuclides reached the Culebra in approximately 10% of the sample vectors. The largest release to the Culebra was 20 EPA Units. However, the transport of the radionuclides limited the amount reaching the accessible environment with the partition coefficient for sorption isotherms being the limiting factor. As the retardation increases (calculated from the partition coefficient), the transport distance decrease.

Other factors that have a small effect on the increase of nuclide transport are fluid velocity and fracture spacing.

3. CONCERNS

The EEG's concerns of the computational efficacy of the CCA performance assessment for the WIPP disposal system does not imply any lack in scientific integrity by the DOE. Instead, it allows an unbiased investigation to ensure the robustness and completeness of the work to dispose of TRU waste effectively. However, it is believed that some of the parameters and ranges used in modeling the performance assessment of WIPP may be in error, or lack justification (Clemo et al. 1996). The DOE applied "conservatism" to many of the parameter and ranges, assuming that a larger range would incorporate all the experimental evidence. Without conducting a full scale sensitivity analysis on the parameters, this conservative approach becomes less meaningful.

3.1. Conservatism

By claiming conservatism in the performance assessment calculations, the DOE took shortcuts on some of its scientific investigations. Conservatism was claimed for many conceptual models and parameters to show that the process would over predict releases to the accessible environment. However, it is not easy to forecast the implications of such assumed conservatism. The calculated releases may diverge from the actual releases, and a bound on the difference is very difficult. For example, an investigation into the microbial decay parameter, which is a major gas producer in the repository, shows one of three choices, (1) no degradation, (2) gas generation through microbial activity of cellulosics, and (3) biodegradation of cellulosics with rubber and plastics. The switch concedes to a 50% probability on any generation of gas through microbial activity. This estimated value was assumed to be conservative, since the possibility of degradation was unknown and no experiments were conducted to prove the possibility of gas generation with the addition of a magnesium oxide backfill. The MgO backfill is predicted to increase repository pH to 10 (U.S. DOE 1996). *"In general, rigorous microbial activity ceases above pH 10.5, although there may be few exceptions."* (Biddle et al. 1987). Figure 3.1. shows that there were higher average releases associated with lower microbial activity for an intrusion associated with the S3 Scenario due to the availability of brine. Other scenarios showed the opposite behavior.

3.2. Parameter Issues

EEG's main issues with the assumptions used in the performance assessment calculations were outlined in the letters to the DOE and EPA on September 11, 1996 (EEG 1996), February 7, 1997 (EEG 1997a), and March 14, 1997 (EEG 1997b). Some major issues which will be discussed in this report are as follows:

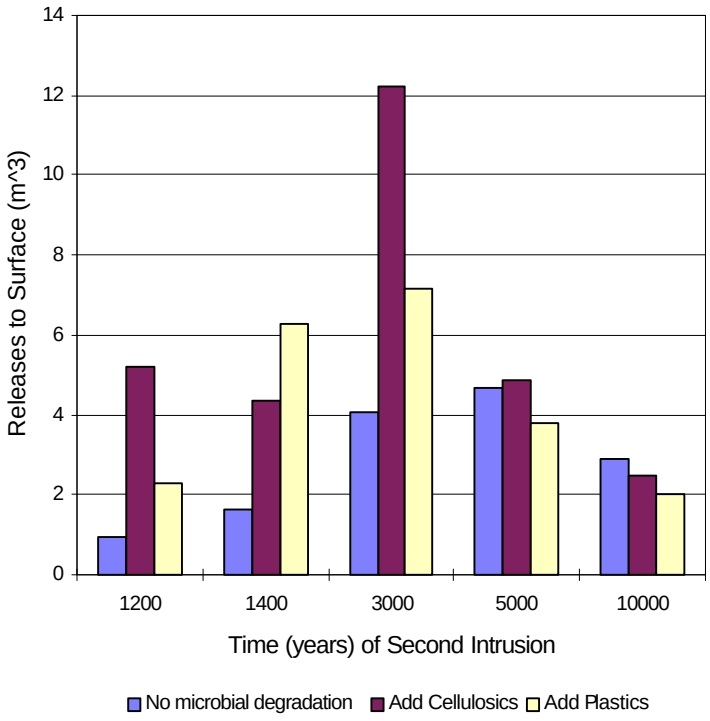

Figure 3.1. Releases from S3 Scenario (Replicate 1) for Microbial Decay

3.2.1. Brine Reservoir Interception

For performance assessment calculations in the CCA, an 8% probability was assigned to the parameter for intercepting a pressurized brine reservoir in the Castile formation. This seems unjustified, considering the data that was overlooked for the WIPP-12 borehole, located within the WIPP site. The reservoir at WIPP-12 was estimated to contain 2.7 million m^3 of brine, and extends more than 3 km in diameter. The values assumed in the CCA for the volume of the reservoir ranged from 32,000 to 160,000 m^3. A value of at least 60% probability should be assigned to the parameter. This report explores the consequence of higher probabilities of encountering a brine reservoir.

3.2.2 Actinide Solubility

The solubility of actinides play an important role in the performance assessment calculations. The parameter determines how much of the radionuclide mass per cubic meter of brine will be transported from the repository up the borehole to the Culebra or to the surface. More specifically, the solubility of plutonium, which constitutes 87% of the initial radioactivity in the waste, was modeled as oxidation states III and IV in the CCA calculations with a 50% probability that it will be one or the other. DOE maintains that the conditions of the repository will be a reducing environment, not allowing the actinide to go above an oxidation state of IV, which would

inherently increase the solubility by 10,000 in some cases. Furthermore, experiments were never conducted to establish the solubilities of Pu(III) and Pu(IV), and were extrapolated from thermodynamic data conducted on Nd(III). Therefore, modeling experiments were conducted by the EEG to test the impact of solubility of actinides in brine.

3.2.3. Chemical Retardation in the Culebra

The chemical retardation in the Culebra determines how the radionuclides will react with the surrounding dolomite matrix. Retardation infers that the contaminants will sorb onto the matrix, and the amount is determined by a coefficient called the partition (or distribution coefficient, K_d). DOE made laboratory measurements of K_d for various actinides (Brush and Storz 1996).

The EEG has a number of concerns on K_d, which were raised in a meeting between Sandia and EEG. First, the applicability of the oxidation state analogy for Pu(III) from Pu(V), which was initially from Am(III), seemed weak at best. Several of EEGs' consultants noted that the assumptions for this analogy were based on questionable data and interpretations of experiments conducted with dilute groundwater from the Yucca Mountain site, a proposed high level waste repository in Nevada (Neill et al. 1998). Similarly, Pu(IV) was derived from Th(IV).

Another concern for the K_d values was the range and distributions used to establish these parameters in the LHS sampling method. The uranium data, for example, exhibited negative values in experimentation. Though physically impossible, they should have been averaged into the parameter's range. The lower end of K_d for uranium was 0.03 ml/g in the CCA, but should have been zero, due to the extreme uncertainty in the value. A model value of 3 ml/g was shown (Blaine 1997) to retard any actinide sufficiently from crossing the LWB. Therefore, it is very important to assign the correct values with a large enough uncertainty of K_d for actinides that exhibit values less than 3 ml/g.

These and other issues surrounding the K_d issue prompted the EEG to conduct their own transport modeling study, which changes the K_ds for several key parameters.

3.2.4. Castile Reservoir Parameters

The pressurized brine pockets contained within the Castile formation were grossly under represented in the performance assessment calculations. After the submittal of the CCA, recommendations were made (Beauheim 1997) to characterize the formation by what is referred to as the "productivity ratio". This ratio is the product of the volume and the pore compressibility to porosity. The recommended range for this ratio was 0.0007 to 0.04 m^3/Pa based on values from the ERDA-6 and WIPP-12 borehole data, respectively.

It should be noted that the ERDA-6 borehole lies outside the WIPP area at approximately 5 miles northeast from the repository center. The WIPP-12 well, on the other hand, is only 1 mile north of the site and values to describe the Castile for disposal system modeling would be more representative if this borehole data is used.

3.2.5. Potash Mining

The extent of potash mining above the repository horizon for PA calculations included the possibility of two scenarios, which included partial and full mining. The two scenarios were based on the possible future extent of mining both inside and outside the disposal system with respect to ore grade. The extent of the partial mining maps were established on historically leased areas with economic grade ore, and the full mining was based on the a report by the New Mexico Bureau of Mines and Mining Resources (U.S. DOE 1996-Appendix Mass).

The BLM has established a map on the possible economic minable ore around the WIPP site. The CCA has identified this as the most conservative mapping of ore, but has refused to include it stating that a significant volume of potash is not minable by today's economic conditions. Furthermore, the BLM map does not include nonminable regions for the existence of hydrocarbon holes. The EEG conducted a modeling study, which extends the area of minable resources, while keeping all other modeling philosophy the same as it was in the CCA. The EEG does not believe that this resolves the modeling problems associated with that used in the CCA, and extensive modeling will be conducted in the future.

3.2.6. Spallings' Calculations

The issue of spallings is very sensitive, with respect to codes, performance, and parameters. Initially, the DOE used a spallings code to calculate the effects of high repository pressures on releases during a human intrusion scenario in the CCA. The code was found inadequate by the Conceptual Models Peer Review Group (U.S. DOE 1996-Appendix Peer 5). However, the committee found the results in the CCA to be "reasonable" with further evidence from additional modeling.

This further evidence uses more realistic conceptual models than were presented in the CCA, implemented in a series of spreadsheets and numerical codes. Further investigation of the codes, by the EEG, found them to be inadequate to model all expected repository conditions. For example, a slightly lower waste permeability than that in the CCA, caused the results (volume of failed material that could reach the surface) to be quite unrealistic, with values as high as 500 m^3. Other parameters used in the code, such as gas viscosity and drilling mud density, also cause unexpected values. It is EEG's belief that none of the codes, in their present

form, can adequately model all expected repository conditions to establish “justifiable” values for releases to compare with 40 CFR Part 194.

4. PROBABILITY MODELING OF DRILL INTRUSION RATES

4.1. Summary

This investigation included changing the deep drilling intrusion rates at the WIPP to estimate the safety margin between assumed drilling rates and the drilling rate that first violates the standards for compliance. The CCA used a drilling rate of 4.68×10^{-3} boreholes/km^2/yr over the 10,000 year period of the repository. The rates were increased in two simulations. Additional modeling was also performed with a 2.34×10^{-3} boreholes/km^2/yr drilling rate to investigate the potential for larger spallings releases due to higher pressures with a less frequent drilling rate. The results show a linear relationship between drilling rates and release limits. A factor of safety of 23 was calculated for the CCA drilling rate, with all other factors remaining the same as used in the CCA.

4.2. Introduction

The consequence of future human intrusion scenarios into the Waste Isolation Pilot Plant was investigated in the CCA (U.S. DOE 1996). These scenarios were established according to the EPA guidelines in 40 CFR Part 194 (U.S. EPA 1996b), and included the possibility of mining and deep and shallow drilling for resources.

The guidelines state in 40 CFR Part 194.33 that the likelihood of a drilling intrusion into the Delaware Basin for the future 10,000 years must be calculated by considering the frequency of drilling for all resources over the past 100 years. These numbers were calculated in the CCA, Appendix DEL (Tables DEL-3 through DEL-7) and were used to calculate the CCDF curves for the performance assessment calculations of the CCA. A total of 46.8 boreholes per km^2 were estimated based on past drilling of resources at depths greater than 2150 meters, which equal 10,804 boreholes in 23,102.1 km^2 (area of Delaware Basin).

The drill intrusion rate for the 10,000 year future of the WIPP was directly implemented in the CCDF model, and was calculated to be equal to 0.00468 boreholes/km^2/yr. However, since the future human activities are uncertain, the rate was changed to test the effects on the CCA calculations. The rates were increased by one and two orders of magnitude, and also decreased by one-half. New CCDF curves were generated based on the changes.

4.3. Methodology

The modeling of new drill intrusion rates were started at the code CCDFGF. All steps up to generating the new CCDF curves were exactly the same as CCA calculations. The files needed to conduct the modeling were fetched from the CMS library. Figure 4.1. lists the steps involved

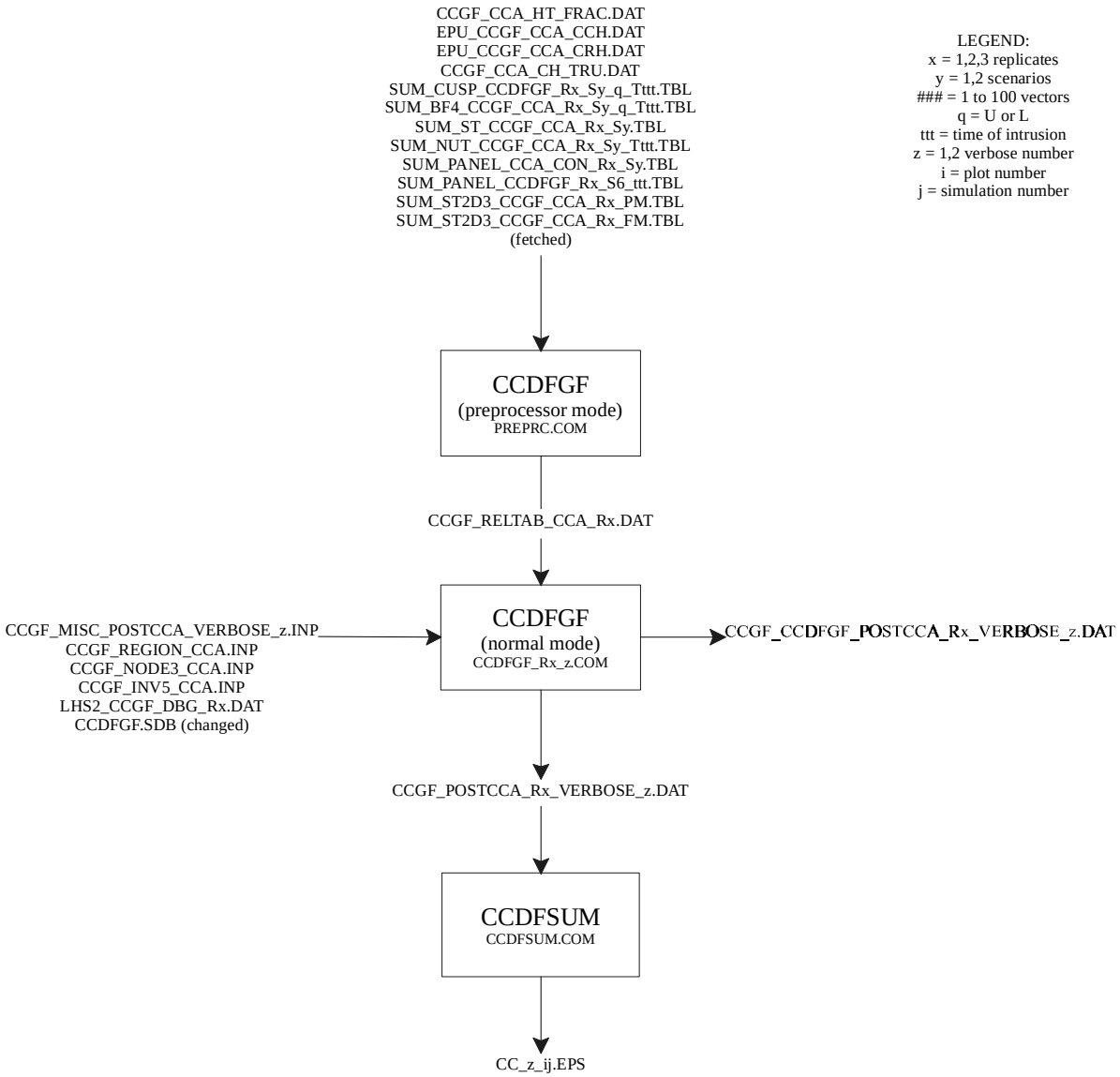

Figure 4.1. CCDFGF Flowchart

in the modeling process with all input and output files.

The change of the drill intrusion rate was made in the file CCDFGF.SDB, a secondary database file used in both preprocessing mode and normal mode of the CCDFGF code. The parameter LAMBDAD (number 3494) was changed, and the specifications can be found in Appendix PAR, Table PAR-53 of the CCA (U.S. DOE 1996). Drilling rates were changed to 4.68×10^{-2} boreholes/km^2/yr, 4.68×10^{-1} boreholes/km^2/yr, and 2.34×10^{-3} boreholes/km^2/yr in three successive simulations.

Minor changes had to be made to the CCDFGF code in order to accommodate the higher drill intrusion rates. Currently, the maximum number of boreholes allowed in the code is 100; MAXBH in CCDFGF.FOR limited the total number. Therefore, the variable MAXBH was increased from 100 to 100,000 in every subroutine of CCDFGF.FOR to allow for a greater number of boreholes. The code was recompiled with the specifications used for the CCA.

The CCDFGF was first run in preprocessor mode to generate the release table data, then in normal mode. The output files created by the normal mode of CCDFGF were postprocessed by CCDFSUM, which created the printable ADOBE style postscript files.

4.4. Results

New CCDF curves were calculated for the changed drill intrusion rates, and are plotted in Figure 4.2. , which also shows the results from the CCA. As expected, the increasing rate produces an increase in releases, in as much to exceed the EPA maximum release limit at 4.68×10^{-1} boreholes/km^2/yr. The relationship between drilling rate and actinide release also seems to be approximately linear; one order of magnitude increase in drilling rate produces approximately one order of magnitude increase in release. Table 4.1. lists the releases for all three simulations and the results for the CCA at a release probability of 10^{-3}. All releases are in EPA Units.

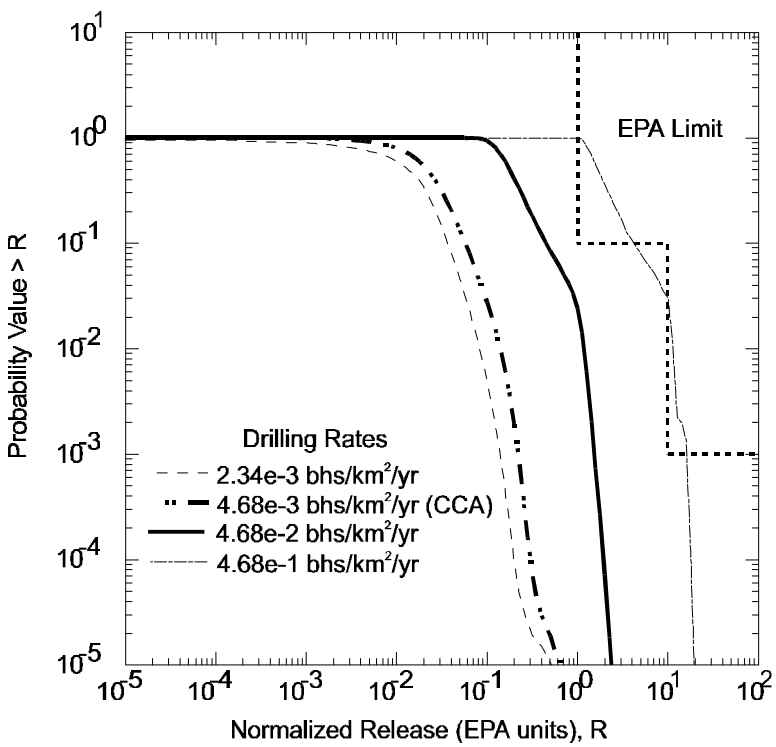

Figure 4.2. Total Normalized Release Limits for Changing Drilling Rates

Simulation	Deep Drilling Rate (bhs/km^2/yr)	Total Normalized Releases at a probability of 10^{-1} (U.S. EPA Units)	Total Normalized Releases at a probability of 10^{-3} (U.S. EPA Units)
1 (CCA)	4.68×10^{-3}	0.059	0.21
2	4.68×10^{-2}	0.44	1.7
3	4.68×10^{-1}	4.1	17
4	2.34×10^{-3}	0.035	0.12

Table 4.1. Total Normalized Release Limits at Different Deep Drilling Rates

The drilling rate was also reduced by half to test a hypothesis about the increased gas pressures with less intrusions. The effect would most likely be seen in the low probability range, however the releases decreased linearly with respect to drilling rate.

4.5. Conclusions

Drilling rates were changed from the original CCA calculations to test the effects of future uncertainty. The changes included two CCDFGF simulations which increased the deep drilling rates by one and two orders of magnitude, and a simulation that decreased the deep drilling rate by one-half. The results are presented in Table 4.1. and Figure 4.2..

The future drilling rate used in the CCA, as specified by the EPA, estimated that the number of boreholes for the next 10,000 years was an average from the last 100 years. Of course there is no possible way to predict human scenarios and the numbers used were more or less arbitrary. However, the present study looks at several different drilling rates, and concludes that the relationship is approximately linear between releases and drilling rates. A drilling rate 23 times greater than that prescribed by EPA and used in the CCA is needed to reach the EPA release limit at a probability of 10^{-1} from values used in the CCA. The overall mean for the highest release at 0.468 boreholes/km^2/yr exceeds the EPA limit of 10 EPA Units at a probability of 10^{-3}. While the drilling rate in the immediate vicinity of WIPP has been documented to be higher than 0.3 boreholes/km^2/yr, that drilling rate was not anticipated to be sustained for any length of time (Silva, 1994).

5. INDIVIDUAL AND COMBINED INFLUENCE OF PLUTONIUM SOLUBILITY ON DIRECT BRINE RELEASE AND THE PROBABILITY OF HITTING CASTILE BRINE

5.1. Summary

This investigation describes the influence of plutonium solubility and the probability of hitting Castile brine on the potential and consequences of brine release to the surface through blowout. The effects of these two parameters on the performance assessment, without changes to other parameters, are investigated both individually and in combination. Results are presented as a comparison of CCDF for blowout and the total normalized surface release. Changing these parameters to more realistic values than used in the CCA increases releases but not substantially. Even calculations using plutonium solubility set to unrealistically high values do not exceed the EPA standards for potential radioactive nuclide releases to the accessible environment through a direct brine release scenario. At the largest solubility values, the entire plutonium inventory is in solution. The release is, however, limited by the fraction of repository brine brought to the surface.

The codes PANEL and CCDFGF are the primary codes used in this investigation. The investigation made use of the intermediate results of the performance assessment calculations. The PANEL code created intermediate data files that are used later to incorporate plutonium solubility influences in investigations of other parameters such as the Castile brine reservoir parameters.

5.2. Introduction

The standards issued by the EPA for the safe disposal of TRU waste at WIPP require a performance assessment of the WIPP repository in order to provide a reasonable assurance that the potential radioactive nuclide releases to the accessable environment will not exceed the limits established by the EPA. The DOE has submitted an application (CCA) for the EPA to certify that the DOE has demonstrated compliance with the EPA standards. One of the potential pathways for radionuclide release to the environment is through unintended drilling into the repository in the distant future. If the pressure buildup in the repository due to chemical reactions in the waste is sufficiently large then venting of the repository through a borehole could bring radioactive brine to the surface. The EEG contends that the oxidation states within the repository assumed for plutonium in the CCA performance assessments are in error. The oxidation state assumption has a major influence on the amount of plutonium that may be in solution in the repository brine and hence on the amount plutonium brought to the surface as a consequence of drilling.

The oxidation states of plutonium in certain WIPP brines have been the subject of some recent studies (Reed et al. 1994, 1996; Rao 1996) and conclusions show that plutonium will exist in oxidation state VI, reducing to V in some instances. However, modeling of plutonium for the CCA was conducted on Pu(III) and Pu(IV) using solubilities predicted by the FMT code, contrary to the above experiments. The range for the plutonium solubility in the Salado brine for the CCA was 4.4×10^{-8} M to 1.1×10^{-4} M. The range for plutonium solubility in Castile brine was 5.7×10^{-11} M to 1.4×10^{-7} M. The changed oxidation states will effect the solubility of plutonium in the waste, and change the amount of actinide release to the surface and Culebra.

The solubility of plutonium was changed from values used for oxidation states III and IV to those measured in Reed et al. (1996). The solubility of plutonium in the Salado brine was increased by a factor of 20, and fell within the range suggested by the FMT calculations. A more substantial change was made in the solubility of plutonium in the Castile brine, increasing by almost 4 orders of magnitude. Table 5.1. lists the solubilities used in the CCA, suggested by DOE (1996) using the FMT calculations, and the experimental results shown by Reed et al. (1996).

5.3. Methodology

The solubility change was implemented in the PANEL calculations for blowout considerations only; the changes impacted the direct brine release portion of the CCDFs. The change was made to the source term file ALG_ST_CCA_Sy.inp, where Sy are the scenario numbers 1 and 2. Only the first two scenarios are needed to obtain Salado and Castile brine radionuclide concentrations.

The changed parameter in the source term file, DIS (dissolved solubility), was converted to a constant equalling the solubilities measured in Reed et al. (1996) using ALGEBRA. It was previously a sampled parameter, with a range of -2 to 1.4 orders of magnitude difference from that in the FMT calculations. This was the only changed parameter, and the steps involved prior to running the CCDFGF code follow the PANEL Concentration simulations in Stockman et al. (1997). The flowchart in Figure 5.1. shows the steps involved through the entire process. The changed input file for ALGEBRA is identified in Figure 5.1. as input to the ALGEBRA Source Term.

	FMT Calculations	Reed et al. 1996
Castile Brine	5.7 e-9 M	8.0 e-5 M
Salado Brine	4.4 e-6 M	9.0 e-5 M

Table 5.1. Solubility of Plutonium as Determined by Experiment and FMT Calculations

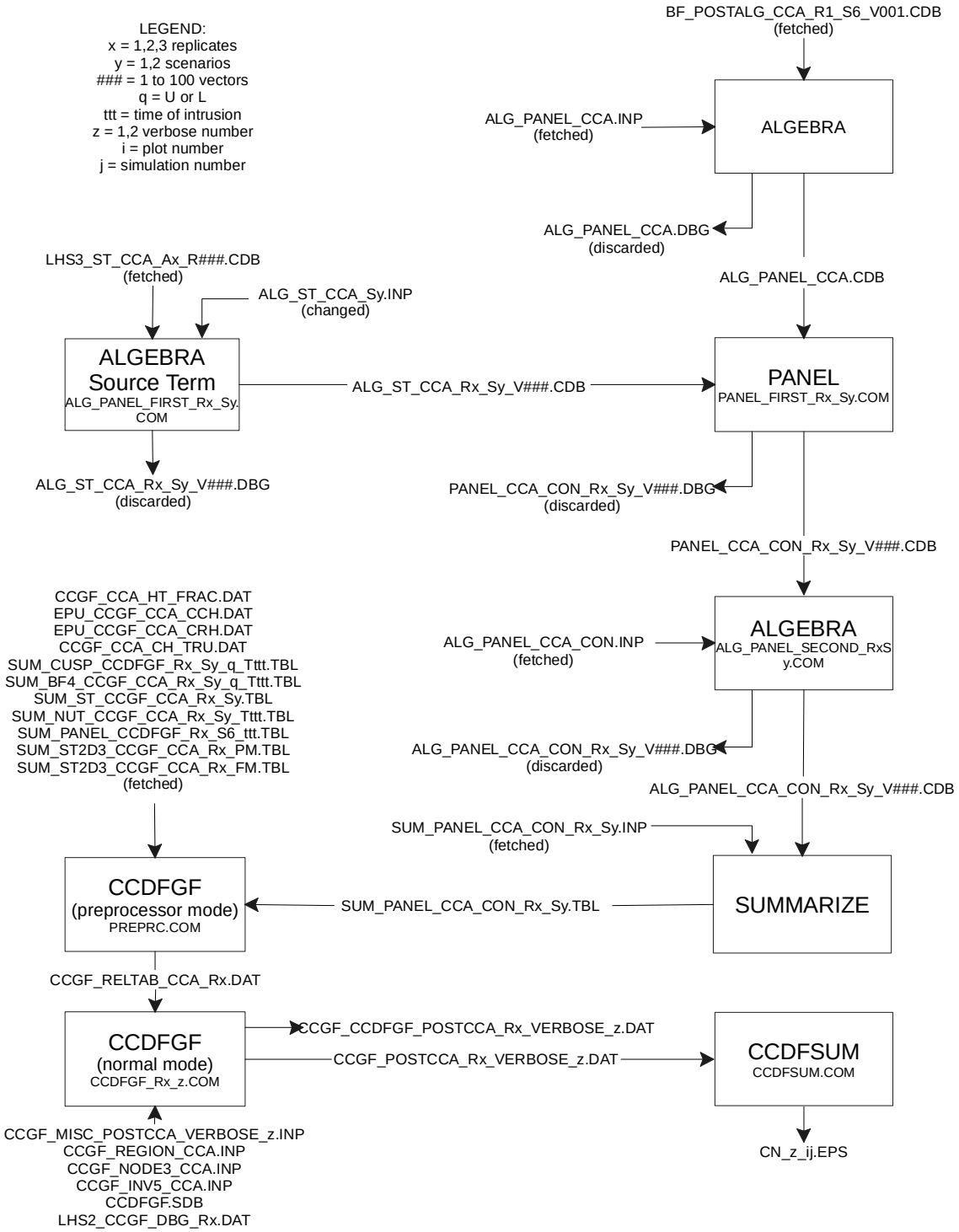

Figure 5.1. Flowchart of PANEL Simulations

Figure 5.1. shows a listing of all the programs needed to run the entire PANEL concentration simulation, and are represented as rectangles. The rectangles list the names of the executable code and the script (if available) used to run the code. Arrows in and out of the rectangle show which files went into and came out of the code execution.

Script files were created to automate the process of running all one hundred vectors for each replicate and scenario for each step. These script files also help to ensure reproduceability of the calculations. Any additional files needed for code execution were fetched from the CMS library, and erased after use. For example, LHS files were needed to run the source term portion of ALGEBRA. The files LHS3_ST_CCA_Ax_R###.CDB (where Ax represents the replicate number and R### are the vectors 1-100) were fetched from the library LHS, and discarded afterward to conserve drive space.

The PANEL calculations were postprocessed by SUMMARIZE and used in CCDFGF to generate new CCDF plots. The CCDFGF was first run in the pre-processor mode, then in normal mode to produce the results. The CCDFGF calculations were then post-processed by CCDFSUM to produce postscript files that are printable.

5.4. Results

The CCDF plot created from CCDFSUM for blowout calculations can be seen in Figure 5.2., with the corresponding CCA plot in Figure 5.3.. Each line represents the probability of a magnitude of release in EPA Units for different vectors of sampled parameter values. The plots are from replicate R1. The highest release from a vector at 10^{-3} probability is less than 1.0 EPA Units. However, this is an increase from the CCA calculations which show the highest vector at less than 0.2 EPA Units at the same probability level.

The plot in Figure 5.4. shows an overall mean increase in blowout normalized release for the increased solubility and the CCA calculations. At the 10^{-3} probability level, the release increases in EPA Units from 0.04 to approximately 0.13. This does not violate the EPA release limit, which limits a release of 10.00 EPA Units (3440 Ci) at 10^{-3} probability.

Further experimentation of the blowout calculations included changing the parameter which controls the probability of a drill intrusion into the Castile brine. In the CCA calculations, this parameter was set to 8 %. The influence of this parameter was tested at higher values at 50 and 100%. These values were based on the potential that the Castile reservoir size encountered by WIPP-12 (Chaturvedi et al. 1997) extends below the waste area. It should be noted that the

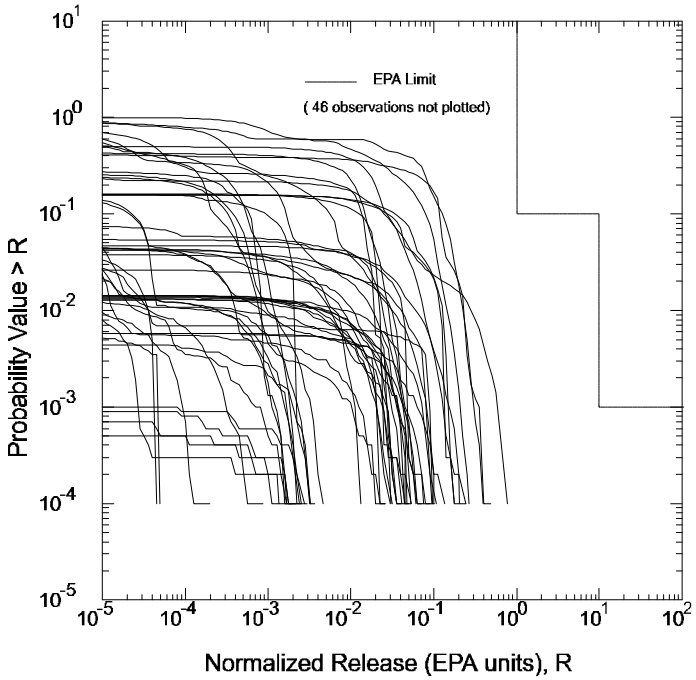

Figure 5.2. Blowout Releases for Increased Solubility

probability parameter is located in the 'Region and Panel Parameters File' (CCGF_REGION_CCA.INP) at position 9, but is overwritten by parameter 3493 in the secondary database file (CCDFGF.SDB).

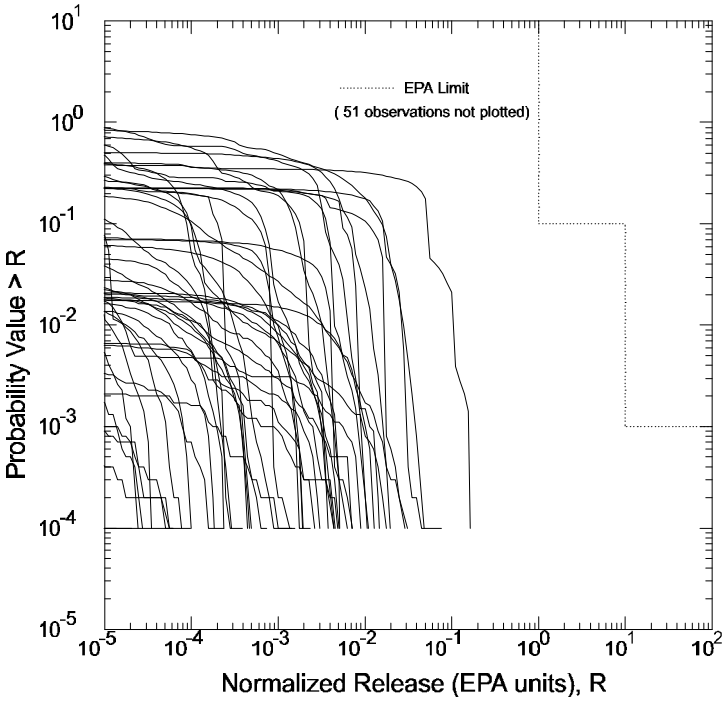

Figure 5.3. Blowout Releases for CCA Calculations

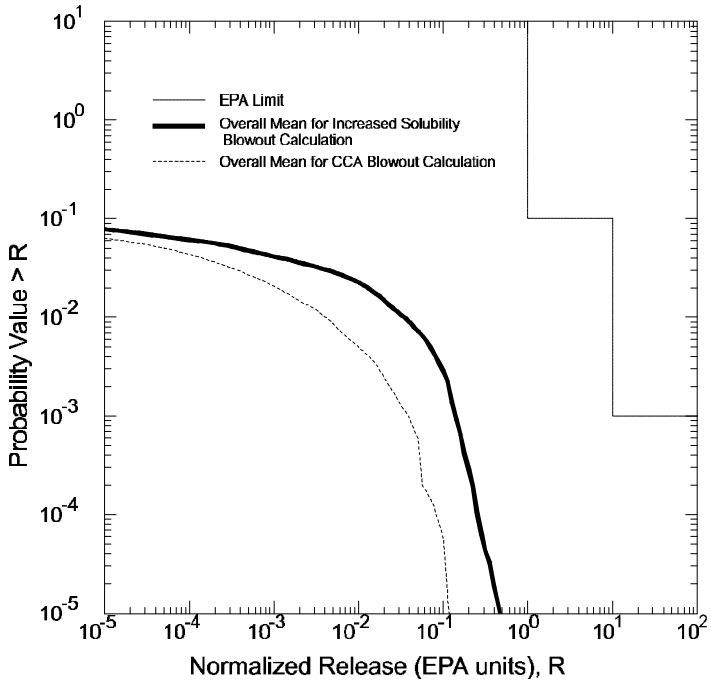

Figure 5.4. Overall Mean of Blowout Normalized Releases

Figure 5.5. shows the overall mean from the total normalized release calculations from the three simulations of 8, 50, and 100% probability as it compares to the CCA. The greatest release came from the 100% probability of Castile brine intrusion, with a value of 0.31 EPA Units at a probability of 10^{-3}, which is less than the 10.0 EPA Units established by the EPA as the maximum allowable release limit. The calculated releases at the 10% level are only slightly effected.

Lastly, the solubility of the plutonium in the Castile and Salado brines was increased further to test the limits and compare values for the previous simulations. The solubilities were increased from 8.0×10^{-5} M and 9.0×10^{-4} M to 8.0×10^{-4} M, 8.0×10^{-3} M, and 8.0×10^{-1} M for both brines. These values have no justification other than testing the limits of the code with respect to more suitable values. The probability of hitting a brine reservoir was returned to 8%. The results were plotted in Figure 5.6., showing the increased solubilities compared to the the CCA calculations and solubility of 8.0×10^{-5} M and 9.0×10^{-5}M in the Castile and Salado, respectively. For each increased solubility simulation, the release increased to a threshold limit at approximately 8.0×10^{-3} M, above which the solubility had no further effect on the calculations. All releases stayed below the EPA limit, with the maximum reaching 1.3 EPA Units at solubilities of 8.0×10^{-3} M and above.

Table 5.2. lists all simulations conducted showing releases at 10^{-3} probability.

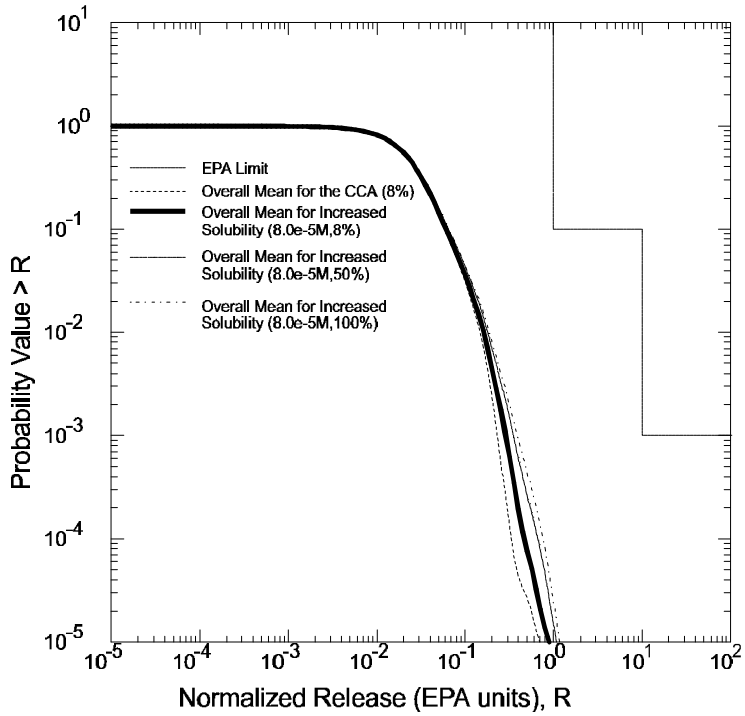

Figure 5.5. Total Normalized Releases with Increasing Probability of Hitting Castile Brine Reservoir

5.5. Conclusions

Additional PANEL simulations were performed to test the effect of plutonium solubility on the CCDF calculations in the CCA. The solubility was changed in both the Castile and Salado brine from a ranged parameter to a constant value. Six simulations were conducted that tested the overall effectiveness of the changes, which included changes in the solubility and Castile brine intrusion probability. Table 5.2. lists the results from each simulations as compared to the CCA calculations.

Simulation Number	Simualtion Description	Blowout Release Overall Mean (U.S. EPA Units)	Total Release Overall Mean (U.S. EPA Units)
1	CCA	0.04	0.21
2	8.0×10^{-5}M, 8% probability	0.13	0.29
3	8.0×10^{-5}M, 50% probability	0.17	0.30
4	8.0×10^{-5}M, 100% probability	0.18	0.31
5	8.0×10^{-4}M, 8% probability	1.0	1.0
6	8.0×10^{-3}M, 8% probability	1.3	1.3
7	8.0×10^{-1}M, 8% probability	1.3	1.3

Table 5.2. Releases for PANEL Simulations at 10^{-3} Probability

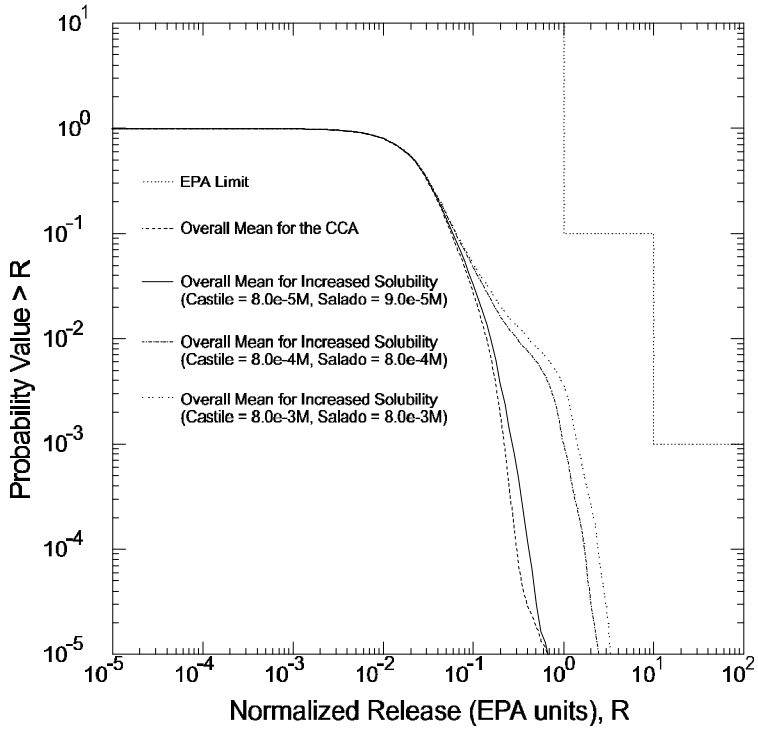

Figure 5.6. Overall Mean of Blowout Releases with Increasing Solubility

As expected, the simulations seemed to be more sensitive to the increased solubilities than the increased Castile intrusion probability. The one order of magnitude increase in solubility from 8.0×10^{-5} M to 8.0×10^{-4} M increased releases by 0.87 EPA Units, whereas the one order of magnitude increase in probability of hitting the Castile brine resevoir from 8% to 100% only increased the releases by 0.08 EPA Units. The releases continued to increase with increasing solubility to a threshold of 8.0×10^{-3} M. Above this solubility no additional increase was calculated, and was most likely limited by the amount of direct brine release. Also, one should note the nonconstant increases in total normalized releases compared to the blowout normalized releases of Table 5.2. The increased solubility of plutonium affects the direct brine release calculation enough to make it a dominate release mechanism for Simulation #5, for probabilities lower than 10^{-2}. Lower solubilities (less than 8×10^{-4} M) mask the effect of the actinides in solution.

The curves represented in Figure 5.6. show the increasing total normalized releases with increasing plutonium solubility in both the Castile and Salado brine, with a maximum release of 1.3 EPA Units at 8.0×10^{-3} M at a 10^{-3} probability. The EPA limit suggests that releases remain below 10.0 EPA Units at the probability of 10^{-3}, therefore rendering all justifiable plutonium solubilities conservative with the current amount of brine release. Additional studies should be conducted in which the amount of brine volume increases with the increasing solubility.

6. TRANSPORT MODELING OF K_dS

6.1. Summary

A modeling study was performed to investigate the roles of chemical retardation through the Culebra aquifer at the WIPP repository. The transport code SECOTP2D was used by varying the values of the partition coefficient (K_d) from that used in the Performance Assessment of the Compliance Certification Application for several key actinides. The results show that the assumed sorption of radionuclides to the surrounding rock matrix coupled with the amount of actinides reaching the Culebra produce very low releases compared to the 40 CFR 191(U.S. EPA 1996a) containment requirements.

6.2. Introduction

The concern of actinide transport through the Culebra has prompted a modeling study by the EEG that investigates the consequences of radioactive wastes to sorb onto the aquifer material through the evaluation of K_ds. The matrix partition coefficient, or K_d, is a species dependent property that varies depending on the sorbing material type, which describes the amount of waste that can be chemically bonded to the matrix adsorbed through ion exchange.

Results of various laboratory experiments to determine the K_d of plutonium, uranium, americium, thorium, and neptunium were reported by Brush and Storz (1996). However, the values obtained from the experiments and the statistical representations that are used for modeling the coefficients were questioned by the EEG (EEG 1997a; 1997c). The EEG argues that the data for K_d values are too limited to justify the current range in the CCA, the amount of organic ligands that will bind with the actinides is much higher than that assumed by the DOE, and a uniform distribution as a representation for all data is unjustified. Therefore, transport modeling of the transuranics using other K_d values were investigated to determine whether chemical retardation is needed to meet compliance standards established by the EPA.

6.3. Methodology

The modeling of the partition coefficient was conducted using the Sandia transport code, SECOTP2D version 1.30. For the present study, the groundwater flow calculations were not rerun and grid velocity files were fetched from the CMS.

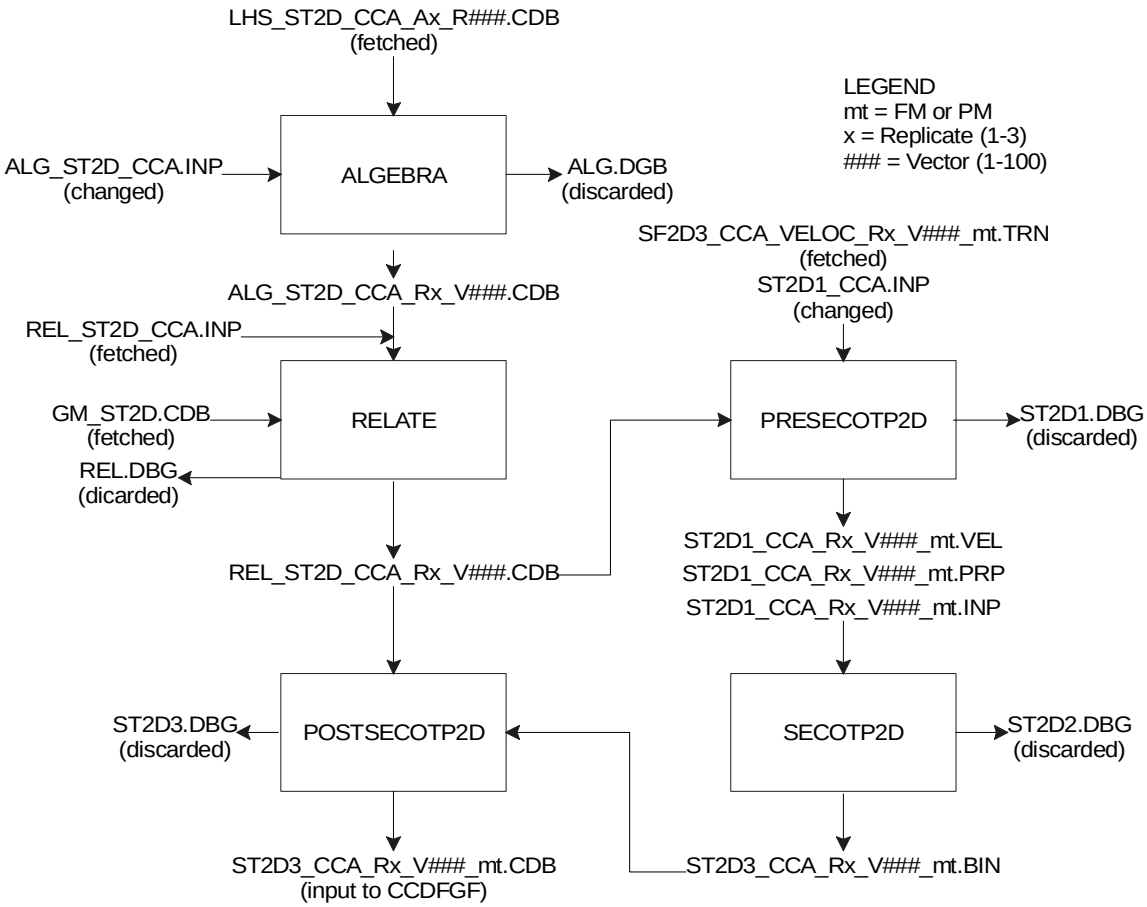

Figure 6.1. Flowchart of SECOTP2D Runs

The only files that were modified for transport simulations were the input file for the ALGEBRA code and the input file for SECOTP2D. The ALGEBRA file, ALG_ST2D_CCA.INP was altered by changing the way the retardation was being calculated. A new value was substituted for the partition coefficient. The input file for SECOTP2D was changed by specifying the transport of only one actinide. Figure 6.1. shows the stream of codes used in modeling with SECOTP2D.

6.4. Transport Modeling Of Plutonium

The importance of the partition coefficient was investigated by Blaine (1997). The investigation found that a value of 3 $^{ml}/_{g}$ was sufficient to retard plutonium through the Culebra for a “worst case” vector. The study was meant to test minimum values of K_d for violation of the EPA standards. The worst case vector included the minimum advective porosity of the Culebra matrix (0.0001), the maximum diffusive porosity of the Culebra matrix (0.25), and the largest half matrix block length (0.5) that were estimated in the CCA. The vector was also tested against

larger half matrix block lengths, of up to 1.0 m. The latter model showed that a value of 15 $^{ml}/_{g}$ for K_d was needed to chemically retard the species adequately to meet EPA regulations.

The above experiment studied the phenomenon of small K_d quite thoroughly. However, K_ds smaller than 1 $^{ml}/_{g}$ were never investigated. Therefore, the present study changes the CCA K_d values from that generated from a range for performance assessment calculations to a model that assumes a very small mass fraction (1%) of the radionuclides have a K_d equal to zero. This effect allows the waste to move through the aquifer unretarded.

The justification for using K_d of zero is summarized in Channell (1997). The evidence, reproduced here, that support the 1% K_d=0 $^{ml}/_{g}$:

(1) A fraction of the actinides is likely to be in organic complexes or chelated. Experimental evidence suggests that these conditions will drastically reduce K_d values.

(2) Column infiltration experiments have shown that small fractions of transuranic radionuclides will move through natural rock columns at or near the speed of water. These radionuclides are not in complex or chelated form.

The first experiment simulated plutonium moving through the Culebra with a fraction of the contaminate having a zero K_d. The original PA groundwater flow calculations from SECOFL2D were used to obtain velocity and discretization (spatial and temporal) information for transport calculations. The original PA assumed that 1 kg of waste would be brought to the surface through a human intrusion borehole. The 1 kg was assumed to be a unit mass of release to the Culebra and is coupled later with the actual amount that is released from the repository through the code CCDFGF. Hence, 0.01 kg was accepted for a 1% K_d =0 $^{ml}/_{g}$ transport simulation.

Transport simulations were conducted on 100 vectors of both full and partial mining of the first replicate. Results of the modeling efforts are presented as integrated discharge and contour plots of waste concentration. Figure 6.2. shows the partial mining scenario with integrated discharges at 10,000 years (on $\log_{10}$ scale) as a function of vector number. The integrated discharge is the fraction of waste mass that crosses the Land Withdraw Boundary (LWB) at a given time. Hence, an integrated discharge value of 0.001 kg is equavelent to 10% of the original waste mass crossing the LWB in 10,000 years. All parameters for the present study were kept the same as that used in the CCA, except for the partition coefficient.

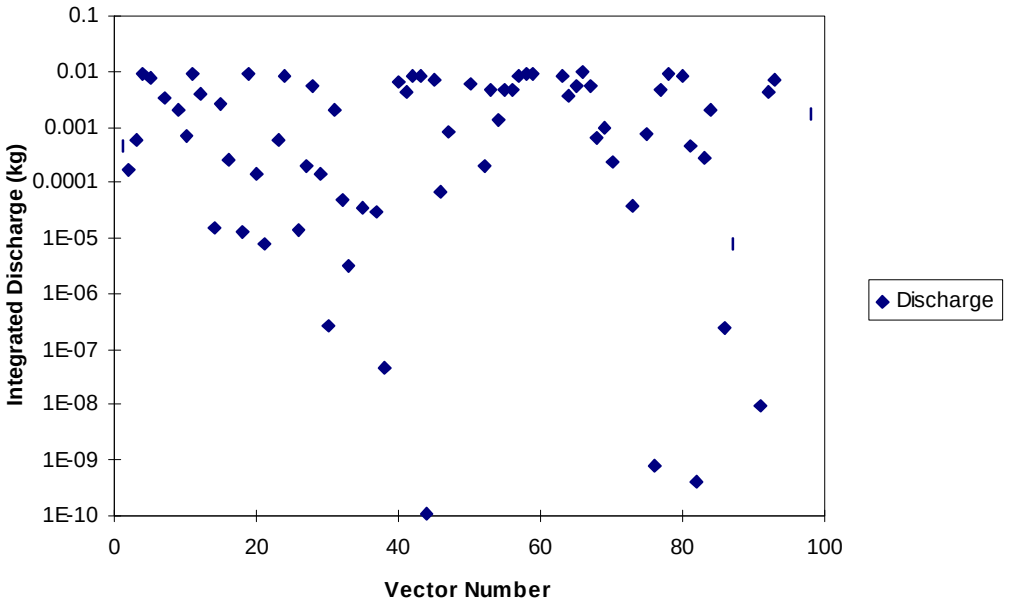

Figure 6.2. Integrated Discharge vs. Vector Number for Partial Mining Scenario at 10,000 Years

In the CCA calculations, there were no vectors with discharge across the boundary at 10,000 years for the first replicate. All actinides were retarded sufficiently and were kept from migrating any substantial distance from the intrusion borehole. Retardation values for plutonium ranged from 216 to 455492 in the PA and were calculated from a linear isotherm. Plutonium retardation for the present model was a single value of 1.0 for all vectors. As a result of lower retardation, a substantial number of vectors showed releases across the LWB.

Figure 6.3. shows a contour plot of vector 4 of replicate 1 for plutonium migration with 1% of the K_d=0 $^{ml}/_{g}$ for the partial mining scenario at 10,000 years. The isopleth concentration levels in kg/m^3 are equivalent to that seen in the Analysis Package, Task 3 (Ramsey and Wallace 1997) with darker shades indicating lower concentrations. The integrated discharge for the plot is 91.9%. The areal view of the figure indicates the location of the Waste Panel Area and the Land Withdraw Boundary in relation to the plume's spread, with the ordinate and abscissa marking 1000 m distances between ticks. An asterisk around the center of the plume designates the highest concentration in kg/m^3, which is not to be confused with the centroid of the plume. The figure shows that the plutonium moves quite quickly (relative to 10,000 years) through the Culebra, and a significant amount passes through the Land Withdraw Boundary in 10,000 years.

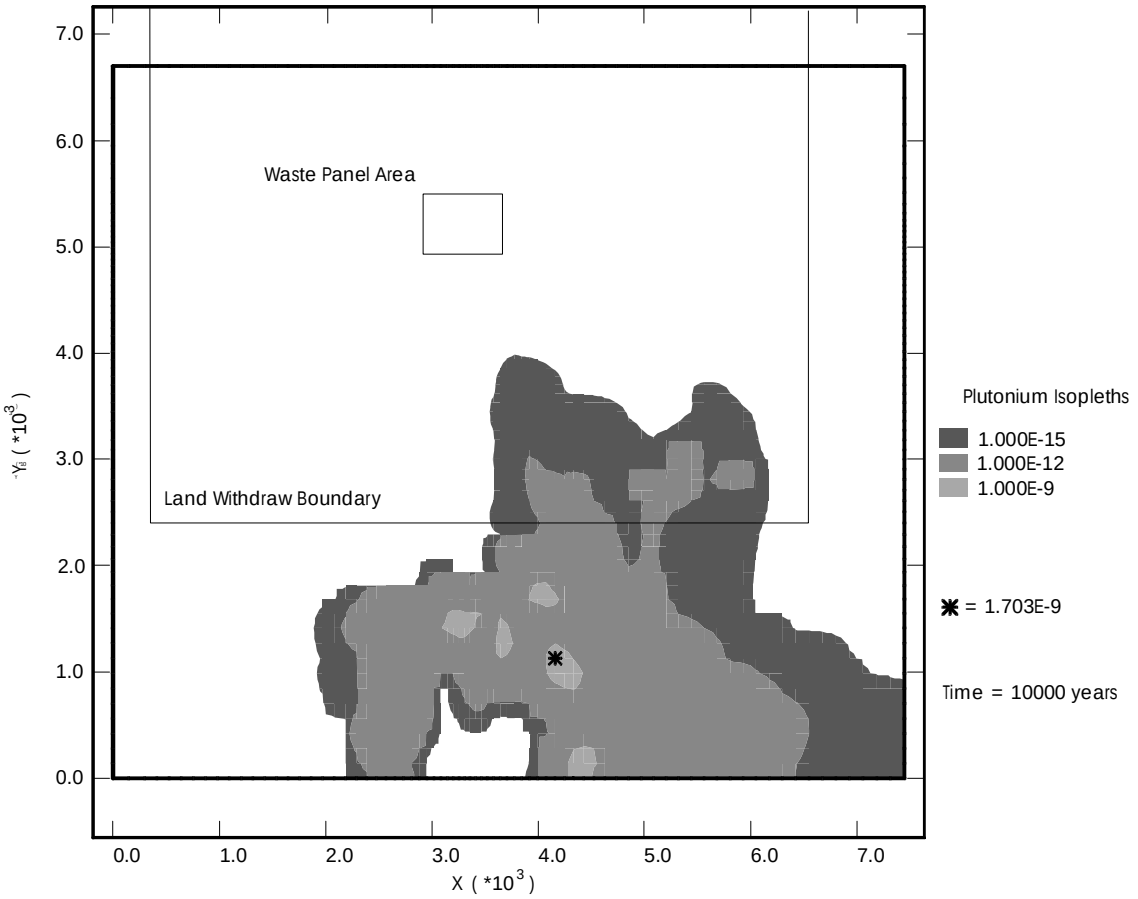

Figure 6.3. Plutonium Concentration (kg/m^3) for Replicate 1, Vector 4, Partial Mining

Figure 6.4. shows the releases for the vectors of the full mining scenario of replicate 1. Again, none of the PA calculated vectors in the CCA had releases across the LWB in 10,000 years. This is a large contrast to the present model, where a substantial number of vectors crossed the LWB. Approximately half of the total vectors have at least 1% discharge across the Land Withdraw Boundary in 10,000 years in both full and partial mining scenarios.

Though many vectors seem to have a high release, one vector in particular, Vector 20, stands out as a possible error. The discharge across the LWB is 0.0135 kgs, normalized to 135% of the original mass entering the Culebra. The obvious error of the overcalculated mass could be attributed to the large mass balance error (-0.3619 kgs) associated with the calculation. These errors are documented for SECOTP2D version 1.30 by the EPA (U.S. EPA 1997) and the DOE (U.S. DOE 1997c). The EPA's request for additional information about the mass balance calculations in the PA prompted a study in (Ramsey and Treadway 1997) on the extent of the errors associated with the code. Their findings demonstrated that the major problems of mass conservation are attributed to the boundary conditions on the southern-most boundary. The total

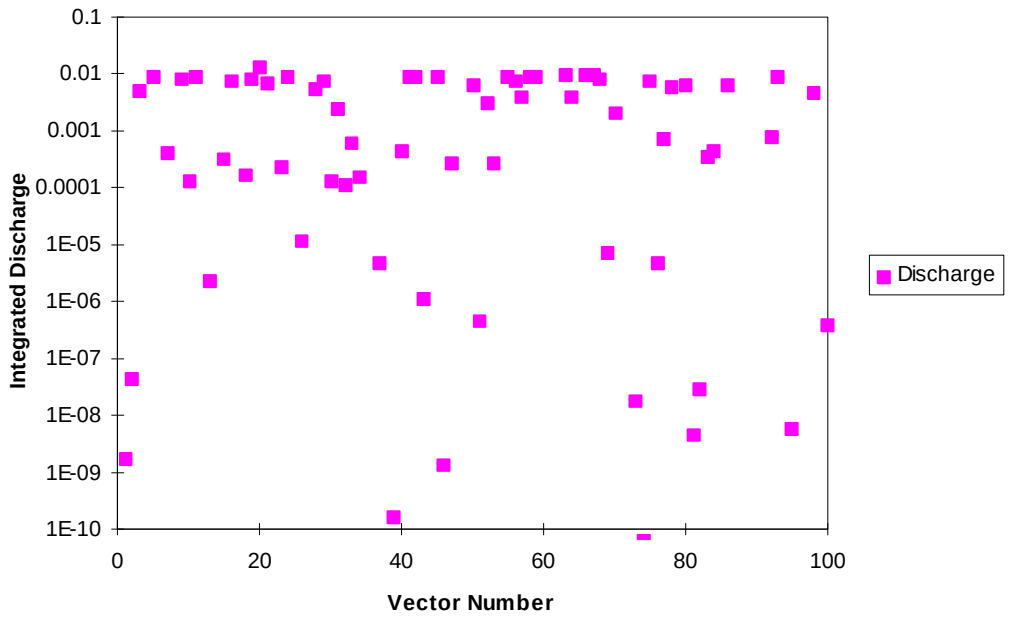

Figure 6.4. Integrated Discharge vs. Vector Number for Full Mining Scenario at 10,000 Years with 1% of Plutonium Having a K_d of Zero

variation diminishing (TVD) differencing scheme in combination with large Courant numbers were the culprit and was subsequently fixed in version 1.40. However, this version was unavailable at the time of these simulations.

The effect of the nonconservative models is uncertain. The problem lies on the southern boundary, where most of the nuclides are transported across the LWB. The mass balance error has been quantified in a single vector (EEG 1997b) for all five nuclides as approaching 100%. The error shows a large underestimation of transport decreasing in time, and yet it cannot be reasonably assumed that all vectors are underestimated, since Vector 20 in the present model shows an overestimation of 35%.

Figure 6.5. shows a similar plot to that of Figure 6.3.: plutonium concentrations for Vector 58 of the full mining scenario. The discharge across the LWB for Vectors 58 is 88.6%. The slight difference in discharge between the two figures is compensated greatly in Figure 6.5. by the areal extent of higher concentrations. The isopleths indicating 1.0×10^{-9} kg/m^3 has a farther and more continuous reach than seen in Figure 6.3. Conceptually, this could have a greater impact on future generations who may drill into the aquifer, especially if they were in a direct downstream pathway from the source of the highest concentration.

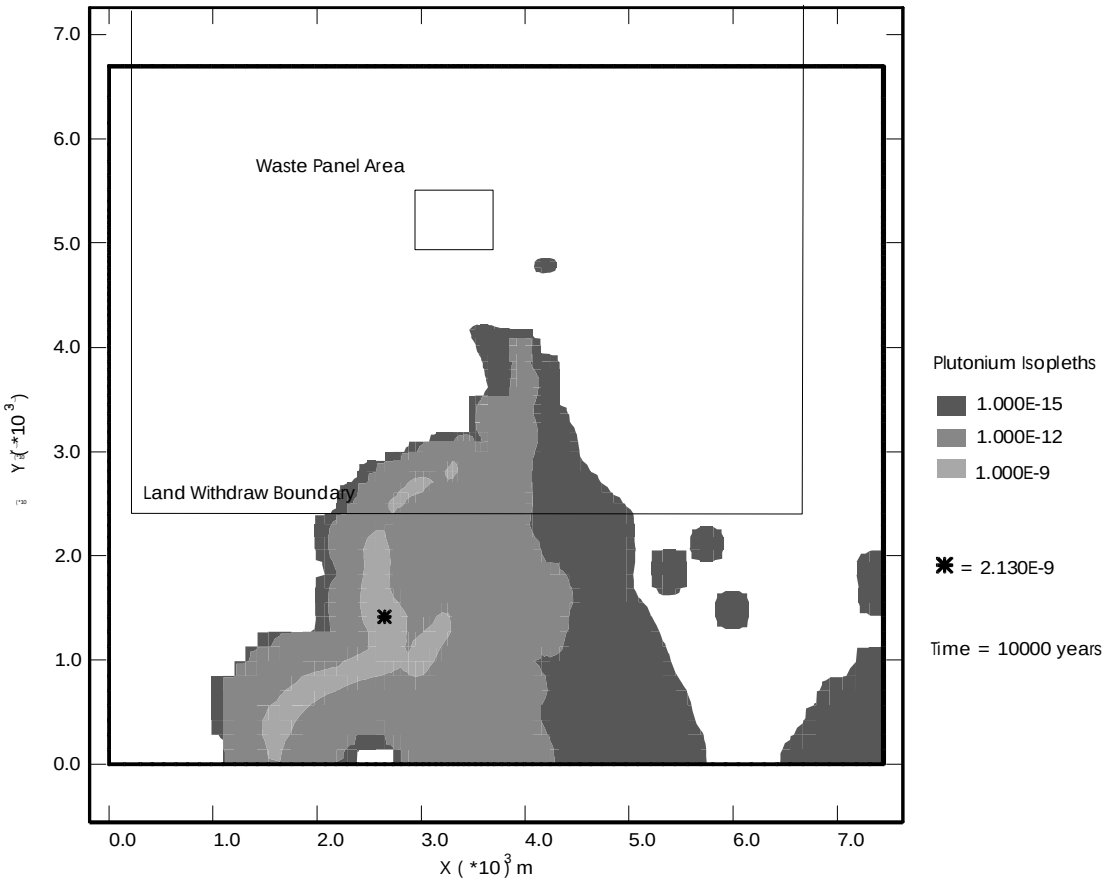

Figure 6.5. Plutonium Concentration (kg/m^3) for Replicate 1, Vector 58, Full Mining

The combined effort of the partial and full mining scenario modeling with a 1% K_d=0 $^{ml}/_g$ can be seen in the CCDF plots of Figure 6.6. The plot demonstrates a probability associated with a release from the Culebra in EPA units. This figure shows that the consequence of a one percent, zero matrix distribution coefficient for plutonium has virtually no effect on compliance. Only 10 vectors appeared on the plot, with the mean of all vectors superimposed on the figure. At a probability level of 10^{-3}, less than 10^{-4} EPA units will be released from the Culebra. The EPA limit for a 10^{-3} probability is 10 EPA units. The extremely low consequence is attributed to the coupling of the releases to the Culebra that were calculated through NUTS and PANEL. Table 6.1. lists the releases of plutonium-239 and the total for all actinides for scenarios 2 through 6 to the Culebra. Scenario 1 assumes no human intrusion, therefore no waste is released from the repository to reach the Culebra aquifer. The low releases seen in Table 6.1. confirms the low probabilities associated with the radionuclides reaching the assessible environment.

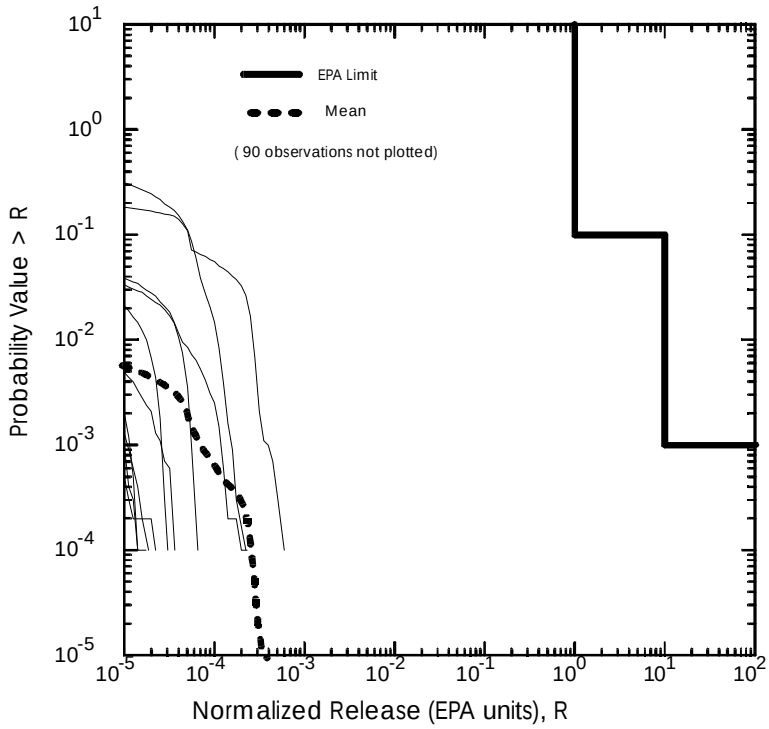

Figure 6.6. Total Normalized Releases from Culebra for 1% K_d=0 ml/g for Plutonium Simulation

Scenario	Intrusion Time (yr)	Pu-239 Releases (U.S. EPA units)	Total for all Actinides (U.S. EPA units)
2	100	0.045	6.62
	350	0.044	6.04
	1000	0.044	2.19
	3000	0.32	0.36
3	5000	0.24	0.24
	7000	0.14	0.14
	9000	0.035	0.04
4	100	20.8	21.1
	350	20.1	20.4
	1000	18.2	18.4
	3000	11.5	11.6
5	5000	5.57	5.62
	7000	1.09	1.10
	9000	0.027	0.03
	100	0.43	95.0
	350	0.42	68.7
6	1000	0.41	26.0
	2000	0.39	5.57
	4000	0.66	0.79
	6000	0.47	0.49
	9000	0.18	0.20

Table 6.1. Maximum Releases of Plutonium-239 and Total for all Actinides to the Culebra

6.5. Probability Modeling Of Actinides

Finally, the CCDF code was run assuming that 100% of all actinides that reached the Culebra crossed the boundary, instantaneously. This scenario can be used as an upper end bounding case for transport through the Culebra. The simulation was run for the first replicate only, and was found to fail the EPA compliance criteria at 10^{-3} probability, as seen in Figure 6.7. Yet, one should not reach a conclusion that K_d could have significance from this plot. Further investigation shows that the failure is due to a single vector of high plutonium release to the Culebra. The transport coupled with the actinide source calculations from NUTS and PANEL may pose a possible threat in the 10,000 year future of the repository, but the transport alone, keeping all other parameters the same, is inconsequential.

6.6. Conclusions

The main focus of this study was to model the transport actinides through the Culebra Dolomite at the WIPP with a small portion of the radionuclides being nonreactive to the surrounding dolomite rock. Plutonium and uranium were simulated with a matrix partition coefficient (Kd) equal to zero. Probability modeling was also conducted on all actinides to test the robustness

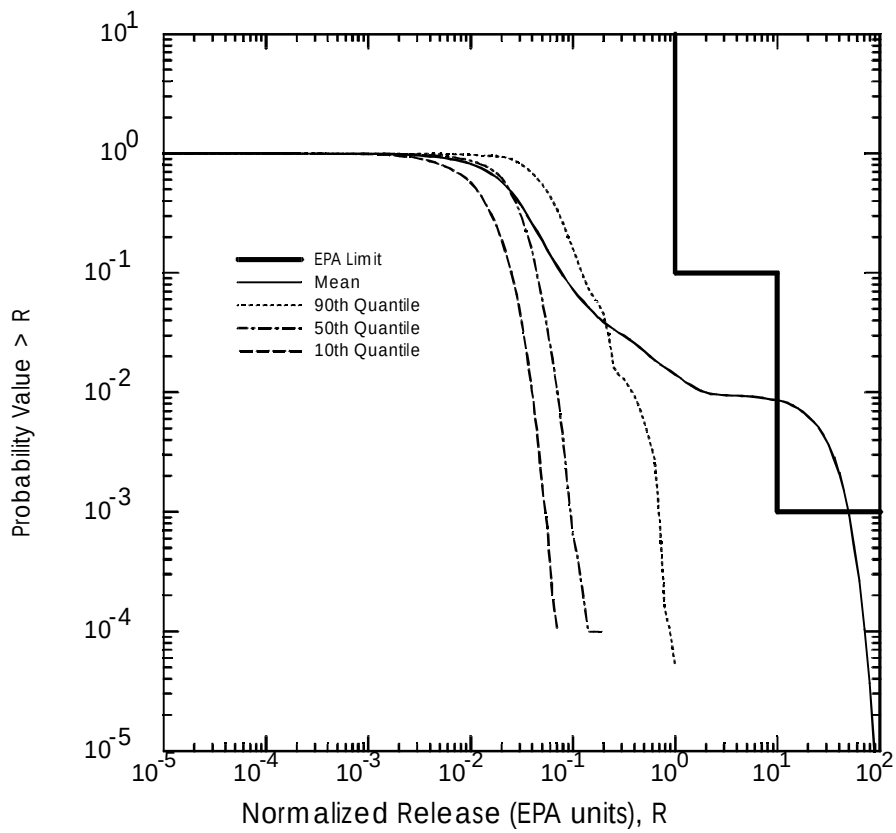

Figure 6.7. Total Normalized Releases for all Actinides Crossing the LWB

and consequences of all the actinides crossing the LWB in 10,000 years.

The plutonium simulations included 100 vectors for each partial and full mining scenarios for a single replicate. The results were summarized and incorporated into the CCDF curves of the CCA, as seen in Figure 6.6. Over half of the vectors (approximately 100 out of 200 vectors) had releases of at least 1% across the accessible boundary, which is substantial compared to the number that crossed in the CCA (zero out of 200). However, after coupling these unit releases with the actinide sources in NUTS and PANEL, the releases were shown to have negligible effect on the overall CCDF.

7. CASTILE BRINE RESERVOIR PARAMETERS

7.1. Summary

The results of a sensitivity analysis for several key parameters dealing with the Castile Reservoir and waste permeability are reported in this chapter. The modeling starts with flow calculations within the Salado Formation using BRAGFLO, and finishes by incorporating the results of the amount of solid waste and brine that may be ejected from an inadvertent human intrusion using CUTTINGS_S and BRAGFLO_DBR into a CCDF. The changed modeling parameters include Castile Reservoir volume, rock compressibility and permeability, and waste residual brine saturation and permeability. The results show that the overall mean of the CCDF does not increase above that seen in the CCA when all other performance assessment assumptions are used. The CCDF shows a trivial increase in releases when the probability of actually hitting the Castile reservoir increases from 8 to 100%.

7.2. Introduction

The pressurized Castile brine reservoir that underlies the Waste Isolation Pilot Plant has been the subject of many debates on its extent and importance (EEG 1997b; 1997d; Silva 1994; U.S. DOE 1997a; Beauheim 1997). The scientists who setup the CCA performance assessment calculations recognized the fact that the brine could play a significant role in the degradation of wastes and waste container, if an inadvertent drilling intrusion were to pass through the repository to the brine reservoirs below, by assigning two of the six scenarios to calculate the effects of the breach. However, the characterization of the parameters associated with the reservoir were undermined by associating them to data that clearly lies outside of the domain of the repository. The more realistic parameter values proposed by the EEG could potentially demonstrate higher direct brine releases to the surface, affecting the compliance of EPA standards in the 40 CFR 191. Therefore, additional calculations were performed using more reasonable parameters for the simulation of Castile brine migrating into the repository. These calculations are referred to as the Castile Simulation.

7.3. Reservoir Parameters

Reservoir parameters used in performance assessment calculations were derived from borehole information that lie mainly outside the domain of the WIPP repository. The distance to these boreholes ranged from 3.75 miles to over 11 miles from the repository center. Figure 7.1. shows the location of some of the boreholes used to characterize the Castile brine reservoirs. Two boreholes in particular, WIPP-12 and ERDA-6, stand out, as they were used most frequently to define Castile Reservoir parameters. The depths of these two boreholes vary significantly.

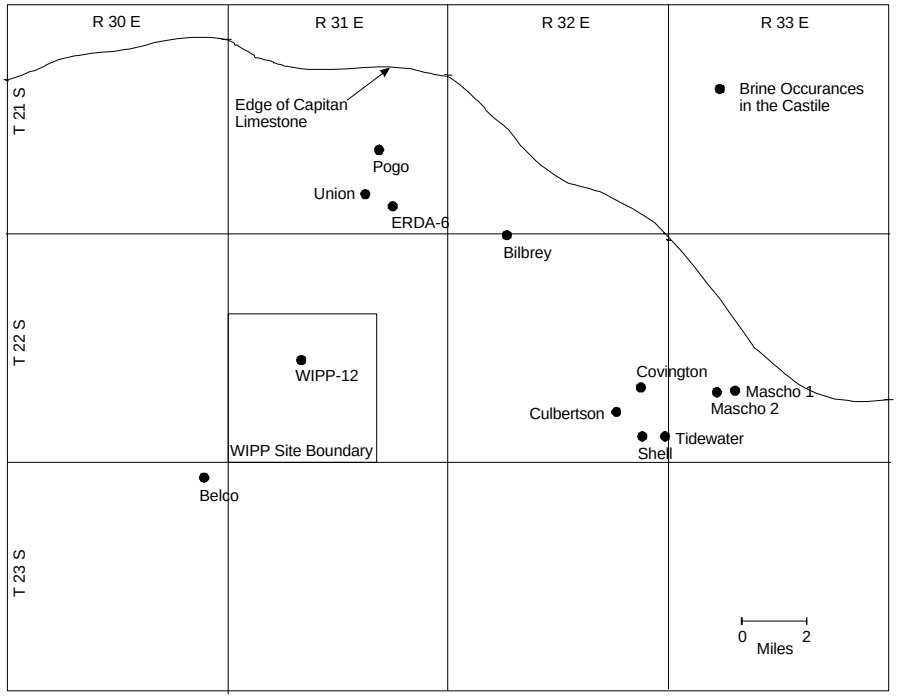

Figure 7.1. Location of Boreholes in the Castile Formation that were used to Characterize a Castile Brine Reservoir

WIPP-12 was bored into the Anhydrite I layer of the Castile to 3925 feet, whereas ERDA-6 had a total depth of 2775 feet into the Anhydrite II layer.

New values were assigned to several parameters that describe the Castile brine reservoir based on WIPP-12 data that is more closely identified to the conditions at the repository. The WIPP-12 borehole, is located within the WIPP site, one mile north of the repository. The borehole was originally drilled in 1978 and deepened in 1981 at the request of the EEG, which caused the repository to be moved south after brine was encountered at the borehole. The borehole experienced brine flow to the surface when drilling reached a depth of 3012 feet (D'Appolonia 1982). While extending the borehole to depths greater than 3,900 feet, a total of 80,000 barrels was allowed to flow from the borehole.

7.3.1. Productivity Ratio

The parameters associated with describing the Castile brine reservoir include reservoir volume, rock compressibility, reservoir pressure, and permeability. The correlation of volume and rock compressibility was recognized when Beauheim (1997) described a ratio based on these parameters. The productivity ratio is the product of the brine volume and rock compressibility by the porosity: $PR = V\frac{C_r}{q}$, where V is volume, C_r is rock compressibility, and θ is porosity. This

value was identified by Beauheim (after CCA calculations were completed) to a range of 0.0007 m^3/Pa to 0.04 m^3/Pa. The range was based on more relevant data. The CCA calculations had a range that varied from 5.3×10^{-5} m^3/Pa to 0.06 m^3/Pa.

Beauheim's new range was based on borehole data from ERDA-6 and WIPP-12. Both borehole encountered brine in the Castile formation, and it was assumed conservative that parameter values should include data from both boreholes to cover the uncertainty in a possible reservoir under the repsoitory. However, using the lower value of the range, calculated from the ERDA-6 borehole, seems unjustified for the repository. The borehole is located approximately 6.4 km (4 miles) northeast of the site, and much less brine was encountered, compared to the WIPP-12 borehole. The upper value in the range was calculated from WIPP-12 data. Figure 7.2. shows the productivity ratios of the CCA with the new range suggested by Beauheim and where the WIPP-12 data lie.

A single productivity ratio value for WIPP-12 is the basis for additional simulations by the EEG. The value of 0.04 m^3/Pa eliminates the dependence on boreholes in the far field, and places it solely on the importance of WIPP-12. The value is constructed by choosing a single value for the brine volume size and rock compressibility, and using the CCA value for porosity. The basis for the new volume and compressibility values are discussed below.

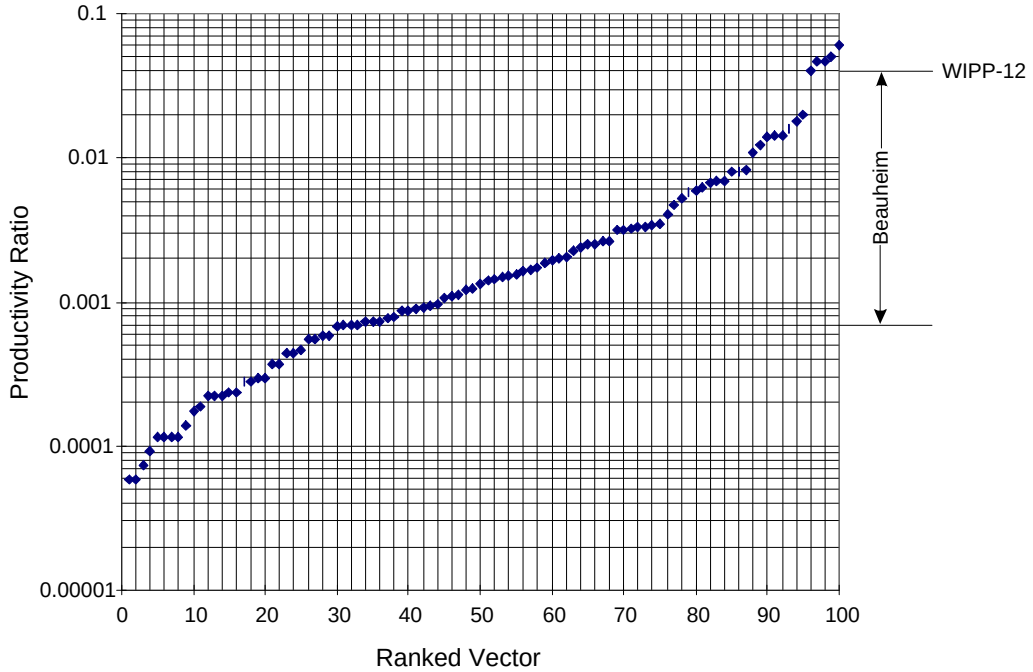

Figure 7.2. Productivity Ratio of the CCA for Replicate 1

7.3.1.1. Castile Brine Volume

Though unimportant as an individual concern in calculating the reservoir's function in the performance of the disposal system, the volume of the Castile brine may show the extent to which the reservoir attenuates underneath the repository. Chapter 5 of this report discusses the possibility of a higher probability associated with striking a pressurized brine reservoir. If the volume is grossly underestimated, then the likelihood of an encounter is low. The CCA values in the performance assessment used five different volumes: 32,000 m^3, 64,000 m^3, 96,000 m^3, 128,000 m^3, and 160,000 m^3. The smallest of these was calculated from WIPP-12 data assuming a compressibility of 5 x 10^{-12} Pa^{-1} and porosity of 0.008 (Larson and Freeze 1996). A maximum calculated reservoir volume of 64,000,000 m^3, based on a compressibility of 10^{-8} Pa^{-1}, was rejected by assuming either that multiple intrusions into the reservoir would deplete the availability of brine, or that the brine reservoirs were not interconnected with highly conductive fractures to produce a single large combined volume. It was theorized that small, highly pressurized brine reservoirs would produce higher brine flow to the repository than large depressurized pockets.

The report describing the WIPP-12 brine reservoir data (D'Appolonia 1983) lists a calculated volume of 2,700,000 m^3, based on pore compressibility values different from the CCA values (discussion below). When the range was suggested by Beauheim (1997) to be 100,000 - 1,700,000 m^3, the performance assessment calculations were already complete and the change was postulated to have no effect on compliance due to the single importance of the productivity ratio. However, new calculations should be performed to include a more reasonable brine reservoir volume from more relevant data.

7.3.1.2. Rock Compressibility of Castile Reservoir

The rock compressibility data for the performance assessment calculations were established on laboratory measurements of an Anhydrite III core from the WIPP-12 borehole, in-situ hydraulic testing of Salado anhydrite and halite, and textbook ranges (Freeze and Cherry 1979) of fracture rock compressibility. The compressibility was calculated from Equation 6-3 in (Beauheim et al. 1990),

$$C_r = \frac{1}{K + \frac{4G}{3}},$$

where K is the grain modulus (or bulk modulus) and G is the shear modulus. The bulk modulus of the Anhydrite III core was estimated to be 6.9x10^{10} Pa, but a value of shear modulus was not

known. It was determined that G was approximately 1/3 K for Salado anhydrites (Beauheim et al. 1990), and again was used in calculating the compressibility for Castile anhydrite. Hence, the core data indicates $C_r = 1x10^{-11}$ Pa. However, the range was changed based on hydraulic testing performed on Salado anhydrites and halites. The lower compressibility value in the CCA range was calculated to be $5x10^{-12}$ Pa^{-1}, and the upper value was from the textbook value of $1x10^{-8}$ Pa^{-1} based on the potential effects of the fracture on formation compressibility.

The compressibility was determined in an earlier report (D'Appolonia 1983) based solely on the bulk modulus and porosity from the equation,

$$C_r = \frac{1}{f\ K},$$

where ϕ is the porosity and ranges from 0.001 to 0.01 in Castile anhydrites. This definition of compressibility was derived from the basic understanding of the compressibility in porous media. The values for compressibility were calculated to be $1.45x10^{-7}$ Pa^{-1} to $2.9x10^{-9}$ Pa^{-1} with bulk moduli ranging from $6.9x10^{9}$ Pa to $3.45x10^{10}$ Pa. Therefore, it is possible that the range used in the CCA are too small. A larger value is suggested here, that would correlate with the volume to produce a productivity ratio of 0.04 m^3/Pa.

7.3.2. Castile Reservoir Pressure

The initial pressures of the Castile reservoir ranged from 11.1 MPa to 17.0 MPa in the CCA calculations based on observed data from four boreholes drilled to depths of the Castile formation. The WIPP-12 data were clearly the best measured values with a pressure at 12.7 MPa (Larson and Freeze 1996), but the range was extended to include the Covington (Figure 7.1.) and ERDA-6 data and adjusted for lithostatic pressures at the WIPP level. The adjusted range for CCA calculations should have been 11.1 MPa to 16.4 MPa, but was increased to 17.0 MPa. Although higher values are more conservative, the most reasonable value should be used. EEG used a fixed Castile reservoir pressure of 12.7 MPa.

7.3.3. Castile Reservoir Permeability

The permeability of the Castile reservoir ranged from $1.6x10^{-10}$ m^2 to $2.0x10^{-15}$ m^2 in the CCA calculations. The calculations performed by the EEG used slightly different values, ranging from $5.8x10^{-11}$ m^2 to $5.8x10^{-15}$ m^2. The new values used a median of $5.8x10^{-13}$ m^2 based on Beauheim (1997) and were increased and decreased by two orders of magnitude to create the upper and lower values in the range, to cover uncertainty. The role of the Castile permeability is relatively unimportant, and does not affect the amount of brine that eventually migrates upward to the Culebra. The flow of brine up the borehole is controlled by the borehole permeability.

However, the Castile brine movement will affect the amount of brine that will reach the repository to be released through a breach. With the small changes in this parameter, it is unlikely that it would have a significant affect on the new calculations.

7.3.4. Other Parameter Changes

Since the simulations using the changed parameters as suggested by the EEG would take a considerable amount of time to complete, it was reasoned that two additional parameters would be included in the Castile Simulation. The two parameters are waste permeability and waste room residual brine saturation, and each describe different processes of the repository.

7.3.4.1. Waste Permeability

The permeability of the waste in the repository was a constant in the CCA, equal to 1.7×10^{-13} m^2. This value was derived from consolidated waste made from sludge, combustibles, and metals. However, a peer review (U.S. DOE 1996-Appendix Peer 1) of the work found an error in the calculation and suggested a new value of 2.4×10^{-13} m^2. The new value will allow a higher brine flow through the repository, up the borehole, and to the surface. It will directly impact the amount of direct brine releases, and a constant value of permeability is more conservative than a range of values, which would incorporate lower values.

7.3.4.2. Residual Brine Saturation

The parameter for residual brine saturation is used in calculating the relative permeability of brine in the waste and to define the capillary pressure curves for the models of partial saturation. The number is expressed as a fraction between 0 and 1, and brine is immobile when the brine saturation is below the value of the parameter. Therefore, this parameter may be very important in postulating the amount of brine that will move through the waste area up the borehole to the surface. Numbers that are too large will inhibit brine movement.

The data used in calculating the residual brine saturation in the CCA does not relate to any material from the waste or the disposal system. Instead, the data are typical values from literature for unconsolidated material, ranging from 0.0783 to 0.560. However, the largest value in the range is from a consolidated sandstone. The EEG believed that this value should be ignored, and the range reduced with an upper value of 0.318 (from fragmented sandstone). The EEG has since concluded that the original range used in the CCA was appropriate and that the calculations performed in this analysis are conservative, due to the consolidation of waste after creep closure of the rooms.

7.4. Methodology

The objective of the new calculations was to determine the change in the amount of radionuclide release from the repository due to the changes in the Castile reservoir and waste area parameters. This was accomplished by (1) running BRAGFLO to determine the brine saturations, pressures, and repository porosities, (2) running CUTTINGS to determine the amount of solid material that would be brought to the surface and to establish initial conditions to be used in BRAGFLO_DBR and (3) running BRAGFLO_DBR, which uses the data from CUTTINGS and BRAGFLO to calculate the volume of brine released from the repository. Each code required a set of separate steps to run, and are presented below.

7.4.1. BRAGFLO Calculations

The only changes in running the suite of codes was in BRAGFLO. Table 7.1. lists the parameters and the values that were used in the CCA, suggested ranges by Beauheim (1997),

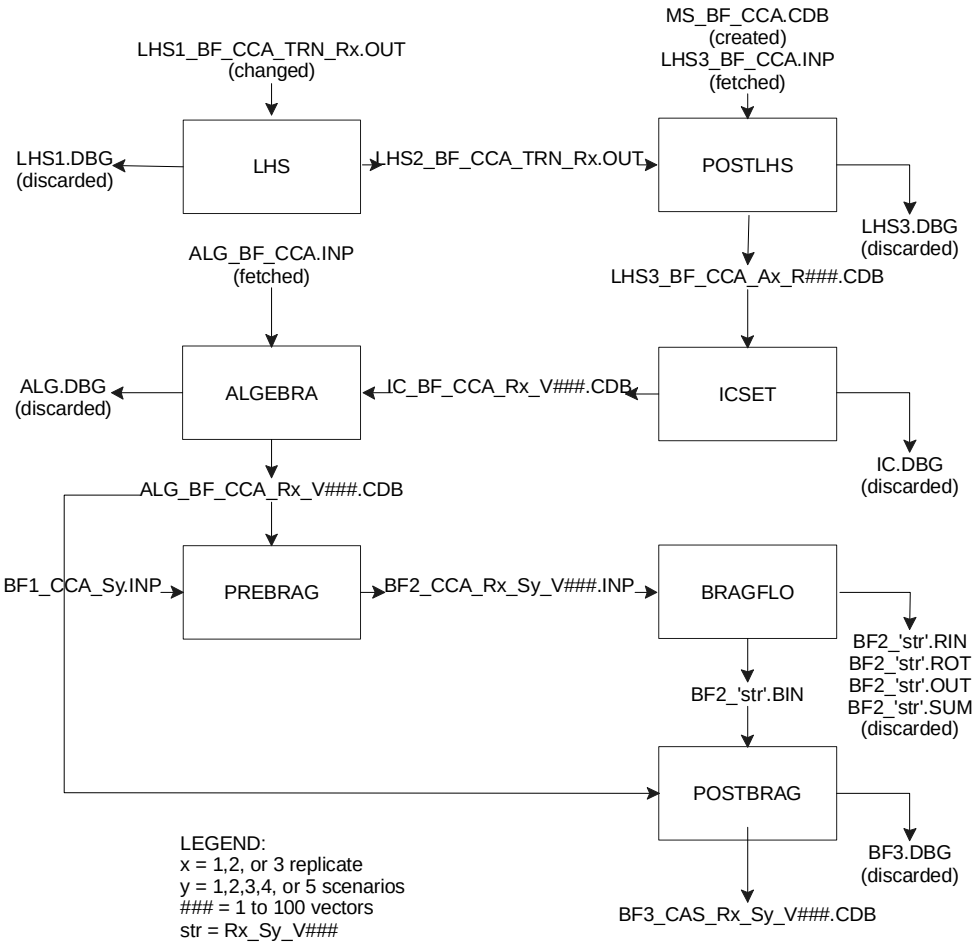

Figure 7.3. Flowchart for BRAGFLO Calculations

Simulation	Log Reservoir Permeability (log m^2)	Initial Pressure (MPa)	Log Rock Compressibility (log Pa^{-1})	Reservoir Volume (m^3)	Waste Permeability (m^2)	Waste Room Residual Brine Saturation
CCA	-9.8 to -14.7	11.1 to 17.0	-8 to -11.3	32,000 to 160,000	1.7×10^{-13}	0 to 0.552
Beauheim (1997)	-10.2 to -14.7	11.1 to 16.5	-9 to -10.7	100,000 to 1,700,000	NA	NA
EEG*	-10.23 to -14.23	12.7	-8.66*	160,000*	2.4×10^{-13}	0 to 0.318

Table 7.1. Castile Reservoir Parameter Suggestions

*BRAGFLO only allowed the choice of 5 volume sizes: 32,000 m^3, 64,000 m^3, 96,000 m^3, 128,000 m^3, and 160,000 m^3. The largest volume size available was chosen and the compressibility was calculated based on a productivity ratio of 0.04 m^3/Pa. The porosity for the calculation remained at 0.0087. If the recommended volume of 2,700,000 m^3 could have been chosen as the measured size, then the log compressibility value would be -9.88 log Pa^{-1} (1.28×10^{-10} Pa^{-1}).

and the new range for the present EEG calculations.

The changes in the simulations started at the LHS files. The values and ranges were modified to reflect the new selected parameters. Figure 7.3. shows the flowchart of the BRAGFLO suite of codes and where the changes were made. The massive amount of files created from the

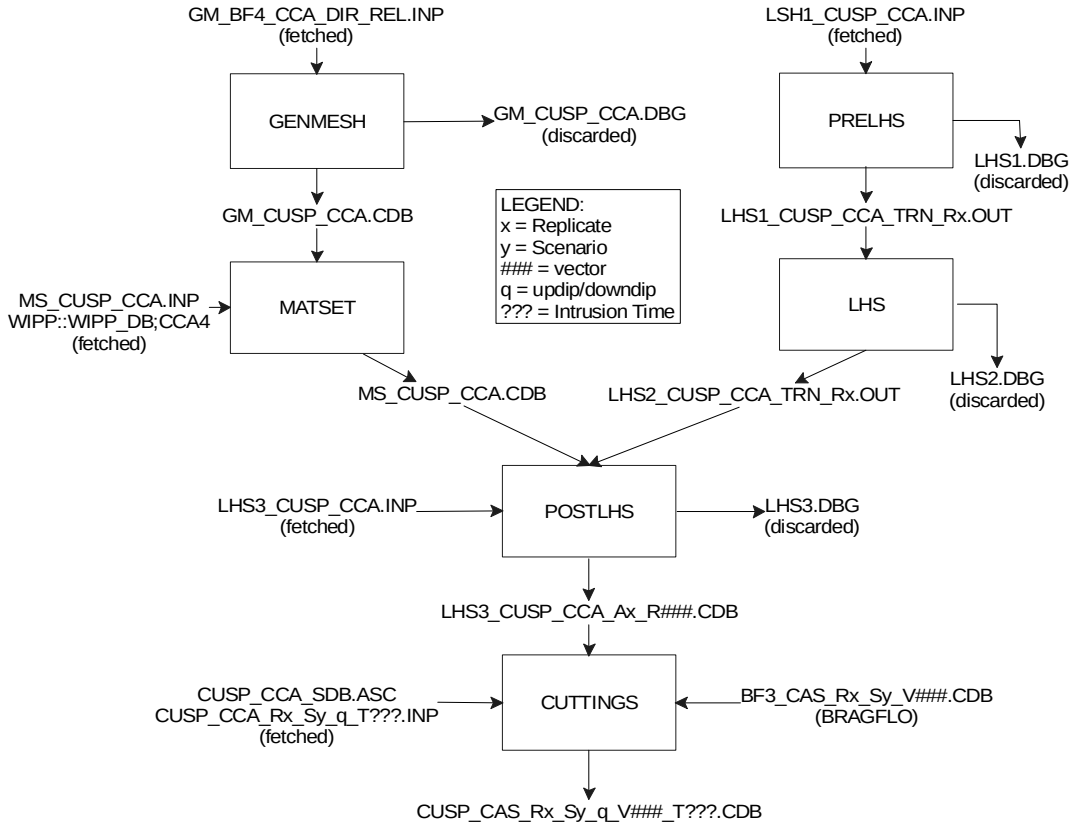

Figure 7.4. Flowchart of CUTTINGS_S Simulations

simulation allowed only two files from each vector to be retained, the postprocessed BRAGFLO file, BF3_CAS_R1_Sy_V###.CDB and the input file for BRAGFLO, BF2_CAS_R1_Sy_V###.INP, where 'y' is the scenario and '###' is the vector number. Both files are important to running other codes.

Due to time and disk space constraints, only two scenarios of one replicate could be simulated. The two scenarios, S2 and S3, deal with an E1 intrusion. The E1 intrusion describes the possibility of a drill intrusion through the repository to the pressurized brine pockets below. The remaining four scenarios would be unaffected by the changes in Castile brine reservoir parameters, but would show slightly different releases due to the waste area parameter changes.

7.4.2. CUTTINGS_S Calculations

The release of solid materials from a drill intrusion was calculated in CUTTINGS_S. The code extracted information from the BRAGFLO simulation to establish the amount of material brought to the surface. Figure 7.4. shows the steps involved in running the CUTTINGS_S suite and where the BRAGFLO output file is read.

As explained in Chapter 2, the CUTTINGS code calculates the effects of a drill intrusion at other times than specified by the scenario number. An S2 scenario assumes an E1 initial intrusion at 350 years, and uses that information to calculate an E2 intrusion at 550, 750, 2,000, 4,000, and 10,000 years. The S3 scenario assumes an E1 initial intrusion at 1,000 years, and calculates an E2 at 1,200, 1,400, 3,000, 5,000, and 10,000 years. The large number of time intrusions allow the CCDFGF code to scale the releases over the 10,000 year future of the repository.

The CUTTINGS_S code also calculates an intrusion into two areas of the repository. The repository is on a 1° slope to the south, and is divided into updip and downdip regions. The downdip includes Panels 4 and 5, whereas the updip includes Panels 1,2,3,6,7,and 8. It is suspected that the downdip panels will fill with brine sooner than in the updip due to gravity, producing a higher activity of gas generation from corrosion and microbial activity. The gas generation will increase the pressures in that area until pressure is equilibriated with the surrounding rock. If the repository is breached, the downdip region should release more waste and brine to the surface. The updip portion of the repository remains virtually closed off from the downdip as a result of creep closure and low permeability of waste, thus prohibiting migration of brine to the area. Therefore, a totally separate calculation is performed for the two areas.

Unlike the other two codes in the sequence, CUTTINGS_S also indirectly calculates the amount of radionuclides released to the surface. Therefore, the files are retained for input to the CCDFGF code for probability assessment.

7.4.3. BRAGFLO_DBR Calculations

Lastly, the BRAGFLO_DBR code is used to calculate the amount of brine released directly to the surface. The code uses the CUTTINGS and BRAGFLO results for initial conditions and extracts the parameters needed for calculations. Figure 7.5a. and Figure 7.5b. lists the configuration of a direct brine release calculation. The time intrusion calculations for the direct brine release are the same as for CUTTINGS.

The direct brine release calculation uses only the downdip CUTTINGS files. The downdip panels have higher pressures, producing higher saturations and releases. However, releases are not calculated for every simulation. Some vectors do not result in a release, i.e., the pressures and/or saturations in the repository may not be high enough to overcome the column of drilling

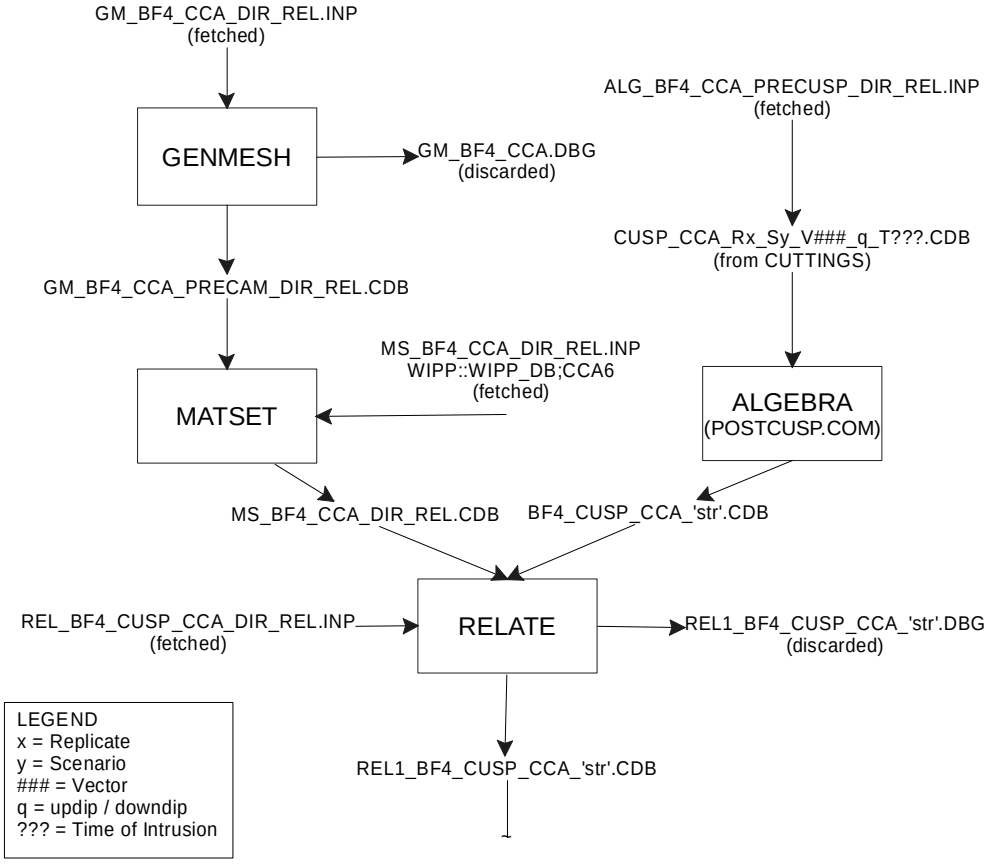

Figure 7.5a. Flowchart of BRAGFLO_DBR

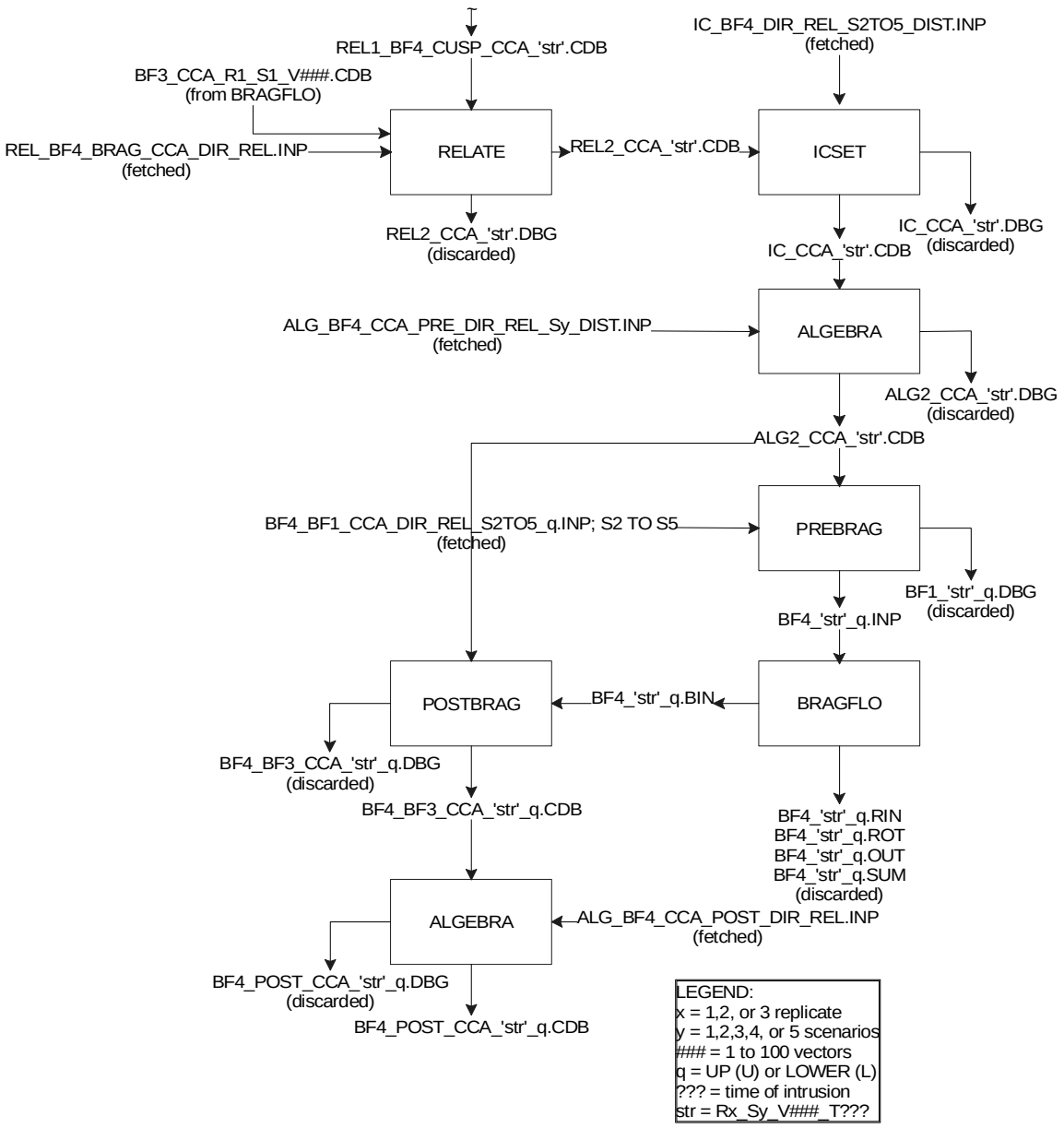

Figure 7.5b. Flowchart of BRAGFLO_DBR (cont.)

mud or there may not be an availability of brine due to consumption from corrosion or microbial activity. Those that do qualify undergo a 50 day simulation, with blowout lasting a minimum of three days. This is the estimated time it takes to drill through the repository to the Castile reservoir and cement the casing. If there is a significant amount of gas flow from the repository, the driller may lose control and brine releases may last longer. The releases will accumulate until the gas flow rate drops below an arbitrary value, set to 100,000 ft^3/d in the CCA calculations. The maximum blowout duration is 11 days, and is based on the time it took to control the South Culebra Bluff Well Unit # 1, which blew on January 1978 (Stoelzel and O'Brien 1996).

7.5. Results

The results of the amount of brine released to the surface are as predicted. With an increase in productivity ratio and waste permeability, coupled with a decrease in the range for residual brine saturation, an overall increase in the volume of brine was observed to be released.

7.5.1. BRAGFLO Results

7.5.1.1. The Repository

The BRAGFLO calculations performed on the two scenarios that modeled intrusion into the Castile reservoir showed higher brine pressures and higher brine volumes in the repository than what was modeled in the CCA. Higher pressures will allow more releases from spall and direct brine release. Higher brine volumes indicate more brine to (1) corrode waste containers, which will produce high pressures, and (2) be released through a direct brine release scenario. Though more brine with less gas would intuitively indicate more releases to the surface, a limit is seen, after which this is not the case because gas is needed to drive the brine up the borehole. If pressurized gas is eliminated, then no brine would reach the surface without pumping.

The results of the BRAGFLO simulations were postprocessed by codes described in the Analysis Package, Task 1 (Bean et al. 1996). The codes calculated average values in each area of the repository for elemental cells and created a total of 215 time history variables (pressure, saturation, volume of brine consumed, etc.) that were plotted in SPLAT (CMS plotting program). The results herein mainly use the average value for all vectors as comparison.

Figure 7.6. shows a comparison of repository pressures in the waste area of the Castile simulation to repository pressures of the CCA. The figure shows two plots. The left plot shows the mean results of an E1 intrusion at 350 years for both simulations, and the right shows the mean results with an intrusion at 1,000 years. The pressures are averaged over the entire volume of the waste area only, and excludes pressures from the operations and experimental regions. It is clearly evident that both plots in the figure show higher pressures for the Castile Simulation. The difference between the Castile Simulation and the CCA in average pressures at 350 years for S2 is approximately 3.25 MPa. The pressures rise sharply up to the intrusion point due to gas generation from the availability of iron in the waste and waste containers, and from the organics (cellulosics, rubber, plastic, etc.). After intrusion, the borehole is assumed to be plugged immediately, with plug lifetime lasting 200 years. Once the plug degrades, the gas in the repository is vented, until eventually creep reduces the borehole permeability at 550 years postclosure, allowing pressures to rebuild until most of the cellulosic inventory is exhausted

(around 1,500 years). A steady decline in pressure for the remaining 8,500 years is noticed, with the Castile simulation always being at least 1.8 MPa higher.

The simulation with the intrusion borehole entering the Castile Formation at 1,000 (S3) years exhibits similar behavior as the S2 scenario. The pressure builds in the repository until gas and brine is allowed to escape. The pressure declines after plug degradation, and rebuilds until all organic material is consumed. The pressures eventually decrease steadily for the remaining time of the repository history. The differences in the Castile simulation and CCA, though not as drastic as the previous S2 simulation, are still substantial. The differences are around 1.75 MPa at the time of intrusion, and decrease to 1.3 MPa around 10,000 years. The higher pressures in the repository of S3 compared to S2 would indicate higher releases to the upper layers above the repository and to the surface, and will be discussed later.

The higher pressures are a result of more brine entering the repository from the Castile brine reservoirs' below. The brine mixes with the waste and degrades the organic material, which produces gas. Figure 7.7. shows, for both scenarios, the amount of brine entering the whole repository from the Castile reservoir. The flow of brine from the Castile up the borehole to the repository is an effect of the high differential pressure between the Castile and repository. The values were calculated by subtracting the net inflow of brine from the marker beds and the brine volume consumed through corrosion and degredation. Again, both plots show a higher amount of brine entering the repository from the Castile simulation. This may be from the combination of the set constant value of 160,000 m^3 for Castile Reservoir volume and productivity ratio. The CCA used a range from 32,000 to 160,000 m^3, with a 1/32 chance of getting the 160,000 value

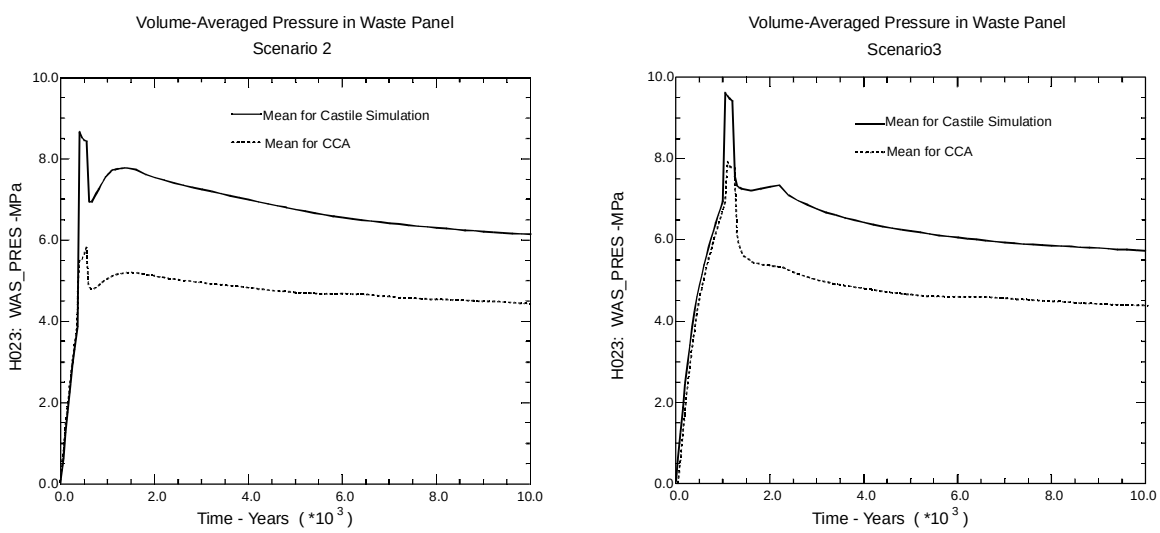

Figure 7.6. Volume Averaged Pressures of 10,000 Year Time History for Left) Scenario 2 and Right) Scenario 3

for volume and a range of 0.0007 to 0.04 m^3/Pa for productivity ratio.

The differences in the two simulations are very notable, varying by as much as 20,000 m^3 in S2. Both simulations also follow the same pattern. For the scenario of borehole intrusion at 350 years, the repository quickly fills with brine after closure, decline linearly as brine is consumed through corrosion of iron and degradation of organics. When the intrusion borehole hits the brine pockets below the repository, it fills at a higher rate until a pressure equilibrium is reached between the repository and brine pockets. A steady decline marks the remaining future of the repository, with minor amounts of brine being consumed and the rest being leaked to the stratigraphic units that lie above the repository and minor amounts flowing back down the borehole to the reservoir.

The S3 scenario behaves slightly differently from S2 with less total brine entering the repository. After the intrusion at 1,000 years, the amount of brine does not immediately decrease, but increases slightly for approximately 1,000 years (between 1,000 and 2,000 years postclosure). The gain of almost 2,000 m^3 of brine in both the CCA and Castile Simulation can be attributed to the pressure recovery seen in Figure 7.6. After the intrusion, the pressure for S3 does not recover like that seen in S2, allowing more brine to enter, and pressure equilibrium is reached approximately 500 - 1,000 years after intrusion (1,500 to 2,000 years postclosure). The mean

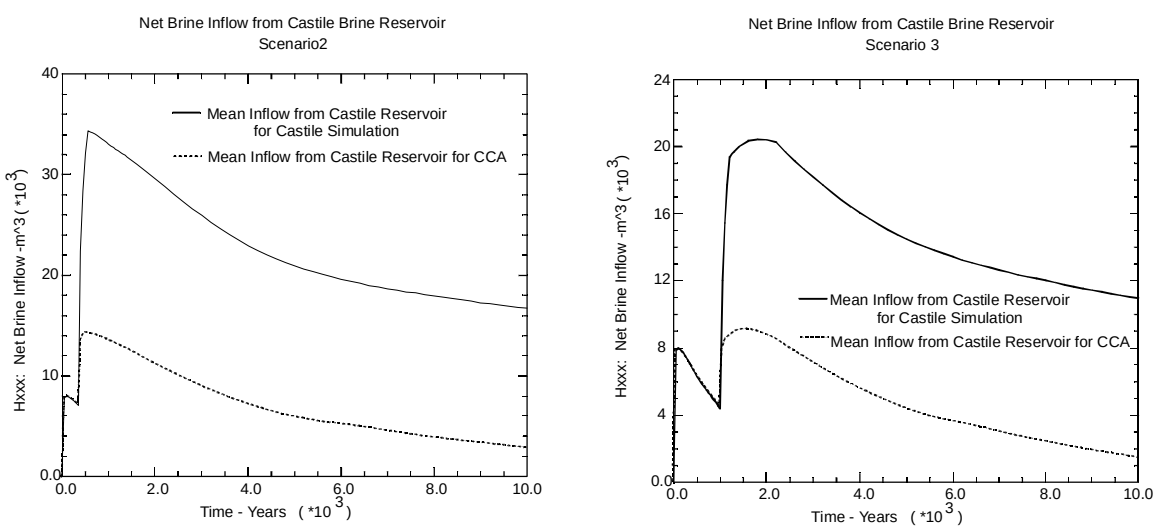

Figure 7.7. Net Inflow of Brine from Castile Reservoir for CCA and Castile Simulation for Left) Scenario 2 and Right) Scenario 3

	S 2		S 3	
	CCA	Castile	CCA	Castile
Fraction of Steel Remaining after 10000 years	55.06	42.04	57.60	50.59
Fraction of Cellulose Remaining after 10000 years	50.02	50.01	50.02	50.01

Table 7.2. Fraction of Steel and Cellulosics Remaining after 10000 Years
for CCA and Castile Simulations for S2 and S3

pressure curves of Figure 7.6. are dominated by vectors that exhibit low corrosion rates in that region.

With the inflow of brine to the repository, gas volumes also soar after intrusion. Figure 7.8. shows total mean of gas volumes generated from corrosion and microbial degradation (both humid and inundated) for the CCA and Castile simulation for Scenarios 2 and 3. The Castile simulation follows the CCA's calculated gas volumes before the intrusion, then increases significantly there after. The increase in the amount of brine reaching the repository has a direct effect on the amount of gas generated, as seen in the figure. As the Castile simulation allows more brine to enter the repository, more gas is generated. Even though microbial decay ceases for the most part after 1500 years, corrosion of the steel drums continue for the entire 10,000 years. The fraction of steel and cellulosics remaining after 10,000 years can be seen in Table 7.2. The amount of steel remaining for the Castile simulation offers a good insight on the differences seen in Figure 7.8.

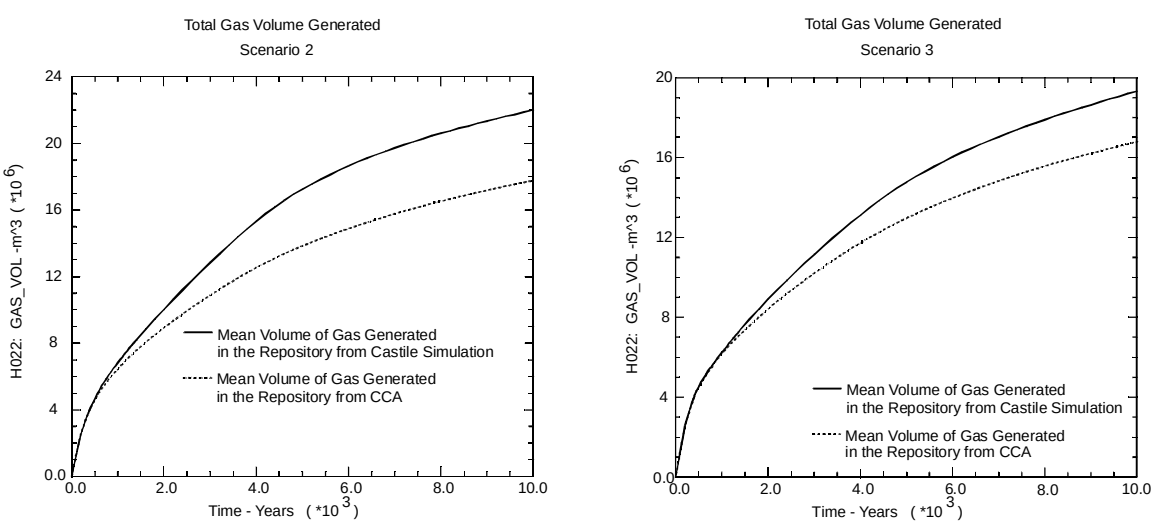

Figure 7.8. Total Gas Volumes Generated from Corrosion and Microbial Degradation for CCA and Castile Simulation for Left) Scenario 2 and Right) Scenario 3

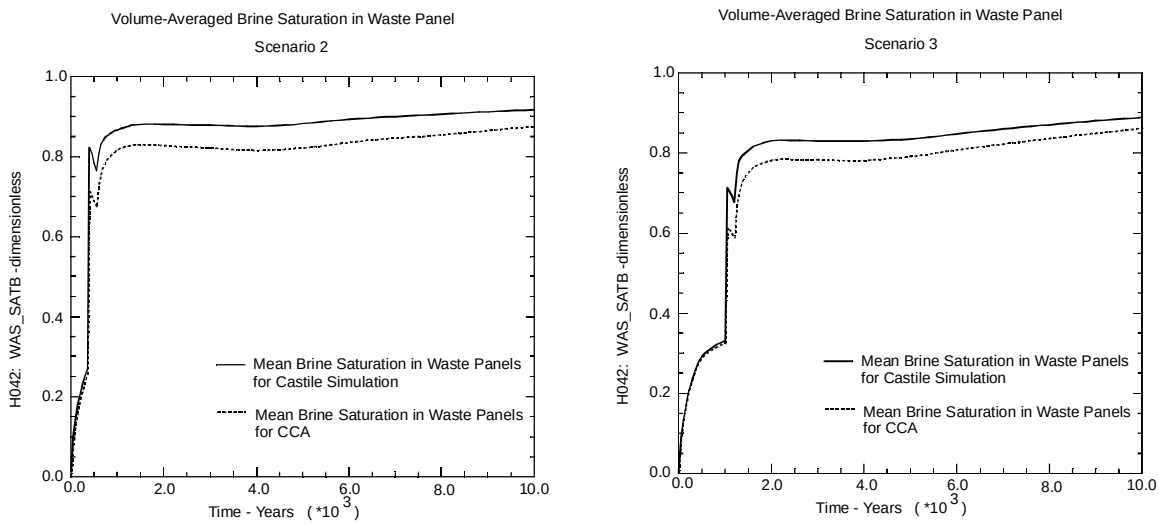

Figure 7.9. Volume Averaged Brine Saturation in Waste Panels for CCA and Castile Simulation for Left) Scenario 2 and Right) Scenario 3

Lastly, the saturation of brine plays an important role in the availability of gas as a mechanism for pushing the brine out through the borehole. Figure 7.9. shows how the fraction of brine as compared to gas increases through time, as brine enters from the Castile reservoir. The Castile simulation follows the CCA up to the time of intrusion for both scenarios, with the Castile simulation increasing in saturation after intrusion. The differences between the Castile simulation and the CCA are around 0.1 at the time of intrusion, but remain at 0.05 for the rest of the time history of the repository for both scenarios. The availability of brine to be released is definitely increased in the Castile simulation, but Figure 7.9. may indicate that the ratio of brine to gas may be too high to push the brine up the borehole.

7.5.1.2. Fluid Flow through the Borehole

The flow of brine and gas up the borehole to the upper stratigraphic members is linked closely to the values for permeabilities selected by the LHS code. Following the intrusion, brine and gas from the repository move up and/or down the borehole, depending on the pressures, permeabilities, and the time of occurance. Figure 7.10. shows the cumulative brine flow up the borehole to the top of the panels. The individual vectors are represented here to demonstrate the influence of chosen parameters on the system.

The discharge of brine out through the borehole to the units above the repository for the Castile simulation is higher than what was calculated in the CCA. The CCA's maximum release was 22,500 m^3 for S3 with only four vectors releasing above 4,000 m^3. This is about 14,000 m^3 less than the Castile simulation's maximum release, which had 20 vectors above 4,000 m^3. The vector showing the highest release in Figure 7.10. for the Castile simulation, Vector 23, is the

same vector with the highest release in the CCA, indicating the physics of the system is roughly the same.

Scatter plots of permeability versus brine discharged up the borehole to the top of the waste panels reveal that the permeability of the degraded concrete plug, BH_SAND, is more closely related to the discharge than any other permeability investigated, with a correlation coefficient (r^2) of 0.846. This indicates that as the permeability of the degraded borehole plug increases, the amount of brine flowing upwards increases. Figure 7.11. shows four scatter plots, using sampled permeabilities from different regions of the disposal system with the correlation coefficient located in the lower right-hand corner of each plot. The figure shows, from upper left to lower right, 1) the plots for permeability of degraded borehole, 2) Castile reservoir, 3) surrounding undisturbed halite, and 4) Marker Bed 139. The scatter plot is for the Castile simulation, Scenario 2 only. It is interesting to note that when the vector of highest brine flow is removed (Vector 23-36,000 m^3), the r^2 for BH_SAND increases to 0.912, and the other three essentially become zero.

Once the brine passes the top of the repository, it moves further up the borehole to the Culebra and eventually to the surface. However, as it moves upward, the brine loses energy through interactions with the borehole wall and overcoming the gravitational effects, and many of the vectors do not make it to the upper layers. Figure 7.12. shows the flow of brine in the borehole to the top of the Rustler Formation. Similar to Figure 7.10., this figure shows the individual vectors for S2 and S3 of the Castile simulation only. The figure reveals that little to no brine makes it this high up the borehole, with a maximum of 1.55 m^3 for S2 and 5.0 m^3 for S3. Further investigation shows that no brine reaches the surface for either scenario. Figure 7.12. shows

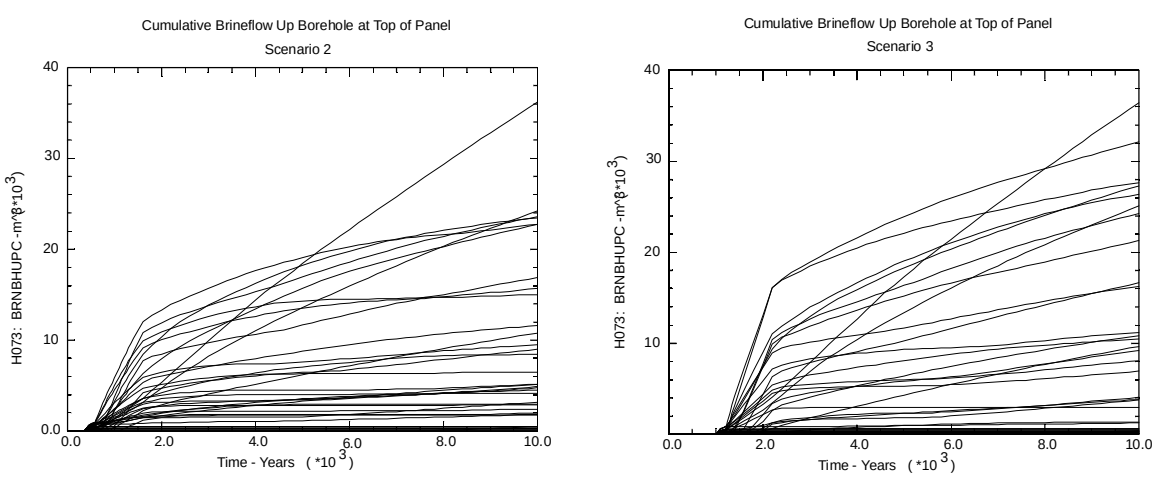

Figure 7.10. Cumulative Brine Flow up the Borehole from Waste Panels to the Top of the Panel for Castile Simulation of Left) Scenario 2 and Right) Scenario 3

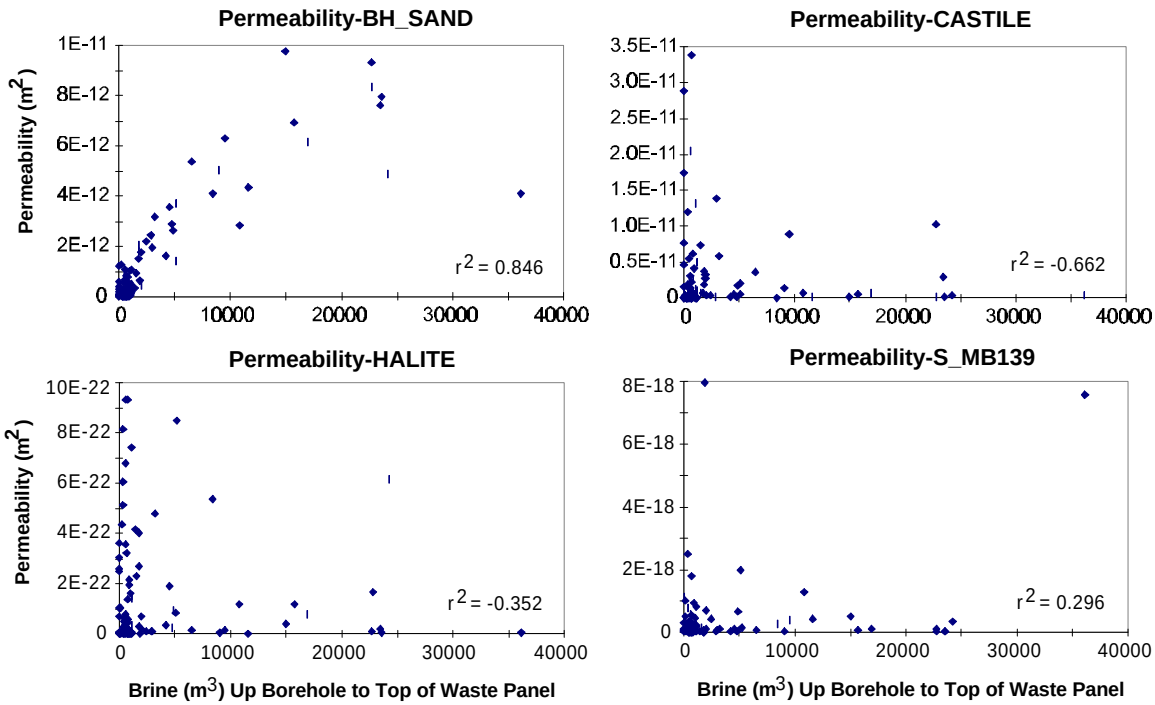

Figure 7.11. Scatter Plot for Volume of Brine Reaching the Top of The Waste Panels through an Intrusion Borehole and Permeabilities from Regions of the Disposal System with Permeabilities Described from Upper Left to Lower Right: 1) Degraded Concrete Plug (Silty-Sand), 2) Castile Reservoir, 3) Halite that does not Include the Disturbed Rock Zone (DRZ), and 4) Marker Bed 139

that if the brine can make it as far as the Dewey Lake Formation, it does so very quickly, with S3 contributing more brine than S2 due to the pressure differences in the two simulations.

The flow of brine up the exhaust shaft is considered minimal when compared to the borehole. At most 49 m^3 flowed up the shaft to the Salado, with no brine reaching the Rustler Formation for the Castile simulation. This is comparable to the CCA, which only had a maximum of 48 m^3 of brine up the shaft, because the assumption of pressure, borehole permeability, and the mechanisms of loss of pressure were the same.

7.5.2. Cuttings, Cavings, and Spallings Results

The borehole and solid waste material removal were calculated using CUTTINGS_S, a cuttings and cavings code that also incorporates spallings. The CCA identified both mechanisms as major contributors to radionuclides reaching the accessible environment, and calculations were made to quantify the effects of both. The following discussion compares results of the CCA to those calculated by changing the Castile reservoir parameters.

7.5.2.1. Cuttings and Cavings

The cuttings and cavings calculations were performed at several times throughout the repository future. Section 7.4.2. lists the times that were used for borehole removal. At each time calculation, the amount of material removed through cuttings and cavings were the same for the CCA and the Castile simulation. Since the parameters for cutting rate, depth, drill bit size, and waste characteristics remained the same in both simulations, the values for this mechanism of waste removal also remained the same.

The CUTTINGS_S code was only concerned with the actual waste from the repository that was brought to the surface, and not the cuttings or cavings from the borehole of inert stratigraphic material (uncontaminated geologic material) above the repository. Figure 7.13. shows the volume of material brought to the surface from cuttings and cavings for 100 vectors versus waste shear strength for Scenario 2, at 4,000 years after the repository is closed. However, this figure is representative of all times for both S2 and S3, and the waste shear strength will be discussed below. The cuttings volume of material was calculated by

$$V = AH\,(1-\varphi),$$

where A is the area of the drill bit, H is the compacted repository height (calculated from BRAGFLO), and φ is the porosity at the time of intrusion. The volume of cavings is much more complicated, involving an iterative method to find the final borehole radius from erosion of material due to turbulent flow of mud between the drill collar and the borehole wall. Total volume for both mechanisms, as seen in Figure 7.13. is 2.86 m^3, with a mean volume of 0.606 m^3 and a median volume of 0.508 m^3. For the CCA, the approximate average compacted room height was 1.3 m and waste panel porosity was 0.52. Therefore, the cavings portion contributed roughly 90% to the total volume extracted.

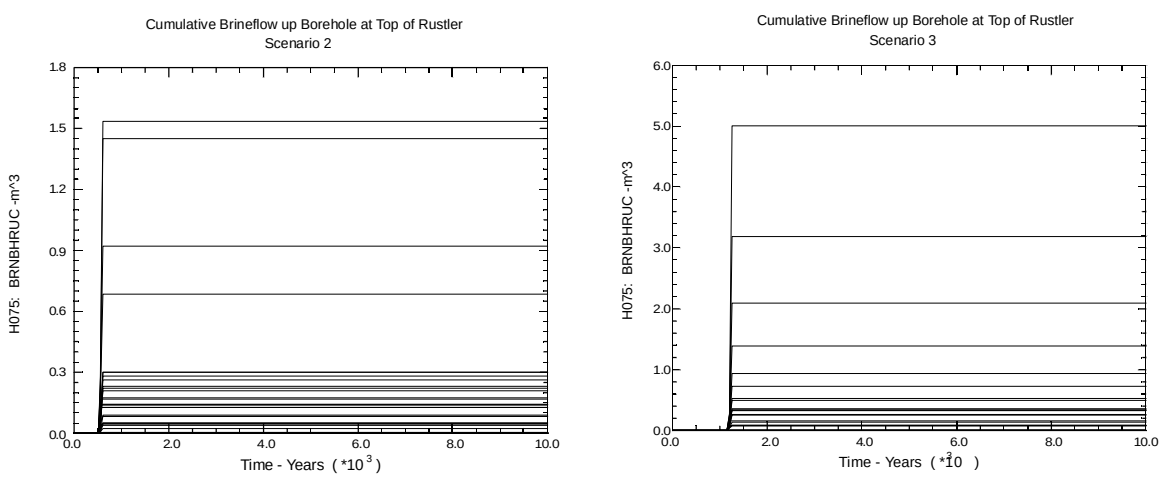

Figure 7.12. Brine Volume (m^3) Reaching the Top of the Rustler Formation for Castile Simulation for Left) Scenario 2 and Right) Scenario 3

The volume of material through cavings is linked closely to waste shear strength, by the relationship,

$$R_1 = R_o - \frac{\tau_o - \tau_{fail}}{\frac{d\tau}{dR}\Big|_0},$$

where R_1 is the eroded radius, R_o is the radius of the borehole, τ_o is the borehole wall shear stress, and τ_{fail} is the material shear stress (Berglund 1996). Intuitively, as the waste shear stress decreases, the radius of the borehole wall increases, allowing higher volumes of waste to be brought to the surface. The CCA range, as seen in Figure 7.13. uses a uniform distribution to describe possible values of waste shear strength between 0.05 Pa and 10 Pa. Small values of shear strength are destructive to the system, with values below 1.0 Pa contributing to the major releases. Future simulations should use a loguniform distribution to describe the possible values of shear strength that vary by over an order of magnitude.

7.5.2.2. Spallings

The calculation of spalled material from the borehole only included the possibility of blowout, and dismissed stuck pipe and gas erosion by the estimation of a cutoff level for waste permeability in which values above the cutoff will reduce the probability of the two phenomena from happening. The cutoff permeability was 10^{-16} m^2 (See CUTTINGS_S Manual for additional information on stuck pipe and gas erosion (Berglund 1996). The waste permeability in the CCA was 1.7×10^{-13} m^2, but was calculated incorrectly and thus updated for the Castile simulation to be 2.4×10^{-13} m^2. If waste permeability were to fall within the region of stuck pipe and gas erosion (below the

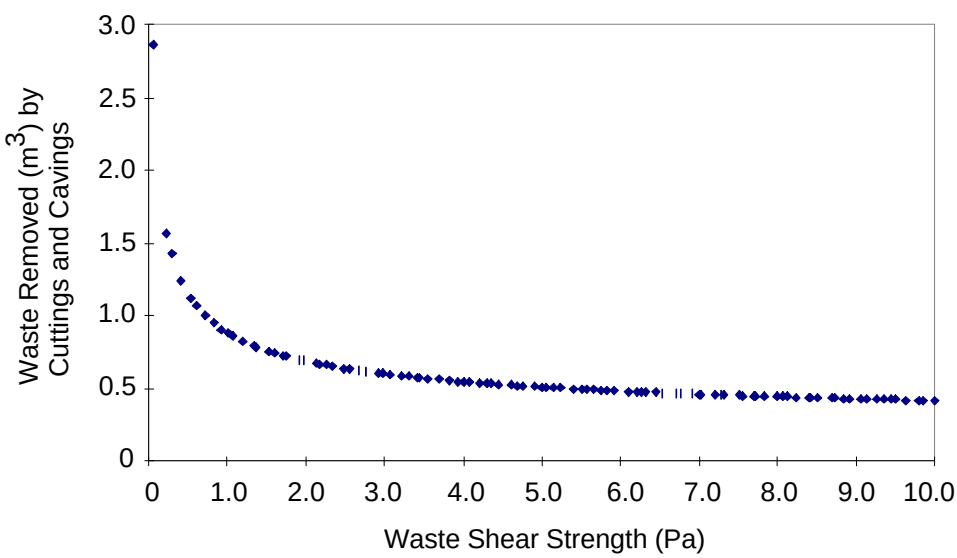

Figure 7.13. Waste Removed (m^3) by Cuttings and Cavings vs. Waste Shear Strength, Scenario 2, at Time 4000 Years Post Closure

arbitrary limit of 10^{-16} m^2 with pressures above hydrostatic), releases could range between 43 to 365 m^3 (Berglund 1996), 100 times the releases of cuttings and cavings.

The spallings calculations in the CCA were proven to be flawed, but the values of the blowout volume were accepted as being reasonable by the DOE's Conceptual Model Peer Review Group (Wilson et al. 1997). The CCA had a maximum blowout release of approximately 4 m^3. The Castile simulation did not exhibit larger releases, though it did have more realizations with blowout occurring, with at least twice as many occurrences at each time intrusion calculation than in the CCA. Figure 7.14. shows a frequency distribution of the number of blowout realizations versus blowout volume. The figure is for S3 at a calculated time intrusion of 1200 years into panel 5 (downdip intrusion). The time, scenario, and borehole location was chosen to display the maximum number of releases. As the average pressure drops, the number of realizations that produce a blowout also drops, as seen in Figure 7.6.

The figure of spalled volume should not be taken as a literal interpretation of the actual spalled volume that will be ejected from the borehole. The conceptual model for the code was proven inadequate, and the calculated results do not reflect the correct volumes. It does show, however, that the Castile simulation exhibits higher pressures than calculated in the CCA, causing CUTTINGS_S to calculate more releases. Experiments on a new code, after the submittal of the CCA, showed the spalled volume would be no more than 0.25 m^3 for WIPP conditions (Hansen et al. 1997). The results of Hansen et al. (1997) showed that the values obtained in the CUTTINGS_S were higher, therefore they were believed reasonable by the Conceptual Models Peer Review Group (Wilson et al. 1997). Chapter 9 of this report explores the analysis of Hansen et al. more closely.

7.5.3. Direct Brine Release

Once an intrusion breaches the repository with sufficient pressures from gas generation, the brine in the waste will move towards the cavity and be expelled out of the borehole. The pressure near the borehole or flowing bottom hole pressure (FBHP) must be above hydrostatic, in this case 8 MPa (density of brine = 1215 kg/m^3, length of borehole = 655 m, and friction = ~0.2MPa). The amount of brine ejected from the waste panels range from a few thousandths of a cubic meter up to a few tens of cubic meters. Figure 7.15. shows a frequency distribution of brine released to the accessible environment for all time intrusions for both the CCA and the Castile simulation of Scenarios 2 and 3. The Castile simulation, as one might expect, has higher releases than in the CCA.

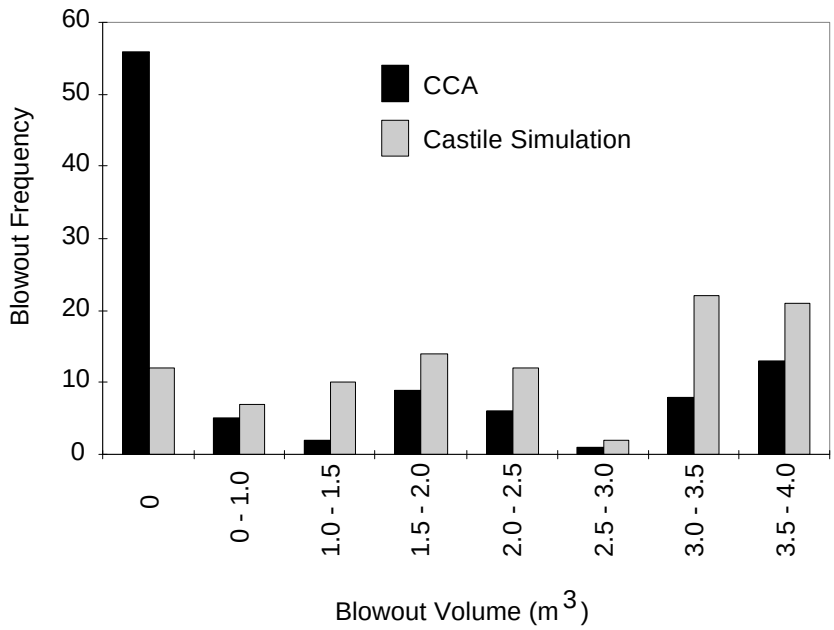

Figure 7.14. Frequency Distribution of Spalled Blowout Volume from an Initial Intrusion at 1,000 Years (Scenario 3) and a Subsequent Intrusion into Panel 5 at 1,200 Years with both CCA and Castile Simulation Values Displayed

The brine releases from an intrusion borehole is directly related to the repository pressure and brine saturation. Figure 7.16. shows the two relationships as scatter plots of brine release vs. pressure on the left and brine release vs. saturation on the right. The plots are for S3 at 1,200 years post closure of the Castile simulation. The first striking feature of the figure is the relationship between the volume of brine released and pressure. The releases are zero for pressures less than 8 MPa and increase linearly from 8 to 9 MPa. At 9 MPa, the releases sharply increase, and then decrease to nearly zero again for pressures above 9 MPa. This is a unique feature of this simulation and is only observed in early times of the repository's projected history. A similar feature is noticed at 1,400 years, but essentially dissolves at 3,000 years and beyond. A possible explanation for the phenomena is the control that the Castile reservoir pressure has on the repository in early times. Since the Castile reservoir pressure is constant in all 100 realizations, the pressure in the repository is directly affected by the amount of brine flow to the repository.

However, the pressure in the repository is affected by other key parameters as well, and not just by the amount of brine flow from the Castile reservoir. Figure 7.17. shows a scatter plot of pressure in the repository for S3 at 1,200 years post closure for the Castile simulation versus the inundated steel corrosion rate. As the corrosion rate increases, the pressure increases, and again is dependent on a third parameter. The probability of degradation of cellulosics, plastics and rubbers separates the scatter plot into two regions. The parameter, PROBDEG, is the

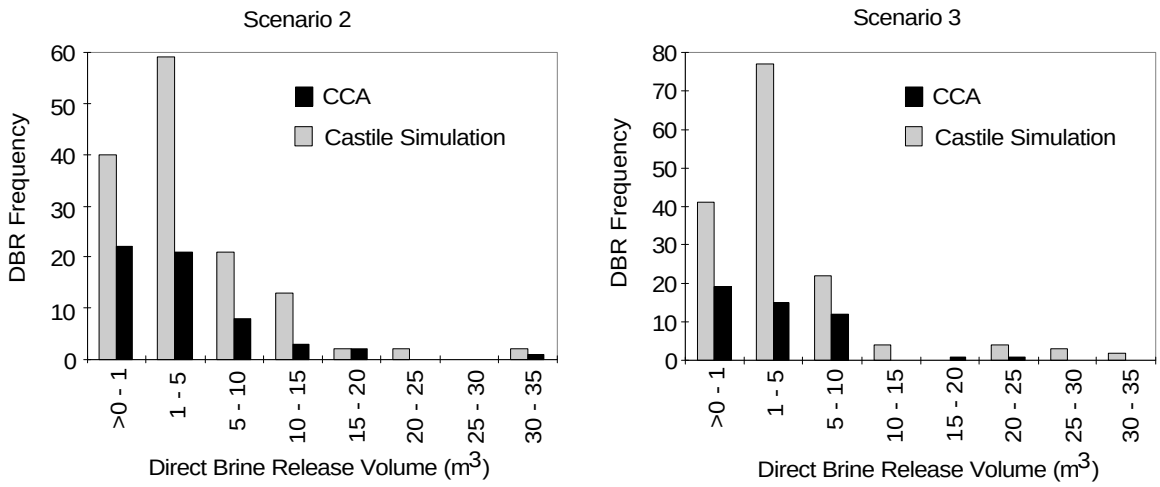

Figure 7.15. Frequency Distribution of Direct Brine Release Volumes (m^3) for CCA and Castile Simulation for Left) Scenario 2 and Right) Scenario 3

second LHS sampling variable, and can have values of 0, 1, or 2. A “0” indicates no microbial degradation of organic material and has a probability of 50%. The selection of “1” means that only the cellulosics will degrade, and “2” denotes cellulosics, plastics and rubber will degrade, with a 25% probability each. The region of high pressure in Figure 7.17. is from a PROBDEG of 2. These diamonds are black, meaning there was no significant direct brine release. The gray diamonds indicate a notable brine release, which fall in the region of pressures seen in Figure 7.16. to have the major releases. Excluding those realizations with a PROBDEG of 2, the plot has a correlation coefficient of 0.68, and a correlation coefficient of 0.67 considering only those with a PROBDEG equal to 2. This is higher than the coefficient of 0.14 if all realizations are included.

Relating back to Figure 7.16. and the second plot with brine release versus waste panel brine saturation: the optimum brine saturation for large release is approximately 0.65 with minimal releases above 0.85 and no significant releases below 0.4. The saturation can be thought of as a brine to gas relationship. If too much gas (low saturation) is present, then the availability of brine to be ejected is limited, and is directly related to the extremely high pressures and corrosion rate of Figure 7.17. Also, if there is too much brine and not enough gas, the pressures in the repository will not be high enough to lift the brine out of the borehole. Therefore, an optimum (or detrimental) saturation is observed for the Castile simulation at early times after the intrusion.

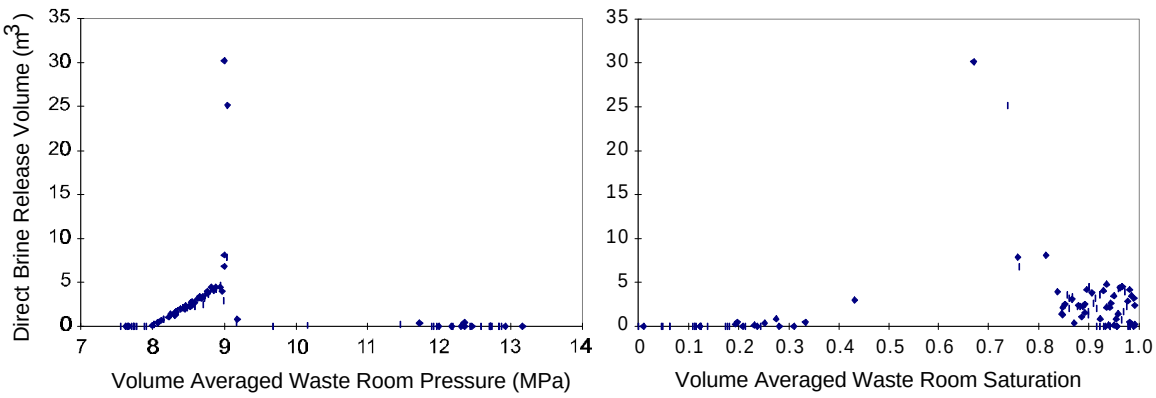

Figure 7.16. Direct Brine Release (m^3) for Scenario 3 for Castile Simulation for the Second Intrusion at 1,200 Years for Left) Volume Averaged Waste Room Pressure (MPa) and Right) Volume Average Waste Room Saturation (Unitless)

It is stressed at this point that the above phenomenon is only for the Castile simulation, Scenario 3, at early times in the repository's projected history after the initial intrusion. Since a few of the key parameters were held constant, the predicted behavior of the disposal system was better understood. A similar response of Scenario 2 for the Castile simulation can be seen, yet differences between the two scenarios are still recognized. For example, the brine release

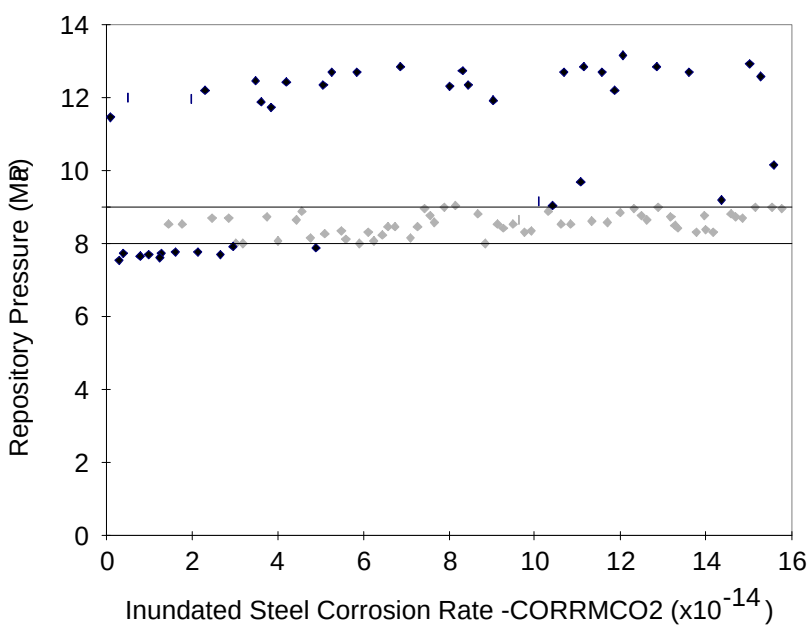

Figure 7.17. Scatter Plot of The Pressure in the Repository (MPa) for Castile Simulation, Scenario 3, 1,200 Years Post Closure Versus Inundated Steel Corrosion Rate (CORRMCO2-Parameter 1 in LHS Sampling) with Banded Region of Gray Diamonds Showing Those Vectors that had a Significant (>0.1 m^3) Direct Brine Release

versus brine saturation shows that brine can be ejected at saturations as low as 0.2. These are very low releases, usually less than 0.5 m^3 of brine. However, since the CCA has more varying parameters over large ranges, the behavior of the system is less predictable.

7.5.4. Probability Modeling with Results from Castile Simulation

The final step in assessing the results of the Castile simulation and how they will affect the overall performance of the disposal system, is to replace the results of the CCA with those of the Castile simulation in a CCDFGF calculation. The individual vectors of CUTTINGS_S and BRAGFLO_DBR were summarized into formats for probability modeling and modeled with the CCA results of SECOTP2D, NUTS and PANEL. Figure 7.18. shows the CCDF curves of several simulations.

The results of the Castile simulation show that Castile brine assumptions do not have a significant effect on the overall CCDF. In fact, the figure shows that the CCA may have slightly higher releases at equivalent probabilities with the same probabilistic assumptions (drilling rate, AICs, probability of hitting a Castile brine pocket, etc). Even when the probability of hitting brine is increased from 8 to 100%, the releases are not increased by any significant amount.

7.6. Conclusions

A model is presented to investigate the importance of the Castile brine reservoir parameters at the WIPP. The Castile reservoir underlies the repository and is a major source of brine that may contribute to gas generation from the corrosion of metals and biodegradation of organic materials. The production of gas will increase the pressure in the repository, thus ejecting brine and waste to the accessable environment upon a breach of the repository.

The Compliance Certification Application presents data for the creation of reservoir parameters that may be extraneous. The data were derived from wells that clearly lie outside a reasonable distance for consideration of brine pockets underneath the repository. Therefore, data from a single well, one mile north of the repository, was used to simulate the effects of the reservoir. The data included reservoir volume, rock compressibility, permeability, and pressure.

In addition, two parameters describing the waste area were changed to what were considered more reasonable values. The waste permeability was increased by 41%, and has been well documented to show the error in the calculation of the original value. Also, the residual brine saturation range was decreased by reducing the upper value by 57%. This range is no longer considered to be more reasonable than the range used in the CCA calculations, due to the consolidation of waste in the repository.

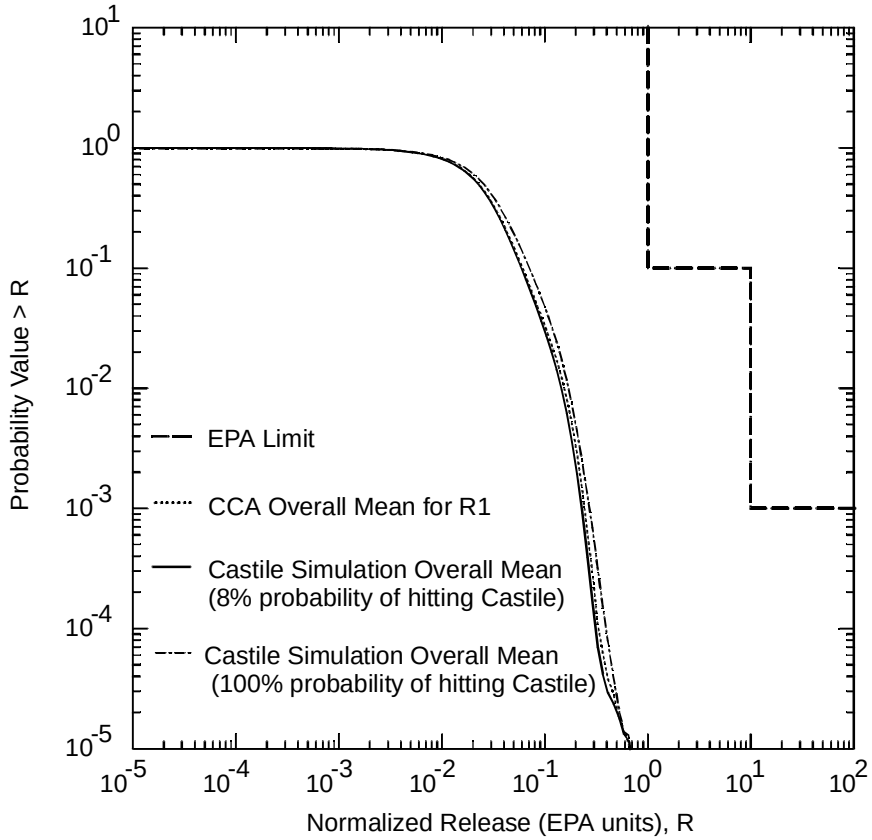

Figure 7.18. CCDF for Castile Simulation and CCA. The Castile Simulation Includes Two Probability Models: 8% and 100% Probability that the Intruding Borehole will hit the Castile Reservoir

The modeling started with two-phase flow of brine and gas through the repository using BRAGFLO. The changes in the Castile reservoir parameters affected the pressures, flow, and saturation of brine and gas through the waste. The pressures were much higher than in the CCA, with increased flow rates due to increased waste permeability.

The modeling of a human intrusion was completed by the code CUTTINGS_S, which simulates a drill string breaching a pressurized repository and releasing solid waste up the borehole to the accessable environment. The calculations showed that the amount of waste brought to the surface would not change, but the number of realizations that possibly could result in a release would increase. The increase of a spalled events from an highly pressurized repository doubled from the CCA to the Castile simulation.

The flow of brine up an intruded borehole was calculated separately in BRAGFLO_DBR. The results proved that the increased pressures in the repository from changing the selected parameters would result in higher and more incidents of releases to the surface.

Finally, CCDFGF modeled the probability of releases from the results of the above calculations. The outcome showed that there is no significant change in releases due to the minor addition of releases from a spalled or brine release. The releases calculated in CUTTINGS_S and BRAGFLO_DBR were not significantly more than those of the CCA. The constant values used for the Castile brine reservoir pressure is suspected to be the largest culprit for no change in the releases. However, the releases are subject to the concentration of radionuclides in the waste, and it is suspected that changes in the solubility, which would increase the concentrations of the radionuclides, would have a more profound effect on the Castile simulation than the CCA.

8. CULEBRA FLOW AND TRANSPORT USING BLM MAP FOR ECONOMIC POTASH RESOURCES OF EDDY COUNTY

8.1. Summary

A new Culebra flow and transport model with a modified extent of potash mining is presented here to demonstrate the effect of mining on the performance assessment caused by a change in flow patterns. The CCA assumes limited mining within the controlled area of the WIPP repository. A new model was justified because of the expected mining of lower grade ore due to the increase in use of fertilizers and development of more effecient mining methods. The results show that the new flow velocities in the Culebra aquifer could be important when considering lower K_ds, as the process of sorption dominates that of advection.

8.2. Introduction

The possibility of mining above the WIPP repository for potash resources has been identified as a possible scenario for human disturbance of the disposal system in the EPA's criteria for the compliance standards, 40 CFR Part 194.32 (b) (U.S. EPA 1996b). The performance assessment calculations of the CCA included a mining scenario with a probability of occurrence equaling that which has transpired over the last 100 years, as stated in the guidelines. The consequences of mining would cause subsidence in the geologic units above the repository, increasing the amount of fracturing and possibly decreasing travel time of the radionuclides through those overlying units if a release occurred.

The extent of the potash reserves overlying the repository and how it affects the flow field of the Culebra Dolomite member of the Rustler Formation is investigated in this chapter. Originally, the CCA identified two possible mining scenario: full and partial mining. These scenarios were based on studies of known potash leases and economic- and lease-grade potash reserves in the Delaware Basin. The full mining scenario includes regions outside the controlled area of the repository identified by the Bureau of Land Management (BLM 1993), excluding oil and gas well buffer zones, and regions within the controlled zones based on economic grade potash ore from the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) report (U.S. DOE 1996-Appendix MASS). The partial mining zones excludes mining within the controlled area, with the exception of those areas mined before the Land Withdraw Act was established. The maps do not distinguish between the two types of ore, sylvite and langbeinite.

The future of potash mining is the limiting factor on estimating the economic extent of potash reserves. Currently, 40% of the world's agricultural production uses nitrogen based fertilizer, derived from the potash industry (Smil 1997). With the exponential increase in human

population, fertilizers usage should also increase, directly affecting potash production in the Delaware Basin. The increased demand for potash will prompt the industry to mine lower grade ore, and use methods of extraction that are more profitable.

Solution mining has been considered for the extraction of potash in the region of the Delaware Basin. The process of mineral dissolution was determined to have the lowest operational cost compared to other methods (Gruschow 1992). Therefore, the extraction of lower quality potash minerals could be economically feasible, and the extent of reserves are much greater than originally predicted. The CCA failed to recognize the possibility of solution mining around the repository, and the area affected by mining is much less than predicted. The EEG modeling of this report considers all possible potash reserves inside and outside the controlled area based solely on the BLM map (BLM 1993). The area inside the controlled area changed significantly from that in the CCA, whereas the outside was virtually unaltered. This scenario is referred to as the Modified Mining (MM) scenario.

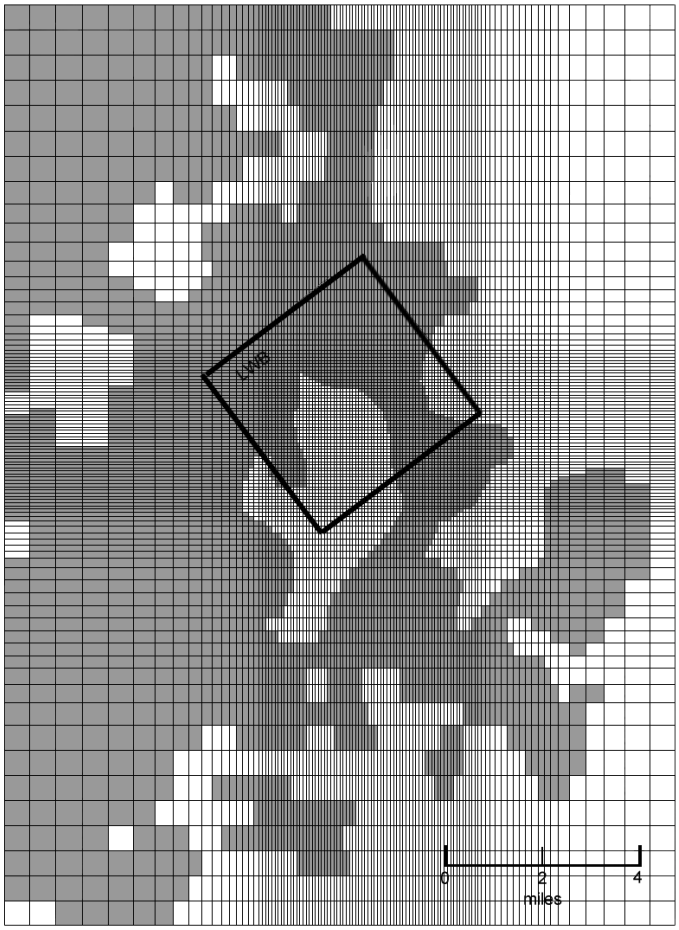

Figure 8.1. Areal Extent of Known Potash Reserves from the BLM Map (BLM 1993)

Figure 8.1. shows the new areal extent of potash reserves, superimposed on the regional modeling domain. This domain is used in the flow code for simulating flow through the Culebra. The area shows the region affected by mining, where subsidence would fracture the flow system. The EPA guidelines for subsidence are very specific about how the area is to be treated in the performance assessment. A multiplier of no more than 1000 is required to increase the transmissivity. This was a sampled parameter in the performance assessment calculations, and remained unaltered for the calculations in this report.

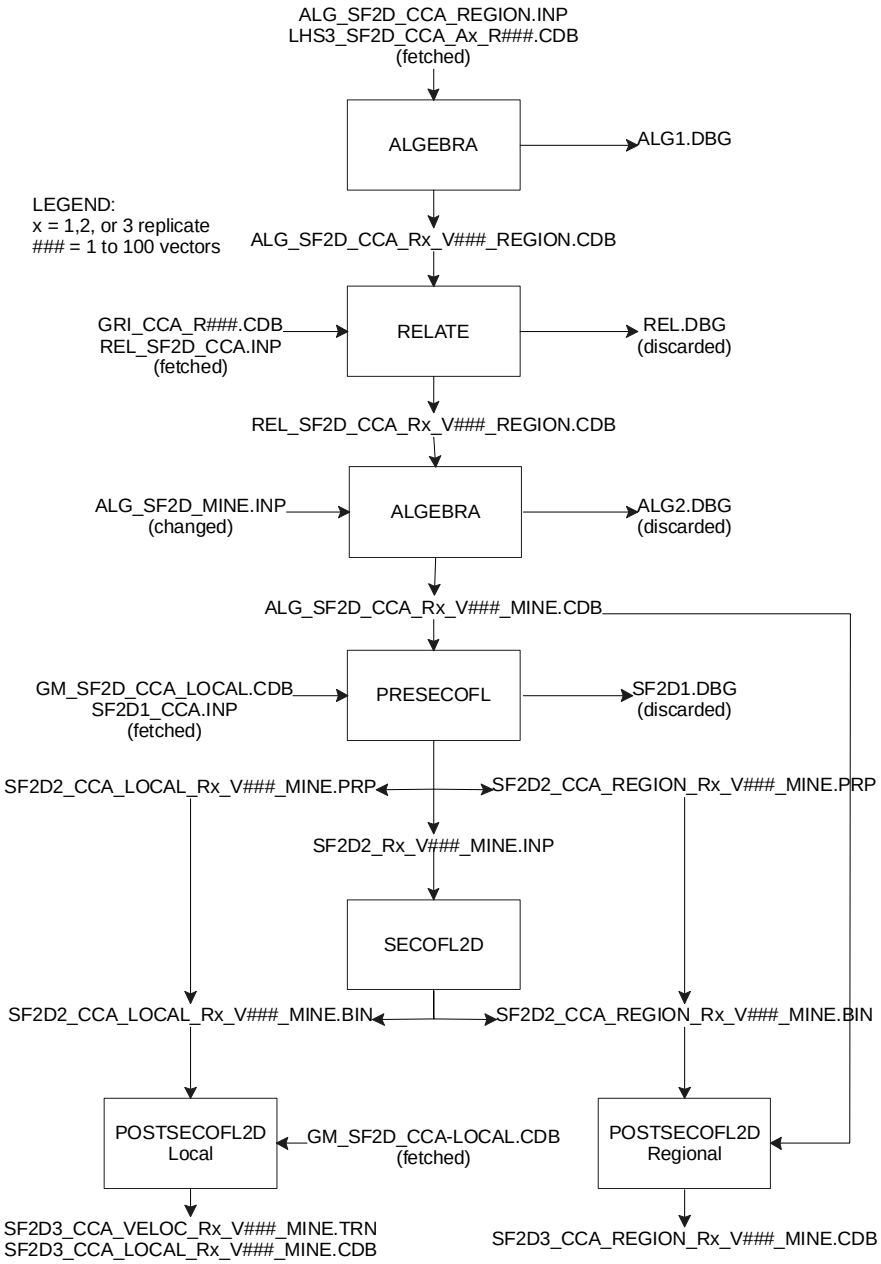

Figure 8.2. Flowchart of SECOFL2D Simulations

8.3. Methodology

The purpose of this modeling experiment was to change the existing regions of the potash minable resource areas to test the effects on the flow and transport of radionuclides through the Culebra. This was accomplished by first running the flow code, SECOFL2D, a two dimensional regional flow code that solves the Darcian flow equation. The flow velocities were then used to solve the transport equation in SECOTP2D. Figure 8.2. shows the flowchart of the flow code used in modeling the mined area. The only change for modeling the new potash region was the file that controlled which transmissivity cells of the flow grid were multiplied by the increased factor for higher fracturing. All cells of the region were multiplied by the same value. The actual file is included as an attachment to this chapter for reproducibility. The transport flowchart for SECOTP2D can be found in Chapter 6.

A total of 100 vectors were completed for the flow calculations with hydraulic head being computed for both a regional and local domain. The flow field was first solved on the regional grid. The local grid acquired its boundary conditions from the regional flow characteristics. The local velocities were then used as the input to solve the transport of radionuclides on the local grid.

Two experiments were simulated with the transport equation with 100 vectors being generated for each simulation. One included plutonium with a 1% K_d=0 to compare with results of Chapter 6, and the other ran uranium with K_ds generated from the LHS sampling technique to compare with CCA results. The generated K_ds were slightly different, correcting for the range as specified in Ramsey and Wallace (1997). The new range decreased the values used in the new simulations, allowing the Uranium to migrate further downstream. The complete set of vector calculations enables the results to be incorporated into the CCDFGF code.

8.4. Results

8.4.1. Culebra Flow

The flow field of the new mined area (MM Scenario) showed slightly different hydraulic head values than the ‘fully mined’ solution of the CCA calculations. Figure 8.3. compares the regional head contours of a simulation where the transmissivity multiplier (parameter MINP_FAC) was the lowest generated value from the LHS sampling technique. Figure 8.4. also compares the regional head contours, taking the vector with the highest generated multiplier. The low and high values for MINP_FAC are 5.1 and 996.4, respectively. Contours are in meters above sea level.

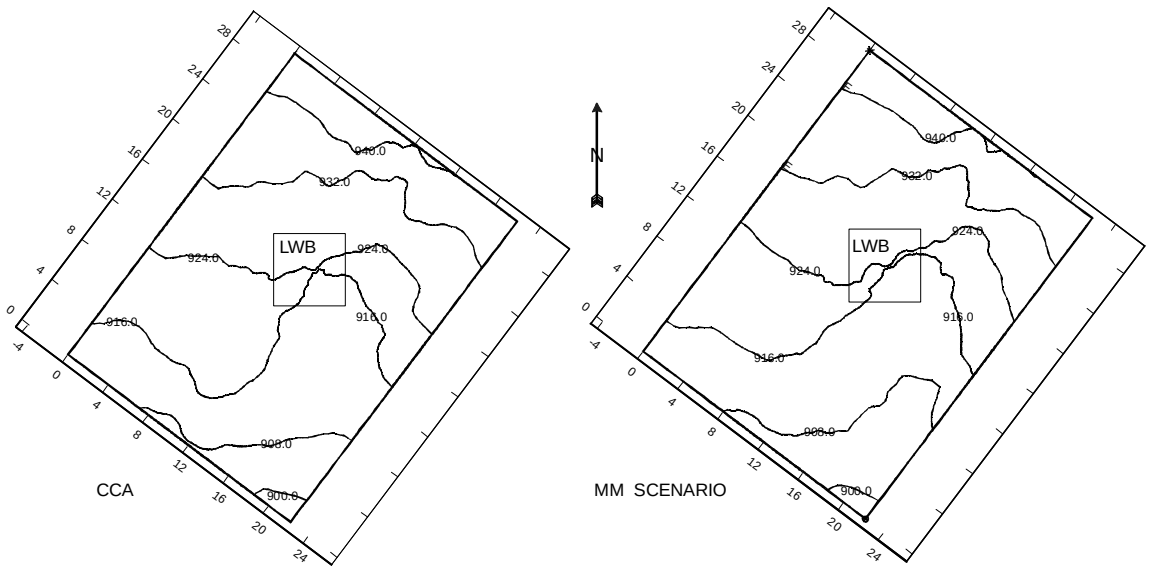

Figure 8.3. Regional Flow Contours of Vector 11. Left) CCA Right) MM Scenario

The only significant difference in head contours was in Figure 8.4., where the contour of 916 m for the MM Scenario is much further south than the CCA calculations. At first glance, this would indicate lower velocities for the MM Scenario through the controlled area, and speeding up through the south. However, due to the extreme heterogeneity of the site (as seen in Figure 8.5.), a generalization about the velocities cannot be inferred from the difference. Therefore, a velocity profile was constructed from the velocities calculated in SECOFL2D. Figure 8.6. shows the velocity vectors for both mining scenarios with correct angle and proportioned magnitude for

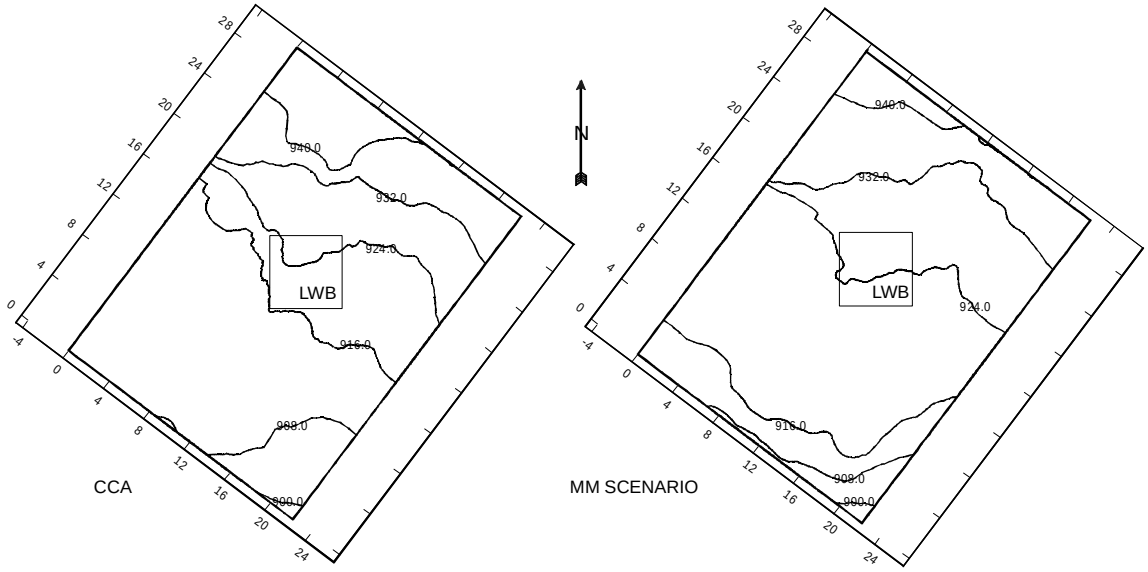

Figure 8.4. Regional Flow Contours of Vector 62. Left) CCA Right) MM Scenario

Vector 62. The velocities were extracted from the local grid to show the direction of the plume's migration in the transport calculations. The outline of the transition of small vectors and large vectors clearly shows the areas where the transmissivities were multiplied by MINP_FAC.

The velocities of Figure 8.6. range from 2.3×10^{-14} m/s to 2.9×10^{-6} m/s for the CCA calculation, and 2.3×10^{-12} m/s to 1.1×10^{-5} m/s for the MM Scenario. Since both modeling scenarios used the same transmissivity field, the higher velocities in the MM Scenario suggest that the area to be multiplied by MINP_FAC overlaps a region of slightly higher transmissivity than in the CCA, i.e.

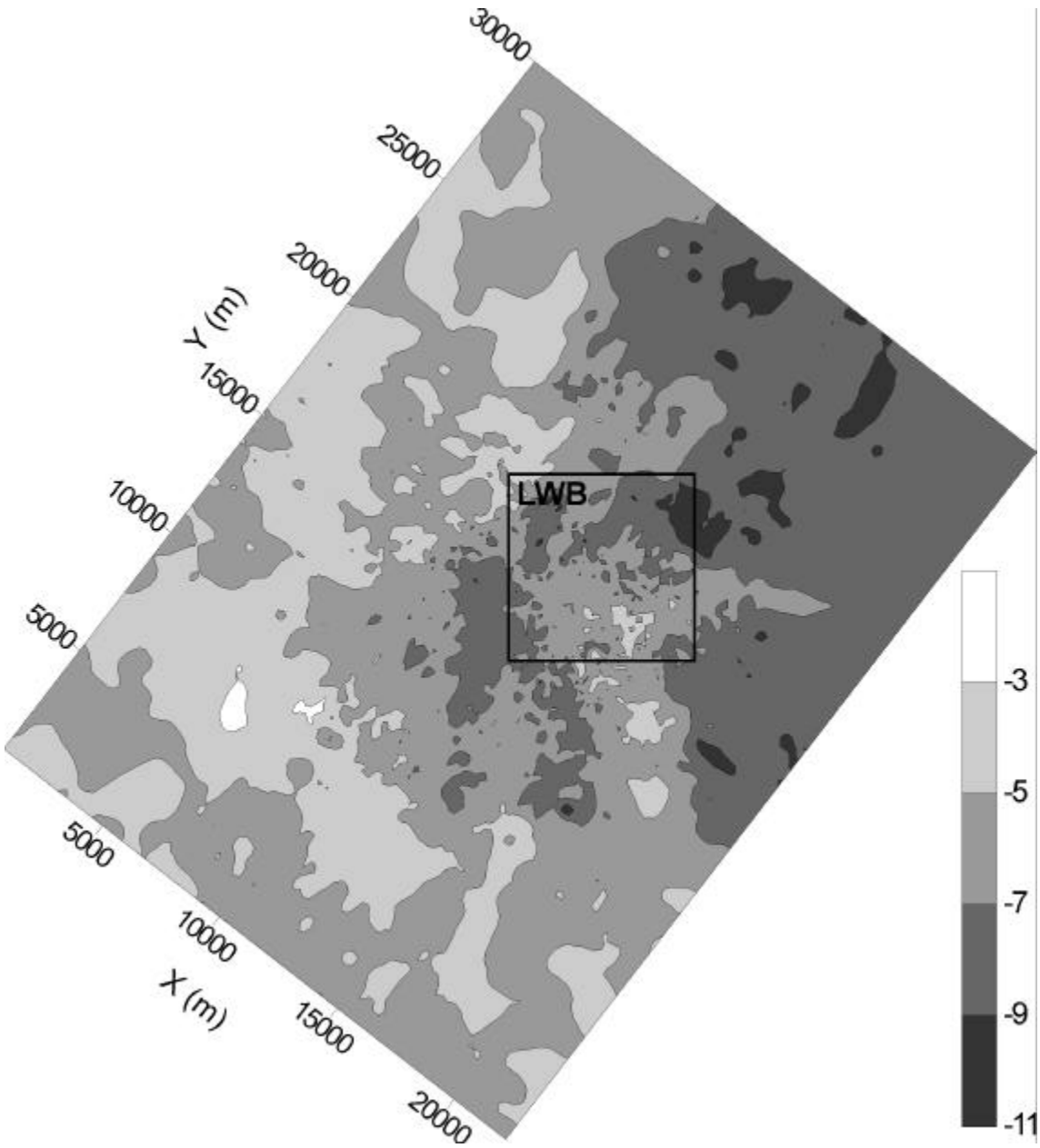

Figure 8.5. Transmissivity Field (Log_{10} m^2/s) of Vector 62

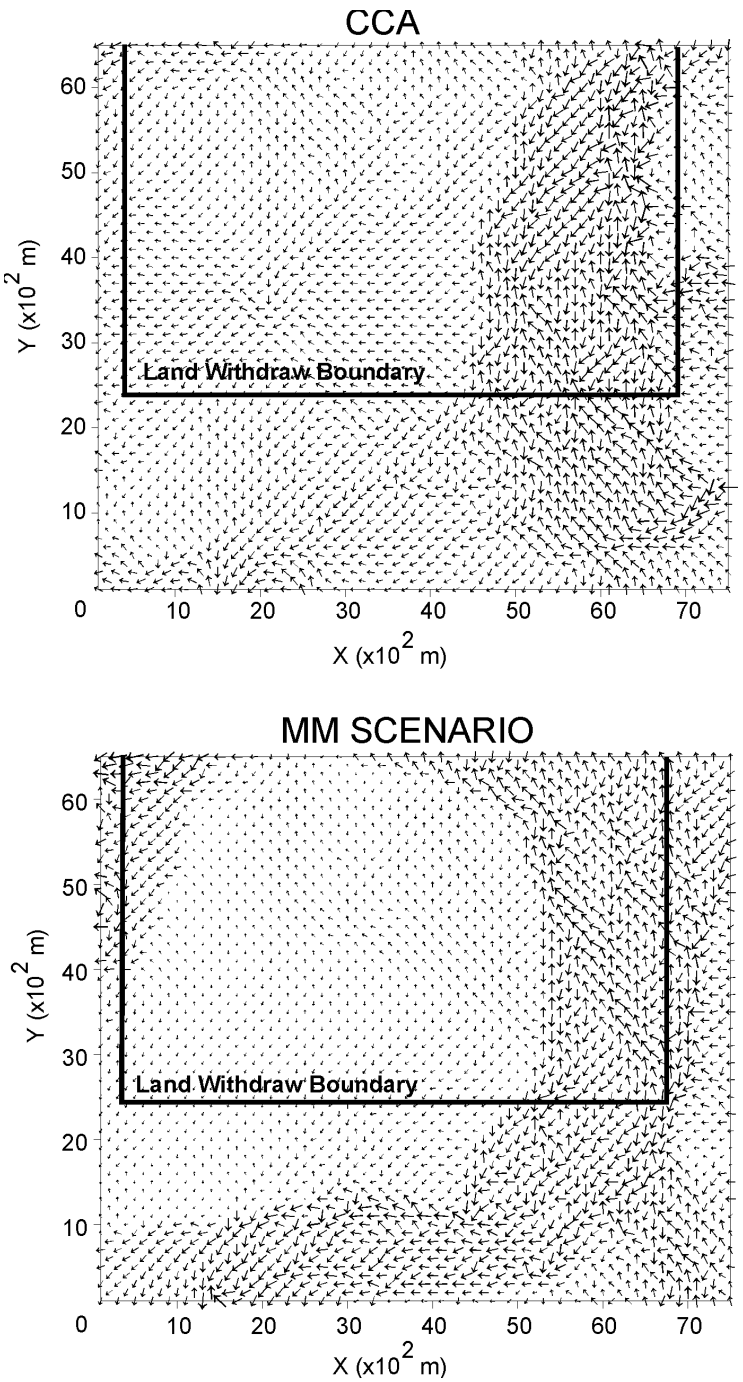

Figure 8.6. Velocity Profile of Vector 62 on Local Grid for Top) CCA and Bottom) MM Scenario

the region that is multiplied as shown in Figure 8.1. This is important, as the results of the radionuclide transport calculations will differ significantly from the outcome of the flow field functions.

8.4.2. Culebra Transport

8.4.2.1. Plutonium Transport Calculations with K_d=0

SECOTP2D was first used to simulate transport of plutonium with a K_d=0 through the Culebra aquifer. The combination of zero sorption and higher velocities allowed higher masses of the radionuclide to migrate across the Land Withdraw Boundary (LWB). The discharge mass of the Modified Mining Scenario was compared to results from transport calculations performed in Chapter 6, which simulated changes in the K_d only. In approximately 60% of the vectors, discharges were higher for the MM Scenario than for those seen in the Chapter 6 calculations. Figure 8.7. shows vectors that discharged mass fraction higher than 10^{-6} for the MM Scenario and the results of Chapter 6. The figure also displays a histogram for the frequency of vectors lying between the given ranges. The actual fractional discharge for both studies ranged from 10^{-2} to less than 10^{-15} (machine zero), but the limit was cut off at 10^{-6}. Below this discharge, the low-consequence eliminates the vector from consideration in the complementary cumulative distribution functions (CCDFs). Both plots clearly demonstrate that the MM Mining Scenario produces faster flow fields and is more conservative in its assumptions.

During the last step of probability modeling to create the CCDF curves for comparison with the EPA limits established in 40 CFR Part 191 (U.S. EPA 1996), the fractional discharge is multiplied by the actual amount of radionuclides that reach the Culebra. In most cases, the amount is negligible, and the fact that a vector had a high fractional discharge is often eliminated by the low concentrations. To demonstrate this affect, Figure 8.8. shows the discharge across

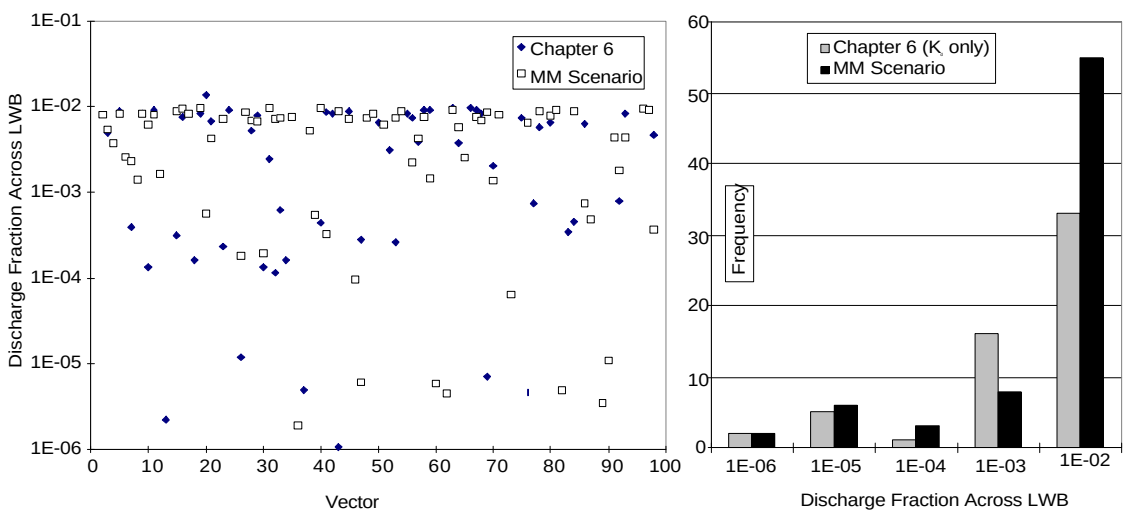

Figure 8.7. Left) Plutonium Fractional Discharge across the LWB for Chapter 6 Results (Full Mining) and MM Scenario with both having 1% of the Initial Mass with a K_d=0 $^{ml}/_{g}$ Right) Frequency Distribution of both Mining Scenarios for Vectors with Significant Discharge across LWB

the Land Withdraw Boundary in EPA Units. The plots in the figure show the discharge of plutonium for the S2 and S3 scenarios at 10000 years for those vectors with discharges of at least 10^{-6} EPA Units. The fractional discharge is multiplied by the mass in Curies calculated from each of the scenarios, and divided by 344 to obtain the mass in EPA Units. The figure reveals that for the S2 scenario (left plot), the Modified Mining has the highest release in 10000 years with six vectors showing at least 10^{-5} EPA Units crossing the LWB. The right plot of the S3 scenario also shows the highest release, however, with less vectors actually being above the 10^{-6} threshold than the results of Chapter 6.

8.4.2.2. Uranium Transport Calculations with LHS Generated K_ds

The flow velocities from the BLM Mining Scenario were also used to model uranium with higher K_ds than the plutonium simulations. The K_ds were generated from the Latin Hypercube Sampling (LHS) code. The range of values for K_ds were modified from those used in the CCA to values suggested in the Analysis Package, Task 3 (Ramsey et al. 1997). The new range for generated K_d values are lognormally distributed from 0.03 $^{ml}/_{g}$ to 20 $^{ml}/_{g}$, changed from 0.03 $^{ml}/_{g}$ to 30 $^{ml}/_{g}$. The new upper value, along with a lognormal distribution for the range, created smaller values of K_ds, and thus smaller retardation values. The result is more vectors with higher discharge.

In the CCA calculation only one vector from the third replicate showed any release, with an integrated discharge across the Land Withdraw Boundary equal to 0.91 kgs. The present calculations were performed on the first replicate, with no releases to compare. Figure 8.9. shows releases across the LWB only for the present model.

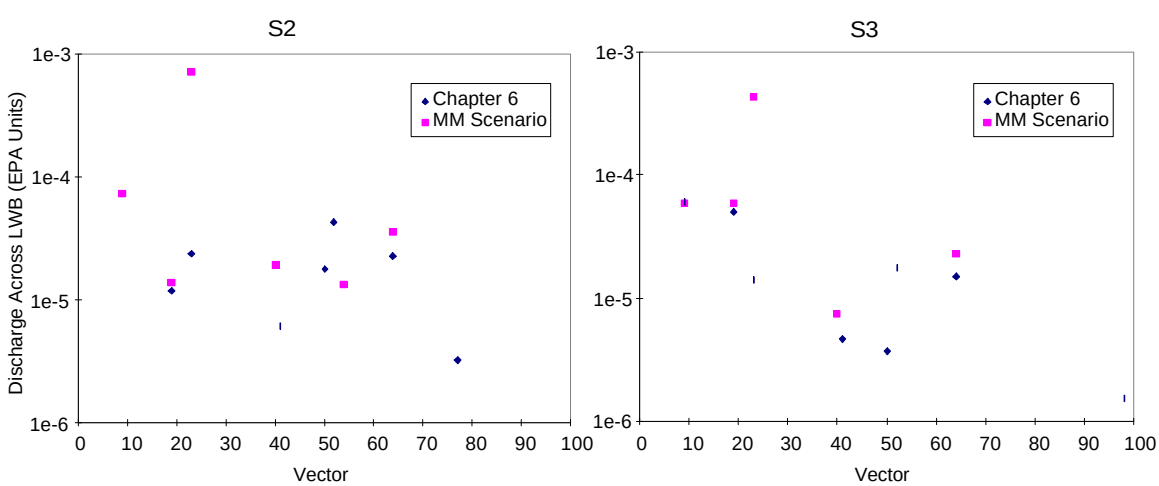

Figure 8.8. Discharge in EPA Units at 10,000 Years from CCA NUTS Concentrations for the Results Presented in Chapter 6 and the MM Scenario for Left) Scenario 2 and Right) Scenario 3

Of the 100 vectors, only six had significant releases (fractional dicharge>1e-6) across the LWB. The calculated retardation value from the generated K_ds ranged from 1.57 to 170412.2 (dimensionless), and the six vectors that showed discharge had a range of retardation values from 1.57 to 2.99. However, a strong correlation does not exist between retardation and discharge. Several vectors had no release across the LWB with retardation values less than 3. The geostatistical representation of the transmissivity field was such that it prevented any escape of uranium to the accessible environment. The CCA calculated retardation for uranium ranged from 24.8 to 431089.

The comparison for flow calculations used Vector 62, because of its high multiplier for the transmissivity field. However, the value of the newly calculated retardation coefficient for this vector was incredibly high (15763, dimensionless), and the uranium did not migrate outside of the waste panel area. To keep the comparison alive and consistent, Vector 62 was rerun with a smaller K_d=0.046 $^{ml}/_{g}$ (retardation=2.0). Time was also extended out to 100000 years to find when the maximum release would occur.

Figure 8.10. shows six snapshots of uranium concentration isopleths at 1875, 3875, 5250, 7150, 8650, and 10000 years after an intrusion. The isopleths range from $1x10^{-15}$ kg/m^3 to $1x10^{-6}$ kg/m^3, dark to light. The observed behavior of the uranium plume shows it to remain in the near

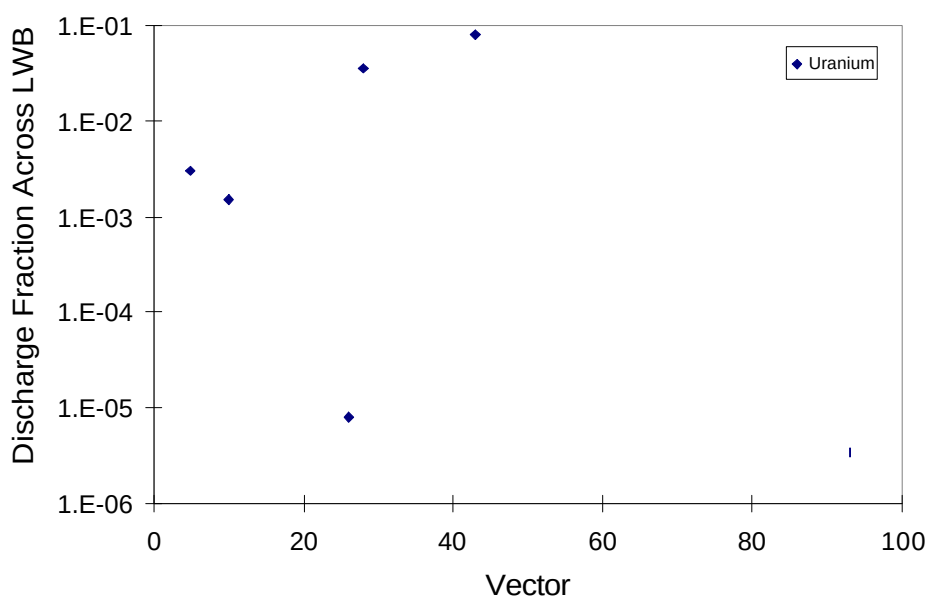

Figure 8.9. Discharge of Uranium across the LWB for MM Scenario for LHS Generated K_ds

field (near the borehole) for approximately the first 5200 years, moving slowly to the southeast. At year 7150 the plume is then noticed to enter an area of high velocities, where it shoots relatively quickly in a southwest direction. The size and location of the highest isopleth concentration of $1x10^{-6}$ kg/m^3 remains virtually unchanged through the time history of the simulation. Though bound up around the borehole for a long period of time by a low transmissivity field, the plume moves quite quickly southward, across the LWB.

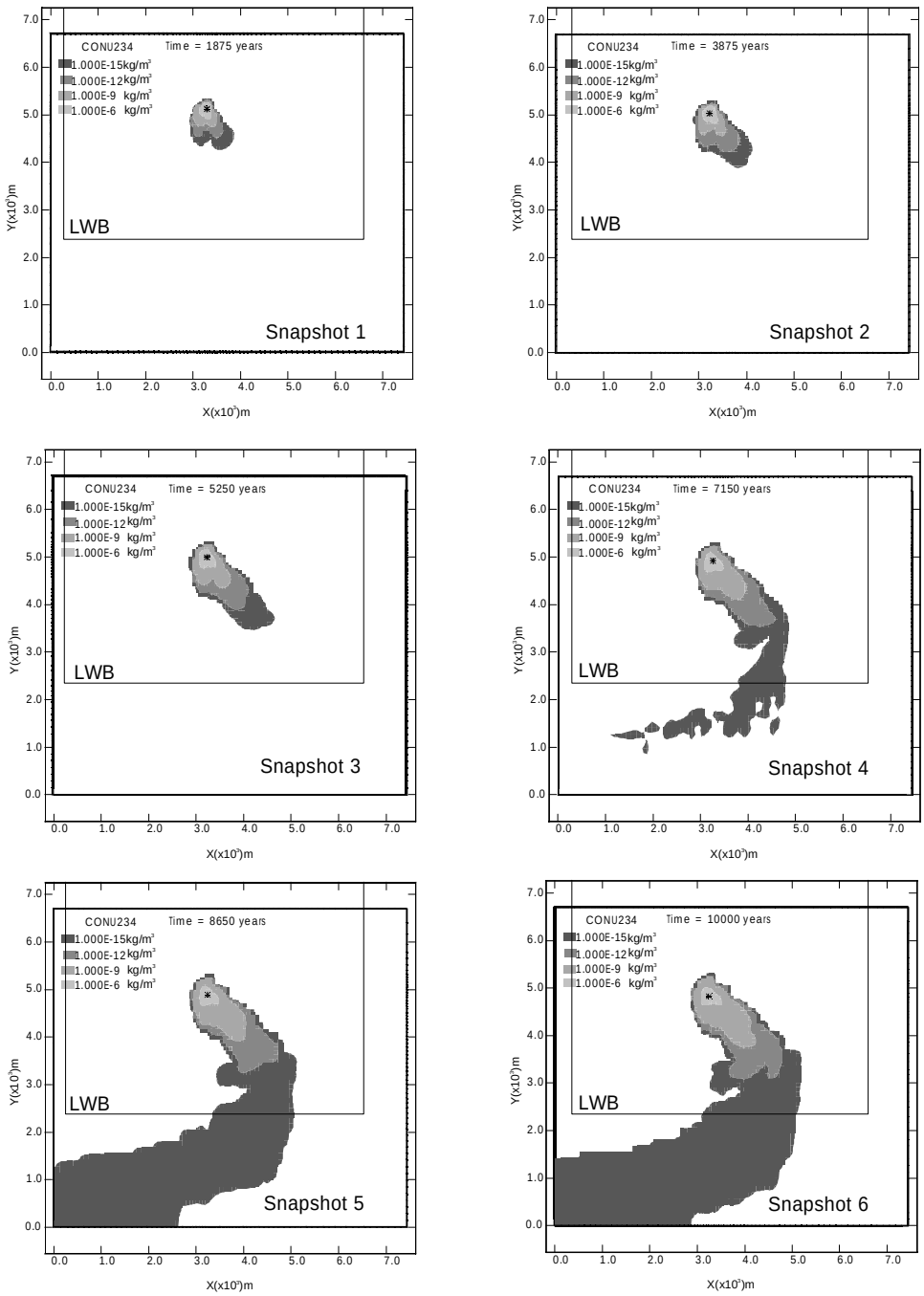

Figure 8.10. Uranium Isopleths for Vector 62 with Retardation of 2.0, MM Scenario

The discharge across the Land Withdrawl Boundary as a function of time can be seen in Figure 8.11. The simulation was extended beyond the regulatory timeframe, to 100000 years. The figure also notes the position of the snapshots from Figure 8.10. At 10000 years the fractional discharge is approximately 1.4×10^{-5} kgs. However, beyond the 10000 years, the discharge of uranium increases exponentially to 70000 years, where it levels off at 0.89 kgs. Regulatory compliance only requires 10000 year calculations, yet significant transport does not appear to take place until 30000 to 70000 years.

8.5. Probabilistic Modeling of Uranium and Plutonium

Though interesting, this chapter does not intend to discuss the regulatory timeframe in which encapsulated waste must be contained for safe disposal. It is meant to give an overall picture on the performance of the disposal system, weighting several factors not considered in the CCA. The chapter began with the formulation of a new scenario and ends with the results as compared to those submitted in the CCA. The last step in that comparison is to formulate a probabilistic model for the prediction of radionuclides reaching the accessible boundary anytime during the 10000 year future of the repository. The code CCDFGF was used to do this type of modeling.

The probabilistic model used all the results from the CCA, with the exception of transport. The new transport calculations were integrated into the CCA calculations to produce the CCDF curves, as presented in Figure 8.12. The CCDFGF code calculated curves for both plutonium with a K_d=0 and uranium with newly generated K_ds, and Figure 8.12. compares the results to

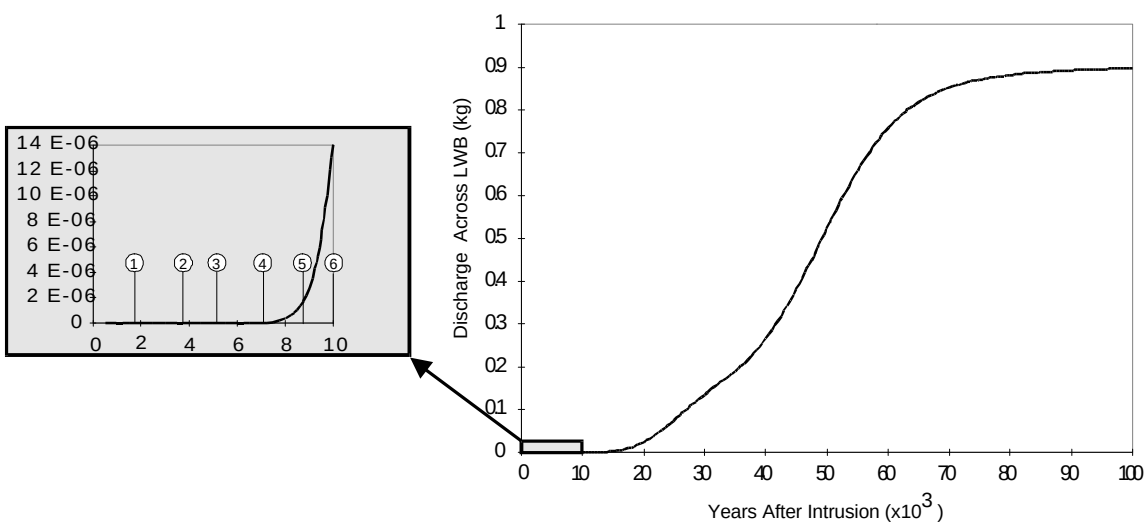

Figure 8.11. Integrated Discharge of Mass Across the LWB from 0 to 100,000 Years with Blowout Section from 0 to 10,000 Years with Snapshots from Figure 8.9. Shown as Circled Numbers in Blowout Section

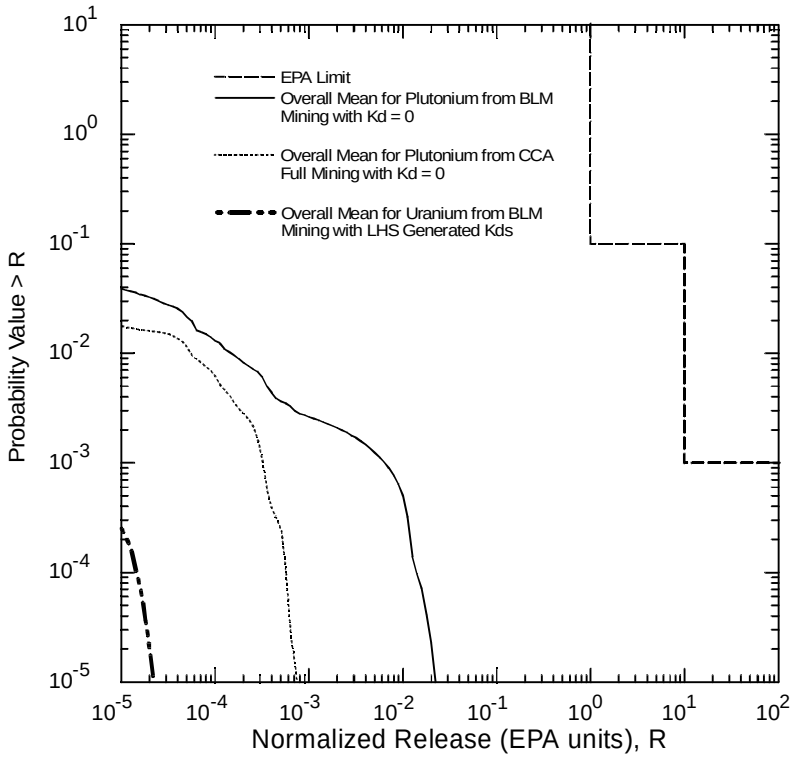

Figure 8.12. CCDF Curves for Overall Mean Releases from Culebra, Comparing Modified Mining to CCA Mining

those of the plutonium modeling with CCA Mining assumptions and 1% K_d=0 (from Chapter 6). The CCA results are not presented, since no vector crossed the LWB in the first replicate.

The combination of higher velocities from the modified mining scenario and K_d=0 demonstrates higher release probabilities from the Culebra than any other model, including mining or the elimination of retardation modeled separately. However, when considering the two scenarios separately, the elimination of retardation dominates the release probabilities by almost two orders of magnitude. The curves of Figure 8.12. shows plutonium with a K_d=0 with the BLM Mining as the right-most curve, plutonium with CCA Mining Scenario (Full Mining only) and K_d=0 in the middle, and uranium with the MM Scenario and LHS generated K_ds to the left. These results suggest that the sorption mechanism is more important than the way the velocity field behaves.

8.6. Conclusions

The mining of potash in the McNutt Potash Zone of the Salado formation was to be considered as a possible human intrusion scenario in the performance assessment, as stipulated in 40 CFR Part 194. The effects of such mining will change the characteristics of the overlying Culebra

Dolomite member of the Rustler Formation by increasing the fractures, and hence increasing the effective transmissivity of the region.

Modeling of mining in the CCA assumed two distinct scenarios, based on the probability of mining within the controlled area (or Land Withdraw Boundary) of the WIPP repository, namely the Full and Partial Mining scenarios. The Full Mining scenario assumes that limited mining would occur within the controlled area with consideration of present and future oil and gas wells, and the quality of present economic grade potash. The regulations of such wells mandate a 0.25 mile or 110% of the well length radius around the well to be undisturbed to insure no damage would occur to the well during mining. The Partial Mining scenario does not consider future mining in the controlled area, but only past mining conducted in the region. Outside the controlled area, both scenarios are the same, and are based primarily on the Bureau of Land Management's 1993 Map on the extent of potash in the Delaware Basin (BLM 1993).

The uncertainty of mining within the controlled area prompted an additional modeling study, which does not consider wells or the elimination of lower grade potash. The use of better extraction methods for potash, such as solution mining in combination with the increase on dependence of potash as an artificial fertilizer for world food production, has justified the present model to assume the full extent of potash mining as dictated by the BLM's 1993 map. Dubbed the BLM Mining Scenario, the new model only changes the extent of mining for flow modeling. The changes can be seen in Figure 8.1.

The transport of radionuclides through the Culebra was also modeled, with slight changes from what was assumed in the CCA performance assessment. Two experiments were conducted using the flow results of the Modified Mining Scenario to compare the results to previous modeling studies. The first experiment simulated plutonium through the Culebra unretarded, and were compared to the findings in Chapter 6. The second experiment modeled uranium with generated K_ds to compare the results with those in the performance assessment.

Figure 8.12. shows the results of the modeling conducted with the new assumed extent of potash mining within the controlled area. Modeling plutonium with no sorption to the surrounding matrix with BLM flow characteristics demonstrated to have the highest release probabilities. The experiment used a 1% K_d=0 $^{ml}/_{g}$ with the remaining 99% high K_ds generated from the LHS code showing no releases to the accessible environment. When compared to the 1% K_d=0 $^{ml}/_{g}$ with purely Full Mining of the CCA, release differences of up to 1.5 orders of magnitude are noticed. However, when comparing the Full Mining with no sorption to BLM Mining with sorption, the Full

Mining Scenario dominates the release probabilities, indicating that low sorption is much more important than high velocities.

9. GASOUT MODELING OF THE WIPP

9.1. Summary

The GASOUT code has been applied to the spallings scenario of the WIPP's disposal system to assess the conservatism of the results calculated in the Compliance Certification Application (CCA) (U.S. DOE 1996). A report on the application of the code (Hansen et al. 1997) states that a maximum of 0.27 m^3 of waste would fail in the borehole cavity from an intruding drill string and would be transported to the accessible environment through a blowout event. This calculated volume was used to verify the amount of spalled material calculated in the CCA as reasonable. However, an exercise with the code for an analysis on the sensitivity of several input assumptions shows that the code may be too sensitive, and the range of parameter values too small to judge the behavior of the disposal system accurately. It is suggested that the code be modified to allow a wide range of repository conditions to be modeled, so that an actual maximum spall can be calculated.

9.2. Introduction

The blowout of spalled material reaching the accessible environment through an inadvertent human intrusion through a borehole into the WIPP repository could cause major problems with the compliance of the EPA's limit established in the 40 CFR Part 191 (U.S. EPA 1996a). EEG (1997e) has shown that spalled volume, ranging from 8 m^3 to 64 m^3 can violate these standards. DOE's published results have shown that a blowout would purge less than 4.0 m^3 of waste from the repository, with 0.27 m^3 being a more typical volume (Hansen et al. 1997). This chapter discusses the problems in using the GASOUT code as contained in Hansen et al. (1997).

Spall is waste that has been introduced into the drilling fluid due to radially channeled, highly pressurized gas flow from within the repository to a lower pressure borehole. Gas will continue to flow until the system comes to pressure equilibrium between the repository and the borehole. The high flow rates of gas will cause some of the material to fail in tension or shear, break off from the borehole cavity, and be introduced into the return stream of the drilling fluid. If gas flow is sufficiently high, it will force all the drilling fluid out of the borehole at the surface. This phenomenon is known as blowout, and is a common occurrence among drilling rigs encountering pressurized pockets of natural gas.

Spall can also occur by the mechanisms of stuck pipe and gas-induced erosion. These phenomena may dominate a spalled event if the gas flows are too low to cause blowout. Stuck pipe is a process of spall that, due to very low permeability and extremely high repository

pressures, may cause failed waste to press against the drill string sufficiently hard to prevent normal drilling. The solution of a jammed bit is to pull the drill string up and start drilling again. If the pressures remain high, the driller may have to bring the bit up several times, thus allowing significant quantities of waste to be brought to the surface through the return stream of the drilling mud. Gas erosion is spall that is eroded by the drilling mud due to high repository pressures and low waste permeability. The spall from gas erosion is slower than stuck pipe due to slightly lower pressures in the repository (just above hydrostatic), and may release waste into the drilling mud at a rate undetectable by the driller. Gas erosion would continue until the repository pressure is in equilibrium with the drilling fluid, and may also bring significant quantities of waste to the surface.

Stuck pipe and gas erosion releases will occur if the waste permeability is less than $1x10^{-16}$ m^2, as stated in Berglund (1994), and repository pressures are greater than the pressure exerted by the drilling mud. The CCA states that the waste permeability can be represented by a constant value of $1.7x10^{-13}$ m^2, which is much greater than the threshold for stuck pipe. Additional studies show that waste surrogates based on current understanding of waste mixtures could have a permeability of $2.1x10^{-15}$ to $5.3x10^{-15}$ m^2 (Hansen et al. 1997), and that the threshold for when blowout ceases and stuck pipe/gas erosion begins is questionable (EEG 1997e)

The DOE has made attempts at calculating the amount of material that will spall through a blowout. The code CUTTINGS_S (U.S. DOE 1996-Appendix CUTTINGS_S) incorporates the spallings calculations with calculations of the amount of cuttings and cavings from a drill string cutting through the repository. The calculations showed that a maximum of 4.0 m^3 would fail in the borehole cavity and be forced out of the borehole to the surface. However, an independent peer review found the code to be conceptually flawed. The DOE's Conceptual Model Peer Review Group (U.S. DOE 1996-Appendix Peer 1) stated that the "Development of this [spallings] model is not sufficiently complete to determine uncertainties specific to the channel movement of waste to the existing borehole". The threshold for waste permeability and stuck pipe was also based on the findings of this code.

The spallings volume was re-calculated by using a second code, GASOUT (Shatz 1997), along with several other methods, to assess whether the results of the spalled material calculated in the CCA were reasonable. The GASOUT code was accepted by the Conceptual Model Peer Review Group (Wilson et al. 1997) based only on the conceptual model, without any independent testing or validation. Calculations with the GASOUT yielded a maximum of 0.27 m^3 to reach the accessible environment upon a breach (Hansen et al. 1997). The main assumptions used in the code to derive at the calculated volume was a waste permeability of $1.7x10^{-13}$ m^2, a repository

pressure of 14.8 MPa, and a waste tensile strength of 10 psi (0.068 MPa). Despite better understanding of the waste and measured values of the waste permeability, 4.0×10^{-15}, as described in Hansen et al. (1997), the CCA value of permeability (1.7×10^{-13}) was used for this investigation.

GASOUT uses a semi-analytic approach of a mechanistic conceptual model that couples the numerical calculations of a finite difference fluid flow code and a finite element rock mechanics code. This approach has been dubbed "the cavity growth method", because it progressively calculates the region of radial tensile failure within the cavity. Hansen et al. (1997) stated that there is no tensile failure of waste below repository gas pressures of 14 MPa "under realistic but conservative assumptions".

The conceptual model of the code during the blowout process was described as being divided into two stages. The first stage is characterized by the ejection of the drilling mud by high pressure gases, and the response of the waste to the high pressure gradients during blowout. Following the blowout, the second stage is identified by the rapid flow of gas from the repository, including the entrainment of solid waste particles. In the first stage of initial depressurization, gas velocities are small while the mud column is being expelled from the borehole. The velocities will increase during stage two, as the borehole path is clear for rapid gas movement. The larger eroded waste particles will typically be lofted to the surface during this stage.

In addition to the analysis using GASOUT, a "quasi-static" and "fully coupled" approach to solving the spallings problem was employed. The quasi-static used a spread sheet analysis to solve the porous flow equations by a sequence of steady state profiles (Hansen et al. 1997, pg. 3-24), and the conceptual model used in the quasi-static was identical to the cavity growth (GASOUT) method. The major difference in the two models is that the cavity within the quasi-static model does not change with the calculation of tensile failed waste removal. The results from the GASOUT calculation without failed material removal (removal of failed material is a toggle switch that can be turned on and off in the code), show almost perfect agreement with the quasi-static results under identical initial assumptions. Tensile failed material calculations for the quasi-static model showed 1.17 m^3 of spall with initial pressure conditions of 14.7 MPa and tensile strength of 15 psi. The cavity growth model calculated an equivalent 0.07 m^3 of spall.

The fully coupled approach used a purely numerical code (as opposed to the semi-analytic approach in GASOUT) to calculate the flow of gas within the waste region to the intruded borehole. The mathematical model of the fully coupled approach assumes a one-way coupling of the two-phase pressure decay following an intrusion with a decoupled two-phase pressure

response within the simulated waste region. The fluid flow and waste pressure response were solved by the code TOUGH28W with the poromechanical waste response of stress and strain invoked in the code SPECTROM-32.

Though the code did not explicitly calculate failure, it did calculate stresses within the waste. From the results using SPECTROM-32, the normal stresses show a semi-hemispherical distribution at very early times. If the initial assumptions for repository pressure are 14.8 MPa (lithostatic), and the waste tensile strength is 10 psi (0.04 MPa), then the code would indicate an elastic failure radius of 0.8 m (Hansen et al. 1997-Figure 4-9, time=0.001 s), or 2.1 m^3 uncompacted volume. The same figure shows a stress distribution extended out to one second, but without considering the possibility of waste removal. The removed waste would have a significant impact on the stresses in the cavity.

Though the GASOUT code was just a piece in the series of the spallings calculations performed in the investigation led by Dr. Frank Hansen, this chapter is basically restricted to the GASOUT code and will assess the performance of GASOUT for a wide variety of situations that are plausible for the WIPP disposal system. Furthermore, it will show the limitations associated with the code outside designated ranges of assumptions used for the investigation presented in Hansen et al. (1997).

9.3. Discussion

GASOUT was run on a number of cases, by changing the initial permeability, the waste tensile strength, the initial repository pressure, mud density and the gas viscosity. The initial permeability refers to the permeability of the waste in the repository. Measured values of permeability from experiments on simulated waste specimens showed that the permeability is typically on the order of 4.0×10^{-15} m^2 (Hansen et al. 1997). However, none of the permeability experiments included the proposed backfill material, magnesium oxide, and permeability could actually decrease further with the added affect of cementation from the MgO backfill (U.S. DOE 1997b).

Waste tensile strength is the strength of the compacted waste in the repository that can withstand the flow of repository gas pressures before failing in tension. Measured values of waste tensile strength based on laboratory specimens of surrogate waste forms found a mean strength value to be 0.074 MPa with a standard deviation of 0.04 MPa (10.7 $\pm$5.8 psi) (Hansen et al. 1997).

The repository gas pressure dictates the flow rate of gas from the internal rooms in each panel towards the borehole cavity. Higher repository pressures will result in higher gas flow rates, limited of course by the permeability of the waste matrix or the viscosity of the fluid. The maximum calculated pressure in the CCA, using the two-phase flow code, BRAGFLO, was 16.3 MPa in the waste panels for the undisturbed scenario, and 14 MPa for the disturbed scenario. The EPA's PAVT (U.S. DOE 1997d) calculated a maximum pressure of 16.8 MPa and 15.6 MPa for the undisturbed and disturbed scenarios, respectively. These maximum calculated pressures are higher than the lithostatic, since the lithostatic pressure at the depth of the repository is 14.8 MPa. Therefore, to reduce complications associated with fracturing within the repository, the highest repository pressure investigated will be 14.8 MPa.

GASOUT progressively reports the maximum tensile failed radius, and contiguous failed radius of the hemispherical cavity as the pressure gradient across the waste causes it to fail. During most simulations, these two radii will be equal. However, some simulations will report failure zones outside of the cavity, which are considered not to be spalled waste, and will not be carried out of the borehole through a blowout event. The extraneous cavities are not considered in the contiguous failed radius value.

The compacted and uncompacted failed waste calculated from the failure radius are identified in Hansen et al. (1997) by the following two equations,

$$V_0 = \frac{1-\varphi}{(1-\varphi_0)} V \qquad (1)$$

$$V = \frac{2}{3}\pi r^3 \qquad (2)$$

where V_0 is the uncompacted spalling volume, V is the compacted volume, r is the radius of tensile failure, φ is the compacted porosity of the waste (taken as 0.7) and φ_0 is the uncompacted porosity of the waste (the value 0.848 was used in BRAGFLO). Simplifying, the expression yields $V_0 = 1.97V$, where V is dependent on the length of the failed radius.

Figure 3-12 of Hansen et al. (1997) shows the failure radius of a typical case throughout the time history of the model simulation. The effect is a "stair-step" behavior that represents failed events in the cavity. As the cavity grows from tensile failure, stress is lowered near the boundary of the cavity wall. As time ensues, the stress builds again until another failure event takes place, and the cavity grows as the result of waste breaking off.

The GASOUT results depend solely on the input assumptions provided in its evaluation. For comparison with the WIPP disposal system calculations of Hansen et al. (1997), the assumptions

remained the same for the present study with the “typical” case of the Hansen Investigation, and reasonable changes in certain parameters were conducted to test the code’s effectiveness under varying repository conditions. Through correspondence with John Schatz, the author of the code, it was noted that the code will work only for a narrow range of parameters, despite the unconditionally stable explicit solver used in the numerical (finite difference gas flow through the waste) potion of the code. Outside the designated range of values, the code calculates failure that are interpreted as meaningless, i.e., the code shows the radial failure of waste to cascade, and several “zones” of discretized waste will fail during a single timestep. Once the cascading affect starts, the stresses through the waste become discontinuous.

Table 9.1. lists the input values used as the typical case of this investigation. Table 9.1. represents the “Base” case of the present study and all analyses of sensitivity will be deviations from these assumptions.

Input Parameter	Current, EEG Investigation
Wellbore Diameter (m)	0.3111
Pipe Diameter (m)	0.2032
Outer Radius (m)	19.2
Surface Elevation (m)	1035.5
Base Elevation (m)	380.5
Base Height (m)	2.0
Initial Pressure (MPa)	14.5
Far Field Pore Pressure (MPa)	14.5
Initial Porosity	0.70
Initial Permeability (m^2)	1.7E-13
Gas Base Density (kg/m^3)	0.082 - reported as 11.33
Gas Viscosity (Pa*s)	10E-06 - reported as 9.2E-6
Mud Density (kg/m^3)	1249.3 - reported as 1211
Mud Friction Factor	0.02
Gas Friction Factor	0.02
Far Field Stress (MPa)	14.8
Tensile Failure Velocity (m/s)	1000
Tensile Strength (psi)	15
Cohesion (psi)	18.85
Friction Angle (rad)	0.785
Max Time (s)	5
Eject Mud	True
No Flow Outer Boundary	True
Spherical	True
Allow Material Removal	True
Permeability From Porosity	False

Table 9.1. Input Assumptions for Base Case Study and from Hansen et al. (1997)

9.4. Base Case

The Base Case was run for the typical five second time period that was stated in Hansen et al. (1997) to be well within the first stage of the blowout process, and the amount of tensile failed material for this simulation matches the results presented in the Hansen Investigation, showing a failed radius of 0.25 m and a failed uncompacted volume of 0.05 m^3. During the first five seconds, as seen in Figure 9.1., the acceleration and velocity of the mud column as well as the bottomhole pressure asymptotically reach a steady value. The left plot of Figure 9.1., shows that the acceleration of the mud column reduces significantly after the first second, when the mass flux of gas into the borehole has also significantly reduced. The figure matches quite well with Figure 3-3 of Hansen et al. (1997).

The middle plot of Figure 9.1. (below) shows velocity as a function of time for the first five seconds of blowout. Again, the plot reaches a steady value within a couple of seconds with a velocity of 6.36 m/s. This is slightly higher than presented in Hansen et al. (1997 - Figure 3-2), which reaches a steady value of approximately 5.8 m/s. The discrepancies between the two figures are slight, yet they exist. Small discrepancies are also seen for the pressure curves (Figure 9.3.-4 of Hansen et al. 1997 and the pressure plot of Figure 9.1., below). However, after running GASOUT at a lower initial repository pressure of 14.3 MPa, the velocity and pressure plots of Hansen et al. (1997) resemble the lower initial repository pressure distributions more closely.

The amount of uncompacted failed material volumes as a function of initial repository pressure and waste tensile strength presented from the Hansen Investigation (Table 1-1) are from a five second blowout simulation, and it is questionable as to what the length of time the code can run for meaningful results. The code simulates a compressible gas flow through porous media to the borehole cavity. From the flow calculation, pressure in the cavity is calculated, and is used to

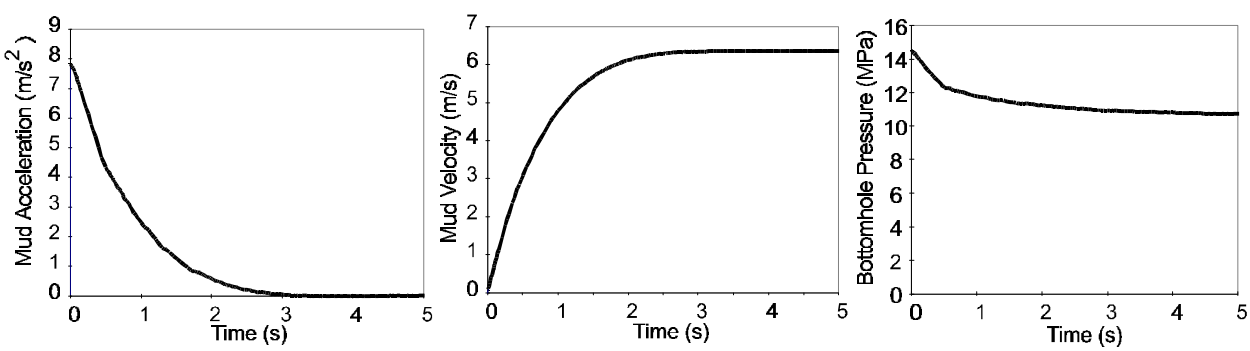

Figure 9.1. Verification of Typical Case Presented in Hansen et al. (1997) for Left) Mud Column Acceleration; Middle) Mud Column Velocity; and Right) Bottomhole Pressure

calculate the force required to push the mud column up, and out of the borehole annulus. The driving pressure of the gas for mud motion does not assume compressible flow, and is valid only when the gas pressures are high, and the mud column has moved a negligible distance. However, when the mud column has moved a considerable distance, the physics of the gas changes, and compressible flow will be an important consideration at later times of blowout.

It is suggested here that the five second results may be misleading. Though the code is questionable beyond the initial 5-10 second simulation, the Base Case shows a larger blowout release when the code is extended to 20 seconds and further to 50 seconds. By 20 seconds, the mud column has only reached 133 m, or 20% of the total borehole length, and the velocity of the mud moving up the borehole has increased from 6.36 m/s to 7.73 m/s. The tensile failed radial increased from 0.25 m (0.05 m^3 uncompacted volume) for a five second simulation to 0.27 m (0.066 m^3 uncompacted volume) for 20 seconds, and to 0.44 m (0.36 m^3 uncompacted volume) for 50 seconds.

Figure 9.2. shows the contiguous tensile radial failure, and mud motion velocity through time, of the Base Case simulation for an extended time of 50 seconds. It is clear that the two curves on the figure correlate, and as the velocity of the mud motion increases, the radial failure increases. However, it is unclear where the interpretation of reasonable radial failure should stop. Field conditions indicate that blowout is almost never ceased within a minute, if blowout preventers are not invoked. Therefore, it is reasonable to assume that spall would continue as long as the pressure gradient in the waste would cause failure.

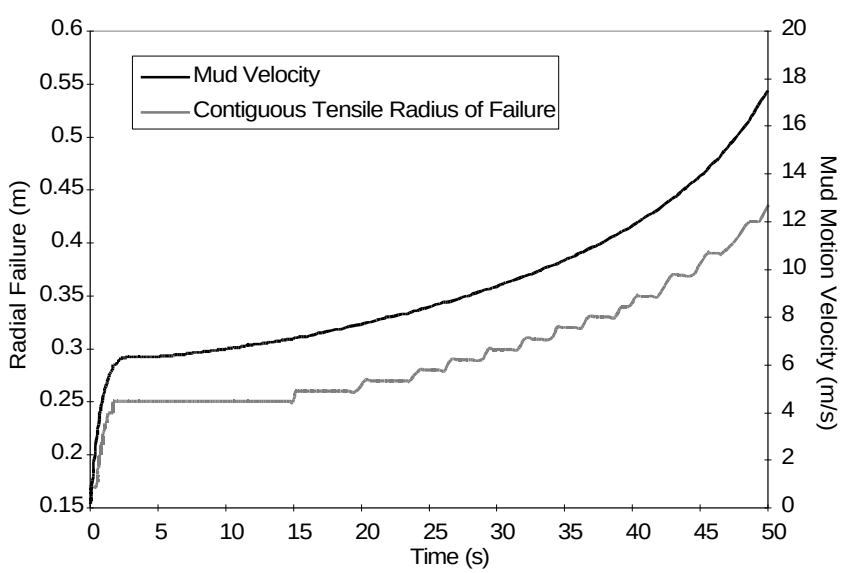

Figure 9.2. Contiguous Tensile Radial Failure and Mud Motion Velocity vs. Time for Base Case at Late Times

The duration of spall at later times would depend on the pressure gradient across the waste form, and its ability to remain high to cause failure. Figure 9.3. shows several pressure curves versus radial distance from the borehole, at 0.5, 5, 20, and 50 seconds during the Base Case simulation. The figure reveals that the pressure drop within 1 meter of the borehole center (the borehole center is marked as 0 on the abscissa) is high from 0.5 seconds to 5 seconds, much lower from 5 to 20 seconds, and becomes quite substantial from 20 to 50 seconds with a maximum drop of 2.5 MPa at 0.45 m from the borehole center. Though the pressure in the borehole cavity is low at 50 seconds (9.37 MPa), the pressure gradient across the waste at 0.5 meters from the cavity wall is higher than at 0.5 seconds. At 50 seconds, the pressure increases 3.4 MPa from the cavity wall at 0.44 m from the borehole center to 0.94 m from borehole center. The same distance of 0.5 meters from the borehole cavity at 0.5 seconds is 2 MPa. Furthermore, the radial and tangential (shear) stress distributions through the waste show smooth transitions during the time stepping and radial failure, and the simulation up to 50 seconds did not cascade waste at high rates. The only noticeable problem with the extended time simulation was the incompressible gas flow up the borehole. It is theorized that at later times when the gas expands from the lower compressive forces of the lighter mud column, the pressure in the borehole cavity will be even smaller. This will create an even higher pressure gradient across the waste, and more spall.

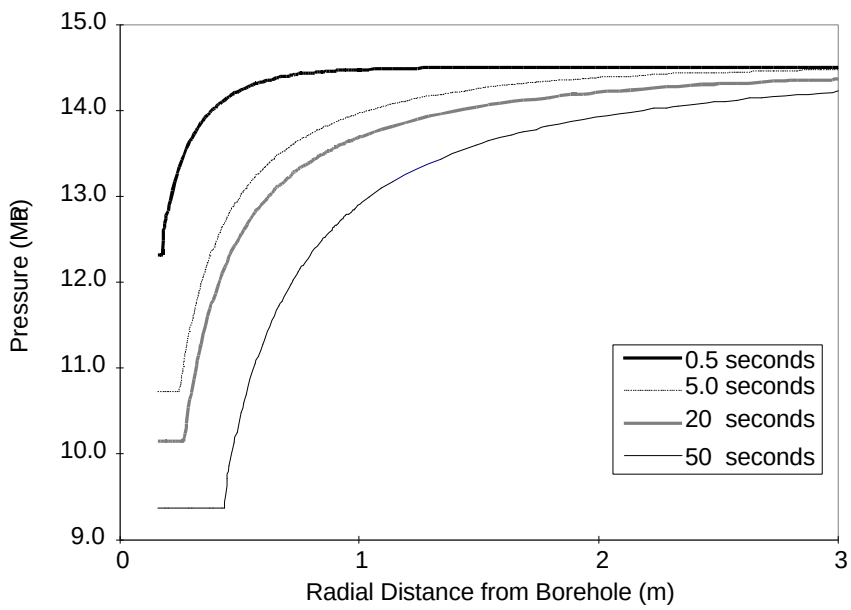

Figure 9.3. Pressure Distribution through the Repository after Intrusion with the Datum on the Abscissa Representing the Center of the Borehole, which has a Radius of 0.156 m.

9.5. Sensitivity to Permeability and Initial Repository Pressure

The GASOUT code was seen to be very insensitive to the initial permeability value chosen in this study. However, the code's use of a small number of parameters kept the sensitivity analysis to a minimum, and true sensitivity could not be established. The range of values narrowed as the initial repository pressure increased, and waste tensile strength decreased.

Initially, the permeability value that was used in the CCA (1.7×10^{-13} m^2) was assumed in the present study to allow comparisons with the results in Hansen at al. (1997), despite a better understanding of permeability investigated in that report, and the value used in the CCA is under question here. The single value questioned was calculated from assumed future waste conditions.

Butcher (1990) ran permeability experiments on different and separate waste types to determine the overall waste permeability of the repository, looking for a value that could represent conditions for performance assessment calculations. These types included metals, combustibles (plastic, rubber, and wood), and sludges. Each waste type exhibited a range of permeabilities, with minimum, median, and maximum values presented in Table 9.2.

The values obtained in Table 9.2. are questionable. First, the representative materials for each type of waste do not cover the possibility of materials that will exist in the repository in the future. The combustibles, for example, used 1" pine cubes, which were to represent wood chips and sawdust (Butcher 1989). In 1,500 years, most (<90%) of the wood will be degraded, and the compaction of degraded wood would cause a lower permeability. Degraded metals would be another example, in which 50% magnetite and 50% 1" metal chips represent the average of degraded steel, aluminum, nails, and lead sheeting.

The volumes of each type of material were also considered in calculating the effective permeability of a drum. For the CCA, 40% combustibles, 40% metals, and 20% sludges were assumed from an average waste drum (U.S. DOE 1996-Appendix Peer 1). These values also varied from drum samples, and from each generating site. The Los Alamos National Laboratory volume (by percentage) of combustibles had an averaged value of 20, whereas the Savannah River Plant averaged 70 (Butcher 1989-Table 2.). These variances in volume could cause the expected value of 1.7×10^{-13} to decrease significantly.

The calculated value for waste permeability did not consider the effect of the proposed backfill (magnesium oxide) that will be placed around the waste to decrease gas generation, lower pH,

and help in the cementation of waste to increase waste strength. It is suspected that MgO precipitation will decrease the permeability by providing material for interstitial cementation, which was concluded by the Particle Size Expert Elicitation Panel (U.S. DOE 1997b) to be a major contributor to increased waste strength. The volume of the emplaced backfill will be approximately 25% of the total repository volume, and the permeability of cemented MgO, called Sorel cement, is much like Portland cement (Zheng et al. 1991), with values around $1x10^{-16}$ m^2.

Lastly, a measured value of permeability on waste surrogates were reported in Hansen et al. (1997). The permeability of typical specimens were approximately $4x10^{-15}$ m^2. It is, therefore, reasonable to assume that waste permeability could vary significantly from the single value of $1.7x10^{-13}$ m^2, and simulations using smaller values of permeability in GASOUT are quite substantiated.

The results of spalled material failing in a borehole cavity using GASOUT over a wide range of permeabilities were not meaningful, and the code was simulated using a very narrow range. For the Base Case simulation for example, the waste permeability could only range from $0.8x10^{-13}$ to $4.4x10^{-13}$ m^2. Above and below these permeabilities, the code predicted extremely large failed volumes. The results of the failed volume for a five second simulation can be seen in Figure 9.4. The figure shows failed volume versus the permeability range that was applicable. The reported failed volume is the maximum contiguous failed volume, calculated from Equations 1 and 2 above. The figure also shows results of varying waste tensile strength, from 10 to 20 psi. The three curves represented in the figure give the upper and lower bounds of the permeability that result in meaningful values.

The reported failed volumes outside the range for the Base Case are extremely high, resulting in as much as 22.5 m^3 for a permeability of $0.5x10^{-13}$ m^2 due to the cascading affect of multiple zone failure. The geometry of the borehole cavity was discretized and solved on a hemispherical coordinate system. The layers of the hemisphere were kept to a minimum (0.01 meters) to avoid instability. When the waste in the borehole fails, it is assumed that the whole layer fails, and peels off like an onion skin. When the code calculates a large failed volume, as in the case with $0.5x10^{-13}$ m^2 permeability, the effect is several layers peeling off in one time

	Min	Med	Max
Combustibles (m^2)	2.00E-15	1.70E-14	2.00E-13
Metals (m^2)	4.00E-15	5.00E-13	1.20E-12
Sludge (m^2)	1.10E-17	1.20E-16	1.70E-16

Table 9.2. Permeability Values Used to Calculate the Waste Permeability in the CCA

step, cascading until an equilibrium is reached with the high pressure gradient that existed at a longer time period. It is assumed that when the cascading effect is exhibited, the results become meaningless.

Figure 9.4. shows some interesting results as the waste permeability increases. All the waste strengths tested showed an exponentially decreasing failed volume, up to a permeability of 2.5×10^{-13} m^2. Permeabilities above this value caused larger failed volumes than values below it within the range where cascading waste is not a factor in failed volume. The upper limit on permeability shows that the code is reliable to 2.5×10^{-15} m^2 for waste strengths that were measured in the report by Hansen et al. (1997) and initial repository pressure of 14.5 MPa. The lower permeability limit is 1.0×10^{-13} m^2 for 10 psi waste strength, and decreases to 0.8×10^{-13} m^2 for waste strengths of 15 and 20 psi.

When the initial pressure is increased to its maximum of 14.8 MPa, the range is more narrow than discussed above. For all waste strengths investigated, confidence was only in waste permeabilities between 1.7×10^{-13} m^2 and 2.0×10^{-13} m^2. The narrow range that the code is applicable decreases the likelihood that the code can represent the disposal system accurately. The code should be modified to allow more representative values to be modeled.

The simulation of the repository with a homogeneous waste in GASOUT is an over simplification

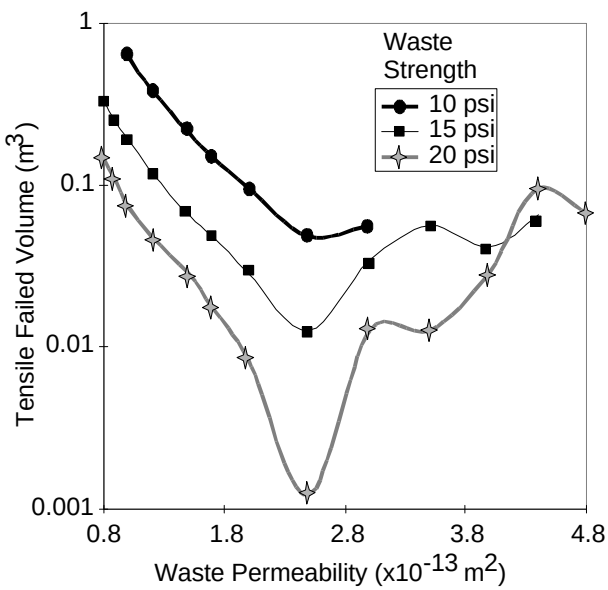

Figure 9.4. Contiguous Failed Volume as a Function of Increasing Waste Permeability for Different Waste Strengths with an Initial Repository Pressure of 14.5 MPa

of the repository model. It is likely that the waste permeability will actually be lower than that assumed in the CCA. The representation of a random permeability was explored in Hansen et al. (1997) using a fully coupled numerical code to solve the flow of gas through the repository. TOUGH28W did not calculate the amount of waste failure, but could calculate the pressure distribution through the waste for varying conditions. The code showed that a lower permeability, with values ranging from $1x10^{-12}$ to $1x10^{-16}$ m^2 would have a much higher pressure gradient near the borehole, than the permeability assumed in the CCA. It also showed that homogeneous waste with lower permeabilities will have higher pressure gradients. This further strengthens the argument for modifying GASOUT to represent the repository more accurately.

9.6. Sensitivity of Gas Viscosity

The gas viscosity parameter, along with porosity and permeability, is used to calculate the hydraulic conductivity of gas through porous media, K, by the relationship of

$$K = \frac{k}{2\phi\mu} \qquad (3)$$

where k is permeability, ϕ is porosity, and μ is gas viscosity. The original equation for the flow of gas through porous media can be found in Chan et al. (1993) , and is equivalent to the non-linear diffusion equation. The viscosity of Equation 3 is indirectly proportional to the gas conductivity, and as viscosity increases, conductivity decreases. The relationship also shows that a constant ratio of permeability to viscosity will yield the same conductivity.

The experiment with permeability demonstrated that values less than $1x10^{-13}$ m^2 for an initial pressure of 14.5 MPa would render the results meaningless. The viscosity used in the experiments was $10x10^{-6}$ Pa*s, and the ratio of permeability to viscosity yields $1x10^{-8}$. Values less than this ratio causes the code to predict cascading failure of waste. With the original permeability of $1.7x10^{-13}$ m^2, viscosity values greater than $17x10^{-6}$ Pa*s causes the code to give erroneous results. The ratio for failure criterion increases to $1.7x10^{-8}$ for an initial repository pressure of 14.8 MPa and waste tensile strength of 10 psi. A simulation with the ratio of $1x10^{-8}$ m^2/Pa/s, an initial pressure of 14.5 MPa, and tensile waste strength of 10 psi yields a failed volume of 0.63 m^3.

The possibility of larger viscosity values is not ill conceived. The viscosity value obtained for hydrogen gas was the standard temperature and pressure value (STP), and viscosity increases moderately as pressure or temperature increases.

The components of the repository gas will also increase the viscosity. Through microbial degradation of plastics, rubbers, and other combustible material, O_2, CO_2, CH_4, N_2, N_2O and H_2S will be created. Francis et al. (1996) conducted experiments of microbial gas generation under expected WIPP repository conditions and found that the percentage of N_2 varied between 61.9% to 91.4%, CO_2 varied between 0.4% and 34.3%, and H_2 varied between 0% and 12.8%. These other constituents have a much higher viscosity than H_2, with N_2 being as high as 19.2×10^{-6} Pa*s (STP), which will undoubtedly increase with an increased repository pressure.

Even though microbial degradation may create higher quantities of CO_2, and N_2 than H_2, the process itself will be limited. It is uncertain whether the colonies of microbes can exist under repository conditions, and was therefore assigned a 50% chance in the CCA. Iron corrosion on the other hand will produce massive quantities of H_2 and it is certain that iron will corrode when brine fills the repository. Approximately 2×10^{9} moles of H_2 (Telander and Westerman 1996) will be produced from the iron in WIPP. However, the other gaseous constituents could play a small role if microbial degradation does produce gas. Figure MASS-1 (U.S. DOE 1996-Appendix MASS) shows that at lithostatic pressure, if the mole fraction of H_2 to CO_2 is reduced from 100% to 90%, then the viscosity would increase from 9×10^{-6} Pa*s to 16×10^{-6} Pa*s. Therefore, it is suggested that the code be modified to allow a larger spectrum of values to be modeled.

9.7. Sensitivity to Mud Column Density

The density of the mud column in the borehole is dependent on the type of drilling mud used. For the WIPP, it is most likely that the drilling mud will come from the Salado Formation with additives to increase the average mud density to 10 - 11 lb/gal (1200-1320 kg/m^3). The GASOUT code used a density of 1249.3 kg/m^3 in the Hansen Investigation, and it is possible that this value could vary over the range mentioned above.

Figure 9.5. shows the results of varying the parameter from 1200 to 1320 kg/m^3 for a 10 second simulation and an initial repository pressure of 14.8 MPa. The figure shows three curves of different waste strength, with all other parameters remaining the same as used in the Base Case simulation. The most outstanding feature of Figure 9.5. is the disjointed curve of failed waste (left) and mud motion (right) of the 10 psi tensile waste strength simulation. The code had trouble calculating failed waste for mud densities below 1228 kg/m^3, resulting in the cascading affect described above. The code also had trouble at 1240 and 1250 kg/m^3, and if results were plotted for these densities (failed waste and mud motion), sharp spikes would exist in the curve.

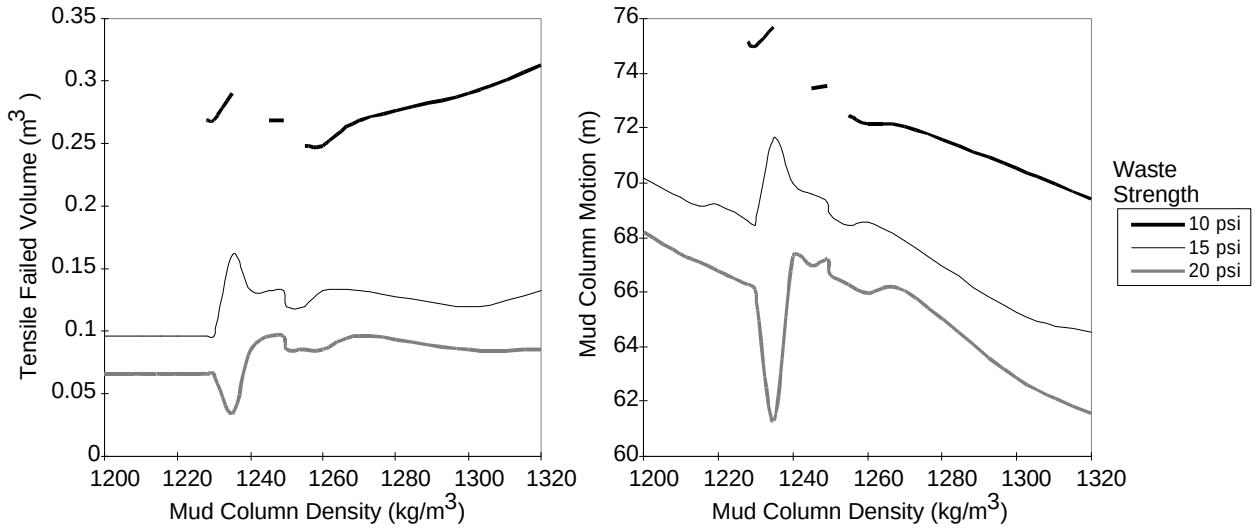

Figure 9.5. Left) Tensile Failed Volume as a Function of Mud Column Density for Several Waste Strengths and Right) Mud Column Motion as a Function of Mud Column Density

For the higher waste strengths (and subsequently lower repository pressures) of 15 and 20 psi, the mud density simulations were able to calculate failed volumes for all density values investigated. However, the results seemed almost as unreliable as the lower waste strength. Though a trend can be seen in the failed volume and mud motion, variances from those trends are high. Both graphs in Figure 9.5. show trouble with the code when densities are between 1230 and 1270 kg/m^3.

9.8. Sensitivity to Waste Porosity

Lastly, the code was investigated to test the effect of waste failure with changing (decreasing) porosity. If the porosity is lower, then the velocity of the gas moving through the repository to a borehole intrusion is higher. Hansen et al. (1997) report a porosity of 0.7, which was said to be typical of waste porosity when the pressure reached over 14.8 MPa. However, after investigating the relationship between pressure and porosity, it was found that porosity during the long-term performance of the repository was approximately 0.2 for high pressures, and less for lower pressures. Figure 9.6. shows the relationship of porosity to pressure for the undisturbed scenario of the performance assessment for the CCA. The figure shows two separate times, at 5,000 and 10,000 years postclosure using the results of BRAGFLO.

Porosity from the two-phase calculations of brine and gas flow through the repository clearly show the porosity will be quite low. The response of the code to lower repository porosities show slightly higher releases. For a porosity of 0.2, with initial conditions of 14.8 MPa repository pressure, and 10 psi waste strength, the uncompacted spalled volume is 0.47 m^3, and decreases

smoothly up to the original porosity of 0.7 and a calculated failed volume of 0.27 m^3. However, porosities above 0.7 and below 0.2 caused the calculated waste to cascade. Additional experiments using a variety of repository pressures and their expected porosities from Figure 9.6., does not show any further problems within the code.

9.9. Conclusions

A sensitivity analysis has been performed on the spallings code, GASOUT. GASOUT along with several other codes were used by the DOE to prove that the spalled volume calculated in the Compliance Certification Application (CCA) were reasonable, because the GASOUT calculated a much smaller spalled volume than those calculated in the CCA. The results of the experiment were documented in Hansen et al. (1997), which showed that a maximum of 0.27 m^3 would spall through blowout upon breach of the repository. The volume of spalled material calculated in the CCA ranged from 0.5 to 4.0 m^3.

The simulated blowout in the Hansen et al. simulations only lasted for five seconds. Blowout usually takes several minutes to control, and it is believed that much higher volumes of failed material would be derived if the simulations were run for longer periods of time. Sensitivity analysis in this chapter showed that as much as six times the volume would fail, if the experiments were extended in the GASOUT code from five seconds to approximately 50 seconds. Discounting the late time effect of spall when the velocities are allowed to flow faster from the waste underestimates the total amount of failed material that will reach the surface.

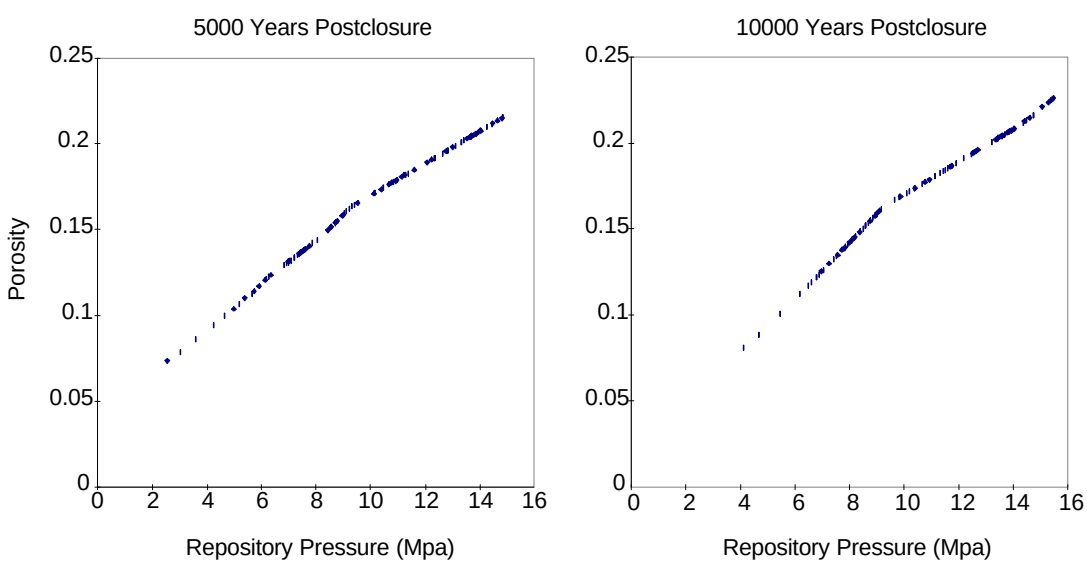

Figure 9.6. Porosity Versus Pressure Profiles for Undisturbed Scenarios of the CCA

GASOUT was also tested for its response to a range of waste permeabilities. The permeability of the waste used in the CCA was 1.7×10^{-13} m^2, and thus was carried over to the analysis in Hansen et al. (1997). However, the same report also measures a new value of permeability, based on a better understanding of simulated waste forms. These surrogates for the WIPP waste exhibited a permeability on the order of 4×10^{-15} m^2 for "typical" specimens. None of the surrogates that measured permeability contained magnesium oxide, the proposed backfill material that is said to occupy 25% of the repository's volume, and precipitation is expected to decrease the permeability of the waste.

An analysis of permeability with GASOUT showed that the code can only be applied to a small range of parameter values. For the most extreme case, using an initial pressure of 14.8 MPa and waste strength of 10 psi, the range is 1.7×10^{-13} to 2.0×10^{-13} m^2. The range is extended when waste strength is increased and pressure is decreased. The small range of permeabilities prohibits the use of the code under varying repository conditions. Hansen et al. (1997) shows that lower permeabilities will have high pressure gradients through the waste, thus inducing more spall.

The code also showed sensitivity to gas viscosity. Viscosity, along with permeability and porosity are used to calculate an effective gas conductivity for the flow of gas through the repository upon an inadvertent human intrusion. It is reasonable to assume that viscosity will be higher than the ideal value for hydrogen at standard temperature and pressure. It will also be higher if other gas constituents are added to the repository. Yet, as viscosity increases to values that are reasonable and defensible, the code calculates a very high failed volume due to the cascading effect noticed from low permeabilities.

Lastly, a sensitivity of the mud column density showed that the code does not promote a strong confidence in the results obtained from GASOUT. The analysis varied the parameter over a range of expected values at the WIPP, and found the code to behave erratically to small changes in values. Figure 9.5. shows the results of the experiment, and demonstrates the problems associated with using a wide range of values. The figure represents a high initial pressure using several different waste strengths, which proves that the code can only work well under non-extreme conditions. The maximum reported spalled volume in Hansen et al. (1997) is only the maximum for a narrow set of repository conditions, and the code is shown to fail otherwise.

Hansen et al. (1997) claim conservatism in the approach to modeling the WIPP waste under a spall scenario. First, the waste form was considered homogeneous in GASOUT. Arguments

have been made to explain that homogeneity is very conservative, and heterogeneous waste will decrease spall. Yet it can be seen in the fully coupled numerical code that heterogeneity will increase the pressure gradient, and possibly the amount of spalled material. Hansen et al. (1997) show that inelastic behavior of the waste will increase tensile strength, and reduce the amount of waste failing in tension. However, inelastic behavior is attributed to saturated (wet) waste, which is ductile and will have a lower strength than dry waste. Dry waste forms will most likely be brittle, and will fail elastically. They also claim that tensile failure will induce fracturing within the waste, increasing the permeability of the cracked region, causing the system to stabilize more quickly. However, this too can be detrimental; the turbulent flow of gas will impose additional forces (e.g., drag forces) on the waste that may erode the waste and cause more spall. In short, the claimed conservatisms applied to the models for calculating the release of spalled material are actually simplifications, which are necessary in order to construct reasonable mathematical and numerical models; they are not conservative assumptions.

This analysis does not question these mathematical and numerical models used to design the GASOUT code; it addresses the working of the code itself. The code responds erratically to small changes in the input assumptions, and sometimes gives misleading results. It is suggested that the code be examined more closely, before judging the results of Hansen et al. (1997) as the maximum amount of failed material that will reach the surface, and the spalled volumes calculated in the CCA as reasonable.

10. SOLUBILITY MODELING ASSUMING NO MgO BACKFILL AND WITH THE MgO MINERAL PHASE OF NEQUEHONITE

10.1. Summary

A modeling study was conducted to accommodate DOE's reported observation that nesquehonite was the only identified observed product from the MgO-carbon dioxide study. The modeling study parallels the EPA requested PAVT calculations in that the magnesium compound was assumed to persist throughout the 10,000 year regulatory period. There is a difference, however, as the PAVT calculations recommended by the EPA assumed the presence of hydromagnesite, which was not observed in the DOE experiments. The study assumed the presence of nesquehonite, which was observed in the DOE experiments. Moreover, this study also calculated releases using the modeled solubilities in the case of no backfill.

As shown, these higher solubilities have a dramatic impact on the cumulative release of radionuclides to the accessible environment for the 10,000 year period. Assuming the results of the FMT calculations for solubility are correct, the calculated release for a system without backfill or a system with backfill induced nesquehonite is very close to the EPA containment requirement. While these calculations, based on DOE's own solubility values, do not violate the containment requirements, they also show that there is little margin for error.

10.2. Introduction

Chapter 5 explained EEG's concern's about assuming the oxidation of plutonium to states III and IV. To determine the sensitivity of the release calculations to solubility, the solubility was increased, assuming all plutonium was in oxidation state V. The results showed that as solubility increased, the releases increased, but was limited by the amount of brine in the repository. This chapter further investigates the relevance and consequence of brucite speciation to magnesite and its effects on solubility.

The idea of adding MgO as backfill around the waste in the WIPP repository began shortly before the CCA was issued to the EPA, and consequently no analysis was performed in the Baseline Inventory Report (U.S. DOE 1996-Appendix BIR). In response, the DOE Peer Review Committee had to reconvene several times to be convinced of its effects, with the main issue being the effectiveness of $Mg(OH)_2$ to react with CO_2 to act as a buffer to increase to pH of the brine and reduce the fCO_2 for reaction with the brine. Experiments had not been performed by the time of application submittal, and it was unclear how effective the backfill would be.

It was anticipated that large quantities of CO_2 would be generated in the repository (U.S. DOE 1996-Appendix Peer 1). The CO_2 would react with the brine, forming carbonic acid. The acid would decrease the pH of the Salado brine from 9.4 to approximately 4-5. Under acidic conditions (pH lower than 4), the solubility of actinides could increase by 5 orders of magnitude in brine, causing problems in the inadvertent human intrusion scenario. The higher solubilities would allow a higher mass of actinides to go into solution, and hence higher releases to the accessible environment upon breech. The original intent of the MgO was to maintain a high brine pH.

The concern was not the chemical reaction pathway however, it was the effectiveness of the design in the placement of the MgO around the waste to allow reaction with the large amounts of CO_2. The DOE needed to perform experiments to demonstrate the effectiveness of MgO in increasing the pH and reducing the fCO_2. The results were presented to the Third Supplemental Peer Review on April 25, 1997. It was the intention of that Peer Review for DOE to prove that the MgO will act quickly and completely with the CO_2 to reduce carbonate ligands from solution and to decrease gas pressures and rate of gas pressurization by the removal of CO_2. The subsequent report (Papenguth et al. 1997) showed the results of the experimentation, which were used for modeling data in the FMT code to establish solubilities for the various actinides under those chemical conditions (Novak 1997).

Recently, several issues were brought to light about the inherent problems and conclusions of that study (Neill et al. 1998). First, it was assumed that by 1000 years after the formation of CO_2, that the precipitates from the reactions would form magnesite. This conclusion was extrapolated (linearly) from literature data at different temperatures. Yet, the extrapolation seemed to be a poor justification that the reaction would go to completion (to magnesite) within the time frame of the WIPP projected history. If the extrapolation were assumed to be another function, then the time could extend to the order of 10^5 - 10^6 years. Secondly, the intermediate phases between brucite ($Mg(OH)_2$) and magnesite ($MgCO_3$) were unclearly defined in their function, length of time, and composition. It was concluded that nesquehonite ($MgCO_3 \bullet 3H_2O$) would exist for a very short time before going to hydromagnesite [$(MgCO_3)_4 \bullet Mg(OH)_2 \bullet 4H_2O$]. Yet, hydromagnesite was never positively identified, and a mineral species, that was noted to be hydromagnesite-like, existed instead. The composition [$MgCO_3 \bullet 3H_2O \bullet MgCl(OH)$] looked closer to nesquehonite than hydromagnesite.

Lastly, the results from FMT were questioned for solubilities of actinides in the presence of the various mineral species and the use of the oxidation state analogy for actinides in the same

oxidation state. For example, the concentration of $Th(SO_4)_2$ in Castile ERDA-6 brine was $1.35x10^{-5}$ mol/kg. When Mg^{++} was added to the solution, to increase it from 0.021 to 0.039 mol/kg, the concentration of $Th(SO_4)_2$ reduced to $9x10^{-22}$ mol/kg. Nothing in the chemistry of the brine would contribute to such a large discrepancy in the values given for thorium sulfate.

Though sulfate complexes were assumed to be minor, the same problems were carried over to the carbonate species of thorium. Thorium is an important consideration in these experiments, because by the oxidation state analogy thorium was used to establish all IV actinides (Pu, U, and Th). It was seen that the errors of one actinide carried through to the other major actinides.

Novak (1997) provided projected actinide solubilities in the presence of nesquehonite and also without the presence of MgO backfill (no backfill), in addition to magnesite and hydromagnesite values. Due to the uncertainties associated in the model and laboratory experiments, it was decided to use these higher solubilities from species that were not considered in either the CCA or the EPA's verification calculations, called the Performance Assessment Verification Test (PAVT), in a new set of calculations using PANEL and NUTS. The results were then used to compare the CCDFs from the CCA (DOE) and PAVT (EPA) to acquire a better understanding of long-term performance.

The median model solubility values used for the CCA, PAVT, and for other species of brucite-magnesite complexes can be seen in Table 10.1. (reproduced from Novak 1997). The CCA used magnesite as the interactive species and the PAVT used hydromagnesite. Neither used nesquehonite, the only identified observed species. Hence, nesquehonite and No Backfill solubilities are used here. One outstanding feature of Table 10.1. is the difference in solubility of +4 actinides in Castile brine between No Backfill and nesquehonite. The experimental model values show that the +4 state is more soluble in the presence of nesquehonite than without any addition of MgO.

10.3. Methodology

In the CCA, the model (median) values from FMT were given an uncertainty range of -2 and

Brine Type	Salado				Castile			
Condition	+3 (M)	+4 (M)	+5 (M)	+6 (M)	+3 (M)	+4 (M)	+5 (M)	+6 (M)
magnesite (CCA)	5.8e-7	4.4e-6	2.3e-6	8.7e-6	6.5e-8	6.0e-9	2.2e-6	8.7e-6
No Backfill	4.0e-3	5.0e-4	2.0e-4	8.0e-5	2.0e-3	7.0e-5	6.0e-4	8.0e-5
hydromagnesite (PAVT)	9.4e-8	1.2e-8	1.2e-7	8.7e-6	1.3e-8	4.1e-8	4.6e-7	8.7e-7
nesquehonite	3.2e-7	6.3e-4	1.2e-7	8.7e-6	2.1e-6	1.0e-3	7.8e-7	8.7e-6

Table 10.1. Median Solubility Values Used in Various Performance Assessment Calculations

	nesquehonite		No Backfill	
	SOLCIM	SOLSIM	SOLCIM	SOLSIM
SOLAM3	1.51616	-.27709	4.48678	3.83714
SOLPU3	1.51616	-.27709	4.48678	3.83714
SOLPU4	5.23242	2.15588	4.06695	2.05552
SOLU4	N/A	2.15588	N/A	2.05552
SOLU6	0.95861	0.96357	0.95861	0.96357
SOLTH4	5.23242	2.15588	4.06695	2.05552

Table 10.2. Solubility Factors for SOLCIM and SOLSIM

+1.4 orders of magnitude. Incidentally, the 1992 PA (Sandia 1992) had many of the parameter ranges of the actinides span 13 orders of magnitude to capture the uncertainty. The range in the CCA was given a constructed distribution, where the majority of the values (59%) fell -1.0 and 0.0 orders of magnitude from the values of Table 10.1. For the present study, the ranges have been eliminated, with each realization having the same constant value.

Running the new values for solubility of various actinides began at the Source Term files. These files contained the multiplication factors from which the median values would be modified. For example, the solubility of ^{241}Am in Castile brine was given a range, as explained above. This range was sampled in LHS, and a number was identified in each realization (vector). If the

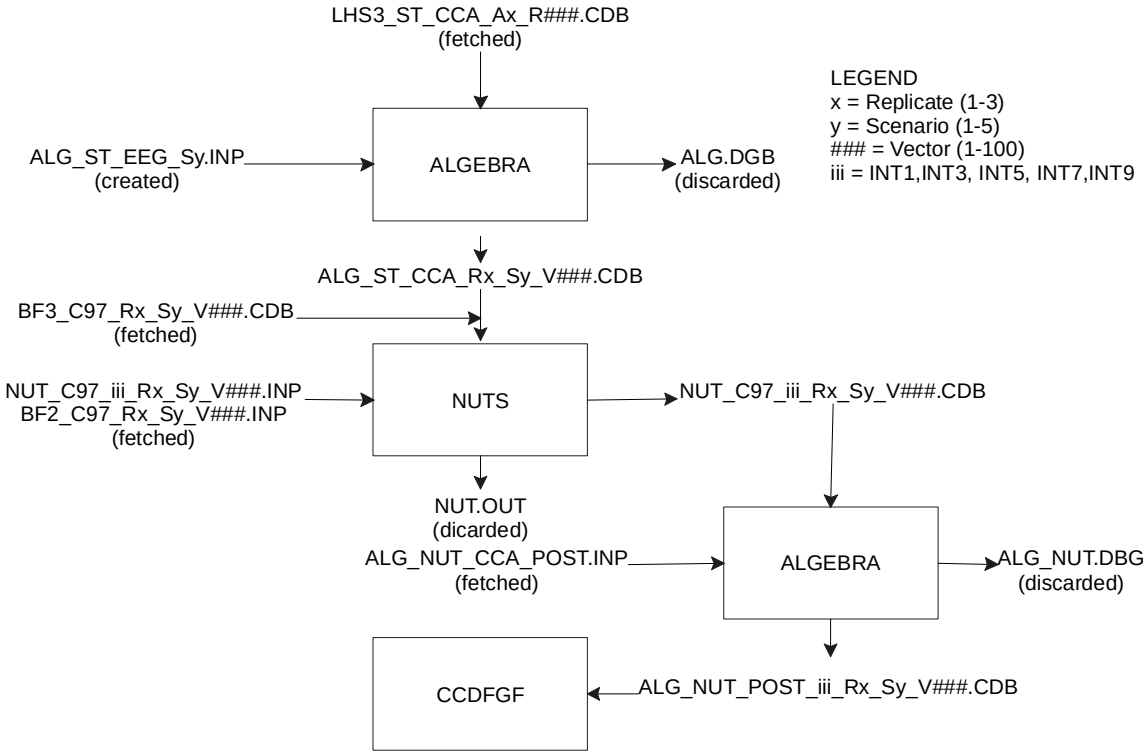

Figure 10.1. Flowchart for NUTS Time Intrusion Calculations

sampled value in LHS was -1.0, then the median value was multiplied by $10^{-1.0}$. In the transport experiments of this study, these values were replaced by the values in Table 10.2. for every realization. The parameter names are retained from CCA nomenclature.

After modifying the Source Term files, PANEL and NUTS were run with the new files. For this study, the BRAGFLO files from the PAVT study were used, since this would give the maximum effect for the changes. The PAVT, compared to the CCA, calculated much higher releases to the surface due to the higher pressures in the repository.

The flowchart of PANEL execution can be seen in Figure 5.1., and the flowchart for NUTS execution can be seen in Figure 10.1. The flow chart only represents one set of NUTS calculations, but represents the processes of all three sets. These sets include SRC, ISO, and INT calculations, and are further explained in Chapter 2. Figure 10.1. shows the detailed steps involved in running the INT (Time Intrusion) calculations.

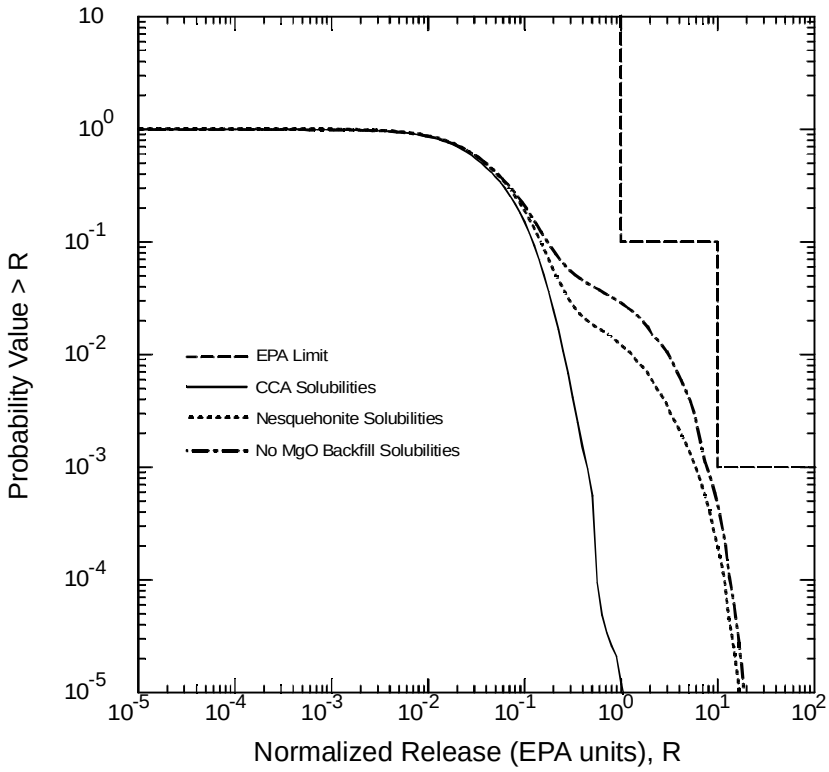

Figure 10.2. Overall Mean of Normalized Releases for Modeling of Increased Solubilities Using Nesquehonite and 'No Backfill' Values Compared to CCA Values

10.4. Results

The results of running the new set of solubility calculations can be seen in Figure 10.2. The figure shows the overall mean from all combined release mechanisms for No Backfill and nesquehonite solubilities from Table 10.1. In addition, the PAVT direct brine releases were combined with the CCA solubilities from CCA NUTS calculations to give another perspective of calculated solubility values. The curves show that neither release scenarios cross the EPA compliance standard, indicating that even the highest reported solubilities do not violate these standards, with all other parameters remaining the same.

The effects of increasing the solubility values for the new calculations show a substantial increase below the 10^{-1} probability. The increase, in the form of a shoulder, is attributed to the increased effect of the direct brine release mechanism. Figure 10.3. shows the breakdown of all mechanisms to form the total release. The figure presents each mechanism as the overall mean from all realizations of one replicate from the nesquehonite solubility calculation. Clearly, the direct brine release calculations stand out as the largest mechanism for release at the 10^{-3} probability.

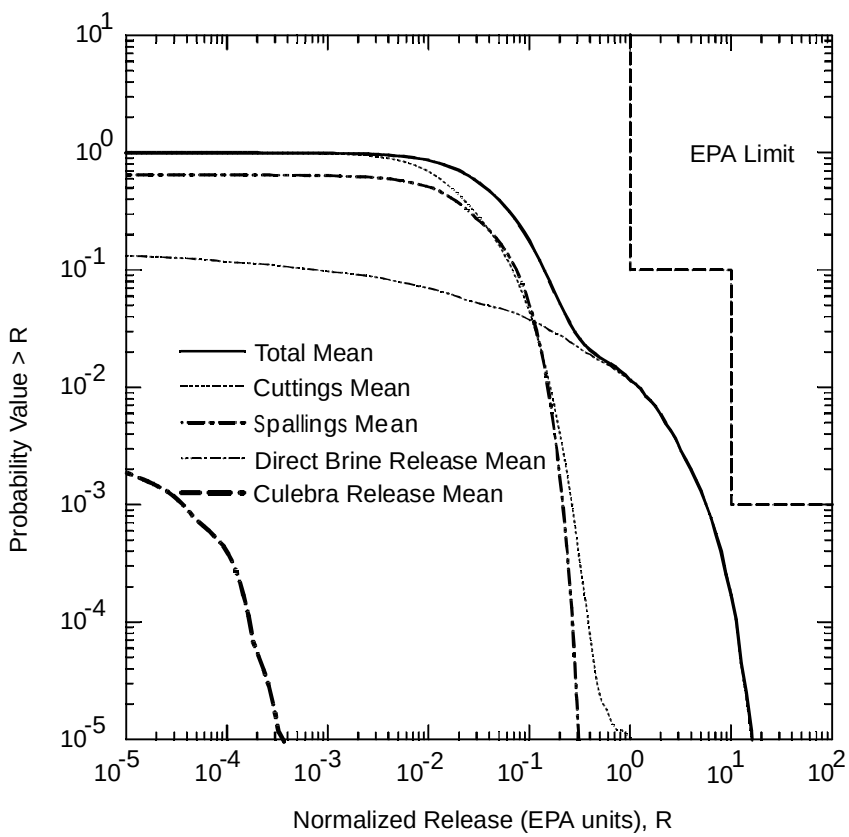

Figure 10.3. Overall Mean from all Release Mechanisms for Solubility Modeling With Nesquehonite

In addition to the results of the PAVT, the solubility modeling of nesquehonite and No Backfill was combined with other chapters of this report, namely the Culebra Transport Modeling, to assess the effects of higher initial masses injected into the Culebra. Conclusions from previous chapters stated the limitation of the Culebra releases due to the amount that would initially reach the Culebra from transport out of the repository. The combination from previous results with the present study was a simple task, since all mechanisms are calculated separately and combined in the end through the code CCDFGF.

Figure 10.4. shows the Culebra releases from Chapters 6 and 8 with the nesquehonite solubilities of Chapter 10. The conclusions of the two earlier chapters that the releases are mass limited is verified here. If the initial amount of mass that reaches the Culebra are increased, such as with increased solubility, then the effect will be quite strong on the Culebra releases, as seen by the increases in releases in the CCDF curves of plutonium at 1% K_d=0 ml/g. However, in itself, solubility has little effect, and must be coupled with large fractional discharges calculated with 1% K_d=0. This can be seen when comparing the two curves in Figure 10.4., which come from the Chapter 8 analysis on increased mining. The uranium releases are very small and the

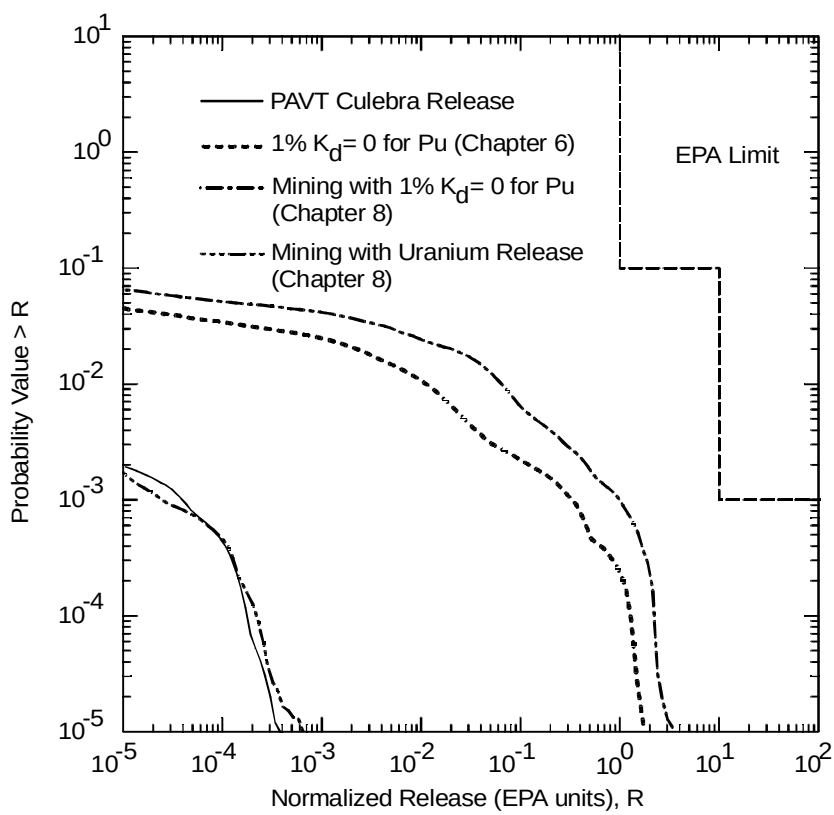

Figure 10.4. Nesquehonite Solubility Calculations Combined with Culebra Transport Calculations from Chapters 6 and 8

plutonium releases are quite large, even though both have an increase in initial mass. It is clear then that high solubilities and low K_ds will cause quite a threat to the integrity of the disposal system.

10.5. Conclusions

A modeling study has been presented in which the solubilities of actinides from the CCA and PAVT are questioned. New values are presented in Table 10.1. with the assumption of the persistence of an intermediate phase between brucite and magnesite to exist for the entire 10,000 year proposed history of the WIPP repository. The modeling of the intermediate phase, nesquehonite, is much like the modeling of the PAVT, in which hydromagnesite was assumed to persist throughout the 10,000 years. In addition, No MgO Backfill model solubilities were studied.

The consequence of higher solubilities, as seen in Figure 10.2. are quite high. The overall mean release for the CCA and PAVT were 0.2 and 0.4 EPA Units at 10^{-3} probability, respectively. The overall mean for the increased solubilities of nesquehonite and 'No Backfill' are 6.0 and 8.0 EPA Units at the 10^{-3} probability, respectively. The limit for compliance, according to 40 CFR Part 194 is 10 EPA Units. Therefore, it readily appears that even high solubility values do not cause the disposal to be out of compliance with EPA regulations. However, the large consequences of small changes of solubility values raises an important question: Are we certain that the solubility of plutonium or uranium, in any oxidation state, is less than the values presented in the CCA or the PAVT? How did we arrive at these numbers? Is there experimental evidence to back up the claims made in the CCA that deals with the oxidation state analogy between Am+3 and Pu+3? Once one really delves into the reasoning behind many of the fixed numbers associated with these actinides, many drawbacks appear in the reasoning, and confidence in the values used to show compliance is shaken.

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Acronyms

AIC	Active Institutional Control
BLM	Bureau of Land Management
CCA	Compliance Certification Application
CCDF	Complementary Cumulative Distribution Functions
CH	Contact Handled
DBR	Direct Brine Release
DOE	U.S. Department of Energy
DRZ	Disturbed Rock Zone
EEG	Environmental Evaluation Group
EPA	U.S. Environmental Protection Agency
ERDA	Energy Resource and Development Administration
FBHP	Flowing Bottomhole Pressure
FEP	Features, Events, Processes
LHS	Latin Hypercube Sampling
LWB	Land Withdrawal Boundary
NMBMMR	New Mexico Bureau of Mines and Mineral Resources
PA	Performance Assessment
PAVT	Performance Assessment Verification Test
PIC	Passive Institutional Control
PSI	Pounds per Square Inch
RH	Remote Handled
SAR	Safety Analysis Report
STP	Standard Temperature and Pressure
TRU	Transuranic Waste
TVD	Total Variation Diminishing
WIPP	Waste Isolation Pilot Plant

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EVALUATION OF RISKS AND WASTE CHARACTERIZATION REQUIREMENTS FOR THE TRANSURANIC WASTE EMPLACED IN WIPP DURING 1999

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May 2000

EEG-75
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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U. S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the compliance of the generator sites with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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ACRONYMS

ADF	Air Dispersion Factor
AK	Acceptable Knowledge
amu	Atomic Mass Unit
ASTM	American Society for Testing and Materials
CAMs	Continuous Air Monitors
CAO	Carlsbad Area Office
CARs	Corrective Action Reports
cfm	Cubic feet per minute
CFRs	Code of Federal Regulations
DCF	Dose Conversion Factor
DOE	U. S. Department of Energy
DQOs	Data Quality Objectives
ECS	Exhaust Shaft Concentration
EEG	Environmental Evaluation Group
EPA	U. S. Environmental Protection Agency
GC/ECD	Gas Chromatography/Electron Capture Detection
GC/FID	Gas Chromatography/Flame Ionization Detection
GC/MS	Gas Chromatography/Mass Spectroscopy
HQ	Hazard Quotient
HI	Hazard Index
HSG	Head Space Gas
HWA	New Mexico Hazardous Waste Act
HWDU	Hazardous Waste Disposal Unit
ICP-MS	Inductively Coupled Plasma - Mass Spectroscopy
INEEL	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
MDC	Minimum Detectable Concentration
MIR	Maximum Individual Receptor
MRL	Method Reporting Limit

NMAC	New Mexico Administrative Codes
NMED	New Mexico Environment Department
PDP	Performance Demonstration Program
ppbv	Parts per billion by volume
PRQL	Program Required Quantitation Limit
QAOs	Quality Assurance Objectives
QAPD	Quality Assurance Program Document
QAPjP	Quality Assurance Project Plan
QAPP	Quality Assurance Program Plan
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
RDF	Risk to Dose Factor
RFETS	Rocky Flats Environmental Technology Site
RPD	Relative Percent Difference
RSD	Relative Standard Deviation
RRF	Average Response Factor
RTR	Real-time Radiography
SAR	Safety Analysis Report
SPCCs	System Performance Check Compounds
SVOC	Semi-volatile Organic Compound
SWB	Standard waste box
TRU	Transuranic
UCL_{90}	90% Upper Confidence Level
UG	Underground
VE	Visual Examination
VOC	Volatile Organic Compound
WAC	Waste Acceptance Criteria
WAP	Waste Analysis Plan
WID	Waste Isolation Division
WIPP	Waste Isolation Pilot Plant
WWIS	WIPP Waste Information System

EXECUTIVE SUMMARY

The U. S. Department of Energy's (DOE) Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, has been constructed for the disposal of long-lived transuranic (TRU) waste. The New Mexico Environment Department (NMED) issued a Hazardous Waste Facility Permit (the Permit) to dispose of mixed waste at WIPP effective November 26, 1999. This Permit does not regulate the radioactivity in the waste. The DOE emplaced 44 shipments of non-mixed transuranic waste in Room 7 of Panel 1 before the Permit became effective. There also are a large number of waste containers at the generating sites that have been at least partially characterized prior to the effective date of the Permit.

Section IV.B.2.b of the NMED Permit contained language which appeared to prohibit emplacement of non-mixed wastes that were not characterized in accordance with the requirements of the Permit's Waste Analysis Plan (WAP). The justification for adding Section IV.B.2.b was that mixing WAP-certified wastes with pre-Permit wastes created unknown risks that should not be a part of Permit performance standards. Statements were made during Permit public hearings and in written testimony that the risks might be substantial but there was no indication of the nature of these risks or their magnitude.

This report provides a technical evaluation, conclusions, and recommendations of the following Section IV.B.2.b issues:

1. A comparison of pertinent WAP requirements with pre-Permit waste characterization;

2. A risk analysis of the pre-Permit waste emplaced in Room 7. Expected and bounding risks from routine operations and possible accidents are evaluated.

Conclusions:

1. The NMED approved WAP has made explicit many of the undocumented assumptions and implied good practices from the DOE's pre-Permit waste characterization program. Although there are differences between the pre-Permit and WAP characterization programs, the pre-Permit program appears to substantially meet the technical requirements in the WAP.

2. Deviations granted by DOE during pre-Permit waste characterization and premature closures of some corrective actions generated during independent audits may be the most significant differences from the Permit waste characterization requirements.

3. Estimated carcinogenic risks to an underground worker, a surface worker, and a member of the public due to routine operations from all the TRU wastes emplaced in Room 7 in 1999 are six to eight orders of magnitude less than risk levels allowed by the Permit. Non-carcinogenic risks are seven to ten orders of magnitude below allowed risks.

4. Even if VOC emissions are much higher than risk calculations estimate, the Confirmatory VOC Monitoring Plan in use at WIPP would detect concentrations that are three orders of magnitude below allowable Permit limits.

5. Risks to the surface worker and member of the public from low probability accidents are essentially all from radionuclide releases and are lower than the allowable Permit risks from routine VOC releases. Risk to the underground worker is significant (1.7×10^{-3} if the accident occurs).

Recommendations:

Questionable data for the individual container lots of pre-Permit waste could be reviewed by NMED for conformance with the WAP requirements if necessary. This determination should consider all deviations and include input from the DOE.

The calculated non-accidental risks from the pre-Permit waste in Room 7 are too low to justify any remedial or other actions involving these wastes.

Radionuclide risks to underground workers from low probability spontaneous fire and roof fall accidents should be considered when setting restrictions on worker access to the south 1600 and east 300 drifts.

1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Project is located in southeastern New Mexico (see Figure 1-1). WIPP has been constructed by the U.S. Department of Energy (DOE) to provide permanent disposal of long-lived transuranic (TRU) waste from the U. S. defense activities and programs.

Approximately 60% of the wastes to be disposed at WIPP is believed to be "mixed wastes"--wastes containing not only transuranic radionuclides but also hazardous materials regulated under the federal Resource Conservation and Recovery Act (RCRA). Regulation of WIPP under RCRA has been delegated by the U. S. Environmental Protection Agency (EPA) to the New Mexico Environment Department (NMED), acting under the New Mexico Hazardous Waste Act (HWA). In October 1999 NMED granted a Hazardous Waste Facility Permit (the Permit) to WIPP that became effective on November 26, 1999 (NMED 1999b). This Permit regulates the management, storage, and disposal of only the hazardous waste components of the contact-handled transuranic mixed waste at WIPP. The Permit also requires that waste brought to the WIPP meet waste characterization requirements found in the Waste Analysis Plan (WAP), a series of appendices to the Permit (the "B" appendices).

During the eight months prior to the promulgation of the Permit, the DOE disposed of 44 shipments of TRU (non-mixed) waste in Panel 1, Room 7, of the WIPP. This waste consisted of 101 standard waste boxes (SWBs) containing heat-source waste, 152 55-gallon drums of graphite waste, and 574 55-gallon drums of residues in pipe containers. These waste containers were characterized in a manner similar to, but not identical with, the Permit requirements contained in the WAP. The difference between the pre-Permit waste characterization program and the WAP requirements is of great importance due to Section IV.B.2.b of the Permit, as described in the next section.

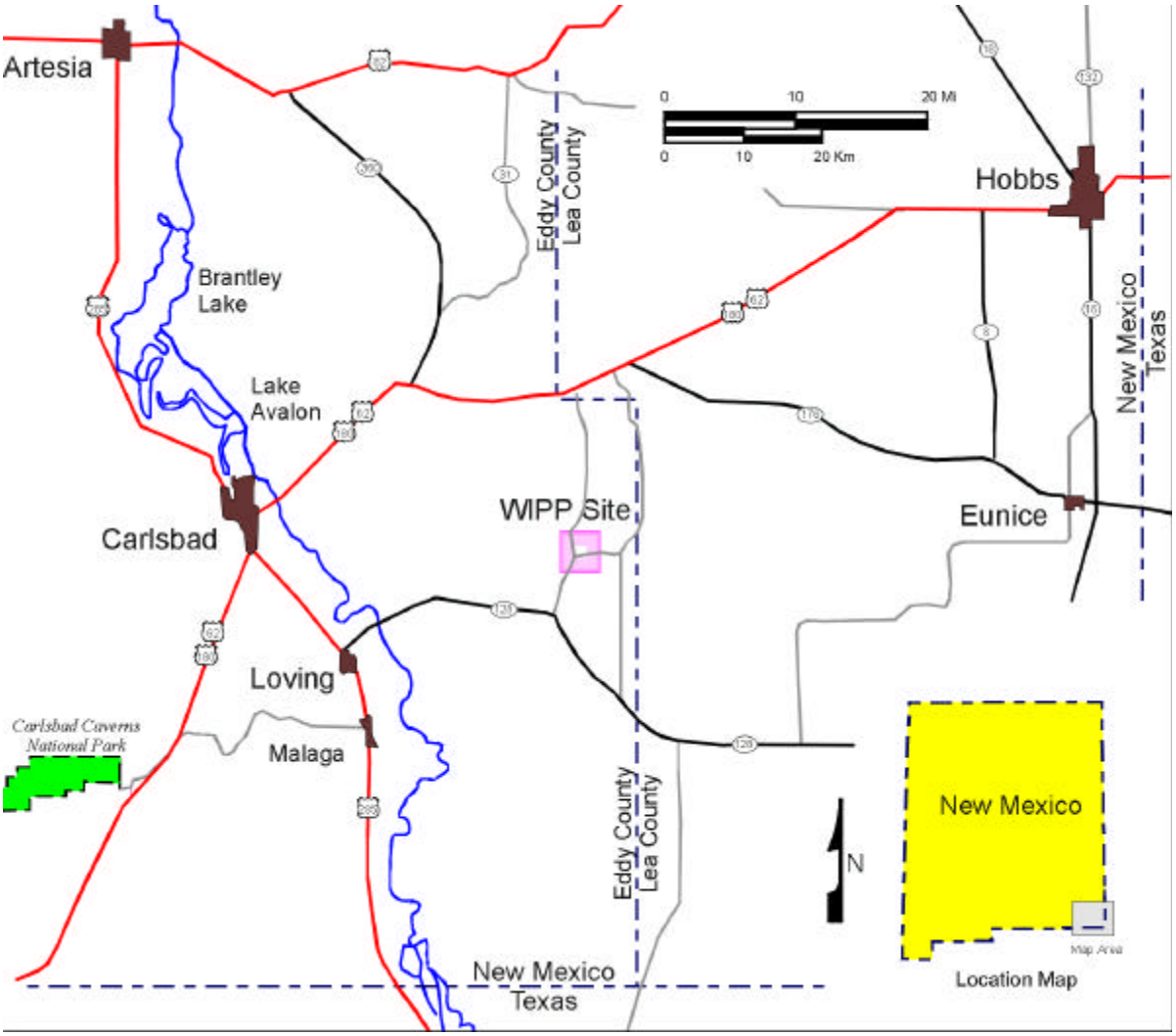

Figure 1-1. WIPP Site Location in Southeastern New Mexico

1.1 The IV.B.2.b Requirement

Section IV.B.2.b of the Permit contains the following statement:

> Specific prohibition -- After this permit becomes effective, (1) the Permittees shall not dispose non-mixed TRU waste in any underground HWDU unless such waste is characterized in accordance with the requirements of the WAP specified in permit Condition II. C.1 , and (2) the Permittees shall not dispose TRU mixed waste in any underground HWDU if the underground HWDU contains non-mixed TRU waste not characterized in accordance with the requirements of the WAP.

A WIPP underground hazardous waste disposal unit (HWDU) is a single waste disposal panel of seven rooms. There was considerable testimony about the pros and cons of Section IV.B.2.b requirements during public hearings and written testimony on the Permit. The justification for adding the requirement was that mixing WAP-certified wastes with pre-Permit characterized wastes created unknown risks that should not be a part of the RCRA performance standards of the repository. While some testimony indicated that these risks might be substantial, no one identified what these risks were or their possible magnitude.

The IV.B.2.b requirement poses two potential problems for the WIPP. A prohibition against adding of wastes certified under the WAP to the wastes already emplaced in Room 7 of Panel 1 could mean that Panel 1, which was designed to dispose of about 81,000 drum-equivalents of waste, would be limited to only the 1,400 drum-equivalents of pre-Permit waste already emplaced. The abandonment of the rest of Panel 1 could reduce the design capacity of WIPP by about 10%, and would delay emplacement of any more waste until mining of Panel 2 is completed (currently scheduled for October 1, 2000). Such a delay could have significant impact not only on operations at the WIPP but at the DOE's TRU-waste generating sites as well.

A second problem from Section IV.B.2.b depends on whether pre-Permit characterization of wastes is determined to have been "characterized in accordance with the requirements of the WAP." In the pre-Permit waste characterization program, sites could begin characterizing waste for shipment to the WIPP as soon as the site Quality Assurance Project Plan (QAPjP) was

deemed acceptable by the Carlsbad Area Office (CAO). Waste generator sites have been characterizing both mixed and non-mixed wastes for years under the pre-Permit waste certification requirements.

1.2 Scope of this Report

Both of the IV.B.2.b problems described in Section 1.1 are obviously controlled by the determination of whether pre-Permit wastes were " ...characterized in accordance with the requirements of the WAP." This report presents a technical evaluation of considerations related to the IV.B.2.b issues described in Section 1.1. No evaluation was made of legal or regulatory aspects of Section IV.B.2.b.

Specifically the Report:

1. Compares requirements of the WAP that are pertinent from a technical viewpoint with the WIPP pre-Permit waste characterization program;

2. Presents the results of a risk analysis of the currently emplaced wastes. Expected and bounding risks from routine operations and possible accidents are evaluated; and

3. Provides conclusions and recommendations.

2. COMPARISON OF WAP TO WIPP PRE-PERMIT WASTE CHARACTERIZATION REQUIREMENTS

2.1 Introduction

This chapter focuses on the most pertinent requirements of the WAP from a technical viewpoint, and compares them to the requirements of the WIPP waste characterization program in operation to process pre-Permit wastes. Where possible, an evaluation of the impact of any differences is then expressed.

The DOE's TRU waste characterization program during the pre-Permit waste characterization period was governed principally by the Transuranic Waste Characterization Quality Assurance Program Plan (QAPP), Revision 0, with interim changes of February 1996 and November 15, 1996 (US DOE 1996d). Accordingly, the WAP requirements will be primarily compared to statements in US DOE 1996d. Other DOE documents that may be cited will be referenced in the text.

The CAO has granted variances from QAPP requirements during the pre-Permit period, labeling these variances at various times as equivalencies, clarifications, and guidances. A formal process for granting these variances has not been published and EEG probably does not have documentation for all the changes granted. While these variances were granted to individual waste characterization sites, they could apparently be used for characterization at the other sites also. Since these variances also affect the comparison of the pre-Permit program to the WAP requirements, any variances that the EEG is aware of are also included in this analysis.

It is worth noting that there were effectively no changes in the WIPP waste characterization quality assurance program from the pre-Permit to the post-Permit period. While the QAPP was cancelled as a part of the move to comply with the Permit, the quality assurance program elements in it were moved to the CAO Quality Assurance Program Document (QAPD),

Revision 3 (US DOE 1999f), which governs generator site waste characterization quality assurance programs.

2.1.1 Pre-Permit Waste Streams

The pre-Permit non-mixed wastes emplaced in the WIPP are from four different waste streams. Graphite mold waste streams from Rocky Flats Environmental Technology Site (RFETS) and Idaho National Engineering and Environmental Laboratory (INEEL) are divided into separate waste streams (RF 003.01 and IN W276.001). These two waste streams were apparently both created at RFETS from the same process. The other waste streams are a ^{238}Pu debris waste stream from Los Alamos National Laboratory (LANL) (TA-55-43.01) and the pyrochemical salt waste stream from RFETS (RF 005.001). Other waste streams accepted by the CAO that may have been characterized during the pre-Permit period include IN-W276.02, RF001.1, RF 002.01, and RF 004.01. Since submission of waste stream designations to the CAO during the pre-Permit period was not required before waste container characterization could begin,[1] it is likely that containers from other waste streams were also characterized.

2.1.2 Data Quality Objectives (DQOs) and Quality Assurance Objectives (QAOs)

The WAP contains approximately 1500 individual statements that could be considered requirements, though a number of them are essentially duplicative. For example, there are multiple statements of the requirement that visual examination must be used to verify a statistically determined portion of radiographic results. The core requirements, however, are the data quality objectives (DQOs), which specify the waste characterization data necessary to meet the RCRA and HWA requirements.

[1]During the pre-Permit period, characterization of waste could begin on acceptance by the CAO of the generator site's waste characterization program documents. Characterization requirements were based on the summary category group (debris, homogeneous solids, or soil/gravel) assigned to each waste container.

The WAP establishes specific data quality objectives in Section B-4a(1). In order to have confidence that the data reported meets the DQOs, various quality assurance objectives (QAOs) are also established in the WAP (Appendix B3, Sections B3-2 through B3-9). If these DQOs and QAOs can be shown to have been met, then the sampling and analysis portions of the characterization could be considered complete (though reviews of these data may still be in question). As a subset of the complete requirements, the DQOs and QAOs would provide a sample of the kinds of problems the pre-Permit waste characterization program would have in demonstrating compliance with WAP requirements.

2.2 WAP DQOs

Section B-4a(1) of the draft WAP, entitled Data Quality Objectives, states that the following DQOs are established to satisfy the RCRA regulatory compliance requirements (pp. B-18 and B-19)[2]:

- Headspace-Gas Sampling and Analysis
  - To identify VOCs and quantify the concentrations of VOC constituents in the total waste inventory to ensure compliance with the environmental performance standards of 20 NMAC 4.1.500 (incorporating 40 CFR, §264.601(b)), and to confirm hazardous waste identification by acceptable knowledge.
- Homogeneous Waste Sampling and Analysis
  - To compare UCL_{90} values for the mean measured contaminant concentrations in a waste stream with specified toxicity characteristic levels in 20 NMAC 4.1.200 (incorporating 40 CFR §261), to determine if the waste is hazardous, and to confirm hazardous waste identification by acceptable knowledge.
  - To report the average concentration of hazardous constituents in a waste stream, as specified in 20 NMAC 2.1.200 (incorporating 40 CFR

[2]VOCs are Volatile Organic Compounds; UCL_{90} is the 90% Upper Confidence Level (see Section B2-3 of the WAP for the formula); NMAC are the New Mexico Administrative Codes, the state analog of the Code of Federal Regulations (CFRs); PRQL is the Program Required Quantitation Limit.

§261) Appendix VIII, with a 90 percent confidence interval, with all averages greater than PRQL considered a detection and subsequent assignment of the waste (if an adequate explanation for the constituent cannot be determined) as a hazardous waste, and to confirm hazardous waste identification by acceptable knowledge.

- Radiography
  - To verify the TRU mixed waste streams by Waste Matrix Code for purposes of physical waste form identification and determination of sampling and analytical requirements, to identify prohibited items, and to confirm the waste stream delineation by acceptable knowledge.
- Visual Examination
  - To verify the TRU mixed waste streams by Waste Matrix Code for purposes of physical waste form identification, determination of sampling and analytical requirements, and to identify prohibited items.
  - To provide a process check on a sample basis by verifying the information determined by radiography, and to confirm the waste stream delineation by acceptable knowledge.

The wording of these WAP DQOs is significantly different than those found in the QAPP (Section 1.5, pp. 1-31 and 1-32), but for the most part the WAP DQOs are reflected as requirements found elsewhere in the QAPP, as described below.

2.2.1 DQOs Related to Confirmation of Acceptable Knowledge

Several of the above DQOs establish a need to confirm acceptable knowledge information; in the QAPP, this requirement is found in several places, and a single statement in QAPP Section 4.2.2 covers the bulk of the WAP DQOs (p. 4-6):

> Waste characterization (i.e., radiography, headspace gas sampling and analysis, and solidified waste sampling and analysis) will be used to confirm acceptable knowledge information. Figure 4-2 illustrates the process sites will use to confirm acceptable knowledge.

The QAPP Figure 4.2 (p. 4-7) is a flow chart showing what comparisons are to be made, and the basis for either success or failure of the comparison. The terminology used above needs some interpretation: "Solidified waste sampling and analysis" as used in the QAPP is the equivalent to the WAP's "homogeneous waste sampling and analysis"; and visual examination (VE) is considered in the QAPP as an adjunct to radiography. Section 4.2.2.1 of the QAPP more clearly establishes the requirement for VE and radiography to confirm acceptable knowledge (p. 4-6):

> Radiography or visual examination must be used to confirm the matrix parameter category and waste material parameters identified using acceptable knowledge.

Other DQO requirements need to be addressed individually. Each DQO listed in Section 2.2 above is addressed in the following sections.

2.2.2 WAP Headspace Gas DQO

The WAP headspace gas DQO is for identification and quantification of VOC constituents in the waste to ensure compliance with the environmental performance standards of 20 NMAC 4.1.500, "incorporating 40 CFR, §264.601(b)." Section 40 CFR 264.601(b) is a list of considerations that must be taken into account concerning migration of wastes from a HWDU. The 40 CFR 264.601(b) reference in the WAP may be an error, as subparagraph (b) is more applicable to solid and liquid wastes ("migration of waste constituents in surface water, or wetlands or on the soil") rather than VOCs. Subparagraph (c), which covers "migration of waste constituents in the air" would seem to be the more pertinent citation. In any case, meeting this DQO is clearly a function of meeting the QAOs for headspace gas, as described in Section 2.3 below.

2.2.3 WAP Homogeneous Waste Sampling and Analysis DQOs

The DQO for comparing UCL_{90} values for the mean concentrations in each homogeneous waste stream with the 40 CFR 261 toxicity values is also a DQO in the QAPP (Section 1.5, p. 1-32). The DQO for reporting average waste stream concentrations of the 40 CFR 261 Appendix VIII

hazardous wastes with a 90% confidence for all averages greater than the PRQL is briefly described in the QAPP in Section 1.4 (pp. 1-29 and 1-30):

> TRU waste classified as homogenous solids and soil/gravel must be statistically sampled and analyzed for the constituents listed in Table 1-3 as VOCs, SVOCs, and metals. The mean concentration of hazardous constituents (40 CFR Part 261, Appendix VIII) must also be calculated by waste stream and then reported to CAO with an upper 90-percent confidence limit (UCL_{90}) as described in Section 3.3 of this QAPP.

Section 4.2.2.2 of the QAPP adds the requirement that averages greater than the PRQL must be re-evaluated. However, this requirement applies only to spent solvents, rather than all of the Appendix VIII listing (p. 4-8):

> Sites must confirm the assignment of spent solvent EPA hazardous waste numbers (40 CFR §261.31) by evaluating the mean concentrations of each VOC detected in container headspace gas and/or solidified waste matrix. The UCL_{90} for the mean constituent concentration must be compared to the PRQL for the constituent.

Appendix VIII contains hazardous materials that are not spent solvents but will still be in WIPP wastes. For example, lead, which will likely be the most prevalent hazardous material disposed of in the WIPP repository, is listed in Appendix VIII. The WAP DQO for reporting of Appendix VIII wastes in quantities greater than the PRQL does not appear to be completely met in a clear manner for all of the DOE's pre-Permit waste characterization processes.

2.2.4 WAP DQO for Radiography

The WAP DQO is essentially identical to the QAPP DQO in that radiography is to verify the waste matrix code assigned to each waste stream (Section 1.4, p. 1-32):

> To verify the TRU waste streams by matrix parameter category, as described in the BIR, for purposes of physical waste form identification and determination of sampling and analytical requirements.

"Waste matrix code" is not defined in the Permit, though it may be a term defined in the RCRA and HWA regulations referenced by Section I.D. In the DOE documentation, "waste matrix code" and "matrix parameter category" are identical terms, meaning the five-digit alphanumeric codes used to classify wastes for treatment as found in the *DOE Waste Treatability Group Guidance* (Kirkpatrick 1995). That these are identical terms is made explicit in Section 1.4 of the QAPP (p. 1-18 and 1-19).

The WAP DQO also states that radiography is to identify prohibited items, apparently meaning the items listed in Section B-1c, Waste Prohibited at the WIPP Facility, that are amenable to radiographic identification (liquids, explosives, compressed gases, and perhaps non-radionuclide pyrophoric materials). The QAPP does not include mention of prohibited items as a DQO, though it does specify that radiography operators be trained to find these items (in language which is nearly identical to that used in the WAP). The requirement for identification of prohibited items is also not clearly spelled out in the QAPP, but Section 4.2.1 does contain the following statement (p. 4-3):

> Sites must ensure radiography and visual examination procedures include a list of nonconforming items that the operator must verify are not present in each container of waste (i.e., corrosives, ignitables, reactives, incompatible waste).

2.2.5 WAP DQOs for VE

The QAPP contains no explicit DQOs for visual examination but the WAP visual examination DQOs are included as requirements in the QAPP in other ways. The WAP DQOs require that VE verify waste matrix codes, identify prohibited items, verify radiography information, and confirm waste stream delineation by acceptable knowledge.

The QAPP considers use of VE in two ways: as verification of radiography findings (which in turn verifies acceptable knowledge) for retrievably stored wastes, and as confirming acceptable knowledge for newly generated wastes or repackaged wastes. For verification of waste matrix codes (matrix parameter categories) Section 3.2 of the QAPP states (p. 3-6):

> ...radiography and visual examination are complementary techniques yielding similar data for determining the matrix parameter category and waste material parameter weights of waste present in a waste container. Therefore, visual examination results shall be used to verify the matrix parameter category and waste material parameter weights determined by radiography as described in Section 10.0.

The QAPP requirement for use of both VE and radiography to identify prohibited items is in Section 4.2.1 (see radiography discussion above), and individuals performing VE must also be trained to recognize prohibited items. The QAPP Section 4.2.1 clearly requires verification of acceptable knowledge for newly generated wastes (p. 4-5):

> For newly generated waste streams, sites must describe how acceptable knowledge information is confirmed using visual examination prior to or during waste packaging.

While the QAPP does not specifically state that VE will be used to verify waste stream delineation for retrievably stored wastes, it is an implicit assumption in the QAPP that this activity will be performed. For example, Section 4.2.2.1 states the following (which also addresses waste matrix codes; p. 4-5):

> For all waste streams, sites must describe how acceptable knowledge information is re-evaluated if radiography or visual examination results in the reassignment of a different matrix parameter category [e.g., Plastic/Rubber (S5310) versus Paper/Cloth (S5330)]. For all waste streams, sites must describe how waste is reassigned to a different waste stream and appropriate EPA hazardous waste numbers assigned.

Verification of radiography by VE is required in the QAPP in Section 5.0 (p. 5-4):

> Retrievably stored waste containers from waste streams in all matrix parameter categories (S3000, S4000, and S5000 summary categories) must be selected for visual examination to confirm the results of radiography following the statistical approach specified in Section 5.4.1.

The statistical approach described in the QAPP and the WAP are the same with one significant difference. The QAPP invokes the use of statistics over the entire drum population, whereas the WAP requires that it be applied to each waste stream. This WAP requirement could easily result in a ten-fold increase in the number of drums that must be examined by each generator site in a year. The WAP also requires an initial statistical selection of drums based on an 11% miscertification rate whereas the QAPP requires an initial selection based on a 2% miscertification rate. The WAP miscertification rate would also increase the number of containers that should undergo visual examination. This potential increase does not significantly affect the pre-Permit wastes in the repository, since nearly all underwent visual examination during repackaging, but other wastes characterized by generator sites in the pre-Permit period may be significantly affected.

The requirements quoted above are usually found multiple times within the QAPP. Except for the frequency of visual examination to verify radiography, the pre-Permit waste characterization program appears to meet the WAP DQOs for visual examination.

2.3 WAP QAOs

The DQOs are reached through meeting QAOs for each of the areas described. The following sections compare the QAOs in the WAP to the WIPP pre-Permit program requirements. The WAP QAOs are not always reflected in the QAPP as QAOs, but can still usually be found as requirements within the document. Headspace gas QAOs will be addressed first, since these are a primary consideration in concerns related to the Room 7 risk analysis.

2.3.1 Headspace Gas QAOs

For VOC analysis the WAP clearly establishes the link between DQOs and QAOs. Section B3-5, Gas Volatile Organic Compound Analysis, in the portion labeled Quality Assurance Objectives, states:

> The development of data quality objectives (**DQO**) specifically for this program has resulted in the QAOs listed in Table B3-2. The specified QAOs represent the required quality of data necessary to draw valid conclusions regarding program objectives. WAP-required limits, such as the program required quantitation limits (**PRQL**) associated with VOC analysis, are specified to ensure that the analytical data collected satisfy the requirements of all data users.

The WAP Table B3-2, Gas Volatile Organic Compounds Target Analyte List and Quality Assurance Objectives, is identical in all technical respects to QAPP Table 12-1, for the GC/MS (gas chromatography followed by mass spectroscopy) or GC/FID (gas chromatography followed by flame ionization detection) methods used for all pre-Permit characterization activities.[3] For these QAOs, the pre-Permit waste characterization program requirements are identical to those specified in the WAP.

Table B3-2 covers headspace gas analysis only. There are also QAOs for headspace gas sampling (also listed in Section B3-2). The first of these states (p. B3-6):

> Headspace-gas sampling will occur from the headspace within each drum of transuranic (TRU) mixed waste.

This WAP statement is unduly limiting since standard waste boxes sent to WIPP also need headspace gas sampling. The use of the term "drum" rather than "waste container" was probably an unintended error. In the QAPP, the requirement is more inclusive (Section 4.2.2.2, p. 4-8):

> Headspace gas sampling and analysis must be conducted on all TRU waste to be sent to the WIPP facility.

[3] The Fourier Infrared Transform Spectroscopy (FTIRS) MDL column in the WAP Table B3-2 does not appear in Table 12-1 of the QAPP, though the same MDL values for all but formaldehyde and hydrazine appear in Table 1 of the QAPP's February 1996 Interim Change (p. 4). FTIRS analysis, however, was not approved for use in TRU waste characterization at any DOE site during the pre-Permit period, and none of headspace gas results for pre-Permit activities were performed by FTIRS. The QAPP Table 12-1 also includes three additional analytes (to address a transportation requirement) not listed in the WAP Table B3-2.

There have been deviations from this requirement for pre-Permit wastes, and there is a qualification in the WAP QAOs that may arguably allow these deviations. See Section 2.3.2 for a fuller discussion of the deviations.

A second QAO for headspace gas is that the precision and accuracy of the drum headspace gas sampling operations must be assessed by analyzing field quality control (QC) head space gas sample to include equipment blanks, field reference standards, field blanks, and field duplicates. The identical wording from Section B3-2 in the WAP is in Section 7.1 of the QAPP (p. 7-3).

QAOs for precision, accuracy, completeness, comparability, and representativeness of the headspace gas samples are also found in Section B3-2. Each of these QAOs consist of several statements containing individual requirements, and all of the requirements in these statements are addressed by various portions of the QAPP (though not necessarily as QAOs) except for the following items.

1. The WAP precision QAO for headspace gas requires *sequential* collection of field duplicates from manifold sampling operations. The QAPP does not specify sequential collection of field duplicates from manifold sampling--the requirement is for field duplicates to be collected *simultaneously*, whether for manifold or direct canister sampling.

   The WAP requirement for manifold collection would establish a slightly more rigorous check of sampling than is required by the QAPP, if a cleaning of the manifold between the two samples had been specified, or some other change to the system between collection of samples. However, the logic for requiring sequential sampling from manifolds instead of simultaneous sampling is not clear. Other sections of the WAP indicate that simultaneous collection is sufficient. For example, Section B1-1a(1), Manifold Headspace Gas Sampling (p. B1-3) states:

   > If using canister-based sampling methods, a sufficient number of ports shall be available to allow simultaneous collection of headspace-gas samples and duplicates for VOC analyses.

The “canister-based sampling methods” are not to be confused with “direct canister sampling”; using a manifold, samples can either be stored in canisters (canister-based sampling method), or directed to an on-line analytical system for immediate processing. Direct canister headspace gas sampling does not use a manifold.

2. The WAP completeness QAO for headspace gas sampling requires that sampling completeness is to be calculated for each waste stream, and must be 90% or greater. While the requirement for 90% sampling completeness is in the QAPP, there is no specification for calculation *by waste stream* for headspace gases (or any of the other waste characterization parameters). The QAPP does, however, require that (Section 3.3.1, pp. 3-9 and 3-10):

> ...the site project manager will ensure that all data generated meet the DQOs provided in Section 1.5 of this QAPP. To do so, the site project manager must assess whether data of sufficient type, quality, and quantity have been collected...
>
> For each waste stream characterized the site program manager must determine if sufficient data have been collected to determine the following Program-required waste parameters: ...Average concentration of hydrogen, methane, and each VOC in the headspace gas of waste containers in the waste stream.

Section 7.1 of the QAPP (p. 7-3) also requires the site project QA officer to evaluate the importance of any lost or contaminated headspace gas samples, and initiate corrective action if appropriate. While these statements are not the equivalent of the WAP requirement, they do indicate that the sufficiency of headspace gas data for each of the waste streams that have already been placed into the WIPP has been specifically evaluated and deemed acceptable, and that any samples not used have also been assessed for their importance to the quality of data.

3. The WAP comparability QAO for headspace gas sampling requires laboratories analyzing WIPP samples to *successfully participate* in the CAO’s Performance Demonstration

Program (PDP; blind test samples are processed by the labs at least annually to help assess lab compliance with QAOs).[4] The QAPP only requires that laboratories *participate* in the PDPs (Section 2.3, p. 2-7), and comply with the PDP Plans.[5]

The original Headspace Gas PDP Plan (US DOE 1995a) does require any laboratory that fails to meet the PDP criteria for accuracy or precision to cease analytical operations for WIPP samples (see Rev. 0 paragraph 6.2.5.6.2, p. 25), which would seem to clearly meet the WAP requirement. Revision 1 (US DOE 1999b) no longer requires laboratories to cease analysis of WIPP samples until a successful PDP cycle has been obtained; under Revision 1 laboratories may "choose to proceed at risk," though any data obtained "may be found unacceptable to WIPP" (Section 5.2.5 p. 26). The WAP, however, was developed using Revision 0, and successful participation in the PDP would seem to mean meeting the PDP criteria. After April 14, 1999--when Revision 1 was promulgated-- the WIPP waste characterization program does not meet this WAP QAO for headspace gas. It may be, however, that DOE-certified generator sites (LANL, INEEL, and RFETS) have consistently met the PDP criteria in the relatively short intervening period.

4. The WAP comparability QAO for headspace gas sampling also requires the generator site to take corrective action if uniform procedures, equipment, or operations are not followed, unless the deviations have been justified and approved. The QAPP does not address this requirement in these terms, but Section 2.1 (p. 2-1) states:

> Corrective action shall be taken if any condition, or significant condition, adverse to quality is detected during an audit or assessment. The cause of any adverse condition, identified by any means, that affects compliance with the QA/QC requirements specified in this QAPP shall be promptly determined and action taken to preclude its recurrence. The identification, cause, and corrective action(s) for

[4]The inclusion of the PDP requirement in a QAO for headspace sampling seems out of place--the Headspace PDP does not include testing of sampling processes, only testing of laboratory analytical capability.

[5]The requirement to comply with the PDP plans are found in the November 1996 Interim Change to the QAPP, Table AC-1 (US DOE 1996d).

> conditions not complying with the quality requirements of the Program must be documented and reported to appropriate levels of management as indicated throughout this section.

Section 2.1.2.1 of the QAPP (p. 2-3) covers nonconformances, defined as uncontrolled and unapproved deviations from an approved plan (including the QAPP), procedure, or expected result. Nonconformances can be identified and reported by anyone performing WIPP project activities, and are to be tracked to completion by the site project QA officer. Completion of corrective action for nonconformances must also be verified by the site project QA officer.

There have been some deviations from the requirements in the QAPP for the wastes that are now in the WIPP repository. However, as specified in this QAO, these have been justified and approved, as is indicated in the next section.

2.3.2 Deviations From QAPP Waste Characterization Requirements For Headspace Gas

Two major deviations from headspace gas requirements in the QAPP for pre-Permit waste characterization are listed in the following comments.

1. Headspace gas samples from the LANL TA-55-43.01 waste stream were taken prior to repackaging of these wastes, when the waste container was a 55-gallon drum; the contents of each of these drums was later repackaged into one or more standard waste boxes in order to meet hydrogen gas generation requirements (a transportation requirement, not a RCRA one). Each SWB received waste from only one drum. Standard waste boxes provide a much greater headspace volume than do drums, so that headspace gas concentrations that met requirements while in drums would assuredly meet the same requirements in SWBs.

   Since the QAPP did not specify when samples are to be taken, LANL requested guidance on the issue from the CAO. The CAO responded with a July 8, 1998, letter to LANL (Hunter 1998b) that states:

> ...if retrievably stored waste is repackaged after headspace gas sampling, then it is not necessary to resample the waste.

The organization responsible for enforcing the WIPP RCRA permit, the New Mexico Environment Department, was extensively involved in reviewing waste characterization for this waste stream, and eventually agreed with the DOE that the waste stream contained no reportable RCRA hazardous constituents. Accordingly, the lack of a headspace gas sample from the final waste containers (the SWBs) may meet the WAP headspace gas comparability QAO for justification and approval of deviation from the WAP headspace gas process.

It should be noted that the WAP QAOs for headspace gas do not require sampling of SWBs; the QAO only specifies drums (the EEG has informed the NMED about this apparent terminology oversight in the WAP).

2. No headspace gas samples were collected for the RFETS waste stream RF 005.01 since it consists of solid salt waste which is heated to a liquid 800 degrees Celsius and stirred for approximately two hours in the presence of an oxidant. The process should remove any RCRA headspace gas-generating materials or volatile organic compounds that might be present in the salt.

   RFETS requested an exemption from the CAO for headspace gas sampling of these salt wastes, and a February 12, 1998, letter from the CAO's Office of National TRU Waste Operations (Hunter 1998a) granted the exemption, noting that the post-heating packaging would prevent re-introduction of headspace gas constituents into the waste. There appears to be no technical reason for performing headspace gas sampling of the post-heating wastes from this waste stream.

3. An October 9, 1998, CAO letter (Hunter 1998g) grants a RFETS request to deviate from a waste container temperature equilibrium requirement. The requirement is stated in the QAPP as follows (Section 6.4.1):

> Waste containers and their contents must be allowed to equilibrate to the temperature of the sampling area. The equilibrium period must be, at a minimum, 72 hours prior to sampling.

The letter notes that the requirement is only to allow the waste container and its contents to equilibrate to the temperature of the sampling area, not reside at the sampling area for the 72 hour period, and that even if containers were left at the freezing point for a short period of time they could still be brought to 64.4°F (18°C) in less than 72 hours.

The WAP requirement (Section B1-1a) specifies equilibration for 72 hours at 18°C or higher. This would ensure that headspace gases would reach equilibrium conditions at that temperature. The CAO's October 9, 1998, interpretation does not meet this intent.

4. A January 12, 1999, CAO letter to Mobile Characterization Services (Brown 1999a) allows use of a heated syringe for collection of duplicate samples, stating that because the syringe method has been shown to meet program quality assurance objectives and the syringe will collect a sufficient volume, the duplicate would be equivalent to the SUMMA canister collection system required by the QAPP. Transportation and storage requirements for the syringe method were not discussed in the letter.

   The WAP contains no provisions for using syringes to obtain duplicate headspace gas samples. Any duplicates obtained by this method would be suspect.

2.3.3 Homogeneous Solids and Soil/Gravel Sampling QAOs

The WAP homogenous solids and soil/gravel sampling QAOs are, like the headspace gas QAOs, usually found as identical requirements within the QAPP. Differences between the WAP and QAPP requirements are as follows:

1. The WAP Section B3-3 (p. B3-9) states that "25 to 30 pairs of co-located cores or samples" are to be used to establish control charts for the relative percent difference (RPD) between

field duplicate samples. The QAPP requires "at least 30" pairs of co-located samples. The QAPP requirement is the more conservative--the more samples used to establish the control limits the more likely the controls will accurately reflect the mean and variance of the population.

2. The WAP Section B3-3 (p. B3-9) requires that RPD control charts establish limits at three standard deviations. The QAPP states (Section 8.3, p. 8-8a):

> The limits may be as much as three standard deviations from the mean.

That is, the control limits may be *less* than three standard deviations, but not more; again, the QAPP is more conservative than the WAP requirement.

3. The WAP Section B3-3 QAOs for accuracy (p. B3-9) requires that:

> Sampling accuracy as a function of sampling cross-contamination will be measured.

The QAPP contains no comparable statement. However, the WAP does not indicate how measuring sampling accuracy as a function of sampling cross-contamination might be done--there is no other mention of it in the entire permit. The utility of performing this action seems technically dubious unless a creditable methodology is available, and criteria for the results are specified.

4. The WAP Section B3-3 QAOs for accuracy (p. 3-9) requires that "corrective action must be taken" if equipment blanks from a cleaning batch sample analysis shows hazardous constituents that exceed three times the minimum detectable levels; the QAPP specifies that the corrective action (reclean the entire cleaning batch and take a new sample, pp 8-8c and 8-9). The WAP permits other corrective action, including disposal of the cleaning batch.

5. The WAP Section B3-3 QAOs requires laboratories analyzing WIPP samples to *successfully participate* in the CAO's Performance Demonstration Program. As was true with the headspace gas PDP, the QAPP only requires that laboratories *participate* in the PDPs (Section 2.3, p. 2-7) and comply with the PDP Plans.

   As with the headspace gas PDP Plan, the original PDP Plan for solidified wastes (US DOE 1995b) required analytical labs to cease operations when the PDP criteria are not met. Revision 1 (US DOE 1996a), submitted to the administrative record for the Permit, kept the requirement. However, Revision 2 (US DOE 1999c), allows the laboratories to "choose to proceed at risk," though any data obtained "may be found unacceptable to WIPP." Since successful participation in the PDP would seem to mean meeting the PDP criteria, the WIPP waste characterization program does not meet this WAP QAO after the April 14, 1999 issuance of Revision 2.

   However, only two waste generating sites have been certified to perform solid sampling by the DOE. These two sites may have continued to meet the PDP criteria; one of the sites (LANL) may not have characterized solids since the change in the PDP Plan.

6. The WAP Section B3-3 QAOs for representativeness (p. B3-10) require that in coring, the entire depth of the waste "minus a site defined approved safety factor" is to be taken; the QAPP does not explicitly make an allowance for the safety factor.

7. The WAP Section B3-3 QAOs for representativeness (p. 3-10) require that, in taking a core sample, if an insufficient (<50% of the total length possible) portion of the initial core is not obtained, that a second core is to be taken; "the core with the best core recovery shall be used for the sample." The QAPP specifies that in this situation the second core is always to be used regardless of the recovery length (Section 8.1, p. 8-3).

   The WAP requirement is based on one aspect of achieving a representative sample (taking samples from a more representative core length), the QAPP requirement

perhaps based on another-- the length of time before samples are removed from the core. The second core, even if shorter, would be more likely to retain VOCs than the first core, as the first core could be losing VOCs by diffusion while the second core is taken.

2.3.4 Deviations From QAPP Waste Characterization Sampling Requirements For Homogenous Solids

There are several deviations from the QAPP waste sampling and preservation requirements for homogeneous wastes.

1. Pre-Permit samples from the RFETS salt waste stream RF 005, a homogeneous solid at normal temperatures, have not all been obtained by coring as is specified in the QAPP. These wastes were heated to a liquid state as a part of their processing, stirred for approximately two hours, then a liquid sample was dipped from the mix. RFETS requested allowance for this practice from the CAO, and received it (Hunter 1998a, p. 2). The CAO approval noted that an SW-846[6] (US EPA 1996) process allowed such sampling, as the stirring addressed the vertical inhomogeneity issue that was a caveat in the SW-846 process.

   The WAP contains no provisions that would allow this process, but there seems to be no technical reason for considering such samples to be less valid than those obtained by the allowed coring methodology. The CAO approval letter states that the RFETS process will yield a more representative sample, which seems reasonable, although the CAO cited no studies to support the conclusion.

2. A July 14, 1998, CAO letter (Hunter 1998c) grants RFETS exemption from preserving samples of waste stream RF 005 salt waste by storing them at 4°C. The requirement is to

[6] "SW-846" is the EPA's *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, a compendium of methods for sampling and analysis of RCRA wastes. The CAO letter cites Section 9.2.3, *Sample Plan Implementation Containers.*

prevent volatilization of mercury and chromium from the sample; the letter points out that the mercury would be removed from the waste during the two-hour 800°C heating process, and the SW-846 methods for total chromium analysis (as opposed to hexavalent chromium analysis) do not require cooling of the sample. The WAP requirements for chromium seem to have been effectively met, as SW-846 procedures are specified for metals analysis.

A September 29, 1998, CAO letter (Hunter 1998f) notes that, despite the heating process, samples did show the presence of trace concentrations of mercury. The letter states that:

> ...the Carlsbad Area Office (CAO) agrees with your determination that the presence of mercury in two of over 200 samples, and at trace concentrations, does not invalidate the CAO approval to eliminate the need to cool salt residue samples to 4 degrees. The rationale provided, along with the letters from two outside technical experts, sufficiently documents the validity of the preservation protocol used for these types of samples.

While it seems unlikely that cooling the samples would have resulted in detection of higher concentrations of mercury, the deviation from the QAPP sampling requirements makes that determination only a highly logical conjecture rather than a technically justified conclusion. This process does not meet WAP requirements, but again, the technical consequence seems minor.

3. A February 25, 1999, CAO letter (Brown 1999b) notes that duplicate samples from liquified RF 005 waste stream are not necessary, specifying that relative percent differences were to be calculated from sub-samples of single samples taken. The homogeneity of the liquified salt and the quality of the sampling process itself would have been confirmed by a complete duplication of the process, and this change does not meet WAP requirements. However, individual small containers of liquid waste are constantly stirred for an hour before the sample is taken, and the composition of sub-samples would likely have the same variance as multiple samples; the granting of this change would not seem to significantly affect analytical results.

4. An August 21, 1998, CAO letter (Hunter 1998d) grants RFETS exemption from coring of homogeneous residue salts (a different group of salt residues than the RF 005 waste stream discussed above). The alternate methodology approved includes size reduction, use of a mixing and sampling process based on ASTM C702-93, and use of SW-846 approved containers and procedures for storing and handling the resulting sample.

   The letter states that:

   > The processes that generated these salts preclude organics (size reduction will not alter the concentration of hazardous constituents)

   One purpose of the sampling and analysis program is to confirm data concerning processes that generated the wastes. The process of reducing the size of the particles, and mixing and sampling them using the ASTM C702-93 methods greatly increases opportunity for volatile compounds to escape from the sample before further analysis. Thus, confirmation that there are no volatile organic waste hazardous constituents in the salt is somewhat compromised, and the quality of the acceptable knowledge becomes the controlling factor in acceptance of these salt residues. This change would not be allowed by the WAP, but its technical impact would seem to be marginal unless the acceptable knowledge is inadequate.

5. An August 26, 1998, CAO letter (Hunter 1998e) grants RFETS a similar exemption for ash residues, noting:

   > It must be demonstrated that mechanical blending will not significantly affect the concentration of constituents in the sampled material. This can be shown by analysis of smaller particles compared with material analyzed after size reduction and blending or by acceptable knowledge demonstrating that volatile constituents will not be present in the waste.

   This statement misses one of the principal purposes of sampling and analysis waste characterization, to confirm acceptable knowledge. If acceptable knowledge was used to

meet the additional requirement imposed by the CAO then acceptable knowledge is being used to confirm itself.

The *Final Environmental Impact Statement on Management of Certain Plutonium Residues and Scrub Alloy Stored at the Rocky Flats Environmental Technology Site* (US DOE 1998a) notes that several types of ash residues contain organic material (Volume 2, Section B.3.2, p. B-10). Any pre-Permit ash residues characterized using only acceptable knowledge do not meet WAP requirements. However, the presence of these organic materials was established by chemical analyses that are a part of the acceptable knowledge record; since neither the individual concentrations nor total amount of organic material in the ash residues are likely to be affected by reanalysis to any significant degree, the impact of this change is likely insignificant.

2.3.5 WAP Radiography QAOs

The WAP Section B3-4 QAOs for radiography are not all in the QAPP QAOs or other documents. Those that cannot be found or differ from the WAP are as follows:

1. The WAP requires that if the QAOs are not met, then corrective action is to be taken. The QAPP Section 10.1 (p. 10-1) contains a similar statement, but the QAPP QAOs are not the same as the WAP QAOs. However, any of the WAP QAOs that are contained in other QAPP requirements would fall under the corrective action plan specified by the CAO's Quality Assurance Program Document (US DOE 1996b and US DOE 1998b), which is applicable at the waste generating/storage sites where waste will be characterized.

2. A WAP radiography precision QAO is to verify precision prior to use in waste characterization by viewing an image test pattern to demonstrate compliance with QAOs. Though Section 10.5 of the QAPP requires visualization of a test pattern image prior to use (p. 10-9), it does not require the test pattern check to demonstrate compliance with QAOs. However, none of the WAP QAOs establish visualization criteria for real-time radiography

(RTR) beyond the ability to visualize prohibited items and identify waste matrix items; in practical terms, there is no difference between the WAP QAO and the QAPP requirement.

3. A WAP radiography accuracy QAO requires the Site Project QA Officer to calculate and report the miscertification rate of waste containers that are assigned to a different waste matrix code, or are found to contain prohibited items, when visually examined. The QAPP accuracy QAO does not require inclusion of prohibited items in calculating miscertification rates (Section 10.1, p. 10-1):

> The accuracy with which the matrix parameter category and waste material parameter weights can be determined must be documented through visual examination of a randomly selected statistical portion of waste containers (Section 5.4.2). The percentage of waste containers which requires a new matrix parameter category after visual examination must be calculated and reported by the site project QA officer as a measure of radiography accuracy.

In the QAPP, there appears to be an attempt to separate radiography performed for RCRA purposes from radiography performed to meet transportation requirements. Section 5.4.2 of the QAPP, where calculation of miscertification rates is described, contains the following statements (p. 5-18):

> The data obtained from the visual examination must also be used to determine, with acceptable confidence, the percentage of miscertified waste containers. Miscertified containers are those that radiography indicates meet the WIPP-WAC radiography-determined and TRAMPAC requirements [sic] but visual examination indicates do not meet these requirements. Note that the radiography requirements of Section 10.0 are separate from the radiography requirements of WIPP-WAC and TRAMPAC certification.

Since the TRAMPAC (transportation) certification requires checking for prohibited items, there may have been an interpretation that a miscertification rate could be calculated for prohibited items for transportation concerns, and a second miscertification rate calculated

from errors in applying waste matrix codes. If so, no great effort was made to clearly establish this distinction in the QAPP.

Despite the discussion above, it should be noted that the calculated rate of miscertifications at LANL included prohibited item discoveries. This calculation was used to change the initial miscertification rate for all sites in the Permit--another contentious issue that is included in the DOE lawsuits on the Permit.

4. A WAP Radiography DQO requires that RTR recordings and data forms be validated as indicated in Section B3-10; Section B3-10 contains a requirement that radiography tapes be (p. 3-24):

> ...reviewed on a waste container basis at a minimum of once per testing batch or once per day of operation, whichever is more frequent. The radiography tape will be reviewed against the data reported on the radiography form to ensure that the data are correct and complete.

A "testing batch" can be up to 20 waste containers. The comparable QAPP requirement specifies that at a minimum the tape from every 10th waste container is to be reviewed (Section 3.1.1, p. 3-3). The pre-Permit characterization may have been more conservative than the WAP requirements, or less conservative, depending on the number of waste containers radiographed each day.

2.3.6 Deviation From QAPP Waste Characterization Sampling Requirements For Radiography

Table 10-1 of the QAPP lists the waste material parameters types for which QAPP Section 10.1 states weights are to be estimated. A May 8, 1998, CAO letter to LANL (Stroud 1998) notes that RTR operators should attempt to estimate weights in terms of the Table 10-1 list, but also allows the operators to combine categories into more general descriptions when individual types cannot be easily distinguished. One example given is to combine cellulose, rubber, and plastic materials into a single classification.

WAP Table B3-1 is identical to QAPP Table 10-1, and there are no provisions in the WAP (as there were not in the QAPP) for alternative methods of classifying the waste. Confirmation of radiography by visual examination is required (both in the WAP and the QAPP) to compare waste material parameter weights, with no provisions for combined categories. The discussions in both documents emphasize that radiography operators are to be trained to make judgments based on the material parameter weights.

However, the material parameter wastes are not hazardous wastes, and are apparently only included in the WAP because the DOE's application contained these requirements. Waste material parameters were originally included in WIPP documents because of the effects these materials might have on the radionuclide component of the waste for long-term repository performance. There are no requirements in the WAP or in the rest of the RCRA permit concerning material parameter weights other than those listed above--no calculations to be performed, no assessment of the effect these components would have on hazardous materials, no required considerations of how these materials might become hazardous wastes. The effect of this deviation is therefore negligible.

2.3.7 Total VOC Analysis QAOs (Section B3-6)

Total VOCs are collected from homogeneous solids and soil/gravel; VOC considerations for the pyrochemical salt wastes emplaced in the WIPP during the pre-Permit period are described in the headspace gas QAO discussion above. Other homogeneous solids have been characterized under the pre-Permit WIPP waste characterization program at INEEL, and there are differences between the WAP requirements and the pre-Permit characterization program. These are as follows:

1. Initial calibration requirements for GC/MS equipment appear to be slightly tighter in the WAP than in the pre-Permit waste characterization requirements. The WAP Table B3-5, referenced by both accuracy and calibration QAOs in Section B3-6, adds a requirement that the System Performance Check Compounds (SPCCs) have a minimum average response

factor (RRF) as specified in the SW-846 method used, and an RRF $\geq$ 0.01 for all other compounds, for the initial 5-standard calibration. These requirements are not a part of initial calibration criteria in the comparable table in the QAPP (Table 13-3). However, the QAPP table does require that the SPCCs exceed the current SW-846 requirements during the continuing calibration checks that are performed at the beginning of every 12 hours of operation.

2. One portion of the initial calibration requirements for GC/FID equipment was significantly changed from those in the pre-Permit waste characterization program. The WAP Table B3-5 requires the calibration curve correlation coefficient to be greater than 0.990 or the percent relative standard deviation (%RSD) be less than 20 for all analytes in comparing results from the three different standards used in the calibration; the QAPP specifies the correlation coefficient must be greater then 0.93, or the %RSD be less than or equal to 35. The *Transuranic Waste Characterization Sampling and Analysis Methods Manual* (US DOE 1996c), however, specifies a %RSD $\leq$ 20 in the GC/FID methods (440.1 and 440.2), and was a requirements document during the period pre-Permit wastes were characterized.

   SW-846 Method 8000 clearly states (Section 7.5.2; the GC/FID Method 8015 references Method 8000 for calibration requirements):

   > The regression calculation will generate a correlation coefficient (r) that is a measure of the "goodness of fit" of the regression line to the data. A value of 1.00 indicates a perfect fit. In order to be used for quantitative purposes, r must be greater than or equal to 0.99.

   Any use of GC/FID during the pre-Permit characterization of wastes that utilized the correlation coefficient method specified in the QAPP would seem to be questionable. It may be that GC/FID was not used for WIPP pre-Permit waste processing.

3. Section B3-6 of the WAP requires that laboratory blanks be assessed to determine laboratory contamination, and that these trigger corrective action when control limits are

exceeded. The WIPP pre-Permit waste characterization was performance-based in this respect--if laboratory blanks failed to meet criteria (the same criteria that are in the WAP), then corrective action (a nonconformance report) was to be initiated, but there was no requirement that the lab specifically assess possible laboratory contamination.

4. The Section B3-6 total VOC analysis completeness QAO defines valid results as results that meet not only precision, accuracy, completeness and detection limit criteria but also the criteria for calibration, representativeness, and comparability found in the section. The QAPP defines valid results in terms of meeting the Table 13-1 criteria, which only specify precision, accuracy, completeness and detection limit boundaries.

5. A Section B3-6 total VOC analysis comparability QAO requires waste characterization to use SW-846 sample preparation methods; the QAPP merely specifies standard methods. However, since the WIPP pre-Permit waste characterization program also specified use of the WIPP Methods Manual (US DOE 1996c), which was based on the SW-846 methods, the differences are likely minimal.

6. A Section B3-6 total VOC analysis comparability QAO requires that all waste characterization sites successfully participate in the PDP. This requirement is addressed in Section 2.3.3, Item 5, of this report

7. A Section B3-6 total VOC analysis representativeness QAO requires that samples be collected as described in the Permit Attachment B1. Section B1-2a(2) includes a requirement that cores are to be divided into three equal-length subsections, and a sub-sample is to be taken from random locations in each of the three subsection. The sub-samples are then to be combined for analysis. The pre-Permit waste characterization program specified only a single sampling site randomly chosen from the entire length of the core.

This difference has been deemed by the DOE to be significant enough that it was included in both the DOE federal and state court lawsuits on the WIPP RCRA permit, in an apparent effort to eliminate re-sampling of homogeneous drums that have already been characterized. Since some of the homogeneous solidified drums were created with multiple processes--that is, a mixture of waste and solidifying agent were poured in and allowed to harden, then later other similar mixtures were added--and stratification by settling may be a factor in sludge drums stored over long periods, the RCRA permit three sub-sample system may seem to produce a more representative sample. However, the SW-846 description of sampling (Chapter 9) does not address such sub-sampling. In fact, SW-846 states that simple random sampling is likely the better method unless nonrandom heterogeneity is known to exist (Chapter 9, pp. 8-9). If such knowledge is available, then SW-846 indicates that the specific strata are to be sampled, implying separate analyses rather than the compositing required by the permit. In brief, neither the pre-Permit sampling nor the WAP method seem to be entirely in accord with the RCRA sampling guidelines outlined in SW-846. Without evidence of nonrandom heterogeneity, however, the pre-Permit sampling process does seem to be closer to SW-846 guidelines than those included in the RCRA permit.

2.3.8 Total Semivolatile Organic Compound (SVOC) Analysis QAOs (Section B3-7)

All SVOC pre-Permit waste characterization differences from the WAP QAOs are directly analogous to individual total VOC differences as discussed for the QAOs from WAP Section B3-6. The same minor calibration concerns for GC/MS is present for GC/ECD (see item 1 discussion in VOC analysis QAO in Section 2.3.7), the requirements differences for GC/ECD was discussed in item 2 for GC/FID, the pre-Permit program did not require assessment of laboratory contamination (item 3), the pre-Permit requirement was only to participate in the PDP rather than to *successfully* participate (item 6), and samples were taken from a single core site in homogeneous solids rather than the three sub-sampling areas required by the permit (item 7). For homogeneous solids SVOC sampling, however, both the QAPP and the WAP specify the same alternative ASTM procedure may be used instead of the three sub-sample requirement.

2.3.9 Total Metal Analysis QAOs (Section B3-8)

The WAP metal analysis QAOs contain some unique differences from the QAPP, but most of the differences are analogous to deviations discussed above. These anomalies are as follows:

1. Daily calibration requirements for inductively coupled plasma-mass spectroscopy (ICP-MS) in the WAP (Table B3-9) specify that the replicate %RSD be ≤5, whereas the QAPP Table 15-4 requires only ≤10% RSD. For the same daily calibration the WAP requirement for mass calibration is that it be within 0.9, with a resolution of <1.0 amu full width at 10% of the peak height, while the QAPP specified 0.1 amu for the mass calibration. Both the WAP and the QAPP require nonconformance reports to be written if these requirements are not met.

   The WAP requirement for the %RSD appears to be based on a misinterpretation of the SW-846 method (Method 8020). The method requires in Section 7.4 that the 5% RSD be established for four replicate measurements to verify that the ICP-MS instrument has reached an equilibrium *before* performing the calibrations specified in Section 7.5 and 7.6. The implication is that if the 5% RSD is exceeded then more time should be allowed to reach equilibration, and new measurements taken and compared--the 5% RSD is simply to verify that the instrument is ready for calibration. Immediately *after* calibration, the method requires in section 7.8 that verification of calibrations to be within 10%, or analyses are to be terminated and corrective actions are to be instituted.

   The WAP 0.9 atomic mass unit (amu) mass calibration requirement also seems to be a misinterpretation of Method 8020. Method 8020 specifies 0.1 amu for mass calibration in Section 7.5, the same as in the QAPP; the section also requires ≤0.9 amu full width at 10% of peak height as an additional requirement--but this is not the mass calibration. Note that both the WAP and QAPP requirements exceed the full width at 10% of peak height requirement slightly.

As the QAPP requirements are nearly in accord with the SW-846 method, and the WAP QAO seems to be unsupported, the technical significance of this difference would seem to be very slight.

2. A WAP metal analysis QAO adds a requirement that *laboratory sample duplicates* be assessed for precision as well as the QAPP-required laboratory matrix spike duplicates, replicate analysis of laboratory-control samples, and PDP blind-audit samples. However, the WAP contains no definition for *laboratory sample duplicates*, so that without clarification these appear to be merely a subset of the *replicate analyses of laboratory-control samples* found in both the WAP and the QAPP.

3. A WAP metal analysis accuracy QAO adds *serial dilutions and interference check samples* to the QAPP list (laboratory matrix spikes, PDP blind-audit samples, and laboratory-control samples) that must be analyzed for accuracy.

   The addition is technically significant, and would increase confidence in the accuracy of metal measurements. SW-846 Method 6020 (for ICP-MS, one of the more commonly used analysis instruments for metal analysis) clearly requires (Section 8.4) that interference checks must be made in order to perform measurements correctly, and states that dilution tests for each batch of each matrix must also be performed (Section 8.5). The Method Manual Procedure 630.1, Section 10.1, also clearly states that these steps of Method 6020 are to be followed. While the EEG has not checked all Methods Manual procedures for all types of metals analysis instrumentation it seems probable that the WAP QAO would be met by following the required Methods Manual procedures. However, the results would not likely be reported as a part of the accuracy determination.

4. As with the WAP headspace VOC QAOs and homogeneous waste VOC and SVOC QAOs, there is a metals analysis QAO related to laboratory contamination. The discussion found in Section 2.3.7, Item 3, applies to the analogous QAO here, also.

5. A WAP comparability QAO for total metals analysis requires that SW-846 sample preparation methods be used; the QAPP merely specifies standardized methods.

   The QAPP Table 15-2, Total Metal Analytical Methods, specifies only SW-846 methods, implying compliance with the WAP QAO. However, the QAPP also allows alternative methods to be proposed to CAO, and the Preface to the Methods Manual specifies the submittal and approval process to be followed (this process was submitted as a part of the Permit application but is not a part of the Permit). While it is not clear that the Methods Manual process was used, CAO has granted RFETS approval of an alternative method for metals analysis sample preparation (Hunter 1998a)--but the method is an SW-846 Method (3050).

6. A WAP representativeness QAO for total metals analysis requires the collection and preparation of samples in the laboratory be performed using "representative and unbiased methods." The QAPP contains no comparable statement.

   The WAP contains no characteristics or criteria for unbiased methods. As cited above, the QAPP required use of SW-846 methods for total metals analysis, and use of these procedures are accepted throughout the WAP. Pre-Permit analyses for total metals are unlikely to be affected by this additional requirement.

2.3.10 Acceptable Knowledge

The importance of acceptable knowledge (AK) is noted by the DQOs, in that all other waste characterization activities are used principally to ascertain the validity of AK conclusions. Section B3-9 of the WAP notes that acceptable knowledge provides qualitative information that is not amenable to assessment according to specific data quality goals; however, the section does list data quality requirements for precision, accuracy, completeness, comparability, and representativeness, all of which were considered for the various analytical techniques considered

above. Differences between the pre-Permit acceptable knowledge data quality goals and those listed in the WAP are as follows:

1. The WAP requires the Permittees (the CAO, and the Waste Isolation Division currently managed by Westinghouse Corporation) to perform a "Final Confirmation" that appropriate analytical and testing results are used to confirm the characterization of wastes based on acceptable knowledge (referencing Section B4-4 of Permit Attachment B-4). The QAPP (Section 3.1.3) required only that the CAO verify that data packages contained specified information, without confirming the appropriateness of the data.

   While the change in required roles for CAO is significant, the effect on pre-Permit waste characterization would likely be insignificant. Since the Hazardous Waste Permit does not directly control out-of-state generator sites this WAP requirement may have been added to provide a basis for regulatory action if appropriate results were found to be lacking.

2. Section B3-9 requires as a part of the comparability data quality requirements that sites are to assign hazardous waste codes "...in accordance with Permit Attachment B4-4...." Permit Attachment B4-4 is titled Additional Final Confirmation of Acceptable Knowledge at the WIPP Facility, and does not specify methods for assigning hazardous waste codes, nor does there appear to be any one specific section of the WAP that does list all the criteria for assignment of hazardous waste codes. It does appear that the basic methods listed in the WAP (assign hazardous waste codes based on acceptable knowledge, apply them conservatively, use all available knowledge, follow a written procedure for assigning hazardous waste codes, etc.) are a part of Chapter 4 of the QAPP.

3. Another requirement of Section B3-9 is that any inconsistencies between acceptable knowledge documentation and results of confirmatory analytical techniques (chemical analysis, radiography, or visual examination) are to be reported to CAO/WID within 5 days (written report) followed by a nonconformance report within 30 days. The pre-Permit waste characterization program had no such reporting requirements. The effect of this

difference would seem to be minimal, as in both cases the site remains responsible for assessing and correcting the inconsistency before certifying affected waste for shipment to the WIPP.

4. Section B3-9 requires tracking of inconsistencies within acceptable knowledge data and documenting the results of acceptable knowledge confirmation from the confirmatory analytical techniques. The pre-Permit process did not require this tracking and documentation, but the QAPP does briefly cover consequences of consistent discrepancies with acceptable knowledge information (Section 4.4.4). The tracking and documenting required by the WAP would seem to be an important and useful process, but would also seem likely to have only minimal impact on pre-Permit waste characterization activities.

2.3.11 QAO Relating to Pre-Permit Waste Analysis Procedures Based on Deleted SW-846 Methods

The WAP includes a comparability QAO for each type of analytical process (VOC, total VOC, SVOC, and metals) stated as follows:

> Any changes to SW-846 methodology that results in the elimination of sample preparation or analytical methods in use at generator/storage sites must be addressed as a corrective action to address the comparability of data before and after the SW-846 modification.

Final Update III (December 1996) to SW-846 lists several procedures that were deleted in that update (see p. 7 of Instructions). The procedures were not superseded--they were simply removed, with no explanation provided. Among the deleted procedures are:

8240B Volatile Organics by Gas Chromatography/Mass Spectrometry (GC/MS)

8250A Semivolatile Organic Compounds by Gas Chromatography/Mass Spectroscopy (GC/MS)

These two methods are major constituents of procedures for VOC, total VOC, and SVOC in the Methods Manual, in use during the pre-Permit waste characterization period (the last update of the Methods Manual was Revision 1, approved in April 1996). The two deleted SW-846 methods listed above were used in the Methods Manual as follows:

1. Methods Manual Procedure 430.2, *Modified Method 8240B/8260A for the Determination of Volatile Organic Compounds in Waste Container Headspace* used 8240B with 8460A (still in SW-846) as its basis. Method 430.2 states (Section 1.2, p. 1),

   > This procedure only details the sections of SW-846 Methods 8240B and 8260A that need to be modified to allow the analysis of gas samples. Analysts must refer to SW-846 Methods 84240B and 8260A for additional guidance.

   It may be that the Method 8240B and 8260A were sufficiently identical that the deletion of 8240A would have minor, if any, effect on the quality of pre-Permit headspace gas measurements for WIPP wastes. It also may be possible that the Method 430.2 was not used, as the Methods Manual contains another method (Method 430.1) which could also be used to analyze headspace VOCs.

2. Methods Manual Procedure 430.3, *Method 8240B for the determination of Total Volatile Organic Compounds in Homogeneous Solids and Soil/Gravel*, is completely dependant on SW-846 Method 8240B for total VOC analysis. Section 1.2 states that the analyst should refer to SW-846 Method 8240B for the "specific requirements of this procedure"; Section 8.0, which contains the specific procedural steps to be followed, simply refers the analyst to steps in 8240B.

   Procedure 430.3 is not the only method for total VOC analysis in the Methods Manual--430.4, based on SW-846 Method 8260A, could also be used. However, it appears that any pre-Permit homogeneous waste analysis for total VOCs performed in accordance with 430.3 was not in compliance with the EPA guidelines required in the RCRA permit.

3. Methods Manual Procedure 430.5, *Method 8250A for the Determination of Total Semi-volatile Organic Compounds in Homogeneous Solids and Soil/Gravel*, is completely dependant on SW-846 Method 8250A for total VOC analysis. The statements in Section 1.2 and Section 8.0 are the same as those in 430.3, only changing the references to Method 8250A. Similarly, there is another Methods Manual Procedure that could be used for SVOC analysis (430.6); however, as with 430.3, any analyses that may have been performed using 430.5 do not appear to have been performed in accordance with the EPA guidelines required in the RCRA permit.

If utilized at all, the impact of the deleted SW-846 methods on waste characterization during pre-Permit waste characterization may not seem to be of major significance. The deleted methods were initially promulgated by the EPA, and were current at the time the last update to the Methods Manual was made. It is unfortunate that SW-846 does not list the reasons for deleting the procedures; however, since the reasoning is not supplied, it is unlikely that the procedures contained any major defects.

It would also be unfortunate if the DOE did not ensure that required methods were in conformance with EPA guidelines when WIPP waste characterization activities were performed. A CAO letter to some of the sites (Watkins 1997) states (p. 2):

> Several SW-846 methods which the Methods Manual is based on have been revised. Sites can update their procedures to the latest SW-846 procedure. When SW-846 is revised, the latest information should be included in site procedures and in the Methods Manual as soon as practical.

The philosophy espoused is in conformance with the WAP--but the Methods Manual had not been updated two years later in November 1999. The letter does not inform other waste generator sites of the change. It may be that individual laboratories characterizing wastes noted the deletion of the two applicable SW-846 methods and used the Methods Manual alternative procedures.

2.3.12 QAOs Related to Data Usability Criteria

Data usability criteria are required to be met for headspace gas and homogenous solids sampling, and analysis for VOCs, total VOCs, SVOCs, and metals, specified either as a part of the completeness requirements (VOC and SVOC) or the comparability requirements (all others). The requirement for data usability consideration is in Section B3-1 (p. B3-4) as follows:

> The comparability of waste characterization data shall be ensured through the use of generator/storage site data usability criteria. The Permittees shall ensure that data usability criteria are consistently established and used by the generator/storage sites to assess the usability of analytical and testing data. The criteria shall address, as appropriate, the following:
>
> - Definition or reference of criteria used to define and assign data qualifier flags based on Quality Assurance Objective results,
> - Criteria for assessing the usability of data impacted by matrix interferences,
> - Criteria for assessing the usability of data based upon positive and negative bias as indicated by quality control data, of data qualifiers, and qualifier flags,
> - Criteria for assessing the usability of data due to
> - Severe matrix effects,
> - Misidentification of compounds,
> - Gross exceedance of holding times,
> - Failure to meet calibration or tune criteria
> - Criteria for assessing the usability of data that does not meet minimum detection limit requirements.
>
> The Permittees shall be responsible for evaluating generator/storage site data usability and shall assess implementation through the generator/storage site audit.

There are no comparable requirements in the QAPP for establishing criteria related to data usability. However, it should be noted that in the pre-Permit waste characterization process data which failed to meet QAOs or other expected results became a part of the nonconformance process as specified in the QAPP Section 2.1.2.1. Nonconformance reports were required to provide "...an indication of the potential ramifications and overall usability [of] the data, if

applicable" (QAPP, p. 2-4). The effect of the lack of requirements for data usability criteria would seem to be minimal.

2.3.13 SW-846 Modification and Representativeness QAOs

The WAP includes a representativeness QAO for each type of analytical process (VOC, total VOC, SVOC, and metals) stated as follows:

> Any changes to SW-846 methodology that results in the elimination of sample preparation or analytical methods in use at generator/storage sites must be addressed as a corrective action to address the comparability of data before and after the SW-846 modification.

The QAPP does not contain any comparable statements. However, the Methods Manual requires that specific versions of SW-846 methods be followed (US EPA 1996), so that the possibility of changing from one method to its revision was not a part of the pre-Permit waste characterization program.

2.3.14 Cancellation of Corrective Action Reports Related to the QAPP and Methods Manual

A January 18, 2000, CAO memorandum (Vega 2000) closed a series of Corrective Action Reports (CARs) from the pre-Permit waste characterization program, based on the argument that the cancellation of the QAPP and Methods Manual eliminated the requirements the CARs were written against. CARs cancelled include five for INEEL, five for LANL, and none from the RFETS program.

Many, if not all, of these CARs relate to QAPP and/or Methods Manual practices that are required by the WAP. For instance, two of the cancelled INEEL CARs (US DOE 1999d and US DOE 1999e) concerns inadequate sample handling and custody control, a necessary consideration for hazardous waste samples; WAP Attachment B1-4 contains requirements that cover the same area. WAP Attachment B13-4 requires that identified corrective actions be examined for the

extent and cause of the deficiency, and that remedial actions to preclude recurrence be planned, reported, completed, and verified before closure of the CAR. Since this process was apparently not completed for the CARs at INEEL and LANL, the pre-Permit waste characterization program cannot be said to be in accordance with the WAP. The significance of this deviation from WAP requirements cannot be accurately assessed without examining the extent and cause of the deficiencies for each of the CARs pertinent to characterization of hazardous waste.

2.4 Conclusions and Recommendations

1. The WAP appears to have made explicit many of the undocumented assumptions and implied good practices from the DOE's pre-Permit waste characterization program as specified in the TRU Waste Characterization QAPP.

2. There appears, on the surface, to be significant differences between the pre-Permit waste characterization program and the WAP requirements. A more thorough technical review, however shows that the essence of the requirements appear to have been met despite the apparent differences. The pre-Permit waste analysis process appears to meet the bulk of the technical requirements in the WAP.

3. Deviations from the fundamental documentation of the pre-Permit waste characterization program may be the most pertinent differences from WAP requirements. Variances from the requirements were not fully documented. Though it is unlikely that most of these would be major differences from WAP requirements, there remains the potential that at least some of these--solid coring, failure to sample headspace gases, drum temperature equilibration and perhaps others-- may be a factor in consideration of pre-Permit wastes. The premature closure of independent audit corrective actions for numerous deficiencies at INEEL and LANL, and the possibility that internal audit corrective actions may also have been cancelled or prematurely closed, may also create a perception that pre-Permit wastes were not characterized in accordance with the WAP.

4. There are enough known differences between the pre-Permit program and the WAP that, should the IV.B.2.b requirement become an issue, the data for the individual container lot sampling and analysis could be reviewed to determine compliance or noncompliance with the WAP. Since some of the evidence of compliance might not be easily deciphered, representatives from the DOE could be allowed to be present during the review so as to be able to point out data that might cover requirements. The Hazardous Waste Permit regulators would make the final determination.

3. RISK ANALYSIS FROM ROUTINE OPERATIONS

3.1 Introduction

The risks from emplacement of wastes at WIPP during routine (non-accident) operations are from: (1) external radiation received by those involved in waste handling operations; and (2) inhalation of VOCs that emanate from the filtered waste drums and boxes. Persons that might be exposed to VOCs include underground workers that are down wind from waste storage rooms, surface workers who may be exposed to discharges from the exhaust ventilation shaft, and members of the public that are off-site.

Risks from VOCs, hazardous metals, and radionuclides were evaluated for routine and accident conditions in EEG-72 (Channell and Neill 1999) and in the WIPP Safety Analysis Report (SAR) (US DOE 1999a) for full repository conditions. DOE's Application to NMED (the Application) (US DOE 1997) for the Permit evaluated risks from VOCs for routine and accident conditions.

The purpose of this analysis is to compare the risk from pre-Permit wastes in the repository with WAP-certified wastes that are to be emplaced after the Permit is issued. The routine operations analysis presented in this report will not include risks from radionuclides or hazardous metals. Radionuclide analyses are not included in the WAP and the external radiation doses received during waste emplacement will be incurred regardless of when the wastes are emplaced. Hazardous metal analyses and/or acceptable knowledge are required by the WAP, but the results are not used to calculate risks or set control limits. Also, no hazardous metal exposures are expected during routine operations.

3.2 Scenario Assumptions

The pre-Permit waste containers were emplaced in the exit drift (south 1600 Drift) portion of Room 7 of Panel 1. There is a temporary metal bulkhead with 2 louvers for flow of ventilation air

from the downstream portion of the room. Ventilation air at a rate of 35,000 cubic feet per minute (cfm) flows from the working face of the emplacement stack over the waste, through the louvers, down the south 1600 drift to the east 300 drift and up the exhaust shaft. An exhaust shaft flow rate of 260,000 cfm is used in these calculations[7] (see Figures 3.1 and 3.2). Scenario assumptions are almost identical to those used in EEG-72 and the Application.

Underground workers are exposed to VOC emissions from Room 7 while changing filters on the continuous air monitors (CAMs) located on the downstream side of the temporary metal bulkhead. In the Permit, NMED set room based concentration limits (RBCLs) on VOCs in order to protect the underground worker from lower explosive limit (LEL) and immediately dangerous to life and health (IDLH) concentrations due to a roof fall accident but not from long-term carcinogenic or non-carcinogenic risks (NMED 1999a). This report will calculate the carcinogenic and non-carcinogenic risks to underground workers.

The expected risk from VOCs to persons above ground during WIPP's operating lifetime is assumed to be due to emissions from all waste emplaced in open rooms, closed rooms, and closed panels. These risk calculations assume that containers with average concentrations of VOCs are emplaced at an average rate for the repository's operating lifetime (US DOE 1997). Emissions from a full open room have been estimated to be about 125 times those from a full closed room for carcinogenic VOCs and 75 times for non-carcinogenic VOCs (Channell and Neill 1999). Thus, the only way risks can be greater than expected is from either: (1) bringing in containers with above average concentrations of VOCs early (because they will emanate longer through closed rooms and panels); and (2) leaving waste in an open room for a longer than average period.

[7]The Permit requires a minimum running annual average mine ventilation exhaust rate of 260,000 standard cfm and a minimum active room ventilation rate of 35,000 standard cfm when workers are present (Section IV.E.3.b). At present an exhaust ventilation rate of 425,000 cfm is typical. The use of 260,000 cfm is conservative (i.e., it leads to higher calculated above ground concentrations).

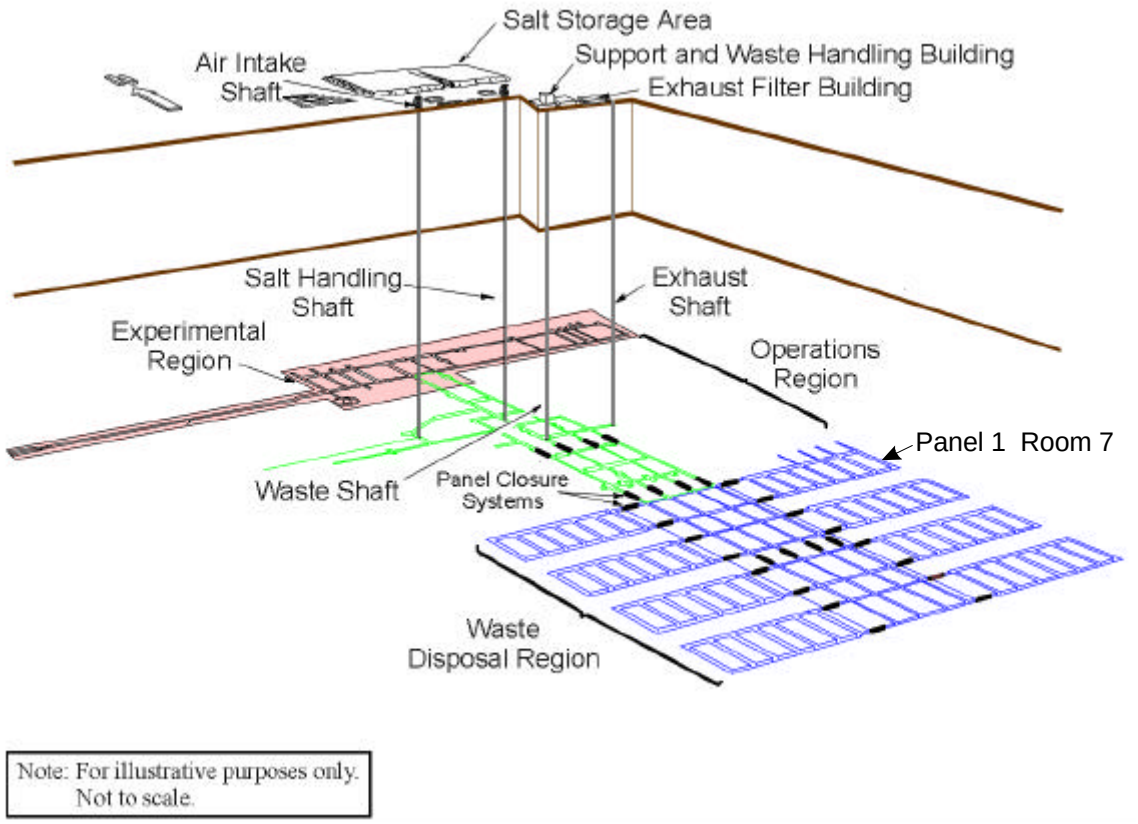

Figure 3-1. The WIPP facility includes surface support buildings, a waste handling building, four shafts, and the mined underground operations area. The repository is located approximately 658 m (2150 ft) below the surface, within the Salado Formation, a Permian sequence of bedded salt with minor amounts of anhydrite and clay. The excavations are accessible from the surface by four verticle shafts. Only one of the eight panels has been excavated to date. Each panel consistes of seven rectangular rooms, 10 m wide and 91 m long, separated by 30.5 m wide pillars. Source: DOE 1996b

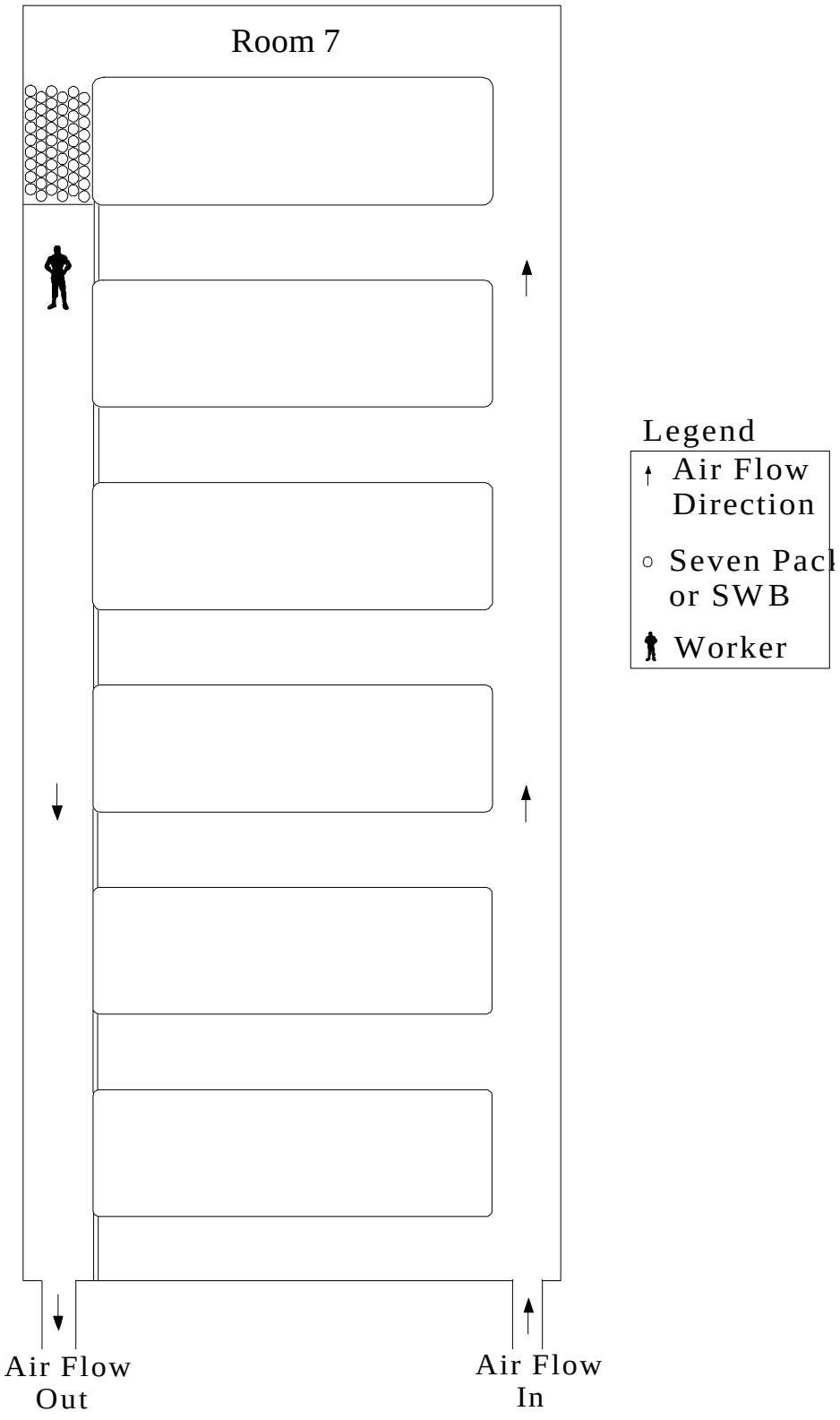

Figure 3-2. Waste Emplacement Process (Source: DOE 1999).

Pre-Permit waste containers emplaced in Room 7 have a lower than average VOC concentration. However, the early emplacement has resulted in the room being left open longer because of the slow shipping rate and the November 1999 - March 2000 period when shipments were not allowed. A waste room will be filled in about six months at the average 35-year emplacement rate. WIPP received its first waste on March 26, 1999, and Room 7 will probably not be filled and closed before early 2001. Bringing in pre-Permit waste early will probably cause open room exposure conditions to exist for approximately 12 additional months. The emissions from Room 7 during this additional one-year period are assumed to be a new source of exposure that was caused by bringing in pre-Permit waste.

3.3 Determination of VOC Source Term

In determining the VOC source term it was assumed that the values measured in the pre-Permit waste containers are accurate. Obviously one cannot be certain of the accuracy of non-WAP certified waste. However, the analysis in Chapter 2 suggests the analysis is probably similar and acceptable knowledge indicates that VOC concentrations in non-mixed waste should be low. Chapter 3.5 provides a bounding risk for the assumption that VOC concentrations are completely unreliable.

The VOC source term was determined from all the wastes emplaced in Room 7 as of October 25, 1999. VOC concentrations are from the WIPP Waste Information System (WWIS), a DOE database that includes waste characterization data for each waste container. The total waste emplaced was: (1) 101 Standard Waste Boxes from LANL; 126 drums of graphite wastes from the INEEL; and 408 drums of residues and 26 drums of graphite waste from RFETS. An additional 166 RFETS residue drums were received before the Permit became effective. These additional shipments were ignored because the exact number was unknown at the time the calculations were performed and the effect would be minor (e.g., 166 additional RFETS residue drums would increase carcinogenic risk by about 8% and non-carcinogenic risk by about 3%).

Reported VOC concentrations are low in all cases (as would be expected for non-mixed wastes). Most VOC measurements were less than the minimum detectable concentration (MDC) and only four had any values greater than the PRQL.

Only five of the approximately 25 VOCs analyzed were retained for the risk analyses. Those retained had a fair percentage of J values (greater than the MDC, but less than the PRQL, and considered to be detected) and average concentrations from at least one of the three generating sites of about 1 ppmv or greater. Two flammable VOCs that met these criteria (acetone and methanol) are not considered by EPA to have carcinogenic or non-carcinogenic risks and were also deleted from the risk analysis. The VOCs used along with their weighted average concentrations are shown in Table 3-1. Only three of these VOCs (methylene chloride, toluene, and 1,1,1-Trichloromethane) are among the nine VOCs listed in the Permit. Details of the calculation are in Appendix A.

Table 3-1. VOCs Used in Risk Analysis

VOC	Health Effect	Average Concentration ppmv
Methylene Chloride	carcinogen	0.41
Benzene	carcinogen	0.39
1,1,1 - Trichloromethane	non-carcinogen	2.9
Methyl Ethyl Ketone	non-carcinogen	4.6
Toluene	non-carcinogen	0.69

3.4 Risks to Surface Worker, Underground Worker, and Member of Public

Details of the risk calculation to an on-site surface worker, an underground worker, and to a member of the public (the Maximum Individual Receptor-MIR) located at the WIPP site boundary are in Appendix A. Results are summarized in Table 3-2. These are the total estimated incremental risks during the lifetime of WIPP operations from pre-Permit wastes at the repository.

Table 3-2. Risks to Surface Worker, Underground Worker, and Member of Public

VOC	Surface Worker	MIR at Boundary	Underground Worker
Carcinogens			
Methylene Chloride	7.20×10^{-15}	2.56×10^{-16}	2.94×10^{-13}
Benzene	1.56×10^{-13}	5.54×10^{-15}	6.36×10^{-12}
Total Cancer Risk	1.6×10^{-13}	5.8×10^{-15}	6.7×10^{-12}
Non Carcinogens			
1,1,1-Trichloromethane	4.00×10^{-10}	1.42×10^{-11}	1.63×10^{-8}
Methyl Ethyl Ketone	2.57×10^{-10}	9.16×10^{-12}	1.05×10^{-8}
Toluene	1.13×10^{-10}	4.02×10^{-12}	4.52×10^{-9}
Hazard Index	7.7×10^{-10}	2.7×10^{-11}	3.1×10^{-8}

These risks are so low that they are difficult to comprehend. Perspectives on these values are discussed separately for carcinogens and non-carcinogens.

3.4.1 Carcinogenic Risks

The Permit considers the highest acceptable lifetime cancer risk from VOCs to be 1×10^{-5} for the surface worker (called a non-involved worker) and 1×10^{-6} for the MIR. Maximum room based concentration limits are prescribed in the Permit so that these values will not be exceeded. The calculated risks for the expected quantity of VOCs in the repository are 5.6×10^{-8} for the underground worker, 9.7×10^{-8} for the surface worker, and 9.4×10^{-9} for the MIR (Channell and Neill 1999).

Allowable exposures at WIPP (25 millirem per year from routine operations) (US EPA 1997) to a member of the public from radioactive materials are equivalent to a carcinogenic risk of 3.4×10^{-4} over the 35-year emplacement period (340 times the target risk level of VOC in the Permit). Actual risks to a real individual are expected to be less than one percent of allowable.

Carcinogenic risks of less than 10^{-12} for a surface worker and 10^{-14} for a member of the public are seven and eight orders of magnitude below allowable Permit risk levels. They are also five and six orders of magnitude below expected lifetime risks from the entire WIPP inventory over the 35-year operating lifetime. Risks to the underground worker are four orders of magnitude less than expected from the full repository and six orders of magnitude below the allowable risk for surface workers. Actions which increase risks by less than one part in ten thousand have negligible effects.

3.4.2 Non-Carcinogenic Risks

The non-carcinogenic Hazard Index (HI) for the pre-Permit waste is calculated to be less than: 10^{-9} for the surface worker; 10^{-7} for the underground worker; and less than 10^{-10} for the public member. Values for the full inventory are estimated to be 2.4×10^{-5} for the surface worker, 1.4×10^{-5} for the underground worker, and 2.4×10^{-6} for the MIR. A hazard index less than 1.0 has no real meaning because these are threshold phenomena. The calculated values for the pre-Permit wastes are seven to ten orders of magnitude below a hazard level and are two to four orders of magnitude below the HI values for the full repository. Hence, they are negligible.

3.5 Bounding VOC Carcinogenic Risks

Because the values calculated above are based on data that were not obtained under a WAP-certified program, it could be argued that the VOC concentrations and risks could be much higher. A bounding limit can be calculated from the grab samples that are taken two times a week in the exhaust ventilation drift as a part of the Confirmatory VOC Monitoring Plan (Attachment N of the Permit). These samples have a required sensitivity well below the concentrations of concern established in the Permit to assure that the room based concentration limits are not exceeded. The method reporting limit (MRL) values for the individual VOCs are either two or five parts per billion by volume (ppbv) for the target VOC. DOE reports all data for the nine target VOCs in its Annual Site Environmental Report (Westinghouse 1999). The three VOCs used in this report were the only ones that had any values greater than the MRL.

Methylene chloride is the only one of our two carcinogenic VOCs that is a target VOC in the Permit (Table IV.B.1). Benzene is one of the additional VOCs that is determined in the analysis. Also, the statement is made in Appendix D-20 of the Application and Attachment N of the Permit: "Non-target sample contaminants identified by NIST library searches will be reported as tentatively identified compounds, and concentration calculations will be based on the response of the nearest internal standard." Based on this we assume that benzene or any other VOC detected at the 5 ppbv level would be reported.

The 5 ppbv concentration can be considered to be the exhaust shaft concentration. The risks can then be calculated using the Appendix A methodology. Results are shown in Table 3-3.

Table 3-3. Carcinogenic Risks at MRL[a] Values

VOC	MRL Values		Carcinogenic Risks	
	ppbv	$\mu g/m^3$	Surface	Boundary
Methylene Chloride	5	17.4	3.94×10^{-10}	1.40×10^{-11}
Benzene	5	16.0	6.40×10^{-9}	2.28×10^{-10}
TOTAL(Rounded)			6.8×10^{-9}	2.4×10^{-10}

[a]MRL = Method Reporting Limit

These risks are still low compared to the already low lifetime risks predicted from the expected quantity of VOCs emplaced in the full repository (9.7×10^{-8} for the surface worker and 9.4×10^{-9} at the site boundary, EEG-72). Thus, the Confirmatory VOC Monitoring Plan would be able to determine a lifetime risk that is 7% for the surface worker and 3% for the MIR of that expected (and accepted) in the Permit. These detectable risks are also 0.07% (surface worker) and 0.02% (MIR) of those allowed under conditions of the Permit. Clearly, if the allowed Permit risks are acceptable these risks from presently emplaced wastes are acceptable. The risk to an underground worker would be less than 3% of that allowed for the surface worker.

4. RISKS ANALYSIS FROM ACCIDENTS

4.1 Introduction

Accidents could cause a fraction of the contents of a waste container to be released and result in exposure due to VOCs, hazardous metals, and radionuclides. The risks from a roof fall accident and a spontaneous underground fire were evaluated. Scenario assumptions are similar to those used in the 1998 SAR, in Appendix D9 of the Application, and in EEG-72. These two accident scenarios were chosen because they could both occur in the open Room 7. Since the early emplacement of these wastes will result in the room remaining open for about one additional year, any risks resulting from these accidents can be considered an additional risk.

Other accidents considered in the SAR (e.g., drum drop, puncture, spontaneous fire in the Waste Handling Building, and hoist failure) were not evaluated. All of these accidents occur during waste receipt, handling, and emplacement and none occurred during emplacement of the pre-Permit wastes.

Releases evaluated from the accident scenario included VOCs and radionuclides. Hazardous metal releases were not evaluated because the average risk was found in EEG-72 to be $5x10^{-7}$ of the risk from radionuclides being released (using the same release fraction assumptions). Data from sampling the LANL waste and RFETS residues indicated that the hazardous metal concentrations per drum are lower than those used in EEG-72. Hence, the hazardous metals risk should be less than $5x10^{-7}$ of the radiological risk.

4.2 Spontaneous Fire Scenario

4.2.1 Scenario Description

Spontaneous ignition was assumed to occur in a drum or SWB emplaced in Room 7. This is considered an unlikely event even for a container that does not fully conform to the WIPP Waste Acceptance Criteria (WAC). It is further assumed that the fire does not propagate to additional waste containers.

The methodology used in the SAR (Chapter 5 and Appendix D) to develop the probability of sustained combustion in a one-half full waste room led to an estimated frequency of 5.3×10^{-6} per year. This calculation assumed specific percentages of each final waste form that would be processed or repackaged. The SAR assumes that processed or repackaged containers have only 10% the probability of a fire as a drum not processed or repackaged (because there is less chance of a repackaged drum not conforming to the WAC). When the emplaced waste volume (309 m^3) is compared to the 1503 m^3 assumed in the SAR and the actual percentages repackaged (100% for LANL and RFETS residues and 0% for graphite wastes) the probability becomes 6.8×10^{-7} per year. This accident would be considered less than extremely unlikely by DOE (because it is less than 1×10^{-6} per year) and not evaluated. The scenario was retained for conservatism and because the probability was reasonably close to 1×10^{-6} per year.

4.2.2 VOC Release and Risk

The SAR assumed that all of the headspace gas in a waste container would be released instantaneously. For computational purposes in this report the release period was assumed to be one minute. The fire was assumed to occur in a LANL SWB with average VOC and radionuclide concentrations. A LANL SWB was chosen because it has the highest carcinogenic VOC concentrations and the largest amount of headspace gas volume. Since the radionuclide quantities in the RFETS residue drums are 4.5 times greater than in the LANL SWBs, these calculations maximize VOC risks rather than radionuclide risks.

Lifetime fatal cancer risks from VOC releases are calculated in Appendix B. The risk to the surface worker is 1.9×10^{-15} and the risk to the MIR is 1.8×10^{-17}. Note that all the accident risk values are really the risks that result if the accident occurs. The overall annual risk is much less because it is the product of the annual probability of occurrence and the risk if the accident occurs.

4.2.3 Radionuclide Release and Risk

The assumptions of the SAR on fractional releases from the SWB were used. The radionuclide release from 4.24 Ci and an overall release fraction of 5×10^{-4} is 2.12×10^{-3} Ci. Calculations for releases, doses, and cancer risks are in Appendix B.

Doses and risks to the surface worker from this scenario were 28 mrem and 2.8×10^{-6}. An underground worker would receive a dose of 17 rem and incur a risk of 17×10^{-3}. For the MIR the doses and risks are 0.27 mrem and 2.7×10^{-8}. A member of the public at the exclusive use area boundary would receive a dose of 1.7 mrem and incur a risk of 1.7×10^{-7}. There are no VOC risk limits in the Permit or radionuclide risk limits for accidents.

VOC and radionuclide risks are shown in Table 4-1.

Table 4-1. Radionuclide and VOC Carcinogenic Risks from Spontaneous Fire Scenario[a]

Source	Surface Worker	Site Boundary Resident	Exclusive Use Boundary Resident
VOC			
Concentration(ug/m^3)[b]	1.2×10^{-2}	1.2×10^{-4}	7.3×10^{-4}
Risk	1.9×10^{-15}	1.8×10^{-17}	1.1×10^{-16}
Radionuclide			
Dose (mrem/y)	28.	0.27	1.7
Risk	2.8×10^{-6}	2.7×10^{-8}	1.7×10^{-7}
Total Risk	2.8×10^{-6}	2.7×10^{-8}	1.7×10^{-7}
Radionuclide/VOC Ratio	1.5×10^{9}	1.5×10^{9}	1.5×10^{9}

[a] Risks assume the probability of the scenario is 1.0
[b] Combined concentration for both VOCs

4.3 Roof Fall Scenario

4.3.1 Scenario Description

The SAR roof fall scenario was patterned after the roof fall that occurred in the experimental area of the repository in Site Preliminary Design Validation Room 1 in 1991. This roof fall was in the shape of an elongated pyramid, approximately 33 feet wide by seven feet high by 180 feet long, and weighed about 700 tons. The scenario was assumed to occur in an active disposal room where waste containers are still being emplaced. Falling salt knocks seven SWBs off the top stack and five of these are breached. All (100%) of the VOC headspace gas is released from these five SWBs. The aerosolized and respirable radionuclide release is 1.0×10^{-5} of the contents of a SWB. For five SWBs with 4.24 Ci/SWB this results in a source term of 2.12×10^{-4} Ci. Released material is transported in room ventilation air to the surface.

4.3.2 Scenario Probability

The SAR developed a rationale and fault tree to arrive at an annual probability of 4.7×10^{-7} that an unexpected roof fall will occur in an unisolated (open) waste room. This scenario would not have to be evaluated according to DOE procedures because the probability is $<1 \times 10^{-6}$/y. Several factors combine to create this low probability value and a major factor is the belief that there are enough signs in the days or weeks leading up to a roof fall that an imminent fall would almost certainly be detected beforehand.

Emphasis is placed in the SAR analyses on an unexpected roof fall because of the belief that even with a few minute warning the area could be evacuated and ventilation exhaust switched to filtration. With a few days warning the affected area could be isolated with emergency barriers and emplacement operations elsewhere be abandoned if necessary .

There are several reasons why preparation for an imminent roof fall may not be as simple and effective as described in the SAR. For example, the DOE may be reluctant to: (1) put workers in the downstream ventilation path to install a ventilation barrier; (2) stop all waste emplacement operations in the affected and adjacent rooms for many days; and (3) operate in the filtration mode for long periods of time (which also precludes waste emplacement). Also if the fall were to occur in the off-shift there would be no two minute warning to activate a switch to filtration before a release. Therefore, EEG believes that even if there are signs of an imminent roof fall the timing of mitigative measures may not ensure complete containment of a release.

4.3.3 EEG Views on Roof Fall Probability in Panel 1.

Panel 1 room stability has been a cause of concern for many years and the SAR recognized that Panel 1 is more susceptible to roof fall. The basic problem is the length of time the rooms have been open. Mining of the panel began in May 1986 and was completed in June 1988. This schedule was to accommodate the anticipated first receipt of wastes in 1988. Concern arose about the useful lifetime of these rooms when the schedule slipped and it became apparent the

panel would not be filled with waste for many years. A group of geotechnical experts was assembled by DOE in April 1991 to provide advice on the useful life span of Panel 1 and recommend remedial measures. The group concluded that the rooms would remain stable without additional support with high confidence until 1993 and with decreasing confidence until 1997. All of the rooms in Panel 1 were fitted with three meter roof bolts in the 1988-89 period. Additional support systems have been installed in portions of Panel 1 since 1989. Room 7, which is our primary concern in this evaluation, completed a tertiary support system in May 1998.

EEG retained a mining engineer, Hamid Maleki, as a consultant in 1996 and in 1998 to evaluate the stability of Panel 1. Dr. Maleki had previously evaluated WIPP mine safety for the U.S. Bureau of Mines in 1993, 1994, and 1995. Dr. Maleki concluded after his 1996 evaluation (Maleki and Chaturvedi 1996) that there were remedial steps that could be taken to enhance stability during emplacement operations. However, he also said, "To 'assure stability' and safety, it is best to abandon Panel 1 and mine a new panel as soon as all permitting processes are complete". In his 1998 report Dr. Maleki stated "Time of roof collapse cannot be estimated with a high degree of confidence if internal tertiary support systems are used without external support systems, such as cribs. The potential for roof falls is expected to be low within the first year and increase significantly in some locations approximately 2 years after installation of tertiary support" (Maleki 1998).

Because of the concerns expressed by others and our own evaluations, EEG has recommended that DOE certify each room in Panel 1 before waste emplacement operations begin. At design emplacement rates a room would be filled in about six months and the one to two year stability period predicted by Maleki would be more than adequate. On July 21, 1999, Westinghouse cleared Room 7 for waste emplacement operations until June 30, 2000 (Patchet 1999). However, because of the slow emplacement rate the room will not be filled until late in the year 2000 or early in 2001. Inspections and remedial measures in the portion of Room 7 already filled with waste will be difficult because of access problems.

For the above reasons EEG believes a roof fall in Room 7 has a probability much greater than $1x10^{-6}$/y and the scenario needs to be evaluated.

4.3.4 VOC Release and Risk

Since 100% of the headspace gas is assumed to be released from each of the five SWBs breached in the roof fall scenario the release and the risks from this accident would be five times as great as in the underground (UG) fire scenario. The risks are $9.3x10^{-15}$ for the surface worker and $9.1x10^{-17}$ for the public member at the WIPP Site Boundary.

4.3.5 Radionuclide Release and Risk

The SAR assumed radionuclide release from the roof fall scenario to be 10% of the release from the UG fire scenario. This lower release occurs because the roof fall damage ratio is 1%, the airborne release factor is two times and the material at risk is five times that in the UG fire scenario. The calculated radionuclide risks are $1.7x10^{-4}$ for the UG worker, $2.8x10^{-7}$for the surface worker, $2.1x10^{-9}$ for the MIR, and $1.7x10^{-8}$ for a public member at the northern exclusive use area boundary.

4.4 Radionuclide to VOC Risks

The risk from radionuclide releases is $1.5x10^{9}$ times the VOC release for the UG fire scenario. In the roof fall scenario the radionuclide risk is $3.0x10^{7}$ times the VOC risk. So, the risk from VOC releases is negligible compared to that from radionuclide releases.

The radionuclide risk to a surface worker from the UG fire scenario accident is greater than $1x10^{-6}$. This is very small, but not negligible. However, the overall annual risk would be much smaller because this is an unlikely accident.

5. CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The WAP requirements for waste characterization are often more prescriptive than the QAPP requirements used for pre-Permit characterization but the essence of the technical requirements appears to be similar.

Deviations granted by DOE during pre-Permit waste characterization and the premature closure of some corrective actions required by independent audits may result in the most significant differences in waste characterization.

Estimated carcinogenic risks to a surface worker and member of the public from routine operations involving TRU wastes emplaced in Panel 1, Room 7 during 1999 are seven to eight orders of magnitude less than allowed by the Permit and five to six orders of magnitude less than expected from the entire WIPP Project over 35 years. Non-carcinogenic risks are nine to ten orders of magnitude below the allowed limit and two to four orders of magnitude below expected risks for the repository.

Estimated carcinogenic risk to the underground worker from routine operations are six orders of magnitude below the allowable risk level for surface workers. Non-carcinogenic risks are seven orders of magnitude below a hazard level.

Even if VOC emissions are much higher than expected, the Confirmatory VOC Monitoring Plan at WIPP would detect concentrations that are three orders of magnitude below allowable Permit limits. Any hazardous emissions from pre-Permit wastes would likely be reported and acted on long before Permit limits were reached.

Risks from low probability accidents are within an order of magnitude of the allowable Permit limits from routine emissions of VOCs. These risks are essentially all from inhalation of released radionuclides with the radiation/VOC risk ratio being $\geq 3 \times 10^{7}$.

Radiation doses and risks to an underground worker for the spontaneous fire scenario are significant (17 rem and 1.7×10^{-3} risk). Doses from the roof fall scenario are one-tenth of those from the spontaneous fire scenario.

5.2 Recommendations

The data for the individual container lots of pre-Permit waste can be reviewed for being "characterized in accordance with the WAP," if this becomes necessary. This determination by NMED should consider all deviations and include input from the DOE.

The estimated non-accidental risks from the presently stored waste in Room 7 are so low that they should not be used as a justification for any remedial or other actions involving these wastes.

Radionuclide risks to underground workers from low probability spontaneous fire and roof fall accidents should be considered when setting restrictions on worker access to the south 1600 and east 300 drifts.

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APPENDICES

APPENDIX A

CALCULATION OF RISK ANALYSIS FOR ROUTINE OPERATIONS

A.1 Development of VOC Source Term

A.1.1 Available Data

Data used in risk analysis calculations was taken from the WIPP Waste Information System (WWIS). Head Space Gas (HSG) analyses were available for all LANL Standard Waste Boxes (SWBs), all INEEL drums, and for the 26 RFETS graphite waste drums. There were no data for the 408 residue drums from RFETS.

The LANL HSG measurements were taken from the parent drums of heat source waste. Subsequent to the HSG analyses each parent drum was divided into several daughter drums so that the curie content would be low enough to ship in the TRUPACT-II package. Each of the daughter drums was placed into a SWB without its drum lid and with three empty drums. LANL took the measured VOC concentrations in each parent drum and assigned the full value to each of that drum's daughter drums. This same HSG concentration was assumed to be the HSG concentration in the SWB. (Rogers 1999). This is undoubtedly a conservative assumption but the amount of conservatism is unknown. The values assigned by LANL were used in this report.

No corrections were made for the HSG concentrations for the graphite waste stream drums from INEEL (120 drums) and RFETS (26 drums).

The RFETS residues are pyro-oxidized salts that have been heat treated at sufficiently high temperatures to drive off any VOCs present. This was the basis for the DOE Carlsbad Area Office to grant RFETS an exemption from HSG Sampling (Hunter 1998a) The WAP requires all containers to have HSG sampling and contains no procedure for granting exemptions.

A lack of HSG data for the residues creates an uncertainty in this risk analysis. Although the argument that the pyro-oxidation process would drive off all VOCs is reasonable, it should be noted that the LANL wastes which have been shown to be non-RCRA wastes contain detectable amounts of VOCs in about one-half of the SWBs. This risk analyses assumes that the residues contain the same HSG concentration as the 26 drums of RFETS graphite wastes. This is probably a conservative assumption but there is uncertainty.

A.1.2 Selection of VOCs

Approximately 25 VOCs were analyzed by the generator sites. The proposed NMED Permit requires room based concentration limits for only nine of these VOCs which contain about 99% of the expected total carcinogenic and non-carcinogenic risk. This risk screening was based on a combination of the projected weighted average concentrations in the repository and the risk coefficients for the individual VOCs.

EEG's screening for this risk analysis considered the nine VOCs included in the Permit as well as those VOCs that were frequently detected and had average concentrations ≥ 1 ppmv at one or more of the generator sites.

Reported VOC concentrations are low in all cases, as would be expected for wastes shipped as non-RCRA wastes. Most VOC measurements are less than the minimum detectable concentration (MDC) and the value reported is the MDC with a U designator. Most of the values greater than the MDC are less than the program required quantitation limit (PRQL) and are designated J. The only VOCs with any values greater than the PRQL were acetone at LANL and 1,1, 1-trichloroethane, toluene (1 only), and carbon tetrachloride (1 only) at INEEL. In calculating average values, those concentrations designated U were assigned one-half the reported value and J designated concentrations were assigned the full value.

Five of the VOCs met the screening criteria and were retained for the risk analyses. Only three of these (1,1,1-trichloroethane, methylene chloride and toluene) were among the nine VOCs for

which environmental monitoring measurements are required by the Permit. Table A-1 includes a total of nine VOCs that had sufficient concentrations and levels of detection to warrant calculation. Acetone and methanol had the highest average concentrations and are of concern in shipping because they are flammable. However, neither are a carcinogenic or non-carcinogenic risk and so are not included in the risk analysis.

The weighted average value per container was determined by weighing the average concentration from each site by its fraction of the total containers employed in WIPP as of October 26, 1999, (101 SWBs from LANL, 126 drums from INEEL, and 434 drums from RFETS). LANL SWBs were counted as two drum equivalents because they contain two filters and >6 times the head space gas volume of a drum. The fractions of total drum equivalents is 0.265 for LANL, 0.165 from INEEL, and 0.570 for RFETS.

Table A-1. VOC Concentrations in Pre-Permit Waste at WIPP

	Average Concentrations - ppmv			Weighted Average (ppmv)	Comments
VOC	LANL	RFETS	INEEL		
Acetone	60.2	4.6	5.9	19.6	delete, not HW Risk
Methanol	22.1	9.1	6.8	12.2	delete, not HW Risk
1,1,1-Trichloroethane	1.0	0.1	15.9	2.9	non-carcinogen
Methylene Chloride	1.0	0.09	0.54	0.41	carcinogen
Methyl Ethyl Ketone	16.1	0.37	0.47	4.6	non-carcinogen
Toluene	1.9	0.28	0.17	0.69	non-carcinogen
Carbon Tetrachloride	0.9	0.1	0.4	0.37	delete, few J values
Benzene	1.1	0.14	0.12	0.39	carcinogen
Trichloroethylene	0.9	0.00	0.2	0.27	delete, no J values

A.2 Exhaust Shaft and Environmental Concentrations

The weighted VOC concentration for each VOC from Table A-1 can be related to the exhaust shaft concentration (ECS) by the following expression (from Appendix D9 of the Application):

$$ECS = x \frac{[D_{voc}\ (MF)_{voc}]\ MW_{voc}(1x10^{6}\ \mu g/g)}{V(.0283)m^{3}/ft^{3}\ (.01667\ min/s)} \qquad \textbf{(A-1)}$$

where:

x = number of drum equivalents, 762

D_{voc} = diffusion rate through an NFT-013 filter, moles/s-mole fraction-drum

Mw_{voc} = molecular weight of VOC, grams per mole

MF_{voc} = mole fraction mole/mole

V = exhaust ventilation rate, (260,000) cubic feet per minute

When constant values are combined, Equation A-1 reduces to:

$$ECS = 6.21x10^{6}\ D_{voc}\ MF_{voc}\ (MW_{voc})\ \mu g/m^{3} \qquad \textbf{(A-2)}$$

Filter specific diffusion rates for each VOC relative to H_2 gas were calculated from Equation D9-7 in Appendix D9 of the Application. Molecular weight, critical pressure, and critical temperature of a VOC are factors in determining the diffusion rate.

Exhaust shaft concentrations are shown in Table A-2. The annual air dispersion factors (ADF) for determining VOC concentrations in the environment were taken from Appendix D9. These values are $1.23x10^{-2}$ for the aboveground worker and $1.2x10^{-4}$ at the WIPP site boundary. The calculated VOC concentrations at these two locations are also shown in Table A-2.

Table A-2. VOC Concentrations in Exhaust Ventilation & Environment From Pre-Permit Waste at WIPP

VOC	D_{voc} Mole/s-mole fraction-drum	Mole Fraction	Molecular wt.	Concentrations -µg/m^3		
				Exhaust Shaft	Above Ground	Site Boundary
Methylene Chloride	1.47×10^{-6}	4.1×10^{-7}	84.94	3.18×10^{-4}	3.91×10^{-6}	3.81×10^{-8}
Benzene	2.06×10^{-6}	3.9×10^{-7}	78.11	3.89×10^{-4}	4.78×10^{-6}	4.67×10^{-8}
1,1,1-Trichloroethane	1.21×10^{-6}	2.9×10^{-6}	133.42	2.90×10^{-3}	3.57×10^{-5}	3.48×10^{-7}
Methyl Ethyl Ketone	1.30×10^{-6}	4.6×10^{-6}	72.11	2.67×10^{-3}	3.28×10^{-5}	3.20×10^{-7}
Toluene	1.19×10^{-6}	6.9×10^{-7}	92.13	4.69×10^{-4}	5.77×10^{-6}	5.63×10^{-8}

A.3 Risk to Surface Worker

The surface worker is assumed to be exposed to VOC emissions from the repository exhaust ventilation shaft for a period of 1920 hours a year. This calculation also assumed Room 7 will remain open for a period of one year before being filled and sealed. Room 7 could be open less than one year if the decision is made to seal the partially filled room before bringing in RCRA regulated waste. However, it will probably be some time in the year 2001 before the room will be completely filled. Carcinogenic risks from each VOC can be determined for the surface worker by the following relationship:

$$Risk = ECS\ (ADF)s\ (URF)\ Fs \qquad \textbf{(A-3)}$$

where:

URF = cancer unit risk factor (for a lifetime exposure) in m^3/µg

(ADF)s = air dispersion factor for surface worker, dimensionless

Fs = fraction of lifetime exposed, dimensionless

Current unit risk factors (URF) were obtained from EPA's IRIS data base. The URF is expressed in reciprocal concentration units so that the product of Equation A-3 is dimensionless. The air dispersion factor is 1.23 x 10^{-2} and Fs is 0.00392 (1920 hours exposure in one year at 1.2 m^3/h inhalation rate divided by a lifetime inhalation of 588,000 m^3). Any exposure to carcinogens is assumed to result in a risk, regardless of the concentration (i.e., there is no threshold below which no damage occurs). The total VOC carcinogenic risk can be obtained by summing the total carcinogenic risks from all the carcinogenic VOCs.

Non-carcinogenic effects are evaluated using a hazard quotient from each VOC_i (HQ_i) defined as:

$$HQ_i = \frac{average\ \ exposure\ \ concentration, VOC_i}{RfC_i}\ (F) \qquad \textbf{(A-4)}$$

where:

RfC_i = the chronic reference dose for exposure by inhalation from VOC_i, µg/m^3

F = fraction of a 35 year working lifetime exposed

Values of RfC_i are obtained from the IRIS data base. In this case F is 0.00784 (2340 m^3 inhaled in one year divided by 294,000 m^3).

The sum of the HQ_i values for all radionuclides can be summed into a Hazard Index (HI):

$$HI = \sum_{i=1}^{i=t} HQ_i \qquad \textbf{(A-5)}$$

For HI values less than 1.0 adverse health effects are unlikely and, because non-carcinogens have a threshold below which damage does not occur, values much below 1.0 have no precise meaning. Long-term non-carcinogenic health effects are possible for HI exposures greater than 1.0. The HI is definitely not probabilistic, i.e., a value of 0.01 does not imply a 1% probability of an effect.

Risks to surface workers from carcinogens and non-carcinogens are shown in Table A-3. These risks are extremely low. The implications of these values are discussed in Chapter 3.

Table A-3. Annual Risks to Surface Worker from Carcinogens and Non-Carcinogens From Pre-Permit Wastes at WIPP

VOC	ECS(ADF)F $\mu g/m^3$	URF ($m^3/\mu g$)	Risk
Carcinogens			
Methylene Chloride	1.53×10^{-8}	4.7×10^{-7}	7.20×10^{-15}
Benzene	1.88×10^{-8}	8.3×10^{-6}	1.56×10^{-13}
Total			1.63×10^{-13}
Non- Carcinogen		RfC	HQ
1,1,1-Trichloroethane	2.80×10^{-7}	700	4.00×10^{-10}
Methyl Ethyl Ketone	2.57×10^{-7}	1000	2.57×10^{-10}
Toluene	4.52×10^{-8}	400	1.13×10^{-10}
Total			HI = 7.70×10^{-10}

A.4 Risk at WIPP Site Boundary

The Maximum Individual Receptor (MIR) is defined as a member of the public who resides at the WIPP site boundary. Residence time is assumed to be 100% for the year. The methodology for calculating the risk is the same as for the surface worker and the only values changed are ADF (1.2×10^{-4}), F for carcinogens (.0143), and F for non-carcinogens (0.0286). The results are shown in Table A-4.

Table A-4. Annual Risks to Member of the Public from Carcinogens and Non-Carcinogens From Pre-Permit Waste at WIPP

VOC	ECS(ADF)F ($\mu g/m^{3)}$	URF ($m^3/\mu g$)	Risk
Carcinogens			
Methylene Chloride	5.45×10^{-10}	4.7×10^{-7}	2.56×10^{-16}
Benzene	6.68×10^{-10}	8.3×10^{-6}	5.54×10^{-15}
Total			5.80×10^{-15}
Non-Carcinogen		RfC	HQ
1,1,1-Trichloroethane	9.95×10^{-9}	700	1.42×10^{-11}
Methyl Ethyl Ketone	9.16×10^{-9}	1000	9.16×10^{-12}
Toluene	1.61×10^{-9}	400	4.02×10^{-12}
Total			HI= 2.74×10^{-11}

A.5 Risk to Underground Workers

Underground workers are estimated to be in the south 1600 exit panel drift for 20 minutes each time they enter to inspect and service the CAMs located at the Room 7 bulkhead. For two entries per day and 200 days per year this amounts to approximately 130 hours of exposure per year. The exit air flow from Room 7 and in the drift is assumed to be 35,000 cubic feet per minute and the VOC emissions to be fully mixed at the location of the underground workers. The flow and mixing assumptions do not reflect actual conditions for two reasons: (1) The 35,000 cfm flow was used during the waste emplacement period. However, during much of the time between emplacement of the last of the pre-Permit wastes prior to November 26, 1999, and about March 13, 2000, when waste emplacement resumed, the flow through Room 7 was reduced to very low levels by installation of a brattice cloth at the inlet to the room; and (2) it is likely that much of the time workers were near the bulkhead and at the location of the CAMs they were exposed to air that contained a lower concentration of VOCs than would occur once there was

complete mixing. The first condition would result in higher VOC concentrations at the exit louvers but probably less mixing and could cause higher exposures than calculated for the time-period of low flow. Condition 2, if it exists, would decrease calculated exposures. There are no data available to quantitatively evaluate conditions 1 and 2.

VOC concentrations in the drift can be obtained by modifying Equation A-1 to reflect the lesser dilution (35,000 cpm) in the drift to that in the exhaust shaft (260,000 cfm). The drift concentration is thus 7.43 times the ECS.

The carcinogenic risk to the underground worker is calculated from modifying Equation A-3. The concentration is 7.43 ECS and the ADF is 1.0. URF values are unchanged. The F value (for 130 hours at 1.2 m^3/h) is 2.65×10^{-4}.

Non-carcinogenic risks can be calculated from Equations A-4 and A-5. The F value (for a 35 year working lifetime) is twice the Fs value used for the carcinogenic risk (5.30×10^{-4}). Carcinogenic and non-carcinogenic risks are shown in Table A-5.

Table A-5. Annual Carcinogenic and Non-Carcinogenic Risks to an Underground Worker from Pre-Permit Wastes at WIPP

VOC	Drift Concentration ($\mu g/m^3$)	Risk/Hazard Quotient
Carcinogens		
Methylene Chloride	2.36×10^{-3}	2.94×10^{-13}
Benzene	2.89×10^{-3}	6.36×10^{-12}
Total Risk		6.65×10^{-12}
Non-Carcinogens		
1,1,1-Trichloroethane	2.15×10^{-2}	1.63×10^{-8}
Methyl Ethyl Ketone	1.98×10^{-2}	1.05×10^{-8}
Toluene	3.48×10^{-3}	4.61×10^{-9}
Hazard Index		3.14×10^{-8}

APPENDIX B
RISK ANALYSIS FROM ACCIDENTS

The calculation of exposures, doses, and risks from VOC and radionuclide releases is similar for both the spontaneous underground fire and the roof fall scenarios.

B.1 VOC Risks

The ECS for accidental releases can be determined by an expression similar to expression (A-1) in Appendix A. The difference is due to replacement of the diffusion term from multiple drums by the fraction of a mole of HSG released in one minute. The ECS term becomes:

$$(ECS)_{acc} = 5570(m^3 HSG)\ (MW)(MF)\ \frac{\mu g}{m^3} \qquad \textbf{(B-1)}$$

The WWIS lists an average LANL standard waste box fill volume of 44%. This results in a headspace gas volume of 1.064m^3 for the 1.9m^3 SWB. For the underground fire accident equation B-1 becomes:

$$(ECS)_{acc} = 5930\,(MW)(MF)\frac{\mu g}{m^3} \qquad \textbf{(B-2)}$$

The risk to a surface worker for a one minute exposure is calculated from Equation A-3 when using an Fs value of 3.40x10^{-8}. The risk at the WIPP site boundary is obtained from using an ADF of 1.2x10^{-4} and the 3.40x10^{-8} Fs value.

Results of the VOC carcinogenic risk calculation to a surface worker from the underground fire scenario are presented is Table B-1.

Table B-1. VOC Lifetime Fatal Cancer Risk to a Surface Worker from an Underground Fire Scenario at WIPP[a]

VOC	Molecular wt.	Mole Fraction	URF $m^3\mu g$	Risk	
				Surface W	S. Boundary
Methylene Chloride	84.94	1.0×10^{-6}	4.7×10^{-7}	9.90×10^{-17}	9.67×10^{-19}
Benzene	78.11	1.1×10^{-6}	8.3×10^{-6}	1.77×10^{-15}	1.73×10^{-17}
Total				1.87×10^{-15}	1.83×10^{-17}

[a]Risks assume the probability of the scenarios is 1.0.

The release from the roof fall accident is five times that from the spontaneous underground fire accident because five SWBs are breached. Therefore, the VOC carcinogenic risk would be 9.35×10^{-15} for the surface worker and 9.15×10^{-17} for the public member at the WIPP site boundary.

B.2 Radionuclide Risk

B.2.1 Radionuclide Source Term

The expression used in the SAR (Section 5.2.1) for determining the quantity of radioactivity (Q in curies) released is:

$$Q = MAR(DR)(ARF)(RF)(LF) \qquad \textbf{(B-3)}$$

where:

MAR = Material at Risk in Curies. Contents of one SWB (4.24 Ci) for underground fire and 5 SWB (21.2 Ci) for roof fall

DR = Damage Ratio, 1.0 for UG fire, 0.010 for roof fall

ARF = Airborne Release Factor, 5×10^{-4} for UG fire, 1×10^{-3} for roof fall.

RF = Respirable Fraction, 1.0 for both scenarios

LF = Leakpath Fraction, 1.0 for both scenarios

With these assumed parameter values the radionuclide releases (Q) are 2.12×10^{-3} Ci for the UG fire and 2.12×10^{-4} Ci for the roof fall. The roof fall values are less because the DR value for a roof fall is less than for the UG fire.

B.2.2 Radionuclide Cancer Risk

The radionuclide quantity inhaled by the surface worker or the MIR can be obtained with an expression similar to A-3. Then, multiplication by the dose conversion factor (DCF rem/Ci inhaled) and the cancer risk to dose factor (RDF) (cancer risk per rem) give the cancer risk for the radionuclide release. The risk becomes:

$$Risk = \frac{Q(ADF)(1.2\frac{m^3}{hr}\ inhaled)(DCF)(RDF)}{2.6x10^5\ \frac{ft^3}{\min}\ (.0283\ \frac{m^3}{ft^3})\ 60\frac{\min}{hr}} \qquad \textbf{(B-4)}$$

where:

ADF = Air Dispersion Factor, 1.23×10^{-2} for surface worker, 1.2×10^{-4} for boundary

DCF = 3.92×10^{8} rem per Ci for ^{238}Pu (US EPA 1988)

RDF = 1×10^{-4} risk per rem (NAS 1988)

The resulting cancer risks for the UG fire scenario are 2.78×10^{-6} for the surface worker and 2.71×10^{-8} for the resident at the site boundary. For the roof fall scenario the risks are 2.78×10^{-7} for the surface worker and 2.71×10^{-9} for the MIR. Risks to the underground worker would be 1.69×10^{-3} from the UG fire scenario and 1.69×10^{-4} for the roof fall scenario.

A member of the public could be at the exclusive use area boundary and be exposed to the accidental release. The maximum ADF value shown in Appendix D9 is 7.5×10^{-4} at the northern exclusive use area boundary. Resulting risk to a member of the public would be 1.69×10^{-7} for the UG fire scenario and 1.69×10^{-8} for the roof fall scenario.

B.3 Radiation to VOC Risk Ratio

The relative risk from VOC releases compared to radionuclide releases can be obtained from the above calculations. The radionuclide risk is 1.49×10^9 times the VOC risk for the underground fire scenario and it is 2.97×10^7 times the VOC risk for the roof fall scenario.

B.4 Comparison with SAR Exposures

The values for exposure from radionuclides and VOCs in Appendix E, Revision 3 of the Safety Analysis Report are much higher than the values calculated here. There are several reasons for this:

1. The SAR used an 80 PE-Ci quantity in the container compared to the use here of the average value in the LANL SWBs (4.24 Ci).

2. The radionuclide dose conversion factor used in the SAR was 5.1×10^8 rem/Ci for ^{239}Pu rather than the EPA value of 3.92×10^8 rem/Ci for ^{238}Pu.

3. SAR radionuclide dispersion values were obtained using the χ/Q methodology and this report used the Long-Term Version of the Industrial Source Complex (ISCLT3) model (EPA) that resulted in the Appendix D9 Air Dispersion Factors. The SAR methodology resulted in concentrations about 50 times greater than the ADFs.

Agreement with the SAR values was within one percent when these differences are incorporated.

The radionuclide dispersion calculations require greater discussion. Use of the ADF methodology, which uses annual average dispersion values, would not be conservative for the low probability one-hour conditions that might occur during an accident. The χ/Q methodology calculates the dispersion of particles, atoms, or molecules and does not consider dilution prior to exhaust from the ventilation shaft. The unfiltered exhaust volume from WIPP varies between

260,000 and 425,000 cfm (123 to 200 m^3/sec). The concentration calculated from the χ/Q methodology at 100 m is 63% of the concentration in the exhaust shaft at a 260,000 cfm ventilation rate and 103% at a 425,000 cfm rate. There is no apparent physical means by which concentrations would increase after leaving a stack. U. S. Nuclear Regulatory Commission Regulatory Guide 1.145 (US NRC 1983) assumptions lead to a prediction that the size of the WIPP exhaust plume would increase by a factor of about 3.7 at 100 m during very stable (G) atmospheric stability conditions. For moderately stable (F) atmospheric stability the plume size would increase by a factor of about 24.

It is concluded that the atmospheric dispersion factors used may be non-conservative by a factor of up to 5 for very stable Class G atmospheric conditions while the χ/Q value would usually be conservative by an order of magnitude. The use of worst case meteorological condition may be appropriate in a consequence analysis for very low probability events where doses may be high enough to cause acute effects, but is not necessary for a risk calculation.

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EEG-77

PLUTONIUM CHEMISTRY UNDER CONDITIONS RELEVANT FOR WIPP PERFORMANCE ASSESSMENT

Review of Experimental Results and Recommendations for Future Work

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September 2000

EEG-77
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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U. S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the compliance of the generator sites with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of radioactivity in air, water, and soil, both on-site and off-site.

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ABSTRACT

The Waste Isolation Pilot Plant (WIPP), located at a depth of 650 m in bedded salt at a site approximately 40 km east of Carlsbad, New Mexico, was constructed by the US Department of Energy for the disposal of transuranic wastes arising from defense-related activities. The disposal site is regulated by the US Environmental Protection Agency (EPA). During the process leading to certification of the site for initial emplacement of waste, EEG and their contractors reviewed the DOE Compliance Certification Application (CCA) and raised a number of issues. This report reviews the issues related to the chemistry of plutonium as it will affect the potential for release of radioactivity under WIPP conditions. Emphasis is placed on conditions appropriate for the Human Intrusion scenario(s), since human intrusion has the largest potential for releasing radioactivity to the environment under WIPP conditions. The most significant issues that need to be addressed in relation to plutonium chemistry under WIPP conditions are (1) the effects of heterogeneity in the repository on Pu concentrations in brines introduced under the human intrusion scenario, (2) the redox state of Pu in solution and potential for plutonium in solid phases to have a different redox state from that in the solution phase, (3) the effect of organic ligands on the solubility of Pu in WIPP-relevant brines, and (4) the effects of TRU waste characteristics in determining the solubility of Pu. These issues are reviewed with respect to the treatment they received in the DOE CCA, DOE's response to EEG's comments on the CCA, and EPA's response to those comments as reflected in the final EPA rule that led to the opening of the WIPP. Experimental results obtained in DOE's Actinide Source-Term Test Program (STTP) during the last two years are reviewed and interpreted in the light of other developments in the field of Pu solution chemistry. This analysis is used as the basis for a conceptual model for Pu behavior under WIPP conditions.

This report identifies three issues that can be addressed as part of the five-year re-certification cycles mandated by the WIPP Land Withdrawal Act (U.S. Congress, 1996, '8.(f)(1)) and implemented in the EPA Final Rule (U.S. EPA, 1998a). First, the impact of organic ligands on the complexation of a system with multiple cations could be delineated by some simple experiments with Th (IV), citrate,

EDTA, Ca^{2+} and one or more transition metals. An experiment with Pu (IV) could be designed to determine the lability of Pu oxidation states in the presence of organic ligands. Second, the issue of using analogs for Pu could be addressed with appropriate experiments using U and Pu at redox conditions in the range anticipated at the WIPP. Attention to the published experimental results of U and Pu could make a considerable contribution to this effort. Third, the issue of uncertainty in calculated actinide solubility can be resolved with experimental data for Pu (IV) compounds of appropriate compositions. The report also recommends starting by constructing a data base for U and Pu using the published, peer-reviewed OECD/NEA U and Pu data bases.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) was constructed by the US Department of Energy (DOE) to serve as a disposal site for transuranic radioactive wastes that arose through defense-related activities. The WIPP facility was built in a bedded salt formation at a depth of 650 m and is located approximately 40 km east of Carlsbad, New Mexico. The disposal facility is regulated by the US Environmental Protection Agency (EPA) through their Radiation Protection Standards for disposal of transuranic waste. The regulatory process involves DOE filing with EPA a Compliance Certification Application. (CCA). This was done in October, 1996 (DOE, 1996). The Environmental Evaluation Group (EEG), which conducts independent technical evaluations of the impact of the WIPP project on public health and on the environment, identified a number of concerns arising from the CCA. One of these concerns was a group of issues related to the chemistry of actinide elements, especially plutonium, under conditions that are relevant for assessment of the long term behavior of the WIPP facility (Chaturvedi et al., 1997).

The EPA published its technical review of the DOE WIPP source term program and modeling in October, 1997. EEG then asked Dr. V. Oversby to evaluate the DOE modeling efforts and the EPA review. That review, which was communicated to EEG as a letter report, identified many of the issues that were subsequently summarized in a letter from EEG to EPA (December 31, 1997, contained as Appendix 8.3 in EEG-68, 1998). Detailed reviews of the DOE Chemical Conditions Model, the actinide solubility calculations, and the SOTERM appendix to the CCA were also provided to EEG by Dr. Oversby, and are contained in Appendix 8.4a of EEG-68. Dr. Oversby's review of the EPA technical support document issued in 1997 was reproduced on pages 45-56 of EEG-68.

A meeting was held in Albuquerque, NM, on February 20, 1998, so that EEG, Dr. Oversby, and scientists from Sandia National Laboratories and their contractors could discuss EEG's concerns. Following that meeting, DOE sent a response to the EEG comments to the WIPP Program Manager at

EPA, with a copy to EEG (letter dated February 24, 1998). The relevant technical content of EEG's concerns and DOE responses are discussed in the following section.

On May 18, 1998, EPA issued its final rule certifying the WIPP facility and identifying the requirement for a five-year recertification cycle (EPA, 1998a). EPA also published a separate document that responded to comments that had been received during the public comment period for WIPP certification. The details of the EPA responses, where they are relevant to plutonium chemistry issues, are discussed in the next section.

PLUTONIUM CHEMISTRY ISSUES

There are four major factors that will determine the effective solubility of plutonium in the WIPP environment. These are (1) the redox conditions, (2) the brine composition, (3) the availability of ligands through degradation of the waste, and (4) the effects of slow kinetics of reaction due to lack of lability of species (i.e., persistence of metastable species). The brine composition, itself, will be affected by the persistence of metastable reaction products, especially those formed by backfill materials, such as MgO.

The DOE CCA attempted to predict the solubility of plutonium and other actinides under WIPP conditions by using a chemical modeling code, FMT. The FMT code was developed at Sandia National Laboratory for use in performance assessment exercises for the WIPP project. FMT used the Pitzer formalism for dealing with the corrections to activity of solution species in high ionic strength brines. DOE chose to use an oxidation state analogy for dealing with actinide chemistry. This analogy treated each possible oxidation state in isolation and did not allow for the different oxidation states of a single element to interact in response to other conditions in the reacting system. For the actinide (IV) oxidation state, DOE used thorium data in the model calculations and claimed that this was conservative because thorium would be more soluble than plutonium in the (IV) oxidation state.

In her review of the DOE CCA, Oversby (1997) discussed each of the factors listed above and recommended experimental work to provide data needed to improve the modeling efforts and also recommended improvements to the modeling itself. In particular, a sensitivity analysis to determine the effects of uncertainties in the solubility measurements and stability constants used in the FMT data base as well as the uncertainties in the Pitzer parameters used to estimate activity coefficients in brines was recommended. The appendices to the Oversby (1997) report discussed in detail issues that arose through the review of the DOE CCA and selected supporting documents. These reviews and the review by Oversby of the EPA technical review of the DOE WIPP source term program and modeling led EEG to conclude that the following items were of concern (cited from EEG-68):

"1. The FMT model is unique to WIPP. EEG found that the model predicts differences for actinide sulfate and carbonate solubilities that can not be explained by chemistry, thus leaving the reliability of the calculations suspect. The unexpected results need to be explained or the model needs to be re-examined for possible problems with the code.

2. Rather than use an extensive plutonium data base, the FMT predictions relied on thermodynamic data for other elements and an oxidation state analogy argument. EEG recommends that the calculations be performed using data for plutonium and the values for solubility and complex ion formation contained in the peer-reviewed data compilation by OECD/NEA.

3. EEG agrees with EPA's documentation of the shortcomings of the solubility uncertainty ranges advanced by DOE. However, EPA has accepted the ranges as adequate based on a weak argument. EEG recommends that the uncertainty range needs to be determined with the appropriate plutonium data.

4. In the solubility calculations, the CCA inappropriately discounts the role of organic ligands on plutonium solubility by arguing that EDTA is the strongest complexing agent. But citrate forms very strong complexes with actinides in the +4 oxidation state and very weak complexes with other cations. Thus, the solubility of a stable plutonium-citrate complex in individual waste containers needs to be calculated.

5. There are serious unanswered questions about the impact of magnesium oxide backfill on the solubility of the actinides. It is proposed that magnesium oxide will reduce the solubility of the actinides by controlling pH. But, it is not known how long the early reaction product, nesquehonite, will persist. The FMT model calculates that the presence of nesquehonite drives the solubility of the +4 actinides, such as plutonium, higher than in the no backfill case. This requires further investigation."

The comments by Oversby concerning the EPA "Technical Support Document 194.24: EPA's Evaluation of DOE's Actinide Source-Term" as reproduced in EEG-68 (1998) included

> "The EPA evaluation of expected redox states, solubility, and speciation of actinides under WIPP disposal conditions was very narrow in its scope. In general, only the references cited by DOE and the work done by the DOE contractors was discussed. The evaluation would be considerably strengthened, and might reach different conclusions, if relevant results published in the open literature of studies conducted by other scientists were discussed.
>
> The EPA has limited their review of the DOE solubility calculations to an exercise in which EPA used the Sandia computers, codes, and databases to determine whether they could get the same numerical values for results if they tried to duplicate the work done by DOE. It would have been very surprising if they had failed to find agreement under those conditions. A more reasonable evaluation would require a comparison of the results of calculations using a code that is used more widely in the modeling community with those obtained by the Sandia FMT code.
>
> There has been no evaluation by EPA of the thermodynamic properties data used in the database for the solubility calculations. There has been no attempt by EPA to assess the degree to which the calculations might represent the conditions expected for WIPP disposal. Both of these tasks are needed in order to determine whether the DOE calculations have any validity.
>
> In evaluation of the effect of organic ligands on the mobilization of actinides, EPA considers only the case of homogeneous equilibrium, in which the entire actinide inventory in the repository is well-mixed with a very large volume of brine that inundates the repository. This is an unrealistic and non-conservative model for evaluation of the effect of organics. In addition, EPA bases their evaluation of the ability of organics to mobilize actinides on an analysis that only considers EDTA. While this analysis gives the correct result for the importance of EDTA, it does not speak to the issue of the importance of citrate in the waste and its ability to increase the mobility of Pu."

The specific comments by Oversby on each section of the EPA evaluation of DOE's source term were also reproduced in EEG-68 (1998). This EEG report was submitted to EPA as comments on the proposed rule. The limitations of the oxidation state analogy were discussed, and it was noted

> "The oxidation states expected by DOE for Pu in the WIPP repository are III and IV. Any Pu(V) formed is expected to be rapidly reduced by iron. EPA concurs with this conclusion; however, Pu(V) is observed as a long-lived transient in many laboratory experiments. Pu(V) may be formed as a result of radiolysis reactions in the brines and while its total abundance in the repository is likely to be low, it might be significant as a transient species in some waste containers. The release scenarios considered important for WIPP are those involving human intrusion, with drilling through the repository to a brine-containing formation below the repository. Upwelling of brine from this lower layer through the repository might allow rapid transport of brines containing some Pu(V) to the surface."

The issue of heterogeneity in the repository was raised by Oversby (cited in EEG-68, 1998) during a discussion of section 7 of EPA's evaluation document, which concerns the effect of complex ion formation on enhancement of solubility. EPA concluded that organic ligands would not increase actinide mobility. In their analysis, EPA used the same assumption used by DOE that the system could be modeled assuming homogeneous equilibrium of brine and actinides. In her discussion of this point, Oversby stated

> "both DOE and EPA assumed that the actinides would be evenly distributed throughout the repository and that the brines would be well-mixed and have a uniform composition throughout the repository. This is unlikely to be the case and is certainly not appropriate for evaluation of the development of dissolved actinides inside a partially destroyed waste container, a scenario that is important with respect to assessment of human intrusion consequences."

> and

> "To model the behavior of Pu with citrate, we must also consider heterogeneous equilibria for organic complexation with the actinides. The main difficulty arises because the Pu in the waste is probably located in the same drums as the citrate, which is the dominant organic ligand. This is because these wastes arise from chemical separations of Pu and are not the type of waste described in the general descriptions of TRU waste as contaminated equipment, clothing, etc. To get an accurate estimate of the effect of organic ligands on Pu solubility, one must calculate the concentration of Pu as citrate complex inside a waste drum that has been breached, but can still provide a hindrance to mixing of the brine inside the drum with a larger pool of brine outside the drum. This will give a high concentration of Pu in solution as the citrate complex. Other ions will not compete with Pu sufficiently to prevent complex formation because the stability for (IV) actinide complexation – as shown by the stability constant for Th(IV) on p. 39 of the SOTERM appendix – is orders of magnitude larger than that for other ion complexes with citrate."

EEG met with EPA WIPP project staff on December 10, 1997, in Albuquerque, NM to discuss some of EEG's concerns with the draft EPA rule on WIPP. A summary of the issues discussed, as well as a summary of several other issues that had been raised previously, was sent to Mr. Frank Marcinowski (EPA Radiation Protection Division, Washington, DC) by letter dated December 31, 1997, with copies to other interested parties including DOE and the EPA Docket for WIPP (A-93-02). DOE arranged a meeting between Sandia staff working on the WIPP project, their contractors, EEG, and their consultants in Albuquerque on February 20, 1998, to discuss the actinide solubility issues in detail. Following that meeting, DOE responded to the comments contained in the EEG letter of December 31, 1997, by letter dated February 24, 1998, to Ms. Mary Kruger (WIPP Program Manager for EPA). The DOE responses contained in the February 24, 1998, letter did not address the substance of the solubility issues raised by EEG in their letter of December 31, 1997, and at the meeting held on February 20, 1998. DOE restated their previously published arguments. An independent observer at the meeting, Prof. R. C. Ewing, who had been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant, sent written comments to EEG after the meeting. These comments, contained in a letter dated February 22, 1998, to Mr. Robert H. Neill, Director of EEG,

highlighted the need for further experimental work on actinide chemistry and the need to go beyond the simple Th analog model to actual experiments with plutonium. Prof. Ewing stated in particular (letter reproduced in EEG-68, 1998) that "The project is still not in a position to present and discuss models of the longer term evolution of the chemistry of the WIPP system."

The DOE response concerning the use of the Th(IV) analog for plutonium(IV) behavior did not address the central issue in actinide chemistry where multiple oxidation states are possible. It is the lability between the various oxidation states and the details of the chemical environment that determine the formal oxidation state of actinides such as Pu, U, and Np. It is also well known that the solution species oxidation state may be different from that in the solid (e.g., U(VI) in solutions in contact with air and with uranium(IV) dioxide solid). The use of Th(IV) to model Pu(IV) behavior has the intrinsic limitation that Th can only exist in geologic systems as Th(IV). This point will be discussed in more detail in the section concerning recent experimental results obtained by workers outside the WIPP project.

The other issue raised by EEG was that of homogeneous versus heterogeneous equilibria. DOE maintained the assumption of homogeneity for the chemical conditions in the repository, which was a consequence of mixing of chemical species through the solution phase in a fully saturated brine environment. Further, the CCA stated that no chemical microenvironments that influence the chemical environment are expected to persist, which can be viewed as a tacit recognition that microenvironments could have an impact on the overall chemical environment. The assumption of a repository fully saturated with brine is not the expected condition for the WIPP repository, to which access of brine is expected to be limited under normal geologic conditions.

When EPA issued its Final Rule concerning the certification of the WIPP facility, they also published a response-to-comments document (EPA 1998b) to provide a record of the comments received and their disposition. The EPA response to issues related to actinide solubility (other than those associated with MgO) are discussed below. Of the issues that EEG raised, EPA discussed the effect of organic ligands on solubility (Issue V, pp. 6-60 to 6-66), the oxidation state analogy (Issue Y, pp. 6-71 to 6-76), solubility uncertainty range problems (Issue Z, pp. 6-76 to 6-80), and plutonium (VI) (Issue CC, pp. 6-84 to 6-86). In addition, EPA discussed issues raised that involved the long-term behavior of the MgO

backfill and its effects on brine chemistry and actinide solubility, as well as issues related to the FMT computer code and its data base. In this report, we will focus on the issues related to actinide solubility for which we have recommendations for further experimental work and limit our discussion of issues related specifically to the MgO backfill and the FMT computer code.

We recognize that MgO is a key component of the repository chemistry, but there are limited data from the WIPP Source Term Program for MgO Backfill. At the time the STTP experiments were begun in 1995, other material, such as bentonite, was considered a leading backfill candidate and was included in the test matrix. The idea to use MgO as the only backfill in the WIPP repository came as a late development in the application process (NEA/ IAEA, 1997). MgO was added to only one of the liter-scale tests in the Source Term Program in February 1997. The waste was a pyrochemical salt immersed in brine and maintained under 60 bar of CO_2 pressure. Prior to adding MgO, that container had exhibited a very high actinide solubility. The results of the MgO addition are discussed briefly in this report; the observations do not change the recommendations for further experimental work to resolve the identified actinide solubility issues. Moreover, the behavior of MgO in brines has far-reaching implications and merits its own investigation.

As discussed above, concerns about the use of the FMT computer code have been documented previously. Rather than revisit that conceptual model and computer code, this report promotes two approaches to address our documented concerns. First, directly tackle the issue of model uncertainty by generating experimental data for plutonium in brines of appropriate chemical composition. Second, starting with a peer-reviewed database for plutonium and uranium, adjust solution species activity as a function of ionic strength using Specific Ion Interaction Theory, rather than try to determine Pitzer parameters, which can have very large uncertainties for highly charged species, for use in the FMT code. Details can be found in the final section of this report.

In their discussion of the effect of organic ligands, EPA echoed the argument DOE had used in the CCA. They assumed a well-mixed, homogeneous repository and calculated average concentrations of organics and actinides in the case of brine saturation of the repository. They also cited a calculation

showing that EDTA formed the strongest complexes of all organic ligands with actinide(IV) species and, further, that other divalent cations in the brine, such as Fe(II) and Ni(II) would be able to use up most of the EDTA, so there would not be much left for the actinides. EPA then concluded that since EDTA formed the strongest An(IV) complexes and would not significantly increase An(IV) mobility, then no other organic complex would either. This reasoning does not accommodate the observation that citrate forms strong complexes with An(IV) cations and not with divalent cations, so there is no competitive reaction that eliminates citrate from the brine. We believe that the issue of the effect of organic ligands, especially citrate, on the mobility of plutonium under the Human Intrusion scenario remains unresolved. We will, therefore, recommend in the final section of this report some simple experiments that could resolve the issue.

The EPA addressed comments on the limitations of the use of Th(IV) as an analog for Pu(IV) chemistry by confining their comments to the behavior of the An(IV) oxidation state. They did not consider the possibility for Pu(IV) in the solid waste forms to coexist with a Pu(V) or Pu(VI) solution species in the brines. Work conducted during the last two years, both within and outside the WIPP program, indicates that dealing with the Pu(IV) oxidation state in isolation is an oversimplification of the actual chemistry of Pu-bearing systems (see next two sections). We believe that the issue of description of the behavior of Pu under scenarios relevant to Human Intrusion at WIPP must be addressed by relevant experiments using Pu-bearing wastes that are representative of those that may be disposed of at WIPP. Particular attention should be paid to experiments using wastes such as pyrochemical salts, since these may contain high percentages of Pu as discussed in the section on the WIPP Source Term Program. An outline of some appropriate experiments is given in the final section of this report.

The uncertainty range used by DOE for solubility estimates attracted several criticisms that were discussed in the EPA response to comments. (Note: In the Response to Comments document EPA used the terms “Am(VI)” and “Am(IV)”. These should be An(VI) and An(IV), where An stands for any actinide element.) EPA stated (p. 6-77) that in the uncertainty analysis “solubility data for actinides in the +6 oxidation state were not used. This decision seems appropriate in view of the fact that the CCA source term was unable to develop a solubility model for U(VI), which is the only hexavalent

actinide species expected under WIPP conditions." In view of recent experimental results that strengthen the possibilities that Pu(VI) as well as U(VI) may be important species in WIPP-related brines, EPA is urged to reconsider this position. Exclusion of An(IV) data from the uncertainty analysis because of difficulties that DOE contractors had with extrapolation of such data, including (apparently) data for Th(IV), exposes the weakness of both the uncertainty estimates for An(IV) species as well as the potential unreliability of the solubility calculations for these species. For these reasons, we recommend that appropriate experiments be conducted that can give an estimate of the range of solution concentrations and solution species identities that might exist in WIPP brines under potential Human Intrusion scenario conditions.

The EPA response to comments concerning the potential for Pu(V) or Pu(VI) to exist in the WIPP repository was two-fold. They argued first that the cited experimental observations were not relevant to WIPP because of the use of non-representative experimental conditions. They further argued that the presence of organic ligands in the repository would make Pu(V) and Pu(VI) unstable relative to Pu(IV). In light of recent experimental results (discussed below), this issue needs to be revisited. Work to address the possibility for Pu(V) and Pu(VI) species to exist in WIPP brines under conditions relevant to the Human Intrusion scenario and the effects of organic ligands are discussed in the final section of this report.

WIPP SOURCE-TERM PROGRAM

The DOE has sponsored an "Actinide Source-Term Waste Test Program" (STTP), conducted at the Los Alamos National Laboratory. The purpose of this testing program is to provide quantitative measurements of the mobile actinide concentrations in WIPP brines in continual contact with actual Contact-Handled Transuranic (CH-TRU) wastes. Additional objectives of the tests are to determine the influence of chemical additives on actinide concentrations and speciation and to measure the rate of gas generation in the test systems. Results from this test program, which included the detection of Pu(V) and Pu(VI) in four liter-scale containers, were presented to EEG at a briefing in Albuquerque on November 23, 1999, by Robert Villarreal (Los Alamos). EEG was given copies of viewgraphs used at the presentation; these viewgraph materials form the basis of the discussion that follows. Eight of the viewgraphs referenced in this report are reproduced in the Appendix.

This report was drafted prior to meetings held with EEG, EPA and DOE in April and June, 2000. The author has had an opportunity to ask the principal investigator of the STTP tests clarifying questions about the materials from the November meeting and has chosen to limit specific discussion to those materials. The discussions and materials presented at the subsequent meetings in April and June do not change the interpretations and recommendations in this report. Moreover, we have also been advised that some of the references cited in these subsequent discussions are in various stages of review prior to publication. For example, the material presented by L. Brush at the April and June meetings included reference to the work of Clark et al., LANL, for which the text is not available because it is still in internal review at Los Alamos. Other investigators at Los Alamos are also in the process of completing their analyses of the complex STTP systems. It would be more appropriate to reserve comment on the materials presented at the April and June meetings until after that work has been finalized, published, and is available for a detailed review.

The STTP program includes 15 drum-scale tests with heterogeneous wastes (combustibles, lab wastes, metals, etc.), 33 liter-scale tests with homogeneous wastes (sludges, cemented or solidified wastes,

pyrochemical salts), and 6 pressurized liter-scale tests with homogeneous wastes. We will focus discussion on the 33 liter-scale tests, of which 22 used Brine A (Salado formation brine) and 11 used Castile brine. [Note: In the Human Intrusion scenario, it is penetration of the Castile anhydrite formation accompanied by penetration of a brine pocket in the Castile that would cause brine to be brought up to the repository level and, through interaction with waste, potentially lead to releases of radioactivity at the surface via transport up the drill hole. For this scenario, it is actinide concentrations in the Castile formation brines that are most important, rather than the Salado formation brines.] All STTP tests were conducted in titanium vessels. The tests began in 1995 and had been running for at least 4 years at the time of the presentation in November, 1999.

The Castile brine, which is most relevant for the Human Intrusion scenario is a sodium chloride brine with minor sulfate and borate and small amounts of magnesium and bromine. The Salado Brine is a magnesium chloride brine with lesser amounts of sodium and potassium chloride and minor amounts of sulfate, borate, calcium, bicarbonate, and bromide.

Liter-scale tests L01-L12 were conducted with Portland Cement and solidified aqueous inorganic sludges. In addition to these components, L04-L06 were pressurized to 60 bars with carbon dioxide, and L10-L12 contained ^{241}Am as an additive. The Am would increase the total radioactivity in the test and enhance any effects due to radiolysis in the solution. The concentrations of actinides in the waste were not given in the presentation materials; however, the amount of Pu present can be calculated using a “Theoretical Pu Conc. (ng/ml)” value. We estimate a total Pu amount in the tests ranging from 30 to 200 mg in 0.25 to 1.3 kg of waste, implying a Pu concentration in the vicinity of 0.01%.

The results from non-pressurized tests with Portland cement showed that Th concentrations were uniformly less than 1 ppb in the brines, U concentration ranged from < 1 ppb to 8 ppb with no obvious correlation with test conditions, Pu had 2 results at <0.5 ppb, one at 0.5 ppb, 3 results at 1.0 to 1.1 ppb, one at 1.6 ppb, one at 7.8 ppb and one at 11.3 ppb. The two highest results for Pu occurred in the tests with Am added conducted in Salado brine, and may be due to enhanced solubility resulting from oxidation of Pu by radiolysis products and higher solubility of Pu at the pH found in tests with

Salado as compared to Castile brines (pH 9 versus pH 13). Results for Np concentration were erratic, with 6 values less than 1 ppb and one each at 9, 33, and 264 ppb. All of the high values for Np were found in Salado brine tests; however, since 3 other, nominally equivalent tests (except for a higher solution to solid ratio in the tests with high Np concentrations) gave results of < 1 ppb, it is hard to postulate a rational explanation for the results. Am concentrations were uniformly less than 1 ppb, even in the tests where Am was added to the system.

Th concentrations in the non-pressurized Portland cement tests were, with one exception, lower to much lower than concentrations found for U and Pu. This provides strong evidence that Th "solubility" is unlikely to be a realistic or conservative analog for Pu and U under WIPP disposal conditions.

Tests in Portland cement with carbon dioxide pressure at 60 bars gave much higher concentrations of U and Pu, but Th concentrations remained below 10 ppb. The U results showed extreme variability between the 3 different pressurized tests, but were more consistent within a given test as a function of time. Results for U were 9 to 15 ppm for the L04 test (i.e., about 10,000 times higher than Th concentrations for the same test), 0.3 to 0.7 ppm for the L05 test, and 3 to 5 ppm for the L06 test. Concentrations of Pu were also higher in the pressurized tests as compared with the non-pressurized tests, but the results were very erratic. The L04 test showed values for Pu starting at about 2 ppb and climbing (exponentially) to 255 ppb. The L05 test started at 2 ppb, reached 184 ppb by the second reported result, and then dropped to 5 to 25 ppb (in random order) for the last 4 sampling periods. The L06 test started at 25 ppb, peaked at 638 ppb at the 4th sampling period, and ended at 319 ppb at the 7th sampling. Results for Np were, with two exceptions, lower than those for U and Pu, and showed similar irregularities in solution concentration with time as did Pu. Again, the results show that Th concentrations are lower to very much lower than Np, Pu, and U concentrations and argue strongly against the use of Th as an analog for the chemistry of Np, Pu, and U.

Envirostone is a mixture of 80 to 90 % calcium sulfate with 10 to 20 % melamine-formaldehyde resin and about 0.1 % ammonium chloride. Results of tests using aqueous wastes absorbed onto Envirostone gave high to very high solution concentrations for U, very erratic concentrations for Pu, ranging from low (2.4 ppb) to high (1013 ppb), and also very erratic results for Np and Th, but with concentrations for

those elements generally less than found for Pu. There was no obvious pattern to the results. Tests using cemented wastes with Envirostone showed lower concentrations, probably due to the beneficial effects of the cement. Uranium concentrations, however, were still rather high, ranging from 0.3 to 0.8 ppm.

Fifteen tests were conducted using pyrochemical salts. These tests are particularly important since the amount of plutonium in pyrochemical salts is not a trivial fraction of the WIPP inventory and may be present in high concentrations in some cases. Estimates for the total amount of plutonium to be disposed of at the WIPP range between 13 and 16 metric tons (see, for example, Table 4, page 14 in Rechard et al., 2000). The pyrochemical salt residues to be sent from Rocky Flats contain about 1 metric ton of plutonium contained in 14.9 metric tons of pyrochemical salts (U.S. DOE, 1998a). The material falls into three categories; (1) electrorefining salts, (2) molten salt extraction salts, and (3) low-Pu and high-Pu-concentration direct oxide reduction salts. In two records of decision, the DOE has stated its intentions to;

1) repackage the low plutonium concentration direct oxide reduction salt residues to prepare them for disposal at WIPP (U.S. DOE, 1998b),
2) repackage the molten salt extraction/electrorefining salt residues, with possible blending at Rocky Flats to get below the 10 percent plutonium safeguards termination limit, for disposal at WIPP (U.S. DOE, 1999),
3) pyro-oxidize as much of the high plutonium concentration direct oxide reduction salt residues as possible, and probably all, and then repackage, with possible blending at Rocky Flats to get below the 10 percent plutonium safeguards termination limit, for disposal at WIPP (U.S. DOE, 1999).

Because the Pu concentration in pyrochemical salts that might be sent from Rocky Flats to WIPP could be very high, we believe that particular importance should be placed on the results of STTP tests that used pyrochemical salts. In the STTP series, all tests with pyrochemical salts were done using 2 parts liquid to 1 part solid, with the exception of tests using $Ca(OH)_2$ with chelating agents, which used a 3:1

ratio. General observations are that Pu concentrations for these tests are very much higher than for tests with the other waste types. The highest solution concentration of Pu was reported for the L27 test with Castile brine and pyrochemical salts (no additives) and was 30 ppm Pu. This is 30,000 times higher than for tests using cemented sludges. It should also be noted that the pH of this test was 11.1, so the result is far from easy to explain using equilibrium concentration calculations for Pu(IV) in Castile brine. Results for other actinides are also higher in these tests as compared to cemented waste tests, but the differences are no where near as large as for Pu. [Note: The tests using pyrochemical salts began in May, 1995, and (at least for some tests) continued through November, 1998, or later.]

Tests using pyrochemical salts in brine equilibrated with bentonite (L31-L33) produced lower Pu concentrations (0.12 to 0.21 ppm), but higher U concentrations in 2 cases. [The higher U may be due to complexation with carbonate released from the bentonite on equilibration with the brine. No chemical composition of the solution analyzed is given, so this hypothesis cannot be checked with the presently available information.]

Tests using pyrochemical salts with $Ca(OH)_2$ and chelating agents (L34-L36) gave relatively low concentrations of Pu in the Salado brine (0.1 ppm at pH 8.3 and 0.01 ppm at 8.8), but a very high concentration in the Castile brine (4.6 ppm at pH 11.3). Concentrations of Np, on the other hand, were higher in the Salado brine (1.25 ppm at pH 8.3 and 0.15 ppm at pH 8.8) than in the Castile (0.02 ppm at pH 11.3). Concentrations of Pu in these tests were always higher than those of Th and, in the case of the Castile brine, the difference was a factor of 65.

Tests of pyrochemical salts with Am added were also conducted. It is not clear whether these tests contained other additives. These tests gave the lowest concentrations of Th, Np, and U of all the pyrochemical salt tests, and among the lowest results for Pu. The highest Pu concentration was, again, in the Castile brine, with Pu = 1.25 ppm at pH 9.5. There is certainly no evidence from these tests of an enhancement of solubility due to radiolysis effects.

Tests of pyrochemical salts in brines pressurized with carbon dioxide to 60 bars (L28-L30) have generally high concentrations of Pu and U, and of Np in Salado brine. The highest Pu concentrations were found in one of two nominally identical tests in Salado brine. Test L28 had [Pu] = 6 ppm at the first reported point, while test L29 had [Pu] = 0.16 ppm at the same point. Similar differences persisted through the test period. Tests with Castile brine pressurized with carbon dioxide resulted in Pu concentrations of 1 to 2 ppm, uranium concentrations of 3 to 8 ppm, while Th concentrations were very much lower (0.01 to 0.05 ppm). Magnesium oxide was added to test L28 after the 4th sampling period, which had a [Pu] = 91 ppm. The next sampling period showed a lower Pu result (18 ppm), but subsequent samplings showed increasing Pu concentrations, rising to 42 ppm at the next sampling and then to 174 and 198 ppm at the two final reported sampling points.

For some tests that had high Pu concentrations, spectroscopy was done to determine speciation of the Pu. Pu(VI) was positively identified in tests L26 and L28. The Pu(VI) appears to have been present after the MgO was added to L-28. Pu(VI) is suspected, but was not positively identified, in test L27. All of these tests contained fresh Fe mesh and were found to have hydrogen gas in the head space over the brine, indicating actively reducing conditions. This is clear evidence that thermodynamic equilibrium has not been achieved in these systems, and should raise a cautionary flag concerning the use of equilibrium thermodynamic calculations to predict the potential for releases under the dynamic conditions expected for the Human Intrusion scenario.

The drum scale tests produced relatively low actinide concentrations in the brines, except for the tests using combustible materials with chelating agents. The results for D07-D09 were [Pu] between 1 and 3 ppm, [Th] between 7 and 14 ppm, [U] between 12 and 17 ppm, and [Np] between 15 and 18 ppm. In this case, concentrations of Th are higher than those of Pu and similar to those of U and Np. The chelating agents used were acetamide, acetate, citrate, oxalate, and thiocyanate at 160 ppm each. Similar tests without chelating agents gave [Pu] between 1.7 and 2.0 ppb, indicating that the presence of chelating agents increased the solubility of Pu by a factor of about 1000. This is in direct contradiction to the claims made by DOE in the CCA that chelating agents would not increase the solubility of actinides (U.S. DOE, 1996, SOTERM.5).

Some general conclusions can be drawn from the results of the STTP tests.

1. Solution concentrations of actinides in the presence of pyrochemical salts can be rather high.

2. Thorium is not a conservative analog for the behavior of Pu.

3. Concentrations of Pu in brines increase if chelating agents are present.

4. The addition of MgO to a test that contained a high concentration of both Pu(VI) and carbon dioxide gas did not produce a long-term decrease in plutonium concentration in the test system, provided a level of Pu(VI) that could be detected by spectroscopy, and appeared to raise questions about the arguments that MgO would lower plutonium solubility.

5. It can not be assumed that equilibrium will be achieved rapidly, even in the relatively homogeneous conditions that pertained in the STTP tests.

6. Pu(VI) can exist, at least as a long-term transient species, in brines that are held under actively reducing conditions (i.e., redox conditions buffered by the corrosion of metallic iron to produce hydrogen gas).

ADVANCES IN PLUTONIUM AND URANIUM CHEMISTRY OUTSIDE THE WIPP PROGRAM

The chemistry of plutonium has been studied most extensively because of the use of plutonium in nuclear weapons. Research has focused on the production of weapons grade Pu in nuclear reactors, separation of the Pu from the much larger quantity of matrix (target) material, and subsequent purification of the Pu prior to conversion to metal. Studies of plutonium chemistry under conditions that are relevant for natural, geologic systems have been conducted only in recent years. Some of the results obtained at high temperatures or in acid solutions that constitute the "conventional wisdom" concerning plutonium chemistry may not be appropriate to the near neutral pH conditions and lower temperatures that pertain under geologic disposal conditions.

Studies of the reaction of plutonium dioxide with water by Haschke et al. (2000) have recently shown that a PuO_{2+x} phase is formed, where $x \leq 0.27$. This phase, which is analogous to the UO_{2+x} phase, where $x \leq 0.25$, has been synthesized at temperatures between 25°C and 350°C. The PuO_{2+x} phase decomposed in vacuum if heated at 500°C. As x increases from 0 to 0.27, the lattice constant of the solid phase of plutonium increases only very slightly. Given the difficulty of working with highly radioactive solids, it is not surprising that earlier work failed to identify the PuO_{2+x} phase by x-ray diffraction analysis. One method of identification that is simple, once one has the proof of existence of the PuO_{2+x} phase, is color. High-fired Pu-oxide, which is the stoichiometric PuO_2 phase, is yellow to buff colored, while the PuO_{2+x} phase has an intense green color. Haschke et al. (2000) also note that the existence of the PuO_{2+x} phase also explains one of the "mysteries" of Pu chemistry. It has long been known that so-called low-fired oxides, which are Pu-oxides prepared at relatively low temperatures, dissolved quite easily, while high-fired oxides that had been heated to high temperatures were nearly impossible to dissolve. Haschke et al. (2000) postulate that the PuO_{2+x} phase releases Pu(VI) to solution, especially in cases where aqueous solutions are in contact with air, which can continue the formation of the PuO_{2+x} phase. This accounts for the predominant species in water coexisting with PuO_2 being Pu(VI) for solutions where air is present. Given the difficulties of eliminating all oxygen from

experimental systems, it may be that some PuO_{2+x} phase is always present, either due to residual air in the experimental system or to autoradiolysis of the plutonium oxide.

The mechanisms discussed by Haschke et al. (2000) for the formation and dissolution of PuO_{2+x} would also be possible in brines. Thus, the observations of Pu(VI) in the STTP tests may be explained by the presence of the PuO_{2+x} phase in these tests. For tests with lower concentrations of Pu than those for the pyrochemical salts, the chemical form of the plutonium may not be Pu-oxide, but rather some other chemical compound in which Pu exists as a trace constituent. In that case, one might expect quite different behavior, dominated by the chemistry of the host phase in which Pu plays a minor role.

Until recently, positive identification of Pu(V) and Pu(VI) in solution has been limited to cases where the concentration of Pu has been rather high. During the last few years Stefan Röllin, working at Studsvik Nuclear (Nyköping, Sweden) has developed a method for chemical separation by ion chromatography as a pretreatment to analysis by ICP-MS. The method was developed for use with spent fuel leaching experiments conducted at Studsvik for the Swedish Nuclear Fuel and Waste Management Company (SKB) (Röllin, 1999). The ion chromatography step provided clear separation of Pu(III), Pu(IV), Pu(V) and Pu(VI); the ICP-MS detection of the separated valence states of plutonium can then be done at sub-ppb levels. If valence states are changed during the ion chromatography column separation step, the peak positions and shapes are affected. This allows detection of alterations of the chemistry due to analytical methods to be detected. This method, if adapted for use with WIPP brines, could be used to determine speciation of Pu in all of the STTP tests.

Advances have been made in the understanding of uranium chemistry under reducing conditions, both in solutions of low ionic strength and in brines. Experiments were conducted at Finland's VTT Technical Research Centre by Kaija Ollila as part of the European Union's Nuclear Fission Safety R&D Programme (1996-1998) under the project "Source term for performance assessment of spent fuel as a waste form". Ollila (1999) found that the solubility of uranium dioxide under reducing conditions (Eh -0.2 to -0.3 V) and pH about 9 was approximately 1×10^{-9} M, both in saline solutions without carbonate present and in dilute solutions with 0.003 M bicarbonate content. Experiments in dilute

groundwater solutions were conducted both from oversaturation and from undersaturation. Results obtained from oversaturation gave [U] in solution that was about a factor of 2 lower than that obtained by dissolution of uranium dioxide pellets that most likely had an outer layer of UO_{2+x} phase. Speciation of U in solution showed that for experiments conducted under anaerobic, but not actively reducing, conditions the U was present as U(VI) to the extent of 85% or more. For actively reducing conditions, the speciation was 60-70% U(VI) in dilute groundwaters and 20-37% U(VI) in saline solutions. The "solubility" measured for anaerobic conditions was one order of magnitude higher than that measured for actively reducing conditions.

Ollila (1999) concluded that the presence of U(VI) in solution, caused by dissolution of the outer layer of the uranium dioxide pellets, had more effect on the measured "solubility" than the chemistry of the solutions used in the experiments (dilute synthetic groundwater or saline solution). Ollila's results, showing the limited effect of salinity on solubility for uranium dioxide, suggest that the WIPP project should reconsider the use of the OECD/NEA data bases for U and Pu and the relatively simple methods suggested in these data bases for correction of ion activities as a function of ionic strength. This would eliminate the need for Pitzer parameters for complex actinide solution species and eliminate a number of uncertainties in the chemical calculations used by DOE to support the performance assessment estimates for WIPP.

A CONCEPTUAL MODEL FOR PU BEHAVIOR UNDER WIPP DISPOSAL CONDITIONS

The work of Haschke et al. (2000) documenting the existence of PuO_{2+x} for $x \leq 0.27$ highlights the similarities between the chemistry of U and Pu and can be used together with the data obtained by several national high level waste disposal programs to construct a conceptual model for the behavior of Pu under WIPP disposal conditions. The PuO_{2+x} phase is not stable at temperatures above 500°C, so would not be present initially on high-fired PuO_2. It may, however, form slowly on the surface of high-fired oxides that are exposed to air atmosphere before disposal, or may form due to radiation effects even in the absence of air. We will, therefore, assume that all Pu-oxides contain some excess oxygen in their structure after disposal at WIPP.

The PuO_{2+x} phase releases Pu (VI) to solution when it is contacted with an aqueous phase, either dilute groundwater or brine. This is a direct analogy to the behavior of UO_2 solid, which forms a UO_{2+x} phase on its outer surface when exposed to an air atmosphere or to an aqueous solution that is in contact with air, and then releases U(VI) to the solution phase, even though the predominant redox state in the solid is U(IV). This behavior explains the higher than expected Pu concentrations found in SKB tests of spent fuel conducted under anaerobic or reducing conditions. Some level of PuO_{2+x} phase may be expected on any Pu-oxide in the repository, even if the general conditions are reducing through the corrosion of metallic iron. This is because the PuO_{2+x} phase could form by autoradiolysis effects in the Pu-oxide and will not encounter the general reducing conditions until it is formed. The general reducing environment may not be sufficiently powerful to reduce the PuO_{2+x} phase once it has formed. Likewise, Pu(VI) in solution may not reduce directly to Pu(IV) in solution, but may require an active surface to assist in the electron transfer operations.

The PuO_{2+x} phase would be expected to occur in pyrochemical salt wastes, where the concentration of Pu is high and the Pu would be present in relatively pure oxide form. Other waste types, such as solidified aqueous wastes, might have Pu present in dilute solid solution in a matrix of non-radioactive oxides. In this case, the predominant redox state of Pu may be Pu(IV), without any tendency to form

the higher mixed oxide phase. The conceptual model for Pu behavior in WIPP should consist, therefore, of two types of Pu-oxides: (1) waste containing rather high purity PuO_{2+x} phase as the main Pu-bearing component in the waste, and (2) waste containing low levels of Pu dispersed in a matrix that is capable of dominating the chemistry of the Pu. Type 1 wastes would be likely to release Pu(VI) directly to solution, while type 2 wastes may not.

RECOMMENDATIONS FOR FUTURE WORK TO IMPROVE PLUTONIUM RELEASE ESTIMATES AND RESOLVE OUTSTANDING ISSUES

Results of experiments and tests within the WIPP program and by other, independent research workers during the past several years have provided evidence that the issues raised by EEG during the period prior to certification of the WIPP facility have basis in fact. These issues should be addressed during recertification of the WIPP facility. To assist in planning a program to address these issues, we summarize below the original basis for EEG's concerns and a brief outline of experiments or activities that could resolve these issues.

(I) ISSUE: EFFECT OF ORGANIC LIGANDS

There are two underlying issues that are important for the consideration of organic ligands and their effect on the solubility of actinides. The first issue is whether a scenario that provides a potentially higher release from the repository has been overlooked in the analysis of "features, events, and processes" for the PA calculations. The second issue is whether the ligand chosen for the "bounding calculations" is appropriate for estimation of the largest potential effect on actinide solubilities.

The DOE and EPA assume that the repository contents are well mixed in a brine solution. The EPA response to comments states that "consideration of every possible combination of potential events for chemical mixture in specific drums would present an impossible number of hypothetical situations to represent in a performance assessment". We agree with that statement, but disagree that DOE actually performed the correct bounding calculation. The appropriate bounding calculation would use the organic ligand for which the An(IV) species have the highest ratio of stability constant as compared with other cations in solution.

The appropriate bounding calculation must also consider the type of waste that produces the largest amount of Pu and citrate together in a single waste container. Selection of this scenario should have

occurred during the required "features, events, and processes" (FEPs) analysis that is intended to identify FEPs that can have an impact on total calculated releases. The feature of Pu and citrate being collocated in a waste drum is highly probable and the penetration of such a drum during a drilling event under the human intrusion scenarios would be proportional to the potential number of such drums. Thus, the calculation could easily be included in the potential scenarios used to construct the CCDF without considering an impossibly large number of individual cases.

The DOE and EPA have assumed that the organic ligand that has the largest complexation constant with actinides, especially An(IV), will be the most important in changing solubilities of these actinides. They then calculate the competition between other cations in solution and the dissolved actinides for EDTA, the ligand with the largest An(IV) complexation constant, and conclude that almost all of the EDTA will be bound to transition metal ions and, therefore, will not affect An(IV) solubility.

The conclusion for EDTA is correct. The $\log_{10}$ of the stability constant for EDTA with Th(IV) at 0.3 molal NaCl is given in SOTERM as 15.56, while that for Fe(II) is given as 14.3 at 0.1 molal total ionic strength. While the slight differences in ionic strength will give some changes in the complex stabilities, it is the ratio of the stability constants that is important. The affinity of Th(IV) for EDTA is only a bit over 10 times that of Fe(II) for EDTA. Since the concentration of dissolved Fe(II) in the WIPP site is expected to be much higher than that of Th(IV), the EDTA will be consumed in complexing the Fe(II) and will not have a large effect on the Th(IV) solubility.

The conclusion reached by DOE and EPA that complexation will not have a significant effect on An(IV) solubility if the ligand is citrate should be revisited in light of the following observations. The $\log_{10}$ of the stability constant for Th(IV) with citrate at 0.1 molal NaCl is given in SOTERM at 9.31, while that for Fe(II) with citrate is given as 4.4 at 0.1 molal total ionic strength. The ratio of the strength of the complex ions in this case is approximately 100,000 in favor of Th(IV). It should be noted that the EEG assessment of the potential importance of organic ligands in enhancing the mobility of actinides is in keeping with the experimental results found recently under the DOE STTP testing with organic ligands

present. Moreover, the WIPP inventory contains 140 metric tons of citrate in comparison to 23 kg of EDTA.

It is also important to remember that for the calculation of competition for organic ligands between two cations in solution, it is only the concentrations of the cations in solution that comes into play – not the total amount of the element present in the repository. If we consider the competition between Th(IV) and Fe(II) for citrate ligands, it cannot be assumed that there is a readily available supply of soluble Fe(II) to replace any ions that are tied up in complexes. The bulk of the iron in the repository will be there as elemental Fe and must first oxidize before it can dissolve.

ISSUE RESOLUTION

Some rather simple experiments involving Th(IV), citrate, EDTA, Ca^{2+} and one or more transition metals dissolved in brine could demonstrate the extent of complexation of each type of cation in the presence of other cations. Additional experiments using Pu(IV) as the starting actinide could also address the lability of Pu oxidation states in the presence of organic ligands. The results of these experiments could be used in tests of the validity of calculations of solution equilibria done by the chemical modeling codes used in performance assessment calculations.

(II) ISSUE: USE OF TH(IV) AS AN ANALOG FOR U(IV) AND PU(IV) CHEMISTRY

The key issue is whether the chemistry of an element that can assume many different valence states can be adequately represented by considering the solution state of each possible valence state in isolation. The possibility of self-oxidation of an actinide element through the effects of radiolysis induced in the environment is particularly important in this respect.

EPA states that "A peer review panel of scientists found that the use of solubility data for Am(III) solids for representing Pu(III) and solubility data for Th(IV) solids for representing Pu(IV) was a reasonable approach" (p. 6-69 in EPA Response to comments). This position contrasts with that taken by a

National Research Council review team, who stated in their report (Appendix E, p. 129) "Although the oxidation state model (the assumption that the chemistry of a given oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviations from the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy." (NRC, 1996).

The solubility of freshly prepared Th(IV) amorphous hydrous oxide in NaCl and $MgCl_2$ brines has been shown to be higher than that of the equivalent U(IV) amorphous hydrous oxide under conditions of equal hydrogen ion concentration (Rai et al., 1997). The issue for solubility in the WIPP case is whether the U species in solution will be (IV) and whether the Pu species in solution will be Pu(IV). In order to measure the "solubility" of amorphous U(IV), extreme precautions had to be taken to avoid oxidation of the U from (IV) to (VI). The experimental systems included metallic iron powder (325 mesh) and 70 mg/l $EuCl_2$ (approximately 3×10^{-4} moles/liter). Even with these extreme measures, some of the U solutions seemed to show evidence for the presence of U(VI). Conditions in the WIPP will include metallic iron in the form of solid waste containers. That form of iron will be much less reactive than 325 mesh Fe powder. The solid metal pieces in the WIPP will be likely to form a layer of corrosion products on their surfaces, which will further decrease their reactivity. Thus, while the precautions taken in the experiments of Rai et al. (1997) were appropriate for the purpose of determining the thermodynamic properties of the amorphous U(IV) material, the conditions used may not be appropriate for evaluation of WIPP. It is possible that under the ambient conditions at the WIPP the solubility of U in solution will be more similar to that measured by other scientist for amorphous U(IV) solids, where less extreme measures were taken to ensure extremely reducing and reactive conditions.

For plutonium, the use of Th(IV) to estimate the solubility of Pu(IV) solids neglects the contribution of radiolysis to the local redox conditions surrounding the waste materials. Oxidative conditions can be produced in the immediate vicinity of the Pu solids, leading to production of Pu(V) and/or Pu(VI) solution species. If there are chelating agents, such as citrate, in the waste, these will form ligands for the Pu and reduce the Pu to (IV). In the absence of chelating agents, the Pu(V) and Pu(VI) in solution

may be rather long-lived. Thus, the use of Th(IV), for which changes in oxidation state are not possible, as an analog for Pu(IV) excludes relevant chemical processes from consideration.

Rai et al. (1997) noted that "thermodynamic predictions are reliable when interpolated, but questionable when extrapolated". The use of a different chemical element (e.g., Th) to predict the chemistry of Pu in brines under WIPP conditions must be seen as an even larger extrapolation than that of estimation of expected solubilities of Pu or U in WIPP using data obtained by scientists for brines of somewhat different composition than those expected for WIPP. An indication of significant difference in solution chemistry of Th(IV) and U(IV) can be found in the large differences in treatment needed for the Pitzer parameters for U(IV) and Th(IV) in chloride media. (A large, negative β^2 value was needed for Th^{+4}-Cl^- interactions, while no such value was needed for U^{+4}-Cl^- interactions.)

The new experimental results cited above for Pu-bearing solutions and for the possible oxidation states of Pu in solids reinforce the need for experimental data for systems that contain Pu. These results also underline the dangers in using an chemical analog for Pu that does not have the same range of valance states available for responding to changes in environmental conditions.

ISSUE RESOLUTION

This issue could be resolved if appropriate experiments were done using U and Pu at redox conditions that were in the range of those possible for WIPP. A significant contribution to resolution of this issue could be made by consideration of the published experimental results of U and Pu studies – including studies of leaching of spent nuclear fuel and radioactive waste glasses – that have been conducted in brines.

The specific scenario of Human Intrusion should be investigated by conducting tests using pyrochemical salt wastes together with materials to represent corroding waste drums. An injection of Castille brine together with some air to represent a sudden influx of brine via a drill hole that penetrates a brine pocket below the repository could be added to a vessel containing the pyrochemical salt wastes and the

corroding metal pieces. The evolution of the solution chemistry, especially Pu concentration and speciation, should then be monitored. Measurements using the sensitive analytical method developed by Röllin (1999) would be most informative.

(III) ISSUE: UNCERTAINTY RANGE FOR SOLUBILITY ESTIMATES

The basic issue here is whether the uncertainty in calculated solubility/solution concentrations of Pu(IV) and U(VI) and the possible existence of Pu(V) and Pu(VI) solution species can be estimated without examination of actual data for these species.

There are two components for this problem. The first is what is the uncertainty in the chemical environment in the repository. This includes, among other things, determination of the phase assemblage relevant to MgO (or other backfill material) alteration in the presence of brines and the influence of heterogeneous distribution of waste materials, such as citrate complexes in the repository. The second component is the uncertainty in the thermodynamic data and in the Pitzer parameters used in the DOE calculations and the propagation of those uncertainties through the calculations of solubility and solution concentrations.

The estimation of uncertainty in solubility estimates as described in SOTERM addressed only the second factor and only the An(III) and An(V) oxidation states. It is stated that An(VI) was not included in the uncertainty analysis because "the CCA source term was unable to develop a solubility model for U(VI), which is the only hexavalent actinide species expected under WIPP conditions." (p. 6-77, EPA Response to Comments). This position was taken by DOE despite the fact that work had been funded by WIPP on the topic of a U(VI) model, there is a peer-reviewed thermodynamic database for U species (Grenthe et al., 1992, issued by the Nuclear Energy Agency), and that the work accomplished by early 1996 under contract to WIPP appears to have at least as sound a footing as the database for Th(IV) used as a model for all An(IV) species.

The An(IV) species were eliminated from the uncertainty analysis because "The data available for the +4 model were found to have significant problems in the extrapolated regions and were thus determined to be inadequate for use in this analysis." (Quoted from a reference cited as "Bynum [1996b]" on p. 6-78 of Response to Comments. Reference not included in references under issue Z). EPA correctly notes that this position seems to be inconsistent with the statements made in SOTERM that data for Th(IV) were available and that these data were used for describing the speciation and solubility of Th(IV) in brines.

It is, basically, very difficult to justify the use of data to form a model for safety analysis purposes and then claim that the data are so poor that you cannot estimate from the data themselves the uncertainties associated with their use. It is, further, very difficult to understand how one can then claim that the uncertainty in a well-studied population – in this case the lanthanides [Ln(III)] and An(III) actinides – can be used as the value for the uncertainty for calculations of An(IV) solubility, when the An(IV) data have just been stated to have "significant problems". In most technical circles, the term "significant problems" as applied to data has a direct correspondence with "significant uncertainties".

While EPA seems to have understood the limitations of the uncertainty analysis conducted by DOE, they conclude that "the experimental procedures for determining the solublities of +IV actinide solids are not substantially different from those used to determine the solubilites of +III and +V actinide solids, hence EPA concludes that the uncertainties determined for the +III and +V actinide solids would be inclusive of those that would be obtained for the +IV actinide solids." (p. 6-79, Response to Comments). If the only problem were the attempt to use the same methods to measure solubilities, we would not have the need for statements concerning "significant problems" with data. Unfortunately, it is the solution chemistry of the An(IV) elements that presents the difficulties, not the methods used in the analysis.

The complexities of the solution chemistry carries forward into the attempts to calculate solubilities using computer models. In the case of the FMT calculations used by DOE, the use of Pitzer parameters for calculation was selected. This method requires the estimation of the Pitzer parameters from existing

experimental data on the solubility of appropriate An(IV) species. For highly charged solution species, such as are frequently encountered with the An(IV) elements, there are significant uncertainties in the estimation of the Pitzer parameters. This was encountered in speciation calculations for $Th(CO_3)_5^{-6}$, which forms under high carbon dioxide conditions. Even after "correction" of the Pitzer parameters, which lowered the calculated Th(IV) solubility by many orders of magnitude - i.e., a lot more than +1.4/-2.0 log units - the speciation calculated still indicates that the Pitzer parameters have not been correctly and completely determined for the Th(IV) systems.

ISSUE RESOLUTION

The uncertainty in Pu(IV) solubility for safety analysis of the WIPP repository can only be assessed if there are appropriate experimental data for Pu(IV) compounds in brines of appropriate compositions. If such experimental data were available, a direct analysis of expected Pu solubility under WIPP conditions could be conducted, thereby avoiding the uncertainties of extrapolations of Th(IV) data to the polyvalent element, Pu. In addition to the experiments suggested for resolution of issues in previous sections, we would recommend that DOE construct a data base for U and Pu using the published, peer-reviewed OECD/NEA U and draft, peer-reviewed Pu databases as a starting point. The method for correction of activities of solution species as a function of ionic strength recommended by the OECD/NEA review teams is much simpler to use than the Pitzer parameter method used by DOE in the CCA. Considering the small differences in measured solubility for uranium dioxide found by Ollila (1999) for solutions ranging from very dilute synthetic groundwaters to saline solutions, it would seem that the OECD/NEA method should be sufficient. Predictive calculations could then by done by DOE to simulate the conditions for the STTP tests that showed high Pu and U concentrations. This would provide information that could be used to either validate the data base used or provide guidance for improvement of the data base.

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APPENDIX

Selected Overheads from November 23, 1999 Presentation by Robert Villareal

The Actinide Source-Term Waste Test Program Experimental Results & Status

Presented to:

DOE - Carlsbad Area Office

NM Environmental Evaluation Group

Presented by: Robert Villarreal
Los Alamos National Laboratory

November 23, 1999
Albuquerque, NM

Results of Portland Cement - LS

Liter #	Nd	Th	Np	U	Pu	Am	pcH
L01	<0.5	<0.2	8.6	1.4	<0.5	<0.1	8.79
L02	< 0.8	0.6	0.5	1.9	1.0	0.6	10.22
L03	< 0.5	0.6	0.5	5.5	1.1	0.5	12.89
L07	0.9	0.6	264.0	8.3	1.0	0.5	8.72
L08	1.0	0.3	0.5	<0.3	1.6	0.3	9.13
L09	0.9	0.3	0.6	3.1	0.5	0.4	12.96
L10	1.7	0.6	33.0	7.3	11.3	0.9	8.72
L11	1.9	0.9	<0.3	1.9	7.8	0.4	9.54
L12	1.0	0.3	0.4	0.4	<0.5	0.3	12.97

Portland Cement-Pressurized

Liter #	Nd	Th	Np	U	Pu	Am	pcH
L04	<0.9	1.2	421.0	9999.0	1.6	<0.2	7.34
	<0.9	0.4	8.1	10632.0	2.0	<0.2	7.34
	<0.3	1.4	8.6	10268.0	6.0	0.2	7.32
	<0.4	1.4	12.9	11160.0	17.2	0.1	7.43
	1.1	7.9	21.0	15390.0	66.0	0.5	7.39
	<0.5	6.3	15.9	8507.0	255.0	0.7	7.34
L05	<0.9	<0.3	1.5	696.0	1.7	<0.2	7.44
	<0.9	5.1	26.3	560.7	184.0	0.8	7.12
	<0.3	3.7	15.8	398.0	75.0	0.4	7.34
	<0.4	0.6	1.7	319.0	8.5	<0.1	7.27
	<0.2	0.7	2.5	374.0	24.1	0.3	7.08
	<0.7	2.0	4.2	546.0	5.3	0.1	7.00
	<0.5	0.6	1.7	479.0	13.9	<0.1	7.35
L06	<0.9	<0.3	11.1	2934.0	25.0	<0.2	7.87
	<0.9	2.1	7.4	3680.7	23.6	<0.2	7.49
	0.5	1.5	5.7	3988.0	22.9	0.2	7.69
	<0.4	2.9	13.3	4872.0	638.0	1.4	7.70
	3.9	1.8	3.2	4477.0	57.0	0.5	7.57
	2.7	1.9	7.0	4660.0	281.0	0.9	7.81
	2.7	3.0	11.4	3675.0	319.0	0.9	7.56

Results of Envirostone - LS

Liter #	Nd	Th	Np	U	Pu	Am	pcH
L13	1.0	8.4	0.8	1367.0	13.0	0.2	6.99
L14	5.0	7.6	1.2	1019.0	32.0	0.4	6.99
L15	28.0	8.8	174.3	3454.0	165.7	1.3	6.95
L16	45.0	261.9	179.0	168.0	1013.0	2.3	7.46
L17	1.2	0.6	0.9	271.0	2.4	0.3	7.83
L18	<0.5	0.4	21.0	11027.0	4.0	0.3	7.83
L19	3.5	0.5	20.5	659.0	8.9	0.5	7.88
L20	2.0	1.2	1.1	241.0	1.6	0.3	7.60
L21	<0.5	0.2	4.9	668.0	1.2	0.1	8.10
L22	2.4	0.9	0.9	841.0	1.6	0.3	7.20
L23	<0.7	<0.4	0.7	731.0	<0.5	0.3	7.18
L24	<0.4	0.6	1.1	273.0	3.0	0.5	7.78

Envirostone = 80-90% $CaSO_4$ + 10-20% $C_4H_8N_6O.CH_2O$ (melamine-formaldehyde resin) + ~0.1% NH_4Cl

Results of Pyrochemical Salts

Liter #	Nd	Th	Np	U	Pu	Am	pcH
L25	2.8	0.6	273.0	3.5	61.0	0.6	7.86
L26	1.7	1.4	2.0	2.4	5642.0	33.0	7.88
L27	208.0	307.0	70.0	47.0	30127.0	76.0	11.07
L31	4.0	2.4	138.0	728.0	209.0	0.6	8.75
L32	5.0	1.1	73.0	400.0	171.0	0.6	8.72
L33	0.6	0.4	5.7	2.4	121.0	0.7	9.65
L34	0.6	4.8	152.0	46.0	10.0	0.4	8.77
L35	0.7	85.0	1251.0	51.0	111.0	0.8	8.30
L36	<0.5	71.0	18.0	11.0	4650.0	17.0	11.28
L37	1.1	0.6	0.6	<0.3	79.0	0.7	7.67
L38	1.0	0.6	0.5	0.7	8.3	0.3	7.84
L39	1.0	0.8	8.3	28.4	1251.0	1.9	9.48

Pyrochemical Salt-Pressurized

Liter #	Nd	Th	Np	U	Pu	Am	pcH
L28	15.4	178.0	3549.0	5230.0	5989.0	34.8	5.35
	10.1	248.0	8150.0	7099.0	8731.0	58.7	4.90
	10.3	312.0	8179.0	6290.0	15678.0	80.0	4.74
	31.5	1359.0	13931.0	10833.0	90942.0	352.0	4.48
MgO Add	8.9	151.4	350.7	106.4	18097.5	40.1	
	5.3	36.0	166.0	155.0	41822.0	69.0	
	53.8	368.0	2049.0	4520.0	174367.0	330.0	5.24
	57.0	531.0	1528.0	1550.0	197984.0	392.0	5.01
L29	<0.9	2.8	17.5	54.0	161.0	1.1	5.68
	2.1	124.0	392.0	4840.0	440.0	11.2	5.04
	3.1	183.0	882.0	6194.0	1326.0	17.6	4.98
	3.0	193.0	1127.0	6706.0	1514.0	19.8	4.77
	5.9	360.0	2838.0	6850.0	3384.0	22.0	4.88
	6.1	437.0	3666.0	6152.0	8446.0	37.0	5.06
	6.9	377.0	8179.0	9513.0	6865.0	36.6	4.73
L30	69.0	8.8	34.8	5663.0	2166.0	12.4	6.16
	20.6	46.5	143.0	8134.0	2226.0	12.6	5.94
	11.7	25.5	72.5	8069.0	1750.0	7.7	5.90
	10.2	55.0	90.0	5748.0	1297.0	4.8	6.32
	11.0	26.0	74.0	3030.0	1243.0	4.1	6.08
	1.6	8.6	31.9	4989.0	555.0	1.3	6.38
	6.0	32.9	135.0	2787.0	1011.0	2.8	6.59

Test Containers with Potential Pu(VI)

- L26 (Pyrochemical Salt Waste)

  Pu^{6+} developed slowly - Peaked - Declined

- L27 (Pyrochemical Salt Waste)

  Soluble Pu concentration increased Rapidly - Peaked - Declined
  Pu^{6+} was not identified

- L28 (Pyrochemical Salt Waste; CO_2; MgO

  Pu precipitated with MgO - Increased - Rapid Increase
  Pu^{6+} Identified

- All three test containers: Contain Fe mesh
  Have H_2 Headspace >50%

- Potential Oxidation Mechanisms
  - Basic Solution
  - H_2O_2; NaOCl

Latest Drum-Scale Results

Drum #	Nd	Th	Np	U	Pu	Am	pcH	Remarks:
D01	5.5	10.2	45.0	70.0	2.0	0.2	7.67	-
D02	2.6	16.0	54.0	260.0	1.7	0.3	7.68	-
D03	1.1	0.9	0.8	166.0	1.7	0.4	6.88	-
D04	1.5	2.6	4.4	25.0	2.1	0.3	7.39	bentonite
D05	0.7	0.7	1.2	35.8	0.8	0.3	7.11	bentonite
D06	0.7	0.4	4.8	12.5	0.8	0.1	7.17	bentonite
D07	1841.0	9598.0	17841.0	16985.0	1138.0	4.6	7.37	chelators
D08	1881.0	13916.0	15078.0	12360.0	3228.0	17.3	7.19	chelators
D09	2713.0	7012.0	16081.0	15482.0	2302.0	13.0	7.16	chelators
D10	<2.0	18.6	330.0	76.0	15.0	<0.4	7.52	NO_3/PO_4
D11	<2.0	<1.2	<0.9	17.0	<1.3	<0.4	7.47	NO_3/PO_4
D12	<2.0	<1.2	<0.9	18.0	16.0	<0.4	6.57	NO_3/PO_4
D13	31.0	<1.2	1.2	3.3	<1.3	<0.4	5.78	Fe
D14	10.0	<1.2	1.4	54.0	<1.3	<0.4	6.76	Fe
D15	<2.0	<1.2	3.5	19.0	<1.3	<0.4	7.79	Fe

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EEG-82

EVALUATION OF PROPOSED PANEL CLOSURE MODIFICATIONS AT WIPP

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December 2001

EEG-82
DOE/AL58309-82

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December 2001

FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment of New Mexico. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U. S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the compliance of the generator sites with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts associated with WIPP. Another important function of EEG is the independent on- and off-site environmental monitoring of radioactivity in air, water, and soil.

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ACKNOWLEDGMENTS

The EEG authors wish to thank Dr. John Abel and Dr. Rusty Morgan for their technical assistance on this project and timely review of the draft report. Also thanks to Ms. Jill Shortencarier for final word processing and compilation of the report and Ms. Linda Kennedy for the final edit and references check.

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ACRONYMS

AAR	Alkali aggregate reactivity
DOE	U.S. Department of Energy
EEG	Environmental Evaluation Group
EPA	U.S. Environmental Protection Agency
TRU	Transuranic
WIPP	Waste Isolation Pilot Plant

EXECUTIVE SUMMARY

A key component in the design of the WIPP repository is the installation of concrete structures as panel seals in the intake and exhaust drifts after a panel has been filled with waste containers. As noted in the EPA final rule, the panel seal closure system is intended to block brine flow between the waste panels at the WIPP. On April 17, 2001, the DOE proposed seven modifications to the EPA concerning the design of the panel closure system.

EPA approval of these modifications is necessary since the details of the panel design are specified in EPA's final rule as a condition for WIPP certification. However, the EPA has not determined whether a rulemaking would be required for these proposed design modifications. On September 4, 2001, the DOE withdrew the request, noting that it would be resubmitted on a future date.

The Environmental Evaluation Group (EEG) contracted with two engineers, Dr. John Abel and Dr. Rusty Morgan, to evaluate the proposed modifications. The EEG has accepted the conclusions and recommendations from these two experts: 1) replacement of Salado Mass Concrete with a generic salt-based concrete; 2) replacement of the explosion wall with a construction wall; 3) replacement of freshwater grouting with salt-based grouting; 4) option to allow surface or underground mixing; and 5) option to allow up to one year for completion of closure. The proposed modification to allow local carbonate river rock as aggregate is acceptable pending demonstration that no problems will exist in the resulting concrete. The proposed modification to give the contractor discretion in removal of steel forms is not supported. Instead, several recommendations are made to specifically reduce the number of forms left, thereby reducing potential migration pathways.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Project, located in Southeastern New Mexico has been constructed by the U.S. Department of Energy (DOE) to provide permanent disposal of long-lived transuranic (TRU) waste from the U.S. defense activities and programs. The facility must comply with 40 CFR 191, Subpart A during the period when radioactive waste are being emplaced (operating period) and with 40 CFR 191, Subpart B and 40 CFR 194 for long-term disposal. The U.S. Environmental Protection Agency (EPA) concluded that WIPP met the requirements of 40 CFR 191 and 194 and made a Certification Decision in May 1998 (EPA 1998). The repository began receiving radioactive TRU wastes in March 1999.

The underground WIPP facility design includes eight panels for disposing of transuranic waste (see Figure 1). At the present time waste is being emplaced in Panel 1 and excavation of Panel 2 has been completed. Each panel includes seven waste disposal rooms as well as a ventilation intake drift and a ventilation exhaust drift.

A key component in the design of the WIPP repository is the installation of concrete structures as panel seals in the intake and exhaust drifts after a panel has been filled with waste containers. The panel seals are required to rectify the damage done to the natural formation by excavation and are, at best, an imperfect attempt to recapture the characteristics of the original rock (Silva and Chaturvedi 1995). As noted in the EPA final rule, the panel seal closure system is intended to block brine flow between the waste panels at the WIPP. The DOE application (DOE 1996a) identified four design options. As a specific condition of compliance, the EPA mandated the use of Option D. But the agency also determined that the use of a Salado Mass Concrete – using brine rather than fresh water – would produce concrete seal permeabilities in the repository more consistent with the values used in the DOE performance assessment (EPA 1998, 27355).

In an April 17, 2001 letter from Dr. Inés Triay to Mr. Frank Marcinowski of EPA (Appendix A), the Carlsbad Field Office (CBFO) of the DOE proposed several panel closure design

WIPP Facility and Stratigraphic Sequence

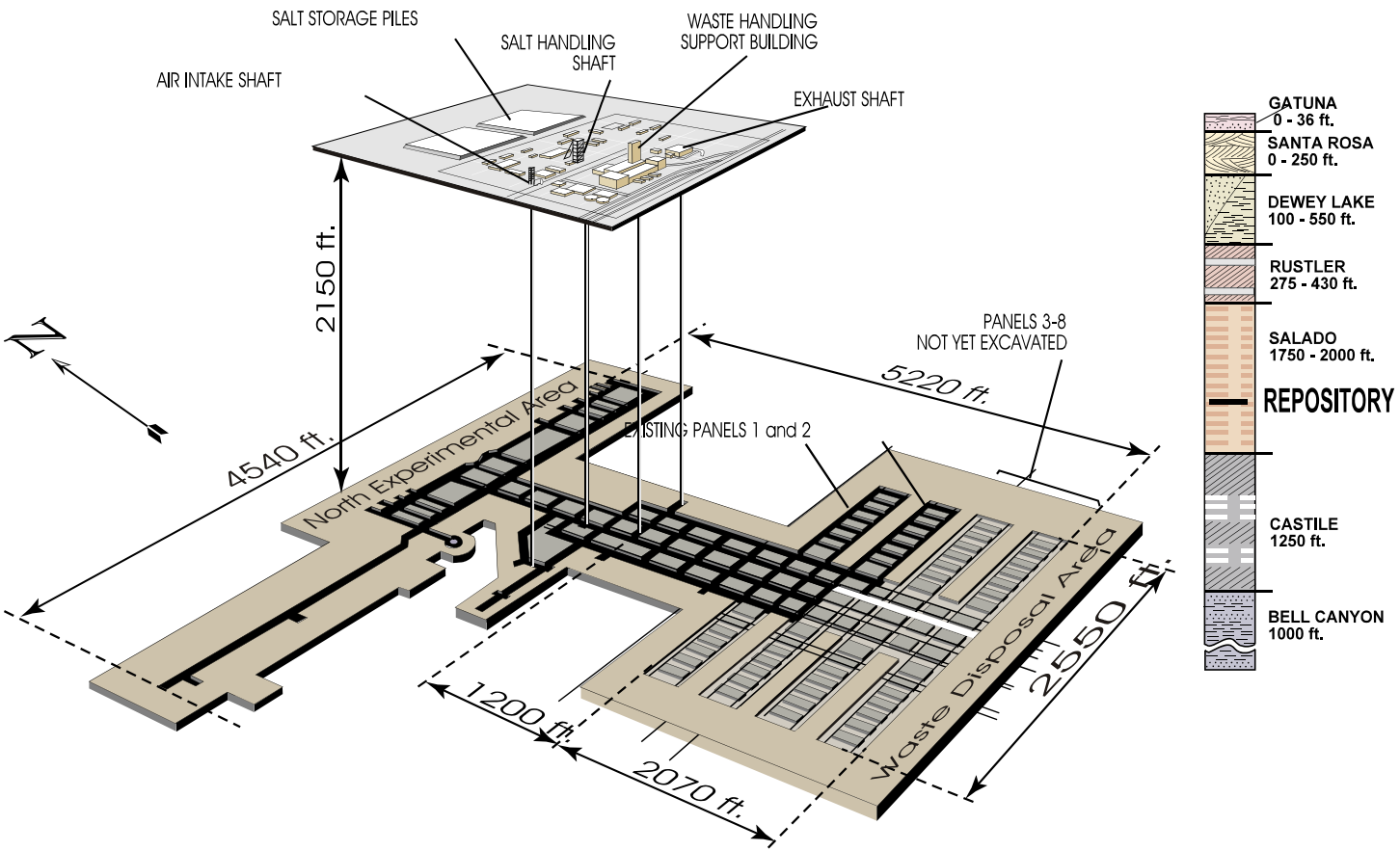

Figure 1. The WIPP facility and stratigraphic sequence. Panel 1 is currently in use. The mining of Panel 2 was completed on October 13, 2000. SOURCE: DOE, 2000.

modifications. EPA approval of the changes proposed by DOE is required since the details of the panel designs are specified in EPA's final rule as a condition for WIPP certification (EPA 1998, 27355). The EPA final rule allows for a modification to the design of the facility. Significant modification requires a rulemaking in accordance with the WIPP compliance criteria (40 CFR §§ 194.65-66). [1]

The Environmental Evaluation Group (EEG), in its role of providing technical evaluations on the design, construction, and operation of the WIPP Project, contracted with two engineers that are expert in relevant aspects of panel seal design and construction to evaluate these proposed enhancements. Dr. John F. Abel, Jr., a Mining Engineer from Golden, Colorado, evaluated the proposed enhancements concentrating on bulkhead and masonry wall stability. Dr. D. R. Morgan, a Materials Engineer from Vancouver, B.C., Canada, evaluated three of the proposed enhancements: (a) changes in proposed aggregate; (b) change to a salt-based grout; and (c) change in mass concrete requirements. The reports of Dr. Abel and Dr. Morgan are included as Appendices B and C to this report. The EEG has accepted the conclusion and recommendations contained in these two reports as summarized below.

The proposed enhancements were subsequently withdrawn from consideration by DOE in Dr. Triay's letter to Mr. Marcinowski, dated September 4, 2001 (Appendix D). This letter indicated that the topic was expected to be revisited at some time in the future. Toward this end, and because of the time spent in evaluation of the proposed modifications, EEG decided to proceed with this report on the proposed modfications.

2.0 PROPOSED PANEL CLOSURE DESIGN MODIFICATIONS

The proposed enhancements are discussed in the order used in Dr. Triay's letter of April 17, 2001. More details can be obtained from the appended reports.

---

[1] The EPA has not yet published an opinion as to whether or not the changes proposed by DOE constitute a modification.

2.1 Replace Salado Mass Concrete with a Generic Salt-based Concrete

This proposed enhancement is acceptable and probably preferable since it gives the Contractor more flexibility and responsibility in meeting performance-based objectives. However, in order to ensure adequate performance, the project specification should be written in rigorous performance-based specification language. In addition, more detail should be provided in the specification regarding permissible constituent materials for the mass concrete components such as salt and shrinkage compensating materials.

It is appropriate that the Contractor be supplied with pertinent information regarding specifications for Salado Mass Concrete. This information can provide the Contractor with a starting point for generic salt-based mixture proportioning. However, the responsibility for concrete performance would reside with the Contractor.

2.2 Replace the Explosion Wall with a Construction Wall

This proposed enhancement is acceptable. The analysis in Dr. Abel's report indicates that the 12-foot thick explosion-isolation masonry wall is not needed. The panel closure bulkhead will adequately protect against the design basis 480 psi methane explosion which cannot occur prior to (at least) 15 years after panel closure. The strength of the 4-foot thick construction-isolation masonry walls is sufficient to protect against the design pressure generated by a roof fall within the panel.

2.3 Replace Freshwater Grouting with Salt-based Grouting

EEG agrees with the proposal to replace the freshwater grout with a salt-based grout since it will counteract the tendency for dissolution (and hence void formation) of fresh water based grouts. This is apparently only a point for clarification. The design report detailing the original panel closure options (DOE 1996), specifies that if the Salado Mass Concrete is used instead of a fresh

water/plain cement concrete, the contractor shall use a salt saturated grout. This would be the case for any salt-based concrete.

2.4 Option to Allow Local Carbonate River Rock Aggregate in Lieu of Crushed Quartz

It may be possible to demonstrate that this option is acceptable. However, Dr. Morgan raised three concerns. One concern is that the coefficient of thermal expansion of the aggregate influences the coefficient of expansion of the concrete containing such aggregate. Dr. Morgan states, "Serious differences in the coefficients of thermal expansion have been reported to occur with aggregates with very low expansion, such as certain granites, limestones, and marbles." Therefore, it will be necessary to demonstrate that this is not a problem with the proposed local carbonate river rock.

A second concern is that naturally rounded gravels used in concrete production are better if they have a certain "crush-count". Dr. Morgan states, "There are certain advantages to having partially fractured faces in a sufficient percentage of the aggregate particles, including enhanced compressive, flexural and tensile strength development in the concrete made with such particles, compared to concrete made with natural rounded particles only." Consideration should be given to using aggregate with a partial crush-count if this option is chosen.

A final concern is that some carbonate aggregate is chemically reactive, resulting in deleterious expansion of the concrete. Therefore, an evaluation of the alkali aggregate reactivity (AAR) susceptibility should be conducted.

2.5 Option to Allow Surface or Underground Mixing

This proposed enhancement is acceptable. Dr. Abel concluded that either surface or underground mixing was adequate, provided the critical time between mixing and placement in the form is met. It may be easier to meet the time limitation by underground mixing. In fact, as with Proposed Enhancement I (replacement of Salado Mass Concrete with a generic salt-based

concrete), it gives the contractor more flexibility and responsibility in meeting performance based objectives.

2.6 Option to Allow Steel Forms to be Left in Place or Removed

This option is more complicated than the title implies because it also would allow the contractor the flexibility to modify the design of the bulkhead. Abel's analysis of the current design and his recommendations should be seriously considered. The current four cell design with the steel forms remaining is inferior to a monolithic single cell because there are many more potential leakage flow paths through the bulkhead. However, the size of these bulkheads exceeds that of known continuous pours. Abel recommends the following approach for dealing with this dilemma:

It is recommended that the panel bulkhead specifications:

1) provide an incentive for the contractor to minimize the number of cells (preferably to one).
2) require that each cell be filled as a continuous monolithic concrete pour,
3) require the contractor support the fluid concrete in all cells with external structures,
4) require the contractor to remove the support structures and forms between internal cells,
5) provide for a rough form surface between internal cell walls (possibly with a layer of burlap),
6) assure that some grout points are located at the roof concrete/rock salt contact and
7) prevent the use of all internal form spacer supports.

2.7 Option to Allow up to One-year for Completion of Closure in Lieu of 180 Days

This option is acceptable. Significant gas generation concentrations take much longer than one year to occur and it is preferable to do the construction properly without the pressure of an artificial deadline.

3.0 CONCLUSIONS

Of the seven proposed modifications, the EEG readily accepts five: 1) replacement of Salado Mass Concrete with a generic salt-based concrete, 2) replacement of the explosion wall with a construction wall, 3) replacement of freshwater grouting with salt-based grouting, 4) option to allow surface or underground mixing, and 5) option to allow up to one-year for completion of closure. The proposed modification to allow local carbonate river rock is acceptable pending demonstration that no problems will exist in the resulting concrete. The proposed modification to give the contractor discretion in removal of steel forms is not supported by the EEG. Instead, the EEG has proposed a number of recommendations to specifically reduce the number of forms which are left, thereby reducing potential migration pathways.

REFERENCES

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40 CFR 191 Subpart B. 2001. Environmental standards for disposal. Title 40, Protection of environment; Chapter I, Environmental Protection Agency; Code of Federal Regulations. Washington (DC): National Archives and Records Administration.

40 CFR 194. 2001. Criteria for the certification and recertification of the Waste Isolation Pilot Plant's compliance regulations. Title 40, Protection of environment; Chapter I, Environmental Protection Agency; Code of Federal Regulations. Washington (DC): National Archives and Records Administration.

Silva, Matthew; Chaturvedi, Lokesh. 1995. Need for engineered barriers at the Waste Isolation Pilot Plant. In Transactions of the American Nuclear Society, October 29- November 2, 1995. La Grange Park (IL): American Nuclear Society, TANSAO 73:123-124.

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[EPA] US Environmental Protection Agency. 1998 May 18. Criteria for the certification and recertification of the Waste Isolation Pilot Plant's compliance with 40 CFR 191 disposal regulations: certification decision; final rule. Federal Register 63(5):27354-27406.

APPENDICES

APPENDIX A

April 17, 2001 letter, Triay to Marcinowski

Department of Energy
Carlsbad Area Office
P. O. Box 3090
Carlsbad, New Mexico 88221

April 17, 2001

RECEIVED
APR 2 4 2001
ENVIRONMENTAL EVALUATION GROUP

Mr. Frank Marcinowski
Office of Radiation and Indoor Air
U.S. Environmental Protection Agency
401 M. Street, S. W.
Washington, DC 20460

Dear Mr. Marcinowski:

This purpose of this letter is to inform the Environmental Protection Agency (EPA), per the requirements of the Title 40 CFR Part 194 Final Rule, Supplementary Information, Section VIII.A.1.(b), regarding minor enhancements proposed to the panel closure construction specifications for the Waste Isolation Pilot Plant (WIPP) repository. As you are aware, the purpose of the panel closures is for the hazardous waste disposal unit closure and to control potential volatile organic compound (VOC) releases during waste management operations.

Secondarily, in terms of long-term performance, the Compliance Certification Application and the EPA final rule note that the closure system will also influence fluid connections between waste panels. The present panel closure design, as required in the EPA final rule, is extremely conservative (restricting VOC releases to levels that are more than two orders of magnitude less than the applicable standard). We previously briefed your agency regarding this subject on April 13, 2000 in Washington, DC and on December 12, 2000 in Carlsbad, NM.

The enhancements were identified during our continuing evaluation of engineering issues associated with operating the WIPP. The identified improvements include the following:

- Replace Salado Mass Concrete with a generic salt-based concrete
- Replace the Explosion Wall with a Construction Wall
- Replace freshwater grouting with salt-based grouting
- Option to allow local carbonate river rock aggregate in lieu of crushed quartz
- Option to allow surface- or underground-mixing
- Option to allow steel forms to be left in place or removed
- Option to allow up to one-year for completion of closure in lieu of 180-days

CBFO:ORC:DDM:SJJ:01-0753:UFC:5486

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The enclosed package contains a detailed description of the enhancements and our analysis of their effects. Included also are edited versions of the technical specifications for the panel closures which incorporate the enhancements. Our analysis demonstrates that these enhancements are clearly minor, will not compromise the performance of the closures, and do not impact long-term compliance. However, we believe that implementation of these enhancements would allow construction flexibility which will increase worker safety and greatly improve the constructibility of the panel closures and better ensure the closures perform as required.

If you or your staff have any questions regarding this matter, please contact Daryl Mercer at (505) 234-7452.

Sincerely,

Inés Triay

Dr. Inés R. Triay, Manager
Carlsbad Field Office

Enclosure: Panel Closure Enhancements

cc w/ enclosure:
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S. Ghose, EPA-ORIA
C. Byrum, EPA-ORIA
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M. Silva, EEG
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H. Johnson, DOE/CBFO

CBFO:ORC:DDM:SJJ:01-0753:UFC:5486

APPENDIX B

Review of Panel Closure Bulkhead Enhancements, Waste Isolation Pilot Plant

John F. Abel

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REVIEW OF PANEL CLOSURE BULKHEAD ENHANCEMENTS

WASTE ISOLATION PILOT PLANT (WIPP)

Report to

Mr. Mark Levin
Mining and Environmental Services, LLC
772 Stanley Road
Idaho Springs, CO 80452

by

John F. Abel, Jr.
Mining Engineer
Colorado P.E. 5642

July 18, 2001

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EXECUTIVE SUMMARY

As indicated on Table 1, the strength of the 4,000 psi plain concrete panel closure bulkheads (Figure 1) is sufficient to resist the 480 psi design pressure from the postulated methane explosion, during and after the planned 35-year life of the facility. The strength of the 4-ft thick construction-isolation masonry walls is sufficient to isolate the panel closure bulkhead construction areas from the design pressure generated by a panel room roof fall. The 12-ft thick explosion-isolation masonry wall, (2,500 psi) solid concrete blocks (3,500 psi) mortared with cement (2,500 psi) and hitched 6-in into the adjacent rock salt, designed for the Intake Drift and the Exhaust Drift is insufficient to resist the 480 psi methane explosion pressure (Figure 2). There is no apparent reason for an explosion-isolation wall during the six-month or one year construction of the panel closure bulkheads. Methane concentration will not increase until panel ventilation is stopped, which should only start when construction starts on the isolation walls (Figure 3).

The "Panel Closure Enhancements" refer to the main panel closure bulkheads as "The concrete monolith ---". Water retaining bulkheads (Figure 4) are normally designed and constructed as monolithic, i.e. continuous, pours without cold joints or interior form walls. The planned four cell panel closure bulkhead construction will not provide a uniform massive bulkhead but will contain three interior steel form walls. Even if a way is found to remove the three interior steel form walls, after the concrete has set in each cell, a smooth surfaced cold joint will still be present between cells. In order of declining potential effectiveness, the following panel closure bulkhead construction modifications should decrease the bulkhead leakage potential,

1) constructing truly monolithic panel closure bulkheads or
2) externally supporting the bulkhead cell forms, i.e. eliminating the form spacers, or
3) reducing the number of cells.

The size of these bulkheads, approximately 990 cu yds for the 36-ft thick Intake Drift and approximately 565 cu yd for the 26-ft thick Exhaust Drift, exceeds known continuous monolithic bulkhead pours. The Jackpot Mine west decline tapered bulkhead, approximately 20.4-ft wide by 15.5-ft high by 25-ft thick, involved only 311 cu yds of monolithic concrete pour. At West Driefontein Mine four approximately 350 cu yd monolithic sand/cement plugs were constructed in twenty days, during a mine flooding emergency.

Penetrations through a water retaining bulkhead are normally minimized, whenever possible, because they represent potential leakage flow paths through bulkheads. Essential penetrations, such as a bypass pipe, include waterstops to assure no leakage along the penetrations. The forms are externally braced. The planned 4 cell panel closure bulkhead (Figure 1) includes the use of longitudinal 1-in diameter form spacers, which also support the form wall until the concrete sets. Figure 5 indicates 55 form spacer penetrations across Cell #2 and Cell #3. Figure 6 indicates 22 form spacer penetrations across Cell #1 and Cell #4. Multiple potential flow paths are apparent across the individual cells and the steel plate and angle forms provide multiple potential connections between form spacers in adjacent cells.

The forms for water impoundment bulkheads are typically constructed of timber posts hitched into the roof and floor and braced externally by pipe columns to floor, wall and roof anchors for temporary support of the fresh concrete during construction. This would eliminate the form spacer bars. However, the bulkhead volumes will probably require at least one internal cold joint. An airtight panel closure seal may be difficult to achieve, by any method, but more so with multiple bulkhead penetrations.

The panel closure bulkheads would be classed as tapered two-way pressure bulkheads, i.e. to resist equal pressure from either side. Tapered water retaining bulkheads are typically installed to increase the shear resistance of a low-strength rock from a hydrostatic pressure acting in only one direction. If the panel closure bulkheads are airtight, closure within the panel rooms could potentially increase to 100 psi on the waste side of the bulkheads 35 years after construction (Figure 7). The two-way taper of the panel closure bulkheads was apparently designed to permit the safe excavation of the disturbed rock zones (DRZ) above and below the intake and exhaust drifts.

The strength of the concrete is critical to the strength of the panel closure bulkheads. The aggregate strength is a minor concrete strength factor which can be compensated for, if necessary, by increasing the cement in the mix. In addition, carbonate aggregate concrete probably has a lower coefficient of thermal expansion than quartz aggregate. Figure 8 indicates that concrete with quartz aggregate has a higher coefficient of expansion (approximately 6.6 millionths per °F) than either limestone aggregate concrete (approximately 3.8 millionths per °F) or dolomite aggregate concrete (approximately 5.3 millionths per °F).

Table 1. Bulkhead stability for Intake Drift (20-ft by 13-ft) and Exhaust Drift (14-ft by 12-ft)

Bulkhead or Barrier Location	Bulkhead or Barrier Type	Bulkhead Thickness (ft)	Pressure Gradient FS	Concrete/ Masonry Shear FS	Rock Salt Shear FS	Worst-Case Bending Stress FS	Best-Case Bending Stress FS
Intake Drift	Plain Concrete Bulkhead	36 31.3[1]	2.40	2.40	5.50	3.61	8.55
Exhaust Drift	Plain Concrete Bulkhead	26 21.3[1]	1.54	2.92	1.75	3.85	5.24
Intake Drift	Masonry Explosion-Isolation	12	1.03	0.63	6.37[2]	0.32	0.75
Exhaust Drift	Masonry Explosion-Isolation	12	1.03	0.77	7.68[2]	0.65	0.88
Intake Drift	Masonry Construction-Isolation[3]	4	>2300	>1450	14.6[2]	44.7	>190

Notes: [1] - Sloping face of waste disposal (pressure) side of plain concrete barrier does not provide rock salt shear resistance from the force developed by 480 psi factored design explosion pressure applied to barrier face. The rock salt shear path was therefore reduced. The bond strength between the concrete and the rock salt was conservatively assumed to be negligible. [2] - Hitched 6 inches into roof, ribs and floor rock salt. [3] - Pressure from roof fall in central part of nearest panel room.

Figure 1. Exhaust drift longitudinal cross section through panel closure bulkhead

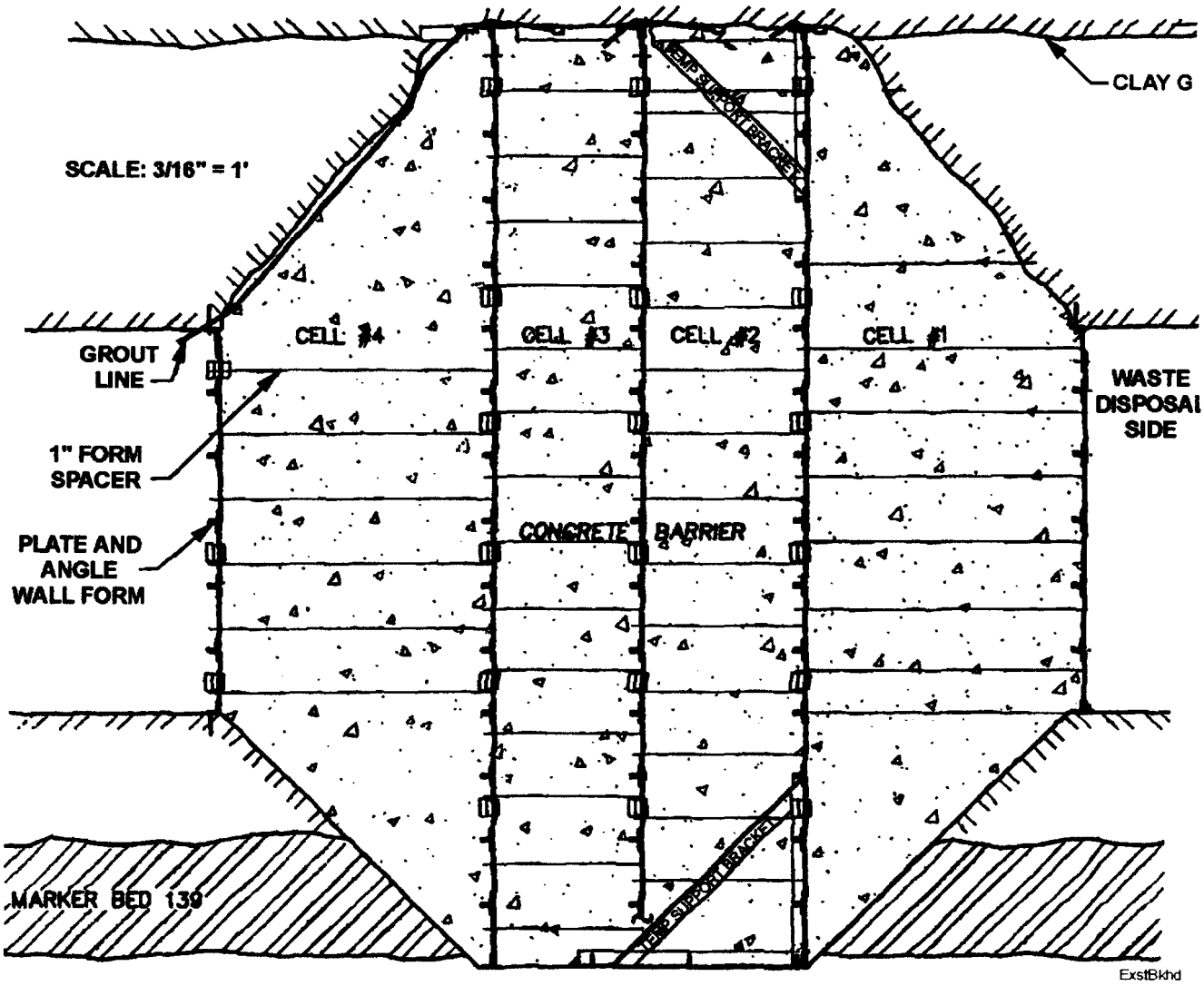

Figure 2. Explosion-isolation masonry wall bulkhead

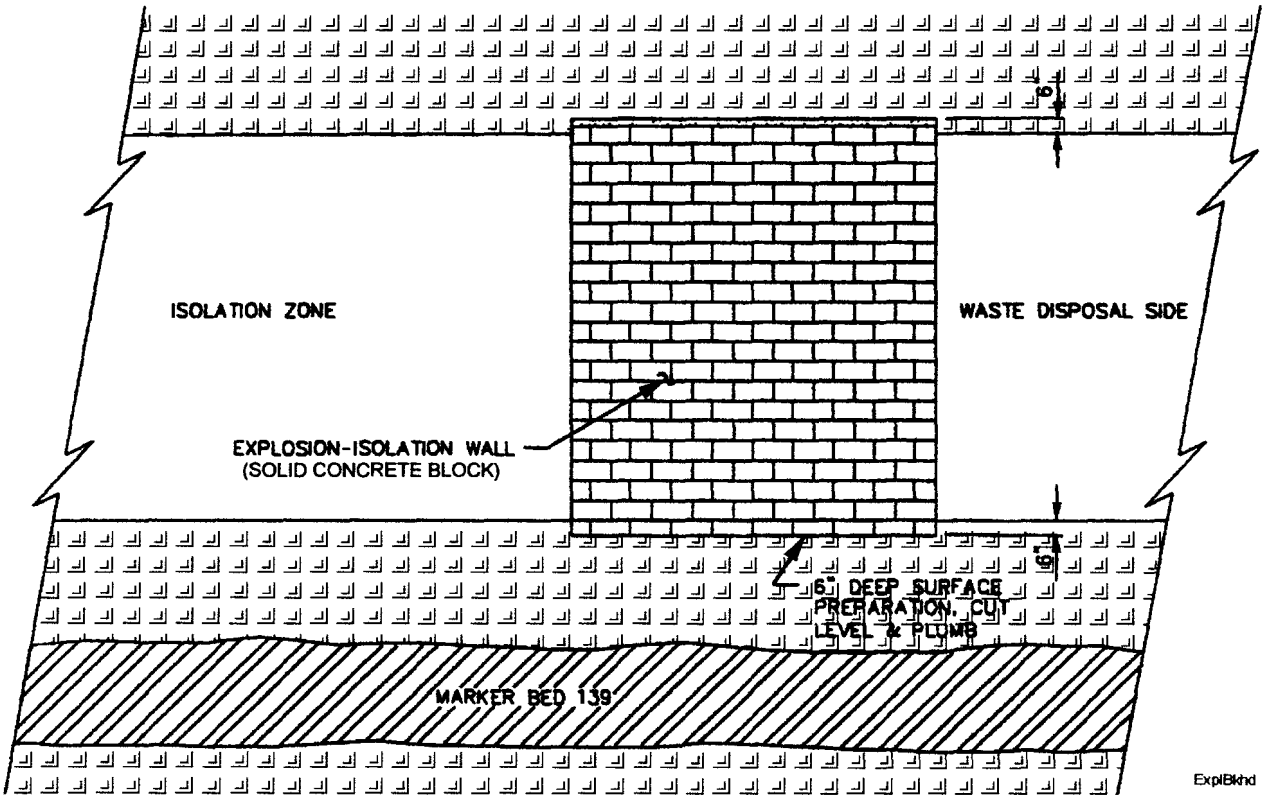

Figure 3. Methane concentration in waste panel over time

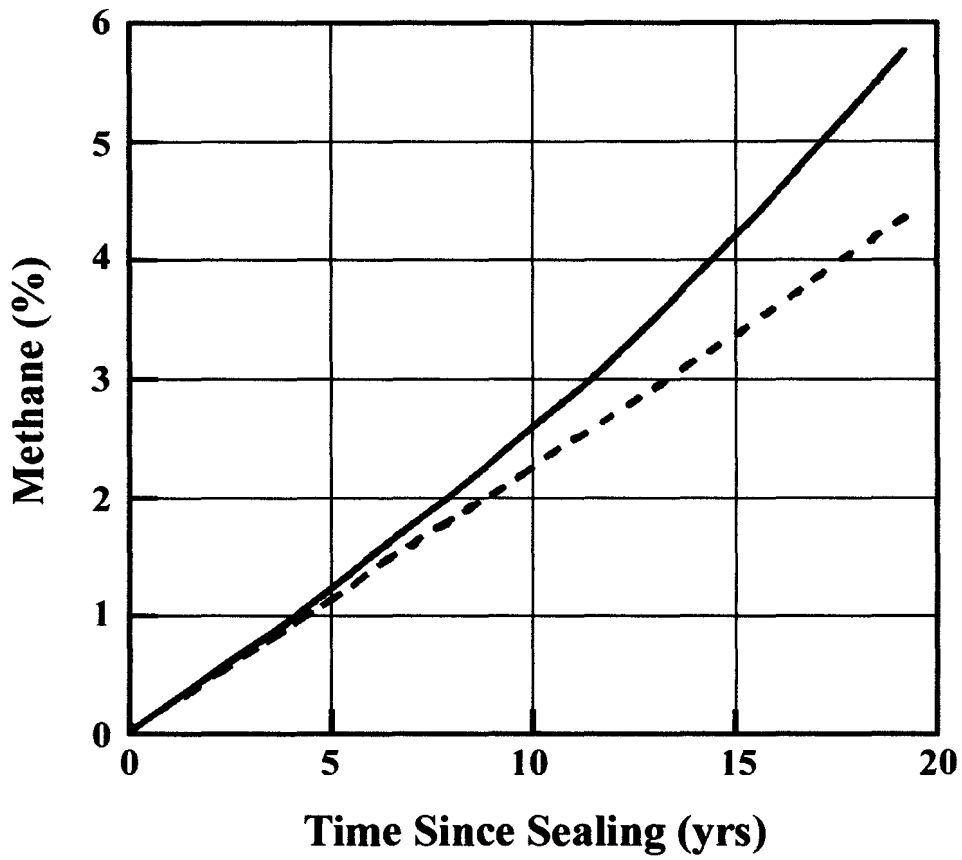

— With Closure 0.1 Mole per drum per year
-- Without Closure

Methane concentration in waste panel over time

(modified from Dykes, et. al., 1997)

MthnTime

Figure 4. Water impoundment bulkhead types

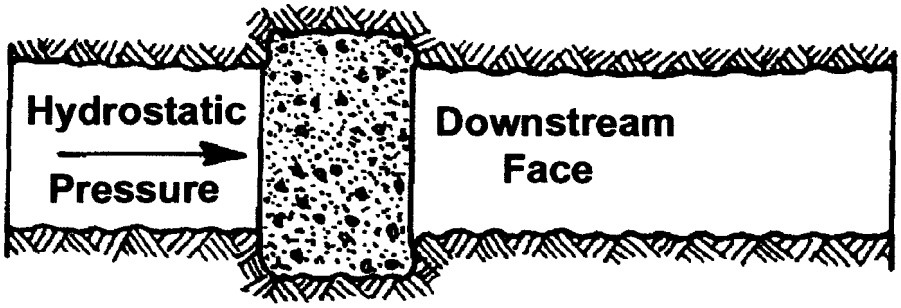

Slab keyed into walls

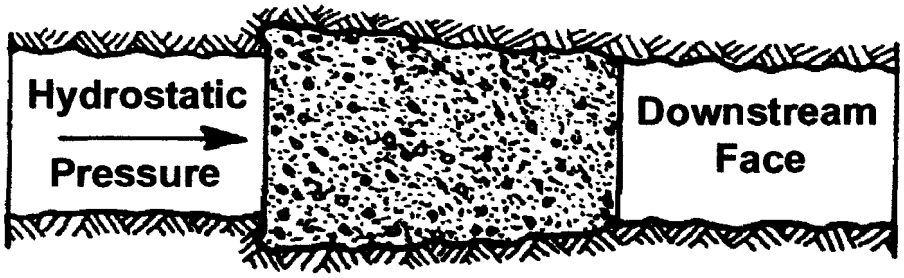

Taper plug

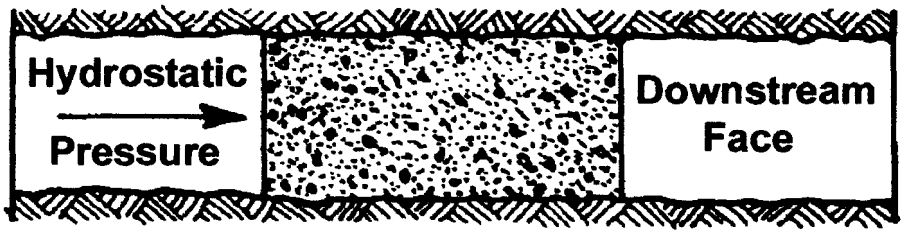

Parallel plug

(Adapted from Garrett & Campbell Pitt, 1958) Blkhtyps

Figure 5. Intake drift lateral cross section through center of closure bulkhead

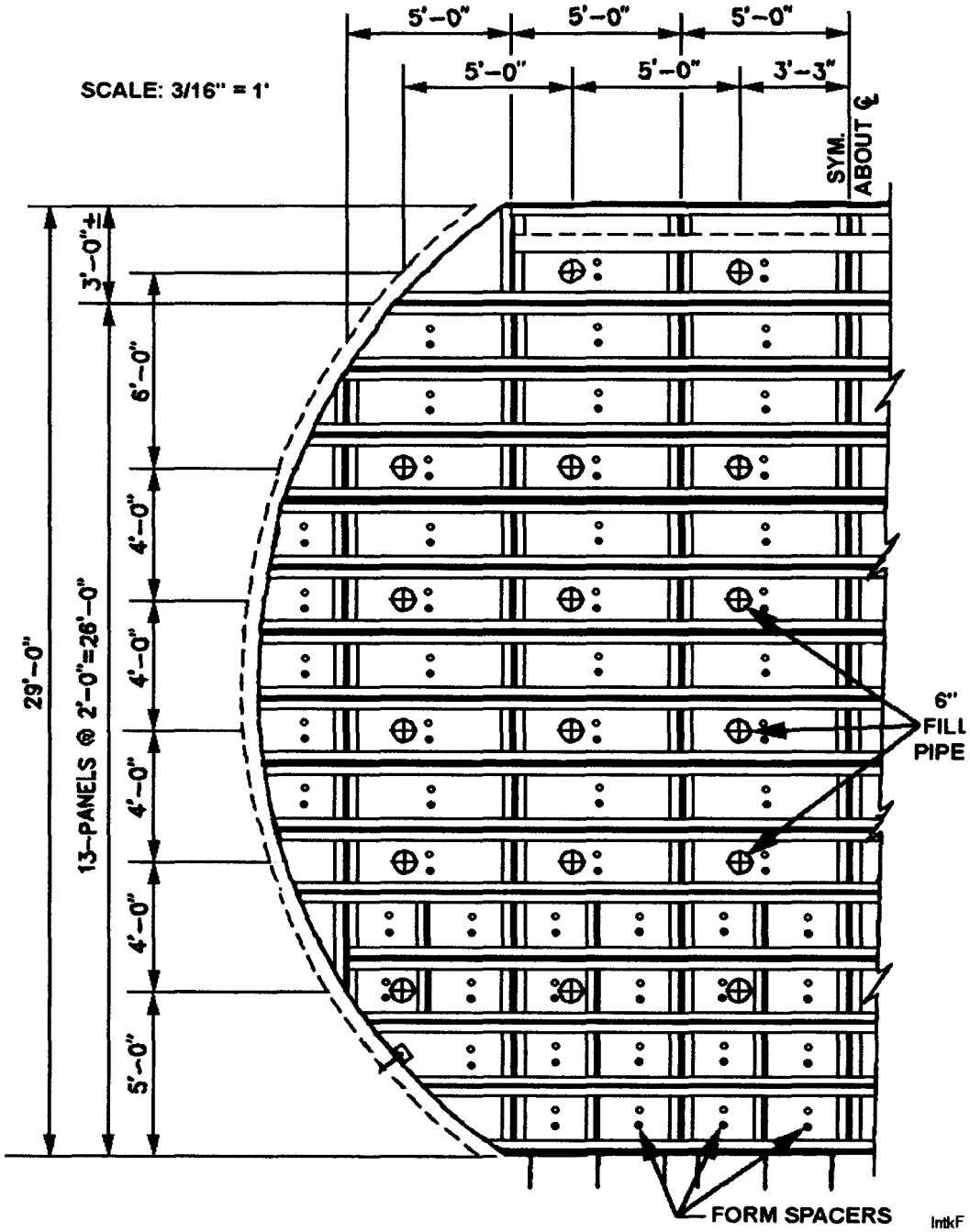

Figure 6. Intake drift lateral cross section inside panel closure bulkhead face

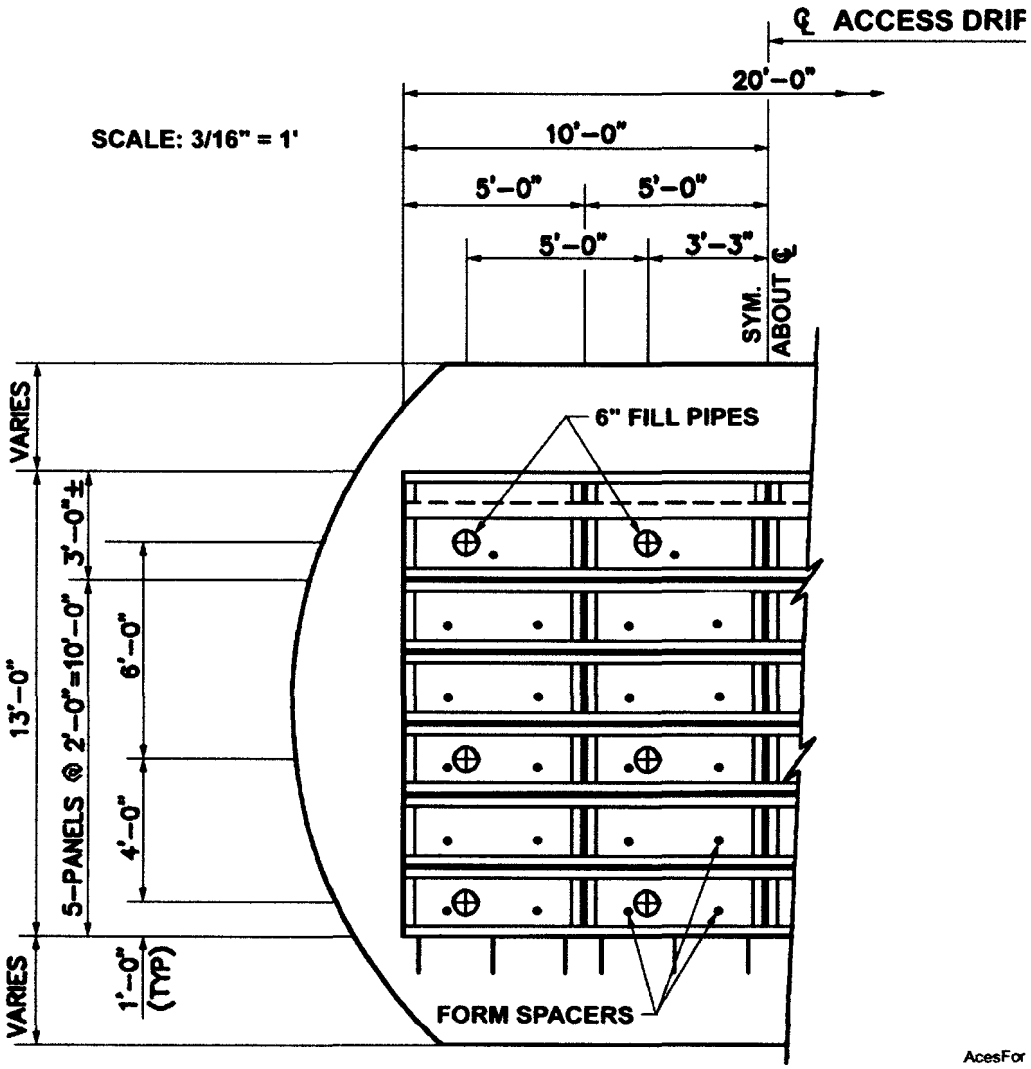

Figure 7. Pressure buildup from panel closure after panel closure bulkhead construction

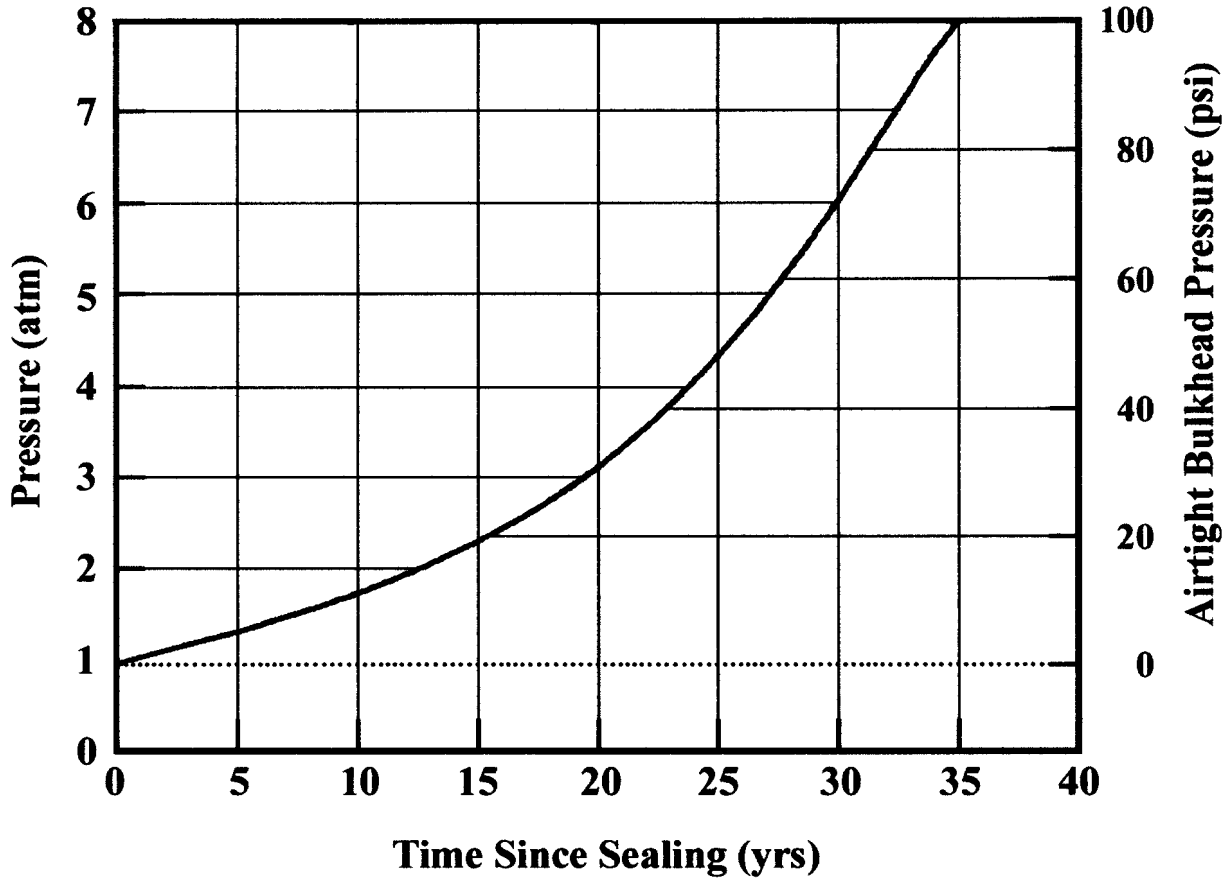

Pressure buildup in a panel after closure
(modified from Dykes, et. al., 1997)

PanlPres

Figure 8. Thermal coefficients of expansion of neat cements, mortars and concretes

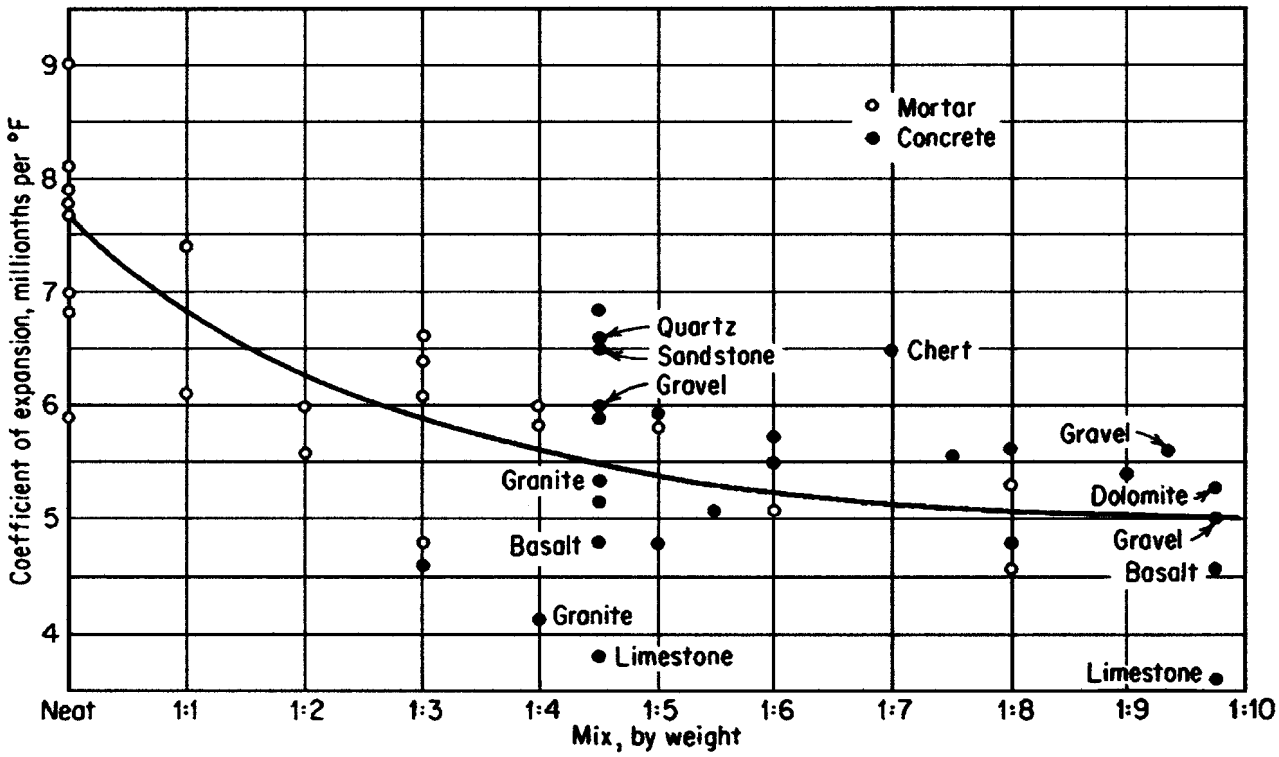

Fig. 12.8. Thermal coefficients of expansion of neat cements, mortars, and concretes. (*From U.S. Bureau of Reclamation* [106].)

TempExpn

INTRODUCTION

This report was prepared as directed by Matthew K. Silva of the Environmental Evaluation Group and Mark Levin of Mining and Environmental Services LLC for the purpose of reviewing the proposed Panel Closure Enhancements to the panel closure system area bulkheads and isolation walls, shown on Figure 9. The original optional designs for the panel closure systems are presented on Figure 10. The proposed enhancements to the Panel Closure System are described in the Compliance Certification Application (CCA). This review is specifically directed at evaluating the ability of the enhanced panel closure bulkheads and walls to provide an equivalent, or improved, panel closure. The specific enhancements proposed and reviewed are:

1) replacing the 12-ft thick explosion-isolation wall with the 4-ft construction-isolation wall,

2) allowing the use of a generic salt-based concrete in lieu of Salado-based concrete,

3) allowing the use of local carbonate river rock aggregate in lieu of crushed quartz aggregate,

4) allowing either surface or underground mixing of the concrete,

5) allowing flexibility in the bulkhead forming practices,

6) replacing freshwater grout with salt-based grout and

7) extending the construction period from 180 days to up to one year.

Item 1) relates to the necessity for and ability of the 12-ft thick explosion-isolation masonry wall to protect the workers constructing the panel bulkheads from the design methane explosion pressure. Items 2), 3), 4), 6) and 7) relate primarily to the resulting strength of the concrete in the panel closure bulkheads, over the minimum operational period of 35 years. Item 5) relates to the ability of the resulting flexibly formed panel closure bulkheads to resist both short term methane explosion pressure and long term panel closure-induced gas pressure and to prevent long term brine flow from the panels.

Figure 9. Location of panel closure system areas

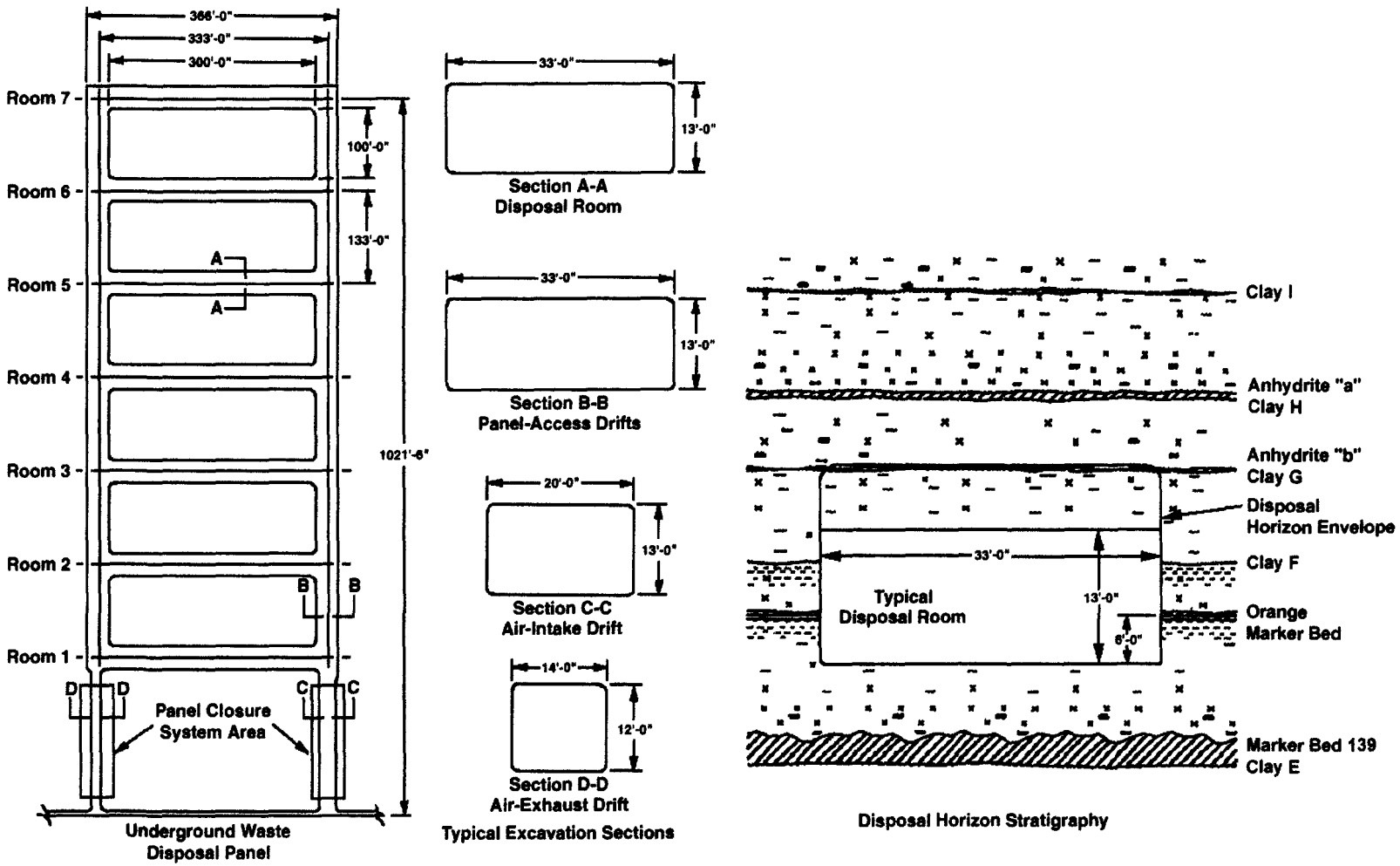

Note: Figure is not to scale. All dimensions shown are nominal.

Location of panel closure system areas (from DOE/WIPP-96-2150)

WPBlkhd2

Figure 10. Optional designs for panel closure systems

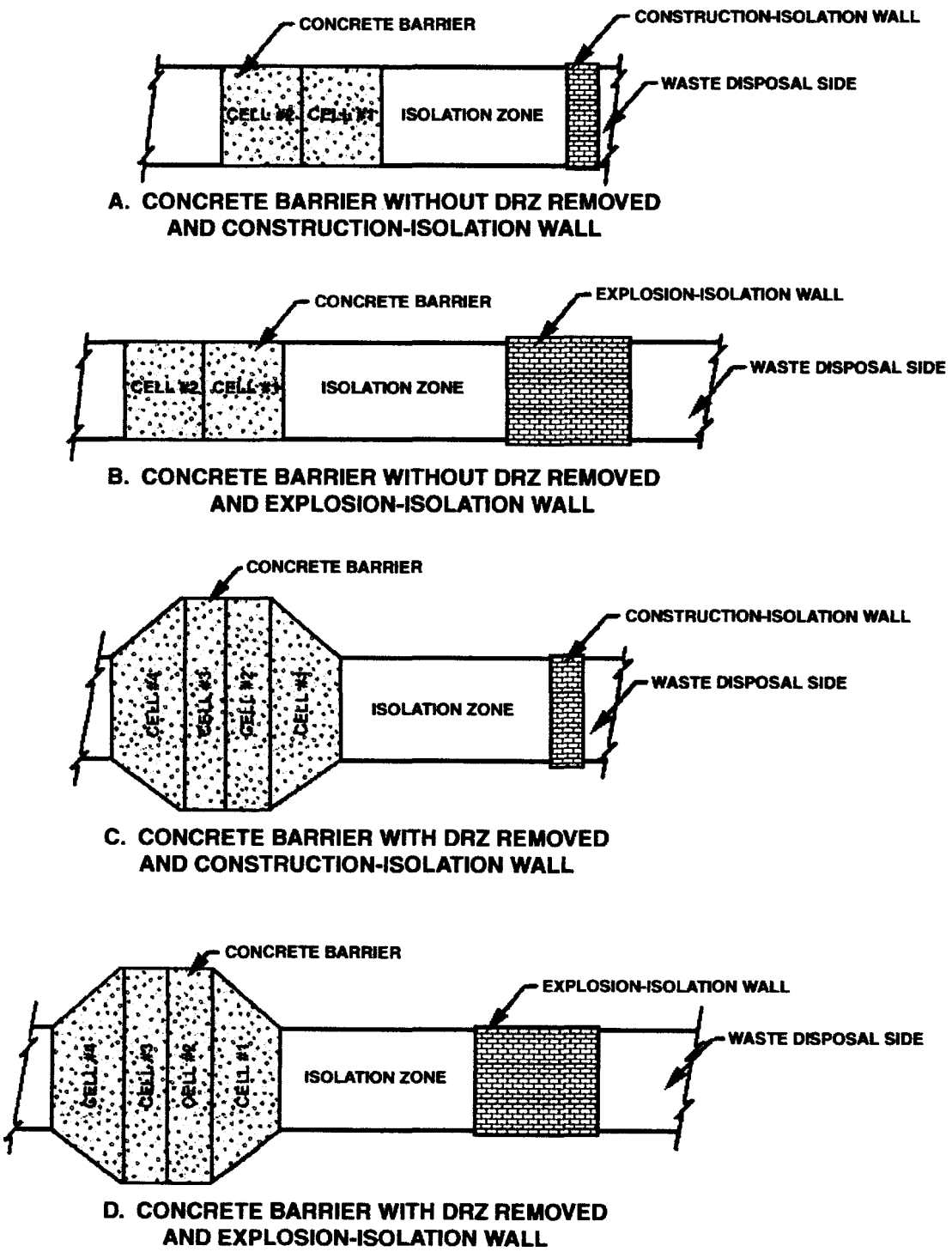

Optional designs for panel closure systems

(modified from DOE/WIPP-96-2150)

WPBlkhd1

CONCRETE BULKHEAD AND MASONRY WALL STABILITY

The 4,000 psi concrete panel closure bulkheads must be capable of resisting the transient 480 psi design overpressure from a methane explosion within closed panels during the planned 35 year life of the facility. The panel closure bulkheads must also be capable of containing the continuous and rising air pressure resulting from the creep closure of the of the panel rooms for the planned 35 year life of the facility. Figure 7 indicates the air pressure inside a sealed panel could increase to approximately 100 psi over 35 years. The panel closure bulkhead designed for the 14-ft wide by 12-ft high Exhaust Drift (Figure 1) is 26-ft thick, 29-ft high and 33.5-ft wide. The panel closure bulkhead designed for the 20-ft wide by 13-ft high Intake Drift is 36-ft thick, 29-ft high and 35.5-ft wide.

In addition, it was postulated that "selection of a thick enough" optional explosion-isolation wall could isolate the main panel closure bulkheads from the design methane explosion pressure. A 12-ft thick, 3500 psi solid masonry concrete block wall mortared with 2500 psi mortar was selected for the explosion-isolation wall.

A 4-ft thick construction-isolation masonry wall is specified "to provide isolation during construction of the main concrete barrier." The panel closure bulkhead construction area will be isolated from the overpressure developed by a possible roof fall in the nearest waste filled room during the 6-month to one-year bulkhead construction period.

PANEL CLOSURE BULKHEADS

The purpose of the panel closure bulkheads, located in the Intake and Exhaust Drifts where indicated on Figure 9, is to seal the waste emplaced in the seven panel rooms from the remaining active, operational, part of the WIPP. Figure 11 shows a typical active panel with waste emplaced in two rooms and indicates the continuing ventilation of the waste filled rooms and panel access drifts. The tapered concrete bulkheads were also designed to block potential leakage paths along Clay G in the near roof and in the anhydrite Marker Bed 139 beneath the floor. Bed separation at Clay G and low angle shear fractures in the roof salt starting at the ribside and angling up to Clay G that preceded the two roof falls in the Site and Preliminary Design Validation (SPDV) area demonstrate the progressive damage in the immediate rock salt roof. Similarly, the fracturing and heave of room floors has been traced to upward buckling of the anhydrite Marker Bed 139. The need to remove the damaged rock zones (DRZ) and block the potential leakage paths in the roof and floor is

the reason that the two-way tapered plain concrete bulkheads, shown on Figure 1, were designed.

The essentially rigid concrete panel closure bulkheads will draw load as the salt creeps toward the adjacent open drifts and rooms. The vertical and lateral horizontal stress acting on the roughly spherical panel closure bulkheads could eventually approach twice the overburden pressure, approximately 4,300 psi (Goodier, 1933; Edwards, 1955). The high stress concentration against the panel closure bulkheads will resist fracture propagation in the rock salt over, under and around the bulkheads, as indicated on Figure 12. The applied pressure would have to overcome (exceed) the rock salt/concrete contact pressure to propagate a fracture around the panel closure bulkheads.

The ground pressure applied to all sides of the panel closure bulkheads during the 17 years needed to reach an explosive 5% methane concentration (Figure 3) will grip the top, bottom and sides of the bulkheads. The force of this grip will resist flexure of the bulkhead concrete, in effect forming a fixed-end circular deep plate. The fixity of the panel bulkheads will reduce the bending moment developed when the bulkhead is loaded by the design explosion pressure applied from the waste emplacement side.

The ability of the planned plain concrete panel closure bulkheads was conservatively checked using the water impoundment bulkhead design method (Abel, 1998). The panel closure bulkheads are fully capable of resisting the 480 psi design methane explosion pressure. The 480 psi design methane explosion pressure is equal to the hydrostatic head of 1,108 feet of water. The panel closure bulkheads are effectively plain concrete because no tensile reinforcement is provided, or necessary, to resist the deep-beam bending stresses. The bulkhead lengths are sufficient to reduce the flexural bending stresses to less than the American Concrete Institute (ACI) allowable 206 psi tensile strength of 4,000 psi compressive strength concrete. Appendix A presents the calculations for the Intake Drift bulkhead and Appendix B for the Exhaust Drift bulkhead. Table 1 presents the various factors of safety for the panel closure bulkheads. The lowest factor of safety for the 36-ft thick Intake Drift bulkhead is 2.40 against both pressure gradient and concrete shear and for the 26-ft thick Exhaust Drift bulkhead is 1.54 against pressure gradient and 2.92 against concrete shear. The water impoundment bulkhead method only considers the grout pressure along the rock/concrete contact and does not provide any credit for the pressure from creep closure pressure of the rock salt.

The panel closure bulkhead design (Figure 1 and Figure 10) is not a monolith because it is planned to be built using four

cells. The steel forms will restrain the concrete pumped into each cell until the initial set, which will take approximately 4 hours (Figure 13). Most water retaining bulkheads (Figure 4) are designed and constructed as monolithic, i.e. continuous, pours without cold joints or interior form walls. Figure 14 provides a longitudinal cross section of the reinforced concrete American Tunnel Bulkhead #1, designed to resist a 1550-ft head (670 psi) and supporting 1010-ft (438 psi). Note the waterstops on the bypass pipe and the grout holes drilled through the concrete to low-pressure grout the roof and rib contact between the 11,000 psi compressive strength latite porphyry and the 3,000 psi concrete.

Some multi-cell bulkheads have been constructed when construction problems or emergencies required. At the Summitville Mine a second 20-ft long cell was added when water loss through the 129 psi compressive strength altered latite porphyry and over the initial 6.5-ft long Chandler Adit bulkhead became excessive. At the West Driefontein Mine, in response to a 67,000 gpm water inrush, a three cell bulkhead was progressively constructed on the 12-Level, the initial "temporary" sand and cement bag diversion plug, followed by a 15-ft long thickening bulkhead against the "temporary" plug and the final 60-ft long sand-concrete extension bulkhead. At the Rocanville Mine, in response to a 6,250 gpm brine inrush into the potash mine, an 87-ft thick five cell bulkhead was constructed, an initial 8-ft thick bulkhead, a 16-ft thick second cell, a 25-ft thick third cell and a final 37-ft thick cell (Figure 15). In every case, the cell forms were externally supported and the internal bulkhead forms were stripped before constructing the subsequent cell. The planned four cell panel closure bulkhead construction would not provide a monolithic, i.e. uniform and continuous, bulkhead but could contain as many as three interior steel form walls supported during filling by the form spacers.

Penetrations through a water retaining bulkhead are normally minimized, whenever possible, because they represent potential leakage paths through bulkheads. Essential penetrations, such as bypass and sampling and pressure monitoring pipes, include waterstops to assure no leakage along the penetrations. The planned 4 cell panel closure bulkhead (Figure 1) includes the use of longitudinal 1-in diameter form spacers, which also support the facility side plate and angle form wall until the concrete sets. Figure 5 indicates 55 form spacer penetrations across Cell #2 and Cell #3. Figure 6 indicates 22 form spacer penetrations across Cell #1 and Cell #4. Multiple potential flow paths are apparent across the individual cells. If not removed after the cell is filled, the steel plate and angle forms provide multiple potential leakage paths between form spacers in adjacent cells. The bond strength between the steel plates and the concrete is

necessarily low. Even if a way is found to remove the three interior steel form walls, after the concrete has set in each cell, a smooth surfaced cold joint will still be present between cells.

In order of declining potential effectiveness, the following panel closure bulkhead construction modifications should decrease the bulkhead leakage potential,

1) constructing truly monolithic single-cell panel closure bulkheads or
2) externally supporting the bulkhead cell forms, i.e. eliminating the form spacers, or
3) reducing the number of cells.

The panel closure bulkheads are tapered two-way pressure bulkheads, i.e. designed to resist equal pressure from either side. The panel closure bulkheads are apparently designed to be airtight for the 35-year life of the facility. Closure of the panel rooms and panel access drifts is predicted to result in 100 psi of effective pressure on the waste side of the bulkheads over a 35 years period after completion of the panel closure bulkheads (Figure 7). The two-way taper of the panel closure bulkheads was apparently designed to permit the safe excavation of the disturbed rock zones (DRZ) above and below the intake and exhaust drifts. The ample panel closure bulkhead factors of safety against the 480 psi design methane explosion pressure should be more than quadrupled for the closure pressure.

Tapered bulkhead water containment bulkheads are normally constructed when the rock shear strength is lower than the concrete design shear strength. Figure 4 shows a typical tapered water containment bulkhead, designed to resist hydrostatic pressure from one side. Successful tapered bulkheads have been constructed at the Summitville Mine, the Jackpot Mine declines and at IMC's K2 Mine. Tapering a bulkhead increases the length of the worst-case potential shear surface in the lower strength rock adjacent to the rock/concrete interface and tightens the concrete bulkhead against the rock when hydrostatic pressure is applied. In most water impoundment cases, when the rock strength exceeds the concrete strength, parallel plugs have proven to be effective. Loofbourow in the Society of Mining Engineers (SME) Mining Engineering Handbook (1973, Sec 26.7.4) states "no indication of structural failure resulting from thrust was noted" in the case of ten bulkheads subjected by hydraulic pressures in excess of 1000 psi and which relied solely on normal rock surface irregularities, referred to as a "parallel plug" on Figure 4. Garrett and Campbell-Pitt (1961) reported the successful results from 26 mine bulkheads,

twelve with parallel plugs, that relied solely on the irregularity of the tunnel walls, and 14 with taper plugs.

Parallel panel closure bulkheads would probably be successful in resisting the potential applied pressures, Options A and B on Figure 10. However, the progressive deterioration of the adjacent rock salt and anhydrite and clay layer bed separations suggests that the two-way tapered bulkhead will assure the long term functioning of airtight panel closure bulkheads.

EXPLOSION-ISOLATION MASONRY WALLS

The 12-ft thick explosion-isolation masonry walls for the Intake Drift and the Exhaust Drift (Figure 2) are planned to be built with solid concrete blocks (3,500 psi) mortared with cement and hitched 6-in into the roof, ribs and floor. The explosion-isolation masonry wall is apparently designed to resist the 480 psi methane explosion pressure during the six months to one year of panel bulkhead construction.

The ability of the planned explosion-isolation masonry walls to resist the 480 psi methane explosion pressure was conservatively checked using the water impoundment bulkhead design method (Abel, 1998). Table 1 presents the results of this analysis. The calculations for the Intake Drift are presented in Appendix C and for the Exhaust Drift in Appendix D. The results of this analysis predicts that the planned 12-ft thick explosion-isolation masonry walls would not be capable of resisting the 480 psi design methane explosion pressure. The predicted failure of the explosion-isolation wall is indicated on Figure 12. In the Intake Drift, the thickness of an explosion-isolation masonry bulkhead would have to be approximately 20-ft to contain the 480 psi methane explosion pressure and in the Exhaust Drift approximately 15-ft.

Figure 3 presents the predicted 17+ year methane concentration time interval between cessation of panel ventilation and the methane concentration reaching the minimum 5% lower explosive limit. The predicted methane concentration should not exceed approximately 0.25% during a one-year panel closure bulkhead construction period. Therefore, a methane explosion should not be possible, and an explosion-isolation masonry wall not necessary.

CONSTRUCTION-ISOLATION MASONRY WALLS

A 4-ft thick construction-isolation masonry wall has been designed to isolate the panel closure bulkhead construction from the emplaced waste in a completed panel and from the transient overpressure from a 15,000 ton roof fall in central 140-ft of Room 1 in the completed panel, closest to the Intake and Exhaust Drifts. The design roof fall is equal in weight and length to the roof fall in Site and Preliminary Design Validation Room 1 (SPDV1). The SPDV1 fall distance was the 13-ft room height, whereas the fall distance with emplaced waste drums is limited to 3.5-ft. Figure 16 presents the predicted 0.4 PSF (0.003 psi) maximum overpressure and the design 10.1 PSF (0.070 psi) air overpressure from the roof fall.

The ability of the planned construction-isolation masonry walls to resist the 0.070 psi design roof fall pressure was conservatively checked using the water impoundment bulkhead design method (Abel, 1998). Table 1 presents the results of this analysis. The calculations for the 4-ft thick Intake Drift construction-isolation masonry wall are presented in Appendix E.

The 4-ft thick construction-isolation masonry wall planned for the 20-ft wide by 13-ft high Intake Drift is fully capable of resisting the roof fall design overpressure. A similar 4-ft thick construction-isolation masonry wall planned for the 14-ft wide by 12-ft high Exhaust Drift will have even higher factors of safety against the roof fall design overpressure.

Figure 11.Typical active panel configuration with ventilation splits

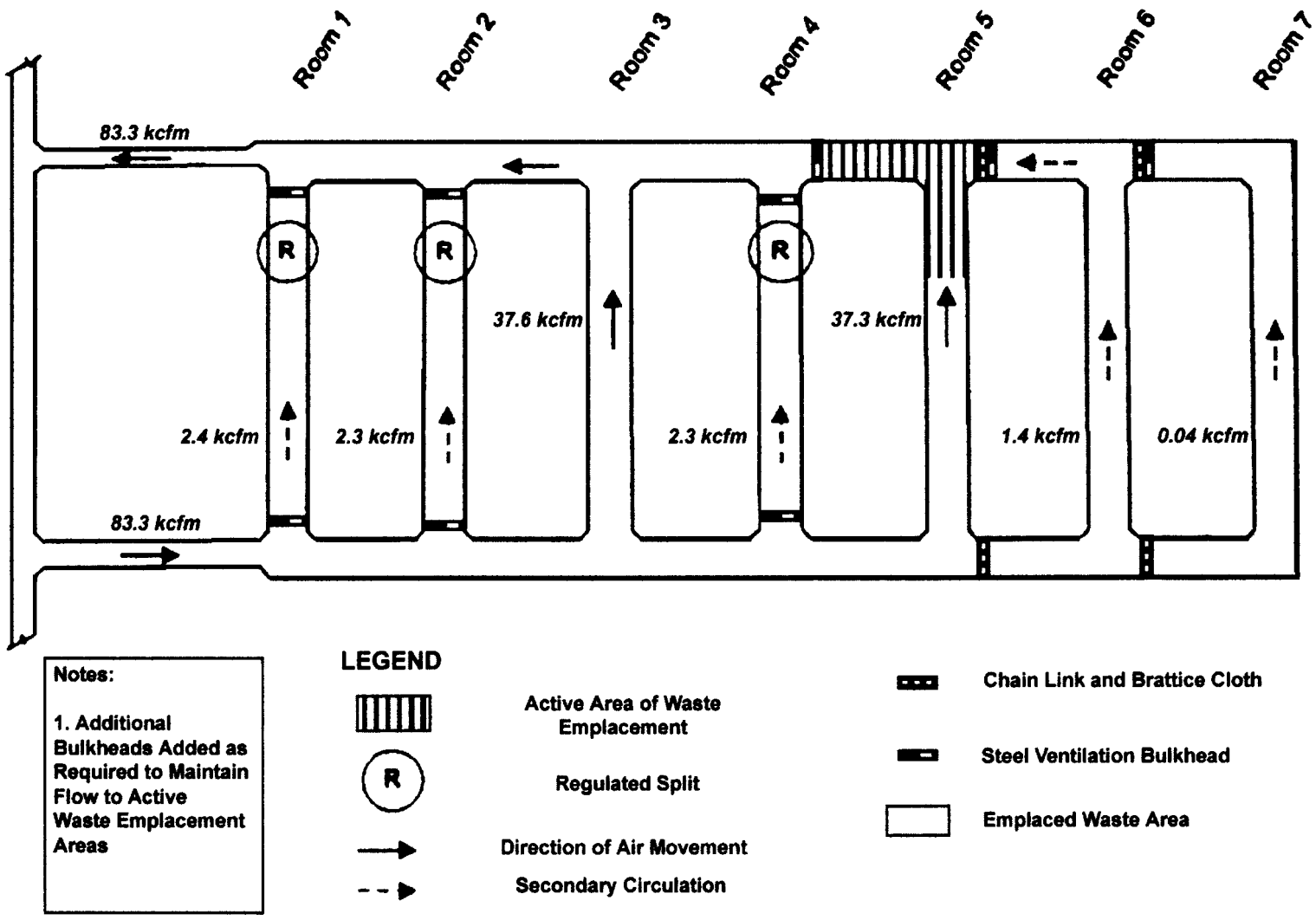

Typical active panel configuration with ventilation splits (from Dykes, et. al., 1997)

WPnlCnf2

Figure 12. Fracture propagation modes of bulkhead failure

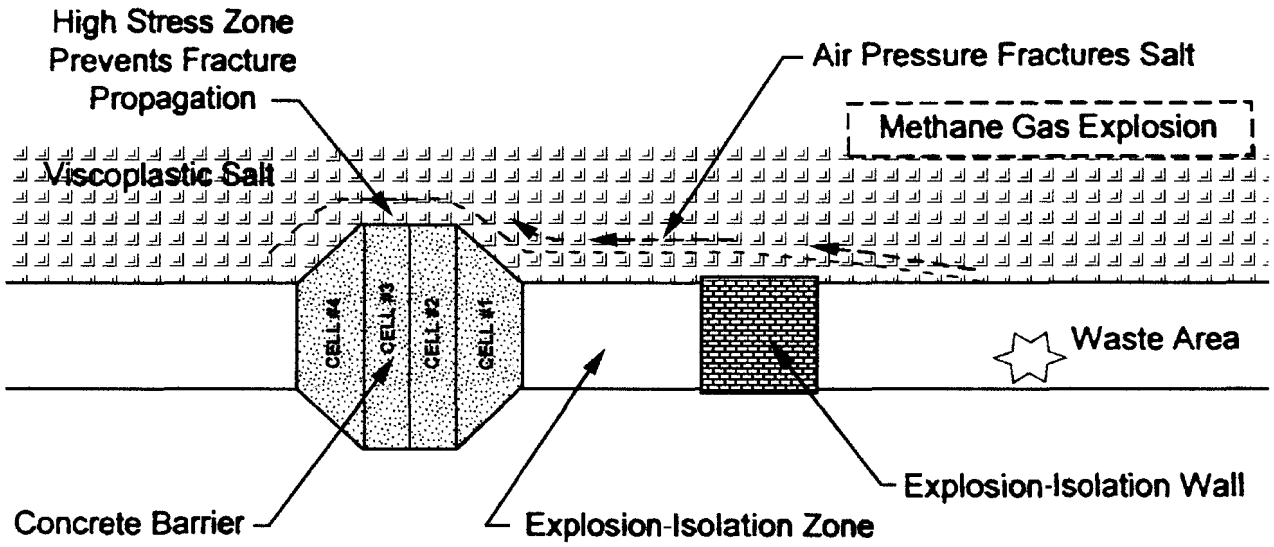

Fracture propagation mode of failure with stable explosion-isolation wall
(modified from Dykes, et. al., 1997)

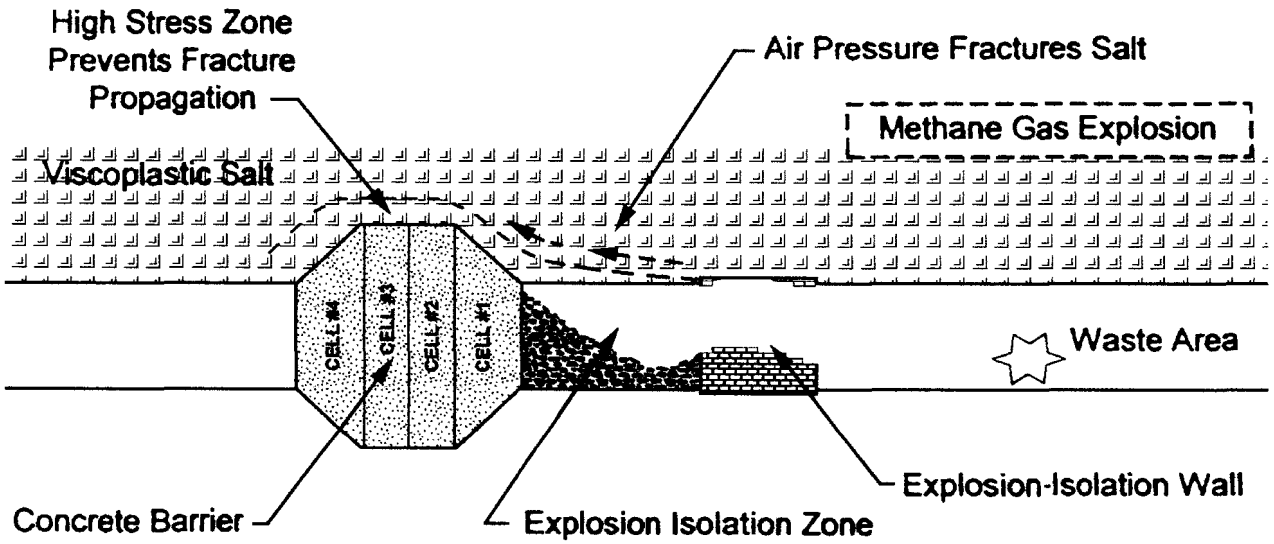

Fracture propagation mode of failure for explosion-isolation wall failure
(modified from Dykes, et. al., 1997)

ExploBk1

Figure 13. Example of effect of temperature on setting time of concrete

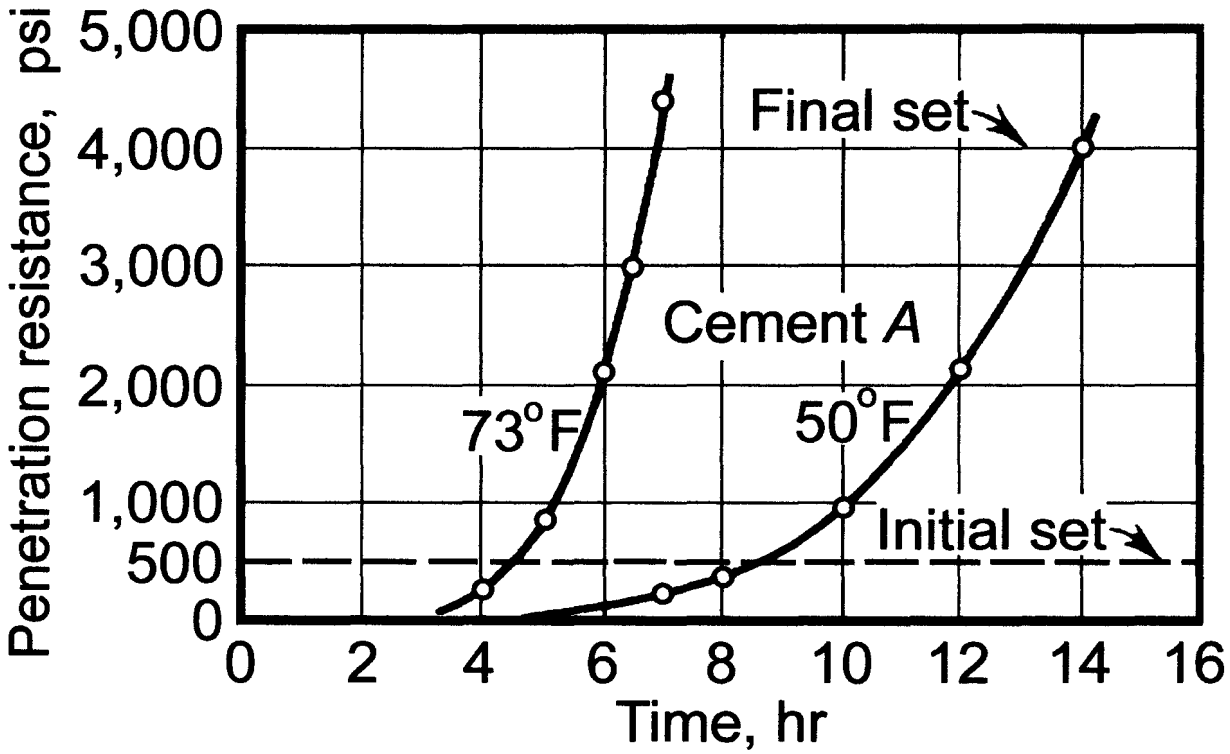

Example of effect of temperature on setting time of concrete
(Troxell, et. al., 1968)

SetTime2

Figure 14. Cross section through monolithic bulkhead (Abel, 1998)

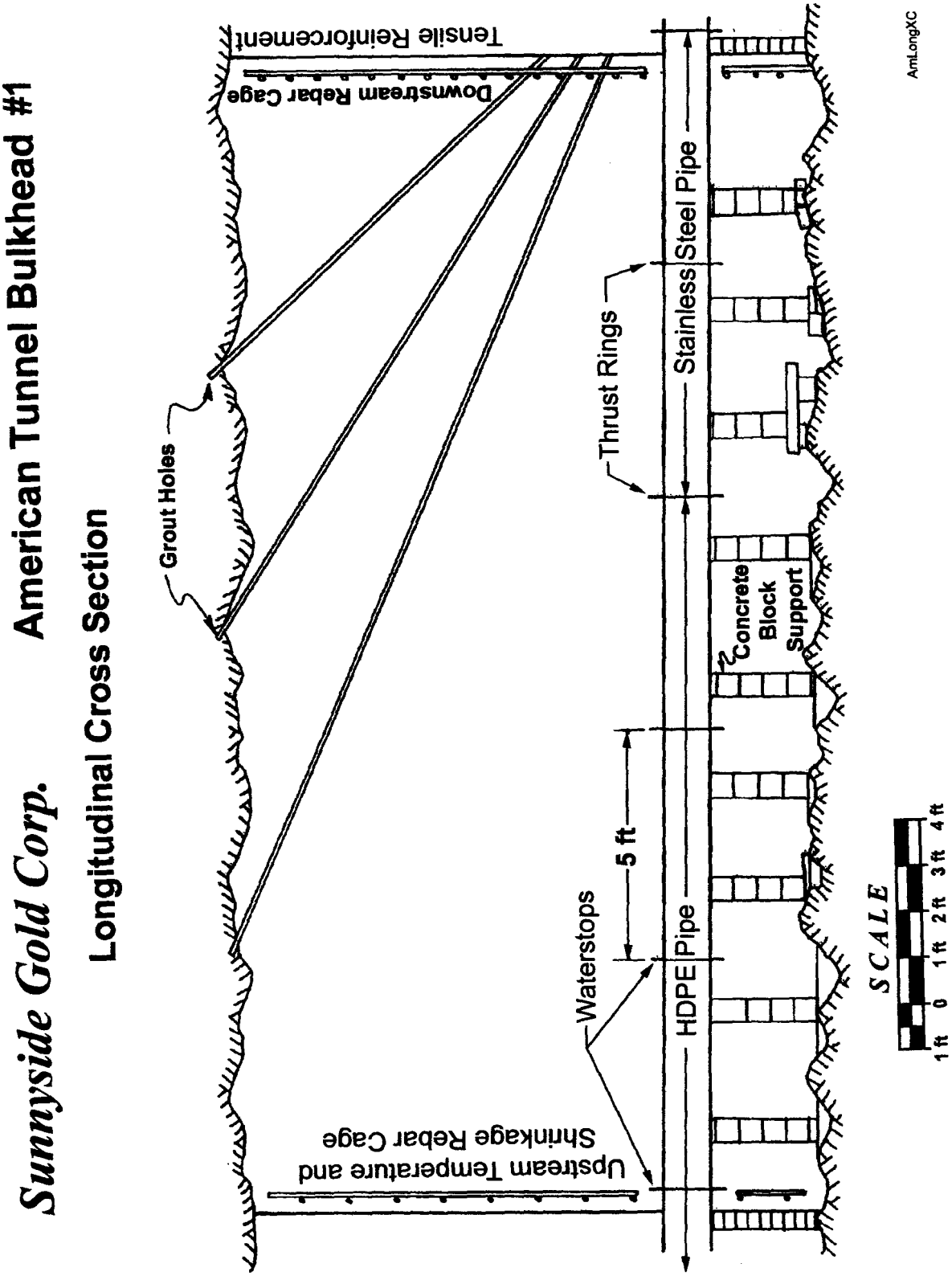

Figure 15. Rocanville inflow tunnel bulkheads and plugs

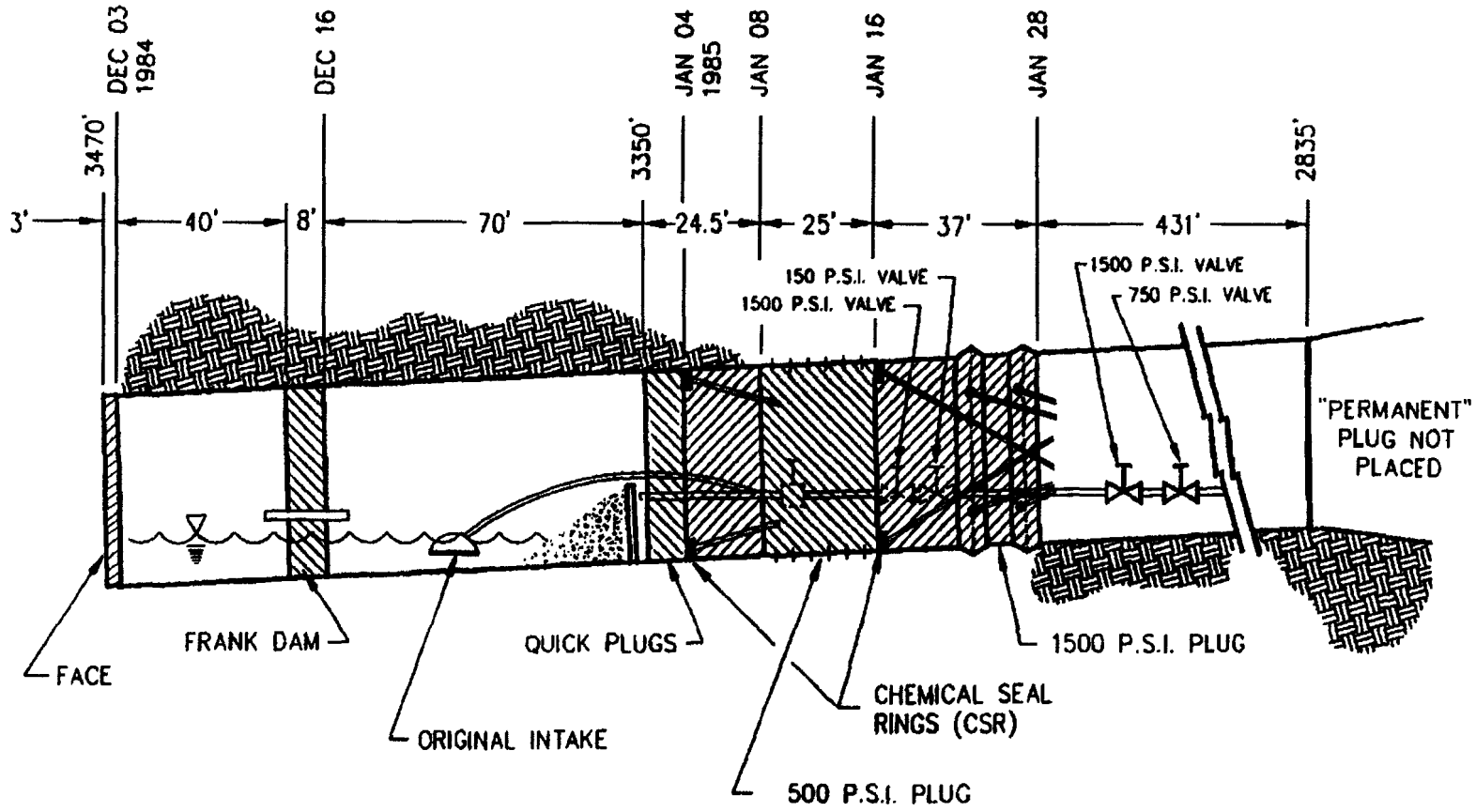

Rocanville inflow tunnel bulkheads and plugs (Eyermann, et. al., 1995)

Figure 16. Pressure transient from a roof fall

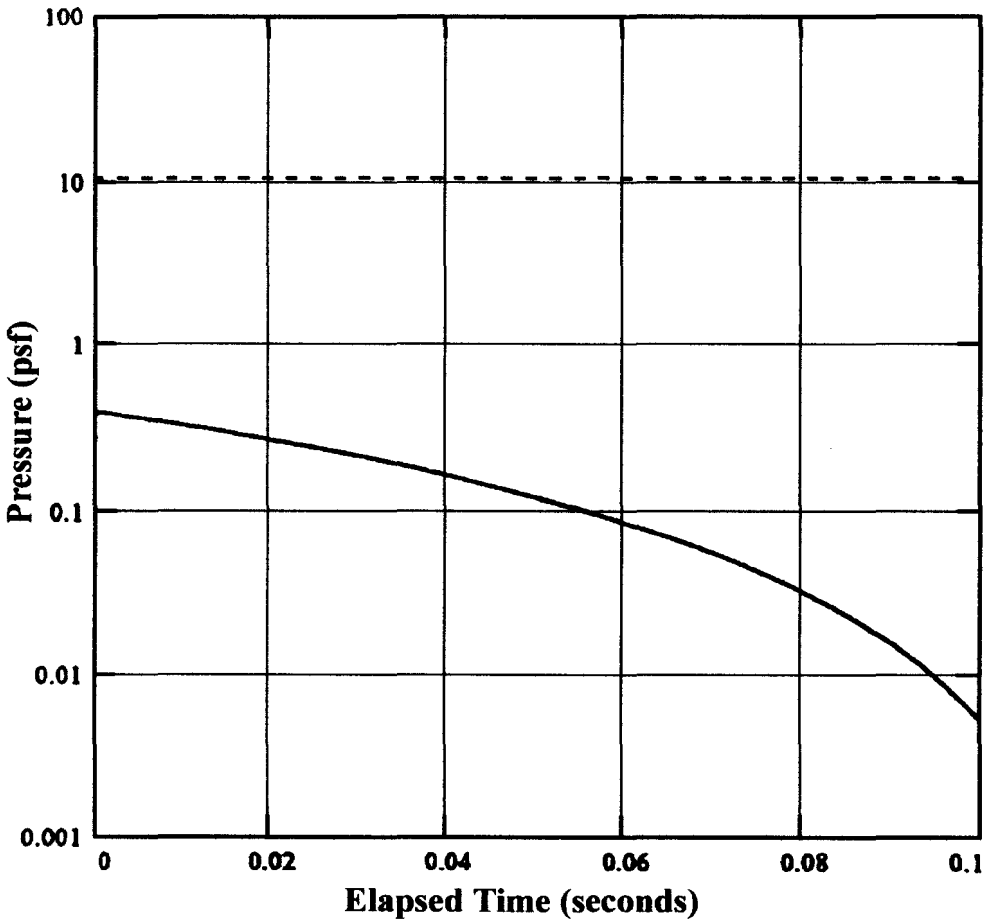

— Predicted Pressure Loading
- - Design Pressure Loading

Pressure transient for a roof fall
(modified from Dykes, et. al., 1997)

RoofFall

CONSTRUCTION ENHANCEMENTS

The remaining panel closure enhancements relate primarily to the resulting strength of the concrete in the panel closure bulkheads, over the minimum operational period of 35 years. The strength of the concrete is critical to the strength of the panel closure bulkheads.

The proposal to allow the mass concrete to utilize any rock salt in the mix depends on the ability to consistently meet the strength specification. The unconfined compressive strength of the 16 Permian evaporite beds tabulated in Appendix F ranges from 2300 psi to 5880 psi and the cohesion from 540 to 1580 psi. The unconfined compressive strength of the evaporite beds tabulated in Appendix G, including the Permian beds in Appendix F, ranges from 2260 psi to 7510 psi and the cohesion from 540 to 1790 psi. The random selection of the salt from any tested salt bed should be capable of providing equivalent strength properties. In addition, the strength variation across a single evaporite bed in the Salado formation is significant. The unconfined compressive strength of the Mississippi Potash Company's Cycle 7 bed (> 85% salt) ranged from 1610 psi to 4950 psi, as shown on Figure 17. The important factor would appear that the salt component of the mix be consistent, i. e. well mixed from one source.

Aggregate strength is a minor concrete strength factor which can be compensated for, if necessary, by increasing the cement in the mix and verified by testing. In addition, carbonate aggregate concrete probably has a lower coefficient of thermal expansion that quartz aggregate. Figure 8 indicates that concrete with quartz aggregate has a higher coefficient of expansion (approximately 6.6 millionths per °F) than either limestone aggregate concrete (approximately 3.8 millionths per °F) or dolomite aggregate concrete (approximately 5.3 millionths per °F). It should be possible to use either the Pennsylvanian Atoka limestone or the Permian, Guadalupian, Bell Canyon limestone river rock for concrete aggregate. Rounded river rock should facilitate slick line pumping and form filling.

Surface or underground mixing of the concrete is of no significance. Sunnyside Cold Corp. has constructed five water impoundment bulkheads using underground mixing and pumping stations, four using supersacks, surface mixing and pumping and one with surface mixing and transporting by rail in Moran cars. The critical factor is limiting the time between mixing and placement in the form. Troxell, et. al. (1968) state:

Figure 17. Strength of Mississippi Potash Co.'s Cycle 7 bed

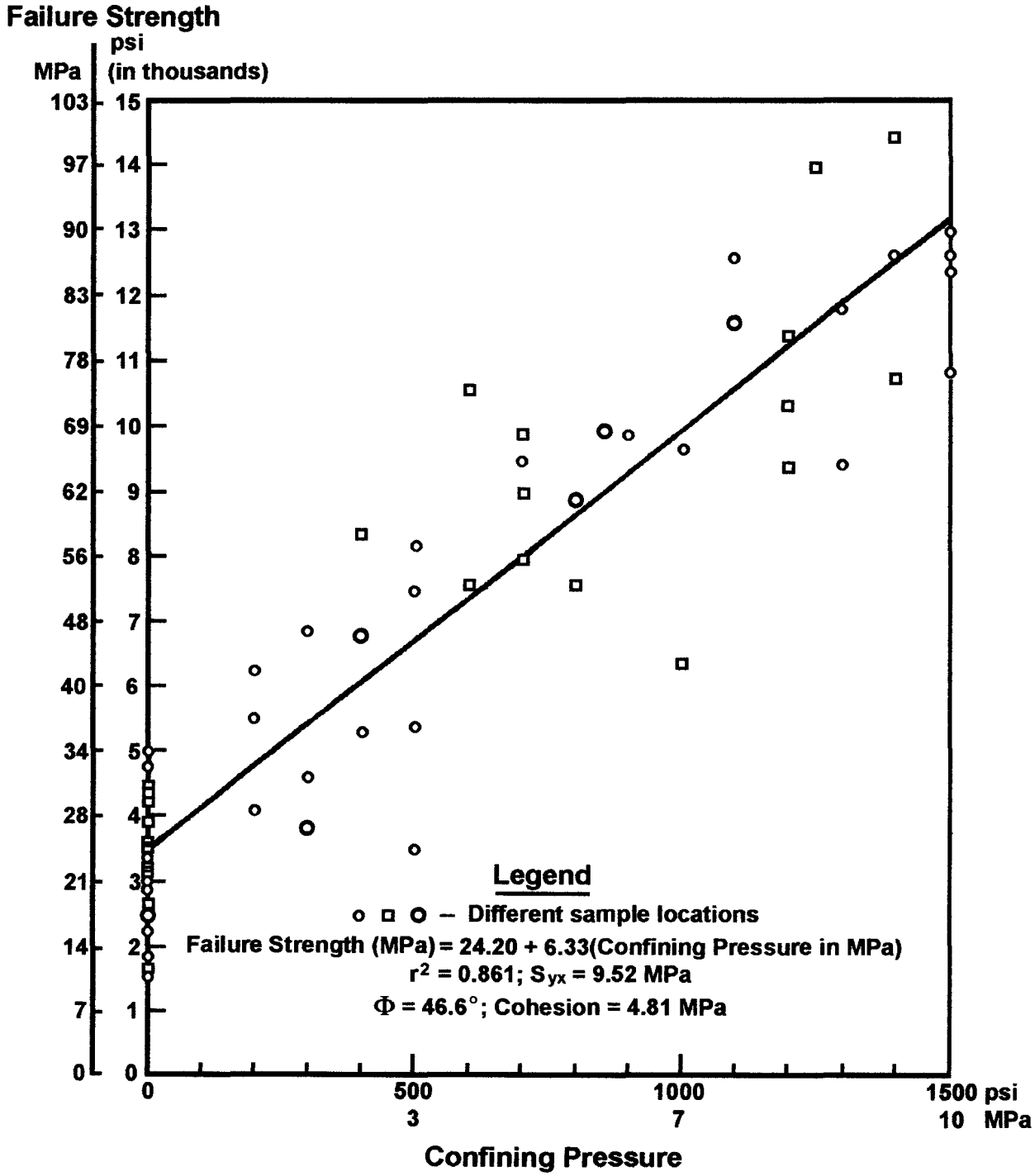

Strength of Mississippi Potash Co.'s Cycle 7 bed (Abel and Djahanguiri, 1984) SaltNuc5

> Current specifications for ready-mixed concrete require that the concrete be discharged from the truck within 1-1/2 hr or before the drum has had 300 revolutions (whichever comes first) after the water is added to the batch, or the cement to the moist aggregate. Under specially favorable conditions, periods up to 2 and 3 hr may be allowed. Conversely, under unfavorable conditions where air temperatures are unusually high, or the ingredients of the concrete are such that an unusually quick time of set or loss of plasticity may occur, it may be necessary to substitute a shorter period.

If the water is added to the bulkhead concrete on the surface, it will be difficult to meet the time limitation. Transporting supersacks underground and adding the water and mixing close to the bulkhead sites would appear to be the most reasonable method.

Replacing freshwater grout with salt-based grout should be done in order to minimize salt dissolution in the adjacent rock salt and in the salt-based concrete. Salt dissolution could weaken the contact zone and potentially provide a leakage path for brine, methane explosion pressure and closure compressed gas pressure behind the panel closure bulkheads.

It should be expected that the best contractor bid will result from the least restrictive specification. There is no apparent reason to require panel closure construction within six months rather than one year.

CONCLUSIONS AND RECOMMENDATIONS

The most important of the specific enhancements proposed, allowing flexibility in the bulkhead forming practices is troubling because the planned bulkhead design contains multiple potential leakage paths within cells, between cells and through the panel closure bulkheads. It is recommended that the panel bulkhead specifications:

1) provide an incentive for the contractor to minimize the number of cells (preferably to one),
2) require that each cell be filled as a continuous monolithic concrete pour,
3) require the contractor support the fluid concrete in all cells with external structures,
4) require the contractor to remove the support structures and forms between internal cells,
5) provide for a rough form surface between internal cell walls, (possibly with a layer of burlap),
6) assure that some grout points are located at the roof concrete/rock salt contact and
7) prevent the use of all internal form spacer supports.

If built as recommended, the panel closure bulkheads should be capable of providing more than the required 35 years of protection from brine migration, 480 psi of methane explosion pressure and 100 psi of panel closure pressure.

The planned 12-ft thick explosion-isolation masonry walls should not be built. The methane concentration will take more than 17 years to rise to the 5% lower explosive limit after stopping panel ventilation. If built, the planned 12-ft thick explosion-isolation masonry walls would probably be incapable of resisting the design 480 psi methane explosion pressure.

The 4-ft thick construction-isolation wall is recommended to isolate the panel closure construction areas. The 4-ft thick construction-isolation walls are more than adequate to support the potential roof fall overpressure.

Generic salt-based concrete should be equally as effective as Salado-based concrete.

It should be possible to use local limestone or dolomite river rock for concrete aggregate. Limestone aggregate concrete should have a lower coefficient of thermal expansion than crushed quartz aggregate concrete. River rock should pump more readily than crusher product.

The contractor should be allowed to use either surface or underground mixing of the concrete. However, underground mixing of supersacks is recommended to assure sufficient time for placing the concrete in the forms.

Salt-based grout is recommended to eliminate the possibility of weakening the salt-based concrete along the rock salt/concrete contact by dissolution. Grouting across the roof contact is essential to assure that voids are filled.

There does not appear to be a time imperative requiring a 180-day construction period rather than a one year period.

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APPENDIX A. INTAKE DRIFT BULKHEAD DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = concrete shear strength $\left(2\sqrt{f'_c} = 126 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Intake Drift width (20 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
T_e = effective bulkhead thickness (28 ft)
V_c = concrete shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ_a = allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w = water density (62.4PCF)
ϕ = plain concrete strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = concrete comp strength (4,000 psi)
f_{cl} = concrete tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{4000} = 206 \text{ psi}\right]$
h = Intake Drift height (13 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (36 ft)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_d = dynamic pressure head (240 psi)
γ_c = concrete density (151PCF)
γ_s = salt density (140 PCF)
σ_s = flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of concrete-rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Intake Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Required bulkhead thickness with low pressure grouting on concrete/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Appendix A. Intake Drift bulkhead design calculations (Continued)

Pressure gradient along minimum effective bulkhead thickness T_e= 28 ft

$$\rho_g = \frac{\rho}{28} = \frac{480}{28} = 17.1 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along concrete/rock salt contact around 28-ft effective bulkhead thickness is:

$$\underline{FS} = \frac{41}{17.1} = \underline{2.40}$$

Allowable concrete shear on Intake Drift perimeter:

$$f'_s = 2\sqrt{f'_c} = 2\sqrt{4000} = 126 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h \ell}{2(h+\ell)f'_s}$$

$$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(36)(13+20)126}{13(20)} = \frac{299400}{260} = 1152 \text{ psi}$$

$$W = \rho_d h\ell = 480(13)20(144) = 17{,}970{,}000 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{17970000}{[2(13+20)]36(144)} = \frac{17970000}{342100} = 52.5 \text{ psi}$$

Factor of Safety against concrete shear failure = $\frac{f'_s}{v_s} = \frac{126}{52.5} = 2.40$

Allowable rock salt shear force along concrete/rock salt contact, Intake Drift bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to concrete/rock salt contact:

$$L_{rs} = \sqrt{8^2 + 8^2} + 0.5 + 9.75 + 9.75 = 31.3 \text{ ft}^2\text{/ft of perimeter}$$

Minimum rock salt perimeter = 2(13+20) = 66 ft

Total effective bulkhead shear area = 2,066 ft^2

Maximum rock salt shear resistance = 2066(1070)144 = 318,300,000 lb

Appendix A. Intake Drift bulkhead design calculations (Continued)

Maximum shear force on panel side bulkhead face and outward inclined panel side concrete/rock salt contact potentially opened by explosion gas pressure:

Face area = 13(20) = 260 ft^2

Vertical component of sloping area = $2(13+20)8 + \frac{\pi 8^2}{4} = 528 + 50 = 578\ ft^2$

Design maximum thrust = (578+260)(480)144 = 57,920,000 lb

Factor of Safety against rock salt shear failure = $\frac{318{,}300{,}000}{57{,}920{,}000} = 5.50$

Plain concrete deep beam bending stress design, Intake Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1)

for 480 psi design dynamic pressure head:

$\omega = U = 2\rho_d(144) = 2(240)144 = 69{,}120\ \left(\frac{lb}{ft^2}\right)$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$M_n = \frac{\omega \ell^2}{24} = \frac{69120(20^2)}{24} = 1{,}152{,}000\ ft{\cdot}lb$

$M_u = \frac{M_n}{0.65} = \frac{1152000}{0.65} = 1{,}772{,}000\ ft{\cdot}lb$

$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$

$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206\ psi$

$f'_{cl} = 206 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{1772000}{\frac{144T^2}{6}} = \frac{73830}{T^2}$

$T = \sqrt{\frac{73830}{206}} = \sqrt{358.4} = 18.9$ ft thick plain concrete bulkhead is required for worst-case rib to rib fixed bulkhead.

$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{1772000}{\frac{144(36^2)}{6}} = \frac{1772000}{31100} = 57.0\ psi$

$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{57.0} = 3.61$

Therefore, a 36-ft thick plain-concrete bulkhead worst-case griped at both ribs of the 20-ft wide Intake Drift, is acceptable as a panel closure bulkhead.

Appendix A. Intake Drift bulkhead design calculations (Continued)

Bulkhead deep beam griped at Intake Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(13^2)}{24} = 486{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{486700}{0.65} = 748{,}800 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206 \text{ psi}$$

$$f'_{cl} = 206 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{748800}{\frac{144T^2}{6}} = \frac{31200}{T^2}$$

$T = \sqrt{\frac{31200}{206}} = \sqrt{151.5} = 12.3$-ft thick plain concrete bulkhead is required for best-case roof to floor fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{748800}{\frac{144(36^2)}{6}} = \frac{748800}{31100} = 24.1 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{24.1} = 8.55$$

Therefore, a 36-ft thick plain-concrete bulkhead, best-case griped at roof and floor of the 13-ft high Intake Drift, is acceptable as a panel closure bulkhead.

APPENDIX B. EXHAUST DRIFT BULKHEAD DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = concrete shear strength $\left(2\sqrt{f'_c} = 126 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Exhaust Drift width (14 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
T_e = effective bulkhead thickness (18 ft)
V_c = concrete shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ_a = allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w = water density (62.4PCF)
ϕ = plain concrete strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = concrete comp strength (4,000 psi)
f_{cl} = concrete tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{4000} = 206 \text{ psi}\right]$
h = Exhaust Drift height (12 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (26 ft)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_d = dynamic pressure head (240 psi)
γ_c = concrete density (151PCF)
γ_s = salt density (140 PCF)
σ_s = flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of concrete-rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Exhaust Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Required bulkhead length with low pressure grouting on concrete/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Appendix B. Exhaust Drift bulkhead design calculations (Continued)

Pressure gradient along minimum effective bulkhead thickness T = 18 ft

$\rho_g = \frac{\rho}{18} = \frac{480}{18} = 26.7$ psi/ft

Factor of Safety against leakage of explosion gasses along concrete/rock salt contact around 18-ft effective bulkhead thickness is:

$\underline{FS} = \frac{41}{26.7} = \underline{1.54}$

Allowable concrete shear on Exhaust Drift perimeter:

$f'_s = 2\sqrt{f'_c} = 2\sqrt{4000} = 126$ psi (ACI 318-95, Sec 11.3.1.1)

$T = \frac{\rho_a h \ell}{2(h+\ell)f'_s}$

$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(36)(12+14)126}{12(14)} = \frac{235900}{168} = 1404$ psi

$W = \rho_d h\ell = 480(12)14(144) = 11{,}610{,}000$ lb

$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{11610000}{[2(12+14)]36(144)} = \frac{11610000}{269600} = 43.1$ psi

Factor of Safety against concrete shear failure $= \frac{f'_s}{v_s} = \frac{126}{43.1} = 2.92$

Allowable rock salt shear force along concrete/rock salt contact, Exhaust Drift bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to concrete/rock salt contact:

$L_{rs} = \sqrt{8^2 + 8^2} + 0.5 + 4.75 + 4.75 = 21.3$ ft²/ft of perimeter

Minimum rock salt perimeter = 2(12+14) = 52 ft

Total effective bulkhead shear area = 1,108 ft²

Maximum rock salt shear resistance = 1108(1070)144 = 170,700,000 lb

Appendix B. Exhaust Drift bulkhead design calculations (Continued)

Maximum shear force on panel side bulkhead face and outward inclined panel side concrete/rock salt contact potentially opened by explosion gas pressure:

Face area = 12(14) = 168 ft^2

Vertical component of sloping area = $2(12+14)8 + \frac{\pi 8^2}{4} = 416 + 50 = 466\ ft^2$

Design maximum thrust = (466+168)(1070)144 = 97,690,000 lb

Factor of Safety against rock salt shear failure = $\frac{170,700,000}{97,690,000} = 1.75$

Plain concrete deep beam bending stress design, Exhaust Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1)

for 480 psi design dynamic pressure head:

$\omega = U = 2\rho_d(144) = 2(240)144 = 69,120\ \left(\frac{lb}{ft^2}\right)$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$M_n = \frac{\omega \ell^2}{24} = \frac{69120(14^2)}{24} = 564,500$ ft·lb

$M_u = \frac{M_n}{0.65} = \frac{564500}{0.65} = 868,500$ ft·lb

$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$

$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206$ psi

$f'_{cl} = 206 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{868500}{\frac{144T^2}{6}} = \frac{36190}{T^2}$

$T = \sqrt{\frac{36190}{206}} = \sqrt{175.7} = 13.3$ ft thick plain concrete bulkhead is required for worst-case rib to rib fixed bulkhead.

$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{868500}{\frac{144(26^2)}{6}} = \frac{868500}{16220} = 53.5$ psi

$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{53.5} = 3.85$

Therefore, a 26-ft thick plain-concrete bulkhead, worst-case griped at both ribsides of the 14-ft wide Exhaust Drift, is acceptable as a panel closure bulkhead.

Appendix B. Exhaust Drift bulkhead design calculations (Continued)

Bulkhead deep beam griped at Exhaust Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(12^2)}{24} = 414{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{414700}{0.65} = 638{,}000 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206 \text{ psi}$$

$$f'_{cl} = 190 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{638000}{\frac{144T^2}{6}} = \frac{26580}{T^2}$$

$T = \sqrt{\frac{26580}{206}} = \sqrt{129.0} = 11.4$-ft thick plain concrete bulkhead is required for best-case roof to floor fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{638000}{\frac{144(26^2)}{6}} = \frac{638000}{16220} = 39.3 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{39.3} = 5.24$$

Therefore, a 26-ft thick plain-concrete bulkhead, best-case griped at roof and floor of the 12-ft high Exhaust Drift, is acceptable as a panel closure bulkhead.

APPENDIX C. INTAKE DRIFT EXPLOSION-ISOLATION MASONRY WALL DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = masonry shear strength $\left(2\sqrt{f'_c} = 100 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Intake Drift width (20 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_a= allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w= water density (62.4PCF)
ϕ= plain masonry strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = masonry comp strength (2,500 psi)
f_{cl} = masonry tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{2500} = 162 \text{ psi}\right]$
h = Intake Drift height (13 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (12 ft)
V_c = masonry shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ = design pressure head (480 psi)
ρ_d = dynamic pressure head (240 psi)
γ_c = masonry density (151PCF)
γ_s = salt density (140 PCF)
σ_s= flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of masonry/rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Intake Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Appendix C. Intake Drift explosion-isolation masonry wall design calculations (Continued)

Required bulkhead thickness with low pressure grouting on masonry/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Pressure gradient along bulkhead thickness T = 12 ft

$$\rho_g = \frac{\rho}{28} = \frac{480}{12} = 40.0 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along masonry/rock salt contact around 12-ft effective bulkhead thickness is:

$$\underline{FS} = \frac{41}{40.0} = \underline{1.03}$$

Allowable masonry shear on Intake Drift perimeter:

$$f'_s = 2\sqrt{f'_c} = 2\sqrt{2500} = 100 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h\ell}{2(h+\ell)f'_s}$$

$$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(12)(13+20)100}{13(20)} = \frac{79200}{260} = 304.6 \text{ psi}$$

$$W = \rho_d h\ell = 480(13)20(144) = 17{,}970{,}000 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{17970000}{[2(13+20)]12(144)} = \frac{17970000}{114000} = 157.6 \text{ psi}$$

Factor of Safety against masonry shear failure $= \frac{f'_s}{v_s} = \frac{100}{157.6} = \underline{\mathbf{0.63}}$

Required masonry wall thickness to resist design methane explosion pressure

$$T = \frac{\rho h\ell}{2(h+\ell)f'_s} = \frac{480(13)20}{2[13+20]100} = \frac{124800}{6600} = 18.9 \text{ ft}$$

Allowable rock salt shear force along masonry/rock salt contact, Intake Drift explosion-isolation bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to masonry/rock salt contact:

L_{rs} = 12 ft^2/ft of perimeter

Appendix C. Intake Drift explosion-isolation masonry wall design calculations (Continued)

Minimum rock salt perimeter = 2(14+21) = 70 ft
based on perimeter hitched 6-in into roof, ribs and floor of Intake Drift

Total effective bulkhead shear area = 840 ft^2

Maximum rock salt shear resistance = 840(1070)144 = 129,400,000 lb

Maximum shear force on masonry/rock salt contact potentially opened by explosion gas pressure:

Face area = 14(21) = 294 ft^2

Design maximum thrust = (294)(480)144 = 20,320,000 lb

Factor of Safety against rock salt shear failure = $\frac{129,400,000}{20,320,000} = 6.37$

Masonry explosion-isolation beam bending stress design, Intake Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1) for 480 psi design dynamic pressure head:

$$\omega = U = 2\rho_d(144) = 2(240)144 = 69,120\left(\frac{lb}{ft^2}\right)$$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$$M_n = \frac{\omega\ell^2}{24} = \frac{69120(20^2)}{24} = 1,152,000 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{1152000}{0.65} = 1,772,000 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 150 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{1772000}{\frac{144T^2}{6}} = \frac{73830}{T^2}$$

$T = \sqrt{\frac{73830}{162.5}} = \sqrt{454.3} = 21.3$ ft thick masonry bulkhead is required for worst-case rib to rib fixed explosion-isolation bulkhead

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{1772000}{\frac{144(12^2)}{6}} = \frac{1772000}{3456} = 512.7 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{512.7} = \underline{\mathbf{0.32}}$$

Appendix C. Intake Drift explosion-isolation masonry wall design calculations (Continued)

Therefore, 12-ft thick cement-mortared masonry block bulkhead, worst-case griped at both ribsides of the 20-ft wide Intake Drift, is NOT acceptable as an explosion-isolation bulkhead.

Masonry bulkhead deep beam griped at Intake Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(13^2)}{24} = 486{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{486700}{0.65} = 748{,}800 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 162.5 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{748800}{\frac{144T^2}{6}} = \frac{31200}{T^2}$$

$T = \sqrt{\frac{31200}{162.5}} = \sqrt{192.0} = 13.8$-ft thick concrete block masonry bulkhead is required for best-case roof to floor fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{748800}{\frac{144(12^2)}{6}} = \frac{748800}{3456} = 216.7 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{216.7} = \underline{\mathbf{0.75}}$$

Therefore, 12-ft thick cement-mortared masonry block bulkhead, best-case griped at roof and floor of the 13-ft high Intake Drift, is NOT acceptable as an explosion-isolation bulkhead.

APPENDIX D. EXHAUST DRIFT EXPLOSION-ISOLATION MASONRY WALL DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = masonry shear strength $\left(2\sqrt{f'_c} = 100 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Exhaust Drift width (14 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_a = allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w = water density (62.4PCF)
ϕ = plain masonry strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = masonry comp strength (2,500 psi)
f_{cl} = masonry tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{2500} = 162 \text{ psi}\right]$
h = Exhaust Drift height (12 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (12 ft)
V_c = masonry shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ = design pressure head (480 psi)
ρ_d = dynamic pressure head (240 psi)
γ_c = masonry density (151PCF)
γ_s = salt density (140 PCF)
σ_s = flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of masonry/rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Exhaust Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Appendix D. Exhaust Drift explosion-isolation wall design calculations (Continued)

Required bulkhead length with low pressure grouting on masonry/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Pressure gradient along bulkhead thickness T = 12 ft

$$\rho_g = \frac{\rho}{12} = \frac{480}{12} = 40.0 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along masonry/rock salt contact around 12-ft effective bulkhead thickness is:

$$FS = \frac{41}{40.0} = 1.03$$

Allowable masonry shear on Exhaust Drift perimeter:

$$f'_s = 2\sqrt{f'_c} = 2\sqrt{2500} = 100 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h\ell}{2(h+\ell)f'_s}$$

$$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(12)(12+14)100}{12(14)} = \frac{62400}{168} = 371.4 \text{ psi}$$

$$W = \rho_d h\ell = 480(12)14(144) = 11{,}610{,}000 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{11610000}{2(12+14)12(144)} = \frac{11610000}{89860} = 129.2 \text{ psi}$$

Factor of Safety against masonry shear failure $= \frac{f'_s}{v_s} = \frac{100}{129.2} = \underline{\mathbf{0.77}}$

Required masonry wall thickness to resist design methane explosion pressure

$$T = \frac{\rho h\ell}{2(h+\ell)f'_s} = \frac{480(12)14}{2[13+20]100} = \frac{81640}{6600} = 12.2 \text{ ft}$$

Allowable rock salt shear force along masonry/rock salt contact, Exhaust Drift explosion-isolation bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to masonry/rock salt contact:

L_{rs} = 12 ft^2/ft of perimeter

Appendix D. Exhaust Drift explosion-isolation wall design calculations (Continued)

Minimum rock salt perimeter = 2(13+15) = 56 ft
based on perimeter hitched 6-in into roof, ribs and floor of Exhaust Drift

Total effective bulkhead shear area = 672 ft^2

Maximum rock salt shear resistance = 672(1070)144 = 103,500,000 lb

Maximum shear force on panel side bulkhead face and outward inclined panel side masonry/rock salt contact potentially opened by explosion gas pressure:

Face area = 13(15) = 195 ft^2

Design maximum thrust = (195)(480)144 = 13,480,000 lb

Factor of Safety against rock salt shear failure = $\frac{103,500,000}{13,480,000} = 7.68$

Masonry explosion-isolation beam bending stress design, Exhaust Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1) for 480 psi design dynamic pressure head:

$\omega = U = 2\rho_d(144) = 2(240)144 = 69,120 \left(\frac{lb}{ft^2}\right)$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$M_n = \frac{\omega \ell^2}{24} = \frac{69120(14^2)}{24} = 564,500$ ft·lb

$M_u = \frac{M_n}{0.65} = \frac{564500}{0.65} = 868,500$ ft·lb

$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$

$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5$ psi

$f'_{cl} = 150 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{868500}{\frac{144T^2}{6}} = \frac{36190}{T^2}$

$T = \sqrt{\frac{36190}{162.5}} = \sqrt{222.7} = 14.9$ ft thick masonry bulkhead is required for worst-case rib to rib fixed explosion-isolation bulkhead.

$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{868500}{\frac{144(12^2)}{6}} = \frac{868500}{3456} = 251.3$ psi

$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{251.3} = \underline{\mathbf{0.65}}$

Appendix D. Exhaust Drift explosion-isolation wall design calculations (Continued)

Therefore, 12-ft thick cement mortared masonry block wall, worst-case griped at both ribsides of the 14-ft wide Exhaust Drift, is NOT acceptable as an explosion-isolation bulkhead.

Masonry bulkhead deep beam griped at Exhaust Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(12^2)}{24} = 414{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{414700}{0.65} = 638{,}000 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 162.5 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{638000}{\frac{144T^2}{6}} = \frac{26580}{T^2}$$

$T = \sqrt{\frac{26580}{162.5}} = \sqrt{177.2} = 13.3$-ft thick concrete block masonry bulkhead is required for best-case roof to floor fixed beam bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{638000}{\frac{144(12^2)}{6}} = \frac{638000}{3456} = 184.6 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{184.6} = \underline{\mathbf{0.88}}$$

Therefore, 12-ft thick cement mortared masonry block wall, best-case griped at roof and floor of the 12-ft high, Exhaust Drift is NOT acceptable as an explosion-isolation bulkhead.

APPENDIX E. INTAKE DRIFT CONSTRUCTION-ISOLATION WALL DESIGN CALCULATIONS (ROOF FALL PRESSURE)

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = masonry shear strength $\left(2\sqrt{f'_c} = 100 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Intake Drift width (20 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_d= dynamic pressure head (0.035 psi)
γ_c = masonry density (151PCF)
γ_s = salt density (140 PCF)
ϕ= plain concrete strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = masonry comp strength (2,500 psi)
f_{cl} = masonry tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{2500} = 162 \text{ psi}\right]$
h = Intake Drift height (13 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (4 ft)
V_c = concrete shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ = design pressure head (0.070 psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w= water density (62.4PCF)
σ_s= flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of masonry/rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Intake Drift bulkhead, 10 psf design dynamic pressure head = $L\rho_d = 2(0.035) = 0.070$ psi

Appendix E. Intake Drift construction-isolation wall design calculations (Continued)

Required bulkhead thickness with low pressure grouting on masonry/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{0.070}{41} = 0.0002 \text{ ft}$$

Pressure gradient along bulkhead thickness T = 4 ft

$$\rho_g = \frac{\rho}{T} = \frac{0.070}{4} = 0.0175 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along masonry/rock salt contact around 28-ft effective bulkhead thickness is:

$$\underline{FS} = \frac{41}{0.0175} = >2300$$

Allowable masonry shear on Intake Drift perimeter:

$$f'_s = 2\sqrt{f'_c} = 2\sqrt{2500} = 100 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h\ell}{2(h+\ell)f'_s}$$

$$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(4)(13+20)100}{13(20)} = \frac{26400}{260} = 101.5 \text{ psi}$$

$$W = \rho_d h\ell = 0.070(13)20(144) = 2621 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{2621}{[2(13+20)]4(144)} = \frac{2621}{38020} = 0.0689 \text{ psi}$$

Factor of Safety against masonry shear failure $= \frac{f'_s}{v_s} = \frac{100}{0.0689} = >1450$

Allowable rock salt shear force along masonry/rock salt contact, Intake Drift constructon-isolation bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to masonry/rock salt contact:

$L_{rs} = 4 \text{ ft}^2/\text{ft}$ of perimeter

Minimum rock salt perimeter = 2(14+21) = 70 ft
(6-in inset in roof, walls and floor)

Total effective bulkhead shear area = 280 ft^2

Appendix E. Intake Drift construction-isolation wall design calculations (Continued)

Maximum rock salt shear resistance = $2(14+21)12(1070)144 = 129{,}400$ lb
based on perimeter hitched 6-in into roof, ribs and floor of Intake Drift

Maximum shear force on masonry/rock salt contact potentially opened by roof fall overpressure:

Face area = $14(21) = 294$ ft^2

Design maximum thrust = $(294)(0.070)144 = 2{,}964$ lb

Factor of Safety against rock salt shear failure = $\frac{129{,}400}{2{,}964} = 43.7$

Masonry construction-isolation beam bending stress design, Intake Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1)

for 0.070 psi design dynamic roof fall pressure head:

$$\omega = U = 2\rho_d(144) = 2(0.035)144 = 10.1\left(\frac{lb}{ft^2}\right)$$

Simply supported 4-ft thick bulkhead beam supported at rock salt ribs by contact grout pressure (worst-case)

$$M_n = \frac{\omega \ell^2}{8} = \frac{10.1(21^2)}{8} = 556.8 \text{ ft}\cdot\text{lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{556.8}{0.65} = 856.6 \text{ ft}\cdot\text{lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 150 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{856.6}{\frac{144T^2}{6}} = \frac{35.69}{T^2}$$

$T = \sqrt{\frac{35.69}{162.5}} = \sqrt{0.220} = 0.47$ ft thick masonry concrete bulkhead is required for worst-case rib to rib simply-supported construction-isolation bulkhead

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{856.6}{\frac{144(4^2)}{6}} = \frac{856.6}{384.0} = 2.23 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{2.23} = >73$$

Appendix E. Intake Drift construction-isolation wall design calculations (Continued)

Therefore, 4-ft thick cement-mortared concrete block masonry bulkhead, worst-case, simply-supported at both ribsides of the hitched in 21-ft wide Intake Drift, is acceptable as a construction-isolation bulkhead.

Simply supported 4-ft thick bulkhead beam supported at roof and floor by contact grout pressure (best-case)

$$M_n = \frac{\omega \ell^2}{8} = \frac{10.1(13^2)}{8} = 213.4 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{213.4}{0.65} = 328.3 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 162.5 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{328.3}{\frac{144T^2}{6}} = \frac{13.68}{T^2}$$

$T = \sqrt{\frac{13.68}{162.5}} = \sqrt{0.0842} = 0.29$ ft thick masonry bulkhead is required for best-case rib to rib simply-supported construction-isolation bulkhead

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{328.3}{\frac{144(4^2)}{6}} = \frac{328.3}{384.0} = 0.855 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{0.855} = >190$$

Therefore, 4-ft thick cement-mortared concrete block masonry bulkhead, best-case simply-supported at roof and floor of the hitched 13-ft high Intake Drift, is acceptable as a construction-isolation bulkhead.

APPENDIX F. TRIAXIAL PROPERTIES OF PERMIAN EVAPORITES

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
AEC-7 & ERDA-9 boreholes, rock salt	3230	29.6°	940	0-3000	8
from 1900 to 2800 ft, Carlsbad, NM (GCR, Chapter 4)					
Mississippi Chemical Corp., Carlsbad, NM					
Cycle 7, Potash salt (CSM Lab, 1982)	3520	46.6°	700	0-1500	64
Cycle 5, Potash salt (CSM Lab, 1991)	2880	36.9°	720	0-1500	34
Cycle 5, Roof rock salt	3170	39.3°	750	0-2000	25
Cycle 5, Floor clayey rock salt (CSM '92)	3580	38.1°	870	0-2000	20
PCS Mining, Ltd., Rocanville Div., Saskatchewan (Molavi & Wooley, 1986)					
Esterhazy potash salt mbr.	2300	27.3°	700	Unknown	??
RE/SPEC, Inc., Paradox Basin, UT (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 6, Rock salt	4970	33.7°	1330	0-2200	4
Cycle 6, Carnalite	5660	32.0°	1570	0-2200	4
Cycle 7, Rock salt	5880	33.5°	1580	0-2200	4
RE/SPEC, Inc., Permian Basin, TX (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 5, Rock salt	5000	31.2°	1410	0-2200	10
Cycle 4, Rock salt	4150	30.8°	1180	0-2200	4
Dettin Well, Rock salt, 1900-ft depth	4640	33.8°	1240	0-2200	6
Dettin Well, Rock salt, 2250-ft depth	4280	36.0°	1090	0-2200	6
Zeeck Well, Rock salt, 28-2900-ft depth	4750	33.4°	1280	0-2200	9
Carey Salt Co., Hutchinson, KS (CSM Lab, 1985)					
Rock salt	2900	49.1°	540	0-1000	24
Independent Salt Co., Kanapolis, KS (CSM Lab, 1987)					
Roof rock salt	4330	31.2°	1220	0-3000	16
Averages	4080	35.2°	1070		
Standard Deviations	1040	5.9°	330		

APPENDIX G. TRIAXIAL PROPERTIES OF SELECTED EVAPORITES

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
Minerales Para La Industria, Sal-Gema, Hidalgo, N.L., Mexico (CSM & Adv Terra Testing Labs 1992)					
Grueso Brecha Domo Sal, Barreno30	3630	48.4°	690	0-2000	9
Intermedio Brecha Domo Sal, Bar 30	3180	49.3°	590	0-2000	7
Fino Brecha Domo Sal, Barreno 30	3150	48.8°	600	0-2000	9
All Barreno 30 Brecha Sal Pruebas	3340	48.7°	630	0-2000	25
Upper Brecha Sal, Barreno 36	7510	44.9°	1560	0-2000	5
Lower Brecha Sal, Barreno 36	5230	47.8°	1010	0-2000	5
All Barreno 36 Brecha Sal Pruebas	6350	46.4°	1270	0-2000	10
ALL BRECHA SAL PRUEBAS, Bars 30-36	4110	48.4°	780	0-2000	35
Minerales Para La Industria, Sal-Gema, Hidalgo, N.L., Mexico (ATT Lab 1992)					
Yeso, Caliza y Anhidrita Brecha Barreno 36	5050	47.2°	990	0-2000	5
Minerales Para La Industria, Sal-Gema, Hidalgo, N.L., Mexico (ATT Lab 1992)					
Red Brecciated Salt, Barreno 20	2260	20.0°	790	0-2000	3
AEC-7 & ERDA-9 boreholes, rock salt from 1900 to 2800 ft, Carlsbad, NM (GCR, Chapter 4)	3230	29.6°	940	0-3000	8
Cote Blanche Mine, Cote Blanche, LA (Hansen, 1977)					
Cote Blanche, dome salt	4130	40.1°	960	0-1500	9
Cote Blanche, yellow dome salt	6840	34.5°	1800	0-1500	3
German Democratic Republic (Menzel, et al, 1972)					
Rock salt	5590	34.8°	1460	0-4250	8
"Hartsalz"	6950	35.5°	1790	0-4250	8
Carnolite	4730	30.6°	1350	0-4250	8
"Sylinit"	6730	34.0°	1790	0-4250	8

APPENDIX G. TRIAXIAL PROPERTIES OF SELECTED EVAPORITES (Continued)

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
Mississippi Chemical Corp., Carlsbad, NM					
Cycle 7, Potash salt (CSM Lab, 1982)	3520	46.6°	700	0-1500	64
Cycle 5, Potash salt (CSM Lab, 1991)	2880	36.9°	720	0-1500	34
Cycle 5, Roof rock salt	3170	39.3°	750	0-2000	25
Cycle 5, Floor clayey rock salt (CSM Lab, 1992)	3580	38.1°	870	0-2000	20
PCS Mining, Ltd., Rocanville Div., Saskatchewan (Molavi & Wooley, 1986)					
Esterhazy potash salt mbr.	2300	27.3°	700	Unknown	??
RE/SPEC, Inc., Paradox Basin, UT (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 6, Rock salt	4970	33.7°	1330	0-2200	4
Cycle 6, Carnalite	5660	32.0°	1570	0-2200	4
Cycle 7, Rock salt	5880	33.5°	1580	0-2200	4
RE/SPEC, Inc., Permian Basin, TX (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 5, Rock salt	5000	31.2°	1410	0-2200	10
Cycle 4, Rock salt	4150	30.8°	1180	0-2200	4
Dettin Well, Rock salt, 1900-ft depth	4640	33.8°	1240	0-2200	6
Dettin Well, Rock salt, 2250-ft depth	4280	36.0°	1090	0-2200	6
Zeeck Well, Rock salt, 28-2900-ft depth	4750	33.4°	1280	0-2200	9
RE/SPEC, Inc., LA salt domes (Pfeifle, Mellegard & Senseny, 1982)					
Richton Dome	3280	35.7°	840	0-2200	4
Vacherie Dome	3340	36.6°	840	0-2200	4
RE/SPEC, Inc., Avery Island, LA (Hansen & Mellegard, 1979)					
Dome rock salt	3640	35.4°	940	0-3000	7
Meadowbank Mine, Cheshire, Great Britain (Sen, 1962)					
Rock salt	4640	40.9°	1060	0-1000	3

APPENDIX G. TRIAXIAL PROPERTIES OF SELECTED EVAPORITES (Continued)

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
Carey Salt Co., Hutchinson, KS (CSM Lab, 1985)					
__Rock salt	2900	49.1°	540	0-1000	24
TG Chemicals, Inc., Granger, WY (CSM Lab, 1985)					
__Bed # 21, Trona	3900	43.9°	830	0-2000	49
General Chemical Corp., Green River, WY (CSM Lab, 1987)					
__Bed # 17, Trona	5860	42.8°	1280	0-3000	72
Independent Salt Co., Kanapolis, KS (CSM Lab, 1987)					
__Roof rock salt	4330	31.2°	1220	0-3000	16
Morton Salt Co., Fairport Harbor Mine, Painesville, OH (CSM Lab, 1987)					
__Rock salt	4020	39.0°	960	0-4000	30
Gold Bond Building Products Co., Shoals Mine, IN, (CSM Lab 1988-89)					
__Gypsum	2880	34.0°	765	0-1300	22
Averages	4390	36.2°	1100		
Standard Deviations	1320	6.3°	350		

APPENDIX C

Waste Isolation Pilot Plant, Review of Proposed Panel Closure Enhancements

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WASTE ISOLATION PILOT PLANT REVIEW OF PROPOSED PANEL CLOSURE ENHANCEMENTS

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10 July 2001

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EXECUTIVE SUMMARY

The panel closure system for the Waste Isolation Pilot Plant (WIPP) Project near Carlsbad, New Mexico, is comprised in part of a mass concrete plug, together with installation of a grout to fill any voids between the concrete plug and host halite rock. The specification for the project provided a prescription based formulation for the *Salado Mass Concrete* for the closure panel. The specification also required the use of a crushed quart aggregate. With respect to the grout, the specification required the use of a fresh-water based grout.

AMEC has been asked to review and comment on three proposed *Panel Enclosure Enhancements:*

(a) A change to the specifications to allow the use of a well-rounded carbonate-based coarse aggregate in lieu of the originally specified crushed quartz aggregate in the mass concrete.
(b) A change in the grout used from a fresh-water grout to a salt-based grout.
(c) A change for the mass concrete requirements from a prescription-based specification (which gives a recipe for the *Salado Mass Concrete*) to a performance-based specification which requires the Contractor to formulate the mass concrete mixture design and meet a prescribed set of performance specifications.

In brief, AMEC concurs in principle with the above-proposed *Panel Closure Enhancements* as detailed in the report, which follows. AMEC has, however, provided a number of recommendations as to issues which should be addressed by the specifiers with respect to the proposed changes. In particular, with respect to the proposed change to a *well-rounded carbonate-based rock*, it is recommended that it be demonstrated that:

- The carbonate-based rock is physically and chemically suitable for it's intended purpose, i.e. it should be shown to not be susceptible to deleterious alkali-carbonate reactivity, or salt-induced chemical degradation, and should display satisfactory thermal properties.
- The coarse aggregate should have suitable bonding characteristics to the past fraction (the use of particles with a partial *crush-count* should be considered).

With respect to the proposed use of a salt-based grout, AMEC concurs with this proposed conge, since it will counteract the tendency for dissolution (and hence void formation) of fresh-water based grouts. Also, review of the literature indicates enhanced long-term chemical stability of salt-saturated grouts placed in salt formations, compared to fresh-water grouts.

Finally, with respect to the proposal to change from a prescriptive *Saslado Mass Concrete* specification to a *Generic Salt-Based Concrete* specification for the closure panel concrete, AMEC concurs with this recommended change, since it gives the Contractor more freedom to adjust the mass concrete mixture properties to optimize the concrete construction process. Also, it places responsibility for performance of the concrete with the Contractor. This is contractually preferable for the Owner. The project specification should, however, then be written in rigorous performance-based specification language. In addition, more specifics should be provided in the specification regarding permissible constituents materials for the mass concrete for components such as the salt (type and saturation level required) and shrinkage compensating materials.

1.0 INTRODUCTION

AMEC Earth & Environmental Limited (AMEC), was retained by Mining and Environmental Services LLC (MES) to review certain proposed panel closure enhancements for the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico USA. Specifically AMEC was provided with a *Panel Closure Enhancement* (1) report by MES and asked to:

(a) Review the proposed change to the specifications to allow the use of well-rounded carbonate coarse aggregate in the panel closure concrete, in lieu of the crushed quartz aggregate specified in the *detailed design report for an operational phase panel closure system.*
(b) Review the proposed change to the specifications to allow the use of a salt-based grout, in lieu of the fresh water grout specified in the initial design report.
(c) Comment briefly on the proposed change to the specification to permit the use of a generic salt-based concrete in the panel closure concrete in lieu of the Salado Mass Concrete specified in the initial design report. (This was an addition to the initial terms of reference)

In addition to reviewing the report detailing the proposed *Panel Closure Enhancements* (1) provided by MES, AMEC conducted a literature search on the subject and reviewed relevant papers including Sandia National Laboratories Reports provided to AMEC by the Environmental Evaluation Group in Albuquerque, New Mexico. AMEC also communicated with a grouting specialist, Alex Naudts of ECO Grouting Specialists Ltd. in Ontario, Canada, with experience in the use of salt-based cement grouts in potash mines and other salt formations.

The report, which follows, provides a brief review of the preceding proposed panel closure enhancements. This report is written by Dr. D. R. Morgan, P.Eng, a civil engineer with particular experience in concrete technology, including concrete and grout mixture designs and construction monitoring and testing for civil and mining projects. While Dr. Morgan is not a chemist, he has considerable experience with respect to the hydration and durability of portland cement based systems, as affected by the addition of chemical admixtures, supplementary cementing materials and ingress of external aggressive agents. He also has experience in the design and construction of mass concrete structures in civil and mining applications. This report is written from this perspective.

2.0 LITERATURE REVIEW

AMEC conducted a literature search using key words: brine + salt + concrete + grout + potash + Salado in various combinations. Cited references are listed in Appendix A. A general list of references is provided in Appendix B. Readers wanting more details regarding any of the technical issues discussed in this report are invited to examine the cited references and if necessary general references. This reference list should not be considered as all-inclusive. Many more references are contained in the cited and listed references. It does, however provide a listing of key publications on the subjects of interest.

With respect to the proposed use of salt-based grout and generic salt-based panel closure concrete, it should be recognized that the performance of such products is likely to be very *salt-specific.* Thus, while there is value in examining the results of test on salts and performance of concretes and grouts from locations other than the Waste Isolation Pilot Plant (WIPP), most emphasis should be placed on WIPP tests and observations. From review of the literature, it is apparent that the majority of the testing and evaluation for the WIPP project has been conducted by the Sandia National Laboratories in Albuquerque, New Mexico. Most emphasis should thus be placed on the findings of these reports.

3.0 CHANGE IN GENERAL AGGREGATE SPECIFICATIONS

3.1 General

A proposed enhancement to the panel closure is to expand the specification for the coarse aggregate to be used in the mass concrete to allow for the use of well-rounded natural carbonate materials in place of the specified crushed quartz aggregate. The main reason for this proposed change is to improve the workability of the concrete in general, and pumpability in particular. A second reason for the proposed change is the fact that crushed quartz is not available within a 50-mile radius of the WIPP site, whereas natural rounded carbonate aggregates are locally available.

It is reported that the carbonate aggregate mineralogy is such that it should not adversely affect properties. This should be verified by:

(a) Examination of a petrographic analysis of the aggregate (ASTM C295) (2)
(b) Examination of conformance of the aggregate to the ASTM C33-99a *Standard Specification for Concrete Aggregates* (3)

In particular, the aggregate should be demonstrated to conform to the requirements in ASTM C33-99a, Tables 2 and 3 for:

- Gradation, including percent passing the 75 µm (No. 200) sieve;
- Deleterious particles (e.g. clay clumps, friable particles, chert, coal, etc).
- Magnesium sulphate soundness loss.

3.2 Alkali Aggregate Reactivity

Evaluation of the alkali aggregate reactivity (AAR) susceptibility of the aggregate should be carried out. More specifically it is recommended that records be produced demonstrating that the carbonate aggregate is non-reactive when evaluated against the:

- ASTM C 586-99 *Standard Test Method for Potential Reactivity of Carbonate Rocks as Concrete Aggregates* (*Rock-Cylinder Method*) (4) ;
- ASTM C1105-95 *Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock Reaction* (5) (12 month prism test).

Additional guidance with respect to evaluation and testing of carbonate-based aggregates for AAR can be found in CSA A 23.1-00, *Concrete Materials and Methods of Concrete Construction, Appendix B Alkali Aggregate Reaction* (6) and CSA A 23.2-27A *Standard Practice to Identify Degree of Alkali-Reactivity of Aggregates and Measures to Avoid Deleterious Expansion in Concrete* (7).

3.3 Chemical Stability in Brine

It is reported by Nowak et al (8) and Wakeley et al (9) that a certain dolomitic aggregate near Carlsbad, NM, has shown vulnerability to chemical alteration by reaction with brines in concrete. (Note: Dolomite, $MgO.CO_3.CaO.CO_3$.). It should be demonstrated that the carbonate aggregate selected for use is not susceptible to such deterioration.

3.4 Thermal Considerations

In addition to the above-recommended tests to demonstrate the suitability of the carbonate-based aggregate for it's intended use in the mass concrete closure panels, consideration should be given to the differences in thermal properties of the carbonate-based aggregates compared to the previously approved quartz-based aggregates. There are three thermal properties of aggregate that may be significant in the performance of the mass concrete: coefficient of thermal expansion, specific heat and conductivity. It is recommended that these thermal properties of the carbonate-based aggregate be determined and compared against those of the original crushed quartz aggregate specified. The design engineers for the closure panels should then evaluate the significance of any differences between the thermal properties of the two aggregate types on the expected behaviour of the mass concrete closure panels.

It is not proposed in this brief review report to elaborate on the test methods for the determination of thermal properties of the aggregates (or concrete) and the significance of these thermal properties with respect to the short and long term performance of the mass concrete closure panels. Good guidance in this regard can however, be found in publications such as: Cook, *Thermal Properties* (10,11) and Neville, *Properties of Concrete* (12).

A few thermal considerations are nevertheless worth pointing out:

- The coefficient of thermal expansion of the aggregate influences the coefficient of thermal expansion of the concrete containing such aggregate.
- It is desirable to have a coefficient of thermal expansion in the coarse aggregate which does not differ too much from the coefficient of thermal expansion of the hydrated portland cement paste in the concrete. Serious differences in the coefficients of thermal expansion have been reported to occur with aggregates with very low expansion, such as certain granites, limestones, and marbles (12). In such concretes, a large change in temperature (e.g. such as induced by the heat of hydration of the concrete) may introduce differential movement between the aggregate particles and paste, sufficient to break bond. This could result in microcracking, sufficient to impact on the durability of the concrete.

Thus for the carbonate aggregates proposed for use in the mass concrete closure panels at WIPP, it is recommended that the coefficient of thermal expansion of the aggregate be determined, to verify that it is suitable for use in it's intended application.

3.5 Workability/Pumpability

The prime reason for the proposed change from crushed quartz aggregate to a well-rounded carbonate-based rock is to enable production of a concrete with enhanced *workability* (mixing, pumping, placing, and consolidation characteristics) for the mass concrete closure panels. While quarried crushed rock is used to produce concrete with acceptable *workability* in several parts of North America (particularly the Eastern USA and Eastern Canada), natural rounded fluvial or glaciofluvial gravels typically produce concretes with superior *workability*, which are easier to mix, pump, place, consolidate and finish.

It should, however, be noted that most gravels used in concrete production are usually partially crushed, i.e. have a certain *crush-count*. There are certain advantages to having partially fractured faces in a sufficient percentage of the aggregate particles, including enhanced compressive, flexural and tensile strength development in the concrete made with such particles, compared to concrete made with natural rounded particles only. This observation, however, only applies if the particle crushing process produces aggregate particles with suitable shape i.e. particles that are more *equant* (cubical to round), as opposed to excessive quantities of particles that are flat, platy or elongated.

With respect to the proposed change to the use of natural rounded aggregates it should be cautioned that aggregate particles with very dense, smooth (polished) surfaces will typically have lower bond strengths than aggregates with rougher surface texture. Partial crushing of natural rounded aggregates is beneficial in that fracture faces on the aggregate particles typically have greater surface roughness. This enhances bond strength to the paste and consequently improves compressive, flexural and tensile strength development in the concrete.

To summarize, the proposed enhancement to use natural well-rounded aggregates to improve *workability* (including pumpability) of the closure panel concrete is considered appropriate. Consideration should, however, be given to producing an aggregate with a partial *crush-count*, to enhance paste to aggregate bond and consequent physical concrete properties.

4.0 SALT-BASED GROUT

It is understood that the *Environmental Protection Agency (EPA) Certified Closure* for the panel closure design approved the use of a *fresh water grout*. The proposed enhancement is to use a salt saturated grout instead. The purpose of the grout is to fill any voids that develop at the *back* (overlying roof) between the panel closure concrete, and the host halite formation as a result of sedimentation and bleeding, etc. in the mass concrete.

The concern with respect to using a *fresh water grout* is twofold:

(a) The liquid grout has the potential to dissolve the host halite material during placement, which is counterproductive to it's intended void sealing function;
(b) There is potential for a reduction in the long term stability and durability for the hardened grout because of the *chemical gradient* developed between the fresh water grout and the host halite formation; i.e. magnesium and other ions moving from the halite formation into the grout can result in calcium dissolution and depletion, which in turn can cause a loss of strength and degradation of the grout. Details regarding this dissolution mechanism can be found in publications by Wakeley and Burkes (13), Tumidajski and Chan (14), Wakeley et al, (15), Lambert et al (16) and Pool et al, (17).

Thus the proposed enhancement to use a salt-based grout is intended to negate the above concerns with using a *fresh water grout*. The use of a suitable salt solution (typically sodium chloride) as a mixing fluid in the grout minimizes the potential for the fresh grout to dissolve the host halite formation during placement and reduces the chemical gradient between the host halite formation, hardened grout, and proposed salt-based concrete (13, 14, 15, 16,17). In addition, Wakeley et al (15) report that salt-free grouts, when placed in contact with halite form no bond with the host rock. By contrast, a salt-saturated cementitious material bonds well with the halite.

There is precedence for the use of salt-saturated mixing water in cement-based grouts for void sealing of salt formations. Details can be found in publications such as Eyermann et al (18), Al-Manaseer et al (13) and others.

In addition to a review of the literature on this subject, Dr. Morgan of AMEC spoke with Alex Naudts at ECO Grouting Specialists Ltd., in Ontario, Canada, who has considerable experience in grouting in potash and salt mines. At AMEC's request, he provided a brief *capability statement* (20) of his experience in this regard. A copy of this statement is attached in Appendix B.

Notable examples of the use of salt-saturated grouts for void sealing purposes in salt formations include:

- Rocanville, Potash Mine, Saskatchewan, 1985 (19, 20)
- Esterhazy (K2) Mine, Saskatchewan, 1986 (19,20)
  (The writer was involved in the design and construction of one of the four bulkheads constructed on this project).
- Kali & Salz Potash Mine, Kassel, Germany (20)
- Potocan Potash Mine, New Brunswick (20)

Naudts (20) drew the conclusion that: *Most parties agree that it is not appropriate to use fresh water in grouts in contact with salt or potash ore (halite, carnalite, etc.) because of the migration of sodium, calcium or magnesium ions into the gelling grout, leaving a porous matrix near and at the contact zone.*

Review of the literature indicates that great care should be exercised in formulating salt-based portland cement grouts. Sodium chloride typically acts as a set retarder and water reducer. Chemical admixtures which work well in conventional portland cement-based grouts (without

salt addition) may however, not be compatible with salt-based portland cement grouts. For example, certain water reducers and retarders are reported to not be suitable for use in salt-based grouts because of problems such as very high air contents, foaming, excessively rapid rate of slump loss and excess set retardation (9, 20, 21, 22). Also, bentonite is reported to not be compatible with salt-based grouts (20).

By contrast, supplementary cementing materials, such as fly ash (type F or type C) are reported to be beneficial with respect to improving both the plastic and hardened properties of the grout. The addition of fly ash results in a stable suspension, with reduced bleeding and hence provides a more homogenous grout. Similarly, silica fume is reported to have been beneficially used for such purposes (20, 22). In addition, it is reported that hardened grouts with fly ash addition displayed enhanced bond to halite (13) and superior *long term* performance, compared to grouts with no fly ash, with respect to parameters such as compressive and flexural strength and modulus of elasticity, when the grouts were submerged in containers with brine at various confining pressures (21).

An argument can thus be made that the salt-based grouts should be formulated with a supplementary cementing material, such as fly ash (and / or silica fume) for the WIPP project.

An example of a formulation for a salt-based grout with fly ash addition, is the Grout BCT-1F described below, which is given in the *WIPP Project Specification Section 02722 Section 2.1* (23).

Table 1: Salt-Saturated Grout (BCT-1F)

Component	Percent of total Mass (wt.)
Class H cement	48.3
Class C fly ash	16.2
Cal Seal (plaster – from Halliburton)	5.7
Sodium Chloride	7.9
Dispersant	0.78
Defoamer	0.02
Water	21.1

The specification states: *The following formulation is suggested to the contractor as an initiation point for selection of the grout mix.* The specification does, however, not provide any performance requirements for the grout. As such, the specification is likely to be interpreted as a *prescription specification* by the contractor. This creates potential contractual conflicts if the contractor simply adopts the BCT-1F formulation and the grout does not perform as intended. It is thus recommended that WIPP develop a set of *performance specifications* for the grout, and require the contractor to demonstrate conformance of the grout to these *performance specifications.*

Parameters of interest with respect to *performance specifications* for the grout could include:

- Chloride saturation, including a statement on what type of salt is permissible. Note: While halite is comprised mainly of sodium chloride, it can contain lesser amounts of salts such as calcium sulphate, calcium chloride and magnesium chloride (28);
- Water /cementing materials ratio (likely variable, depending on size of voids to be filled and distance grout has to travel);
- Viscosity, as measured by the Marsh Flow Cone Test e.g. API RP 13B-1;
- Early age volume change e.g. ASTM C 287-95a *Standard Test Method for Change in Height at Early Ages of Cylindrical Specimens for Cementitious Mixtures* (24).
- Volume change at later ages (1, 14, 28 days) as measured by CRD C 621 (25).
- Bleeding and Expansion e.g. ASTM C 940-98a, *Standard Test Method for Expansion and Bleeding of Freshly Mixed Grouts for Preplaced-Aggregate Concrete in the Laboratory* (26).
- Setting time e.g. ASTM C953 *Standard Test Method for Time of Setting of Grouts for Preplaced-Aggregate Concrete in the Laboratory* (27).
- Specific Gravity e.g. API RP 13B-1.

It is recommended that appropriate testing methodologies be selected and a set of performance requirements be established for the salt-based grout(s). This approach would be consistent with the proposed *Panel Closure Enhancement* (1) for the *Generic Salt-Based Concrete*, which represents a change from a prescription to a performance-based specification.

Finally the Panel Closure Enhancement (1) Section 3.6 statement that: *No strength specifications for grout is appropriate, since any grout injected would serve in a lithostatic stress state and not compromise a structural element of the barrier*, is noted. This reviewer concurs with this statement and so setting compressive strength performance requirements for the grout would not appear to be warranted.

5.0 SALT-BASED CONCRETE

AMEC has been asked to comment briefly on the proposed *Panel Closure Enhancement* (1) to permit the use of a generic salt-based concrete in the panel closure concrete in lieu of the Salado Mass Concrete specified in the initial design report. This was an additional item to the original terms of reference, and while we have conducted a literature search on the subject (and done pertinent background reading on the subject) this review is brief, because of time and budget constraints.

In principle, AMEC concurs with this proposed change to the specifications. It is recognized that considerable research has been conducted by the Sandia National Laboratories (8, 9, 15, 16, 17, 18) and others in developing the Salado Mass Concrete for the WIPP Project.

The Panel Closure Cast-in-Place Concrete Specification, Section 03300, provides a list of so-called *Target Properties of the Concrete Mix*, in clause 2.5. For convenience of referral, this clause is produced below.

2.5 Target Properties of the Concrete Mix

The Contractor shall develop and proportion a salt-saturated mix for use in constructing the concrete barrier. The Contractor shall demonstrate by trial mix that the proposed concrete meets the following properties:

Table 2: Target properties for Barrier Concrete

Property	*Comment*
4-hr working time	*Indicated by 8-inch slump (ASTM C 142) after 3-hr intermittent mixing, or an appropriate measure of pumpability.*
Less that 25°F heat rise prior to placement	*Difference between initial condition and temperature after 4 hr.*
4,000 psi compressive strength (f'_c)	*At 56 days after casting (ASTM C 39)*
Volume stability	*Length change between +0.05 percent and-0.02 percent (ASTM C 490)*
Minimal entrained air	*2 percent to 3 percent air*

The Contractor shall provide certified copies of test data from an approved laboratory demonstrating compliance with the above target properties.

In addition to the target properties the Contractor shall provide certified test data for the trial mix for the following properties:

- *Heat of hydration* — *ASTM C-186*
- *Concrete set* — *ASTM C-403*
- *Thermal Diffusivity* — *USACE CRD-C36*
- *Water Permeability* — *USACE CRD-C43*

The specifications then provide what amounts to a *prescription* formulation for the Salado Mass Concrete, as detailed below.

An example of initial proportioning for the concrete is the salt-saturated concrete shown below:

Table 3 : Salt-Based Concrete Mixture Proportions

Component	*Percent of Total Mass*
Class H cement (API 10)	*4.93*
Chem Comp III (ASTM C-845 Type K)	*2.85*
Class F fly ash (ASTM C-618)	*6.82*
Fine aggregate	*33.58*
Coarse aggregate	*43.02*
Sodium chloride	*2.18*
Defoaming agent	*0.15*
Sodium citrate	*.009*
Water	*6.38*

The specification then goes on to say: The Contractor shall prepare a trial mix and provide certified test data from an approved testing laboratory for slump, compressive strength, heat rise, heat of hydration, concrete set time, thermal diffusivity, and water permeability.

Despite the wording in the specifications, the above approach is tantamount to a *Prescription Specification*, i.e. the Contactor is being told what mass concrete mixture proportions to use. There are potential contractual concerns with this approach, since if the concrete supplied failed to meet the required performance parameters, the Contractor could argue, with some justification that it is not his responsibility, but that if the specifying authority.

In AMEC's view, it is preferable to write the specification as *a Performance-Based Specification*, with the responsibility for the concrete mixture proportioning residing with the Contractor. The specifier should write a rigorous performance-based specification, including provision of specifics regarding all constituent materials permitted to be used in the *generic salt-based concrete*. In particular, specifics should be provided regarding the salt that is permitted to be added to the concrete, and which shrinkage compensative materials will be permitted to be added.

The Specifier should make available to the Contractor pertinent material regarding *Salado Mass Concrete* developed for the WIPP Project. This material can then provide the Contractor with a starting point for his *generic salt-based mixture proportioning*. In this way, the Contractor can adjust the mixture design, if required during construction, to facilitate the construction process. The responsibility for performance of the concrete would however, reside with the Contractor.

6.0 Limitations and Closure

This report has been prepared for the exclusive use of Mining and Environmental Services LLC for the purpose described in the report. Any use which a third party makes of this report, or any reliance on or decisions made based on it, are the responsibility of such third parties. AMEC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report. It has been prepared in accordance with generally accepted materials engineering practices. No other warranty, expressed or implied, is made.

AMEC thanks you for this opportunity to have been of service. We trust that this report satisfies your current requirements. Should you have any questions, please contact this office.

Yours Truly,

AMEC Earth & Environmental

Original signed by

D. R. Morgan, Ph.D., P. Eng
Chief Materials Engineer

Reviewed by:

Original signed by

John Laxdal, P. Eng
Regional Manager

APPENDIX A :

CITED REFERENCES

CITED REFERENCES

(1) *Panel Closure Enhancements,* Report provided to AMEC by Mining and Environmental Services LLC

(2) ASTM C 295-98, *Guide for Petrographic Examination of Aggregates for Concrete.*

(3) ASTM C33-99a, *Standard Specification for Concrete Aggregates.*

(4) ASTM C586-99, *Standard Test Method for Potential Reactivity of Carbonate Based Rocks as Concrete Aggregates (Rock-Cylinder Method).*

(5) ASTM C1105-95, *Standard Test Method for Length Change of Concrete due to Alkali – Carbonate Rock Reaction.*

(6) CSA A23.1-00, *Concrete Materials and Methods of Concrete Construction, Appendix B, Alkali Aggregate Reaction*, Canadian Standards Association, 2000.

(7) CSA A23.2-27A, *Standard Practice to Identify Degree of Alkali Aggregate Reactivity of Aggregates and Measures to Avoid Deleterious Expansion in Concrete*, Canadian Standards Association, 2000.

(8) Nowak, E.J., Wakeley, L.S., Poole, T.S., and Burkes, J.P., *Investigations of Deteriorated Concrete from the Liner of the Waste Isolation Pilot Shaft,* SAND 91-2733.UC-721.

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(18) Eyermann, T.J., Sambeek, L.L., and Hansen, F.D, *Case Studies of Sealing Methods and Materials Used in the Salt and Potash Mining Industries*, SAND95-1120•UC-721.

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(20) Naudts, A., *Personal Communication Regarding the use of Salt-Based Grouts prepared for Dr. Morgan at AMEC Earth & Environmental*, July, 2001.

(21) Al-Manaseer, A.A. and Haug, M.D., *Long Term Performance of Grout Containing Fly Ash and Brine*, American Concrete Institute, STP-153, pp. 109-123.

(22) Naudts, A., *Curtain Grouting from 900 Metres Deep Donut Shaped Tunnel to Dry Up Leaking Shaft at IMC's K2 Mine*, ATTI Proceedings, Soil and Rock Improvements in Underground Works, Milano, March, 1991.

(23) Specification for Panel closure Construction at WIPP. (Cover sheet not provided; thus date of preparation of document not known)

(24) ASTM C827-95a *Standard Test Method for Change in Height at Early Ages of Cylindrical Specimens from Cementitious Mixtures.*

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APPENDIX C :

PRIVATE COMMUNICATION FROM A. NAUDTS

ECO

ECO GROUTING SPECIALISTS LTD

293199 8th Line, RR 1, Grand Valley, ON, Canada L0N 1G0 Phone: (519) 928-5949 Fax: (519) 928-5968
e-mail: ecogrout@ecogrout.com Home Page Internet Address: ecogrout.com

July 3, 2001

ATTN: Dr. Rusty Morgan
AMEC Earth and Environmental Ltd.
2227 Douglas Road
Burnaby, BC
V5C 5A9

amec
Earth & Environmental

JUL 05 2001

RECEIVED

Dear Dr. Morgan:

Re : Capability statement regarding cement based suspension grouts using saturated brines as carrier for the particles, to be used in salty environments

This note is further to our conversation of this afternoon. It was good to hear from you after all those years.

ECO has done extensive work developing and testing cement based suspension grouts to be used in saline environments using brine as carrier for the particles.

Most parties agree that it is not appropriate to use fresh water in grouts in contact with salt or potash ore (halite, carnalite, etc), because of migration of sodium, calcium or magnesium ions into the gelling grout, leaving a porous salt matrix near and at the contact zone.

The following is an oversight of some of the work we did in potash and salt mines (formulating and testing):

1. We first developed cement based suspension grouts for Kali & Salz in Germany for a potash mine near Kassel during the late seventies. We established basic fluid and set characteristics. The use of additives and admixtures such as styrene butadieen, clay-phyllosilicates and first generation superplasticisers were novelties at the time. We used a saturated locally found mine brine as the carrier.

We were aiming at low matrix permeability and high strength with the highest fluidity possible. From our on-going relationship with this client, we have learned that the performance of this type of grouts has been satisfactory over the life time. The tests involved bleed-tests, viscosity tests (marsh) and specific gravity test (Mud balance) as well as unconfined compressive strength tests and I believe we also did bond-strength tests from grout to the potash ore.

2. During the eighties we performed lab testing for PCS during the Rocanville flooding. Our design for the plug was implemented. The plug is still standing up under a pressure of 1200 psi (since March 1985). We formulated both regular cement based grouts, microfine cement based grouts and solution grouts using the brine from the mine as carrier. We found that some of the water reducing agents were not compatible with the brine or some of the additives and admixtures. We predominantly used the following additives and admixtures to the brine: super plasticiser, type F-flyash, silica fume (first time we used this) and slag. We found out that bentonite was not compatible with brine. (we should have pre-hydrated the bentonite in fresh water and added this to the mix). We also made samples of grouts and bubbled hydrogen sulphide through the suspension and let the suspension grouts cure in this saturated environment. Three years ago a sealed jar with this smelly gas and cured grout broke when we moved to our present lab-location. The (slag based microfine cement) grout looked "perfect" after 13 years. I remember that some grouts never reached final set and only made it to "somewhere between initial and final set" (Vicat needle).

3. During the IMC potash inflow-crisis in 1986, ECO was asked by this organisation to perform a series of tests to develop "durable cement based grout formulations" for a variety of applications. The tests were actually conducted in the lab of BBT in Saskatoon.

We used similar admixtures as during the tests in Rocanville, but included a portland cement based microfine cement based grout. We also used type C fly-ash (not aware at the time of the critical maximum contents BWOC) and kiln dust. A series of formulations were developed and reports were made. Some of the formulations were used in various phases of the project.

4. ECO performed lab-testing for the grouting around shaft plugs in an abandoned salt mine in Dearborn (Michigan). The actual grouting was never performed because the permitting to use this abandoned mine as a landfill site was never approved.

5. During 1992 ECO performed extensive lab-testing for the installation of a pilot grout-curtain in an abandoned limestone mine in Acron (Ohio), which was to be deepened to be used for the power house for a power generating system (pump storage). The water bearing zones in the limestone were saturated with hydrogen sulphide and brine. A variety of grouts were developed with different rheology, viscosity, cohesion, resistance against pressure filtration, thixotropy, gel times, set times etc.

At the time we used much more sophisticated mixes, using admixtures and additives such as metha glycol cellullose to curtail run-away situations, F-fly-ash, de-airing agents, super plasticisers, slag, pumice and bentonite slurries. The tests were also more sophisticated and included resistance against pressure filtration tests, initial and final gelation and set tests, cohesion tests etc.

6. In 1997, for Potocan (and its German part-owner, Kali & Salz) ECO performed a substantial grout formulation and testing program for one of the biggest grouting ever performed. From over 200 formulations, six formulations were retained with distinctive fluid and set characteristics. The formulations contained in addition to most of the

aforementioned admixtures and additives also modern day bio-polymers and the third generation of super plasiticisers and for the first time we used iso-propyl alcohol to delay the curing of the grout. Brine from this New Brunswick potash mine was used as the carrier of the particles.

7. ECO is involved in an elaborate seal-grouting project for the Werra potash mine in the former East Germany for its owner Kali & Salz. This is a group effort involving an international panel of specialists, all with different expertise. We established grout formulations and test procedures both for regular and microfine cement based grouts. This project is ongoing.

8. ECO has done several grout test programs for manufacturers of microfine cement based grouts. Some of these formulations were made for use in saline environments. Brine saturated solutions were typically used for these tests.

After all those years of testing and evaluating performance of grouts, I must admit that there is still a lot to be learned about the application of suspension grouts in saline environments, especially if magnesium brines are present.

We would be very interested to participate in testing programs or review information by others. You can find more information about our firm on our site: www.ecogrout.com. We are completely independent and have no links or ties with manufacturers nor contractors nor distributors. Thank you for contacting us. We look forward to contribute to this project

Regards,

Alex Naudts, P.Eng.

APPENDIX D

September 4, 2001 letter, Triay to Marcinowski

Department of Energy
Carlsbad Field Office
P. O. Box 3090
Carlsbad, New Mexico 88221

September 4, 2001

RECEIVED
SEP - 6 2001
ENVIRONMENTAL EVALUATION GROUP

Mr. Frank Marcinowski
Office of Radiation and Indoor Air
U.S. Environmental Protection Agency
401 M. Street, S. W.
Washington, DC 20460

Dear Mr. Marcinowski:

On April 17, 2001 we submitted a request to you seeking approval of several proposed enhancements to the WIPP panel closure system. Based on communications with your staff during our recent working meetings, we respectfully withdraw our request for approval of those modifications. In view of the approval of our panel 1 utilization request and our current and projected throughput rates, we wish to re-evaluate our panel closure strategy.

At the conclusion of our evaluation, we expect to revisit this topic with the EPA. We appreciate the effort already expended by your staff in the review of our April submittal. If you or your staff have any questions regarding this matter, please contact Mr. Daryl Mercer at (505) 234-7452.

Sincerely,

Inés Triay

Dr. Inés R. Triay
Manager

cc:
D. Huizenga, EM
S. Monroe, EPA
S. Ghose, EPA
C. Byrum, EPA
N. Stone, EPA
S. Zappe, NMED
M. Silva, EEG

CBFO:ORC:DMM:VW:01-1340:UFC:5400

APPENDIX E
LIST OF EEG REPORTS

LIST OF EEG REPORTS

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EEG-83

IDENTIFICATION OF ISSUES RELEVANT TO THE FIRST RECERTIFICATION OF WIPP

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment of New Mexico. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned the EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC04-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

The EEG performs independent technical analyses on a variety of issues. Now that the WIPP is operational, these issues include facility modifications and waste characterization for future receipt and emplacement of remote-handled waste, generator site audits, contact-handled waste characterization issues, the suitability and safety of transportation systems, mining of new panels, and analysis of new information as part of the five year recertification cycles as mandated by the WIPP Land Withdrawal Act. Review and comment is provided on the annual Safety Analysis Report and Proposed Modifications to the Hazardous Waste Facility Permit. The EEG also conducts an independent radiation surveillance program which includes a radiochemical laboratory.

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ACRONYMS

CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CRA	Compliance Recertification Application
CH TRU	Contact Handled Transuranic waste
DOE	U.S. Department of Energy
EEG	Environmental Evaluation Group
EPA	U.S. Environmental Protection Agency
LANL	Los Alamos National Laboratory
LWA	Land Withdrawal Act
PA	Performance Assessment
STTP	Source-Term Waste Test Program
TRU	Transuranic
UIC	Underground Injection Control
WIPP	Waste Isolation Pilot Plant

EXECUTIVE SUMMARY

One goal of the WIPP Land Withdrawal Act was to assure the safe disposal of the nation's defense transuranic waste into a deep repository in southeast New Mexico. The governing legislation required the U.S. Department of Energy (DOE) to provide to the U.S. Environmental Protection Agency (EPA) analyses of the anticipated performance of the repository. Disposal operations could not begin until the EPA determined that the project demonstrated compliance with EPA Standards (40 CFR 191) and EPA Criteria (40 CFR 194) for such disposal. The Land Withdrawal Act inherently recognized that the EPA Certification would have to rely on best available knowledge at the time when the application was submitted. The Act also recognized that after the initial certification of WIPP and start of disposal operations, operating experience and ongoing research would result in new technical and scientific information. Thus, the legislation requires recertification of the WIPP every five years, following the first receipt of waste. This report updates issues that the Environmental Evaluation Group (EEG) considers important as the Department of Energy (DOE) works towards the first recertification. These issues encompass a variety of technical areas including actinide solubility, fluid injection scenarios, solution mining, Culebra flow and transport, spallings modeling, and non-random waste emplacement.

Given the 24,000-year half life of ^{239}Pu, understanding the characteristics of plutonium in the WIPP environment is obviously important to the validity of long-term performance assessment of the repository. Some uncertainty remains in the understanding of the persistence of higher oxidation states because of reliance on modeling (with its associated assumptions) and limited experimental results. The EEG recommends additional experimental work towards parameters for a proposed conceptual kinetic model of plutonium solubility. In addition, the EEG recommends an intrusion scenario during performance assessment which would account for a heterogeneous, non-inundated repository which may include persisting higher oxidation states of plutonium.

Intrusion scenarios including the consequences of fluid injection were rejected at the time of the Compliance Certification Application (CCA). With increasing drilling activity in the vicinity of the WIPP (Figure 1), fluid injection scenarios should be re-examined for recertification performance assessment. These scenarios should consider potential consequences from oil field secondary recovery techniques such as waterflooding in addition to ancillary injection operations such as brine disposal and pressure maintenance wells. The WIPP resides in a resource rich locale and performance assessment should consider all reasonable activities associated with such a location.

Likewise, solution mining scenarios should also be reconsidered during recertification. Solution mining should be anticipated for extraction of potash reserves as well as for the excavation of salt caverns for storage of natural gas, oil field wastes, and chemical feedstocks. Consideration of solution mining for potash extraction is a natural alternative for a maturing mineral district as ore-grades decrease below the economic cutoff necessary for traditional mining methods. Dissolution of halite for creation of underground storage caverns is a practice already used in the Delaware Basin for oil field waste and natural gas. Research suggests that it may also be a viable method for storage of other items such as chemical feedstocks.

The Culebra dolomite unit of the Rustler Formation is acknowledged as a likely pathway for breach of the WIPP repository. Hence, long-term performance assessment requires an accurate understanding and modeling of flow and potential actinide transport.

Most of the issues concerning the Culebra that were raised at the time of the CCA resulted from poor discretization of the modeling grid and the inherent heterogeneity of the aquifer. The DOE had originally planned to replace the previous flow code with MODFLOW and implement a finer grid. This coupled with a new transport code, STAMMT-L, would have addressed problems with numerical dispersion and spatial truncation errors. In addition, STAMMT-L incorporates a dual-porosity, multi-rate approach, which the DOE demonstrated to be a superior representation of transport within the heterogeneous character of the Culebra. The DOE had originally planned to address issues concerning the Culebra, but now plans no changes to the conceptual model during recertification.

The EEG remains concerned over the continuing water level increases in the Culebra aquifer. The DOE is currently engaged in an effort to determine the source, or sources, of the rising water elevations, which have continued to increase for the last 14 years. Until a cause is determined, the validity of the Culebra conceptual model used for performance assessment is in question.

The EEG recommends that the DOE reconsider its decision **not** to change the Culebra modeling codes and grid discretization. In addition, the EEG urges the DOE to conclusively determine the source of the water level increases and adjust the conceptual model accordingly.

Spallings consist of repository waste material that fails due to a rapid reduction of pressure caused by penetration of the repository by a drill hole. The failed material would be transported up the drill hole to the surface by gas flow. The CCA performance assessment demonstrated the importance of spallings as a potential release mechanism. The spallings model used during the CCA did not adequately characterize the physical processes of spall. Work was in progress by the DOE on a new spallings model that was intended for use during recertification. This model was to improve predictions of long-term performance, reduce uncertainty, and enhance public confidence. However, the DOE has recently announced that the new model would only be used for impact analysis and not for recertification performance assessment. The EEG urges the DOE to reconsider and to use the new model for performance assessment.

Random emplacement of waste in the repository was assumed during the CCA performance assessment. However, waste emplacement practice since the 1999 opening has demonstrated that random emplacement is not likely. Specific waste streams shipments to WIPP depend on the DOE's agreements with the host states, and, on the readiness of particular waste streams for shipment. It has been previously demonstrated by the DOE that non-random emplacement could increase the mean release values. The EEG recommends that DOE develop a waste loading plan based on their shipment schedule. All intrusion scenarios could then consider non-random emplacement, providing better estimates of releases.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Project, located in Southeastern New Mexico was constructed by the U.S. Department of Energy (DOE) to provide permanent disposal of long-lived transuranic (TRU) waste from the U.S. defense activities and programs. The WIPP Land Withdrawal Act (LWA) requires that the facility must comply with 40 CFR 191, Subpart A during the period when radioactive waste is being emplaced and with 40 CFR 191, Subpart B and 40 CFR 194 for long-term disposal. Moreover, the U.S. Environmental Protection Agency (EPA) was assigned the responsibility to make that determination. In May 1998, the EPA certified that the WIPP met the requirements of 40 CFR 191 and 194.

The LWA inherently recognizes that the disposal facility represents a pioneering effort. Undoubtedly, as more scientific and technical information becomes available, there will be a need to revisit the certification decision. Hence, the enabling legislation requires recertification of the WIPP every five years after the first receipt of waste. The repository began receiving CH TRU wastes in March 1999. The first recertification by the EPA is required by March 2004, the second recertification by March 2009, etc. until the closure of the repository shafts.

The EPA standards specify the maximum allowable amount of radioactive material that can escape from the repository to the accessible environment for the regulatory period of 10,000 years. Because this is such a long time, the cumulative releases were predicted with performance assessment calculations. Specifically, the calculations attempt to represent the amount of material released as the result of some future drilling effort inadvertently penetrating the long forgotten repository. By definition, the performance assessment: (1) identifies the features, events and processes that might affect the disposal system, (2) examines their impact on the behavior of the disposal system, and (3) considering associated uncertainties, estimates the cumulative releases of radionuclides.

Experience has shown that the performance assessment must be viewed as an iterative process. As such, the contributions of various factors can achieve greater or lesser significance, depending on the performance assessment models. For example, three performance assessments

were published in 1990 (Bertram-Howery et al. 1990), 1991 (SNL 1991), and 1992 (SNL 1992). During that time frame, the calculated releases were most sensitive to the drilling rate, actinide solubility, and actinide retardation (Helton et al. 1992). After a performance assessment publication hiatus of three years and a redesign of the conceptual models, the calculated releases from the 1996 performance assessment (DOE 1996) were reported to be most sensitive to three drilling phenomena - spalling, cavings, and cuttings.

In the ensuing time period since the Certification Decision (EPA 1998), the Environmental Evaluation Group (EEG) has identified unresolved Performance Assessment (PA) issues pertinent to the Compliance Recertification Application (CRA), (Chaturvedi et al. 1999; Silva et al. 1999 (Appendix A); Rucker et al. 2000; Silva 2000). This report updates the EEG's views on the following issues: (1) actinide solubility, (2) fluid injection, (3) solution mining, (4) Culebra transport, (5) spallings, and (6) non-random waste emplacement.

In November 2001, the DOE issued the Recertification Project Plan (DOE 2001a) outlining the intended activities and timeline for completion of the CRA. Since the Recertification Project Plan was issued, three CBFO/EPA Working Meetings (DOE 2001b; 2002a; 2002b) have been conducted for presentation of information and studies pertaining to the recertification.

The EEG considered that an update of these unresolved issues would be important and timely as the DOE is focusing efforts toward compilation of the CRA. The DOE had originally planned to address several of these issues as part of the recertification, but have since modified their plans. It is recognized that the Recertification Project Plan reflects a snapshot in time, and that the DOE's schedules and activities may change because of unforeseen events or as the result of ongoing investigations. Therefore, this report reflects the EEG's understanding of the DOE's intent at the time of writing.

2.0 UPDATE ON UNRESOLVED ISSUES

Since the EPA Certification Decision in 1998, the EEG has commented on issues which they considered to be unresolved following the Compliance Certification Application (CCA) (DOE

1996). In light of several ongoing investigations by the DOE, as well as the DOE's stated objectives in the Recertification Project Plan, the EEG decided to update the previously identified issues for possible consideration in the 2004 CRA.

2.1 Actinide Solubility

Plutonium (Pu), specifically ^{239}Pu, is the major actinide of concern for long-term repository performance. With a 24,000-year half-life, ^{239}Pu will retain approximately 75 percent of its radioactivity over the 10,000-year regulatory period. Therefore, it is important to know the characteristics of Pu in the WIPP environment, particularly given that previous iterations of performance assessment were found be sensitive to actinide solubility (Helton et al., 1992). These characteristics include: (1) potential oxidation states, (2) solubility in the WIPP brines, and (3) its ability to complex with other waste constituents, such as chelating agents, to form more soluble or less sorptive species. Americium-241 (^{241}Am) with a 432 year half-life, is significant to performance assessment during the first 1500 to 2000 years but its solubility is more predictable. Other actinides, with shorter half-lives, will decay substantially during the regulatory period.

2.1.1 Potential Oxidation States

Understanding the potential oxidation states for plutonium is important for performance assessment. The higher states, Pu (V) and Pu (VI), are more soluble in brine than the lower states. This would increase the amount of radioactivity which would be brought to the surface during a human intrusion event. For the CCA, the DOE assumed that Pu would exist only in oxidation states III and IV. The DOE argued that the reduction potential of iron in the waste and waste containers would keep Pu from persisting in the higher oxidation states of V and VI for any substantial length of time. However, Pu (V) and Pu (VI) have been observed in a number of experiments conducted in brines (Villarreal 2002).

Unfortunately Pu chemistry studies with solutions at near-neutral pH are limited. Most Pu studies were conducted for the separation procedures necessary for defense purposes and done under low pH conditions. Hence, there is little literature pertaining to Pu under the WIPP environmental conditions. Also, complicating its study, Pu is capable of existing in a number of valence states. It may have one valence state in the solution phase and a different valence state in the solid phase in contact with the solution (Haschke and Oversby 2002).

To understand the behavior of Pu under the WIPP disposal conditions, the similarities between the chemistry of uranium (U) and Pu were used together with data from several high level waste disposal programs to construct a conceptual model (Oversby 2000). This model starts with the work of Haschke et al. (2000) which showed evidence for the formation of PuO_{2+x} from PuO_2 and moisture. Experimental data show that the value of x in PuO_{2+x} is as high as 0.27. The model, summarized by Haschke and Oversby, describes the reaction scheme for steady-state solution concentrations of Pu and demonstrates the presence of Pu(V) and Pu(VI) in solution:

1. Pu(V) accumulates in PuO_{2+x} as x is increased by spontaneous reaction of PuO_2 with H_2O.
2. The rate of PuO_2^+ dissolution increases with increasing value of x in PuO_{2+x} until it equals the rate of Pu(V) formation and a steady state is established.
3. PuO_2^+ accumulates until its rate of disproportionation into PuO_2^{2+} (i.e. Pu(VI)) and Pu^{4+} equals its rate of entry into solution and a steady state is established.
4. PuO_2^{2+} accumulates until disproportionation and reduction reform PuO_2^{2+} at a rate equal to half the PuO_2^+ dissolution rate and a steady state is established.
5. Pu^{4+} accumulates until its concentration satisfies the K_{sp} for $Pu(OH)_4$ precipitation and the equilibrium of Pu(IV) concentration is established.
6. Metastable $Pu(OH)_4$ spontaneously transforms into PuO_2 and subsequently back to PuO_{2+x}.

A quantitative model could be developed from this conceptual model. Rate constant data would need to be available for steps 1, 3, and 4, and equilibrium thermodynamic data for step 5.

2.1.2 Solubility in WIPP Brines

To characterize the solubility of plutonium in brine, the DOE used an oxidation state analogy. The oxidation state analogy assumes that species of similar oxidation states behave in a similar manner. For example, rather than determining its solubility experimentally, the DOE estimated Pitzer parameters for Pu (IV) from data reported for thorium (Th) (IV). The DOE then argued that the Pu (IV) estimates were conservative because Th (IV) solubility would be consistently higher than Pu (IV) solubility (Triay 2001). However, experiments conducted at the Los Alamos National Laboratory (LANL) (Villareal 2002) with containers of transuranic waste measured higher dissolved concentrations of Pu rather than Th. This strongly suggests "that Th solubility is unlikely to be a realistic or conservative analog for Pu or U under WIPP disposal conditions" (Oversby 2000).

In response to the Oversby (2000) report, the DOE (Triay 2001) reiterated their position for use of the oxidation state analogy and continued, "The key to oxidation state analogy then lies in understanding the chemical conditions where it is and is not applicable, and also understanding the appropriate use, including limitations, as applied to a real problem." The EEG agrees with this statement as it goes to the very point of the EEG's argument, i.e., the analog method cannot account for the ability of Pu to assume higher oxidation states. The total solubility of Pu in solution cannot be predicted by the oxidation state analogy because the lability of Pu between different oxidation states cannot be treated by analogy.

The above mentioned experiments conducted by LANL were termed "The Actinide Source-Term Waste Test Program" (STTP) which attempted to determine actinide behavior in WIPP-like brines. A portion of this study was devoted to the analysis of waste similar to that which resulted from the pyrochemical processing of weapons-grade Pu conducted at Rocky Flats. The residues from this processing are mostly solidified chloride salts used as molten solvents in several extraction processes, i.e. direct oxide reduction (PuO_2 to metal), molten salt extraction (Am from Pu), and molten salt electrorefining (Villarreal 2002).

The STTP was designed to approach the WIPP repository conditions for actinide transport and assumes total brine immersion of wastes (Villarreal 2002). In one publication, the EEG (Haschke and Oversby 2002) has concentrated on the results from the general pyrochemical salt liter-scale tests, i.e. pyrochemical salt tests without additional components such as CO_2, bentonite, etc. These tests were designated L-25, L-26, and L-27. Results from these experiments showed that solution concentrations of Pu rose gradually in L-26 and more rapidly for L-27. The peak concentration for L-27 was about three times higher than for L-26, although they reported similar loading amounts. Pu then decreased and approached an apparent steady-state condition with concentrations of about 4 ppm for L-26 and between 25 to 30 ppm for L-27. Meanwhile L-25 with a much lower initial loading, peaked at 0.17 ppm and decreased to 0.06 ppm. L-27 contained Castile brine while L-25 and L-26 contained Brine A, a simulated Salado brine. These results suggest that the amount of Pu in the system influences the steady-state concentration of Pu and that a mechanism other than thermodynamic equilibrium solubility controls the concentration.

Also, according to the DOE, L-26 showed Pu (VI) which persisted for 1.5 years while L-27's high Pu concentration was identified with Pu (V). The iron mesh did not seem to maintain a reducing environment in these tests (Triay 2001).

The DOE maintains that: (1) pyrochemical salts constitute a small fraction of the waste, and (2) that oxidized Pu would only be produced in microenvironments and would not persist in large quantities in the repository. However, actual persistence and what constitutes "significant quantities" is unknown. Oversby (2001) argues:

> "Discussion of persistence of oxidation states is only appropriate for steady-state conditions. Long-lived transients are likely to be important in at least some human intrusion scenarios. Concentrations of Pu exceeding those predicted in the CCA persisted in the STTP tests for periods of up to 5 years. These high Pu concentrations were probably caused by the presence of Pu (V) and/or Pu (VI)."

The conceptual model presented in Section 2.1.1 has been applied in explaining these STTP results (Haschke and Oversby 2002). Kinetic equations for the model were obtained from

analysis of published data. This model predicts the presence of Pu as Pu(V) and Pu(VI). Observed steady-state Pu concentrations in excess of the model predictions are explained by the presence of high Cl^- concentrations and Fe, which promote reduction of Pu(V) and complexation of the Pu(III) product. These results suggest that equilibrium modeling does not adequately predict dissolution behavior of Pu. Kinetic factors should be considered.

2.1.3 Use of FMT For Solubility Modeling

The FMT solubility model was developed for use at WIPP and has not gained widespread acceptance elsewhere. The EEG discovered that the model predicted large differences in actinide sulfate solubilities for different brines that could not be explained on the basis of chemistry. This raised questions concerning the validity of the code. The EEG also disagreed with the EPA's methodology for verification of the code as it was not subjected to comparisons with more widely used codes, nor did it demonstrate the ability of the first model to reproduce results consistent with relevant published data.

The DOE was considering the use of a more widely used code, EQ3/6, for recertification (Knowles et al. 1999; Knowles in DOE 2001b). However, the DOE has apparently reconsidered its decision and is planning on the use of FMT (Patterson 2002).

2.1.4 Complexation With Waste Constituents

The ability of plutonium to complex with other waste constituents involves the effects of organic ligands on the solubility and the partitioning coefficient of plutonium and other major actinides in WIPP brines. Some organic ligands that are known to be in significant quantity in the WIPP waste will act as chelating agents, binding to the actinide, which will keep the actinide from binding with the solid material. This binding will increase solubility by allowing less plutonium to be attached to solid matter in the waste. It will also decrease the partitioning coefficient, a measure of how contaminants are sorbed onto a host rock once it reaches a viable aquifer. However, the potential effects of organic ligands were not included as part of the CCA performance assessment calculations.

The experimental results from the STTP tests showed that the presence of organic ligands (acetamide, acetate, citrate, oxalate, and thiocyanate) elevates Pu solubilities by a factor of 1000 (Oversby 2000). The DOE assumed a well-mixed, homogenous repository and average concentration of the ligands to calculate the affinity of the ligands binding with plutonium. In reality, the repository will not likely be mixed, creating an extremely heterogeneous environment of actinide reactants with ligands. In addition, the DOE argued that the organic ligand, EDTA, would form the strongest complexation with actinides in the IV oxidation state (or An (IV), and that other divalent cations, such as Fe (II) and Ni (II) would use up most of the EDTA, so there would be less to react with An (IV)). On this basis, the impact of citrate was eliminated from further consideration. However, the 140 metric tons of citrate in the waste will form strong complexation species with An (IV) with little competitive reaction from other divalent cations. Therefore, citrate will be bound to a significant portion of Pu (IV) or U (IV) in the WIPP waste (Oversby 2000).

2.1.5 Recommendations

The EEG recommends that, for performance assessment, the DOE consider the effects of increased Pu solubility resulting from complexation with organic ligands. This is especially significant in scenarios which reflect non-random waste emplacement (Section 2.6), in which the repository environment is a heterogeneous mixture of actinides and organic ligands.

The EEG recommends that the DOE explore the development of a conceptual kinetic model of Pu solubility. Additional experimental work is suggested (Oversby 2002) which would allow the application of this model. Necessary parameters are:

(1) The rate of Pu(V) production in $Pu(OH)_4$ as a function of [NaCl] and pH,
(2) The rate of disappearance of Pu(V) from solution as a function of [NaCl] and pH, and
(3) The rate of disappearance of Pu(VI) from solution as a function of [NaCl] and pH.

Determination of these parameters can be limited to a range covering the WIPP conditions. Data for (2) and (3) already exist at pH 7.1 and [NaCl] = 2.4 M. Oversby goes on to provide specific recommendations:

> "If data were produced for [NaCl] = 0.1 and 4.8 M at pH 7.1, the chloride dependence of these reactions rates could be evaluated. If the dependence of rates on [NaCl] is not too great, the pH dependence of the rates could be evaluated at a single [NaCl], for example 2.4 M. Tests at pH 9 and 11, together with the existing data at pH 7.1 would give the pH dependence of the rates. The effect of Fe could be evaluated initially by using a single pH and [NaCl] together with two experimental conditions – one with an initial concentration of Fe(II) without a replenishment source and one with an actively corroding piece of Fe metal to provide a constant source of Fe(II) ions. A similar experimental matrix for the oxidation of $Pu(OH)_4$ as a function of [NaCl] and pH would complete the reaction rate data needs. If any of the reaction rates turned out to be a sensitive function of one of the experimental parameters, more detailed studies could be planned."

The EEG urges the DOE to reconsider its decision to use FMT for recertification. The DOE has apparently invested considerable effort in the application of EQ3/6 to the WIPP data and demonstration of its use should enhance public confidence in solubility modeling.

2.2 Fluid Injection

The issues regarding fluid injection have been previously discussed in detail by the EEG (Neill et al. 1998). The 1996 performance assessment calculations did not include scenarios of fluid injection for enhanced oil recovery, a current practice throughout the Delaware Basin (Silva 1996). The DOE rejected its inclusion on the basis that the EPA regulations did not require it. The regulation states: "With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole (EPA 1996)." Also, any affects from fluid injection wells adjacent to the WIPP were not included on the basis of a low probability argument. Figure 1 shows the increase in oil and gas related drilling activity since the time of the CCA.

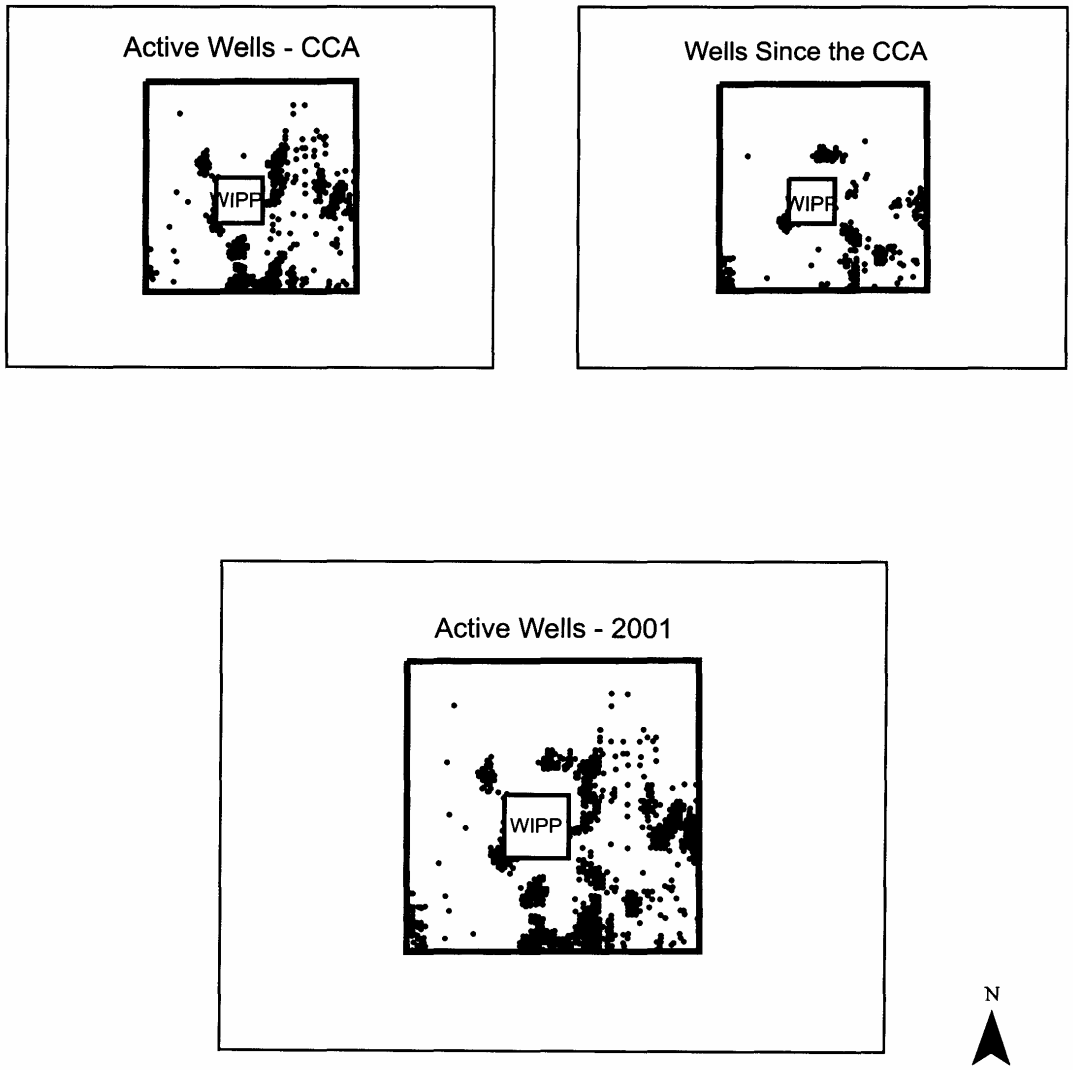

Includes oil, gas, pressure maintanance, and salt water disposal wells

Figure 1
Comparison of Active Wells - CCA to 2001
Nine-Township Boundary

2.2.1 Waterflooding

In the EEG's opinion this issue is worthy of re-examination during recertification based on the continuing practice of waterflooding for oil recovery enhancement. As of 2001 there were three major waterflooding projects in the New Mexico portion of the Delaware Basin (DOE 2001c).

Waterflooding is a secondary recovery technique used to enhance crude oil recovery by restoring reservoir energy lost during primary production (Willhite 1986). During waterflooding, pressurized water is injected through the well bore into the reservoir. This forces oil, that may be unrecoverable by primary methods, to flow toward the producing well. Waterflooding and other secondary and tertiary recovery methods are encouraged by the State of New Mexico through severance tax relief, promoting maximum extraction of resources.

However, waterflooding has historically presented problems for some oil-bearing zones underlying the Salado Formation. It has been documented in various instances that water has escaped from the collection zone and migrated through the Salado Formation to adjacent properties (Ramey 1976). Probably the most notorious waterflood incident resulted in the Hartman vs. Texaco lawsuit (Complaint CIV93 1349M) filed in the Federal Court for the District of New Mexico. Mr. Hartman claimed that the Texaco Rhodes Yates waterflood project allowed large quantities of injected water to escape out of the approved zone, part and dissolve the Salado Formation, and migrate to Hartman's Bates Lease (Hartman 1993). This lawsuit resulted in compensation to Mr. Hartman.

The EPA concluded that a probability of such a waterflood event occurring in the Salado Formation in the vicinity of the WIPP is extremely low (EPA 1998c). They relied on geological comparisons based on geological descriptions of the Hartman vs. Texaco location provided in a summary of the case and on the DOE characterization, and hence conceptual model, of the Salado Formation at the WIPP. Also, the EPA suggested that the relatively young age of the wells in the vicinity of the WIPP provide some measure of assurance because of better construction and operational practices than those involved in the Hartman case. However, it

should be noted that a hypothesized cause of the Culebra water level increase is a leaky injection well in the vicinity of the WIPP (Beauheim 2002).

2.2.2 Brine Disposal

The most common type of injection well in the Delaware Basin is for the disposal of brine water resultant to production of oil and gas. Salt water disposal wells are necessary as a result of an EPA ruling that formation water may no longer be disposed of on the surface.

There are currently 33 salt water disposal wells in the nine-township area surrounding the WIPP site (DOE 2001c). This number is up considerably over the 10 salt water disposal wells in the same area as reported from 1993 (Broadhead et al.1995).

The DOE relies on a low consequence argument and the administration of the Underground Injection Control (UIC) regulations (OCD 2002) as a safeguard against possible consequences from fluid injection. The determination of low consequence is again based upon DOE's modeling and hence conceptualization of Salado Formation (Stoelzel et al. 1996; Stoelzel and Swift 1997). Indeed, alternate modeling suggested that the DOE's modeling may be unrealistic and non-conservative (Bredeheoft 1997a; 1997b).

As for the UIC regulations, despite the required testing and verification by the New Mexico Oil Conservation Division, strong circumstantial evidence suggested a connection between a salt water disposal well and Culebra monitoring well H-9 (LaVenue 1991; Beauheim 1995). The reliance on this program as a safeguard may be in question if injection wells are found to be, in part, responsible for the current Culebra water level increases.

The EPA used a low probability argument to justify the exclusion of fluid injection scenarios. However, the EPA analysis resulted in three different probability values which spanned four orders of magnitude (Silva et al. 1999). This highlights the uncertainty in assigning probabilities for the series of individual events for calculation of the total probability of a leaking well impacting the repository.

The fact that fluid injection scenarios were not included in the CCA performance assessment does not preclude their inclusion during recertification. Recertification can incorporate a re-evaluation of previous information as well as new information. Given the increase in development of wells in the vicinity of the WIPP, there is an increased expectation that extraction from known oil reserves will be optimized by secondary and tertiary recovery techniques.

The OECD/NEA-IAEA Joint International Review Group, in a Peer Review commissioned by the DOE, expressed reservations about rejecting a scenario solely on the basis of regulatory considerations:

> "It would improve the confidence of the reader if the DOE presented the logical or physical arguments for not considering these processes in the assessment, in addition to noting that they are not required in a compliance demonstration. Otherwise, there is an impression that processes that might deserve consideration from a safety perspective have been eliminated" (NEA/IAEA 1997).

The EEG believes that the increasing number of brine disposal wells, along with economic incentives for the use of secondary recovery techniques, reflects on the necessity of screening in fluid injection scenarios into recertification performance assessment calculations. In addition, the DOE should realistically assess potential flow paths in the Salado based on documentation of other fluid injection events. Also, unexplained water level increases in the Culebra aquifer, which raises questions concerning the Underground Injection Control program, undermines the reliance that the DOE puts on the program as a safeguard measure.

2.3 Solution Mining

Consideration of solution mining was not included in the CCA on the basis that it was not occurring in the Delaware Basin in 1996. However, underground storage caverns already exist and interest is growing in solution mining of potash for extraction of minerals. An expansion of

the role of salt caverns for storage of natural gas, oil field wastes, and chemical feedstocks is expected (Veil et al. 1996; Bauer et al. 1998; Veil et al. 1998).

Consideration of solution mining for extraction of minerals is the natural progression of alternatives in the life of a mine. Companies which mine various commodities, including potash, consider solution mining following the extraction of higher grade ores through more predictable traditional methods. In addition, ores which were once considered as too low grade become economical with the refinement of new technologies. With this in mind, it is reasonable to assume that solution mining will be considered in the vicinity of the WIPP project for extraction of minerals (NMBMMR 1995). This is especially true since the U.S. Bureau of Land Management has delayed development of oil and gas reserves surrounding the WIPP in favor of prioritizing the extraction of potash. The prioritization policy will push forward in time a decision by potash companies concerning final development of potash reserves. Figure 2 shows the potash reserves and resources in the vicinity of the WIPP.

Another emerging technology is the use of solution mining for dissolution of underground caverns for storage purposes. The DOE has funded considerable research in this area, especially for disposal of oil field waste (Veil et al.1996; Tomasko et al. 1997; Veil et al. 1998). Sites for the underground disposal of oil field waste are typically caverns created by the solution mining of halite for use as brine during oil field drilling, a practice already occurring in the Delaware Basin (Neill et al. 1998).

Solution mining, whether for extraction of resources or for excavation of underground storage, should be considered. Plausible scenarios related to this activity should be evaluated and screened for each recertification as technology in this area continues to be refined.

2.4 Culebra Flow and Transport

The Culebra dolomite unit of the Rustler Formation is acknowledged as a likely pathway for breach of the WIPP repository. This observation underscores the need for an accurate understanding and modeling of Culebra flow and transport by the DOE.

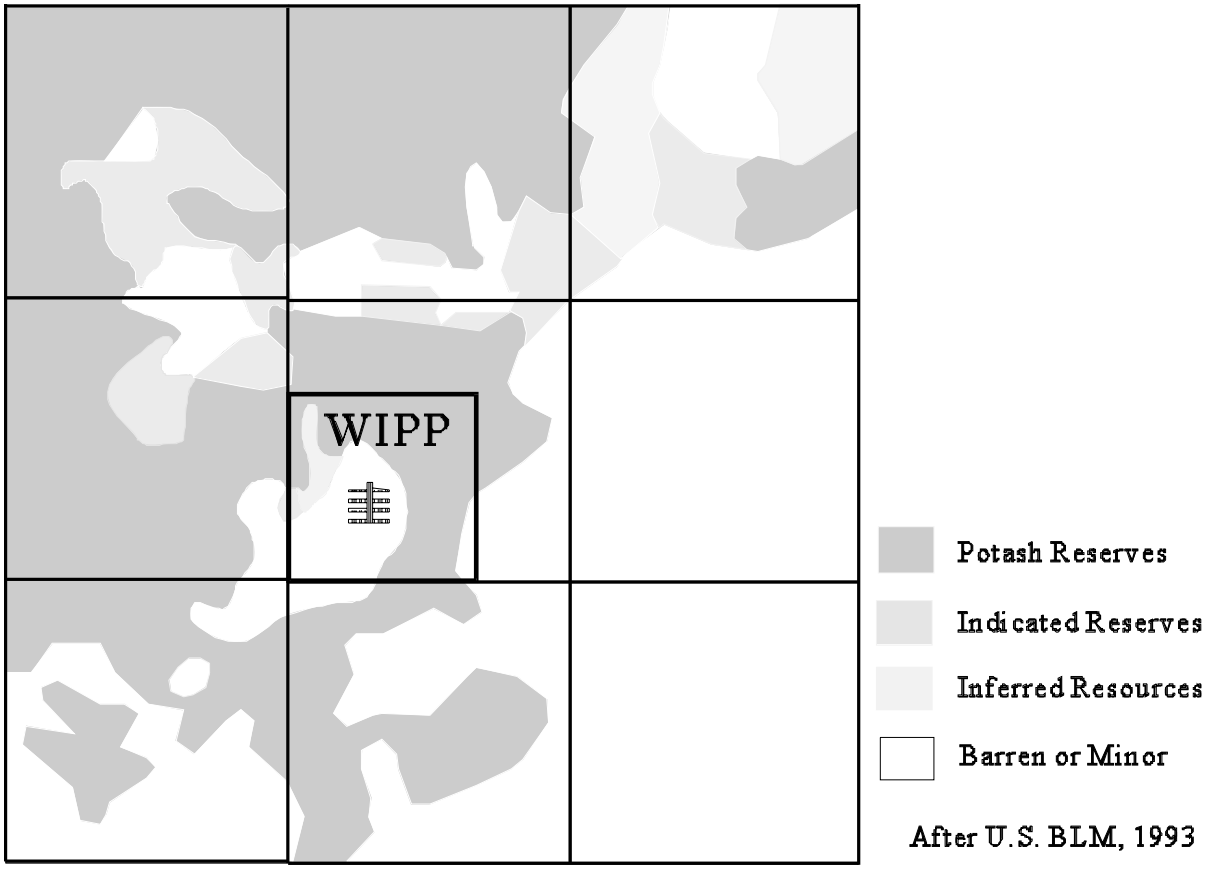

Figure 2
Potash Resources In the Vicinity of WIPP

The National Academy of Sciences WIPP Committee (NAS/NRC 1996) and the EEG (Neill et al. 1998) raised issues regarding the conceptual and numerical model of transport through the Culebra. The DOE had planned to address some of these issues during the first CRA (DOE 2001b), but now plans no changes to the conceptual model (Patterson 2002).

In addition to the issues concerning transport, continuing increases in water level elevations in the Culebra and other formations, raises uncertainty in the flow model. As the transport model follows from the flow model, this also increases uncertainty in the transport model. Figure 3 illustrates the generalized dip of the Culebra and monitoring wells in the vicinity of the WIPP.

2.4.1 Water Level Increases

The water level in the Culebra began increasing in April, 1988 (Beauheim 1990; Silva 1996) and continues to rise through the date of this report. These increases are also observed in the Magenta unit of the Rustler Formation as well as in some of the more shallow formations (Beauheim 2002).

These increases are of concern in the recertification because 21 of 28 monitoring wells now show water elevations in the Culebra aquifer outside the ranges used for calibration of the CCA transmissivity fields. This may cast doubt on the validity of the steady-state flow model used in the CCA. Also, the reliability of the transmissivity estimates were determined using inverse methods that assumed the Culebra was a non-leaky, two-dimensional aquifer. Increasing water elevations suggest a likely connection of the Culebra with other water-bearing units, raising questions concerning the validity of this assumption as well.

During January 2002, the DOE convened a workshop to address the issues of the water level rises. The stated purpose of this workshop was “to demonstrate an understanding of the WIPP hydrologic system by developing scenarios that account for the observed changes and show that the CCA modeling results remain valid for recertification” (Beauheim 2002). Figure 4 shows the difference in water elevations between the time of the CCA and 2001.

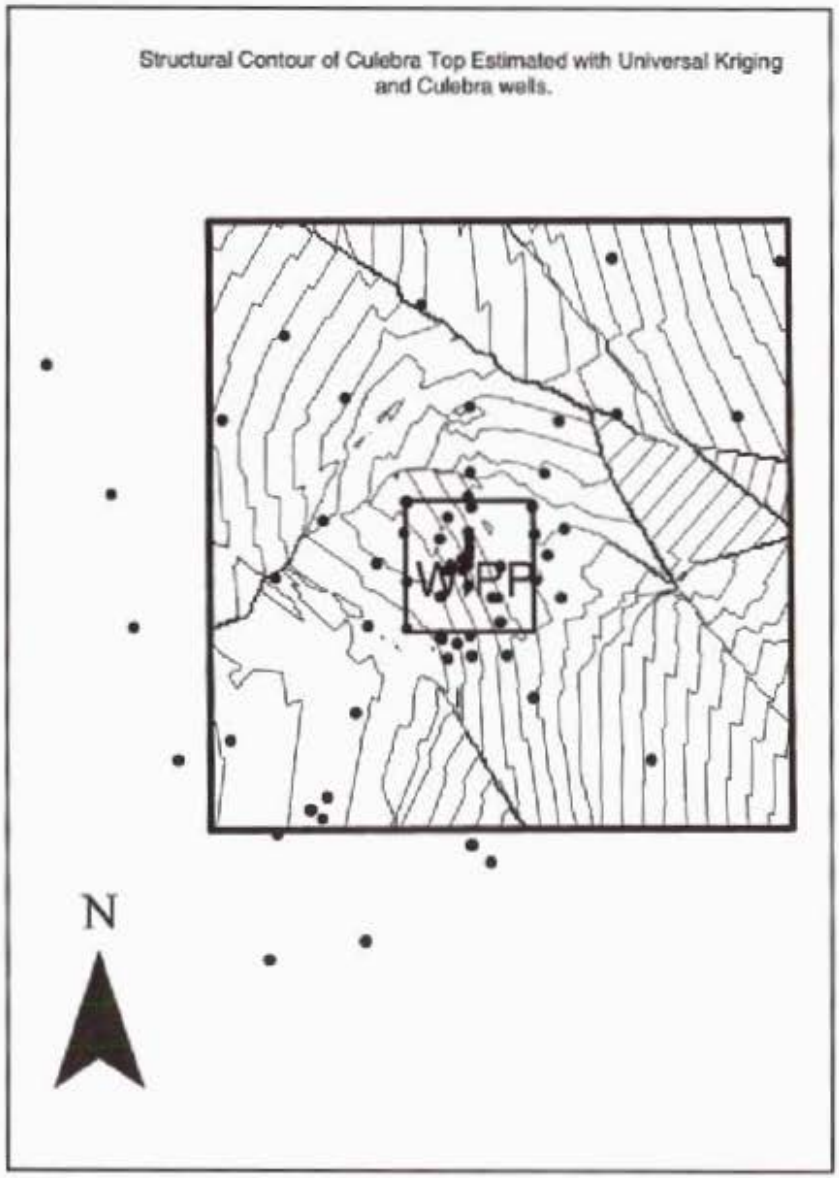

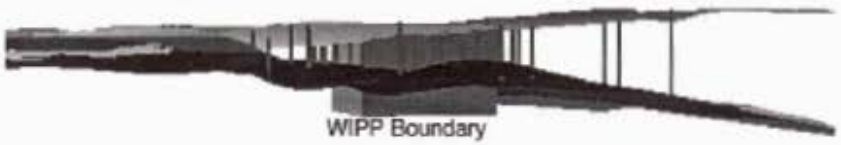

Cross section looking north
showing dip of Culebra to the east

Figure 3
Culebra Top with Wells and WIPP Boundary

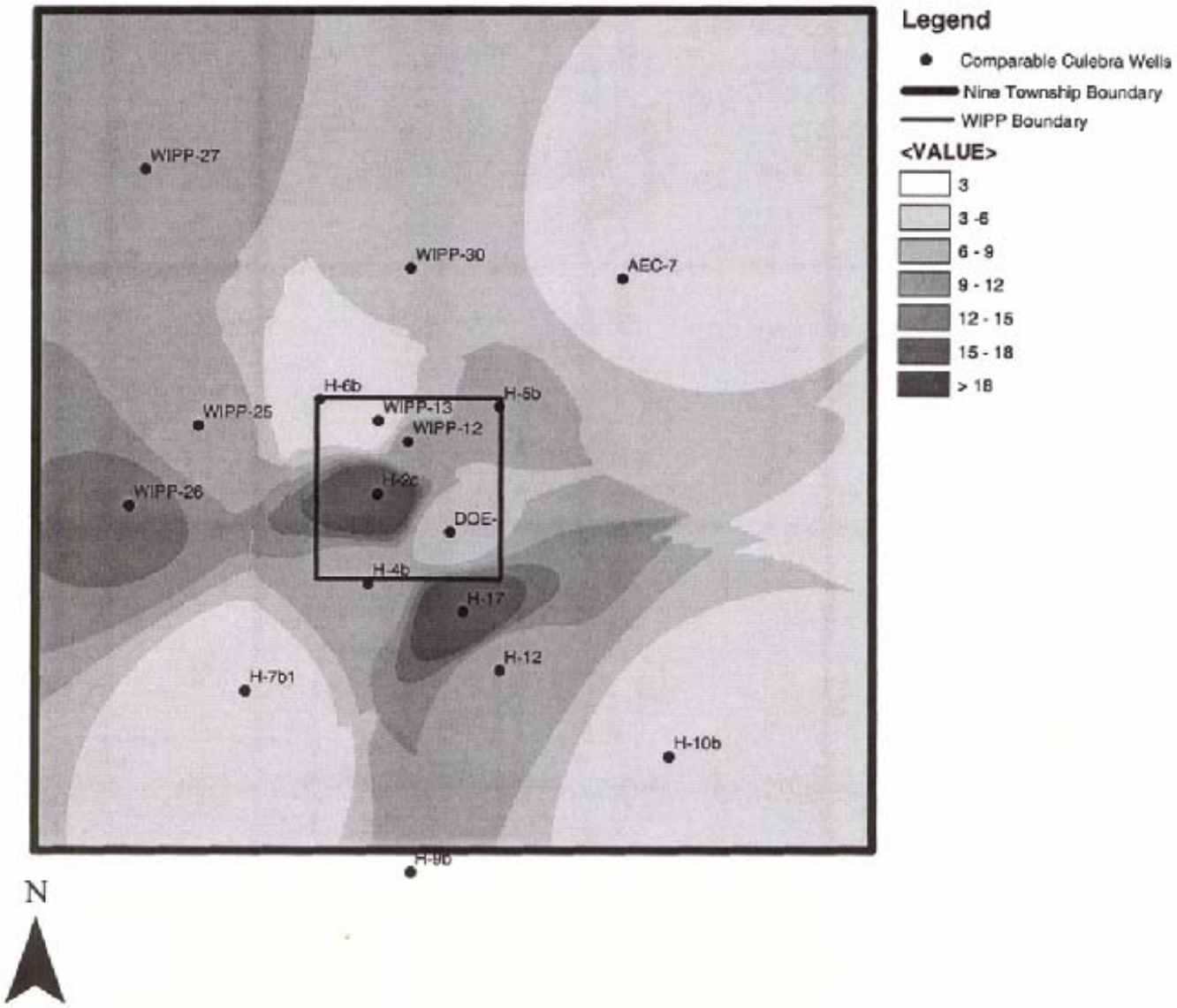

Figure 4
Culebra Head (ft) Difference
CCA to 2001

The workshop developed seven scenarios which could potentially explain the water level changes in the Culebra:

(1) Recharge from potash tailings ponds,
(2) Leakage through wells from shallower units,
(3) Leakage through wells from deeper units (including injection),
(4) Precipitation,
(5) Changes in karst resulting in high-transmissivity conduits,
(6) Mine subsidence,
(7) Subsidence related to oil and gas production.

It is likely that some combination of these seven possibilities would account for the changes in the Culebra water levels. It is unfortunate that the DOE only recently convened this workshop to address these issues, since the water levels have been increasing and have been unexplained for 14 years. Arriving at an explanation for the increases from these (or other) multiple probable causes will undoubtedly take considerable time and may not be satisfactorily answered before the first recertification.

The EEG expressed their concern for the lack of an explanation in 1998 (Neill et al. 1998). Moreover, the EPA expressed concern in 1996:

> "The statement 'they remain unexplained' is insufficient, particularly if the reason for the rise could be interpreted to affect long term hydrologic conditions within the Culebra or be caused by ongoing oil and gas exploration and development activities, such as brine disposal into underlying units" (Trovanto 1996).

The DOE plans to test the validity of the CCA transmissivity fields using the current water head observations. Since the transmissivity fields were conditioned by both the heads as well as transient response data, it is possible that the fields are still valid given the current observations. If not valid, transmissivity fields will need to be re-generated, possibly using a geology-based method. However, the ability to calibrate transmissivity values does not necessarily validate the

conceptual model. Until a source is determined for the water level increases, the validity of the Culebra conceptual model remains in question.

2.4.2 Heterogeneity and Model Discretization

During development of the CCA, several modeling errors were identified which resulted in an artificial spreading in the calculated width of a potential contaminant plume at the expense of its length. This would result in non-conservative travel times to the regulatory boundary. These errors included numerical dispersion and spatial truncation errors in the transport code, poor resolution from using a grid that was too coarse for the scale of the problem, and overestimation of the size of the solute source area (Konikow 1997). These errors are especially apparent in a heterogeneous aquifer such as the Culebra. If a plume spread out laterally due to numerical dispersion, the wider plume will move downgradient a shorter distance than would be the case if a finer grid were used during modeling (Figure 5).

The DOE had planned to address these issues during the recertification (DOE 2001b). The previously used SECO suite of codes were to have been replaced by MODFLOW, STAMMT-L and DTRKCDB. MODFLOW was to have been used for modeling of the flow field. DTRKCDB was to have computed one-dimensional particle velocity paths for input into STAMMT-L. This code incorporates a dual-porosity, multi-rate concept which better addresses heterogeneity and allows for a better representation of the diffusive process. (Haggerty and Gorelick 1995; Haggerty and Reeves 2000).

However, the DOE now plans to retain the SECO models for recertification (Knowles 2002), despite the previously identified problems. In addition, the DOE research on transport in the Culebra showed a superior fit of experimental data with a multi-rate diffusion code such as STAMMT-L (Altman and Meigs 1999). The EEG encourages DOE to reconsider its decision and to implement the previously planned changes to the Culebra models.

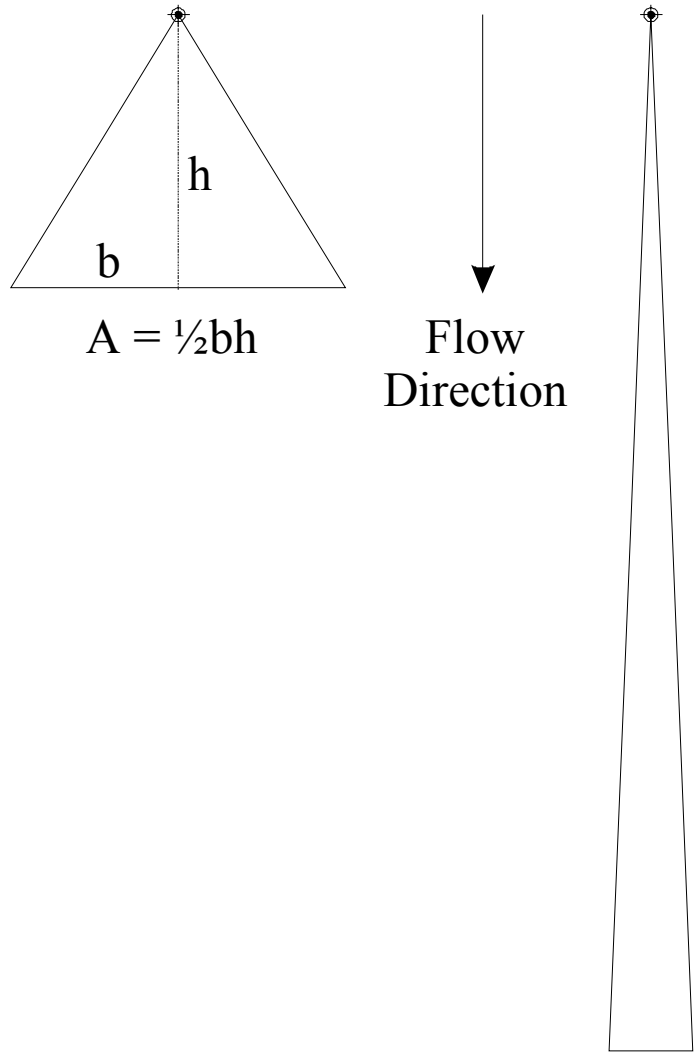

Conceptual Diagram Of Contaminant Plumes Represented As Simple Triangles, Showing Different Travel Distances For A Relatively Wide Plume Compared To That Of A Relatively Narrow Plume, Where Both Plumes Encompass Equal Volumes Of Fluid And Equal Masses Of Solute.

Figure 5

Conceptual Diagram of Contaminant Plume Showing Potential For Numerical Dispersion (From EEG-68).

2.4.3 Sampling Procedures for Input Parameters

The co-regionalization of spatial parameters was not considered in the CCA. Hydrogeologic variables that were correlated were sampled independently. This could result in realizations that may be based on unlikely combinations of parameters, and may produce a bias.

For example, transmissivity, fracture spacing, and porosity generally exhibit co-regionalized behavior and are positively correlated (NRC 1996). That is, high transmissivity is related to a higher density of fractures and high porosity. If these correlations are ignored, realizations would be generated that may have high transmissivity, with a low density of fractures and low porosity. While this may still happen under a model of co-regionalization, a higher frequency of realizations representing this scenario will occur under an assumption of variable independence. The EEG recommends an analysis of co-regionalization for spatial variables and co-simulation for those which are highly correlated.

2.4.4 Consistency Between Performance Assessment Models

The connections between some of the performance assessment models and parameters are not always transparent. The EEG had previously recommended that a mass balance be documented to ensure that the fluxes between the various models are coherent (Neill et al. 1998).

For example, it was determined during the 1998 Annual Sensitivity Analysis that BRAGFLO results were skewed by the WSTOCOR term for the corrosion of steel (Helton 1998). In order to represent the hydration of MgO in the analysis, this term was allowed a range of values not representative of the actual steel corrosion process. This linked steel corrosion to hydration of MgO and caused the brine that is associated with the hydration process to disappear, creating mass balance problems. These mass balance problems affected estimated releases from spallings, direct brine releases, and releases through the Culebra.

In the Culebra, actinide transport results from radionuclide releases from brine flow up boreholes that penetrate the repository. In the 1998 Annual Sensitivity Analysis, the brine flows were

skewed low because of the large quantities of brine that disappeared. This problem illustrates how nontransparent links between models may produce improper results.

Therefore, it should be demonstrated that the total mass of fluid and solute that the human intrusion borehole model computes to enter the Culebra over 10,000 years should equal the total mass of fluid and solute that is actually added to the Culebra model over the 10,000 year period. This would identify potential problems, increase confidence in the models, and promote an understanding of the performance assessment process.

2.5 Spallings

Spallings consist of repository waste material that experiences failure caused by a rapid reduction of pressure as an intruding drill hole approaches or penetrates the repository. This material would then enter the drilling fluid due to radially channeled, pressurized gas flow from the repository to the lower pressure drill hole. This flow will continue until pressure equilibrium is achieved between the repository and the drill hole. This failed material would then be transported up the drill hole to the surface via gas flow.

The importance of spallings as a potential release mechanism of radionulides into the environment has been demonstrated through the 1996 iteration of the performance assessment calculations. The EEG has consistently stated their concern about the treatment of spallings during the CCA and PAVT analyses (Neill et al.1998; Fairhurst 1998; Silva et al.1999). Neill et al. (1998, pp 57-82) discusses in detail EEG's unresolved issues pertaining to spallings.

The initial spall model proposed by the DOE for the CCA was found inadequate by the conceptual model peer review (Wilson et al. 1996). However, the DOE schedule for submittal left insufficient time for development of a suitable replacement.

The DOE then developed a different model for prediction of radionuclide release. Use of this model predicted much lower releases due to spallings than the original model. However, sensitivity testing by the EEG (Rucker 1998; Silva et al. 1999) revealed instability problems with

the model if run outside a range of waste permeabilities between 1.7 to 2.0 x 10^{-13} m^2. The EEG recommended that the DOE begin development of a coherent and straightforward model which characterizes the physical processes of spall (Neill et al. 1998; Silva et al. 1999).

Work has been in progress by the DOE on a new spallings model that was intended for use during recertification (DOE 2001b). This model was to incorporate a modified wellbore hydrualics model with mixing equations for solids and fluids, a drillbit damage model, and a solids transport mechanism up the drill hole annulus (DOE 1999). The stated objective of this new model was to improve predictions of long-term performance (Knowles 1999).

However, the DOE has recently announced that the new model would not be used for recertification performance assessment, but only for an impact analysis (Patterson 2002). The EEG urges the DOE to reconsider the new model's use for the reasons stated above.

2.6 Non-random Waste Emplacement

Waste emplacement practice since the March 1999 opening of the WIPP has demonstrated that random emplacement is not likely. Specific waste streams will be campaigned depending on DOE's agreements with the various states which host TRU waste and the readiness of particular waste streams for shipment from the other sites (DOE 2000).

For example, as of April 22, 2002 (WWIS 2002), the EEG calculated the average radionuclide activity for waste emplaced to date in Panel 1. These calculations indicate that the emplaced activity of ^{239}Pu is 4.24 times, ^{240}Pu is 3.53 times, and ^{241}Am is 5.65 times the projected repository average for the space occupied by waste. Obviously, a future intrusion into Panel 1 would result in a different potential release than from a panel in which average radionuclide activities were emplaced.

In the CCA performance assessment, under a random emplacement assumption, the contents of a waste container removed by cuttings and cavings were randomly sampled from 569 separate waste streams. A drill hole intruding a room and intersecting each of three stacked containers

would have resulted in each of the three containers being randomly sampled with the probability of hitting a particular waste stream weighted according to its relative quantity. However, in reality it is likely that all three containers would be from the same waste stream.

It has been previously demonstrated by the DOE that non-random emplacement could increase the mean release values (Dials 1997). The EEG recommends that the DOE develop a waste loading plan based on their shipment schedule. While this schedule will certainly change over time, it is the best information currently available and presents a more realistic assumption than random waste emplacement. All intrusion scenarios could then consider non-random emplacement, providing better estimates of releases in brine, cuttings, cavings, and spallings.

3.0 CONCLUSIONS

Performance Assessment is an iterative process that should incorporate the best understanding of all of the integrated components at the time it is being done. For recertification, this "best understanding" may translate into modifications of conceptual models based on ongoing research or operating experience gained during the emplacement of waste. It may also mean consideration of scenarios that were previously screened out, but may warrant inclusion because of new information or to allay public concern.

In accordance with 40 CFR 194.15(a), the DOE must present an updated performance assessment with the CRA. This performance assessment must describe relevant new information and system changes since 1998 (Marcinowski 2002). The DOE had planned to submit several changes that would have addressed some of the ongoing unresolved issues presented in this report. However, the DOE has now modified their plans and are proposing minimal changes to the conceptual models for the first recertification. This change in plan likely coincides with the EPA's guidance found in the above mentioned letter, "Some of the changes currently included as part of the Technical Baseline Migration may necessitate a rulemaking to modify our Certification Decision." The DOE has allowed insufficient time for submission of planned changes that may require a rulemaking.

However, some of the withdrawn changes may reflect new information. These include:

(1) Continuing changes to the Culebra water levels and their reflection on the validity of conceptual model,
(2) Interpretation of Culebra tracer tests demonstrating the superiority of a multi-rate diffusion code,
(3) Improved characterization of the physical process of spall using an improved model,
(4) Experience indicating the non-random emplacement of waste.

Other planned changes such as the use of EQ3/6 instead of the FMT model would have improved public confidence. In addition, public confidence in the performance assessment process would be enhanced through serious consideration of fluid injection and solution mining scenarios.

Issues involving actinide chemistry and the Culebra modeling will likely be ongoing issues. Well-planned research programs should be conducted to adequately address their effect on long-term repository performance. For example, in actinide chemistry the EEG recommends the development of a conceptual kinetic model for solubility. For the Culebra, a three-dimensional, regional hydrogeological model should be developed to facilitate understanding of the relationship between hydrogeological units. Such a model would be useful in determination of the Culebra water elevation increases.

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APPENDIX A

Resolution of the Long-Term Performance Issues at the Waste Isolation Pilot Plant

Matthew K. Silva, Dale F. Rucker, Lokesh Chaturvedi

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Resolution of the Long-Term Performance Issues at the Waste Isolation Pilot Plant

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The Waste Isolation Pilot Plant (WIPP) is a geological repository for disposal of U.S. defense transuranic radioactive waste. Built and operated by the U.S. Department of Energy (DOE), it is located in the Permian age salt beds in southeastern New Mexico at a depth of 655 m. Performance assessment for the repository's compliance with the 10,000-year containment standards was completed in 1996 and the U.S. Environmental Protection Agency (EPA) certified in 1998 that the repository meets compliance with the EPA standards 40 CFR 191 and 40 CFR 194. The Environmental Evaluation Group (EEG) review of the DOE's application for certification identified a number of issues. These related to the scenarios, conceptual models, and values of the input parameters used in the calculations. It is expected that these issues will be addressed and resolved during the first 5-year recertification process that began with the first receipt of waste at WIPP on March 26, 1999, and scheduled to be completed in March 2004.

KEY WORDS: WIPP; radioactive waste; repository; performance assessment; transuranic waste.

1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a geological repository built by the U.S. Department of Energy (DOE) for the disposal of defense transuranic (TRU) waste in bedded salt, at a depth of 655 m, about 40 km east of Carlsbad, New Mexico. The DOE submitted its compliance certification application (CCA)[1] to the U.S. Environmental Protection Agency (EPA) on October 29, 1996. EPA certified that the facility met the EPA Standards[2] and Criteria[3] for the disposal of TRU waste on May 18, 1998.[4] The waste bound for WIPP contains chemically hazardous materials regulated by the Resource Conservation and Recovery Act (RCRA) in addition to the radioactive components. A RCRA permit from the New Mexico Environment Department (NMED) is therefore required for WIPP in addition to certification by the EPA. The NMED is expected to announce its decision on the RCRA permit in October 1999. The WIPP began receiving nonmixed TRU waste on March 26, 1999.

The EPA certification required the DOE to provide a performance assessment (PA) of the repository. Performance assessment is defined in the Standards[2] as an analysis that:

1. Identifies the processes and events that might affect the disposal system.
2. Examines the effects of these processes and events on the performance of the disposal system.
3. Estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events.

The EPA disposal standards contain four re-

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quirements: the containment requirements, assurance requirements, individual protection requirements, and groundwater protection requirements. Performance assessment is used to determine compliance with each of these except for the assurance requirements. The assurance requirements were intended to compensate for the inherent uncertainty in a 10,000-year projection of events.

The performance assessment requires the (1) development of potential scenarios for release of radionuclides to the environment, (2) screening of all features, events, and processes, and the combination of features, events, and processes that may affect the disposal system, (3) identification and selection of the most appropriate conceptual models, (4) selection or development of appropriate computer codes, (5) determination of the input parameters for the analyses, and (6) calculation of the cumulative release in the form of complementary cumulative distribution functions.

The DOE has analyzed the probabilities and quantities of radionuclide releases to the environment for the undisturbed repository and the repository inadvertently disrupted by drilling. The outcome of the performance assessment is controlled by the conceptual models and the values for the input parameters used. These include gas pressurization, mechanics of human intrusion, characteristics of the waste including actinide solubility, mechanics of rock fracturing, and retardation processes in actinide transport through the overlying aquifer. The numerical values of the parameters are ideally determined by scientific investigations in the laboratory and/or the field.

Various iterations of the WIPP performance assessment were published from 1990 to 1992.[5–7] The 1996 PA may thus be viewed as an iteration in this ongoing process. Recertification for compliance is required at least every 5 years after first receipt of waste. The first recertification is due in March 2004. In addition to the 5-year recertification cycle, the DOE must submit periodic reports on any activities or conditions at the WIPP that differ significantly from the information contained in the most recent compliance application. The EPA may also, at any time, request additional information to determine whether the certification must be modified, suspended, or revoked. Hence, the EPA certification requires continued scientific investigation and technical review.

The Environmental Evaluation Group has reviewed[8] the scientific effort leading to certification. This paper summarizes the major technical issues identified by the certification process, the status of each issue, and a course of action for resolution as part of the recertification. Limited computations to examine the impact of these issues were published by EEG in 1998.[9]

2. THE ENVIRONMENTAL EVALUATION GROUP

The Environmental Evaluation Group (EEG) was created in 1978 to provide a full-time independent technical review of the WIPP to ensure protection of the public health, safety and the environment of New Mexico. The impact of EEG on previous PA efforts can be seen in the following areas:

1. Continuation[10] of performance assessment work after the disposal standards were vacated by the court in 1987, thus not losing time when the standards were repromulgated in 1993.
2. The DOE decision to abandon the *in situ* experiments with TRU waste at WIPP and redirect its efforts toward completing the performance assessment calculations and obtaining EPA certification.[11]
3. DOE's experimental programs to obtain data for parameters such as actinide solubility and retardation.
4. EPA's Criteria and Guidance for the WIPP.[12,13]
5. DOE's PA analyses.[14,15]
6. Testing the sensitivity of the PA models to various parameters including the borehole intrusion rate, actinide solubility, chemical retardation, the presence of a brine reservoir, and subsidence due to mining.[9]

3. GEOHYDROLOGICAL SETTING OF WIPP

The WIPP repository is located in the northern part of the Delaware Basin that is well known for its thick sequence of Permian age evaporites and economic deposits of potash and hydrocarbons (oil and gas). Figure 1 shows a geologic cross section at the center of the WIPP site. The repository is located at a depth of 653 m in the lower part of the approximately 610-m-thick Salado Formation, consisting of bedded salt (halite) and interbeds of anhydrite and

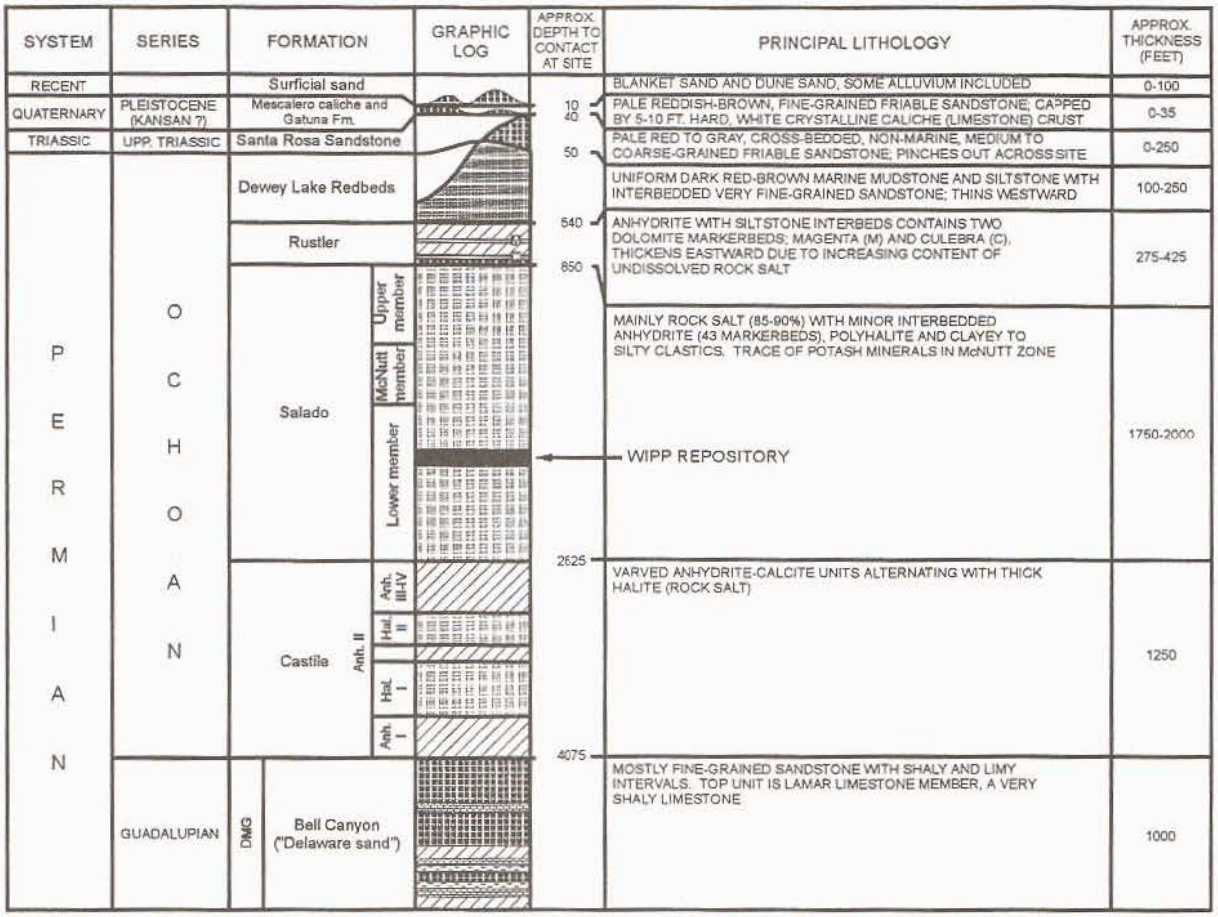

Fig. 1. Gereralized stratigraphy at the WIPP site.

clay. The upper part of the Salado Formation contains a 122-m-thick zone rich in potash minerals known as the McNutt Potash Member. The bottom of this zone is approximately 122 m above the WIPP repository. A 95-m-thick Rustler Formation overlies the Salado and it contains two 8.6-m-thick fractured dolomite water-bearing zones, the Magenta and the Culebra. The more permeable Culebra is considered to be a potential pathway for migration of radionuclides to the biosphere in case of a breach of the repository. The Culebra aquifer is about 435 m above the repository.

The Castile Formation underlies the Salado and its upper unit consists of varved alternating layers of anhydrite and calcite. At least 27 boreholes within 16 km of the WIPP site have encountered pressurized brine in this unit, about 244 m below the repository level (Fig. 2).

The 6.4 km × 6.4 km WIPP site is situated in a region rich in potash, oil, and gas. There were 163 producing oil and gas wells in a 3.2-km zone surrounding the WIPP site at the end of 1998 (Fig. 3). The nearest production of potash is currently about 2 km from the southwestern corner of the site, although potash leases are held immediately surrounding the WIPP site. Drilling for oil and gas through the potash reserves is restricted until potash mining is completed.

4. ISSUES TO BE RESOLVED

The geohydrologic conceptual models for WIPP and the issues associated with them have been described by Chaturvedi and Anderson.[16] Many conceptual models are presented in the CCA.[1] The EEG raised issues with a number conceptual models during the WIPP certification process. Similarly, several is-

sues relate to the values of the input parameters used in the CCA. The EEG looks forward to resolution of these issues during the recertification process.

4.1. Conceptual Model of the Castile Pressurized Brine Reservoir

Within a few miles of the WIPP site there are at least 27 reported encounters of pressurized brine in the upper anhydrite layer of the Castile Formation (Fig. 2). Two of these encounters (ERDA-6 and WIPP-12) were in the WIPP project boreholes and the rest have been reported by oil and gas drilling companies. When borehole WIPP-12, located within the WIPP site, hit brine at a depth of 920 m, brine started flowing out of the well at a rate of 22 liters/sec and more than 8 million liters of brine were unavoidably produced during drilling, logging, and between testing.[17] Based on an extensive series of flow tests, the brine reservoirs penetrated by the WIPP-12 and ERDA-6 boreholes were estimated to contain 2.7 billion and 100 million liters of brine, respectively. The different pressure potentials and geochemical data from the two encounters suggested a lack of communication between the ERDA-6 and WIPP-12 brine reservoirs. There was no consensus on the origin and the age of the brine reservoirs.

The originally planned configuration of the WIPP repository and the WIPP experimental areas would have brought the waste within 140 m south of the WIPP-12 borehole. The EEG recommended moving the repository in 1982 and the DOE rotated the repository configuration to relocate the nonwaste experimental area to the north and the repository itself 2 km south of WIPP-12. In 1983, EEG proposed geophysical investigations to delineate the extent of pressurized brine in the Castile Formation underlying the WIPP site and particularly under the new location of the repository. Time-domain electromagnetic (TDEM) geophysical survey was conducted by the DOE above the WIPP repository in 1987, and the results gave a clear indication of the presence of brine under the WIPP repository.[18]

There are two areas of clustered brine encounters, northeast and east of the WIPP site (Fig. 2). The DOE used geostatistical modeling to ascertain the probability of pressurized brine directly below the repository. A correlation length of clustered brine encounters represents the average size of a brine reservoir in the Delaware Basin. Brine encounters are defined by reports of intersection of pressurized brine filed by the drillers to the State of New Mexico. All wells without a report of pressurized brine were considered to not have intercepted brine. The data on brine encounters during commercial drilling for

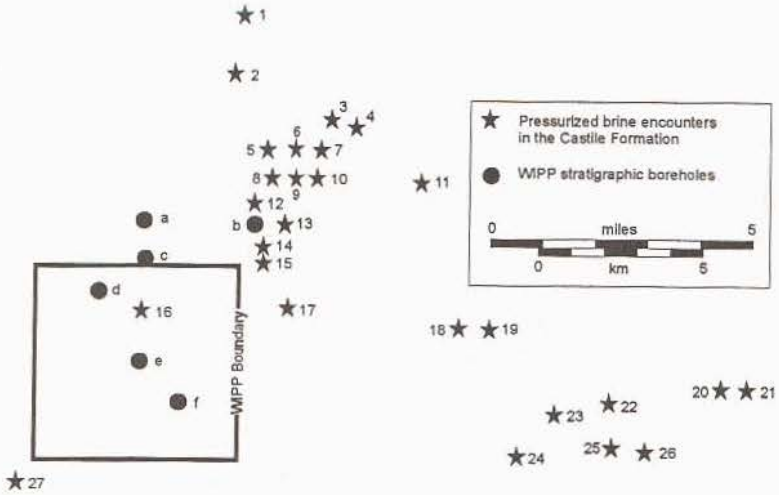

1. Pogo
2. Union
3. Luke Fed 1
4. AEC-7
5. ERDA-6
6. AIS State 1
7. AIS State 4
8. Molly State 3
9. Molly State 1
10. Unocal AHU 1
11. Bilbrey
12. Pogo 2-3
13. Pogo 12-8
14. Martha
15. AIK 3&4
16. WIPP-12
17. Neff 13-5
18. Kiwi AKX
19. Lechusa Fed 1
20. Mascho 2
21. Mascho 1
22. Covington
23. Culbertson
24. Red Tank
25. Shell
26. Tidewater
27. Belco Hudson
a. WIPP-11
b. AEC-8
c. DOE-2
d. WIPP-13
e. ERDA-9
f. DOE-1

Fig. 2. Boreholes reported to have encountered pressurized brine in the upper Castile Formation in the vicinity of WIPP.

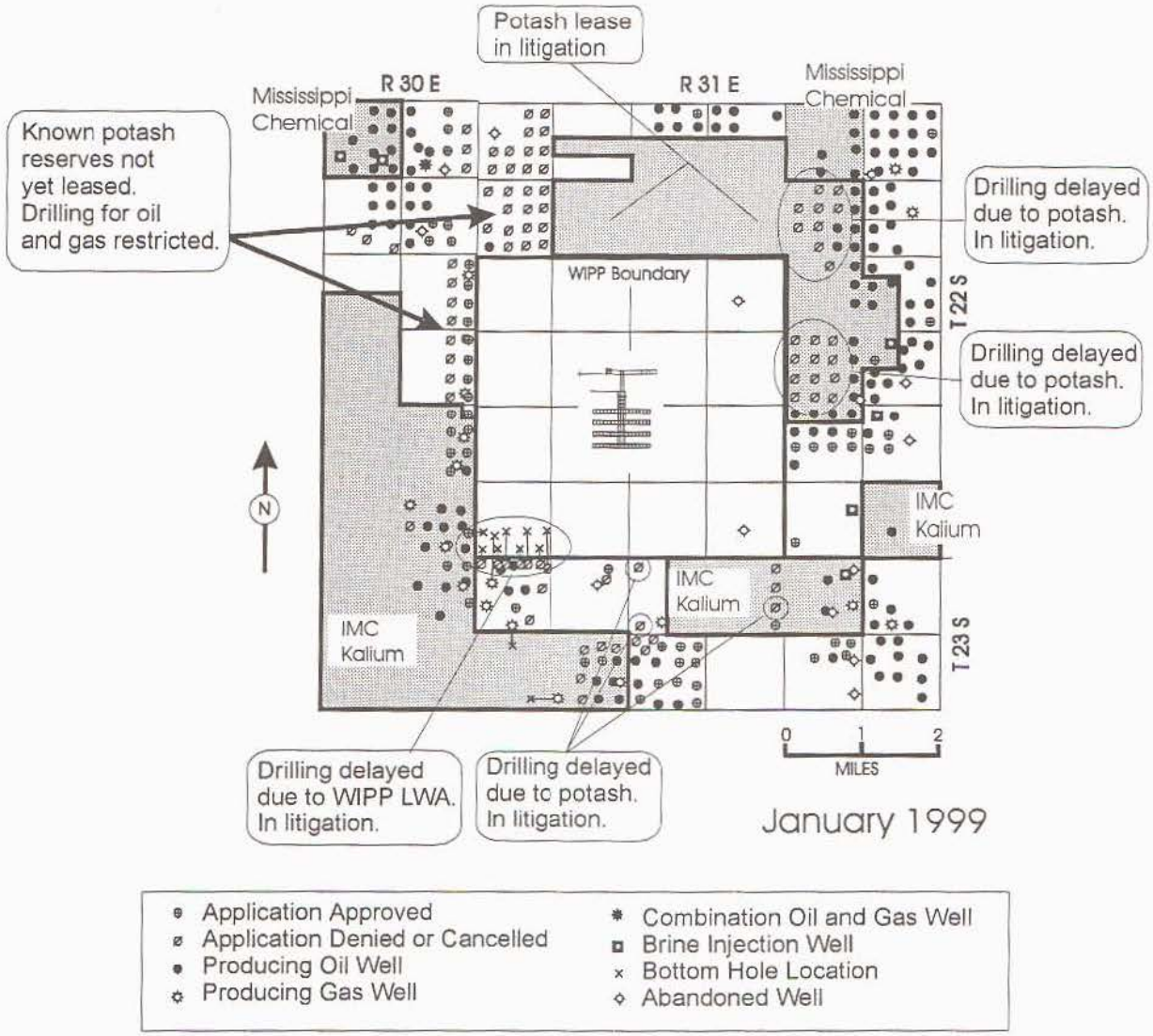

Fig. 3. Current interest in potash, oil, and gas resources surrounding the WIPP.

oil and gas contain no information on testing for the size of the brine reservoir. The DOE used the estimate of correlation length to determine the probability of the WIPP-12 brine reservoir extending below the repository to be 8%.

The best interpretation of the pore volume of the WIPP-12 brine reservoir is 2,700,000 m^3.[17] Assuming the maximum thickness of 24 m[19] for the anhydrite layer containing the brine, a porosity of 0.008 (mean value in the CCA), and a pore compressibility of 10^{-10} Pa^{-1}, the radius of a circle representing the footprint of a cylinder of brine reservoir is 2 km (Fig. 4). Constrained by several boreholes in which brine was not encountered , such a circle easily envelopes the entire repository.

Given the magnitude of the brine reservoir encountered by WIPP-12 and the results of the TDEM survey,[18] it appears logical to assume that the reservoir intercepted by WIPP-12 extends under the WIPP repository. The 8% probability of a future borehole at the WIPP repository encountering brine in the Castile Formation, assumed in the CCA,[1] therefore remains unjustified.

The CCA proposed a brine encounter of 8% based on the argument that the brine resides in subvertical fractures that have an 8% probability of en-

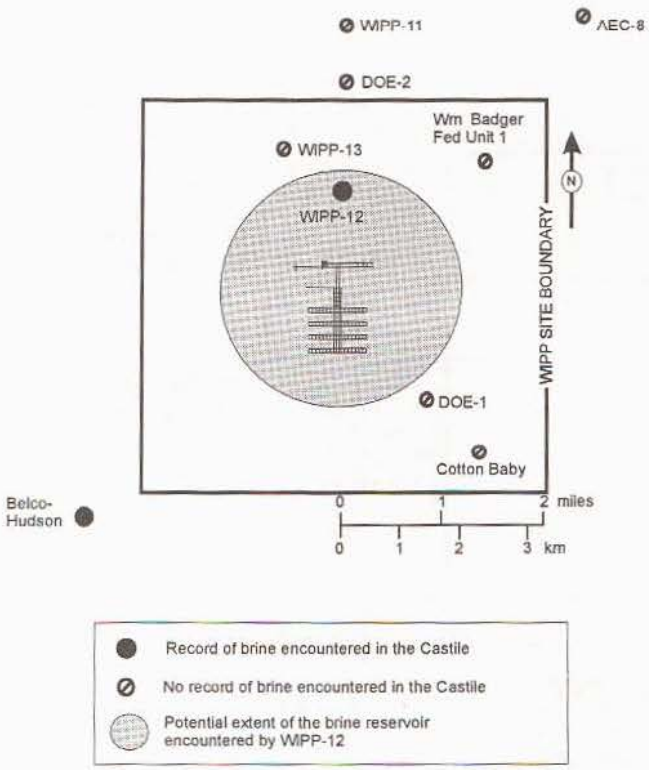

Fig. 4. Potential extent of WIPP-12 brine reservoir using WIPP-12 pressure recovery data, rock compressibility of 1×10^{-10} Pa^{-1}, and reservoir thickness of 24 m.

counter by a vertical drill hole. The EEG recommended a 100% probability on the basis that the WIPP-12 brine reservoir was large enough to extend underneath the repository, a conclusion also confirmed by geophysical testing directly above the repository. The TDEM data may be interpreted to indicate the brine to be under 60% of the repository. The EPA agreed that 8% was not representative and decided that the probability should be sampled from a range of 1% to 60%. There is no technical basis for the 1% value nor does it make sense to use the probability of a probability. A fixed value of 60% should be used in recertification calculations.

The CCA assumes a pore volume of the brine reservoir underlying the repository to vary from 32,000 to 160,000 m^3. The much lower volume is partly based on the unjustified assumption that the parts of the reservoir extending beyond the repository will get depleted by multiple intrusions in the area outside the repository. Thus, both the probability and the volume of the potential brine reservoir underlying the repository have been grossly underestimated in the CCA.

The EPA Performance Assessment Validation Test (PAVT) required the calculations to be repeated assuming a brine volume of 17 million m^3. The increased volume had a noticeable effect on releases, but compliance was still met. From this calculation, the EPA suggested that the PAVT justified the original CCA brine reservoir parameters as adequate for use in PA. The calculation does not justify this conclusion. There are many other parameter values and conceptual and numerical models that may be changed and these changes will affect the outcome of future calculations. There is no rational basis for finding an unjustified value to be acceptable unless it is justified based on observations, experiments, or widely known facts.

4.2. Radionuclide Transport Through the Culebra

Transport of radionuclides to the accessible environment through the Culebra dolomite aquifer overlying the repository has been postulated to be the major pathway for breach of the WIPP repository. The EPA concluded that the very low contribution to the total releases from this pathway, as calculated in the CCA, was due to the assumed values for chemical retardation (K_d). In fact, the calculated low releases from the groundwater pathway are due to a number of assumptions made in the CCA. The amount of radionuclides introduced in the Culebra is low due to the assumptions of actinide solubility, brine reservoir characteristics, and the intrusion borehole characteristics. There are other factors in calculating transport through the Culebra besides the assumption of K_d values that result in low releases. These factors are discussed below.

The National Academy of Sciences WIPP Committee (Chapter 6 and Appendix F of Ref. 20) raised a number of issues regarding the conceptual model and numerical model of transport through the Culebra aquifer. These issues do not appear to have been addressed by the EPA in the certification decision. Neither the EPA's "Technical Support Document for 194.23: Ground Water Flow and Contaminant Transport Modeling at WIPP" nor the "Compliance Application Review Document (CARD) No. 23: Models and Computer Codes" directly address these issues. These issues are described in detail by EEG[9] and are summarized below.

4.2.1. Heterogeneity and Model Discretization

Much recent hydrogeologic research has clarified the importance of heterogeneity in controlling solute transport. What constitutes an adequate scale of definition of formation heterogeneity for a flow model may be inadequate for solving the transport equation in the same formation. Konikow[21] presented results of numerical experiments indicating that the CCA consistently underpredicted the migration distance of a plume emanating from a human intrusion borehole. In the CCA model of the Culebra, it appears that errors arising from several sources cause an artificial spreading of the calculated width of the plume at the expense of its length. If the plume spreads out laterally more than would actually occur, for a given mass of contaminant released from a leaky borehole, the wider plume will necessarily move downgradient a shorter distance than the narrower plume. The sources of these errors include numerical dispersion and spatial truncation errors in the transport code, poor resolution from using a grid that is too coarse for the scale of the problem, and overestimates of the size of the solute source area.

The solute-transport model used in the CCA is based on a finite-difference grid having a minimum spacing of 50 m. An alternative analyses was performed using the MOC3D model[22] in which the transmissivity variations are represented on a much smaller scale, using a 2-m grid spacing rather than the original 50-m grid spacing. This finer scale representation of the heterogeneity and of the borehole source area results in a much longer, but narrower, plume that would have a significantly shorter travel time to the regulatory boundary for equivalent concentration levels.

4.2.2. Heterogeneity of Other Transport Parameters and Processes

The CCA model of the Culebra assumes that most properties of the system, except the transmissivity, are homogeneous and uniform within each simulation realization, but that these properties varied from run to run. Field tests at WIPP, however, indicate significant variability in many of these properties. For example, the effective porosity of the aquifer varies by almost an order of magnitude, even over a distance of only 50 m (the size of one cell of the model grid). Porosity has a strong control on transport velocities and times. Hence, the variability in porosity induces variability in velocity, which means that some parts of the plume may move faster than the local average velocity. This effect cannot be captured by assuming that porosity is uniform in each simulation. One would expect other properties, such as K_d and fracture spacing, to similarly exhibit large spatial variations. The PA procedure inherently assumes that heterogeneity in these variables has no significant impact on transport, or that its effects can be adequately represented by varying uniform properties among all the realizations. Either way, the CCA has not demonstrated that this is indeed the case and that it is reasonable to ignore the spatial variability in all of these critical parameters.

4.2.3. Sampling Procedures for Input Parameters

To generate the statistical distributions from which the risks are calculated, many simulations of hydrogeologic processes are performed to generate an adequate sample size. The approach to varying the values of the many parameters in the multiple realizations can introduce errors into the final analysis. In particular, if hydrogeologic variables that are highly correlated are sampled independently and if the correlations are ignored, then some of the realizations may be based on unreasonable or very unlikely combinations of parameters. Such individual simulations should not be incorporated into the final analysis because they may skew the statistical results. For example, the CCA separately sampled and independently varied aquifer transmissivity, fracture spacing, and porosity. Yet there is good reason to suspect that these variables are interrelated. The concern is that the net effect of independently sampling correlated parameters could yield a biased risk assessment, as described in more detail in Ref 8.

4.2.4. Consistency Between Performance Assessment (PA) Models

The PA procedure uses one model to calculate the fluid and solute flux up and out of a human intrusion (HI) borehole. This outflow flux should then be equal to the input flux (source term) in the Culebra model that is used to calculate transport distances and times. However, the source term in the Culebra flow model is apparently not represented as a specified fluid flux, so it is unclear that the flux out of the borehole is equal to the flux into the Culebra for

each set of realizations (or even for the mean of all realizations). The PA models should compute mass balances and budgets, to demonstrate that the two boundary conditions are indeed equivalent. Specifically, the total mass of fluid and solute that the borehole model computes to enter the Culebra over 10,000 years should equal the total mass of fluid and solute that is added to the Culebra over 10,000 years in the Culebra model. It appears possible that representing the HI borehole solute flux as an initial condition in the transport equation without an accompanying fluid flux could lead to a consistent underestimate of the solute spreading away from the finite-difference cell where the HI borehole is assumed to be located.

4.2.5. Other Concerns About the Culebra Parameters and Processes

The NAS WIPP Committee report (Chapter 6 and Appendix F of Ref. 20) included a number of criticisms of the conceptual models and numerical models of the Culebra, many of which remain unresolved. The most critical issues relate to the use of homogeneous and uniform K_d values in each realization, and whether the very simple retardation factor concept adequately represents all of the complex reaction chemistry. This has certainly not been adequately demonstrated at the field scale. A related important issue is the accuracy of the definition of matrix diffusion processes and parameters. Another concern is the reliability of the regional transmissivity estimates for the Culebra, which were determined using inverse methods that assumed a nonleaky two-dimensional aquifer. Three-dimensional analyses by Sandia[23] clearly indicated that there is significant leakage into the Culebra. A Climate Index has been used as a multiplication factor in the CCA to enhance the magnitude of flow of the Culebra flow field to compensate for the lack of consideration of the additional flux through the system. However, we have not seen any rigorous analysis and documentation of the consequences of such errors, or the sufficiency of corrections applied.

4.2.6. Current Efforts to Resolve the Culebra Transport Issues

Many of the shortcomings listed above arise from the fact that the models developed for the flow and transport of radionuclides through the Culebra are computationally expensive to perform, i.e., have very long run times. Adding complexity from the suggested comments would only further increase these run times. To help combat the strain of additional development on transport calculations, a new 1D, semianalytical approach was taken on the latest round of sensitivity analyses.[23] The calculations used a particle tracking code to map out a series of curvilinear paths from the steady-state flow velocities, on which a 1D analytical transport calculation was performed. The calculations experienced decreased run times, with comparable results to the CCA. The results open the door for increased complexity and more realistic model assumptions.

In addition to the increased modeling effort, extensive laboratory and field investigations are being conducted to understand the diffusive nature of transport in the fractured media. Field tracer experiments suggest that breakthrough curves are best replicated with a dual-porosity, multi-rate diffusion model.

4.3. Chemical Retardation

The values for sorption coefficient K_d used in the PA impact the postulated releases of radionuclides through the Culebra pathway. Independent checks of the CCA calculations by the EPA and the EEG show that only a 3 ml/g value for K_d is sufficient for showing compliance with the containment requirement of the EPA standards (40 CFR 191.13). This conclusion relies on keeping all the other parameters and assumptions in the CCA unchanged. It is difficult to accept a particular value or a range of values for any of the input parameters on the basis of partial sensitivity analyses. To have confidence in the calculations, the values of all input parameters should be independently verifiable to be robust and based on valid experimental data. The EEG recommended[8] resolution of the following issues to justify properly the K_d values.

4.3.1. Limitations of Laboratory Data

The EEG has accepted the validity of using the laboratory-determined K_d values to get an estimate of the values to be used for modeling contaminant transport in the field because groundwater diffusion into the rock matrix will provide opportunities for

chemical retardation to occur. This does not mean, however, that a one-to-one correspondence may be assumed between the laboratory and field values. The K_d range determined from batch tests applies only to the matrix porosity, and not to retardation in the fracture system with advective porosity.

4.3.2. Limited K_d Database

The experimental database for the K_d values used in the CCA remains insufficient. In the absence of measured K_d values for plutonium at oxidation states III and IV and inconclusive results for Am^{III} the K_d values for these three most important actinides in the WIPP inventory have had to be estimated. These estimations are based on two questionable assumptions. The first is that K_d values for actinide cations of the same charge should roughly be the same. The weakness of this assumption lies in not considering the effect of the speciation behavior of the cations on their adsorption properties. The second assumption is that predictable trends exist for the K_d values of actinide cations of different charge. The DOE used this assumption to argue that Pu^{V} data can be used for Am^{III}. This assumption is based on questionable data and interpretations of the experiments conducted with dilute groundwater from the Yucca Mountain site, even though, fortuitously, the same trend has been reported by some other experimenters. Results of the intact core column tests are probably of questionable value as well. The Am and Pu input concentrations to the cores were so close to saturation with solids that precipitation rather than adsorption may have occurred.

The net result of these assumptions is the use of unjustified K_d values for the three most dominant radionuclides in the WIPP inventory. Pu^{V} data have been used for Pu^{III} through a two-step process, both of which are questionable: first, through the predictable trend argument for Am^{III}, and then through the oxidation state analogy for Pu^{III}. Similarly, Th^{IV} data have been used for Pu^{IV}.

The oxidation state analogy is most useful as a starting point for designing an appropriate experiment, but the answer is not known until the experimental measurement is actually determined. As stated in the NAS/NRC WIPP Committee report, "Although the oxidation state model (the assumption that the chemistry of a given oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviation for the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy."[20]

Besides the inherent limitations of the oxidation state analogy, there is an additional problem of an inapplicable brine (from ERDA-6 brine reservoir) having been used for the Th^{IV} experiments. The mean K_d values measured in the ERDA-6 brine are greater than the values determined using the WIPP repository brines.

4.3.3. Use of Laboratory Data

The EEG expressed concern[8] with the CCA values for the lower and upper bounds of the K_d probability distribution and how these bounds are defined relative to the type of brine used in the batch experiments. The ranges for K_d relative to brine type were selected based on the average value of the sample distribution. For example, the range for Pu^{V} (and by extrapolation, for Pu^{III} and Am^{III}) used in the CCA calculations is 20–500 ml/g, which reflects values from the batch tests using deep brines. The lowest K_d value using the Culebra brine was 9.8. The assumed range for Pu^{V} should have been 9.8–500 ml/g.

4.4. Solubility of Actinides

The solubility of actinides is very important in calculating releases from the repository. The FMT model used in the CCA predicts differences for actinide sulfate solubilities that cannot be explained by chemistry, thus raising questions about the reliability of this model. DOE is considering replacement of the FMT code with EQ3/6 for the first recertification.[25,26]

Rather than using an extensive plutonium database, the FMT predictions relied on thermodynamic data for other elements and an oxidation state analog argument. EEG recommends that the calculations be performed using thermodynamic data for plutonium.

The CCA discounts the role of organic ligands on plutonium solubility. It argues that the entire repository waste is a homogeneous blend and that the chelating compound EDTA is the strongest complexing agent and the amount of it present in the inventory is not enough to make a difference. But citrate forms stronger complexes with actinides in the +IV oxidation state than with other cations. The solubility

of a stable plutonium–citrate complex in individual waste containers needs to be determined.

Plutonium constitutes 82% of the radionuclide inventory of the repository. The PA efforts of 1991 and 1992 attempted to capture the effects of oxidation state on solubility throughout the full range of the four possible oxidation states for plutonium in the repository: III, IV, V, and VI. To the contrary, the 1996 PA was based on calculations which assumed that the iron in the repository would force a reducing environment, thus allowing only Pu^{III} or Pu^{IV}; there would be no Pu^{V} or Pu^{VI} which can have higher solubilities. However, some of the experimental results from the Source Term Test Program, with liters and drums of TRU waste, show very high solubilities, suggesting the existence of either Pu^{V} or Pu^{VI} despite the presence of iron. The observation tends to undermine the assumption that all plutonium will be in either oxidation state III or IV. This issue needs to be resolved.

4.5. Direct Release Through Human Intrusion

As one of the dominant modes of release, a valid model for the spall of waste into an intrusive borehole is needed. Spall is waste that has been introduced into the drilling fluid due to radially channeled, highly pressurized gas flow from within the repository to a lower pressure borehole. The conceptual model peer review[27] found the spall model initially proposed by DOE to be conceptually inadequate. The DOE schedule for submittal of the application left insufficient time for development of an appropriate model. The DOE provided the panel with additional experimental information and results from other modeling efforts and asked the panel to consider whether the spalling volumes predicted by the original inadequate model was acceptable for use in the PA. It was argued by the DOE that the inaccurate predictions were acceptable because the predictions overestimated the release during a spall event. The peer review group accepted the inaccurate model based on that argument.[28] After DOE submitted additional information, EPA also accepted the model results for the purposes of PA.

The overestimated prediction stems from the development of an additional model for release calculations. This new model predicted releases about 1/20 of the original calculations, thus leaving the impression that the original model made a conservative prediction. However, both are inadequate and hence it is unknown which model's prediction is closer to reality. Testing of the new model[8,9] revealed serious instability problems outside a narrow range of waste permeabilities as shown in Fig. 5. For the waste strengths investigated there can be no confidence in waste permeabilities outside the narrow range of 1.7 to 2.0×10^{-13} m^2.

The EPA maintains that the code behaves quite reasonably under expected repository conditions. Assuming "expected conditions" is suspect given the uncertainty that arises from the geologic and hydrogeologic response of the repository system, along with the gas generation from the degrading waste. The fundamental philosophy behind the PA is to sample the input parameters from an expected range. To state that one set of conditions, for which the model is applicable, correctly captures all uncertainty inherent in long-term modeling underestimates the importance of accommodating such uncertainty. A new approach is needed to develop a coherent and straightforward model to address the important issue of spall supported by a suite of appropriately designed experiments by which to determine waste strength.

As a part of the recertification effort by DOE, work is in progress to capture adequately the physics of spall in a new model. The new model will incorporate a modified wellbore hydraulics model with mixing equations for solids and fluids, a drillbit damage

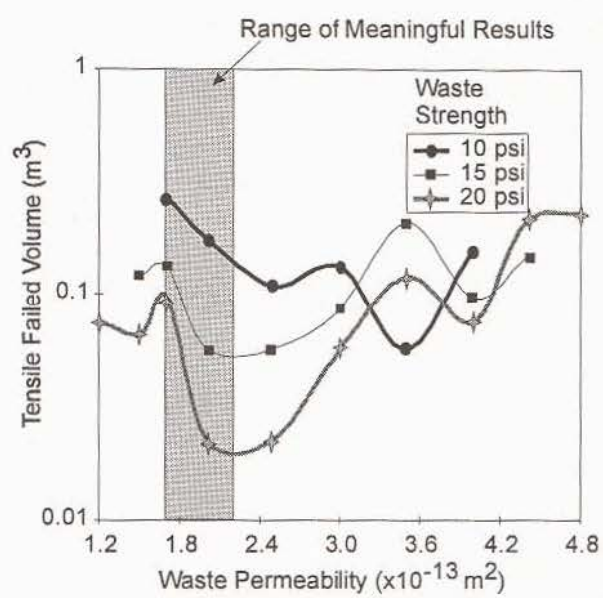

Fig. 5. Tensile failed volume from GASOUT predictions for various waste strengths and waste permeabilities.

model, and a solids transport up the borehole annulus. Previous models assumed that all of the material that failed in the bottom of the borehole would be transported to the surface. However, by actually modeling the phenomenon, the likely result would be that only a fraction of the material would reach the surface and reduce the overall effects of spallings on the CCDFs.

4.6. Fluid Injection

Brine injection for saltwater disposal and enhanced oil recovery is already underway near the WIPP and throughout the Delaware Basin.[29,30] The history of water migrating away from leaking injection wells through the Salado Formation in southeast New Mexico is well documented.[30–32] Nonetheless, fluid injection for oil recovery within the designated WIPP boundary was not included in the 1996 performance assessment calculations. The DOE rejected the scenario on the basis that the EPA regulations did not require it. Only the drilling event was included.

The first step in a performance assessment is to screen features, events, and processes (FEP). Two grounds for rejecting a relevant scenario from consideration in the PA calculations are low probability or low consequence. Probability and consequence, however, are not considered if a scenario has already been eliminated on the basis of regulation. The regulation states: "With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole."[3]

The regulation does not preclude DOE from including the fluid injection scenario as part of the recertification effort. In some instances, the EPA certification identifies the need to further evaluate a scenario that was eliminated on the basis of regulation. For example, the EPA determined that DOE did not need to include air drilling in the PA because it was not a current practice and thus it was ruled out on the basis of regulation. Nonetheless, EPA conducted further analysis "solely to allay the public's concern"[4] on the issue. Given the presence of oil reserves, the probability of future drilling, and the reasonable expectation that the reserves will be recovered by methods including fluid injection, it would seem prudent for the recertification effort to revisit the issue of fluid injection within the WIPP site boundary.

The OECD/NEA–IAEA Joint International Review Group also expressed reservations about rejecting a scenario solely on the basis of regulatory considerations: "It would improve the confidence of the reader if the DOE presented the logical or physical arguments for not considering these processes in the assessment, in addition to noting that they are not required in a compliance demonstration. Otherwise, there is an impression that processes that might deserve consideration from a safety perspective have been eliminated."[33]

Recertification can also incorporate new information from the expanding fluid injection practices surrounding the WIPP site. The effects of leaking injection wells adjacent to the site were screened out from the performance assessment calculations on the basis of low consequence by the DOE[1] and low probability by the EPA.[4] The DOE had chosen to examine consequence rather than probability, recognizing that certain petroleum practices are hard to define in a probabilistic sense.[34]

The EPA Certification relies on the DOE's low-consequence argument as the basis for rejecting fluid injection as a scenario.[4] However, the EPA acknowledges that certain scenarios can be constructed that inject large volumes of fluid into the repository. In these cases, EPA relies on its own probability calculation to screen out certain combinations of natural and human events (pp. 24–25 of Ref. 35).

The EPA multiplied the probability of each event to determine the probability of an injection well impacting the repository. Initially, EPA determined the probability of an injection well impacting the repository as 1 in 667 million (Table Q of Ref. 36), a value which was widely cited by others (p. 111 of Ref. 8; p. 45 of Ref. 37; p. 27 of Ref. 38). The final technical support document maintains that the original value was 1 in 58,000.[39] Based on new estimates of individual events, the probability of a leaking well impacting on the repository was then estimated to be 1 in 171,000.[4] Thus, the EPA analysis advanced three different values of probability, spanning four orders of magnitude. The uncertainty lends support to the DOE position that it would be difficult to defend the probability argument because it would be difficult to define the performance of individual components in a probabilistic sense.[34]

In summary, recertification should consider the effect of fluid injection just outside the site to accommodate the reasonable expectation that there will be an effort to produce the crude oil reserves by waterflooding and there will be saltwater disposal of produced brines. The recertification also needs to

examine developing information from the saltwater disposal, oil field pressure maintenance, and oil field waterflooding activities adjacent to the WIPP for inclusion into future PA calculations. Just as a scenario can be screened out, a scenario can also be screened in, based on new information or a reexamination of existing information.

4.7. Solution Mining

The one impact of potash mining that has been considered in the CCA is the alteration of the transmissivity of the overlying Culebra aquifer as a result of subsidence due to conventional mining. The EPA argues that near-future activities, such as solution mining for potash, can be eliminated on the basis that it is not now occurring in the Delaware Basin and to assume its occurrence in the future would be speculative. Nonetheless, solution mining is a proven technology that has near-future potential. The EPA criteria require consideration of near-future activities. The EPA guidance specifies that this includes plans for new mines in the vicinity of WIPP.[40]

By delaying the development of oil and gas reserves surrounding the WIPP (Fig. 3), the U.S. Bureau of Land Management has indicated its plans to first allow the mining of the potash. Meanwhile, the New Mexico Bureau of Mines and Mineral Resources,[41] at the request of DOE, identified one feasible future technique for potash recovery—solution mining of the remaining sylvite reserves. The report notes, "all mines have held open the option of using solution mining once their sylvite deposits are fully mined out."[41]

With the continued production of potash, PA needs to screen plausible scenarios with each recertification. The actual impact on the transmissivity of the overlying aquifers needs to be monitored. At this time the PA calculations rely on estimating the range of modification to the transmissivity of the Culebra aquifer. Changes in the transmissivity are multiplied by a factor sampled from a range of 1 to 1,000. As potash mining continues, it would be worthwhile to obtain a measurement of the change in the transmissivity to determine if this range is appropriate. In addition, other parameters, such as fracture density and aperture, diffusion, and dispersion, should be accommodated during a subsidence event.

4.8. Engineered Barrier

Like the spall model, the use of MgO backfill was another late development in the performance assessment that proved troublesome during the conceptual model peer review[27] and later during the EPA rule-making. Rather than decrease uncertainty in the calculated performance of the repository, the addition of MgO may increase uncertainty. First, there is no consensus on the behavior of the system. Experiments with MgO showed that various mineral phases would form, but nesquehonite was the only mineral phase that could be identified. It is also not known how long the nesquehonite phase would persist. For purposes of certification, the EPA accepted the initial DOE argument that the nesquehonite would be short-lived and the system would be dominated by other mineral phases. To further complicate the issue, the DOE later argued that the nesquehonite would never form under repository conditions.[37] The solubility model used in the 1996 PA calculated a substantial increase in plutonium solubility due to the presence of nesquehonite. EEG's calculations with the performance assessment model shows that while such a solubility does not result in a violation of the release limits, there is very little margin for error.[9]

5. RECOMMENDATIONS

Future iterations of performance assessment, as part of each recertification, need to consider the following recommendations.

1. The available data strongly suggests a 60% probability of drilling into a high-pressure brine and this value should be used for PA calculations.
2. The use of grid refinement for transport through the Culebra should be thoroughly explored and rigorously tested. Moreover, the effects of the heterogeneity of parameters, such as porosity and retardation, should be captured.
3. Chemical retardation values should be experimentally determined for the actinides of interest.
4. The actinide solubility of plutonium should be based on thermodynamic data for plutonium.
5. The spalling model needs to reflect the results of a carefully designed experimental program

to determine waste strength and a workable conceptual and numerical model.

6. Each recertification will need to consider new information from resource recovery activities, such as fluid injection and solution mining, as part of the first step in PA scenario development.
7. The behavior of the only engineered barrier, magnesium oxide, needs to be experimentally determined.

ACKNOWLEDGMENTS

Section 4.2 of this paper contains a summary of concerns brought to the EEG's attention by Dr. Leonard Konikow of the U.S. Geological Survey. Dr. Konikow developed these concerns while he served on the National Academy of Sciences WIPP Committee from 1989 to 1996. These were sent to L.C. as personal communication in February 1998. These issues are described in detail in Section 2.9 of Ref. 8 (EEG-68). The authors are also grateful to Dr. Jon C. Helton for providing an informal review of the paper.

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APPENDIX B

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ANALYSIS OF EMPLACED WASTE DATA AND IMPLICATIONS OF NON-RANDOM EMPLACEMENT FOR PERFORMANCE ASSESSMENT FOR THE WIPP

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May 2003

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment of New Mexico. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned the EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC04-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

The EEG performs independent technical analyses on a variety of issues. Now that the WIPP is operational, these issues include facility modifications and waste characterization for future receipt and emplacement of remote-handled waste, generator site audits, contact-handled waste characterization issues, the suitability and safety of transportation systems, mining of new panels, and analysis of new information as part of the five year recertification cycles as mandated by the WIPP Land Withdrawal Act. Review and comment is provided on the annual Safety Analysis Report and Proposed Modifications to the Hazardous Waste Facility Permit. The EEG also conducts an independent radiation surveillance program which includes a radiochemical laboratory.

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The analysis described in this report was reviewed by Dr. Bruce Davis of Centennial, Colorado. Dr. Davis is a consulting geostatistician with extensive experience in statistical and geostatistical applications to problems in the environmental, mining, and petroleum industries. The authors wish to thank Dr. Davis for his comments and suggestions.

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ACRONYMS

CCA	Compliance Certification Application
CCDF	Complimentary Cumulative Distribution Function
DOE	US Department of Energy
EEG	Environmental Evaluation Group
EPA	US Environmental Protection Agency
GSLIB	Geostatistical Software Library
LWA	Land Withdrawal Act
PE-Ci	Plutonium-239 Equivalent Curie
POC	Pipe Overpack Container
SNL	Sandia National Laboratories
SWB	Standard Waste Box
TDOP	Ten-Drum Overpack
TRU	Transuranic
WIPP	Waste Isolation Pilot Plant
WTS	Washington TRU Solutions
WWIS	WIPP Waste Information System

EXECUTIVE SUMMARY

The WIPP Land Withdrawal Act recognized that after the initial certification of the WIPP and start of disposal operations, operating experience and ongoing research would result in new technical and scientific information. The Environmental Evaluation Group (EEG) has previously reported on issues that it considers important as the Department of Energy (DOE) works towards the first recertification. One of these issues involves the assumption of random emplacement of waste used in the performance assessment calculations in support of the initial certification application. As actual waste emplacement data are now available from four years of disposal, the EEG performed an analysis to evaluate the validity of that initial assumption and determine implications for performance assessment.

Panel 1 was closed in March 2003. The degree of deviation between actual emplaced waste in Panel 1 and an assumption of random emplacement is apparent with concentrations of ^{239}Pu being 3.20 times, ^{240}Pu being 2.67 times, and ^{241}Am being 4.13 times the projected repository average for the space occupied by the waste.

A spatial statistical analysis was performed using available Panel 1 data retrieved from the WWIS and assigned room coordinates by Sandia National Laboratories. A comparison was made between the waste as emplaced and a randomization of the same waste. Conversely, the distribution of waste as emplaced is similar to the distribution of waste in the individual containers and can be characterized as bi-modal and skewed with a long high-concentration tail. The distribution of randomized waste is fairly symmetrical, as would be expected from classical statistical theory. In the event of a future drilling intrusion, comparison of these two distributions shows a higher probability of intersecting a high-concentration stack of the actual emplaced waste, over that of the same waste emplaced in a randomized manner as was assumed in the certified performance assessment calculations. This suggests that the methodology used during the certification performance assessment calculations underestimated potential releases by cuttings and cavings. That methodology sampled each layer in a stack separately and used the mean concentration for each waste stream.

The DOE performed a spallings release bounding analysis at the time of the initial certification. However, the selection of the statistical sample size of the bounding analysis assumed independence of samples, which is not characteristic of non-random waste emplacement. Instead it is demonstrated that the emplaced waste is spatially dependent. Therefore, the bounding analysis may not be adequate in the event of continued non-random emplacement. As for cuttings and cavings releases, the probability of a high-concentration intersection during an intrusion is increased because of non-random emplacement. Performance assessment calculations should either incorporate this increased probability or an adequate bounding calculation should be performed using spatial statistical methodology.

The use of Pipe Overpack Containers for isolation of the high ^{239}Pu waste may reduce the amount of material brought to the surface as a result of an intrusion. However, the integrity of these containers over the regulatory period has not yet been demonstrated. If the DOE wishes to take credit for the container, the DOE needs to provide an analysis of structural integrity and the potential effects resulting from the use of Pipe Overpack Containers.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP), built and operated by the US Department of Energy (DOE), serves as a geologic repository for disposal of defense transuranic (TRU) waste. The WIPP Land Withdrawal Act (LWA) required initial certification of compliance of the WIPP by the US Environmental Protection Agency (EPA) (LWA 1992). In addition, a recertification decision by EPA is required by the LWA at least every five years, dated from the initial receipt of waste. Recertification must consider new information resulting from operating experience of the facility and ongoing scientific investigation. The first recertification application is due to EPA by March 2004.

The Environmental Evaluation Group (EEG), in its role of providing independent technical oversight of the WIPP project on behalf of the State of New Mexico, previously identified ongoing issues relevant to the first recertification performance assessment calculations (Allen et al. 2002). These calculations attempt to represent the amount of radioactive material released as the result of some future drilling effort inadvertently penetrating a long forgotten repository. The performance assessment calculations for demonstration of compliance with EPA's standards assumed random emplacement of waste. Operational experience however, confirms non-random emplacement of waste.

In response to EEG's non-random emplacement concerns at the time of the initial certification (Neill 1997), the DOE provided a bounding analysis to demonstrate compliance, assuming contiguous emplacement of a high-activity waste stream (Dials 1997). This analysis was accepted by the EPA.

With the availability of operational data, this issue should be re-visited in the performance assessment calculations for the first recertification. Using emplaced waste data through September 2002, the EEG performed an analysis of the effects of non-random emplacement. This included: 1) comparison of emplaced activity for Panel 1 with the average activity, 2) analysis of the effects of random versus non-random emplacement on vertical stacking of waste containers, 3) analysis of volume/variance implications on the DOE bounding analysis, and 4) analysis of the potential positive effects of waste emplaced in pipe overpack containers.

The spatial distribution of waste in the repository is an issue for compliance because of the possibility of future human intrusions during the 10,000 year regulatory period. The WIPP is located in an area rich in oil, gas, and potash resources (Silva 1994). Performance assessment calculations include intrusion scenarios involving drilling into the repository which results in solids released due to cuttings, cavings and spallings (DOE 1996). Each intrusion is assumed to penetrate each container in a particular stack. For cuttings and cavings, it was assumed in the initial certification performance assessment that potential radioactivity that may be released into the environment can come from different waste streams, each having different amounts of activity at the time of the intrusion. This was accomplished by sampling the distribution of waste stream activity three times, once for each layer of waste in the stack, weighted by the waste stream volumes, and averaging to determine the released activity. Therefore, there was no correlation between layers of waste, which is inconsistent with the manner in which waste arrives and is actually emplaced. DOE's analysis resulted in cuttings and cavings releases that were greater than would occur from assuming average repository radionuclide concentrations, but were still a relatively small amount of allowed releases (Neill 1997).

A spallings release, which results from a pressurized repository, may be much larger. The initial performance assessment assumed that a spallings event would release material from multiple drums and multiple waste streams and could be approximated by the average activity of all contact-handled waste at the time of the intrusion. This is essentially an assumption of a homogenous distribution of radionuclides throughout the repository. It was calculated that the material removed by a spallings release would be between two and nineteen times the internal volume of a 55-gallon drum.

2.0 EMPLACEMENT OF WASTE

The underground WIPP facility design includes eight panels for disposal of transuranic waste (see Figure 1). Each panel consists of seven disposal rooms. Haulage drifts may be utilized as Panels 9 and 10 following emplacement of waste in the eight designed panels. Panel 1 was partially filled and closed by March 2003. At the present time waste is being emplaced in Panel 2 and excavation of Panel 3 is underway.

WIPP Facility and Stratigraphic Sequence

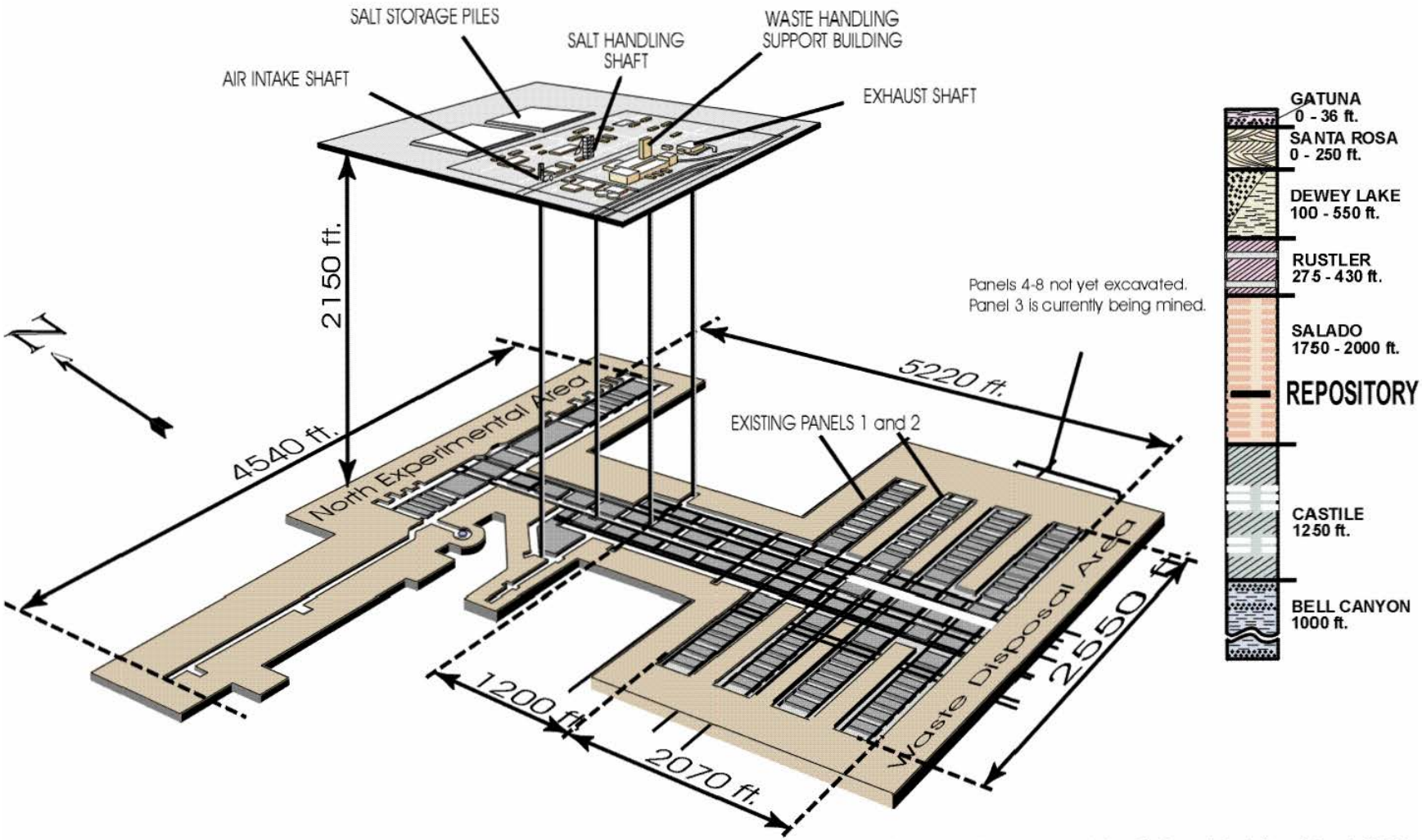

Figure 1. The WIPP facility and stratigraphic sequence. Panel 2 is currently in use. Waste emplacement was completed in Panel 1 during March 2003
Source of Figure: DOE.

Waste emplaced in Panel 1 was contained in: 1) drums, 2) standard waste boxes (SWB), 3) pipe overpack containers (POC), or 4) the recently permitted ten drum overpack (TDOP). Figure 2 shows schematics of these containers. Panel 1 drums are a 55-gallon drum which are constructed of steel and have an internal volume of 0.208 m^3. Seven drums are typically banded together for transportation to WIPP and emplacement in the underground (7 pack).

A SWB is also constructed of steel and has an internal volume of 1.88 m^3. If used for overpacking, each SWB contains up to the equivalent volume of four 55-gallon drums. However, more waste volume may be emplaced into a SWB if directly loaded. POCs fit within a 55 gallon drum, providing additional isolation of the waste. These were used for the high ^{239}Pu residues emplaced in Panel 1 (WTS 2002). TDOPs were used only recently and were not included in the Panel 1 data available at the time of analysis. To date these have been used for lower concentration TRU waste.

SWBs and drums are emplaced in stacks of three containers. Figure 3 shows a stack of three SWBs (center) and two 7 packs with a SWB on top (reader's right).

3.0 ANALYSIS OF WASTE EMPLACEMENT DATA

The EEG analysis of waste emplacement data included:

1) Comparison of emplaced activity for Panel 1 with the average activity.
2) Analysis of the effects of random versus non-random emplacement on vertical compositing of waste container activity.
3) Analysis of volume/variance implications on the DOE bounding analysis.
4) Analysis of the potential positive effects on performance assessment of waste emplaced in POCs.

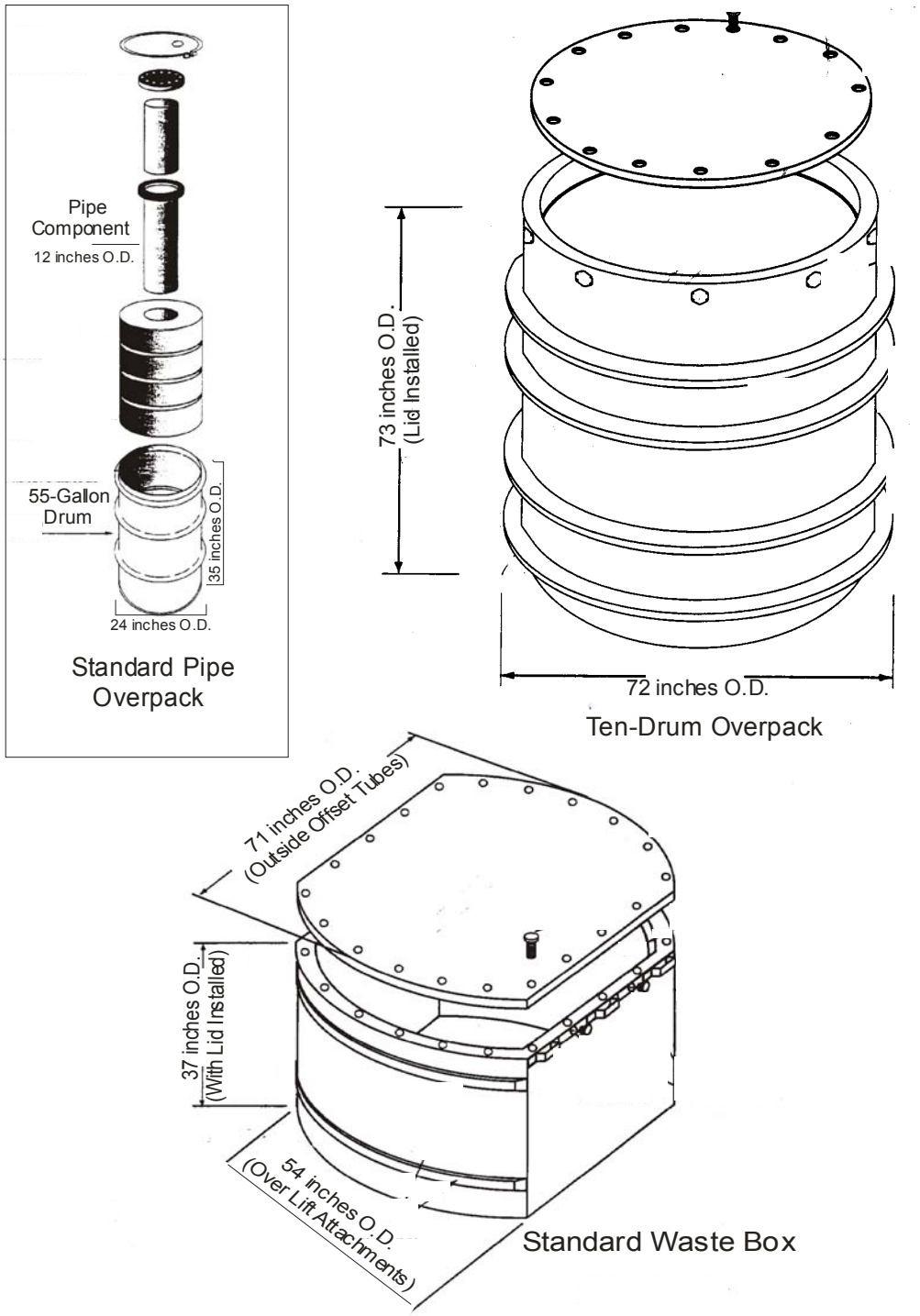

Figure 2. Waste containment packages used in Panel 1 (WTS 2002).

Figure 3. Waste being emplaced in Panel 1. Note stacks of three containers with MgO on top of each stack.

The first analysis was done using all emplaced waste data for Panel 1. The final three analyses used data provided by the DOE during January 2003 and consisted of emplaced waste through September 2002. These data were retrieved from the WIPP Waste Information System (WWIS) and assigned room coordinates by Sandia National Laboratories (SNL) (Stein 2002). Data were complete for rooms three and seven, for about one-half of room two, the intake drifts for rooms four through six, and the exit drifts for rooms two, three, and seven. Waste was only emplaced in the intake drift portion of rooms four through six because of degrading room condition resulting from the time interval between mining and first receipt of waste.

The exact size of each containment package (7 pack or standard waste box) and the exact spacing between packages is not recorded. Therefore, "real" coordinates were not available from SNL. For this analysis, the EEG took the SNL room coordinates and transformed them into a master grid containing all rooms. It was assumed that grid points have a spacing of seven feet. Each grid location is a stack of containment packages in which three layers of waste are emplaced: top, middle, and bottom.

3.1 Emplaced Activity in Panel 1

Non-random emplacement of waste results from the campaigning of specific waste streams to the WIPP depending on the DOE's agreements with the various states which host TRU waste and the readiness of particular waste streams for shipment from the other sites (DOE 2000). Table 1 compares important emplaced radionuclides to date with the average concentration assumed for the repository (DOE 2003). With the final emplacement of waste in Panel 1 during March 2003, the degree of deviation between actual emplaced waste and an assumption of random emplacement is apparent. ^{239}Pu is 3.20 times, ^{240}Pu is 2.67 times, and ^{241}Am is 4.13 times the projected repository average for the space occupied by waste. These averages are based on a total volume of waste of 10,496 m^3.

Table 1

Comparison of Emplaced Panel 1 Ci with
Compliance Certification Application Projections

Radionuclide	Curies (Ci)	Ci/m^3	CCA* Ci/m^3	Actual/CCA
^{239}Pu	152,000	14.48	4.52	3.20
^{240}Pu	34,290	3.27	1.22	2.67
^{241}Am	120,200	11.45	2.77	4.13
^{238}Pu	6,186	0.59	11.02	0.05
^{241}Pu**	482,024	45.92		

*Table 4-6, CCA (DOE 1996)
**Not a tracked radionuclide but important because of its daughter product, ^{241}Am

It is worth noting that only a very small fraction of the high wattage ^{238}Pu has been shipped and emplaced. This suggests the possibility of some future shipping campaign for the waste streams containing primarily ^{238}Pu, although the relatively short half-life is unlikely to have a significant effect on repository performance.

3.2 Analysis of Effects on Vertical Stacking

For each layer at each grid location, the total number of Plutonium-239 equivalent Curies (PE-Ci) was computed from the contents of each container according to the formula and weighting factors (DOE 2002):

$$PE-Ci = \frac{^{233}U}{3.9} + \frac{^{237}Np}{1.0} + \frac{^{236}Pu}{3.2} + \frac{^{238}Pu}{1.1} + \frac{^{239}Pu}{1.0} + \frac{^{240}Pu}{1.0} + \frac{^{241}Pu}{51.0} + \frac{^{242}Pu}{1.1} + \frac{^{241}Am}{1.0} + \frac{^{243}Am}{1.0} + \frac{^{242}Cm}{30.0} + \frac{^{244}Cm}{1.9} + \frac{^{252}Cf}{3.9}.$$

PE-Ci were used in this analysis, eliminating the need to analyze multiple radionuclides. However, for performance assessment calculations it is necessary to use individual radionuclide data.

Using the internal volume of each waste container (drum, POC, or SWB), the volume of waste was computed at each grid point. Finally, the total concentration (PE-Ci/m^3) was calculated for each stack of three containers. Figure 4a shows the spatial distribution of emplaced waste as expressed by PE-Ci/m^3.

To compare the actual emplaced waste with what could have been emplaced had the waste been emplaced in a random fashion, the following methodology was employed:

1) The concentration (PE-Ci/m^3) at each grid point for each layer (top, middle, and bottom) was calculated.
2) Using a random number generator, the order of each grid location was randomized by layer.
3) The combined concentration was then recalculated for each stack of three containers.

Figure 4b shows this hypothetical spatial distribution of random emplacement. When compared to Figure 4a it may be observed, at least qualitatively, that there are no longer specific areas of high or low activity, but a spatially uniform distribution of concentration.

Emplaced waste and randomized waste distributions were plotted and are shown in Figure 5. The means of the two distributions are essentially the same, but the distribution of actual emplaced waste is bi-modal with a higher standard deviation with a long high-concentration tail. This results from the physical process of non-random emplacement. High-concentration containers will likely be stacked together vertically, as will low-concentration containers.

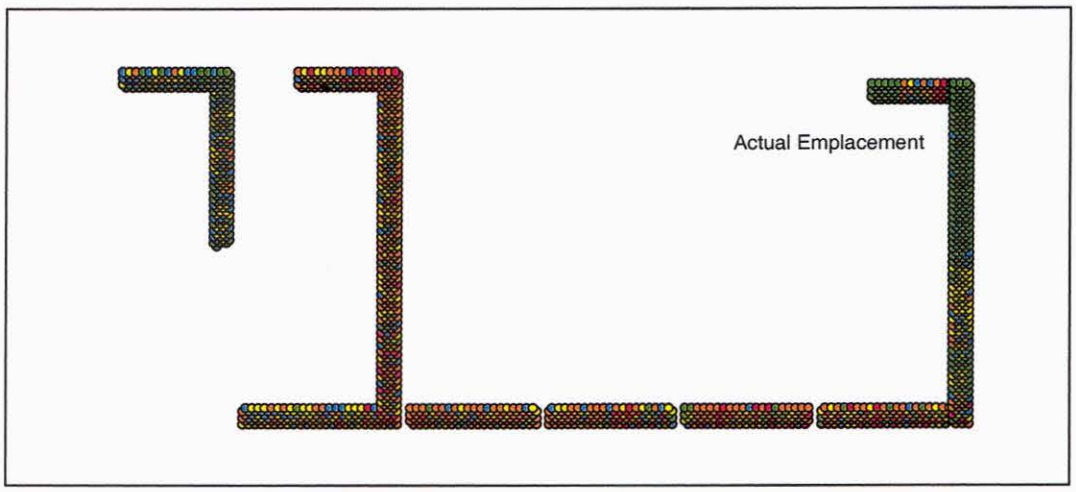

Fig 4a

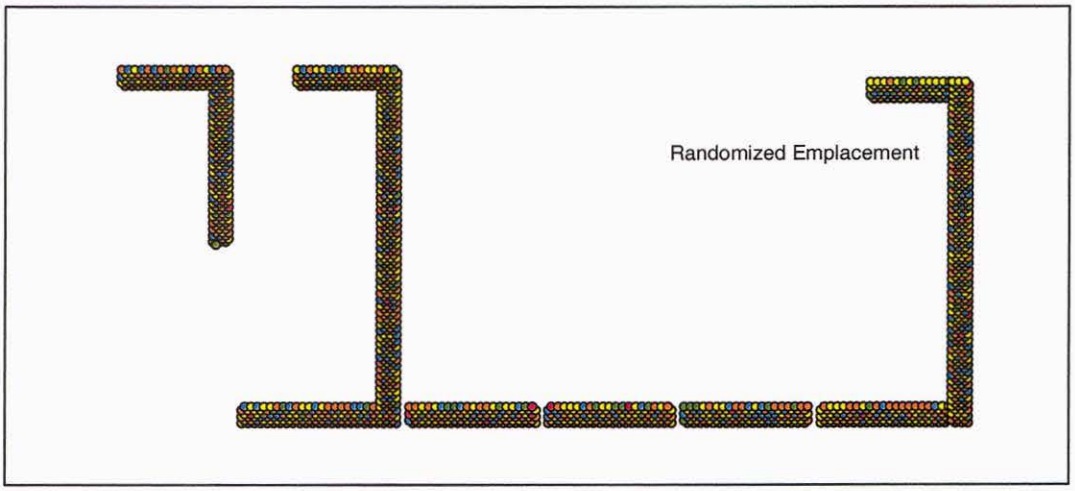

Fig 4b

Legend

PECi/m3

- 0. - 10.
- 10. - 25.
- 25. - 50.
- 50. - 100.
- 100. - 200.

Figure 4. Panel 1. Actual and randomized emplacement.

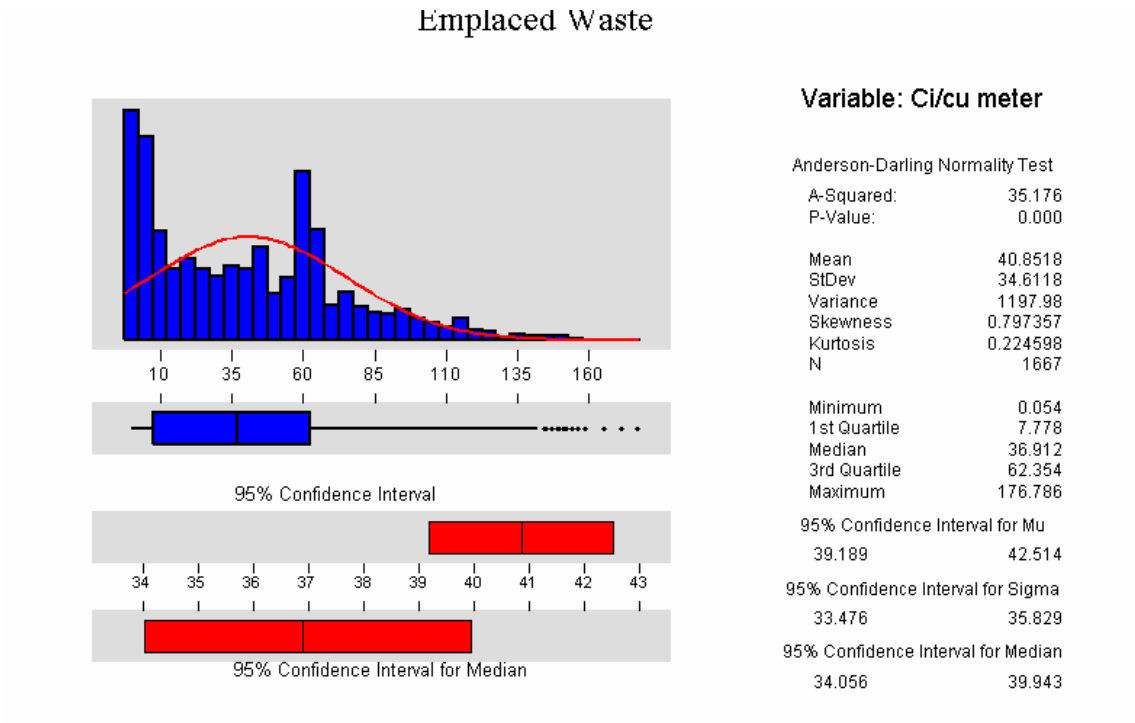

Fig 5a

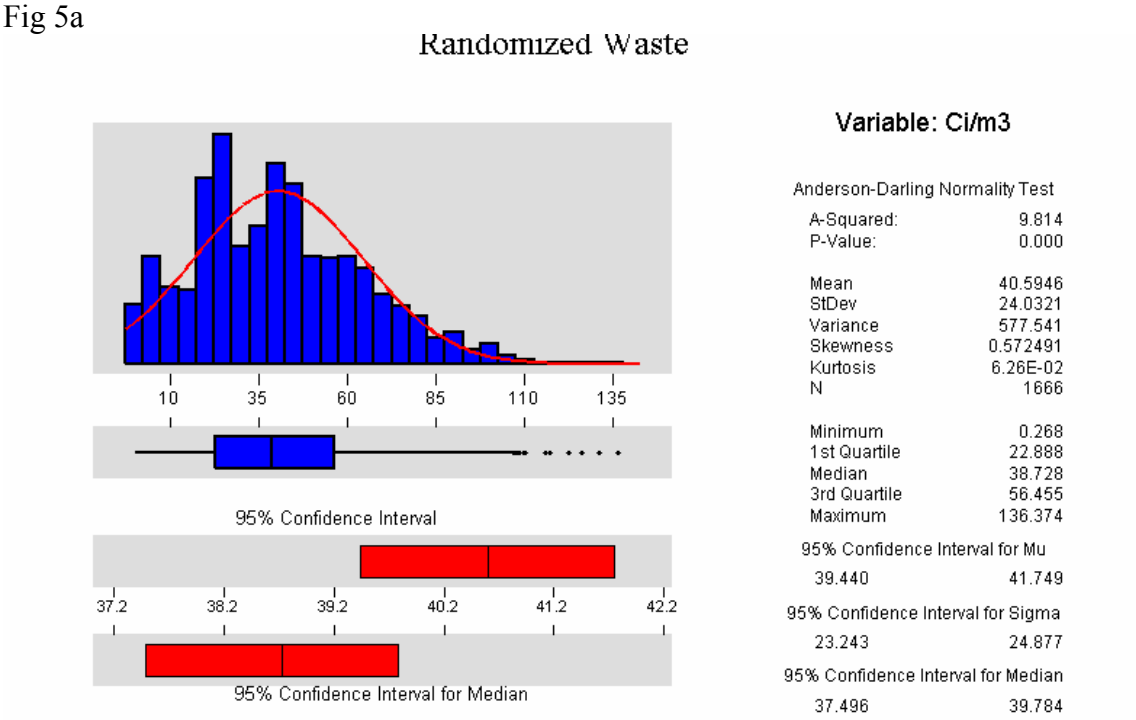

Fig 5b

Figure 5. Histograms and statistical summaries of actual and randomized emplaced waste.

Figure 6 shows the distribution PE-Ci in individual containers used in this analysis. This distribution is similar to that of the stacks of actual emplaced waste. As was seen in Figure 5, randomizing the spatial location prior to stacking results in a distribution of stacks that is closer to a normal distribution, or a state of maximum entropy as would be predicted from classical statistical theory. Non-random loading results in a skewing of that randomized distribution, with a lower median value but a longer high-concentration tail, more closely resembling the distribution of individual containers.

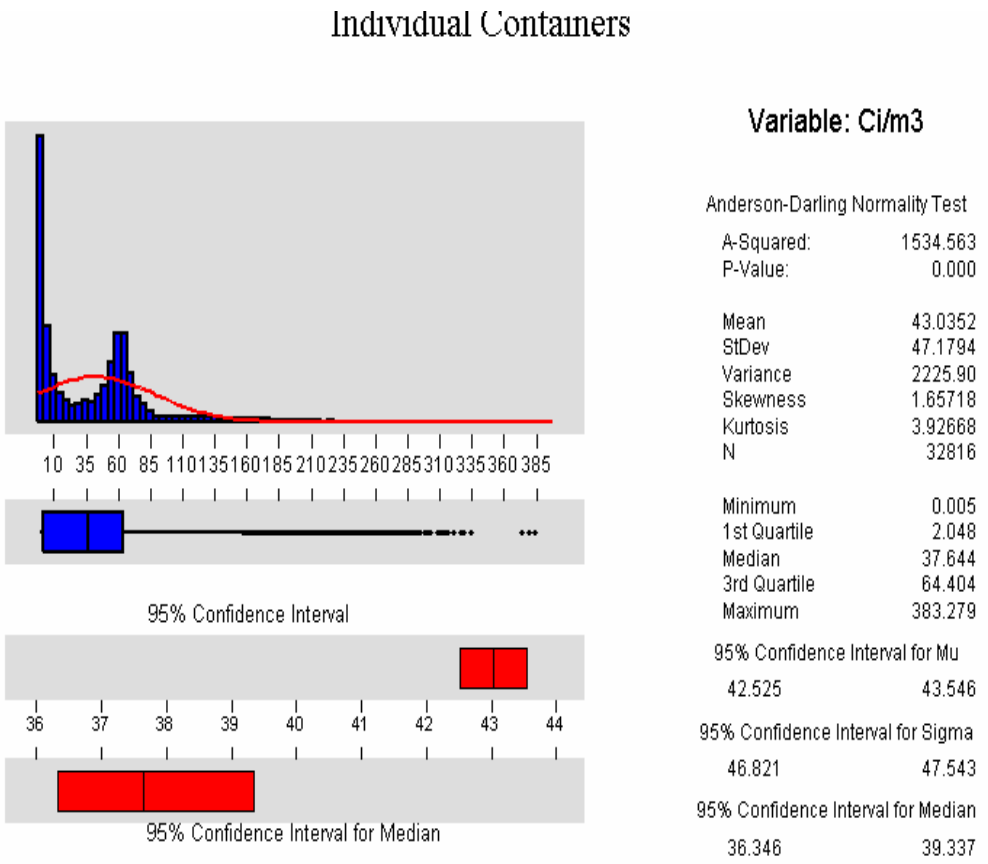

Figure 6. Distribution of individual containers used in the analysis.

The change of shape from the distribution of individual containers (Figure 6) to the stacks of randomized containers (Figure 5b) results from a change in volume, or statistical support. This volume change causes a change in variation that is affected by the spatial correlation of the containers. The similarity between the distribution of individual containers and that of actual stacks of emplaced waste (Figure 5a), i.e. permanence of distribution (Journel and Huijbregts

1978), and their deviation from the randomized distribution, illustrates the degree of non-random emplacement practiced in Panel 1. As the data are randomized and become spatially uncorrelated, classical statistics (independence of samples) would predict the empirical results demonstrated in Figure 5b. That is, that the distribution of emplaced waste would become more symmetrical.

The degree to which the distribution deviates from a randomized case is dependent on the actual data, but the probability of intersecting a high-concentration stack of three containers will increase because of the nature of non-random emplacement. This is shown for the Panel 1 actual and randomized distributions in a probability plot (Figure 7). It shows that the probability of intersecting high-concentration stacks is significantly higher in the non-random distribution versus the randomized distribution. For example, computing the projected average concentration of the Rocky Flats residues from the CCA information and assuming 20,100 drum equivalents of volume results in a value of 84.2 PE-Ci/m^3. From Figure 7, the probability of intersecting a stack greater than this average is 5% for the randomized case, but is 11% for actual emplacement.

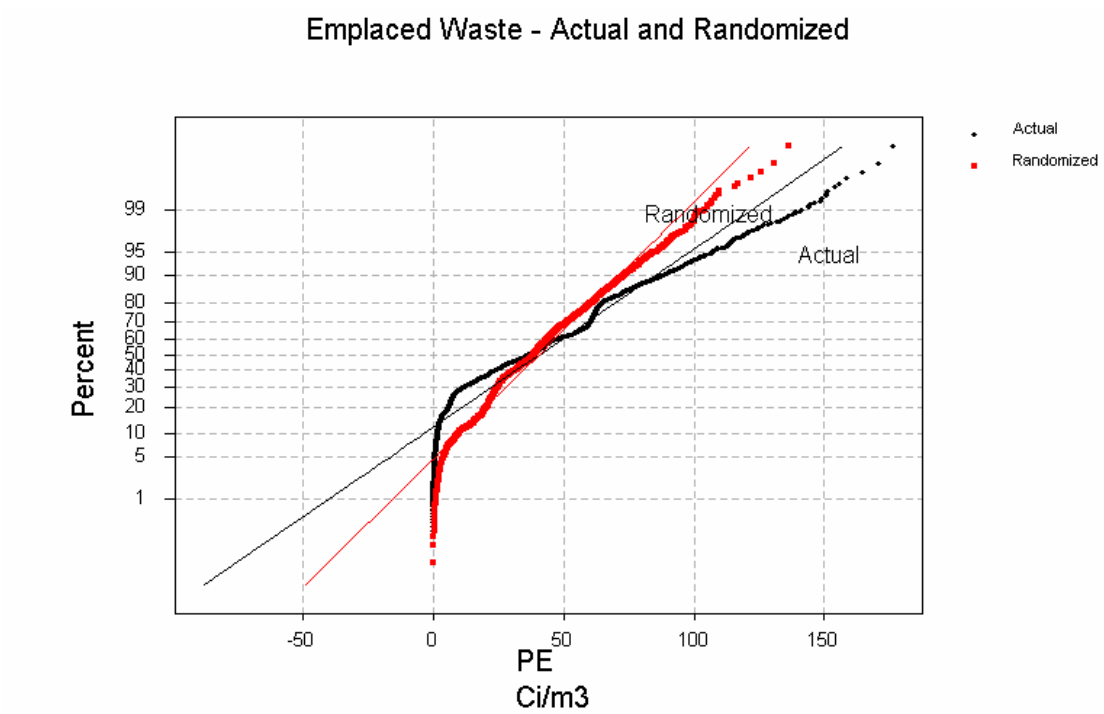

Figure 7. Probability plots of actual and randomized distributions.

Chapter 4 of the CCA (DOE 1996) states that, "A sampling of 10,000 futures is large enough that the *relatively low* probability combination of three of the waste streams with higher activity loading occurring in a single drilling event is captured in the CCDFs presented …" (italics added). It goes on to state, "… the CCDF is not impacted by sampling uncertainty so the assumption of random emplacement of containers is not important to the location of the CCDF and a load management plan is not necessary to support performance assessment assumptions". The change in distribution away from randomness caused by non-random emplacement of waste, and the subsequent increase in probability of high concentration intersection during an intrusion, casts doubt on these performance assessment assumptions.

3.3 Volume/Variance Implications of Non-Random Emplacement

In response to the EEG's concerns about the random emplacement assumption in the Compliance Certification Application (DOE 1996), the DOE performed a bounding analysis which assumed contiguous emplacement of the Rocky Flats residue waste (Dials 1997). This waste stream was selected because it was the highest activity contact-handled waste that had at least 810 drum equivalents volume. The 810 value was one one-thousandth of the total number of drum equivalents to be emplaced in the WIPP. Therefore, this waste stream would have a probability (conditional on the occurrence of a single intrusion) of intersection of more than 0.001, the probability limit established in 40 CFR § 191.13(a) (CFR 2002). However, this probability was based on the assumption of independence of samples and would therefore be a bounding case for random emplacement, not non-random emplacement.

As discussed in Section 3.1, about 11 percent of the emplaced three-layer stacks have average concentrations over the Rocky Flats residue average. The spatial distribution of these stacks are shown in Figure 8. The actual average emplaced value of the residues was only about 76 PE-Ci/m^3. If the actual value had been 84.2 PE-Ci/m^3, the discrepancy between randomized and actual would have been even greater. The probability of intersecting high-concentration stacks can be examined for the distribution of a spallings-sized event versus the distribution of an 810 drum-sized unit. The use of the spall-sized volume in an intrusion scenario is similar to the concept of a selective mining unit (smu) in ore reserve estimation (Journel and Huijbregts 1978) or a volume of selective remediation (vsr) in environmental cleanup (Desbarats 1995).

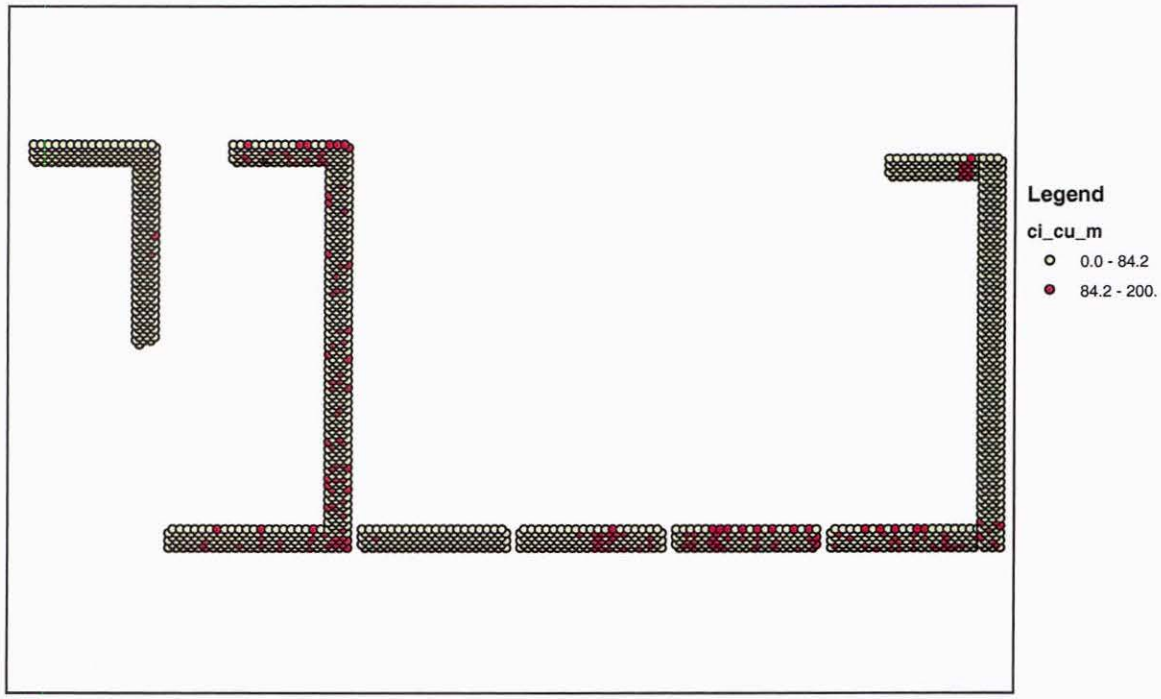

Figure 8. Panel 1. Emplaced PE-Ci over residue average.

The distribution of a spallings-sized event can be approximated by the distribution of stacks, already shown in Section 3.1. Assuming the volume of three stacked 7-packs, each grid node (or stack) would equal 4.4 m^3. The actual value may be slightly less because of the use of SWB and TDOP as overpack containers. Therefore, the volume of each stack would be close to the 4 m^3 volume in a maximum spallings event. A volume of 810 drums is approximately 40.5 times the volume of a stack of containers. This could be represented by a block with dimensions of square root of 40.5 times the assumed grid size representing a stack, or 7 ft. This would result in a block of 44.5 ft. by 44.5 ft. The distribution of these blocks could be calculated from a change of support technique such as Hermite Polynomial Transformation (Journel and Huijbregts 1978).

Hermite Polynomial Transformation requires a variance reduction factor which can be computed after deriving the variance between blocks (810 drum units) and the overall domain. This variance between blocks is computed (Isaaks and Srivastava 1989):

$$\sigma^2(v,V) = \sigma^2(.,V) - \sigma^2(.,v)$$

where:

$\sigma^2(v,V)$ = variance between blocks of size v within domain V.

$\sigma^2(.,V)$ = variance of a point within the domain.

$\sigma^2(.,v)$ = variance of a point within a block of size v, or dispersion variance.

The total variance is shown in Figure 5a as 1198 $(PE\text{-}Ci/m^3)^2$. The dispersion variance may be estimated from a variogram model of the samples, or stacked containers (David 1977).

An experimental variogram of the emplaced waste was computed using the GSLIB program GAMV (Deutsch and Journel 1998). This variogram was fitted with a spherical model as shown in Figure 9. The dispersion variance for a point within the 810 drum unit was computed with kriging program subroutines in GSLIB, using this variogram function, and resulted in the variance reduction factor, $\sigma^2(.,v)/\sigma^2(.,V)$, equal to 0.18.

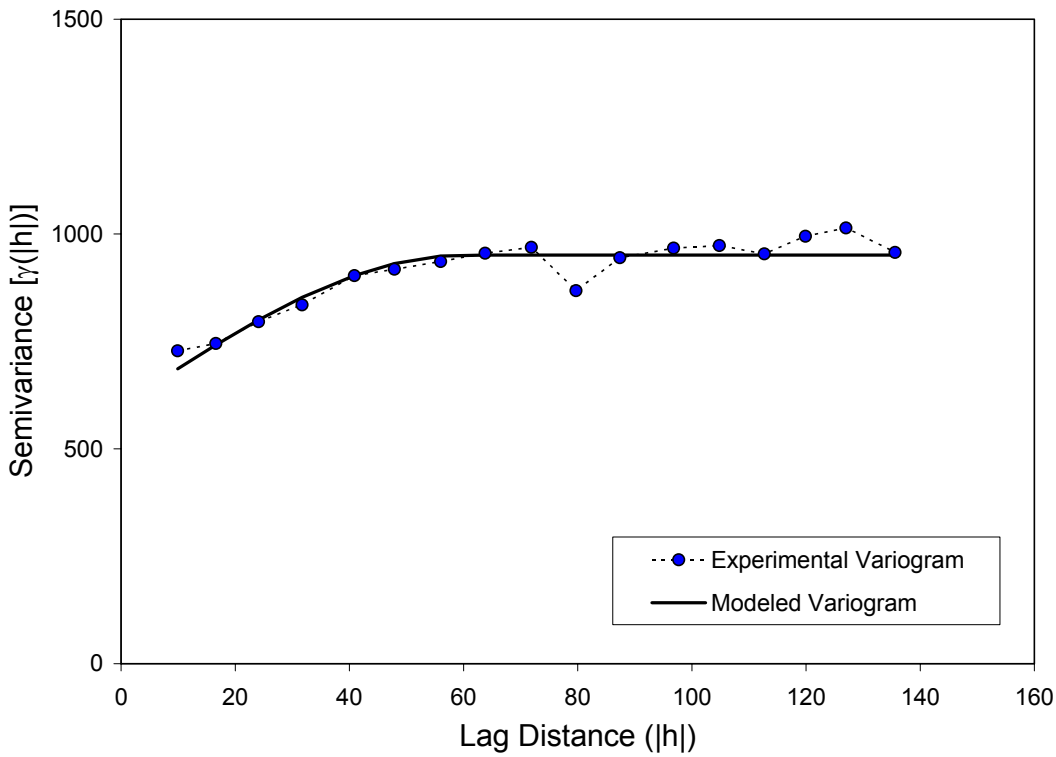

Figure 9. Experimental variogram fitted with spherical model: Co = 600, C1 = 350, R = 60 ft.

Using a program for Hermite Polynomial Change of Support (Guertin 1984) a hypothetical distribution of 810 drum units was constructed from the distribution of stacked containers. The probability plots for this distribution as well as the original distribution of stacked containers

(spall units) are shown in Figure 10. As can be seen, the probability of intersection of a high-concentration stack during an intrusion scenario will be underestimated by assuming volumes of 810 drum units. Therefore, an analysis conditional on a minimum of 810 drums may not represent an adequate bounding case for non-random emplacement of waste.

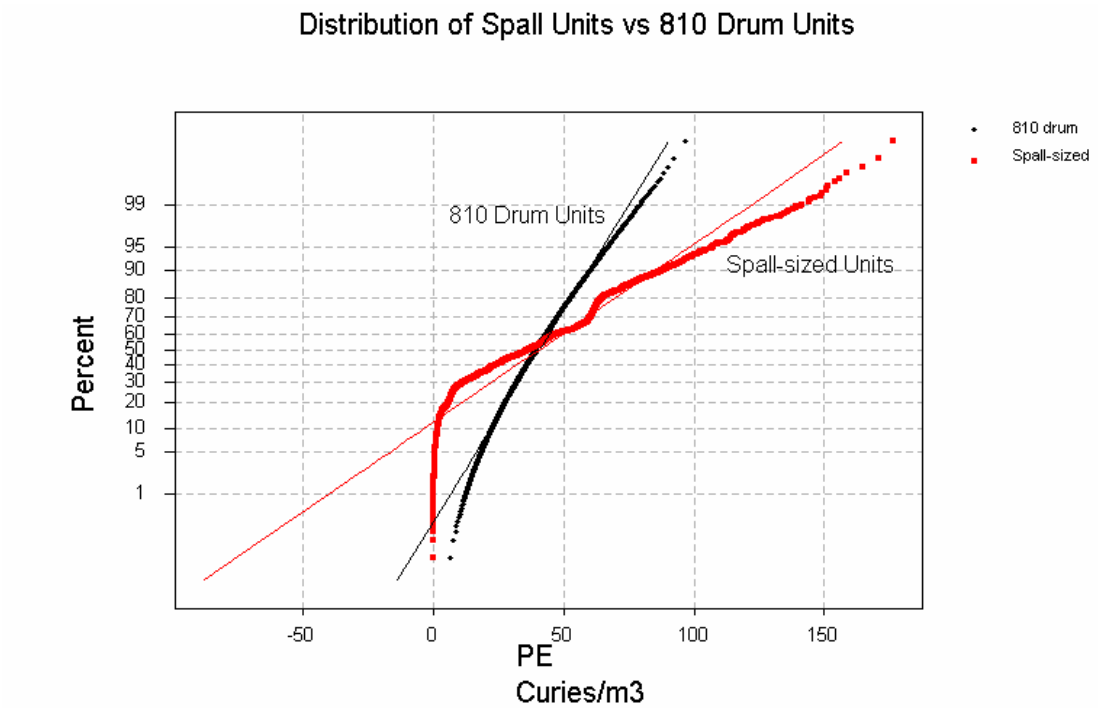

Figure 10. Distribution of stacked containers (approximate spall units) and the hypothetical distribution of units containing 810 drums.

3.4 Pipe Overpack Containers

POCs have been used to isolate much of the high ^{239}Pu waste emplaced in Panel 1. No credit has been suggested or taken for the use of these POCs in performance assessment. Further, EEG is unaware of any studies conducted to determine the effect of the POC during an intrusion scenario.

However, if it could be demonstrated by the DOE that POCs retain their integrity and effectively reduce the potential of activity release over the regulatory period, they could be a means of reducing the amount of material brought to the surface from an intrusion into a high-concentration stack. This is shown in Figure 11 where all emplaced material contained in POCs was removed prior to calculation of the probability plot. In addition, the probability of

intersecting waste would be slightly reduced because of differences in volume between the actual drum and the POC contained within.

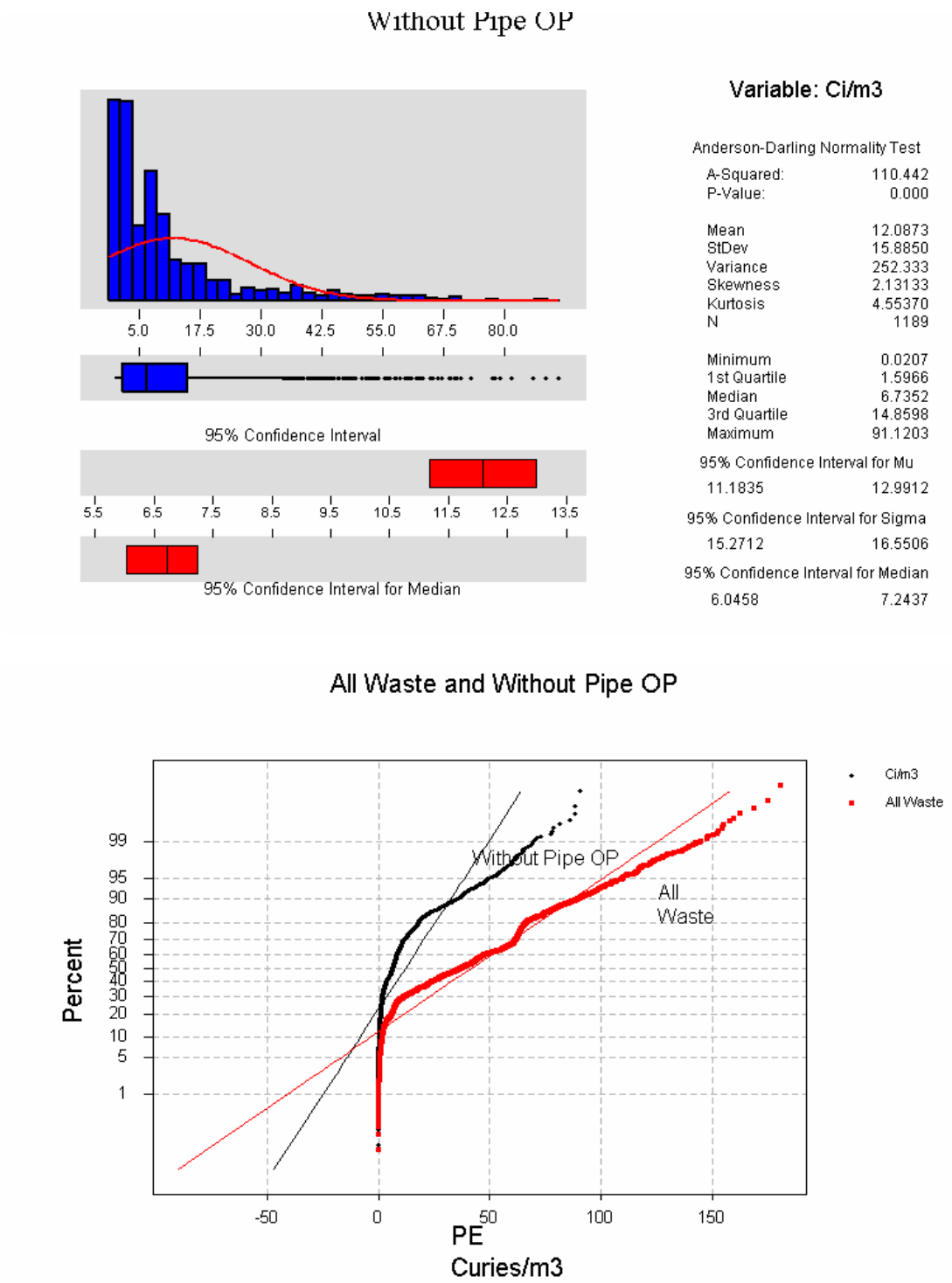

Figure 11. Histogram and probability plot of emplaced waste disregarding that contained in POCs.

4.0 CONCLUSIONS

The shipping campaign priority of residues from Rocky Flats has resulted in the non-random emplacement of waste in Panel 1 and in elevated emplaced activity. ^{239}Pu is 3.20 times, ^{240}Pu is 2.67 times, and ^{241}Am is 4.13 times the projected repository average for the space occupied by waste. Moreover, the non-random emplacement process skews the distribution of emplaced waste, as compared with a randomized case, resulting in higher concentration tails and increasing the probability that an intrusion will intersect a high-concentration stack. This suggests that for cuttings and cavings scenarios, the practice of sampling waste streams independently (and using their means) for each layer in a stack would underestimate the potential releases.

Furthermore, the practice of non-random emplacement may invalidate the premise of the performance assessment bounding analysis for spallings. The DOE bounding analysis assumed independence of samples for selection of the minimum waste stream volume to be analyzed. Independence of samples is not inherent in non-random emplacement, which results in the spatial dependence between sample locations. The hypothetical distribution of potentially spalled units shows an increased probability of high-concentration intersection over the distribution of volumes assumed in the bounding case.

It has been demonstrated that the practice of non-random emplacement of waste results in spatial dependence of waste containers. Therefore, classical statistical techniques do not properly address this issue. Instead, spatial statistical (geostatistical) methods are necessary for analysis, performance assessment implementation, and bounding calculations.

5.0 RECOMMENDATIONS

The EEG recommends that:

1) The DOE should develop a waste loading scheme for performance assessment which is based upon their shipping schedule. While this schedule will change over time, it is the best information currently available and presents a more realistic assumption than random emplacement. A spallings event should then be based upon this spatial distribution of waste instead of the mean value of waste.

Alternatively, the DOE should develop a bounding case based on the distribution of potentially spalled units, recognizing the effects of skewed distributions which results from the non-random emplacement process. One possibility would be to use geostatistical simulation with different variograms (with a range of spatial correlations) to show the consequences of different emplacement sequences for the future.

2) The DOE should develop and use, in the recertification performance assessment calculations, a methodology for non-random waste emplacement for cuttings and cavings scenarios. This methodology should recognize the likelihood of similar material occurring for a stack of three containers instead of randomly sampling for each layer in the stack and be based on anticipated shipping schedules. It should also acknowledge the increased probability of high-concentration intercepts, which result from non-random loading instead of using mean values of entire waste streams.

3) If the DOE wishes to take credit for the container, the DOE needs to provide an analysis of the potential effects resulting from the use of pipe overpacks, which may provide a more secure containment of radionuclides within the repository.

4) The DOE should continue to build a spatial data base of emplaced waste for ongoing analysis and for use during future recertifications.

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EEG-86

CONTACT HANDLED TRANSURANIC WASTE CHARACTERIZATION REQUIREMENTS AT THE WASTE ISOLATION PILOT PLANT

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September 2003

EEG-86
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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment of New Mexico. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned the EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC29-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

The EEG performs independent technical analyses on a variety of issues. Now that the WIPP is operational, these issues include facility modifications and waste characterization for future receipt and emplacement of remote-handled waste, generator site audits, contact-handled waste characterization issues, the suitability and safety of transportation systems, mining of new panels, and analysis of new information as part of the five year recertification cycles as mandated by the WIPP Land Withdrawal Act. Review and comment is provided on the annual Safety Analysis Report and Proposed Modifications to the Hazardous Waste Facility Permit. The EEG also conducts an independent radiation surveillance program which includes a radiochemical laboratory.

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ACRONYMS

AK	Acceptable Knowledge
ALARA	As Low As Reasonably Achievable
C of C	Certificate of Compliance
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CFR	Code of Federal Regulations
CH	Contact Handled
CH WAC	Contact Handled Waste Acceptance Criteria for WIPP, rev 0; rev 0.1
CPR	Cellulose, Plastic and Rubber
DAC	Drum Age Criteria
DOE	Department of Energy
EEG	Environmental Evaluation Group
EPA	Environmental Protection Agency
FGE	Fissile Gram Equivalent
HSG	Headspace Gas
HWFP	Hazardous Waste Facility Permit
IDC	Item Description Code
INEEL (INEL)	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
LWA	Land Withdrawal Act
NAS/NRC	National Academy of Sciences. National Research Committee
NDA	Non-Destructive Assay
NETL/CABE	National Energy Technology Laboratory/Center for Acquisitions and Business Excellence
NMAC	New Mexico Administrative Code
NMED	New Mexico environment Department
NRC	Nuclear Regulatory Commission
PCB	Polychlorinated Biphenyls

ACRONYMS (continued)

PE-Ci	Plutonium Equivalent Curies
PMR	Permit Modification Request
QA	Quality Assurance
QA/QC	Quality Assurance/Quality Control
QAPD	Quality Assurance Program Document
RCRA	Resource Conservation and Recovery Act
RFETS	Rocky Flats Environmental Technology Site
RH	Remote Handled
RIPB	Risk-Informed and performance-based
RTR	Real Time Radiography
SAR	Safety Analysis Report
SARP	Shipping Package Safety Analysis Report
SPM	Site Project Manager
SPQAO	Site Project QA Officer
SRS	Savannah River Site
SVOC	Semivolatile Organic Chemicals
TRAMPAC	TRUPACT-II Authorized Methods for Payload Control
TRU	Transuranic
TSCA	Toxic Substance Control Act
TSR	Technical Safety Requirements
VOC	Volatile Organic Chemicals
VE	Visual Examination
WAC	Waste Acceptance Criteria for WIPP, rev 0 through rev 7
WAP	Waste Analysis Plan
WIPP	Waste Isolation Pilot Plant
WSPF	Waste Stream Profile Forms
WWIS	WIPP Waste Information System

EXECUTIVE SUMMARY

Protection of the safety, health, and the environment at the Department of Energy (DOE) Waste Isolation Pilot Plant (WIPP) relies in part on the quality and completeness of the information about the waste that is shipped to the WIPP. This quality and completeness of the information is created through the waste characterization requirements identified in various regulatory documents. Waste characterization requirements are specified by the three WIPP regulatory agencies and the DOE: (1) the New Mexico Environment Department (NMED) through the Hazardous Waste Facility Permit (HWFP), (2) the U.S. Environmental Protection Agency (EPA) through the transuranic waste disposal Certification, (3) the U.S. Nuclear Regulatory Commission (NRC) through the TRUPACT II Authorized Methods for Payload Control (TRAMPAC), and (4) the Department of Energy through the Waste Acceptance Criteria (WAC). Of the four agencies, the requirements of the NMED for the Hazardous Waste Facility Permit tend to be the most prescriptive.

The Environmental Evaluation Group (EEG) has been evaluating the development of waste acceptance criteria since 1979. This report consolidates the findings and recommendations of the EEG's technical reviews and our current positions with respect to waste characterization requirements.

All waste characterization requirements were, at the time they were proposed and put in place, believed to be important for the protection of the worker safety, public health and the environment. The current waste characterization requirements were not developed ad hoc, but through much technical discussion, reference to accepted standards and codes, and considerable effort by DOE employees, DOE contractors, regulatory agency staff, regulatory agency contractors, the EEG staff, interested organizations, and/or members of the public.

The DOE has submitted several Class 2 and Class 3 Permit Modification Requests to NMED WIPP Hazardous Waste Facility Permit. Some have been accepted, some rejected, some withdrawn, and some are pending as tabulated in this report. EEG has provided a technical review of each. DOE has secured relief from a number of requirements. For example, by using

the permit modification process, the DOE has obtained a reduction of the headspace gas sampling requirement for thermally treated waste from Rocky Flats Environmental Technology Site (RFETS), a reduction in the visual examination requirement for waste from RFETS, and a reduction in headspace gas analysis for waste from the Idaho National Engineering and Environmental Laboratory (INEEL). These reductions in waste characterization requirements saved $30 million, saved $19 million, and allowed DOE to meet a deadline to remove 3100 m^3 from INEEL, respectively. From the time of application through the time of approval, these changes were each achieved in four months or less.

The waste characterization requirements from the various agencies contain many of the same requirements. Despite this overlap, the methods for meeting these requirements are somewhat different. The most complete methods of reaching compliance when requirements overlap, are usually found in the HWFP or the 40 CFR 194 compliance implementation found in Appendix A of the contact handled CH WAC. When considering a requirement change to either of these documents, the effect on all requirements, including those issued by other agencies, should be noted and evaluated for any potential impacts across agencies.

Based on our reviews, EEG offers the following observations and recommendations for waste characterization requirements:

Acceptable Knowledge: Acceptable Knowledge (AK) is the principle waste characterization technique for all of the regulatory agencies. AK is necessary and should be retained. At this time EEG supports the use of the HWFP AK requirements since they are the most explicit.

Headspace Gas Sampling and Analysis: It is desirable to maintain a comprehensive Headspace Gas (HSG) program for WIPP CH TRU waste. However, it should be possible to require less than 100% headspace gas sampling in some cases. Our primary concern is with organic sludges and older waste containers where knowledge of the waste is of lesser quality.

Drum Age Criteria: Drum Age Criteria (DAC) is necessary to ensure that Headspace Gas sampling of waste containers will measure gas concentrations that are at least 90% of

equilibrium. DAC values are required in both the HWFP and the TRAMPAC. The EEG supports this requirement.

Real Time Radiography: All WIPP waste containers are required to undergo either radiography or visual examination by the HWFP. Usually retrieved wastes undergo Real Time Radiography (RTR) and newly generated wastes are examined by visual examination. RTR has been a very effective means of verifying AK and discovering prohibited items in waste containers. It is also used to show compliance with several EPA and TRAMPAC requirements. The overall radiography program is an important part of the WIPP waste characterization program and should be retained. It may be possible to reduce some of the detailed procedural requirements in the HWFP.

Visual Examination for Retrievably Stored Waste: A small percentage (currently less than 2%) of retrievably stored waste is required by the HWFP to undergo visual examination for confirmation of RTR. The Visual Examination (VE) process has the potential for slightly greater radiation exposure than the other waste characterization requirements, although the EEG has seen no data to indicate that exposures are significant enough to justify reducing the requirement. The DOE has been successful in modifying the HWFP on retrievably stored visual examination and this would be the preferred process for seeking further reductions.

Visual Examination for Newly Generated Waste: VE is the method DOE usually prefers for newly generated waste because it can be done at the time the waste container is being filled. The EEG has not objected to any part of this requirement except to state that the requirement for two trained VE operators to perform the visual process "may be overkill" and that a single verification should be adequate.

Coring Sampling and Analysis: Currently the EEG continues to believe that the homogeneous sampling and analysis are unnecessary characterization requirements in the HWFP. Our principal reason for this position is that the data are not used for any additional regulatory control (metals releases from accidents or long-term processes would be controlled by radionuclide control requirements and VOCs and SVOC by HSG or the Confirmatory VOC Monitoring Plan).

Level II Management and Waste Certification HWFP Requirements: The DOE has listed these management and certification requirements as characterization activities in a recent cost analysis. EEG has not previously commented on these requirements. However, our current evaluation indicates that the required procedures are very detailed and somewhat redundant. This may be one of the areas to which the general EEG comment, "We believe waste characterization requirements are excessive," applies.

Characterization Support HWFP Requirements: EEG remains supportive of the WIPP audit and surveillance program. We have also said that we do not believe the relaxation of audit requirements and QA/QC is an appropriate way to reduce the regulatory burden.

EPA Non-Radiological Requirements: EPA's residual liquids, non-ferrous metal and cellulose, plastic and rubber requirements should remain and can continue to be determined as they are now, by the RTR and VE requirements of the HWFP. The ferrous metal requirement can continue to be met by counting waste containers emplaced in the repository.

EPA Radiological Requirements: The EEG agrees with the radioassay requirements for contact-handled transuranic waste specified in Appendix A of the CH WAC and the current procedures for modifying the document.

Current requirements for reporting the 10 required radionuclides should remain. ^{241}Pu should also be reported. The current requirement that all radioassay should be performed by WIPP-certified assay systems should be maintained.

Justification for less than 100% quantification and determination of isotopic ratios may be possible for some, but certainly not all, waste streams.

NRC Container Properties: The TRAMPAC requirements for residual liquids, filter vents and the sealed container prohibition should be retained. These are all verified by requirements in the current HWFP.

NRC Nuclear Properties: All nuclear property requirements should be retained and Appendix A of the CH WAC methodology should be used.

NRC Gas Generation Requirements: Requirements for measuring the chemical, payload classification, and radionuclide concentrations necessary to ensure hydrogen gas concentration criteria are met must be retained. There have been many changes, via the Certificate of Compliance (C of C) revision process, which have allowed additional containers to be shipped without changing the hydrogen gas criteria and additional changes may be justifiable in the future.

The flammable gas concentration limit of ≤ 500 ppm should be retained as described in the current revision of the TRAMPAC. Alternate methods (with appropriate QA) will be necessary if future changes to the HWFP affects the use of HSG sampling as the method for meeting this criteria.

WIPP Waste Acceptance Criteria: The WAC has served a useful historic purpose in developing initial criteria that have been adopted by the other three regulatory agencies. Currently it is a useful document for listing most of the requirements from all four sets of criteria. It would be more useful if the technical justification for each criteria or requirement were restored.

The unique role of the WAC in including any necessary operational safety and health requirements not included elsewhere is very important and must be constantly evaluated via the technical safety requirements (TSR) portion of the CH TRU Safety Analysis Report, and any necessary changes incorporated into the CH WAC.

Summary Observations and Recommendations

EEG's views on waste acceptance criteria and waste characterization continue to evolve. Shortly after the WIPP began receiving waste in 1999, the EEG published calculations comparing the risks from the hazardous constituents and the radioactive constituents in the WIPP inventory. The carcinogenic risks were quite low for both categories, with the expected carcinogenic risk

from the hazardous constituents four orders of magnitude less than the expected risk from the radiological constituents to workers from routine operations and operational accidents. Prudence suggests that mitigating the relatively small risk from the non-radiological constituents should not be the primary cost in waste characterization. Waste characterization efforts should focus on reducing the risk of release of radiological constituents.

Any proposed relaxation of waste characterization requirements needs to be evaluated in sufficient detail to convince the regulatory agencies, the EEG, and others that the modification is justified. Implicit in this approach is the understanding that any changes need to be made in a step-by-step transparent process and through existing regulatory procedures of the NMED, the EPA, and the NRC. This approach requires adequate justification and has worked effectively to obtain approval for a number of changes from all three non-DOE regulatory agencies. Moreover, as noted by the DOE, the regulatory agencies have indicated a preference for this approach.

1.0 PURPOSE AND SCOPE

Protection of the safety, health, and the environment at the Department of Energy (DOE) Waste Isolation Pilot Plant (WIPP) relies in part on the quality and completeness of the information about the waste that is shipped to the WIPP. This quality and completeness is created through the waste characterization requirements established in various regulatory documents.

This report is a compilation of the Environmental Evaluation Group's (EEG) comments since the operational phase of WIPP began and EEG's current positions on the existing waste characterization requirements by three regulatory agencies and the DOE. The report includes discussions about: (1) the process for changing requirements, (2) a comparison of risks due to various constituents in the waste, (3) whether current requirements are necessary, adequate or excessive, and (4) the continued need for the audit/QA process. The rationale for each conclusion and recommendation is also given.

The EEG has been evaluating the development of the WIPP waste characterization criteria since 1979. The WIPP began receiving contact handled (CH) transuranic (TRU) waste in March 1999. Later that same year, the project received its Hazardous Waste Facility Permit (HWFP) from the New Mexico Environment Department (NMED) and began receiving and emplacing mixed CH TRU waste.

The EEG has made several sets of comments since 1999 explaining our evaluations and evolving positions on waste characterization requirements. These were submitted as: (1) comments to the DOE in September 1999 concerning Waste Characterization Task Force recommendations, (2) comments to DOE in January 2002 on the proposed Appendix A changes to the WIPP CH Waste Acceptance Criteria (CH WAC), and (3) statements to the National Academy of Sciences/National Research Council (NAS/NRC) Committee on Optimizing the Characterization and Transportation of Transuranic Waste for the Waste Isolation Pilot Plant in October 2002, January 2003, and May 2003[1]. These comments and statements are included in Appendix A of

[1] EEG understands that the anticipated NAS/NRC committee report is under internal discussion.

this report. The EEG has also provided technical reviews on every Class 2 and Class 3 permit modification request submitted by DOE to the NMED, which is discussed in more detail in Chapter 4. All of these materials are available on EEG's web site (http://www.eeg.org).

This report references waste acceptance criteria, waste characterization requirements, and waste characterization methods cognizant of the DOE statement that, "in some cases the acceptance criteria and regulatory requirements are synonymous." (DOE 1999, p 3-8). The waste characterization methods are also specified in the permit and certificates, and arguably might be viewed as a requirement.

This report concentrates on EEG's position on the various waste characterization requirements, not the details of procedures required to show compliance. We recognize that the procedural requirements are a significant part of the waste characterization issue, but they are outside the scope of this report.

1.1 Overview of Waste Characterization Requirements

The U.S. Department of Energy (DOE), the U.S. Nuclear Regulatory Commission (NRC), the U.S. Environmental Protection Agency (EPA), and the New Mexico Environment Department (NMED) all have requirements for characterization of WIPP waste. A number of the waste characterization requirements are included in more than one set of requirements.

The DOE was self-regulating (except for the U.S. Department of Transportation shipping requirements) for all waste characterization criteria prior to 1989. The DOE, through its Orders and policies as far back as 1979 began to develop criteria protective of worker and public health and safety for anticipated operations. The criteria in the original WAC included limitations on: free liquids; pyrophoric, toxic and corrosive materials; explosive and compressed gas; gas generation and criticality. Container and certification requirements were also included (DOE 1980). Subsequent revisions of the WAC have consolidated into this one document requirements by each regulatory agency as these requirements became applicable. In April 2002, the WAC

was revised to contain only criteria for CH TRU waste. Up to this time, the WAC covered both CH TRU and remote-handled (RH) TRU waste.

The first set of requirements from a regulatory agency came from the NRC issuance of the Certificate of Compliance (C of C) of the TRUPACT-II Type B Package (NRC 71-9218) in 1989. These requirements included physical, nuclear and chemical properties and are included in a document called the TRUPACT-II Authorized Methods for Payload Control (TRAMPAC). Many of the properties were similar to those already in the WAC. In addition, there were extensive requirements dealing with control of the concentration of hydrogen, methane, and flammable volatile organic chemical (VOC) concentrations. Quality assurance (QA) requirements for packaging were also specified in the TRAMPAC.

The 1992 Land Withdrawal Act (LWA) specified that waste coming to WIPP must be transuranic waste (defined in the LWA as, "waste containing more than 100 nanocuries of alpha emitting transuranic isotopes per gram of waste with half-lives greater than 20 years."). Moreover, it was limited to waste generated by atomic energy defense activities of the United States. The LWA also specified a regulatory role for the EPA in ensuring long-term compliance of the WIPP repository. This role for EPA led to several additional waste characterization criteria.

EPA waste characterization requirements provide the most stringent requirements for quantification of radionuclides and also include several other requirements. The official methodology for radionuclide assay is primarily non-destructive assay (NDA) and is contained in Appendix A of the CH WAC (currently DOE 2002b). Modifications to Appendix A require EPA approval. The NDA methodology prescribed in Appendix A is also used in quantifying NRC and DOE radiological requirements.

The HWFP (NMED 1999) became effective in December 1999. The HWFP adds several waste characterization requirements and provides specific details of procedures that must be applied in meeting the requirements. Several NRC and EPA requirements are included in the HWFP and

the methodology specified in the HWFP for meeting the NMED, NRC, and EPA requirements is quite prescriptive.

1.2 Overlap of Waste Characterization Requirements

In our reviews of proposed changes, EEG has found that the waste characterization requirements from the three regulatory agencies and the DOE contain considerable overlap (i.e., contain the same requirements). Despite this overlap, the methods to be used for meeting these requirements are somewhat different. The most complete methods of reaching compliance when requirements coincide are usually those found in the HWFP (NMED) and the 40 CFR 194 (EPA) radioassay compliance implementation found in Appendix A of the CH WAC (DOE).

For example, the maximum of 325 fissile gram equivalent (FGE) requirement in each TRUPACT-II is in the TRAMPAC. Yet, the most complete waste characterization method to ensure compliance with this requirement is specified in Appendix A of the CH WAC, where radionuclide measurement requirements are specified to meet the 40 CFR 194.24 criteria.

Similarly, requirements for limitation of liquids to less than 1% by volume in waste containers are specified by the waste characterization requirements of each agency—as part of the TRAMPAC (free liquids), 40 CFR 194.24 (free water), the HWFP (residual liquid), and the CH WAC (free water, residual liquid, currently total residual liquid). For the purposes of this report, EEG refers to the presence of liquids. The most complete method for determining the presence of liquids, however, is the HWFP requirement that each container must undergo either radiography or visual examination. A further discussion of "overlap" issues is in Chapter 4.0 and Table 4-2.

A change in one set of requirements could have implications for other requirements. For example, if headspace gas (HSG) sampling and analysis was eliminated as a HWFP requirement, it would be necessary to use an alternate methodology to ensure adequate control of flammable gas requirements in the TRAMPAC. Alternate methods exist, but they would need to be

incorporated into the HWFP or some other regulatory document with appropriate QA in order to sustain an adequate level of assurance.

The overlap of requirements of each agency inherently complicates change. When considering a requirement change in either the HWFP or Appendix A of the CH WAC, the effect on all requirements, including those issued by other agencies, should be noted and evaluated for its impact on requirements across agencies.

1.3 EEG Waste Characterization Evaluations and Philosophy

1.3.1 Evaluation History

The EEG has reviewed waste characterization requirements as they were being developed and modified over the years. Our comments are contained primarily in letters or presentations rather than EEG reports. There are EEG reports on specific issues related to waste acceptance criteria (Little 1980), flammability of CH TRU waste drums (Neill and Channell 1983; Silva 1990; 1991), safety documents (primarily the WIPP Safety Analysis Report [SAR]; EEG 1989), and applications to regulatory agencies (the Compliance Certification Application [CCA] from DOE to EPA; Neill and others 1996; 1998) that led to the development or retention of some waste characterization requirements.

Our evaluations concentrated on the specific purpose of each of the criteria or regulatory documents. The initial WAC comments were primarily concerned with operational health and safety at WIPP. Reviews of NRC requirements concentrated on gas generation and adequacy of the TRUPACT-II package itself. These two issues were instrumental in adoption of the legal requirement that all waste shipments to WIPP be in NRC certified Type B packages. The EEG review (Neill and others 1996; 1998) of the DOE application and EPA proposed certification focused on requirements necessary to assure that the WIPP complied with 40 CFR 191 and 40 CFR 194.

EEG's reviews of the HWFP and proposed permit modification requests (PMRs) included detailed technical evaluations of whether the HWFP or a PMR would accomplish the required regulatory objectives. However, with our review of modification requests to the HWFP, we have also evaluated the effect that changes would have on existing requirements of the NRC, the EPA, and DOE (in the CH WAC). This is because the HWFP is usually the most prescriptive in specifying how the requirement will be met. The prescriptiveness of the HWFP increases the assurance that the requirements of the other regulatory agencies will be satisfactorily met.

1.3.2 EEG Philosophy on Waste Characterization Requirements

Much of EEG's overall philosophy on waste characterization requirements can be found in various statements and reports. These are summarized below.

(1) We believe overall waste characterization requirements are excessive. However, any proposed relaxation needs to be evaluated in sufficient detail to convince regulatory agencies, the EEG, and stakeholders that the modification is justified.

(2) Implicit in statement (1) is the belief that any changes need to be made in a transparent, step-by-step approach and through the existing regulatory procedures of NMED, EPA, and NRC. This approach requires adequate justification and has worked effectively to get approval for a number of changes from all three regulators.

(3) Our conclusions on individual waste characterization requirements are based on health and safety, and environmental considerations. The EEG does not speak for the regulatory agencies in offering opinions of legal and regulatory requirements. EEG's current positions on specific waste characterization issues are also subject to change if justified by new evaluations.

(4) Since EEG has concluded that the radiological risk is about 10,000 times that of the hazardous waste risk, we concentrate on those waste characterization requirements that affect the transuranic waste during our health and safety evaluations.

(5) It is important to recognize that a number of the requirements in the Hazardous Waste Facility Permit (HWFP) have a role in ensuring that radiological, transportation, and operational requirements are met.

(6) The relaxation of audit and Quality Assurance and Quality Control (QA/QC) requirements is not an appropriate way to reduce the regulatory burden.

(7) Another factor which EEG has never stated explicitly is our recognition that considerable uncertainty exists in the characteristics of wastes that may come to WIPP in the future. For this reason, our evaluations of waste characterization requirements attempt to also address the potential future characterization needs for presently uncharacterized waste streams.

(8) Claims have been made in the past (see Section 2.1) that removal of unnecessary waste characterization requirements can result in increased shipping rates to WIPP. EEG considers whether a requirement is necessary for health, safety, and environmental reasons and does not factor schedule implications into our conclusions.

Two other issues often discussed by the DOE when proposing reductions in waste characterization requirements are minimizing the risk and exposure to workers performing waste characterization and costs.

EEG has no reason to believe that radiation doses to waste characterization workers are significant and, in the absence of data indicating otherwise, should not be a justification for eliminating or reducing a waste characterization requirement (see Section 3.3).

Costs of waste characterization are significant and it would be desirable to continue to reduce or eliminate those requirements where it is prudent. However, significant non-waste characterization costs were also incorporated into the initial design and operation of the WIPP project; a prudent procedure for a first of a kind deep geologic repository. Few of the waste characterization requirements can be evaluated exclusively by a traditional cost/benefit

comparison. A rigorous evaluation via the regulatory process is the best way to decide on acceptable changes to any waste characterization requirements.

2.0 WASTE CHARACTERIZATION REQUIREMENTS CHANGE PROCESSES

Since the original receipt of waste at the WIPP in March of 1999, the DOE has successfully completed changes to waste characterization requirements specified by each of the different regulatory agencies. The process for creating these changes is significantly different for each of these regulatory agencies, as discussed in the following sections.

2.1 NMED: HWFP Waste Characterization Requirements Change Process

The non-radiological hazardous waste characterization requirements fall under the jurisdiction of the New Mexico Environment Department and are principally (and most completely) specified in Attachment B, including B-1 through B-6 of the HWFP, collectively known as the Waste Analysis Plan (WAP) (currently NMED 2003). Changes to the WAP are therefore subject to the same process as those for the entire HWFP. The New Mexico Administrative Code (20 NMAC 4.1) simply references the EPA-established requirements contained in the Code of Federal Regulations (CFR) for these changes. Either the regulatory agency (under 40 CFR 270.41) or the permittees (under 40 CFR 270.42) can initiate modifications of a permit. The regulatory agency's ability to modify a permit is much more limited than that of the permittee, the implication being that it is incumbent on the regulator to ensure that the initial permit is sufficient.

There are three classes of permit modification requests. The "Classification of Permit Modification" table (Appendix I to 40 CFR 270.42) identifies the process to be used for each class. For those modifications that do not match table entries, the permittees can request that the regulatory agencies make the designation, but the regulation also specifies the criteria under which the regulatory agencies are allowed to do so.

Class 1 modifications are to be used for minor upgrades. Examples include updating the administrative information in the permit (names, titles, etc.), replacement of equipment with functionally equivalent components, or correction of typographical errors. These modifications

keep the permit current with routine changes to the facility or its operation. These changes do not substantially alter the permit conditions (40 CFR 270.42(d)(i)). The Class 1 change process is very simple. The permittee can implement the modification immediately, with notification of the change provided to the regulator within seven days. Other organizations and individuals on the facility mailing list are to be notified within 90 days of the modification. One disadvantage of a Class 1 modification is that there is no requirement that the regulator formally accept the modification. Moreover, the regulator can reject a Class 1 modification at any time for cause. One way to avoid a belated Class 1 modification rejection is to use the Class 2 process.

Class 2 modifications enable a permittee to respond to common variations in the types and quantities of wastes managed, technological advances, and non-trivial changes associated with new regulations. The process to implement these requires a formal submittal of a PMR to the regulator and a subsequent 60-day public comment period. The public comment period must include a permittee-organized public meeting. Within 90 days of the initial submission the regulator must either: (1) approve the modification request (with or without changes), (2) deny the request, or (3) determine that the modification must follow the Class 3 process. Two other options are available. The modification can be temporarily approved for up to 180 days, or the regulator can simply notify the permittee that the decision will be forthcoming in the next 30 days (only one such extension is allowed).

The Class 3 process may be required to accommodate significant public concern or a complex change. Like the Class 2 process, the Class 3 process requires the 60-day public comment period and public meeting. After that the Class 3 can be considerably more complicated and lengthy. The decision making process allows the regulator to request additional information and file formal notices of deficiency on the application. Even after this portion of the process, it may be necessary to create a draft permit including the proposed modification, conduct a more formal public hearing by an independent hearing officer, reopen the public comment period, and produce a hearing officer's report. This would all need to be completed before the regulator makes a decision on the modification.

Class 1 modifications to the HWFP under these processes have usually been successful. However, Class 1 modifications related to waste characterization have suffered a relatively high rate of rejection, usually ascribed to misclassification under 40 CFR 270.42. All changes to the waste sampling and analysis methods should be designated as Class 2 (Appendix I to 40 CFR 270.42). These would be waste characterization changes that are not related to conformation with EPA guidance or regulations, multi-source leachates, or changes associated with underlying hazardous constituents in ignitable or corrosive wastes sampling. Thus, most common waste characterization changes would be Class 2 changes.

The EEG has commented on every Class 2 and Class 3 PMR during the public comment period. For the past two years, any Class 2 comments submitted by the EEG have been submitted to both the NMED and the DOE several days prior to the comment period deadline, so that the DOE could address the concern or respond to the comments in other ways during that same public comment period. EEG comments on PMRs may be viewed at http://www.eeg.org.

The bulk of Class 2 and Class 3 PMRs have been related to waste characterization. The EEG published an analysis of experience with the PMRs that were extant after 18 months experience, noting several areas of concern about the DOE's submissions and suggesting a possible solution (Walker and Silva 2002). Table 2-1 lists all of the HWFP modifications submitted by the DOE so far, and their current status. Despite the complexity of the process for HWFP changes, the DOE has obtained some relief in a timely manner using the modification process. According to the DOE, a Class 2 PMR to allow compositing of headspace gases greatly aided the completion of the Idaho National Engineering and Environmental Laboratory (INEEL) 3100 m^3 Project. Also, a Class 2 PMR allowing reduction in headspace gas measurements for thermally treated wastes saved over $30 million at the Rocky Flats Environmental Technology Site (RFETS). Finally, a Class 2 PMR reducing the number of drums requiring visual examination saved $19 million (DOE 2002c). From the time of application through the time of approval, these changes were each achieved in four months or less.

Table 2-1. WIPP HWFP Class 2 and 3 Modification Proposals

Proposal Date	Mod Class	Item #	Proposed Modification	Disposition	Action Date
03/30/00	2	1	Alter accuracy acceptance criteria for cresols and pyridines	Accepted	08/08/00
		2	Use hgas statistical sampling of homogeneous containers when AK does not indicate hazardous VOCs	Accepted	08/08/00
		3	Use hgas statistical sampling of containers when waste was thermally treated	Accepted	08/08/00
04/20/00	2	1	Add allowance for 3 sub-samples to be taken from solidified container cores	Accepted	08/08/00
		2	Change miscertification rate to SCG from waste stream	Accepted	08/08/00
		3	Use gross alpha/beta measurements for groundwater sampling	Accepted	08/08/00
07/21/00	2	1	Perform waste characterization at the WIPP	Withdrawn	09/29/00
		2	Combine data package reviews; eliminate off-site audits for SQS	Withdrawn	09/29/00
12/07/00	2	1	Change headspace has drum age criteria (DAC-1)	Rejected	03/26/01
01/22/01	2	1	Perform visual examination by tomography (DR/CT)	Withdrawn	03/23/01
03/06/01	2	1	Move inspection forms from the HWFP to the operating record	Accepted w/minor changes	07/06/01
		2	Change the frequency of firefighter I training	Accepted	07/06/01
		3	Eliminate portions of RCT training	Accepted	07/06/01
		4	Add new hazardous waste numbers to HWFP	Accepted all but U-134 (HF)	07/06/01
		5	Extend time for groundwater monitoring reports	Accepted	07/06/01
04/27/01	2	1	Allow additional storage space for TDOPs	Rejected	08/30/01
04/27/01	(2) 3	1	Change headspace gas drum age criteria (Revised; DAC-2)	Accepted w/modifications	12/31/02
06/06/01	3	1	Allow Central Characterization Facility (CCF) at the WIPP	Withdrawn	01/14/03
		2	Add storage capacity for the CCF	Withdrawn	01/14/03
		3	Increase allowed storage time at the WIPP to one year	Withdrawn	01/14/03
		4	Allow prohibited items to be received at the WIPP	Withdrawn	01/14/03
08/28/01	2	1	Allow compositing of headspace gas samples for analysis	Accepted	11/27/01
		2	Alter random sampling for visual examination to allow for site safety considerations	Rejected	11/27/01
		3	Allow hgas samples to be taken through existing filter openings	Accepted, but limited to POCs	11/27/01
06/27/02	2	1	Revised addition of HF hazardous waste number (U-134)	Accepted w/minor changes	11/25/02
		2	Elimination of control charting for repackaged solidified wastes	Accepted w/minor changes	11/25/02
		3	Record keeping and auditing of classified information	Accepted	11/25/02
		4	Add HalfPACT to shipping containers	Accepted	11/25/02
		5	Use of radiography instead of VE for newly generated wastes	Accepted w/minor changes	11/25/02
06/27/02	2	1	Add direct loaded 85-gal and 100-gal drums, and TDOPs	Accepted w/modification	11/25/02
06/27/02	(2)3	1	Data Management Update	Moved to Class 3 (in progress)	
06/28/02	3	1	Add RH-TRU	In process	
10/07/02	3	1	Change panel closures from Option D to WPC design	Proposed as Class 2, accepted as 3 (in progress)	

Table 2-1. WIPP HWFP Class 2 and 3 Modification Proposals (Continued)

Proposal Date	Mod Class	Item #	Proposed Modification	Disposition	Action Date
05/14/03	2	1	DAC for 85-gallon & 100 gallon drums, and TDOPs	Rejected (needs more data)	09/11/03
		2	Removal of booster fans in the underground	Accepted	09/11/03
		3	Eliminate LANL sealed sources waste streams hgas sampling and analysis	Rejected (suggested resubmittal with statistical sampling)	09/11/03
		4	Remove formaldehyde as a required analytical parameter for LANL	Accepted	09/11/03
		5	Add New HWNs (cyanides, DMS, Acetonitrile, 1,4Dioxane, hexaclorobutadiene)	Accepted	09/11/03
05/14/03	3	1	Add new hazardous waste disposal units (panels 4-8)	NMED review period	
05/21/03	2	1	Eliminate PCB prohibition from HWFP	Accepted	09/11/03

"AK" = acceptable knowledge
"DAC" = drum age criteria
"DR/CT" = digital radiography/computerized tomography
"HF" = hydrofluoric acid
"HWN" = hazardous waste number
"hgas" = headspace gas
"homogeneous containers" = containers of solidified or soil/gravel wastes
"POC" = pipe overpack container
"RCT" = radiation control technician
"RH-TRU" = remote-handled transuranic waste
"RTR" = real time radiography
"SCG" = summary category group (debris wastes, solidified wastes, and soil/gravel are the 3 SCGs)
"SQS" = small quantity sites
"TDOP" = ten-drum overpack containers
"U-134" = hazardous waste code, hydrofluoric acid, Chemical Abstract Number 7664-39-3
"VE" = visual examination
"VOC" = volatile organic compound
"WPC" = WIPP panel closure

2.2 EPA: 40 CFR 194 Waste Characterization Requirements Change Process

The most restrictive requirements for radionuclide waste characterization derive from the EPA decision (1998) to certify the WIPP to receive waste as required by the WIPP LWA. 40 CFR 194 contains the criteria the EPA established for the WIPP to be certified. 40 CFR 194.24 requires the DOE to have a system of controls to measure and track the waste components that affect the long-term performance of the repository. These components were identified as ten radionuclides (four plutonium isotopes, three uranium isotopes, americium-241, strontium-90, and cesium-137), cellulosic materials (cellulose, plastic, and rubber), free water, and as two

separate categories, ferrous and non-ferrous metals (DOE 1996; EPA 1998). The amount of the ferrous metal component is easily satisfied by counting waste drums. But the other components required waste characterization methods to measure them. The ten radionuclides are identified and their activity measured principally by NDA techniques. The other components are identified and measured by either radiography (x-ray imaging of container contents) or visual examination (VE) techniques.

Changes to the methods for identifying and measuring these components are relatively informal, except for severe changes to the requirements. The EPA established a rule-making process in 40 CFR 194.65, but has retained a fairly wide latitude in determining whether a change requires a rule-making. For changes that the EPA determines do not require rule-making, the process is informal. The DOE simply negotiates with the EPA on proposed changes, then submits the proposed change to the EPA for evaluation. The EPA sends a letter to the DOE announcing their approval of the elements of the change.

Since late 1999 the 40 CFR 194 radioassay waste characterization requirements have been placed in Appendix A of the CH WAC (currently DOE 2002b). The informal, non-rule system has been used to successfully modify the NDA requirements several times. While there is no formal comment process, the EEG has been notified by either the DOE or the EPA during the latter phase of these negotiations and has submitted technical comments for consideration. Thus far, the EEG has had no objections to the informal process used for modifying waste characterization requirements.

The DOE has initiated several informal changes to the 40 CFR 194 mandated requirements which have been approved by the EPA. These include changes to the NDA Performance Demonstration Program and two non-waste characterization items (a reduction in the requirements for backfill in the repository, and a change to the repository horizon). A more formal change to the implementation of 40 CFR 194, to allow both the EPA and the DOE additional flexibility in several areas, is currently in the final stages.

2.3 NRC: Transportation Waste Characterization Requirements Change Process

Transportation waste characterization requirements are established in the documentation supporting the NRC Certificate of Compliance (C of C) for the transportation package, as required by 10 CFR 71. Changes to any waste characterization requirements in this documentation are initiated by submitting the changed documentation to the NRC; 10 CFR 71.13(c) and 10 CFR 71.31(b) provide criteria by which the NRC evaluates these or any other proposed changes, and revised C of Cs are used to express the NRC's acceptance of these proposals.

The two criteria by which the changes are evaluated are not complex, even though the evaluation itself may be very complex. 10 CFR 71.13(c) states that modifications are not to significantly impact the design, operating characteristics, or fissile material package with respect to criticality, in relation to the stringent testing requirements of the shipping package. 10 CFR 71.31(b) simply requires that modification of the authorized contents of the packaging provide sufficient information to demonstrate that the package will remain in conformance with the package standards in effect at the time the modification is requested.

WIPP CH TRU waste is transported in the Transuranic Package Transporter-II (TRUPACT-II), for which the C of C's principal supporting documentation concerning waste characterization is the *TRUPACT-II Authorized Methods for Payload Control* (TRAMPAC) (DOE 2003a), currently issued as a separate document, but still a part of the *TRUPACT-II Contact Handled Transuranic Waste Shipping Package Safety Analysis Report* (SARP) (DOE 2003b). The SARP specifies the waste characterization methods that will be used to meet the criteria established or referenced in the C of C is in Revision 16 (NRC 2003); while all of these revisions were not necessarily concerned with waste characterization requirements, most of the recent ones (C of C revisions 13 through 16) have adjusted waste characterization criteria.

2.4 DOE: CH WAC Characterization Requirements Change Process

The CH WAC (currently DOE 2002a) contains statements of waste characterization requirements that originate from operational activities at the WIPP. These requirements are

derived from the *Waste Isolation Pilot Plant Contact-Handled (CH) Safety Analysis Report* (CH SAR) (DOE 2003c), and are listed in the Technical Safety Requirements (TSR) attachment 1 (DOE 2003d) to the CH SAR. 10 CFR 830 requires nuclear facilities to establish and maintain a documented safety analysis. The published CH SAR has been updated annually since 1992 and any modifications to waste characterization requirements take place as a part of the ongoing review of this document. EEG is responsible for the review of the CH SAR on behalf of the State of New Mexico. The process for modification is simply to include the changes in the annual CH SAR, a process not necessarily simple in itself. Initiation of the change, review, comment resolution, and signature release are all necessary. These changes are then reflected in the next revision of the CH WAC, except for Appendix A which must be approved by EPA. For example, this process was used in 1999 to change the maximum radiotoxicity limit for 55-gallon drums (from 1000 PE-Ci to 1100 PE-Ci; see Chapter 7 for a discussion of PE-Ci).

The CH WAC also lists the DOE's interpretation of the regulatory criteria for the HWFP, NRC, and EPA. In the past the WAC contained not only the waste acceptance criteria—that is, the data that waste characterization would need to supply, but also a discussion of the source of each criterion from each regulatory organization. In promulgating the immediate predecessor of the current CH WAC, the information presented was changed so that it only reflected the most restrictive criteria in each area. The WAC no longer cites either the source for that most restrictive criterion or the various regulatory sources that place restrictions on that area. Moreover, the CH WAC no longer contains a discussion of the technical justification for each criteria as it once did in the earlier versions. EEG has gone on record urging DOE to restore that discussion into the document (EEG 2002a).

3.0 RISK PERSPECTIVES

When designing and operating a nuclear waste repository, it is necessary to evaluate the risks associated with the wastes being disposed and to use this information to minimize operational and long-term risks to workers, the public, and the environment. Waste characterization should be sufficient to provide the information necessary to ensure that the "mixed" (radiological and hazardous wastes) wastes being shipped and emplaced, meet these operational and long-term safety requirements.

3.1 EEG Evaluations and Statements

The EEG published EEG-72, *A Comparison of the Risks from the Hazardous Waste and Radioactive Waste Portions of the WIPP Inventory*, (Channell and Neill 1999). The six major conclusions from this study were:

1. Risks are low in all cases. Lifetime carcinogenic risks are expected to be about 1×10^{-3} for workers and about 1×10^{-8} for members of the public.

2. The expected radiological carcinogenic risks to workers from routine operations and from operational accidents were at least four orders of magnitude greater than the carcinogenic risk from the hazardous waste constituents. Under maximum conditions, the radiological risks are more than two orders of magnitude greater than the hazardous waste risks.

3. During routine operations, a member of the public residing at the WIPP Site Boundary would receive a very low carcinogenic risk (less than 10^{-8} lifetime) from Volatile Organic Compounds (VOCs) and no radiological risk. The radiological risk to a member of the public from average operational accidents is over five orders of magnitude greater than the hazardous waste risk.

4. Radionuclide annual risks to a resident farmer from average releases to the surface following human intrusion 1000 years after WIPP closure are one order of magnitude greater than total risks from VOCs. These long-term risks are two orders of magnitude lower than risks during the operational period and are less likely to occur.

5. Non-carcinogenic risks from VOCs during operation are less than 2% of the Hazard Index and are not important relative to the carcinogenic risks.

6. The evaluations confirmed the intuitive assumption that radiological risk from WIPP wastes are much greater than the risks from hazardous wastes.

In May 2000 EEG published EEG-75, *Evaluation of Risks and Waste Characterization Requirements for the Transuranic Waste Emplaced in WIPP during 1999*, (Channell and Walker 2000). The waste emplaced during the first year of WIPP operation was non-mixed (did not meet the regulatory definition of hazardous wastes although low concentrations of VOC's were present in headspace gas samples) and with low radionuclide concentrations. The EEG found that risks from VOCs were extremely low (lifetime cancer fatality risks of 10^{-11} to 10^{-14}).

The EEG-72 and EEG-75 conclusions have several implications for waste characterization requirements and priorities. These conclusions have been pointed out by EEG subsequent to July 1999. While many of these comments are quoted elsewhere in this report, the more relevant EEG statements have been:

1. We see no scientific reason why it is necessary to analyze for hazardous metals in waste solids (see discussion in Section 4.7).

2. VOC releases will occur routinely and have a quantifiable, albeit low, risk. Thus, there is a logical reason to quantify VOC releases.

3. In EEG-75, EEG concluded that the Confirmatory VOC Monitoring Plan in the WIPP underground would detect concentrations that are three orders of magnitude below allowable Permit limits.

4. EEG stated in an April 2001 paper at the 9th International High-Level Radioactive Waste Management Conference (Neill and Silva 2001):

> The cost of complying with non-radioactive hazards (Resource Conservation and Recovery Act [RCRA] regulations) may be much more than complying with the radiological hazards, which are about 10,000 times greater. Predicting releases over 100 years for the non-radiological constituents should not be the primary cost in comparison to limiting radiological releases over 10,000 years.

5. In an October 4, 2001 statement to the National Academy of Science/National Research Council Committee on the Characterization of Remote-Handled Transuranic Wastes we said, "… The fact that radiological risks are much greater than hazardous risks needs to be kept in mind by DOE, regulatory agencies, peer review groups, this Committee and oversight agencies when addressing possible changes to waste characterization requirements." (EEG 2001).

3.2 Risk-Based Approach to Characterization

The DOE has proposed at various times since 2000 that a "risk-based" or "performance based" system should be used to determine waste characterization requirements (Moody 2002). These two terms have not been precisely defined by DOE, but presumably refer to only those waste characterization requirements believed to serve a useful purpose in controlling risks.

The NRC has attempted to include the use of probabilistic risk assessment in a Risk-Informed and Performance-Based (RIPB) system since 1995. RIPB analyses are to be used along with traditional deterministic approaches in setting priorities for regulations. The NRC and others

believe this process will encourage more transparent regulatory approaches and focus on requirements that lead to actual reduction in risk. This is apparently the general intent of the DOE thrust in reduction of CH TRU waste characterization requirements.

EEG believes that an RIPB assessment should be included in developing CH TRU waste characterization requirements. A requirement that does not have a health or safety basis should be reevaluated. These considerations have been the general philosophy in EEG's recommendations to date, which have usually been limited to health and safety issues. However, this concept is more easily stated than implemented because the risk being addressed is often not quantifiable. The evaluation of individual CH TRU waste characterization requirements should consider two questions: (1) are the data collected used for any purpose (for example, elimination of waste containers for shipment to WIPP; or controlling quantitative limits for transportation, operations, or long-term performance), and (2) is the particular test being used or it's frequency (for example, 100%) the most cost-effective approach.

3.3 Hazards to Waste Characterization Workers

References have been made to the extra radiation doses incurred by workers performing "unnecessary" waste characterization activities (NAS/NRC 2001, p 33). The DOE was asked to address questions relating personnel radiation exposure (dose) to various characterization activities at the generator sites. The DOE acknowledged that it does not have, "information relative to dose from TRU waste characterization activities… Dosimetry groups at the various DOE sites differentiate dose by individual rather than by tasks." At best, the DOE was only able to address the questions with a qualitative answer and the promise to provide the information if and when it became available (DOE 2002d, p 23).

The EEG has not received any data that the DOE may have on actual doses received by workers characterizing CH TRU wastes. The EEG's present belief is that these doses are very low and cannot be used as a justification for reducing waste characterization requirements. Another reason for this preliminary conclusion is that (even though it is not waste characterization) the external collective radiation doses received by waste handlers and radiation control technicians

handling and emplacing drums at WIPP are so low (0.06 mrem per container from 3/99 through 12/31/02).

This conclusion is consistent with the DOE response in which the DOE noted that the risk for radiological exposure is very low for NDA, RTR, and HSG sampling and analysis during normal operations. VE is considered to be a moderate risk. As noted by DOE, the impact of VE/repackaging is controlled by ALARA (as low as reasonably achievable) principles, which normally result in very low exposures to workers. Personal protective equipment and procedures are used to prevent inhalation of airborne contamination. DOE does caution that repackaging campaigns for special cases such as ^{238}Pu and high-wattage ^{239}Pu require extra measures to avoid significant doses (DOE 2002d, p 4-7).

4.0 HWFP WASTE CHARACTERIZATION REQUIREMENTS AND EEG COMMENTS

The DOE/CBFO requested that the DOE National Energy Technology Laboratory's Center for Acquisition and Business Excellence (NETL-CABE) prepare an analysis on the cost of waste characterization (NETL/CABE 2003) that estimates the CH TRU waste characterization costs per container. Table 4-3 from this study, *Average Cost of Characterization Activities*, is reproduced here as Table 4-1. Table 4-1 is being used in the report for two reasons: (1) it gives a relative idea of the costs for each "characterization activity" (which are significant), and (2) the "characterization activity" breakdown is a convenient one to use in addressing our waste characterization conclusions and recommendations. A review of the cost study is outside the scope of this report and EEG uses the cost figures as provided, without offering an opinion of their accuracy.

Table 4-2 is an EEG-developed table that shows how the overlap of the waste characterization requirements analyzed in Table 4-1 is used to meet the requirements. The table shows which of these methods are required or used by each agency. A "required" characterization method ***must*** be used either 100% of the time or part of the time to meet the indicated requirement. The term "used" is for a waste characterization method that, in some cases, ***may*** be used to meet a requirement, but the method is not specifically mandated. For example, the HWFP requires HSG sampling and analysis, whereas, to satisfy the TRAMPAC limits on flammability, HSG sampling and analysis is not specifically required but may be, and has been used. The associated average cost of characterization per container from the DOE cost study is also included. The EEG notes that some of the categories are not regulatory requirements. For example, the "Segregation/Rework" must be performed in some cases even though it is not required by any regulatory agency. These categories have been included to retain consistency with the DOE cost study.

It is clear from these tables that nearly all of these requirements and a major part of waste characterization costs can be attributed to meeting the requirements of the HWFP. The following sections describe these requirements.

Table 4-1 Average Cost of Characterization Activities.

Characterization Activity	Percentage of Containers Requiring Activity	Average Unit Cost to Characterize	Average Cost of Characterization per Container
Non-Destructive Assay	100%	$840	$840
Headspace Gas Sampling	100%	$620	$620
Real-Time Radiography	32.8%	$730	$240
Visual Examination/ Retrievably Stored	1.2%	$22,500	$270
Visual Examination/ Newly Generated	67.2%	$540	$360
Solids Coring and Sampling	0.5%	$24,000	$120
Solids Analysis	0.5%	$63,000	$310
Acceptable Knowledge	100%	$87	$87
Drum Venting	1.8%	$120	$2
Level II Management	100%	$160	$160
Gas Generation	9%	$670	$60
Drum Age Criterion	68.7%	$46	$32
Segregation/Rework	30%	$1,400	$420
Waste Certification	100%	$330	$330
Characterization Support Activities	8%	$648	$52
Average Cost of Characterization per Container			**$3,900**

Source: NETL/CABE 2003

Table 4.2. Overlap of Regulatory Agencies and DOE Waste Characterization Requirements and Associated Cost Per Container.

	NMED		EPA		NRC		DOE		
Characterization Requirement	Used by HWFP	Req. by HWFP	Used by §194.24	Req. by §194.24	Used by TRU-PACT-II	Req. by TRU-PACT-II	Used by WIPP CH WAC	Req. by WIPP CH WAC	Average Cost of Characterization per Container [b]
Non-Destructive Assay	No	No	Yes[a]	Yes	Yes	Yes	Yes	No	$840
Headspace Gas Sampling	Yes	Yes	Yes	No	Yes	No	No	No	$620
Real-Time Radiography	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	$240
Visual Examination/ Retrievably Stored	Yes	Yes	Yes	No	Yes	No	No	No	$270
Visual Examination/ Newly Generated	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	$360
Solids Coring and Sampling	Yes	Yes	No	No	No	No	No	No	$120
Solids Analysis	Yes	Yes	No	No	No	No	No	No	$310
Acceptable Knowledge	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	$87
Drum Venting	Yes	Yes	No	No	Yes	Yes	Yes	Yes	$2
Level II Management	Yes	Yes	No	No	No	No	No	No	$160
Gas Generation	No	No	No	No	Yes	Yes	No	No	$60
Drum Age Criteria	Yes	Yes	No	No	Yes	Yes	No	No	$32
Segregation/ Rework	No	No	No	No	No	No	No	No	$420
Waste Certification	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	$330
Characterization Support Activities	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	$52
							TOTAL		**$3,900**

[a] In the required (req) column, "yes" means the method ***must*** be performed 100% of the time or part of the time. In the used column, "yes" means the method ***may*** be performed to meet a requirement, but the specific method is not mandated by that requirement.

[b] The cost of activity spread over all the containers shipped to WIPP.

4.1 HWFP: Acceptable Knowledge (AK) Requirements

AK is the principal waste characterization requirement for all of the regulatory agencies. As shown in Table 4-1, the DOE cost study indicates AK to be one of the least costly of the waste characterization techniques at $87/container. However, the AK package is developed on a waste stream basis rather than on individual containers.

Several slightly differing definitions of the term are in use on the WIPP project; the HWFP states:

> Acceptable knowledge includes a number of techniques used to characterize transuranic (TRU) mixed waste, such as process knowledge, records of analysis acquired prior to RCRA, and other supplemental sampling and analysis data (EPA 1994). (NMED 2003, Attachment B4-1).

Process knowledge" is the knowledge of the waste based on the materials and processes used to generate the waste, and "EPA 1994" is an EPA guidance document on waste characterization for facilities that treat, store, or dispose of hazardous wastes (the WIPP is a storage and disposal facility). Thus, acceptable knowledge is effectively the compilation of all useful knowledge about the waste. Container analyses by other waste characterization methods become a part of the AK for the waste stream, as does any other information related to the waste that is discovered. The HWFP requires AK to be organized in a report on each waste stream, from general facility information (areas and facilities) to specific information for the waste stream (description of the generating process to include buildings, process flow diagrams, material inputs, types and quantities generated, and storage locations). An overall AK summary report is generated after records are found, documents are indexed, and applicable waste and facility information has been organized.

The EEG has not commented specifically on the need for AK as a waste characterization requirement. There has never, to the EEG's knowledge, been any question of the need for an AK-like data accumulation. The HWFP's AK requirements are the most prescriptive of any of

the regulatory agencies. At this time the EEG supports the continued use of the HWFP AK requirements.

4.2 HWFP: Headspace Gas Sampling and Analysis Requirements

The AK requirements section of the HWFP also states:

> Radiography and/or visual examination, headspace gas sampling and analysis, and homogeneous waste sampling and analysis ...are used to acquire supplemental sampling and analysis data to meet the requirements of the Waste Analysis Plan (WAP) specified in Permit Attachment B. (NMED 2003, Attachment B4-1).

More often, the HWFP addresses these techniques as "confirmation of AK"; the EEG views these techniques more as a process for discovering deviations from the currently known AK.

At $620/container, headspace gas sampling and analysis is one of the more expensive costs-per-container waste characterization techniques listed in Table 4-1. According to DOE:

> Headspace gas is measured both to meet transportation requirements and to meet NMED requirements. Several methods are used to collect a sample of gas from inside the top of the container. One method involves drawing a sample of gas through the existing filter by inserting a needle through the filter core. The punctured filter is then removed and a new filter installed. A second method involves using a self-tapping replacement filter that first taps a hole in the waste container. Next the samples are drawn through the self-tapping filter assembly. A third method uses a self-tapping sampling port through which a sample is drawn, and then the port is sealed.
>
> Headspace gas sampling is done in a structure that prevents radioactive particulate from the waste container from escaping into the atmosphere. Precautions are taken around the puncture area to prevent releases of radioactive particulate to the

> atmosphere and to prevent drawing outside air into the container during sampling (DOE 2002d, p 5).

Analysis is targeted to determine the presence and concentrations of about 30 different hazardous chemicals within each headspace gas sample, and the HWFP also requires analysts to look for, and identify, other chemicals in the sample from each container. If these other chemicals are on the hazardous waste list, and appear in 25% or more of the individual containers analyzed in each waste stream, then they are added to the target list for that waste stream also. The analysis is performed according to procedures modified from the EPA's *Test Methods for Evaluating Solid Wastes* (EPA 1996) and *Determination of Volatile Organic Compounds (VOCs) in Ambient Air Using Specially Prepared Canisters With Subsequent Analysis by Gas Chromatography* (EPA 1999). Included in the HWFP requirements are the many sample control methods for quality assurance and quality control. Those also contribute to the cost of headspace gas sampling and analysis.

The EEG has commented on HWFP headspace gas requirements, stating to the NAS/NRC WIPP CH Waste Characterization Committee in 2002 that though headspace gas sampling and analysis helps meet the 40 CFR 264.13(a)(1) requirement for a detailed chemical analysis of a representative sample of the waste, "...we do not see why 100% headspace gas sampling at the sites should be necessary to ensure compliance with Room Based Concentration Limits" (EEG 2002c). The HWFP establishes concentration limits for VOCs in the underground rooms, primarily as a protection for underground and above ground workers and members of the public. The headspace gas analysis results are one of two checks to ensure that these concentrations are not exceeded; the other check is by sampling of the air from these underground rooms (confirmatory VOC monitoring). The EEG went on to state the following:

> The Code of Federal Regulations requirement for a detailed chemical analysis of a representative sample of waste is addressed only by headspace gas analysis for most of the debris waste. These analyses do provide additional information on the contents of waste containers. Additional waste streams have been defined because of the results of these analyses, and on occasion additional RCRA

> hazardous waste numbers have been added to waste streams. The importance of these functions has occasionally been denigrated, primarily because this additional information is not used to control quantities of VOCs coming to WIPP other than to show compliance with the room based concentration limits (EEG 2002c).

In more recent comments to the same NAS/NRC committee, the EEG again noted that room-based concentration limits can be met by confirmatory VOC monitoring at the WIPP, that "A comprehensive HSG [headspace gas] sampling program is also the most direct means of ensuring compliance with the flammable gas concentration limits for transportation that are included in the TRAMPAC", and that:

> HSG sampling is the primary way DOE has chosen to meet the "detailed chemical analysis...of a representative sample of the waste" that is specified in the New Mexico Administrative Code. This information is used (in conjunction with acceptable knowledge) to assign hazardous waste numbers to each container. However, EEG is not aware that these hazardous waste numbers are used to exclude waste from the WIPP or to otherwise control the hazardous waste. These data probably provide the incidental benefit of confirming AK and ensuring the various Waste Acceptance Criteria (WAC) requirements for stability of waste are met.
>
> EEG believes that it is desirable to maintain a comprehensive HSG program for WIPP CH-TRU wastes. However, it should be possible to require less than 100% sampling in some cases. This determination needs to be made on small batches or waste streams where there is reason to believe that relative uniformity exists. Also, the detailed approach necessary to ensure that representative data is still obtained needs to be justified by a proposed modification request (PMR) to the HWFP in the same manner that existing PMRs are justified (EEG 2003b).

One of EEG's concerns about the complete elimination of HSG sampling is that knowledge of the waste may be much less certain on retrievably stored waste which has not yet been characterized.

As noted above, the quality control and quality assurance (QA/QC) requirements for headspace gas sampling and analysis processes would appear to contribute to the DOE's estimated cost for headspace gas activity. The EEG has stated several times a variant of the following:

> The relaxation of audit requirements and QA/QC is not an appropriate way to reduce the waste characterization burden. These requirements should maintain the current level of stringency. The appropriate way to reduce the waste characterization burden is to eliminate unnecessary requirements, not to reduce the degree of compliance. (EEG 2002c).

Other EEG comments have noted that headspace gas analysis is often used to ensure that flammable gas limits for transportation are met, and the HWFP itself notes that headspace gas is useful for determining potential flammability.

As noted in Section 2.1, the DOE has successfully pursued modifications related to headspace gas requirements in the HWFP that the DOE believes will result in savings of tens of millions of dollars. It should also be noted that the DOE has itself endorsed continuation of some headspace gas analysis (DOE 2002d, p 17-18).

Reduction in the HSG requirement should be possible if the DOE submits detailed PMRs on specific waste streams.

4.3 HWFP: Drum Age Criteria (DAC) Requirements

The DAC is the time after the closing of a container necessary to ensure that VOC and flammable gas concentrations in the headspace of the container have achieved at least 90% of equilibrium concentration. The times vary widely, currently from four days to 283 days,

depending on the waste type, packaging configuration, and the container filters. The DOE cost study (NETL/CABE 2003) considered the DAC as a separate requirement with a cost of $32/container, but the DAC is solely for purposes of establishing the representativeness of the headspace gas in a container, and is really a part of the sampling process for headspace gases. The DAC is also used as a part of the TRUPACT-II requirements when flammable gases are to be actually measured.

The DOE eventually succeeded in obtaining changes to the initial DAC values in the HWFP, but three modifications were submitted before this success was obtained. In a paper (Walker and Silva 2002) presented at the conference Waste Management '02 conference midway through these attempts, the EEG used the DAC modifications as the principal example to point out four observed difficulties in the DOE's approach to the permit change process. Three of these difficulties delayed the DAC permit modification request.

First, the modification was not properly classified. The DOE submitted the revised DAC as a Class 1. This was immediately rejected by the NMED. Second, when submitted as a Class 2 proposal, the DOE did not provide sufficient data and information. Third, the DOE failed to meet the expectations of the regulator. In rejecting the first PMR, the NMED cautioned DOE to submit the request as a Class 3. Nonetheless, DOE submitted the request as a Class 2. NMED was forced into the process for changing the request to Class 3. The action by DOE contributed to further delay.

The DAC modification was an important change to the HWFP and TRAMPAC. It decreased the storage times on many waste containers by several months. The modification process for the eventual Class 3 request to the HWFP also underscored the value of public involvement as specified in the process. The EEG requested that the DOE provide the input and output files for the DAC computer model. These were later provided to the EEG by the DOE at the insistence of the NMED. The public review process identified six discrepancies between the output files and the DAC tables that until then had not been identified.

4.4 HWFP: Real-Time Radiography (RTR) Requirements

All WIPP waste containers are required by the HWFP to undergo either radiography or VE. RTR is a non-destructive examination technique that utilizes x-ray technology to create images of the interior of waste containers. The "real-time" component is important. It allows the radiography technician to increase and decrease the energy of the x-rays so as to create images of different density materials within the container. Thus, lower energy x-rays can produce an image of loose plastic material in the containers, and adjustments can also be made to observe the interior of metal cans or bottles or other denser material that may be in the container.

With some training, an operator can distinguish between different kinds of metals (lead, steel, aluminum, by their different densities), determine the number of layers of plastic packaging around waste, and detect any free liquid in bottles or cans that are in the waste. Thus, radiography can be used to create a record of the physical contents of the container. The HWFP requires that operators of radiography equipment be trained both formally and by on-the-job techniques. The operator must successfully demonstrate an ability to identify a specific list of objects in the waste prior to performing official scans. Operators must then be further trained to the waste streams they are reviewing, an audio-visual recording of the examination of each container must be made. A similarly-trained independent reviewer must confirm the information in the records created by the operator. Once each day, or once each testing batch, (20 or fewer containers) a replicate analysis must be performed by an independent operator. Operators are required to determine the Waste Matrix Code for the waste, estimate material parameter weights, and look for prohibited items in the waste.

It is worth noting that the 40 CFR 194.24 waste characterization requirements to quantify non-ferrous metals and cellulosic materials are met primarily through radiography. These are some of the material parameters that the HWFP requires radiography operators to estimate. In the absence of HWFP requirements, a comparable program would either be needed to address the 40 CFR 194.24 waste characterization criteria or alternate methods (visual examination) would be necessary.

As with AK, few substantive concerns have been raised about radiography requirements and the EEG's comments on radiography have been brief. In 1999, as part of a broader statement, an EEG comment was that:

> EEG agrees with the generic policy that data that is not going to be used should not be collected. This includes data for all requirements, not just VE. However, it is necessary to do thorough evaluations to show that RTR and/or VE are not providing useful data in a waste stream. At the recent SRS audit, 15% of the first batch of drums was rejected by RTR. (EEG 1999).

Radiography was introduced in lieu of visual examination of waste, so that the DOE's HWFP application expected that only visual examination would be used for newly generated waste. The HWFP initially followed this track, but at least one waste characterization program found radiography to be so useful, the DOE submitted a PMR to allow radiography as well as VE to be used for newly generated waste. The PMR was quickly approved, and either method may now be used for newly generated wastes.

The overall radiography program is an important part of the WIPP waste characterization program and should be retained. It may be possible to reduce some of the detailed procedural requirements in the HWFP.

4.5 HWFP: Visual Examination for Retrievably Stored Waste Requirements

VE may be used as an alternative to RTR for retrievably stored wastes, but this alternative may not have been used yet. However, because RTR is merely an imaging technique, a radiography operator cannot, for instance, read the label on a bottle, or estimate a weight by lifting the object. The HWFP also requires that a statistically determined sample of radiographed containers undergo confirmatory VE. The size of the statistical sample is based on the number of mis-certifications found from the previous year at that site, from each of the three summary category groups (debris, solidified wastes, and soil/gravel wastes). Thus far, less than 2% of retrievably

stored containers undergo VE. Nonetheless, the process is an expensive component of the waste characterization program. The DOE estimates the cost to be $22,500 per container examined, or $270 per container over the entire population sent to the WIPP.

The HWFP requirements for VE include those for RTR (determine Waste Matrix Code, measurement, rather than estimation, of material parameter weights), but also requires that "all discernable waste items" are to be identified, as well as residual and packaging materials. A VE expert is required to be present. This individual's discretion determines whether bags or cans inside the container must also be opened (weights of the contents are to be estimated if it is not opened). The packaging configuration, type and number of filters, and other information necessary for determining the DAC are also to be recorded. Audio-visual recordings of the process are to be made, and operators (as well as the much more thoroughly trained VE expert) must undergo formal and on-the-job training.

The EEG has stated that:

> Claims are often made that VE is dangerous because of additional radiation exposures and possibility of contamination. EEG has discussed this issue with persons doing VE at INEEL, RFETS, and LANL and found they don't feel VE is dangerous and do not have data on incremental radiation exposures. More specific data and evaluations are needed if danger is to be used as an argument against VE. Also, plans to use 100% VE for newly generated wastes appear to be inconsistent with expressed safety concerns. (EEG 1999, p 8).

The DOE has been successful in modifying the HWFP on retrievably stored VE, producing great cost savings, as noted in Section 2.1.

4.6 HWFP: Visual Examination/Newly Generated Requirements

For newly generated wastes, the original HWFP (based on the DOE's application) specified only VE as a method for determining the required detailed physical analysis of a representative

sample of the waste. The process actually specified in the HWFP has the advantage of allowing verification at the time the container is being filled and is somewhat different from retrievably stored VE, and has often been referred to as "visual verification" (V-squared) to distinguish it from the retrievably stored process. No audio/video recording is required, but two visual examination operators are required to observe the loading of waste into containers and record the data. The same data is to be recorded as for retrievably stored VE.

The EEG has not commented specifically on the visual verification process, except when commenting on the PMR to allow radiography as well as visual verification. In those comments the EEG noted that visual verification is a much higher quality process than radiography, and that the requirement for two trained visual examination operators to perform the visual process:

> ...may be overkill; the HWFP could be modified to require generator site procedures be developed and implemented that would require, for each waste container, that a data form be used to document the contents of the container, and then require a single verification of the information on the data form (EEG 2002b).

As noted previously, the PMR submitted by the DOE was successfully integrated into the HWFP.

4.7 HWFP: Solids Coring and Sampling, and Solids Analysis (Homogeneous) Requirements

The DOE's waste characterization cost analysis in Table 4-1 shows solids (solidified wastes and soil/gravel) coring and sampling costs separate from the chemical analysis of these solids. For the 0.5% of drums that will be cored, sampled and analyzed, the estimated cost per drum is $24,000 for coring and sampling and $63,000 for analysis. When spread over all containers shipped to WIPP, for sampling, the cost per drum shipped is estimated at $120; for the analysis, the cost is $310. The overall estimate of $430 per container shipped is among the highest waste characterization method costs.

"Coring" is a process wherein a container of solids is opened, and a hollow drill bit is inserted near the bottom of the container. The core is taken from the bit and "sampled" by removing either one or three thin sections from along its length. These sections become the sample.

For retrievably stored wastes, the HWFP states that homogeneous sampling and analysis is used to determine the toxicity "characteristic" in the waste; that is, the hazardous compounds that are considered toxic only if present above the threshold concentrations listed in 40 CFR 261.24, or if the "listed" wastes under Subpart D of 40 CFR 261 are present. Sampling of these waste streams is statistical, rather than each of the containers; five randomly selected containers must be sampled initially, then chemically analyzed. The average concentration and standard deviation of each hazardous compound is then computed and used, along with the threshold concentrations (or program required quantification limit, if it is a "listed" waste in Subpart D) to calculate the total number of containers from the waste stream that must be sampled. For most (perhaps all) of the homogeneous waste streams analyzed so far, the initial five samples suffice.

The HWFP requires analysis of homogeneous samples for total VOCs, semivolatile organic compounds (SVOCs), and analysis for metals. Tables in the HWFP list over 30 chemicals for the VOC analysis, 11 for the SVOC analysis, and 14 metals that are the primary targets, but other hazardous constituents may be added to the list for a waste stream if they are found in more than 25% of the samples from that waste stream. A test for Polychlorinated Biphenyls (PCBs) is also currently required, but a PMR is currently in process to eliminate those requirements now that the DOE has obtained an approval from the EPA under the Toxic Substances Control Act (TSCA) to dispose of PCB-contaminated wastes at the WIPP. A full panoply of QA/QC requirements are also established for homogenous sample analysis, and radiation protection activities associated with opening of containers and processing the samples also contribute to the homogeneous sampling and analysis program.

The EEG has commented several times on homogeneous waste sampling and analysis, eventually concluding that these requirements are not needed. In 1999, comments on two DOE documents, in a section entitled, "Homogeneous Waste Sampling and Analysis", the EEG first

stated that metals analysis was not needed, and deferred an opinion on the homogeneous VOC and SVOC requirements:

> For the following reasons, EEG sees no scientific reason why it is necessary to analyze for metals at all:
>
> $ DOE apparently did not feel that metals concentration data were important enough to include in the RCRA application. The State apparently concurred since they did not request that the data be include[d].
>
> $ The required hazardous metals data are not to be used for any regulatory control under the Draft Permit.
>
> $ Evaluations in EEG-72 concluded that human exposures to hazardous metals at WIPP would only occur from the types of operational and human intrusion accidents that released radioactive materials. The calculated radionuclide risks (Excess Cancer Fatalities) were $2x10^6$ times the hazardous metals release for operational accidents and $5x10^5$ times for long term releases. Furthermore, methods used to clean up radionuclide contamination would also be effective in cleaning up hazardous materials.
>
> $ EEG has no opinion at this time on sampling for VOCs and SVOCs in homogeneous wastes. The decision should be based on whether any useful information will be obtained for VOC control under the RCRA permit... (EEG 1999).

In 2002, in comments for the NAS/NRC CH waste characterization committee, the EEG added the homogeneous VOC and SVOC analyses to metals:

> The HWFP requires a fraction of homogeneous waste containers to be analyzed for toxic metals, other hazardous chemicals, volatile VOCs [sic], and semi-volatile VOCs [sic] (SVOCs). The EEG has stated that we see no technical reason why it is necessary to analyze for metals and chemicals at all. Our reasons are...[Followed by the information in the first three bullets of the previous quote] (EEG 2002c, p 8).

Currently, the EEG continues to believe that the homogeneous sampling and analysis are unnecessary characterization requirements in the HWFP.

The DOE has successfully pursued changes to the HWFP on homogeneous sampling and analysis issues, the major change being to add to the statistical quality control method initially required for newly generated homogenous wastes so that the retrievably stored process could also be used. Quality control requirements for SVOC specific analytes (pyridines and cresols) were changed in another PMR, and one of the first HWFP PMRs successfully altered the requirement for core sampling to allow one sample to be taken from the core rather than the three samples from each core that was previously required.

4.8 HWFP: Level II Management (Project Level) and Waste Certification Requirements

This is the first time EEG has commented on these Level II and Waste Certification Requirements. "Level II Management" requirements are estimated to cost $160 per container by the DOE. "Level II Management" requirements are apparently those activities addressed in the HWFP as "Project Level" requirements. These are solely HWFP requirements, though they appear to be closely intertwined to the "Waste Certification" requirements (at $330 per container) also shown in Table 4-1. Further, the quality assurance provided by these checks supports non-HWFP requirements as well. The two activities, Level II Management and Waste Certification, from Table 4-1 will be covered as a single topic in this section. It should be noted that the 40 CFR 194 waste certification process does not specify these activities, but a

comparable program would likely need to be developed specifically for the 40 CFR 194 required program were it not specified in the HWFP.

Project level activities are principally performed on data packages developed at the "data generation level" (radiography or visual examination test batch data reports, headspace gas and homogeneous waste sampling batch data reports, and headspace gas and homogeneous analytical data reports). These data packages are compilations of the data specified to be collected during the activity (including quality control information such as independent technical review forms, supervisor review forms, quality assurance review forms, reports on non-conforming items or processes during the activity, chain-of-custody forms, evidence of sample preservation, quality control sample results, etc.). Although radioactive materials are not a part of the HWFP function, data packages for the radioactive component waste characterization are also developed and processed based on the requirements specified in the HWFP.

At the project level, the Site Project QA Officer (SPQAO) is then required to review and sign all batch data reports supplied from the data generation level for completeness. This includes verification that quality control checks were properly performed, and that the quality assurance objectives specified in the HWFP were properly met. The Site Project Manager (SPM) also must sign off on the package; the SPM must ensure that the DAC is valid, that the necessary generation level reviews were performed and ensure that the checklists are complete, and that the data meet the required quality assurance objectives. Both the SPQAO and the SPM must prepare summary reports that include validation checklists, discussion of any nonconformances within the data package, signatures of the individuals. When a new waste stream is proposed, the Site Project Office must determine that sufficient information is available in the preliminary data packages to establish the waste stream. Site project offices are responsible for preparing the Waste Stream Profile Forms (WSPF) that officially document the new waste stream, and a characterization information summary from the preliminary data packages that is required along with the WSPF.

Other project level activities include performing the statistical calculations for random sampling. The site project offices also calculate the confidence levels from analyses, and document that

these are within the quality assurance objectives established in the HWFP. The site project office also is responsible for putting waste characterization and transportation information into the WIPP Waste Information System (WWIS), and negotiating with the WIPP site reviewers of this information.

The EEG has not commented on the project level HWFP requirements, but the data package review and approval process may be one of the areas to which the general EEG comment that, "We believe waste characterization requirements are excessive" applies. We suspect that many of these requirements were provided from a legal perspective, rather than a technical one, and therefore may be useful on that level. However, from a technical perspective, the data package review-and-approval process invoked by the HWFP appears excessive.

The DOE submitted a Class 2 PMR which would have virtually eliminated project level waste characterization activities, among other changes. This modification was later withdrawn by the DOE.

4.9 HWFP: Characterization Support Requirements

The HWFP requires the DOE to conduct an audit and surveillance program to ensure that waste characterization sites conduct waste characterization activities in accordance with the HWFP Waste Analysis Plan, and that the information supplied by each site is managed properly (records management). The HWFP also requires specific training for all areas discussed above. The 40 CFR 194 criteria also require these activities, as does the DOE itself.

The EEG has commented several times on the WIPP audit and surveillance program over the years. These comments have generally been supportive of the program and we have observed it to be a very good QA program. The basic EEG comment has been that waste characterization requirements may be changed, but not the auditing/surveillance program. For example, in a comment to the NAS/NRC committee, the EEG stated:

> Quality assurance requirements in the CBFO Quality Assurance Program Document (QAPD) are applied to waste characterization activities; while

> the EPA has mandated those in use for those processes related to 40 CFR 191/194, the HWFP only requires that the quality assurance practices in the CBFO QAPD be followed, and there may be a way of altering the requirements for non-radioactive waste characterization. However, for a variety of reasons, the EEG believes that a change in the QA requirements would not substantially decrease waste characterization requirements and would likely result in less assurance that the program was in compliance. (EEG 2003a).

Requirements for training are included in the CBFO QAPD, so that this EEG comment would appear to cover training, also. The EEG has not commented on TRUPACT-II loading, equipment and facilities, waste storage, or records maintenance in terms of their importance to the WIPP project.

5.0 40 CFR 194 (EPA) REQUIREMENTS

Title 40 CFR 194.24(c) requires the DOE to specify limiting values for waste components that are to be emplaced at WIPP. The primary analyses are quantification of radionuclides. However, there are three non-radiological waste materials that need to be quantified.

(1) free water (other regulatory agencies use the term free liquids or residual liquids)
(2) ferrous and non-ferrous metals
(3) cellulose, plastic, and rubber (CPR)

These materials are currently quantified principally by use of radiography and visual examination methods, except for the ferrous metal requirement. Chapter 4 provides the discussion of radiography and visual examination waste characterization methods. Both the radiological and non-radiological quantification is to include measurement error statistics (EPA 1998).

Under 40 CFR 194 criteria, radionuclide quantification requirements can be met by either destructive (radiochemical analysis) methods or NDA methods. Nearly all (if not all) radionuclide quantities reported to date have been by NDA. The DOE estimated that the average cost per container for NDA measurements was $840, thus making NDA the single most expensive waste characterization method (see Table 4-1).

5.1 EPA's Non-Radiological Waste Criteria

5.1.1 EPA: Free Water Requirements

EPA's Compliance Certification Decision (EPA 1998) limits the total amount of free water in the repository to 1685m^3, which is equivalent to an average of 1% of the volume of a waste container. This limitation is required because of the assumptions DOE used for waste room modeling in the Compliance Certification Application (DOE 1996). This requirement could be satisfied by a repository (or waste panel) average rather than on each waste container. However,

transportation, HWFP, and WIPP Operations and Safety requirements all limit free water to 1% on each container.

EEG believes the free water limit of 1% on each container should not be changed since it is required for the transportation, HWFP, and WIPP criteria, and is probably the most cost-effective way to ensure the EPA's requirement is met.

5.1.2 EPA: Metals Requirements

The EPA has a minimum requirement for the quantity of ferrous metals in the repository, to maintain a reducing chemical environment in the repository in order to minimize radionuclide mobility. Waste drums and other containers provide more than the minimum ferrous metals requirement. The method of compliance is to simply count the containers in the repository and multiply the number of containers by the amount of iron in each container. The DOE has stated that enough containers have already been placed in the repository to meet the ferrous metal requirement.

EEG has stated that this requirement should be tracked at a waste panel (rather than entire repository) level. However, we have also said "there may be an argument for eliminating further tracking of this parameter" (EEG 2002c). This is really a non-problem and will continue to be unless there are future changes that allow non-ferrous waste containers to be emplaced.

Non-ferrous metals are included in the EPA's requirements because it was argued that these materials will reduce or eliminate the possibility that the radioactive components would attach to organic ligands (EPA 1998). The non-ferrous metals will attach to the binding sites on these ligands (EPA 1998). The amount of non-ferrous metals in each waste container is estimated by radiography or measured (weighed) during visual examination; a discussion of these methods can be found in Chapter 4.

5.1.3 EPA: Cellulose, Plastic and Rubber (CPR) Requirements

The presence of cellulose, plastic, and rubber could cause generation of gas in sealed repository rooms which could affect the release of radionuclides from the repository. Because of this

potential, the EPA has set a maximum repository limit on the kilograms of CPR. At present the mass of CPR is estimated or measured in each container during either radiography or visual examination.

This quantification continues to be necessary because the limit is important to assumptions used in the performance assessment for the repository. However, it does not seem to be difficult to stay below the limit. EEG has stated, "…, quantification on a waste stream (rather than individual container) basis should be acceptable if properly estimated." (EEG 2002c).

5.2 EPA's Radiological Waste Characterization Requirements

The principal EPA radiological waste characterization requirements are for the purpose of tracking the quantities of ten radionuclides emplaced in the repository to ensure that the radiological limits established for the repository are met. This continuously updated radionuclide inventory is also important for evaluation of long-term compliance during the performance assessments required at each five-year recertification. Radionuclide quantification is required on each waste container.

There are additional radiological waste characterization requirements for transportation and for the WIPP repository. These requirements will be discussed in Chapters 6 and 7. However, it is important to recognize that these transportation and WIPP requirements also require determination of some individual radionuclides which would have to be obtained even in the absence of EPA requirements.

Appendix A of the CH WAC of the Waste Isolation Pilot Plan (DOE 2002a) specifies the Radioassay Requirements for CH TRU in considerable detail. The EEG commented on the Draft Appendix A during its development (EEG 2002a).

5.2.1 EPA: The Ten Required Radionuclides

The ten required radionuclides are ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{241}Am, ^{233}U, ^{234}U, ^{238}U, ^{90}Sr and ^{137}Cs. Some of the radionuclides are more important for long-term compliance. The most

significant are ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Am. Since their half-lives and specific activities vary considerably, each of the four present a different hazard and their activities should be separately determined. The other tracked radionuclides (^{233}U, ^{234}U, ^{238}U, ^{242}Pu, ^{137}Cs, and ^{90}Sr) have less effect on repository performance but could affect certain scenarios either because of the possibility of "early" human intrusions (that is, within hundreds of years of closure) or non-random emplacement of waste in the repository.

There are other reasons for tracking several of these radionuclides. Uranium-233 must be determined because of the NRC FGE requirement. Uranium-235 is not one of the ten EPA tracked radionuclides, but it is required to be tracked by the NRC FGE requirements. Also, if minor radionuclides in an assay are recognized, there is more assurance that the major contributors are correctly identified.

One important radionuclide not included in the 10 required radionuclides is ^{241}Pu. It is the primary contributor to total WIPP activity (60% of the activity emplaced to date) and it decays with a 14.4 year half-life to ^{241}Am, which is an important radionuclide. The sites are reporting ^{241}Pu now, although not required to do so, and this reporting should continue.

The EEG believes that all ten of the radionuclides should be tracked and reported. Also, ^{241}Pu tracking should be required.

5.2.2 EPA: Other Non-Destructive Assay Issues

EEG has provided opinions on two issues concerning NDA requirements. These are: (1) the EPA requirement that determination of isotopic ratios be on each waste container (rather than on a waste stream); and (2) use of non-WIPP certified instruments to perform waste characterization.

EEG believes justification for less than 100% quantification and determination of isotopic ratios may be possible for <u>some</u>, but certainly not all, waste streams (EEG 2002c).

The DOE has proposed to use non-WIPP certified assay systems used for Safeguards measurements for NDA analysis of WIPP waste. EPA has rejected this DOE proposal. EEG currently agrees with the EPA position. We do not believe that quality control of NDA measurements should be relaxed. Also, it has not been shown that radionuclides other than ^{239}Pu and ^{240}Pu can be reliably determined with these instruments. The EEG has stated:

> EEG believes that quantification of radionuclides and confirmation of isotopic ratios should continue to be obtained as they are now, i.e., by using WIPP-certified NDA systems. These determinations, unlike some other required waste characteristics that cannot be directly measured, can be obtained directly by measurement. Any additional efforts to produce more accurate AK in order to reduce the NDA burden will inevitably result in less accurate radionuclide values (EEG 2002a).

6.0 NRC (TRUPACT-II) TRANSPORTATION REQUIREMENTS

The NRC has extensive payload requirements for shipment of wastes in the TRUPACT-II package. These requirements include:

(1) container and physical properties
(2) nuclear properties
(3) chemical properties
(4) gas generation
(5) payload assembly
(6) quality assurance.

These requirements are specified in detail in the TRUPACT-II TRAMPAC (DOE 2003a). Compliance is through generator or storage site programmatic or waste-specific TRAMPACs. The DOE Carlsbad Field Office (CBFO) is responsible for approving these site-specific TRAMPACs and verifying compliance. The NRC does not become directly involved with this characterization process.

Payload requirements 1 through 4 above include waste characterization requirements. These waste characterization requirements are similar to those required in either the HWFP or in EPA's NDA requirements and are incorporated in these two waste characterization programs.

6.1 TRUPACT-II Container Properties

Most container properties involve weights and listing of acceptable containers. However, there are three container properties that are obtained from waste characterization requirements of the HWFP. These are:

(1) Filter vents are required in each waste container.

(2) Residual liquids shall not be more than 1% of the volume in any payload container. This is verified by RTR, VE, or AK.

(3) Sealed containers greater than four liters (nominal) are prohibited unless in waste material Type II.2 packaged in a metal container. Compliance is determined by RTR, VE, or AK.

6.2 TRUPACT-II Nuclear Properties Characterization

6.2.1 Nuclear Criticality

In order to ensure that nuclear criticality will not occur during shipments it is necessary to limit the FGE in individual waste containers. Requirements in Appendix A of the CH WAC are currently used to satisfy all NRC radioassay requirements even though this is not mandated by the TRAMPAC. This requires quantification of all fissile radionuclides. Although a number of transuranic radionuclides can be fissionable, the most important ones at WIPP are ^{239}Pu, ^{235}U, and ^{233}U. Therefore, it is necessary to determine the quantity of these three radionuclides through the NDA process discussed in Chapter 5. As mentioned in Chapter 5, ^{235}U quantification is not required by the EPA. In many cases the FGE value will be well below allowable container and TRUPACT-II limits and this requirement can be satisfied by AK.

6.2.2. Radiation Dose Rates

External radiation dose rates are limited to 200 millirem per hour at the surface of waste containers. This is a mandatory measurement, but is not a waste characterization requirement.

6.2.3 Decay Heat Limits

Ionization caused by radioactive decay can generate hydrogen gas which must be controlled in the TRUPACT-II. The decay heat value, which is a gas generation requirement, is used in determining the payload shipping category. Decay heat values are calculated from the

radioactivity of each radionuclide in the container. Therefore, it is necessary for the NDA to quantify all significant radionuclides in the waste. The EPA requirements for NDA provide adequate information to determine decay heat values.

6.3 TRUPACT-II Chemical Properties Characterization

Pyrophoric materials are limited to small residual amounts (< 1% by weight). Explosives, corrosives, and compressed gases are prohibited. Chemical composition is required to be known in order to determine gas generating properties. Chemical compatibility is also required by complying with, *A Method for Determining the Compatibility of Hazardous Waste*, (Hatayama and others 1980).

Compliance with the requirements is demonstrated via AK, VE, or RTR. These same criteria are also required under the HWFP, which as noted, requires more robust waste characterization methods (see Chapter 4).

6.4 Gas Generation Requirements

6.4.1 Payload Shipping Category

The payload shipping category determines the decay heat limit that is necessary to ensure that hydrogen gas concentrations will be no more than 5% by volume in the innermost bags within the waste container. In addition to the decay heat value determined from NDA, it is necessary to determine the waste type from the chemical properties and tables of allowed materials. Chemical properties are determined from AK, VE, or RTR. The number of layers of bags in a container, as well as the presence of a rigid liner is both necessary to determine the payload shipping category and these are confirmed by RTR or VE.

6.4.2 Flammable (Gases and VOCs) Concentration Limits

The TRAMPAC also limits the presence of methane and flammable VOCs as well as hydrogen, to ensure the absence of flammable mixtures in TRU waste payloads. The limit of flammable VOCs in the headspace of a waste container is ≤ 500 parts per million.

Procedures for showing compliance with the Gas Generation Requirements can become very complex. If the decay heat limit requirement is met and AK is adequate to verify that the ≤ 500 parts per million flammable VOC requirement can be met, the container falls into the Analytical Category and the requirement can be satisfied by analysis. Otherwise, containers fall into the Test Category.

Test Category containers may be able to show compliance either by measurement of the headspace of payload containers or by Full-Drum Testing. Headspace gas analysis, required in the HWFP, can be used to satisfy the flammable VOC limit requirement.

6.5 EEG Positions on NRC Requirements

The three waste characterization requirements in the Container Properties should be retained. Other changes in Container Properties (primarily specifying appropriate waste containers) would be acceptable if approved by the NRC's Revision Process.

There should not be any changes made in Nuclear Property requirements.

The basic gas generation requirements (hydrogen gas concentrations of < 5% by volume in the innermost bag and flammable VOC concentrations ≤ 500 ppm in the headspace of waste containers) should remain as described in the current version of the TRAMPAC (DOE 2003a). The procedures for showing compliance with the gas generation requirements were quite conservative in the original Certificate of Compliance in 1989. This was because of the lack of sufficient data or demonstration of alternative analytical procedures. There have been many changes in these procedures over the years and it is now possible to show compliance for many waste containers that would not have originally been shippable. EEG has considered this revision process and NRC's evaluations to be an acceptable process. We believe it is appropriate for DOE to continue to propose procedure modifications and that NRC should critically evaluate these before approval.

7.0 THE WIPP CH WAC AND WIPP OPERATIONAL WASTE REQUIREMENTS

7.1 History of the WIPP WAC and Waste Characterization

Waste characterization has been an important consideration for the WIPP since its earliest days. As early as 1976 the WIPP scientific advisor, Sandia National Laboratories, began, "...to gather the diverse input required to establish appropriate criteria," for waste characterization. These were later published in the1980 *Report of the Steering Committee on TRU Waste Acceptance Criteria for the Waste Isolation Pilot Plant*, which was the first of a series of documents referred to as the "WIPP WAC" (DOE 1980). This first WAC contained similar or identical criteria to many of the waste acceptance criteria in the most recent version (DOE 2002a), including elements that are now considered to be HWFP, 40 CFR 194, and TRAMPAC requirements. These include requirements for residual liquids, free water, and free liquids respectively (HWFP, 40 CFR 194, and TRAMPAC), pyrophoric, corrosive, and explosive materials (HWFP, TRAMPAC), compressed gases (HWFP, TRAMPAC), toxic materials (HWFP), waste certification requirements (HWFP, TRAMPAC), physical description of the waste (HWFP, TRAMPAC), combustibility (HWFP TRAMPAC), surface dose rates (TRAMPAC), thermal power (TRAMPAC), container requirements (TRAMPAC, HWFP), and hazardous materials (HWFP). These and other criteria were all included based on internal DOE Order and policy requirements current at that time.

Earlier versions of the WAC contained a discussion of the technical rationale for each criteria and justification to the criteria. The CH WAC no longer includes such rationale or justification. EEG has stated:

> EEG objects to the continued practice of deleting the history and technical justification of criteria when the CH-WAC is revised. Our concern is that a contractor or review group might propose to revise or delete a criteria because they were unaware of the technical basis and that CBFO would too quickly adopt those recommendations. Also, we

> have a concern that future revisions to the CH-WAC may not critically evaluate the need for revised or new requirements that would improve safety at WIPP. EEG, in its role of representing the State of New Mexico in review of the Safety Analysis Report (SAR), will keep this concern in mind during future WAC and SAR reviews (EEG 2002a).

In 1984 DOE Order 5820.2 changed the definition of transuranic from >10 nCi/g of long-lived alpha-emitting waste to >100 nCi/g. Revision 2 of the WAC (DOE 1985) included that definition, but it was not until Revision 3 (DOE 1989) that the definition became a WAC criterion. In 1992, the WIPP Land Withdrawal Act (LWA) included and extended this definition, making it federal law as well as a DOE requirement.

In 1989 the TRAMPAC added criteria and requirements (see previous Chapter), and the NRC became a second regulator of the WIPP waste characterization. To this time the WAC had been the single most important WIPP waste characterization document extant. With first the TRAMPAC, then the applications to the NMED and EPA, and finally the resultant 40 CFR 194 Certification by the EPA (1998) and promulgation of the HWFP (1999), the criteria in the WAC also became less authoritative. The WAC became more the DOE's working version of the criteria included in these other documents.

At the waste characterization level, other more specific requirement documents began at least as early as 1991, implementing the methods used to meet the criteria from these upper-tier documents. In 1979 the INEEL (then INEL) had set up a program to, "...confirm that drums shipped from Rocky Flats contained the assigned item description code (IDC), and to determine the possible hazardous constituents in the waste." (Haily1995). The waste characterization methods of visual examination and gas sampling were used. A 1983-1985 program at the INEL pioneered real-time radiography, headspace gas sampling, solids sampling and analysis, and radioassay (gamma only) in the first attempt to examine waste for compliance with the WAC (Clements and others 1985). Extensive visual examination was also performed. In 1985 neutron NDA—the basic component of current NDA systems–was used in still another INEL program (Hailey 1995).

By 1991 intermediate-level requirements documents were developed by the WIPP. These documents translated the WAC criteria into waste characterization methods and requirements for the transuranic waste generating and storage sites in the DOE complex. The 1995 *Transuranic Waste Characterization Quality Assurance Program Plan* (DOE 1995) included the TRAMPAC waste characterization requirements and also established the waste characterization requirements that the EPA accepted as a part of the 40 CFR 194 certification of the WIPP. This document also contained equivalent methods and requirements to those later promulgated in the WIPP HWFP in 1999 (Channell and Walker 2000).

7.2 Current DOE Waste Acceptance Criteria

The current WAC is for CH TRU waste only (a draft WAC for RH is a part of a DOE submittal currently under evaluation by the EPA for approval of RH TRU waste characterization). Most of the waste characterization criteria found in the CH WAC has been addressed in earlier chapters of this document in one form or another; the remaining area are primarily those self-required by the DOE. As is noted in Section 2.4 of this report, these are primarily from the WIPP site Safety Analysis Report (SAR) (currently DOE 2003c), and more specifically are collected in the Technical Safety Requirements (TSRs) (currently DOE 2003d) which is an attachment to the SAR.

Statements in the TSRs clearly indicate that the WIPP Waste Acceptance Criteria, which drive the waste characterization program, is very important for the safety, health, and environment of the WIPP. The quality and completeness of the waste characterization effort is critically important to WIPP operational activities and some of the requirements are only covered in the CH WAC. It is very important that operational health and safety requirements are constantly evaluated via the TSR portion of the CH TRU SAR and any necessary changes be incorporated in the CH WAC.

The SAR and TSR waste characterization criteria are developed by applying DOE Orders and other DOE internal regulatory documents to the WIPP site. The WIPP TSR criteria include many prohibited wastes that are also prohibited by other WIPP waste characterization

regulations, including the less-than-1% liquids prohibition described in Chapters 4, 5, and 6; the prohibition against pyrophoric materials; prohibition of explosive and compressed gases (Chapters 4 and 6); and the prohibition of RCRA characteristic wastes considered ignitable, corrosive , and reactive (Chapter 4). These criteria can be characterized in the waste by AK, chemical tests (headspace gas or homogeneous analysis) and radiography or visual examination.

The WIPP TSRs add one additional radiological requirement, limiting the plutonium-equivalent activity (PE-Ci) in the waste. The PE-Ci represents a normalization of the radiotoxicity of prominent radionuclides expected to be in the waste to equivalency with ^{239}Pu. To characterize this component of the waste the amounts of these prominent individual radionuclides are necessary. While PE-Ci can be calculated from AK information if the AK contains radioassay values for the radionuclides; these values are currently obtained from the EPA-required assay of each container.

The CH WAC still contains the >100 nCi/g of alpha-emitting transuranic isotopes with half-lives of 20 years criterion, which is also met through the NDA program established to meet the 40 CFR 194 radioassay requirements.

The CH WAC combines the TSR criteria for acceptable waste with those from the HWFP, the TRUPACT-II criteria in the TRAMPAC, and the 40 CFR 194 waste characterization criteria. The waste characterization methods discussed in Chapters 4-6 of this report are used to ensure that these criteria are met.

8. CONCLUSIONS

Waste characterization criteria, requirements/methods, and procedures for WIPP are specified in the DOE Waste Acceptance Criteria, the NRC Certificate for transportation, the EPA Certificate for disposal, and the NMED Hazardous Waste Facility Permit for disposal. EEG has provided a technical review of these measures over many years. Our reviews have considered the need for a requirement as well as whether a proposed change is justified.

The summary below presents EEG's current assessment of the key components of the waste characterization requirements for the more significant requirements/methods. Our views continue to evolve to reflect new information and analyses.

8.1 Overlap of Requirements

Between the four entities, there is considerable overlap in waste characterization requirements. The HWFP and Appendix A of the CH WAC are the more prescriptive for specifying compliance. When considering a requirement change to either of these documents, the effect of the change on all requirements, including those issued by other agencies, should be noted and evaluated for its potential impact across agencies.

8.2 The Change Processes

The DOE, NMED, EPA, and NRC each have different processes for changing the requirements and these vary considerably in the degree of formality and participation by outside organizations. All processes have proved to be workable and effective. The proposed modifications are implemented more effectively and expeditiously if they are considering smaller, less comprehensive changes. The EEG believes that in the future, proposed changes to the waste characterization requirements should continue to use the existing processes.

8.3 Risk Considerations

The radiological risk from routine operations, operational accidents, and long-term releases is orders of magnitude greater than the risk from hazardous waste. Therefore, a risk based approach to waste characterization should concentrate on those requirements that affect the radiological risk.

No data have been provided by the DOE to indicate that exposures to workers performing CH TRU waste characterization are large enough to be a significant reason for reducing waste characterization requirements.

8.4 Acceptable Knowledge Requirement

Acceptable Knowledge is a principal waste characterization technique for all the regulatory agencies. AK is necessary and should be retained. At this time the EEG supports the use of the HWFP AK requirements since they are the most prescriptive.

8.5 Headspace Gas Sampling and Analysis

DOE has indicated that HSG sampling and analysis is one of the most expensive waste characterization requirements and the HWFP requires this be conducted in 100% of all non-thermally treated waste containers. HSG sampling is the primary way DOE has chosen to meet the "detailed chemical analysis…" specified in the New Mexico Administrative Code. Data from HSG sampling is used to verify that VOC concentrations in waste storage rooms meet the Room Based Concentration limits in the HWFP. However, these limits can also be verified by data obtained from the Confirmatory VOC Monitoring Plan in the WIPP underground. Since HSG is required by the HWFP, it is a convenient (but not the only) way of assuring that flammable gas concentration limits in the TRAMPAC are met.

EEG believes it is desirable to maintain a comprehensive HSG program for WIPP CH TRU wastes. However, it should be possible to require less than 100% sampling in some cases. Our primary concerns are with organic sludges and older waste containers where information may be less reliable.

8.6 Drum Age Criteria Requirements

Drum Age Criteria is necessary to ensure that HSG sampling of waste containers will measure gas concentrations that are at least 90% of equilibrium. DAC values are required in both the HWFP and the TRAMPAC. The EEG supports this requirement.

8.7 Real Time Radiography

All WIPP waste containers are required to undergo either radiography or visual examination by the HWFP. Usually retrieved wastes undergo RTR and newly generated wastes are examined by visual examination. RTR has been a very effective means of verifying AK and discovering prohibited items in waste containers. It is also used to show compliance with several EPA and TRAMPAC requirements.

The overall radiography program is an important part of the WIPP waste characterization program and should be retained. It may be possible to reduce some of the detailed procedural requirements in the HWFP.

8.8 Visual Examination/Retrievably Stored Waste

A small fraction (currently less than 2%) of retrievably stored waste is required by the HWFP to undergo visual examination for confirmation of RTR. The VE process has the potential for slightly greater radiation exposure than the other waste characterization requirements, although the EEG has not been provided any data from the DOE to indicate that exposures are significant enough to justify reducing the requirement.

The DOE has been successful in modifying the HWFP on retrievably stored visual examination and this would be the preferred process for seeking further reductions.

8.9 Visual Examination/Newly Generated Waste

VE is the method DOE prefers for newly generated waste because it can be done at the time the waste container is being filled. The EEG has not objected to any part of this requirement except to state that the requirement for two trained VE operators to perform the visual process “may be overkill” and that a single verification should be adequate.

8.10 Solids Coring and Sampling and Solids Analysis

The EEG continues to believe that the homogeneous sampling and analysis are unnecessary waste characterization requirements in the HWFP. Our principal reason for this position is that the data are not used for any additional regulatory control (metals releases from accidents or long-term processes would be controlled by radionuclide control requirements and VOCs and SVOCs by HSG or the Confirmatory VOC Monitoring Plan).

8.11 Level II Management and Waste Certification HWFP Requirements

The DOE has listed these management and certification requirements as characterization activities in a recent cost analysis. EEG has not previously commented on these requirements. However, our current evaluation indicates that the required procedures are very detailed and somewhat redundant. This may be one of the areas to which the general EEG comment, "We believe waste characterization requirements are excessive," applies.

8.12 Characterization Support HWFP Requirements

EEG has been supportive of the WIPP audit and surveillance program and has observed it to be a very good QA program. The EEG does not believe the relaxation of audit requirements and QA/QC is an appropriate way to reduce the regulatory burden.

8.13 EPA Non-Radiological Requirements

EPA's free water, non-ferrous metal and cellulose, plastic and rubber requirements should remain and can continue to be determined as they are now, by the RTR/VE requirements of the HWFP. However, the required CPR data could be provided to EPA on a waste stream rather than individual container basis. The ferrous metal requirement can continue to be met by counting waste containers emplaced in the repository.

8.14 EPA Radiological Requirements

The EEG agrees with the radioassay requirements for contact-handled transuranic waste specified in Appendix A of the CH WAC and the current procedures for modifying the document.

Current requirements for reporting the 10 required radionuclides should remain. The EEG recommends that ^{241}Pu be added to the list of EPA tracked radionuclides. The current requirement that all radioassay should be performed by WIPP-certified assay systems should be maintained.

Justification for less than 100% quantification and determination of isotopic ratios may be possible for some, but certainly not all, waste streams.

8.15 NRC Container Properties

The TRAMPAC requirements for residual liquids, filter vents, and the sealed container prohibition should be retained. These are all verified by requirements in the HWFP.

8.16 NRC Nuclear Properties

All nuclear property requirements should be retained and the methodology in Appendix A of the CH WAC should be used.

8.17 NRC Gas Generation Requirements

Requirements for measuring the chemical, payload classification, and radionuclide concentrations necessary to ensure hydrogen gas concentration criteria are met must be retained. There have been many changes, via the revision process, which have allowed additional containers to be shipped without changing the hydrogen gas criteria and additional changes may be justifiable in the future.

The flammable gas concentration limit of ≤ 500 ppm should be retained as described in the current revision of the TRAMPAC. Alternate methods (with appropriate QA) will be necessary if future changes to the HWFP affects the use of HSG sampling as the method for meeting this criteria.

8.18 WIPP Waste Acceptance Criteria

The WAC has served a useful historic purpose in developing initial criteria that have been adopted by the three regulatory agencies. Currently it is a useful document for listing most of the characterization requirements. It would be more useful if the technical justification for each criteria or requirement were restored.

The unique role of the CH WAC in including any necessary operational safety and health requirements not included elsewhere is very important and must be constantly evaluated via the TSR portion of the CH TRU SAR, and any necessary changes incorporated into the CH WAC.

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APPENDIX B

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CARLSBAD FIELD OFFICE

QUALITY ASSURANCE PROGRAM DOCUMENT

DOE/CBFO-94-1012

REVISION 5

May 2003

U.S. DEPARTMENT OF ENERGY
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QUALITY ASSURANCE PROGRAM DOCUMENT

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REVISION 5

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U.S. DEPARTMENT OF ENERGY
CARLSBAD FIELD OFFICE

U.S. DEPARTMENT OF ENERGY

CARLSBAD FIELD OFFICE

QUALITY ASSURANCE PROGRAM DOCUMENT

DOE/CBFO-94-1012

REVISION 5

Prepared by: _____ **Date:** 5/14/03
QA Manager, CBFO

Approved by: _____ **Date:** 5/16/03
Manager, CBFO

POLICY STATEMENT

The mission of the Carlsbad Field Office (CBFO) is to protect human health and the environment by opening and operating the Waste Isolation Pilot Plant (WIPP) for safe disposal of transuranic (TRU) waste and by establishing an effective system for management of TRU waste from generation to disposal.

To help fulfill this mission and to ensure that the risks and environmental impacts are identified and minimized and that safety, reliability, and performance are optimized, it is the policy of the CBFO to establish, implement, and maintain an effective quality assurance (QA) program that supports compliance with applicable Federal, State, and local regulations and U.S. Department of Energy (DOE) orders and requirements.

Further, it is the intent of the CBFO to establish a culture and work environment that encourages setting and maintaining effective standards, identifying and resolving problems, emphasizing a continual pursuit of improvement, and fostering mutual respect and effective communication within the CBFO and among its participants, their suppliers, the public, and other stakeholders.

The *CBFO Quality Assurance Program Document* (QAPD) establishes QA program requirements for all quality-affecting programs, projects, and activities sponsored by the CBFO. The CBFO and organizations supporting the CBFO shall implement the applicable requirements of this QAPD within their systems for management and control of these activities.

It is the responsibility of all personnel assigned to CBFO-sponsored activities to achieve quality, identify problems, and recommend improvements. CBFO organizations define and achieve quality, recommend and promote improvements in the quality of items and processes, and identify, document, and resolve problems. CBFO quality assurance organizations verify the achievement of quality. CBFO management establishes and cultivates principles and practices that integrate QA program requirements and performance standards into their management approach and control systems. Additionally, CBFO management provides personnel who perform work with the proper qualifications, training, resources, oversight, and support to achieve the CBFO organizational and mission objectives.

The CBFO QA program requirements, as described in this QAPD, have my full endorsement and complete support. Implementation of the applicable QAPD requirements, responsibilities, and authorities is mandatory for all CBFO personnel.

In support of this policy statement, all CBFO personnel are expected to demonstrate their personal commitment to the achievement of quality through their active involvement in the implementation of the CBFO QA program.

Inés Triay

Dr. Inés Triay
Manager, Carlsbad Field Office

5/16/03
Date

CHANGE HISTORY

Revision:	Changes to the QAPD
Rev 1	The QAPD has been substantially rewritten, the structure has been reorganized, and the content has been supplemented to broaden its scope from a CAO internal requirements and participant guidance document to a CAO program-wide requirements document. The document elements that defined the extent of applicability regarding specific QA program requirements have been clarified through the identification of "general" and "additional" requirements. Requirements for the grading of management controls have been clarified and more fully developed. The requirement for Sandia National Laboratories (SNL) and Westinghouse Waste Isolation Division (WID) QAPD's was deleted. A requirement was added for each organization to prepare, submit for review, and maintain a QA implementing procedures matrix. Revisions were made to incorporate all the requirements of 40 CFR Part 194, ANSI/NCSL Z540-1, and stakeholder comments. The use of the terms "will" and "shall" are interchangeable and denote requirements. Editorial changes were made throughout.
Rev 2	The section describing the organization and responsibilities for CAO personnel have been deleted from section 1 and incorporated into a policy statement (Appendices C and D). The QA program document hierarchy (Table I-1), has been updated to reflect current regulatory requirements commitment and guidance documents. Requirements have been clarified in the areas of 1) grading, 2) the control of conditions adverse to quality, and 3) the preparation and maintenance of document review comments. Section 6.0, *Software,* has been rewritten to include both general and additional requirements. Definitions in the glossary have been added, deleted, and clarified. Editorial changes have been made throughout the document.
Rev 3	Changes in Revision 3 have been limited to those necessary to achieve full compliance with the Waste Analysis Plan (WAP) in the WIPP Hazardous Waste Facility Permit and to incorporate certain TRU waste QA requirements contained in the CAO QAPP, which is to be inactivated. Refer to the following list of pages affected by Revision 3.

List of Pages Affected by QAPD Revision 3

Change History	iv to v
Table of Contents	vi to xii
List of Acronyms	xiii to xiv
Introduction	I-1 to I-2
Section I - Management	1-1 to 1-23
Appendix A - Glossary	A-1 to A-10
Appendix B - References	B-1
Appendix C - CAO Organization	C-1 to C-2
Appendix D - CAO QA Manager Responsibilities	D-1 to D-2
Appendix E - TRU Sites Organization	E-1 to E-4

The pages in Revision 3 that are not listed above (Sections 2.0 through 6.0) remain effective.

Rev 4 The changes in Revision 4 were made to incorporate the DOE name change from the Carlsbad Area Office (CAO) to the Carlsbad Field Office (CBFO) and reflect current CBFO organization titles and responsibilities, rewrite the Quality Improvement section, update the source requirements documents listed in Table I-1, make changes to capture the wording used in the requirements documents, add more specific detail to the QA functional responsibilities of the CBFO management, and eliminate divisions between “general requirements” and “additional requirements.” Editorial, formatting, and paragraph number changes have been made throughout the document. Change markings are present for those revisions that affect content. Changes related to editorial and formatting revisions are not marked. Technical revisions were made to the following specific sections:

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1.1.2.2	Procedures Matrix	1-5
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1.1.2.4	Grading Items and Activities and Applying Management Controls	1-6
1.2.1	Qualification Requirements	1-8
1.2.2	Training Requirements	1-8
1.3	Quality Improvement	1-9 to 1-15
1.4.B	Documents	1-15
1.5.2	Generating QA Records	1-17 to 1-18

1.5.4	Classifying QA Records	1-19 to 1-20
1.5.6.1	Records Classification and Disposition	1-22
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3.2.A	Independent Assessment	3-1
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5.4	Qualification of Existing Data	5-4 to 5-6
5.5	Quality Assurance Compliance Data (new section)	5-6
Appendix A	Glossary	A-1 to A-2, A-5 to A-7, A-9 to A-10
Appendix C	CBFO Organization, Responsibilities, and Interfaces	C-1
Appendix D	CBFO Quality Assurance Manager Responsibilities	D-1 to D-2
Appendix E	TRU Waste Characterization and Certification Organizational and Individual Responsibilities	E-1

Rev 5

The changes in revision 5 were made to address an EPA finding from the annual EPA QA audit conducted on January 7 – 9, 2003. This finding concerned the language in the QAPD regarding the responsibilities for achievement and verification of quality not matching the requirements from NQA-1. In addition to the change made to address the EPA finding, the following changes were made:

- The requirement for program participants to maintain a QAPD procedures matrix has been deleted; because this matrix is not required by NQA-1, 2, or 3, or other regulatory document.
- The requirement for organizations receiving records to return a receipt acknowledgment to the sender has been deleted, because this also is not required by NQA-1, 2, or 3, or other regulatory document.
- The requirement that CBFO and participant organization ensure

that they comply with the Federal Acquisition Regulations was deleted because the QAPD is not the appropriate document to specify this requirement.

- The requirement to maintain records related to the characterization of the mixed transuranic waste form as lifetime QA records was deleted. Records classification of mixed waste characterization records is specified in the Hazardous Waste Facility Permit.
- The requirement to maintain audit and surveillance checklists as QA records was deleted, because this is not a requirement of NQA-1, 2, or 3, or other regulatory document.
- The requirement for calibration laboratories to comply with ANSI/NCSL Z540-1 was deleted because this is not a requirement of NQA-1, 2, or 3, or other regulatory document.
- The safety analysis report for the HalfPACT shipping package was added as a regulatory source document to Table I-1
- Section 5.5 was deleted. The requirements for data quality evaluation during scientific investigation planning are addressed in Section 5.1.G of the QAPD. Section 5.5 was redundant and specified requirements for the content of compliance applications, which was not appropriate for the QAPD.
- Changes were also made to correct typographical errors and incorrect section references.

Technical revisions were made to the following specific sections:

Section	Section Title
	Policy Statement
	Introduction
1.1.1	Organization
1.1.1.1.D	Management
1.1.1.3	Quality Assurance Management
1.1.2.2	Procedures Matrix (deleted)
1.2.1	Qualification Requirements
1.3.2.5	Disposition of Nonconforming Items or Data
1.5.4.B and E	Classifying QA Records
1.5.6.A	Storage, Preservation, Safekeeping, and Disposition of QA Records
2.1.B	Work Processes
2.3	Procurement
2.3.4	Procurement Document Requirements
2.4.6	Use and Control of M&TE

2.4.7	Calibration
3.2.2.10	Audit Records
Appendix C	CBFO Organization, Responsibilities, and Interfaces
Appendix D	CBFO Quality Assurance Manager Responsibilities

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LIST OF ACRONYMS AND ABBREVIATIONS

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASNT	American Society of Nondestructive Testing
ASTM	American Society for Testing and Materials
CAP	Corrective Action Plan
CAQ	Condition Adverse to Quality
CAO	Carlsbad Area Office
CBFO	Carlsbad Field Office
CFR	Code of Federal Regulations
DQO	Data Quality Objective
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FRC	Federal Records Center
HWFP	Hazardous Waste Facility Permit
M&DC	Monitoring and Data Collection Equipment
M&TE	Measuring and Test Equipment
M&O	Management and Operating Contractor
NARA	National Archives and Records Administration
NDE	Nondestructive Examination
NEPA	National Environmental Policy Act
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NMED	New Mexico Environment Department
NQA	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
NTP	National TRU Program
NUREG	Nuclear Regulatory Commission Report designation

QA	Quality Assurance
QAPD	Quality Assurance Program Document
QAPjP	Quality Assurance Project Plan
QAPP	Transuranic Waste Characterization Quality Assurance Program Plan (CAO-94-1010)
QC	Quality Control
RIDS	Records Inventory and Disposition Schedule
SCAQ	Significant Condition Adverse to Quality
SNL	Sandia National Laboratories
SQA	Software Quality Assurance
TRAMPAC	TRUPACT-II Authorization Methods for Payload Control
TRU	Transuranic
TRUPACT-II	Transuranic Package Transporter, Model II
UL	Underwriter's Laboratory
WAP	Waste Analysis Plan
WID	Westinghouse Waste Isolation Division
WIPP	Waste Isolation Pilot Plant
WTS	Washington TRU Solutions

INTRODUCTION

The Carlsbad Field Office (CBFO) Quality Assurance Program Document (QAPD) is the document that describes and establishes the CBFO Quality Assurance (QA) program. The provisions of this QAPD apply to all programs and projects managed by the CBFO which require a QA program, including activities related to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the Waste Isolation Pilot Plant (WIPP) facility. This document identifies the sources of all applicable QA program requirements. The subject requirements are based on criteria contained, or incorporated by reference, in source documents listed in Table I-1. These documents have been placed into one of three categories:

A. Regulatory documents, including those incorporated by reference, that define the requirements necessary for the WIPP to be granted a certificate of compliance by the Federal Government and permit(s) by State governmental agencies to dispose of transuranic (TRU) and mixed TRU wastes in the WIPP repository, or that define requirements applicable to the management of the WIPP as a U.S. Department of Energy (DOE) non-reactor nuclear facility

B. Commitment documents that are imposed by DOE management

C. Guidance documents that provide additional information that is useful in developing and implementing the CBFO QA program

The purpose of the QAPD is to describe the applicability and requirements of the CBFO QA program as applied within the CBFO management infrastructure. In this context, the management infrastructure includes all CBFO program participants (e.g., Sandia National Laboratories [SNL] as Science Advisor; Washington TRU Solution [WTS] as the Management and Operating [M&O] contractor of the WIPP, and various DOE organizations and contractors performing work under the direction of the CBFO). This program is developed and maintained through an ongoing process that selectively applies the varied QA program criteria. This process provides due consideration to the extent of source requirement applicability, a graded-approach, available guidance, and the current foreseeable activities expected to be performed under the direction of CBFO.

The requirements in this QAPD are based on the principle that work shall be planned, documented, performed under controlled conditions, and periodically assessed to establish work item quality and process effectiveness and to promote improvement. Management, line personnel, and organizations are responsible for planning and achieving quality and for promoting continuous improvement. Quality assurance organizations and personnel are responsible for the verification of the achievement of quality. This QAPD further delineates the quality contributions expected of all

personnel and encourages their active participation in implementing the CBFO QA program.

Table I-1 QA Program Source Documents

MAJOR REGULATORY REQUIREMENTS DOCUMENTS	TITLE
10 CFR Part 21	Reporting of Defects and Nonconformances
10 CFR Part 71	Packaging and Transportation of Radioactive Material
10 CFR Part 830	Nuclear Safety Management
40 CFR Part 191	Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes
40 CFR Part 194	Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations
ASME NQA-1-1989 (incorporated by reference in 40 CFR Part 194)	Quality Assurance Program Requirements for Nuclear Facilities
ASME NQA-2a-1990 addenda, Part 2.7 (incorporated by reference in 40 CFR Part 194)	Quality Assurance Requirements of Computer Software for Nuclear Facility Applications
ASME NQA-3-1989 excluding Section 2.1 (b) and (c) and Section 17.1 (incorporated by reference in 40 CFR Part 194)	Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Nuclear Waste Repositories
NM 48901 39088 – TSDF/WIPP	WIPP Hazardous Waste Facility Permit
NRC Docket 71-9212	RH-TRU 72-B Safety Analysis Report
NRC Docket 71-9218	TRUPACT-II Safety Analysis Report
NRC Docket 71-9279	HalfPACT Safety Analysis Report
NUREG-1297 (1988) (incorporated by reference in 40 CFR Part 194)	Peer Review for High-Level Nuclear Waste Repositories
COMMITMENT DOCUMENTS	**TITLE**
DOE O 414.1a, Change 1	Quality Assurance
SNT-TC-1A-1980	American Society of Nondestructive Testing (ASNT) "Recommended Practice No. SNT-TC-1A, Personnel Qualification and Certification in Nondestructive Testing," August 1980
GUIDANCE DOCUMENTS	**TITLE**
DOE, G-414.1-2	Quality Assurance Management System Guide for Use with 10 CFR Part 830.120 and DOE O 414.1
NUREG/BR-0167 (1993)	Software Quality Assurance Program and Guidelines

SECTION I – MANAGEMENT REQUIREMENTS

This section describes the fundamental elements related to the organization and management of the CBFO QA program, as well as the fundamentals to be applied in managing the work of the program.

1.1 ORGANIZATION AND QUALITY ASSURANCE PROGRAM

This section describes the requirement for the organizational structure, primary interfaces, functional responsibilities, and levels of authority required to implement the CBFO QA program. In addition, this section describes the basic elements of the QA program and their applicability.

1.1.1 Organization

Effective implementation of the CBFO QA program is dependent on the efforts at all levels of the program participants. The organizational structures and the responsibility assignments of program participants shall be such that those organizations that have been assigned responsibility for performing the work are responsible for achieving and maintaining quality. Management is responsible for defining quality, developing appropriate plans to attain quality, and supporting the workers in pursuit of quality. QA organizations of the program participants are responsible for verifying the achievement of quality in the implementation of the CBFO QA program. CBFO organizational and individual responsibilities are addressed in Appendices C and D. Organizational and individual responsibilities for TRU waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility are addressed in Appendix E.

1.1.1.1 Management

A. Management has overall responsibility for successfully accomplishing activities subject to this QAPD. Management provides the necessary planning, organization, direction, control, resources, and support to achieve their defined objectives. Management is responsible for planning, performing, and improving the work.

B. Management is responsible for establishing and implementing policies, plans, and procedures that control the quality of work, consistent with the provisions of this QAPD.

C. Management quality responsibilities include:

1. Ensuring that adequate technical and QA training is provided for personnel performing activities subject to this QAPD

2. Ensuring compliance with all applicable regulations, DOE orders and requirements, and applicable Federal, State, and local laws

3. Ensuring that personnel adhere to procedures for the generation, identification, control, and protection of QA records

4. Exercising the authority and responsibility to stop unsatisfactory work such that cost and schedule do not override environmental, safety, or health considerations

5. Developing, implementing, and maintaining plans, policies, and procedures that implement this QAPD

6. Identifying, investigating, reporting, and correcting quality problems

D. Quality achievement is the responsibility of those performing the work. Line organizations are responsible for achieving quality in their areas.

E. Management empowers employees by delegating authority and decision making to the lowest appropriate level in the organization.

1.1.1.2 Employees

Each program participant employee is responsible for the quality of his or her work and for promptly reporting all existing, developing, or potential conditions adverse to quality to the responsible management for evaluation and action.

1.1.1.3 QA Management

An organization's QA management has the authority and overall responsibility to independently assess the organization's effective implementation of the QA program to verify the achievement of quality.

A. QA management shall:

1. Schedule and conduct QA assessments

2. Maintain liaison with participant QA organizations and other affected organizations

3. Ensure preparation, review, and issuance of QA plans and procedures that implement the provisions of this QAPD

4. Review and approve supplier and subcontractor QA plans

5. Track or perform trend analysis of quality problems, and report quality problem areas

6. Provide for the administrative processing of documentation concerning conditions adverse to quality

7. Have direct access to responsible management at a level where appropriate action can be effected

8. Be sufficiently independent from cost and schedule considerations

9. Have the organizational freedom to communicate with management

10. Have no assigned responsibilities unrelated to the QA program that would prevent appropriate attention to QA matters

11. Develop, establish, and interpret QA policy and ensure effective implementation

12. Interface, as appropriate, with the CBFO staff, participants, and other stakeholders on QA matters

13. Assist subordinate organizations with quality planning, documentation, quality measurement, and problem identification and resolution

14. Provide guidance to all applicable subordinate organizations concerning identification, control, and protection of QA records

B. The QA organization shall have sufficient authority, access to work areas, and organizational freedom to:

1. Identify quality problems

2. Recommend solutions

3. Verify implementation of solutions

4. Ensure that unsatisfactory conditions are controlled until proper disposition has occurred

1.1.1.4 Communication and Interface Responsibilities

A. Communication Responsibilities

Participating organizations at all management levels shall establish communication channels that provide timely and wide dissemination of information pertinent to quality performance, such as:

1. The status of development and implementation of the QA program

2. The status and resolution of significant quality problems

3. The lessons learned from significant quality problems and adverse conditions

4. Quality management practices and improvements

5. Trend analysis results

B. Interface Responsibilities

1. Where more than one organization is involved in the execution of activities covered by this QAPD, the responsibility and authority of each organization shall be clearly established, defined, and documented. The external interfaces between organizations, the internal interfaces between organizational units, and interface changes shall be documented. Interface responsibilities shall be defined and documented and shall include the requirements for management, performance, and assessment.

2. CBFO-sponsored activities, performed by organizations external to the CBFO, include, but are not limited to, compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility. Responsible CBFO organizations shall ensure the effective implementation of the CBFO QA program.

1.1.1.5 Delegation of Work

Individuals or organizations responsible for establishing, planning, accomplishing, and assessing the work may delegate work to other individuals or organizations. However, the individuals or organizations making the delegation shall retain overall responsibility for the delegated work.

1.1.1.6 Resolution of Disputes

Differences of opinion involving the definition and implementation of QA program requirements will be brought to the attention of the appropriate QA manager and the responsible manager. If not resolved, the issues will be elevated progressively to successively higher levels of management as necessary.

1.1.2 Implementation of the CBFO QA Program

1.1.2.1 Quality Assurance Program Documents

Program participants shall develop and follow plans and procedures that effectively implement the requirements described in this QAPD along with those requirements contained within the Resource Conservation and Recovery Act (RCRA) Permit Waste Analysis Plan (WAP), Quality Assurance Project Plans (QAPjPs), Certification QA Plans, Waste Acceptance Criteria (WAC), and TRUPACT-II Certification of Compliance, including TRUPACT-II Authorized Methods for Payload Control (TRAMPAC), as applicable.

1.1.2.2 Applicability of QAPD Requirements

The terminology “items or activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility” is used generically throughout this QAPD to refer to the following:

A. WIPP site activities or operations that process or store radioactive liquid or solid waste, perform waste management activities involving radioactive materials, or design, manufacture, or assemble items for use with radioactive materials in such a form and quantity that a nuclear hazard exists

B. Waste characterization activities

C. Environmental monitoring, monitoring the performance of the disposal system, and sampling and analysis activities

D. Field measurements of geological factors, ground water, meteorology, and topography

E. Computations, codes, models, and methods used to demonstrate compliance with disposal regulations

F. Expert judgment elicitation to support applications for recertification or determination of compliance

G. Design of the disposal system and actions taken to ensure compliance with design specifications

H. The collection of data and information used to support compliance application(s) and/or any modifications to the compliance application

I. Other systems, structures, components, and activities important to the isolation of waste in the disposal system

J. Those items and activities related to Nuclear Regulatory Commission (NRC) licensed packaging (e.g., Transuranic Package Transporter Model II [TRUPACT-II]), design, purchase, fabrication, handling, shipping, storage, cleaning, assembly, inspection, testing, operation, maintenance, repair, and modification or components of packaging that are important to safety

1.1.2.3 Grading Items and Activities and Applying Management Controls

A. The graded approach is the process by which the level of analysis, documentation, verification, and other controls necessary to comply with QA program requirements are developed commensurate with the following factors:

1. The importance of an item or activity with respect to safety, waste isolation, and regulatory compliance

2. The importance of the data to be generated

3. The need to demonstrate compliance with specific regulatory design and QA requirements

4. The impact on the results of performance assessments and engineering analyses

5. The magnitude of a hazard or the consequences of failure

6. The life-cycle stage of a facility or item

7. The programmatic mission of a facility

8. The particular characteristics of a facility, item, or activity (e.g., complexity, uniqueness, history, or the necessity for special controls or processes)

9. The relative importance of radiological and non-radiological hazards

B. The extent of management and QA controls applied to an item or activity will vary as a function of the degree of confidence needed to achieve the desired quality of the item or activity. The grading process provides the flexibility to design and implement controls that best suit the facility or activity. Each organization should develop their own method to determine that the defined grading process is effective. The use of the graded approach shall determine the appropriate level of controls necessary to manage the items, systems, and activities necessary to ship TRU waste to WIPP.

C. Grading methods for each organization shall provide for:

   1. The assignment of management and QA control levels

   2. The definitive criteria used in selecting those levels

   3. Detailed descriptions of the management and QA control provisions corresponding to those levels, based on the above requirements

D. Program participant procedures that establish and implement a graded approach for items and activities under the cognizance of the CBFO shall be submitted to the CBFO QA Manager for approval for use in CBFO programs.

1.1.2.4 Planning Work

Planning shall be performed and documented to ensure that work is accomplished under suitably controlled conditions. As appropriate, planning elements shall include:

A. Definition of work scope, objectives, and a listing of the primary tasks involved

B. Identification of scientific approaches or technical methods used to collect, analyze, or study results of applicable work

C. Identification of field and laboratory testing standards and quality criteria

D. Identification of applicable implementation documents (appropriate nationally recognized standards shall be used whenever possible)

E. Identification of field and laboratory testing equipment or other equipment

F. Identification of, or provisions for the identification of, required records and the recording of objective evidence of the results of the work performed

G. Identification of prerequisites, special controls, specific environmental conditions, processes, or skills

H. Identification of computer software

1.1.2.5 Peer Reviews

Peer reviews performed in support of WIPP compliance activities shall be documented, as shall all peer review processes. Peer reviews of the following activities shall be conducted in a manner consistent with NUREG-1297, *Generic Technical Position on Peer Review for High-Level Nuclear Waste Repositories:*

A. Conceptual models selected and developed by the DOE

B. Waste characterization analysis as required in 40 CFR § 194.24(b)

C. Engineered barrier evaluation as required in 40 CFR § 194.44

1.2 PERSONNEL QUALIFICATION AND TRAINING

Personnel shall be trained and qualified to ensure they are capable of performing their assigned tasks and to ensure that job proficiency is maintained.

1.2.1 Qualification Requirements

Qualification requirements for CBFO and participant positions or job functions shall be established for activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility. The evaluation shall be documented. At a minimum, these positions include managers, designers, scientists, independent assessment personnel, operators, maintenance personnel, technicians, and inspectors.

The responsible organization shall:

A. Analyze each job position to determine the task responsibilities of the position subject to the QAPD. The analysis shall identify minimum education, experience, and training prerequisites for each position involved in the planning, performance, or verification of activities subject to the QAPD, commensurate with the scope, complexity, and nature of the work.

B. Ensure that personnel selected to perform or verify activities subject to the QAPD have education, experience, and training commensurate with the minimum requirements specified. The qualification of an individual shall be based upon evaluation of education and experience, which is compared to the established requirements for the position.

1.2.2 Training Requirements

CBFO and participant personnel performing activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility shall receive related training in accordance with the following requirements. Training shall emphasize the correct performance of work, describe why the applicable quality and nuclear safety requirements exist, and describe the fundamentals of the work and the context. Training shall be subject to ongoing review to determine instruction and training program effectiveness and shall be upgraded whenever needed improvements or enhancements are identified. Management shall:

A. Ensure that personnel receive indoctrination and training, including on-the-job and hands-on training, as needed, to achieve initial proficiency; maintain proficiency; and adapt to changes in technology, methods, job responsibilities, and quality assurance implementing procedures, prior to performing any tasks subject to the QAPD

B. Ensure that personnel receive indoctrination in the following:

   1. General criteria, including applicable QA plans, codes, regulations, and standards

   2. Specific criteria, including applicable QAPjPs and implementing procedures

C. Ensure that records generated during qualification, general indoctrination and training, or specific skill training activities are collected and maintained as QA records.

1.3 QUALITY IMPROVEMENT

Quality improvement is a management process carried out to improve items, services, products, or processes. All aspects of work that affect quality and the management system are subject to continuous improvement through assessment and feedback processes.

1.3.1 Quality-Affecting Problems

Quality-affecting problems and items, services, and processes that do not meet established requirements shall be identified, documented, reported, controlled, and corrected. Quality problems may be identified by the organization or by an external source.

1.3.1.1 Problem Identification

All personnel shall be responsible for identifying quality problems and shall be encouraged by management to suggest improvements. CBFO and participant organizations foster a “no-fault” attitude for quality problems and prioritize and focus resources on preventive actions and on those quality problems that have the greatest potential for:

A. Posing adverse risks to the environment and human health

B. Adversely impacting the quality, safety, and reliability of waste operations

C. Affecting the ability to meet quality requirements

1.3.1.2 Problem Types

Quality-affecting problems may involve:

A. Noncompliance with a QA program requirement. A noncompliance is classified as a Condition Adverse to Quality (CAQ) or Significant Condition Adverse to Quality (SCAQ)

B. Nonconforming items, including suspect/counterfeit items or data, that do not conform to specified requirements.

1.3.2 Nonconformances

Items or data that do not conform to established requirements shall be controlled to prevent inadvertent installation or use.

1.3.2.1 Documenting and Evaluating Nonconforming Items

The documentation and evaluation of nonconforming items shall be accomplished by:

A. Clearly identifying and describing the characteristics that do not conform to specified criteria

B. Reviewing nonconformance documentation and proposed recommended disposition of the nonconforming item or data. The review shall include a determination of the need for corrective action in accordance with the requirements of Section 1.3.3, *Corrective Action*. In addition, organizations affected by the nonconformance shall be notified.

C. Evaluating and approving of recommended dispositions

D. Ensuring that personnel performing evaluation or recommending disposition have demonstrated competence in the specific area they are evaluating or dispositioning, and have an adequate understanding of the requirements

E. Implementing procedures that specify the responsibility and authority for reviewing, evaluating, approving the disposition, and closure of the nonconformance

1.3.2.2 Identifying Nonconforming Items or Data

A. Nonconforming items shall be physically identified by marking, tagging, segregation, or other methods that do not adversely affect the end use. The identification shall be legible and easily recognizable, and shall be traceable to the reporting documentation.

B. If physical identification of each nonconforming item is not practical, the container, package, or segregated storage area, as appropriate, shall be physically identified as in A above.

1.3.2.3 Reporting Nonconformances

Organizations affected by a nonconformance shall be notified. The QA Manager and the National TRU Programs Assistant Manager, CBFO shall be notified in writing within 5 calendar days of identification of any non-administrative nonconformance related to applicable requirements specified in the WIPP Hazardous Waste Facility Permit (HWFP) Waste Analysis Plan (WAP), which is first identified at the site project manager's signature release level (i.e., a failure to meet a data quality objective [DQO]). Notification is also required if the results of the confirmatory analytical techniques specified in the Permit Attachment B are inconsistent with acceptable knowledge documentation. The nonconformance report shall be submitted to CBFO within 30 calendar days of identification of the deficiency.

1.3.2.4 Segregating Nonconforming Items

A. Further processing, delivery, installation, or use of nonconforming items shall be controlled pending the evaluation and approval of the disposition.

B. Nonconforming items shall be segregated, when practical, by placing them in a clearly identified and designated hold area until properly dispositioned.

C. If segregation is impractical or impossible due to physical condition, other precautions shall be employed to preclude inadvertent use.

1.3.2.5 Disposition of Nonconforming Items or Data

The disposition of nonconforming characteristics shall be accomplished as follows:

A. The nonconformance characteristics shall be reviewed, and recommended dispositions of nonconforming items or data shall be proposed and approved in accordance with documented procedures. Personnel performing evaluations to determine a disposition shall have demonstrated competence in the specific area they are evaluating, have adequate understanding of the requirements, and have access to pertinent background information.

B. The dispositions “use-as-is,” “reject,” “repair,” or “rework” for nonconforming items or data shall be identified and documented.

C. The technical justification for the acceptability of a nonconforming item or data that has been dispositioned “use-as-is” or “repair” shall be documented.

D. Items that do not meet original design requirements that are dispositioned “use-as-is” or “repair” shall be subject to design control measures commensurate with those applied to the original design, and

   1. If changes to the specifying document are required to reflect the as-built condition, then the disposition shall require action to change the specifying document to reflect the accepted nonconformance.

   2. Any document or QA record change required by the disposition of the nonconformance shall be identified in the nonconformance documentation and, when a document or record is changed, the justification for the change shall reference the nonconformance documentation.

E. The disposition of an item to be reworked or repaired shall contain a requirement to re-examine (inspect, test, or examine by nondestructive examination) the item to verify acceptability. Repaired or reworked items shall be re-examined using the original process and acceptance criteria unless the nonconforming item disposition has established alternate acceptance criteria.

1.3.2.6 Quality Trending of Nonconformances

Nonconformance documentation shall be periodically analyzed by the QA organization to identify quality trends in accordance with Section 1.3.3, *Corrective Action*.

1.3.3 Corrective Action

1.3.3.1 Identifying Conditions Adverse to Quality (CAQ)

A CAQ occurs when a QA requirement has not been met.

1.3.3.2 Classification of Conditions Adverse to Quality

Classification of CAQs is based on the effect the CAQ has on compliance to regulatory requirements for safety, operability, TRU waste characterization, TRU waste site certification, TRU waste containment, and the effective implementation of the QAPD. Any CAQ that is determined to be noncompliant with an HWFP condition or requirement shall be treated as an SCAQ.

1.3.3.3 Conditions Adverse to Quality

A. CAQs shall be documented and reported to the appropriate levels of management responsible for the condition and to the QA organization for tracking.

B. Responsible management shall determine the extent and impact of the adverse condition and, at a minimum, complete remedial action as soon as practical.

1.3.3.4 Significant Conditions Adverse to Quality

A. Implementing documents shall include criteria for determining if a condition adverse to quality is significant. These criteria shall be based on the criteria in the definition of conditions adverse to quality included in Appendix A.

B. SCAQs shall be investigated, documented (including the extent of the condition and the impact on completed work), and reported to the management responsible for the condition, their senior management, and the QA organization for tracking.

C. Responsible management shall determine when an SCAQ related to the WIPP HWFP (i.e., a waste characterization process currently certified by the CBFO at a TRU waste site) requires accelerated corrective action. The required time interval for accelerated corrective action shall be established by the CBFO QA Manager.

1.3.3.5 Corrective Action Planning

Corrective action plans (CAPs) are required for all SCAQs. SCAQ CAPs shall address:

A. Remedial Action: actions necessary to resolve the initial problem
B. Investigative Actions: assessment of the extent and impact of the SCAQ
C. Root Cause Determination: identification of the root cause of the SCAQ
D. Actions to Preclude Recurrence: actions necessary to prevent recurrence of the SCAQ
E. Schedule: milestones for completion of the CAP, including expected completion dates and identification of responsible individuals

1.3.3.6 Work Suspension

If a work suspension condition has been identified, responsible management shall take appropriate action to lift and close the work suspension, based on the resolution of the related SCAQ. The QA organization shall verify and document the completion of applicable corrective actions prior to any management action releasing the work suspension.

1.3.3.7 Corrective Action Follow-up

A system shall be established to verify the effective implementation of scheduled corrective actions and to complete corrective actions in a timely manner. The QA organization shall evaluate the adequacy of corrective actions planned, assign responsibility for follow-up verification, and perform and document verification results. If results of verification are unsatisfactory, the CAP shall be revised appropriately, and corrective actions and verification performed.

1.3.3.8 Recurring Conditions Adverse to Quality

For recurring CAQs, management shall:

A. Determine the events leading up to the occurrences

B. Develop an understanding of the technical and work activities associated with the CAQ

C. Ascertain and identify any generic implications and impacts on completed work

D. Determine the extent to which similar quality problems, or precursors to the problem, have been identified

E. Determine the effectiveness of corrective actions that have been taken

F. Consider suspending work associated with the applicable activity, as appropriate

G. Suggest actions that can be taken by the responsible organization to preclude recurrence, as appropriate

1.3.3.9 Quality Trending

The need for quality improvement is accomplished through quality analysis and trending. To provide reliable trending information, the following activities shall be performed:

A. Quality performance data shall be identified, collected, and routinely analyzed to identify opportunities to improve items, services, activities, and processes. This analysis shall consider information from external sources and not be limited to one type of work or to one organization.

B. The analyses shall be performed semi-annually to provide for prompt identification of trends adverse to quality. Reports of CAQs, including those identified during quality assurance audits as Corrected During the Audit/Surveillance (CDAs/CDSs), shall be evaluated to identify adverse quality trends and root causes, with results reported to the organization responsible for corrective actions.

C. Program participants will report trending information to responsible management and to the applicable organization.

1.4 DOCUMENTS

A. Documents shall be prepared, reviewed, approved, issued, used, and revised to prescribe processes, specify requirements, or establish design.

B. Documents that specify requirements, prescribe processes, or establish design important to the compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility, such as instructions, procedures, drawings, test plans, management plans, technical reports, performance reports, and test reports, shall be controlled according to the requirements listed below to ensure that the correct documents are being used.

1.4.1 Document Preparation, Review, Approval, and Issuance

A. Documents shall be reviewed for adequacy, correctness, and completeness prior to approval and issuance. Program participants shall identify the individuals or organizations responsible for the preparation, review, approval, and issuance of controlled documents.

B. Documents shall be controlled during the review and approval phase in accordance with approved procedures.

C. The requesting organization shall identify the applicable criteria for the review. These criteria shall consider technical adequacy, accuracy, completeness, and compliance with established requirements.

D. Pertinent background information or data shall be made available by the organization requesting the review if the information is not readily available to the reviewer.

E. The review will be performed by individuals other than the originator.

F. Reviewers will be technically competent in the subject area being reviewed.

G. The organization or technical discipline affected by the document shall review the document according to the established review criteria.

H. The appropriate quality assurance organization shall review documents that translate CBFO QAPD or other CBFO requirements.

I. Review comment documentation shall be resolved in accordance with approved procedures. Evidence of review comment resolution shall be maintained by the originating organization.

J. Documents shall be approved for release by authorities designated in accordance with approved procedures.

K. Documents shall be issued by designated individuals or organizations in accordance with approved procedures.

1.4.2 Document Distribution and Use

The distribution and use of controlled documents and forms that document or prescribe work, including changes and editorial corrections to documents, shall be controlled to meet the following requirements:

A. Documents shall be distributed to affected personnel and used at the work location.

B. Effective dates shall be established and identified on the approved documents.

C. The disposition of obsolete or superseded documents and forms shall be controlled to avoid their inadvertent use.

D. Controls shall be established and maintained to identify the current status or revision of controlled documents and forms.

E. Controls shall provide for identification of documents to be controlled and their distribution.

1.4.3 Document Changes

A. Changes to documents, other than those defined below as editorial changes, shall be reviewed and approved by the same organizations that performed the original review and approval, unless other organizations are specifically designated in accordance with approved procedures.

B. Document changes shall be:

1. Reviewed by the organizations or technical disciplines affected

2. Clearly indicated in the changed document

C. Editorial or minor changes may be made without the same level of review and approval as the original or otherwise changed document. The following items are considered editorial or minor changes:

1. Correcting grammar or spelling (the meaning has not changed)

2. Renumbering sections or attachments

3. Updating organizational titles

4. Changes to non-quality affecting schedules

5. Revising or reformatting forms, providing the original intent of the form has not been altered

6. Attachments marked "Example," or "Sample," or exhibits that are clearly intended to be representative only

7. Clarification changes that do not affect the purpose of the document

D. A change in an organizational title accompanied by a change in responsibilities is not considered an editorial change.

E. The organization responsible for preparing the document shall identify and approve editorial changes.

1.5 RECORDS

A. Records shall be specified, prepared, reviewed, approved, and maintained.

B. A "QA record" is an authenticated record that provides objective evidence of the quality of items or activities. QA records shall be controlled in accordance with the following requirements.

1.5.1 Records System

A. A QA records system shall be established by the responsible organization at the earliest practical time, consistent with the schedule for accomplishing work activities. The QA records system shall be defined, implemented, and enforced in accordance with written procedures, instructions, or other documentation.

B. This does not prohibit the management of QA records within a general records system, nor does this require a separate records system for QA records, as long as the applicable provisions of this section are satisfied for the control of QA records.

1.5.2 Generating QA Records

A. Prior to conducting a work activity, the responsible organization shall:

   1. Identify those documents that shall become QA records

   2. Identify the organization responsible for submitting the QA records to the records system

B. QA records shall be legible, accurate, and completed appropriate to the work accomplished.

C. Individuals handling documents intended to become QA records shall provide reasonable protection for the records from damage or loss until the records are submitted to the records system (this includes documents generated during field operations).

D. Documents shall be considered valid QA records only if stamped, initialed, or signed and dated by authorized personnel, or otherwise authenticated. If the nature of the record (such as magnetic or optical media) precludes stamping or signing, then other means of authentication by authorized personnel are required. This authentication represents a certification as to the content of the record by those individuals with knowledge of the related facts, whether by direct personal knowledge or through the direct reports of others. The authentication should not be confused with any subsequent reviews of the content.

E. Once authenticated, QA records shall be submitted to the records system as prescribed by approved procedures. Upon completion of a project or other discrete task or activity, responsible management shall verify that the contents of the applicable QA records package are stored in the records system.

F. QA records may be originals or reproducible copies unless otherwise required.

G. Documents referenced by final reports, except readily available references such as encyclopedias, dictionaries, engineering handbooks, and national codes and standards, shall be retrievable from records files. Preparers of such records shall ensure that the documents are entered into the records system.

1.5.3 Indexing QA Records

The records system shall provide for the indexing of QA records according to the following requirements:

A. An individual or organization shall be assigned the responsibility of indexing and maintaining QA records.

B. The indexing system shall include, at a minimum, record retention times and the location of the record within the records system. These and other features of the records system shall facilitate the disposition of scheduled QA records and ensure the retrievability of any QA records entered.

1.5.4 Classifying QA Records

A. QA records shall be classified as either "post-closure," “lifetime,” or "nonpermanent." Post-closure QA records may be required to be maintained for periods of several hundred years and in a manner that will permit future generations to maintain them longer, if desired, using reasonably available technology. Records that fall into one or more of the following categories shall be classified as "post-closure" QA records:

   1. Records assisting prevention of actions that could impair the long-term isolation of the waste

   2. Records preserving information that would prevent inadvertent human intrusion, such as the nature and hazard of the waste and the locations of the geologic repository operations area, the underground facility, boreholes and shafts, and boundaries of the controlled area

   3. Records providing information relevant to post-closure monitoring and assessment of performance of the repository system

   4. Records preserving for future generations information regarding the geologic setting relevant to mitigation of releases of radioactive materials

   5. Records of significant value in exercising the retrieval option for waste packages after decommissioning and closure of the repository

B. Records not falling into the categories listed above, but falling into one or more of the following categories, shall be classified as "lifetime" QA records:

1. Records used for repository permitting or certification

2. Records used to identify and assess the performance capabilities of those engineered and natural barriers important to waste isolation

3. Records of computer programs and mathematical models needed to perform ongoing correlations between performance assessment predictions and actual tests and data analyses

4. Records of significant value in demonstrating the capability for safe operation of the WIPP respository or in determining the cause of an accident or a malfunction of an item in the WIPP repository

5. Records of significant value in maintaining, reworking, repairing, replacing, or modifying WIPP repository systems, components, or structures

6. Records needed during decommissioning and closure of the repository

7. Records relating to site characterization samples and data

8. Records relating to data used in performance assessment of the WIPP facility

9. Records documenting regulatory compliance

10. Records providing required baseline data for in-service inspections

C. Lifetime QA records are required to be retained and preserved in an acceptable condition for the operating life of the repository (i.e., until termination of the repository permit). Prior to destruction of any lifetime record, it shall be evaluated for upgrade to a post-closure record

D. Records that provide objective evidence that the QA program has been properly implemented, but that do not meet the above criteria for post-closure or lifetime records shall be classified as “nonpermanent” QA records. The retention period for nonpermanent records shall be established in writing.

E. Records related to waste characterization shall be classified in accordance with the requirements of the HWFP, *TRUPACT-II Authorized Methods for Payload Control* (TRAMPAC), and the *Quality Assurance Program Plan for TRUPACT-II Gas Generation Test Program*, DOE/WIPP 01-3187. In the case of conflicts between the records requirements contained in these documents, the most stringent requirements shall be used in determining the records classification.

1.5.5 Receiving QA Records

Each organization responsible for the receipt of QA records shall designate the person or organization responsible for receiving the records. The designee shall be responsible for organizing and implementing a system of controls for the receipt of QA records for permanent and temporary storage. At a minimum, the receipt control system shall include:

A. Provisions to permit a current and accurate assessment of the status of QA records

B. A method for identifying the records required to be included in the records system

C. A method for identifying the records that have been received

D. Procedures for the receipt and inspection of incoming records, including verification that the QA records received are in agreement with the transmittal document and that the records are legible

E. Provisions to control and protect the records from damage or loss during the receiving processes

F. A method for submittal of completed records to the storage facility without unnecessary delay

1.5.6 Storage, Preservation, Safekeeping, and Disposition of QA Records

A. QA records shall be stored and preserved in predetermined storage facilities in accordance with approved QA implementing procedures that provide a:

   1. Description of the storage facility

   2. Description of the filing and indexing systems used

   3. Description of controls governing QA records access, retrieval, and removal

   4. A method for filing supplemental information and documenting the authorization for corrections

B. The records storage arrangements shall provide adequate protection of records, including special processed records (such as radiographs, photographs, negatives, microfilm, and magnetic media) to preclude damage from moisture, temperature, rodent infestation, excessive light, electromagnetic fields, or stacking, as appropriate for the type of record being stored.

C. Records that require special processing and control, such as software and related documentation or information on high density media or optical disks, or hardware

and software required to maintain and access records, shall be controlled to ensure that the records are useable.

1.5.6.1 Records Disposition

A. Lifetime QA records shall be retained and preserved in an acceptable condition for the operating life of the WIPP repository (i.e., until termination of the operating permits), or for the particular item while it is installed in the repository or is being stored for future use. Lifetime records shall be evaluated for the need to be upgraded to post-closure records prior to their destruction.

B. Waste characterization data and related QA/Quality Control (QC) records in the generator/storage site project files for TRU waste to be shipped to the WIPP facility are designated as either lifetime records or non-permanent records as specified in Attachment B of the WIPP Hazardous Waste Facility Permit. Records that are designated as lifetime records shall be maintained for the life of the waste characterization program at a participating generator/storage site plus six years, then offered to CBFO for permanent archiving, or transferred to the appropriate Federal Records Center (FRC). Waste characterization records designated as non-permanent records shall be maintained for ten years from the date of (record) generation and then dispositioned according to their approved records inventory and disposition schedule (RIDS). If a generator/storage site ceases to operate, records shall be transferred before site closure.

C. Records relevant to an enforcement action under the WIPP Hazardous Waste Permit, regardless of assigned dispositions, shall be maintained at the TRU waste site until the NMED determines that they are no longer needed for enforcement actions, and then dispositioned as required.

D. Waste characterization data for each TRU mixed waste container transmitted to WIPP shall be maintained by CBFO for the active life of the WIPP facility plus two years. The active life of the WIPP facility is defined as the period from the initial receipt of TRU mixed waste at the facility until NMED receives certification of final closure of the facility. After their active life, records shall be retired to the FRC and maintained for 30 years.

E. Design and construction of a single records storage facility shall meet the applicable requirements of NQA-1-1989, NQA-3-1989, 10 CFR 71, and current requirements of the National Archives and Records Administration (NARA).

F. The construction details shall be reviewed by a person who is competent in the technical field of fire protection and fire extinguishing to determine the adequacy of protection of contents. If the facility is located within a building or structure, the environments and construction of that building can provide a portion or all of these criteria.

G. The following criteria are acceptable alternatives to the current NARA requirements and NQA-1-1989 criteria for a single storage facility:

1. Two-hour fire-rated vault meeting the National Fire Protection Association (NFPA) 232-1986, *Standards for the Protection of Records,* or NFPA 232AM-1986, or both

2. Two-hour fire-rated Class B file containers meeting the requirements of NFPA 232-1986, or NFPA 232AM-1986, or both

3. Two-hour fire-rated file room meeting the requirements of NFPA 232-1986, or NFPA 232AM-1986, or both, with the following additional provisions:

   a. Early warning fire detection and automatic fire suppression capability with electronic supervision at a constantly attended central station

   b. Records storage in fully enclosed metal cabinets

   c. Adequate access and aisle ways

   d. Prohibition in the room of work not directly associated with record storage or retrieval

   e. Prohibition of smoking, eating, or drinking

   f. Two-hour fire-rated dampers or doors in all boundary penetrations

H. If storage at dual facilities for each record is provided, the facilities shall be at locations sufficiently remote from each other to eliminate the chance of exposure to a simultaneous hazard. Each facility is not required to satisfy the requirements of sections E , F, or G above, but shall meet all other records storage requirements prescribed in this QAPD.

I. When temporary storage of records (such as for processing, review, or use) is required by an organization's procedures, the records shall be stored in a 1-hour fire-rated container. The procedures shall specify the maximum allowable time limit for temporary storage. The container shall bear a UL label (or equivalent) certifying one-hour fire protection, or be certified by a person competent in fire protection.

J. Access to storage facilities shall be controlled. A list designating personnel who are permitted access to the QA records shall be maintained and posted. Measures shall be established to preclude the entry of unauthorized personnel into the storage area. These measures shall guard against theft and vandalism.

K. Measures shall be taken to provide for replacement, restoration, or substitution of lost or damaged records.

L. QA records shall not be destroyed until the following conditions are met:

1. The appropriately assigned NARA authorized disposition specifies destruction
2. Regulatory requirements are satisfied
3. Operational status permits the disposal of such records
4. The related contractual requirements have been satisfied

1.5.7 Correcting Information in QA Records

A. Corrections to records will include the initials or signature of the authorized person making the correction and the date the correction was made.

B. Corrections to QA records shall be authorized by the originating organization.

C. Corrections to QA records should be made using a single line through and shall not obliterate the prior entry. QA records shall not be corrected with correction fluids or tapes.

SECTION 2 – PERFORMANCE REQUIREMENTS

2.1 WORK PROCESSES

A. Work shall be performed in accordance with established technical standards and administrative controls. Work shall be performed under controlled conditions using approved instructions, procedures, or other appropriate means. Items shall be identified and controlled to ensure their proper use. Items shall be maintained to prevent their damage, loss, or deterioration. Equipment used for process monitoring or data collection shall be calibrated and maintained.

B. The intent of this section is to establish the policy that those who have been assigned responsibility for performing work are responsible for achieving and maintaining quality. Those performing work have the goal of doing work correctly the first time. To ensure that those doing the work achieve that goal, management is responsible for establishing processes and procedures to ensure that all work is planned and performed under controlled conditions by personnel who are knowledgeable of the work requirements, and that these individuals are capable of accomplishing the work in accordance with the requirements of this QAPD.

C. This section further establishes management involvement in the work processes through their interactions with personnel performing the work and through their review and assessment of ongoing and completed work. This helps to ensure that the definition of "acceptable work performance" is clearly communicated and that personnel are provided the necessary training, resources, and administrative controls to properly accomplish their tasks.

2.1.1 Work

A. Personnel performing work are responsible for the quality of their work. Because the individual worker is the first line in ensuring quality, personnel will be knowledgeable of requirements for work they perform and the capability of the tools and processes they use.

B. Line managers will ensure that personnel working under their supervision are qualified and are provided the necessary training, resources, and administrative controls to accomplish assigned tasks. Criteria describing acceptable work performance shall be defined for the worker.

C. Line managers will review work and related information to ensure that the desired quality is achieved and to identify areas needing improvement.

D. Work shall be planned, authorized, and accomplished under controlled conditions using technical standards, QA requirements, and implementing procedures

commensurate with applicable control levels.

2.1.2 Implementing Procedures

A. Implementing procedures shall be developed, reviewed, and approved by technically competent personnel.

B. Implementing procedures shall include the following information, as appropriate to the work to be performed:

   1. Responsibilities of the organizations affected by the document

   2. Technical, regulatory, quality assurance, or other program requirements

   3. Sequential description of the work to be performed, including any allowance for out-of-sequence processing

   4. Quantitative or qualitative acceptance criteria sufficient for determining that activities were satisfactorily accomplished

   5. Prerequisites, limits, precautions, process parameters, and environmental conditions

   6. Special qualification and training requirements

   7. Verification points and hold points

   8. Methods for demonstrating that the work was performed as required (such as provisions for recording inspection and test results, check-off lists, or sign-off blocks)

   9. Identification and classification of QA records to be generated by the implementing procedure

C. Individuals performing work shall comply with implementing procedures; however, when work cannot be accomplished as described in the implementing procedure or accomplishment of such work would result in an undesirable situation, a condition adverse to quality, or an unacceptable safety risk, the work shall be suspended until the appropriate procedure change provisions are implemented.

2.1.3 Item Identification and Control

A. Processes shall be established and maintained to identify, control, and maintain items to prevent their damage, loss, or deterioration. The identification of items shall be maintained to ensure appropriate traceability. Traceability requirements shall be specified in design documents or implementing procedures. Processes shall be established and implemented to control consumables and items with limited operating or shelf life and to prevent the use of incorrect or defective items.

B. The following controls shall be established to ensure that only correct and accepted items are used or installed:

1. Items shall be identified and traced from the time of receipt, up to and including installation or end use. Records shall be maintained to ensure that the item can be traced at all times, from its source through installation or end use.

2. Item identification methods shall include physical markings. If physical markings are either impractical or insufficient, other appropriate means shall be employed (such as physical separation, labels or tags attached to containers, or procedural controls). When used, physical markings shall:

   a. Be applied using materials and methods that provide clear, permanent, and legible identification

   b. Not be detrimental to the function or service life of the item

   c. Be transferred to each part of an identified item when the item is subdivided

   d. Not be obliterated or hidden by surface treatments, coatings, or installation unless other means of identification are substituted

3. If codes, standards, or specifications include specific identification or traceability requirements (such as identification or traceability of the item to applicable specification or grade of material; heat, batch, lot, part, or serial number; or specified inspection, test, or other record(s)), then identification and traceability methods shall be implemented to ensure the special requirements are met.

4. Item identification control system records shall provide the inspection, test, and operating status of items. Items that have satisfactorily passed the required inspections and tests shall be identified. The identification methods shall preclude the inadvertent installation, use, or operation of items that have not passed required inspections and tests.

5. The status of inspections and tests shall be identified either on the items or in documents traceable to the items. Status shall be maintained through the use of

status indicators (such as tags, markings, labels, or stamps) or other means (such as inspection or test records), and the authority for applying and removing status indicators shall be specified.

2.1.4 Special Processes

A. Processes shall be considered as special processes if they meet any one or a combination of the following criteria:

   1. The results are highly dependent on the control of the process

   2. The results are highly dependent on the skill of the operator

   3. The quality of the results cannot be readily determined by inspection or test of the product

B. Implementing procedures shall be developed and implemented to ensure that special process parameters are controlled and specified environmental conditions are maintained. In addition to the requirements provided in Section 2.1.2, special process implementing procedures shall include or reference:

   1. The requirements for training/qualification of personnel and quality processes/equipment

   2. The conditions necessary for completion of the special process, including equipment, statistical process control, controlled parameters of the process, and calibration requirements

2.1.5 Handling, Storage, and Shipping

A. Handling, storage, cleaning, shipping, and other means of preserving, transporting, and packaging of items shall be conducted in accordance with established work and inspection procedures, shipping instructions, or other specified documents.

B. If required for critical, sensitive, perishable, or high-value articles, specific implementing procedures for handling, storage, cleaning, packaging, shipping, and other preservation shall be prepared and used.

C. Measures shall be established and implemented for the marking and labeling of items for packaging, shipping, handling, and storage as necessary to adequately identify, maintain, and preserve the item. Markings and labels shall indicate the presence of special environments or the need for special controls, as necessary, and shall be applied and removed by authorized personnel.

D. If required for protection or maintenance of particular items, special equipment (such as containers, shock absorbers, and accelerometers) and special protective environments (such as inert gas and specific moisture and temperature levels) shall be specified, planned for, and provided.

   1. If special protective equipment and environments are used, provisions shall be made for verifying their adequacy.

   2. Special handling tools and equipment shall be used and controlled, as necessary, to ensure safe and adequate handling.

   3. Special handling tools and equipment shall be inspected and tested at specified intervals and in accordance with implementing procedures to verify that the tools and equipment are adequately maintained.

   4. Operators of special handling and lifting equipment shall be sufficiently experienced and trained to use the equipment.

E. If storage of items is required, methods shall be established for the control of item identification records that are commensurate with the planned duration and conditions of storage. These methods shall provide for, as applicable:

   1. Maintenance or replacement of markings and identification tags damaged during handling or aging

   2. Protection of identification markings that are subject to excessive deterioration due to environmental exposure

   3. Update of related identification records and documentation

F. Status indicators, such as tagging valves and switches to prevent inadvertent operation, shall be used to indicate the operating status of items. Status indicators, such as lockout tags, shall also be used where appropriate and shall be applied and removed by authorized personnel.

2.2 DESIGN CONTROL

A. Items and processes shall be designed using sound engineering and scientific principles and appropriate standards. Design work, including changes, shall incorporate appropriate requirements, such as general design criteria and design bases. Design interfaces shall be identified and controlled.

B. The adequacy of design products shall be verified by individuals or groups other than those who performed the design work. Required verification and validation shall be completed before approval and implementation of the design.

C. Designs (from conceptual through final) shall be defined, controlled, and verified. In establishing design controls, management is responsible for ensuring that design inputs are technically correct; that design interfaces are identified; that authorities, responsibilities, and lines of communication are clearly defined; and that the design processes clearly define the acceptance criteria for the product.

2.2.1 Design Input

Applicable design inputs such as design bases, conceptual design reports, performance requirements, regulatory requirements, codes, and standards shall be controlled by those responsible for the design in accordance with the following requirements:

A. Design inputs shall be identified and documented and their selection reviewed and approved by those responsible for the design.

B. Design inputs shall be specified and approved on a timely basis to the level of detail necessary to permit the design work to be carried out correctly in a manner that provides a consistent basis for making design decisions, accomplishing design verification, and evaluating design changes.

C. Changes from approved design inputs and reasons for the changes shall be identified, approved, documented, and controlled.

D. Design inputs based on assumptions that require reverification shall be identified and controlled.

2.2.2 Design Process

The design process shall be controlled according to the following requirements:

A. Appropriate standards shall be identified and documented and their selection reviewed and approved. Changes from specified standards, including the reasons for the change, shall be identified, approved, documented, and controlled.

B. Design work shall be prescribed and documented on a timely basis and to the level of detail necessary to permit the design process to be carried out correctly.

C. Design documents shall be adequate to support design, fabrication, construction, and operation.

D. Design documents shall be sufficiently detailed as to purpose, method, assumptions, design input, references, and units such that a person technically

E. qualified in the subject can understand the documents and verify their adequacy without recourse to the originator.

F. Controls for identifying assemblies or components that are part of the item being designed shall be established. If a commercial grade assembly or component is modified or selected by special inspection or testing to meet requirements that are more restrictive than the supplier's published product description, then the assembly or component shall be represented as different from the commercial grade item in a manner traceable to a documented definition of the difference.

G. Controls for selecting and reviewing design methods, materials, parts, equipment, and processes essential to the function of an item shall be established.

H. Drawings, specifications, and other design output documents shall contain appropriate inspection and testing acceptance criteria.

2.2.3 Design Analyses

A. Design analyses shall be planned, controlled, and documented.

B. Documentation of design analyses shall include

1. Definition of the objective of the analyses

2. Definition of design inputs and their sources

3. Results of literature searches or other applicable background data

4. Identification of assumptions and designation of those assumptions that shall be verified as the design proceeds

5. Identification of any computer calculations, including computer type, computer software name, revision identification, inputs, outputs, and the bases (or reference thereto) supporting application of the software to the specific physical problem.

6. Identification of the reviewer and the approver

C. Calculations shall be identifiable by subject (including structure, system, or component to which the calculation applies), originator, reviewer, and date, or by other designator such that the calculations are traceable.

D. Computer software used to perform design analyses shall be developed, qualified, and used according to the requirements of Section 6.

2.2.4 Design Interface

A. Design interfaces shall be identified, documented, and controlled so that efforts are coordinated among participating organizations.

B. Design interface controls shall including the assignment of responsibility and the establishment of implementing procedures among participating design organizations for the review, approval, release, distribution, and revision of documents involving design interfaces

C. Design information transmitted across interfaces shall be documented and controlled.

D. The status of the design information or issued design documents shall be identified in transmittals. Where necessary, incomplete designs that require further evaluation, review, or approval shall be identified.

2.2.5 Design Verification

The acceptability of design work and documents, including design inputs, processes, outputs, and changes, shall be verified. The following design control requirements shall be applied to verify the adequacy of design:

A. Design verification shall be performed using one or a combination of the following methods:

    1. Design review

    2. Alternate calculations

    3. Qualification testing

B. The particular design verification method shall be identified and its use justified.

C. The results of design verification shall be clearly documented, including the identification of the verifier.

D. Design verification shall be performed by competent individuals or groups other than those who performed the original design (but they may be from the same organization). If necessary, this design verification may be performed by the originator's supervisor, provided that:

    1. The supervisor did not specify a singular design approach or rule out certain design considerations and did not establish the design inputs used in the design.

2. The supervisor is the only individual in the organization competent to perform the verification.

3. The determination to use the supervisor is documented and approved in advance.

E. Design verification shall be performed at appropriate times during the design process.

1. Verification shall be performed before release for procurement, manufacture, construction, or release to another organization for use in other design work.

2. Design verification shall be completed before relying on an item to perform its function.

F. The extent of the design verification required shall be based on the complexity, risk, uniqueness of design, complexity of design, degree of standardization, state of the art, and similarity to previously proven designs. When the design has been subjected to a verification process in accordance with this QAPD, the verification process need not be duplicated for identical designs.

G. Use of previously proven designs shall be controlled according to the following requirements:

1. The applicability of standardized or previously proven designs shall be verified with respect to meeting pertinent design inputs for each application.

2. Known problems affecting standard or previously proven designs and their effects on other features shall be considered.

3. The original design and associated verification measures shall be adequately documented and referenced in the files of subsequent application of the design.

4. Changes in previously verified designs shall require reverification. Such reverifications shall include the evaluation of the effects of those changes on the overall previously verified design and on any design analyses upon which the design is based.

2.2.6 Design Reviews

A. Design reviews shall be controlled, documented, and performed, and shall consider the following:

1. Design inputs were correctly selected and incorporated.

2. Assumptions necessary to perform the design work were adequately described, reasonable, and reverified as necessary.

3. Appropriate design methods were used.

4. Design output is reasonable compared to design inputs.

5. The necessary design input and verification requirements for interfacing organizations were specified in the design documents or in supporting implementing procedures.

B. Disposition of design review comments shall be documented.

2.2.7 Alternative Calculations

Alternative calculations are calculations or analyses that are made using alternate methods to verify correctness of the original calculations or analyses. The appropriateness of any assumptions, the input data used, any computer programs, or other calculation methods used, shall be evaluated.

2.2.8 Qualification Testing

If design adequacy is to be verified by qualification tests, the tests shall be pre-identified. When qualification testing is used, the following requirements shall apply:

A. The test configuration shall be defined and documented.

B. Testing shall demonstrate the adequacy of performance under conditions that simulate the most adverse design conditions. Operating modes and environmental conditions in which the item must perform satisfactorily shall be considered in determining the most adverse conditions.

C. If the tests verify only specific design features, the other features of the design shall be verified by other means.

D. Test results shall be documented and evaluated by the responsible design organization to ensure that test requirements have been met.

E. If qualification testing indicates that a modification to an item is necessary to obtain acceptable performance, the modification shall be documented and the modified item retested or otherwise verified to ensure satisfactory performance.

F. Scaling laws shall be established and verified when tests are being performed on models or mockups.

G. The results of model test work shall be subject to error analysis, where applicable, before the results are used in final design work.

2.2.9 Design Change

Design changes shall be controlled in accordance with the following requirements:

A. Changes to final designs, field changes, and nonconforming items dispositioned "use as is" or "repair" shall be justified and shall be subject to design control measures commensurate with those applied to the original design.

B. Design control measures for changes shall include provisions to ensure that the design analyses for the item are still valid.

C. Changes shall be approved by the same groups or organizations that reviewed and approved the original design documents, with the following considerations:

   1. If an organization that originally was responsible for approving a particular design document is no longer responsible, the new responsible organization shall be designated.

   2. The cognizant design organization shall have demonstrated competence in the specific design area of interest and have an adequate understanding of the requirements and intent of the original design.

D. When a design change is approved other than by revision to the affected design documents, measures shall be established to incorporate the change into these documents, where such incorporation is appropriate.

E. If a significant design change becomes necessary because of an incorrect original design, the design process and design verification methods and implementing procedures shall be reviewed and modified as appropriate. These design deficiencies shall be documented according to the requirements provided in Section 1.3.2.

F. Field changes shall be incorporated into the applicable design documents.

G. Design changes that affect related implementing procedures or training programs shall be communicated to the appropriate organizations.

2.3 PROCUREMENT

CBFO and participant organizations shall ensure that procured items and services meet established technical and QA requirements, and that they perform as specified.

Prospective suppliers shall be evaluated and selected on the basis of documented criteria. The responsible organization shall verify that approved suppliers continue to provide acceptable items and services.

2.3.1 Procurement Planning Requirements

Procurement activities shall be planned as early as possible and documented to ensure a systematic approach to the procurement process. Procurement planning shall:

A. Identify procurement methods and organizational responsibilities, including the appropriate QA organization

B. Identify and document the sequence of actions and milestones needed to effectively complete the procurement

C. Provide for the integration of the following activities:

1. Procurement document preparation, review, and change control
2. Selection of procurement sources
3. Proposal or bid evaluation and award
4. Purchaser evaluation of supplier performance
5. Purchaser verifications including any hold-point and witness-point notifications
6. Control of nonconformances
7. Corrective action
8. Acceptance of the item or service
9. Identification of QA records

2.3.2 Supplier Selection

A. Supplier selection shall be based on evaluation of the supplier's capability to provide items or services in accordance with procurement document requirements

B. Organizations responsible for supplier source selection shall be identified and shall include the appropriate QA organization.

C. Measures for selecting procurement sources shall include one or more of the following elements:

1. An evaluation of the supplier's history for providing an identical or similar product that performs satisfactorily in actual use

2. An evaluation of the supplier's current QA documentation, supported by any documented qualitative and quantitative information

3. An evaluation of the supplier's technical and QA capability, based on an evaluation of the supplier's facilities, personnel, and quality program implementation

D. The results of procurement source selection shall be documented.

2.3.3 Proposal/Bid Evaluation

A. The proposal or bid evaluation process shall include a determination of the extent of conformance to the procurement document requirements. This evaluation shall be performed by designated, technically qualified personnel, including the quality assurance organization, and shall include, at a minimum, the following:

1. Technical considerations

2. QA program requirements

3. Supplier personnel skills

4. Supplier production capabilities

5. Supplier past performance

6. Alternatives proposed by the supplier

7. Exceptions taken by the supplier

B. Before the contract is awarded, the purchaser shall resolve, or obtain commitments to resolve, deficiencies identified during the proposal or bid evaluation.

C. Supplier QA provisions shall be accepted by the purchaser QA management before the supplier is authorized to start work.

2.3.4 Procurement Document Requirements

Procurement documents shall include the following, as applicable to the item or service being procured:

A. The scope of work

B. Technical requirements, including the following:

1. Design bases shall be identified or referenced.

2. Specific documents (such as drawings, codes, standards, regulations, DOE orders, procedures, or instructions) that describe the technical requirements of the items or services to be furnished shall be identified. The revision level or change status of these documents shall also be identified.

3. Tests, inspections, hold points, or acceptance criteria that the purchaser shall use to monitor and evaluate the performance of the supplier shall be specified.

C. QA provisions specified by the purchaser QA organization shall include:

1. The requisite QA and documentation requirements, depending on the control level of the item or service being procured

2. The pass-down requirements that the supplier shall incorporate into any sub-tier procurement document

3. When deemed appropriate, the purchaser may permit some or all supplier work to be performed under the purchaser QA program, provided that the requirements are adequately implemented. In these cases, procurement documents shall specify that the purchaser's QA implementing procedures are applicable to the supplier and that the purchaser shall provide these applicable documents to the supplier.

4. Right of access to supplier facilities and records for inspection and audit by the purchaser, CBFO, or other designee authorized by the purchaser

5. The requirements of Section 1.5 and provisions for disposition, if the supplier is required to maintain QA records

6. Requirements for the supplier to report nonconformances and obtain purchaser approval of supplier-recommended dispositions

7. Spare and replacement parts or assemblies and the appropriate technical and QA requirements for ordering

2.3.5 Procurement Document Review and Approval

A. A review of the procurement documents and any changes thereto shall be made to verify that documents include appropriate provisions to ensure that items or services meet the prescribed requirements. Procurement document changes shall be subject to the same degree of control as the original documents.

B. Procurement document reviews shall be performed and documented prior to the document being issued to the supplier.

C. Reviews shall be performed by personnel who have access to pertinent information and who have adequate understanding of the requirements and scope of the procurement.

D. Procurement document reviews shall include representatives from the technical and QA organizations and shall be approved by responsible management.

2.3.6 Supplier Performance Evaluation

The purchaser of items and services shall establish measures to interface with the supplier and to verify supplier performance, as deemed necessary by the purchaser. The measures shall include:

A. Establishing an understanding between the purchaser and supplier of the requirements and specifications identified in the procurement documents

B. Requiring the supplier to identify planning techniques and processes to be used in fulfilling procurement document requirements

C. Reviewing supplier documents that are prepared or processed during work performed to fulfill procurement requirements

D. Identifying and processing necessary change information

E. Establishing the method to be used to document information exchanges between purchaser and supplier

F. Establishing the extent of assessment activities and inspection

2.3.7 Acceptance of Items or Services

2.3.7.1 Source Verification

A. The purchaser may accept an item or service by monitoring, auditing, surveilling, witnessing, or observing activities performed by the supplier. This method of acceptance is called source verification.

B. The extent of source verification shall be a function of the relative importance, complexity, and quantity of items or services being procured, as well as the supplier's quality of performance. Source verifications shall be accomplished as early as possible, but prior to the start of those activities that are required to be controlled, and shall include the active involvement of the purchaser's QA organization. In addition:

1. Source verification shall be accomplished consistent with the supplier's planned inspections, examinations, or tests and performed at intervals consistent with the importance and complexity of the item.

2. Documented evidence of acceptance of source-verified items or services shall be furnished to the party receiving the item, to the purchaser, and to the supplier.

3. Source verification shall be performed by qualified personnel.

C. For procurement of services only (such as third party inspection, engineering and consulting services), and installation, repair, overhaul, or maintenance work, the purchaser shall accept the service by any or all of the following methods:

1. Technical verification of data produced

2. Surveillance and/or audit of the activity

3. Review of objective evidence for conformance to the procurement document requirements such as certifications or test reports

2.3.7.2 Receiving Inspection

When a receiving inspection is used to accept an item:

1. The inspection shall include consideration of source assessments, verifications and audits and the demonstrated quality performance of the supplier.

2. The inspection shall be performed in accordance with established inspection procedures or instructions.

3. The inspection shall verify, as applicable, proper configuration; identification; dimensional, physical, and other characteristics; freedom from shipping damage; and cleanliness.

4. The inspection shall be planned and executed in accordance with the applicable requirements of Section 2.4.

5. Receiving inspection shall include a review of the adequacy and completeness of any required supplier documentation.

2.3.7.3 Post-Installation Testing

When post-installation testing is used as a method of acceptance, post-installation test requirements and acceptance documentation shall be mutually established and agreed upon by the purchaser and supplier.

2.3.7.4 Supplier Certificate of Conformance

When a certificate of conformance is used, the following, at a minimum, shall be met:

A. The certificate shall identify the purchased material or equipment, including the purchase order and item number or other identification that is traceable to the requirements of the procurement document.

B. The certificate shall identify the specific procurement requirements met by the purchased material or equipment, such as codes, standards, and other specifications. The procurement requirements identified shall include any approved changes, waivers, or deviations applicable to the subject material or equipment.

C. The certificate shall identify any procurement requirements that have not been met, together with an explanation and the means for resolving the nonconformances.

D. The certificate shall be signed or otherwise authenticated by an official of the supplier organization, whose function and position are described in the supplier's QA program.

E. The certification system, including the procedures to be followed in filling out a certificate and the administrative procedures for review and approval of the certificate, shall be described in the purchaser or supplier QA program.

F. Means shall be provided to verify the validity of supplier certificates and the effectiveness of the certification system, such as during the performance of audits of the supplier or independent inspection or test of the items. Such verification shall be conducted by the purchaser at intervals commensurate with the supplier's past quality performance.

2.3.8 Control of Supplier Nonconformances

The purchaser and supplier shall establish and document the process for dispositioning items and services that do not meet procurement document requirements in accordance with the following:

A. The supplier shall submit a report of nonconformance to the purchaser that includes supplier-recommended disposition (for example, "use as is" or "repair") and provide technical justification for such disposition.

B. Reports of nonconformances to procurement document requirements or documents approved by the purchaser shall be submitted to the purchaser for approval. Examples of conditions requiring a report of nonconformance include:

1. Failure to meet technical or material requirements

2. Failure to meet a requirement in supplier documents that have been approved by the purchaser

3. The nonconformance cannot be corrected by continuation of the original manufacturing process or by rework

4. The item does not conform to the original requirement even though the item can be restored to a condition such that its capability to function is unimpaired

C. The purchaser shall evaluate the supplier-recommended disposition.

D. The purchaser shall verify implementation of the disposition.

2.3.9 Commercial Grade Items

Where the design specifies the use of commercial grade items, the following requirements are an acceptable alternative to other requirements of this section.

A. The commercial grade item shall be identified in an approved design output document, such as a drawing, specification, or other document translated from a design input document. An alternative commercial grade item may be applied as long as the responsible design organization provides verification that the alternative commercial grade item performs the intended function and meets design requirements that are applicable to both the replaced item and its application.

B. Source evaluation and selection, where determined necessary by the purchaser based on complexity and importance to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility, shall be in accordance with Section 2.3.2.

C. Commercial grade items shall be identified in the procurement document by the manufacturer's published product description.

D. After receipt of a commercial grade item, the purchaser shall ensure that:

1. Damage was not sustained during shipment

2. The item received was the item ordered

3. Inspection or testing is accomplished, to the extent determined by the purchaser, to ensure conformance with the manufacturer's published requirements

4. Documentation, as applicable to the item, was received and is acceptable

2.4 INSPECTION AND TESTING

A. Inspections and testing shall be performed in accordance with approved implementing procedures. An essential part of the work planning process is to identify the items and processes to be inspected or tested, the parameters or characteristics to be evaluated, the techniques to be used, the acceptance criteria, any hold points, and the organizations responsible for performing the tests and inspections. Inspection for acceptance shall be performed by personnel other than those who performed or directly supervised the work being inspected. Inspection and testing of specified items and processes shall be conducted using established acceptance and performance criteria. The acceptance of items and processes shall be made by and documented by qualified and authorized personnel. Equipment used for inspections and tests shall be calibrated and maintained.

B. Inspection and testing activities shall be conducted in accordance with the following requirements, as applicable.

2.4.1 Qualification of Inspection and Test Personnel

This section provides amplified requirements for the qualification of personnel who perform inspection and testing to verify conformance to specified requirements for the purpose of acceptability. The requirements of this section do not apply to the qualification of personnel for performance of nondestructive examination. Qualification of personnel for nondestructive examination is addressed in Section 2.4.2.

A. The responsible organization shall designate those activities that require qualified inspection and test personnel and the minimum requirements for such personnel. Further, the responsible organization shall establish written procedures for the qualification of inspection and test personnel and for the assurance that only those personnel who meet the requirements of this section are permitted to perform applicable inspection and test activities.

B. When a single inspection or test requires implementation by a team or a group, personnel not meeting the requirements of this section may be used in data-taking assignments or in plant or equipment operation, provided they are supervised or overseen by a qualified individual.

C. Personnel selected for performing inspection and test activities shall have the experience or training commensurate with the scope, complexity, or special nature of the activities.

D. Provisions shall be made for the indoctrination of personnel to the technical objectives and requirements of the applicable codes and standards and the QA program controls that are to be employed.

E. The need for a formal training program shall be determined, and such training activities shall be conducted as required to qualify personnel that perform such inspections and tests. On-the-job training shall also be included in the program, as appropriate, with emphasis on first-hand experience gained through actual performance of inspections and tests.

F. The capabilities of a candidate for certification shall be initially determined by a suitable evaluation of the candidate's previous education, experience, training, and either test results or capability demonstration.

G. The job performance of inspection and test personnel shall be reevaluated for capability at periodic intervals, not to exceed three years. Reevaluation shall be by evidence of continued satisfactory performance or redetermination of capability in accordance with the above requirements. If, during this evaluation or at any other time, it is determined by the responsible organization that the capabilities of an individual are not in accordance with the qualification requirements specified for the job, that person shall be removed from that activity until such time as the required capability has been demonstrated. Any person who has not performed inspection or testing activities in their qualified area for a period of one year shall be reevaluated for the required capability in accordance with the above requirements.

H. The qualification of personnel shall be certified in writing in an appropriate form and shall include the following information:

1. Employer’s name

2. Identification of person being certified

3. Activities certified to perform

4. Basis used for certification, including such factors as: (1) education, experience, indoctrination, and training; (2) test results, where applicable; and (3) results of capability demonstration

5. Results of periodic evaluation

6. Results of physical examinations, when required

7. Signature of the employer’s designated representative responsible for such certification

8. The date of certification and date of certification expiration

I. The responsible organization shall identify any special physical characteristics needed in the performance of each activity, including the need for initial and subsequent physical examination.

J. Records of personnel qualification shall be established and maintained by the employer. These records shall include the information required above for certification.

2.4.2 Qualification of Nondestructive Examination Personnel

This section identifies the requirements for the qualification of personnel who perform nondestructive examination (NDE) (radiographic, magnetic particle, ultrasonic, liquid penetrant, eddy current, neutron radiographic, leak testing, and visual testing) to verify conformance to specified requirements, for nondestructive examination activities performed at the WIPP site.

A. The American Society of Nondestructive Testing (ASNT) Recommended Practice No. SNT-TC-1A, June 1980 Edition, and its applicable supplements, shall apply as requirements for personnel performing the above methods of NDE.

B. The responsible organization shall establish written procedures for the control and administration of the training, examination, and certification of NDE personnel.

C. Records of personnel qualification shall be established and maintained by the employer.

2.4.3 Inspection

2.4.3.1 Inspection Planning

A. Inspection planning shall be performed and documented and shall include:

1. Identification of work operations where inspections are necessary

2. Identification of the characteristics to be inspected and when during the work process inspections are to be performed

3. Identification of inspection or process monitoring methods to be employed

4. Identification of acceptance criteria

5. Identification of sampling requirements

6. Methods to record inspection results

7. Selection and identification of the measuring and test equipment (M&TE) to be used to perform the inspection

8. Process used to ensure that the equipment being utilized for inspection or testing is calibrated and is of the proper type, range, accuracy, and tolerance to accomplish the intended function

B. When statistical sampling is to be used to verify the acceptability of a group of items, the sampling method shall be based on recognized standard practices.

2.4.3.2 Inspection Hold Points

Hold points are used to control work that is not to proceed without the specific consent of the organization placing the hold point. The specific hold points shall be indicated in appropriate documents. Only the organization responsible for the hold point may waive the hold point. Approval to waive specified hold points shall be documented before continuing work beyond the designated hold point.

2.4.3.3 In-Process Inspections and Monitoring

A. Items in process shall be inspected as necessary to verify quality. If inspection of processed items is impossible or disadvantageous, indirect control by monitoring of processing methods, equipment, and personnel shall be provided. Both inspection and process monitoring shall be conducted when control is deemed inadequate, using only one of these methods.

B. When a combination of inspection and process monitoring methods is used, monitoring shall be performed systematically to ensure that the specified requirements for control of the process and the quality of the item are met throughout the duration of the process.

C. Controls shall be established and documented for the coordination and sequencing of the work at established inspection points during successive stages of the process.

2.4.3.4 Final Inspections

A. Final inspections shall include a review of the results and the verification of the resolution of all nonconformances identified by earlier inspections.

B. Finished items shall be inspected for completeness, markings, calibration, protection from damage, or other characteristics, as required to verify the quality and conformance of the item to the applicable requirements.

C. Records review shall be performed to ensure adequacy and completeness.

D. Item modifications, repairs, or replacements that are performed subsequent to final inspection shall require reinspection or retest, as appropriate, to verify acceptability.

2.4.3.5 In-service Inspections

A. Required in-service inspection or surveillance of structures, systems, or components shall be planned and executed by or for the organization responsible for their operation.

B. Inspection methods shall be established and executed to verify that the characteristics of an item continue to remain within specified limits.

C. Inspection methods shall include evaluations of performance capability of essential emergency and safety systems and equipment, verification of calibration and integrity of instruments and instrument systems, and verification of maintenance, as appropriate.

2.4.3.6 Inspection Documentation

Inspection documentation shall identify:

A. The item inspected and the date of the inspection

B. The name or unique identifier of the inspector who documented, evaluated, and determined acceptability

C. The method of inspection

D. The inspection criteria, sampling plan, or reference documents (including revision designation) used to determine acceptance

E. The results

F. The M&TE used during the inspection, including the identification number and the calibration due date

G. Reference to any information on actions taken in connection with nonconformances, as applicable

2.4.4 Test Requirements

Testing shall be used to determine the capability of an item to meet specified requirements by subjecting the item to a set of physical, chemical, environmental, or operating conditions. Examples of such tests include prototype qualification tests, production tests, proof tests prior to installation, construction tests, and pre-operational tests.

2.4.4.1 Test Planning

Test planning shall include:

A. The identification of the implementing procedures to be developed to control and perform the test. In lieu of specially prepared written test procedures, appropriate sections of related documents such as American Society for Testing and Materials (ASTM) methods may be used. If used, they shall incorporate the information directly into the approved test implementing procedure, or shall be incorporated by reference.

B. The identification of the item to be tested and the test requirements and acceptance limit, including the required levels of precision and accuracy

C. The identification of the M&TE to be used to perform the test to ensure that the equipment being utilized is calibrated and is of the proper type, range, accuracy, and tolerance to accomplish the intended function

D. Any test prerequisites, including test equipment, instrumentation and software needs, personnel training and qualification, and suitably controlled environmental conditions

E. Any mandatory hold points

F. The methods to be used to record data and results

G. The provisions for ensuring that prerequisites for the given test have been met

2.4.4.2 Test Documentation

Test documentation shall identify:

A. The applicable test requirements, plans, and procedures, including revisions

B. The item or work product tested

C. The date of the test

D. The name of the tester and data recorders

E. The type of observation and method of testing

F. The identification of test criteria or reference documents used to determine acceptance

G. The results and acceptability of the test

H. The actions taken in connection with any noted nonconformances

I. The name of the person evaluating the test results

J. The identification of the M&TE used during the test (including the identification number and calibration due date)

2.4.4.3 Test Results

Test results shall be documented and their conformance with acceptance criteria shall be evaluated by a qualified individual within the responsible organization to ensure that all test requirements have been satisfied.

2.4.5 Monitoring, Measuring, Testing, and Data Collection Equipment

The following sections establish requirements to ensure that equipment used for inspection and testing is properly controlled, calibrated, and maintained. Equipment discussed in the following sections includes inspection and test equipment, measuring and data collection equipment, equipment (either hand-held or installed) used for data indication, and other equipment used for data indication, collection, or evaluation. These are called M&TE.

Calibration and control measures may not be required for rulers, tape measures, levels, and other such devices, if normal commercial equipment provides adequate accuracy.

2.4.6 Use and Control of M&TE

Each organization using M&TE shall:

A. Establish and document a system to control the use and calibration of M&TE

B. Have a program to recall for calibration, or remove from service, M&TE that has exceeded its calibration interval; has broken calibration seals; has been modified, repaired, or has had components replaced; or is suspected to be malfunctioning because of mishandling, misuse, or unusual results

C. Establish and maintain documented procedures to evaluate the adequacy of the calibration system and to ensure compliance with the requirements of this QAPD

D. Maintain records documenting that established M&TE schedules and procedures have been followed. These records shall include an individual record of calibration, or other means of control, providing:

   1. A description or identification of the item

   2. Calibration interval

   3. Date calibrated

   4. Identification of the calibration source

   5. Calibration results (data and status)

   6. Calibration action taken (e.g., adjusted, repaired, new value assigned, derated)

   7. Evaluation and corrective action taken in response to out-of-calibration conditions

E. Label all M&TE to indicate the calibration status, the date calibrated, the calibration due date or usage equivalent, and the identification of any limitations. (When it is impractical to apply a label directly to an item, the label may be affixed to the instrument container or some other suitable means may be used to reflect calibration status.)

F. Evaluate the validity of previous inspection and test results and the acceptability of related items, data collected, and processes monitored, when M&TE is found to be out-of-calibration

G. Handle, store, and transport M&TE in a manner that does not adversely affect the accuracy of the equipment

H. Give due consideration to temperature, humidity, lighting, vibration, dust control, cleanliness, electromagnetic interference, and any other factors affecting the results of measurements. Where pertinent, these factors shall be monitored and recorded and, when appropriate, correcting compensations shall be applied to measurement results.

2.4.7 Calibration

A. M&TE requiring calibration shall be calibrated at periodic intervals established and maintained to ensure acceptable reliability, where reliability is described as the probability that M&TE will remain in tolerance throughout the interval.

B. Intervals shall be established for all M&TE requiring calibration unless the equipment is regularly monitored through the use of check standards in a documented measurement assurance process. Check standards must closely represent the item parameters normally tested in the process, and the check standard must be verified periodically.

C. Where intervals are used to ensure reliability, the interval setting system must be systematically applied and shall have stated reliability goals and a method of verifying that the goals are being attained.

D. Intervals may be based on usage or time since last calibration.

E. All exemptions from periodic calibration shall be approved and documented.

F. The recall system may provide for the temporary extension of the calibration due date for limited periods of time under specified conditions that do not unreasonably impair the satisfaction of task objectives.

G. If any M&TE is found to be significantly out-of-tolerance during the calibration process, the cognizant organization shall provide for the notification to the user and cognizant QA management of the out-of-tolerance condition, with the associated measurement data, so that appropriate action can be taken.

SECTION 3 – ASSESSMENT REQUIREMENTS

3.1 MANAGEMENT ASSESSMENT

Managers at every level shall periodically assess the performance of their organization to determine the effectiveness of QA program provisions that enable the organization to meet customer requirements and expectations. This assessment shall emphasize the use of human and material resources to achieve organizational goals and objectives.

A. The management assessment should include an introspective evaluation to determine if the entire integrated management system effectively focuses on meeting strategic goals.

B. Managers shall retain overall responsibility for management assessments. Direct participation by senior management is essential to the success of the process because management is in the position to view the organization as a total system.

C. Management assessments should focus on the identification and resolution of both systemic and management issues and problems. Strengths and weaknesses affecting the achievement of organizational objectives should be identified so that meaningful action can be taken to improve quality.

D. Processes being assessed should also include strategic planning, organizational interfaces, cost control, use of performance indicators, staff training and qualifications, and supervisory oversight and support. Effective management assessments should evaluate such conditions as the state of employee knowledge, motivation, and morale; the amount of mutual trust and communication among workers and organizations; the existence of an atmosphere of creativity and improvement; and the adequacy of human and material resources.

E. Management assessments of the QA program shall be conducted regularly and reported at least annually to an identified senior management level with sufficient authority to effect corrective measures, as necessary.

F. Management assessment results should be used as input to the organizational continuous improvement process.

3.2 INDEPENDENT ASSESSMENT

A. Planned and periodic independent assessments shall be conducted to measure item and service quality, process effectiveness, and promote improvement. The organization performing assessments shall have sufficient authority and freedom from the activities being assessed to carry out its responsibilities. Persons conducting independent assessments shall be technically qualified and

knowledgeable of the items and activities being assessed.

B. The types and frequencies of independent assessments shall be based upon the relevant control levels assigned to the items and activities under the cognizance of the organization.

C. The CBFO and participant organizations responsible for the performance of activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP site shall implement a program of surveillance and audits. The program shall be planned and documented and shall include both routine surveillance of those activities and audits to verify compliance with all aspects of the quality assurance program and to determine its adequacy and effectiveness.

3.2.1 Surveillances

A. A program of surveillance of the activities referenced above shall be planned, performed, documented, and reported to appropriate management personnel. The surveillance process consists of monitoring or observing to verify whether an item, activity, system, or process conforms to specified requirements.

B. Surveillances shall accomplish the following:

1. Monitor work in progress

2. Document compliance or noncompliance with established requirements and procedures

3. Identify actual and potential conditions adverse to quality

4. Obtain timely corrective action commitment from cognizant managers for identified conditions adverse to quality

5. Provide notification to responsible managers of the status and performance of work under surveillance

6. Verify timely implementation of corrective actions

C. Audits or other independent assessments of the subject activities, conducted by the responsible organization, may be counted as satisfying the requirement to do surveillances of related activities in the corresponding surveillance schedule period.

3.2.2 Audits

The following sections describe the audit process requirements.

3.2.2.1 Scheduling Audits

A. Audits shall be scheduled to begin as early in the life of a project or activity as practicable and continue at intervals consistent with the schedule for accomplishing the work and commensurate with assigned control level.

B. Periodically scheduled QA program audits shall be supplemented by, or integrated with, either audits or surveillances of a technical nature (e.g., performance-based audits) which assess the quality of selected work products and work processes.

3.2.2.2 Planning and Preparation for Audits

The organization performing the audit shall develop and document a plan for each audit.

A. The plan shall include the scope, requirements, purpose, audit personnel, activities to be audited, organizations to be notified, applicable documents, schedule, and written procedures or checklists to be used.

B. Audit planning shall include a review of past assessment results to determine the nature of problems that have occurred. When recurring problems are found, the audit team shall review corrective actions that have been taken and attempt to determine whether the corrective actions were effective in preventing recurrence.

C. Audit preparation shall include review of pertinent background information, procedures, and technical documents so that audit team members are familiar with the work being audited.

D. Audits shall include technical evaluations of the applicable procedures, instructions, activities, and items, as appropriate.

E. The scope shall include related corrective actions taken since the previous assessment.

3.2.2.3 Audit Team Selection

A. Audit team members shall be identified prior to the start of the audit activity. The team members shall be selected on the basis of technical qualifications and knowledge of the item or process being audited and shall be independent from the items or processes being audited. Audit team members shall have sufficient authority and organizational freedom to carry out their assigned responsibilities. In the case of internal audits, personnel having direct responsibility for performing the activities being audited shall not be involved in the selection of the audit team.

B. An audit team leader shall be appointed to provide indoctrination and supervision of the team, organize and direct the audit, and coordinate the preparation and issuance of the audit report.

C. Before starting the audit, the audit team leader shall ensure that the assigned personnel collectively have experience and training commensurate with the scope, complexity, or special nature of the work to be audited.

D. Technical specialists, with appropriate technical expertise or experience in the work being audited, shall be used when auditing the adequacy of technical processes.

3.2.2.4 Auditor Qualification

Auditors shall be technically qualified in their assigned roles. In addition, they shall have appropriate training or orientation to develop their competence for performing audits. Competence of personnel performing various audit functions shall be developed by one or more of the following methods:

A. Orientation to provide a working knowledge and understanding of the QA program requirements and the auditing organization's implementing procedures used to perform audits and report audit results

B. Training programs that provide general and specialized training in audit performance, including fundamentals, objectives, characteristics, organization, performance, and results of quality auditing. Training shall include methods of examining, questioning, evaluating, and documenting specific audit items and methods of evaluating the effectiveness of corrective actions for conditions adverse to quality.

C. On-the-job training, guidance, and counseling under the direct supervision of a lead auditor. Such training shall include audit planning, performing, reporting, and follow-up actions.

3.2.2.5 Technical Specialist Qualification

Technical specialists selected for audit assignments shall receive indoctrination commensurate with the scope, complexity, or special nature of the work being audited. In addition, they shall be trained to the requirements of the audit process associated with their duties.

3.2.2.6 Lead Auditor Qualification

A lead auditor shall be capable of organizing and directing audits, reporting audit results, and evaluating planned and implemented corrective action. A lead auditor also shall be certified as meeting the requirements provided in this section for education and

experience, communication skills, training, audit participation, and the successful completion of a lead auditor examination.

A. Lead Auditor Education and Experience:

The prospective lead auditor shall have verifiable evidence that a minimum of 10 credits have been accumulated under the following scoring system:

1. Education (four credits maximum)

    a. An associate's degree from an accredited institution scores one credit. If the degree is in engineering, physical sciences, mathematics, or QA, it scores two credits.

    b. A bachelor's degree from an accredited institution scores two credits. If the degree is in engineering, physical sciences, mathematics, or QA, it scores three credits. In addition, score one more credit for a master's degree (or higher) in engineering, physical sciences, business management, or QA from an accredited institution.

2. Experience (nine credits maximum)

    a. The prospective lead auditor shall have participated in a minimum of five QA audits or equivalent verifications (such as management assessments, pre-award surveys, or comprehensive surveillance, as long as the parameters of the audit process are met) within three years prior to the date of certification, one of which shall be a nuclear QA audit within the year prior to qualification. In addition, for technical experience in such areas as scientific investigation, site characterization, nuclear waste management, production, transportation, engineering, manufacturing, construction, operation, or maintenance, or experience applicable to the auditing organization's area of responsibility, score one credit for each full year, with a maximum of five credits.

    b. If two years of this experience have been in a nuclear field, score one additional credit; or

    c. If two years of this experience have been in QA, score two additional credits; or

    d. If two years of this experience have been in auditing or assessment, score three additional credits; or

    e. If two years of this experience have been in nuclear-related QA, score three additional credits; or

f. If two years of this experience have been in nuclear-related QA auditing or assessment, score four additional credits.

3. Professional Competence (two credits maximum)

   For certification of competency in engineering, science, or QA specialties, issued and approved by a state agency or national professional or technical society, score two credits.

4. Rights of Management (two credits maximum)

   When determined appropriate, the organization performing the qualification may grant up to two credits for other performance factors applicable to auditing that are not explicitly called out in this section (such as leadership, sound judgment, maturity, analytical ability, tenacity, past performance, and completed QA training courses).

B. Lead Auditor Communication Skills

The prospective lead auditor shall have the capability to communicate effectively both in writing and orally. These skills shall be attested to in writing by the candidate's supervisor.

C. Lead Auditor Training

Prospective lead auditors shall be trained to the extent necessary to ensure their competence in skills as established by the organization responsible for performing audits. Training in the following areas shall be accomplished and its completion verified based upon a management evaluation of the particular needs of each prospective lead auditor:

1. Knowledge and understanding of the participant organization’s QA program and other program-related procedures, codes, standards, regulations, DOE orders, and regulatory guides, as applicable

2. General structure of QA plans and implementation procedures as a whole

3. Auditing techniques of examining, questioning, evaluating, reporting, and methods of identifying, following up, and closing corrective actions

4. Audit planning in functional areas of nuclear QA

D. Lead Auditor Examination

The prospective lead auditor shall pass an examination that evaluates his or her comprehension of, and ability to apply, the audit knowledge described in this section.

The examination may be oral, written, practical, or any combination thereof.

The development and administration of the examination for a lead auditor is the responsibility of the organization responsible for the auditing program. This organization shall:

1. Maintain the integrity of the examination through confidentiality of files and, where applicable, proctor examinations

2. Develop and maintain objective evidence regarding the type and content of the examination

E. Lead Auditor Certification

Lead auditors shall be certified by the organization responsible for the auditing program as being qualified to lead audits. This certification will document the:

1. Name of the organization performing the certification

2. Name of the lead auditor

3. Date of certification or recertification

4. Basis of certification (such as education, experience, communication skills, and training)

5. Signature of the designated representative of the organization responsible for the certification

F. Lead Auditor Proficiency Maintenance

1. Lead auditors shall maintain their proficiency through one or a combination of the following:

   a. Regular and active participation in the audit process

   b. Review and study of codes, standards, QA implementation procedures, instructions, and other documents related to QA program auditing

   c. Participation in training programs

   d. Management of the auditing organization shall evaluate the proficiency of lead auditors annually. Based on the evaluation, management shall choose to extend the qualification, require retraining, or require requalification. Management evaluations shall be documented.

2. Lead auditors who fail to maintain their proficiency for a two-year period shall require requalification to the requirements of this section of the QAPD. However, participation in only one nuclear audit is required.

3.2.2.7 Performing Audits

A. Audits shall be performed using the written procedures or checklists related to the activity being audited.

B. Elements that have been selected for audit shall be evaluated against specified requirements. Objective evidence shall be examined to the depth necessary to determine if those elements are being implemented effectively.

C. Audit results shall be documented by audit personnel and reported to and reviewed by management having responsibility for the area audited. Conditions requiring prompt corrective action shall be reported immediately to management of the audited organization.

D. Conditions adverse to quality shall be documented and corrected according to the requirements of Section 1.3.3.

3.2.2.8 Reporting Audit Results

A. The audit report shall be prepared and signed by the audit team leader and issued to the management of the audited organization and any affected organizations. The audit report shall include the following, as appropriate:

1. A description of the audit scope

2. Identification of the auditors

3. Identification of persons contacted during the audit

4. A summary of the documents reviewed, persons interviewed, and the specific results of the reviews and interviews (i.e., a summary of the checklist contents)

5. A summary of audit results, including a statement of the QA program adequacy, implementation, and effectiveness, as appropriate to the scope

6. A description of each reported condition adverse to quality in sufficient detail to enable corrective action to be taken by the audited organization

7. A description of commendable quality practices

B. Additionally, common audit findings shall be grouped in the report whenever possible so that related or systematic breakdowns in the QA program are identified. Findings

or deficiencies shall be categorized based on their relative importance to indicate their degree of impact on compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, or management and operation of the WIPP facility.

3.2.2.9 Audit Response and Follow Up

Management of the audited organization will investigate conditions adverse to quality; determine and schedule corrective actions, including measures to preclude recurrence; and notify the auditing organization in writing of the actions planned or taken. The adequacy of audit responses shall be evaluated by or for the auditing organization. Follow-up action shall be taken to verify that corrective action is accomplished as scheduled.

3.2.2.10 Audit Records

The following documents, when developed in fulfillment of the audit requirements of this QAPD, shall be controlled as QA records in accordance with Section 1.5 of this QAPD: audit plans, audit reports, audit responses, and documentation of corrective action completion and follow-up.

SECTION 4 – SAMPLE CONTROL REQUIREMENTS

This section identifies the requirements for controlling samples of waste and environmental media. The control measures shall include provisions for the identification, handling, storage, shipping, archiving, and disposition of the samples, including those identified as nonconforming.

4.1 SAMPLE CONTROL

A. Samples shall be controlled and identified in a manner consistent with their intended use.

B. Implementing procedures shall define responsibilities, including organizational interfaces, related to documenting and tracking sample possession from sample collection and identification through handling, preservation, shipment, transfer, analysis, storage, and final disposition.

C. Sample control measures shall include provisions for the identification of the in situ orientation of samples, where appropriate.

D. A chain-of-custody record form shall be maintained. The chain-of-custody record shall provide a document trail of all persons who have custody of a given sample, including the date and time of its transfer.

E. Sample control measures, including identification and documentation, shall ensure that samples can be traced at all times, from collection through final disposition.

F. Where samples have a maximum life expectancy or expiration date, methods shall be employed that preclude the use of the sample beyond its specified life.

G. Representative archival samples from difficult-to-repeat sample collection activities, such as principal bore holes, shall be maintained.

H. Implementing procedures shall specify the representative samples to be archived if the need to archive samples is identified.

4.2 SAMPLE IDENTIFICATION

A. Each sample shall be uniquely identified from its initial collection through the final disposition of the sample.

B. Sample identification shall be verified and documented before each transfer or release for testing, analysis, or disposition.

C. Identification shall be maintained by placing the identification directly on the samples wherever possible or in a manner that ensures identification is maintained. If direct physical markings are either impractical or insufficient, other appropriate means shall be employed (e.g., physical separation, labels or tags attached to containers, or procedural control). When used, physical markings shall:

1. Be applied using materials and methods that provide clear and legible identification

2. Not effect the sample content or form

3. Be transferable to each identified sample part when the sample is subdivided

4. Not be obliterated or hidden by surface treatments or sample preparation unless other means of identification are substituted

D. If sample storage is required, methods shall be established for the control of sample identification that are commensurate with the planned duration and storage conditions. As applicable, these methods shall provide for:

1. The maintenance or replacement of markings and identification tags that have been damaged because of age or during handling

2. The protection of identification markings from excessive deterioration due to environmental exposure

4.3 HANDLING, STORING, AND SHIPPING SAMPLES

A. Handling, storing, cleaning, packaging, shipping, and preserving samples shall be conducted in accordance with established work and inspection implementing procedures. Controls shall provide for the maintenance of sample characteristics, sample integrity, and sample identification during storage.

B. The controls shall be consistent with planned duration and storage conditions and shall describe actions to be taken where maximum sample life expectancy limits are identified.

C. Storage methodology shall be developed and implemented to ensure that samples are maintained in predetermined environmental conditions commensurate with their intended use and purpose.

D. Samples shall be controlled to preclude the mixing of like samples.

E. Samples on which analysis or tests have been performed shall be identified and maintained in a separate part of the storage area.

F. If required for critical, sensitive, perishable, or high-value samples, specific measures for the handling, storage, cleaning, packaging, shipping, and sample preservation shall be identified and used.

G. Measures shall be established for sample marking and labeling for packaging, shipping, handling, and storage as necessary to adequately identify, maintain, and preserve the sample. Markings and labels shall indicate the need for and the presence of special environments or the need for other special controls, if necessary.

H. Samples requiring special protective equipment (such as containers) and special protective environments (such as inert gas or limits on moisture and temperature) shall be specified, employed, verified, and documented.

4.4 DISPOSITION OF NONCONFORMING SAMPLES

A. Samples that do not conform to requirements specified in work controlling documents (such as job packages, travelers, or work requests) shall be identified, documented, evaluated, and segregated in accordance with Section 1.3.

B. The disposition for nonconforming samples shall be identified and documented and shall be limited to "use-as-is," "limited use," or "discard."

C. Samples that have lost their identity shall be documented as nonconforming and shall not be used.

SECTION 5 – SCIENTIFIC INVESTIGATION REQUIREMENTS

Scientific investigations shall be defined, controlled, verified, and documented. Process variables affecting scientific investigations shall be measured and controlled. Test processes conducted in support of such investigations shall be controlled in accordance with the requirements of Sections 2.4, *Inspection and Testing*, 2.4.4, *Test Requirements*, and 2.4.5, *Monitoring, Measuring, Testing, and Data Collection Equipment*, as applicable, and as supplemented by the requirements of this section.

5.1 PLANNING SCIENTIFIC INVESTIGATIONS

A. Variables that affect interrelated scientific investigations shall be identified and controlled appropriately in each related investigation.

B. The intended use of the data shall be documented before collection as part of the planning for data processing. Any alternate use of the data shall be evaluated for appropriateness and the justification for use shall be documented.

C. Planning shall consider the compatibility of data processing with any conceptual or mathematical models used at each applicable stage.

D. The technical adequacy of procedures for conducting scientific investigations and their implementation shall be reviewed and approved by qualified persons other than those who prepared the procedures. Changes to procedures for conducting scientific investigations shall be reviewed and approved in a manner commensurate with the original procedure.

E. Development activities used to establish new methods or procedures for conducting scientific investigations shall be documented. The results of developmental testing shall be reviewed for adequacy and approved by qualified persons prior to implementation of the procedures for data collection.

F. Planning shall be coordinated with organizations providing input to or using the results of the investigation.

G. Planning shall include the establishment of acceptance criteria for data quality evaluation to ensure that the data generated are valid and satisfy documented requirements for the following characteristics, as appropriate: data precision, data accuracy, data representativeness, data comparability, and data completeness.

H. Planning shall include the identification of known sources of error and uncertainty, as well as any input data that are suspect or whose quality is beyond the control of the performing organizations.

5.2 PERFORMING SCIENTIFIC INVESTIGATIONS

A. Scientific investigations shall be performed in accordance with requirements documented in test plans, procedures, and scientific notebooks.

B. If deviation from test standards or the establishment of specially prepared test procedures is deemed appropriate (e.g., no nationally recognized test standards exist), the modified or new test procedures shall be documented in sufficient detail to be repeatable and shall be justified, evaluated, and approved by the cognizant technical organization.

C. Scientific notebooks shall contain, at a minimum:

   1. A statement of the objectives and description of work to be performed or reference to an approved plan that describes the work

   2. The methods used

   3. Identification of the samples

   4. The M&TE used

   5. A description of the work performed and the results obtained, the names of individuals performing the work, and dated initials or signature, as appropriate, of individuals making the entries

   6. A description of changes made to methods used, as appropriate

   7. The potential sources of uncertainty and error in test plans, procedures, and parameters that must be controlled and measured to ensure that tests are valid

D. Scientific results shall be periodically reviewed by an independent qualified individual to verify that there is sufficient detail to retrace the investigation and confirm the results, if feasible, or repeat the investigation and achieve comparable results without recourse to the original investigator.

E. Practices, techniques, equipment, and manual or computerized methods used to obtain and analyze data shall be verified to ensure that they are technically sound and have been properly selected. Controls shall be established for these processes to ensure that they are properly implemented, including controls to prevent tampering.

F. Data collection and analysis shall be controlled by procedures of sufficient detail to allow the processes to be repeated. Where appropriate, quality control checks shall be performed using recognized methods such as replicate, spike, and split samples;

control charts; blanks; reagent checks; replication of the methods used to obtain the results; or alternate analysis methods.

G. Test media (e.g., fluids), when used, shall be characterized and controlled in accordance with test procedures.

H. Scientific notebooks and technical implementation documents shall be maintained as QA records.

5.3 DATA DOCUMENTATION, CONTROL, AND VALIDATION

5.3.1 Data Identification and Usage

A. All data shall be recorded so that they are clearly identifiable and traceable to the test, experiment, study, or other source from which they were generated. Identification and traceability of the data shall be maintained for the lifetime of the WIPP.

B. The method of data recording (e.g., scientific notebooks, log books, data sheets, or computerized instrumentation systems) shall be controlled to avoid data loss and permit data retrievability. Controls shall be established to ensure that data integrity and security are maintained wherever data are stored. Controls shall prescribe how specific types of data will be stored with respect to media, conditions, location, retention time, security, and access. Data shall be suitably protected from damage and destruction during their prescribed lifetime and shall be readily retrievable.

C. Data transfer and reduction controls shall be established to ensure that data transfer is error free (or within a prescribed permissible error rate), that no information is lost in transfer, and that the input is completely recoverable. Data transfer and reduction will be controlled to permit independent reproducibility by another qualified individual. Examples of data transfer include copying raw data from a notebook into computerized data form, or copying from computer tape to disk.

D. Data that are determined to be erroneous, rejected, superseded, or otherwise unsuited for their intended use shall be controlled to prevent their inadvertent use. Controls shall include the identification, segregation, and disposition of inadequate data. The basis for the disposition of erroneous data shall be justified and documented.

E. All processes which change either the form of expression or quantity of data, values, or number of data items (data reduction) shall be controlled by prescribed methods that allow for the validation of the conversion process.

F. Data collection and analysis shall be critically reviewed and questions resolved before the results are either used or reported. Uncertainty limits shall be assigned to the data prior to their use.

5.3.2 Data Validation

Data validation is a systematic process used to review data to ensure that the required data quality characteristics have been obtained. Results of the review may require that qualifiers be placed on the use of the data.

A. Validation methods shall be planned and documented. The documentation shall include the acceptance criteria used to determine if the data are valid.

B. All applicable data collected shall be validated. Validation shall include the following:

   1. The relevant documentation is reviewed to evaluate the technical adequacy, the suitability for the intended use, and the adequacy of the QA record.

   2. The results of the data review shall be documented.

   3. The reviewer shall be independent of the collection activities.

C. Data validation shall be controlled to permit independent reproducibility by another qualified individual.

D. Data considered as established fact by the scientific and engineering community, such as engineering handbook data or critical tables, do not require validation.

5.4 QUALIFICATION OF EXISTING DATA

A. This section contains requirements unique to the post-qualification of data and information that are relied upon to support the WIPP compliance application and were collected prior to the implementation of this QAPD. While the qualification process shall be conducted in accordance with the program control requirements of the CBFO QAPD, it is not intended that the QAPD identify the data that are subject to this process or the technical requirements of the qualification process. The qualification process shall be conducted in accordance with approved procedures that provide for documentation of the decision process, the factors used in arriving at the choice of the qualification method, and the decision that the data are qualified for their intended use.

B. Existing data shall be qualified using one or a combination of the following methods:

   1. Determination that the data were collected under a QA program that is equivalent in effect to ASME NQA-1-1989 edition; ASME NQA-2a-1990 addenda, Part 2.7, to ASME NQA-2-1989 edition; and NQA-3-1989. Factors to be considered include:

      a. Qualifications of personnel or organizations generating the data

b. Technical adequacy of the equipment and procedures used to collect and analyze the data

c. Environmental conditions under which the data were obtained (if germane)

d. Quality and reliability of the measurement control program under which the data were generated

e. Extent to which data demonstrate properties of interest (e.g., physical, chemical, geologic, or mechanical)

f. Extent to which conditions generating the data may partially meet requirements of this QAPD

g. Prior uses of the data and the associated verification processes

h. Prior peer or other professional reviews of data and their results

i. Extent and reliability of the documentation associated with the data

j. Extent and quality of corroborating data or confirmatory testing results

k. Degree to which data generating processes were independently audited

l. The importance of the data in showing that the repository design meets the performance objectives

2. The use of corroborating data, with the data relationships and inferences clearly identified and justified

3. Confirmatory testing that is performed and documented

4. Peer review conducted in a manner that is compatible with NUREG-1297, *Peer Review for High-Level Nuclear Waste Repositories*

   a. Peer reviews shall be performed when the adequacy of information or the suitability of procedures and methods essential to showing that a repository system meets its performance requirements with respect to safety and calculations, or reference to previously established standards and practices.

   b. Peer reviews performed in support of WIPP compliance activities shall be documented, as shall all peer review processes.

5. Peer reviews are used for the following activities:

   a. Conceptual models selected and developed by DOE

b. Waste characterization analysis as required in 40 CFR 194.24(b)

c. Engineered barrier evaluation as required in 40 CFR 194.44

SECTION 6 – SOFTWARE REQUIREMENTS

This section of the QAPD establishes software quality assurance (SQA) requirements for CBFO participants who develop, acquire, maintain, or use computer software that is important to compliance application and waste characterization.

6.1 APPLICABILITY

A. The requirements in this section apply to computer software used in the manipulation or production of data that are, in turn, used in the processing, gathering, or generation of information whose output is relied upon to make design, analytical, operational, or compliance-related decisions with respect to the performance of the waste confinement, waste characterization, waste transportation, or waste acceptance processes. The application of these requirements shall be prescribed in written plan(s), policies, procedures, or instructions.

B. The **basic requirements** defined in this section apply to those activities involved in the processing, control, or measurement of the hazardous, radioactive, and waste matrix materials of the TRU or TRU mixed waste. Waste matrix materials include but are not limited to metals, cellulosics, chelating agents, water, and other liquids, plastics, and rubber.

C. The **NQA-2 Part 2.7 requirements** defined in this section apply to software used in the processing, control, or measurement of the radioactive and waste matrix materials of the TRU waste. These requirements also apply to software used to model the performance of the WIPP for purposes of compliance application and/or reapplication.

D. Exempt from the requirements of this section of the QAPD is software that is considered to be "systems software" (e.g., operating systems, administrative and management systems, system utilities, compilers, assemblers, translators, interpreters, query languages, word processing programs, spreadsheets, database managers, and graphing programs) or other software that does not generate data that are used in the formulation of conclusions. Software utilized in conjunction with the documents prepared to comply with the National Environmental Policy Act (NEPA) is also excluded from the requirements of this section except to the extent that the results of the NEPA analysis are used as the basis for establishing how activities related to the items listed in Table I-1 are performed. These activities include those related to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility. Specific applications supporting Section 6.1A., written for use within these types of software (e.g., detailed formulas or macros) that can be verified by hand calculations or other means, shall meet the following requirements of this section:

1. A listing of the version of the software used shall be developed and maintained.

2. Documentation shall be prepared to indicate that the specific application provides the correct results for the specified range of input parameters.

6.2 Basic Requirements for Inventory and Classification of Software

A. An inventory of all applicable software shall be maintained that identifies the software name, version, classification, exemption status, operating environment, and the person and organization responsible for the software.

B. Software governed by this section of the QAPD shall be categorized. The criteria for classification shall be documented in the inventory and shall address the purpose of the software relative to its use in engineering, scientific, testing, data collection, design, analysis, and operations activities, as well as its importance to safety or its significance in managing information or augmenting mission-essential decisions.

6.3 Software Quality Assurance

6.3.1 Basic Requirements for Software Quality Assurance

Controls governing applicable software development projects shall be identified in controlled and documented plans. The plans shall be formally reviewed and approved. Controls governing the configuration and use of the software shall be identified in plans or procedures appropriate to the organizations using the software. The following activities shall be addressed in plans or procedures:

A. Software development

B. Software verification and validation

C. Software configuration control

D. Software operation and maintenance

Plans may be issued separately or as a single, composite plan, depending on the nature and complexity of the project. The software control plans may be a section of the overall project plan, provided that each software item is addressed and the software control portion of the plan prescribes the documentation, reviews, and controls required by this section.

6.3.2 NQA-2 Part 2.7 Requirements for Software Quality Assurance

Plans for ensuring software quality shall be prepared for each new software project at the start of the software life cycle. For acquired software, the software quality plan shall be prepared before the software enters the purchaser organization. Plans may be prepared individually for each software project, may exist as a generic document to be applied to software prepared within or procured by an organization, or may be

incorporated into the overall QA program. The plan shall identify:

A. The software products governed by the plan

B. The types of documentation to be prepared, reviewed, and maintained during the software design, development, implementation, test, and use

C. The organizations responsible for performing the work and achieving software quality, and their tasks and responsibilities

D. The process for reporting and documenting software discrepancies, evaluating the impact of discrepancies on previous calculations, and determining the appropriate corrective action(s)

E. The standards, conventions, techniques, or methodologies that guide the software development, as well as the methods used to ensure implementation of requirements

F. The procedure(s) used for establishing and maintaining the integrity of data, embodied mathematical models, and output files

6.4 SOFTWARE PROCUREMENT

6.4.1 Basic Requirements for Software Procurement

This section of the QAPD identifies responsibilities of the sponsoring organization for acquired software upon receipt of the software.

All procured software governed by this section shall be tested in accordance with documented and approved test procedures using approved test-case specifications to ensure that the acquired software will perform satisfactorily in its operating environment. The installation tests (including the test procedures), the test case specifications, and the results of the installation tests shall be identified, documented, and maintained as records according to established procedures.

6.4.2 NQA-2 Part 2.7 Requirements for Software Procurement

A. The procurement of software and related services shall be performed in accordance with Section 2.3 of this QAPD.

B. Once the software has been installed, but before its use, the sponsoring organization shall perform user acceptance to verify the functional capability of the software and the acceptability of the supplier's supporting documentation (e.g., the user manual, technical specifications, and the results of supplier testing).

C. For procured software, the supplier shall report software errors and failures to the

sponsoring organization. The sponsoring organization shall also report software errors to the supplier.

6.5 SOFTWARE DEVELOPED UNDER OTHER QA PROGRAMS

6.5.1 Basic Requirements

Software that has not been developed or approved in accordance with this QAPD shall be evaluated to determine its adequacy to perform intended functions. The evaluation shall be documented. The software shall be uniquely identified and controlled prior to the evaluation, clearly traceable to the software requirements, accepted by the sponsoring organization, and placed under configuration control prior to use.

6.5.2 NQA-2 Part 2.7 Requirements

The evaluation of existing software developed in accordance with other QA programs shall serve as the basis to

A. Determine the adequacy of existing verification and validation activities and software documentation to support operations and maintenance.

B. Identify the activities to be performed and the documentation necessary to accept the software for its intended use and place it under configuration control. The evaluation shall be documented and shall contain, at a minimum:

   1. User application requirements

   2. Test plans and test cases required to validate software acceptability

   3. User documentation as described in Section 6.9.2.6

6.6 SOFTWARE DEVELOPMENT AND LIFE CYCLE

6.6.1 Basic Requirements

The developmental activities of software projects subject to this QAPD shall be identified in documented and approved plans to ensure that the project proceeds in an orderly and traceable manner. Sufficient information shall be provided to clearly indicate the necessary tasks, the deliverables and baselines for each phase, the required reviews, appropriate milestones, and the responsibilities associated with each task.

Software project development plans shall identify the items that need to be baselined and the methods to be used for controlling the configuration of those baselines throughout the development process. Configuration control planning for software are addressed in Section 6.8 of this QAPD.

6.6.2 NQA-2 Part 2.7 Requirements

A. The activities associated with the evolution of the software shall be accomplished using an iterative or sequential approach. The approach shall include the analysis of the problem under study, the transformation of the analysis into the design, the implementation of the design into validated computer software, and the development of sufficient documentation to demonstrate that the specified requirements have been successfully included in the computer software.

B. The iterative or sequential approach to software development consists of phases, with each phase leading to the development of a specific work product representing components of the software baseline. The software phases are:

   1. Definition of requirements
   2. Design
   3. Implementation
   4. Testing
   5. Installation and checkout
   6. Operations and maintenance
   7. Retirement

C. Following the development of the software quality plan, no strict sequence of performing activities is required (i.e., activities may be performed serially or recursively) provided that all the specified requirements for each software development phase have been met and the intent of the requirements has not been subverted.

6.6.2.1 Requirements Phase

Software requirements shall be specified, documented, and reviewed. These requirements shall pertain to functionality, performance, design constraints, data attributes, and external interfaces (e.g., hardware limitations) as outlined in Section 6.9.2.2 Each requirement shall be specified in sufficient detail to permit the accomplishment of design and validation activities. Software requirements shall be traceable throughout the software development cycle, and a verification and validation plan shall be prepared after the software requirements have been documented and approved.

6.6.2.2 Design Phase

The software design shall be based on the software requirements and shall be documented and reviewed. The design shall specify the overall structure (control and data flow) and the reduction of the overall structure into physical solutions (algorithms, equations, control logic, and data structures). The design may necessitate the modification of the requirements documentation and the verification and validation plans.

6.6.2.3 Implementation Phase

The software design shall be translated into a form (programming language) suitable for processing by a computer. The executable software shall be analyzed to identify and correct errors.

6.6.2.4 Testing Phase

A. Test requirements and acceptance criteria shall be specified, documented, and reviewed and shall be based upon applicable design or other pertinent technical bases. Appropriate tests, such as verification tests, requirements-driven tests, hardware integration tests, and in-use tests, shall be controlled. Software testing, using documented test plans, test cases, and test results are the primary methods of software validation.

B. Testing of software shall be performed to the extent that unintended functions are identified and reviewed and their impact determined and corrected. If appropriate, determine if modifications are needed to the requirements, design, implementation, or test plans and test cases.

C. Design-driven tests shall be used to demonstrate the capability of the software to produce valid results for test problems encompassing the range of intended use as defined by the software documentation. Testing of software used for operational control shall demonstrate the required performance over the entire range of the controlled function or process. Acceptable test methods consist of:

1. Hand calculations

2. Calculations using comparable proven problems

3. Empirical data and information from confirmed published data and correlations or technical literature

4. Comparison with other validated software of similar purpose

5. Manual inspections or qualitative checks not involving numerical manipulation (examples include visual inspection of database reformatting or data plotting)

D. Requirements-driven tests shall be used to validate software by comparing test results of software execution with objective evidence obtained by the above methods. The results of this evaluation shall be of sufficient scope and depth to prove the capabilities and limitations delineated in the software documentation.

6.6.2.5 Installation and Checkout Phase

A. During installation and checkout, the software becomes part of a system consisting of applicable software components, hardware, and data. The process of integrating the software with other applicable components may consist of installing both the hardware and software, converting or creating databases, and verifying that all components of the system have been included in the installation. Test problems shall be developed and documented to permit confirmation of the acceptable performance of the software in its operating environment. Installation and checkout of software shall consist of:

1. Execution of tests for installation and integration

2. Documented acceptance of the software for operational use

3. Placement of the software under configuration control prior to use

B. Completion of the installation and checkout activities establishes the software baseline.

6.6.2.6 Operations and Maintenance Phase

A. Operation of the software is conducted by the user in accordance with the operation and usage instructions described in the software user documentation. Once the software has been made available for use, the software requirements and the design integrity shall be maintained. Maintenance activities shall be performed and documented in a traceable, planned, and orderly manner.

B. In all cases, verification and validation of software shall be completed and approved and corrective actions performed, as necessary, prior to relying upon the software to perform its intended function.

1. Post Installation Maintenance

Software shall be maintained to remove latent errors (corrective maintenance), to respond to new or revised requirements (perfective maintenance), or to adapt the software to changes in the operating environment (adaptive maintenance). Software modifications shall be approved by authorized personnel, documented, verified, validated, and controlled.

2. In-Use Tests:

Test problems shall be run whenever the software is installed on a different computer or when significant hardware or system software configuration changes are made. These tests shall be documented, performed by an individual technically competent in the subject area(s), and serve as the basis for determining if the software still meets specified requirements.

Periodic in-use manual or automatic self-check routines shall be prescribed and performed for that software where computer failure or electronic drift can affect required outcomes.

6.6.2.7 Retirement Phase

Criteria shall be developed to determine when software can be retired from use. Methods shall be developed to prevent the use of software that is no longer controlled. Upon retirement, user support for a software product is terminated.

6.7 SOFTWARE VERIFICATION AND VALIDATION

6.7.1 Basic Requirements

A. Verification and validation of software shall include the review of software activities, documentation, and tests to ensure that the software:

   1. Adequately and correctly performs all intended functions

   2. Does not perform any unintended function that either by itself, or in combination with other functions, can degrade the intended outcomes of the software

B. Verification and validation shall be performed by any competent individual(s) or group(s) other than those who performed the software design. The individuals may be from the same organization and may include the designer's supervisor, provided the supervisor:

   1. Did not specify a singular design approach

   2. Did not rule out certain design considerations

   3. Did not establish the design inputs used

   4. Is the only individual in the organization competent to perform the verification or validation

6.7.2 NQA-2 Part 2.7 Requirements

6.7.2.1 Verification

Verification is a formal checking activity performed throughout the evolution of the software life cycle. Verification activities shall be clearly documented, including the identification of those performing and approving the verification. The reviewed documents shall be updated and placed under configuration control. Documentation of review comments and their disposition shall be retained. Unincorporated comments and their disposition shall also be retained in accordance with established procedures.

6.7.2.2 Requirements

Verification review(s) of software requirements shall ensure that the requirements are complete, verifiable through testing, consistent, and technically feasible as described in Section 6.6.2.1.

6.7.2.3 Design

Verification review of software design shall evaluate the technical adequacy of the design approach and ensure that all the requirements have been addressed and that the design is complete, verifiable (through testing, using approved test plans and test cases), consistent, technically feasible, and traceable to the software requirements as described in Section 6.6.2.2.

6.7.2.4 Implementation

Verification of the implementation of software design shall consist of the examination of software logic and source code to ensure adherence to standards and conventions and to ensure that the design has been implemented as described in Section 6.6.2.3.

6.7.2.5 Testing

Verification of software testing shall consist of reviews to ensure that the specified test criteria, the expected results, and the software development documentation have been met as described in Section 6.6.2.4.

6.7.2.6 Installation and Checkout

Verification of installation and checkout activities consists of reviews to ensure that the software baseline has been established.

6.7.3 Validation

A. Software validation is primarily a formal testing activity that shall be performed prior

to installation and checkout. It shall be used to demonstrate that the computational model embodied in the software is an acceptable representation of the process or system for which it is intended and that the software produces correct solutions within defined limits for each parameter employed.

B. Validation methods, test data, software-generated results, and conclusions shall be documented in a form that can be understood by an independent individual technically competent to use the software for the particular problem under study. The documentation shall be reviewed to assess the adequacy and correctness of the documentation in meeting the requirements of this section of the QAPD and the overall acceptability of the software for the intended use.

C. When the adequacy of the conceptual, mathematical, or computational models or the suitability of procedures and methods cannot be established through testing, alternate calculations, or reference to previously established standards and practices, a documented peer review shall be performed to meet the software validation requirements.

D. The validation of software modifications shall be subject to selective regression testing to

   1. Detect errors introduced during the modification of the systems or system components

   2. Verify that the modifications have not caused unintended adverse effects

   3. Verify that the modified systems or system components still meet specified requirements

6.8 SOFTWARE CONFIGURATION MANAGEMENT

6.8.1 Basic Requirements

A. Implementation of baseline and change control processes are fundamental to configuration management. A baseline is a collection of all approved components of the software development cycle. As each component is approved, it is added to the overall software baseline. A software baseline serves as the basis for further development and maintenance that can be changed only through the use of formal change control procedures. Change control is the process by which a change to a baseline is proposed, evaluated, and approved or rejected.

B. Software configuration controls shall be planned, including the identification of organizational positions that are authorized to make changes, and the methods, procedures, and instructions to be used to control the identification of, access to, changes to, and the status of computer software. Configuration control documents shall indicate how changes will be validated, including regression testing, and how

the tests will be documented. These control documents shall be formally reviewed, approved, and in place before the software is released for use.

6.8.2 NQA-2 Part 2.7 Requirements

6.8.2.1 Configuration Identification

Software shall be placed under configuration control as each configuration item is approved. A software baseline shall define the most recent approved software configuration. The configuration items and their associated documentation shall be traceable to one another. A labeling system for configuration items shall be implemented that:

A. Uniquely identifies each configuration item

B. Identifies changes to configuration items by revision or version identifier

C. Provides the ability to uniquely identify each approved configuration of the revised software that is available for use

6.8.2.2 Configuration Change Control

A. Changes to software shall be systematically proposed, evaluated, documented, and approved to ensure that the impact and rationale for making the change is carefully assessed prior to updating the software baseline. Changes to previously accepted software shall be subject to the same level of control as the original software.

B. Information concerning approved changes shall be transmitted to all affected organizations. All changes shall be formally evaluated and approved by the organization responsible for the original design, unless an alternate organization has been given the authority to approve the changes. Only authorized changes shall be made to software baselines. Software verification activities shall be performed for the change as necessary to ensure that the change is appropriately reflected in the software documentation and to ensure that traceability is maintained. The degree of software validation shall be commensurate with the nature and scope of the change.

6.8.2.3 Configuration Status Accounting

Information shall be maintained that reflects the current status of the software baseline. This includes the identity and version of the approved configuration and the status of any proposed and approved changes to the baseline components. This information shall be available to all designated users of the software upon request.

6.9 DOCUMENTATION

6.9.1 Basic Requirements

Software shall be described in one or more documents that detail user instructions, technical bases, functional requirements, and maintenance-related information sufficient to allow independent verification and maintenance and to provide traceability of the documentation to the software. The documentation shall be reviewed by an individual competent in the technical subject area for which the use of the software is intended. The review shall verify that the documentation adequately and accurately reflects the software that constitutes the system, and is sufficient to objectively demonstrate that the software requirements have been successfully implemented. Appropriate documentation shall be made available to all designated users of the software.

6.9.2 NQA-2 Part 2.7 Requirements

6.9.2.1 Procurement Documentation

The applicable quality assurance requirements shall be specified and the required vendor-supplied software documentation, plans, and procedures shall be identified in the software procurement documentation.

6.9.2.2 Requirements Documentation

A. Software requirements documentation shall outline the requirements that the proposed software must satisfy. The software requirements shall, as applicable, address the following:

   1. Functionality - the functions the software performs

   2. Performance - the time-related issues of software operation such as speed, recovery time, and response time

   3. Constraints – limits imposed on implementation activities; any elements that will restrict design options

   4. Attributes - non-time-related issues of software operation such as portability, acceptance criteria, access control, and maintainability

   5. External interfaces - interactions with people, hardware, and other software

B. Software requirements shall be traceable throughout the software development cycle.

6.9.2.3 Design and Implementation Documentation

Software design and implementation documentation consists of a document or series of documents that:

1. Describe the major components of the software design as they relate to the software requirements

2. Describe the theoretical basis, embodied mathematical model, control flow, control logic, and data structure(s) of the software

3. Describe the allowable or prescribed ranges for inputs and outputs

4. Describe the design in a manner that can be translated into executable code

6.9.2.4 Verification and Validation Documentation

A. Software verification and validation documentation shall consist of associated plans and shall describe the activities (including the results of reviews and tests) and the criteria for accomplishing the verification of the software throughout the software evolution process. The documentation shall also specify the hardware and software configurations pertinent to the software verification and validation.

B. Software verification and validation documentation shall be organized in a manner that allows traceability from the software requirements to both the software design and to the validated capabilities of the software.

6.9.2.5 Change Documentation

Changes to software shall be formally documented. This documentation shall contain a description of the change, the rationale for the change, and the identification of affected configuration items of the software baseline.

6.9.2.6 User Documentation

User documentation should be sufficient to allow any qualified user (i.e., one having adequate technical background) to install and run the software and properly respond to errors. User documentation, at a minimum, shall include:

A. The software name and version identifier

B. Statements of functional requirements and system limitations, including hardware

C. An explanation of the mathematical models and derivation of the numerical methods used in the software design (physical and mathematical assumptions on which the

software is based shall be included, along with an explanation of the capabilities and limitations inherent in the software)

D. Instructions that describe user interaction with the software, user messages initiated as a result of improper input and how the user can respond, the identification and description of input and output specifications and formats, and input parameters

E. A description of any required training necessary to use the software

F. Information for obtaining operation and maintenance support

6.9.2.7 Error Documentation

Documentation of errors detected during the use of the software following installation and checkout shall be maintained. This documentation can be used for process improvement and to prevent recurrence of errors during the development and maintenance of other software. This documentation shall contain the identity of the software, the classification of the error in terms of its significance to the integrity of the software output, and the corrective action(s).

6.10 PROBLEM REPORTING AND CORRECTIVE ACTION

6.10.1 Basic Requirements

Problems (e.g., errors, faults, failures) detected in released software shall be promptly reported in accordance with documented procedures. When problems are detected in a software item, work previously performed using versions of the software that contain that problem shall be evaluated to determine the impact on the completed work. The evaluations shall be documented and retained in accordance with records requirements.

6.10.2 NQA-2 Part 2.7 Requirements

A. A system shall be established and maintained to record, classify, analyze, track, and report software problems (in released versions) and the associated corrective actions. Problems shall be promptly reported to any affected organizations and the resolution shall be formally processed.

B. When problems are discovered in software or software results, the sponsoring organization shall determine the affect on previous uses and the need for corrective action based on sufficient information obtained from the affected users. Corrective action shall ensure that

   1. Problems are identified, evaluated, documented and, if required, corrected

   2. Problems are assessed for their impact on past and present uses of the software

3. Changes to software are in accordance with the software configuration management requirements of this section of the QAPD

4. Results are provided to the affected users, along with any revised software documentation

C. Problems that could significantly affect decisions based upon prior use or that require significant modification to the software shall be identifiable to all users. Errors that have been determined to represent a condition adverse to quality shall be controlled in accordance with Section 1.3 of this QAPD.

6.11 ACCESS CONTROL

To the extent appropriate, controls shall be established to permit authorized and prevent unauthorized access to software that has been accepted in accordance with this section.

APPENDIX A – GLOSSARY

Acceptance: The documented determination by the receiving organization that a work project is suitable for the intended purpose.

Acquired Software: Computer software obtained that was not developed by the user organization.

Alternative Calculations: Calculations that are made with alternative methods to verify correctness of the original calculation.

Approval: The documented determination by a responsible individual that a work product is suitable for the intended purpose and shall be used as required.

Assessment/Evaluation: The act of reviewing, inspecting, testing, checking, conducting surveillances, auditing, or otherwise determining and documenting whether items, processes, or services meet specified requirements. Assessments are performed by or for management. Evaluations are performed by the line organization.

Assessment, External: An assessment of those portions of an organization's quality assurance program not under the direct control or within the organizational structure of the auditing organization.

Assessment, Internal: An assessment of those portions of an organization's quality assurance program retained under its direct control and within its organizational structure.

Assessor: An individual who is qualified to perform assigned portions of an assessment.

Audit: A planned and documented independent assessment to determine by investigation, examination, or evaluation of objective evidence the adequacy of and compliance with established procedures, instructions, drawings, and other applicable documents, and the effectiveness of implementation. An audit should not be confused with surveillance or inspection activities performed for the sole purpose of process control or product acceptance.

Auditor: An individual who is qualified to perform assigned portions of an audit.

Audit (or Assessment) Team Leader: A lead auditor (or assessor) who is assigned to direct the efforts of an audit (or assessment) team.

Calibration: The set of operations which establish, under specified conditions, the relationship between values indicated by a measuring instrument or measuring system, and the corresponding standard or known values derived from the standard.

Certificate of Conformance: A document signed or otherwise authenticated by an authorized individual certifying the degree to which items or services meet specified requirements.

Certification: The act of determining, verifying, and attesting to, in writing the qualifications of personnel, processes, procedures, or items in accordance with specified requirements.

Characteristic: A property or attribute of an item, process, or service that is distinct, describable, and measurable.

Commercial Grade Item: An item that is (1) not subject to design or specification criteria unique to a CBFO program or facility, (2) used in applications other than the nuclear industry, and (3) ordered from the manufacturer or supplier on the basis of specifications set forth in the manufacturer's published product description.

Compliance Certification Application: The compliance certification application submitted to the EPA pursuant to section 8 (d) (1) of the WIPP Land Withdrawal Act of 1992 (Pub.L. 102-579, 106 Statue 4777) or any compliance re-certification applications submitted to the EPA pursuant to section 8(f) of the WIPP Land Withdrawal Act.

Condition Adverse to Quality: An all-inclusive term used in reference to any of the following: failures, malfunctions, deficiencies, defective items, nonconformances, and technical inadequacies. A condition adverse to quality is considered significant when

- if uncorrected, the condition adverse to quality could have a serious effect on safety, operability, waste isolation, TRU waste site certification, regulatory compliance demonstration, or effective implementation of the QA program
- the condition adverse to quality is non-compliant with the HWFP
- the condition adverse to quality requires immediate notification of regulatory entities (e.g., 10 CFR Part 21)
- the condition adverse to quality indicates a significant failure or breakdown in the implementation of QA Program requirements
- repeated attempts to resolve a condition adverse to quality have been unsuccessful
- the condition adverse to quality is identified in items or activities important to safety or waste isolation and compromises the ability to prevent or mitigate the consequences of an accident, thereby presenting a significant hazard to safety and health of workers and/or the public

Configuration Control: The process of identifying and defining the configuration items in a system, controlling the release and change of these items throughout the system

life cycle, and the recording and reporting of the status of configuration items and change requests.

Configuration Item: A collection of hardware or software elements treated as a unit for the purpose of configuration control.

Controlled Document: A document that is prepared, reviewed, approved, and distributed in accordance with established implementation procedures. Controlled documents are subject to controlled distribution and to a defined and controlled change process.

Corrective Action: Measures that are taken to rectify conditions adverse to quality and, where necessary, to preclude recurrence.

Corrective Action Report (CAR): A document used to identify and rectify conditions adverse to quality (CAQ), and track the associated corrective actions. CARs address CAQs that are primarily programmatic in nature, as opposed to nonconformance reports (NCRs) which address CAQs relating to a specific item(s) such as a piece of hardware or data. The category of CARs includes: corrective action reports or corrective action requests, nonconformance corrective action reports (NCARs), management corrective action reports (MCARs), deficiency reports (DRs), process deficiency reports (PDRs), audit findings, condition adverse to quality reports(CAQR), etc.

Data Accuracy: The degree to which data agree with an accepted reference or true value. Accuracy is a measure of the bias in a system.

Data Comparability: A measure of the confidence with which one data set can be compared to another.

Data Completeness: A measure of the amount of valid data obtained compared to the amount that was planned.

Data Precision: A measure of the mutual agreement between comparable data gathered or developed under similar conditions, usually expressed in terms of a standard deviation.

Data Representativeness: The degree to which data accurately and precisely represent a characteristic of a population, a parameter, variations at a sampling point, or environmental conditions.

Data Quality Objectives (DQOs): Qualitative and quantitative statements derived from outputs of the first six steps of the DQO Process (see below). DQOs; 1) clarify the study objective, 2) define the most appropriate type of data to collect, 3) determine the most appropriate conditions from which to collect the data, and 4) specify tolerable limits on decision errors which will be used as the basis for establishing the quantity and

quality of data needed to support compliance decisions. DQOs are used to develop a scientific and resource-effective data collection design.

DQO Process: A strategic planning approach based on the Scientific Method that is used to prepare for a data collection activity. The DQO process provides a systematic procedure for defining the criteria that a data collection design should satisfy, including when to collect samples, where to collect samples, the tolerable level of decision errors for the study, and how many samples to collect. By using the DQO process, DOE will assure that the type, quantity, and quality of environmental data used in decision making will be appropriate for the intended application. In addition, DOE will guard against committing resources to data collection efforts that do not support a defensible decision. The DQO process consists of seven steps and is more fully described in EPA 1994b.

Design Basis: Information that identifies the specific functions to be performed by items and the specific values or ranges of values chosen for controlling parameters as reference bounds for design.

Design Input: Those criteria, parameters, bases, or other design requirements upon which the detailed final design is based.

Design Output: Drawings, specifications, and other documents resulting from the translation of design input requirements.

Design Process: The technical process that begins with the identification of design input and ends with the issuance of design output documents.

Design Review: A documented evaluation of design output during the design process to determine the design adequacy and the conformance to specified acceptance criteria.

Disposal System: Any combination of engineered and natural barriers that isolate transuranic waste after disposal. For the purposes of the WIPP, this will include the combination of the repository/shaft system and the controlled area.

Document: Written or pictorial information that describes, specifies, reports, or certifies activities, requirements, procedures, or results.

Document Control: The process that provides for document adequacy review, approval for release by authorized personnel, and distribution for use at the prescribed work locations.

Error: A discrepancy between a computed, observed, or measured value or condition and the true, specified, or theoretically correct value or condition.

Graded Approach: The process by which the level of analysis, documentation, verification, and other controls necessary to comply with QA program requirements are developed commensurate with specified factors.

Independent Assessment: An assessment, conducted by a group or organization having authority and freedom from the line organization, to evaluate the scope, status, adequacy, programmatic implementation, or effectiveness of a program or process.

Item: An all-inclusive term used in place of any of the following: appurtenance, assembly, component, equipment, material, module, part, structure, subassembly, subsystem, system, unit, support system, or data.

Lead Auditor: An individual trained, qualified, and certified to organize and direct an audit, report audit findings, and evaluate corrective actions.

Lifetime Records: Records required to be maintained for the useful life of the items to which they pertain while the items are installed in the plant or facility (life of the item), or for the lifetime of the equipment, facilities, or programs to which the records apply.

Line Management: Those management positions that are directly responsible for task products and services. Includes CBFO supervisors and team leaders and contractor management within the context of the definition.

Line Organization: The organization directly responsible for task products and services. Includes CBFO offices and teams and contractor organizations within the context of the definition.

Macro: Single computer instructions invoked by a symbol, name, or key that represents commands, actions, or keystrokes.

Management Assessment: Assessment performed by management that focuses on how well the integrated quality assurance program is working. The management assessment should identify management problems that hinder the organization from achieving its objectives in accordance with quality, safety, and environmental requirements.

Measuring and Test Equipment: All devices used to calibrate, measure, gage, test, inspect, or otherwise determine compliance with prescribed technical requirements.

Monitoring and Data Collection (M&DC) Equipment: A subcategory of M&TE that is used in the collection of measurement data for the establishment of test conditions and general information and the collection of general measurement data not utilized to verify the conformance of an item or equipment to specified criteria.

Nonconformance: A deficiency in a characteristic or record that renders the quality of an item or sample unacceptable or indeterminate.

Nonpermanent Records: Records having value for a specific, limited time and authorized by the National Archives and Records Administration to be destroyed after that time.

Nonreactor Nuclear Facility: Those activities or operations that involve radioactive or fissionable materials in such form and quantity that a nuclear hazard potential exists to the employees or the general public. Incidental use and the generation of radioactive materials in a facility operation (e.g., check and calibration sources, radioactive isotopes used in research and experimental and analytical laboratory activities, electron microscopes, and x-ray machines) would not ordinarily require the facility to be included in this definition. The transportation of radioactive materials, accelerators, and reactors and their operations are not included.

Participant: A DOE contractor organization that furnishes items or services in support of CBFO-sponsored programs, including those TRU waste generator and storage sites participating in the National TRU Waste Program.

Peer: A person having technical expertise in the subject matter to be reviewed to a degree at least equivalent to that needed for the original work.

Peer Review: A documented, critical review performed by peers who are independent of the work being reviewed. A peer review is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn in the original work. Peer reviews confirm the adequacy of work.

Periodic: Occurring or recurring at regular intervals. For the purposes of this QAPD, these intervals are determined by the responsible management unless otherwise specified.

Post-Closure QA Records: QA records required to be maintained beyond the operating life of the WIPP repository, for periods of several hundreds of years, and in a manner that would permit future generations to maintain them longer, if desired, using present reasonably available technology.

Procedure: A document that specifies or describes how an activity is to be performed. The term "procedure" also includes instructions and drawings.

Process: A series of actions that achieve an end or result.

Procurement Document: Purchase orders, contracts, specifications, or other documents used to define technical and quality assurance requirements for the procurement of items or services.

Qualification (Personnel): The characteristics or abilities gained through education, training, or experience, as measured against established requirements such as standards or tests, that qualify an individual to perform a required function.

Qualification Testing: A test that is intended to provide a desired level of confidence that an item meets specified criteria.

Quality: The condition achieved when an item, service, or process meets or exceeds the user's requirements and expectations.

Quality Assurance: All those planned and systematic actions necessary to provide adequate confidence that an item will perform satisfactorily in service.

Quality Assurance Objectives: Objectives that represent the required quality of data necessary to draw valid conclusions regarding program objectives.

Quality Assurance Program: The program established to assign responsibilities and authorities, define policies and requirements, and provide for the performance and assessment of work.

Quality Assurance Record: A completed record or any authenticated portion of a record that provides objective evidence of the quality of items or activities.

Quality System: See *Quality Assurance Program*.

RCRA Related Deficiency: A deficiency that is a violation of the requirements of the WIPP Hazardous Waste Facility Permit.

Readiness Review: A systematic documented review of the readiness for startup or continued extended use of a facility, process, or activity. Readiness reviews are typically conducted before proceeding beyond project milestones and prior to commencement of a major phase of work activities.

Receipt Inspection: A method of accepting an item or related service from a supplier by examination or testing of the item or related service to verify conformance to specified requirements.

Records: Books, papers, maps, photographs, machine readable materials or other documentary materials, regardless of physical form or characteristics, made or received by an agency of the United States Government under Federal law or in connection with the transaction of public business and preserved or appropriate for preservation by that

agency or its legitimate successor as evidence of the organization, functions, policies, decisions, procedures, operations or other activities of the government or because of the informational value of the data they contain.

Records Holding Facility: A CBFO records storage facility meeting regulatory requirements for the storage of inactive records pending their final disposition.

Repair: The process of restoring an item to a condition such that the capability of an item to function reliably and safely is unimpaired even though that item still does not conform to the original requirement.

Rework: The process by which an item is restored to original specifications by completion or correction.

Sample: A subset of a population (e.g., wastes, environmental media, materials, cores) whose properties are used to gain information about the population.

Scientific and Engineering Software: Software that uses numerical methods to complete scientific, engineering, and mathematical calculations.

Scientific Investigation: Any research, experiment, test, study, or activity that is performed for the purpose of investigating a natural system or the man-made aspects of a geologic repository, including the investigations that support design of the facilities and the waste package.

Scientific Notebook: A record of the methods and results of scientific investigations that is used when the work involves a high degree of professional judgment or trial and error methods, or both.

Service: The performance of work, such as design, construction, fabrication, inspection, nondestructive examination, testing, environmental qualification, equipment qualification, repair, installation, or similar activities.

Significant Condition Adverse to Quality: See *Condition Adverse to Quality*.

Site Characterization: The program of exploration and research both in the laboratory and the field that is undertaken to establish the natural conditions and the ranges of parameters of a particular site.

Software: Computer programs, procedures, rules, and associated documentation and data pertaining to the operation of a computer system.

Software Baseline: An item or product that has been formally reviewed and agreed upon, that serves as the basis for further development, and that can be changed only through formal change control procedures.

Software Quality Assurance Plan: A plan for the development of software products necessary to provide adequate confidence that the software conforms to established requirements.

Software Routine: A collection of computer macros or script files, a spreadsheet application, or other stand-alone software application (either acquired or developed) that generally operates within another program, such as a spreadsheet, and must be independently verified by visual inspection and/or hand calculation.

Software Validation: The process of test and evaluation of the completed software to ensure compliance with software requirements.

Software Verification: The process of determining whether or not the product of a given phase of the software development cycle fulfills the requirements imposed by the previous phase.

Software Verification and Validation: The process of determining whether the requirements for a system or component are complete and correct, the products of each development phase fulfill the requirements or conditions imposed by the previous phase, and the final system or component complies with specified requirements.

Source Verification: A purchaser method of accepting an item or related service from a supplier by monitoring, auditing, surveillance, witnessing, or observing activities performed by the supplier.

Special Process: A process, the results of which are highly dependent on the control of the process or the skill of the operators, or both, and in which the specified quality cannot be readily determined by inspection or test of the product.

Supplier: Any individual or organization who furnishes items or services in accordance with a contract. An all-inclusive term used in place of any of the following: vendor, seller, source, participant, contractor, or subcontractor.

Surveillance: The act of monitoring or observing to verify whether an item, activity, system, or process conforms to specified requirements. Surveillance of a technical work activity is normally done in real time (i.e., the surveillance is accomplished as the work is being performed).

System Software: Software which is used exclusively in the preparation, installation, or operation of executable software applications. Examples of such software include operating systems, administrative and management systems, system utilities, compilers, assemblers, translators, interpreters, automated protocols, utilities and tools, teleprocessing managers, and query languages.

Technical Review: A documented critical review of work that has been performed within the state of the art. The review is accomplished by one or more qualified reviewers who are independent of the work but collectively have equivalent technical expertise to those who performed the original work. The review is an in-depth analysis and evaluation of documents, activities, material, data, or items that require technical verification or validation for applicability, correctness, adequacy, completeness, and assurance that established requirements are satisfied.

Technical Specialist: An individual assigned to an assessment team when the scope, complexity, or special nature of the work to be examined warrants assessment of the technical adequacy of the work or the effectiveness of the technical process.

Testing: An element of verification to determine the capability of an item to meet specified requirements or processes that facilitate the collection of data in conducting scientific investigations by subjecting the item or environment to a set of physical, chemical, environmental, or operating conditions.

Traceability: The ability to trace the history, application, and location of an item, data, or sample using recorded documentation. As related to metrology, traceability means the ability to relate individual measurement results through an unbroken chain of calibrations to one or more of the following:

- U.S. national standards maintained by National Institute of Standards and Technology or the U.S. Naval Observatory
- Fundamental or natural physical constants with values assigned or accepted by the National Institute of Standards and Technology
- National standards of other countries which are correlated with NIST

Transuranic Waste: Waste containing more than 100 nCi of alpha-emitting TRU isotopes per gram of waste, with half-lives greater than 20 years, except for (1) high-level radioactive waste, (2) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations, or (3) waste that the NRC has approved for disposal on a case-by-case basis in accordance with 10 CFR § 61.

TRU Mixed Waste: TRU waste that is also a hazardous waste as defined by the Hazardous Waste Act and 20 NMAC 4.1.200 (incorporating 40 CFR § 261.3).

Use As Is: A disposition permitted for a nonconforming item when it can be established that the item is satisfactory for its intended use.

Validation: An activity that demonstrates or confirms that a process, item, data set, or service satisfies the requirements defined by the user.

WIPP: The Waste Isolation Pilot Plant, as authorized pursuant to Section 213 of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub.L. 96-164; 93 Stat. 1259, 1265) to provide a research and development facility for demonstrating the safe disposal of radioactive wastes produced by national defense activities.

Work: The process of performing a defined task or activity, for example, research and development, operations, maintenance and repair, administration, software development and use, inspection, safeguards and security, data collection, and analysis.

Work Suspension: A formal directive issued by management that work must be stopped until the related significant condition adverse to quality or nonconformance has been resolved.

APPENDIX B – REFERENCES

10 CFR Part 71, Subpart H, *Packaging and Transportation of Radioactive Material, Quality Assurance*

10 CFR Part 830, *Nuclear Safety Management*

40 CFR Part 194, *Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with 40 CFR Part 191 Disposal Regulations*

ASME NQA-1-1989, *Quality Assurance Program Requirements for Nuclear Facilities*

ASME NQA-2a-1990 addenda, Part 2.7, *Quality Assurance Requirements of Computer Software for Nuclear Facility Applications*

ASME NQA-3-1989, *Quality Assurance Program Requirements for the Collection of Scientific and Technical information for Site Characterization of High-Level Nuclear Waste Repositories*

DOE/WIPP- 02-3122, *Contact-Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant*

DOE, Division of Nuclear Safety, G-830.120*, Implementation Guide for use with 10 CFR Part 830.120 Quality Assurance*

DOE O 414.1A, *Quality Assurance*

National Fire Protection Association (NFPA) Standard 232-1986, *Standards for the Protection of Records*

NUREG-1297 (1988), *Peer Review for High-Level Nuclear Waste Repositories*

NUREG/BR-0167 (1993), *Software Quality Assurance Program and Guidelines*

SNT-TC-1A, Current Revision, *The American Society of Nondestructive Testing (ASNT) Recommended Practice*

Waste Isolation Pilot Plant Hazardous Waste Facility Final Permit, EPA No. NM4890139088

APPENDIX C – CBFO ORGANIZATION, RESPONSIBILITIES, AND INTERFACES

Effective implementation of the CBFO QA program is dependent on efforts at all CBFO levels. The CBFO organization is structured such that those assigned responsibility for performing the work are responsible for achieving and maintaining quality. Management is responsible for defining quality, developing appropriate plans to attain quality, and providing support of the workers in pursuit of quality. Persons or organizations not directly responsible for performing the work verify quality achievement. Management empowers employees by delegating authority and decision making to the lowest appropriate level in the organization.

The CBFO Manager is responsible for overall implementation of DOE programs, policies, orders, and guidance pertaining to the National TRU Waste Program (NTWP). The CBFO Manager is responsible for overall implementation of TRU waste disposal at WIPP. As such, the Manager provides policy direction and oversight of activities that affect TRU waste characterization and grants DOE waste certification authority to the TRU waste sites. This responsibility includes policy direction and oversight for waste characterization, certification, packaging, and transportation activities at participating sites. Overall responsibility for the development and implementation of the CBFO QA program belongs to the CBFO Manager. Authority for execution of the QA function, which ensures effective implementation, is delegated to the CBFO QA Manager.

The Assistant Manager, Office of the National TRU Program is responsible to ensure that program requirements are met with regard to TRU waste testing, sampling, analysis, sample handling and custody, and associated data management.

CBFO Assistant Managers are responsible for planning, organizing, directing, controlling, and evaluating those activities in their area of responsibility that support the CBFO mission and implement the QAPD. Their responsibilities include, but are not limited, to

- Ensuring that adequate technical and QA training is provided for personnel performing activities important to the satisfaction of CBFO organizational and quality objectives

- Ensuring compliance with all applicable regulations, DOE orders, applicable state, and local laws, and other requirements applicable to CBFO programs

- Ensuring that personnel adhere to procedures for the generation, identification, control, and protection of QA records

- Exercising the authority and responsibility to stop unsatisfactory work such that cost and schedule do not override environmental, safety, health, or

quality considerations

- Developing, implementing, and maintaining plans, policies, and procedures that implement the QAPD

- Identifying, investigating, reporting, and correcting quality problems

Each CBFO employee, including contractor personnel working to CBFO procedures, is responsible for the quality of his or her work and for promptly reporting all existing, developing, or potential conditions adverse to quality to the responsible management for evaluation and action.

Organizations at all management levels shall establish communication channels that provide timely, routine, and wide dissemination of information pertinent to quality performance.

Where more than one CBFO organization is involved in the execution of activities covered by the QAPD, the responsibility and authority of each organization shall be clearly established and documented. The internal interfaces between organizational units are depicted in CBFO organizational charts. CBFO external interfaces include other DOE elements, CBFO program participants, suppliers, the Environmental Protection Agency, the Environmental Evaluation Group, and the New Mexico Environment Department.

APPENDIX D – CBFO QUALITY ASSURANCE MANAGER RESPONSIBILITIES

The CBFO Manager has overall responsibility for the CBFO QA program. Authority for execution of the CBFO QA function, including the independent verification of effective implementation, is delegated to the CBFO QA Manager. It is the policy of CBFO to grant the CBFO QA organization sufficient authority, freedom, and access to all work areas to:

- Identify quality problems
- Recommend solutions
- Verify implementation of solutions
- Ensure that unsatisfactory conditions are controlled until proper disposition has occurred

The CBFO QA Manager shall:

- Have direct access to responsible management at a level where appropriate action can be effected
- Be sufficiently independent from cost and schedule considerations
- Have the organizational freedom to communicate with management
- Have the authority and responsibility to stop unsatisfactory work such that cost and schedule do not override environmental, safety, or health considerations
- Have no other assigned responsibilities related to the quality assurance program that would prevent adequate attention to quality assurance matters

The CBFO QA Manager has the authority and overall responsibility to independently assess the effective implementation of the CBFO QAPD, both within the CBFO organization and in those participant organizations supporting CBFO.

The CBFO QA Manager has the following additional authorities and responsibilities:

- The organizational freedom to communicate with management
- Scheduling and conducting independent QA assessments, including WIPP core participant organizations

- Scheduling and conducting audits of activities related to waste generating site certification when notified by the Assistant Manager, Office of the National TRU Program, that the waste generating site is ready

- Scheduling and conducting recertification audits and surveillances of waste generating sites

- Preparing, as appropriate, and reviewing internal procedures that implement the provision of the QAPD

- Tracking, performing trend analysis, and reporting quality problem areas

- Developing, establishing, and interpreting CBFO QA policy and ensuring effective implementation

- Preparing, issuing, and maintaining the CBFO QAPD

- Interfacing with the CBFO staff, participants, and other stakeholders on quality assurance matters

- Reviewing and approving subordinate QA plans, including participant Quality Assurance Project Plans

- Performing adequacy reviews of QA program documents

- Certifying all CBFO lead auditors and qualifying auditors and technical specialists

- Assuring the independence of lead auditors, auditors, and technical specialists

APPENDIX E – TRU WASTE CHARACTERIZATION AND CERTIFICATION ORGANIZATIONAL AND INDIVIDUAL RESPONSIBILITIES

1. CBFO Assistant Manager, Office of the National TRU Program

   The Assistant Manager (AM), Office of the National TRU Program (NTP) executes program functions related to characterization of waste for disposal at the WIPP. The AM NTP manages the National TRU Waste Program (NTWP) team, which is responsible for TRU waste characterization. The AM NTP also manages activities that prepare waste sites for certification and notifies the CBFO QA Manager when new sites are ready for independent audit.

2. CBFO Assistant Manager, Office of Regulatory Compliance

   The Assistant Manager, Office of Regulatory Compliance (ORC), is responsible for regulatory compliance of the WIPP. The ORC AM manages the Compliance team, which is responsible for environmental activities at the WIPP. The ORC AM is responsible for the preparation of compliance documentation and the implementation of programs to meet the requirements specified in final operating permits for the WIPP facility.

3. CBFO Assistant Manager, Office of Safety and Operations

   The Assistant Manager, Office of Safety and Operations, is responsible for operations, safety and health oversight at the WIPP.

4. DOE Field Office

   The DOE field offices are responsible for ensuring that the requirements of the QAPjPs are in compliance with all DOE orders and that the resources and funding are available to accomplish Program activities. The DOE field offices are responsible for providing a liaison between the site contractors and the CBFO.

5. TRU Waste Sites

   Each participating site shall develop and implement a QAPjP that demonstrates compliance with and implementation of WIPP TRU waste characterization requirements and the applicable requirements of the WIPP Hazardous Waste Facility Permit and its associated Waste Analysis Plan. These QAPjPs shall include or reference the appropriate management and technical criteria of the Program, as well as qualitative or quantitative criteria for determining that Program activities are being satisfactorily performed. QAPjPs shall identify the organizations and positions responsible for their implementation. The QAPjPs

shall also reference site-specific documentation that details how each of the required elements of the Program will be performed. QAPjPs and subsequent revisions must be reviewed for concurrence by the Site Project Manager, Site Project QA Officer, the cognizant DOE Field Officer, the CBFO NTP AM and the CBFO QA Manager.

Prior to the implementation of Program activities at participating sites, standard operating procedures (SOPs) will be developed for all activities affecting Program quality that require written instructions or procedures. For the purposes of the Program, the term SOP refers to any site-specific implementing document. Compliance with SOPs will ensure that tasks are performed in a consistent manner that results in achieving the quality required for the Program. The organization, format, content, and designation of SOPs must be described in the QAPjPs.

6. Site Project Manager

Each participating site's contractor designates a site project manager to oversee characterization program activities at the site. A description of the site project manager's role in relation to the other organizational functions at the site must be included in the site's QAPjP. The site project manager (or designee) reviews and recommends approval of the site QAPjP and subsequent revisions before it is submitted to CBFO for review. Specific Program responsibilities assigned to the site project manager include the following:

- Waste selection and tracking
- Data validation/verification
- Data reconciliation with DQOs
- Assignment of EPA Hazardous Waste Numbers
- QA/QC reports to DOE field office
- Data transmission to CBFO

7. Site Project Quality Assurance Officer.

Each participating site's contractor designates a site project QA officer and provides a detailed description of this position in the site QAPjP. The site project QA officer (or designee) reviews the site QAPjP and subsequent revisions, verifies that the QA requirements have been implemented, and provides day-to-day guidance to the project staff on quality-related matters. This individual will have the authority to stop Program activities at a participating site if quality is not assured or controlled. Specific Program responsibilities assigned to the site project QA officers include the following:

- Laboratory/testing facility assessment
- Nonconformance tracking
- Corrective action verification

- Data validation/verification
- Data QA documentation verification
- Evaluating trends in compliance with Program objectives
- QA/QC reports to site project manager

The site project QA officer shall summarize all relevant information on the QA/QC activities during the period in a semiannual report. This semiannual report shall be distributed to the DOE field office and the site project manager at the same time. The site project manager shall review the report, comment if appropriate, and then forward a copy of the report with comments to the DOE field office.

8. Site Waste Certification Official. Each participating site's contractor designates a waste certification official who must document and certify that all TRU waste payload containers prepared for shipment to WIPP meet all the requirements specified in the *Contact Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant* (CH-WAC; DOE 2002) and transmit the waste certification data to the WIPP M&O contractor.

9. Site Transportation Certification Official. Each participating site's contractor designates a transportation certification official who documents and certifies that payload assemblies for shipment to WIPP meet all the requirements of the *TRUPACT-II Authorized Methods for Payload Control* (TRAMPAC; NRC 1997).

Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix TRU WASTE

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix TRU WASTE

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ACRONYMS AND ABBREVIATIONS

AK	acceptable knowledge
BRAGFLO	BRine And Gas FLOw code
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CFR	Code of Federal Regulations
CH-TRU	contact-handled transuranic (waste)
CRA	Compliance Recertification Application
DOE, USDOE	United States Department of Energy
EDTA	ethylene diamine tetra-acetate
EPA, USEPA	United States Environmental Protection Agency
FEP	feature, event, and process
FR	Federal Register
K_d	equilibrium constant for distribution between solution and solid
LANL	Los Alamos National Laboratory
LWA	Land Withdrawal Act
NDA	nondestructive assay
NUTS	NUclide Transport System code
PA	performance assessment
PAPDB	Performance Assessment Parameter DataBase
PAVT	Performance Assessment Verification Test
RH-TRU	remote-handled transuranic (waste)
SNL	Sandia National Laboratories
TRU	transuranic
TWBIR	TRU Baseline Inventory Report
TWBID	TRU Waste Baseline Inventory Data Base
WAC	Waste Acceptance Criteria
WAP	Waste Analysis Plan
WIPP	Waste Isolation Pilot Plant
WSPF	Waste Stream Profile Form
WUF	waste unit factor
WWIS	WIPP Waste Information System

TRU WASTE-1.0 INTRODUCTION

The transuranic (TRU) waste inventory is expected to be updated for each recertification application. The updated inventory will be evaluated to determine the effect of the waste and waste characteristics on the long-term performance of the repository. The proper implementation of the following five steps will ensure compliance with Title 40 Code of Federal Regulations (CFR) Section 194.24:

(1) Collect/scale inventory data. As shown in Figure TRU WASTE-1, the update cycle begins with the compilation of waste inventory data. This includes the waste that has been emplaced in the repository and the waste that is anticipated for emplacement over the operational life of the Waste Isolation Pilot Plant (WIPP). The anticipated waste inventory data consist of waste that has been stored at TRU waste sites and projected estimates of waste to be generated. For the purposes of performance assessment (PA), the projected waste is then scaled to the allowable capacity that remains in the repository after accounting for the stored and emplaced waste. The combined data (emplaced plus stored plus scaled projected) account for the total WIPP waste inventory. The results of conducting Step 1 of this process for CRA-2004 are reported in Appendix DATA, Attachment F.

(2) Perform waste characterization analysis. The inventory is analyzed for new waste components and/or changes to existing waste components that might affect the repository system. This is a screening step using sensitivity analyses. If a component is determined to impact repository performance it is placed on the list of "significant" waste components. Some waste components indirectly influence repository performance and are placed on the list of "negligible" waste components. All other components are screened out and are not included in the PA calculations. The results of conducting Step 2 of this process for the CRA-2004 are reported in Section TRU WASTE-2.0.

(3) Establish repository waste component limits. Waste components identified as "significant" are examined to determine if changes in the previously established limits are needed. If the inventory update shows substantial changes to the "significant" waste components, the change may necessitate a new or different limit. A new or different waste component limit will be established based upon the impact to the repository. The results of conducting Step 3 of this process for the CRA-2004 are reported in Section TRU WASTE-3.0.

(4) Characterize Waste. Waste characterization methods are developed or refined to quantify the significant waste components. Waste characterization programs implement other regulatory requirements, but for purposes of CRA-2004, this appendix will only address those elements relevant to long-term compliance. The results of conducting Step 4 of this process for the CRA-2004 are reported in Section TRU WASTE-4.0.

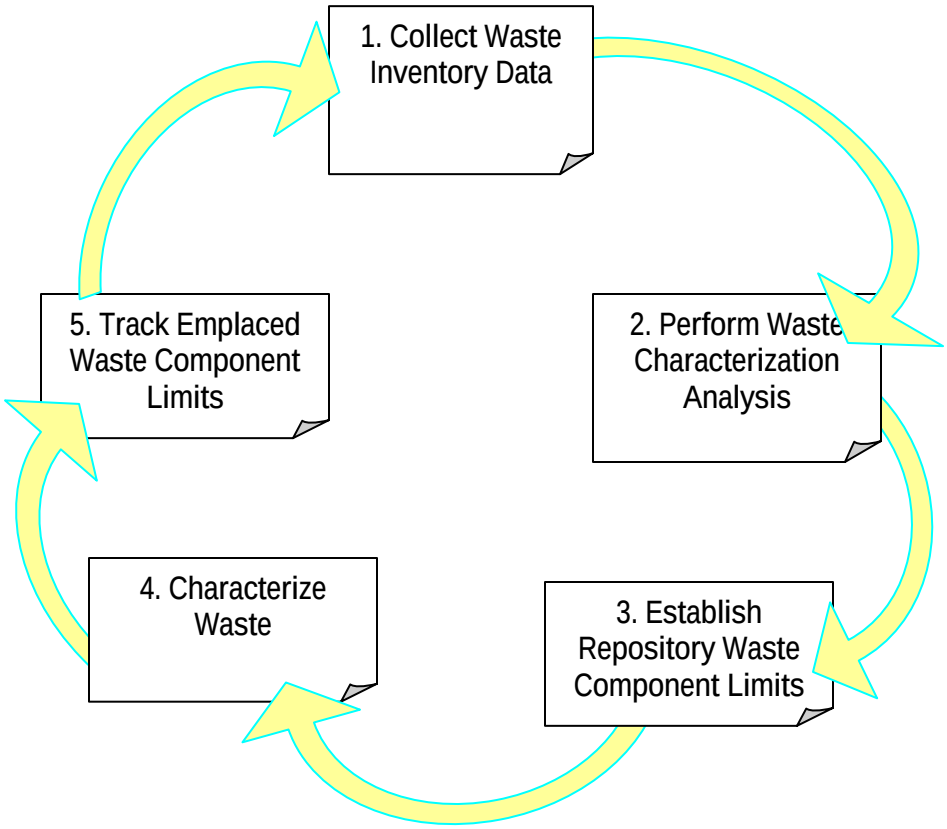

Figure TRU WASTE-1. Waste Characterization Cycle

(5) Track emplaced waste component limits. Waste component data are tracked and reported. The WIPP Waste Information System (WWIS) is used to capture the waste component data for waste emplaced in the repository. The WWIS is a tool used by the personnel at the TRU waste sites and at WIPP to control and track the waste emplaced in the repository. Once a year, the Department of Energy (DOE) provides the Environmental Protection Agency (EPA) with a report containing the values for each of the significant waste components. The emplaced waste data is compiled every five years (or as necessary) for updating the waste inventory, and the cycle repeats itself. The description of Step 5 of this process is reported in Section TRU WASTE-5.0.

TRU WASTE-1.1 Purpose

This appendix provides information in accordance with 40 CFR § 194.24 for the waste characteristics and components important to the containment of waste in the disposal system over the regulatory performance period of 10,000 years. The characteristics and components of the waste are based on the current TRU waste descriptions and inventory presented in Appendix DATA, Attachment F. This appendix describes the assessment of the waste characteristics associated with the chemical, radiological, and physical composition of existing and projected TRU waste destined for disposal at the WIPP. It also identifies those waste components that

significantly influence waste characteristics, and establishes reasonable upper and lower waste component disposal limits. Based on the component limits and their associated uncertainties, a set of characterization techniques are established. Waste components are controlled, tracked, and inventoried upon emplacement in the repository. The cycle represented in Figure TRU WASTE-1 repeats as this characterization information provides key input data for future PAs to determine the impacts on the long-term containment of the disposal system.

Section TRU WASTE-2.0 addresses the requirements specified in 40 CFR § 194.24(b) to identify those waste components and their characteristics that can influence the containment of waste and that are included as inputs to the computer models used in PAs. This section identifies and assesses these parameters based on the DOE's current understanding of the disposal system behavior and the updated waste descriptions and inventory totals since submittal of the Compliance Certification Application (CCA). Section TRU WASTE2.3 also discusses the rationale for exclusion of specific waste characteristics or components expected not to influence releases from the disposal system.

Section TRU WASTE-3.0 shows the total limits for each identified significant component. This section addresses the requirement of 40 CFR § 194.24(c)(1) to establish limiting values for each component identified in Section TRU WASTE-2.0 as important to the performance of the repository system. The rationale for these limits is also discussed.

Section TRU WASTE-4.0 identifies and describes the methods used to quantify the limits for the waste components identified as potentially significant to the long-term performance of the disposal system. This section addresses the requirements of 40 CFR § 194.24(c)(2) and (3).

Section TRU WASTE-5.0 describes a system of controls (WWIS) that address the requirements of 40 CFR § 194.24(c)(4) and (5).

TRU WASTE-1.2 Scope

This appendix supercedes the information previously presented in the following appendices of the CCA:

- Appendix WCA, Waste Characterization Analysis. The modeled long-term performance of the disposal system is evaluated based on current inventory information contained in Appendix DATA, Attachment F and on current disposal system behavior assumptions.

- Appendix WCL, Waste Component Limits. The limits for waste components determined important to the disposal system are established based on results of the CRA-2004 PA and the outcome of the current waste characterization analysis.

- Appendix WAP, Waste Analysis Plan. The characterization methods used to quantify the waste components determined important to the performance of the disposal system are established. Existing documentation that details the current characterization methods is referenced.

TRU WASTE-2.0 WASTE CHARACTERIZATION ANALYSIS

Section TRU WASTE-2 summarizes relevant information on the emplaced and anticipated TRU waste inventories (detailed in Appendix DATA, Attachment F), identifies changes to PA and compliance assessment, and provides conclusions pertaining to whether the waste characteristics and waste components previously identified as significant to performance remain significant.

TRU WASTE-2.1 Introduction

TRU WASTE-2.1.1 Scope

Waste components are the elements that make up the waste (e.g., radionuclides, paper and other cellulosic materials, steel drums that contain the waste, solidified organic and inorganic sludges, etc.). These components have characteristics with the potential to impact disposal system performance. For example, paper is a component of the waste and a substrate for microbes in the repository. The ability of the paper to act as a substrate for microbial gas production is a characteristic of the paper. Microbes metabolizing paper can produce carbon dioxide, methane, and other gaseous metabolic products, which can increase the pressure in a waste panel and potentially impact the performance of the repository.

Sensitivity analysis is used to determine limiting values and associated uncertainties in the waste characteristics and components as required in 40 CFR § 194.24 (c). Sensitivity analyses and calculations related to features, events, and processes (FEPs) associated with the CCA, Performance Assessment Verification Test (PAVT) (DOE 1997), and Appendix PA have identified those waste characteristics and components that are included or excluded in the PA. Sections TRU WASTE-2.2 through 2.5 identify those waste components and waste characteristics and components that influence the containment of waste and thus are included as inputs to the computer codes used in PA.

TRU WASTE-2.1.2 Updated Estimate of TRU Waste Inventory

In the certification of WIPP, the EPA concluded that the estimates provided in Appendix BIR of the CCA represented the best information available at that time (Federal Register [FR] 63 27354, May 18, 1998). The EPA recognized that the WIPP waste inventory may change as the DOE characterizes the contents of containers of TRU waste prior to shipment to WIPP and as new wastes are generated in the future. The EPA also concluded that the WIPP waste inventory estimates provided in Appendix BIR of the CCA were sufficient for purposes of PA.

The inventory volume defined for WIPP emplacement to be used for PA calculations is the "disposal inventory." The WIPP Land Withdrawal Act (LWA), Pub. L. No. 104-201, 110 Stat. 2422 defines the total amount of TRU waste allowed in the WIPP as 175,564 m^3 (6,200,000 ft^3). The "Agreement for Consultation and Cooperation" limits the remote-handled (RH)-TRU waste inventory to 7,079 m^3 (250,000 ft^3) (State of New Mexico vs. DOE 1981). By difference, the contact-handled (CH)-TRU waste inventory is limited to 168,485 m^3 (5,950,000 ft^3).

Since submittal of the CCA, DOE has updated its estimates of the TRU waste inventory destined for disposal in the WIPP. A complete description of that process and its results are presented in Appendix DATA, Attachment F. The following tables summarize information from Appendix

DATA, Attachment F that pertains to waste characterization analysis. Table TRU WASTE-1 summarizes the current densities for the waste materials in the disposal inventory. Table TRU WASTE-2 summarizes the current activities for the radionuclides in the disposal inventory. Table TRU WASTE-3 summarizes the current mass of other important components in the disposal inventory.

Table TRU WASTE-1. Summary of Densities of Waste Materials

Waste Material	Average Mass Density in CH-TRU Waste (kg/m^3)	Average Mass Density in RH-TRU Waste (kg/m^3)
Fe-base Metal/Alloys	1.1×10^2	1.1×10^2
Al-base Metal/Alloys	1.4×10^1	2.5×10^0
Other Metal/Alloys	3.0×10^1	3.2×10^1
Other Inorganic Materials	4.2×10^1	3.5×10^1
Cellulosic Materials	5.8×10^1	4.5×10^0
Rubber Materials	1.4×10^1	3.1×10^0
Plastic Materials	4.2×10^1	4.9×10^0
Solidified Inorganic Material	7.7×10^1	3.9×10^1
Cement (Solidified)	2.9×10^1	8.7×10^{-1}
Vitrified Material	6.2×10^0	5.7×10^{-2}
Solidified Organic Material	1.6×10^1	4.0×10^0
Soils	1.9×10^1	2.6×10^1
Packaging Material, Steel	1.7×10^2	4.8×10^2
Packaging Material, Plastic	1.6×10^1	1.4×10^0
Packaging Material, Lead	1.4×10^{-2}	4.4×10^2

Source: Appendix DATA, Attachment F. Data reported in Appendix DATA, Attachment F includes information known by the TRU waste sites as of September 30, 2002.

Table TRU WASTE-2. Summary of Activities for Radionuclides in the Disposal Inventory (Decayed through 12/31/01)

Radionuclide	CH-TRU Waste Concentration (Ci/m^3)	RH-TRU Waste Concentration (Ci/m^3)	CH-TRU Waste (Ci)	RH-TRU Waste (Ci)
^{225}Ac	9.21×10^{-6}	5.20×10^{-6}	1.55×10^0	3.68×10^{-2}
^{227}Ac	3.00×10^{-6}	5.65×10^{-10}	5.06×10^{-1}	4.00×10^{-6}
^{228}Ac	2.84×10^{-5}	2.02×10^{-5}	4.79×10^0	1.43×10^{-1}
^{109m}Ag	7.49×10^{-10}	NR	1.26×10^{-4}	NR
^{110}Ag	2.61×10^{-16}	2.71×10^{-15}	4.40×10^{-11}	1.92×10^{-11}
^{110m}Ag	1.98×10^{-14}	2.06×10^{-13}	3.34×10^{-9}	1.46×10^{-9}

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Table TRU WASTE-2. Summary of Activities for Radionuclides in the Disposal Inventory (Decayed through 12/31/01) — Continued

Radionuclide	CH-TRU Waste Concentration (Ci/m^3)	RH-TRU Waste Concentration (Ci/m^3)	CH-TRU Waste (Ci)	RH-TRU Waste (Ci)
^{241}Am	2.38×10^{0}	1.93×10^{0}	4.01×10^{5}	1.36×10^{4}
^{242}Am	2.79×10^{-7}	1.20×10^{-7}	4.70×10^{-2}	8.52×10^{-4}
^{242m}Am	2.83×10^{-7}	2.77×10^{-5}	4.78×10^{-2}	1.96×10^{-1}
^{243}Am	1.25×10^{-4}	1.01×10^{-4}	2.10×10^{1}	7.15×10^{-1}
^{245}Am	7.79×10^{-16}	NR	1.31×10^{-10}	NR
^{217}At	9.22×10^{-6}	5.21×10^{-6}	1.55×10^{0}	3.69×10^{-2}
^{137m}Ba	5.38×10^{-2}	4.74×10^{1}	9.06×10^{3}	3.36×10^{5}
^{210}Bi	1.53×10^{-5}	2.98×10^{-11}	2.58×10^{0}	2.11×10^{-7}
^{211}Bi	2.97×10^{-6}	5.58×10^{-10}	5.00×10^{-1}	3.95×10^{-6}
^{212}Bi	3.47×10^{-5}	3.82×10^{-4}	5.84×10^{0}	2.70×10^{0}
^{213}Bi	9.20×10^{-6}	5.20×10^{-6}	1.55×10^{0}	3.68×10^{-2}
^{214}Bi	3.73×10^{-5}	1.92×10^{-10}	6.29×10^{0}	1.36×10^{-6}
^{249}Bk	5.39×10^{-11}	NR	9.07×10^{-6}	NR
^{250}Bk	2.17×10^{-17}	NR	3.65×10^{-12}	NR
^{14}C	7.19×10^{-6}	2.90×10^{-4}	1.21×10^{0}	2.05×10^{0}
^{109}Cd	7.58×10^{-10}	NR	1.28×10^{-4}	NR
^{113m}Cd	NR	2.31×10^{-5}	NR	1.64×10^{-1}
^{141}Ce	NR	5.33×10^{-23}	NR	3.77×10^{-19}
^{144}Ce	2.11×10^{-9}	2.56×10^{-4}	3.56×10^{-4}	1.82×10^{0}
^{249}Cf	4.53×10^{-7}	1.18×10^{-7}	7.64×10^{-2}	8.37×10^{-4}
^{250}Cf	1.09×10^{-6}	2.11×10^{-6}	1.83×10^{-1}	1.50×10^{-2}
^{251}Cf	2.16×10^{-9}	2.25×10^{-8}	3.64×10^{-4}	1.59×10^{-4}
^{252}Cf	1.23×10^{-6}	2.50×10^{-6}	2.08×10^{-1}	1.77×10^{-2}
^{242}Cm	2.34×10^{-7}	1.01×10^{-7}	3.94×10^{-2}	7.15×10^{-4}
^{243}Cm	2.36×10^{-6}	6.92×10^{-5}	3.97×10^{-1}	4.90×10^{-1}
^{244}Cm	6.86×10^{-2}	3.82×10^{-2}	1.16×10^{4}	2.70×10^{2}
^{245}Cm	5.00×10^{-8}	1.50×10^{-6}	8.42×10^{-3}	1.06×10^{-2}
^{246}Cm	9.21×10^{-6}	9.53×10^{-5}	1.55×10^{0}	6.74×10^{-1}
^{247}Cm	1.65×10^{-15}	1.33×10^{-3}	2.77×10^{-10}	9.44×10^{0}
^{248}Cm	5.43×10^{-7}	2.58×10^{-7}	9.14×10^{-2}	1.83×10^{-3}
^{250}Cm	3.94×10^{-16}	NR	6.64×10^{-11}	NR
^{60}Co	5.85×10^{-6}	2.38×10^{-1}	9.85×10^{-1}	1.68×10^{3}
^{134}Cs	1.22×10^{-7}	4.75×10^{-3}	2.05×10^{-2}	3.36×10^{1}
^{135}Cs	NR	9.75×10^{-9}	NR	6.90×10^{-5}
^{137}Cs	5.73×10^{-2}	5.15×10^{1}	9.65×10^{3}	3.65×10^{5}
^{152}Eu	1.16×10^{-5}	9.82×10^{-2}	1.95×10^{0}	6.95×10^{2}
^{154}Eu	9.82×10^{-6}	5.98×10^{-2}	1.65×10^{0}	4.23×10^{2}
^{155}Eu	3.99×10^{-7}	2.61×10^{-3}	6.73×10^{-2}	1.85×10^{1}

Table TRU WASTE-2. Summary of Activities for Radionuclides in the Disposal Inventory (Decayed through 12/31/01) — Continued

Radionuclide	CH-TRU Waste Concentration (Ci/m^3)	RH-TRU Waste Concentration (Ci/m^3)	CH-TRU Waste (Ci)	RH-TRU Waste (Ci)
^{55}Fe	NR	5.93×10^{-6}	NR	4.20×10^{-2}
^{221}Fr	9.20×10^{-6}	5.20×10^{-6}	1.55×10^{0}	3.68×10^{-2}
^{223}Fr	4.10×10^{-8}	7.71×10^{-12}	6.91×10^{-3}	5.45×10^{-8}
^{152}Gd	2.61×10^{-19}	2.76×10^{-15}	4.40×10^{-14}	1.95×10^{-11}
^{3}H	1.29×10^{-3}	1.62×10^{-4}	2.17×10^{2}	1.15×10^{0}
^{129}I	3.04×10^{-9}	1.16×10^{-5}	5.12×10^{-4}	8.20×10^{-2}
^{85}Kr	2.74×10^{-6}	1.59×10^{-5}	4.62×10^{-1}	1.13×10^{-1}
^{54}Mn	NR	2.58×10^{-4}	NR	1.82×10^{0}
^{22}Na	2.32×10^{-12}	4.17×10^{-5}	3.91×10^{-7}	2.95×10^{-1}
^{93m}Nb	NR	3.88×10^{-8}	NR	2.75×10^{-4}
^{95}Nb	NR	1.06×10^{-17}	NR	7.53×10^{-14}
^{95m}Nb	NR	3.56×10^{-20}	NR	2.52×10^{-16}
^{59}Ni	4.54×10^{-7}	3.25×10^{-3}	7.64×10^{-2}	2.30×10^{1}
^{63}Ni	2.21×10^{-5}	1.58×10^{-1}	3.72×10^{0}	1.12×10^{3}
^{237}Np	2.85×10^{-5}	9.41×10^{-5}	4.80×10^{0}	6.66×10^{-1}
^{238}Np	1.40×10^{-9}	6.05×10^{-10}	2.36×10^{-4}	4.28×10^{-6}
^{239}Np	1.23×10^{-4}	8.87×10^{-6}	2.08×10^{1}	6.28×10^{-2}
^{240m}Np	7.75×10^{-12}	1.57×10^{-7}	1.31×10^{-6}	1.11×10^{-3}
^{231}Pa	7.19×10^{-6}	2.53×10^{-9}	1.21×10^{0}	1.79×10^{-5}
^{233}Pa	2.82×10^{-5}	3.26×10^{-7}	4.75×10^{0}	2.31×10^{-3}
^{234}Pa	5.49×10^{-8}	3.99×10^{-7}	9.25×10^{-3}	2.82×10^{-3}
$^{234}Pa^{m}$	4.22×10^{-5}	3.07×10^{-4}	7.11×10^{0}	2.17×10^{0}
^{209}Pb	9.21×10^{-6}	5.20×10^{-6}	1.55×10^{0}	3.68×10^{-2}
^{210}Pb	1.55×10^{-5}	3.02×10^{-11}	2.61×10^{0}	2.13×10^{-7}
^{211}Pb	2.97×10^{-6}	5.59×10^{-10}	5.01×10^{-1}	3.95×10^{-6}
^{212}Pb	3.46×10^{-5}	3.80×10^{-4}	5.82×10^{0}	2.69×10^{0}
^{214}Pb	3.74×10^{-5}	1.92×10^{-10}	6.30×10^{0}	1.36×10^{-6}
^{107}Pd	NR	4.07×10^{-10}	NR	2.88×10^{-6}
^{147}Pm	1.08×10^{-5}	4.96×10^{-2}	1.82×10^{0}	3.51×10^{2}
^{210}Po	1.55×10^{-5}	3.01×10^{-11}	2.60×10^{0}	2.13×10^{-7}
^{211}Po	9.05×10^{-9}	1.70×10^{-12}	1.53×10^{-3}	1.20×10^{-8}
^{212}Po	2.21×10^{-5}	2.43×10^{-4}	3.72×10^{0}	1.72×10^{0}
^{213}Po	9.01×10^{-6}	5.09×10^{-6}	1.52×10^{0}	3.60×10^{-2}
^{214}Po	3.74×10^{-5}	1.92×10^{-10}	6.30×10^{0}	1.36×10^{-6}
^{215}Po	2.97×10^{-6}	5.59×10^{-10}	5.00×10^{-1}	3.95×10^{-6}
^{216}Po	3.45×10^{-5}	3.80×10^{-4}	5.82×10^{0}	2.69×10^{0}
^{218}Po	3.68×10^{-5}	1.89×10^{-10}	6.19×10^{0}	1.34×10^{-6}
^{144}Pr	2.07×10^{-9}	2.51×10^{-4}	3.49×10^{-4}	1.78×10^{0}
^{236}Pu	2.60×10^{-9}	NR	4.38×10^{-4}	NR

Table TRU WASTE-2. Summary of Activities for Radionuclides in the Disposal Inventory (Decayed through 12/31/01) — Continued

Radionuclide	CH-TRU Waste Concentration (Ci/m^3)	RH-TRU Waste Concentration (Ci/m^3)	CH-TRU Waste (Ci)	RH-TRU Waste (Ci)
^{238}Pu	9.55×10^{0}	5.10×10^{-1}	1.61×10^{6}	3.61×10^{3}
^{239}Pu	3.92×10^{0}	7.59×10^{-1}	6.60×10^{5}	5.38×10^{3}
^{240}Pu	6.35×10^{-1}	2.37×10^{-1}	1.07×10^{5}	1.68×10^{3}
^{241}Pu	1.43×10^{1}	1.58×10^{1}	2.40×10^{6}	1.12×10^{5}
^{242}Pu	1.58×10^{-4}	6.69×10^{-5}	2.67×10^{1}	4.74×10^{-1}
^{243}Pu	1.63×10^{-15}	1.32×10^{-3}	2.74×10^{-10}	9.33×10^{0}
^{244}Pu	7.68×10^{-12}	1.56×10^{-7}	1.29×10^{-6}	1.10×10^{-3}
^{223}Ra	3.00×10^{-6}	5.64×10^{-10}	5.06×10^{-1}	3.99×10^{-6}
^{224}Ra	3.45×10^{-5}	3.80×10^{-4}	5.81×10^{0}	2.69×10^{0}
^{225}Ra	9.22×10^{-6}	5.21×10^{-6}	1.55×10^{0}	3.69×10^{-2}
^{226}Ra	3.78×10^{-5}	1.95×10^{-10}	6.37×10^{0}	1.38×10^{-6}
^{228}Ra	3.36×10^{-5}	2.38×10^{-5}	5.66×10^{0}	1.69×10^{-1}
^{106}Rh	9.36×10^{-10}	9.59×10^{-6}	1.58×10^{-4}	6.79×10^{-2}
^{219}Rn	2.97×10^{-6}	5.58×10^{-10}	5.00×10^{-1}	3.95×10^{-6}
^{220}Rn	3.45×10^{-5}	3.80×10^{-4}	5.82×10^{0}	2.69×10^{0}
^{222}Rn	3.74×10^{-5}	1.93×10^{-10}	6.31×10^{0}	1.36×10^{-6}
^{106}Ru	9.46×10^{-10}	9.60×10^{-6}	1.59×10^{-4}	6.79×10^{-2}
^{125}Sb	2.99×10^{-8}	6.18×10^{-4}	5.04×10^{-3}	4.38×10^{0}
^{126}Sb	NR	5.89×10^{-9}	NR	4.17×10^{-5}
^{126m}Sb	NR	4.21×10^{-8}	NR	2.98×10^{-4}
^{79}Se	7.84×10^{-10}	6.29×10^{-6}	1.32×10^{-4}	4.46×10^{-2}
^{147}Sm	2.83×10^{-15}	9.69×10^{-13}	4.78×10^{-10}	6.86×10^{-9}
^{151}Sm	3.37×10^{-4}	8.20×10^{-2}	5.68×10^{1}	5.80×10^{2}
^{121m}Sn	NR	7.28×10^{-8}	NR	5.15×10^{-4}
^{126}Sn	NR	4.21×10^{-8}	NR	2.98×10^{-4}
^{90}Sr	3.41×10^{-1}	3.48×10^{1}	5.75×10^{4}	2.46×10^{5}
^{99}Tc	9.93×10^{-4}	2.25×10^{-2}	1.67×10^{2}	1.59×10^{2}
^{123}Te	4.02×10^{-10}	NR	6.78×10^{-5}	NR
^{123m}Te	2.96×10^{-24}	NR	4.98×10^{-19}	NR
^{125m}Te	7.24×10^{-9}	1.50×10^{-4}	1.22×10^{-3}	1.06×10^{0}
^{227}Th	2.92×10^{-6}	5.50×10^{-10}	4.93×10^{-1}	3.89×10^{-6}
^{228}Th	3.49×10^{-5}	3.85×10^{-4}	5.89×10^{0}	2.72×10^{0}
^{229}Th	9.23×10^{-6}	5.21×10^{-6}	1.55×10^{0}	3.69×10^{-2}
^{230}Th	6.02×10^{-7}	5.31×10^{-8}	1.01×10^{-1}	3.76×10^{-4}
^{231}Th	2.10×10^{-6}	7.38×10^{-6}	3.53×10^{-1}	5.23×10^{-2}
^{232}Th	3.92×10^{-5}	3.08×10^{-5}	6.61×10^{0}	2.18×10^{-1}
^{234}Th	4.23×10^{-5}	3.07×10^{-4}	7.12×10^{0}	2.17×10^{0}
^{207}Tl	2.95×10^{-6}	5.55×10^{-10}	4.98×10^{-1}	3.93×10^{-6}
^{208}Tl	1.24×10^{-5}	1.37×10^{-4}	2.09×10^{0}	9.71×10^{-1}

Table TRU WASTE-2. Summary of Activities for Radionuclides in the Disposal Inventory (Decayed through 12/31/01) — Continued

Radionuclide	CH-TRU Waste Concentration (Ci/m^3)	RH-TRU Waste Concentration (Ci/m^3)	CH-TRU Waste (Ci)	RH-TRU Waste (Ci)
^{209}Tl	2.03×10^{-7}	1.14×10^{-7}	3.41×10^{-2}	8.10×10^{-4}
^{232}U	9.76×10^{-6}	3.57×10^{-4}	1.64×10^{0}	2.53×10^{0}
^{233}U	7.34×10^{-3}	4.82×10^{-3}	1.24×10^{3}	3.41×10^{1}
^{234}U	9.95×10^{-4}	3.07×10^{-3}	1.68×10^{2}	2.17×10^{1}
^{235}U	7.84×10^{-6}	1.33×10^{-4}	1.32×10^{0}	9.42×10^{-1}
^{236}U	7.70×10^{-7}	2.01×10^{-4}	1.30×10^{-1}	1.42×10^{0}
^{237}U	1.28×10^{-4}	2.48×10^{-6}	2.15×10^{1}	1.75×10^{-2}
^{238}U	1.45×10^{-4}	1.83×10^{-2}	2.44×10^{1}	1.30×10^{2}
^{240}U	7.60×10^{-12}	1.54×10^{-7}	1.28×10^{-6}	1.09×10^{-3}
^{90}Y	3.41×10^{-1}	3.43×10^{1}	5.74×10^{4}	2.43×10^{5}
^{91}Y	NR	1.15×10^{-16}	NR	8.11×10^{-13}
^{65}Zn	1.38×10^{-15}	NR	2.32×10^{-10}	NR
^{93}Zr	6.68×10^{-9}	4.79×10^{-5}	1.13×10^{-3}	3.39×10^{-1}
^{95}Zr	NR	4.84×10^{-18}	NR	3.43×10^{-14}
Total:	3.16×10^{1}	1.88×10^{2}	5.33×10^{6}	1.33×10^{6}

Note: NR = Not Reportable
Source: Appendix DATA, Attachment F. Data reported in Appendix DATA, Attachment F includes information known by the TRU waste sites as of September 30, 2002.

Table TRU WASTE-3. Summary of Masses for Other Important Components

Component	Mass Contained in the Disposal Inventory (kg)
Acetic Acid	1.42×10^{2}
Sodium Acetate	8.51×10^{3}
Citric Acid	1.19×10^{3}
Sodium Citrate	4.00×10^{2}
Oxalic Acid	1.38×10^{4}
Sodium Oxalate	3.39×10^{4}
Sodium EDTA	2.56×10^{1}
Nitrate	2.51×10^{6}
Sulfate	4.21×10^{5}
Phosphate	1.05×10^{5}
Cement	1.2×10^{7}

Source: Appendix DATA, Attachment F. Data reported in Appendix DATA, Attachment F includes information known by the TRU waste sites as of September 30, 2002. Masses reported here are based on the disposal volume as defined in Appendix TRU WASTE, Section 2.1.2.

TRU WASTE-2.2 Summary of Waste Components and Characteristics

TRU WASTE-2.2.1 Waste Characterization Analysis

Tables TRU WASTE-4, TRU WASTE-5, and TRU WASTE-6 summarize the waste characteristics and waste components considered in this section. These tables provide:

- a list of the waste characteristics and components expected to have significant effect on disposal system performance (included in PA),
- a list of the waste characteristics and components expected to have negligible effect on disposal system performance, and
- a list of waste characteristics and components that were considered and excluded.

Table TRU WASTE-4 lists the waste characteristics and components that are included in PA because they would be expected to have a significant impact on repository performance. The waste characteristics and components listed in Table TRU WASTE-4 are identical to those listed in Table WCA-2 of the CCA. None of the inventory changes described in Appendix DATA, Attachment F led to an alternate conclusion regarding the relative importance of individual waste characteristics and components for PA.

Table TRU WASTE-4. Waste Characteristics and Components Used in Performance Assessment: Characteristics Expected to Have a Significant Effect on Disposal System Performance

Characteristic	Component	Effect on Performance	Section of Appendix TRU WASTE
Radioactivity of Each Isotope	Radionuclides	Used in Calculating Normalized Releases	2.3.1, 2.3.2
TRU Radioactivity at Closure	α-Emitting TRU Radionuclides, half-life > 20 Years	Determines Waste Unit Factor (WUF)	2.3.1
Solubility	Radionuclides	Actinide Mobility	2.4.1
Colloid Formation	Radionuclides, Soils, Cellulosic, Plastic, and Rubber (CPR) Materials	Actinide Mobility	2.4.2
Redox State	Radionuclides	Actinide Mobility	2.4.1
Redox Potential	Ferrous Metals	Actinide Oxidation State; Actinide Mobility	2.4.1.1
Gas (H_2) Generation	Ferrous Metals	Increase in H_2 Pressure	2.4.1.2, 2.5.1
Microbial Substrate: CH_4 Generation	Cellulosic Materials	Increase in Gas Pressure	2.4.1.2, 2.5.1
Microbial Substrate: CH_4 Generation	Plastic, Rubber Materials	Increase in Gas Pressure	2.4.1.2, 2.5.1
Particle Diameter	Solid Waste Components	Spalling Release	2.5.2

Table TRU WASTE-4. Waste Characteristics and Components Used in Performance Assessment: Characteristics Expected to Have a Significant Effect on Disposal System Performance — Continued

Characteristic	Component	Effect on Performance	Section of Appendix TRU WASTE
Microbial Nutrients: CH_4 Generation	Sulfates	Increase in Gas Pressure	2.5.1
Microbial Nutrients: CH_4 Generation	Nitrates	Increase in Gas Pressure	2.5.1
Compressibility and Shear Strength	Solid Waste Components	Effect on Creep Closure, Cuttings, Caving, Spallings	2.5.2

Table TRU WASTE-5 lists the waste characteristics and components that are included in PA, but would be expected to have a negligible impact on performance. For example, the impact of microbially generated CO_2 on performance is insignificant because the CO_2 will react with the MgO, forming Mg carbonate minerals that greatly reduce the impact of CO_2 on pH. The waste characteristics and components listed in Table TRU WASTE-5 are identical to those listed in Table WCA-3 of the CCA. None of the inventory changes described in Appendix DATA, Attachment F led to an alternate conclusion regarding the relative importance of individual waste characteristics and components for PA. Actual sensitivities of the analysis to waste characteristics and components are described in Appendix PA. The relationships between components, characteristics, and PA codes are illustrated in Figure TRU WASTE-2.

Table TRU WASTE-5. Waste Characteristics and Components Used in Performance Assessment: Characteristics Expected to Have a Negligible Effect on Disposal System Performance

Characteristic	Component	Effect on Performance	Section of Appendix TRU WASTE
Permeability	Solid Waste Components	Negligible Effect on Brine Movement, Gas Storage	2.5.2
Porosity	Solid Waste Components	Negligible Effect on Brine Movement	2.5.2
Microbial Nutrients, CO_2 Generation	Sulfates[1]	Negligible: MgO Reacts with CO_2	2.4.1.2
Microbial Nutrients, CO_2 Generation	Nitrates[1]	Negligible: MgO Reacts with CO_2,	2.4.1.2, 2.5.1
Microbial Substrate: CO_2 Generation	Cellulosic Materials	Negligible: MgO Reacts with CO_2	2.4.1.2, 2.5.1
Microbial Substrate: CO_2 Generation	Plastic Materials, Rubber Materials	Negligible: MgO Reacts with CO_2	2.4.1.2, 2.5.1
Gas Generation	Water in the Waste	Enhances Initial Gas Generation	2.5.1

[1] These components are significant to gas generation and are therefore also listed in Table TRU WASTE-4.

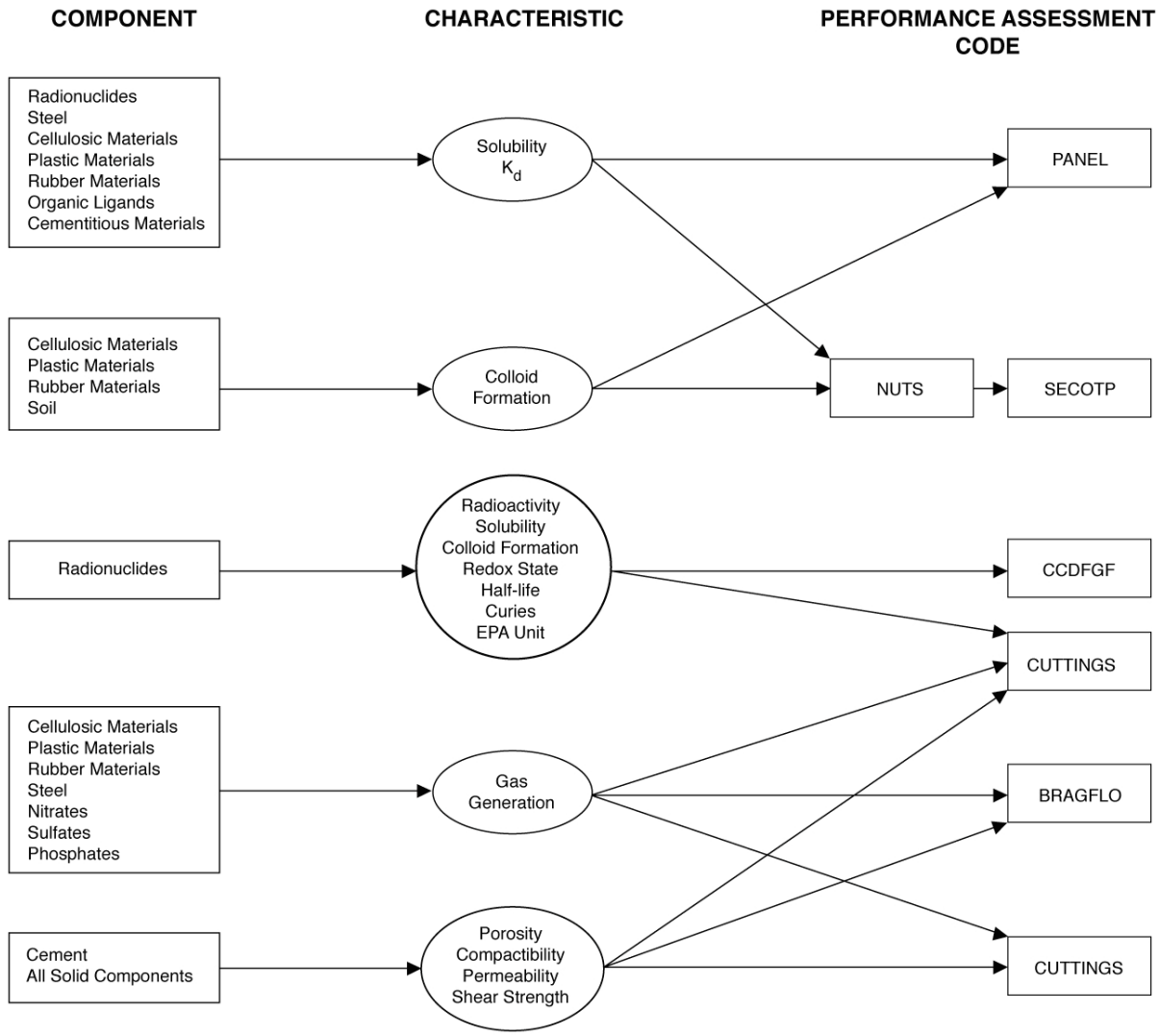

Figure TRU WASTE-2. Waste Components, the Associated Waste Characteristics, and a Performance Assessment Code Related to Each Characteristic

Table TRU WASTE-6 lists the waste characteristics and components that are excluded from PA. Some of these excluded characteristics, however, can indirectly influence performance. For example, the ability of nonferrous metals to bind organic ligands prevents those ligands from increasing +IV actinide solubility, which is considered in PA analyses. The waste characteristics and components listed in Table TRU WASTE-6 are identical to those listed in Appendix WCA, Table WCA-4, in the CCA. None of the inventory changes described in Appendix DATA, Attachment F led to an alternate conclusion regarding the relative importance of individual waste characteristics and components for PA.

Table TRU WASTE-6. Waste Characteristics and Components Not Used in Performance Assessment

Characteristic	Component	Effect on Performance
Cellulosic Materials Radiolysis	Radionuclides	Negligible Effect On Total CO_2
Explosivity	Other Organic Compounds	None
Brine Radiolysis	Radionuclides	Negligible Effect On Actinide Valence
Galvanic Action	Nonferrous Metals	Negligible
Complexation With Actinides[1]	Soil And Humic Material[1]	Actinide Mobility
Buffering Action[1]	Cement[1]	Negligible: Reacts With CO_2 And $MgCl_2$
Heat Of Solution	Cement	Negligible
Ca^{2+} Binding To Organic Ligands	Cement	Negligible Compared To Other Metals
Binding To Organic Ligands[1]	Ferrous Metals[1]	Can Reduce Actinide Mobility
Buffering Action[1]	Ferrous Metals[1]	Actinide Mobility
Galvanic Action	Ferrous Metals	Negligible
Binding To Organic Ligands[1]	Ferrous Alloy Components[1]	Can Reduce Actinide Mobility
Redox Reactions	Nonferrous Metals	Negligible Compared To Iron
Binding To Organic Ligands[1]	Nonferrous Metals[1]	Can Reduce Actinide Mobility
Complexation With Actinides	Organic Ligands	Negligible
Gas Generation	Al And Other Nonferrous Metals	Negligible Relative To Steels
Microbial Nutrients, CO_2 Generation	Phosphates	Negligible Because MgO Reacts With CO_2
Microbial Nutrients: CH_4 Generation	Phosphates[1]	Negligible
Heat Generation	RH-TRU	Negligible
Electrochemical Processes	Sulfate, Nitrate, Phosphate	Negligible

[1] Waste characteristics and components that influence performance indirectly by influencing components and characteristics listed in Table TRU WASTE-5.

Each waste characteristic shown in Tables TRU WASTE-4 and TRU WASTE-5 is reflected in one or more parameters that are used in PA. The PA parameters are compiled in the Performance Assessment Parameter Database (PAPDB) (presented in Appendix PA, Attachment PAR).

TRU WASTE-2.2.2 Relationship Between Inventory Data and Performance Assessment

Appendix DATA, Attachment F provides both WIPP-level data and waste stream-level data on the radionuclide inventory for the WIPP. Performance assessment models generally use the WIPP-level data, normalized to a base year (2001) and scaled up to the full WIPP capacity. The one exception to this approach is the cuttings/caving model, which uses scaled waste stream level data to capture potential variations in the CH-TRU waste.

The relationship between Appendix DATA, Attachment F data and PA is shown in Figure TRU WASTE-3. As Figure TRU WASTE-3 shows, the waste stream level data are used only in modeling direct release by cuttings and cavings (see Appendix PA for additional information). This direct release scenario includes the probability of penetrating each of the 693 CH-TRU waste streams or a single RH-TRU waste stream that represents all of the 86 RH-TRU waste streams, as discussed in Section 6.4.12.4 and in Appendix PA.

This approach for cuttings and cavings releases represents the potential variations in the CH-TRU waste. This approach is necessary because the size scale for cuttings and cavings is on the order of the drill bit diameter, which is less than the diameter of a 55-gallon drum (8- to 12 in versus 24 in). A cuttings and cavings intrusion would, therefore, extract waste from three specific drums (assuming that drums are stacked three high in the disposal rooms), rather than sampling from a larger volume of waste.

In contrast, scenarios in which radionuclides would be released in brine, either directly to the surface or through the Culebra reservoir, assume that the mobility of radionuclides in brine results in an essentially homogeneous mixture of radionuclides. Brine flow would contact a much larger portion of the waste than the direct release of cuttings and cavings. For brine-related release pathways, the total radionuclide inventory is more applicable than the inventory of a particular waste stream. Performance assessment, therefore, uses the average (WIPP-level) inventory from all TRU waste sites, as shown in Figure TRU WASTE-3. In a similar fashion, spall releases use WIPP-level data because this mechanism is assumed to release waste from a volume larger than several drums, averaging out variations in waste streams.

Decay of radionuclides in the TRU waste will produce some radioactive daughter products that must be accounted for in the waste inventory. Therefore, to provide a current inventory estimate for the CRA-2004, all radionuclide values reported in Appendix DATA, Attachment F are decayed to the end of 2001. The PA calculations begin at the time of closure of the WIPP facility. Therefore, PA calculations further decay the inventory to the end of year 2033.

TRU WASTE-2.3 Components That Affect Performance: Curie Content

The radioactivity of a particular radionuclide, often called the activity, is significant to two different aspects of compliance: (1) inclusion in the waste unit factor, which is the normalization factor for the release limits given in Table TRU WASTE-7, and (2) inclusion in the source term for the compliance demonstration. The waste unit factor is based only on TRU wastes that are alpha (α)-emitters with a half-life greater than 20 years, while the complementary cumulative distribution function (CCDF) is based on the full inventory of all radionuclides in the repository. This section, therefore, includes two subsections: TRU WASTE-2.3.1, components relevant to inclusion in the waste unit factor; and TRU WASTE-2.3.2, components relevant to inclusion in CCDFs for each applicable scenario.

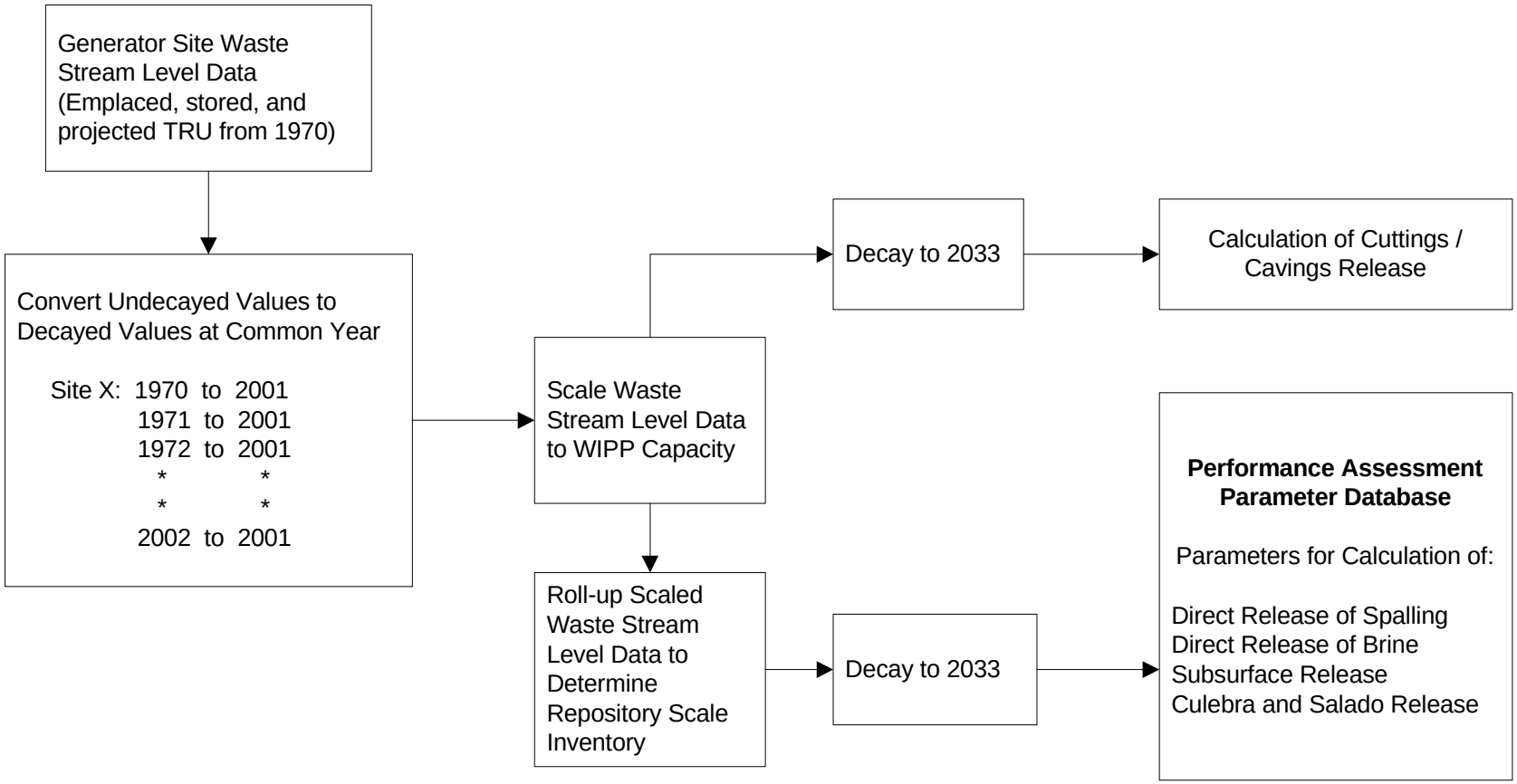

Figure TRU WASTE-3. Flow Chart for Inventory Input into Performance Assessment Waste Components, the Associated Waste Characteristics, and a Performance Assessment Code Related to Each Characteristic

Table TRU WASTE-7. EPA Release Limits and Normalized Release Limits for Radionuclides

Radionuclide	Release Limit per Million Ci of TRU Radionuclides[1] (Ci)	Release Limit for the WIPP Normalized by Total from Table TRU WASTE-8 (Ci)
Americium: ^{241}Am or ^{243}Am	100	248
Carbon: ^{14}C	100	248
Cesium: ^{135}Cs, or ^{137}Cm	1,000	2,480
Iodine: ^{129}I	100	248
Neptunium: ^{237}Np	100	248
Plutonium: ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu	100	248
Radium: ^{226}Ra	100	248
Strontium: ^{90}Sr	1,000	2,480
Technetium: ^{99}Tc	10,000	24,800
Thorium: ^{230}Th or ^{232}Th	10	24.8
Tin: ^{126}Sn	1,000	2,480
Uranium: ^{233}U, ^{234}U, ^{235}U, ^{236}U, or ^{238}U	100	248
Any other α-emitting radionuclide with a half-life greater than 20 years	100	248
Any other radionuclide with a half-life greater than 20 years that does not emit α particles	1,000	2,480

[1] In Appendix A of 40 CFR Part 191, this column is in terms of metric tons heavy metal, and the equivalence to Ci of TRU is presented in Footnote e to the table.

TRU WASTE-2.3.1 Radioactivity Included in the Waste Unit Factor

The WUF is the number of millions of curies (Ci) of α-emitting TRU radionuclides with half-lives longer than 20 years (40 CFR Part 191, Appendix A), based on the TRU waste inventory to be disposed. In the WIPP, 2.48 $\times 10^6$ Ci (see Table TRU WASTE-8) of TRU waste are estimated to be in the repository at closure, so the WUF is 2.48. In CCA Section 4.2.1, the DOE reported the activity of TRU isotopes that contribute to the WUF at closure to be[1] 3.44 $\times$ 10^6 Ci, with a WUF of 3.44. The current WUF (now 2.48 at closure) reflects the updated TRU waste inventory as described in Section TRU WASTE-2.1.2 (greater detail is available in Appendix DATA, Attachment F).

The number of EPA units of a radionuclide is the activity (in Ci) of the radionuclide divided by the release limit for that radionuclide. EPA units are important because the containment requirement for the repository is expressed in EPA units. Section TRU WASTE-2.3.1 discusses current EPA units in more detail.

[1] The value for the WUF in the CCA was inconsistently described; Chapter 4, Section 4.2.1 correctly listed the WUF that was used in the CCA PA as 3.44. CCA Appendix WCA Sections 1.4.2 and WCA Attachment WCA 8.1 incorrectly stated the 1995 decayed value of 4.07 was used in the CCA PA, however the preface to Attachment WCA.8.2 identified and corrected the error. During the EPA's review of the CCA, EPA required DOE to recalculate a new WUF of 3.59 that was ultimately included in the EPA's PAVT (EPA 1998). After the certification, the DOE incorporated the PAVT WUF value of 3.59 in the compliance baseline through an EPA approved change request (EPA 2002).

Table TRU WASTE-8. Radionuclides That Contribute to the Waste Unit Factor

Nuclide	Half-Life (years)	Inventory at Closure (Ci)	Percent of Waste Unit Factor
^{241}Am	4.33×10^{2}	4.58×10^{5}	1.82×10^{1}
^{242m}Am	1.41×10^{2}	2.11×10^{-1}	8.48×10^{-6}
^{243}Am	7.37×10^{3}	2.17×10^{1}	8.63×10^{-4}
^{249}Cf	3.51×10^{2}	7.24×10^{-2}	2.88×10^{-6}
^{251}Cf	9.00×10^{2}	5.10×10^{-4}	2.03×10^{-8}
^{243}Cm	2.91×10^{1}	4.07×10^{-1}	1.62×10^{-5}
^{245}Cm	8.50×10^{3}	1.92×10^{-2}	7.62×10^{-7}
^{246}Cm	4.76×10^{3}	2.22×10^{0}	8.80×10^{-5}
^{247}Cm	1.56×10^{7}	9.45×10^{0}	3.75×10^{-4}
^{248}Cm	3.48×10^{5}	9.32×10^{-2}	3.70×10^{-6}
^{237}Np	2.14×10^{6}	1.01×10^{1}	4.00×10^{-4}
^{238}Pu	8.77×10^{1}	1.25×10^{6}	4.98×10^{1}
^{239}Pu	2.41×10^{4}	6.65×10^{5}	2.64×10^{1}
^{240}Pu	6.56×10^{3}	1.08×10^{5}	4.30×10^{0}
^{242}Pu	3.75×10^{5}	2.71×10^{1}	1.08×10^{-3}
^{244}Pu	8.00×10^{7}	1.10×10^{-3}	4.38×10^{-8}
TOTAL		2.48×10^{6}	-

Source: Leigh 2003a

As an example, using EPA units, the ^{239}Pu inventory at closure would be 6.65×10^{5} Ci (Table TRU WASTE-8), and the release limit for ^{239}Pu would be 248 Ci, so the number of EPA units is calculated as:

$$\frac{6.65 \times 10^{5}\ \text{Ci}}{248\ \text{Ci}} = 2.68 \times 10^{3}\ \text{EPA units.} \qquad (1)$$

The release limit for ^{239}Pu is given by the waste unit factor (2.48) multiplied by the release limit per million Ci of TRU. The release limit per million Ci is given in Table TRU WASTE-7, which is a copy of Table 1 in Appendix A, 40 CFR Part 191. The value for ^{239}Pu is 100 Ci, giving a release limit of 248 Ci. The calculation of WUF, EPA units, and release limits uses the method established for the CCA (described above).

With a mix of radionuclides, each radionuclide is normalized with respect to its release limit, and the sum of all releases must have

- less than one chance in 10 of exceeding the release limit, and
- less than one chance in 1,000 of exceeding ten times the release limit.

The sum of releases in EPA units is expressed by

$$Rj = \frac{1}{fw}\left[\frac{Q1j}{L1} + \frac{Q2j}{L2} + \ldots\right] = \sum_{i=1}^{nR} \frac{Qij}{fwLi} \leq \begin{Bmatrix} 1 \textit{ with a probability of } 0.1 \\ 10 \textit{ with a probability of } 0.001 \end{Bmatrix} \quad (2)$$

where

R_j is the total release in EPA units under scenario j,

f_w is the WUF,

Q_{ij} is the cumulative release for radionuclide i under scenario j,

L_i is the EPA release limit for radionuclide i, and

nR is the number of radionuclides contributing to the release.

The regulatory time period over which these releases are summed is 10,000 years. A brief explanation of these release limits is given in Sanchez (1996), and a comprehensive discussion of the background for these limits is provided in EPA (1985).

Figure TRU WASTE-4 is a flow diagram for the selection of those radionuclides in the inventory that contribute to the WUF. As noted above, not all radionuclides are included in this factor. For example, ^{90}Sr is excluded because it is not a TRU radionuclide, and is not an α-emitter. Even uranium is excluded because it is not a TRU radionuclide, defined as elements with atomic numbers greater than 92.

The radionuclides that are included in the WUF are listed in Table TRU WASTE-8. As noted in the table, the relevant inventory at closure is 2.48×10^6 Ci, resulting in a WUF of 2.48. This analysis was performed using data from Appendix DATA, Attachment F.

It is worthwhile to note that the inventory in Table TRU WASTE-8 is dominated by americium and plutonium, the same elements that dominated the inventory for the CCA. More specifically, the radionuclides ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Am capture 99.9 percent of the WUF. The combined activity at emplacement of ^{241}Am, ^{238}Pu, ^{239}Pu, and ^{240}Pu is orders of magnitude greater than the combined activity of the remaining radionuclides.

TRU WASTE-2.3.2 Radioactivity Included in the Source Term for Performance Assessment

Unlike the WUF, all reported radionuclides are included in a demonstration of compliance and must therefore be considered for inclusion in the source term for PA. A comprehensive list of radionuclides in the waste is in Appendix DATA, Attachment F, which provides the inventory basis for the CRA-2004. Many of these radionuclides are present in such small quantities that their impact on long-term performance is negligible. That is, their total combined initial inventory in EPA units is much less than one percent so they will have negligible impact on compliance.

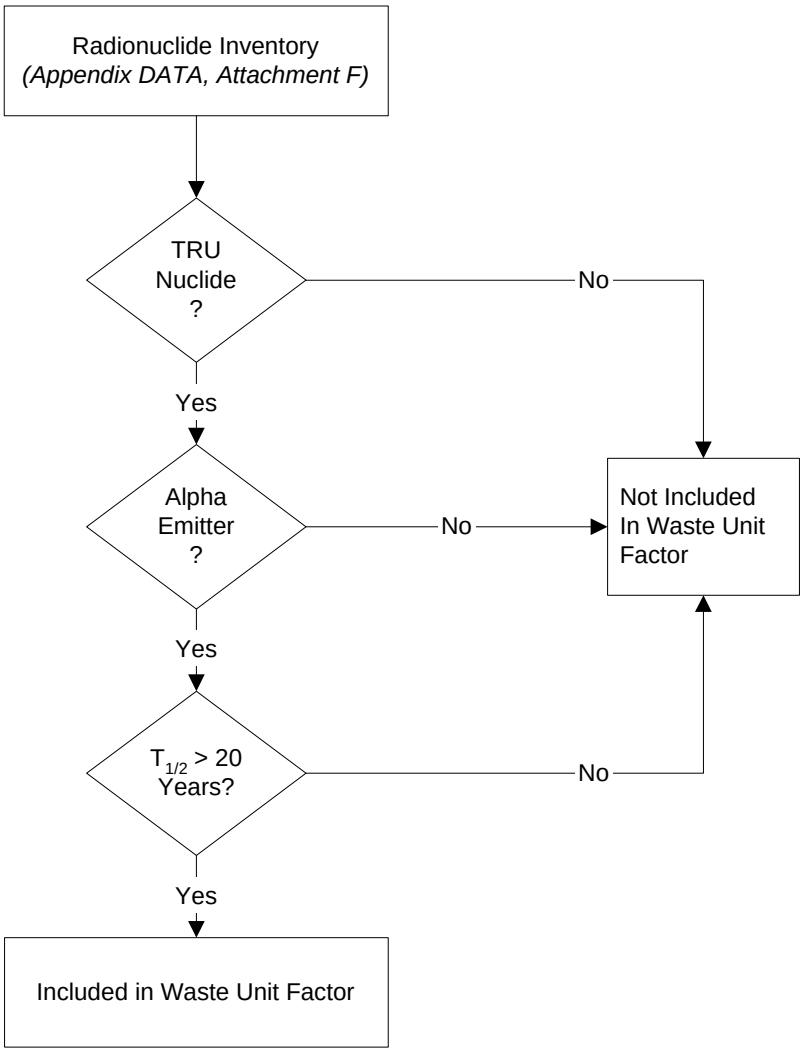

Figure TRU WASTE-4. Flow Diagram for Including Radionuclides in the Waste Unit Factor

Two different release pathways are used in PA: (1) direct releases comprised of (a) material brought to the surface by cuttings, cavings, spalling, and (b) brine under pressure that flows to the surface during a drilling intrusion through the repository; and (2) releases to the accessible environment in brine that moves through the subsurface, primarily the Culebra aquifer. Note that the time scales for these two releases are quite different. The direct release during drilling events (Item 1) occurs within a few days. The flow and transport of radionuclides through the Culebra (Item 2) will require hundreds to thousands of years.

Different radionuclides are used for these pathways because of the time-scale differences and different release media (solid particles containing radionuclides or brine containing radionuclides) as well as the computational efficiency of each computer code used in the PA calculations. Figure TRU WASTE-5 is a flow diagram for selecting radionuclides for different release mechanisms according to the criteria of Table TRU WASTE-7. The result of applying these criteria to the radionuclides in Appendix DATA, Attachment F is shown in

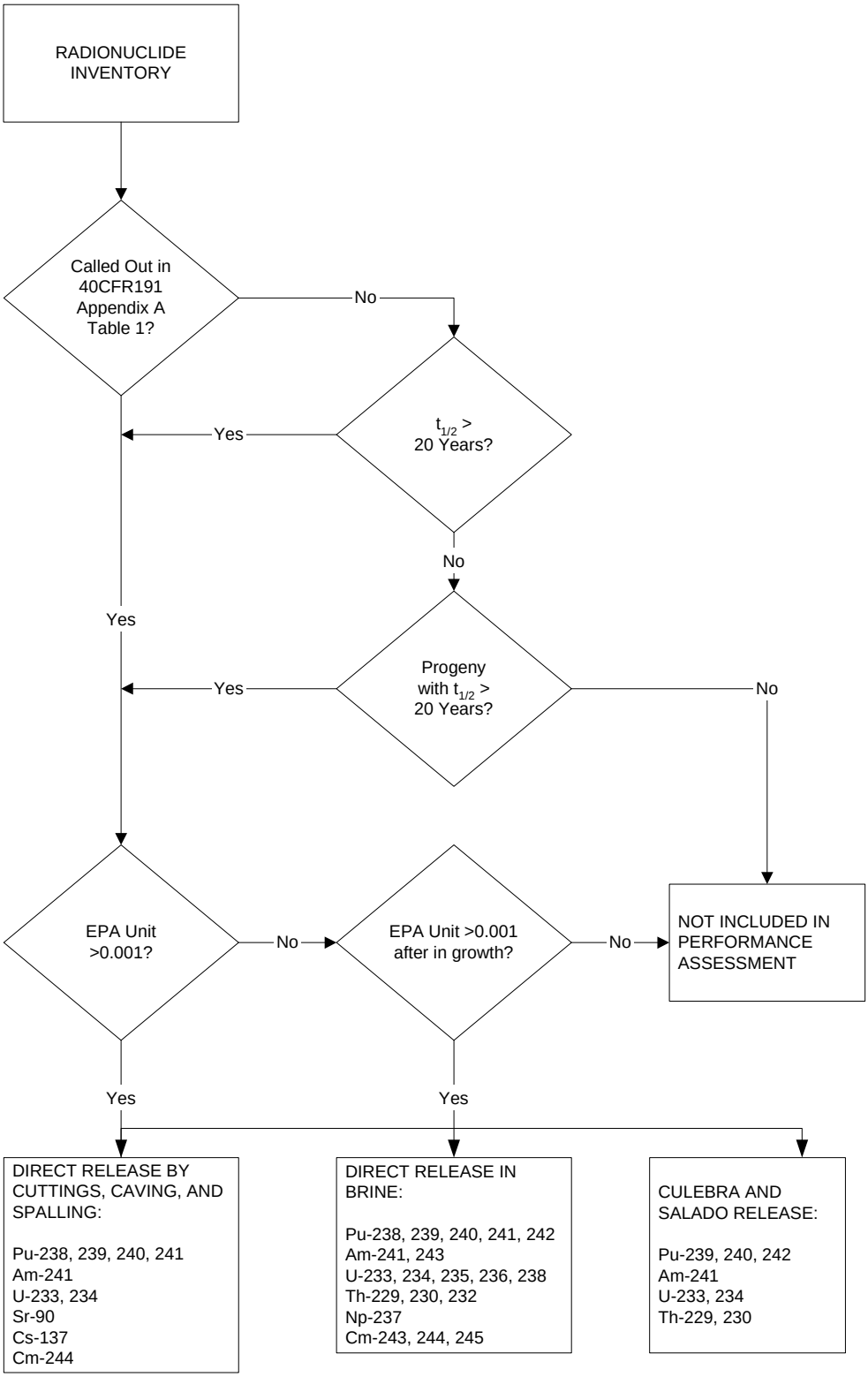

Figure TRU WASTE-5. Flow Diagram for Selecting Radionuclides for the Release Pathways Conceptualized by Performance Assessment (The top part of the diagram describes the criteria for selecting radionuclides in Table TRU WASTE-9)

Table TRU WASTE-9. Radionuclides Included in the Performance Assessment Source Term

Radionuclide	Current Inventory Values			Release Calculations (1)			
	Inventory at Closure (Ci)	EPA Units		Cuttings, Cavings, & Spall Release	Direct Brine Release	Salado Release	Culebra Release
		At Closure	At 10,000 years				
^{238}Pu	1.25×10^{6}	5.04×10^{3}	2.61×10^{-23}	×	×	(2)	(2)
^{239}Pu	6.65×10^{5}	2.68×10^{3}	2.01×10^{3}	×	×	×	×
^{241}Am	4.58×10^{5}	1.84×10^{3}	2.48×10^{-4}	×	×	×	×
^{240}Pu	1.08×10^{5}	4.36×10^{2}	1.51×10^{2}	×	×	c	c
^{137}Cs	1.79×10^{5}	7.19×10^{1}	0.00×10^{0}	×	--	--	--
^{90}Sr	1.42×10^{5}	5.71×10^{1}	0.00×10^{0}	×	--	--	--
^{233}U	1.27×10^{3}	5.12×10^{0}	4.91×10^{0}	×	×	c	c
^{229}Th	5.39×10^{0}	2.17×10^{-2}	3.04×10^{0}	--	×	c	c
^{234}U	3.19×10^{2}	1.28×10^{0}	3.03×10^{0}	×	×	×	×
^{230}Th	1.76×10^{-1}	7.07×10^{-3}	2.64×10^{0}	--	×	×	×
^{238}U	1.54×10^{2}	6.21×10^{-1}	6.21×10^{-1}	--	×	--	--
^{237}Np	1.01×10^{1}	4.06×10^{-2}	4.27×10^{-1}	--	×	--	--
^{232}Th	6.83×10^{0}	2.75×10^{-1}	2.75×10^{-1}	--	×	--	--
^{226}Ra	6.28×10^{0}	2.53×10^{-2}	2.07×10^{-1}	--	--	--	--
^{210}Pb	4.94×10^{0}	1.99×10^{-2}	2.07×10^{-1}	--	×	--	--
^{242}Pu	2.71×10^{1}	1.09×10^{-1}	1.07×10^{-1}	--	×	c	c
^{243}Am	2.17×10^{1}	8.75×10^{-2}	5.74×10^{-2}	--	×	--	--
^{236}U	1.65×10^{0}	6.66×10^{-3}	8.62×10^{-2}	--	×	--	--
^{235}U	2.28×10^{0}	9.18×10^{-3}	3.21×10^{-2}	--	×	--	--
^{14}C	3.25×10^{0}	1.31×10^{-2}	3.90×10^{-3}	--	--	--	--
^{232}U	3.07×10^{0}	1.23×10^{-2}	0.00×10^{0}	--	--	--	--
^{227}Ac	9.57×10^{-1}	3.85×10^{-3}	8.06×10^{-3}	--	--	--	--
^{231}Pa	1.21×10^{0}	4.88×10^{-3}	8.06×10^{-3}	--	--	--	--
^{243}Cm	4.07×10^{-1}	1.64×10^{-3}	0.00×10^{0}	--	×	--	--
^{248}Cm	9.32×10^{-2}	3.75×10^{-4}	3.68×10^{-4}	--	×	--	--
^{245}Cm	1.92×10^{-2}	7.72×10^{-5}	3.97×10^{-5}	--	×	--	--
^{244}Pu	1.10×10^{-3}	4.44×10^{-6}	4.47×10^{-6}	--	×	--	--
^{244}Cm	2.51×10^{3}	(3)	(3)	×	×	--	--
^{241}Pu	5.38×10^{5}	(3)	(3)	×	×	--	--
Percent of EPA Units at closure represented by nuclides in source term				99.98%	98.71%	48.95%	48.95%
Percent of EPA Units at 10,000 years represented by nuclides				99.65%	99.99%	99.92%	99.92%

Source: Leigh 2003b

(1) See Section 6.3 for a discussion of scenarios analyzed by PA and the release pathways.

(2) ^{238}Pu was included in the Salado transport calculations but the release to the Culebra was too low to merit calculation of its transport within the Culebra. The EPA unit percent total at closure increases to 98.71% with ^{238}Pu added; the percent at 10,000 years is unaffected.
^{241}Pu and ^{244}Cu are not regulated by 40 CFR Part 191, but are included because their daughters, ^{241}Am and ^{240}Pu respectively, are significant to performance.

× indicates an isotope included in calculation

c indicates isotopes that are combined for transport with isotopes having similar characteristics

Table TRU WASTE-9. The inventory analysis that follows Figure TRU WASTE-5 is documented in Leigh (2003b). Table TRU WASTE-9 also lists the radionuclides used for specific release mechanisms. The EPA unit at 10,000 years (the end of the regulatory period) is also shown in Table TRU WASTE-9, because some nuclides experience considerable ingrowth, but not enough to affect the domination by the most prevalent radionuclides ^{239}Pu and ^{240}Pu. The ^{241}Am component is also important for the first 3,000 years after closure.

TRU WASTE-2.3.2.1 Radionuclides Included in Direct Releases by Cuttings, Cavings, and Spalling

The 10 isotopes listed in the column headed "Cuttings/Cavings/Spall Release" in Table TRU WASTE-9 are used to model direct release by cuttings, cavings, or spalling. Release is assumed to occur when containers of CH-TRU or RH-TRU waste are breached during a borehole intrusion. The amount of radionuclides in the source term is estimated from the inventory per drum of the waste stream penetrated, including decay and ingrowth. Details of the EPA unit distribution in the waste streams are provided in Fox (2003). The direct release scenario is discussed in greater detail in Section 6.4.12.4.

Eight of the listed isotopes comprise more than 99.9 percent of the EPA units for the entire regulatory period and are identified in Leigh (2003b) as important radionuclides for direct release. The other two are included because they are parent nuclides of significant daughters. Inclusion of 99 percent or more of the EPA unit provides an accurate representation of the source term, while maintaining efficiency in computation by limiting the total number of isotopes to 10. The addition of the many radionuclides that make up the final 0.1 percent does not provide additional benefit in understanding the long-term behavior of the repository (see Leigh 2003b).

TRU WASTE-2.3.2.2 Radionuclides Included in Direct Releases of Brine to the Surface

Direct release of brine to the surface can carry radionuclides that are dissolved in the brine or sorbed on colloidal particles.

The radionuclides released in direct release of brine to the surface include several isotopes that comprise negligible fractions of the total EPA unit, but must be included in the source term because of their influence on the total quantity of dissolved radionuclides. This influence occurs because the isotopes of a radionuclide will dissolve based on mass ratio, rather than the activity ratio, in which they are present in the waste. That is, if 90 percent of the mass of uranium in the waste is ^{238}U (for example), 90 percent of the dissolved uranium in moles/liter will be ^{238}U, even though 90 percent of the radioactivity will not be from ^{238}U.

The EPA units of ^{90}Sr and ^{137}Cs at closure are large enough that an explanation is needed for not including them in the source term for direct release of brine. Although the EPA units of ^{90}Sr and ^{137}Cs are initially large (57 for ^{90}Sr and 72 for ^{137}Cs), rapid decay from a short half-life (about 30 years) results in negligible impact on the PA for these two isotopes. The lack of impact on compliance is explained below.

The ^{90}Sr and ^{137}Cs components decay by about 90 percent during the first 100 years after closure, when borehole intrusions are excluded due to the active institutional controls that will be

implemented following WIPP closure. During this time period, the EPA unit of ^{137}Cs decays from 72 down to 7.1 for the whole repository, while ^{90}Sr decays from 57 to 5.3. At 200 years, the EPA unit for both ^{137}Cs and ^{90}Sr is below 1.0, again for the whole repository.

In addition to the rapid decay, the results of the PA show that were an individual borehole intrusion to occur at 100 years, it would release about six EPA units (5.5 units, see Appendix PA), which is much less than the total inventory. Even at 350 years, when either isotope decays down to 0.03 percent of the initial inventory, the maximum volume of brine release would be only 0.01 m^3. In summary, the rapid decay of ^{137}Cs and ^{90}Sr and the negligible volumes of brine release at early times provide the basis for excluding these isotopes from the inventory.

The ^{14}C component is not included in this (or any) source term. Any ^{14}C transported out of the repository will be diluted by the large excess of nonradioactive carbon. This was demonstrated in Wang (1996a) in which there were 0.2 moles of ^{14}C out of 3×10^8 moles of carbon in the cellulosic materials, or one part in 100 million. Although the ^{14}C inventory has been updated, the ratio of ^{14}C to nonradioactive carbon remains the same.

TRU WASTE-2.3.2.3 <u>Radionuclides Included in Releases to the Culebra Aquifer</u>

Release of brine from the repository to the Culebra also potentially carries dissolved and colloidal radionuclides. The nine radionuclides in the source term for Culebra release include those that dominate the EPA unit for all but the earliest part of the regulatory period. Other less prevalent radionuclides are excluded because they would comprise a negligible fraction of the EPA unit or because transport through the Culebra is sufficiently slow that shorter-lived radionuclides would decay to negligible amounts before reaching the accessible environment. The selection of the nine radionuclides is discussed in Leigh (2003b).

Of the nine radionuclides, only ^{239}Pu, ^{241}Am, ^{234}U, and ^{230}Th are transported separately in PA. Isotopes of the same element will be transported together, unless their half-lives differ greatly. The movement of most of the radionuclides can be calculated indirectly. This concept was presented in detail in Garner (1996):

- The ^{233}U component can be combined with ^{234}U for transport because their half-lives are similar.
- Similarly, ^{229}Th can be combined with ^{230}Th, because they will be in a fixed ratio to each other. The ^{232}Th component can be dropped because it is a constant small fraction of the EPA unit throughout the regulatory period.
- The ^{240}Pu and ^{242}Pu components can be combined with ^{239}Pu; their long half-lives also indicate a fixed ratio between them.
- The ^{238}Pu component will have decayed to about 0.5 percent of its initial inventory after 700 years, and its contribution to the EPA unit will be negligible because travel time in the Culebra is much greater than 700 years.

The ^{239}Pu and ^{240}Pu components dominate the EPA limit during the regulatory period, and ^{241}Am is also a factor for the first 3,000 years. Toward the end of the regulatory period, ^{230}Th has

grown by about 2.5 orders of magnitude, ^{229}Th by about 1.5 orders of magnitude, and ^{234}U by a factor of three, but all are still small fractions of the EPA unit. The ^{226}Ra component grows during the regulatory period, but even at 10,000 years would comprise a very small fraction of the EPA limit.

Calculation of radionuclide inventories for this transport mechanism is presented in Leigh (2003c.)

TRU WASTE-2.3.2.4 Radionuclides Included in Releases Through the Salado

In the PA results (Appendix PA), there is one vector in which brine is released through the Salado to the accessible environment. As a result, the radionuclides that could potentially contribute to releases via this pathway are considered.

Release of brine from the repository through the Salado (either to the Culebra or to the accessible boundary) can also potentially carry dissolved and colloidal radionuclides. The nine radionuclides in the source term for Salado release include those that dominate the EPA unit for all but the earliest part of the regulatory period. Other less prevalent radionuclides are excluded, because they would comprise a negligible fraction of the EPA unit or because transport through the Salado is sufficiently slow that shorter-lived radionuclides would decay to negligible amounts before reaching the accessible environment. The selection of the nine radionuclides is discussed in Leigh (2003b.)

TRU WASTE-2.3.2.5 Radionuclides Excluded From Source Terms

A large number of radionuclides were not included in any source term because they did not survive the screening process outlined in Figure TRU WASTE-5. Table TRU WASTE-10 lists those excluded radionuclides that have not already been discussed, and indicates (marked with an "×" in Table TRU WASTE-10) the reason for their exclusion.

TRU WASTE-2.4 Radionuclide Characteristics: Solubility and Colloid Formation

The major characteristics of the radionuclides that are expected to affect disposal system performance are (1) solubility and (2) the tendency to form or sorb to colloidal particles. Except for direct release from drilling (cutting) and caving, in which particles containing radionuclides will be released with circulation of drilling mud, radionuclides are mobilized for transport from the repository either in brine or as colloidal particles transported by brine. Gas-phase transport is not expected to occur (see Appendix PA, Attachment SCR).

All isotopes of a particular radioactive element exhibit essentially identical characteristics of solubility, colloid formation, and sorption.

Table TRU WASTE-10. Radionuclides Excluded From All Source Terms

Radionuclide	Reason for Exclusion[3]		
	Short Half-life and Progeny with Short Half-life[1]	Small EPA Unit	Negligible[2] Ingrowth
^{225}Ac	×	NA	NA
^{227}Ac	×	NA	NA
^{228}Ac	×	NA	NA
^{109m}Ag	×	NA	NA
^{110}Ag	×	NA	NA
^{110m}Ag	×	NA	NA
^{242}Am	×	NA	NA
^{242m}Am	NA	×	×
^{245}Am	×	NA	NA
^{217}At	×	NA	NA
^{137m}Ba	×	NA	NA
^{210}Bi	×	NA	NA
^{211}Bi	×	NA	NA
^{212}Bi	×	NA	NA
^{213}Bi	×	NA	NA
^{214}Bi	×	NA	NA
^{249}Bk	×	NA	NA
^{250}Bk	×	NA	NA
^{14}C	NA	×	NA
^{109}Cd	×	NA	NA
^{113m}Cd	×	NA	NA
^{141}Ce	×	NA	NA
^{144}Ce	×	NA	NA
^{249}Cf	NA	×	×
^{250}Cf	×	NA	NA
^{251}Cf	NA	×	NA
^{242}Cm	×	NA	NA
^{246}Cm	NA	×	×
^{247}Cm	NA	NA	×
^{250}Cm	NA	NA	×
^{60}Co	NA	×	NA
^{134}Cs	×	NA	NA

Table TRU WASTE-10. Radionuclides Excluded From All Source Terms — Continued

Radionuclide	Reason for Exclusion[3]		
	Short Half-life and Progeny with Short Half-life[1]	Small EPA Unit	Negligible[2] Ingrowth
^{135}Cs	NA	×	NA
^{152}Eu	×	NA	NA
^{154}Eu	×	NA	NA
^{155}Eu	×	NA	NA
^{55}Fe	×	NA	NA
^{221}Fr	×	NA	NA
^{223}Fr	×	NA	NA
^{152}Gd	NA	×	NA
^{3}H	×	×	NA
^{129}I	NA	×	×
^{85}Kr	×	NA	NA
^{54}Mn	×	NA	NA
^{22}Na	×	NA	NA
^{93m}Nb	×	NA	NA
^{95}Nb	×	NA	NA
^{95m}Nb	×	NA	NA
^{144}Nd	NA	NA	×
^{59}Ni	NA	×	×
^{63}Ni	NA	NA	×
^{238}Np	×	NA	NA
^{239}Np	×	NA	NA
^{240m}Np	×	NA	NA
^{233}Pa	×	NA	NA
^{234}Pa	×	NA	NA
^{234m}Pa	×	NA	NA
^{209}Pb	×	NA	NA
^{211}Pb	×	NA	NA
^{212}Pb	×	NA	NA
^{214}Pb	×	NA	NA
^{107}Pd	NA	×	NA
^{210}Po	×	NA	NA
^{211}Po	×	NA	NA
^{212}Po	×	NA	NA
^{213}Po	×	NA	NA

Table TRU WASTE-10. Radionuclides Excluded From All Source Terms — Continued

Radionuclide	Reason for Exclusion[3]		
	Short Half-life and Progeny with Short Half-life[1]	Small EPA Unit	Negligible[2] Ingrowth
^{214}Po	×	NA	NA
^{215}Po	×	NA	NA
^{216}Po	×	NA	NA
^{218}Po	×	NA	NA
^{144}Pr	×	NA	NA
^{236}Pu	×	NA	NA
^{243}Pu	×	×	NA
^{223}Ra	×	NA	NA
^{224}Ra	×	NA	NA
^{225}Ra	×	NA	NA
^{106}Rh	×	NA	NA
^{219}Rn	×	NA	NA
^{220}Rn	×	NA	NA
^{222}Rn	×	NA	NA
^{106}Ru	×	NA	NA
^{125}Sb	×	NA	NA
^{126}Sb	×	NA	NA
^{126m}Sb	×	NA	NA
^{79}Se	NA	×	×
^{147}Sm	NA	×	NA
^{148}Sm	NA	NA	×
^{151}Sm	NA	NA	×
^{121m}Sn	NA	×	NA
^{126}Sn	NA	×	NA
^{99}Tc	NA	×	×
^{123}Te	NA	NA	×
^{123m}Te	×	NA	NA
^{125m}Te	×	NA	NA
^{227}Th	×	NA	NA
^{228}Th	×	NA	NA
^{231}Th	×	NA	NA
^{234}Th	×	NA	NA
^{207}Tl	×	×	NA
^{208}Tl	×	×	NA

Table TRU WASTE-10. Radionuclides Excluded From All Source Terms — Continued

Radionuclide	Reason for Exclusion[3]		
	Short Half-life and Progeny with Short Half-life[1]	Small EPA Unit	Negligible[2] Ingrowth
^{209}Tl	×	NA	NA
^{232}U	NA	×	×
^{237}U	×	NA	NA
^{240}U	×	NA	NA
^{90}Y	×	NA	NA
^{91}Y	×	NA	NA
^{65}Zn	×	NA	NA
^{93}Zr	NA	×	×
^{95}Zr	×	NA	NA

[1] "Short" half-life means $t_{½}$ < 20 years. Radionuclides with $t_{½}$ < 20 years are not regulated by 40 CFR Part 191 Subparts (b) and (c).
[2] Negligible ingrowth includes ingrowth of the progeny that are radionuclides already predominant in the inventory.
[3] NA indicates that the column heading does not apply to the particular isotope.

Solubility and colloid formation are discussed for thorium, uranium, neptunium, plutonium, and americium. The experimental determination and modeling of solubility and colloid formation, and the manner in which they are taken into account by PA, are discussed in detail in Appendix PA. Cesium and strontium are assumed to be extremely soluble and their concentrations will be limited by their inventories (see Appendix WCA, Section WCA.3.2.2, in the CCA). Thus, the two elements are not considered in this section. Radium is excluded from the source term because of its short half-life.

Actinide mobility depends on the particular chemical environment (brine pH, fugacity of CO_2, redox potential, organic ligand concentration, etc). That environment will be controlled by the MgO reacting with brine. Magnesium oxide is added to mitigate the effect of CO_2 generated by microbial degradation of organic materials and to control the pH of any brines in the repository. The mechanism of the control is discussed in Appendix BARRIERS and Appendix PA, Attachment SOTERM.

Actinide mobility also depends on the formation of colloids. Actinides can either form intrinsic colloids by condensation of hydrolyzed ions, or can be sorbed on to nonradioactive colloidal particles.

TRU WASTE-2.4.1 Components and Characteristics Influencing Solubility

In the absence of MgO, the factors that would most directly affect solubility in the repository are pH, CO_2 fugacity, redox conditions, the availability of complexing agents, and the source and composition of the brine (clearly not a waste characteristic). The important waste components that affect actinide solubility are steel, cellulosic, plastic, rubber, organic ligand, and cementitious materials. Actinide solubility also depends on temperature. However, the

temperature in the repository will remain almost constant (about 300 K) and the thermal effect of exothermal chemical reactions among brine, waste component, and MgO will be negligible (see Appendix WCA, Section WCA-5.3.1 in the CCA and Wang 1996b). Repository pressure does not influence solubility until it is at least an order of magnitude higher than lithostatic pressure and this will not occur (Butcher et al. 1991). The following subsections discuss the influence of waste characteristics and components on each of these factors, as well as those that have little or no influence on solubility.

TRU WASTE-2.4.1.1 Components Influencing Redox Environment

The components of the waste that greatly influence the redox environment in the inundated WIPP repository are steels and biodegradable organic materials (CPR materials). The radionuclides contributing to the brine release source terms are all actinides. Because of their electronic structure, these elements can form a wide variety of inorganic compounds that dissolve in aqueous solutions like brine in several different valence or oxidation states. In the WIPP environment, the solubilities of these compounds can vary from about 10^{-9} Molar (M) to about 10^{-5} M (see Appendix PA, Attachment SOTERM). In general, for both plutonium and the other actinides, the higher oxidation states (V and VI) are more soluble than the lower oxidation states (III and IV). The redox environment determines which of these oxidation states are likely to be stable in solution under WIPP conditions—an important determinant of solubility because of the differences among oxidation states. Although a detailed discussion of the experimental determination of oxidation state distribution is found in Appendix PA, Attachment SOTERM, a brief discussion is given here.

Anoxic conditions will be dominant during the whole time period of 10,000 years. At the time of the CCA, it was believed that anoxic steel corrosion would produce both hydrogen and $Fe(OH)_2$ (see Wang and Brush 1996). A small amount of oxygen, trapped at emplacement, will be used quickly by oxic corrosion and microbial action. Based on recent experimental work (described in Appendix PA, Attachment SOTERM), anoxic corrosion of steel could produce hydrogen, and Fe(II) or Fe(II,III)-bearing corrosion products. It has been shown that both metallic iron and Fe^{2+} ($Fe(OH)_2$) in simulated WIPP brine, under anoxic conditions, will reduce Pu(+VI) stoichiometrically to the much less soluble Pu(+IV). Plutonium (+V) is seen in this chemical reaction as an unstable intermediate. It is expected, therefore, that Pu(+VI) and Pu(+V) will not be stable in solution in WIPP brines. The iron in the drums and waste boxes is enough to provide several thousand-fold excess over what is needed stoichiometrically, even if all the emplaced plutonium existed in the +VI oxidation state. The other metals in the waste may also be able to reduce the actinides, but their effect would be negligible compared to the effect of iron, because they are present in smaller quantities.

The oxidation state distribution used in PA, based on experimental data as well as the published literature, is (Katz et al. 1986; Hobart 1990; Clark et al. 1995; Felmy et al. 1996; Rai and Strickert 1980; Rai et al. 1982; Kim et al. 1985; Pryke and Rees 1987; Nitsche and Edelstein 1985):

thorium: +IV
uranium: +IV and +VI
neptunium: +IV and +V

plutonium: +III and +IV
americium: +III

Curium exhibits essentially the same chemical behavior and oxidation state as americium. In PA, half of the realizations will include the lower oxidation states of uranium, neptunium, and plutonium; the other half will include the higher oxidation states (CCA Appendix SOTERM, Section 4.7; Katz et al. 1986; Weiner 1996).

TRU WASTE-2.4.1.2 Components Influencing pH and CO_2 Fugacity

In the absence of MgO, actinide solubility would be highly dependent on pH and CO_2 fugacity of the brine. Lower pH and higher CO_2 fugacity could result in higher actinide solubility. Original Salado and Castile brines exhibit pH values of about 6 and 7, respectively (Brush 1990, Tables 2-2 and 2-3). The production of CO_2 by microbial degradation in the repository would acidify the brine and lower the brine pH to about 4.5, if no MgO were added (CCA Appendix SOTERM, SOTERM.2). Microbial CO_2 production can be described by the following sequential reactions (Wang and Brush 1996):

$$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow 7.4H_2O + 6CO_2 + 2.4N_2 \quad (3)$$

$$C_6H_{10}O_5 + 6H^+ + 4.8SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S \quad (4)$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CO_2 + 3CH_4 . \quad (5)$$

Nitrate and sulfate are used as electron acceptors in these reactions and determine CO_2 yield per mole of organic carbon. Based on the inventory estimates for nitrate and sulfate, over 94% (see Appendix BARRIERS) of organic materials (CPR materials) would be biodegraded via the third reaction, methanogenesis, in which one mole of organic carbon will produce one half of a mole each of CO_2 and CH_4.

Based on the inventory estimate for organic carbon (Appendix DATA, Attachment F) and the estimated CO_2 yield per mole of organic carbon, to mitigate the negative effect of microbially produced CO_2, 1.41×10^9 moles of MgO will be added to the repository (see Appendix BARRIERS). At the time of the CCA, it was estimated that 2×10^9 moles of MgO would be required. However, as discussed below, DOE's understanding of the chemical interaction of MgO and components of the waste has evolved.

In the CCA, the waste components of organic carbon, nitrate, and sulfate were used to determine the amount of MgO needed. It was stated that hydrated MgO would react with CO_2:

$$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O. \quad (6)$$

The above reaction would buffer the pH at approximately 9.4 in Salado brine and 9.9 in Castile brine and CO_2 fugacity at 10^{-7} atm for both brines. Actinide solubility calculated for the brine in equilibrium with $Mg(OH)_2$ and $MgCO_3$ is minimal (CCA Appendix SOTERM, SOTERM.3). Now, however, the quantities of CPR materials, nitrate, and sulfate are used to determine the amount of MgO needed, based on the understanding that hydrated MgO will react with CO_2:

$$5Mg(OH)_2 + 4CO_2 \rightarrow Mg_5(CO_3)_4(OH)_2 + 4H_2O \quad (7)$$

under conditions in which microbial activity produces gas, and

$$Mg(OH)_2 + Ca^{2+} + CO_2 \rightarrow CaCO_3 + Mg^{2+} + H_2O \quad (8)$$

under conditions in which microbial activity does not occur (see Appendix BARRIERS).[2]

The above reactions will buffer pH at approximately 9 in both Salado and Castile brines, and CO_2 fugacity at $10^{-6.2}$ to $10^{-5.5}$ atm for both brines.

Cementitious waste (that contains calcium oxide and/or calcium hydroxide) could also be expected to raise the pH, and the waste is currently estimated to contain a total of about 1.2×10^7 kg cementitious material (Appendix DATA, Attachment F). This amount of cementitious material contains about 9×10^6 moles of $Ca(OH)_2$. However, this amount of $Ca(OH)_2$ would not be enough to affect pH or brine composition significantly. It was shown that $Ca(OH)_2$ could be consumed by reaction with microbial generated CO_2 or with $MgCl_2$ in the Salado brine and thus the repository chemistry would be dominantly controlled by the $Mg(OH)_2$ / Mg CO_3 buffer, rather than the $Ca(OH)_2$ / $CaCO_3$ buffer (CCA, Wang 1996a and Wang 1996c). Because of the additional MgO that will be added, other components of the waste are unlikely to affect the pH.

TRU WASTE-2.4.1.3 Waste Components That Directly Enhance Solubility

A number of organic compounds are capable of forming strong complexes with actinide ions, thereby stabilizing the actinide in the solution. Of the about 60 organic compounds in the waste (Drez and James-Lipponer 1989; Brush 1990; Drez 1996), 4 of these (acetate, citrate, oxalate, and ethylene diamine tetra-acetate [EDTA]) have been identified to have an effect on actinide mobility, because they are water-soluble and present in significant quantities (Appendix DATA, Attachment F).

. Ligand concentrations in the repository were calculated by dividing the current mass of each ligand in the inventory by the brine volume of 29,841 m3, “the smallest quantity of brine required to be in the repository [for] transport away from the repository (Larson, 1996). The effect of these organic ligands on the solubility of actinides in both Salado and Castile brines has been studied, and is discussed in detail in Appendix PA, Attachment SOTERM.

To estimate the effectiveness of other metals in binding organic ligands and thereby reducing the free ligand concentrations, some simple competition calculations were performed (for the CCA) using parameters obtained in dilute solutions, because parameters for concentrated salt solutions like the WIPP brines were not available. These metal species included iron (Fe), nickel (Ni), chromium (Cr), vanadium (V), and manganese (Mn), because the steels used for the waste drums contain on average at least 0.001 weight percent of Ni, Cr, V, and Mn as minor constituents. Based on at least 1.9×10^9 moles of steels destined to be disposed of in the WIPP, there should

[2] The conceptual model for the repository maintains a probability of significant microbial degradation of CPR materials of 0.5. Thus, there is no microbial activity and concomitant gas generation in about half of the PA vectors (Brush and Xiong 2003a; 2003b).

be at least 1×10^4 moles of each of Ni, Cr, V, and Mn in the repository (CCA Appendix SOTERM). There are also expected to be more than 6×10^7 moles of lead (Pb). Additionally, several other metals that can sequester organic ligands will be present in small quantities.

Table TRU WASTE-11 presents complexation constants for several metals with EDTA. These values were measured in dilute solution. For comparison, for EDTA in 5 molal (moles of solute per kilogram of solvent) NaCl, the magnesium association constant is log K_{Mg} = 6.6 (Martell and Smith 1982).

Table TRU WASTE-11. Complexation Constants for Selected Metals[1]

Species	log K
Fe^{2+}	14.3
Cr^{2+}	13.6
Ni^{2+}	18.4
Mn^{2+}	13.9
V^{2+}	12.7
Cu^{2+}	18.9
Pb^{2+}	18

[1] From Martell and Smith (1982).

To assess the ability of these metals to sequester the organic ligands, the calculations for competition between these metals and actinides for organic ligands were performed by the DOE. The calculation results show that under expected WIPP conditions, 99.8% of the EDTA was complexed by Ni, effectively rendering it unavailable for complexation with the actinides (CCA, Appendix SOTERM).

TRU WASTE-2.4.2 Components and Characteristics Influencing Colloidal Actinide Mobility

The waste components that directly contribute to actinide colloid formation include mineral fragments, and humic substances (soil). CPR materials can contribute to the quantity of humic colloids. Actinides can form intrinsic colloids or can be sorbed on to nonradioactive colloidal particles. A complete discussion of colloid formation in the WIPP can be found in CCA Appendix SOTERM and Papenguth (1996a through 1996e). A summary of that discussion follows.

In principle, intrinsic colloids are formed by condensation (or polymerization) of hydrolyzed actinide ions. Examples of polymeric species of many of the actinides of importance to the WIPP have been found in the literature (see Papenguth and Behl (1996) for an extensive literature review). However, except for Pu, the intrinsic colloids of other actinides (Am, U, Th, and Np) do not develop to sizes large enough to affect transport behavior of these actinides relative to their dissolved form. Therefore, the intrinsic colloid concentrations for Am, U, Th, and Np are modeled as zero in the disposal room and only intrinsic plutonium colloids have any impact on performance. Plutonium(IV) readily forms an intrinsic colloid; evidence suggests that

the initial polymerization, or condensation, of hydrolyzed Pu(IV) produces a macromolecule that becomes progressively more crystalline with time. As the Pu polyelectrolytes mature, they are expected to be kinetically destabilized and immobilized by the high ionic strength of the WIPP brines, then coagulate and settle out of solution.

Within the repository, mineral fragment colloids could form from corrosion of iron-bearing waste, soils, and portland cement-based matrices. Because a wide range of mineralogies with different sorptive behavior are present at the WIPP, a bounding approach is used to estimate the maximum concentration of actinides bound to mineral fragment colloids. Mineral fragments are expected to be kinetically destabilized in the high-ionic strength brines present in the disposal room. Experimental information, combined with a conservative estimate of adsorption site density, provided a most likely value of 2.6×10^{-9} mole of colloidal mineral-fragment-bound actinides per liter of dispersion; the experimental results were increased by a factor of two to account for the possibility that the indigenous mineral fragment colloids in the Culebra could sorb dissolved actinides. This value is presumed to be the same for all five key actinides. Although mineral fragments contribute to actinide mobility and are included in PA, their contribution is negligible and they do not impact repository performance (see Appendix PA).

Humic colloids will be present in the repository, both (a) in soil and humic material that is part of the emplaced waste and (b) in colloids that will be formed if the CPR materials in the waste are microbially degraded. The contribution of humic colloids to repository performance is therefore calculated by quantifying humic-actinide complexation coupled with solubilities of humic substances in WIPP brines, and expressing the result as the ratio of moles of humic-bound actinide to moles of dissolved actinide. The range of ratios is from about 4.3×10^{-4} to about 6.3 in Castile brine and from about 5.3×10^{-5} to about 6.3 in Salado brine.

To compute the concentration of actinides bound to humic substances, several parameters, such as solubility of humic substances, site binding capacity, actinide complexation factors, and stability constants, were measured or obtained from published literature (Papenguth 1996c). The oxidation state analogy was also used to develop parameter values for actinides expected to have multiple oxidation states in the WIPP disposal rooms. In addition, the theoretical maximum concentration of actinides that can be bound to humic substances was also computed and found to be 1.1×10^{-5} M.

The other major source of colloidal material in the repository is the microbes themselves, though they are not necessarily waste components. Microbes are known to actively bioaccumulate actinides intercellularly, as well as act as substrates for passive extracellular sorption. Naturally occurring halophilic and halotolerant microbes have been observed in the Salado brines at the WIPP site (Brush 1990 and Francis and Gillow 1994). The waste material in the disposal room would serve as a nutrient and substrate for microbes, and consequently increase the microbe population, making them potentially important to actinide mobility.

The uptake of actinides by microbes and humic substances is quantified through two parameters for each actinide and substrate: proportionality constants (with PA parameter designations PROPMIC, PHUMSIM, and PHUMCIM) that describe the amount of each actinide bound to mobile microbes and humic colloids, respectively; and the maximum concentrations (CAPMIC and CAPHUM) of each actinide associated with mobile microbes and humics, respectively. As

discussed above, the concentrations of mineral-fragment-bound actinides and intrinsic actinides are very small, and are presented as concentrations (CONCMIN and CONCINT) only. A series of bioaccumulation and toxicity experiments were performed to obtain the following values of PA parameters for each actinide shown in Table TRU WASTE-12.

Table TRU WASTE-12. Colloid Concentration Factors

	Concentration on Mineral Fragments[1]	Concentration as Intrinsic Colloid[1]	Proportion Sorbed on Microbes[2]	Maximum Sorbed on Microbes[1]	Proportion Sorbed on Humics[2]		Maximum Sorbed on Humics[1]
					Salado	Castile	
Th	2.6×10^{-8}	0.0	3.1	0.0019	6.3	6.3	1.1×10^{-5}
U(IV)	2.6×10^{-8}	0.0	0.0021	0.0023	6.3	6.3	1.1×10^{-5}
U(VI)	2.6×10^{-8}	0.0	0.0021	0.0023	0.12	0.51	1.1×10^{-5}
Np(IV)	2.6×10^{-8}	0.0	12.0	0.0027	6.3	6.3	1.1×10^{-5}
Np(V)	2.6×10^{-8}	0.0	12.0	0.0027	9.1×10^{-4}	7.1×10^{-3}	1.1×10^{-5}
Pu(III)	2.6×10^{-8}	0.0	0.3	6.8×10^{-5}	0.19	1.1	1.1×10^{-5}
Pu(IV)	2.6×10^{-8}	1.0×10^{-9}	0.3	6.8×10^{-5}	6.3	6.3	1.1×10^{-5}
Am	2.6×10^{-8}	0.0	3.6	NA	0.19	1.1	1.1×10^{-5}

[1] in units of moles total mobile actinide per liter
[2] in units of moles microbial actinide per moles dissolved actinide

As evident in Table TRU WASTE-12, microbial colloids can transport concentrations of actinides that are several multiples of the dissolved concentration, and thus increase the potential for actinide mobility considerably. Humic colloids are waste components, and microbial colloids increase in quantity as they metabolize waste components. Both types of colloids are incorporated in PA (details are discussed in Appendix PA) and are expected to affect disposal system performance.

The treatment of colloids in CRA-2004 is like that of the CCA. The only difference between the CCA colloid assumptions and values and CRA-2004 colloid assumptions and values is in relation to the microbial colloids. In the CCA, microbial colloids were present in all calculations as described above. For CRA-2004, in the absence of microbes (PA assumes that microbes are present in only 50 percent of the calculations), microbial colloids are not included in the calculations.

TRU WASTE-2.5 Nonradioactive Waste Components and Characteristics

TRU WASTE-2.5.1 Gas Generation

The waste components that contribute to gas generation are: (a) ferrous and nonferrous metal, (b) CPR materials, and (c) nitrate and sulfate. Water content of the waste also contributes to the generation of gas. The mechanisms and reactions for gas generation are discussed in Wang and Brush 1996.

Metal can contribute to gas generation through corrosion. The anoxic corrosion reaction of iron is:

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2(g) \quad (9)$$

The hydrogen gas produced by this reaction contributes to total gas pressure, but does not affect repository chemistry. In addition, steel corrosion is likely to consume water in the repository; this effect is taken into account in the computer code BRAGFLO. Nonferrous metals such as aluminum alloys can also corrode, producing H_2, but their contribution to total gas pressure is negligible, because they are present in much smaller quantities than iron (Appendix DATA, Attachment F).

CPR materials and nitrate and sulfate control microbial gas generation. CPR materials can be used as substrates by anaerobic microbes in the WIPP. Nitrate and sulfate can be used as electron acceptors by microbes to oxidize the organic materials. Organic materials are likely to be biodegraded through reactions:

$$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow + 7.4H_2O + 6CO_2 + 2.4N_2(g) \quad (10)$$

$$C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S(g) \quad (11)$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4(g) + 3CO_2(g) \quad (12)$$

The above reactions will proceed sequentially according to the energy yield per mole of carbon in each reaction. Based on the inventory estimates for nitrate and sulfate, the third reaction is expected to be dominant. Because the CO_2 produced by these reactions will be removed by reaction with MgO, methane is the primary, microbially generated gas that will contribute to the total gas in the repository.

Phosphate in the waste may enhance microbial activity in the repository. The rates of cellulosic material biodegradation used in PA are derived from the incubation experiments amended with nutrients including phosphate. Thus, the effect of phosphate on microbial reactions is captured indirectly in the parameters submitted to PA (Francis and Gillow 1994).

Based on the inventories of steels and organic materials and the rates of gas generation estimated, microbially produced gases may dominate early in the repository's history. Gas pressure can affect repository performance. Pressure in the repository may approach lithostatic, initiating or propagating fractures within the interbeds, and clay seams in the Salado. Gas pressure will not exceed lithostatic (Butcher et al. 1991) because gas can leak out through the interbeds.

Gas pressure is incorporated into PA through parameters in BRAGFLO calculations.

The initial water content of the waste also contributes to the generation of gas because it defines how much brine is immediately available for the corrosion reaction. All of the liquid in the waste is assumed to be aqueous with no volume correction. A mean value of 0.06 percent is assumed in PA for the initial free unbound water saturation of the waste, based on waste

characterization data and transportation restrictions on the amount of free liquid that the waste can contain (Appendix PAR, Table PAR-39 in the CCA).

Materials such as dry portland cement, vermiculite, and other sorbents have intentionally been added to the waste to absorb any excess water that may be present. Sorbed water is much less readily available than any brine available from the surrounding rock. Therefore, the effect of initial water content on gas generation is negligible.

TRU WASTE-2.5.2 Components and Characteristics Influencing Physical Properties

As noted in Tables TRU WASTE-4 and TRU WASTE-5, the following physical properties of the solid waste components are used in PA:

Compressibility: This property is a measure of deformational stress-strain response of the waste material. The response of the waste is modeled to represent the conventional 55-gallon drums, pipe overpack configurations, and the supercompacted waste.

Strength: Strength of the waste is only of concern in the highly degraded state. Strength properties enter directly into PA human intrusion scenarios, whereby a driller inadvertently intersects a repository room. If high pressures exist in the disposal room, a pressure gradient pulse could induce tensile failure and transport of waste particulate into the wellbore—the spalling event. In addition, the drill bit and drilling fluid circulate in the advancing wellbore and set up fluid shear stress in the degraded waste. The effects of waste strength on room closure are included in the discussion of compressibility.

Porosity: Initial porosity of the waste room is modified by salt creep. The waste inventory establishes the initial porosity as well as mechanical resistance to the impinging salt. Waste porosity is directly incorporated into the PA via a porosity surface.

Permeability: Permeability controls movement of fluids in the waste rooms, and therefore is an important parameter for the Salado fluid flow calculations. Permeability is also a key consideration within the human intrusion conceptual model, as it enters into the calculations of material transport to well bore.

TRU WASTE-2.5.2.1 <u>Compressibility</u>

An important characteristic of the WIPP repository is the closure of the disposal rooms over time due to the creep response of the surrounding salt in response to the presence of the mined openings. This ability of salt to deform with time, eliminate voids, and create an impermeable salt barrier around waste is one of the principal reasons for locating the WIPP repository in a bedded salt formation, as suggested by the National Academy of Sciences (NAS-NRC 1957). This closure process is rather complex, and the rate at which it occurs depends in large part on the balance of forces tending to close the repository (the far-field lithostatic stresses) and those resisting the closure. These resisting forces are the tendency of the waste to resist deformation, measured in terms of its compressibility, and the effect of any gas pressure within the rooms.

At the time of the CCA, the compressibility of the waste was determined from laboratory experiments on 55-gallon drums (Butcher et al. 1991). Waste containers other than the 55-gallon

drum package have been delivered to WIPP and other forms, such as supercompacted waste, are anticipated to be sent. Therefore, the response model incorporated into the CRA-2004 calculations was enhanced to account for a range of structural responses. Updated coefficients developed for the volumetric plasticity model were based on modeling analysis of other waste forms (Weatherby et al. 1991; Park and Hansen 2003). The wastes were characterized by their general structural form, which predominantly depends on the packaging. Appendix PA describes the calculations that were used to evaluate the competing conditions of creep closure, waste rigidity, and gas generation to yield porosity histories that are compiled into a porosity surface for incorporation into PA calculations.

TRU WASTE-2.5.2.2 Strength

Shear and tensile strength are important parameters in the models for cavings and spallings releases, respectively. It is likely that alternative waste forms, such as the pipe overpacks and the supercompacted wastes, will be less likely to degrade and corrode than standard waste forms, and as such their mechanical strengths may be expected to be equal to or higher than standard waste.

Degraded material property estimates were recently summarized for the spallings model peer review (Hansen et al. 2003). The authors assert that degraded waste properties determined for the new spall model, DRSPALL, represent extreme bounds of the future possible states of the waste because strengthening processes are not included in the minimal shear and tensile strength properties determined for surrogate degraded waste. It is likely that the new waste forms, such as the pipe overpacks, would render the waste less vulnerable to collapse and more resistant to massive corrosion.

Shear Strength. The shear strength implemented in PA is used to calculate the volume of cavings release, hence, it is a measure of erosional shear resistance. In the CCA, the waste shear strength was sampled from a uniform distribution from 0.05 to 10 Pascal (Pa) Pa, which is conservatively based on properties of marine clays (Appendix PA, Attachment MASS, Table MASS-1). For the PAVT, the waste shear strength was estimated based on particle size distribution determined by an expert elicitation panel. With this approach, the calculated critical shear strength ranged from 0.64 to 77 Pa. The EPA then retained the original lowest value and assigned a log-uniform distribution ranging from 0.05 to 77 Pa. Based on work by Jepsen et al. (1998), the lower value of 0.05 Pa is considered to be extremely conservative. Using the 50 percent degraded waste surrogates that represent the extreme possibilities for degradation of the WIPP waste (Hansen et al. 1997, Hansen et al. 2003), an average critical shear strength of 1.4 Pa was determined. The minimal critical shear strength could approach this measured value only if massive degradation of waste ensues and no cementation or compaction of degraded waste occurs. The current minimum value sampled for the waste shear strength is thus at least 30 times smaller than the minimum value supported by empirical data.

Tensile Strength. Tensile strength is used in the calculation of spall volumes following a drilling intrusion. In the CCA, spall volumes were computed by a model of gas flow through fractures. Tensile strength entered the calculation of spall volumes by defining an effective gravity coefficient, which resisted particle mobilization in the flowing gas. The CCA calculations used a constant tensile strength of 0.0069 megapascal (MPa) (1 psi) (Helton et al. 1998). In response to

EPA's review of the CCA, a new mechanistic model for spallings was developed in which gas flow in the waste may induce tensile failure of the waste material, and thus lead to spallings. The mechanistic model, called DRSPALL, served as the basis for a replacement for the CCA spallings model. In support of DRSPALL, a separate analysis determined an appropriate distribution for tensile strength would range from 0.12 MPa to 0.17 MPa (Hansen et al. 2003).

The range of tensile strength reported by Hansen et al. (2003) assumes that the waste is a weakly consolidated particulate material, representing an extreme case of waste degradation. The characteristics of the more robust waste forms (supercompacted and pipe overpack waste) would tend to less degradation, so the tensile strength of these waste forms would certainly be greater than the minimal values currently used in DRSPALL (Hansen et al. 2003). Therefore, the current range of tensile strength proposed for the DRSPALL model and for the CRA-2004 is conservative.

TRU WASTE-2.5.2.3 Permeability

The likely mechanical and physical form of the supercompacted and pipe overpack wastes over time indicates that the permeability of these waste forms will be at least as great as that of standard waste, and may be higher.

In the CCA, the waste permeability was assigned a value of 1.7×10^{-13} m^2 (Butcher 1996) based on the value used in the 1991 PA. The 1991 PA value was a composite value based on the relative quantities of three different types of materials (combustible, metals/glass, and sludges) each with an inherent range of permeabilities, which had previously been determined for compressed surrogate wastes (Luker et al. 1990). In their review of the data used in the CCA, the EPA recalculated this value as 2.4×10^{-13} m^2, although they conceded that the difference was small enough to be inconsequential (EPA 1997). This revised value is being used in the current PA calculations.

A constant value for permeability is used in PA, even though it is expected that there will be some variability in this parameter. The reason for this single value being acceptable is primarily because this permeability value is much higher than the surrounding salt and the disturbed rock zone, as discussed in 1991 PA. In addition, the coefficient of variation for the uncertainty in measured permeabilities is too small to justify treating waste permeability as an uncertain parameter (Rechard and Tierney 2003). Finally, Vaughn et al. (1995) discuss whether permeability should be a function of porosity, since porosity is treated as a time-varying quantity in BRAGFLO while permeability is a constant. Their analysis concluded that including a dynamic model for permeability had an insignificant effect on waste room conditions (pressure and saturation), and an insignificant effect on resulting releases.

Waste Permeability of the New Waste Forms. The underlying assumption with respect to the new waste forms is that the pipe overpacks and supercompacted wastes will be more durable than the original baseline package of the 55-gallon drum. The rigidity of the waste and its packaging, such as the pipe overpack and supercompacted waste, tends to hold the room open and preserve the structural integrity of the waste stack. The logical evolution involved with disposal of a more rigid and armored waste package would be preservation of a large portion of the waste in its original, intact form as it will deform only modestly as compared to the standard

waste form. Thus, the architecture of the waste comprises bulky, compressed steel containers that envelope the waste, and the rigid structure would tend to maintain the open channels between individual drums and packages, so that much of the original porosity inherent in the three-dimensional disposal configuration would be preserved. Permeability of this future state of the waste would tend to be high relative to the values implemented in the CCA and PAVT. This conclusion is reinforced by the results of the porosity surface calculations, which show that in the absence of gas generation the long-term porosity of the supercompacted and pipe overpack wastes is considerably higher than for standard waste, while with high gas generation rates the porosities are essentially the same (Park and Hansen 2003).

Waste Permeability in Process Models. Other conclusions can be drawn about the possible effects of waste heterogeneity on brine and gas flow in the repository. Vaughn et al. (1995, DR6) discuss how heterogeneity in the waste may cause flow to follow channels or preferential paths, and result in spatially varying saturations referred to as "puddling." Their analysis demonstrated that inclusion of puddling in the BRAGFLO model had an insignificant effect on waste room conditions (pressure and saturation), and an insignificant effect on resulting releases.

Waste Permeability in Direct Release Models. Waste permeability can affect the models for spallings and for direct brine releases. A pertinent study of the effects of spatially variable waste permeability was conducted as part of the spalling model investigations reported in Hansen et al. 1997. Calculations of gas flow through the porous waste regions were conducted to evaluate the influence of model assumptions on the predicted two-phase pressure response of the disposal rooms during a drilling intrusion. Results of the modeling indicated that the effect of waste heterogeneity is to reduce the pore pressure gradient close to the intruded wellbore; because this gradient is the major cause of tensile failure, any possible spall volumes are reduced.

TRU WASTE-2.5.3 Components and Characteristics Affecting Heat Generation

Heat generation is a characteristic of some components of the waste, or of their interactions. The WIPP includes two possibly significant sources of heat: the heat generated by RH-TRU waste (DOE 1995), and the heat generated by MgO hydration and carbonation, aluminum corrosion, cement hydration, and organic biodegradation.

TRU WASTE-2.5.3.1 Exothermal Reactions

MgO hydration and carbonation, aluminum corrosion, cement hydration, and organic biodegradation are all exothermal reactions. Evaluation of the ability of each of these reactions to produce heat while conservatively accounting for the repository's ability to dissipate the resulting heat generated has provided the following maximum temperature increases (Wang 1996d and Appendix PA, Attachment SCR), as shown in Table TRU WASTE-13:

Table TRU WASTE-13. Maximum Temperature Increases

Reaction Number	Maximum Temperature Increase (K)
MgO hydration	4.7
MgO carbonation	0.7
Cement hydration	2.5
Microbial degradation	1.4
Aluminum corrosion	6.8

In the worst case, a temperature increase of 6.8 K could be experienced (Appendix PA, Attachment SCR). However, these temperature extremes will not persist, if they are ever reached at all. Because all but one reaction consume brine, possible reactions will be competing with each other for what brine may enter the repository and will therefore temper the heat increase that could be predicted based on the most exothermic reaction alone. To evaluate the worst case possible, for the maximum temperature increase to be realized from the corrosion of aluminum, all of the aluminum would have to be corroded within 2.5 years, after which the heat would be dissipated very rapidly. Therefore, if such a condition were to be created, it would be transitory on the repository time scale and its influence inconsequential.

The effect of small temperature increases arising from exothermal reactions was previously screened out of the PA on the basis of low consequence to factors such as creep closure, seal performance, transport, etc. (see Appendix PA, Attachment SCR). The effect of heat generated by radiolysis has been considered as part of the repository conditions (Brush 1990) and utilized in the specification of experimental parameters, thus yielding data consistent with the anticipated conditions. Additionally, the small temperature increases cited above for exothermic reactions are insignificant to the thermodynamic modeling of solubility. For example, a temperature increase of 7ºK would result in an approximately three percent change in the free energy of formation of any species contained within the model. This value is well within the model parameter bounds.

TRU WASTE-2.5.3.2 RH-TRU Thermal Heat Load

The “worst case” heat load from RH-TRU emplaced in the WIPP is estimated to be between 47 and 54 watts per cubic meter, which would result in a temperature rise near the canister of between 1.87ºK and 2.09 K (2.85 – 3.19 K in the CCA). The expected WIPP average temperature increase from RH-TRU heat loading is between 0.23 K and 0.29 K (0.38 – 0.49 K in the CCA). The RH-TRU thermal heat load is small enough that there is no impact on repository performance. A more complete discussion and analysis is given in Djordjevic (2003) and Appendix PA, Attachment SCR.

TRU WASTE-2.6 Summary

The waste characteristics and components expected to be most significant to performance are the predominant radionuclides and those characteristics and components affecting actinide mobility.

The waste characteristics and components expected to be significant to performance are summarized in Table TRU WASTE-14.

It should be noted that these components and characteristics have both positive and negative effects on performance. Iron has a beneficial effect because it reduces actinides to lower, less soluble oxidation states. Nonferrous metals are beneficial because they compete with the actinides for the binding sites on organic ligands, thereby reducing the solubilities of the actinides. Mobility enhancers like colloidal substrates, on the other hand, have a detrimental effect. Gas buildup can both enhance and detract from repository performance. Although gas can open fractures, it can also keep brine from entering the repository, thereby reducing transport of soluble actinides (SNL 1991).

Table TRU WASTE-15 summarizes those characteristics and components with an insignificant impact on performance.

Table TRU WASTE-14. Waste Characteristics and Components Expected to be Most Significant to Performance

Component	Characteristic	Reason for Significance
^{239}Pu, ^{240}Pu, ^{241}Am, ^{233}U, and ^{234}U	Activity	99 percent of EPA unit after 2,000 years
^{238}Pu	Activity	Dominates EPA Unit at early times
Pu and Am	Solubility	Large EPA Unit; mobility depends on solubility
^{238}U	Activity	Very low activity; dilutes Higher-Activity Uranium Isotopes For Brine-Based Releases
Iron	Corrosion	1. Maintains reducing environment; lower, less soluble oxidation states of actinides predominate 2. Corrosion produces hydrogen, increasing gas pressure
CPR Materials, Nitrate, Sulfate	Nutrient for microbes	Microbial nutrients are metabolized to methane and other gases, increasing gas pressure; formation of colloids
Humic Materials, Cellulosic Materials breakdown products	Colloid formation	Form humic colloids that sorb and transport actinides
Organic Complexation	Nonferrous metals	Reduce actinide solubilities by competing with the actinides for the binding sites on organic ligands.
Tensile and Shear strength	Waste strength	Important to spalling and cavings

Table TRU WASTE-15. Waste Characteristics and Components Expected to be Not Significant

Characteristics/Component	Reason for insignificant impact
Radionuclides (other than those in Table TRU WASTE-14)	EPA Unit is negligible fraction of total, even with ingrowth
Substances that may affect pH[1]	pH is buffered by MgO
Substances that produce CO_2[1]	CO_2 is removed by reaction with MgO
Intrinsic and mineral fragment colloids	Fraction of actinides mobilized by these colloids is insignificant
Organic ligands	Removed by binding with Mg and nonferrous metal
Heat generated by exothermic reactions	Temperature rise is negligible; heats of formation are very small paired with a large thermal mass of the repository
Fluid in the waste	Negligible compared to brine volume

[1] These components are significant for gas generation, but not for actinide solubility.

TRU WASTE-3.0 WASTE COMPONENTS LIMITS

The objective of this section is to satisfy the requirements specified in 40 CFR.194(c)(1) as stated in Section TRU WASTE-1.1.

This section updates Appendix WCL in the CCA by presenting the rationale for the upper and lower limits for waste components identified as potentially significant to disposal system performance (Table TRU WASTE-4). The sensitivity analysis in Appendix PA supports the conclusions that the disposal system performance is not sensitive to most properties of the emplaced waste and limits remain unnecessary for the components identified in Tables TRU WASTE-5 and TRU WASTE-6.

Table TRU WASTE-16 shows:

- Waste components listed as potentially significant in Table TRU WASTE-4,
- Waste characteristics these components influence,
- Constituents of the components for which assaying during emplacement is required, and
- Limits for emplacement of each component, if necessary.

This table illustrates that most components, associated characteristics, assay requirements, and emplacement limits have not changed since the CCA. The following discussion provides the rationale for the proposed assaying and emplacement limits for each component listed in Table TRU WASTE-16. All of the components listed in Tables TRU WASTE-5, TRU WASTE-6 and TRU WASTE-15 were found to be insignificant to disposal system performance, as was true for the CCA. Therefore, it is not necessary to establish emplacement limits for them other than limits based on the current TRU waste inventory or imposed on waste through limitations in the Contact Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant (DOE 2002a).

The emplacement limits identified in Table TRU WASTE-16 provide an envelope of fixed inventory values on a repository scale, without an associated uncertainty. That is, the limiting values are imposed to ensure compliance, and in fact represent the upper “end” of an uncertain range. To ensure these waste component limits are not exceeded, inventory quantities and uncertainty in those quantities will be tracked during the operational phase of the repository. This tracking is accomplished using the WWIS. If inventory estimates change over the operational life of the WIPP, new inventory estimates will be used in PA and revised limits for waste components will be developed based on the PA results in a future recertification application.

TRU WASTE-3.1 Radionuclide Components

As discussed in Section TRU WASTE-2.3, the following radionuclides have activities greater than one EPA unit at closure: ^{241}Am, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{233}U, ^{234}U, ^{90}Sr, and ^{137}Cs.

Table TRU WASTE-16. Emplacement Limits for Waste Components

Components	Associated Characteristics	Constituent Components Requiring Assaying	Emplacement Limits
Radionuclides	Radioactivity at closure Radioactivity after closure Solubility Colloid formation Redox state	^{241}Am ^{238}Pu ^{239}Pu ^{240}Pu ^{242}Pu ^{233}U ^{234}U ^{238}U ^{90}Sr ^{137}Cs	none[1]
Ferrous metals (iron)	Redox potential H_2 gas generation complexing with organic ligands	None	Minimum = 2.0×10^7 kg (amount from containers)[2]
CPR materials	Gas generation Humic colloids (see below)	Sum	Maximum = 2.2×10^7 kg[3]
Sulfates	Gas generation	None	None[4]
Nitrates	Gas generation	None	None[4]
Solid components	Particle size Effective shear resistance to erosion Tensile strength	None	None
Free water emplaced with waste	Gas generation	None	Maximum = 1684 m^3 (limit of one percent total waste volume as set by the WAC)[5]
Humic substances	Radionuclide-bearing humic colloids	None	None
Nonferrous metals (metals other than iron)	Reduce actinide solubilities by competing with the actinides for the binding sites on organic ligands.	None	Minimum = 2.0×10^3 kg[6]
Organic ligands	Solubility	None	None[4]

[1] Inventory curie content will be tracked.
[2] Minimum sets to ensure sufficient reactants for reducing radionuclides to lower and less soluble oxidation states.
[3] Maximum set to ensure sufficient MgO is available to react with CO_2 produced.
[4] For the current waste generation processes that are documented in Appendix DATA.
[5] One percent of the design basis values for CH-TRU of 168,485 m^3.
[6] Minimum quantity for complexing with organic ligands (see Appendix PA, Attachment SOTERM).

The total activity of the waste at emplacement and during the entire 10,000-year performance period is dominated by the activities of four emplaced radionuclides: ^{241}Am, ^{238}Pu, ^{239}Pu, and ^{240}Pu. The radionuclides, ^{242}Pu, ^{233}U and ^{234}U, have significantly less total activity than the other Am and Pu components, but since their activities exceed one EPA unit they are not excluded from assaying requirements. The ^{238}U component is to be assayed as well, because its large mass fraction and low activity dilutes the overall activity of transported uranium species. The ^{90}Sr and ^{137}Cs components can contribute to direct releases at the surface resulting from inadvertent intrusion during the first several hundred years or so after closure.

Because of radioactive decay and ingrowth, the major contributors to the overall activity of the repository among these radionuclides change during 10,000 years. For the first several hundred years, ^{241}Am, ^{238}Pu, ^{239}Pu, and ^{240}Pu are important contributors to the total activity of the waste. At the present and projected inventory level, ^{90}Sr and ^{137}Cs may be important for about 200 years. The ^{241}Am component continues to be important for about 3,000 years. At 10,000 years, ^{239}Pu and ^{240}Pu remain as the only significant contributors to the total activity of the waste. Because the activities of these radionuclides in existing and projected waste overwhelmingly exceed the activities of all other radionuclides combined, they are the most important for repository performance modeling.

The total activity of the waste is not important for compliance with the criteria at 40 CFR § 194.24(c) because the containment requirements are normalized to the initial inventory. However, the PA is sensitive to relative changes in inventory curie content as a function of radionuclide decay and ingrowth over time. The magnitude of change in the total curie content depends on the initial ratios of the total activities of the assayed radionuclides at the time of repository closure. Accordingly, the results of the PA are conditional on the initial ratios in the inventory. The criteria in 40 CFR § 194.15(a)(5) state that:

> In submitting documentation of continued compliance pursuant to section 8(f) of the WIPP LWA,….. Updated documentation shall include:… A description of all waste emplaced in the disposal system since the most recent compliance certification or recertification application.

The PA for this and future recertifications must therefore incorporate the adjusted inventory curie content reflecting any significant changes relative to projected values for the important radioisotopes (plus ^{238}U) that are being accumulated. At repository closure, the ratios of the activities of the ten listed radionuclides (Table TRU WASTE-15) may or may not be similar to those ratios used in this assessment, but compliance with the containment requirements of 40 CFR §191.13 will be maintained for the full capacity of emplaced waste at the WIPP.

TRU WASTE-3.2 Ferrous and Ferrous Alloy Components

Ferrous and ferrous-alloy metal components in the waste have two significant effects on the repository. Ferrous and ferrous-alloy metal may corrode, thus creating gas, and they provide reducing conditions in the repository (see Section TRU WASTE-2.4.1).

The results of the CRA-2004 PA demonstrate that total normalized release from the repository is relatively insensitive to gas generation by corrosion. As shown in Figures PA-97 through PA-99 in Appendix PA, at probabilities greater than 0.01, total normalized release is dominated by cuttings and cavings releases. The cuttings and cavings release mechanism is completely independent of repository hydrologic conditions, such as gas pressure or brine saturation, at the time of the intrusion. This independence from repository pressure leads to the conclusion that total normalized release will be insensitive to gas generation. The other two direct release mechanisms for the CRA-2004 PA, spallings and direct brine release, are dependent on the quantity of gas generated. These two release mechanisms occur only if the pressure in the repository exceeds 8 MPa (Appendix PA, Sections PA.4.6 and PA.4.7.1). This pressure (8 MPa) corresponds to the hydrostatic pressure at the repository depth in a column of drilling mud.

The waste inventory contains sufficient ferrous and ferrous-alloy components that gas could be generated sufficiently in excess of that required to reach 8 MPa in the repository. In fact, there is always an excess of ferrous and ferrous-alloy metals, in the sense that the inventory of these metals is never depleted in any of the 300 realizations for the CRA-2004 PA (Stein and Zelinski 2003b). In this situation, PA already uses an extreme value for the mass of ferrous and ferrous-alloy metals, so that a maximum value for the mass of ferrous and ferrous-alloy metals would be extraneous (have no impact) on PA.

In summary, the dominance of the cuttings/cavings mechanism for total normalized release, and the excess mass of ferrous and ferrous-alloy metals in the initial inventory imply that it is unnecessary to place restrictions on the quantity of ferrous and ferrous-alloy metals emplaced for the purpose of controlling the quantity of gas generated.

On the other hand, ferrous and ferrous-alloy metals (and their corrosion products) provide the reactants that reduce radionuclides to lower and less-soluble oxidation states. As discussed in Section TRU WASTE-2.4.1.1, the anticipated quantity of these metals, principally from waste containers, to be emplaced in the WIPP is orders of magnitude in excess of the quantity required to assure reducing conditions. Therefore, no upper or lower limit need be established for the quantity of ferrous and ferrous-alloy metals that may be emplaced, beyond the CCA projection of the ferrous and ferrous-alloy metals in the waste containers.

TRU WASTE-3.3 CPR Materials, Nitrate, and Sulfate Components

The CPR materials, nitrate, and sulfate components of the waste influence the production of CH_4 gas in the repository by microbial action. Although the PA assigns a probability of 0.5 that microbial degradation will produce significant quantities of gas, the lower limit for these materials is effectively zero. As discussed in the preceding section, releases are dominated by cuttings/cavings, which is independent of repository pressure at the time of the intrusion. In addition, direct brine release and spallings are not sensitive to the quantity of gas generated, and the inventory of ferrous and ferrous-alloy metals is in excess of that required to produce a significant amount of gas (pressures of 8 MPa, or greater). Therefore, the additional components influencing microbial degradation have negligible impact on performance, and it is unnecessary, with respect to gas generation, to assign an upper limit on the amount of these materials that may be emplaced in the repository.

However, an upper limit on the total amount of CPR materials is still necessary to ensure that the amount of emplaced MgO is adequate. The current waste inventory indicates that there will be 2.19×10^7 kg of CPR materials disposed in WIPP. Since the amount of MgO currently projected for the WIPP is greater than the amount needed to react with the CO_2, the upper limit for CPR materials is set to 2.2×10^7 kg. Additional information on the safety factor for MgO relative to the emplaced mass of CPR materials is provided in Appendix BARRIERS-2.5.

TRU WASTE-3.4 Solid Components

Solid components in the waste affect the waste characteristics of effective shear resistance to erosion, particle size, and tensile strength. These properties affect releases from cavings and spallings during a drilling intrusion. The basic conceptualization for the assignment of these

properties is that fully degraded waste will have the least favorable properties, and will eventually be similar to granular materials whose properties can be measured today. The actual properties of the waste over the 10,000-year regulatory period are unknown, since the physical nature of the degraded waste is unknown. For these reasons, the parameter values assigned are chosen to conservatively reflect measured properties of natural and constructed materials.

These properties are reasonable analogs for degraded waste. The effective shear resistance to erosion used to calculate cavings is based on the erodibility of unconsolidated marine clays and other easily eroded materials, and is considered to be near a physical limit for the minimum value of this property (Parameter 58 in Attachment PAR to Appendix PA). The minimum particle size used in the range for the spallings model is based on assuming an average pore diameter consistent with an average waste permeability; this value is considered conservative because waste will not have a uniform distribution of permeability. The larger particles will define the more permeable pathways, along which most gas will flow during a spalling event, and larger particles are less likely to spall than smaller particles. Last, the tensile strength of the waste assigned for the spalling process is uncertain, ranging from 0.12 MPa to 0.17 MPa (Hansen et al. 2003 - DRSPALL parameter report). Tensile strength was developed from laboratory experiments on surrogate materials, which represented highly degraded residuals from typical waste inventory. These values are felt to represent extreme, low-end tensile strengths because they do not account for several strengthening mechanisms, such as MgO hydration and halite precipitation/cementation (see Hansen et al. 1997).

The properties assumed for solid components in PA bound the least favorable behavior of these components. Therefore, the PA analysis is not conditional on the quantities and kinds of solid components that will be emplaced. Upper or lower limits are not necessary for solid waste components because parameter values have been chosen conservatively.

TRU WASTE-3.5 Water Components

The amount of water emplaced with the waste can affect the rate at which gas is generated for a short period soon after closure, but the small quantity of water acceptable in the waste is not a concern for long-term performance. Consequently, there is no need to monitor water in the waste for compliance with 40 CFR § 194.24(c). In fact, the quantity of water in the waste used for PA calculations is greater than the Waste Acceptance Criteria allows, so the only limit on free water content of the waste is set by the Waste Acceptance Criteria. The FEPs screening analysis (Appendix PA, Attachment SCR) assumes no more than one percent volume of free liquid by container.

TRU WASTE-3.6 Humic Substances Components

Humic substances are likely to be introduced into the repository as a component of wastes containing soils or may form in situ from reactions involving microbial metabolites produced during degradation of cellulosic materials. Humic substances will dissolve until a solubility limit is reached. Dissolved humic substances are colloidal in nature and may complex radionuclides. The radionuclide-bearing humic colloids may be transported in moving liquid and contribute to a radionuclide release.

In PA, a steady-state concentration of humic colloids is assumed to exist in the repository during the performance period. This concentration is not inventory limited; in other words, it is assumed in PA that sufficient source materials exist that a constant concentration of humic colloids will be present at all times. Because it is assumed that there is sufficient solid material present for a steady-state concentration to exist at all times in the repository, PA results are not conditional on the quantity of total humic substances present, and there is no need to provide a maximum or minimum limit for the quantity of humic substances that may be emplaced in the repository.

TRU WASTE-3.7 Nonferrous Metal Components

The nonferrous metals present in the waste stream impact PA because they will dissolve and bind to organic ligands, thereby reducing the impact of organic ligands on the solubility of radionuclides (see Section TRU WASTE-2.4.1.3). No upper or lower limit need be established for the quantity of non-ferrous metals beyond the present projection of the non-ferrous metals in waste containers, and assay is not required for these metals.

TRU WASTE-3.8 Organic Ligands Components

The effects of organic ligands are directly considered in the CRA-2004 PA (Appendix PA, Attachment SCR, Section SCR-6.5.6. Including acetate, citrate, EDTA, and oxalate in the FMT speciation and solubility calculations had essentially no effect on An(IV) solubility, a modest effect on An(III) solubility, and increase An(V) solubility significantly. However, base on the effects of organics on the solubilities of the +III, +IV, and +V actinides, the overall effects on the long-term performance of the repository are still negligible.. Therefore, no upper or lower limit need be established for the quantity of organic ligands in the waste.

TRU WASTE-4.0 WASTE CHARACTERIZATION

The regulation 40 CFR § 194.24(c)(2) and (3) require that the DOE identify and describe the methods used to quantify the limits presented in Section TRU WASTE-3.0 for the waste components identified as potentially significant to the long-term performance of the disposal system. These waste components are radionuclides, free water, ferrous metals, nonferrous metals and CPR materials. The repository limits and the associated approved characterization methods for each of these components is summarized below:

- Although Section TRU WASTE-3.0 does not specify limiting values for the activities and masses of specific radionuclides, the cumulative total activities of the specified radionuclides (^{241}Am, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{233}U, ^{234}U, ^{238}U, ^{90}Sr, and ^{137}Cs) must be reported and tracked to ensure that the total radionuclide inventory of the repository is consistent with the levels used for the current PA. The presence of these specific radionuclides, in terms of activities and masses, including associated total measurement uncertainties, is determined from acceptable knowledge (AK) and radioassay.

- The acceptance criterion specified in the CH-WAC states that there shall be no more than 2.5 cm (1 in) in the bottom of internal containers and the total residual liquid in any payload container shall not exceed 1% by volume of that payload container. The FEPs screening analysis (Appendix PA, Attachment SCR) assumes no more than one percent volume of free liquid by container. Therefore, the repository limit for free liquid is a maximum of 1,684 m^3 (1% by volume liquid per container × the expected number of containers). The qualitative methodologies of AK, radiography, or visual examination, used either singly or in combination, verify adherence to the compliance limits.

- The repository limit for ferrous metals is a minimum of 2.0×10^7 kg. This limit will be met in the total repository inventory by the quantity of ferrous metals that make up the payload containers alone; thus, the number and type of payload containers emplaced in the repository are tracked.

- The repository limit for nonferrous metals is a minimum of 2.0×10^3 kg (which was already met with the waste emplaced in the repository as of September 30, 2002). This limit will be met in the total repository inventory by the quantity of nonferrous metals that make up the payload containers alone; thus the number and type of payload containers emplaced in the repository are tracked.

- The repository limit for CPR materials is a maximum of 2.2×10^7 kg. The TRU waste sites are required to determine the CPR material weights in the waste by AK supplemented by radiography and/or visual examination.

The methods used to quantify the above waste components are summarized below with more detailed descriptions in the following documents:

- Contact-Handled Transuranic Waste Acceptance Criteria (CH-WAC), Appendix A (DOE 2002a)

- WIPP Hazardous Waste Permit, Waste Facility Analysis Plan (WAP), Attachments B through B6 (DOE 2003a)

This section does not repeat the provisions of the WAP and the CH-WAC. References to the WAP and WAC will direct the reader to more detailed information on the CH-TRU waste characterization methods, where appropriate. The RH-TRU waste characterization methods are pending EPA approval and are not discussed here. Information on the proposed RH-TRU waste characterization program is contained in DOE (2002b).

TRU WASTE-4.1 Acceptable Knowledge

AK is the compilation of process knowledge and available existing information to characterize a TRU waste stream. AK includes information regarding the physical form of the waste, the base materials composing the waste, and the process that generates the waste. AK is discussed in the WAP and CH-WAC. AK discussions in the WAP delineate waste streams and characterize the chemical and physical properties of the waste, such as the amount of free liquid and waste material parameters. The CH-WAC discusses AK characterization requirements for the nuclear properties (i.e., as radionuclide activity and the distribution of the 10 WIPP-tracked isotopes) that each TRU waste site must obtain.

TRU WASTE-4.2 Radioassay

The EPA requires radiological characterization data to track the WIPP radionuclide inventory, by isotopic distribution and activity, of the ten WIPP-tracked radionuclides (^{241}Am, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{233}U, ^{234}U, ^{238}U, ^{90}Sr, and ^{137}Cs). This requisite data is derived from AK, radioassay or both. DOE-approved radioassay techniques are discussed in Attachment A of the CH-WAC (DOE 2002a).

Nondestructive analysis is a noninvasive radioassay method allowing the radiological characteristics of a waste container to be determined without altering its physical or chemical form. A variety of nondestructive assay (NDA) methodologies are effective in meeting the requirements of the CH-WAC.

Radiochemical analysis, another approved radioassay method, is more time consuming and has an inherently higher risk of exposure to the personnel performing the assay. Exposure to radiation is minimized when NDA methods are employed in place of intrusive measurement methods, making NDA the preferred choice for waste assay.

TRU WASTE-4.3 Radiography

Radiography is a nondestructive technique that involves x-ray examination of waste containers to identify and verify waste container contents; specifically to verify the physical form of the waste to identify and assess the quantity of CPR materials.

TRU WASTE-4.4 Visual Examination

Visual examination consists of an evaluation of the waste container contents. It verifies and augments the description of waste container contents derived from AK or radiography by

opening the container and physically inspecting the contents. TRU waste sites may opt to substitute visual examination in place of radiography as long as all waste containers are inspected.

TRU WASTE-5.0 WIPP WASTE INFORMATION SYSTEM

All TRU waste sites planning to ship TRU waste to WIPP will supply the required characterization data to the computerized data management system known as the WWIS. The system continues to be used to gather, store, and process information pertaining to TRU waste destined for or disposed at the WIPP and includes automatic certification-based compliance limit and quality assurance checks. The WWIS is designed, maintained and operated in compliance with nuclear quality assurance requirements for computer software for nuclear facility applications.

To ensure compliance with the data requirements, CBFO reviews the data package for each container of each shipment for completeness and adequacy before notifying the shipping site of acceptance. Thus, the WWIS becomes an integral part of the waste information screening process. DOE provides EPA with an annual report using information generated from the WWIS on waste parameters as identified in Table TRU WASTE-16.

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1.0 INTRODUCTION

This Compliance Recertification Application (CRA) documents the U.S. Department of Energy's (DOE's) demonstration of the continuing compliance of the Waste Isolation Pilot Plant (WIPP) with the long-term disposal regulations in Title 40 of the Code of Federal Regulations (CFR) Part 191, Subparts B and C (U.S. Environmental Protection Agency [EPA], Volume 50 Federal Register (FR) 38084, Sept. 19, 1985, as amended at 50 FR 40003, Oct. 1, 1985. Redesignated at 58 FR 66414, Dec. 20, 1993). The information provided in this application has been developed in accordance with the criteria established by the EPA (40 CFR Part 194) (61 FR 5235, Feb. 9, 1996).

The DOE is responsible for the disposition of transuranic (TRU) waste generated in whole or in part by atomic energy defense activities. It is estimated that approximately 115,000 cubic meters of these wastes have been generated and are currently stored at government installations across the country. The U.S. Congress established criteria for the management and operation of the WIPP in 1992 by its passage of the WIPP Land Withdrawal Act (LWA [Public Law 102-579, 106 Stat. 4777, 1992; as amended by Public Law 104-201, 110 Stat. 2422, 1996]). The LWA required that, prior to opening the WIPP for the disposal of TRU waste, the EPA certify that the WIPP facility will comply with the final disposal regulations. The DOE submitted the Compliance Certification Application (CCA) in October 1996. This compliance application documented the suitability of the geological, hydrological, physical, chemical, and environmental characteristics of the WIPP site, located near Carlsbad, New Mexico, and demonstrated how these characteristics, along with engineered features of the facility, lead to a reasonable expectation that compliance will be maintained for the required 10,000-year regulatory period. The EPA reviewed the CCA, requested additional information and studies, and also performed independent analyses during its evaluation of compliance. Public input was solicited throughout this process. Information developed through the certification process is available for review by the public in EPA WIPP dockets A-93-02 and A-98-49. On May 18, 1998 (63 FR 27405), the EPA certified that the WIPP did comply with the final disposal regulations and criteria of 40 CFR Parts 191 and 194, and on March 26, 1999, disposal operations began.

Section 8(f) of the LWA requires that the DOE submit to the EPA and the State of New Mexico documentation of continued compliance with the final disposal regulations not later than five years after the initial receipt of waste for disposal at WIPP and every five years thereafter until the end of the decommissioning phase of the project. Based on the DOE submittal, the EPA must determine whether the WIPP facility continues to be in compliance with the final disposal regulations. This recertification application has been prepared by the DOE and submitted to the EPA in accordance with these provisions of the law.

This application builds upon material presented in the CCA. The CCA included a performance assessment (PA) to demonstrate that, under the stringent conditions dictated by the disposal standards and certification criteria, the WIPP will comply with quantitative release limits, individual exposure standards, and groundwater protection standards over the 10,000-year regulatory period. The performance assessment provided in this recertification application updates the original performance assessment for the CCA with new waste inventory information, with changes made to the WIPP facilities, and with experience gained during the first years of

repository operation. The CRA-2004 PA demonstrates that the WIPP continues to comply with all requirements mandated in 40 CFR Part 191 Subparts B and C. In addition, this application documents the measures that the DOE has taken, or is required to take, at the time of facility closure to provide further assurance that the quantitative limits will be met.

The criteria established for selection of a site for the safe disposal of TRU waste were developed to ensure that a disposal location had certain favorable characteristics that were thought to be desirable for long-term waste isolation. The WIPP site meets these criteria. For example, the site has favorable geological characteristics in that:

- the host rock formation behaves plastically and will therefore encapsulate buried waste;
- the effects of dissolution at the site are minimal and predictable;
- excavation of the repository is relatively easy;
- future resource development is predictable and minimal; and
- the repository host rock is relatively uncomplicated lithologically and structurally.

Hydrologically, the site exhibits:

- a host rock that contains little interstitial brine and is very impermeable (i.e., transmits the brine very poorly);
- a location where the effects of groundwater flow are minimal and predictable;
- an area where probable future groundwater use is low and where there are no permanent surface waters; and
- a repository host rock that will not likely be affected by potential long-term climate changes within 10,000 years.

Finally, the WIPP site:

- maximized the use of federal lands while avoiding existing drill holes and minimizing the impacts on potash deposits;
- avoided endangered species and critical habitats; and
- is in a seismically stable area.

All of these favorable factors contribute to the WIPP's ability to comply with the long-term disposal regulations and more than compensate for less favorable features such as nearby hydrocarbon production and potash mining.

The information presented in the CCA and this recertification application is the culmination of over 25 years of scientific work specifically dedicated to evaluating TRU waste isolation in the

WIPP repository. Throughout this process, the DOE and its predecessor agencies have ensured that qualified individuals were available to address the technical questions surrounding the long-term performance of the disposal system. These experts have included members of federal and state government agencies, several national laboratories, academia, and industry. In addition, the DOE has ongoing technical oversight of the project by the National Academy of Sciences (NAS), the Environmental Evaluation Group (EEG), and the New Mexico Governor's Consultation Task Force on Radioactive Waste. Frequent consultation with these organizations has served to identify and resolve important issues in a timely manner. In addition, the DOE has involved the public in the decision-making process throughout the compliance demonstration process. Finally, the DOE has maintained a documented Quality Assurance program to ensure that objective evidence exists to support the quality of the work that has been performed.

The remainder of this chapter provides an overview of the recertification application, including a summary of the 1998 EPA certification decision conditions and the regulatory basis for the application, a discussion of the WIPP mission, a summary of the site selection process, a summary of the approach taken in this recertification application to demonstrate continued compliance with the performance standards, a summary of major changes since the CCA, and a brief description of the contents of the remaining chapters.

1.1 EPA Certification Decision Conditions

The EPA certified that the WIPP complied with the final disposal regulations and criteria of 40 CFR Parts 191 and 194 on May 18, 1998 (63 FR 27405). The certification of compliance was made subject to the following conditions:

> Condition 1: § 194.14(b), Disposal system design, panel closure system. The Department shall implement the panel seal design designated as Option D in Docket A-93-02, Item II-G-1 (October 29, 1996, Compliance Certification Application submitted to the Agency). The Option D design shall be implemented as described in Appendix PCS of Docket A-93-02, Item II-G-1, with the exception that the Department shall use Salado mass concrete (consistent with that proposed for the shaft seal system, and as described in Appendix SEAL of Docket A-93-02, Item II-G-1) instead of fresh water concrete.
>
> Condition 2: § 194.22: Quality Assurance. The Secretary shall not allow any waste generator site other than the Los Alamos National Laboratory to ship waste for disposal at the WIPP until the Agency determines that the site has established and executed a quality assurance program, in accordance with §§ 194.22(a)(2)(i), 194.24(c)(3) and 194.24(c)(5) for waste characterization activities and assumptions. The Agency will determine compliance of site-specific quality assurance programs at waste generator sites using the process set forth in § 194.8.
>
> Condition 3: § 194.24: Waste Characterization. The Secretary may allow shipment for disposal at the WIPP of legacy debris waste at the Los Alamos National Laboratory ("LANL") that can be characterized using the systems and processes inspected by the Agency and documented in Docket A-93-02, Item II-I-70. The Secretary shall not allow shipment of any waste from any additional LANL waste stream(s) or from any waste generator site other than LANL for disposal at the WIPP until the Agency has approved the processes for characterizing those waste streams for shipment using the process set forth in § 194.8.
>
> Condition 4: § 194.43, Passive institutional controls.

(a) Not later than the final recertification application submitted prior to closure of the disposal system, the Department shall provide, to the Administrator or the Administrator's authorized representative:

(1) a schedule for implementing passive institutional controls that has been revised to show that markers will be fabricated and emplaced, and other measures will be implemented, as soon as possible following closure of the WIPP. Such schedule should describe how testing of any aspect of the conceptual design will be completed prior to or soon after closure, and what changes to the design of passive institutional controls may be expected to result from such testing.

(2) documentation showing that the granite pieces for the proposed monuments and information rooms described in Docket A-93-02, Item II-G-1, and supplementary information may be: quarried (cut and removed from the ground) without cracking due to tensile stresses from handling or isostatic rebound; engraved on the scale required by the design; transported to the site, given the weight and dimensions of the granite pieces and the capacity of existing rail cars and rail lines; loaded, unloaded, and erected without cracking based on the capacity of available equipment; and successfully joined.

(3) documentation showing that archives and record centers will accept the documents identified and will maintain them in the manner identified in Docket A-93-02, Item II-G-1.

(4) documentation showing that proposed recipients of WIPP information other than archives and record centers will accept the information and make use of it in the manner indicated by the Department in Docket A-93-02, Item II-G-1 and supplementary information.

(b) Upon receipt of the information required under paragraph (a) of this condition, the Agency will place such documentation in the public dockets identified in § 194.67. The Agency will determine if a modification to the compliance certification in effect is necessary. Any such modification will be conducted in accordance with the requirements at §§ 194.65 and 194.66.

The DOE has proposed a modification to Condition 1 and a new panel closure design which is equally protective but simpler to construct; however, the EPA has stated that it will not consider the proposal until after WIPP recertification. In the interim, waste emplacement in Panel 1 has been completed, and the Option D explosion wall has been constructed in each of the access-ways to the panel. The EPA has agreed that construction of the remainder of the panel closure system in Panel 1 can be delayed until a decision has been made regarding the proposed new design. As discussed in Chapter 6.0, the PA representation of the repository has been modified to represent the Option D panel closure.

All sites planning to ship TRU waste to WIPP are required to comply with Conditions 2 and 3. Prior to shipment of waste, the EPA, using the process set forth in 40 CFR § 194.8, must determine that the site has established and executed a quality assurance program, in accordance with 40 CFR §§ 194.22(a)(1), 194.22(a)(2)(i), 194.24(c)(3) and 194.24(c)(5) for waste characterization activities and assumptions. The EPA must also approve the processes for characterizing those waste streams for shipment. During the period covered by this recertification application, the EPA has conducted numerous audits or inspections of DOE audits to ensure the quality and efficacy of waste characterization programs prior to a site gaining approval to ship a particular waste stream to WIPP. Further details are provided in Chapter 4.0 and in Appendix TRU WASTE of this application.

The DOE has initiated activities as part of the Passive Institutional Controls (PICs) program to ensure that the permanent markers, archiving, and awareness triggers can be fully implemented and submitted to the EPA for final approval. As mandated by Condition 4, the DOE will provide the required information no later than the final recertification application (prior to closure). Chapter 7.0 provides more information on the PICs program and activities.

1.2 Applicable Regulations

The regulatory framework for demonstrating the continued compliance of the WIPP with the disposal standards is primarily provided in 40 CFR Part 191, Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, and in 40 CFR Part 194, Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations; Final Rule.

In addition to the applicable regulations cited above, the EPA has provided guidance in the implementation of 40 CFR 191 and 40 CFR 194; i.e., the Compliance Application Guidance for 40 CFR Part 194 and in the Guidance to the U.S. Department of Energy on Preparation for Recertification of the Waste Isolation Pilot Plant with 40 CFR Parts 191 and 194.

1.2.1 40 CFR Part 191

The EPA is responsible for developing environmental standards for the protection of the public and the environment from radioactivity. The statutory authority cited by EPA for establishing and implementing the regulatory standards applicable to the operation, closure, and long-term performance of the WIPP facility are found in the LWA Atomic Energy Act of 1954, and the Reorganization Plan Number 3 of 1970. The regulations affecting the radioactive waste disposal operations at the WIPP are found in 40 CFR Part 191.

Since the mid-1970s, the EPA has been developing guidance and standards for the management and disposal of radioactive waste. The EPA's final rule, 40 CFR Part 191, was published on September 19, 1985. This standard was vacated and remanded to the EPA by a Federal Court of Appeals in 1987. The LWA of 1992 reinstated the 1985 disposal standard Subpart B of 40 CFR 191 except for the three aspects of 40 CFR § 191.15 and 40 CFR § 191.16 that were specifically questioned by the court. On December 20, 1993, the EPA promulgated effective January 19, 1994, final disposal standards.

Title 40 CFR Part 191 contains three subparts. Subpart A addresses radiation doses during the operational phase (i.e., management and storage) of WIPP. Subparts B and C establish long-term (apply to a 10,000-year period) standards for the disposal of radioactive waste. Specifically, Title 40 CFR Part 191 Subparts B and C establish standards and measures of performance for the following aspects of a disposal system:

- isolation of radionuclides sufficient to meet the containment requirements of the disposal system.

- protection of individuals from radiation exposures for a period of 10,000 years, and

- protection of groundwater from radioactive contamination for 10,000 years.

To demonstrate that a disposal system will comply with 40 CFR Part 191, the DOE must show a reasonable expectation that each performance measure will be satisfied.

In addition to numeric requirements, the qualitative assurance standards set out in 40 CFR § 191.14 were promulgated in order to provide the confidence needed for long-term compliance with the containment requirements in 40 CFR § 191.13. They include (1) active and passive institutional controls to preclude or mitigate the potential for human disturbance of the repository for an extended period of time, (2) the concept of multiple (natural and engineered) barriers, and (3) other measures taken to enhance confidence in the disposal system performance.

The DOE demonstrated that the WIPP complies with the disposal standards in 40 CFR Part 191 in the original 1996 certification process. As required by the LWA, this application documents that the WIPP continues to comply with the disposal standards of 40 CFR Part 191 Subparts B and C. A regulatory cross reference of compliance for each of the requirements in 40 CFR Part 191 Subparts B and C is provided at the end of this chapter in Table 1-1. The final mean complementary cumulative distribution function (CCDF), which is the measure of compliance for containment, is shown in Figure 1-1. Based on this CCDF, the DOE has a reasonable expectation that the disposal system will perform in compliance with the containment requirements of 40 CFR Part 191.

1.2.2 40 CFR Part 194

The EPA was mandated by the LWA to issue criteria for evaluating the DOE's compliance demonstrations. The EPA met this requirement on February 9, 1996, with the publication of 40 CFR Part 194. In the summary of the rule, the EPA states that

> The Environmental Protection Agency (EPA) is promulgating criteria for determining if the Waste Isolation Pilot Plant (WIPP) will comply with EPA's environmental radiation protection standards for the disposal of radioactive waste. If the Administrator of EPA determines that the WIPP will comply with the standards for disposal, then the Administrator will issue to the Secretary of Energy a certification of compliance which will allow the emplacement of transuranic waste in the WIPP to begin, provided that all other statutory requirements have been met. If a certification is issued, EPA will also use this final rule to determine if the WIPP has remained in compliance with EPA's environmental radiation protection standards, once every five years after the initial receipt of waste for disposal at the WIPP. (61 FR 5224)

In its preamble to the rule, the EPA stated that "[w]ith today's rulemaking, the Agency establishes criteria by which to judge whether the WIPP is in compliance with the 'disposal regulations' and sets forth procedural requirements for this determination." To this end, the rule contains four subparts.

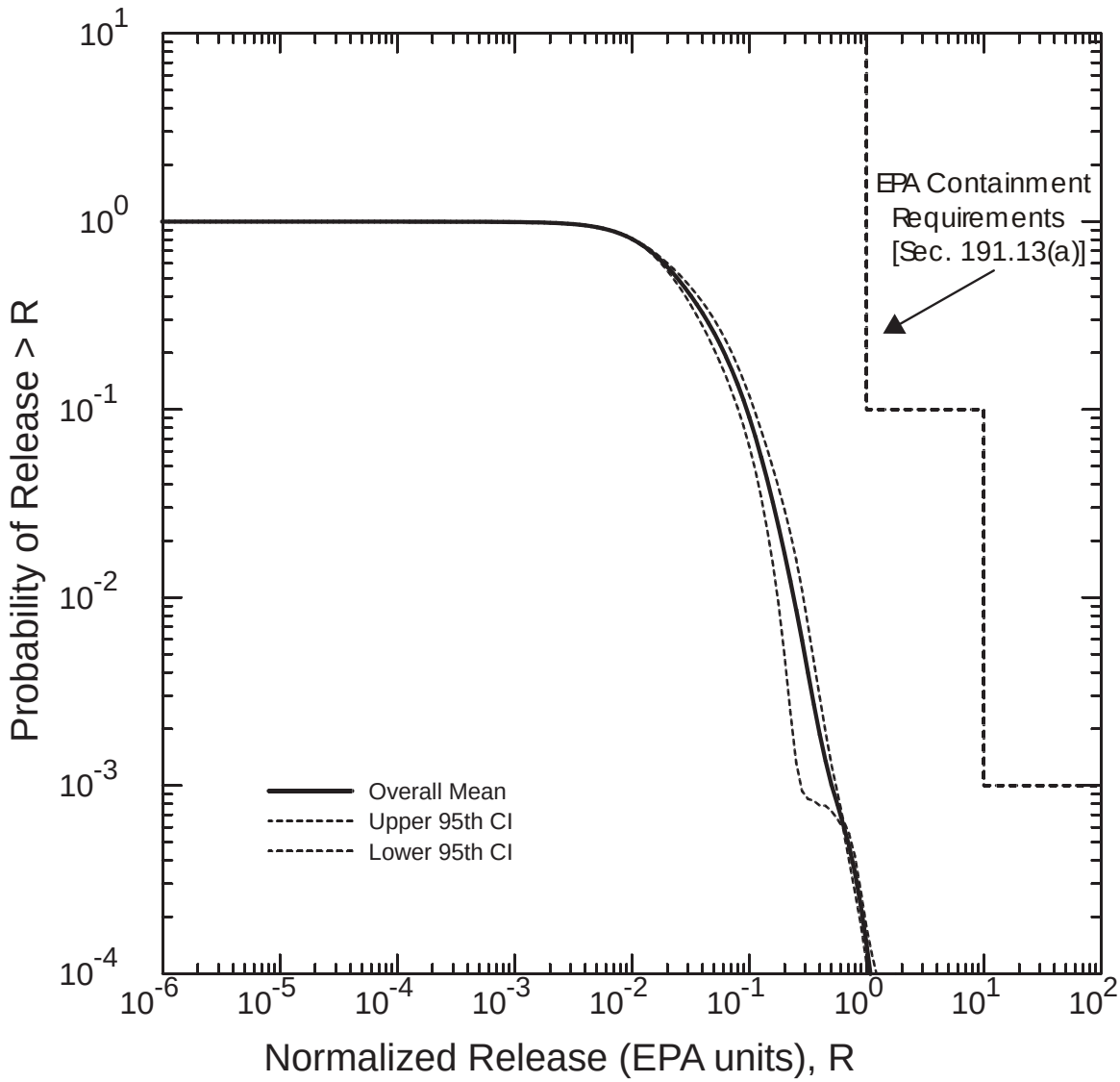

Figure 1-1. Final WIPP CCDF

- Subpart A establishes provisions related to the structure of the 40 CFR Part 194, including purpose, scope and applicability; definitions; substitution of alternative provisions for those promulgated in the final rule; and procedures that shall be followed in communications and written reports submitted by the DOE to EPA.

- Subpart B sets forth requirements for the submission format and content of compliance applications.

- Subpart C establishes the requirements that apply to the performance assessments and compliance assessments that will be used to demonstrate compliance with the requirements of the disposal regulations.

- Subpart D establishes procedures that the EPA will use to involve the public in the decisions on certification and recertification and requires the EPA to publish notices of its actions in the Federal Register.

In its certification decision for the WIPP (63 FR 27654), the EPA acknowledged that the DOE met all of the criteria established by the EPA in 40 CFR Part 194. The documentation for demonstrating continued compliance, as defined in the criteria in 40 CFR Part 194, is contained in this application. A crosswalk relating the criteria to the various sections of the application is provided in Table 1-1.

Criteria specific to the development of a recertification application are included in 40 CFR 194.15, which states:

> §194.15 Content of Compliance Re-Certification Application(s).
>
> (a) In submitting documentation of continued compliance pursuant to section 8(f) of the WIPP LWA, the previous compliance application shall be updated to provide sufficient information for the Administrator to determine whether or not the WIPP continues to be in compliance with the disposal regulations. Updated documentation shall include:
>
> (1) All additional geologic, geophysical, geochemical, hydrologic, and meteorologic information;
>
> (2) All additional monitoring data, analyses and results;
>
> (3) All additional analyses and results of laboratory experiments conducted by the Department or its contractors as part of the WIPP program;
>
> (4) An identification of any activities or assumptions that deviate from the most recent compliance application;
>
> (5) A description of all waste emplaced in the disposal system since the most recent compliance certification or re-certification application. Such description shall consist of a description of the waste characteristics and waste components identified in §194.24(b)(1) and §194.24(b)(2);
>
> (6) Any significant information not previously included in a compliance certification or re-certification application related to whether the disposal system continues to be in compliance with the disposal regulations; and
>
> (7) Any additional information requested by the Administrator or the Administrator's authorized representative.
>
> (b) To the extent that information required for a re-certification of compliance remains valid and has been submitted in previous certification or re-certification application(s), such information need not be duplicated in subsequent applications; such information may be summarized and referenced.

This recertification application contains the required information, and the WIPP continues to comply with the provisions of 40 CFR Parts 191 and 194.

1.2.3 Compliance Application Guidance for 40 CFR Part 194

Following the issuance of 40 CFR Part 194, the EPA issued guidance for implementation entitled "Compliance Application Guidance for 40 CFR Part 194" (EPA 1996b). The Compliance Application Guidance (CAG) is a companion to 40 CFR 194 and summarizes and explains EPA's expectations of the format and content of compliance certification applications based on a section-by-section discussion of the requirements of 40 CFR 194 and how they can be met.

1.2.4 Guidance to the U.S. Department of Energy on Preparation for Recertification of the Waste Isolation Pilot Plant with 40 CFR Parts 191 and 194

After its certification decision, and in anticipation of the initial recertification application, the EPA issued additional guidance specific to the recertification process entitled "Guidance to the U.S. Department of Energy on Preparation for Recertification of the Waste Isolation Pilot Plant with 40 CFR Parts 191 and 194" (EPA 2000). In this document, the EPA provided specific guidance to the DOE for the preparation and submission of a CRA. The guidance provides suggestions regarding the content and format of the CRA document and discusses the time frames and evaluation process that EPA will utilize to review this application. The purpose of this guidance is to assist DOE with the preparation of recertification applications, first by identifying the regulatory requirements pertinent to recertification and second by describing EPA's own approach to planning for recertification.

1.3 Project Background

The DOE began the development of the WIPP facility by selecting a site. Several alternative sites were evaluated, and the present site was selected as the best alternative based on a considerable amount of existing geotechnical information that was confirmed by extensive research and testing. Subsequent research and review have increased the understanding of the geologic, hydrologic, geochemical, and mechanical properties of the host rock and surrounding strata of the site. A Final Environmental Impact Statement (FEIS) (DOE 1980), which evaluated alternatives for the safe, long-term isolation of TRU waste, was completed by DOE in 1980. In its Record of Decision for the FEIS, the DOE concluded that the phased development of the WIPP facility was appropriate (DOE 1981).

The site preliminary design and validation phase followed the selection of the repository location. During this validation, the DOE constructed two shafts, excavated an underground testing area, and investigated various geologic, hydrologic, and other geotechnical features, further increasing understanding of the site's characteristics. In addition, the DOE evaluated methods for assessing the long-term performance of the WIPP facility. A series of geologic and hydrologic studies were conducted in accordance with an agreement between the DOE and the state of New Mexico.

The construction of the WIPP facility followed the site preliminary design and validation phase. Surface structures for receiving waste were built and underground excavations were mined, including one panel for waste emplacement and numerous areas for in-situ experiments. The data collected from these experiments and investigations were used to evaluate the potential short-term and long-term impacts of the WIPP facility.

The WIPP facility began waste disposal operations in 1999. During the disposal operations, which the DOE assumes for the purposes of this application to last 25 years, the DOE will receive, handle, and emplace TRU and TRU mixed waste in the repository.

Decommissioning of the WIPP facility will follow the operational period. At that time, the repository will be prepared for permanent closure, i.e., surface facilities will be decontaminated and decommissioned, underground excavations will be closed, and shaft seals will be emplaced. Decommissioning is expected to require about 10 years to complete.

Active and passive institutional controls will be implemented following the operating period. Active institutional controls include activities such as control of access to the site, maintenance, clean-up, and monitoring. Such controls will be implemented in a manner that is consistent with applicable regulations and requirements. Consistent with 40 CFR Part 191, 40 CFR Part 194, and the WIPP certification decision, only the first 100 years of active institutional controls have been included in the assessment of the disposal system's performance. Passive institutional controls include notification devices such as permanent markers and archives. These controls have been designed to reduce the likelihood of inadvertent human intrusion to the extent practicable, but no credit has been taken for these controls in the performance assessment for this recertification.

1.4 Site Selection Process

In 1957, the NAS National Research Council recognized salt as a medium well suited for radioactive waste disposal. Salt has favorable plastic (creep) properties, which allow significant deformation without fracturing. The existence of large salt deposits demonstrates isolation from circulating groundwaters for long periods of geologic time. Similarly, the depositional nature and preservation of large intact salt deposits demonstrate that the region has been stable for long periods of time.

The site selection process for the WIPP began in 1973 with a review of information on potential disposal media. This work focused on salt beds and salt domes. The preliminary selection criteria used in the initial stage of the process emphasized radiation and mine safety, hydrologic isolation, and ease of construction. In addition to salt lithological factors, the criteria specified the following conditions: 305 to 762 meters (1,000 to 2,500 feet) depth to salt, 61 meters (200 feet) minimum of salt thickness, lateral extent of salt sufficient to protect against dissolution, favorable tectonics (low historical seismicity and no salt-flow structures nearby), minimal groundwater, low resource potential, minimal number of existing boreholes, low population density, and maximum use of federal lands. The U.S. Geological Survey (USGS) and the Oak Ridge National Laboratory (ORNL) selected eastern New Mexico as the area with bedded salt that best satisfied the preliminary selection criteria.

During the second stage of the selection process, two of the three locations in this region were determined to be inadequate: the Clovis-Portales site because shallow salt formations had a significant clay content and the purer salt formations were too deep, and the Mescalero Plains area because of extensive oil field development. After shifting the potential site twice (in order to avoid borehole penetrations of the salt within 3.2 kilometers [2 miles] of the repository border), ORNL selected a site in the Delaware Basin for extensive characterization.

In the final stage of the process, eight areas in the Delaware Basin in Eddy and Lea counties were evaluated. Exploratory drilling at the first site recommended for characterization indicated unsuitable geology (see Chapter 2.0), and in 1975 the USGS and SNL reexamined the Delaware Basin for a more favorable location. This reexamination led to the selection of the Los Medaños site. Selection criteria considered at this stage of the process included:

1. the site should be at least 10 kilometers (6 miles) from the Capitan Limestone to avoid any possible deformation hazard related to the nearness of this reef structure;

2. to minimize potential conflicts with exploration of mineral resources, the central 10 square kilometers (4 square miles) of the repository itself should not be in the known Potash District, and as little as possible of the surrounding buffer zone should be in the district;

3. no part of the central area should be less than 1.6 kilometers (1 mile) away from holes drilled through the Castile Formation (hereafter referred to as the Castile) into underlying rocks in order to avoid dissolution by water flowing upward through an inadequately plugged borehole;

4. known oil and gas stratigraphic trends should be avoided;

5. the nearest dissolution front in the Salado Formation should be at least 1.6 kilometers (1 mile) from the site;

6. the bedding of geological strata should be as nearly flat as can be determined by surface geophysical investigations to ensure mine safety and ease of construction and to avoid the need for numerous exploratory holes that could pose a subsequent risk to the integrity of the repository;

7. salt of high purity should be available at depths between 305 and 914 meters (1,000 and 3,000 feet) to ensure mine safety and ease of construction. In addition, a salt thickness of 61 meters (200 feet) or more is preferred to confine thermal and mechanical effects to the salt; and

8. the use of state and private land should be minimized, especially in the central area, to simplify land acquisition and to avoid any relocation of residents.

The FEIS provided the basis for making the final decision regarding siting the WIPP facility at the Los Medaños site (the present WIPP location). This decision weighed the numerous advantages of the location and its suitability against potentially adverse environmental impacts. The WIPP site (Figure 1-2) was selected as the best of the alternatives. The specific horizon in the bedded salt was selected because of its desirable stratigraphic features. The stratigraphy is continuous throughout a large geographic area and major clay seams and interbeds of anhydrite or polyhalite are absent from the repository horizon. The facility has been constructed at a horizon such that operational and rock-support problems are minimized. Subsequent validation and construction activities have confirmed that the site's features are suitable for the long-term isolation of TRU waste. The DOE has concluded, based on the information in this application,

that these favorable features continue to offset any enhanced risk of human intrusion associated with extraction of resources in the vicinity.

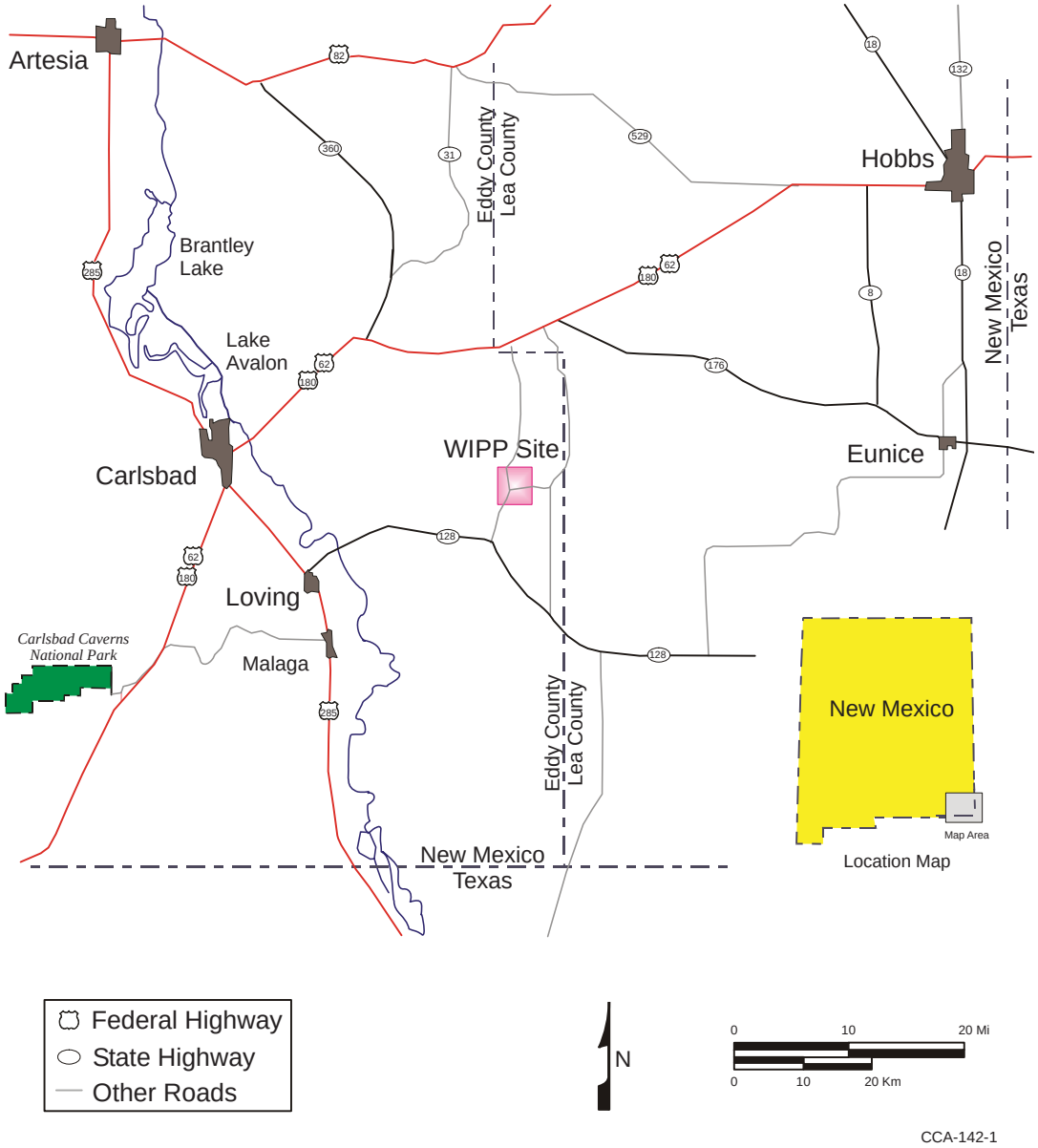

Figure 1-2. WIPP Location in Southeastern New Mexico

1.5 Program for Evaluating Long-Term Performance

When ORNL scientists recommended siting criteria for selecting a waste disposal location in salt, they had a general understanding of how a salt disposal system should perform, given the nature of the waste to be managed. Siting criteria emphasized stratigraphic factors to take full advantage of: creep properties of salt, purity to minimize the presence of complicating or unfavorable properties, isolation from aquifers to minimize impacts of circulating groundwaters, tectonic stability to ensure long-term isolation of waste, minimizing the presence of existing boreholes that could become conduits for release or dissolution, and minimizing resource activity

that could disrupt the disposal system. This understanding was, in a broad sense, a conceptual model that linked waste isolation to key features and processes that describe or affect the disposal system (ORNL 1973).

As site selection and site characterization proceeded, emphasis was placed on obtaining additional information on those features, events, and processes (FEPs) that define disposal system performance. For the CCA, about 240 FEPs that could operate on the WIPP disposal system were identified and addressed by the DOE (see CCA Appendix SCR). This information led to (1) the development of detailed conceptual models of various disposal system components such as salt creep, salt hydrology, groundwater hydrology, and waste degradation, as well as investigations to determine regional processes such as tectonism; and (2) scenarios of disposal system performance to be addressed by the modeling. The development of conceptual models required that several detailed laboratory and field experimental and investigation programs be conducted to answer questions about parameter values and uncertainty. Ultimately, the interaction between the various components of the disposal system was modeled to produce estimates of expected disposal system performance. CCA Appendix MASS contains a historical discussion of the evolutionary process that led to the conceptual model of the disposal system that is used in this application. This recertification application updates and refines that model. The FEPs baseline was assessed to evaluate the potential impacts that new information and operational changes had on the original screening decisions. The assessment concluded that no substantive changes to the FEPs baseline or conceptual models are necessary for this recertification application (see Appendix PA, Attachments SCR and MASS).

To evaluate the long-term performance of the disposal system, the DOE uses a technique developed especially for predicting the behavior of geologic repositories over the thousands of years required for waste isolation. This technique is performance assessment. Performance assessment is a multidisciplinary, iterative, analytical process that uses available information about the waste and the disposal system (the design of the repository, the repository seals, and the natural barriers provided by the host rock and the surrounding formations). Performance assessment is used to estimate the releases of radionuclides, based on the probabilities of relevant FEPs occurring, a knowledge of the system and the conceptual models developed to represent the system. Sensitivity analyses are used to determine which characteristics of the disposal system exert the greatest effect on performance. The results of sensitivity analyses are provided in this application in Appendix PA. The results of performance assessment are used in the 40 CFR Part 191 compliance program to assess disposal system behavior and possible environmental releases.

The WIPP performance assessment uses relevant information about the disposal system and the waste to simulate performance over the regulatory time periods. The WIPP PA process has been reviewed by the NAS and experts inside and outside of the United States. This process is schematically represented by the flow diagram in Figure 1-3, which shows how information describing the disposal system is used to develop scenarios, scenario probabilities, the consequence models used to estimate performance, and where these items are discussed in this application.

Uncertainty associated with the WIPP disposal system has been addressed through careful site, facility, and waste characterization. Remaining uncertainty is incorporated into the

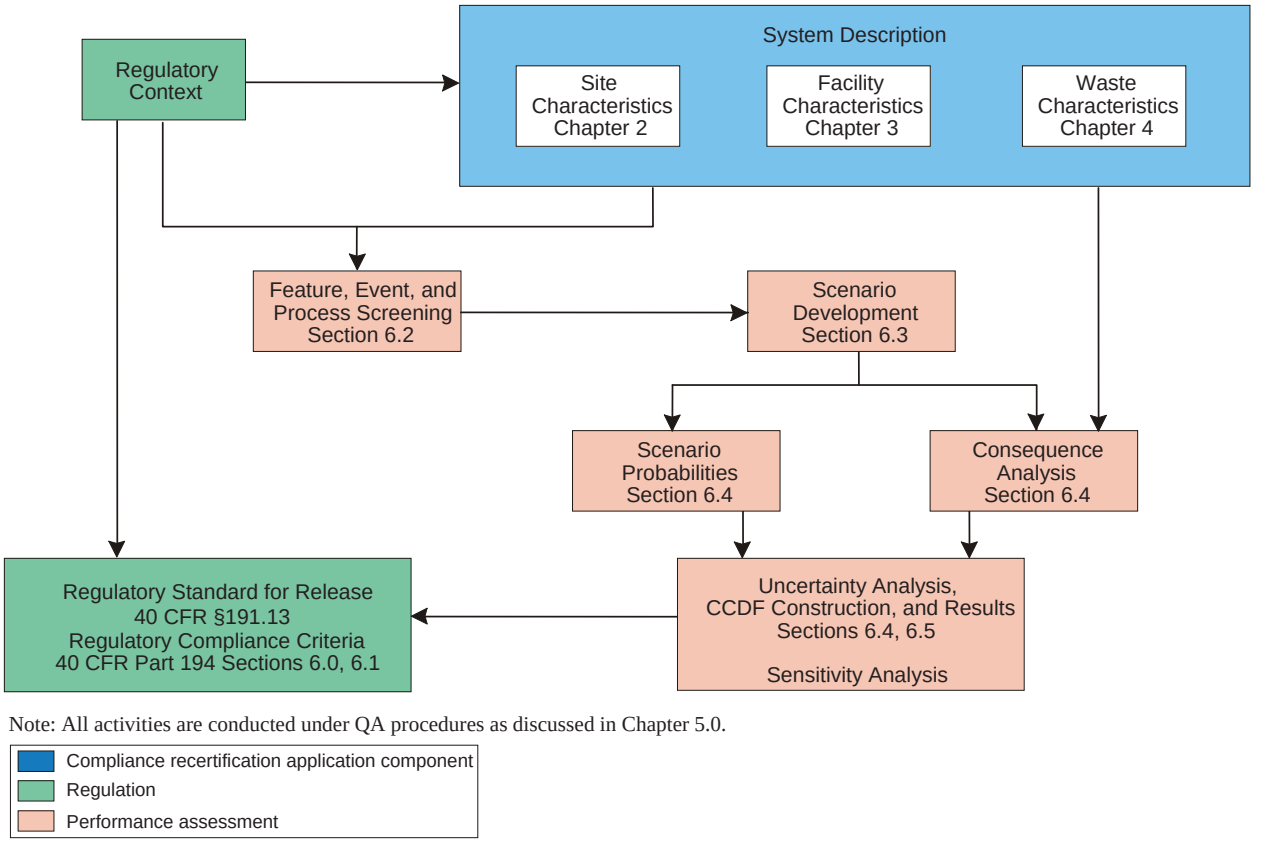

Figure 1-3. Methodology for Performance Assessment of the WIPP

performance assessment through the use of reasonable assumptions about models and parameter values. Uncertainty, and how it is handled in the analysis, plays a major role in the formulation of a performance assessment strategy. The EPA anticipates that uncertainty in long-term predictions will be inevitable and substantial (see 40 CFR § 191.13[b]). Because of this, the EPA applies a reasonableness test to the outcome of performance assessments. In other words, the EPA examines the information provided to determine if there is a reasonable expectation that compliance will be achieved.

This uncertainty is incorporated in the probabilistic nature of the complementary cumulative distribution function (CCDF). In this application, the mean CCDF, which is the measure of compliance for containment, displays the probability that radionuclide releases from the WIPP disposal system will exceed the regulatory requirements. In general, an attempt has not been made to include conservative assumptions that might bias the outcome of performance assessment. The mean CCDF represents a best estimate of the expected (and in the case of human intrusion, prescribed) performance of the disposal system. However, where realistic approaches to incorporating uncertainty are unavailable or impractical, and where the impact of the uncertainty on performance is small, the analysis has often been simplified by implementing

conservative assumptions.[1] The conservatism in the analysis is reviewed in Section 6.5.4 and discussed in Appendix PA, Attachment MASS, Table MASS-1. The review concludes that the conservatism does not significantly affect the location of the mean CCDF in Figure 1-1.

The format of this application is consistent with the process discussed in Section 6.1 and depicted in Figure 1-3. Basic input information is discussed in Chapters 2.0 through 5.0. Subsequent chapters use the input information to predict compliance as discussed in the following section.

1.6 Compliance Recertification Application Synopsis

This document contains the information necessary to demonstrate WIPP's continuing compliance with EPA requirements. Guidance provided by the EPA was used in preparing this application. All chapters and appendices provided in this application are described in Table 1-1 and are related to their CCA counterparts.

This application contains new information, and it references previously submitted information that is required for a recertification application. Where required information contained in the CCA remains valid, that information is referenced as provided by 40 CFR 194.15(b) and is not physically included in this recertification application. The information necessary to demonstrate compliance is included in a number of chapters, the contents of which are summarized below. Supporting, and more detailed, information is included in a series of appendices and attachments that are needed to make the application complete; therefore the appendices and attachments are integral parts of this application.

Chapter 2.0 describes the site and surrounding area as it existed prior to construction of the WIPP repository. Geological descriptions include both regional and local geology including structure, subsurface geology, geomorphology, geologic stability, soils, and topography. This chapter's purpose is to (1) explain the characteristics of the site, (2) describe background environmental quality, and (3) discuss features of the site that are important for inclusion in a quantitative performance assessment. The information in Chapter 2.0 has been used to develop and screen FEPs (see Appendix PA, Attachment SCR) to determine which ones are important to repository performance and to develop conceptual, mathematical, and computational models to evaluate the efficacy of the natural barriers in meeting the environmental performance standards (see Section 6.4). Numerical values have been derived for key parameters used to describe characteristics of the natural system. Information that supports these characteristics is discussed in Chapter 2.0; however, the specific parameter values used in the performance assessment are provided in Appendix PA, Attachment PAR.

Chapter 2.0 is supported by several appendices. These include basic site characterization reports, which were contained in the CCA (Appendices GCR, HYDRO, SUM, DEF, CLI, RBP, SER, and FAC). These appendices are included by reference in this recertification application and are summarized in Table 1-1. Other appendices, including Appendix PA (Attachments SCR, MASS

[1] Conservative assumptions are defined in this document as assumptions that result in the overestimation, rather than the underestimation, of any phenomenon that could contribute to the release of radionuclides from the disposal system.

and TFIELD) and Appendix DATA, were prepared specifically for this application and are also discussed in Table 1-1.

Chapter 3.0 provides technical information about those engineered systems at the WIPP that are important in meeting the disposal standards of 40 CFR Part 191. Descriptions relevant to long-term containment are provided for underground waste disposal and support facilities, and engineered barriers. In addition, details are provided for systems that significantly impede the movement of radionuclides to the accessible environment. These systems include shaft and borehole seals, panel closures, and an engineered barrier. Chapter 3.0 is supported by CCA Appendices SEAL, PCS, DVR, and EBS, that are included in the CRA by reference, and by Appendices PA (Attachment SCR), BARRIERS and QAPD, that are included with this recertification application.

Chapter 4.0 describes the wastes to be managed and disposed of at the WIPP facility. The waste description includes the definition, sources, types, components, and characteristics of TRU waste planned for emplacement in the repository. Those physical, chemical, and radiological characteristics of the waste that may singly or in combination affect the ability of the WIPP disposal system to meet the environmental performance standards in 40 CFR Part 191 are identified. An analysis of the waste inventory has been performed to determine those components of the waste that are important to the performance of the disposal system. This analysis is described in Appendix PA, Attachment SOTERM, and Appendix TRU WASTE and is supported by CCA Appendix WCA (included by reference). Inventory estimates of waste components are used as input into the PA to determine acceptable ranges for those components. Ranges determined acceptable based on the waste parameter values used in the CRA-2004 PA are imposed as limits through the waste acceptance process. Inventory estimates of TRU waste and specific information regarding the waste already emplaced in the repository are provided in Appendix DATA.

Chapter 5.0 describes the WIPP QA program. The certification criteria in 40 CFR Part 194 emphasize QA because a strong QA program can provide significant confidence in measured data and in complex computational models. The chapter provides the information required by 40 CFR § 194.22 and confirms that the DOE has had a QA program that is consistent with the requirements of the American Society of Mechanical Engineers (ASME)-Nuclear Quality Assurance (NQA)-1 for many years at the WIPP facility. The Carlsbad Field Office (CBFO) QAPD also mandates, in addition to NQA-1, the ASME NQA-2a-1990 addenda to NQA-2-1989, Part 2.7, and ASME NQA-3-1989 requirements. All WIPP participants who perform work that affects quality are required to have QA programs that meet the requirements of the CBFO QAPD to ensure that the data used in the performance assessment and compliance assessments meet the EPA requirements. All QA records (including many technical documents) related to this application are available for inspection in records facilities in Carlsbad, Albuquerque, and at other WIPP participant sites. Chapter 5.0 is supported by Appendix AUD and Appendix QAPD.

Chapter 6.0 discusses compliance with the containment requirements of 40 CFR § 191.13. The chapter includes a description of the overall system performance assessment methodology used to evaluate the performance of the WIPP disposal system; a list of FEPs that might affect the disposal system performance, the screening methodology applied to that list, and the result of the screening process; a summary of the development of the scenarios used in the PA; details of the

conceptual and computational models used in the PA, the overall flow of information in the PA, and the construction of the performance measure for comparison to the disposal standards; and a discussion of the results and the reliability of the performance assessment.

Chapter 6.0 is supported by numerous appendices and attachments including Appendices PA, BARRIERS, and DATA, which describe or support major numerical codes used in the analysis. Performance assessment parameters are provided in Appendix PA, Attachment PAR. Modeling assumptions used in the construction of the conceptual models and the implementation of the mathematical models are presented in Appendix PA, Attachment MASS. Justification for the source term used in the analysis is discussed in Appendix PA, Attachment SOTERM. In addition, Appendix PA, Attachment SCR, and CCA Appendices SEAL, CLI, and DEL support Chapter 6.0.

Chapter 7.0 describes the implementation of each of the 40 CFR Part 191 assurance requirements. This chapter and associated appendices describe plans, programs and/or analyses for compliance with active institutional control, passive institutional control, multiple barrier, monitoring, resource disincentives, and waste removal requirements. Chapter 7.0 is supported with numerous appendices. Appendix MON describes the rationale for the monitoring program and addresses the criteria for an analysis of sensitive disposal system parameters. Other supporting appendices include CCA Appendices AIC, D&D, DMP, EBS, EMP, EPIC, GTMP, LMP, GWMP, PIC, SMP, VCMP and WRAC. Supporting information provided in this recertification application includes Appendices MON, BARRIERS, and DATA.

Chapter 8.0 describes the DOE's compliance with the individual and groundwater protection requirements in 40 CFR Part 191. Chapter 8.0 is supported by CCA Appendix USDW, which identifies underground sources of drinking water in the vicinity of the controlled area.

Chapter 9.0 summarizes the results of peer reviews relevant to this application. The certification criteria mandated that the DOE perform peer reviews of the conceptual models, the waste characteristics analysis, and the engineered barrier study. In addition, the DOE conducted other peer reviews. The peer reviews related to waste characterization, engineered barriers, and conceptual models are found in Appendix PEER of the CCA. Additional peer reviews, including reviews by oversight and scientific organizations, performed since the certification are also discussed in Chapter 9.0 of this recertification application. Complete reports of peer reviews and scientific/oversight reviews, and associated documents, are included in Appendix PEER-2004 of this application.

1.7 Summary of Changes Since the CCA

Several changes have occurred to the WIPP facility and its operations since the CCA was developed and submitted to the EPA. These changes involve many aspects of the repository and the associated systems and processes. Changes relevant to this application include:

- TRU waste inventory estimates have been updated and are provided in this application, in addition to information about waste already emplaced in WIPP. This updated waste inventory information has been incorporated into the WIPP performance assessment conducted for and described in this CRA.

- A small change in the excavated horizon (elevated 2.4 m) for part of the repository was made to facilitate ground control and enhance worker safety.

- Waste was not emplaced in the main portions of Rooms 4, 5 and 6 of Panel 1 because of the advanced age of Panel 1, and no RH-TRU wastes were emplaced in Panel 1.

- The practice of attaching magnesium oxide “mini-sacks” in the waste containers in the repository was discontinued in order to enhance worker safety and improve operational efficiency.

- Three of the 24 conceptual models employed in the original performance assessments of the repository were modified to better represent the panel closure system selected by the EPA in the original certification of WIPP. These changes were examined by a peer review panel and were found to be reasonable and appropriate.

- A new spallings model was developed and underwent peer review. The peer review panel judged the revised model to be reasonable and appropriate for use in performance assessment of the WIPP.

- A single PA parameter set was adopted from a combination of the performance assessment parameters used in the CCA and in the EPA performance assessment verification test.

- Computing hardware and key software were upgraded to optimize computational performance and avoid obsolescence of the performance assessment computing environment.

These changes were evaluated and approved by the EPA and are discussed in more detail in this recertification application.

Table 1-1. Description of CRA-2004 Content Compared to the CCA

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Site Characterization – Describes the site and surrounding area. Descriptions include both regional and local geology including structure, subsurface geology, geomorphology, geologic stability, soils, and topography.	Ch. 2	Ch. 2
Facility Description – Technical information on engineered systems important in meeting the radioactive waste disposal standards. Descriptions relevant to long-term containment provided for underground waste disposal system, supporting facilities, and engineered barriers are included.	Ch. 3	Ch. 3
Waste Description – Summary description of the TRU wastes to be managed and emplaced in the disposal system. The waste description includes sources, types, components, and characteristics of TRU waste. This chapter identifies the principal waste aspects that may be important to long-term behavior of the disposal system, as well as the methods used to characterize and track these during pre-closure period.	Ch. 4	Ch. 4
Quality Assurance – Describes the DOE, WIPP participant, and TRU waste site QA programs, their implementation and applicability to activities described in this application.	Ch. 5	Ch. 5
Containment Requirements – Describes the overall system performance assessment (PA) methodology used to evaluate the performance of the WIPP disposal system. Includes a list of considered features, events, and processes (FEPs), the screening methodology applied to that list, and the result of the screening process; a summary of the scenarios used in PA; descriptions of the conceptual and computational models, the overall flow of information, and the construction of the performance measure for comparison to the disposal standards; and the overall PA results along with a discussion of the reliability of those results.	Ch. 6	Ch. 6
Assurance Requirements – Describes the assurance measures required by the disposal standards, and the implementation, plans and/or investigations for ensuring that active institutional control, pre-closure and post-closure monitoring, passive institutional control, multiple barrier, resource disincentives, and waste removal requirements are satisfied.	Ch. 7	Ch. 7
Individual and Groundwater Protection Requirements – Describes the approach and compliance basis of meeting the individual and groundwater protection requirements in 40 CFR Part 191 Subpart C.	Ch. 8	Ch. 8
Peer Review – Summarizes the results of NUREG-1297 peer reviews, and other reviews relevant to this compliance application. Previous information from the CCA is also summarized in this chapter.	Ch. 9	Ch. 9

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Active Institutional Controls – This CCA appendix includes the DOE's plans for active institutional controls that will be used following facility closure. The appendix provides the rationale and details of the various measures that the DOE intends to implement for the 100-year period of active controls. Active institutional controls are summarized in Chapter 7.0.	AIC	No update of this appendix needed for this application.
Audits – Descriptions of the QA assessments (audits and surveillances) of WIPP participants and TRU waste sites. Information is provided to demonstrate compliance with the requirements of NQA-1, NQA-2, Part 2.7, and NQA-3. The AUD-2004 appendix is a supplement to the information provided in the CCA. Documentation in this application applies to audits and surveillances conducted between November 1998 and May 2003.	AUD	AUD-2004
Barriers, Engineered – Description of the use and effectiveness of magnesium oxide and the related long-term performance aspects of the disposal system.	BACK	BARRIERS
Barriers (Multiple) – Description of engineered and disposal system barriers. Compilation of the salient information tied to continued compliance, and to satisfy the certification criteria of 40 CFR § 194.44.	Information not applicable to CCA.	BARRIERS
Environmental Compliance (general) – Biennial report summarizing WIPP compliance with a wide range of environmental requirements. No longer part of the compliance certification basis.	BECR	This portion of CCA eliminated from this and future compliance recertification applications.
Boreholes – Technical descriptions of existing boreholes drilled in the WIPP vicinity. Numerous boreholes have been drilled around the WIPP site for characterization purposes and for monitoring. These include holes for geological, hydrological, potash and soil investigations. A compendium of these holes, along with summary physical and geological information is provided, along with reference tables for non-WIPP holes (such as oil wells) that have been used in both site and regional studies by various investigators.	BH	DATA, Attachment G
TRU Waste Inventory – Original reports (TWBIR 2 and 3) established the baseline of TRU waste inventory data. The updated inventory data is provided in Appendix DATA, Attachment F.	BIR	DATA, Attachment F
Brine and Gas Flow – The CCA provided a description of the purpose of BRAGFLO and "Users manual" describing the codes that calculate brine flow estimates. The description of the BRAGFLO code has been updated in Appendix PA, and the user manual and other software and hardware documentation are referenced.	BRAGFLO	PA

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
CCDF – Description of the program designed to construct complementary cumulative distribution functions (CCDFs) from Monte Carlo sampling of PA modeling output. CCDFGF is used to calculate and present statistical performance assessment results. CCDFGF scales BRAGFLO and SECOTP2D results to match radionuclide outputs calculated by NUTS and PANEL. Use of the program results in CCDF plots of the overall predicted performance of the disposal system by combining the calculated release data and simulating many different repository histories, generating random sequences of future events, and calculating the probabilities associated with those random sequences.	CCDFGF	PA
Climate (long-term) – Technical study that was performed to determine climate changes in the recent past as a means of anticipating further changes in the next 10,000 years. Climate variation is modeled as part of the PA system.	CLI	No update of this appendix needed for this application.
Codes Links – Describes the conceptual links between computer codes for PA, overviews of and backgrounds for the principal codes, and the principal code-linkage sequences that support the 1996 performance assessment. Updated information on the relationships between codes is described in Appendix PA.	CODELINK	PA
Cuttings – This computer code estimates the direct removal of radionuclides from the repository as the result of penetration by a borehole drilled into the disposal system at some time in the future. These mechanically based releases to the surface are modeled to occur at the time of drilling.	CUTTINGS	PA
Data – Extensive supporting numerical and descriptive information, including monitoring and TRU waste inventory data collected since the development of the CCA.	Information not applicable to CCA.	DATA
Decommissioning – Post-operational plan that describes the activities planned for the decontamination and decommissioning and closure phase.	D&D	No update of this appendix needed for this application.
Deformation – Description of conclusions from investigating the effect of salt dissolution and evaporite deformation. DOE conducted numerous investigations to resolve the issues surrounding deformation of the evaporites and dissolution of salt. This CCA appendix summarizes those investigations and the conclusions reached as the result. This information is referenced in Chapter 2.0.	DEF	No update of this appendix needed for this application.
Delaware Basin Study – Historical drilling evaluation and prediction of future drilling rates. This information includes a summary of historical and current drilling practices, current well-plugging practices, presents an inventory of deep and shallow wells, and proposes assumptions for the inadvertent human intrusion scenarios in the performance assessment. This information is considered in the performance assessment parameters and calculations.	DEL	MON-2004 and DATA

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Delaware Basin Drilling Surveillance Plan – Summary of the Delaware Basin drilling activity surveillance program. This program will focus on drilling activities whose changes over time may impact the disposal system. These may include drilling rates, drill diameters, and borehole plugging practices.	DMP	MON-2004 and DATA
Disposal System Design – Description of the analysis used to validate the design of the disposal system. This is a compliance certification basis document, and is not replicated in the CRA-2004.	DVR	No update of this appendix needed for this application.
Selection of Barriers – The DOE performed an evaluation of potential engineered barriers in accordance with the certification criteria. Both natural and engineered barriers were considered with a multitude of alternatives. This information supports the concept of multiple barriers in Chapter 7.0. The final report is part of the compliance basis documentation and is not reproduced in this application.	EBS	No update of this appendix needed for this application.
Environmental Monitoring – This plan describes the activities of the environmental monitoring performed at and around the WIPP site. Portions applicable to the general and assurance requirements are provided in this application.	EMP	MON-2004
Evaluation of Passive Institutional Controls – Analysis of the effectiveness of the Passive Institutional Controls.	EPIC	No update of this appendix needed for this application.
Deposition – The WIPP shafts provided the opportunity to study the sediments and evaporites at the WIPP site. This report provides in-depth interpretations of the geological evidence in the shafts and proposes depositional theories for the rocks of the site region. This report is referenced as part of the detailed lithological information in Chapter 2.0.	FAC	No update of this appendix needed for this application.
Geological Characterization – A compendium of the geological studies that characterized the WIPP site. This 1978 Geological Characterization Report was prepared by Sandia National Laboratories (SNL) as a summary of the investigations performed for the WIPP. It includes a summary of work performed in the area by numerous other scientists, as well as studies designated for selecting a radioactive waste disposal facility site. The basic geological features such as stratigraphy, lithology, geomorphology, physiography are established in this report. This information remains as part of the compliance certification basis, and is not replicated in this application.	GCR	No update of this appendix needed for this application.
Dose Estimate (undisturbed path) – The method of calculating dose from undisturbed release pathways was through utilization of a computer code. The CCA provided the user's manual describing the exposure/dose computer code in an appendix. The CRA-2004 describes a simplified method utilized to quantify the dose for this type of release.	GENII	PA
Geotechnical Monitoring Plan – Describes the program established to monitor the behavior of surface and subsurface strata, within and near the disposal system.	GTMP	MON-2004

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Groundwater Monitoring Plan – Describes the program established to monitors the groundwater behavior of the Culebra Formation.	GWMP	MON-2004
Geology and Hydrology – A comprehensive discussion of studies conducted by the U.S. Geological Service (USGS) and other organizations of the formations near the location of the WIPP disposal system.	HYDRO	No update of this appendix needed for this application.
Resource Disincentive – An evaluation of the potential resources surrounding the WIPP site.	IRD	No update of this appendix needed for this application.
Statistical Sampling – Intermediate results and description of a statistical analysis of time-dependent parameters.	IRES	PA
Land Management – Required by the Land Withdrawal Act, this plan details the land management practices implemented throughout the 16-square miles of the WIPP site boundary. This portion of the CCA has been eliminated from this and future compliance applications	LMP	This portion of CCA eliminated from this and future compliance recertification applications.
Modeling Assumptions – Description of the assumptions used in the PA modeling applicable to numerical, mathematical, computational, and conceptual models.	MASS	PA, Attachment MASS
Pre- and Post-Closure Monitoring Plan – Description of surveillance and monitoring programs that the DOE has implemented to demonstrate compliance with 40 CFR 194.42.	MON	MON-2004
Radionuclide Transport (in fractured media) – A summary and users' manual describing the code used to calculate radionuclide decay and transport through fractured media.	NUTS	PA
Radionuclide Transport (in brine) – Descriptive summary and users' manual describing the code used to calculate radionuclide decay and transport in a brine mixture.	PANEL	PA
Performance Assessment (Total System) – A comprehensive appendix and set of attachments that provide descriptions of the performance assessment basis, conceptual models, methodology, and related supporting information provided in attachments. This is the primary appendix supporting the information in Chapter 6.0.	Information not applicable to CCA.	PA
Parameters – Description and rationalization of the parameters selected and used in the performance assessment calculations.	PAR	PA, Attachment PAR
Panel Closure System – Reproduction of an engineering report that describes the systems of panel closures available to close individual waste panels. The CRA-2004 captures the applicable portions of the similar information in a new appendix.	PCS	BARRIERS
Peer Reviews – Reproduction of NUREG-1297 peer review reports, and related documents published by independent organizations. Each report captures evaluations of specific topics associated with WIPP compliance. Two NUREG-1297-compliant peer reviews were performed in support of this application.	PEER	PEER-2004

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Passive Institutional Controls – Documentation consisting of the conceptual designs and plans for awareness triggers, archiving, and permanent markers. This document has not been updated since the CCA, though the current status of this endeavor is summarized in Chapter 7.0.	PIC	No update of this appendix needed for this application.
Salado (Repository) Behavior – Creep closure of the excavation and the presence of either brine or gas in the waste disposal region both influence the time-dependent changes in void volume in the waste disposal region. In order to vary them in a computationally efficient manner, a porosity surface is generated. This surface is used by the BRAGFLO code to indirectly couple mechanical closure of the excavation and gas generation to the two-phase fluid flow calculations.	PORSURF	PA
Quality Assurance Program – The Quality Assurance Program Document (QAPD) defines the QA requirements that are applicable to WIPP and TRU waste site activities. The QAPD establishes the foundation for which all WIPP-related QA programs must adhere, and outlines the approach used to demonstrate compliance with 40 CFR, Section 194.22.	QAPD	QAPD
Radiological Baseline (background) – This CCA appendix was provided as reference information describing the effort to establish a WIPP radiological baseline, with the first five years of environmental radiological sampling (1985-1989). The background radiation data for air, soil, water, biota, and fauna were complied to establish the radiological baseline (described in Chapter 2.0). Future sampling data will be compared to the baseline.	RBP	No update of this appendix needed for this application.
Sensitivity Analysis – The 1996 application provided limited descriptions of the post-processing evaluation of modeling sensitivities and uncertainties within the system PA. Since then, extensive analyses have been performed for both the CCA PA and PA verification test. The discussion of the sensitivity analyses is provided in this application as part of the overall PA system description.	SA	PA
Features, Events, and Processes (FEPs) screening – A description of the basis for the modeling foundation and all inputs considered for scenario and model development. SCR documents the screening process and decisions. Those that are retained (not screened out) are included in the conceptual models of repository performance as described in Chapter 6.0.	SCR	PA, Attachment SCR
Shaft Seals – Description of the plan and design of the repository shaft seals expected to be used in the D&D and closure phase. The CCA provides the complete description of designs and plans, while the CRA-2004 summarizes this information.	SEAL	BARRIERS
Culebra Flow – The CCA described the use of users' manual describing the computer code that calculates the groundwater flow-field of the Culebra. For the CRA-2004, the mathematical and computation models are executed through use of MODFLOW-2000. Information on the implementation is provided in Appendix PA.	SECOFL2D	PA and PA, Attachment TFIELD

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Culebra Transport – The CCA provided a description and users' manual for the computer code used to estimate material transport within the Culebra. The CRA-2004 provides updated information within the PA appendix and related attachment TFIELD	SECOTP2D	PA and PA, Attachment TFIELD
Annual Environmental Report – Annual report that describes the results of the environmental monitoring for the reporting year. The CCA provided a copy of the 1995 report as an appendix. The applicable information for this application is captured in Chapter 2.0 and the appendices shown.	SER	MON-2004 and DATA
Subsidence Monitoring – Description of the subsidence surveillance program that DOE implements to gage the surface movement in response to the excavated portions of the disposal system. Subsidence predictions will be compared to actual measurements to investigate any potential deviations that may indicate a change in repository performance.	SMP	MON-2004
Actinide Source Term – Explanation of the actinide source term for the WIPP performance calculations. The source term is defined by the sum of dissolved actinide species and mobile colloidal actinide species. Estimates of the mobile concentration of actinides that may be released from the repository are provided.	SOTERM	PA, Attachment SOTERM
Site Characterization – Compilation of the findings related to site-specific testing and studies ranging over a period from 1977 to 1987. Following the final selection of the site in 1980 and a review by the NAS and the EEG, numerous additional studies were identified to resolve specific site-related issues. These investigations included regional studies, site studies, and underground tests. DOE prepared a summary of the findings and offered interpretations of geological relationships. These results were definitive in developing conceptual models for the WIPP disposal system.	SUM	No update of this appendix needed for this application.
Culebra Transmissivity – Hydrological transmissivity of the Culebra is highly variable. Numerous measurements have been made to characterize this parameter. These data have been processed geo-statistically to produce an array of transmissivity fields for use in the transport calculations that are part of the performance assessment. The process for generating these fields and the results themselves are included in this application.	TFIELD	PA, Attachment TFIELD
Underground Sources of Drinking Water – Evaluation of potential drinking water sources (groundwater) in the WIPP and surrounding area. This appendix includes a description of available groundwater information and concludes that there are three possible underground sources of drinking water near the WIPP-controlled area. Theses sources are within the Dewey Lake Formation, the Santa Rosa Formation, and the Culebra Member of the Rustler Formation. Updated information in Chapter 8.0 supplements this baseline appendix.	USDW	No update of this appendix needed for this application.

Table 1-1. Description of CRA-2004 Content Compared to the CCA — Continued

Summary Description	CCA Chapter or Appendix	CRA-2004 Chapter or Appendix
Volatile Organic Compounds – In 1996, DOE included a plan that described the program established to monitor potential VOCs. This information is no longer part of the compliance certification basis, and will not be addressed in this or future applications.	VCMP	This portion of CCA eliminated from this and future compliance recertification applications.
Waste Characterization – Descriptions of sampling and analysis techniques, and reference to documentation that establishes the data quality objectives for characterization. This portion also summarizes the methodology for collecting and using acceptable knowledge in the characterization process.	WAP	TRU WASTE
Waste Characterization Analysis – Identification of TRU waste characteristics and components expected to be important to disposal system performance.	WCA	TRU WASTE
Waste Component Limits – Based on identification of key waste components, this portion describes the limits established for each. In calculating the performance of the disposal system, the DOE has set bounding values for each waste component. Within these values, the analyses are valid, and the WIPP can be reasonably expected to comply with the disposal standards.	WCL	TRU WASTE
Waste Removal – Plan that describes the future removal of the repository waste This appendix contains a feasibility study for the removal of most of the waste from the disposal system at some time in the future. Conventional mining techniques, coupled with remote-handled (RH) technology, are discussed to show that, even with current technology, such removal would be possible at any time after facility closure.	WRAC	No update of this appendix needed for this application.
Reference citations – Specific list of reference citations used in the CCA. This information has not been replicated for the CRA-2004.	XRE	No update of this appendix needed for this application.

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2.0 SITE CHARACTERIZATION

The U.S. Department of Energy (DOE) uses the performance assessment (PA) methodology described in Chapter 6.0 to demonstrate that the Waste Isolation Pilot Plant (WIPP) disposal system will meet the environmental performance standards of Title 40 of the Code of Federal Regulations (CFR) Part 191 Subparts B and C. In order to effectively use PA, three inputs are necessary: What can happen to the disposal system? What are the chances of it happening? What are the consequences if it happens? The answers to these questions are derived from many sources, including field studies, laboratory evaluations, experiments, and, in the case of some features not amenable to direct characterization, professional judgment. The information used in PA is described in terms of features of the disposal system that can be used to describe its isolation capability, events that can affect the disposal system, and processes that are reasonably expected to act on the disposal system.

The DOE selected the Los Medaños region and present site for the WIPP based on certain defined siting criteria. The site selection process, which was focused on sites that contained certain favorable features while other unfavorable features were excluded, was applied by the DOE with the intent of finding the area that best met the siting criteria. The siting process is discussed in CCA Appendix GCR. Chapters 3.0, 4.0, and 6.0 and several appendices provide additional information supporting this chapter.

Conceptual models of the WIPP disposal system simulate the interaction between the natural environment (described in this chapter), the engineered structures (described in Chapter 3.0) and the waste (described in Chapter 4.0). One starting point in developing conceptual models of the WIPP disposal system is an understanding of the natural characteristics of the site and of the region around the site. Site characterization and model development is an interactive process that the DOE has used for many years. Basic site information leads to initial models. Initial model sensitivity studies indicate the need for more detailed information. More site characterization then leads to improved models. In addition, an assessment of the impacts of uncertainty inherent in the parameters used to numerically simulate geological features and processes has also led the DOE to conduct more in-depth investigations of the natural system. These investigations generally proceeded until uncertainty was sufficiently reduced or to the point where no further information could be reasonably obtained.

The discussion of conceptual models and initial and boundary conditions is in Section 6.4 and Appendix PA, Attachment MASS. Conceptual models implement scenarios about the future. Scenario development is discussed in Section 6.3. Scenario development requires as inputs information about the natural features, events, and processes (FEPs) that can reasonably be expected to act on the disposal system. While the list of possible FEPs is derived independently of the disposal system, their screening (in Section 6.2 and Appendix PA, Attachment SCR) is based on an understanding of the geology, hydrology, and climatology of the region and the site in particular. The screening methodology follows U.S. Environmental Protection Agency (EPA) criteria on the Scope of Performance Assessments (40 CFR § 191.32). This basic understanding is provided in this chapter and its associated appendices.

Table 2-1 shows the tie between the list of natural FEPs that were identified and screened for the WIPP and the sections of this chapter or Appendix PA, Attachment SCR. Those FEPs that have

been retained for inclusion in the modeling are shown in bold in Table 2-1. These generally receive a greater level of detail in the following discussions and are supported by additional discussion in Chapter 6.0, Appendix PA, Attachments MASS and SCR. In addition, parameter values that have been derived for these FEPs are included in Appendix PA, Attachment PAR.

In this chapter, the DOE describes the WIPP site geology, hydrology, climatology, air quality, ecology, and cultural and natural resources. This chapter's purpose is to (1) explain characteristics of the site, (2) describe background environmental quality, and (3) discuss features of the site that might be important for inclusion in a quantitative PA. The DOE has used this information to develop and screen FEPs and to develop conceptual, mathematical, and computational models to evaluate the efficacy of natural and engineered barriers in meeting environmental performance standards (Chapter 6.0). Results of these predictive models are used by the DOE to demonstrate that the DOE has a reasonable expectation that compliance with applicable regulations will be achieved. This chapter has been prepared to describe the site prior to excavating the repository. Excavation of the repository and its associated effects, such as the disturbed rock zone (DRZ), are discussed in Chapter 3.0.

The DOE located the WIPP site 42 km (26 mi) east of Carlsbad, New Mexico, in Eddy County (Figure 2-1). Additional details related to the location of the WIPP site can be found in Section 2.1.4.2 and in Figure 3-1 (see Chapter 3.0). The latitude of the WIPP site center is 32°22' 11" N and the longitude is 103°47' 30" W. The region surrounding the WIPP site has been studied for many years, and exploration of both potash and hydrocarbon deposits has provided extensive knowledge of the geology of the region. Two exploratory holes were drilled by the federal government in 1974 at a location northeast of the present site; that location was abandoned in 1975 as a possible repository site after U.S. Energy Research and Development Administration (ERDA) 6 borehole was drilled and unacceptable structure and pressurized brine were encountered. The results of these investigations are reported in Powers et al. (1978, 2 – 6; included in CCA Appendix GCR). During late 1975 and early 1976, the ERDA identified the current site, and an initial exploratory hole (ERDA-9) was drilled. By the time an initial phase of site characterization was completed in August 1978, 47 holes had been or were being drilled for various hydrologic and geologic purposes. Geophysical techniques were applied to augment data collected from boreholes. Since 1978, the DOE has drilled additional holes to support hydrologic studies, geologic studies, and facility design. Geophysical logs, cores, basic data reports, geochemical sampling and testing, and hydrological testing and analyses are reported by the DOE and its scientific advisor, Sandia National Laboratories (SNL), in numerous public documents. Many of those documents form the basis for the DOE's positions in this application. As necessary, specific references from these documents are cited to reinforce statements being made.

Biological studies of the site began in 1975 to gather information for the Environmental Impact Statement (DOE 1980). Meteorological studies began in 1976, and economic studies were initiated in 1977. Baseline environmental data were initially reported in 1977 and are now updated annually by the DOE.

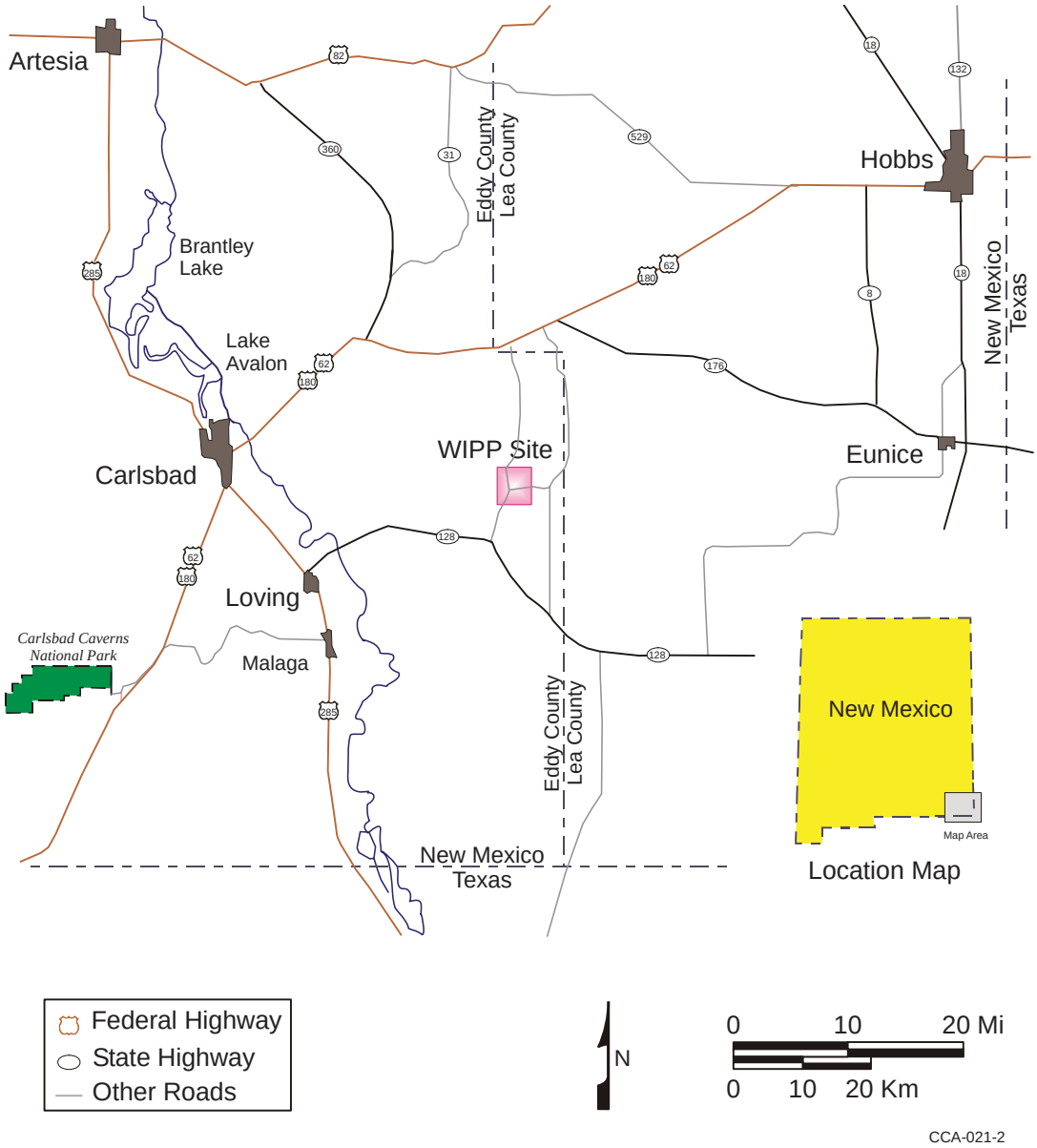

Figure 2-1. WIPP Site Location in Southeastern New Mexico

Table 2-1. Issues Related to the Natural Environment That Were Evaluated for the WIPP PA Scenario Screening

Features, Events, and Processes (FEPs)	EPA FEP No.	Discussion
NATURAL FEPs		
Stratigraphy		
Stratigraphy	N1	Section 2.1.3
Brine reservoirs	N2	Section 2.2.1.2.2
Tectonics		
Changes in regional stress	N3	Section 2.1.5.1
Regional tectonics	N4	Section 2.1.5.1
Regional uplift and subsidence	N5	Section 2.1.5.1
Structural FEPs		
Deformation		
Salt deformation	N6	Section 2.1.6.1
Diapirism	N7	Appendix PA, Attachment SCR
Fracture development		
Formation of fractures	N8	Section 2.1.5
Changes in fracture properties	N9	Section 2.1.5
Fault movement		
Formation of new faults	N10	Section 2.1.5
Fault movement	N11	Section 2.1.5.3
Seismic activity		
Seismic activity	N12	Section 2.6
Crustal processes		
Igneous activity		

Table 2-1. Issues Related to the Natural Environment That Were Evaluated for the WIPP PA Scenario Screening — Continued

Features, Events, and Processes (FEPs)	EPA FEP No.	Discussion
Volcanic activity	N13	Section 2.1.5.4
Magmatic activity	N14	Appendix PA, Attachment SCR
Metamorphic activity		
Metamorphism	N15	Appendix PA, Attachment SCR
Geochemical FEPs		
Dissolution		
Shallow dissolution	N16	Section 2.1.6.2
Lateral dissolution	N17	Section 2.1.6.2
Deep dissolution	N18	Section 2.1.6.2
Solution chimneys	N19	Section 2.1.6.2
Breccia pipes	N20	Section 2.1.6.2
Collapse breccias	N21	Section 2.1.6.2
Mineralization		
Fracture infills	N22	Section 2.1.3.5.2
SUBSURFACE HYDROLOGICAL FEPs		
Groundwater characteristics		
Saturated groundwater flow	N23	Section 2.2.1
Unsaturated groundwater flow	N24	Section 2.2.1
Fracture flow	N25	Section 2.2.1
Density effects on groundwater flow	N26	Section 2.2.1
Effects of preferential pathways	N27	Section 2.2.1
Changes in groundwater flow		
Thermal effects on groundwater flow	N28	Appendix PA, Attachment SCR
Saline water intrusion	N29	Appendix PA, Attachment SCR
Freshwater intrusion	N30	Appendix PA, Attachment SCR
Hydrological effects of seismic activity	N31	Appendix PA, Attachment SCR
Natural gas intrusion	N32	Appendix PA, Attachment SCR
SUBSURFACE GEOCHEMICAL FEPs		
Groundwater geochemistry		
Groundwater geochemistry	N33	Section 2.2.1.4.1.2
Changes in groundwater geochemistry		
Saline water intrusion	N34	Appendix PA, Attachment SCR
Freshwater intrusion	N35	Appendix PA, Attachment SCR
Changes in groundwater Eh	N36	Appendix PA, Attachment SCR
Changes in groundwater pH	N37	Appendix PA, Attachment SCR

Table 2-1. Issues Related to the Natural Environment That Were Evaluated for the WIPP PA Scenario Screening — Continued

Features, Events, and Processes (FEPs)	EPA FEP No.	Discussion
Effects of dissolution	N38	Appendix PA, Attachment SCR
GEOMORPHOLOGICAL FEPs		
Physiography		
Physiography	N39	Section 2.1.4
Meteorite impact		
Impact of a large meteorite	N40	Appendix PA, Attachment SCR
Denudation		
Weathering		
Mechanical weathering	N41	Appendix PA, Attachment SCR
Chemical weathering	N42	Appendix PA, Attachment SCR
Erosion		
Eolian erosion	N43	Section 2.1.3.10
Fluvial erosion	N44	Section 2.1.3.6
Mass wasting	N45	Appendix PA, Attachment SCR
Sedimentation		
Eolian deposition	N46	Appendix PA, Attachment SCR
Fluvial deposition	N47	Appendix PA, Attachment SCR
Lacustrine deposition	N48	Appendix PA, Attachment SCR
Mass wasting (deposition)	N49	Appendix PA, Attachment SCR
Soil development		
Soil development	N50	Section 2.1.3.10
SURFACE HYDROLOGICAL FEPs		
Fluvial		
Stream and river flow	N51	Section 2.2.2
Lacustrine		
Surface water bodies	N52	Section 2.2.2
Groundwater recharge and discharge		
Groundwater discharge	N53	Section 2.2.1
Groundwater recharge	N54	Section 2.2.1
Infiltration	N55	Section 2.1.3 Section 2.2.1
Changes in surface hydrology		
Changes in groundwater recharge and discharge	N56	Section 2.2.1
Lake formation	N57	Section 2.2.2
River flooding	N58	Section 2.2.2

Table 2-1. Issues Related to the Natural Environment That Were Evaluated for the WIPP PA Scenario Screening — Continued

Features, Events, and Processes (FEPs)	EPA FEP No.	Discussion
CLIMATIC FEPs		
Climate		
Precipitation (for example, rainfall)	N59	Section 2.5.2.3
Temperature	N60	Section 2.5.2.2
Climate change		
Meteorological		
Climate change	N61	Section 2.5
Glaciation		
Glaciation	N62	Section 2.5.1
Permafrost	N63	Appendix PA, Attachment SCR
MARINE FEPs		
Seas		
Seas and oceans	N64	Appendix PA, Attachment SCR
Estuaries	N65	Appendix PA, Attachment SCR
Marine sedimentology		
Coastal erosion	N66	Appendix PA, Attachment SCR
Marine sediment transport and deposition	N67	Appendix PA, Attachment SCR
Sea level changes		
Sea level changes	N68	Appendix PA, Attachment SCR
ECOLOGICAL FEPs		
Flora and fauna		
Plants	N69	Section 2.4.1
Animals	N70	Section 2.4.1
Microbes	N71	Appendix PA, Attachment SCR
Changes in flora and fauna		
Natural ecological development	N72	Section 2.4.1

*NOTE: Additional information for FEPs N1-N72 is located in Appendix PA, Attachment SCR.

The DOE located the WIPP disposal horizon within a rock salt deposit known as the Salado Formation at a depth of 650 m (2,150 ft) below the ground surface. The Salado is regionally extensive, includes continuous beds of salt without complicated structure, is deep with little potential for dissolution in the immediate vicinity of the WIPP, and is near enough to the surface to make access reasonable. Particular site selection criteria narrowed the choices when the present site was located during 1975 and 1976, as is discussed in CCA Appendix GCR and summarized by Weart (1983).

2.1 Geology

The DOE and its predecessor agencies determined at the outset of the geological disposal program that the geological characteristics of the disposal system are extremely important because the natural barriers provided by the geological units have a significant impact on the performance of the disposal system. Among the DOE's site selection criteria was the intent to maximize the beneficial impacts of the geology. This was accomplished when the DOE selected (1) a host formation that behaves plastically, thereby creeping closed to encapsulate buried waste, (2) a location where the effects of dissolution are minimal and predictable, (3) an area where deformation of the rocks is low, (4) an area where excavation is relatively easy, (5) an area where future resource development is predictable and minimal, and (6) a repository host rock that is relatively uncomplicated lithologically and structurally. Therefore, a thorough and accurate description of the WIPP facility's natural environmental setting is considered crucial by the DOE for a demonstration of compliance with the disposal standards and is an EPA certification criterion in 40 CFR § 191.14(a). The DOE is providing the detail necessary to assess the achievable degree of waste isolation. In this chapter, the DOE addresses environmental factors and long-term environmental changes that are important for assessing the waste isolation potential of the disposal system. The first of these environmental factors is geology.

Geological data have been collected from the WIPP site and surrounding area to evaluate the site's suitability as a radioactive waste repository. These data have been collected principally by the DOE, the DOE's predecessor agencies, the United States Geological Survey (USGS), the New Mexico Bureau of Mines and Mineral Resources (NMBMMR), and private organizations engaged in natural resource exploration and extraction. The DOE has analyzed the data and has determined that the data support the DOE's position that the WIPP site is suitable for the long-term isolation of radioactive waste.

Many issues have been discussed, investigated, and resolved in order for the DOE to conclude that the site is suitable. The DOE discusses these issues in the following sections. Most of the data collected have been reported or summarized in CCA Appendices GCR, SUM, HYDRO, and FAC. These appendices represent the majority of the site characterization results for the WIPP site which ended in 1988. A number of more focused geological and hydrological studies continued after this date. These latter studies provided detailed information needed to construct the conceptual models for disposal system performance that are discussed in Section 6.4. An example of these studies is the H-19 multiwell tracer test that was completed in early 1996. Results of this test were incorporated into the discussions in this chapter and into the conceptual models described in Section 6.4.6. Model parameters derived from the data are displayed in Appendix PA, Attachment PAR. A discussion of the data is included in CCA Appendix MASS; and Appendix PA, Attachment MASS.

Geological field studies designed to collect data pertinent to the WIPP PA continue. The Culebra Dolomite Member and Magenta Dolomite Members are the two carbonates in the Rustler Formation, the youngest evaporite-bearing formation in the Delaware Basin. Geologic data related to the Culebra and Magenta remain of particular interest, as these members are the most significant transmissive units at the WIPP site.

The EPA's December 19, 1996 letter (A-93-02, Docket II-I-01) made a request to the DOE for recent studies that had provided detailed information used in developing conceptual models for disposal system performance. In a response letter to EPA dated February 26, 1997 (Docket A-93-02, Item II-I-10), the DOE cited Holt (1997) for detailed information on the recent enhancement of the conceptual model for transport in the Culebra. Holt (1997) discusses interpretation and conceptual insights obtained from field and laboratory tracer tests and core studies that support the double-porosity conceptual model of the Culebra, in which Culebra porosity is divided into advective and diffusive components.

Geological data provide the basis for a different approach to estimating the transmissivity field for modeling fluid flow and transport in the Culebra (Beauheim 2002). Geological data correlate strongly with Culebra transmissivity (Holt and Yarbrough 2002), and they are available from many more locations, such as industry (oil, gas, potash) drillholes, than are transmissivity data. With this correlation, Culebra properties can be inferred over a wide area, leading to an improved computational model of the spatial distribution of Culebra transmissivity. Initial results from this computational model of the spatial distribution of Culebra transmissivity have been incorporated in the PA; they are discussed in more detail in Section 2.2.1.4.1.2, and are incorporated in Appendix PA, Attachment TFIELD. Additional data in support of this modeling are being collected through field activities, including drilling and testing of new wells, to improve understanding of the Culebra and to assess the causes(s) of rising water levels (see Section 2.2.1.4.1.2).

2.1.1 Data Sources

The geology of southeastern New Mexico has been of great interest for more than a century. The Guadalupe Mountains have become a common visiting and research point for geologists because of the spectacular exposures of Permian-age reef rocks and related facies (see Shumard 1858, Crandall 1929, Newell et al. 1953, and Dunham 1972 in the CCA bibliography). Because of intense interest in both hydrocarbon and potash resources in the region, a large volume of data exists as background information for the WIPP site, though some data are proprietary. Finally, there is the geological information developed directly and indirectly by studies sponsored by the DOE for the WIPP project; it ranges from raw data to interpretive reports.

Elements of the geology of southeastern New Mexico have been discussed or described in professional journals or technical documents from many different sources. These types of articles are an important source of information, and where there is consistency among the technical community, the information in these articles is referenced when subject material is relevant. Implicit rules of professional conduct for research and reporting have been assumed, as have journal and editorial review. Elements of the geology presented in such sources have been deemed critical to the WIPP and have been the subject of specific DOE-sponsored WIPP studies.

The geological data that the DOE has developed explicitly for the WIPP project have been produced over a 25-year period by different organizations and contractors using applicable national standards (Quality Assurance Program history is described in Section 5.1.2). During a rulemaking in 1988 related to the underground injection of hazardous wastes, the EPA addressed the use of older geological data in making a long-term demonstration of repository performance. In response to comments on a proposed rule regarding the permitting of underground injection

wells, the EPA concluded that "[e]xcluding historical data or information which might have been gathered off-site by methods not consistent with certain prescribed procedures may be counterproductive." The EPA further stated that such data should be used as long as their limitations are accounted for. In the final rule, the EPA stipulated "that only measurements pertaining to the waste or that result from testing performed to gather data for the petition demonstration comply with prescribed procedures." Further, the EPA stated that "the concerns about the accuracy of geologic data are addressed more appropriately by requiring that the demonstration identify and account for the limits on data quality rather than by excluding data from consideration" (EPA 1988).

As site characterization activities progressed, the DOE, along with independent review groups such as the National Academy of Sciences (NAS), the Environmental Evaluation Group (EEG), and the state of New Mexico acting through the Governor's Radioactive Waste Consultation Task Force, identified natural FEPs that required additional detailed investigation. Because these investigations, in many cases, were to gather data that would either be used in developing conceptual models or in the prediction of disposal system performance, the quality assurance (QA) standards applied to these investigations were more stringent, thereby ensuring accuracy and repeatability to the extent possible for geologic investigations.

Geological data from site characterization have been developed by the DOE through a variety of WIPP-sponsored studies using drilling, mapping or other direct observation, geophysical techniques, and laboratory work. Most of the techniques and statistics of data acquisition will be incorporated by specific discussion. The processes used in deriving modeling parameters from field and laboratory data are discussed in records packages which support the conceptual models in Section 6.4 and the parameters in Appendix PA, Attachment PAR. Pointers to these records packages are provided principally in Appendix PA, Attachment PAR. Records packages are stored in the Sandia WIPP Records Center in Carlsbad. Access to review of these records packages can be obtained by contacting the person designated in Table 1-10. Borehole investigations are a major source of geological data for the WIPP and surrounding area. Borehole studies provide raw data (for example, depth measurements, amount of core, geophysical logs) that support point data and interpreted data sets. These data sets are used in developing other analysis tools such as structure maps for selected stratigraphic horizons or isopachs (thicknesses) of selected stratigraphic intervals.

The borehole data set that was used specifically for obtaining WIPP geologic information is included as reference information in CCA Appendix BH. A map of some borehole locations in the data set is provided in Figure 2-2. Figure 2-3 shows Culebra monitoring wells within the site boundary as of December 2002, including well C-2737, which was drilled and completed in 2001 (Powers 2002c). Figure 2-4 shows Culebra monitoring wells outside the WIPP site as of December 2002; plugged and abandoned wells formerly monitored are not included in this figure. Figure 2-5 shows the locations of wells configured to monitor the Magenta, including well C-2737. Other hydrostratigraphic units are monitored in wells shown in Figure 2-6, including well C-2811, which was drilled and completed in 2001 to monitor a shallow saturated zone developed since the WIPP surface structures were constructed (Powers and Stensrud 2003). Other holes are not shown because they were not of sufficient depth, were not cored, or were not drilled for purposes of site characterization. A more comprehensive drillhole database of the

entire Delaware Basin is addressed in Section 2.3.1.2 and is presented in Appendix DATA. This database includes all drillholes used in evaluating human intrusion rates for the WIPP PA.

2.1.2 Geologic History

In this section, the DOE summarizes the more important points of the area's geologic history within about 320 km (200 mi) of the WIPP site, with emphasis on more recent or nearby events. Figure 2-7 shows the major elements of the area's geological history from the end of the Precambrian Period.

The geologic time scale that the DOE uses for WIPP is based on the compilation by Palmer (1983, pp. 503 – 504) for *The Decade of North American Geology* (DNAG). There are several compiled sources of chronologic data related to different reference sections or methods (see, for example, Harland et al. 1989 and Salvador 1985. Although most of these sources show generally similar ages for chronostratigraphic boundaries, there is no consensus on either reference boundaries or most-representative ages. The DNAG scale is accepted by the DOE as a standard that is useful and sufficient for WIPP purposes, as no known critical performance assessment parameters require more accurate or precise dates.

The geologic history in this region can be conveniently subdivided into three general phases:

- A Precambrian Period, represented by metamorphic and igneous rocks ranging in age from about 1.5 to 1.1 billion years;
- A period from about 1.1 to 0.6 billion years ago, from which no rocks are preserved. Erosion may have been the dominant process during much of this period; and
- An interval from 0.6 billion years ago to the present represented by a more complex set of mainly sedimentary rocks and shorter periods of erosion and dissolution.

This latter phase is the main subject of the DOE's detailed discussion in this text.

Only a few boreholes in the WIPP region have bored deep enough to penetrate Precambrian crystalline rocks, and, therefore, relatively little petrological information is available. Foster (1974, Figure 3) extrapolated the elevation of the Precambrian surface under the area of WIPP as being between 4.42 km (14,500 ft) and 4.57 km (15,000 ft) below sea level; the site surface at WIPP is about 1,036 m (3,400 ft) above sea level. Keesey (1976, Vol. II, Exhibit No. 2) projected a depth of about 5,545 m (18,200 ft) from the surface to the top of Precambrian rocks in the vicinity of the WIPP. The depth projection is based on the geology of the nearby borehole in Section 15, T22S, R31E.

Precambrian rocks of several types crop out in the following locations: the Sacramento Mountains northwest of WIPP; around the Sierra Diablo and Baylor Mountains near Van Horn, Texas; west of the Guadalupe Mountains at Pump Station Hills; and in the Franklin Mountains

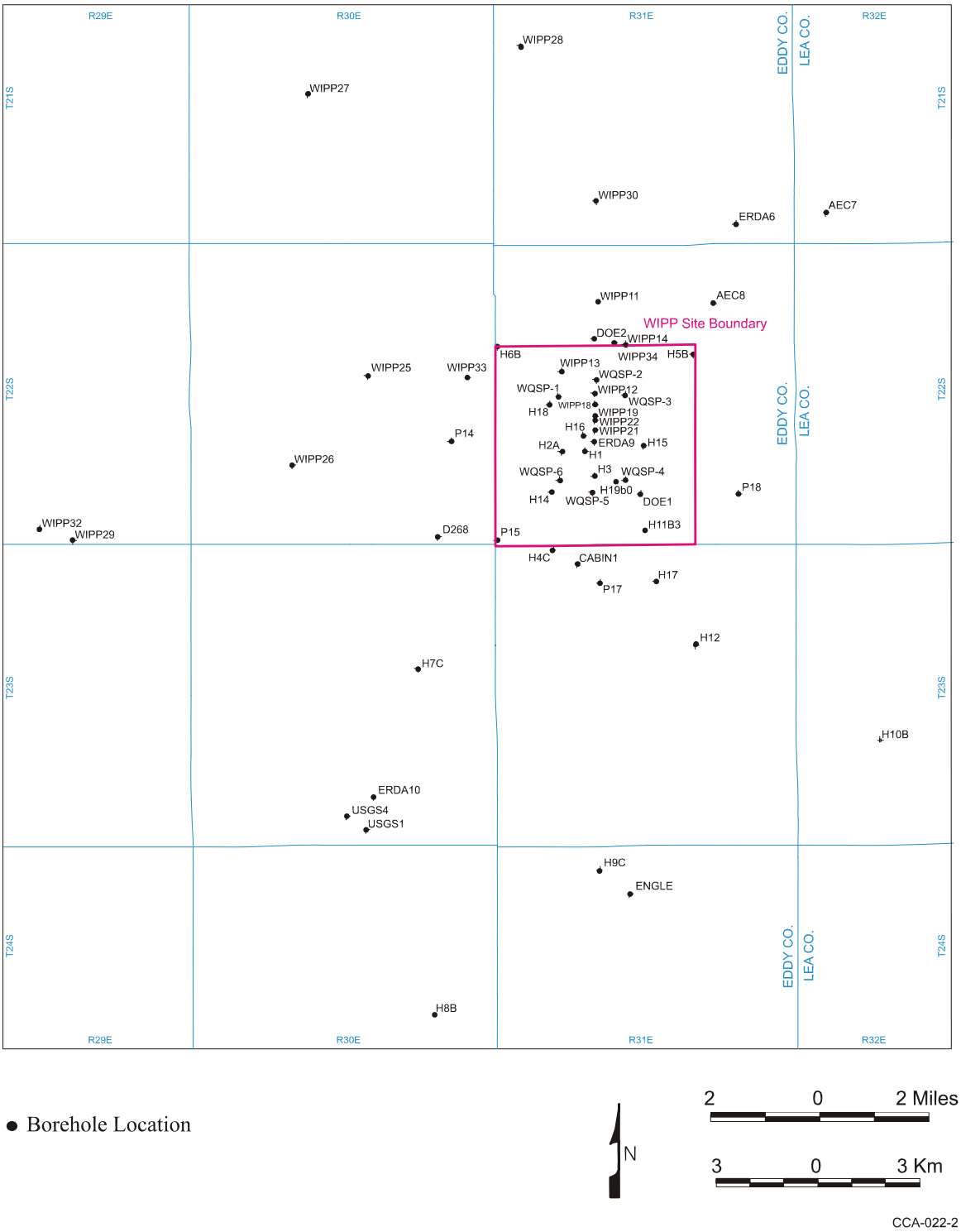

● Borehole Location

Figure 2-2. WIPP Site and Vicinity Borehole Location Map (partial)

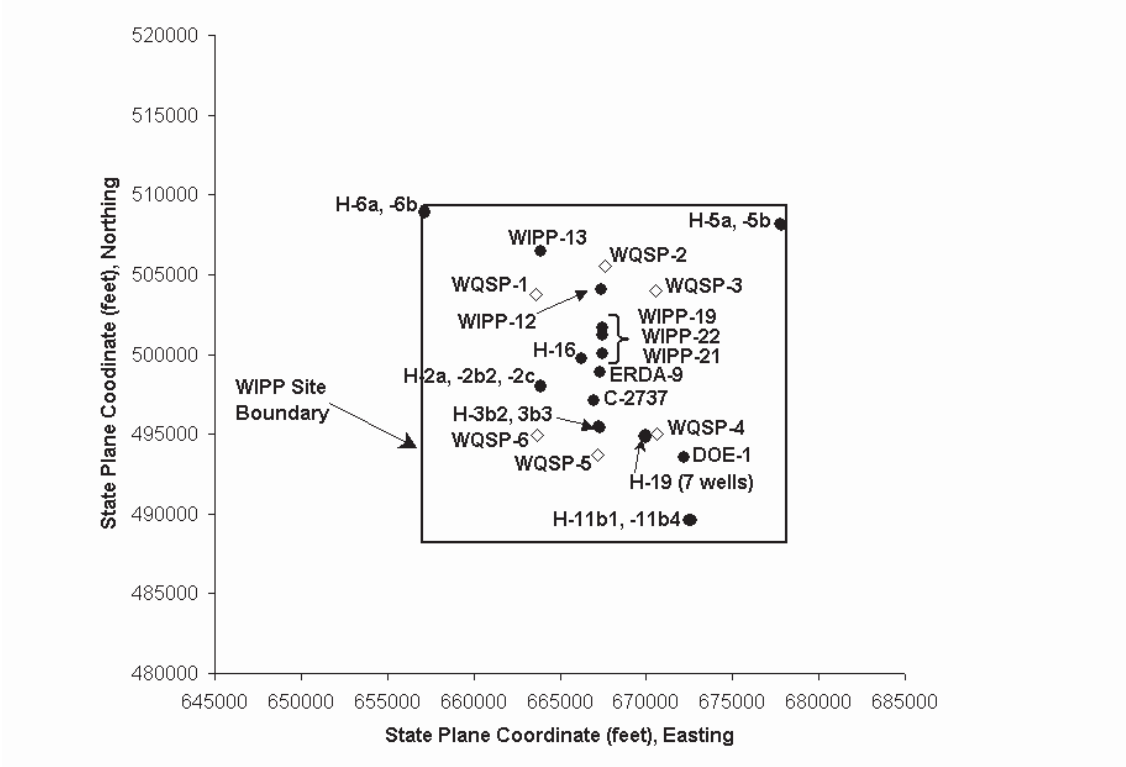

Figure 2-3. Locations of Culebra Monitoring Wells Inside the WIPP Site Boundary

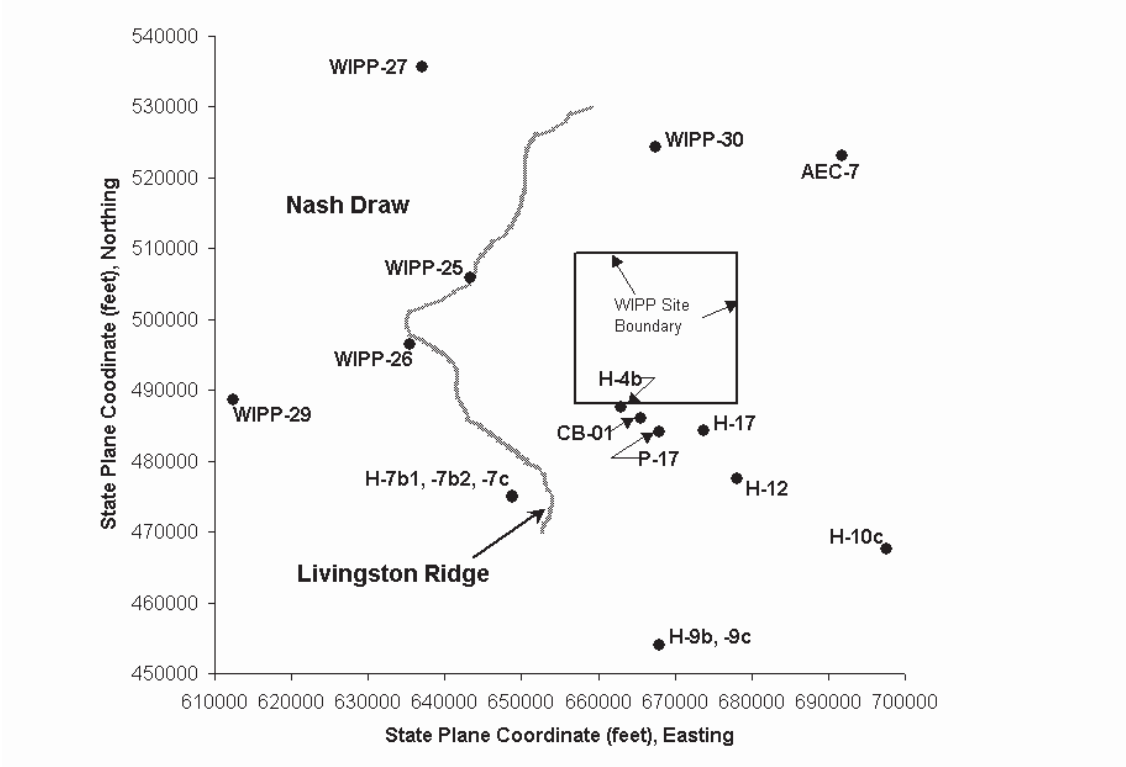

Figure 2-4. Locations of Culebra Monitoring Wells Located Outside the WIPP Site Boundary

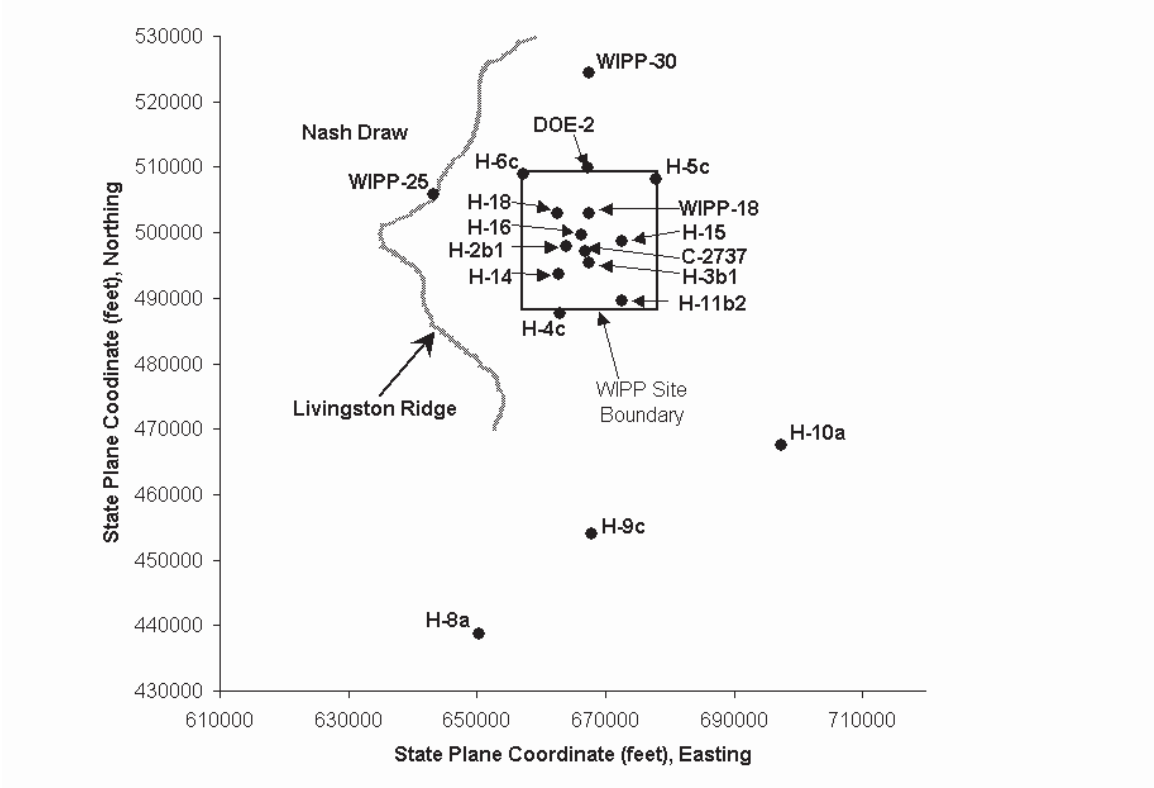

Figure 2-5. Locations of Magenta Monitoring Wells

near El Paso, Texas. East of the WIPP, a relatively large number of boreholes on the Central Basin Platform have penetrated the top of the Precambrian (Foster 1974, Figure 3). As summarized by Foster (1974, 10), Precambrian rocks in the area considered similar to those in the vicinity of the site range in age from about 1.14 to 1.35 billion years.

For about 500 million years (1.1 to 0.6 billion years ago), there is no certain rock record in the region around the WIPP. The most likely rock record for this period may be the Van Horn sandstone (McGowan and Groat 1971), but there is no conclusive evidence that it represents part of this time period (CCA Appendix GCR, Section 3.3.1). The region is generally thought to have been subject to erosion for much of the period until the Bliss sandstone began to accumulate during the Cambrian.

There is additional geologic history information contained in the EPA Technical Support Document for Section 194.14: Content of Compliance Certification Application, Section IV (Docket A-93-02, Item V-B-3).

2.1.3 Stratigraphy and Lithology in the Vicinity of the WIPP Site

The conceptual model of the disposal system uses information about the geometry of the various rock layers as a model input as described in Section 6.4.2.1. This means that stratigraphic information (thickness and lateral extent) provided in the following sections are important inputs.

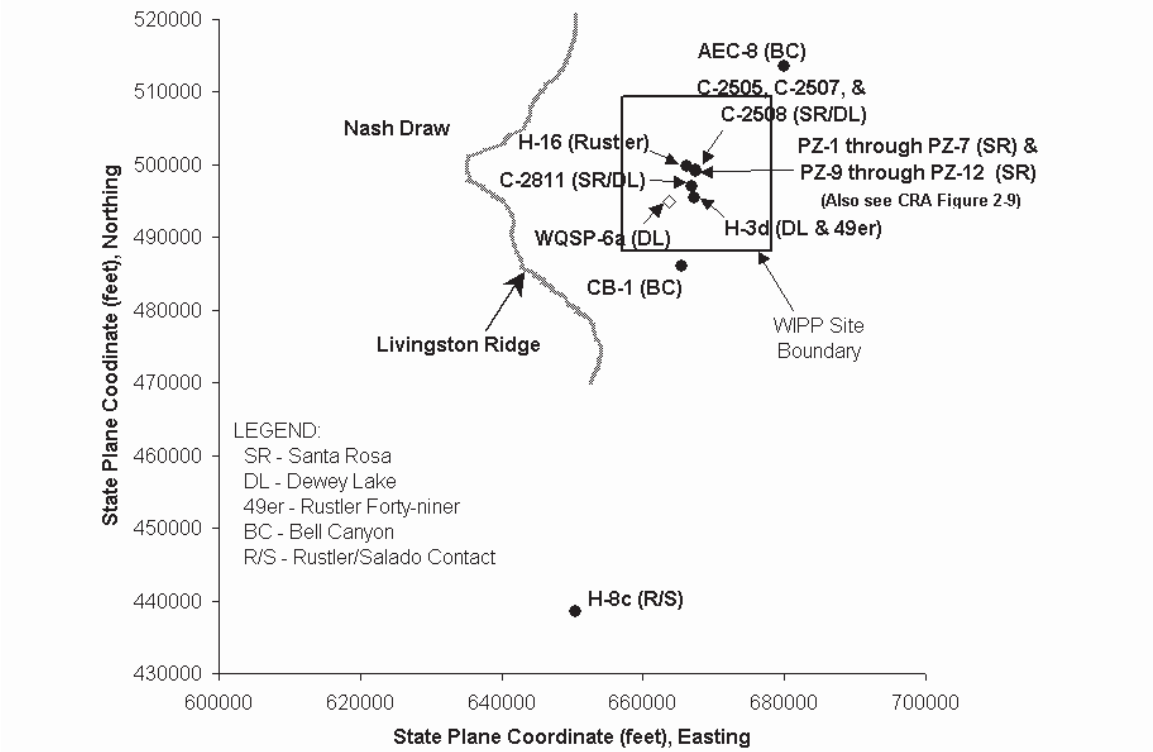

Figure 2-6. Locations of Monitoring Wells Completed to Hydrostratigraphic Units Other Than the Culebra and Magenta Dolomite Members (See also Figure 2-39).

In addition, less important features such as the lithology and the presence of geochemically significant minerals are provided to support screening arguments in Appendix PA, Attachment SCR. Consequently, this discussion has focused on the general properties of the various rock units as determined from field studies. Specific parameters used in the modeling described in Sections 6.4.5 and 6.4.6 are summarized in Appendix PA, Attachment PAR. Stratigraphy-related parameters are input as constants. Stratigraphic thicknesses of units considered in modeling are compiled in Appendix PA, Attachment PAR, Table PAR-49.

This section describes the stratigraphy and lithology of the Paleozoic and younger rocks underlying the WIPP site and vicinity (Figure 2-8), emphasizing the units nearer the surface. After briefly describing pre-Permian rocks, the section provides detailed information on the Permian (Guadalupian) Bell Canyon Formation (hereafter referred to as the Bell Canyon)—the upper unit of the Delaware Mountain Group—because this is the uppermost transmissive formation below the evaporites. The principal stratigraphic data are the chronologic sequence, age, and extent of rock units, including some of the nearby relevant facies changes. For deeper rocks, characteristics such as thickness and depth are summarized from published sources, and for shallower rocks, they are mainly based on data sets presented in CCA Appendix BH (above the Bell Canyon). The lithologies of upper formations and some formation members are described. A comprehensive discussion of stratigraphy in the WIPP area is presented in CCA Appendix GCR. Detailed referencing to original investigations by the USGS and others is included.

ERA	PERIOD	EPOCH	YEARS DURATION	YEARS BEFORE PRESENT	MAJOR GEOLOGIC EVENTS - SOUTHEAST NEW MEXICO REGION
CENOZOIC	Quaternary	Holocene	10,000		Eolian and erosion/solution activity. Development of present landscape.
		Pleistocene	1,590,000	1,600,000	Continued deposition of Gatuña sediments.
	Tertiary	Pliocene	3,700,000		Deposition of Gatuña sediments. Formation of caliche caprock. Regional uplift and east-southeastward tilting; Basin-Range uplift of Sacramento and Guadalupe-Delaware Mountains.
		Miocene	18,400,000		
		Oligocene	12,900,000		Erosion dominant. No Early to Mid-Tertiary rocks present.
		Eocene	21,200,000		
		Paleocene	8,600,000	66,400,000	Laramide revolution. Uplift of Rocky Mountains. Mild tectonism and igneous activity to west and north.
MESOZOIC	Cretaceous		77,600,000	144,000,000	Submergence. Intermittent shallow seas. Thin limestone and clastics deposited.
	Jurassic		64,000,000	208,000,000	Emergent conditions. Erosion, formation of rolling terrain.
	Triassic		37,000,000	245,000,000	Deposition of fluvial clastics. Erosion. Broad flood plain develops.
PALEOZOIC	Permian		41,000,000	286,000,000	Deposition of evaporite sequence followed by continental redbeds. Sedimentation continuous in Delaware, Midland, Val Verde basins and shelf areas.
	Pennsylvanian		34,000,000	320,000,000	Massive deposition of clastics. Shelf, margin, basin pattern of deposition develops.
	Mississippian		40,000,000	360,000,000	Regional tectonic activity accelerates, folding up Central Basin platform. Matador arch, ancestral Rockies. Regional erosion. Deep, broad basins to east and west of platform develop.
	Devonian		48,000,000	408,000,000	Renewed submergence. Shallow sea retreats from New Mexico; erosion. Mild epeirogenic movements. Tobosa basin subsiding. Pedernal landmass and Texas Peninsula emergent until Middle Mississippian.
	Silurian		30,000,000	438,000,000	
	Ordovician		67,000,000	505,000,000	Marathon-Quachita geosyncline, to south, begins subsiding. Deepening of Tobosa basin area; shelf deposition of clastics, derived partly from ancestral Central Basin platform and carbonates.
	Cambrian		65,000,000	570,000,000	Clastic sedimentation - Bliss sandstone.
	PRECAMBRIAN				Erosion to a nearly level plain. Mountain building, igneous activity, metamorphism, erosional cycles.

Figure 2-7. Major Geologic Events - Southeast New Mexico Region

SYSTEM/ Series		Group	Formation	Members
QUATER-NARY	Holocene		surficial deposits	
TERTIARY	Pleisto-cene		Mescalero caliche	
	Pliocene		Gatuña	
	Miocene			
TRIASSIC		Dockum	Santa Rosa	
	Ochoan		Dewey Lake	
PERMIAN			Rustler	*Forty-niner* *Magenta Dolomite* *Tamarisk* *Culebra Dolomite* *Los Medaños*
			Salado	*upper* *Vaca Triste Sandstone* *McNutt potash zone* *lower*
			Castile	
	Guadalupian	Delaware Mountain	Bell Canyon	
			Cherry Canyon	
			Brushy Canyon	

Figure 2-8. Partial Site Geologic Column

2.1.3.1 General Stratigraphy and Lithology below the Bell Canyon

As stated previously, the Precambrian basement near the site is projected to be about 5,545 m (18,200 ft) below the surface (Keesey 1976, Vol. II, Exhibit No. 2), consistent with information presented by Foster in 1974. Ages of similar rock suites in the region range from about 1.14 to 1.35 billion years.

A detailed discussion of the distribution of Precambrian rocks in southeastern New Mexico and Texas can be found in CCA Appendix GCR. Figure 3.4-2 in CCA Appendix GCR provides a structure contour map of the Precambrian. The basal Paleozoic units overlying Precambrian rocks are clastic rocks commonly attributed either to the Cambrian Bliss sandstone or the Ellenberger Group (Foster 1974, p. 10), considered most likely to be Ordovician in age in this area. The Ordovician System comprises the Ellenberger, Simpson, and Montoya Groups in the northern Delaware Basin. Carbonates are predominant in these groups, with sandstones and shales common in the Simpson Group. Foster (1974, Figure 4) reported 297 m (975 ft) of Ordovician-age rocks north of the site area and extrapolated a thicker section of about 396 m (1,300 ft) at the present site (Foster 1974, Figure 5). Keesey (1976, Vol. II, Exhibit No. 2) projected a thickness of 366 m (1,200 ft) for the Ordovician System within the site boundaries.

Silurian-Devonian rocks in the Delaware Basin are not stratigraphically well defined, and there are various notions for extending nomenclature into the basin. Common drilling practice is not to differentiate, though the Upper Devonian Woodford shale at the top of the sequence is frequently distinguished from the underlying dolomite and limestone (Foster 1974, p. 18). Foster (1974, Figure 6) showed a reference thickness of 384 and 49 m (1,260 and 160 ft) for the carbonates and the Woodford shale, respectively; he estimated thickness of these units at the present WIPP site to be about 351 m (1,150 ft) (Foster 1974, Figure 7) and 52 m (170 ft) (Foster 1974, Figure 8), respectively. Keesey (1976, Vol. II, Exhibit No. 2) projected 381 m (1,250 ft) of carbonate and showed 25 m (82 ft) of the Woodford shale.

The Mississippian System in the northern Delaware Basin is commonly attributed to Mississippian limestone and the overlying Barnett shale (Foster 1974, p. 24), but the nomenclature is not consistently used. At the reference well used by Foster (1974, 25), the limestone is 165 m (540 ft) thick and the shale is 24 m (80 ft); isopachs at the WIPP are 146 m (480 ft) (Foster 1974, Figure 10) and less than 61 m (200 ft). Keesey (1976, Vol. II, Exhibit No. 2) indicates 156 m (511 ft) and 50 m (164 ft), respectively, within the site boundaries.

The nomenclature of the Pennsylvanian System applied within the Delaware Basin is both varied and commonly inconsistent with accepted stratigraphic rules. Chronostratigraphic, or time-stratigraphic, names are applied from base to top of these lithologic units: the Morrow, Atoka, and Strawn (Foster 1974, p. 31). Foster (1974, Figure 13) extrapolated thicknesses of about 671 m (2,200 ft) for the Pennsylvanian at the WIPP site. Keesey (1976, Vol. II, Exhibit No. 2) reports 636 m (2,088 ft) for these units. The Pennsylvanian rocks in this area are mixed clastics and carbonates, with carbonates more abundant in the upper half of the sequence.

The Permian is the thickest system in the northern Delaware Basin, and it is divided into four series from the base to top: Wolfcampian, Leonardian, Guadalupian, and Ochoan. According to Keesey (1976, Vol. II, Exhibit No. 2), the three lower series total 2,647 m (8,684 ft) near the site.

Foster (1974, Figures 14, 16, and 18) indicates a total thickness for the lower three series of 2,336 m (7,665 ft) for a reference well north of WIPP. Foster's isopach maps of these series (Foster 1974, Figures 15, 17, and 19) indicate about 2,591 m (8,500 ft) for the WIPP site area. The Ochoan Series at the top of the Permian is considered in more detail later because the formations host and surround the WIPP repository horizon. Its thickness at DOE-2, about 3.2 km (2 mi) north of the site center, is 1,200 m (3,938 ft), according to Mercer et al. (1987, p. 23).

The Wolfcampian Series is also referred to as the Wolfcamp Formation (hereafter referred to as the Wolfcamp) in the Delaware Basin. In the site area, the lower part of the Wolfcamp is dominantly shale with carbonate and some sandstone, according to Foster (1974, Figure 14); carbonate increases to the north (Foster 1974, p. 36). Clastics increase to the east toward the margin of the Central Basin Platform. Keesey (1976, Vol. II, Exhibit No. 2) reports the Wolfcamp to be 455 m (1,493 ft) thick at a well near the WIPP site.

The Leonardian Series is represented by the Bone Spring Limestone or Formation (hereafter referred to as the Bone Spring). According to Foster (1974, pp. 35 - 36), the lower part of the formation is commonly interbedded carbonate, sandstone, and some shale, while the upper part is dominantly carbonate. Near the site the Bone Spring is 990 m (3,247 ft) thick, according to Keesey (1976, Vol. II, Exhibit No. 2).

The Guadalupian Series is represented in the general area of the site by a number of formations exhibiting complex facies relationships (Figure 2-9). The Guadalupian Series is known in considerable detail west of the site from outcrops in the Guadalupe Mountains, where numerous outcrops are present and subsurface studies have been undertaken. (See, for example, King 1948, Newell et al. 1953, and Dunham 1972 in the CCA bibliography.)

Within the Delaware Basin, the Guadalupian Series, known as the Delaware Mountain Group, comprises three formations: Brushy Canyon, Cherry Canyon, and Bell Canyon, from base to top. These formations are dominated by submarine channel sandstones with interbedded limestone and some shale. The Lamar limestone generally tops the series, immediately underneath the Castile Formation (hereafter referred to as the Castile). Around the margin of the Delaware Basin, reefs developed when the Cherry Canyon and Bell Canyon were being deposited. These massive reef limestones, the Goat Seep and Capitan Limestones, are equivalent in time to the basin sandstone formations but were developed topographically much higher around the basin margin. A complex set of limestone-to-sandstone and evaporite beds was deposited further away from the basin, behind the reef limestones. The Capitan Reef and back-reef limestones are well known because numerous caves, including the Carlsbad Caverns, are partially developed in these rocks.

2.1.3.2 The Bell Canyon

As will be discussed in Section 2.1.3.3, the Castile is a 427-to-487m (1,400-to-1,600ft) thick layer of nearly impermeable anhydrites and halites that isolate the Salado from the

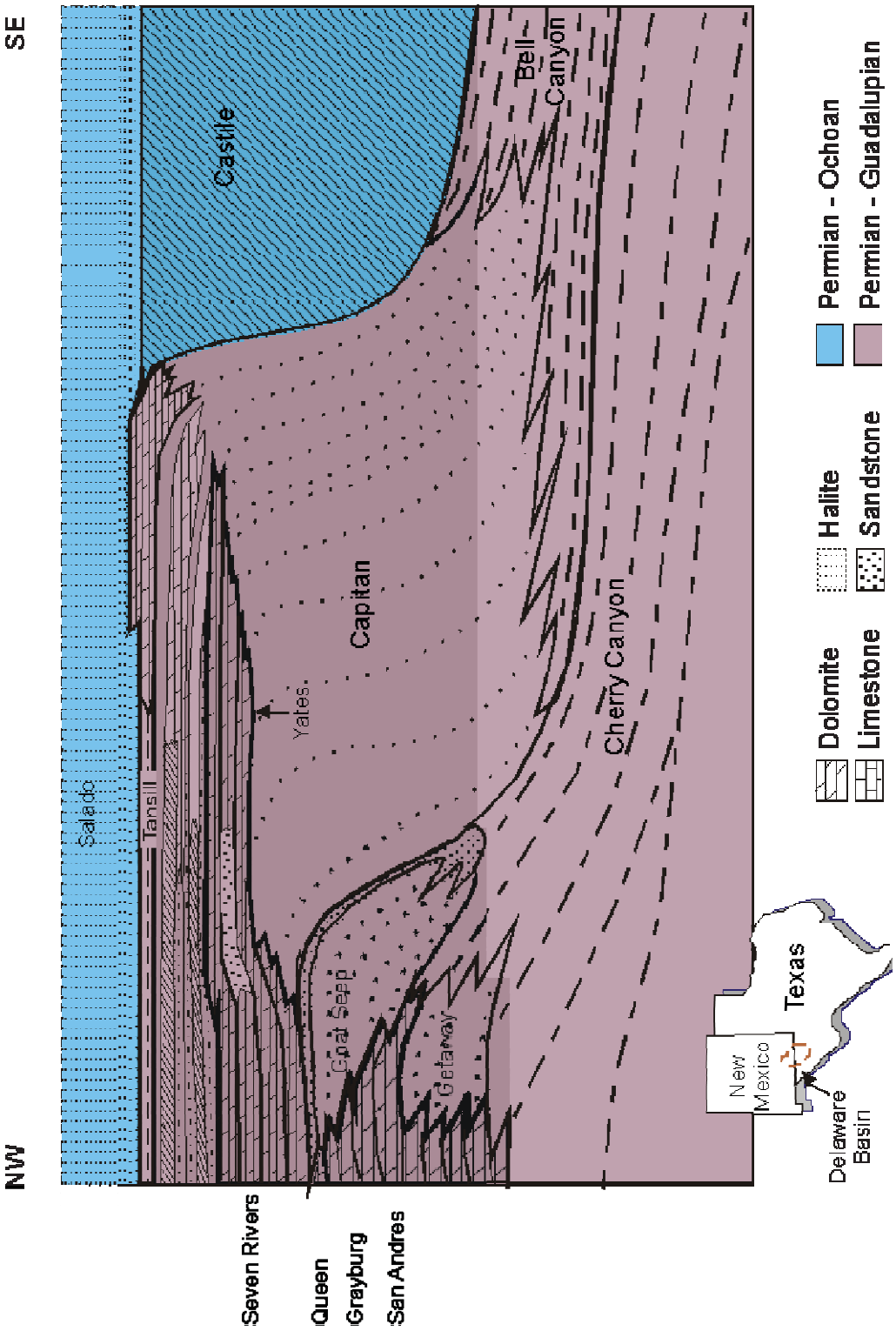

Figure 2-9. Schematic Cross-Section from Delaware Basin (southeast) through Marginal Reef Rocks to Back-Reef Facies (based on King 1948)

deeper water-bearing rocks. This notwithstanding, the DOE is interested in the Bell Canyon because it is the first laterally continuous transmissive unit below the WIPP repository. The significance of this unit is related to the FEP in Table 2-1 for deep dissolution. In evaluating this FEP, the DOE considers the potential for groundwater to migrate from the Bell Canyon or lower units into the repository and cause dissolution. The following discussion summarizes the basic understanding of the Bell Canyon lithology. Dissolution is discussed in Section 2.1.6. Bell Canyon hydrology is presented in Section 2.2.1.2. A thorough discussion of dissolution is in CCA Appendix DEF.

The Bell Canyon is known from outcrops on the west side of the Delaware Basin and from subsurface intercepts for oil and gas drilling. Several informal lithologic units are commonly named during such drilling. Mercer et al. (1987, p. 28) stated that DOE-2 penetrated the Lamar limestone, the Ramsey sand, the Ford shale, the Olds sand, and the Hays sand. This informal nomenclature is used for the Bell Canyon in some other WIPP reports.

The Clayton Williams Badger Federal borehole (Section 15, T22S, R31E) intercepted 961 feet (293 meters) of Bell Canyon, including the Lamar limestone, according to Keesey (1976, Vol. II, Exhibit No. 2). Reservoir sandstones of the Bell Canyon were deposited in channels that are straight to slightly sinuous. In their 1988 paper, Harms and Williamson proposed that density currents flowed from shelf regions, cutting channels and depositing the sands.

Within the basin, the Bell Canyon (Lamar limestone) Castile contact is distinctive on geophysical logs because of the contrast in low natural gamma of the basal Castile anhydrite compared to the underlying limestone. Density or acoustic logs are also distinctive because of the massive and uniform lithology of the anhydrite compared to the underlying beds. In cores, the transition is sharp, as described by Mercer et al. (1987, 312) for DOE-2. A structure contour map of the top of the Bell Canyon is shown in Figure 2-10. Also see CCA Appendix MASS, MASS Attachment 18-6, Figure 5.3-3. According to Powers et al. (1978) (CCA Appendix GCR, 4–59), this structure does not reflect the structure of deeper formations, suggesting different deformation histories. The rootless character of at least some of the normal faulting in the lower Permian suggests these are shallow-seated features.

2.1.3.3 The Castile

The Castile is the lowermost lithostratigraphic unit of the Late Permian Ochoan Series (Figure 2-11) and is part of the thick layer of evaporites within the WIPP disposal system. It was originally named by Richardson (1904, p. 43) for outcrops in Culberson County, Texas.

The Castile crops out along a lengthy area of the western side of the Delaware Basin. The two distinctive lithologic sequences now known as the Castile and the Salado were separated into the Upper and Lower Castile by Cartwright (1930). Lang (1939) clarified the nomenclature by restricting the Castile to the lower unit and naming the upper unit the Salado. By defining an anhydrite resting on the marginal Capitan limestone as part of the Salado, Lang in 1939 effectively restricted the Castile to the Delaware Basin inside the reef rocks.

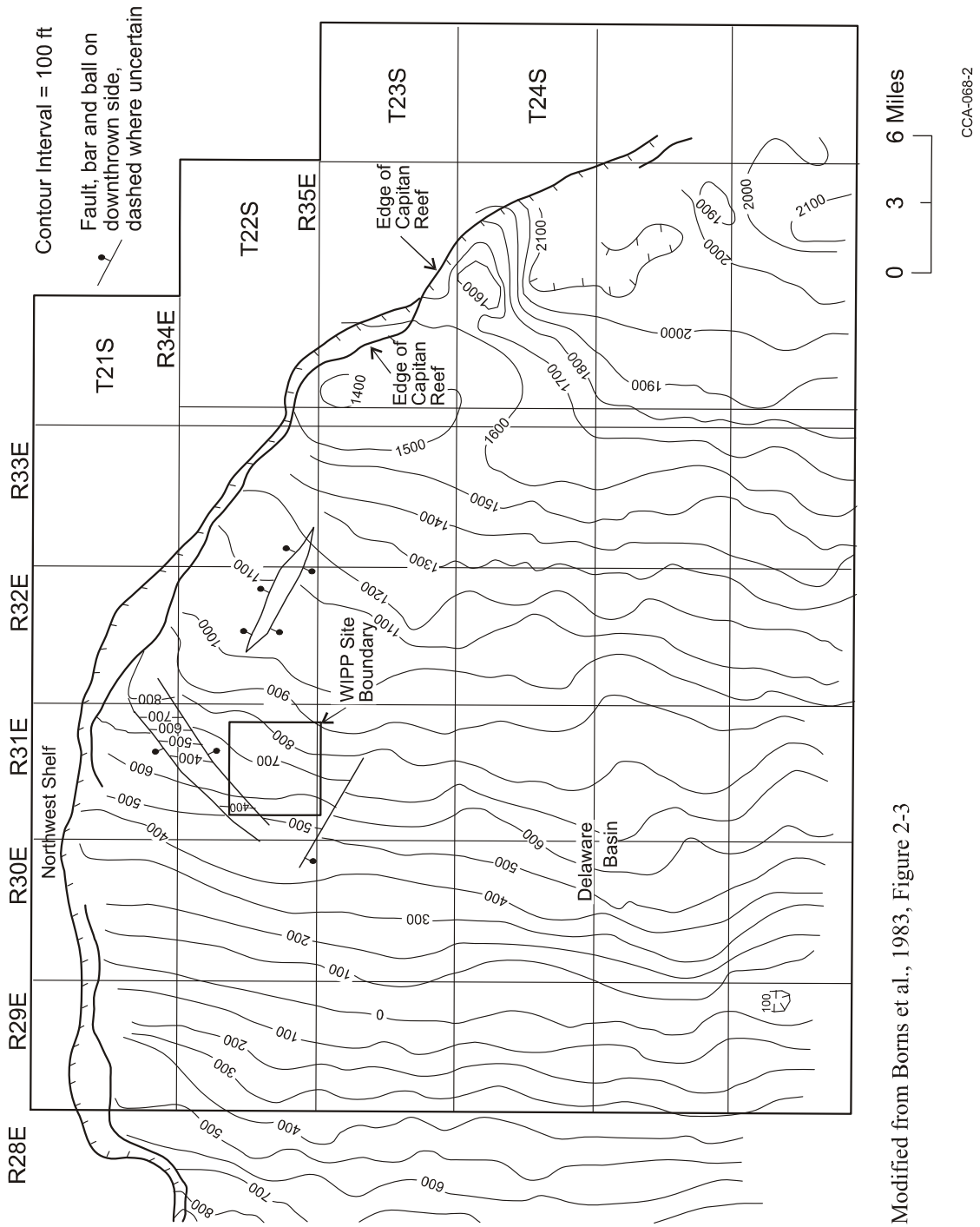

Modified from Borns et al., 1983, Figure 2-3

Figure 2-10. Structure Contour Map of Top of Bell Canyon

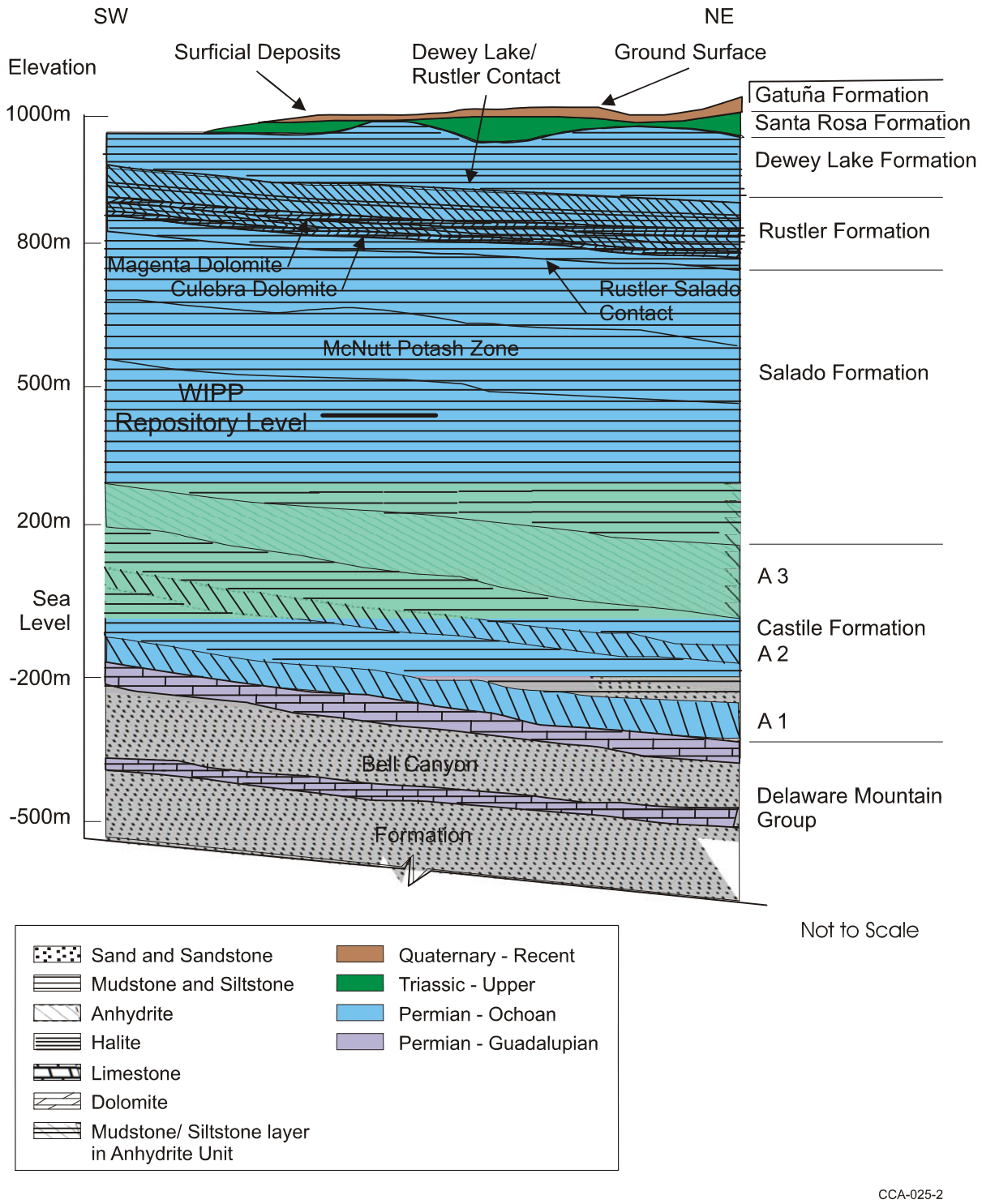

Figure 2-11. Generalized Stratigraphic Cross Section above Bell Canyon Formation at WIPP Site

Through detailed studies of the Castile, Anderson et al. (1972) introduced an informal system of names that is widely used and included in many WIPP reports. The units are named from the base as anhydrite I (A1), halite I (H1), anhydrite II (A2), etc. The informal nomenclature varies through the basin from A3 up because of complexity of the depositional system. The Castile consists almost entirely of thick beds of two lithologies: (1) interlaminated carbonate and anhydrite, and (2) high-purity halite.

In the eastern part of the Delaware basin, the Castile thickness ranges from about 299 to 616 m (980 to 2,022 ft) (derived from Powers et al. 1996, Figure 5.3-1; see also Borns and Shaffer 1985, Figures 9, 11, and 16 for an earlier range based on fewer drillholes). At DOE-2, the Castile is 301 m (989 ft) thick. The Castile is thinner in the western part of the Delaware Basin, and it lacks halite units.

Anderson et al. (1978) and Anderson (1978, Figures 1, 3, 4, and 5) correlated geophysical logs throughout the WIPP region, interpreting thin zones equivalent to halite units as dissolution residues. Anderson et al. (1972, p. 81) further attributed the lack of halite in the basin to its removal by dissolution. A structure contour map of the top of the Castile is reported in Figure 4.4-6, CCA Appendix GCR based on seismic data gathered for site characterization. In addition, Borns et al. (1983) prepared a seismic time structure of the middle Castile for identifying deformation. This map is shown in Figure DEF-2.2 in CCA Appendix DEF. Powers et al. (1996; Figures 5.2-1, 5.2-2, and 5.2-3) provide comparative figures of the elevations of the top of the Bell Canyon, top of Anhydrite 2 (of the Castile), and top of Anhydrite 3 (of the Castile), respectively, based on geophysical log data from oil and gas wells.

For borehole DOE-2, a primary objective was to ascertain whether a series of depressions in the Salado 3.3 km (2 mi) north of the site center was from dissolution in the Castile and related processes, as proposed by Davies (1984, p. 175) in his doctoral thesis. Studies have suggested that these depressions were not from dissolution but from halokinesis in the Castile (see, for example, Borns 1987). Robinson and Powers (1987, pp. 22 and 78) interpreted one deformed zone in the Castile in the western part of the Delaware Basin as partly caused by synsedimentary, gravity-driven, clastic deposition and suggested that the extent of dissolution may have been overestimated by previous workers. No Castile dissolution is known to be present in the immediate vicinity of the WIPP site. The process of dissolution and the resulting features are discussed later in this chapter. See CCA Appendix DEF, Section DEF.3 for a more in-depth discussion of the study of dissolution in the Castile.

In Culberson County, Texas, the Castile hosts major native sulfur deposits. The outcrops of Castile on the Gypsum Plain south of White's City, New Mexico, have been explored for native sulfur without success, and there is no reported indication of native sulfur anywhere in the vicinity of the WIPP.

In part of the area around the WIPP, the Castile has been significantly deformed and there are pressurized brines associated with the deformed areas; borehole ERDA-6 encountered both deformation and pressurized brine. WIPP-12, 1.6 km (1 mi) north of the site center, revealed lesser Castile structure, but it also encountered a zone of pressurized brine within the Castile. Castile deformation is described and discussed in Section 2.1.5 and in CCA Appendix DEF,

which detail structural features. Pressurized brine is described in Section 2.2.1, which details the area's hydrology.

Where they exist, Castile brine reservoirs in the northern Delaware Basin are believed to be fractured systems, with high-angle fractures spaced widely enough that a borehole can penetrate through a volume of rock containing a brine reservoir without intersecting any fractures and therefore not produce brine. They occur in the upper portion of the Castile (Popielak et al. 1983). Appreciable volumes of brine have been produced from several reservoirs in the Delaware Basin, but there is little direct information on the areal extent of the reservoirs or the interconnection between them. The presence of a pressurized brine pocket is treated in the conceptual model of WIPP as discussed in Section 6.4.8.

The Castile continues to be an object of research interest unrelated to the WIPP program as an example of evaporites supposedly deposited in deep water. Anderson (1993, pp. 12-13) discusses alternatives and contradictory evidence. Becker et al. (2002) presented a data set yielding a total Pb/U isochron age of 251.5 ± 2.8 million years (Ma) for calcite from the Castile and inferred that the Permo-Triassic boundary could be younger than this date. This discussion contrasts with other data regarding age of the Salado, Rustler, and Dewey Lake Formations (see later sections), including evidence that later formations yield slightly older radiometric ages. Although these discussions and a resolution might eventually affect some concepts of Castile deposition and dissolution, this issue is largely of academic interest and bears no impact on the suitability of the Los Medaños region for the WIPP site. Additional discussion of Castile deformation and the associated WIPP studies appears in Section 2.1.6.1 and CCA Appendix DEF. The Castile is included in the conceptual model as described in Section 6.4.8. As shown in Appendix PA, Attachment PAR, Table PAR-43, no stratigraphic or lithologic parameters are of importance for this unit. Important hydrological parameters are discussed subsequently.

The EPA questioned DOE's geologic and geophysical basis for the probability (i.e., eight percent probability) of intercepting pressurized brine in the Castile Formation beneath the WIPP disposal panels, and therefore required this distribution to be revised (to a uniform distribution with a range of 0.01 to 0.6) in Performance Assessment Verification Testing (PAVT) (Docket A-93-02, Item II-I-25). The formation of Castile brine pockets as a result of Castile deformation was described in the CCA, and although DOE's discussion of the distribution and nature of fractures in the Castile was limited, parameters were modified to include larger Castile brine pockets in the PAVT. Further information on this topic is contained in EPA Technical Support Document for Section 194.14: Content of Compliance Certification Application, Section IV.C (Docket A-93-02, Item V-B-3), EPA Technical Support Document for Section 194.23: Parameter Justification Report (Docket A-93-02, Item V-B-14), and EPA Technical Support Document for Section 194.23: Review of TDEM Analysis of WIPP Brine Pockets (Docket A-93-02, Item V-B-30).

2.1.3.4 The Salado

The Salado is of interest because it contains the repository horizon and provides the primary natural barrier for the long-term containment of radionuclides. The following section provides basic information regarding the genesis and lithology of the Salado. Subsequent sections discuss

Salado deformation, Salado dissolution, and Salado hydrology. CCA Appendix GCR provides detailed information about the Salado from early site characterization studies.

The Salado is dominated by halite, in contrast to the underlying Castile. The Salado extends well beyond the Delaware Basin, and Lowenstein (1988, p. 592) has termed the Salado a saline "giant."

While the Fletcher Anhydrite Member, which is deposited on the Capitan Reef rocks, is defined by Lang (1939; 1942) as the base of the Salado, some investigators consider that the Fletcher Anhydrite Member may interfinger with anhydrites normally considered part of the Castile. The Castile-Salado contact is not uniform across the basin, and whether it is conformable is unresolved. Around the WIPP site, the Castile-Salado contact is commonly placed at the top of a thick anhydrite informally designated A3; the overlying halite is called the infra-Cowden salt and is included within the Salado. Bodine (1978, pp. 28 - 29) suggests that the clay mineralogy of the infra-Cowden in ERDA-9 cores changes at about 4.6 m (15 ft) above the lowermost Salado and that the lowermost clays are more like Castile clays. At the WIPP site, the DOE recognizes the top of the thick A3 anhydrite as the local contact for differentiating the Salado from the Castile and notes that the distinction is related only to nomenclature and has no relevance to the performance of the WIPP disposal system.

The Salado in the northern Delaware Basin is broadly divided into three informal members. The middle member is known locally as the McNutt Potash Zone (hereafter referred to as McNutt) or Member, and it includes 11 defined potash zones, 10 of which are of economic significance in the Carlsbad Potash District. The lower member and the upper member remain unnamed. The WIPP repository level is located below the McNutt in the lower member. Figure 2-12 shows details of the Salado stratigraphy near the excavated regions. Elements of this stratigraphy are important to the conceptual model. The conceptual model for the Salado is discussed in Section 6.4.5. The thicknesses used in the model are given in Appendix PA, Attachment PAR, Table PAR-49.

Within the Delaware Basin, a system is used for numbering the more significant sulfate beds within the Salado, designating these beds as marker beds (MBs) from MB 100 (near the top of the formation) to MB 144 (near the base). The system is generally used within the Carlsbad Potash District as well as at and around the WIPP site. The repository is located between MB 139 and MB 138.

In the central and eastern part of the Delaware Basin, the Salado is at its thickest, ranging up to about 600 m (2,000 ft) thick and consisting mainly of interbeds of sulfate minerals and halite, with halite dominating. The thinnest portions of the Salado consist of a brecciated residue of insoluble material a few tens-of-feet thick, which is exposed in parts of the western Delaware Basin. The common sulfate minerals are anhydrite ($CaSO_4$), gypsum ($CaSO_4 \cdot 2H_2O$) near the surface, and polyhalite ($K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$). They form interbeds and are also found along halite grain boundaries. Isopach maps of various intervals of the Salado above the repository horizon have been provided to assist in understanding regional structure. These are Figures 4.3-4 to 4.3-7 in CCA Appendix GCR. A structure contour map of the Salado can be found in CCA Appendix GCR (Figure 4.4-10).

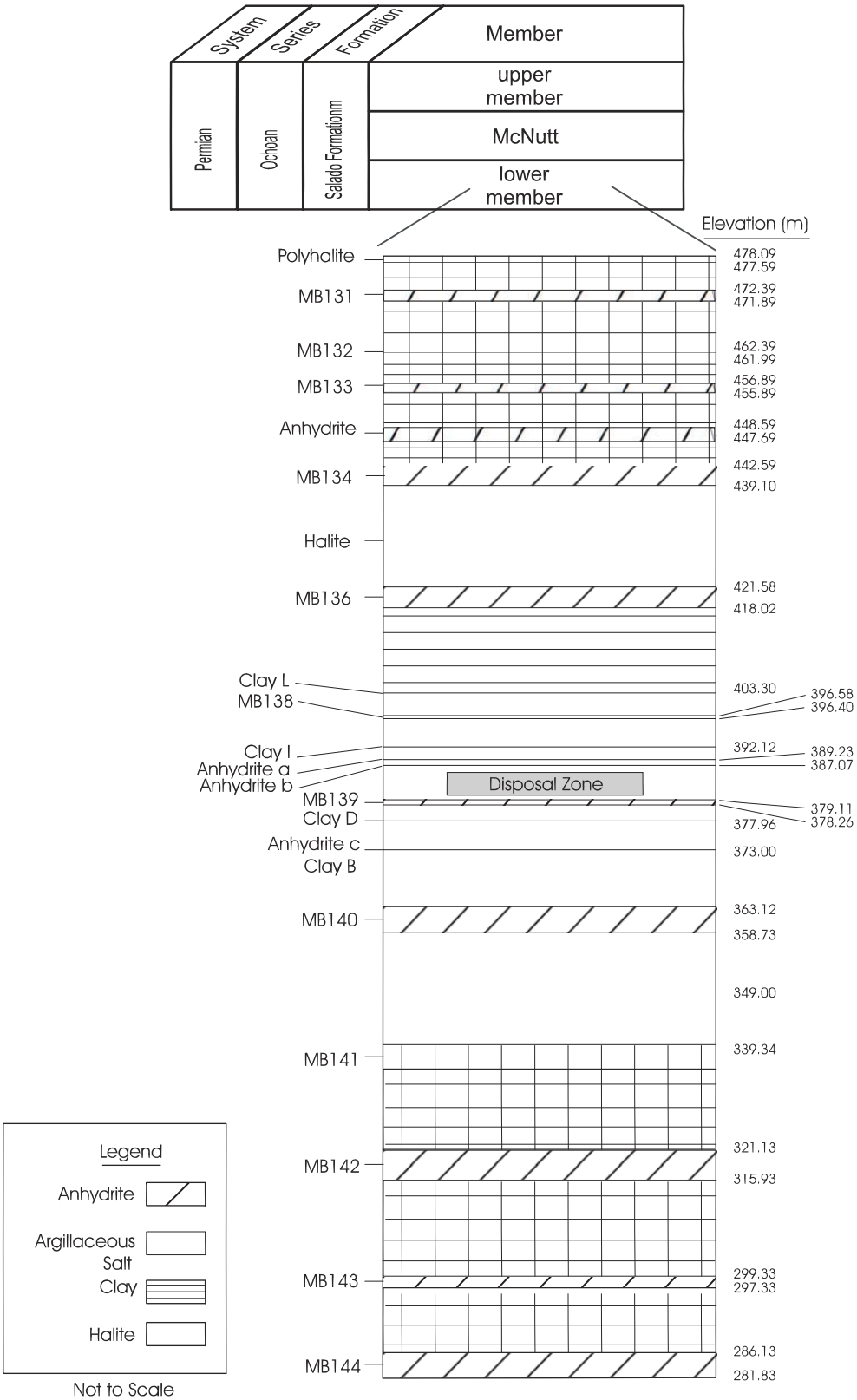

Figure 2-12. Salado Stratigraphy in the Vicinity of the WIPP Disposal Zone

Table 2-2. Chemical Formulas, Distributions, and Relative Abundances of Minerals in the Castile, Salado, and Rustler Formations

Mineral	Formula	Occurrence and Abundance
Amesite	$(Mg_4Al_2)(Si_2Al_2)O_{10}(OH)_8$	S, R
Anhydrite	$CaSO_4$	CCC, SSS, RRR (rarely near surface)
Calcite	$CaCO_3$	S, RR
Carnallite	$KMgCl_3 \bullet 6H_2O$	SS
Chlorite	$(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$	S, R
Corrensite	mixed-layer chlorite and smectite	S, R
Dolomite	$CaMg(CO_3)_2$	RR
Feldspar	$(K,Na,Ca)(Si,Al)_4O_8$	C, S, R
Glauberite	$Na_2Ca(SO_4)_2$	C, S (never near surface)
Gypsum	$CaSO_4 \bullet 2H_2O$	CCC (only near surface), S, RRR
Halite	NaCl	CCC, SSS, RRR (rarely near surface)
Illite	$K_{1-1.5}Al_4[Si_{7-6.5}Al_{1-1.5}O_{20}](OH)_4$	S, R
Kainite	$KMgClSO_4 \bullet 3H_2O$	SS
Kieserite	$MgSO_4 \bullet H_2O$	SS
Langbeinite	$K_2Mg_2(SO_4)_3$	S
Magnesite	$MgCO_3$	C, S, R
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \bullet 2H_2O$	SS, R (never near surface)
Pyrite	FeS_2	C, S, R
Quartz	SiO_2	C, S, R
Serpentine	$Mg_3Si_2O_5(OH)_4$	S, R
Smectite	$(Ca_{1/2},Na)_{0.7}(Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4 \bullet nH_2O$	S, R
Sylvite	KCl	SS

Legend:

C = Castile
S = Salado
R = Rustler
3 letters = abundant
2 letters = common
1 letter = rare or accessory

In the vicinity of the repository, authigenic quartz (SiO_2) and magnesite ($MgCO_3$) are also present as accessory minerals. Interbeds in the salt are predominantly anhydrite with seams of clay. The clays within the Salado are enriched in magnesium and depleted in aluminum (Bodine 1978, p. 1). The magnesium enrichment probably reflects the intimate contact of the clays with brines derived from evaporating sea water, which are relatively high in magnesium.

Powers et al. (Chapter 7 of CCA Appendix GCR) studied the geochemistry of the rocks in the vicinity of the disposal system. A partial list of minerals found in the Delaware Basin evaporites, together with their chemical formulas, is given in Table 2-2. The table also indicates the relative abundances of the minerals in the evaporite rocks of the Castile, Salado, and Rustler. Minerals found either only at depth, removed from influence of weathering, or only near the surface, as weathering products, are also identified.

Although the most common Delaware Basin evaporite mineral is halite, the presence of less soluble interbeds (dominantly anhydrite, polyhalite, and claystone) and more soluble admixtures (for example, sylvite, glauberite, kainite) has resulted in chemical and physical properties of the bulk Salado that are significantly different from those of pure halite layers contained within it. In particular, the McNutt, between MB 116 and MB 126, is locally explored and mined for potassium-bearing minerals of economic interest. Under differential stress, interbeds (anhydrite, polyhalite, magnesite, dolomite) may fracture while, under the same stress regime, pure halite would undergo plastic deformation. Fracturing of relatively brittle beds, for example, has locally enhanced the permeability, allowing otherwise nonporous rock to carry groundwater. Some soluble minerals incorporated in the rock salt can be radiometrically dated, and their dates indicate the time of their formation. The survival of such minerals is significant, in that such dating is impossible in pure halite or anhydrite.

Liquids were collected from fluid inclusions in the Salado halite and from seeps and boreholes within the WIPP drifts. Analysis of these samples indicated that there is compositional variability in the fluids that shows the effects of various phase transformations on brine composition. The fluid inclusions belong to a different chemical population than do the fluids emanating from the walls. It was concluded that much of the brine is completely immobilized within the salt and that the free liquid emanating from the walls is present as a fluid film along intergranular boundaries, mainly in clays and in fractures in anhydrites. Additional information can be found in CCA Appendix GCR, Sections 7.5 and 7.6.

Early investigators of the Salado recognized a repetitious vertical succession or cycle of beds in the Salado: clay - anhydrite - polyhalite - halite and minor polyhalite - halite. Later investigators described the cyclical units as clay - magnesite - anhydrite or polyhalite or glauberite - halite - argillaceous halite capped by mudstone. Lowenstein (1988, pp. 592 - 608) defined a depositional cycle (Type I) consisting of (1) basal mixed siliciclastic and carbonate (magnesite) mudstone, (2) laminated to massive anhydrite or polyhalite, (3) halite, and (4) halite with mud. Lowenstein also recognized repetitious sequences of halite and halite with mud as incomplete Type I cycles and termed them Type II cycles. Lowenstein (1988, pp. 592 - 608) interpreted the Type I cycles as having formed in a shallowing upward, desiccating basin beginning with a perennial lake or lagoon of marine origin and evaporating to saline lagoon and salt pan environments. Type II cycles are differentiated because they do not exhibit features of prolonged subaqueous deposition and also have more siliciclastic influx than do Type I cycles.

From detailed mapping of the Salado in the air intake shaft (AIS) at WIPP, Holt and Powers (1990a, pp. 2-26) interpreted depositional cycles of the Salado in terms of modern features such as those at Devil's Golf Course at Death Valley National Monument, California. The evaporative basin was desiccated, and varying amounts of insoluble residues had collected on the surface through surficial dissolution, eolian sedimentation, and some clastic sedimentation from temporary flooding caused from surrounding areas. The surface developed local relief that could be mapped in some cycles, while the action of continuing desiccation and exposure increasingly concentrated insoluble residues. Flooding, most commonly from marine sources, reset the sedimentary cycle by depositing a sulfate bed.

The details available from the shaft demonstrated the important role of syndepositional water level to water table changes that created solution pits and pipes within the halitic beds while they

were at the surface. Holt and Powers (1990a, Appendix F) concluded that passive halite cements filled the pits and pipes, as well as less dramatic voids, as the water table rose. Early diagenetic to synsedimentary cements filled the porosity early and rather completely with commonly clear and coarsely crystalline halite, reducing the porosity to a very small volume according to Casas and Lowenstein (1989).

Although Holt and Powers (1990a) found no evidence for postdepositional halite dissolution in the AIS, dissolution of the upper Salado halite has occurred west of the WIPP. Effects of dissolution are visible in Nash Draw and at other localities where gypsum karst has formed, where units above the Salado such as the Rustler Formation, Dewey Lake Redbeds, and post-Permian rocks have subsided. Dissolution studies are summarized in CCA Appendix DEF, Section DEF.3. The dissolution margin of upper Salado halite (see Figure 2-13), based on changes in thickness of the interval from the Culebra dolomite to the Vaca Triste Sandstone Member of the Salado, has been interpreted in detail by Powers (2002a, 2002b, 2003a), Holt and Powers (2002), and Powers et al. (2003). Powers (2002a, 2002b, 2003a) examined data from additional drillholes and noted that the upper Salado dissolution margin appears relatively narrow in many areas, and it directly underlies much of Livingston Ridge. The hydraulic properties of the Culebra correlate in part with dissolution of halite from the upper Salado (Holt and Yarbrough 2002; Powers et al. 2003), and the relationships are further described in Section 2.2.1.4.1.2.

Within Nash Draw, Robinson and Lang (1938, pp. 87-88) recognized a zone equivalent to the upper Salado but lacking halite. Test wells in southern Nash Draw produced brine from this interval, and it has become known as the brine aquifer. Robinson and Lang (1938) considered this zone a residuum from dissolution of Salado halite (see Section 2.1.6.2). Jones et al. (1960) remarked that the residuum should be considered part of the Salado, though in geophysical logs it may resemble the lower Rustler. The approximate eastern limit of the residuum and brine aquifer lies near Livingston Ridge (the eastward margin of Nash Draw) and is marked by a thickening of the Salado (see Section 2.1.6.2.2).

At the center of the site, Holt and Powers (1984, pp. 4-9) recognized clasts of fossil fragments and mapped channeling in siltstones and mudstones above the halite; they considered these beds to be a normal part of the transition from the shallow evaporative lagoons and desiccated salt pans of the Salado to the saline lagoon of the lower Rustler. Although some Salado halite dissolution at the WIPP may have occurred before deposition of the Rustler clastics, this process was quite different from the subsurface removal of salt from the Salado in more recent time that caused the residuum and associated brine aquifer in Nash Draw.

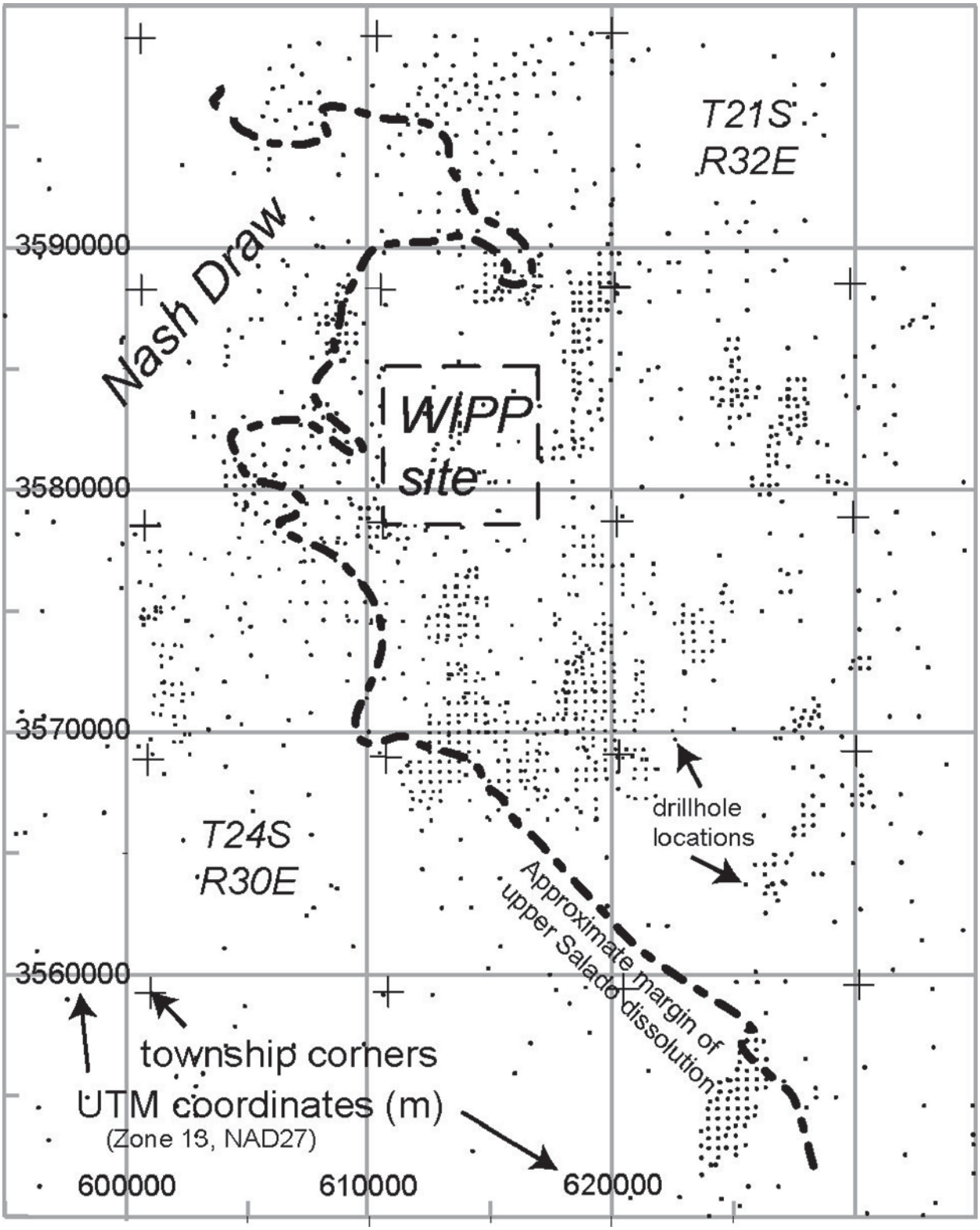

Figure 2-13. Dissolution Margin for the Upper Salado

Geochronological investigations provide a means to confirm the physical evidence indicating that little or no rock-water interactions have occurred in the Salado at the WIPP since the Late Permian Period. Radiometric techniques provide a means of determining the approximate time of the latest episode of regional recrystallization of evaporite minerals, which can be inferred as the approximate time of the latest episode of freely circulating groundwater. Radiometric dates for minerals of the Salado are available from mines and boreholes in the vicinity of the WIPP (Register and Brookins, 1980, pp. 30-42; Brookins, 1980, pp. 29-31; Brookins, et al. 1980, pp. 635-637; Brookins, 1981; and Brookins and Lambert, 1987, pp. 771-780). The distribution of dates shows that many of the rubidium-strontium (Rb-Sr) isochron determinations on evaporite minerals, largely sylvite (214 ± 14 million years ago), are in good agreement with potassium-argon (K-Ar) determinations on pure polyhalites (198 to 216 million years ago). (Potassium-argon ages for sylvite are significantly younger than Rb-Sr ages for the same rocks because of the loss of radiogenic argon. Radiogenic strontium, as a solid, is less mobile than argon and therefore the Rb-Sr isochron method is preferred for sylvite.) Renne et al. (1998) sampled langbeinite crystals from the Salado and obtained Ar-39/Ar-40 plateau ages of 251 ± 0.2 Ma and 251 ± 0.4 Ma. Clay minerals have both Rb-Sr and K-Ar ages significantly older (390 ± 77 million years [Register, 1981]) than the evaporite minerals, presumably reflecting the detrital origin of the clays.

One significantly younger recrystallization event has been identified in evaporites in the WIPP region and is a contact phenomenon associated with the emplacement of an Oligocene igneous dike (see Section 2.1.5.4). Polyhalite near the dike yields a radiometric age of 21 million years, compared to the 32- to 34-million-year age determined for the dike (Brookins, 1980, pp. 29-31; and Calzia and Hiss, 1978, p. 44) (this number was recalculated to 34.8 ± 0.8 million years; CCA Appendix GCR, pp. 3 - 80). This exception notwithstanding, the results of radiometric determinations argue for the absence of pervasive recrystallization of the evaporites in the Salado in the last 200 million years. This conclusion is supported by the number of replicate determinations, the wide distribution of similarly dated minerals throughout the Delaware Basin, and the concordance of dates obtained by various radiometric methods.

The notion of extensive recrystallization of Salado evaporites has been raised again since the CCA was submitted. Hazen and Roedder (2001), reiterating some arguments presented by Roedder (1984) and O'Neill et al. (1986), suggested that halite has been extensively recrystallized by water moving through the Salado at unknown times. Stable isotope data from fluid inclusions within coarse, clear halite crystals were interpreted as signifying that modern meteoric water constituted part of the fluid inclusion. O'Neill et al. (1986) noted as well that the stable isotope data are consistent with meteoric water falling on a desiccated Salado salt pan surface. Powers and Hassinger (1985) and Holt and Powers (1990a, 1990b) interpret syndepositional dissolution pipes as a common feature of the Salado, with coarse, clear halite with large fluid inclusions formed on a desiccated salt pan. Powers et al. (2001) summarized the arguments against extensive recrystallization of Salado halite. Stein and Krumhansl (1988) found variable compositions of large fluid inclusions, and show that inclusion chemistry differs significantly from intercrystalline brines, indicating that fluid movement is very limited. Satterfield et al. (2002) also concluded that the coarse halite cements found in certain beds of the Salado are synsedimentary, based on ionic concentrations in fluid inclusions. Moreover, Beauheim and Roberts (2002) find extremely low permeability in Salado halite, showing that fluid movement, especially vertically, through the Salado is too limited and slow to create the

purported recrystallization. These findings are also consistent with indications that salt pan deposits are cemented quickly and thoroughly at shallow depths of burial (Casas and Lowenstein 1989). The conclusion that Salado halite has not been pervasively recrystallized remains sound.

The Salado is of primary importance to the containment of waste. Because it is the principal natural barrier, many of the properties of the Salado have been characterized by the DOE, and numerical codes are used by the DOE to simulate the natural processes within the Salado that affect the disposal system performance.

Two conceptual models of the Salado are used in the performance assessment. One models the creep closure properties of the Salado and the other, the hydrological properties. The creep closure of the Salado is discussed in Appendix PA, Attachment PORSURF. This model uses key parameters derived from both in-situ measurements and laboratory testing on Salado core samples. Summaries of these parameters are in Butcher (1997). Appendix PORSURF Attachment 1, Table 2.

The second conceptual model is titled the Salado conceptual model and is discussed in Section 6.4.5. This model divides the Salado into two lithologic units: impure halite and Salado interbeds. The impure halite in this conceptual model is characterized entirely by its hydrological parameters as shown in Table 6-16. The interbeds are characterized by both hydrological parameters in Table 6-17 and fracture properties in Table 6-19. This latter information is needed since the model in Section 6.4.5.2 incorporates the possibility of interbed fracturing should pressures in the repository become high enough. The modeling assumptions surrounding the fracturing model are discussed in Appendix PA, Attachment MASS, Section MASS-13.

2.1.3.5 The Rustler

The Rustler is the youngest evaporite-bearing formation in the Delaware Basin. It was originally named by Richardson in 1904 for outcrops in the Rustler Hills of Culberson County, Texas. Adams (1944, p. 1614) first used the names Culebra Member and Magenta Member to describe the two carbonates in the formation, indicating that Lang favored the names, although Lang did not use these names to subdivide the Rustler in his 1942 publication. Vine (1963, p. B1) extensively described the Rustler in Nash Draw and proposed the four formal names and one informal term that were used for the stratigraphic subdivisions of the Rustler. These are as follows (from the base): unnamed lower member, Culebra Dolomite Member, Tamarisk Member, Magenta Dolomite Member, and Forty-niner Member (Figure 2-14). Powers and Holt (1999) formalized the nomenclature for the lower Rustler, naming the Los Medaños Member for the exposures of the former “unnamed lower member” in the WIPP shafts and in boreholes in the vicinity of Los Medaños near the WIPP site. Four studies of the Rustler since Vine’s 1963 work contribute important information about the stratigraphy, sedimentology, and regional relationships while examining more local details as well. Eager (1983) published a report on relationships of the Rustler observed in the southern Delaware Basin as part of sulfur exploration in the area. Holt and Powers (1988, Section 5.0), reproduced

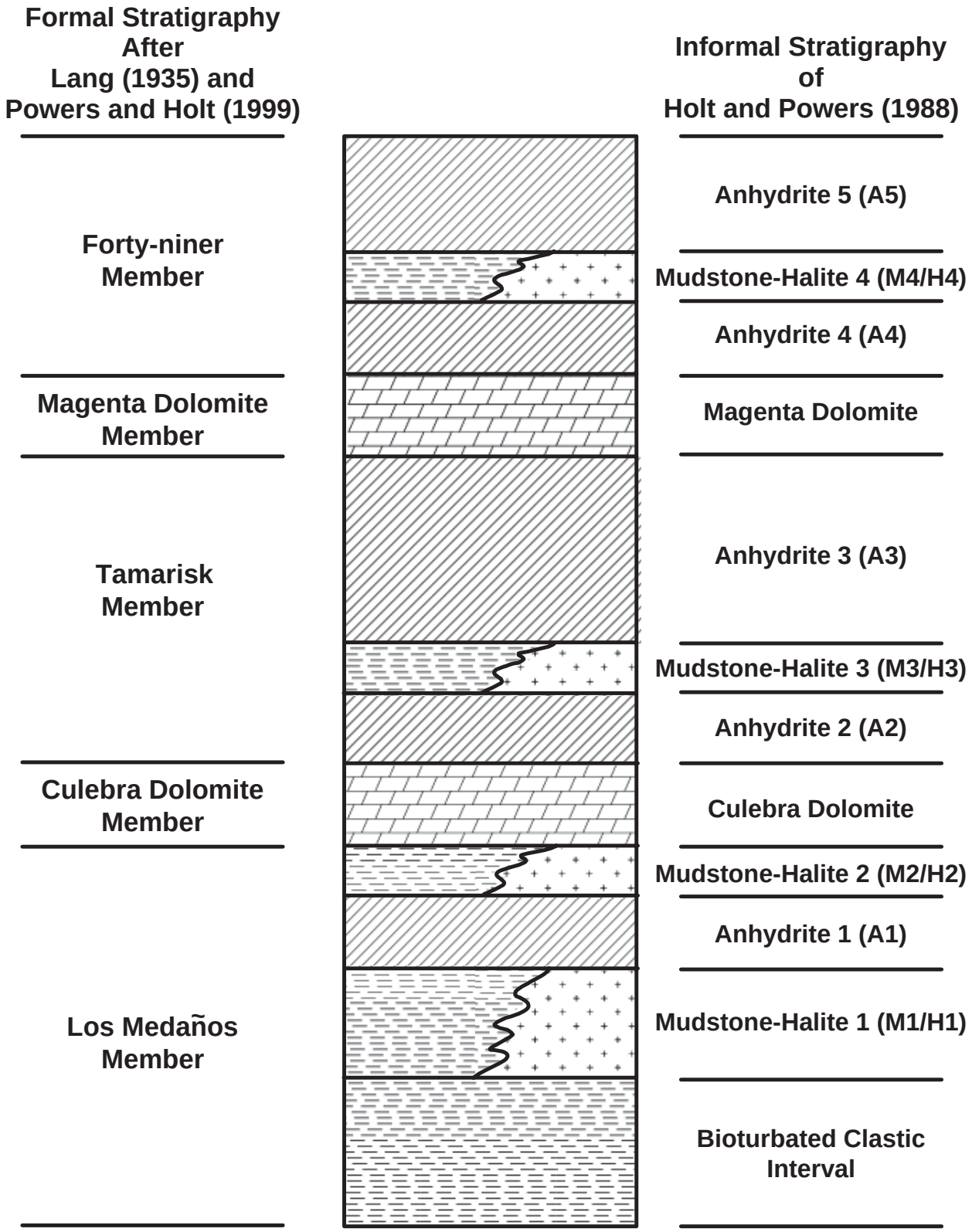

Figure 2-14. Rustler Stratigraphy

as CCA Appendix FAC, reported the details of sedimentologic and stratigraphic studies of WIPP shafts and cores as well as of geophysical logs from about 600 boreholes in southeastern New Mexico. Their work resulted in the more detailed subdivisions of the Rustler indicated in the right-hand column of Figure 2-14.

The Rustler is regionally extensive; a similar unit in the Texas panhandle is also called the Rustler. Within the area around WIPP, evaporite units of the Rustler are interbedded with significant siliciclastic beds and the carbonates. Both the Magenta and the Culebra extend regionally beyond areas of direct interest to the WIPP. In the general area of the WIPP, both the Tamarisk and the Forty-niner have similar lithologies: lower and upper sulfate beds and a middle unit that varies principally from mudstone to halite from west to east (Figure 2-14). In a general sense, halite in the Los Medaños broadly persists to the west of the WIPP site, and halite is found east of the center of the WIPP in the Tamarisk and the Forty-niner (Figure 2-15).

Two different explanations have been proposed over the history of the project to account for the observed distribution of halite in the non-dolomite members of the Rustler. The earliest researchers (e.g., Bachman [1985] and Snyder [1985]) assumed that halite had originally been present in all the non-sulfate intervals of the Forty-niner, Tamarisk, and Los Medaños Members, and that its present-day absence reflected post-depositional dissolution.

An alternative interpretation was presented by Holt and Powers (1988) following detailed mapping of the Rustler exposed in the WIPP ventilation (now waste) and exhaust shafts in 1984. Fossils, sedimentological features, and bedding relationships were identified in units that had previously been interpreted from boreholes as dissolution residues. Cores from existing boreholes, outcrops, geophysical logs, and petrographic data were also reexamined to establish facies variability across the area.

As a result of these studies, the Rustler was interpreted to have formed in variable depositional environments, including lagoon and saline playas, with two major episodes of marine flooding which produced the carbonate units. Sedimentary structures were interpreted to indicate synsedimentary dissolution of halite from halitic mudstones around a saline playa and fluvial transport of more distal clastic sediments. The halite in the Rustler, by this interpretation, has a present-day distribution similar to that at the time the unit was deposited. Some localized dissolution of halite may have occurred along the depositional margins, but not over large areas. Hence, the absence of halite in Rustler members at the WIPP site more generally reflects non-deposition than dissolution.

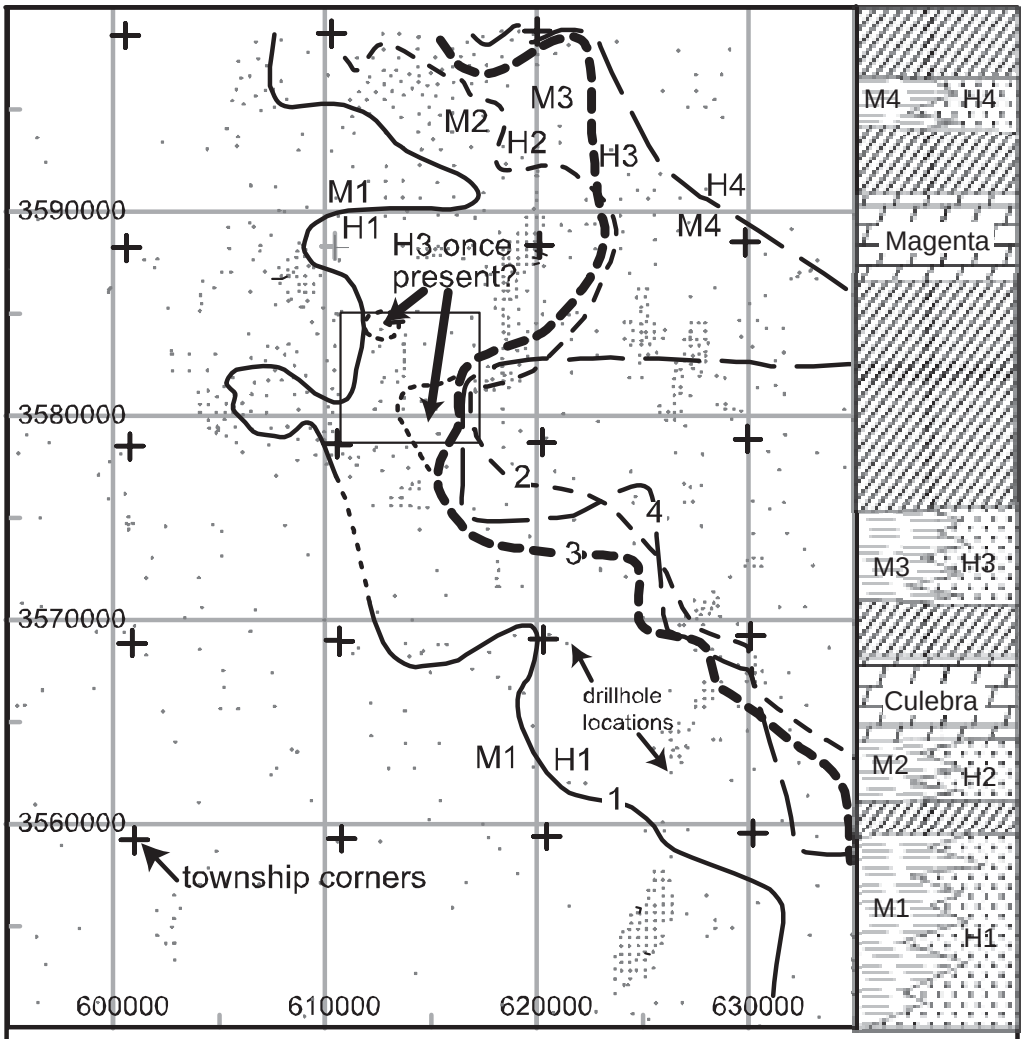

Explanation

M#, H# indicate mudstone and halitic facies on each side of estimated halite margin (numbered line on map) for stratigraphic intervals as indicated in the column to the right (key on Figure 2-14).

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.

Two zones within the WIPP site boundary ("H3 once present?") indicate where halite may have been present west of the current boundary of H3 (marked by ▬▬▬▬).

Figure 2-15. Halite Margins for the Rustler Formation Members

This hypothesis was tested and refined by subsequent investigations (e.g., Powers and Holt 1990, 1999, 2000; Holt and Powers 1990a) and is now considered the accepted explanation for the present-day distribution of halite in the Rustler. Powers and Holt (1999) thoroughly described the sedimentary structures and stratigraphy of the Los Medaños as part of the procedure for naming the unit. This shows the basis for interpreting the depositional history of the member and for rejecting significant post-burial dissolution of halite in that unit. Powers and Holt (2000) further describe the lateral facies relationships in other Rustler units, especially the Tamarisk, developed on sedimentologic grounds, and rejected the concept of broad, lateral dissolution of halite from the Rustler across the WIPP site area.

As discussed in Section 2.2.1.4, regional Culebra transmissivity shows about six orders of magnitude variation across the area around the site and about three orders of magnitude across the site itself. Although some investigators have called attention to the broad relationship between the distribution of halite in the Rustler and variations in Culebra transmissivity and have attributed the variation to fracturing resulting from postdepositional dissolution of Rustler halite (see, for example, Snyder 1985, p. 10; and CCA Appendix DEF, Section DEF-3.2), CCA Appendix FAC and Powers and Holt 1990, 1999, 2000) largely rule out this explanation. Variations in transmissivity of the Culebra were correlated qualitatively to the thickness of overburden above the Culebra (see discussion in Section 2.1.5.2), the amount of dissolution of the upper Salado, and the distribution of gypsum fillings in fractures in the Culebra (Beauheim and Holt 1990). Subsequently, Holt and Yarbrough (2002) and Powers et al. (2003) related the variation in Culebra transmissivity more quantitatively to overburden thickness and dissolution of upper Salado halite. The DOE believes that variations in Culebra transmissivity are primarily caused by the relative abundance of open fractures in the unit, which may be related to each of these factors. As discussed in Section 6.4.6.2 and Appendix PA, Attachment TFIELD, uncertainty in spatial variability in the transmissivity of the Culebra has been incorporated in the PA.

In the region around the WIPP, the Rustler reaches a maximum thickness of more than 152 m (500 ft) (Figure 2-16), while it is about 91 to 107 m (300 to 350 ft) thick within most of the WIPP site. Much of the difference in Rustler thickness can be attributed to variations in the amount of halite contained in the formation. Variation in Tamarisk thickness accounts for a larger part of thickness changes than do variations in either the Los Medaños or the Forty-niner. Details of the Rustler thickness can be found in CCA Appendix GCR, 4-39 to 4-42 and Figure 4.3-8. See also CCA Appendix FAC.

Much project-specific information about the Rustler is contained in CCA Appendix FAC. The WIPP shafts were a crucial element in Holt and Powers' 1988 study, exposing features not previously reported. Cores were available from several WIPP boreholes, and their lithologies were matched to geophysical log signatures to extend the interpretation throughout a larger area in southeastern New Mexico. These data are included in CCA Appendix FAC, Appendix II.

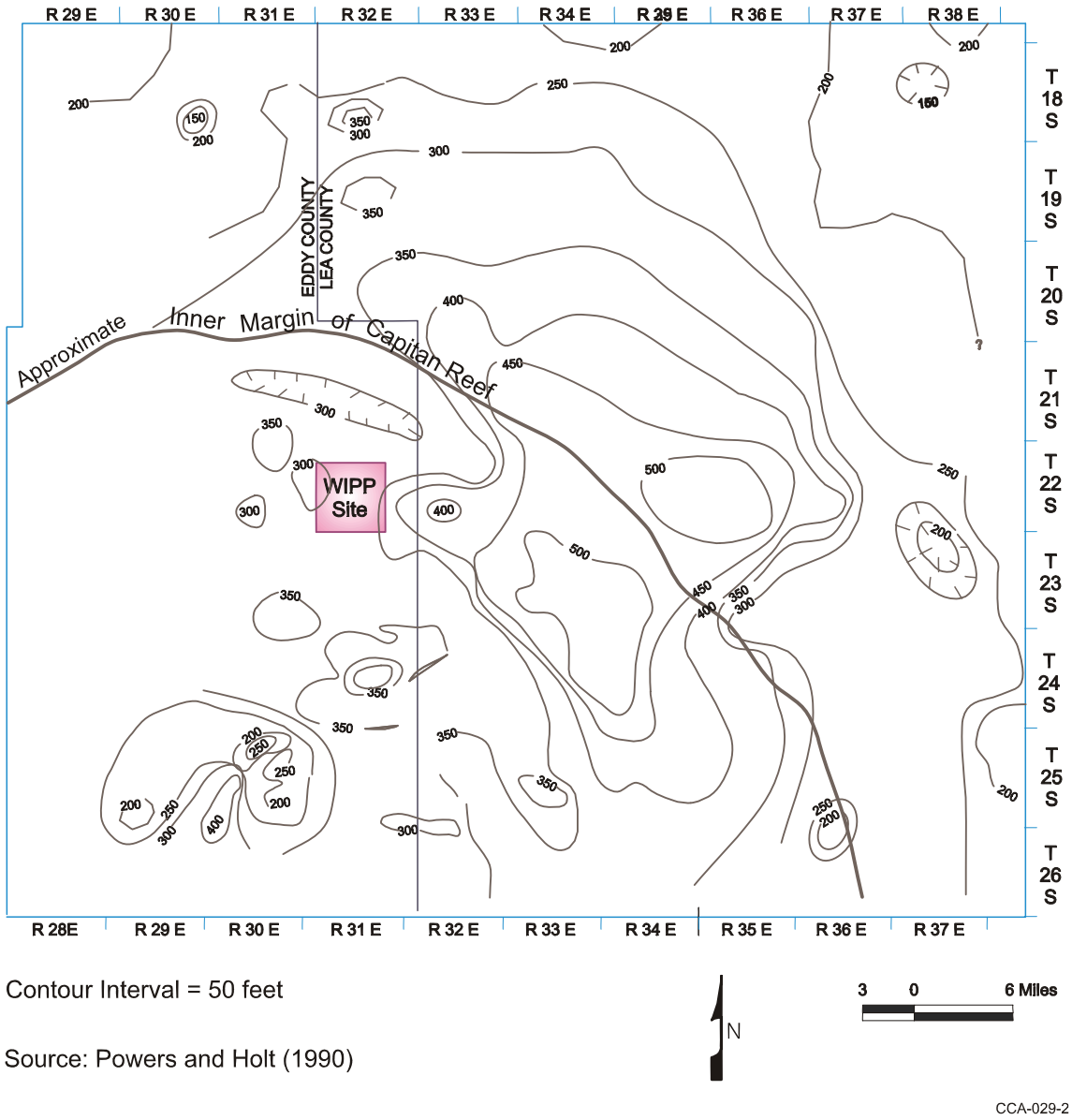

Figure 2-16. Isopach Map of the Entire Rustler

2.1.3.5.1 Los Medaños Member

The unit formerly referred to as the unnamed lower member has been named the Los Medaños Member. The Los Medaños rests on the Salado with apparent conformity at the WIPP site. It consists of significant proportions of bedded and burrowed siliciclastic sedimentary rocks with cross-bedding and fossil remains. These beds record the transition from strongly evaporative environments of the Salado to saline lagoonal environments. The upper part of the Los Medaños includes halitic and sulfatic beds within clastics. CCA Appendix FAC, pp. 6-8 and Powers and Holt (1999) interpret these as facies changes within a saline playa or lagoon environment, not dissolution residues from postdepositional dissolution.

According to CCA Appendix FAC, Figure 4-4, the Los Medaños ranges in thickness from about 29 to 38 m (96 to 126 ft) within the site boundaries. The maximum thickness recorded during that study was 63 m (208 ft) southeast of the WIPP site. An isopach of the Los Medaños is shown as Figure 4-7 in CCA Appendix FAC.

Halite is present in the M1/H1 unit of the Los Medaños west of most of the site area (see Figure 2-15 for an illustration of the halite margins). The drilling initiated during CRA-2004 preparation to investigate Culebra transmissivity variations based on overburden and Salado dissolution will develop additional detailed information about distribution of halite in the Los Medaños. Cross-sections based on geophysical log interpretations by Holt and Powers (CCA Appendix FAC) and Powers and Holt (2000) show that the unit is thicker to the east where the halite is more abundant. The Los Medaños is incorporated into the conceptual model as described in Section 6.4.6.1. Model parameters are in Appendix PA, Attachment PAR, Table PAR- 27.

2.1.3.5.2 The Culebra Dolomite Member

The Culebra rests with apparent conformity on the Los Medaños, though the underlying unit ranges from claystone to its lateral halitic equivalent in the site area. West of the WIPP site, in Nash Draw, the Culebra is disrupted from dissolution of underlying halite. Holt and Powers (CCA Appendix FAC, Section 8.9.3) principally attribute this to dissolution of Salado halite, noting the presence of sedimentologic features in the lower Rustler (see also Powers and Holt 1999). Culebra hydrology and its significance to disposal system performance are discussed in detail in Section 2.2.1.4.1.2.

The Culebra was described by Robinson and Lang (1938, p. 83) as a dolomite 11 m (35 ft) in thickness. The Culebra is generally brown, finely crystalline, locally argillaceous and arenaceous dolomite with rare to abundant vugs with variable gypsum and anhydrite filling; Adams (1944, p. 1614) noted that oölites are present in some outcrops as well. Holt and Powers (CCA Appendix FAC, pp. 5 - 11) describe the Culebra features in detail, noting that most of the Culebra is microlaminated to thinly laminated, while some zones display no depositional fabric. Holt and Powers (1984) described an upper interval of the Culebra consisting of medium brown, microlaminated carbonate that thickens up to 0.6 m (2 ft) in the vicinity of dome structures and is of probable algal origin. This is underlain by a 0.64-to 2.54-cm (0.25-to-1-in) thick bed of cohesive black claystone. Because of the unique organic composition of this thin layer, Holt and Powers (1988) did not include it in the Culebra for thickness computations, and this will be

factored into discussions of Culebra thickness. Based on core descriptions from the WIPP project, Holt and Powers (CCA Appendix FAC) concluded that there is very little variation of depositional sedimentary features throughout the Culebra.

Vugs are an important part of Culebra porosity. They are commonly zoned parallel to bedding. In outcrop, vugs are commonly empty. In the subsurface, vugs range from open to partially filled or filled with anhydrite, gypsum, or clay (Holt and Powers 1990a, pp. 3-18 to 3-20). Lowenstein (1987, pp. 19 - 20) noted similar features. Holt and Powers (CCA Appendix FAC) attributed vugs partly to syndepositional growth as nodules and partly as later replacive textures. Lowenstein (1987, pp. 29 - 31) also described textures related to later replacement and alteration of sulfates. Vug or pore fillings vary across the WIPP site and contribute to the porosity structure of the Culebra. As pointed out by Holt and Powers (see CCA Appendix FAC, Section 8.8), natural fractures filled with gypsum are common east of the WIPP site center and in a smaller area west of the site center (Figure 2-17). Section 2.1.5.2 discusses Culebra fracture mechanisms. Additional discussion of Culebra fractures and their role in groundwater flow and transport is in Section 2.2.1.4.1.1, Appendix PA, Attachment MASS, Sections MASS.14.4 and MASS.15.

Holt (1997) reexamined geological and hydrological data for the Culebra and developed a conceptual model for transport processes. In this document, Holt (1997) recognized several porosity types for the Culebra, and separated four Culebra units (CU) informally designated CU-1 through CU-4 from top to bottom. CU-1 differs from underlying units because it has been disrupted very little by syndepositional processes. Microvugs and interbeds provide most of the porosity, and the permeability of CU-1 is relatively limited. CU-2 and CU-3 likely contribute most of the flow in the Culebra, and the significant difference is that CU-2 includes more persistent silty dolomite interbeds. CU-2 and CU-3 include “small-scale bedding-plane fractures, networks of randomly oriented small-scale fractures and microfractures, discontinuous silty dolomite interbeds, large vugs hydraulically connected with microfractures and small-scale fractures, microvugs hydraulically connected with microfractures and intercrystalline porosity, blebs of silty dolomite interconnected with microfractures and intercrystalline porosity, and intercrystalline porosity” (Holt 1997, p. 2-19). Bedding-plane fractures dominate CU-4 at the base of the Culebra, and the unit shows some brittle deformation. CU-4 has not been isolated for hydraulic testing.

Holt (1997, p. I) also related porosity and solute transport, conceptualizing the medium “as consisting of advective porosity, where solutes are carried by the groundwater flow, and fracture-bounded zones of diffusive porosity, where solutes move through slow advection or diffusion.” Holt (1997) noted that length or time scales will govern how each porosity type will contribute to solute transport.

Sewards et al. (1991, pp. IX-1) report that the Culebra is primarily dolomite with some quartz and clay. Clay minerals include corrensite, illite, serpentine, and chlorite. Clay occurs in bulk

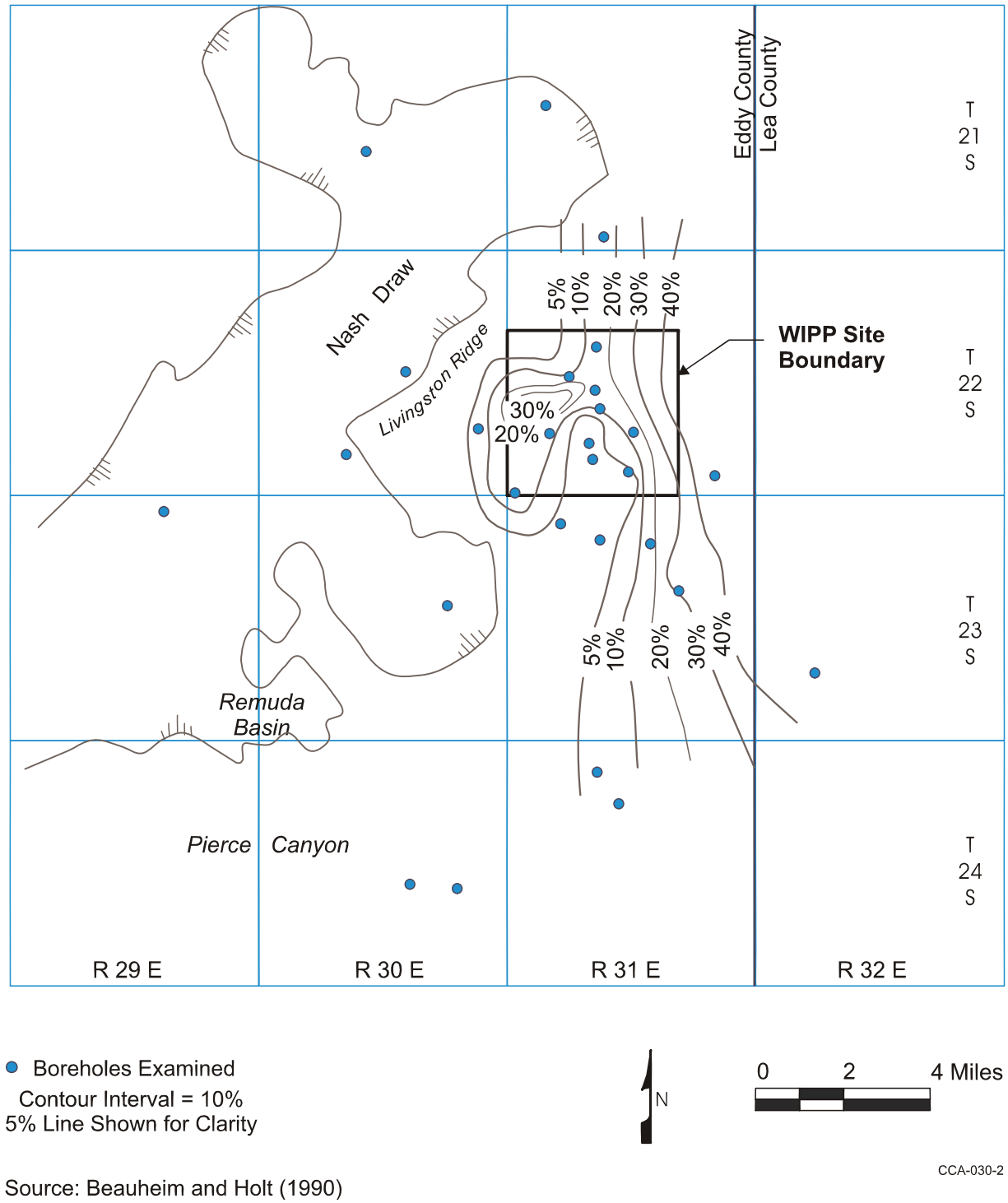

Source: Beauheim and Holt (1990)

Figure 2-17. Percentage of Natural Fractures in the Culebra Filled with Gypsum

rock and on fracture surfaces. Even though these clays occur, the conceptual model discussed in Section 6.4.6.2.1 takes no credit for their presence.

In the WIPP area, the Culebra varies in thickness. Depending on the area considered and the horizons chosen for the upper and lower boundaries of the Culebra, different data sources provide varying estimates (Table 2-3). Holt and Powers (CCA Appendix FAC, p. 4-4) considered the organic-rich layer at the Culebra-Tamarisk contact separately from the Culebra in interpreting geophysical logs.

Comparing data sets, Holt and Powers (CCA Appendix FAC) typically interpret the Culebra as being about 1 m (about 3 ft) thinner than do other interpretations. In general, this reflects the difference between including or excluding the unit at the Culebra-Tamarisk contact. The isopach of the Culebra is shown as Figure 4.8 in CCA Appendix FAC.

LaVenue et al. (1988, Table B.1) calculated a mean thickness of 7.7 m (25 ft) for the Culebra within their model domain based on thicknesses measured in 78 boreholes. Mercer (1983, reproduced as CCA Appendix HYDRO) reported a data set similar to that of LaVenue et al. The borehole database for the region of interest is provided in CCA Appendix BH.

The treatment of the Culebra in the conceptual model is discussed in Section 6.4.6.2 and associated parameter values in Table 6-20. A more thorough discussion of Culebra features, such as fractures, is provided in Appendix PA, Attachment MASS, Section MASS.15.

Table 2-3. Culebra Thickness Data Sets

Source	Data Set Location								
	T22S, R31E			T21-23S, R30-32E			Entire Set		
	n	ave	std dev	n	ave	std dev	n	ave	std dev
Richey (1989)	7	7.5 m	1.04 m	115	7.9 m	1.45 m	633	7.7 m	1.65 m
CCA Appendix FAC	35	6.4 m	0.59 m	122	7.0 m	1.26 m	508	6.5 m	1.89 m
LaVenue et al. (1988)							78	7.7 m	
Source	**WIPP Potash Drillholes**								
Jones (1978)				21	7.5 m	0.70 m			
CCA Appendix FAC				21	6.3 m	0.50 m			

Legend:

n	number of boreholes or data points
ave	average or mean
std dev	standard deviation
m	meters

2.1.3.5.3 The Tamarisk Member

Vine (1963, B14) named the Tamarisk for outcrops near Tamarisk Flat in Nash Draw. Outcrops of the Tamarisk are distorted, and subsurface information was used to establish member

characteristics. Vine reported two sulfate units separated by a siltstone, about 1.5 m (5 ft) thick, interpreted by Jones et al. in 1960 as a dissolution residue.

The Tamarisk is generally conformable with the underlying Culebra. The transition is marked by an organic-rich unit interpreted as being present over most of southeastern New Mexico. The Tamarisk around the WIPP site consists of lower and upper sulfate units separated by a unit that varies from mudstone (generally to the west) to mainly halite (to the east). Near the center of the WIPP site, the lower anhydrite was partially eroded during deposition of the middle mudstone unit, as observed in the WIPP waste-handling and exhaust shafts. The lower anhydrite was completely eroded at WIPP-19. Before shaft exposures were available, the lack of the Lower Tamarisk anhydrite at WIPP-19 was interpreted as the result of dissolution and the mudstone was considered a cave filling.

Jones (1978) interprets halite to be present east of the center of the WIPP site based on geophysical logs and drill cuttings. Based mainly on cores and cuttings records from the WIPP potash drilling program, Snyder prepared a map showing the halitic areas of each of the noncarbonate members of the Rustler (Snyder 1985, Figure 4). A very similar map based on geophysical log characteristics was prepared by Holt and Powers (1988).

CCA Appendix FAC describes the mudstones and halitic facies in the middle of the Tamarisk and postulate that the unit formed in a salt-pan-to-mudflat system. Powers and Holt (2000) cited sedimentary features and the lateral relationships as evidence of syndepositional dissolution of halite in the marginal mudflat areas.

The Tamarisk thickness varies greatly in southeastern New Mexico, principally as a function of the thickness of halite in the middle unit. Within T22S, R31E, the thickness ranges from 26 to 56 m (84 to 184 ft) for the entire Tamarisk and from 2 to 34 m (6 to 110 ft) for the interval of mudstone-halite between lower and upper anhydrites (CCA Appendix FAC, Figures 4-9 and 4-11). Expanded geophysical logs with corresponding lithology illustrate some of the lateral relationships for this interval (Figure 2-18; see also Powers and Holt 2000).

The Tamarisk is modeled as discussed in Section 6.4.6.3. Tamarisk parameter values are given in Appendix PA, Attachment PAR, Table PAR-24.

2.1.3.5.4 The Magenta Dolomite Member

Adams (1944, p. 1614) attributes the name Magenta Member to Lang, based on a feature named Magenta Point north of Laguna Grande de la Sal. According to CCA Appendix FAC the Magenta is a gypsiferous dolomite with abundant primary sedimentary structures and well-developed algal features. It does not vary greatly in sedimentary features

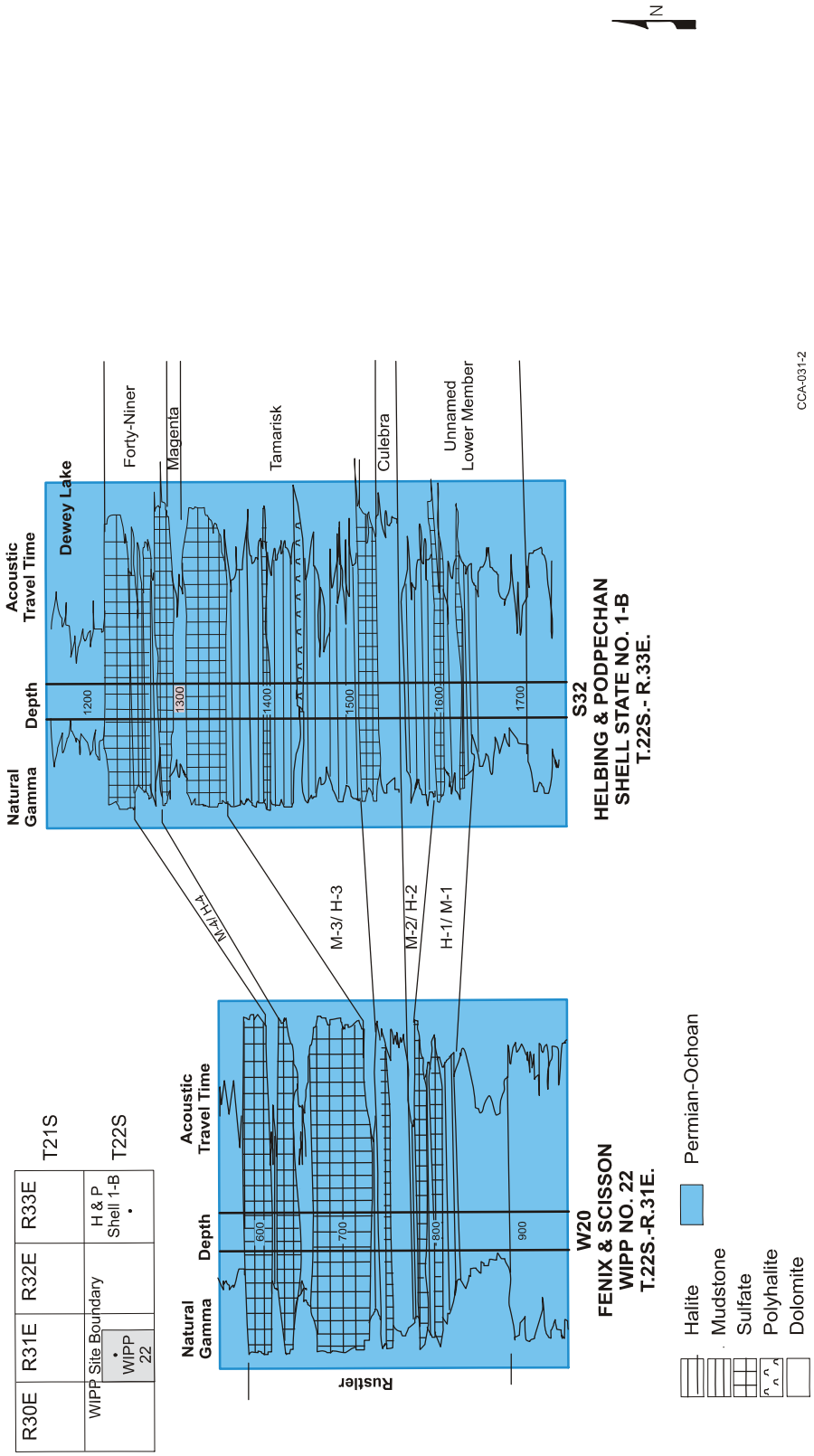

Figure 2-18. Log Character of the Rustler Emphasizing Mudstone-Halite Lateral Relationships

across the site area. CCA Appendix FAC, 5-22 reported that the Magenta varies from 7.0 to 8.5 m (23 to 28 ft) around the WIPP site. CCA Appendix FAC did not include a regional Magenta isopach. Additional detail on the Magenta can be found in Section 4.3.2 of CCA Appendix GCR and in Sections 4.1.4, 4.2.4, and 5.4 of CCA Appendix FAC. The Magenta is included in the conceptual model as discussed in Section 6.4.6.4. Modeling values are in Table 6-24.

2.1.3.5.5 The Forty-niner Member

Vine (1963) named the Forty-niner for outcrops at Forty-niner Ridge in eastern Nash Draw, but the unit is poorly exposed there. In the subsurface around the WIPP, the Forty-niner consists of basal and upper sulfates separated by a mudstone. It is conformable with the underlying Magenta. As with other members of the Rustler, geophysical log characteristics can be correlated with core and shaft descriptions to extend geological inferences across a large area (Holt and Powers 1988).

The Forty-niner varies from 13 to 23 m (43 to 77 ft) thick within T22S, R31E. East and southeast of the WIPP, the Forty-niner exceeds 24 m (80 ft), and some of the geophysical logs from this area indicate that halite is present in the beds between the sulfates. A regional isopach map of the Forty-niner is in CCA Appendix FAC (Figure 4-13). See also Powers and Holt (2000).

Within the waste-handling shaft, the Forty-niner mudstone displayed sedimentary features and bedding relationships indicating sedimentary transport. These beds are not known to have been described in detail prior to mapping in the waste-handling shaft at WIPP, and the features found there led Holt and Powers (CCA Appendix FAC) to reexamine the available evidence for, and interpretations of, dissolution of halite in Rustler units.

The inclusion of the Forty-niner in the conceptual model is discussed in Section 6.4.6.5.

2.1.3.6 The Dewey Lake

The nomenclature for rocks included in the Dewey Lake Formation was introduced during the 1960s to clarify relationships between these rocks assigned to the Upper Permian and the Cenozoic Gatuña Formation.

There are three main sources of data about the Dewey Lake in the area around WIPP. Miller reported the petrology of the unit in 1955 and 1966. Schiel (1988) described outcrops in the Nash Draw areas and interpreted geophysical logs of the unit in southeastern New Mexico and west Texas to infer the depositional environments and stratigraphic relationships in 1988 and 1994. Holt and Powers (1990a) were able to describe the Dewey Lake in detail at the AIS for WIPP in 1990, confirming much of Schiel's (1988) information and adding data regarding the Lower Dewey Lake.

The Dewey Lake overlies the Rustler conformably, though local examples of the contact (for example, the AIS described by Holt and Powers (1990a) show minor disruption by dissolution of some of the upper Rustler sulfate. The formation is predominantly reddish-brown fine sandstone to siltstone or silty claystone with greenish-gray reduction spots. Thin bedding, ripple cross-

bedding, and larger channeling are common features in outcrops, and additional soft sediment deformation features and early fracturing from the lower part of the formation are described by Holt and Powers (1990a). Schiel (1988, p. 143; 1994, p. 9) attributed the Dewey Lake to deposition on "a large, arid fluvial plain subject to ephemeral flood events."

There is no direct faunal or radiometric evidence of the age of the Dewey Lake in the vicinity of the WIPP site. It is assigned to the Ochoan Series, considered historically to be Late Permian in age, and it is regionally correlated with units of similar lithology and stratigraphic position. Schiel (1988, 1994) reviewed the limited radiometric data from lithologically similar rocks (Quartermaster Formation) and concluded that much of the unit could be Early Triassic in age. Renne et al. (1996) resampled tephra from the Quartermaster in the Texas panhandle area and found that radiometric data support the idea that the Quartermaster is mainly Triassic in age rather than Permian. Others have begun to infer as well that the Dewey Lake in the vicinity of the WIPP may be mostly Triassic (e.g., Powers and Holt 1999). These age relationships continue to be of academic interest because of the geologic significance of the Permo-Triassic boundary, but there is no significance for waste isolation at the WIPP.

Near the center of the WIPP site, Holt and Powers (1990a, Figure 5) mapped 152 m (498 ft) of the Dewey Lake (Figure 2-19). The formation is thicker to the east (Schiel 1994, Figure 2) of the WIPP site, in part because western areas were eroded before the overlying Triassic rocks were deposited.

The Dewey Lake contains fractures, which are filled with minerals to varying degrees. Both cements and fracture fillings have been examined and used to infer groundwater infiltration. Holt and Powers (1990a, pp. 3-10) described the Dewey Lake as cemented by carbonate above 50 m (164.5 ft) in the AIS; some fractures in the lower part of this interval were also filled with carbonate, and the entire interval surface was commonly moist. Below this point, the cement is harder and more commonly anhydrite (Powers 2003b), the shaft is dry, and fractures are filled with gypsum. Powers (2002c; 2003b) reports core and geophysical log data supporting these vertical changes in natural mineral cements in the Dewey Lake over a larger region at a horizon that is believed to underlie known natural groundwater occurrences in the Dewey Lake. In areas where the Dewey Lake has been exposed to weathering after erosion of the overlying Santa Rosa, this cement boundary tends to generally parallel the eroded upper surface of the Dewey Lake, suggesting that weathering has affected the location of the boundary. Where the Dewey Lake has been protected by overlying rocks of the Santa Rosa, the cement change appears to be stratigraphically controlled but the data points are too few to be certain. Holt and Powers (1990a, pp. 3 - 11, Figure 16) suggested that the cement change might be related to infiltration of meteoric water. They also determined that some of the gypsum-filled fractures are syndepositional. Dewey Lake fractures include horizontal to subvertical trends, some of which were mapped in detail (Holt and Powers 1986, Figures 6, 7, and 8).

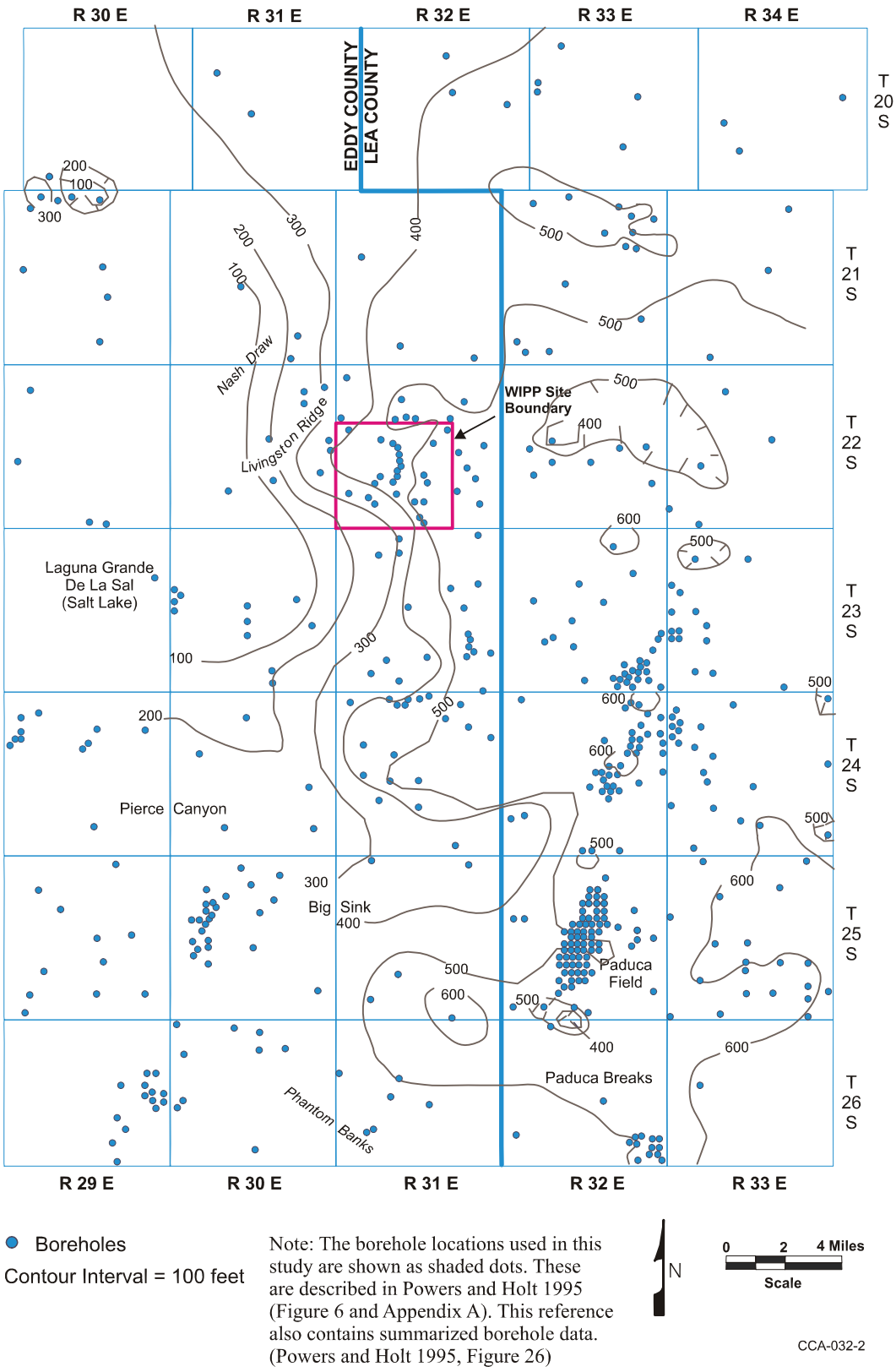

Figure 2-19. Isopach of the Dewey Lake

Lambert (1991, pp. 5 - 65) analyzed the deuterium/hydrogen (D/H) ratios of gypsum in the Rustler and gypsum veins in the Dewey Lake. He suggest that none of the gypsum formed from evaporitic fluid such as Permian seawater but that the D/H ratios all show influence of meteoric water. Furthermore, Lambert (1991, 5 – 66) infers that the gypsum D/H ratio is not consistent with modern meteoric water; it may, however, be consistent with older meteoric fluids. There is no obvious correlation with depth to indicate infiltration. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) indicate no intermixing or homogenization of fluids between the Rustler and the Dewey Lake, but there may have been lateral movement of water within the Dewey Lake (Lambert 1991, pp. 5 - 54). Dewey Lake carbonate-vein material shows a broader range of strontium ratios than does surface caliche, and the ratios barely overlap.

The treatment of the Dewey Lake in the conceptual model can be found in Section 6.4.6.6. Dewey Lake parameter values are in Table 6-25.

2.1.3.7 The Santa Rosa

There have been different approaches to the nomenclature of rocks of Triassic age in southeastern New Mexico. Bachman (1974) generally described the units as “Triassic, undivided” or as the Dockum Group, without dividing it. Vine (1963) used “Santa Rosa Sandstone,” and Santa Rosa has become common usage. Lucas and Anderson (1993a, 1993b) import other formation names that are unlikely to be useful for WIPP.

The Santa Rosa has been called disconformable over the Dewey Lake by Vine (1963, B25). These rocks have more variegated hues than the underlying uniformly colored Dewey Lake. Coarse-grained rocks, including conglomerates, are common, and the formation includes a variety of cross-bedding and sedimentary features (Lucas and Anderson 1993a, pp. 231 - 235).

Within the WIPP site boundary, the Santa Rosa is relatively thin to absent (Figure 2-20). At the AIS, Holt and Powers (1990a, Figure 5) attributed about 0.6 m (2 ft) of rock to the Santa Rosa. The Santa Rosa is a maximum of 78 m (255 ft) thick in potash holes drilled for WIPP east of the site boundary. The Santa Rosa is thicker to the east. The geologic data from design studies (Sergent et al. 1979) were incorporated with data from drilling to investigate shallow subsurface water in the Santa Rosa to provide structure and thickness maps of the Santa Rosa in the vicinity of the WIPP surface structures area (Powers 1997). These results are consistent with the broader regional distribution of the Santa Rosa.

The Santa Rosa and younger rocks are modeled in the WIPP PA as a single region as discussed in Section 6.4.6.7. The model parameters for this supra-Dewey Lake region are given in Table 6-26.

2.1.3.8 The Gatuña

Lang (in Robinson and Lang 1938, p. 84) named the Gatuña for outcrops in the vicinity of Gatuña Canyon in the Clayton Basin. Rocks now attributed to the Gatuña in Pierce Canyon were once included in the Pierce Canyon Formation with rocks now assigned to the Dewey Lake. The

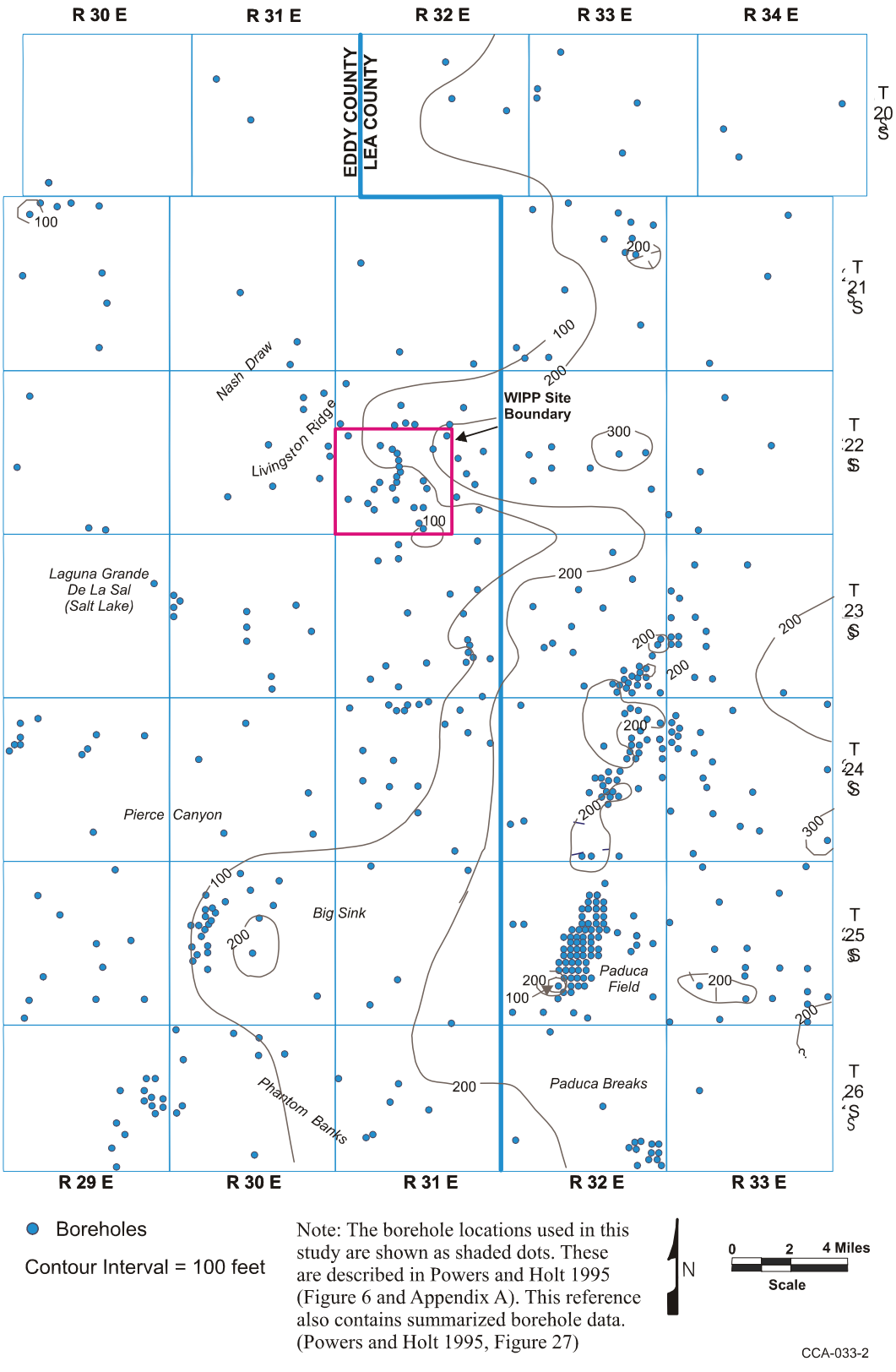

Figure 2-20. Isopach of the Santa Rosa

formation has been mapped from the Santa Rosa, New Mexico, area south to the vicinity of Pecos, Texas. It is unconformable with underlying units.

Vine (1963) and Bachman (1974) provided some limited description of the Gatuña. The most comprehensive study of the Gatuña is based on WIPP investigations and landfill studies for the City of Carlsbad and Eddy County (Powers and Holt 1993). Much of the formation is colored light reddish-brown. It is broadly similar to the Dewey Lake and the Santa Rosa, though the older units have more intense hues. The formation is highly variable, ranging from coarse conglomerates to claystones with some highly gypsiferous sections. Sedimentary structures are abundant. Analysis of lithofacies indicates that the formation is dominantly fluvial in origin with areas of low-energy deposits and evaporitic minerals.

The thickness of the Gatuña is not very consistent regionally, as shown in Figure 2-21. The thickness of the Gatuña ranges up to 91 m (300 ft) at Pierce Canyon, with thicker areas generally subparallel to the Pecos River. To the east, the Gatuña is thin or absent. Holt and Powers (1990a) reported about 2.7 m (9 ft) of undisturbed Gatuña in the AIS at WIPP. Powers (1997) integrated data from facility design geotechnical work (Sergent et al. 1979) and drilling to investigate shallow water to develop maps of the Gatuña in the vicinity of the WIPP surface facility. These maps are consistent with the broader regional view of the distribution of the Gatuña.

The Gatuña has been considered Pleistocene in age based on a volcanic glass in the Upper Gatuña along the eastern margin of Nash Draw that has been identified as the Lava Creek B ash, dated at 0.6 million years by Izett and Wilcox (1982). This upper-limit age is corroborated by the age determinations from the Mescalero caliche (hereafter referred to as the Mescalero) that overlies the Gatuña (see Section 2.1.3.9). An additional volcanic ash from the Gatuña in Texas yields consistent K-Ar and geochemical data, indicating that it is about 13 million years old at that location (Powers and Holt 1993, p. 271). Thus, the Gatuña ranges in age over a period of time that may be greater than that spanned by the Ogallala Formation (hereafter referred to as the Ogallala) on the High Plains east of WIPP.

2.1.3.9 Mescalero Caliche

The Mescalero caliche is an informal stratigraphic unit apparently first differentiated by Bachman in 1974, though Bachman (1973, p. 17, p. 27) described the caliche on the Mescalero Plain. He differentiated the Mescalero from the older, widespread Ogallala caliche or caprock on the basis of textures, noting that breccia and pisolitic textures are much more common in the Ogallala caliche. The Mescalero has been noted over significant areas in the Pecos drainage, including the WIPP area, and it has been formed over a variety of substrates. Bachman (1973) described the Mescalero as a two-part unit: (1) an upper dense laminar caprock and (2) a basal, earthy-to-firm, nodular calcareous deposit. Machette (1985, p. 5) classified the Mescalero as having Stage V morphologies of a calcic soil (the more mature Ogallala caprock that occurs east of the WIPP site reaches Stage VI).

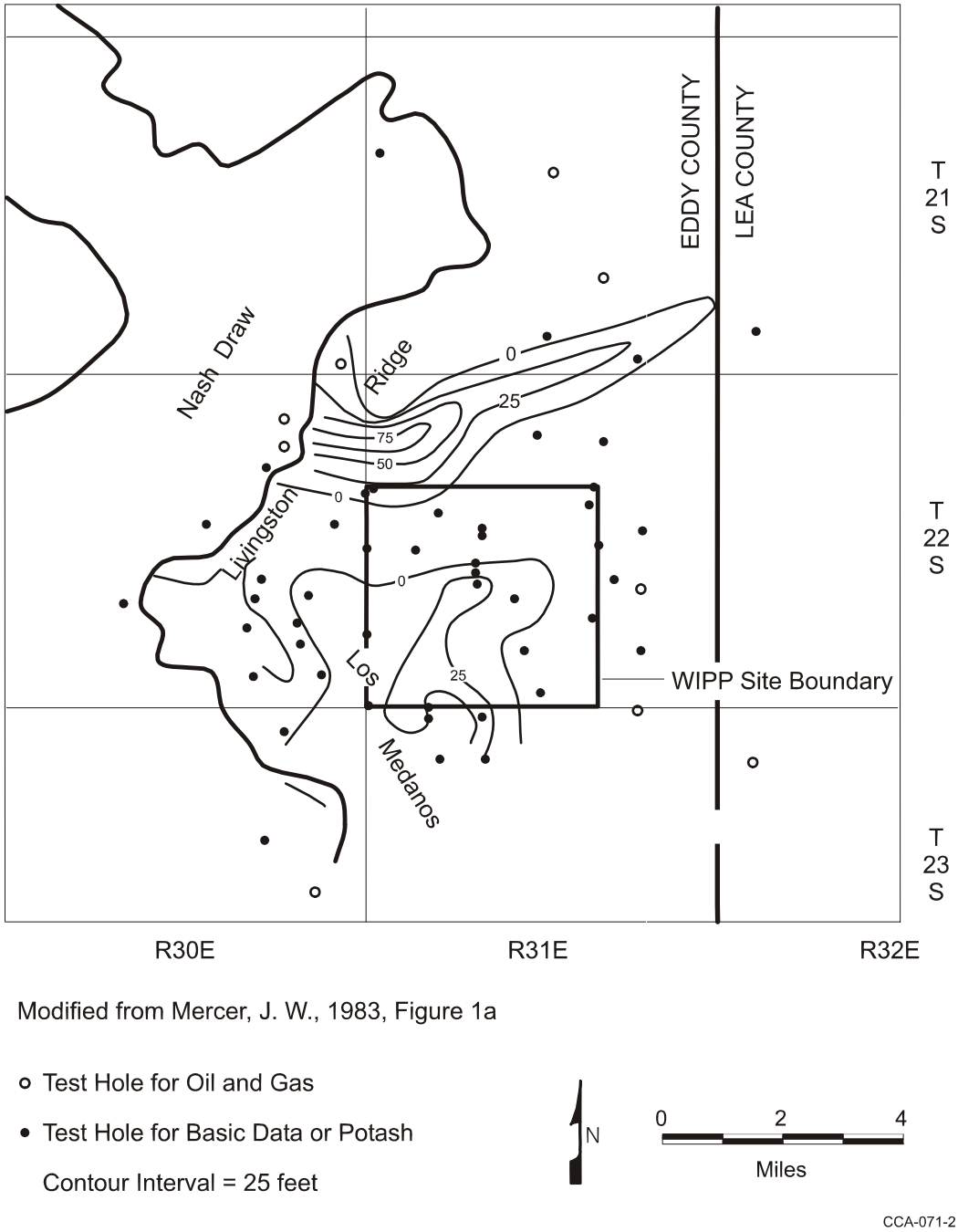

Figure 2-21. Isopach of the Gatuña

Bachman (1976, Figure 8) provided structure contours on the Mescalero caliche for a large area of southeastern New Mexico, including the WIPP site. From the contours and Bachman's discussion of the Mescalero as a soil, it is clear that the Mescalero is expected to be continuous over large areas. Explicit WIPP data are limited mainly to boreholes, though some borehole reports do not mention the Mescalero. The unit may be as much as 3 m (10 ft) thick.

The Mescalero overlies the Gatuña and was interpreted by Bachman (1976) on basic stratigraphic grounds as having accumulated during the early-to-middle Pleistocene. Samples of the Mescalero from the vicinity of the WIPP were studied using uranium-trend methods.

Based on early written communication from Rosholt, Bachman (1985, p. 20) reports that the basal Mescalero began to form about 510,000 years ago and the upper part began to form about 410,000 years ago; these ages are commonly cited in WIPP literature. The samples are interpreted by Rosholt and McKinney (1980, Table 5) in the formal report as indicating ages of 570,000 ± 110,000 years for the lower part of the Mescalero and 420,000 ± 60,000 years for the upper part.

According to Bachman (1985, p. 19), where the Mescalero is flat-lying and not breached by erosion, it is an indicator of stability or integrity of the land surface over the last 500,000 years. An additional discussion of the Mescalero caliche can be found in CCA Appendix GCR, Section 4.2.2.

2.1.3.10 Surficial Sediments

Soils of the region have developed mainly from Quaternary and Permian parent material. Parent material from the Quaternary System is represented by alluvial deposits of major streams, dune sand, and other surface deposits. These are mostly loamy and sandy sediments containing some coarse fragments. Parent material from the Permian System is represented by limestone, dolomite, and gypsum bedrock. Soils of the region have developed in a semiarid, continental climate with abundant sunshine, low relative humidity, erratic and low rainfall, and a wide variation in daily and seasonal temperatures. Subsoil colors are normally light brown to reddish brown but are often mixed with lime accumulations (caliche) that result from limited, erratic rainfall and insufficient leaching.

A soil association is a landscape with a distinctive pattern of soil types (series). It normally consists of one or more major soils and at least one minor soil. There are three soil associations within 8.3 km (5 mi) of the WIPP site: the Kermit-Berino, the Simona-Pajarito, and the Pyote-Maljamar-Kermit. Of these three associations, only the Kermit-Berino soil series has been mapped across the WIPP site by Chugg et al. (1952, Sheet No. 113). These are sandy soils developed on eolian material. The Kermit-Berino soils include active dune areas. The Berino soil has a sandy A horizon; the B horizons include more argillaceous material and weak-to-moderate soil structures. A and B horizons are described as noncalcareous, and the underlying C horizon is commonly caliche. Bachman (1980, p. 44) interpreted the Berino soil as a paleosol that is a remnant B horizon of the underlying Mescalero. Rosholt and McKinney (1980, Table 5) applied uranium-trend methods to samples of the Berino soil from the WIPP site area. Rosholt and McKinney (1980) interpreted the age of formation of the Berino soil as 330,000 ± 75,000 years.

Generally, the Berino Series, which covers about 50 percent of the site, consists of deep, noncalcareous, yellow-red to red sandy soils that developed from wind-worked material of mixed origin. These soils are described as undulating to hummocky and gently sloping (zero to three percent slopes). The soils are the most extensive of the deep, sandy soils in the Eddy County area. Berino soils are subject to continuing wind and water erosion. If the vegetative

cover is seriously depleted, the water-erosion potential is slight, but the wind-erosion potential is very high. These soils are particularly sensitive to wind erosion in the months of March, April, and May, when rainfall is minimal and winds are highest. These soil characteristics are a consideration for the design of long-term passive controls such as monuments and markers (see CCA Appendix PIC, Section III).

The Kermit Series consists of deep, light-colored, noncalcareous, excessively drained loose sands, typically yellowish-red fine sand. The surface is undulating to billowy (from 0 to 3 percent slopes) and consists mostly of stabilized sand dunes. Kermit soils are slightly to moderately eroded. Permeability is very high, and, if vegetative cover is removed, the water-erosion potential is slight, but the wind-erosion potential is very high.

Surface soils appear to play a role in the infiltration of precipitation. Mercer (CCA Appendix HYDRO) points out that where surface deposits are thickest, they may contain localized perched zones of groundwater. A more thorough discussion of this topic can be found in CCA Appendix HYDRO.

2.1.3.11 Summary

The stratigraphy and lithology at the WIPP site has been summarized from the lowermost pre-Cambrian units to the surface soils. While these are important for an understanding of the site and its stability, not all of these units are important to the performance of the disposal system. As a result, the DOE has developed a conceptual model that describes the lithology as 13 discrete model regions ranging from the Castile to a region that generally includes units above the Dewey Lake. In this model, emphasis is placed on the Castile, the Salado, the five members of the Rustler, the Dewey Lake, and the supra-Dewey Lake units. The Salado is divided into five stratigraphic units to capture the variations in properties near the horizon of the repository (see Figure 6-14). The identification and definition of the appropriate modeling units is based on the identification of FEPs that can impact the performance of the disposal system. Details of the conceptual model can be found in Section 6.4.2.

2.1.4 Physiography and Geomorphology

In this section, the DOE presents a discussion of the physiography and geomorphology of the WIPP site and surrounding area. This information is taken from DOE 1980 (pp. 7-21 to 7-23). Geomorphology and physiography are determined by the DOE (1980) to be features that are potentially important to disposal system performance. They are included in the consequence analysis through consideration of the topography and its influence on the regional water table. (See discussion of regional water table characteristics in Section 2.2.1.) Consequently, topographic information is presented in this section. In addition, several geomorphological processes have been screened out on the basis of either low consequence or low probability, as discussed in Appendix PA, Attachment SCR. These include weathering, erosion, sedimentation, and soil development. Information is presented in this section to support this screening. In order to perform this screening, such factors as slopes, proximity to watercourses, dissection, and historic and existing processes are important. These are presented in this section in terms of the regional and local physiographic and geomorphological characteristics. Tectonic processes that may alter the physiography of the region or site area are discussed in Section 2.1.5. In addition,

Section 2.1.6 presents more specific details on nontectonic processes identified during site characterization as having the potential for affecting the repository over the longer term and as requiring detailed investigation. These include halite deformation and dissolution.

2.1.4.1 Regional Physiography and Geomorphology

The WIPP site is in the Pecos Valley section of the southern Great Plains physiographic province (Figure 2-22), a broad, highland belt sloping gently eastward from the Rocky Mountains and the Basin and Range Province to the Central Lowlands Province. The Pecos Valley section itself is dominated by the Pecos River Valley, a long north-south trough that is from 8.3 to 50 km (5 to 30 mi) wide and as much as 305 m (1,000 ft) deep in the north. The Pecos River System has evolved from the south, cutting headward through the Ogallala sediments and becoming entrenched some time after the Middle Pleistocene. It receives almost all the surface and subsurface drainage of the region; most of its tributaries are intermittent because of the semiarid climate. The surface locally has a karst terrain containing sinkholes, dolines, and solution-subsidence troughs from both surface erosion and subsurface dissolution. The valley has an uneven rock- and alluvium-covered floor with widespread solution-subsidence features, the result of dissolution in the underlying Upper Permian rocks. The terrain varies from plains and lowlands to rugged canyonlands, and contains such erosional features as scarps, cuestas, terraces, and mesas. The surface slopes gently eastward, reflecting the underlying rock strata. Elevations vary from more than 1,829 m (6,000 ft) in the northwest to about 610 m (2,000 ft) in the south.

The Pecos Valley section is bordered on the east by the virtually uneroded plain of the Llano Estacado. The Llano Estacado is part of the High Plains section of the Great Plains physiographic province and is a poorly drained eastward-sloping surface covered by gravels, wind-blown sand, and caliche that has developed since early-to-middle Pleistocene time. Few and minor topographic features are present in the High Plains section, formed when more than 152 m (500 ft) of Tertiary silts, gravels, and sands were laid down in alluvial fans by streams draining the Rocky Mountains. In many areas, the nearly flat surface is cemented by a hard caliche layer.

To the west of the Pecos Valley section are the Sacramento Mountains and the Guadalupe Mountains, part of the Sacramento section of the Basin and Range Province. The Capitan escarpment along the southeastern side of the Guadalupe Mountains marks the boundary between the Basin and Range and the Great Plains provinces. The Sacramento section has large basinal areas and a series of intervening mountain ranges (DOE 1980).

2.1.4.2 Site Physiography and Geomorphology

The land surface in the area of the WIPP site is a semiarid, wind-blown plain sloping gently to the west and southwest, and is hummocky with sand ridges and dunes. A hard caliche layer (Mescalero rocks) is typically present beneath the sand blanket and on the surface of the underlying Gatuña. Figure 2-23 is a topographic map of the area. Elevations at the site range from 1,088 m (3,570 ft) in the east to 990 m (3,250 ft) in the west. The average east-to-west slope is 9.4 m per kilometer (50 ft/mi).

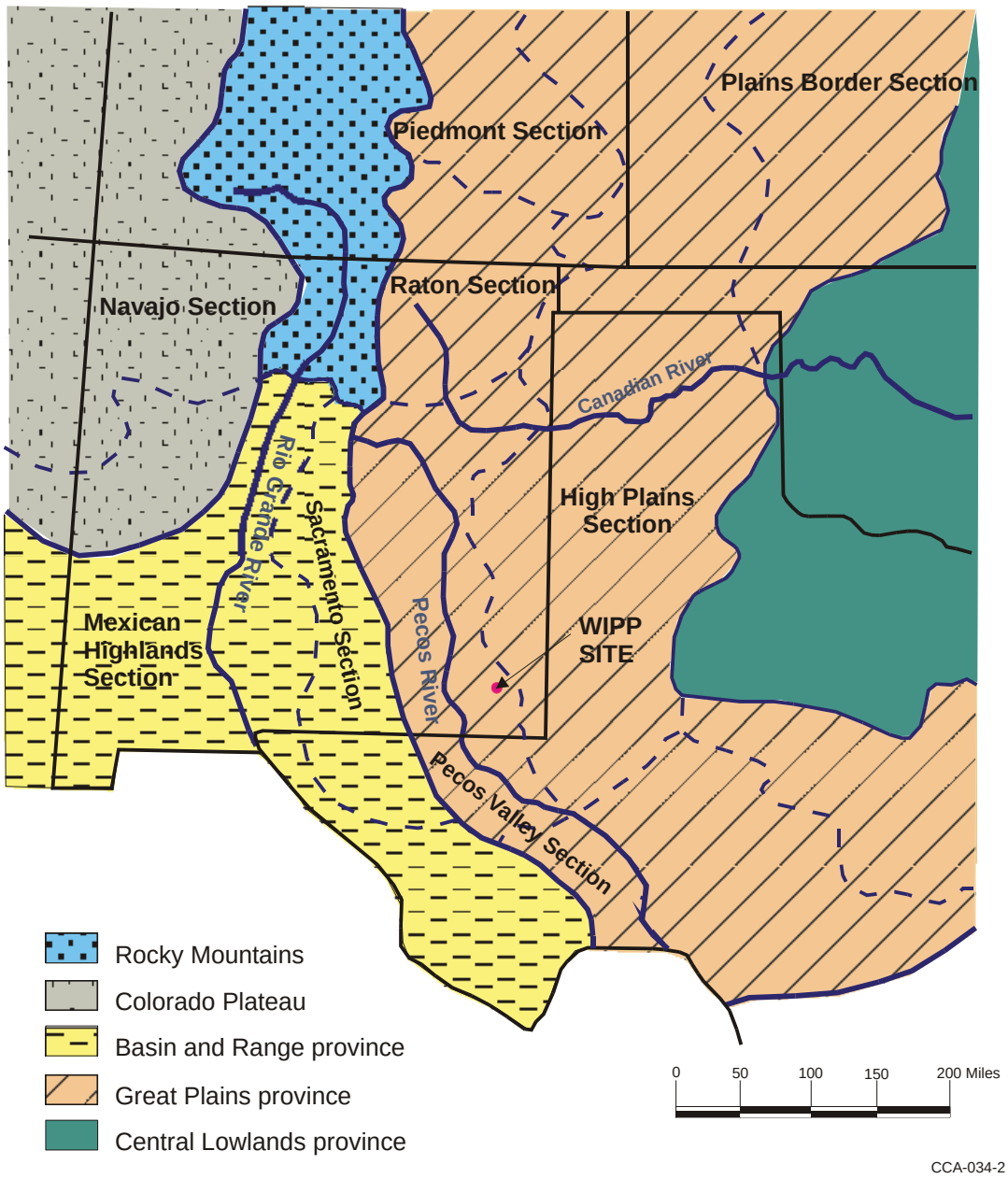

Figure 2-22. Physiographic Provinces and Sections

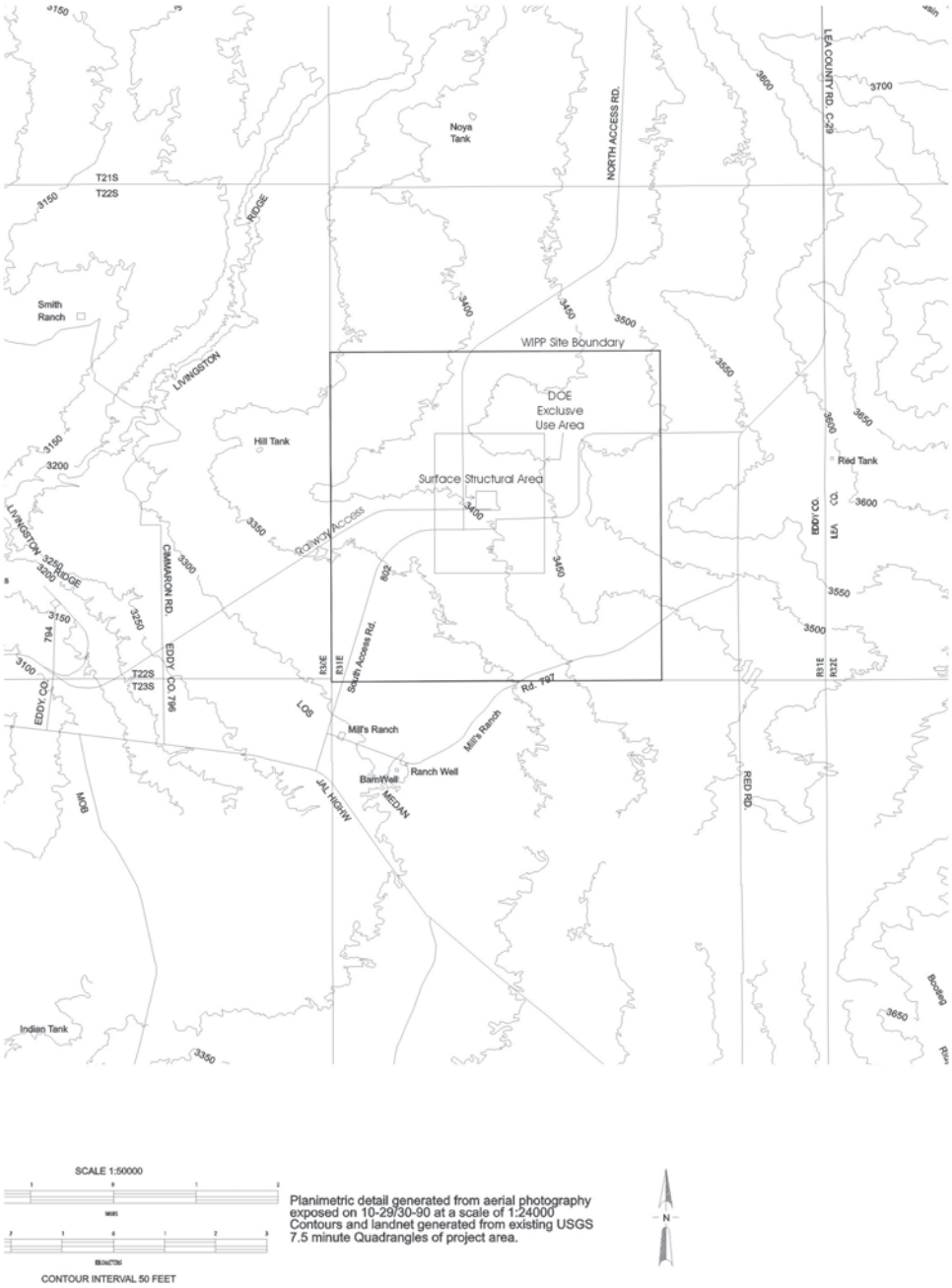

Figure 2-23 Topographic Map of the Area Around the WIPP Site

Livingston Ridge is the most prominent physiographic feature near the site. It is a west-facing escarpment that has about 23 m (75 ft) of topographic relief and marks the eastern edge of Nash Draw, the drainage course nearest to the site (see Figure 2-23). Nash Draw is a shallow 8-km-wide (5-mi-wide) basin, 61 to 91 m (200 to 300 ft) deep and open to the southwest. It was caused, at least in part, by subsurface dissolution and the accompanying subsidence of overlying sediments. Livingston Ridge is the approximate boundary between terrain that has undergone erosion and/or solution collapse to the west and terrain that has been little affected to the east.

About 24 km (15 mi) east of the site is the southeast-trending San Simon Swale, a depression caused, at least in part, by subsurface dissolution. Between San Simon Swale and the site is a broad, low mesa named the Divide. Lying about 9.7 km (6 mi) east of the site and about 30 m (100 ft) above the surrounding terrain, it is a boundary between southwest drainage toward Nash Draw and southeast drainage toward San Simon Swale. The Divide is capped by the Ogallala and the overlying caliche, upon which have formed small, elongated depressions similar to those in the adjacent High Plains section to the east.

Surface drainage is intermittent; the nearest perennial stream is the Pecos River, 19 km (12 mi) southwest of the WIPP site boundary. The site's location near a natural divide protects it from flooding and serious erosion caused by heavy runoff. Should the climate become more humid, any perennial streams should follow the present basins, and Nash Draw and San Simon Swale would be the most eroded, leaving the area of the Divide relatively intact.

2.1.5 Tectonic Setting and Site Structural Features

The DOE has screened out, on the basis of either probability or consequence or both, all tectonic, magmatic, and structural related processes. The screening discussions can be found in Appendix PA, Attachment SCR. The information needed for this screening is included here and covers regional tectonic processes such as subsidence and uplift and basin tilting, magmatic processes such as igneous intrusion and events such as volcanism, and structural processes such as faulting and loading and unloading of the rocks because of long-term sedimentation or erosion. Discussions of structural events, such as earthquakes, are considered to the extent that they may create new faults or activate old faults. The seismicity of the area is considered in Section 2.6 for the purposes of determining seismic design parameters for the facility.

2.1.5.1 Tectonics

The processes and features included in this section are those more traditionally considered part of tectonics, processes that develop the broad-scale features of the earth. Salt dissolution is a different process that can develop some features resembling those of tectonics.

Most broad-scale structural elements of the area around the WIPP developed during the Late Paleozoic (CCA Appendix GCR, pp. 3-58 to 3-77). There is little historical or geological evidence of significant tectonic activity in the vicinity, and the level of stress in the region is low. The entire region tilted slightly during the Tertiary, and activity related to Basin and Range tectonics formed major structures southwest of the area. Seismic activity is specifically addressed in a separate section.

Broad subsidence began in the area as early as the Ordovician, developing a sag called the Tobosa Basin. By Late Pennsylvanian to Early Permian time, the Central Basin Platform developed (Figure 2-24), separating the Tobosa Basin into two parts: the Delaware Basin to the west and the Midland Basin to the east. The Permian Basin refers to the collective set of depositional basins in the area during the Permian Period. Southwest of the Delaware Basin, the Diablo Platform began developing either in the Late Pennsylvanian or Early Permian. The Marathon Uplift and Ouachita tectonic belt limited the southern extent of the Delaware Basin.

According to Brokaw et al. (1972, p. 30), pre-Ochoan sedimentary rocks in the Delaware Basin show evidence of gentle downwarping during deposition, while Ochoan and younger rocks do not. A relatively uniform eastward tilt, generally from about 14 to 19 m/per km (75 to 100 ft/mi), has been superimposed on the sedimentary sequence.[1] King (1948, pp. 108 and 121) generally attributes the uplift of the Guadalupe and Delaware mountains along the west side of the Delaware Basin to the later Cenozoic, though he also notes that some faults along the west margin of the Guadalupe Mountains have displaced Quaternary gravels.

[1] Local dip of the Salado has been determined by mapping in the WIPP underground excavations. This dip is modeled as one degree to the south, as discussed in Section 6.4.2.1.

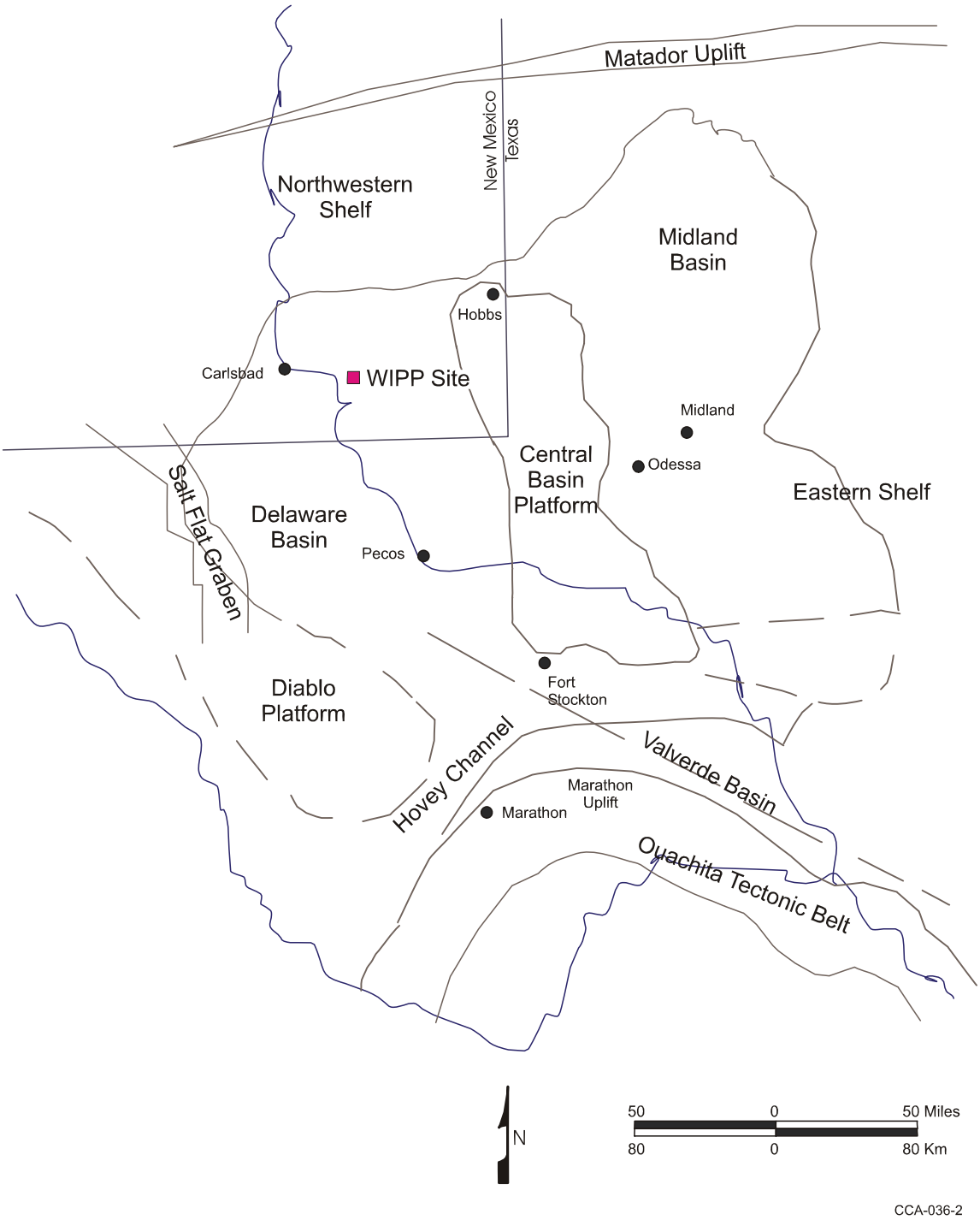

Figure 2-24. Structural Provinces of the Permian Basin Region

King (1948, p. 144) also infers the uplift from the Pliocene-age deposits of the Llano Estacado. Subsequent studies of the Ogallala of the Llano Estacado show that it varies in age from Miocene (about 12 million years before present) to Pliocene (Hawley 1993). This is the most likely range for uplift of the Guadalupe Mountains and broad tilting to the east of the Delaware Basin sequence.

Analysis of the present regional stress field indicates that the Delaware Basin lies within the Southern Great Plains stress province. This province is a transition zone between the extensional stress regime to the west and the region of compressive stress to the east. An interpretation by Zoback and Zoback (1991, p. 350) of the available data indicates that the level of stress in the Southern Great Plains stress province is low. Changes to the tectonic setting, such as the development of subduction zones and a consequent change in the driving forces, would take much longer than 10,000 years to occur.

To the west of the Southern Great Plains province is the Basin and Range province, or Cordilleran Extension province, where according to Zoback and Zoback (1991, pp. 348 - 351), normal faulting is the characteristic style of deformation. The eastern boundary of the Basin and Range province is marked by the Rio Grande Rift. Sanford et al. (1991, p. 230) note that, as a geological structure, the rift extends beyond the relatively narrow geomorphological feature seen at the surface, with a magnetic anomaly at least 500 km (300 mi) wide. On this basis, the Rio Grande Rift can be regarded as a system of axial grabens along a major north-south trending structural uplift (a continuation of the Southern Rocky Mountains). The magnetic anomaly extends beneath the Southern Great Plains stress province, and regional-scale uplift of about 1,000 m (3,300 ft) over the past 10 million years also extends into eastern New Mexico.

To the east of the Southern Great Plains province is the large Mid-Plate province that encompasses central and eastern regions of the conterminous United States and the Atlantic basin west of the Mid-Atlantic Ridge. The Mid-Plate province is characterized by low levels of paleo- and historic seismicity. Where Quaternary faulting has occurred, it is generally strike-slip and appears to be associated with the reactivation of older structural elements.

Zoback et al. (1991) report no stress measurements from the Delaware Basin. The stress field in the Southern Great Plains stress province has been defined from borehole measurements in west Texas and from volcanic lineaments in northern New Mexico. These measurements were interpreted by Zoback and Zoback (1991, p. 353) to indicate that the least principal horizontal stress is oriented north-northeast and south-southwest and that most of the province is characterized by an extensional stress regime.

There is an abrupt change between the orientation of the least principal horizontal stress in the Southern Great Plains and the west-northwest orientation of the least principal horizontal stress characteristic of the Rio Grande Rift. In addition to the geological indications of a transition zone as described above, Zoback and Zoback (1980, p. 6134) point out that there is also evidence for a sharp boundary between these two provinces. This is reinforced by the change in crustal thickness from about 40 km (24 mi) beneath the Colorado Plateau to about 50 km (30 mi) or more beneath the Southern Great Plains east of the Rio Grande Rift. The base of the crust within the Rio Grande Rift is poorly defined but is shallower than that of the Colorado Plateau (Thompson and Zoback 1979, p. 152). There is also markedly lower heat flow in the Southern

Great Plains (typically < 60 mWm^{-2}) reported by Blackwell et al. (1991, p. 428) compared with that in the Rio Grande Rift (typically > 80 mWm^{-2}) reported by Reiter et al. (1991, p. 463).

On the eastern boundary of the Southern Great Plains province, there is only a small rotation in the direction of the least principal horizontal stress. There is, however, a change from an extensional, normal faulting regime to a compressive, strike-slip faulting regime in the Mid-Plate province. According to Zoback and Zoback (1980, p. 6134), the available data indicate that this change is not abrupt and that the Southern Great Plains province can be viewed as a marginal part of the Mid-Plate province.

2.1.5.2 Loading and Unloading

Loading and unloading during the geological history since deposition is considered an influence on the hydrology of the Permian units because of its possible effect on the development of fractures.

The sedimentary loading, depth of total burial, and erosion events combine in a complex history reconstructed here from regional geological trends and local data. The history is presented in Figure 2-25 with several alternatives, depending on the inferences that are drawn, ranging from minimal to upper-bound estimates (Powers and Holt 1995, Section 5.3). Borns (1987) also made a generalized estimate of loading that is similar. The estimates are made with a reference point and depth to the Culebra at the AIS.

Given the maximum local thickness of the Dewey Lake, the maximum load at the end of the Permian was no more than approximately 240 m (787 ft). Given the present depth to the Culebra from the top of the Dewey Lake in the AIS, approximately 35 m (115 ft) of Dewey Lake might have been eroded during the Early Triassic before additional sediments were deposited. The Triassic thickness at the AIS is approximately 8 m (26 ft). Northeast of the WIPP site (T21S, R33E), Triassic rocks (Dockum Group) have a maximum local thickness of approximately 373 m (1,233 ft). This thickness is a reasonable estimate of the maximum thickness also attained at the WIPP site prior to the Jurassic Period. At the end of the Triassic, the total thickness at the WIPP site may have then attained approximately 586 m (1,863 ft) in two similar loading stages of a few million years each, over a period of approximately 50 million years.

The Jurassic outcrops nearest to the WIPP site are in the Malone Mountains of west Texas. There is no evidence that Jurassic rocks were deposited at or in the vicinity of the WIPP site.

As a consequence, the Jurassic is considered a time of erosion or nondeposition at the site, though erosion is most likely.

Widespread erosion during the Jurassic obviously cannot be broadly inferred for the area or there would not be thick Triassic rocks still preserved. Triassic rocks of this thickness are preserved nearby, indicating either pre-Jurassic tilting or that erosion did not occur until later (but still after tilting to preserve the Triassic rocks near the WIPP site). It is also possible that the immediate site area had little Triassic deposition or erosion, but very limited Triassic deposition (that is, 8 m [26 ft]) at the WIPP site seems unlikely.

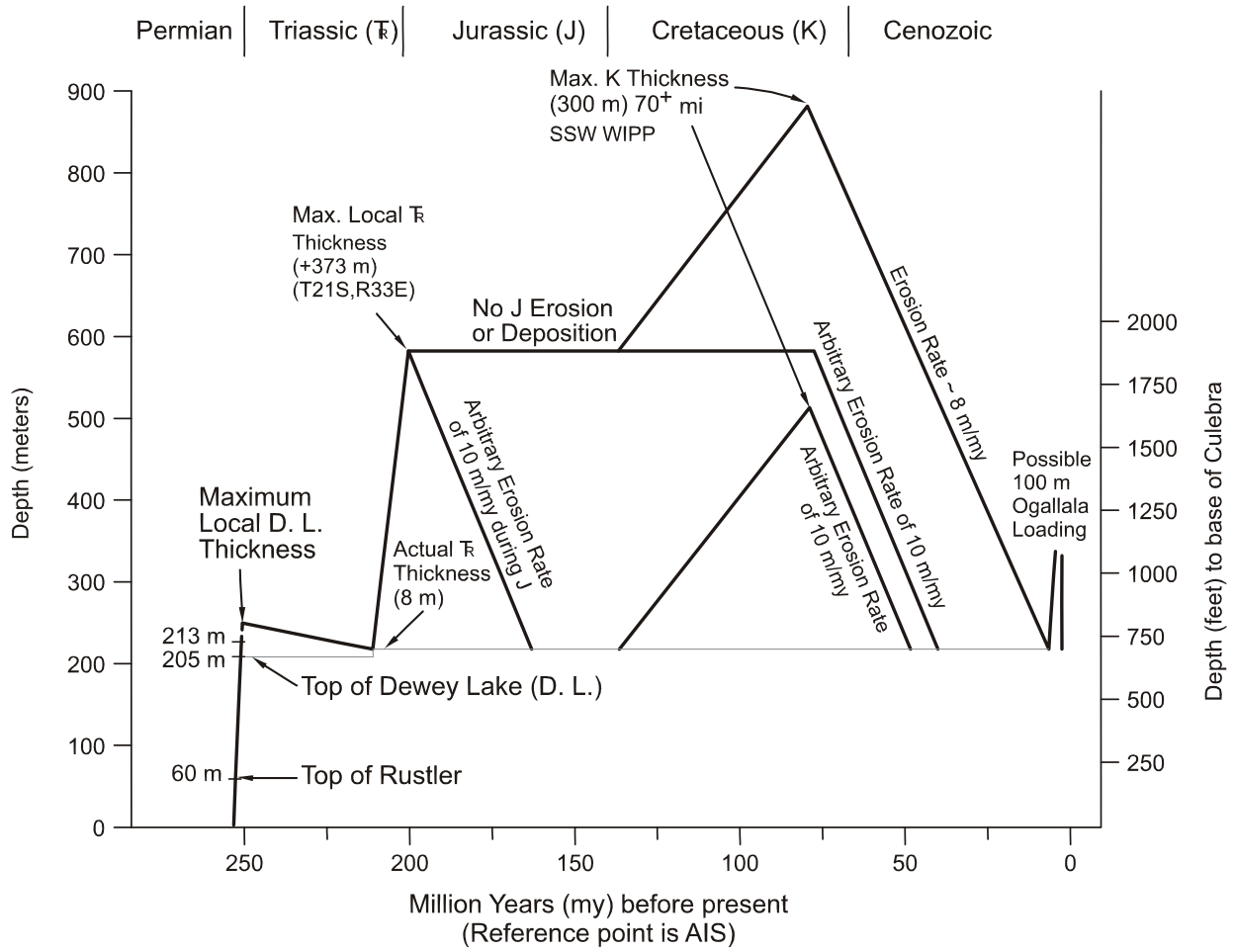

Note: The estimates are made with a reference point and depth to the base of the Culebra at the AIS. Source: Powers and Holt 1995, Figure 34.

Figure 2-25. Loading and Unloading History Estimated to the Base of the Culebra

Lang (1947) reported fossils from Lower Cretaceous rocks in the Black River Valley southwest of the WIPP site. Bachman (1980, p. 28) also reported similar patches of probable Cretaceous rocks near Carlsbad and south of White's City. From these reports, it is likely that some Cretaceous rocks were deposited at the WIPP site. Approximately 110 km (70 mi) south-southwest of the WIPP site, significant Cretaceous outcrops of both Early and Late Cretaceous age have a total maximum thickness of approximately 300 m (1,000 ft). Southeast of the WIPP, the nearest Cretaceous outcrops are thinner and represent only the Lower Cretaceous. Based on outcrops, a maximum thickness of 300 m (1,000 ft) of Cretaceous rocks could be estimated for the WIPP site. Compared to the estimate of Triassic rock thickness, it is less likely that Cretaceous rocks were this thick at the site. The uppermost lines of Figure 2-25 summarize the assumptions of maximum thickness of these units.

A more likely alternative is that virtually no Cretaceous rocks were deposited, followed by erosion of remaining Triassic rocks during the Late Cretaceous to the Late Cenozoic. Such erosion may also have taken place over an even longer period, beginning with the Jurassic Period. Ewing (1993) favors Early Cretaceous uplift and erosion for the Trans-Pecos Texas area, but does not analyze later uplift and erosional patterns.

In the general vicinity of the WIPP site, there are outcrops of Cenozoic rock from the Late Miocene (Gatuña and Ogallala Formations). There is little reason to infer any significant Early Cenozoic sediment accumulation at the WIPP site. Erosion is the main process inferred to have occurred during this period and an average erosion rate of approximately 10 m (33 ft) per million years is sufficient during the Cenozoic to erode the maximum inferred Triassic and Cretaceous thickness prior to Gatuña and Ogallala deposition. Significant thicknesses of Cretaceous rocks may not have been deposited, however, and average erosion rates could have been lower.

Maximum-known Gatuña thickness in the area around the WIPP is approximately 100 m (330 ft); at the WIPP site, the Gatuña is very thin to absent. Ogallala deposits are known from the Divide east of the WIPP site, as well as from the High Plains further east and north. On the High Plains northeast of the WIPP, the upper Ogallala surface slopes to the southeast at a rate of approximately 4 m/km (20 feet per mile). A straight projection of the 1,250-m (4,100-ft) contour line from this High Plains surface intersects the site area, which is at an elevation slightly above 1,036 m (3,400 ft). This difference in elevation of 213 m (700 ft) represents one estimate, probably near an upper bound, of possible unloading subsequent to deposition of the Ogallala Formation.

Alternatively, the loading and unloading of the Ogallala could have been closer to 100 m (330 ft). In any case, it would have occurred as a short-lived pulse over a few million years at most.

While the above inferences about greater unit thicknesses and probable occurrence are permissible, a realistic assessment suggests a more modest loading and unloading history (Powers and Holt 1995). It is likely that the Dewey Lake accumulated to near local maximum thickness of approximately 240 m (787 ft) before being slightly eroded prior to the deposition of Triassic rocks. It also is most probable that the Triassic rocks accumulated at the site to near local maximum thickness. In two similar cycles of rapid loading, the Culebra was buried to a depth of approximately 650 m (2,132 ft) by the end of the Triassic.

It also seems unlikely that a significant thickness of Cretaceous rock accumulated at the WIPP site. Erosion probably began during the Jurassic, slowed or stopped during the Early Cretaceous as the area was nearer or at base level, and then accelerated during the Cenozoic, especially in response to uplift as Basin and Range tectonics encroached on the area and the basin was tilted more. Erosional beveling of Dewey Lake and Santa Rosa suggest considerable erosion since tilting in the mid-Cenozoic. Erosion rates for this shorter period could have been relatively high, resulting in the greatest stress relief on the Culebra and surrounding units. Some filling occurred during the Late Cenozoic as the uplifted areas to the west formed an apron of Ogallala sediment across much of the area, but it is not clear how much Gatuña or Ogallala sediment was deposited in the site area. From general reconstruction of Gatuña history in the area (Powers and Holt 1993, p. 281), the DOE infers that Gatuña or Ogallala deposits likely were not much thicker at

the WIPP site than they are now. The loading and unloading spike (Figure 2-25) representing Ogallala thickness probably did not occur. Cutting and headward erosion by the Pecos River has created local relief and unloading by erosion.

At the WIPP site, this history is a little complicated by dissolution, though locally (for example, Nash Draw) the effects of erosion and dissolution are more significant. The underlying evaporites have responded to foundering of anhydrite in less dense halite beds. These have caused local uplift of the Culebra (as at ERDA 6) but little change in the overburden at the WIPP. Areas east of the WIPP site are likely to have histories similar to that of the site. West of the site, the final unloading is more complicated by dissolution and additional erosion leading to exposure of the Culebra along stretches of the Pecos River Valley.

2.1.5.3 Faulting

Fault zones are well known along the Central Basin Platform, east of WIPP, from extensive drilling for oil and gas, as reported by Hills (1984). Holt and Powers performed an analysis in 1988 (CCA Appendix FAC, p. 4-14) of geophysical logs from oil and gas wells to examine the regional geology for the Rustler. This analysis showed that faults along the margin of the Central Basin Platform displaced Rustler rocks of at least Late Permian age. The overlying Dewey Lake shows marked thinning along the same trend, according to Schiel (1988, Figure 21), but the structure contours of the top of the Dewey Lake are not clearly offset. Schiel (1988) concluded that the fault was probably reactivated during the Dewey Lake's deposition, but movement ceased at least by the time the Santa Rosa was deposited. No surface displacement or fault has been reported along this trend.

Muehlberger et al. (1978) mapped Quaternary fault scarps along the Salt Basin graben west of both the Guadalupe and Delaware mountains. These are the nearest known Quaternary faults of tectonic origin to the WIPP. Kelley (1971) inferred the Carlsbad and Barrera faults along the eastern escarpment of the Guadalupe Mountains based mainly on vegetative lineaments. Hayes and Bachman (1979) reexamined the field evidence for these faults in 1979 and concluded that they were nonexistent. Figure 2-26 illustrates major regional structures, including faults.

On a national basis, Howard et al. (1971, sheets 1 and 2) assessed the location and potential for activity of young faults. For the region around the WIPP site, Howard et al. (1971, sheet 1) located faults along the western escarpment of the Delaware and Guadalupe mountain trend. These faults were judged to be Late Quaternary (approximately the last 500,000 years) or older.

In summary, there are no known Quaternary or Holocene faults of tectonic origin that offset rocks at the surface nearer to the site than the western escarpment of the Guadalupe Mountains. A significant part of the tilt of basin rocks is attributed to a mid-Miocene to Pliocene uplift trend along the Guadalupe-Sacramento Mountains that is inferred on the basis of High Plains sediments of the Ogallala.

2.1.5.4 Igneous Activity

Within the Delaware Basin, only one feature of igneous origin is known to have formed since the Precambrian. An igneous lamprophyre dike or series of dikes occurs along a linear trace about

120 km (75 mi) long from the Yeso Hills south of White's City to the northeast of the WIPP site

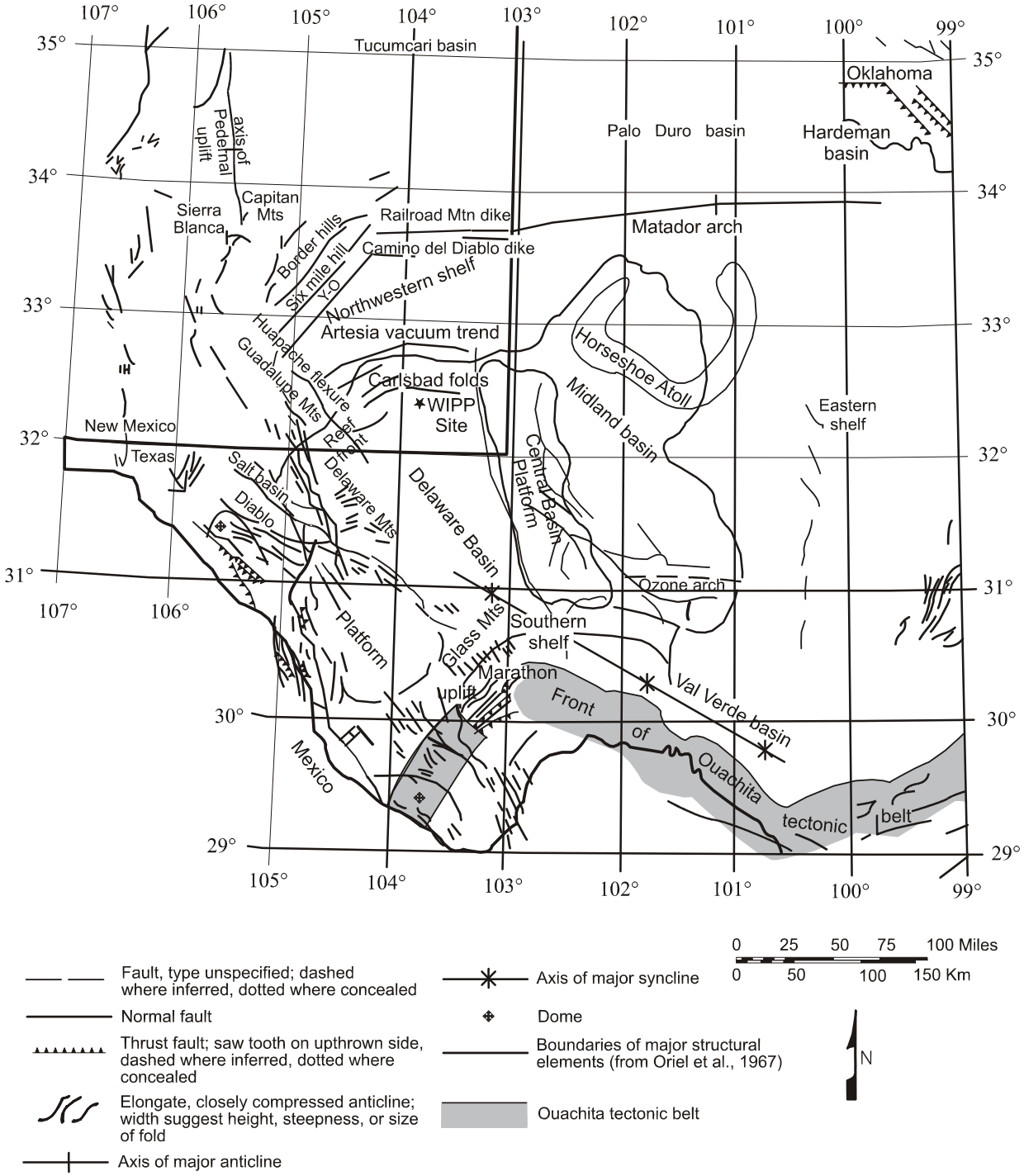

Figure 2-26. Regional Structures

(Elliot Geophysical Company 1976). At its closest, the dike trend passes about 13 km (8 mi) northwest of the WIPP site center, as shown in Figure 2-27. Evidence for the extent of the dike includes outcroppings at Yeso Hills, subsurface intercepts in boreholes and mines, and airborne magnetic responses.

An early radiometric determination for the dike by Urry (1936) yielded an age of 30 ± 1.5 million years. Work on dike samples by Calzia and Hiss (1978) is consistent with earlier work, indicating an age of 34.8 ± 0.8 million years.[2] Work by Brookins (1980) on polyhalite samples in contact with the dike indicated an age of about 21.4 million years. Volcanic ashes found in the Gatuña (Section 2.1.3.8) were airborne from distant sources and do not represent volcanic activity at the WIPP site.

2.1.6 Nontectonic Processes and Features

Nontectonic processes and features, which include evaporite deformation and dissolution of strata, are known to be active in the Delaware Basin. These processes are of interest because they represent mechanisms that are potentially disruptive to the repository in the long term. Both processes have been investigated extensively. The conclusions from these investigations are summarized in this section.

Halite in evaporite sequences is relatively plastic, which can lead to the process of deformation; it is also highly soluble, which can lead to the process of dissolution. Both processes (deformation and dissolution) can produce structural features similar to those produced by tectonic processes. The features developed by dissolution and deformation can be distinguished from similar-looking tectonic features where the underlying units do not reflect the same feature as do the evaporites. As an example, the evaporite deformation commonly does not affect the underlying Bell Canyon. Beds underlying areas of dissolved salt are not affected, but overlying units to the surface may be affected. The deformation in the Castile and Salado also tends to die out in overlying units, and the Rustler or the Dewey Lake may show little, if any, effects from deformed evaporites.

2.1.6.1 Evaporite Deformation

The most recent review of evaporite deformation in the northern Delaware Basin and original work to evaluate deformation is summarized here. More detail is provided in CCA Appendix DEF.

2.1.6.1.1 Basic WIPP History of Deformation Investigations

The Castile has been known for many years to be deformed in parts of the Delaware Basin, especially along the northern margin. Jones et al. (1973) clearly showed the Castile to be thicker from the northwestern to northern part of the basin margin, just inside the Capitan Reef. A dissertation by Snider (1966, Figures 11 and 14) and a paper by Anderson et al. (1972, Figure 10) also presented maps showing some evidence of thicker sections of Castile next to the

[2] Calzia and Hiss (1978, p. 44) reported 32.2 to 33.9 million years. However, Powers et al. 1978 (CCA Appendix GCR, p. 3-80) reported a recalculated value of 34.8 ± 0.8 million years based on a change in measured decay constant.

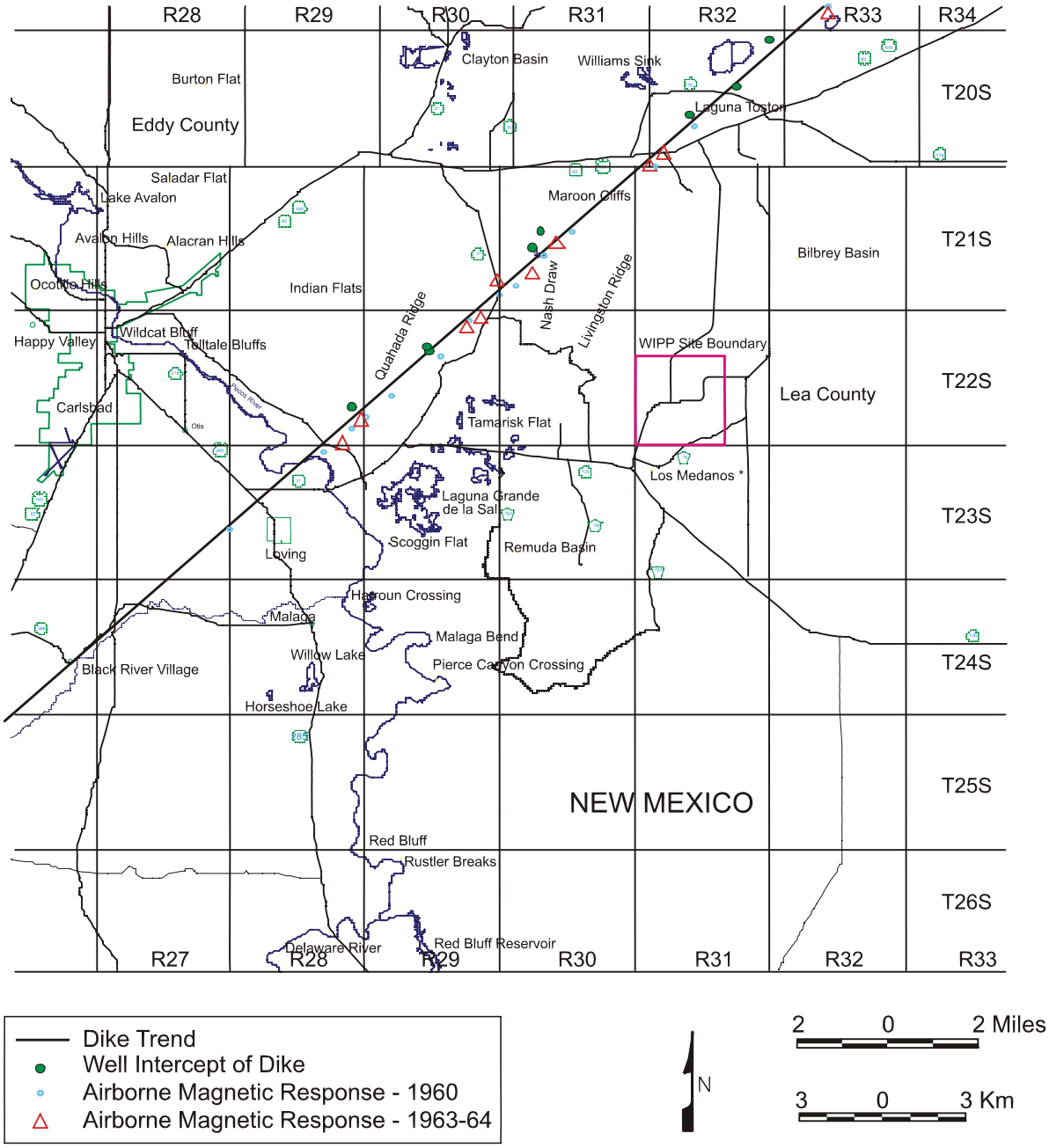

Source: Elliot (1976)

CCA-076-2

Figure 2-27. Igneous Dike in the Vicinity of the WIPP Site

Capitan. ERDA-6 was drilled during 1975 as part of the program to characterize an initial site for WIPP. The borehole penetrated increasingly deformed beds through the Salado into the Castile, and, at 826 m (2,711 ft) depth, the borehole began to produce pressurized brine and gas. Anderson and Powers (1978, p. 79) and Jones (1981a) interpreted beds to have been displaced structurally by as much as 289.5 m (950 ft). Some of the lower beds may have pierced overlying beds. The beds were considered too structurally deformed to mine reasonably along single horizons for a repository. Therefore, the site was abandoned in 1975, and the current site was located in 1976 (CCA Appendix GCR). The deformed beds around ERDA-6 were considered part of a deformed zone within about 10 km (6 mi) of the inner margin of the Capitan Reef. As a consequence, the preliminary selection criteria were revised to prohibit locating a new site within 10 km (6 mi) of the Capitan margin.

General criteria for the present site for the WIPP appeared to be met based on initial data from drilling (ERDA-9) and geophysical surveys. Beginning in 1977, the new site was more intensively characterized through geophysical surveys, including seismic reflection and drilling. Extensive seismic reflection work revealed good reflector quality in the southern part of the site and poor-quality or disturbed reflectors in a sector of the northern part of the site (see CCA Appendix DEF, Figure DEF-2.2). The area of disturbed reflectors became known as the disturbed zone, the area of anomalous seismic reflectors, or the zone of anomalous seismic reflection data. (The disturbed zone based on poor Castile seismic reflectors is completely different from the DRZ that describes the deformation around mined underground openings at the WIPP.)

Powers et al., in CCA Appendix GCR, Figures 4.4, 4.5, and 4.6, generally shows the disturbed zone beginning about 1.6 km (1 mi) north of the WIPP site center. Borns et al. (1983), included two areas south of the WIPP site as showing the same features of the disturbed zone. Neill et al.(1983) summarized the limits of the disturbed zone based on differing interpretations and included the area less than 1.6 km (1 mi) north of the site center, where the dip in the Castile begins to steepen. WIPP-11 was drilled in early 1978 about 5 km (3 mi) north of the site center over part of the disturbed zone where proprietary petroleum company data had also indicated significant seismic anomalies. The borehole encountered highly deformed beds within the Castile and altered thicknesses of halite units, but no pressurized brine and gas were found.

Less than 1.6 km (1 mi) north of the site center, seismic data indicated possible faulting of the upper Salado and the lower Rustler over the area of steepening Castile dips. Four boreholes (WIPP-18, -19, -21, -22) were drilled into the upper Salado and demonstrated neither faulting nor significant deformation of the Rustler-Salado contact. Lateral changes in the seismic velocity of the upper sections contributed to the interpretation of a possible fault and thus complicated interpretations of deeper structure.

WIPP-12 was located about 1.6 km (1 mi) north of the center of the site and drilled during 1978 to a depth of 850 m (2,785 ft) in the upper Castile to determine the significance of structure on possible repository horizons. The top of the Castile was encountered at an elevation about 49 m (160 ft) above the same contact in ERDA-9 at the site center.

WIPP-12 was deepened during late 1981 to a depth of 1,200 m (3,925 ft) to test for possible brine and gas in the deformed Castile. The probability of encountering brine and gas was

considered low because ERDA-6 and other known brine reservoirs in the Castile occurred in areas with greater deformation. During drilling, fractured anhydrite in the upper Castile (lower A3) began to yield pressurized brine and gas. The borehole was deepened to the basal anhydrite (A1) of the Castile. Subsequent reservoir testing (Popielak et al. 1983) was conducted to estimate reservoir properties (see Section 2.2.1.2.2 and Section 6.4.8).

As a consequence of discovering pressurized brine and gas in WIPP-12, the EEG recommended that the design of the facility be changed and that proposed waste disposal areas in the north be moved or reoriented to the south. After additional drilling of DOE-1, the DOE concluded that the design change had advantages, and the disposal facilities were placed south of the site center.

A microgravity survey of the site was designed to delineate further the structure within the disturbed zone, based on the large density differences between halite and anhydrite. The gravity survey was unsuccessful in yielding any improved resolution of the Castile structure.

DOE-2 was the last WIPP borehole to examine structure within the Castile. Potash drillhole data suggested a low point in Salado units about 3.3 km (2 mi) north of the site center. It was proposed by Davies (1984, p. 175) that the Salado low might indicate deeper dissolution of Castile halite, somewhat similar to the dissolution causing breccia pipes (see Section 2.1.6.2 on evaporite dissolution). The borehole demonstrated considerable Castile deformation, but there was no indication that halite had been removed by dissolution (Mercer et al. 1987; Borns 1987).

2.1.6.1.2 Extent of the Disturbed Zone at the Site

Nearby surface drilling, shafts, and underground drilling during early excavations at WIPP showed that the repository horizon varies modestly from the regional structure over the central part of the site; north of the site center, the beds dip gently to the south. Borns (1987) suggested that the south dip is probably related to the dip on the underlying Castile.

The upper surface of MB 139, under the repository horizon, exhibited local relief in the exploratory salt-handling shaft. Jarolimek et al. (1983, pp. 4 - 6) interpreted the relief as mainly caused by syndepositional growth of gypsum at the water-sediment interface to form mounds and by subsequent partial crushing. Jarolimek et al. (1983) concluded that the MB relief was not caused by deformation because the base of the MB showed no comparable relief. Based on concerns of the EEG, MB 139 was reevaluated. Borns (1985) found less relief on the upper surface of the MB in the areas they examined; he also concluded that depositional processes were responsible for the relief. In both cases, deformation is not thought to have caused the relief on MB 139.

For the investigation of geologic factors related to hydraulic properties of the Culebra, Powers (2002a; 2002b; 2003a) constructed elevation maps of the top of the Culebra for the region around the WIPP site. A simplified version (Figure 2-28) showing the elevations of the top of the Culebra in meters above mean sea level (m amsl) illustrates that deformation of the Castile propagated upward through the Culebra to the northeast of the WIPP site, forming a northwest-southeast trending anticline informally termed “the Divide anticline.” Across the

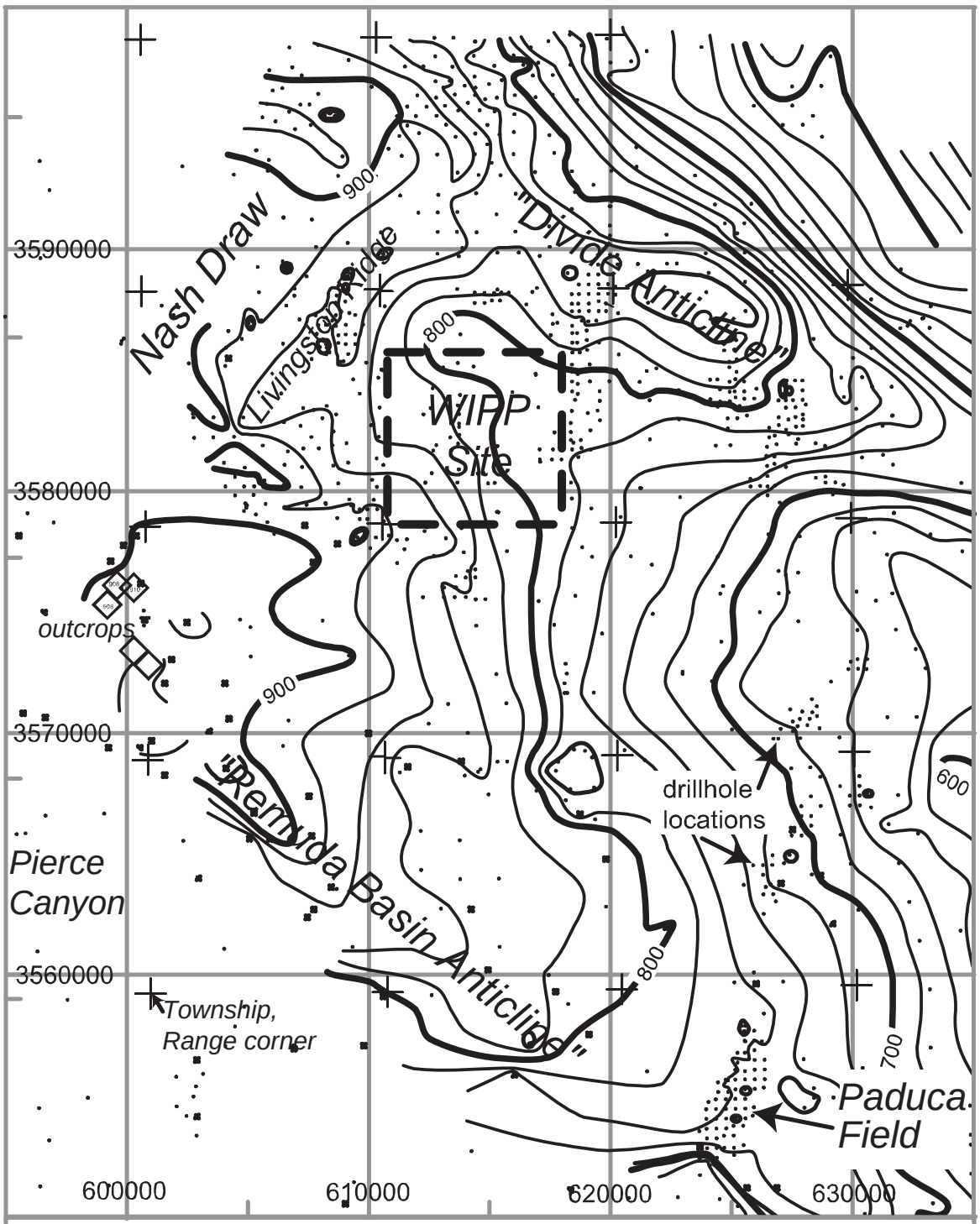

Explanation

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.
The contours for the elevation of the top of the Culebra are in meters (m) above mean sea level (amsl) (after Powers et al. 2003). Contour interval is 20 m.

Figure 2-28. Elevations of the Top of the Culebra Dolomite Member

WIPP site, the Culebra is slightly deformed by the deeper deformation, and the "disturbed zone" defined earlier geophysically is slightly evident at this horizon.

2.1.6.1.3 Deformation Mechanisms

In analyzing Castile structure in the northern Delaware Basin, Borns et al. (1983, p. 3) proposed five processes as the principal hypotheses to explain the structure: gravity foundering, dissolution, gravity sliding, gypsum dehydration, and depositional processes. Gravity foundering is the most comprehensive and best-accepted hypothesis of the five. It is based on the fact that anhydrite is much more dense (about 2.9 g/cm^3) than halite (about 2.1 g/cm^3), and anhydrite beds therefore have a potential for sinking into underlying halite. Regardless of which mechanism caused the disturbed zone, the important consideration is the long-term future effects. To evaluate this, Borns et al. (1983) postulated that both gravity-driven deformation mechanisms could be ongoing. The strain rates from such deformation are such that deformation would progress over the next 250,000 years and that such deformation would not directly jeopardize the disposal system.

2.1.6.1.4 Timing of Deformation of the Disturbed Zone at the Site

Jones (1981a, p. 18) estimated that deformation of the Castile and overlying rocks took place before the Ogallala Formation was deposited, as he believes the unit is undeformed. Anderson and Powers (1978, p. 79) inferred that data from ERDA-6 indicate that the Castile was deformed after the basin was tilted. Though these lines of evidence could be consistent with mid-Miocene deformation, there are other interpretations consistent with older deformation. There is no known evidence of surface deformation or other features to indicate recent deformation.

2.1.6.2 Evaporite Dissolution

Because evaporites are much more soluble than most other rocks, project investigators have considered it important to understand the dissolution processes and rates that occur within the site being considered for long-term isolation. These dissolution processes and rates constitute the limiting factor in any evaluation of the site. Over the course of the WIPP project, extensive resources have been committed to identify and study a variety of features in southeastern New Mexico interpreted to have been caused by dissolution. The subsurface distribution of halite for various units has been mapped. Several different kinds of surface features have been attributed to dissolution of salt or karst formation. The processes proposed or identified include point-source (brecciation), deep dissolution, shallow dissolution, and karst. These are each discussed in more detail in CCA Appendix DEF, Section DEF.3. Screening arguments relative to dissolution are presented in Appendix PA, Attachment SCR, FEPs N17 and N21 (including dissolution associated with abandoned boreholes in the discussion for FEP H34). These arguments are based principally on the observed rates and processes in the region. These are described below.

2.1.6.2.1 Brief History of Project Studies

Well before the WIPP project, several geologists recognized that dissolution is an important process in southeastern New Mexico, and that it contributed to the subsurface distribution of halite and to the surficial features. Early studies include those by Lee (1925), Maley and

Huffington (1953), and Olive (1957) Robinson and Lang (1938, p. 100) identified an area under Nash Draw where brine occurred at about the stratigraphic position of the upper Salado-basal Rustler and considered that salt had been dissolved to produce a dissolution residue. Vine (1963, p. B38 and B40) mapped Nash Draw and surrounding areas. Vine (1963) reported surficial domal structures, later called breccia pipes and identified as deep-seated dissolution and collapse features.

As the USGS and Oak Ridge National Laboratory (ORNL) began to survey southeastern New Mexico as an area in which to locate a repository site in salt, Brokaw et al. (1972) prepared a summary of the geology that included solution and subsidence as significant processes in creating the features of southeastern New Mexico. Brokaw et al. (1972) also recognized a solution residue at the top of the salt in the Salado in the Nash Draw area, and the unit commonly became known as the brine aquifer because it yielded brine. Brokaw et al. (1972) also interpreted the east-west decrease in thickness of the Rustler to be a consequence of removal by dissolution of halite and other soluble minerals.

During the early 1970s, the basic ideas about shallow dissolution of salt (generally from higher stratigraphic units and within a few hundred feet of the surface) were set out in a series of reports, as discussed in the following sections. Piper (1973; 1974) independently evaluated the geological survey data for ORNL. Claiborne and Gera (1974) concluded that salt was being dissolved too slowly from the near-surface units to affect a repository for several million years, at least.

By 1978, shallower drilling around the WIPP site to evaluate potash resources was interpreted by Jones (1978, p. 9), who felt that the Rustler included “dissolution debris, convergence of beds, and structural evidence for subsidence.” Halite in the Rustler has been reevaluated by the DOE, but there are only minor differences in inferred distributions among the various investigators. These investigators do have different explanations about how this distribution occurred (see Section 2.1.3.5 on Rustler stratigraphy): (1) through extensive dissolution of the Rustler’s halite after the Rustler was deposited, or (2) through syndepositional dissolution of halite from saline mud flat environments during Rustler deposition.

Anderson (1978) and Anderson et al. (1978) reevaluated halite distribution in deeper units, especially the Castile and Salado formations. They identified local anomalies proposed as features developed after deep dissolution of halite by water flowing upward from the underlying Bell Canyon. Anderson (1978) mapped geophysical log signatures of the Castile and interpreted lateral thinning and change from halite to non-halite lithology as evidence of lateral dissolution of deeper units (part of deep dissolution), and proposed that deep dissolution might threaten the WIPP site. In response to Anderson’s (1978) developing concepts, ERDA-10 was drilled south of the WIPP area during the latter part of 1977. ERDA-10 intercepted a stratigraphic sequence without evidence of solution residues in the upper Castile.

A set of annular or ring fractures is evident in the surface around San Simon Sink, about 30 km (18 mi) east of the WIPP site. Nicholson and Clebsch (1961, p. 14) suggested that San Simon Sink developed as a result of deep-seated collapse. WIPP-15 was drilled at about the center of the sink to a depth of 245 m (811 ft) to obtain samples for paleoclimatic data and stratigraphic data to interpret collapse. Anderson (1978) and Bachman (1980) both interpret San Simon Sink

as dissolution and collapse features, and the annular fractures are not considered evidence of tectonic activity.

Following the work by Anderson, Bachman (1980, 1981) mapped surficial features in the Pecos Valley, especially at Nash Draw, and differentiated between those surface features in the basin that were formed by karst and those that were formed by deep collapse features over the Capitan. WIPP-32, WIPP-33, and two boreholes over the Capitan Reef were eventually drilled. Their data, which demonstrated the concepts proposed by Bachman (1980, 1981), are documented in Snyder et al. (1982, p. 65).

A final program concerning dissolution and karst was initiated following a microgravity survey of a portion of the site during 1980. Based on localized low-gravity anomalies, Barrows et al. (1983) interpreted several areas within the site as locations of karst. WIPP-14 was drilled during 1981 at a low-gravity anomaly. It revealed normal stratigraphy through the zones proposed to be affected by karst. As a follow-up, Bachman (1985) also reexamined surface features around the WIPP and concluded that there was no evidence for active karst within the WIPP site. The nearest karst feature is northwest of the site boundaries at WIPP-33.

2.1.6.2.2 Extent of Dissolution

Within the Rustler, dissolution of halite is believed to have occurred only near the depositional margins, as discussed in Section 2.1.3.5. Figure 2-15 shows the only two areas where evidence has been found for halite dissolution from the M3/H3 horizon in the Tamarisk.

Upper intervals of the Salado thin dramatically west and south of the WIPP site (Figure 2-29) compared to deeper Salado intervals. There are no cores for further consideration of possible depositional variations. As a consequence, this zone of thinning is interpreted by the DOE as the edge of dissolution of the upper Salado.

2.1.6.2.3 Timing of Dissolution

The dissolution of Ochoan evaporites through the near-surface processes of weathering and groundwater recharge has been studied extensively (Anderson 1981; Lambert 1983a; Lambert 1983b; Bachman 1984; and CCA Appendix FAC). The work of Lambert (1983a) was specifically mandated by the agreement between the DOE and the state of New Mexico to evaluate in detail the conceptual models of evaporite dissolution proposed by Anderson (1981). There was no clear consensus among investigators on the volume of rock salt removed. Hence,

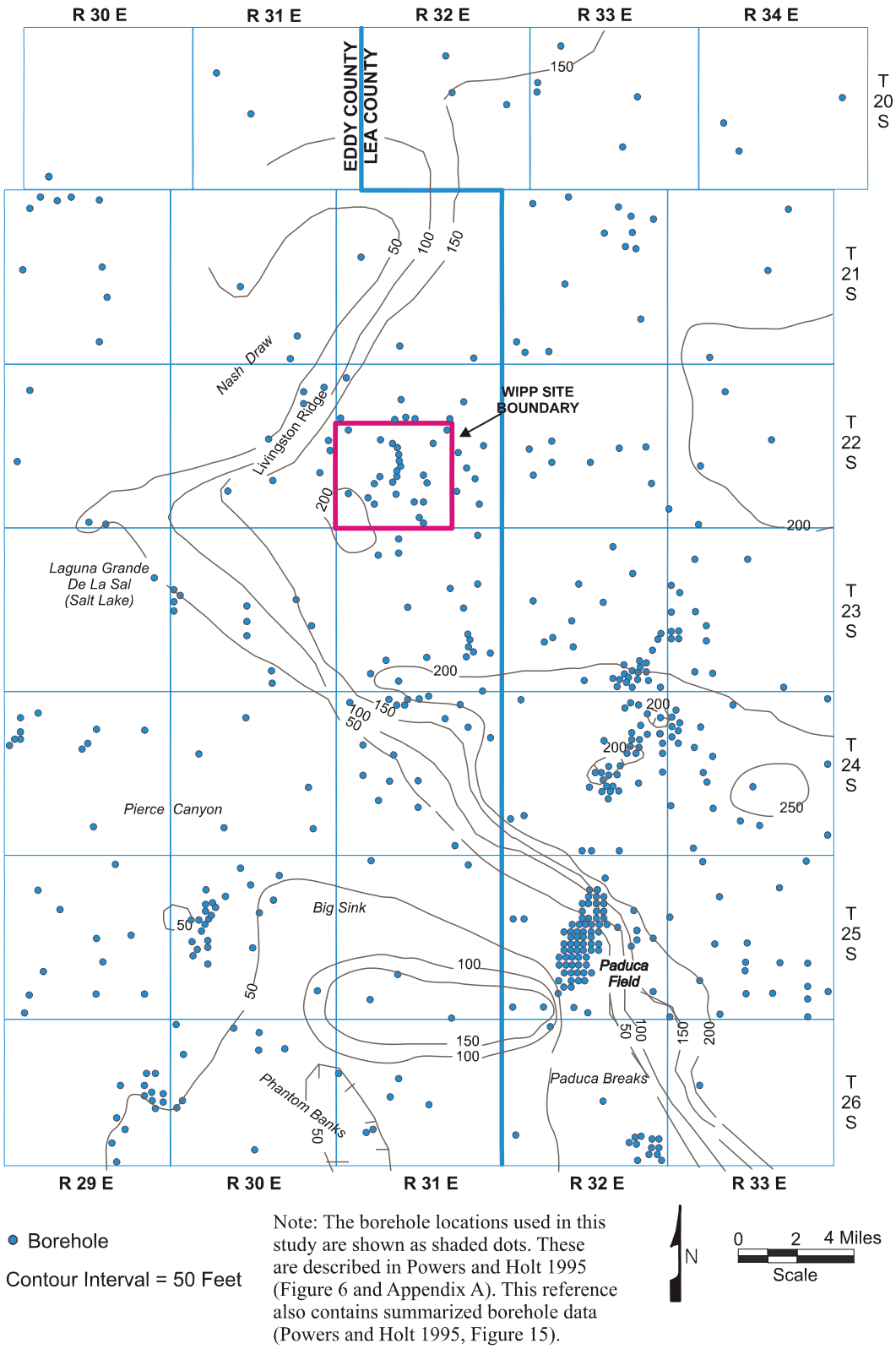

Figure 2-29. Isopach from the Base of MB 103 to the Top of the Salado

estimates of the instantaneous rate of dissolution vary significantly. Dissolution may have taken place as early as the Ochoan, during or shortly after deposition. For the Delaware Basin as a whole, Anderson (1981) proposed that up to 40 percent of the rock salt in the Castile and Salado formations was dissolved during the past 600,000 years. Lambert (1983b, p. 292) suggested that in many places the variations in salt-bed thicknesses inferred from borehole geophysical logs that were the basis for Anderson's (1981) calculation were depositional in origin, compensated by thickening of adjacent nonhalite beds, and were not associated with the characteristic dissolution residues. Borns and Shaffer (1985, p. 44 – 45) also suggested in 1985 a depositional origin for many apparent structural features attributed to dissolution.

Snyder (1985, p. 8), as well as earlier workers (for example, Vine 1963; Lambert 1983b; and Bachman 1984), attribute the variations in thickness in the Rustler, which crops out in Nash Draw, to postdepositional evaporite dissolution. Holt and Powers (CCA Appendix FAC, p. 9-2) have challenged this view and attribute the east-to-west thinning of salt beds in the Rustler to depositional facies variability rather than postdepositional dissolution. Bachman (1974, 1976, 1980) envisioned several episodes of dissolution since the Triassic, each dominated by greater degrees of evaporite exhumation and a wetter climate, interspersed with episodes of evaporite burial and/or a drier climate. Evidence for dissolution after deposition of the Salado and before deposition of the Rustler along the western part of the Basin was cited by Adams (1944, p. 1612). Others have argued that the evaporites in the Delaware Basin were above sea level and therefore potentially subject to dissolution, during the Triassic, Jurassic, Tertiary, and Quaternary periods. Because of discontinuous deposition, not all of these times are separable in the geological record of southeastern New Mexico. Bachman (1980) contends that dissolution was episodic during the past 225 million years as a function of regional base level, climate, and overburden.

There have been several attempts to estimate the rates of shallow dissolution in the basin. Bachman (1974) provided initial estimates of dissolution rates based on a reconstruction of Nash Draw relationships, including the observation that portions of the Gatuña were deposited over areas of active dissolution and subsidence of the underlying evaporites. Though these rates indicate no hazard to the WIPP related to Nash Draw dissolution, Bachman (1980, p. 85) later reconsidered the Nash Draw relationships and concluded that pre-Cenozoic dissolution had also contributed to salt removal. Thus, the initial estimated rates were too high.

With regard to deep dissolution, Anderson concluded in 1978 that the integrity of the WIPP to isolate radioactive waste would not be jeopardized by dissolution within about one million years. Anderson and Kirkland (1980, pp. 66 - 69) expanded on the concept of brine density flow proposed by Anderson (1978) as a means of dissolving evaporites at a point by circulating water from the underlying Bell Canyon. Wood et al. (1982, p. 100) examined the mechanism and concluded that, while it was physically feasible, it would not be effective enough in removing salt to threaten the ability of the WIPP to isolate transuranic (TRU) waste.

2.1.6.2.4 Features Related to Dissolution

Bachman (1980, p. 97) separated breccia pipes, formed over the Capitan Reef by dissolution and collapse of a cylindrical mass of rock, from evaporite karst features that appear similar to breccia pipes. There are surficial karst features, including sinks and caves, in large areas of the basin.

Nash Draw is the result of combined dissolution and erosion. Within the site boundaries, there are no known surficial features caused by dissolution or karst.

The subsurface structure of the Culebra is shown in Figure 2-28. South of the WIPP site, an antiformal structure informally called the "Remuda Basin anticline" has been created by dissolution of salt from the underlying Salado to the southwest of the anticline. Beds generally dip to the east, and salt removed to the west created the other limb of the structure. Units below the evaporites apparently do not show the same structure.

2.2 Surface Water and Groundwater Hydrology

The DOE has determined that the hydrological characteristics of the disposal system are important because contaminant transport via fluid flow has a potential to impact the performance of the disposal system. In addition, the EPA has provided numerous criteria related to groundwater in 40 CFR § 194.14(a). At the WIPP site, one of the DOE's selection criteria was to choose a location that would minimize this impact. This was accomplished when the DOE selected (1) a host formation that contains little groundwater and transmits it poorly, (2) a location where the effects of groundwater flow are minimal and predictable, (3) an area where groundwater use is low, (4) an area where there are no permanent surface waters, (5) an area where future groundwater use is unlikely, and (6) a repository host rock that will not likely be affected by anticipated possible long-term climate changes within 10,000 years.

The following discussion summarizes the characteristics of the groundwater and surface water at and around the WIPP site. This summary is based on data collection programs that were initiated with the WIPP program and that continue to some extent today. The purpose of these programs was to provide information sufficient for the development and use of predictive models of the groundwater movement at the WIPP site.

For a comprehensive understanding of the impact of groundwater and surface water on the disposal system, the following factors have been evaluated:

Groundwater

- Horizontal and vertical flow fluxes and velocities,
- Hydraulic interconnectivity between rock units,
- Hydraulic parameters (porosity, etc.),
- General groundwater use, and
- Chemistry (including, but not limited to, salinity, mineralization, age, Eh, and pH).

Surface Water

- Regional precipitation and evapotranspiration rates,
- Location and size of surface-water bodies,

- Water volume, flow rate, and direction,
- Drainage network,
- Hydraulic connection with groundwater,
- Soil hydraulic properties (infiltration), and
- General water chemistry and use.

Changes to the hydrological system due to human activity are evaluated in Chapter 6.0.

The specifics of groundwater modeling are found in Section 6.4.6, Appendix PA, Attachment MASS, Section MASS.14.2. The hydrological system is divided into four segments for the discussion in this chapter. These are: (1) the rock units below the Salado, which may impact the disturbed (human intrusion) performance of the disposal system, (2) the Salado, which mostly addresses the undisturbed performance of the disposal system, (3) the rock units above the Salado, which essentially impact only the disturbed (human intrusion) performance of the disposal system, and (4) the surface waters. The groundwater regime is discussed in Section 2.2.1, and the surface-water regime in Section 2.2.2.

The WIPP site lies within the Pecos River drainage area (Figure 2-23, see also Section 2.2.2, Figure 2-43). As discussed in the Final Environmental Impact Statement (FEIS) (DOE 1980, Section 7.1.1), the climate is semiarid, with a mean annual precipitation of about 0.33 m (13 in.), a mean annual runoff of 2.5 to 5 mm (0.1 to 0.2 in.), and a mean annual pan evaporation of more than 2.5 m (100 in.). Runoff is practically nonexistent and the WIPP does not have a well defined drainage pattern. The general movement of runoff can be inferred from the topography in Figure 2-23. Only one stream flow gaging station has been operated in the vicinity. This is at the location shown as Hill Tank in Figure 2-23. Observations at Hill Tank are discussed in Section 2.2.2.

Additional information about climatic conditions at the WIPP is given in Section 2.5.2. Brackish water with total dissolved solids (TDS) concentrations of more than 3,000 parts per million is common in the shallow wells near the WIPP site. Surface waters typically have high TDS concentrations, particularly of chloride, sulfate, sodium, magnesium, and calcium. Additional information about water quality is given in Section 2.4.2.

2.2.1 Groundwater Hydrology

At the WIPP site, the DOE has obtained groundwater hydrologic data from conventional and special-purpose test configurations in multiple surface boreholes. Geophysical logging of the boreholes has provided hydrologic information on the rock strata intercepted. Pressure measurements, fluid samples, and ranges of rock permeability have been obtained for selected formations through the use of standard and modified drill-stem tests. Slug injection or withdrawal tests and other flow-rate tests have provided data to aid in the estimation of transmissivity and storage. The hydraulic heads of groundwaters within many water-bearing zones in the region have been mapped from measured depths to water in the boreholes. Since the

CCA was submitted to the EPA in 1996, the DOE has implemented a number of monitoring programs (see Appendix MON-2004), including the Groundwater Monitoring Program, to meet the assurance requirements of 40 CFR § 191.14(b). In addition to the groundwater monitoring program, other hydrologic data gathered since the CCA come from logging of new or replacement wells, piezometers, special-purpose field investigations, and surveys of drilling practices in the Delaware Basin. A data summary of all these activities is provided in Appendix DATA.

Historically, the DOE has obtained hydrological data principally from a conventional well-monitoring network (Figures 2-3 through 2-6 are maps of the well locations) comprising 71 wells located on 45 separate wellpads (DOE 2003). Most of the 71 wells are completed only to a single hydrologic unit; however, six are multiple-completions to allow monitoring of two or more units in the same well. Hydrologic information (such as hydraulic head) is obtained at 80 completion intervals within the 71 wells. The focus of the hydrological monitoring is the Rustler (comprising 72 of the 80 monitored intervals) because this formation contains two of the most transmissive saturated units, the Culebra and Magenta Dolomites, which are important to the modeling of releases during various human intrusion scenarios. Limited hydrological monitoring of the Bell Canyon, Dewey Lake, and Santa Rosa also occurs.

Rock units that are shown in the conceptual models in Section 6.4 to be important to disposal system performance from a hydrological standpoint are the Castile, the Salado, the Rustler, and the Dewey Lake (Figures 2-30 and 2-31). However, other units which are discussed due to their significance in screening hydrological processes or because they are less important to the conceptual model include the Bell Canyon, the Capitan, the Rustler-Salado contact zone, and the supra-Dewey Lake units. These will also be discussed because they are features of the groundwater flow system of the WIPP region.

The Bell Canyon is of interest to the DOE because it is the first regionally continuous water-bearing unit beneath the WIPP and is the target stratigraphic horizon for salt-water injection by industry outside of the WIPP site boundary. The halite and anhydrite layers of the Castile provide a hydrologic barrier between the Salado and the underlying Bell Canyon. The Castile is of interest to PA because it contains isolated high-permeability zones containing pressurized brine. As discussed in Section 2.1.6.1, several such zones of pressurized brine have been intercepted by boreholes near the WIPP site, and one or more of these zones may exist at the WIPP site.

The Salado comprises low-permeability beds of variable composition. The low permeability of the Salado provides a hydrologic barrier in all directions between the repository and the accessible environment or more transmissive beds. At the repository horizon, a much higher

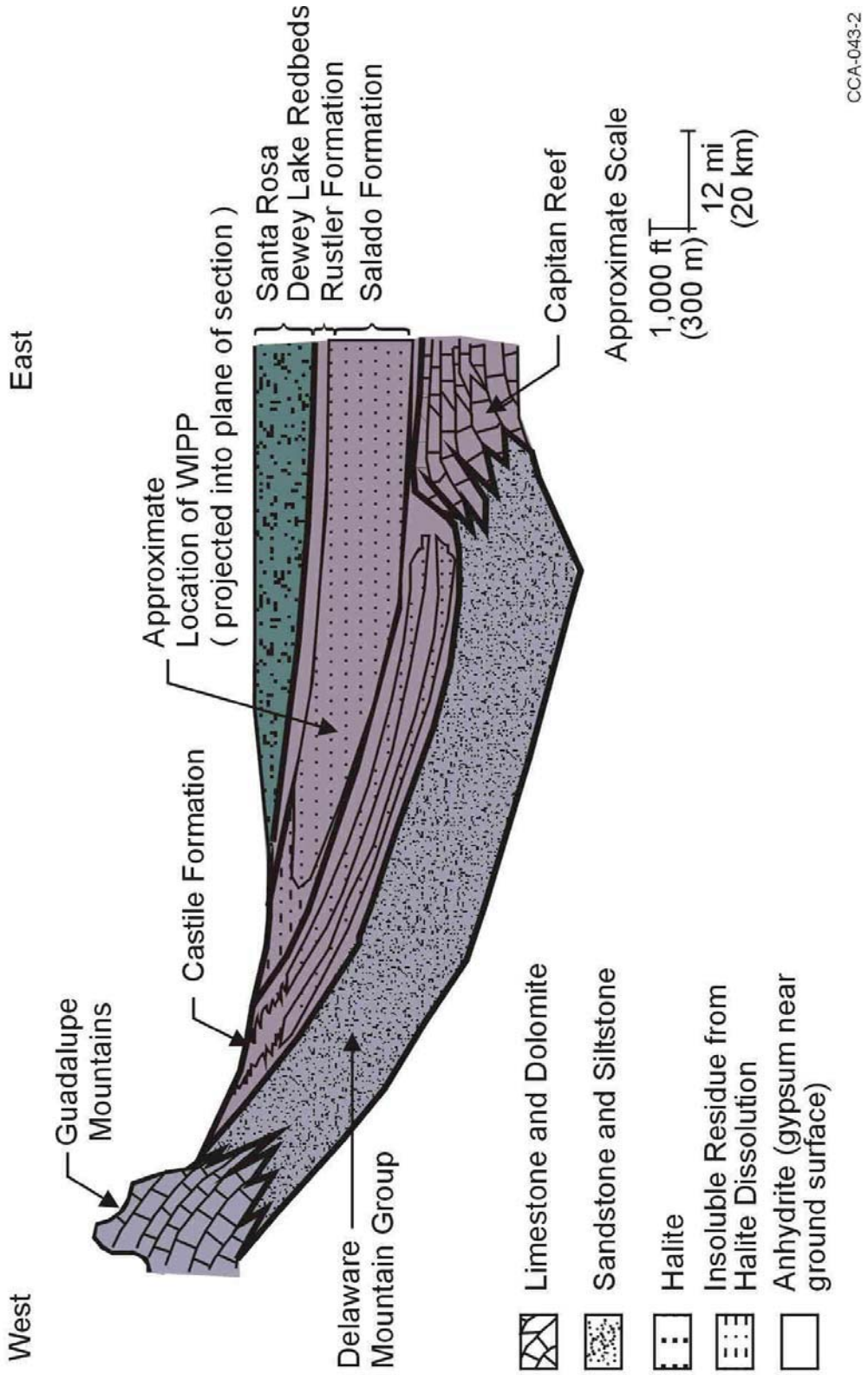

Figure 2-30. Schematic West-East Cross Section through the North Delaware Basin

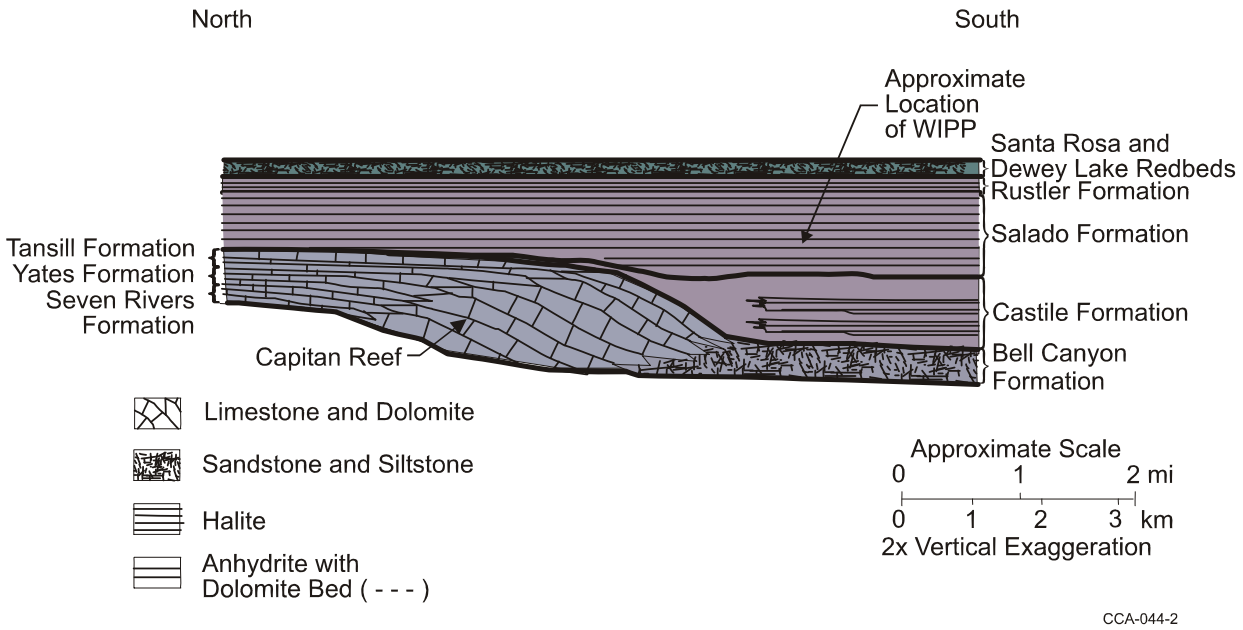

Figure 2-31. Schematic North-South Cross Section through the North Delaware Basin

permeability DRZ forms locally in the salt around the waste emplacement rooms and operational drifts. As described in Appendix DATA, the DRZ is of limited extent compared to the significant thickness of the Salado low-permeability beds surrounding the repository horizon.

The Rustler contains two laterally transmissive members. The Culebra is the first laterally continuous unit located above the WIPP underground facility to display hydraulic conductivity sufficient to warrant investigation for lateral contaminant transport. It is also the most transmissive continuously saturated unit above the WIPP repository. Therefore, except for a release directly to the surface, the Culebra provides the most direct pathway between the WIPP underground and the accessible environment. The hydrology and fluid geochemistry of the Culebra are complex and, as a result, have received a great deal of study (see, for example, LaVenue et al. 1988, 1990; Haug et al. 1987; and Siegel et al. 1991. The Magenta, although more transmissive than the anhydrite and claystone members of the Rustler, has lower transmissivity than the Culebra, and is unfractured at the WIPP.

There was no inflow of water from the Dewey Lake into the WIPP shafts after they were completed and prior to their lining, indicating unsaturated conditions or low transmissivity. However, since 1995, routine inspections of the WIPP exhaust shaft have revealed water entering the shaft at a depth of approximately 24 m (80 ft) at a location where no water had been observed during construction (the DOE is investigating the source and extent of this water; see Sections 2.2.1.4.2.1 and Appendix DATA). The quantity and quality of water in the Dewey Lake is also monitored in a deeper fractured zone in the Dewey Lake at well WQSP-6a (WIPP MOC 1995).

The Santa Rosa is shallow and unsaturated at the site (with the exception of a perched water table directly below the WIPP surface structures; see Section 2.2.1.4.2.2 and Appendix DATA), and apparently receives recharge only through infiltration.

In conclusion, at the WIPP site, the DOE recognizes the Salado as the most significant nontransmissive unit and the Culebra and the Magenta as the most significant transmissive units. Other units are considered to have less important roles. The DOE's sampling and analysis of non-Salado groundwater has focused on the Culebra and Magenta, and their hydrologic background, presented here, is more detailed than for other non-Salado rock units. Table 2-4 provides an overview of the hydrologic characteristics of the Rustler rock units at the WIPP site and the Rustler-Salado contact zone in Nash Draw. In developing this position on modeling the hydrology of the WIPP, the DOE considered several modeling approaches. These are summarized in CCA Appendix MASS, Section MASS.14.1 in general and Section MASS.15.1 for the Culebra. The DOE's conceptual models for hydrology are in Sections 6.4.5 and 6.4.6.

Table 2-4. Hydrologic Characteristics of the Rustler at the WIPP and in Nash Draw

Member	Thickness (meters)		Transmissivity (square meters per second)		Porosity	
	max	min	max	min	max	min
Forty-niner	23	13	8×10^{-8}	3×10^{-9}	—	—
Magenta	8.5	7	4×10^{-4}	1×10^{-9}	0.25	0
Tamarisk	56	26	2.7×10^{-11}	—	—	—
Culebra	11.6	4	1×10^{-3}	1×10^{-9}	0.30	0.03
Los Medaños	38	29	2.9×10^{-10}	2.2×10^{-13}	—	—
Rustler-Salado Contact Zone in Nash Draw	18	3	8.6×10^{-6}	3.2×10^{-11}	0.33	0.15

The EPA sought information supporting the conceptualization of the disposal system and the major site-related characteristics included in the PA modeling during the compliance review process for Section 194.14(a)(3). In general, the EPA concluded that the groundwater hydrology information for the various geologic and hydrostratigraphic units at the WIPP site identified the important characteristics of the PA and was therefore technically sufficient. The EPA also noted that the primary hydrogeologic units of concern relative to containment capability of the WIPP are the Castile, Salado, Rustler, and the Dewey Lake.

The EPA noted that the potential for fluid migration through Salado marker beds and the Culebra were acknowledged by DOE and included in the PA calculations. While the Dewey Lake is a potential underground source of drinking water (Section 8.2.2), DOE's modeling indicated that radionuclides will not reach the Dewey Lake, thus removing the formation as a unit needing consideration as a pathway (Docket A-93-02, Item II-G-26 and Docket A-93-02, Item II-G-28). The EPA concluded that Salado marker beds, and the Culebra were adequately identified and characterized to the level necessary for PA calculations.

2.2.1.1 Conceptual Models of Groundwater Flow

The DOE addresses issues related to groundwater flow and radionuclide transport within the context of a conceptual model of how the natural hydrologic system works on a large scale. The conceptual model of regional flow around the WIPP that is presented here is based on widely accepted concepts of regional groundwater flow in groundwater basins (see, for example, Hubbert 1940; Tóth 1963; and Freeze and Witherspoon 1967).

See CCA Appendix MASS, Sections MASS.14.1 and MASS.14.2 for a summary of the DOE's activities leading to the acceptance of the groundwater basin model as a reasonable representation of groundwater flow in the region.

An idealized groundwater basin is a three-dimensional closed hydrologic unit bounded on the bottom by an impermeable rock unit (units with much smaller permeability than the units above), on the top by the ground surface, and on the sides by groundwater divides. The water table is the upper boundary of the region of saturated liquid flow. All rocks in the basin are expected to have finite permeability; in other words, hydraulic continuity exists throughout the basin. This means that the potential for liquid flow from any unit to any other units exists, although the existence of any particular flow path is dependent on a number of conditions related to gradients and permeabilities. All recharge to the basin is by infiltration of precipitation to the water table and all discharge from the basin is by flow across the water table to the land surface.

Differences in elevation of the water table across an idealized basin provide the driving force for groundwater flow. The pattern of groundwater flow depends on the lateral extent of the basin, the shape of the water table, and the heterogeneity of the permeability of the rocks in the basin. Water flows along gradients of hydraulic head from regions of high head to regions of low head. The highest and lowest heads in the basin occur at the water table at its highest and lowest points, respectively. Therefore, groundwater flows from the elevated regions of the water table, downward across confining layers (layers with relatively small permeability), then laterally along more conductive layers, and finally upward to exit the basin in regions where the water table (and by association, the land surface) is at low elevations. Recharge is necessary to maintain relief on the water table, without which flow does not occur.

Groundwater divides are boundaries across which it is assumed that no groundwater flow occurs. In general, these are located in areas where groundwater flow is dominantly downward (recharge areas) or where groundwater flow is upward (discharge areas). Topography and surface-water drainage patterns provide clues to the location of groundwater divides. Ridges between creeks and valleys may serve as recharge-type divides, and rivers, lakes, or topographic depressions may serve as discharge-type divides.

In the groundwater basin model, rocks can be classified into hydrostratigraphic units. A hydrostratigraphic unit is a continuous region of rock across which hydraulic properties are similar or vary within described or stated limits. The definition of hydrostratigraphic units is a practical exercise to separate rock regions with similar hydrologic characteristics from rock regions with dissimilar hydrologic characteristics. Although hydrostratigraphic units often are defined to be similar to stratigraphic units, this need not be the case. Hydrostratigraphic unit boundaries can reflect changes in hydraulic properties related to differences in composition,

fracturing, dissolution, or a variety of other factors that may not be reflected in the definition of stratigraphic formations.

Confining layers in a groundwater basin model can be characterized as allowing vertical flow only. The amount of vertical flow occurring in a confining layer generally decreases in relation to the depth of the layer. Flow in conductive units is more complicated. In general, flow will be lateral through conductive units. The magnitude (in other words, volume flux) of lateral flow is related to the thickness, conductivity, and gradient present in the unit. Gradients generally decrease in deeper units. The direction of flow is generally related to the distance the unit is from the land surface. Near the land surface, flow directions are influenced primarily by the local slope of the land surface. In deeper conductive units, flow directions are generally oriented parallel to the direction between the highest and lowest points in a groundwater basin. Thus, flow rates, volumes, and directions in conductive units in a groundwater basin are generally not expected to be the same.

In the WIPP region, the Salado provides an extremely low-permeability layer that forms the base for a regional groundwater-flow basin in the overlying rocks of the Rustler, Dewey Lake, and Santa Rosa. The Castile and Salado together form their own groundwater system, and they separate flow in units above them from that in units below. Because of the plastic nature of halite and the resulting low permeability, fluid pressures in the evaporites are more related to lithostatic stress than to the shape of the water table in the overlying units, and regionally neither vertical nor horizontal flow will occur as a result of natural pressure gradients in time scales relevant to the disposal system. (On a repository scale, however, the excavations themselves create pressure gradients that may induce flow near the excavated region.) Consistent with the recognition of the Salado as the base of the groundwater basin of primary interest, the following discussion is divided into three sections: hydrology of units below the Salado, hydrology of the Salado, and hydrology of the units above the Salado. The DOE has implemented the groundwater basin model in the conceptual model for groundwater flow within the rocks above the Salado. The details of the model are discussed in Section 6.4.6. Key modeling assumptions associated with the implementation are provided in Appendix PA, Attachment MASS, Section MASS.14.2.

Technical issues related to the Castile brine, Salado marker bed permeability, and Culebra hydraulic properties (e.g., transmissivity variation) were raised by the EPA in a letter dated December 19, 1996 (Docket A-93-02, Item II-I-01). The DOE provided additional information regarding these issues in letters dated January 24, 1997; February 7, 1997; April 15, 1997; June 13, 1997; June 27, 1997; and July 3, 1997 (Docket A-93-02, Items II-I-03, II-I-07, II-I-24, II-H-44, II-H-45, and II-H-46, respectively).

A request was made in the December 19, 1996 EPA letter (Docket A-93-02, Item II-I-01) that DOE provide general hydraulic characteristic information for all geologic units within the disposal system by revising a partially complete table included in the letter. The DOE letter, dated February 14, 1997 (Docket A-93-02, Item II-I-08), transmitted the summary table providing the EPA with additional groundwater hydrology information related to hydraulic conductivity, storage coefficients, transmissivity, permeability, thickness, matrix and fracture characteristics, and hydraulic gradients for each of the geologic units in the WIPP disposal system. This information was reproduced as Figure IV-10 in EPA Technical Support Document

for Section 194.14: Content of Compliance Certification Application (Docket A-93-02, Item V-B-3).

In addition, the EPA in the December 19, 1996 EPA letter (Docket A-93-02, Item II-I-01) required the DOE to include the following in the discussion of conceptual models for groundwater flow: (1) the estimated infiltration at the surface and to the Dewey Lake, and (2) the estimated vertical flow of groundwater into other transmissive units within the area surrounding the WIPP. The DOE provided the estimates in a letter dated February 26, 1997 (Docket A-93-02, Item II-I-10) to EPA.

2.2.1.2 Units Below the Salado

Units of interest to the WIPP project below the Salado are the Bell Canyon and the Castile. These units have quite different hydrologic characteristics. Because of its potential to contain brine reservoirs below the repository, the hydrology of the Castile is regarded as having the most potential of all units below the Salado to impact the performance of the disposal system.

2.2.1.2.1 Hydrology of the Bell Canyon Formation

The Bell Canyon is considered for the purposes of regional groundwater flow to form a single hydrostratigraphic unit about 300 m (1,000 ft) thick. Tests at five boreholes (Atomic Energy Commission [AEC]-7, AEC-8, ERDA-10, DOE-2, and Cabin Baby [CB]-1) (CCA Appendix HYDRO, pp. 29-31; Beauheim et al. 1983, pp. 4-9 to 4-12; Beauheim 1986, p. 61-1]) indicate a range of hydraulic conductivities for the Bell Canyon from 1.7×10^{-7} to 3.5×10^{-12} m/s (5×10^{-2} ft/day to 1×10^{-6} ft/day). The pressure measured in the Bell Canyon at the DOE-2 and CB-1 boreholes at the time of the CCA ranged from 12.6 to 13.3 megapascals. Under the current groundwater-monitoring program, Bell Canyon water levels are measured in only two wells: CB-1 and AEC-8 (see locations in Figure 2-6).

After recovery from well work in 1999, the Bell Canyon water levels at CB-1 have remained steady for more that three years at 919 m (3,015 ft) above mean sea level (SNL 2003a). In contrast, since the beginning of 1994, the Bell Canyon water levels at AEC-8 have steadily risen by more than 32 m (106 ft) at a rate of approximately 0.5 m/month (1.6 ft/month) and stood at over 933.4 m (3,062 ft) above mean sea level (SNL 2003a) at the end of 2002. This water-level rise is hypothesized to be the result of deterioration of the well and not a response to actual Bell Canyon hydrologic conditions at this location. The well will be inspected and repaired or plugged and abandoned, as necessary, according to the requirements of DOE's groundwater monitoring program (see Appendix MON-2004).

Fluid flow in the Bell Canyon is markedly influenced by the presence of the extremely low-permeability Castile and Salado above it, which effectively isolate the Bell Canyon from interaction with overlying units except where the Castile is absent because of erosion or nondeposition, such as in the Guadalupe Mountains, or where the Capitan Reef is the overlying unit (Figures 2-30 and 2-31). Because of the isolating nature of the Castile and Salado, fluid flow directions in the Bell Canyon are sensitive only to gradients established over very long distances. At the WIPP, the brines in the Bell Canyon flow northeasterly under an estimated hydraulic gradient of 4.7 to 7.6 m/km (25 to 40 ft/mi) and discharge into the Capitan aquifer.

Velocities are on the order of tenths of feet per year, and groundwater yields from wells in the Bell Canyon are 2.3 to 5.8 liters (0.6 to 1.5 gallons) per minute. The fact that flow directions in the Bell Canyon under the WIPP are inferred to be almost opposite to the flow directions in units above the Salado (see Section 2.2.1.4) is not of concern because, as discussed above, the presence of the Castile and Salado makes the flow in the Bell Canyon sensitive to gradients established over long distances, whereas flow in the units above the Salado is sensitive to gradients established by more local variations in water table elevation.

As discussed in Appendix DATA, oil companies are currently involved in deep-well injection at several locations outside of the WIPP site boundary. Specifically, salt water (brine) produced during oil-field exploitation is injected into the Bell Canyon and Brushy Canyon Formations. For nearly four years, the DOE has monitored injection rates and pressures for a cluster of six of these salt water injection wells located approximately 1.6 to 2.4 km (1 to 1.5 mi) northeast of well H-9. Table 2-5 summarizes the depth intervals of the injection zones for each well. The cluster of six wells is currently injecting approximately 800 to 950 m^3 per day (5,000 to 6,000 barrels per day) of salt water; however, in previous years, injection has ranged from approximately 480 to 1270 m^3 per day (3,000 to 8,000 barrels per day) (SNL 2003a). Wellhead injection pressures typically range between 5.5 to 6.9 MPa (800 to 1,000 psi). Because only two Bell Canyon wells are currently being monitored, the effect of salt-water injection on Bell Canyon water levels is speculative, but water levels in the Bell Canyon monitoring well nearest the cluster (i.e., CB-1, Figure 2-6) indicate no response to the injection. Additional discussion on potential effects of salt-water injection on the WIPP hydrologic setting is provided below in Section 2.2.1.4.

2.2.1.2.2 Castile Hydrology

As described in Section 2.1.3, the Castile is dominated by low-permeability anhydrite and halite zones. However, fracturing in the upper anhydrite has generated isolated regions with much greater permeability than the surrounding intact anhydrite. These regions are located in the area of structural deformation, as discussed in Section 2.1.6.1.1. The higher-permeability regions of the Castile contain brine at pressures greater than hydrostatic and have been referred to as brine reservoirs (see Figure 2-32). The fluid pressure measured by Popielak et al. (1983) in the WIPP-12 borehole (12.7 megapascals) is greater than the nominal hydrostatic pressure for a column of equivalent brine at that depth (11.1 megapascals).

Therefore, under open-hole conditions, brine could flow upward to the surface through a borehole.

Results of hydraulic tests performed in the ERDA-6 and WIPP-12 boreholes suggest that the extent of the highly permeable portions of the Castile is limited. As discussed in Section 2.1.3.3 and modeled in Section 6.4.8, the vast majority of brine is thought to be stored in low-permeability microfractures; about five percent of the overall brine volume is stored in large

Table 2-5. Depth Intervals of the Injection Zones of Six Salt-Water Injection Wells Located Near Well H-9 (after SNL 2003a)

Injection Well	Depth Interval of Injection Zone, feet[1]
Cal Mon #5	4,484 – 5,780[2]
Sand Dunes 28F#1[3]	4,295 – 5,570[2]
Pure Gold B F#20[3]	7,740 – 7,774[4]
Todd 26F#2	4,460 – 5,134[2]
Todd 26F#3	4,390 – 6,048[2]
Todd 27F#16	4,694 – 5,284[2]

(1) Below ground surface, bgs
(2) Bell Canyon Formation
(3) Wells hydraulically connected to same manifold
(4) Brushy Canyon Formation

open fractures. The volumes of the ERDA-6 and WIPP-12 brine reservoirs were estimated by Popielak et al. (1983) to be 100,000 m^3 (3.5×10^6 ft^3) and 2,700,000 m^3 (9.5×10^7 ft^3), respectively. The conceptual model of the Castile brine region is discussed in Section 6.4.8. The model uses parameter values derived from the ERDA-6 and WIPP-12 tests for quantifying some reservoir characteristics. The derivation of some model parameters in Appendix PA, Attachment PAR, Table PAR-44 from the data discussed here is also given in CCA Appendix MASS, Section MASS.18.

A geophysical survey using time-domain electromagnetic (TDEM) methods was completed over the WIPP-12 brine reservoir and the waste disposal panels (The Earth Technology Corporation 1988). The TDEM measurements detected a conductor interpreted to be the WIPP-12 brine reservoir and also indicated that similar brine occurrences may be present within the Castile under a portion of the waste disposal panels. Powers et al. (1996) used 354 drill holes and 27 Castile brine occurrences to establish that there is an eight percent probability of a hole drilled into the waste panel region encountering brine in the Castile. This analysis was included as CCA Appendix MASS, Attachment 18-6.

Initially, the EPA found that DOE's discussion of the size, orientation, and repressurization potential of the Castile brine reservoirs was not well supported (Docket A-93-02, Item II-I-27). The EPA required the probability of encountering a brine reservoir to be sampled between a range of 1 and 60 percent in the PAVT (Docket A-93-02, Item II-G-26 and Docket A-93-02, Item II-G-28). In addition, the EPA modified the values for parameters such as bulk compressibility of Castile rock so that the brine reservoir sampling used in the PA would better represent the larger, higher-end possible brine volumes. Further information on the EPA review of these parameters may be found in CARD 23—Models and Computer Codes (EPA 1998f), EPA Technical Support Document for Section 23: Models and Computer Codes (Docket A-93-02, Item V-B-6), and EPA Technical Support Document for Section 23: Ground

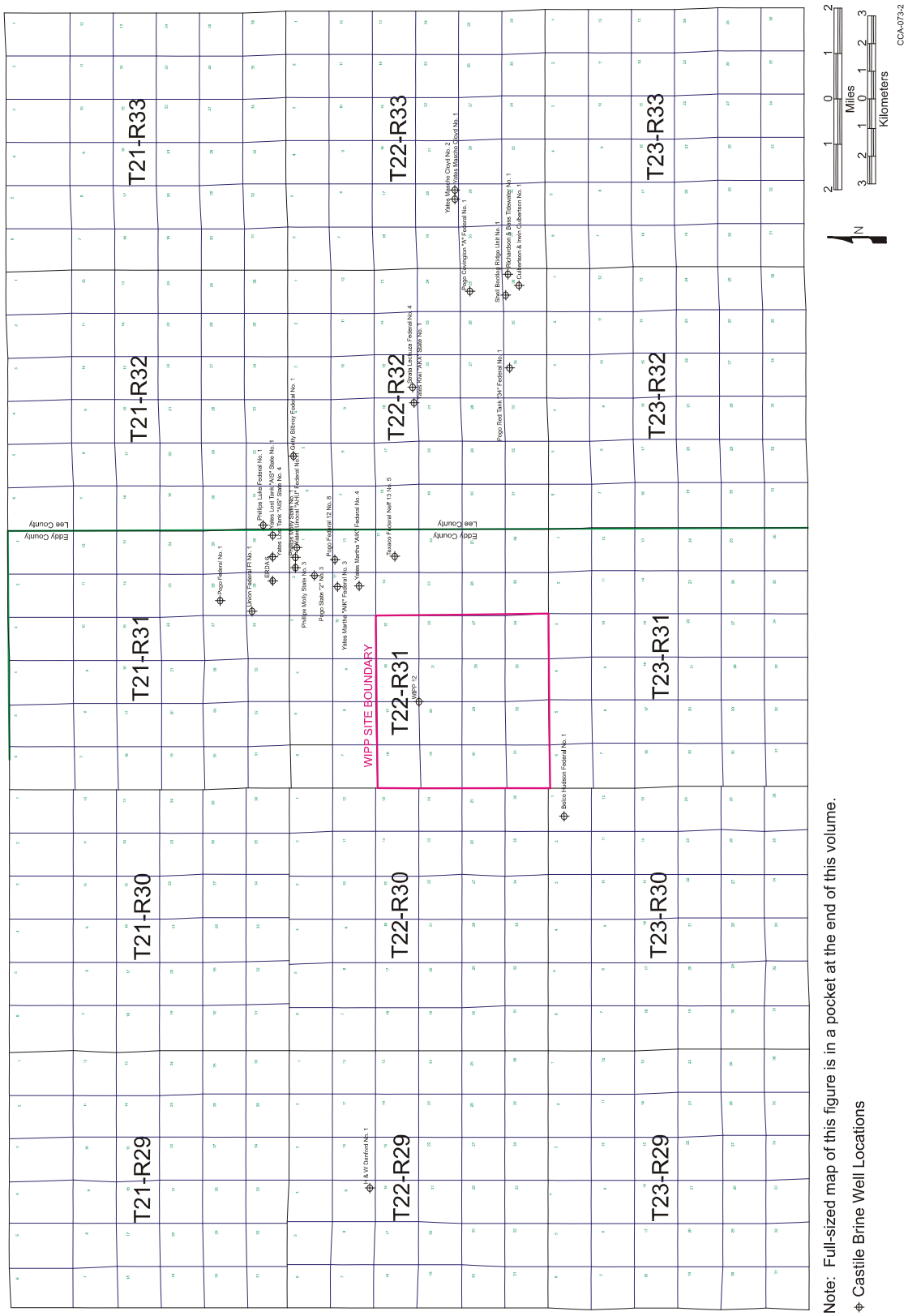

Note: Full-sized map of this figure is in a pocket at the end of this volume.

⌖ Castile Brine Well Locations

Figure 2-32. Recent Occurrences of Pressurized Brine in the Castile

Water Flow and Contaminant Transport Modeling at WIPP (Docket A-93-02, Item V-B-7). The PAVT used modified Castile brine reservoir characteristics and showed that the WIPP still meets the containment requirements (Docket A-93-02, Item II-G-26, Figure 7-2).

Based on these analyses, there was no significant impact on releases over the range of probabilities sampled. However, the DOE identified this parameter as a compliance monitoring parameter (see Appendix DATA) and conducts annual surveys as part of the Delaware Basin Monitoring Program (see Appendix MON-2004) to identify Castile brine encounters by drillers in the basin. Since the CCA, these surveys have identified five additional brine encounters. Appendix DATA provides extensive information pertinent to the brine reservoirs. The Delaware Basin Monitoring Annual Report (DOE 2002a), for example, documents three of the five Castile brine encounters. Two were located near well ERDA-6 northeast of the WIPP site and one was located to the southwest of the site. In the two encounters northeast of the site, reports indicated several hundred barrels of brine per hour were produced, but all brine was contained within the pits; thus, it was not necessary to file a report with the New Mexico Oil Conservation Division. In the other encounter, initial flows of from 64 to 79 m^3 (400 to 500 barrels) per hour were observed, but flow dissipated within hours of the encounter. Because of the relatively large number of boreholes (345 wells in the nine-township area drilled between 1996 and 2002), the five brine encounters that occurred do not substantially change the probability defined by Powers et al. (1996) and are unlikely to have any significant impact on PA given the large range of probabilities sampled in the PAVT analyses.

The origin of brine in the Castile has been investigated geochemically. Popielak et al. (1983, p. 2) concluded that the ratios of major and minor element concentrations in the brines indicate that these fluids originated from ancient seawater and that no evidence exists for fluid contribution from present meteoric waters. The Castile brine chemistries from the ERDA-6 and WIPP-12 reservoirs are distinctly different from each other and from local groundwaters. These geochemical data indicate that brine in reservoirs has not mixed to any significant extent with other waters and has not circulated. The brines are saturated, or nearly so, with respect to halite and, consequently, have little potential to dissolve halite. The chemical composition of Castile brine is given in Table 2-6. It's the use of the chemical composition of Castile brine as a parameter in the conceptual model of repository performance is discussed in Appendix PA.

2.2.1.3 Hydrology of the Salado

As described in Section 2.1.3, the Salado consists mainly of halite and anhydrite. A considerable amount of information about the hydraulic properties of these rocks has been collected through field and laboratory experiments. Appendix PA summarizes this information.

Hydraulic testing in the Salado in boreholes in the WIPP underground repository provided quantitative estimates of the hydraulic properties controlling brine flow through the Salado (Beauheim et al. 1991a; Beauheim et al. 1993; Domski et al. 1996; Roberts et al. 1999). This work was summarized by Beauheim and Roberts (2002). The stratigraphic intervals tested

Table 2-6. WIPP Salado and Castile Brine Compositions

	Salado Brine Average (n between 82 and 96)		Castile ERDA-6	Castile WIPP-12
Specific Gravity	1.22	± 0.01	1.216	1.215
pH	6.1		6.17	7.06
Sodium	79100	± 2,100	112000	138000
Potassium	15900	± 800	3800	2900
Calcium	282	± 38	490	350
Magnesium	22700	± 1,400	450	1600
Boron	1450	± 120	680	990
Lithium	nd		240	280
Silicon	1.6	± 0.7	21	27
Strontium	1.6	± 0.6	18	19
Ammonium	148	± 16	1119	476
Nitrate	0.8	(median)	2746	2436
Chloride	193000	± 4,000	170000	178000
Sulfate	17000	± 900	16000	18000
Bromide	1500	± 60	880	510
Iodide	14.8	± 3.1	28	24
Alkalinity (as HCO_3^- equivalent)[1]	883	± 123	2600	2700
Total Organic Carbon	54	± 50	nd	nd
Total Dissolved Solids	374000	± 13,000	330000	328000

[1] Alkalinity measured to an endpoint pH of 2.5 and expressed as equivalent bicarbonate.

Legend:

nd not determined

Note: All determinands reported in units of milligrams per liter (mg/L), except for pH and Specific Gravity. Only determinands with a concentration in excess of 10 mg/L in at least one of the brines are shown. Data taken from DOE (1994, Table 3-3) and Popeliak et al. (1983, Table C.2).

include both pure and impure halite, as well as anhydrite. Tests influence rock as far as 10 m (33 ft) distant from the test zone and therefore provide results representative of rock beyond the zone of mechanical disturbance associated with drilling of the test boreholes. Because tests close to the repository are within the DRZ that surrounds the excavated regions (see Section 3.2), results of the tests farthest from the repository are most representative of undisturbed conditions.

Fifty-nine intervals were isolated and monitored and/or tested in 27 boreholes. Thirty-five of the intervals isolated halite beds, and 24 isolated anhydrite beds. Permeability estimates were obtained from 14 of the halite intervals and 16 of the anhydrite intervals. Interpreted

permeabilities using a Darcy-flow model vary from 2×10^{-23} to 3×10^{-16} m^2 for impure halite intervals, with the lower values representing halite with few impurities and the higher values representing intervals within the DRZ of the excavations. Interpreted formation pore pressures vary from atmospheric to 9.8 MPa for impure halite, with the lower pressures showing the effects of the DRZ. Tests in pure halite show no observable response, indicating either extremely low permeability ($<10^{-23}$ m^2), or no flow whatsoever, even though appreciable pressures are applied to the test intervals.

Interpreted permeabilities using a Darcy-flow model vary from 2×10^{-20} to 9×10^{-18} m^2 for anhydrite intervals. Interpreted formation pore pressures vary from atmospheric to 14.8 MPa for anhydrite intervals (Beauheim and Roberts 2002 p. 82). Lower values are caused by depressurization near the excavation.

As discussed in Beauheim and Roberts (2002), permeabilities of some tested intervals have been found to be dependent on the pressures at which the tests were conducted, which is interpreted as the result of fracture apertures changing in response to changes in effective stress. Flow dimensions inferred from most test responses are subradial, meaning that flow to/from the test boreholes is not radially symmetric but is derived from a subset of the rock volume. The subradial flow dimensions are believed to reflect channeling of flow through fracture networks, or portions of fractures, that occupy a diminishing proportion of the radially available space, or through percolation networks that are not “saturated” (that is, fully interconnected). This is probably related to the directional nature of the permeability created or enhanced by excavation effects. Other test responses indicate flow dimensions between radial and spherical, which may reflect propagation of pressure transients above or below the plane of the test interval or into regions of increased permeability (e.g., closer to an excavation). The variable stress and pore-pressure fields around the WIPP excavations probably contribute to the observed non-radial flow dimensions.

The properties of anhydrite interbeds have also been investigated in the laboratory. Tests were performed on three groups of core samples from MB 139 as part of the Salado Two-Phase Flow Laboratory Program. The laboratory experiments provided porosity, intrinsic permeability, and capillary pressure data. Analysis of capillary pressure test results indicates a threshold pressure of less than 1 MPa. Both laboratory and field data were used to establish hydraulic parameters for the Salado for PA as summarized in CCA Appendix PAR (Tables PAR-6 and PAR-7).

The EPA believed the DOE’s initial information on anhydrite characteristics and response to high pressure was unclear. In response, the DOE provided the EPA with data on modeling implementation and anhydrite characterization clarifying DOE’s approach to anhydrite fracture properties under pressurized conditions. The EPA concluded that while fracture distribution and subsequent fluid flow in the Salado marker beds cannot be detailed, the general application of fracturing and subsequent fluid flow appears to be an adequate representation of overall site conditions. The EPA also concluded that DOE’s modeling of fractures within Salado anhydrite marker beds is acceptable. For further discussion on this topic, see CARD 23—Models and Computer Codes, Section 1.3.2.

Fluid pressure above hydrostatic is a hydrologic characteristic of the Salado (and the Castile) that plays a potentially important role in the repository behavior. It is difficult to measure natural

pressures in these formations accurately because the boreholes or repository excavations required to access the rocks decrease the stress in the region measured. Stress released instantaneously decreases fluid pressure in the pores of the rock, so measured pressures must be considered as a lower bound of the natural pressures. Stress effects related to test location and the difficulty of making long-duration tests in lower-permeability rocks result in higher pore pressures observed to date in anhydrites. The highest observed pore pressures in halite-rich units, near Room Q, are on the order of 9 MPa, whereas the highest pore pressures observed in anhydrite are approximately 12 MPa (Beauheim and Roberts 2002, p. 82). Far-field pore pressures in halite-rich and anhydrite beds in the Salado at the repository level are expected to be similar because the anhydrites are too thin and of too low permeabilities to have liquid pressures much different than those of the surrounding salt. For comparison, the hydrostatic pressure for a column of brine at the depth of the repository is about 7 MPa, and the lithostatic pressure calculated from density measurements in ERDA-9 is about 15 MPa.

Fluid pressures in sedimentary basins that are much higher or much lower than hydrostatic are referred to as abnormal pressures by the petroleum industry, where they have received considerable attention. In the case of the Delaware Basin evaporites, the high pressures are almost certainly maintained because of the large compressibility and plastic nature of the halite and, to a lesser extent, the anhydrite. The lithostatic pressure at a particular horizon must be supported by a combination of the stress felt by both the rock matrix and the pore fluid. In highly deformable rocks, the portion of the stress that must be borne by the fluid exceeds hydrostatic pressure but cannot exceed lithostatic pressure.

Brine content within the Salado is estimated at 1 to 2 percent by weight, although the thin clay seams have been inferred by Deal et al. (1993, pp. 4-3) to contain up to 25 percent brine by volume. Where sufficient permeability exists, this brine will move towards areas of lower hydraulic potential, such as a borehole or mined section of the Salado.

Observation of the response of pore fluids in the Salado to changes in pressure boundary conditions at walls in the repository, in boreholes without packers, in packer-sealed boreholes, or in laboratory experiments is complicated by low permeability and low porosity. Qualitative data on brine flow to underground workings and exploratory boreholes were collected routinely between 1985 and 1993 under the Brine Sampling and Evaluation Program (BSEP) and have been documented in a series of reports (Deal and Case 1987; Deal et al. 1987, 1989, 1991a, 1991b, 1993, and 1995). A discussion of alternative conceptual models for Salado fluid flow is given in Appendix PA, Attachment MASS, Section MASS.7. Additional data on brine inflow are available from the Large-Scale Brine Inflow Test (Room Q). Flow has been observed to move to walls in the repository, to boreholes without packers, and to packer-sealed boreholes. These qualitative and relatively short-term observations suggest that brine flow in the fractured DRZ is a complex process. In some locations, evidence for flow is no longer observed where it once was; in others, flow has begun where it once was not observed. In many cases, observations and experiments must last for months or years to obtain useful results.

For PA modeling, brine flow is a calculated term dependent on local hydraulic gradients and properties of the Salado units. Data on pore pressure and permeability of halite and anhydrite layers are available from the Room Q tests and other borehole tests as summarized in Beauheim

and Roberts (2002), and these data form the basis for the quantification of the material properties used in the PA. See Section 6.4.3.2 for a description of the repository fluid flow model.

Because brine is an important factor in repository performance, several studies of its chemistry have been conducted. Initial investigations were reported in Powers et al. (CCA Appendix GCR, Section 7.5) and were continued once access to the underground was established. The most comprehensive data were developed by the BSEP (Deal and Case 1987; Deal et al. 1987, 1989, 1991a, 1991b, 1993, 1995). Results are summarized in Table 2-6. CCA Appendix SOTERM discusses the role of brine chemistry in the conceptual model for actinide dissolution. The conceptual model is described in Section 6.4.3.5.

2.2.1.4 Units Above the Salado

In evaluating groundwater flow above the Salado, the DOE considers the Rustler, Dewey Lake, Santa Rosa, and overlying units to form a groundwater basin with boundaries coinciding with selected groundwater divides as discussed in Section 2.2.1.1. The model boundary follows Nash Draw and the Pecos River valley to the west and south and the San Simon Swale to the east (Figure 2-33). The boundary continues up drainages and dissects topographic highs along its northern part. These boundaries represent groundwater divides whose positions remain fixed over the past several thousand years and 10,000 years into the future. For reasons described in Section 2.2.1.2.1, the lower boundary of the groundwater basin is the upper surface of the Salado. Nash Draw and the Pecos River are areas where discharge to the surface occurs. Hunter (1985) described discharge at Surprise Spring and into saline lakes in Nash Draw. She reported groundwater discharge into the Pecos River between Avalon Dam north of Carlsbad and a point south of Malaga Bend as approximately 0.92 m^3/s (32.5 ft^3/s), mostly in the region near Malaga Bend.

Within this groundwater basin, hydrostratigraphic units with relatively high permeability are called conductive units, and those with relatively low permeability are called confining layers. The confining layers consist of halite and anhydrite and are perhaps five orders of magnitude less permeable than conductive units.

In a groundwater basin, the position of the water table moves up and down in response to changes in recharge. The amount of recharge is generally a very small fraction of the amount of rainfall; this condition is expected for the WIPP. Modeling of recharge changes within the groundwater basin as a function of climate variation is discussed in Section 6.4.9. The water table would stabilize at a particular position if the pattern of recharge remained constant for a long time. The equilibrated position depends, in part, on the distribution of hydraulic conductivity in all hydrostratigraphic units in the groundwater basin. However, the position of the water table depends mainly on the topography and geometry of the groundwater basin and the hydraulic conductivity of the uppermost strata. The position of the water table can adjust slowly to changes in recharge. Consequently, the water table can be at a position that is very much different from its equilibrium position at any given time. Generally, the water table drops

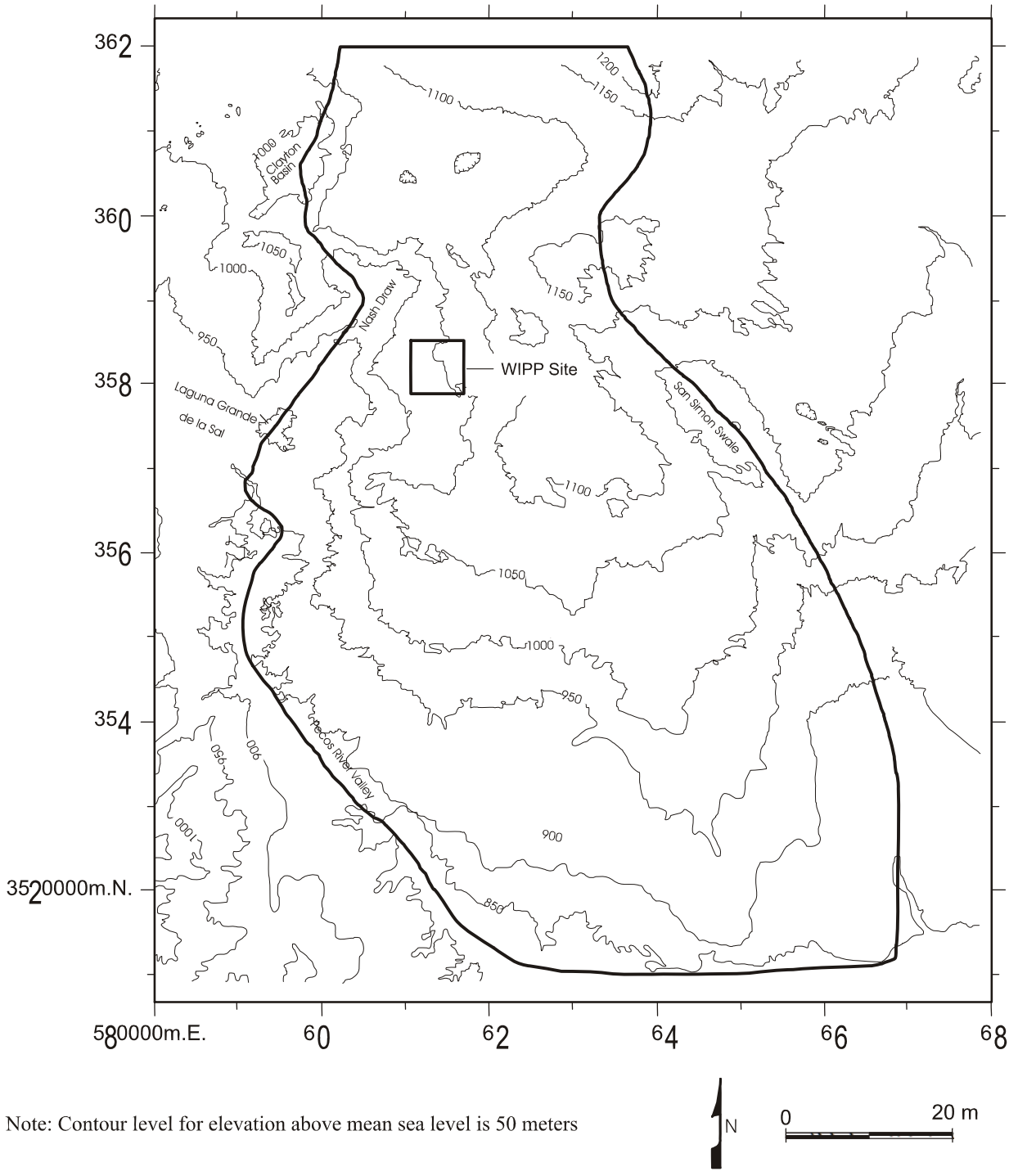

Note: Contour level for elevation above mean sea level is 50 meters

Figure 2-33. Outline of the Groundwater Basin Model Domain on a Topographic Map

very slowly in response to decreasing recharge but might rise rapidly in times of increasing recharge.

The asymmetry of response occurs because the rate at which the water table drops is limited by the rate at which water flows through the entire basin. In contrast, the rate at which the water table rises depends mainly on the recharge rate and the porosity of the uppermost strata. From groundwater basin modeling, the head distribution in the groundwater basin appears to equilibrate rapidly with the position of the water table.

The groundwater basin conceptual model (Corbet and Knupp 1996) described above has been implemented in a numerical model, as described in CCA Appendix MASS, Section MASS.14.2. This model has been used to simulate the interactive nature of flow through conductive layers and confining units for a variety of possible rock properties and climate futures. Thus, this model has allowed insight into the magnitude of flow through various units. The DOE has used this insight as a basis for model simplifications used in PA that are described here and in Chapter 6.

One conclusion from the regional groundwater basin modeling is pertinent here. In general, vertical leakage through confining layers is directed downward over all of the controlled area. This downward leakage uniformly over the WIPP site is the result of a well-developed discharge area, Nash Draw and the Pecos River, along the western and southern boundaries of the groundwater basin. This area acts as a drain for the laterally conductive units in the groundwater basin, causing most vertical leakage in the groundwater basin to occur in a downward direction. This conclusion is important in PA simplifications related to the relative importance of lateral flow in the Magenta versus the Culebra, which will be discussed later in this chapter and in Section 6.4.6.

Public concern was expressed that groundwater flow to the spring supplying brine to Laguna Grande de la Sal could be related to the presence of karst features. The EPA examined information regarding the hydrology of the units above the Salado and DOE's conceptualization of the groundwater flow model, including supplementary information submitted in letters dated May 2, 1997 (Docket A-93-02, Item V-B-6 (6)), and May 14, 1997 (Docket A-93-02, Item II-I-31), and the EPA concluded that the information was adequate.

The EPA concluded, based on WIPP field observations and site-specific hydrologic information, there is no indication that any cavernous or other karst-related flow is present within the WIPP site boundary. The EPA concurred with DOE's conceptualization of groundwater flow in the Culebra, which includes the presence of fractures within the Culebra and recharge and discharge areas for groundwater that are more consistent with potential discharge to areas south and west of the WIPP.

2.2.1.4.1 Hydrology of the Rustler Formation

The Rustler is of particular importance for WIPP because it contains the most transmissive units above the repository. Fluid flow in the Rustler is characterized by very slow rates of vertical leakage through confining layers and faster lateral flow in conductive units. To illustrate this point, regional modeling with the groundwater basin model indicates that lateral specific

discharges in the Culebra, for example, are perhaps two to three orders of magnitude greater than the vertical specific discharges across the top of the Culebra.

Because of its importance, the Rustler continues to be the focus of studies to understand better the complex relationship between hydrologic properties and geology, particularly in view of water-level rises observed in the Culebra and Magenta (e.g., SNL 2003a; also see Appendix DATA). An example of the complex nature of Rustler hydrology is the variation in Culebra transmissivity (T). Culebra T varies over three orders of magnitude on the WIPP site itself and over six orders of magnitude on the scale of the regional groundwater basin model with lower T east of the site and higher T west of the site in Nash Draw (e.g., Beauheim and Ruskauff 1998). As discussed below, site investigations and studies (e.g., Holt and Powers 1988; Beauheim and Holt 1990; Powers and Holt 1995; Holt 1997; Holt and Yarbrough 2002; Powers et al. 2003) suggest that the variability in Culebra T can be explained largely by the thickness of Culebra overburden, the location and extent of upper Salado dissolution, and the occurrence of halite in the mudstone units bounding the Culebra (see Section 2.1.3.5).

2.2.1.4.1.1 Los Medaños

The unnamed lower member was named the Los Medaños by Powers and Holt (1999). The Los Medaños is treated as a single hydrostratigraphic unit in WIPP models of the Rustler, although its composition varies. Overall, it acts as a confining layer. The basal interval of the Los Medaños, approximately 19.5 m (64 ft) thick, is composed of siltstone, mudstone, and claystone and contains the water-producing zones of the lowermost Rustler. Transmissivities of 2.9×10^{-10} m^2/s (2.7×10^{-4} ft^2/day) and 2.4×10^{-10} m^2/s (2.2×10^{-4} ft^2/day) were reported by Beauheim (1987a, p. 50) from tests at well H-16 that included this interval. The porosity of the Los Medaños was measured in 1995 as part of testing at the H-19 hydropad (TerraTek 1996). Two claystone samples had effective porosities of 26.8 and 27.3 percent. One anhydrite sample had an effective porosity of 0.2 percent. The transmissivity values correspond to hydraulic conductivities of 1.5×10^{-11} m/s (4.2×10^{-6} ft/day) and 1.2×10^{-11} m/s (3.4×10^{-6} ft/day). Hydraulic conductivity in the lower portion of the Los Medaños is believed by the DOE to increase to the west in and near Nash Draw, where dissolution at the underlying Rustler-Salado contact has caused subsidence and fracturing of the sandstone and siltstone.

The remainder of the Los Medaños contains mudstones, anhydrite, and variable amounts of halite. The hydraulic conductivity of these lithologies is extremely low. It is for this reason the Los Medaños is treated as a single hydrostratigraphic unit that overall acts as a confining unit. The conceptual model incorporating the Los Medaños is discussed in Section 6.4.6.1. Important hydrologic model properties of the Los Medaños are summarized in Appendix PA.

As described in Section 2.1.3.5, the Los Medaños contains two mudstone layers: one in the middle of the Los Medaños and one immediately below the Culebra. An anhydrite layer separates the two mudstones. The lower and upper Los Medaños mudstones have been given the designations M1/H1 and M2/H2, respectively, by Holt and Powers (1988). This naming convention is used to indicate the presence of halite in the mudstone at some locations at and near the WIPP site. Powers (2002a) has mapped (Figure 2-15) the margins delineating the occurrence of halite in both mudstone layers. Whereas early researchers (e.g., Snyder 1985) interpreted the absence of halite west of these margins as evidence of dissolution, Holt and

Powers (1988) interpreted it as reflecting changes in the depositional environment, not dissolution. However, Holt and Powers (1988) concluded that dissolution of Rustler halite may have occurred along the present-day margins. The presence of halite in the Los Medaños mudstones is likely to affect the conductivity of the mudstones, but its greater importance is the implications it has for the conductivity of the Culebra. As discussed in Section 2.2.1.4.1.2, the Culebra transmissivity in locations where halite is present in M2/H2 and M3/H3 (a mudstone in the lower Tamarisk Member of the Rustler) is assumed to be an order of magnitude lower than where halite does not occur (Holt and Yarbrough 2002).

Fluid pressures in the Los Medaños have been continuously measured at well H-16 since 1987. During this period, the fluid pressure has remained relatively constant at between 190 and 195 psi or a head of approximately 137 m (450 ft). Given the location of the pressure transducer (an elevation of 811.96 m amsl), the current elevation of the Los Medaños water level at H-16 is approximately 949 m amsl. No other wells in the WIPP monitoring network are completed to the Los Medaños. Thus, H-16 provides the only current head information for this member.

2.2.1.4.1.2 The Culebra Dolomite Member

The Culebra is of interest because it is the most transmissive saturated unit above the WIPP repository and hydrologic research has been concentrated on the unit for nearly two decades. Although it is relatively thin, it is an entire hydrostratigraphic unit in the WIPP hydrological conceptual model, and it is the most important conductive unit in this model. Implementation of the Culebra in the conceptual model is discussed in detail in Section 6.4.6.2. Model discussions cover groundwater flow and transport characteristics of the Culebra. These are supported by parameter values in Table 6-20, 6-21, 6-22, and 6-23. Additional background for the Culebra model is in CCA Appendix MASS, Sections MASS.14 and MASS.15.

The two primary types of field tests used to characterize the flow and transport characteristics of the Culebra are hydraulic tests and tracer tests.

The hydraulic testing consists of pumping, injection, and slug testing of wells across the study area (for example, Beauheim 1987a, p. 3). The most detailed hydraulic test data exist for the WIPP hydropads (for example, H-19). The hydropads generally comprise a network of three or more wells located within a few tens of meters of each other. Long-term pumping tests have been conducted at hydropads H-3, H-11, and H-19 and at well WIPP-13 (Beauheim 1987b; 1989; Beauheim et al. 1995; Meigs et al. 2000). These pumping tests provided transient pressure data at the hydropad and over a much larger area. Tests often included use of automated data-acquisition systems, providing high-resolution (in both space and time) data sets. In addition to long-term pumping tests, slug tests and short-term pumping tests have been conducted at individual wells to provide pressure data that can be used to interpret the transmissivity at that well (Beauheim 1987a). (Additional short-term pumping tests have been conducted in the WQSP wells [Beauheim and Ruskauff 1998]). Detailed cross-hole hydraulic testing has been conducted at the H-19 hydropad (Beauheim 2000).

The hydraulic tests are designed to yield pressure data for the interpretation of such characteristics as transmissivity, permeability, and storativity. The pressure data from long-term pumping tests and the interpreted transmissivity values for individual wells are used for the

generation of transmissivity fields in PA flow modeling (see Appendix PA, Attachment TFIELD, Sections TFIELD 5.0 and TFIELD-6.0). Some of the hydraulic test data and interpretations are also important for the interpretation of transport characteristics. For instance, information about the vertical distribution of permeability interpreted from the hydraulic tests at a given hydropad is needed for interpretations of tracer test data at that hydropad.

To evaluate transport properties of the Culebra, a series of tracer tests were conducted at six locations (the H-2, H-3, H-4, H-6, H-11, and H-19 hydropads) near the WIPP site. Tests at the first five of these locations consisted of two-well dipole tests and/or multiwell convergent flow tests and are described in detail in Jones et al. (1992). Tracer tests at the H-19 hydropad and additional tracer tests performed at the H-11 hydropad are described in Meigs et al. (2000). The 1995-1996 tracer test program consisted of single-well injection-withdrawal tests and multi-well convergent flow tests (Meigs and Beauheim 2001). Unique features of this testing program include the single-well test at both H-19 and H-11, the injection of tracers into six wells during the H-19 convergent-flow test, the injection of tracer into upper and lower zones of the Culebra at the H-19 hydropad, repeated injections under different convergent-flow pumping rates, and the use of tracers with different free-water diffusion coefficients. The 1995-1996 tracer tests were specifically designed to evaluate the importance of heterogeneity (both horizontal and vertical) and diffusion on transport processes.

The Culebra is a fractured dolomite with nonuniform properties both horizontally and vertically. Examination of core and shaft exposures has revealed that there are multiple scales of porosity within the Culebra including fractures ranging from microscale to potentially large, vuggy zones, and interparticle and intercrystalline porosity (Holt 1997). Porosity measurements made on core samples give porosity measurements ranging from 0.03 to 0.30 (Kelley and Saulnier 1990; TerraTek 1996). This large range in porosity for small samples is expected given the variety of porosity types within the Culebra. However, the effective porosity for flow and transport at larger scales will have a smaller range due to the effects of spatial averaging. The core measurements indicate that the Culebra has significant quantities of connected porosity.

Flow in the Culebra occurs within fractures, within vugs where they are connected by fractures, and to some extent within interparticle porosity where the porosity (and permeability) is high, such as chalky lenses. At any given location, flow will occur in response to hydraulic gradients in all places that are permeable. When the permeability contrast between different scales of connected porosity is large, the total porosity can effectively be conceptualized by dividing the system into advective porosity (often referred to as fracture porosity) and diffusive porosity (often referred to as matrix porosity). The advective porosity can be defined as the portion of the porosity where flow is the dominant process (for example fractures and to some extent vugs connected by fractures and interparticle porosity). Diffusive porosity can be defined as the portion of the porosity where diffusion is the dominant process (for example, intercrystalline porosity and to some extent microfractures, vugs and portions of the interparticle porosity.)

For the Culebra in the vicinity of the WIPP site, defining advective porosity is not a simple matter. In some regions the permeability of the fractures is inferred to be significantly larger than the permeability of the other porosity types, thus advective porosity can be conceptualized as predominantly fracture porosity (low porosity). In some regions, there appear to be no high permeability fractures. This may be due to a lack of large fractures or may be the result of

gypsum fillings in a portion of the porosity. Where permeability contrasts between porosity types are small, the advective porosity can be conceptualized as a combination of fractures, vugs connected by fractures, and permeable portions of the interparticle porosity. In each case, the diffusive porosity can be conceptualized as the porosity where advection is not dominant.

The major physical transport processes that affect actinide transport through the Culebra include advection (through fractures and other permeable porosity), diffusion from the advective porosity into the rest of the connected porosity (diffusive porosity) and dispersive spreading due to heterogeneity. Diffusion can be an important process for effectively retarding solutes by transferring mass from the porosity where advection (flow) is the dominant process into other portions of the rock. Diffusion into stagnant portions of the rock also provides access to additional surface area for sorption. Further discussion of transport of actinides in the Culebra as either dissolved species or as colloids is given in Section 6.4.6.2. Parameter values determined from tests of the Culebra are given in CCA Appendix PAR and are described in Section 6.4.6.2.2. A summary of input values to the conceptual model is in Tables 6-22 and 6-23.

Fluid flow in the Culebra is dominantly lateral and southward except in discharge areas along the west or south boundaries of the basin. Where transmissive fractures exist, flow is dominated by fractures but may also occur in vugs connected by microfractures and interparticle porosity. Regions where flow is dominantly through vugs connected by microfractures and interparticle porosity have been inferred from pumping tests and tracer tests. Flow in the Culebra may be concentrated along zones that are thinner than the total thickness of the Culebra. In general, the upper portion of the Culebra is massive dolomite with a few fractures and vugs, and appears to have low permeability. The lower portion of the Culebra appears to have many more vuggy and fractured zones and to have significantly higher permeability (Meigs and Beauheim 2001).

There is strong evidence that the permeability of the Culebra varies spatially and varies sufficiently that it cannot be characterized with a uniform value or range over the region of interest to the WIPP. The transmissivity of the Culebra varies spatially over six orders of magnitude from east to west in the vicinity of the WIPP (Figure 2-34). Over the site, Culebra transmissivity varies over three to four orders of magnitude. CCA Appendix TFIELD, Section TFIELD.2 contains the data used to develop Figure 2-34, which shows variation in transmissivity in the Culebra in the WIPP region. Attachment TFIELD to Appendix P provides the modeling rationale and addresses how data collected over a number of years were correlated for the generation of transmissivity fields.

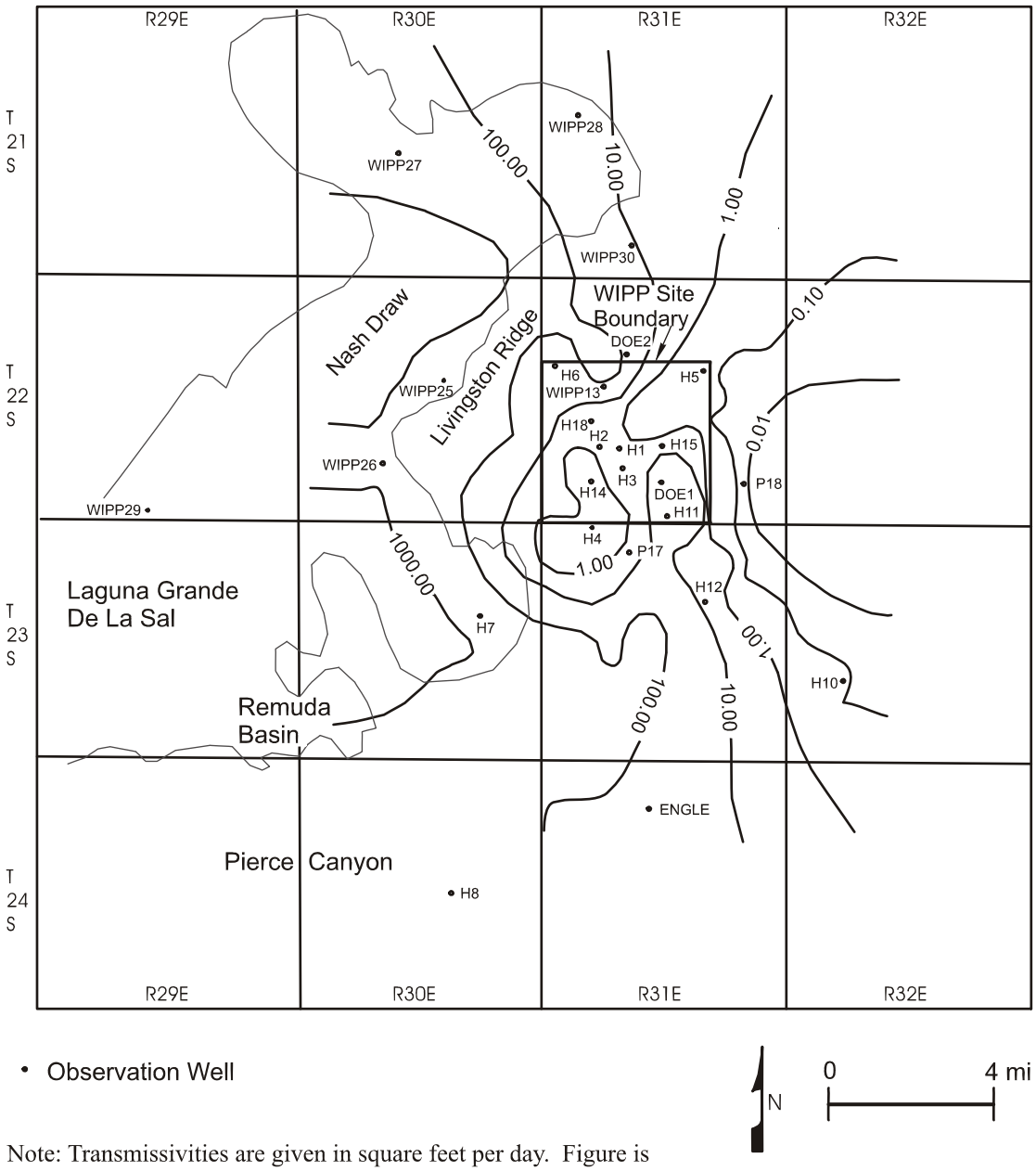

Note: Transmissivities are given in square feet per day. Figure is modified from Cauffman et al. 1990 (Figure 5.22a). See Appendix TFIELD for details of the performance assessment implementation.

Figure 2-34. Transmissivities of the Culebra

Transmissivities are from about 1×10^{-9} m^2/s (1×10^{-3} ft^2/day) at well P-18 east of the WIPP site to about 1×10^{-3} m^2/s (1×10^{3} ft^2/day) at well H-7 in Nash Draw (see Figure 2-2 for the locations of these wells and see Figure 4-8 in CCA Appendix FAC for a Culebra isopach map).

Transmissivity variations in the Culebra are believed to be controlled by the relative abundance of open fractures rather than by primary (that is, depositional) features of the unit. Lateral

variations in depositional environments were small within the mapped region, and primary features of the Culebra show little map-scale spatial variability, according to Holt and Powers (CCA Appendix FAC). Direct measurements of the density of open fractures are not available from core samples because of incomplete recovery and fracturing during drilling, but observation of the relatively unfractured exposures in the WIPP shafts suggests that the density of open fractures in the Culebra decreases to the east.

Recent investigations have made a significant contribution to the understanding of the large variability observed for Culebra transmissivity (e.g., Holt and Powers 1988; Beauheim and Holt 1990; Powers and Holt 1995; Holt 1997; Holt and Yarbrough 2002; Powers et al. 2003). The spatial distribution of Culebra transmissivity is believed to be due strictly to deterministic post-depositional processes and geologic controls (Holt and Yarbrough 2002). The important geologic controls include Culebra overburden thickness, dissolution of the upper Salado, and the occurrence of halite in the mudstone Rustler units (M2/H2 and M3/H3) above and below the Culebra (Holt and Yarbrough 2002). Culebra transmissivity is inversely related to thickness of overburden because stress relief associated with erosion of overburden (see Section 2.1.5.2) leads to fracturing and opening of preexisting fractures. Culebra transmissivity is high where dissolution of the upper Salado has occurred and the Culebra has subsided and fractured. Culebra transmissivity is observed to be low where halite is present in overlying and/or underlying mudstones. Presumably, high Culebra transmissivity leads to dissolution of nearby halite (if any). Hence, the presence of halite in mudstones above and/or below the Culebra can be taken as an indicator for low Culebra transmissivity. Details of the geologic-based transmissivity model for the Culebra are given in Attachment TFIELD (Section TFIELD-3.0) to Appendix PA and summarized below.

The Culebra has been tested hydraulically at 42 locations, yielding reliable transmissivity values. These values (log T) are plotted as a function of depth to Culebra (overburden thickness) in Figure 2-35. As shown, the Culebra transmissivities fall into two populations separated by a cutoff (termed ‘high-T’ cutoff) equal to -5.4 (log T [m^2/s]). These data suggest a bimodal distribution for transmissivity with one population having high transmissivity and the other low transmissivity, with the difference attributed to open, interconnected fractures (“fracture interconnectivity”) for the high-transmissivity population (Holt and Yarbrough 2002). Using these data, Holt and Yarbrough (2002) constructed a linear Culebra transmissivity model relating log T to the deterministic geologic controls described above. The linear model is expressed as follows:

$$Y(\mathbf{x}) = \beta_1 + \beta_2 d(\mathbf{x}) + \beta_3 I_f(\mathbf{x}) + \beta_4 I_D(\mathbf{x}), \tag{2.1}$$

where Y(x) is log T (x), β_i (I = 1 to 4) are regression coefficients, x is a two-dimensional location vector, d(x) is the overburden thickness at x (expressed in UTM coordinates and

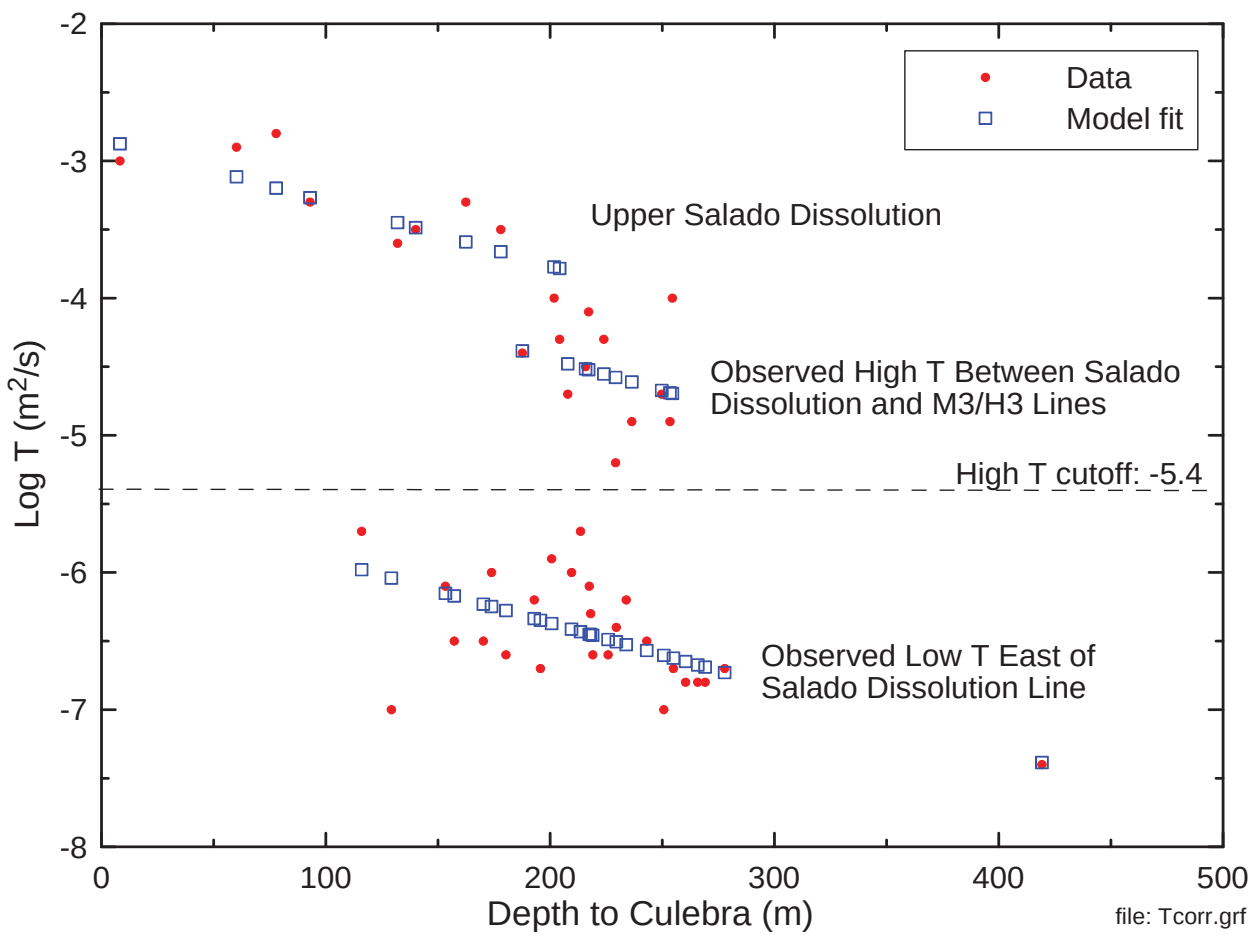

Figure 2-35. Correlation Between Culebra Transmissivity (log T (m^2/s)) and Overburden Thickness for Different Geologic Environments (after Holt and Yarbrough 2002)

meters), I_f (x) is the fracture-interconnectivity indicator at x (equal to 1 when log T (m^2/s) > -5.4 or 0 when log T (m^2/s) < -5.4), and I_D (x) is the dissolution indicator (equal to 1 when Salado dissolution has occurred at (x) and 0 when it has not). In this model, coefficient β_1 is the intercept value, β_2 is the slope of Y(x)/d(x), and β_3 and β_4 represent adjustments to the intercept for the occurrence of open, interconnected fractures and Salado dissolution, respectively. Based on linear-regression analysis, Holt and Yarbrough (2002) estimated the coefficients in Equation (2.1). These estimates are summarized in Table 2-7. Predictions of the Culebra transmissivity model represented by Equation (2.1) are shown in Figure 2-35.

The regression model expressed by Equation (2.1) cannot adequately predict transmissivity in the regions where halite is present both in M2/H2 and M3/H3. In these regions, Culebra

Table 2-7. Estimates of Culebra Transmissivity Model Coefficients

β_1	β_2	β_3	β_4
-5.441	-4.636 × 10-3	1.926	0.678

porosity is thought to be at least partially filled with halite, reducing transmissivity. For these regions, Equation (2.1) is modified as follows:

$$Y(\mathbf{x}) = \beta_1 + \beta_2 d(\mathbf{x}) + \beta_3 I_f(\mathbf{x}) + \beta_4 I_D(\mathbf{x}) + \beta_5 I_H(\mathbf{x}). \tag{2.2}$$

I_H (x) is a halite indicator function equal to 1 in locations where halite occurs in both the M2/H2 and M3/H3 intervals and 0 otherwise. The coefficient β_5 is equal to –1 to assure that the model in Equation (2.2) reduces the predicted transmissivity values by one order of magnitude where halite occurs in both the M2/H2 and M3/H3 intervals.

In the region east of the upper Salado dissolution margin and west of the M2/H2 and M3/H3 margins, high transmissivity depends, in part, on the absence of gypsum fracture fillings. No method has yet been determined for predicting whether fractures will or will not be filled with gypsum at a given location, so the distribution of high and low transmissivity is treated stochastically in this region. Predictions of transmissivity in this region make use of an isotropic spherical variogram model. Fitted parameters for the variogram model are described in Attachment TFIELD (Section TFIELD-4.3) of Appendix PA.

Geochemical and radioisotope characteristics of the Culebra have been studied. There is considerable variation in groundwater geochemistry in the Culebra. The variation has been described in terms of different hydrogeochemical facies that can be mapped in the Culebra (see Section 2.4.2). A halite-rich hydrogeochemical facies exists in the region of the WIPP site and to the east, approximately corresponding to the regions in which halite exists in units above and below the Culebra (Figure 2-15), and in which a large portion of the Culebra fractures are gypsum filled (Figure 2-17). An anhydrite-rich hydrogeochemical facies exists west and south of the WIPP site, where there is relatively less halite in adjacent strata and where there are fewer gypsum-filled fractures.

The Culebra groundwater geochemistry studies continue. Culebra water quality is evaluated semiannually at six wells, three north (WQSP-1, WQSP-2, and WQSP-3) and three south (WQSP-4, WQSP-5, and WQSP-6) (WIPP MOC 1995) of the surface structures area (see Figure 2-3 for well locations). Five rounds of semiannual sampling of water quality completed before the first receipt of waste at the WIPP were used to establish the initial Culebra water-quality baseline for major ion species including Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, and HCO_3^{2-} (Crawley and Nagy 1998). In 2000, this baseline was expanded to include five additional rounds of sampling that were completed before first receipt of RCRA-regulated waste (IT Corporation 2000). Table 2-8 gives the 95 percent confidence intervals presented in SNL (2001) for the major ion species determined from the 10 rounds (semiannual sampling for 5 years) of baseline sampling. Culebra water quality is extremely variable among the six sampling wells, as shown by the Cl^- concentrations that range from approximately 6,000 mg/L at WQSP-6 to 130,000 mg/L at WQSP-3.

Radiogenic isotopic signatures suggest that the age of the groundwater in the Culebra is on the order of 10,000 years or more (see, for example, Lambert 1987, Lambert and Carter 1987, and Lambert and Harvey 1987). The radiogenic ages of the Culebra groundwater and the geochemical differences provide information potentially relevant to the groundwater flow directions and groundwater interaction with other units and are important constraints on

Table 2-8. Ninety-Five Percent Confidence Intervals for Culebra Water-Quality Baseline

Well I.D.	Cl^- Conc. (mg/L)	SO_4^{2-} Conc. (mg/L)	HCO_3^- Conc. (mg/L)	Na^+ Conc. (mg/L)	Ca^{2+} Conc. (mg/L)	Mg^{2+} Conc. (mg/L)	K^+ Conc. (mg/L)
WQSP-1	31100-39600	4060-5600	45-54	15850-21130	1380-2030	940-1210	322-730
WQSP-2	31800-39000	4550-6380	43-53	14060-22350	1230-1730	852-1120	318-649
WQSP-3	113900-145200	6420-7870	23-51	62600-82700	1090-1620	1730-2500	2060-3150
WQSP-4	53400-63000	5620-7720	31-46	28100-37800	1420-1790	973-1410	784-1600
WQSP-5	13400-17600	4060-5940	42-54	7980-10420	902-1180	389-535	171-523
WQSP-6	5470-6380	4240-5120	41-54	3610-5380	586-777	189-233	113-245

conceptual models of groundwater flow. Previous conceptual models of the Culebra (see for example, Chapman 1986, Chapman 1988, LaVenue et al. 1990, and Siegel et al. 1991) have not been able to consistently relate the hydrogeochemical facies, radiogenic ages, and flow constraints (that is, transmissivity, boundary conditions, etc.) in the Culebra.

The groundwater basin modeling that was conducted, although it did not model solute transport processes, provides flow fields that can be used to develop the following concepts that help explain the observed hydrogeochemical facies and radiogenic ages. The groundwater basin model combines and tests three fundamental processes: (1) it calculates vertical leakage, which may carry solutes into the Culebra; (2) it calculates lateral fluxes in the Culebra (directions as well as rates); and (3) it calculates a range of possible effects of climate change. The presence of the halite-rich groundwater facies is explained by vertical leakage of solutes into the Culebra from the overlying halite-containing Tamarisk by advective or diffusive processes. Because lateral flow rates here are low, even slow rates of solute transport into the Culebra can result in high solute concentration. Vertical leakage occurs slowly over the entire model region, and thus the age of groundwater in the Culebra is old, consistent with radiogenic information. Lateral fluxes within the anhydrite zone are larger because of higher transmissivity, and where the halite and anhydrite facies regions converge, the halite facies signature is lost by dilution with relatively large quantities of anhydrite facies groundwater. Response of groundwater flow in the Culebra as the result of increasing recharge is modeled through the variation in climate, discussed in Section 6.4.9.

Groundwater levels in the Culebra in the WIPP region were measured prior to the CCA in numerous wells (Figure 2-2). The Culebra monitoring wells as of the end of 2002 are shown in Figures 2-3 and 2-4; plugged and abandoned wells are not shown in these figures. Beginning in 1989, a general

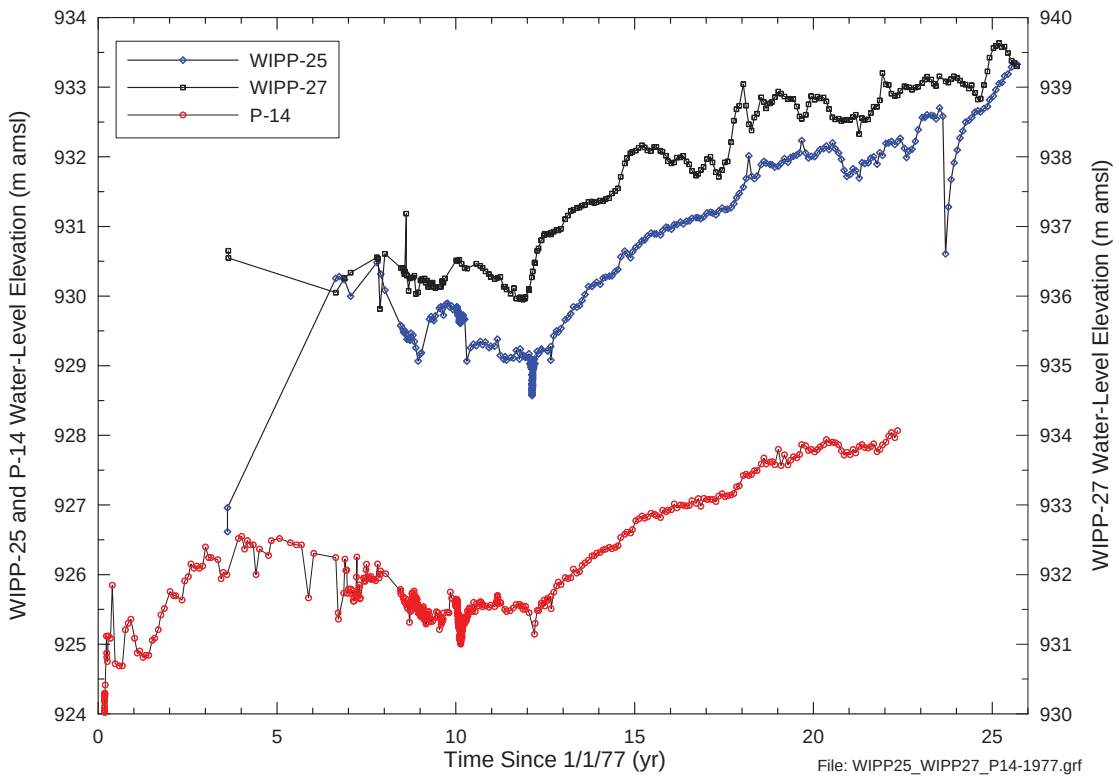

Figure 2-36. Water-level Trends in Nash Draw Wells and at P-14 (see Figure 2-2 for well locations)

long-term rise has been observed in both Culebra and Magenta water levels (Figure 2-36) over a broad area of the WIPP site including Nash Draw (SNL 2003a). At the time of the CCA this long-term rise was recognized, but was thought (outside of Nash Draw) to represent recovery from the accumulation of hydraulic tests that had occurred since the late 1970s and the effects of grouting around the WIPP shafts to limit leakage. Water levels in Nash Draw were thought to respond to changes in the volumes of potash mill effluent discharged into the draw (Silva 1996); however, correlation of these water levels with potash mine discharge cannot be proven because sufficient data on the timing and volumes of discharge are not available. As the rise in water levels has continued since 1996, observed heads have exceeded the ranges of uncertainty established for the steady-state heads in most of the 32 wells used in the calibration of the transmissivity fields described in CCA Appendix TFIELD. Although recovery from the hydraulic tests and shaft leakage has unquestionably occurred, the DOE has implemented a program to identify other potential causes for the water-level rises (SNL 2003b).

Potentiometric surface maps of the freshwater head in the Culebra in December 1998 and December 2002 are shown in Figures 2-37a, 2-37b and 2-37c, respectively. The maps are generally similar and indicate no changes in flow directions across the WIPP site over that period. Figure 2-37c shows the changes in heads at the wells monitored in both December 1998 and December 2002. Freshwater heads in most wells increased by 2-4 ft from 1998 to 2002. The largest rise was 4.84 ft at DOE-1. Only one well, AEC-7, showed a drop over this period (-0.85 ft) larger than potential measurement error.

Although Culebra heads have been rising, the head distribution in the Culebra (see Figures 2-37a, 2-37b and 2-37c) is consistent with groundwater basin modeling results (discussed in Appendix PA, Attachment MASS, Section MASS.14.2) indicating that the generalized direction of groundwater flow remains north to south. However, caution should be used when making assumptions based on groundwater-level data alone. Studies in the Culebra have shown that fluid density variations in the Culebra can affect flow direction (Davies 1989, p. 35). The fractured nature of the Culebra, coupled with variable fluid densities, can also cause localized flow patterns to differ from general flow patterns. Water-level rises in the vicinity of the H-9 hydropad, about 10.46 km (6.5 mi) south of the site, are not thought to be caused by either WIPP activities or potash mining discharge and have been included in the DOE program to investigate Culebra water-level rises in general. The DOE continues to monitor groundwater levels throughout the region, but only water-level changes at or near the site have the potential to impact the prediction of disposal system performance. The DOE has implemented water-level changes in its conceptual model through variations in climate as discussed in Section 6.4.9. These variations bring the water table to the surface for some calculations. The DOE has also used recent (late 2000) Culebra heads in flow and transport calculations for this recertification application, as discussed in Appendix PA, Attachment TFIELD, Section TFIELD-6.2.

Inferences about vertical flow directions in the Culebra have been made from well data collected by the DOE. Beauheim (1987a) reported flow directions toward the Culebra from both the Los Medaños and the Magenta over the WIPP site, indicating that the Culebra acts as a drain for the units around it. This indication is consistent with results of groundwater basin modeling. A more detailed discussion of Culebra flow and transport can be found in Appendix PA, Attachment TFIELD

In response to an EPA letter dated March 19, 1997 (Docket A-93-02, Item II-I-17), supplemental information to the CCA pertinent to groundwater flow and geochemistry within the Culebra was provided by the DOE in a letter dated May 14, 1997 (Docket A-93-02, Item II-I-31). In that letter, the DOE explained the conceptual model of Culebra groundwater flow used in the CCA. The CCA conceptual model, referred to as the groundwater basin model, offers a three-dimensional approach to treatment of supra-Salado rock units, and assumes that vertical leakage (albeit very slow) occurs between rock units of the Rustler (where hydraulic gradients exist). Flow in the Culebra is considered transient, but is not expected to change significantly over the next 10,000 years. This differs from previous interpretations, wherein no flow was assumed between the Rustler units.

In an attachment to the May 14, 1997 letter, the DOE concluded that the presence of anhydrite within the Rustler units did not preclude slow downward infiltration, as previously argued by the DOE, and that the observed geochemistry and flow directions can be explained with different recharge areas and Culebra travel paths. The EPA reviewed the groundwater flow and recharge conceptualization and concluded that it provides a realistic representation of site conditions.

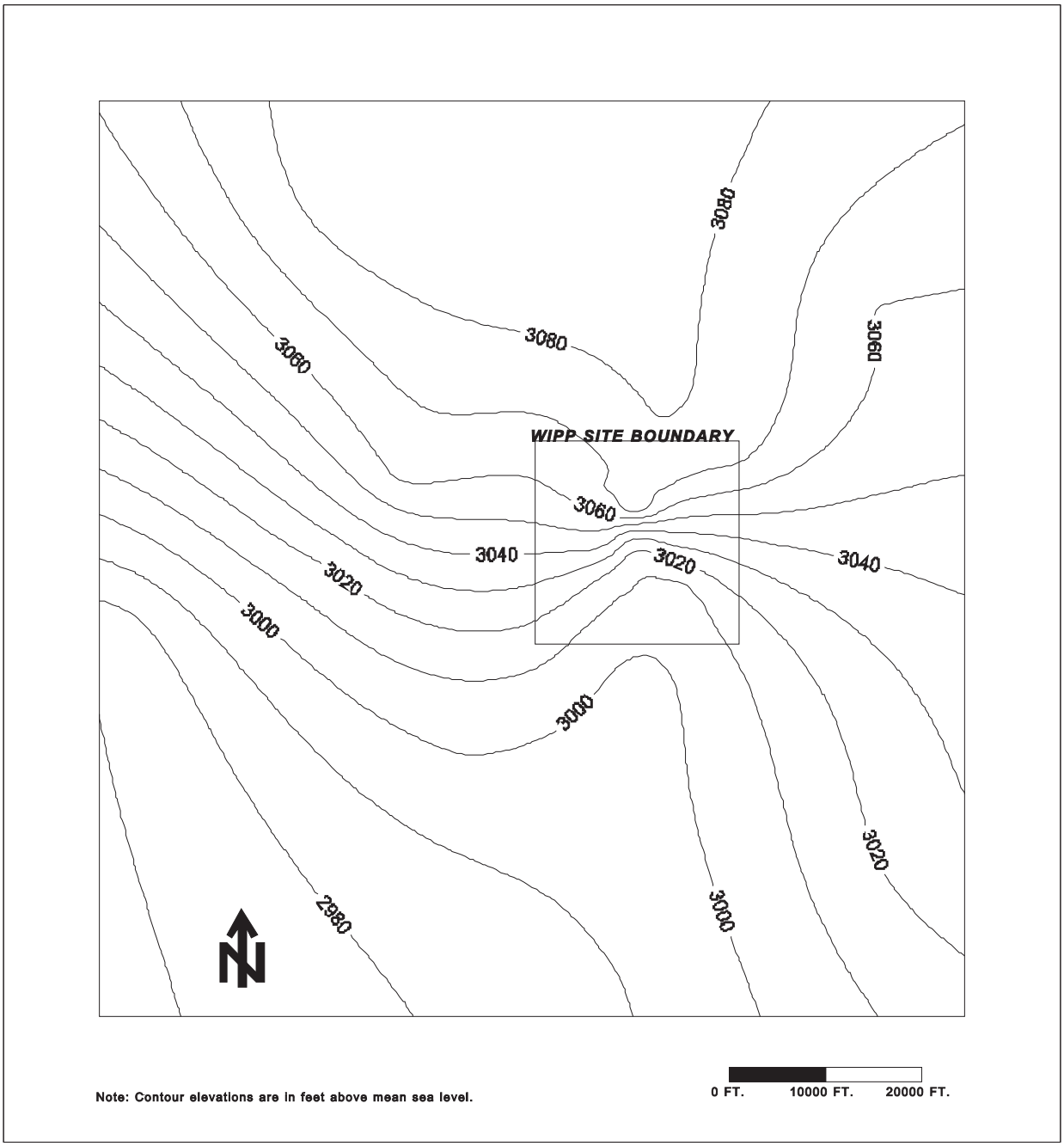

Figure 2-37. Hydraulic Heads in the Culebra

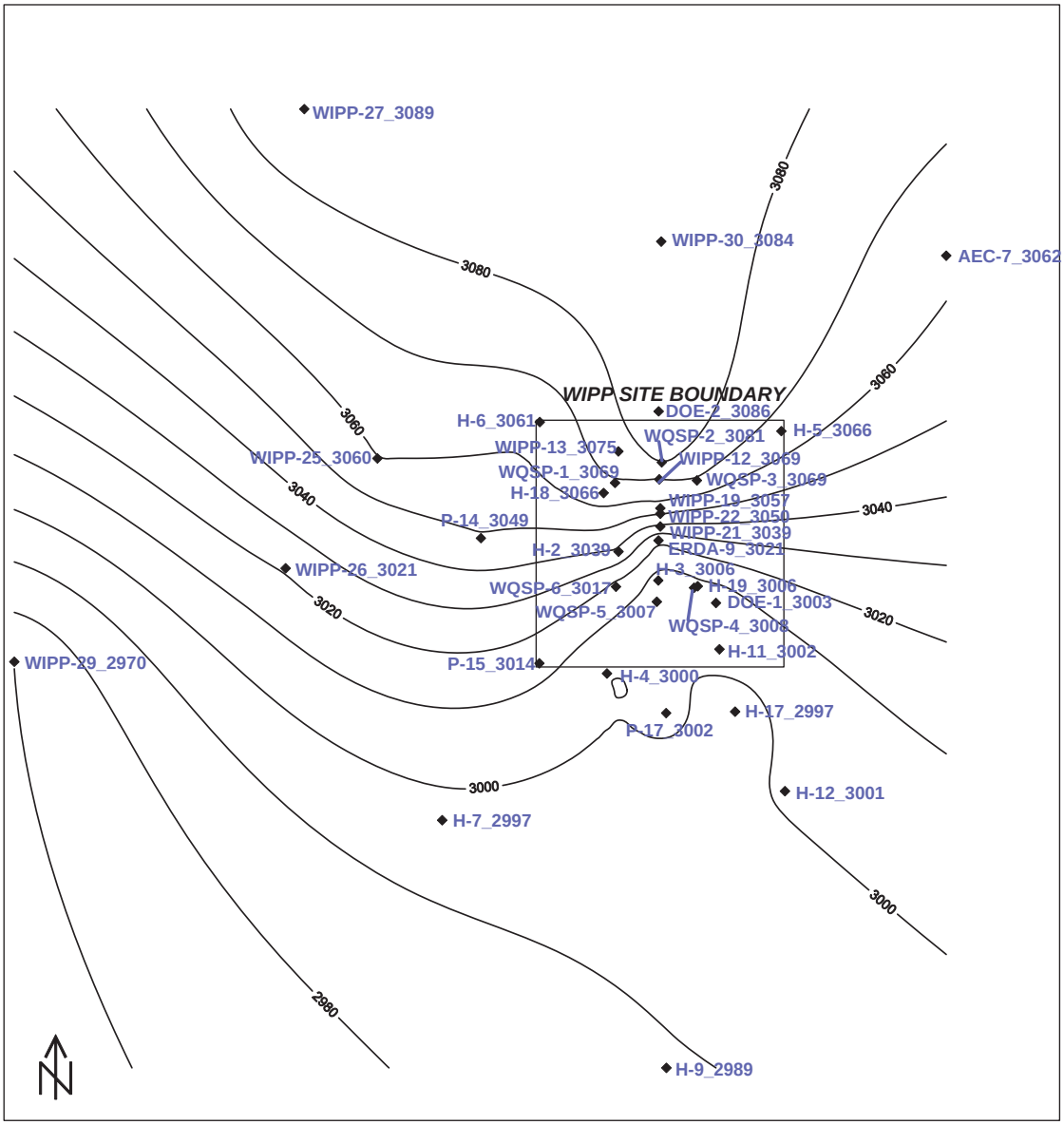

Note: Contour elevations are in feet above mean sea level,
Freshwater Head Elevations are given after the well ID

0 Ft 20000 Ft 40000 Ft

Figure 2-37a. Potentiometric Surface. Exprssesed as Equivalent Freshwater Head, of the Culebra in December 1998.

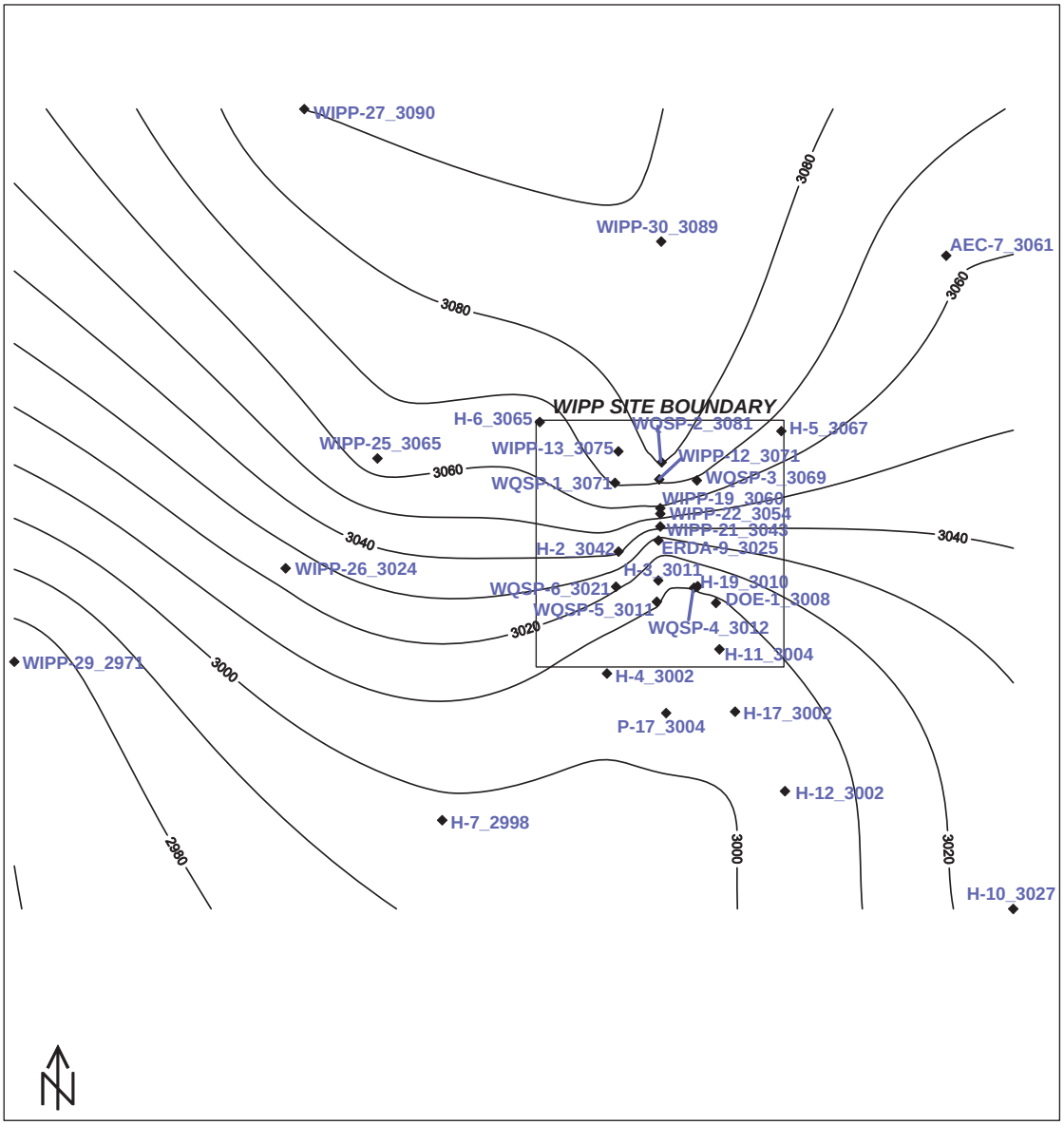

Note: Contour elevations are in feet above mean sea level
Freshwater Head Elevations are given after well ID

0 Ft 20000 Ft 40000 Ft

Figure 2-37b. Potentiometric Surface, Expressed as Equivalent Freshwater Head, of the Culebra in December 2002.

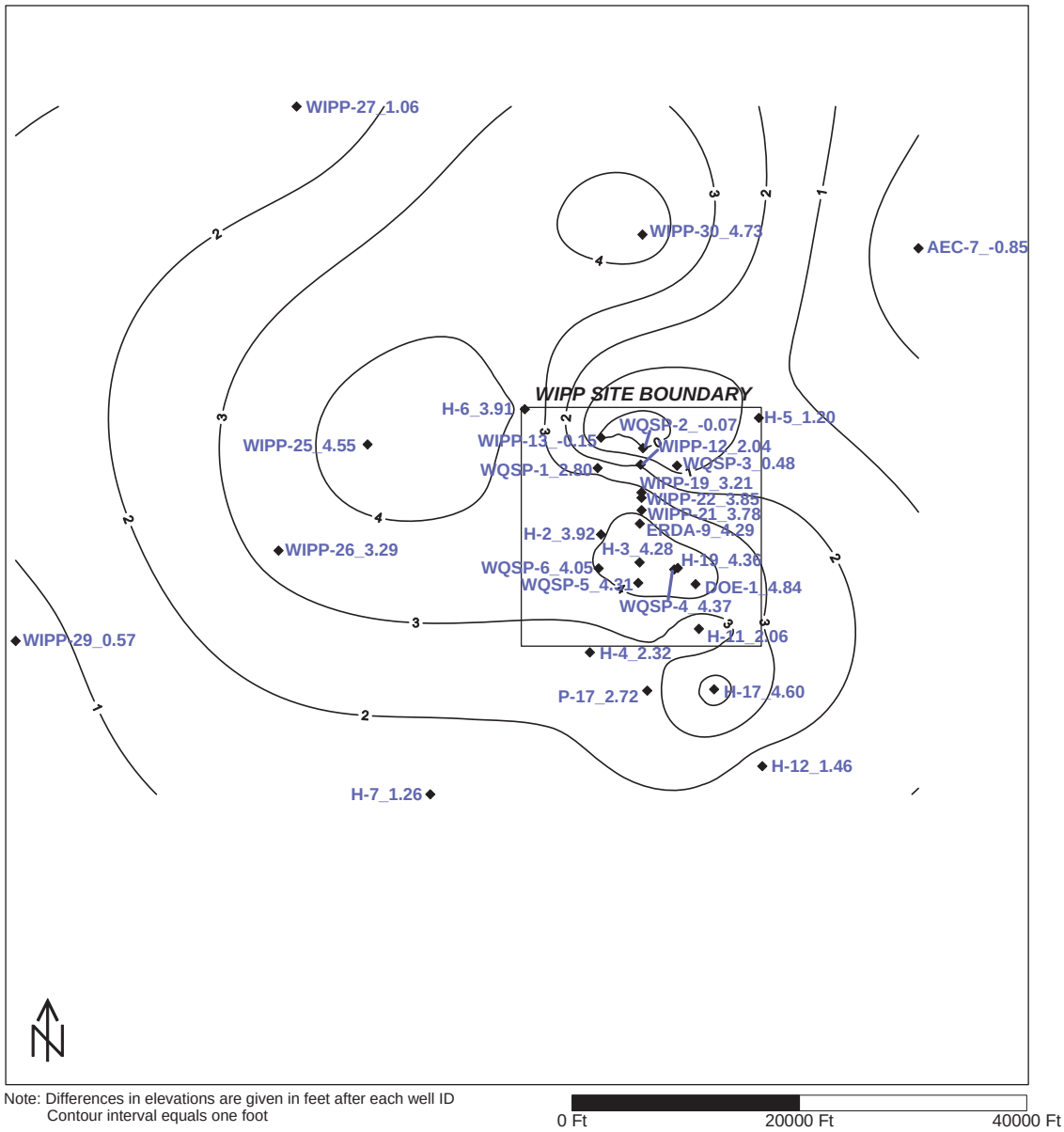

Figure 2-37c. Changes in Freshwater Heads in the Culebra Between December 1998 and December 2002.

During the CCA review, the EPA found that information on the Culebra in the CCA lacked a detailed discussion on the origin of the transmissivity variations relative to fracture infill/dissolution, integration of climatic change, and loading/unloading events. These are important aspects to understanding not only current transmissivity differences, but also potential future transmissivity variations that could affect PA calculations. The EPA's review stated, however, that the determination of the specific origin of fractures was not necessary because conditions were not expected to change during the regulatory period.

The DOE provided supplemental information in letters in 1997 (Docket A-93-02, Items II-I-03, II-I-24, II-I-31, II-H-44, and II-H-46) indicating that dissolution of fracture fill (which has the potential to alter fracture permeability) is unlikely to occur. The EPA accepted the DOE's position that infiltrating waters would most likely become saturated with calcium sulfate and consequently would not dissolve anhydrite or gypsum fracture fill. Further information on the EPA review of anhydrite and gypsum fracture fill dissolution is contained in EPA Technical Support Document for Section 194.14: Content of Compliance Certification Application, Section IV.C (Docket A-93-02, Item V-B-3).

The Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment reports the annual assessment of the Compliance Monitoring Parameters (COMPs) pursuant to the SNL Analysis Plan, AP-069. The first assessment, for calendar year 1998 (SNL 2000a), showed that changes in Culebra water levels were considered minor. During the assessment of the COMP 'changes in groundwater flow' for calendar year 2001 (SNL 2002), estimated freshwater Culebra heads in 15 wells were identified as above the ranges of uncertainty estimated for steady-state conditions at those wells. At 8 of the 15 wells, the measured water levels exceed the uncertainty range before being converted to freshwater head. In these cases, conversion to freshwater head using any feasible fluid density can only increase the deviation from the range. The freshwater head values from late 2000 were used to calibrate the Culebra transmissivity (T) fields used to simulate the transport of radionuclides through the Culebra (Appendix PA, Attachment TFIELD).

Because transport through the Culebra is a minor component of the total predicted releases from the repository, these changes in head values have little or no effect on the total releases to the accessible environment. The COMP assessment for the calendar year 2001 concluded that the current head values do not indicate a condition adverse to the predicted performance of the repository. However, because Culebra water levels are above expected values at most wells, work has been initiated to investigate the reason for the change and further evaluate the impact on performance.

Additional background for the Culebra model is in Appendix PA, Attachment TFIELD. Additional information on long-term pumping test data is documented in Meigs et al. (2000) and slug tests and short-term pumping tests are documented in Beauheim et al. (1991b) and Beauheim and Ruskauff (1998).

Several new publications on the Culebra updating the original CCA information have been released. Transport properties and tracer tests of the Culebra performed at the H-11 and H-19 hydropads are described in Meigs et al. (2000). The 1995-96 tracer test program, which consisted of single-well injection-withdrawal tests and multiwell convergent flow tests, is documented in Meigs and Beauheim (2001). The higher permeability of the lower Culebra has been addressed in Meigs and Beauheim (2001, p. 1116).

2.2.1.4.1.3 Tamarisk

The Tamarisk acts as a confining layer in the groundwater basin model. Attempts were made in two wells, H-14 and H-16, to test a 2.4-m (7.9-ft) sequence of the Tamarisk that consists of claystone, mudstone, and siltstone overlain and underlain by anhydrite. Permeability was too

low to measure in either well within the time allowed for testing; consequently, Beauheim (1987a, pp. 108-110) estimated the transmissivity of the claystone sequence to be one or more orders of magnitude less than that of the tested interval in the Los Medaños (that is, less than approximately 2.7×10^{-11} m^2/s [2.5×10^{-5} ft^2/day]). The porosity of the Tamarisk was measured in 1995 as part of testing at the H-19 hydropad (TerraTek 1996). Two claystone samples had an effective porosity of 21.3 to 21.7 percent. Five anhydrite samples had effective porosities of 0.2 to 1.0 percent.

Fluid pressures in the Tamarisk have been measured continuously at well H-16 since 1987. From 1998 through 2002, the pressures increased approximately 20 psi, from 80 to 100 psi (185 to 230 ft of water), probably in a continuing recovery response to shaft grouting conducted in 1993 to reduce leakage. Given the location of the pressure transducer, the elevation of Tamarisk water level has increased from 899 to 913 m amsl (2,950 to 2,995 ft amsl) during this period. Currently, no other wells in the WIPP monitoring network are completed to the Tamarisk. Thus, H-16 provides the only information on Tamarisk head levels.

Similar to the Los Medaños, the Tamarisk includes a mudstone layer (M3/H3) that contains halite in some locations at and around the WIPP site. This layer is considered to be important because of the effect it has on the spatial distribution of transmissivity of the Culebra as described in Section 2.2.1.4.1.2. The M3/H3 margin is described in Section 2.1.3.5 and mapped in Figure 2-15.

The Tamarisk is incorporated into the conceptual model as discussed in Section 6.4.6.3. The role of the Tamarisk in the groundwater basin model is in CCA Appendix MASS, Section MASS.14.1. Tamarisk hydrological model parameters are in Appendix PA, Attachment PAR, Table PAR-25.

2.2.1.4.1.4 Magenta

The Magenta is a conductive hydrostratigraphic unit about 7.9 m (26 ft) thick at the WIPP. The Magenta is saturated except near outcrops along Nash Draw, and hydraulic data are available from 22 wells including 7 wells recompleted to the Magenta between 1995 and 2002 (SNL 2003a). According to Mercer (CCA Appendix HYDRO, p. 65), transmissivity ranges over five orders of magnitude from 1×10^{-9} to 4×10^{-4} m^2/s (4×10^{-3} to 3.75×10^{2} ft^2/day). A slug test performed in H-9c, a recompleted Magenta well (see Figure 2-5 for well location), yielded a transmissivity of 6×10^{-7} m^2/s (0.56 ft^2/day), which is consistent with Mercer's findings (SNL 2003a). The porosity of the Magenta was measured in 1995 as part of testing at the H-19 hydropad (TerraTek 1996). Four samples had effective porosities ranging from 2.7 to 25.2 percent.

The hydraulic transmissivities of the Magenta, based on sparse data, show a decrease from west to east, with slight indentations of the contours north and south of the WIPP that correspond to the topographic expression of Nash Draw. In most locations, the hydraulic conductivity of the Magenta is one to two orders of magnitude less than that of the Culebra. The Magenta does not have hydraulically significant fractures in the vicinity of the WIPP. Treatment of the Magenta in the model is discussed in Section 6.4.6.4 with modeling parameters in Table 6-24.

Based on Magenta water levels measured in the 1980s (Lappin et al. 1989) when a wide network of Magenta monitoring wells existed, the hydraulic gradient in the Magenta across the site varies from 3 to 4 m/km (16 to 20 ft/mi) on the eastern side, steepening to about 6 m/km (32 ft/mi) along the western side near Nash Draw (Figure 2-38).

Regional modeling using the groundwater basin model indicates that leakage occurs into the Magenta from the overlying Forty-niner and out of the Magenta downward into the Tamarisk. Regional modeling also indicates that flow directions in the Magenta are dominantly westward, similar to the slope of the land surface in the immediate area of the WIPP. This flow direction is different than the dominant flow direction in the next underlying conductive unit, the Culebra. This difference is consistent with the groundwater basin conceptual model, in that flow in shallower units is expected to be more sensitive to local topography.

Inferences about vertical flow directions in the Magenta have been made from well data collected by the DOE. Beauheim (1987a, p. 137) reported flow directions downwards out of the Magenta over the WIPP site, consistent with results of groundwater basin modeling.

However, Beauheim (1987a, p. 139) concluded that flow directions between the Forty-niner and Magenta would be upward in the three boreholes from which reliable pressure data are available for the Forty-niner (H-3, H-14, and H-16), which is not consistent with the results of groundwater modeling. This inconsistency may be the result of local heterogeneity in rock properties that affect flow on a scale that cannot be duplicated in regional modeling.

As is the case for the Culebra, groundwater elevations in the Magenta have changed over the period of observation. The pattern of changes is similar to that observed for the Culebra (see Section 2.2.1.4.1.2), and is being investigated under the current DOE hydrology program (SNL 2003b).

2.2.1.4.1.5 Forty-niner

The Forty-niner is a confining hydrostratigraphic layer about 20 m (66 ft) thick throughout the WIPP area and consists of low-permeability anhydrite and siltstone. Tests by Beauheim (1987a, 119-123 and Table 5-2) in H-14 and H-16 yielded transmissivities of about 3×10^{-8} to 8×10^{-8} m^2/s (3×10^{-2} to 7×10^{-2} ft^2/day) and 3×10^{-9} to 6×10^{-9} m^2/s (5×10^{-3} to 6×10^{-3} ft^2/day), respectively, for the medial siltstone unit of the Forty-niner. Tests of the siltstone in H-3d provided transmissivity estimates of 3.8×10^{-9} to 4.8×10^{-9} m^2/s (3.5×10^{-3} to 4.5×10^{-3} ft^2/day) (Beauheim et al. 1991b, Table 5-1). The porosity of the Forty-niner was measured as part of testing at the H-19 hydropad (TerraTek 1996). Three claystone samples had effective porosities ranging from 9.1 to 24.0 percent. Four anhydrite samples had effective porosities ranging from 0.0 to 0.4 percent. Model consideration of the Forty-niner is in Section 6.4.6.5. Modeling parameters are in CCA Appendix PAR, Table PAR-27.

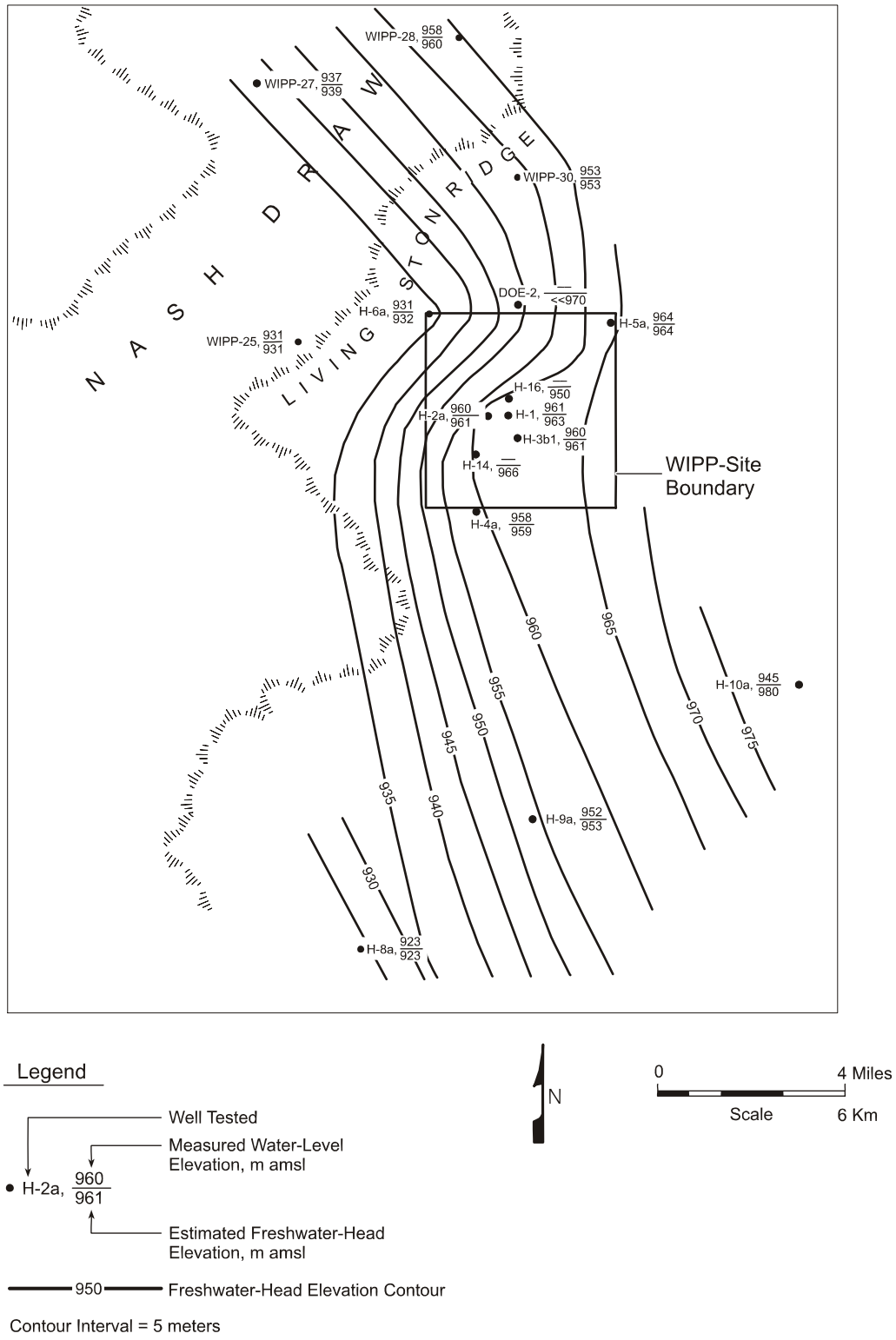

Figure 2-38. Hydraulic Heads in the Magenta (1980s)

Fluid pressures in the Forty-niner have been measured continuously at well H-16, approximately 13.9 m (45.6 ft) from the well of the AIS, since 1987. The pressures cycle in a sinusoidal fashion on an annual basis. These cycles correlate with cycles observed in rock bolt loads in the WIPP shafts (DOE 2002c), and presumably reflect seasonal temperature changes causing the rock around the shafts to expand and contract. From 1998 through 2002, the pressures have cycled between 40 and 70 psi (90 and 160 ft of fresh water). Given the location of the pressure transducer, the elevation of Forty-niner water level has varied between 899 to 920 m (2,950 to 3,020 ft) amsl during this period. Through April 2002, Forty-niner water levels were also measured monthly at H-3d as part of the WIPP groundwater monitoring program. Measurements were discontinued after April 2002 because of an obstruction in the well. The April 2002 Forty-niner water level elevation determined at H-3d was 942 m (3,092 ft) amsl. Differences in Forty-niner water levels at H-16 and H-3d are probably due, in part, to differences in the densities of the fluids in the wells. No other wells in the WIPP monitoring network are completed to the Forty-niner.

2.2.1.4.2 Hydrology of the Dewey Lake and the Santa Rosa

The Dewey Lake and the Santa Rosa, and surficial soils, overlie the Rustler and are the uppermost hydrostratigraphic units considered by the DOE. The Dewey Lake and overlying rocks are more permeable than the anhydrites at the top of the Rustler. Consequently, basin modeling indicates that most (probably more than 70 percent) of the water that recharges the groundwater basin (that is, percolates into the Dewey Lake from surface water) flows only in the rocks above the Rustler. As modeled, the rest leaks vertically through the upper anhydrites of the Rustler and into the Magenta or continues downward to the Culebra. More flow occurs into the Rustler units at times of greater recharge. Even though it carries most of the modeled recharge, lateral flow in the Dewey Lake is slow because of its low permeability in most areas.

A saturated, perched-water zone has been identified in the lower Santa Rosa directly below the operational area of the WIPP (DOE 1999; INTERA 1997a; INTERA 1997b; DES 1997). The zone occurred at a location that previously had been dry or only partially saturated. Details are provided in Appendix DATA and a summary provided in Section 2.2.1.4.2.2.

2.2.1.4.2.1 Dewey Lake

The Dewey Lake contains a productive zone of saturation, probably under water-table conditions, in the southwestern to south-central portion of the WIPP site and south of the site. Several wells operated by the J.C. Mills Ranch south of the WIPP site produce sufficient quantities of water from the Dewey Lake to supply livestock. Short-term production rates of 5.7 to 6.8 m^3/hr (25 to 30 gpm) were observed in boreholes P-9 (Jones 1978, Vol. 1., pp. 167- 168), WQSP-6, and WQSP-6a (see CCA Appendix USDW). Based on a single hydraulic test conducted at WQSP-6a (Figure 2-6), Beauheim and Ruskauff (1998) estimated the transmissivity of a 7.3m (24ft) fractured section of the Dewey Lake at 3.9×10^{-4} m^2/s (360 ft^2/day). The productive zone is typically found in the middle of the Dewey Lake, 55 to 81 m (180 to 265 ft) below ground surface and appears to derive much of its transmissivity from open fractures. Where present, the saturated zone may be perched or simply underlain by less transmissive rock. Fractures below the productive zone tend to be completely filled with gypsum. Open fractures

and/or moist (but not fully saturated) conditions have been observed at similar depths north of the zone of saturation, at the H-1, H-2, and H-3 boreholes (CCA Appendix HYDRO, p. 69).

Under the groundwater monitoring program (Appendix MON-2004), water levels are measured in two Dewey Lake wells, WQSP-6a and H-3d, located south of the WIPP site center (Figure 2-6). Water levels in these two wells are currently 975 and 937 m (3,198 and 3,075 ft) amsl, respectively. Water levels at WQSP-6a remain relatively constant. Over the past several years, water levels at H-3d have risen about 0.3 m/yr (1 ft/yr). Future changes in the Dewey Lake water table due to wetter conditions are part of the conceptual model discussed in Sections 6.4.6 and 6.4.9.

Similar to the six Culebra WQSP wells (WQSP-1 through WQSP-6), Dewey Lake water quality is determined semiannually at WQSP-6a. Baseline concentrations for major ion species have also been determined from ten rounds of sampling. The 95 percent confidence intervals for the major ion species presented in SNL (2001) are shown in Table 2-9 and indicate the Dewey Lake water at this location is relatively fresh. Major ion concentrations have been stable within the baseline 95 percent confidence intervals for all 14 rounds of sampling conducted through May 2002 (Kehrman 2002).

Table 2-9. Ninety-Five Percent Confidence Intervals for Dewey Lake Water-Quality Baseline

Well I.D.	Cl^- Conc. (mg/L)	SO_4^{2-} Conc. (mg/L)	HCO_3^- Conc. (mg/L)	Na^+ Conc. (mg/L)	Ca^{2+} Conc. (mg/L)	Mg^{2+} Conc. (mg/L)	K^+ Conc. (mg/L)
WQSP-6a	433-764	1610-2440	97-111	253-354	554-718	146-185	1.8-9.2

Powers (1997) suggests that what distinguishes the low-transmissivity lower Dewey Lake from the high-transmissivity upper Dewey Lake is a change in natural cements from carbonate (above) to sulfate (below). Resistivity logs correlate with this cement change and show a drop in porosity across the cement-change boundary. Similarly, porosity measurements made on eight core samples from the Dewey Lake from well H-19b4 showed a range from 14.9 to 24.8 percent for the four samples from above the cement change, and a range from 3.5 to 11.6 percent for the four samples from below the cement change (TerraTek 1996). In the vicinity of the surface structures area of the WIPP, Powers (1997) proposed the surface of the cement change is at a depth of approximately 50 to 55 m (165 to 180 ft), is irregular, and trends downward stratigraphically to the south and west of the site center.

During site characterization and initial construction of the WIPP shafts, the Dewey Lake did not produce water within the WIPP shafts or in boreholes in the immediate vicinity of the panels. However, since 1995, water has been observed leaking into the exhaust shaft at a depth of approximately 24.4 m (80 ft) at the location of the Dewey Lake/ Santa Rosa contact (Docket A-93-02, Item number 11-1-07, 1999; INTERA 1997a; INTERA 1997b). As described below in Section 2.2.1.4.2.2, the water is interpreted to be from an anthropogenic source, including infiltration from WIPP rainfall-runoff retention ponds and the WIPP salt storage area and

evaporation pond located at the surface. At the site center, thin cemented zones in the upper Dewey Lake retard, at least temporarily, downward infiltration of modern waters.

Saturation of the uppermost Dewey Lake was observed for the first time in 2001 as well C-2737 was being drilled (Powers 2002c). Well C-2811 was then installed nearby to monitor this zone (Powers and Stensrud 2003). Because of the proximity of these two wells to the WIPP surface structures area, and the absence of water at this horizon when earlier wells were drilled, the saturation is assumed to be an extension of the anthropogenic waters described in the following section.

For modeling purposes, the hydraulic conductivity of the Dewey Lake, assuming saturation, is estimated to be 10^{-8} m/sec (3×10^{-3} ft/day), corresponding to the hydraulic conductivity of fine-grained sandstone and siltstone (Davies 1989, p. 110).

The Dewey Lake is the uppermost important layer in the hydrological model. Its treatment is discussed in Section 6.4.6.6 and Appendix PA, Attachment MASS, Section MASS.14.2. Model parameters are in Table 6-25 and in Appendix PA, Attachment PAR, Table PAR-22.

2.2.1.4.2.2 Santa Rosa

The Santa Rosa ranges from 0 to 91 m (0 to about 300 ft) thick and is present over the eastern half of the WIPP site. It is absent over the western portion of the site. It crops out northeast of Nash Draw. The Santa Rosa near the WIPP site may have a naturalwater-saturated thickness of limited extent. It has a porosity of about 13 percent and a specific capacity of 0.029 to 0.041 L/s/m (0.14 to 0.20 gallons per minute per foot (gpm/ft) of drawdown, where it yields water in the WIPP region.

In May 1995, a scheduled inspection of the WIPP exhaust shaft revealed water emanating from cracks in the concrete liner at a depth of approximately 24.4 m (80 ft) below the shaft collar. Because little or no groundwater had been encountered at this depth interval previously (Bechtel 1979; DOE 1983; Holt and Powers 1984, 1986), the DOE implemented a program in early 1996 to investigate the source and extent of the water. The program included installation of wells and piezometers, hydraulic testing (pumping tests), water-quality sampling and analysis, and water-level and precipitation monitoring (Docket A-93-02, Item number 11-1-07, DOE 1999; INTERA 1997a; DES 1997; INTERA 1997b).

In the initial phases of the investigation, three wells (C-2505, C-2506, and C-2507) and 12 piezometers (PZ-1 through PZ-12) were installed within the surface structures area of the WIPP site (Figure 2-39). The three wells were located near the exhaust shaft and completed to the Santa Rosa/Dewey Lake contact (approximately 15 m [50 ft] below ground surface). Similarly, the piezometers were also completed to the Santa Rosa/Dewey Lake contact (approximately 16 to 23 m [55 to 75 ft] below ground surface). All wells and piezometers, with the exception of PZ-8, encountered a saturated zone just above the Santa Rosa/Dewey Lake contact, but water did not appear to have percolated significantly into the Dewey Lake. PZ-8, the piezometer located farthest to the east in the study area, was a dry hole.

Subsequent to the well and piezometer installations, water-level, water-quality, and rainfall data were collected. In addition, hydraulic tests were performed to estimate hydrologic properties and

water production rates. These data suggest that the water present in the Santa Rosa below the WIPP surface structures area represents an unconfined, water-bearing horizon perched on top of the Dewey Lake (DES 1997). Pressure data collected from instruments located in the exhaust shaft show no apparent hydrologic communication between the Santa Rosa and other formations located stratigraphically below the Santa Rosa.

A water-level-surface map of the Santa Rosa in the vicinity of the WIPPsurface structures area indicates that a potentiometric high is located near the salt water evaporation pond and PZ-7 (Figure 2-40). The water level at PZ-7 is approximately 1 m (3.3 ft) higher than the water levels in any other wells or piezometers. Water is presumed to move radially from this potentiometric high. The areal extent of the water is larger than the 80-acre investigative area shown in Figure 2-39 (DES 1997) as evidenced by drilling records of C-2737 (Powers 2002c) located outside of and south of the WIPP surface structures area that indicate a Santa Rosa/Dewey Lake perched-water horizon at a depth of approximately 18 m (60 ft). The study of this water is ongoing.

Water-quality data for the perched Santa Rosa waters are highly variable and appear to be dominated by two anthropogenic sources: (1) runoff of rainfall into and infiltration from the retention ponds located to the south of the WIPP surface facilities, and (2) infiltration of saline waters from the salt storage area, the salt storage evaporation pond, and perhaps remnants of the drilling and tailings pit used during the construction of the WIPP salt shaft. The total dissolved solids (TDS) in the perched water range from less than 3,000 mg/L at PZ-10 to more than 160,000 mg/L at PZ-3 (DES 1997). Concentration contours are known to shift with time. For example, the high-TDS zone centered at PZ-3 moved observably to the northeast toward PZ-9 between February 1997 and October 2000 (DOE 2002b).

Hydraulic tests (Docket A-93-02, Item number 11-1-07, DOE; INTERA 1997a; DES 1997) conducted in the three wells and 12 piezometers indicate that the Santa Rosa behaves as a low-permeability, unconfined aquifer perched on the Dewey Lake. Hydraulic conductivity ranges from 2.6×10^{-8} to 5.5×10^{-5} m/s (7.4×10^{-3} to 16 ft/day). The wells are capable of producing at rates of about 0.3 to 1.0 gpm. The estimated storativity value for the Santa Rosa is 1×10^{-2}.

2.2.1.5 Hydrology of Other Groundwater Zones of Regional Importance

The groundwater regimes in the Capitan Limestone, which is generally regarded as the northern boundary of the Delaware Basin, and Nash Draw have been evaluated by the DOE as part of the WIPP project because of their importance in some processes, notably dissolution features, that the DOE has determined to be of low probability at the WIPP site.

2.2.1.5.1 Capitan Limestone

The Capitan Limestone (hereafter referred to as the Capitan), which outcrops in the southern end of the Guadalupe Mountains, is a massive limestone unit that grades basinward into recemented, partly dolomitized reef breccia and shelfward into bedded carbonates and evaporites. A deeply incised submarine canyon near the Eddy-Lea county line has been identified (Hiss 1976). This

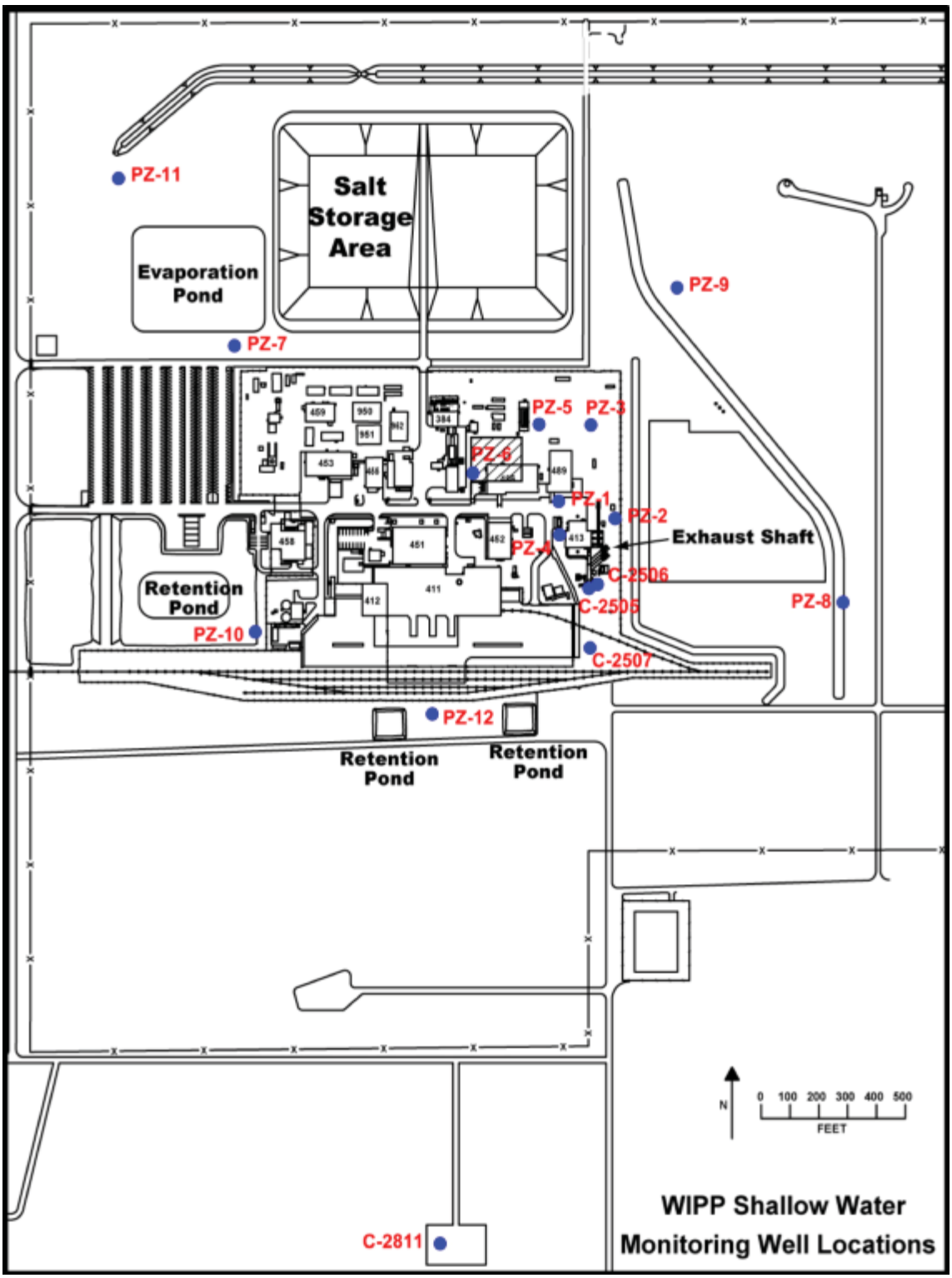

Figure 2-39. Site Map of WIPP Surface Structures Area Showing Location of Wells (e.g., C-2505) and Piezometers (e.g., PZ-1) (after INTERA 1997)

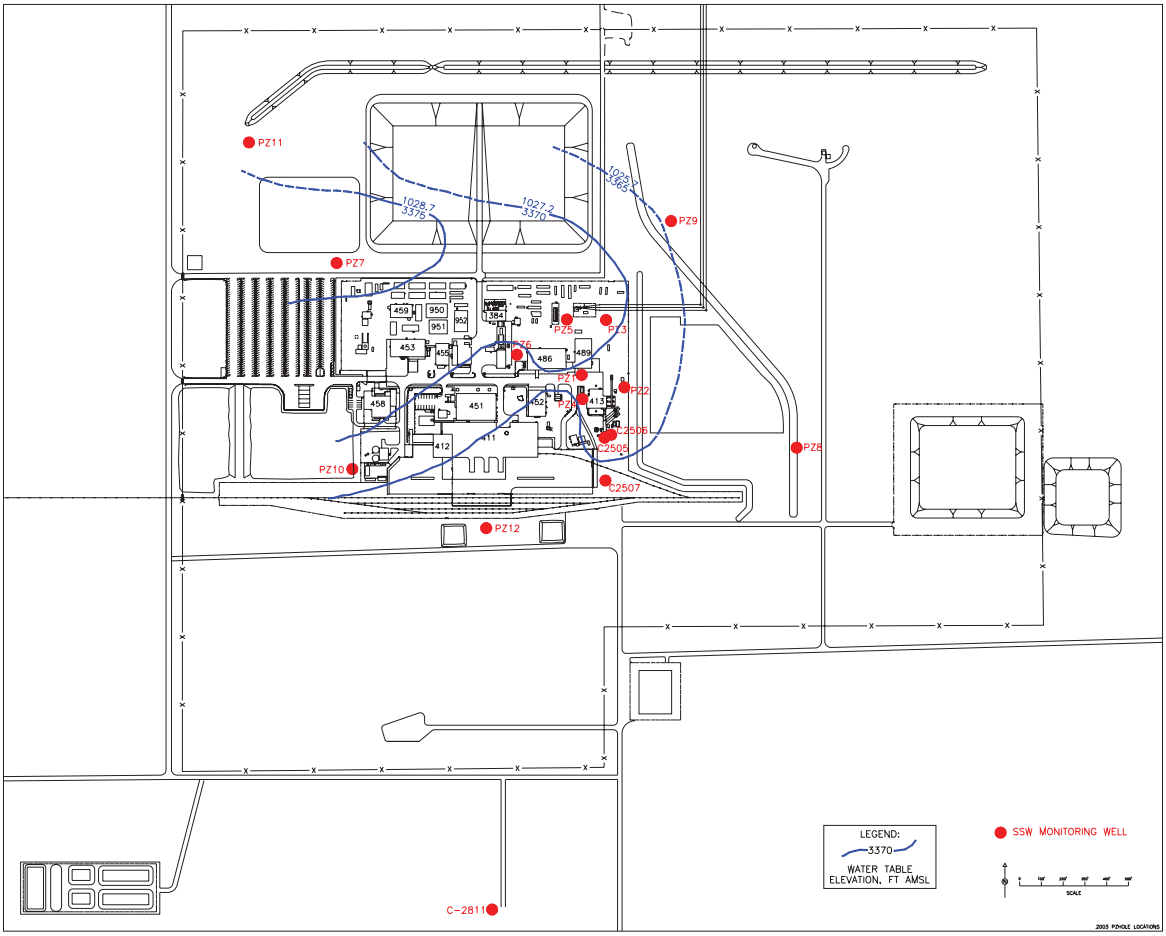

Figure 2-40. Santa Rosa Potentiometric Surface Map

canyon is filled with sediments of lower permeability than the Capitan and, according to Hiss (1975 p. 199), restricts fluid flow. The hydraulic conductivity of the Capitan ranges from 3×10^{-6} to 9×10^{-5} m/s (1 to 25 ft/day) in southern Lea County and is 1.7×10^{-5} m/s (5 ft/day) east of the Pecos River at Carlsbad (CCA Appendix HYDRO, p. 34). Hiss (1975, p. 199) reported in 1975 that average transmissivities around the northern and eastern margins of the Delaware Basin are 0.01 m^2/s (10,000 ft^2/day) in thick sections and 5.4×10^{-4} m^2/s (500 ft^2/day) in incised submarine canyons. Water table conditions are found in the Capitan aquifer southwest of the Pecos River at Carlsbad; however, artesian conditions exist to the north and east. The hydraulic gradient to the southeast of the submarine canyon near the Eddy-Lea county line has been affected by large oil field withdrawals. The Capitan is recharged by percolation through the northern shelf aquifers, by flow from the south and west from underlying basin aquifers (see information on the Bell Canyon, Section 2.2.1.2.1), and by direct infiltration at its outcrop in the Guadalupe Mountains. The Capitan is important in the regional hydrology because breccia pipes in the Salado have formed over it, most likely in response to the effects of dissolution by groundwater flowing in the Castile along the base of the Salado. See CCA Appendix DEF, Section DEF.3.1 for a more thorough discussion of breccia pipe formation.

2.2.1.5.2 Hydrology of the Rustler-Salado Contact Zone in Nash Draw

As discussed in Sections 2.1.3.4 and 2.1.6.2.1, in Nash Draw the contact between the Rustler and the Salado is an unstructured residuum of gypsum, clay, and sandstone created by the dissolution of halite and has been known as the brine aquifer, Rustler-Salado residuum, and residuum. The residuum is absent under the WIPP site. It is clear that dissolution in Nash Draw occurred after deposition of the Rustler (see CCA Appendix DEF, Section DEF.3.2 for a discussion of lateral dissolution of the Rustler-Salado contact). As described previously, the topographic low formed by Nash Draw is a groundwater divide in the groundwater basin conceptual model of the units above the Salado. The brine aquifer is shown in Figure 2-41.

Robinson and Lang (1938) described the brine aquifer (Section 2.1.3.4) and suggested that the structural conditions that caused the development of Nash Draw might control the occurrence of the brine; thus, the brine aquifer boundary may coincide with the topographic surface expression of Nash Draw, as shown in Figure 2-33. Their studies show brine concentrated along a strip from 3.3 to 13 km (2 to 8 mi) wide and about 43 km (26 mi) long. Data from the test holes that Robinson and Lang (1938) drilled indicate that the residuum (containing the brine) ranges in thickness from 3 to 18 m (10.5 to 60 ft) and averages about 24 feet (7 meters).

Hydraulic properties were determined by Hale et al. (1954) primarily for the area between Malaga Bend on the Pecos River and Laguna Grande de la Sal. They calculated a transmissivity value of 8.6×10^{-3} m^2/s (8,000 ft^2/day) and estimated the potentiometric gradient to be 0.27 m/km (1.4 ft/mi). In this area, the Rustler-Salado residuum apparently is part of a continuous hydrologic system, as evidenced by the coincident fluctuation of water levels in the test holes (as far away as Laguna Grande de la Sal) with pumping rates in irrigation wells along the Pecos River.

In the northern half of Nash Draw, the approximate outline of the brine aquifer as described by Robinson and Lang (1938) has been supported by drilling associated with the WIPP hydrogeologic studies. These studies also indicate that the main differences in areal extent occur along the eastern side where the boundary is very irregular and, in places (test holes P-14 and H-07), extends farther east than previously indicated by Robinson and Lang (1938).

Other differences from the earlier studies include the variability in thickness of residuum present in test holes WIPP-25 through WIPP-29. These holes indicate thicknesses ranging from 3.3 m (11 ft) in WIPP-25 to 33 m (108 ft) in WIPP-29 in Nash Draw, compared to 2.4 m (8 ft) in test hole P-14, east of Nash Draw. The specific geohydrologic mechanism that has caused dissolution to be greater in one area than in another is not apparent, although a general increase in chloride concentration in water from the north to the south may indicate the effects of movement down the natural hydraulic gradient in Nash Draw.

The average hydraulic gradient within the residuum in Nash Draw is about 1.9 m/km (10 ft/mi); in contrast, the average gradient at the WIPP site is 7.4 m/km (39 ft/mi) (CCA Appendix HYDRO, p. 50). This difference reflects the changes in transmissivity, which are as much as five orders of magnitude greater in Nash Draw. The transmissivity determined from aquifer tests in test holes completed in the Rustler-Salado contact residuum of Nash Draw ranges from

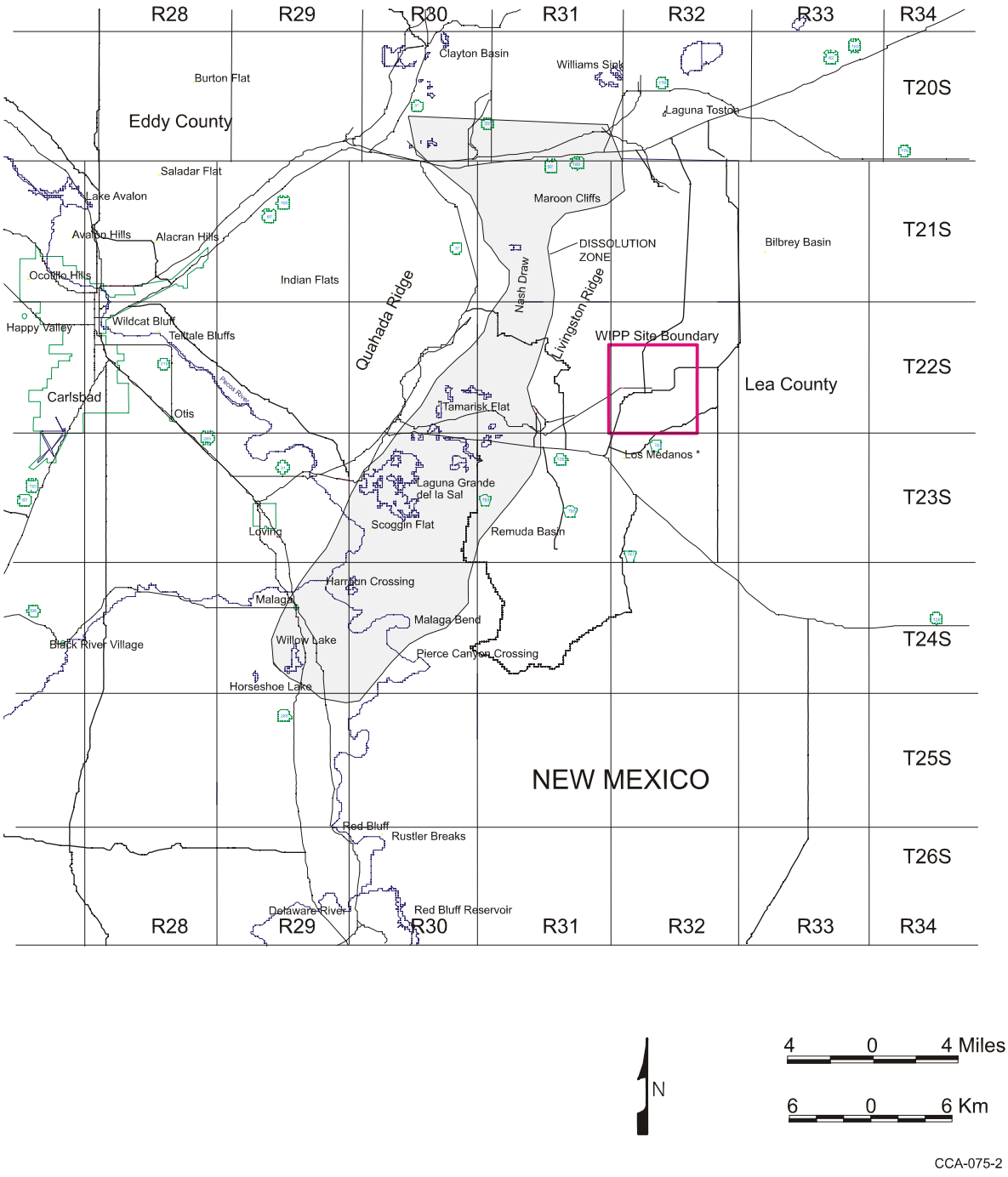

Figure 2-41. Brine Aquifer in the Nash Draw (Redrawn from CCA Appendix HYDRO, Figure 14)

2.1×10^{-10} m^2/s (2×10^{-4} ft^2/day) at WIPP-27 to 8.6×10^{-6} m^2/s (9 8 ft^2/day) at WIPP-29. This is in contrast to the WIPP site proper, where transmissivities range from 3.2×10^{-11} m^2/s (3×10^{-5} ft^2/day) at test holes P-18 and H-5c to 5.4×10^{-8} m^2/s (5×10^{-2} ft^2/day) at test hole P-14 (CCA Appendix HYDRO, p. 50). Locations and estimated hydraulic heads of these wells based on water-level measurements made in the 1980s (Lappin et al. 1989) are illustrated in Figure 2-42.

Hale et al. (1954) believed the Rustler-Salado contact residuum discharges to the alluvium near Malaga Bend on the Pecos River. Because the confining beds in this area are probably fractured because of dissolution and collapse of the evaporites, the brine (under artesian head) moves up through these fractures into the overlying alluvium and then discharges into the Pecos River.

According to CCA Appendix HYDRO, p. 55, water in the Rustler-Salado contact residuum in Nash Draw contains the largest concentrations of dissolved solids in the WIPP area, ranging from 41,500 mg/L in borehole H-1 to 412,000 mg/L in borehole H-5c. These waters are classified as brines. The dissolved mineral constituents in the brine consist mostly of sulfates and chlorides of calcium, magnesium, sodium, and potassium; the major constituents are sodium and chloride. Concentrations of the other major ions vary according to the spatial location of the sample, are probably directly related to the interaction of the brine and the host rocks, and reflect residence time within the rocks. Residence time of the brine depends upon the transmissivity of the rock. For example, the presence of large concentrations of potassium and magnesium in water is correlated with minimal permeability and a relatively undeveloped flow system.

The EPA's initial review of the CCA found the discussion of the Rustler/Salado contact to require clarification, particularly with respect to the possibility of the continued development and characteristics of a dissolution front along this contact, and the impact that continued dissolution within the brine aquifer residuum would have on the overlying units of the Rustler. The DOE discussed the rate and extent of dissolution processes further in supplemental information provided in a letter dated June 13, 1997 (Docket A-93-02, II-H-44). Based upon this information, the EPA concluded that, while dissolution may occur along the Rustler/Salado contact, it would not affect the WIPP's containment capabilities during the regulatory time period. Further discussion of this topic is contained in EPA Technical Support Document for Section 194.14: Content of Compliance Certification Application, Section IV.C.3 (Docket A-93-02, Item V-B-3).

2.2.2 Surface-Water Hydrology

The WIPP site is in the Pecos River basin, which contains about 50 percent of the drainage area of the Rio Grande Water Resources Region. The Pecos River headwaters are northeast of Santa Fe, and the river flows to the south through eastern New Mexico and western Texas to the Rio Grande. The Pecos River has an overall length of about 805 km (500 mi), a maximum basin width of about 209 km (130 mi), and a drainage area of about 115,301 km^2 (44,535 mi^2). (About 53,075 km^2 [20,500 mi^2] contained within the basin have no external surface drainage and their surface waters do not contribute to Pecos River flows.) Figure 2-43 shows the Pecos River drainage area.

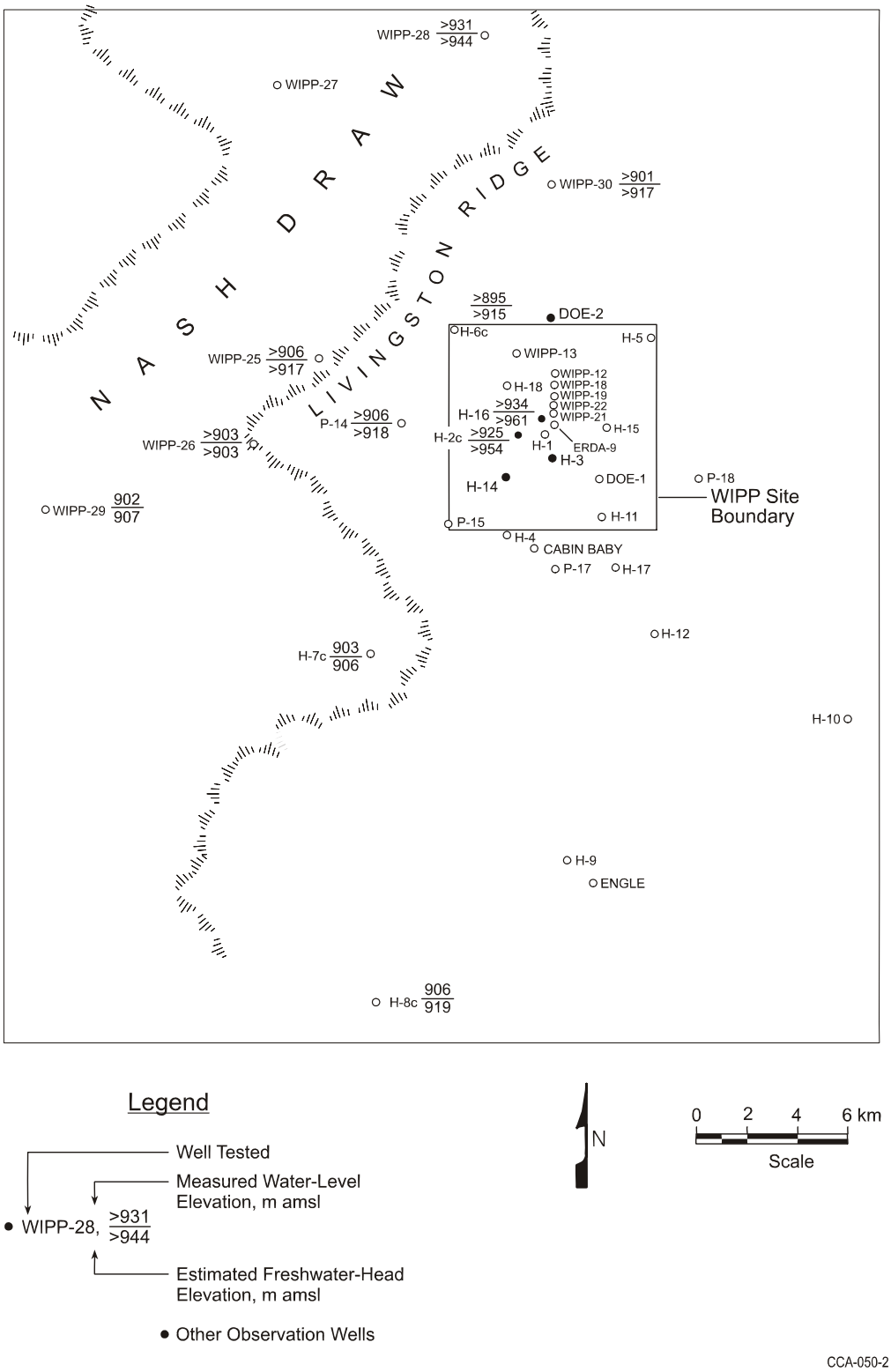

Figure 2-42. Measured Water Levels of the Los Medaños and Rustler-Salado Contact Zone (1980s)

The Pecos River generally flows year-round, except in the reach below Anton Chico where the low flows percolate into the stream bed. The main stem of the Pecos River and its major tributaries have low flows, and the tributary streams are frequently dry. About 75 percent of the total annual precipitation and 60 percent of the annual flow result from intense local thunderstorms between April and September.

There are no perennial streams at the WIPP site. At its nearest point, the Pecos River is about 19 km (12 mi) southwest of the WIPP site boundary. A few small creeks and draws are the only westward flowing tributaries of the Pecos River within 32 km (20 mi) north or south of the site. Nash Draw, the largest surface drainage feature east of the Pecos River in the WIPP region, is a closed depression and does not provide surface flow into the Pecos. Potash mining operations in and near Nash Draw likely contribute to the flow in Nash Draw. For example, the Mississippi Potash Inc. East operation located 11 to 13 km (7 to 8 mi) due north of the WIPP site disposes of mine tailings and refining-process effluent on its property and has done so since 1965. Records obtained from the New Mexico Office of the State Engineer show that since 1973, an average of 3×10^6 m^3 (2,400 acre-feet [ac-ft]) of water per year has been pumped from local aquifers (Ogallala and Capitan) for use in the potash-refining process at that location (SNL 2003b). Based on knowledge of the potash refining process, approximately 90 percent of the pumped water is estimated to be discharged to the tailings pile. Geohydrology Associates (1978) estimated that approximately half of the brine discharged onto potash tailings piles in Nash Draw seeps into the ground annually, while the remainder evaporates. The Black River (drainage area: 1,035 km^2 [400 mi^2]) joins the Pecos from the west about 25 km (16 mi) southwest of the site. The Delaware River (drainage area: 1,812 km^2 [700 mi^2]) and a number of small creeks and draws also join the Pecos River along this reach. The flow in the Pecos River below Fort Sumner is regulated by storage in Sumner Lake, Brantley Reservoir, Lake Avalon, and several other smaller irrigation dams.

Five major reservoirs are located on the Pecos River: Santa Rosa Lake, Sumner Lake, Brantley Reservoir, Lake Avalon, and the Red Bluff Reservoir, the last located just over the border in Texas (Figure 2-43). The storage capacities of these reservoirs and the Two Rivers Reservoir in the Pecos River Basin are shown in Table 2-10.

With regard to surface drainage onto and off of the WIPP site, there are no major natural lakes or ponds within 8 km (5 mi) of the site. Laguna Gatuña, Laguna Tonto, Laguna Plata, and Laguna Toston are playas more than 16 km (10 mi) north and are at elevations of 1,050 m (3,450 ft) or higher. Thus, surface runoff from the site (elevation 1,010 m [3,310 ft] above sea level) would not flow toward any of them. To the northwest, west, and southwest, Red Lake, Lindsey Lake, and Laguna Grande de la Sal are more than 8 km (5 mi) from the site, at elevations of 914 to 1,006 m (3,000 to 3,300 ft). A low-flow investigation has been initiated by the USGS within the Hill Tank Draw drainage area, the most prominent drainage feature near the WIPP site. The drainage area is about 10.3 km^2 (4 mi^2), with an average channel slope of 1 to 100, and the drainage is westward into Nash Draw. Two years of observations showed only four flow events. The USGS estimates that the flow rate for these events was under 0.057 m^3/s (2 ft^3/s) (DOE 1980, pp. 7- 74).

As discussed in Section 2.5.2.3, the mean annual precipitation in the region is 0.33 m (13 in.), and the mean annual runoff is 2.5 to 5 mm (0.1 to 0.2 in.). The maximum recorded 24-hour

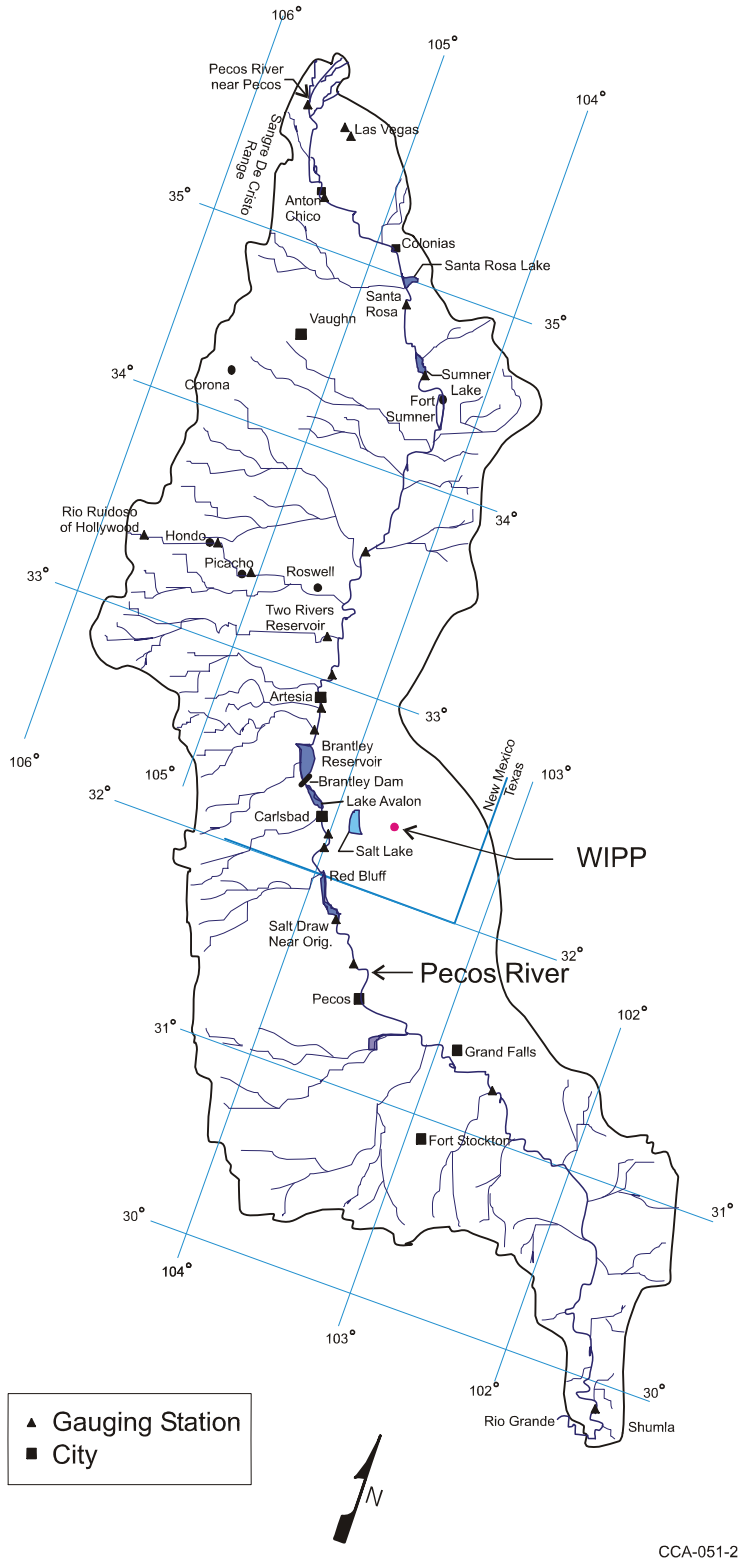

Figure 2-43. Location of Reservoirs and Gauging Stations in the Pecos River Drainage Area

Table 2-10. Capacities of Reservoirs in the Pecos River Drainage

Reservoir	River	Total Storage Capacity[a] (ac-ft)	Use[b]
Santa Rosa	Pecos	282000	FC
Sumner	Pecos	122100	IR, R
Brantley	Pecos	42000	IR, R, FC
Avalon	Pecos	5000	IR
Red Bluff	Pecos	310000	IR, P
Two Rivers	Rio Hondo	167900	FC

[a] Capacity below the lowest uncontrolled outlet or spillway.
[b] Legend:

FC flood control
IR irrigation
R recreation
P hydroelectric

precipitation at Carlsbad was 130 mm (5.12 in.) in August 1916. The predicted maximum 6-hour, 100-year precipitation event for the site is 91 mm (3.6 in.) and is most likely to occur during the summer. The maximum recorded daily snowfall at Carlsbad was 254 mm (10 in.) in December 1923.

The maximum recorded flood on the Pecos River occurred near the town of Malaga, New Mexico, on August 23, 1966, with a discharge of 3,396 m^3 (120,000 ft^3) per second and a stage elevation of about 895 m (2,938 ft) amsl. The minimum surface elevation at the WIPP is over 91 m (300 ft) above the elevation of this maximum historic flood (DOE 1980, Section 7.4.1).

As discussed in the FEIS (DOE 1980, pp. 7- 71), more than 90 percent of the mean annual precipitation at the site is lost by evapotranspiration. On a mean monthly basis, evapotranspiration at the site greatly exceeds the available rainfall; however, intense local thunderstorms may produce runoff and percolation.

Water quality in the Pecos River basin is affected by mineral pollution from natural sources and from irrigation return flows (see Section 2.4.2.2 for discussion of surface-water quality). At Santa Rosa, New Mexico, the average suspended-sediment discharge of the river is about 1,497 metric tons/day (1,650 tons/day). Large amounts of chlorides from Salt Creek and Bitter Creek enter the river near Roswell. River inflow in the Hagerman area contributes increased amounts of calcium, magnesium, and sulfate; and waters entering the river near Lake Arthur are high in chloride. Below Brantley Reservoir, springs flowing into the river are usually submerged and difficult to sample; springs that could be sampled had TDS concentrations of 3,350 to 4,000 mg/L. Concentrated brine entering at Malaga Bend adds an estimated 64 metric tons/day (370 tons/day) of chloride to the Pecos River (CCA Appendix GCR, pp. 6-7).

2.3 Resources

At the outset of the repository program, the DOE understood the importance of resources in the vicinity of a disposal system. Several of the siting criteria emphasized avoidance of resources that would impact the performance of the disposal system. In this regard, the DOE selected a site that (1) maximized the use of federal lands, (2) avoided known oil and gas trends, (3) minimized the impacts on potash deposits, and (4) avoided existing drill holes. While the DOE could not meet all these criteria totally, it is shown that the favorable characteristics of the location compensate for any increased risks due to the presence of resources. Consequently, the DOE has prepared this section to discuss resources that may exist at or beneath the WIPP site. The topic of resources is used to broadly define both economic (mineral and nonmineral) and cultural resources associated with the WIPP site. These resources are important because they (1) provide evidence of past uses of the area and (2) indicate potential future use of the area with the possibility that such use could lead to disruption of the closed repository. Because of the depth of the disposal horizon, it is believed that only the mineral resources are of significance in predicting the long-term performance of the disposal system. However, the nonmineral and cultural resources are presented for completeness because they are included in the FEP screening discussions in Chapter 6 and Appendix PA, Attachment SCR. Information needed to make screening decisions includes natural resource distributions, including potable groundwaters, the distribution of drillholes, mines, excavations, and other man-made features that exploit these resources, the distribution of drillholes and excavation used for disposal or injection purposes, activities that significantly alter the land surface, agricultural activities that may affect the disposal system, archaeological resources requiring deep excavation to exploit, and technological changes that may alter local demographics. This information is presented here or is referenced.

With respect to minerals or hydrocarbons, reserves are the portion of resources that are economic at today's market prices and with existing technology. For hydrocarbons, proved (proven) reserves are an estimated quantity that engineering and geologic data analysis demonstrates, with reasonable certainty, is recoverable in the future from discovered oil and gas pools. Probable resources (extensions) consist of oil and gas in pools that have been discovered but not yet developed by drilling. Their presence and distribution can generally be surmised with a high degree of confidence. Probable resources (new pools) consist of oil and gas surmised to exist in undiscovered pools within existing fields. (Definitions are from NMBMMR 1995, V-2 and V-3.)

Mineral resource discussions are focused principally on hydrocarbons and potassium salts, both of which have long histories of development in the region. Development of either resource potentially could be disruptive to the disposal system. The information regarding the mineral resources concentrates on the following factors:

- number, location, depth, and present state of development, including penetrations through the disposal horizon,
- type of resource,
- accessibility, quality, and demand, and

- mineral ownership in the area.

The specific impacts of resource development are discussed in Section 6.4.6.2.3, where scenarios related to mineral development are included for evaluation of disposal system performance. This discussion uses information presented in CCA Appendices DEL and MASS as indicated in the following text. The discussion of cultural and economic resources is focused on describing past and present land uses unrelated to the development of minerals. The archaeological record supports the observation that changes in land use are principally associated with climate and the availability of forage for wild and domestic animals. In no case does it appear that past or present land use has had an impact on the subsurface beyond the development of shallow groundwater wells to water livestock.

2.3.1 Extractable Resources

The geologic studies of the WIPP site included the investigation of potential natural resources to evaluate the impact of denying access to these resources and other consequences of their occurrence. Studies were completed in support of the FEIS to ensure knowledge of natural resources, and the impacts of denying access were included in the decision-making process for WIPP. Of the natural resources expected to occur beneath the site, five are of practical concern: the two potassium salts sylvite and langbeinite, which occur in the McNutt; and the three hydrocarbons, crude oil, natural gas, and distillate liquids associated with natural gas, all three of which occur elsewhere in strata below the Castile. Other mineral resources beneath the site are caliche, salt, gypsum, and lithium; enormous deposits of these minerals near the site and elsewhere in the country are more than adequate (and more economically attractive) to meet future requirements for these materials. In 1995, the NMBMMR performed a reevaluation of the mineral resources at and within 1.6 km (1 mi) around the WIPP site. The following discussion is based in part on information from NMBMMR (1995).

2.3.1.1 Potash Resources at the WIPP Site

Throughout the Carlsbad Potash District, commercial quantities of potassium salts are restricted to the middle portion of the Salado, locally called the McNutt. A total of 11 zones (or distinct ore layers) have been recognized in the McNutt. Horizon Number 1 is at the base, and Number 11 is at the top. The 11th ore zone is not mined.

The USGS uses three standard grades—low, lease, and high—to quantify the potash resources at the site. The USGS assumes that the lease and high grades comprise reserves because some lease-grade ore is mined in the Carlsbad Potash District. Most of the potash that is mined, however, is better typified as high-grade. Even the high-grade resources may not be reserves, however, if properties such as high clay content make processing uneconomical. The analysis in NMBMMR (1995) distinguishes between lease-grade ore and economically mineable ore.

The NMBMMR (1995) study contains a comprehensive summary of all previous potash resource evaluations. NMBMMR (1995, Chapter VII) used 40 existing boreholes drilled on and around the WIPP site to perform a reevaluation of potash resources. He selected holes that were drilled using brine so that the dissolution of potassium salts was inhibited. The conclusion reached is

that only the 4th and 10th ore zones contain economic potash reserves. The quantities are summarized in Table 2-11.

Table 2-11. Current Estimates of Potash Resources at the WIPP Site

		Recoverable Ore (10^6 tons)	
Mining Unit	**Product**	**Within the WIPP site**	**One-Mile Strip Adjacent to the WIPP site**
4th Ore Zone	Langbeinite	40.5 at 6.99%*	126.0 at 7.30%
10th Ore Zone	Sylvite	52.3 at 13.99%	105.0 at 14.96%

Source: NMBMMR 1995, Chapter VII.

* For example, read as 40.5×10^6 tons of ore at a grade of 6.99 percent or higher.

Within the Carlsbad Known Potash Leasing Area, exploration holes have been drilled to evaluate the grade of the various ore zones. These are included in the drillhole database in CCA Appendix DEL. None of the economically minable reserves identified by the NMBMMR lies directly above the waste panels. The known potash leases within the Delaware Basin are shown in Figure 2-44 and are detailed in CCA Appendix DEL, Figure DEL-8. From information in this figure and other data which is provided in CCA Appendix MASS, Attachment 15-5, DOE evaluates the extent of future mining outside the land withdrawal area. The extent of possible future mining within the controlled area is shown in Figure 2-45. The DOE also addresses this subject with respect to PA in Section 6.4.6.2.3.

The EPA concluded that neither the DOE's nor the Department of Interior's (DOI) estimate shows the area above the WIPP waste panels as containing mineable reserves. The DOE provided supplemental information in a letter dated May 14, 1997, indicating that potash solution mining and brine extraction do not need to be considered for the PA, based on low consequence to the containment capability of the repository (Docket A-93-02, Item II-I-31). The EPA reviewed the supplemental data and concurred with the DOE's conclusion. To obtain further discussion on this topic, CARD 32-Section 32.B, CARD 33-Section 33A, and CARD 32-Section 32 F (Docket A-93-02, item III-B-2) may be referenced. Additional information is found in FEPs screening discussions for solution mining for potash and solution mining for other resources (FEPs H58 and H59) in Appendix PA, Attachment SCR.

2.3.1.2 Hydrocarbon Resources at the WIPP Site

In 1974, Foster of the NMBMMR conducted a hydrocarbon resource study in southeastern New Mexico under contract to the ORNL. The study included an area of 3,914 km^2 (1,512 mi^2). At the time of that study, the proposed repository site was about 8 km (5 mi) northeast of the current site. The 1974 NMBMMR evaluation included a more detailed study of a four-township area centered on the old site; the present site is in the southwest quadrant of that area. The 1974 NMBMMR hydrocarbon resources study (Foster 1974) is presented in more detail in the FEIS (DOE 1980, Section 9.2.3.5). The reader is referred to the FEIS or the original study for additional information.

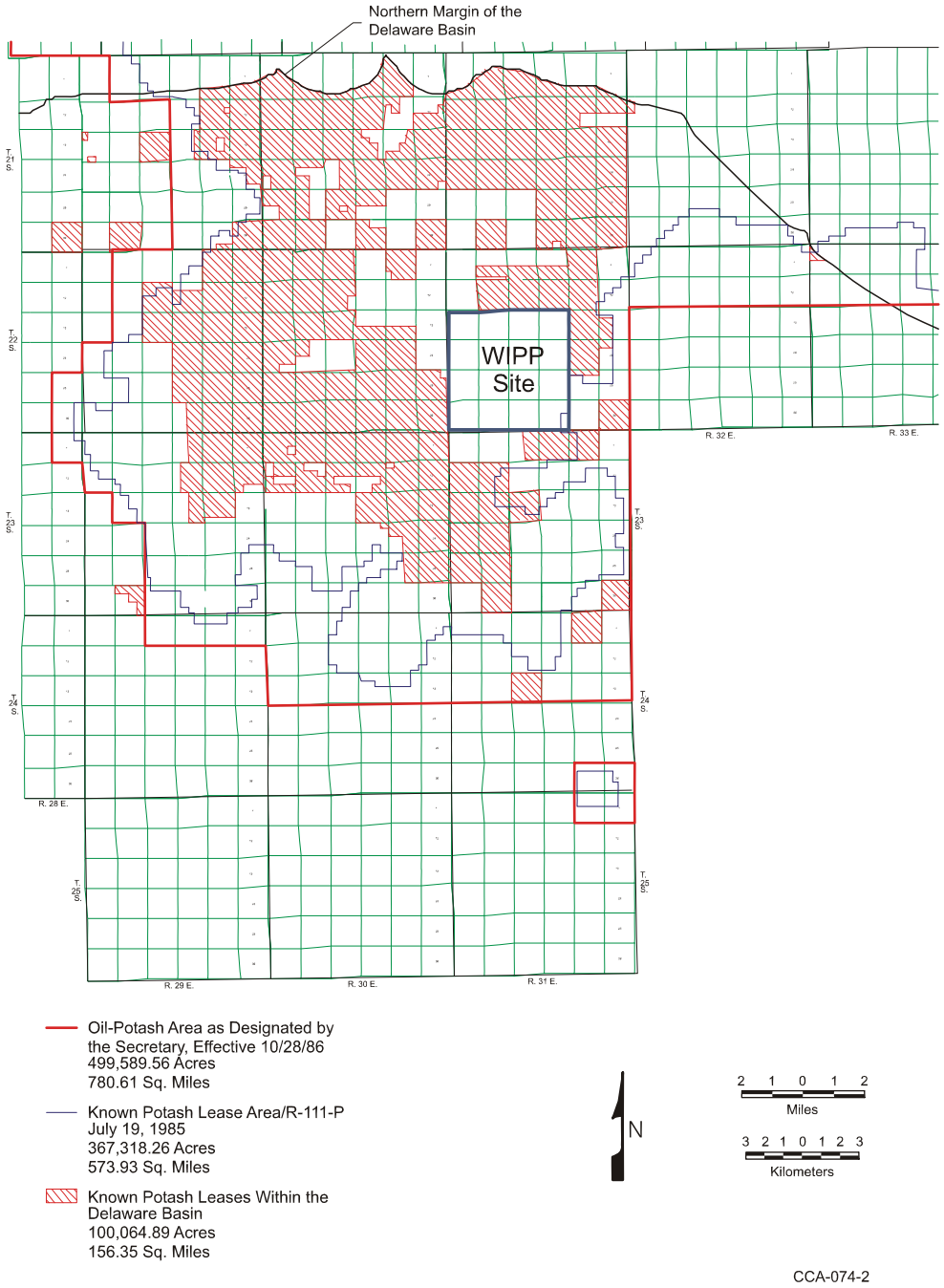

Figure 2-44. Known Potash Leases Within the Delaware Basin

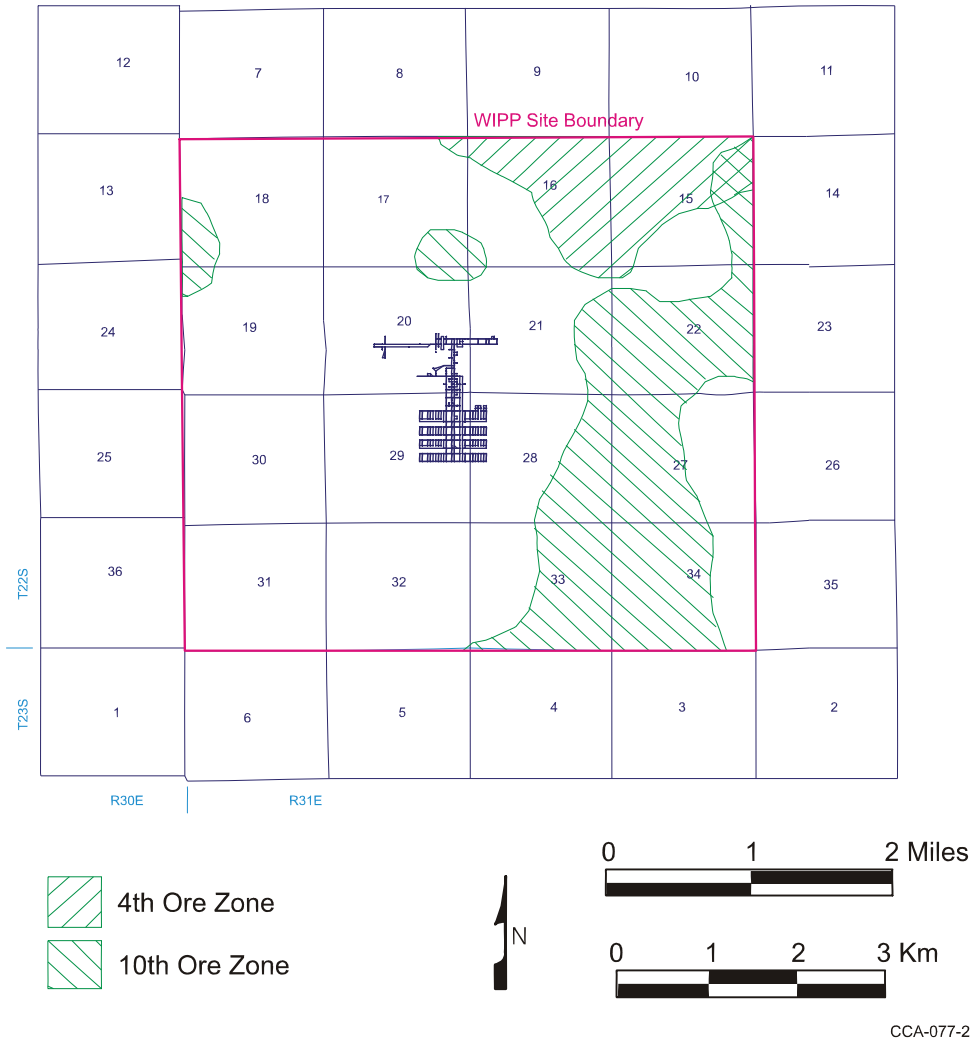

Figure 2-45. Extent of Economically Mineable Reserves Inside the Site Boundary (Based on NMBMMR Report)

The resource evaluation was based both on the known reserves of crude oil and natural gas in the region and on the probability of discovering new reservoirs in areas where past unsuccessful drilling was either too widely spread or too shallow to have allowed discovery. Potentially productive zones were considered in the evaluation; therefore, the findings may be used for estimating the total hydrocarbon resources at the site. A fundamental assumption in the study was that the WIPP area has the same potential for containing hydrocarbons as the larger region studied for which exploration data are available. Whether such resources actually exist can be satisfactorily established only by drilling at spacings close enough to give a high probability of discovery.

The NMBMMR 1995 mineral resource reevaluation contains a comprehensive summary of all previous evaluations. NMBMMR (1995, Chapter XI) provided a reassessment of hydrocarbon

resources within the WIPP site boundary and within the first mile adjacent to the boundary. Calculations were made for resources that are extensions of known, currently productive oil and gas resources that are thought to extend beneath the study area with reasonable certainty (called probable resources in the report). Qualitative estimates are also made concerning the likelihood that oil and gas may be present in undiscovered pools and fields in the area (referred to as possible resources). Possible resources were not quantified in the study. The results of the study are shown in Tables 2-12 and 2-13.

Table 2-12. In-Place Oil within Study Area

Formation	Within WIPP Site (10^6 bbl[a])	1-Mile Strip Adjacent to the WIPP Site (10^6 bbl)	Total (10^6 bbl)
Delaware	10.33	20.8	31.13
Bone Spring	0.44	0.8	1.25
Strawn	0.4	0.4	0.8
Atoka	1.1	0.1	0.2
Total	12.3	22.9	35.3

Source: NMBMMR (1995, Chapter XI)
a bbl = barrel = 42 gallons

Table 2-13. In-Place Gas within Study Area

Formation	Gas Reserves (Mcf)[a]	
	Within WIPP Site	1-Mile Strip Adjacent to the WIPP
Delaware	18176	32873
Bone Springs	956	1749
Strawn	9600	9875
Atoka	123336	94410
Morrow	32000	28780

Source: NMBMMR (1995, Chapter XI)
[a] Mcf = thousand cubic feet

The DOE compiled statistics on the historical development of hydrocarbon resources in the Delaware Basin and included them in CCA Appendix DEL. For these purposes, the Delaware Basin is described as the surface and subsurface features that lie inside the boundary formed to the north, east, and west by the innermost edge of the Capitan Reef and formed to the south by a straight line drawn from the southeastern point of the Davis Mountains to the southwestern point of the Glass Mountains (see Figure 2-46).

Several important modeling parameters result from the study of hydrocarbon resources and the history of their exploitation. These include parameters related to the number of human intrusions, the size of boreholes, the operational histories of such holes, the plugging of these

holes, and the use of such holes for other purposes, such as liquid disposal. Each of these topics is discussed in detail in CCA Appendix DEL and Appendix PA, Attachment MASS, Section MASS.16 and is addressed in Sections 6.4.7 and 6.4.12. The distribution of existing boreholes is shown in Figure DEL-4 (CCA Appendix DEL) for the entire Delaware Basin and Figure 2-47 for the vicinity of the WIPP site. In addition, CCA Appendix DEL includes an assessment of current drilling and plugging practices in the Delaware Basin. CCA Appendix DEL also discusses the regulatory constraints placed on the use of wells for injection.

2.3.1.3 Other Resources

While the focus of studies at the WIPP has been on potash and hydrocarbon, other resources are known to occur within the Delaware Basin and are considered in the screening. For example, sulfur is produced in the vicinity of Orla, Texas. Sulfur wells are included in CCA Appendix DEL; however, no sulfur resources have been identified in the vicinity of the WIPP; therefore, there are no projected impacts. Another resource that is extensively produced is groundwater. Potable water occurs in numerous places within the Delaware Basin. Several communities rely solely on groundwater sources for drinking water. CCA Appendix DEL includes a distribution of groundwater wells in the Delaware Basin. All such wells in the vicinity of the WIPP are shallow, generally no deeper than the Culebra. An evaluation of underground sources of drinking water in the vicinity of the disposal system is presented in CCA Appendix USDW. Figure USDW-4 shows the distribution of groundwater wells in the vicinity of the disposal system. Sand, gravel, and caliche are produced in numerous areas within the Delaware Basin. In all cases, these are surface quarries that are generally shallow (10s of feet). No impact to the disposal system is expected from these activities.

2.3.2 Cultural and Economic Resources

The demographics, land use, and history and archaeology of the WIPP site and its environs are characterized in the sections that follow.

2.3.2.1 Demographics

The WIPP facility is located 42 km (26 mi) east of Carlsbad in Eddy County in southeastern New Mexico and includes an area of 10,240 ac (approximately 41 km^2) (16 mi^2). The facility is located in a sparsely populated area with fewer than 30 permanent residents living within a 16-km (10-mi) radius of the facility. The area surrounding the facility is used primarily for grazing, potash mining, and hydrocarbon production. No resource development that would affect WIPP facility operations or the long-term integrity of the facility is allowed within the 10,240 ac that have been set aside for the WIPP project.

The permanent residence nearest to the WIPP site boundary is the J.C. Mills Ranch, which is 2 km (1.2 mi) to the south. The community nearest to the WIPP site is the town of Loving, New Mexico, 29 km (18 mi) west-southwest of the site center. The population of Loving increased from 1,243 in 1990 to 1,326 in 2000. The nearest population center is the city of Carlsbad, New Mexico, 42 km (26 mi) west of the site. The population of

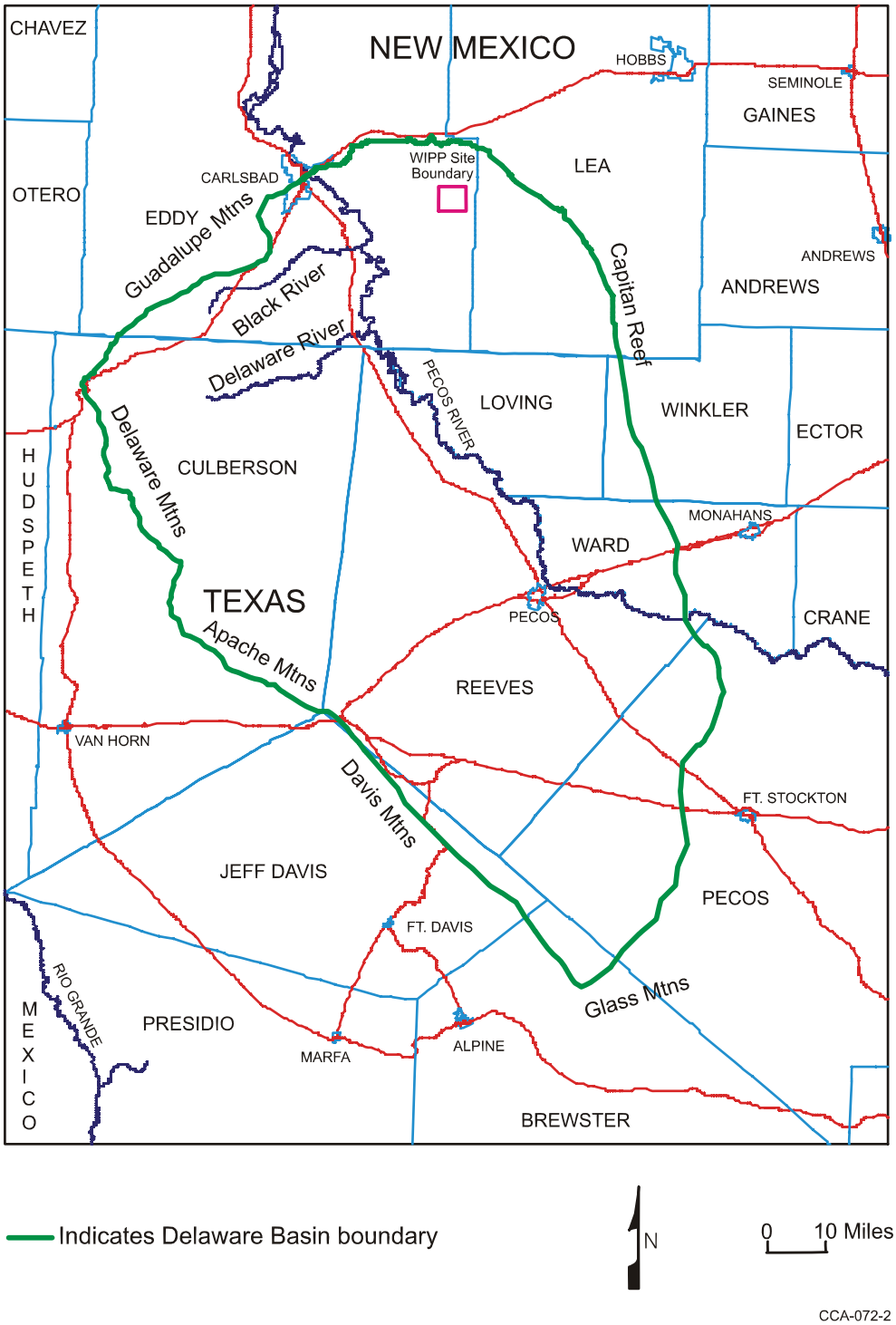

Figure 2-46. Delaware Basin Boundary

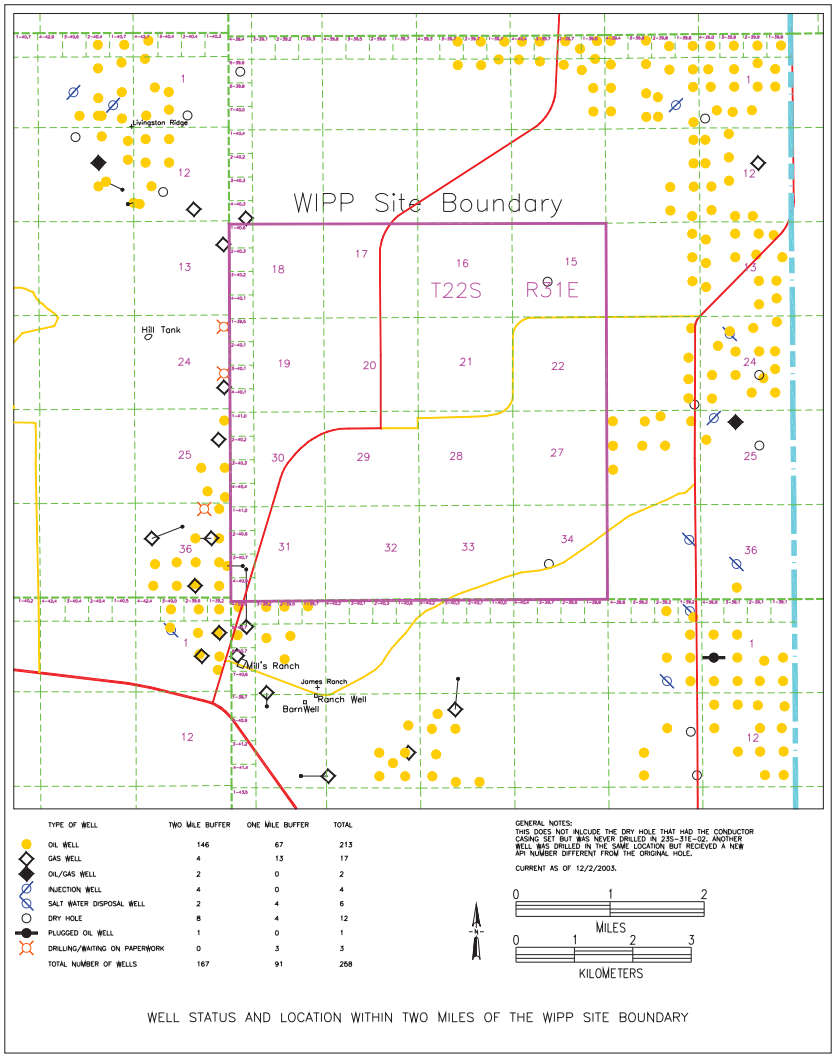

Figure 2-47. Distribution of Existing Petroleum Industry Boreholes Within Two Miles of the WIPP Site

Carlsbad increased from 24,896 in 1990 to 26,870 in 2000. Hobbs, New Mexico, 58 km (36 mi) to the east of the site, had a population decrease from 29,115 in 1990 to 28,657 in 2000. Eunice, New Mexico, 64 km (40 mi) east of the site, had a 1990 population of 2,731 decrease to 2,562 in 2000. Jal, New Mexico, 72 km (45 mi) southeast of the site, had a population of 2,153 in 1990 decrease to 1,996 in 2000.

The WIPP site is located in Eddy County near the border of Lea County, New Mexico. The Eddy County population increased from 48,605 in 1990 to 51,658 in 2000. The Lea County population decreased from 55,765 in 1990 to 55,511 in 2000. Population figures are taken from the 1990 census (U.S. Department of Commerce,1990) and the 2000 census (U.S. Census Bureau, 2000).

2.3.2.2 Land Use

At present, land within 16 km (10 mi) of the site is used for potash mining operations, active oil and gas wells, activities associated with hydrocarbon production, and grazing.

The WIPP Land Withdrawal Act (LWA) (U.S. Congress 1992) withdrew certain public lands from the jurisdiction of the Bureau of Land Management (BLM). The law provides for the transfer of the WIPP site lands from the DOI to the DOE and effectively withdraws the lands, subject to existing rights, from entry, sale, or disposition; appropriation under mining laws; or operation of the mineral and geothermal leasing laws. The LWA directed the Secretary of Energy to produce a management plan to provide for grazing, hunting and trapping, wildlife habitat, mining, and the disposal of salt and tailings.

Between 1978 and 1988, DOE acquired all active potash and hydrocarbon leases within the WIPP site boundary. These were acquired either through outright purchase or through condemnation. In one condemnation proceeding, the court awarded DOE the surface and top 1.82 km (6,000 ft) of Section 31 and allowed the leaseholder to retain the subsurface below 1.82 km (6,000 ft). This was allowed because analysis showed that wells developed within this lease below the 1.82-km (6,000ft) limit would be too far away from the waste panels to be of consequence to the WIPP (see, for example, Brausch et al. 1982). This is corroborated by the results of PA discussed in Section 6.2.5.1; and Appendix PA, Attachment SCR, FEP 56. Consequently, as the result of the DOE's acquisition activities, there are no producing hydrocarbon wells within the volumetric boundary defined by the land withdrawal (T22S, R31E, S15-22, 27-34). Two active wells were drilled to tap the oil and gas resources on the leases beneath Section 31. The James Ranch #13, drilled in 1982, is a gas well, and the James Ranch #27, drilled in 2000, is an oil well. Both wells are located on surface leases outside the WIPP site boundary. Both wells enter Section 31 below a depth of 1.82 km (6,000 ft) beneath ground level. Except for the leases in Section 31, the LWA prohibits all drilling into the controlled area unless such drilling is in support of the WIPP.

Grazing leases have been issued for all land sections immediately surrounding the WIPP facility. Grazing within the WIPP site lands occurs within the authorization of the Taylor Grazing Act of 1934, the Federal Land Policy and Management Act (FLPMA), the Public Rangelands Improvement Act of 1978, and the Bankhead-Jones Farm Tenant Act of 1973.

The responsibilities of DOE include supervision of ancillary activities associated with grazing (for example, wildlife access to livestock water development), tracking of water developments inside WIPP lands to ensure that they are configured according to the regulatory requirements, and ongoing coordination with respective allottees. Administration of grazing rights is in cooperation with the BLM according to the memorandum of understanding (MOU) and the coinciding Statement of Work through guidance established in the East Roswell Grazing Environmental Impact Statement. The WIPP site is composed of two grazing allotments administered by the BLM: the Livingston Ridge (No. 77027), and the Antelope Ridge (No. 77032) (see Figure 7-2).

2.3.2.3 History and Archaeology

From about 10,000 B.C. to the late 1800s, the WIPP site and surrounding region were inhabited by nomadic aboriginal hunters and gatherers who subsisted on various wild plants and animals. From about A.D. 600 onward, as trade networks were established with Puebloan peoples to the west, domesticated plant foods and materials were acquired in exchange for dried meat, hides, and other products from the Pecos Valley and Plains. In the late 1500s, the Spanish Conquistadors encountered Jumano and Apachean peoples in the region who practiced hunting and gathering and engaged in trade with Puebloans. After the Jumanos abandoned the southern Plains region, the Comanches became the major population of the area. Neighboring populations with whom the Comanches maintained relationships ranging from mutual trade to open warfare included the Lipan, or Southern Plains Apache, several Puebloan Groups, Spaniards, and the Mescalero Apaches.

The best documented indigenous culture in the WIPP region is that of the Mescalero Apaches, who lived west of the Pecos. The lifestyle of the Mescalero Apaches represents a transition between the full sedentism of the Pueblos and the nomadic hunting and gathering of the Jumanos. In 1763, the San Saba expedition encountered and camped with a group of Mescaleros in Los Medaños. Expedition records indicate the presence of both Lipan and Mescalero Apaches in the region.

A peace accord reached between the Comanches and the Spaniards in 1786 resulted in two historically important economic developments: (1) organized buffalo hunting by Hispanic and Puebloan ciboleros, and (2) renewal and expansion of the earlier extensive trade networks by Comancheros. These events placed eastern New Mexico in a position to receive a wide array of both physical and ideological input from the Plains culture area to the east and north and from Spanish-dominated regions to the west and south. Comanchero trade began to mesh with the Southwest American trade influence in the early nineteenth century. However, by the late 1860s, the importance of Comanchero trade was cut short by Texan influence.

The first cattle trail in the area was established along the Pecos River in 1866 by Charles Goodnight and Oliver Loving. By 1868, Texan John Chisum dominated much of the area by controlling key springs along the river. Overgrazing, drought, and dropping beef prices led to the demise of open-range cattle ranching by the late 1880s.

Following the demise of open-range livestock production, ranching developed using fenced grazing areas and production of hay crops for winter use. Herd grazing patterns were influenced by the availability of water supplies as well as by the storage of summer grasses for winter feeding.

The town of Carlsbad was founded as Eddy in 1889 as a health spa. In addition to ranching, the twentieth century brought the development of the potash, oil, and gas industries that have increased the population eightfold in the last 50 years.

Although technological change has altered some of the aspects, ranching remains an important economic activity in the WIPP region. This relationship between people and the land is still an important issue in the area. Ranch-related sites dating to the 1940s and 1950s are common in

parts of the WIPP area. These will be considered historical properties within the next several years, and thus will be treated as such under current law.

The National Historic Preservation Act (NHPA) (16 USC Part 470 et seq.) was enacted to protect the nation's cultural resources in conjunction with the states, local governments, Indian tribes, and private organizations and individuals. The policy of the federal government includes: (1) providing leadership in preserving the prehistoric and historic resources of the nation, (2) administering federally owned, administered, or controlled prehistoric resources for the benefit of present and future generations, (3) contributing to the preservation of nonfederally owned prehistoric and historic resources, and (4) assisting state and local governments and the national trust for historic preservation in expanding and accelerating their historic preservation programs and activities. The act also established the National Register of Historic Places (National Register). At the state level, the State Historic Preservation Officer (SHPO) coordinates the state's participation in implementing the NHPA. The NHPA has been amended by two acts: the Archeological and Historic Preservation Act (16 USC Part 469 et seq.), and the Archeological Resource Protection Act (16 USC Part 470aa et seq.).

To protect and preserve cultural resources found within the WIPP site boundary, the WIPP submitted a mitigation plan to the New Mexico SHPO describing the steps to either avoid or excavate archaeological sites. A site was defined as a place used and occupied by prehistoric people. In May 1980, the SHPO made a determination of "no adverse effect from WIPP facility activities" on cultural resources. The Advisory Council on Historic Preservation concurred that the WIPP Mitigation Plan is appropriate to protect cultural resources.

Known historical sites (more than 50 years old) in southeastern New Mexico consist primarily of early twentieth century homesteads that failed, or isolated features from late nineteenth century and early twentieth century cattle or sheep ranching, or military activities. To date, no Spanish or Mexican sites have been identified. Historic components are rare but are occasionally noted in the WIPP area. These include features and debris related to ranching.

Since 1976, cultural resource investigations have recorded 98 archaeological sites and numerous isolated artifacts within the 41km^2 (16mi^2) area enclosed by the WIPP site. In the central 10.4km^2 (4mi^2) area, 33 sites were determined to be eligible for inclusion on the National Register as archaeological districts. Investigations since 1980 have recorded an additional 14 individual sites outside the central 10.4km^2 (4mi^2) area that are considered eligible for inclusion on the National Register. The following major cultural resource investigations to date are broken out in the list that follows. Additional information can be found in the bibliography of CCA Chapter 2.

1977. The first survey of the area was conducted for SNL by Nielson of the Agency for Conservation Archaeology (ACA). This survey resulted in the location of 33 sites and 64 isolated artifacts.

1979. MacLennan and Schermer of ACA conducted another survey to determine access roads and a railroad right-of-way for Bechtel, Inc. The survey encountered two sites and 12 isolated artifacts.

1980. Schermer conducted another survey to relocate the sites originally recorded by Nielson. This survey redescribed 28 of the original 33 sites.

1981. Hicks (1981a, 1981b) directed the excavation of nine sites in the WIPP core area.

1982. Bradley (Lord and Reynolds 1985) recorded one site and four isolated artifacts in an archaeological survey for a proposed water pipeline.

1985. Lord and Reynolds (1985) examined three sites within the WIPP core area that consisted of two plant-collecting and processing sites and one base camp used between 1000 B.C. and A.D. 1400. The artifacts recovered from the excavations are in the Laboratory of Anthropology at the Museum of New Mexico in Santa Fe.

1987. Mariah Associates, Inc. identified 40 sites and 75 isolates in an inventory of 2,460 ac in 15 quarter-section units surrounding the WIPP site. In this investigation, 19 of the sites were located within the WIPP site's boundary. Sites encountered in this investigation tended to lack evident or intact features. Of the 40 new sites defined, 14 were considered eligible for inclusion in the National Register, 24 were identified as having insufficient data to determine eligibility, and 2 were determined to be ineligible for inclusion. The eligible and potentially eligible sites have been mapped and are avoided by DOE in its current activities at the WIPP site.

1988–1992. Several archaeological clearance reports have been prepared for seismic testing lines on public lands in Eddy County, New Mexico.

All archaeological sites are surface or near-surface sites, and no reasons exist (either geological or archeological) to suspect that deep drilling would uncover or investigate archaeological sites.

No artifacts were encountered during cultural resource surveys performed from 1992 until present. The following list provides examples of WIPP projects that required cultural resource surveys. All investigations were performed and reported in accordance with requirements established by the New Mexico Office of Cultural Affairs (OCA) and administered by the SHPO.

- SPDV site investigation into status of a previously recorded site (#LA 33175) to determine potential impacts from nearby reclamation activity. Assessment included minor surface excavation.

- WIPP well bore C-2737. Cultural resource investigation for well pad and access road.

- WIPP well bores WQSP 1-6 and 6a. Individual cultural resource investigations conducted for construction of each respective well pad and access road.

- WIPP well bores SNL 1, 2, 3, 9 and 12. Cultural resource investigations conducted for construction of each respective well pad and access road.

- WIPP well bore WTS 4. Cultural resource investigation conducted in support of siting and constructing reserve pits for well drilling and development.

- North Salt Pile Expansion. Cultural resource investigation conducted in support of the expansion of the North Salt Pile, a project designed to mitigate surface water infiltration.

All of the aforementioned archeological investigations received determinations of "No Adverse Affect" from the OCA and the SHPO. This determination serves as a clearance to proceed with work.

The Delaware Basin has been used in the past for an isolated nuclear test. This test, Project Gnome, took place in 1961 at a location approximately 13 km (8 mi) southwest of the WIPP. The primary objective of Project Gnome was to study the effects of an underground nuclear explosion in salt. The Gnome experiment involved the detonation of a 3.1-kiloton nuclear device at a depth of 361 m (1,200 ft) in the bedded salt of the Salado (Rawson et al. 1965). The explosion created a cavity of approximately 28,000 m^3 (1,000,000 ft^3) and caused surface displacements over an area of about a 360m (1,200ft) radius. Fracturing and faulting caused measurable changes in rock permeability and porosity at distances up to approximately 100 m (330 ft) from the cavity. No earth tremors were reported at distances over 40 km (25 mi) from the explosion. Project Gnome was decommissioned in 1979.

2.4 Background Environmental Conditions

Background environmental conditions at and near the WIPP site were characterized prior to the initiation of the operation of the facility and are described in CCA Section 2.4. Because background characterization focuses on environmental conditions existing prior to operations, it is not meaningful to redefine background environmental conditions after operations began. Accordingly, information presented in CCA Section 2.4 is not repeated and updated in this recertification application.

2.5 Climate and Meteorological Conditions

The DOE did not consider climate directly in its site selection process, although criteria such as low population density and large tracts of federally owned land tend to favor arid and semi-arid areas in the western United States. The semi-arid climate around the WIPP is beneficial since it is a direct cause of the lack of a near surface water table and the minimization of radiation exposure pathways that involve surface or groundwater. Data used to interpret paleoclimates in the American southwest come from a variety of sources and indicate alternating arid and subarid to subhumid climates throughout the Pleistocene. The information in this section was taken from Swift (1992), and included in CCA Appendix CLI and references therein.

2.5.1 Historic Climatic Conditions

Prior to 18,000 years ago, radiometric dates are relatively scarce, and the record is incomplete. From 18,000 years ago to the present, however, the climatic record is relatively well constrained by floral, faunal, and lacustrine data. These data span the transition from the last full-glacial maximum to the present interglacial period; given the global consistency of glacial fluctuations described below, they can be taken to be broadly representative of extremes for the entire Pleistocene.

Early and middle Pleistocene paleoclimatic data for the southwestern United States are incomplete and permit neither continuous reconstructions of paleoclimates nor direct correlations between climate and glaciation prior to the last glacial maximum, which occurred 22,000 to 18,000 years ago. Stratigraphic and soil data from several locations, however, indicate that cyclical alternation of wetter and drier climates in the Southwest had begun by the Early Pleistocene. Fluvial gravels in the Gatuña exposed in the Pecos River Valley of eastern New Mexico suggest wetter conditions 1.4 million years ago and again 600,000 years ago. The Mescalero caliche, exposed locally over much of southeastern New Mexico, suggests drier conditions 510,000 years ago, and loosely dated spring deposits in Nash Draw west of the WIPP imply wetter conditions occurring again later in the Pleistocene. The Blackwater Draw Formation of the southern High Plains of eastern New Mexico and western Texas, correlating in time to both the Gatuña Formation and the Mescalero caliche, contains alternating soil and eolian sand horizons that show at least six climatic cycles beginning more than 1.4 million years ago and continuing to the present.

Data used to construct the more detailed climatic record for the latest Pleistocene and Holocene come from six independent lines of evidence dated using carbon-14 techniques: plant communities preserved in packrat middens throughout the southwest, including sites in Eddy and Otero counties, New Mexico; pollen assemblages from lacustrine deposits in western New Mexico and other locations in the southwest; gastropod assemblages from western Texas; ostracod assemblages from western New Mexico; paleolake levels throughout the southwest; and faunal remains from caves in southern New Mexico.

Prior to the last glacial maximum 22,000 to 18,000 years ago, evidence from faunal assemblages in caves in southern New Mexico, including the presence of species such as the desert tortoise that are now restricted to warmer climates, suggests hot summers and mild, dry winters. Lacustrine evidence confirms the interpretation of a relatively dry climate prior to and during the glacial advance. Permanent water did not appear in what was later to become a major lake in the Estancia Valley in central New Mexico until some time before 24,000 years ago, and water depths in lakes at higher elevations in the San Agustin Plains in western New Mexico did not reach a maximum until sometime between 22,000 and 19,000 years ago. Ample floral and lacustrine evidence documents cooler, wetter conditions in the southwest during the glacial peak. These changes were not caused by the immediate proximity of glacial ice. None of the Pleistocene continental glaciations advanced farther southwest than northeastern Kansas, and the most recent, late-Wisconsinan ice sheet reached its limit in South Dakota, approximately 1,200 km (750 mi) from WIPP. Discontinuous alpine glaciers formed at the highest elevations throughout the Rocky Mountains, but these isolated ice masses were symptoms, rather than causes, of cooler and wetter conditions and had little influence on regional climate at lower elevations. The closest such glacier to WIPP was on the northeast face of Sierra Blanca Peak in the Sacramento Mountains, approximately 220 km (135 mi) to the northwest.

Global climate models indicate that the dominant glacial effect in the southwest was the disruption and southward displacement of the westerly jet stream by the physical mass of the ice sheet to the north. At the glacial peak, major Pacific storm systems followed the jet stream across New Mexico and the southern Rocky Mountains, and winters were wetter and longer than either at the present or during the previous interglacial period.

Gastropod assemblages at Lubbock Lake in western Texas suggest mean annual temperatures 5º C (9º F) below present values. Both floral and faunal evidence indicate that annual precipitation throughout the region was 1.6 to 2.0 times greater than today's values. Floral evidence also suggests that winters may have continued to be relatively mild, perhaps because the glacial mass blocked the southward movement of arctic air. Summers at the glacial maximum were cooler and drier than at present, without a strongly developed monsoon.

The jet stream shifted northward following the gradual retreat of the ice sheet after 18,000 years ago, and the climate responded accordingly. By approximately 11,000 years ago, conditions were significantly warmer and drier than previously, although still dominated by winter storms and still wetter than today. Major decreases in total precipitation and the shift toward the modern monsoonal climate did not occur until the ice sheet had retreated into northeastern Canada in the early Holocene.

By middle Holocene time, the climate was similar to that of the present, with hot, monsoon-dominated summers and cold, dry winters. The pattern has persisted to the present, but not without significant local variations. Soil studies show that the southern High Plains were drier from 6,500 to 4,500 years ago than before or since. Gastropod data from Lubbock Lake indicate the driest conditions from 7,000 to 5,000 years ago (precipitation, 0.89 times present values; mean annual temperature, 2.5º C [4.5º F] higher than present values), with a cooler and wetter period 1,000 years ago (precipitation, 1.45 times present values; mean annual temperature, 2.5º C [4.5º F] lower than present). Plant assemblages from southwestern Arizona suggest steadily decreasing precipitation from the middle Holocene to the present, except for a brief wet period approximately 990 years ago. Stratigraphic work at Lake Cochise (the present Willcox playa in southeast Arizona) shows two mid-Holocene lake stands, one near or before 5,400 years ago and one between or before 3,000 to 4,000 years ago; however, both were relatively short-lived, and neither reached the maximum depths of the Late Pleistocene high stand that existed before 14,000 years ago.

Inferred historical precipitation indicates that during the Holocene, wet periods were relatively drier and shorter in duration than those of the late Pleistocene. Historical records over the last several hundred years indicate numerous lower-intensity climatic fluctuations, some too short in duration to affect floral and faunal circulation. Sunspot cycles and the related change in the amount of energy emitted by the sun have been linked to historical climatic changes elsewhere in the world, but the validity of the correlation is uncertain. Correlations have also been proposed between volcanic activity and climatic change. In general, however, causes for past short-term changes are unknown.

The climatic record presented here should be interpreted with caution because its resolution and accuracy are limited by the nature of the data used to construct it. Floral and faunal assemblages change gradually and show only a limited response to climatic fluctuations that occur at frequencies that are higher than the typical life span of the organisms in question. For long-lived species such as trees, resolution may be limited to hundreds or even thousands of years. Sedimentation in lakes and playas has the potential to record higher-frequency fluctuations, including single-storm events, but only under a limited range of circumstances. Once water levels reach a spill point, for example, lakes show only a limited response to further increases in precipitation.

With these observations in mind, three significant conclusions can be drawn from the climatic record of the American southwest. First, maximum precipitation in the past coincided with the maximum advance of the North American ice sheet. Minimum precipitation occurred after the ice sheet had retreated to its present limits. Second, past maximum long-term average precipitation levels were roughly twice the present levels. Minimum levels may have been 90 percent of the present levels. Third, short-term fluctuations in precipitation have occurred during the present relatively dry, interglacial period, but they have not exceeded the upper limits of the glacial maximum.

Too little is known about the relatively short-term behavior of global circulation patterns to accurately predict precipitation levels over the next 10,000 years. The long-term stability of patterns of glaciation and deglaciation, however, do permit the conclusion that future climatic extremes are unlikely to exceed those of the late Pleistocene. Furthermore, the periodicity of glacial events suggests that a return to full-glacial conditions is highly unlikely within the next 10,000 years.

2.5.2 Recent Climatic Conditions

Recent climatic conditions are provided to allow for the assessment of impacts of these factors on the disposal unit and the site. Data are taken from the WIPP environmental monitoring reports (see WEC 1991a, 1991b, 1992, 1993, 1994, 1995, 1996, 1997, 1998; WGESC 1999; ESRF 2000, 2001, 2002; and WRES 2003).

2.5.2.1 General Climatic Conditions

The climate of the region is semiarid, with generally mild temperatures, low precipitation and humidity, and a high evaporation rate. Winds are mostly from the southeast and moderate. In late winter and spring, there are strong west winds and dust storms. During the winter, the weather is often dominated by a high-pressure system situated in the central portion of the western United States and a low-pressure system located in north-central Mexico. During the summer, the region is affected by a low-pressure system normally situated over Arizona.

2.5.2.2 Temperature Summary

Temperatures are moderate throughout the year, although seasonal changes are distinct. The mean annual temperature in southeastern New Mexico is 63º F (17º C). In the winter (December through February), nighttime lows average near 23º F (-5º C), and maxima average in the 50s. The lowest recorded temperature at the nearest Class-A weather station in Roswell was -29º F (-34º C) in February 1905. In the summer (June through August), the daytime temperature exceeds 90°F (32º C) approximately 75 percent of the time. The National Weather Service documented 122º F (50º C) at the WIPP site as the record high temperature for New Mexico. This temperature was recorded on June 27, 1994. Table 2-14 shows the annual average, maximum, and minimum temperatures from 1990 through 2002.

2.5.2.3 Precipitation Summary

Precipitation is light and unevenly distributed throughout the year, averaging 28.2cm (11.1in.) per year from 1995 through 2002. Winter is the season of least precipitation, averaging less than 1.5 cm (0.6 in.) of rainfall per month. Snow averages about 13 cm (5 in.) per year at the site and seldom remains on the ground for more than a day. Approximately half the annual precipitation comes from frequent thunderstorms in June through September. Rains are usually brief but occasionally intense when moisture from the Gulf of Mexico spreads over the region. Monthly average, maximum, and minimum precipitations recorded at the WIPP site from 1990 through 2002 are summarized in Figure 2-48.

2.5.2.4 Wind Speed and Wind Direction Summary

The frequencies of wind speeds and directions are depicted by wind roses in Figures 2-49 through 2-56 for the WIPP site.

Table 2-14. Annual Average, Maximum, and Minimum Temperatures

Year	Annual Average Temperature		Maximum Temperature		Minimum Temperature	
	(^oC)	(^oF)	(^oC)	(^oF)	(^oC)	(^oF)
1990	17.8	64	46.1	115	−13.9	7
1991	17.2	63	42.8	109	−7.8	18
1992	17.2	63	42.8	109	−10	14
1993	17.8	64	42.8	109	−18.9	−2
1994	17.8	64	50	122	−14.4	6
1995	17	63	42	107	-7	19
1996	17	63	41	106	-7	19
1997	16.3	61.4	38.6	101.5	-11.4	11.4
1998	18.3	64.9	41.6	106.9	-10.8	12.6
1999	18.1	64.6	40.9	105.6	-7.9	17.8
2000	17.4	63.3	40.2	104.4	-6.8	19.7
2001	17.5	63.5	39.5	103.2	-7.8	18.0
2002	17.5	63.5	39.8	103.7	-8.9	16.0
Average	17.5	63.5	42.2	107.9	-0.2	13.9

2.6 Seismology

The DOE used tectonic activity as a siting criterion. The intent was to avoid tectonic conditions such as faulting and igneous activity that would jeopardize waste isolation over the long term and to avoid areas where earthquake size and frequency could impact facility design and operations. The WIPP site met both aspects of this criterion fully. Long-term tectonic activity is discussed in Section 2.1.5. The favorable results of the seismic (earthquake) studies are discussed here. The purpose of the seismic studies is to build a basis from which to predict ground motions that the WIPP repository may be subjected to in the near and distant future. The concern about seismic effects in the near future, during the operational period, pertains mainly to the design requirements for surface and underground structures for providing containment during seismic events. The concern about effects occurring over the long term, after the repository has been decommissioned and sealed, pertains more to relative motions (faulting) within the repository and possible effects of faulting on the integrity of the salt beds and/or shaft seals. Updated seismic activity information is provided in Figures 2-57 and 2-58. In this discussion, the magnitudes are reported in terms of the Richter scale, and all intensities are based on the

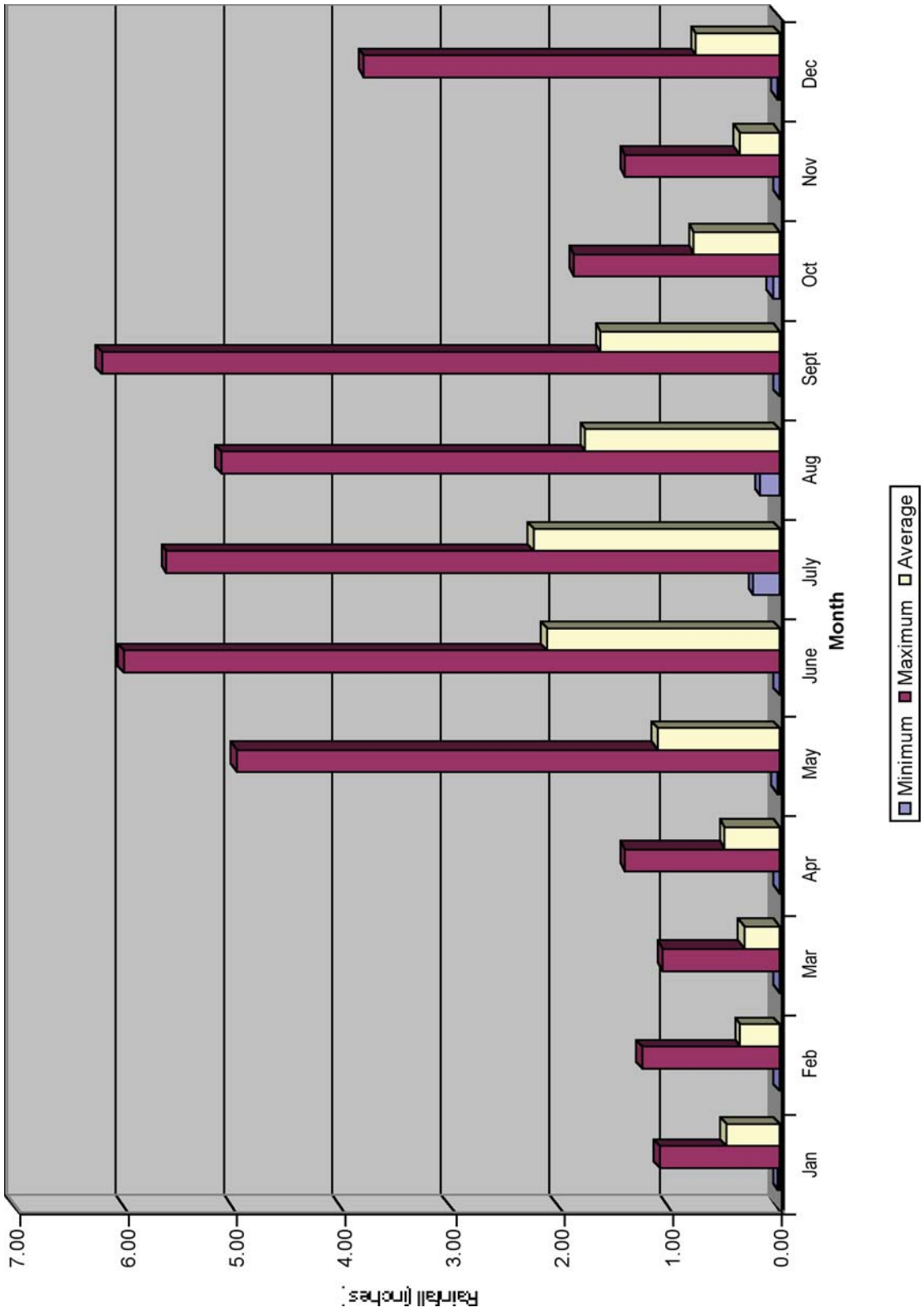

Figure 2-48. Monthly Precipitation for the WIPP Site from 1990-2002

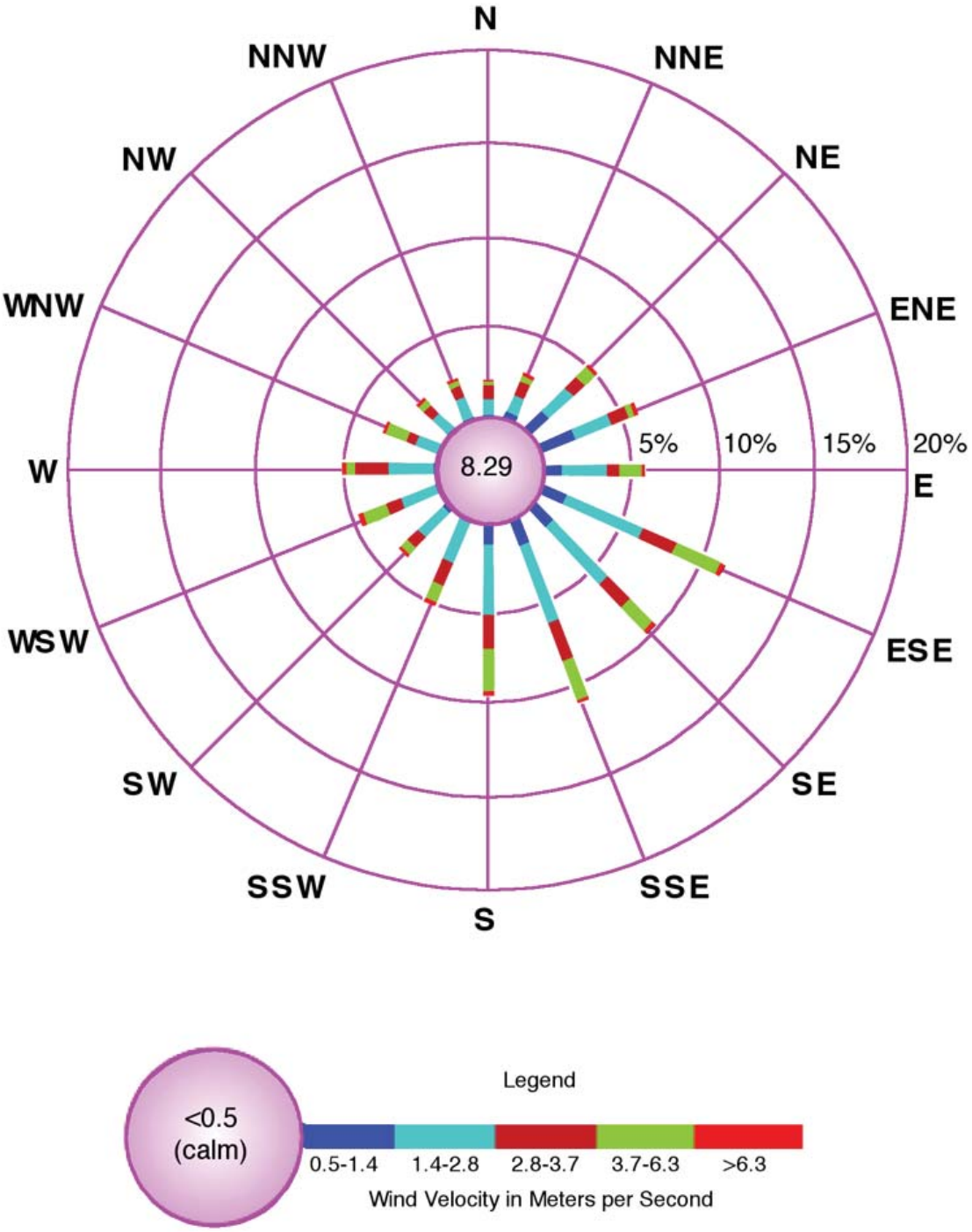

Figure 2-49. 1995 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

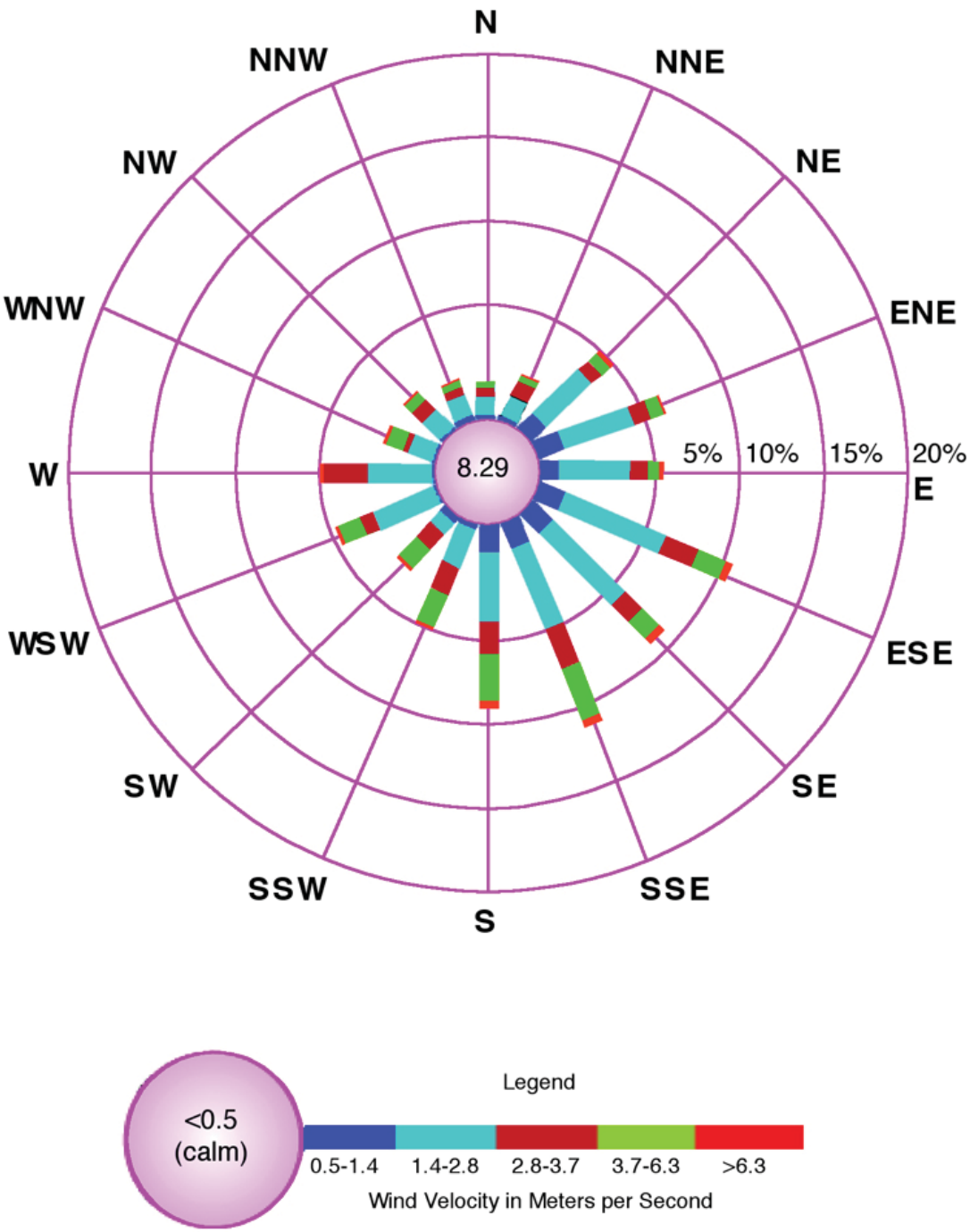

Figure 2-50. 1996 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

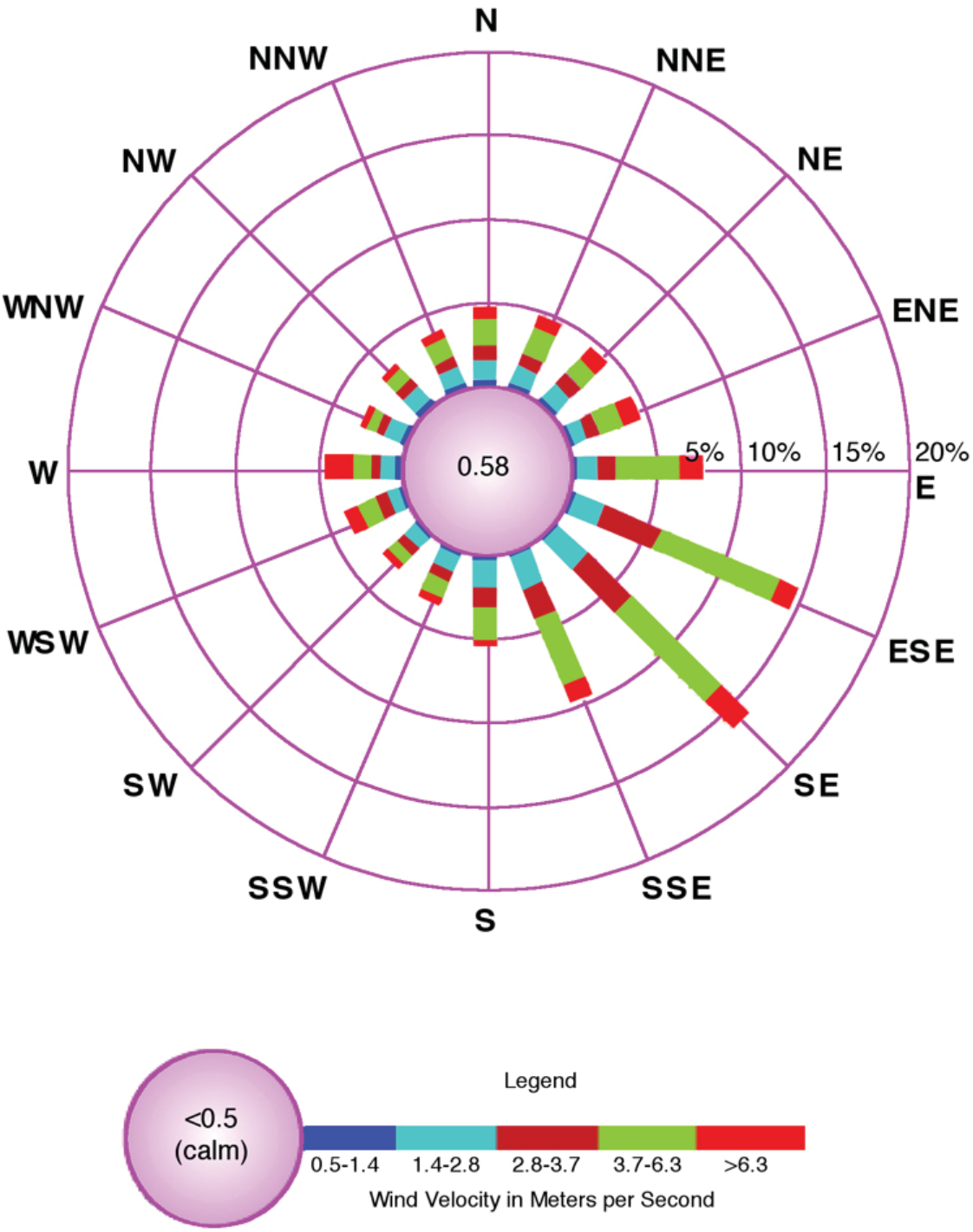

Figure 2-51. 1997 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

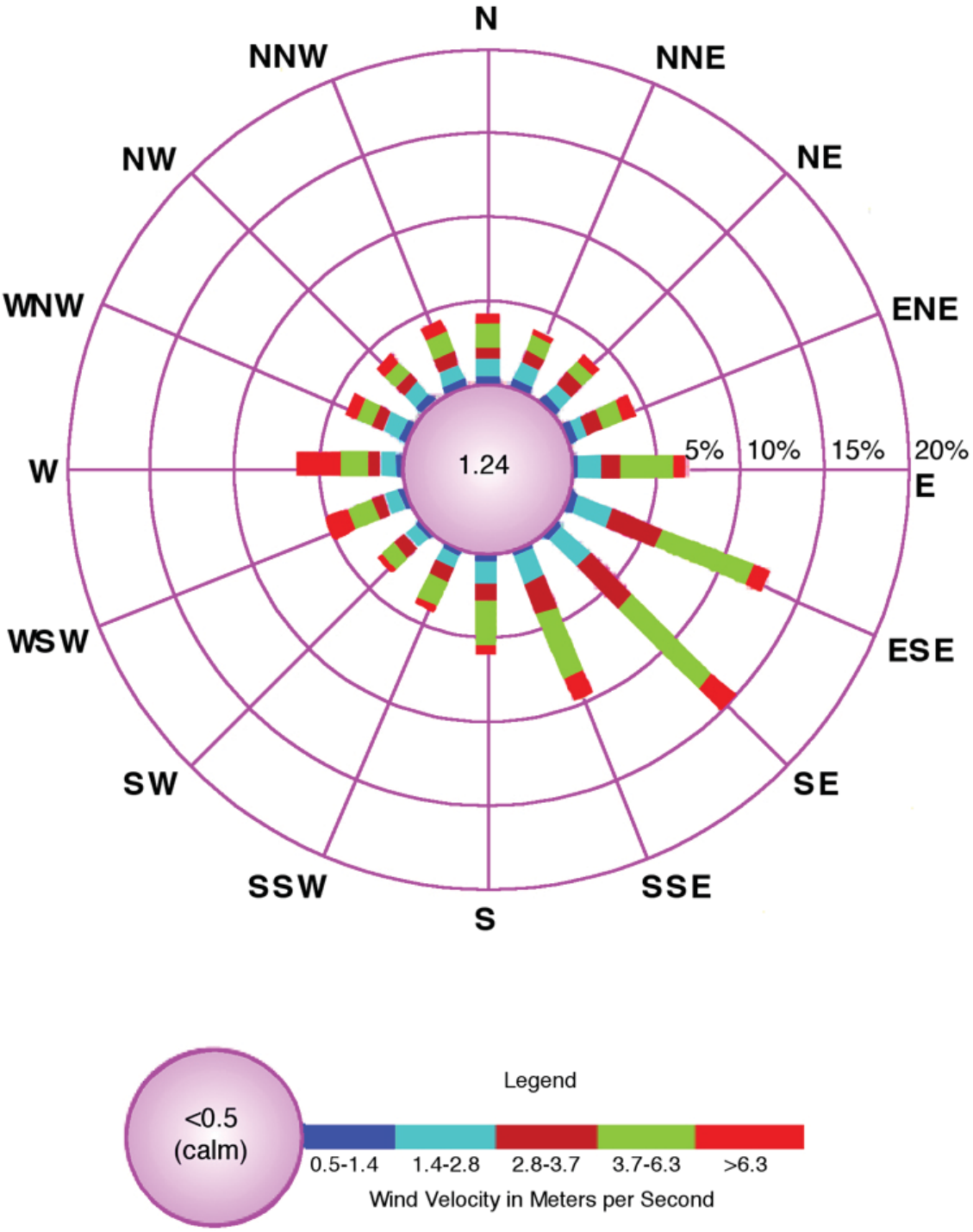

Figure 2-52. 1998 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

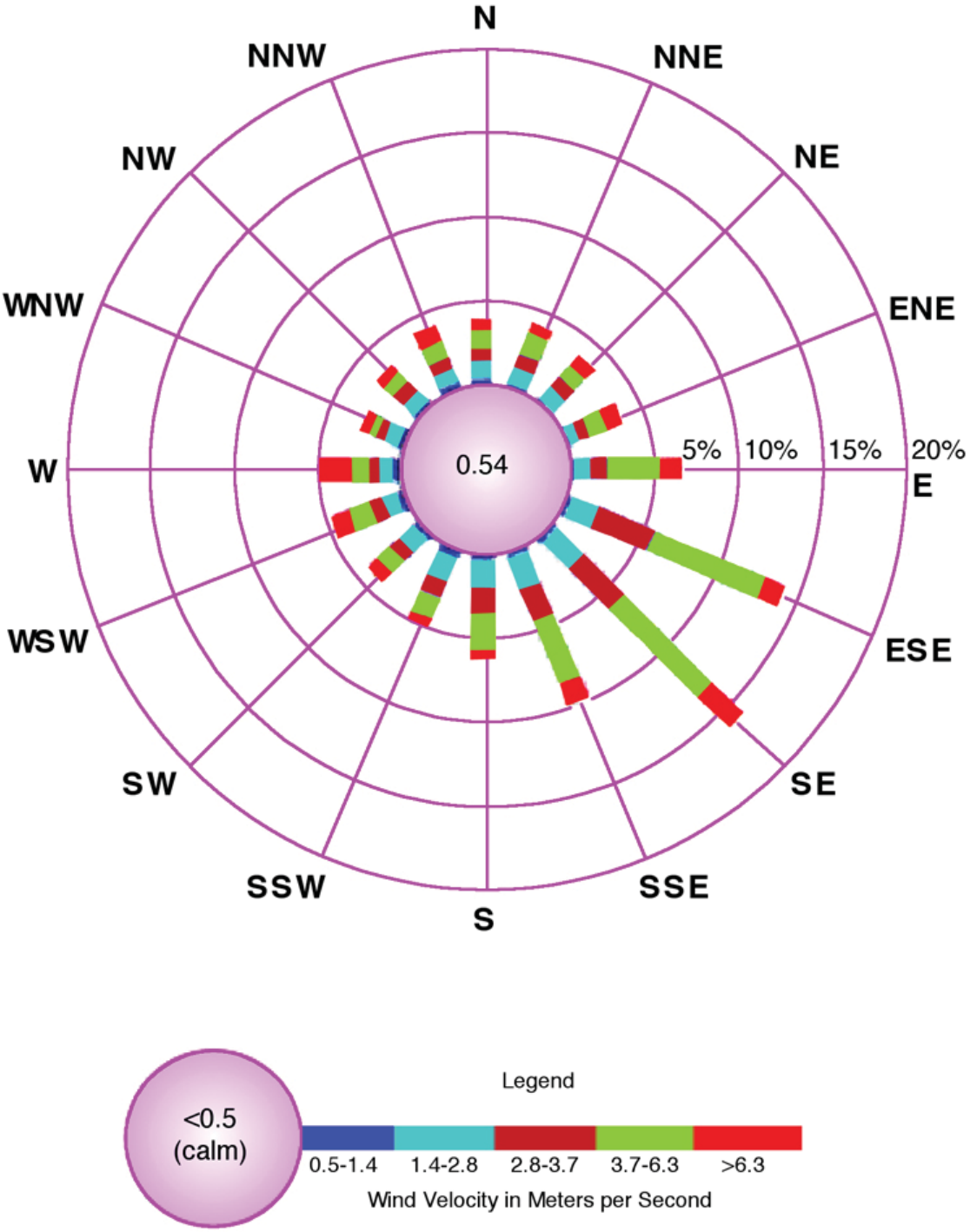

Figure 2-53. 1999 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

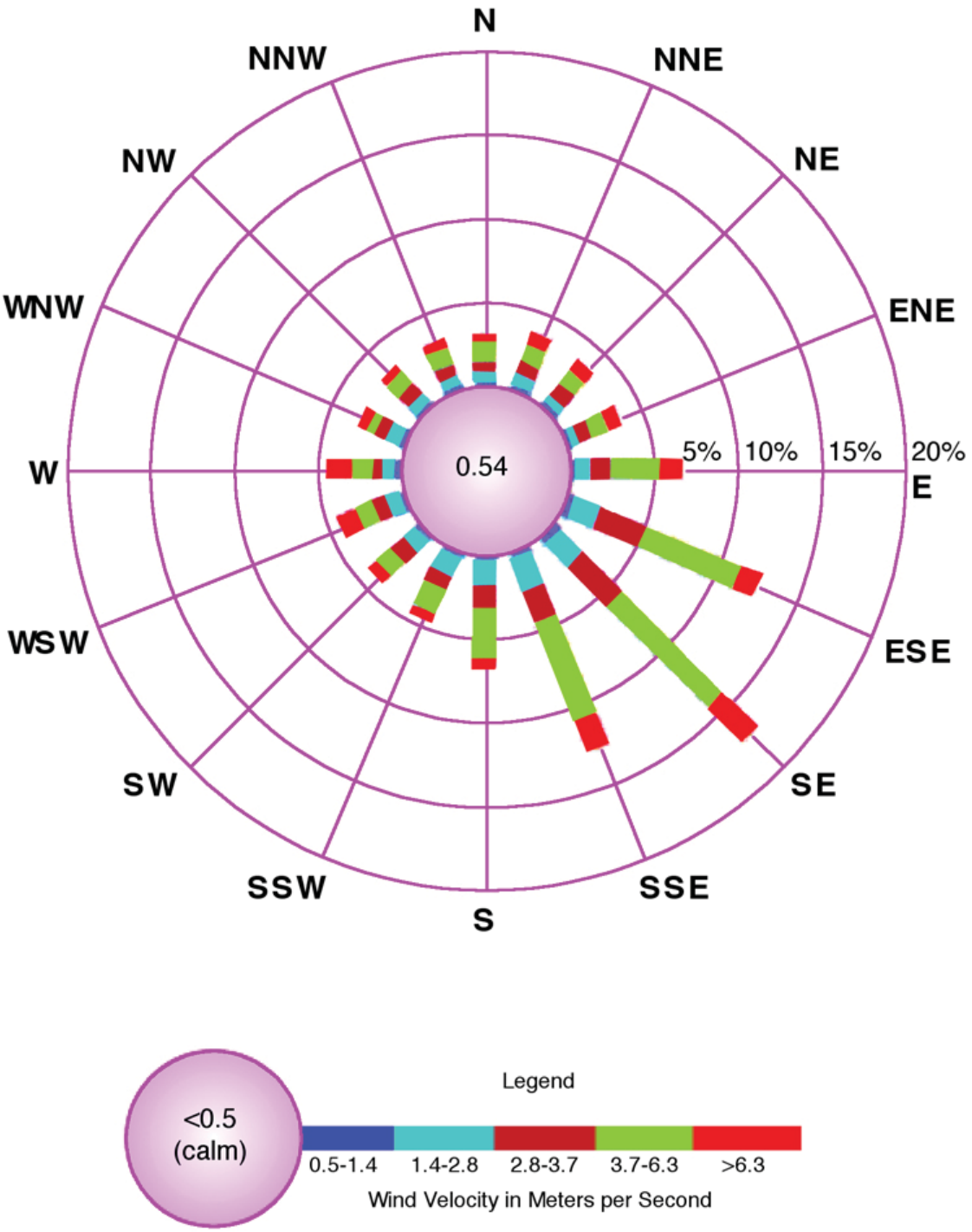

Figure 2-54. 2000 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

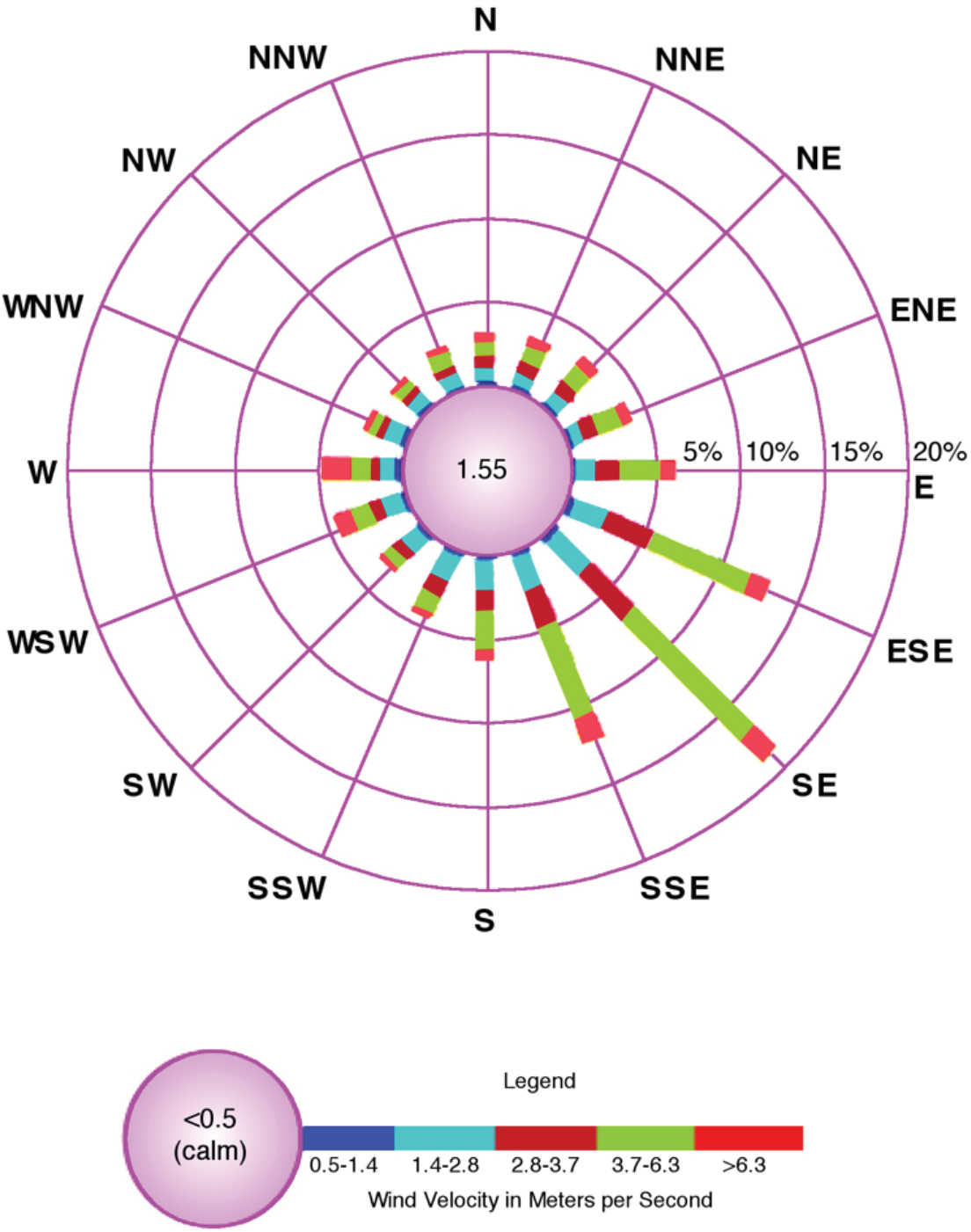

Figure 2-55. 2001 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

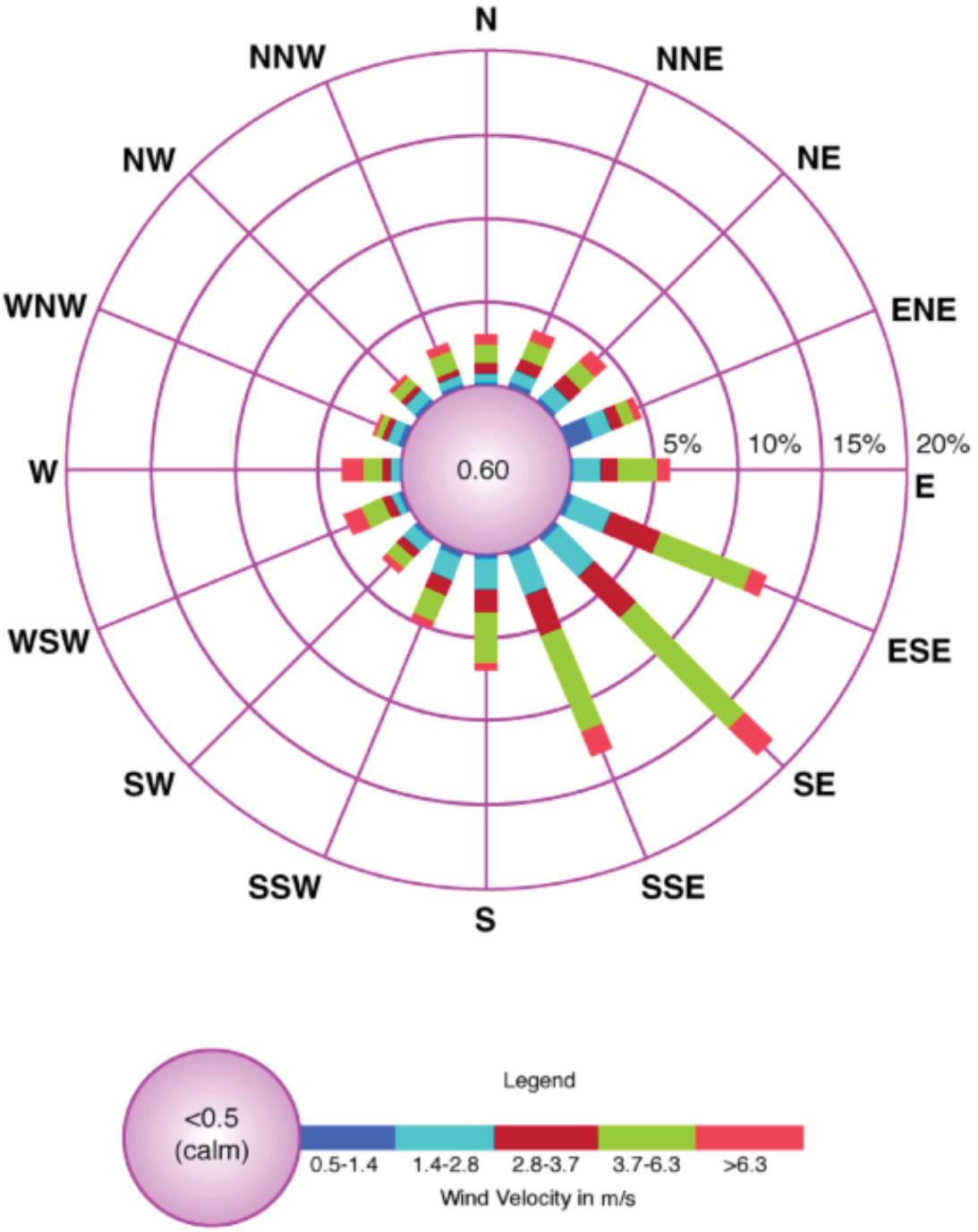

Figure 2-56. 2002 Annual Wind Rose at 10-m (33-ft.) Height at WIPP Site

modified Mercalli intensity scale. Most of the magnitudes were determined by the New Mexico Institute of Mining and Technology or are described in CCA Appendix GCR and references therein.

2.6.1 Seismic History

Seismic data are presented in two time frames, before and after the time when seismographic data for the region became available. The earthquake record in southern New Mexico dates back only to 1923, and seismic instruments have been in place in the state since 1961. Various records have been examined to determine the seismic history of the area within 180 mi (288 km) of the site. With the exception of a weak shock in 1926 at Hope, New Mexico (approximately 64 km [40 mi] northwest of Carlsbad), and shocks in 1936 and 1949 felt at Carlsbad, all known shocks in the region before 1961 occurred to the west and southwest of the site more than 160 km (100 mi) away.

The strongest earthquake on record occurring within 288 km (180 mi) of the site was the Valentine, Texas earthquake of August 16, 1931. It has been estimated to have been of magnitude 6.4 on the Richter scale (Modified Mercalli Intensity of VIII). The Valentine earthquake was 208 km (130 mi) south-southwest of the site. Its Modified Mercalli Intensity at the site is estimated to have been V; this is believed to be the highest intensity felt at the site in this century.

In 1887, a major earthquake occurred in northeast Sonora, Mexico. Although about 536 km (335 mi) west-southwest of the site, it is indicative of the size of earthquakes possible in the eastern portion of the Basin and Range Province, west of the province containing the site. Its magnitude was estimated to have been 7.8 (VIII to IX in Modified Mercalli Intensity). It was felt over an area of 1.3 million km^2 (0.5 million mi^2) (as far as Santa Fe to the north and Mexico City to the south); fault displacements near the epicenter were as large as 18 m (26 ft).

Since 1961, instrumental coverage has become comprehensive enough to locate most of the moderately strong earthquakes (local magnitude >3.5) in the region. Instrumentally determined shocks that occurred within 288 km (180 mi) of the site between 1961 and 1994 are shown in Figure 2-57. The distribution of these earthquakes may be biased by the fact that seismic stations were more numerous and were in operation for longer periods north and west of the site. Pre-1961 earthquakes can be found in CCA Appendix GCR, Figure 5.2-1.

Except for the activity southeast of the site, the distribution of epicenters since 1961 differs little from that of shocks before that time. There are two clusters, one associated with the Rio Grande Rift on the Texas-Chihuahua border and another associated with the Central Basin Platform in Texas near the southeastern corner of New Mexico. The latter activity was not reported before 1964. It is not clear from the record whether earthquakes were occurring in the Central Basin Platform before 1964, although local historical societies and newspapers tend to confirm their absence before that time.

The April 14, 1995, earthquake near Marathon, Texas, was located 240 km (150 mi) south of the WIPP site. The USGS estimated that moment magnitude for this event was 5.7. At a distance of

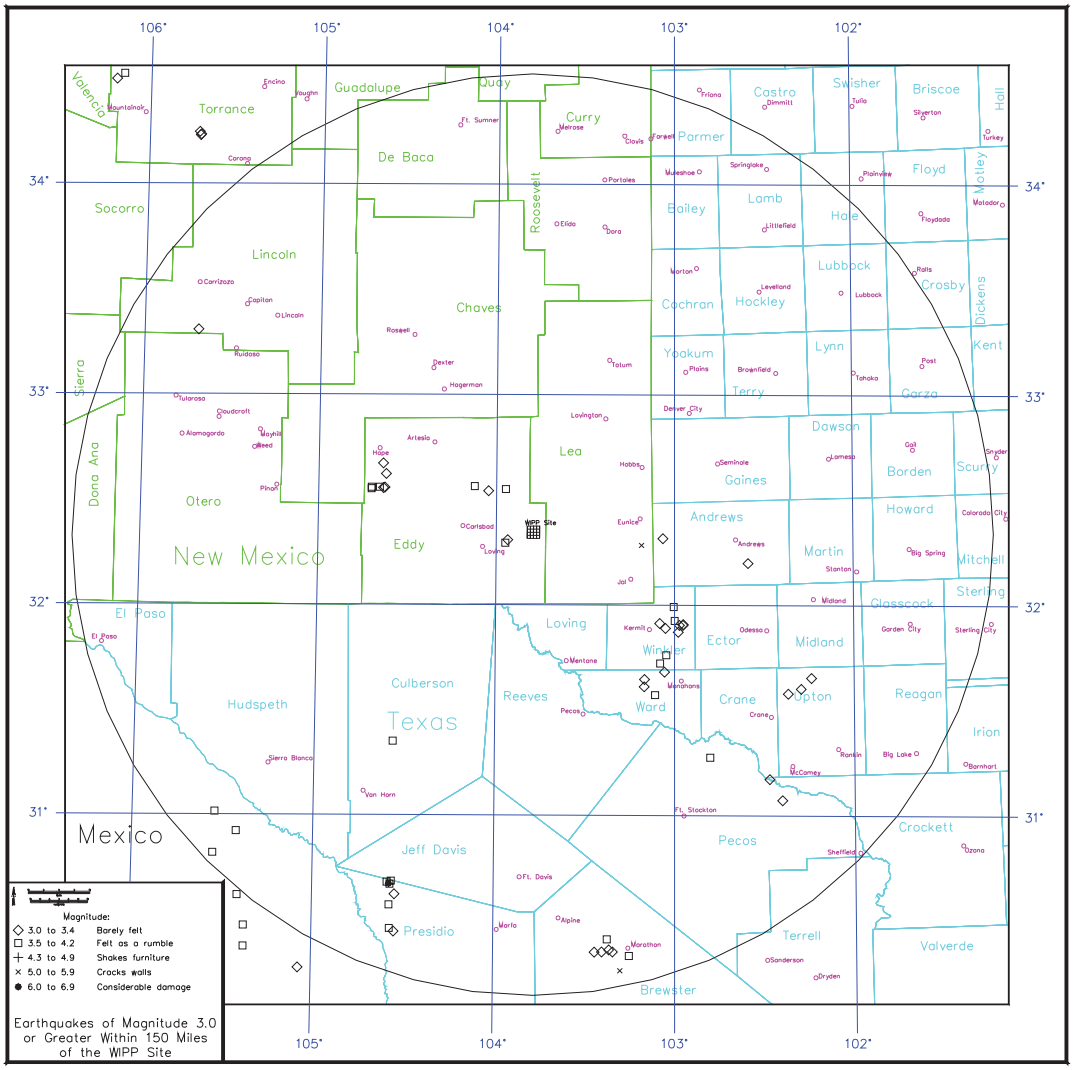

Figure 2-57. Regional Earthquake Epicenters Occurring between 1961 and 2002

240 km (149 mi), an event of magnitude 5.7 would produce a maximum acceleration at the WIPP site of less than 0.01 g (acceleration due to gravity).

The Marathon earthquake should not be considered an unanticipated event. The shock occurred in the Basin and Range Province, a seismotectonic province with evidence for 24 Quarternary faults in West Texas and adjacent parts of Mexico. Two of these faults had recent surface-faulting events in the Holocene. Strong earthquakes have occurred within the West Texas part of the Basin and Range Province, most notably the M_W = 6.4 (Richter) Valentine, Texas earthquake on August 15, 1931.

The WIPP site is located within the Great Plains seismotectonic province, a region that has no evidence of Quarternary faulting, even above major buried structures such as the Central Basin Platform. Because the Great Plains seismotectonic province is geologically distinct from the Basin and Range Province and lacks evidence for recent faulting, the maximum possible or

credible earthquake for this region would be substantially smaller than that for the Basin and Range Province of West Texas.

2.6.2 Seismic Risk

Procedures exist that allow for formal determination of earthquake probabilistic design parameters. In typical seismic risk analyses of this kind, the region of study is divided into seismic source areas within which future events are considered equally likely to occur at any location. For each seismic source area, the rate of occurrence of events above a chosen threshold level is estimated using the observed frequency of historical events. The sizes of successive events in each source are assumed to be independent and exponentially distributed; the slope of the log number versus frequency relationship is estimated from the relative frequency of different sizes of events observed in the historical data. This slope, often termed the b value, is determined either for each seismic source individually or for all sources in the region jointly. Finally, the maximum possible size of events for each source is determined using judgement and the historical record. Thus, all assumptions underlying a measure of earthquake risk derived from this type of analysis are explicit, and a wide range of assumptions may be employed in the analysis procedure.

In this section, the particular earthquake risk parameter calculated is peak acceleration expressed as a function of annual probability of being exceeded at the WIPP site. The particular analysis procedure applied to the calculation of this probabilistic peak acceleration is taken from a computer program written by McGuire (1976). In that program, the seismic source zones are modeled geometrically as quadrilaterals of arbitrary shape. Contributions to site earthquake risk from individual source zones are integrated into the probability distribution of acceleration, and the average annual probability of exceedence then follows directly.

In the analysis, the principal input parameters are as follows: site region acceleration attenuation, source zone geometry, recurrence statistics, and maximum magnitudes. Based on these parameters, several curves showing probabilistic peak acceleration are developed, and the conclusions that may be drawn from these curves are considered. The data treated in this way are used to arrive at a general statement of risk from vibratory ground motion at the site during its active phase of development and use.

2.6.2.1 Acceleration Attenuation

The first input parameters considered have to do with acceleration attenuation in the site region as a function of earthquake magnitude and hypocentral distance. The risk analysis used in this study employs an attenuation law of the form

$$a = b_1 \exp(b_2 M_L) R - b_3 , \qquad (2.3)$$

where a is acceleration in cm/s^2, M_L is Richter local magnitude, and R is the distance in km. The particular formula used in this study is based on a central United States model developed by Nuttli (1973). The formula coefficients $b_1 = 17$, $b_2 = 0.92$, and $b_3 = 1.0$ were selected. A justification for this assumption can be found in CCA Appendix GCR, Section 5.3.2.

2.6.2.2 Seismic Source Zones

Geologic, tectonic, and seismic evidence indicates that three seismic source zones may be used to adequately characterize the region. These are well approximated by the Basin and Range subregion, the Permian Basin subregion exclusive of the Central Basin Platform, and the Central Basin Platform itself. Specific boundaries are taken from a 1976 study by Algermissen and Perkins (1976) of earthquake risks throughout the United States. Additional details on this study are in CCA Appendix GCR, Section 5.3.2.

Site region seismic source zones are shown in Figure 2-58. Superposed on these zones are the earthquake epicenters of Figure 2-57. The zonation presented generally conforms with historical seismicity. The source zonation of Figure 2-58 has no explicit analog to the Permian Basin subregion exclusive of the Central Basin Platform. This is considered part of the broad background region.

For the purposes of this study, some minor modifications of the Algermissen and Perkins (1976) source zones were made. Geologic and tectonic evidence suggests that the physiographic boundary between the Basin and Range and Great Plains provinces provides a good and conservative approximation of the source zones (CCA Appendix GCR). In addition, information from the Kermit seismic array (Appendix to Rogers and Malkiel 1979) indicates that the geometry used to model the limits of the Central Basin Platform source zone may be modified somewhat from the original analogous Algermissen and Perkins (1976) zone. These modifications are shown in Figure 2-59 and constitute the preferred model for the WIPP site region seismic source zones in this study. This model is preferred because it more completely considers geologic and tectonic information, as well as seismic data, and because it results in a more realistic development of risks at the WIPP facility.

With regard to earthquake focal depth, there is little doubt that the focal depths of earthquakes in the WIPP facility region should be considered shallow. Early instrumental locations were achieved using an arc intersection method employing travel-time-distance curves calculated from a given crustal model, and the assumption of focal depths of 5 km (3.1 mi), 10 km (6.2 mi), or, for later calculations, 8 km (5 mi). Good epicentral locations could generally be obtained under these assumptions. For conservatism, a focal depth of 5 km (3.1 mi) is used in all source zones of this study including that of the site. For smaller hypocentral distances, the form of the attenuation law adopted here severely exaggerates the importance of small, close shocks in the estimation of probabilistic acceleration at the WIPP site. Additional discussion is included CCA Appendix GCR, Chapter 5.

2.6.2.3 Source Zone Recurrence Formulas and Maximum Magnitudes

The risk calculation procedure used in this study requires that earthquake recurrence rates for each seismic source zone be specified. This is done formally by computing the constants a and b in the equation

$$\log N = a - bM , \qquad (2.4)$$

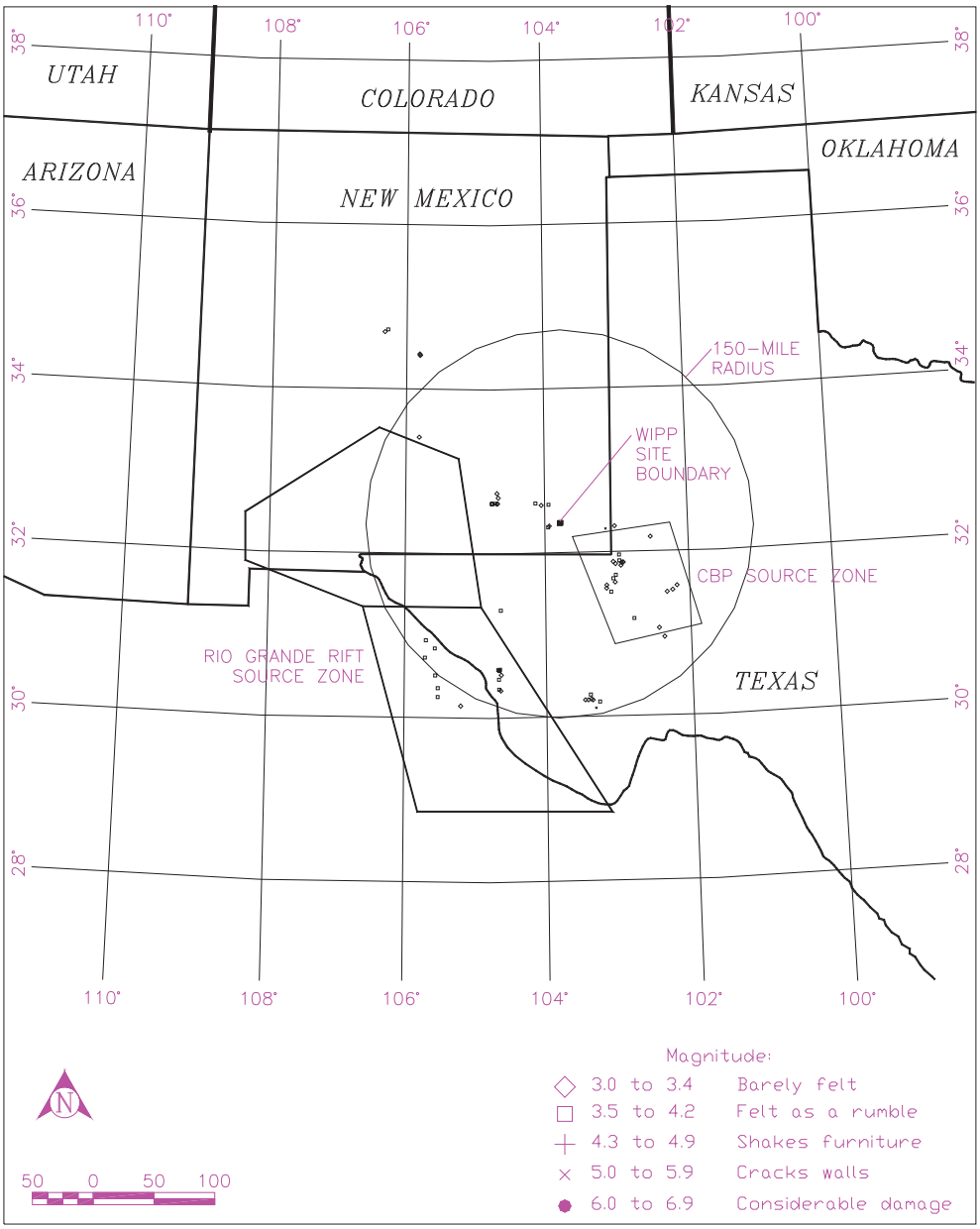

Figure 2-58. Seismic Source Zones

where N is the number of earthquakes of magnitude greater than or equal to M within a specified area occurring during a specified period.

For the WIPP facility region, three formulas of this type are needed: one for the province west and southwest of the site (the Basin and Range subregion or Rio Grande Rift source zone), another for the province of the WIPP facility exclusive of the Central Basin Platform (the Permian Basin subregion or background source zone), and a final one for the Central Basin Platform. In practice, the difficulties in finding meaningful recurrence formulas for such small areas in a region of low historical earthquake activity are formidable.

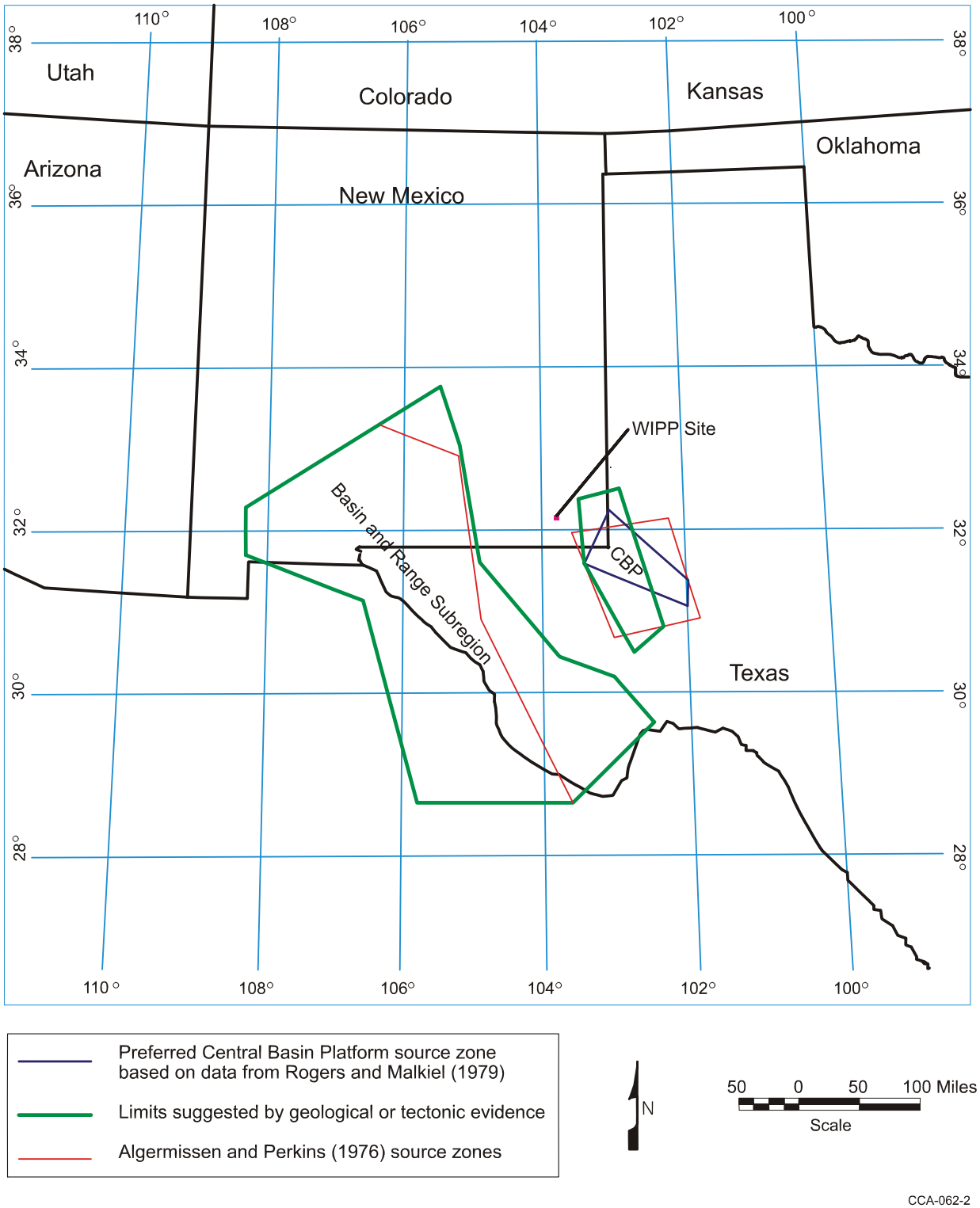

Figure 2-59. Alternate Source Geometries

The formulas have been determined to be

- $\log N = 2.43 - M_{CORR}$ Site source zone (background) (2.5)
- $\log N = 3.25 - M_{CORR}$ Basin and Range subregion (2.6)
- $\log N = 3.19 - 0.9\ M_{CORR}$ Central Basin Platform (2.7)

The rationale for their development and the relationship used to determine M_{CORR} can be found in CCA Appendix GCR, Section 5.3.

2.6.2.4 Design Basis Earthquake

The term Design Basis Earthquake (DBE) is used for the design of surface confinement structures and components at the WIPP facility. As used here, the DBE is equivalent to the design earthquake used in Regulatory Guide 3.24 (Nuclear Regulatory Commission [NRC] 1974). That is, in view of the limited consequences of seismic events in excess of those used as the basis, the DBE is such that it produces ground motion at the WIPP facility with a recurrence interval of 1,000 years. In practice, the DBE is defined in terms of the 1,000-year acceleration and design response spectra.

The generation of curves expressing probability of occurrence or risk as a function of peak WIPP facility ground acceleration is discussed in detail in CCA Appendix GCR, Section 5.3, for a number of possible characterizations of WIPP facility region source zones and source zone earthquake parameters. The most conservative (and the least conservative) risk curves are shown in Figure 2-60.

From this figure, the most conservative calculated estimate of the 1,000-year acceleration at the WIPP facility is approximately 0.075 g. The geologic and seismic assumptions leading to this 1,000-year peak acceleration include the consideration of a Richter magnitude 5.5 earthquake at the site, a 6.0 magnitude earthquake on the Central Basin Platform, and a 7.8 magnitude earthquake in the Basin and Range subregion. These values, especially the first two, are considered quite conservative, as are the other parameters used in the 0.075g derivation. For additional conservatism, a peak design acceleration of 0.1 g is selected for the WIPP facility DBE. The design response spectra for vertical and horizontal motions are taken from Regulatory Guide 1.60 (NRC 1973) with the high-frequency asymptote scaled to this 0.1g peak acceleration value.

This DBE and the risk analysis that serves an important role in its definition are directly applicable to surface confinement structures and components at the WIPP facility. Underground structures and components are not subject to DBE design requirements because according to Pratt et al. (1979), mine experience and studies on earthquake damage to underground facilities show that tunnels are not damaged at sites having peak surface accelerations below 0.2 g.

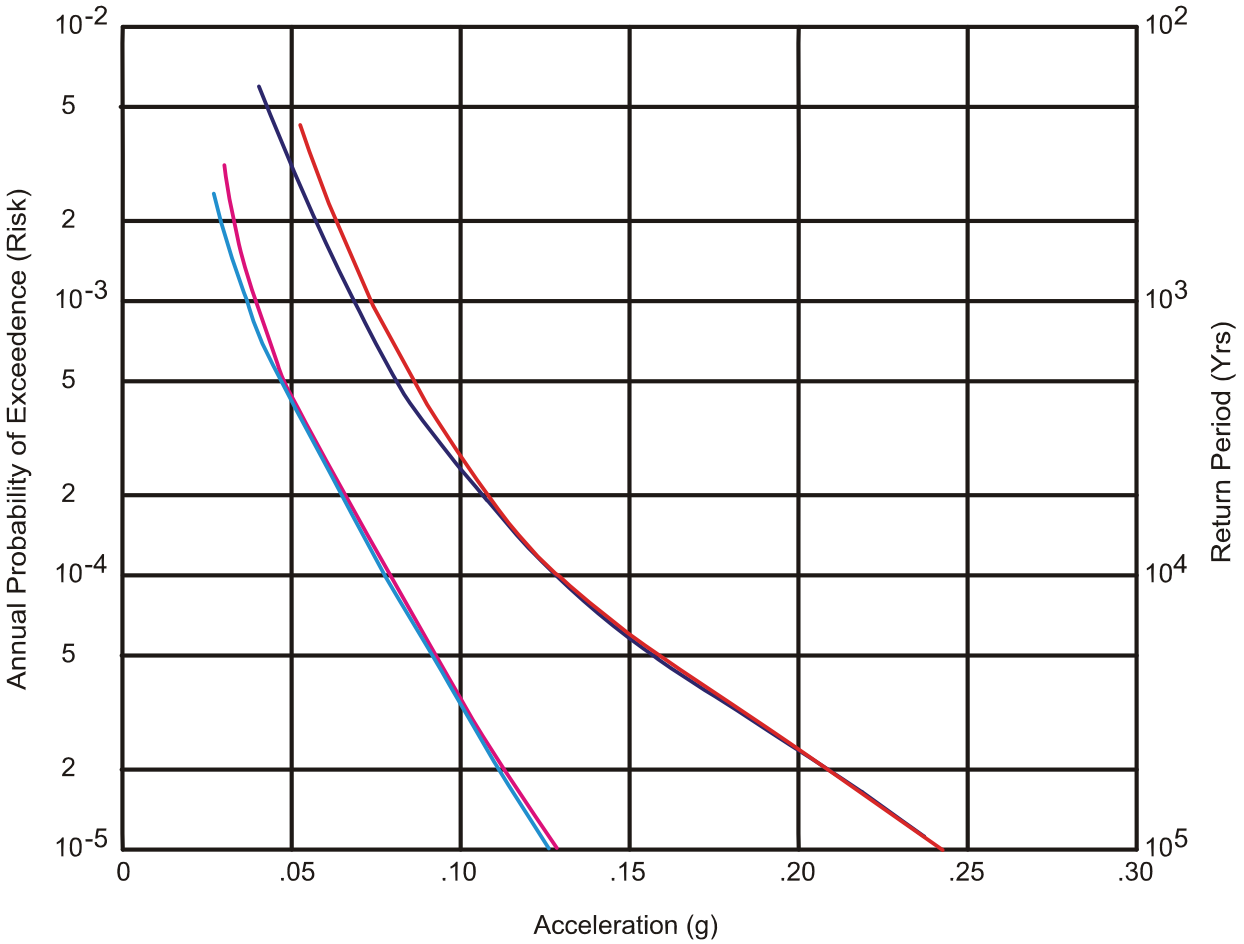

Curve 1	———	Risk from site source zone assuming a maximum magnitude of 4.5.
Curve 2	———	Risk from site and Central Basin Platform source zones assuming maximum magnitudes of 4.5 and 5.0, respectively.
Curve 3	———	Risk from the site source zone assuming a maximum magnitude of 5.0.
Curve 4	———	Risk from the site and Central Basin Platform source zones assuming a maximum magnitude of 5.0 for both.

Note: Risk curves generated by using worst and best case assumption from the parameter variation considered for site region source zones. See Appendix GCR, Figure 5.3-7 for further details.

CCA-063-2

Figure 2-60. Total WIPP Facility Risk Curve Extrema

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3.0 FACILITY DESCRIPTION

Chapter 3.0 provides technical information about those engineered systems at the Waste Isolation Pilot Plant (WIPP) disposal system that are important to meeting the disposal standards of Title 40 of the Code of Federal Regulations (CFR) Part 191 Subparts B and C (EPA 1993). The U.S. Department of Energy (DOE) developed a facility design that facilitates the rapid encapsulation of emplaced waste by creep closure of salt, forming a nearly impermeable barrier around the waste. In addition, the DOE has taken a defense in depth approach in the design of engineered shaft sealing systems to ensure the shafts will not become pathways for radionuclide release. Shaft seals incorporate multiple engineered materials and compacted crushed salt which will effectively reduce the permeability of the shaft-seal system to values near those of unexcavated intact salt. The DOE also employs an engineered barrier to chemically condition any brine that may reach the waste in order to reduce radionuclide solubility. Finally, the DOE will close each panel of waste with a panel closure system to provide for operational protection of workers, the public and the environment from emplaced waste.

In this chapter, descriptions are provided for the shafts, the underground waste disposal excavations, and engineered systems that may be significant to long-term performance of the disposal system. Of these engineered systems, the Environmental Protection Agency (EPA) has determined that only magnesium oxide (MgO) meets the regulatory definition of an “engineered barrier” (63 Federal Register [FR] 27397, May 18, 1998). Detailed information on other aspects, such as general facility operations, waste handling, repository mining, ground control, ventilation, transportation, emergency preparedness, training, and maintenance are covered, as appropriate, in other WIPP documents, such as the WIPP Disposal Phase Supplemental Environmental Impact Statement (SEIS-II) (DOE 1997), Contact-Handled Waste Safety Analysis Report (DOE 2003), and other documents available from the DOE.

The facility has been divided into four areas designated for protection of human health and the environment: (1) the property protection area, which is surrounded by a chain-link security fence that encloses approximately 13.7 hectares (34 acres) and provides security and protection for all major surface structures; (2) the exclusive use area, which is approximately 112 hectares (277 acres) restricted exclusively for the use of the DOE, its contractors, and subcontractors in support of the project and posted against trespass and use by the general public; (3) the off limits area, which consists of approximately 5.9 km^2 (1,454 acres) posted and managed as off limits by the DOE; and (4) the WIPP land withdrawal area, the 41.4-km^2 (16 mi^2) federal land area under jurisdiction of the DOE and bounded by the WIPP site boundary (see Figure 3-1). The WIPP land withdrawal area is the controlled area for purposes of demonstrating compliance to 40 CFR Part 191 Subparts B and C. The waste area of the repository lies within the bounds of the off limits area, and within the WIPP land withdrawal area.

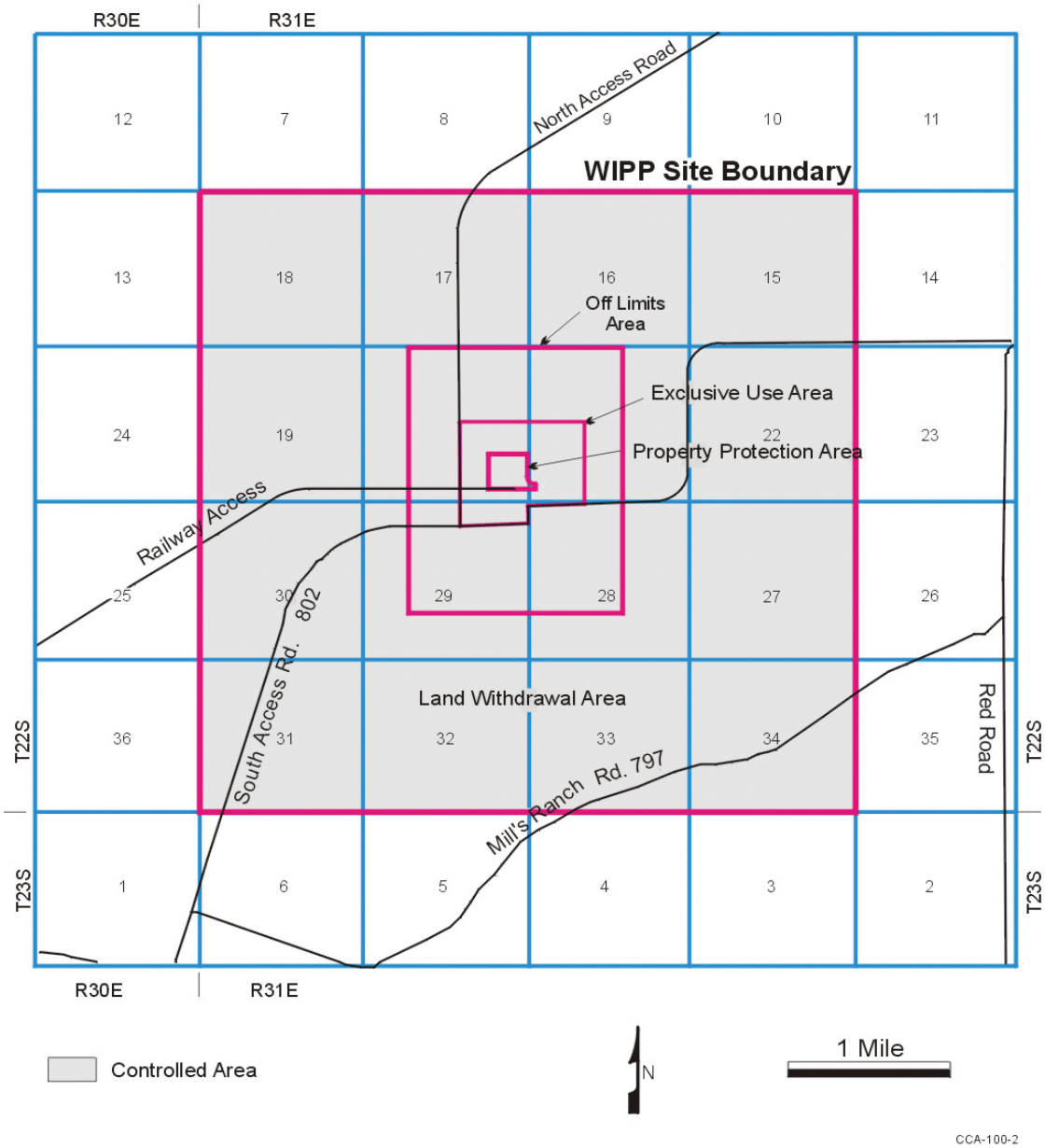

Figure 3-1. WIPP Property Sector Designators

The amount of waste to be received at the WIPP is governed by the WIPP Land Withdrawal Act, Pub. L. No. 104-201, Stat. 2422 (U.S. Congress 1992), which sets the total volume for contact-handled (CH-) and remote-handled (RH-) transuranic (TRU) waste combined at a maximum of 175,600 m^3 (6.2 million ft^3). The 6.2 million ft^3 technically corresponds to 175,564 m^3 but will be routinely represented in this application with four significant digits. The Land Withdrawal Act restricts RH-TRU waste to a maximum activity of 23 curies per liter and not to exceed a total of 5.1 million curies (U.S. Congress 1992) (see Chapter 4 for a description of the waste). There is a volume limit of 0.25 million ft^3 for RH-TRU waste (Agreement for Consultation and Cooperation, DOE 1988). The waste disposal area of the WIPP facility consists of eight panels, each of which contains seven rooms, and the access drifts and crosscuts adjacent to the disposal

panels. This latter region has been labeled Panels 9 and 10 for convenience as shown in Figure 3-2. At the end of the operational period, the DOE will begin the process of sealing the shafts, which is a part of final facility closure.

Disposal operations in Panel 1 are complete and an explosion-isolation wall has been installed. In a typical configuration, waste will be emplaced in all seven rooms of a panel as shown in Figure 3-3 with RH-TRU waste inserted into the walls. Figure 3-4 provides the layout of the waste as it is emplaced in Panel 1. This is not the configuration typically described for WIPP (Compliance Certification Application [CCA]).

In a submittal dated April 26, 2001 [Docket A-98-49, II-B-3, Item 19], the DOE requested that EPA approve a different utilization plan for Panel 1. The flexibility to vary the utilization of Panel 1 was important from both a worker safety and operational efficiency perspective. The rooms of Panel 1 were over 12 years old at the time of the proposed change. The natural processes of room closure had reduced the vertical clearance to the extent that re-mining would be necessary to provide sufficient headroom and acceptable floor conditions for waste to be emplaced as described in the CCA, i.e., three containers high. Based upon the analyses performed by Sandia National Laboratories (SNL), the DOE concluded that this request was not a significant departure from the original design and that aspects of the repository system important to waste containment would not be affected or changed. The EPA agreed with DOE's conclusion in a letter dated August 7, 2001 [Docket A-98-49, II-B-3, Item 19], stating "DOE's proposed alternative use of Panel 1 is compliant with terms and conditions of WIPP's certification." There is no RH-TRU waste disposed in Panel 1.

Table 3-1 delineates pertinent site features of the WIPP facility.

3.1 General Facility Design

The DOE has designed the WIPP facility to accomplish four primary goals:

1. to receive, handle, and dispose of TRU waste and TRU-mixed waste (in this document, the term TRU waste is used to describe both TRU and TRU-mixed waste unless otherwise noted);

2. to protect the health and safety of workers, the public, and the environment;

3. to comply with applicable radiation protection standards; and

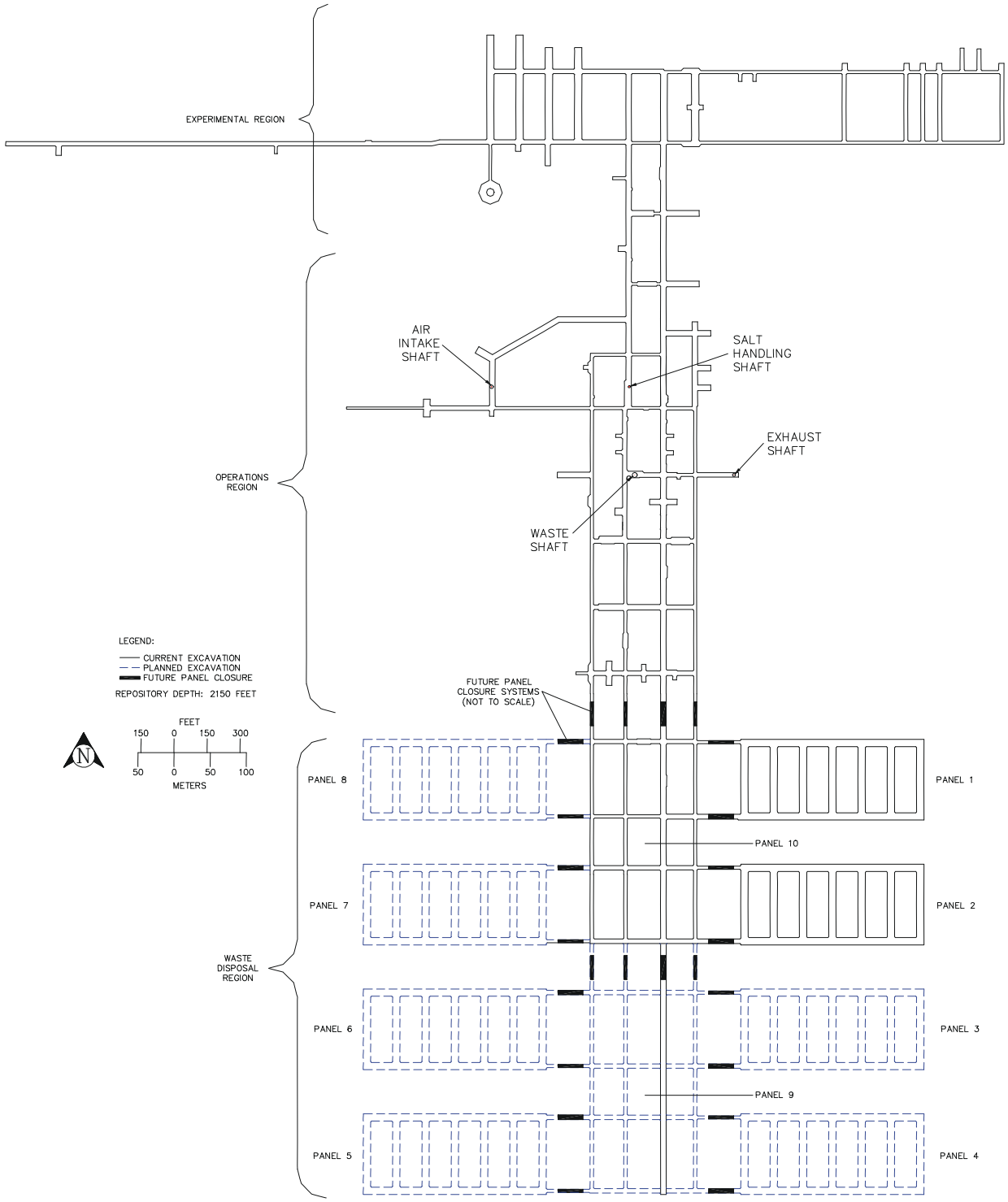

Figure 3-2. Plan View of WIPP Underground Facility and Panel Closure Systems

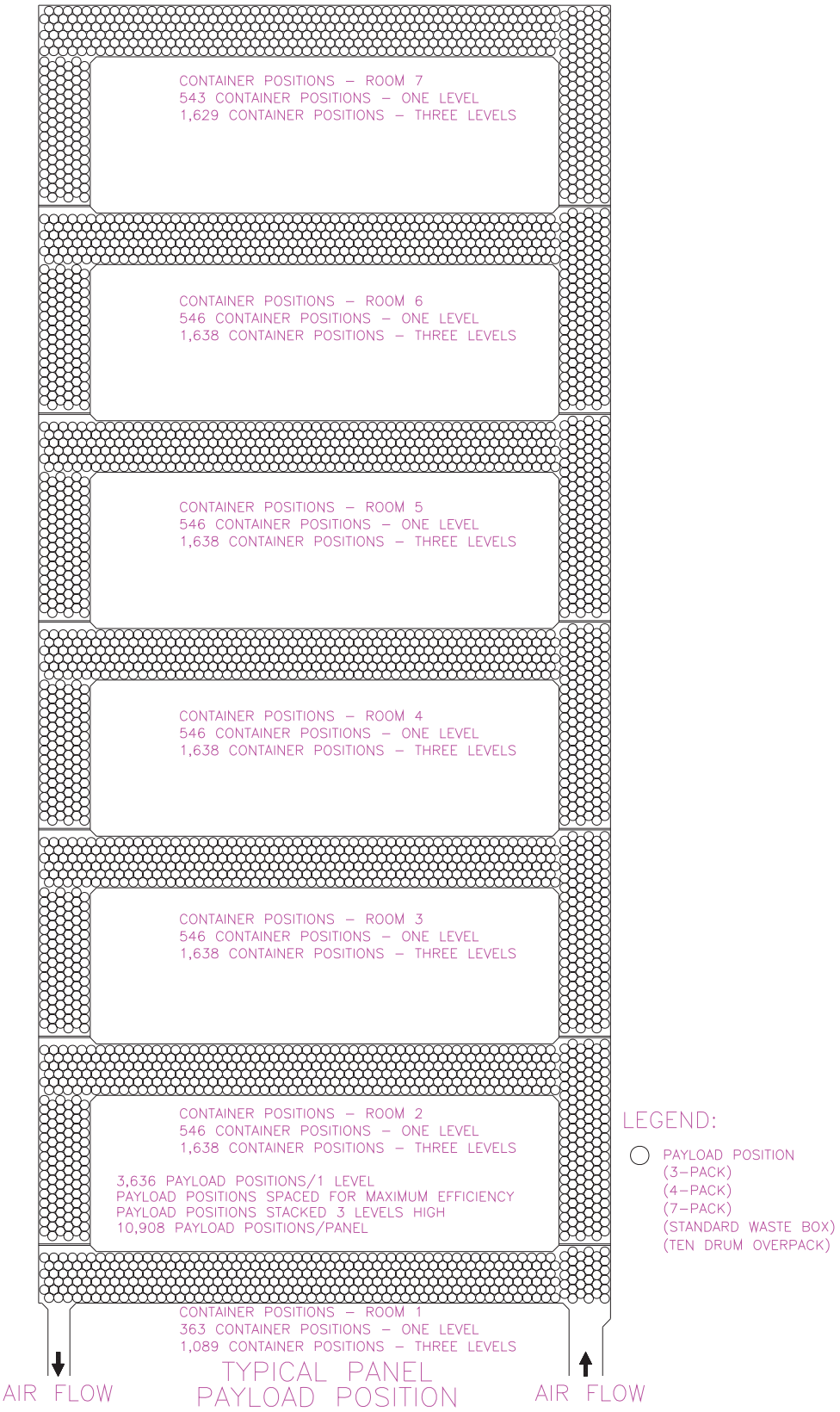

Figure 3-3. Typical Panel Waste Emplacement

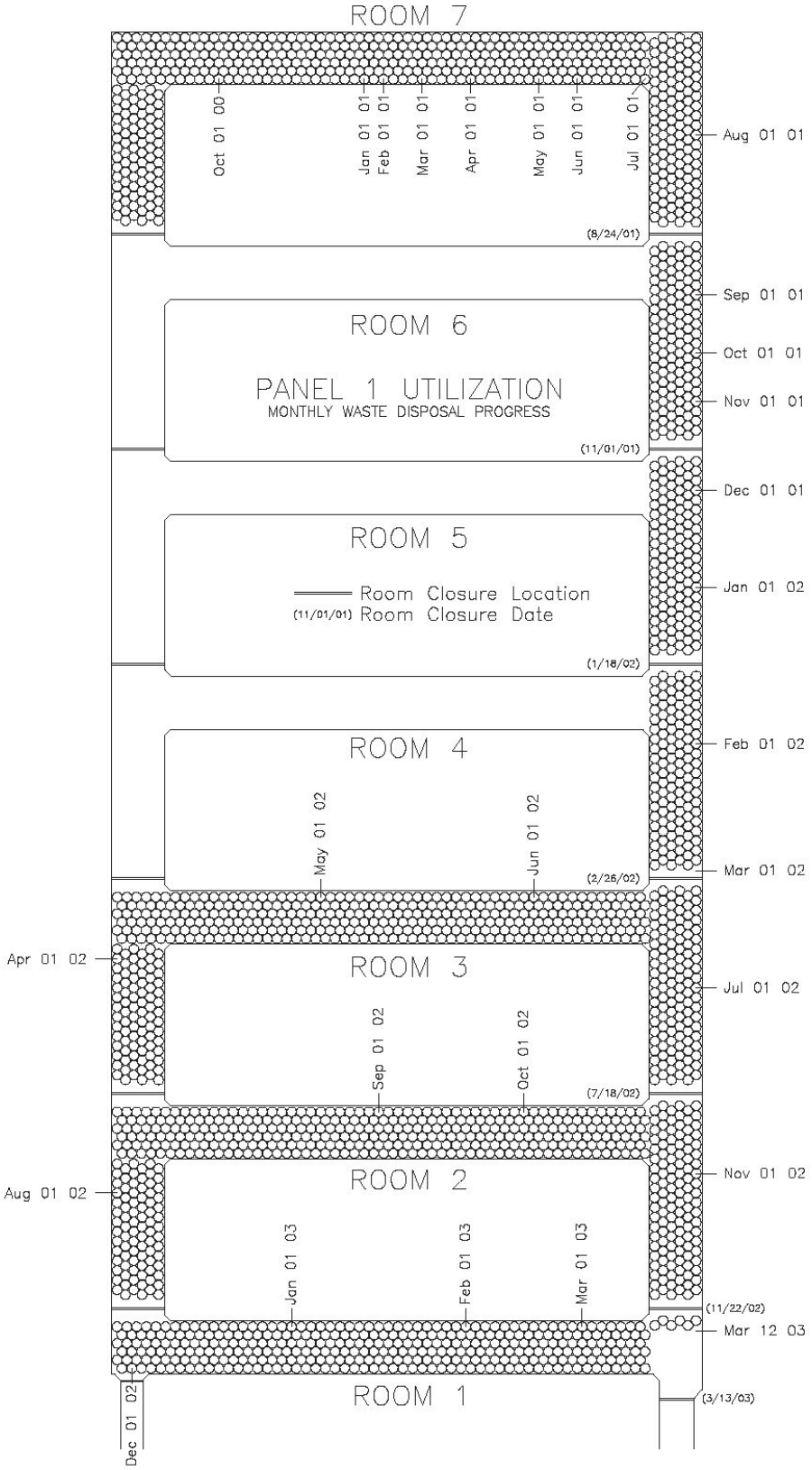

Figure 3-4. Panel 1 Waste Emplacement

Table 3-1. WIPP Site Features

Facility Name	Waste Isolation Pilot Plant (WIPP)
EPA Identification Number	NM 4890139088
Location	41.84 km (26 miles) east of Carlsbad, New Mexico
Latitude	32°22'11"N
Longitude	103°47'30"W
County	Eddy
Section	15-22 and 27-34
Township	22S
Range	31E
Land Withdrawal Area	41.4 km^2 (16 mi^2)
Property Protection Area	13.7 hectares (34 acres)
Depth to repository horizon	655 meters (2,150 feet) below grade level

4. to comply with other environmental statutes and regulations, and requirements of federal, state, and local agencies as discussed in the WIPP Biennial Environmental Compliance Reports (DOE 2002, et seq.).

The surface facilities at the WIPP accommodate the personnel, equipment, and support services required for the safe receipt and transfer of TRU waste from the surface to the underground repository. The surface structures are located within a perimeter security fence. This area is the property protection area on Figure 3-1. Access is controlled by security officers 24 hours a day. Four vertical shafts connect the surface facilities to the underground. The underground facilities include the

- waste disposal area,
- shaft pillar area, and
- associated support facilities.

Figure 3-5 provides a spatial view of the WIPP facility.

The DOE acquisition process that was used for the design and construction of the WIPP determined the steps and processes taken to assure that the WIPP was constructed consistent with applicable codes and standards. This process defined key activities and milestones that were applicable and specified such project management activities as initial and final design, independent review, acceptance testing, start-up, and quality assurance (QA). Additional detail is provided in the following sections.

3.1.1 DOE Facility Acquisition Process

Federal facility acquisition policies were applied to the design and construction of the WIPP facility. WIPP structures are designed to meet the Carlsbad Field Office (CBFO) Functions,

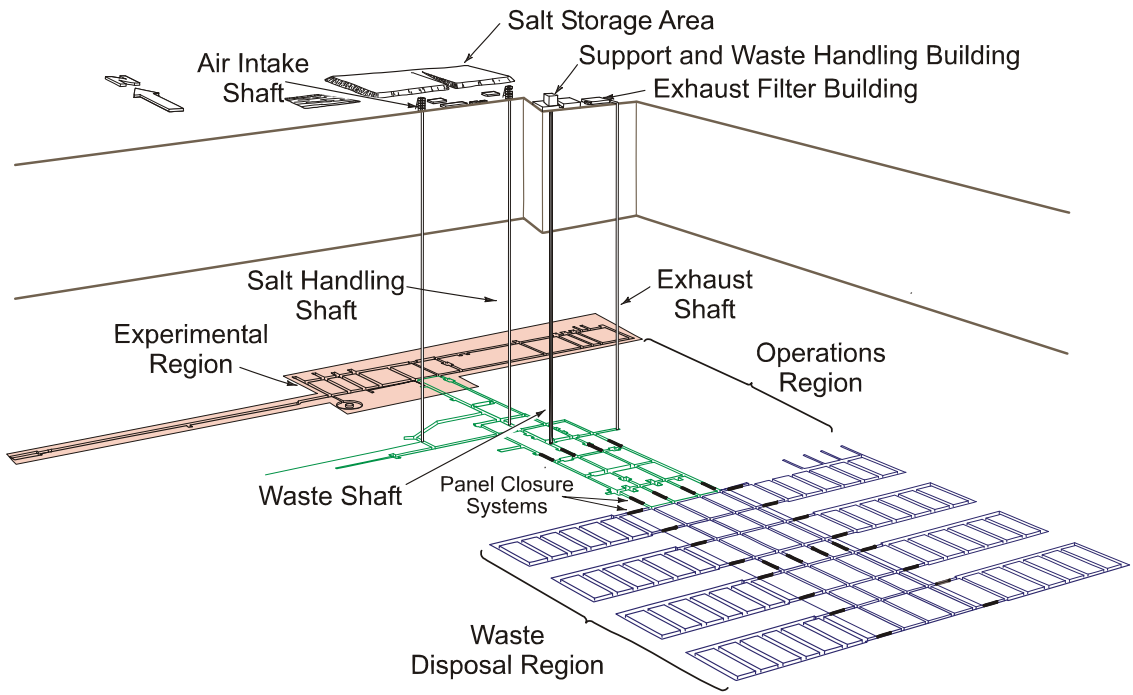

Note: For illustrative purposes only.
Not to scale.

CCA-087-2

Figure 3-5. Spatial View of the WIPP Facility

Responsibilities, and Authorities Manual (DOE/WIPP 98-2287, 2001), 10 CFR Part 830, Subpart B (design qualifications), and the Quality Assurance Program Document (QAPD) (DOE 1996) for general issues of quality. Appropriate structures, systems and components are designed to meet the requirements applicable to Design Class II structures, systems, and components for nonreactor nuclear facilities. The design class designations are categorized in accordance with their importance relative to health and safety of the public and on-site personnel during plant operations.

3.1.2 Configuration Control

The DOE mandates that the configuration control of the WIPP facility be accomplished through written procedures and policies as set forth in DOE Orders and regulations. For example, the WIPP System Design Descriptions provide a framework for the configuration control. Any changes to the facility, and subsequently configuration documentation (design descriptions, as-built drawings, specifications, etc.), must be reviewed and approved by cognizant personnel. These documented reviews determine if the change will affect the ability of the facility to comply with applicable environmental, safety, and health requirements. The DOE must approve proposed changes that impact the safety of the facility and may elect to conduct an independent review of analyses supporting the change.

Quality assurance requirements applicable to the WIPP facility design and configuration control activities are founded on the basic and supplemental requirements of the American Society of Mechanical Engineers' QA program requirements for nuclear facilities (American Society of Mechanical Engineers' NQA-1 1989). As discussed in Section 5.2, the DOE now implements these requirements through the CBFO's QAPD, which is provided in Appendix QAPD. Design QA elements include (1) documentation, review, and approval of design inputs; (2) control of design analyses, design verification, and design changes; and (3) institution of design interface controls and records management practices. These and other applicable configuration management QA requirements are discussed in Section 5.3.3.

3.1.3 Surface Structures

WIPP surface structures accommodate the personnel, equipment, and support services required for the receipt, preparation, and transfer of waste from the surface to the underground areas. These surface structures serve the operational functions of the WIPP and are not intended to serve long-term performance functions. The surface facilities are located in the Property Protection Area within the perimeter fence. The principal surface structure is the Waste Handling Building; other surface structures include the following:

- hoist houses,
- support building,
- guard and security building,
- office trailers,
- exhaust filter building,
- warehouse and shops,
- water pump house,
- training building,
- engineering building,
- materials, tools, and electronics and tool crib building,
- safety and emergency services building.

In addition to these structures, the DOE has employed a system of berms and ditches to divert storm-water runoff away from the surface facilities. The WIPP facility drainage system is designed so that storm runoff caused by the probable maximum precipitation (PMP) event will not flood the WIPP facility (DOE 1995).

The WIPP facility does not lie within a 100-year floodplain. There are no major surface-water bodies within eight km (five mi) of the site, and the nearest river, the Pecos River, is

approximately 19 km (12 mi) away. The general ground elevation in the vicinity of the surface facilities (approximately 1,036 m [3,400 ft] above mean sea level) is about 152 m (500 ft) above the riverbed and 122 m (400 ft) above the 100-year floodplain. (Chapter 2.0 provides more information on surface hydrology and climate.) Protection from flooding or ponding caused by PMPevents is provided by the diversion of water away from the WIPP facility by a system of peripheral interceptor diversions. Additionally, grade elevations of roads and surface facilities are designed so that storm water will not collect on the site under the most severe conditions.

Repository shafts are elevated at least 15.2 cm (6 in.) to prevent surface water from entering the shafts. The floor levels of all surface facilities are above the levels calculated for local flooding due to PMP events.

The mean annual precipitation in the region is about 30 cm (12 in.), and the mean annual runoff is 0.25 to 0.50 cm (0.1 to 0.2 in.). The maximum recorded 24-hour precipitation at Carlsbad was 13 cm (5.12 in.) in August 1916. The six-hour, 100-year precipitation event for the site is 9.1 cm (3.6 in.) and is most likely to occur during the summer. The maximum daily snowfall at Carlsbad was 76 cm (10 in.) in December 1923.

The WIPP facility design includes four shafts: the waste shaft, the salt handling shaft, the exhaust shaft, and the air intake shaft (AIS). Each shaft includes a shaft collar, a shaft lining, and a shaft key section. The shaft and shaft liner design information is discussed in detail in the Site Characterization and Validations studies from 1983 to 1987. The shaft design features have not changed.

The reinforced concrete shaft collars extend from the surface to the top of the underlying consolidated sediments. Each collar serves both to retain adjacent unconsolidated sands and soils and to prevent surface runoff from entering the shaft. The shaft linings extend from the base of the collar to the top of the salt beds approximately 259.1 m (850 ft) below the surface. The shaft lining serves to inhibit water seepage into the shafts from water-bearing formations, such as the Magenta and Culebra members of the Rustler. The liners are also designed to retain loose rock. The shaft liners are concrete except in the salt handling shaft, in which a steel shaft liner has been grouted in place.

The shaft key is a circular reinforced concrete section emplaced in each shaft below the liner at the base of the Rustler Formation and extending about 30.5 m (100 ft) below and into the Salado Formation. The shaft key functions to resist lateral pressures and to contain the water seals.

Two separate water-seal rings are incorporated in each key. Performance of the seals is monitored by inspection of the bottom of the key for seepage. If groundwater is detected flowing past the upper ring, this condition can be corrected by injecting chemical sealants or cementitious grouts to stop the leakage.

On the inside surface of each shaft, excluding the salt handling shaft, there are three water collection rings. The first is located just below the Magenta interval, the second just below the Culebra interval, and the last at the lowermost part of the key section. These collection rings function to collect any groundwater that may seep into the shaft through the liner. Therefore,

flooding of the WIPP repository as a result of PMP events is not a credible event because of the site-runoff design.

Flood-control structures are inspected as part of a general facility inspection at least annually. During this inspection, the structures are checked to assure that there has been no wind or rain erosion or animal-caused damage that would cause the structures to fail. Further, the areas around the structures are inspected to ensure they are free of vegetation, debris, or other items that would impede the diversion of water. Experience with these structures has shown that annual structural inspections are adequate for the climate and soil conditions at the WIPP facility; however, inspections are also conducted after severe natural events, such as severe storms or earthquakes.

3.2 Repository Configuration

A preliminary design of the WIPP repository was presented in the Final EIS (DOE 1980). Validation efforts for the WIPP repository preliminary design began in 1981 with the Site and Preliminary Design Validation (SPDV) program. The SPDV program was implemented to further characterize and validate the WIPP site geology and to provide preliminary validation of the underground excavation. The SPDV program involved the excavation of four full-sized disposal rooms, excavated 4 m (13 ft) high, 10 m (33 ft) wide, and 91 m (300 ft) long, and separated by 31-m (100-ft)-wide pillars. Data obtained from geologic field activities and geomechanical instrumentation were analyzed to determine the suitability of the design criteria and design bases and to provide confirmation of the underground opening reference design. Analyses of these preliminary designs performed by the WIPP architect and engineer can be found in CCA Appendix DVR. These analyses considered expected creep closure rates in determining disposal room sizes. Information in CCA Appendix DVR (Section DVR.6.4.2) meets the criterion specified in 40 CFR § 194.14(b)(2). Figures 12-21 and 12-22 of the Final Design Validation Report in CCA Appendix DVR show the creep closure histories used for designing the disposal rooms. The specified size was selected to ensure no CH-TRU containers would breach due to creep closure while a panel is being filled with waste. A nominal five-year life is used for operational purposes for mining, emplacement, and closure with no risk of CH-TRU waste containers breaching. Remote-handled containers will not breach in this time period due to the canister wall thickness and the 5.08 to 10.16 cm (2 to 4 in.) creep tolerance in each RH-TRU emplacement hole.

The WIPP underground facilities are located on the repository horizon 655 m (2,150 ft) beneath the surface (see Figure 3-2). In Chapter 2.0, Figure 2-12 shows a stratigraphic column which displays the repository and its position relative to mean sea level. These facilities include the waste disposal region, the operations region, an experimental region, and associated support facilities. The underground support facilities service and maintain underground equipment for mining and disposal operations, monitor for radioactive contamination, and allow limited decontamination of personnel and equipment.

Waste panels consist of seven rooms. Each room has nominal dimensions of 91 m (300 ft) long, 10.1 m (33 ft) wide, and 4.0 m (13 ft) high. Pillars between rooms are 30 m (100 ft) thick. Eight waste panels will be separated from each other and the main entries by nominally 61-m (200-ft) pillars. In addition to the eight panels, the main north-south and east-west access drifts in the

waste regions are available for waste disposal. These have been designated Panels 9 and 10 for permitting and modeling purposes (see Figure 3-2). Section 6.4.2.1 describes the treatment of all waste panels in BRAGFLO. Additional information can also be found in Appendix PA, Attachment MASS.5. Rockbolts, or related types of ground support, are used as necessary to maintain safe underground personnel access. In the panels, this will typically consist of localized bolting when needed. All panels will be closed using the panel closure system described in Section 3.3.3.

The underground is connected to the surface by four vertical shafts: the waste shaft, the salt handling shaft, the exhaust shaft, and the AIS. The waste shaft, salt handling shaft, and the air intake shaft have permanently installed hoists capable of moving personnel, equipment, and materials between the surface and the repository. All shafts will eventually be sealed using the seal design described in Section 3.3.2. A summary of information describing existing WIPP shafts is given in Appendix BARRIERS, Section BARRIERS-3.0.

Mining of the shafts and underground passages within the repository gives rise to a disturbed rock zone (DRZ) that is important to repository performance. The DRZ forms as a consequence of unloading the rock in the vicinity of the excavation. Increased permeability is created by microfractures along grain boundaries and by bed separation along lateral seems. The DRZ development begins immediately after excavation and continues as salt creeps into the opening. The DRZ surrounding the shafts is symmetrical and has been characterized and incorporated into the shaft seal design as discussed in Appendix BARRIERS. As shaft seal elements resist inward creep, the stress state becomes compressive and gives rise to fracture healing, and a return of the disturbed salt to its original extremely low permeability. The lateral DRZ along passages in the underground includes fracture in nonhalitic rock, such as anhydrite, and bed separation on clay seams. These zones will not naturally heal in a manner similar to healing of halite. Rigid components of the panel closure system will prevent further development of the DRZ.

In a letter dated June 26, 2000 [Docket A-98-49, II-A-3, Item 24, Attachment 1], the CBFO submitted a planned change to raise the repository horizon in Panels 3, 4, 5, 6, and 9 by approximately 2 m (6.6 ft) so that the back (roof) is at Clay Seam G. Positioning the back at Clay Seam G results in a more stable back configuration and improves repository ground conditions. Raising the horizon also reduces the rate of roof-beam deformation and slows the development of fractures, thus reducing risks during mining and waste handling in the underground repository. This change also results in less maintenance being required to assure acceptable ground conditions. In a letter dated August 11, 2000 [Docket A-98-49, II-A-3, Item 24], the EPA agreed "… that (this change) will enhance operational safety without significantly affecting the long-term performance of the facility." (Chapter 6.0 provides more detail related to Clay Seam G.)

3.3 Disposal-System Barriers

Disposal system barriers are used in the DOE's design of the WIPP to isolate waste and delay the migration of radionuclides to the accessible environment. Disposal-system barriers include the geology and hydrology of the disposal system or natural barriers, engineered systems, and an engineered barrier designed to meet the regulatory requirements of 40 CFR § 194.14(d). In

addition, the incorporation of disposal-system barriers (both engineered and natural barriers) satisfies the criterion stated in 40 CFR § 194.44(a).

> Disposal systems shall incorporate engineered barrier(s) designed to prevent or substantially delay the movement of water or radionuclides toward the accessible environment.

In the CCA, the DOE proposed four elements of the disposal system as engineered barriers:

(1) shaft seals,

(2) panel closures,

(3) MgO around the waste, and

(4) borehole plugs.

In its certification decision, the EPA concluded that only MgO meets the regulatory definition of an engineered barrier. The certification decision includes the following regarding engineered barriers (63 FR 27397, May 18, 1998):

> The EPA finds that DOE complies with Sec. 194.44. The EPA found that DOE conducted the requisite analysis of engineered barriers and selected an engineered barrier designed to prevent or substantially delay the movement of water or radionuclides toward the accessible environment. The DOE provided sufficient documentation to show that MgO can effectively reduce actinide solubility in the disposal system. The DOE proposed to emplace a large amount of MgO around waste drums in order to provide an additional factor of safety and thus account for uncertainties in the geochemical conditions that would affect CO_2 generation and MgO reactions.

Although shaft seals, panel closures, and borehole plugs are not defined by EPA as engineered barriers, these features may affect disposal system performance and thus are included in the performance assessment (PA) (Appendix PA, Section PA-4.2). Shaft seals and borehole plugs will limit migration of liquid and gases in the WIPP shafts and boreholes. Panel closures will limit the communication of brine and gases among waste disposal panels. Designs of shaft seals, borehole plugs, and panel closures use common engineering materials that possess low permeability, appropriate mechanical properties, and durability.

The DOE performed an Engineered Alternatives Cost/Benefit Study (see CCA Appendix EBS) to examine the benefits and detriments associated with an array of engineered barrier alternatives. This study, in combination with past sensitivity and other analyses, was used to make a decision about MgO, which the DOE has chosen to buffer the chemical composition of brine that may enter the repository over the 10,000-year regulatory period. The principal beneficial performance characteristic resulting from MgO is a reduction in actinide solubilities in brine. Specific performance information on MgO is presented in Section 6.4.3 and Appendix BARRIERS.

3.3.1 MgO Engineered Barrier

The DOE has concluded that it is desirable to add MgO to the repository to improve the performance of the disposal system (see Appendix BARRIERS). This additive is being protected in supersacks until the supersacks are broken during creep closure of the room. The

MgO is being packaged in polypropylene supersacks for emplacement in the underground. Emplacement in supersacks (1) facilitates handling and emplacement of MgO; (2) minimizes potential worker exposure to dust; and (3) minimizes the exposure of periclase, the main, reactive constituent of MgO, to atmospheric carbon dioxide (CO_2) and water prior to rupturing of the supersacks. Supersacks, which contain 1900 $\pm$ 23 kg (4200 $\pm$ 50 lbs), are handled and placed using normal waste-handling techniques. Once each row of waste units is in place, a layer of supersacks is placed on top of them as shown in Figure 3-6. The supersacks are constructed of woven polypropylene, which serves as a barrier to CO_2 and moisture. The supersacks are placed on support sheets so that they can be handled and placed in a manner that is identical to how waste units are emplaced. Typically, the space above a stack of containers is 90 to 122 cm (36 to 48 in.), of which about (45 cm (18 in.) will contain MgO .

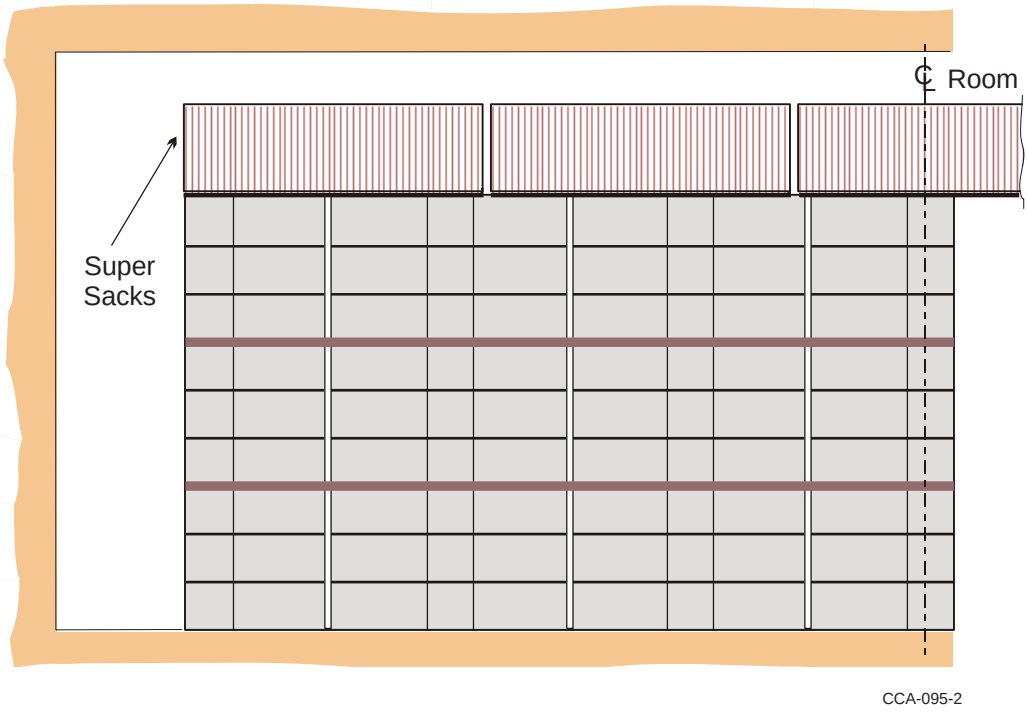

Figure 3-6. Room Cross-Section Showing the Position of Supersacks

The performance of MgO and its impacts on the disposal system are discussed in more detail in Section 6.4.3.4. Appendix BARRIERS provides the rationale for the use of MgO as an engineered barrier and contains information regarding its effects on chemical conditions in the repository. Laboratory experiments and thermodynamic modeling were used to predict the long-term effects of MgO on chemical conditions. Appendix PA, Attachment SOTERM describes how these conditions were used to calculate actinide solubilities.

Initially, MgO was emplaced in both minisacks and supersacks. Minisacks, which contained 11 kg (25 lbs.) of MgO, were placed among the waste containers and on the floor between the waste containers and the ribs. Supersacks, which contain 1900 $\pm$ 23 kg (4200 $\pm$ 50 lb) of MgO, are handled and emplaced using normal waste-handling techniques. Once each stack of waste containers is emplaced, a layer of supersacks is emplaced on top of them. Two changes related

to MgO have occurred since the submittal of the CCA. These changes and their effects are described below.

3.3.1.1 Change of MgO Supplier

After the original supplier stopped producing MgO in 2000, another supplier was selected. The new MgO is slightly less dense than the previous product. To compensate for this, the volume of MgO emplaced in the repository was increased by approximately two percent to ensure the emplacement of the same mass of MgO proposed in the CCA. The product provided by the new supplier meets all of the technical specifications for MgO. The DOE evaluated the properties of the new MgO and concluded that the change has no impact on its expected performance as the engineered barrier (see Appendix BARRIERS).

3.3.1.2 Elimination of MgO Minisacks

In order to enhance worker safety and operational efficiency, DOE requested EPA approval of the elimination of the MgO minisacks. Elimination of the minisacks resulted in a 15 percent reduction in the total mass of MgO to be emplaced in the WIPP. An impact assessment carried out to support the DOE modification request demonstrated that the elimination of minisacks and the associated 15 percent reduction of MgO would not affect its performance as the engineered barrier (consumption of CO_2 from possible microbial activity and concomitant reduction of actinide solubilities). The assessment also demonstrated that the reduction of MgO would not reduce the additional benefits of brine consumption and constant chemical conditions.

In a letter from the EPA dated January 11, 2001 [Docket A-98-49, II-B-3, Item 15], the EPA approved the elimination of the MgO minisacks. Appendix BARRIERS provides additional information on MgO.

3.3.2 Shaft Seals

The purpose of the shaft seal system is to limit fluid flow within four existing shafts after the WIPP is decommissioned. Such a seal system will not be implemented for several decades, but in order to establish performance requirements now that can be achieved at a later date, a shaft seal system has been designed possessing excellent durability, performance, and constructability using existing technology. The design approach is conservative, with redundant functional elements and various common materials. Because this design is not the only possible combination of materials and construction strategies that would adequately limit fluid flow within the shafts, future developments may change the design.

Material specifications and construction techniques for the shaft seal system are given in Appendix BARRIERS; and in CCA Appendix SEAL in SEAL 5.0 and 6.0. Section SEAL 5.0 also provides the rationale and quantification methods used to develop parameter distribution functions. Appendix PA, Section PA-4.2.6 summarizes the representation of the shafts in PA; Appendix PA, Attachment PAR, Table PAR-17 provides parameter values in the modeling. The presently envisaged shaft seal system is described in this section at a summary level with detail provided in Appendix BARRIERS.

The shaft seal design explores function and performance of the WIPP shaft seal system and provides well-documented assurance that such a shaft seal system can be constructed using available materials and methods. Sections of CCA Appendix SEAL provide hydrologic and structural calculations, material specifications and properties, construction methods, and engineering drawings. Documentation of material properties and their satisfactory application in the site-specific environment for regulatory time periods aid in assuring that the WIPP shaft seal system will meet performance expectations. Documentation of the analyses conducted and the results can be referenced in CCA Appendix SEAL (Chapter 2.4 of Appendix A, and Chapter 3.1.2 of Appendix D).

3.3.2.1 Site Setting

The geologic setting and groundwater hydrology in the proximity of the WIPP site are presented in Sections 2.1 and 2.2. These sections describe low brine-flow quantities and low hydrologic gradients, both very positive features with regard to sealing shafts or boreholes. As noted in Section 2.2, one of DOE's site selection criteria was a favorable geologic setting that minimizes fluid flow as a transport mechanism. Although these positive hydrologic attributes are documented, the shaft seal design concentrates on further mitigating fluid transport. For the purposes of the hydrologic sealing evaluation, the lithologies have been divided into the Rustler (and overlying strata) and the Salado. The fluid transport phenomena of seal materials within Salado lithologies are the primary design concerns.

3.3.2.2 Design Objectives

Design objectives for the shaft seal system address the need for the WIPP to comply with system requirements and to follow accepted engineering practices using demonstrated technology. Shaft seal design objectives are summarized as follows:

- limit radionuclides from reaching regulatory boundaries,
- restrict groundwater flow through the sealing system,
- use engineered materials possessing good long-term stability,
- protect against structural failure of system components,
- minimize subsidence and prevent accidental entry, and
- use available construction methods and materials.

Details of the design respond to these qualitative design objectives and present an implementation approach. The shaft seal system design was completed under the QA program described in Chapter 5.0 and includes review by independent, qualified experts. Reviewers examined the complete design including conceptual, mathematical, and numerical models, and computer codes. The design reduces uncertainty associated with any particular element by using multiple sealing system components constructed from different materials.

3.3.2.3 Design Description

A schematic of the shaft seal system as configured for the AIS is shown in Figure 3-7. Slight differences in seal element geometry occur within the four shafts owing to different shaft diameters or stratigraphic variations. The shaft seal system has 13 elements that fill the shaft with engineered materials possessing high density and low permeability. Components of the seal system within the Salado provide the primary barrier by limiting fluid transport along the shaft

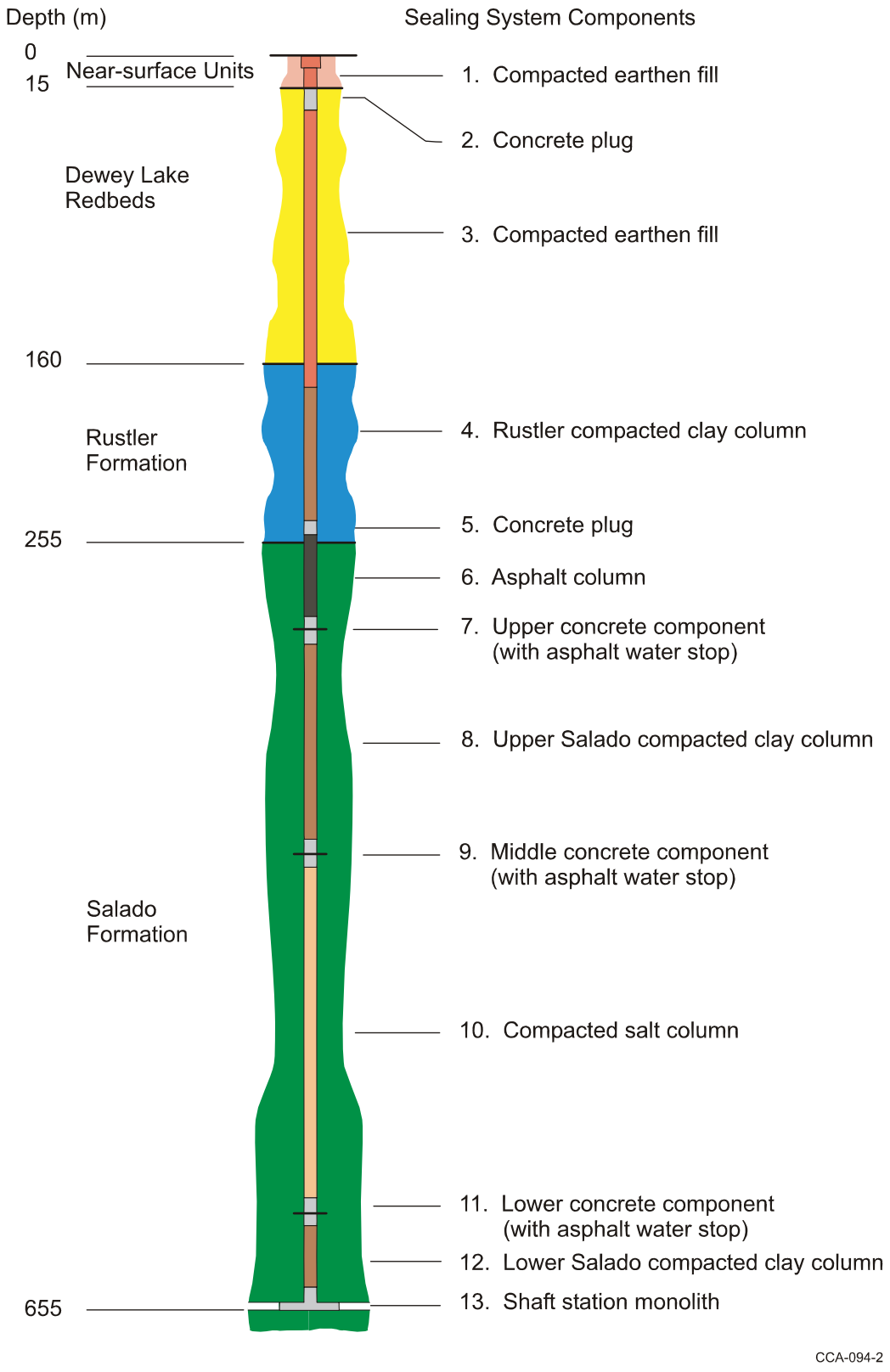

Figure 3-7. Proposed Seal Design for the WIPP AIS

during the 10,000-year regulatory period. Components of the seal system within the Rustler limit commingling of groundwater between water-bearing members. Components of the seal system overlying the Rustler fill the shaft with common materials of high density, consistent with good engineering practices. Appendix BARRIERS provides a detailed description of the shaft seal system and detailed design drawings for each shaft seal.

3.3.3 Panel Closure System

In its final certification decision for WIPP (63 FR 27354), the EPA added a new Appendix A to 40 CFR Part 194. The new appendix specifies four conditions that apply to the certification. Condition 1 pertains to panel closures. It states:

> Condition 1: § 194.14(b), Disposal system design, panel closure system. The Department shall implement the panel seal design designated as Option D in Docket A-93-02, Item II-G-1 (October 29, 1996, Compliance Certification Application submitted to the Agency). The Option D design shall be implemented as described in Appendix PCS of Docket A-93-02, Item II-G-1, with the exception that the Department shall use Salado mass concrete (consistent with that proposed for the shaft seal system, and as described in Appendix SEAL of Docket A-93-02, Item II-G-1) instead of fresh water concrete.

Option D involves installation of a concrete block “explosion-isolation wall,” removal of the DRZ along a section of the panel access drifts, and emplacement of a concrete monolith composed of Salado Mass Concrete in that section of each access drift.

The EPA Preamble to 40 CFR Part 194 Final Rule Section VIII.A.b stated “if a design different from those listed above is identified, the appropriate permit modification will be sought.” Since the certification of WIPP by the EPA, DOE has reevaluated a number of its engineering and construction aspects, including the panel closure systems. Therefore, DOE submitted a proposed change request to EPA on October 7, 2002 (DOE CBFO letter 2002). The EPA responded to DOE with a letter dated November 15, 2002. In this letter, EPA concluded that the panel closure request requires a modification to the rulemaking and “…will likely take a minimum of 12 months to complete from receipt of “complete” information on the requested changes. … Since the rulemaking likely would not be completed before we receive the WIPP compliance recertification application, … we are deferring review of this proposal until after we have issued our recertification decision.” Consistent with this direction from EPA, the PA calculations assume a panel closure with characteristics consistent with Option D (see Figures 3-8 and 3-9). In the same letter, EPA agreed to a delay in completing the panel closure system.

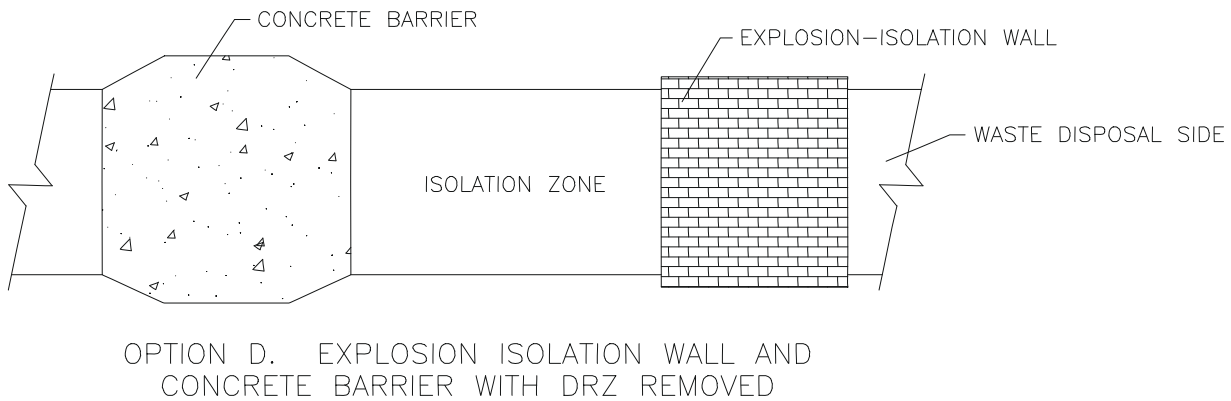

Figure 3-8. Panel Closure

Panel closures have been included for the purpose of Resource Conservation and Recovery Act disposal unit closure and to prevent potentially unacceptable levels of volatile organic compound release during waste management operations. The panel closure system was not designed or intended to support long-term repository performance. The panel closure system has been designed according to a number of operational objectives set out by the DOE, the main elements of which are:

1. the panel closure system shall restrict flow from the panels,

2. the panel closure system should perform its intended functions under loads generated by creep closure, and in general under the most severe ground conditions expected in the waste disposal area during the operational phase,

3. the panel closure system should be capable of containing and continuing to perform its intended function under conditions of a postulated methane explosion,

4. the panel closure system should be constructed of materials that are compatible with its emplacement environment and function,

5. engineering design of the panel closure system should include structural analyses using WIPP specific data, and should address such issues as the thermal cracking of concrete, and

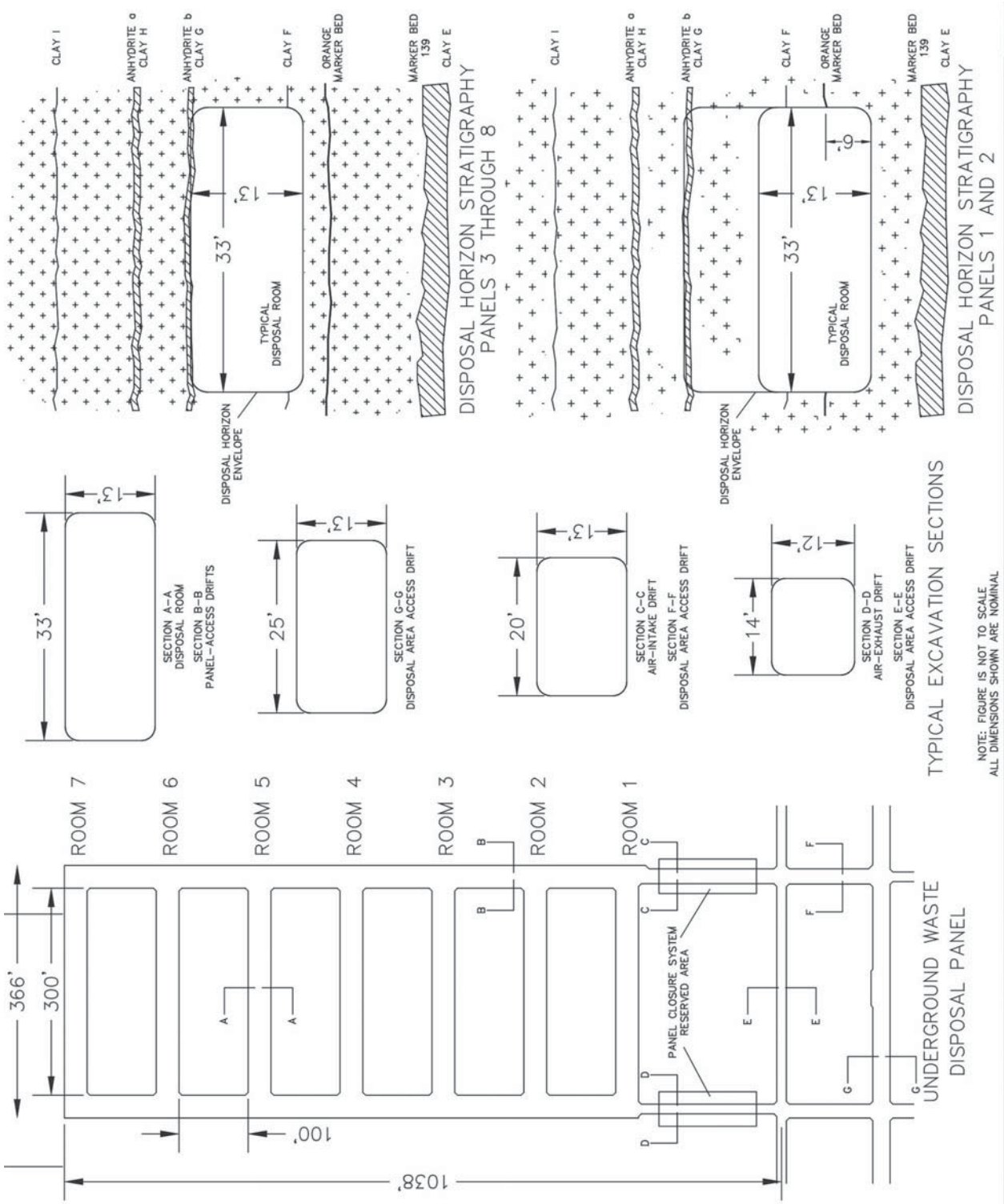

Figure 3-9. Location of Panel Closure System

6. the panel closure system should be designed and constructed using conventional mining practices, with full consideration of shaft and underground access and services. It should be constructed to generally accepted national design and construction standards, with a QA and quality control program used to verify material properties and construction practices.

See Appendix BARRIERS for a detailed discussion of panel closure. Representation of the panel closures in PA is described in Appendix PA, Section PA-4.2.7; parameters relevant to the panel closures are provided in Appendix PA, Attachment PAR, Table PAR-19.

3.3.4 Borehole Plugs

Figure 3-10 identifies existing unplugged boreholes that lie within the controlled area. Of these boreholes, four are deep boreholes that exceed the depth of the repository, and the remainder are shallow boreholes that do not reach the repository horizon.

To mitigate the potential for migration of contaminants toward the accessible environment, the DOE has specified that borehole plugs be designed to limit the volume of water that could be introduced to the repository from the overlying water-bearing zones and to limit the volume of contaminated brine released from the repository to the accessible environment.

Grout-plugging procedures are routinely performed in standard oil-field operations; however, quantitative measurements of plug performance are rarely obtained. The Bell Canyon Test reported by Christensen and Peterson (1981, 25) was a field test demonstration of the use of cementitious plugging materials and modification of existing industrial emplacement techniques to suit repository plugging requirements. The test was performed in an 20 cm (8 in.) well bore near the top of the Bell Canyon. The test bore intercepted an aquifer at a depth of 1,370 m (4,495 ft) with a shut in pressure of 1,800 psi (12.4 megapascals). A 2-m (6-ft) grout plug was emplaced above the aquifer and tested by unloading the hole (that is, removing fluids) above the plug to allow the full pressure in the aquifer to bear on the plug. This plug was observed to reduce the flow by five orders of magnitude, to 0.6 liters per day (0.2 gallons per day).

Cement emplacement technology was found to be generally adequate to satisfy repository plugging requirements. Christensen and Peterson (1981) also report

> that grouts can be effective in sealing boreholes, if proper care is exercised in matching physical properties of the local rock with grout mixtures.

A significant amount of research has been completed by the DOE to optimize concrete mixtures for the conditions expected in the Salado. The results of this research have been used to design the shaft sealing system as discussed in CCA Appendix SEAL. (Concrete is discussed in Appendix A of CCA Appendix SEAL, Section A2.1.) Consequently, the DOE has identified materials that will provide suitable plugs for boreholes. In addition, appropriate national standards such as the American Petroleum Institute Specification 10 and American Society for Testing Materials specification Volume 04.02 are available to assure the quality of borehole plugging material and installation. Section 2.1.4 of the CAO QAPD (see Appendix QAPD) provides the quality assurance requirements for the control of special processes such as plugging.

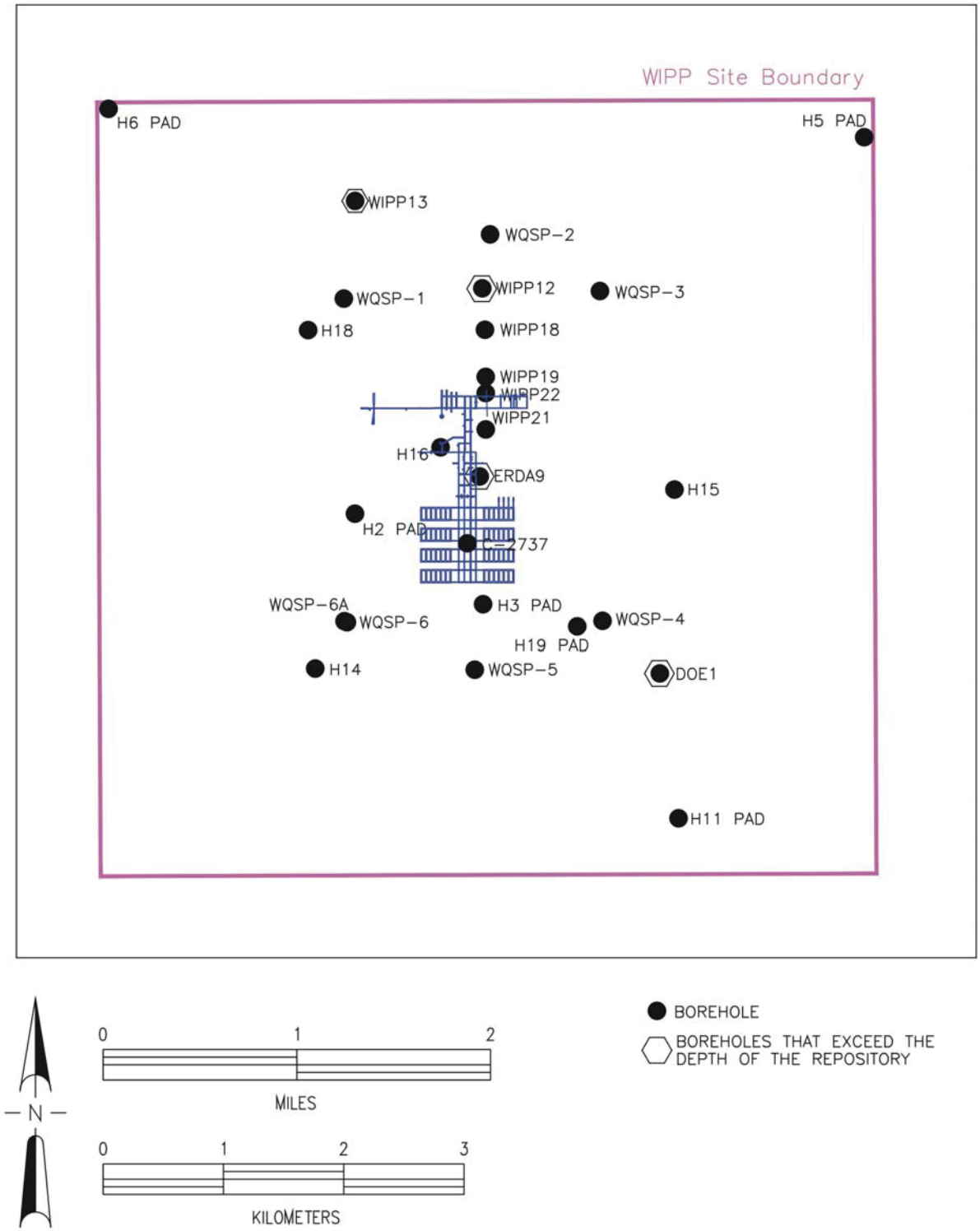

Figure 3-10. Approximate Locations of Unplugged Boreholes

As a result of the Christensen and Peterson (1981) report and subsequent evaluations of plugging materials, the DOE concluded that boreholes within the controlled area, which were previously plugged in accordance with the appropriate state and federal regulations in effect at the time plugging, will mitigate the potential for migration of fluids beyond the repository horizon. Shallow unplugged boreholes within the controlled area will be plugged in accordance with the current state or federal regulations using materials shown to be compatible with the underground environment. Deep unplugged boreholes within the controlled area will be plugged according to the state of New Mexico, Oil Conservation Division (1988), Order R-111-P (see Appendix BARRIERS). The governing regulations for plugging and/or abandonment of boreholes are summarized in Table 3-2. These solid cement plugs will go through the salt section and any water-bearing horizon to prevent liquids or gases from entering the hole above or below the salt section. The boreholes not being used for monitoring will be plugged at decommissioning. Appendix PA, Section PA-4.2.9 summarizes the representation of the borehole plugs in PA; Appendix PA, Attachment PAR, Tables PAR-14, PAR-15, and PAR-16 provide parameter values used in the modeling.

Table 3-2. Governing Regulations for Borehole Abandonment

Federal or State Land	Type of Well or Borehole	Governing Regulation	Summary of Requirements
Both	Groundwater Wells	State of New Mexico (1995), Rules and Regulations Governing Drilling of Wells and Appropriation and Use of Groundwater in New Mexico, Article 4-14	Any specific plugging requirements and provisions made by the state engineer shall be set forth in the permit.
Federal	Oil and Gas Wells	43 CFR Part 3160, 3162.3 4 (DOI 1995a)	The operator shall promptly plug and abandon, in accordance with a plan first approved in writing or prescribed by the authorized officer.
Federal	Potash	43 CFR Part 3590, 3593.1 (DOI 1995b)	(b) Surface boreholes for development or holes for prospecting shall be abandoned to the satisfaction of the authorizing officer by cementing and/or casing or by other methods approved in advance by the authorized officer. The holes shall also be abandoned in a manner to protect the surface and not endanger any present or future underground operation, any deposit of oil, gas, or other mineral substances, or any aquifer.
State	Potash	State of New Mexico (1995), Rules and Regulations Governing Drilling of Wells and Appropriation and Use of Groundwater, Article 4-20.2	In the event that the test or exploratory well is to be abandoned, the state engineer shall be notified. Such well shall be plugged in accordance with Article 4-19.1 so that the fluids will be permanently confined to the specific strata in which they were originally encountered.
State	Oil and Gas Well Outside the Oil-Potash Area	State of New Mexico, Oil Conservation Division (1991), Rule 202 (eff. 3-1-91)	B. Plugging (1) Prior to abandonment, the well shall be plugged in a manner to permanently confine all oil, gas, and water in the separate strata where they were originally found. This can be accomplished by using mud-laden fluid, cement, and plugs singly or in combination as approved by the Division on the notice of intention to plug. (2) The exact location of plugged and abandoned wells shall be marked by the operator with a steel marker not less than 10.16 cm (4 in.) in diameter, set in cement, and extending at least 1.22 m (4 ft) above mean ground level. The metal of the marker shall be permanently engraved, welded, or stamped with the operator name, lease name, and well number and location, including unit letter, section, township, and range.
State	Oil and Gas Wells Inside the Oil-Potash Area	State of New Mexico, Oil Conservation Division (1988), Order No. R-111-P (eff. 4-21-88)	F. Plugging and Abandonment of Wells (1) All existing and future wells that are drilled within the potash area shall be plugged in accordance with the general rules established by the Division. A solid cement plug shall be provided through the salt section and any water-bearing horizon to prevent liquids or gases from entering the hole above or below the salt selection. It shall have suitable proportions—but no greater than three percent of calcium chloride by weight—of cement considered to be the desired mixture when possible.

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4.0 WASTE DESCRIPTION

This chapter describes the type of waste that is emplaced and will be emplaced in the Waste Isolation Pilot Plant (WIPP) and provides an appraisal of the inventory of physical, chemical, and radionuclide components of the waste. This information supports the development of the performance assessment (PA) models that are used in predicting the long-term behavior of the repository. This chapter includes a waste description based on the inventories of existing and projected waste reported for the CCA (1996a) reported in the transuranic (TRU) Waste Baseline Inventory Report (TWBIR) (included in CCA Appendix BIR) and updated for CRA-2004 in Appendix DATA, Attachment F. This chapter also includes a description of the projected waste inventory, waste limits derived from both the PA and operational safety and health considerations, and methods of control to ensure compliance with the identified waste limits. Finally, this chapter provides a discussion of the applicable qualitative and quantitative waste characterization methodologies.

Inventory estimates provided in the CCA (Appendix BIR) represented the information available at that time. It was anticipated that WIPP waste inventory estimates would change as the U.S. Department of Energy (DOE) characterized the contents of waste containers prior to shipment to WIPP and as new TRU wastes were generated. Data on emplaced waste and updated estimates of the entire projected waste inventory are provided in Appendix DATA, Attachments D, E, F and H. The waste-inventory estimates reported in Appendix DATA and in this chapter are based on the available information as of September 30, 2002, unless otherwise noted.

Objectives of this chapter are to:

1. Report quantities and characteristics of the waste emplaced in the repository since certification;

2. Describe the current understanding of the WIPP waste inventory (emplaced, stored, and projected waste) in terms of waste components and characteristics;

3. Update waste inventory information for PA and compliance assessment calculations;

4. Reassess waste components and characteristics and associated waste-emplacement limits that may be important to long-term repository behavior; and

5. Identify changes or new information related to the WIPP waste characterization program that have occurred since certification.

Section 194.24(a) of 40 CFR Part 194 specifies that the DOE shall provide information pertaining to the chemical, radiological, and physical composition of the waste planned to be emplaced in the repository. Specifically, the criterion states

> Any compliance application shall describe the chemical, radiological and physical composition of all existing waste proposed for disposal in the disposal system. To the extent practicable, any compliance application shall also describe the chemical, radiological and physical composition of to-be-generated waste proposed for disposal in the disposal system. These descriptions shall include a list of waste components and their approximate quantities in the waste. The list may be

derived from process knowledge, current non-destructive examination/assay, or other information and methods.

This waste description includes the definition, sources, types, components, and characteristics of the waste planned for emplacement in the WIPP. The description provided in this chapter, along with the waste characterization analysis in Appendix TRU WASTE, Section TRU WASTE-2.0, identifies those physical, chemical, and radiological components of the waste that may singly or in combination affect the ability of the WIPP disposal system to meet the environmental performance standards contained in Part 191. This chapter is supported with several appendices. For example, waste related parameters used in PA are discussed in Appendix PA, Attachment PAR and Appendix TRU WASTE, Section TRU WASTE-2.0. Results of sensitivity analyses with respect to total releases used to generate the mean complementary cumulative distribution function (CCDF) in Section 6.5 are discussed in Appendix PA. The impact of waste components and characteristics on WIPP performance is discussed in Appendix TRU WASTE, Section TRU WASTE-2.0. Limits for waste components are discussed in CCA Appendix WCL; and in Appendix TRU WASTE, Section TRU WASTE-3.0 and summarized in this chapter. This chapter also summarizes methods of control that will be employed by the DOE to ensure that only those wastes that are consistent with those on which the PA is based are actually emplaced in the repository. One such control is the WIPP Waste Information System (WWIS) database for controlling the receipt of and tracking the emplacement of waste (see Section 4.3.2).

Before the final PA for the CCA was designed, DOE performed waste characterization analyses based on iterative preliminary PAs, related sensitivity analyses, and dedicated process studies for specific components and characteristics of the waste. A list of waste components and characteristics that were considered during these analyses, the list of and rationale for the ones retained for inclusion in the final PA, and the ones not included are documented in CCA Appendix WCL. This process has been updated for this recertification application (CRA-2004); waste components and characteristics retained for CRA-2004 PA are documented in Appendix TRU WASTE, Section TRU WASTE-2.0. Retained waste components are assigned fixed values in the final PA (see Appendix PA, Attachment PAR) based on information reported in Appendix DATA, Attachment F. Therefore, during the PA, plausible combinations of fixed values for waste components are included in all PA scenario analyses. Important imprecisely known waste characteristics are assigned ranges and distributions (see Appendix PA) from which values are drawn using a Latin hypercube sampling (LHS) technique that ensures that samples are taken from across the entire range of the distribution (see Section 6.1.5.2).

Since results demonstrate compliance with the quantitative containment requirements in Section 191.13, the individual protection requirements in Section 191.15, and the groundwater protection requirements in Section 191.24, the fixed values used for waste components define a profile of waste suitable for disposal at WIPP. Following the final PA for the CCA, sensitivity analyses determined the contribution of uncertainty in individual input variables to the uncertainty in model predictions (that is, final releases). In that sensitivity analysis, there were no waste characteristics that had a significant impact on the uncertainty about and the location of the mean CCDF reported in CCA Figure 6-39 (see CCA Appendix SA for a discussion of this uncertainty). Therefore, setting waste component limits is not based on PA results but is based on ensuring the validity of repository conditions modeled by PA (see CCA Appendix WCL). The same is true for the CRA-2004. In addition, the limits are repository-scale limits applicable to the inventory

at the time of decommissioning. The process for demonstrating compliance with these limits is to track the waste-component quantity and the uncertainty associated with that quantity as waste is emplaced in the repository. For example, the curie content for plutonium (Pu) and its uncertainty (based on the fact that a large percentage of the waste has yet to be generated) can be accumulated as waste is emplaced throughout the operational phase. Then, at the time of decommissioning, when these repository limits apply, the total curie content for Pu may be provided with a specified level of confidence, such as 95 percent, to demonstrate compliance with the waste component limits.

Figure 4-1 illustrates the information flow pertaining to the waste description and its relationship to other sections of this chapter as well as Chapter 6.0 and appendices to this application.

4.1 Waste Inventory

The waste inventory is defined as the quantity of waste that is anticipated to be emplaced in the WIPP and that waste that is already emplaced. This inventory is generally characterized as the nonradionuclide inventory that consists of both physical and chemical waste constituents, generally expressed in units of density or concentration (kg/m^3); and the radionuclide inventory, which is a tabulation, by specific isotope, of anticipated radionuclides in the waste expressed in units of curies (Ci).

The term TRU waste is defined in the WIPP Land Withdrawal Act (LWA) (Public Law 102-579 as amended by Public Law 104-201) as

> waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for (A) high-level radioactive waste; (B) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations ; or (C) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with part 61 of title 10, Code of Federal Regulations.

TRU waste that was disposed of in on-site, shallow landfill-type configurations prior to the early 1970s is referred to as buried waste. In 1970, the U.S. Atomic Energy Commission concluded that TRU waste should be stored in anticipation of the creation of more confining disposal facilities. TRU waste generated since that date has been segregated from other waste types and placed in retrievable storage. Waste generated after 1970, but before implementation of CBFO certified waste quality assurance (QA) program, is referred to as retrievably stored waste. Waste generated after a site's implementation of CBFO certified QA program is defined as newly generated. These and other relevant terms are defined in Appendix DATA, Attachment F.

Newly generated waste will be characterized in a similar manner to retrievably stored waste, but it will incorporate more real-time, as opposed to historical, acceptable knowledge. As of September 30, 2002, approximately 65 percent of the waste to be disposed of at the WIPP was expected to be newly generated waste, as described in the TWBIR (CCA Appendix BIR). At the time of the data call for CRA-2004 (September 30, 2002), approximately five percent of the waste DOE plans to dispose in the WIPP had been emplaced in the repository. Approximately 73 percent of the waste to be disposed of in the WIPP is classified as retrievably stored waste, approximately 22 percent of the waste identified by the TRU waste sites to be disposed of at the WIPP is expected to be newly generated waste (see Appendix DATA; Attachment F).

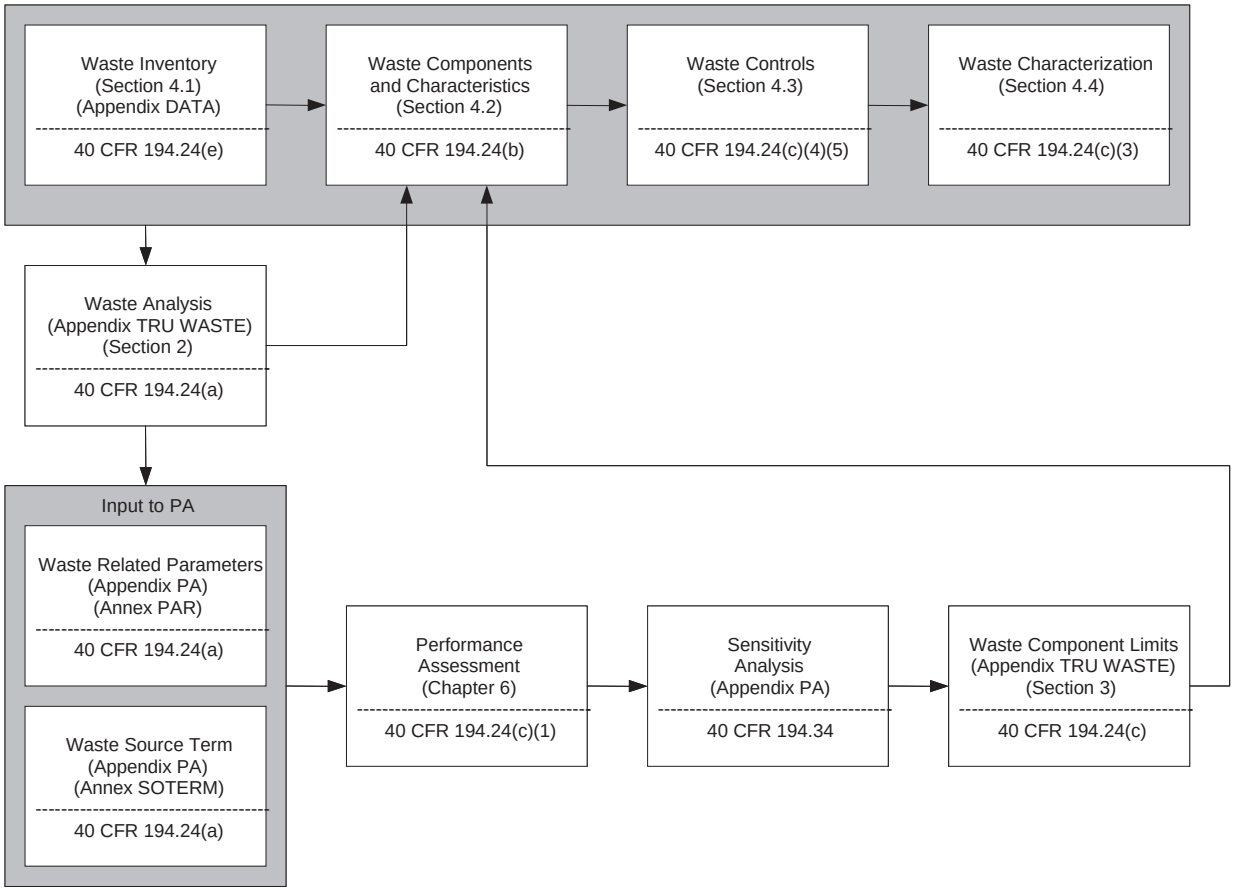

Figure 4-1. Waste Description Information Flow

TRU waste is classified as either contact-handled (CH) or remote-handled (RH) based on the contact dose rate at the surface of the waste container. If the contact dose rate is less than 200 millirem per hour (2 milliSievert per hour), the waste is defined as CH-TRU (DOE 1988). If, on the other hand, the contact dose rate is greater than or equal to 200 millirem per hour (2 milliSievert per hour), the waste and its container are defined as RH-TRU (DOE 1988). Consistent with the LWA, only RH-TRU waste less than or equal to 1000 rem per hour (10 Sievert per hour) is eligible for disposal at the WIPP. Also, to meet the requirements as set forth in the LWA, the total U capacity of WIPP by volume is 6.2 million ft3 (175,564 m3) of TRU waste. Moreover, the LWA also specifies that the emplaced RH-TRU waste is not to exceed a total activity of 5.1 million Ci (~ 18.9×10^{16} Becquerel) and a total activity concentration of 23 Ci per liter maximum activity level (averaged over the volume of the canister). No more than five percent of the emplaced RH-TRU waste may exhibit a dose rate in excess of 100 rem per hour (1 Sievert per hour).

4.1.1 Sources of TRU Waste

The DOE's TRU waste, as described in this chapter, is derived primarily from Pu fabrication and processing, research and development (R&D), decontamination and decommissioning (D&D),

and environmental restoration (ER) programs at DOE sites. Most TRU waste generated at the TRU waste sites results from specific processes and activities that are well defined and well controlled, enabling the sites to characterize the waste on the basis of acceptable knowledge concerning the process, input materials, and finished products. Some examples of these operations include

- Production of nuclear products. Production of nuclear products includes reactor operation, radionuclide separation and finishing, and weapons fabrication and manufacturing. The majority of the TRU waste was generated by weapons fabrication and radionuclide separation and finishing processes. More specifically, wastes typically consist of TRU-contaminated material derived from chemical processes, air and liquid filtration, casting, machining, cleaning, product quality sampling, analytical activities, and maintenance and refurbishment of equipment and facilities.

- Pu recovery. Pu recovery wastes are TRU-contaminated items and materials from the recovery of valuable Pu, including contaminated molds, metals, glass, plastic materials, rags, salts used in electrorefining, precipitates, firebrick, soot, and filters.

- R&D. R&D projects include a variety of hot-cell or glove-box activities that often simulate full-scale operations described above, producing similar TRU wastes. Other types of R&D projects include metallurgical research, actinide separations, process demonstrations, and chemical and physical properties determinations.

- D&D. Facilities and equipment that are no longer needed or usable are decontaminated and decommissioned, resulting in TRU wastes consisting of scrap materials, cleaning agents, tools, piping, filters, Plexiglas, gloveboxes, concrete rubble, asphalt, cinder blocks, and other building materials. This is expected to be the largest category by volume of TRU waste to be generated.

- ER Programs. The implementation of environmental restoration programs at various DOE sites results in the generation of a variety of materials including contaminated soil, building materials and equipment.

Operations carried out in glove boxes and hot cells generate both combustible and noncombustible wastes. Combustible waste contains mixtures of paper, plastic materials, rags, cloth clothing, and wood resulting from Pu operations. Cloth and paper wipes are used to clean parts and glove boxes. Depending on the operations, damp combustibles are usually used and then wrung out, drained, or dried. Noncombustibles consist primarily of glass and metal. Much of this waste is laboratory equipment and glassware from R&D activities.

Filters are sometimes combinations of combustibles and non-combustibles and come from a variety of sources including high-efficiency particulate air (HEPA) filters, filter media, processed filter media, and prefilters. Prefilters and HEPA filters are used on all ventilation intake and exhaust systems associated with Pu operations. Filter frames can be either wood, aluminum, or stainless steel; and the filter media may be paper, Fiberglass, Nomex, or similar material. Filter media are generated from splitting absolute dry box and HEPA filters apart from their frames in the Pu process areas. Loose particulate materials that are dislodged from the filters are stabilized

and packaged separately from the media. Filter media are packaged in plastic bottles or bags. Filter media may also be mixed with portland cement to neutralize any residual nitric acid.

Graphite waste is produced from molds that are broken, cleaned, or scraped in glove boxes to remove excess Pu. Graphite is a uniform, well-defined material.

Benelex™ and Plexiglas™ are well-defined materials that are used as neutron shielding material and in glove-box construction. Benelex™ consists mainly of cellulose with residual amounts of the phenolic resin. Plexiglas™ is a polymethyl methacrylate polymer used for glove-box windows and is generated as waste during the change-out of the glove-box windows.

Inorganic process solids include residues from evaporator and other types of storage tanks, grit, firebrick fines, ash, salts, metal oxides, and filter sludge. This waste is typically solidified in portland- or gypsum-based cements.

Soil, asphalt, and sand contaminated from spills or generated from D&D activities may also be present in the waste.

To isolate the radiological and hazardous contaminants of these wastes from humans and the environment during handling and other life-cycle operations, a primary confinement barrier is used. Both CH-TRU and RH-TRU waste at the WIPP facility will be managed using payload containers that meet the requirements of the U.S. Department of Transportation (DOT) for Type A or equivalent containers (DOE 1995c). The term payload container in this document refers to drum, drum overpack, canister, standard waste box, or ten-drum overpack unit. Internal to these payload containers may be other secondary layers of confinement, including rigid plastic inner liners and multiple layers of plastic bagging. Each container is vented using one or more filters.

4.1.2 TRU Waste Sites

The major TRU waste sites (referred to as large quantity sites [LQSs]) that are in the process of shipping or are planning to ship their TRU waste to the WIPP for disposal include

- Hanford Richland (Hanford-RL); TRU wastes at Hanford under the purview of the DOE Richland Operations Office
- Hanford River Protection (Hanford-RP); TRU wastes at Hanford under the purview of the DOE Office of River Protection
- Idaho National Engineering and Environmental Laboratory (INEEL)
- Los Alamos National Laboratory (LANL)
- Oak Ridge National Laboratory (ORNL)
- Rocky Flats Environmental Technology Site (RFETS)
- Savannah River Site (SRS)

Since certification, Lawrence Livermore National Laboratory (LLNL) and the Nevada Test Site (NTS) have been recategorized as small quantity sites (SQSs). In addition, TRU waste at the Hanford Reservation has been divided into two categories: (1) TRU waste overseen by the DOE Richland Operations Office (Hanford-RL) which corresponds to the TRU waste reported by Hanford for the CCA inventory estimate, and (2) TRU waste overseen by the DOE Office of River Protection (Hanford-RP). The DOE Office of River Protection may send both CH-TRU and RH-TRU waste to the WIPP. The Hanford-RP waste was not included in the Hanford Reservation waste reported for the CCA but is included in the 2004 CRA. The inventories for the SQSs and LQSs are reported in Appendix DATA, Attachment F, Annex J.

At the time of the CCA, INEEL, LANL, and RFETS were expected to be among the first of the major TRU waste sites to begin shipping TRU waste to the WIPP. As of September 30, 2002, the WIPP had received 1,255 shipments totaling 7,716 m^3 (2.7×10^5 ft^3) of CH-TRU waste, primarily from INEEL, LANL, and RFETS. SRS and Hanford-RL have also made shipments. Emplaced, stored, and projected waste volumes, by TRU waste site, are provided in Tables 4-1 and 4-2. No RH-TRU waste has yet been shipped to the WIPP.

Table 4-1. Emplaced, Stored, and Projected CH-TRU Waste Inventory as of September 30, 2002[1]

TRU Waste Site	Emplaced CH-TRU Volume (m^3)	Stored CH-TRU Inventory (m^3)	Projected CH-TRU Inventory (m^3)	Disposal CH-TRU Inventory[3] (m^3)
Hanford-RL	9.8×10^1	1.3×10^4	1.3×10^4	4.1×10^4
Hanford-RP	0.0×10^0	3.9×10^3	0.0×10^0	3.9×10^3
INEEL	2.9×10^3	6.1×10^4	1.2×10^2	6.4×10^4
LANL	2.7×10^2	1.2×10^4	3.3×10^3	1.9×10^4
ORNL	0.0×10^0	0.0×10^0	4.5×10^2	9.5×10^2
RFETS	4.3×10^3	5.4×10^3	2.7×10^3	1.5×10^4
SRS	2.0×10^2	1.3×10^4	2.4×10^3	1.8×10^4
SQS[2]	0.0×10^0	1.2×10^3	2.8×10^3	7.1×10^3
Totals	7.7×10^3	1.1×10^5	2.5×10^4	1.7×10^5

Source: Appendix DATA; Attachment F.

[1] Volume reported by the TRU waste sites as of September 30, 2002. It is not scaled to the disposal volume.

[2] Includes currently identified SQSs; at some TRU waste sites, determinations that waste is generated through defense activities have yet to be made. Inventories for those TRU waste sites are not included in this number.

[3] This is the TRU waste site inventory scaled as follows: emplaced + stored + 2.11 (projected).

As TRU waste sites develop the prerequisite certification programs required for TRU waste disposal at the WIPP, they too will commence shipping waste to the WIPP. Effective implementation by the TRU waste sites of DOE Quality Assurance Program Document (QAPD) (see CCA Appendix QAPD) is a prerequisite for granting TRU waste certification authority to the TRU waste sites. A letter granting such authority will specify the date that the subject TRU waste sites effectively implemented their characterization and certification program. Any limitations imposed on the certification authority will be described in the letter.

As part of the certification for the project (63 FR 27404), the EPA promulgated a new section to the rule, Title 40 CFR 194.8. Section 194.8 establishes the approval process that must be completed before an individual TRU waste site may ship waste to the WIPP. The EPA approval considers the application of QA provisions to the waste-characterization process, including EPA audits or inspections DOE audits of TRU waste site waste-characterization

Table 4-2. Stored and Projected RH-TRU Waste Inventory as of September 30, 2002[1]

TRU Waste Site	Stored RH-TRU Inventory (m^3)	Projected RH-TRU Inventory (m^3)	Disposal RH-TRU Inventory[3] (m^3)
Hanford-RL	3.8×10^2	9.4×10^3	2.0×10^3
Hanford-RP	4.5×10^3	0.0×10^0	4.5×10^3
INEEL	2.2×10^2	0.0×10^0	2.2×10^2
LANL	1.2×10^2	0.0×10^0	1.2×10^2
ORNL	0.0×10^0	6.6×10^2	1.1×10^2
RFETS	0.0×10^0	0.0×10^0	0.0×10^0
SRS	0.0×10^0	2.3×10^1	4.0×10^0
SQS[2]	9.5×10^1	3.3×10^2	1.5×10^2
Totals	5.3×10^3	1.0×10^4	7.1×10^3

Source: Appendix DATA; Attachment F.

[1] Volume reported by the TRU waste sites as of September 30, 2002. It is not scaled to the disposal volume.

[2] Includes currently identified SQSs; at some TRU waste sites, determinations that waste is generated through defense activities have yet to be made. Inventories for those TRU waste sites are not included in this number.

[3] This is the TRU waste site inventory scaled as follows: emplaced + stored + 0.172 (projected)

programs, and provides for public review and comment. Section 194.8 also applies to the application of process knowledge by the TRU waste sites for waste characterization. The DOE must also implement a system of controls at the TRU waste sites to confirm that the total amount of each waste component emplaced in the disposal system will not exceed established limiting values.

Current information on the EPA approval of TRU waste sites to ship waste to WIPP consistent with the requirements of section 194.8 is provided in Table 4-3. In addition to these TRU waste sites, the Central Characterization Project (CCP) has been initiated by DOE and operates using mobile waste characterization equipment. As of September 30, 2003, CCP was operating and approved to ship waste from SRS, Argonne National Laboratory – East (ANL-E), and Nevada Test Site (NTS).

Table 4-3. Approved TRU Waste Site QA and Waste Characterization Programs as of September 30, 2002

TRU Waste Site
Hanford-RL
INEEL
LANL
RFETS
SRS

Source: WWIS

In addition to the major TRU waste sites, there are currently numerous SQSs planning to dispose TRU waste at the WIPP. Options to facilitate disposal of the SQS waste at the WIPP include either direct shipment to the WIPP after on-site characterization and certification or shipment to an interim facility for performing waste consolidation, treatment, and/or characterization and certification in accordance with WIPP requirements. The current list of SQSs that plan to ship directly to WIPP or to a larger site pending shipment to WIPP includes:

- Argonne National Laboratory – East (ANL-E),
- Argonne National Laboratory – West (ANL-W),
- Battelle Columbus Laboratories (BCL),
- Bettis Atomic Power Laboratory (BAPL),
- Knolls Atomic Power Laboratory (KAPL),
- Knolls Atomic Power Laboratory-Nuclear Fuel Services (KAPL-NFS),
- Lawrence Berkeley National Laboratory (LBNL),
- Lawrence Livermore National Laboratory (LLNL),
- Nevada Test Site (NTS),
- Paducah Gaseous Diffusion Plant (PGDP),
- Sandia National Laboratories/NM (SNL), and U.S. Army Material Command (USAMC).

As waste-management plans evolve at these TRU waste sites, the list is expected to change. Some TRU waste sites, for example, may ship waste to alternate facilities for processing pending shipment to WIPP. However, as of September 30, 2002, plans for shipment to alternate facilities had not been finalized. The inventories for these SQSs are reported in Appendix DATA, Attachment F, Annex J.

Six SQSs have shipped their waste to an LQS. These include:

- ARCO Medical Products Company (ARCO) – Shipped to LANL,

- Energy Technology Engineering Center (ETEC) – Shipped to Hanford-RL,
- Mound Plant – Shipped to SRS,
- Missouri University Research Reactor (MURR) – Shipped to ANL-E,[1]
- Pantex Plant - Shipped to LANL, and
- Teledyne Brown Engineering – Shipped to RFETS.

The inventories for these several SQSs are included in the LQS inventories.

Several SQSs plan to ship waste to WIPP, but their waste had not been determined to be defense waste as of September 30, 2002. These include:

- Babcock & Wilcox – Nuclear Engineering Services (B&W-NES),
- Brookhaven National Laboratory (BNL),
- Framatome,
- General Electric Vallecitos Nuclear Center (GE-VNC),
- Separations Process Research Unit (SPRU), and
- West Valley Demonstration Project (WVDP).

The inventories for these SQSs are reported in Appendix DATA, Attachment F, Annex I.

4.1.3 TRU Waste Inventory

A summary of the quantity of stored and projected TRU waste and TRU waste components is contained in Appendix DATA, Attachment F. Appendix DATA, Attachment F documents DOE's current understanding of the total inventory of TRU waste and includes both the TRU waste that is planned to be disposed at the WIPP site and the TRU waste that is not planned to be sent to WIPP as of September 30, 2002. Only the WIPP portion of the TRU waste inventory is used in PA calculations that support the development of CRA-2004.

In preparing CRA-2004, DOE initiated a "data call" to obtain current waste inventory information from its TRU waste sites similar to the data call that was conducted prior to 1995 in preparation for the CCA. Each TRU waste site was asked to review previous data submitted regarding its TRU waste and revise those data based on current knowledge of waste at the TRU waste site.

The results of the "data call" were compiled in a database called the Transuranic Waste Baseline Inventory Database (TWBID) Revision 2.1. Data from the TWBID are reported in detail in

[1] Shipment of MURR waste to ANL-E occurred after September 30, 2002.

Appendix DATA, Attachment F and are summarized here. For the CCA, there were essentially two categories of waste: stored waste and projected waste (see CCA Section 4.1.3.1 for definitions). For CRA-2004, there are three categories of waste: emplaced waste, stored waste, and projected waste (see Section 4.1.3.1 for definitions).

For DOE to consider disposal system performance at full capacity, it is necessary to scale the waste volumes reported by the TRU waste sites. This is because the volume identified by the TRU waste sites is less than the available volume of the repository, 175,564 m^3 (6.2 million ft^3). The projected inventory reported by the TRU waste sites is scaled, to achieve a disposal inventory equal to the repository volume specified by the WIPP LWA. The repository volume remains unchanged.

As of September 30, 2002, the TRU waste sites reported a total CH-TRU waste stored inventory of 1.1×10^5 m^3 (3.9×10^6 ft^3) and a total RH-TRU waste stored inventory of 5.3×10^3 m^3 (1.9×10^5 ft^3) (see Tables 4-1 and 4-2). This is DOE's current estimate of the stored inventory destined for WIPP. In addition to identified stored volumes, the TRU waste sites project that an additional 2.5×10^4 m^3 (8.8×10^5 ft^3) of CH-TRU waste and 1.0×10^4 m^3 (3.5×10^5 ft^3) of RH-TRU waste will be generated in the future.

The stored CH-TRU waste inventory currently reported by the TRU waste sites is larger than the same inventory reported in the CCA. SRS, RFETS, Hanford, and INEEL all reported increased stored CH-TRU volumes based on new information about their waste and increased accessibility to the waste. The Hanford-RP waste was not included in the previous Hanford estimate used in the CCA, although the TWBIR indicated that it might be included in the WIPP inventory at some time in the future. Several SQSs (BCL, BAPL, KAPL, and PGDP) have identified small inventories of CH-TRU stored waste since the CCA was submitted.

While the TRU waste sites are reporting larger quantities of CH-TRU waste in storage, they are reporting smaller quantities of CH-TRU waste in the projected category. The shift from reporting waste as stored rather than projected reflects progress at the TRU waste sites towards cleanup and closure.

Overall, the anticipated CH-TRU waste inventory (stored plus projected) remaining for disposal at WIPP has decreased by an amount that is essentially equivalent to the inventory of CH-TRU waste emplaced in the repository. The total inventory (emplaced plus anticipated) of CH-TRU waste is less than the disposal limit of 168,485 m^3. Therefore, for PA calculations, the CH-TRU waste projected inventory is scaled to produce a disposal inventory equal to the repository limit.

The stored RH-TRU waste inventory currently being reported by the TRU waste sites represents an increase in the stored RH-TRU waste inventory reported in the CCA inventory estimate. Hanford-RP and Hanford-RL both reported more stored RH-TRU waste based on new information about it and increased accessibility to the waste. ANL-E, BAPL, and SNL added small amounts of stored RH-TRU waste to their inventories. ORNL moved all of their RH-TRU waste into the projected waste category because they plan to process the waste using segregation, size reduction, and evaporative drying. As its entire RH-TRU waste inventory will be processed, the ORNL RH-TRU waste is reported only as a projected inventory.

While the stored RH-TRU estimates have increased in the CRA-2004, the projected RH-TRU inventory estimates for CRA-2004 are less than what they were in the CCA inventory estimate. The greatest decrease in projected RH-TRU waste inventory was reported by Hanford-RL. The TRU waste sites report a decrease in the anticipated (stored plus projected) RH-TRU waste inventory for disposal at WIPP, a drop from over 2.6×10^4 m^3 (9.2×10^5 ft^3) reported in the CCA to about 1.0×10^4 m^3 (3.5×10^5 ft^3) as of September 30, 2002.

Nevertheless, the anticipated volume of RH-TRU reported for the CRA-2004 is greater than the repository limit for RH-TRU. Therefore, for PA calculations, the RH-TRU projected inventory is scaled down so the total disposal volume of RH TRU equals the repository limit of 7,079 m^3 (2.5×10^5 ft^3).

In support of the CCA PA, it was necessary for DOE to roll-up waste information on a repository scale. To this end, the TWBIR describes a process for grouping individual waste streams with similar physical and chemical properties into waste profiles, based on the waste matrix code (WMC) assigned by DOE TRU waste sites. The same process was followed for CRA-2004 (see Appendix DATA, Attachment F and Appendix TRU WASTE, Section TRU WASTE-2.0). Waste profiles with similar WMCs are combined across the DOE TRU waste system to provide estimated total volumes and total waste material parameters (WMPs). WMPs and waste components (as used in Section 194.24) are synonymous. Individual waste streams are evaluated to estimate the occurrence and quantities of WMPs (for example, cellulosic materials, iron-base metal and alloys, etc.) and are identified in Appendix TRU WASTE, Section TRU WASTE-2.0 as having either a significant or negligible effect on the performance of the WIPP repository.

4.1.3.1 Inventory Terminology

The following definitions are provided to help clarify the information contained in this chapter. Most of the definitions from the CCA have been included in this section without change. For CRA-2004, some definitions have been refined and others have been added.

Anticipated waste inventory – The sum of the stored and projected TRU waste inventories at DOE TRU waste sites that have not been emplaced at WIPP.

As-Generated Waste – The chemical and physical status of waste when it is generated. The as-generated term applies to both stored and projected waste.

Disposal Inventory – The volume used for CRA-2004 PA calculations. The LWA sets the total amount of TRU waste allowed in the WIPP at 175,564 m^3 (6,200,000 ft^3).

The “Agreement for Consultation and Cooperation” limits the RH-TRU inventory to 7,079 m^3 (250,000 ft^3) (DOE/NM 1981).

Emplaced waste inventory – Waste that has been placed in the repository as of September 30, 2002.

Final Waste Form – The expected physical form of a waste stream. The use of the final waste form helps to group waste streams that are expected to have similar physical and chemical properties at the time of disposal. Waste is assigned to one of 11 final waste forms: solidified inorganics, salt, solidified organics, soils, uncategorized metal, lead/cadmium metal, inorganic non-metal, combustible, graphite, heterogeneous, and filter.

September 30, 2002 (the inventory date) – The date used for determining the emplaced waste inventory included in CRA-2004 and the date TRU waste sites have used as the basis for their revised inventory estimates.

Projected Inventory – The part of the TRU inventory that has not been generated but is estimated to be generated at some time in the future by the TRU waste sites. The projected inventory is the same as the to-be-generated waste referred to in Section 194.24(a).

Stored Inventory – Also referred to as "retrievably stored" inventory. The part of the anticipated waste inventory stored in such a fashion that it can be readily retrieved. Retrievably stored waste includes waste stored at the TRU waste sites since the early 1970s in buildings or berms with earthen cover and does not include waste generated prior to 1970. Retrievably stored waste also includes waste in underground storage tanks, ponds, and as decontamination and decommissioning material identified for disposal that requires retrieval at the TRU waste sites.

Scaling – The process of adjusting, if needed, the projected inventory to the repository limit (disposal inventory) is called scaling. Scaling is needed in *PA* to model the WIPP repository at full capacity (6.2 million ft^3 as set by the LWA). The scaling factor used in the CRA-2004 for CH-TRU waste is 2.11. This is only applied to the projected component of a waste stream. The scaling factor for RH-TRU waste is 0.172, which is also only applied to the projected component of a waste stream.

Scaled Inventory – Synonymous with disposal inventory. The scaled inventory is the volume that fills WIPP capacity and is used for PA calculations. This volume is calculated as the sum of the disposal volumes for all WIPP-eligible waste streams after application of RH-TRU waste and CH-TRU waste scaling computations to each WIPP-eligible projected TRU waste stream.

WIPP Waste Inventory – The sum of the emplaced waste inventory and the anticipated waste inventory.

Waste Characteristic – Section 194.2 defines waste characteristic as a property of the waste that has an impact on the containment of waste in the disposal system.

Waste Component - Section 194.2 defines waste component as an aspect of the total inventory of the waste that influences a waste characteristic.

Waste Matrix Codes (WMCs) – Codes developed by DOE, in response to the Federal Facility Compliance Act (Public Law 102-386), to aid in categorizing mixed waste streams in the DOE system into a series of five-digit alphanumeric codes (for example, S5400; Heterogeneous Debris) that represent different physical and chemical matrices. Using guidance prepared by DOE (DOE 1995e), the WMC is assigned by the TRU waste sites for all mixed waste streams and unmixed waste streams. CRA-2004 has adopted this system to remain consistent with

common terminology used by the DOE TRU waste sites. WMCs are verified with radiographic examination (using either real-time radiography [RTR] or an equivalent methodology) and/or visual examination.

Waste Stream Profile – This is a description of a CH-TRU or RH-TRU waste stream. Waste stream profiles include

- waste stream description;
- waste stream source description, waste stream identification codes, final waste form;
- as-generated waste form volumes and final waste form volumes,
- estimated average values for WMP densities;;
- identification of whether the waste is CH-TRU or RH-TRU;
- final waste form radionuclide inventory (activity in Ci per cubic meter); and
- comments provided by the TRU waste sites to further explain the data provided.

WIPP Waste Profile – The WIPP waste profile represents a summary of TRU wastes at all TRU waste sites that have an identical final waste form. WIPP waste profiles include:

- the final waste form that the profile represents;
- a listing of the TRU waste sites (represented by the same final waste form) that are included in the WIPP waste profile; final waste form volumes of stored and projected waste for each TRU waste site; and
- a summary of the WMP average densities.

Waste Material Parameters (WMP) – This is one or more of the TRU waste stream constituents. The 12 WMPs have been grouped by their chemical and physical properties as shown in the following list.

<u>Inorganics</u>

- Iron-based metals and alloys — includes iron and steel alloys in the waste and does not include the waste container materials.
- Aluminum-based metals and alloys.
- Other metal and alloys — includes all other metals found in the waste materials (for example, copper, lead, zirconium, tantalum, etc.). The lead portion of lead rubber gloves and aprons is also included in this category.
- Other inorganic materials — includes inorganic nonmetal waste materials such as concrete, glass, firebrick, ceramics, sand, and inorganic sorbents.

- Vitrified materials — includes waste that has been melted or fused at high temperatures with glass-forming additives such as soil or silica to form a homogeneous glass-like matrix.

Organics

- Cellulosic Materials — includes those materials generally derived from high-polymer plant carbohydrates. Examples are paper, cardboard, kimwipes, wood, cellophane, cloth, etc.

- Rubber — includes natural or synthetic elastic latex materials. Examples are Hypalon®, neoprene, surgical gloves, leaded-rubber gloves (rubber part only), etc.

- Plastics — includes generally synthetic materials, often derived from petroleum feedstock. Examples are polyethylene, polyvinylchloride, Lucite®, Teflon®, etc.

Solidified Materials

- Inorganic matrix — includes any homogenous materials consisting of sludge or aqueous-based liquids that are solidified with cement, Envirostone™, or other solidification agents. Examples are wastewater treatment sludge, cemented aqueous liquids, inorganic particulates, etc.

- Organic matrix — includes cemented organic resins, solidified organic liquids, and sludges.

- Cement — includes the cement used in solidifying liquids, particulates, and sludges.

Soils

- Soils — generally consists of naturally occurring soils that have been contaminated with inorganic radioactive waste materials.

Although not considered to be a waste component, the associated packaging materials are also listed because they also provide input to the PA calculations.

Packaging Materials

- Steel — weight of the steel component of the standard container. Any necessary overpacking is included in the weight of steel.

- Plastics — weight of any standard plastic secondary confinement within the container.

- Lead — weight of the lead shielding.

The estimated WMP information is expressed in units of kilograms per cubic meter corresponding to the volume the waste package will occupy in the repository. This unit

facilitates scaling the material parameters to address various volumes for PA calculations and sensitivity analysis.

4.1.3.2 Nonradionuclide Inventory Roll-Up

The DOE uses the eleven final waste forms as an intermediate step in determining the inventory of nonradionuclide waste components. These final waste forms are a convenient way for the DOE to categorize waste for the purpose of waste management and waste characterization prior to shipment to the WIPP. Waste streams at each TRU waste site with similar WMCs are grouped together into one of the 11 final waste forms. The grouping of individual waste stream profiles into a WIPP waste profile is based on the similar physical and chemical properties of the waste streams. Current estimates of the final waste form volumes for CH-TRU and RH-TRU waste are provided in Table 4-4. For comparison, estimates of the final waste-form volumes for CH-TRU and RH-TRU waste from the CCA are also provided in Table 4-4. The relative contribution of heterogeneous debris, solidified organics, and filters to the current reported CH-TRU waste volume has increased when compared to the CCA inventory estimate. The most notable increase is in the heterogeneous debris category. SRS, LANL, RFETS, and INEEL all reported larger expected volumes of heterogeneous debris in the CRA-2004 data call than they reported for the CCA inventory estimate. Larger volumes of heterogeneous debris are expected to come from the FB (F-Canyon at SRS) and HB (H-Canyon at SRS) process lines, facility and equipment operations at LANL, decontamination and decommissioning at RFETS, and the start-up of the Advanced Mixed Waste Treatment Facility (AMWTF) at INEEL.

The relative contribution of uncategorized metal, graphite, soil and combustibles to the current reported CH-TRU waste volume has decreased when compared to the CCA inventory estimate. The most notable decrease is in the uncategorized metal category. Hanford-RL, LANL, and INEEL all reported smaller expected volumes of uncategorized metal in the CRA-2004 data call than in the CCA inventory estimate due primarily to reassignment of the waste to other forms based on new characterization information.

The relative contribution of inorganic non-metal, filters, soils, solidified organics, and solidified inorganics to the current reported RH-TRU waste volume has increased when compared to the CCA estimate. The most notable increase is in the solidified inorganic category. Hanford-RP and Hanford-RL reported larger expected volumes of solidified inorganics in the CRA-2004 data call than in the CCA inventory estimate. Larger volumes of solidified inorganics are expected from Hanford-RP due to the waste in underground storage tanks.

The relative contribution of uncategorized metal to the currently reported RH-TRU volume has decreased when compared to the CCA estimate. Hanford-RL reassigned a significant volume of waste that was reported as uncategorized metal in the CCA to other forms based on new characterization information.

To establish the nonradioactive waste component inventory, DOE accumulated WMP information (as WMP average densities in units of kg/m^3) in the CRA-2004 data call by final waste form. This accumulation is shown as a series of tables (Tables DATA-F-10 through DATA-F-30 in Appendix DATA, Attachment F).

These average densities are further summed to determine the total WIPP waste component disposal inventory for CH-TRU and RH-TRU waste and are given in Tables DATA-F-31 and DATA-F-32 of Appendix DATA, Attachment F, and are reproduced here with a comparison to the CCA inventory values in Tables 4-5 (CH-TRU waste) and 4-6 (RH-TRU waste), respectively. It should be noted that MgO is not listed in these tables. Since MgO is not a component of the waste, it is not regarded as a WMP. A discussion of the MgO is contained in Chapter 3.0; CCA Appendix BACK and CCA Appendix SOTERM; Appendix BARRIERS; and Appendix PA, Attachment SOTERM.

Table 4-4. Nonradionuclide TRU Waste Inventory for the WIPP

Final Waste Forms	Current Inventory Volumes (m^3)				Volumes Reported in the CCA (m^3) [1]			
	Emplaced	Stored	Projected	WIPP Disposal	Emplaced	Stored	Projected	WIPP Disposal
	CH-TRU Waste				CH-TRU Waste			
Combustible	6.1×10^2	4.3×10^3	1.9×10^3	8.9×10^3	--	5.8×10^3	4.6×10^3	1.4×10^4
Filter	3.4×10^2	9.9×10^2	5.9×10^2	2.6×10^3	--	2.2×10^2	5.1×10^2	1.2×10^3
Graphite	0.0×10^0	1.2×10^2	1.3×10^0	1.2×10^2	--	5.1×10^2	4.8×10^1	6.0×10^2
Heterogeneous	5.7×10^2	4.9×10^4	9.7×10^3	7.0×10^4	--	2.7×10^4	1.3×10^4	5.1×10^4
Inorganic Nonmetal	9.7×10^2	1.1×10^4	6.8×10^1	1.2×10^4	--	3.1×10^3	9.4×10^2	4.9×10^3
Lead and Cadmium Metal Waste	8.1×10^1	1.4×10^2	3.2×10^1	2.9×10^2	--	3.5×10^1	3.3×10^2	6.6×10^2
Salt Waste	1.5×10^3	1.5×10^2	1.9×10^2	2.1×10^3	--	2.1×10^1	3.3×10^2	6.4×10^2
Soils	0.0×10^0	3.0×10^2	6.0×10^3	1.3×10^4	--	4.1×10^2	6.0×10^3	1.2×10^4
Solidified Inorganics	3.3×10^3	3.5×10^4	7.3×10^2	4.0×10^4	--	9.6×10^3	4.5×10^3	1.8×10^4
Solidified Organics	0.0×10^0	5.2×10^3	3.8×10^2	6.0×10^3	--	9.1×10^2	7.5×10^1	1.1×10^3
Uncategorized Metal	3.6×10^2	2.4×10^3	5.1×10^3	1.4×10^4	--	1.1×10^4	2.3×10^4	5.4×10^4
Total CH-TRU Waste Volumes	7.7×10^3	1.1×10^5	2.5×10^4	1.7×10^5	--	5.8×10^4	5.4×10^4	1.6×10^5

Source: Current inventory volumes - Appendix DATA, Attachment F; Volume reported in the CCA – TWBIR Revision 3

[1] Comparisons between the current inventory values and the values reported in the CCA are made in detail in Appendix DATA, Attachment F, Annex B

[2] The WIPP is limited to 7,079 m^3 of RH-TRU waste by agreement with the State of New Mexico.

Table 4-4. Nonradionuclide TRU Waste Inventory for the WIPP — Continued

Final Waste Forms	Current Inventory Volumes (m^3)				Volumes Reported in the CCA (m^3) [1]			
	Emplaced	Stored	Projected	WIPP Disposal	Emplaced	Stored	Projected	WIPP Disposal
	RH-TRU Waste				RH-TRU Waste			
Combustible	--	1.8×10^1	8.9×10^{-1}	1.8×10^1	--	3.6×10^1	4.9×10^1	--
Filter	--	8.9×10^0	8.9×10^0	1.0×10^1	--	--	--	--
Heterogeneous	--	6.1×10^2	3.8×10^3	1.3×10^3	--	2.3×10^3	5.5×10^3	--
Inorganic Non-Metal	--	4.3×10^1	4.4×10^1	5.1×10^1	--	4.6×10^1	2.1×10^1	--
Lead and Cadmium Metal Waste	--	1.2×10^1	7.1×10^0	1.3×10^1	--	7.1×10^0	6.7×10^1	--
Soils	--	0.0×10^0	2.0×10^2	3.4×10^{-1}	--	--	--	--
Solidified Inorganics	--	4.5×10^3	3.3×10^2	4.6×10^3	--	1.1×10^3	2.3×10^2	--
Solidified Organics	--	9.5×10^0	0.0×10^0	9.5×10^0	--	3.6×10^0	0.0×10^0	--
Uncategorized Metal	--	8.4×10^1	6.1×10^3	1.1×10^3	--	1.2×10^2	1.7×10^4	--
Total RH-TRU Waste Volumes[2]	--	5.3×10^3	1.0×10^4	7.1×10^3	--	3.6×10^3	2.3×10^4	– –
Total TRU Waste Volumes	7.7×10^3	1.1×10^5	3.5×10^4	1.8×10^5	-	6.2×10^4	7.7×10^4	1.7×10^5

Source: Current inventory volumes - Appendix DATA, Attachment F; Volume reported in the CCA – TWBIR Revision 3

[1] Comparisons between the current inventory values and the values reported in the CCA are made in detail in Appendix DATA; Attachment F, Annex B

[2] The WIPP is limited to 7,079 m^3 of RH-TRU waste by agreement with the State of New Mexico.

DOE reports the average density for WMPs because these values are used to generate the waste-related inputs for PA. Section 3.4 of the TWBIR recommends use of the average value, based on the methodology used to obtain and report data. CRA-2004 also uses average values for the WMPs to generate waste-related inputs for PA.

Analysis of the current inventory estimate and the CCA inventory estimate for CH-TRU waste shows that waste materials expected for shipment to WIPP have changed slightly since the CCA. The relative occurrence (expressed as the kg/m^{3}of a given material in the waste) of iron (Fe), aluminum (Al), and other metal alloys is smaller in the current inventory estimate than it was in the CCA inventory estimate. In addition, the relative occurrence of solidified organics, cement, soils, and vitrified material is smaller in the current inventory estimate than it was in the CCA inventory estimate. In contrast, the relative occurrence of cellulosic, plastic, and rubber (CPR) materials and other inorganic materials is larger in the current inventory estimate than it was in the CCA inventory estimate. The current inventory estimate reflects a shift from an expected waste form consisting of 40 percent metals, 15 percent CPR materials and 45 percent other materials reported in the CCA to a waste form that consists of 34 percent metals, 25 percent CPR materials and 41 percent other materials. The current inventory estimate reflects a higher occurrence of CPR materials primarily because of a process change at INEEL. At the time of the CCA, INEEL expected to thermally treat a significant quantity of waste that contained higher than average quantities of CPR materials. Through the process of thermal treatment, the CPR materials in the waste would be destroyed. INEEL currently plans to supercompact the waste that they had originally planned to thermally treat. Supercompaction does not destroy CPR materials in the waste. As a consequence, the waste expected to come to WIPP from INEEL has increased CPR materials relative to those reported for the CCA.

Table 4-5. WIPP CH-TRU Waste and Container Material Disposal Inventory

Waste Materials	Average Density Based on Current Inventory (kg/m^3)	Average Density Reported in the CCA (kg/m^3)
Waste Materials		
Fe-Base Metal/Alloys	1.1×10^2	1.7×10^2
Al-Base Metal/Alloys	1.4×10^1	1.8×10^1
Other Metal/Alloys	3.0×10^1	6.7×10^1
Other Inorganic Materials	4.2×10^1	3.1×10^1
Vitrified Materials	6.2×10^0	5.5×10^1
Cellulosic Material	5.8×10^1	5.4×10^1
Rubber	1.4×10^1	1.0×10^1
Plastic	4.2×10^1	3.4×10^1
Solidified Inorganic Materials	7.7×10^1	5.4×10^1
Solidified Organic Materials	1.6×10^1	5.6×10^0
Cement (Solidified)	2.9×10^1	5.0×10^1
Soil	1.9×10^1	4.4×10^1
Container Materials		

Steel	1.7×10^{2}	1.4×10^{2}
Plastic and Liners	1.6×10^{1}	2.6×10^{1}
Lead	1.4×10^{-2}	0.0×10^{0}

Source: Appendix DATA, Attachment F.

Table 4-6. WIPP RH-TRU Waste and Container Material Disposal Inventory

Waste Materials	Average Density Based on Current Inventory (kg/m^3)	Average Density Reported in the CCA (kg/m^3)
Waste Materials		
Fe-Base Metal/Alloys	1.1×10^{2}	1.0×10^{1}
Al-Base Metal/Alloys	2.5×10^{0}	7.1×10^{0}
Other Metal/Alloys	3.2×10^{1}	2.5×10^{2}
Other Inorganic Materials	3.5×10^{1}	6.4×10^{1}
Vitrified Materials	5.7×10^{-2}	4.7×10^{0}
Cellulosic Material	4.5×10^{0}	1.7×10^{1}
Rubber	3.1×10^{0}	3.3×10^{0}
Plastic	4.9×10^{0}	1.5×10^{1}
Solidified Inorganic Materials	3.9×10^{1}	2.2×10^{1}
Solidified Organic Materials	4.0×10^{0}	9.3×10^{-1}
Cement (Solidified)	8.7×10^{-1}	1.0×10^{0}
Soil	2.6×10^{1}	
Container Materials		
Steel	4.8×10^{2}	4.5×10^{2}
Plastic and Liners	1.4×10^{0}	3.1×10^{0}
Lead	4.4×10^{2}	4.7×10^{2}

Source: Appendix DATA, Attachment F

The container materials for CH-TRU waste are primarily steel, plastic, and lead. The current inventory estimate reflects a higher occurrence of steel, a lower occurrence of plastic, and a higher occurrence of lead in the packages coming to WIPP when compared to the CCA inventory estimate. Additional steel in packages currently planned to come to WIPP results from the planned increased use of overpacks (Type A or equivalent packages, pipe overpacks, ten-drum overpacks, 100-gallon drum overpacks, etc.). The increased use of overpack containers in the current inventory estimate also leads to a reduction in the use of plastic liners in packages coming to WIPP. Thus, the density of plastic packaging material is smaller than it was in the CCA inventory estimate.

The inventory of chemical components of the waste (needed for scoping calculations to determine their importance on performance) was requested in the CRA-2004 data call. The information requested by DOE was specific to solidified waste forms destined for disposal at the WIPP and included complexing agents, nitrates, sulfates, phosphates, and cement. A summary of this information can be found in Appendix DATA, Attachment F. Additional information addressing the impact, limits, and characterization (or noncharacterization) of these chemical

components is provided in Appendix TRU WASTE, Sections TRU WASTE-2.0 and TRU WASTE-3.0. The importance of these chemical components to PA is assessed in Appendix TRU WASTE, Section TRU WASTE-2.0.

4.1.3.3 Radionuclide Inventory Roll-Up

Estimates of the radionuclide inventory are included in Appendix DATA, Attachment F. TRU waste sites derive these estimates based on acceptable knowledge including any quantitative results that may be available. In the data call for CRA-2004, TRU waste sites reported estimated values for radionuclide activities on a waste stream basis including both the stored and projected components. The actual activity of disposed waste is determined quantitatively prior to shipment, as discussed in Section 4.4.2.

The disposal radionuclide inventory for PA is a calculated value based on the radionuclide activities reported for emplaced, stored, and projected waste. The radionuclide activities in the projected component of the waste are scaled using the scaling factor and added to the radionuclide activities for stored and emplaced components of the waste.

This calculation is based on all radionuclide activities decayed to the end of 2001. Radioactive decay and build-up calculations were performed using the commercially available code ORIGEN2 (Croff 1980). The levels of radioactivity reported include contributions from both parent and daughter decay products. For CH-TRU waste, the total Ci for each radionuclide is divided by the CH-TRU disposal volume to obtain a Ci per cubic meter concentration for each radionuclide on a repository level. For RH-TRU waste, the total decayed WIPP Ci for each radionuclide is divided by the RH-TRU disposal volume to obtain a radionuclide concentration in Ci per cubic meter.

The WIPP disposal radionuclide inventory used in PA for both CH-TRU and RH-TRU wastes is shown in Table 4-7. Activities at closure (2033) are used in PA. The table shows individual radionuclide activity in Ci for both CH-TRU and RH-TRU waste. Based on the total Ci shown in Table 4-7 and to the extent to which each radionuclide is regulated by Section 191.13, approximately 98.6 percent of the regulated CH-TRU activity at repository closure is contributed by ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Am.

Table 4-7. Radionuclides Considered in PA

Radionuclide	Current Inventory Values			Values Reported in the CCA			Release Calculations (1)			
	Inventory at Closure (Ci)	EPA Units		Inventory at Closure (Ci)	EPA Units		Cuttings, Cavings, and Spall Release	Direct Brine Release	Salado Release	Culebra Release
		At Closure(4)	At 10,000 years		At Closure	At 10,000 years				
^{238}Pu	1.25×10^{6}	5.04×10^{3}	2.61×10^{-23}	1.94×10^{6}	5.64×10^{3}	1.32×10^{-22}	x	x	(2)	(2)
^{239}Pu	6.65×10^{5}	2.68×10^{3}	2.01×10^{3}	7.95×10^{5}	2.31×10^{3}	1.73×10^{3}	x	x	x	x
^{241}Am	4.58×10^{5}	1.84×10^{3}	2.48×10^{-4}	4.88×10^{5}	1.42×10^{3}	1.78×10^{-4}	x	x	x	x
^{240}Pu	1.08×10^{5}	4.36×10^{2}	1.51×10^{2}	2.14×10^{5}	6.22×10^{2}	2.16×10^{2}	x	x	c	c
^{137}Cs	1.79×10^{5}	7.19×10^{1}	0.00×10^{0}	9.31×10^{4}	2.71×10^{1}	0.00×10^{0}	x	--	--	--
^{90}Sr	1.42×10^{5}	5.71×10^{1}	0.00×10^{0}	8.73×10^{4}	2.54×10^{1}	0.00×10^{0}	x	--	--	--
^{233}U	1.27×10^{3}	5.12×10^{0}	4.91×10^{0}	1.95×10^{3}	5.67×10^{0}	5.44×10^{0}	x	x	c	c
^{229}Th	5.39×10^{0}	2.17×10^{-2}	3.04×10^{0}	9.97×10^{0}	2.90×10^{-2}	3.40×10^{0}	--	x	c	c
^{234}U	3.19×10^{2}	1.28×10^{0}	3.03×10^{0}	7.51×10^{2}	2.18×10^{0}	4.10×10^{0}	x	x	x	x
^{230}Th	1.76×10^{-1}	7.07×10^{-3}	2.64×10^{0}	3.06×10^{-1}	8.90×10^{-3}	3.55×10^{0}	--	x	x	x
^{238}U	1.54×10^{2}	6.21×10^{-1}	6.21×10^{-1}	5.01×10^{1}	1.46×10^{-1}	1.46×10^{-1}	--	x	--	--
^{237}Np	1.01×10^{1}	4.06×10^{-2}	4.27×10^{-1}	6.49×10^{1}	1.89×10^{-1}	4.83×10^{-1}	--	x	--	--
^{232}Th	6.83×10^{0}	2.75×10^{-1}	2.75×10^{-1}	1.01×10^{0}	2.94×10^{-2}	2.94×10^{-2}	--	x	--	--
^{226}Ra	6.28×10^{0}	2.53×10^{-2}	2.07×10^{-1}	1.14×10^{1}	3.31×10^{-2}	2.77×10^{-1}	--	--	--	--
^{210}Pb	4.94×10^{0}	1.99×10^{-2}	2.07×10^{-1}	8.75×10^{0}	2.54×10^{-2}	2.77×10^{-1}	--	x	--	--
^{242}Pu	2.71×10^{1}	1.09×10^{-1}	1.07×10^{-1}	1.17×10^{3}	3.40×10^{0}	3.34×10^{0}	--	x	c	c
^{243}Am	2.17×10^{1}	8.75×10^{-2}	5.74×10^{-2}	3.25×10^{1}	9.45×10^{-2}	3.69×10^{-2}	--	x	--	--
^{236}U	1.65×10^{0}	6.66×10^{-3}	8.62×10^{-2}	6.72×10^{-1}	1.95×10^{-3}	1.16×10^{-1}	--	x	--	--
^{235}U	2.28×10^{0}	9.18×10^{-3}	3.21×10^{-2}	1.75×10^{1}	5.09×10^{-2}	7.06×10^{-2}	--	x	--	--
^{14}C	3.25×10^{0}	1.31×10^{-2}	3.90×10^{-3}	1.28×10^{1}	3.72×10^{-2}	1.11×10^{-2}	--	--		
^{232}U	3.06×10^{0}	1.23×10^{-2}	0.00×10^{0}	1.79×10^{1}	5.20×10^{-2}	0.00×10^{0}	--	--	--	--
^{227}Ac	9.57×10^{-1}	3.85×10^{-3}	8.06×10^{-3}	5.05×10^{-1}	1.47×10^{-3}	1.28×10^{-2}	--	--	--	--
^{231}Pa	1.21×10^{0}	4.88×10^{-3}	8.06×10^{-3}	4.67×10^{-1}	1.36×10^{-3}	1.28×10^{-2}	--	--	--	--
^{243}Cm	4.07×10^{-1}	1.64×10^{-3}	0.00×10^{0}	2.07×10^{1}	6.02×10^{-2}	0.00×10^{0}	--	x	--	--
^{248}Cm	9.32×10^{-2}	3.75×10^{-4}	3.68×10^{-4}	3.72×10^{-2}	1.08×10^{-4}	1.06×10^{-4}	--	x	--	--
^{245}Cm	1.92×10^{-2}	7.72×10^{-5}	3.97×10^{-5}	1.15×10^{-2}	3.40×10^{-5}	$1.85 \times 10\text{-}^{5}$	--	x	--	--

Table 4-7. Radionuclides Considered in PA — Continued

Radionuclide	Current Inventory Values			Values Reported in the CCA			Release Calculations (1)			
	Inventory at Closure (Ci)	EPA Units		Inventory at Closure (Ci)	EPA Units		Cuttings, Cavings, and Spall Release	Direct Brine Release	Salado Release	Culebra Release
		At Closure(4)	At 10,000 years		At Closure	At 10,000 years				
^{244}Pu	1.10×10^{-3}	4.44×10^{-6}	4.47×10^{-6}	1.51×10^{-6}	4.34×10^{-9}	1.26×10^{-8}	--	x	--	--
^{244}Cm	2.51×10^{3}	(3)	(3)	7.44×10^{3}	(3)	(3)	x	x	--	--
^{241}Pu	5.38×10^{5}	(3)	(3)	3.94×10^{5}	(3)	(3)	x	x	--	--
Percent of EPA Units at closure represented by nuclides in source term							99.98%	98.71%	48.95%	48.95%
Percent of EPA Units at 10,000 years represented by nuclides in source term							99.65%	99.99%	99.92%	99.92%

Source: Appendix TRU Waste, Section TRU Waste-2.0

1. See Section 6.3 for a discussion of scenarios analyzed by PA and the release pathways.
2. Pu-238 was included in the Salado transport calculations but the release to the Culebra was too low to merit calculation of its transport within the Culebra. The EPA unit percent total at closure increases to 98.71% with Pu-238 added; the percent at 10,000 years is unaffected.

3. Pu-241 and Cm-244 are not listed by Part 191 of the Code of Federal Regulations but are included because their daughters, ^{241}Am and ^{240}Pu, respectively, are significant to performance
4. At closure is decayed through 2033.

x indicates an isotope included in calculation.
c indicates isotopes that are combined for transport with isotopes having similar characteristics.

Approximately 99.5 percent of the regulated RH-TRU activity at repository closure is contributed by ^{137}Cs, ^{90}Sr, ^{239}Pu, ^{240}Pu, ^{241}Am, and ^{238}Pu (derived from data in TRU WASTE, Section TRU WASTE-2.0, Table TRU WASTE-9). The same radionuclides were identified in the CCA as the largest contributors to the regulated CH-TRU waste and RH-TRU waste activity at repository closure (see CCA Appendix WCA, Section 8.2). Overall, activity for all TRU radionuclides has decreased from 3.44×10^6 Ci (at 2033) reported in the CCA to 2.48×10^6 Ci (at 2033) in the current inventory estimate. The results for RH-TRU waste show variations in individual radionuclide activity and an overall increase in reported activity since the CCA.

The values presented in Table 4-7 are used as input to the PA calculations. A more detailed examination of the programs prepared by DOE to collect supplemental radiological data are provided in Section 4.4.

In addition to the inventory in Table 4-7, DOE has determined the average radionuclide inventory for each of the 779 (693 CH-TRU waste streams and 86 RH-TRU waste streams) CH-TRU and RH-TRU waste streams (see Appendix DATA, Attachment F). In the conceptual model for PA, the distribution of 693 CH-TRU waste streams and one RH-TRU waste stream (representing all of 86 the RH-TRU waste) are randomly sampled in the PA to determine releases due to inadvertent human intrusion. This process is discussed in Section 6.4.12.4 and assumes that each container in the waste stream has the average radionuclide inventory for that stream.

4.2 Waste Components and Characteristics

This section of the application is provided to document compliance with the provisions of Section 194.24(b) and describes, in summary fashion,

- those components or characteristics of the waste that are most important in terms of their impact on the performance of the WIPP disposal system and
- the limits imposed by DOE on the significant components or characteristics of the waste to ensure that emplaced waste will behave in a manner that is consistent with the inventory assumed for the performance calculations.

4.2.1 Identification and Qualification

The waste characteristics and components expected to be most significant to performance are the predominant radionuclides and their associated characteristics and components affecting actinide mobility. These are summarized in Table 4-8; they are unchanged from the CCA.

Table 4-8. Waste Characteristics and Components Expected to be Most Significant to Performance

Component	Characteristic	Reason for Significance
^{239}Pu, ^{240}Pu, ^{241}Am, ^{233}U, and ^{234}U	Activity	99 percent of EPA unit after 2,000 years
^{238}Pu	Activity	Dominates EPA unit at early times
Pu and Am	Solubility	Large EPA unit; mobility depends on solubility
^{238}U	Activity	Very low activity; dilutes higher-activity uranium isotopes for brine-based releases
Iron	Redox Potential	Sustains reducing environment so that lower, less soluble oxidation states of actinides predominate
Cellulosic material, plastic, rubber, nitrate, sulfate	Nutrient for Microbes	Microbial nutrients that are metabolized to methane and several other gases, increasing gas pressure; formation of colloids
Humic materials, cellulose breakdown products	Colloid Formation	Formation of humic colloids that sorb and transport actinides
Nonferrous metals	Organic Complexation	Prevent increase in actinide solubility by binding with ligands
Waste	Shear Strength	Important to spalling and cavings

Source: Appendix TRU Waste, Section 2

The waste unit factor is the number of millions of Ci of alpha-emitting TRU radionuclides with half-lives longer than 20 years (Part 191 of the Code of Federal Regulations, Appendix A). In the WIPP, 2.48[2] million Ci of TRU waste will be in the repository at closure, so the waste unit factor is 2.48. The radionuclides that contribute to the waste unit factor are based on an analysis (see Appendix TRU WASTE, Section TRU WASTE-2.0) of the radionuclide inventory in Appendix DATA, Attachment F and are presented in Table 4-9 (decayed to the end of 2033). The radionuclide contributions to the waste unit factor from the CCA are also presented in Table 4-9. Waste characteristics and components with an insignificant impact on performance are summarized in Table 4-10. This table remains unchanged from CCA Table 4-9.

4.2.2 Repository Limits

The following discussion describes the criteria in Sections 194.24(c)(1) and 194.24(c)(2).

[2] The value for the waste unit factor (WUF) in the CCA was inconsistently described; Chapter 4, Section 4.2.1 correctly listed the WUF that was used in the CCA PA as 3.44. CCA Appendix WCA Sections 1.4.2 and WCA Attachment WCA.8.1 incorrectly stated the 1995 decayed value of 4.07 was used in the CCA PA, however the preface to Attachment WCA.8.2 identified and corrected the error. During the EPA's review of the CCA, EPA required DOE to recalculate a new WUF of 3.59 that was ultimately included in the EPA's PAVT (EPA 1998). After the certification, the DOE incorporated the PAVT WUF value of 3.59 in the compliance baseline through an EPA approved change request (EPA 2002).

Waste components are the controlling factors for the waste characteristics. Therefore, limits imposed on the waste components necessarily serve to limit the waste characteristics. In the case where a characteristic is benign with respect to repository performance, no control of the corresponding component is necessary and no limits need be imposed on that component. Conversely, should repository performance be sensitive to a particular waste characteristic, then control of the corresponding component is mandated and limits are established to restrict the maximum or minimum amounts of that component allowed for disposal.

Based on the PA calculations and the rationale described in Appendix TRU WASTE, Table 4-11 identifies the characteristics of the components for which determination prior to emplacement is required. Table 4-11 also lists any applicable repository-based emplacement limits for the components. Discussions of the rationale for the proposed assaying and emplacement limits for each component are presented in Appendix TRU WASTE. All of the components identified in

Table 4-9. Radionuclides That Contribute to the Waste Unit Factor

Nuclide	Half-Life (years)	Current Inventory Values		Values Reported in the CCA(1)	
		Inventory at Closure (Ci)	Percent of Waste Unit at Closure	Inventory at Closure (Ci)	Percent of Waste Unit at Closure
^{241}Am	4.33×10^{2}	4.58×10^{5}	1.82×10^{1}	4.88×10^{5}	1.42×10^{1}
^{243}Am	7.37×10^{3}	2.17×10^{1}	8.63×10^{-4}	3.25×10^{1}	9.45×10^{-4}
^{249}Cf	3.51×10^{2}	7.24×10^{-2}	2.88×10^{-6}	6.38×10^{-2}	1.85×10^{-6}
^{251}Cf	9.00×10^{2}	5.10×10^{-4}	2.03×10^{-8}	3.67×10^{-3}	1.07×10^{-7}
^{243}Cm	2.91×10^{1}	4.07×10^{-1}	1.62×10^{-5}	2.07×10^{1}	6.02×10^{-4}
^{245}Cm	8.50×10^{3}	1.92×10^{-2}	7.62×10^{-7}	1.15×10^{-2}	3.34×10^{-7}
^{246}Cm	4.76×10^{3}	2.22×10^{0}	8.80×10^{-5}	1.02×10^{-1}	2.97×10^{-6}
^{247}Cm	1.56×10^{7}	9.45×10^{0}	3.75×10^{-4}	9.51×10^{-9}	2.76×10^{-13}
^{248}Cm	3.48×10^{5}	9.32×10^{-2}	3.70×10^{-6}	3.72×10^{-2}	1.08×10^{-6}
^{237}Np	2.14×10^{6}	1.01×10^{1}	4.00×10^{-4}	6.49×10^{1}	1.89×10^{-3}
^{238}Pu	8.77×10^{1}	1.25×10^{6}	4.98×10^{1}	1.94×10^{6}	5.64×10^{1}
^{239}Pu	2.41×10^{4}	6.65×10^{5}	2.64×10^{1}	7.95×10^{5}	2.31×10^{1}
^{240}Pu	6.56×10^{3}	1.08×10^{5}	4.30×10^{0}	2.14×10^{5}	6.22×10^{0}
^{242}Pu	3.75×10^{5}	2.71×10^{1}	1.08×10^{-3}	1.17×10^{3}	3.40×10^{-2}
^{244}Pu	8.00×10^{7}	1.10×10^{-3}	4.38×10^{-8}	1.51×10^{-6}	4.39×10^{-11}
Total	---	2.48×10^{6}	9.86×10^{1}	3.44×10^{6}	9.99×10^{1}

Source: Appendix TRU WASTE, Section TRU WASTE-2.0.
(1) Radionuclide activities and the WUF were reported with conflicting values in several places in the CCA. The values used in this table were the actual values used in the performance assessment for the CCA as recorded in the PAPDB.

Table 4-10. Waste Characteristics and Components Expected to be Insignificant

Characteristics and Component	Reason for insignificant impact
Radionuclides other than those in Table 4-8	EPA unit is negligible fraction of total, even with ingrowth
Substances that may affect pH[1]	pH is buffered by MgO backfill
Substances that produce CO_2 [1]	CO_2 is removed by reaction with MgO backfill
Intrinsic and mineral fragment colloids	Fraction of actinides mobilized by these colloids is insignificant
Organic ligands	Removed by binding with Mg and nonferrous metal
Heat generated by exothermic reactions	Heats of formation are small and thermal mass of repository is large so that temperature rise is negligible
Fluid in the waste	Negligible compared to brine volume

Source: Appendix TRU WASTE [1] These components are significant for gas generation, but not for actinide solubility.

Table 4-11. Repository-Based Emplacement Limits Related to PA

Waste Components	Associated Waste Characteristics	Components Requiring Quantification	Emplacement Limits
radionuclides	radioactivity at closure radioactivity after closure solubility colloid formation reduction-oxidation state	^{241}Am ^{238}Pu ^{239}Pu ^{240}Pu ^{242}Pu ^{233}U ^{234}U ^{238}U ^{90}Sr ^{137}Cs	none[1]
ferrous metals (iron)	reduction-oxidation potential H_2 gas generation complexing with organic ligands	none	minimum = 2×10^7 kilograms (amount from containers)[2]
cellulosic, plastic, rubber materials	gas generation humic colloids (see below) gas generation	sum of emplaced components	maximum = 2.2×10^7 kilograms[3]
sulfates	gas generation	none	none[4]
nitrates	gas generation	none	none[4]
solid components	particle size effective shear resistance to erosion tensile strength	none	none
free liquid emplaced with waste	gas generation	none	maximum = 1684 cubic meters for CH-TRU (limit of 1 percent total waste volume as set by the WAC) [e]
humic substances	radionuclide-bearing humic colloids	none	none
nonferrous metals (metals other than iron)	bind with organic ligands and prevent increased solubility	none	minimum = 2×10^3 kilograms[5]
organic ligands	solubility	none	none[4]

Source: Appendix TRU WASTE, Section TRU WASTE-3.0

1 Inventory curie content will be tracked.

2 Minimum set to ensure sufficient reactants for reducing radionuclides to lower and less soluble oxidation states. .

3 Maximum set to ensure sufficient MgO backfill is available to react with CO_2 produced.

4 For the current waste generation processes that are documented in the Transuranic Waste Inventory Update Report--Supporting Information for the 2004 WIPP Compliance Recertification Application.

5 Minimum quantity for complexing with organic ligands (see Appendix PA, Attachment SOTERM).

CCA Appendix WCA and Appendix TRU WASTE, Section TRU WASTE.2-0 were found to be insignificant to disposal system performance. Therefore, it is not necessary to establish additional container-based emplacement limits for these components.

Table 4-12 is a supplement to Table 4-11; that is, it lists the repository limits imposed by the LWA . Collectively, Tables 4-11 and 4-12 define the WIPP repository-based emplacement limits on the waste.

Since the first waste shipment arrival at the WIPP, DOE has tracked the quantities of materials identified in Tables 4-11 and 4-12 that have been emplaced in the repository. The quantities of these materials emplaced in WIPP since its opening through September 30, 2002, are listed in Tables 4-13 and 4-14.

4.2.3 Waste Container Limits

Waste limits have been established by DOE as part of the WIPP's design development and by the WIPP LWA. Waste container limits relevant to the requirements of the WIPP LWA are identified in Table 4-15. The CH-TRU Waste Acceptance Criteria (WAC) restrict the physical, chemical, and radiological properties of the waste to mitigate conditions that will have adverse impacts on human health and the environment.

DOE requires the TRU waste sites to prepare a waste-certification plan that lists the methods and techniques used to determine compliance with the CH-TRU WAC and the QA program (see Appendix QAPD-2004). This includes QA and quality control criteria that are applied to the generator's waste certification program. Each participating TRU waste site is responsible for developing and implementing specific TRU waste program documents (plans) that address all activities pertaining to TRU waste characterization, certification, packaging, and transportation of TRU waste to the WIPP. These plans include the TRU Waste Certification Plan and associated QA plan, the TRUPACT-II Authorized Methods for Payload Control and associated QA plans, and the TRU waste characterization QAPjP. Methods of compliance with each criterion and requirement are documented or specifically referenced and include procedural and administrative controls.

Table 4-12. Repository-Based Emplacement Limits Imposed by the LWA

Waste Components	Emplacement Limits
Total Capacity (CH- and RH-TRU)	6.2 million ft^3 (175,564 m^3)
RH-TRU waste total Ci	5.1 million Ci (~18.9×10^{16} Becquerels)
RH-TRU waste total dose rate	No more than five percent by volume of RH TRU waste may exceed 100 rems per hour

Table 4-13. Quantities of Radionuclides Emplaced in the Repository as of September 30, 2002[1,2]

NR=Not reported or reported at values less than 10^{-13}

Radionuclide	Quantity (Ci)	Radionuclide	Quantity (Ci)
^{227}Ac	3.64×10^{-4}	^{147}Pm	NR
^{241}Am	1.17×10^{5}	^{238}Pu	5.64×10^{3}
^{243}Am	4.81×10^{-3}	^{239}Pu	1.38×10^{5}
^{14}C	NR	^{240}Pu	3.10×10^{4}
^{249}Cf	NR	^{241}Pu	4.37×10^{5}
^{251}Cf	NR	^{242}Pu	2.96×10^{0}
^{252}Cf	NR	^{244}Pu	NR
^{243}Cm	NR	^{226}Ra	7.88×10^{-6}
^{244}Cm	NR	^{228}Ra	NR
^{245}Cm	NR	^{79}Se	NR
^{246}Cm	NR	^{151}Sm	NR
^{247}Cm	NR	$^{121}Sn^{m}$	NR
^{248}Cm	NR	^{126}Sn	NR
^{60}Co	3.47×10^{-7}	^{90}Sr	NR
^{135}Cs	NR	^{99}Tc	NR
^{137}Cs	3.41×10^{-9}	^{229}Th	NR
^{129}I	NR	^{230}Th	2.41×10^{-5}
^{40}K	2.87×10^{-5}	^{232}Th	2.61×10^{-6}
^{22}Na	5.34×10^{-6}	^{232}U	NR
^{59}Ni	NR	^{233}U	2.73×10^{-1}
^{63}Ni	NR	^{234}U	1.26×10^{0}
^{237}Np	4.00×10^{-1}	^{235}U	1.22×10^{-1}
^{231}Pa	5.04×10^{-4}	^{236}U	NR
^{210}Pb	NR	^{238}U	6.53×10^{0}
^{107}Pd	NR	^{93}Zr	NR

Source: WWIS

[1] These data were taken from the WWIS and differ slightly from the data reported for WIPP in Appendix DATA Attachment F. This is because all data in Appendix DATA Attachment F have been decayed to a single base year 2001 (i.e., decayed through 2001) while the data provided in the WWIS are reported values based on assay and have not been decayed to a single base year.

[2] Isotopes other than the 10 listed in Table 4-11 are not required to be tracked unless required by DOT regulations.

Table 4-14. Quantities of Non-Radionuclide Waste Components Emplaced in the Repository as of September 30, 2002, and Associated Emplacement Limits

Waste Components	Quantity	Emplacement Limit
Ferrous metal (iron)	2,487,261 kilograms	Minimum = 2×10^7 kilograms
Cellulosic, plastic, and rubber materials	700,981 kilograms	Maximum = 2.2×10^7 kilograms
Nonferrous metals (metals other than iron)	31,059 kilograms	Minimum = 2×10^3 kilograms

Source: WWIS

Table 4-15. Container-Based Limits

Waste Component or Characteristic	Limit
CH-TRU and RH-TRU waste activity	> 100 nCi/gram of waste
CH-TRU waste surface dose rate	< 200 mrem/hour (CH)
RH-TRU waste surface dose rate	≤ 1000 rem/hour (RH)
RH-TRU waste Ci per liter	23 Ci/liter averaged over the container

Based on the acceptance of the site-specific waste characterization and QA program, the CBFO Manager is responsible for granting and revoking the program certification that allows the TRU waste site to characterize and to ship waste to WIPP. The CBFO performs certification audits of the TRU waste sites to assess the implementation of and compliance with the approved plans. On the basis of acceptable results of the certification audits, the DOE grants TRU waste certification authority and transportation authority to the TRU waste site. DOE provides continuing oversight of TRU waste sites through periodic audits of TRU waste characterization, certification, and transportation activities.

Consistent with the provisions of section 194.8, the EPA also has a role in the approval process. The EPA determines compliance with requirements for site-specific QA programs.

CH-TRU WAC provides the limits for the physical, radiological, and chemical characteristics of the waste in addition to specifications for the waste packaging. Waste that is characterized according to and approved program and meets the requirements of the CH-TRU WAC can be shipped to the WIPP. Additional information regarding the TRU waste site waste characterization and QA program requirements is provided in Appendix TRU WASTE.

Appropriate changes to the CH-TRU WAC will be published to reflect new restrictions and conditions imposed by permits and certifications. These changes will be communicated to the TRU waste sites as a change to the CH-TRU WAC. Those retrievably stored or newly generated waste streams that do not meet the CH-TRU WAC, however, may require processing (including repackaging and/or treatment) until compliance can be attained. Any such processing is the responsibility of the site proposing to ship the waste to the WIPP. TRU waste that has been characterized in accordance with prior revisions of the CH-TRU WAC may be reconciled with current requirements. This reconciliation is documented and filed at the TRU waste site.

Changes related to waste characterization documents have occurred since the initial certification. Waste characterization elements of the QAPP (TRU Waste Characterization Quality Assurance Program Plan, CAO [CBFO] 94-1010) have been incorporated into recent revisions of the CH-TRU WAC, the WAP, and the QAPD. The QAPP and the TRU Waste Characterization Sampling and Analysis Methods manual (DOE 1995b) have been cancelled.

4.3 Waste Controls

This section describes those processes that ensure compliance with the limits for CH-TRU waste and RH-TRU waste to be emplaced in the WIPP disposal system.

4.3.1 Load Management

The following discusses compliance with Section 194.24(d) and (f).

Load management is the process of controlling the shipment and emplacement of TRU waste in order to achieve a predetermined (that is, nonrandom) distribution of waste within the disposal system. DOE must assess whether the spatial distribution of waste in the repository could have significance for human intrusion on long-term repository performance. As described in Section 6.4.12, drilling events are assumed to be random in time and space. The location of each intrusion borehole within the waste disposal region is sampled randomly. Each intrusion borehole that penetrates waste may encounter CH-TRU waste or RH-TRU waste. For calculating direct releases to the accessible environment, containers are assumed to be placed in the WIPP from the various waste streams which comprise CH-TRU waste in a random manner. In calculating direct releases resulting from a drill bit penetrating containers, each of the three stacked containers can come from different waste streams and have different activity loading. As described in Section 6.5, direct release from cuttings and cavings are the most important releases in assessing compliance with the quantitative containment requirements in Section 191.13(a) for both the CCA and CRA-2004.

The CCDFs presented in Section 6.5 are constructed by estimating cumulative radionuclide releases to the accessible environment for 10,000 different possible futures. The estimated release for each future includes the randomly sampled waste streams for each of the various intruding boreholes that comprise that sampled future. A sampling of 10,000 futures is large enough that the relatively low probability combination of three of the waste streams with higher activity loading occurring in a single drilling event is captured in the CCDFs presented in Section 6.5. As described in Section 6.5, the CCDF is not impacted by sampling uncertainty so the assumption of random emplacement of containers is not important to the location of the CCDF and a load management plan is not necessary to support PA assumptions.

In support of CRA-2004, DOE investigated the impact of non-homogeneous patterns of waste emplacement in the repository. The investigation verified that non-homogeneous emplacement will not have a significant impact on PA. The results of the investigation are reported in Chapter 6.0.

4.3.2 WIPP Waste Information System

The following discusses compliance with the criteria at Sections 194.24(c)(4), (c)(5), and (e).

The WWIS is an electronic data management system used by DOE to gather, store, and process information pertaining to TRU waste destined for or disposed at the WIPP. The system supports those organizations that have responsibility for managing TRU waste by collecting information into one source and providing data in a uniform format that has been verified or certified as being accurate. The WWIS is used to store information pertaining to characterization, certification, and emplacement of waste at the WIPP. Information in this system is supplied by the TRU waste sites and the WIPP facility. Figure 4-2 depicts the process and flow of data from the TRU waste sites to the WWIS.

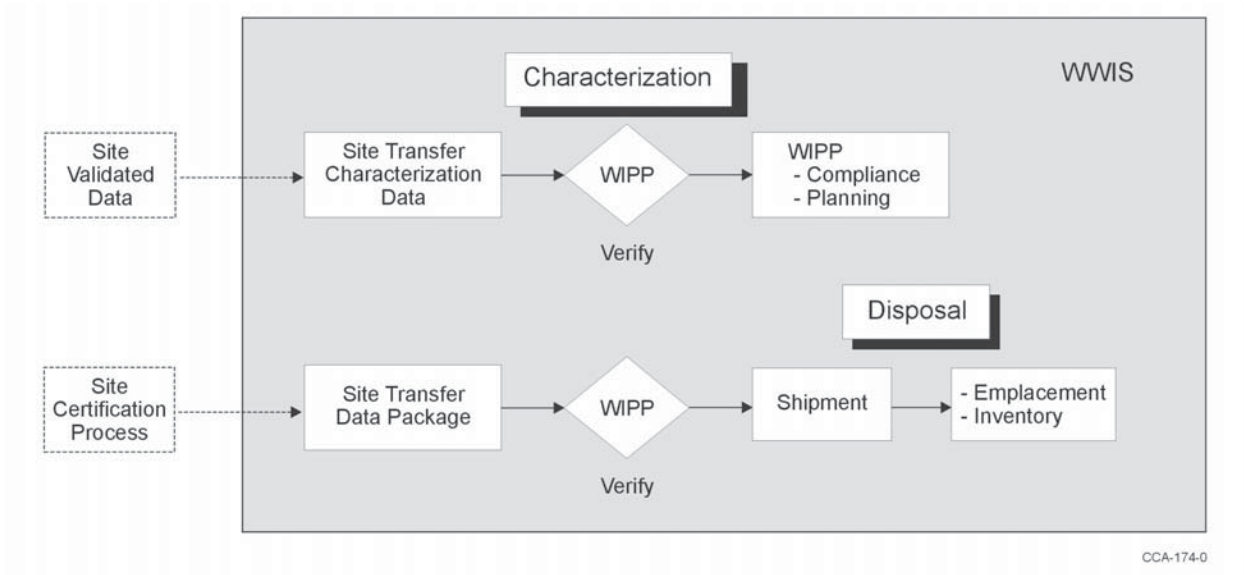

Figure 4-2. WIPP Waste Information System Process and Data Flow

At the time of the CCA, the WWIS used the Oracle (Version 7) database management system that followed American National Standards Institute (ANSI) standard query language. The database management system was resident on a Digital Equipment Corporation hardware platform, compliant with the majority of existing computer hardware throughout the DOE complex. UNIX was the operating system and supported multiuser and multitasking environments. The current computing system remains unchanged except that the software employed now is Oracle Version 9. Additional computing system upgrades may be implemented in the future.

Minor upgrades and improvements have been made to the WWIS since the EPA certification. Minor changes to several documents related to the design and operation of the system have also been made. All changes improved the system or updated information. The WWIS is available seven days a week, 24 hours a day except for periodic maintenance and supports the maximum number of simultaneous users determined by the database management system license agreement and the operating system license agreement. The network communication protocol of the WWIS is Transmission Control Protocol/Internet Protocol (TCP/IP). Other features include automatic

limit, range, and QA checks; automatic report generation; and compliance with QA requirements for computer software for nuclear facility applications (American Society of Mechanical Engineers [ASME], Nuclear Quality Assurance [NQA]-1, NQA-2, Part 2.7, and NQA-3 [ASME 1989a, 1989b, and 1989c]).

The following WWIS documentation has been identified as necessary and sufficient to document the software lifecycle:

- WWIS Evaluation & Recommendation – provides an evaluation of hardware and software configurations for the WWIS and recommends an approach for implementation.

- WWIS Software Quality Assurance Plan – identifies and defines the standards and methodologies required to ensure conformance to accepted quality standards during the development, maintenance, and operation of the WWIS. This plan ensures that products conform to established technical requirements.

- WWIS Software Verification and Validation Plan – describes the criteria for verification and validation activities for the requirements, design, testing, and all necessary documentation.

- WWIS Software Requirements Specification – defines the requirements essential to the WWIS based on the WWIS Functional and Operational Requirements Document. All requirements shall be internally consistent and verifiable through demonstration, analysis, or testing.

- WWIS Software Design Description – defines the major features of the WWIS including the operating environment, databases, tables, external and internal interfaces, overall structure, sizing, modeling, and system throughput.

- WWIS Software Configuration Management Plan – describes the methods used for identifying software configuration items, controlling and implementing changes, and recording and reporting change implementation status.

- WWIS Security Plan – details the information for handling the security needs of the system (data, software, and hardware). This plan also describes password and access control procedures.

- At the time of the CCA, the DOE identified more than 130 data fields for inclusion in the WWIS. An alphabetical listing and description of these data fields is found in the WAP (NMED 2002). The majority of these data fields are considered pertinent to demonstrate compliance with TRU waste transportation and disposal requirements. These listings are now updated and maintained in the WWIS User's Manual (DOE 2001).Radionuclides present in container

- Activity of individual radionuclides

- Uncertainty associated with the activity of individual radionuclides

- Mass of the individual radionuclides
- Uncertainty associated with the mass of individual radionuclides
- Estimated weight of waste material parameters
- Date of assay

To ensure compliance with the data requirements, personnel at the WIPP review the WWIS information on each data package for completeness and adequacy before notifying the shipping site of acceptance. Thus, the WWIS becomes an integral part of the waste information screening process described in the WAP.

4.3.3 Quality Assurance

The implementation of a formal QA program demonstrates the commitment of DOE to perform all work activities and operations to the highest standards of quality. DOE has established an effective QA program that complies with applicable sections of NQA-1, NQA-2 (Part 2.7), and NQA-3. The management controls defined by the various QA plans and procedures ensure that all work is planned, documented, performed under controlled conditions, and periodically assessed to establish work item quality and process effectiveness and to promote improvement. The complexity, inherent risk, and significance of the work to the overall project and to public safety are key factors in determining applicable quality management requirements. Internal and external organizational interfaces and responsibilities are described in detail in Chapter 5.0.

The DOE TRU Waste Characterization QAPP (DOE 1995a) and the TRU Waste Characterization Sampling and Analysis Methods Manual (DOE 1995b) were replaced as of November 26, 1999. Figure 4-3 shows the revised QA document hierarchy for waste characterization.

Additional information regarding the quality assurance and quality controls used in ascertaining the waste description is given in Chapter 5.0.

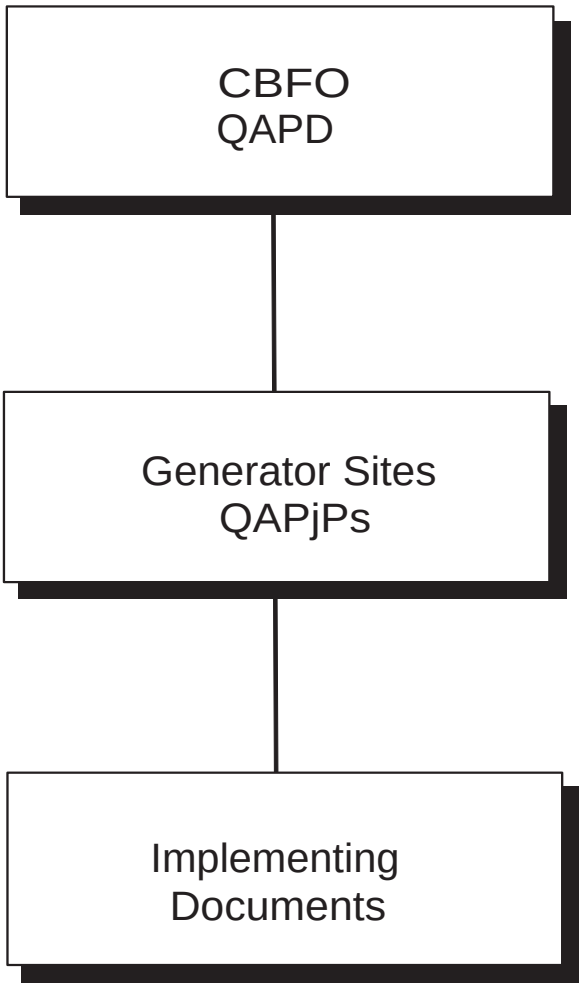

Figure 4-3. QA Documents Hierarchy

4.3.3.1 Performance Demonstration Programs

Another aspect of the waste-characterization QA process that has changed is related to the Performance Demonstration Program (PDP). The program evaluates the capability of sites to perform waste characterization within acceptable limits. Initially, participating laboratories were required to participate in the PDP twice per year. The CBFO has reduced the required frequency from twice per year to once per year. The CBFO described this change to the EPA in correspondence dated November 10, 1998, and April 22, 1999. Based on this information, the EPA determined that the changes reported did not require a modification, suspension, or revocation of the initial certification (EPA June 3, 1999).

The CBFO is the revising and approving authority for the NDA PDP and plans. The CBFO uses the PDP as part of the assessment and approval process for measurement facilities supplying characterization services for the NDA of TRU wastes intended for disposal at WIPP. The NDA PDP is similar to a blind sample program. The NDA PDP plans use 55-gallon drums or SWB's with simulated waste matrix and source standards. The NDA plans identify the elements that comprise the program, the criteria used to evaluate NDA system performance and the

responsibilities of the program participants. The PDP NDA plans are revised as required. NDA analysis of drums or boxes is performed by measurement systems that have demonstrated acceptable PDP performance.

4.4 Waste Characterization

The process of waste characterization identifies the significant physical, chemical, and radiological properties of the waste using a variety of methodologies. The measured waste properties obtained by the TRU waste sites are either on a container or waste stream basis and serve to demonstrate compliance with the limits imposed by transportation requirements (DOT), the Type B package certificate of compliance, the Hazardous Waste Facility Permit (HWFP), and operational safety requirements (DOE). In contrast, the waste component limits described in Appendix WCL are on a repository basis and serve as an upper bound for the accumulative waste inventory. As described in Section 4.3.2, the linkage between the collective waste inventory and the repository limits is provided by the WWIS.

Recognizing that the CH-TRU WAP and the CH-TRU WAC provide the waste characterization requirements for waste destined for the WIPP, it is necessary to understand the complementary role played by the radiological characterization of waste. Figure 4-4 shows the requirements hierarchy governing the characterization of waste for purposes of transportation, disposal, and long-term regulatory compliance. The implementation of waste characterization occurs on a waste-stream basis at the lowest tier of the diagram through the Standard Operating Procedures (SOPs). The next higher tier of Figure 4-4 includes the CH-TRU WAC, followed by progressively higher-tier requirements. The waste characterization requirements for compliance with the EPA's regulations are implemented by the SOPs.

The WAP includes requirements necessary for compliance with the New Mexico Hazardous Waste Act — specifically the identification and quantification of their hazardous components (see Attachment B of the WAP [NMED 2002]). A combination of five waste characterization methodologies is employed by the WAP and includes acceptable knowledge, radiography, visual examination, headspace gas sampling and analysis, and solidified waste sampling and analysis. The capabilities and applicabilities of these five methodologies to TRU mixed waste are discussed in considerable detail in the WAP. Except for a brief overview of acceptable knowledge, radiography, and visual examination, a description of the five waste characterization methodologies presented in the WAP will not be repeated in this document. Radiological characterization of TRU waste is needed for compliance demonstrations to 40 CFR Parts 191 and 194. A quantitative determination of the radionuclides listed in Table 4-11 results from the need to demonstrate compliance with the release limits as specified in Appendix A to Part 191 and the RH-TRU waste curie limit established by the LWA (see Table 4-12).

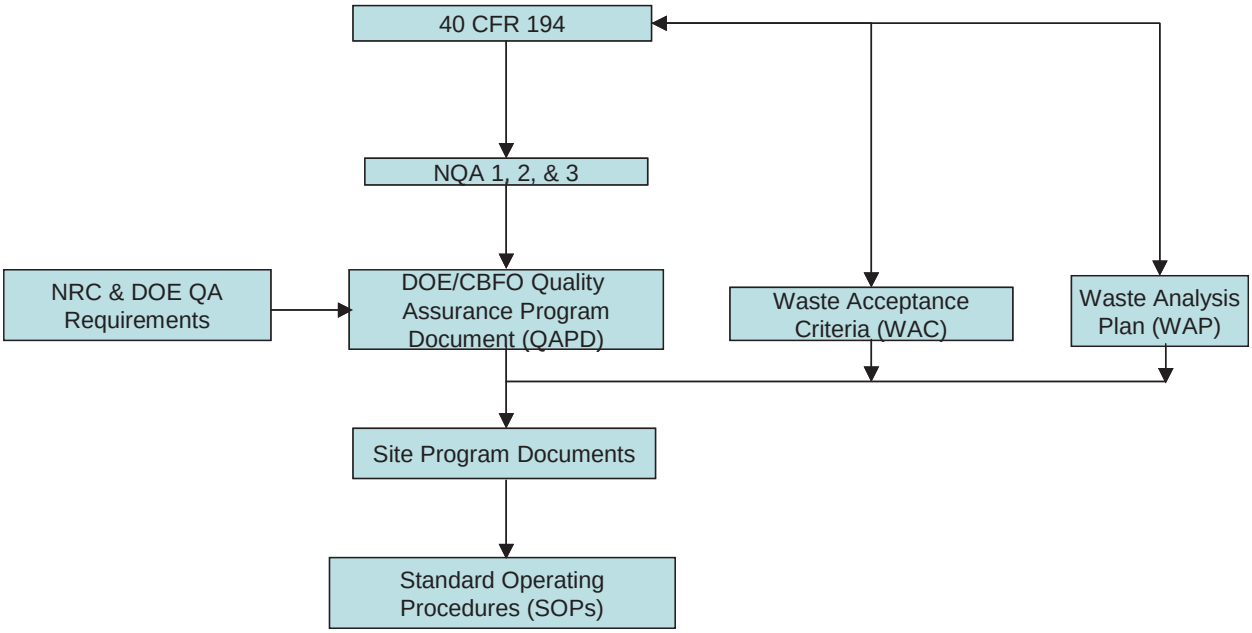

Figure 4-4. Program QA Document Hierarchy

Collectively, those elements of the waste characterization program that support long-term regulatory compliance include the determination of the radionuclide inventory (for purposes of normalizing radionuclide releases as required for comparison with Section191.13(a)), the identification of the physical and chemical waste form inventories (if applicable), and the verification that no wastes are emplaced in the WIPP that exceed the disposal system's safety and/or performance limitations.

In a manner analogous to the WAP, the WIPP waste radioassay characterization program is conducted by TRU waste site personnel and is implemented in accordance with the requirements of the CH-TRU WAC. TRU waste sites may propose alternative characterization methods, either because of the availability of newer technologies offering enhanced performance or the modification of older technologies to facilitate meeting the requirements of Appendix A of the CH-TRU WAC. In these instances, method performance must be demonstrated and approved in accordance with Section 194.8 prior to its use in characterization of TRU waste for disposal at the WIPP.

Implementation of the TRU waste characterization program at DOE TRU waste sites requires that all waste characterization activities be conducted in accordance with approved documentation that describes the management, operations, and QA aspects of the program. Conformance with applicable regulatory, programmatic, and operational requirements is monitored by CBFO audits and surveillances. Refer to Chapter 5 and CCA Appendix QAPD for a more detailed discussion of the CBFO audit and surveillance program. The documentation requirements important to the implementation of the TRU Waste Characterization Program at each TRU waste site are briefly discussed below.

- QA requirements. Implementation of individual site-specific waste certification and characterization programs must meet the QA requirements contained in the CBFO

QAPD, which are traceable to the applicable sections of ASME NQA-1 through NQA-3 (ASME 1989a, 1989b, and 1989c in the References). The WAP and the CH-TRU WAC describe the specific QA objectives (QAOs) for the TRU Waste Characterization Program. The WAP and the CH-TRU WAC, delineate approved analytical methods for meeting regulatory requirements.

- QAPjPs. TRU waste sites prepare site-specific QAPjPs that describe waste characterization activities in support of the TRU waste characterization program. These documents, developed in accordance with the applicable requirements in the CBFO QAPD and the WAP, define QA management and program elements that provide for planning, implementation, and assessment of the TRU waste characterization data-collection activities.

- SOPs. The QAPD requires that each DOE TRU waste site develop, implement, and control written SOPs that provide detailed descriptions of routine, standardized, or critical waste characterization activities. The SOPs serve as the basis for quality assessments of waste characterization activities at the site level because they provide detailed descriptions of required activities.

- PDPs. Analytical facilities characterizing waste for disposal at the WIPP must successfully participate in the applicable portions of the PDP. The PDP supports the determination of a facility's ability to meet the QA requirements identified in the CBFO QAPD. A more detailed description of the PDP can be found in Section 4.3.3.1.

As the TRU waste sites complete the necessary program documentation, they commence waste characterization activities. Information derived from these activities is on a waste-stream basis and is used in preparing the site's waste-stream profile forms required for waste acceptance at the WIPP. The waste characterization data are electronically backed-up in databases at the sites and downloaded into the WWIS database (DOE 1996b). The WWIS is described in Section 4.3.2.

TRU waste sites prepare documented and approved programs controlling their TRU waste characterization, certification (which includes characterization), and transportation processes. Site-specific TRU waste certification plans document how compliance with the CH-WAC is accomplished. Site certification is granted by the CBFO manager upon approval of the following documentation:

1. TRU waste certification plan (including QA),

2. QAPjP(s),

3. NRC Type B packaging methods for payload compliance TRU package transporter, Model 2 (TRUPACT II) Authorized Methods for Payload Compliance,

4. Packaging QA plan, and

5. Performance in applicable PDPs.

In addition to approval of this site-specific documentation, TRU waste sites must pass an initial TRU waste site certification audit where adequate and effective implementation of these programs is assessed (see Sections 5.1 and 5.3.19). Also, as described in Section 4.1.2, EPA approval of QA program documentation and implementation is also required.

Each site that is characterizing TRU waste is recertified by the CBFO annually. A recertification consists of reviewing (if applicable):

1. Site-specific program documents that are written and approved to the latest CH-TRU WAC;

2. Program implementation as determined by a TRU waste site certification audit;

3. Reports from surveillances conducted during the past year;

4. Performance in shipping TRU waste to the WIPP; and

5. Performance in the PDPs.

To ensure that DOE TRU waste sites comply with the WIPP TRU waste certification program, audits are conducted by the CBFO. An initial audit is conducted at each TRU waste site performing waste characterization activities prior to the formal acceptance of the waste-stream profile forms and/or any waste characterization data supplied by TRU waste site personnel. This formal acceptance is referred to as TRU waste site certification. Audits are performed at least annually thereafter, including the possibility of unannounced (not regularly scheduled) audits. These audits verify that the site has implemented a QA program for all certification activities. The accuracy of the physical waste description and the subsequent waste stream assignment are verified by a review of acceptable knowledge documentation, radiography data, and visual examination results (if applicable). Table 4-16 summarizes the characterization requirements and methods detailed in the CH-TRU WAC and the WAP that support this application. The EPA often observes the DOE audits in fulfilling its obligations defined in Section 194.8 (see Section 4.1.2).

Additional information regarding RH-TRU waste characterization has been developed by DOE and has been submitted to the EPA (letter from DOE to EPA December 16, 2002). No RH-TRU waste has been shipped to the WIPP at the time of CRA-2004. EPA approval of DOE's proposed RH-TRU waste characterization procedure is pending.

Table 4-16. Applicable CH- and RH-TRU Waste Component Characterization Methods

Waste Properties	Waste Components	Waste Characterization Methods
Nuclear	Radionuclides	NDA OR previous isotopic distribution from destructive radiochemistry OR previous radioassay data reconciled with CH-TRU WAC requirements
Physical	ferrous metals nonferrous metals cellulosic, plastic, rubber materials solid components free water humic substances	radiography with statistical selection for visual examination OR visual examination and documentation of container content at time of waste packaging for newly generated waste OR documentation and verification (random sampling) for newly generated waste
Chemical	sulfates nitrates organic ligands	No upper or lower limits apply to these chemicals; therefore no waste characterization methods are applied.

4.4.1 Qualitative Methodologies

The criteria at Section 194.24(a) require a description of the physical, chemical, and radiological composition of the TRU waste to be emplaced in the WIPP disposal system. With regard to the waste's nonhazardous physical and chemical components (such as cellulosic materials), there are three qualitative methodologies, used either singularly or in combination, for verifying adherence to the compliance limits. These methodologies include acceptable knowledge, nonintrusive examination using penetrating radiation such as X-ray (referred to as either RTR, radiographic examination, radiometric examination, or nondestructive examination (NDE)), and intrusive visual examination consisting of opening the container and recording the contents. The use of Acceptable Knowledge information is presented in the WAP and the CH-TRU WAC.

4.4.1.1 Acceptable Knowledge

The following discusses compliance with criteria at Section 194.24(c)(3).

Acceptable knowledge is defined in the EPA Guidance Manual (EPA 1994). Acceptable knowledge includes information regarding the physical form of the waste, the base materials composing the waste, and the process that generated the waste. Waste characterization will be used to confirm acceptable knowledge information. The WAP and the CH-WAC provide details regarding the application of acceptable knowledge.

Consistency among DOE TRU waste sites in using acceptable knowledge information to characterize TRU waste involves a three-phase process: (1) compiling the minimum acceptable knowledge documentation in an auditable record, (2) confirming acceptable knowledge information, and (3) auditing acceptable knowledge records.

Acceptable knowledge documentation provides qualitative information that cannot be assessed according to specific data quality objectives that are used for analytical techniques. QAOs for analytical results are described in terms of precision, accuracy, completeness, comparability, and representativeness. Analytical results will be used to confirm the characterization of wastes based on acceptable knowledge.

The acceptable knowledge process and waste stream documentation must be evaluated through internal assessments by QA organizations and assessments by auditors external to the organization (that is, the CBFO).

The CBFO has conducted and will continue to conduct an initial audit of each TRU waste site prior to certifying the TRU waste site for shipment of TRU waste to the WIPP facility (see the Hazardous Waste Facility Permit [NMED 2002] Attachment B through B6, including Figure B4-3). This initial audit will establish an approved baseline that will be reassessed annually.

4.4.1.2 Nondestructive Examination

NDE is a qualitative technique that involves the use of X-rays examination of waste containers to identify and verify the contents. NDE is used to verify the absence of prohibited items and to determine the appropriate methodologies to be used for waste characterization. NDE is not required for newly generated waste because controls exist to verify compatibility of the matrix material(s) and the absence of prohibited items prior to and during waste packaging.

All activities required to achieve the radiography objectives must be described in TRU waste site QAPjPs and SOPs. Retrievably stored containers will have this type of permanent record on file throughout the life of the WIPP project. As a quality control check on NDE, a statistically determined number of retrievably stored containers within the population subjected to NDE will be randomly selected and visually examined.

4.4.1.3 Visual Examination

Visual examination is used by DOE to provide an acceptable level of confidence in NDE. There is no equivalent method in the EPA sampling and analysis guidance documents. TRU waste site personnel develop training programs that are based on waste form and waste management operations. These training programs are used to assess operator performance. The QAPjPs and supporting SOPs specify the training requirements and other activities required to achieve the visual examination objectives. The visual examination expert must be familiar with the waste generating processes that have taken place at that TRU waste site and also with the types of waste being characterized at the site. For an explanation of the hypergeometric approach used in determining the number of containers to be statistically sampled by visual examination, see the WAP.

4.4.2 Quantitative Methodologies

To minimize exposure, the quantitative methodology used to determine the radionuclide inventory of the waste is NDA. The nonintrusive methodology of NDA employs radiation detection techniques for determining the waste's isotopic content and activity. This is the preferred approach because of the safety hazards involved in opening waste containers having radioactive contaminants. Although the data generated by radioassay serve many functions including the calculation of the ^{239}Pu equivalent activity, the ^{239}Pu fissile gram equivalent, and the decay heat of waste containers, the purpose of these data relative to long-term regulatory compliance with 40 CFR Part 191 is to provide corroborative data relating to the radionuclide inventory reported in the CRA-2004 and furnish radionuclide information on a container basis to maintain a running inventory of TRU waste emplaced in the WIPP disposal system.

TRU nuclides emit both ionizing radiation (including alpha particles, beta particles, and gamma rays) and nonionizing radiation (neutrons). Based on detection of these emissions, several technologies have been developed to measure one or more of these radiations as they emerge from the waste container. Although most of the ionizing radiation (alpha and beta particles) are not able to penetrate the walls of the waste container, both gamma rays and neutrons can penetrate the waste matrix as well as the waste container to varying degrees. Combining gamma ray measurements, other advanced particle detection techniques specific to neutrons, and acceptable knowledge provides the precision and accuracy required by the QAOs contained in the CH-TRU WAC Appendix A. Mass spectroscopy and radiochemistry also provide the precision and accuracy to meet the QAO requirements in the CH-TRU WAC Appendix A.

Special techniques, instrumentation, and detectors have been developed to measure the gamma ray energies. Because there are many different gamma rays originating from any one radionuclide with each gamma ray having a unique energy and rate of occurrence characteristic of the radionuclide from which it originated, the resulting distribution or spectrum of gamma ray energies provides a fingerprint or signature of that particular radionuclide. In practice, with the application of appropriate correction factors and the utilization of acceptable knowledge, gamma ray and neutron NDA systems provide radioisotope inventory information about the waste without the need for opening the container.

All radioassay systems must be calibrated using a variety of matrix and source standards to simulate the various waste compositions, source distributions, and interferences common to the waste streams originating from a particular TRU waste site. By applying the resulting correction factors to the measurements, an accurate assessment of the radionuclide inventory within the waste container is feasible. NDA methods appropriate to a particular waste stream profile are used in the radionuclide analysis.

4.4.2.1 Nondestructive Assay

A variety of NDA methodologies are effective in meeting the requirements of the CH-TRU WAC Appendix A. NDA instruments can be classified as belonging to one or more of the four categories listed below:

- gamma ray measurements

- low- and high-resolution spectroscopy using a sodium iodide and intrinsic germanium detector,
- transmission-corrected gamma ray measurement using a segmented gamma ray scanner, and
- transmission-corrected gamma ray measurement using a computed tomographic gamma ray scanner.

- passive neutron measurements
  - passive neutron coincidence counter,
  - advanced matrix-corrected passive neutron counter (add-a-source), and
  - shielded neutron-assay probe totals counter.
- passive and active neutron measurements
  - Am-lithium source-driven coincident counter,
  - californium delayed-neutron counter (shuffler),
  - neutron generator differential die-away counter, and
  - combined thermal and epithermal neutron counter.
- thermal neutron capture
  - californium delayed-neutron counter,
  - neutron generator differential die-away counter, and
  - combined thermal and epithermal neutron counter.

The list is neither complete nor limiting and is meant to illustrate the breadth of choice available. QAOs may be met with the listed systems or by modifications, functionally equivalent alternatives, multiple combinations, or hybrids of the systems.

For each of the radionuclide components identified in Table 4-11 as being significant to PA and requiring assay, any of the above NDA methodologies, either singularly or in combination, may be used in determining the activity and corresponding uncertainty. In the case of 100-percent sampling, these measurements are performed on a container basis. For the case of less than 100-percent sampling, the reported values are on a waste stream basis. Upon receipt of the waste at the WIPP, the measured activity of these significant radionuclide components, plus their associated uncertainty, are accumulated by the WWIS in order to ensure that the volume and activity limits of the repository are not exceeded.

4.4.3 Additional Change to the Waste Characterization Program

Since the certification of the WIPP, an additional change related to the waste characterization program has occurred. In the past, DOE planned to declassify any classified materials in waste before shipment to WIPP. In 2002, the RFETS proposed sending waste containing classified shapes to WIPP, where the associated radiography and VE records would be classified and require a DOE security clearance for review and audit. In 2003, the EPA determined that classified waste may be shipped to WIPP provided DOE meets certain specified requirements (EPA letter of February 11, 2003, to DOE CBFO).

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5.0 QUALITY ASSURANCE

The information in this chapter is a complete revision of the text in the Compliance Certification Application (CCA).

5.1 Introduction

This chapter was revised primarily to incorporate program changes, improve discussion of the characteristics and parameters of the Quality Assurance (QA) program, and clarify implementation of criteria from upper tier requirements documents. The following paragraphs provide an overview of the Carlsbad Field Office (CBFO) Quality Assurance Program Document (QAPD) development since submittal of the CCA.

In November 1999, Revision 3 of the QAPD incorporated transuranic (TRU) waste QA requirements contained in the Carlsbad Area Office (CAO) Quality Assurance Program Plan (QAPP), which was inactivated.

In August 2002, Revision 4 of the QAPD incorporated the Department of Energy (DOE) name change from the CAO to the CBFO, changes to the CBFO organization titles and associated responsibilities, and updated the Quality Improvement Section. It also provided an update of the source requirements documents for the QAPD, added specific QA functional responsibilities of the CBFO management, and eliminated divisions between “general requirements” and “additional requirements.” Editorial, formatting, and paragraph number changes were also incorporated.

The latest revision, Revision 5, of the QAPD was issued in May 2003. This revision was issued to address an Environmental Protection Agency (EPA) finding that the QAPD did not adequately incorporate the Quality Assurance Program Requirements for Nuclear Facilities, ASME NQA-1, 1989 edition criteria regarding assignment of organizational responsibilities for achievement of quality and verification of quality. In addition, Revision 5 deleted the requirement for organizations receiving records to return a receipt acknowledgment to the sender, for TRU waste program participants to maintain a QAPD procedures matrix (neither is required by NQA-1, -2, -3, or other regulatory documents) and deleted references to compliance with the Federal Acquisition Regulations. It also deleted the requirements for maintaining records related to the characterization of mixed TRU waste form as lifetime records, maintaining audit and surveillance checklists as QA records. The revision also changed the requirement for calibration laboratories to comply specifically with ANSI/NCSL Z540-1 to the requirement for compliance to national standards. Finally, Revision 5 added the Safety Analysis Report (SAR) for the HalfPACT shipping package as a source document, deleted Section 5.5 (criteria addressed in Section 5.1G), and corrected typographical errors and section references.

5.1.1 Mission and Policy

In Title 40 of the Code of Federal Regulations (CFR) Part 194, the U.S. EPA establishes the QA requirements criteria for determining compliance with 40 CFR 191 Subparts B and C, which specifies environmental radiation protection standards for disposal of TRU waste. The mission of the U.S. DOE is to protect human health and the environment of the Waste Isolation Pilot Plant (WIPP) for safe disposal of TRU waste, and to manage TRU waste from its acceptance to

its disposal. It is the policy of the DOE to maintain an effective QA program consistent with the criteria in 40 CFR Part 194, and consistent with other applicable federal, state, and local laws and regulations, including applicable DOE Orders. This policy helps to direct the CBFO mission and to ensure that the risks, safety, and environmental impacts are identified and minimized, and that safety, reliability, and performance are optimized.

5.1.2 Quality Assurance Program History

Previous QA program history is given in the CCA. In 1996, the CAO (now CBFO) implemented the QA requirements of 40 CFR § 194.22(a)(1). In addition, both DOE Order 5700.6C, Quality Assurance, and 10 CFR § 830 Subpart A – Quality Assurance Requirements were implemented through the DOE, CBFO QAPD.

In 1999 WIPP began disposal operations by receiving waste. By that time, all applicable regulatory requirements had been incorporated into the QAPD. These include 40 CFR § 194.22(a)(1), 10 CFR Part 830 Subpart A, DOE Order 414.1A, Quality Assurance, and NUREG 1297, Peer Review for High-Level Nuclear Waste Repositories. These requirements continue to be specified and implemented in the QAPD.

5.2 Quality Assurance Program Requirements

5.2.1 Requirements in the Code of Federal Regulations

5.2.1.1 <u>40 CFR Part 194</u>

40 CFR Part 194 sets forth the QA criteria necessary for compliance with 40 CFR 191 Subparts B and C. 40 CFR § 194.8(a), Quality Assurance Programs at Waste Generator Sites, establishes a site-specific QA program plan that addresses the applicable nuclear quality assurance (NQA) criteria of 40 CFR § 194.22(a)(1) for items and activities identified in § 194.22(a)(2), § 194.24(c)(3), and § 194.24(c)(5). The QA Program applied to the National TRU Program was certified in March 1999, and is audited annually by the EPA using the criteria for audits or inspections, including publishing notices in the Federal Register as set forth in § 194.8(a)(2).

5.2.1.2 <u>40 CFR § 194.22, Quality Assurance</u>

The following documents and regulation establish the requirements for the WIPP QA program. Figure 5-1 is a flow-down chart of these requirements documents.

- ASME NQA-1-1989 edition, Quality Assurance Program Requirements for Nuclear Facilities;

- ASME NQA-2-1989 edition, Quality Assurance Requirements for Nuclear Facilities Applications. ASME NQA-2a-1990 addenda, part 2.7, Quality Assurance Requirements of Computer Software for Nuclear Facility Applications;

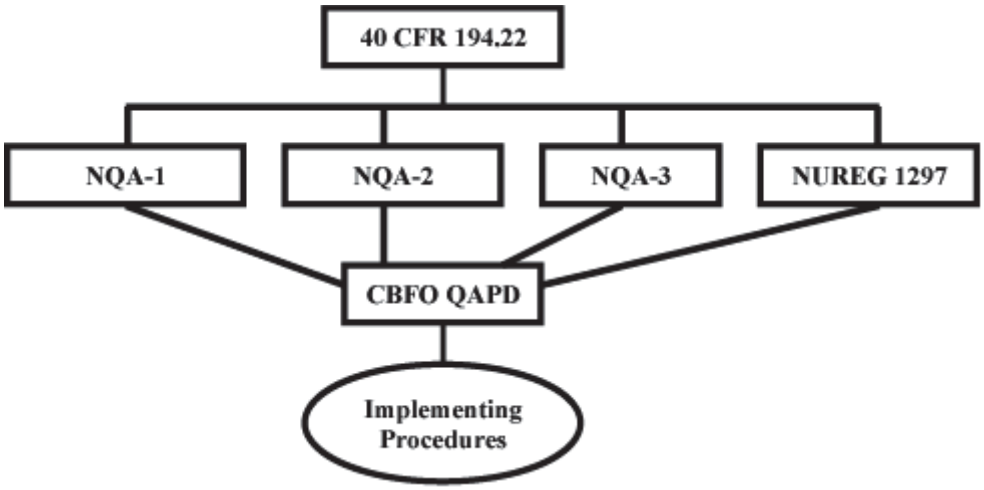

Figure 5-1. Requirements Flow-Down Chart

- ASME NQA-3-1989 edition, Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Nuclear Waste Repositories (excluding Section 2.1 (b) and (c), and Section 17.1); and

- NUREG 1297, Peer Review for High-Level Nuclear Waste Repositories (required by 40 CFR § 194.22(b) for "qualification of data and information," § 194.27 for compliance application documents associated with "conceptual models," § 194.24(b) for "waste characterization analyses," and § 194.44 for "engineered barrier evaluation").

5.2.2 Other Requirements and Standards

The WIPP QA program incorporates QA requirements in 10 CFR Part 71(H), Quality Assurance. The WIPP-related QA program applies to design, purchase, fabrication, handling, shipping, storing, cleaning, assembly, inspection, testing, operation, maintenance, repair, and modifications of components of packaging, transportation, and handling of TRU waste that are important to safety. The WIPP-related QA program also applies to the requirements and standards found in the WIPP Hazardous Waste Facility Permit (HWFP), 10 CFR 830 Subpart A, DOE Orders, and National Consensus Standards. Applicable requirements from these documents are incorporated into the QA program applied to the National TRU Program.

5.3 Incorporation of 40 CFR § 194.22 Criteria in the QAPD

The following section lists 22 criteria incorporated in the CBFO QAPD. These criteria were taken from the requirements documents and regulation described in Section 5.2.1.2. Criteria 1 through 18 were taken from NQA-1-1989; Criterion 19 from NQA-2-1990a, Part 2.7; Criterion 20, 21, and 22 from NQA-3-1989; 40 CFR § 194.22(b) and (c), and NUREG 1297.

5.3.1 Criterion 1 – Organization

The CBFO is structured so that the individual performing the work is responsible for achieving and maintaining quality. Management is responsible for defining quality, developing appropriate

plans to attain quality, supporting the workers in pursuit of quality, and evaluating quality achievement within their area of responsibility. Figure 5-2 illustrates the authority and reporting structures of the CBFO QA and its major program participants.

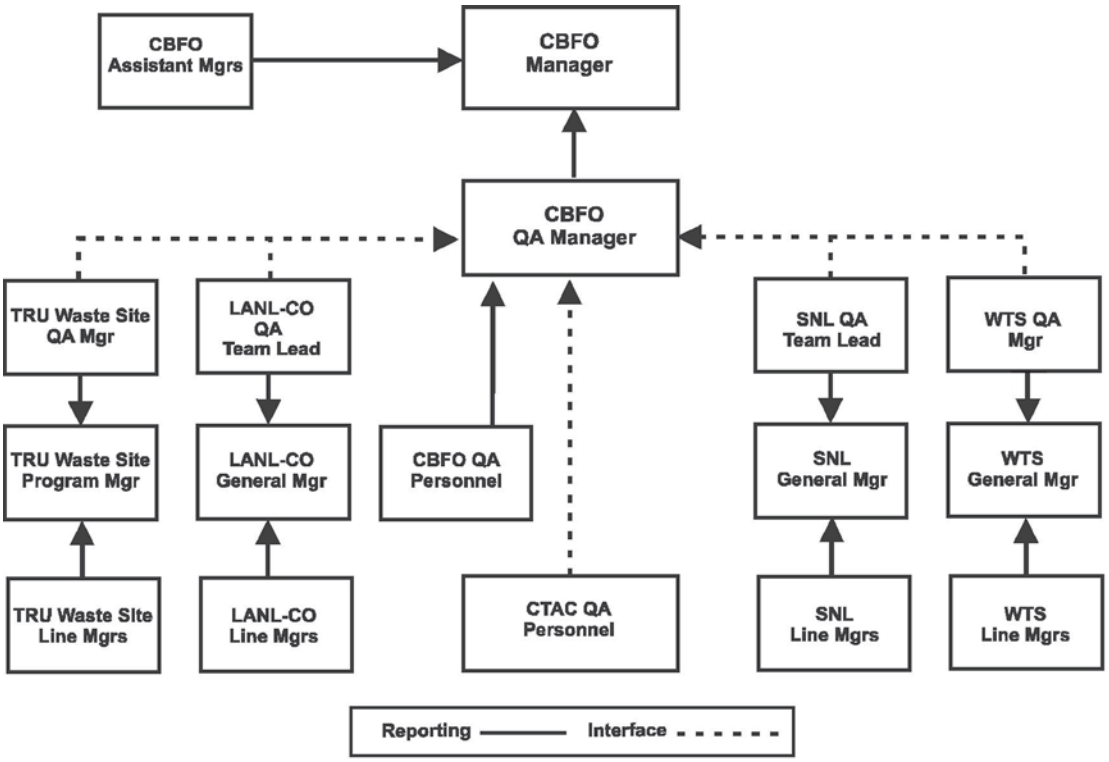

Figure 5-2. Reporting Interface Diagram

All program participants have the authority, organizational freedom, and the overall responsibility to independently assess the effective implementation of the QA program. Reporting is made to a management level so that the required authority and organizational freedom is provided, including sufficient independence from cost and schedule considerations. The QA organizations have sufficient authority, access to work areas, and organizational freedom to:

- verify, through checking, auditing, and inspecting, that quality-affecting activities have been performed correctly;
- identify quality problems;
- initiate, recommend, or provide solutions to quality problems through designated channels;
- verify implementation of solutions; and
- ensure that further processes, delivery, installation, or use is controlled until proper disposition of a nonconformance, deficiency, or condition adverse to quality has occurred.

The CBFO QAPD requires personnel conducting assessments and other quality-affecting activities to be technically qualified and knowledgeable about the item(s) and processes being assessed, and be independent of any direct responsibility for the performance of the activities being assessed. To manage any perceptions of assessment bias, CBFO requires the Carlsbad Field Office Technical Assistance Contractor (CTAC) organization to ensure independence through the implementation of an organizational and individual conflict of interest avoidance and mitigation process.

5.3.2 Criterion 2 – Quality Assurance Program

5.3.2.1 Quality Assurance Program Overview

The CBFO QA program is described in the QAPD and includes QA requirements from multiple sources. The QA organizational structures, primary interfaces, functional responsibilities, and levels of authority for activities affecting quality are described and documented in the QAPD. The major QA organizational interfaces are illustrated in Figure 5-2.

The CBFO Manager directs activities to effectively and efficiently meet DOE and WIPP missions and safety expectations. The Manager reports directly to the DOE Assistant Secretary for Environmental Management for program policy and direction. The Manager is responsible for and maintains a QA program that ensures work activities meet customer requirements, including federal, state, and local laws and regulations, permit requirements, and DOE Orders and requirements. The Manager provides technical direction in interpreting QA requirements and in reviewing and concurring with QA plans and programs.

The CBFO QA Manager has been delegated the authority for executing the QA function by the CBFO Manager and reports directly to the CBFO Manager. The QA Manager has the authority and overall responsibility to independently assess the adequacy, implementation, and effectiveness of the TRU waste QA programs, within both the CBFO organization and program participant organizations. Participant QA managers have the authority and responsibility to independently assess the effective implementation of the applicable QAPD requirements within both their participant organization and any lower-tier organizations.

The following are program participant responsibilities:

- Program participants have the responsibility for TRU waste QA program development, implementation, and assessment within their own and lower-tier organizations. CBFO reviews and accepts the WIPP waste-related QA program documents of Sandia National Laboratories (SNL), Washington TRU Solutions (WTS), the TRU waste generator sites, and other TRU waste program participants, e.g., Los Alamos National Laboratory-Carlsbad (LANL-CO). CBFO performs QA audits and surveillances of these organizations to verify compliance with QA and technical program requirements.

- Washington TRU Solutions has the responsibility for implementing and maintaining the QA program for the operation and maintenance of the WIPP site, monitoring the site environment, and for the receipt of waste. WTS is also responsible for the Central Characterization Project (CCP), which is tasked with characterizing and certifying TRU

waste at specified waste generator sites for disposal at the WIPP. The CBFO Manager and Assistant Manager for the Office of National Transuranic Program provide overall policy direction for the CCP. Specific details of this organization are described in the CCP TRU Waste Certification Plan, CCP-PO-002.

- Sandia National Laboratories has the responsibility for implementing and maintaining a QA program for activities involved in the development, confirmation, and verification of models used to simulate long-term repository performance. SNL's QA program covers research, experiments, and tests performed to collect the data needed for input to the models.

  In January 1999, the SNL QA program converted from a system of QA procedures (QAPs) to an improved system of revised nuclear waste management QA procedures (NPs). The NPs were issued with two objectives. First, the NPs were written to be responsive to requirements contained in the latest CBFO QAPD. These NPs were also verified to be compliant with the CBFO QAPD by completing an extensive matrix to map the upper-tier requirements for each procedure. Second, the NPs were streamlined, and additional information was added to make them easier to use. For example, several QA plans that addressed the same subject area (analyses) have been combined into one NP (NP 9-1).

  These changes implement the same QA program requirements but improve the implementing processes. They do not represent significant changes in activities or conditions pertaining to the disposal system. The SNL QA program is routinely subject to CBFO audits and EPA inspections.

- Los Alamos National Laboratory – Carlsbad has the responsibility for implementing and maintaining a QA program for activities involved in actinide chemistry and for the Transuranic Waste Baseline Inventory Report (TWBIR) (see Appendix BIR). The TWBIR is the inventory source document that provides the waste data used in the performance assessment of the WIPP site.

- Sites intending to send TRU waste to the WIPP are responsible for implementing and maintaining a QA program that meets the applicable requirements of the QAPD, for characterizing TRU waste, for meeting the WAC, and for participating in the waste certification and recertification programs.

5.3.2.2 Grading

Quality assurance grading is used to identify the controls applied to activities that support the TRU waste QA program. Grading is based upon an evaluation of the complexity and importance of the activity to quality, safety, risk, and the environment. Based on the results of the evaluation, appropriate procedural controls are identified. The rigor of QA controls is commensurate with, but not limited to, the following criteria:

- the function or end-use of the item;

- the importance and end-user of the data generated;
- the probability of failure;
- the complexity or uniqueness of the design, fabrication, or implementation;
- the reproducibility of the results;
- the quality history of the item or service;
- the necessity for special controls or processes; and
- the ability to demonstrate functional compliance with applicable regulations.

The CBFO staff and program participants perform management assessments to ensure the QA program meets customer requirements and expectations.

The extent of management and QA controls applied to an item or activity varies as a function of the degree of confidence needed to achieve the desired quality. The grading process provides the flexibility to design and implement controls that best suit the facility or activity but is not intended to reduce or in any way degrade the compliance with applicable requirements.

5.3.2.3 Quality Assurance Program Documents

The CBFO and program participants implement the requirements of the CBFO QAPD in accordance with QA program documents and implementing procedures prepared and maintained by their organizations.

A table of QA program documents that implement the various TRU waste QA programs is presented in Section 5.4 along with a description of the CBFO QAPD and a listing of CBFO procedures.

When the CBFO QAPD is revised, lower-tier documents such as site Quality Assurance Project Plans (QAPjPs), certification documents, QA plans, and program participants implementing procedures are evaluated and appropriately revised to ensure that the QA program of each organization meets all the applicable requirements of the CBFO QAPD.

5.3.2.4 Qualification and Training

Personnel performing work are qualified and capable of performing their assigned tasks. Program participants have established formal methods for the evaluation, selection, indoctrination, training, and qualification of personnel performing work to ensure compliance with the CBFO QAPD requirements.

In the case of Lead Auditors, a comprehensive process, including training and an examination, is required, along with specific experience and education requirements that must be met in order to obtain Lead Auditor certification.

5.3.2.5 Management Assessments

Management assessments are performed by the CBFO and program participants to determine the effectiveness of the QA programs established and implemented to meet customer requirements and expectations.

Key elements of management assessments that help to determine effectiveness include:

- the conduct of regular assessments of the QA program with reports at least annually to senior managers who have sufficient authority to effect corrective measures; and

- the use of management assessment results as a means for determining and taking the necessary actions to correct quality problems, achieve quality, and ensure the proper application of resources to achieve and verify quality.

5.3.3 Criterion 3 – Design Control

Design work, including changes, incorporates appropriate controls and requirements such as general design criteria, design bases, and control of inputs. Design interfaces are identified and controlled. The adequacy of design products is verified by individuals or groups independent from those who performed the work. Verification is completed before approval and implementation of the design. The control of design activities also includes design reviews and qualification testing.

5.3.4 Criterion 4 – Procurement Document Control

Procurement documents address the scope of work, technical requirements, design bases, appropriate codes, standards, regulations, procedures, instructions, tests, inspections, hold points, acceptance criteria, and documentation requirements.

Quality-affecting procurement documents are reviewed to verify that the documents include appropriate provisions for ensuring that items and services meet the prescribed requirements. CBFO requires that these procurement documents be reviewed by technical and QA personnel. The reviewers are required to have access to pertinent information and an adequate understanding of the requirements and scope of the procurement. CBFO conducts audits and surveillances to verify that these requirements are being met.

5.3.5 Criterion 5 – Instructions, Procedures, and Drawings

Activities affecting quality are prescribed by and performed in accordance with the appropriate established, documented, and approved instructions, procedures, or drawings. Instructions, procedures, and drawings are developed, reviewed, and approved by technically competent personnel. The documents contain specific information appropriate to the work to be performed, including the following required elements:

- responsibilities;

- program requirements;

- description of the work;
- acceptance criteria;
- prerequisites, limits, precautions, process parameters, and environmental conditions;
- special qualifications and training requirements;
- verification and hold points;
- methods for demonstrating that the activity was performed as required; and
- identification and classification of QA records to be generated.

The CBFO implementing procedures are listed in Section 5.4.9. Each of the program participants develops implementing documents that address the quality activities applicable to his or her QA program requirements and work scope.

5.3.6 Criterion 6 – Document Control

Documents affecting quality that specify quality requirements, prescribe processes, or establish designs important to compliance with 40 CFR 191 Subparts B and C and 40 CFR Part 194, such as instructions, procedures, drawings, test plans, and management plans, which are controlled to ensure that the correct documents are being employed. Controlled documents are reviewed by competent personnel, using specified criteria for adequacy, correctness, and completeness before approval and issuance. Review comment documentation is maintained by the originating organization. Responsibilities for document preparation are specified and the documents are controlled during the preparation, review, approval, issuance, use, and revision processes.

5.3.7 Criterion 7 – Control of Purchased Items and Services

Controls are established to ensure that procured items and services meet applicable technical and QA requirements and performance specifications. Prospective suppliers are evaluated and selected on the basis of documented criteria. Procurement controls are in place to ensure that approved suppliers continue to provide acceptable items and services. Procurement controls include, as appropriate:

- procurement planning,
- supplier selection and performance evaluation,
- proposal and bid evaluation,
- procurement documents,
- source verification and supplier certification of conformance,
- receipt inspections and post-installation testing,

- control of supplier nonconformances, and
- commercial-grade items.

5.3.8 Criterion 8 – Identification and Control of Items

"Item" is an all-inclusive term used in place of any of the following: appurtenance, assembly, component, equipment, material, module, part, structure, subassembly, subsystem, system, unit, support system, or data.

Items used in support of 40 CFR Part 191 Subparts B and C and 40 CFR Part 194 are identified and controlled. Processes have been established to identify, control, and maintain items from receipt through installation and end-use. Item identification ensures the appropriate traceability as specified in design documents, codes, standards, specifications, and implementing procedures. An identification marking is placed on the item or in documents traceable to the item. Acceptable methods and materials for characteristics and markings are prescribed, and the authority for applying and removing status indicators and markings is also specified.

5.3.9 Criterion 9 – Control of Processes

Work processes that support compliance with 40 CFR Part 191 Subparts B and C and 40 CFR Part 194 are performed in accordance with established, approved, and documented technical standards and administrative controls. Work is planned, authorized, and performed under controlled conditions using approved instructions, procedures, drawings, or other appropriate means. Implementing procedures are developed, reviewed, and approved by qualified and competent personnel. The procedures contain information, including the following elements, appropriate to the work being performed:

- prerequisites, limits, precautions, process parameters, and conditions necessary for performing the process, including calibration requirements;
- special qualifications and training requirements; and
- acceptance criteria, including applicable codes and standards.

Personnel performing work are responsible for complying with appropriate instructions, which include or reference procedure, personnel, and equipment qualification requirements. Handling, storage, cleaning, shipping, and other processes that are implemented to preserve, transport, and package items are conducted in accordance with established work and inspection procedures, shipping instructions, or other specified documents.

Processes that are highly dependent on the control of the process and on the skill of the operator where quality results cannot be readily determined by inspection or test of the product are considered "special processes." Implementing procedures for special processes are required to include the conditions necessary for completion of the special process, including equipment, statistical process control, controlled parameters of the process, and calibration requirements.

5.3.10 Criterion 10 – Inspection

Inspections determine acceptance or rejection of a process, product (item), or service. Inspection documentation required of program participants includes:

- approved implementing procedures;
- identification of the items and processes to be inspected, the parameters or characteristics to be evaluated, the techniques to be used, the acceptance criteria, and any hold points;
- the acceptance of items and processes by qualified and authorized persons; and
- identification of any measuring and test equipment used, including the equipment identification number and the calibration due date.

5.3.11 Criterion 11 – Test Control

Tests determine the capability of an item to meet specified requirements by subjecting the item to a set of defined operating conditions. Tests included as part of scientific investigations are conducted in accordance with the methods described in Section 5.3.20. Test planning is required and includes:

- identification of the procedures and related requirements documents used to control and perform the test (for example, test plans);
- identification of the item to be tested, test requirements, and acceptance criteria;
- identification of the measuring and test equipment (M&TE) including the type, range, accuracy, and tolerance;
- test prerequisites and provisions to ensure that all test requirements and objectives have been met;
- any designated hold points; and
- recording methods used to collect and record the data.

In addition, the documentation of test results identifies (1) the test date, (2) the personnel performing the test, (3) the data collected and the results of the tests, (4) the actual measuring and test equipment used, (5) the actions taken when unexpected results are obtained, and (6) the personnel evaluating the test results. A qualified person evaluates the results to ensure that all test requirements have been met.

5.3.12 Criterion 12 – Control of Measuring, Monitoring, Data Collection and Test Equipment

The M&TE control system is established for monitoring, measuring, testing, and the proper use of data collection equipment to ensure that suspect and out-of-tolerance equipment that could affect quality are not used. If such equipment is inadvertently used, the control system provides

for the segregation of the defective equipment and the evaluation of the data obtained while the out-of-tolerance or defective equipment was used. In addition, the calibration system includes provisions for:

- using documented procedures that describe the calibration system and the detailed calibration methods;
- using qualified calibration services that meet the requirements of the CBFO QAPD;
- developing a schedule for the initial calibration of M&TE and for periodic recalibration to ensure acceptable reliability;
- documenting the results of the calibration;
- labeling and identifying all M&TE to provide the information needed for recalibration and to ensure that adequate standards are traceable to the M&TE;
- identifying any needed precautions for handling, storing, and transporting equipment to prevent damage or out-of-tolerance conditions;
- providing the environment needed to calibrate the M&TE and to take measurements; and
- using calibration standards traceable to nationally recognized standards or physical constants. When such standards do not exist, the bases for calibration are documented.

5.3.13 Criterion 13 – Handling, Storage, and Shipping

Handling, storage, cleaning, packaging, shipping, and preservation of items are controlled to prevent damage or loss and to minimize deterioration. Items supporting compliance with 40 CFR Part 191 Subparts B and C and 40 CFR Part 194 are managed and controlled using approved implementing documents. Precautions taken include the following:

- preparing procedures that describe the methods to be applied, the proper controls, and the records to be generated;
- using and documenting special equipment and environments when required; and
- creating and maintaining markings and labeling that identify the item, any special environments required, and the need for any other special controls as necessary.

5.3.14 Criterion 14 – Inspection, Test, and Operating Status

Authorized persons apply and remove status indicators on items, as appropriate. These status indicators help prevent inadvertent installation, use, or operation of items that have not passed the required inspections or tests. The specific status indicators, their use, and the authority to apply or remove them are delineated in applicable QA plans or implementing procedures. Status indicator processes identify provisions for:

- using and maintaining status indicators to indicate if an item has completed the required inspections or tests and to indicate the operating status of items;
- placing status indicators on the items or in documents traceable to the items;
- using tags, markings, labels, stamps, travelers, inspection and test records, or other appropriate means as status indicators; and
- using and maintaining a lockout/tagout system for setting and maintaining specific conditions.

5.3.15 Criterion 15 – Control of Nonconforming Items

Items that do not conform to specified requirements are controlled to prevent their installation, use, or operation before correction. Nonconforming items may be identified at any time by anyone.

When appropriate, further work on the item is halted until the appropriate actions have been taken and verified. The nonconformance control process is documented in applicable QA plans. The process identifies implementing procedures for identifying nonconforming items, methods that do not adversely affect the end-use of the item, and methods designed to prevent damage or loss and to minimize deterioration. Precautions taken include:

- preparing procedures that describe the methods to be applied, the proper controls, and the records to be generated;
- using and documenting special equipment and environments when necessary;
- creating and maintaining markings and labeling that identify the item, any special environments required, and the need for any other special controls;
- segregating nonconforming items, when practical;
- assigning the responsibility to halt or control further work on the item;
- evaluating and dispositioning nonconforming items by authorized persons; and
- reexamining the item to verify acceptability after rework or repair.

In addition, suppliers are required to identify items that do not meet the requirements of the procurement documents, to document the nonconforming condition and the proposed disposition, and to provide technical justification for the disposition.

5.3.16 Criterion 16 – Corrective Action

“Corrective actions” are measures that are taken to rectify a condition that is adverse to quality and, where necessary, to preclude recurrence.

All personnel are responsible for identifying conditions adverse to quality. Conditions adverse to quality are evaluated, the appropriate corrective actions are defined and implemented, and the completion and effectiveness of the corrective action are verified. If the condition adverse to quality is determined to be significant, corrective action is identified, investigative action is taken, the root cause is determined, and appropriate actions are taken to preclude recurrence. A significant condition adverse to quality is defined as a condition, which, if uncorrected, could have a serious effect on safety, operability, waste confinement, TRU waste site certification, compliance demonstration, or the effective implementation of the QA program.

When appropriate, further work on the item, activity, or process is halted until the appropriate actions have been taken and verified. The corrective action process for conditions adverse to quality is documented in appropriate QA plans and implementing procedures. The process used to identify and control conditions adverse to quality includes provisions for:

- identifying and documenting conditions adverse to quality;
- assigning the responsibility to halt or control further work on the item, activity, or process;
- evaluating and dispositioning conditions adverse to quality by authorized persons;
- notifying management of the results of evaluations of significant conditions adverse to quality;
- preparing corrective action plans that include remedial actions, investigative actions, root cause determinations, expected completion dates, and responsible persons, as appropriate;
- evaluating the corrective action plans and verifying the completion and effectiveness of the corrective actions taken; and
- assigning unique numbers to each corrective action request generated, maintaining a log of the specific status of each request until it is closed, and regularly reporting and reviewing the status of all open corrective action requests.

5.3.17 Criterion 17 – QA Records

Records generated under the QA program are specified, prepared, reviewed, approved, maintained, and disposed of in accordance with the CBFO QAPD. Records provide evidence of work quality and evidence that the QA program has been properly implemented during work performance. The records management system is documented in appropriate QA plans and implementing procedures and includes:

- identifying those documents that will become QA records and identifying the organizations responsible for submitting the QA records to the records system;
- generating records that are legible, accurate, and complete;
- protecting documents that will become QA records during generation and use;

- authenticating the QA record;
- indexing QA records to ensure retrievability and to identify record retention times and the location of the record within the records system;
- classifying QA records as either lifetime, nonpermanent, or postclosure;
- designating the organization that receives and controls QA records;
- storing QA records using methods and facilities that meet the requirements of the CBFO QAPD; and
- correcting, replacing, restoring, and substituting records for any incorrect, lost, or damaged QA records in the QA records system.

The generation, classification, indexing, and retention of QA records are controlled in accordance with appropriate plans and records-related procedures.

5.3.18 Auditor and Technical Specialist Skills and Background

Auditors and Technical Specialists that conduct CBFO audits are qualified and certified in accordance with the CBFO Team Procedure (TP) 10.1, Qualification of Audit Personnel and Certification of Lead Auditors.

The Auditors possess a comprehensive knowledge of ASME NQA-1, DOE Orders, and Codes of Federal Regulations applicable to hazardous waste facilities. These individuals possess knowledge of CBFO program documents including the QAPD, Waste Analysis Plan (WAP), Contact-Handled Transuranic Waste Acceptance Criteria (WAC) For The Waste Isolation Pilot Plant, TRUPAC-II Authorized Methods for Payload Control (TRAMPAC) sufficient to successfully assess assigned activities during an audit. In addition, the audit team possesses experience with and a working knowledge of the corrective action process to properly identify problems, assess corrective action plans, and verify the closure and effectiveness of corrective actions.

Technical Specialists are trained in the audit process. They possess a comprehensive knowledge of the WIPP HWFP and the Program Documents. They have experience in either hazardous or nuclear waste generation or waste management, the Compliance Certification Application, or in a technical discipline associated with the operation of a nuclear facility or laboratory. Technical Specialists have a working knowledge of industry standards, operational methods, and regulations associated with the discipline in which the individual has expertise. In addition, they have a working knowledge of visual examination (VE), nondestructive examination (NDE), acceptable knowledge (AK), data verification and validation (V&V), and nondestructive assay (NDA).

Technical Specialists, Auditors, and Lead Auditors complete training commensurate with the activities they perform during audits. Auditors and Lead Auditors must successfully complete the CBFO Auditor/Lead Auditor Course for qualification. In addition, Lead Auditors must meet educational and experience requirements and pass a comprehensive written examination before

certification. Lead Auditors are required to maintain their proficiency through audit participation, training, or reading assignments. Failure of Lead Auditors to maintain proficiency requires recertification.

Qualification of Technical Specialists and Auditors and the certification of Lead Auditors are documented and maintained as QA records. Lead Auditor maintenance of proficiency is also documented and maintained as a QA record.

With the current audit staff, Lead Auditors, on the average, have over 20 years of experience and expertise in performing audits. Auditors typically average over 15 years of experience in auditing, and Technical Specialists average over 20 years of experience in their technical disciplines

5.3.19 Criterion 18 – Audits and Surveillances

Audits and surveillances verify that the various QA programs properly reflect the requirements of the CBFO QAPD and that they are being effectively implemented.

The CBFO has designated specific meanings that apply to the terms adequacy, implementation, and effectiveness. Adequacy refers to the migration of requirements contained in upper-tier documents into implementing procedures. An adequate procedure is one that contains all appropriate upper-tier requirements. Implementation refers to the performance of the process steps identified in the procedures. An implemented procedure is one for which all steps have been completed as identified within the procedure. Effectiveness refers to a process that produces the desired (specified) end-product or end-service. These terms are used to describe assessment activities throughout this chapter.

The management and control of audits and surveillances are documented in QA plans or implementing procedures. The audit and surveillance processes include provisions for:

- scheduling;
- using qualified, certified, and independent personnel;
- reporting results to the management of the audited or surveilled organization and to other affected organizations;
- requiring a written response to any noted conditions adverse to quality; and
- ensuring that the audited or surveilled organization has taken the appropriate corrective actions and that the corrective actions are effective.

Audits and surveillances conducted since the CCA have been rolled up into summary tables in Appendix AUD 2004. These tables reflect the extensive and comprehensive auditing and surveillance efforts that CBFO has implemented in order to ensure adequacy, implementation, and effectiveness of the TRU waste program.

5.3.20 Criterion 19 – Software Quality Assurance

Software QA controls are in place to ensure that the software meets its intended use and is controlled. These controls apply to software that manipulates or produces data that are, in turn, used to process, gather, or generate information and whose output is relied upon to make design, analytical, operational, or compliance-related decisions affecting the performance of the waste isolation or waste characterization processes. The application of these requirements is prescribed in written plans, policies, procedures, or instructions.

Software controls include inventorying and classifying appropriate software. Plans are prepared at the start of the software life cycle to document the software basis and the objectives of the software to meet its intended use.

The sponsoring organization for software acquisition and related services verifies the capability of the software and the acceptability of the supporting documentation. Any software errors and failures are reported to the sponsoring organization for analysis and then forwarded to the supplier and users, if applicable.

Software not developed under a QA program meeting the requirements of the CBFO QAPD, including preexisting software, is evaluated, uniquely identified, and controlled in accordance with the requirements of the CBFO QAPD, Section 6.0. When accepted, the software is placed under configuration control before use. QA records (for software) are controlled and stored as described in Section 5.3.17.

Software is controlled using an iterative or sequential approach during the various life cycle phases, which include:

- definition of requirements;
- design;
- implementation;
- testing, including verification and validation tests;
- installation and checkout;
- operations and maintenance, including in-use tests; and
- retirement.

Verification and validation of the software, including a review of the completed software activities, documentation, and tests, are performed to ensure that the software adequately and correctly performs all intended functions and does not perform any unintended functions, in accordance with the requirements of the CBFO QAPD. Software verification is performed during the software development phases to verify that the requirements of the previous phase have been fulfilled. Software validation is performed to ensure that the software satisfies all requirements.

Controlled software is placed under configuration management to ensure that changes are controlled and that the appropriate version of the software is used. Configuration management includes the maintenance of unique identification, configuration change control, and configuration status accounting. When appropriate, access is controlled.

Software documentation generated and retained during software development includes:

- procurement documentation for procured software,
- software requirements documentation,
- design and implementation documentation,
- verification and validation documentation,
- any change documentation,
- user documentation, and
- any error and disposition documentation.

For released versions, software problems are documented, evaluated, and if appropriate, corrected. The evaluation of software problems includes the identification of any impact on previous use and any appropriate corrective action. Problems that significantly impact decisions based upon prior use or that require significant modification to the software are identified. Errors that qualify as a condition adverse to quality are controlled as described in Section 5.3.16.

5.3.21 Criterion 20 – Scientific Investigation

Technical investigations and design-development data collection activities are defined, controlled, verified, and documented. Process variables affecting scientific investigations are measured and controlled. Planning for scientific investigations ensures that the appropriate information is collected and that outside factors are eliminated or their effects are minimized. Planning is coordinated with other organizations that provide input or use the results. Planning for scientific investigations includes provisions for:

- identifying and appropriately controlling variables that affect interrelated scientific investigations;
- documenting the intended use of the data before collection;
- verifying the compatibility of data processing with any conceptual or mathematical models used at each applicable stage;
- reviewing and approving the technical acceptability of procedures;
- reviewing and approving the documented development activities used to establish new methods or procedures;

- establishing acceptance criteria for the data quality evaluation;
- identifying known sources of error and uncertainty; and
- identifying input data that are suspect or whose quality is beyond the control of the performing organizations.

Scientific investigations are performed according to requirements and are documented in scientific notebooks or technical implementation documents or both. If no nationally recognized test standard exists, special test procedures are developed and used. Scientific notebooks contain the results of the investigations and are periodically reviewed by a qualified individual for completeness.

Methods used in the investigations are reviewed to ensure that they are technically sound and have been properly selected. Data collection and analyses are controlled by procedures that allow the processes to be replicated. Test media are characterized and controlled in accordance with test procedures.

Data are recorded, identified, and traceable to the scientific investigation from which they are generated. Data collection and analysis are critically reviewed and questions are resolved before the results are used or reported. Uncertainty limits are assigned to the data before their use. Data are controlled to:

- prevent data loss and to permit data retrievability;
- maintain data integrity and security;
- ensure error-free transfer, reduction, and change in the expression or the quality of the data; and
- prevent the use of erroneous, rejected, superseded, or otherwise unsuitable data.

Data used for compliance with 40 CFR Part 191 Subparts B and C and 40 CFR Part 194 that were not collected under a QA program meeting the CBFO QAPD requirements are qualified through one or a combination of five methods detailed in Section 5.3.22. If peer reviews are necessary, the CBFO uses an approved procedure and process that is consistent with NUREG 1297 (1988), Peer Review for High-Level Nuclear Waste Repositories.

5.3.22 Criterion 21 – Data Quality Characteristics

40 CFR § 194.22 (c) stipulates that to the extent practicable, data used to support compliance will be assessed to ensure data accuracy, precision, representativeness, completeness, and comparability. The DOE applies these data characteristics to tasks involving the quantification of specific constituents in an environmental medium through sampling and analysis. The DOE applies these requirements to activities such as the determination of the presence or absence of constituents within TRU waste streams. Waste characterization and environmental monitoring are examples of the types of activities in which data quality characteristics are applied. In these

cases, the performance measurement is the concentration of the constituent of interest. Data quality measures include:

- data accuracy – a measure of the bias in a system, which is the degree of agreement of a measurement with an accepted reference or true value;
- data precision – a measure of mutual agreement among individual measurements of the same property, usually expressed in terms of standard deviation;
- data representativeness – the degree to which data accurately and precisely represent a characteristic of a population, parameter variations at a sampling point, or an environmental condition;
- data completeness – a measure of the amount of valid data obtained from a measurement system compared to the amount that was planned; and
- data comparability – a measure of the confidence with which one data set can be compared to another.

The performance measure that addresses compliance with 40 CFR § 191(B) is the cumulative release of radionuclides to the accessible environment over the next 10,000 years. This measure is estimated using mathematical models. The performance assessment process requires the use of mathematical models for the repository, which, in general, require that parameters be assigned to geologic, hydrologic and waste properties. Since many of these parameters are not amenable to direct measurement, they must be treated as uncertain variables rather than precisely determined quantities, and they are characterized as probability distributions.

Data are used to develop conceptual models and support distributions for parameter values. Between the point of data collection and the final computational model, uncertainty is introduced (for example, experimental design, extrapolation of the experimental results to spatial or temporal scales, etc.). These parameter distributions may span several orders of magnitude, and many parameters derived from data measurements need to be known only within orders of magnitude of their true value.

Uncertainty and sensitivity analyses respectively assess the uncertainty in system performance measures and identify modeling areas and parameters in which reductions in uncertainty can increase confidence. If the uncertainty of a parameter is of importance to the performance of the WIPP, more data may be collected to reduce the uncertainty.

It is often not practicable to document the data quality characteristics for the scientific investigation and characterization of natural systems. As an example, data accuracy would be very difficult, if not impossible, to assess for geologic site characterization activities because reference or true values do not exist.

Instead of quality characteristics, other steps are used to ensure that data are of adequate quality. Upper-tier quality requirement documents specifically define QA requirements for the collection of scientific and technical information. Section 5 of the CBFO QAPD, Scientific Investigation

Requirements, identifies the current requirements and processes used for data collection. For inclusion in compliance calculations, the data must be collected under an approved QA plan or otherwise be qualified as existing data.

In summary, it is not practicable to apply data quality characteristics to most scientific investigations that are used to support a performance assessment in which there is uncertainty in the conceptual models and the resultant ranges of parameters. Instead, controls established by the QA program ensure the necessary quality.

5.3.23 Criterion 22 – Qualification of Data

Data can be qualified by using one or more of the following methods:

- data used in performance assessment have been obtained under an approved QA program that implements the QA requirements referenced in Section 5.2.1.2;
- existing data collected before the implementation of a qualified QA program have been qualified by showing that the data were obtained under a QA program that is equivalent to one satisfying the NQA requirements referenced in Section 5.2;
- existing data have been qualified by peer review conducted in a manner compatible with NUREG 1297, Peer Review for High-Level Nuclear Waste Repositories;
- corroborating data processes may also be used to qualify the data; or
- confirmatory testing may be performed.

For data qualified by the implementation of a QA program meeting the criteria of 40 CFR 194 (first method above), the supporting documents and controls include the QA plan, audits and surveillances of the work that produced the data, and other objective evidence of QA implementation. If the audits show the program to be adequate and effectively implemented, then the data may be qualified. If audits identify significant deficiencies, then data whose quality is affected by those deficiencies are not qualified until impact assessments are completed and corrective actions have been implemented and verified.

Peer reviews are performed when necessary to verify the technical adequacy of work done and to qualify data. The peer review process and peer reviews conducted to support data qualification are described in Chapter 9.0, Peer Review.

Corroborating data are existing data used to support or substantiate other existing data. Existing data may be qualified through the use of corroborating data. Inference drawn to corroborate the existing data needs to be clearly identified, justified, and documented. The level of confidence associated with corroborating data is related to the quality of the program under which it was developed and the number of independent data sets. The amount of corroborating data needed is determined on a case-by-case basis in the documented qualification reviews.

Confirmatory testing is testing conducted under a QA program that investigates the properties of interest (e.g., physical, chemical, geologic, mechanical) of an existing database. Existing data

may be qualified through confirmatory testing. One example of confirmatory testing is testing that is conducted under the same environmental conditions and with the same or similar procedures, test material, and equipment as the original test that generated the existing data. Another type of confirmatory testing is testing conducted by different test methods and equipment but which still investigates the same properties of interest. The amount of confirmatory testing required is determined on a case-by-case basis in the documented qualification reviews.

40 CFR §194.27, Peer Review, requires CBFO to conduct peer reviews on the following:

- conceptual models selected and developed by the Department;
- waste characterization analyses as required in §194.24(b); and
- engineered barrier evaluation as required in §194.44.

5.4 The Carlsbad Field Office Quality Assurance Program Document

5.4.1 Purpose of the Quality Assurance Program Document

The CBFO QAPD describes the QA program requirements that apply to programs and projects managed by the CBFO. This program-wide requirements document describes the TRU waste QA controls applicable to all program participants within the TRU waste management structure.

5.4.2 U.S. Environmental Protection Agency Requirements in the Quality Assurance Program Document

The QAPD meets all EPA criteria for those items important to the containment of TRU waste, including the following items and activities:

- waste characterization activities and assumptions;
- environmental monitoring, monitoring of disposal system performance, and sampling and analysis activities;
- field measurements of geological, groundwater, meteorologic, and topographic characteristics;
- computations, computer codes, models, and methods to demonstrate compliance with 40 CFR Part 194;
- procedures for implementation of expert judgment elicitation to support the applications for certification and recertification of compliance with 40 CFR Part 194;
- design of the disposal system and actions taken to ensure compliance with design specifications;
- collection of data and information to support compliance application(s); and

- other systems, structures, components, and activities important to the containment of waste in the disposal system.

5.4.3 Use of the Graded Approach

The use of a graded approach supports the proper implementation of QA program requirements for items and activities important to compliance with 40 CFR Part 191 Subparts B and C and 40 CFR Part 194. The grading process is described in Section 5.3.2.3.

5.4.4 Quality Assurance Program Document Implementation

Based upon requirements from the QAPD, program participants have developed, implemented, and assessed their management systems and controls to ensure that items, processes, and services meet or exceed applicable requirements.

The adequacy and the effectiveness of implementation of these management systems and controls are verified through audits and surveillances conducted by the DOE and the program participants. The audits and surveillances are used to assess the adequacy, implementation, and effectiveness of the individual QA programs. The adequacy, implementation, and effectiveness of the various TRU waste QA programs are discussed in Section 5.6.

5.4.5 Quality Assurance Program Document Changes

Limited changes to the QAPD have been made since submittal of the CCA. The changes have been made to clarify application of requirements because new source requirement documents have been added to the TRU waste program.

Additional changes incorporated into the QAPD include CBFO organization and responsibility changes. Clarifications have been made in the areas of grading, control of conditions adverse to quality, and the preparation and maintenance of commitment and guidance documents.

5.4.6 Quality Assurance Program Participant Support

The CBFO identifies the QA program requirements applicable to all WIPP participants through the QAPD. The QAPD requirements are further supported and amplified by CBFO and program participant implementing procedures.

In addition to identifying applicable QA requirements through program documents, the participating organizations conduct the following activities in support of the QA program:

- audits and surveillances (external and internal) to evaluate the adequacy, implementation, and effectiveness of the applicable QA programs; and

- development, approval, and issuance of participant implementing documents and the review and approval of lower-tier implementing documents.

5.4.7 Structure of the QAPD

The QA requirements for quality-affecting activities for all program participants (as applicable to the scope of work) are described in the six sections of the QAPD. The QAPD is presented in Appendix QAPD.

5.4.8 Quality Assurance Program Document Crosswalk to NQA-1, -2, and -3 Requirements

Table 5-1 presents a crosswalk of QAPD and NQA requirements.

Table 5-1. QAPD vs. NQA-1, -2, and -3 Requirements

Criteria	Title	QAPD Reference
NQA-1, Criterion 1	Organization	Section 1
NQA-1, Criterion 2	Quality Assurance Program	Section 1
NQA-1, Criterion 3	Design Control	Section 2.2
NQA-1, Criterion 4	Procurement Document Control	Sections 2.3.4 and 2.3.5
NQA-1, Criterion 5	Instructions, Procedures, and Drawings	Sections 1.4 and 2.1.2
NQA-1, Criterion 6	Document Control	Section 1.4
NQA-1, Criterion 7	Control of Purchased Items and Services	Section 2.3
NQA-1, Criterion 8	Identification and Control of Items	Section 2.1.3
NQA-1, Criterion 9	Control of Processes	Section 2.1
NQA-1, Criterion 10	Inspection	Section 2.4
NQA-1, Criterion 11	Test Control	Section 2.4.4
NQA-1, Criterion 12	Control of Measuring and Test Equipment	Section 2.4.6
NQA-1, Criterion 13	Handling, Storage, and Shipping	Section 2.1.5
NQA-1, Criterion 14	Inspection, Test, and Operating Status	Section 2.4
NQA-1, Criterion 15	Control of Nonconforming Items	Section 1.3.2
NQA-1, Criterion 16	Corrective Action	Section 1.3.3
NQA-1, Criterion 17	Quality Assurance Records	Section 1.5
NQA-1, Criterion 18	Audits	Section 3.2.2
NQA-2, Part 2.7, Criterion 19	Software Quality Assurance	Section 6
NQA-3, Criterion 20	Scientific Investigation	Section 5
NQA-3, Criterion 21	Data and Sample Management	Section 4
NQA-3, Criterion 22	Qualification of Data	Section 5

5.4.9 CBFO Implementing Procedures

The CBFO implements Sections 1.4 and 2.1.2 of the QAPD through the use of Management Procedures (MPs) and Team Procedures (TPs):

- MP – An implementing document that specifies the process (methods and controls) for performing activities.
- TP – An implementing document that specifies the process (methods and controls) for performing functional activities within a specific, singular organizational area.

CBFO procedures include:

- MP 1.2, Selection of Quality Levels;
- MP 2.1, Personnel Qualification and Training;
- MP 3.1, Corrective Action Reporting;
- TP 3.2, Trend Identification and Reporting;
- MP 4.1, Preparation and Maintenance of CBFO Procedures;
- MP 4.2, Document Review;
- MP 4.4, Document Preparation and Control;
- MP 4.5, Generating, Receiving, Storing, and Controlling Active CBFO Project Records;
- MP 4.6, Records Filing, Inventorying, Scheduling, and Dispositioning;
- MP 4.7, Disposal of Nonpermanent Records;
- MP 4.8, Records Transfer and Retrieval;
- MP 4.9, Quality Assurance Records;
- MP 4.10, Processing of TRU Waste Site Documents;
- MP 5.2, TRU Waste Site Certification/Recertification;
- MP 5.3, Correspondence Standards;
- MP 7.1, QA Requirements for Procurement of Services;
- MP 9.1, Management Assessment;
- TP 10.1, Qualification of Audit Personnel and Certification of Lead Auditors;
- MP 10.2, Surveillances;
- MP 10.3, Audits;

- MP 10.5, Peer Review; and
- MP 10.7, Operational Assessments.

5.5 Applicability of the QA Program

The CBFO QAPD establishes and describes the QA program requirements. The QA program applies to all CBFO and participant activities affecting quality for the containment of TRU waste in support of the WIPP, including the eight programmatic areas addressed for compliance application (40 CFR § 194.22(a)(2)) demonstration. The QA program has been established as described in this chapter. The following program participants have quality assurance programs approved by the CBFO:

- CBFO Technical Assistance Contractor (CTAC)
- Sandia National Laboratories (SNL) – Carlsbad
- Los Alamos National Laboratory (LANL)
- Los Alamos National Laboratory Carlsbad (LANL-CO)
- Hanford site
- Idaho National Engineering and Environmental Laboratory (INEEL)
- Rocky Flats Environmental Technology Sites (RFETS)
- Savannah River Site (SRS)
- Washington TRU Solutions (WTS)
- Central Characterization Project (CCP)
- Advanced Mixed Waste Treatment Project (AMWTP)
- Argonne National Laboratory – East (ANL-E)

5.5.1 Waste Characterization Activities and Assumptions

The transuranic waste is inventoried and updated to provide an inventory source of waste data used in the performance assessment.

The WAC serves as the primary directive for ensuring that only waste that meets the legal definition of defense TRU waste and can be safety transported, handled, and disposed of is received at the WIPP. The WAC also identifies criteria to ensure generator and storage sites properly certify waste. Revised waste acceptance criteria have been provided to the EPA. In addition, information pertaining to the radiological properties of the waste and other disposal information from the obsolete QAPP has been added to the WAC (See Appendix TRU WASTE).

The Performance Demonstration Program (PDP) is used to evaluate the capability of the generator and storage sites to perform NDA for TRU waste characterization within acceptable limits. Initially, participating laboratories were required to participate in the PDP twice per year. The DOE has reduced the required frequency from twice per year to once per year and described this change to the EPA in correspondence dated November 10, 1998, and April 22, 1999 (Docket A-98-49). Based on this information, the EPA determined that the changes reported did not require modification, suspension, or revocation of the initial certification (refer to Chapter 4, Section 4.3.3.1).

Following is a list of waste generator sites certified to ship waste to the WIPP.

- Nevada Test Site (using CCP) – as of August 2002,
- LANL – as of December 2002,
- Rocky Flats Environmental Technology Site – as of March 2003,
- INEEL – as of May 2003,
- Hanford Site – as of June 2003,
- SRS (using CCP) – as of October 2002,
- Argonne National Lab (East) (using CCP) – as of September 2002, and
- Advanced Mixed Waste Treatment Project – as of August 2003.

5.5.2 Environmental Monitoring, Monitoring of the Performance of the Disposal System, and Sampling and Analysis Activities

All environmental and performance monitoring activities related to compliance with the requirements of 40 CFR Part 191 Subparts B and C and 40 CFR Part 194 are described in Appendix MON 2004.

5.5.3 Design of the Disposal System and Actions Taken to Ensure Compliance with Design Specifications

A change to elevate the horizon at which Panels 3, 4, 5, 6, and 9 are mined was approved by the EPA on August 11, 2000. The change went through the design verification process to ensure compliance with identified requirements. Design controls specified in the WTS QAPD are in place to track and verify the design process. These controls ensure that new designs and design changes are subject to specifications commensurate with the original design and verify that the design analyses remain valid.

5.5.4 Collection of Data and Information to Support Compliance Application(s)

SNL collects information and data from experimental programs that serve multiple purposes in the WIPP project:

- Data relevant to the chemical or physical characteristics of the WIPP site;
- Data that allow estimation of the behavior of the wastes and the system during the 10,000-year regulatory period;
- To develop data to be used in testing alternative conceptual models and selecting the most appropriate model(s) of engineered system behavior for use in the performance assessment modeling process; and
- Scientific data collected in the areas of rock mechanics, actinide source term, chemical transport, disposal room, gas generation, non-Salado flow and transport, Salado Formation hydrology and transport.

5.6 Quality Assurance Program Adequacy, Implementation, and Effectiveness

Audits and other assessments are scheduled and conducted to verify the adequacy, implementation, and effectiveness of the QA program. The DOE, SNL, LANL-CO, and WTS QA programs have been determined to be adequate and effectively implemented in accordance with adequate procedures that meet the CBFO QAPD.

The CBFO maintains and implements an assessment schedule to assess initial and continuing CBFO, SNL, LANL-CO, WTS, and TRU waste generator site QA program adequacy, implementation, and effectiveness. Assessment scheduling is a dynamic process that requires frequent changes to respond to DOE and participant needs. The CBFO assessment schedule is updated monthly and is distributed to WIPP participants and other stakeholders. The assessment schedule accommodates the routine, recurring, and any focused or special purpose assessments that are determined to be appropriate by management.

5.6.1 Adequacy of the Quality Assurance Program

The adequacy of the QA program refers to an approved and documented QA program that meets the applicable requirements addressed in the CBFO QAPD. Adequacy is determined by the review of participant QA programs to ensure that upper-tier requirements have been incorporated into the appropriate documents.

The flow-down of requirements in the established QA program is presented in Figure 5-1. Organizations establishing a QA program or making changes to an established program must evaluate all the requirements addressed in the CBFO QAPD for applicability to their activities and document these criteria in new or revised implementing documents in order to meet the applicable requirements.

The adequacy of the documented QA program and any changes to an established QA program are verified before performing independent reviews for implementation and effectiveness (e.g., determining whether the documentation addresses the proper migration of requirements from the QAPD into the implementing documents).

5.6.2 Implementation of the Quality Assurance Program

Implementation of a QA program is determined by the extent to which the organization complies with its QA and technical procedures. QA program implementation is verified during audits and assessments of the program. Audits are scheduled to begin as early in the life of a project or activity as practicable and continue at intervals consistent with the schedule for accomplishing the work and commensurate with the assigned control levels. Audits, surveillances, management assessments, and other reviews are conducted to determine the acceptability of the procedural implementation.

5.6.3 Effectiveness of the Quality Assurance Program

Effectiveness refers to a process that produces the desired (specified) end-product or end-service. Effectiveness can be determined by:

- Technical Specialists being used to determine the effectiveness of technical processes and documents,
- management assessments being used to determine continued effectiveness, and
- trend analysis data and other information being used to assure process effectiveness.

5.7 The Carlsbad Field Office Audit Process

5.7.1 Overview of the Carlsbad Field Office Assessment Processes

Audits are conducted of CBFO activities (internal audits) and activities performed by organizations outside the CBFO (external audits). External organizations include the WTS, SNL, LANL, TRU waste sites, and other program participants conducting work for the CBFO. The audits are conducted to assess QA and technical activities that relate to regulatory compliance, safety, certification, transportation, and waste isolation.

The CBFO QA Manager coordinates with the CBFO assistant managers to identify appropriate assessments. These assessments are included in the CBFO assessment schedule. The following factors are considered when scheduling audits:

- work activities, level of effort, risk, and importance to regulatory compliance, safety, TRU waste site certification, or waste isolation issues;
- reviews of documentation furnished by, or regarding the work of, the organization or supplier (e.g., certificates of conformance, nonconforming notices, and corrective actions);
- consideration of previous assessment results, trends, corrective actions, effectiveness, and ancillary information (e.g., information from other sources such as industry or other DOE organizations, and regulatory agencies);

- reviews of previous assessments from identical or similar products or services furnished by the same organization or supplier; and
- results of surveillance activities.

Scheduled audits are supplemented, as necessary, to provide continuing coverage of work activities for any of the following reasons:

- to determine the adequacy, implementation, and effectiveness of contractor activities after contract award;
- to assess the impact of any significant changes made to a program or organizational structure;
- to evaluate the cause and impact of any declining trends in quality performance; and
- to verify implementation of extensive, large-scale corrective action activities.

Audit Team Leaders are selected from a list of certified Lead Auditors. The Audit Team Leader selects qualified Auditors and Technical Specialists, as required to meet the scope of the audit. The members of the audit team are selected based on independence from the organization or activities being audited. They have sufficient authority and organizational freedom to objectively conduct the audit.

The Audit Team Leader develops the audit plan and obtains the approval of the CBFO QA Manager. An audit notification letter addressed to the key auditee individual is transmitted to the organization to be audited. The Audit Team Leader provides audit team orientation and notifies any observers. Audit team members prepare the audit checklists, which are approved by the Audit Team Leader. The Audit Team Leader forwards the approved checklists to the audited organization before the audit.

The Audit Team Leader conducts the preaudit meeting and manages the conduct of the audit. The audit team meets daily to discuss audit concerns, status, and exemplary practices. Results are summarized and discussed. A daily meeting is held with the management of the audited organization(s) to inform them of any audit results and the audit status. Deficiencies are documented on Corrective Action Reports (CARs). Isolated deficiencies corrected during the audit are documented as “corrected during the audit” (CDAs). CDAs are documented in the audit report for trending purposes.

The audit report is prepared by the Audit Team Leader and submitted to the CBFO QA Manager for review and approval. The CBFO QA Manager distributes the report to the CBFO Manager, the appropriate management of the audited organization, the responsible CBFO assistant managers, the EPA, the State of New Mexico, and other interested parties in a timely manner.

5.7.2 Auditor and Technical Specialist Independence

Independent assessments of program participants are performed by Lead Auditors, Auditors, and Technical Specialists who are independent of the work and organization being assessed.

Whenever audit team independence may be an issue, a mitigation procedure is utilized to provide alternatives and controls to ensure that audit team independence is achieved and maintained. Examples of mitigation controls include the reassignment of personnel, Audit Team Leader discussions relative to independence with audit team members, and an Audit Team Leader review of the activities and results of those performing the audits. In the event that an audit team member has performed program development activities for a program participant, the individual is not permitted to perform audit activities in those areas until a subsequent independent audit has been performed of those activities (usually one year).

5.7.3 Audit History

The assessment summaries in Tables AUD-1 through AUD-11 of Appendix AUD 2004 reflect assessments that have been performed from 1999 to 2003 of TRU waste generator sites, SNL, LANL-CO, WTS, suppliers performing quality-affecting work, and the CBFO.

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U.S. Department of Energy (DOE). 2003. CBFO Quality Assurance Program Document, DOE/CBFO-94-1012. Carlsbad, NM.

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6.0 CONTAINMENT REQUIREMENTS

6.0.1 Introduction

Because of the amount and complexity of the material presented in Chapter 6.0, an introductory summary is provided below. Detailed discussions of the topics covered in this summary are found in the remainder of the chapter, which is organized as follows.

- Section 6.1 – The overall system performance assessment (PA) methodology used to evaluate compliance with the containment requirements.
- Section 6.2 – A comprehensive list of features, events, and processes (FEPs) that might affect disposal system performance, the screening methodology applied to that list, and the results of the screening process.
- Section 6.3 – Development of the scenarios considered in the system-level consequence analysis.
- Section 6.4 – The conceptual and computational models used to perform the system-level consequence analysis PA, the overall flow of information in the PA, the scenario probabilities, and the construction of a performance measure for comparison with the standard.
- Section 6.5 – The results of the PA.

Additional information supporting this chapter is provided in appendices. See Table 1-1 for a list of these appendices.

The U.S. Department of Energy (DOE) continues to use the same PA methodology for the recertification of WIPP. In general, changes that have been made since the U.S. Environmental Protection Agency (EPA) certified WIPP do not impact PA methodology.

6.0.2 Overview of Chapter 6.0

The EPA determined that the WIPP is in compliance with the Containment Requirements of Title 40 Code of Federal Regulations (CFR) § 191.13 in 1998 (EPA 1998a). The DOE has conducted a new PA for the WIPP. The WIPP Land Withdrawal Act (LWA), Public Law 02-579 as amended by Pubic Law No. 104-201, requires DOE to provide the EPA with documentation of continued compliance with the disposal standards within five years of first waste receipt and every five years thereafter. During review of the initial certification application, EPA required many changes to PA parameters, which have been included in the PA for this recertification application (EPA 1998b). The DOE has also made additional changes to the PA to better represent repository features, such as panel closures, and to account for new information. Table 6-1 summarizes the changes to the PA since the Compliance Certification Application (CCA); additional information is provided in Appendix PA (Attachment MASS, Section 2).

Table 6-1. WIPP Project Changes and Cross References

WIPP Project Change	Cross Reference
Incorporation of 1997 Performance Assessment Verification Test (PAVT) Parameters	
Credit for Passive Institutional Controls	6.4.12.1
K_d (Dissolved-Actinide Matrix Distribution Coefficient)	6.0.2.3.7, 6.4.6.2.2
Probability of Encountering a Brine Reservoir	6.0.2.3.8, 6.4.8, 6.4.12.6
Brine Reservoir Rock Compressibility	6.4.8
Brine Reservoir Porosity	6.4.8
Drill String Angular Velocity	Appendix PA, Attachment MASS (Section16) and Attachment PAR
Waste Permeability	6.4.3.2
Waste Unit Factor	Appendix TRU WASTE
Long-term Borehole Permeability	6.4.7.2
Borehole Plug Permeability	6.4.7.2
Waste Shear Strength and Erodability	Appendix PA, Attachment MASS (Section 16)
DRZ	6.4.5.3, 6.4.10.1
Actinide Solubility	6.4.3.5
Inundated Steel Corrosion Rate	6.4.3.3
Operational Changes	
Option D Panel Closure	6.4.3, 6.4.4
Inventory Update	6.4.3.1, 6.4.3.3
Culebra Water Levels	6.4.6.2, and Appendix PA, Attachment MASS
Spallings Model	6.0.2.3.2; Appendix PA (Section 4.6) and Attachment MASS (Section 16.0)
Drilling Rate	6.0.2.3, 6.2.5.2; Appendix DATA (Section 2 and Attachment A)
Organic Ligands	6.0.2.3.4, 6.4.3.4; Appendix PA, Attachments SOTERM and SCR
FEPs Reassessment	6.2.6; Appendix PA, Attachment SCR
Borehole Plugs Configuration Probability	6.4.7.2
Mining Disposal Horizon to Clay G	Appendix PA, Attachment MASS (Section 20)

From this assessment, the DOE has demonstrated that the WIPP continues to comply with the Containment Requirements of 40 CFR § 191.13. The Containment Requirements are stringent and state that the DOE must demonstrate a reasonable expectation that the probabilities of cumulative radionuclide releases from the disposal system during the 10,000 years following closure will fall below specified limits. The PA analyses supporting this determination must be quantitative and consider uncertainties caused by all significant processes and events that may affect the disposal system, including future inadvertent human intrusion into the repository. A

quantitative PA is conducted using a series of linked computer models in which uncertainties are addressed by a Monte Carlo procedure for sampling selected input parameters.

As required by regulation, results of the PA are displayed as complementary cumulative distribution functions (CCDFs) that display the probability that cumulative radionuclide releases from the disposal system will exceed the values calculated for scenarios considered in the analysis. These CCDFs are calculated using reasonable and, in some cases conservative conceptual models based on the scientific understanding of the disposal system's behavior. Parameters used in these models are derived from experimental data, field observations, and relevant technical literature. Changes to the CCA's parameters and models that have been necessary since the original certification have been incorporated into the PA. Information on the waste already disposed and new estimates of current and projected waste inventories are also incorporated. The overall mean CCDF continues to lie entirely below the specified limits, and the WIPP therefore continues to be in compliance with the containment requirements of 40 CFR Part 191, Subpart B (see Section 6.5.2, Figure 6-1). Sensitivity analysis of results shows that the location of the mean CCDF is dominated by radionuclide releases that could occur on the surface during an inadvertent penetration of the repository by a future drilling operation. Releases of radionuclides to the accessible environment resulting from transport in groundwater through the shaft seal systems and the subsurface geology are resulting negligible, with or without human intrusion, and make no contribution to the location of the mean CCDF. No releases whatsoever are predicted to occur at the ground surface in the absence of human intrusion. The natural and engineered barrier systems of the WIPP provide robust and effective containment of transuranic (TRU) waste even if the repository is penetrated by multiple boreholes.

A list of changes and a citation to where they are discussed is shown in Table 6-1.

6.0.2.1 Conceptual Basis for the Performance Assessment

The foundations of PA are a thorough understanding of the disposal system and the possible future interactions of the repository, waste, and surrounding geology. The recertification application is organized so that site characterization, facility design, and waste characterization are described separately in Chapters 2.0, 3.0, and 4.0, respectively. The DOE's confidence in the results of the recertification PA is based in part on the strength of the original research done during site characterization, experimental results used to develop and confirm parameters and models, the robustness of the facility design, and the knowledge of the updated inventory. Quality assurance (QA) activities, described in Chapter 5.0, demonstrate that the information gathered during these activities is qualified to meet the QA criteria in 40 CFR 194.

Chapters 2.0, 3.0, and 4.0 provide basic descriptions of the disposal system main components. The interactions of the repository and waste with the geologic system, and the response of the disposal system to possible future inadvertent human intrusion, are described in Section 6.4.

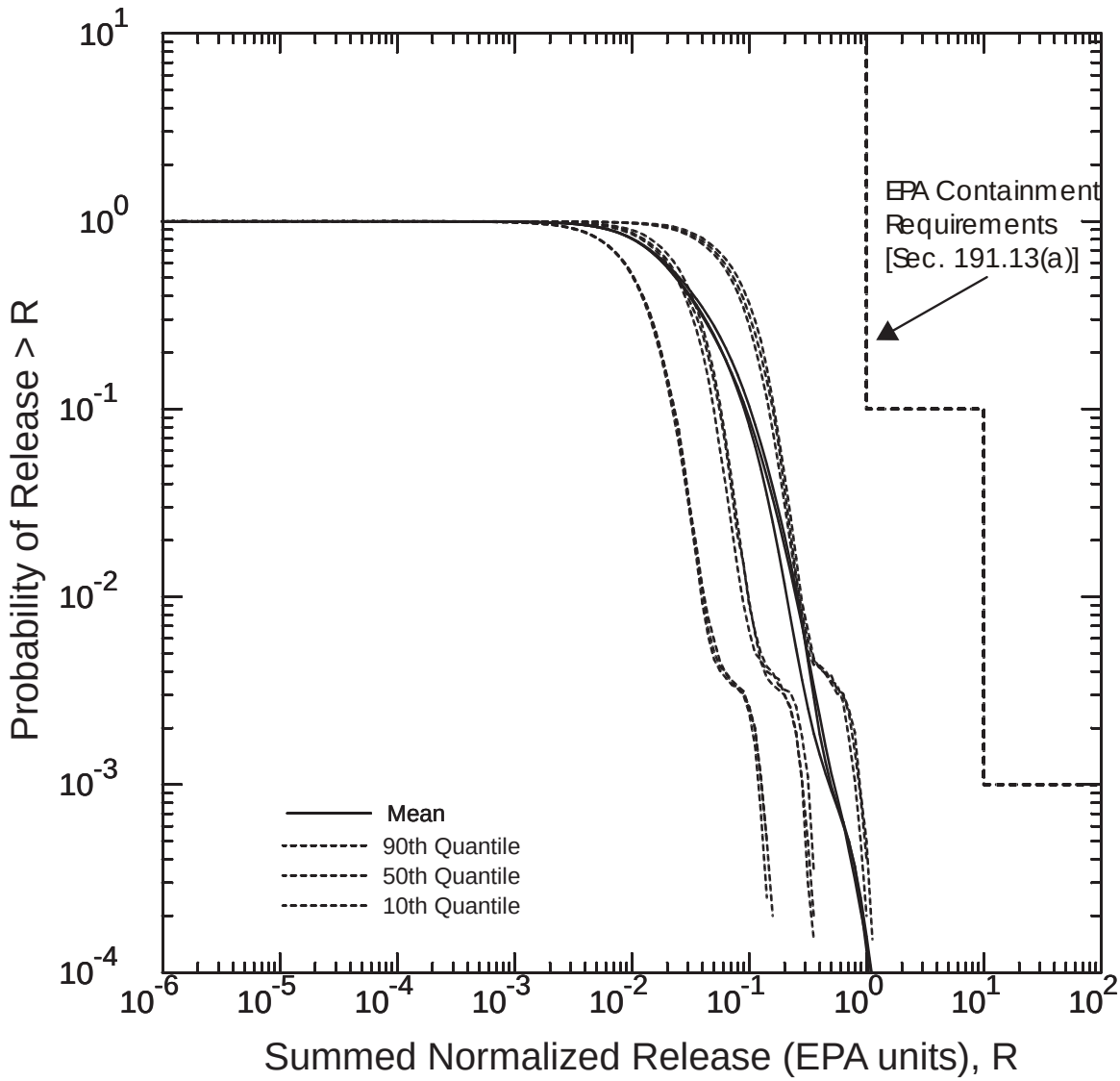

Note: Mean, median, and 10th and 90th percentile CCDFs are shown together with the overall mean. These CCDFs are based on the distributions of CCDFs shown in Figure 6-34, 6-35, and 6-36.

Figure 6-1. Summary CCDFs for Replicates 1, 2, and 3

6.0.2.2 Undisturbed Performance

An evaluation of undisturbed performance, which is defined to exclude human intrusion and unlikely disruptive natural events, is required by regulation (see Sections 191.15 and § 191.24). Evaluation of past and present natural geologic processes in the region indicate that none has the potential to breach the repository within 10,000 years. Disposal system behavior is dominated by the coupled processes of rock deformation surrounding the excavation, fluid flow, and waste degradation. Each of these processes can be described independently, but the extent to which each process occurs is affected by the others.

Deformation of the rock immediately around the repository begins as soon as excavation creates a disturbance in the stress field. Stress relief results in some degree of brittle fracturing and the

formation of a disturbed rock zone (DRZ), which surrounds excavations in all deep mines, including the repository. For the WIPP, the DRZ is characterized by an increase in permeability and a decrease in pore pressure, and may ultimately extend a few meters from the excavated region. Salt will also deform by creep processes, which are a result of deviatoric stress, causing the materials to move inward to fill voids. Salt creep will continue until deviatoric stress is dissipated and the system is once again at stress equilibrium.

The ability of salt to creep, thereby healing fractures and filling porosity, is one of its fundamental advantages as a medium for geologic disposal of radioactive waste and one reason it was recommended by the National Academy of Sciences (NAS). Salt creep provides the mechanism for crushed salt compaction in the shaft seal system, yielding properties approaching those of intact salt within 200 years. Salt creep will also cause the DRZ surrounding the shaft to heal rapidly around the concrete components of the seal system. In the absence of elevated gas pressure in the repository, salt creep would also substantially compact the waste and heal the DRZ around the disposal region. The coupling of salt creep with fluid flow and waste degradation processes results in fluid pressure within the waste disposal region maintaining significant porosity within the disposal region throughout the performance period.

Characterization of the Salado Formation (hereafter referred to as the Salado) indicates that fluid flow does not occur on time scales of interest in the absence of an artificially imposed hydraulic gradient. This lack of fluid flow is the second fundamental reason for the choice of salt as a medium for geologic disposal of radioactive waste. Lack of fluid flow is a result of the extremely low permeability of the evaporite rocks that make up the Salado. Excavation of the repository has disturbed the natural hydraulic gradient and rock properties and has resulted in fluid flow. Small quantities of interstitial brine present in the Salado move toward regions of low hydraulic potential and brine seeps are observed in the underground. The slow flow of brine from halite into more permeable anhydrite marker beds and then through the DRZ into the repository is expected to continue as long as the hydraulic potential within the repository is below that of the far field. The repository environment will also involve gas, and fluid flow that must be modeled as a two-phase process. Initially, the gaseous phase will consist primarily of air trapped at the time of closure, although other gases may form from waste degradation. In the PA, the gaseous phase pressure will rise due to creep closure, gas generation, and brine inflow, creating the potential for flow from the excavated region.

Consideration of waste degradation processes indicates that the gaseous phase in fluid flow and the repository's pressure history will be far more important than if the initial air were the only gas present. Waste degradation can generate significant additional gas by two processes:

1. the generation of hydrogen (H_2) gas by anoxic corrosion of steels, other iron-base (Fe-based) alloys, and aluminum (Al) and Al-based alloys, and

2. the generation of carbon dioxide (CO_2) and methane (CH_4) by anaerobic microbial consumption of waste containing cellulosic, plastic, or rubber materials.

Coupling these gas-generation reactions to fluid flow and salt creep processes is complex. Gas generation will increase fluid pressure in the repository, thereby decreasing the hydraulic gradient and deviatoric stress between the far field and the excavated region and inhibiting the

processes of brine inflow and salt creep. Anoxic corrosion will also consume brine as it breaks down water to oxidize steels and other Fe-based alloys and release H_2. Thus, corrosion has the potential to be a self-limiting process, in that as it consumes all water in contact with steels and other Fe-based alloys, it will cease. Microbial reactions also require water, either in brine or the gaseous phase. It is assumed that microbial reactions will result in neither the consumption nor production of water.

The total volume of gas generated by corrosion and microbial consumption may be sufficient to result in repository pressures that approach lithostatic. Sustained pressures above lithostatic are not physically reasonable within the disposal system, and fracturing of the more brittle anhydrite layers is expected to occur if sufficient gas is present. The conceptual model implemented in the PA causes permeability and porosity of the anhydrite marker beds to increase rapidly as pore pressure approaches and exceeds lithostatic. This conceptual model for pressure-dependent fracturing approximates the hydraulic effect of pressure-induced fracturing and allows gas and brine to move more freely within the marker beds at higher pressures.

Overall, the behavior of the undisturbed disposal system will result in extremely effective isolation of the radioactive waste. Concrete, clay, and asphalt components of the shaft seal system will provide an immediate and effective barrier to fluid flow through the shafts, isolating the repository until salt creep has consolidated the compacted crushed salt components and permanently sealed the shafts. Around the shafts, the DRZ in halite layers will heal rapidly because the presence of the solid material within the shafts will provide rigid resistance to creep. The DRZ around the shaft, therefore, will not provide a continuous pathway for fluid flow. Similarly, the Option D panel closure will provide rigid resistance to creep and rapidly eliminate the DRZ locally by a compressive state of stress. The DRZ is not expected to heal completely around the disposal region, or the operations and experimental regions, and pathways for fluid flow may exist indefinitely to the overlying and underlying anhydrite layers (e.g., Marker Bed (MB)139 and anhydrites a and b). Some quantity of brine will be present in the repository under most conditions and may contain actinides (which dominate the radionuclide inventory and are therefore the elements of primary regulatory interest) mobilized as both dissolved and colloidal species. Gas generation by corrosion and microbial degradation is expected to occur and will result in elevated pressures within the repository. These pressures will not significantly exceed lithostatic, because fracturing within the more brittle anhydrite layers will occur and provide a pathway for gas to leave the repository. Fracturing due to high gas pressures may enhance gas and brine migration from the repository, but gas transport will not contribute to the release of actinides from the disposal system. Brine flowing out of the waste disposal region through anhydrite layers may transport actinides as dissolved and colloidal species, but the quantity of actinides that may reach the accessible environment boundary during undisturbed performance through the interbeds is insignificant and has no effect on the compliance determination. No migration of radionuclides whatsoever is expected to occur vertically through the Salado or through the shaft seal system.

6.0.2.3 Disturbed Performance

Performance assessment is required by regulation to consider scenarios that include intrusions into the repository by inadvertent and intermittent drilling for resources. In the CCA, the probability of these intrusions was based on a future drilling rate of 46.8 boreholes per square

kilometer per 10,000 years. This rate was based on the past record of drilling events in the Delaware Basin, consistent with regulatory criteria. Since the CCA, additional drilling in the Delaware Basin has raised the drilling rate to 52.5 boreholes per square kilometer per 10,000 years (see Appendix DATA, Section DATA-2.0 and Attachment A). Active institutional controls are assumed to be completely effective in preventing intrusion during the first 100 years after closure. Passive institutional controls were originally assumed in the CCA to effectively reduce the drilling rate by two orders of magnitude for the 600 years following the 100 years of active control. However, in certifying the WIPP, EPA denied the application of credit for the effectiveness of passive controls for 600 years. Although the Compliance Recertification Application 2004 PA (2004 PA) does not include a reduced drilling intrusion rate to account for passive institutional controls, future PA may do so. Future drilling practices are assumed to be the same as current practice, also consistent with regulatory criteria. These practices include the type and rate of drilling, emplacement of casing in boreholes, and the procedures implemented when boreholes are plugged and abandoned.

PA results indicate that human intrusion provides the only potential mechanism for significant releases of radionuclides from the disposal system. These releases could occur by five mechanisms:

(1) cuttings, which include material intersected by the rotary drilling bit;

(2) cavings, which include material eroded from the borehole wall during drilling;

(3) spallings, which include solid material carried into the borehole during rapid depressurization of the waste disposal region;

(4) direct brine releases, which include contaminated brine that may flow to the surface during drilling; and

(5) long-term brine releases, which include the contaminated brine that may flow through a borehole after it is abandoned.

The first four mechanisms operate immediately following the intrusion event and are collectively referred to as direct releases. The accessible environment boundary for these releases is the ground surface. The fifth mechanism, actinide transport by long-term groundwater flow, begins when concrete plugs are assumed to degrade in an abandoned borehole and may continue throughout the regulatory period. The accessible environment boundary for these releases may be the ground surface or the lateral subsurface limit of the controlled area.

Repository conditions prior to intrusion will be the same as those for undisturbed performance and all processes active in undisturbed performance will continue to occur following intrusion. Because intrusion provides a pathway for radionuclides to reach the ground surface and to enter the geological units above the Salado, additional processes will occur that are less important in undisturbed performance. These processes include the mobilization of radionuclides as dissolved and colloidal species in repository brine and groundwater flow, and actinide transport in the overlying units. Flow and transport in the Culebra Member of the Rustler Formation (hereafter referred to as the Rustler) are of particular interest because modeling indicates this is the unit to which most flow from a borehole may occur.

6.0.2.3.1 Cuttings and Cavings

In a rotary drilling operation, the volume of material brought to the surface as cuttings is calculated as the cylinder defined by the thickness of the unit and the diameter of the drill bit. The quantity of radionuclides released as cuttings is therefore a function only of the intersected waste activity and the diameter of the intruding drill bit. Like all parameters that describe future drilling activities, the diameter of a drill bit that may intersect waste is speculative. The DOE uses a constant value of 0.311 m (12.25 in.), consistent with bits currently used at the WIPP depth in the Delaware Basin. The intersected waste activity may vary depending on the type of waste intersected, and the DOE considers random penetrations into remote-handled (RH)-TRU waste and each of the 693 different waste streams identified for contact-handled (CH)-TRU waste (569 waste streams were used in the CCA).

The volume of particulate material eroded from the borehole wall by the drilling fluids and brought to the surface as cavings may be affected by the drill bit diameter, the effective shear resistance of the intruded material, the speed of the drill bit, the viscosity of the drilling fluid and the rate at which it is circulated in the borehole, and other properties related to the drilling process. The most important of these parameters, after drill bit diameter, is the effective shear resistance of the intruded material. In the absence of data describing the reasonable and realistic future properties of degraded waste and magnesium oxide (MgO), the DOE used conservative parameter values based on the properties of fine-grained sediment. Other properties are assigned fixed values consistent with current practice. The quantity of radionuclides released as cavings depends on the volume of eroded material and its activity, which is treated in the same manner as the activity of the cuttings.

6.0.2.3.2 Spallings

Unlike releases from cuttings and cavings, which occur with every modeled borehole intrusion, spalling releases will occur only if pressure in the waste-disposal region exceeds the hydrostatic pressure in the borehole. At lower pressures, below about 8 megapascals, fluid in the waste-disposal region will not flow toward the borehole. At higher pressures, gas flow toward the borehole may be sufficiently rapid to cause additional solid material to enter the borehole. If spalling occurs, the volume of spalled material will be affected by the physical properties of the waste, such as its tensile strength and particle diameter. The DOE has based the parameter values used in the PA on reasonable and conservative assumptions. Since the original certification, a revised conceptual model for the spallings phenomena has been developed (see Appendix PA, Section 4.6 and Attachment MASS, Section 16). Model development, execution, and sensitivity studies necessitated implementing parameter values pertaining to waste characteristics, drilling practices and physics of the process. The parameter range for particle size was derived by expert elicitation (EPA 1997, II-G-24).

The quantity of radionuclides released as spalled material depends on the volume of spalled waste and its activity. Because spalling may occur at a greater distance from the borehole than cuttings and cavings, spalled waste is assumed to have the volume-averaged activity of CH-TRU waste rather than the sampled activities of individual waste streams. RH-TRU waste is isolated from the spallings process and does not contribute to the volume or activity of spalled material.

6.0.2.3.3 Direct Brine Flow

Radionuclides may be released to the accessible environment if repository brine enters the borehole during drilling and flows to the ground surface. The quantity of radionuclides released by direct brine flow depends on the volume of brine reaching the ground surface and the concentration of radionuclides contained in the brine. As with spallings, direct releases of brine will not occur if repository pressure is below the hydrostatic pressure in the borehole. At higher repository pressures, mobile brine present in the repository will flow toward the borehole. If the volume of brine flowing from the repository into the borehole is small, it will not affect the drilling operation, and flow may continue until the driller reaches the base of the evaporite section and installs casing in the borehole. This time is estimated to be 72 hours, consistent with current practice. Larger brine flows or large gas flows could cause the driller to lose control of the borehole, and fluid flow, in this case, could continue until repository pressure drops or the hole is contained. The maximum length of time that such flow could continue before the driller controlled the borehole is estimated to be 11 days, consistent with observed drilling events in the Delaware Basin (Appendix PA, Section PA-4.7.8 and Attachment MASS, Section 16.0).

6.0.2.3.4 Mobilization of Actinides in Repository Brine

Actinides may be mobilized in repository brine in two principal ways:

(1) as dissolved species, and

(2) as colloidal species.

The solubilities of actinides depend on their oxidation states, with the more reduced forms (for example, the +III and +IV oxidation states) being less soluble than the oxidized forms (+V and +VI). Conditions within the repository will be strongly reducing because of the large quantity of metallic Fe in the steel containers and the waste, and – in the case of plutonium (Pu) – only the lower-solubility oxidation states (Pu(III) and Pu(IV)) will persist. Microbial activity, if it occurs, will also create reducing conditions. Solubilities also vary with pH. The DOE is therefore emplacing MgO in the waste-disposal region to ensure conditions that favor minimum actinide solubilities. MgO consumes CO_2 and buffers pH, lowering actinide solubilities in WIPP brines. Solubilities in the PA are based on the chemistry of brines that might be present in the waste-disposal region, reactions of these brines with the MgO engineered barrier, and strongly reducing conditions produced by anoxic corrosion of steels and other Fe-based alloys.

The waste contains organic ligands that could increase actinide solubilities by forming complexes with dissolved actinide species. However, these organic ligands also form complexes with other dissolved metals, such as magnesium (Mg), calcium (Ca), Fe, vanadium (V), chromium (Cr), manganese (Mn), and nickel (Ni), that will be present in repository brines due to corrosion of steels and other Fe-based alloys. The CRA-2004 PA speciation and solubility calculations (Attachment SOTERM) confirmed that actinide solubilities are not significantly affected by organic ligands.

Colloidal transport of actinides has been examined and four types have been determined to represent the possible behavior at the WIPP. These include microbial colloids, humic substances, actinide intrinsic colloids, and mineral fragments. Concentrations of actinides

mobilized as these colloidal forms are included in the estimates of total actinide concentrations used in PA.

6.0.2.3.5 Long-Term Brine Flow up an Intrusion Borehole

Long-term releases to the ground surface or groundwater in the Rustler or overlying units may occur after the borehole has been plugged and abandoned. In keeping with regulatory criteria, borehole plugs are assumed to have properties consistent with current practice in the basin. Thus, boreholes are assumed to have concrete plugs emplaced at various locations. Initially, concrete plugs effectively limit fluid flow in the borehole. However, under most circumstances, these plugs cannot be expected to remain fully effective indefinitely. For the purposes of PA, discontinuous borehole plugs above the repository are assumed to degrade 200 years after emplacement. From then on, the borehole is assumed to fill with a silty sand-like material containing degraded concrete, corrosion products from degraded casing, and material that sloughs into the hole from the walls. Of six possible plugged borehole configurations in the Delaware Basin, three are considered either likely or found to adequately represent other possible configurations; one configuration (a two-plug configuration) is explicitly modeled.

If sufficient brine is available in the repository, and if pressure in the repository is higher than in the overlying units, brine may flow up the borehole following degradation of the plugs. In principle, this brine could flow into any permeable unit or to the ground surface if repository pressure were high enough. For modeling purposes, brine is allowed to flow only into the higher permeability units and to the surface. Lower permeability anhydrite and mudstone layers in the Rustler are treated as if they were impermeable, to simplify the analysis while maximizing the amount of flow occurring into units where it could potentially contribute to releases from the disposal system. Model results indicate that essentially all flow occurs into the Culebra, which has been recognized since the early stages of site characterization as the most transmissive unit above the repository and the most likely pathway for subsurface transport.

6.0.2.3.6 Groundwater Flow in the Culebra

Site characterization activities in the units above the Salado have focused on the Culebra. These activities have shown that the direction of groundwater flow in the Culebra varies somewhat regionally, but in the area that lies over the site, flow is southward. Regional variation in groundwater flow direction in the Culebra is influenced by the transmissivity observed and also by the shape of and distribution of rock types in the groundwater basin where the WIPP is located. Site characterization activities have demonstrated that there is no evidence of karst groundwater systems in the controlled area, although groundwater flow in the Culebra is affected by the presence of fractures, fracture fillings, and vuggy pore features. Other laboratory and field activities have focused on the behavior of dissolved and colloidal actinides in the Culebra. These characterization and modeling activities conducted in the units above the Salado confirm that the Culebra is the most transmissive unit above the Salado. The Culebra is the unit into which actinides are likely to be introduced from long-term flow up an abandoned borehole.

Basin-scale regional modeling of three-dimensional groundwater flow in the units above the Salado demonstrates that it is appropriate, for the purposes of estimating radionuclide transport, to conceptualize the Culebra as a two-dimensional confined aquifer. Uncertainty in the flow

field is incorporated in the analysis by using 100 different geostatistically-based transmissivity fields, each of which is consistent with available head and transmissivity data.

Groundwater flow in the Culebra is modeled as a steady-state process, but two mechanisms considered in the PA could affect flow in the future. Potash mining in the McNutt Potash Zone (hereafter referred to as the McNutt) of the Salado, which occurs now in the Delaware Basin outside the controlled area and may continue in the future, could affect flow in the Culebra if subsidence over mined areas causes fracturing or other changes in rock properties. Climatic changes during the next 10,000 years may also affect groundwater flow by altering recharge to the Culebra.

Consistent with regulatory criteria, mining outside the controlled area is assumed to occur in the near future, and mining within the controlled area is assumed to occur with a probability of 1 in 100 per century (adjusted for the effectiveness of active institutional controls during the first 100 years following closure). Consistent with regulatory guidance, the effects of mine subsidence are incorporated in the PA by increasing the transmissivity of the Culebra over the areas identified as mineable by a factor sampled from a uniform distribution between 1 and 1000. Transmissivity fields used in the PA are therefore adjusted and steady-state flow fields calculated accordingly; once for mining that occurs only outside the controlled area, and once for mining that occurs both inside and outside the controlled area. Mining outside the controlled area is considered in both undisturbed and disturbed performance.

The extent to which the climate will change during the next 10,000 years and how such a change will affect groundwater flow in the Culebra are uncertain. Regional three-dimensional modeling of groundwater flow in the units above the Salado indicates that flow velocities in the Culebra may increase by a factor of 1 to 2.25 for reasonably possible future climates. This uncertainty is incorporated in the PA by scaling the calculated steady-state specific discharge within the Culebra by a sampled parameter within this range.

6.0.2.3.7 Actinide Transport in the Culebra

Field tests have shown that the Culebra is best characterized as a double-porosity medium for estimating contaminant transport in groundwater. Groundwater flow and advective transport of dissolved or colloidal species and particles occurs primarily in a small fraction of the rock's total porosity and corresponding to the porosity of open and interconnected fractures and vugs. Diffusion and slower advective flow occur in the remainder of the porosity, which is associated with the low-permeability dolomite matrix. Transported species, including actinides, if present, will diffuse into this porosity.

Diffusion from the advective porosity into the dolomite matrix will retard actinide transport by two mechanisms. Physical retardation occurs simply because actinides that diffuse into the matrix are no longer transported with the flowing groundwater. Transport is interrupted until they diffuse back into the advective porosity. In situ tracer tests have been conducted to demonstrate this phenomenon. Chemical retardation also occurs within the matrix as actinides are sorbed onto dolomite grains. The relationship between sorbed and liquid concentrations is assumed to be linear and reversible. The distribution coefficients (K_ds) that characterize the extent to which actinides will sorb on dolomite were based on experimental data. Based on their

review of the CCA, the EPA required the DOE to use the same ranges but to change the distribution from uniform to log uniform. The DOE continues to use EPA's distributions in CRA-2004 PA. The DOE also corrected a minor error in the calculation of K_ds (see Appendix PA, Attachment PAR).

Modeling indicates that physical and chemical retardation, as supported by field tests and laboratory experiments, will be extremely effective in reducing the transport of dissolved actinides in the Culebra. Experimental work has demonstrated that transport of colloidal actinides is not a significant mechanism in the Culebra. As a result, actinide transport through the Culebra to the subsurface boundary of the controlled area is not a significant pathway for releases from the WIPP. As discussed in Section 6.5.3, the location of the mean CCDF that demonstrates compliance with the containment requirements of 40 CFR § 191.13 is, determined entirely by direct releases at the ground surface during drilling (cuttings, cavings, and spallings).

6.0.2.3.8 Intrusion Scenarios

Human intrusion scenarios evaluated in the PA include both single intrusion events and combinations of multiple boreholes. Two different types of boreholes are considered:

(1) those that penetrate a pressurized brine reservoir in the underlying Castile Formation (hereafter referred to as the Castile), and

(2) those that do not.

The presence of a brine reservoir under the repository is speculative, but cannot be ruled out on the basis of current information. A pressurized brine reservoir was encountered at the WIPP-12 borehole within the controlled area to the northwest of the disposal region and other pressurized brine reservoirs that are associated with regions of deformation in the Castile have been encountered elsewhere in the Delaware Basin. Based on a geostatistical analysis of the distribution of brine encounters in the region, the DOE has estimated that there was a 0.08 probability that a random borehole that penetrates waste in the WIPP will also penetrate an underlying brine reservoir. Upon their review of the CCA, the EPA determined that the DOE should treat this probability as uncertain, ranging from 0.01 to 0.60 in the PAVT. This recertification application uses the EPA's PAVT range (see Appendix PA, Section PA-3.5). The EPA also required the DOE to modify the assumptions concerning Castile properties to increase the brine reservoir volumes (EPA 1998 VII.B.4.d). The EPA determined that changing the rock compressibility of the Castile and the Castile porosity effectively modified the sampled brine reservoir volume to include the possibility of larger brine reservoir volumes like those encountered by the WIPP-12 borehole.

The primary consequence of penetrating a pressurized reservoir is to provide an additional source of brine beyond that which might flow into the repository from the Salado. Direct releases at the ground surface resulting from the first repository intrusion would be unaffected by additional Castile brine even if it flowed to the surface, because brine moving straight up a borehole will not mix significantly with waste. However, the presence of Castile brine could increase radionuclide releases significantly in two ways. First, the volume of contaminated brine that could flow to the surface may be greater for a second or subsequent intrusion into a

repository that has already been connected by a previous borehole to a Castile reservoir. Second, the volume of contaminated brine that may flow up an abandoned borehole after plugs have degraded may be greater for combinations of two or more boreholes that intrude the same panel if one of the boreholes penetrates a pressurized reservoir. Both processes are modeled in the PA.

6.0.2.4 Compliance Demonstration Method

The DOE's approach to demonstrating continued compliance is the PA methodology described in Section 6.1. The PA process comprehensively considers the FEPs relevant to disposal system performance. Those FEPs shown by screening analyses to potentially affect performance are included in quantitative calculations using a system of linked computer models to describe the interaction of the repository with the natural system, both with and without human intrusion. Uncertainty is incorporated in the analysis by a Monte Carlo approach in which multiple simulations (or realizations) are completed using sampled values for 64 imprecisely known or naturally variable input parameters. Distribution functions are constructed that characterize the state of knowledge for these parameters, and each realization of the modeling system uses a different set of sampled input values. A sample size of 100 results in 100 different values of each parameter. Therefore, there are 100 different sets (vectors) of input parameter values. Quality assurance (QA) activities, described in Chapter 5.0, demonstrate that the parameters, software, and analysis used in the PA were the result of a rigorous process conducted under controlled conditions.

Scenario probabilities composed of specific combinations of FEPs are estimated based on regulatory criteria (applied to the probability of future human action) and the understanding of the natural and engineered systems. Cumulative radionuclide releases from the disposal system are calculated for each scenario considered and scenario probabilities are summed for each modeling system realization to construct distributions of CCDFs. Input parameter sampling was performed in three separate replicates, resulting in three independent distributions of CCDFs and allowing the construction of three independent mean CCDFs, each based on 100 individual CCDFs.

6.0.2.5 Results of the Performance Assessment

Section 6.5 addresses the Containment Requirements of 40 CFR Part 191 and the associated criteria of 40 CFR § 194.34. Section 6.5 presents distributions of CCDFs for each replication of the analysis, mean CCDFs, and an overall mean CCDF with the 95 percent confidence interval estimated from the three independent mean distributions.

Families of CCDFs and mean CCDFs for each of the three replicates are also shown in Section 6.5. All 300 individual CCDFs lie below and to the left of the limits specified in 40 CFR § 191.13(a). The overall mean CCDF determined from the three replicates lies entirely below and to the left of the limits specified in 40 CFR § 191.13(a). Thus, the WIPP continues to comply with the containment requirements of 40 CFR Part 191. Comparing the results of the three replicates indicates that the sample size of 100 in each replicate is sufficient to generate a stable distribution of outcomes. Within the region of regulatory interest (that is, at probabilities greater than $10^{-3}/10^{4}$ yr), the mean CCDFs from each replicate are essentially indistinguishable from the overall mean.

As discussed in Section 6.5, examining the normalized releases from cuttings and cavings, spallings, and direct brine release provides insight into the relative importance of each release mode's contribution to the mean CCDF's location and the compliance determination. Releases from cuttings and cavings dominate the mean CCDF. Spallings make a small contribution. Direct brine releases are less important and have very little effect on the location of the mean. Subsurface releases resulting from groundwater transport are less than 10^{-6} EPA units and make no contribution to the mean CCDF's location.

Uncertainties characterized in the natural system and the interaction of waste with the disposal system environment have little effect on the location of the mean CCDF, providing additional confidence in the compliance determination. The natural and engineered barrier systems of the WIPP provide robust and effective containment of TRU waste even if the repository is penetrated by multiple borehole intrusions.

6.1 Performance Assessment Methodology

The EPA, in 40 CFR Part 191, specifies the generally applicable environmental standards for protecting public health and the environment from the disposal of TRU and high-level radioactive wastes. In this section, the DOE addresses compliance with the Containment Requirements of 40 CFR § 191.13 and the associated portions of 40 CFR Part 194 for TRU waste.

Section 191.13 states:

> (a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based on performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:
>
> (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and
>
> (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).
>
> (b) Performance assessments need not provide complete assurance that the requirements of § 191.13(a) will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with § 191.13(a) will be achieved.

The term accessible environment is defined as: "(1) The atmosphere; (2) land surfaces; (3) surface waters; (4) oceans; and (5) all of the lithosphere that is beyond the controlled area" (40 CFR § 191.12). Further, controlled area means: "(1) A surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the

original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location" (40 CFR § 191.12). The controlled area established by the LWA is shown in Figure 3-1. The release limits listed in Appendix A of 40 CFR Part 191 are reproduced as Table 6-2.

For a release to the accessible environment that involves a mix of radionuclides, the limits in Table 6-2 are used to determine a normalized release (nR) of radionuclides for comparison with the release limits

$$nR = \sum_i \left(Q_i / L_i\right)\left(1 \times 10^6\ Ci/C\right), \tag{6.1}$$

where:

Q_i = cumulative release in curies (Ci) of radionuclide i into the accessible environment during the 10,000-year period following repository closure.
L_i = release limit in curies for radionuclide i given in
C = amount of TRU waste curies to be emplaced in the repository (as described in Section 4.1, TRU wastes contain alpha-emitting transuranic radionuclides with half-lives greater than 20 years).

As indicated in Note 1(e) to Table 1 in Appendix A of 40 CFR Part 191, the "other unit of waste" for TRU waste shall be "an amount of transuranic wastes containing 1 million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years."

PAs are the basis for addressing the containment requirements. 40 CFR § 191.12 defines performance as follows:

> "Performance assessment" means an analysis that: (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events.

The DOE's methodology for PA uses information about the disposal system and the waste to evaluate performance in a regulatory context over the 10,000-year regulatory time period.

The general theory for conducting a PA is presented in this section together with details specific to the PA conducted for the WIPP. Figure 6-2 illustrates the general, high-level steps used by the DOE for this final PA of the WIPP. In this figure, the sections of this chapter are indicated that discuss these steps in detail, and several important features of the WIPP PA are shown.

Table 6-2. Release Limits for the Containment Requirements (EPA 1985, Appendix A, Table 1)

Radionuclide	Release Limit L_i per 1,000 MTHM [1] or Other Unit of Waste (curies)
^{241}Am or ^{243}Am	100
^{14}C	100
^{135}Cs or ^{137}Cs	1,000
^{129}I	100
^{237}Np	100
^{238}Pu, ^{239}Pu, ^{240}Pu, or ^{242}Pu	100
^{226}Ra	100
^{90}Sr	1,000
^{99}Te	10,000
^{230}Th or ^{232}Th	10
^{126}Sn	1,000
^{233}U, ^{234}U, ^{235}U, ^{236}U, or ^{238}U	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1,000

[1] Metric tons of heavy metal exposed to a burnup between 25,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM.

Section 6.1 presents the basis for the methodology shown in Figure 6-2. Section 6.1.1 presents the conceptualization of risk, Section 6.1.2 discusses the characterization of uncertainty in risk, Section 6.1.3 discusses regulatory criteria for the quantification of risk, Section 6.1.4 discusses calculation of risk, and Section 6.1.5 discusses techniques for probabilistic analysis.

6.1.1 Conceptualization of Risk

The WIPP PA is fundamentally concerned with evaluating risk, for which comparative measures are defined by regulatory standards. The DOE uses a conceptualization for risk similar to that developed for risk assessments of nuclear power plants. This description provides a structure on which both the representation and calculation of risk can be based.

Kaplan and Garrick (1981, 11-12) have represented risk as a set of ordered triples. The DOE uses this representation and defines risk to be a set R of the form

$$\mathrm{R} = \left[\left(S_i,\ pS,\ \mathbf{cS}_i \right),\ i = 1, \ldots, nS \right], \tag{6.2}$$

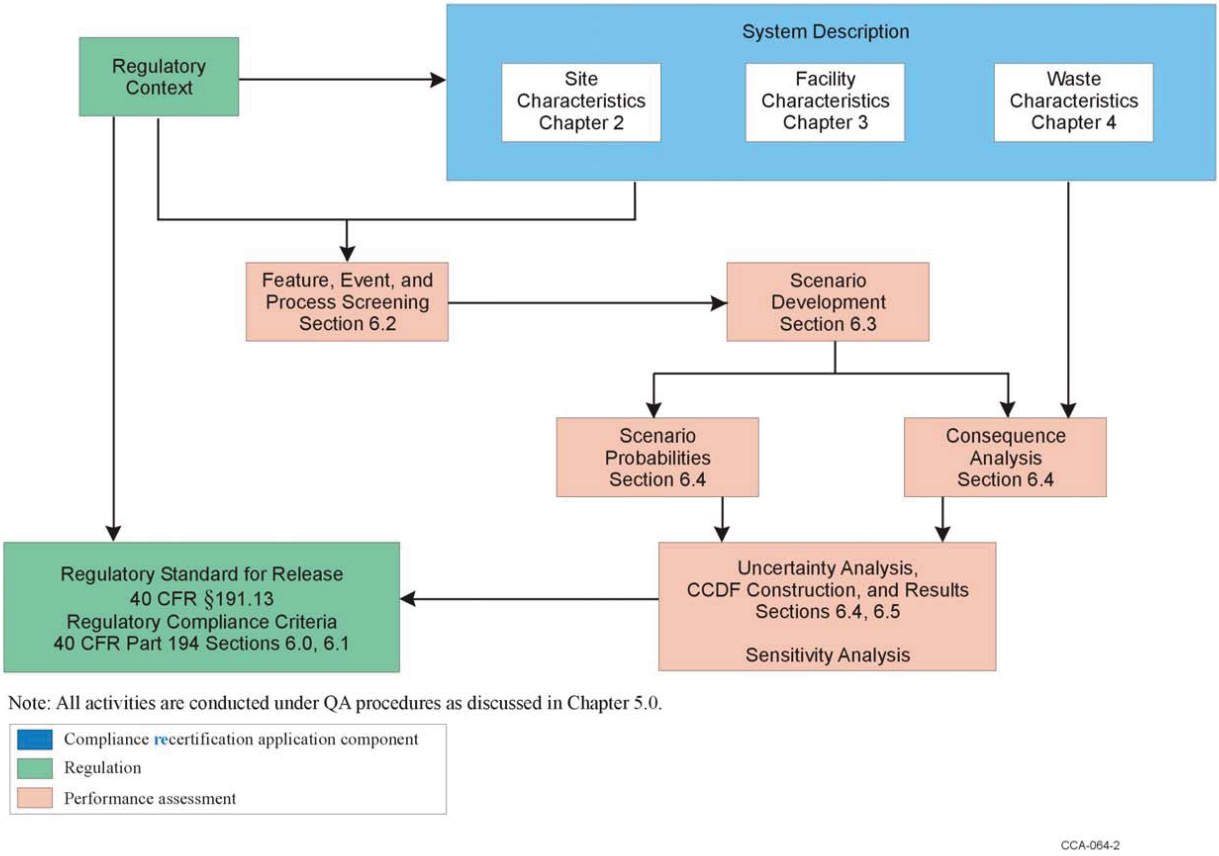

Figure 6-2. Methodology for PA of the WIPP

where

S_i	=	a set of similar occurrences
pS_i	=	probability that an occurrence in set S_i will take place
cS_i	=	a vector of consequences associated with S_i
nS	=	number of sets selected for consideration

and the sets S_i have no occurrences in common (that is, the S_i are disjoint sets). This representation formally decomposes risk into what can happen (the S_i), how likely things are to happen (the pS_i), and the consequences of what can happen (the cS_i). In the WIPP PA, the S_i are scenarios, the pS_i are scenario probabilities, and the vector cS_i contains consequences associated with scenario S_i. Scenario development for the WIPP is discussed in Sections 6.1.2, 6.2, and 6.3. Scenario probabilities and consequence determination are discussed in Section 6.4.

As discussed in the following sections, risk in the set R can be displayed using CCDFs, as required by the EPA. As stated in 40 CFR § 194.34(a),

> The results of performance assessments shall be assembled into "complementary, cumulative distribution functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events.

In the context of Equation (6.2), CCDFs provide information about the consequences cS_i and the probabilities pS_i associated with the scenarios S_i. The probability that cS exceeds a specific consequence value x is determined by the CCDF F defined by

$$F(x) = \sum_{j=i}^{nS} pS_j, \tag{6.3}$$

where the particular consequence result cS under consideration is ordered so that $cS_i \le cS_{i+1}$ for $i = 1, \ldots, nS-1$, and i is the smallest integer such that $cS_i > x$. The function F represents the probabilities that consequence values plotted on the abscissa will be exceeded. An example estimation of F is shown in Figure 6-3. The steps in the CCDF shown in Figure 6-3 result from the evaluation of F with a discrete number of possible occurrences (that is, futures) represented in the sets S_i. Unless the underlying processes are inherently disjoint, using more sets S_i will tend to reduce the size of these steps and, in the limit, result in a smooth curve. To avoid a broken appearance, the DOE plots estimated CCDFs with vertical lines added at the discontinuities.

6.1.2 Characterization of Uncertainty in Risk

Uncertainty in the analysis can be either stochastic or subjective. Stochastic uncertainty derives from lack of knowledge about the future. Subjective uncertainty derives from lack of knowledge about quantities, properties, or attributes believed to have single or certain values. Stochastic uncertainty can be further subdivided into completeness, aggregation, and stochastic variation. Completeness refers to the extent that a PA includes all possible occurrences that could affect performance for the system under consideration. In terms of the risk representation in Equation (6.2), completeness deals with whether all significant occurrences are included in the union of the sets S_i. The DOE addresses completeness in its development of scenarios, discussed here and

in Sections 6.2 and 6.3. Aggregation refers to the division of the possible occurrences into the sets S_i. Resolution is lost if the S_i are defined too coarsely (for example, if nS is too small). Computational efficiency is affected if nS is too large. Aggregation gives rise to the steps in a single CCDF, as shown in Figure 6-3. The DOE addresses aggregation uncertainty in Sections 6.1.4 and 6.4.13. Stochastic variation is represented by the probabilities pS_i, which are functions of the many factors that affect the occurrence of the individual sets S_i. The DOE addresses stochastic variation in Sections 6.1.4 and 6.4.12.

Stochastic uncertainty is taken into account in PA by evaluating the probability of future events (for example, by assuming that the occurrence of certain future events will be random in space and time), and by considering imprecisely known system properties directly associated with the future events. These imprecisely known system properties can be expressed as variables represented by the vector

$$x_{st} = [x_{st,1}, x_{st,2}, \ldots, x_{st,nV(st)}] , \tag{6.4a}$$

where each $x_{st,j}$ [j = 1, 2, …, nV(st)] is an imprecisely known property required in the analysis, nV is the total number of such properties associated with stochastic uncertainty, and the subscript st denotes stochastic uncertainty.

Subjective uncertainty results from incomplete data or measurement uncertainty. These uncertainties are addressed in Section 6.4. Subjective quantities, properties, or attributes may be associated with stochastic uncertainties (events that might occur in the future).

Subjective uncertainty can be characterized in PA by considering system properties that are imprecisely known. These imprecisely known system properties can be expressed as variables represented by vectors

$$x_{su} = [x_{su,1}, x_{su,2}, \ldots, x_{su,nV(su)}] , \tag{6.4b}$$

where each $x_{su,j}$ [j = 1, 2, …, nV(su)] is an imprecisely known property required in the analysis, nV is the total number of such properties associated with subjective uncertainty, and the subscript su denotes subjective uncertainty.

If the analysis has been developed so that each x_j is a quantity for which the overall analysis requires a single value, the representation for risk in Equation 6.2 can be restated as a function of x_{st} and x_{su}:

$$R(x_{su}) = [S_i(x_{su}), pS_i(x_{su}), cS_i(x_{st,i}, x_{su}), i = 1, ..., nS(x_{st} ,x_{su})] , \tag{6.5}$$

where $x_{st,i}$ is included in S_i. Probability distributions are then assigned to the individual variables $x_{su,j}$ and $x_{st,j}$, as defined in Equation 6.4. These probability distributions are of the form

$$D_{st,1}, D_{st,2}, \ldots, D_{st,nV(st)} , \tag{6.6a}$$

$$D_{su,1}, D_{su,2}, \ldots, D_{su,nV(su)} , \tag{6.6b}$$

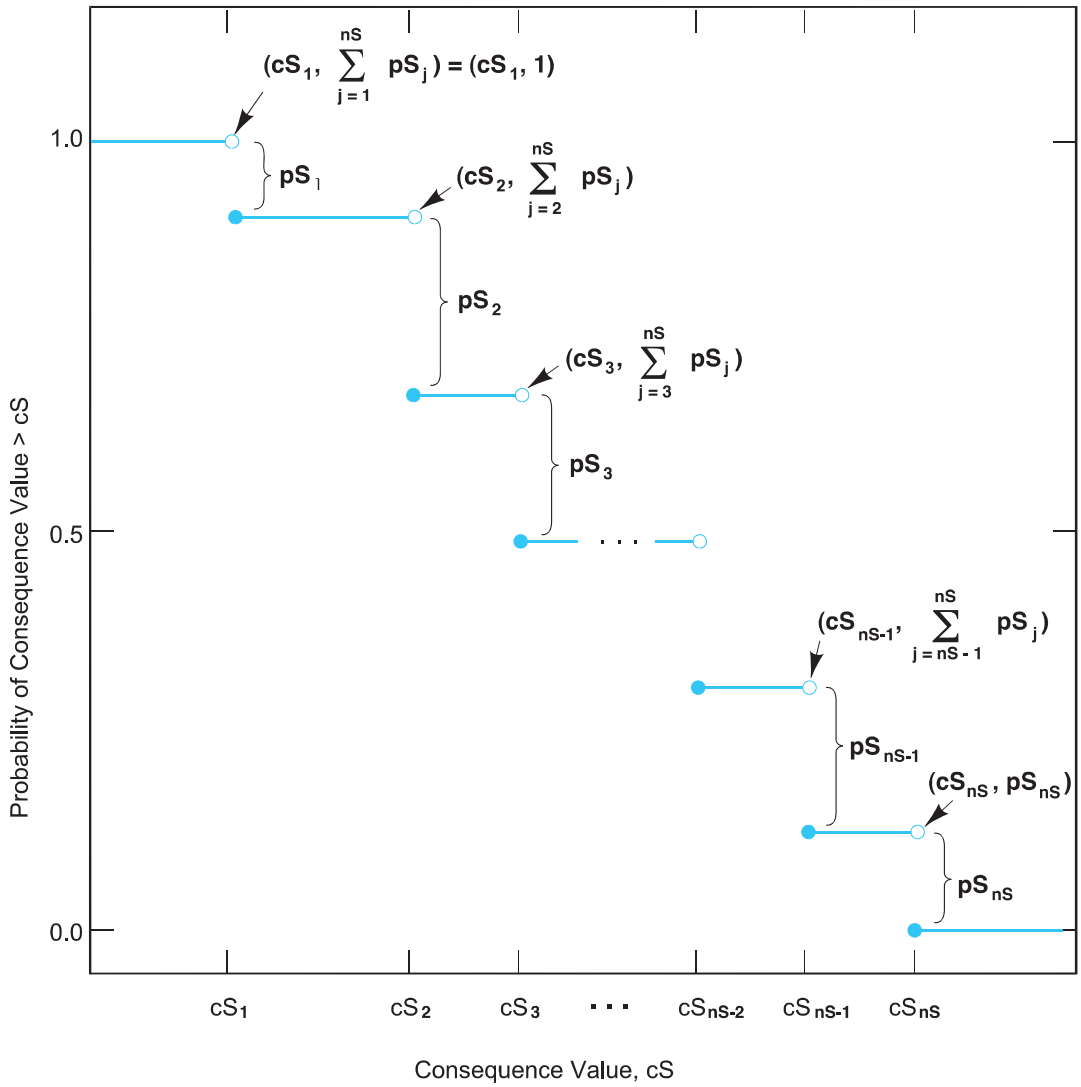

Note: The open and solid circles at the discontinuities indicate the points included on (solid circles) and excluded from (open circles) the CCDF.

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Figure 6-3. Estimated CCDF For Consequence Results

where the D_js are the distributions developed for the variables x_j, $j = 1, 2,...nV$, and the subscripts *st* and *su* denote distributions associated with x_{st} or x_{su}. The definition of these distributions may also be accompanied by the specification of correlations and various restrictions that further define the possible relations among the x_j. These distributions (along with specified correlations or restrictions) probabilistically specify what the appropriate input to use in the PA calculations might be, given that the analysis is structured so that only one value can be used for each variable, x_j, under consideration for a particular calculation.

Monte Carlo techniques can be used to determine the uncertainty in $R(x_{su})$ associated with both x_{st} and x_{su}. The theory of this technique is similar for characterizing both stochastic and

subjective uncertainty. This technique as applied to determining the risk $R(x_{su})$ associated with x_{su} is developed in the following paragraphs.

Once the distributions in Equation 6.6b have been developed, a sample

$$x_k = (x_{k1}, x_{k2}, \ldots, x_{k,nV}),\ k = 1, \ldots, nK \tag{6.7}$$

is generated according to the specified distributions and restrictions where nK is the size of the sample. PA calculations are then performed for each sample element x_k, which yields a sequence of risk results of the form

$$R(x_k) = \{[S_i(x_k), pS_i(x_k), cS_i(x_k)],\ i = 1, \ldots, nS(x_k)\}\ . \tag{6.8}$$

Each set $R(x_k)$ is the result of one complete set of calculations performed with a set of inputs (that is, x_k) obtained from the distributions assigned in Equation 6.6b. Further, associated with each risk result $R(x_k)$ in Equation 6.8 is a weight[1] that can be used in making probabilistic statements about the distribution of R(x).

A single CCDF can be produced for each set $R(x_k)$ of results shown in Equation 6.8, yielding a family of CCDFs of the form shown in Figure 6-4. The distribution of CCDFs in Figure 6-4 can be summarized with the mean and percentile curves shown in Figure 6-5. These curves result from connecting the mean and percentile values corresponding to individual consequence values on the abscissa of Figure 6-4. The percentile curves probabilistically represent the estimated exceedance probability given a fixed consequence value. For example, the probability is 0.8 that the exceedance probability for a particular normalized release is located between the 10 and 90 percentile curves.

To summarize, considering a family of CCDFs allows a distinction between stochastic uncertainty that controls the shape of a single CCDF and subjective uncertainty that results in a distribution of CCDFs. The stepwise shape of a single CCDF reflects aggregation of future events into similar groups. A family of CCDFs arises from imperfect knowledge of quantifiable properties, or, in other words, subjective uncertainty. The distribution arising from subjective uncertainty involves an infinite number of CCDFs; a family of CCDFs is a sample of finite size.

6.1.3 Regulatory Criteria for the Quantification of Risk

The representation for risk in Equation 6.2 provides a conceptual basis for calculating the CCDF of normalized releases specified in 40 CFR § 194.34(a). Further, this representation provides a structure that can be used for both the incorporation of uncertainties and the representation of the effects of uncertainties, as stated in 40 CFR § 194.34.

[1] In random or Latin hypercube sampling (LHS), this weight is the reciprocal of the sample size (that is, $1/nK$) and can be used in estimating means, cumulative distribution functions, and other statistical properties. This weight is often referred to as the probability for each observation (that is, sample x_k). However, this usage is not technically correct. If continuous distributions are involved, the actual probability of each observation is zero.

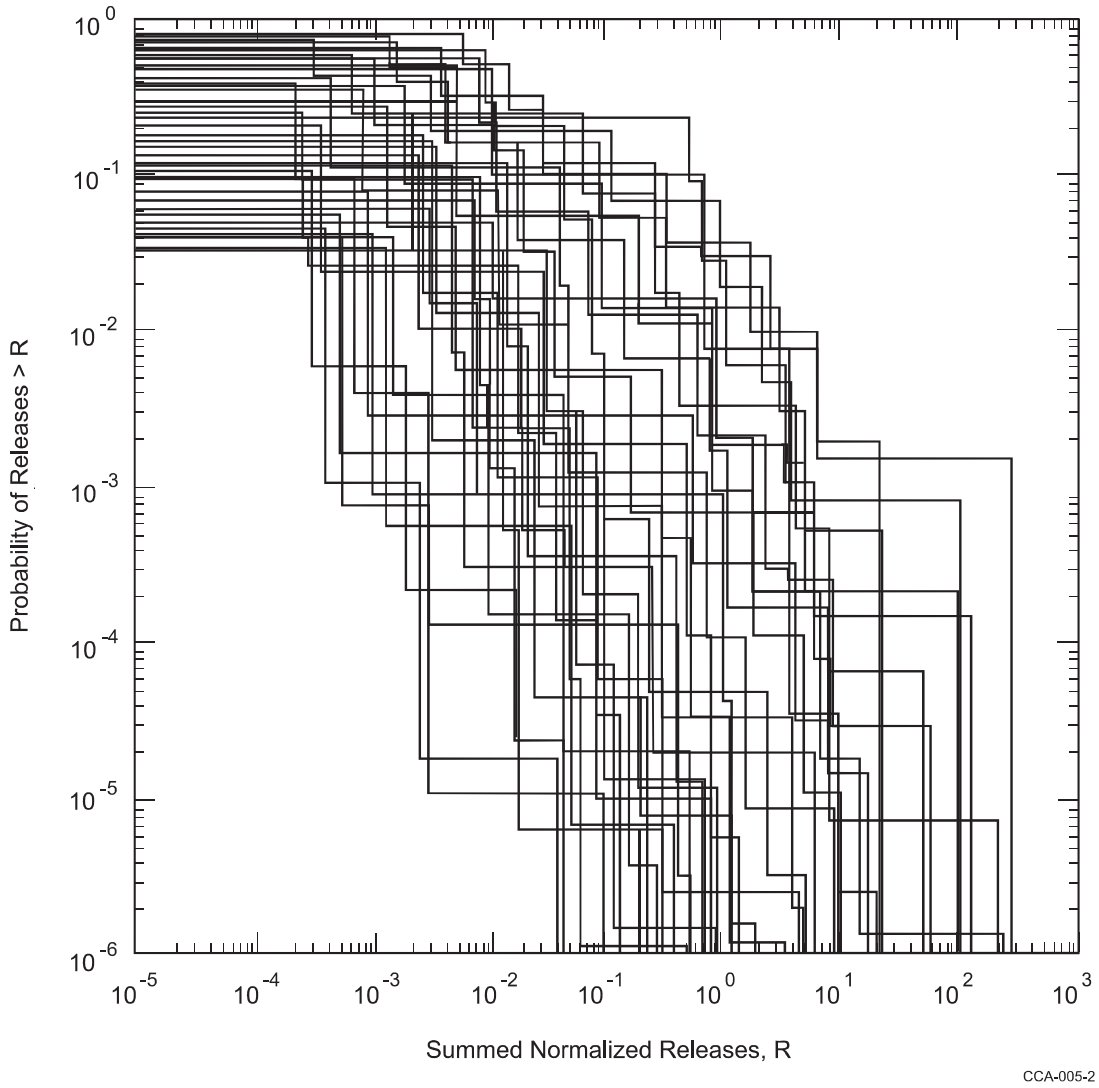

Figure 6-4. Example Distribution of a Family of CCDFs Obtained by Sampling Imprecisely Known Variables

In 40 CFR § 194.34(b), the EPA states that "probability distributions for uncertain disposal system parameter values used in performance assessments shall be developed and documented in any compliance application." The treatment of uncertain parameter values in the performance assessment is discussed in Sections 6.1.4, 6.1.5, and 6.4. Further discussion of distributions assigned to uncertain parameter values is provided in Appendix PA, Attachment PAR.

In 40 CFR § 194.34(c), the EPA states that documentation of the computational techniques used to generate random samples shall be provided. The sampling techniques used are discussed in Section 6.1.5.2. Sampled values are reproduced in tabular form in Appendix PA, Attachment PAR.

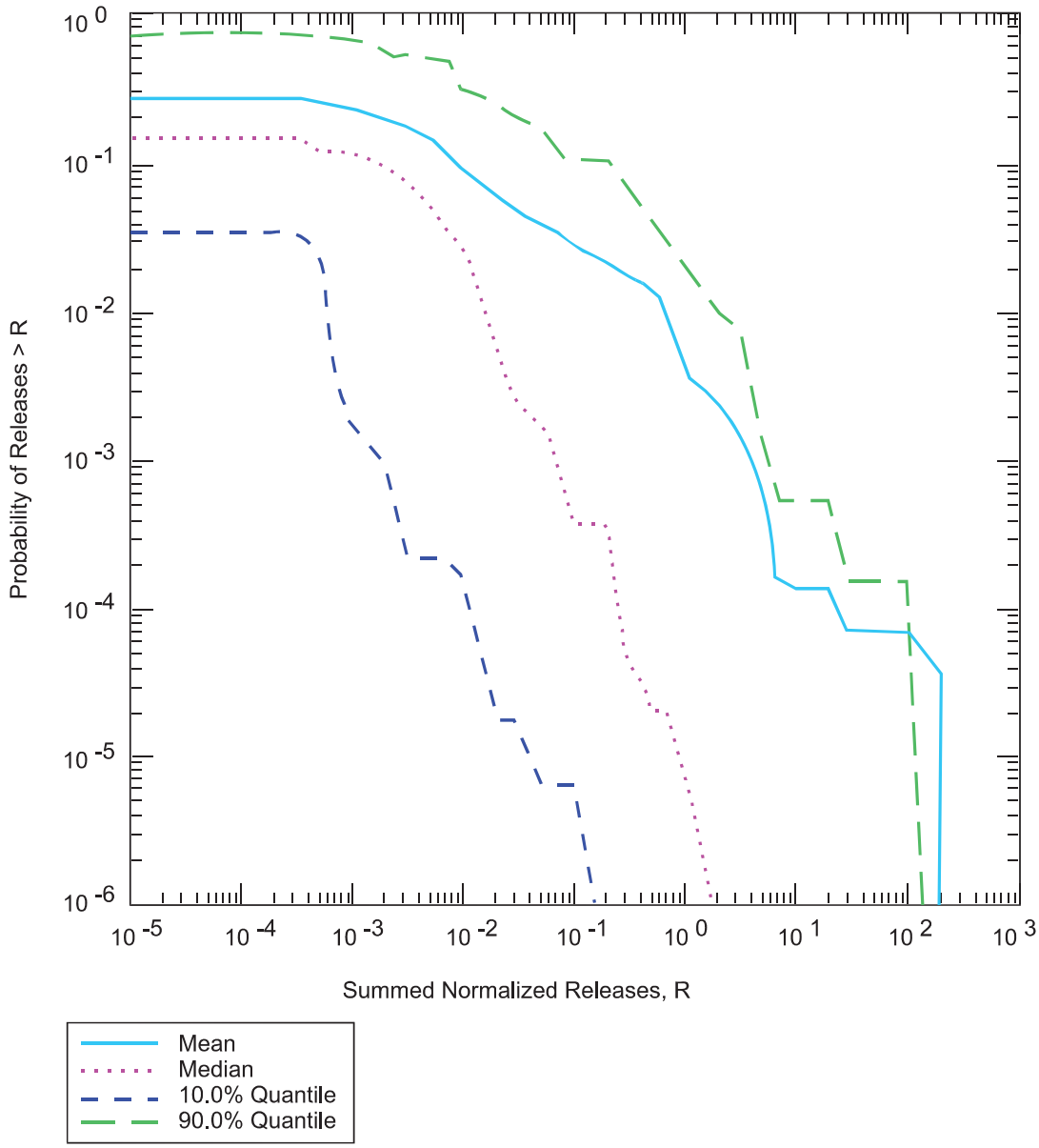

Note: The curves in this figure were obtained by calculating the mean and the indicated percentiles for each consequence value on the abscissa in Figure 6-3. The 90th-percentile curve crosses the mean curve because of highly skewed distributions for exceedance probability. This skew also results in the mean curve being above the median curve.

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Figure 6-5. Example Summary Curves Derived from an Estimated Distribution of CCDFs

In 40 CFR § 194.34(d), the EPA states that "the number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability." The CCDFs resulting from this PA are provided in Section 6.5, with a demonstration that the total number of CCDFs is sufficiently large.

In 40 CFR § 194.34(e), the EPA states that "any compliance application shall display the full range of CCDFs generated." The full range of CCDFs generated is displayed in Section 6.5.

In 40 CFR § 194.34(f), the EPA states that "any compliance application shall provide information which demonstrates that there is at least a 95 percent level of confidence that the mean of the population of CCDFs meets the containment requirements . . . ." Section 6.5 contains a display of the mean CCDF and evidence demonstrating level of confidence.

6.1.4 Calculation of Risk

The methodology presented in Sections 6.1.1and 6.1.2 is based on the work of Kaplan and Garrick (1981) and is one way to estimate the effects of uncertain but characterizable futures. In the Kaplan and Garrick (1981) procedure, the possible futures are defined as literal entities (S_i), and each is associated with a probability of occurrence (pS_i) and a consequence of occurrence (cS_i).

Calculating the probabilities and consequences of future occurrences begins by determining the sets S_i, which are the scenarios to be analyzed. Scenarios are determined through a formal process similar to that proposed by Cranwell et al. (1990, 5-10) and the process used in preliminary PAs for the WIPP. This process has four steps.

1. The FEPs potentially relevant to the WIPP are identified and classified.
2. Certain FEPs are eliminated according to well-defined screening criteria as unimportant or irrelevant to the performance of the WIPP.
3. Scenarios are formed from the remaining FEPs in the context of regulatory performance criteria.
4. Scenarios are specified for consequence analysis.

Through steps 1 and 2 of the scenario development process, the DOE identifies "all significant processes and events that may affect the disposal system" as required by 40 CFR § 191.13(a) and as further addressed in 40 CFR § 194.32. These steps are described in Section 6.2. The grouping of retained FEPs to form scenarios, and the specification of scenarios for consequence analysis, is presented in Section 6.3.

These four steps were used to develop the PA and compliance assessment used in the CCA. This CRA uses the same PA method and basis as that used in the CCA. The steps outlined here were revisited to determine that the basis for the original PA has not been impacted by events, additional information, or regulatory changes that have occurred since the original demonstration of compliance with EPA's disposal standard (as discussed in the following paragraphs).

As discussed in Section 6.2, the DOE eveloped a comprehensive initial list of FEPs for PA. This list assured that the identification of significant processes and events is complete, potential interactions between FEPs are not overlooked, and responses to possible questions are available and well documented. For the CRA-2004, DOE has revisited the initial FEPs list to determine if the screening decisions should be changed as a result of information collected since the EPA certification decision. Specifically, 120 FEPs required updates to their FEP descriptions and/or

screening arguments, and seven of the original baseline FEP screening decisions required a change from their original screening decision. Four of the original baseline FEPs have been deleted or combined with other closely related FEPs. Finally, two new FEPs have been added to the baseline. These two FEPs were previously addressed in an existing FEP; they have been separated for clarity. Table SCR-1 summarizes the changes in the FEP baseline since the CCA. The evaluation of the CCA FEPs list is discussed in Appendix PA, Attachment SCR.

Once scenarios are defined, a calculational methodology for evaluating their consequences must be developed. The calculational methodology must address stochastic uncertainty related to aggregation and stochastic variation, and subjective uncertainty, because of (for example) measurement difficulties or incomplete data. The DOE uses a system of linked computer models to calculate scenario consequences cS_i. As discussed in Section 6.4, these computer models are based on conceptual models that describe the processes relevant to disposal system performance for the defined scenarios. These conceptual models are, in turn, based on site-specific experimental and observational data and the general scientific understanding of natural and engineered systems.

For practical purposes, the DOE separates the calculation of risk because of stochastic uncertainty (represented in an individual CCDF) from risk because of subjective uncertainty (represented by the family of CCDFs). This can be represented mathematically as a double integral of a function with the function representing the probability of exceedance associated with any particular consequence. The inner integral evaluates stochastic uncertainty, or the probability of exceedance associated with any particular consequence. The outer integral evaluates subjective uncertainty and leads to a distribution of exceedance probabilities for any given consequence value. An analytical method for its solution is not available because of the complexity of this double integral for the WIPP. Instead, the DOE approximates the solution of this double integral with a linked system of computer codes. In this computational framework, thePA analysis can be thought of as a double sum, presented here in a stylized form for clarity as

$$\sum_{su}\sum_{st} F(x). \tag{6.9}$$

Here, F(x) is a procedure for estimating the normalized release to the accessible environment associated with each scenario that could occur at the WIPP site. The inner sum denoted with the subscript st is a probabilistic characterization of the uncertainty associated with parameters used to characterize stochastic uncertainty (the x_{st} and D_{st} in Equations 6.4a and 6.6a, respectively). It is the evaluation of F(x) through the inner sum that develops an individual CCDF, as shown in Figure 6-3. The outer sum denoted with the subscript su is a probabilistic characterization of the uncertainty associated with parameters used to characterize subjective uncertainty (the x_{su} and D_{su} in Equations 6.4b and 6.6b, respectively). It is the combined evaluation in the outer sum of the inner sum with F(x) that develops the family of CCDFs, as shown in Figure 6-4.

A separate probabilistic analysis is required to evaluate each sum. Associated with each analysis are parameter distributions representing uncertainty (the D_{st} and D_{su} of Equations 6.6a and 6.6b). For example, uncertainty in the number and time of intrusion boreholes may be associated with the inner sum. The outer sum includes a probabilistic characterization of site properties, such as the permeability of specific rock types.

For the methodology adopted by the DOE to evaluate stochastic uncertainty in the inner sum, consequence calculations are required for model configurations with a set of fixed values for subjective parameters x_{su} taken from their distributions D_{su}, as well as for defined sequences and times of events associated with scenarios. These calculations are referred to in Section 6.4.11 and later sections as deterministic calculations (or deterministic futures). To evaluate stochastic uncertainty and construct a CCDF, the consequences of futures generated probabilistically by random sampling (probabilistic futures) are evaluated in the context of these deterministic futures. This process is discussed in detail in Sections 6.4.12 and 6.4.13.

In certain cases, it may not be obvious whether a particular uncertainty should be classified as subjective or stochastic. For example, whether currently observed geologic properties persist through time could be thought of as either subjective or stochastic uncertainty. For the WIPP, the DOE treats uncertainty associated with significant future human actions as stochastic (for example, drilling for natural resources), and uncertainty in disposal system properties subject to ongoing physical processes as subjective (for example, climate change or gas generation). In particular, DOE's formal separation of evaluating stochastic uncertainty from subjective uncertainty into different probabilistic analyses allows clear understanding of how a particular uncertainty is incorporated.

Once the scenarios are determined and their consequences calculated using the appropriate conceptual and computational models, scenario probabilities must be determined for a CCDF to be constructed. This process is described in Section 6.4.12. CCDF construction is also described in Section 6.4.13.

6.1.5 Techniques for Probabilistic Analysis

Once scenarios are defined, conceptual models are defined, and the computational modeling system developed, DOE uses probabilistic techniques to evaluate the double sum presented above. Monte Carlo analysis is the technique used for probabilistic analysis of the WIPP. Monte Carlo analyses can involve five steps:

1. selecting the variables to be examined and the ranges and distributions for their possible values,
2. generating the samples to be analyzed,
3. propagating the samples through the analysis,
4. performing the uncertainty analysis, and
5. conducting a sensitivity analysis.

These steps are described briefly in the following sections.

Within the general framework of Monte Carlo analysis, PA uses two methods, random sampling and Latin Hypercube Sampling (LHS), to generate the samples propagated through the model system. Random sampling is used to generate samples for stochastic uncertainty, and LHS is used to characterize subjective uncertainty. Each of these methods uses the five steps

summarized in the preceding paragraph, but differs in steps (2) through (5) to account for both subjective and stochastic uncertainty.

6.1.5.1 Selection of Variables and Their Ranges and Distributions

Monte Carlo analyses use a probabilistic procedure for the selection of model input. Therefore, the first step in a Monte Carlo analysis is to select uncertain variables and assign ranges and distributions that characterize them. These variables are typically input parameters to computer models, and the impact of the assigned ranges and distributions can be great; for a given set of conceptual and mathematical models, PA results are largely controlled by the choice of input. Results of uncertainty and sensitivity analyses, in particular, strongly reflect the characterization of uncertainty in the input data.

Information used in the CCA about the ranges and distributions of possible values were drawn from a variety of sources, including field data, laboratory data, and literature. Where sufficient data were not available, the documented solicitation of experts was used. A review process led from the available data to the construction of the distribution functions that characterize uncertainty in input parameters in PA (Appendix PA, Attachment PAR, PAR.2). This addressed the scaling of data collected at experimental scales of observation to the parameter ranges applied to scales of interest in the disposal system. The nature of the available data and the type of analysis unavoidably involved some judgment from investigators and analysts involved. A discussion of parameter ranges developed by this process for the CRA-2004 PA is provided in Appendix PA, Attachment PAR (Section 3). The QA procedures associated with this review process are identified in Section 5.4.2 and Appendix PA, Attachment PAR (Section 2).

The outcome of the review process is a cumulative distribution function (CDF) *D(x)* of the form shown in Figure 6-6 for each independent variable of interest. For a particular variable x_j, the function *D* is defined such that

$$\text{prob}(x < x_j \leq x + \Delta x) = D(x + \Delta x) - D(x) \; . \qquad (6.10)$$

That is, $D(x+\Delta x) - D(x)$ is equal to the probability that the appropriate value for x_j in the particular analysis under consideration falls between x and $x+\Delta x$.

6.1.5.2 Generation of the Sample

Various techniques are available for generating samples from the assigned distribution functions for the variables, including random sampling, stratified sampling, and LHS. The DOE's PA for WIPP uses random sampling and LHS.

Randomly sampling the occurrence of possible future events is used to generate the possible futures (probabilistic futures) that comprise a CCDF. This sampling is used to select values of uncertain parameters associated with future human activities, or in other words, to incorporate stochastic uncertainty into the WIPP PA. This sampling is used for parameters evaluated in the inner sum of the double sum and included in the parameter set x_{st} with associated distributions D_{st}, as shown in Equations 6.4a and 6.6a respectively. Generating futures comprising a CCDF by random sampling, rather than importance or stratified sampling, as used in previous preliminary PAs, largely eliminates errors from aggregation.

LHS, in which the full range of each variable is subdivided into intervals of equal probability and samples are drawn from each interval, is used to select values of uncertain parameters associated with the physical system being simulated. In other words, LHS incorporates subjective uncertainty into the WIPP PA. This sampling is used for parameters that are evaluated in the outer sum of the double sum and are included in the parameter set x_{su} with associated distributions D_{su}, as shown in Equations 6.4b and 6.6b, respectively. The restricted pairing technique of Iman and Conover (1982, 314-319) is used to prevent spurious correlations within the sample.

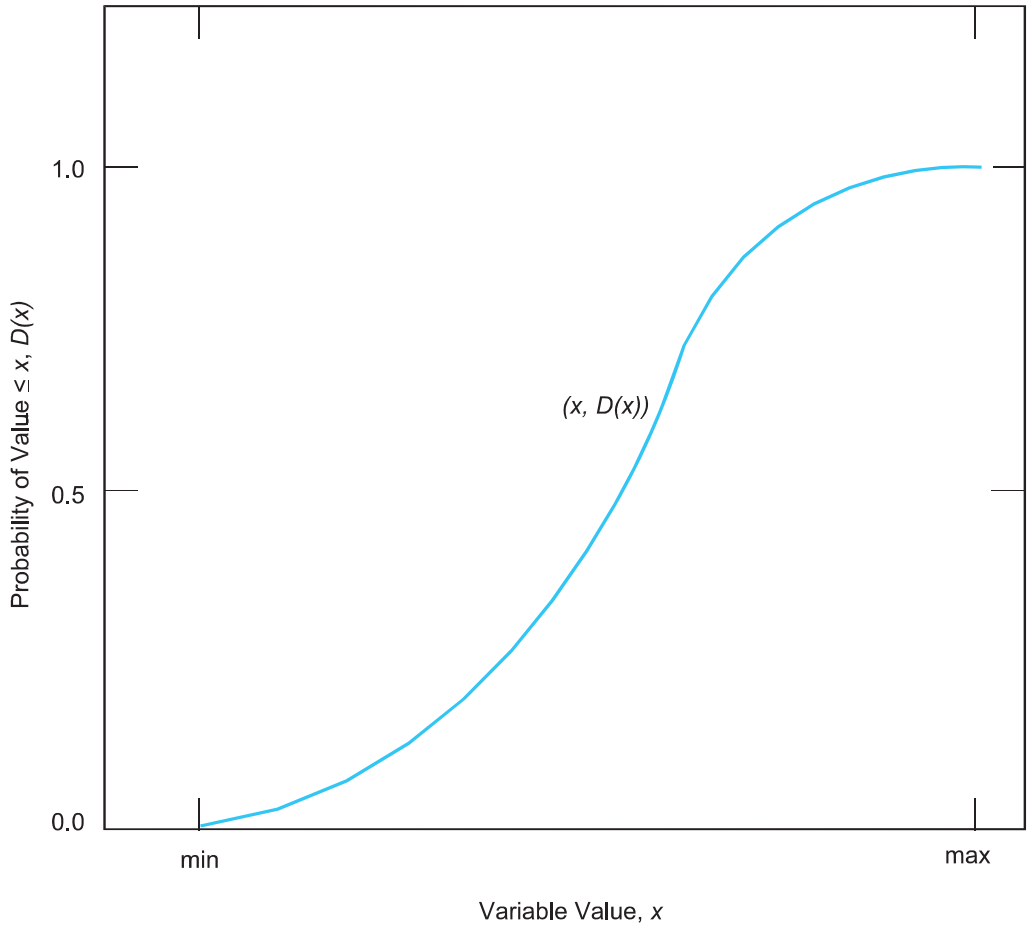

Note: For each value *x* on the abscissa, the corresponding value *D(x)* on the ordinate is the probability that the appropriate value to use in the analysis is less than or equal to *x*.

CCA-008-2

Figure 6-6. Distribution Function for an Imprecisely Known Variable

6.1.5.3 Propagation of the Sample through the Analysis

The next step is the propagation of the sample through the analysis. Each element of the sample is supplied to the model system as input, and the corresponding model system predictions are saved for later use in uncertainty and sensitivity studies. The Software Configuration Management System (SCMS) was developed to facilitate the complex calculations performed by the model system and to store the input and output files from each program.

6.1.5.4 Uncertainty Analysis

Uncertainty analyses evaluate uncertainty in performance estimates that results from uncertainty about imprecisely known input parameters. Once a sample has been generated and propagated through the modeling system, uncertainty in the outcome can be interpreted directly from the display of the results. For the WIPP PA, stochastic uncertainty is represented by the shape of the individual CCDFs displayed in Section 6.5. Subjective uncertainty is represented by the family of CCDFs displayed in Section 6.6.

6.1.5.5 Sensitivity Analysis

Sensitivity analyses determine the contribution of individual input variables to the uncertainty in model predictions. This is the final step in a probabilistic study. Sensitivity analyses can identify parameters for which reductions in uncertainty (that is, narrowing the range of values from which the sample used in the Monte Carlo analysis is drawn) have the greatest potential to increase confidence in the estimate of the disposal system's performance. However, because results of these analyses are inherently conditional on the models, data distributions, and techniques used to generate them, the analyses cannot provide insight on the correctness of the conceptual models and data distributions used. Qualitative judgment about the modeling system must be used with sensitivity analyses to set priorities for PA data acquisition and model development. Sensitivity analyses conducted as part of the WIPP PA are described in Appendix PA.

6.2 Identification and Screening of Features, Events, and Processes

The EPA has provided criteria concerning the scope of PAs in 40 CFR § 194.32. In particular, criteria relating to the identification of potential processes and events that may affect the performance disposal system are provided in Section 194.32(e), which states that

> Any compliance application(s) shall include information which:
>
> (1) Identifies all potential processes, events or sequences and combinations of processes and events that may occur during the regulatory time frame and may affect the disposal system;
>
> (2) Identifies the processes, events or sequences and combinations of processes and events included in performance assessments; and
>
> (3) Documents why any processes, events or sequences and combinations of processes and events identified pursuant to paragraph (e)(1) of this section were not included in performance assessment results provided in any compliance application.

This section, CCA Appendix SCR, and Appendix PA, Attachment SCR fulfill these criteria by documenting DOE's identification, screening, and screening results of all potential processes and events consistent with the criteria specified in 40 CFR § 194.32(e).

As discussed in Section 6.1.4, the first two steps in scenario development involve the identification and screening of FEPs potentially relevant to the performance of the disposal system. This section discusses the development of a comprehensive initial set of FEPs used in the CCA, the methodology and criteria used for screening, the method used to reassess the CCA

FEPs for the CRA-2004, and a summary of the FEPs retained for scenario development. Detailed discussion of the basis for eliminating or retaining particular FEPs is provided in Appendix PA, Attachment SCR. The scenarios formed from retained FEPs are discussed in Section 6.3, and the scenarios specified for consequence analysis are addressed in Section 6.4.12.

The original FEPs generation and screening were documented in the CCA and the resulting FEPs list became the FEPs compliance baseline. The baseline contained 237 FEPs and was documented in Appendix SCR of the CCA. The EPA compliance review of FEPs was documented in EPA's Technical Support Document 194.32: Scope of PA (EPA 1998, V-B-21). The EPA numbered each FEP with a different scheme than the DOE used for the CCA. The DOE has since adopted EPA's numbering scheme.

6.2.1 Identification of Features, Events, and Processes

The first step of the scenario development procedure is identifying and classifying FEPs potentially relevant to the disposal system performance. Catalogs of FEPs have been developed in several national radioactive waste disposal programs, as well as internationally. In constructing a comprehensive list of FEPs for the WIPP, the DOE drew on these other radioactive waste disposal programs.

As a starting point, the DOE assembled a list of potentially relevant FEPs from the compilation developed by Stenhouse et al. (1993) for the Swedish Nuclear Power Inspectorate *Statens Kärnkraftinspektion* (SKI). The SKI list was based on a series of FEP lists developed for other disposal programs and is considered the best documented and most comprehensive starting point for the WIPP. For the SKI study, an initial, raw FEP list was compiled from nine different FEP identification studies (Table 6-3). No additional lists of potentially relevant FEPs have been identified since the initial certification.

The compilers of the SKI list eliminated a number of FEPs as irrelevant to the particular disposal concept under consideration in Sweden; these FEPs were reinstated for the WIPP effort, and several FEPs on the SKI list were subdivided to facilitate WIPP screening. Finally, to ensure comprehensiveness, other FEPs specific to the WIPP were added based on a review of key project documents and a broad examination of the preliminary WIPP list by both project participants and stakeholders. The initial, unedited list is contained in CCA Appendix SCR, Attachment 1. The initial, unedited FEP list was restructured and revised to derive the comprehensive WIPP FEP list in the CCA. The number of FEPs was reduced to 237 to avoid the ambiguities caused by using a generic list. Restructuring the list did not remove any substantive issues from the discussion. As discussed in more detail in CCA Appendix SCR, Attachment 1, the following steps were used to create the WIPP FEP list in the CCA.

- References to subsystems were eliminated because the SKI subsystem classification was not appropriate for the WIPP disposal concept. For example, in contrast to the Swedish disposal concept, canister integrity does not have a role in postoperational performance of the WIPP, and the terms near-field, far-field, and biosphere are not unequivocally defined for the WIPP site.

- Duplicate FEPs were eliminated. Duplicate FEPs arose in the SKI list because individual FEPs could act in different subsystems. FEPs have a single entry in this application list whether they are applicable to several parts of the disposal system, or to a single part only. For example, the FEP *Gas Effects: Disruption* appears in the seals, backfill, waste, canister, and near-field subsystems in the initial FEP list. These FEPs are represented by the single FEP *Disruption Due to Gas Effects* for this application.

Table 6-3. FEP Identification Studies Used in the SKI Study

Study	Country	Number of FEPS Identified
Atomic Energy of Canada Limited (AECL) study of disposal of spent fuel in crystalline rock (Goodwin et al. 1994)	Canada	275
SKI & Swedish Nuclear Fuel and Waste Management Company (SKB) study of disposal of spent fuel in crystalline rock (Andersson 1989)	Sweden	157
National Cooperative for the Storage of Radioactive Waste (NAGRA) Project Gewähr study (NAGRA 1985)	Switzerland	44
UK Department of the Environment Dry Run 3 study of deep disposal of low- and intermediate-level waste (L/ILW) (Thorne 1992)	United Kingdom	305
UK Department of Environment assessment of L/ILW disposal in volcanic rock at Sellafield (Miller and Chapman 1992)	United Kingdom	79
UK Nuclear Industry Radioactive Waste Executive (NIREX) study of the deep disposal of L/ILW (Hodgkinson and Sumerling 1989)	United Kingdom	131
Sandia National Laboratories (SNL) study of deep disposal of spent fuel (Cranwell et al. 1990)	United States	29
NEA Working Group on Systematic Approaches to Scenario Development (OECD 1992)	International	122
International Atomic Energy Agency (IAEA) Safety Series (IAEA 1981)	International	56

- FEPs that are not relevant to the WIPP design or inventory were eliminated. Examples include FEPs related to high-level waste, copper canisters, and bentonite backfill.

- FEPs relating to engineering design changes were eliminated because they are not relevant to a compliance application based on the DOE's design for the WIPP. Examples of such FEPs are Design Modifications: Canister and Design Modification: Geometry.

- FEPs relating to constructional, operational, and decommissioning errors were eliminated. The DOE has administrative and quality control procedures to ensure that the facility will be constructed, operated, and decommissioned properly.

- Detailed FEPs relating to processes in the surface environment were aggregated into a small number of generalized FEPs. For example, the SKI list includes the biosphere FEPs *Inhalation of Salt Particles, Smoking, Showers and Humidifiers*, *Inhalation and*

Biotic Material, Household Dust and Fumes, Deposition (wet and dry), Inhalation and Soils and Sediments, Inhalation and Gases and Vapors (indoor and outdoor), and *Suspension in Air*, which are represented by the FEP *Inhalation* in this application.

- FEPs relating to the containment of hazardous metals, volatile organic compounds (VOCs), and other chemicals that are not regulated by 40 CFR Part 191 were not included.

- A few FEPs were renamed to be consistent with terms used to describe specific WIPP processes (for example, *Wicking*, *Brine Inflow*).

6.2.2 Criteria to Screen Features, Events, and Processes and Categorization of Retained Features, Events, and Processes

FEP screening identifies those FEPs that should be accounted for in PA calculations, and those that need not be considered further. The DOE's process of removing FEPs from consideration in PA calculations involved the structured application of explicit screening criteria. The criteria used to screen out FEPs are explicit regulatory exclusions (SO-R), probability (SO-P), or consequence (SO-C). As discussed in Section 6.2.2.1, all three criteria are derived from regulatory requirements. FEPs not screened as SO-R, SO-P, or SO-C have been retained for inclusion in PA calculations and are classified as undisturbed performance (UP) or disturbed performance (DP) FEPs. These screening criteria and FEP classifiers are discussed in this section, and FEP screening is discussed in Sections 6.2.3, 6.2.4, and 6.2.5.

6.2.2.1 Eliminating Features, Events, and Processes Based on Regulation, Probability, or Consequence

Regulation. Specific FEP screening criteria are established by 40 CFR Part 191 and 40 CFR § 194.25, § 194.32 and § 194.54. These criteria relating to the applicability of particular FEPs represent screening decisions made by the EPA. That is, in the process of developing and demonstrating the feasibility of the 40 CFR Part 191 standard and the 40 CFR Part 194 criteria, EPA considered the relevance, consequence, and/or probability of occurrence of particular FEPs and, in so doing, eliminated some FEPs from consideration. For example, 40 CFR § 194.25 outlines consideration of future states. Future human activities are assumed to be as they are today; therefore other regulations that pertain to human activities can be used to screen FEPs (i.e., State and Federal oil well plugging requirements can be used to screen borehole related FEPs). Section 6.2.5 describes the regulatory screening criteria that pertain to limitations on the type of human-initiated events and processes that need be analyzed.

Probability of occurrence of a FEP leading to significant release of radionuclides. Low-probability events can be excluded based on the criterion provided in 40 CFR § 194.32(d), which states that "PAs need not consider processes and events that have less than one chance in 10,000 of occurring over 10,000 years." In practice, for most FEPs screened out on the basis of low probability of occurrence, it has not been possible to estimate a meaningful, quantitative probability. In the absence of quantitative probability estimates, a qualitative argument has been provided.

Potential consequences associated with the occurrence of the FEPs. The DOE identified two applications of this criterion:

1. FEPs can be eliminated from PA calculations on the basis of insignificant consequence. Consequence can refer to effects on the repository or site or to radiological consequence. In particular, 40 CFR § 194.34(a) states that "The results of PAs shall be assembled into "complementary, cumulative distribution functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events" (emphasis added). The DOE has omitted events and processes from PA calculations where there is a reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed by such omissions.

2. FEPs that are potentially beneficial to subsystem performance may be eliminated from PA calculations, if necessary, to simplify the analysis. This argument may be used when there is uncertainty as to exactly how the FEP should be incorporated into assessment calculations or when incorporation would incur unreasonable difficulties.

In some cases, the effects of a particular event or process, although not necessarily insignificant, can be shown to lie within the range of uncertainty of another FEP already accounted for in the PA calculations. In such cases, the event or process may be considered implicitly included in PA calculations, within the range of uncertainty associated with the included FEP.

The distinctions between the screened out-regulation (SO-R), screened out-probability (SO-P), and screened out-consequence (SO-C) classifications are summarized in Figure 6-7. Although some FEPs could be eliminated from PA calculations based on more than one criterion, the most practical screening criterion was used for classification. In particular, a regulatory screening classification was used in preference to a probability or consequence screening classification, as illustrated in Figure 6-7. FEPs that were not screened out based on any one of the three criteria are included in the PA.

6.2.2.2 Undisturbed Performance Features, Events, and Processes

FEPs classified as UP are accounted for in calculations of undisturbed performance of the disposal system. Undisturbed performance is defined in 40 CFR § 191.12 as "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." The UP FEPs are accounted for in the PA calculations to evaluate compliance with the Containment Requirements in 40 CFR § 191.13.

6.2.2.3 Disturbed Performance Features, Events, and Processes

FEPs classified as DP are accounted for only in assessment calculations for DP. The DP FEPs that remain following the screening process relate to the potential disruptive effects of future drilling and mining events in the controlled area. Consideration of both DP and UP FEPs is required to evaluate compliance with 40 CFR § 191.13.

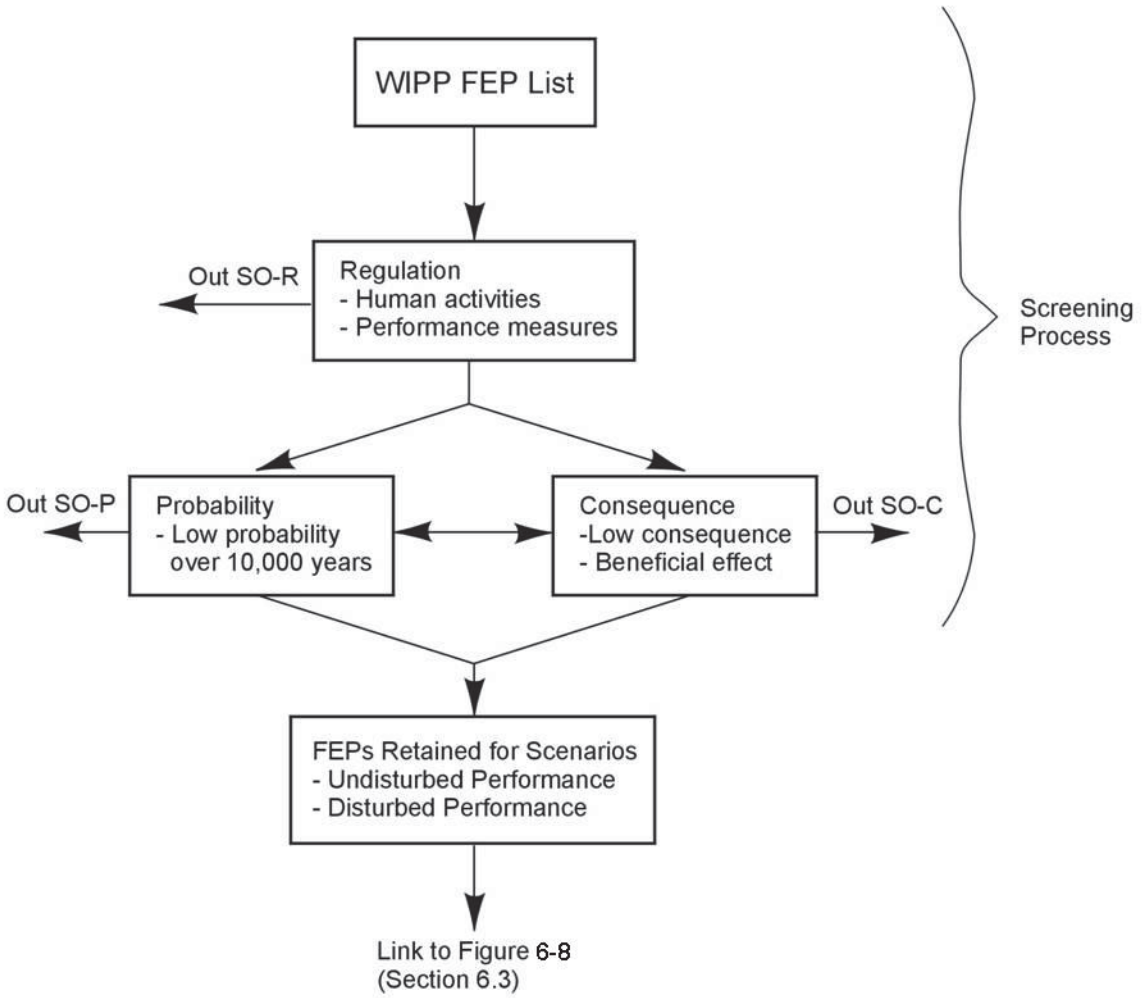

Figure 6-7. Screening Process Based on Screening Classifications

In the following sections, FEPs are discussed under the categories Natural FEPs, Waste- and Repository-Induced FEPs, and Human-Initiated Events and Processes (EPs).

This also allows an evaluation of compliance with the individual dose criterion in 40 CFR § 191.15 and the groundwater protection requirements in 40 CFR § 191.24 (see Chapter 8.0).

6.2.3 Natural Features, Events, and Processes

This subsection briefly discusses natural FEPs with the potential to affect long-term performance of the WIPP disposal system. These FEPs and their screening classifications are listed in Table 6-4; the DOE's detailed screening arguments for natural FEPs are contained in Appendix PA, Attachment SCR. Screening natural FEPs fulfills, in conjunction with the PA calculations, the criterion of the Future States Assumptions in 40 CFR § 194.25(b) that DOE shall "document in any compliance application, to the extent practicable, effects of potential future hydrogeologic, geologic and climatic conditions on the disposal system over the regulatory time frame."

Consistent with Section 194.32(d), the DOE has screened out several natural FEPs from PA calculations based on a low probability of occurrence at or near the WIPP site. In particular, natural events for which there is no evidence indicating that they have occurred within the Delaware Basin were screened on this basis. In this analysis, the probabilities of these events occurring are assumed to be zero. Quantitative, nonzero probabilities for such events, based on numbers of occurrences, cannot be ascribed without considering regions much larger than the Delaware Basin (see for example, FEP N 40, Impact of a Large Meteorite in Appendix PA, Attachment SCR), thus neglecting established geological understanding of the events and processes that occur within particular geographical provinces. No disruptive natural FEPs are likely to occur during the regulatory time frame that could create new pathways or significantly alter existing pathways.

In considering the overall geological setting of the Delaware Basin, the DOE eliminated many FEPs from PA calculations based on low consequence. Events and processes that have had little effect on the characteristics of the region in the past are expected to be of low consequence for the regulatory time period.

6.2.4 Waste- and Repository-Induced Features, Events, and Processes

The waste- and repository-induced FEPs are those that relate specifically to the waste material, waste containers, shaft seals, MgO, panel closures, repository structures, and investigation boreholes. All FEPs related to radionuclide chemistry and radionuclide migration are included in this category. FEPs related to radionuclide transport from future borehole intersections of the WIPP excavation are defined as waste- and repository-induced FEPs. Waste- and repository-induced FEPs and their screening classification are listed in Table 6-5. The DOE's detailed screening discussions for these FEPs are contained in Appendix PA (Attachment SCR).

The DOE has screened out many FEPs in this category on the basis of low consequence to the performance of the disposal system. For example, the DOE has shown that the heat generated by radioactive decay of emplaced RH- and CH-TRU waste will not increase temperature sufficiently to induce significant thermal convection, thermal stresses and strains, or thermally induced chemical perturbations within the disposal system (see Appendix PA, Attachment SCR, FEP W13 and FEP W72). Also, hydration of the emplaced concrete seals and chemical conditioner will be exothermic, but DOE has shown that the heat generated will not significantly affect the disposal system performance (see Appendix PA, Attachment SCR, FEP W72).

Other waste- and repository-induced FEPs were eliminated from PA calculations based on beneficial effect to the performance of the disposal system, if necessary to simplify the analysis.

Waste- and repository-induced FEPs eliminated on the basis of low probability of occurrence over 10,000 years are generally those for which no mechanisms were identified that

Table 6-4. Natural FEPs and Their Screening Classifications

FEPs	Screening Classification	Comments	FEP Number
GEOLOGICAL FEPS			
Stratigraphy			
Stratigraphy	UP		N1
Brine reservoirs	DP		N2
Tectonics			
Changes in regional stress	SO-C		N3
Regional tectonics	SO-C		N4
Regional uplift and subsidence	SO-C		N5
Structural FEPs			
Deformation			
Salt deformation	SO-P	UP near repository.	N6
Diapirism	SO-P		N7
Fracture development			
Formation of fractures	SO-P	UP near repository.	N8
Changes in fracture properties	SO-C	UP near repository.	N9
Fault movement			
Formation of new faults	SO-P		N10
Fault movement	SO-P		N11
Seismic activity			
Seismic activity	UP		N12
Crustal processes			
Igneous activity			
Volcanic activity	SO-P		N13
Magmatic activity	SO-C		N14
Metamorphism			
Metamorphic activity	SO-P		N15
Geochemical FEPs			
Dissolution			
Shallow dissolution	UP		N16
Deep dissolution	SO-P		N18
Breccia pipes	SO-P		N20
Collapse breccias	SO-P		N21
Mineralization			
Fracture infills	SO-C		N22
SUBSURFACE HYDROLOGICAL FEPS			
Groundwater characteristics			
Saturated groundwater flow	UP		N23
Unsaturated groundwater flow	UP	SO-C in Culebra.	N24
Fracture flow	UP		N25

Table 6-4. Natural FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Density effects on groundwater flow	SO-C		N26
Effects of preferential pathways	UP	UP in Salado and Culebra.	N27
Changes in groundwater flow			
Thermal effects on groundwater flow	SO-C		N28
Saline intrusion	SO-P		N29
Freshwater intrusion	SO-P		N30
Hydrological response to earthquakes	SO-C		N31
Natural gas intrusion	SO-P		N32
SUBSURFACE GEOCHEMICAL FEPS			
Groundwater geochemistry			
Groundwater geochemistry	UP		N33
Changes in groundwater chemistry			
Saline intrusion	SO-C		N34
Freshwater intrusion	SO-C		N35
Changes in groundwater Eh	SO-C		N36
Changes in groundwater pH	SO-C		N37
Effects of dissolution	SO-C		N38
GEOMORPHOLOGICAL FEPS			
Physiography			
Physiography	UP		N39
Meteorite impact			
Impact of a large meteorite	SO-P		N40
Denudation			
Weathering			
Mechanical weathering	SO-C		N41
Chemical weathering	SO-C		N42
Erosion			
Aeolian erosion	SO-C		N43
Fluvial erosion	SO-C		N44
Mass wasting	SO-C		N45
Sedimentation			
Aeolian deposition	SO-C		N46
Fluvial deposition	SO-C		N47
Lacustrine deposition	SO-C		N48
Mass wasting	SO-C		N49
Soil development			
Soil development	SO-C		N50
SURFACE HYDROLOGICAL FEPS			
Fluvial			

Table 6-4. Natural FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Stream and river flow	SO-C		N51
Lacustrine			
Surface water bodies	SO-C		N52
Groundwater recharge and discharge			
Groundwater discharge	UP		N53
Groundwater recharge	UP		N54
Infiltration	UP	UP for climate change effects.	N55
Changes in surface hydrology			
Changes in groundwater recharge and discharge	UP		N56
Lake formation	SO-C		N57
River flooding	SO-C		N58
CLIMATIC FEPs			
Climate			
Precipitation (for example, rainfall)	UP		N59
Temperature	UP		N60
Climate change			
Meteorological			
Climate change	UP		N61
Glaciation			
Glaciation	SO-P		N623
Permafrost	SO-P		N63
MARINE FEPs			
Seas			
Seas and oceans	SO-C		N64
Estuaries	SO-C		N65
Marine sedimentology			
Coastal erosion	SO-C		N66
Marine sediment transport and deposition	SO-C		N67
Sea level changes			
Sea level changes	SO-C		N68
ECOLOGICAL FEPs			
Flora & fauna			
Plants	SO-C		N69
Animals	SO-C		N70
Microbes	SO-C	UP for colloidal effects and gas generation	N71
Changes in flora & fauna			

Table 6-4. Natural FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Natural ecological development	SO-C		N72

Legend:

UP FEPs accounted for in the assessment calculations for undisturbed performance for 40 CFR § 191.13 (as well as 40 CFR § 191.15 and Subpart C of 40 CFR Part 191).

DP FEPs accounted for (in addition to all UP FEPs) in the assessment calculations for disturbed performance for 40 CFR § 191.13.

SO-R FEPs eliminated from PA calculations on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR § 194.25, .32 and .54

SO-C FEPs eliminated from PA (and compliance assessment) calculations based on consequence.

SO-P FEPs eliminated from PA (and compliance assessment) calculations based on low probability of occurrence.

Table 6-5. Waste- and Repository-Induced FEPs and Their Screening Classifications

FEPs	Screening Classification	Comments	FEP Number
WASTE AND REPOSITORY CHARACTERISTICS			
Repository characteristics			
Disposal geometry	UP		W1
Waste characteristics			
Waste inventory	UP		W2
Heterogeneity of waste forms	DP		W3
Container characteristics			
Container form	SO-C		W4
Container material inventory	UP		W5
Seal characteristics			
Seal geometry	UP		W6
Seal physical properties	UP		W7
Seal chemical composition	SO-C	Beneficial SO-C	W8
Backfill characteristics			
Backfill physical properties	SO-C		W9
Backfill chemical composition	UP		W10
Postclosure monitoring			
Postclosure monitoring	SO-C		W11
RADIOLOGICAL FEPs			
Radioactive decay			
Radionuclide decay and ingrowth	UP		W12
Heat from radioactive decay			
Heat from radioactive decay	SO-C		W13
Nuclear criticality			
Nuclear criticality: heat	SO-P		W14
Radiological effects on material properties			
Radiological effects on waste	SO-C		W15
Radiological effects on containers	SO-C		W16
Radiological effects on seals	SO-C		W17
GEOLOGICAL AND MECHANICAL FEPs			
Excavation-induced fracturing			
Disturbed rock zone	UP		W18
Excavation-induced changes in stress	UP		W19
Rock creep			
Salt creep	UP		W20
Changes in the stress field	UP		W21
Roof falls			

Table 6-5. Waste- and Repository-Induced FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Roof falls	UP		W22
Subsidence			
Subsidence	SO-C		W23
Large scale rock fracturing	SO-P		W24
Effects of fluid pressure changes			
Disruption due to gas effects	UP		W25
Pressurization	UP		W26
Effects of explosions			
Gas explosions	UP		W27
Nuclear explosions	SO-P		W28
Thermal effects			
Thermal effects on material properties	SO-C		W29
Thermally induced stress changes	SO-C		W30
Differing thermal expansion of repository components	SO-C		W31
Mechanical effects on material properties			
Consolidation of waste	UP		W32
Movement of containers	SO-C		W33
Container integrity	SO-C	Beneficial SO-C	W34
Mechanical effects of backfill	SO-C		W35
Consolidation of seals	UP		W36
Mechanical degradation of seals	UP		W37
Underground boreholes	UP		W39
SUBSURFACE HYDROLOGICAL AND FLUID DYNAMICAL FEPs			
Repository-induced flow			
Brine inflow	UP		W40
Wicking	UP		W41
Effects of gas generation			
Fluid flow due to gas production	UP		W42
Thermal effects			
Convection	SO-C		W43
GEOCHEMICAL AND CHEMICAL FEPs			
Gas generation			
Microbial gas generation			
Degradation of organic material	UP		W44
Effects of temperature on microbial gas generation	UP		W45
Effects of pressure on microbial gas generation	SO-C		W46

Table 6-5. Waste- and Repository-Induced FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Effects of radiation on microbial gas generation	SO-C		W47
Effects of biofilms on microbial gas generation	UP		W48
Corrosion			
Gases from metal corrosion	UP		W49
Galvanic coupling	SO-C		W50
Chemical effects of corrosion	UP		
Radiolytic gas generation			
Radiolysis of brine	SO-C		W52
Radiolysis of cellulose	SO-C		W53
Helium gas production	SO-C		W54
Radioactive gases	SO-C		W55
Chemical speciation			
Speciation	UP	UP in disposal rooms and Culebra. SO-C elsewhere, and beneficial SO-C in cementitious seals.	W56
Kinetics of speciation	SO-C		W57
Precipitation and dissolution			
Dissolution of waste	UP		W58
Precipitation	SO-C	Beneficial SO-C	W59
Kinetics of precipitation and dissolution	SO-C	Kinetics of waste dissolution is a beneficial SO-C	W60
Sorption			
Actinide sorption	UP	UP in the Culebra and Dewey Lake. Beneficial SO-C elsewhere	W61
Kinetics of sorption	UP		W62
Changes in sorptive surfaces	UP		W63
Oxidation-reduction chemistry			
Effect of metal corrosion	UP		W64
Oxidation-reduction fronts	SO-P		W65
Oxidation-reduction kinetics	UP		W66
Localized reducing zones	SO-C		W67
Organic complexation			
Organic complexation	UP		W67
Organic ligands	UP		W69
Humic and fulvic acids	UP		W70
Kinetics of organic complexation	SO-C		W71

Table 6-5. Waste- and Repository-Induced FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Exothermic reactions			
Exothermic reactions	SO-C		W72
Concrete hydration	SO-C		W73
Chemical effects on material properties			
Chemical degradation of seals	UP		W74
Chemical degradation of backfill	SO-C		W75
Microbial growth on concrete	UP		W76
CONTAMINANT TRANSPORT MODE FEPs			
Solute transport			
Solute transport	UP		W77
Colloid transport			
Colloid transport	UP		W78
Colloid formation and stability	UP		W79
Colloid filtration	UP		W80
Colloid sorption	UP		W81
Particulate transport			
Suspensions of particles	DP	SO-C for undisturbed conditions	W82
Rinse	SO-C		W83
Cuttings	DP	Repository intrusion only	W84
Cavings	DP	Repository intrusion only	W85
Spallings	DP	Repository intrusion only	W86
Microbial transport			
Microbial transport	UP		W87
Biofilms	SO-C	Beneficial SO-C	W88
Gas transport			
Transport of radioactive gases	SO-C		W89
CONTAMINANT TRANSPORT PROCESSES			
Advection			
Advection	UP		W90
Diffusion			
Diffusion	UP		W91
Matrix diffusion	UP		W92
Thermochemical transport phenomena			
Soret effect	SO-C		W93
Electrochemical transport phenomena			
Electrochemical effects	SO-C		W94
Galvanic coupling	SO-P		W95

Table 6-5. Waste- and Repository-Induced FEPs and Their Screening Classifications — Continued

FEPs	Screening Classification	Comments	FEP Number
Electrophoresis	SO-C		W96
Physicochemical transport phenomena			
Chemical gradients	SO-C		W97
Osmotic processes	SO-C	Beneficial SO-C	W98
Alpha recoil	SO-C		W99
Enhanced diffusion	SO-C		W100
ECOLOGICAL FEPs			
Plant, animal, and soil uptake			
Plant uptake	SO-R	SO-C for 40 CFR § 191.15	W101
Animal uptake	SO-R		W102
Accumulation in soils	SO-C	Beneficial SO-C	W103
Human uptake			
Ingestion	SO-R	SO-C for 40 CFR § 191.15	W104
Inhalation	SO-R	SO-C for 40 CFR § 191.15	W105
Irradiation	SO-R	SO-C for 40 CFR § 191.15	W106
Dermal sorption	SO-R	SO-C for 40 CFR § 191.15	W107
Injection	SO-R	SO-C for 40 CFR § 191.15	W108

Legend:

UP FEPs accounted for in the assessment calculations for undisturbed performance for 40 CFR § 191.13 (as well as 40 CFR § 191.15 and Subpart C of 40 CFR Part 191).

DP FEPs accounted for (in addition to all UP FEPs) in the assessment calculations for disturbed performance for 40 CFR § 191.13.

SO-R FEPs eliminated from PA calculations on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR § 194. 25, .32 and .54.

SO-C FEPs eliminated from PA (and compliance assessment) calculations based on consequence.

SO-P FEPs eliminated from PA (and compliance assessment) calculations based on low probability of occurrence.

could result in their occurrence within the disposal system. Such FEPs include explosions resulting from nuclear criticality, and the development of large-scale reduction-oxidation fronts.

6.2.5 Human-Initiated Events and Processes

Assessments of compliance with the Containment Requirements in 40 CFR § 191.13 require consideration of "all significant processes and events," including human-initiated EPs. These EPs and their screening classifications are listed in Table 6-6. The DOE's detailed screening arguments for human-initiated EPs are presented in Appendix PA, Attachment SCR.

The scope of PA is clarified with respect to human-initiated events and processes in 40 CFR § 194.32. Section 194.32(a) states that

> Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.

Thus, PA must conside human-initiated EPs relating to mining and drilling activities that might take place during the regulatory time frame. In particular, PAs must consider the potential effects of such activities that might take place within the controlled area at a time when institutional controls cannot be assumed to completely eliminate the possibility of human intrusion.

Further criteria concerning the scope of PAs are provided at 40 CFR § 194.32(c):

> Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

Table 6-6. Human-Initiated EPs and Their Screening Classifications

EPs	Screening Classification		Comments	FEP Number
	Historical/ Ongoing/ Near Future	Future		
GEOLOGICAL EPs				
Drilling			DP for boreholes that penetrate the waste and boreholes that penetrate Castile brine underlying the waste disposal region. SO-C for other future drilling.	
Oil and gas exploration	SO-C	DP		H1
Potash exploration	SO-C	DP		H2
Water resources exploration	SO-C	SO-C		H3
Oil and gas exploitation	SO-C	DP		H4
Groundwater exploitation	SO-C	SO-C		H5
Archeological investigations	SO-R	SO-R		H6
Geothermal	SO-R	SO-R		H7
Other resources	SO-C	DP		H8
Enhanced oil and gas recovery	SO-C	DP		H9
Liquid waste disposal	SO-R	SO-R		H10
Hydrocarbon storage	SO-R	SO-R		H11
Deliberate drilling intrusion	SO-R	SO-R		H12
Excavation activities				
Conventional underground potash mining	UP	DP	UP for mining outside the controlled area. DP for mining inside the controlled area.	H13
Solution mining for potash	SO-R	SO-R	New to FEP Baseline	H58
Solution mining for other resources	SO-R	SO-R	New to FEP Baseline	H59
Other resources	SO-C	SO-R		H14
Tunneling	SO-R	SO-R		H15
Construction of underground facilities (for example storage, disposal, accommodation)	SO-R	SO-R		H16
Archeological excavations	SO-C	SO-R		H17
Deliberate mining intrusion	SO-R	SO-R		H18
Subsurface explosions				
Resource recovery				

Table 6-6. Human-Initiated EPs and Their Screening Classifications — Continued

EPs	Screening Classification		Comments	FEP Number
	Historical/ Ongoing/ Near Future	Future		
Explosions for resource recovery	SO-C	SO-R		H19
Underground nuclear device testing				
Underground nuclear device testing	SO-C	SO-R		H20
SUBSURFACE HYDROLOGICAL AND GEOCHEMICAL EPs				
Borehole fluid flow				
Drilling-induced flow				
Drilling fluid flow	SO-C	DP	DP for boreholes that penetrate the waste. SO-C for other future drilling.	H21
Drilling fluid loss	SO-C	DP	DP for boreholes that penetrate the waste, SO-C for other future drilling	H22
Blowouts	SO-C	DP	DP for boreholes that penetrate the waste and boreholes that penetrate Castile brine underlying the waste disposal region. SO-C for other future drilling.	H23
Drilling-induced geochemical changes	UP	DP	SO-C for units other than the Culebra.	H24
Fluid extraction				
Oil and gas extraction	SO-C	SO-R		H25
Groundwater extraction	SO-C	SO-R		H26
Fluid injection				
Liquid waste disposal	SO-C	SO-C		H27
Enhanced oil and gas production	SO-C	SO-C		H28
Hydrocarbon storage	SO-C	SO-C		H29
Fluid-injection induced geochemical changes	UP	SO-R	SO-C for units other than the Culebra	H30
Flow through abandoned boreholes			Classification distinguishes the time when drilling occurs.	

Table 6-6. Human-Initiated EPs and Their Screening Classifications — Continued

EPs	Screening Classification		Comments	FEP Number
	Historical/ Ongoing/ Near Future	Future		
Natural borehole fluid flow	SO-C	DP	DP for boreholes that penetrate Castile brine underlying the waste disposal region. SO-C for other future boreholes.	H31
Waste-induced borehole flow	SO-R	DP	DP for boreholes that penetrate the waste. SO-C for other future boreholes.	H32
Borehole-induced solution and subsidence	SO-C	SO-C		H34
Borehole-induced mineralization	SO-C	SO-C		H35
Borehole-induced geochemical changes	UP	DP	SO-C for units other than the Culebra	H36
Excavation-induced flow			Classification distinguishes the time when excavation occurs.	
Changes in groundwater flow due to mining	UP	DP	UP for mining outside the controlled area. DP for mining inside the controlled area.	H37
Changes in geochemistry due to mining	SO-C	SO-R		H38
Explosion-induced flow				
Changes in groundwater flow due to explosions	SO-C	SO-R		H39
GEOMORPHOLOGICAL EPs				
Land use and disturbances				
Land use changes	SO-R	SO-R		H40
Surface disruptions	UP	SO-R		H41
SURFACE HYDROLOGICAL EPs				
Water control and use				
Damming of streams or rivers	SO-C	SO-R		H42
Reservoirs	SO-C	SO-R		H43
Irrigation	SO-C	SO-R		H44
Lake usage	SO-R	SO-R		H45
Altered soil or surface water chemistry by human activities	SO-C	SO-R		H46

Table 6-6. Human-Initiated EPs and Their Screening Classifications — Continued

EPs	Screening Classification		Comments	FEP Number
	Historical/ Ongoing/ Near Future	Future		
CLIMATIC EPs				
Anthropogenic climate change				
Greenhouse gas effects	SO-R	SO-R		H47
Acid rain	SO-R	SO-R		H48
Damage to the ozone layer	SO-R	SO-R		H49
MARINE EPs				
Marine activities				
Coastal water use	SO-R	SO-R		H50
Seawater use	SO-R	SO-R		H51
Estuarine water use	SO-R	SO-R		H52
ECOLOGICAL EPs				
Agricultural activities				
Arable farming	SO-C	SO-R		H53
Ranching	SO-C	SO-R		H54
Fish farming	SO-R	SO-R		H55
Social and technological developments				
Demographic change and urban development	SO-R	SO-R		H56
Loss of records	NA	DP		H57

Legend:

UP FEPs accounted for in the assessment calculations for undisturbed performance for 40 CFR § 191.13 (as well as 40 CFR § 191.15 and Subpart C of 40 CFR Part 191).

DP FEPs accounted for (in addition to all UP FEPs) in the assessment calculations for disturbed performance for 40 CFR § 191.13.

SO-R FEPs eliminated from performance assessment calculations on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR § 194. 25, .32 and .54.

SO-C FEPs eliminated from PA (and compliance assessment) calculations based on consequence.

SO-P FEPs eliminated from PA (and compliance assessment) calculations based on low probability of occurrence.

NA FEPs not applicable to the particular category.

PAs must consider all human-initiated EPs relating to activities that have taken place or are reasonably expected to take place outside the controlled area in the near future.

In order to implement the criteria in Section 194.32 relating to the scope of PA, the DOE has divided human activities into three categories: (1) human activities that are currently taking place and those that took place prior to the time of the compliance application, (2) human activities that might be initiated in the near future after submission of the compliance application, and (3) human activities that might be initiated after repository closure. The first two categories

of EPs are considered under undisturbed performance; EPs in the third category lead to disturbed performance conditions.

(1) Historical and current human activities include resource extraction activities that have taken place and are currently taking place outside the controlled area. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. Current human activities taking place within the controlled area are essentially those associated with development of the WIPP repository. Historical activities include existing boreholes.

(2) Near-future human activities include resource extraction activities that may occur outside the controlled area based on existing plans and leases. Thus, the near future includes the expected lives of existing mines and oil and gas fields, and the expected lives of new mines and oil and gas fields that the DOE expects will be developed based on existing plans and leases. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. The only human activities expected to occur within the controlled area in the near future are those associated with WIPP repository development. The DOE assumes that any activity in the near future, based on existing plans and leases, will be initiated prior to repository closure. Activities initiated prior to repository closure are assumed to continue until their completion.

(3) Future human activities include activities that might be initiated within or outside the controlled area after repository closure. This includes drilling and mining for resources within the disposal system when institutional controls cannot be assumed to completely eliminate the possibility of such activities. Future human activities could influence the transport of contaminants within and outside the disposal system by directly removing waste from the disposal system or altering the geological, hydrological, or geochemical characteristics of the disposal system.

To satisfy the criteria in 40 CFR § 194.32, PAs must consider the potential effects of historical, current, near-future, and future human activities on the disposal system performance. The criterion in 40 CFR § 194.25(a) concerned with predicting the future states of society requires that PAs and compliance assessments "shall assume that the characteristics of the future remain what they are at the time the compliance application is prepared." This criterion has been applied to eliminate the following human-initiated EPs from PA calculations:

- drilling associated with geothermal energy production (H7), liquid waste disposal (H10), hydrocarbon storage (H11), and archeological investigations (H6);
- excavation activities associated with tunneling (H15) and construction of underground facilities (H16) (for example, storage, disposal, and accommodation);
- changes in land use (H40);
- anthropogenic climate change (H47, H48 and H49);

- changes in agricultural practices (H53, H54 and H55);
- demographic change, urban developments, and technological developments (H56); and
- solution mining (H58 and H59).

As discussed in Chapter 8.0, compliance assessments (to determine compliance with 40 CFR § 191.15 and Subpart C of 40 CFR Part 191) need to consider the UP of the disposal system.

6.2.5.1 Historical, Current, and Near-Future Human Activities

Historical, current, and near-future human activities could affect WIPP site characteristics after the submission of this application, and could influence the disposal system performance. The hydrogeological impacts of historical, current, and near-future potash mining outside the controlled area are accounted for in calculations of the undisturbed performance of the disposal system. Near-future potash mining is assumed to continue for the expected economic life of each mine. The potential consequences to the disposal system performance from other human-initiated EPs expected to occur in the Delaware Basin in the near future are discussed in Appendix PA, Attachment SCR, which describes how these EPs are eliminated based on low consequence.

6.2.5.2 Future Human Activities

PA (but not compliance assessments, as discussed in Chapter 8.0) must consider the effects of future human activities on the disposal system performance. The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), which limits the scope of consideration of future human actions in PAs to mining and drilling.

6.2.5.2.1 Criteria Concerning Future Mining

The EPA provides additional criteria concerning the type of future mining that should be considered by the DOE in 40 CFR § 194.32(b):

> Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.

Thus, considering future mining may be limited to mining within the controlled area at locations of resources that are similar in quality and type to those currently extracted from the Delaware Basin. Potash is the only resource identified within the controlled area in quality similar to that currently mined from underground deposits elsewhere in the Delaware Basin. Within the controlled area, the McNutt of the Salado provides the only potash of appropriate quality. The hydrogeological impacts of future potash mining within the controlled area are accounted for in DP calculations of the disposal system. Consistent with 40 CFR § 194.32(b), all economically

recoverable resources in the vicinity of the disposal system (outside the controlled area) are assumed to be extracted in the near future.

6.2.5.2.2 Criteria Concerning Future Drilling

With respect to future drilling, in the preamble to 40 CFR Part 194, the EPA "reasoned that while the resources drilled for today may not be the same as those drilled for in the future, the present rates at which these boreholes are drilled can nonetheless provide an estimate of the future rate at which boreholes will be drilled." Criteria concerning the consideration of future deep and shallow drilling[2] in PAs are provided in 40 CFR § 194.33. These criteria require that, to calculate future drilling rates, the DOE should examine the historical rate of drilling for resources in the Delaware Basin. Historical drilling for purposes other than resource exploration and recovery (such as WIPP site investigation) need not be considered in determining future drilling rates.

In particular, when calculating the frequency of future deep drilling, 40 CFR § 194.33(b)(3)(i) states that the DOE should

> Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.

Oil and gas are the only known resources below 655 m (2,150 ft) that have been exploited over the past 100 years in the Delaware Basin. However, some potash and sulfur exploration boreholes have been drilled in the Delaware Basin to depths in excess of 2,150 feet (655 meters) below the surface relative to where the drilling occurred. Thus, consistent with 40 CFR § 194.33(b)(3)(i), the DOE used the historical record of deep drilling associated with oil, gas, potash and sulfur exploration, and oil and gas exploitation in the Delaware Basin to determine the rate of deep drilling within the controlled area and throughout the basin in the future, as discussed in Appendix DATA, Section 2 and Attachment A. Deep drilling may occur within the controlled area after the end of active institutional control (100 years after disposal).

In calculating the frequency of future shallow drilling, 40 CFR § 194.33(b)(4)(i) states that the DOE should

> Identify shallow drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.

An additional criterion with respect to calculating future shallow drilling rates is provided in 40 CFR § 194.33(b)(4)(iii):

> In considering the historical rate of all shallow drilling, the Department may, if justified, consider only the historical rate of shallow drilling for resources of similar type and quality to those in the controlled area.

[2] The EPA has defined two types of drilling in 40 CFR § 194.2: deep drilling, defined as "drilling events in the Delaware Basin that reach or exceed a depth of 2,150 ft below the surface relative to where such drilling occurred"; and shallow drilling, defined as "drilling events in the Delaware Basin that do not reach a depth of 2,150 ft below the surface relative to where such drilling occurred."

As an example, EPA states in the preamble to 40 CFR Part 194 that "if only non-potable water can be found within the controlled area, then the rate of drilling for water may be set equal to the historical rate of drilling for non-potable water in the Delaware Basin over the past 100 years." Thus, the DOE may limit the rate of future shallow drilling based on a determination of the potential resources in the controlled area. Shallow drilling associated with water, potash, sulfur, oil, and gas extraction has taken place in the Delaware Basin over the past 100 years. However, of these resources, only water and potash are present at shallow depths (less than 655 m [2,150 ft] below the surface) within the controlled area. Thus, consistent with 40 CFR § 194.33(b)(4), the DOE used the historical record of shallow drilling associated with water and potash extraction in the Delaware Basin in calculations to determine the rate of shallow drilling within the controlled area, as discussed in Appendix DATA, Section 2 and Attachment A.

The EPA also provides a criterion in 40 CFR § 194.33(d) concerning the use of future boreholes subsequent to drilling:

> With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

Thus, PAs need not consider the effects of techniques used for resource extraction and recovery that would occur after the drilling of a future borehole.

The EPA provides an additional criterion to limit the severity of human intrusion scenarios that must be considered in PAs. In 40 CFR § 194.33(b)(1), EPA states that

> Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario.

Thus, human intrusion scenarios involving deliberate intrusion need not be considered in PAs.

6.2.5.2.3 Screening of Future Human-Initiated EPs

Future human-initiated EPs accounted for in PA calculations for the WIPP are those associated with mining and deep drilling within the controlled area at a time when institutional controls cannot be assumed to completely eliminate the possibility of such activities. All other future human-initiated EPs, if not eliminated from PA calculations based on regulation, have been eliminated based on low consequence or low probability. For example, the effects of future shallow drilling within the controlled area were eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. These screening decisions are listed in Table 6-6 and are discussed in Appendix PA, Attachment SCR.

6.2.6 Reassessment of Features, Events, and Processes for the Compliance Recertification

As part of the recertification effort, the DOE assessed the impacts of new information on the original FEPs baseline to determine if changes to the original decisions are necessary. The FEPs baseline could be affected by new information from literature, experiments, observations from monitoring programs, or changes implemented by the DOE (moving the WIPP horizon to Clay G, for example). The processes and results of the FEPs baseline reassessment are documented in Appendix PA, Attachment SCR.

The FEP assessment resulted in the addition of two new FEPs to better represent solution mining (H57 and H58) and the deletion of four FEPs (by combining the deleted FEPs into other related FEPs). Seven screening decisions were also changed as a result of new information. However, only three FEPs previously screened out were screened into the CRA-2004 PA. The impact of organic ligands (W68 and W69) was screened into the CRA-2004 PA as a result of new information. This FEP screening decision change is the only impact to the PA system. The inclusion of ligands is discussed in Section 6.4.3.4. The FEP Surface Disruptions (H41) was also screened in. This FEP was already implicitly included in PA through past site characterization and current monitoring data (Appendix PA, Attachment SCR). The changes to the FEPs baseline are summarized in Table 6-7.

6.3 Scenario Development and Selection

This section addresses scenarios formed from FEPs that were retained for PA calculations, and introduces the specification of scenarios for consequence analysis. Probabilities associated with scenarios are discussed in Section 6.4.12.

Logic diagrams are used to illustrate the formation of scenarios for consequence analysis from combinations of FEPs that remain after FEP screening (Cranwell et al. 1990) (Figure 6-8). Each scenario shown in Figure 6-8 is defined by a combination of occurrence and

Table 6-7. FEPs Reassessment Summary Results

EPA FEP I.D.	FEP Name	Summary of Change
FEPs Combined with other FEPs		
N17	Lateral Dissolution	Combined with N16, “Shallow Dissolution.” N17 removed from baseline.
N19	Solution Chimneys	Combined with N20, “Breccia Pipes.” N19 removed from Baseline.
H33	Flow Through Undetected Boreholes	Combined with H31, “Natural Borehole Fluid Flow.” H33 removed from baseline.
W38	Investigation Boreholes	Addressed in H31, “Natural Borehole Fluid Flow,” and H33, “Flow Through Undetected Boreholes.” W38 removed from baseline.
FEPs With Changed Screening Decisions		
W50	Galvanic Coupling	SO-P to SO-C
W68	Organic Complexation	SO-C to UP
W69	Organic Ligands	SO-C to UP
H27	Liquid Waste Disposal	SO-R to SO-C
H28	Enhanced Oil and Gas Production	SO-R to SO-C
H29	Hydrocarbon Storage	SO-R to SO-C
H41	Surface Disruptions	SO-C to UP (HCN)
New FEPs for CRA-2004		
H58	Solution Mining for Potash	Separated from H13, “Potash Mining.”
H59	Solution Mining for Other Resources	Separated from H13, “Potash Mining.”

nonoccurrence of all potentially disruptive EPs. Disruptive EPs are defined as those that create new pathways, or significantly alter existing pathways for fluid flow and, potentially, radionuclide transport within the disposal system. Each of these scenarios also contains a set of features and nondisruptive EPs that remain after FEP screening. As shown in Figure 6-8, undisturbed performance (UP) and disturbed performance (DP) scenarios are considered in consequence modeling for the WIPP PA. The (UP) scenario, as discussed in Chapter 8.0, is used for compliance assessments. Important aspects of (UP) and (DP) are summarized in this section.

6.3.1 Undisturbed Performance

Undisturbed performance is defined in 40 CFR § 191.12 to mean "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." Considering only (UP) is required for compliance assessments with respect to the Individual and Groundwater Protection Requirements (40 CFR § 191.15 see Chapter 8.0). Undisturbed performance is also considered with (DP) for PAs with respect to the Containment Requirements (40 CFR § 191.13).

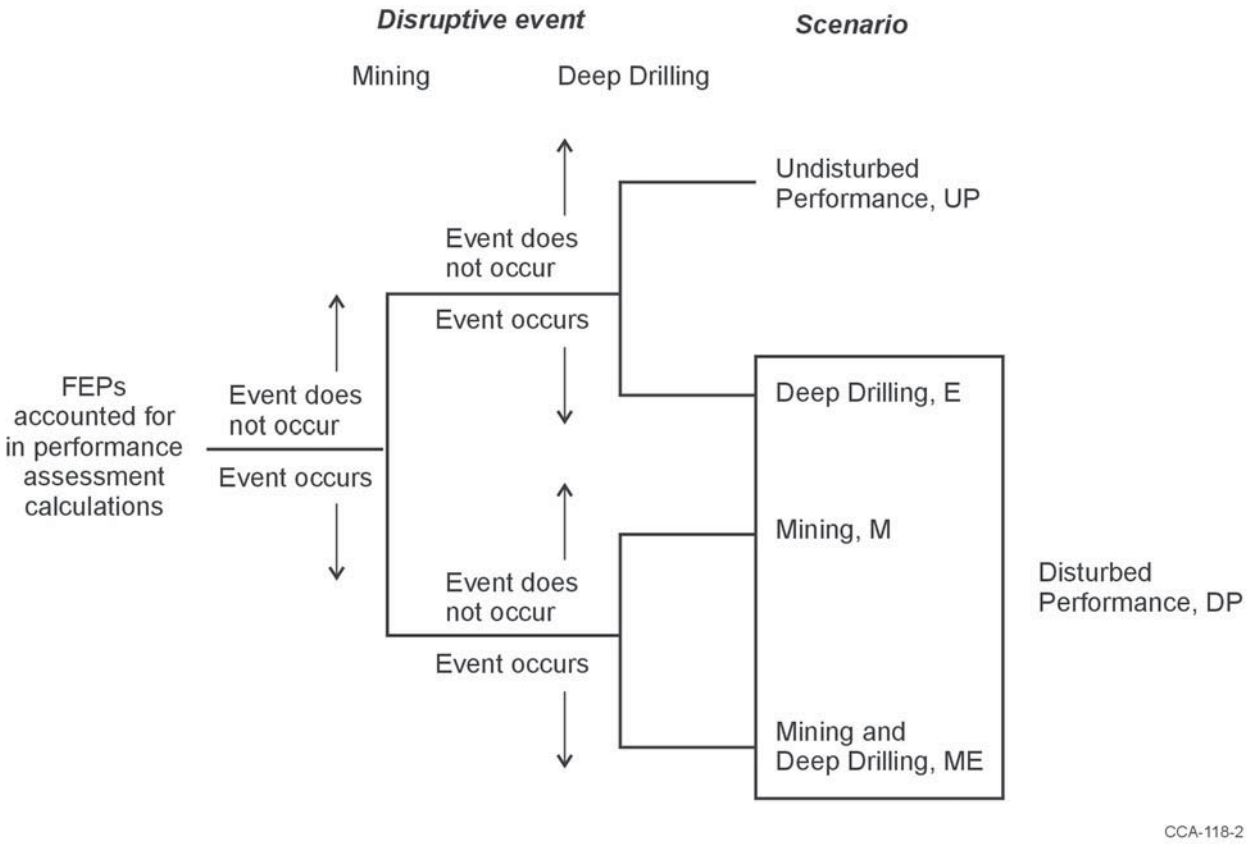

Figure 6-8. Logic Diagram for Scenario Analysis

No potentially disruptive natural EPs are likely to occur during the regulatory time frame (Section 6.2.3 and Appendix PA, Attachment SCR). Therefore, all naturally occurring EPs retained for scenario construction are nondisruptive and are considered as part of (UP). The only natural features and waste- and repository-induced FEPs retained after screening that are not

included in the (UP) scenario but are included in (DP) are those directly associated with the potential effects of future deep drilling within the controlled area. These drilling-related FEPs are discussed in Section 6.3.2. Potash mining outside the controlled area does not constitute a disruption of the disposal system by human intrusion and is included in the (UP) scenario. In total, 70 (UP) FEPs were identified (Section 6.2.3). These FEPs have been assigned a screening designator (UP) in tables in Section 6.2.3 and are listed separately in Table 6-8. Table 6-8 also contains references to text in Section 6.4 that describes the conceptual models, which account for the UP FEPs.

Among the most significant FEPs that will affect the (UP) within the disposal system are excavation-induced fracturing, gas generation, salt creep, and MgO in the disposal rooms.

- The repository excavation and consequent changes in the rock stress field surrounding the excavated opening will create a DRZ immediately adjacent to excavated openings. The DRZ will exhibit mechanical and hydrological properties different than those of the intact rock.

- Organic material in the waste may degrade because of microbial activity, and brine will corrode metals in the waste and waste containers, with concomitant generation of gases. Gas generation may result in pressures sufficient to both maintain or develop fractures and change the fluid flow pattern around the waste disposal region.

- At the repository depth, salt creep will tend to heal fractures and reduce the permeability of the DRZ and the crushed salt component of the long-term shaft seals to near that of the host rock salt.

- The MgO engineered barrier emplaced in the disposal rooms will react with CO_2 and maintain mildly alkaline conditions. Corrosion of metals in the waste and waste containers will maintain reducing conditions. These effects will decrease radionuclide solubility.

Radionuclides can become mobile as a result of waste dissolution and colloid generation following brine flow into the disposal rooms. Colloids may be generated from the waste (humics, mineral fragments, and actinide intrinsic colloids) or from other sources (humics, mineral fragments, and microbes).

Conceptually, there are several pathways for radionuclide transport within the undisturbed disposal system that may result in releases to the accessible environment (Figure 6-9). Contaminated brine may migrate away from the waste-disposal panels if pressure within the panels is elevated by gas generated from corrosion or microbial consumption. Radionuclide transport may occur laterally, through the anhydrite interbeds toward the subsurface boundary of the accessible environment in the Salado, or through access drifts or anhydrite interbeds to the base of the shafts. In the latter case, if the pressure gradient between the panels and overlying strata is sufficient, contaminated brine may migrate up the shafts. As a result, radionuclides may be transported directly to the ground surface, or laterally away from the shafts, through permeable strata such as the Culebra, toward the subsurface boundary of the accessible environment. These conceptual pathways are shown in Figure 6-9.

The modeling system described in Section 6.4 includes potential radionuclide transport along other pathways, such as migration through Salado halite. However, the natural properties of the undisturbed system make radionuclide transport to the accessible environment via these other pathways unlikely.

6.3.2 Disturbed Performance

Assessments for compliance with 40 CFR § 191.13 need to consider the potential effects of future disruptive natural and human-initiated EPs on the performance of the disposal system. As discussed in Section 6.2.3, no potentially disruptive, natural EPs are considered sufficiently likely to require inclusion in analyses of either (UP) or (DP). The only future human-initiated EPs retained after FEP screening are those associated with mining and deep drilling (but not the subsequent use of a borehole) within the controlled area when institutional controls cannot be assumed to eliminate the possibility of such activities (Sections 6.2.5.2 and 6.4.12.1). In total, 21 (DP) FEPs associated with future mining and deep drilling have been identified. These FEPs were assigned a screening designator "DP" in tables in Section 6.2 and are listed separately in Table 6-9. Table 6-9 also contains references to text in Section 6.4 that describes the conceptual models which account for the DP FEPs.

For evaluating the consequences of (DP), the DOE has defined the mining scenario, M, the deep drilling scenario, E, and a mining and drilling scenario, ME. These scenarios are described in the following sections.

6.3.2.1 The Disturbed Performance Mining Scenario

The (DP) mining scenario, M, involves future mining within the controlled area.

Consistent with the criteria stated by the EPA in 40 CFR § 194.32 (b) for PA calculations, the effects of potential future mining within the controlled area are limited to changes in hydraulic conductivity of the Culebra that result from subsidence (as described in Section 6.4.6.2.3.

Radionuclide transport may be affected in the M scenario if a head gradient between the waste-disposal panels and the Culebra causes brine contaminated with radionuclides to move from the waste-disposal panels to the base of the shafts and up to the Culebra. The changes in the Culebra transmissivity field may affect the rate and direction of radionuclide transport within the Culebra. Features of the M scenario are illustrated in Figure 6-10.

The three disturbed performance FEPs labeled "M" in Table 6-9 relate to the occurrence and effects of future mining. The modeling system used for the M scenario is similar to that developed for the UP scenario, but with a modified Culebra transmissivity field in the controlled area to account for the mining effects.

6.3.2.2 The Disturbed Performance Deep Drilling Scenario

The DP deep drilling scenario, E, involves at least one deep drilling event that intersects the waste disposal region. The EPA provides criteria for analyzing the consequences of future drilling events in PAs in 40 CFR § 194.33(c):

Performance assessments shall document that in analyzing the consequences of drilling events, the Department assumed that:

(1) Future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. Such future drilling practices shall include, but shall not be limited to: the types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of such boreholes that are sealed by humans; and

Table 6-8. Undisturbed Performance FEPs

UP FEPs	Section
NATURAL FEPs	
Geological	
Stratigraphy	
Stratigraphy	6.4.2
Structural effects	
Seismic activity	
Seismic activity	6.4.5.3
Geochemical	
Dissolution	
Shallow dissolution	6.4.6.2
Subsurface hydrological	
Groundwater characteristics	
Saturated groundwater flow	6.4.5 6.4.6
Unsaturated groundwater flow	6.4.6
Fracture flow	6.4.6.2
Effects of preferential pathways	6.4.6.2
Subsurface geochemical	
Groundwater geochemistry	
Groundwater geochemistry	6.4.3.4 6.4.6.2
Geomorphological	
Physiography	
Physiography	6.4.2
Surface hydrological	
Groundwater recharge and discharge	
Groundwater discharge	6.4.10.2
Groundwater recharge	6.4.10.2
Infiltration	6.4.10.2
Changes in surface hydrology	
Changes in groundwater recharge and discharge	6.4.9
Climatic	
Climate	
Precipitation (for example, rainfall)	6.4.9
Temperature	6.4.9
Climate change	
Meteorological	
Climate change	6.4.9

Table 6-8. Undisturbed Performance FEPs — Continued

UP FEPs	Section
WASTE- AND REPOSITORY-INDUCED FEPs	
Waste and repository characteristics	
Repository characteristics	
Disposal geometry	6.4.2.1
Waste characteristics	
Waste inventory	6.4.3.3
Container characteristics	
Container material inventory	6.4.3.3
Seal characteristics	
Seal geometry	6.4.3
Seal physical properties	6.4.4
Backfill characteristics	
Backfill chemical composition	6.4.3.4
Radiological	
Radioactive decay	
Radionuclide decay and ingrowth	6.4.5.4.2 6.4.12.4
Geological and Mechanical	
Excavation-induced fracturing	
DRZ	6.4.5.3
Excavation-induced changes in stress	6.4.3.1
Rock creep	
Salt creep	6.4.3.1
Changes in the stress field	6.4.3.1
Roof falls	
Roof falls	6.4.5.3
Effects of fluid pressure changes	
Disruption due to gas effects	6.4.5.2
Pressurization	6.4.5.2
Effects of explosions	
Gas explosions	6.4.5.3
Mechanical effects on material properties	
Consolidation of waste	6.4.3.1
Consolidation of seals	6.4.4
Mechanical degradation of seals	6.4.4
Underground boreholes	6.4.5.3
Subsurface hydrological and fluid dynamics	
Repository-induced flow	

Table 6-8. Undisturbed Performance FEPs — Continued

UP FEPs	Section
Brine inflow	6.4.3.2
Wicking	6.4.3.2
Effects of gas generation	
Fluid flow due to gas production	6.4.3.2
Geochemical and chemical	
Gas generation	
Microbial gas generation	
Consumption of organic materials	6.4.3.3
Effects of temperature on microbial gas generation	6.4.3.3
Effects of biofilms on microbial gas generation	6.4.3.3
Corrosion	
Gases from metal corrosion	6.4.3.3
Chemical effects of corrosion	6.4.3.3
Chemical speciation	
Speciation	6.4.3.4 6.4.3.5
Precipitation and dissolution	
Dissolution of waste	6.4.3.5
Sorption	
Actinide sorption	6.4.3.6 6.4.6.2.1
Kinetics of sorption	6.4.6.2.1
Changes in sorptive surfaces	6.4.6.2.1
Reduction-oxidation chemistry	
Effect of metal corrosion	6.4.3.5
Reduction-oxidation kinetics	6.4.3.5
Organic complexation	
Organic complexation	6.4.3.4
Organic ligands	6.4.3.4
Humic and fulvic acids	6.4.3.6 6.4.6.2.2
Chemical effects on material properties	
Chemical degradation of seals	6.4.4
Microbial growth on concrete	6.4.4
Contaminant transport mode	
Solute transport	

Table 6-8. Undisturbed Performance FEPs — Continued

UP FEPs	Section
Solute transport	6.4.5.4 6.4.6.2.1
Colloid transport	
Colloid transport	6.4.6.2.2
Colloid formation and stability	6.4.3.6
Colloid filtration	6.4.6.2.2
Colloid sorption	6.4.6.2.2
Microbial transport	
Microbial transport	6.4.6.2.2
Contaminant transport processes	
Advection	
Advection	6.4.5.4 6.4.6.2
Diffusion	
Diffusion	6.4.5.4 6.4.6.2
Matrix diffusion	6.4.6.2
HUMAN-INITIATED EPs	
Geomorphological	
Surface disruptions	6.4
Geological	
Excavation activities	
Potash mining outside controlled area	6.4.6.2.3 6.4.12.8 6.4.13.8
Subsurface hydrological and geochemical	
Borehole fluid flow	
Drilling-induced flow	
Drilling induced geochemical changes	6.4.6.2
Fluid injection	
Fluid injection-induced geochemical changes	6.4.6.2
Flow through abandoned boreholes	
Borehole-induced geochemical changes	6.4.6.2
Excavation-induced flow	
Changes in groundwater flow due to mining	6.4.6.2.3 6.4.12.8 6.4.13.8

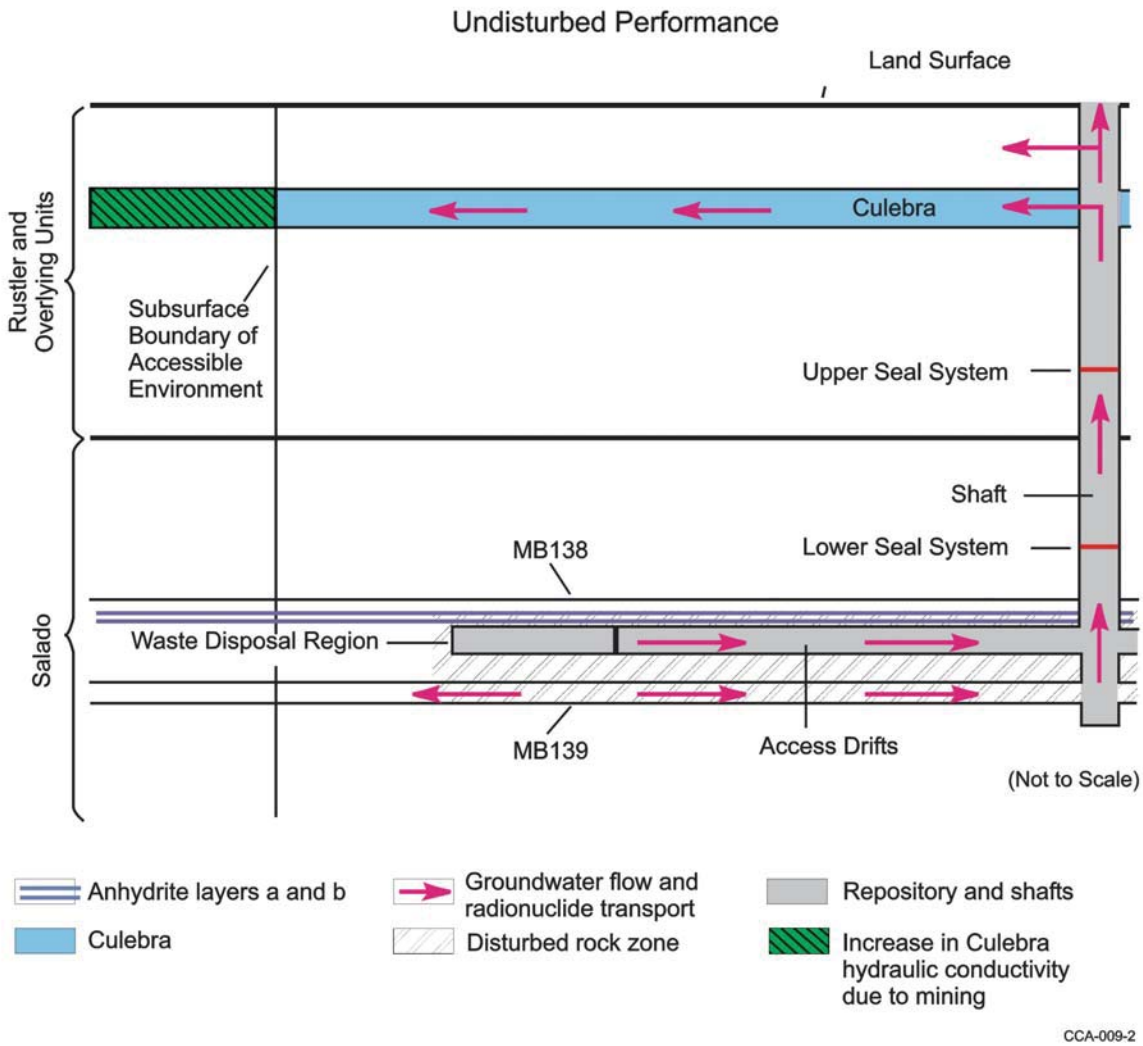

Figure 6-9. Conceptual Release Pathways for the Undisturbed Performance Scenario

(2) Natural processes will degrade or otherwise affect the capability of boreholes to transmit fluids over the regulatory time frame.

Consistent with these criteria, there are several pathways for radionuclides to reach the accessible environment in the E scenario. Before any deep drilling intersects the waste, potential release pathways are identical to those in the UP scenario.

If a borehole intersects the waste in the disposal rooms, releases to the accessible environment may occur as material entrained in the circulating drilling fluid is brought to the surface, as discussed in Section 6.4.7.1. Particulate waste brought to the surface may include cuttings, cavings, and spallings. Cuttings are the materials cut by the drill bit as it passes through waste. Cavings are the materials eroded by the drilling fluid in the annulus around the drill bit. Spallings are the materials forced into the circulating drilling fluid if there is

Table 6-9. Disturbed Performance FEPs

(FEPs)	Scenario	Section
ALL UP FEPs		
NATURAL FEPs		
Geological		
Stratigraphy		
Brine reservoirs	E1	6.4.8 6.4.12.6
WASTE- AND REPOSITORY-INDUCED FEPs		
Waste and repository characteristics		
Waste characteristics		
Heterogeneity of waste forms	E1, E2	6.4.12.4
Contaminant transport mode		
Particulate transport		
Suspensions of particles	E1, E2	6.4.7.1
Cuttings	E1, E2	6.4.7.1
Cavings	E1, E2	6.4.7.1
Spallings	E1, E2	6.4.7.1 6.4.13.7
HUMAN-INITIATED EPs		
Geological		
Drilling		
Oil and gas exploration	E1, E2	6.4.7 6.4.12.2
Potash exploration	E1, E2	6.4.7 6.4.12.2
Oil and gas exploitation	E1, E2	6.4.7 6.4.12.2
Other resources	E1, E2	6.4.7 6.4.12.2
Enhanced oil and gas recovery	E1, E2	6.4.7 6.4.12.2
Excavation activities		
Potash mining	M	6.4.6.2.3 6.4.12.8 6.4.13.8
Subsurface hydrological and geochemical		
Borehole fluid flow		
Drilling-induced flow		
Drilling fluid flow	E1, E2	6.4.7.1
Drilling fluid loss	E2	6.4.7.1.1
Blowouts	E1, E2	6.4.7.1.1

Table 6-9. Disturbed Performance FEPs — Continued

(FEPs)	Scenario	Section
Drilling-induced geochemical changes	E1, E2	6.4.6.2
Flow through abandoned boreholes		
Natural borehole fluid flow	E1, E2	6.4.7.2 6.4.12.7 6.4.13
Waste-induced borehole flow	E1, E2	6.4.7.2 6.4.12.7 6.4.13
Borehole-induced geochemical changes	E1, E2	6.4.6.2
Excavation-induced flow		
Changes to groundwater flow due to mining	M	6.4.6.2.3 6.4.12.8 6.4.13.8
Ecological		
Social and technological developments		
Loss of records	M, E1, E2	6.4.7 6.4.12.1

Legend:
M Mining within the controlled area.
E1 Deep drilling that intersects the waste disposal region and a brine reservoir in the Castile.
E2 Deep drilling that intersects a waste disposal panel.

sufficient pressure in the waste disposal panels. During drilling, contaminated brine may flow up the borehole and reach the surface, depending on fluid pressure within the waste disposal panels.

When abandoned, the borehole is assumed to be plugged in a manner consistent with current practice in the Delaware Basin (see Section 6.4.7.2; and Appendix DEL, Sections DEL.5 and DEL.6; Appendix DATA, Section 2, and CCA Appendix PA, Attachment MASS, Section.16.3). An abandoned intrusion borehole with degraded casing and/or plugs may provide a pathway for fluid flow and contaminant transport from the intersected waste panel to the ground surface if the fluid pressure within the panel is sufficiently greater than hydrostatic. Additionally, if brine flows through the borehole to overlying units, such as the Culebra, it may carry dissolved and colloidal actinides that can be transported laterally to the accessible environment by natural groundwater flow in the overlying units.

Alternatively, the units intersected by an intrusion borehole may provide sources for brine flow to a waste panel during or after drilling. For example, in the northern Delaware Basin, the Castile, which underlies the Salado, contains isolated volumes of brine at fluid pressures greater than hydrostatic (as discussed in Section 2.2.1.2.2). The WIPP-12 penetration of one of these reservoirs provided data on one brine reservoir within the controlled area. The location and properties of brine reservoirs cannot be reliably predicted; thus, the possibility of a deep borehole penetrating both a waste panel and a brine reservoir is accounted for in consequence analysis of the WIPP, as discussed in Section 6.4.8. Such a borehole could provide a connection for brine

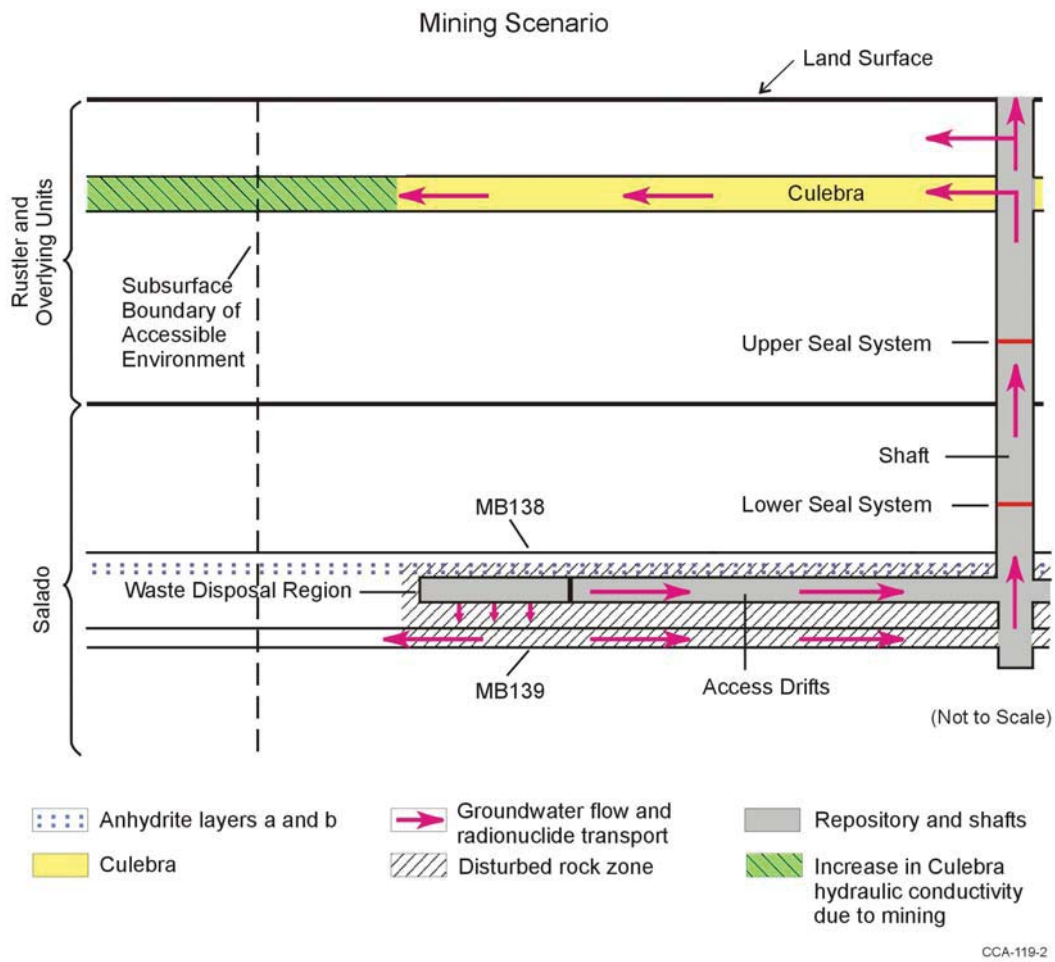

Figure 6-10. Conceptual Release Pathways for the Disturbed Performance Mining Scenario

flow from the Castile to the waste panel, thus increasing fluid pressure and brine volume in the waste panel.

A borehole that is drilled through a disposal room pillar, but does not intersect waste, could also penetrate the brine reservoir underlying the waste disposal region. Such an event would, to some extent, depressurize the brine reservoir, and thus would affect the consequences of any subsequent reservoir intersections. The PA does not take credit for possible brine reservoir depressurization.

The DOE has distinguished two types of deep drilling events by whether or not the borehole intersects a Castile brine reservoir. A borehole that intersects a waste disposal panel and penetrates a Castile brine reservoir is designated an E1 event. The 18 DP FEPs labeled “E1” in Table 6-9 relate to the occurrence and effects of an E1 drilling event. A borehole that intersects a waste panel but does not penetrate a Castile brine reservoir is designated an E2 event. The 18 DP FEPs labeled “E2” in Table 6-9 relate to the occurrence and effects of an “E2” drilling event.

In order to evaluate the consequences of future deep drilling, the DOE has divided the E scenario into three drilling subscenarios; E1, E2, and E1E2, distinguished by the number of E1 and E2 drilling events that are probabilistically assumed to occur in the regulatory time frame. These subscenarios are described in order of increasing complexity in the following sections.

6.3.2.2.1 The E2 Scenario

The E2 scenario is the simplest scenario for inadvertent human intrusion into a waste disposal panel. In this scenario, a panel is penetrated by a drill bit; cuttings, cavings, spallings, and brine flow releases may occur; and brine flow may occur in the borehole after it is plugged and abandoned. Sources for brine that may contribute to long-term flow up the abandoned borehole are the Salado or, under certain conditions, the units above the Salado. An E2 scenario may involve more than one E2 drilling event. Features of the E2 scenario are illustrated in Figure 6-11. A modeling system has been developed to evaluate the consequences of an E2 scenario during which single or multiple E2 events occur.

6.3.2.2.2 The E1 Scenario

Any scenario with one inadvertent penetration of a waste panel that also penetrates a Castile brine reservoir is called E1. Features of this scenario are illustrated in Figure 6-12.

Sources of brine in the E1 scenario are the brine reservoir, the Salado and, under certain conditions, the units above the Salado. However, the brine reservoir is conceptually the dominant source of brine in this scenario. The model configuration developed for the E1 scenario evaluates the consequences of futures that have only one E1 event.

6.3.2.2.3 The E1E2 Scenario

The E1E2 scenario is defined as all futures with multiple penetrations of a waste panel of which at least one intrusion is an E1. One case of this scenario, with a single E1 event and a single E2 event penetrating the same panel, is illustrated in Figure 6-13. However, the E1E2 scenario can include many possible combinations of intrusion times, locations, and types of event (E1 or E2). The sources of brine in this scenario are those listed for the E1 scenario, and multiple E1 sources may be present. The E1E2 scenario has a potential flow path not present in the E1 or E2 scenarios: flow from an E1 borehole through the waste to another borehole. This flow path has the potential to (1) bring large quantities of brine in direct contact with waste and (2) provide a less restrictive path for this brine to flow to the units above the Salado (via multiple boreholes) compared to either the individual E1 or E2 scenarios. It is both the presence of brine reservoirs and the potential for flow through the waste to other boreholes that make this scenario different in terms of potential consequences from combinations of E2 boreholes. The extent to which flow occurs between boreholes, as estimated by modeling, determines whether combinations of E1 and E2 boreholes at specific locations in the repository should be treated as E1E2 scenarios or as independent E1 and E2 scenarios in the consequence analysis.

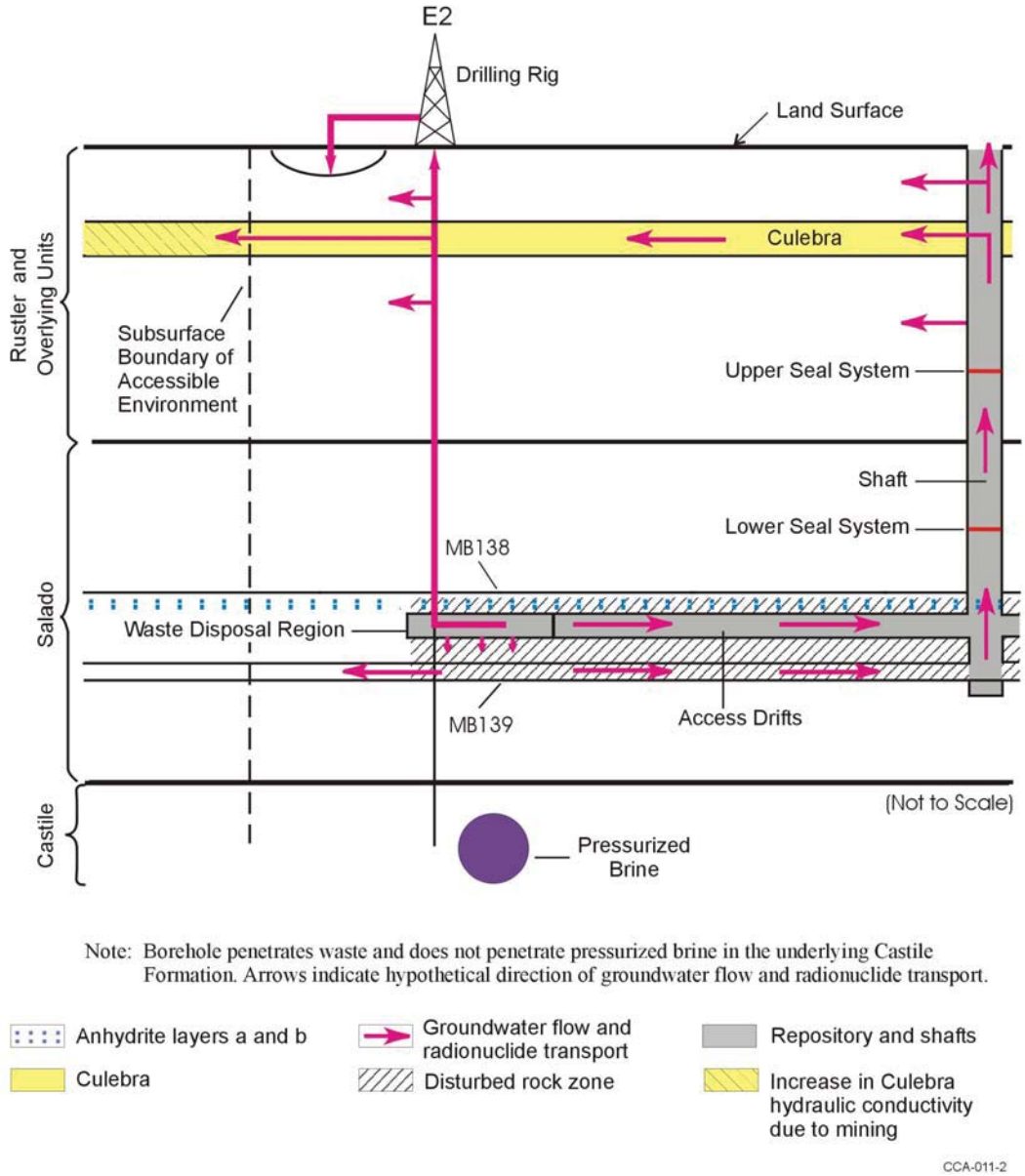

Figure 6-11. Conceptual Release Pathways for the Disturbed Performance Deep Drilling E2 Scenario

The possible combinations of drilling events make the modeling configuration for the E1E2 scenario differ in significant ways from that used to evaluate E1 and E2 scenarios. This configuration is described in Section 6.4.13.5.

6.3.2.3 The Disturbed Performance Mining and Deep Drilling Scenario

Mining in the WIPP site (the M scenario) and deep drilling (the E scenario) may both occur in the future. The DOE calls a future in which both of these events occur the ME scenario. The

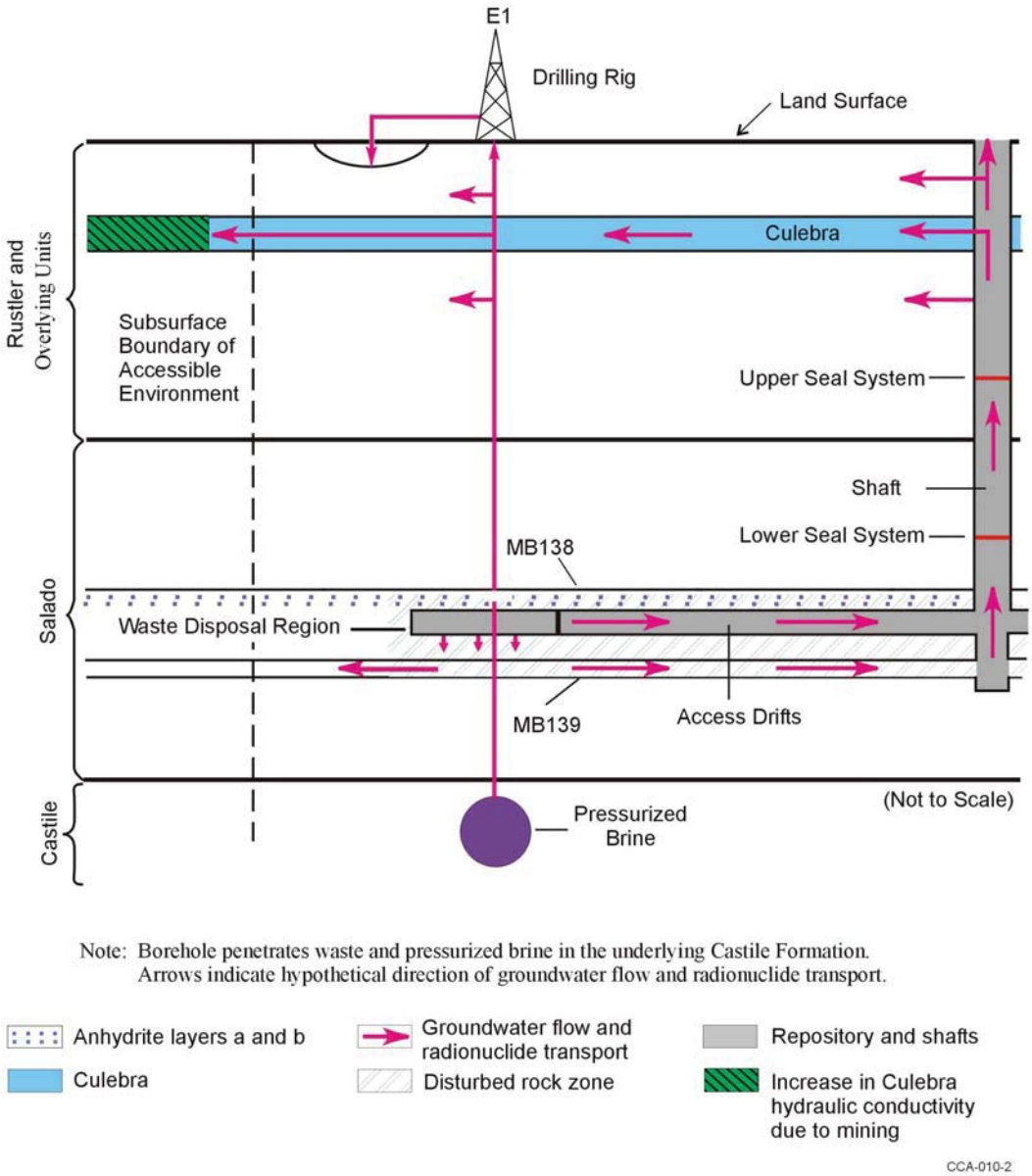

Figure 6-12. Conceptual Release Pathways for the Disturbed Performance Deep Drilling Scenario E1

occurrence of both mining and deep drilling do not create processes beyond those already described separately for the M and E scenarios. For example, the occurrence of mining does not influence any of the interactions between deep boreholes and the repository or brine reservoirs. Nor does the occurrence of drilling impact the effects of mining on Culebra hydrogeology. The difference between the M and E scenarios considered separately and the ME scenario is that the combination of borehole transport to the Culebra (E) and a transmissivity field impacted by mining (M) may result in more rapid transport of actinides to the accessible environment. For example, because the M scenario does not include drilling the only pathway for actinides to reach the Culebra is up the sealed shafts. For clarity in describing

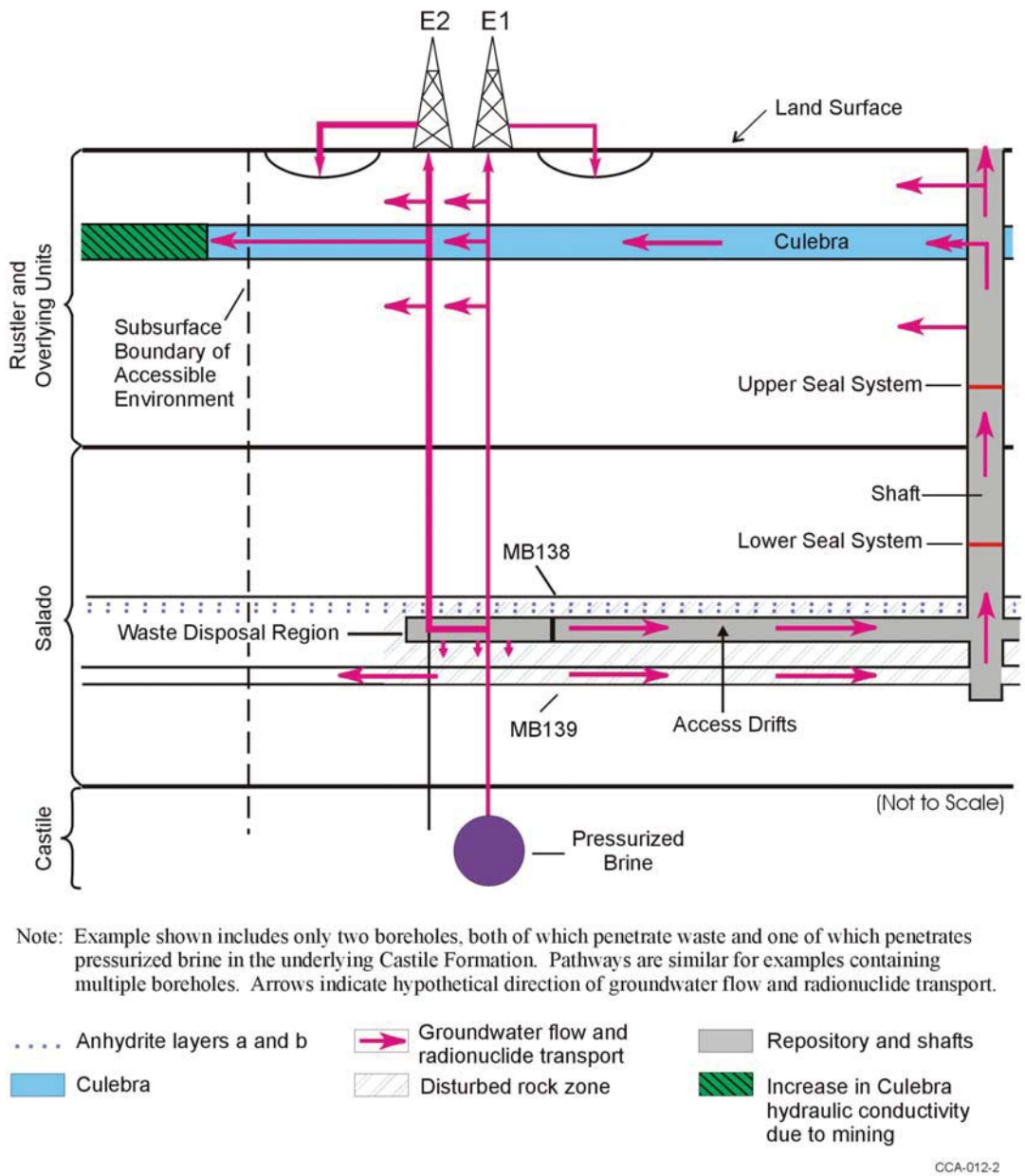

Figure 6-13. Conceptual Release Pathways for the Disturbed Performance Deep Drilling Scenario E1E2

computational results, the ME scenario has been subdivided according to the types of deep drilling subscenarios into the ME1 scenario (M and E1), the ME2 scenario (M and E2), and the ME1E2 scenario (M and E1E2).

The system used to model flow and transport in the Culebra for the ME scenario is similar to that used for the E scenario. However, in the ME scenario, the Culebra transmissivity field is modified to account for mining within the controlled area.

6.3.3 Scenarios Retained for Consequence Analysis

The scenarios described in Sections 6.3.1 and 6.3.2 have been retained for consequence analysis to determine compliance with the Containment Requirements in 40 CFR § 191.13. The modeling systems used to evaluate the consequences of these UP and DP scenarios are discussed in Section 6.4. For consequence analysis, the scenarios and subscenarios are further subdivided into scenarios, S_i. The S_i scenarios are distinguished by, for example, the time of occurrence of disruptive events. The S_i scenarios are generated, and their probabilities determined, by probabilistic sampling of selected processes and events (see Sections 6.1.5.2 and 6.4.12).

6.4 Calculation of Scenario Consequences

Scenario consequence, cS_i, is the third element of the ordered triples shown in Equation (6.2) in Section 6.1.1. Estimating cS_i requires quantitative modeling. PA uses a linked system of individual computer codes. This section discusses the conceptual and computational models and some parameter values used to estimate the consequence of the scenarios described in Section 6.3. Additional discussion of conceptual models and modeling assumptions is provided in Appendix PA, Section PA-2. Additional descriptions of sampled parameter values are included in Appendix PA, Section 5.0 and Attachment PAR.

6.4.1 Types of Models

A single modeling system was used to represent the disposal system and calculate the CCDFs presented in Section 6.5. The modeling system, however, can be conveniently described in terms of various submodels, with each describing a part of the overall system. This section provides, for each submodel defined, an integrated, summary description of the conceptual model, mathematical model, numerical model, computational model, experimental data, and model parameters used. These terms are described below.

The models used in the WIPP PA, as in other complex analyses, exist at four different levels:

(1) **Conceptual models** are a set of qualitative assumptions that describe a system or subsystem for a given purpose. At a minimum, these assumptions concern the geometry and dimensionality of the system, initial and boundary conditions, time dependence, and the nature of the relevant physical and chemical processes. The assumptions should be consistent with one another and with existing information within the context of the given purpose.

(2) **Mathematical models** represent the processes at the site. The conceptual models provide the context within which these mathematical models must operate and define the processes they must characterize. The mathematical models are predictive in the sense that, once provided with the known or assumed properties of the system and possible perturbations to the system, they predict the response of the system. The processes represented by these mathematical models include fluid flow, mechanical deformation, radionuclide transport in groundwater, and removal of waste through intruding boreholes.

(3) **Numerical models** are developed to approximate mathematical model solutions because most mathematical models do not have closed-form solutions.

(4) The complexity of the system requires computer codes to solve the numerical models. The implementation of the numerical model in the computer code with specific initial and boundary conditions and parameter values is generally referred to as the **computational model**.

Data are descriptors of the physical system being considered, normally obtained by experiment or observation. Parameters are values necessary in mathematical, numerical, or computational models. The distinction between data and parameters can be subtle. Parameters are distinct from data, however, for three reasons. First, data may be evaluated, statistically or otherwise, to generate model parameters to account for uncertainty in data. Second, some parameters have no relation to the physical system, such as the parameters in a numerical model to determine when an iterative solution scheme has converged. Third, many model parameters are applied at a different scale than one directly observed or measured in the physical system. The distinction between data and parameter values is described further in Appendix PA, Attachment PAR, where distribution derivations for specific parameters are given. The interpretation and the scaling of experimental and field data are discussed in Appendix PA, Attachment PAR for individual and sampled parameters, as appropriate.

6.4.2 Model Geometries

Although the specific geometries used in PA models are developed after the conceptual and mathematical models are defined, they are introduced here because they provide a useful framework for presenting the full discussion of the modeling system. PA represents the three-dimensional geometry of the disposal system (repository, shafts, and controlled area) using two primary two-dimensional simplifications. In the first geometry, processes that act on the entire disposal system occur within the repository and are simulated in the BRAGFLO (BRine And Gas FLOw) computer code using a geometry that approximates a north-south vertical cross section through the disposal system and some surrounding rock. This geometry simulates processes in the disposal system, such as two-phase flow and movement of actinides, as well as processes acting only within the repository, such as creep closure of disposal rooms and gas generation. In the second geometry, groundwater flow and actinide transport in the Culebra, which provides a potential pathway for lateral transport of actinides to the accessible environment, are simulated in the MODFLOW-2000 and SECOTP2D computer codes using a two-dimensional horizontal geometry that treats the Culebra as a single layer. These two geometries are discussed in the following sections. PA codes and the flow of numerical information through the PA are described in Section 6.4.11 and referenced appendices.

6.4.2.1 Disposal System Geometry

A single disposal system geometry is used in the BRAGFLO computational model (see Appendix PA, Section PA-4.2) with four different maps of material properties: one for undisturbed conditions; one for the E1 intrusion event; one for the E2 intrusion event; and one for the E1E2 intrusion event (see Section 6.4.13.5). The geometry and material maps used in BRAGFLO are similar; each models fluid flow calculations that represent the three-dimensional physical system in a two-dimensional plane cutting vertically through the repository and surrounding strata. Side views of the vertical cross section and two of the material maps are presented in Figures 6-14 and 6-15. In these figures, the boundaries of grid blocks discretized in

the model are shown with dashed lines; each grid block is associated with material properties representing an important feature of the disposal system. These associations between grid blocks and material properties are shown by color and number in the figures. The two figures differ in that the material property map used for E1 intrusion events (Figure 6-15) includes a material region representing the borehole (Column 26) that is not present in the undisturbed case (Figure 6-14). The borehole region vertically transects other material regions and connects the single panel (Rows 10, 11, and 12) with the Castile brine reservoir (Rows 1 and 2), marker beds, overlying units, and the surface. The E2 intrusion event material regions are similar to those of E1, except that the modeled borehole region does not extend below the repository and therefore does not contact a brine reservoir.

Figures 6-14 and 6-15 show the relationship among material regions in the model and how connections are made within the finite-difference scheme. However, by illustrating equidimensional grid blocks, the volumetric relationship between grid blocks is greatly distorted. To show the volumetric relationship among nodal blocks and between the repository and host formations, a scaled side view of the vertical cross section used in BRAGFLO is shown in Figure 6-16. An undistorted 1:1 vertical:horizontal scale side view is in the upper left corner of Figure 6-16; at this scale, important model features are not resolvable. Therefore, two other views are provided in which the vertical scale has been exaggerated to show model features. Notice that the modeling system extends 14 miles (22.4 km) from the edge of the excavated repository in each direction, north and south. The borehole is not centered; rather it is located 24.17 km from the north boundary and 22.46 km from the south boundary. Figure 6-16 colors are consistent with colors for material regions in Figures 6-14 and 6-15.

Effects of flow in the third (out-of-plane) dimension are approximated with a two-dimensional element configuration that simulates convergent or divergent flow to the north and south centered on the repository in intact rocks laterally away from the repository. In this text, the term width corresponds to the x (lateral) dimension of nodes, thickness refers to the y (vertical) dimension, and depth refers to the z (out-of-plane) dimension. The effects of the grid assumptions on fluid flow processes in the Salado are discussed in Appendix PA, Attachment MASS, Section 4.1.

Based on observations in the existing excavations, the DOE approximates the regionally variable dip in the Salado by incorporating a 1-degree dip to the south in the BRAGFLO computational mesh. This dip is not indicated in Figures 6-14, 6-15, and 6-16.

The BRAGFLO definition of hydrostratigraphic units follows formation and member divisions. Inside the Salado, however, further subdivision of hydrostratigraphy has been made based on the observed permeability differences between anhydrite-rich interbeds and halite-rich intervals.

This further subdivision has been made only at elevations near the repository horizon, because only in this region are such distinctions important. The models and assumptions representing the various regions of material properties shown in Figures 6-14 and 6-15 are discussed in Section 6.4.3 and Appendix PA, Section 4.2. The thickness of hydrostatigraphic units used in BRAGFLO are tabulated in Appendix PA, Attachment PAR, Table PAR-49.

6.4.2.2 Culebra Geometry

Although the BRAGFLO model contains a discretization of the Culebra and calculates flow there, the DOE uses a more detailed representation to estimate potential radionuclide releases to the accessible environment resulting from lateral subsurface transport through the Culebra. The conceptual model for flow and transport in this geometry is discussed in Section 6.4.6.2. The boundary and initial conditions applied to this geometry are discussed in Section 6.4.10.2. MODFLOW-2000 and SECOTP2D are used to simulate groundwater flow and radionuclide transport in the Culebra. The SECOFL2D code was used in the CCA to simulate groundwater flow and has been replaced with MODFLOW-2000. The groundwater flow and transport conceptual models have not changed; the implementation of the groundwater model has been updated. The manner in which this geometry is linked to the BRAGFLO geometry described in the preceding section is discussed in Sections 6.4.6.2, 6.4.11, and Appendix PA, Section 4.9. The grids used to model the Culebra are discussed in Section 6.4.6.2 and Appendix PA, Section 4.8 (see also Appendix PA, Attachments MASS and TFIELD).

6.4.3 The Repository

The repository, as shown in Figure 3-2, is represented by areas marked Waste Panel and rest of repository (RoR) north and south in Figures 6-14 and 6-15. These regions include a waste disposal panel, panel closures (DRF_PCS, CONC_PCS, Anhydrite AB, and DRZ_PCS), two areas that represent the other panels and access drifts in the rest of the waste disposal region (RoR north and south), the operations region (Ops), and the experimental region at the north end of the repository (Exp). The shaft (which is further subdivided into two primary regions marked Upper Shaft and Lower Shaft) intersects the repository between the operations region and the experimental region. The shaft is discussed in Section 6.4.4. For human-intrusion events, the borehole intersects the waste disposal region in the Panel. In two-dimensional fluid flow codes, a grid block's length, volume, and cross-sectional area of faces connected to other grid blocks are important model features. For each region of the repository depicted, the BRAGFLO model geometry preserves the excavated volume. Lateral dimensions have been determined to preserve volume and retain important cross-sectional areas and distances between defined regions, as discussed below. These simplifications are conservative with respect to fluid contact with waste, which is a critical factor in determining the quantity of actinides mobilized in the aqueous phase. The simplifications are conservative because (1) all pillars have been removed from the modeled panel, resulting in homogeneous waste regions through which fluid can flow directly; and (2) the panels in the rest of the repository areas do not have pillars, resulting in a large homogeneous region that is assigned an average permeability within the range of those experimentally determined (see Section 6.4.3.2 and Appendix PA, Attachment MASS Section 3.1).

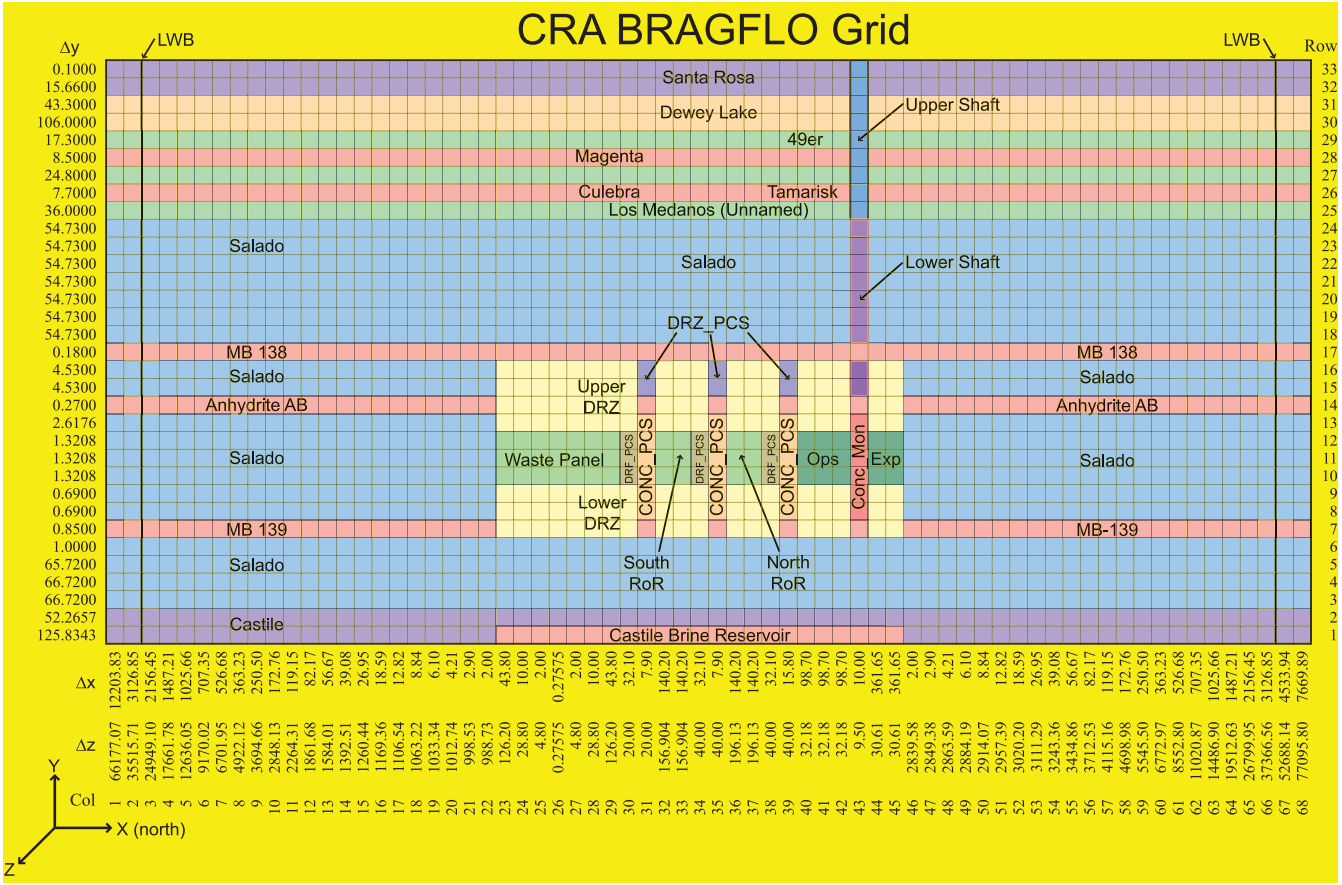

Figure 6-14. A Side View of the BRAGFLO Elements and Material Regions Used for Simulation of Undisturbed Performance

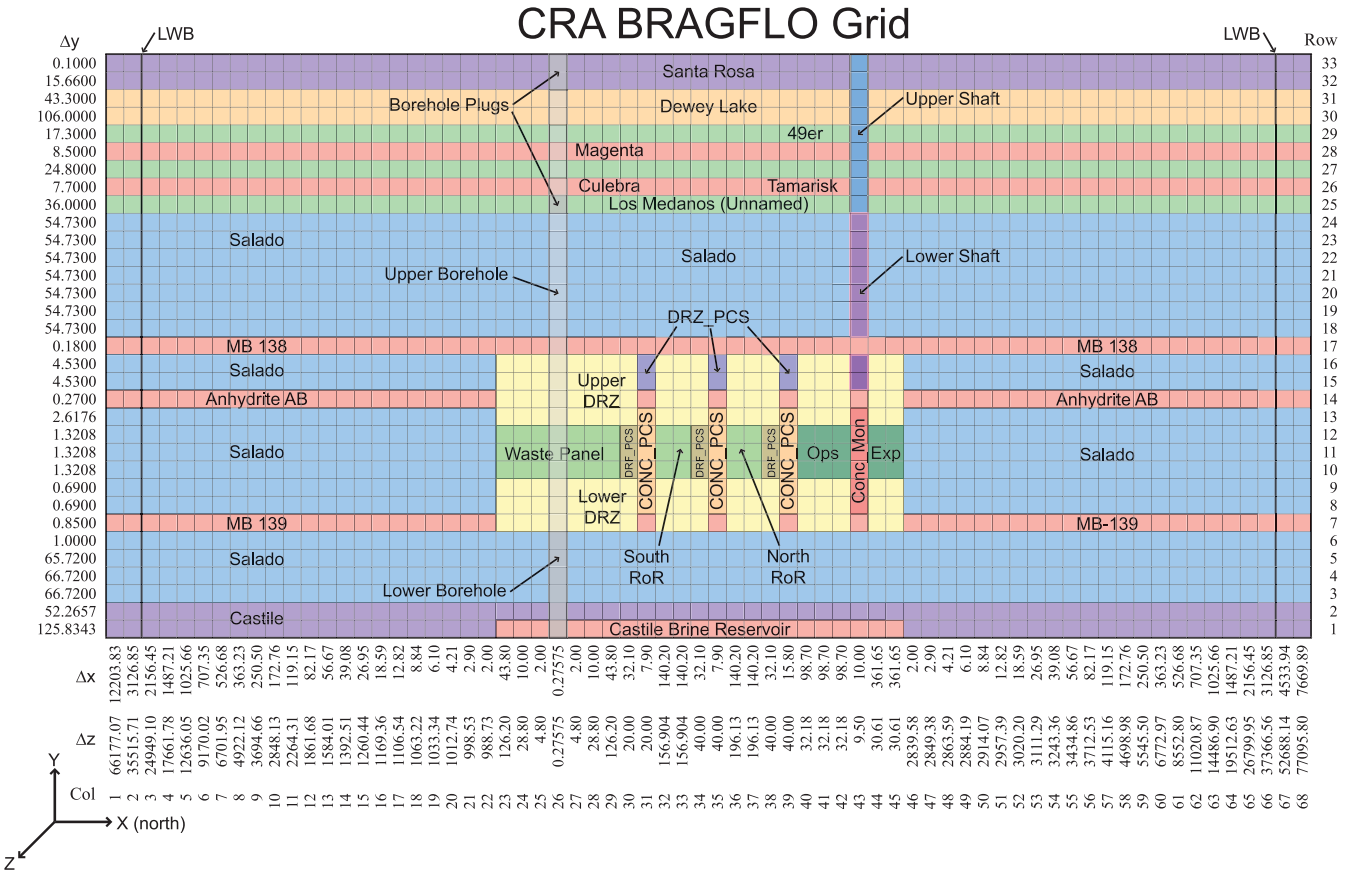

Figure 6-15. A Side View of the BRAGFLO Elements and Material Regions Used to Simulate the E1 Event

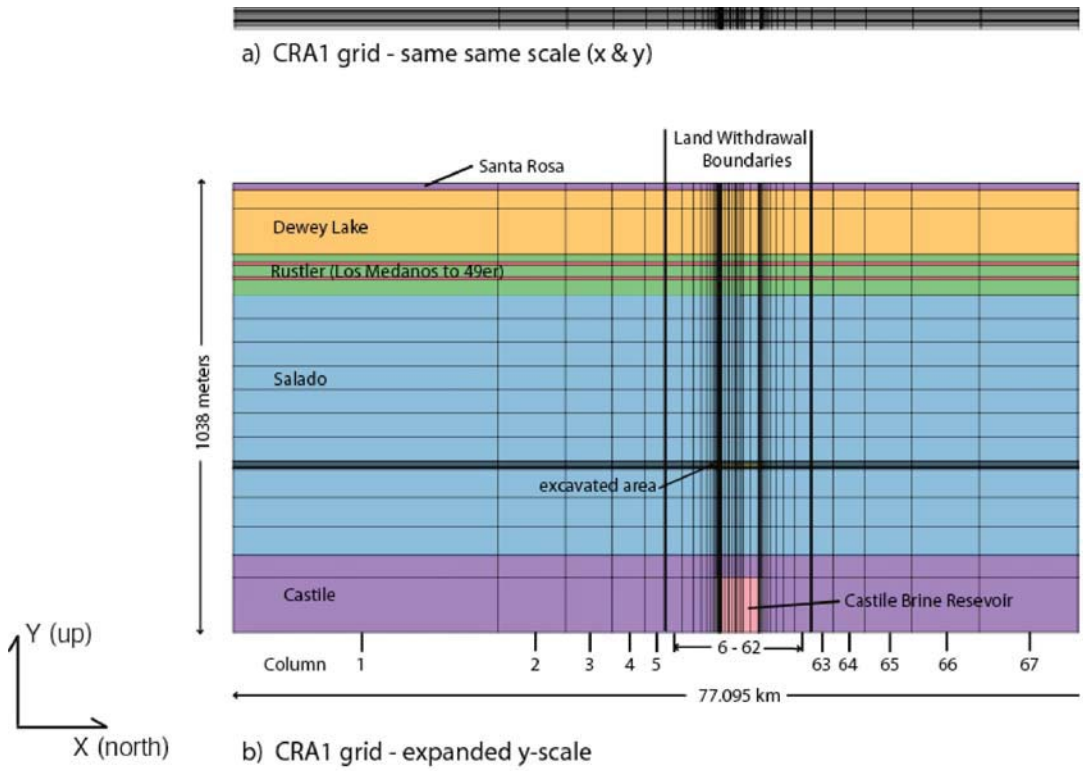

Figure 6-16. A Side View of the BRAGFLO CRA-2004 Geometry Drawn to Scale

The single panel that is represented individually (Panel) is discretized to simulate radial flow to and from the borehole that intersects it. In the CCA grid, the distance from the borehole to the shaft was 1260 m (4133.8 ft), the true distance from the shaft to the south end of the waste disposal region. In the current grid, the distance is 1097 m (3599 ft). The distance was reduced during the re-gridding process that accounted for the Option D panel closures and refinements to represent two RoRs (see Appendix PA, Attachment MASS, Section 4.2.4). In BRAGFLO, the single panel region is the southernmost portion of the repository. It occupies this position because separate modeling activities indicate that slightly larger releases may result from a panel in this position than from alternative placements (see Vaughn et al. 1995).

Panel closures were originally represented generically, since there were four options for the panel closure design. A condition of the original WIPP certification requires the DOE to use the Option D panel closure design constructed with Salado Mass Concrete (SMC). The closure representation for this analysis is modified in the models to better represent the Option D panel closures (see Appendix PA, Section 4.2.8, Attachment MASS, and Chapter 9.0). The panel closure between the panel and the rest of the repository has a cross-sectional area equal to the cross-sectional area of the drifts between panels. The length and total volume of modeled panel closures is consistent with the Option D design. The panel closure between the rest of the repository and the operations regions has a cross-sectional area equal to the cross-sectional area of the drifts between the north end of the waste disposal region and the operations regions. Because there are two closures between the waste disposal region and the shafts in the operations

regions, the modeled panel closures between the rest of the repository and the operations regions have a length and volume consistent with two panel closures.

A number of submodels have been defined within the repository region and are described in this section. The submodels that have been defined for repository processes are Creep Closure (6.4.3.1), Repository Fluid Flow (6.4.3.2), Gas Generation (6.4.3.3), Chemical Conditions in the Repository (6.4.3.4), Dissolved Actinide Source Term (6.4.3.5), and Source Term for Colloidal Actinides (6.4.3.6).

6.4.3.1 Creep Closure

Salt creep occurs naturally in the Salado halite in response to deviatoric stress. Inward creep of rock and the repository response is generally referred to as creep closure. Creep closure of excavated regions begins immediately because of excavation-induced deviatoric stress. If the rooms were empty, closure would proceed to the point where the void volume created by the excavation would be eliminated as the surrounding formation returns to a uniform stress state. In the waste disposal region, waste consolidation continues until loading in the surrounding rock is uniform, at which point salt creep and waste consolidation ceases. The amount of waste consolidation that occurs and the time it takes to consolidate are governed by properties of the waste (waste strength, modulus, etc.), properties of the surrounding rock, the dimensions and location of the room, and the quantities of fluids present.

Fluids that could affect closure are brine that may enter the repository from the Salado or an intrusion borehole, air present in the repository when it is sealed, and gas produced by reactions occurring during waste degradation. Closure and consolidation can be slowed by fluid pressure in the repository. This can be quantified according to the principle of effective stress:

$$\sigma_T = \sigma_e + p \,, \tag{6.11}$$

where σ_T is the stress caused by the weight of the overburden (an essentially constant value), p is the pressure of the repository pore fluid, and σ_e is the stress applied to the waste matrix. In this formulation, the waste is considered a skeleton structure containing pore fluids. As the pore pressure increases, an increasing amount of overburden stress is supported by pore fluid pressure, p, and less overburden stress is supported by the strength of the waste matrix. Waste consolidation will cease when the sum of the stresses felt by the waste matrix and fluid pressure reaches lithostatic pressure. If gas and brine quantities in the repository stabilize, creep closure will act to establish a constant pressure and pore volume.

In summary, creep closure of waste disposal areas will cause their volume to decrease as the Salado deforms to consolidate and encapsulate the waste, changing waste porosity and permeability. Resistance to creep closure will be caused by waste strength and fluid pressure.

Three major material-response models are required for closure analyses. The first model describes how the halite creeps as a function of time and stress. The second model describes the state of waste consolidation as a function of applied stress. A third constitutive model is used to model inelastic behavior of anhydrite marker beds (see Appendix PA, Attachment MASS, Section 13.0).

Halite deformation is predicted using a multimechanism deformation steady-state creep model with work hardening and recovery transient response. For the conditions of the WIPP, creep mechanisms are governed by the temperature and shear stress at a given location in the surroundings at any time. Although WIPP conditions are expected to be nearly isothermal at the ambient natural underground temperature, several mechanisms can be active at the same time because of the large range of stress states that occur around underground rooms and shafts. The focus of the model's mechanistic part is definition of steady-state creep strain, with transient creep strain described through a multiplier on the steady-state rate, thus accommodating both transient changes in stress loading and unloading.

The volumetric plasticity model is the mathematical model for room closure and waste consolidation. The model is discussed further and the experimental data used in this model are summarized and interpreted in Butcher and Mendenhall (1992), Butcher et al. (1991, 65-76) and Luker et al. (1991).

The volumetric plasticity model, multimechanism deformation model, and the inelastic constitutive model for anhydrite were numerically implemented in the SANTOS computer code to calculate the closure of disposal rooms for PA (Appendix PA, Attachment PORSURF).

As a boundary condition, SANTOS requires fluid pressure estimates and hence the quantity of gas present in a disposal room. These estimates are obtained using the average stoichiometry model of gas generation (Section 6.4.3.3) with different rates of gas generation that reflect different assumptions about the quantity of brine available in a waste disposal room. The different rates of gas generation used in SANTOS bound the possible conditions for gas content in the repository. With the volumetric plasticity model and the fluid pressure boundary condition, SANTOS calculates the pore volume of the disposal room through time.

In PA, SANTOS calculates the time-dependent effects on volume as a result of creep closure. These effects are linked to the fluid-flow code BRAGFLO by a porosity surface, which is a look-up table relating porosity (void volume) to (1) time after sealing and (2) gas pressure. At the beginning of a time step, BRAGFLO evaluates the pressure of a cell in the waste disposal regions; the pressure is sensitive to brine and gas flow and the previous pore volume of the cell. The code then consults the porosity surface to find the appropriate void volume of the cell for a given time and pressure. The void volume in the cell is iteratively adjusted during a time step for consistency with gas generation, fluid movement, and repository pressure. Additional details about the porosity surface method are included in Appendix PA, Attachment PORSURF. The porosity surface method of incorporating the creep closure's dynamic effect in PA has been compared to more complex techniques that are computationally impractical in a PA (Freeze et al. 1995). In these comparisons, the porosity surface method was found to reasonably represent behavior observed in more complex models.

The operations area and experimental area (Columns 40 to 45 in Figures 6-14 and 6-15) are modeled as unfilled after closure in this PA. The operations and experimental areas are expected to close in less than 200 years and do not require a porosity surface, in contrast to the region containing waste (Vaughn et al. 1995). These areas are assumed to be "pre-closed" and are assigned a constant low porosity (18 percent) over the entire regulatory time frame.

Additional modeling confirmed that new waste types (compacted waste forms) and waste containers (pipe overpacks) do not impact the adequacy of the original porosity surface modeled in the CCA PA. The porosity surface used in the CCA is used in this analysis.

6.4.3.2 Repository Fluid Flow

Fluid flow modeling within the repository is concerned with (1) fluid flow and distribution in the waste, (2) fluid flow to and from the Salado and shafts, and (3) fluid flow between the repository and intrusion boreholes. These are important in assessing gas generation rates (Section 6.4.3.3), repository pressure, and the mobility of radionuclides in the disposal system. Additional discussion of this topic is provided in Appendix PA, Section PA-4.2.

Disposal region fluid flow is affected by the geometrical association of pillars, rooms, drifts, panel closures, possible borehole locations, time-dependent properties of waste areas resulting from creep closure, flow interactions with other parts of the disposal system, and reactions that generate gas. As described in Section 6.4.3.1, creep closure changes disposal region porosity. Depending on material properties and conditions, brine may flow into the disposal region through the DRZ, or, during disturbed conditions, through a borehole. Brine contained in the Salado may flow to the waste disposal region because of pressure gradients created by the excavation. Brine flow into the repository may be reduced as repository pressure increases, and brine may be expelled from the repository if pressure in the repository exceeds brine pressure in the immediately surrounding rock or borehole. Gas may be generated as waste decomposes, causing a pressure increase. Gas may flow away from the waste area to the anhydrite marker beds by hydrofracturing processes in the DRZ and anhydrite interbeds. Gas flow into intact, halite-rich rock is not expected because of the expected high threshold pressure of halite (see Section 6.4.5.1).

Fluid flow in the disposal system is conceptualized using principles of multiphase flow, except for Culebra flow and transport modeling. In multiphase flow, a residual brine saturation (S_{br}), is defined, which is the minimum saturation at which the brine phase has a nonzero relative permeability; below this saturation, brine is immobile. In accordance with two-phase flow theory, the residual gas saturation (S_{gr}) in the disposal system corresponds to the gas saturation necessary to create an incipient gas-phase relative permeability; below this saturation, waste-generated gas is immobile. The multiphase flow techniques adopted by the DOE are described in Appendix PA, Section 4.2 and Attachment MASS, Section 3.0.

The intrinsic permeability of waste at a given time can influence repository system performance by affecting the flow rate of gas or brine through the waste. Tests reported by Luker et al. (1991, 693-702) on simulated waste have shown material permeabilities of 10^{-12} to 10^{-16} m^2 on waste compacted under a lithostatic load. PA assigns waste permeability as a constant at 2.4×10^{-13} m^2 (Table 6-10). This permeability value was adopted from the value used in the PA verification test (EPA 1998, TSD V-B-14).

Because two-phase relationships have not been measured for waste, PA determines a range of possible two-phase conditions for the repository by applying the LHS technique to parameters within the Brooks-Corey two-phase equations. These and other parameters in the disposal room and repository flow model are shown in Tables 6-10 and 6-11. Details about the two-phase

equations and parameters used in PA are included in Appendix PA, Section 4.2; Attachment MASS, Section 3.0; and Attachment PAR (Parameters 6 and 7).

Material properties in the waste are assumed to be homogeneous and are distributed in the BRAGFLO model to cells whose volumes are much larger than an individual waste container.

Two processes that may occur on scales smaller than the cell volumes in BRAGFLO are wicking (the retention of brine in a capillary fringe) and puddling (the capture of brine in isolated pockets of waste caused by waste heterogeneity). Wicking is accounted for in the gas generation model (Section 6.4.3.3). Vaughn et al. (1995) found that puddling can be neglected.

The experimental and operations regions (Columns 44 and 45 and 40 through 42, respectively, in Figures 6-14 and 6-15) are represented in PA with a porosity of 18 percent and a permeability of 10^{-11} m^2 as a conservative upper bound. For postoperational performance, the panel closures (Columns 31, 35, and 39 in Figures 6-14 and 6-15) are represented with a porosity of 5 percent and a median permeability of 1.78×10^{-19} m^2, as discussed in Appendix PA, Section 4.2, Attachment PAR, Parameter 10, and Attachment MASS, Section 19.0.

6.4.3.3 Gas Generation

Gas will be produced in the repository by a variety of chemical reactions, primarily those occurring among brine, metals, microbes, cellulosic, plastic, and rubber materials, and release of the dissolved gases produced by these reactions to the gaseous phase. The dominant processes are anoxic corrosion of steels and other Fe-based alloys in the waste containers, and the waste and microbial consumption of cellulosic, plastic, and rubber materials. Anoxic corrosion of steels and other Fe-based alloys and Al, and Al-base alloys by water in the brine will occur, producing H_2. Microbial consumption of cellulosic, plastic, and rubber materials could produce a variety of gases; however, for the current waste inventory, CO_2 and CH_4 are expected to dominate (as predicted at the time of the CCA). Radiolysis was demonstrated by laboratory experiment and model calculations to be insignificant (see Appendix PA, Attachment SCR, FEP W15 and W53).

Table 6-10. Repository[1] and Panel Closures Parameter Values

Parameter (units)	Maximum	Minimum	Median or Constant
Permeability, k (square meters) – Waste Region	–	–	2.4×10^{-13}
Permeability, k (square meters) – Operations and Experimental Regions	–	–	10^{-11}
Permeability (square meters) – Panel Closures	1×10^{-17}	2.00×10^{-21}	1.78×10^{-19}
Initial Effective Porosity (percent) – Waste Region	–	–	84.8
Effective Porosity (percent) – Operations and Experimental Regions	–	–	18.0
Effective Porosity (percent) – Panel Closures	–	–	5
Threshold Pressure, P_t (pascals) – Repository [1]	–	–	0
Threshold Pressure, P_t (pascals) – Panel Closures [2]	–	–	1.72×10^{6}
Residual Brine Saturation, S_{br} (unitless) – Repository	0.552	0	0.276
Residual Brine Saturation, S_{br} (unitless) – Operations and Experimental Regions	–	–	0
Residual Brine Saturation, S_{br} (unitless) – Panel Closures	0.60	0	0.20
Residual Gas Saturation, S_{gr} (unitless) – Repository	0.15	0	0.075
Residual Gas Saturation, S_{gr} (unitless) – Operations and Experimental Regions	–	–	0
Residual Gas Saturation, S_{gr} (unitless) – Panel Closures	0.40	0	0.20
Pore Distribution Parameter, λ (unitless) – Repository	5.78	1.44	2.89
Pore Distribution Parameter, λ (unitless) – Operations and Experimental Regions	–	–	0.7
Pore Distribution Parameter, λ (unitless) – Panel Closures	8.10	0.11	0.94
Maximum Capillary Pressure (pascals) – Repository and Panel Closures	–	–	10^{8}
Pore Compressibility (1/pascals) – Repository [3]	–	–	0
Pore Compressibility (1/pascals) – Panel Closures	–	–	6×10^{-11}

[1] Unless specifically listed, Repository refers to operations, experimental, and waste regions.

[2] Threshold pressure (P_t) determined from the relationship: $P_t = PCT_A \cdot k^{PCT_EXP}$ where PCT_A and PCT_EXP are constants and k is the permeability.

[3] Accounted for in porosity surface.

Gas generation will affect repository pressure, which is important in other submodels of the disposal system, such as those calculating creep closure (Section 6.4.3.1), interbed fracturing (Section 6.4.5.2), two-phase flow (Section 6.4.3.2), and the radionuclide releases associated with spallings during an inadvertent drilling intrusion (Section 6.4.7). Thus, gas generation must be estimated in PA.

Table 6-11. BRAGFLO Fluid Properties

Parameter (units)	Value
Reference Temperature (kelvin)[1]	300.15
Liquid Density (kilograms per cubic meter) [1,2] at	
Atmospheric Pressure	1,220.0
8 megapascals	1,223.0
15 megapascals	1,225.7
Liquid Viscosity (pascals * seconds) [2]	2.1×10^{-3}
Liquid Compressibility (1/pascals) [2]	3.1×10^{-10}
Gas Density (kilograms per cubic meter) [1,2] at:	
Atmospheric Pressure	0.0818
8 megapascals	6.17
15 megapascals	11.1
Gas Viscosity (pascals * seconds) [2]	8.93×10^{-6}

[1] These values applied to fluids in all material regions in BRAGFLO.
[2] See Appendix PA (Section 4.2) for equations of state.

PA uses the average-stoichiometry model to estimate gas generation occurring in the waste-disposal region. This model was developed for WIPP PA based on gas-generation experiments performed for the WIPP (see CCA Appendix MASS, Section MASS.8 and MASS Attachment 8-2). The average-stoichiometry model accounts for gas formed by anoxic corrosion of steels and other Fe-based alloys, and microbial consumption of cellulosic, plastic, and rubber materials. For calculating repository pressure and gas flow, the density and viscosity of the generated gas are assumed to be those of H_2. In the average-stoichiometry model, gas is assumed to be generated at a rate dependent on the availability of brine in the computational cell. Gas can be generated by anoxic corrosion in all realizations, and is assumed to be generated by microbial activity in half of the realizations. The average-stoichiometry model is based on experimental data on the rates of gas generation from anoxic corrosion of steels and microbial consumption of papers under inundated and humid conditions. These data were used to develop ranges of possible gas-generation rates, as shown in Table 6-12. In BRAGFLO, a gas-generation rate is determined from the rates listed in Table 6-12 by a linear-interpolation method that combines humid and inundated rates based on the effective liquid saturation (Appendix PA, Section PA-4.2.5).

The effective liquid saturation in a computational cell of BRAGFLO for the purpose of gas generation is the computed liquid saturation in that cell plus an adjustment for uncertainty in the capillary rise (wicking) characteristics of the waste. Refer to Attachment PA, Sections PA-4.2.5 and PA-4.2.6, Attachment PAR (Parameter 8) for details on the treatment of wicking in the gas-generation model.

Anoxic corrosion is represented by a generic equation given in Appendix PA (Section PA-4.2.4). This equation accounts only for corrosion of steels and other Fe-based alloys in the repository by the reaction expected to dominate.

Table 6-12. Average-Stoichiometry Gas Generation Model Parameter Values

Parameter (units)	Maximum	Minimum	Median or Constant
Inundated Corrosion Rate for Steel without CO_2 Present (meters per second)	3.17×10^{-14}	0	1.59
Humid Corrosion Rate for Steel	–	–	0
Probability of Microbial Consumption of Plastic and Rubber Materials in the Waste in the Event of Significant Microbial Gas Generation (see Figure PAR-1) where 0 represents corrosion and no significant microbial gas generation. 1 represents cellulosic degradation only, and 2 represents cellulosic, plastic, and rubber consumption	2	0	2
Rate for Microbial Activity Under Humid Conditions (mole per kilogram ∗ second)	1.27×10^{-9}	0	6.34×10^{-10}
Rate for Microbial Activity under Brine-Inundated Conditions (mole per kilogram ∗ second)	9.51×10^{-9}	3.17×10^{-10}	4.92×10^{-9}
Factor β for Microbial Reaction Rates (unitless)	1.0	0	0.5
Anoxic Corrosion Stoichiometric Factor X (unitless)	–	–	1.0
Average Density of Cellulosic Materials in CH-TRU Waste (kilograms per cubic meter)	–	–	58
Average Density of Cellulosic Materials in RH-TRU Waste (kilograms per cubic meter)	–	–	4.5
Average Density of Steels and Other Fe-Based Alloys in CH-TRU Waste (kilograms per cubic meter)	–	–	110.0
Average Density of Steels and Other Fe-Based Alloys in RH-TRU Waste (kilograms per cubic meter)	–	–	110.0
Average Density of Plastic Materials in CH-TRU Waste (kilograms per cubic meter)	–	–	42.0
Average Density of Plastic Materials in RH-TRU Waste (kilograms per cubic meter)	–	–	4.9
Average Density of Rubber Materials in CH-TRU Waste (kilograms per cubic meter)	–	–	14.0
Average Density of Rubber Materials in RH-TRU Waste (kilograms per cubic meter)	–	–	3.1
Bulk Density of Steel Containers, CH-TRU Waste (kilograms per cubic meter)	–	–	170.0
Bulk Density of Steel Containers, RH-TRU Waste (kilograms per cubic meter)	–	–	480.0
Bulk Density of Plastic Liners, CH-TRU Waste (kilograms per cubic meter)	–	–	16.0
Bulk Density of Plastic Liners, RH-TRU Waste (kilograms per cubic meter)	–	–	1.4
Total Volume of CH-TRU Waste (cubic meters)	–	–	1.69×10^{5}
Total Volume of RH-TRU Waste (cubic meters)	–	–	7.08×10^{3}
Wicking Saturation (unitless)	1.0	0	0.5

Because the total quantity of Al and Al-base alloys is small compared to the quantity of steels and other Fe-based alloys, corrosion of Al is omitted for simplicity. The steels and other Fe-based alloys are depleted separately in each computational cell (that is, a cell-by-cell basis), and gas generation can continue in cells, depending on parameter values, until all the steels and other Fe-based alloys are consumed. Brine in cells is consumed as gas generation proceeds. If a cell has a brine saturation equal to zero, it cannot produce gas by anoxic corrosion.

It is assumed there is no passivation of steels or other Fe-based alloys by CO_2 and H_2S produced by microbial activity because microbial gas generation is too slow and also because CO_2 will be removed from the gaseous phase by reacting with MgO. Details of the equations and parameter values are given in Appendix PA, Attachment PAR (Parameters 1 through 5) and Appendix BARRIERS.

Microbial activity occurs in only half the realizations because of uncertainties associated with this process (Appendix PA, Attachment MASS, Section 8.0). Like anoxic corrosion, microbial gas production is represented by a generic equation, given with other details in Appendix PA (Section 4.2.5). The inventory of cellulosic, plastic, and rubber materials is depleted on a cell-by-cell basis. Depending on parameter values, gas generation by microbial activity can continue until all cellulosic materials in the cell are degraded. Reaction with the MgO engineered barrier consumes CO_2 (see Section 6.4.3.4 and Appendix PA, Attachment SOTERM). Thus, the net quantity of gas developed by microbial consumption of cellulosic, plastic, and rubber materials is correlated with constituents of the waste disposal region. It is assumed that microbial activity neither produces nor consumes water, but its rate is dependent on the amount of liquid present in a computational cell.

Microbes may also consume plastic and rubber materials in the repository. The DOE assumes that in half of the simulations where microbial consumption of cellulosic materials occurs, microbes also consume plastic and rubber materials in the waste-disposal region. As with cellulosic materials, these plastic and rubber materials are depleted on a cell-by-cell basis. Parameter values for the average-stoichiometry model are summarized in Table 6-12 and detailed in Appendix PA, Attachment PAR (Parameters 1 through 5).

6.4.3.4 Chemical Conditions in the Repository

The chemical conditions in the repository determine actinide solubilities, parameters demonstrated in past analyses as important to disposal-system performance. In scenarios with the potential to cause releases to the accessible environment, the DOE has determined that chemical conditions can be modeled in PA as homogeneous throughout the waste-disposal area and constant (with the exception of brine content) throughout the 10,000-year regulatory period. This use of constant, homogeneous conditions is based on the assumption of equilibria (for most processes) among brine (the composition of which is determined by the scenario being considered), minerals that are abundant in the Salado, the MgO engineered barrier, and the actinides in the waste. Some exceptions to this assumption are present in performance-assessment models and are discussed where appropriate. In addition to the following discussion, information supporting this position is presented in Appendix PA, Attachments SOTERM and BARRIERS.

Brine and waste within the WIPP repository are modeled as a homogeneous mixture of dissolved and solid-state species. Thermodynamic equilibrium is assumed for dissolved actinide concentrations, but oxidation-reduction reactions between the actinides and other waste components are not assumed to reach equilibrium. Although materials in the waste will actually dissolve at different rates, the assumption of instantaneous solubility equilibria and, along with assumed disequilibrium oxidation-reduction conditions, yields the largest reasonable concentration of dissolved and colloidal actinides in the repository. No chemical microenvironments that influence the overall chemical environment are expected to persist, nor is supersaturation expected during the 10,000-year regulatory period. The average temperature of the WIPP is expected to increase by less than 10°C from its ambient value of 28°C as a result of radioactive decay and exothermic reactions, such as MgO hydration and carbonization, and the effect of this small increase is assumed negligible (see Appendix PA, Attachment SCR, FEPs W72 and W73).

Brine composition in the repository can vary depending on the sequence of future human events. Calculating brine mixing from different sources is not feasible in PA. The DOE has made the reasonable simplification that in the undisturbed performance and E2 scenarios, which do not include penetration of a Castile brine reservoir, all brine in the repository will have the composition of Salado brine (see Appendix PA, Attachment SOTERM). In these scenarios, there is no process that could introduce Castile brine into the repository. For the E1 and E1E2 scenarios, which include penetration of a brine reservoir in the Castile, brine in the repository is assumed to have the composition of Castile brine at all times. Even though some Salado brine may enter the repository in these scenarios, it is reasonable to assume that Castile brine dominates because the quantity of brine that can flow from a reservoir through a borehole and into the repository is substantial compared to the quantity of brine entering from the Salado.

The chemical environment in the repository after closure is expected to be strongly reducing (that is, lowered oxidation states are expected for elements that can occur in more than one oxidation state). Any gaseous or dissolved oxygen present in the repository will be consumed quickly either by aerobic microbial activity or by oxic corrosion after repository closure. Moreover, the repository will contain large amounts of metallic Fe, and anoxic corrosion has been shown to produce considerable quantities of H_2, Fe(II) oxides and hydroxides, and dissolved Fe(II) species under expected repository conditions (see Appendix MASS, MASS Attachment 8-3 of the CCA). Despite the overall reducing conditions, however, a condition of oxidation-reduction disequilibrium is assumed in that oxidation-reduction reactions between dissolved actinides in possible oxidation states are not assumed to occur.

MgO in polypropylene “supersacks” is emplaced on top of the three-layer waste stacks to create conditions that reduce actinide solubilities in the repository (see Section 3.3.3; Appendix BARRIERS; and Appendix PA, Attachment SOTERM, Section SOTERM-2.0). If brine flows into the repository, MgO will react with water in brine and in the gaseous phase to produce brucite ($Mg[OH]_2$). MgO will react with essentially all of the CO_2 that could be produced by complete microbial consumption of the cellulosic, plastic, and rubber materials in the waste, and will initially create hydromagnesite with the composition $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ and will eventually form magnesite with the composition $MgCO_3$ (Appendix BARRIERS; Appendix PA, Attachment SOTERM, Section 2). The most important MgO hydration and carbonation reactions that will occur in the WIPP are:

$$MgO + H_2O(aq\ or\ g) \rightarrow Mg(OH)_2 \quad (6.12)$$

$$5Mg(OH)_2 + 4CO_2(aq\ or\ g) \rightarrow Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O. \quad (6.13)$$

$$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O + CO_2(aq\ and/or\ g) \rightarrow 5MgCO_3 + 5H_2O \quad (6.14)$$

In these equations, "aq or g" indicates that the H_2O or CO_2 that reacts with MgO or brucite could be present in the aqueous phase (brine) or the gaseous phase. In the CCA, it was assumed that magnesite would be the dominant Mg carbonate in the repository during the 10,000-year regulatory period, and that the brucite-magnesite carbonation reaction (Reaction 6.14) will buffer f_{CO_2} in WIPP whether or not significant microbial CO_2 production occurs. For the PAVT, the EPA specified that the brucite-hydromagnesite carbonation reaction (6.13) will buffer f_{CO_2} in the WIPP whether or not significant microbial CO_2 production occurs (BARIERS-2.4.1). For the CRA-2004 PA, the brucite-hydromagnesite carbonation reaction (6.13) will buffer (control) the fugacity (essentially the partial pressure) of CO_2 at a relatively low value of about $10^{-5.50}$ atm if significant microbial activity occurs. If microbial activity occurs, the predicted value of f_{CO_2} will be identical for both Salado and Castile brine. The brucite-hydromagnesite buffer will control f_{CO_2} effectively because: (1) the DOE is emplacing more than enough MgO to ensure the consumption of essentially all CO_2 that could be produced in the repository, and (2) the reactivity of the MgO being emplaced in the WIPP is such that its carbonation rate exceeds the CO_2 production rate. The brucite dissolution reaction

$$Mg(OH)_2 \rightleftharpoons Mg^{2+} + 2OH^- \quad (6.15)$$

will buffer the pH at about 9 in both Salado and Castile brine if microbial activity occurs (see Appendix PA, Attachment SOTERM, Section 2). For the CRA-2004 PA vectors with microbial activity, the composition of Salado or Castile brine at equilibrium with major Salado minerals such as halite and anhydrite, the f_{CO_2} established by Reaction 13, and the pH established by Reaction 6.15, have been used to calculate actinide solubilities.

The CRA-2004 PA does not assume the same reaction will control f_{CO_2} for vectors without significant microbial CO_2 production. In the absence of microbial activity, the carbonation reaction

$$Mg(OH)_2 + Ca^{2+} + CO_2(aq\ and/or\ g) \rightleftharpoons CaCO_3 + Mg^{2+} + H_2O(aq\ or\ g) \quad (6.16)$$

will buffer f_{CO_2} at $10^{-5.48}$ atm in Salado brine and at $10^{-6.15}$ atm in Castile brine (see BARRIERS-2.4.2.3). Reaction 6.15 will buffer the pH at about 9 in both Salado and Castile brine (see Appendix PA, Attachment SOTERM, Section 2). For the 2004 PA vectors without microbial activity, the composition of Salado or Castile brine at equilibrium with major Salado minerals, the f_{CO_2} established by Reaction 6.16, and the pH established by Reaction 6.15, have been used to calculate actinide solubilities.

There is a relatively small amount of portlandite $Ca(OH)_2$ associated with the Portland cement used to dewater process sludges. The quantity of portlandite is too small, however, to overcome the buffer capacity of the reactions described above.

The DOE will emplace significantly more MgO than is needed to maintain the chemical conditions discussed above. The excess MgO emplaced relative to the amount that is needed has been termed a safety factor. The MgO safety factor is defined as:

$$\text{MgO safety factor} = (\text{MgO}_{\text{emplaced}}) \div (\text{MgO}_{\text{required}}), \tag{6.17}$$

where $\text{MgO}_{\text{emplaced}}$ is the quantity of MgO to be emplaced in the repository and $\text{MgO}_{\text{required}}$ is the quantity of MgO required to consume the maximum amount of CO_2 produced by microbial consumption of all of the emplaced cellulosic, plastic, and rubber materials. This analysis uses: (1) current in the emplaced TRU waste and emplaced materials, and (2) the quantity of MgO emplaced. The EPA has specified a 1.67 safety factor be maintinaed in the repository. Therefore, there will be more than enough MgO to ensure that the conditions described above will be established in the repository (see Appendix BARRIERS, Sections BARRIERS-2.0 and BARRIERS-2.6).

NOTE TO TECH EDITOR: A new equation was added and all subsequent equation numbers and reference to them will need to be revised.

The waste contains organic ligands that could dissolved complexes with actinides and thus increase their solubilities. There are four organic ligands of potential concern in the waste: acetate, citrate, ethylenediaminetetraacetic acid (EDTA), and oxalate. These organic ligands could increase the solubilities of the actinides in the waste because: (1) they are soluble in aqueous solutions such as WIPP brines, and (2) they are known to form complexes with the actinides (see Appendix PA, Attachment SOTERM, Section SOTERM-5.0) Therefore, the effects of acetate, citrate, EDTA, and oxalate have been included in the Fracture-Matrix Transport (FMT) calculations of actinide solubilities for the CRA-2004 PA. These organic ligands will also form complexes with dissolved, cationic species of several metals present in the repository. These metals will thus compete with the actinides for the binding sites on these organic ligands. The effects of two of these metals, Mg^{2+} and Ca^{2+}, have been included in the solubility calculations for the CRA-2004 PA. Including complexation of actinides and of Mg^{2+} and Ca^{2+} by acetate, citrate, EDTA, and oxalate in the solubility calculations for the CRA-2004 PA has confirmed the conclusion in the CCA that organics will not increase the solubilities of the actinides significantly (see CCA Appendix SOTERM, Section SOTERM.5.0).

6.4.3.5 Dissolved Actinide Source Term

The actinide source term used in the CRA-2004 PA calculations represents the aqueous concentrations of thorium (Th), uranium (U), Pu, and americium (Am) in the repository. The source term is the sum of the dissolved species (solubility) and the mobile suspended (colloidal) species of each of these actinides (see Section 6.4.3.6). The source term represents the mobile concentrations of Th, U, Pu, and Am that could be released from the repository in brine.

The actinide source term is limited to those radionuclides that could significantly affect the long-term performance of the WIPP. These radionuclides are all isotopes of Th, U, Pu, and Am. Their potential effects on the long-term performance of the repository can be ordered as Pu ≈ Am >> U > Th (Helton 1998). Other actinides, especially neptunium (Np), were included in the

laboratory and modeling studies used to develop the actinide source term because it was not known which actinides could significantly affect the long-term performance of the repository.

Although commonly referred to as "actinide," these radioelements are almost always present in the waste as solid actinide oxides or solid actinide salts and, if they dissolve in WIPP brines, will form complex species (usually referred to as "complexes") with nonradioactive, inorganic, dissolved species such as carbonate ion (CO_3^{2-}), chloride ion (Cl^-) or hydroxide ion (OH^-), or with nonradioactive, organic, dissolved species such as acetate, citrate, EDTA, or oxalate (see Section 6.4.3.4).

The postclosure chemical environment in the repository will be strongly reducing (see Section 6.4.3.4; Appendix PA, Attachment SOTERM, Section SOTERM-2.0). Previous studies of actinide chemistry imply that, under these conditions, Th will exist as Th(IV) (Appendix PA, Attachment SOTERM, Section 4.1); U will exist as U(IV) or U(VI) (Section 4.2); Np will speciate as Np(IV) or Np(V) (Section 4.3); Pu will exist as Pu(III) and Pu(IV) (Section 4.4); and Am will speciate as Am(III) (Section 4.5). Several actinide oxidation states will be unstable under the strongly reducing conditions expected in the repository. These include Np(VI), Pu(V), Pu(VI), and Am(V). Pu(V) and Pu(VI) could occur in isolated microenvironments in the repository, however, the DOE concludes that would not persist in significant quantities because diffusive transport through any brine present and (especially in the event of human intrusion) advective transport of brine would expose any oxidized Pu to reducing materials like metallic Fe from waste containers and Fe-based materials in the waste, Fe(II)-bearing solids produced by anoxic corrosion of metallic Fe, dissolved Fe(II) species, and metallic Al in the waste (Appendix SOTERM, Sections SOTERM-2 and SOTERM-4; Marcinowski 2001). Microbial activity, if it occurs, would also help create reducing conditions.

The DOE incorporated the uncertainties regarding the oxidation states of U and Pu in PA by assigning a probability of 0.5 that they will exist in the U(IV) and Pu(III) oxidation states, and a probability of 0.5 that these elements will speciate in the U(VI) and the Pu(IV) oxidation states (see also Appendix PA, Section SOTERM-5.2). The oxidation state for both elements is selected by a single variable in the LHS. Therefore, in approximately half of the PA realizations, the oxidation states of the transported actinides are Th(IV), U(IV), Pu(III), and Am(III); and, in the other half of the realizations, the oxidation states are Th(IV), U(VI), Pu(IV), and Am(III).

Laboratory studies with neodymium(III) (Nd(III)), Am(III), and Cm(III) were used to develop a solubility model for the +III actinides, and this model was used to predict the solubilities of Pu(III) and Am(III). Similarly, Th(IV) was used to develop a solubility model for the +IV actinides, which was used for Th(IV), U(IV), Np(IV), and Pu(IV). Literature data for Np(V) were used to develop a solubility model for the +V actinides, which was used only for Np(V). The +V model was not used for other actinides because Pu(V) would not persist in significant quantities in the WIPP. Using the oxidation-state analogy to extend the +III and +IV solubility models to Pu(III) and to U(IV), Np(IV), and Pu(IV), respectively, is valid for these reasons: First, the chemical behavior, especially the speciation and solubilities, of Nd(III), Pu(III), Am(III), and Cm(III) is very similar. Second, the chemical behavior of Th(IV), U(IV), Np(IV), and Pu(IV) is similar, although the solubility of Th(IV) is higher those of U(IV), Np(IV), and especially Pu(IV). Third, Nd, Am, and Cm speciate only in the +III oxidation state, and Th speciates only in the +IV oxidation state under typical laboratory conditions, thus making

experiments with these actinides much easier to carry out and interpret than those with actinides that occur in more than one oxidation state, such as Pu.

The FMT calculations of actinide solubilities for the CRA-2004 PA featured the establishment of equilibrium of Salado brine (GWB) or Castile brine (ERDA-6) with halite and anhydrite, minerals present in large quantities in the Salado at the repository horizon. (These brines are described in Appendix PA, Attachment SOTERM, Section SOTERM-2.2.1). The effects of the MgO included the equilibrium of Salado brine or Castile brine with brucite and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) in the performance-assessment vectors with microbial activity, and with brucite and calcite in the vectors without microbial activity (see Appendix BARRIERS, Section 2; and Appendix PA, Attachment SOTERM). For the 1997 PAVT, it was assumed that Salado brine (Brine A) or Castile brine (ERDA-6) would be in equilibrium with brucite and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) in all of the performance-assessment vectors (both with and without microbial activity) (EPA 1998a, 1998b). For the CCA, equilibria among Salado brine (Brine A) and Castile brine (ERDA-6) and brucite and magnesite were assumed (CCA Appendix BACK).

The FMT calculations for the CRA-2004 PA also included the effects of acetate, citrate, EDTA, and oxalate on the speciation and solubilities of the +III, +IV, and +V actinides (see Appendix PA, Attachment SOTERM). The FMT calculations for the CCA PA and the 1997 PAVT did not include organic ligands.

Table 6-13 provides the solubilities calculated for the +III, +IV, and +V actinides and estimated for the +VI oxidation state for the CRA-2004 PA, and compares them to the solubilities calculated or estimated for the CCA PA and the 1997 PAVT. An uncertainty range of +1.4 orders of magnitude and -2.0 orders of magnitude was applied to the FMT predictions for the CRA-2004 PA (see Appendix PA, Attachment SOTERM, Section SOTERM-3.6). This is the same uncertainty range used for the CCA PA and the 1997 PAVT. LHS was used to sample solubilities from these ranges.

A thermodynamic speciation and solubility model was not developed for U(VI); instead, literature data estimated the solubilities of U(VI) in the repository (Appendix PA, Attachment SOTERM, Section SOTERM-3.0; based on Hobart and Moore [1996]). These estimates have not been used for other actinides in the repository because Np and Pu will not persist in significant quantities in the +VI oxidation state.

The actinide inventory is depleted on a cell-by-cell basis by the computer code NUTS (NUclide Transport Systems) for the undisturbed, E1, and E2 scenarios. The treatment of the E1E2 scenario is described in Section 6.4.13.5. In a computational cell, the processes affecting dissolved actinide concentrations are dissolution of solid actinide compounds, advection of dissolved actinides by brine flow from neighboring cells, and interaction with colloidal particles (see Section 6.4.3.6). NUTS dissolves each actinide until the maximum concentrationdetermined by the actinide-source-term algorithms is obtained or an inventory limit is reached. In the

Table 6-13. Actinide Solubilities (M) Calculated (+III, +IV, and +V) or Estimated (+VI) for the CRA-2004 PA, the 1997 PAVT, and the CCA

Actinide Oxidation State and Brine	CRA-2004 Solubilities, Microbial Vectors[1]	CRA-2004 Solubilities, Nonmicrobial Vectors[1]	1997 PAVT Solubilities[2]	CCA Solubilities[3]
+III, Salado brine	3.07×10^{-7}	3.07×10^{-7}	1.2×10^{-7}	5.82×10^{-7}
+III, Castile brine	1.69×10^{-7}	1.77×10^{-7}	1.3×10^{-8}	1.3×10^{-8}
+IV, Salado brine	1.19×10^{-8}	1.24×10^{-8}	1.3×10^{-8}	4.4×10^{-6}
+IV, Castile brine	2.47×10^{-8}	5.84×10^{-9}	4.1×10^{-8}	6.0×10^{-9}
+V, Salado brine	1.02×10^{-6}	9.72×10^{-7}	2.4×10^{-7}	2.3×10^{-6}
+V, Castile brine	5.08×10^{-6}	2.13×10^{-5}	4.8×10^{-7}	2.2×10^{-6}
+VI, Salado brine[4]	8.7×10^{-6}	8.7×10^{-6}	8.7×10^{-6}	8.7×10^{-6}
+VI, Castile brine[4]	8.8×10^{-6}	8.8×10^{-6}	8.8×10^{-6}	8.8×10^{-6}

[1] Brush and Xiong (2003a) and Downes (2003a,b).

[2] Trovato (1997, Attachment 2), U.S. EPA (1998a, Table 5), U.S. EPA (1998b, Subsection 4.10.4, Tables 4.10-1, 4.10-3 and 4.10-4; and Subsection 12.4, Table 12.4-1), and U.S. EPA (1998c, Subsections 5.26–5.32 and Section 6.0, Table 6.4).

[3] CCA Appendix SOTERM, Table SOTERM-2; based on Novak et al. (1996, Table 1, columns entitled "@Mg"), except that Novak et al. (1996) used molal instead of molar units.

[4] Hobart and Moore (1996).

repository, the transfer of actinides between solid phases and solution is tracked to preserve mass balance of the actinide inventory. Outside the repository, the model does notprecipitate actinides into the solid phase, thereby giving a conservative measure of mobile actinide concentrations (see Appendix PA, Attachment SCR, FEP W59).

See Appendix PA, Attachment SOTERM, Section SOTERM-7.0, for a detailed description of the implementation of the actinide source term in PA.

6.4.3.6 Source Term for Colloidal Actinides

Colloidal actinides are discussed in greater detail in Appendix PA, Attachment SOTERM Section 6. Colloidal particles form in the repository through a variety of processes, including waste degradation, microbial activity, rock decomposition, and chemical condensation. These particles may also be carried into the repository by liquids moving from the Salado or through boreholes. Because of the presence of soils, nutrients, and cellulosic substrates for microbial action in WIPP waste (see Appendix TRU WASTE), humic substances and microbes will be present in disposal room brines, or may form in situ. Actinide-intrinsic colloids may form in the disposal rooms from condensation of dissolved actinides. Mineral fragments, as well as humic substances and microbes, may provide surfaces on which dissolved actinides could sorb.

Four types of colloidal particles are believed to cover the range of possible behavior of all colloid types (see Appendix PA, Attachment SOTERM). The four particle types considered in PA are microbes, humic and fulvic acids (humic substances), actinide-intrinsic (intrinsic), and mineral

fragments. The concentration of actinides carried by each colloidal particle type depends on many of the same chemical conditions that govern the concentration of dissolved actinides.

Actinide concentrations associated with humic substances and microbes are linked to dissolved actinide concentrations through proportionality constants based on experimental results. For humic substances, actinide complexation constants from WIPP-specific experiments or published literature are coupled with experimentally determined site-binding densities and solubilities of different types of humic substances in WIPP brines. For microbes, actinide uptake was experimentally determined through experiments with WIPP-relevant bacteria cultures. Actinide concentrations associated with mineral fragment-type colloidal particles are based on results from experiments designed to determine mobile concentrations in brines, coupled with site-binding densities of mineral substrates. For the plutonium(IV) polymer, actinide concentrations are determined through solubility experiments conducted from over- and undersaturated ranges of pmH values. Intrinsic colloids of other actinides were determined to be negligible and are eliminated from PA calculations. For more discussion on this topic, refer to Appendix PA, Attachment SOTERM.

Actinides associated with microbes and humics are related to the concentration of dissolved actinides in the repository through proportionality constants determined from interpretation of WIPP-relevant experiments and the literature (Appendix PA, Attachment SOTERM). The proportionality-constant relationship is not based on thermodynamic equilibrium but is simply an empirical relationship. The concentration of actinides associated with the plutonium(IV) polymer is a constant value determined from experimental results at the pmH conditions dictated by the presence of the MgO engineered barrier. Likewise, the concentration of actinides associated with mineral colloids is also a constant value, not linked to the concentration of dissolved actinides. Actinides associated with humics and microbes represent most of the colloidal actinide source term. Consequently, the colloidal actinide source term is closely related to the dissolved actinide source term. As discussed in Section 6.4.6.2, however, the source terms are considered separately for transport in the Culebra.

For PA, the concentration of each actinide element on each colloidal particle type during a realization is a fixed value. The concentration parameters are summarized in Table 6-14. Actual values of actinide concentrations on colloidal particles are constrained by inventory limits.

The concentrations of colloidal actinides indicated in this section are assumed to be actinides mobilized on colloidal particles. The indicated concentrations will be entrained in moving brine. For conservatism, it is assumed that no actinides sorb onto colloidal particles that are not mobile in the repository. Thus, all actinides in the repository will be present in the solid phase, dissolved in the aqueous phase, or colloidal actinides suspended in the aqueous phase.

When actinide inventory in a model cell is sufficient, the concentration of colloidal actinides will be at the values indicated in Table 6-14. The total concentration of an actinide in solution and suspension is limited by the amount of solids available from the inventory. This condition is called “inventory-limited.”

Colloid concentrations are calculated by the source-term procedure described in Appendix PA, Section SOTERM-4.3.2. Processes affecting the transport of colloids in the Culebra are addressed in Section 6.4.6.2.2.

6.4.4 Shafts and Shaft Seals

The four shafts connecting the repository to the surface are represented in PA with a single shaft, represented by two primary regions above the repository, and a concrete monolith (Figures 6-14 and 6-15). This single shaft has a cross section and volume equal to the total cross section and volume of the four real shafts it represents and is separated from the waste disposal regions by the true north-south distance from the waste to the nearest shaft (the Waste Shaft). Upon closure of the repository, the shafts will be sealed as described in Section 3.3.1. The seal system was originally represented in the CCA PA by 11 discrete modeled regions in the shaft. The representation was simplified by modeling the behavior of these 11 regions with two primary regions (Upper Shaft and Lower Shaft in Figures 6-14 and 6-15) that have properties simulating the behavior of the original 11 regions (see Appendix PA, Section PA-4.2.7). An analysis of the CCA results concluded that no significant flow of gas or brine would occur within the shaft seal system over the 10,000-year regulatory period. The new shaft model underwent peer review as required by 40 CFR § 194.27 and was incorporated in BRAGFLO (see Appendix PA, Section PA-4.2.7; Section 9.3.1.3.4; and Appendix PEER). The current

Table 6-14. Colloid Concentration Factors

	Concen-tration on Mineral Fragments [1]	Concen-tration as Intrinsic Colloid [1]	Proportion Sorbed on Microbes[-2 5]	Maximum Sorbed on Microbes [3]	Proportion Sorbed on Humics [2]		Maximum Sorbed on Humics [1]
					Salado	Castile	
Th(IV)	2.6×10^{-8}	0.0	3.1	0.0019	6.3	6.3	1.1×10^{-5}
U(IV)	2.6×10^{-8}	0.0	0.0021	0.0021	6.3	6.3	1.1×10^{-5}
U(VI)	2.6×10^{-8}	0.0	0.0021	0.0023	0.12	0.51	1.1×10^{-5}
Np(IV)	2.6×10^{-8}	0.0	12.0	0.0027	6.3	6.3	1.1×10^{-5}
Np(V)	2.6×10^{-8}	0.0	12.0	0.0027	9.1×10^{-4}	7.4×10^{-3}	1.1×10^{-5}
Pu(III)	2.6×10^{-8}	0.0	0.3	6.8×10^{-5}	0.19	1.37d	1.1×10^{-5}
Pu(IV)	2.6×10^{-8}	1.0×10^{-9}	0.3	6.8×10^{-5}	6.3	6.3	1.1×10^{-5}
Am(III)	2.6×10^{-8}	0.0	3.6	NA	0.19	1.37d	1.1×10^{-5}

[1] In units of moles colloidal actinide per liter
[2] In units of moles colloidal actinide per mole dissolved actinide
[3] In units of moles total mobile actinide per liter
[4] A cumulative distribution from 0.065 to 1.60 with a mean value of 1.1 was used.
[5] Microbial colloids are not included in futures without microbial gas generation.

NOTE: The colloidal source term is added to the dissolved source term to arrive at a total source term. Mineral fragments were provided with distributions, but the maximum was used as described in Appendix PA, Attachment SOTERM. Humic proportionality constants for III, IV, and V were provided with distributions, but only the Castile Am(III) and Pu(III) were sampled.

model divides the shaft into an upper region with all elements above the Salado and a lower region with all Salado elements. These regions are assigned material property distributions that

represent the combined properties of all the individual materials in series. Seal material parameter values used in the PA are provided in Table 6-15.

Conceptually, the shafts are assumed to be surrounded by a DRZ in the Salado. Within the bedded halite, the DRZ begins to form immediately after excavation and develops progressively from unloading as the formation creeps toward the excavated area. From a sealing perspective, the most important characteristic of the DRZ is the higher permeability that results from dilatant deformation and increased pore volume.

The properties of the DRZ are known to vary with the type of adjacent material, time, and depth. When the shaft seals are emplaced, back pressures will progressively develop as the surrounding salt creeps inward. The back pressure applied by the seal material will progressively reduce the magnitude of the stress differential, which is the source for the DRZ microfracturing mechanism. The back pressure also results in a higher mean stress, which induces DRZ healing. The shaft DRZ permeability will, over time, approach that of the intact halite. Also, since the creep rate of the salt surrounding the shafts depends on depth, the back pressures supplied by the seal materials will result in DRZ healing at rates that increase with depth. The relative stiffness of the seal material is a factor, as well.

The DRZ surrounding the shaft is not explicitly represented in the BRAGFLO mesh (Figures 6-14 and 6-15). Rather, the mesh was simplified to represent only the cross-sectional area of the four WIPP shafts, and the permeability values of the seal components at different times have been adjusted (in the parameter database) to account for the shaft DRZ. This adjustment, which yields effective permeabilities, can be done because in Darcy flow, the flux through a porous medium is a linear function of the product of the permeability and the cross-sectional area across which flow occurs. Thus, the flux that would occur through a shaft and its surrounding DRZ can be modeled equivalently using the shaft cross-sectional area with a higher seal component permeability. Equations for the derivation of the effective permeabilities are given in Appendix PA, Attachment PAR (Parameters 64 and 65).

6.4.5 The Salado

The Salado is the principal natural barrier to fluid flow between the waste disposal panels and the accessible environment. Fluid flow in the Salado under natural (undisturbed) conditions is discussed in Section 2.2.1.3. Repository excavation has altered natural pressure gradients in the Salado, creating the potential for fluid flow into the excavation. Fluid flow, gas generation, and volume changes from creep closure alter the pressure gradients through time. Salt creep, as well as possible fracturing from high repository pressure, alters the permeability and other flow properties of the rock near the repository. Depending on pressure gradients and altered material properties, gas and brine flow may be enhanced in affected portions of the Salado.

For PA, the DOE conceptualizes the Salado as a porous medium composed of several rock types arranged in layers, through which flow occurs according to Darcy's law. Two rock types, impure halite and anhydrite, are used to represent the intact Salado. Once sampled, model parameters for all layers are uniform and constant, with two exceptions: porosity and permeability. The assumption of constant properties is based on observed compositional and

structural regularity in layers exposed by the repository and on inferred small For several meters above and below the repository, a DRZ has higher permeability than intact rock and offers little

Table 6-15. Shaft Materials Parameter Values

Parameter (units)	Maximum	Minimum	Median or Constant
UPPER SHAFT MATERIAL			
Residual Brine Saturation, S_{br} (unitless)	0.6	0	0.2
Residual Gas Saturation, S_{gr} (unitless)	0.4	0	0.2
Maximum Capillary Pressure (pascals) [1]	–	–	10^8
Permeability (square meters)	3.16×10^{-17}	3.16×10^{-21}	5.01×10^{-19}
Porosity (percent)	–	–	29.1
LOWER SHAFT MATERIAL (0 to 200 years)			
Initial Brine Saturation, (unitless)	–	–	5.34×10^{-1}
Permeability (square meters) [2]	3.16×10^{-17}	1.0×10^{-20}	6.31×10^{-19}
Maximum Capillary Pressure (pascals)[1]	–	–	10^8
Effective Porosity (percent)	–	–	11.3
LOWER SHAFT MATERIAL (200 to 10,000 years)			
Initial Brine Saturation, (unitless)			5.34×10^{-1}
Permeability (square meters)[2]	1×10^{-18}	3.16×10^{-23}	7.94×10^{-21}
Maximum Capillary Pressure (pascals)[a]	–	–	10^8
Effective Porosity (percent)	–	–	11.3

[1] Capillary pressure for all shaft materials is set to 0.
[2] These values represent the permeabilities of the seal material incorporating the surrounding DRZ

resistance to flow between anhydrite interbeds and the repository. Porosity can vary from its initial value due to pressure-dependent compressibility. As discussed in Section 6.4.5.2, a model has been implemented in interbeds to simulate the effects of fracturing caused by high repository pressure as pore pressure approaches or exceeds lithostatic.
Specific information about the three submodels used to represent impure halite, Salado interbeds, and the DRZ is presented in the following sections.

6.4.5.1 Impure Halite

The PA uses a single porous medium with spatially constant rock and hydrologic properties (labeled "Salado" in Figures 6-14 and 6-15) in PA to represent intact, halite-rich layers in the Salado and minor interbeds contained within layers that are not explicitly represented. A comparison was made between the simplified stratigraphy used in the PA model and a model with a more detailed stratigraphy in the vicinity of the repository. This comparison supports use of stratigraphic representation for PA. This model comparison is described in Christian-Frear and Webb (1996).

Gas may not be able to flow through intact, halite-rich strata of the Salado under realistic conditions for the repository. Gas flow in liquid-saturated rock depends on the gas pressure required to overcome capillary resistance to initial gas penetration and interconnected gas

pathways that allow gas flow (threshold pressure). While the permeability of halite is known to be low, its threshold pressure has never been measured. An empirical relationship between threshold pressure and permeability in non-WIPP rocks (Davies 1991, 17-19) suggests that threshold pressure will be high enough that gas will be unable to flow through the halite-rich strata of the Salado under any conditions foreseeable for the WIPP (see Appendix PA, Attachment MASS, Section MASS-13.1). The DOE values for halite threshold pressure are consistent for generic material of low permeability and prevent gas flow into the impure halite regions (Table 6-16). This is a conservative assumption because gas flow in halite would decrease the pressure in the repository and the driving force available for flow elsewhere. Table 6-16 shows various parameter values used in modeling the Salado impure halite. Additional information on parameter values is contained in Appendix PA, Attachment PAR (Parameters 17 through 19 and Table PAR-2).

Table 6-16. Salado Impure Halite Parameter Values

Parameter (units) [1]	Maximum	Minimum	Median or Constant
Permeability (square meters)	10^{-21}	10^{-24}	3.16×10^{-23}
Effective Porosity (percent)	3.0	0.10	1.0
Threshold Pressure, P_t (pascals) [2]	1.13×10^{8}	1.03×10^{7}	3.41×10^{7}
Residual Brine Saturation, S_{br} (unitless)	0.60	0	0.3
Residual Gas Saturation, S_{gr} (unitless)	0.40	0	0.2
Pore Distribution Parameter, λ (unitless)	1.0	0.20	0.7
Maximum Capillary Pressure (pascals)	–	–	10^{8}
Rock Compressibility (1/pascals)[3]	1.92×10^{-10}	2.94×10^{-12}	9.75×10^{-11}

[1] See Table 6-11 for fluid properties.

[2] Threshold pressure (P_t) determined from the relationship: $P_t = PCT_A \cdot k^{PCT_EXP}$ where PCT_A and PCT_EXP are constants and k is the permeability.

[3] Pore compressibility = rock compressibility/effective porosity.

6.4.5.2 Salado Interbeds

Three distinct anhydrite interbeds are modeled in BRAGFLO, representing MB138 (see Figures 6-14 and 6-15), anhydrite layers a and b (Anhydrite AB), and MB139. The three interbeds have the same set of model parameters, and the parameters are initially spatially constant. Porosity and permeability can vary spatially during a simulation, depending on the extent of interbed fracturing. The interbeds differ only in position and thickness.

The three interbeds explicitly represented in the BRAGFLO model are included because they exist in the disturbed region, as modeled around the repository within which fluid is expected to be able to flow with relative ease compared to the surrounding formation. MB139 and anhydrite layers a and b are present within the DRZ that forms around excavations, as shown by Park and Holland (2003) in their analysis of the effects of raising the repository horizon 2.34 meters (7.67 feet). MB138 is included along with a thick DRZ because of uncertainty in the extent and properties of the DRZ and the associated long-term isolation of MB138 from the repository. A more detailed examination of the DRZ was necessary to incorporate the Option D panel closure

into the PA grid. Even though the DRZ would not reach MB 138, PA models the potential for a hydraulic connection between MB 138 and the repository through the DRZ.

In BRAGFLO, brine flows between the Salado and the repository in response to fluid potential gradients that may form over time. Because of the impure halite's low permeability and relatively small surface area, direct brine flow between the impure halite and the repository is relatively small. The interbeds included in the BRAGFLO model of the Salado, however, serve as conduits for brine flow between the impure halite and the repository. Conceptually, brine flows laterally along higher permeability interbeds towards or away from the repository and vertically between the interbeds and the lower permeability halite. Because the interbeds have a very large contact area with adjacent halite-rich rock, even a very small flux from the halite into the interbeds (for brine inflow) or to the halite from the interbeds (for brine outflow) can accumulate significant quantities of brine. In this manner, halite serves as a source or sink for brine in the repository. It is expected that, because of density differences between gas and brine and their stratification within the repository, brine outflow will be predominantly in MB139, and gas outflow will occur in anhydrite a and b or MB138. However, the model does not preclude other flow patterns.

Interbeds contain natural fractures that may be partially healed, but anhydrite lithologies proximal to disposal rooms will be highly distorted as the rooms creep closed. Fractured and distorted anhydrite would not be expected to heal in a manner expected of the DRZ in salt. If high pressure is developed in an interbed, its preexisting fractures may dilate or new fractures may form, altering its porosity and permeability. Pressure-dependent changes in permeability are supported by experiments conducted in the WIPP and in the laboratory (Beauheim et al. 1993). Accordingly, the DOE has implemented in BRAGFLO a porous-media model of interbed dilation and fracturing that causes the porosity and permeability of an interbed's computational cell to increase as its pore pressure rises above a threshold value. Model details are presented in Appendix PA, Section PA-4.2 and Attachment MASS, Section MASS-13.0. To the extent that it occurs, interbed dilation or fracturing is expected to increase the transmissivity of interbed intervals. The threshold pressure of dilated or fractured interbeds is expected to be low because apertures of the fractures increase; thus, fluid is expected to flow outward readily if adequate pressure dilates the interbeds.

The model used to simulate the effects of interbed dilation or fracturing is explained in detail in Appendix PA, Attachment MASS, Section MASS-13.0. In summary, it assigns a fracture initiation pressure above the initial pressure at which local fracturing takes place. Changes in permeability and porosity occur above this pressure. Below this fracture initiation pressure, an interbed has the permeability and compressibility assigned by LHS to represent intact rock. Below the fracture initiation pressure, the initial sampled porosity is modified slightly with pressure caused by compressibility. Above the fracture initiation pressure, the local compressibility of the interbed is assumed to increase linearly with pressure. This greatly increases the rate at which porosity increases with increasing pore pressure. Additionally, permeability increases by a power function of the ratio of altered porosity to initial porosity. For numerical reasons (that is, to prevent unbounded changes in parameter values that would create numerical instabilities in codes), a pressure is specified above which porosity and permeability change no further.

Parameters associated with the interbeds are shown in Table 6-17. Table 6-18 lists parameters used to model interbed dilation and fracture. Additional information about interbed parameters is included in Appendix PA, Attachment PAR, Table 2, and Parameters 20 through 25.

Table 6-17. Parameter Values for Salado Anhydrite Interbeds a and b, and MB138 and MB139

Parameter (units) [1]	Maximum	Minimum	Median or Constant
Permeability (square meters)	7.94×10^{-18}	10^{-21}	1.29×10^{-19}
Effective Porosity (percent)	1.7	0.60	1.1
Threshold Pressure, P_t (pascals) [2]	5.28×10^{6}	2.32×10^{5}	9.74×10^{5}
Residual Brine Saturation, S_{br} (unitless)	0.174	0.00778	0.084
Residual Gas Saturation, S_{gr} (unitless)	0.197	0.014	0.077
Pore Distribution Parameter, λ (unitless)	0.842	0.491	0.644
Maximum Capillary Pressure (pascals)	–	–	10^{8}
Rock Compressibility (1/pascals) [3]	2.75×10^{-10}	1.09×10^{-11}	8.26×10^{-11}

[1] See Table 6-11 for fluid properties.

[2] Threshold pressure (P_t) determined from the relationship: $P_t = PCT_A \cdot k^{PCT_EXP}$ where PCT_A and PCT_EXP are constants and k is the permeability.

[3] Pore compressibility = Rock compressibility/effective porosity.

Table 6-18. Fracture Parameter Values for Salado Anhydrite Interbeds a and b, and MB138 and MB139

Parameter (units)	Constant
Fracture initiation pressure at MB139, base of shaft (pascals)	12.7×10^{6}
Increment to give full fracture porosity (percent), MB139 and MB138 [1]	3.9
Increment to give full fracture porosity (percent), Anhydrite a and b [1]	23.9
Full fracture permeability (square meters)	10^{-9}
Increment above fracture initiation pressure to obtain full fracture pressure (pascals) [1]	3.8×10^{6}

[1] A fitting parameter to yield desired dilation over a variation in pressure.

6.4.5.3 DRZ

In the DRZ (see Figures 6-14 and 6-15) near the repository, permeability and porosity are expected to generally increase in both halite and interbeds. These increases are due to a variety of processes. Creep closure and stress-field alterations as the result of the excavation are the dominant causes, similar to the processes discussed for forming the DRZ around the shaft (see Section 6.4.4). The increases in permeability and porosity in interbeds are not likely to be completely reversible with creep closure of the disposal rooms. The increase in DRZ permeability increases the ability of fluid to flow from interbeds to the waste disposal region. The increase in DRZ porosity provides a volume in which some fluid could be retained so that it does not contact waste or slow actinide movement.

In approximating the effects of the DRZ, PA conservatively overestimates brine flow toward the repository (see Appendix PA, Attachment MASS, Section 13). In the model, the permeability of this region is increased relative to intact Salado rock for the duration of a realization. The porosity of the modeled DRZ is increased by a fixed value of 0.0029 (0.29 percent) above the sampled porosity of the intact Salado impure halite. The modeled DRZ extends above and below the repository from the base of MB138 to MB139, thereby retaining the geometry used in the CCA and 1997 PAVT. The PA treatment of the DRZ creates a region that may allow fluid flow between the repository and affected interbeds. Table 6-19 shows parameter values used in the PA representation of the DRZ.

Table 6-19. DRZ Parameter Values

Parameter (units) [1]	Maximum	Minimum	Median or Constant
Permeability (square meters)	3.16×10^{-13}	3.98×10^{-20}	10^{-16}
Effective porosity (percent) [2]	3.3	0.04	1.29
Threshold pressure, P_t (pascals)	–	–	0
Residual brine saturation, S_{br} (unitless)	–	–	0
Residual gas saturation, S_{gr} (unitless)	–	–	0
Pore distribution parameter, λ (unitless)	–	–	0.7
Maximum capillary pressure (pascals)	–	–	10^8
Rock compressibility (1/pascals) [3]	–	–	7.41×10^{-10}

[1] See Table 6-11 for fluid properties.
[2] The DRZ effective porosity value for each realization is equivalent to the sampled value for the Salado halite plus 0.0029 (0.0029 is the difference between the medians for the DRZ and the halite).
[3] Pore compressibility = rock compressibility/effective porosity.

The DOE originally used a constant permeability for the DRZ over the 10,000-year regulatory time frame. However, the EPA required the DOE to treat the DRZ permeability as uncertain during the PAVT (EPA 1998, TSD V-B-14). The range is sampled to determine a fixed value for each realization over the 10,000-year period. Additionally, in the 1997 PAVT, the anhydrite fracture model was applied to the DRZ to capture the effects of halite fracture under high repository pressures. As was done in the 1997 PAVT, the CRA-2004 PA treats the DRZ permeability as an uncertain parameter, and the anhydrite fracture model is also applied to the DRZ. The parameter values are shown in Table 6-19.

6.4.5.4 Actinide Transport in the Salado

The DOE considers actinide transport in the Salado to be a possible mechanism for release to the accessible environment. As in other areas of the disposal system, actinides in the Salado may be transported as dissolved species or as colloidal particles. Actinide transport is affected by a variety of processes that may occur along the flow path.

The DOE uses the NUTS code (see Appendix PA, Section PA-4.3) to model the migration of radionuclides in the repository and surrounding formations. NUTS models radionuclide transport within all regions for which BRAGFLO computes brine and gas flow, and uses as input

for each realization the corresponding BRAGFLO velocity field, pressures, porosities, saturations, and other model parameters including (for example) the geometrical grid, residual saturation, material map, and compressibility.

The PA uses NUTS in two ways. First, the code is used in a computationally fast tracer mode to identify those BRAGFLO realizations for which it is unnecessary to do full transport calculations because contaminated brine never reaches the top of the salt or the accessible environment within the Salado. Such realizations cannot contribute to the total integrated release of radionuclides from the disposal system. If the tracer calculation indicates a possibility of consequential release, a computationally slow calculation of the full transport of each radionuclide is performed (see Appendix PA, Section 6.7.2).

6.4.5.4.1 NUTS Tracer Calculations

All BRAGFLO realizations are evaluated using NUTS in a tracer mode to identify realizations for which there is no possibility of radionuclides reaching the accessible environment. The tracer simulations consider an infinitely soluble, nondecaying, nondispersive, and nonsorbing species as a tracer element. The tracer is given a unit concentration in all waste disposal areas of 1 kilogram per cubic meter. If this tracer does not reach the selected boundaries (the top of the Salado and the land withdrawal boundary within the Salado) in a cumulative mass greater than or equal to 10^{-7} kilograms within 10,000 years, it is assumed there is no consequential release to these boundaries. If a cumulative mass greater than or equal to 10^{-7} kilograms does reach the selected boundaries within 10,000 years, a complete transport analysis is conducted. The value of 10^{-7} kilograms is selected because, regardless of the isotopic composition of the release, it corresponds to a normalized release less than 10^{-6} EPA units, the smallest release displayed in CCDF construction. The largest normalized release would be 9.98×10^{-7} EPA units, which corresponds to 10^{-7} kilograms of ^{241}Am, if the release was entirely ^{241}Am

6.4.5.4.2 NUTS Transport Calculations

For BRAGFLO realizations with greater than 10^{-7} kilograms reaching the boundaries in the tracer calculations, NUTS models the transport of five different species of radionuclides (^{241}Am, ^{239}Pu, ^{238}Pu, ^{234}U, and ^{230}Th). These radionuclides represent a larger number of radionuclides, as discussed in Appendix TRU WASTE. For decay purposes, radionuclides were grouped together based on similarities such as isotopes of the same element and those with similar half-lives, to simplify the calculations, as discussed in CCA Appendix WCA.3.2.3. For transport purposes, solubilities are lumped to represent both dissolved and colloidal forms. These groupings simplify and expedite calculations.

NUTS models radionuclide transport by advection (see Appendix PA, Attachment MASS). NUTS disregards sorptive and other retarding effects throughout the entire flow region. Physically, some degree of retardation must occur at locations within the repository and the geologic media, and the disregard of retardation processes is therefore conservative. NUTS also disregards reaction-rate aspects of dissolution and colloid formation processes, and mobilization is assumed to occur instantaneously. Neither molecular nor mechanical dispersion is modeled in NUTS. These processes are assumed to be insignificant in comparison to advection, as discussed further in Appendix PA, Attachment MASS.

Colloidal actinides are subject to retardation by chemical interaction between colloids and solid surfaces and by clogging of small pore throats (that is, sieving). There will be some interaction of colloids with solid surfaces in the anhydrite interbeds. The low permeability of intact interbeds is reason to expectpore apertures are small and some sieving will occur. However, colloidal particles, if not retarded, are transported slightly more rapidly than the average velocity of the bulk liquid flow. Because the effects on transport of slightly increased average pore velocity and retarding interactions with solid surfaces and sieving are offsetting, the DOE assumes residual effects of these opposing processes will be either small or beneficial and does not incorporate them in modeling of actinide transport in the Salado interbeds.

If brine that has been in the repository moves into interbeds, it is likely that mineral precipitation reactions will occur. Precipitated minerals may contain actinides as trace constituents. The beneficial effects of the possible mineral co-precipitation process are neglected in PA. Furthermore, colloidal-sized precipitates will behave like mineral-fragment colloids, which are destabilized by brines, quickly agglomerating and settling by gravity. The beneficial consequence of colloid precipitation is also disregarded in PA.

Additional processes that may impact transport in Salado interbeds are related to fractures, channeling, and viscous fingering. Interbeds contain natural fractures. Because of the low permeability of unfractured anhydrite, most fluid flow occurring in interbeds will occur in fractures. Even though some properties of naturally fractured interbeds are characterized by in-situ tests (see Section 2.2.1.3), other uncertainty exists in the characteristics of the fracture network that may be created if gas pressure in the repository becomes high. The PA modeling system accounts for the possible effects on porosity and permeability of fracturing through use of a fracturing model (see Section 6.4.5.2). The processes and effects associated with fracture dilation or fracture propagation that are not already captured by the PA fracture model are negligible (see CCA Appendix MASS, Section MASS.13.3 and MASS Attachment 13.2). Of those processes not already incorporated, channeling is considered to have the greatest potential effect.

Channeling is the movement of fluid through the larger aperture portions of a fracture network (that is, areas of local high permeability). It could locally enhance actinide transport. However, it is assumed that the effects of channeled flow in existing or altered fractures will be negligible on the scale of the disposal system. The DOE believes this assumption is reasonable because processes that act to limit the effectiveness of channels or disperse actinides in them are likely to occur. First, if gas is present in the fracture network, it will be present as the nonwetting phase and will occupy the portions of the fracture network with relatively large apertures, where the highest permeabilities will exist locally. The presence of gas thus removes the most rapid transport pathways from the contaminated brine and decreases the impact of channeling. Second, brine penetrating the Salado from the repository is likely to be completely miscible with in-situ brine. Because of miscibility, diffusion or other local mixing processes will probably broaden fingers (reduce concentration gradients) until the propagating fingers are indistinguishable from the advancing front.

Gas will likely penetrate the liquid-saturated interbeds as a fingered front rather than as a uniform front. Fingers form because of the difference in viscosity between the invading fluid (gas) and the resident fluid (liquid brine), and because of channeling effects. This process does

not affect actinide transport, however, because actinides of interest are transported only in the liquid phase, which will not displace gas in the relatively high-permeability regions because of capillary effects.

6.4.6 Units Above the Salado

The geology and hydrology of units above the Salado are discussed in Sections 2.1.3 and 2.2.1.4, respectively. In this section, the assumptions, simplifications, and models used in PA of these units are described. Because it is unlikely that these units will be impacted by UP, modeling these units is performed mainly because regulations require considering the effects of inadvertent human intrusions. See Appendix PA, Attachment MASS, Section 14 for additional discussion on the units above the Salado.

The principal purpose of BRAGFLO calculations for units above the Salado is to determine the quantity of brine entering each unit from an intrusion borehole or the shaft. It is unrealistic to assume that all flow up an intrusion borehole enters the Culebra. Accordingly, BRAGFLO parameters are specified so that brine flow from the intrusion borehole is possible not only into the Culebra but also into the Magenta, Dewey Lake, and overlying units (as well as to the ground surface), depending on whether liquid rises above the Culebra in the intrusion borehole. Some of the assumptions regarding the properties of units above the Salado are made specifically to allow model simplification and are conservative with respect to actinide transport in the Culebra (that is, overestimate releases).

Consistent with accepted stratigraphic conventions for the area, discussed in Section 2.1.3, the units above the Salado are subdivided into seven layers in PA; these are, in order of lowest to highest, the Los Medaños, the Culebra, the Tamarisk, the Magenta, the Forty-niner, the Dewey Lake, and the units above the Dewey Lake. The conceptual model for each of these layers is described sequentially in the following sections.

A fundamental assumption in the PA conceptual model for modeling actinide transport to the accessible environment in units above the Salado is that lateral actinide transport through rock formations is possible within the next 10,000 years only in the Culebra. This assumption is appropriate for several reasons relating to the properties of other rock units and the groundwater basin conceptual model, discussed in following sections.

Section 2.2.1.4 describes the hydrology of the units above the Salado in terms of the groundwater basin conceptual model. Insight into groundwater basin processes indicates that it is possible to significantly simplify the hydrologic models in the units above the Salado to obtain reasonable estimates of actinide transport (see Corbet and Knupp 1996; Appendix PA, Attachment MASS, Section MASS-14). Therefore, the DOE calculates actinide transport in the units above the Salado with a two-dimensional conceptual and mathematical model. The models used for actinide transport in the units above the Salado are a simplified implementation of the groundwater basin conceptual model. The mathematical model is implemented in the computer codes MODFLOW-2000 and SECOTP2D (see Appendix PA, Section PA-4.8).

6.4.6.1 The Los Medaños

The Los Medaños (formerly the unnamed lower member of the Rustler, Row 25 in Figures 6-14 and 6-15) rests above the Salado. Its transmissivity was measured (see Section 2.2.1.4.1.1) and found to be low, which is consistent with expectations based on its anhydrite, gypsum, halite, clay, and siltstone composition (see Section 2.1.3.5.1). In PA, this member is treated as impermeable, which prevents liquid flow and actinides from entering this unit. The DOE assumes that because of the low permeability of the Los Medaños assumption any brine entering it from an intrusion borehole would be contained well within the site boundary for more than 10,000 years. This treatment is conservative because allowing flow from a borehole or shaft into the Los Medaños would, if anything, decrease flow into the Culebra. This would reduce the release of actinides from the Culebra to the accessible environment. In PA, the thickness of Los Medaños is 36 m (118 ft), and its permeability is zero.

6.4.6.2 The Culebra

The Culebra is represented in BRAGFLO as Row 26 in Figures 6-14 and 6-15. The model geometries for Culebra flow calculations and transport calculations are discussed in this section. Boundary and initial conditions for this geometry are discussed in Section 6.4.10.2. Supplementing the discussion in this section are additional details about the Culebra modeling provided in Section 6.4.13 and Appendix PA, Section PA-4.9.

Conceptually, radionuclides might be introduced into the Culebra through brine flow up the sealed shafts. However, the chief source of actinides in the Culebra is modeled as long-term releases from a borehole that intersects the repository. If radionuclides are introduced into the Culebra, they may be transported from the point of introduction by groundwater flowing naturally through the Culebra.

The Culebra is conceptualized as a confined aquifer. For fluid flow, it is conceptualized as a heterogeneous porous medium represented by variations in transmissivity. A heterogeneous velocity field is used for transport calculations, but all other rock properties (e.g., porosity, K_d) are conceptualized as constant (homogeneous) across the model area. The Culebra is conceptualized as having two types of porosity; a portion associated with high-permeability features where transport occurs by advection, and the rest associated with low-permeability features where flow does not occur and retardation occurs by physical processes (diffusion) and chemical processes (sorption). This type of conceptual model is commonly referred to as "double-porosity." In this conceptual model, transport and retardation of colloidal particles are also considered. This section addresses fluid flow in the Culebra. The transport and retardation of dissolved actinides will be discussed principally in Section 6.4.6.2.1. The transport and retardation of colloidal particles will be discussed principally in Section 6.4.6.2.2.

In the Culebra conceptual model used in PA, the spatial distribution of transmissivity in the Culebra is important. Other potentially important processes acting on Culebra flow and transport are climate change (Section 6.4.9 and CCA Appendix MASS, Section MASS.17) and the effects of subsidence caused by potash mining in the McNutt (Section 6.4.6.2.3 and CCA Appendix MASS, Section MASS.15.4).

The MODFLOW-2000 code uses two-dimensional horizontal grids to simulate groundwater flow. A regional grid approximately 14 miles × 19 miles (22 kilometers × 30 kilometers) (Figure 6-17) with spatially varying transmissivity determines the flow fields in the WIPP region from hydraulic head distributions controlled by distant topographic and hydrologic features (that is, boundary conditions). The grid is made up of 68,768 uniform 100 m × 100 m (328.08 ft) cells. Because this grid is used to define the boundary conditions for the flow and transport calculations, it is discussed in detail in Section 6.4.10.2, along with the specification of boundary conditions. Details about the development and calibration of the flow fields are given in Appendix PA, Attachment TFIELD. For transport in the region of interest, a local grid 7.5 km × 5.4 km (4.5 mi × 3.1 mi) with finer discretization is used in SECOTP2D (Figure 6-18). The grid for the transport domain contains 150 columns and 108 rows of 50 m × 50 m (164 ft) cells, resulting in 16,200 grid blocks.

The local SECOTP2D domain boundaries (Figure 6-18) were chosen to capture all flow paths from the modeled release point above the center of the disposal panels to the accessible environment. Because past analyses indicated that transport in the Culebra occurs within a region that lies from southeast of the repository to west of the repository, the transport domain extends slightly beyond the southern and western boundaries of the controlled area. Because it is not needed, a strip in the northern portion of the controlled area has been omitted from the SECOTP2D domain to ease the computational burden.

Flow directions and transmissivities in the Culebra vary significantly from location to location within and past the site boundary. Consequently, the effects of flow in the region around the WIPP site are important in the conceptual model. The boundaries to the flow model are discussed in Section 6.4.10.2; the domain itself is shown in Figure 6-17.

The conceptual model for the Culebra assumes that fluid fluxes and directions in the future will be the same as at repository closure, unless future mining within the site occurs, in which case changes to fluid flow are calculated. A steady-state flow field is used to represent this assumption. Conditions assumed at site closure are the subsidence effects of mining in the near future outside the site boundary, climate change, and heads similar to those measured in late 2000 (see Appendix PA, Attachment MASS, Sections MASS-15.4 and MASS-14.2, and Attachment TFIELD).

The factors controlling fluid flow in the Culebra are the hydraulic gradient, distribution of transmissivity, and porosity. The hydraulic gradient and transmissivities used in PA are coupled because they are calibrated to observed conditions by a process described in Appendix PA, Attachment TFIELD. Flow fields are calculated with the code MODFLOW-2000 assuming homogeneous porosity in the Culebra. This single value is the total porosity for the Culebra, including both advective and diffusive porosity, as discussed below. Using a single porosity for the flow calculation does not introduce inconsistency with transport calculations because (1) steady-state flow fields are used so flux through the system is not dependent on porosity, and (2) the velocity of liquid for transport is calculated based on a double-porosity model implemented in SECOTP2D. Thus, the important factors for flow calculations are the hydraulic gradient and transmissivity variation.

Because BRAGFLO models a vertical section of the disposal system, the spatial distribution of transmissivity cannot be represented in the BRAGFLO grid. The source term of actinides in the Culebra is calculated in part from BRAGFLO flow fields, so parameters for the Culebra are required in BRAGFLO. Specifically, a single value of Culebra permeability representative for the Culebra in the area immediately over the waste-emplacement panels is input to partition fluid flow among the stratigraphic units along the human-intrusion borehole.

BRAGFLO calculates gas flow and brine flow that may occur up a borehole (see Section 6.4.7). The MODFLOW-2000 code models flow of the liquid phase only. The possible effects of gas on Culebra flow are not modeled. This simplification is reasonable because after gas pressure is relieved by flow to the surface during drilling, little gas will remain in the repository. This gas will move up the borehole at low rates and tend to move directly to the top of the liquid-saturated section of the borehole, bypassing the Culebra. Any gas that does enter the Culebra will tend to displace brine from fractures and reduce the potential for actinide transport. Based on previous modeling (Lappin et al. 1989, Appendix E.1.5.1), the effect of the mass of brine being injected into the Culebra on the natural flow is negligible. Parameter values used in BRAGFLO to describe the Culebra are shown in Table 6-20. Parameter values used in MODFLOW-2000 are shown in Table 6-21. See Appendix PA, Attachment PAR, Table 2 for additional Culebra parameter information.

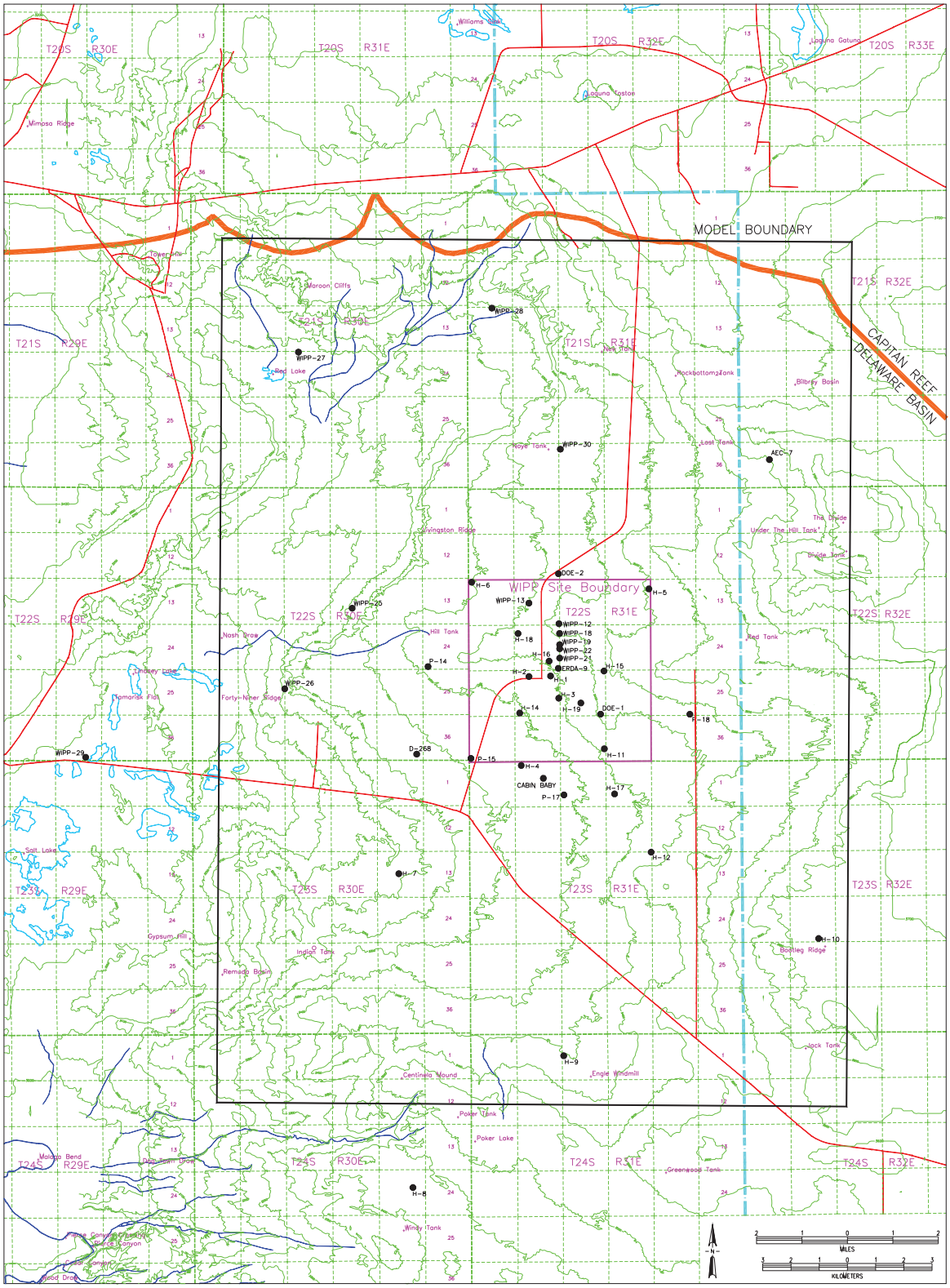

Figure 6-17. The MODFLOW-2000 Domain Used in the Groundwater Model of the Culebra

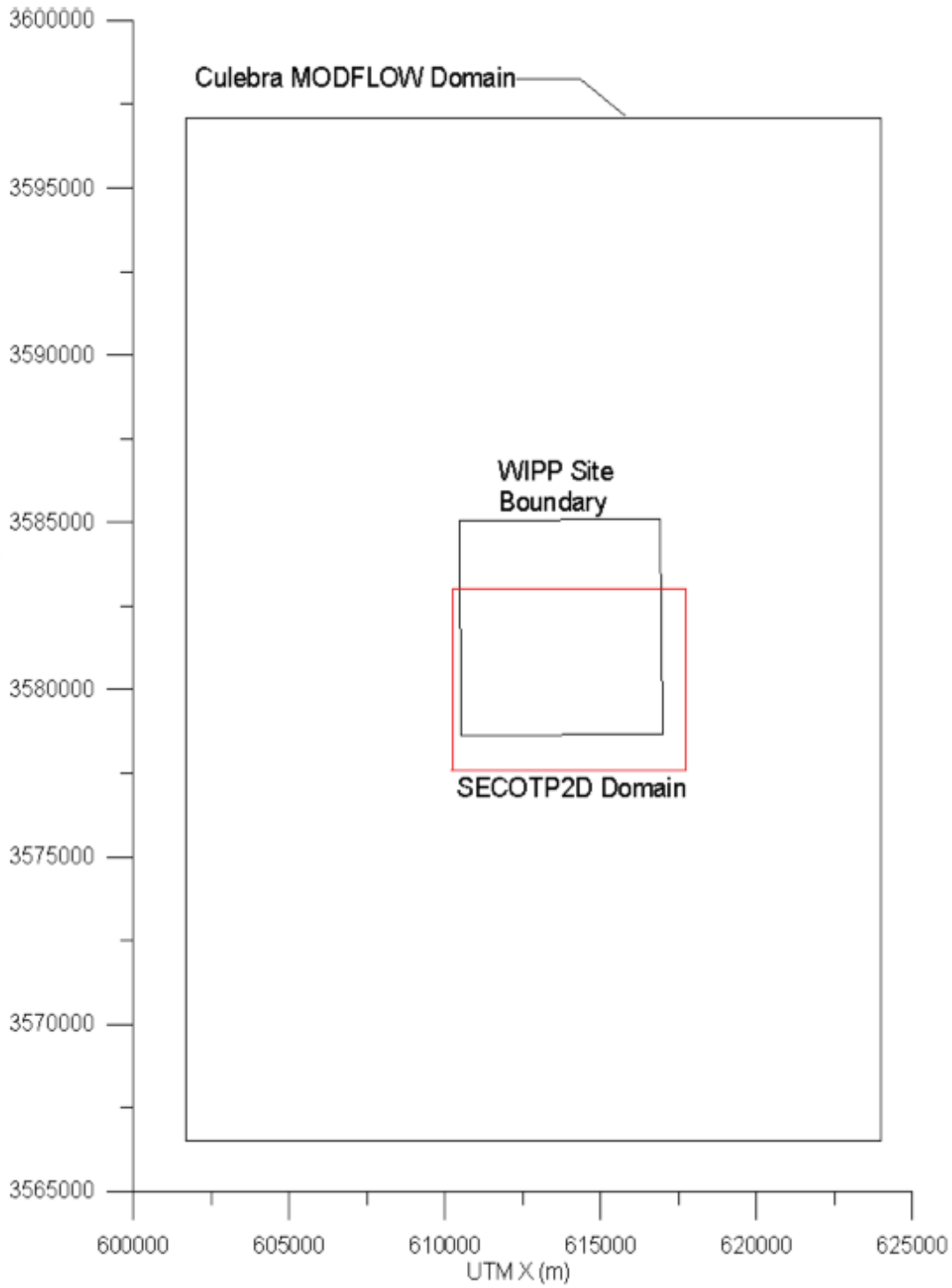

Figure 6-18. Extent of SECOTP2D Domain with Respect to the MODFLOW-2000 Culebra Domain and WIPP Site Boundary

Three different thicknesses of the Culebra were assumed in PA modeling. BRAGFLO uses a thickness of 7.7 m (25.3 ft), representative of the Culebra over the waste disposal panels. For calibrating transmissivity fields (see Appendix PA, Attachment TFIELD) and calculating flow in the Culebra with MODFLOW-2000, a thickness of 7.75 m (25.4 ft) is assumed, consistent with an average thickness over the area modeled. For transport calculations using SECOTP2D, a thickness of 4 m (13 ft) is assumed, consistent with the observed thickness of the Culebra active in transport, which is discussed in Section 6.4.6.2.1. Using different thicknesses does not introduce inconsistencies in the modeling, however, because the transmissivities used in these codes are consistent, and transmissivity governs the total flux of fluid through the Culebra. Furthermore, the fluid flux used in the SECOTP2D model is calculated by MODFLOW-2000, ensuring consistency.

The spatial variation in transmissivity observed in the Culebra is incorporated by assigning different transmissivity values to every computational cell in the model. Because there is uncertainty in the estimated value of Culebra transmissivity where measurements have

Table 6-20. Culebra Parameter Values for the BRAGFLO Model

Parameter (units) [1]	Value
Permeability (square meters)	7.73×10^{-14}
Effective porosity (percent)	15.1
Rock compressibility (1/pascals) [2]	10^{-10}
Threshold pressure, P_t (pascals) [3]	1.5×10^{4}
Residual brine saturation, S_{br} (unitless)	0.084
Residual gas saturation, S_{gr} (unitless)	0.077
Pore distribution parameter, λ (unitless)	0.644
Maximum capillary pressure (pascals)	10^{8}
Thickness (meters)	7.70
Initial Pressure (pascals)	9.14×10^{5}

[1] See Table 6-11 for fluid properties in BRAGFLO.

[2] Pore compressibility = rock compressibility/effective porosity.

[3] Threshold pressure (P_t) determined from relationship: $P_t = PCT_A \cdot k^{PCT_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

Table 6-21. MODFLOW-2000 Fluid Properties

Parameter (units)	Value
Liquid density (kilograms per cubic meter)	1,000
Liquid compressibility (1/pascals)	4.4×10^{-10}

not been made, 100 different transmissivity fields were developed. Each transmissivity field statistically represents the natural variation in transmissivity that honors measured data according to certain criteria. Monte Carlo simulations using a large number of equally-likely transmissivity fields are a statistically sound method of characterizing the uncertainty associated with

transmissivity in the Culebra. For details of the generation and use of transmissivity fields and criteria, refer to Appendix PA, Attachment TFIELD.

Regional flow directions and fluxes are calculated with the regional domain, as described earlier and shown in Figure 6-18. To increase resolution of transport processes a finer grid is used. Within MODFLOW-2000, each 100-m × 100-m cell is divided into four 50-m ×-50 m cells with exactly the same transmissivity as the 100-m × 100-m cell. Darcy velocities are calculated in the 50-m × 50-m cells and then mapped directly into the SECOTP2D grid (Figure 6-18), which also consists of 50-m × 50-m cells. Consistency between the flow calculated in the regional domain and flow in the local domain is important, and is assured by interpolation of the boundary conditions and transmissivity field properties of the regional domain onto the local domain. This process of calculating two flow fields with domains of different extent and resolution is for practical reasons only. It is a method of incorporating regional effects in finely discretized local flow fields that has relatively low computational burden, compared to other possible methods. Additional discussion of this process is provided in Section 6.4.10.2.

In summary, flow in the Culebra is calculated with the code MODFLOW-2000, using a conceptual model of a confined aquifer, regional flow effects, uniform porous medium, steady state, and transmissivity variation. In addition, the effects of subsidence caused by potash mining in the McNutt are incorporated during the flow calculation, as discussed in Section 6.4.6.2.3.

6.4.6.2.1 Transport of Dissolved Actinides in the Culebra

Actinides may be introduced into the Culebra by brine flowing up a borehole or up the shaft. Three principal processes have been demonstrated to occur naturally that affect the transport and retardation of dissolved actinides. Dissolved actinides will be carried by advection in the natural flow of Culebra groundwater. Dissolved actinides will diffuse into the matrix. Dissolved actinides will sorb to varying extents onto the different minerals lining pore walls or fractures. It is possible that dissolved actinides may participate as trace constituents in reactions between water and rock and be bound in newly formed minerals, but this phenomenon is not included in the conceptual model. These processes are complicated to characterize because of known stratigraphic variation in the Culebra and expected heterogeneity in solution chemistry along the possible flow paths from the injection point to the accessible environment.

The basic stratigraphy of the Culebra is continuous across the WIPP site (CCA Appendix FAC, Section FAC.4.1.2), and contains layers with significantly different properties (Holt and Powers 1984, 1986, 1990, and CCA Appendix FAC, Section FAC.5.2). Hydraulically, there are two distinct layers in the Culebra. Mercer and Orr (1979) report the result of a tracer and temperature survey that suggests there is no significant flow in the upper 4.3 m (14 ft) of the Culebra. Culebra hydraulic testing at well H-14 indicates generally low permeabilities but a slightly higher permeability in the upper portion (Beauheim 1987). In descriptions from the air intake shaft, Holt and Powers (1990) noted that most of the fluid produced came from the lower portion of the Culebra. Hydraulic tests at the H-19 hydropad indicate that the permeability of the Culebra's upper portion is significantly lower than the permeability of the lower portion (Beauheim 2000). Consistent with hydraulic indicators, tracer tests conducted at H-19 confirmed that the Culebra's upper portion makes no significant contribution to the transport of dissolved

species, although it may retard solute transport by diffusion into it (Meigs et al. 2000). The Culebra at the WIPP site is conceptualized as having very low permeability in the upper approximately 3 m (9.8 ft), and variable permeability in the lower portion, which can be lower than the upper portion in regions where the Culebra as a whole is relatively impermeable. Thus, the bulk of the data indicates that the majority of the flow and transport takes place in the lower portions of the Culebra. Accordingly, for transport calculations, an effective thickness of 4 m (13.1 ft) is assumed (Meigs and McCord 1996).

There is considerable variability in the structure and size of porous features in the Culebra, including fractures (of a variety of dimensions and interconnectedness), vugs, and interparticle and intercrystalline porosity (Holt 1997). The principal flow occurs in features with the high permeability, and slower flow and diffusion are primary processes in lower permeability features. Tracer test interpretations indicate that at some locations, flow occurs predominantly through fractures (advective porosity is low) and at other locations, slower transport indicates that flow occurs in other permeable features, such as vugs connected by microfractures, and possibly interparticle porosity (higher advective porosity). Tracer test interpretations also indicate that matrix diffusion is an important process in high-permeability regions of the Culebra. In other words, at least two scales of porosity are needed to represent the transport processes in the Culebra (that is, a double-porosity model). At some locations of low permeability, fractures may be absent or filled with gypsum. An alternative conceptual model for transport at these locations is uniform single porosity with a high porosity. To simplify calculations, the uniform single-porosity model was not implemented; the double-porosity model implemented results in faster transport.

In SECOTP2D, advective porosity represents the porous features in which flow occurs. Advective porosity values are low, which is representative of flow in fractures. Diffusive porosity represents those porous features in which no flow occurs and diffusion and sorption occur. Diffusive porosities are large relative to advective porosity, representing the vugs, interparticle, and intercrystalline porosity of the bulk rock.

The processes that occur in the advective porosity portion of the Culebra are advection (flow), dispersion (spreading caused by heterogeneity), diffusion within the advective porosity, and diffusion into the diffusive porosity. Important factors in this conceptual model are the velocities of fluid in the advective porosity, free-water diffusion coefficients, and dispersion coefficients. The most important factor is the fluid velocity. Free-water tracer diffusion coefficients are specified for actinides. Dispersive spreading at the scale of disposal-system modeling is dominated by the effects of heterogeneities explicitly incorporated in the transmissivity fields input to MODFLOW-2000. This eliminates the need to account for larger-scale features by specifying a modeling dispersion coefficient larger than those observed at the hydropad-test scale.

Fluid velocity in SECOTP2D is coupled to the results of the fluid flow modeling conducted with MODFLOW-2000 (see the preceding section). Fluid flow directions and volumetric fluxes in SECOTP2D are calculated in MODFLOW-2000. The flow velocities in the transport calculation are determined using the fluxes from the fluid flow calculation, the Culebra thickness specified for the transport calculation, and the advective porosity specified for the transport calculation.

Because a different transmissivity field is used and the values of several important parameters are sampled, each realization uses a different velocity field.

Retardation is conceptualized as a function of physical effects of diffusion into diffusive porosity and sorption. Diffusion is parameterized by the diffusive porosity (which is essentially a reservoir for diffusion), tortuosity, matrix block length, and free-water diffusion coefficient. Tortuosity represents the tortuous structure of the porosity within the matrix; it slows the diffusion process. The matrix block length is a conceptual construct representing the ratio of the surface area between advective and diffusive porosity to the volume of diffusive porosity features; physical retardation increases as the matrix block length decreases. Physical retardation also increases if tortuosity or the free-water diffusion coefficient of diffusive porosity are larger. See Appendix PA, Sections 4.8 and 4.9 and Attachment MASS, Section 15.2 for more details.

Chemical retardation of dissolved actinides is conceptualized to occur by sorption onto dolomite grains exposed in diffusive porosity because of the large amount of dolomite present in the Culebra. Chemical retardation increases if diffusive porosity is smaller, because there is a larger volume of rock for sorption. Although clay minerals are present and would sorb actinides in the Culebra, their effects are not included in the conceptual model or specified parameter values. Effective properties for the rock matrix, which is assumed to be homogeneous, and solution chemistry are assumed and are incorporated directly in the specified parameters for the retardation model (see Appendix PA, Attachment MASS, Section 15.2, and Attachment PAR, Parameters 49 through 57).

The PA uses a linear isotherm model to represent the retardation that occurs as dissolved actinides are sorbed onto dolomite. This model uses a single parameter K_d to express a linear relationship between sorbed concentration and liquid concentration. The K_ds used in PA were determined from experimental data and are conservatively chosen. Thus, the model predictions of sorption are less than or equal to actual sorption expected along the possible flow paths in the Culebra should a release occur (Appendix PA, Attachment MASS, Section MASS-15.2; and CCA Appendix MASS, Attachment 15-1). Other important parameters in the linear isotherm model are the diffusive porosity and the grain density of the Culebra because these determine the mass of dolomite available on which sorption can occur. Consistent with the assumption of homogeneous rock properties in the conceptual model, K_ds and grain densities are selected, applied to the entire transport domain, and held constant for an entire realization. See CCA Appendix SECOTP2D (Section 7, User Interactions, Input and Output Files) and Appendix PA, Attachment PAR (Parameters 49 through 57) for details of parameter definitions and values.

Selecting the parameter values required by the SECOTP2D model for physical retardation and chemical retardation is performed in LHS according to the CDFs described in Appendix PA, Attachment PAR. Important parameter values are summarized in Table 6-22 and Table 6-23.

Table 6-22. Matrix Distribution Coefficients (K_ds) and Molecular Diffusion Coefficients for Dissolved Actinides in the Culebra

Actinide	K_d (cubic meters per kilogram)			Molecular Diffusion Coefficients (square meters per second) [1] Constant
	Maximum	Minimum	Median	
U(IV)	10.0	0.70	2.6	1.53×10^{-10}
U(VI)	0.020	3.0×10^{-5}	7.7×10^{-4}	4.26×10^{-10}
Th(IV)	10.0	0.70	2.6	1.53×10^{-10}
Pu(III)	0.40	0.02	0.09	3.00×10^{-10}
Pu(IV)	10.0	0.70	2.6	1.53×10^{-10}
Am(III)	0.40	0.02	0.09	3.00×10^{-10}

[1] See Attachment MASS

Table 6-23. Culebra Parameters Required for SECOTP2D

Parameter (units)	Maximum	Minimum	Median or Constant
Advective porosity (percent)	1.0	0.01	0.10
Diffusive porosity (percent)	25.0	10.0	16.0
Half matrix block length (meters)	0.50	0.05	0.275
Longitudinal dispersivity, αL (meters)	–	–	0
Transverse dispersivity, αT (meters)	–	–	0
Grain density (cubic kilograms per cubic meter)	–	–	2.82
Effective thickness (meters)	–	–	4.0
Fracture tortuosity (unitless)	–	–	1.0
Diffusive tortuosity (unitless)	–	–	0.11

In summary, the conceptual model for dissolved actinide transport includes the following: transport in advective porosity, physical retardation (diffusion) into diffusive porosity, chemical retardation (sorption) in diffusive porosity, homogeneous rock properties, and a linear isotherm to describe the sorption process. Some of the more important parameters are advective porosity, diffusive porosity, tortuosity, matrix block length, molecular diffusion coefficients, K_d, and the grain density of dolomite in the Culebra.

6.4.6.2.2 Transport of Colloidal Actinides in the Culebra

Colloidal particles are subject to many of the same processes that affect dissolved actinides, but because of their size, several additional processes affect them. There are three process differences. Colloidal particles in general are preferentially carried in the center of pore throats by faster-moving fluid, which could cause slightly increased rates of transport compared to dissolved species. Colloidal particles can be filtered from flowing groundwater when they encounter small-aperture features in the pore network. Finally, colloidal particles may undergo different sorption processes than dissolved species.

The primary distinction in the transport behavior of the different colloidal particles is whether particles diffuse into the matrix from fractures. This is controlled by the difference between the size of colloidal particles and the mean pore-throat diameters in the diffusive porosity of the Culebra. Colloidal particles that are smaller than the pore throats can diffuse into the diffusive porosity. Actinide intrinsic colloids and humic materials are small enough for this to occur. The conceptual model for these particles includes the processes of advection, diffusion, and dispersion in the advective porosity; diffusion into diffusive porosity; and sorption of actinides in diffusive porosity. This model is analogous to that specified for dissolved actinides, although the parameter values are different. The conceptual model assumes that other retardation processes (for example, filtration) will not occur for actinide-intrinsic colloids and humic materials.

In contrast, colloidal particles larger than pore throats will be excluded from the matrix and will remain in advective porosity. Microbes and mineral fragments are conceptualized as larger than the mean pore-throat diameter in Culebra diffusive porosity. The conceptual model for these particles includes the processes of advection and filtration by small-aperture features that occur within advective porosity. See Appendix PA, Attachment MASS, CCA Section MASS.15.3 for additional discussion.

Experiments demonstrated that mineral fragments and microbes are attenuated so effectively by the advective porosity in the Culebra that it was unnecessary to include those colloids in PA calculations. Under the neutral to slightly basic geochemical conditions expected in the Culebra, humic substances did not influence the sorption behavior of dissolved actinides. Therefore, actinides associated with humic substances were treated as dissolved species in the PA calculations. The only actinide-intrinsic colloid found in significant concentrations was Pu(IV)-polymer. At the WIPP, the total amount of Pu(IV)-polymer introduced to the Culebra was insignificant with respect to the EPA normalized release limit, and so was not included in transport calculations. See Appendix PA, Attachment SOTERM (Section SOTERM-6.0) and Appendix PA, Attachment MASS (Section MASS-15.3.1) for details. See Appendix PA, Attachment MASS (Section MASS-15.3.3) for alternative modeling approaches considered.

Indigenous microbes, humics, and mineral fragment colloids in the Culebra may react with dissolved actinides introduced to the Culebra to create new colloidal actinides. Newly formed actinide-bearing microbial and mineral colloids, however, will be attenuated similarly to colloidal actinides introduced from the repository. Therefore, disregarding the impact of newly formed microbial and mineral fragment colloidal actinides is conservative. Experimental results indicate that humics do not interact with dissolved actinides under Culebra geochemical conditions. Consequently, the quantity of newly formed humic actinides will be insignificant.

6.4.6.2.3 Subsidence Due to Potash Mining

Subsidence effects caused by potash mining are included in this PA because of specific criteria in the EPA's 40 CFR Part 194. To incorporate the effects of subsidence caused by mining, PA uses the conceptual model provided by EPA in 40 CFR Part 194 and supporting documents.

The conceptual model for mining is based on information found in 40 CFR § 194.32 (b) and (c) and clarified in the Preamble and Background Information. These subparts of Section 194.32 (b) and (c) state:

> (b) Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that the mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such minerals resources shall be assumed to occur only once during the regulatory time frame.
>
> (c) Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are reasonably expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

Section 194.32 establishes assumptions as to what gets mined, when it gets mined, and the effects of mining on the disposal system—a conceptual model. Within the disposal system, mineral resources similar in quality and type to those currently mined outside the disposal system may be mined at an uncertain time in the future. Outside the disposal system, mineral resources reasonably expected to be mined in the near future should be assumed to be mined. These effects are included in analyses of both disturbed and undisturbed performance. Inside the disposal system, whether and when a mining event occurs after the active institutional control period is determined by a probabilistic model. Outside the disposal system, what is reasonably expected to be mined is assumed to be mined by the end of WIPP disposal operations. With respect to consequence analysis, mining affects only the hydraulic conductivity of the disposal system units.

The DOE has identified areas assumed to be mined in a manner consistent with the conceptual model and other guidance presented by the EPA in 40 CFR Part 194. The only natural resource currently mined near WIPP is potash in the McNutt, and it is the only mineral considered for future mining. Appendix PA, Attachment TFIELD, Section 9 describes the method used to determine the extent of mining in the McNutt both inside and outside the disposal system. This description also presents additional relevant discussion by the EPA on the extent of mining. The extent of mining outside the disposal system used in this PA is shown in Figure 6-19. It is based on the map of existing leases presented in Chapter 2.0 (Figure 2-44), setbacks from existing boreholes, and the presence of ore in the lease (see Appendix PA, Attachment MASS, Section MASS-15). Inside the disposal system, a region that could be mined in the future is specified based exclusively on the quality and type of ore present. This region was presented in Figure 2-45 (see Chapter 2.0).

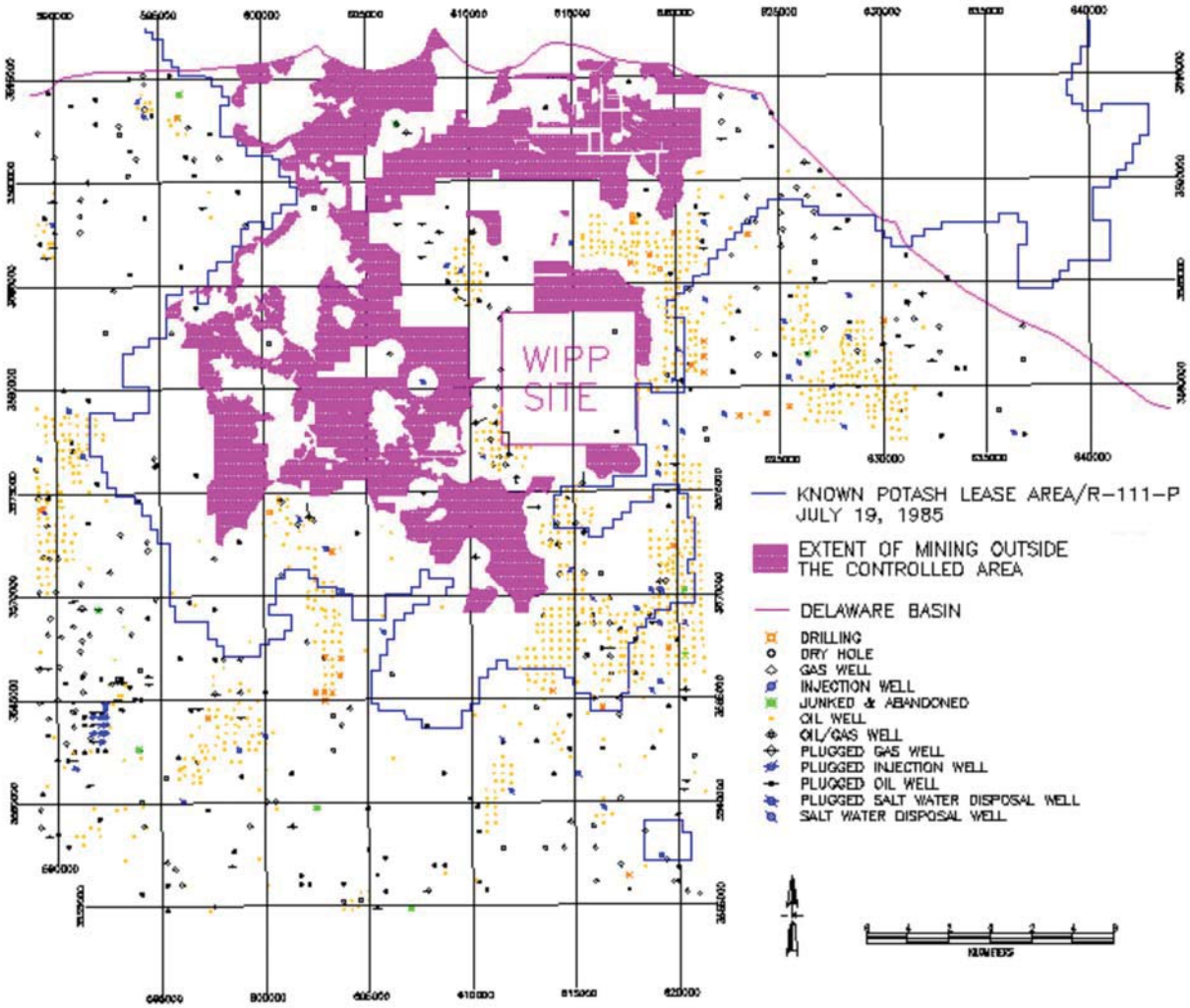

Figure 6-19. Extent of Mining in the McNutt in Undisturbed Performance within MODFLOW-2000 Regional Model Domain

The EPA clarified its conceptual model on the effects of mining on hydraulic conductivity of the disposal system units in the Preamble to 40 CFR Part 194 (EPA 1996a, 61 FR 5229). The EPA states

> Some natural resources in the vicinity of WIPP can be extracted by mining. These natural resources lie within the geologic formations found at shallower depths than the tunnels and shafts of the repository and do not lie vertically above the repository. Were mining of these resources to occur, this could alter the hydrologic properties of overlying formations—including the most transmissive layer in the disposal system, the Culebra dolomite—so as to either increase or decrease groundwater travel times to the accessible environment. For the purposes of modeling these hydrologic properties, this change can be well represented by making corresponding changes in the values for the hydraulic conductivity. The Agency has conducted a review of the data and scientific literature discussing the effects mining can induce in the hydrologic properties of a

> formation. Based on its review of available information, the Agency expects that mining can, in some instances, increase the hydraulic conductivity of overlying formations by as much as a factor of 1,000, although smaller and even negligible changes can also be expected to occur. Thus, the final rule requires DOE to consider the effects of mining in performance assessments. In order to consider the effects of mining in performance assessments, the DOE may use the location-specific values of hydraulic conductivity, established for the different spatial locations within the Culebra dolomite, and treat them as sampled parameters varying between unchanged and increased 1,000-fold relative to the value that would exist in the absence of mining.

This section adds four important clarifying concepts. First, the EPA concluded that there are no minerals vertically above the repository similar in quality and type to those currently extracted elsewhere in the Delaware Basin. Second, the EPA does not draw conclusions about whether mining will increase or decrease groundwater travel times to the accessible environment. Third, it may be assumed that the important effects of change in hydraulic conductivity occur only in the Culebra. Fourth, the spatially variant hydraulic conductivities established in the Culebra by the DOE may be multiplied, where impacted by mining, by a factor from 1 to 1,000. The DOE applied EPA's guidance regarding hydraulic conductivity to the transmissivity at Culebra locations.

In using the EPA's conceptual model for mining, the DOE makes assumptions with respect to two topics in order to formulate the mathematical model. The angle of draw is a parameter necessary to translate the area mined in the McNutt to the area affected in the Culebra. In its Background Information Document for 40 CFR Part 194, the EPA discusses the possible range in the value of angle of draw (EPA 1996b, 9-36). The DOE examined the Background Information for 40 CFR Part 194 (see EPA 1996b, 9-47) and concluded that a 45° angle of draw is the value most consistent with the EPA's discussions and calculations. Second, the Agency does not specify a distribution to the multiplicative factor. As discussed in Appendix PA, Attachment PAR (Parameter 46), the DOE has assigned a uniform distribution to this variable. As discussed in the introduction to Appendix PA, Attachment PAR, a uniform distribution is appropriate when only lower and upper bounds of the range are known.

Applying the angle of draw to the mined areas presented in 6-20 and 6-21 makes the area impacted in the Culebra larger than the area actually mined in the McNutt. The area in the Culebra impacted by mining is shown in Figure 6-20 for outside the controlled area, and in Figure 6-21 for inside and outside the controlled area. These figures are plotted on the regional domain of the MODFLOW-2000 model, which calculated the effects of subsidence caused by mining on flow directions and rates in PA.

The effects of mining outside the disposal system are included in the undisturbed performance scenario, and, therefore, the effects are included in all scenarios. In other words, all calculations of transport in the Culebra include the effects of mining outside the controlled area. This is the undisturbed mining case because mining within the controlled area has not occurred.

These effects are incorporated by multiplying location-specific values in the transmissivity field in the area labeled "Mining Zones " in Figure 6-21 by a factor (mining multiplier) between 1 and 1,000 that is randomly sampled in LHS. The same factor is applied to all affected nodal blocks. In every vector of the LHS, the steady-state flow fields used in the 10,000-year transport simulation incorporate this change to the transmissivity field. These simulations, followed by a

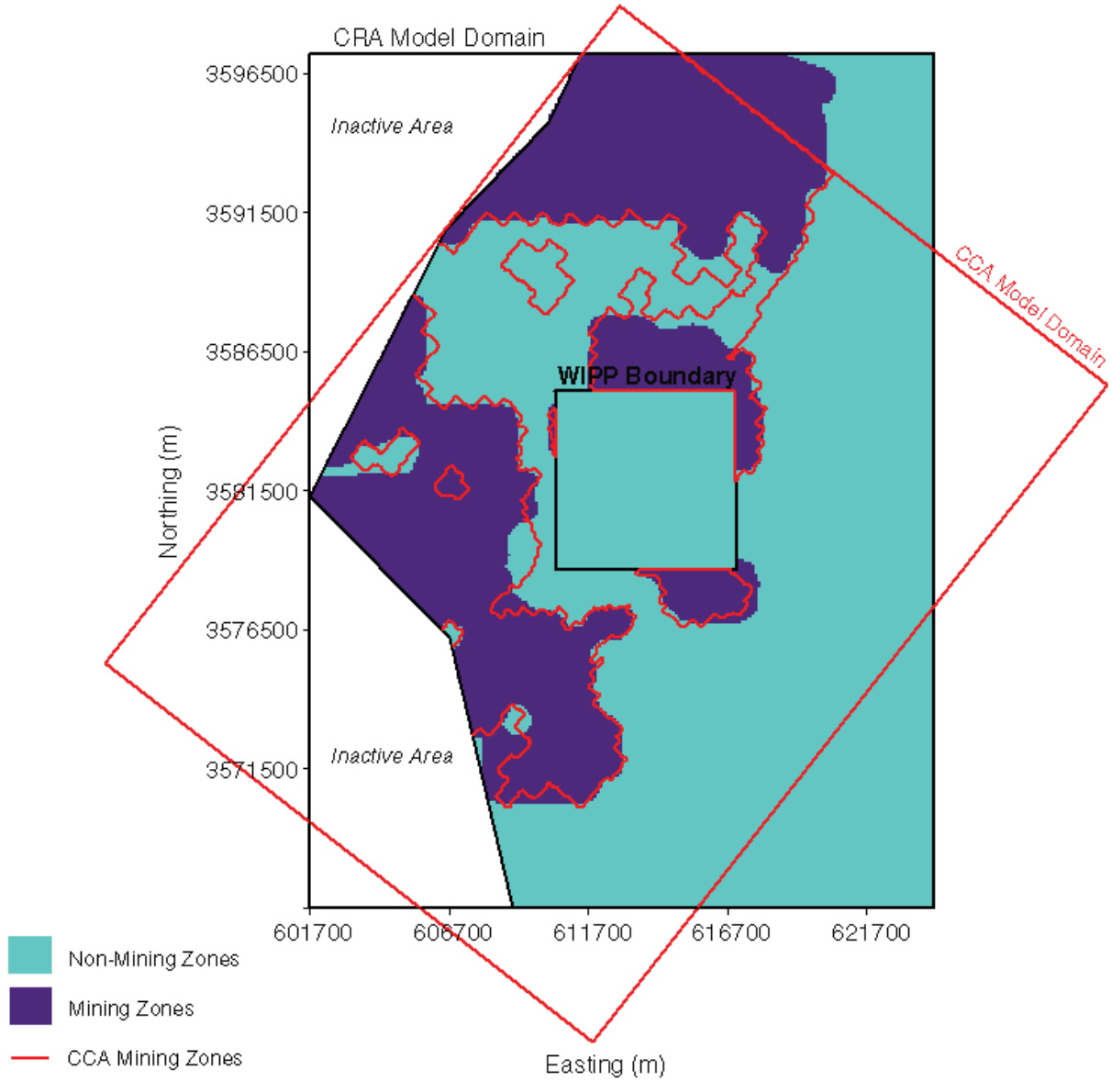

Figure 6-20. Extent of Impacted Area in the Culebra from Mining in the McNutt Potash Zone of the Salado Outside the Controlled Area for Undisturbed Performance

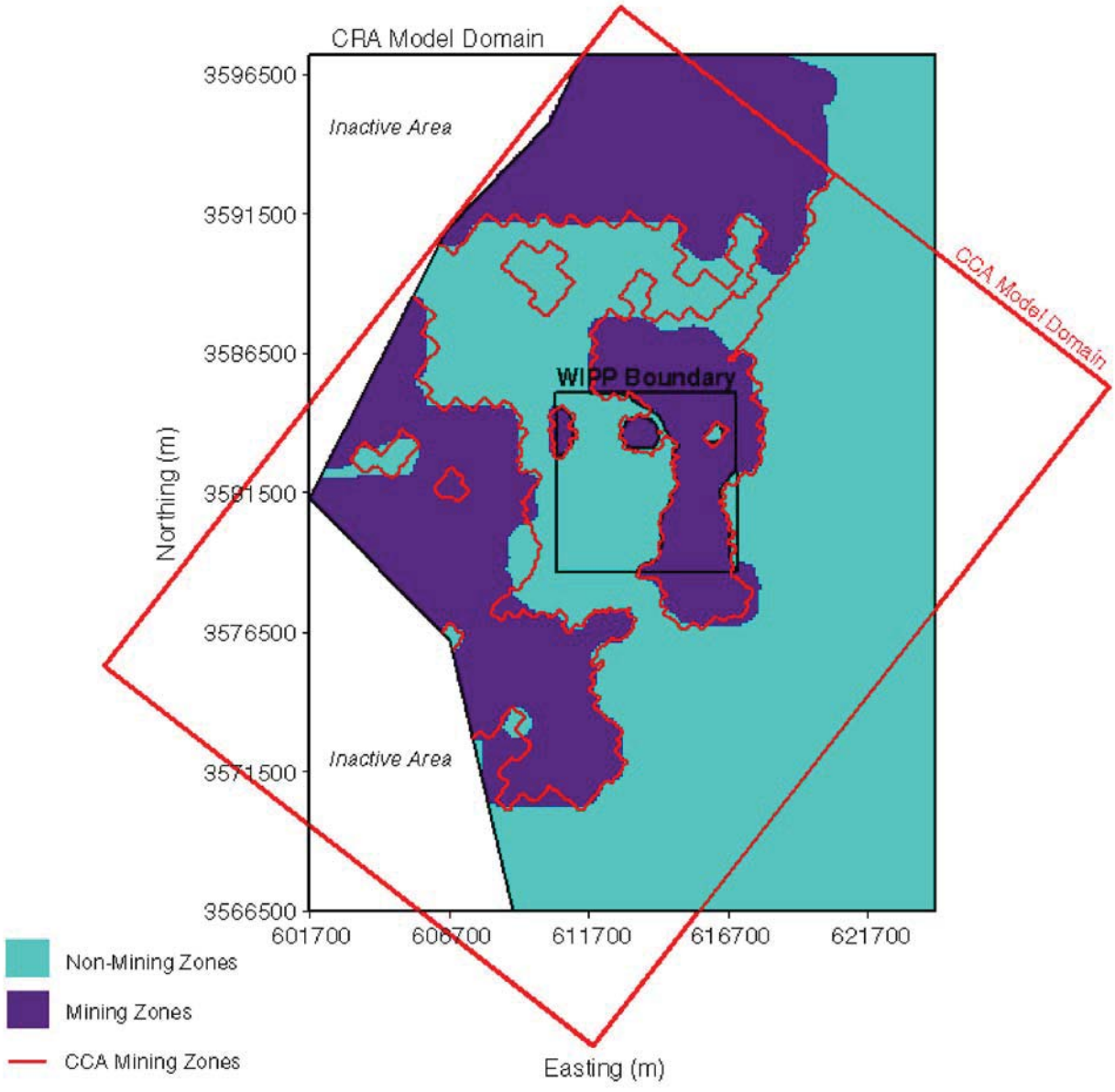

Figure 6-21. Extent of Impacted Area in the Culebra for Disturbed Performance if Mining in the McNutt Potash Zone of the Salado Occurs in the Future Within and Outside of the Controlled Area

transport simulation (as discussed in preceding sections), develop reference conditions for the transport of actinides in the Culebra in the undisturbed mining case.

If mining occurs within the controlled area, an area of the Culebra inside and outside the disposal system is affected. This is the disturbed mining case. To evaluate the impact of disturbed mining, a second simulation of Culebra flow directions and rates is executed. In this second simulation, the affected location-specific values in the transmissivity field within the controlled area are multiplied by the same mining multiplier used for the undisturbed mining case outside the controlled area. These simulations, followed by a transport simulation (as discussed in preceding sections), develop reference conditions (see Section 6.4.11) for transporting actinides following mining inside the controlled area.

The implementation of the EPA's probability model for future mining is presented in Section 6.4.12.8. A discussion of how the reference simulations for the undisturbed and disturbed mining cases are used in CCDF construction is presented in Section 6.4.13.

6.4.6.3 The Tamarisk

The Tamarisk (Row 27 in Figures 6-14 and 6-15) rests between the more transmissive Culebra and Magenta. An in-situ hydraulic test determined that the transmissivity of the Tamarisk is lower than the transmissivity of the Los Medaños (see Section 2.2.1.4.1.3). This low transmissivity is consistent with expectations because of its anhydrite, gypsum, and clay composition (see Section 2.1.3.5.3). In PA, this member is treated as impermeable. This may cause increased flow through the adjacent Culebra and Magenta. This treatment is considered conservative in that allowing flow from the intrusion borehole or shaft into the Tamarisk would, if anything, decrease flow into the Culebra, which would reduce the consequence of radionuclide release to the Rustler. In PA, the thickness of the Tamarisk is assumed to be 24.8 m (81.4 ft) and its permeability is effectively zero (Appendix PA, Attachment PAR).

6.4.6.4 The Magenta

The Magenta is described in Sections 2.1.3.5.4 and 2.2.1.4.1.4 and is shown as Row 28 in Figures 6-14 and 6-15. Transport of actinides through the Magenta to the accessible environment is not modeled. The assumption that no releases will occur from the Magenta is based on the hydraulic test results from wells on the WIPP site (Beauheim 1987, 110-118), which indicate that the Magenta is a porous medium with no hydraulically significant fractures (in contrast to the Culebra), and that its conductivity is lower than that of the Culebra. Early numerical simulations of flow and transport in the Magenta suggested much slower transport than in the Culebra (Barr et al. 1983, 26-27). Therefore, no radionuclides entering the Magenta will reach the accessible environment boundary within the 10,000-year time frame. Accordingly, the BRAGFLO model geometry reasonably approximates the effects of Magenta flow. The Magenta permeability is chosen conservatively as the lowest of measured values near the center of the WIPP site, in order to yield a lower reasonable amount of brine (and radionuclide) storage within the Magenta while continuing to yield an upper bounding flow into the Culebra. The volumes of brine and radionuclides to be stored in the Magenta are tracked and documented, however. Magenta parameter values are summarized in Table 6-24 and are described in more detail in Appendix PA, Attachment PAR.

6.4.6.5 The Forty-niner

In evaluations of radionuclide transport, flow in the Forty-niner is considered insignificant because of its low transmissivity (see Section 2.2.1.4.1.5). As with the Tamarisk and Los Medaños, the Forty-niner is assigned a permeability of effectively zero in PA (Appendix PA, Attachment PAR). This treatment is considered conservative because allowing flow from the intrusion borehole or shaft into the Forty-niner would, if anything, decrease flow into the Culebra, which would reduce the consequence of radionuclide release to the Rustler. Its modeled thickness is 17.3 m (56.8 ft). It is shown as Row 29 in Figures 6-14 and 6-15.

6.4.6.6 Dewey Lake

Release of actinides to the accessible environment from transport in the Dewey Lake is assumed not to occur even if contaminated brine reaches the unit, because the sorptive capacity of this unit appears large. This assumption is based on an analysis (Wallace et al. 1995) that demonstrated that the potential sorption capacity of the Dewey Lake is sufficient to prevent releases for 10,000 years. This analysis consisted of (1) a literature review on the sorptive capacity of redbeds and (2) an estimate of the minimum sorption required to prevent actinide releases that enter the Dewey Lake to the accessible environment in 10,000 years.

Comparison of the sorption values for the Dewey Lake analogues established by literature review with the minimum sorption required to prevent release indicates that the likely sorptive capacity of the Dewey Lake is orders of magnitude greater than required to prevent release. Therefore, the DOE assumes that chemical retardation occurring in the Dewey Lake will prevent release within 10,000 years of any actinides that might enter it. Geological and hydrological information on the Dewey Lake is presented in Sections 2.1.3.6 and 2.2.1.4.2, respectively. Dewey Lake parameter values are summarized in Table 6-25 (see also Appendix PA, Attachment PAR). The Dewey Lake is shown in Figures 6-14 and 6-15.

Table 6-24. Model Parameter Values for the Magenta

Parameter (units)	Minimum	Maximum	Mean or Constant
Permeability (square meters)			6.31×10^{-16}
Effective porosity (percent)	2.7	25.2	13.8
Rock compressibility (1/pascals) [1]	1.16×10^{-10}	4.55×10^{-10}	2.64×10^{-10}
Threshold pressure, P_t (pascals) [2]			5.06×10^{4}
Residual brine saturation, S_{br} (unitless)			0.084
Residual gas saturation, S_{gr} (unitless)			0.077
Pore distribution parameter, λ (unitless)			0.644
Maximum capillary pressure			10^{8}
Thickness (meters)			8.5
Initial pressure (pascals)			9.47×10^{5}

[1] Pore compressibility = rock compressibility/effective porosity.

[2] Threshold Pressure (P_t) determined from the relationship: $PCT_A \cdot k^{PCT_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

Table 6-25. Dewey Lake Parameters for the BRAGFLO Model

Parameter (units)	Minimum	Maximum	Mean or Constant
Permeability (square meters)			5.01×10^{-17}
Effective porosity (percent)	3.5	24.8	14.3
Rock compressibility (1/pascals) [1]			10^{-8}
Threshold pressure, P_t (pascals) [2]			0
Residual brine saturation, S_{br} (unitless)			0.084
Residual gas saturation, S_{gr} (unitless)			0.077
Pore distribution parameter, λ (unitless)			0.644
Maximum capillary pressure (pascals)			10^8
Thickness (meters)			149.3
Initial pressure (below water table at 980 m, 43.3 m below top of formation) (pascals)			hydrostatic
Initial pressure, 20% liquid saturation above water table (atmospheres)			1

[1] Pore compressibility = rock compressibility/effective porosity.

[3] Threshold pressure (P_t) determined from the relationship: $PCT_A \cdot k^{PCT_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

6.4.6.7 Supra-Dewey Lake Units

The units overlying the Dewey Lake are discussed in Sections 2.1.3.7 through 2.1.3.10 and are shown as Rows 32 and 33 in Figures 6-14 and 6-15. Because these units are thin and predominantly unsaturated at the WIPP site, brine that might enter from the borehole (assuming brine can reach this elevation) is assumed to flow downward to the Dewey Lake, where any actinides will be sorbed. These units are included in BRAGFLO, however, and the possibility of actinide transport into them from a borehole is considered in the PA. Actinide transport within the Supra-Dewey Lake units is not modeled, and it is assumed that there can be no actinide release to the accessible environment through these units. For PA, the units overlying the Dewey Lake are represented as a single hydrostratigraphic unit whose parameters are shown in Table 6-26.

6.4.7 The Intrusion Borehole

In accordance with the requirements of 40 CFR § 194.33(b)(1), DOE models consequences of inadvertent and intermittent intrusion into the repository during drilling for natural resources as the most severe human intrusion scenario that could affect long-term performance of the disposal system. This section discusses the conceptual models used for drilling (particulate release during drilling, direct brine release during drilling, and long-term brine flow) and refers to appropriate discussions of numerical modeling codes.

This section does not address the likelihood that inadvertent human intrusion will occur.

Table 6-26. Supra-Dewey Lake Unit Parameters for the BRAGFLO Model

Parameter (units)	Value
Permeability (square meters)	10^{-10}
Effective porosity (percent)	17.5
Rock compressibility (1/pascals) [1]	5.71×10^{-8}
Threshold pressure, P_t (pascals) [2]	0
Residual brine saturation, S_{br} (unitless)	0.084
Residual gas saturation, S_{gr} (unitless)	0.077
Pore distribution parameter, λ (unitless)	0.644
Maximum capillary pressure (pascals)	10^8
Thickness (meters)	15.76
Initial pressure, 8.36% liquid saturation (atmospheres)	1

[1] Pore compressibility = rock compressibility/effective porosity.

[2] Threshold pressure (P_t) determined from the relationship: $PCT_A \cdot k^{PCT_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

The DOE's treatment of the probability of inadvertent human intrusion is discussed in Section 6.4.12.

Human intrusion scenarios require simulating penetration of an intrusion borehole into the waste disposal region. There are two effects associated with drilling: releases from the drilling itself and possible releases from the long-term effects on fluid flow in the disposal system after the borehole casing and plugs have degraded. Both types of releases are estimated for two different types of intrusions: those that intersect pressurized brine in the Castile (E1 events; see Section 6.3.2.2.2), and those that do not (E2 events: see Section 6.3.2.2.1).

6.4.7.1 Releases During Drilling

Consistent with the criterion of 40 CFR § 194.33(c)(1), releases that may occur during and immediately following the drilling event are modeled assuming that future drilling practices will be the same as at present (see CCA Appendix DEL, Sections DEL.5, DEL.6 and Appendix DATA, Section 2.0 and DATA, Attachment A, for a complete description of historical and present drilling practices). Figure 6-22 shows a schematic representation of a standard rotary drilling operation inadvertently penetrating the repository. A drill bit is attached to the bottom of a string of steel pipe, the lowest segments of which are reinforced collars. The drill bit, collars, and pipe are collectively referred to as the drill string. As the drill string rotates, liquid, referred to as drilling mud, is pumped down the interior of the pipe and out through the bit. The drilling fluid cools and lubricates the bit and then returns to the surface outside the pipe in the annulus between the pipe and the borehole wall.

During its return flow, the mud carries the cuttings to the surface where they settle out in a mud pit. The mud is typically a water-based brine that is weighted with additives to maintain a hydrostatic pressure in the borehole equal to or greater than the normally anticipated fluid pressures in the formations being drilled. Salt-saturated brines are generally used in evaporites

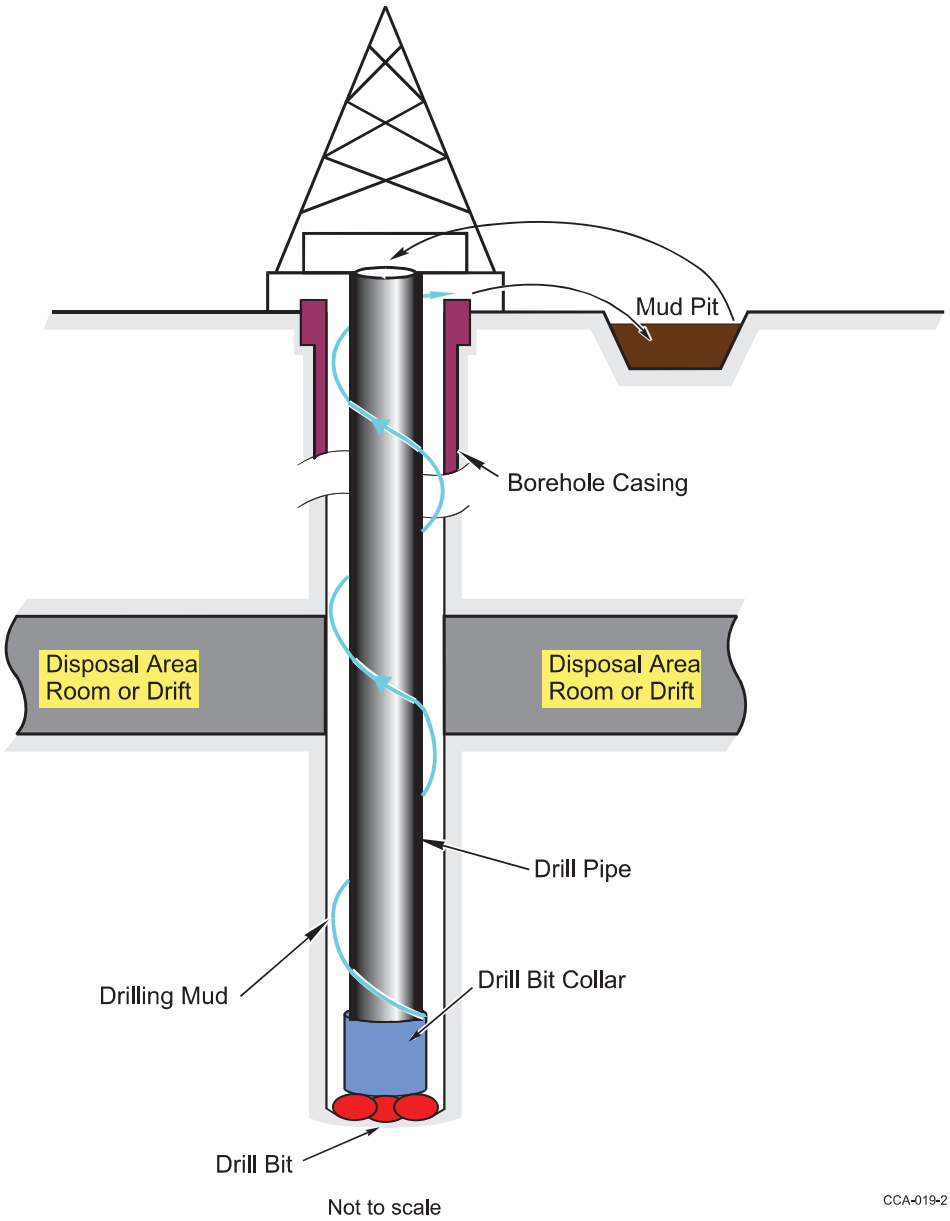

Figure 6-22. Schematic Representation of a Rotary Drilling Operation Penetrating the Repository

to prevent dissolution of the formation. Steel casing is installed in boreholes before entering the salt section to protect the near-surface units from contamination with fluids from deeper units and, after drilling through the salt section, to prevent hole closure on the drill string and subsequent in-hole hardware.

If a rotary drill bit penetrates the waste, radionuclides may be brought to the surface by four means. First, some quantity of cuttings that contain material intersected by the drill bit will be

brought to the surface. Second, cavings, which contain material eroded from the borehole wall by the circulating drill fluid, may also be brought to the surface by the circulating drilling mud. Third, releases of radionuclides may occur if the repository contains fluids at pressures higher than the pressure exerted by the drilling fluid. Spalling of waste material into the borehole may occur if high-pressure gas flows into the borehole. Brine, as well as gas, may enter the borehole from the repository if the driller is unable to control the pressure within the well or chooses not to control the pressure. The brine may flow to the surface, and if it has been in contact with waste, it may contain dissolved or suspended radionuclides.

Releases of particulate waste material (that is, cuttings, cavings, and spallings) are modeled using the CUTTINGS_S and DRSPALL codes, as described in Section 6.4.11 and Appendix PA, Sections PA-4.5 and PA-4.6 Attachment MASS (Section 16.1) discusses the conceptual basis for the model. As discussed in Section 6.4.12.4, cuttings and cavings are calculated separately for CH-TRU and RH-TRU waste, with distinct waste streams considered. Spallings are calculated as homogeneous waste obtained by averaging over all CH-TRU waste. For all releases during drilling, appropriate corrections are made for radioactive decay. Releases of dissolved or suspended radionuclides contained in brine are modeled using the BRAGFLO and PANEL codes, as described in the next section. Casing is assumed to be intact through the Rustler and overlying units during drilling, and there is assumed to be no communication between the borehole and those units. For all direct releases, actinides that enter the borehole are conservatively assumed to reach the surface.

6.4.7.1.1 Direct Brine Release During Drilling

Direct brine release refers to the possibility that brine containing actinides may flow from the waste panels up a borehole to the surface during drilling (Appendix PA, Section PA-4.7 and Attachment MASS, Section 16.2). It is conceptualized that direct brine release to the surface will not occur every time a borehole penetrates the waste panels but rather that it can occur only when two conditions are met. The first condition is the presence of mobile brine in the waste panels. Because of brine consumption by corrosion and low initial saturation, it is possible for liquid saturations below the residual saturation to exist in the repository, in which case direct brine release cannot occur. The second condition is that the pressure in the waste panels must be greater than the pressure at the base of the drilling mud column. Drillers in the Delaware Basin use a salt-saturated mud with a specific gravity of about 1.23 while drilling through the Salado. This corresponds to a pressure of approximately 8 megapascals at the repository horizon (see Appendix PA, Attachment MASS, Section 16.2 and CCA Appendix MASS, Attachment 16-2). If fluid in the waste panels is below this pressure, no direct brine release during drilling can occur because liquid flow in the repository is away from the borehole.

In the conceptual model, resolution of the details of flow near the borehole is considered important, as the changing physical conditions over the short duration of this flow can significantly impact estimates of the total volume released. It is not assumed that a direct brine release would be noticed by the driller (EPA 1996a, 61 FR 5230). Also important to the conceptual model is how long direct brine release occurs. There are several ways in which the direct brine release could be stopped. A driller might detect higher flow rate to the mud pit and take action to mitigate consequences. Alternatively, direct brine release will stop when the driller cases the hole after reaching the base of the salt section. As discussed in Appendix PA,

Section PA-4.7 and CCA Appendix DEL (Section 7.5), the DOE assumes that for low volumes of fluid flow, the borehole will be controlled and cased within 72 hours after penetrating the repository. In all cases, all fluid flow to the surface during drilling is assumed to cease within 11 days after penetrating the repository.

In the conceptual model for direct brine release, several other assumptions are related to other conceptual models. The processes of direct solids release from cuttings, cavings, spall, and direct brine release are treated separately, although the direct brine release model does account for the effects of solids removal (spall) on fluid flow near the well bore. Direct brine release will affect the pressure and saturation in the repository. However, it is assumed that these effects are negligible over the long term because of their transient and local nature; thus, they are not accounted for in long-term (10,000-year) BRAGFLO disposal system calculations. This assumption simplifies modeling because it allows detailed consideration of direct brine release over a short time period, without having to couple the results of these calculations back into the disposal system simulations.

The area over which fluid flow can occur during direct brine release is assumed to be the rooms and drifts of waste panels, the DRZ, room pillars, and panel closures. Because local-scale, short-duration flow is important, the geometry of the waste panels is considered important and is represented in the model. It is assumed that the flow interactions with the Salado other than the DRZ are unimportant during direct brine release. For this model, pillars are arbitrarily assumed to have the properties of the DRZ rather than intact halite, although in reality their properties are probably like a DRZ at their edge and intact halite in their core. Since the DRZ permeability is greater than the permeability of intact halite, this assumption is conservative. A two-dimensional geometry is used parallel to the repository horizon, with a 1 degree dip from north to south. The geometry of the grid used is shown in Figure 6-23.

The BRAGFLO code is used to calculate direct brine release; the mathematical and computational model is called the BRAGFLO direct brine release model (Appendix PA, Section PA-4.7). The initial and boundary conditions for this model are derived from the corresponding BRAGFLO disposal system simulation through several codes, including CUTTINGS_S. Some of the parameters derived from the BRAGFLO disposal system model are permeabilities, porosities, two-phase flow properties, and the height of the waste region. Initial saturations and pressures in the BRAGFLO direct brine release model are mapped from the BRAGFLO disposal system model. Other parameters used in the BRAGFLO direct brine release models are consistent with those used in the BRAGFLO disposal system model (Appendix PA, Section PA-4.7).

It is possible that a direct brine release could occur from a panel connected by a previously-drilled, abandoned borehole to a brine reservoir in the Castile. If this happened, flow directly between the two boreholes, analogous to the E1E2 scenario for long-term performance, might affect the estimate of the total brine released. The direct brine release for this possibility is calculated by BRAGFLO (direct brine release) by placing a

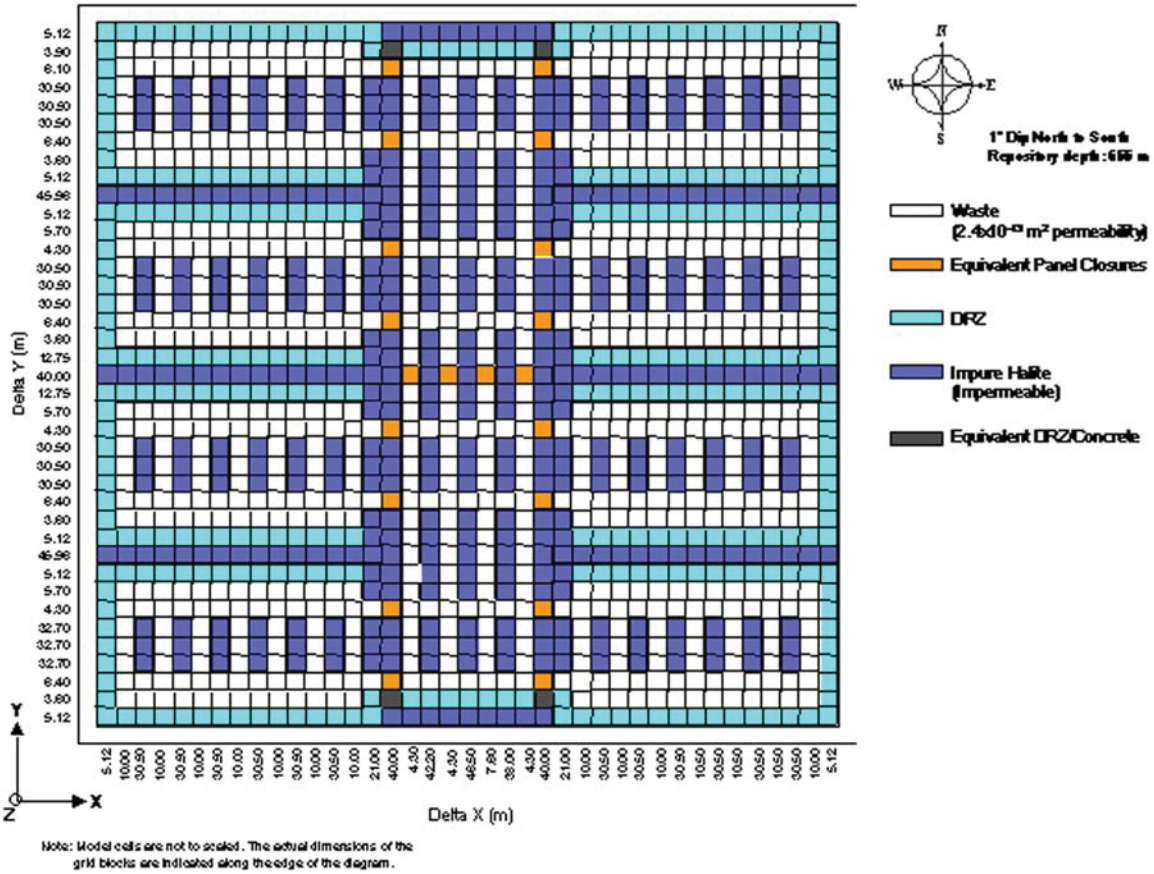

Figure 6-23. Repository-Scale Horizontal BRAGFLO Mesh Used for Direct Brine Release Calculations

constant-pressure, flowing injection well as a boundary condition in the model. The locations of these boreholes are shown in Figure 6-23. It is assumed that a direct brine release from a panel with a previously-drilled, abandoned borehole of the E2 type is unaffected by the presence of the other borehole. Thus, reference direct brine release conditions are calculated for previously unintruded and E2-intruded panels, and for previously-intruded E1 panels. Details about the properties assigned to the flowing-well boundary condition are discussed in Appendix PA, Section PA-4.7. Details about how the consequences of direct brine releases from other possible combinations of boreholes are accounted for in the CCDF are discussed in Section 6.4.13.

A borehole could penetrate the repository anywhere. For simplification, the BRAGFLO direct brine release model assumes that calculating direct brine release from several defined locations provides meaningful reference results for the possible variation in release because of location. The locations of boreholes from which representative results are calculated are indicated in Figure 6-23. In construction of a CCDF (see Section 6.4.13), the direct brine release associated with a borehole whose position is randomly selected is correlated with the reference release most consistent with the geometry near the location of the random borehole.

Accurate representation of the flow into the borehole is important in the BRAGFLO direct brine release model. Accordingly, a number of mathematical methods that are not used to calculate

long-term releases are applied to the conditions in the borehole for calculating direct brine releases. The methods used appear in Appendix PA, Section PA-4.7.

6.4.7.2 Long-Term Releases Following Drilling

Long-term releases to the ground surface or into groundwater in the Rustler or overlying units may occur after the hole has been plugged and abandoned (Appendix PA, Attachment MASS, Section 16.3). As required by regulation, the plugging and abandonment of future boreholes are assumed to be "consistent with practices in the Delaware Basin at the time a compliance application is prepared" [40 CFR § 194.33(c)(1)]. Examining current practices in the Delaware Basin indicates that all boreholes abandoned recently are plugged to meet state and federal regulatory requirements protecting groundwater and natural resources (see Appendix DATA, Section DATA-2.0 and Attachment A; CCA Appendix DEL, Sections DEL.5.5 and DEL.6]; Appendix PA, Attachment MASS, Section MASS-16.3). These plugs will effectively prevent flow in abandoned boreholes for some period of time after emplacement. However, some plugs may fail and radionuclides may be transported in brine flowing up the borehole.

Borehole plug configurations used today in the Delaware Basin vary based on the local stratigraphy encountered in the hole, its total depth, and the types of fluids present. All holes are plugged with some combination of solid concrete plugs isolating different fluid-bearing horizons from each other and from the ground surface. As discussed in detail in Appendix PA, (Attachment MASS (Section 16.3), SNL (2003),) and CCA Appendix DEL (DEL Attachment 7), six different plug configurations are identified that are potentially relevant to future borehole abandonment practice at the WIPP. As discussed in Appendix PA, Attachment MASS (Section 16.3.3) and SNL (2003), these six plug configurations can be approximated for PA by three conceptual plugging patterns. The three plugging configurations addressed in the PA are described in the following section. Probabilities of occurrence for each of these three plugging configurations are discussed in Section 6.4.12.7. Parameters used to describe the borehole and its plugs are summarized in Table 6-27.

6.4.7.2.1 Continuous Concrete Plug through the Salado and Castile

In this configuration, a continuous concrete plug is assumed to exist throughout the Salado and Castile (Appendix PA, Attachment MASS, Section 16.3 and SNL (2003). Such a plug could be installed in keeping with current regulatory requirements of the New Mexico Oil Conservation Division Order R-111-P (State of New Mexico 1988, 10), which is applicable within the potash leasing area that includes the WIPP site. The continuous plug protects potash mining operations from possible hydrocarbon contamination. A continuous concrete plug is also used to approximate flow in boreholes with numerous concrete plugs throughout the salt section.

Examples of such plugging configurations currently used in the Delaware Basin are described in Appendix PA, Attachment MASS, Section 16.3.

Because concrete within a continuous plug will be physically confined and will have very little brine flow through it, degradation will be minimal and limited to the upper and lower ends of the plug (see Appendix PA, Attachment MASS, Section 16.3.3, Appendix C). For the CCA PA the

Table 6-27. Intrusion Borehole Properties for the BRAGFLO and CUTTINGS_S Models

Parameter (units)	Maximum	Minimum	Median or Constant [1]
Permeability of open hole (0 to 200 years) (square meters)	–	–	10^{-9}
Permeability of concrete plugs (0 to 200 years in Rustler and at surface) (square meters) [2]	1×10^{-17}	1×10^{-19}	10^{-18}
Permeability of borehole fill material (>200 years) (square meters) [2]	1×10^{-11}	1×10^{-14}	3.16×10^{-13}
Permeability of lower borehole fill material (>1,200 years) (square meters) [2]	1×10^{-12}	5×10^{-17}	2.24×10^{-14}
Effective porosity (percent)	–	–	0.32
Pore compressibility (1/pascals)	–	–	0
Diameter (meters)	–	–	0.311
Threshold pressure, P_t (pascals)	–	–	0
Pore distribution parameter, λ (unitless)	–	–	0.94
Residual brine saturation, S_{br} (unitless)	–	–	0
Residual gas saturation, S_{gr} (unitless)	–	–	0

[1] Parameters with no maximum and minimum values are treated as constants in the PA.
[2] Borehole permeabilities are for the two-plug case. Continuous three-plug case is treated as undisturbed performance.

permeability of the continuous concrete plug was 5×10^{-17} m^2 for all the plugging configurations. For this application, the DOE adopted EPA's 1997 PAVT range of 10^{-17} to 10^{-19} m^2. Because of the small cross-sectional area and low permeability of the potential pathway, long-term releases through a continuous concrete plug are not calculated explicitly for the PA, and are assumed to be zero.

6.4.7.2.2 The Two-Plug Configuration

In the two-plug configuration, two concrete plugs are assumed to have a significant effect on long-term flow in the borehole (Appendix PA, Attachment MASS, Section16.3 and CCA Appendix MASS Attachment 16-3, Figure 2). The lower plug of interest is assumed to be located somewhere between the hypothetical Castile brine reservoir and underlying formations. A second plug is located within the lower portion of the Rustler, immediately above the Salado. Additional plugs that have little effect on long-term flow are also assumed to be present deeper in the hole and at the land surface.

In E1-type intrusions with two plugs, the brine reservoir and the repository are assumed to be in direct communication through an open cased hole immediately following drilling. The plugs are located in the borehole Column 26 of the BRAGFLO mesh in Figure 6-15 in Rows 32 and 33 (the surface plug) and Row 25 (the Los Medaños). The plugs located below the brine reservoir are not modeled explicitly. Plugs are assigned initial sampled permeabilities of 10^{-17} to 10^{-19} square meters pursuant to EPA's 1997 PAVT parameters. The open segments of borehole between the plugs are assigned an initial permeability of 10^{-9} m^2. Steel casing above the Salado is assumed to begin to degrade within decades after abandonment and is assumed to have failed

completely after 200 years. The concrete plugs above the Salado are also assumed to fail after 200 years, as a result of chemical degradation where they are in contact with brine. The plug below the Castile brine reservoir is in a less aggressive chemical environment, and its properties remain constant in PA.

After the upper plugs and casing have failed, the borehole is assumed to be filled by a silty, sand-like material containing degraded concrete, corrosion products, and material that sloughs into the hole from the walls. Thus, 200 years after the time of intrusion, the entire borehole region in the BRAGFLO model, including the sections previously modeled as concrete plugs, is assigned a permeability corresponding to silty sand. This permeability is sampled from a log-uniform distribution from 10^{-11} square meters to 10^{-14} square meters.

One thousand years after the plug at the base of the Rustler has failed, permeability of the borehole region below the waste-disposal panel in the BRAGFLO model used for E1-type intrusions is decreased from its sampled value by one order of magnitude. For the remainder of the 10,000-year period, the borehole is modeled with its sampled permeability value above the repository and the adjusted value below. Conceptually, the decrease in permeability below the panel corresponds to compaction of the silty, sand-like material by partial creep closure of the borehole's lower portion. As discussed in Appendix PA, Attachment MASS, Section 16, creep closure of boreholes will not be significant above the repository horizon but will be effective at greater depths because of the greater lithostatic stress. Nowhere in the borehole is creep closure assumed to close the hole completely in the regulatory time frame, but closure will be sufficient at depths below the repository to reduce the permeability of the material filling the hole.

6.4.7.2.3 The Three-Plug Configuration

In the three-plug configuration, three concrete plugs are assumed to affect long-term flow in the borehole (Appendix PA, Attachment MASS, Section 16.3). Two of the plugs are identical to those modeled in the two-plug configuration. The third plug is located within the Castile above the brine reservoir and below the waste-disposal panel. This plug is assumed to behave the same as the lower plug in the two-plug configuration: that is, its properties remain unchanged in PA. Otherwise, all portions of the borehole in the three-plug configuration are assumed to have the same material properties as the corresponding regions in the two-plug configuration, with adjustments to borehole-fill permeability occurring 1,000 years after failure of the overlying plug (Appendix PA, Attachment MASS, Section).

Because the three-plug configuration isolates the repository from the brine reservoir for the time period during which the middle plug remains effective, and because the portion of the borehole above the middle plug will already be filled with silty, sand-like material before the middle plug fails, the DOE chose not to model this configuration explicitly in the BRAGFLO calculations. Boreholes in which the three-plug configuration is emplaced are assumed to result in long-term releases comparable to those calculated for E2 intrusions, regardless of whether they penetrate a Castile brine reservoir. Consequences of E1-type intrusions with the three-plug configuration are assumed for the purposes of CCDF construction to be identical to those of E2 intrusions occurring at the same time.

6.4.8 Castile Brine Reservoir

As discussed by Section 2.2.1.2.2, high-pressure Castile brine was encountered in several WIPP area boreholes, including the WIPP-12 borehole within the controlled area and the ERDA-6 borehole northeast of the site. Consequently, the conceptual model for the Castile includes the possibility that brine reservoirs underlie the repository. The E1 and E1E2 scenarios include borehole penetration of both the repository and a brine reservoir in the Castile. The properties of the borehole are discussed in Section 6.4.7.

Unless a borehole penetrates both the repository and a brine reservoir in the Castile, the Castile is conceptually unimportant to PA because of its expected low permeability. Two regions are specified in the Castile horizon in the disposal system geometry: the Castile (Rows 1 and 2 in Figure 6-14) and a reservoir (Row 1, Columns 23 to 45 in Figure 6-15). The Castile region has an extremely low permeability, which prevents it from participating in fluid flow processes.

It is unknown whether a brine reservoir exists below the repository. As a result, the conceptual model for the brine reservoirs is somewhat different from those for known major properties of the natural barrier system, such as stratigraphy. The principal difference is that a reasonable treatment of the uncertainty of the existence of a brine reservoir requires assumptions about the spatial distribution of such reservoir and the probability of intersection (see Appendix MASS, Section MASS.18.1 and CCA MASS Attachment 18-6 for the development of the probability used in the CCA). The EPA required the DOE to use a range of probabilities for a borehole hitting a brine reservoir of 0.01 to 0.60 in the 1997 PAVT (EPA 1998, VII.B.4.d). The DOE added a parameter representing this range of subjective uncertainty for the CRA-2004 PA (Appendix PA, Section PA-3.5).

In addition to the stochastic uncertainty in the location and hence in the probability of intersecting reservoirs, there is also uncertainty in the properties of reservoirs. The manner in which brine reservoirs would behave if penetrated is treated as subjective uncertainty (see Section 6.2.2), and is incorporated in the BRAGFLO calculations of disposal system performance. The conceptual model for the behavior of such brine reservoir is discussed below.

Where they exist, Castile brine reservoirs in the northern Delaware Basin are believed to be fractured systems, with high-angle fractures spaced widely enough that a borehole can penetrate through a volume of rock containing a brine reservoir without intersecting any fractures and therefore not producing brine. They occur in the upper portion of the Castile (Popielak et al. 1983, G-2). Appreciable volumes of brine have been produced from several reservoirs in the Delaware Basin, but there is little direct information on the areal extent of the reservoirs or the existence of the interconnection between them. Data from WIPP-12 and ERDA-6 indicate that fractures have a variety of apertures and permeabilities, and they deplete at different rates. Brine occurrences in the Castile behave as reservoirs—that is, they are bounded systems. The properties specified for brine reservoirs are pressure, permeability, compressibility and porosity. Brine reservoir parameter values used in this PA are shown in Table 6-28.

Brine reservoir pressure in the PA is based on measured pressures in Castile and Salado anhydrites. These values are determined by analyzing brine pressures observed in Salado and Castile anhydrites, corrected for the difference in depth between the observed location and

WIPP-12. The analysis is documented in CCA Appendix MASS (Section 18 and MASS Attachments 18-1 and 18-2) and Appendix PA (Attachment PAR, Parameter 27).

Table 6-28. Parameter Values Used for Brine Reservoirs in the BRAGFLO Calculations

Parameter (units)	Maximum	Minimum	Median or Constant [1]
Permeability (square meters)	1.58×10^{-10}	2.0×10^{-15}	1.58×10^{-12}
Effective porosity (percent)	0.9208	0.1842	0.87
Rock compressibility (1/pascals) [2]	10^{-10}	2.0×10^{-11}	4×10^{-11} (mode)
Initial pressure (pascals)	1.70×10^{7}	1.11×10^{7}	1.27×10^{7}
Threshold pressure, P_t (pascals) [3]	4.59×10^{-6}	2.28×10^{-4}	4.6×10^{-5}
Pore distribution parameter, λ	–	–	0.70
Residual brine saturation, S_{br} (unitless)	–	–	0.20
Residual gas saturation, S_{gr} (unitless)	–	–	0.20

[1] Parameters with no maximum and minimum values are treated as constants in the PA.

[2] Pore compressibility = rock compressibility/effective porosity.

[3] Threshold pressure (P_t) determined from the relationship: $PCT_A \cdot k^{PCT_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

The permeability of brine reservoirs is based on analyzing brine reservoirs tested by DOE in drillholes ERDA-6 and WIPP-12 (Popielak et al. 1983, Sections H-3.4.3 and H-3.4.4). Values used in the PA are shown in Table 6-28. The derivation of these values from the referenced study is documented in Appendix PA, Attachment PAR.

The bulk compressibility range is based on a reanalysis of WIPP-12 data that was requested by the EPA in their 1997 PAVT (EPA 1998). Beauheim (1997) provides a detailed description of this analysis and parameter range.

An effective porosity is defined for the reservoir portion of the Castile in the disposal system geometry (Row 1, Columns 23 to 45 in Figure 6-15). In the EPA's 1997 PAVT (EPA 1998), the EPA specified a range of brine volumes for the reservoir based on an EPA reanalysis of the amount of brine in the reservoir encountered by WIPP-12. The analysis concluded that PA should represent a total volume of brine in the brine reservoir that ranges between 3.40×10^{6} and 1.70×10^{7} m^3. Since the brine reservoir is represented by a region of constant volume, the effective porosity is used to provide the total brine volume in the reservoir rather than representing the actual value, and is not representative of the actual host rock's porosity. This treatment results in an effective porosity range between 0.1842 and 0.9208. The effective porosity is correlated to the values for the bulk compressibility (see Appendix PA, Section 4.2.1 for a detailed discussion of this relationship).

The CRA-2004 PA treatment of brine reservoir volume and porosity is consistent with the 1997 PAVT. In contrast, the CCA PA used a discrete distribution of brine volumes in the reservoir (see CCA Appendix MASS, Section MASS.18 and MASS Attachment 18-3).

The threshold pressure, pore distribution parameter, and residual saturations are parameters describing two-phase flow behavior and are required by BRAGFLO. Because saturations in the brine reservoir remain very near 1.0 in all preliminary and current PAs, the values of these parameters were not important to the model results. The parameter values used in the CRA-2004 PA are the same as those in the 1997 PAVT.

6.4.9 Climate Change

The present climate at the WIPP and the geologic record of past climate change in southeastern New Mexico are discussed in Section 2.5 and Appendix CLI of the CCA. Although meaningful quantitative predictions of future climate for the next 10,000 years are not feasible, effects of reasonably possible climate changes on disposal system performance must be considered. For the WIPP, uncertainty about these effects is incorporated in the PA by considering the effects of various possible future climates on groundwater flow and potential radionuclide transport in groundwater. Direct effects of climate change that do not involve groundwater flow do not affect the long-term performance of the WIPP because of its depth below the land surface. Examples of such direct effects are changes in wind patterns, thermal effects related to changes in surface temperature, and near-future impacts on surface facilities. Long-term effects of climate change on the near-surface portions of the shaft seal system (see Section 6.4.4) are not incorporated in the analysis because BRAGFLO modeling indicates that system performance is unaffected by the behavior of the shaft seal system's upper portion. Additional aspects of climate change screened out from the PA, including glaciation at the site and possible future anthropogenic changes, are discussed in Appendix PA, Attachment SCR (FEPs N62 and H47 through H49).

The effects of postulated climate change on groundwater flow were evaluated outside of the PA calculations using a regional three-dimensional groundwater basin model based on the basin hydrology introduced in Section 2.2.1.1. For the regional analysis, climate-related factors that might affect groundwater flow (such as precipitation, temperature, and evapotranspiration) are treated through a single model parameter, potential recharge, which controls the rate at which water is added to the model at the water table. As described in Appendix PA, Attachment MASS, Section MASS-17.0, changes in this parameter allow simulation of regional groundwater flow under a range of different future states in which the climate may be wetter, the water table may be higher, and groundwater velocity in all units may increase. These and other simulations discussed in CCA Appendix MASS (Section MASS.15 and MASS Attachment 15-7) show that the regional, three-dimensional effects of climate change can be reasonably approximated in PA by directly scaling specific discharge in the two-dimensional, steady-state groundwater velocity field of the Culebra. The velocity field is calculated using MODFLOW-2000, as described in Section 6.4.6.2. Radionuclide transport in the Culebra is then calculated by SECOTP2D using the scaled velocity fields.

Scaling the two-dimensional velocity field is done using the Climate Index (Table 6-29), a dimensionless factor by which the specific discharge in each grid block of the SECOTP2D domain is multiplied. As summarized in Appendix PA, Attachment PAR (Parameter 48), the Climate Index is a sampled parameter in the PA with a bimodal distribution ranging from 1.00 to 1.25 and from 1.50 to 2.25. A single value of the Climate Index is chosen in LHS for each sample element and held constant throughout the 10,000-year SECOTP2D simulation. Each

realization of disposal system performance thus represents a different approximation of future climate. Those

Table 6-29. Climate Change Properties for the SECOTP2D Model

Parameter (units)	Maximum	Minimum	Median
Climate index (dimensionless)	2.25	1.00	1.17

realizations in which the sampled value is close to its maximum of 2.25 represent the most extreme changes in groundwater flow that may result from climatic change.

Sampled values close to the minimum of 1.00 represent climatic changes that have little effect on groundwater-flow velocities. Because all sampled values of the Climate Index are greater than 1.00, climate change as implemented in the PA can only increase the rate of groundwater flow.

The distribution assigned to the Climate Index parameter is based on the results of three-dimensional basin modeling that considers future changes in the temporal pattern of potential recharge (see CCA Appendix MASS, Section MASS.17 and MASS Attachment 17-1, Section F). Potential recharge is defined as the maximum rate at which water can be added at the water table. Recharge itself is a model result and ranges from zero to the potential recharge. For those areas where the water table is at the ground surface and modeling indicates that water is discharging to the land surface through a seepage face, the potential recharge does not enter the model and has no effect on groundwater flow. In areas where the water table is below the land surface, potential recharge becomes actual recharge and tends to cause the water table to rise. If potential recharge is zero, the water table in an idealized basin will tend to fall until it is a horizontal plane with an elevation equal to the lowest topographic point in the basin. Sufficiently large values of potential recharge will cause the water table to rise to the land surface everywhere. Smaller, nonzero values result in solutions with water tables at the land surface at topographic lows (discharge areas) and at some distance below the land surface at topographic highs (recharge areas). Changes in potential recharge cause the elevation of the water table to rise or fall. In the three-dimensional modeling of the WIPP region, potential recharge was assumed to be spatially invariant across the regional model domain and assumed to change through time in response to climate changes.

Both steady-state and transient three-dimensional regional analyses were executed with values of potential recharge varied so that the elevation of the water table ranged from approximately its present position to at or near the land surface. The latter condition provides an upper bound for regional groundwater-flow velocities during future wetter climates. For all simulations examining the effects of climate change, recharge is assumed to be greater at some time in the future than it is at present. Present recharge is assumed to be the same as its minimum value during the Holocene. The dominant effects on climate change during the next 10,000 years are assumed to be natural rather than anthropogenic. This assumption is consistent with regulatory guidance provided by the EPA indicating that considering the effects of climate change should be limited to natural processes (EPA 1996a, 61 FR 5227).

Because of uncertainty about recharge rates during future wet periods and the timing of these periods, transient analyses use two fundamentally different patterns for the change in potential recharge. The first pattern used in the analysis corresponds to a continuation of the inferred climate patterns of the Holocene (see Section 2.5.1 and CCA Appendix CLI, Section 3), with wetter peaks occurring 500, 2,000, 4,000, 6,000, 8,000, and 10,000 years in the future. Potential recharge is assumed to increase and decrease linearly during the wet periods 500 years before and after the peaks, and the wet periods are each separated by 1,000 years of a drier climate, like that of the present. Several different values were examined for the maximum potential recharge imposed at the wet peaks; the largest value was chosen to provide a steady-state solution with the water at, or close to, the land surface throughout the model domain. As discussed in Appendix MASS (CCA Section MASS.17 and MASS Attachment 17-1, Section F), a continuation of the Holocene climatic variability is considered likely during the next 10,000 years, and is assigned a relatively high probability of occurrence (0.75). This recharge function and its probability of occurrence are reflected in the lower portion of the bimodal distribution assigned to the Climate Index parameter.

The second recharge pattern assumes that potential recharge will increase from its present value to a specified larger value 500 years in the future, and that potential recharge will then remain constant throughout the rest of the 10,000-year simulation. As with the Holocene pattern, several different values were examined, the largest resulting in a steady-state solution with the water table at, or close to, the land surface throughout the model domain. Conceptually, this pattern corresponds to a future in which the climate either becomes continuously wetter or the frequency of wetter periods becomes large enough that the hydrologic response is indistinguishable from that of a continuously wetter climate. Step-increase recharge functions were used to simulate the effects of major disruptions of the Holocene climate, analogous to those that might occur during the next 10,000 years in a transition from the present warm interglacial climate to the early stages of a future glacial climate. As discussed in CCA Appendix MASS (Section MASS.17), such disruptions to the Holocene climate are considered unlikely, and the step function is assigned a relatively low probability of occurrence (0.25). This recharge pattern and its probability of occurrence are represented by the upper portion of the bimodal distribution assigned to the Climate Index parameter.

As reported in CCA Appendix MASS (Section MASS.17 and MASS Attachment 17-1, Section E), 17 transient and 54 steady-state, regional, three-dimensional, groundwater-flow simulations were run to examine effects of climate change. Simulations considered both potential recharge functions with varying peak recharge rates and different sets of assumptions about regional rock properties. Total specific discharge into and out of the Culebra within a model region was calculated for each simulation approximately corresponding to the controlled area. Values for the Climate Index parameter were determined by comparing the total lateral specific discharge calculated for each simulation. The largest observed increase in flow for those simulations using realistic values of rock properties was a factor of 2.1. Although some simulations produced a slight reduction in flow, Climate Index parameter values less than 1.0 are not considered in the PA. Changes in flow direction in the Culebra were also noted in some three-dimensional simulations, with a shift in flow toward the west corresponding to a regional increase in the elevation of the water table. These potential changes in flow direction are not incorporated in the two-dimensional flow and transport modeling to simplify the computational process. This treatment is conservative with respect to radionuclide transport because the most

rapid transport possible under any climate conditions will be through the most conductive portion of the Culebra south and east of the repository. Any shift of the flow away from this high conductivity zone would result in slower transport through less permeable rock. Restricting the effects of climate change to a uniform linear scaling of specific discharge in the SECOTP2D model is, therefore, a conservative assumption.

6.4.10 Initial and Boundary Conditions for Disposal System Modeling

The solution of many mathematical models used in PA requires specification of a starting point, called initial conditions, and specification of how the region modeled (that is, volume) interacts with the regions not modeled (boundary conditions). Initial values are required for all of the parameters appearing in a computer code. In practice, however, the term "initial conditions" refers to the values assigned to the primary variables used to describe the system, examples of which may be pressure, composition, and saturation. The term "boundary condition" refers to the specification of primary variables that control the interaction of the modeled region with the regions excluded from the model. In many studies, applied boundary conditions are static in time, although computer codes that implement time-dependent boundary conditions are not uncommon. A common practice in modeling groundwater flow is to place modeled system boundaries somewhat distant from the region in which model results are of interest. This helps ensure that uncertainty in the natural boundaries of the system does not unduly influence model results in the region of interest. The DOE adopts this practice in its application of BRAGFLO and MODFLOW-2000 to the WIPP.

The following sections describe the initial and boundary conditions specified for the major codes used in this PA. Initial values of parameters not discussed in the following sections are set equal to the values assigned from the PA database or LHS sampling discussed elsewhere in Section 6.4.

6.4.10.1 Disposal System Flow and Transport Modeling (BRAGFLO and NUTS)

In BRAGFLO, initial conditions to simulate the regulatory period are consistent with the following:

1. there are no gradients for flow in the far-field Salado;

2. Salado far-field pore pressures are elevated above hydrostatic from the surface but below lithostatic; and

3. near the repository, excavation and waste emplacement results in partial drainage of the DRZ, subsequent evaporation of drained brine into mine air, and removal from the modeled system by air exchanged to the surface.

The term "far-field" refers to the region that is not influenced by the DRZ drainage mentioned in (3). For units above the Salado, initial pressures are consistent with observed pore pressures or normal hydrostatic gradients (Appendix PA, Section 4.2.2).

Estimating the effects of drainage of the DRZ that occurs during the operational period, (3) above, is not simple. For each vector sampled in LHS, the DOE estimates this by using

BRAGFLO to simulate a period of time representing disposal operations. This calculation is called the start-up simulation and covers five years from t = ~5 years to t = 0 years, corresponding to the amount of time a typical panel is expected to be open during disposal operations. Most of the initial parameters used during the regulatory period simulation (t = 0 to t = 10,000 years) are also assigned for the start-up simulations, with some exceptions, described below.

The initial pressures in the Salado for the start-up simulation are based on a sampled pressure at the elevation of MB139 at the shaft and adjusted throughout the Salado and the DRZ to account for changes in hydraulic head due to elevation change. This parameter is discussed in Appendix PA, Attachment PAR (Parameter 26). The adjustment assumes hydrostatic equilibrium. The DRZ permeability is set at 10^{-17} square meters for the start-up simulation. Based on observed changes in the DRZ, the DRZ porosity is adjusted upwards 0.0029 (0.29 percent) from the sampled value for intact, impure halite. Initial pressure for the start-up simulation in the excavated regions is set to atmospheric. The shaft exists and is modeled as unfilled with the same physical properties as the excavation.

For the start-up simulation, an initial water-table surface is specified within the Dewey Lake at an elevation of 980 m (3,215 ft) above mean sea level. This elevation is consistent with observations discussed in Chapter 2, Section 2.2.1.4.2.1. Above the water table, pressure is maintained at one atmosphere, 0.101 megapascals; liquid saturations in these computational cells are held constant at residual liquid saturation (Section 6.4.6.6, Table 6-25). Below the water table, initial liquid saturations in all regions except the repository and shaft are 100 percent. Pressures are set consistent with a hydrostatic gradient below the water table within the Dewey Lake, as well as in the Rustler, except for the Magenta and Culebra. Initial pressures in the Culebra and Magenta are set at 0.9141 and 0.9465 megapascals, respectively. These values are based on fluid level and fluid density data collected from well C-2737, which is located directly over the waste panels (Beauheim 2003). Even though the natural properties of units above the Salado vary considerably over the domain modeled by BRAGFLO, the BRAGFLO initial condition of constant pressure and constant properties for each layer is considered reasonable because BRAGFLO calculates the long-term flux of brine from the borehole or shaft to each unit or to the surface. For this purpose, the pressure and properties at the borehole or shaft are important, but details of regional hydraulic head and unit properties are not.

For the start-up simulation, permeabilities of all units above the Salado are set to zero so that flow cannot occur from these units into the shaft. This modeling assumption is adopted as a simple method of accounting for the effective liners in the shafts during disposal operations.

No-flow boundary conditions are assigned in the BRAGFLO model of the disposal system along all of the exterior boundaries of the computational mesh, except at the far field boundaries of the Culebra and Magenta and the top of the model (that is, the ground surface, Appendix PA, Section PA-4.2.10). The ground surface is maintained at atmospheric pressure. The boundaries of the Culebra and Magenta are maintained at pressures of 0.9141 megapascals and 0.9465 megapascals, respectively, corresponding to the initial pressure conditions used in the Culebra and Magenta. The pressure in the Castile brine reservoir is set at its sampled value for the start-up simulation.

During the start-up simulation, fluid flow calculated by BRAGFLO from the Salado and the DRZ into the excavated region simulates the effect of drainage into the repository during the operational period. Following the start-up simulations, initial conditions are specified for the regulatory period simulation. Boundary conditions for the regulatory period simulation are the same as those for the start-up simulation.

The regulatory period simulation begins with conditions consistent with the sealing of the repository by shaft seals. Certain properties assigned for the start-up simulation are changed to make model conditions consistent with the emplacement of waste and completion of sealing. The liquid saturation in the waste-disposal region of the repository is set at 0.015, which is a conservative value (Butcher 1996), and other areas of the excavation are assigned zero liquid saturation (100 percent gas saturation) regardless of the quantity of brine that may have flowed into the excavation during the start-up simulations. This is consistent with the observed ability of circulating mine air to remove any inflowing brine by evaporation. The entire repository is assigned an initial pressure of one atmosphere. Pressures and saturations in model regions representing rock remain as they were at the end of the start-up simulation. Permeabilities of the units above the Salado are reset to the values specified as discussed in Section 6.4.6. The shaft is assigned properties for shaft seal materials discussed in Section 6.4.4 and Appendix PA, Section PA-4.2.6. Waste is emplaced in the waste-disposal regions at a density of 1.17×10^2 kg/m^3 for ferrous metals and 5.55×10^1 kg/m^3 for biodegradable materials. Other waste properties are assigned as discussed in Section 6.4.3.2. Panel closure properties discussed in Section 6.4.3.2 are assigned to the panel closure regions. Permeability in the DRZ is sampled for each realization and remains constant for the regulatory period (see Appendix PA, Attachment PAR). Corrosion and biodegradation reactions that produce gas are modeled to begin at the start of the regulatory period simulation, and their rates depend on the sampled parameter values for the gas generation model (see Section 6.4.3.3) and the availability of brine. Modeling of creep consolidation through the use of the porosity surface also begins at this time (see Section 6.4.3.1).

6.4.10.2 Culebra Flow and Transport Modeling (MODFLOW-2000, SECOTP2D)

Two principal factors were considered when selecting the boundaries for the MODFLOW-2000 model of the Culebra. First, model boundaries should coincide with natural groundwater divides where feasible, or be far enough from the area of most interest (the SECOTP2D transport domain) to have minimal influence in that area. Second, the model domain should encompass all features with the potential to affect Culebra water levels at the WIPP site (e.g., potash tailings ponds).

The modeling domain is approximately 22.3 km (14 mi) east-west by 30.6 km (19 mi) north-south, aligned with the compass directions (see Figure 6-17 in Section 6.4.6.2). This is the same as the domain used by LaVenue et al. (1990), except that the current domain extends 1 km farther to the west. The modeling domain is discretized into 68,768 uniform 100-m × 100-m cells. The northern model boundary is slightly north of the end of Nash Draw, 12 km (7.5 mi) north of the northern WIPP site boundary. The eastern boundary lies in a low-transmissivity region that contributes little flow to the modeling domain. The southern boundary lies 12.2 km (7.6 mi) south of the southern WIPP site boundary, slightly over 1.7 km (1 mi) south of the southernmost well (H-9) and far enough from the WIPP site to have little effect on transport rates

on the site. These boundaries are all assigned constant-head conditions based on head measurements made in model domain wells. The western model boundary passes through the IMC tailings pond due west of the WIPP site in Nash Draw. However, a no-flow boundary (a flow line) is specified in the model from this tailings pond up the axis of Nash Draw to the northeast, reflecting the concept that groundwater flows down the axis of Nash Draw, forming a groundwater divide. Similarly, another no-flow boundary is specified from the tailings pond down the axis of the southeastern arm of Nash Draw to the southern model boundary, coinciding with a flow line in the regional modeling of Corbet and Knupp (1996). Thus, the northwestern and southwestern corners of the modeling domain are specified as inactive cells in MODFLOW-2000, leaving 53,769 active cells.

Initial conditions are not required for the Culebra flow calculations because these are steady state. Initial actinide concentrations in the transport simulations are assumed to be zero.

6.4.10.3 Initial and Boundary Conditions for Other Computational Models

In addition to BRAGFLO, MODFLOW-2000, and SECOTP2D, several other codes are used in PA that require initial and boundary conditions. In general, these codes are strongly coupled to BRAGFLO, analogous to the manner in which SECOTP2D is coupled to MODFLOW-2000. These additional codes are NUTS, PANEL, the BRAGFLO direct brine release model (BRAGFLO), and CUTTINGS_S.

NUTS transports radionuclides through the BRAGFLO domain based on fluid flow characteristics as calculated by BRAGFLO and, therefore, does not need explicit definition of flow boundary conditions. As actinide transport is not of concern until the repository contains waste and is sealed, a start-up simulation is not executed with NUTS. Boundary conditions for advective transport are consistent with the boundary conditions assumed for fluid flow. Molecular transport boundary conditions for NUTS simulations consist of no diffusion or dispersion in the normal direction across far-field boundaries. Initial actinide concentrations are zero in all regions except the waste. Actinide concentrations in the waste region brine are assigned as discussed in Section 6.4.3.5 (Table 6-13).

PANEL estimates the transport of radionuclides from the repository to the Culebra for the E1E2 scenario (Appendix PA, Section PA-4.4). PANEL assumes homogeneous mixing within a panel of the waste disposal region to determine a source term for radionuclides. PANEL is strongly coupled to BRAGFLO, in that the flux of liquid up the borehole and out the separate panel in BRAGFLO is provided as the flux of liquid leaving the mixing volume in PANEL. Liquid leaving the mixing cell in PANEL is assumed to arrive at the Culebra, thereby maximizing the source of actinides to the Culebra.

Models for direct release to the surface are also strongly coupled to BRAGFLO. CUTTINGS_S (cuttings, cavings, and spall) and BRAGFLO (for direct brine release) acquire fluid pressure, fluid saturation, and other necessary quantities from the appropriate BRAGFLO disposal system model simulation. It is assumed in the direct release models that radionuclides, once entrained in drilling fluid, remain in the drillhole until they reach the surface. In other words, there is no interaction between drilling fluid and the formations between the repository and the surface.

Boundary conditions in the direct brine release model are no-flow except for the sources and sinks of brine through borehole nodes and at the surface.

6.4.11 Numerical Codes Used in Performance Assessment

To evaluate scenario consequences for both undisturbed and disturbed performance, DOE uses many computer codes to simulate relevant features of the disposal system. The flow of information and primary roles of the codes used are discussed in this section; the mathematical models implemented by the codes are discussed in Appendix PA. Parameter values and disposal system conditions must be passed between codes several times in an assessment.

The codes are executed under the requirements of the SCMS), which creates and maintains a complete record of the input data and results of each calculation, along with the exact codes used to create those results. For this application, PA codes used in conjunction with LHS or random sampling were executed under the SCMS.

The major computer codes and the flow of information among them are illustrated in Figure 6-24. As discussed in Section 6.1.4 and indicated in Figure 6-24, some of these codes are used to calculate reference conditions for deterministic futures associated with the parameters in x_{su} (Equation 6.4b [Section 6.1.2]) and their associated uncertainty characterized by distributions D_{su} (Equation 6.6b [Section 6.1.2]). The results of these codes are then used constructing the consequences of probabilistic futures. There are three major steps in evaluating scenario consequences for deterministic futures: (1) preparing input from submodels executed independent of LHS (for example, SANTOS, PEST), (2) LHS of the variables x_{su} in the PA parameter database, and (3) executing the sampling-dependent PA codes (those within the deterministic futures box indicated by dashed lines in Figure 6-24).

Some PA codes are used to calculate probabilistic futures; that is, future events that occur randomly in time and space, and uncertainty of associated parameters in x_{st} (Equation 6.4a [Section 6.1.2]) and characterized by distributions in D_{su} (Equation 6.6a [Section 6.1.2]). There are two major steps in evaluating scenario consequences for probabilistic futures: (1) random sampling of the parameter database, and (2) executing the codes.

Figure 6-24 indicates only those codes that perform the bulk of the computational effort related to simulating the significant physical processes occurring within the disposal system. In addition, a variety of additional codes are used in this PA. These additional codes are transfer data between codes, prepare input files, model output processing, and perform similar tasks. These codes are also executed within the SCMS.

Because these additional codes are not expressly used to simulate physical processes, they have been omitted from discussion here and on Figure 6-24 for clarity. A comprehensive description of the coupling of codes used in this PA is provided in Appendix PA.

Figure 6-25 shows an alternative method of visualizing how the various PA codes relate to each other and to the estimation of scenario consequences. This figure shows a vertical cross section of the disposal system, associating the major codes with the particular components of the system each code simulates. As shown in the figure, BRAGFLO, SANTOS, NUTS, and PANEL address the Salado. PEST, MODFLOW-2000, and SECOTP2D address the Culebra.

CUTTINGS_S, BRAGFLO (direct brine release), DRSPALL, and PANEL address the immediate consequences of inadvertent human intrusion through one or more exploratory boreholes. Combined, Figures 6-24 and 6-25 illustrate the flow of information through major PA codes and the relationship between the codes and the physical system being simulated.

The parameter database is the initial element in the PA process. The database includes the parameters used in PA codes that pertain to the technical aspects of disposal system performance. Parameters pertaining only to the execution of the codes (for example, convergence criteria for Newton-Raphson numerical solvers) are generally not included in the database, but are recorded in input files and traceable through the SCMS. Parameters in the database fall into two categories: those that are assigned fixed values, and those that are uncertain and are therefore assigned a range of values according to a CDF.

Vectors (sets) of parameter values are created from the uncertain variables in the database by LHS of each variable for a set of simulations in the PA. In this PA, 64 parameters are sampled using LHS, and 100 vectors are assembled in each replicate (see Section 6.5). The values assigned to each sampled parameter in each of the vectors in this PA are included in Appendix PA, Attachment PAR. Each of the fixed parameter values from the database and a vector of sampled parameter values are combined to form a realization (a set of input parameters). Each realization is then propagated through the PA codes within the dashed lines shown in Figure 6-24.

Assessing each realization requires that the codes shown in Figure 6-24 for deterministic futures be executed under four code sequence configurations, one each for the undisturbed performance scenario (E0), the E1 scenario, the E2 scenario, and the E1E2 scenario.

Each intrusion scenario may occur with or without mining. The techniques used for each scenario are described in Section 6.4.13.

As shown in Figure 6-25, information for some of the major codes comes from the following additional sources: the SANTOS, PEST, DRSPALL, and FMT codes.

The SANTOS code develops the porosity surface, describing porosity as a function of time and pressure; this information is used in the BRAGFLO code (see Appendix PA, Section PA-4.2 and Attachment PORSURF). PEST is coupled with MODFLO-2000 to calculate numerous possible and equally likely Culebra transmissivity fields; these transmissivity fields are used inthe MODFLOW-2000 code (see Appendix PA, Attachment TFIELD). FMT is used to calculate solubility parameters entered into the parameter database. These parameters, as well as sampled solubility distribution parameters, calculated solubilities for the PA. Actinide solubility in the repository is used by the codes NUTS and PANEL. DRSPALL calculates the volume of solid material that could be removed from the repository by spallings for a set if initial pressure conditions and uncertain parameters. The code CUTTINGS_S uses the DRSPALL results to determine the volume removed by spallings for intrusions at different times and locations.

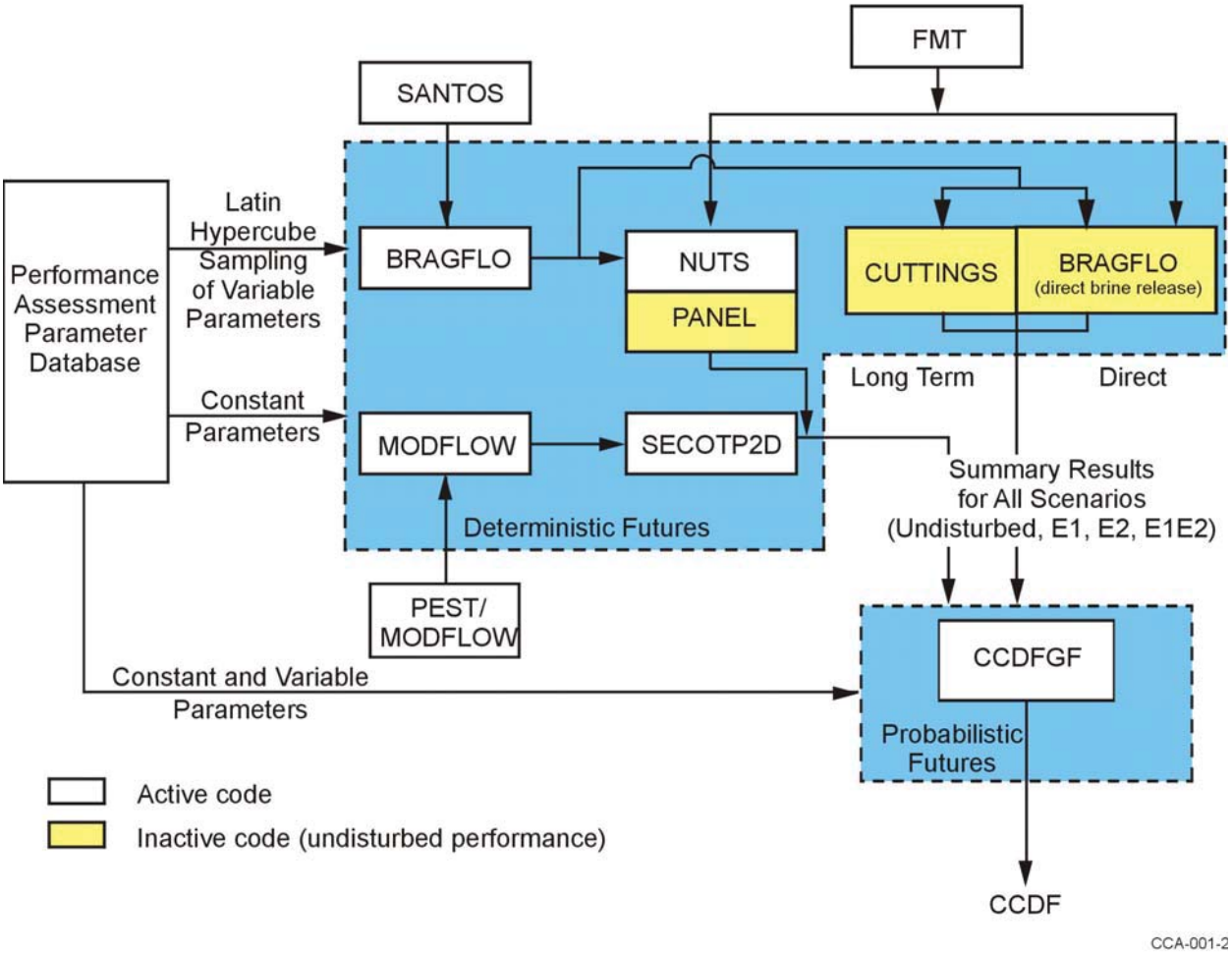

Figure 6-24. Major Codes, Code Linkages, and Flow of Numerical Information in WIPP PA

The PA codes are executed sequentially. Following LHS, BRAGFLO is the first major code executed. Notice that BRAGFLO is listed twice in this sequence. BRAGFLO is used in two applications for PA. In the first application, BRAGFLO calculates the overall movement of gas and brine in the repository and from the Castile to the surface; this movement forms the basis for estimating radionuclide releases to the accessible environment (Appendix PA Sections 4.2 and 6.7). BRAGFLO also contains subsystem models for estimating gas generation in the repository, disposal room closure and consolidation, and interbed fracturing (Appendix PA, Section PA-4.2). BRAGFLO does not calculate the movement of radionuclides. The second application of BRAGFLO is discussed below.

NUTS calculates the overall movement and decay of radionuclides in the repository and disposal system. NUTS uses the same geometry as BRAGFLO, the brine and gas flow fields calculated by BRAGFLO, and the radionuclide source concentrations (solubilities) in the repository defined by the actinide source term models. In simulations of the E1 scenario, NUTS also tracks brine originating in the Castile brine reservoir, including the Castile brine that has flowed out from the borehole and into the waste in the repository. See Appendix PA, Section PA-4.3 for additional

information on the use of NUTS in PA. PANEL calculates actinide source term to the Culebra for the E1E2 scenario, as discussed in Section 6.4.13.5. PANEL is described in detail in Appendix PA, Section PA-4.4.

In all scenarios, the quantity of brine flowing up the shafts or a degraded exploratory borehole to the Culebra is calculated by BRAGFLO, and the concentration of radionuclides in that brine, calculated by NUTS or PANEL, determines the quantity of radionuclides released to the Culebra.

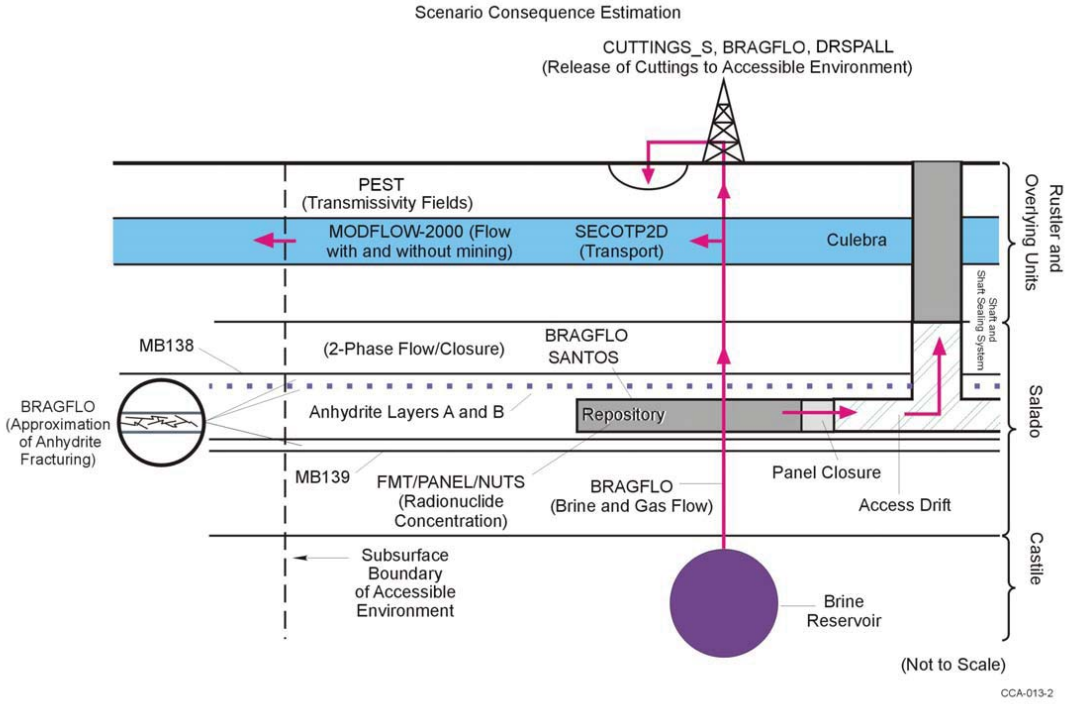

Figure 6-25. Schematic Side View of the Disposal System Associating PA Codes with the Components of the Disposal System Each Code Simulates

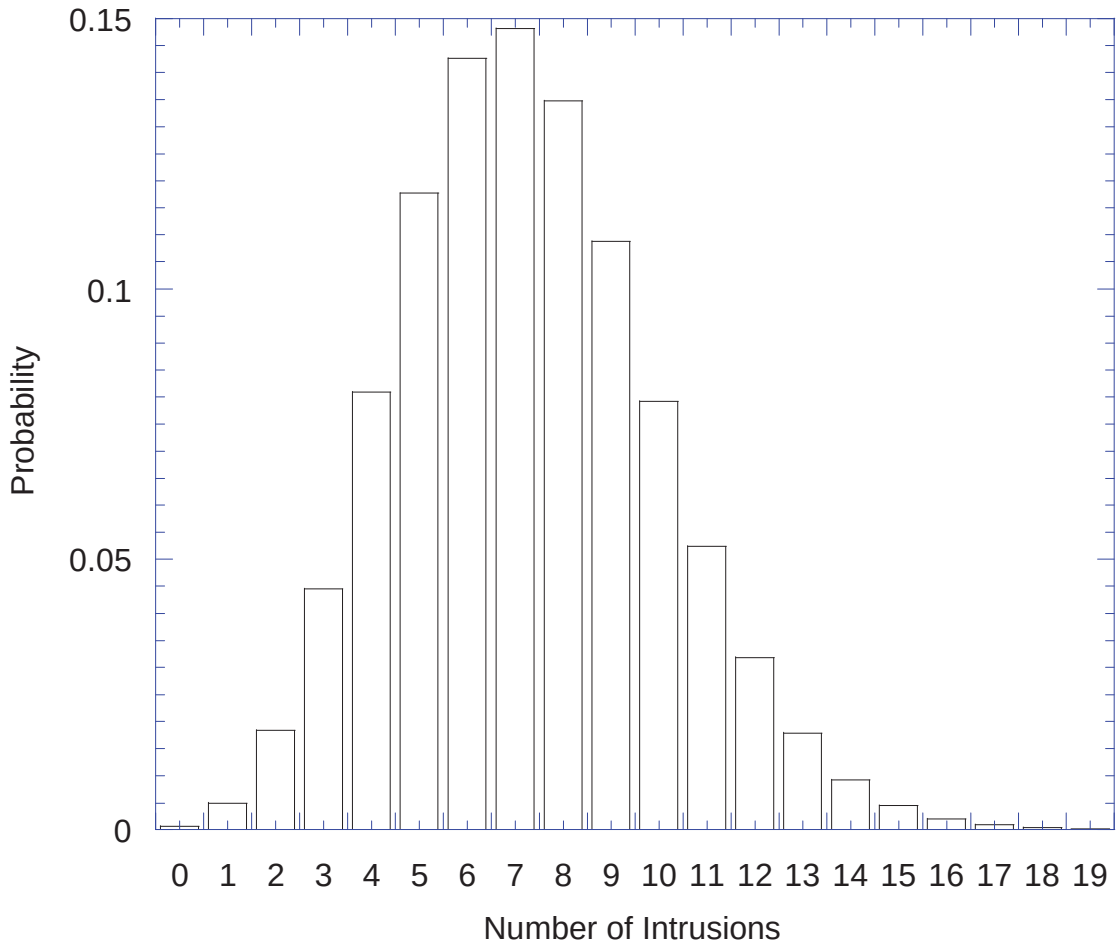

Figure 6-26. Probability of Intrusions in 10,000 Years with Active Institutional Control

CUTTINGS_S and BRAGFLO (direct brine release) evaluate the immediate consequences of inadvertent human intrusion through exploratory drilling. Solid material and brine may be transported to the surface in the drilling fluid. After pressure in the repository is relieved through the first borehole, subsequent boreholes may release less material to the surface. CUTTINGS_S calculates the quantity of solid material transported to the accessible environment at the surface during the drilling activities. This includes material removed directly from the borehole (cuttings), along with cavings and spallings. The code is discussed in Appendix PA, Section PA-4.5. BRAGFLO (direct brine release) calculates the quantity of brine transported up the borehole to the surface.

MODFLOW-2000 and SECOTP2D calculate the detailed movement of radionuclides in the Culebra that occurs if radionuclides flow up the shafts or through a degraded exploratory borehole. MODFLOW-2000 calculates regional Culebra flow fields using an assumption that flow occurs in a single-porosity medium. MODFLOW-2000 uses the transmissivity fields calibrated using PEST (one field in each simulation). SECOTP2D calculates radionuclide transport in a double-porosity medium, accounting for advection in fractures, matrix diffusion, retardation, and decay, as described in Section 6.4.6.2. MODFLOW-2000 and SECOTP2D are

discussed in Appendix PA, Section PA-48 and PA-49, respectively. The NUTS and PANEL codes calculate the actinide source term to the Culebra.

The computer code CCDFGF is used to (1) determine random sequences of future events that may occur over the next 10,000 years at the WIPP site; (2) estimate the radionuclide releases resulting from these random sequences of future events using the results of calculations described thus far; and (3) construct a CCDF for each realization. The manner in which CCDFGF determines random sequences of future events is the subject of Section 6.4.12.

Estimating consequences and constructing a CCDF for these sequences of future events is the subject of Section 6.4.13.

6.4.12 Sequences of Future Events

For this application, sequences of future events that may occur are determined using a random sampling procedure described in Appendix PA, Section PA-3.0. A general description of the technique is presented in this section.

The incorporation of stochastic uncertainty in the PA is based on repeatedly generating independent sequences of events that may occur at the WIPP over the next 10,000 years. Each 10,000-year sequence is generated by randomly sampling six parameters that repeatedly characterize stochastic uncertainty about future events. These parameters include (1) the interval of time between drilling intrusions (which yields both the number and time of intrusions), (2) the location of each drilling intrusion, (3) the activity of the waste penetrated by each drilling intrusion, (4) the plug configuration in the intrusion borehole, (5) the penetration of a Castile brine reservoir, and (6) the occurrence of mining. Probability distribution functions are assigned to each of these six parameters and are discussed in the following sections. Random sampling from these distributions generates 10,000 equally likely, independent futures of the WIPP for each realization executed and CCDF constructed. The computer code CCDFGF (Appendix PA, Sections 3 and PA-6.0) randomly samples sequences of future events, constructs consequences of these sequences, and assembles CCDFs. As described in Section 6.4.13, normalized integrated radionuclide releases to the accessible environment are estimated for each history using the consequence modeling system.

The probability assigned to the occurrence of certain future events at the WIPP site is affected by regulatory guidance and DOE actions taken to deter activities detrimental to WIPP performance. Active and passive institutional controls are discussed extensively in Chapter 7.0. A summary of their use in PA is in this section.

6.4.12.1 Active and Passive Institutional Controls in Performance Assessment

Active institutional controls and passive institutional controls will be implemented at the WIPP site to deter human activity detrimental to repository performance. Active institutional controls and passive institutional controls are described in detail in Chapter 7.0 and in appendices referenced in Chapter 7.0. In this section, the impact of active institutional controls and passive institutional controls on PA is described.

Active institutional controls will be implemented at the WIPP after final facility closure to control site access and ensure that activities detrimental to disposal system performance do not occur within the controlled area. The active institutional controls will preclude human intrusion in the disposal system. A limitation for considering the effectiveness of active institutional controls in PA is established in 40 CFR Part 191. That limitation is 100 years. Because of the nature of the active institutional controls to be implemented and regulatory restrictions, the PA assumes there are no inadvertent human intrusions or mining in the controlled area for 100 years following repository closure.

Passive institutional controls deterr inadvertent human intrusion into the disposal system in PA. Only minimal assumptions were made about future society when designing the passive institutional controls to comply with the assurance requirements. The preamble to 40 CFR Part 194 limits any credit for passive institutional controls in deterring human intrusion to 700 years after disposal (EPA 1996a, 61 FR 5231). Although the DOE originally included credit for passive institutional controls in PA, the CRA-2004 PA does not include such credit. The EPA directed DOE not to take credit for passive institutional controls in the CCA during the certification (EPA 1998, 194.VIII.D.3).

6.4.12.2 Number and Time of Drilling Intrusions

The number of drilling intrusions associated with each 10,000-year history is based on 40 CFR § 194.33(b)(2) and § 194.33(b)(3):

> In performance assessments, drilling shall be assumed to occur in the Delaware Basin at random intervals in time and space during the regulatory time frame. [40 CFR 194.33(b)(2)]
>
> The frequency of deep drilling shall be calculated in the following manner:
>
> (i) Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.
>
> (ii) The total rate of deep drilling shall be the sum of the rates of deep drilling for each resource. [40 CFR 194.33(b)(3)]

The DOE's implementation of these criteria is described in this and the following sections.

Mathematically, events that are random in time can be described as following a Poisson process that can be written as

$$P\left[E_n\left(\Delta t\right)\right] = \frac{\left[\lambda\left(\Delta t\right)\right]^n}{n!} e^{-\lambda \Delta t}, \tag{6.18}$$

where $p[E_n(\Delta t)]$ is the probability (p) that some number (n, an integer) of events (E) will occur in a time interval (Δt) given a rate constant λ with units of events per time.

Inadvertent human intrusions may occur at any time between 100 years and 10,000 years after the decommissioning of the facility. Both the number and time of intrusions are determined sequentially by sampling from a CDF derived from the Poisson model that probabilistically describes the time period elapsing between an intrusion at a fixed time and the next intrusion.

The time interval to the next intrusion following an intrusion may vary from 0 years to greater than 9,900 years, with a probability determined by the rate constant λ. The rate constant is derived from the drilling rate established for the Delaware Basin and the area of the waste disposal region, 0.126 km^2 (0.049 mi^2). The drilling rate used in this analysis was 52.5 boreholes per square kilometer per 10,000 years. As discussed in Appendix DATA, Attachment A, this rate is based on a review of past and present drilling activity in the Delaware Basin. The rate constant λ is assigned different values for two time periods. While active institutional controls are effective, it is equal to zero; after active institutional controls cease, λ is assigned to 52.5 boreholes per square kilometer per 10,000 years.

Intrusion times are determined by random sampling. If the sampled time is greater than 9,900 years (100 + 9,900 = 10,000), no intrusions occur between 100 and 10,000 years. If the sampled time is less than 9,900 years, an intrusion occurs at 100 years plus the sampled time. The post-active institutional controls CDF is sampled iteratively to determine whether intrusions occur in the time interval between the last intrusion and 10,000 years until an intrusion is determined to occur after 10,000 years.

The most likely number of intrusions into the waste disposal region during 10,000 years is seven, with a probability of 0.1482. Zero intrusions occur with a probability of 0.0007. The largest number of intrusions that occur with a probability greater than 10^{-3} per 10,000 years (and which can contribute to releases for comparison with the quantitative release limits) is 16, occurring with a probability of 0.0020. Probabilities for other numbers of intrusions within 10,000 years are given in Table 6-30. These probabilities are shown as a histogram in Figure 6-26.

6.4.12.3 Location of Intrusion Boreholes

Drilling events are assumed to be random in time and space, and the location of each intrusion borehole within the waste disposal region is sampled randomly. This is done in the analysis by discretizing a plan view of the area within the passive institutional control berms (see CCA Appendix PIC, Section VIII) into 144 separate regions and requiring each intruding borehole to penetrate a single region (Figure 6-27). The probability of intersecting each location is equal to 1/144 (about 0.00694), and slight variations in the size of regions are disregarded as unimportant.

Each of the 144 regions contains both excavated and unexcavated areas at the repository horizon. A borehole has an approximately 20 percent chance of intruding excavations and an approximately 80 percent chance of passing through unexcavated Salado (see Appendix PA, Section PA-3.4). The berm area and the proportion of excavated to unexcavated regions at the repository horizon are important in the Castile brine reservoir model, as discussed in Section 6.4.12.6.

Boreholes that penetrate excavations may penetrate either CH-TRU waste or RH-TRU waste For long-term releases and direct brine releases, all penetrations into excavations are treated as if CH-TRU waste is penetrated, and the RH-TRU waste inventory is averaged into the CH-TRU waste inventory for source-term determination. For cuttings and cavings direct releases, there is an approximately 12 percent chance that RH-TRU waste canisters are penetrated and an 88 percent chance that CH-TRU waste is penetrated, corresponding to the relative plan-view areas of each waste type (see Appendix PA, Section PA-3.7).

Table 6-30. Probabilities of Different Numbers of Intrusions into the Waste Disposal Region (for 100 years of active institutional control and 9,900 years of uncontrolled activity)

Number of Intrusions	Probability of Occurrence
0	0.0007
1	0.0050
2	0.0183
3	0.0445
4	0.0809
5	0.1177
6	0.1426
7	0.1482
8	0.1348
9	0.1089
10	0.0792
11	0.0524
12	0.0318
13	0.0178
14	0.0092
15	0.0045
16	0.0020
17	0.0009
18	0.0004
19	0.0001

For cuttings and cavings direct releases, the small area of the panel closures is treated as CH-TRU waste and is included in the CH-TRU waste probability. Because of the low permeability of the region surrounding each RH-TRU waste canister, intrusions into RH-TRU waste are not assumed to produce spallings releases or direct brine releases.

6.4.12.4 Activity of the Intersected Waste

Waste shipped to the WIPP will contain quantities of radionuclides that will vary from container to container. Radioactivity may vary by several orders of magnitude from those waste containers with the largest quantities of radionuclides to those with the smallest.

Information about waste radioactivity has been compiled at several different levels (Figure 6-28). The waste-stream level includes information about waste activities from different processes at generator sites that create TRU waste. At this level, a separate waste stream

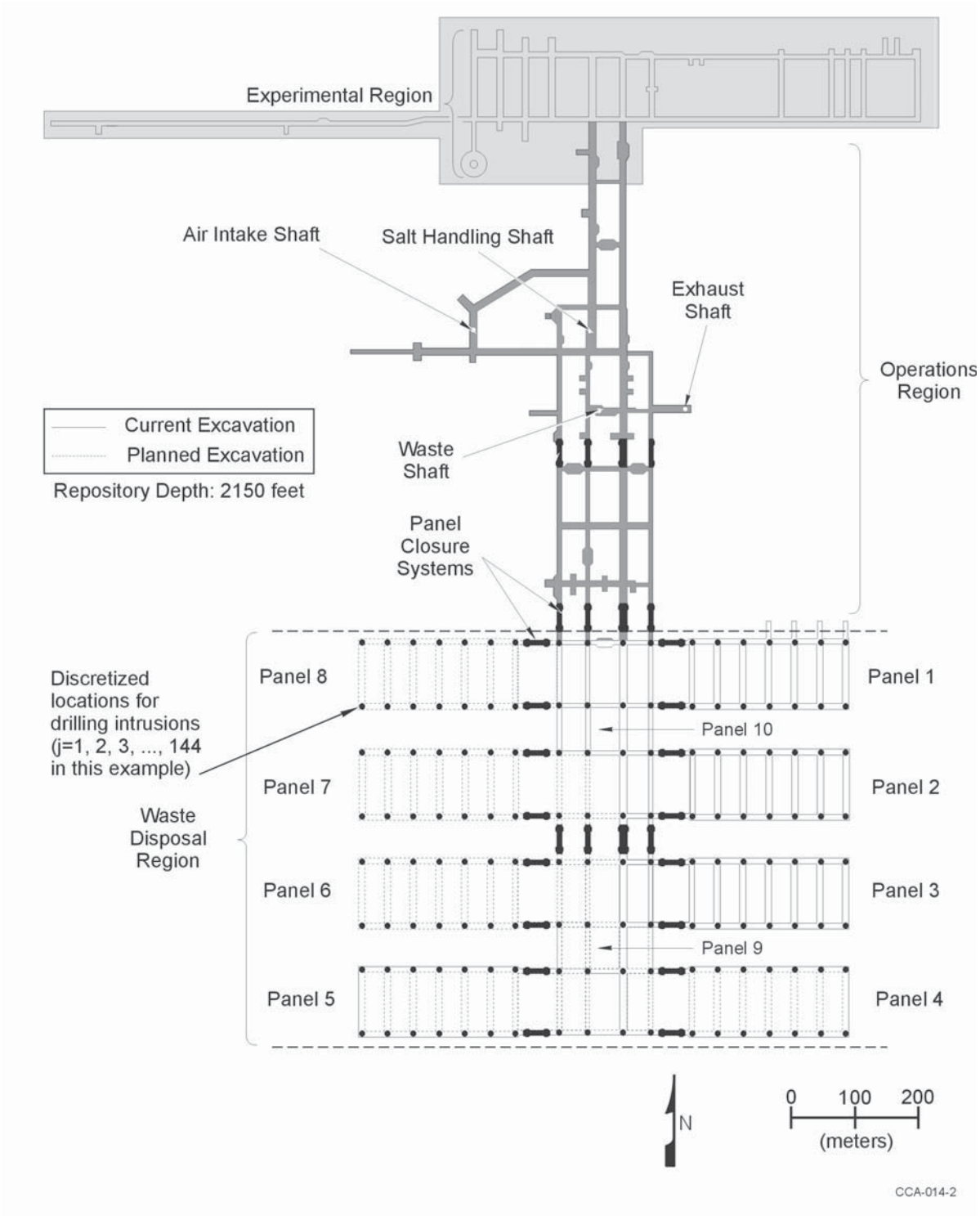

Figure 6-27. Discretized Locations for Random Intrusion by an Exploratory Borehole

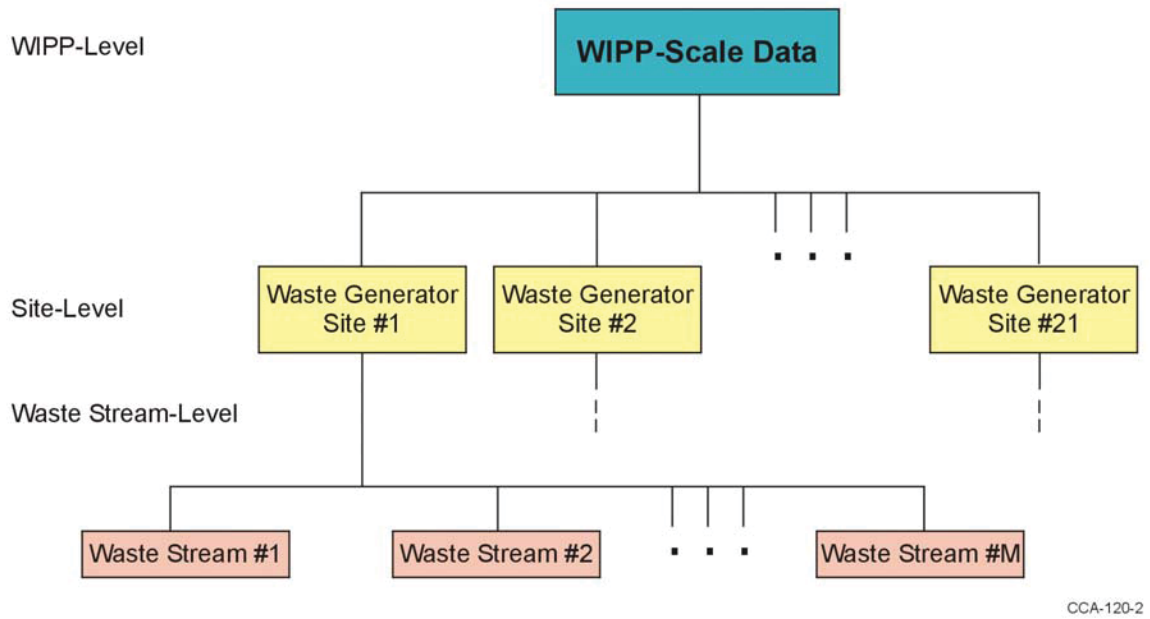

Figure 6-28. Levels of Information Available in the TWBID

characteristic is maintained for RH-TRU. In total, there are approximately 779 CH- and RH-TRU waste streams, of which 693 are CH-TRU. Because the RH-TRU is approximately one percent (actually 1.5 percent) of the total EPA units (not activity) of CH-TRU waste, all the RH-TRU waste was grouped together into one equivalent or average (WIPP-scale) RH-TRU waste stream. Variability in this small fraction is assumed to be negligible. The waste-generator site level includes information integrated over the scale of a generator site. There are 27 generator sites identified for the WIPP (see Section 4.1.2). The WIPP-scale level includes integrated information about all waste destined for the WIPP, including CH- and RH-TRU. Data are present for existing waste and estimates were made for future (to-be-generated) waste. The integration of waste data with the PA is illustrated in Figure 6-29. In the CCA, this information was compiled from the Transuranic Waste Baseline Inventory Database (TWBID), an electronic version of information present in the Transuranic Waste Baseline Inventory Report (TWBIR), Rev. 3, (see CCA Appendix BIR). New information concerning waste inventory has been included in PA for emplaced, stored, and projected waste. The new information is discussed in Chapter 4 and Appendix TRU WASTE (see also Appendix DATA, Section 7.0, Attachment F).

To calculate radionuclide releases from groundwater transport (including direct brine release) and from spallings, spatial variability in the waste activity is assumed to have no significant impact. Concentrations of radionuclides mobilized in repository brine and quantities transported to the ground surface in spallings are assumed to be derived from a sufficiently large volume of waste that container-scale variability can be neglected. Long-term releases and direct brine releases are calculated using WIPP-scale data assuming homogeneous accessibility of RH- and CH-TRU waste activities by liquid in the repository. As discussed previously, spallings releases are not calculated for RH-TRU waste;

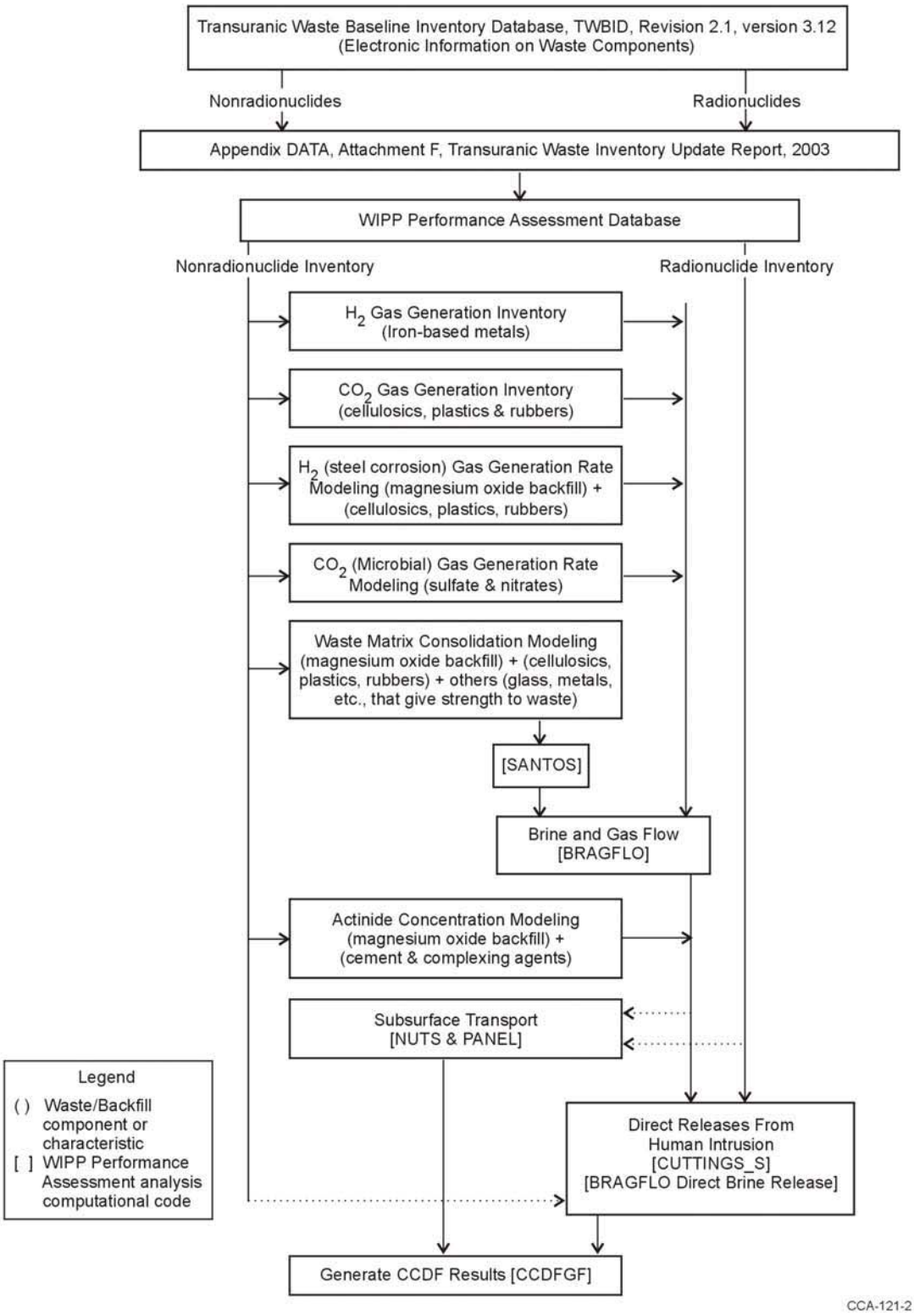

Figure 6-29. Flowchart Showing Integration of TWBID Data in PA Calculations

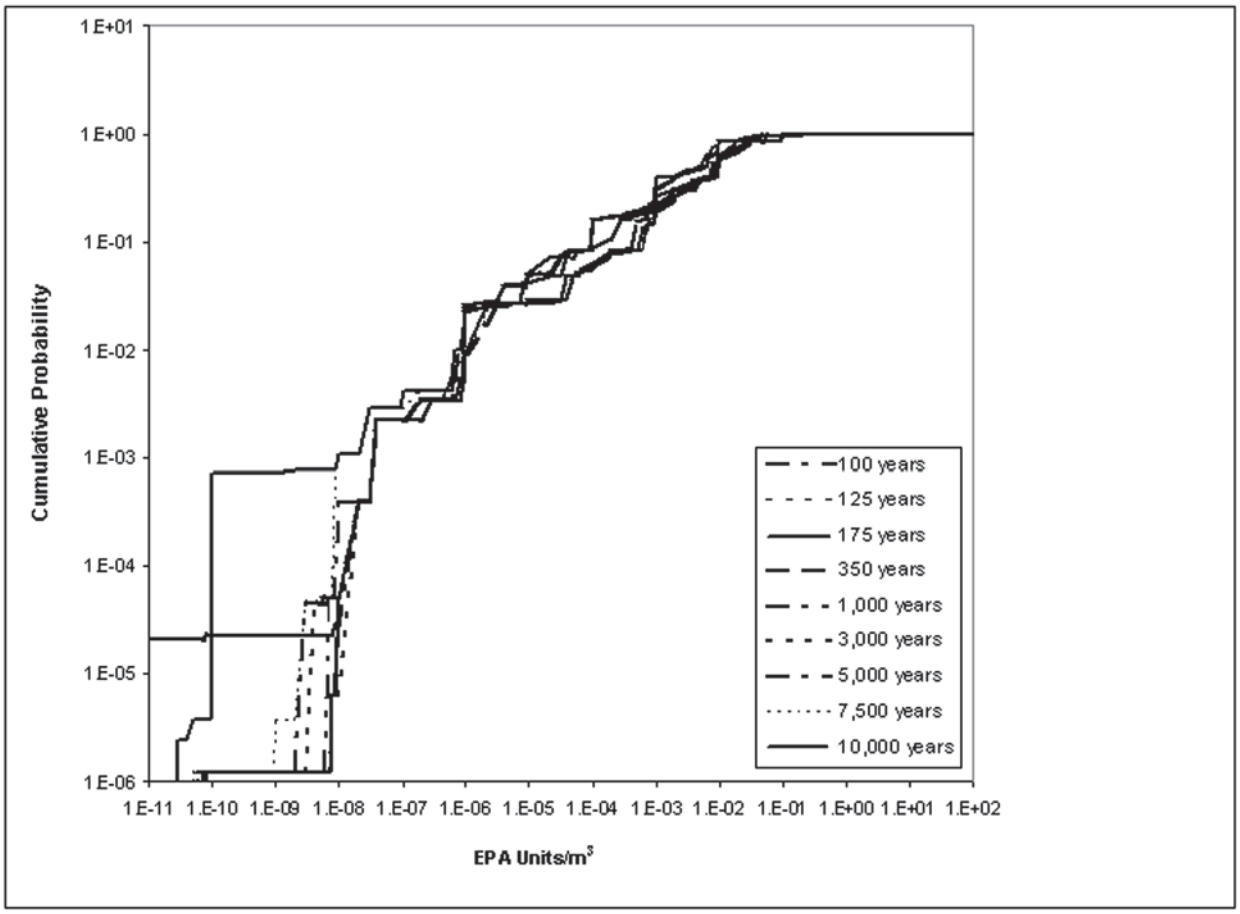

Figure 6-30. Cumulative Distribution Function for Waste Stream EPA Units/Volume

consequently, spallings release activities are determined assuming homogeneous accessibility for only CH-TRU waste.

Direct releases caused by cuttings and cavings access discrete and relatively small portions of the waste, and estimates of the quantity of radioactivity released to the accessible environment may be sensitive to variability in activity loading. The radioactivity of cuttings and cavings releases is calculated using data from the waste-stream level in the following manner.

Containers are assumed to be randomly placed in the WIPP from the various waste streams (see Appendix PA, Attachment MASS, Section 21). Because waste containers are stacked three-high for disposal, a drill bit is assumed to penetrate three containers. The direct-release consequence resulting from a drill bit hitting the edges of containers and generating releases from more than three containers is assumed similar to the consequence of penetrating three containers only (see Appendix PA, Section PA-6.8.3). Each of the three containers penetrated by the drill bit can come from different waste streams and have different associated activities. The waste streams penetrated are randomly sampled according to the relative quantity of waste in each waste stream. Figure 6-30 shows the discretized activities, expressed as the EPA normalized release density, of the 693 CH-TRU waste streams as a CDF and the decay of the waste stream activities through time. Waste stream activities are maintained in PA at 100, 125, 175, 350, 1,000, 3,000,

5,000, 7,500, and 10,000 years. Activities for cuttings and cavings releases at other times are interpolated from these values.

The code CUTTINGS_S calculates the volume of repository material brought to the surface by cuttings and cavings. Of the repository volume removed, approximately 40 percent is waste material; the rest is void space, MgO (backfill), and drum packing material. It is assumed that one-third of the waste material released comes from each of three containers assumed to be intersected. The activity of the release to the surface during drilling by cuttings and cavings is the summed products of one-third the release volume times the three waste stream activities randomly sampled. If random sampling determines that the borehole penetrates RH-TRU waste, 100 percent of the material removed is assumed to be waste and the activity of the release is equal to the volume calculated by CUTTINGS_S times the activity of RH-TRU waste.

6.4.12.5 Diameter of the Intrusion Borehole

Historical Delaware Basin drilling records were reviewed to determine the diameter of a typical intrusion borehole. In PA, the borehole diameter parameter value is held constant for all future drilling and is equal to 0.311 m (12.25 in.). Appendix DATA, Attachment A and CCA Appendix DEL, Attachment 1 discusses current and historical drill stem and drill collar diameters used to drill oil and gas wells in the Delaware Basin. CCA Appendix DEL illustrate a generalized circular cross section of a well plugged according to current practice (see CCA Section DEL.6.1.2.2l and Appendix DATA).

6.4.12.6 Probability of Intersecting a Brine Reservoir

As discussed in Section 6.4.8, there is uncertainty about the existence of brine reservoirs and the probability of intersecting a brine reservoir with a deep borehole. The DOE has examined available data and concluded that there is no reasonable basis to eliminate the possibility of a brine reservoir existing under the site. Therefore, the DOE assumes that a brine reservoir may exist under the waste panels. The DOE determined a reasonable basis for the probability of intersecting a brine reservoir and had pursued three investigations relevant to this issue: geophysical methods, geological structure analysis, and geostatistical correlation (see CCA Section 6.4.8, Appendix MASS Section 18, and MASS Attachments 18-1, 2 and 3 for the investigations that led to the CCA's representation of the brine reservoir). As discussed in Section 6.4.8, the DOE adopted the EPA's representation of the brine reservoir used in the 1997 PAVT (the EPA's basis for this representation is documented in the Technical Support Document for Section 194.23: Parameter Justification Report, A-93-02, V-B-14 and in a technical support document entitled Technical Report Review of TDEM Analysis of WIPP Brine Pockets, A-93-02, V-B-30).

For the CRA-2004 PA, the DOE assumes there is one reservoir under the waste panels and uses probability of a deep borehole hitting the reservoir of between 0.01 to 0.60 (see EPA 1998, VII.B.4.d). The location of boreholes in this area is sampled. They may lie over repository excavations, or over rock in pillar cores, or between panels. The brine reservoir under the waste panels is not assumed to be depleted during the 10,000-year regulatory period by subsequent boreholes drilled anywhere within this area. Boreholes randomly located over rock have the same probability of intersecting the brine reservoir as boreholes located over excavations.

Boreholes located over the excavations are assumed to penetrate waste, and the consequences are modeled as described in Section 6.4.

BRAGFLO calculates the long-term pressure and production of brine from the reservoir for only one two-plug configuration borehole. Subsequent penetrations are assumed to behave identically to the first (see Appendix PA, Section PA-6.8).

6.4.12.7 Plug Configuration in the Abandoned Intrusion Borehole

As stated in Section 6.4.7, three different plug configurations can represent possible future configurations of plugged and abandoned intrusion boreholes. Based on a survey of current practice (see Appendix PA, Attachment MASS, Section 16.0, the two-plug configuration borehole is considered most likely and is assigned a probability of 0.696. The three-plug configuration is considered less likely and is assigned a probability of 0.289. The continuous concrete plug is considered least likely and is assigned a probability of 0.015 (SNL 2003).

6.4.12.8 Probability of Mining Occurring within the Land Withdrawal Area

The EPA has specified the probability of mining in the future. In 40 CFR § 194.32 (b), the EPA states, "Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame."

Also in 40 CFR § 194.32(b), the EPA limits the occurrence of mining to a maximum of once per 10,000 years. The DOE interpreted this probability as a Poisson model with a mining probability of 10^{-4} per year (Appendix PA, Section PA-3.0). The occurrence of mining is sampled from a CDF of the time until mining in a manner similar to the procedure described for the time between drilling intrusions, except that multiple mining events cannot occur.

6.4.13 Construction of a Single CCDF

Construction of a single CCDF requires combining the results of numerical simulations performed using different sets of subjective parameter values (sets selected by LHS) with the probabilistic futures determined by random sampling stochastic parameters (that is, those associated with intermittent drilling) (see Appendix PA, Section PA-3.0). The variety of sequences of events represented in a single CCDF and the impossibility of modeling the details of each future separately requires building a CCDF using methods to construct consequences for any probabilistic future from a limited number of calculations for deterministic, idealized futures. Although this methodology is conceptually straightforward, the details of the process are highly dependent on model and system-specific considerations (see Appendix PA, Section PA-6). Accordingly, insight gained from previous, preliminary PAs as well as analysis of early results for this PA help configure the methodology used for CCDF construction.

Depending on the scenario into which probabilistic futures are classified, different techniques are used for estimating their consequences. The deterministically determined undisturbed performance scenario consequences require no special techniques for application to probabilistic futures. For E1, E2, and E1E2 scenarios, the CCDF construction methodology is primarily based on the principle of scaling, with some simplifying assumptions made for the E2 scenario. Scaling is estimating the consequences of probabilistic futures based on consequence estimates from

deterministic futures. The use of scaling and the building of a CCDF with it is discussed in this section. Note that all of the discussions in Section 6.4.13 are for one vector of parameter values included in the subjective uncertainty analysis. In other words, this section addresses only stochastic variation resulting from uncertainty in the sequence of future events that may occur at the WIPP (see Section 6.1.2).

6.4.13.1 Constructing Consequences of the Undisturbed Performance Scenario

All probabilistic futures in which drilling intrusion and mining within the controlled area do not occur are included in the undisturbed performance scenario. Because there is no stochastic uncertainty for this scenario, all futures within a single LHS vector of undisturbed performance have the same releases to the accessible environment. The following major codes are used to estimate the consequences of undisturbed performance: BRAGFLO, NUTS, and, if actinides reach the Culebra, MODFLOW-2000 and SECOTP2D. To illustrate the flow of information for the undisturbed performance scenario, these codes and the connections between them are highlighted in Figure 6-31. For undisturbed performance, no special techniques are required to modify the results of the deterministic calculation to fit probabilistic futures. Therefore, for a single consequence of undisturbed performance, BRAGFLO is executed once and NUTS is executed once. These calculations determine the release to the accessible environment from transport in the Salado or up the shaft to the surface. If any actinides reach the Culebra following these calculations, MODFLOW-2000 and SECOTP2D determine whether actinides released to the Culebra reach the lateral accessible environment. This information is sufficient to construct consequences for all probabilistic futures that have no intrusion events. This information is also used to evaluate compliance with 40 CFR § 191.15 and 40 CFR § 191.24, described in Chapter 8.0.

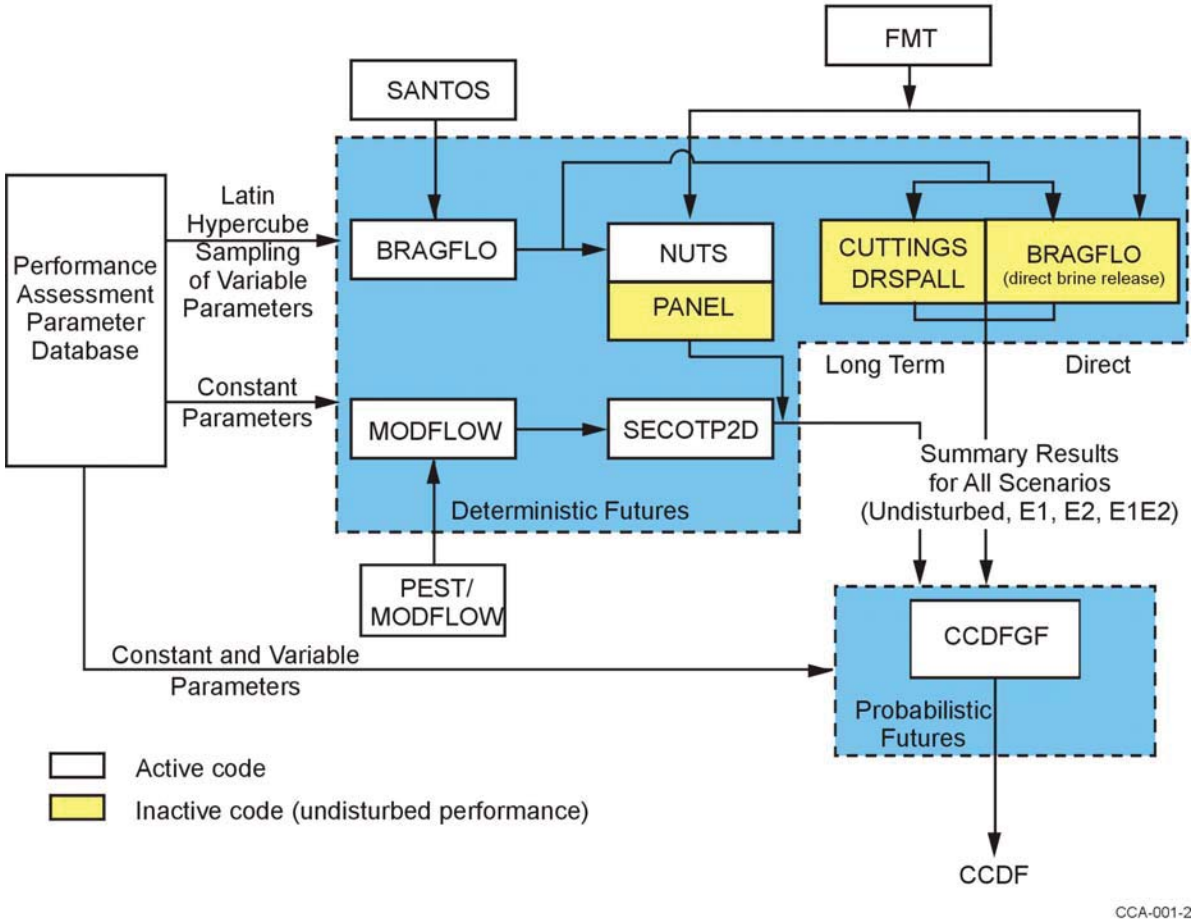

Figure 6-31. Code Configuration for the UP Scenario

6.4.13.2 Scaling Methodology for Disturbed Performance Scenarios

Although 10,000 probabilistic futures are generated to construct a CCDF, the major codes used in PA are executed far fewer times. The results of these calculations are used in part to construct the consequences of all of the probabilistic futures comprising a CCDF in a process called scaling.

The scaling methodology is simple, in concept. First, several simulations are performed with a code to develop a reference behavior for a particular event or process. Each simulation has a defined event occurring at a different time. Then, a large set of futures is developed probabilistically by random sampling. The behavior of the particular event or process in each of the probabilistically sampled futures is estimated by scaling the results of the limited number of deterministic calculations. This scaling is generally simple linear interpolation. For events or processes involving radionuclides, however, scaling becomes more complicated, since it incorporates the effects of radioactive decay and ingrowth. Because scaling is generally less intensive computationally than solving the matrix equations encountered in many PA codes, scaling is an efficient way to develop multiple probabilistic consequence estimates from a

limited number of deterministic calculations. Without scaling, fewer futures would be possible, and resolution in the CCDF would be reduced.

For example, assume that the process of interest is actinides released to the surface during drilling. It is impossible to explicitly model the infinite possibilities present in a probabilistic conceptualization of the future. Thus, scaling is used. To develop a reference behavior for scaling, the CUTTINGS_S code is executed several times with different intrusion times. A probabilistic method is then used to develop a large number of possible, different future intrusion times. To estimate the release to the surface in probabilistic futures, scaling is used in which release at the times in the deterministic calculations closest to the probabilistic time of interest are used as reference points for scaling or interpolation.

Scaling is used for all futures with intrusion boreholes. The times when various codes are executed to develop reference behavior, and how this reference behavior is used by other codes, is the subject of the next two sections. In presenting complete descriptions of the process for each scenario, there will be some duplication of discussion.

6.4.13.3 Estimating Long-Term Releases from the E1 Scenario

The E1 scenario is defined as a single penetration of a panel by a borehole that also intersects a brine reservoir. The code configuration with which the long-term consequences of E1 scenarios are estimated is illustrated in Figure Figure 6-32. For the E1 scenario, BRAGFLO is executed twice more for each CCDF (assuming the undisturbed performance run has already been executed), with the E1-type intrusion occurring at 350 years and 1,000 years. These three BRAGFLO calculations form the foundation for transport modeling that is used for scaling consequences to probabilistic futures.

Consistent with the BRAGFLO intrusion times, NUTS is executed with intrusions occurring at 350 and 1,000 years. These calculations form the basis for (1) estimating releases to the accessible environment via Salado interbeds, or to the surface; and (2) forming the actinide source term to the SECOTP2D code for Culebra transport. For computational efficiency, an intermediate scaling step is conducted prior to calculating the releases associated with probabilistic futures. In this intermediate step, NUTS reference conditions for Culebra releases by an intrusion at 100 years are calculated by using borehole flow from the 350-year intrusion. NUTS reference conditions for intrusions at 3,000, 5,000, 7,000, and 9,000 years are calculated by using borehole flow from the 1,000-year calculation. Thus, to scale consequences of E1 intrusions in probabilistic futures, reference conditions calculated by NUTS are available for 100, 350, 1,000, 3,000, 5,000, 7,000, and 9,000 years postclosure.

Consistent with the BRAGFLO intrusion times, reference behavior for actinide transport in the Culebra is calculated by SECOTP2D for the E1 intrusion occurring at 350 and 1,000 years. Because the equations governing actinide transport and retardation in SECOTP2D are linear, scaling releases to probabilistic E1 penetrations occurring at other times is easily accomplished.

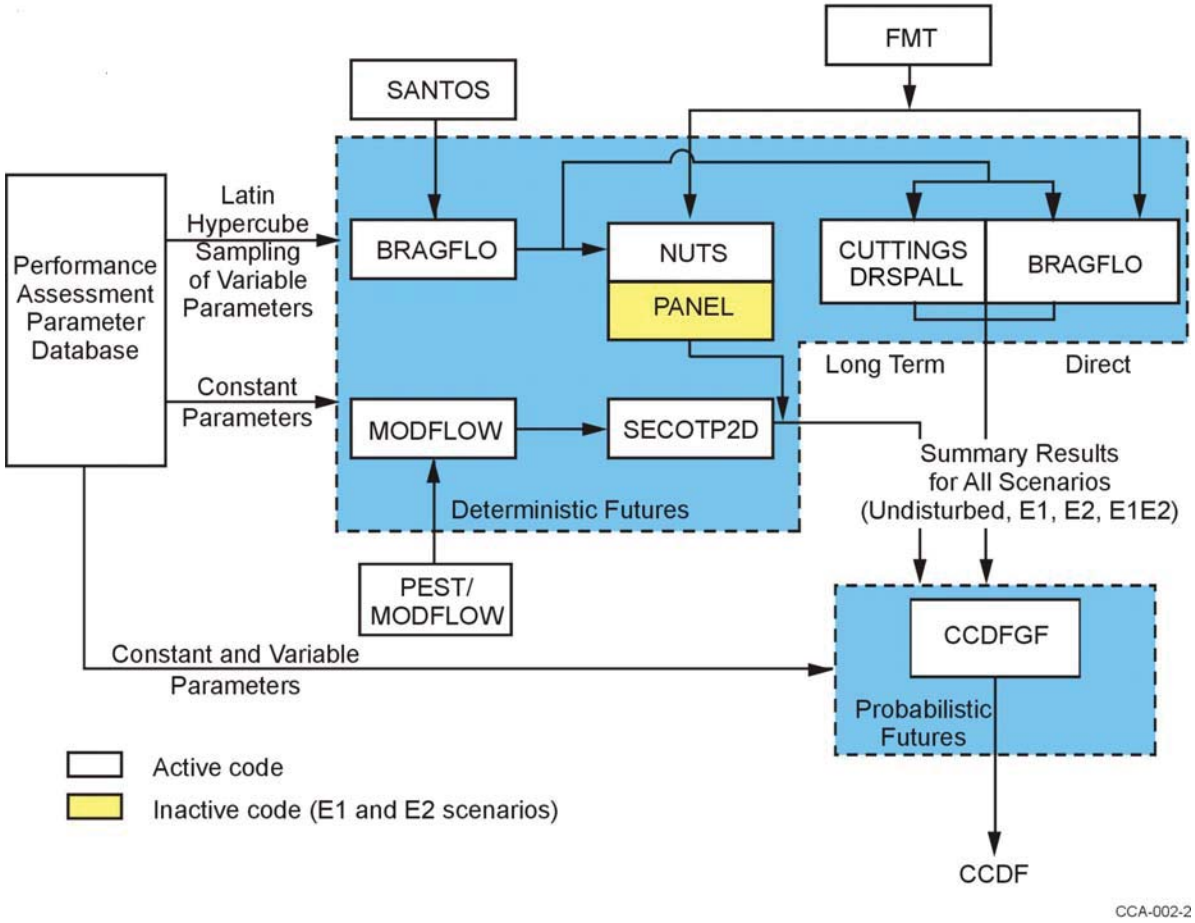

Figure 6-32. Code Configuration for DP Scenarios E1 and E2

6.4.13.4 Estimating Long-Term Releases from the E2 Scenario

The E2 scenario includes all futures with one or more exploratory borehole penetrations of a panel, none of which hits a brine reservoir. Estimating long-term releases from the E2 scenario is slightly more complex than the E1 scenario because the E2 scenario includes the possibility of multiple E2-type intrusions. The same codes used to construct the E1 scenario consequences are used to construct the E2 scenario consequences. These are indicated in Figure 6-33.

As with the E1 scenario, BRAGFLO is executed twice more for each CCDF (assuming the undisturbed performance run has already been executed), with the E2-type intrusion occurring at 350 years and 1,000 years. These three BRAGFLO calculations form the foundation for transport modeling to scale consequences to probabilistic futures.

NUTS is executed with intrusions occurring at 350 and 1,000 years, consistent with the BRAGFLO times of intrusion. These calculations form the basis for (1) estimating releases to the accessible environment via Salado interbeds, or to the surface; and (2) forming the actinide

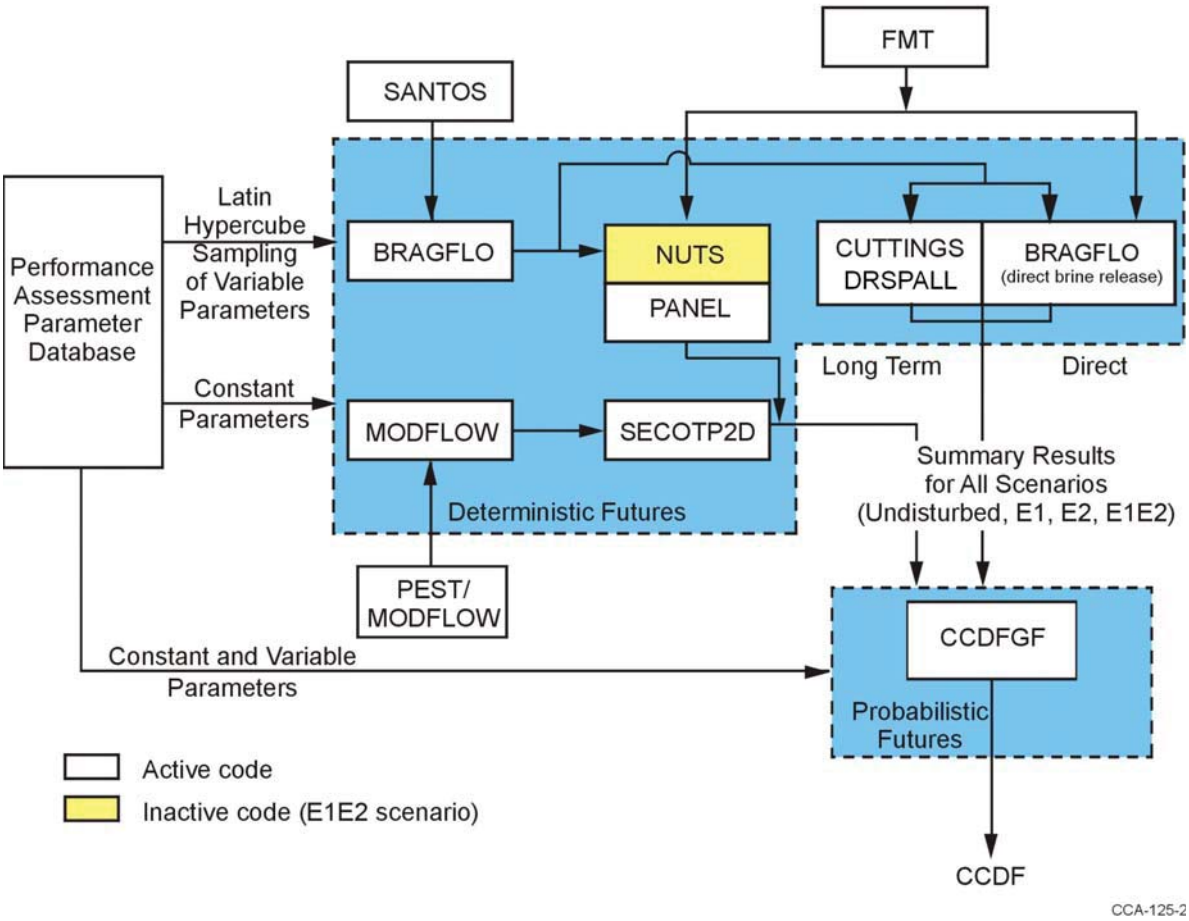

Figure 6-33. Code Configuration for DP Scenario E1E2

source term to the SECOTP2D code for Culebra transport. For computational efficiency, an intermediate scaling step is conducted prior to calculating the releases associated with probabilistic futures. In this intermediate step, NUTS reference conditions for Culebra release by an intrusion at 100 years are estimated by scaling borehole flow from the 350-year intrusion. NUTS reference conditions for intrusions at 3,000, 5,000, 7,000, and 9,000 years are estimated by scaling from the 1,000-year calculation. Thus, to scale consequences of E2 intrusions in probabilistic futures, reference conditions from NUTS calculations are available for 100, 350, 1,000, 3,000, 5,000, 7,000, and 9,000 years.

Consistent with the BRAGFLO intrusion times, reference behavior for actinide transport in the Culebra is calculated by SECOTP2D for the E2 intrusion occurring at 350 and 1,000 years. Because the equations governing actinide transport and retardation in SECOTP2D are linear, scaling releases to probabilistic E2 penetrations occurring at other times is easily accomplished. For futures with two or more E2-type intrusions (and no E1-type intrusions), a simplifying assumption is made. The additional increment to the Culebra's source term for the second and subsequent intrusions is assumed to be zero. This is considered reasonable because in the E2 scenario, the flux of brine to the Culebra is limited by the rate of flow from the Salado to the

waste panels, rather than by borehole properties. For second and subsequent E2 scenarios, only the direct releases to the surface are considered in CCDF construction.

6.4.13.5 Estimating Long-Term Releases from the E1E2 Scenario

The E1E2 scenario is defined as multiple boreholes intersecting a single waste panel, at least one of which is an E1 penetration of a brine reservoir (Section 6.3.2.2.3). The DOE uses both scaling and simplification to develop the consequences of this scenario. Similar to the E1 and E2 scenarios, BRAGFLO and related computer codes are executed with a deterministic sequence of future events to develop reference behavior for the E1E2 consequences (see Figure 6-33). Scaling estimates the consequences for events occurring at different times than those in the BRAGFLO calculations. Simplifying assumptions are used to develop the consequences of E1E2 occurrences in different waste panels, or the consequences of a different sequence of future events leading to the E1E2 scenario, than assumed in the deterministic BRAGFLO calculation.

Reference behavior for brine flow to the Culebra in the E1E2 scenario is predicted by the BRAGFLO disposal system model. This is the same model used to predict brine flow to the Culebra for the E1 and E2 scenarios. The geometry of the grid used is the same as that depicted in Figures 6-14 through 6-16; however, different assumptions are used about the borehole development through time. Even though the E1E2 scenario includes at least two boreholes intersecting the panel, the model used included only one borehole column. As described below, the assumptions used about the way brine mixes in the intruded panel are such that two boreholes are not needed to represent flow through the waste. The assumptions about the development of the borehole are related to the most likely (that is, most probable) sequence of events that gives rise to the E1E2 scenario.

It is most probable that the first borehole into any panel is an E2 borehole (see Section 6.4.12.6). In a BRAGFLO calculation after 1,000 years of undisturbed performance, the properties of the column of elements in BRAGFLO representing the borehole are changed. The changed properties represent the E2 borehole after the Rustler plug has degraded and silty sand fills the borehole. The period during which the plug is effective is not modeled to develop reference behavior for the E1E2 Culebra releases because relatively little happens in the disposal system when the Rustler plug is effective. Reference conditions are developed with the E1 intrusion that follows the initial E2 intrusion occurring after the 200 years it takes Rustler plugs to degrade because it is more probable that a subsequent E1 intrusion occurs after the Rustler plug has degraded. It is assumed that the E1 intrusion occurs 1,000 years after the E2 borehole becomes filled with silty sand, at a simulation time of 2,000 years. At 2,000 years, the properties of the borehole section below the repository horizon are changed to represent an open borehole (the E1 intrusion), allowing flow between the Castile brine reservoir and the repository. After another 200 years, the lower section is assumed to fill with silty sand; after another 1,000 years, the permeability of the lower section is decreased one order of magnitude because of salt creep. These changes are documented in Table 6-31.

Table 6-31. Changes in BRAGFLO Borehole Properties in Developing Reference Behavior for the E1E2 Scenario

Time (years)	Borehole Portion	Properties
0 – 1,000	All	Undisturbed conditions
1,000 – 2,000	Above waste panel Below waste panel	Silty sand Undisturbed conditions
2,000 – 2,200	Above waste panel Below waste panel	Silty sand Open borehole between panel and Castile
2,200 – 3,200	Above waste panel Below waste panel	Silty sand Silty sand
3,200 – 10,000	Above waste panel Below waste panel	Silty sand Silty sand, permeability decreased 1 order of magnitude

Thus, above the waste panel, the E1E2 borehole evolves as an E2 borehole from 1,000 years to 10,000 years. Below the waste panel, the borehole evolves as an E1 borehole from 2,000 to 10,000 years. At 2,200 years, there will be two boreholes above the waste panels with silty-sand properties. The assumption about upper borehole permeability most consistent with that for this scenario of complete mixing in the panel (discussed below) is that the upper portion of the E1 borehole is relatively impermeable and all flow is diverted to the E2 borehole. Therefore, the permeability of the upper borehole remains that of the E2 borehole at 2,200 years.

The concentration of actinides in liquid moving up the borehole assumes homogeneous mixing within the panel and is calculated with the code PANEL. PANEL is a mixing-cell model that sums BRAGFLO fluxes into the waste panel from the boreholes and Salado as inputs to the cell and subtracts the flow up the borehole as a depletion from the model. Brine moving up the borehole is assumed to be at its greatest possible actinide concentration according to the dissolved and colloidal actinide source term models (Sections 6.4.3.5 and 6.4.3.6). In PANEL calculations, all actinides that enter the borehole are conservatively assumed to reach the Culebra.

Random sampling of future events can produce different timing of borehole penetrations. From the time the E2 borehole penetrates until the E1 borehole penetrates, the consequences are determined as they are in the E2 scenario. When the E1 is drilled, completing the E1E2 configuration, the consequences are assumed to be similar to those modeled after the E1 penetration for the reference calculation, accounting for radionuclide decay and ingrowth.

Randomly sampling future events can also produce a different sequence of borehole types. In a randomly sampled future with many E2 intrusions into a waste panel prior to the E1, the consequences are determined as they are for the E2 scenario until the E1 occurs, at which time the E1E2 consequences are used. In a randomly sampled future with the sequence E1 then E2, the consequences are assumed to be similar to an E1 event until the E2 is drilled, whereupon the consequences are assumed to be similar to the E1E2 event following the E1 drilling. In a randomly sampled future with two E1 boreholes, the consequences are assumed to be similar to an E1 borehole until the second E1 is drilled, at which time the consequences are assumed to be similar to the E1E2 behavior.

For computational simplicity, the E1E2 calculations are scaled to E1 intrusions following a prior E2 intrusion occurring at 100, 350, 3,000, 5,000, 7,000, and 9,000 years, similar to the treatment of the E1 and E2 reference conditions.

6.4.13.6 Multiple Scenario Occurrences

For long-term brine flow into the Culebra, scenario occurrences are effectively defined at the panel scale for this PA. It was recognized in preliminary analysis of BRAGFLO results for this analysis that liquid flow between the separate panel and the rest of the repository sections is slow enough that the panel is effectively independent from the rest of the repository. Gas flow does occur, and for this reason, calculations of direct release to the surface are performed at the repository scale. For long-term brine flow to the Culebra, it is considered more reasonable, based on BRAGFLO results, to assume independent panel behavior in developing the CCDF than an interconnected repository.

It is very important to distinguish between model results and model assumptions on this point. For disposal system performance, the DOE is not assuming that panel closures isolate panels from one another. Rather, the DOE has assigned reasonable properties to the panel closures as input to the BRAGFLO calculations and has found that they result in limited liquid flow through the panel closures. Because simplification and scaling must be used to develop CCDFs, the DOE has to assume either that the repository is well interconnected or that the panels behave fairly independently. Based on model results for this analysis, the DOE has established that it is more reasonable in constructing a CCDF to assume that brine does not flow between panels. This simplification of detailed modeling results conducted in BRAGFLO is necessary for CCDF construction. It is not an assumption used in developing conceptual models of disposal system performance. This assumption does affect how scenario consequences are developed.

There are ten panels in the repository and the possibility of many intrusions. If panels behave independently, as they are assumed to in developing consequences of long-term brine flow in the CCDF, it is possible for different configurations of boreholes (scenarios) to occur in different panels. For example, an E1E2 type situation might occur in one panel, an E2 situation in a different panel, and an E1 situation in a third panel. In this example, there are essentially three scenario types occurring. For long-term release, the repository behaves as ten small modules (each comprising one panel), and a different borehole scenario can develop in each of those ten modules. Long-term releases in CCDF construction are based on the premise that releases from each of these modules are independent and that the cumulative release from the repository is equal to the sum of the cumulative releases from the different modules.

6.4.13.7 Estimating Releases During Drilling for All Scenarios

The reference behavior for cuttings and cavings from the first intrusion into a pressurized repository, regardless of whether it is an E1 or E2 intrusion, is established by calculations performed in the CUTTINGS_S code. Cavings releases are also dependent on the effective shear resistance to erosion and the angular velocity of the drill string (Appendix PA, Section PA-4.5). The effects of radioactive decay are captured by calculating reference behavior for cuttings and cavings by the CUTTINGS_S code at 100, 125, 175, 350, 1,000, 3,000, 5,000, 7,500, and 10,000 years.

Spall and direct brine releases during drilling are also dependent on pressure conditions in the repository, and reference releases are calculated by CUTTINGS_S for spall and BRAGFLO (direct brine release) at 100, 350, 1,000, 3000, 5,000, and 10,000 years for intrusions into lower, middle, and upper panels (Appendix PA, Section PA-4.7).

Radionuclide releases from the processes in the CUTTINGS_S code and direct brine release for intrusions occurring at intermediate times are scaled from the closest calculated releases, correcting for radioactive decay (see Section 6.4.12.3 and Figure 6-27). The cuttings and cavings portion of the CUTTINGS_S releases are further adjusted to account for the distribution of CH- and RH-TRU waste streams (see Sections 6.4.12.3 and 6.4.12.4). The processes of spallings and direct brine release are assumed to involve a large enough volume of waste that it is reasonable to use homogeneous waste with average activity to estimate releases.

For multiple-intrusion scenarios, the pressure in the repository at the time of the second and subsequent intrusions may be quite different from that at the time of the first intrusion. This is expected because of the assumptions of relatively permeable boreholes adopted in PA. Therefore, estimates of drilling releases to the accessible environment need to be formed for penetrations of a previously intruded repository. The reference behavior for these subsequent intrusion releases is calculated by the CUTTINGS_S code from BRAGFLO histories with E1- and E2-type intrusions at 350 and 1,000 years. Repository conditions calculated for the effects of a subsequent E1-type penetration are used in consequence analysis for both E1- and E2-type intrusions that follow an E1 intrusion. Conditions from the subsequent E2 calculations are used for intrusions that follow E2 intrusions only. E1 conditions are used for multiple combinations of boreholes that include at least one E1 intrusion, assuming that repository conditions will be dominated by Castile brine if any borehole connects to a brine reservoir. For futures in which more than two E2-type intrusions occur (and no E1-type intrusions occur), third and subsequent spall and direct brine releases are assumed to be the same as for the second release.

For both E1 and E2 conditions following a 350-year intrusion, spall and direct brine release calculations are performed at 550, 750, 2,000, 4,000, and 10,000 years. For the 1,000-year E1 and E2 intrusions, spall and direct brine release calculations are performed at 1,200, 1,400, 3,000, 5,000, and 10,000 years. Because the subsequent intrusion may penetrate either a previously-intruded panel or an unintruded panel, these calculations are done twice, once with initial conditions drawn from the previously-intruded panel in BRAGFLO, and once with conditions drawn from the BRAGFLO subsequent intrusion of the waste-disposal region. As with the first intrusion into a previously undisturbed repository, radionuclide releases from spall and direct brine release for intrusions occurring at intermediate times are scaled from the closest calculated releases, correcting for radioactive decay.

After flow through the repository has occurred for some time, in an E1E2 scenario, portions of the repository may be depleted of actinides. In the estimate of releases during drilling, however, the possibility is not considered that random drilling might penetrate portions of the repository already depleted of actinides from processes initiated by previous drilling. This is conservative because it tends to overestimate releases during drilling.

6.4.13.8 Estimating Releases in the Culebra and the Impact of the Mining Scenario

Ten thousand-year SECOTP2D calculations are performed with Culebra transmissivity fields reflecting undisturbed performance (no future mining within the Land Withdrawal Area) and disturbed performance (see Section 6.4.6.2.3). These calculations are performed with a unit source term of one kilogram of the actinide species of interest at 100 years. Because transport as modeled is a linear process, scaling is used to estimate the consequences of time-variable concentrations and different times of intrusion (see Appendix PA, Section PA-6.8.7). As well, mining may occur at random times in the future. The effect of mining on releases in the Culebra is determined in the following manner.

Boreholes intersecting the repository may provide a source of actinides to the Culebra with concentrations that vary through time. Until mining occurs, the transport behavior of actinides from these borehole sources is estimated by scaling the results of the undisturbed performance Culebra transport calculations. All actinides introduced into the Culebra by the time of mining are transported exclusively in the undisturbed performance flow fields. In other words, actinides in transit in the Culebra when mining occurs are not assumed to be affected and continue to be transported in the undisturbed flow field. Once mining occurs (assumed to be instantaneous), the transport behavior of all actinides subsequently introduced into the Culebra is estimated by scaling the results of the disturbed performance flow fields.

6.4.13.9 Final Construction of a Single CCDF

After consequences for all of the sampled probabilistic futures are estimated by the methodologies presented in the preceding sections, the information necessary to plot the CCDF associated with the probabilistic futures and the particular LHS vector is available.

The sequences of future events used in this PA were generated by random sampling. Thus, each sampled future is assigned an equal weight of occurrence to construct a CCDF. Each sequence of future events is assigned a weight of 1/10,000 of occurrence because 10,000 futures are used for each CCDF. Before plotting, an additional step is performed in which the weights of futures with similar consequences are summed. The first step in the plotting process is to order the grouped futures according to normalized release, as discussed in Section 6.1.1, from lowest normalized release to highest. Following this, the CCDF can be plotted by summing, for a given value of EPA normalized release, the probabilities of all futures whose normalized release exceeds the given value, and where the probabilities are assumed to be equal to the weights. Because the releases cS have been ordered so that $cS_i \leq cS_{i+1}$ for i=1 …, nS-1, the probability that cS exceeds a specific consequence value x is determined by the summation routine (duplicated from Section 6.1.1)

$$F(x) = \sum_{j=i}^{nS} pS_j, \tag{6.19}$$

where i is the smallest integer, that $cS_i > x$. This completes an analysis of stochastic uncertainty for a particular vector of variable values from the LHS sampling.

6.4.14 CCDF Family

The process of CCDF construction described in Section 6.4.13 is repeated once for each vector of subjectively uncertain variable values created by LHS. This process yields a family of CCDFs like those presented in Section 6.5. This family of CCDFs provides a complete display of both stochastic and subjective uncertainty as discussed in Section 6.1.2.

6.5 Performance Assessment Results

This section contains results of the recertification PA and demonstrates that the WIPP continues to comply with the quantitative containment requirements in 40 CFR § 191.13(a). See Section 6.1 for a discussion of the containment requirements. Criteria for presenting the results of PAs are provided by the EPA in 40 CFR § 194.34, and are discussed in Section 6.1.3. These criteria are also summarized here for clarity.

This CRA-2004 PA is different than the original certification PA in the CCA because it includes additional information, changes and new data required by 40 CFR§194.15 recertification application requirements. Section 6.0 details the changes and new information included in this PA. The results of this recertification PA conclude that the repository continues to comply with the disposal standards.

Additional detail about the results of the CRA-2004 PA is contained in Appendix PA, Section PA-9.0, which describes sensitivity analyses conducted as the final step in the Monte Carlo analysis. These sensitivity analyses indicate the relative importance of each of the sampled parameters in terms of their contribution to uncertainty in the estimate of disposal system performance. Analyses also examine the sensitivity of intermediate performance measures to the sampled parameters. Examples of such intermediate performance measures include the quantity of radionuclides released to the accessible environment by any one mechanism (for example, cuttings or direct brine releases), and other model results that describe conditions of interest such as disposal region pressure.

6.5.1 Demonstrating Convergence of the Mean CCDF

As discussed in Sections 6.4.13 and 6.4.14, individual CCDFs for the WIPP are constructed by estimating cumulative radionuclide releases to the accessible environment for 10,000 different possible futures. Each CCDF is calculated for a single LHS vector of input parameters and is conditional on the occurrence of that particular combination of parameter values. Multiple realizations of the PA calculations yield a family of CCDFs in which each individual CCDF is generated from a different LHS vector. Families of CCDFs calculated for the WIPP PA are based on 100 LHS vectors drawn from distributions of values for 64 imprecisely known parameters. As discussed in Section 6.1.2, mean and percentile CCDFs are constructed from families and provide summary measures of disposal system performance.

Criteria provided by the EPA in 40 CFR Part 194.34 address the statistical interpretation of CCDFs:

> The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at

> least a 0.95 probability. Values of cumulative release shall be calculated according to Note 6 of Table 1, Appendix A of Part 191 of this chapter. (40 CFR § 194.34(d))

> Any compliance application shall provide information which demonstrates that there is at least a 95 percent level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 of this chapter. (40 CFR § 194.34(f))

Information provided by the EPA in the Background Information Document for 40 CFR Part 194 clarifies the intent of these criteria.

In 40 CFR Part 194, EPA decided that the statistical portion of the determination of compliance with 40 CFR Part 191 will be based on the sample mean. The LHS sample sizes should be demonstrated operationally (approximately 300 when 50 variables are considered) to improve (reduce the size of) the confidence interval for the estimated mean. The underlying principle is to show convergence of the mean. (EPA 1996b, 8-41)

The DOE has chosen to demonstrate convergence of the mean and to address the associated criteria of 40 CFR Part 194 using an operational approach of multiple replication as proposed by Iman (1982). The complete set of PA calculations was repeated three times with all aspects of the analysis identical except for the random seed used to initiate the LHS procedure. Thus, PA results are available for three replicates, each based on an independent set of 100 LHS vectors drawn from identical CCDFs for imprecisely known parameters and propagated through an identical modeling system. This technique of multiple replication allows evaluation of the adequacy of the sample size chosen in the Monte Carlo analysis and provides a suitable measure of confidence in the estimate of the mean CCDF used to demonstrate compliance with 40 CFR § 191.13(a).

6.5.2 Complementary Cumulative Distribution Functions for the WIPP

Families of CCDFs for each of the three replicates are shown in Figures 6-36, 6-37, and 6-38. Each figure contains 100 CCDFs. These figures address the criterion stated in 40 CFR § 194.34(e):

> Any compliance application shall display the full range of CCDFs generated.

Figures 6-34 through 6-36 show that all 300 CCDFs lie below and to the left of the limits specified in 40 CFR § 191.13(a). They also show qualitatively that the three replicates yield very similar results. Quantitative verification of the similarity of the three replicates is demonstrated in Figure 6-37, which shows the mean CCDFs calculated for each of the three replicates, together with an overall mean CCDF that is the arithmetic mean of the three individual mean CCDFs. Figure 6-37 demonstrates two key points. First, the

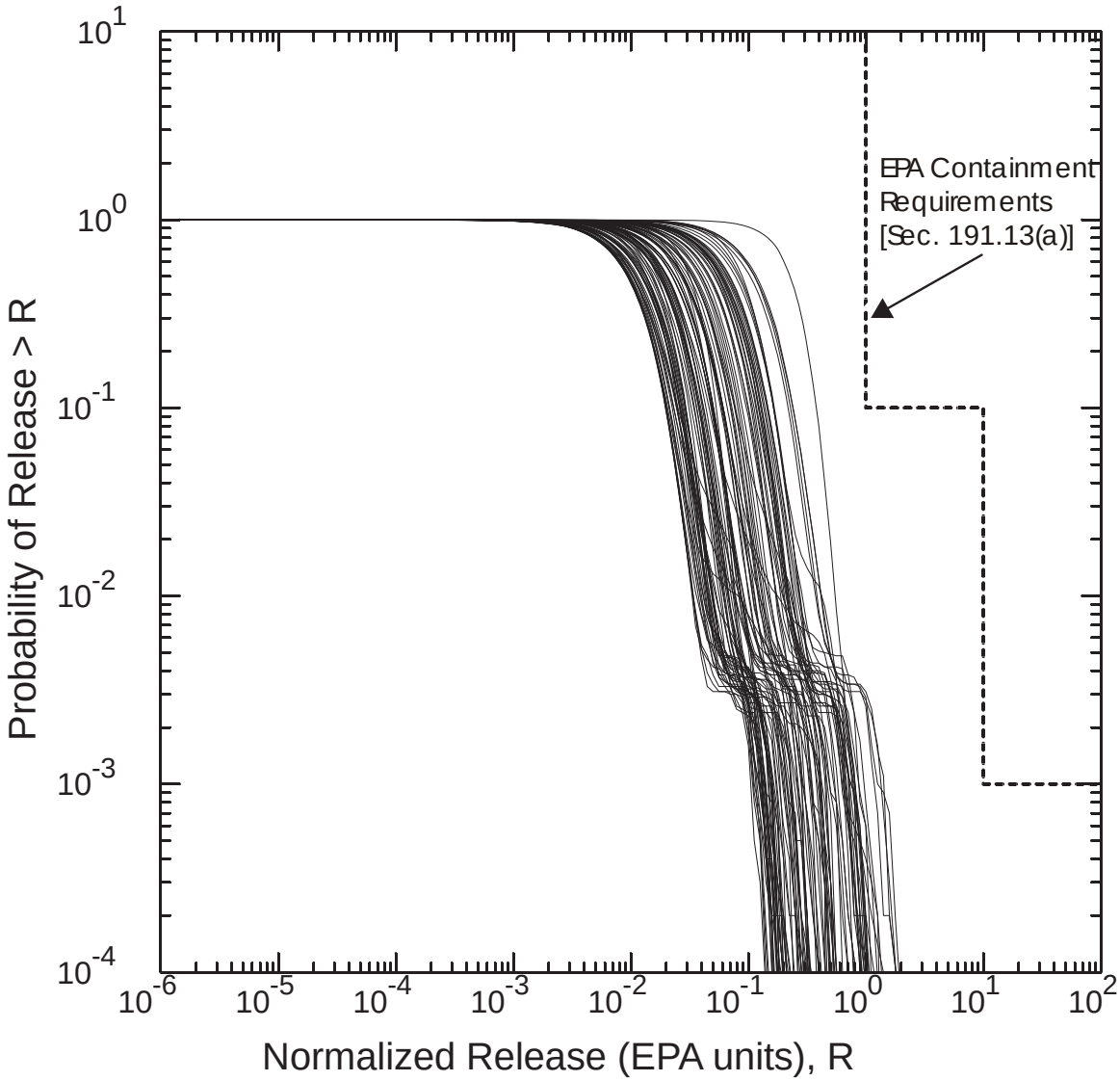

Figure 6-34. Distribution of CCDFs for Normalized Radionuclide Releases to the Accessible Environment from the WIPP, Replicate 1.

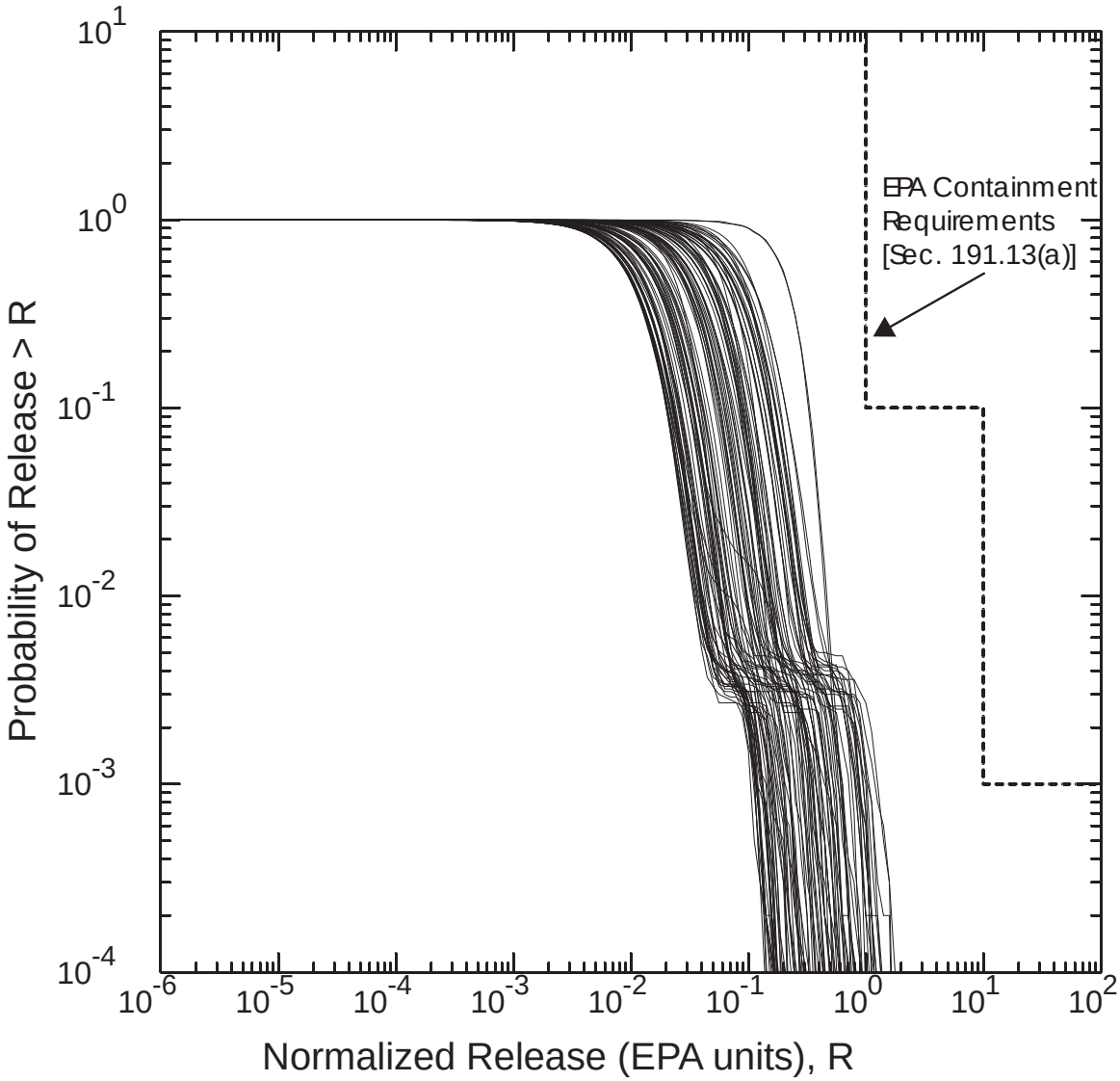

Figure 6-35. Distribution of CCDFs for Normalized Radionuclide Releases to the Accessible Environment from the WIPP, Replicate 2.

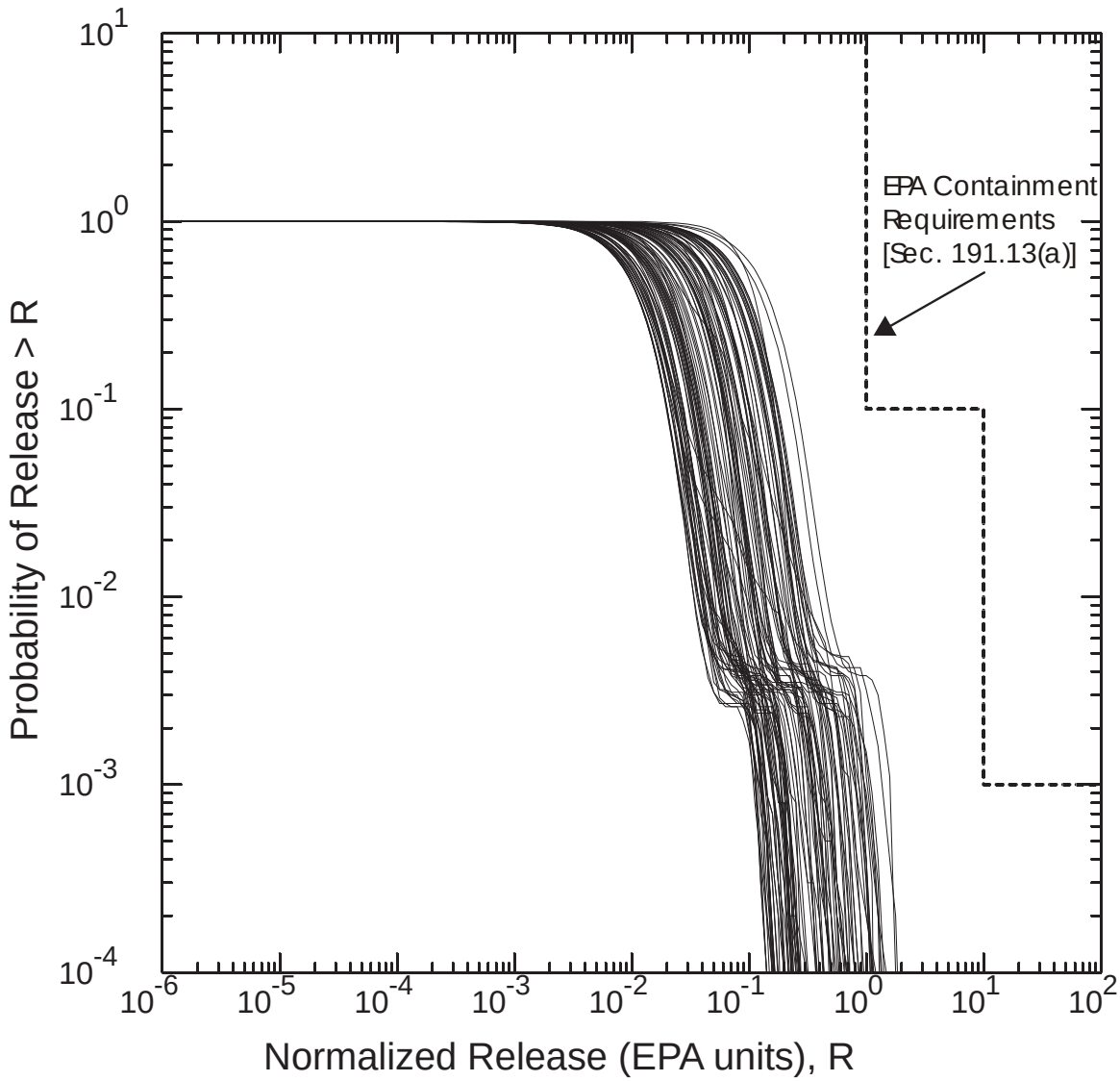

Figure 6-36. Distribution of CCDFs for Normalized Radionuclide Releases to the Accessible Environment from the WIPP, Replicate 3

overall mean CCDF lies entirely below the limits specified in 40 CFR § 191.13(a). Thus, the WIPP is in compliance with the containment requirements of 40 CFR Part 191. Second, the sample size of 100 in each replicate is sufficient to generate a stable distribution of outcomes. Within the region of regulatory interest (that is, at probabilities greater than $10^{-3}/10^{4}$ yr), the mean CCDFs from each replicate are essentially indistinguishable from the overall mean at the resolution of the figure. Figure 6-38 provides quantitative confirmation of the sufficiency of the sample size, by displaying the overall mean together with the 0.95 confidence interval of the Student's t-distribution estimated from the individual means of the three independent replicates (Iman 1982), as shown in Figure 6-37.

Figure 6-1 provides additional summary information about the distributions of CCDFs resulting from the three replicates. This figure shows CCDFs representing the mean,

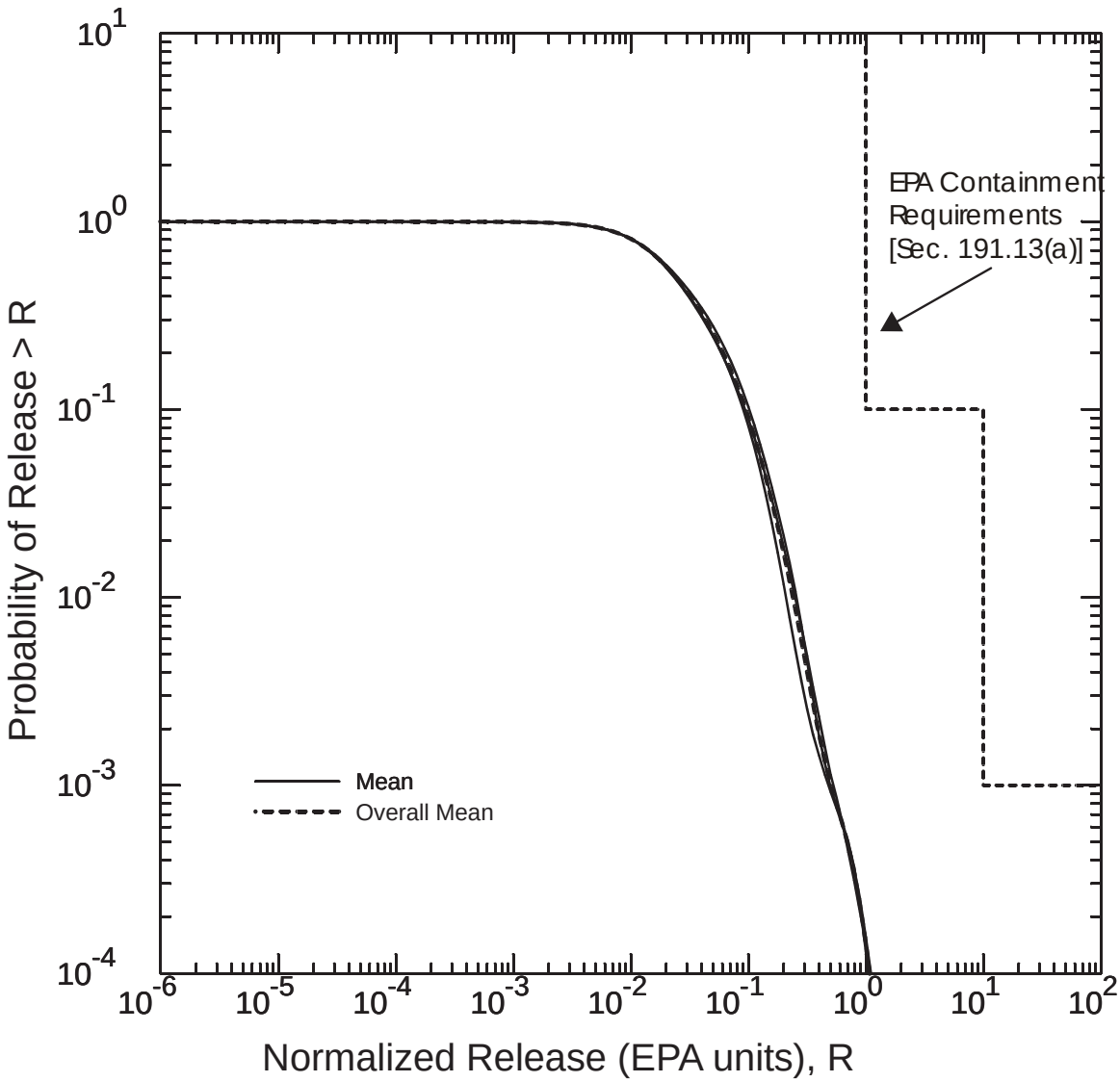

Note: Four CCDFs are shown, including three individual mean CCDFs calculated for each of the three distributions of CCDFs calculated for the three replicates and shown in Figures 6-34, 6-35, 6-36, and an overall mean CCDF that is the arithmetic mean of the three individual mean CCDFs."

Figure 6-37. Mean CCDFs for Normalized Radionuclide Releases to the Accessible Environment

median, and 10th and 90th percentile CCDFs from each replicate, together with the overall mean. Note that for each type of CCDF (for example, the 10th percentile), curves from each replicate overlie closely. This provides quantitative verification of the qualitative observation that distributions from each replicate appear similar.

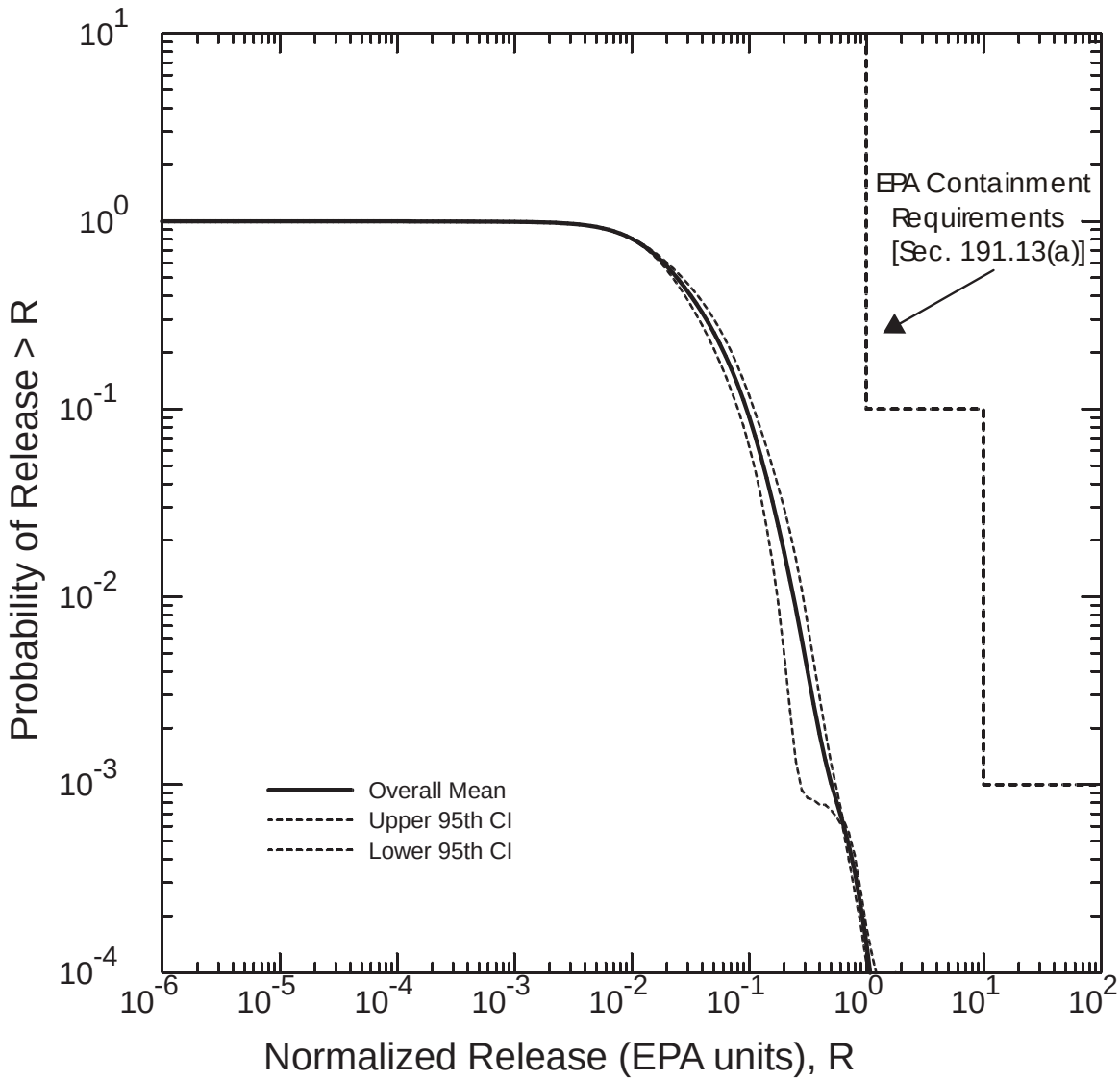

Note: The overall mean CCDF shown in Figure 6-37 is repeated together with the 0.95 confidence interval of the Student-t distribution estimated from the three individual mean CCFDs.

Figure 6-38. Confidence Levels for the Mean CCDF

6.5.3 Release Modes Contributing to the Total Radionuclide Release

Radionuclide releases to the accessible environment can be grouped into four categories according to their mode of release:

(1) cuttings and cavings releases,

(2) spallings releases,

(3) releases resulting from the direct release of brine at the surface during drilling, and

(4) releases in the subsurface following transport in groundwater.

Each of these four modes has the potential to contribute to the total quantity of radionuclides released from the repository, and therefore each has the potential to affect the position of the mean CCDF.

Figure 6-39 provides a display of the relative contribution of each mode to the total release. Releases for each of the three replicates are similar, and results are shown for replicate 1 only for simplicity. Mean CCDFs are shown for the total normalized release (this curve is also shown in Figure 6-1 and is the mean of the family shown in Figure 6-34) and for the normalized releases resulting from cuttings and cavings, spallings, and direct brine release. The mean CCDF for subsurface releases resulting from groundwater transport is not shown because those releases were less than 10^{-6} EPA units and the CCDF cannot be shown at the scale of this figure. Releases from cuttings and cavings are shown to be the most important contributors to the location of mean CCDF, with spallings also making a small contribution. Direct brine releases

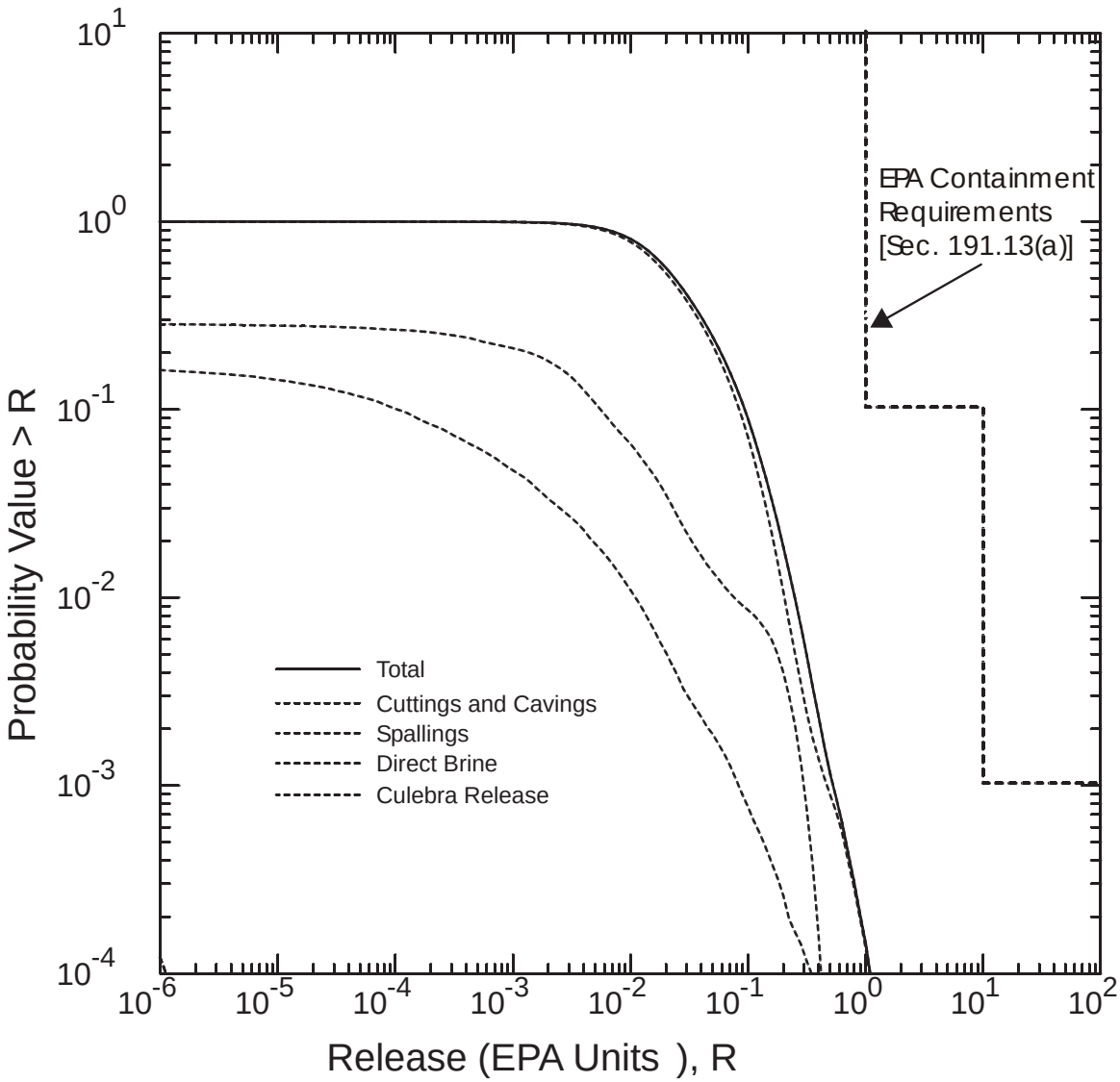

Note: Mean CCDFs are shown for the total normalized release (this curve is also shown in Figure 6-1 and is the mean of the family shown in Figure 6-34) and for the normalized releases resulting from cuttings and cavings, spallings, and direct brine release. The mean CCDF for subsurface releases resulting from groundwater transport is not shown because those releases were less that 10-6 EPA units and the CCDF cannot be shown at the scale of this figure.

Figure 6-39. Mean CCDFs for Specific Release Modes, Replicate 1

are less important, and have very little effect on the location of the mean CCDF. Subsurface groundwater releases are not important, and have essentially no effect on the mean CCDF. See Appendix PA, Section PA-9.0 for additional discussion of the relative importance of the release modes.

6.5.4 Uncertainty and the Role of Conservatism in the Compliance Demonstration

As defined in 40 CFR § 191.12, PAs must "estimate the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant events and processes."

Site characterization, repository design, and waste characterization activities, as described in Chapters 2.0, 3.0, and 4.0, respectively, have removed much uncertainty from the analysis. Uncertainties remain, however, about how best to characterize some aspects of the disposal system and how best to model the complex interactions between the waste and its surrounding environment. These remaining uncertainties have been incorporated in the performance assessment to the extent practicable through the use of reasonable and realistic assumptions about models and parameter values.

In general, the DOE has not attempted to bias the PA toward a conservative outcome, and the mean CCDF represents a reasonable estimate of the expected and, in the case of future human activities including intrusion, prescribed, performance of the disposal system. However, where realistic approaches to incorporating uncertainty are unavailable or impractical and where the impact of the uncertainty on performance is small, the DOE has chosen to simplify the analysis by implementing reasonable and conservative assumptions. These conservative assumptions are reviewed here, not because they bias the location of the mean CCDF, but rather because an understanding of their effects contributes qualitatively to the "reasonable expectation, on the basis of the record before the implementing agency, that compliance with [§] 191.13(a) will be achieved," as required by Section 191.13(b).

As noted in Section 6.2 and Appendix PA, Attachment SCR, in some cases processes have been omitted from the modeling system for simplicity because the only possible effects of including them would be beneficial to system performance. Examples include the decision to model radionuclide dissolution as an equilibrium process (assuming instantaneous leaching and dissolution), and the decision not to model sorption of radionuclides in the Salado or in the seal system.

In other cases, the DOE has made conservative decisions during the design of the conceptual and computational models, as listed in Table 6-32. Some conservative assumptions listed in this table are mentioned below. For example, within the repository portion of the BRAGFLO model, fluid flow in a single panel is treated as if all rooms were a single void (that is, pillars are omitted). This treatment allows brine flow to and from an intrusion borehole to contact more waste than it would if it followed a more realistic flow path between rooms. The effect is conservative with respect to brine flow up a plugged and abandoned borehole. Similarly, the DOE has chosen to model fluid flow through plugged and abandoned boreholes as if all intrusions occurred into a down-dip (that is, southern) panel. As modeled, downdip panels tend to have more brine in them than up-dip panels (see Appendix PA, Section PA-8.0) and this assumption therefore may result in overestimating the amount of brine present in intruded panels.

Radionuclide dissolution to solubility limits is modeled as instantaneous. For E1E2 scenarios, complete mixing is assumed within the intruded panel, and all brine that flows out of the panel and up the borehole is assumed to have been in contact with waste.

Within the shaft seal system, concrete components are modeled as if they degrade after emplacement, underestimating their potential to limit fluid flow over the long-term. For direct releases and E1E2 releases to the Culebra, processes of actinide transport and retardation are not modeled within the intrusion borehole and all actinides that enter the borehole are assumed to be transported to the surface or into an overlying transmissive unit. Within the Culebra (which

modeling indicates will be the only transmissive unit that will receive long-term flow from the borehole), hydraulically significant fractures are assumed for modeling simplicity to be present everywhere, even though test data indicate that the portions of the Culebra above the waste disposal region behave as an unfractured, single porosity matrix.

These conservative assumptions have not significantly affected the location of the mean CCDF, which, as shown in Section 6.5.3, is dominated by cuttings and cavings releases that are, with one exception, independent of the conservative simplifications described here. As discussed in Appendix PA, the parameter making the largest contribution to uncertainty in the location of the mean CCDF is the effective shear resistance of the waste, which affects the quantity of waste eroded from the borehole wall and transported to the surface as cavings. In the absence of data describing the reasonable and realistic future properties of degraded waste and MgO, effective shear resistance of the waste is a parameter for which the DOE has selected a conservative distribution (see Appendix PAR, Parameter 33).

6.5.5 Summary of the Demonstration of Compliance with the Containment Requirements

The WIPP continues to comply with the containment requirements of 40 CFR § 191.13(a), as shown by Figures 6-34 through 6-38. Figures 6-37 and 6-38 demonstrate that the sample size of 100 chosen for this analysis is sufficient to provide the level of statistical confidence specified in 40 CFR § 194.34.

Additional confidence in the compliance determination comes from examination of Figure 6-39, which shows that the location of the mean CCDF depends almost entirely on the relatively simple processes that contribute to cuttings and cavings releases resulting from inadvertent human intrusion by drilling. Uncertainties related to the characterization of the natural system and the interaction of waste with the disposal system environment have little effect on long-term performance. The natural and engineered barrier systems, as described in Chapters 2.0 and 3.0, will provide robust and effective containment of TRU waste even if the repository is penetrated by multiple borehole intrusions.

Table 6-32. Conservative Model and Parameter Assumptions Used in PA (from Appendix PA, Attachment MASS, Table MASS-1)

Conservative Assumption	Code	Cross-Reference
Long-term flow up plugged and abandoned boreholes is modeled as if all intrusions occur into a down-dip (southern) panel.	BRAGFLO	Section 6.4.3
Pillars, individual drifts and rooms are not modeled for long-term performance, and containers provide no barrier to fluid flow.	BRAGFLO	Section 6.4.3, Appendix PA, Attachment MASS, Section 5.0
Brine in the repository will contain a uniform mixture of dissolved and solid-state species. All actinides have instant access to all repository brine.	NUTS PANEL	Section 6.4.3.4 Appendix PA, Attachment SOTERM, Section 2.2
Radionuclide dissolution to solubility limits is instantaneous.	NUTS PANEL	Sections 6.4.3.5 and 6.4.3.4 (Appendix PA, Attachment SOTERM, Section 3.3,)
Radionuclides are not retarded by shaft seals.	NUTS	Section 6.4.4
Shaft concrete components of the lower shaft are modeled as if they degrade after emplacement.	BRAGFLO	Section 6.4.4 Appendix PA, Attachment PAR
The permeability of the DRZ is sampled with the low value similar to intact halite and the higher value representing a fractured material.	BRAGFLO	Section 6.4.5.3 Appendix PA, Attachment MASS, Section 13.4
The Los Medaños member of the Rustler, Tamarisk, and Forty-niner are assumed to be impermeable.	BRAGFLO SECOFL2D	Sections 6.4.6.1, 6.4.6.3, and 6.4.6.5 Appendix PA, Attachment MASS, Section 14.0
Sorption of actinides in the borehole is not modeled.	NUTS	Section 6.4.5.4 Appendix PA, Attachment MASS, Section 13.5
Sorption occurs on dolomite in the matrix. Sorption on clays present in the Culebra is not modeled.	SECOTP2D	Section 6.4.6.2.1 Appendix PA, Attachment MASS, Section 15.2
Particle waste shear is based on properties of marine clays, considered a worst case.	CUTTINGS_S	Section 6.4.7.1 Appendix PA, Attachment PAR
The concentration of actinides in liquid moving up the borehole in the E1E2 scenario assumes homogeneous mixing within the panel.	CCDFGF PANEL	Section 6.4.13.5

Table 6-32. Conservative Model and Parameter Assumptions Used in PA (from Appendix PA, Attachment MASS, Table MASS-1) — Continued

Conservative Assumption	Code	Cross-Reference
For all direct releases to the surface and the E1E2 source term to the Culebra, any actinides that enter the borehole are assumed to reach the surface or Culebra, respectively.	CUTTINGS_S DRSPALL BRAGFLO PANEL CCDFGF	Section 6.4.7.1 Section 6.4.13.5
A hemispherical geometry with one-dimensional spherical symmetry defines the flow field and cavity in the waste	DRSPALL	Section 6.4.7.1 MASS.16.1
Tensile strength, based on completely degraded waste surrogates, is felt to represent extreme, low-end tensile strengths because it does not account for several strengthening mechanisms	DRSPALL	Section 6.4.7.1 MASS.16.1
Shape factor is 0.1, corresponding to particles that are easier to fluidize and entrain in the flow	DRSPALL	Section 6.4.7.1 MASS.16.1
Retardation is assumed to not occur in the Salado.	NUTS CCDFGF	Section 6.4.5.4.2
Depletion of actinides in parts of the repository that have been penetrated by boreholes is not accounted for in calculating the releases from subsequent intrusions at such locations.	CUTTINGS_S	Section 6.4.13.7
Hydraulically-significant fractures are assumed to be present everywhere in the Culebra.	SECOTP2D	Section 6.4.6.2.1

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7.0 ASSURANCE REQUIREMENTS

In the Preamble to Title 40 of the Code of Federal Regulations (CFR) Part 191 (EPA 1985) (50 FR 30879), the U.S. Environmental Protection Agency (EPA) points out that:

> There are too many uncertainties in projecting the behavior of natural and engineered components for many thousands of years—and too many opportunities for mistakes or poor judgments in such calculations—for the numerical requirements on overall system performance in Subpart B to be the sole basis to determine the acceptability of disposal systems for these very hazardous wastes.

In view of this, the EPA developed assurance requirements (40 CFR § 191.14) to ensure that implementing agencies act cautiously and take steps to reduce the impacts of these uncertainties. According to the EPA, these assurance requirements are considered an essential complement to the containment requirements, which, when implemented, should ensure that the level of protection desired by the EPA is achieved. Contained in 40 CFR § 191.14 are these six separate assurance requirements:

- active institutional controls,
- monitoring,
- passive institutional controls,
- use of different types of barriers,
- resource disincentives, and
- waste removal.

Figure 7-1 provides a timeline illustrating the implementation of these assurance requirements. Waste removal is not included in Figure 7-1 because it is not a planned activity. Waste removal is discussed in CCA Appendix WRAC. See Table 1-7 for a list of appendices that provide additional information supporting this chapter.

The provisions of 40 CFR 194 (EPA 1996a) contain detailed criteria that the U.S. Department of Energy (DOE) is to use in implementing the assurance requirements contained in 40 CFR 191. The following sections detail the DOE's compliance with the assurance requirements of 40 CFR 191 and the associated certification criteria in 40 CFR 194. In addition to addressing the six assurance requirements stated above, the DOE used some conservative assumptions in the performance assessment that provide additional assurance. Use of conservative assumptions is discussed in Section 6.5.4.

7.1 Active Institutional Controls

Active institutional controls and passive institutional controls satisfy two roles:

(1) they meet assurance requirements per 40 CFR 191 and 194, and

(2) they contribute to performance assessment per 40 CFR 194.

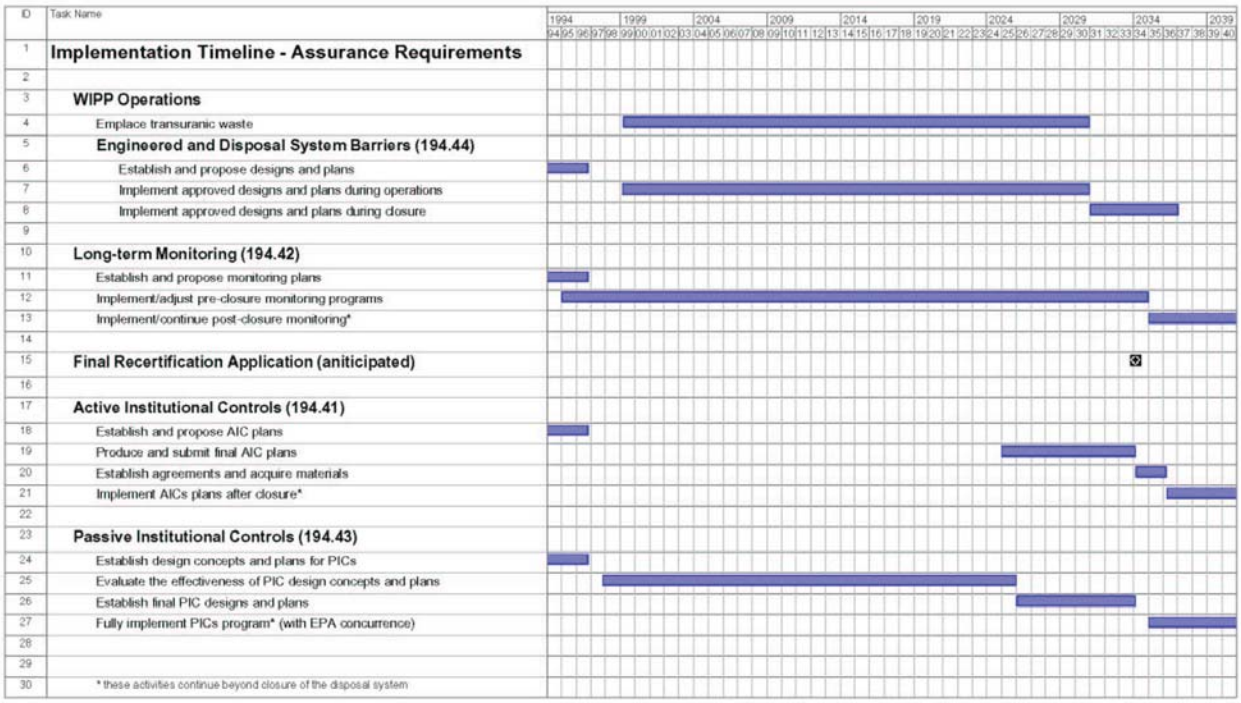

Figure 7-1. Implementation Timeline – Assurance Requirements

Once the facility at the Waste Isolation Pilot Plant (WIPP) is decommissioned and decontaminated (D&D), positive actions (active institutional controls) will be taken to ensure site access control. Active institutional controls begin after final facility closure. The EPA has specified that no more than 100 years of active institutional controls can be assumed in predictions of long-term performance. The DOE interprets this requirement to mean that control programs should be implemented as long as such controls are useful and practical, but credit for active institutional controls cannot be considered in the performance assessment beyond 100 years from the final closure of the repository. Therefore, performance assessment does not consider credit for active institutional controls beyond 100 years.

The EPA defines active institutional controls as "(1) controlling access to a disposal site by any means other than passive institutional controls, (2) performing maintenance operations or remedial actions at the site, (3) controlling or cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance" (40 CFR § 191.12). Active institutional controls to be used by the DOE include facility guarding, evaluation of land use in the area, postoperational monitoring, land reclamation, and maintenance of fences and buildings. In addition, active institutional controls are integrated with the D&D activities described in CCA Appendix D&D. That appendix remains unchanged and, therefore, is not included in this recertification application.

During the rulemaking process for the original WIPP certification, the DOE developed and provided the following to the EPA:

(1) detailed information regarding the schedule for implementing the active institutional controls,

(2) DOE's approach to maintaining and replacing active institutional controls, and

(3) minimum standards that will be applied during construction and maintenance of the active institutional controls.

This information was provided to the EPA via letter dated February 7, 1997 (Docket A-93-02, Item II-I-07, Enclosure 1c).

The DOE also provided sample inspection checklists for site surveillance and maintenance and a discussion of training requirements that will be applied to site patrol personnel. The DOE conducted a "capabilities survey" of regional security firms and concluded that the surveillance requirements for the WIPP site were within the scope of current local capabilities. The EPA contacted the Eddy County Sheriff's Office and confirmed that, while the Sheriff's Office may be able to patrol the site after closure, the services of a private firm would have to be contracted for routine patrols. On the basis of the documentation provided by the DOE, the EPA found the active institutional controls plans to be adequate and that the implementation may be effective for 100 years after disposal (63 FR 27395; see also CARD 41 located in EPA Docket A-93-02, Item V-B-2).

7.1.1 Requirements for Active Institutional Controls

In prescribing active institutional controls, the EPA has specified that "active institutional controls over disposal sites should be maintained for as long a period of time as is practicable after disposal" (40 CFR § 191.14[a]). The EPA addresses the effectiveness of these controls and the length of the time for which such controls should be considered effective for the performance assessment.

Section 194.41(a) specifies that "any compliance application shall include detailed descriptions of proposed active institutional controls, the controls' location, and the period of time the controls are proposed to remain active." Section 194.41(a) also states that any assumptions pertaining to the effectiveness of active controls in preventing inadvertent human intrusion should be supported by such descriptions. This section provides support for the assumptions pertaining to the active institutional controls program for the WIPP facility. Prior to decommissioning of the facility and full implementation of the active controls program, the DOE will reevaluate the proposed active controls program and make any changes necessary as indicated by experience and evaluation of data. The design of the DOE's active controls program is described in CCA Appendix AIC.

For the purposes of this application, the DOE will begin the active controls period within sixty days of completion of final facility closure.

7.1.2 Objectives for Active Institutional Controls

The primary goal of DOE's active institutional controls program is to prevent unauthorized use of the WIPP site. Because of the massive body of rock that separates the waste from the accessible environment, there are not many activities that pose a threat to the WIPP disposal system. The threats that are severe enough or likely enough to consider are addressed in Appendix PA, Attachment SCR and in the conceptual models description located in Section 6.4. The DOE has identified four objectives for the design of the active controls program: (1) eliminating those site features that would cause future populations to develop the WIPP site (see Section 7.1.3.1), (2) identifying allowed and disallowed activities, (3) identifying and minimizing the impacts of the intentional user, and (4) controlling allowed activities and preventing unallowed activities. In addition, the DOE will install and protect monitoring equipment and any test facilities established for evaluating the long-term marker system.

In order to design an active controls program around these four objectives, the DOE has assumed the following:

- site restoration will be to as near the original condition as practicable,
- future authorized site uses will not be significantly different than they are now, as described in CCA Appendix LMP, and
- a threat of future unauthorized use exists.

The WIPP Land Management Plan (LMP) (DOE/WIPP 93-004) provides guidance for managing the land withdrawn for the WIPP through project decommissioning. Active institutional controls

are implemented after decommissioning and, by definition, the LMP is not part of the WIPP active institutional controls program. A planned change pursuant to 40 CFR § 194.4(b)(3) was submitted to the EPA in January 2002 requesting removal of CCA Appendix LMP from the Compliance Baseline. In a letter sent to the DOE dated March 15, 2002 (Marcinowski to Triay; EPA Docket A-98-49, II-B-3, Item 24), the EPA approved the planned change allowing CCA Appendix LMP to be eliminated from future recertification applications.

Restoration of the WIPP site includes any activities associated with demobilization following D&D. In addition, as part of the active institutional controls program, the DOE will implement monitoring systems suitable for assessing disposal system performance. The objectives of the active institutional controls program, the monitoring program, and the decommissioning plan overlap; therefore, the DOE believes it is both prudent and within the EPA's intent to conduct these programs simultaneously. This provides for a more comprehensive understanding of the multitude of activities that will be taking place during the active controls period.

7.1.3 Implementation of the Active Institutional Controls Program

The first step in the process of implementing the active institutional controls program was to identify measures needed to satisfy the active institutional controls requirements. Certain characteristics of active institutional controls measures have been identified, such as minimizing features that would attract future development of the site, warning of potential hazards through signage, implementing the measures for at least 100 years, addressing the standards, and preventing development. These characteristics were used to develop conceptual designs for active institutional controls.

Some active institutional controls were obvious at the outset, including site access control, site remedial actions, site maintenance, and site monitoring. Information and specifications useful in implementing these and possibly other controls have been gathered. A detailed explanation of the resulting active institutional controls is provided in CCA Appendix AIC (Section 2). The plan will be reviewed periodically and updated as appropriate during WIPP's operations phase. Ongoing review and evaluation will ensure that the active institutional controls implemented are appropriate for the conditions that may exist at that time. The DOE will review the design prior to implementation, and should it be determined the design should be modified, the changes shall be reported per the change requirements at 40 CFR § 194.4.

The final operational activity at the repository will be closing the waste disposal area and sealing the shafts. All surface structures, except for the concrete hot cell structure (CCA Appendix AIC), and a sufficient quantity of salt tailings to support construction of the permanent marker berm (CCA Appendix PIC) will be removed and the site regraded and revegetated to as near its original condition as practicable.

In order to determine the active controls that would be beneficial, the DOE analyzed the types of land uses anticipated and, based on that analysis, developed a design plan for active institutional controls. The following two sections summarize the analysis and the design plan.

7.1.3.1 Analysis of Activities

The purpose of the analysis of activities is to determine the types of disturbances that may be associated with each activity, the depth of such disturbances, and the need for any mitigation of these activities. These activities are supported with screening decisions in Appendix PA, Attachment SCR. This section addresses the following activities:

- ranching,
- farming,
- hunting,
- scientific activities,
- utilities and transportation,
- groundwater pumping,
- surface excavation,
- potash exploration,
- hydrocarbon exploration,
- construction, and
- hostile and illegal activities.

Table 7-1 indicates the active institutional controls that will be applied to prevent unauthorized activities.

7.1.3.1.1 Ranching

Description of the Activity: Ranching involves the management of herds of cattle on the public lands surrounding and including the WIPP. These activities are regulated on federal lands such as the WIPP under a permitting process administered by the Bureau of Land Management (BLM). There is little surface-disturbing activity associated with ranching except for the construction of fences, the construction and operation of watering facilities, and the occasional drilling of groundwater wells. Currently, only the 277 acres within the Exclusive Use Area are not used for ranching. In the future, barbed wire enclosures will be constructed to provide security for monitoring facilities, test areas, and construction areas. Eventually, the entire surface is expected to be released for ranching activities. Only those activities associated with groundwater use could have any impact on the disposal system. These are discussed in Section 7.1.3.1.6. Figure 7-2 depicts the current grazing allotments on the WIPP site.

Goal of Active Controls: Active controls will ensure that grazing leases are administered consistently and in compliance with applicable regulations. Fencing will be needed to protect government property. In addition, areas will be fenced as needed to prevent cattle from disturbing reclaimed areas until vegetation has been reestablished.

7.1.3.1.2 Farming

Description of the Activity: Farming includes soil preparation, planting, irrigation, and harvesting. Significant quantities of water are needed to support crops in the Delaware Basin.

Table 7-1. Effectiveness of Active Controls Activities

Active Institutional Controls	*Activities*										
	Ranching	*Farming*	*Hunting*	*Scientific Activities*	*Utilities and Transpor-tation*	*Ground-water Pumping*	*Excavation*	*Potash Explora-tion*	*Hydrocarbon Exploration*	*Con-struction*	*Hostile and Illegal Activities*
Fence	●[1]	●	●				●			●	
Roadway				●	●	●					
Signs		●	●		●		●	●	●	●	●
Contract for Inspection and Maintenance	●	●	●	●	●	●	●	●	●	●	●
Security Surveillance	●	●	●	●	●	●	●	●	●	●	●
Testing				●	●						
Disposal System Monitoring				●		●					
Permanent Marker System Installation				●							
Response	●	●	●	●	●	●	●	●	●	●	●
Reporting	●	●	●	●	●	●	●	●	●	●	●

[1] "●" Indicates component addressed by active institutional controls

Crops grown in the farming area nearest to the WIPP include cotton, alfalfa, peppers, and pecans. Small quantities of other crops are also grown. Farming using irrigation would require access to large amounts of fresh water, either through the diversion of surface water or the construction of groundwater wells. There is currently no known farming near the WIPP because of the lack of good quality water and the poor soil composition. Farming, therefore, is screened out of the performance assessment on the basis that any impacts are of low consequence to the disposal system (see Appendix PA, Attachment SCR, Arable Farming FEP H53).

Goal of Active Controls: While farming is unlikely, the fence, signs, and other measures will prevent farming activities from disturbing test areas or affecting monitoring locations.

7.1.3.1.3 Hunting

Description of the Activity: Currently, hunting occurs outside the WIPP Off Limits Area. The prohibition from hunting is mandated by DOE policy. Unless the restrictions are lifted, hunting will continue to be prohibited in this 1,454-acre (590-hectare) area. The restriction has been placed to provide protection for facilities and personnel working at the WIPP. Game animals in the vicinity include deer, small mammals, and birds. There are no hunting activities that are anticipated to impact the disposal system. Figure 7-3 depicts the area within the WIPP site boundary where hunting is allowed.

Goal of Active Controls: Protection of facilities and personnel engaged in monitoring, reclamation, and testing activities will be needed throughout the active controls period. Local and state hunting laws and restrictions will apply.

7.1.3.1.4 Scientific Activities

Description of the Activity: Scientific activities can include both those conducted by the DOE for the WIPP and those conducted by outside organizations. Types of activities include archeological investigations, wildlife studies, vegetation studies, grazing studies, geomorphic studies, passive marker testing, passive marker construction, hydrologic studies, disposal system monitoring, and others. Prolonged studies of vegetation, geomorphic features, or grazing impacts may require the construction of fenced enclosures. Some may involve the placement of monitoring or other types of equipment or monuments that need to be protected from vandalism.

Goal of Active Controls: In the case of scientific studies, active controls will ensure that scientific activities can proceed undisturbed without impacting the disposal system. Specific needs for protection may be identified with each study proposed for the area.

7.1.3.1.5 Utilities and Transportation

Description of the Activity: Currently, the WIPP site boundary is traversed by several pipelines (natural gas), buried telephone lines, power lines, a highway, and a railroad. Future transportation needs are expected to remain the same. Construction and maintenance of utilities

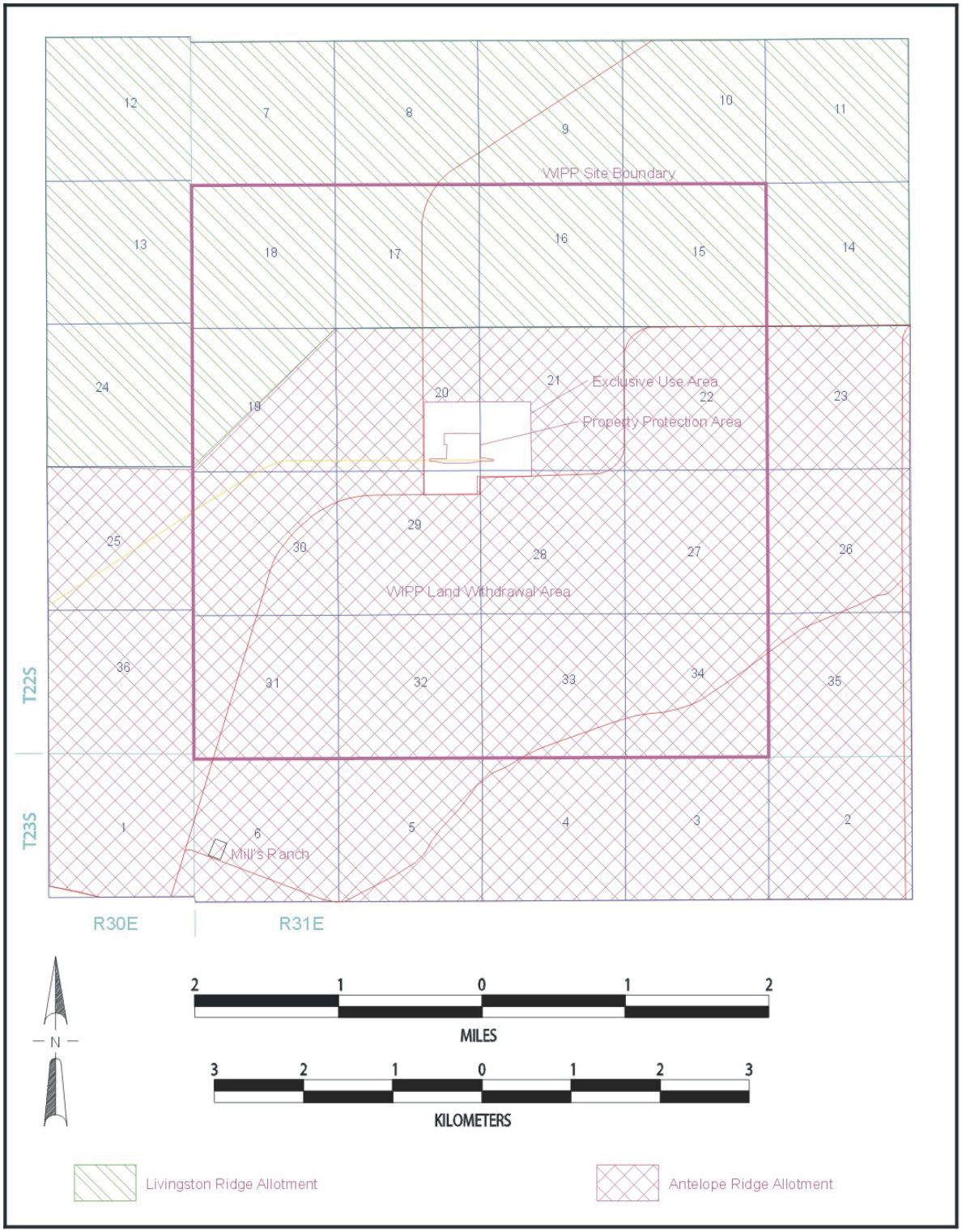

Figure 7-2. Grazing Allotments on the WIPP Site as of September 2002

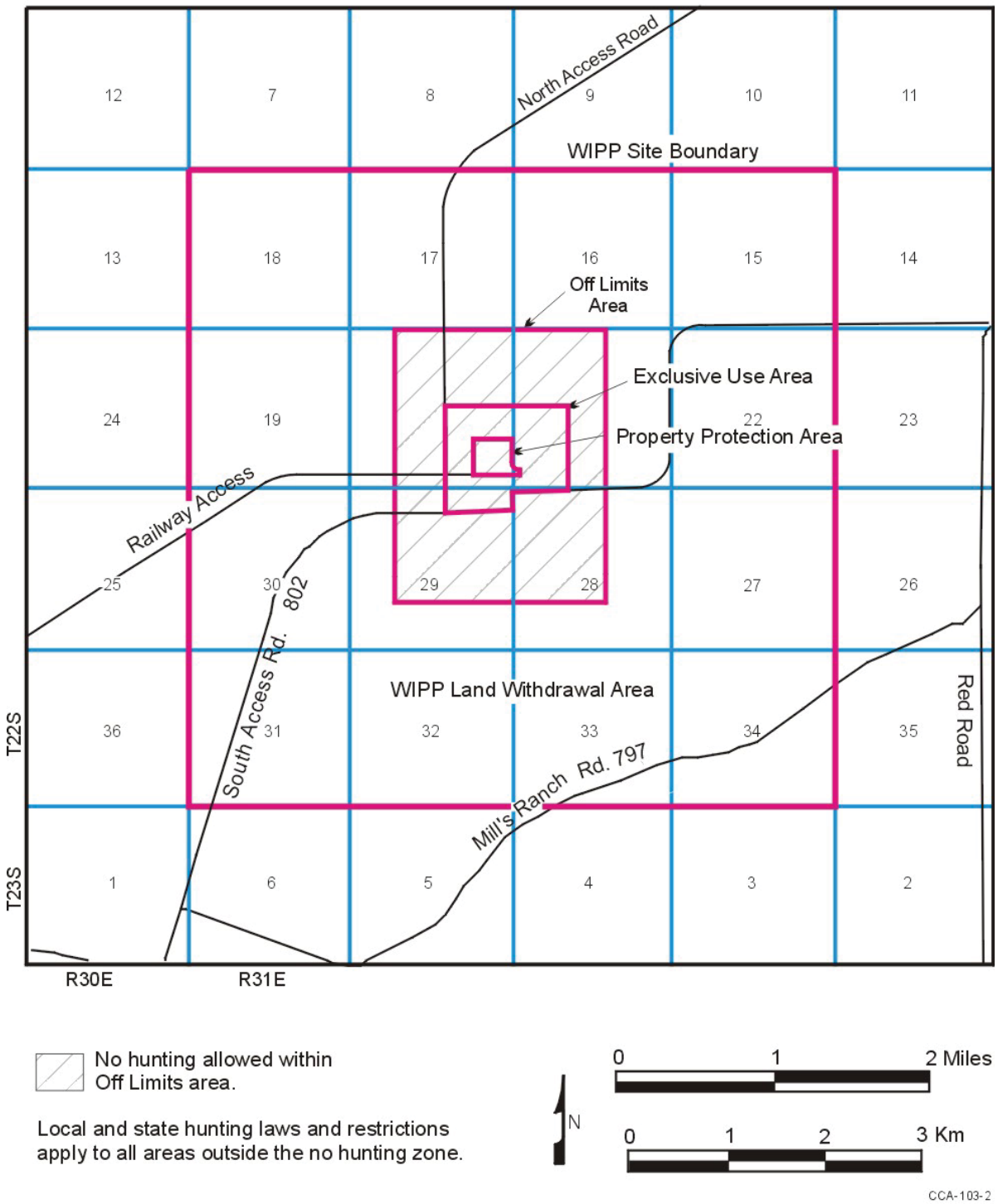

Figure 7-3. Area Where Hunting is Permitted Within the WIPP Site Boundary

and transportation facilities involve significant surface-disturbing activities. However, they are confined to the upper several meters of soil and will not impact the disposal system. Currently, the construction of utilities and transportation facilities are controlled by a permitting process administered by the DOE for the WIPP and the BLM for other federal lands. The BLM ensures that operators remain within designated rights-of-way and that they comply with applicable environmental protection regulations. Figure 7-4 depicts the current rights-of-way that have been granted for utilities or transportation on the WIPP site.

Goal of Active Controls: Active controls will ensure that utility and transportation activities are conducted in a manner that is consistent with permits and that locations are selected to avoid conflicts with permanent markers. Measures, such as fences, may be needed to provide mutual protection for personnel, livestock, and rights-of-way uses.

7.1.3.1.6 Groundwater Pumping

Description of the Activity: Groundwater wells are drilled for several uses near the WIPP. The most common use within the controlled area is in support of the WIPP groundwater monitoring program. These wells generally target water in the Culebra Member of the Rustler Formation. . Before a groundwater well can be drilled, a permit must be obtained and the State Engineer must be notified of the final well configuration and its use. Wells are abandoned in accordance with state regulations that govern the plugging of such wells (see Section 3.3.4). Groundwater well drilling unrelated to the DOE is prohibited by the LWA within the WIPP site boundary. Figure 7-5 shows the location of wells monitored for groundwater composition within the WIPP site boundary.

Goal of Active Controls: The active controls program will ensure that the prohibition on drilling groundwater wells and fluid injection within the WIPP site boundary is enforced and that those wells that currently exist, or that are drilled to support future WIPP activities, are plugged and abandoned in accordance with applicable regulations.

7.1.3.1.7 Surface Excavation

Description of the Activity: Both sand and caliche are mined locally for use in construction. Mining for sand and caliche is always limited to surface quarries. To mine these materials on public lands, a permit must be obtained from the DOE or the BLM. The permit limits the quantity that can be removed and specifies appropriate environmental protections, including reclamation. Sand or caliche removal will have no impact on the disposal system (Appendix PA, Attachment SCR, Other Resources FEP H8).

Many surface quarries within the WIPP site boundary have been remediated, which included recontouring the surface and planting vegetation. Others will be remediated either during the operational phase or as part of postdecommissioning land management. The development of surface quarries unrelated to the DOE is prohibited by the LWA. Figure 7-6 shows the location of surface quarries within the WIPP site boundary.

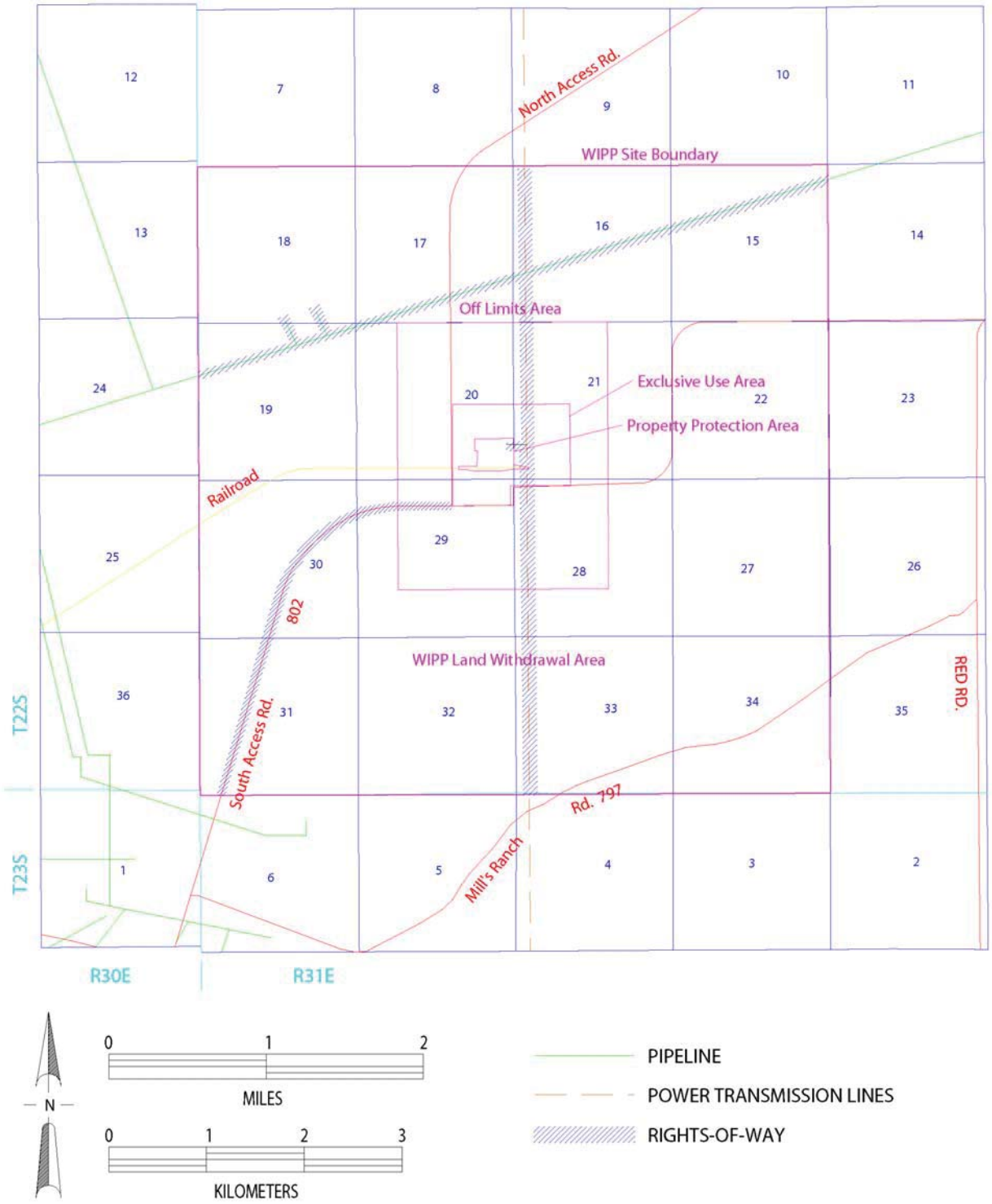

Figure 7-4. Locations of Rights-of-Way Within the WIPP Site Boundary as of September 2002

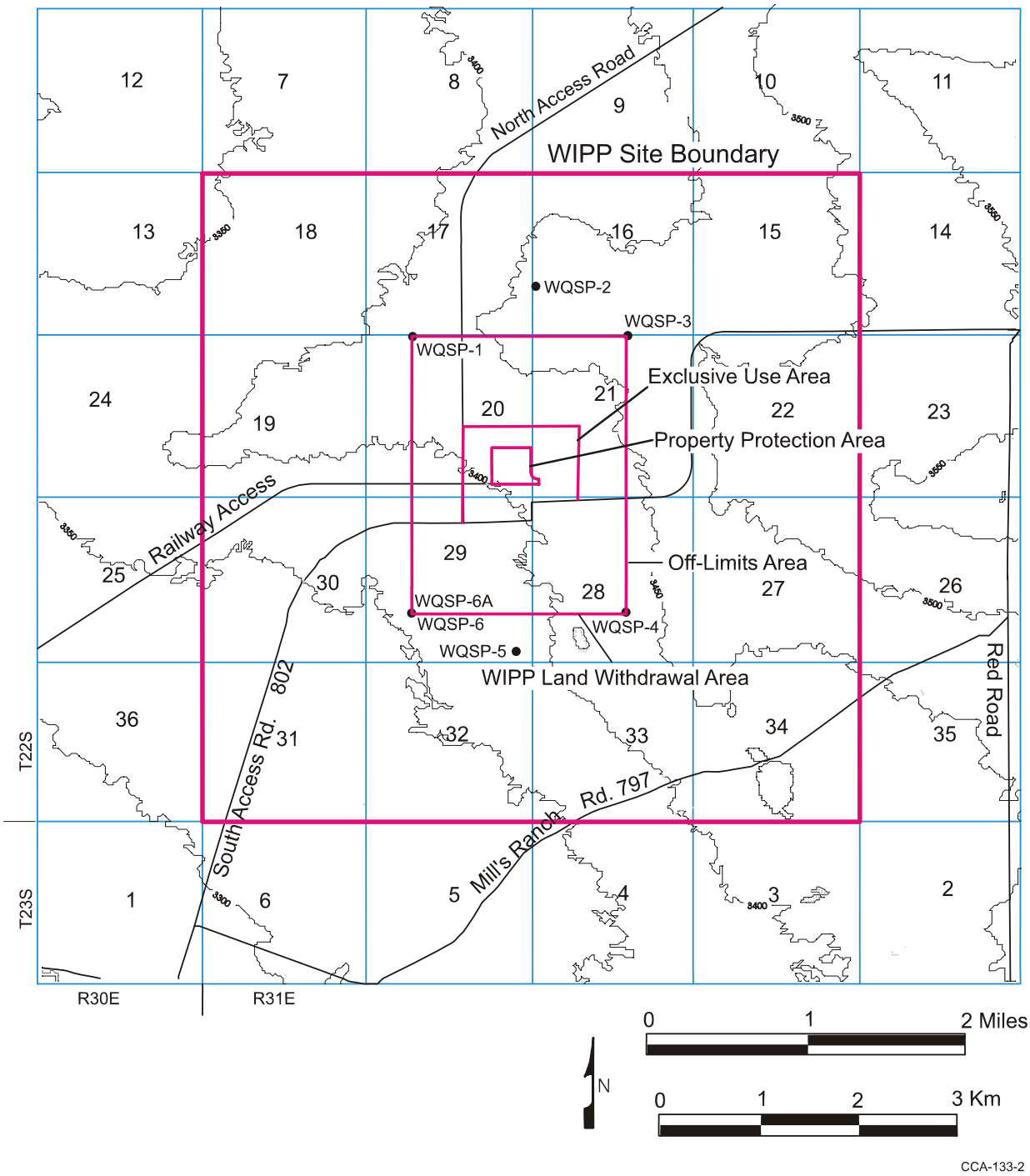

Figure 7-5. Locations of Water Quality Sampling Wells

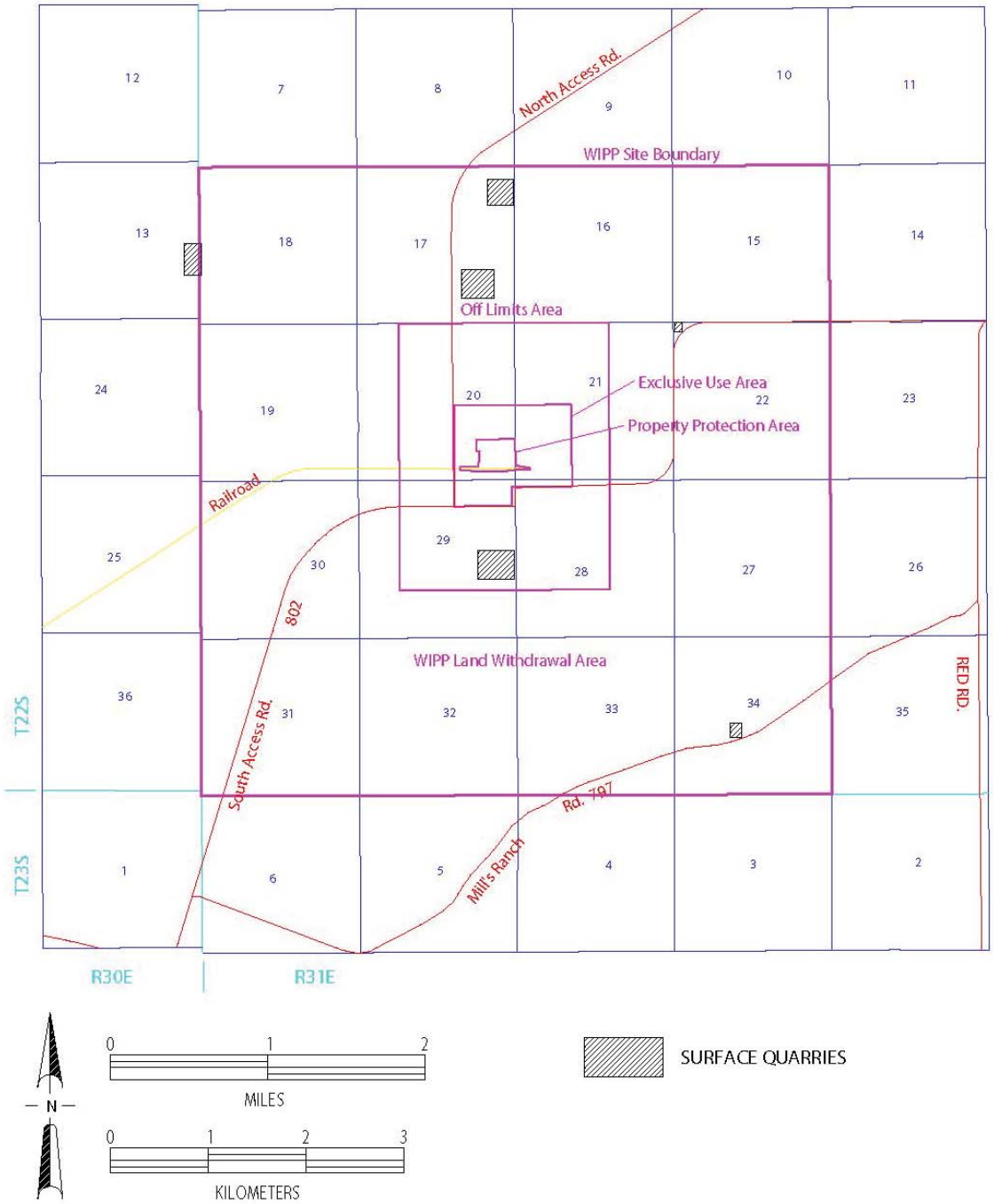

Figure 7-6. Location of Surface Quarries Within the WIPP Site Boundary as of September 2002

Goal of Active Controls: The objective of the DOE with respect to surface excavation is to ensure that the development of mineral leases does not affect the integrity of the disposal system. In accordance with the LWA requirement that no surface or subsurface mining unrelated to the DOE may be conducted within the boundaries of the land withdrawal area, the DOE and the state of New Mexico have entered into a memorandum of understanding (MOU). This MOU dictates that the state will forward any mining and reclamation plans to the DOE for review and comment in determining issuance of such permits within one mile of the withdrawal area boundary. In addition to the commitments in the MOU, the DOE will conduct perimeter surveillance and evaluate potential encroachment of ancillary activities associated with mines.

7.1.3.1.8 Potash Exploration and Extraction

Description of the Activity: Potash mineralization is known to exist beneath the WIPP site (see Section 2.3.1.1). The extent of mineralization is generally determined through the drilling of core holes and the examination and analysis of rock cores. Sufficient core holes have already been drilled within the WIPP site boundary to characterize the resident mineralization. Future drilling, however, is prohibited by the LWA. Holes drilled for the exploration of potash must be closed in accordance with state or federal regulations, depending on the location of the potash lease (see CCA Appendix DEL, Section DEL.5.5). The closure of potash holes within the WIPP site boundary is discussed in Section 3.3.4.

Extraction of potash in the Delaware Basin is accomplished through the use of conventional underground mining technologies. Development of resources within the WIPP site boundary would require that a mine be built in the vicinity or that an existing mine be expanded to include the WIPP. Potash mining is conducted in accordance with the rules and regulations of the BLM on federal lands and the State of New Mexico on state lands. The impacts of mining are evaluated in the performance assessment in accordance with the requirements of 40 CFR § 194.32(b) and are discussed in Section 6.4. Figure 7-7 shows a map of the distribution of potash exploration holes and the extent of currently economically minable reserves.

Goal of Active Controls: The active controls program, especially routine security patrols, will ensure that mineral leasing and development within the WIPP site boundary are prevented and that existing or near future mines do not encroach on the site.

7.1.3.1.9 Hydrocarbon Exploration

Description of the Activity: Hydrocarbon resources are assumed to exist below the WIPP site. The amount of these resources and their locations are projected from information that the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) compiled and interpreted for the DOE in 1995. (See Section 2.3 for a discussion of this report.) Exploration companies use surface-based geophysical techniques to determine likely locations for hydrocarbon accumulations and then investigate the prospect using deep drilling. Both the geophysical and the drilling activities have historically occurred on the WIPP site, but further drilling is prohibited by the LWA. Figure 7-8 shows the location of hydrocarbon wells within the WIPP site boundary.

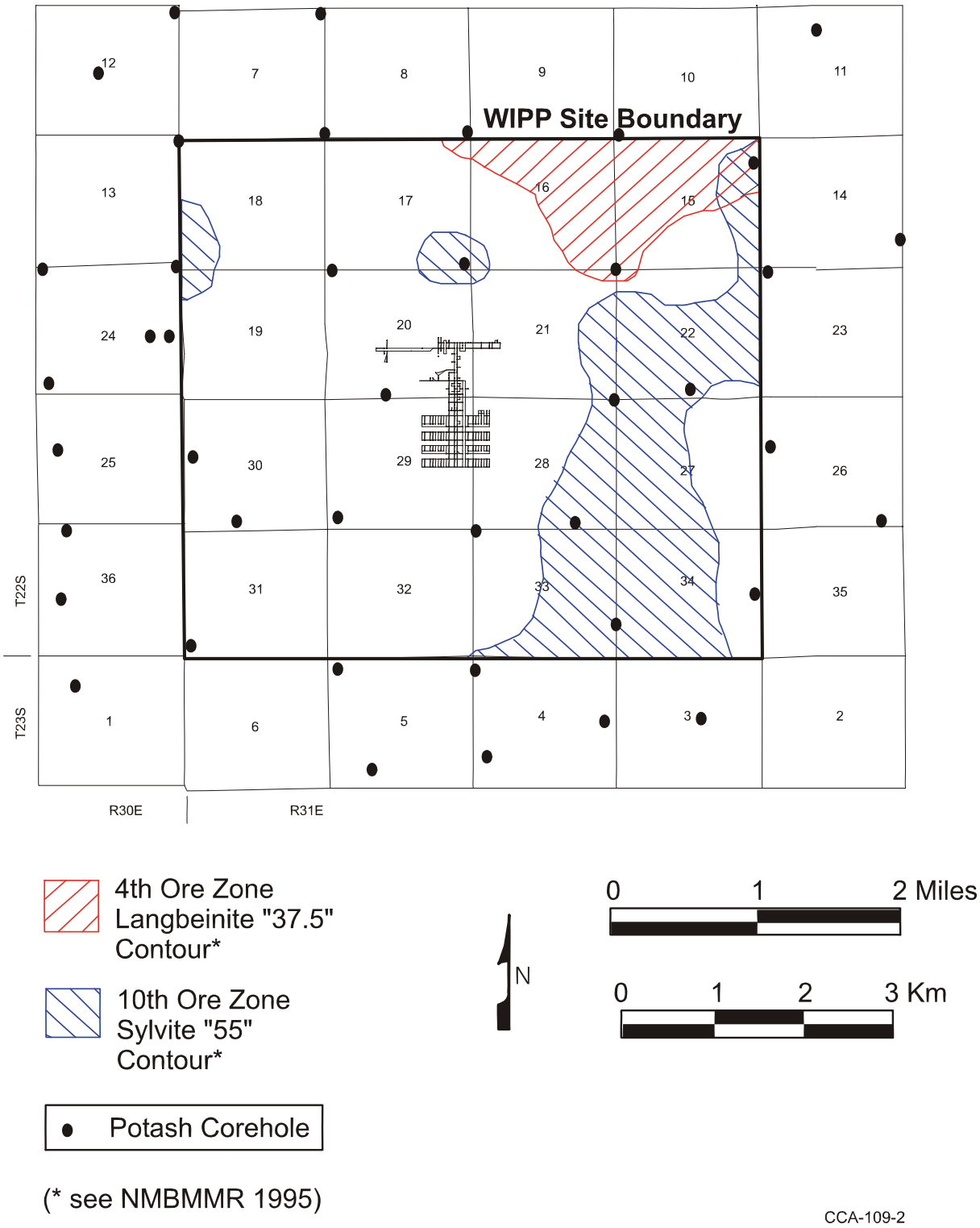

Figure 7-7. Location of Potash Exploration Holes and Economically Minable Potash Within the WIPP Site Boundary as of September 2002

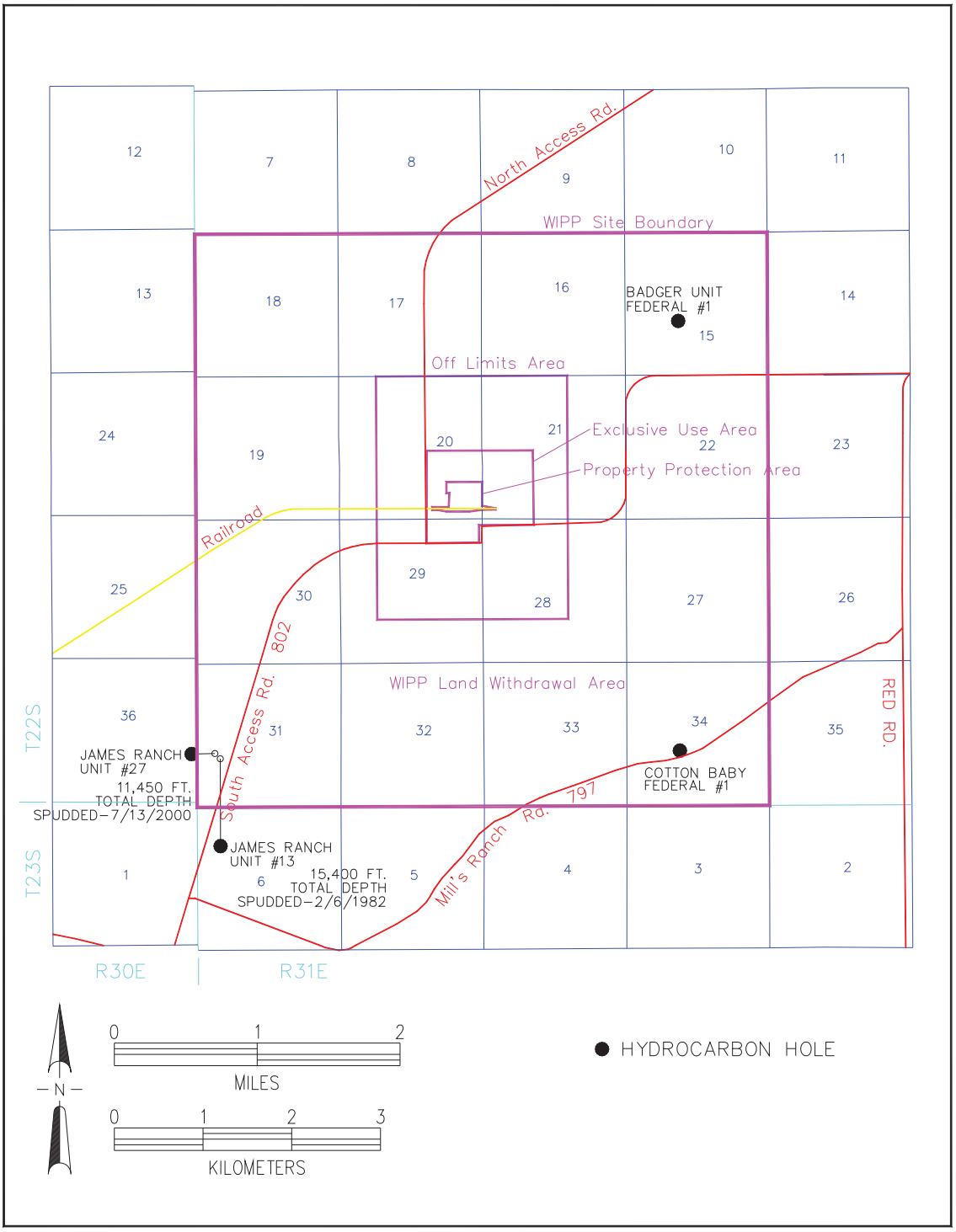

Figure 7-8. Hydrocarbon Holes Located Within the WIPP Site Boundary as of September 2002

Goal of Active Controls: The active controls program will ensure that the prohibition on the drilling of hydrocarbon wells is enforced. In addition, the BLM and the state of New Mexico will administer permits to perform geophysical investigations.

7.1.3.1.10 Construction

Description of Activity: The construction of a permanent building typically involves activities that disturb the surface only to a depth of a few meters, with the exception of the drilling of a groundwater well. Construction is currently prohibited by the DOE for public protection reasons during disposal operations. Because the WIPP site is federally owned, only federal facilities can be built there and any construction will require federal permits. After the conclusion of operations and during the active institutional controls period, construction will not be allowed within the areas reserved for the permanent marker system.

Goal of Active Controls: Controls will ensure that construction does not occur within the WIPP site boundary prior to the end of the active institutional controls period and that no construction will interfere with the goals of the passive controls system.

7.1.3.1.11 Hostile and Illegal Activities

Description of Activity: Activities in this category include vandalism, sabotage, theft, and artifact hunting. All of these activities are prohibited by federal and state law. None is expected to have an impact on the disposal system, although they could impact monitoring efforts, the construction and preservation of permanent markers, the integrity of fences and test areas, and other authorized uses.

Goal of Active Controls: Active controls will prevent the occurrence of hostile and illegal activities to the extent practicable within the WIPP site boundary. Controls may include access control and other security measures.

7.1.3.2 Active Controls Design Features

Based on these possible land uses, the DOE has specified the following design features for the active controls system. Additional detail is presented in CCA Appendix AIC (Section 1).

- Signage will be established to control access to the WIPP site. A fence will be erected along the perimeter of the repository surface footprint. The fence will have gates placed approximately midway along each of the four sides.

- Roadways will be constructed as needed to provide easy visual inspection and ready vehicle access to any point around the fenced perimeter and to facilitate maintenance of the fence line. These roadways will connect to the paved south access road.

- The fence line and the WIPP site perimeter will be posted with signs having as a minimum a legend reading “Danger—Unauthorized Personnel Keep Out” and a warning against entering the area without specific permission of the DOE. Signs prohibiting hunting will also be posted as appropriate. In addition, the DOE will include the area in the local one-call system.

- Upon installation of the permanent marker system, the active institutional controls program will be revised as deemed appropriate.

- Guidelines will be developed for identifying and implementing the appropriate corrective measures to address any abnormal conditions identified during periodic surveillance and inspections.

- Reports of activities associated with the postdisposal active access controls will be prepared in accordance with regulatory requirements for submittal to the appropriate regulatory and legislative authority.

7.1.3.3 Description of Active Institutional Controls Features

Most of the active institutional controls measures, such as long-term site monitoring and site remedial actions, will be implemented simultaneously with facility closure and D&D. It may be possible, however, to implement some measures earlier. For example, salt disposal may begin prior to final facility closure. Reclamation and restoration of unused disturbed surface areas have already begun. Guarding and maintenance activities, which are in place, could evolve into an appropriate type of postclosure activity.

During the disposal phase, the DOE will manage and store waste in a manner that limits the public's exposure to radiation in accordance with the standards of 40 CFR 191, Subpart A. Subsequent to disposal and after shafts are backfilled and sealed, radioactive releases to the accessible environment, exposures to humans, and concentrations in groundwater cannot exceed the standards of 40 CFR Part 191, Subparts B and C. The periods of active institutional controls and passive institutional controls begin when the disposal phase ends, and according to the EPA, run concurrently for at least 100 years. Also per the EPA, after 100 years, credit for active controls must end, but credit for passive controls may continue for up to 700 years after final facility closure (see Section 7.3.4.2).

The active controls program design described above is implemented through the following components. Additional detail is provided in CCA Appendix AIC (Section 2):

- Signage that indicates the areal extent of the WIPP and a fence that restricts access to the repository footprint, respectively, and includes the area in which the passive markers will be constructed. This area (shown in Figure 7-9) is referred to as the repository footprint and represents the surface projection of all areas underground that contain waste. Note that additional fencing may be needed for remote locations that are used for disposal system monitoring. Such fences will meet the same construction specifications as those for the perimeter footprint.

- A 16-foot (4.9 meter) wide roadway around the perimeter of the WIPP site boundary. Roads to remote sites will also be constructed and maintained as needed.

- Surveillance that includes drive-by patrolling two or three times per week. This frequency will be sufficient to detect and remove the most severe threats to the disposal system, such as drilling.

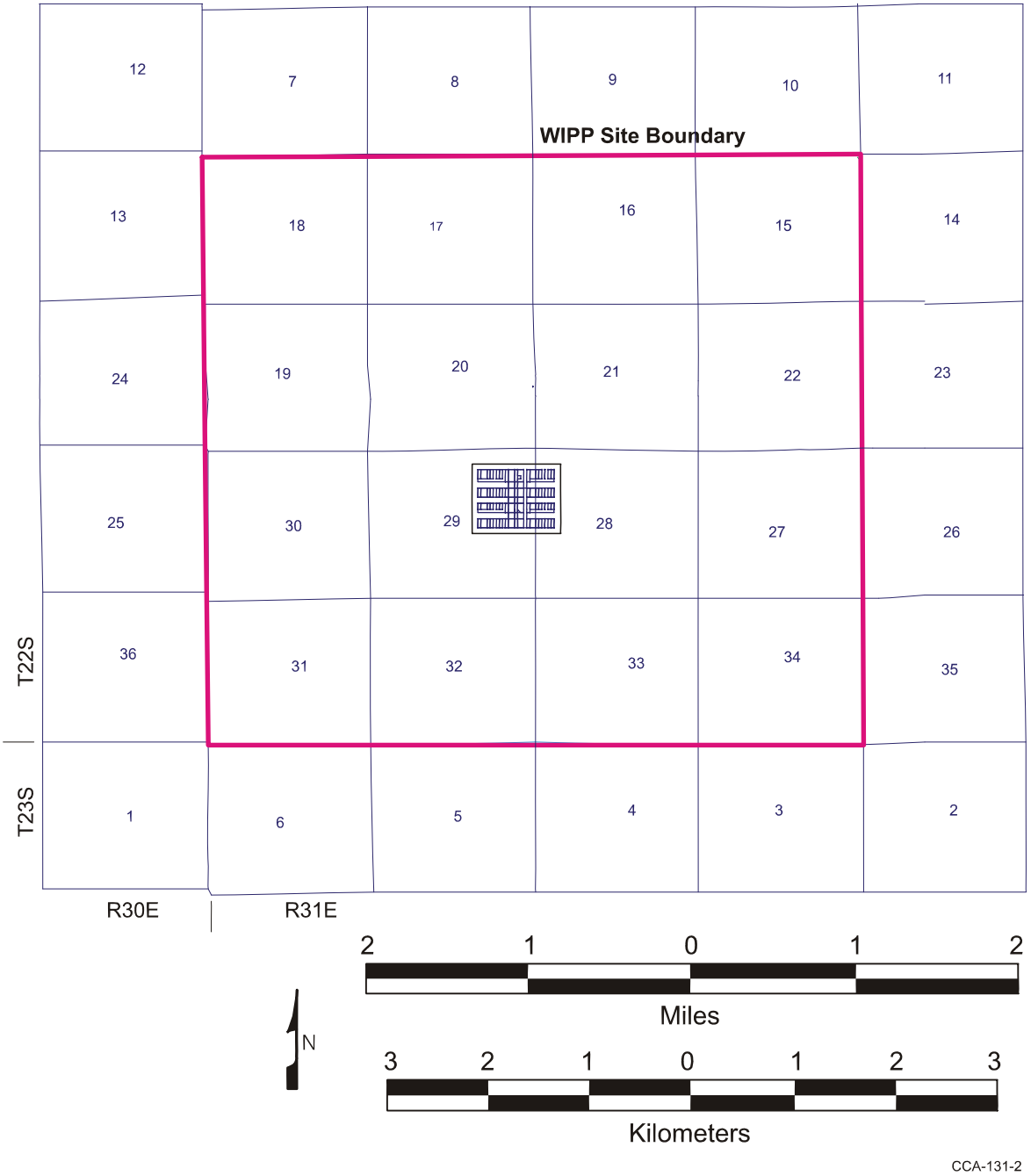

Figure 7-9. Planned Repository Footprint

- Maintenance services for fences, gates, cattle guards, signs, and monitoring equipment.
- Site restoration activities in accordance with the postclosure land management plan.
- Agreements with the BLM to administer grazing and other permitted land uses consistent with the DOE's postclosure land management plan.
- Monitoring of the disposal system.
- Construction of a permanent marker system.

7.1.4 Effectiveness of the Active Institutional Controls Program

Performance assessment for the WIPP assumes that the active institutional controls program will be one hundred percent effective in preventing human intrusion into the repository for the 100 years immediately following disposal. The DOE believes that this assumption is supported by the proposed design features alone (that is, fencing, postings, perimeter inspections, surveillance, and mitigation measures) and the defense-in-depth nature of the features and resulting controls. The DOE believes that taking one hundred percent credit for 100 years of active controls is justified by the repetitive and redundant nature of the active controls that will be implemented at the WIPP site. The DOE is committed to retaining active control over the site for as long as is practicable, but at least for 100 years.

Governments have successfully controlled and protected facilities of national importance for hundreds of years. The U.S. Government has existed and effectively maintained many facilities under its control for over 200 years. The DOE and its predecessor agencies have successfully maintained (preventing intrusion) several major facilities for over 50 years. Therefore, the DOE believes there is a reasonable expectation that active institutional controls will be effective for at least the assumed 100-year institutional control period, and are likely to be effective for substantially longer periods.

In its certification decision (63 FR 27395), EPA ". . . found it reasonable for DOE to assume credit in the PA for 100 years. The EPA found the assumptions regarding longevity and efficacy of the proposed AICs to be acceptable based on the fact that the types of inadvertent intrusion which AICs are designed to obviate are not casual activities, but require extensive resources, lengthy procedures for obtaining legal permission, and substantial time to set up at the site before beginning."

7.2 Monitoring

The requirements for disposal system monitoring are stated in 40 CFR § 191.14(b). In order to certify the DOE's compliance with these requirements, the EPA has established certification criteria that the DOE must satisfy in its application for certification. These criteria are stated in 40 CFR § 194.42. The requirements and the criteria form the basis for the DOE's monitoring program. Appendix MON-2004, Pre-Closure and Post-Closure (Long-Term) Monitoring Plan, describes the details of the DOE's monitoring program.

The criteria provided in 40 CFR § 194.42(a) state

The Department shall conduct an analysis of the effects of disposal system parameters on the containment of waste in the disposal system and shall include the results of such analysis in any compliance application. The results of the analysis shall be used in developing plans for preclosure and postclosure monitoring required pursuant to paragraphs (c) and (d) of this section. The disposal system parameters analyzed shall include, at a minimum:

(1) Properties of backfilled material, including porosity, permeability, and degree of compaction and reconsolidation;

(2) Stresses and extent of deformation of the surrounding roof, walls, and floor of the waste disposal room;

(3) Initiation or displacement of major brittle deformation features in the roof or surrounding rock;

(4) Ground water flow and other effects of human intrusion in the vicinity of the disposal system;

(5) Brine quantity, flux, composition, and spatial distribution;

(6) Gas quantity and composition; and

(7) Temperature distribution.

Attachment 1 (MONPAR) to CCA Appendix MON is an "Analysis of the Effects of Disposal System Parameters on Waste Containment" that the DOE has used to base decisions regarding disposal system monitoring. 40 CFR § 194.42 dictates the manner in which the stated analysis will be used in deriving the monitoring program, including the specification that the program consider preclosure monitoring as an integral component of meeting the monitoring requirements.

CCA Appendix MON, Attachment 1's (MONPAR's) scope of analyzed parameters exceeds the minimum parameters identified in 40 CFR § 194.42(a). The following is a summary of the results of the analysis with respect to those parameters identified in 40 CFR § 194.42(a).

(1) *Properties of backfilled material, including porosity, permeability, and degree of compaction and reconsolidation;*

Backfill Material Properties. The mechanical and hydrologic properties of the backfill are not significant to the performance assessment. Therefore, they will not be monitored during the preclosure or postclosure periods. See CCA Appendix MON (Attachment 1, MONPAR, Section MONPAR.3.5) for additional detail regarding DOE's analysis of backfill.

(2) *Stresses and extent of deformation of the surrounding roof, walls, and floor of the waste disposal system;*

(3) *Initiation or displacement of major brittle deformation features in the roof or surrounding rock;*

Stress and Extent of Deformation. Creep closure of the repository will occur, and is included within compliance assessment and performance assessment models as a control on waste consolidation and other time-dependent disposal room conditions. The

individual creep closure parameters are not significant to performance assessment. Sufficient data have been collected for the purposes of verifying the underlying rock mechanics models. The numerical models of the repository used in performance assessment are based upon assumptions about long-term behavior that are not applicable to behavior during the operational period. Further monitoring of creep closure and stress would not provide information that is useful for calculating disposal system performance, nor would it lead to additional confidence in the performance assessment models.

The initiation or displacement of major brittle deformation features in the roof or surrounding rock, beyond that already accounted for in performance assessment calculations is not significant to the containment of waste. The individual parameters that are used in modeling the mechanical behavior of brittle anhydrite interbeds are not significant to performance assessment. Monitoring mechanical behavior of the interbeds would not provide information that is useful for calculating system performance, nor would it lead to additional confidence in the performance assessment models.

Monitoring of creep closure and mechanical behavior is being conducted during preclosure monitoring to provide information that is relevant to repository operations.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.3.1 and MONPAR.3.2) for additional detail regarding DOE's analysis of creep closure and deformation features.

(4) *Ground water flow and other effects of human intrusion in the vicinity of the disposal system;*

Drilling Intrusions. Intrusion into the repository through drilling may occur during the regulatory time period. In accordance with regulatory requirements, such intrusions are modeled to occur randomly in time and space. Drilling leads to direct releases during the drilling itself and possible long-term releases due to effects on fluid flow in the disposal system. The drilling rate (boreholes per square kilometer per 10,000 years) is significant to repository performance. The DOE uses a drilling rate in performance assessment that is based on historical rates in the Delaware Basin.

The DOE will monitor the drilling activity in the Delaware Basin during the preclosure and postclosure periods and will use the results in performance calculations performed in support of recertification.

Borehole Properties. The properties of a borehole change over time, and are incorporated into performance assessment. The properties are established to be "consistent with practices in the Delaware Basin at the time a compliance application is prepared" (40 CFR § 194.33[c][1]). These parameters are significant to compliance. The current practices will be monitored and changes will be incorporated into the performance assessment models of borehole properties in future calculations in support of recertification.

Groundwater Flow. Historical, current, and near-future human activities in the vicinity of the repository could affect groundwater flow in the Culebra prior to closure of the repository, as well as subsequent to repository closure. The significance of these human activities depends on the extent and magnitude of the induced hydrological, geochemical, and mechanical disturbance. Changes in groundwater in the Culebra are moderately significant to performance. Such changes are incorporated into performance assessment as described in CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.4.4 and MONPAR.4.5). Changes to brine flow in the Salado as a result of any current or near future human activities in the vicinity of the repository are not anticipated, and therefore are not significant to performance assessment.

The DOE will monitor water levels and groundwater flow direction in the Culebra during the operational period. Monitoring of groundwater flow conditions in the Salado could create additional pathways for radionuclide transport, and would potentially jeopardize long-term performance of the disposal system; thus the DOE will not perform such monitoring.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.4.1, MONPAR.4.3, and MONPAR.4.4) for additional detail regarding DOE's analysis of drilling intrusions, borehole properties, and groundwater flow in the vicinity of the repository.

(5) Brine quantity, flux, composition, and spatial distribution;

Salado Hydrology. Hydrologic properties (quantity, flux, and spatial distribution) of the intact Salado Formation are incorporated into performance assessment through parameters that are consistent with extensive experimental observations. Variations in these parameters have a moderate effect on system performance assessment. There is no indication that properties of the intact (far-field) Salado will change during the regulatory period; thus, they will not be monitored during the operational period nor during the postclosure period. Composition of Salado brines has been well established through investigations. Brine composition is significant and is incorporated into performance assessment calculations. Based on the extensive experimental evidence collected, there is no indication that Salado brine composition will change over the regulatory period; thus it will not be routinely monitored during the operational period nor during the postclosure period.

The presence of a disturbed rock zone (DRZ) surrounding the repository has also been incorporated into performance assessment calculations. The properties of the DRZ have been well characterized; they include altered hydrologic properties that are expected to allow enhanced near-field flow both to and from the repository. The initial conditions and enhanced fluid flow are moderately significant to disposal system performance. In an effort to simplify the calculations, the effects are maximized by the conceptual model and altered properties of the DRZ. This treatment is believed to be a conservative choice with respect to the ultimate impact on predicted release.

Mechanical and hydrologic properties of the disposal room are incorporated into performance assessment as they affect gas generation and fluid flow into and out of the repository. These properties and parameters are moderately significant to disposal system performance. Additional properties are significant in the event of intrusion into the repository; these are discussed in CCA Appendix MON (Attachment 1, MONPAR, Section MONPAR.4.2.). The conceptual model of disposal room behavior is based on extensive experimental data that support a number of assumptions about long-term behavior that will not be applicable during the preclosure period. The closed disposal room will not achieve the expected long-term properties predicted in performance assessment during the operational or active control periods. Therefore, monitoring the mechanical and hydrologic properties would not provide relevant information or verify assumptions used in performance assessment. Thus the disposal room properties will not be monitored during the operational period nor during the postclosure period.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.2.1, MONPAR.2.2, MONPAR.3.3, and MONPAR.3.4) for additional detail regarding DOE's analysis of these parameters.

Culebra Hydrology. Hydrologic properties (quantity, flux, and spatial distribution) of the undisturbed Culebra Member of the Rustler Formation exhibit spatial variability and are incorporated into performance assessment through both fixed values and parametric ranges that are consistent with experimental observations to date. Variations in some of the parameters are significant to overall disposal system performance. Culebra groundwater is less saline than Salado and Castile brines. The Culebra groundwater is spatially variable, and its composition has been well established through investigations. Groundwater composition is incorporated into performance assessment calculations; however, it is not significant to performance. Based on extensive experimental evidence, there is no indication that Culebra groundwater composition will change over the regulatory period; however, monitoring will provide information that is relevant to a comprehensive environmental monitoring program.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.2.3 and MONPAR.2.4) for additional details regarding DOE's analysis of these parameters.

Castile Hydrology. The Castile Formation underlying the WIPP may contain reservoirs of pressurized brine. This is incorporated into performance assessment through use of input parameters that address hydrologic properties and the probability that a reservoir will be encountered during an intrusion event. The hydrologic properties are significant to disposal system performance in such an intrusion event. The Castile is not significant to system performance except for the brine reservoirs. There is no indication that the properties of the undisturbed reservoirs will change over the regulatory period. It is not possible to completely define the location and extent of brine reservoirs without jeopardizing the integrity of the disposal system. Composition of brines from two Castile brine reservoirs is moderately significant and is incorporated into performance assessment calculations. There is no evidence to suggest that the brine composition will change over the regulatory period. It is not possible to further investigate composition of any brine that may be present below the repository without jeopardizing the integrity

of the disposal system. Therefore, no further investigations or monitoring will be performed neither during the preclosure period nor during the postclosure period. However, monitoring of drilling activity in the Delaware Basin for instances of encountering pressurized brine reservoirs in the Castile will be a part of the preclosure and postclosure monitoring programs.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.2.5 and MONPAR.2.6) for additional details regarding DOE's analysis of the Castile hydrology parameters.

(6) *Gas quantity and composition;*

Gas Quantity and Composition. Gas generated in the repository may retard creep closure, may fracture the anhydrite interbeds in the DRZ (enhancing fluid flow), and may enhance direct releases (CCA Appendix MON, Attachment 1, MONPAR, Section MONPAR.4.2). These effects are moderately significant and are accounted for in performance assessment. Gas composition (carbon dioxide concentration) and the corrosion rate of metals are controlled chemically by the backfill and are not significant. Gas generation is moderately significant to system performance. The conceptual model of gas generation processes is based on experimental data and incorporates a number of assumptions about long-term behavior that will not be applicable during the operational period (such as anoxic conditions). Monitoring the quantity and composition of gas generated in the closed panels would not provide information that is useful for calculating system performance, nor would it lead to additional confidence in the performance assessment models.

See CCA Appendix MON (Attachment 1, MONPAR, Section MONPAR.3.6) for additional detail regarding DOE's analysis of gas generation.

(7) *Temperature distribution.*

Temperature Distribution. Natural geological thermal gradients have been well characterized and are not significant: they will not affect repository performance, either directly by affecting the containers and repository chemistry, or indirectly by altering fluid flow through the Salado or the Culebra. Similarly waste-induced and repository-induced thermal gradients in the repository are not significant: they will not affect repository performance, either directly by affecting the containers and repository chemistry, or indirectly by altering fluid flow through the Salado or the Culebra. Therefore, natural thermal gradients, waste-induced thermal gradients, and repository-induced thermal gradients will not be monitored during the preclosure period or during the postclosure period.

See CCA Appendix MON (Attachment 1, MONPAR, Sections MONPAR.2.7 and MONPAR.3.8) for additional detail regarding DOE's analysis of natural temperature distribution.

The criteria state that the DOE is to base decisions regarding disposal system monitoring on "an analysis of the effects of disposal system parameters on the containment of waste in the disposal

system and shall include the results of such analysis in any compliance application." The rule goes on to dictate the manner in which the stated analysis will be used in deriving the monitoring program, including the specification that the program consider preclosure monitoring as an integral component of meeting the monitoring requirements.

The DOE has completed the analysis and has designed a monitoring program (including both preclosure and postclosure monitoring techniques) that meets the requirements of 40 CFR § 191.14(b). The program is documented in a manner that addresses the certification criteria of 40 CFR § 194.42, and is described in this section. More detailed information is provided in CCA Appendix MON.

Additional parametric areas of analysis included in MONPAR (Attachment 1 of CCA Appendix MON) are:

- repository chemical conditions,
- shaft seal system,
- radionuclide transport and retardation,
- direct releases, and
- mining.

Table 7-2 is a list of the specific disposal system parameters discussed in CCA Appendix MON, Attachment 1, MONPAR.

As part of the recertification effort, the analysis documented in CCA Appendix MON, Attachment 1, MONPAR was reviewed to determine if changes to PA methods or results of monitoring programs have impacted the conclusions in CCA Appendix MON, Attachment 1, MONPAR. The PA methodology has not changed since the CCA with the exception of additional refinements in Culebra groundwater modeling.

Results of Culebra monitoring have prompted additional groundwater investigations. These investigations are ongoing and involve additional well drilling and hydrological testing. The

Table 7-2. Potentially Significant Disposal System Parameters

NATURAL PARAMETERS	
Impure halite effective porosity	Culebra diffusional porosity
Impure halite permeability	Culebra longitudinal dispersivity
Impure halite pore compressibility	Climate change index
Impure halite far-field pore pressure	Culebra groundwater quantity
Anhydrite permeability	Culebra groundwater flux
Anhydrite pore compressibility	Culebra groundwater spatial distribution
Anhydrite two-phase flow model choice	Culebra groundwater composition
Salado pore shape	Castile brine volume in reservoir
Salado residual brine saturation	Castile brine reservoir volume selection index
Salado residual gas saturation	Castile brine reservoir pressure
Salado brine quantity	Castile brine reservoir permeability
Salado brine flux	Castile brine reservoir rock compressibility
Salado brine spatial distribution	Castile brine composition
Salado brine composition	Castile brine flux
Culebra transmissivity	Castile brine spatial distribution
Culebra advective porosity	Natural temperature distribution
Culebra fracture spacing	
WASTE AND REPOSITORY PARAMETERS	
Closure rates and stresses	Probability factor for types of microbial degradation
Extent of deformation	Gas quantity
Initiation of brittle deformation	Gas composition
Displacement of major deformation features	Choice of oxidation state distribution
DRZ permeability	Solubility of nine radionuclides in Salado brine
DRZ effective porosity	Solubility of nine radionuclides in Castile brine
DRZ brine flux	Humic colloid concentration in Salado brine
DRZ brine quantity	Humic colloid concentration in Castile brine
Waste area residual gas saturation	Clay shaft seal member permeability
Waste area residual brine saturation	Concrete shaft seal member permeability
Brine wicking	Asphalt shaft seal member permeability
Waste area permeability	Shaft DRZ permeability
Backfill porosity	Crushed salt seal component permeability (permeability selection index)
Backfill permeability	Seal residual gas saturation
Degree of backfill compaction	Seal residual brine saturation
Backfill reconsolidation	Seal pore shape
Inundated steel corrosion rate with CO_2	Waste- and repository-induced temperature distribution
Inundated steel corrosion rate without CO_2	Salado K_ds for dissolved radionuclides
Inundated microbial degradation rate	Culebra K_ds for six dissolved radionuclides
Humid microbial degradation rate	Salado K_ds for colloidal radionuclides
β-factor for microbial degradation process	
Drilling rate	Borehole permeability
Waste particle diameter	Borehole plugging pattern (probability index)
Effective shear resistance to erosion	Change in Salado brine flow

Table 7-2. Potentially Significant Disposal System Parameters— Continued

HUMAN-INITIATED PARAMETERS	
Mud pump rate	Change in Culebra groundwater flow
Drill penetration rate	Probability that mining will occur
Time between intrusions	Mining index for adjusting Culebra transmissivity
Borehole location	Waste activity
Probability of encountering a Castile brine reservoir	Waste tensile strength
Borehole diameter	

information gathered since the CCA as part of the groundwater monitoring program has been addressed in the implementation of the groundwater conceptual model (see Section 2.2.1.4.1.2, Section 6.4.6.2 and Appendix DATA, Section DATA-11). Culebra groundwater monitoring was derived from the CCA Appendix MON, Attachment 1, MONPAR analysis and has proven to be an important element of the WIPP operational monitoring program. The program continues to monitor Culebra groundwater to ensure that changes to important activities and conditions related to WIPP long-term performance are identified and addressed. Future results of the ongoing investigations may necessitate changes to the monitoring program; however, the current monitoring parameters have not changed.

7.2.1 Monitoring Program Requirements

Requirements for monitoring of a disposal system[1] are included in the final disposal regulations as follows:

> Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardize the isolation of the wastes and shall be conducted until there are no significant concerns to be addressed by further monitoring (§ 191.14[b]).

Within this context, monitoring becomes one of several activities to be implemented at the WIPP facility during the active institutional controls period. Monitoring the WIPP disposal system is designed to address significant concerns associated with the performance of the isolation system. The EPA points out that monitoring approaches to address significant concerns should be limited to those that can provide meaningful data in a relatively short period of time (50 FR 38081). In addition, the EPA points out that monitoring must not become a reason to relax the degree of care with which the compliance determination is made. Finally, the EPA specifies that monitoring must not jeopardize the integrity of the disposal system (50 FR 38081).

7.2.2 Monitoring Program Design

The requirements in 40 CFR § 191.14(b) and the criteria in 40 CFR § 194.42 can be translated into five screening criteria for selecting monitoring parameters and for developing monitoring plans. The monitoring plan should

[1] Disposal system means “any combination of engineered and natural barriers that isolate...radioactive waste after disposal” (40 CFR § 191.12).

- address significant disposal system parameters,
- address important disposal system concerns,
- obtain meaningful data in a short time period (50 FR 38081),
- preserve disposal system integrity, and
- be complementary with other regulatory programs.

Each of these screening criteria is discussed below.

7.2.2.1 Significant Disposal System Parameters

In the certification criteria, the EPA states that

> The Department shall conduct an analysis of the effects of disposal system parameters on the containment of waste in the disposal system and shall include the results of such analysis in any compliance application. The results of the analysis shall be used in developing plans for preclosure and postclosure monitoring required pursuant to paragraphs (c) and (d) of this section (40 CFR § 194.42[a]).

The EPA also states that to the extent practicable, preclosure monitoring shall be conducted of significant disposal system parameter(s) as identified by the analysis conducted pursuant to paragraph (a) of this section (40 CFR § 194.42[c]). Though not explicitly stated in the criteria, it is appropriate that the same requirement hold for postclosure monitoring. The EPA defines significant parameters as follows: “A disposal system parameter shall be considered significant if it affects the system’s ability to contain waste or the ability to verify predictions about the future performance of the disposal system” (40 CFR § 194.42[c]).

The terms significant, important, and sensitive have been used in the WIPP program to describe parameters with variability that impact the outcome of performance assessment. While these terms are for the most part interchangeable, the term significant is used in this discussion to maintain consistency with the terminology in the 40 CFR Part 194 criteria.

The DOE has conducted the requisite study of parameters that are inputs to the performance assessment. CCA MONPAR (Attachment 1 of Appendix MON) provides a description of the methodology and results of that study. The DOE has implemented the criteria for significance in CCA Appendix MON.

Verification of parameters used in the system performance analysis may occur in one or both of the following ways:

- measurement of physical or chemical conditions to see if they remain consistent with expected conditions or within the range of conditions incorporated into the assumptions and models, and
- measurement of physical and chemical processes that are currently based on professional judgment or regulatory guidance because data are not available.

The DOE considered the major processes and models described in Section 6.4 and the regulations and developed an initial list of potentially significant parameters as discussed in Attachment 1 to CCA Appendix MON (MONPAR). Parameters were screened for inclusion in the list based on the following criteria:

- the parameter represents one or more important aspects of a chemical or physical process or model,
- the parameter represents subjective uncertainty (such as spatial variability in a physical property or process),
- the parameter represents stochastic uncertainty (such as drilling rate), and
- the parameter proved to be moderately to highly sensitive in terms of modeling results in previous preliminary performance assessments.

The parameters identified through this screening process are summarized in Table 7-2 and discussed in CCA MONPAR (Attachment 1 of Appendix MON).

The parameters identified in Table 7-2 are assigned high, medium, and low significance values (EPA 1996c). Those parameters that would significantly affect a release are assigned a HIGH level. Parameters that influence a release are assigned a MEDIUM value. Parameters that are not significant (represent spatial variability or an uncertainty in a given value) are assigned a LOW value. Those that were determined as having a high significance are shown in Table 7-3.

Table 7-3. Disposal System Parameters Determined to be of Highest Significance to Disposal System Performance

Parameter	Significance to Containment	Significance to Verification
NATURAL PARAMETERS		
Salado anhydrite permeability	HIGH	HIGH
Salado brine composition	HIGH	HIGH
Culebra fracture spacing	HIGH	HIGH
Castile brine reservoir volume selection index	HIGH	HIGH
Castile brine reservoir pressure	HIGH	HIGH
Castile brine reservoir permeability	HIGH	HIGH
Castile brine reservoir rock compressibility	HIGH	HIGH
Castile brine reservoir volume selection index	HIGH	HIGH
Castile brine flux	HIGH	HIGH
Castile brine spatial distribution	HIGH	HIGH
Castile brine composition	HIGH	HIGH
WASTE AND REPOSITORY PARAMETERS		
Inundated steel corrosion rate without CO_2	HIGH	HIGH
Choice of oxidation state distribution	HIGH	HIGH
Solubility of nine radionuclides in Salado brine	HIGH	HIGH
Solubility of nine radionuclides in Castile brine	HIGH	HIGH
Humic colloid concentration in Salado brine	HIGH	HIGH
Humic colloid concentration in Castile brine	HIGH	HIGH
Culebra K_ds for dissolved radionuclides	HIGH	HIGH
Crushed salt seal component permeability (permeability selection index)	HIGH	HIGH
HUMAN INITIATED PARAMETERS		
Drilling rate	HIGH	HIGH
Waste particle diameter	HIGH	HIGH
Borehole permeability	HIGH	HIGH
Borehole plugging pattern (probability index)	HIGH	HIGH
Time between intrusions	HIGH	HIGH
Borehole location	HIGH	HIGH
Probability of encountering Castile brine reservoir	HIGH	HIGH
Waste activity	HIGH	HIGH
Effective shear resistance to erosion	HIGH	HIGH

7.2.2.2 Important Disposal System Concern

This criterion is closely tied with the first in that, in the final analysis, the most significant parameters are related to important disposal system concerns. However, the DOE has included this category as a separate criterion to identify any other parameters that, while they are not

significant in performance assessment, do describe important disposal system features. For example, the creep properties of the Salado can be considered an important feature of the disposal system, although the parameter analysis identified them as having a minor effect on the outcome of the analysis. Creep properties are identified in CCA Appendix MON (Attachment 1, MONPAR) because they can provide a body of information that allows the DOE to evaluate its conceptual model of Salado creep closure.

In order to select these parameters for further evaluation, the DOE divided the disposal system into five major components: Salado and repository physical properties, Salado and repository hydrological properties, non-Salado hydrological properties, waste properties, and engineered barrier properties. Based on this division, the DOE revisited the list of potentially significant parameters and determined those parameters that were related to a measurable property of the disposal system. Those parameters are shown in Table 7-4.

7.2.2.3 Meaningful Data in a Relatively Short Time

The amount of time available for the DOE to obtain data regarding important disposal system parameters is limited. This period consists of a preclosure period and 100 years of active institutional controls. However, the DOE will continue monitoring programs for as long as needed if meaningful data are collected or are expected.

In screening parameters using this criterion, the DOE applied two qualifications. First, parameters had to be amenable to measurement within the disposal system and, second, parameter changes expected to occur within the first 127 years and affecting long-term disposal system performance had to be predictable. For example, parameters such as the shape of pore spaces cannot be reasonably measured and, therefore, would not become candidates for a monitoring program. Likewise, changes in parameters such as the actual brine concentration within the Salado are likely to be rapid initially and not necessarily diagnostic of the steady state that will exist over most of the regulatory time period.

The results of the screenings of the parameters in Tables 7-3 and 7-4 are given in Table 7-5.

In some cases, the parameter is indicated as a measurable parameter, meaning that it can either be directly monitored or be deduced from a monitoring program. Other parameters are indicated as observed. This means that the parameter represents an event that occurs at unspecified intervals or changes too slowly or too intermittently to be a viable monitoring candidate. For example, displacements of deformation features occur intermittently and can be observed only when they occur, even though other processes leading up to displacement (such as creep) can be monitored.

7.2.2.4 Preservation of Disposal System Integrity

Disposal system integrity could be compromised by drill holes, conduits, or other entries that are left in place to allow access to monitoring equipment. The requirement to avoid such conditions leads to the conclusion that the only viable monitoring systems are those that can be operated directly during operations, those that can transmit information without cabling (telemetry), and

Table 7-4. Parameters Related to Measurable Disposal System Properties

Parameter	Significance to Containment	Significance to Verification
SALADO PHYSICAL PARAMETERS		
Creep closure and stresses	LOW	LOW
Extent of deformation	LOW	LOW
Initiation of brittle deformation	LOW	LOW
Displacement of major deformation features	LOW	LOW
Natural temperature distribution	LOW	LOW
SALADO HYDROLOGICAL PARAMETERS		
Impure halite pore compressibility	LOW	LOW
Impure halite far-field pore pressure	MEDIUM	MEDIUM
Salado pore shape	MEDIUM	MEDIUM
Impure halite effective porosity	MEDIUM	MEDIUM
Impure halite permeability	MEDIUM	MEDIUM
Anhydrite permeability	HIGH	HIGH
Anhydrite pore compressibility	MEDIUM	MEDIUM
Salado residual brine saturation	MEDIUM	MEDIUM
Salado residual gas saturation	MEDIUM	MEDIUM
Salado brine quantity	LOW	LOW
Salado brine flux	MEDIUM	MEDIUM
Salado brine spatial distribution	LOW	LOW
Salado brine composition	HIGH	HIGH
Salado K_ds for dissolved radionuclides	LOW	LOW
Salado K_ds for colloidal radionuclides	LOW	LOW
Salado change in groundwater brine	LOW	LOW
Natural temperature distribution	LOW	LOW
DRZ permeability	MEDIUM	MEDIUM
DRZ effective porosity	MEDIUM	MEDIUM
DRZ brine flux	MEDIUM	MEDIUM
DRZ brine quantity and spatial distribution	LOW	LOW
NON-SALADO HYDROLOGICAL PROPERTIES		
Culebra transmissivity	MEDIUM	MEDIUM
Culebra advective porosity	MEDIUM	MEDIUM
Culebra fracture spacing	HIGH	HIGH
Culebra diffusional porosity	MEDIUM	MEDIUM
Culebra longitudinal dispersivity	LOW	LOW
Culebra groundwater quantity	LOW	LOW
Culebra groundwater flux	MEDIUM	MEDIUM
Culebra groundwater spatial distribution	LOW	LOW
Culebra groundwater composition	LOW	LOW

Table 7-4. Parameters Related to Measurable Disposal System Properties — Continued

Parameter	Significance to Containment	Significance to Verification
Castile brine reservoir pressure	HIGH	HIGH
Castile brine reservoir permeability	HIGH	HIGH
Castile brine reservoir rock compressibility	HIGH	HIGH
Castile brine reservoir brine volume	HIGH	HIGH
Castile brine flux	HIGH	HIGH
Castile brine spatial distribution	HIGH	HIGH
Castile brine composition	MEDIUM	MEDIUM
Natural temperature distribution	LOW	LOW
Culebra K_ds for six dissolved radionuclides	HIGH	HIGH
Culebra K_ds for humic and actinide-intrinsic colloidal radionuclides	MEDIUM	MEDIUM
Drilling rate	HIGH	HIGH
Effective decay constant for microbes	MEDIUM	MEDIUM
Culebra change in groundwater flow	MEDIUM	MEDIUM
WASTE RELATED PARAMETERS		
Waste area residual gas saturation	MEDIUM	MEDIUM
Waste area residual brine saturation	MEDIUM	MEDIUM
Waste area permeability	MEDIUM	MEDIUM
Brine wicking	MEDIUM	MEDIUM
Inundated steel corrosion rate with CO_2	LOW	LOW
Inundated steel corrosion rate without CO_2	MEDIUM	MEDIUM
Inundated microbial degradation rate	LOW	LOW
Humid microbial degradation rate	LOW	LOW
Gas quantity	MEDIUM	MEDIUM
Gas composition	LOW	LOW
Choice of oxidation state distribution	HIGH	HIGH
Solubility of nine radionuclides in Salado brine	HIGH	HIGH
Solubility of nine radionuclides in Castile brine	HIGH	HIGH
Humic colloid concentrations in Salado brine	HIGH	HIGH
Humic colloid concentrations in Castile brine	HIGH	HIGH
Waste particle diameter	HIGH	HIGH
Effective shear resistance to erosion	MEDIUM	MEDIUM
Waste activity	HIGH	HIGH
Waste tensile strength	HIGH	HIGH
Mud pump rate	LOW	LOW
Drill penetration rate	LOW	LOW

Table 7-4. Parameters Related to Measurable Disposal System Properties — Continued

Parameter	Significance to Containment	Significance to Verification
ENGINEERED BARRIER PROPERTIES		
Shaft DRZ permeability	MEDIUM	MEDIUM
Backfill porosity	LOW	LOW
Backfill permeability	LOW	LOW
Degree of backfill compaction	LOW	LOW
Backfill reconsolidation	LOW	LOW
Clay seal member permeability	MEDIUM	MEDIUM
Concrete seal member permeability	MEDIUM	MEDIUM
Asphalt seal member permeability	MEDIUM	MEDIUM
Seal residual gas saturation	LOW	LOW
Seal residual brine saturation	LOW	LOW
Seal pore shape	LOW	LOW
Long-term borehole permeability	HIGH	HIGH

Table 7-5. Parameters That Can Produce Meaningful Data During Monitoring Period

Parameter	Comment
SALADO PHYSICAL PARAMETERS	
Creep closure and stresses	Can be measured during operations
Extent of deformation	Can be measured during operations
Initiation of brittle deformation	Can be measured during operations
Displacement of deformation features	Can be observed during operations
SALADO HYDROLOGICAL PARAMETERS	
Salado brine composition	Can be measured during operations
NON-SALADO HYDROLOGICAL PROPERTIES	
Culebra groundwater composition	Can be measured for entire period
Castile brine reservoir location	Can be observed for entire period
Drilling rate	Can be observed for entire period
Culebra change in groundwater flow	Can be observed for entire period
WASTE RELATED PARAMETERS	
Waste activity	Can be calculated using measurements made during waste characterization

those that can be used to evaluate parameters using remote sensing techniques. Each is discussed briefly below. Table 7-6 shows the final screening of parameters in order to determine those that are candidates for a monitoring program. Table 7-7 identifies those parameters included in the preclosure and postclosure monitoring programs. The presence of a DRZ surrounding the repository has been

Table 7-6. Parameters That Can Be Measured Without Violating Repository Integrity

Parameter	Comment
SALADO PHYSICAL PARAMETERS	
Creep closure	Direct measurement in open areas of the repository
Extent of deformation	Direct measurement in open areas of the repository
Initiation of brittle deformation	Direct measurement in open areas of the repository
Displacement of deformation features	Directly observed from other open areas of the repository
NON-SALADO HYDROLOGICAL PROPERTIES	
Culebra groundwater composition	Can be measured using existing or additional groundwater surveillance wells
Probability of encountering a Castile brine reservoir	Can be developed based on observations of drilling activity in Delaware Basin
Drilling rate	Can be developed based on observations of drilling activity in Delaware Basin
Culebra change in groundwater flow	Can be determined using existing or additional groundwater surveillance wells
WASTE RELATED PARAMETERS	
Waste activity	Limited to observations during waste characterization activities

Table 7-7. Preclosure and Postclosure Monitored Parameters

Monitored Parameter	Preclosure	Postclosure
Culebra groundwater composition	X	X
Culebra change in groundwater flow	X	X
Probability of encountering a Castile brine reservoir	X	X
Drilling rate	X	X
Subsidence measurements	X	X
Waste activity	X	
Creep closure and stresses	X	
Extent of deformation	X	
Initiation of brittle deformation	X	
Displacement of deformation features	X	

incorporated into performance assessment calculations. The properties of the DRZ have been characterized; they include altered hydrologic properties that are expected to enhance near-field fluid flow both to and from the repository. The initial conditions and enhanced fluid flow are considered moderately significant to disposal system performance. Monitoring the DRZ hydrologic properties would not provide relevant information or verify assumptions used in performance assessment; therefore they will not be monitored during the operational period or during the postclosure period. For more detail regarding DRZ-related parameters, see CCA Appendix MON (Attachment 1, MONPAR, Section MONPAR.3.3).

Composition of Salado brines has been established through investigations. Brine composition is significant and is incorporated into performance assessment calculations. Based on the extensive experimental evidence collected, there is no indication that Salado brine composition will change over the regulatory period; thus it will not be routinely monitored during the operational period or during the postclosure period. For more detail regarding Salado brine composition, see CCA Appendix MON (Attachment 1, Section MONPAR.2.2).

7.2.2.4.1 Evaluation of Monitored Parameters

The preclosure and postclosure parameters identified in Table 7-7 have been evaluated for this CRA (see Appendix DATA) as a part of the plan described in Appendix MON-2004. Significant deviations in expected values of any of these parameters from those ranges of values in the performance assessment models have been and will continue to be evaluated. Where applicable, any new information will be incorporated into the performance assessment conducted for recertification. Parameter values outside of expected ranges will also prompt the evaluation of models and their modification, where appropriate, for use in recertification performance assessment activity.

Culebra groundwater composition, Culebra changes in groundwater flow, Castile brine reservoir encounters, Castile brine reservoir pressure, and drilling rate parameters are evaluated to substantiate that they remain within the range of values assumed in model development and performance assessment. Should there be a significant change outside the assumed range of values used in the 2004 PA models, the DOE will evaluate and, where appropriate, modify models for incorporation into the next performance assessment recertification.

In the unlikely event that subsidence values fall significantly outside the range of values predicted and experienced elsewhere in the Delaware Basin, additional evaluation of the potential effects of such deviations will be conducted. If the evaluation requires changes to models used in the performance assessment, these changes will be made and the revised models incorporated into a future recertification performance assessment.

The waste activity (see Appendix TRU WASTE for a detailed discussion) is monitored to ensure compliance with the requirements of the LWA and that the values are within the range of values used in PA models. New inventory data, including waste activity information, have been incorporated into the 2004 PA; these values are tracked in the preclosure monitoring program. Any significant deviation from the values used in the PA baseline will be addressed by the DOE in a timely fashion to avoid any violation of the compliance certification.

Creep closure and stresses, extent of deformation, initiation of brittle deformation, and displacement of deformation features are all parameters that reflect on the geomechanical nature of the repository. Evaluation of these parameters influence the operational aspects of safe operation of the repository. However, should any of these parameters exhibit properties that are significantly outside the experience and expectations of the information baselines developed to date, the DOE will evaluate the impact on the design of the repository and the design of the shaft seal system.

The EPA will be notified of any deviation that the DOE evaluates as significant with respect to complying with the regulations or the certification of the WIPP as a safe repository.

7.2.2.4.2 Direct Measurement

Direct measurement includes current programs such as the underground geomechanical monitoring program and the groundwater surveillance program. In such cases, the monitoring equipment can be inspected, calibrated, and used with high reliability. Malfunctioning equipment can be easily repaired or replaced. Power requirements are met with portable power units such as rechargeable batteries or generators. In some cases, analog measurements can be made mechanically and recorded in notebooks. In other cases, digital logging equipment is available to record large quantities of data and information. Direct measurement allows for changing the measurement parameters as environmental conditions change. Replicate samples can be taken easily if needed. Unusual conditions can be investigated to provide unambiguous interpretation of data.

7.2.2.4.3 Telemetry Systems

In the early 1970s to the mid 1980s, the U.S. Bureau of Mines and the Mine Safety and Health Administration demonstrated that reliable communications can be established between underground mines and the surface for the purpose of locating and rescuing trapped miners (see Powell 1976; Murphy and Parkinson 1978, p. 42). Low-frequency radio equipment was demonstrated in numerous mine environments and at many depths. The systems evaluated used low-duty cycle transmitters connected to loop antennae powered by miners' cap lamp batteries. Although through-the-earth transmission of signals is feasible, any system that uses this type of telemetry must deal with the following design problems.

First, because the purpose of the telemetry is to obviate the need for cabling to the surface, all power must be self-contained. For the WIPP, this will require extending battery or portable generators beyond the tens of years that can now be achieved for low-duty cycle systems. Second, issues regarding durability must be addressed since the environmental conditions will be severe. Components will have to withstand the brine and gas environments that are predicted, as well as the effects of creep closure and repressurization. Third, reliability will have to be addressed since failed sensors cannot be replaced nor can calibrations be performed or adjustments made. Finally, in addition to the equipment issues, there are concerns about interpreting results in an environment where interference, such as background electromagnetic noise, can only be, at best, poorly characterized. While these issues and concerns can be addressed with technology development programs, it is doubtful that the high cost is justifiable for the limited amount of data that may be obtained from such systems.

7.2.2.4.4 Remote Sensing Systems

The use of remote techniques to determine the characteristics of the earth have been well established. Generally classified as geophysical measurements, these systems look for variations in a parameter within the earth in order to determine geological relationships. Typical parameters that are measured remotely are resistivity, acoustic velocity, magnetism, density, temperature, moisture content, radioactivity, and radiometry (infrared). The general conclusion

is that the changes in the repository are too small (in scale), too far from the surface, and too slow to be detectable using remote techniques.

7.2.2.5 Complementary With Other Regulatory Programs Monitoring is performed by the DOE at and near the WIPP site to comply with the requirements of other regulatory programs. This includes groundwater monitoring in support of the Resource Conservation and Recovery Act (RCRA) program for the project. None of the monitoring activities implemented by the DOE in support of 40 CFR Part 191 and Part 194 compliance demonstrations interfere with or contradict monitoring performed for other regulatory programs.

Based on the approach the DOE has taken to monitoring program implementation, the criterion of compatibility with other regulatory programs is met.

7.2.3 Monitoring Program Description

Based on the parameter screening described above and the analysis in CCA Appendix MON, the DOE has selected a monitoring program with the following components:

- preclosure monitoring

  - Geomechanical monitoring parameters until closure:
    Creep closure and stresses,
    Extent of deformation,
    Initiation of brittle deformation, and
    Displacement of deformation features.

  - Waste Characterization monitoring parameters until last waste shipment :

Waste activity

- preclosure and postclosure monitoring parameters (100 years after closure or until DOE can demonstrate that there are no significant concerns to be addressed by further monitoring)

  - groundwater surveillance:

    Culebra groundwater composition,

    Change in Culebra groundwater flow

  - observation of drilling activities (100 years after closure):[2]

    Probability of encountering a Castile brine reservoir, and
    drilling rate.

- postclosure monitoring parameter (100 years after closure or until DOE can demonstrate that there are no significant concerns to be addressed by further monitoring)

- subsidence monitoring.

The rationale for eliminating the volatile organic compound (VOC) monitoring component of the program is described in Section 7.2.3.2. Other changes to this list have been made to more clearly indicate DOE's intent.

Each of these programs is described in the following sections. Individual program plans are included in CCA Appendices GWMP, SMP, and DMP. Relevant information from these CCA appendices has been consolidated into Appendix MON-2004. Consistent with EPA concurrence (EPA letter of March 15, 2002 to DOE; EPA Docket A-98-49, II-B-3, Item 24), CCA Appendices GWMP, SMP, and DMP are not repeated in this recertification application.

Waste monitoring is not discussed in the following sections because it is tracked in the WIPP Waste Information System (WWIS), as described in Chapter 4.0.

7.2.3.1 Geomechanical Monitoring Program

The geomechanical monitoring program at the WIPP facility is an integral part of the DOE's ground control program. Disposal rooms, drifts, and operational area excavations will be monitored to provide confirmation of structural integrity. Geomechanical data on the performance of the repository shafts and excavated areas are currently collected as part of the geotechnical field monitoring program. The results of the geotechnical investigations are reported annually. The report describes monitoring programs and geomechanical data collected during the previous year.

The instrumentation in Table 7-8 is available for use in support of the geomechanical program. The minimum instrumentation for Panels 2 through 8 is one borehole extensometer installed in the roof at the center of each disposal room. The roof extensometers will monitor the dilation of the immediate salt roof beam and possible bed separations along clay seams. Additional instrumentation may be installed as conditions warrant. Panel 1 is more extensively instrumented than subsequent panels because it was the first panel excavated and because it remained open for a relatively long period of time. After the last emplacement of waste in Panel 1, the communication cables from the instrumentation were cut and geomechanical monitoring ceased in the panel. In a similar manner, other waste panels will be monitored until each is full and panel seals are emplaced.

Polling of the geomechanical instrumentation will be performed at least once every month. This frequency may be increased to accommodate any changes that may develop. The results from the remotely read instrumentation will be evaluated after each scheduled polling. Documentation of the results are provided annually in the Geotechnical Analysis Report.

The instrumentation system provides for data maintenance, retrieval, and presentation. The instrumentation system cognizant engineer first retrieves the data from the instrumentation system and verifies their accuracy by assuring the measurements were taken in accordance with applicable instructions and procedures. Next, the cognizant engineer reviews the data after each polling to assess the performance of the instrument and the excavation. Data that look anomalous are detected during this polling and are investigated to determine the cause (for

Table 7-8. Instrumentation Used in Support of the Geomechanical Monitoring System

Instrument Type	Features	Parameter Measured	Range
Borehole extensometer	The extensometer provides for monitoring the deformation parallel to the borehole axis. Units suitable for up to five measurement anchors in addition to the reference head.	Cumulative deformation	0-2 inches
Borehole television camera	Closed circuit television may be used for monitoring areas otherwise inaccessible, such as boreholes or shafts.	Video image	N/A
Convergence points and tape extensometers	Mechanically anchored eyebolts to which a portable tape extensometer is attached.	Cumulative deformation	2-50 feet
Convergence meters	Includes wire and sonic meters. Mounted on rigid plates anchored to the rock surface.	Cumulative deformation	2-50 feet
Inclinometers	Both vertical and horizontal inclinometers are used. Traversing type of system in which a probe is moved periodically through casing located in the borehole whose inclination is being measured.	Cumulative deformation	0-30 degrees
Rock bolt load cells	Spool type units suitable for use with rock bolts. Tensile stress is inferred from strain gauges mounted on the surface of the spool.	Load	0-300 kips
Earth pressure cells	Installed between concrete keys and rock. Preferred type is a hydraulic pressure plate connected to a vibrating wire transmitter.	Lithostatic pressure	0-1,000 pounds per square inch
Piezometer pressure transducers	Located in shafts and of robust design and construction. Periodic checks on operability required.	Fluid pressure	0-500 pounds per square inch
Strain gauges	Installed within the concrete shaft key. Suitably sealed for the environment. Two types used—surface mounted and embedded.	Cumulative deformation	0-3,000 microinches per inch (embedded) 0-2,500 microinches per inch (surface)

example, instrumentation problem, error in recording, or changing rock conditions). The data are then processed to calculate various parameters such as the change between successive readings and deformation rates. The results of this assessment are reported to the ground control cognizant engineer and operations personnel. The stability of an open panel excavation is generally determined by the rock deformation rate. Unexpected deformation rates are investigated by Geotechnical Engineering to determine if remediation is needed.

The evaluation of the performance of the excavation is also performed by Geotechnical Engineering. These evaluations will provide an estimate of the stand-up time of the excavation. If the trend is toward adverse (unstable) conditions, then the results of these assessments are reported to the operations manager to determine appropriate operational responses.

Roof conditions are assessed from observation boreholes and extensometer measurements. Measurements of room closure, rock displacements, and observations of fracture development i the immediate roof beam are used to evaluate the performance of a panel. A summary of the Panel 1 monitoring program was presented to the members of the Geotechnical Experts Panel ir 1991, who concurred that the monitoring was adequate to determine deterioration within the rooms and could provide early warning of deteriorating conditions.

The assessment and evaluation of the condition of WIPP excavations is an iterative, continuous process using the data from the monitoring programs. Criteria for corrective action are continually reevaluated and reassessed based on total performance to date. Actions taken are based on these analyses and on planned utilization of the excavation. Because WIPP excavatior are in a natural geologic medium, there is inherent variability from point to point. The principle adopted is to anticipate potential ground control requirements and implement them in a timely manner rather than to wait until a need arises.

Both creep closure of the excavation and the development of the DRZ are included in the conceptual model of disposal system performance. Creep closure is discussed in Section 6.4.3.1 and Appendix PA, Attachment PORSURF. The numerical model for predicting creep closure has been developed based on both theoretical considerations and observations. The goal of monitoring is to detect any substantial and detrimental deviations from the expected behavior of Salado halite and to determine the significance of such deviations. Data are analyzed after each round of measurements and results are distributed for use in making ground control decisions. A compilation of data (current and previous) is published annually in the Geotechnical Analysis Report. This compilation is useful determining long-term trends in the behavior of undergrounc openings and can be a diagnostic tool for determining substantial and detrimental deviations from expected performance.

The DRZ is modeled as discussed in Section 6.4.5.3. It is assumed that the DRZ maintains its permeability throughout the model period as shown in Table 6-19. Marker bed (MB) 138 and 139 are modeled to be separate geological units with permeabilities lower than those in the DRZ as shown in Table 6-18. Substantial and detrimental deviations from these expectations may impact repository performance. Consequently, as discussed in Section 4.3 of CCA Appendix GTMP, observations of excavation effects, along with the other geotechnical measurements wil be useful to detect deviations in expectations for near-term DRZ development.

7.2.3.2 VOC Confirmatory Monitoring Program

In Docket A-93-02, Compliance Application Review Document No. 42, Section 42.C.5, the EP concludes:

> The VOC monitoring acts only as a secondary indicator of creep closure because there is not a direct relationship between VOC levels and creep closure rates. While VOC levels might indicate changes in creep closure rates, such changes would be observed earlier and would be better defined by direct geomechanical monitoring, which will be conducted throughout the operation of the WIPP. DOE stated that VOC monitoring will also provide data on gas producing processes (p. 7-58). The DOE did not include gas producing processes as one of the parameters to be monitored, however, because the modeling of gas-producing processes is based on data and assumptions about long-term behavior that will not be applicable during the operational period (p. 7-36).

The EPA indicated that VOC monitoring is not necessary as a secondary indicator of creep closure or to fulfill the requirements of Section 194.42. A planned change per 40 CFR § 194.4(b)(3) was submitted to the EPA in January 2002 requesting removal of CCA Appendix VCMP from the compliance baseline. In March 2002, the EPA approved the request to eliminate CCA Appendix VCMP from the WIPP certification basis. Based on the approval letter, this section and all references to CCA Appendix VCMP are eliminated from future recertification applications.

7.2.3.3 Groundwater Surveillance Program

In the development of the WIPP monitoring programs, potential pathways for release of hazardous constituents to the environment were evaluated. This evaluation indicated no credible release pathway via surface water. Comparisons between data sets are performed using standard statistical tests. The selection of the specific test is dependent upon the relative power of the test and the degree to which the underlying requirements of the test are met. In addition to tests comparing data from distinct locations and times, trend analyses are performed on time series where sufficient data exist.

Citation of the source of the test method or the software used to perform the tests will be made when results are reported. Data and subsequent calculated values are reported in the annual site environmental report.

The two parameters of interest from the groundwater surveillance program are the composition of the Culebra groundwater and water levels. Significant and persistent changes in the composition of the Culebra groundwater are investigated and impacts to the modeling assumptions for long-term performance in Section 6.4.6.2 are evaluated. Large and rapid water-level fluctuations may be diagnostic of nearby human activity such as potash mining and fluid injection and withdrawal. Water-level changes within the groundwater modeling domain in Section 6.4.6.2 that cannot be explained either based on observed trends or on past experience are being investigated and assessed relative to the assumptions made in the regional groundwater flow model (see Appendix DATA, Section DATA-11).

7.2.3.4 Observation of Drilling Activities

As part of the ongoing compliance activities, the DOE has continued to populate and maintain the database of drilling activity within the Delaware Basin. In addition, the DOE has an ongoing program of field checking each well that is drilled within one mile of the WIPP site boundary. Field checking includes verifying the location as listed on the Application for Permission to Drill (APD), monitoring drilling and completion activities, and noting abandonment and plugging. Both the maintenance of the database and the field observation program will be continued throughout the operational period to develop additional statistics on the following parameters:

- drilling rates,
- drilling practices,
- Castile brine reservoirs encountered,

- Castile brine characteristics (where available), and
- plugging practices.

Data collected are addressed as appropriate in the recertification process. Any analyses that indicate parameter values are changing are studied to evaluate the impact of the changes.

Significant changes in drilling practices, such as borehole diameters, plug and abandonment practices, mining techniques, Castile brine occurrence, and injection well use are evaluated for potential impacts on disposal system performance. Any significant deviations are reported to the EPA.

Annual reports of the Delaware Basin Monitoring Program provide the total number of deep boreholes drilled within the Delaware Basin. This information is reported in compliance with 40 CFR § 194.33(b)(3), which specifies the manner in which the frequency of deep drilling events assumed in performance assessments shall be determined. The rule specifies that the DOE shall:

> (i) Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.

In addition, the rule specifies that:

> (ii) The total rate of deep drilling shall be the sum of the rates of deep drilling for each resource.

The specification of a 100-year period "prior to the time at which a compliance application is prepared" has had the effect of increasing the deep drilling frequency that must be assumed in performance assessment calculations. This is because significant deep drilling activity did not exist within the Basin in the early part of the 20th century, while the last 10 years has been a period of significant oil drilling activity in the basin. Consistent with this, it is anticipated that the intrusion rate assumed in performance assessments will continue to increase throughout the operational period of the WIPP, as long as drilling continues to occur. The intrusion rate calculated in this manner for the CCA in 1996 is 46.8 deep holes per square kilometer over 10,000 years. Based on current information, this rate is 52.2 deep intrusions per square kilometer over 10,000 years (supporting data are provided in Appendix DATA). The implications of this increased rate of deep drilling are addressed in Chapter 6.0.

7.2.3.5 Subsidence Monitoring

Subsidence monitoring is accomplished with leveling surveys having maximum errors not greater than Second Order, Class II specifications. The relevant subsidence monitoring information presented in CCA Appendix SMP is incorporated into Appendix MON-2004.

Although the CCA indicates that surveys will be performed every 10 years, the surveys are currently performed annually. These surveys will be performed during the operational phase and thereafter in accordance with Appendix MON-2004.

The leveling survey procedures ensure that the data are documented and validated. The data are included in the baseline.

The monitoring program includes the following:

- management of the disposal phase monitoring program,
- maintenance of monitoring procedures and quality assurance/quality control documents,
- performance of all necessary field work,
- maintenance of the subsidence network,
- maintenance (and revision as necessary) of the monitoring schedule,
- maintenance and storage of baseline database,
- review of data and evaluation of performance,
- eventual decommissioning of the disposal system monitoring program, and
- archiving of monitoring data.

Subsidence predictions exist for the WIPP. These will be reevaluated at the time of closure. Subsidence measurements will be used to compare actual subsidence with predictions. Significant deviations between expected subsidence and actual subsidence will be investigated to determine if a substantial and detrimental deviation in the expected performance of the repository is indicated.

7.2.4 Reporting

The results of the DOE's monitoring program are submitted annually. The report includes the results from the previous year, plus any cumulative information that is useful in interpreting the data. The annual report contains a summary assessment of results to ensure that the performance of the repository can be evaluated on a continuous and consistent basis. Other reports, such as those stipulated in 40 CFR § 194.4 (b)(3), are issued when necessary.

Since the submittal of the CCA, the DOE has prepared over 20 annual reports pertaining to geomechanical monitoring, groundwater surveillance, subsidence monitoring, Delaware Basin monitoring, and waste characteristics monitoring. Data resulting from the various monitoring programs are reported in Appendix DATA. These reports are submitted to the EPA with the Annual 194.4(b)(4) Change Report.

7.2.5 Compliance Monitoring Parameter Data Results

In the EPA certification of compliance (63 FR 27354, May 18, 1998), the EPA concurred on the list of 10 compliance monitoring parameters (compliance parameters) that DOE proposed to monitor during the operational period of the project. The 10 compliance parameters are:

- Culebra groundwater composition,
- change in Culebra groundwater flow,
- probability of encountering a Castile brine reservoir,
- drilling rate,
- subsidence measurement,
- waste activity,
- creep closure and stresses,
- extent of brittle deformation,
- initiation of brittle deformation, and
- displacement of deformation features.

These parameters have been continually monitored over a period of several years, most of them before the initial receipt of waste. Existing WIPP monitoring programs gather data and information to develop the compliance parameter values. These programs are described in Appendix MON-2004; data resulting from these monitoring programs are provided in Appendix DATA.

The EPA also requires the DOE to report any negative condition that may indicate the repository will not function as predicted or a condition that is substantially different from the information contained in the most recent compliance application. Annual assessments of compliance parameters allow the DOE to monitor the predicted performance of the repository and report any condition adverse to waste containment.

All monitoring activities performed as part of the compliance parameters program have generated data within expected ranges, except for the changes in Culebra groundwater flow compliance parameter (the drilling rate was changed for PA; however, this parameter is monitored as a regulatory requirement and not to ensure it is within an expected range). For this compliance parameter, data related to water levels in monitoring wells have been recorded that are outside expected ranges. The implications of these unexpected monitoring parameter values are described in Chapters 2.0 and 6.0 of this recertification application.

7.3 Passive Institutional Controls

Passive institutional controls, as opposed to active institutional controls, are controls that once established, can be expected to remain effective with no on-site human support. The DOE will implement passive institutional controls that involve multiple types and multiple levels of passive controls to make human intrusion into the disposal site unlikely. To accomplish this, the DOE intends to use several types of monuments and markers, land ownership, and written notations in land records in numerous locations (see Section XVI of CCA Appendix PIC).

Written documentation will include information on the location, design, and disposal contents and hazards, as well as stipulations on allowable land uses. Components of the passive controls system will be instituted at the site and at remote locations (see CCA Appendix PIC).

As technology advances, this design concept will be revisited over the operational lifetime of the WIPP. If the DOE believes the design can be enhanced, changes will be proposed during the recertification process for EPA approval. The program described in CCA Appendix PIC will fulfill the requirements of 40 CFR Part 191 and satisfy the certification criteria of 40 CFR Part 194.

7.3.1 Requirements for Passive Institutional Controls

The EPA has specified that "[d]isposal sites shall be designated by the most permanent markers, records, and other passive institutional controls practicable" (40 CFR § 191.14[c]). The EPA then goes on to define passive institutional controls to mean "(1) permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system" (40 CFR § 191.12[e]). The DOE has interpreted this regulatory language to mandate the development and implementation of a system of passive institutional controls consistent with those components listed in the EPA's definition in order to protect the integrity of the disposal system for as long as practicable after disposal.

Guidance is provided by the EPA in 40 CFR § 194.43 on what subject areas must be addressed in order to demonstrate compliance with the regulation. Three subject areas must be addressed: (a) detailed descriptions of the passive institutional controls must be provided, (b) the period of time that the passive institutional controls are expected to endure and be understood must be estimated, and (c) credit for the passive institutional controls in reducing the likelihood of inadvertent human intrusion in performance assessments must be justified for the proposed time period. Additional guidance is provided in EPA (1996b) indicating what documentation is required in the compliance application to address 40 CFR § 194.43(a), the need for rationales to explain the estimates of how long the passive institutional controls are expected to endure and be understood in 40 CFR § 194.43(b), and the limitations of effectiveness and duration of the effectiveness of the passive institutional controls in performance assessment to address 40 CFR § 194.43(c).

In addition, as part of the initial EPA certification decision, the EPA added Condition 4. This condition is applicable to the implementation of the passive institutional controls, and has been included in 40 CFR Part 194 as Appendix A. The appendix provides that not later than the final recertification application submitted before closure of the disposal system, the DOE will provide the following to the EPA:

1. A schedule for implementing passive institutional controls that demonstrates markers will be fabricated and emplaced and other measures will be implemented as soon as possible following closure of the WIPP. The schedule will also describe how testing of any aspect of the conceptual design will be completed before or soon after closure and what changes to the design of passive institutional controls may be expected to result from such testing.

2. Documentation showing that the granite pieces for the proposed monuments and information rooms described in Docket A-93-02, Item II-G-1, may be quarried (cut and removed from the ground) without cracking due to tensile stresses from handling or isostatic rebound; engraved on the scale required by the design; transported to the site, given the weight and dimensions of the granite pieces and the capacity of existing rail cars and rail lines; loaded, unloaded, and erected without cracking based on the capacity of available equipment; and successfully joined.

3. Documentation showing that archives and record centers will accept the documents identified and maintain them in the manner identified in Docket A-93-02, Item II-G-1.

4. Documentation showing that proposed recipients of WIPP information other than archives and record centers will accept the information and make use of it in the manner indicated by the DOE in Docket A-93-02, Item II-G-1, and supplementary information.

7.3.2 Objectives for Passive Institutional Controls

As prescribed by the standards, the objectives of DOE's passive institutional controls for the WIPP are to convey the following:

- location,
- facility design,
- content, and
- hazard.

The passive institutional controls program described within this application will be effective in accomplishing these objectives.

7.3.3 Implementation of the Passive Institutional Controls Program

The DOE began addressing the issue of passive institutional controls in the context of the assurance requirements by convening two panels of experts to identify what future societies might be like (Hora et al. 1991). The panels were convened so that the appropriate types of messages, the contents of the messages, and the types of media for transmitting the messages can be selected and to identify design concepts for the system of markers at the repository footprint (Trauth et al. 1993), which is one of the passive institutional controls. The work of the two panels was completed prior to promulgation of 40 CFR Part 194. To address the issues of the passive institutional controls in addition to the markers at the repository footprint and to incorporate the concept of practicability into the design, the DOE developed a conceptual design, which is included in CCA Appendix PIC. With the promulgation of 40 CFR Part 194, the EPA provided guidance on how credit for the passive institutional controls deterring inadvertent human intrusion can be obtained for use in performance assessment. To address the issue of credit for passive institutional controls, the DOE produced CCA Appendix EPIC.

In addition, the DOE has developed new information pertaining to the permanent markers portion of the passive institutional controls program and furthered the planning process since the development and submittal of the CCA. This material is documented in the following reports:

1. Permanent Markers Testing Program Plan, Waste Isolation Pilot Plant (DOE 2000) – This document presents DOE plans for the program to test reference designs and alternative permanent markers materials, physical configurations, and locations. The markers testing program will develop information useful in materials selection and in the development of final designs. Testing will help to determine the effectiveness and durability of selected and alternative materials and design configurations. The testing plan provides the following information:

   Program Overview – Implementing the testing program will require performing a series of general activities, such as literature reviews and a survey and assessment of existing markers, the development of some testing methods, and the performance of both laboratory and field-scale tests. The coordination and integration of these activities is described.

   Testing Rationale – The rationale for the testing process is described. The testing rationale links individual marker systems, applicable design criteria, and testing objectives and issues. The testing objectives and issues are, in turn, addressed by the performance of specific tests and analyses.

   Tests Specification – Specific tests appropriate to address individual testing objectives and issues are identified for those cases where an appropriate method currently exists. Cases are identified where no method currently exists.

   Detailed Test Plans – Information that must be addressed in detailed test and analysis plans is identified in the plan. These plans must be developed before testing begins and will address topics such as test objectives, management of the testing activity, specific test methods, data quality objectives, data management, reporting, quality assurance (QA) provisions, and others.

   Evaluation of Results – The general manner in which testing and analyses results will be evaluated in the markers systems design process is described.

   Program Organization – The organization of the testing and analysis program in a sequential progression of activities and the general schedule of testing activities are described in the plan.

   QA – QA provisions applicable to the implementation of the testing program are described.

2. Contractor Report, Permanent Markers Monument Survey, Waste Isolation Pilot Plant (John Hart and Associates, P.A. 2000a) – The DOE is currently investigating alternative materials for the construction of permanent markers. One of the important considerations is the ability of the marker material to be inscribed with warning messages and the durability of these messages over very long time frames. In the CCA,

the DOE provides details regarding the implementation of the permanent markers program. An important objective of the program is to optimize the design of the marker systems by evaluating alternative configurations and materials and aiding in the development of final designs. A related activity identified in the CCA is the survey of monuments within 150 miles of the WIPP site to obtain any information useful in the selection of marker materials and the development of marker designs. This report documents the results of a survey performed in the summer of 2000. The objective of this survey was to collect and compile information relevant to the assessment of the durability of ancient inscriptions made on various rock types. Conclusions are provided related to the durability of various rock types, the effects of aspect, the rates of erosion of inscriptions, the effects of inscription form, and the importance of contrast in color and texture in regard to inscription legibility. Recommendations based on study observations and related to the longevity of inscriptions on various rock types are provided. These include:

Rock Types – Rocks of hardness and durability suitable for use as WIPP permanent markers are available within a few hundred miles of the WIPP site. Basalt and sandstone are the most abundant, so one or both of these should be selected for further evaluation. Intrusive igneous rocks that are susceptible to exfoliation should not be used.

Form of Inscriptions – To the extent consistent with the necessary written and symbolic warnings and messages, inscriptions should be as large as possible, with groove widths several times the largest mineral particle size. Unless the rock is very fine-grained, like basalt, it probably will not be practical to inscribe letters smaller than about 25mm minimum plan dimension or less than 5mm deep.

Additional Studies – Given the consistent findings over the 16 sites included in this survey, it is anticipated that additional monument (petroglyph) surveys would not be useful. However, studies on material properties of rock and man-made materials would be useful, with emphasis on surface hardness, methods to create and preserve color contrast, and the effects of rock texture on inscribability and inscription durability.

3. Contractor Report, Permanent Markers Materials Analysis, Waste Isolation Pilot Plant (John Hart and Associates P.A., 2000b) – This report documents assessments of marker materials included in the reference design as well as potential alternative materials. The permanent markers will be constructed of materials that will be selected through an evaluation process. Candidate materials identified in the CCA reference designs will be evaluated against performance criteria. The evaluations are being performed using methods identified in the Permanent Markers Testing Program Plan. Information obtained from literature reviews is provided in this report and has been used to refine the evolving candidate materials lists. The literature review also provides information supporting preliminary evaluations of the candidate materials. This information is also of value in planning laboratory and field tests that will provide additional information necessary to make final marker material selections.

4. Contractor Report, Ancient Cementitious Materials (John Hart and Associates, P.A. 2000c) – The current reference design for WIPP permanent markers calls for granite as the primary construction material for the large surface markers, small surface markers, buried storage rooms, and the information center. Although the reference design specifies granite, the DOE has committed to evaluate alternative materials in an effort to optimize final designs. One potential alternative material is concrete. Accordingly, a literature review was performed to investigate instances in which man-made cementitious materials have survived for very long time periods. The intent of this effort was to determine and document, when possible, the attributes of cementitious materials that contribute to their survival for long periods.

   This literature review showed that cementitious materials used nearly 9,000 years ago have survived intact to the present day. Concretes that have survived over such long periods have been some form of pozzolanic concrete. Results suggest that the blending of ancient and modern concrete technologies may provide a durable, long-lasting concrete meeting the DOE goal to mark the WIPP site for a very long time.

7.3.3.1 Definition of Passive Institutional Design Appropriate for the WIPP

In deciding which passive institutional controls are appropriate for the WIPP, the DOE was guided by the regulatory language in 40 CFR § 191.14(c) that states that the controls should be practicable. The DOE is expected to address the components of the passive institutional controls listed in the definition of 40 CFR § 191.12(e). The components of the passive institutional controls for the WIPP consist of (1) monuments that define the boundary of the withdrawal area, (2) markers at the footprint of the repository that consist of monuments that identify the outer boundary of the subsurface facility, a berm surrounding the repository footprint, an information center on the surface at the center of the repository footprint, a buried room halfway between the information center and the berm, a buried room halfway between the berm and the hot cell, and randomly spaced buried markers distributed across the repository footprint, (3) sets of records distributed to national and international archives, (4) sets of records distributed to records centers locally, nationally, and internationally (both those of a general nature and those specializing in land and resource use), (5) government control and land-use restrictions, and (6) other means of communication, such as encyclopedias, dictionaries, textbooks, and various maps and road atlases. CCA Appendix PIC contains a detailed description of the designs of each of these components.

Trauth et al. (1993) examined a variety of configurations and materials in concluding that a system comprised of natural materials incorporating massive structures with messages provided in an enduring configuration offered the best system for permanently marking the site. The permanent marker system incorporates these concepts and thus is the best system of passive institutional controls for permanently marking the repository. The use of archives and national publications as described in CCA Appendix PIC is the most extensive means of widespread distribution of the WIPP information. Use of radio or television is transient and will not provide the long-term societal memory.

7.3.3.1.1 Markers

Two groups of experts, the Futures Panel and the Markers Panel, were established to examine the issues involved with designing an effective system of permanent markers. Hora et al. (1991) incorporates judgments of the Futures Panel and discusses the underlying physical and societal factors that would influence society and the likely modes of human intrusion at the WIPP site.

The Hora et al. report was an important reference and source of information for the preparation of Trauth et al. (1993). Trauth et al. (1993) reports the results of the Markers Panel, which considered various concepts of marking the site and conveying to future generations information regarding the presence of dangerous waste material and the potential consequence of intrusion into the waste repository. CCA Appendix PIC (Section I) is a modification of the ideas developed by this panel.

CCA Appendix PIC sets forth the permanent markers system for the WIPP facility. This system involves the use of surface monuments, small subsurface warning markers, buried rooms, and large earthen structures marking the WIPP repository footprint on the surface. CCA Appendix EPIC (Section EPIC.6) indicates the period of time during which passive institutional controls will be effective.

The surface monuments are large monuments erected on the surface at both the repository footprint and the controlled area boundaries. To facilitate fabrication and shipping of the monuments, each monument will consist of two separate stones connected by a tendon joint. The large monuments will be engraved with Level II and III messages and Level IV pictographs, as described in CCA Appendix PIC (Section IV).[3] Figures 7-10 and 7-11 provide the

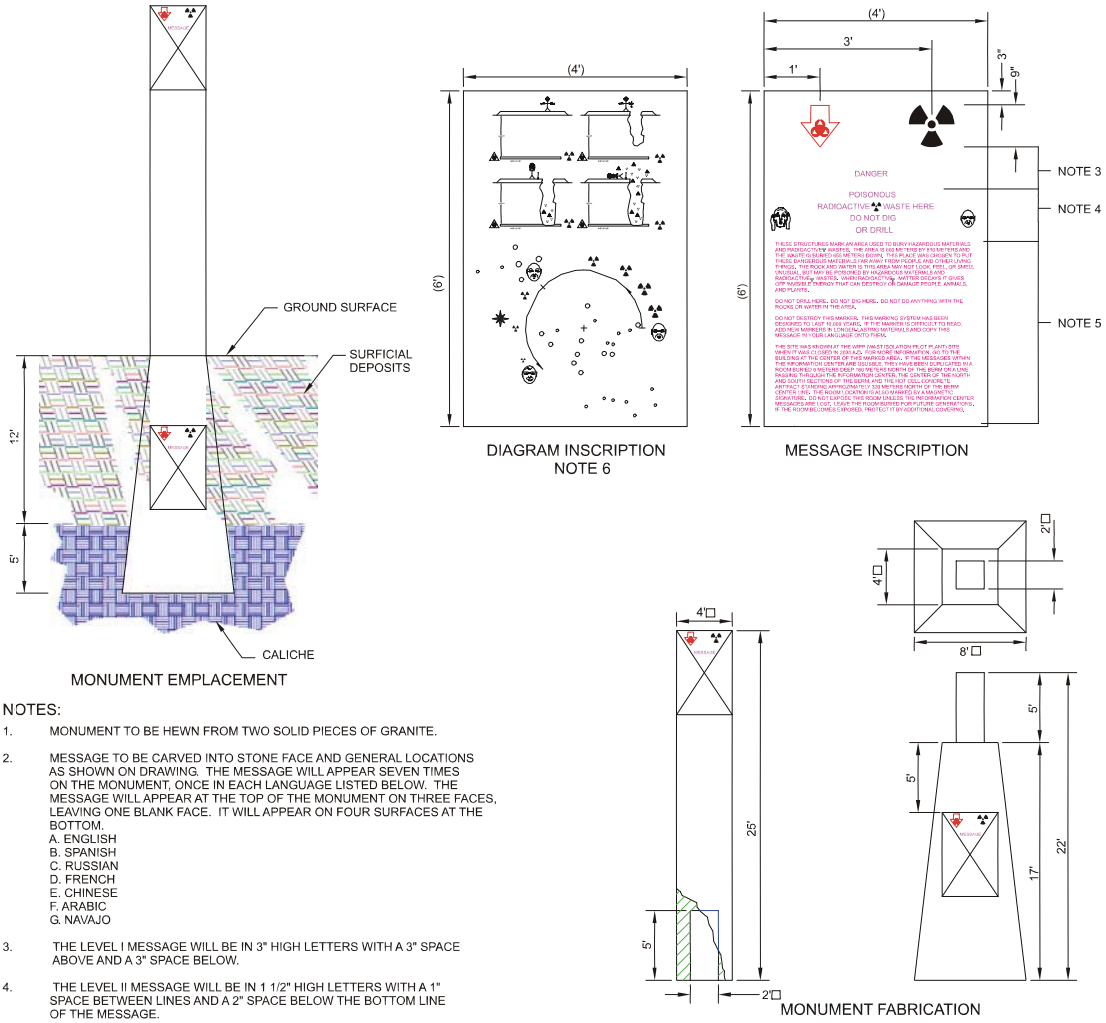

NOTES:

1. MONUMENT TO BE HEWN FROM TWO SOLID PIECES OF GRANITE.
2. MESSAGE TO BE CARVED INTO STONE FACE AND GENERAL LOCATIONS AS SHOWN ON DRAWING. THE MESSAGE WILL APPEAR SEVEN TIMES ON THE MONUMENT, ONCE IN EACH LANGUAGE LISTED BELOW. THE MESSAGE WILL APPEAR AT THE TOP OF THE MONUMENT ON THREE FACES, LEAVING ONE BLANK FACE. IT WILL APPEAR ON FOUR SURFACES AT THE BOTTOM.
   A. ENGLISH
   B. SPANISH
   C. RUSSIAN
   D. FRENCH
   E. CHINESE
   F. ARABIC
   G. NAVAJO
3. THE LEVEL I MESSAGE WILL BE IN 3" HIGH LETTERS WITH A 3" SPACE ABOVE AND A 3" SPACE BELOW.
4. THE LEVEL II MESSAGE WILL BE IN 1 1/2" HIGH LETTERS WITH A 1" SPACE BETWEEN LINES AND A 2" SPACE BELOW THE BOTTOM LINE OF THE MESSAGE.
5. THE LEVEL III MESSAGE WILL BE IN 1" HIGH LETTERS WITH A 5/8" SPACE BETWEEN THE LINES. THERE WILL BE A 1 1/2" SPACE BETWEEN THE PARAGRAPHS OF THE MESSAGE.
6. THE DIAGRAM INSCRIPTION WILL APPEAR ON THE BLANK FACE ON THE TOP OF THE MONUMENT. THE DIAGRAM DESCRIBES THE HAZARDS OF DIGGING HERE AND HOW LONG THAT HAZARD WILL EXIST.

Figure 7-10. Repository Footprint Perimeter Monument Configuration

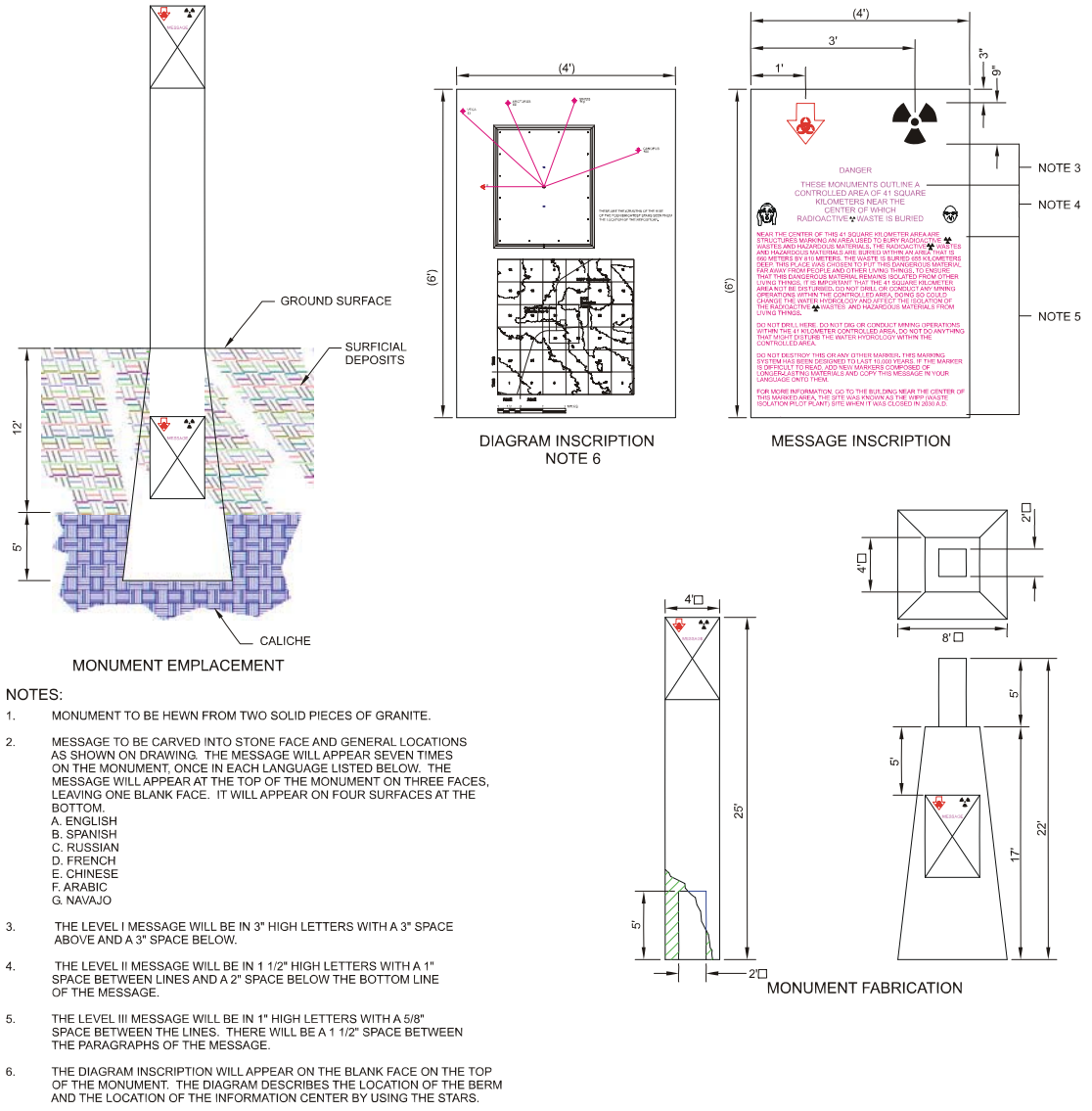

NOTES:

1. MONUMENT TO BE HEWN FROM TWO SOLID PIECES OF GRANITE.
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   A. ENGLISH
   B. SPANISH
   C. RUSSIAN
   D. FRENCH
   E. CHINESE
   F. ARABIC
   G. NAVAJO
3. THE LEVEL I MESSAGE WILL BE IN 3" HIGH LETTERS WITH A 3" SPACE ABOVE AND A 3" SPACE BELOW.
4. THE LEVEL II MESSAGE WILL BE IN 1 1/2" HIGH LETTERS WITH A 1" SPACE BETWEEN LINES AND A 2" SPACE BELOW THE BOTTOM LINE OF THE MESSAGE.
5. THE LEVEL III MESSAGE WILL BE IN 1" HIGH LETTERS WITH A 5/8" SPACE BETWEEN THE LINES. THERE WILL BE A 1 1/2" SPACE BETWEEN THE PARAGRAPHS OF THE MESSAGE.
6. THE DIAGRAM INSCRIPTION WILL APPEAR ON THE BLANK FACE ON THE TOP OF THE MONUMENT. THE DIAGRAM DESCRIBES THE LOCATION OF THE BERM AND THE LOCATION OF THE INFORMATION CENTER BY USING THE STARS.

Figure 7-11. Controlled Area Perimeter Monument Configuration

dimensional characteristics of the large monuments. The monuments intended for marking the controlled area boundaries will differ from the monuments marking the repository footprint. Each footprint monument will be inscribed with the Level II and III messages in seven languages, the six official United Nations languages (English, French, Spanish, Chinese, Russian, and Arabic), and Navajo. The controlled area boundary monuments will be inscribed with warning messages. Trauth et al. (1993, Appendix F) discusses in some detail the selection of these languages by the Markers Panel.

The monuments will be quarried from granite and shipped by rail to the WIPP site. Each monument base will be soundly founded by excavating into the near-surface caliche. After

emplacing the base monument, the excavation will be backfilled and the upper monument will be placed over the base tendon.

The small warning marker is shown in Figure 7-12. The Level II messages placed on the small subsurface warning markers will be in the seven languages previously listed. However, each marker will have the message in only one of the seven languages. Warning markers will be placed throughout the repository footprint and within the berm. The warning markers will be made of a diversity of durable materials, such as granite, aluminum oxide, and fired clay, thus improving the likelihood that at least some of the markers will endure for thousands of years.

Diameter of Disk is 23 cm. (9 in.)
Not to Scale

CCA-114-2

Figure 7-12. Small Buried Warning Marker

The small buried warning markers will be randomly spaced in locations and at depths to provide a reasonable expectation of discovery by any organized exploration effort, but to discourage organized efforts at collecting the markers. The current petroleum industry practice in the Delaware Basin is to remove surface soil down to the caliche layer over an area sufficiently large to set up a drilling rig and dig a mud pit. Nominally, this area is 50,000 ft^2 (4,648 m^2). By placing the small warning markers above the caliche at intervals of a few feet, several of the warning markers should be unearthed during any soil clearing operation.

The inclusion of a berm in Figure 7-13 in the permanent marker design is based upon the following criteria (see CCA Appendix PIC, Section VII, for more detail).

- The surface footprint of the repository should be essentially outlined by some enduring structure.
- The structure should be sufficiently massive to provide reasonable expectation that it will endure for thousands of years.
- The structure's profile should minimize the likelihood that it can become buried by shifting sands or that characteristics of the profile may lead to fabrication stresses affecting the ability of the structure to retain its configuration.
- The structure should be constructable without the need for sophisticated equipment or processes.

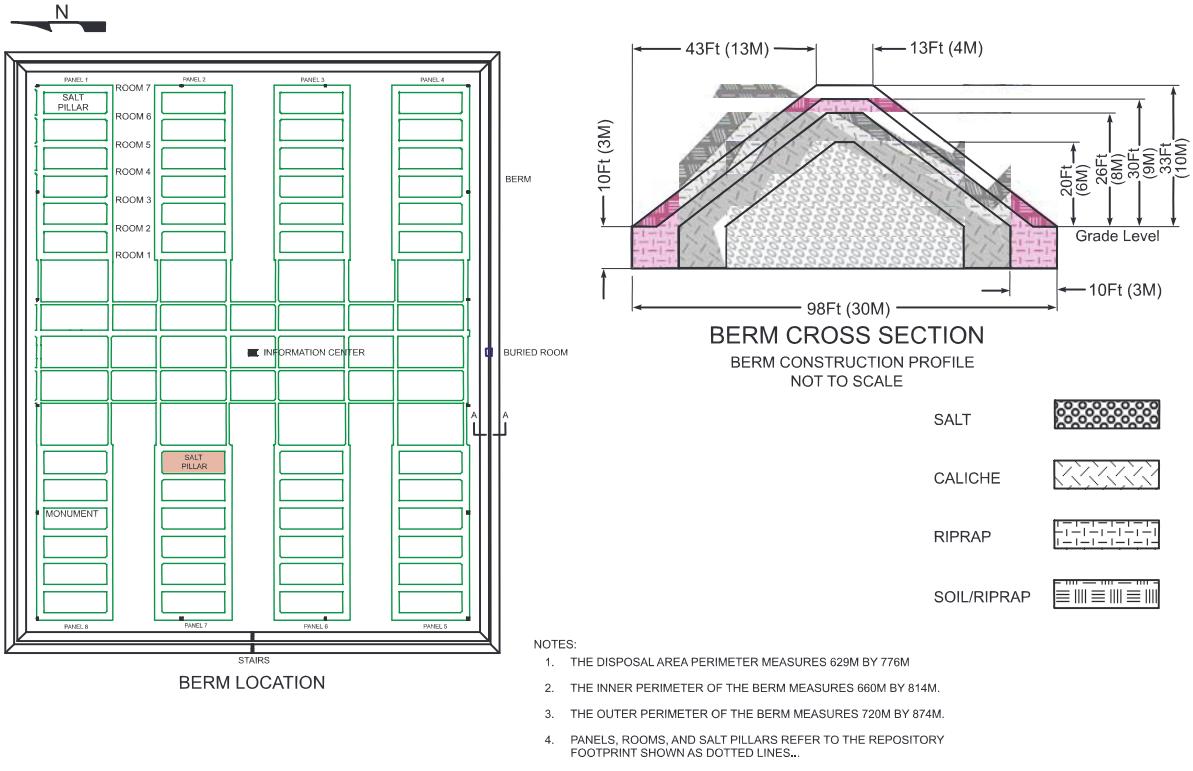

Figure 7-13. Berm Construction

- The construction materials should be reasonably available to the WIPP site and have little intrinsic value.

- The cost should not be disproportionately high for the advantages that the alternative provides.

- To the extent practicable, the nature of the structure should lend itself to testing over a period of two to five decades.

The berm is proposed to encompass the repository footprint. Figure 7-13 also depicts the reference design berm cross section.

As reported in John Hart and Associates, P.A. (2000b), the permanent markers will be constructed of materials selected through an evaluation process. Candidate materials identified in the CCA reference designs will be evaluated against performance criteria. The evaluations will be performed using methods identified in the Permanent Markers Testing Program Plan (DOE 2000).

A variety of earth materials that occur on or close to the WIPP site are available for use in the construction of the berm including native soils and caliche. Salt, excavated from the WIPP underground and stockpiled on site, may not be a good material for use in the berm. Its solubility and low strength make it an unreliable material to form the core of the berm, and use at shallower locations in the berm, while structurally of less consequence, nevertheless may not be feasible because of the closer proximity to infiltrating groundwater and the resulting increased risk of dissolution.

The berm design shown in Figure 7-13, including materials of construction, will be refined through the ongoing design-development process and finalized prior to its construction. Final design specifications will be provided to the EPA for approval prior to construction.

To provide a distinctive magnetic signature for the berm, large permanent magnets or other magnetically distinct materials buried at intervals in the berm will be used. These materials are intended to produce a detectable signature with current airborne detection equipment. The magnetic signal's geometric form will provide strong indication that it could only have been humanly engineered. This magnetic signature should motivate any organization capable of magnetic surveying to further investigate this anomaly prior to initiating drilling activities.

Similarly, to provide a distinctive radar-reflective signature unique from the surrounding terrain, DOE will consider the use of radar-reflective trihedrals for placement within the top layer of the berm.

Another aspect of the marker system includes on-site buried storage rooms containing the Level IV message and associated diagrams. These rooms will be designed to endure for a similar time period as the permanent marker system and will be buried (see CCA Appendix PIC). The design characteristics contributing to this longevity will be the material and environmental conditions associated with construction and location. The rooms will be made of granite with a minimum number of joints. Individual walls, the floors, and the roofs will comprise single granite slabs

joined only at the edges. The configuration minimizes the risk of failure caused by chemical interactions between the construction material and the environment. The message texts contained within the buried storage rooms will be engraved on the walls. To provide redundancy, additional granite slabs engraved with the message text and the diagrams will be held in place against the interior walls. Although some damage could be inflicted by vandals, the granite composition of the message-carrying materials will provide the greatest opportunity for preventing complete destruction of the information contained within the buried rooms.

In addition to the buried storage rooms, an information center, as described in CCA Appendix PIC (Section VII), will be located on the surface, providing access to the same information that is contained in the buried rooms. Details regarding the location of one of the buried storage rooms and identical information will be contained in the information center.

7.3.3.1.2 Records

A significant part of the overall system will be the archiving of important information at sites remote to the repository. The archived material will include information that defines the location, design, content, and hazards associated with the WIPP. The amount of information will be more extensive than that available within the permanent marker system at the repository location. Information will be preserved using practicable materials and techniques at record centers and archives throughout the world. CCA Appendix EPIC (Section EPIC.6) provides justification for a period of time that materials placed in archives and records centers are expected to endure and be understood.

Although DOE has not yet established the specific archival files, examples of the types of documents that will be archived include the following. The specific requirements of 40 CFR § 194.43 (a)(2) are listed and responsive documents are indicated in parentheses.

- (i) The location of the controlled area and the disposal system (detailed maps describing the exact location of the repository, Safety Analysis Report, the Final Environmental Impact Statement (FEIS) for WIPP and the supplement(s) to the FEIS, the RCRA Permit, the last compliance recertification application (CRA))

- (ii) The design of the disposal system (Safety Analysis Report, the FEIS for WIPP and the supplement(s) to the FEIS, the RCRA Permit, the last CRA, drawings defining the construction and configuration of the repository and shafts, design information for the passive institutional controls)

- (iii) The nature and hazard of the waste (Safety Analysis Report, the FEIS for WIPP and the supplement(s) to the FEIS, the RCRA Permit, the last CRA, records of the waste container contents and disposal locations within the WIPP repository)

- (iv) Geologic, geochemical, hydrologic, and other site data pertinent to the containment of waste in the disposal system, or the location of such information (Safety Analysis Report, the FEIS for WIPP and the supplement(s) to the FEIS, the RCRA Permit, the last CRA, environmental and ecological background data collected during the preoperational

phase of WIPP and summaries of data collected during the disposal and decommissioning phases of WIPP)

- (v) The results of tests, experiments, and other analyses relating to backfill of excavated areas, shaft sealing, waste interaction with the disposal system, and other tests, experiments, or analyses pertinent to the containment of waste in the disposal system, or the location of such information. (Safety Analysis Report, the FEIS for WIPP and the supplement(s) to the FEIS, the RCRA Permit, the last CRA, drawings, procedures, and design reports describing how the waste was emplaced, and how the repository was decommissioned, closed and sealed)

The National Archives will be one organization responsible for the permanent storage of this information. As discussed in CCA Appendix PIC, the information will also be distributed to appropriate organizations such as the following for long-term safekeeping:

- federal and state government agencies,
- federal, state, tribal, and local archives and libraries,
- local and state and record repositories (for example, the Eddy County Clerk New Mexico)
- national archives and libraries of nations that possess nuclear weapons and nuclear energy or produce natural gas and oil resources, and
- professional and technical societies.

The archival and record centers identified in CCA Appendix PIC as planned recipients of information were selected based upon one or more of the following criteria:

- representing an international location in a nation which had citizens engaged in the oil and gas exploration and exploitation industry,
- representing an international location in a nation which had the potential to generate radioactive waste,
- representing a local governmental organization frequented by individuals engaged in the oil and gas exploration and exploitation industry,
- representing a National Archival location,
- representing a Regional Library, or
- is a public funded location.

The DOE intends to submit WIPP records to over 100 archives nationally and internationally as identified in CCA Appendix PIC. The final number of archive recipients will depend upon the agreements reached between DOE and the facilities. The initial submittal of these records will

occur after closure and decommissioning of the WIPP. Since this time frame is decades into the future and thus significant changes will occur to some or all of the archives as well as some of the governments, the DOE has not attempted to identify the practices employed by each archive and repository for maintaining records and making them accessible to the public. However, the National Archive-Rocky Mountain Region practices are described and are representative of the National Archives and its regional facilities. The state of New Mexico Archive and the Canadian National Archive were also contacted and their practices are similar to those employed by the U.S. National Archives. There are also international standards for the organization and operation of archives that enable the world's archives to function similarly in many aspects of the practices governing maintenance of records and access to the records by members of the public.

To ensure the proper storage and retrievability of archived material, the DOE archivist will develop a filing code system specifically for the WIPP material. This system will be a part of the overall document submittal the DOE will provide to the various archival locations. In the development of the filing code system and communications with worldwide archives, it is expected that differing cultural issues will be addressed in order that the DOE gain acceptance of the information from as many archives as possible.

To reduce the possibility that future archivists may destroy the provided documents, each volume containing documents will be labeled with a warning that the intent of providing the archived material is to ensure its preservation for the 10,000-year regulatory time frame stipulated in the U.S. Government's regulations controlling the disposal of transuranic waste. It is recognized that the federal government may incur some long-term financial obligations to the archival locations to ensure retention. Within two years following the distribution of archival material and at least every 15 years thereafter during the active institutional controls period, the DOE will conduct audits of selected archival locations to verify retention and retrievability of the historical documents.

As an example of how an archive will handle archived information, the National Archive will use the indexing system provided by the DOE in organizing the WIPP material submitted for archiving and public use. Upon receipt of the material in boxes, the archive staff will examine the documents; remove staples, paper clips, rubber bands, and other miscellaneous materials that may damage or are otherwise incompatible with the records over an extended period of time; enclose any damaged material in individual protective covers; place the records in acid-free boxes; and store those boxes in an environmentally controlled vault. The individual boxes are labeled with coded alpha-numeric designations that tie the contents back to the agency submitting the documents, the year in which the documents were received, and the general content of the documents. Finding aids, content indices, or significant word lists are developed to aid researchers in identifying the material desired. The coded number will also provide information relative to whether or not the documents may be destroyed after a given amount of time. Many government documents are scheduled to be destroyed after 30 years. Other documents are preserved indefinitely.

Title 36 CFR Part 1254, Availability of Records and Donated Historical Materials, regulates the manner in which archival material within the National Archive system is made available to members of the public. In general, researchers must register each day that they enter a research facility and may be required to provide identification. The researcher must sign for the

documents received and again may be required to show identification. The researcher is not permitted to leave the room without notifying the room attendant and placing all documents in their proper containers. Documents must be returned to the research room attendant prior to the room closing. Documents may not be used where there is food, drink, or the presence of ink. Only pencils may be used in the room containing original documents. If the researcher requires copies of documents, the appropriate document must be marked with a paper tab provided by the archive. No paper clips or rubber bands may be used on the documents. The room attendant will provide the copying services for the researcher. Documents must be maintained in order by the researcher; however if the documents become disordered, the room attendant must perform the re-ordering function and not the researcher. Upon exiting a research room, the researcher must present for examination any article that could contain documents.

In addition to the national and state archives, Indian tribes and pueblos (for example, Navajo, Mescalero Apache, and Zuni) were contacted to determine the extent of any archival activity. Only the Zuni were establishing a limited internal archive. Other groups forward archive worthy materials to federal storage facilities. The DOE will continue to work with key nations, tribes, and pueblos to establish pertinent agreements and to ensure that appropriate WIPP records are distributed for archiving and reference purposes.

Finally, the International Atomic Energy Agency (IAEA), with the DOE as a current participatory through the agency of its Scientific Advisor, is developing a procedure for the archiving of records pertinent to the disposal of radioactive waste in deep geological repositories. The procedure, published in July 1999, is titled Maintenance of Records for Radioactive Waste Disposal (IAEA 1999). The DOE embraces this effort.

7.3.3.2 Implementation of Programs to Collect Information

Prior to implementing the passive institutional controls, a testing program will determine whether the specific messages proposed can be expected to convey the intended warnings and information across cultures and whether the proposed media for transmitting the messages will endure to the degree anticipated in the development of the conceptual model. The testing to be conducted will address the refinement of the messages, diagrams, and the method of presentation. As recommended in Trauth et al. (1993), the translated versions of the message text should be evaluated by presentations to groups indigenous to the countries whose language is represented in the message. This process should provide input into how comprehensible the messages are and provide information regarding any idiom changes that may be necessary in the translated versions. When considering that the messages were developed by educated individuals residing in the U.S., it is prudent that the effectiveness of the messages to convey their intended content to a broader cross-section of individuals be thoroughly tested. The testing therefore should include cross-cultural groups in evaluating the effectiveness of conveying the intended messages through diagrams and pictures as well as script. The DOE will continue to develop and review the details of a testing program to ensure that a comprehensive effort is made to test the final written and pictograph message comprehensibility. For those components that include either large volumes of various materials (for example, the berm) or the movement of heavy objects (for example, the sections of granite in the monuments), procedures will be tested for transporting the material and constructing the specified designs. The testing programs are

described in CCA Appendix PIC. See CCA Appendix EPIC for a discussion of the durability of materials to be used to construct passive institutional controls.

7.3.3.3 Passive Institutional Controls Timelines

The DOE has prepared a tentative schedule of the implementation of the passive controls program. The schedule is shown in Figure 7-14. The following is provided as a brief expansion of the timelines provided in Figure 7-14.

- 1996 – 2083 Design and Test Permanent Marker Concepts and Materials. During this period the testing and monitoring described in CCA Appendix PIC related to the permanent marker components, materials, and communication concepts are conducted.
    - 2004-2009 Construct Test Markers. During this period, the DOE will install prototype markers for testing. The types of prototype markers and their materials of construction will be based on results of screening tests.

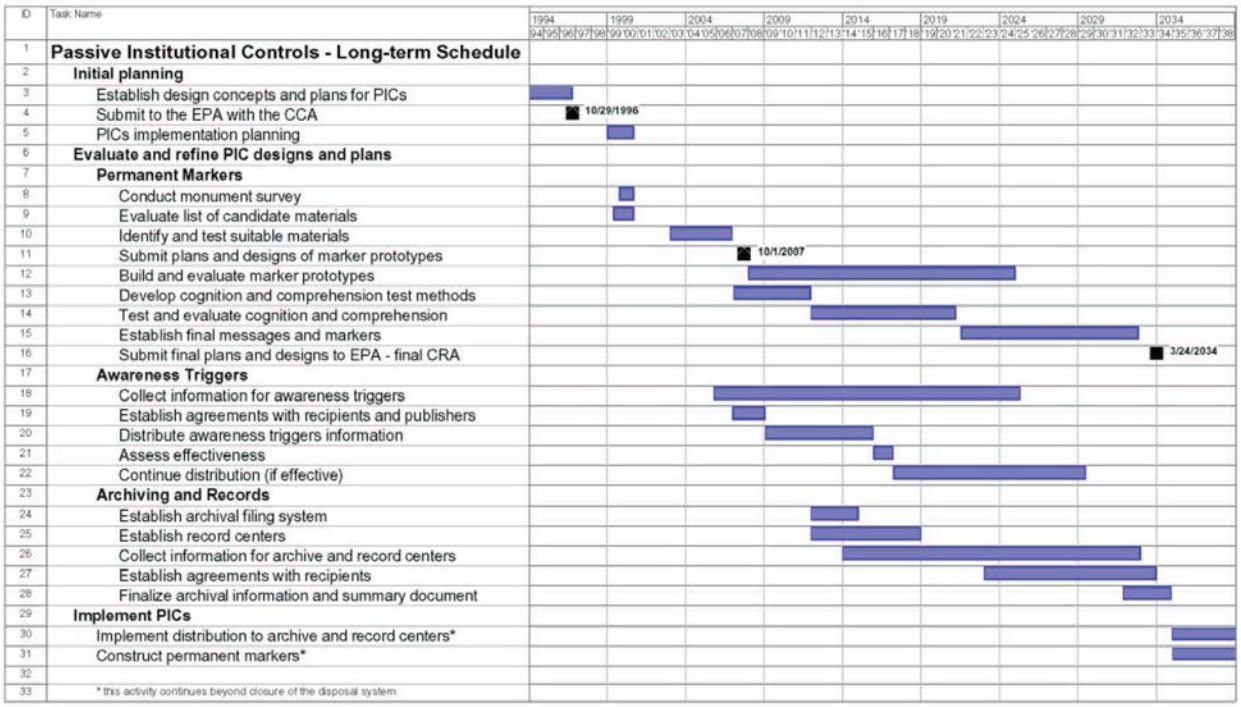

Figure 7-14. Passive Institutional Controls - Long Term Schedule 2007-2083

Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2004

- Monitor Performance of Prototype Markers. During this period, the DOE will monitor the performance of the test structures to develop information for use in the final design.

- 2018 – 2023 Test Message Comprehension. The DOE will gain operational experience for any information that may affect the composition of the intended messages, both narrative and pictogram, and then conduct testing for comprehension by populations indigenous to the countries represented by the languages used in the messages.

- 2083 – 2090 Final Design. During this period, the DOE will complete the final design of the permanent marker system.

- 2090 – 2093 Construct Permanent Marker System. During the period, the permanent marker system will be constructed including installation of messages.

- 1999 – 2093 Implement Information Collection and Establish Archival and Record Center Agreements. During this period the actions required to implement record keeping and record storage aspects of PICs are conducted. Individual actions and associated timelines are:

• 2004 Establish Filing System. The DOE will establish the filing system under which the record center and archival information will be assembled. Completion of the system by 2004 will support the information collection program.

- 2003 – 2033 Collect Operational Information. Collect the information relative to WIPP operation, including decommissioning, which will be included in the promulgated documentation.

- 2033 – 2090 Collect Active Control Period Information and Marker Configuration. Collect the information relative to WIPP active controls and the results of testing of the permanent marker system components and communication concepts.

- 2023 – 2034 Establish Agreements with Recipients. During this period the DOE will communicate with the planned document recipients to develop general agreements with respect to language translation, scope of translated material, format in which the material will be provided, and any financial support required to achieve acceptance by each recipient. Beginning about 2023 when most of the documentation should have been developed, this effort should start. The DOE expects two to three years to establish the agreements and another five to eight years for translation, with completion about the time that decommissioning and decontamination are finished. This provides for the incorporation of information related to decommissioning and decontamination.

- 2033 – 2034 Develop Summary Document. The DOE will develop the WIPP summary document to be provided for ease of public access and understanding of the WIPP.

- 2035 Promulgate Information Accumulated Through WIPP Closure and Decommissioning. The DOE will make a distribution of documents accumulated through the final closure, decontamination, and decommissioning of the WIPP.

- 2023 – 2033 Establish Agreements and Submit Information to Publishers. During this period, the DOE will establish agreements with map makers and text publishers including financial support and provide hazard, history, and location information to be included on maps and various text materials.

- 2083 – 2093 Finalize Archival Information. During this period, the DOE will develop the final additions to the planned submittal, which include information describing the WIPP history during the first 50 to 60 years following closure and the final configuration of the permanent marker system.

- 2093 Promulgate Archival & Records Center Information. The DOE will make the distribution of the final portion of the archived information nationally and internationally.

In a letter dated May 16, 2002 from Dr. Ines Triay to Mr. Frank Marcinowski, the DOE proposed to the EPA changes regarding the submittal of detailed plans and drawings depicting the permanent marker prototypes. The request includes a proposed revised schedule, as detailed in Table 7-9.

The EPA responded to the DOE request in a letter dated November 7, 2002, from Mr. Marcinowski to Dr. Triay (EPA Docket A-98-49, Category IIB-3, Item 41). The EPA response states that the schedule changes proposed by the DOE are insignificant with respect to the Certification Decision (63 FR 27396, May 18, 1998). The EPA also concluded that the DOE plans for testing provide significant details to support the need for additional testing time. As such, the EPA determined that the DOE may proceed with the proposed changes. In addition, the EPA provided the following comments related to the implementation of the passive institutional controls program. These comments serve as guidance to the DOE.

1. The Permanent Markers Testing Program Plan is a welcome development. The EPA appreciates the thoroughness of DOE's approach to this topic, especially the inclusion of references to the Quality Assurance Program Document. The use of reference standards and established quality processes, as well as a methodical approach to testing, will be important factors in demonstrating to the EPA that any future changes to the conceptual design have an adequate technical basis.

2. The DOE is obligated to execute site markers as described in the CCA and subsequent DOE correspondence (February 7, 1997, letter from G. Dials to R. Trovato; Air Docket A-93-02, Item II-I-07). If the DOE determines that the original marker design (including location, number, materials, and configuration) should be altered or

Table 7-9. Activities Related to the Implementation of the Permanent Markers Program

Activity	Reference Event	Original Timeframe	Current Status	Proposed Timeframe
Stone Monument Survey	First five years of operations	1999-2004	Completed	N/A
Identification of suitable source material	First five years of operations	1999-2004	Pending decisions on changes to design and material selection	2007
Submit plans for the test marker system	1st CRA submittal	2003	Proposed change to submit prior to second CRA	2007
Construct and test berm and test markers	Second five years of operations	2004-2009	Pending proposed change and testing program	2008
Monitor performance of test berm and test markers	After construction	2007-2083	Pending proposed change and testing program	2009 - until closure
Testing comprehension of marker messages submittal of testing plans to EPA	Fourth CRA submittal	2018	No change	N/A
Develop final design of markers	Upon termination of testing program	2083-2090	Final design to be submitted with the final CRA	2033 (anticipated)
Finalized Translated Messages	Prior to building of final permanent markers	N/A	Finalized messages will be submitted with the final CRA	2033 (anticipated)

improved, the Department must notify the EPA and receive the Agency's approval before proceeding.

Certain changes (such as different component materials or dimensions) may be possible without modifying the certification, as long as the design itself remains essentially the same. However, the introductory section of the proposal (page 2) states, "DOE plans to re-examine whether…all of the components of the permanent marker system proposed in the CCA are needed." Elimination of one or more components may require modification.

3. Condition 4 of the Certification Decision requires the DOE to show that PICs will be implemented "as soon as possible following closure of the WIPP." DOE's change notice states that all measures in their final form will be presented in the last recertification application before site closure (approximately 2033). Throughout the operational phase of the WIPP, the DOE should present information in each recertification application showing progress with regard to testing and implementation of all PICs (markers, archived records, etc.).

4. Based on conclusions reached by John Hart and Associates, the DOE suggests that "portions of the permanent marker system originally conceptualized…are impractical" (page 1 of the introductory section). Concerns about the specific design of the surface granite monoliths led us to require further information about the monoliths in Section(a)(2) of Condition 4 of the WIPP Certification. Nevertheless, the EPA explicitly concluded in the Certification Decision that the proposed marker system – including the salt-core based berm – was practicable. To justify a departure from the markers that were proposed, the DOE would be expected to provide an adequate technical basis showing that an alternative is likely to be more durable and effective as a marker. EPA believes that further testing and analysis of materials (e.g., basalt), processes (e.g., granite exfoliation), and configurations (e.g., salt core of the berm) should be done before DOE concludes that certain features of the marker system are impractical.

7.3.4 Effectiveness of Passive Controls in Reducing the Rate of Human Intrusion

The EPA raises the issue of the expected ability of the passive institutional controls to convey information to future societies in two areas. In the context of the assurance requirement in which no assumptions can be made to limit the uncertainty of the future states of societies, the EPA states

> Any compliance application shall include the period of time passive institutional controls are expected to endure and be understood. (40 CFR § 194.43[b])

In the context of credit for passive institutional controls in deterring inadvertent human intrusion for use in performance assessments, the EPA goes on to state that

> The Administrator may allow the Department to assume passive institutional controls credit, in the form of reduced likelihood of human intrusion, if the Department demonstrates in the compliance application that such credit is justified because the passive institutional controls are expected to endure and be understood by potential intruders for the time period approved by the Administrator. Such credit, or a smaller credit as determined by the Administrator, cannot be used for more than several hundred years and may decrease over time. In no case, however, shall passive institutional controls be assumed to eliminate the likelihood of human intrusion entirely (40 CFR § 194.43[c]).

To limit the speculation about the state of future society, the EPA has provided additional guidance by stating that "EPA expects that the DOE will establish a framework of assumptions for passive institutional controls that is a prudent extrapolation of the future state assumptions established in 194.25" (EPA 1996b, p. 61) and by providing for the existence of certain societal "common denominators" based on "patterns of human behavior that may be detected throughout history and around the world" (EPA 1996b, p. 61).

Section 7.3.4.1 addresses the issue of how long the passive institutional controls are expected to endure and be understood in the context of the Assurance Requirement (40 CFR § 194.43[b]) and Section 7.3.4.2 addresses the issues of how long these controls are expected to endure and be understood and the resulting credit in deterring inadvertent human intrusion in performance assessment calculations (40 CFR § 194.43[c]).

7.3.4.1 Expected Effectiveness

The passive institutional controls in the Conceptual Design Report (DOE 1994) were developed from the recommendations of the Markers Panel convened in 1991, modifying them for reasons such as constructability or resource requirements. The Markers Panel developed fundamental principles of long-term communication making only the most minimal assumptions about what future societies would be like (for example, they will be human beings similar to what we are today). No assumptions were made about what languages they might be speaking or how technologically sophisticated they might be. Because no assumptions were made about language or technology, the Markers Panel developed strategies that attempt strategies to communicate with individuals in a variety of means and in a systems approach whereby the various components reinforce and supplement the other messages.

Without assumptions about technological sophistication, messages will be provided in various levels of complexity, ranging from the most basic marker of human construction rather than a natural phenomenon, to the entire written record of information about the repository and its certification. Because it is not known what languages will be spoken in the future, the markers will include non-linguistic means of communication, such as pictures of humans, star charts, and the periodic table of the elements. In this way, the design of the markers responds to the EPA's requirement for the "most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location" (40 CFR § 191.14[c]). While the Markers Panel focused its efforts on the repository footprint, based on the 40 CFR 191 definition of human intrusion, the entire withdrawal area will be identified by on-site passive institutional controls to satisfy criteria in 40 CFR § 194.43. Because of the requirement for records and archives, plans have been made to place materials within the existing governmental and scientific systems of recordkeeping.

In addressing the issue of credit for passive institutional controls in performance assessment calculations, the DOE examined historical analogues for the controls components (see CCA Appendix EPIC, Chapter 5). Certain design characteristics of these historical analogues have survived destruction from both societal turmoil and natural processes. By designing the PICs to mimic and enhance these design characteristics, the DOE believes that the passive institutional controls for the WIPP will be capable of surviving at least as long as the historical analogues. Based on the characteristics of the markers, these components have the capability of lasting in excess of several thousand years. This conclusion is consistent with the conclusions of both teams of the Markers Panel whose estimates were based on basically the same design characteristics for the markers and on a wide variety of future states of society. The multiple copies of the records in the records centers and archives, the selection of highly durable materials (that is, archival paper and carbon-black ink), and the fact that the records will have value in the economic and health areas suggest that at least some copies of the records have a high probability of surviving for many hundreds to thousands of years.

The Markers Panel concluded that the messages proposed have a high probability (greater than 0.70) of being understood by all potential levels of technology for at least 2,000 years (Team A estimated at least 5,000 years). Although the Markers Panel considered only the messages on the markers, the same information, both text and pictographs, will be included in the records in

records centers and archives. As a result, the DOE concludes that these records will be interpretable for as long as the documents survive.

7.3.4.2 Credit Taken in Performance Assessment Calculations

In addition to their use for compliance with the assurance requirements, credit for passive institutional controls may be used in PA calculations. In 40 CFR § 194.43(c), EPA allows credit in the form of reduced likelihood of human intrusion. The Preamble to 40 CFR 194 limits any credit for passive institutional controls in deterring inadvertent human intrusion to 700 years after disposal**.** During the certification process, the DOE sought passive institutional controls credit in the CCA based on the conclusions of a designated task force. CCA Appendix EPIC documents the basis for this credit. For the performance assessment calculations in the CCA, the passive institutional controls were considered to be 0.99 effective in deterring inadvertent human intrusion over the entire withdrawal area for 700 years.

However, the EPA performance assessment verification test (PAVT) calculations did not include credit for passive institutional controls (63 FR 27396). In the certification decision (EPA 1998), the EPA concluded its discussion on this matter as follows:

> However, EPA's final decision today applies only to the credit proposal in the CCA and should not be interpreted as a judgement on the use of PICs credit in PAs generally. In the future, DOE may present to EPA additional information derived from an expert elicitation of PICs credit. Any future PICs credit proposals will be considered in the context of a modification rulemaking, and will be subject to public examination (63 FR 27396).

In this recertification application, the DOE claims no credit for the effectiveness of passive institutional controls. As indicated by the EPA, the DOE may claim such credit in future recertification applications.

7.4 Multiple Barriers

The WIPP facility has incorporated multiple natural and engineered barriers, including plugs, seals, and backfill into its design. As a part of the DOE's program to evaluate multiple barriers, an Engineered Alternatives Task Force (EATF) evaluated optional additional engineering measures for the WIPP facility. The findings of the task force are summarized in the *Evaluation of the Effectiveness and Feasibility of the Waste Isolation Pilot Plant Engineered Alternatives* (DOE 1991). A more recent study, the Engineered Alternatives Cost/Benefit Study, updated the 1991 EATF activity and augmented it with more in-depth and comprehensive analyses of the relative benefits and detriments of the alternatives. Benefits and detriments at the waste generation and storage sites were evaluated in this study as well as those at the WIPP. (This study is included in CCA Appendix EBS.)

Beyond the requirements contained in 40 CFR § 191.14(d) relating to multiple barriers, 40 CFR § 194.44 has imposed certification criteria upon the DOE with regard to engineered barriers. The following sections provide a discussion of the manner in which the DOE has complied with the multiple barrier requirement of 40 CFR § 191.14(d) and an overview of the manner in which the engineered barrier criteria of 40 CFR § 194.44 have been met. A detailed discussion of the cost and benefit analysis dictated in 40 CFR § 194.44 is provided in CCA Appendix EBS.

7.4.1 Requirements for Multiple Barriers

By requiring the use of both natural and engineered barrier types as the assurance requirement, the EPA intends to ensure that the impacts of the failure of any single barrier type will be minimized.

In the LWA, Congress mandated that the Secretary will use both natural and engineered barriers. Waste form modifications may be used at the WIPP to isolate waste after disposal to the extent necessary to comply with the final disposal regulations. Therefore, the disposal system design involving the Salado as a natural barrier and the shaft seals as engineered barriers complies with this assurance requirement as indicated by the compliant complementary cumulative distribution functions (CCDFs) shown in Section 6.5.

7.4.2 Objectives for Multiple Barriers

The primary objective for the implementation and the use of multiple barriers at the WIPP facility is to help guard against unexpectedly poor performance from one type of barrier. This is accomplished by a design that includes multiple types of barriers.

7.4.3 Implementation of Multiple Barriers

The baseline design for the WIPP facility includes the concept of multiple barriers for isolation and containment of waste. Barriers that are part of the design include natural barriers (for example, hydrological, geological, and geochemical conditions) and engineered barriers (for example, borehole plugs, shaft seals, panel closures, and backfill). The effectiveness of these barriers is modeled in the performance assessment to demonstrate the ability of the disposal system to meet EPA standards.

Although the DOE plans to apply multiple engineered systems to aid in waste isolation, the EPA specified in the WIPP certification that only MgO backfill meets the regulatory definition of an engineered barrier.

Section 194.44(a) provides a criterion for certification for the analysis of the cost and benefits of various engineered barrier options. The text in the following subsections describes the DOE program that meets the engineered barrier requirements.

7.4.3.1 Engineered Alternatives Cost and Benefit Study

To fulfill the benefit and detriment evaluation criterion contained in 40 CFR § 194.44(b), the DOE published *Engineered Alternatives Cost/Benefit Study; Final Report* (DOE 1995) (see CCA Appendix EBS). The EPA's criterion for this cost and benefit study is as follows:

> In selecting any engineered barrier(s) for the disposal system, the Department shall evaluate the benefit and detriment of engineered barrier alternatives, including but not limited to: cementation, shredding, supercompaction, incineration, vitrification, improved waste canisters, grout and bentonite backfill, melting of metals, alternative configurations of waste placements in the disposal system, and alternative disposal system dimensions. The results of this evaluation shall be included in any compliance application and shall be used to justify the selection and rejection of each engineered barrier evaluated. (40 CFR § 194.44[b])

The primary purpose of this cost and benefit study was to provide the DOE with information for use in selection or rejection of additional engineered barriers that provide assurance in the performance calculations. The current facility baseline, as represented in performance assessment, provides sufficient multiple barriers to obtain compliance with the requirements of 40 CFR § 191.14(d) as described in Sections 6.4.4 (Shaft Seal Engineered Barriers), 6.4.5 (The Salado Formation Natural Barrier), and 6.5 (Performance Assessment Results).

The approach used in the study was to screen potential engineered alternatives compiled from previous studies, the ten technologies specified in 40 CFR § 194.44(b), and input elicited from stakeholders. The screening process used a working group composed of technical professionals from various related fields to compare the proposed engineered alternatives to the established definition of an engineered alternative and then to determine if those alternatives that meet the definition also meet regulatory and technological feasibility criteria. The outputs of the screening process were

- a list of engineered alternatives that did not meet the definition or screening criteria, along with the justification for their rejection, and
- a list of engineered alternatives retained for further consideration.

The screening process evaluated 111 proposed engineered alternatives and screened out all but 54 (see CCA Appendix EBS, Section 2.2.2). The 54 alternatives retained were then subjected to a DOE management-level assessment to determine the set of alternatives that would be retained for full analysis through the study. The basis for this assessment was to:

- develop a set of alternatives that address important WIPP performance issues, such as reducing the solubility of actinides in brine and improving the strength of the waste,
- analyze those alternatives that have high technical feasibility (that is, those alternatives that have been subjected to bench-scale testing at the least), and
- assess those alternatives that have a high likelihood of being permitted in a reasonable amount of time.

This assessment resulted in the selection of 18 alternatives for full analysis through the study. The screening process, including this DOE management-level assessment, was included in the scope of an independent peer review done on the study to address the requirements of 40 CFR § 194.27(a)(3). The peer review panel concluded that the entire screening process was reasonable and acceptable. Details of the peer review are found in CCA Appendix PEER (Section 3.2).

The 18 alternatives finally selected for further study consisted of nine basic alternatives and nine variations. The 18 alternatives were compared to the criteria in 40 CFR § 194.44(c):

> (i) The ability of the engineered barrier to prevent or substantially delay the movement of water or waste toward the accessible environment;

(ii) The impact on worker exposure to radiation both during and after incorporation of engineered barriers;

(iii) The increased ease or difficulty of removing the waste from the disposal system;

(iv) The increased or reduced risk of transporting the waste to the disposal system;

(v) The increased or reduced uncertainty in compliance assessment;

(vi) Public comments requesting specific engineered barriers;

(vii) The increased or reduced total system costs;

(viii) The impact, if any, on other waste disposal programs from the incorporation of engineered barriers (for example, the extent to which the incorporation of engineered barriers affects the volume of waste);

(ix) The effects on mitigating the consequences of human intrusion. (40 CFR § 194.44[c][1])

In addition to the criteria listed above, CCA Appendix EBS includes analyses that evaluated

- existing waste that is already packaged,
- existing waste that is not yet packaged,
- existing waste that is in need of repackaging, and
- to-be-generated waste.

All 18 alternatives met the intent of these criteria. This process is further described in Section 2 and Appendix O of CCA Appendix EBS. The variations originated in the screening process, details of which can be found in Sections 2.2 and 2.3.1 of CCA Appendix EBS.

For comparison, the baseline was considered to be the WIPP facility with no additional engineered barriers beyond shaft seals and panel closures. The 18 final engineered alternatives, along with a brief description of each, are listed below.

- **Supercompact Organics and Inorganics.** Solid organic and inorganic wastes are sorted to remove items that cannot be compacted. Sorted waste is precompacted in 35-gallon (132.6-liter) drums and then supercompacted. Usually, the contents of four supercompacted drums are placed in a 55-gallon (208-liter) drum. Sludges are not processed.

- **Shred and Compact Organics and Inorganics.** Solid organics and inorganics are shredded and compacted in 55-gallon (208-liter) drums using a mechanical shredder and a low-pressure compactor. Sludges are not processed.

- **Plasma Processing of All Wastes.** All wastes are processed through a mechanical shredder and the input waste stream is controlled to ensure a suitable metal to nonmetal

ratio. The waste is processed through a plasma arc centrifugal treatment system and placed into 55-gallon (208-liter) drums.

- **Sand Plus Clay Backfill.** A mixture of medium-grained sand and granulated clay is used as backfill. The mixture is placed around the waste stack and between the drums, filling the void space between drums and unmined host salt in waste emplacement panels. A fifty percent void space is assumed.

- **Salt-Aggregate (Grout) Backfill.** A salt-aggregate grout mixture is used as backfill to fill the void spaces between drums and unmined host salt in waste emplacement panels. This backfill consists of a cementitious-based, salt-aggregate grout with crushed salt aggregate and is pumped around the waste stack and between the drums filling the void spaces. A twenty percent void space is assumed.

- **Cementitious Grout Backfill.** A cementitious grout backfill consisting of ordinary Portland cement, sand, and fresh water is pumped around the waste stack and between the drums filling the void space. A twenty percent void space is assumed.

- **Supercompact Organics and Inorganics, Salt-Aggregate and Grout Backfill.** Monolayer of 2,000 drums in a room that is 6 feet (1.83 meters) high, 33 feet (10.1 meters) wide, and 300 feet (91.4 meters) long.

- **Supercompact Organics and Inorganics, Clay-Based Backfill.** Monolayer of 2,000 drums in a room that is 6 feet (1.83 meter) high, 33 feet (10.1 meter) wide, and 300 feet (91.4 meter) long.

- **Supercompact Organics and Inorganics, Sand and Clay Backfill.** Monolayer of 2,000 drums in a room that is 6 feet (1.83 meter) high, 33 feet (10.1 meter) wide, and 300 feet (91.4 meter) long.

- **Supercompact Organics and Inorganics, CaO Backfill.** Monolayer of 2,000 drums in a room that is 6 feet (1.83 meter) high, 33 feet (10.1 meter) wide, and 300 feet (91.4 meter) long.

- **Salt Backfill with CaO.** A backfill of commercially available granulated lime and crushed salt is placed around the waste stacks and between the drums filling the void space. A fifty percent void space is assumed.

- **Enhanced Cement Sludges, Shred and Add Clay-Based Materials to Organics and Inorganics, No Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly-generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums.

- **Enhanced Cement Sludges, Shred, and Add Clay-Based Materials to Organics and Inorganics, Sand and Clay Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly-generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums. A mixture of medium-grained sand and granulated clay is used as backfill. The mixture is placed around the waste stack and between the drums filling the void space between drums and unmined host salt in waste emplacement panels. A fifty percent void space is assumed.

- **Enhanced Cement Sludges, Shred, and Add Clay-Based Materials to Organics and Inorganics, Cementitious Grout Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly-generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums. A cementitious grout backfill consisting of ordinary Portland cement, sand, and fresh water is pumped around the waste stack and between the drums filling the void space. A twenty percent void space is assumed.

- **Enhanced Cement Sludges, Shred, and Add Clay-Based Materials to Organics and Inorganics, Salt Aggregate Grout Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly-generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums. A salt-aggregate grout mixture is used as backfill to fill the void spaces between drums and unmined host salt in waste emplacement panels. This backfill consists of a cementitious-based, salt-aggregate grout with crushed salt aggregate and is pumped around the waste stack and between the drums filling the void spaces. A twenty percent void space is assumed.

- **Enhanced Cement Sludges, Shred, and Add Clay-Based Materials to Organics and Inorganics, Clay-Based Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly-generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums. A

backfill consisting of commercially available pelletized clay is placed around the waste stack and between the drums, filling the void space. A fifty percent void space is assumed.

- **Enhanced Cement Sludges, Shred, and Add Clay-Based Materials to Organics and Inorganics, CaO and Salt Backfill.** This alternative includes two processes to treat the waste. The first is an enhanced cementation process of previously solidified and as-generated sludge. Existing sludges are fed into a mechanical crusher and shredder. The crushed waste is mixed with an enhanced cement and the product is poured into 55-gallon (208-liter) drums. Newly generated sludges are solidified with the enhanced cement. The second process shreds solid organic and inorganic wastes and adds clay to the shredded waste. This waste product is packaged in 55-gallon (208-liter) drums. A backfill of commercially available granulated lime and crushed salt is placed around the waste stacks and between the drums filling the void space. A fifty percent void space is assumed.

- **Clay-Based Backfill.** A backfill consisting of commercially available pelletized clay is placed around the waste stack and between the drums, filling the void space. A fifty percent void space is assumed.

The product from the evaluation of each factor evaluated was integrated into a quantifiable result called a performance vector. This vector expresses the performance of each engineered alternative relative to the baseline. The results of the factor analyses are presented in detail in CCA Appendix EBS (Section 5.4).

The Engineered Alternatives Cost/Benefit Study (CCA Appendix EBS) was useful to the DOE, as it identified engineered barriers that could be used to improve long-term repository performance. Specifically, the advantages of a backfill that chemically altered the pH of brine in the disposal room were identified in CCA Appendix EBS (Section 3.1) as providing significant benefit in reducing the quantity of mobile actinides. Alkaline earth oxides (such as calcium oxide [CaO]) are known to readily react with water to form hydroxides. These hydroxides are free to react with carbonic acid that may form in the disposal room. The reaction buffers the brines to a pH that reduces the amount of actinide in solution. After further analysis, which is documented in CCA Appendix BACK and discussed in CCA Appendix SOTERM, the DOE selected magnesium oxide (MgO) as the backfill material that provided the desired long-term benefit while minimizing the operational impacts associated with the more caustic CaO. The beneficial effects of MgO backfill are now included in the WIPP performance assessment calculation. Relevant discussions can be found in Sections 3.3.3 and 6.4.3.4. Additional related information developed since the preparation of the CCA is provided in Appendix BARRIERS.

7.4.3.2 Incorporation into Repository Design

In its guidance to implementation of the certification criteria in 40 CFR § 194.44(d), the EPA requested that the DOE describe how engineered barriers are incorporated into the repository. The purpose of this section is to identify the location of these descriptions and the location of the analysis that evaluates the performance of the engineered barriers.

Shaft seals delay the movements of radionuclides toward the accessible environment through the shafts. These shaft seals are described in detail in CCA Appendix SEAL and are summarized in Section 3.3.2. Analysis of the effectiveness of shaft seals is included in CCA Appendix SEAL (Section 8) and Section 6.4.4. Panel closures prevent the movement of radionuclides toward the accessible environment by limiting the magnitude of releases that can occur during certain human intrusion events. The design of panel closures is described in CCA Appendix PCS, summarized in Section 3.3.2, and their role in the repository model is discussed in Section 6.4.3. More recent related information is provided in Appendix BARRIERS**.** Backfill substantially delays the movement of radionuclides toward the accessible environment by limiting, through chemical means, the amount of actinides that can be dissolved in brines that enter the repository. The placement of backfill is described in Section 3.3.1, and its design and functions are described in CCA Appendix SOTERM and Appendix PA, Attachment SOTERM. Actinide mobility is discussed in Section 6.4.3. Borehole plugs are used to limit the volume of water that could be introduced to the repository from overlying water-bearing zones and to limit the volume of contaminated brine that could be released to the accessible environment. Borehole plug design is addressed in Section 3.3.4. In addition, parameter values selected to implement the various engineered components into the PA model are described in Appendix PA, Attachment PAR. Borehole plugs, as described in Section 3.3.4, are also included to mitigate the potential for contaminant migration.

The EPA concluded in its certification that the use of MgO backfill meets the regulatory intent of the engineered barriers portion of the regulation. The certification decision (EPA 1998) includes the following regarding engineered barriers:

> The EPA finds that DOE complies with Section 194.44. The EPA found that DOE conducted the requisite analysis of engineered barriers and selected an engineered barrier designed to prevent or substantially delay the movement of water or radionuclides toward the accessible environment. The DOE provided sufficient documentation to show that MgO can effectively reduce actinide solubility in the disposal system. The DOE proposed to emplace a large amount of MgO around waste drums in order to provide an additional factor of safety and thus account for uncertainties in the geochemical conditions that would affect CO_2 generation and MgO reactions (63 FR 27397).

Since the certification, the DOE has performed additional MgO-related analyses. These analyses are reported in Appendix BARRIERS.

7.5 Resource Considerations

The EPA discourages the location of repositories in areas in which valuable natural resources are present, through the assurance requirements in 40 CFR § 191.14(e). This assurance requirement states that

> Places where there has been mining for resources, or where there is a reasonable expectation of exploration for scarce or easily accessible resources, or where there is a significant concentration of any material that is not widely available from other sources, should be avoided in selecting disposal sites. Resources to be considered shall include minerals, petroleum or natural gas, valuable geologic formations, and ground waters that are either irreplaceable because there is no reasonable alternative source of drinking water available for substantial populations or that are vital to the preservation of unique and sensitive ecosystems. Such places shall not be used for disposal of the wastes covered by this part unless the favorable characteristics of such places compensate for their greater likelihood of being disturbed in the future (40 CFR § 191.14[e]).

The purpose of the requirement is to provide assurance that site selection actions further reduce the likelihood of future intrusion into the repository by giving preference to those sites without currently recognized resources.

In promulgating 40 CFR 194, the EPA provided for a clear manner in which to assess compliance with this requirement, stating that

> If performance assessments predict that the disposal system meets the containment requirements of § 191.13 of this chapter, then the Agency will assume that the requirements of this section and § 191.14(e) of this chapter have been fulfilled (40 CFR § 194.45).

Section 6.5 demonstrates compliance with 40 CFR § 191.13, including resource considerations, and hence compliance with 40 CFR § 194.14(e). The EPA further provides, in its guidance to 40 CFR Part 194, that the DOE

- document that the effects of mining and drilling over the regulatory time frame have been incorporated into performance assessments according to the requirements of § 194.32, § 194.33, and § 194.43;
- document that performance assessments incorporate the effects on the disposal system of any activities that occur in the vicinity of the disposal system or are expected to occur in the vicinity of the disposal system soon after disposal, according to the requirements of § 194.32; and
- document whether the results of performance assessments demonstrate compliance with the containment requirements of § 191.13.

The DOE has satisfied the EPA criteria concerning resource evaluation. This information is documented in Section 6.5.2. The mean CCDFs in Figure 6-36 incorporate both the effects of mining inside the controlled area (see Section 6.4.6.2.3 for a description of the mining conceptual model) and the effects of intermittent and inadvertent drilling (see Section 6.4.7 for a discussion of the drilling conceptual model). In addition, the impacts of resource development outside the controlled area were considered in the development of disposal system conceptual models.

7.5.1 Resource Considerations Prior to 40 CFR Parts 191 and 194

The WIPP site selection occurred prior to promulgation of 40 CFR Parts 191 and 194. Resource considerations were included in the site selection process for the WIPP and are documented in the WIPP FEIS (DOE 1980) and CCA Appendices GCR and IRD. The objective of the program for demonstrating compliance with the resource considerations requirement is to document the rationale used in the decision-making process.

7.5.2 Implementation of Resource Considerations

Resource considerations were included in the site selection process for the WIPP and are documented in the WIPP FEIS (DOE 1980, Section 7.3.7). The FEIS describes a four-step decision-making process that was applied to siting the repository. This process is summarized below:

- Step 1 – Bedded salt was selected as the most promising geologic medium, and geographic regions that contain extensive bedded salt formations were identified. This was accomplished by gathering and evaluating existing information concerning rock types and their geographic distribution. Desirable criteria were identified and the most favorable regions were identified.

- Step 2 – A literature review was performed to narrow the number of regions identified in Step 1. Once a region was selected, candidate sites within the region were chosen. Selection criteria were used to compare the sites. Those sites that satisfied the most criteria were selected for further evaluation. Resource-conflict considerations were applied on a broad scale at this stage of the process.

- Step 3 – The candidate sites identified in Step 2 were subjected to further investigations covering geology, hydrology, archaeology, demography, and biological resources. The results of all the site evaluations were compared, and the site that best met the selection criteria was selected for additional site characterization. At this stage, the types and quantities of natural resources present at the site were considered in detail.

- Step 4 – In this final step, a detailed system analysis was performed. This analysis addressed the specific geologic environment, the waste forms, the disposal facility design, and the potential failure modes with respect to radiation safety and environmental impact.

Based upon the above process, the DOE concluded that the favorable characteristics of the WIPP site (good hydrological characteristics, salt medium, moderate depth, salt thickness, low population density, lack of significant economic conflicts, and others) uniquely qualified it for a repository for defense waste. These characteristics also compensate for any increased likelihood of future disturbance. CCA Appendix IRD provides further analysis of compliance with the resource disincentive requirement. Section 2.3.1 provides a summary of known and inferred resources in the vicinity of the WIPP. CCA Appendix DEL contains resource-development-related information used in the conceptual model of disposal system performance.

7.6 Waste Removal

Removal of the waste any time after emplacement is possible. Because the repository was initially mined to provide access to the repository rooms, access to the waste can be accomplished using similar mining technologies. Location and removal are also possible using similar equipment modified to operate remotely. A remote retrieval demonstration was conducted at the WIPP in April 1992.

7.6.1 Requirements for Waste Removal

With the promulgation of 40 CFR Part 194, and in particular 40 CFR § 194.46, the EPA specifies the criteria for demonstrating compliance with this requirement. Specifically, the EPA mandates that “any compliance application shall include documentation which demonstrates that removal of waste is feasible for a reasonable period of time after disposal.” The EPA states that this

documentation should "include an analysis of the technological feasibility of mining the sealed disposal system, given technology levels at the time a compliance application is prepared."

In promulgating its disposal regulations, the EPA stated that "any current concept for a mined geologic repository meets this requirement without any additional procedures or design features" (EPA 1985, 50 FR 38082).

Because the WIPP facility is a mined repository, no additional actions other than documentation to meet this assurance requirement are necessary. The rationale for this assurance requirement is to preclude use of some disposal technologies that would not allow future generations to recover the wastes, should they decide to do so. According to the EPA, recovery need not be easy or inexpensive but only possible (EPA 1985). CCA Appendix WRAC describes a feasible system for waste removal using available mining technologies.

7.6.2 Implementation of Waste Removal

After determining the existing repository condition, the mining and waste removal operations will be designed to minimize the amount of contamination and exposure to allow limited human access for assessments, equipment retrieval, and repairs. Any radiological work will be performed using standard industry practices and approved procedures.

Radiological sampling activities will be planned and implemented so that recovered wastes can be handled. Packaging the removed waste and any decontamination of containers can be accomplished with standard automation techniques. Plans and procedures will ensure that the amount of additional contaminated material produced during the actual waste removal is minimized.

The removal concept is composed of the following five phases.

Phase 1 – Planning and permitting.

Phase 2 – Initial above ground setup and shaft sinking.

Phase 3 – Underground excavation and facility setup of underground ventilation, radiation control, packaging areas, decontamination areas, maintenance, remote control center, and personnel support rooms.

Phase 4 – Waste location and removal operations, including mining waste removal, packaging, package surveying and decontamination, transportation to surface, staging for off-site transportation, and off-site transportation.

Phase 5 – Closure and D&D of the facility.

Each of the five phases is summarized below and described in detail in CCA Appendix WRAC (Section 5).

7.6.2.1 Planning and Permitting

A decision to remove waste will initiate the planning and permitting phase. Permitting requirements will be based on governing regulations at the time removal is authorized. The planning and permitting program will identify all permits and research the available technologies at that time to determine available removal techniques and the condition of the repository. After initial research is completed, a plan will be drafted to itemize and schedule all removal activities.

7.6.2.2 Initial Above Ground Setup and Shaft Sinking

Above ground support buildings will house the exhaust fans and filters, administration, operations and maintenance facilities, control center waste staging and decontamination areas, the warehouse (containers), and others, as deemed necessary.

7.6.2.3 Underground Excavation and Facility Setup

After the shafts are completed, drifts will be run and ventilation paths will be established using air control regulators. Support rooms will be excavated for maintenance, control rooms, and packaging areas. Air locks will be constructed to provide the necessary level of control and separation. All equipment required for removal, packaging, and related support equipment will be installed.

Excavation will be in two stages. Initial excavation will not contact waste, but will mine support rooms and haulage drifts that provide ventilation and access to the waste. The second stage will remove the waste.

7.6.2.4 Waste Location and Removal Operations

The waste removal will be performed in separate operations. The waste will be removed by mining the area where the waste was emplaced. The mined waste will be transported to the packaging areas. The waste can be removed many ways using standard equipment. CCA Appendix WRAC (Sections 6 and 7) contains a brief description and feasibility of using various mining techniques for waste removal. An appropriate level of radiological controls will be used, depending upon the radioactivity of the mined waste.

7.6.2.5 Closure and D&D of the Facility

After waste is removed from the repository, the facility will be decommissioned according to the current regulations at that time.

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8.0 INDIVIDUAL AND GROUNDWATER PROTECTION REQUIREMENTS

The quantitative release limits set forth in the Containment Requirements provisions of Title 40 of the Code of Federal Regulations (CFR) § 191.13 are one of three long-term numerical performance requirements contained in 40 CFR Part 191 Subparts B and C. The Waste Isolation Pilot Plant (WIPP) must also comply with two other numerical performance standards that are contained in the individual (40 CFR § 191.15) and groundwater (40 CFR Part 191, Subpart C) protection requirements. This section describes the U.S. Department of Energy's (DOE's) demonstration of compliance for the WIPP with both the individual and groundwater protection requirements.

In performing the compliance assessment for the CCA, the DOE applied a bounding-analysis approach using unrealistic assumptions that resulted in an overestimation of potential doses and contaminant concentrations. To provide added assurance, the DOE assumed the presence of an underground source of drinking water (USDW) in close proximity to the WIPP Land Withdrawal Area boundary, even though available data indicate that none exists near the boundary. Using this very conservative approach, the calculated maximum potential dose to an individual was found for the CCA evaluation to be about one-sixteenth of the individual protection standard. Concentrations of contamination in the hypothetical USDW would be less than half of the U.S. Environmental Protection Agency (EPA) groundwater protection limits and potential doses to a receptor who drinks from the hypothetical USDW would be an order of magnitude less.

This conservative approach also assumes that all contaminants reaching the accessible environment are directly available to a receptor. The analysis bounds any potential impacts of underground interconnections among bodies of surface water, groundwater, and any USDW.

In support of its recertification effort, the DOE has reexamined concentrations of radionuclides that could potentially reach the accessible environment under undisturbed conditions. This evaluation shows that the maximum concentration of radionuclides reaching the boundary is now projected to be six orders of magnitude less than the maximum concentration projected in the CCA. Based on this and additional updated information presented in the remainder of this chapter, the DOE concludes that the project continues to comply with the individual and groundwater protection provisions of Part 191, Subparts B and C. (See Table 1-1 in Chapter 1.0 for a list of appendices that provide additional information supporting this chapter.)

8.1 Individual Protection Requirements

The individual protection requirements are contained in 40 CFR § 191.15 of the long-term disposal regulations. 40 CFR § 191.15(a) requires that

> Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual committed effective dose, received through all potential pathways from the disposal system to any member of the public in the accessible environment, to exceed 15 millirems (150 microsieverts).

Undisturbed performance (UP) is defined in Subpart B of 40 CFR Part 191 to mean "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted

behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events" (40 CFR § 191.12). Section 6.3.1 provides a description of UP, the conceptual models associated with UP, and the screening of features, events, and processes (FEPs) that are important to UP.

The method used to evaluate compliance with the individual protection requirements is related to that developed for assessing compliance with the containment requirements. If the evaluation of the UP scenario considered for the containment requirements shows contaminants will reach the accessible environment, the resulting dose to exposed individuals must be calculated and compared to the 15-millirem annual committed effective dose specified in 40 CFR § 191.15.

Further guidance on the implementation of the individual protection requirements is found in 40 CFR Part 194. 40 CFR § 194.51 states that

> Compliance assessments that analyze compliance with § 191.15 of this chapter shall assume that an individual resides at the single geographic point on the surface of the accessible environment where that individual would be expected to receive the highest dose from radionuclide releases from the disposal system.

40 CFR § 194.52 states that

> In compliance assessment that analyze compliance with § 191.15 of this chapter, all potential exposure pathways from the disposal system to individuals shall be considered. Compliance assessments with part 191, subpart C and § 191.15 of this chapter shall assume that individuals consume 2 liters per day of drinking water from any underground sources of drinking water in the accessible environment.

In addition, 40 CFR § 194.25(a) provides criteria related to the assumptions that should be made when undertaking dose calculations:

> Unless otherwise specified in this part or in the disposal regulations, performance assessments and compliance assessments conducted pursuant to the provisions of this part to demonstrate compliance with § 191.13, § 191.15 and part 191, subpart C shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions.

8.1.1 Compliance Assessment of Undisturbed Performance

40 CFR § 194.52 specifies that compliance assessments consider "all potential pathways from the disposal system to individuals." The DOE has considered the following potential pathways for groundwater flow and radionuclide transport:

- existing boreholes, as required by 40 CFR § 194.55(b)(1); and
- potential boreholes, including those that may be used for fluid injection as required, by 40 CFR § 194.32(c) and 40 CFR § 194.54(b)(2).

After considering all of these *pathways***,** the DOE found that contaminated brine may migrate away from the waste-disposal panels if pressure within the panels is elevated by gas generated from corrosion or microbial degradation. Two credible pathways by which radionuclides could reach the accessible environment have been identified.

1. Radionuclide transport may occur laterally, through the anhydrite interbeds toward the subsurface boundary of the accessible environment in the Salado Formation.

2. Transport may occur through access drifts or anhydrite interbeds (primarily Marker Bed [MB] 139) to the base of the shafts. In this case, if the pressure gradient between the panels and overlying strata is sufficient, contaminated brine may migrate up the shafts. As a result, radionuclides may be transported directly to the ground surface, or laterally away from the shafts, through permeable strata such as the Culebra, toward the subsurface boundary of the accessible environment.

These conceptual release pathways for UP are illustrated in Figure 6-9. The modeling system described in Section 6.4 does not preclude potential radionuclide transport along other pathways, such as migration through Salado halite. However, the natural properties of the undisturbed system make radionuclide transport to the accessible environment via these other pathways unlikely.

Although both pathways are possible, the performance assessment (PA) modeling indicates that under undisturbed conditions, only the first is a potential pathway during the 10,000-year period of interest specified in the regulation (see Appendix PA, Section PA-7.2).

The DOE has used the modeling system applied to the PA, as described in Chapter 6.0, to make this determination. Scenario screening for the UP is described in Appendix PA, Attachment SCR. As specified by 40 CFR § 194.54(b)(2), Appendix PA, Attachment SCR identifies activities that may occur in the vicinity of the disposal system prior to or soon after disposal and documents which of these are included in the compliance assessment calculations. Table 6-8 in Section 6.2 identifies FEPs included in the UP modeling. Appendix PA, Attachment SCR also identifies FEPs that were considered, but are not included, in the modeling evaluation and the reasons for their elimination.

As specified by 40 CFR § 194.55(a), uncertainty in the performance of the compliance assessment is documented in Section 6.1.2. Probability distributions for uncertain disposal system parameter values used in the compliance assessment were developed and are documented in Appendix PA, Attachment PAR. Section 8.1.5 identifies sampled parameters used in the compliance assessment.

For both the CCA compliance assessment and the CRA compliance assessment, 300 realizations of the modeling system were generated to evaluate UP. These 300 realizations are composed of three sets of 100 realizations each generated using the Latin hypercube sampling (LHS) method. In both the CCA and CRA evaluations, none of the 300 realizations show any radionuclides reaching the top of the Salado through the sealed shafts.

In the CCA evaluation, nine of the 300 realizations show concentrations of radionuclides greater than zero reaching the accessible environment through the anhydrite interbeds. None of the remaining 291 realizations show radionuclides reaching the accessible environment through the anhydrite interbeds during 10,000 years. Table 8-1 shows the maximum concentrations of radionuclides calculated by the modeling evaluation as reaching the accessible environment in the nine nonzero CCA realizations. The full range of estimated values for radionuclide

concentrations for the CCA evaluation is from zero to the values shown in Table 8-1. The maximum concentration values shown in Table 8-1 occur 10,000 years after the time of decommissioning.

Table 8-1. Maximum Concentrations of Radionuclides Within the Salado Interbeds at the Disposal System Boundary for the CCA Analysis

CCA Realization No.	Maximum Concentrations (curies/liter)					
	Vector No.[1]	^{241}Am	^{239}Pu	^{238}Pu	^{234}U	^{230}Th
1	Replicate 1 Vector 46	1.36×10^{-17}	4.33×10^{-12}	Negligible[2]	5.82×10^{-13}	2.10×10^{-14}
2	Replicate 2 Vector 16	Negligible	5.13×10^{-14}	Negligible	6.77×10^{-15}	1.89×10^{-17}
3	Replicate 2 Vector 25	Negligible	1.35×10^{-15}	Negligible	1.65×10^{-16}	7.00×10^{-18}
4	Replicate 2 Vector 33	1.32×10^{-17}	7.18×10^{-14}	Negligible	9.76×10^{-15}	9.36×10^{-16}
5	Replicate 2 Vector 81	Negligible	6.23×10^{-18}	Negligible	Negligible	Negligible
6	Replicate 2 Vector 90	Negligible	5.20×10^{-16}	Negligible	7.40×10^{-17}	Negligible
7	Replicate 3 Vector 3	3.50×10^{-18}	3.08×10^{-13}	Negligible	4.32×10^{-14}	1.07×10^{-16}
8	Replicate 3 Vector 60	5.98×10^{-17}	7.41×10^{-14}	Negligible	9.09×10^{-15}	2.30×10^{-15}
9	Replicate 3 Vector 64	5.42×10^{-17}	5.85×10^{-12}	Negligible	7.61×10^{-13}	4.68×10^{-15}
10-300		Negligible	Negligible	Negligible	Negligible	Negligible

[1] Parameter values applied to each vector may be found in CCA (Appendix IRES, Tables IRES-2, IRES-3, and IRES-4).
[2] Values less than 10^{-18} curies per liter are considered negligible relative to the other values and are not reported.

The maximum concentrations of radionuclides calculated by the CRA evaluation to reach the accessible environment are shown in Table 8-2. In the CRA evaluation, only one of the 300 realizations shows concentrations of radionuclides greater than zero reaching the accessible environment through the anhydrite interbeds (see Appendix PA, Section PA-7.2). The remaining 299 realizations show no radionuclides reaching the accessible environment during the 10,000-year period. The reduction in the number of realizations showing radionuclides reaching the accessible environment is due to changes in the BRAGFLO grid and enhancements to the PA modeling system that have increased model accuracy and decreased numerical dispersion.

Table 8-2. Maximum Concentrations of Radionuclides Within the Salado Interbeds at the Disposal System Boundary for the CRA Analysis

CRA Realization No.	Vector No.[1]	Maximum Concentrations (curies/liter)				
		^{241}Am	^{239}Pu	^{238}Pu	^{234}U	^{230}Th
1	Replicate 1 Vector 82	Negligible	2.53×10^{-18}	Negligible	Negligible	Negligible
2-300	—	Negligible	Negligible	Negligible	Negligible	Negligible

[1] Parameter values applied to each vector may be found in Appendix PA, Attachment PAR.
[2] Values less than 10^{-18} curies per liter are considered negligible relative to the other values and are not reported.

In this single CRA realization, only one radionuclide has a non-zero concentration reaching the accessible environment. The radionuclide plutonium-239 (^{239}Pu) has a concentration of 2.53×10^{-18} curies per liter (Garner 2003). This compares with the maximum concentration of ^{239}Pu calculated for the CCA evaluation of 5.85×10^{-12} curies per liter. The concentration of ^{239}Pu in the CRA evaluation is six orders of magnitude lower than that shown for the CCA evaluation. In the CRA evaluation, no other radionuclides are calculated in concentrations greater than the 10^{-18} cut-off, where americium-241 (^{241}Am), uranium-234 (^{234}U), and thorium-230 (^{230}Th) all had concentrations exceeding the cut-off in the CCA. Since the CRA evaluation shows only one radionuclide contributing to a potential dose, and the concentration is six orders of magnitude lower than that shown for the CCA evaluation, the CCA dose estimates are bounding. No new dose calculations are necessary.

8.1.2 Dose Calculation

As quoted earlier, 40 CFR Part 194 states that doses must be estimated for an individual who resides at the location in the accessible environment where that individual would be expected to receive the highest exposure to radionuclide releases from the disposal system (40 CFR § 194.51). All potential pathways for exposure associated with the UP of the repository must be assessed (40 CFR § 194.52).

8.1.2.1 Transport Pathway

To perform the required dose calculation, it is necessary to specify possible pathways for the transport of the contaminants from the anhydrite interbeds to a receptor. The specified pathway is an abandoned, deep borehole that intersects the contaminant plume in the accessible environment. Consistent with assumptions described in Section 6.4.7.2 and the information provided in CCA Appendix DEL, the hole is assumed to have the permeability of an uncased hole filled with silty sand after the degradation of a borehole plug in the Rustler Formation. A pressure gradient is assumed to exist because of the pressures in the anhydrite resulting from gas generation in the repository. The pressures are assumed to be sufficient to force contaminants up the abandoned hole to the Culebra Formation or the Dewey Lake Formation. The contaminants would then be available to a receptor through a well used to supply drinking water. This conceptual transport pathway is shown in Figure 8-1. This is the only credible pathway that the DOE has been able to identify. As such, no inhalation or direct radiation exposures are anticipated.

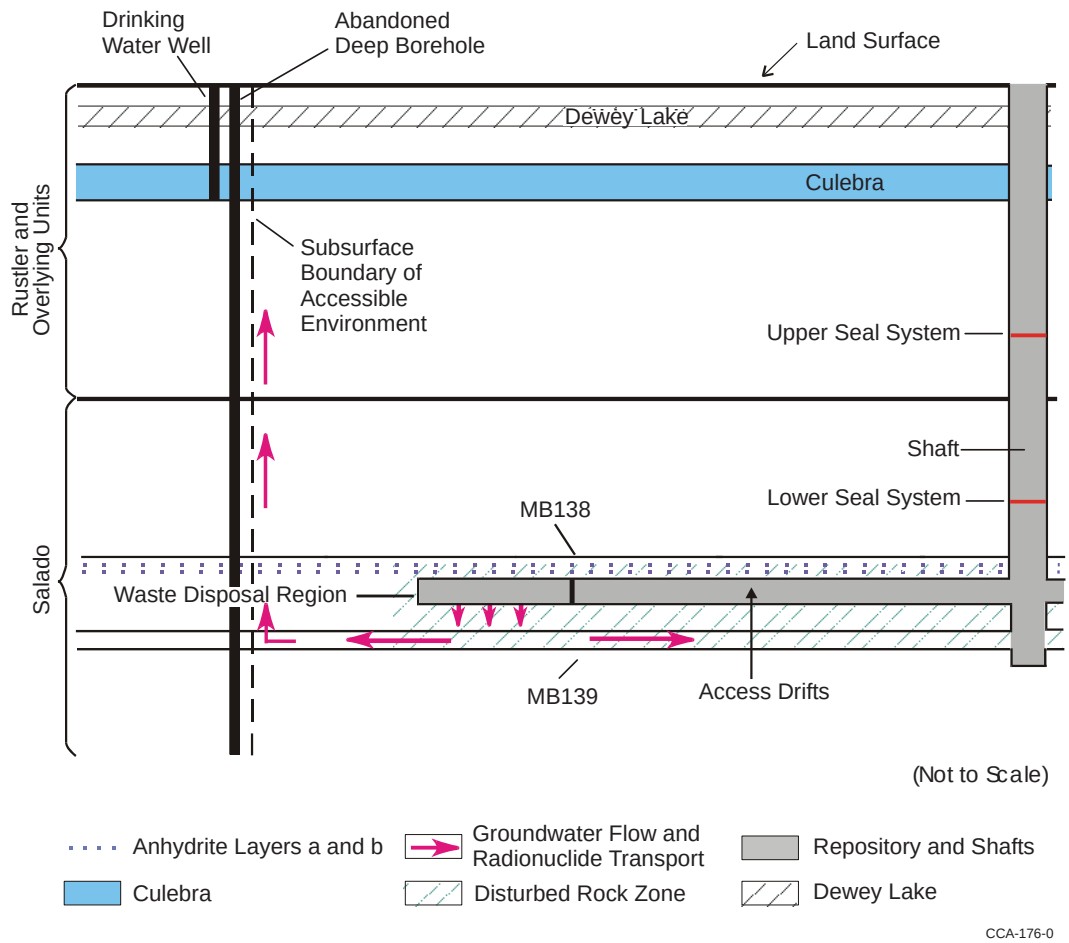

Figure 8-1. Conceptual Transport Pathway

As specified in 40 CFR § 194.54(b), this pathway considers the presence of an existing borehole. As discussed in Section 6.2.5, the influence of other existing boreholes has been evaluated in the FEPs screening for UP.

8.1.2.2 Bounding Analysis

Uncertainty in the calculation of radionuclide concentrations in the anhydrite interbeds is described in Section 6.1.2. Additional uncertainty is involved in the calculation of doses resulting from the specified exposure pathway. Given this uncertainty, the DOE elected for the CCA evaluation to perform a bounding analysis using assumptions that do not represent reality, but that would result instead in a bounding estimate much greater than any reasonably expected dose to a receptor. If this unrealistic, yet bounding, analysis results in calculated doses to the receptor that are below the regulatory limit, compliance with the standard is demonstrated. If subsequent analyses, such as those performed to support this application, have lower initial concentrations than the bounding CCA analysis, recalculation of the doses is unnecessary because the original bounding analysis is conservative and shows results below regulatory limits.

The bounding analysis used for the CCA assessment was based on the following factors and assumptions.

1. No specific transport mechanism was postulated. Instead, all of the contaminants reaching the accessible environment within the anhydrite interbeds during the year of maximum releases (that is, year 10,000) were assumed to be available to a receptor.

2. Brine derived from the anhydrite interbeds had total dissolved solids (TDS) concentrations of about 324,000 parts per million; this represents a concentration that could not be consumed by humans. For the bounding analysis, the calculation includes the dilution of this brine by a factor of 32.4 to a TDS concentration of 10,000 parts per million, which is the upper limit for potable water.

3. The resulting annual committed effective dose was calculated based on a 50-year dose commitment. A 50-year dose commitment was selected because this period is specified in Appendix B of 40 CFR Part 191 and because it is the duration for which published external dose-rate conversion factors are readily available in the literature (DOE 1988).

4. The individual receptor was assumed to drink two liters of water each day (as specified in 40 CFR § 194.52) for one year (in accordance with the specification of an annual committed effective dose in Appendix B of 40 CFR Part 191).

40 CFR § 194.51 states that DOE shall assume an individual resides at the single geographic point where that individual would receive the highest dose. With the bounding analysis, the DOE complies with the intent of this criterion but the specific location of the receptor is not identified, because all of the contaminants reaching the accessible environment within the anhydrite interbeds during the year of maximum releases are assumed to be directly available to the receptor, regardless of the receptor's location. The well from which the receptor drinks is assumed to be located where the contaminants reaching the anhydrite interbeds are delivered directly to the well.

The bounding analysis dose calculation was performed using the GENII-A code. CCA Appendix GENII describes the modeling method. GENII-A incorporates dose-calculation guidance provided in Appendix B of 40 CFR Part 191.

8.1.3 Dose Calculation Results

The maximum doses calculated from the releases listed in Table 8-1, after applying the factors and assumptions listed above, are shown in Table 8-3. These doses are greater than any realistic doses that could be delivered to a receptor. The calculated doses are well below the regulatory standard, which is an annual committed effective dose of 15 millirems.

Table 8-3. Calculated Maximum Annual Committed Effective Doses for the CCA Evaluation

Realization No.	Vector No.[1]	Maximum Annual Committed Effective Dose (millirems)
1	Replicate 1 Vector 46	3.4×10^{-1}
2	Replicate 2 Vector 16	4.3×10^{-3}
3	Replicate 2 Vector 25	1.1×10^{-4}
4	Replicate 2 Vector 33	5.8×10^{-3}
5	Replicate 2 Vector 81	5.1×10^{-7}
6	Replicate 2 Vector 90	4.3×10^{-5}
7	Replicate 3 Vector 3	2.5×10^{-2}
8	Replicate 3 Vector 60	6.2×10^{-3}
9	Replicate 3 Vector 64	4.7×10^{-1}
10-300	—	Negligible[2]

[1] Parameter values applied to each vector may be found in CCA Appendix IRES, Tables IRES-2, IRES-3, and IRES-4.
[2] Doses derived from Table 8-1 concentration values of less than 10^{-18} curies per liter are considered negligible and are not reported.

On February 26, 1997, DOE submitted supplementary information to EPA in response to an EPA request for additional information (Docket A-93-02, Item II-I-10, Enclosure 2h). The supplementary information describes how DOE extended its initial bounding analysis to account for exposure pathways besides direct ingestion of contaminated water by humans. Specifically, the analysis was expanded to include consumption of contaminated water by cattle (leading to the receptor's consumption of contaminated milk and beef), consumption of crops irrigated with contaminated water, and inhalation of airborne dust from soil contaminated by irrigation. DOE found that the contribution of these pathways added 0.46 millirem per year to the calculated dose associated with the realization showing the highest concentration of radionuclides reaching the boundary of the accessible environment under undisturbed conditions. The maximum total dose calculated from all pathways was 0.93 millirem per year, well below the 15-millirem-per-year regulatory standard.

Given that the maximum concentration of radionuclides shown to reach the accessible environment for the CRA analysis is six orders of magnitude less than the maximum value calculated for the CCA evaluation, resulting potential doses to the receptor would also be well below the 15-millirem standard. As such, the CCA dose calculation bounds any possible dose to a receptor for the CRA evaluation and new dose calculations are not needed to demonstrate

compliance. The CCA results are bounding, and continued compliance with the individual protection standard is demonstrated.

8.1.4 Statistical Assessment

EPA criterion 40 CFR § 194.55(d) specifies that the "number of estimates generated pursuant to paragraph (c) of this section shall be large enough such that the maximum estimates of doses and concentrations generated exceed the 99th percentile of the population of estimates with at least a 0.95 probability." The probability that an individual estimate is below the 99th percentile is, by definition, 0.99. This means that only 1 in 100 estimates would have a value exceeding the 99th percentile, or conversely, 99 times out of 100, the estimate would have a value below the 99th percentile. It follows that for two independent events, the probability of both estimates having a value below the 99th percentile is equal to the product (0.99)(0.99), or $(0.99)^2$, and that for n events, the probability that all estimates have a value below the 99th percentile is equal to $(0.99)^n$. To ensure a value exceeds the 99th percentile with a specified probability, the complement $(1 – 0.99^n)$ is used to calculate the number of estimates required.

The probability specified by 40 CFR § 194.55(d) is 0.95, or 95-percent confidence, that the maximum estimates of doses and concentrations generated exceed the 99th percentile of the population of estimates. Therefore, the following equation can be solved for n, and the number of estimates required is

$$1 – 0.99^n = 0.95 \text{ or } n\log(0.99) = \log(0.05), \qquad (8.1)$$

which implies $n > 298$.

The solution requires n to be greater than 298 and was used to determine that 300 realizations of the modeling system is a sufficient number to meet the confidence level specified in 40 CFR § 194.55(d).

The 300 realizations of the modeling system (as described in Section 8.1.1) report concentrations of radionuclides reaching the accessible environment within the Salado anhydrite interbeds and not doses to a receptor, as specified by 40 CFR § 194.55(d). Nevertheless, the maximum possible resulting dose to an individual is 0.93 millirems, the sum of 0.47 millirems, as reported in Table 8-3, plus the additional value of 0.46 millirems, determined to be contributed through additional dose pathways. All other potential doses resulting from the 300 realizations of the modeling system for both the CCA and CRA evaluations are below this value.

EPA criterion 40 CFR § 194.55(f) specifies that DOE shall

> document that there is at least a 95 percent level of statistical confidence that the mean and the median of the range of estimated radiation doses and the range of estimated radionuclide concentrations meet the requirements of § 191.15 and part 191, subpart C of this chapter, respectively.

Because the DOE has developed a bounding analysis, it is not meaningful to calculate and present mean and median dose values. Instead, the bounding analysis provides 100 percent confidence that all potential doses will be below the 0.93 millirem value.

8.1.5 Parameter Values

Parameter values applied to the CCA modeling assessment for UP are described in CCA Appendix PAR and Section 8.1.5. Parameters used in the PA and compliance assessment modeling program for the CRA are described in Appendix PA, Attachment PAR. As provided by 40 CFR § 194.55(b), Appendix PA, Attachment PAR also identifies the probability distributions for these parameters, their units, the models and codes in which the parameters are used, the functional form of the probability distributions used for the sampled parameters, and associated input data.

8.1.6 Summary of Compliance with the Individual Protection Standard

In performing the compliance assessment, DOE applied a bounding-analysis approach using unrealistic assumptions that over-estimate potential doses and contaminant concentrations. This conservative approach assumes that all contaminants reaching the accessible environment are directly available to a receptor. Using this very conservative approach, the calculated maximum potential dose to an individual from the CCA evaluation would be about one-sixteenth of the individual protection standard. Given that modeled maximum radionuclide concentrations in the accessible environment for the CRA evaluation are well below those of the CCA evaluation, the CCA results are bounding and continued compliance with the individual protection standard is demonstrated.

8.2 Groundwater Protection Requirements

The groundwater protection requirements are contained in Subpart C of 40 CFR Part 191. In particular, 40 CFR § 191.24(a)(1) requires that

> *General*. Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that 10,000 years of undisturbed performance after disposal shall not cause the levels of radioactivity in any underground source of drinking water, in the accessible environment, to exceed the limits specified in 40 CFR Part 141 as they exist on January 19, 1994.

EPA rule 40 CFR Part 141 specifies the National Primary Drinking Water Standards. The levels of radioactivity (and dose equivalent in the case of 40 CFR § 141.16[a]) specified in 40 CFR Part 141, as of January 19, 1994 were:

1. Combined ^{226}Ra and ^{228}Ra(40 CFR § 141.15[a]): 5 picocuries per liter;

2. Gross alpha particle activity, including ^{226}Ra but excluding radon and uranium (40 CFR § 141.15[b]): 15 picocuries per liter;

3. Annual dose equivalent to the total body or any internal organ from the average annual concentration of beta particle and photon radioactivity from man-made radionuclides (40 CFR § 141.16[a]): 4 millirem per year.

In addition, Section 194.53 applies to DOE's consideration of USDWs. The criterion specifies that

> In compliance assessments that analyze compliance with part 191, subpart C of this chapter, all underground sources of drinking water in the accessible environment that are expected to be affected by the disposal system over the regulatory time frame shall be considered. In determining whether underground sources of drinking water are expected to be affected by the disposal system, underground interconnections among bodies of surface water, groundwater, and underground sources of drinking water shall be considered.

To assess compliance with these provisions of the regulations, it is first necessary to identify any USDW that may be located near the WIPP. DOE's evaluation of whether any USDW is located near the WIPP is provided as CCA Appendix USDW and is summarized in Section 8.2.2. In developing the CRA, DOE reevaluated the presence of USDWs near the WIPP and supplemented the information presented in CCA Appendix USDW. The supplemental information is also provided in Section 8.2.2. Based on this review, DOE believes that no deviation from the findings and conclusions of the 1996 evaluation is warranted.

8.2.1 Criteria for USDW Determination

In evaluating the presence of any USDW, it is necessary to establish criteria to apply to water quality and quantity data from wells in the vicinity of the WIPP. The criteria must be based on the regulatory definition of a USDW, as provided in 40 CFR § 191.22. A USDW is defined in 40 CFR § 191.22 to mean an aquifer or its portion that

> (1) Supplies any public water system; or
>
> (2) Contains a sufficient quantity of groundwater to supply a public water system; and
>
> (I) Currently supplies drinking water for human consumption; or
>
> (ii) Contains fewer than 10,000 milligrams of total dissolved solids per liter.
>
> "Public water system" means a system for the provision to the public of piped water for human consumption, if such system has at least fifteen service connections or regularly serves at least twenty-five individuals. Such term includes:
>
> (1) Any collection, treatment, storage, and distribution facilities under control of the operator of such system and used primarily in connection with such system; and
>
> (2) Any collection or pretreatment storage facilities not under such control which are used primarily in connection with such system.
>
> "Total dissolved solids" means the total dissolved (filterable) solids in water as determined by use of the method specified in 40 CFR Part 136.

Criteria based on these definitions were developed by the DOE and are used to assess the presence of any USDW near the WIPP. These criteria are defined in the following subsections.

8.2.1.1 Groundwater Quantity

Two subcriteria have been identified by the DOE and applied to the groundwater quantity definition:

1. An aquifer or its portion must be capable of producing water at an adequate rate, and

2. An aquifer or its portion must be capable of producing water for a sufficient duration.

Water-consumption information was evaluated by the DOE to define the first subcriterion (the ability to produce at an adequate rate). The value to be applied is determined by obtaining the following information.

1. The rate, over a 24-hour period, at which water is consumed by 15 service connections.

2. The rate, over a 24-hour period, at which water is consumed by 25 individuals.

To conservatively define a USDW, the lower of these two values is assigned by the DOE to the first subcriterion. Based on calculations presented in CCA Appendix USDW and updated in support of the CRA, a quantity of five gallons per minute is assigned as the first subcriterion. Details on the derivation of the five-gallon-per-minute value are provided below.

For the CCA evaluation, the rate of consumption by 15 service connections was calculated using the data provided in Table 8-4. These are 1990 U.S. Bureau of the Census data for the number of persons per household in southeastern New Mexico communities and water-consumption data for the same communities. The water-consumption data were obtained from the New Mexico State Engineer's Office (Wilson 1992).

Table 8-4. Persons Per Household and Water Consumption Values Used in the CCA

Community	Persons Per Household, 1990	Gallons Per Capita Per Day
Artesia	2.69	285
Carlsbad	2.63	307
Hobbs	2.81	267
Lovington	2.96	264
Roswell	2.66	285
Average	2.75	282

Sources: U.S. Bureau of the Census (1990); Wilson (1992).

As reported in Wilson (1992), the average water usage in these communities was 282 gallons per person per day. The 1990 census statistics for these communities show an average of 2.75 people per household. One household equals one service connection.

Therefore:

2.75 people × 282 gallons per person per day = 775.5 gallons per service connection per day,

775.5 gallons per day per service connection × 15 connections = 11,633 gallons per day, and

11,633 gallons per day/1,440 minutes per day = 8.08 gallons per minute.

The rate of consumption by 15 service connections, based on the 1990 and 1992 statistics, is calculated to be 8.08 gallons per minute.

The rate over a 24-hour period at which water would be consumed by 25 individuals may be calculated using these same data. The average water usage was 282 gallons per person per day in area communities. The consumption of water by 25 people equals:

282 gallons per person per day × 25 people = 7050 gallons per day, and

7050 gallons per day/1,440 minutes per day = 4.89 gallons per minute.

Based on these two calculations, the quantity consumed by 25 individuals (4.89 gallons per minute; nominally 5 gallons per minute) is smaller than the quantity consumed by 15 service connections (8.08 gallons per minute). To conservatively determine the quantity derived from a well that meets this DOE quantity criterion, the five-gallons-per-minute value was applied to the CCA evaluations.

In updating this calculation for the CRA, more current census data and water consumption data were obtained. These more current data are provided in Table 8-5. The updated calculations are provided below.

Table 8-5. Persons Per Household and Water Consumption Values Used in the CRA

Community	Persons Per Household, 2000[1]	Gallons Per Capita Per Day, 2000[2]
Artesia	2.61	390
Carlsbad	2.51	277
Hobbs	2.72	284
Lovington	2.80	289
Roswell	2.58	283
Average	2.64	305

Sources: 1. U.S. Bureau of the Census (2000); 2. New Mexico Office of the State Engineer (2002).

The average water usage in these communities is 305 gallons per person per day. The 2000 census statistics for these communities show an average of 2.64 people per household. One household equals one service connection.

Therefore:

2.64 people × 305 gallons per person per day = 805.2 gallons per service connection per day,

805.2 gallons per day per service connection × 15 connections = 12,078 gallons per day, and

12,078 gallons per day/1,440 minutes per day = 8.39 gallons per minute.

Using updated data, the rate of consumption by 15 service connections is calculated to be 8.39 gallons per minute.

The rate over a 24-hour period at which water would be consumed by 25 individuals may be calculated using these same data. The current average water usage is 305 gallons per person per day in area communities. The consumption of water by 25 people equals:

305 gallons per person per day × 25 people = 7625 gallons per day, and

7625 gallons per day/1,440 minutes per day = 5.30 gallons per minute.

Based on these two calculations, the quantity consumed by 25 individuals (5.30 gallons per minute; nominally 5 gallons per minute) is smaller than the quantity consumed by 15 service connections (8.39 gallons per minute). To conservatively determine the quantity derived from a well that meets the quantity subcriterion, the five-gallons-per-minute value is applied. No change in this subcriterion is warranted as a result of applying current census and water consumption data to the calculation.

The definition of the second quantity subcriterion (the acceptable production duration from a well) is more subjective. Because the creation of a public water supply system involves considerable capital expense, it is reasonable to assume that such a water system would not be constructed unless the water source would continue to be available for some time, at least long enough to recover the capital expense. The Rural Utility Service of the U.S. Department of Agriculture provides loans for funding new rural water supply systems. The loan periods are generally 40 years in duration. Based on this, a duration of 40 years is applied by the DOE to the second quantity subcriterion.

8.2.1.2 Groundwater Quality

A criterion of 10,000 mg/L of TDS is specified in 40 CFR § 191.22. Any aquifer or its portion producing water having TDS concentrations below this level is determined to produce water that meets the quality criterion for a USDW. Any aquifer or its portion producing water TDS concentrations at or above this level is determined to produce water that does not meet the quality criterion and the regulatory definition of a USDW.

8.2.2 Comparison with Underground Source of Drinking Water Determination Criteria

For the CCA evaluation, current conditions and available hydrogeologic data were reviewed by the DOE to assess the presence of USDWs near the WIPP. This assessment compares current conditions and available data to the groundwater quantity and quality criteria described above. The results of this comparison are summarized below and provided in detail in CCA Appendix USDW. In addition, relevant updated information is provided here to support the CRA.

Five geologic units within the vicinity of the WIPP could potentially meet the definition of a USDW under Subpart C of 40 CFR Part 191. These include:

1. the Capitan Aquifer of the Guadalupian reef complex,
2. the Culebra,
3. the Magenta Dolomite Member of the Rustler Formation,

4. the Dewey Lake, and

5. the Santa Rosa Sandstone of the Dockum Group.

Investigations conducted in the vicinity of the WIPP to characterize the hydrology of these formations are described in CCA Appendix USDW. Important sources of relevant information are identified and findings or conclusions related to the presence of USDWs are provided. Based on this work and the recent update performed to support the CRA, the DOE has concluded that USDWs are present in the Culebra, and, because of inconclusive groundwater production data, possible USDWs are present in the Dewey Lake and the Santa Rosa. USDWs in the Culebra are located at WIPP water quality sampling program (WQSP) wells H-07b1, H-08b, and H-09b about 4.8, 14.5, and 10.5 km (3, 9, and 6.5 mi) to the south/southwest of the controlled area boundary, respectively. Possible USDWs may occur in the Dewey Lake, about 1.6 km (1 mi) south of the controlled area boundary, and the Santa Rosa, 12.4 to 14.5 km (7.7 to 9 mi) to the east of the controlled area boundary, where private wells (used predominantly for supplying water to livestock) have not generated available groundwater production data to assess their potential to yield a sufficient quantity to meet 40 CFR § 191.22 requirements. In the absence of such data, and to be conservative, these wells are designated as being located in possible USDWs.

In reevaluating the conclusions presented in CCA Appendix USDW, DOE reviewed available groundwater quality and quantity data for the wells identified in the appendix to determine if any data collected since 1996 are available. No new TDS or groundwater quantity data were obtained by WIPP WQSP personnel after 1996. The WQSP is a detection monitoring program operated under the provisions of the WIPP Hazardous Waste Facility Permit. Data for a variety of parameters are collected through the WIPP WQSP, but not TDS concentrations or water quantity data.

In addition, a review was performed to determine if any wells not reported in CCA Appendix USDW were drilled that may provide groundwater quality (i.e., TDS concentrations) and groundwater quantity data. One new well, identified as well C-2737, was developed at the WIPP site. This well was drilled during February and March of 2001 to replace well H-1, which was plugged and abandoned. In February of 2001, a water sample from the upper Dewey Lake Formation was obtained from this well. Laboratory analysis of this sample showed a TDS concentration of 2,590 ppm (Powers 2002).

Additional wells were installed across the WIPP site to investigate the extent of groundwater at the contact of the Santa Rosa and Dewey Lake Formations. Four monitoring wells and 12 piezometer wells were emplaced. The results of multiple rounds of sampling and analyses from these holes are reported in DES (1997). Samples from several of these holes show TDS concentrations both below and above 10,000 ppm, although it was not possible to pump water from any of these holes at rates of five gallons per minute or more.

In addition, State of New Mexico records indicate that several new wells were drilled in the southwestern portion of the study area evaluated in CCA Appendix USDW. These records, however, include no TDS or production data.

Based on this review, no modification of the USDW determinations reported in CCA Appendix USDW is warranted. The DOE continues to conclude that USDWs are present in the Culebra, and, because of inconclusive groundwater production data, possible USDWs are present in the Dewey Lake and the Santa Rosa Formations.

During its review of the CCA, EPA requested that DOE provide a map or maps showing the location of USDWs. The DOE responded to this request with supplementary information dated February 26, 1997 (Air Docket A-93-02, Item II-I-10, Enclosure 1j). The supplementary information includes a map showing the boundaries of potential USDWs nearest the WIPP in the Culebra, Santa Rosa, and Dewey Lake Formations. The EPA found the map to be sufficient for purposes of compliance assessment because it identifies potential USDWs near the WIPP. No change to this map is deemed appropriate at this time.

8.2.3 Comparison with the National Primary Drinking Water Standards

To provide additional assurance of the safety of the WIPP, the DOE prepared a bounding assessment of the concentrations of contaminants that could occur in a nearby USDW. Bounding doses that could be received by drinking from the USDW are also calculated. As was done to assess compliance with the individual protection standard, the analysis is bounding; the results do not represent reality, but rather illustrate the maximum yet unrealistic concentrations of contaminants in a hypothetical USDW and the maximum yet unrealistic resulting doses. As with the dose calculations, maximum concentrations were summed to develop concentrations for comparison with the National Primary Drinking Water Standards. The conclusions of this work, provided in the following subsections, illustrate that the consequences of the undisturbed repository are negligible, even when unrealistic assumptions are applied to the performance evaluation. The results of the bounding analysis support the position that additional characterization of groundwater near the WIPP to make a more definitive USDW determination is not warranted.

8.2.3.1 Transport Pathway

Section 8.1.2.1 describes the transport pathway assumed for the bounding analysis performed to evaluate compliance with the individual protection standard. This same transport pathway is assessed for the evaluation of compliance with the groundwater protection standard.

This pathway assumes that a USDW is located where the maximum possible concentration of radionuclides could be realized in the USDW and the maximum possible dose to an individual who drinks from the USDW could be delivered to the individual. As such, the analysis bounds the 40 CFR § 194.53 criterion specifying that DOE must consider underground interconnections among bodies of surface water, groundwater, and USDWs.

8.2.3.2 Combined ^{226}Ra and ^{228}Ra

The modeling system employed to simulate the performance of the undisturbed repository tracks the transport of the radionuclides of greatest importance to releases to the accessible environment (see Appendix TRU WASTE). These radionuclides of interest, listed in Table 8-1, are ^{241}Am, ^{239}Pu, ^{238}Pu, ^{234}U, and ^{230}Th. They do not include ^{226}Ra or ^{228}Ra because these radionuclides are

not a prevalent component of the projected inventory of the repository. However, an analysis of ^{226}Ra and ^{228}Ra is required to evaluate compliance with the groundwater protection standard.

To perform the bounding analysis, the results of a NUTS code tracer exercise were used to scale the anticipated releases of ^{226}Ra and ^{228}Ra. The tracer exercise shows that an initial concentration of radionuclides in the repository of 1 kg/m^3 results in a concentration at the accessible environment boundary of 1.025×10^{-7} kg/m^3. By applying this scaling factor to the quantity of ^{226}Ra and ^{228}Ra projected to be emplaced in the repository, it is determined that the maximum concentration of these radionuclides in the accessible environment is 0.07 picocuries per liter (Wagner 2003), which is below the 40 CFR § 141.15(a) standard of 5 picocuries per liter.

This concentration is calculated by transporting the passive tracer in the flow field generated using the BRAGFLO code for Realization 1 (Replicate 1, Vector 82), shown in Table 8-2. The calculation uses the mass and activity loads for ^{226}Ra and ^{228}Ra in the radionuclide inventory at closure and at 10,000 years. These values are provided in Table 8-6. The ORIGEN 2.2 code is used to calculate the activity loads at 10,000 years; these loads are 51.43 curies of ^{226}Ra in contact-handled (CH-) and remote-handled (RH-) transuranic (TRU) waste and 7.95 curies of ^{228}Ra in CH- and RH-TRU waste. The calculated concentration is

Table 8-6. Total Inventory and Mass Loading of ^{226}Ra and ^{228}Ra

Radionuclide	Waste Type	Total Inventory at Closure (Ci)	Total Inventory at 10,000 Years (Ci)	Mass Loading (kilograms)
^{226}Ra	CH	6.28×10^{0}	4.98×10^{1}	6.35×10^{-3}
^{226}Ra	RH	4.99×10^{-5}	1.63×10^{0}	5.05×10^{-8}
^{228}Ra	CH	7.63×10^{0}	7.70×10^{0}	2.81×10^{-5}
^{228}Ra	RH	2.51×10^{-1}	2.54×10^{-1}	9.23×10^{-7}

Source: Leigh (2003)

based on the volume of brine, 5577 m^3 (169,924 ft^3), in the repository at time zero in the BRAGFLO calculation.

The total concentration (CH- and RH-TRU) of either ^{226}Ra or ^{228}Ra 10,000 years at the accessible environment boundary is calculated accordingly.

1. Calculate the total mass load at 10,000 years by multiplying the total mass load at decommissioning by the ratio of activity loadings at 10,000 years and decommissioning, respectively.

2. Calculate the total mass concentration at the accessible environment boundary by dividing by the value of brine from the BRAGFLO simulation and multiplying by the scaling factor.

3. Convert to total concentration of activity at the accessible environment boundary by multiplying by the ratio of activity loading to mass loading at decommissioning.

4. Divide the concentration by the dilution factor 32.4 (See Section 8.1.2.2).

The 0.07 picocurie per liter maximum concentration occurs in the anhydrite interbeds within the Salado and not in a zone that could realistically be a source of drinking water.

In the CCA, this value is reported as 2 picocuries per liter. During the performance of the Performance Assessment Verification Test (PAVT) (SNL 1997), it was determined that the CCA calculation used an inappropriate brine volume value and failed to account for the dilution factor. Accordingly, the PAVT analysis shows that the correct value that should have been reported in the CCA is 0.14 picocuries per liter.

8.2.3.3 Gross Alpha Particle Activity Including ^{226}Ra But Excluding Radon and Uranium

For the CCA evaluation, compliance with the 40 CFR § 141.15(b) standard was assessed by summing the maximum concentration values provided in Table 8-1 for ^{241}Am, ^{239}Pu, ^{238}Pu, and ^{230}Th and adding the value for ^{226}Ra obtained to perform the 40 CFR § 141.15(a) assessment. The value obtained by this method is 7.81 picocuries per liter, which is below the 40 CFR § 141.15(b) standard of 15 picocuries per liter. This concentration occurs in the anhydrite interbeds within the Salado and not in a zone that could realistically be a source of drinking water.

For the CRA evaluation, the only contributing radionuclide is ^{239}Pu with a concentration of 2.53 $\times 10^{-18}$ picocuries per liter (Table 8-2). This value, summed with the 0.07-picocurie-per-liter value derived for the 40 CFR § 141.15(a) assessment, is essentially 0.07 picocuries per liter, well below the 15-picocuries-per-liter standard.

8.2.3.4 Annual Dose Equivalent to the Total Body or Any Internal Organ from the Average Annual Concentration of Beta Particle and Photon Radioactivity from Man-Made Radionuclides

To assess compliance with the 40 CFR § 141.16(a) standard, an annual dose equivalent of 4 millirem per year, the transport of the following radionuclides was evaluated: ^{239}Pu, ^{238}Pu, ^{234}U, and ^{230}Th. The maximum annual committed effective dose calculated for the CCA evaluation from any of these radionuclides is 0.93 millirems, which is the value reported for transport through MB139 and is well below the regulatory standard. The 0.93 millirem value includes alpha particle radioactivity, as well as beta particle and photon radioactivity. Thus, the value is very conservative in that the 4 millirem annual dose equivalent limit is only for beta particle and photon radioactivity.

By comparison, the maximum radionuclide concentration in the accessible environment calculated for the CRA evaluation is six orders of magnitude less than the maximum bounding value calculated for the CCA (see Section 8.1.1). Resulting doses for the CRA case would be correspondingly lower, as well.

8.3 Compliance Summary

In performing the compliance assessment, the DOE applied a bounding-analysis approach using unrealistic assumptions that overestimate potential doses and contaminant concentrations. To provide added assurance, the DOE assumed the presence of a USDW in close proximity to the WIPP Land Withdrawal Area boundary, even though available data indicate that none currently exists near the boundary. Using this very conservative approach, the calculated maximum potential dose to an individual determined for the CCA evaluation would be about one-sixteenth of the individual protection standard.

For the CRA evaluation, this concentration is well below the CCA value. In addition, the maximum concentrations of contamination in the hypothetical USDW would be much less than half of the EPA groundwater protection limits and the maximum potential dose to a receptor who drinks from the hypothetical USDW would be well below one-quarter of the standard.

This conservative approach also assumes that all contaminants reaching the accessible environment are directly available to a receptor. The analysis bounds any potential impacts of underground interconnections among bodies of surface water, groundwater, and underground sources of drinking water.

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9.0. PEER-2004 REVIEW

This chapter describes the regulatory basis for the conduct of peer reviews and summarizes relevant peer reviews performed at the Waste Isolation Pilot Plant (WIPP). Key elements of the U.S. Department of Energy (DOE) Carlsbad Field Office's (CBFO's) peer review program (for example, the review process, reports, selection criteria, and training for review panel members) are discussed. Two categories of peer reviews are reported in this chapter: (1) those conducted after the promulgation of Title 40 of the Code of Federal Regulations (CFR) Part 194 (U.S. Environmental Protection Agency [EPA] 1996a); and (2) those conducted earlier.

Seven peer reviews were initiated subsequent to the promulgation of 40 CFR Part 194 and prior to submission of the Compliance Certification Application (CCA) in 1996. Per the criteria of 40 CFR § 194.27, they were conducted in a manner compatible with NUREG-1297 (Altman, et al. 1988). The subjects of these reviews included: conceptual models; waste characterization analysis; engineered alternatives cost/benefit study (EACBS) ; engineered systems data qualification; waste form and disposal room data qualification; natural barriers data qualification; and passive institutional controls. The conceptual model peer review group published three supplementary reports in 1996 and 1997 after the submission of the CCA. Two additional peer reviews related to conceptual models were completed in 2003 prior to submission of the first Compliance Recertification Application (CRA-2004), and are described in Section 9.3.1. These reviews are summarized in the following sections:

- 9.3.1 – Conceptual Models Peer Review
- 9.3.2 – Waste Characterization Analysis Peer Review
- 9.3.3 – Engineered Alternatives Cost/Benefit Study Peer Review
- 9.3.4 – Engineered Systems Data Qualification Peer Review
- 9.3.5 – Natural Barriers Data Qualification Peer Review
- 9.3.6 – Waste Form and Disposal Room Data Qualification Peer Review
- 9.3.7 – Passive Institutional Controls Peer Review

The applicable peer review plans, complete peer review reports, and selected supporting documentation for peer reviews completed before submission of the CCA in 1996 were provided in CCA Appendix PEER. The plans, reports, and supporting documentation for the peer reviews performed after the submission of the)CCA are provided in Appendix PEER-2004. This chapter also presents the DOE responses to the findings and recommendations of the peer reviews. Additional documentation is available in project record packages in the CBFO Records Holding Facility located in Carlsbad, New Mexico.

Peer reviews that occurred prior to the promulgation of 40 CFR Part 194 were not necessarily conducted in accordance with NUREG-1297 guidelines. Therefore, candidate reviews were evaluated against specific criteria to determine whether they were appropriate for inclusion in

this application. The selected historical reviews were summarized in the following sections of the CCA Chapter 9:

- 9.4.1 – National Academy of Sciences WIPP Panel Reviews (12 reports)
- 9.4.2 – Performance Assessment Peer Review Panel
- 9.4.3 – Shaft Seal Design Independent Review
- 9.4.4 – Engineered Alternatives Task Force Report Peer Review
- 9.4.5 – Blue Ribbon Panel Peer Review
- 9.4.6 – Advisory Committee on Nuclear Facility Safety Review (two reports)
- 9.4.7 – Performance Assessment Review Team (PART)
- 9.4.8 – INTRAVAL
- 9.4.9 – WIPP Conceptual Model Uncertainty Group Review
- 9.4.10 – Environmental Evaluation Group Reviews (15 reports)
- 9.4.11 – Fracture Expert Group Review
- 9.4.12 – Fanghänel Review
- 9.4.13 – Independent Technical Review of the Bin and Alcove Test Programs
- 9.4.14 – Performance Assessment (PA) Reviews
- 9.4.15 – Technical Support Group Reviews (two reports)
- 9.4.16 – National Environmental Policy Act Reviews

The full reports from these reviews and selected supporting material were provided in CCA Appendix PEER.

Summaries of additional reviews performed by oversight organizations since the submission of CCA are included in the following sections:

- 9.4.1.13 to 9.4.1.15 – National Academy of Sciences WIPP Panel Reviews (three reports),
- 9.4.10.16 to 9.4.10.26 – Environmental Evaluation Group (EEG) Reviews (11 reports),

- 9.4.17 – International Atomic Energy Agency (IAEA) and Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) Joint Report (one report),

- 9.4.18 – GEOTRAP (An NEA/OECD project), and

- 9.4.19 – Institute for Regulatory Science (RSI) of the American Society of Mechanical Engineers (ASME) (two reports).

These reviews are in addition to those required by 40 CFR Part 194.27(a), do not meet the requirements of NUREG-1297, and are not used directly by the DOE for the analyses in the CRA. The full reports from these reviews and selected supporting materials are provided in Appendix PEER-2004.

9.1 Regulatory Requirements

The certification criteria in 40 CFR Part 194 prescribes the use of peer reviews to support certain areas of the compliance evaluation. Compliance criteria in 40 CFR § 194.27 state that peer review at the WIPP be performed for several specific aspects of the program and that they be performed in a manner compatible with NUREG-1297. NUREG-1297 provides guidance on the definition of peer reviews, the areas for which a peer review is appropriate, the acceptability of peers, and the conduct and documentation of peer reviews. 40 CFR Part 194 states that "The specific requirements in NUREG-1297 that discuss for which activities peer review should be conducted do not apply, nor do they supersede the requirements of the final rule." (61 Federal Register [FR] 5228) Specific sections of 40 CFR Part 194 and NUREG-1297 provide the regulatory basis for this chapter.

The certification criteria state that any application for certification shall include documentation for the following peer reviews that are to be conducted: conceptual models used in the PA; waste characterization analysis; and engineered barrier evaluation (40 CFR § 194.27[a]). Section 194.27(b) states that these peer reviews, if conducted subsequent to the promulgation of 40 CFR Part 194, should be conducted in a manner that is compatible with NUREG-1297. Section 194.27(c)(2) also requires this application to include documentation of any peer review processes conducted in addition to those of 40 CFR § 194.27(a).

NUREG-1297 defines peer review as "a documented, critical review performed by peers who are independent of the work being reviewed." NUREG-1297 also states that a "peer review is an in-depth critique of the assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn from the original work."

The 40 CFR Part 194 Background Information Document (EPA 1996b) states that peer reviews can be used as part of "a comprehensive quality assurance program" to give "confidence that work completed, underway, or planned was, is, or will be properly performed." The Background Information Document also notes that "additional peer review is also necessary to establish the validity of procedures, methods, or interpretations which may not be addressed by a quality assurance (QA) program . . . ASME-NQA-3-1989 . . . includes peer review among those

activities affecting quality associated with the collection of scientific and technical information, when other established methods cannot be used to establish the adequacy of information."

NUREG-1297 states that for a repository,

> peer reviews should be used as a management tool to achieve confidence in the validity of certain technical and programmatic judgments. The intent of a peer review is to pass judgment on the technical adequacy of the work or data submitted for review, to identify aspects of the work on which technical consensus exists, to identify aspects on which technical consensus does not exist, and to identify aspects of the reviewed work which the reviewers believe to be incorrect or which need amplification. A peer review provides assurance in cases where scientific uncertainties and ambiguities exist but in which technical and programmatic judgments and decisions still must be made.

9.2 Peer Review Process

NUREG-1297 suggests that procedures be developed to "implement the NUREG-1297 guidance" and to "provide methods for initiating a peer review." These procedures, for any given peer review, "should require a planning document that describes the work to be reviewed, the size and spectrum of the peer review group, and the suggested method and schedule to arrive at a peer review report."

WIPP-specific plans and procedures ensure that peer reviews performed subsequent to promulgation of 40 CFR Part 194 were conducted in accordance with the criteria of 40 CFR Part 194 and compatible with NUREG-1297. The most pertinent of the plans and procedures are discussed briefly below.

A Peer Review Management Plan (PRMP) (DOE 1996b) was developed and approved by the CAO to describe the management processes used to control the planning, implementation, and documentation of these reviews. The PRMP defines the management approach, resources, schedule, and technical requirements for using peer reviews to confirm and/or verify the adequacy of data and/or information utilized to support the WIPP application.

CAO Team Procedure (TP) 10.5, Peer Review (DOE 1996c) has been replaced by CBFO Management Procedure (MP) 10.5 (DOE/CBFO 2003). TP 10.5 was used to guide the peer reviews performed prior to submission of the CCA and the three supplementary conceptual model peer reviews performed after CCA in October 1996 to April 1997. MP 10.5 guided the peer reviews performed in 2002-2003. Both procedures define the responsibilities, requirements, and methodologies incorporated in the performance of peer reviews conducted by the CAO (for CCA) and the CBFO (for CRA-2004) pursuant to the criteria of 40 CFR § 194.27. The procedures provided the criteria for determining the size and composition of the review panel and for selecting individual peer review panel members, and outline the orientation and training to be provided for the panelists. The procedures also describe the actual peer review process, provide criteria for development of peer review plans and report preparation, and define the responsibilities of individuals involved in the process. Both TP 10.5 and MP 10.5 were developed in accordance with, and to implement, the guidance in NUREG-1297, "Peer Review for High-Level Nuclear Waste Repositories."

Specific peer review plans were developed for each peer review at the WIPP. These plans documented the planning process for the peer reviews and were prepared and approved prior to performing the particular review (see Section 9.2.1).

As discussed more completely in Chapter 5.0, the Quality Assurance Program Document, Rev.5 (QAPD) (DOE 2003) establishes the minimum requirements for the WIPP QA program. It provides guidance for development and implementation of QA programs for all aspects of the WIPP project. In particular, the QAPD provides general requirements for training, document control, and QA records management.

9.2.1 Peer Review Plan

MP 10.5 requires that the Peer Review Manager ensure that a peer review plan is prepared and approved prior to the performance of each peer review. Specific plans are approved by the CBFO.

The plan documents the planning of the peer review. It provides the scope of the peer review, a description of the work to be reviewed, the intended use of the work, and methods for conducting peer reviews.

40 CFR § 194.27(b) specifies that peer reviews performed subsequent to the promulgation of 40 CFR Part 194 be conducted in a manner compatible with NUREG-1297. NUREG-1297 states that

> The peer review process may vary from case to case, and should be determined by the chairperson of the peer review group, consistent with the guidance provided in this GTP (Generic Technical Position). In meetings and/or correspondence, the peer review group should evaluate and report on: (a) validity of assumptions; (b) alternate interpretations; (c) uncertainty of results and consequences if wrong; (d) appropriateness and limitations of methodology and procedures; (e) adequacy of application; (f) accuracy of calculations; (g) validity of conclusions; (h) adequacy of requirements and criteria. Furthermore, full and frank discussions between the peer reviewers and the performers of the work are encouraged.

The WIPP peer review process consists of an in-depth analysis and evaluation of documented assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn in the original work. MP 10.5 specifically incorporates the above NUREG-1297 requirements into the WIPP peer review process.

9.2.2 Size and Composition of Peer Review Panels

NUREG-1297 states that

> The number of peers comprising a peer group should vary with the complexity of the work to be reviewed, its importance to establishing that safety or waste isolation performance goals are met, the number of technical disciplines involved, the degree to which uncertainties in the data or technical approach exist, and the extent to which differing viewpoints are strongly held within the applicable technical and scientific community concerning the issues under review. The collective technical expertise and qualifications of peer group members should span the technical issues and areas involved in the work to be reviewed, including any differing bodies of scientific thought. Technical areas more central to the work to be reviewed should receive proportionally more representation on the peer review group.

The NUREG-1297 guidance also states that

> The peer review group should represent major schools of scientific thought. The potential for technical or organizational partiality should be minimized by selecting peers to provide a balanced review group.

The size and composition of peer review panels established after the promulgation 40 CFR Part 194 were determined by a selection committee consisting of the Peer Review Manager and two members selected by the Peer Review Manager.

Technical requirements for each peer review panel were established by the Peer Review Manager and provided to the selection committee, which then developed a list of potentially qualified personnel. Once a panel member was officially selected and had agreed to serve, the selection committee members documented the rationale for the selection of that peer review panel member on a "Peer Review Panel Selection, Size and Composition Justification/Decision Form," which is maintained as a QA record.

The number of members selected for a particular panel depended on the amount and complexity of the work to be reviewed, its importance for establishing that safety or waste isolation performance goals are met, the number of technical disciplines involved, the degree to which uncertainties in the data or technical approach exist, and the extent to which differing viewpoints were strongly held within the applicable technical and scientific community concerning the issues under review. The panel members were selected based on their collective technical expertise and qualifications so that they spanned the technical issues and areas involved in the work to be reviewed, including differing bodies of scientific thought. The technical areas more central to the work under review received proportionally more representation on the peer review panel. To the extent practical, the panels represented the major schools of scientific thought pertinent to the subject being reviewed. The selection committee strived to eliminate the potential for technical or organizational partiality by selecting peer reviewers that provided a balanced panel.

9.2.3 Technical Qualifications of Panel Members

NUREG-1297 states that

> The technical qualifications of the peer reviewers, in their review areas, should be at least equivalent to that needed for the original work under review and should be the primary consideration in the selection of peer reviewers. Each peer reviewer should have recognized and verifiable technical credentials in the technical area he or she has been selected to cover. The technical qualifications of each peer, and hence of the peer review group as a whole, should relate to the importance of the subject matter to be reviewed.

MP 10.5 specifies that the acceptability of any peer review panel member be based on the above NUREG-1297 requirements. The Peer Review Manager is required to ensure that education and pertinent experience information is verified and documented prior to the start of the peer review process. This documentation is also maintained as QA records.

9.2.4 Independence of Panel Members

NUREG-1297 states that

> Members of the peer review group should be independent of the original work to be reviewed. Independence in this case means that the peer, a) was not involved as a participant, supervisor, technical reviewer or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to assure the work is impartially reviewed.
>
> Because of DOE's pervasive effort in the waste management area, the lack or unavailability of other technical expertise in certain areas, and the possibility of reducing the technical qualifications of the reviewers in order that total independence is maintained, it may not be possible to exclude all DOE or DOE contractor personnel from participating in a peer review. In those cases where total independence cannot be met, a documented rationale as to why someone of equivalent technical qualifications and greater independence was not selected should be placed in the peer review report.

NUREG-1297 allows both the work under review and the peer review of that work to be funded by DOE. It also provides the caveat that the

> …independence criteria is not meant to exclude eminent scientists or engineers upon whose earlier work certain of the work under review is based so long as a general scientific consensus has been reached regarding the validity of their earlier work.

MP 10.5 provides that the above NUREG-1297 requirements be used in selecting panel members. Each peer review panel member is required to document his or her independence. These documents are reviewed and approved by the Peer Review Manager and maintained as QA records.

9.2.5 Training of Peer Review Panel Members

MP 10.5 requires that the Peer Review Manager ensure all peer review panel members receive adequate training prior to beginning a peer review. Training consists of reading assignments and, if deemed necessary by the Peer Review Manager or the Peer Review Panel Coordinator, briefings and classroom training. Assigned reading includes 40 CFR Parts 191 (EPA 1993) and 194, NUREG-1297, the CBFO QAPD, MP 10.5, and the applicable Peer Review Plans.

MP 10.5 further requires that all panel members receive an orientation prior to the start of the peer review process. The orientation includes information on the peer review process, administrative requirements, the applicable Peer Review Plan, a summary of the technical subject matter, and an overview of MP 10.5. Panel member training and orientation are documented and this documentation is maintained as a QA record.

9.2.6 Peer Review Panel Report

NUREG-1297 states that

> A written report documenting the results of the peer review should be issued. It is usually prepared under the direction of the chairperson of the peer review group, and is signed by each member individually. It should clearly state the work or issue that was peer reviewed and the conclusions reached by the peer review process . . . The report should include individual

> statements by peer review group members reflecting dissenting views or additional comments, as appropriate. The peer review report should contain a listing of the reviewers and any acceptability information (i.e., technical qualifications and independence) for each member of the peer group, including potential technical and/or organizational partiality.

MP 10.5 requires that a peer review report be prepared for each peer review. Each panel member is required to sign and date the report. The report describes the work or issue that was reviewed as well as the conclusions reached by the panel, and provides individual statements by the members reflecting dissenting views or additional comments, as appropriate. Finally, the report lists the peer review panel members and provides technical qualifications and independence information for each member.

9.2.7 Quality Assurance Records Management

NUREG-1297 specifies that written "…minutes should be prepared of meetings, deliberations, and activities of the peer review process."

MP 10.5 requires that written minutes, including graphic or calculated materials used in panel meetings, be prepared for meetings, deliberations, daily caucuses, and other activities. These written minutes are maintained as QA records. MP 10.5 also requires that a QA records management system be developed and implemented to ensure that peer review documents are identified, assembled, and transferred on a timely basis and in an orderly manner to the appropriate records center.

9.2.8 Quality Assurance Oversight

Section V of NUREG-1297 states that "As a minimum, the QA organization should provide surveillance of the peer review process to ensure that the procedures conform to the guidance of this GTP and that they are followed by the peer review group."

The QAPD establishes requirements for implementing the QA program for the WIPP peer review process. The QAPD requires that assessments be conducted to ensure that all aspects of the peer review conform to the guidance of NUREG-1297. Additional details regarding the WIPP QA program are provided in Chapter 5.0.

9.3 Peer Reviews Conducted After Promulgation of 40 CFR Part 194

Seven peer reviews were performed by the WIPP project prior to submitting the CCA in 1996 to address issues deemed necessary by the DOE. These peer reviews included reviews of conceptual models, waste characterization analysis, and an evaluation of the benefits and detriments of potential engineered barriers and alternatives as stated in 40 CFR § 194.27(a); data reviews of engineered systems, waste form and disposal room, and natural barriers as stated in 40 CFR § 194.22(b); and a passive institutional controls review. These peer reviews were conducted subsequent to the promulgation of 40 CFR Part 194 and were conducted in a manner consistent with the NUREG-1297 guidance, as implemented by TP 10.5 and the QAPD.

Specifically, the following peer reviews have been conducted:

- evaluation of the adequacy and reasonableness of the WIPP conceptual models;
- a review of the adequacy and completeness of the waste characterization analysis;
- an assessment of the validity of the assumptions and approach used to select or reject engineered alternatives, as delineated in the EACBS (DOE 1995b) for the WIPP;
- a data qualification review of parameters used to describe engineered systems;
- a data qualification of parameters used to describe natural barriers;
- a data qualification of parameters used to describe the waste form and disposal room; and
- a determination of whether the passive institutional controls have a reasonable expectation of meeting their intended purpose.

The conceptual model peer review group published three supplementary reports in 1996 and 1997 after the DOE submitted the CCA. These were also conducted in a manner consistent with the NUREG-1297 guidance, as implemented by TP 10.5 and the QAPD.

Two additional peer reviews related to conceptual models were completed in 2003. These were conducted in a manner consistent with the NUREG-1297 guidance, as implemented by CBFO's MP 10.5 and the QAPD. These five post-CCA peer review reports are summarized in Section 9.3.1 and the full reports are included in Appendix PEER-2004.

These reviews are discussed, and the WIPP project response to the peer review panel's comments is provided in the following sections. The general process used by the DOE to plan and conduct the seven peer reviews is described in Section 9.2. The complete reports of peer reviews performed before submitting the CCA were included in CCA Appendix PEER, and those performed after submitting the CCA are provided in Appendix PEER-2004. The reports were all consensus documents signed by all members of the specific panel involved: that is, there were no dissenting views on any of the final reports for the seven subject reviews.

9.3.1 Conceptual Models Peer Review

40 CFR § 194.23(a)(3)(v) specifies that this application include documentation that the conceptual models have undergone peer review consistent with 40 CFR § 194.27. A Conceptual Model Peer Review (CMPR) Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of CAO's TP 10.5 (Replaced by MP 10.5 for CRA-2004). The CMPR Plan describes the peer review process used to ensure that the conceptual models used in the WIPP PA reasonably represent possible future states of the disposal system.

In accordance with the provisions of TP 10.5, a peer review panel was selected and organized in April 1996. The six-member panel was composed of the following individuals:

- Charles R. Wilson (Chairman), Private Consultant;

- Florie A. Caporuscio, Informatics Corporation;
- John F. Gibbons II, Private Consultant;
- Eric B. Oswald, Private Consultant;
- Darrell D. Porter, Science Applications International Corporation; and
- Glen L. Sjoblom, Private Consultant.

Florie A. Caporuscio has a Ph.D. in Geology and more than 10 years of applied pertinent experience, including having served as the Acting Section Chief, WIPP Technical Review, at EPA Headquarters' Office of Radiation and Indoor Air and as a Staff Geologist at EPA Region II. In addition to Dr. Caporuscio's highly relevant regulatory expertise, his pertinent technical qualifications include extensive expertise in site characterization, geochemistry, radionuclide transport in geological media, and related conceptual models.

John F. Gibbons II has a Ph.D. in Geomechanics and more than 20 years of relevant experience, including having served as the Technical Director of Applied Research Associates for site characterization technology research and development activities augmented by involvement in numerous site characterizations. Dr. Gibbons' site characterization and technology research and development (R&D) experience is particularly pertinent for peer reviews involving geology, tectonics, hydrology, and related conceptual models.

Eric B. Oswald has a Ph.D. in Hydrology and Water Resources Administration and more than 25 years of applied pertinent technical and regulatory experience. Dr. Oswald's technical qualifications include extensive surface and groundwater flow system analyses and control, contaminant transport, and related conceptual models.

Darrell D. Porter has a Ph.D. in Mineral Engineering and more than 34 years of experience in earth sciences programs with emphasis on rock mechanics. Dr. Porter's pertinent technical qualifications include extensive involvement in site characterization, regulatory compliance, QA, and technical review activities in support of deep geologic repository development.

Glen L. Sjoblom has a M.Sc. in Chemical Engineering and more than 26 years of experience in environmental radiation protection, including having served as the Director of Radiation Programs at the EPA during the development and promulgation of 40 CFR Part 191. Mr. Sjoblom's extensive environmental radiation protection experience also includes serving as Special Assistant to the Director of the Office of Inspection and Enforcement and Deputy Director of the Division of Industrial and Regulatory Medical Nuclear Safety at the NRC. Mr. Sjoblom's pertinent technical qualifications include chemistry, waste characterization, deterministic and stochastic risk and safety analysis, and environmental protection activities in support of deep geologic repository development.

Charles R. Wilson has a Ph.D. in Civil Engineering–Groundwater and more than 26 years of relevant experience in earth sciences programs. Dr. Wilson's pertinent technical qualifications include lead roles in the geology, hydrology, geochemistry, and geotechnical engineering disciplines on teams involved in site characterization, model development, and modeling of

landfills; water resources; groundwater flow systems; contaminant and radionuclide transport; and nuclear waste repositories in the United States and abroad.

Additional details regarding the technical qualifications and independence of the panel members are provided in Appendix A of the July 1996 peer review report (see CCA Appendix PEER). Each panel member's background was carefully reviewed to ensure his strong qualifications, verify his independence from other WIPP work, and confirm the absence of conflicts of interest.

The initial peer review, described in detail in the CCA and summarized in this chapter, was conducted from April through August 1996. After orientation and training, the panel was provided draft conceptual model descriptions and other relevant information and was briefed by WIPP project staff. Panel members also had access to the Sandia National Laboratories (SNL) Nuclear Waste Management Program Library and to reports of prior peer reviews.

The objective of the review was to determine the adequacy and reasonableness of 24 conceptual models representing features, events, and processes (FEPs) involved in assessing the long-term performance of WIPP. As stated in the CMPR report:

> A conceptual model is a statement of how important features, events, and processes) such as fluid flow, chemical processes, or intrusion scenarios are to be represented in performance assessment. To be used in performance assessment, the conceptual model must be successfully translated into analytical statements and mathematical analogs. The Panel reviewed in detail the twenty four conceptual models against criteria of the EPA....The Panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall performance assessment model.

Per the criteria of 40 CFR Part 194, the peer review was conducted in a manner compatible with the provisions of NUREG-1297. The 8 adequacy criteria from NUREG-1297 were used as a basis for review of each model (see Section 9.2.1).

The first CMPR Report was issued in July 1996 (a copy of the CMPR Report is provided in CCA Appendix PEER). The panel initially concluded that 13 of the models were adequate for implementation and that the remaining 11 models were not adequate for use in PA. The DOE provided additional information in response to the panel's concerns, and the panel subsequently determined that the responses for 6 of those 11 models reasonably addressed their concerns. In addition, the panel concluded that some of the responses (multiple concerns were identified for some models) relating to three additional models also reasonably addressed its concerns. Finally, the panel concluded that responses regarding three models did not reasonably address its concerns; however, one of these models was determined to have no consequence to PA. The DOE's justification for using these unresolved models is discussed in Section 9.3.1.2 of the CCA and is briefly described in the same section of this chapter.

The 24 models reviewed by the panel are listed in Table 9-1. Also provided are the panel's conclusions about the adequacy of the models and whether the panel believed that the DOE's responses reasonably addressed its concerns about those models it determined to be inadequate.

Table 9-1. Adequacy of WIPP Conceptual Models

Model	Report Findings	DOE Response Reasonable?
Disposal System Geometry	Adequate	Not Applicable
Culebra Hydrogeology	Not Adequate [1]	Yes
Repository Fluid Flow	Not Adequate	Yes
Salado	Adequate	Not Applicable
Impure Halite	Adequate	Not Applicable
Salado Interbeds	Not Adequate	Yes
DRZ	Adequate	Not Applicable
Actinide Transport in the Salado	Adequate	Not Applicable
Units Above the Salado	Not Adequate [1]	No[1]
Transport of Dissolved Actinides in the Culebra	Adequate	Not Applicable
Transport of Colloidal Actinides in the Culebra	Not Adequate	No
Exploration Boreholes	Not Adequate	Partially[2]
Cuttings and Cavings	Adequate	Not Applicable
Spallings	Not Adequate	Yes
Direct Brine Release (DBR)	Not Adequate	No
Castile and Brine Reservoir	Not Adequate	Partially[3]
Multiple Intrusions	Adequate	Not Applicable
Climate Change	Adequate	Not Applicable
Creep Closure	Adequate	Not Applicable
Shafts and Shaft Seals	Adequate	Not Applicable
Gas Generation	Not Adequate	Yes
Chemical Conditions	Not Adequate	Partially[4]
Dissolved Actinide Source Term	Adequate	Not Applicable
Colloidal Actinide Source Term	Adequate	Not Applicable

[1] Although the model was found to be inadequate, it was determined to have no consequence to PA.
[2] The panel concluded that responses to three of their four concerns were reasonable.
[3] The panel concluded that responses to two of their three concerns were reasonable.
[4] The panel concluded that responses to two of their three concerns were reasonable.

Section 9.3.1.1 provides a brief description of the panel's discussion on the models it deemed adequate. Section 9.3.1.2 of the CCA provided a description of the panel's discussion on the models deemed inadequate; the DOE's responses to the panel's concerns; the panel's comments on those responses; and the DOE's technical position on those concerns wherein the panel concluded that the responses did not reasonably address its concerns. Section 9.3.1.2 of this chapter summarizes that discussion.

The same panel continued additional reviews after the submission of CCA, with supplementary reports published in December 1996, January 1997, and April 1997. These supplementary peer reviews are described in Section 9.3.1.3.

9.3.1.1 Adequate Models

The following excerpts are from the CMPR Report. They address those 13 models the panel determined to be adequate.

9.3.1.1.1 Disposal System Geometry

> The conceptual model for the disposal system geometry provides a suitable framework for modeling the important processes and their interactions in the disposal system. . .The concept that the spatial effects of processes and interactions can be represented in two dimensions is defensible. The simplification in the system representation and computational method to simulate the two dimensions are defensible and adequate for implementation. The basic grid framework for representing the material properties of the disposal system, adjacent DRZ [disturbed rock zone], geologic formations, and intrusion scenarios is adequate and the proposed use of a finite difference method to connect the nodes and generate flow fields is also defensible and adequate for implementation.

9.3.1.1.2 Salado

> Given that the conceptual model predicts that there will be enough brine to corrode the waste and that other assumptions appear conservative, making other impacts unlikely, the model is adequate for its intended use. . .The conclusions appear to be valid. Estimates of inflow volumes from the mechanisms proposed in the model appear to be reasonable. . .The model is adequate for implementation.

9.3.1.1.3 Impure Halite

> Although differences in the behavior of pure and impure halite, variable degrees of impurity, and complexities of stratigraphic distribution of zones of impurity exist, the modeling of all halite rocks in the Salado as impure halite is an acceptable model simplification. . .The model appears to be adequate for the same reasons that the overall Salado model is adequate. Brine inflow sufficient to corrode the waste and to drive biogenic degradation is assumed. For error to be significant, brine inflow would have to be very large, which is unlikely. . .The conclusions drawn on the basis of the impure halite model are valid for PA purposes.

9.3.1.1.4 Disturbed Rock Zone

> All observed considerations of analysis, study, and proposed engineered applications regarding the DRZ and its impacts on effective shaft sealing appear to be valid. The understandings developed of DRZ phenomena and data reveal it is critical to engineering waste containment overall because of its potential for negative impact on shaft seals permeability and integrity and fluid flow in the rooms and their seals. It appears that all considerations of this impact and the conclusions discussed here are sound and

valid. . .The panel concludes that the present DRZ model is adequate to be implemented in performance calculations.

9.3.1.1.5 Actinide Transport in the Salado

It seems DOE has provided a very rational way to “lump” all the various solubilities of dissolved actinides and to describe how the four main types of colloids will be “lumped” for transport. Both of these source terms have complex properties that could have been negated by the “lumping” factor. . .These two philosophies of solubility “lumping” have been clearly explained for dissolved and colloidal actinide transport. . .by the principal investigator and by this means the implementation was determined to be adequate. . .this model is wholly adequate and reasonable for implementation.

9.3.1.1.6 Transport of Dissolved Actinides in the Culebra

It is concluded that a dual porosity model is adequate for dissolved actinide transport analyses if ranges of model parameters are chosen properly in light of uncertainties. . .The conclusion that the actinide transport in the Culebra can be adequately modeled in a dual porosity model, with advective transport in the main flow porosity, diffusion into and physical and chemical retardation in the rock matrix porosity, is valid. . .The conceptual model appears compatible with other models it intersects with directly.

9.3.1.1.7 Cuttings/Cavings

This model is fundamentally appropriate. It is based on straightforward analysis, concepts, and technology that is well developed and believed to be adequate for depicting that part of the consequences of a waste room penetration by a borehole drill that is covered by this model....The CUTTINGS_S model contains well thought out and evaluated mathematics based on researched and established fluid flow technology and science. . .This model is sufficiently developed and uncomplicated that no serious concerns were found. It appears to be capable of accurately representing the waste that might be removed during a drilling intrusion and is fully adequate for implementation in support of the WIPP performance assessment.

9.3.1.1.8 Multiple Intrusions

The conceptual model for multiple intrusions is fundamentally sound and appropriately conservative, given the simplifications that are required to model a complex set of conditions in an efficient manner. . .The application of the conceptual model to the numerical model is adequate, again given the simplifications that are required to model a complex set of conditions in an efficient manner. . .The Multiple Intrusion conceptual model is adequate for implementation in performance assessment.

9.3.1.1.9 Climate Change

The climate change conceptual model represents a reasonable and defensible range of potential future climate extremes for incorporation into the performance assessment. The

conceptual model includes a range of conditions, bounded by reasonably foreseeable future climates and their effects that are adequate to represent impacts to groundwater flows in the Culebra Dolomite Member of the Rustler Formation. In addition to providing adequate representation of conditions for implementation, the background research and analysis supporting the formulation of the conceptual model for climate change provides adequate information for satisfying EPA guidance.

9.3.1.1.10 Creep Closure

The adequacy of the Creep Closure conceptual model is demonstrated by its predictiveness of room closure in existing WIPP excavations. The uncertainties inherent in the model must be assessed through the sensitivity of the porosity surface calculation. The model appears to be adequately predictive. . .The porosity surface calculation appears to address the complex issues of timing among processes and provides a means of choosing representative parameters for individual process with respect to uncertainty about process results and timing during dynamic process evolution.

9.3.1.1.11 Shaft and Shaft Seals

Comments concerning two issues from the preceding section are also applicable to the model's adequacy for implementation: 1) further analysis of the salt compaction data base, firmed up with additional data, is important to support parameter permeability values, and 2) an analysis has not been found to assure the shaft monolith does not create a shear zone at the shaft perimeter interface. Aside from these, the foregoing discussions outline an insightful piece of scientific and engineering work. The shafts and seals program is well thought through and the areas of perceived concern have been addressed to various degrees of detail, each believed sufficiently adequate to support qualifying this model as adequate to proceed in supporting performance assessment.

9.3.1.1.12 Dissolved Actinide Source Term

The true unknowns are to be found in the assumptions that the chemistry rapidly approaches equilibrium and that the waste has uniform characteristics and inventory. These fundamental assumptions are a basis of the conceptual model and are most probably adequate and reasonable. . .This model has turned out to be a very strong representation of how actinides would dissolve in the two major brines (Salado and Castile) of the repository and is adequate to support performance assessment.

9.3.1.1.13 Colloidal Actinide Source Term

Since this model is inexorably linked to the solubility concentrations of the dissolved actinide source term, one may conclude that this model is valid contingent on the validity of the other model (which was determined to be valid, with minor caveats)... The Colloidal Actinide Source Term model is a reasonable, if somewhat overly conservative representation of how actinides would sorb onto colloids in the two major brines (Salado and Castile) available for the repository. This conceptual model is adequate to support performance assessment.

9.3.1.2 Inadequate Models

As indicated above, the CMPR panel initially determined that 11 of the models they reviewed were inadequate. The CMPR panel concerns, the DOE's interpretation of the panel's concerns (Statement of Issue), the DOE response to the panel's concerns (Response to Issue), and the panel's reaction to the interpretation and responses (Peer Reviewer Consideration of Response) are provided in CCA Section 9.3.1.2. In those instances in which the panel determined the response did not reasonably address its concerns, the DOE developed additional information regarding its position (DOE Technical Position versus Panel Issue). These are also provided in CCA Section 9.3.1.2. For pre-CCA peer reviews, the issues raised by the panel and the panel's responses after considering the DOE responses are mentioned in this chapter, but the detailed exchanges between the DOE and the panel are not repeated.

9.3.1.2.1 Peer Review Panel Concerns – Culebra Hydrogeology

> No conceptual model which explains the variability of hydrologic properties and processes in the Culebra at a scale which is useful in correlating those properties in the numerical hydrologic flow model was developed.
>
> An extensive hydrologic testing database and an apparently adequate numerical flow model were developed as a substitute for performance assessment purposes.
>
> Although the Culebra conceptual model was found to be inadequate to support numerical modeling, this inadequacy was inconsequential for performance assessment because an extensive hydrologic database was developed and serves as an adequate substitute to support numerical modeling.

After consideration of the DOE response, the panel concluded that the DOE understood the issues and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.2 Peer Review Panel Concerns – Repository Fluid Flow; First Concern

> The conceptual model and its two-dimensional (2D) numerical implementation may unrealistically restrict brine movement within the repository to the anhydrite interbeds because of the shallow depths of the borehole and shaft model cells. These restrictions could result in underestimating brine migration in the interbeds toward the accessible environment.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and the response reasonably addressed the panel's concern. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.3 Peer Review Panel Concern – Repository Fluid Flow; Second Concern

> The conceptual model and its two-dimensional numerical implementation do not include the presence of the unplugged ERDA-9 borehole within the walls of the operations area. This borehole could provide a pathway for gas and possibly brine to the ground surface,

> and no description of the plugging plan for this hole was seen in the documentation provided by the Panel.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.4 Peer Review Panel Concern – Repository Fluid Flow; Third Concern

> The sensitivity of model results to the selection of constant permeability values for the waste, panel seals, and repository DRZ has not been evaluated for the current PA. Early time permeabilities may be significantly greater than the model parameter for each of these media, and could lead to underestimation of radionuclide releases.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.5 Peer Review Panel Concern – Repository Fluid Flow; Fourth Concern

> The long-term performance of the panel closure seals has not been subjected to a detailed engineering evaluation of the type performed for the shaft seal. The role of the panel seals in restricting brine flow among the waste panels and into other parts of the repository is an important element of the conceptual model and its implementation in PA.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.6 Peer Review Panel Concern – Salado Interbeds

> The conceptual model does not consider how the physical properties of the bounding clay seams affect model fracture propagation and permeability. Ignoring the characteristics of the clay seams may significantly overestimate the threshold pressure at which repository gases may be released.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.7 Peer Review Panel Concern – Units Above the Salado

> The conceptual models and the testing database are inadequate to exclude the Dewey Lake Redbeds and the Magenta Dolomites as potential transport pathways for radionuclides in the event of an intrusion.

After consideration of the DOE response, the panel concluded that the DOE understood the issues; however, the panel concluded that the response did not reasonably address its concerns. The panel noted, however, that the inadequacy of the model is of no consequence to the PA. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.8 Peer Review Panel Concerns – Transport of Colloidal Actinides in the Culebra; First Concern

> The conceptual model does not adequately support the assumption that dissolved actinides will not interact with Culebra colloids. Ignoring this phenomenon could overestimate the travel time calculated for radionuclides to reach the accessible environment.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address its concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.9 Peer Review Panel Concern – Transport of Colloidal Actinides in the Culebra; Second Concern

> The experimental K_ds determined for this model are not fully defensible. Such values may overestimate the retardation of actinides in the Culebra.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address their concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.10 Peer Review Panel Concerns – Transport of Colloidal Actinides in the Culebra; Third Concern

> Recent experimental work to support assumptions and data for this model has not yet been published and were not available for panel review.

After consideration of the DOE response, the panel concluded that insofar as this issue was not based on a technical issue, the panel was not requested to review the response.

9.3.1.2.11 Peer Review Panel Concerns – Exploration Boreholes; First Concern

> The potential for releases or changes in repository conditions from borehole penetrations in the operations and experimental areas of the repository does not appear to have been evaluated. Radionuclides that may have migrated into those areas through the panel closures by diffusion or other transport mechanisms could be released to the ground surface, and gas pressures could be relieved by such boreholes. Also, brine could migrate into those areas from a borehole and then into the waste panels.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.12 Peer Review Panel Concerns – Exploration Boreholes; Second Concern

> The assumption that shorter (40 m) (131.2 ft) borehole plugs beneath the repository horizon will not significantly degrade during the 10,000-year regulatory time frame has not been adequately supported. For the two- and three-plug configurations, degradation of these plugs could result in creation of a low permeability pathway for fluid migration between the Bell Canyon and the repository. For the three-plug configuration, degradation could result in increased fluid migration from a Castile brine reservoir to the repository.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.13 Peer Review Panel Concern – Exploration Boreholes; Third Concern

> The possibility that an effect on the repository could result from Castile brine encountered in an E1 borehole that is assigned a three-plug configuration does not appear to have been considered in the conceptual model. Castile brine could enter the repository during drilling before the borehole is cased and result in increased rates of corrosion, waste degradation, and gas production

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address its concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.14 Peer Review Panel Concerns – Exploration Boreholes; Fourth Concern

> The sensitivity of the performance assessment to the simplified approach taken to determine reference conditions for BRAGFLO output does not appear to have been evaluated for the current model configuration. If reference conditions are not provided at sufficiently frequent time intervals, the modeling results may be erroneous.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.15 Peer Review Panel Concerns – Spallings; First Concern

> The conceptual model for channel flow of gases toward an exploratory borehole appears to be valid but has not been adequately evaluated. Spallings is a potentially important mechanism for direct waste release to the ground surface.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.16 Peer Review Panel Concern – Spallings; Second Concern

> The conceptual model for waste erosion by flowing gases has not been adequately defined. The model describing the source(s) of waste erosion resistance and the parameter(s) characterizing that resistance have not been adequately evaluated. Errors in this conceptual model could lead to over estimating or under estimating the volume of waste released in the spallings process.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.17 Peer Review Panel Concern – Spallings; Third Concern

> The waste has not been adequately characterized and the understanding of its physical properties in its decayed state has not been adequately developed to support the Spallings model. An adequate understanding of waste erosion processes requires an adequate understanding of the properties of the waste.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.18 Peer Panel Concern – Direct Brine Release; First Concern

> The basis for the assumption that radionuclides do not accompany the direct discharge of Castile brine has not been adequately supported. This assumption could lead to underestimating radionuclide releases.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel determined that the response did not reasonably address their concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.19 Review Panel Concern – Direct Brine Release; Second Concern

> Radionuclide transport through entrainment of brine and waste solids in rapid, two-phase liquid/gas releases during inadvertent borehole intrusions does not appear to have been evaluated. This transport mechanism may be an important component of the conceptual model.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address their concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue." The CMPR panel further addressed several issues related to the spallings conceptual model in 1996-97 after submission of the CCA. In addition, a new peer review panel addressed the spallings issues in 2003. Results of these additional peer reviews are discussed in Section 9.3.1.3 and the reports are included in Appendix PEER-2004.

9.3.1.2.20 Peer Review Panel Concern – Direct Brine Release; Third Concern

Releases resulting from flow into an exploration borehole intersecting a disturbed rock zone in the wall of a waste panel do not appear to have been evaluated. Large, open fractures in the walls could significantly increase the local halite permeability, allowing gas and brine to migrate through the borehole to the ground surface.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address their concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.21 Peer Review Panel Concerns – Castile Formation Brine Reservoirs; First and Second Concerns

The basis for excluding larger, potentially depressurized brine reservoirs from performance assessment has not been adequately supported. Larger reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

The basis for the concept of reservoir depletion through previous borehole penetrations has not been adequately supported. Non-depleted reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

After consideration of the DOE response, the panel concluded that the DOE understood the issues and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.22 Peer Review Panel Concern – Castile Formation Brine Reservoirs; Third Concern

The expected probability of encountering pressurized brine beneath the waste panels has not been adequately supported, nor has the basis for apparently ignoring the quantitative value of site-specific geophysical data been presented. Unrealistically low probabilities of encountering brine may result in underestimating radionuclide releases.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address its concern. See CCA Section 9.3.1.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.1.2.23 Peer Review Panel Concern – Gas Generation; First Concern

The conceptual model does not consider aluminum in the waste, steel in the rock bolts and netting, radiolysis of water by undissolved alpha emitters, and radiolysis of plastics and cellulosics as sources of additional hydrogen (H), oxygen (O_2), and other gases. Ignoring gases generated by these effects could result in underestimating the gas pressure in the repository.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.24 Peer Review Panel Concern – Gas Generation; Second Concern

> An adequate basis has not been presented for the assumption of complete and rapid carbon dioxide removal by magnesium oxide (MgO) in the waste panels. The chemical conditions in the repository would significantly change if the MgO did not function as planned, and could result in higher radionuclide releases than the model would estimate.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and the response reasonably addressed this gas generation concern. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.25 Peer Review Panel Concern – Gas Generation; Third Concern

> An adequate basis has not been presented for ignoring the effects of heat generation from corrosion and microbial actions. Higher ambient repository temperatures could increase the rates of chemical reactions, fluid flow, and halite creep.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.26 Peer Review Panel Concern – Chemical Conditions; First Concern

> The combined temperature increase (due to radioactive decay and exothermic reactions) and its effect on repository conditions has not been adequately addressed. Significantly higher repository temperatures could accelerate chemical reactions, fluid flow, and halite creep rates.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.1.2 for details of the DOE response.

9.3.1.2.27 Peer Review Panel Concerns – Chemical Conditions; Second and Third Concerns

> Phase equilibria have not been critically assessed within the chemical parameters of the conceptual model. A major element stable phase that was overlooked could significantly alter the chemical conditions of the repository and vary the actinide source terms.
>
> The MgO backfill has not been demonstrated to be able to react completely with carbon dioxide (CO_2) generated by microbial action. If the MgO backfill did not react as planned, the pH buffering capability of the repository would be significantly compromised, and could result in underestimating the actinide source terms.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel determined that the DOE response did not reasonably address their phase-equilibria concern. The panel did conclude that the response reasonably addressed their

concern regarding the MgO backfill/CO_2 concern. See CCA Section 9.3.1.2 for details of the DOE response, including "DOE Technical Position versus Panel Issues."

9.3.1.3 Post-CCA Conceptual Models Peer Review

The CMPR panel (CMPRP) started its work in April 1996 and submitted its first report in July 1996. The July 1996 report is discussed in Sections 9.3.1.1 and 9.3.1.2, and was included in CCA Appendix PEER. DOE retained this panel after submitting the CCA to continue addressing the issues that were not completely resolved, although acceptable from a PA point of view. The panel issued three supplementary reports between December 1996 and April 1997. The results of these additional reviews are described in Sections 9.3.1.3.1 through 9.3.1.3.3, below, and the three supplementary reports are included in Appendix PEER-2004.

Two additional conceptual models peer reviews on Salado flow and spallings were conducted in 2003. These are described in Sections 9.3.1.3.4 and 9.3.1.3.5 below, and the two reports are included in Appendix PEER-2004.

9.3.1.3.1 Conceptual Models Supplementary Peer Review – October to December 1996

In its July 1996 report (see Section 9.3.1.2), the CMPRP concluded that of the 24 conceptual models, 13 were adequate for implementation and 11 were not, based on the panel review of the available information and the stated EPA criteria. The DOE reconvened the panel in October 1996 to review changes to the conceptual models, the DOE responses to the findings in the July 1996 panel report, and information available in the CCA (DOE 1996a). In December 1996, the panel issued a report (Docket II-G-12) supplementing the July 1996 report that assessed the changes to the models and DOE responses. For the December 1996 supplementary report, the panel evaluated DOE responses to the panel's findings in the July 1996 report, additional information available since the earlier report, changes that were made to 11 of the models, and the results obtained from implementing the models in PA. Based on this evaluation, the panel's concerns were resolved for all but two of the 11 models previously identified as inadequate. In addition, the new information obtained during this supplemental evaluation did not change the panel's previous conclusions of the 13 models that were found to be adequate.

The two models that remained inadequate in the panel's evaluation were the Chemical Conditions and the Spallings.

For the Chemical Conditions model, the panel's concern related to the ability of the MgO backfill to perform as assumed in PA. The panel stated:

> The ability of the MgO backfill to react completely and rapidly with CO_2 to buffer the chemical system and limit actinide solubilities has not been adequately substantiated by experimental physical results that correctly simulate conditions in the repository. Although the pH buffering assumptions are of considerable importance to many other conceptual models, the conclusion that the MgO will in fact perform as assumed has not been adequately supported.

A full discussion of the panel's position on the Spallings model is contained in Section 3.14 of the panel's report (See Appendix PEER-2004, Section PEER-2004-1.1.3). In summary, the panel stated in Section 5.0 of its report:

> An adequate basis for the parameters used in the mathematical expression of the model has not been developed. In particular, ignoring capillary forces and correlating tensile strength with surface erosion have not been adequately supported by either first principles or experiment.
>
> The principal assumptions upon which the mathematical model is based appear to be incomplete. Waste removal by entrainment in gas flow is expected to occur in a highly dynamic sequence principally involving a spalling process driven by gas flow out of the porous waste normal to the eroded surface. Subsequent erosion by gas flow parallel to the eroded surface in pathways that are not expected to be the primary effect controlling the volume of spall, particularly in early times. In addition, the DOE has not adequately shown that the steady-state assumptions of the model conservatively approximate releases associated with the dynamic process of spall, and the possibility of transonic velocities has apparently not been considered.
>
> The experiments conducted in support of this model appear to have been designed to reproduce the assumptions upon which the model is based, rather than to simulate the dynamic repository system. Although the experiments may support adoption of specific model parameters, they do not demonstrate that the model adequately represents future states of the repository.

9.3.1.3.2 Conceptual Models Second Supplementary Peer Review – January 1997

DOE reconvened the Conceptual Models panel in January 1997 to review additional information developed in response to the remaining issues of the two models, Spallings and Chemical Conditions, found inadequate in December 1996. The panel issued a second supplementary report in January 1997 to supplement the panel's July 1996 and December 1996 reports. In summary, the panel concluded that the Spallings model and the Chemical Conditions model remained inadequate to represent the future states of the repository. An account of the DOE's new presentations to the panel and the panel's responses are given below.

9.3.1.3.2.1 *The Spallings Model in the Conceptual Model Second Supplementary Peer Review*

The DOE responded to the panel's continued concerns through the SNL Spallings Release Position Paper (Hansen et al. 1997a), oral presentations, subsequent discussions, and presentations of additional information. The position paper and initial oral presentations addressed the panel's concerns by grouping them into categories of waste characterization, analog comparisons, and conceptual model issues.

The waste characterization information discussed the physical condition of the waste capable of release by a spallings process, the waste strength, and the expected significance of these results relative to spallings releases. Key points made were that any waste capable of spallings release would be at least partially degraded and have some moisture content, because without the presence of brine, the elevated gas pressure that drives the spallings process could not exist. The model assumption that the degraded waste would have the average characteristics of fine sand were considered by DOE to be highly conservative, because not all of the waste would have degraded to that end state during the 10,000-year regulatory period. The 1 psi (6,895 pascals) cementation strength assumed in the model was also considered conservative, and experimental results were presented showing that dried samples of sand saturated with WIPP brine had indirectly determined tensile strengths that averaged 49 psi. Higher average tensile strengths ranging up to 114 psi were found when NaCl and MgO were added to the brine. The DOE concluded that waste strength dominates spallings releases, the assumed waste strength of 1 psi

(6,895 pascals) was conservatively low, and degraded waste will be heterogeneous and cemented, significantly impeding erosion.

Analog comparisons were presented for spallings-type releases induced by pressure surging to stimulate methane (CH_4) production from coal beds, industrial techniques to remove cuttings by air injection during borehole drilling, the downhole pressure gradient requirements for removal of hydrofracture proppants, wellbore stability and sand production as a function of fluid velocities, and the limitations of the borehole as a transport pathway.

A DOE team made preliminary scoping calculations using an elastic, Mohr-Coulomb model of waste that would be released by tensile failure using the pressure-transient data described above and ranges of values for the key waste strength properties. Several cases were run in which assumed waste compressive strength and internal friction were varied. The details of these analyses are presented in Hansen et al. (1997b). The results indicated that the volume released from a 1-m (3.28-ft) thick waste horizon (representing the fully compacted state of the waste) ranged from 0.37 to 0.59 m^3 (13.06 to 20.8 ft^3), and approached approximately 0.6 m^3 (21.1 ft^3) as the waste tensile strength approached zero.

In response to the DOE's presentations, the panel stated that the additional analog, waste strength, model descriptions, and calculational information provided were either not adequately correlated with WIPP repository conditions or not sufficiently complete or supported to determine that either the spallings model or the results obtained from that model were conservative. Details of the panel's response can be found in Appendix PEER-2004, Section PEER-2004-1.1.4.

9.3.1.3.2.2 *Chemical Conditions Model in the Conceptual Model Second Supplementary Peer Review*

The DOE summarized a calculation of complementary cumulative distribution functions (CCDFs) intended to show the importance of MgO on repository system performance. The CCDFs without MgO present showed increased releases compared to those with MgO present. Releases with MgO present predominantly result from cuttings/cavings and spallings, but without MgO present, the contribution from direct brine release (DBR) significantly increases. DOE emphasized that the mean CCDF without MgO present still remained lower than the EPA limit. DOE also provided additional results of experiments with MgO from the ongoing test program.

The panel examined the various assumptions and parameters used to compute the CCDFs without MgO present and felt that the differences in CCDFs with and without MgO represented the degree of the chemical getter's importance to repository performance. The panel stated its belief that adding the MgO would positively benefit and not detract from the repository performance. However, the panel identified a few additional factors to include for such a CCDF calculation to be definitive, including the effect on corrosion rates, gas generation rates, and pressures over time. However, inasmuch as calculations without MgO showed that DBR would become an important contributor to overall releases, the Chemical Conditions model was a significant contributor to the future states of the repository. Furthermore, according to the panel,

the additional results from the ongoing test program, while interesting, were not sufficient to resolve the panel's concerns about MgO effectiveness.

The results presented to the panel concerned the effect of CO_2 diffusion into the MgO pellets. Test runs of four days following dye infusion indicated that in 24 hours, the dye would travel through the reaction rims to the center of the pellet. However, the panel stated that the test runs were short, the reaction rims were thin and may not have been fully formed, and there were no transient information or bounding calculations to support a conclusion regarding the role of the reaction rims in impeding CO_2 diffusion. According to the panel, information was not available on the diffusion rate of CO_2 into the MgO pellets, especially as a function of reaction rim thickening. The panel believed that the aforementioned test program had not sufficiently progressed to provide a definitive verification that the MgO would perform as planned under repository conditions. Therefore, the panel concluded that the Chemical Conditions model was not sufficiently developed to adequately support PA. For the DOE response to this conclusion from the panel and the panel's final conclusion, see Section 9.3.1.3.3.1.

9.3.1.3.3 Conceptual Model Third Supplementary Peer Review – April 1997

In its January 1997 second supplementary report, the panel continued to find two of the models inadequate to represent the future states of the repository. For the two models found inadequate, Spallings and Chemical Conditions, the panel identified the remaining issues. In the third supplementary report (Docket II-G-22), the panel considered the DOE's April 1997 responses to these remaining issues. The DOE's responses as well as the panel's evaluation of these responses, are presented in Section 3 of the third supplementary report (see Appendix PEER-2004, Section PEER-2004-1.1.5).

For the Spallings model, the panel concluded that the predicted volumes of spalled materials presented in the WIPP CCA are reasonable based on additional consideration of processes that could lead to spalled releases. The panel also concluded that the MgO backfill component of the Chemical Conditions model will function as assumed in the CCA and that this model adequately represents the future states of the repository. Details of the DOE submission to the panel in April 1997 (in response to the panel's findings in the first and second supplementary reports) are provided in the panel's third supplementary report (Appendix PEER-2004, Section PEER-2004-1.1.5) and are summarized below.

9.3.1.3.3.1 *The Spallings Model in the Conceptual Model Third Supplementary Peer Review*

In response to the panel's finding that the existing model used to estimate spalling inadequately represented critical components of the spalling process, DOE initiated a new, mechanistically based computational approach. This approach was composed of three new computational methods to develop additional information on the spalling process. These are called the cavity growth, the quasi-static, and the numerical computation methods. This approach represented the first time that borehole hydrodynamics and cavity growth were linked. The cavity growth method was presented as the primary method for estimating spall volumes. The method simulated the entire response period of the system to an intrusion event, not just the end point. Assuming initial gas pressures and waste strength, the method accounted for the progressive mechanical response of the waste to a transient solution of gas flow in the waste and included the

hydrodynamics of mud and waste ejection through the borehole. The cavity growth method predicted small spalling volumes for assumed initial gas pressures below lithostatic (14.8 MPa) (2147 psi) and a maximum spalling volume of 0.25 m^3 (8.8 ft^3).

The quasi-static method also estimated spall volumes using the same mechanisms and approach as the cavity growth method, but not in a fully coupled manner. This method predicted pore pressure gradients from a consideration of borehole and porous media flow, and used these gradients to compute stresses, failure, and spall volumes. The method was applied to estimate gas volumes, gas pressure distributions, and flow rates for comparison to those predicted by the cavity growth. Graphic comparisons of gas flows and pressures predicted by the cavity growth and quasi-static methods illustrated close agreement.

The numerical method was presented as a tool for evaluating complexities not clearly represented by the other methods. The numerical method couples fluid pressure to the stress response in the waste following a drilling intrusion. Numerical calculations implemented through various computer codes were used to investigate solids mass transport, sensitivity of waste panel geometry, and effects of waste heterogeneity, in addition to predictions of gas pressures and flow rates. Numerical calculations were applied to predict gas pressures and flow rates for comparison to semi-analytic results. The numerical calculations consistently predicted lower pressure gradients and gas flow rates than the other methods. The gradients and rates predicted by the numerical method were significantly lower than those of the other methods at early time steps. Investigations of layered and random configurations of heterogeneous waste using numerical calculations resulted in reduced key parameters that determine spalling volume. Solids mass transport was investigated and determined to be limited prior to mud ejection. Tensile strength was determined to govern the system response, thereby minimizing the overall effects of waste panel geometry and flow properties.

In response to the panel's concern about the properties of the waste that would influence the spalling process, the DOE developed analogs for waste based on ranges of waste contents, corrosion, and biodegradation that could be present following extended exposure to WIPP conditions. The surrogate samples contained varying amounts of corroded and uncorroded iron metal, including addition of goethite, crushed glass and soil, salt and concrete, and MgO, in some cases. Physically degraded paper, plastic, and peat were added to represent chemically degraded organics in the waste. These surrogate waste materials were mixed with brine and consolidated to either 5 or 15 MPa (725 to 2176 psi) to simulate repository conditions. Some of the samples were subsequently dried. Standard testing procedures were used, including Brazilian and hollow cylinder tensile tests, unconfined and triaxial compression tests, and permeability tests. Various parameters, including permeability, porosity, cohesion, tensile strength, compressive strength, Young's modulus, and Poisson's ratio were determined from the test results. These parameters were then used in the various analytical calculations. DOE asserted that these parameters adequately represented the degraded waste expected in WIPP.

The panel was also presented with documentation of analogs to the spalling process at WIPP, mostly rooted in petroleum production technology. The dynamic cavitation of wellbores, specifically those through coal beds, was found to have notable attributes analogous to the spalling process at WIPP. Dynamic cavitation has many similarities to the spalling process at WIPP, such as a pressure pulse phenomenon, gas-driven particulate removal, and a highly

similar physical configuration. The ability to apply established computational codes and the available database of results from this analog helped to corroborate testing and/or computational results.

For the spallings model, DOE did not request the panel to reconsider its conclusion that the original model did not adequately represent the future states of the repository, and did not ask the panel to review a new model against the criteria of 40 CFR 194. The panel was instead requested to determine if the predicted volumes of spalled materials presented in the CCA were reasonable, based on additional consideration of processes that could lead to spalled releases.

In its conclusion on this issue, the panel stated:

> Upon reviewing the DOE's written materials, oral presentations, and responses to specific issues raised by the Panel, the Panel concluded that no significant issues remained regarding the reasonableness of the spallings volumes used by DOE in its CCA for the WIPP. Although the additional waste strength, analog information, and calculational results that were presented to the Panel could be further refined, the Panel determined that this information was sufficiently accurate and complete to support a conclusion that the spallings volumes used in the CCA are reasonable, and in fact appear to overestimate the actual waste volumes that would be expected to be released by the spallings process.

Detailed arguments for reaching this conclusion are provided in the panel's report (see Appendix PEER-2004, Section PEER-2004-1.1.5).

9.3.1.3.3.2 *The Chemical Conditions Model in the Conceptual Model Third Supplementary Peer Review*

The panel concluded in the second supplementary report that the ongoing test program did not sufficiently provide a definitive verification that the MgO would perform as planned under repository conditions. The panel was particularly concerned about whether the results of early tests indicated that reaction rims would inhibit the ability of the MgO to react completely and rapidly with CO_2 to buffer the chemical system and limit actinide solubility.

The DOE provided a draft report to the panel, "Chemical Conditions Model: Results of the MgO Backfill Efficacy Investigation," dated April 23, 1997, along with oral briefings on this report. This report summarized the then-available data and analyses developed from SNL Test Plan TP-97-01. DOE indicated that of the various phases formed from brine contact with MgO pellets, the initial phase, and brucite, will crystallize to nesquehonite and hydromagnesite during short to intermediate times and, over long periods, will dehydrate to magnesite. DOE stated that the brine pH and CO_2 fugacity are controlled at levels throughout the process that effectively lead to low actinide solubilities. Earlier short-term experiments at high CO_2 contact rates indicated the formation of reaction rims. The results for longer periods with high CO_2 contact rates indicated the growth of brucite films, followed by increasing density of nesquehonite needles projecting from the pellets. Shortly thereafter, hydromagnesite forms among the nesquehonite needles, as well as farther from the pellets.

DOE concluded that while there was considerable retardation of CO_2 access to the pellets, accessibility for transfer was maintained. DOE further indicated that the predominant chemical

diffusing species were MgOH+ diffusing from the pellets and HCO_3 diffusing toward the pellets. This gave rise to the precipitation of hydrous magnesium carbonates outside the pellets.

DOE further indicated that, in contrast to the experiments where relatively high CO_2 fluxes occur, the brine at WIPP would become saturated with magnesium compounds before significant introduction of CO_2 species occurs. The reactions would occur at nucleation sites still farther from the pellets, further improving the contact between the reacting species and reducing the formation of reaction rims. This supported the conceptual model assumption that the CO_2 would rapidly and completely react with the MgO. The DOE also reiterated that four times the amount of MgO needed to react with the total quantity of CO_2 generated will be emplaced in the repository.

DOE reviewed the effect of MgO control of pH and CO_2 fugacity in actinide solubility, with hydromagnesite being the predominant intermediate carbonate phase. DOE concluded that most solubilities would be lower with hydromagnesite than if the transition to magnesite occurred, as assumed earlier. DOE also concluded that the results of the test program and analyses demonstrated that MgO will function in the WIPP according to the Chemical Conditions model in the CCA.

In response to the DOE's presentation described above, the panel concluded:

> Based on the information presented to the Panel in the written material and in oral discussion, the Panel concludes that the results available provide an adequate basis to determine that the MgO backfill will function according to the Chemical Conditions Conceptual Model, as used in the CCA, with respect to reaction with generated CO2 gas.

Detailed arguments for reaching this conclusion are provided in the panel's report (see Appendix PEER-2004, Section PEER-2004-1.1.5).

9.3.1.3.4 Salado Flow Conceptual Models Peer Review – March 2003

9.3.1.3.4.1 *Introduction*

Three conceptual models (viz., Disposal System Geometry, Repository Fluid Flow, and DRZ) related to the flow in the Salado used in the CCA were revised due to changes invoked by EPA or knowledge gained since the original conceptual models were developed for the CCA. The Salado Flow Conceptual Models Peer Review panel performed a peer review of the three revised conceptual models between April 2002 and March 2003 and published a report, "Salado Flow Conceptual Models Final Peer Review Report" in March 2003. This report is reproduced in Appendix PEER-2004.

This peer review was performed to fulfill the provisions of 40 CFR 194.27 that require peer reviews of all conceptual models used in any compliance application, and was conducted according to the guidance in NUREG-1297.

9.3.1.3.4.2 *Members of the Peer Review Panel*

Dr. Florie Caporuscio, Dr. John Gibbons, Dr. E. B. Oswald, and Dr. Chunhong Li performed this peer review. Their complete biography data are included in the panel's report (Appendix PEER-2004). The following is a summary of their technical qualifications and experience.

Florie A. Caporuscio has a Ph.D. in Geology and more than 10 years of applied pertinent experience, including having served as the Acting Section Chief, WIPP Technical Review, at EPA Headquarters' Office of Radiation and Indoor Air and as a Staff Geologist at EPA Region II. In addition to Dr. Caporuscio's highly relevant regulatory expertise, his pertinent technical qualifications include extensive expertise in site characterization, geochemistry, radionuclide transport in geological media, and related conceptual models.

John F. Gibbons II has a Ph.D. in Geomechanics and more than 20 years of relevant experience, including having served as the Technical Director of Applied Research Associates for site characterization technology research and development activities augmented by involvement in numerous site characterizations. Dr. Gibbons' site characterization and technology R&D experience is particularly pertinent for peer reviews involving geology, tectonics, hydrology, and related conceptual models.

Eric B. Oswald has a Ph.D. in Hydrology and Water Resources Administration and more than 25 years of applied pertinent technical and regulatory experience. Dr. Oswald's technical qualifications include extensive surface and groundwater flow system analyses and control, contaminant transport, and related conceptual models.

Chunhong Li, Ph.D., is a groundwater modeler with experience in numerical modeling for groundwater flow and transport, numerical simulations to study the influence of matrix diffusion on radionuclide transport in fractured media, and solving scaling-related problems in groundwater modeling.

9.3.1.3.4.3 *Results of the Peer Review*

The panel reviewed the three conceptual models of interest in detail, including the assumptions and scientific information used to develop the model, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The panel also assessed the information used and whether the conceptual model was adequate for implementation in an overall WIPP PA. The review process and review criteria are discussed in Section 2 of the panel's report (see Appendix PEER-2004, Section PEER-2004-2.1.3).

The changed models were reviewed in the context of the WIPP PA. The review included an assessment of the reasonableness of changes in performance estimates resulting from changes in parameter ranges and in changes to, or resulting from, single values. The review evaluated changes in the conceptual structure of the models and changes in component process models and compared the performance results of the changed models with the results of the earlier models to confirm that the changes in performance estimates were reasonable in sense and magnitude. Changes in computations or in fundamental model aspects, such as gridding, were also considered. The review considered the impacts of the changed models on the other WIPP conceptual models and related issues, such as the Option D panel closures.

The panel applied the stringent assessment criteria provided in NUREG-1297, Peer Review of High-Level Nuclear Waste Repositories. The panel member qualifications, independence, and lack of organizational conflict of interest are documented in Appendices A, B, and C of the panel's report (see Appendix PEER-2004, Section PEER-2004-2.1.3).

The following is a summary of the panel's evaluation for each of the three revised conceptual models, as contained in the panel's report.

Disposal System Geometry: The changes in the Disposal System Geometry conceptual model retain the necessary features of the original conceptual model, and the grid changes appear reasonable and sound. The Disposal System Geometry conceptual model continues to be adequate. The results of a PA for the Technical Baseline Migration (TBM) illustrated that the effects of changes in the conceptual model are minimal. The Disposal System Geometry conceptual model continues to represent repository performance with no significant change from its representation in the baseline.

Repository Fluid Flow: The Repository Fluid Flow conceptual model was determined to be both reasonable and adequate for its intended purpose. The identified changes (shaft simplification, EPA mandated parameters, cellulosic molecular structure, and fluid flow paths) appear reasonable and are expected to have minimal impact. The interaction of this conceptual model with the Option D Panel closure (with revised anhydrite fracturing and "flow around" features at high pressure), and subsequent gas pressure realizations in waste panels have been illustrated by a series of TBM CCDFs that show very little resultant change. The influence of the model when coupled with the other conceptual models appears appropriate and adequate.

Disturbed Rock Zone: Four changes to the DRZ conceptual model have the potential to impact PA. These are adopting a range of limiting porosity values to replace the CCA single value for the halite and anhydrite layers in which the DRZ is developed; defining a flow path through the floor of the repository openings into Interbed #139; flow paths around the tops and bottoms of panel seals at high pressure; and an elevation change of the waste panels in the southern end of the repository. Based upon data and analyses presented by SNL, these changes appear reasonable. The change of waste panel elevation aids repository operations and is not considered a significant change. The impact of these changes on PA calculations and CCDF plots appears negligible. The impact on releases sensitive to repository pressures, saturation, and brine volume show that changes in the DRZ model do not significantly impact the predicted compliance of the repository.

9.3.1.3.5 Spallings Model Peer Review – September 2003

9.3.1.3.5.1 *Introduction*

In accordance with the requirement of 40 CFR Part 194.27, the CBFO of the DOE has conducted a peer review of the new spallings conceptual model developed for CRA-2004.

The spallings conceptual model is one of 24 conceptual models used in the WIPP PA. This conceptual model describes a potential release of degraded solid waste materials when repository gas pressure exceeds the hydrostatic pressure in the drilling fluid at the bottom of an intrusion borehole. The CMPRP found in 1997 (see Section 9.3.1.3.3.1) that the Spallings conceptual

model implemented in the CCA was inadequate to describe the detailed spallings process. However, the CMPRP also concluded that "the spallings volumes used in the CCA are reasonable, and may actually overestimate the actual waste volumes that could potentially be expected to be released by the spallings process at the WIPP" (Wilson et al. 1997, Section 4). The EPA agreed with the CMPRP that the spallings conceptual model was inadequate but the results were acceptable for use in PA (EPA 1998a, Section viii; 1998b, Section 7).

After the CCA and PAVT were completed, work continued on the development of a new Spallings conceptual model that would be more technically defensible than the original model.

This independent peer review was conducted in July to October 2003 by a three-member interdisciplinary team having the requisite broad experience and expertise to address the range of issues associated with the spallings scenario and the new numerical model developed by DOE to carry out the predictive PA calculations. The peer review was conducted primarily in Albuquerque, New Mexico, at the DOE Energy Training Center (ETC). The peer review panel was given access to the conceptual model descriptions, scientific reports, briefings, and SNL staff. The panel also had access to reports of prior peer reviews and was given the full cooperation of the DOE and SNL throughout the review. Representatives of the EPA, DOE, and the New Mexico Environmental Evaluation Group (EEG) observed the SNL technical presentations and the panel's questions and deliberations.

This peer review met the regulatory requirements of 40 CFR Part 191 and the implementation of those requirements by 40 CFR Part 194. The peer review was conducted in accordance with the NRC's NUREG-1297, Peer Review of High-Level Nuclear Waste Repositories. The adequacy criteria set forth in NUREG-1297 were those used by the peer review panel for reviewing the new Spallings conceptual model. The peer review panel followed the DOE CBFO MP-10.5, Peer Review, to perform the peer review.

9.3.1.3.5.2 *Members of the Peer Review Panel*

Dr. Ching Yew, Dr. Jonathan Hanson, and Dr. Lawrence Teufel served as members of this panel and authored the panel's report. The panel members' qualifications are briefly described below. Their detailed biographies can be found in the report of the panel (Yew et al. 2003), included in Appendix PEER-2004.

Ching Yew, Ph.D., Chairman: Dr. Yew is currently a Consulting Engineer with over 40 years experience in mechanical engineering. He has a Ph.D. in Mechanical Engineering from the University of California at Berkeley. He worked for the University of Texas at Austin providing research and teaching for 32 years. He is now a Professor Emeritus in the Department of Aerospace Engineering and Engineering Mechanics at the University of Texas at Austin. Dr. Yew is a fellow of the American Society of Mechanical Engineers (ASME) and a member of the Society of Petroleum Engineers (SPE).

Jonathan Hanson, Ph.D.: Dr. Hanson has over 18 years experience as a Consulting Geophysicist. His primary focus as consultant is the development, and subsequent software implementation, of research and analysis tools used in the earth sciences, engineering, and technology. Areas within which this work has been carried out include oil field drilling dynamics and drill bit design and

performance optimization, CH_4 desorption in coal, tailored pulse loading for well stimulation, Vertical Seismic Profiling (VSP) acoustic data analysis, and Coordinate Measurement Machine (CMM) analysis software for manufacturing QA.

Dr. Hanson has a Ph.D. in Geophysics from Oregon State University. He was employed by the University of California Lawrence Livermore National Laboratory from 1978 to 1985, where he worked in the Earth Sciences Division. He has published over 50 related articles and reports. He is a member of the Society of Petroleum Engineers.

Lawrence Teufel, Ph.D.: Dr. Teufel is currently a Langdon Taylor Professor in the Petroleum Engineering Department at the New Mexico Institute of Mining and Technology in Socorro, New Mexico. Dr. Teufel has over 24 years experience in petroleum and natural gas industry. He was chairman of the Petroleum Engineering Department at the New Mexico Institute of Mining and Technology Department from 1997 to 2000. He has a Ph.D. in Geology from Texas A&M University.

Dr. Teufel was employed by SNL as a member of the Technical Staff, Geomechanics Department, from 1979 to 1986, Senior Member from 1986 to 1993, and Distinguished Member from 1993 to 1999.

9.3.1.3.5.3 *The New Spallings Model*

As stated above, DOE developed and presented a new spallings model for this peer review. DR_SPALL (from Direct Release Spall) is a new numerical code written to calculate the volume of WIPP solid waste subject to material failure and transport to the surface as a result of an inadvertent drilling intrusion. The code calculates coupled repository and wellbore transient compressible fluid flow before, during, and after the drilling intrusion process. Mathematical models are included for bit penetration, multiphase (mud, salt, waste, and gas) fluid flow in the well, fluid expulsion at the surface, coupling of the well and the drilled repository, repository spalling (tensile) failure, fluidized bed transport of failed waste, and repository internal gas flow. The wellbore model is one-dimensional with linear flow, while the repository model is one-dimensional with either spherical or cylindrical flow.

Previous work (Hansen et al. 1997b) has shown that the parameter extremes most likely to be of importance to spalling releases are high repository gas pressure, low waste mechanical strength, small waste particle size (after failure), and low waste permeability. DR_SPALL was used to confirm these observations and to better establish the ranges of these parameter values that are important. Since conventional drilling practices are assumed, allowances are made for the continuous pumping of mud during drilling, the possible stoppage of the mud pump, continuous drilling after repository penetration, and the possible stoppage of drilling, based on observations made at the surface by the driller. Of course, one possibility is the continuance of pumping and drilling despite the intrusion into a high-pressure subsurface region.

DR_SPALL is based on the theory of one-dimensional, time-dependent compressible isothermal fluid flow. Somewhat different forms of that theory are used, depending on whether the flow is in the wellbore or in the repository, and whether or not the wellbore currently penetrates the repository. The wellbore and repository flows are coupled at a specified boundary by a set of

conditions. Throughout the process, the drillbit can move downward as a function of time, removing salt or waste material. Flow in the well is treated as a compressible, viscous, multiphase mixture of mud, gas, salt, and possibly waste solids. Flow in the repository is treated as viscous, compressible single-phase gas flow in a porous solid. At the cavity forming the repository-wellbore boundary (following penetration), waste solids freed by drilling, tensile failure, and associated fluidization may enter the wellbore flow stream. Between the well and the repository, flow is treated according to the state of penetration.

Thus, the major elements of the new spallings model include:

- Consideration of multiphase flow processes in the intrusion borehole,
- Consideration of fluidization and transport of waste particulates from the intact waste mass to the borehole, and
- A numerical solution for the coupled mechanical/hydrological response of the waste as a porous medium.

9.3.1.3.5.4 *Criteria for the New Spallings Conceptual Model Review*

The nine criteria used by the peer review members are based on the criteria in EPA regulation 40 CFR Part 194.27, NUREG-1297, the EPA Compliance Application Guidance, and peer panel discussions.

9.3.1.3.5.4.1 Information Used to Review the Conceptual Model

This criterion is an evaluation of data and information used to review the conceptual model. It includes attributes of the disposal system learned by SNL during site characterization activities, exercising the model, and a review of the science and concepts the model is based upon. It also includes pertinent information gained during repository operation.

9.3.1.3.5.4.2 Validity of Assumptions

The validity of key assumptions in the model and its application are assessed in terms of how they might affect the validity of the conceptual model. The review addresses the comprehensive inclusion of important FEPs, and other key assumptions. Examples are the assumption of Darcy flow, use of the ideal gas law at high pressures, and the mathematical method chosen to develop the model grid.

9.3.1.3.5.4.3 Alternative Interpretations

This criterion identifies and assesses plausible alternative conceptual models considered, but not used, by DOE and the rationale for why such alternative models were not used.

9.3.1.3.5.4.4 Uncertainty of Results and Consequences if Wrong

This criterion includes an evaluation of the key uncertainties in the selected conceptual model and a discussion of the consequences if aspects of the conceptual model chosen were

inappropriate or incompletely constrained for the site or subject process. This is not an exhaustive evaluation, but it does ask, “What if the model is wrong?”

9.3.1.3.5.4.5 Appropriateness and Limitations of Method and Procedures

Based primarily on the previous four criteria, this criterion assesses whether the individual conceptual model represents a reasonable approximation of the WIPP disposal system performance.

9.3.1.3.5.4.6 Adequacy of Application

This criterion assesses whether the conceptual model is adequately applied into an acceptable overall PA system. This particular assessment does not cover the relationships among conceptual models, but rather whether the significant components of the conceptual model are appropriately implemented in support of PA. For example, are the various geometrical systems and representations of the conceptual model adequately applied within the performance modeling system, or are there discontinuities between the conceptual model and its application? Also, are there alterations of important key assumptions between the conceptual model and its implementation in performance modeling?

9.3.1.3.5.4.7 Accuracy of Calculations

This criterion assesses whether the results of performance modeling using the conceptual model within the performance system are reliable and accurate to adequately simulate the physical and chemical processes represented.

9.3.1.3.5.4.8 Validity of Conclusions

This criterion judges the validity of the key conclusions based on results of the implementation of the conceptual model in the modeling framework. The key question is whether or not conclusions from model implementation appropriately relate to the expected goal of assessing the long-term performance of the WIPP disposal system. This judgment requires an evaluation of output information from the total system PA.

9.3.1.3.5.4.9 Adequacy for Implementation

This is an overall assessment of whether the conceptual model as implemented in the PA represents a reasonable approximation of the actual disposal system.

9.3.1.3.5.5 *Summary Findings of the Spallings Peer Review Panel*

This section describes the findings of the peer review panel as related to the review criteria discussed in Section 9.3.1.3.5.4. The panel reviewed the spallings conceptual model in detail, including the assumptions and scientific information used to develop the model, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall WIPP PA. The Spallings model was reviewed in the context of the overall approach to the WIPP PA. The review evaluated the structure of the conceptual

model and the mathematics used to embody the model in code. The review also included an assessment of the reasonableness of outputs based on sensitivity to parameter inputs.

The panel refers to presentations by SNL. SNL developed the Spallings model and presented it to the panel on behalf of the DOE.

The complete report of the panel (Yew et al. 2003) is included in Appendix PEER-2004, Section PEER-2004-3.1.2. The following are the findings of the panel as stated in the panel's report.

9.3.1.3.5.5.1 Information Used to Review the Conceptual Model

The data and information available was sufficient to allow a thorough technical review. Necessary attributes of the disposal system are well characterized and understood. The science and concepts upon which the model is based are sound. The model has been benchmarked against other quantified experience in coal fields, and sensitivity analyses indicate the model is valid within the range of its intended use.

9.3.1.3.5.5.2 Validity of Assumptions

The validity of key assumptions in the model and its applications has been assessed in terms of how they might affect the validity of the conceptual model. The review addressed the comprehensive inclusion of important FEPs and other key assumptions. Examples are the assumption of Darcy flow, use of the ideal gas law at high pressures, and the mathematical method chosen to develop the model grid. The essential assumptions used by SNL to develop and exercise the Spallings model were found to be appropriate and valid.

Two assumptions of the model were imposed by the requirements of successful numerical implementation. These were: (1) the existence of the Drilling Damage Zone (DDZ) and (2) a characteristic averaging length required for tensile failure. The former was required for numerical stability of the code as the bit approaches and intersects the repository, and the latter is required for spalling to occur at the face of the cavity. Both of these assumptions are reasonable and have been shown, based on a limited sensitivity analysis, likely to have little effect upon model predictions. It must be emphasized, however, that the inclusion of these mechanisms was motivated primarily by numerical purposes and have not been substantiated by laboratory measurement.

9.3.1.3.5.5.3 Alternative Interpretations

During the spallings peer review, information presented and considered by the panel did not include alternatives or options for the Spallings conceptual model. The original Spallings conceptual model can be considered an alternative. In the present model development, it appears that SNL has employed the simplest and the most straightforward approach in modeling this complex and highly coupled problem. Each individual scenario is described by applying the basic physical equations. The panel concluded that this approach would provide a conservative estimation of spalling release.

9.3.1.3.5.5.4 Uncertainty of Results and Consequences if Wrong

The panel concluded that the conceptual model contains all of the necessary components to adequately represent the physics of the spalling problem. This is a highly coupled and nonlinear problem that involves a fluid-filled wellbore, pre-penetration leak-off from the repository, post-penetration depressurization of the repository, and resulting tensile failure of waste and transport of that waste to the surface.

Obviously, there will be uncertainty in the predictions. This uncertainty can be categorized as follows:

1. Uncertainty in the physical model,
2. Uncertainty associated with numerical implementation of the model, and
3. Uncertainty associated with the input parameters to the model.

The panel judged the physical model used to represent the process to be adequate. The uncertainty associated with the numerical implementation of the model falls within the category of features invoked for numerical stability or other reasons that have little justification in terms expected physical processes or actual laboratory measurement. These principally include the existence and characteristics of the DDZ and the requirement of a characteristic averaging length near the cavity wall necessary for tensile failure to occur. Probably the largest effect on prediction error will be the uncertainty associated with the input parameters to the model, most notably the waste properties.

All of these uncertainties will affect the predicted spallings volume. Some limited sensitivity analyses have been carried out at the panel's request to look at the effect of DDZ parameters and tensile stress averaging length on predicted spall volumes. These analyses suggest that, even though these parameters do affect the volumes, the effect is probably small.

The largest uncertainty will be associated with assumed material parameters of the waste that serve as input to the model. These include tensile strength, porosity, permeability, particle size, and so on. Extensive laboratory measurements of these parameters were carried out on simulated waste material under predicted in situ conditions. The uncertainty in these parameters is associated with the uncertainty in how they may be modified by degradation over time in the in situ environment. This cannot be predicted with any degree of certainty. Therefore, one must make a reasonable estimate of the possible range of these parameters and look at the variability of the model output due to this range of input.

The panel concluded that the range of waste material properties used is reasonable based on the current understanding of these parameters and how they may change in time under in situ conditions.

Based on these arguments, the panel concluded that the combined uncertainty in the model, implementation, and input will necessarily lead to some level of model prediction error. This error, however, is expected to be small and acceptable within the context of best practices.

9.3.1.3.5.5.5 Appropriateness and Limitations of Method and Procedures

Based primarily on the previous four criteria, the panel concluded that the methods and procedures used by SNL to develop and present the spallings model are acceptable and reasonably represent future repository performance.

9.3.1.3.5.5.6 Adequacy of Application

The peer review panel found the new spallings conceptual model to be adequate. The model structure is technically sound in mathematical formulation and numerical implementation. The panel also found that the model reasonably approximates the expected WIPP disposal system performance. The panel's assessment did not address the relationships among conceptual models in detail, but rather whether the significant components of the spallings conceptual model are appropriately implemented in support of PA. For example, the various geometrical systems and representations of the conceptual model appear to be adequately applied within the performance modeling system, with no significant inconsistencies in the application of the conceptual model to model the WIPP waste disposal system.

9.3.1.3.5.5.7 Accuracy of Calculations

The results yielded using the Spallings conceptual model appear reliable and reasonably accurate to adequately simulate the physical processes of the WIPP waste disposal system.

9.3.1.3.5.5.8 Validity of Conclusions

There are no specific conclusions drawn, with respect to the Spallings conceptual model, other than its ability to characterize appropriate properties, processes, and features of the repository during a potential spallings event. The panel concludes that the Spallings conceptual model reasonably represents future repository performance.

9.3.1.3.5.5.9 Adequacy for Implementation

The WIPP conceptual models, as interpreted through the various codes, are ultimately integrated at the CCDFGF where results are prepared. The integration of the conceptual models, therefore, identifies the overall WIPP PA model as a complex structure that represents 24 conceptual models through preparatory, process, flow and transport, presentation, and enabling codes.

Applying evaluation criteria to the integration of a given conceptual model, as a step in the assessment of model adequacy, results in most of the discussion focusing on the review criteria discussed in Section 9.3.1.3.5.4. For example, evaluation of information used in the integration, assumptions, uncertainties, adequacies, accuracy, and validity are all based on the conceptual model, or the implementing mathematical representation or code, being evaluated.

Because a total and complete system PA was not available for the panel to review, the overall adequacy for implementation of the spallings model integrated with the other conceptual models can only be judged at this time relative to the criteria discussed earlier in this section. Based on the review of the Spallings conceptual model, the supporting assumptions, and mathematical

implementation, integration of this conceptual model with the other conceptual models is expected to be adequate.

Thus, the panel applied the stringent assessment criteria provided in NUREG-1297, Peer Review of High-Level Nuclear Waste Repositories, and concluded:

- The new Spallings conceptual model appears generally sound in its structure and reasonableness.
- The proposed implementation of the new Spallings model appears reasonable.

9.3.2 Waste Characterization Analysis Peer Review

40 CFR § 194.27(a)(2) states that a compliance application shall include documentation of peer review conducted for "waste characterization analyses as required in § 194.24(b)." 40 CFR § 194.24 (b) states:

> The Department shall submit in the compliance certification application the results of an analysis which substantiates:
>
> (1) That all waste characteristics influencing containment of waste in the disposal system have been identified and assessed for their impact on disposal system performance. The characteristics to be analyzed shall include, but shall not be limited to: solubility; formation of colloidal suspensions containing radionuclides; production of gas from the waste; shear strength; compactability; and other waste-related inputs into the computer models that are used in the performance assessment.
>
> (2) That all waste components influencing the waste characteristics identified in paragraph (b)(1) of this section have been identified and assessed for their impact on disposal system performance. The components to be analyzed shall include, but shall not be limited to: metals; cellulosics; chelating agents; water and other liquids; and activity in curies of each isotope of the radionuclides present.
>
> (3) Any decision to exclude consideration of any waste characteristic or waste component because such characteristic or component is not expected to significantly influence the containment of the waste in the disposal system.

A Waste Characterization Peer Review (WCPR) Plan (see CCA Appendix PEER) was prepared and approved in accordance with the requirements of TP 10.5. The DOE convened a four-member peer review panel, in accordance with the guidance of NUREG-1297, to perform the review. The panel members were:

- Duane C. Hrncir (Panel Chairman), University of Texas, Dallas;
- Evaristo J. Bonano, Beta Corporation International;
- James F. Bresson, Informatics Corporation; and
- Patricia J. Robinson, Energy, Inc.

See CCA Appendix PEER for the qualifications of the panel.

9.3.2.1 General Results

The following excerpts are from the WCPR report (CCA Appendix PEER). They address areas that the panel considered adequate.

- Radionuclide Inventory and Release Limits. The analysis performed in estimating the parameters needed to establish the radionuclide inventory and release limits for estimating the CCDF was very thorough and systematic. This is a solid piece of work.
- Solubility. The median values for actinide solubility are reasonable.
- Colloids. The experiments dealing with colloids in the repository were well done.
- Production of Gas. (Appendix WCA) adequately identifies the major issues of gas generation in the waste.
- Permeability. There are experimental data to support the conclusions about permeability discussed in (Appendix WCA). The panel concurs with the conclusions.
- Heat Generation. The analyses presented in (Appendix WCA) concerning heat generation are well done. The conclusion that this characteristic will have a negligible effect on performance is justified.
- Metals. The assumption that low valent metals in the repository will maintain a reducing atmosphere in the repository is substantiated by experimental data.
- Cellulosics. Cellulosics will be microbially degraded to carbon dioxide and CH_4. They also may provide a source of humic colloids. Treatment of these issues by (Appendix WCA) has been discussed in the appropriate sections above.
- Water and Other Liquids. The panel agrees with the findings in (Appendix WCA). Water in the waste is not an issue in repository performance.
- Exclusion of Waste. (1) The analysis performed to support the exclusion of radionuclides is methodical, complete and well done. (2) The exclusion of hazardous wastes is justified.

9.3.2.2 Waste Characterization Peer Review Panel Concerns

The WCPR panel concluded that several areas they examined were inadequate. The WCPR panel's concerns, the DOE's response to the panel's concerns, and the panel's responses are briefly described below. For details of the DOE and the panel's interactions, see CCA Appendix PEER.

9.3.2.2.1 Peer Review Panel Concern – Radionuclide Inventory and Release Limits

> The analysis used to determine the heterogeneous source term for the intrusion scenario was not clearly presented in CCA Appendix WCA, resulting in an inability to judge its validity and degree of conservation.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.2 Peer Review Panel Concern – Solubility; First Concern

> The median values for actinide solubility are reasonable, but the uncertainty ranges about the median are too low and inconsistent with earlier results from the expert judgment panel study.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.3 Peer Review Panel Concern – Solubility; Second Concern

> The issue of actinide solubility is not adequately addressed in CCA Appendix WCA because the controlling assumption concerning MgO chemistry in the repository has no experimental data to support it.

After consideration of the DOE response, the panel concluded that the DOE understood the issues; however, the panel determined that the response did not reasonably address their concern. See CCA Section 9.3.2.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.2.2.4 Peer Review Panel Concern – Colloids

> The uncertainty given for the colloid actinide source term is not adequate for purposes of PA calculations because the number of experiments performed does not generate meaningful statistical samples from which an uncertainty could be adequately calculated.

After consideration of the DOE response, the panel concluded that the DOE understood the issues and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.5 Peer Review Panel Concern – Production of Gas; First Concern

> The issue of the reaction of carbon dioxide with the MgO backfill is not adequately resolved in CCA Appendix WCA, because of a lack of experimental data which demonstrated that this chemistry occurs under conditions anticipated in the repository.

After consideration of the DOE response, the panel concluded that the DOE understood the issue; however, the panel concluded that the response did not reasonably address their concern. See CCA Section 9.3.2.2 for details of the DOE response, including the discussion "Department of Energy Technical Position versus Panel Issue."

9.3.2.2.6 Peer Review Panel Concerns – Production of Gas; Second and Third Concerns

> CCA Appendix WCA does not adequately address the fate of microbially generated CH_4.

> The treatment of gas generation in CCA Appendix WCA is generally well done. However, the Appendix does not deal with the disposition of the generated CH_4. The gas

> will be produced on a mole per mole basis with carbon dioxide and yet there is no mention of its fate in the repository.

After consideration of the DOE response, the panel concluded that the DOE understood the issues and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.7 Peer Review Panel Concern – Compressibility

> Appendix WCA references studies describing the analysis of waste compressibility; however, it fails to provide any discussion of the results of these studies.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.8 Peer Review Panel Concern – Strength

> CCA Appendix WCA references a study on waste strength, but fails to discuss the results of this study in the context of its impact on disposal system performance.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.9 Peer Review Panel Concern – Porosity

> There are conflicting statements in CCA Appendix WCA concerning the importance of porosity to the performance of the repository. As a result, the panel was unable to evaluate the treatment of this parameter.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.10 Peer Review Panel Concern – Metals

> The position taken in CCA Appendix WCA concerning the uptake of organic ligands by the transition metals is not defensible due to lack of experimental data. It is not correct to apply results from experiments performed in low ionic strength solutions to WIPP brines.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.2.2.11 Peer Review Panel Concern – Chelating Agents

> The position that transition metals will react with the organic ligands in the waste to render them unavailable for reaction with actinides should be justified with experiments done in high ionic strength brines.

After consideration of the DOE response, the panel concluded that the DOE understood the issue and provided a reasonable response. See CCA Section 9.3.2.2 for details of the DOE response.

9.3.3 Engineered Alternatives Cost/Benefit Study Peer Review

Per the criteria of 40 CFR § 194.27(a)(3), a compliance application shall include documentation of a peer review that was conducted for "(e)ngineered barrier evaluation as required in §194.44." 40 CFR § 194.44(b) states

> In selecting any engineered barrier (s) for the disposal system, the Department shall evaluate the benefit and detriment of engineered barrier alternatives, including but not limited to: Cementation, shredding, supercompaction, incineration, vitrification, improved waste canisters, grout and bentonite backfill, melting of metals, alternative configurations of waste placement in the disposal system, and alternative disposal system dimensions. The results of this evaluation shall be included in any compliance application and shall be used to justify the selection and rejection of each engineered barrier evaluated.

In September 1989, DOE established the Engineered Alternatives Task Force (EATF) to identify and screen potential engineered alternatives (EAs) with respect to both effectiveness and feasibility of implementation in addressing concerns about gas generation and human intrusion. EAs are engineered barriers, waste modifications, facility modifications, process changes, or any other approach that enhances disposal system performance or reduces uncertainty in the predictions of disposal system performance.

The EATF, in turn, chartered an Engineered Alternatives Multidisciplinary Panel that qualitatively screened an initial 64 alternatives to 36. The EATF then combined these candidates into 14 logically consistent and potentially actionable EAs. These 14 candidates, plus a base case, were evaluated with respect to relative effectiveness and feasibility in addressing gas generation and inadvertent human intrusion impacts. The EATF issued its final report in July 1991 (DOE 1991). A subsequent peer review of the EATF Report is documented below (Section 9.4.4).

The DOE prepared the Engineered Alternatives Cost/Benefit Study (EACBS) Final Report (DOE 1995b and CCA Appendix BARRIERS, Attachment EBS) in 1995. The EACBS Report includes a qualitative assessment of estimated costs, potential risks and benefits, and relative repository performance impacts resulting from the implementation of EAs .

The EACBS differs from the 1991 EATF in two fundamental ways. First, in the EACBS, EAs are assessed against 8 factors specified in 40 CFR § 194.44(c)(1) that provide the data and information for use in selecting or rejecting an EA. The eight factors are:

1. Long-term repository performance,
2. Uncertainty in compliance assessment,
3. Impact on public and worker exposure,
4. Impact on waste removal,
5. Transportation risk,
6. Public confidence,

7. Impact on system cost and schedule, and

8. Impact on other disposal systems.

Second, the 1991 EATF study was aimed at identifying alternatives which, if needed, would improve disposal system performance to the point where compliance with quantifiable standards was achieved. The EACBS begins with the assumption that compliance is achieved and the comparison of alternatives is to assist future decision making should a need for additional EAs be identified.

An EACBS Peer Review Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of TP 10.5. The plan describes the peer review process used to ensure a sound technical basis for the selection or rejection of EAs should it be determined that additional engineered barriers are needed to satisfy the requirements of 40 CFR Part 191 Subparts B and C.

An independent peer review committee was assembled by the Waste-Management Education and Research Consortium (WERC) to provide the DOE with a review of the EACBS Final Report. The peer review was conducted in 1996, in a manner consistent with NUREG-1297 (NRC 1988) guidance and the requirements of TP 10.5 (DOE 1996c).

The purpose of the EACBS peer review was to assess the validity of the assumptions and the technical approach used in the EACBS and evaluate the adequacy of the work. The peer panel review focused on determining the reasonableness of the report's conclusions.

In accordance with the provisions of TP 10.5, a panel was selected. The nine-member panel was composed of the following individuals:

- Rohinton K. Bhada (Chairman), New Mexico State University;
- Catherine T. Aimone-Martin, New Mexico Institute of Mining and Technology;
- Arturo Duran, Environmental Consulting and Engineering;
- Douglass J. Kuhns, Lockheed-Martin Idaho Technologies Corporation;
- Cindy R. Lewis, Parsons Engineering Science, Inc.;
- James D. Navratil, Rust Federal Services;
- Jamal Rostami, Earth Mechanics Institute;
- Dennis M. Smith, Technical & Management Systems and Services, Inc.; and
- Krishan K. Wahi, Geological Repository Assessment Methodologies, Inc.

See CCA Chapter 9, Section 9.3.3, for the panel members' qualifications and other details regarding the EACB peer review.

Panel members have established academic qualifications, as well as substantial relevant experience, and are independent of the WIPP project. Additional information regarding the technical qualifications of the panel members is provided in the final peer review report (see CCA Appendix PEER). A letter from the Peer Review Manager regarding the verification of independence for panel members is also presented in CCA Appendix PEER (additional information regarding the independence of the panelists is available in the CBFO Record Center.) All technical disciplines needed to perform the review were represented.

After orientation and training, as required by TP 10.5, the panel was briefed by the EACBS report authors and DOE staff. To review the large amount of information provided in the EACBS and supporting documentation, the peer panel divided itself into three subcommittees to address specific factors of the study. The subcommittees were formed on the basis of the expertise that was most appropriate for each set of factors. Eventually, all subcommittee findings were reviewed by the entire panel.

9.3.3.1 General Results

Following its review, the panel prepared a final report on July 10, 1996. The results of the EACBS peer review evaluation are summarized in Table 9-2 and a copy of the complete report is provided in CCA Appendix PEER. The following conclusions are presented in the final report:

- the information presented within the EACBS is of high quality,
- the approach taken is valid,
- the conclusions drawn are reasonable, and
- the analysis was conducted in accordance with 40 CFR § 194.44 criteria.

The EACBS panel report also identifies several findings/concerns/issues. The DOE developed a response to the issues identified in the panel report. The panel's concerns and the DOE responses are discussed in the following sections.

9.3.3.2 Engineered Alternatives Cost/Benefit Study Peer Review Panel Concerns

The DOE conducted an evaluation to assess the relative benefit and associated cost of various EAs for the disposal system. The analytical methodology and final results of the EACBS were critically reviewed for technical merit, adequacy, and accuracy of results by a team of outside experts.

Table 9-2. Summary of the Peer Review of the EACBS Evaluation Factors and Criteria

Engineered Alternatives Evaluation Factors	A. Adequacy of Requirements and Criteria	B. Validity of Assumptions	C. Alternative Interpretations	D. Uncertainty of Results and Consequences if Wrong	E. Appropriateness and Limitations of Methodology and Procedures	F. Adequacy of Application	G. Accuracy of Calculations	H. Validity of Conclusions
Evaluation of the EA Screening Process	Generally considered to be adequate, although some other potential EAs could have been added.	Evaluation was qualitative and was to assess assurance, not compliance. This assumption was prescribed by law and was therefore considered valid.	None.	The screening process was conservative in nature and was thus more inclusive than exclusive.	The screening process was considered to be appropriate. A better description of the process would have enhanced the report.	The sequence of comparing, scoring, prioritizing, etc. was adequate to achieve the results.	The use of algorithms and professional judgement were deemed appropriate.	The final list of EAs selected for further analysis was reasonable.
1. Long Term Repository Performance	Adequate	Broad Level: Appropriate. Detailed Level: Intrusion scenarios assumed to occur at 5,000 years; and actinide solubility assumptions were conservative. Broad Level: Appropriate; Detailed Level: Uncertainty in creep parameters was not considered. Differences in creep closure estimates could affect the quantity and rates of release; early intrusion could result in significantly different releases; and EAs with plasma processing or clay backfill were not credited with enhanced Pu immobilization.	Different creep closure models or model coefficients may affect the relative benefits of EAs; and the effects of future mining nearby could have been considered as an additional human intrusion scenario.	Uncertainty will result due to the uncertainty of input parameters; however, no severe consequences if wrong; conservative parameter estimates were used.	Use of the Design Analysis Model (DAM) model to predict performance was appropriate; however, important advances in creep modeling were not used. Model did not (and cannot) consider stratigraphy (e.g., anhydrite layers) in the mechanical response calculations.	Compressive strengths of waste/backfill EAs is misleading; and intrusion before creep closure not adequately analyzed.	Creep rate calculations checked and qualitatively agree.	Effectiveness of some EAs may have been under-estimated due to simultaneous consideration of pre-closure and post-closure risks.

Table 9-2. Summary of the Peer Review of the EACBS Evaluation Factors and Criteria — Continued

Engineered Alternatives Evaluation Factors	A. Adequacy of Requirements and Criteria	B. Validity of Assumptions	C. Alternative Interpretations	D. Uncertainty of Results and Consequences if Wrong	E. Appropriateness and Limitations of Methodology and Procedures	F. Adequacy of Application	G. Accuracy of Calculations	H. Validity of Conclusions
2. Uncertainty in Compliance Assessment				Relative nature of analysis allows meaningful conclusions to be drawn. Discussion of uncertainty in the results does not fully reflect the uncertainty analysis that was in fact carried out.		Methods used are completely applicable for comparative screening process		
3. Worker and Public Risk	Adequate	Risk assumptions are conservative, conventional, and adequate for the work performed.	None.	Uncertainties err on the side of safety and risks are likely overstated.	Methodology did not account for risks inherent in current waste handling methods. For example, relative risks could have been different for these EAs having long development/ processing time.	Methods are applicable for the comparative screening process.	Calculations are reasonable and consistent.	Risk conclusions for CH-TRU waste appear valid. Risk conclusions for RH-TRU waste are absent.
4. Impact on Waste Removal	200-year period for waste removal requires justification; different time frames have a major impact on the methods used for retrieval.	Assumed excavation technology is appropriate, but the data used in the calculations is not state of the art. For long term retrieval, assumptions and methodology used for mining rate and time estimates are correct; quantitative studies are needed. Short-term retrieval method, rate, and schedule not	Alternative methods for recovery based on different time frames could have been performed.	Uncertainty associated with the compressive strength of the EAs is not critical to the relative comparison of EAs. The waste is removable with today's technology and the decisions made based on the EACBS are not irreversible.	Methodology was appropriate to estimate time required for long-term removal; however, some of the assumptions, data, and terminology were not suitable for the application.	Time of waste removal was not adequately addressed.	Overall, calculations could not be checked for accuracy; there is no reference to machine type, specifications, and utilization.	Although the quantitative results of the analysis can not be directly used for assessment of the EAs, the general conclusions based on a qualitative comparison with the baseline are valid and

Table 9-2. Summary of the Peer Review of the EACBS Evaluation Factors and Criteria — Continued

Engineered Alternatives Evaluation Factors	A. Adequacy of Requirements and Criteria	B. Validity of Assumptions	C. Alternative Interpretations	D. Uncertainty of Results and Consequences if Wrong	E. Appropriateness and Limitations of Methodology and Procedures	F. Adequacy of Application	G. Accuracy of Calculations	H. Validity of Conclusions
		addressed.						acceptable for long-term removal. Consideration of short-term removal could change the results.
5. Transportation Risk	Adequate	Risk analysis assumes 20 year active life, yet the WIPP operational window is for 33 to 35 years. Transportation is by truck only; no explanation why rail is not evaluated. Overall, however, risk assumptions are conservative, reasonable and well within contemporary transportation risk analysis.	There is no reasonable alternative interpretation.	Population densities will be different if the period of transportation and disposal is greater than 20 years. An added risk could occur for those EAs that have a longer time frame.	The methodologies were considered to be generally appropriate. Limitations include addressing only CH-TRU waste, a "bounding" accident not being evaluated, and lack of justification for selected values. The limitations should not compromise the EA evaluation so long as the 20 versus 35 year issue is recognized.	Methods used are applicable for comparative screening process.	Calculations appear to be reasonable and consistent with the methodology.	The conclusions drawn for purposes of a qualitative comparison of the transportation risks of the various EAs appears valid.
6. Public Confidence in the Performance of the Disposal System	Adequate	Assumptions regarding the public's concerns as to content, categorization, timeliness, and affected in-state population are	Slightly different interpretations are possible, but would not affect the	Uncertainty is low regarding the public's position on the EAs and slight misinterpretations are not considered	The methodology used to assess public confidence was appropriate. A limitation is the lack of	Application of the methodology was considered proper.	Categorization of public comments was checked and determined to be relatively	The conclusions appear appropriate.

Table 9-2. Summary of the Peer Review of the EACBS Evaluation Factors and Criteria — Continued

Engineered Alternatives Evaluation Factors	A. Adequacy of Requirements and Criteria	B. Validity of Assumptions	C. Alternative Interpretations	D. Uncertainty of Results and Consequences if Wrong	E. Appropriateness and Limitations of Methodology and Procedures	F. Adequacy of Application	G. Accuracy of Calculations	H. Validity of Conclusions
		reasonable. Although out-of-state populations were not addressed, this is not considered to be a major deficiency.	conclusions of the study.	serious.	opportunity for out of state public comment.		accurate with only minor discrepancies.	
7. System Cost and Schedule	Adequate	Cost and schedule assumptions are considered to be valid with uncertainty of approximately 30 percent associated with the uncertainty of the waste inventories.	A few alternate interpretations may originate from the guidance documents. However, they would have little effect on the study's results.	The estimated costs and schedules were reasonable.	The methodology for cost and schedule evaluation is considered appropriate.	Methodologies were appropriately applied.	Spot checks determined that calculations were performed according to accepted methods and procedures.	In general, the conclusions are valid.
8. Impact on Other Disposal Systems	Adequate	The assumptions of waste type and volume have uncertainties associated with them that may impact other disposal systems. The assumptions used appear reasonable.	The uncertainties associated with waste volume can be interpreted in different ways. Some interpretations will result in higher volumes while others will result in lower volumes.	Uncertainty of results are +10 percent to 25 percent based on waste volume uncertainty. No serious negative consequences should occur because of this uncertainty.	Procedures used are technically defensible. A limitation of the methodology is the reliance on the accuracy of waste volume.	The techniques used were adequate to meet the intended goal.	The basis of calculations was not provided in the EACBS; however, using reasonable assumptions, data spot checks were found to be accurate.	The conclusions reached are valid and support the end use of the report.

The EACBS panel expressed several concerns regarding the EACBS. Details of the EACBS panel's concerns and the DOE's response to the panel's concerns (Response to Issue) are presented in CCA Appendix PEER and CCA Section 9.3.3.2. The panel was asked to review the DOE responses and determine whether they agreed with the responses. The panel's reaction to the responses are also provided in CCA Appendix PEER (Peer Reviewer Consideration of Response). In those instances where panel members disagreed, from a technical-based perspective, with the DOE response, the DOE developed additional information that describes the justification for its final technical position on the concern (DOE Technical Position versus Panel Issue). A summary of the panel's concerns and the panel's reaction to the DOE responses are provided below. For details, see CCA Appendix PEER.

9.3.3.2.1 First Peer Review Panel Concern – Results of the Engineered Alternatives Identification/Screening Process

> Clarification is needed in the text of the report on the steps involved in the identification/screening process, including steps that occurred after the Engineered Alternatives Task Force performed their initial evaluation. Better define what is meant by "screening," "optimization," and "prioritization." Clearly state the criteria used for each stage of the process.

The DOE stated that it understood the confusion surrounding these terms, particularly in light of the multiplicity of the agencies and organizations that have expressed interest in how EAs should be applied to the WIPP. In this application, DOE had attempted to use these terms in a fashion consistent with the EPA's usage in 40 CFR Part 194 and the Compliance Application Guidance (CAG) (EPA 1996c). The three processes are documented in the EACBS. The specifics of the screening process and original prioritization are found in Appendix D. The optimization process is briefly described in Appendix D; this process included management decisions not defined in the report.

Four panel members commented on the DOE response to this concern. Two members agreed with the response and one disagreed. The fourth panelist, although agreeing that the information in the response was adequate, believed this information should be provided in the main part of the EACBS.

The DOE has clarified the process in Section 7.4.3.1 of the CCA, which includes a description of the DOE Management Assessment used to determine the final 18 EA used in the analysis.

9.3.3.2.2 Second Peer Review Panel Concern – Results of the Engineered Alternatives Identification/Screening Process

> Some concern was expressed that the screening process was conducted independent of a consideration of the eight factors used in evaluating the EAs. If the screening process and evaluation of EAs according to the eight factors had been iterative, the list of EAs analyzed as well as the results of both the screening process and the evaluation of the EAs may have been different. However, this would probably be an endless process of iterations and not justified because of cost and time involved.

In response, the DOE stated that to ensure a reasonable menu of alternatives for potential selection of engineered barriers, the DOE elected to separate the screening process from the actual factor analyses. The key screening criteria to select EAs for detailed factor analysis was therefore the impact on improving long-term performance, with additional concern given to technological and regulatory feasibility of implementation. The selected alternatives were then evaluated with respect to the eight factors. Factors such as waste retrieval or public perception were not considered in the selection criteria because these factors are not related to compliance with 40 CFR Part 191 Subparts B and C.

Three panel members commented on the response. One panelist agreed with the response as written and one other disagreed. The third commenter agreed with the response but believed that the DOE should make a stronger case that the EACBS considered the breadth of plausible alternatives.

The DOE's technical position is that the DOE developed a screening process that used a qualitative assessment of the potential benefits on the WIPP disposal system. Good engineering practices were used in this assessment. A pure quantitative rating could not be justified because it would require a complete analysis of each EA by all eight factors. The intent of the screening process was to identify EAs with the highest potential to benefit the disposal system and further analyze their impacts within the multifactor analysis.

9.3.3.2.3 Third Peer Review Panel Concern – Results of the Engineered Alternatives Identification/Screening Process

> Remote-handled waste was not considered. This issue may have implications to the compliance application.

In response, the DOE stated that RH-TRU waste constitutes a maximum of five percent of the inventory by volume. This material is practically identical to CH-TRU waste except that it is contaminated with short-lived beta-gamma emitters, as well as the long-lived actinides present in CH-TRU waste. There is therefore no need to consider RH-TRU waste separately from a long-term performance standpoint. There may have been some differences in the treatment costs for the RH-TRU fraction because of the possible need for a greater degree of shielding, and there may have been additional worker risks involved because of the penetrating radiation. The Engineered Alternatives Screening Working Group concluded, therefore, that the limited volume of RH-TRU waste did not justify separate consideration of this small fraction of the inventory.

The only panel member who commented on the response agreed, in part, with the response; however, the panelist suggested that, for completeness, a factor approach be used that could weigh the risk and cost of handling RH-TRU waste into each EA under evaluation.

The DOE's position is that because the RH-TRU waste is a small percentage of the total WIPP waste inventory, is limited by the Land Withdrawal Area, and will decay to CH-TRU waste levels in a relatively short time, the DOE believes that RH-TRU wastes need not be considered separately in the EACBS.

9.3.3.2.4 Peer Review Concern – Evaluation of Factors 1 and 2: Impacts on Long-Term Repository Performance and Uncertainty in Compliance Assessment

These factors focused primarily on the analyses performed with the DAM computer simulation program. This program was used to predict the future performance of the repository with different EAs given three different human intrusion scenarios. Values for several parameters are required as input to the model. Many input parameters were treated as being uncertain; that is, ranges and distributions were assigned to such parameters. Other parameters were given constant (single point) values. The panel members checked many of these parameters, as well as QA documentation for the computer simulation itself. No major discrepancies or errors were noted. It was noted by the panel members that much of the information used in the model was selected to be consistent with the PA conducted by SNL. The DAM was chosen to determine relative repository performance because it parallels SNL's PA work in a less complex manner, allowing various changes to the inputs to be run quickly on a PC format. For details on a number of subissues under this category, see CCA Chapter 9.0 and CCA Appendix PEER.

9.3.3.2.5 First Peer Review Panel Concern – Evaluation of Factor 3: Impact of Engineered Alternatives on Worker and Public Risk

> An evaluation of the risks associated with the processing of remote-handled (RH) waste is absent. It would be helpful to include a discussion of the possible relative comparison between the risk associated with CH and RH wastes. For example, one can draw conclusions based on radionuclide difference, radionuclide mobility, potential for release, transport mechanisms, and exposure scenarios associated with both waste processing and long-term performance.

The DOE responded that the inventory of RH-TRU waste was combined with the CH-TRU waste and was not considered separately in the EACBS. RH-TRU waste is limited by statute to comprise no more than five percent by volume of the total WIPP waste inventory. This material is practically identical to CH-TRU waste, except that it is contaminated with short-lived beta-gamma emitters as well as the long-lived actinides present in CH-TRU waste. These beta-gamma emitters will rapidly decay in the 100-year postclosure period during active institutional control. Therefore, there is no need to consider RH-TRU waste separately from a long-term performance standpoint.

The only panel member who commented on this response partially agreed with the DOE response. That panelist made the same comment as for the RH-TRU waste concern discussed in Section 9.3.3.2.3.

The DOE's position is that because the inventory of RH-TRU wastes is a small percentage of the total WIPP waste inventory, is limited by the Land Withdrawal Area, and will decay to CH-TRU waste levels in a relatively short time period, the DOE believes that RH-TRU wastes need not be considered separately in the EACBS.

9.3.3.2.6 Second Peer Review Panel Concern – Evaluation of Factor 3: Impact of Engineered Alternatives on Worker and Public Risk

> Many of the assumptions used in assessing worker and public risk appear to be borrowed from the Environmental Management Programmatic Environmental Impact Statement (EMPEIS). While these assumptions may be valid, additional discussion of them in the text of the EACBS would provide further clarification.

The DOE responded that many of the assumptions and initial analysis parameter values were, as the panel has noted, taken from the EMPEIS. This consistency was important to keep the EACBS risk analysis consistent with important aspects of other related DOE risk evaluations nationwide. The entire suite of WIPP National Environmental Policy Act (NEPA) documents is available for review in several locations. The DOE did not see the need to discuss these assumptions in any greater detail within the EACBS.

The only panel member who commented on this response agreed with the DOE response.

9.3.3.2.7 Third Peer Review Panel Concern – Evaluation of Factor 3: Impact of Engineered Alternatives on Worker and Public Risk

> Additional risks posed by allowing the waste to remain above ground for longer time periods necessitated by some of the EAs were not evaluated. This could underestimate risks associated with those EAs.

The DOE responded that the purpose of the EACBS study was to determine relative risks from various TRU waste processing and disposal alternatives, and did not directly include waste storage impacts, as noted. It is true that in some cases waste would be stored aboveground for a longer time for some of the EAs, particularly when a given treatment process has not yet been fully developed for TRU waste. However, ultimately, a long-term disposal decision would be needed. The scope of the EACBS was to look at alternatives to support the disposal decision. It is assumed that the waste containers would be stored for an additional time period within the expected lifetime of the container, and therefore no repackaging related risks would be included. It is further assumed that workers will continue to limit their exposure to stored waste containers in accordance with the as low as reasonably achievable (ALARA) policy. Therefore, the loss of resolution did not affect the DOE decisions in important ways.

The only panel member who commented on this response agreed with the DOE response.

9.3.3.2.8 Peer Review Panel Concern – Evaluation of Factor 4: Waste Removal Impact

The evaluation of Factor 4 was conducted in the context of 40 CFR § 194.44, assuming that the removal of the emplaced waste and backfill (after the regulatory closure) is possible. The factor considers the impact of EAs on waste removal after 200 years with no justification. The methodology used and the conclusions made based on a qualitative comparison using the volume and the time required for removal were acceptable to the panel. However, the panel made some comments with respect to this factor. See CCA Appendix PEER for the details of these comments and their resolution.

9.3.3.2.9 Peer Review Panel Concern – Evaluation of Factor 5: Impact of Engineered Alternatives on Transportation Risk

A number of procedural-type questions were raised by the panel related to the impact of EAs on transportation risk. DOE provided satisfactory explanations for these questions and no outstanding issues remained. See CCA Chapter 9 and CCA Appendix PEER for details.

9.3.3.2.10 Evaluation of Factor 6: Impact of Engineered Alternatives on Public Confidence

The peer review panel did not find any particular areas of concern with the public confidence evaluation, and felt that the methods used and conclusions reached were appropriate and reasonable. There are no specific comments or areas of concern in need of response.

9.3.3.2.11 Evaluation of Factor 7: Total System Cost and Schedule Estimates

The peer review panel found no significant flaws in the cost and schedule analysis. The panel agreed that the development of cost and schedule estimates was reasonable, appropriate, and defensible. There were no specific comments or areas of concern in need of response for this factor.

9.3.3.2.12 Peer Review Panel Concern – Evaluation of Factor 8: Impact on Other Waste Disposal Programs

The peer review panel concluded that the analysis for impacts to other waste disposal programs was conducted using the best available information. However, they felt that the evaluation should be updated as more recent and accurate data become available to ensure adequate facilities and resources are available for disposal. DOE provided additional details that satisfied the panel. See CCA Chapter 9 and CCA Appendix PEER.

9.3.4 Engineered Systems Data Qualification Peer Review

An Engineered Systems Peer Review (ESPR) Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of TP 10.5. The plan describes the peer review process used to ensure that the data used in the models describing engineered systems for rock mechanics and shaft/borehole seals in the PA are qualified to demonstrate compliance.

The DOE used an Independent Review Team (IRT) to carefully review the existing data that was necessary to support the PA. Much of the existing data were qualified because the IRT determined that the QA program in place at the time of its collection was equivalent to American Society of Mechanical Engineers (ASME) nuclear quality assurance (NQA) requirements. It was determined, however, that some data used to describe engineered systems could not be qualified in that manner.

40 CFR § 194.22(b) states that:

> Any compliance application shall include information which demonstrates that data and information collected prior to the implementation of the quality assurance program required pursuant to paragraph (a)(1) of this section have been qualified in accordance with an alternate methodology, approved by the administrator or the administrator's authorized representative, that

> employs one or more of the following methods: peer review, conducted in a manner that is compatible with NUREG-1297....

The purpose of the ESPR was to seek qualification of scientific data by systematically reviewing parameters and subsystems used in the models describing engineered systems. The conceptual models used in the PA of the engineered systems include components of

- disposal room geometry,
- creep closure,
- repository fluid flow,
- shafts and shaft seals, and
- DRZ.

The review was conducted by four panel members. The panel members and their affiliation were

- Dermot Ross-Brown (Chairman), Independent Consultant;
- John Gibbons, Independent Consultant;
- Darrell Porter, Science Applications International Corporation; and
- John Schatz, Independent Consultant.

See CCA Chapter 9 and CCA Appendix PEER for details of the qualifications of the panel members.

The panel performed an in-depth critique of assumptions, alternate interpretations, methodology and acceptance criteria employed, and of conclusions in the original work. According to the "Description of Work Performed" in their final report, the panel members considered:

- sources of the parameters and data: for example, professional judgment, published source material, field tests, laboratory experiments, etc.;
- appropriateness of the parameters and data for their intended use; and
- assumptions, calculations, extrapolations interpretations, methods, appropriateness, validity, sensitivities, and conclusions pertinent to the parameters and data used as input to the WIPP PA.

The data considered by the panel supported the models describing engineered systems and were used to derive parameter values that are incorporated into the models. In some instances, parameters were consolidated into parameter groups.

Fourteen parameters (several of which were actually groups of closely related parameters) were evaluated by the panel. The panel qualified seven of the parameters and two of the parameter groups (properties of halite and anhydrite, and data on final porosity surface). In the panel's opinion, minor changes needed to be made to two of the parameters (pore volume compressibility of Salado Mass Concrete (SMC) and permeability of consolidated waste), and further analysis by SNL was needed on two other of the parameter groups (permeability of crushed salt and the strength of the waste for spalling (blowout) releases. The panel concurred with SNL's general treatment of the remaining parameter (general treatment of the DRZ). Table 9-3 lists the parameters reviewed by the panel and summarizes the panel's conclusions regarding their adequacy.

Table 9-3. Summary of Qualification Status of Parameters, as a Result of the Engineered Systems Peer Review

Subsystem	Parameter Name	Qualification Status of Parameters
Shaft/shaft Seal	Porosity of SMC	Qualified
	Pore Volume Compressibility of SMC	Minor change to value suggested [1]
	Bulk Modulus of Crushed Salt	Qualified
	Permeability of Crushed Salt	Requires further analysis by SNL[1]
	Permeability of SMC	Qualified
	Permeability of Compacted Clay	Qualified
Disposal Room/Rock Mechanics	Initial Density of Waste	Qualified
	Mechanical Properties of Waste	Qualified
	Initial Water Content of Waste	Qualified
	Permeability of Consolidated Waste	Minor change to value suggested [1]
	Strength of Waste for "Blowout"	Insufficient data to qualify [1]
	Properties of Halite and Anhydrite	Qualified, based on limited review[2]
	Data on Final Porosity Surface	Qualified, based on limited review[2]
DRZ	Characterization of DRZ	Concepts qualified

[1] The panel subsequently determined, on the basis of additional input from DOE, that DOE responses had reasonably addressed their concerns.
[2] The panel chose to consider these parameters from an overview approach; however, the panel was able to qualify these parameters.

Initially, the ESPR panel failed to qualify four of the parameters (or parameter groups) they reviewed. Where appropriate, the DOE interpreted the ESPR panel's concern and in all four cases developed a WIPP project response. The ESPR panel's concerns (in italics), the DOE's interpretations of the panel's concerns (Statement of Issue), where appropriate, and their responses (Response to Issue) are provided below. The panel then reviewed the response to determine whether the DOE understood the issue and provided a reasonable response (Peer Reviewer Consideration of Response).

The DOE responses were provided to the panel as individual memoranda. For incorporation into this application, the responses were edited to remove the memorandum format, consolidate references, replace first-person text, insert cross-references where appropriate, and correct typographical errors. Substantive technical content of the responses was not changed.

Based on the additional information the DOE provided in response to the panel's concerns, the panel subsequently concluded that the DOE had reasonably addressed their concerns for all the parameters and parameter groups. The data used to derive the parameters and parameter groups that were reviewed by the ESPR panel were therefore qualified per 40 CFR § 194.22(b).

At the completion of the review, the panel prepared a documented summary of its work and an evaluation of the selected parameters reviewed by the panel. A copy of the Engineered Systems Data Qualification Peer Review Report, dated July 1996, is provided in CCA Appendix PEER. For detailed discussion of the panel's work and the interaction between the panel and the DOE technical staff, see CCA Chapter 9. Since the panel concluded that the DOE had reasonably addressed their concerns for all the parameters and parameter groups, the work of the panel is not further discussed here.

9.3.5 Natural Barriers Data Qualification Peer Review

The DOE used an IRT to carefully review the existing data that was necessary to support the PA. Much of the existing data was qualified because the IRT determined that the QA program in place at the time of its collection was equivalent to ASME NQA requirements. It was determined, however, that some data used to describe natural barrier subsystems could not be qualified in that manner.

A Natural Barriers Peer Review (NBPR) Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of TP 10.5. The purpose of the plan was to describe the NBPR process. The NBPR panel evaluated existing data and information that form the basis of the parameter values used in the mathematical expression of conceptual models for the natural barriers subsystems in the WIPP. The parameters selected for evaluation were those that had not previously been fully qualified for use in PA.

The conceptual models used in the PA of the natural barriers subsystem include components of: (1) disposal system geometry; (2) Culebra model geometry; (3) repository fluid flow; (4) Salado; (5) impure halite; (6) Salado interbeds; (7) DRZ; (8) actinide transport (Salado); (9) units above the Salado; (10) dissolved Actinides (Culebra); (11) colloidal actinides (Culebra); (12) exploration boreholes; (13) cuttings and cavings; (14) spallings; (15) DBR; (16) Castile and brine reservoir; (17) multiple intrusions; and (18) climate changes.

A peer review panel, consisting of the following six members, was convened to undertake the work:

- Darrel E. Dunn (Chairman), Independent Consultant;
- Florie Caporuscio, LANL;
- Paul L. Cloke, Independent Consultant;
- David A. Sommers, Independent Consultant;
- Charles Wilson, Independent Consultant; and

- Chuan-Mian Zhang, Woodward-Clyde Federal Services.

See CCA Chapter 9 and CCA Appendix PEER for details of the panel members' qualifications.

Upon completion of the orientation and training required by TP 10.5, the panel was provided 32 parameter packages for their review. In addition, technical reports and documents were obtained by the panel from the SNL waste management library and records center to supplement the information in the parameter packages. Both formal and informal technical discussions were held with SNL principal investigators to assist the panel members to more fully understand the concepts and parameter derivation and application in the PA.

The NBPR panel evaluated 142 parameters against the eight review criteria cited in NUREG-1297 (NRC 1988). The parameters were organized into 32 parameter packages, some of which contained more than one parameter. The parameter packages were grouped into three subsystems; Salado, Castile, and units above the Salado, to facilitate the review process.

In some subsystems, individual parameter values were evaluated and a determination made of their adequacy as used in the WIPP PA program. In others, sets of parameters were evaluated to determine their collective contribution to a combined parameter value. The panel performed an in-depth critique of assumptions, alternate interpretations, methodology and acceptance criteria employed, and the conclusions drawn in the original work. In evaluating the existing unqualified data, the peer review panel members considered the following:

- The source of the parameters and data (for example, professional judgment, published source material, field tests, laboratory experiments, etc.);
- The appropriateness of the parameters and data for their intended use; and
- The assumptions, calculations, extrapolations, interpretations, methods, appropriateness, validity, sensitivities, and conclusions pertinent to the parameters and data used as input to the WIPP PA.

At the conclusion of its review, the panel developed a final report (August 1996). A copy of the NBPR Report is provided in CCA Appendix PEER.

Table 9-4 provides a listing of the 32 parameter packages, the appropriate subsystem, the number of parameters in the specific packages, and the qualification status of each as determined by the peer review panel. The panel concluded that 31 of the parameter packages were fully qualified. Therefore, the data supporting those parameters are qualified per 40 CFR § 194.22(b). The panel had a concern about one of the 21 data packages for the Culebra transmissivity parameter at well P-18.

Table 9-4. Summary of Parameters Reviewed and Qualification Status

Parameter Package	Subsystem	Number of Parameters	Qualification of Parameter
DRZ Compressibility	Salado	2	Adequate
Undisturbed Halite Pore Pressure		1	Adequate
Undisturbed Halite Compressibility		1	Adequate
Effective Halite Porosity		1	Adequate
Undisturbed Halite Permeability		3	Adequate
Undisturbed Anhydrite Pressure		2	Adequate
Undisturbed Anhydrite Rock Compressibility		3	Adequate
Brine Salt Mass Fraction		1	Adequate
Brine Viscosity		1	Adequate
Brine Density		1	Adequate
Brine Compressibility		1	Adequate
Castile Brine Reservoir Rock Compressibility	Castile	1	Adequate
Castile Brine Reservoir Porosity		1	Adequate
Castile Brine Reservoir Pressure		1	Adequate
Castile Brine Reservoir Permeability		3	Adequate
Castile Brine Reservoir Volume		1	Adequate
Non-Salado Effective Porosity	Units Above the Salado	6	Adequate
Non-Salado Pressure		4	Adequate
Non-Salado Permeability		6	Adequate
Culebra Permeability		3	Adequate
Climate Index		1	Adequate
Culebra Transmissivity Data		100 Values	Adequate[1]
Culebra Thickness		1	Adequate
Culebra Storativity		1	Adequate
Culebra Fluid Density		32 Values	Adequate
Culebra Steady-State Freshwater Heads		31 Values	Adequate
Culebra Dolomite Grain Density		1	Adequate
Effective Culebra Thickness		1	Adequate
Advective Porosity		1	Adequate
Half Matrix Block Length		1	Adequate
Diffusive (Matrix) Porosity		1	Adequate
Diffusive (Matrix) Tortuosity		1	Adequate

[1] One of the 21 data packages for the Culebra Transmissivity parameter was deemed inadequate.

The NBPR panel's concern (in italics), the DOE's interpretation of the panel's concern (Statement of Issue), and the DOE response (Response to Issue) are provided in CCA Appendix PEER. The panel then reviewed the response to determine whether the DOE understood the issue and provided a reasonable response (Peer Reviewer Consideration of Response). The justification for the DOE's continued use of the Well P-18 transmissivity value is also provided (DOE Technical Position versus Panel Issue) in CCA Appendix PEER and is reproduced below.

Regarding the transmissivity value selected for the well P-18, the DOE's technical position is that the appropriate transmissivity value was selected; however, whichever transmissivity value

is used (4.6×10^{-9} m^2 /s or 7.5×10^{-11} m^2 /s) (4.3×10^{-3} ft^2/day or 7×10^{-5} ft^2/day), the well P-18 data point does not substantially influence the critical migration pathways through the Culebra. This interpretation is supported by the panel in Table 1.1 of its report (CCA Appendix PEER), where the Culebra Transmissivity Data was determined to be adequate.

9.3.6 Waste Form and Disposal Room Data Qualification Peer Review

A Waste Form and Disposal Room (WFDR) Peer Review Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of TP 10.5. The plan describes the process used to plan and perform the review. The purpose of the peer review was ensure that the scientific data used in the models describing the waste form and the disposal room closure and chemistry are qualified for use in the WIPP PA.

The DOE used IRTs to carefully review the existing data necessary to support the PA. Many of the existing data were qualified because the QA program in place at the time of its collection was equivalent in effect to ASME NQA requirements. However, some of the data needed to support the waste form and disposal room models were not qualified by the IRTs.

In accordance with 40 CFR § 194.22 (b), a panel consisting of the following two members was selected to review data that had not been qualified by the IRTs:

- Duane C. Hrncir (Chairman), University of Texas at Dallas; and
- Robert D. Knecht, Colorado School of Mines.

Dr. Hrncir is an associate professor of chemistry and former head of the chemistry programs at the University of Texas at Dallas. He has 24 years of experience in research involving the interactions of metals with organic molecules.

Dr. Knecht is a research professor at the Colorado School of Mines and holds a Ph.D. in Chemical-Petroleum Refining Engineering and a Ph.D. in Metallurgical Engineering. He has provided management and technical assistance to a variety of energy, minerals, and waste industries and to government.

The panel members were both highly qualified to conduct this review and were independent of the WIPP PA program. Additional information concerning the qualifications of the panel members is provided in the peer review panel report (see CCA Appendix PEER). Documentation regarding the independence of the panel members is also provided in CCA Appendix PEER.

The panel received administrative orientation and training on the peer review plan, 40 CFR Parts 191 and 194, NUREG-1297, the QAPD, and TP 10.5. During the course of its work, the panel reviewed information packages provided by SNL for each parameter. In addition, technical reports, published literature, and internal documents supplemented information in the parameter packages. Discussions were held with SNL staff to more fully understand the concepts and parameter derivation.

The panel members evaluated existing data and information that form the basis of the parameter values used to mathematically express conceptual models for the waste form and disposal room subsystem. As discussed above, the parameters evaluated had not previously been fully qualified for use in PA. The conceptual models used in the PA of the waste form and disposal room subsystem include components of:

- Gas generation;
- Chemical conditions;
- Dissolved actinide source term; and
- Colloidal actinide source term.

The WFDR peer review panel evaluated 26 parameters against the eight NUREG-1297 review criteria. The parameters were solubilities of the actinides from the repository wastes in brines from the Salado and Castile.

The panel compared each calculated solubility parameter to those published in the peer-reviewed literature, when such data were available. To make this comparison, the panel considered compatibility of solvents, solution pH, and the absence of potentially ligating carbonate. The latter criterion is an imposed condition controlling the disposal room chemistry. When literature values were unavailable, the panel considered experimental data obtained from several different laboratories. In using these data, the panel evaluated the experimental approach to ascertain that the methods used for data acquisition and interpretation were consistent with recognized standards.

When experimental data were not available for particular parameters, the panel examined the method of calculation used to derive the value. The experimental data used as input to the calculation were evaluated and the validity of the calculation result was critiqued relative to similar calculated values where experimental data were available.

The panel members carefully reviewed each of the 26 parameters submitted for peer review. Based on their review, the panel prepared a final report in July 1996. A copy of the final report is provided in CCA Appendix PEER.

Table 9-5 provides a listing and status of the reviewed parameters. As shown in Table 9-5, the panel concluded that all 26 values were qualified for use in the WIPP PA of actinide solubility under repository conditions. Therefore, the data supporting these parameters are qualified per 40 CFR § 194.22(b).

9.3.7 Passive Institutional Controls Peer Review

40 CFR § 194.43 states that

> Any compliance application shall include detailed descriptions of the measure that will be employed to preserve knowledge about the location, design, and contents of the disposal system.

Table 9-5. Listing and Status of Reviewed Parameters

ID number	Species	Brine	Status
A. Inorganic Chemistry Controlled by $Mg(OH)_2/MgCO_3$			
WP037105	Am(III)	Salado	Qualified
WP037106	Am(III)	Castile	Qualified
WP037109	Pu(III)	Salado	Qualified
WP037108	Pu(III)	Castile	Qualified
WP037129	General An(III)	Salado	Qualified
WP037125	General An(III)	Castile	Qualified
WP037110	Pu(IV)	Salado	Qualified
WP037111	Pu(IV)	Castile	Qualified
WP037115	Th(IV)	Salado	Qualified
WP037112	U(IV)	Salado	Qualified
WP037130	General An(IV)	Salado	Qualified
WP037126	General An(IV)	Castile	Qualified
WP037131	General An(V)	Salado	Qualified
WP037127	General An(V)	Castile	Qualified
WP037113	U(VI)	Salado	Qualified
WP037114	U(VI)	Castile	Qualified
WP037132	General An(VI)	Salado	Qualified
WP037128	General An(VI)	Castile	Qualified
B. Organic Chemistry Controlled by $Mg(OH)_2/MgCO_3$			
WP037116	General An(III)	Salado	Qualified
WP037121	General An(III)	Castile	Qualified
WP037117	General An(IV)	Salado	Qualified
WP037122	General An(IV)	Castile	Qualified
WP037118	General An(V)	Salado	Qualified
WP037123	General An(V)	Castile	Qualified
WP037120	General An(VI)	Salado	Qualified
WP037124	General An(VI)	Castile	Qualified

A Passive Institutional Controls Peer Review Plan (see CCA Appendix PEER) was developed and approved in accordance with the requirements of TP 10.5. The plan describes the peer review process used to ensure that the passive institutional controls proposed by the DOE will reasonably preserve knowledge about the location, design, and contents of the WIPP disposal system and reduce the likelihood of inadvertent intrusion.

A three-member panel of experts was convened in May 1996 to conduct an independent peer review of the system of passive institutional controls designed by the DOE. The panel reviewed the findings of the Passive Institutional Controls Task Force (PTF), evaluating detailed

descriptions of the measures intended to preserve knowledge about the location, design, and contents of the WIPP disposal system. The evaluation determined whether the passive institutional controls are adequate and have a reasonable expectation of reducing the likelihood of inadvertent intrusion.

The panel members were:

- Jessica Glicken (Chairman), Ecological Planning and Toxicology, Inc.;
- Elizabeth K. Hocking, Argonne National Laboratory; and
- Paul R. La Pointe, Golder Associates.

The panel members were well-qualified for this review and independent of the WIPP PA program. Additional information concerning the qualifications of the panel members is presented in the panel report (see CCA Appendix PEER). Documentation of the panel member's independence from the WIPP project is also provided in CCA Appendix PEER.

After administrative orientation and training, the panel members familiarized themselves with regulations impacting radioactive waste disposal at the WIPP (40 CFR Parts 191 and 194) and requirements for the conduct of peer reviews (NUREG-1297 and TP 10.5). Following briefings by members of the PTF and other WIPP project staff, panel members were provided two documents that formed the basis of their peer review:

> Effectiveness of Passive Institutional Controls in Reducing Inadvertent Human Intrusion into the Waste Isolation Pilot Plant for Use in Performance Assessments (referred to as the Passive Institutional Controls Efficacy Report; see DOE (1996a, Appendix EPIC); and,
>
> Passive Institutional Controls Conceptual Design Report (referred to as the Conceptual Design Report (CDR); see DOE 1996a, Appendix PIC).

Supplemental information requested by the panel was also used in the evaluation.

The peer review panel evaluated the assumptions and results presented in the Passive Institutional Controls Efficacy Report. The panel's findings, as presented in their final report, dated July 1996, are provided below. A complete copy of the panel's report is provided in CCA Appendix PEER.

The panel identified several concerns during their review. The panel's concerns, the DOE's interpretation of the panel's concerns (Statement of Issue), the DOE's response to the panel's concerns ("Response to Issue"), and the panel's reaction to the interpretation and responses ("Peer Reviewer Consideration of Response") are provided in CCA Chapter 9. When the panel determined the response did not reasonably address their concerns, the DOE's justification for its position (DOE Technical Position versus Panel Issue) was provided (see CCA Chapter 9).

9.4 Peer Reviews Conducted in Addition to Those Required by 40 CFR Part 194.27(a)

40 CFR Part 194 states that

> Additionally, this section requires compliance applications to include documentation of any peer review activities that DOE may have conducted apart from those required by this rule, including those activities which are similar to peer review, such as the reviews conducted by the WIPP Panel of the National Academy of Sciences. (61 FR 5228)

and that

> Peer review which has been conducted prior to today's action must be documented in compliance applications.

Over the course of the WIPP endeavor, the project has undergone extensive review. The reviews included in this section of the CCA were conducted prior to implementing 40 CFR Part 194 and are briefly mentioned in this section. Additional reviews not specifically required by 40 CFR Part 194.27(a) and conducted after submitting the CCA are described in more detail in this section. They provide additional information to the peer reviews specifically stated in 40 CFR § 194.27(a). These reviews were evaluated against criteria developed from 40 CFR Parts 191 and 194 and NUREG-1297 to determine which ones were appropriate for incorporation in this application. The following criteria were used to screen the historical reviews:

1. Was the peer review relevant to this application?

   The purpose of this application is to demonstrate the WIPP's continued compliance with the disposal regulations found in 40 CFR Part 191. 40 CFR Part 194 provides significant detail concerning the necessary contents of the application. Reviews that cover subject matter pertinent to those contents are considered relevant to this application.

2. Was there a formal report by the reviewer?

   NUREG-1297 requires a peer review to be documented.

3. Was the review a peer review, rather than a technical review?

   NUREG-1297 states that

   > A peer review is an in-depth critique of the assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn from the original work. Peer reviews confirm the <u>adequacy</u> of work. In contrast to peer review, the term "technical review," as used in this GTP, refers to a review to verify compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.

4. Was the review a peer review, rather than an expert judgment?

   As discussed above, a peer review confirms the adequacy of the work being reviewed. 40 CFR Part 194 states that

   > Typically, expert judgment is used to elicit two types of information: (1) Numerical values for parameters (variables) which are measurable only by experiments that cannot be conducted due to limitations of time, money and physical situation; and (2) essentially unknowable information, such as which features should be incorporated into passive institutional controls that will deter human intrusion into the repository. (61 FR 5228)

5. Was the technical expertise of the reviewer at least that needed to perform the original work?

   NUREG-1297 states that

   > The technical qualifications of the peer reviewers, in their review area should be at least equivalent to that needed for the original work under review and should be the primary consideration in the selection of peer reviewers. Each peer reviewer should have recognized and verifiable technical credentials in the technical area he or she has been selected to cover. The technical qualifications of each peer, and hence of the peer review group as a whole, should relate to the importance of the subject matter to be reviewed.

6. Were the reviewers independent?

   A. Were they involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed?

   B. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?

   Regarding the reviewers' independence, NUREG-1297 states:

   > Members of the peer review group should be independent of the original work to be reviewed. Independence in this case means that the peer, a) was not involved as a participant, supervisor, technical reviewer or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to assure the work is impartially reviewed.
>
> Because of DOE's pervasive effort in the waste management area, the lack or unavailability of other technical expertise in certain areas, and the possibility of reducing the technical qualifications of the reviewers in order that total independence is maintained, it may not be possible to exclude all DOE or DOE contractor personnel from participating in a peer review. In those cases where total independence cannot be met, a documented rationale as to why someone of equivalent technical qualifications and greater independence was not selected should be placed in the peer review report.
>
> The pervasive nature of DOE's effort in the waste management area also makes it necessary that both the work under review as well as the peer review of this work be allowed to be funded by DOE.
>
> The independence criteria is not meant to exclude eminent scientists or engineer upon whose earlier work certain of the work under review is based so long as a general scientific consensus has been reached regarding the validity of their earlier work.

7. If the answer to any of the above questions is no, is there an overriding consideration that would still serve to qualify the review as an appropriate and acceptable peer review for incorporation into the historical review section of this application?

Interviews with former and current WIPP project personnel were conducted to identify past reviews that should be considered for inclusion in this application. Records of the historical reviews were obtained and evaluated against the above screening criteria to select the specific reviews to document in the application. The selected reviews are discussed below. Copies of the

reports that were published prior to the submission of the CCA were provided in CCA Appendix PEER; those published after the CCA are provided in Appendix PEER-2004.

A historical review may provide an evaluation of completed work by the WIPP project; for example, the Engineered Alternatives Task Force Report (DOE 1991) review. In most cases, however, the reviews were sought by the project to seek guidance and an outside perspective as to appropriate "next steps." It should be remembered that most of these reviews were actually evaluating work in progress. They focus on the status of ongoing work at a specific point in time to guide future emphasis and direction of the work and, by their very nature, tend to accentuate aspects of the work that need improvement. They have been very important to the WIPP project because they have consistently provided an understanding of deficiencies and contributed heavily in guiding the project's future direction and needs. The historical peer reviews provide an overall perspective of the evolution and growth of the project.

9.4.1 NAS WIPP Panel Reviews

The National Research Council was established by the National Academy of Sciences (NAS) in 1916. The Council operates in accordance with Academy general policies under the authority of the NAS congressional charter of 1863. The National Research Council has become a principal NAS operating agency for providing services to the government, the public, and the scientific and engineering communities.

In March 1978, the DOE requested the National Research Council:

> review the scientific and technical criteria and guidelines for designing, constructing and operating a Waste Isolation Pilot Plant for isolating radioactive wastes from the biosphere.

The National Research Council assigned the study to the Committee on Radioactive Waste Management under the Commission on Natural Resources. The Committee organized the panel on the WIPP to:

> …review the scientific and technical adequacy of the site-suitability criteria; the guidelines for the site confirmation studies; the design criteria for the repository, including the waste acceptance criteria, the design philosophy, and the operational philosophy; the criteria for determining the environmental safety of future planned operations, viewed from the perspective of the environmental conditions of the repository site; and the design criteria for the experimental testing program of the behavior of the waste-geologic medium interaction.

Panel members were independent of the WIPP project and were nationally recognized experts in their respective disciplines. The panel was selected to provide an appropriate balance of relevant technical disciplines. The scope of the panel's expertise was very broad and included environmental engineering, geology, geochemistry, nuclear science and technology, nuclear engineering, materials science, and mining engineering. The panel regularly made use of other members of the National Research Council Board of Radioactive Waste Management and/or consultants, as necessary, to provide additional expertise.

The panel remained active from 1979 to 1996, during which time its membership changed due to retirement of some members and induction of new members to fill vacancies or to provide coverage in newly identified subject specialties. However, a continuity of knowledge about the

WIPP project was maintained because of a significant overlap of members. Names and backgrounds of members who served on the initial NAS WIPP panel were provided in CCA Chapter 9 and CCA Appendix PEER. Two additional panels have been constituted since 1997 to address specific issues requested by DOE. The membership of those panels and their work is described later in this section.

Between 1979 and 1996, the first WIPP panel produced several reports reflecting their review efforts. An evaluation of the NAS reviews against the previously described screening criteria is provided in Table 9-6. Summaries of the review reports are provided in the following sections. This chapter includes only the titles of the old reports discussed at length in CCA Chapter 9. The reports published by the new NAS panels after the submission of the CCA are described in this chapter.

9.4.1.1 Letter Report of May 1, 1979

See CCA Section 9.4.1.1 for details.

9.4.1.2 Letter Report of September 10, 1979

See CCA Section 9.4.1.2 for details.

9.4.1.3 Continuing Evaluation of the Carlsbad Site

This July 28, 1980 report (see CCA Appendix PEER) reviewed the Carlsbad site in light of the President's decision to cancel the WIPP project. See CCA Section 9.4.1.3 for details.

9.4.1.4 Review of the Criteria for the Site Suitability, Design, Construction, and Operation of the Proposed Waste Isolation Pilot Plant (WIPP); Progress Report: July 1, 1978, to December 31, 1979

This September 1981 report (see CCA Appendix PEER) recounts the panel's findings through the end of 1979. See CCA Section 9.4.1.4 for details.

9.4.1.5 Review of the Criteria for the Site Suitability, Design, Construction, and Operation of the Proposed Waste Isolation Pilot Plant (WIPP); Interim Report: July 1, 1978, to July 31, 1982

This 1983 report (see Appendix PEER) updates the panel's review of WIPP and recounts the panel's findings through the end of July 1982. See CCA Section 9.4.1.5 for details.

Table 9-6. NAS WIPP Panel Reviews

1. Is the peer review relevant to the CCA?	Yes – The panel has dealt with many WIPP issues and most are directly relevant to the CCA.
2. Was there a formal report prepared by the reviewer?	Yes – There have been a series of formal reports.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – Most of the reviews have addressed the adequacy of PA, site selection, etc., activities at WIPP.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – The reviews have all evaluated the adequacy of work prepared by the WIPP project or others.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – Panel members are nationally recognized experts in their respective fields.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – The panel was established by the National Research Council in the 1970s.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A – However, 40 CFR 194 (Supplementary Information re: §194.27) specifically indicates the NAS Panel reviews are appropriate for the CCA.

9.4.1.6 Review of the Scientific and Technical Criteria for the Waste Isolation Pilot Plant (WIPP)

This 1984 report (see CCA Appendix PEER, Section PEER 9.6) updates the panel's review of the WIPP and recounts the panel's findings through December 31, 1983. See CCA Section 9.4.1.6 for details.

9.4.1.7 Letter Report of April 1987 on Planned Sorbing-Tracer Field Tests

The WIPP panel considered the sorbing-tracer field test planned at WIPP and provided their comments in April 1987 (see CCA Appendix PEER). See CCA Section 9.4.1.7 for details.

9.4.1.8 Report of March 3, 1988 on Brine Accumulation in the WIPP Facility

See CCA Section 9.4.1.8 for details.

9.4.1.9 Letter Report of December 1988 on Experiments of Room Closure Rates

See CCA Section 9.4.1.9 for details.

9.4.1.10 Review Comments on DOE Document DOE/WIPP 89-011: Draft Plan for the Waste Isolation Pilot Plant Test Phase: Performance Assessment and Operations Demonstration

This July 19, 1989 report (see Appendix PEER) documents the WIPP panel's review of the subject document. See CCA Section 9.4.1.10 for details.

9.4.1.11 Letter Report of April 1991, Summary of Recommendations

This April 1991 report (see CCA Appendix PEER) summarizes the views of the WIPP panel on the status of the DOE program to assess the WIPP's ability to isolate TRU waste and to demonstrate compliance with relevant regulations. See CCA Section 9.4.1.11 for details.

9.4.1.12 Letter Report of June 1992

This June 1992 report (see CCA Appendix PEER) addressed the experimental plan for the WIPP and was based principally on a review of various documents submitted to the panel and presentations by the DOE and its contractors before the panel over the preceding three years. See CCA Section 9.4.1.12 for details.

9.4.1.13 The Waste Isolation Pilot Plant: A Potential Solution for the Disposal of Transuranic Waste (NAS 1996)

The final report of the NAS Committee set up in 1978 was published in October 1996. Since this report was published after the submission of the CCA, it was not included in the CCA. The full report is reproduced in Appendix PEER-2004.

The members of the committee, who also authored the report, were:

- Charles A. Fairhurst;
- Howard I. Adler;
- John O. Blomeke;
- Sue B. Clark;
- Fred M. Ernsberger;
- Rodney C. Ewing;
- John B. Garrick;
- Leonard F. Konikow;

- Konrad B. Krauskopf;
- Della M. Roy;
- David A. White;
- Chris G. Whipple; and
- Thomas A Zordan.

Biographies of the members are included in Appendix PEER-2004.

The National Research Council Committee on the WIPP was formed in 1978 at the request of DOE to provide scientific and technical evaluations of DOE investigations at WIPP. The committee's statement of task charged it to report on the current state and progress of the scientific and technical issues that form the core of a submission by DOE to EPA for certification of the WIPP facility. The committee reported the following findings, conclusions, and recommendations. The text in the rest of this section represents the views of the NAS committee and not necessarily those of DOE.

9.4.1.13.1 Findings

With regard to the results of committee evaluations and their implications for the overall suitability of WIPP as a repository for TRU waste, this report presented the following findings:

- Although TRU waste contains long-lived radionuclides that require geologic isolation, the overall level of radioactivity is much lower than that of high-level radioactive waste.
- The early recognition of salt as an attractive medium for geological isolation (e.g., National Research Council/National Academy of Sciences 1957) of radioactive waste has been confirmed by subsequent studies.
- Provided it is sealed effectively and remains undisturbed by human activity, the committee finds that the WIPP repository has the ability to isolate TRU waste for more than 10,000 years. The geologic stability and isolation capability of the Salado, which consists of bedded salt, are the primary factors leading to this finding.
- The only known possibilities for serious release of radionuclides appear to be from poor seals or some form of future human activity that results in repository intrusion. The committee anticipates that the consequences of such human intrusion can be reduced based on available engineering design options and on improved understanding obtained from ongoing scientific studies.
- EPA's regulations (i.e., 40 CFR 191, as specified for WIPP in 40 CFR 194) relating to human intrusion do not take into account that if radionuclide releases to the environment via groundwater pathways at WIPP occur, they will be predominantly in non-potable water. This greatly reduces the risk of human exposure compared to a similar release in potable water.

9.4.1.13.2 General Conclusions and Recommendations

The combination of general considerations, such as those outlined above, and detailed studies described later in this report, led the committee to the following conclusions and recommendations.

Based on available scientific evidence, the only probable threat to satisfactory isolation performance of the repository is the possibility of disturbance by human activity, deliberate or unintentional, that could compromise the repository's integrity. Engineering methods are available, if needed, to reduce the consequences of human intrusion to acceptable levels.

Conclusion: Human exposure to radionuclide releases from TRU waste disposed in WIPP is likely to be low compared to U.S. and international standards.

Considering the consequences of future activities that could violate the natural or undisturbed integrity of the repository is valuable for assessing the relative vulnerability of the repository to such activities and in identifying ways to reduce this vulnerability, but assessing human technologies thousands of years hence is highly conjectural and lacks a sound scientific foundation.

Recommendation: Speculative scenarios of human intrusion should not be used as the sole or primary basis to judge the acceptability of WIPP (and, by extension, any geological repository).

9.4.1.13.3 Findings, Conclusions, and Recommendations on Department of Energy Studies

The following comments of the committee related specifically to the DOE compliance (with 40 CFR Parts 191 and 194) activities. According to the committee, most of the issues discussed below are significant only in the event of human intrusion.

9.4.1.13.3.1 *The Role of Performance Assessment*

PA examines the combined effect of each component of the total system to assess the overall ability of the repository to isolate radionuclides from the biosphere. As used by DOE, PA responds to the question, "Is WIPP in compliance with federal regulations?"

Although PA has made important contributions to the WIPP project, in retrospect, it is clear that the potential of PA is greater, and important opportunities to put PA to good use have been missed. PA is valuable at all stages of the repository evaluation process. It can identify the most critical components of the system, assess the significance of engineered supplements to the natural geological barriers, and aid planning and management decisions on the most effective allocation of staff and project resources.

9.4.1.13.3.2 *Conservatism of Performance Assessment Models*

The PA models currently used by DOE are too conservative in some respects. Such conservatism masks the potential for identifying and assessing the benefits of relatively simple engineering design procedures in reducing the consequences of human intrusion.

The assumption that the DRZ bordering the room excavations remains a relatively high-permeability region throughout the first 10,000 years of the repository appears overly conservative. This is in marked contrast to the assumption (see Chapter 4.0) that the DRZ around the shaft will heal, achieving a permeability of between 10^{-16} m^2 (10^{-15} ft^2) and 10^{-18} m^2 (10^{-17} ft^2) within 50 to 100 years and approaching the essentially impermeable condition of intact salt within a small fraction of 10,000 years. Such a conservative assumption with respect to the DRZ in the PA models may prevent a realistic evaluation of the major benefits of waste compartmentation by room and panel seals in reducing the consequences of repository disturbance by intrusion.

9.4.1.13.3.3 *Complexity of Performance Assessment Models*

DOE's PA modeling of radionuclide releases from WIPP involves such complex combinations of many variables that, to the non-specialist, it is not clear how the predicted releases depend on the component FEPs in the geological isolation system.

The committee recommends that DOE develop, in parallel with the complex PA models, simpler versions that provide a more transparent, traceable path from the model inputs to the predicted releases. The insights gained from the simpler model as to which components of the isolation system are most critical to improved repository performance would serve a very useful role in decision-making and in resource allocation for WIPP. It is essential, of course, that the simpler PA models still identify correctly the key FEPs upon which repository performance depends.

To illustrate this recommendation: because plutonium (Pu) is the dominant radioactive element of concern in the WIPP inventory, a simpler model could focus on Pu in the source term to the exclusion of other radioactive elements. However, understanding and predicting the behavior of Pu in the WIPP system is challenging, and experimental work with other actinides is necessary to develop the parameters for Pu required for the PA models, for both the full model and any simpler version. While studies of other actinides are necessary to support the chemical model developed for Pu, a simpler PA of the kind proposed here would consider only Pu isotopes as a source term, and only the dominant pathway(s) for environmental releases, with no more complexity than needed for an adequate representation.

9.4.1.13.3.4 *Waste Characterization*

The waste characterization program considered by DOE does not appear to be based on the needs for information important to an assessment of the long-term facility performance. Ideally, the PA should be used to determine what characterization is required.

9.4.1.13.3.5 *Nonradioactive Constituents of Transuranic Waste*

Nonradioactive hazardous constituents of TRU waste are considered to pose negligible long-term hazards compared to the radioactive constituents of WIPP waste.

9.4.1.13.3.6 *Behavior of Salt at the Waste Isolation Pilot Plant Site*

Time-dependent deformation of the salt and associated stratigraphic layers at WIPP is now understood well enough to allow reliable long-term calculations of salt deformation behavior as it relates to repository performance.

9.4.1.13.3.7 *Salado Brine*

Small quantities of brine seep from the DRZ in the immediate vicinity of any excavation in the Salado. The amount of brine accumulation is not sufficient to be a credible cause for significant escape of radionuclides from the sealed repository.

9.4.1.13.3.8 *Non-Salado Brine*

Apart from possible effects of deep-well fluid injection in adjacent areas, brine flooding is only likely if, after loss of administrative controls, an intrusion borehole connects the repository with a deeper source of pressurized brine, as has been encountered by some deep boreholes in the vicinity of the repository.

9.4.1.13.3.9 *Gas Generation in the Repository*

Gas generation will be minimal in a dry or nearly dry repository like WIPP because both chemical and biological gas-generating processes (e.g., metal corrosion and bacterial action on organic matter) require a liquid phase for mass transport of the reactants and products that are involved in gas formation.

9.4.1.13.3.10 *Treatment of Waste*

Sophisticated treatment (e.g., incineration) of the TRU waste in a well-engineered WIPP repository is unwarranted to further improve repository performance, because gas generation is not a serious concern (see Chapter 3.0).

9.4.1.13.3.11 *Backfilling and Compartmentation*

Simple repository engineering measures, such as backfilling the rooms and tunnels in which the waste is emplaced, can be valuable and cost-effective methods of reducing the consequences of human intrusion and any associated brine flooding. Room and panel seals via backfill are relatively well-defined engineering procedures for improving the isolation process. In this regard, compartmentation is recommended by the committee to provide effective seals that eliminate hydrological communication between the waste-filled rooms.

9.4.1.13.3.12 *Non-Salado Hydrology*

A more comprehensive understanding of the non-Salado hydrology is needed before a reasonable judgment can be made as to the role of the Rustler and adjacent formations in delaying radionuclide releases in the event of human intrusion. To date, studies have been overly focused on a two-dimensional (2-D) analysis of the Culebra Dolomite. They have not sufficiently considered other possible hydrogeologic release pathways for radionuclides or interconnections

between the Culebra and other formations. Potential releases to the Dewey Lake Red Beds, which are less conductive than the Culebra, but contain some potable water, are recommended for further study.

9.4.1.13.3.13 *Potash Mining*

The consequences to the non-Salado hydrology of subsidence damage due to possible future mining of potash resources above the repository have not yet been evaluated by DOE. If the potential consequences are found to be seriously adverse, it is technically feasible to extract these resources preemptively, in a way that avoids subsidence and associated effects and that reduces the potential for human intrusion by drilling.

9.4.1.13.3.14 *Deep Well Fluid Injection*

The requirement to consider the effects on the repository of fluid injection activities was a relatively new addition to the final version of EPA criteria for certification (40 CFR part 194.32(c)). Neither the probability nor the effects on the repository from nearby injection of water or brine have been evaluated in detail by the committee, nor has DOE published an analysis of this issue. A comprehensive analysis of the risks and consequences of this scenario should be completed and documented.

9.4.1.13.3.15 *Waste Solubility and Transport*

The PA completed by DOE in 1992, and all subsequent analyses, have consistently identified a set of issues with the greatest impact on the compliance of WIPP in the event of human intrusion and associated brine flooding of the repository. Prominent among these issues are:

- actinide solubilities in brine,
- formation and transport of colloids containing radionuclides, and
- retardation of radionuclides during transport through the Culebra.

The EPA has also identified these issues as critical to its evaluation of the CCA.

At the time of this report, the data and models to represent these three issues in the next version of the PA (to support the CCA) were not available for review.

9.4.1.13.3.16 *Continuation of Experiments and Analyses*

Continuation of analyses and experiments initiated in the WIPP program to address concerns related to Non-Salado Hydrology, Deep Well Fluid Injection, and Waste Solubility and Transport is recommended by the committee, even though the results may not be available in time for the compliance submission. Results of such testing could reduce uncertainties in the long-term performance of WIPP, eliminate concern over other issues, and be useful in judging the cost-effectiveness of various waste isolation procedures at WIPP and other repositories.

In summary, the committee offered the following opinions:

- Provided the WIPP repository is sealed effectively and undisturbed by human activity, the committee knows of no credible or probable scenario for release of radionuclides.

- For the WIPP repository disturbed by future human activity, the committee has noted three ways in which confidence in the performance of the repository could be increased:

1. Re-evaluation of the probability and/or consequences assigned to highly speculative scenarios of future human activities may reduce the estimated risk of radionuclide release.

2. Experimental and field programs in progress or planned may show that key parameters (e.g., actinide transport) are well within the range required to reduce the impacts of human activities on radionuclide releases substantially.

3. The implementation of available engineering options (e.g., compartmentation, treated backfill), which have not been considered in published DOE analyses, could reduce the consequences of human intrusion. The cost effectiveness of these options will depend on the outcome of (1) and (2) above.

The committee believes that some combination of the above three considerations will very probably be sufficient to allow DOE to demonstrate that a WIPP repository will keep radionuclide release within acceptable levels for the disturbed case.

9.4.1.14 Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant – Final Report (April 2001)

Following the publication of the NAS WIPP committee's 1996 report described in Section 9.4.1.13, a new NAS WIPP committee was created to carry out the tasks described below. The committee produced an interim report in April 2000 that was included as Appendix A1 of this final report (National Research Council/National Academy of Sciences 2001). The full report is included in Appendix PEER-2004. Since the main findings and recommendations from the interim report have been incorporated into the body of this report, the interim report is not discussed separately in this chapter.

The committee's task was twofold: (1) to identify technical issues that could be addressed to enhance confidence in the safe and long-term performance of the repository, and (2) to identify opportunities for improving the National TRU Program for waste management, especially with regard to the safety of workers and the public.

The following members served on this committee:

- B. John Garrick, Chair, Garrick Consulting, Laguna Beach, California;
- Mark D. Abkowitz, Vanderbilt University, Nashville, Tennessee;
- Alfred W. Grella, Grella Consulting, Locust Grove, Virginia;
- Michael P. Hardy, Agapito Associates, Inc., Grand Junction, Colorado;
- Stanley Kaplan, Bayesian Systems Inc., Rockville, Maryland;
- Howard M. Kingston, Duquesne University, Pittsburgh, Pennsylvania;

- W. John Lee, Texas A&M University, College Station;
- Milton Levenson, Bechtel International, Inc. (retired), Menlo Park, California;
- Werner F. Lutze, University of New Mexico, Albuquerque;
- Kimberly Ogden, University of Arizona, Tucson;
- Martha R. Scott, Texas A&M University, College Station;
- John M. Sharp, Jr., The University of Texas, Austin;
- Paul G. Shewmon, Ohio State University (retired), Columbus;
- James E. Watson, Jr., University of North Carolina, Chapel Hill; and
- Ching H. Yew, The University of Texas (retired), Austin.

In addition, Dalene C. Hoffman and James O. Leckie served as liaisons and Lynda L. Brothers and John T. Smith served as consultants. National Research Council/National Academy of Sciences staff members Barbara Pastina and Thomas E. Kiess served as Study Directors and Angela R. Taylor as Senior Project Assistant. Biographies of the committee members are provided in the report (National Research Council/National Academy of Sciences 2001) (see Appendix PEER-2004).

The text in the rest of this section represents the views of the NAS committee and not necessarily those of DOE.

9.4.1.14.1 Findings and Recommendations

The overarching finding and recommendation of this report is that the activity that would best enhance confidence in the safe and long-term performance of the repository is to monitor critical performance parameters during the long preclosure phase of repository operations (35 to possibly 100 years). Indeed, in the first 50 to 100 years, the rates of important processes such as salt creep, brine inflow (if any), and microbial activity are predicted to be the highest and will be less significant later. The committee recommends that the results of the on-site monitoring program be used to improve the PA for recertification purposes. These results will determine whether the need for a new PA is warranted. For the National TRU Program, the committee finds that the DOE is implementing many of the recommendations of its interim report. It is important that the DOE continue its efforts to improve the packaging, characterization, and transportation of the TRU waste.

The committee's specific findings and recommendations have been grouped into three categories: (1) site performance, (2) site characterization, and (3) the National TRU Program, as described below.

9.4.1.14.1.1 *Site Performance*

- The committee recommends preclosure monitoring to gain information on brine migration and moisture access to the repository. Observation should continue at least until the repository shafts are sealed and longer, if possible. The committee recommends that the results of the on-site monitoring program be used to improve the PA for recertification purposes.

- The committee recommends preclosure monitoring of gas generation rates, as well as of the volume of H, carbon dioxide (CO_2), and CH_4 produced. Such monitoring could enhance confidence in the performance of the repository, especially if no gas generation is observed. Observation should continue at least until the repository shafts are sealed and longer, if possible. The results of the gas generation monitoring program should be used to improve the PA for recertification purposes.

- MgO is used as backfill in WIPP to provide some control of the chemical environment of the waste and, to a lesser extent, to fill voids in the disposal locations, thus enhancing the healing process. The chemical performance of MgO depends on gas generation and brine inflow, as well as other chemical processes taking place in the repository. The committee finds that there is uncertainty about the effectiveness of MgO in controlling the chemical environment of the waste. Therefore, the committee recommends that the net benefit of MgO used as backfill be reevaluated. The option to discontinue emplacement of MgO should be considered.

- The committee recommends preclosure monitoring of the status of room deformation and of the DRZ healing. Seal performance should also be assessed. Observation should continue at least until the repository shafts are sealed and longer, if possible. The results of the monitoring of room deformation and DRZ healing should be included in the PA and used for recertification purposes.

9.4.1.14.1.2 *Site Characterization*

- The committee recommends a monitoring program to characterize the geohydrology of the Culebra Dolomite. Tests and measurements that should be considered include angled boreholes, natural gradient tracer tests, and additional pump or injection tests. These new data should be used to confirm or modify the conceptual and numerical models now proposed as a reasonable simulation of the actual system.

- The committee recommends the use of seismic survey techniques for detecting large brine reservoirs below the repository. In case a brine reservoir was found beneath the WIPP and its size was larger than what is already taken into account in the PA, the DOE should conduct an extensive review of the impact of such a reservoir on the repository performance. A basis would then exist to take appropriate action to ensure repository safety.

- The committee recommends developing a database to collect information on drilling, production enhancement, mining operations, well abandonments, and unusual events (accidents and natural events) in the vicinity of the WIPP site.

- The committee recommends that the DOE continue implementing its plan to sample oil-field brines, petroleum, and solids associated with current and future hydrocarbon production, as necessary, to assess the magnitude and variability of naturally occurring radioactive material (NORM) in the vicinity of the WIPP site for baselining purposes.

9.4.1.14.1.3 *The National Transuranic Program*

9.4.1.14.1.3.1 Waste Characterization and Packaging

The committee recommends that the DOE's efforts to review waste characterization and packaging requirements continue and those changes be implemented over the entire National TRU Program. The committee recommends that the resources required to complete these improvements be made available by the DOE.

9.4.1.14.1.3.2 Total Inventory of Organic Materials Allowed in the Repository

The committee recommends a risk-based analysis of the total organic material regulatory limits in WIPP. If accounting for the organic material is important to the safety of the repository, an inventory record system should be implemented as soon as possible to provide a basis for meaningful safety analysis.

9.4.1.14.1.4 *Waste Transportation*

9.4.1.14.1.4.1 Department of Energy's Communication and Notification Program

The DOE appears to be moving systematically toward the implementation of an efficient, comprehensive, and state-of-the-art communication and notification system called TRANSCOM 2000. The committee recommends that the DOE implement as soon as possible the new TRANSCOM 2000 communication and notification system. Moreover, because the human factor is an important element of transportation system quality, TRANSCOM 2000 should include methods to minimize the occurrence and impact of human errors.

9.4.1.14.1.4.2 Department of Energy's Emergency Response Training

The committee recommends that the DOE facilitate the involvement of states in developing and maintaining an up-to-date, practical, and cost-effective spatial information database system to coordinate emergency responses. The DOE should also develop an ongoing assessment program for states' emergency response capabilities and allocate training resources to address deficiencies in coverage along WIPP routes.

9.4.1.14.1.4.3 Rail as a Transportation Option for Certain Transuranic Waste

The committee recommends that all reasonable transportation options, including reduction in the number of shipments, such as rail and road transportation with better-adapted containers, should

be part of the decision-making process of transporting TRU waste from generator and storage sites to the WIPP. Future transportation studies should consider railway shipments and their impact on both the safety and the cost of the program. The DOE should also continue to pursue the development of packaging alternatives for materials not suitable for TRUPACT-ll containers.

9.4.1.14.1.4.4 Gas Generation Safety Analysis for TRUPACT-II Containers

The committee recommends a risk-informed analysis of WIPP specific shipment issues to identify core problems related to hydrogen generation and, perhaps, provide a basis for alternative cost-effective criteria while reducing risk. The committee recommends the use of such risk-informed analysis in the application for revision of the NRC certificate of compliance concerning hydrogen generation limits for transportation purposes.

9.4.14.1.4.5 *The Department of Energy's Response*

The DOE provided detailed responses to most of these recommendations, which are included in Appendix A2 of National Research Council/National Academy of Sciences (2001) (Appendix PEER-2004). In brief, the DOE agreed with the committee's findings and observations and has implemented most of the recommendations.

9.4.1.15 Characterization of Remote-Handled Transuranic Waste for the Waste Isolation Pilot Plant – Final Report (2002)

In 2001, a new NAS WIPP committee (Committee on the Characterization of Remote-Handled Transuranic Waste for the Waste Isolation Pilot Plant) was established to review a proposed characterization plan for RH-TRU waste and to provide recommendations for improving the plan's technical soundness, protection of worker safety and health, and compliance with regulatory requirements. The committee published its final report in 2002 (National Research Council/National Academy of Sciences 2002).

The following members served on the committee and authored the report:

- Eula Bingham, Chair, University of Cincinnati, Ohio;
- Sanford Cohen, SC&A, Inc., McLean, Virginia;
- Milton Levenson, Independent Consultant, Menlo Park, California;
- Kenneth Mossman, Arizona State University, Tempe;
- Ernest Nieschmidt, Idaho State University, Idaho Falls;
- John Plodinec, Mississippi State University, Starkville; and
- Anne E. Smith, Charles River Associates, Washington, D.C.

Heino Nitsche served as a consultant and Alexander Maclachlan served as liaison to the National Research Council/NAS Board on Radioactive Waste Management. The National Research

Council/NAS staff members were Study Director Barbara Pastina, Senior Project Assistant Angela Taylor, and Research Assistant Darla Thompson.

The text in the rest of this section represents the views of the NAS committee and not necessarily those of DOE.

9.4.1.15.1 Committee's Assessment of Department of Energy's Proposed Characterization Plan

The committee used the criteria listed in the statement of task to assess DOE's proposed characterization plan to address: (1) the context of RH-TRU waste characterization, (2) the characterization plan's technical soundness, (3) protection of worker safety and health, and (4) compliance with regulatory requirements.

9.4.1.15.1.1 *Context of Remote-Handled Transuranic Waste Characterization*

DOE should emphasize the argument that the characterization information collected for most of RH-TRU waste does not need confirmatory measurements because the repackaging or generation of waste will be carried out under a certified QA program. If the volume of RH-TRU waste represents between 2 and 4 percent of the volume of TRU waste, and the information collected for over 95 percent of RH-TRU waste does not need confirmation, then only the remaining 5 percent of the RH-TRU waste inventory (between 0.1 and 0.2 percent of the total inventory) needs confirmation activities.

DOE uses the term Acceptable Knowledge (AK) to indicate both the historical information and the newly generated characterization information collected at the time of waste generation, packaging, or repackaging. However, for 95 percent of the RH-TRU waste inventory, AK refers mostly to the latter. The committee recommended that DOE use a different term than AK for this newly generated information. Using AK for both historical and newly generated information is potentially confusing because AK is generally associated with historical information, which requires some type of confirmation.

9.4.1.15.1.2 *Characterization Plan's Technical Soundness*

The committee found that DOE's proposed characterization plan is not completely performance-based, and that several characterization activities are based on nontechnical considerations. The committee questioned the technical bases of some of these characterization activities. The committee acknowledged that nontechnical considerations may be important for maintaining effective working relationships among DOE, EPA, and NMED; however, DOE should propose only characterization activities that have a technical, health and safety, or regulatory basis.

DOE's proposed characterization plan should address tolerable decision error rates associated with characterization information. These errors should not be overly stringent so as to negatively impact the sites' ability to implement ALARA.

The characterization plan should clarify under which conditions confirmation of historical AK is warranted and the most effective methods proposed. DOE should provide justification for the technologies proposed to obtain confirmatory data and provide evidence of their effectiveness across the entire spectrum of dose rates for RH-TRU waste.

9.4.1.15.1.3 *Protection of Worker Safety and Health*

DOE could strengthen the rationale of its characterization plan for RH-TRU waste by discussing estimates of worker doses and characterization costs in the three site-specific plans accompanying the submittal documents. DOE should continue its effort to ensure sufficient flexibility for generator sites in the implementation of the characterization plan. However, characterization activities that share common elements across sites should be standardized.

9.4.1.15.1.4 *Compliance with Regulatory Requirements*

The committee recommends that DOE evaluate whether existing characterization practices for CH-TRU waste, when applied to the characterization of RH-TRU waste, have an impact on the protection of the environment, health and safety of public and workers, and cost-effectiveness of the characterization program.

The committee recommends that submittal documents focus on regulatory requirements under the relevant agency's purview and distinguish between these requirements and ancillary information describing the context of RH-TRU waste characterization.

9.4.1.15.2 Department of Energy's Response

The DOE has taken into account the committee's recommendations in developing the RH-TRU waste characterization plan.

9.4.2 Performance Assessment Peer Review Panel

The Performance Assessment Peer Review Panel (PAPRP) was established in 1987 as a standing group under contract to the WIPP PA Department at SNL. The PAPRP charter states that the purpose for establishment of the panel was as follows:

> An external Peer Review Panel has been established for significant PA documentation so that the DOE can be assured that the performance evaluation is well-conceived and being carried out with professional competence, and so that scientists and state officials can be assured that the DOE's conclusions as to the suitability of the WIPP as a repository are credible.

An evaluation of the PAPRP reviews against the screening criteria is provided in Table 9-7. Panel members were selected on the basis of their professional stature within the university, scientific and/or engineering communities. The PAPRP membership provides expertise in environmental research, geology, nuclear engineering, hydrogeology, and public policy development. Members were chosen explicitly for their independence from PA work undertaken by SNL. Panel members were:

- G. Ross Heath (Chairman), University of Washington;

Table 9-7. Performance Assessment Peer Review Panel

1. Is the peer review relevant to the CCA?	Yes – the PAPRP evaluates SNL PA efforts.
2. Was there a formal report prepared by the reviewer?	Yes – formal reports are developed.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the PAPRP reviews the adequacy of the SNL PA activities.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the PAPRP performs documented, in-depth, critical evaluations of PA reports and other documentation, addressing validity of basic assumptions, alternative approaches, methodology, uncertainty, supportability of conclusions, and consequences of incorrect assumptions or conclusions.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – all members of the PAPRP are recognized experts in their fields.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the PAPRP operates as a independent group under contract to the SNL PA Department. Uncensored comments by the panel are maintained in the SWCF.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

- Robert J. Budnitz, Future Resources Associates, Inc., Berkeley, California;
- Thomas A. Cotton, JK Research Associates, Inc., Washington, D.C.;
- Peter A. Domenico, Texas A&M University (Until 1990);
- C. John Mann, University of Illinois, Urbana;
- Thomas H. Pigford, University of California, Berkeley; and
- Frank W. Schwartz, Ohio State University (since 1990).

The panel finished its work with the preparation of the CCA. The PAPRP chairman was responsible for ensuring that members did not have a conflict of interest.

Panel members were requested to address the following areas, as applicable, for each review:

1. Validity of basic assumptions and extrapolations;
2. Alternative interpretations or approaches;
3. Appropriateness, logic, and limitations of methodology;
4. Uncertainty of results;
5. Supportability of the conclusions drawn;
6. Consequences of incorrect assumptions or conclusions; and
7. Other issues appropriate to the review subject.

The major issues (and their resolutions) raised by the PAPRP during its review of PA documentation from 1987 to 1995 are provided in CCA Chapter 9 and CCA Appendix PEER, Section PEER.11.

9.4.3 Shaft Seal Design Independent Review

A review plan, titled Shaft Seal System Design for the Waste Isolation Pilot Plant (WIPP), was developed and approved on January 12, 1996 (Hansen 1996). The review plan governed the preliminary and final reviews of the WIPP shaft seal system.

Members of the review panel were selected based on their respective knowledge, experience, and independence from the WIPP shaft seal design effort. The group had expertise in computational geomechanics, rock mechanics, mining engineering, civil engineering, and the design and construction of underground seals and bulkheads. The panel for both the preliminary and final reviews consisted of a review team chairman and three reviewers:

- R.E. Stinebaugh (Chairman), SNL;
- Dr. Malcolm Gray, Atomic Energy of Canada Limited Whiteshell Laboratories;
- Stephen Phillips, Phillips Mining; and
- Dr. John Tinucci, Itasca Consulting Group.

A evaluation of the shaft seal design reviews against the screening criteria used to determine whether this review should be addressed in this application is presented in Table 9-8.

Shaft seal design activities were conducted under an approved QA program. The review was conducted in accordance with the requirements of SNL QAP 3-2, entitled Verification of Design Adequacy, approved 7/31/95 (QA Department 1995), and the provisions of the review

Table 9-8. Shaft Seal System Design Review

1. Is the peer review relevant to the CCA?	Yes – the seal system is directly relevant to PA.
2. Was there a formal report prepared by the reviewer?	Yes – the title of the report is "Final WIPP Shaft Seal System Design Review."
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the review focused on the adequacy of the shaft seal system that was developed by SNL
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the review evaluated the adequacy of the work of others (the design of the shaft seal system).
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the reviewers were specifically chosen because of their expertise in seal design and related disciplines.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – it may appear that the independence could be questioned because of the chairman's affiliation with SNL. However, his organizational independence from the WIPP project and his actual role in the review process (see Section 9.4.3 for additional discussion) preserved the independence of the review.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

plan. Panel members were trained in accordance with the provisions of QAP 3-2 prior to beginning the design review. A member of the SNL QA staff (Organization 6860) briefed the panel at the onset of the review, monitored the review as it progressed, and inspected record-keeping activities. Records of panel training and other QA records concerning this review were maintained in accordance with SNL QA program requirements.

In both reviews, the panel was asked to address the following questions:

1. Will the shaft seal system satisfy design guidance?

2. Are there elements of the design that will prevent the sealing system from meeting design requirements?

3. Can the design be successfully implemented?

A short summary of each review is provided below.

Review of the Preliminary Shaft Seal Design

The preliminary design review considered the adequacy of design concepts summarized in DOE (1995c). The report includes descriptions of the WIPP setting, design guidance derived from the regulations, a description of the design, materials comprising the seal components, and preliminary evaluations of the shaft seal system.

The review of the Sealing System Design Report was initiated in January 1996 and completed in March 1996. Following their review of the Sealing System Design Report, Dr. Gray, Dr. Tinucci, and Mr. Phillips prepared detailed comments. These comments were forwarded to the appropriate design staff and formal responses were prepared. The reviewers evaluated the responses and determined their responsiveness to the concern.

Subsequent to resolution of outstanding issues, the updated information was used to amend the documentation provided to the review panel for its final review (discussed below). At the conclusion of the final review, all of the reviewers, without exception, stated that the actions promised in the responses to the preliminary review comments had been completed.

Review of the Final Shaft Seal System Design

During April 1996, the panel was convened to review the Compliance Submittal Design package for the WIPP shaft sealing system (Hansen 1996). Panel input was subsequently incorporated into the final Compliance Submittal Design report (Repository Isolation Systems Department 1996). The review was based on documentation provided by SNL and briefings by the WIPP technical staff. The documentation included an enhanced, annotated outline for the compliance shaft seal design report, detailed drawings, a material specifications framework, and topical summaries of structural and fluid flow calculations. Briefings provided the panel with additional information covering the design, laboratory and in-situ experimentation results, and analyses that were completed.

Following completion of the review, each panel member prepared specific comments regarding the design (see CCA Appendix PEER). The WIPP staff prepared specific responses to the comments and met with the reviewers to resolve them. In some instances, the WIPP staff, in response to the reviewer comments, promised to make certain changes or additions to the design drawings, the documentation of the analyses, or the report test. In some of these cases, a reviewer conditionally accepted those responses but required a copy of the marked up document to remove the condition for full acceptance. The comments were formally tracked with comment resolution forms. In addition, conditionally accepted comments were formally closed by sending the text changes to the reviewer as evidence of the direct incorporation of his or her comments. Final comment closure was documented in the form of a letter from the reviewer stating full acceptance of the changes.

Each reviewer also prepared a summary statement (see CCA Appendix PEER). The summary statements provided recognition or explanation of specific technical concerns in the final documentation, identified the need for future work prior to emplacement of the seals, provided suggestions for design and analysis enhancements or simplifications, and encouraged more

detailed quantification of design guidance. Each of the reviewers provided "bottom-line" assessments. Excerpts from the summary statements are provided below:

> In summary and conclusion, I consider that when completed as stated immediately above, it is likely that the documents being developed will present a design that will meet the general requirement of shaft sealing systems that will mitigate against water and gas flows from the repository to the biosphere and that can be built using existing technologies or reasonable extrapolation therefrom. (Dr. Malcom Gray)

> It is considered improbable that the seal design, as presented including the revisions recently discussed, can be significantly and practically improved within the limits of existing construction materials and technologies, except in some areas where optimization of materials and methods of emplacement can be achieved. (Mr. Stephen Phillips)

> The design that has been put forth presents one way of efficiently sealing shafts. Recognizing that other ways could also be made to work, the design presented here is similar to others suggested by the scientific community for sealing deep geologic nuclear waste repositories. The concepts presented have been developed from sound engineering judgment and sound analyses techniques. The anticipated performance of individual sealing components are within reasonable expectations based on currently available field and laboratory data, albeit limited. To address the wide scale of uncertainties, the design has been conservatively laid-out with redundant multiple-barrier components so that the overall seal system performance is not dependent on the functionality of an individual component. The design as it exists today is a conceptual design since it describes basic concepts and provides sufficient backup analyses to demonstrate that those concepts will reasonably satisfy the qualitative design guidelines. (Dr. John Tinucci)

9.4.4 Engineered Alternatives Task Force Report Peer Review

The EATF was established by the DOE in 1989. The EATF was tasked to evaluate the effectiveness, feasibility, and risk of implementing alternative facility designs, backfills, and/or waste forms in improving the long-term performance of the WIPP disposal system. The purpose, methodology, assumptions, and conclusions of the EATF are documented in DOE 1991. The author of the report, IT Corporation, convened a peer review panel to review a final draft version of the report during 1991. An evaluation of the EATF review against the screening criteria is provided in Table 9-9. The panel consisted of experts in chemical and nuclear engineering and geology. The members of the panel and their affiliations were as follows:

- Dr. H. Eric Nutall, University of New Mexico and Nutall & Associates, Inc.;
- Dr. Douglas Brookings, University of New Mexico;
- Dr. Robert J. Budnitz, Future Resources Associates, Inc.; and
- Donald E. Shaw, P.E., Engineering and Management Consultant.

A formal comment resolution process was employed to ensure that the reviewers' comments were incorporated into the final version of the report. The comments of the panel can be grouped into three general topics: (1) quality of technical work, (2) utility of a single figure-of-merit, and (3) use of relative versus absolute risk.

Table 9-9. Engineered Alternatives Task Force Report Review

1. Is the peer review relevant to the CCA?	Yes – the review was conducted on the 1991 EATF report which formed the basis for the subsequent EACBS.
2. Was there a formal report prepared by the reviewer?	Yes – the report consists of review comment record forms that were used to formally document the comments, responses, and their dispositions.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the purpose of the review was to determine the adequacy of the EATF report.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the review evaluated the adequacy of the EATF report.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the reviewers were nationally recognized experts in their respective fields.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the reviewers were not involved in the preparation of the work and were free from funding considerations.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

The comments made by the peer review panel (see CCA Appendix PEER) and the WIPP project responses are discussed below.

9.4.4.1 Quality of Technical Work

One reviewer commented that:

> "The complex technical risk analysis work aimed at determining risk-reduction factors of the many different risk endpoints and for 16 different alternative scenarios, is of high quality and deserves commendation. The technical information buried in the back of the Attachments to this report can provide an excellent basis for decision-makers to understand the various risk issues, and make decisions about them. The choice of alternative scenarios, the assumptions made to limit the scope of the analysis, the risk endpoints identified, and the analysis methods used are all fully

> acceptable to me. I am particularly pleased with how the analysis of specific risk endpoints was accomplished in a way that focused on the key issues relevant to the alternative scenarios. This part of the report can be a gold mine for further study by experts, as well as of use to decision-makers if presented properly."

The future value of the work predicted by the reviewers was an accurate prediction because the methodology and models developed for the EATF formed the basis for the subsequent EACBS (DOE 1995b) performed in 1995. The EACBS was recently the subject for another peer review panel (see Section 9.3.3).

9.4.4.2 Utility of a Single Figure-of-Merit

The reviewers questioned the utility of a single figure-of-merit to express the aggregated risk elements. The EATF used a Multi-Attribute Utility Theory approach to combine the risk components for each alternative into a single value for alternative ranking purposes. These risk components included the routine and accidental risks from waste transportation and handling, exposure to radiation and hazardous constituents in the waste during treatment, and cost, schedule, and benefits to future generations from a safer disposal system. One reviewer commented that:

> Although I admire the attempt to come up with a single figure-of-merit useful to decision-makers by which to judge the overall benefit/disbenefit of each of the various scenarios being studied, in my view the effort has not succeeded. The methodology did use established decision-theory methods to identify and calculate such a single figure-of-merit, and seems to break some new ground, but in my opinion, the single figure-of-merit identified is not sufficiently useful to decision-makers to justify the continuation of work along those lines. In fact, I believe that the use of a single figure-of-merit obscures rather than illuminates the situation. Decision-makers are in my opinion fully capable of dealing with multiple attributes presented separately and of weighing them in their own ways for decision-making purposes--this goes on every day in the upper-management board rooms of large enterprises and agencies. But to make these judgements, decision-makers need the best available disaggregated information about the issues at hand, in this case, the best absolute numbers and uncertainties about the specific risk endpoints. I don't believe that high-level decision-makers generally use aggregated information very much or very well, and I don't believe that the aggregated information based on the single figure-of-merit developed in this report will be of much use.

The WIPP project believed that, although dissaggregated information may be used by many decisionmakers in finance and industry, it was not sufficient for the EATF. A compromise was reached in final version of the EATF report. That compromise consisted of providing both the aggregate and individual risk components. This allows a decisionmaker the option to develop an independent figure-of-merit based on personal weighting factors and preferences.

9.4.4.3 Use of Relative versus Absolute Risk

The EATF methodology involved the calculation of relative risk reduction factors rather than absolute risks for each alternative. These relative risk reduction factors were based on a risk of unity for the baseline case (defined as: no waste treatment; a crushed salt backfill; and the current repository design). Risks for each EA were ratioed against the risk for the baseline case, yielding the risk reduction factor. The main advantage of this relative risk approach is that many parameters that affect absolute risk will cancel when calculating relative risk. Uncertainties in those parameter values do not translate into uncertainties in the relative factors. Some reviewers

felt that the calculation of absolute rather than relative risks would have been more useful to decisionmakers. For instance, one reviewer commented that:

> In my view, the approach of identifying and working with risk-reduction factors (RRFs) is a very useful intermediate step toward what is actually needed. Indeed, calculating RRFs is often simpler than calculating absolute magnitudes of risks for reasons cited well in the report. However, I believe that for decision-makers these RRFs cannot adequately substitute for knowing the actual magnitudes of the risks involved, except in special cases, such as when almost no changes occur (RRF near unity) or when absolute risk magnitudes and minuscule small for both the base-case scenario and the alternative scenarios.

The WIPP project concluded that although absolute risks convey a greater amount of information for decisionmakers than relative risks, the calculation of absolute risks were outside the scope of the EATF study and would have entailed a considerably greater effort than was warranted. For instance, calculating absolute long-term risks to future generations for each alternative would require performing a complete PA for each alternative.

9.4.5 Blue Ribbon Panel Peer Review

The Secretary of Energy established the WIPP Blue Ribbon Panel (BRP) in August 1989. The panel was composed of the following five members:

- Dr. Thomas Bahr;
- Robert W. Bishop, esq.;
- Dr. Arthur S. Kubo;
- Leonard C. Slosky; and
- Newal Squyres.

Dr. Bahr, a water quality management expert and the Director of the New Mexico Water Resource Research Institute, was nominated to the BRP by the Governor of New Mexico. Mr. Bishop, General Counsel and Corporate Secretary for the Nuclear Management Resources Council, and Dr. Kubo, a nuclear and civil engineer and a vice president of the BDM Corporation, were appointed to the BRP by the Secretary of Energy. Mr. Slosky, an environmental consultant, and Mr. Squyres, an attorney, were nominated by the Governors of Colorado and Idaho, respectively.

The panel members were each requested to provide an independent technical review of WIPP issues and individually report on the following:

- The concept and timing of DOE's proposed WIPP Operations Demonstration,
- Whether or not the operations demonstrations should be conducted in parallel with the PA, and

- An evaluation of DOE's validation plan for certification of TRU waste to meet the WIPP WAC.

The panel conducted site visits at the WIPP facility and portions of INEL and the Rocky Flats Plant. The panel met with and/or was briefed by staff from the DOE and its contractors, the NAS Board of Radioactive Waste Management WIPP Panel, the EEG, and the EPA. The panel members were provided an extensive amount of documentation and were encouraged to address questions to the above groups. An evaluation of the BRP review against the screening criteria is provided in Table 9-10.

Table 9-10. Blue Ribbon Panel Review

1. Is the peer review relevant to the CCA?	Yes – the reviews addressed waste certification and PA aspects.
2. Was there a formal report prepared by the reviewer?	Yes – each panel member prepared an individual report.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the panel reviewed the adequacy of work being done primarily at WIPP, Rocky Flats Plant, and INEL.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the panel reviewed DOE plans and processes.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – panel members were specifically chosen by the governors and the Secretary of Energy because of their qualifications.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the panel members were not otherwise associated with the WIPP project.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

Following submission of its reports, the BRP was asked to continue its service by providing their observations and recommendations to the DOE in three areas: (1) continued review of DOE plans to characterize Rocky Flats Plant TRU and mixed waste; (2) assist DOE in developing a strategy for achieving compliance with Resource Conservation and Recovery Act (RCRA) and other environmental regulations at WIPP; and (3) evaluate the Final Test Plan and ancillary documents. Subsequently, DOE expanded the BRP charge to include a management review of the WIPP project, review of the rationale and plans to characterize waste for the test phase, and a review of plans for EAs relating to the waste form.

The BRP was also asked in late November 1989 to comment on questions submitted by members of the New Mexico Congressional Delegation. The questions were: (1) what is the rationale for conducting in-situ experiments at the WIPP rather than at existing waste generation and storage sites; (2) how much waste would need to be emplaced at the WIPP for the experiments; and (3) what are the BRP's recommendations regarding DOE's proposed Operational Demonstration experiments?

The BRP provided individual responses to the congressional delegation and provided testimony to the Senate Committee on Energy and Natural Resources on April 26, 1990. The general observations of the panel were provided to the Senate by Dr. Bahr who stated the following:

> At this point Mr. Chairman, rather than going into my specific observations and recommendations and then having each of the panel members do the same, we decided in order to save time that I would very briefly summarize the general observations of the panel to date. The first and most significant observation in my opinion is that each member of the Blue Ribbon Panel has independently arrived at similar conclusions on each of the issues we were asked to evaluate. Also noteworthy is the high level of congruence of our findings with those of the Advisory Committee on Nuclear Facility Safety (Ahearne Committee). We have also participated in meeting with the WIPP Panel of the National Academy of Sciences and I can report that we also generally share the same views on those issues we have both looked into. Let me now highlight those items upon which members of the Blue Ribbon Panel seem to agree.
>
> 1. The deep bedded salt repository at the WIPP appears to be a safe site for long term isolation of transuranic waste; certainly safer than where this waste is presently stored. Radioactive releases over the long term for an <u>undisturbed</u> WIPP site will probably meet EPA standards (40 CFR 191 Subpart B). Meeting this standard having to consider human intrusion scenarios will be more difficult. Treating the waste so as to change the waste form and thereby force the repository environment to known conditions will significantly reduce present uncertainties. The most controllable variable in the design of the repository environment is the waste form.
>
> 2. <u>In situ</u> testing is important and necessary and should begin as soon as possible. Results of bin and alcove testing should significantly increase the confidence of long range predictions undertaken in the performance assessment. Individual members of the Blue Ribbon Panel agree that the quantity of waste emplaced for experimental purposes should not be limited such as to preclude justifiable experiments. A limit of approximately 1% of the WIPP waste capacity is reasonable. A limit of 0.5% may be too restrictive by precluding the opportunity to undertake important Phase III bin testing of different waste forms resulting from different engineered modifications.
>
> 3. Members of the Blue Ribbon Panel agree conceptually that the EPA suggestion of adding two filled rooms for monitoring purposes is worthy of further consideration by DOE. This approach, however, should be evaluated in the context of verifying facility performance and not considered as part of the test phase itself. We have not, however, been asked to evaluate EPA's suggestion.

> 4. On the subject of Operations Demonstration, our panel agrees that such an undertaking will provide valuable information because of the practical experience gained in system-wide operations. We are in general agreement, however, that a full "ramping up" of an Operations Demonstration should be postponed until such time as the final waste form and repository configuration are determined and that there is a high level of certainty that the Subpart B standard can be met.
>
> 5. We also have general agreement that DOE had underestimated the complexity and level of effort required to comply with RCRA in managing its transuranic-mixed wastes.
>
> Mr. Chairman, I have touched the high points and obviously skipped over many details. Other panel members may wish to elaborate on these and other items. In closing, there is one last item of strong agreement expressed by all panel members. We are very impressed by the responsiveness of DOE to our suggestions. Some examples include 1) The significant improvements that have been made in the DOE organization toward overall systems integration, both vertically and horizontally among the varied elements of transuranic and mixed-transuranic waste management; 2) The significant increase in effort being placed on evaluation of engineered alternatives and waste treatment; 3) The accelerated activity and seriousness with which DOE is now placing on dealing with RCRA and in particular on waste characterization issues; and finally 4) The decision by the Secretary to postpone the start up of the Operations Demonstration program.

The full text of the panel's testimony to the Senate and of the independent reports prepared by the individual panel members are provided in Appendix PEER-2004. There have been significant changes as a result of the recommendations of the BRP and other reviews of the project. These changes are especially dramatic with regard to the PA activities and review. All of the findings and recommendations from the BRP were resolved by the WIPP project to the extent that they were formally closed by the individual BRP members.

9.4.6 Advisory Committee on Nuclear Facility Safety Review

The Advisory Committee on Nuclear Facility Safety (ACNFS) was established by DOE on November 13, 1987, on the recommendation of the NAS. The ACNFS was appointed by the Secretary of Energy to provide advice and recommendations on the safety of DOE's nuclear production and utilization facilities. The facilities reviewed by the ACNFS included the WIPP site and the waste generator sites. An evaluation of the ACNFS review with the screening criteria is provided in Table 9-11.

The ACNFS was composed largely of recognized experts (from outside the DOE) in the field of nuclear energy. Specific expertise of the committee members included environmental chemistry, risk assessment, radioactive waste management, medicine, geology, geochemistry, biophysics, health physics, and environmental regulatory compliance. The ACNFS panel was composed of the following members:

- John Ahearne (Chairman), Sigma Xi;
- Jess Cleveland, U.S. Geological Survey;
- Floyd Culler, EPRI;
- Jacob Fabrikant, University of California, Berkeley;

Table 9-11. Advisory Committee on Nuclear Facility Safety

1. Is the peer review relevant to the CCA?	Yes – The review addressed long term performance, gas generation, and EA issues.
2. Was there a formal report prepared by the reviewer?	Yes – There was a formal report.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes –Although much of the ACNFS's scope could be characterized as technical review, there were other issues, such as the adequacy of the WIPP programs to address gas generation, long term performance, and waste characterization that would be better characterized as peer review.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes –ACNFS reviewed DOE operations, processes and documentation.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes –ACNFS members were recognized experts in the field of nuclear energy.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes –ACNFS members were from outside the DOE and were appointed by the Secretary of Energy under the Federal Advisory Committee Act.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

- William Kastenberg, University of California, Los Angeles;
- Terry Lash, Consultant;
- Harold Lewis, University of California, Santa Barbara;
- James Martin, University of Michigan;
- Dana Powers, SNL;
- William Schull, University of Texas;
- Robert Seale, University of Arizona;

- C. Frederick Sears, Northeast Utilities;
- Gerald Tape, Associated Universities; and
- Victoria Tschinkel, Landers and Parsons.

The ACNFS visited WIPP in June 1989, at which time a subcommittee was formed to review safety issues in further detail. The WIPP subcommittee was chaired by Dr. Tape (Paul D. Rice, a consultant, chaired the subcommittee until October 1990). Members included Drs. Kastenberg, Lash, Martin, and Seale. Special consultants to the subcommittee included

- Konrad Krauskopf, Stanford University (until October 1990);
- James Ling, Consultant (until October 1990);
- Thomas Pestorius, Consultant;
- Thomas Pigford, University of California, Berkeley (until October 1990);
- Bernard T. Resnick, Consultant; and
- Frank Rowsome, Consultant (until October 1990).

The subcommittee subsequently revisited WIPP and other related facilities: SNL, INEL, and the Rocky Flats Plant. Areas of review included unresolved short-term technical and operational issues and long-term environmental performance. A report to the Secretary was issued by the ACNFS on December 11, 1989 (see CCA Appendix PEER, Section PEER.15) and a final report was issued in November 1991 (see CCA Appendix PEER) for the WIPP chapter of the final report.

The 1989 report identified several recommendations to resolve issues related to both short-term operations and long-term performance of the repository. The final report, titled “Final Report on Department of Energy Nuclear Facilities” (Document PB92-119809), contained a section that dealt with its review of WIPP. This final report contained the following recommendations to “increase the probability of successful compliance with EPA’s proposed standards in a shorter period of time . . .”

> Prepare a concise report in a timely manner comparing the expected performance of WIPP with the requirements in EPA’s proposed standard (40 CFR 191). This report should specifically focus on those parameters that are currently significantly uncertain and set forth the actions including alternatives, necessary to reduce the uncertainties to acceptable levels for demonstrating regulatory compliance.
>
> Change current project priorities by putting more emphasis on the use of experts. At this time, panels of experts will provide more significant input to the demonstration of compliance with EPA standards than will the results of the Dry Bin Tests. The Bin Test Program should continue to be focused on reducing uncertainties in those parameters that are most important in determining compliance with EPA’s proposed standards.

> Initially dispose only the contact handled TRU waste that will not pose a gas generation problem. Other TRU wastes can be safely stored above ground until it is determined whether they can be buried at WIPP in compliance with regulatory requirements or have to be treated so that disposal at WIPP is acceptable.

> Immediately begin development and implementation of engineered alternative, especially for newly generated waste. DOE should be a technological leader in waste management and this initiative should go forward even if it were not specifically required to demonstrate compliance with EPA's proposed standards.

The WIPP project initiated and continued several activities to resolve the ACNFS concerns. Specific action plans were developed and implemented. In June 1990, the DOE prepared a concise report summarizing the current understanding of expected performance and the potential for demonstrating compliance with 40 CFR Part 191, Subpart B (Bertram-Howery and Swift 1990). Preliminary PAs in 1990, 1991, and 1992 identified significant uncertainties and provided guidance to the project. The experimental program was refocused to meet the needs of the compliance evaluation, and the underground bin and alcove tests were canceled. Chapter 4.0, and CCA Appendices WCA and WCL address which wastes will be emplaced at WIPP. The subject of EAs was reviewed by two recent peer review panels (see Sections 9.3.3 and 9.4.4). The ACNFS recommendations were formally closed by the Advisory Committee.

9.4.7 Performance Assessment Review Team

The Performance Assessment Review Team (PART) was organized in 1992 by the DOE's Director of Environmental Restoration and Waste Management WIPP Project Management Division (EM-342). The purpose of the PART review was "to assess the adequacy of the WIPP PA program for meeting relevant regulatory standards for the disposal of radioactive and hazardous wastes, to identify any deficiencies in the program, and to make recommendations for improvements." The team members were as follows:

- Bryan Bower (Chairman), DOE/EM-342;
- Charles Voss (Deputy Chairman), Golder Associates, Inc.;
- James Russell, Texas A&M University;
- Neville Carter, Texas A&M University;
- Pamela Doctor, Pacific Northwest Laboratory; and
- Charles Cole, Pacific Northwest Laboratory.

The group was very knowledgeable of geologic repositories and included specific expertise in PA methodology, brine migration, flow and transport modeling, creep and room closure, and site operations. The review team was not completely independent because the chairman of the review team was a staff member of DOE/EM-342, which had oversight responsibility for WIPP. Section 1.4.1 of the PART report (the complete report is provided in Appendix PEER) states that

> The Director of EM-342 and the PART chairperson selected the PART members on the basis of their knowledge of components and processes associated with salt repository and their independence from the WIPP Project. More specific criteria included (1) familiarity with geologic repositories; (2) PA expertise or knowledge of risk assessment techniques; (3) knowledge of RCRA and/or 40 CFR 191 requirements; and (4) no direct association with any of the PA activities for the WIPP.

Note that the report findings "reflect the consensus of team members" and that the final report was signed by all team members. It was included in this application because of its insight into the PA effort at a pivotal time in the direction of PA for the WIPP project. An evaluation of the PART review against the screening criteria is provided in Table 9-12.

The review was primarily conducted during the first half of 1993 and a final report was issued in February 1994. All PART activities were conducted and documented in accordance with EM-342's NQA-1 based QA program. The PART reviewed the pertinent PA documents and activities, toured the WIPP site, and interviewed members of the project staff. The team concluded that

> The review team finds that the work on the WIPP has generally been perceptive, incisive and fundamentally sound. However, for compliance with current standards and regulations, substantial progress and improvements will be necessary in certain areas where additional investigations and documentation may be required; the PA department is fully aware of most of them. These areas include PA documentation, parameter evaluation, conceptual model justification, time-dependent behavior of natural and engineered barriers to fluid migration from the coupled disposal system, and a total system model.

Considerable effort was made to resolve the concerns identified in this review. The PA process has changed significantly since the PART report to address issues identified in this report, as well as to document the conformance with the requirements of 40 CFR Part 191 and criteria of 40 CFR Part 194. Finally, note that the PART final report was provided to the recent conceptual models peer review panel (see Section 9.3.1) for its consideration. The issue of EAs, as they relate to PA, was specifically reviewed by recent peer review panels (see Section 9.3.3).

9.4.8 INTRAVAL

The INTRAVAL project was initiated in 1987 in Stockholm as an international effort to validate geosphere models for transport of radionuclides. The project was initiated by the Swedish Nuclear Power Inspectorate and was first formed as an ad-hoc group with representatives from eight organizations. By the 1990s, INTRAVAL grew to include 24 "parties" from 14 countries and was coordinated by the Nuclear Energy Authority (NEA) of the Organization for Economic Cooperation and Development (OECD). The INTRAVAL philosophy was to use results from laboratory and field experiments as well as natural analog studies in a systematic study of the model validation process. The goal was to evaluate conceptual and mathematical models for groundwater flow and radionuclide transport in the context of PA of repositories for radioactive waste, with particular focus on the validity of model concepts. The project ended in 1997.

Table 9-12. PART Independent Review of WIPP PA

1. Is the peer review relevant to the CCA?	Yes – the review dealt directly with the PA.
2. Was there a formal report prepared by the reviewer?	Yes – the report is titled "Performance Assessment Team's Independent Review of WIPP Performance Assessment Activities (40 CFR 191 and 40 CFR 268.6) for EM-342." The report is dated February 1994.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the review focused on the adequacy of then current PA and RCRA activities at WIPP.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the review evaluated the adequacy of the work of others.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – Section 1.4.1 states "The Director of EM-342 and the PART Chairperson selected the PART members on the basis of their knowledge of components and processes associated with salt repository and their independence from the WIPP Project. More specific criteria included (1) familiarity with geologic repositories, especially salt; (2) PA expertise or knowledge of risk assessment techniques; (3) knowledge of RCRA and/or 40 CFR 191 requirements; and (4) no direct association with any of the PA activities for the WIPP."
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	No – the team chairman was a DOE EM-342 employee. EM-342 has oversight responsibility for WIPP. The remaining members were university staff and a professional consultant.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Yes – report findings reflect the consensus of team members and the final report was signed by all team members.

A number of test cases were studied at various locations around the world. These test cases included field tests, mining operations, natural analogs, and laboratory experiments. In 1990, two test cases from the WIPP site were included as part of the INTRAVAL investigations, and were designated as WIPP1 and WIPP2. An evaluation of the INTRAVAL project reviews against the screening criteria is provided in Table 9-13. These two test cases are discussed in INTRAVAL Progress Reports (numbers 5 through 10) (see CCA Appendix PEER).

Table 9-13. INTRAVAL

1. Is the peer review relevant to the CCA?	Yes – although not a review of the WIPP project specifically, INTRAVAL used WIPP site characterization data to validate models of groundwater flow.
2. Was there a formal report prepared by the reviewer?	Yes – annual INTRAVAL reports and journal articles provide summaries of the findings.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the two cases discussed provide independent evaluation of the validity of the conceptual models used for Salado brine inflow and Culebra groundwater flow at WIPP.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the two cases evaluated the validity of conceptual models for the WIPP site.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – reviewers were internationally recognized experts in their respective fields. Many had extensive experience in radioactive waste disposal projects in other countries.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – reviewers were not involved in the WIPP project, were impartial, and were free from funding considerations.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

9.4.9 Waste Isolation Pilot Plant Conceptual Model Uncertainty Group Review

The WIPP Conceptual Model Uncertainty Group (CMUG) was an advisory group formed and operated in 1993 to provide guidance to SNL's WIPP PA effort. An evaluation of the CMUG activities against the screening criteria is provided in Table 9-14. A report of their evaluation of the WIPP PA was prepared September 27, 1993 (see CCA Appendix PEER) and is summarized below.

Table 9-14. Conceptual Model Uncertainty Group

1. Is the peer review relevant to the CCA?	Yes – the CMUG reviewed the 1992 conceptual models used for PA.
2. Was there a formal report prepared by the reviewer?	Yes – meeting summaries were prepared.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – it was a review of the adequacy of the WIPP conceptual models.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Partially – although the CMUG reviewed the existing PA models, its primary thrust was to recommend improvements in the models.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – group members are internationally recognized experts in their respective fields.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the recommendations were provided from an independent and impartial perspective.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Yes – the review conducted a detailed review of the WIPP conceptual models and provided extensive comment on those models.

The CMUG included expertise in hydrology, geology, geochemistry, risk assessment, and environmental modeling. All committee members were consultants who, at that time, worked outside the SNL community. The panel members were as follows:

- Craig Bethke, University of Illinois;
- Rafael Bras, Massachusetts Institute of Technology;
- Jesus Carrera, Universidad Politechnica de Catluta;
- Neil Chapman, Intera Information Technologies Ltd.;

- Ghislain de Marsily, University Pierre et Marie Curie;
- Daniel Galson, Galson Sciences Ltd.;
- Steven Gorelick, Stanford University;
- Jane Long, Lawrence Berkeley Laboratory; and
- Dennis McLaughlin (Chairman), Massachusetts Institute of Technology.

The charter of the CMUG states

> The conceptual model uncertainty ... group is being formed to provide guidance to the WIPP PA program on how to account for uncertainty associated with conceptual models for the groundwater flow and radionuclide transport systems in the Rustler and other non-Salado formations.

The group was also asked to "... help ... on the development of alternative conceptual models and treatment of conceptual model uncertainty ..."

During its first two meetings in March and October of 1993, the CMUG focused on gaps, ambiguities, questionable assumptions, and simplifications that should be resolved before a final PA is submitted. The CMUG's initial reaction was that the WIPP PA has concentrated too much on simulation exercises and too little on identifying potential pathways and processes. They recommended that the PA should devote more effort to understanding the origins and evolution of the non-Salado environment, particularly its geology, geochemistry, and hydrology. Specific concerns were provided in four areas: (1) regional hydrology, recharge, and the effects of climate change; (2) geologic history, evolution, and structure over a range of scales; (3) geochemical evolution and composition of groundwater; and (4) alternative transport pathways. These concerns are documented in the CMUG report, which is provided in CCA Appendix PEER.

Most of the recommendations provided by the CMUG were implemented. In direct response to the CMUG recommendations, an in-house working group was formed in the spring of 1993 to reevaluate conceptual models for use in PA. That group contained representatives of both PA and experimental activities, and made significant progress during the remainder of 1993 in redefining PA conceptual models. The DOE performed a complete rescreening of all FEPs as part of the preparation of this application. CMUG concerns were addressed as part of this activity. Also, the CMUG reports were provided to the CMPR panel (see CCA Section 9.3.1) for consideration in its assessment of the WIPP PA conceptual models.

9.4.10 Environmental Evaluation Group Reviews

The EEG was established in 1978 as an independent technical advisory group to assist in the State review of the WIPP project. The EEG continues to be funded by the DOE through the New Mexico Institute of Mining and Technology.

The following is a list of the EEG staff members and their technical disciplines in October 2003:

- Matthew Silva (Director), Chemical Engineer;

- James Channell (Deputy Director), Environmental Engineer;
- Larry Allen, Geologic Engineer;
- George Anastas, Health Physicist /Nuclear Engineer;
- Sally C. Ballard, Radiochemical Analyst;
- Radene Bradley, Secretary;
- Patricia Fairchild, Secretary;
- Don H. Gray, Laboratory Manager;
- John Haschets, Assistant Environmental Technician;
- Linda Kennedy, Librarian;
- Lanny King, Environmental Technician;
- Tom Klein, Environmental Scientist;
- Jill Shortencarier, Executive Assistant;
- Susan Stokum, Administrative Secretary;
- Ben A. Walker, QA Specialist;
- Scott Webb, Health Physicist II; and
- Judith F. Youngman, Administrative Officer.

The EEG conducts independent technical analyses of numerous aspects of the WIPP project. These analyses include assessments of reports issued by the DOE and its contractors as they relate to the potential health, safety, and environmental impacts from the WIPP. The EEG also performs independent environmental monitoring of background radioactivity in air, water, and soil, both on- and off-site.

The EEG has published 86 reports relating to numerous aspects of the WIPP project since 1978. An evaluation of the EEG reviews against the screening criteria is provided in Table 9-15. When evaluated against the screening criteria, it was determined that most of the reports (and associated work) involved issues outside the scope of this application and/or appear to represent expert judgment or technical review. However, 15 of the reports published

Table 9-15. EEG Reports

1. Is the peer review relevant to the CCA?	Some of the reports address site characterization and other CCA issues.
2. Was there a formal report prepared by the reviewer?	Yes – EEG prepares and publishes formal reports.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Some of the reports fit the NUREG-1297 definition of peer review.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Some of the reports review the adequacy of the work of others.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the EEG is recognized as an expert group.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – EEG was created to provide an independent technical review of WIPP.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Only those reports which pass the above criteria will be incorporated into the CCA.

before the submission of the CCA appeared to qualify as peer reviews, per NUREG-1297, and address issues relevant to the compliance certification application. Those 15 reports were discussed in CCA Chapter 9 and are mentioned by titles and authors only in this chapter. The EEG has published 25 additional reports since August 1996, EEG-62 to EEG-86. Out of these, 11 reports (EEG-62, 64, 66, 68, 69, 75, 77, 82, 83, 85, and 86) appear to qualify as peer reviews, per NUREG-1297, and address issues relevant to the CRA-2004. Each of these 11 reports is discussed below.

The issues and concerns raised by EEG have been continually evaluated by the WIPP project. A considerable amount of additional testing and analysis have been undertaken because of EEG's involvement, and substantial changes have occurred in the WIPP project as a result.

9.4.10.1 EEG-2 (1978): Review Comments on the GCR, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico, SAND78-1596, Volumes I and II

See CCA Chapter 9 for a summary of this report.

9.4.10.2 EEG-3 (1979): Radiological Health Review of the Draft Environmental Impact Statement (DOE/EIS-0026-D) Waste Isolation Pilot Plant, U.S. Department of Energy

See CCA Chapter 9 for a summary of this report.

9.4.10.3 EEG-8 (1980): The Significance of Certain Rustler Aquifer Parameters for Predicting Long-Term Radiation Doses from WIPP

See CCA Chapter 9 for a summary of this report.

9.4.10.4 EEG-9 (1981): An Approach to Calculating Upper Bounds on Maximum Individual Doses from the Use of Contaminated Well Water Following a WIPP Repository Breach

See CCA Chapter 9 for a summary of this report.

9.4.10.5 EEG-10 (1981): Radiological Health Review of the Final Environmental Impact Statement, (DOE/EIS-0026), Waste Isolation Pilot Plant, U.S. Department of Energy

See CCA Chapter 9 for a summary of this report.

9.4.10.6 EEG-11 (1982): Calculated Radiation Doses from Radionuclides Brought to the Surface If Future Drilling Intercepts the WIPP Repository and Pressurized Brine

See CCA Chapter 9 for a summary of this report.

9.4.10.7 EEG-12 (1982): Potential Release Scenario and Radiological Consequence Evaluation of Mineral Resources at WIPP

See CCA Chapter 9 for a summary of this report.

9.4.10.8 EEG-22 (1983): EEG Review Comments on the Geotechnical Reports Provided by DOE to EEG Under the Stipulated Agreement Through March 1, 1983; and EEG-23 (1983): Evaluation of the Suitability of the WIPP Site

See CCA Chapter 9 for summaries of these reports.

9.4.10.9 EEG-29 (1985): Evaluation of the Safety Analysis Report for the Waste Isolation Pilot Plant Project

See CCA Chapter 9 for a summary of this report.

9.4.10.10 EEG-40 (1989): Review of the Final Safety Analysis Report (Draft), DOE Waste Isolation Pilot Plant

See CCA Chapter 9 for a summary of this report.

9.4.10.11 EEG-41 (1989): Review of the Draft SEIS, DOE Waste Isolation Pilot Plant, April 1989

See CCA Chapter 9 for a summary of this report.

9.4.10.12 EEG-50 (1992): Implications of Oil and Gas Leases at the WIPP on Compliance with EPA TRU Waste Disposal Standards

See CCA Chapter 9 for a summary of this report.

9.4.10.13 EEG-57 (1994): An Appraisal of the 1992 Preliminary Performance Assessment for the Waste Isolation Pilot Plant

See CCA Chapter 9 for a summary of this report.

9.4.10.14 EEG-61 (1996): Review of the WIPP Draft Application to Show Compliance with EPA TRU Waste Disposal Standards

See CCA Chapter 9 for a summary of this report.

9.4.10.15 EEG-62 (1996): Fluid Injection for Salt Water Disposal and Enhanced Oil Recovery as a Potential Problem for the WIPP: Proceedings of a June 1995 Workshop and Analysis, by Matthew K. Silva (Silva 1996)

The following is a summary of the EEG report (EEG-62) and therefore represents the views of the EEG and not necessarily those of DOE.

The potential impact of brine injection on the long-term performance of the WIPP prompted the EEG to organize a June 13, 1995 workshop on the issue. This report publishes the workshop presentations and presents the author's analysis of the workshop issues based on information from the scientific literature, public records, the draft compliance application submitted by the DOE to the U.S. EPA, and the WIPP-specific compliance criteria promulgated by the EPA. The workshop included presentations describing the extent of oil and gas resources, the anomalous water level rises in the Culebra Aquifer, the documented effects of water flooding on the Salado, the geology of waterflooded areas in southeast New Mexico, the current petroleum production practices, the treatment of water injection by the PA effort, and the need for a water flooding scenario in the WIPP PA calculations.

The issues identified include questions about (1) the productive life of an oil field in the Delaware Basin, (2) the extent of oil and gas reserves in unexplored areas, (3) the potential for waterflooding and other secondary recovery methods, (4) the volumes of water to be injected, (5) the availability of water for waterflooding, (6) delays in oil and gas drilling due to the presence of potash, (7) the true extent of potash reserves, (8) evidence of communication between

formations above and below the WIPP through vertical pathways possibly created by the improper abandonment of wells, poorly cemented and cased wells, degraded well casings and cement in saline environments, and (9) violation of existing regulations.

In response to the recommendations in this report, the DOE considered fluid injection as a scenario in the PA included in the CCA. The EPA accepted the DOE arguments and analysis (See EPA Docket A-93-02, Item II-I-1, Attachment 2 and Items II-1-9, II-1-7, II-1-25, II-1-27, II-1-32, and II-1-37).

9.4.10.16 EEG-64 (1997): Review of the Draft Supplement to the WIPP Environmental Impact Statement DOE/EIS-0026-S-2, by Robert H. Neill, James K. Channell, Peter Spiegler, and Lokesh Chaturvedi (Neill et al. 1997)

The following is a summary of the EEG report (EEG-64) and therefore represents the views of the EEG and not necessarily those of DOE.

EEG's review of the WIPP Disposal Phase Draft Supplemental Environmental Impact Statement (SEIS-ll) concentrated on the radiological aspects of the proposed action, including transportation. The alternatives were reviewed in less detail. Some calculations were checked, mostly for the proposed action. Because of time constraints, there was little review of hazardous chemicals, economics, or other environmental assessments.

EEG stated that compared to the proposed action, the proposed alternatives dealt with larger volumes of TRU waste continued over a much longer period of time, and were evaluated in a less rigorous manner. According to EEG, there was a need for real options to dispose of TRU wastes not included in the WIPP statutory limits.

EEG checked the transportation calculations in Appendix E of SEIS-II and compared these results to those contained in EEG-46. EEG concluded that the assessment of transportation risks in SEIS-II is reasonable and adequately conservative.

Analyses in SEIS-II indicated potential advantages to using rail rather than truck transportation for wastes. The rail analyses were not as rigorous as those for truck transportation. However, the findings were consistent with analyses in the FEIS, SEIS-I, and other documents. EEG recommended that DOE should take this opportunity to seriously reevaluate the merits of a "truck/rail mix" or a "maximum rail" policy for WIPP wastes.

9.4.10.17 EEG-66 (1998): Individual Radiation Doses from Transuranic Waste Brought to the Surface by Human Intrusion at the WIPP by James K. Channell and Robert H. Neill (Channell and Neill 1998)

The following is a summary of the EEG report (EEG-66) and therefore represents the views of the EEG and not necessarily those of DOE.

The EPA standards 40 CFR Part 191 require the DOE to evaluate the effects of releases from the repository for both undisturbed and disturbed conditions. Releases from undisturbed events must be evaluated for the radiation dose to individuals (§191.15) and the effect on groundwater quality (§191.24), as well as for the cumulative release of TRU to the accessible environment. Most

other countries with nuclear waste require that radiological risk to an individual be assessed for both undisturbed and disturbed scenarios.

The specific purpose of this report was to:

1. Calculate likely individual doses that would result from the same releases predicted by the CCA,

2. Determine whether these calculated doses exceed limits for radiation exposure from other activities,

3. Compare the stringency of an individual dose standard at WIPP with the release limits in 40 CFR Part 191, and

4. Discuss the appropriateness and feasibility of reducing potential doses to an individual from human intrusion at WIPP.

The deterministic calculations in this report rely primarily on drilling-related analyses in the CCA to determine the source term. Details of the scenarios for workers, individual members of the public, and the population within 80 kilometers (50 miles) of the site are adapted from scenarios in prior WIPP reports. Pathway analyses and dose conversion factors primarily use current methodology from EPA and NRC reports.

There are inherent uncertainties in estimating repository conditions, human actions, and individual doses at WIPP over a 10,000-year period. With this caveat, the report reached the following conclusions.

- Calculated doses to drillers and the resident farmer exceeded annual dose limits for occupational radiation workers only for the low-probability scenarios at the 100-year intrusion time.

- Calculated doses to drilling crew members and the resident farmer exceeded 100 mrem (1 mSv) y^{-1} at the 95 percent probability level. This is greater than the limits allowed in other standards regulating radioactive material, waste disposal, and contaminated site cleanup.

- Calculated doses to the resident non-farmer and the non-resident farmer (for the 95 percent probability release) are greater than the 500-mrem (5 mSv) y^{-1} value NRC used for similar scenarios in establishing low-level radioactive waste concentration limits in 10 CFR Part 61.

- Health effects predicted from a very preliminary integrated collective dose calculation are less than, but within an order of magnitude of, the health effects implied from 40 CFR Part 191 for the amounts released in the CCA.

- An individual dose limit of 100 mrem (1 mSv) y^{-1} (at 95 percent probability level) to the resident farmer at WIPP would be an order-of-magnitude more restrictive than the cumulative release limit in 40 CFR 191. Releases predicted in the CCA would be less

than the 100 mrem (1 mSv) y^{-1}limit but releases predicted in the PAVT would be > 100 mrem (1 mSv) y^{-1}.

- Since individual doses can be substantial, DOE should use ALARA designs (such as treating the waste) to limit these doses.

9.4.10.18 EEG-68 (1998): Evaluation of the WIPP Project's Compliance with the EPA Radiation Protection Standards for Disposal of Transuranic Waste by Robert H. Neill, Lokesh Chaturvedi, Dale F. Rucker, Matthew K. Silva, Ben A. Walker, James K. Channell, and Thomas M. Clemo (Neill et al. 1998)

This report provided the EEG's technical evaluation of the CCA and the EPA's proposed rule to certify WIPP (EPA 1997). The full report is included in Appendix PEER-2004.

The rest of the text in this section contains a summary of the EEG report (EEG-68) and therefore represents the views of the EEG and not necessarily those of DOE.

9.4.10.18.1 Solubility

The solubility of actinides is very important to calculating the releases from the repository. The CCA uses a model known as Fracture-Matrix Transport (FMT) to calculate these solubilities. EEG found that the model predicts differences for actinide sulfate solubilities that cannot be explained by chemistry, thus raising questions about the reliability of this model.

Rather than using an extensive plutonium database, the FMT predictions relied on thermodynamic data for other elements and an oxidation state analog argument. EEG recommended that the calculations be performed using data for plutonium and the values for solubility and complex ion formation contained in the peer-reviewed data compilation by the NEA/OECD.

EEG agreed with EPA's documentation of the shortcomings of the solubility uncertainty ranges advanced by DOE. However, EEG questioned EPA's argument that the ranges are adequate. As noted by EPA, there is a lack of data to determine the uncertainty ranges for oxidation states IV and VI. EEG recommended that the uncertainty range needed to be determined with the appropriate plutonium data.

According to EEG, in the solubility calculations, the CCA inappropriately discounted the role of organic ligands on plutonium solubility by arguing that EDTA is the strongest complexing agent and there is not enough present in the inventory to make a difference. But, EEG argued, citrate forms very strong complexes with actinides in the +4 oxidation state and very weak complexes with other cations. Thus, the solubility of a stable plutonium-citrate complex in individual waste containers needed to be calculated.

EEG claimed that there are serious unanswered questions about the impact of MgO backfill on the solubility of the actinides. It is proposed that MgO will reduce the solubility of the actinides by controlling the pH. However, it is not known how long the early reaction product, nesquehonite, would persist. The FMT model calculates that the presence of nesquehonite drives

the solubility of the +4 actinides, such as Pu, higher than in the no-backfill case. EEG suggested that this required further investigation.

9.4.10.18.2 Spallings

The EEG stated that the CCA spallings model was rejected by the DOE's peer review after submission of the CCA, but a new coherent model and a computer code that calculates the projected releases had not been developed. The EEG found the basis of accepting the predicted release volumes due to spallings as determined by the CCA to be both unnecessarily convoluted and faulty. EEG argued that since this is a mechanism for the largest projected releases from the repository, it is essential that it be treated through defensible conceptual and numerical models.

9.4.10.18.3 Air Drilling

The EEG stated that the air drilling scenario proposed by Dr. John Bredehoeft was rejected on the basis of regulation, despite records of such drilling in the Delaware Basin. Low probability and low consequence are also discussed in EPA's Air Drilling Analysis (EPA 1998c), and the scenario was ruled out again. However, the EEG did not believe that the issue had been resolved. Neither EPA nor DOE examined drilling records in the Texas portion of the Delaware Basin. New developments in underbalanced drilling also inhibit a full understanding of the capabilities of this expanding technology. According to EEG, the EPA's analysis of low consequence, in which a spreadsheet model was used, had serious shortcomings.

9.4.10.18.4 Fluid Injection

According to EEG, for fluid injection activities adjacent to the site, the EPA had accepted a "low consequence" argument based on a model that had not been verified with oil field water flood data, despite the availability of such data. According to EEG, EPA offered a low probability argument based on its expectations of fluid injection practices, although DOE maintained that the probability of future fluid injection practices would be difficult to define. The low probability argument had not been reconciled with the common observation of water flowing through the Salado in water flood operations throughout southeast New Mexico. Further, according to EEG, neither the DOE nor the EPA had adequately addressed concerns about future CO_2 flooding in the vicinity of WIPP. The basis for dismissing the Rhodes-Yates incident did not reflect a review of the technical information presented in that case. DOE had not explained the anomalous water level rises observed for the last 10 years in the Culebra aquifer despite the documented concerns of EEG, EPA, and the NAS WIPP Committee. EEG recommended additional effort to explain the Rhodes-Yates water flooding incident. The EEG maintained that the fluid injection scenario could not be dismissed either on the basis of low consequence or low probability.

9.4.10.18.5 Anhydrite Fracturing

The EEG had a number of questions about the validity of the anhydrite fracture model used in the BRAGFLO code. The EEG stated that the model was unusual in that the effect of fracturing was treated using an equivalent porous medium. All the relevant literature examined by EEG treated fractures as distinct porosity. Use of an equivalent porous medium is not in itself unreasonable; however, the DOE had not referenced a description of similar treatment of the dependence of porosity and permeability on pressure as a result of fracturing. The lack of a clear

development of the BRAGFLO model from established models made its review difficult. The EPA should request that the anhydrite fracture model of BRAGFLO be compared to the treatment of fracture development in hydrofracing codes commonly used in the industry. According to EEG, until the model and its assumptions were properly justified, the EEG found it difficult to accept the results derived from this model.

9.4.10.18.6 Solution Mining

EEG stated that the EPA's conclusion that potash solution mining was not likely at WIPP relied on solicited comments that were factually incorrect and inconsistent with the published scientific literature. DOE and EPA maintain that excavation mining captures the effects of solution mining on the hydraulic conductivity of the overlying aquifers. However, according to EEG, the prediction of subsidence above solution mines can be much more complex than the prediction of subsidence due to excavation mining. According to EEG, it appeared incorrect to calculate mining probability based on past potash production, which was inherently dependent on past mineral economics and the availability of high-grade ore. EEG argued that potash is used by the fertilizer industry and is ultimately used for the production of food. It seemed reasonable to EEG to assume that the demand for food would continue and low-grade potash ores would eventually be mined to meet this demand.

9.4.10.18.7 Groundwater Flow and Radionuclide Transport through the Culebra

EEG stated that a number of questions related to the flow and transport through the Culebra had been identified by the EEG that were not addressed by the EPA. These questions relate to the conceptual models of the origin and flow of water in the Culebra aquifer, transport modeling through the Culebra, and justifying the assumed values of the chemical retardation parameter (K_d) in the CCA calculations.

9.4.10.18.8 BRAGFLO 2D/3D Modeling

According to EEG, the results of the DOE's screening analysis for repository processes (FEP S-1) suggest that the 2D BRAGFLO model used in the CCA calculations may misrepresent repository performance at pressures above the anhydrite fracture pressure. There is the potential of substantially greater brine saturation in the repository at higher pressures than calculated for the CCA. The discrepancy between the 2D and 3D versions of BRAGFLO may have underestimated radionuclide releases to the surface. To resolve this issue, the EEG recommended that several three-dimensional (3D) BRAGFLO simulations of the repository should be performed using the parameter values of vectors used in the CCA PA. The 3D BRAGFLO simulations should be used to provide repository conditions for the normal suite of DBR calculations. The calculations should also be assessed in terms of impact on spallings calculations.

The DOE and EEG held a meeting on February 17, 1998 to try and resolve this issue. It was agreed at that meeting that there was sufficient reason to further investigate the potential for greater brine inflow to the repository using 3D modeling compared to the calculated value using the 2D model of the CCA. It was agreed that a simulation corresponding to a parameter vector

that led to high pressure and anhydrite fracturing in the CCA calculations would be sufficient to demonstrate the potentially increased brine inflow compared to the CCA calculation.

9.4.10.18.9 Brine Reservoirs

The EEG raised a number of issues related to the Castile Formation brine reservoirs in commenting on the CCA. The EPA accepted all the EEG suggestions except one related to the assumption of the probability of encountering brine reservoirs. EEG disagreed with the EPA on this issue. The CCA assumed an eight percent probability on the basis of faulty assumptions. The EEG recommended a 100 percent probability on the basis that the WIPP-12 brine reservoir was large enough to most likely extend under the repository. The EPA sampled on a range of 1 to 60 percent, but, according to EEG, provided no basis for assuming less than 60 percent. Based on the arguments that the geophysical (time-domain electro-magnetic survey) data may be interpreted to indicate the brine to be under 60 percent of the repository, and that some boreholes adjacent to the brine-producing boreholes are known to be dry, the EEG was willing to accept the assumption of a fixed 60 percent probability of encounter, and recommended that a new PA calculation be run with that fixed value.

9.4.10.18.10 Waste Issues

DOE calculations showed that nonrandom emplacement of radionuclides in the repository led to significantly higher releases from cuttings and cavings and spallings. EEG recommended that revised calculations should be incorporated into the CCDF even though partial sensitivity analyses indicate that nonrandom emplacement would not, in itself, result in noncompliance.

EEG also stated that the expected quantity of cellulosics, rubber, and plastic (CRP) materials in the repository was slightly greater than the waste repository limit and that the ability to characterize CRP waste with sufficient accuracy had not been shown. EEG recommended that the limit should be controlled on a per-panel basis rather than for the entire repository.

9.4.10.18.11 Assurance Requirements

There are six assurance requirements in the EPA standards (40 CFR 191) that were incorporated to provide additional confidence in the repository because of the inherent uncertainty in projecting the future behavior of natural systems and inadvertent human action. The EEG agreed with the EPA determination of two of these six requirements, the active and the passive institutional controls, but had questions about the other four. According to EEG:

1. The monitoring plan did not appear to meet the intent of the standards.

2. DOE's retrieval plan and the EPA's determination of its compliance with the requirement appeared to give a false sense of security regarding the retrievability of waste.

3. WIPP did not appear to meet the intent of the resource disincentive requirement. EEG argued that this is another reason for additional engineered barriers to be incorporated in the WIPP design for making the waste less respirable and soluble through treatment and repackaging. Since DOE had plans to treat or repackage 85 percent of the existing CH-TRU waste anyway, EEG argued, this recommendation should be easy to implement.

9.4.10.18.12 Individual Protection Requirements

Although EEG had minor disagreements about several DOE assumptions in evaluating the Individual Dose Requirements, they agreed that compliance with these requirements had been demonstrated.

9.4.10.18.13 Environmental Standards for Ground water Protection

EEG believed there was a very low probability of significant Underground Source of Drinking Water (USDW) contamination by an undisturbed release. However, EEG stated that 40 CFR 191.24 specifies that no contamination is permitted if the USDW is initially at or above the radionuclide limits of 40 CFR 141. Therefore, EEG recommended submitting data showing the USDWs were below allowed limits or that there was a zero probability of any contamination reaching the USDW.

The EPA gave serious consideration to all the comments in this report. Their responses were provided in the EPA's Response to Comments (EPA 1998b).

9.4.10.19 EEG-69 (1998): Sensitivity Analysis of Performance Parameters Used in Modeling the WIPP by Dale F. Rucker (Rucker 1998)

The following is a summary of the EEG report (EEG-69) and therefore represents the views of the EEG and not necessarily those of DOE.

This report contains the results of sensitivity analysis on the WIPP PA performed by EEG by changing selected values or the range of selected values that were used in the CCA. This type of sensitivity analysis would distinguish the important parameters of repository performance, while testing the robustness of the codes involved. The analysis also allowed for the testing of the limit to which the disposal system would fail under extreme conditions. This is also useful in characterizing the important parameters. The results are briefly described below. The full report is included in Appendix PEER-2004.

9.4.10.19.1 Borehole Intrusion Rate

The consequence of future human intrusion scenarios into the WIPP was investigated in the CCA, as required by EPA in 40 CFR Part 194 (EPA 1996b), and included the possibility of mining and deep and shallow drilling for resources.

The 40 CFR Part 194.33 criteria state that the likelihood of a drilling intrusion into the Delaware Basin be calculated by considering the frequency of drilling over the past 100 years for all resources and using that rate for the 10,000-year future of the WIPP. A total of 46.8 boreholes per km^2 per 10,000 years were estimated based on past drilling of resources at depths greater than 655 m (2150 ft), which equal 10,804 boreholes per century in 23,102.1 km^2 (14,439 mi^2) (area of Delaware Basin).

The above drill intrusion rate for the 10,000-year future of the WIPP was used by DOE in the CCDFGF model. Due to the uncertainty in predicting future human activities, the effect of altering this rate on the CCA calculations has been assessed in this report.

The modeling associated with an increased borehole rate shows that a factor of approximately 23 is needed to reach the EPA release limit at a probability of 10^{-1} from values used in the CCA. The overall mean for the highest release tested at 0.468 boreholes/km^2/yr (1.2 boreholes/mi^2/yr) exceeds 10 EPA unit limit at the 10^{-3} probability on the CCDF curve. This high rate of borehole intrusion, however, does not seem likely, as the number of boreholes drilled in the Delaware Basin in 10,000 years would have to exceed 1,000,000 per century, or 4,680 boreholes per km^2 (11,981 boreholes per mi^2) per 104 years.

9.4.10.19.2 Probability of Brine Encounter at WIPP

The probability of encountering brine at the WIPP from an intrusion into a Castile brine reservoir is uncertain. The parameter describing the probability was set to eight percent in the CCA, and changed to a range of probabilities from 1 percent to 60 percent in the EPA's PAVT. Since the extent of the reservoir beneath the WIPP is unknown, the influence of this parameter was tested at higher values at 50 percent and 100 percent. These values were based on the potential that the Castile brine reservoir encountered by WIPP-12 extends below the waste area.

The modeling presented in this report only compared CCA release values to the proposed higher probability of encounter, and found the parameter to be unimportant in the CCA. The increase in releases from the 8 percent to 100 percent was only 0.1 EPA units (35 Ci).

9.4.10.19.3 Castile Brine Reservoir Parameters

The reservoir parameters used in the CCA were derived from borehole information that is mainly outside the domain of the WIPP repository. The borehole distances ranged from 6 km (3.75 mi) to over 17.7 km (11 mi) from the repository center. New values were assigned to several parameters that describe a Castile brine reservoir based on WIPP-12 data more closely identified to the conditions at the repository.

The parameters associated with describing a Castile brine reservoir include reservoir volume, rock compressibility, reservoir pressure, and permeability. Assuming an inadvertent human intrusion, modeling of these parameters began with the two-phase flow code, BRAGFLO, and ended with calculations of solid and liquid waste released to the accessible environment. The outcome showed that there is no significant change in releases for the CCDF due to small changes in the reservoir parameters.

9.4.10.19.4 Solubility Modeling of Actinides

The results of the EEG analysis showed that increases in solubility using CCA brine release volumes had limited effect on compliance, with an overall increase on the mean CCDFs by 0.09 EPA units. Even when the solubility was increased to absurdly high values, the maximum release was limited by the availability of the actinide source. At a solubility of 8×10^{-3} M (compared to the CCA's 4.4×10^{-6} M for Pu+4 in Salado brine), the overall mean for DBR was increased from 0.04 to 1.3 EPA units.

Bounding calculations were performed on conditions resulting in the highest solubilities in the repository. These included nesquehonite and no backfill. For the nesquehonite simulations, it was assumed that the mineral would persist for the entire proposed history of the repository.

Only median solubility values were used, as opposed to the CCA, which generated a set of expected values from a range of -2 to +1.4 orders of magnitude from the median to capture the uncertainty. The assumption of the intermediate species being long-lived overestimates the expected conditions, and the EEG does not suggest that MgO should not be used as a backfill material. The models were established to better understand the performance of the repository.

The consequences of higher solubilities were quite high. The overall mean release for the CCA and PAVT were 0.2 and 0.4 EPA units at 10^{-3} probability, respectively. The overall mean for the increased solubilities of nesquehonite and no backfill are 6.0 and 8.0 EPA units at the 10^{-3} probability, respectively. The limit for compliance, according to 40 CFR Part 194, is 10 EPA units. While these calculations, based on DOE's own solubility values, do not violate the containment requirements, they show that there is little margin for error.

9.4.10.19.5 Flow and Transport Modeling within the Culebra

The EEG's concern in the Culebra modeling related to actinide sorption (K_d values), limitations in assumed future mining, and actinide solubility values assumed. The effects of extended mining, low K_ds, and high solubilities were combined in an effort to test the synergistic effect of all the previous results. The overall mean for the release through the Culebra was as high as one EPA unit (or 344 Ci) at a 10^{-3} probability of release. The addition of the Culebra releases to the overall mean of all combined releases moved the CCDF closer to the EPA compliance limit by 12 percent, but did not show noncompliance.

The EPA gave serious consideration to all the comments in this report. The responses were provided in the EPA's Response to Comments (EPA 1998b).

9.4.10.20 <u>EEG-75 (1999): Evaluation of Risk and Waste Characterization Requirements for the Transuranic Waste Emplaced in WIPP during 1999 by James C. Channell and Ben A. Walker (Channell and Walker 2000)</u>

The following is a summary of the EEG report (EEG-75) and therefore represents the views of the EEG and not necessarily those of DOE.

Section IV.B.2.b of the RCRA permit from the NMED contained language that appeared to prohibit placement of non-mixed wastes that were not characterized in accordance with the requirements of the permit's Waste Analysis Plan (WAP). The justification for adding Section IV.B.2.b was that mixing WAP-certified wastes with pre-permit wastes created unknown risks that should not be a part of permit performance standards. Statements were made during permit public hearings and in written testimony that the risks might be substantial, but there was no indication of the nature of these risks or their magnitude.

This report provides a technical evaluation, conclusions, and recommendations of the following Section IV.B.2.b issues:

- A comparison of pertinent WAP requirements with pre-permit waste characterization;
- A risk analysis of the pre-permit waste emplaced in Room 7. Expected and bounding risks from routine operations and possible accidents are evaluated.

9.4.10.20.1 Conclusions

1. The NMED-approved WAP has made explicit many of the undocumented assumptions and implied good practices from the DOE's pre-permit waste characterization program. Although there are differences between the pre-permit and WAP characterization programs, the pre-permit program appears to substantially meet the technical requirements in the WAP.

2. Deviations granted by DOE during pre-permit waste characterization and premature closures of some corrective actions generated during independent audits may be the most significant differences from the permit waste characterization requirements.

3. Estimated carcinogenic risks to an underground worker, a surface worker, and a member of the public due to routine operations from all the TRU wastes emplaced in Room 7 in 1999 are 6 to 8 orders of magnitude less than risk levels allowed by the permit. Noncarcinogenic risks are 7 to 10 orders of magnitude below allowed risks.

4. Even if volatile organic compound (VOC) emissions are much higher than risk calculations estimate, the Confirmatory VOC Monitoring Plan in use at WIPP would detect concentrations that are three orders of magnitude below allowable permit limits.

5. Risks to the surface worker and member of the public from low-probability accidents are essentially all from radionuclide releases and are lower than the allowable permit risks from routine VOC releases. Risk to the underground worker is significant (1.7×10^{-3} if the accident occurs).

9.4.10.20.2 Recommendations

Questionable data for the individual container lots of pre-permit waste could be reviewed by NMED for conformance with the WAP requirements, if necessary. This determination should consider all deviations and include input from the DOE.

The calculated nonaccidental risks from the pre-permit waste in Room 7 are too low to justify any remedial or other actions involving these wastes.

Radionuclide risks to underground workers from low-probability spontaneous fire and roof-fall accidents should be considered when setting restrictions on worker access to the south 1600 and east 300 drifts.

DOE and NMED have successfully resolved these issues.

9.4.10.21 EEG-77 (2000): Plutonium Chemistry Under Conditions Relevant for WIPP Performance Assessment: Review of Experimental Results and Recommendations for Future Work by Virginia Oversby (Oversby 2000)

The following is a summary of the EEG report (EEG-77) and therefore represents the views of the EEG and not necessarily those of DOE.

This report reviewed the issues related to the chemistry of Pu as it may affect the potential for release of radioactivity from the WIPP repository after closure. Emphasis was placed on conditions appropriate for the human intrusion scenario(s), since human intrusion has the largest potential for releasing radioactivity to the environment under WIPP conditions. According to the author, the most significant issues that need to be addressed in relation to Pu chemistry under WIPP conditions are (1) the effects of heterogeneity in the repository on Pu concentrations in brines introduced under the human intrusion scenario, (2) the redox state of Pu in solution and potential for Pu in solid phases to have a different redox state from that in the solution phase, (3) the effect of organic ligands on the solubility of Pu in WIPP-relevant brines, and (4) the effects of TRU-waste characteristics in determining the solubility of Pu. These issues are reviewed with respect to the treatment they received in the CCA (DOE 1996a), DOE's response to EEG's comments on the CCA, and EPA's response to those comments as reflected in the final EPA rule that led to the opening of the WIPP (EPA 1998a). Experimental results obtained in DOE's Actinide Source-Term Test Program (STTP) during the last two years are reviewed and interpreted in the light of other developments in the field of Pu solution chemistry. This analysis is used as the basis for a conceptual model for Pu behavior under WIPP conditions.

This report identifies three issues that, according to the author, can be addressed as part of the five-year recertification cycles. First, the impact of organic ligands on the complexation of a system with multiple cations could be delineated by some simple experiments with thorium (Th) (IV), citrate, EDTA, Ca^{2+}, and one or more transition metals. An experiment with Pu (IV) could be designed to determine the liability of Pu oxidation states in the presence of organic ligands. Second, the issue of using analogs for Pu could be addressed with appropriate experiments using uranium (U) and Pu at redox conditions in the range anticipated at the WIPP. Attention to the published experimental results of U and Pu could make a considerable contribution to this effort. Third, the issue of uncertainty in calculated actinide solubility can be resolved with experimental data for Pu (IV) compounds of appropriate compositions. The report also recommends starting by constructing a database for U and Pu using the published, peer-reviewed NEA/OECD U and Pu databases.

These issues are addressed in CRA-2004 and will continue to be addressed in future recertifications.

9.4.10.22 EEG-82 (2001): Evaluation of Proposed Panel Closure Modifications at WIPP by Lawrence E. Allen, Matthew K. Silva, James K. Channell, John F. Abel, and Dudley R. Morgan (Allen et al. 2001)

The following is a summary of the EEG report (EEG-82) and therefore represents the views of the EEG and not necessarily those of DOE.

A key component in the design of the WIPP repository is the installation of concrete structures as panel seals in the intake and exhaust drifts after a panel has been filled with waste containers. As noted in the EPA final rule, the panel seal closure system is intended to block brine flow between the waste panels at the WIPP. On April 17, 2001, the DOE proposed seven modifications to the EPA concerning the design of the panel closure system.

EPA approval of these modifications is necessary since the details of the panel design are specified in EPA's final rule as a condition for WIPP certification. However, the EPA has not determined whether a rulemaking would be required for these proposed design modifications. On September 4, 2001, the DOE withdrew the request, noting that it would be resubmitted on a future date.

The EEG contracted with two engineers, Dr. John Abel and Dr. Rusty Morgan, to evaluate the proposed modifications. The EEG has accepted the conclusions and recommendations from these two experts:

1. replacement of SMC with a generic salt-based concrete,
2. replacement of the explosion wall with a construction wall,
3. replacement of freshwater grouting with salt-based grouting,
4. allowing surface or underground mixing, and
5. allowing up to one year for completion of closure.

The proposed modification to allow local carbonate river rock as aggregate is acceptable pending demonstration that no problems will exist in the resulting concrete. The proposed modification to give the contractor discretion in removal of steel forms is not supported. Instead, several recommendations are made to specifically reduce the number of forms left, thereby reducing potential migration pathways.

EEG's recommendations have been considered in the DOE's decision-making process.

9.4.10.23 EEG-83 (2002): Identification of Issues Relevant to the First Recertification of WIPP by Lawrence E. Allen, Matthew K. Silva, James K. Channell (Allen et al. 2002)

The following is a summary of the EEG report (EEG-83) and therefore represents the views of the EEG and not necessarily those of DOE.

This report updates issues that the EEG considers important for the first recertification of WIPP. These issues encompass a variety of technical areas, including actinide solubility, fluid injection scenarios, solution mining, Culebra flow and transport, spallings modeling, and nonrandom waste emplacement. The report made the following recommendations.

Some uncertainty remains in understanding the persistence of higher Pu oxidation states because of reliance on modeling (with its associated assumptions) and limited experimental results. The EEG recommends additional experimental work towards parameters for a proposed conceptual kinetic model of Pu solubility. In addition, the EEG recommends an intrusion scenario in PA that would account for a heterogeneous, noninundated repository that may include persisting higher oxidation states of Pu.

Intrusion scenarios including the consequences of fluid injection were rejected at the time of the CCA. With increasing drilling activity in the vicinity of the WIPP, fluid injection scenarios

should be reexamined for recertification PA. These scenarios should consider potential consequences from oil field secondary recovery techniques, such as waterflooding, in addition to ancillary injection operations, such as brine disposal and pressure maintenance wells. The WIPP resides in a resource rich locale, and PA should consider all reasonable activities associated with such a location.

Likewise, solution mining scenarios should also be reconsidered during recertification. Solution mining should be anticipated for extraction of potash reserves as well as for the excavation of salt caverns for storage of natural gas, oil field wastes, and chemical feedstocks. Consideration of solution mining for potash extraction is a natural alternative for a maturing mineral district as ore grades decrease below the economic cutoff necessary for traditional mining methods. Dissolution of halite to create underground storage caverns is a practice already used in the Delaware Basin for oil field waste and natural gas. Research suggests that it may also be a viable method for storage of other items, such as chemical feedstocks.

The Culebra dolomite unit of the Rustler Formation is acknowledged as a likely pathway for breach of the WIPP repository. Hence, long-term PA requires an accurate understanding and modeling of flow and potential actinide transport.

Most of the issues concerning the Culebra raised at the time of the CCA resulted from poor discretization of the modeling grid and the inherent heterogeneity of the aquifer. The DOE had originally planned to replace the previous flow code with MODFLOW and implement a finer grid. This, coupled with a new transport code, STAMMT-L, would have addressed problems with numerical dispersion and spatial truncation errors. In addition, STAMMT-L incorporates a dual-porosity, multirate approach, which the DOE demonstrated to be a superior representation of transport within the heterogeneous character of the Culebra.

The EEG remains concerned over the continuing water level increases in the Culebra aquifer. The DOE is currently engaged in an effort to determine the source, or sources, of the rising water elevations, which have continued to increase for the last 14 years. Until a cause is determined, the validity of the Culebra conceptual for PA is in question. The EEG recommends that the DOE reconsider its decision not to change the Culebra modeling codes and grid discretization. In addition, the EEG urges the DOE to conclusively determine the source of the water level increases and adjust the conceptual model accordingly.

The CCA demonstrated the importance of spallings as a potential release mechanism. The spallings model used in the CCA did not adequately characterize the physical processes of spall. Work was in progress by the DOE on a new spallings model intended for use during recertification. This model was to improve predictions of long-term performance, reduce uncertainty, and enhance public confidence. However, the DOE recently announced that the new model would only be used for impact analysis and not for recertification PA. The EEG urges the DOE to reconsider and to use the new model for PA.

Random emplacement of waste in the repository was assumed in the CCA. However, waste emplacement practice since the 1999 opening has demonstrated that random emplacement is not likely. Specific waste-streams shipments to WIPP depend on the DOE's agreements with the host states, and on the readiness of particular waste streams for shipment. It has been previously

demonstrated by the DOE that nonrandom emplacement could increase the mean release values. The EEG recommends that DOE develop a waste-loading plan based on their shipment schedule. All intrusion scenarios could then consider nonrandom emplacement, providing better estimates of releases.

The DOE has considered all these recommendations in the preparation of CRA-2004.

9.4.10.24 EEG-85 (2003): Analysis of Emplaced Waste Data and Implications of Non-Random Emplacement for Performance Assessment for the WIPP by Lawrence E. Allen and James K. Channell (Allen and Channell 2003)

The following is a summary of the EEG report (EEG-85) and therefore represents the views of the EEG and not necessarily those of DOE.

The WIPP Land Withdrawal Act (LWA) recognized that after the initial certification of the WIPP and start of disposal operations, operating experience and ongoing research would result in new technical and scientific information. The EEG has previously reported on issues that it considers important as the DOE works towards the first recertification. One of these issues involves the assumption of random emplacement of waste used in the PA calculations in support of the initial certification application. As actual waste emplacement data are now available from four years of disposal, the EEG performed an analysis to evaluate the validity of that initial assumption and determine implications for PA.

Panel 1 was closed in March 2003. The degree of deviation between actual emplaced waste in Panel 1 and an assumption of random emplacement is apparent with concentrations of ^{239}Pu being 3.20 times, ^{240}Pu being 2.67 times, and ^{241}Am (americium) being 4.13 times the projected repository average for the space occupied by the waste.

A spatial statistical analysis was performed using available Panel 1 data retrieved from the WWIS and assigned room coordinates by SNL. A comparison was made between the waste as emplaced and a randomization of the same waste. Conversely, the distribution of waste as emplaced is similar to the distribution of waste in the individual containers and can be characterized as bimodal and skewed with a long high-concentration tail. The distribution of randomized waste is fairly symmetrical, as would be expected from classical statistical theory. In the event of a future drilling intrusion, comparison of these two distributions shows a higher probability of intersecting a high-concentration stack of the actual emplaced waste over that of the same waste emplaced in a randomized manner, as was assumed in the certified PA calculations. This suggests that the methodology used during the certification PA calculations underestimated potential releases by cuttings and cavings. That methodology sampled each layer in a stack separately and used the mean concentration for each waste stream.

The DOE performed a spallings release bounding analysis at the time of the initial certification. However, the selection of the statistical sample size of the bounding analysis assumed independence of samples, which is not characteristic of nonrandom waste emplacement. Instead, it is demonstrated that the emplaced waste is spatially dependent. Therefore, the bounding analysis may not be adequate in the event of continued nonrandom emplacement. As for cuttings and cavings releases, the probability of a high-concentration intersection during an intrusion is

increased because of nonrandom emplacement. PA calculations should either incorporate this increased probability or an adequate bounding calculation should be performed using spatial statistical methodology.

The use of Pipe Overpack Containers for isolation of the high ^{239}Pu waste may reduce the amount of material brought to the surface as a result of an intrusion. However, the integrity of these containers over the regulatory period has not yet been demonstrated. If the DOE wishes to take credit for the container, the DOE needs to provide an analysis of structural integrity and the potential effects resulting from the use of Pipe Overpack Containers.

The DOE has addressed the issues raised in this report in the preparation of CRA-2004.

9.4.10.25 EEG-86 (2003): Contact Handled Transuranic Waste Characterization Requirements at the Waste Isolation Pilot Plant by Matthew K. Silva, James C. Channell, Ben A. Walker, and George Anastas (Silva et al. 2003)

The following is a summary of the EEG report (EEG-86) and therefore represents the views of the EEG and not necessarily those of DOE.

The EEG has been evaluating the development of WAC since 1979. This report consolidates the findings and recommendations of the EEG's technical reviews and current positions with respect to waste characterization requirements. Through this report, the EEG has offered the following observations and recommendations for waste characterization requirements

9.4.10.25.1 Acceptable Knowledge

AK is the principle waste characterization technique for all of the regulatory agencies. AK is necessary and should be retained. At this time, EEG supports the use of the Hazardous Waste Facility Permit (HWFP) AK requirements, since they are the most explicit.

9.4.10.25.2 Headspace Gas Sampling and Analysis

It is desirable to maintain a comprehensive Headspace Gas (HSG) program for WIPP CH-TRU waste. However, it should be possible to require less than 100 percent headspace gas sampling in some cases. The primary concern is with organic sludges and older waste containers where knowledge of the waste is of lesser quality.

9.4.10.25.3 Drum Age Criteria

Drum Age Criteria (DAC) is necessary to ensure that HSG sampling of waste containers will measure gas concentrations at least 90 percent of equilibrium. DAC values are required in both the HWFP and the TRAMPAC. The EEG supports this requirement.

9.4.10.25.4 Real Time Radiography

All WIPP waste containers are required to undergo either radiography or visual examination (VE) by the HWFP. Usually retrieved wastes undergo Real Time Radiography (RTR) and newly generated wastes are examined by VE. RTR has been a very effective means of verifying AK

and discovering prohibited items in waste containers. It is also used to show compliance with several EPA and TRAMPAC requirements. The overall radiography program is an important part of the WIPP waste characterization program and should be retained. It may be possible to reduce some of the detailed procedural requirements in the HWFP.

9.4.10.25.5 Visual Examination for Retrievably Stored Waste

A small percentage (currently less than two percent) of retrievably stored waste is required by the HWFP to undergo VE for confirmation of RTR. The VE process has the potential for slightly greater radiation exposure than the other waste characterization requirements, although the EEG has seen no data to indicate that exposures are significant enough to justify reducing the requirement. The DOE has been successful in modifying the HWFP on retrievably stored VE, and this would be the preferred process for seeking further reductions.

9.4.10.25.6 Visual Examination for Newly Generated Waste

VE is the method DOE usually prefers for newly generated waste because it can be done at the time the waste container is filled. The EEG has not objected to any part of this requirement except to state that the requirement for two trained VE operators to perform the visual process "may be overkill" and that a single verification should be adequate.

9.4.10.25.7 Coring Sampling and Analysis

Currently the EEG continues to believe that the homogeneous sampling and analysis are unnecessary characterization requirements in the HWFP. EEG's principal reason for this position is that the data are not used for any additional regulatory control (metals releases from accidents or long-term processes would be controlled by radionuclide control requirements and VOCs and semi-volatile organic compound (SVOC) by HSG or the Confirmatory VOC Monitoring Plan).

9.4.10.25.8 Level II Management and Waste Certification HWFP Requirements

The DOE has listed these management and certification requirements as characterization activities in a recent cost analysis. EEG has not previously commented on these requirements. However, EEG indicated that their current evaluation stated that the required procedures are very detailed and somewhat redundant. This may be one of the areas to which the general EEG comment, "We believe waste characterization requirements are excessive," applies.

9.4.10.25.9 Characterization Support HWFP Requirements

EEG remains supportive of the WIPP audit and surveillance program. EEG has also stated that it does not believe the relaxation of audit requirements and QA/QC is an appropriate way to reduce the regulatory burden.

9.4.10.25.10 EPA Non-Radiological Requirements

EPA's residual liquids, nonferrous metal, and CPR materials requirements should remain and can continue to be determined as they are now, by the RTR and VE requirements of the HWFP.

The ferrous metal requirement can continue to be met by counting waste containers emplaced in the repository.

9.4.10.25.11 EPA Radiological Requirements

The EEG agrees with the radioassay requirements for CH-TRU waste specified in Appendix A of the report and the current procedures for modifying the document.

Current requirements for reporting the 10 required radionuclides should remain. ^{241}Pu should also be reported. The current requirement that all radioassay should be performed by WIPP-certified assay systems should be maintained. Justification for less than 100 percent quantification and determination of isotopic ratios may be possible for some, but certainly not all, waste streams.

9.4.10.25.12 NRC Container Properties

The TRAMPAC requirements for residual liquids, filter vents, and the sealed container prohibition should be retained. These are all verified by requirements in the current HWFP.

9.4.10.25.13 NRC Nuclear Properties

All nuclear property requirements should be retained and Appendix A of the CH-TRU WAC methodology should be used.

9.4.10.25.14 NRC Gas Generation Requirements

Requirements for measuring the chemical, payload classification, and radionuclide concentrations necessary to ensure H gas concentration criteria are met must be retained. There have been many changes, via the Certificate of Compliance (C of C) revision process, which have allowed additional containers to be shipped without changing the H gas criteria and additional changes may be justifiable in the future.

The flammable gas concentration limit of ≤ 500 ppm should be retained as described in the current revision of the TRAMPAC. Alternate methods (with appropriate QA) will be necessary if future changes to the HWFP affects the use of HSG sampling as the method for meeting this criteria.

9.4.10.25.15 Waste Isolation Pilot Plant Waste Acceptance Criteria

The WAC has served a useful historic purpose in developing initial criteria that have been adopted by the other three regulatory agencies. Currently it is a useful document for listing most of the requirements from all four sets of criteria. It would be more useful if the technical justification for each criteria or requirement were restored.

The unique role of the WAC in including any necessary operational safety and health requirements not included elsewhere is very important and must be constantly evaluated via the technical safety requirements (TSR) portion of the CH-TRU Safety Analysis Report, and any necessary changes incorporated into the CH-TRU WAC.

This report was published in late September 2003, during the final preparation phase of CRA-2004. It has been included here for completeness. The DOE will consider these recommendations in dealing with the waste characterization issues in the future.

9.4.11 Fracture Expert Group Review

SNL convened the Fracture Expert Group (FxG) during the spring of 1993. A summary report of the FxG meeting (see CCA Appendix PEER) was prepared in March 1993.

As discussed in the meeting report, the charter of the group was to:

1. Review the current (as of 1993) BRAGFLO model assumptions for permeability and porosity as a function of pressure for their adequacy as first-order representations of the changes in the anhydrite beds adjacent to the waste disposal horizons due to pressurization of the formation.

2. Recommend improvements in the characterization of changes in permeability and porosity in the anhydrite beds adjacent to the waste disposal horizons due to pressurization of the formation.

An evaluation of the FxG review against the screening criteria is provided in Table 9-16. Since the 19-member FxG contained SNL staff, SNL contractors, and external experts, it was not a truly independent review group. However, the group, and especially the 11 external experts, provided a valuable review of the issues and made several valuable recommendations which were, to a large extent, independent. The group included nationally and internationally recognized expertise in experimental mechanics, materials science, fracture and fluid mechanics, and computational fluid dynamics. The group members were as follows:

- Pierre Bérest, Ecole Polytechnique, Palaiseau, France;
- Barry Butcher, SNL;
- Peter Davies, SNL;

Table 9-16. Fracture Expert Group

1. Is the peer review relevant to the CCA?	Partially – although the FxG reviewed the BRAGFLO conceptual model, its focus was primarily related to compliance with Part 268, rather than Part 191, requirements.
2. Was there a formal report prepared by the reviewer?	Yes – meeting summaries were prepared.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the FxG reviewed the adequacy of 1993 BRAGFLO model assumptions as they relate to repository pressurization.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Partially – the FxG's purpose was as much to recommend improvements in BRAGFLO as to evaluate its adequacy.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – group members are recognized experts in their respective fields.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Partially – the 19-member FxG contained SNL staff, SNL contractors, and external experts so it was not a truly independent review group. However, the 11 external experts provided valuable review and recommendations from an independent and impartial perspective.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Yes – the FxG provided valuable review of one of the conceptual models used in PA.

- Chandrakant Desai, University of Arizona;
- Dick Ewing, Texas A&M University;
- Mert Fewell, SNL;
- Mel Friedman, Texas A&M University;
- Bezalel Haimson, University of Wisconsin;
- Samuel W. Key, RE/SPEC Inc.;

- Jane Long, Lawrence Berkeley Laboratory;
- Darrell Munson, SNL;
- Sia Nemat-Nasser, University of California-San Diego;
- Karsten Pruess, Lawrence Berkeley Laboratory;
- Thomas Russel, University of Colorado at Denver;
- Chin-Fu Tsang, Lawrence Berkeley Laboratory;
- Palmer Vaughn, Applied Physics Inc.;
- Wolfgang Wawersik, SNL;
- Stephen Webb, SNL; and
- Teng-Fong Wong, State University of New York-Stonybrook.

The meeting summary report concluded that "The proposed first-order model in BRAGFLO for representing changes in permeability and porosity due to pressure-induced changes in the anhydrite is an acceptable first approximation." The FxG report also made recommendations for additional studies to support an extended and improved second-order model in BRAGFLO for simulating the two-phase flow occurring in the altered anhydrite marker beds (MB 138 and MB 139). These recommendations are summarized in the FxG report (CCA Appendix PEER).

Recommendations by the FxG for additional studies of fracturing were driven by concerns regarding the gas-phase transport of VOCs away from the repository via pressure-induced fractures. Gas-phase transport is not a mechanism that could contribute to actinide releases from the disposal system. The DOE therefore concludes that the current PA model used to approximate the effects of pressure-induced fracturing, which is a refinement of the model presented to the FxG, is adequate for estimating actinide releases from liquid-phase transport. The FxG meeting summaries were provided to the recent conceptual models peer review panel for consideration during its evaluation of the WIPP conceptual models.

9.4.12 Fanghänel Review – WIPP Thermodynamic Model for Trivalent Actinides

Dr. Thomas Fanghänel of the Institut für Nukleare Entsorgungstechnik, Forschungszentrum Karlsruhe, Germany, was contracted to perform an independent review of the thermodynamic models WIPP developed to predict potential dissolved concentrations of actinides in WIPP brines. An evaluation of his review against the screening criteria is provided in Table 9-17.

He was tasked to provide an independent assessment of the methods used to estimate the dissolved concentrations of III, IV, and VI actinides. For the V actinides, he performed an independent assessment of the WIPP augmentation of his neptunium (Np)(V) thermodynamic

Table 9-17. Fanghänel Review of the WIPP Thermodynamic Model for Trivalent Actinides

1. Is the peer review relevant to the CCA?	Yes – the reviewer evaluated one of the models used in the WIPP PA.
2. Was there a formal report prepared by the reviewer?	Yes – a report was prepared.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the work was a review of the WIPP thermodynamic model for predicting dissolved concentrations of trivalent actinides in WIPP brines.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the review evaluated the adequacy of the WIPP thermodynamic model for trivalent actinides.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – Dr. Fanghänel is an internationally recognized expert.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the reviewer is independent of the WIPP project.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

model, as well as its use for estimating dissolved concentrations of V actinides in WIPP brines. He performed the review and submitted his final report, dated May 7, 1996. A copy of the full report is provided in CCA Appendix PEER.

Dr. Fanghänel is an internationally recognized expert regarding the thermodynamic modeling of actinides and is completely independent of the WIPP project. His qualifications include extensive experience with the development and evaluation of thermodynamic models for actinides. He is first author of a journal publication documenting the Np(V) dissolved concentration model that serves as the basis for the WIPP +V actinide dissolved concentration model.

The following paragraphs are quoted from Dr. Fanghänel's report:

> For the WIPP thermodynamic model the ion interaction approach (Pitzer equations) was chosen for modeling the excess properties of the aqueous solution (activity coefficient model). At present, the Pitzer approach is the most sophisticated semiempirical approach for the Gibbs excess energy of a concentrated electrolyte solution. It is widely used and a database with ion interaction parameters covering a large variety of different solution species is available.....
>
> The WIPP model treats the interaction of AN(III) with Cl^- and SO_4^- as strong ion-ion interaction without invoking the formation of complex species. Within the composition range of the WIPP brines, this is a reasonable approach, which was demonstrated in several comparisons between model calculations and data...
>
> The applied assumptions for the development of the WIPP thermodynamic model are conservative and simplify the overall model. This is a prerequisite for calculating dissolved actinide concentrations in the very complex repository system.
>
> In general, the model represents the present state of the knowledge of aqueous solution thermodynamics. The chosen activity coefficient model and the applied data base are, with a few exceptions, suitable for calculating maximum trivalent actinide concentrations in WIPP brines.
>
> The model needs to be improved in some parts. This concerns in particular the hydrolysis equilibria of trivalent actinides which have to be introduced into the model. Moreover, the reviewer recommends that the model regarding the interaction of carbonate complexes in concentrated electrolyte solutions be refined.

In accordance with Dr. Fanghänel's suggested improvement in the model concerning the hydrolysis equilibria of trivalent actinides, the recommended data were incorporated into the CHEMDAT database. Regarding the second suggestion, carbonates are no longer considered to be significant to repository performance due to the implementation of MgO backfill.

9.4.13 Independent Technical Review of the Bin and Alcove Test Programs

The objective of this ITR team assessment of proposed TRU waste experiments at WIPP, as specified in the charter, was to: "Review the need for, and technical validity of, the Bin and Alcove test programs, as defined in the Test Phase Plan, the Technical Needs Assessment Document, and individual test plans."

The team consisted of nine technical personnel from the DOE, LANL, Lawrence Livermore National Laboratory (LLNL), and private consultants. The team members had a large amount of expertise and experience in mechanical, chemical and civil engineering, earth and environmental science, and geology. The team was composed of the following members:

- Stephan Brocoum (Team Leader), DOE, Office of Geologic Disposal;
- Philip Thullen (ITR Team Leader), LANL;
- Deborah Bennett (ITR Team Leader), LANL;
- Richard Beddoes, Golder Associates;
- Corale Brierley, Private Consultant;
- Jan Docka, Roy F. Weston, Inc.;

- Joseph Farmer, LLNL;
- Ron Guimond, Ogden Environmental and Energy Services;
- Stan Kosiewicz, LANL;
- Abraham Lerman, Northwestern University;
- John Shaler, Private Consultant;
- Terry Steinborn, Applied Research Associates, Inc.; and
- Dave Swale, British Nuclear Fuels Limited.

Although the independence of the ITR could be questioned because it had a DOE staff member as Team Leader, Dr. Brocoum, as a Director in the Office of Geologic Disposal, had no responsibility or authority as regards the WIPP project. Further assurance of the independence of the team was provided by the credentials and professional stature of the team members and the direct oversight of the ITR review by the Technical Oversight Board (TOB). The independence and technical qualifications of the ITR members were verified by several parties prior to commencement of work. A summary evaluation of the ITR team against the screening criteria for peer reviews is shown in Table 9-18.

The team began its review in July 1993, and completed a final report (see CCA Appendix PEER) in December of that year. The review process consisted of document review, formal presentations by the DOE and its contractors and other groups, and interviews with personnel. The team met several times to develop consensus on issues and recommendations and to prepare its report.

A TOB was chartered to review all aspects of the ITR team's activities. The TOB was composed of senior level individuals with extensive experience in the development, execution, management, and evaluation of large and technically involved projects. The TOB members included

- Dr. Colin Heath (Chairman), GC Management Associates;
- Mr. Richard Baxter, Independent Consultant;
- Mr. William Hamilton, Independent Consultant;
- Dr. Mujid Kazimi, Massachusetts Institute of Technology;
- Mr. Dennis Lachel, Lachel and Associates, Inc.;
- Mr. John Maddox, Independent Consultant; and
- Ms. Debra Marsh, Marsh Consulting Group, Ltd.

Table 9-18. Independent Technical Review of the Bin and Alcove Test Programs at the WIPP

1. Is the peer review relevant to the CCA?	Yes – this review addresses waste characterization and gas generation issues.
2. Was there a formal report prepared by the reviewer?	Yes – there was a formal report.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – this review addressed the adequacy of plans for testing to be done for waste characterization and PA.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – this review addressed the adequacy of the work and made recommendations for changes.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the team members are recognized as experts in their respective disciplines.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – although the Team Leader was a DOE staff member, he had no organizational responsibility for the WIPP project. Also, the professional stature of the ITR members and the oversight of the TOB ensured the independence of the ITR team review.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

They provided a solid reference point of experience and ideas against which the ITR team tested its ideas regarding lines of inquiry and the logic and validity of findings and conclusions. The results of the review were discussed with the TOB, and their guidance was used in preparation of the ITR report.

The following statements are excerpted from the "Executive Summary" of the ITR report.

> Principal Assessment
>
> The review team concluded that: there is no scientific, regulatory, or operational imperative to perform the Bin or Alcove tests at WIPP with radioactive waste. Other tests can and should be performed at WIPP and elsewhere to confirm information used for regulatory compliance

> demonstration and certification. This is an assessment of the technical justification for the tests, not of the ability of site personnel to perform the tests or of the repository to accept TRU waste.
>
> Path Forward Recommendation
>
> Preparation and submission of compliance and permitting packages at the earliest possible date are the foundation of the recommended path forward. All other near term work elements should support these activities. All regulatory permits, approvals, and certification should be acquired before any in situ confirmatory or operational tests are performed in WIPP with radioactive waste.
>
> A lack of clear guidance from cognizant regulators on specific requirements for regulatory compliance should be the only source of future delay in operating WIPP as a TRU waste repository. While most, although not all, of the relevant regulations exist, no clear statement of what constitutes acceptable submissions has been produced by the regulatory bodies....The ITR team believes that delay will be minimized by making the regulators part of the process through early submission of the regulatory packages.
>
> Although all regulations do not exist and existing regulations may change, the ITR team believes that sufficient gas generation information is available to complete the performance assessments and other elements required to prepare and submit compliance and permitting packages within 18 months. The recommended conceptual compliance and permitting process will allow the TRU waste disposal phase to begin in three years if specified milestones are met...
>
> Bench-scale laboratory tests using simulated and/or actual waste should be continued or completed, and additional tests initiated if required. Results of bench-scale tests will not only explain individual gas generation mechanisms but also the synergistic effects of combined mechanisms....
>
> ..... These tests can be performed above ground, at WIPP or elsewhere, unencumbered by mine safety regulations.

As recommended by the ITR team, the bin and alcove tests were subsequently abandoned and the WIPP program was redirected to completing the regulatory compliance documentation on an accelerated schedule. Bench-scale laboratory tests using actual TRU wastes were conducted at LANL and the INEL.

9.4.14 Performance Assessment Reviews

In 1989, SNL prepared a PA methodology report (Marietta et al. 1989) which provided information on the PA process developed to demonstrate compliance with criteria under development for 40 CFR Part 191, Subpart B. Formal comments on the methodology report were provided to the DOE by the EPA and the NMED. The DOE responses to the comments were subsequently provided in the 1990 PA report.

The DOE, through SNL, published iterative PA reports describing the WIPP disposal system beginning with the first PA report in 1990 (Bertram-Howery et al. 1990), followed by subsequent iterations in 1991 and 1992. Each updated report constituted a substantial revision of the previous document based on new information, experiments, and comments from interested individuals. With regard to comments from interested parties, a number of these reviews could be classified as peer reviews for the purposes of this application. An evaluation of these reviews against the screening criteria for peer reviews is provided in Table 9-19.

Table 9-19. External Review of the WIPP PA Reports

1. Is the peer review relevant to the CCA?	Yes – the reviews specifically focused on the PA reports.
2. Was there a formal report prepared by the reviewer?	Yes – the reviews evaluated the adequacy of the WIPP PA reports.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the reviews addressed the adequacy of the PA reports.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the reviews were based on evaluations of the PA.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the reviewing organizations are recognized as experts in their respective disciplines.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Yes – the reviewers were independent of the WIPP project.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	N/A

9.4.14.1 1990 Performance Assessment Report

The first PA report (Bertram-Howery et al. 1990) was issued in December 1990. As noted above, the 1990 report provided responses to the EPA and NMED comments that had been received on the 1989 methodology document.

Several groups reviewed and commented on the 1990 report. In particular, several requests were made from the NMED and others for additional clarification of several aspects of the report. Specific responses to the comments provided by the various reviews were developed and subsequently documented in the 1991 PA report.

9.4.14.2 1991 Performance Assessment Report

The second PA report (WIPP Performance Assessment Division 1991) was issued in December 1991. The 1991 report included responses to comments that had been received from the reviews of the 1990 report.

Intera, Inc. was requested by the SNL WIPP Performance Assessment Division to review Volumes 1-4 of the 1991 WIPP PA report (WIPP Performance Assessment Division 1991).

Although the independence of the review could be questioned because it was contracted directly by the WIPP PA Division, it is provided here for completeness; the results of the review were important in establishing the direction of PA. The review's purpose, as stated in the Intera report (see Appendix PEER-2004), was to consider "technical questions pertaining to the performance assessment methodology and its application and results, as well as issues of organization, presentation and flow of information between the various sections, chapters and volumes."

The review is contained in a March 1992 report (see CCA Appendix PEER). The report summary states the following:

> Our major technical concerns are in the general area of treatment of uncertainty in the assessment, including in particular treatment of scenario uncertainty, data and parameter uncertainty, and model uncertainty....
>
> We have also suggested a possible modification to the methodology for generating CCDFs for human intrusion events, and have noted that the treatment of human intrusion, as a particular class of scenarios, is imbalanced in places...
>
> With regard to presentation and organization of the report, there is substantial room for improvement.... In particular, the report is excessively long, and very much in need of a good summary of the order of 100 pages (or less). More attention needs to be paid to the relevance of the information presented to the final assessment results, and to the potential audience for the report. Excessive use of mathematics is made throughout the report, and figures are too few in number, are poorly explained or are too complex. In addition, relatively minor errors are rife, particularly in Volume 3.

The Intera comments were carefully considered by SNL while preparing the succeeding report. Accordingly, appropriate modifications were incorporated in the 1992 PA report. Specific responses to the various third-party reviews were documented in the 1992 PA report.

9.4.14.3 1992 Performance Assessment Report

The third PA report (WIPP Performance Assessment Department 1992) was published in December of 1992. This report provided responses to comments that had been received on the 1991 PA report. As with the earlier PA reports, several groups reviewed and provided comments on the 1992 report. In particular, EPA, NMED, EEG, and the Attorney General (AG) provided comments to DOE. Comments received from the EPA, NMED, and the AG are discussed below. Comments from the EEG are discussed in Section 9.4.10.13.

9.4.14.3.1 Environmental Protection Agency Review of the 1992 Performance Assessment Report

The EPA's review of the 1992 iteration of PA was provided in two separate transmittals. The first group of review comments addressed only Volumes 1 through 3. The second set of comments primarily addressed Volumes 4 and 5.

Review of Volumes 1 through 3

In January 1994, the EPA provided extensive comments on Volumes 1 through 3 of the 1992 iteration of the PA. The EPA grouped its discussion of the issues into six primary categories: (1) format and content, (2) access to information, (3) regulatory issues, (4) use of expert panel elicitation and investigator judgement, (5) models, and (6) QA. The EPA comments and the DOE responses for each comment are provided in Appendix PEER-2004.

Volumes 4 and 5

In October of 1994, the EPA provided final comments to the DOE on the 1992 iteration of PA. Although the comments addressed the entire PA, the primary focus was Volumes 4 and 5. The EPA grouped its comments into five primary categories: (1) scenarios, (2) BRAGFLO and SANCHO computer code relationships, (3) Culebra groundwater modeling, (4) inventory, and (5) institutional controls. The EPA comments and the DOE responses for each comment are provided in Appendix PEER-2004.

9.4.14.3.2 New Mexico Attorney General Review of the 1992 Performance Assessment Report

The New Mexico AG also provided comments on the 1992 PA report. These comments are provided in CCA Appendix PEER, along with the DOE responses.

As part of his review, the Attorney General contracted with Dr. Elisabeth Paté-Cornell. Dr. Paté-Cornell is a Professor of Industrial Engineering and Engineering Management at Stanford University and is currently president of the Society for Risk Analysis. She has written and lectured extensively on probabilistic risk assessment and has testified in Congress on proposed legislation on the subject. Dr. Paté-Cornell prepared a report for the AG entitled Conservatism of the Performance Assessment and Decision Criteria for WIPP. The comments are provided in CCA Appendix PEER with a cover letter documenting its transmittal from the AG to DOE.

9.4.14.3.3 NMED Review of the 1992 Performance Assessment Report

The NMED also provided comments on the 1992 PA report. The comments are provided in Appendix PEER together with DOE responses. The NMED's comments were detailed but focused upon several issues relevant to screening scenarios and events for PA. Within this context, NMED provided detailed comments on three primary issues:

1. additional groundwater migration pathways (the Dewey Lake (Redbeds) Formations and Magenta Member of the Rustler),

2. subsidence potential related to dissolution of evaporite units caused by downward percolation of meteoric or groundwater through inner or outer zones of boreholes, and

3. subsidence potential related to extraction of oil and gas adjacent to the facility boundary.

9.4.14.4 Department of Energy Response to Comments on the 1990, 1991, and 1992 Performance Assessment Reports

In summary, DOE responded to comments from interested groups and individuals by revision of subsequent PA reports and by providing specific responses to those comments in the subsequent reports. Chapter 6.0 is the result of many years of work on PA activities by the DOE. PA has undergone extensive revision as a result of input from groups such as EPA, NMED, EEG, and the AG.

9.4.15 Technical Support Group Reviews

During 1993, the Technical Support Group (TSG) was tasked by the DOE to provide recommendations on the following topics:

- Experimental Plan for Tracer Testing in the Culebra Dolomite,
- PA Parameters, and
- Large-Scale Seals Test Program.

Evaluating the resulting reviews against the screening criteria developed for this application indicated that the first two qualify as peer reviews (see Table 9-20). As regards the large-scale seals test program, the review team was mostly comprised of subcontractors with a long working relationship with the WIPP project. The reviewers' independence could also be questioned for the other two reviews; however, the case for the review's independence was stronger. These reviews are included in this application for the sake of completeness and because they were significant in terms of the PA program. The reports were provided to the appropriate recent peer review panels for consideration. A brief discussion of the selected reviews is presented below.

The members of the review teams included expertise in geochemistry, geomechanics, hydrology, physical chemistry, NEPA compliance, PA, and waste management. The members involved in the reviews included the following:

- Paul Drez (TSG Core Member), Independent Consultant;
- Paul Cloke, Science Applications International Corporation – Nevada;
- David Dennison, Advanced Sciences, Inc. – Denver;

Table 9-20. Technical Support Group Reviews

1. Is the peer review relevant to the CCA?	Yes – the reviews involved aspects of site characterization and PA.
2. Was there a formal report prepared by the reviewer?	Yes – reports were prepared.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the reviews addressed the adequacy of WIPP plans and programs.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the reports addressed the adequacy of work prepared by the WIPP project.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Yes – the reviewers are recognized experts in their respective disciplines.
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Partially – although several of the reviewers were independent, some of the TSG members involved in the reports discussed in this section routinely participated in the WIPP project over a period of several years as subcontractors to DOE.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Yes – the reports were significant in terms of their impact on the WIPP PA program. The reports were also provided to the recent peer review panels.

- Darrel Dunn, Advanced Sciences, Inc. – Denver;
- John Kircher, Battelle;
- David Lechel, Independent Consultant;
- John Schatz, Independent Consultant;
- Jim Tollison, Independent Consultant; and
- Rose Zeiler, Advanced Sciences, Inc. – Denver.

9.4.15.1 Review of Experimental Plan for Tracer Testing in the Culebra Dolomite

The review team was asked to address whether additional experiments for fluid flow and transport characterization of the Culebra are necessary. Additionally, if these experiments were determined to be necessary, the team was asked to evaluate whether the planned Culebra Tracer Tests, as described in the proposed Test Plan, would provide the data necessary to establish whether the Culebra retards radionuclide transport sufficiently to demonstrate that the Culebra is an effective geologic barrier.

The formal report prepared by the team as a result of the review is provided in CCA Appendix PEER, along with the transmittal letter to the DOE.

The recommendations from the TSG report on tracer testing in the Culebra dolomite were considered in the planning of ongoing hydrological studies and testing performed at the WIPP site. In addition, the review resulted in enhanced communication between the principal investigators generating data and the PA staff. The TSG report was provided to the recent conceptual models peer review panel for its consideration.

9.4.15.2 Performance Assessment Parameters

A copy of the report that resulted from the TSG review of the PA parameters is provided in CCA Appendix PEER. The purpose of the TSG review, as stated in the transmittal letter to the DOE, was to

> conduct a detailed review of many of the parameters that form the basis for the PA calculations for the WIPP Project. This effort emphasized the key 49 PA parameters that were sampled in the 1992 PA calculations, and, as time permitted, included a preliminary review of an additional 80 parameters. Data type, data quality, data interpretation, and source documentation were evaluated and each reviewer categorized the data based on their professional judgment. A database called PERFORM was developed to help in the management of the reviews.

From the report's "Summary of Findings," the team concluded that "Results of the TSG review of PA parameters indicate that improvement is needed in areas of Data Quality, Data Interpretation, and Source Documentation. It is the opinion of the TSG that this needs to be accomplished to ensure regulatory compliance."

IRTs were subsequently formed to specifically review and qualify, where appropriate, existing data. As discussed in Chapter 5.0, the IRTs were successful in qualifying a large amount of the data that had been collected prior to establishment of a qualified QA program. Data that were not qualified by the IRTs were qualified by three of the recent peer review panels, as discussed in Sections 9.3.4, 9.3.5, and 9.3.6.

PA parameter values were developed and controlled in accordance with the SNL QAPD and QAPs. QAP 9-2 was developed and used to document the selection, development, and entry of parameter values used in the PA. The PA database is controlled and maintained using SNL QAP 9-4. This QAP establishes the process for ensuring that parameter values and their associated documentation are maintained in a traceable, retrievable, and controlled environment and allow for the reproducibility of results.

Once the requirements controlling the development of parameter values (QAP 9-1 or QAP 9-5) are fulfilled, the parameter/distribution development is documented or referenced on the applicable WIPP Parameter Entry Form (Form 464). Form 464 provides a traceable link to the qualification of those portions of the data packages that support the parameter development.

9.4.16 NEPA Reviews

The NEPA requires formal analysis, documentation, and an appropriate level of review for proposed major federal actions involving potentially significant environmental impacts. NEPA documentation and the associated public review and comment periods provided environmental input and opposing viewpoints from a variety of sources for the DOE decisions regarding development of the WIPP. An evaluation of the external NEPA reviews against the screening criteria is provided in Table 9-21.

NEPA documentation of the WIPP includes the 1980 Final Environmental Impact Statement (FEIS) (DOE 1980) and the 1990 Final Supplement Environmental Impact Statement (FSEIS) (DOE 1990a). Another environmental impact statement, the SEIS-II (DOE 1997), was completed in 1997.

A Draft Environmental Impact Statement (DEIS) (DOE 1979) was prepared by the DOE and provided to the public for review in April 1979. The significance of impacts associated with the various alternatives were assessed. Comments on the DEIS were obtained during seven days of public hearings and a 141-day written-comment period. A total of 167 persons presented oral statements on the WIPP during the public hearings that were held in Santa Fe, Carlsbad, and Hobbs, New Mexico; Idaho Falls, Idaho; and, Odessa, Texas. Ninety-three letters, several longer than 50 pages, were received during the written-comments period. Commenters included: federal agencies such as EPA, NRC, the Department of the Interior, and the Department of Health, Education and Welfare; agencies from at least 26 states, including several New Mexico agencies; and groups like the EEG.

In response to the comments, the DEIS was extensively revised to prepare the FEIS, which was published in October 1980. Comments were grouped into 30 major issues, which were then discussed in Chapter 15 of the FEIS. Appendix P of the FEIS reproduced in full the comments received from various federal agencies and the cover letters from all official responses from the various states. Copies of all comments received, including transcripts of the public hearings, were placed in the DOE public reading rooms for WIPP. The DOE Record of Decision, published January 28, 1981, announced the DOE decision to proceed with the construction of surface and subsurface facilities in southeastern New Mexico.

A draft SEIS (DOE 1989) was published and provided to the public in April 1989. During the 90-day comment period, the DOE held nine public hearings at locations in Colorado, Georgia, Idaho, New Mexico, Oregon, Texas, and Utah. In addition to the testimony of nearly 1,000 individuals who spoke at the hearings, the DOE received 1,275 written documents and two petitions with a combined total of approximately 2,200 signatures.

Table 9-21. NEPA Documentation Reviews

1. Is the peer review relevant to the CCA?	Yes – NEPA documentation addresses long-term performance, siting issues, mitigation, etc. which are directly relevant.
2. Was there a formal report prepared by the reviewer?	Yes – the results of the public reviews were submitted to the DOE. The DOE formally compiled comments and responses.
3. Was the review a peer review rather than a technical review? a. A peer review's purpose is to confirm the adequacy of the work being reviewed. b. A technical review verifies compliance to predetermined requirements; industry standards; or common scientific, engineering, and industry practice.	Yes – the reviews focused on the adequacy of NEPA documentation prepared for the DOE.
4. Was the review a peer review rather than an expert judgment? a. A peer review confirms the adequacy of the work being reviewed. b. An expert judgment is used to elicit either numerical values for parameters (variables) or essentially unknowable information.	Yes – the review evaluated the adequacy of environmental documentation produced for the DOE.
5. Was the technical expertise of the reviewer at least that needed to perform the original work?	Mixed – the technical expertise of the reviewers varied widely, but included several public agencies and oversight groups (e.g., NRC, EEG).
6. Were the reviewers independent? a. Were the reviewers involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed? b. Did the reviewers have sufficient freedom from funding considerations to assure the work was impartially reviewed?	Mostly – very few of the reviewers had any affiliation with the WIPP or DOE.
7. If the answer to any of the above questions is no, is there an overriding consideration which would still serve to qualify the review as an appropriate and acceptable peer review?	Yes – the public comments on the WIPP NEPA documents have, in aggregate, provided an extensive and thorough review of many issues, several of which are relevant to the CCA.

The DOE reviewed the comments, categorized them by issue, revised the draft SEIS as appropriate, and prepared a comment-response document (Volume 3 of the FSEIS) that presents synopses of the comments and the DOE's responses. Indices to the comments were provided in Volumes 4 and 5 of the FSEIS and served to help locate specific questions or statements and the DOE response. Volumes 6 through 13 of the FSEIS reproduce the public comments received on the draft SEIS and transcripts of oral testimony provided during the public hearings. The draft SEIS was extensively revised, as a result of the comments, in development of the FSEIS, which was published in January 1990. The Record of Decision, dated June 22, 1990, documented the DOE determination to proceed with the phased development of the WIPP. The Record of

Decision included a commitment to prepare SEIS-II before deciding whether to proceed with the WIPP disposal phase.

Public scoping activities prior to the publication of SEIS-II included:

- publishing a Notice of Intent in the Federal Register on August 23, 1995 and a notice reopening the comment period, published on October 13, 1995;
- a public comment period from August 23, 1995 to October 16, 1995; and
- public scoping meetings held in Carlsbad, Albuquerque, and Santa Fe, New Mexico; in Boise, Idaho; and two meetings in Denver, Colorado.

The Implementation Plan (DOE 1996d), published in May 1996, documents the results of the scoping process and provides guidance for preparing SEIS-II.

SEIS-II (DOE 1997) was published in September 1997. The purpose of this document was to provide information on environmental impacts of the DOE's TRU waste disposal operations at WIPP. SEIS-II evaluated a Proposed Action, three Action Alternatives based on the waste management options presented in the Final Waste Management Programmatic Environmental Impact Statement, and two No Action Alternatives. The Proposed Action described the treatment and disposal of the basic inventory of TRU waste over a 35-year period. The basic inventory is that waste currently permitted in WIPP based on current laws and agreements. The Action Alternatives propose the treatment of the basic inventory and an additional inventory as well as the transportation of the treated waste to WIPP for disposal over a 150- to 190-year period. The three Action Alternatives included the treatment of TRU waste at consolidation sites to meet WIPP planning-basis WAC, the thermal treatment of TRU waste to meet Land Disposal Restrictions, and the treatment of TRU waste by a shred and grout process. The No Action Alternatives proposed the dismantling and closure of WIPP and storage of the waste. One No Action Alternative proposed treating the waste thermally before placing it in retrievable storage.

SEIS-II evaluated environmental impacts resulting from the various treatment options; the transportation of TRU waste to WIPP using truck, a combination of truck and regular rail service, a combination of truck and dedicated rail service, and the disposal of this waste in the repository. Evaluated impacts included those to the general environment and to human health. Additional issues associated with the implementation of the alternatives were discussed to provide further understanding of the decisions to be reached and to provide the opportunity for public input on improving DOE's Environmental Management Program.

9.4.17 International Peer Review by the Nuclear Energy Authority/ International Atomic Energy Agency International Review Group, 1996-97 (NEA/IAEA 1997)

Agreement was reached on June 7, 1996 between the DOE, the NEA OECD, and the International Atomic Energy Agency (IAEA) to organize an international peer review of the long-term safety analysis of the WIPP. The objective of the joint NEA/IAEA peer review was to examine whether the postclosure assessment of the WIPP described in this application is appropriate, technically sound, and in conformity with international standards and practices.

The peer review was organized jointly by the NEA and the IAEA. The agencies appointed an International Review Group (IRG) of seven international experts actively involved in national radioactive waste management programs - from waste management organizations, national regulatory bodies, universities, and scientific consultancies. Two representatives each from the NEA and the IAEA provided a joint secretariat and contributed technically to the review.

None of the members of the IRG had ever worked directly on the WIPP project (or worked as a contractor or subcontractor to the DOE). All, however, had participated in international meetings, projects, and comparison exercises in which the WIPP project had been represented, and had some prior knowledge of the project and of PA as practiced by the DOE. In some cases, this knowledge was extensive and detailed, and gained over many years in bilateral or multilateral exchanges.

The following members served on the IRG:

- Ken Bragg, AECB, Canada, Chairman;
- Jordi Bruno, QuantiSci, Spain;
- Klaus Kühn, Technical University of Clausthal, Germany;
- Sören Norby, SKI, Sweden;
- Richard Storck, GRS, Germany;
- Trevor Summerling, Safety Assessment Management Ltd., U.K.;
- Hiroyuki Umeki, PNC, Japan;
- Arnold Bonne, IAEA, Secretariat;
- Gordon Linsley, IAEA, Secretariat;
- Phillipe Lalieux, NEA/OECD, Secretariat; and
- Claudio Pescatore, NEA/OECD, Secretariat.

The review began in October 1996 and was conducted over a six-month period. The review was based on detailed documentation provided by the DOE, a site visit to the WIPP, and discussions with the specialists in the WIPP project. A report titled “International Peer Review of the 1996 Performance Assessment of the US Waste Isolation Pilot Plant (WIPP)”containing the group’s findings were published in April 1997. The full report is included in Appendix PEER-2004.

The rest of the text in this section is a summary of the IRG report and therefore represents the views of the IRG and not necessarily those of DOE.

9.4.17.1 Objective of the Review

The terms of reference for the review were negotiated between the DOE, the NEA, and the IAEA based on a first proposal by the DOE. The significant parts of the Terms of Reference are reproduced in Appendix 2 of the URG report (NEA/IAEA 1997). Therein, it is stated that:

> The objective of the international review is to examine whether the post-closure performance assessment of the WIPP in the CCA is appropriate, technically sound and in conformity with international standards and practices.

The interpretation of this objective was discussed at length within the IRG, especially the phrase "in conformity with international standards and practices."

The IRG decided to conduct its examination to answer the following broad questions stemming from the above statement.

1. Is the WIPP 1996 post-closure PA appropriate?

   The IRG agreed that this should be interpreted as meaning appropriate in the context of the objective of the CCA, which is to satisfy the EPA regulations. The IRG also agreed that it should not undertake a formal comparison with the EPA regulations since this is the responsibility of the EPA. In this respect, it is emphasized that this review was organized to provide the DOE an independent, international perspective on the 1996 post-closure PA of the WIPP.

2. Is the WIPP 1996 post-closure PA technically sound?

   The IRG agreed that this item should be the primary focus of the review. For example: Have adequate data and process information been used? Are the conceptual models and their underlying assumptions scientifically based or reasonable? Have adequately tested mathematical and computer tools been applied?

3. Is the WIPP 1996 post-closure PA in conformity with international practices? That is, is the scope of the assessment, methods of analysis, and quality of application consistent with good practice in other countries?

4. Is the WIPP 1996 post-closure PA in conformity with international guidance and standards? That is, are the calculated end-points consistent with international guidance and standards in the manner these are formulated in other countries?

9.4.17.2 Scope

The terms of reference identify the CCA (Volume I) as the primary material to be reviewed. After individual examination of this document and joint discussions, the IRG made the following initial observations and decisions:

- The CCA was prepared by the DOE to comply with the EPA regulations. These regulations provide detailed guidance on how to demonstrate compliance and are focused on the evaluation of specific performance indicators.

- The CCA, Volume I does not constitute a self-contained or sufficient description of the 1996 PA. Rather, it is necessary to examine many of the CCA appendices in order to find technical information at the level required by the IRG.

- The iterative program of PA of the WIPP has been the subject of a number of previous independent reviews, notably by the NAS (1996). These other reviews, several of which are summarized in Chapter 9 of the CCA, Volume I, would not be examined as part of this review.

- Preparing a view on the four broad questions identified in Section 9.4.17.1, the IRG considered that it would also be able to examine and comment on other issues indicated by the terms of reference, such as the clarity and transparency of the documentation.

9.4.17.3 Conclusions

9.4.17.3.1 Observations on the Specificity of the Waste Isolation Pilot Plant Case

- The WIPP project and the CCA are different in several respects from geological disposal projects and assessment documentation in other countries.

- The WIPP facility is sited in an area in which mineral resources are being actively and extensively exploited.

- The regulator has provided detailed guidance on the assessment approach, documentation and, for the assessment of future human actions, model assumptions.

- The CCA is tightly focused on compliance with the EPA regulations, and does not represent a full safety case as understood in most other countries.

These observations are statements of fact, not criticisms. Such differences, however, have had a strong influence on the PA carried out by the DOE, and have been taken into account by the IRG in formulating its conclusions.

9.4.17.3.2 Evaluation with Respect to the Terms of Reference

9.4.17.3.2.1 *Appropriateness*

The CCA was specifically designed by the DOE to meet the requirements of the EPA regulations. The IRG has not found any indication that the information presented is not appropriate in the context of the EPA requirement. This, however, is a matter for the EPA to judge.

9.4.17.3.2.2 *Technical Soundness*

The analyses contained in the CCA are based on an extensive geological data set resulting from high quality acquisition programs and compilation of regional data. This has been supplemented by a focused geotechnical and experimental program that has provided a world-leading understanding of processes relevant to rock-salt behaviour. The uncertainty associated with

characterization of the wastes, processes related to waste and backfill evolution in the repository, and chemical speciation of radionuclides in the repository environment are less well understood. In particular:

1. The CCA does not sufficiently explore the possible physical implications of the chemical reactions that the MgO backfill may undergo. These implications may be both favourable and unfavourable to the performance of the facility; and

2. The CCA does not support the assumption, applied in the performance calculations, that the physically and chemically heterogeneous array of waste, packaging, backfill, reaction products, and void space will quickly reach well-mixed homogeneous conditions within the disposal rooms. The basis for this assumption and implications of heterogeneities need to be analysed further.

The CCA indicates good code configuration and management of data flows. The IRG has confidence that the procedures applied in these areas are consistent with best practice for computer simulation internationally. The IRG is also aware of the long involvement of the WIPP project in international comparison exercises, which gives added confidence in the performance of several of the detailed models.

Thus, the IRG has overall confidence in the majority of judgments and assumptions made in developing calculational models of the disposal system and concludes that, in the main, the analyses presented in the CCA are based on appropriate studies and are technically sound.

9.4.17.3.2.3 *Conformity with International Practices*

The methods used to assess the performance of the WIPP facility are generally in conformity with practices used in other countries. These include:

- the selection of FEPs,
- development of scenarios and models representing the evolution of conditions in the repository and the release of radionuclides,
- quantitative analysis of selected scenarios by means of a linked set of models and comparison of the results to regulatory limits.

The probabilistic analysis methods used by the DOE are comparable to those employed in a number of other countries, and the DOE contractors contributed substantially to the development of probabilistic methods in the field of repository postclosure assessment.

Specific aspects of the assessment carried out by the DOE are not in accordance with assessment practices in other countries, and this can be partly traced to the influence of the EPA regulations and the strong focus of the CCA on compliance. For example:

- The probabilistic approach applied by the DOE deals only with parameter-based uncertainty. Conceptual model and scenario uncertainty are not discussed in the CCA. These are considered to be important internationally;

- Results in the CCA focus on the CCDFs of cumulative radionuclide release. Information on the behaviour of intermediate parameters and results of representative deterministic calculations, especially as a function of time, are lacking. Without this, it may not be possible to develop a good understanding of the disposal system's behavior; and

- The EPA has ruled that the DOE only needs to consider a limited set of future human actions and has specified the assumptions to make in assessing these actions. Thus, some scenarios that might affect safety have not been evaluated. The lack of a logically argued explanation for the choice of scenarios analysed, or evaluation of these other scenarios, leads to the impression that the assessment is arbitrary.

9.4.17.3.2.4 *Conformity with International Guidance and Standards*

The CCA focuses on a demonstration of compliance with the EPA containment requirement. The latter is based on collective dose considerations, refers to the total activity in the repository, and cannot be related to the standards based on individual dose and risk adopted in most other countries. Moreover, the EPA regulations do not require the applicant to present descriptions or arguments concerning the performance of the disposal system beyond the 10,000-year regulatory period. Thus, for the general case, the CCA does not present calculated end-points that can be compared with international guidance and standards as implemented in other countries.

The CCA does present dose estimates for the undisturbed performance within the 10,000-year regulatory period based on a conservative hypothetical dose pathway. In this case, the results indicate that the WIPP can easily meet typical performance criteria based on dose to the individual. It is likely that, if undisturbed, the facility could meet individual dose criteria over much longer times, due to the long-term stability of the site and the absence of local, viable fresh water resources.

The IRG asked for information, not included in the CCA, on doses that might be received in the disturbed case from drilling of a borehole into the repository. The results provided by the DOE indicated that, for this scenario, the WIPP facility would meet an individual risk-based standard typical of those used in other countries. The CCA does not demonstrate, however, that no other scenarios could contribute significantly to risk.

9.4.17.3.3 Overall Judgement

The WIPP project and the CCA are markedly different from geological disposal projects and assessment documentation in other countries. In particular, important decisions relating to what is a sufficient method and scope of assessment have already been taken, and the CCA is not required to present a complete PA as understood internationally.

The CCA documentation is not transparent and is difficult to follow even from the point of view of experienced PA practitioners. Technical issues are often difficult to trace and some of the choices made and modeling assumptions are not well supported. This, combined with the specificity of the EPA regulations, made it challenging to distinguish between decisions determined by the regulator and those made by the DOE.

Focusing on the decisions for which the DOE must take technical responsibility, the IRG finds that the PA methodology implemented in the CCA is generally acceptable and conforms to practices in other countries. The IRG also has overall confidence in the majority of judgements and assumptions made in developing calculational models, and believes that the quality of assessment codes and data handling is generally good. Thus, in the main, the analyses contained in the CCA are technically sound.

On specific points, the IRG considers that the DOE should give further attention to:

1. the implications - favourable and unfavourable - that the behaviour of the MgO backfill may have on the performance of the facility, and

2. the basis for assuming that homogeneous conditions will be rapidly reached in the disposal rooms, and the potential consequences of heterogeneities in the source term.

The IRG is of the view that, in the case of undisturbed performance, the WIPP facility would meet radiological performance standards typical of those used in other countries. This judgement is based on the analysis presented in the CCA in respect of the 10,000-year regulatory period and, for times beyond 10,000 years, on the geological stability of the site and the absence of viable fresh water resources. The case of disturbed performance is less clear: supplementary analyses by the DOE indicate that a risk target would be met in respect of an exploratory borehole drilling scenario. The CCA does not (and need not) make the case that this is the most important scenario to consider and, therefore, the IRG cannot reach a definite judgment.

Finally, from the experience of the review, the IRG observes that, by commissioning this international peer review, the DOE has demonstrated a commendable openness and commitment to improving confidence in the PA of the WIPP facility. The DOE and their contractors were very open in their discussions with the IRG, and were able to provide useful responses, often at short notice, on most issues raised. This was very useful and helpful to the review.

9.4.18 GEOTRAP

GEOTRAP is the NEA/OECD Project on Radionuclide Migration in Geologic, Heterogeneous Media. GEOTRAP is devoted to the exchange of information and in-depth discussions on present approaches to acquiring field data and testing and modeling flow and transport of radionuclides in geologic formations for site evaluation and safety assessment of deep repository systems. This information is important for both national waste management programs and the wider scientific community. The WIPP project has actively participated in this project since its inception in 1996.

The project is structured as a series of forum-like workshops at which implementers, regulators, and scientists interact.

The first GEOTRAP workshop, “Field Tracer Experiments: Role in the Prediction of Radionuclide Migration,” was coorganized with the European Commission. It provided an overview of ongoing and planned work in the study of radionuclide transport phenomena and the characterization of relevant geologic media properties.

Variability (heterogeneity) in the properties of the rocks over a wide range of spatial scales is a common feature of most geologic media. Broad agreement exists that its characterization and the corresponding analysis of the consequences for groundwater flow and radionuclide transport form an important part of the safety of deep geologic repositories assessment. The second GEOTRAP workshop, "Modelling the Effects of Spatial Variability on Radionuclide Migration," explored these issues and provided an overview of current developments in the field.

The subject of the third GEOTRAP workshop was "Characterisation of Water-Conducting Features and their Representation in Models of Radionuclide Migration." It investigated how water-conducting features can determine the rate of radionuclide release from the near-field to the far-field, the rate at which radionuclides can migrate with flowing groundwater, and the degree of retention in the geosphere. A key finding of the workshop was that the characterization of the structure and properties of water-conducting features is an important requirement for any PA of deep repository systems.

The fourth GEOTRAP workshop, "Confidence in Models of Radionuclide Transport for Site-specific Performance Assessments," was held in June 1999. The workshop examined the issue of technical confidence building and provided an overview of current developments in this field.

The fifth workshop addressed "Geological Evidence and Theoretical Bases for Radionuclide-Retention Processes in Heterogeneous Media." The Swedish Nuclear Fuel and Waste Management Company (SKB) hosted this workshop in May 2001. The following proceedings of these workshops are available from the OECD Bookshop at www.oecd.org/bookshop.

- Radionuclide Retention in Geologic Media
  Workshop Proceedings, Oskarshamn, Sweden, 7-9 May 2001

- GEOTRAP: Radionuclide Migration in Geologic, Heterogeneous Media
  Summary of Accomplishments (pdf format, 216 kb)

- Confidence in Models of Radionuclide Transport for Site-specific Assessments
  Synthesis and Proceedings of the fourth GEOTRAP Workshop, Carlsbad, New Mexico, United States, 14-17 June 1999

- Water-Conducting Features and their Representation in Models of Radionuclide Migration
  Synthesis and Proceedings from the third GEOTRAP Workshop, Barcelona, Spain, 10-12 June 1998

- Modelling the Effects of Spatial Variability on Radionuclide Migration
  Synthesis and Proceedings from the second GEOTRAP Workshop, Paris, France, 9-11 June 1997

- Field Tracer Experiments: Role in the Prediction of Radionuclide Migration
  Synthesis and Proceedings of an NEA/EC GEOTRAP Workshop, Cologne, Germany, 28-30 August 1996 - Coedition with the European Communities Series Disposal of Radioactive Waste

9.4.19 Institute for Regulatory Science Reviews

RSI is a non-profit scientific and educational organization. It provides independent scientific peer reviews and technical assessments. These reviews and assessments are generally performed in association with professional societies. RSI has performed two peer reviews for the WIPP project. These are briefly described below. Full reports of these reviews are provided in Appendix PEER-2004.

9.4.19.1 Requirements for Disposal of Remote-Handled Transuranic Waste at the Waste Isolation Pilot Plant (2002) (RSI 2002)

This peer review examined methods and techniques DOE proposes to use for characterization of TRU waste and various QA processes. The peer review focused on the DOE's draft Permit Modification Request (Draft Request) to NMED for RH-TRU waste characterization and the corresponding Notification of Proposed Change to EPA.

The RSI review panel (RP) findings are summarized in the following discussion:

Reliance on AK as the analysis tool to meet the waste characterization requirements as listed in the Draft Request can be consistent with the relevant regulations in some instances. In other instances, additional confirmation methodologies in a hierarchy of methods proposed by DOE will be needed to characterize wastes accepted at the WIPP to meet the Data Quality Objectives (DQO). Whether AK alone is sufficient will be dependent upon the nature of the waste and the source and completeness of the data that constitute the AK. The application of the Performance-Based Measurement System approach meets the EPA's guidance on performance-based measurement systems. The Draft Request presents an RH-TRU waste characterization program that is not consistent in all cases with the recommendations of the National Research Council. The Draft Request still includes characterization requirements which the National Research Council criticized as being self-imposed and overly conservative and which have no legal or safety basis.

The Notification of Proposed Change to the EPA 40 CFR Part 194 Certification of the Waste Isolation Pilot Plant describes the nature and scope of the proposed RH-TRU Waste Characterization Program. Consistency with EPA disposal regulations is fully demonstrated and documented in resource documents. The significance of the change is clearly and adequately addressed. The consequences for compliance determinations are clearly stated and technically justified.

The RH-TRU Waste Characterization Program Implementation Plan presented meets the performance factors of the waste characterization program. The waste components have been identified and justified in a general sense, but a detailed description of waste streams from the waste-generating sites is lacking. The programmatic AK steps are somewhat conservative but are sufficient to accomplish the DQOs adopted by DOE- CBFO, and can be reasonably relied upon to meet the DQOs for materials received at WIPP. The distinction between the characterization activities, AK, supplementary, confirmatory, or verification is inadequate in the RH-TRU Waste Characterization Program Implementation Plan, and is made particularly confusing by the definitions.

The Notification of Proposed Change adequately explains and justifies how AK and the WWIS are used to satisfy the quantification and control requirements. The WWIS tracking and control system is currently in use in the CH-TRU waste program, and it is operating satisfactorily. To meet additional tracking and control requirements imposed on RH-TRU waste by the LWA, WWIS will be modified by the addition of data fields.

The RH-TRU Waste Characterization Program Implementation Plan describes a QA program that addresses the appropriate requirements but lacks sufficient detail. Use of the 40 CFR § 194.22 provisions in waste characterization is sufficiently explained. The RH-TRU waste characterization program is reasonably consistent with the report, Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant (National Research Council/National Academy of Sciences 2001), including its finding of self-imposed requirements that have no legal or safety basis. The Draft Request and RH-TRU Waste Characterization Program Implementation Plan are consistent with the ALARA concept.

Based on a careful assessment of the information presented to the RP and the findings developed in response to the review criteria, the RP provides the following recommendations.

1. A detailed procedure for determining whether there is sufficient AK available on a waste should be developed as part of the permit application.

2. In the final request for RCRA Class 3 Permit Modification, a detailed procedure should be provided to go to other characterization methods if AK is found to be insufficient.

3. DOE should implement the National Research Council recommendation that review of characterization and packaging requirements continue, especially implementation "... over the entire National TRU Program."

4. DOE should provide to the EPA a complete inventory of radionuclides and waste forms so that the EPA may verify the repository performance using its own methods for certification.

5. Appropriate interaction with the EPA and the NMED is recommended.

6. Prior to submission, all permit related documents should be reviewed in detail for completeness, specificity, and clarity by a team experienced in the permitting process.

7. The request for RCRA Class 3 Permit Modification must be expanded to include more specifics and examples for clarity and completeness.

8. The discussion for Table 1 of the draft request for RCRA Class 3 Permit Modification should be expanded to justify why sections of the documents require "no action" or "no changes."

9. Supplemental information should be supplied detailing the waste characterization plans for each waste generating site and DOE's procedures for determining that these plans meet the WIPP WAC.

10. Detailed audit procedures for WIPP and the waste-generating sites should be provided.

11. More detail and specificity on WAC using AK, VE, and radiography should be provided in the permit application.

12. DOE should evaluate the necessity of identifying waste streams by EPA hazardous waste numbers or characteristics.

13. A complete review should be made of what is gained from the remote swiping procedure for "clean" RH-TRU containers and how the information will be used.

The DOE accepted many of the recommendations of the RSI's review panel in revising the documents reviewed by the panel.

9.4.19.2 Desirability of Performing Certain Transuranic Waste Characterization Tests (RSI 2003)

The following is a summary of the RSI report, "Desirabilty of Performing Certain Transuranic Waste Characterization Tests":

This report contains the results of an independent peer review performed by the RSI responding to a request from Bob Forrest, Mayor of Carlsbad, New Mexico, to critically review a claim included in a Senate Committee report. The Senate language indicated that the NAS and the EEG had endorsed the elimination of certain tests currently performed to characterize hazardous waste constituents of TRU waste for disposal at the WIPP.

The RP reviewed two relevant reports of the National Research Council (National Research Council 2001, 2002)—the research arm of the NAS, National Academy of Engineering, and the Institute of Medicine. In addition, the RP reviewed a number of documents published by the EEG, an independent group associated with New Mexico Institute of Mining and Technology.

As the principal facility for disposal of the nation's TRU waste generated as a result of nuclear weapons research, development, and production, WIPP must comply with relevant requirements of the EPA and NMED. Where the EPA regulates certain aspects of the radioactivity content of TRU waste, the NMED regulates the hazardous waste constituents of TRU waste. In addition, WIPP must comply with relevant transportation regulations. Waste must be properly characterized to demonstrate that it meets the requirements for transportation to and disposal at WIPP. Waste characterization activities required at the time of the review included the following, although not all of these techniques were used on each container:

1. Radiography, which is an x-ray technique to determine physical contents of containers;

2. VE of opened containers as an alternative way to determine their physical contents or to verify radiography results;

3. HSG sampling to determine VOC contents of gases in the void volume of the containers;

4. Sampling and analysis of waste forms that are homogeneous and can be representatively sampled to determine concentrations of hazardous waste constituents and toxicity-characteristic contaminants of waste in containers;

5. Compilation of AK documentation into an auditable record, including process knowledge and prior sampling and analysis data; and

6. Non-destructive assay, typically segmented gamma scans and passive/active neutron interrogation, to quantify radionuclides.

Confirmation that the waste complies with the requirement of being not ignitable, corrosive, or reactive is accomplished by AK or appropriate tests.

The U.S. Senate Bill S.1424 states that waste confirmation for all waste received for storage and disposal be limited to:

1. Confirmation that the waste contains no ignitable, corrosive, or reactive waste through the use of either radiography or VE of a statistically representative subpopulation of the waste; and

2. Review of the Waste Stream Profile Form to verify that the waste contains no ignitable, corrosive, or reactive waste and that assigned EPA hazardous waste numbers are allowed for storage and disposal by the WIPP HWFP.

Furthermore, the U.S. Senate Bill S.1424 states that compliance with the disposal room performance standards of the WAP shall be demonstrated exclusively by monitoring airborne VOCs in underground disposal rooms in which waste has been emplaced until panel closure.

The RP was asked to respond to three review criteria identified by the Mayor of Carlsbad, New Mexico. After careful review of documents provided to the RP and appropriate deliberations, the RP provided the following principal conclusions.

1. Based on careful evaluation of the two relevant NRC reports, the RP concludes that the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S.1424 is supported by the NRC.

2. It appears that EEG agrees that the current characterization requirements are excessive. It appears that EEG also agrees that monitoring VOCs in underground disposal rooms is sufficient.

3. Based on the information presented to the RP, the permit modification listed under Section 310 of U.S. Senate Bill 1424 is technically defensible. There is no reason to perform waste confirmation tests that (1) provide insignificant health and safety benefits to the U.S. population, and (2) pose serious radiological and occupational health and safety risks to the workers performing these tests.

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1.0 INTRODUCTION

Tables AUD-1 through AUD-11 of this Appendix summarize assessments performed between November 2, 1998, and May 31, 2003, of transuranic (TRU) waste sites, Sandia National Laboratories (SNL), Washington TRU Solutions (WTS), LLC, suppliers performing quality-affecting work, and the Carlsbad Field Office (CBFO), and supplement the information contained in the Compliance Certification Application (CCA). The summaries are grouped in chronological order by audited agency. Each assessment entry outlines the assessment scope and results. Results of the assessment normally determine the adequacy, implementation, and effectiveness of the auditee's quality assurance program. Adequacy addresses the migration of requirements from upper-tier program documents into implementing procedures. Implementation addresses the extent of compliance with procedures. Effectiveness addresses whether the controls established in the implementing procedures produce the desired results or end product. For ease of reference, CBFO is used throughout this appendix to mean CAO (Carlsbad Area Office) or CBFO, as appropriate. Below is a list of sites audited and the table that contains the summaries:

Table 1. Los Alamos National Laboratory (LANL) Audits – Page 2
Table 2. Los Alamos National Laboratory - Carlsbad Operations (LANL-CO) Audits – Page 4
Table 3. Nevada Test Site (NTS) Audits – Page 5
Table 4. Hanford Site Audits – Page 6
Table 5. Rocky Flats Environmental Technology Site (RFETS) Audits – Page 8
Table 6. Idaho National Engineering and Environmental Laboratory (INEEL) Audits – Page 12
Table 7. Washington TRU Solutions (WTS) Audits – Page 16
Table 8. Sandia National Laboratories (SNL) Audits – Page 20
Table 9. Savannah River Site (SRS) Audits – Page 22
Table 10. Carlsbad Field Office (CBFO) Audits – Page 23
Table 11. Carlsbad Field Office (CBFO) Supplier Audits – Page 24

The summary tables include the organization that was assessed, the assessment number, the scope of the assessment, and the results of the assessment expressed as "satisfactory" (S), "marginal" (M), "unsatisfactory" (U), "not applicable" (N/A), or "indeterminate" (I) for the three factors considered during an assessment (i.e., "adequacy," "implementation," and "effectiveness"). Indications of M, U, and I are addressed through the corrective action program to bring them up to S (satisfactory). They have been corrected or satisfactorily addressed and verified through subsequent audits, surveillances, corrective action reports, or other means prior to initial certification or continued certification for shipping to WIPP.

Only those CBFO assessment activities directly related to 40 CFR 191 and 194 are included in this appendix. Additional CBFO assessments are performed in other critical areas. In addition, each participant performs internal assessments of their own activities.

AUDIT SUMMARY TABLES

Table AUD-1. Los Alamos National Laboratory (LANL) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
Los Alamos National Laboratory (LANL)	A-99-04	6/14-17/99 and 6/28-7/1/99	Technical and quality assurance (QA) activities related to LANL TRU waste characterization-certification activities added since the last CBFO recertification audit.	S	S	S
				The QA program was satisfactory in meeting requirements and implementation. Minor concerns were noted in the area of software QA. In the area of acceptable knowledge (AK), the technical processes were determined adequate and implemented. All corrective actions were completed and verified.		
LANL	A-00-03	11/9-10/00	Annual recertification audit of TRU Waste Characterization and Certification QA program.	S	S	S
				The QA program was adequate, satisfactorily implemented and effective.		
LANL	A-00-13	8/21-25/00 and 8/28-31/00	Remainder of the LANL TRU waste characterization activities for waste characterization and transportation activities for debris waste.	S	S	S
				The technical and QA programs were adequate in accordance with the Hazardous Waste Facility Permit (HWFP) requirements, satisfactorily implemented, and effective.		
LANL	A-00-16	9/25-29/00	Technical activities and associated QA program requirements related to the LANL TRU waste characterization and certification programs for debris waste.	S	S	S
				The QA programs and technical programs were adequate, effective, and satisfactorily implemented.		
LANL	A-01-11 (two visits)	5/8-9/01 and 5/14-17/01	Technical activities and associated QA program requirements related to the LANL TRU waste characterization and certification programs for debris wastes. Specifically, the visual examination (VE) technique associated with packaging operations conducted in TA-55, repackaging of containers exceeding the wattage limits in the Waste Characterization, Reduction, and Repository (WCRR) Facility, and packaging source materials for the Off-Site Source Recovery (OSR) Program.	S	S	S
				The LANL program for performing the VE technique for TA-55 and the OSR program was adequate, satisfactorily implemented, and effective.		

Table AUD-1. Los Alamos National Laboratory (LANL) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
LANL	S-01-31	7/16-17/01	The LANL TRU Waste Characterization Project (TWCP) QA and technical program as related to the Document Control program and TRU waste characterization activities.	S	S	S
				QA program requirements related to the activities evaluated during the surveillance were adequate, satisfactorily implemented, and effective.		
LANL	A-02-04	10/22-26/01	The LANL TWCP, including QA, nondestructive assay (NDA), transportation, and WIPP Waste Analysis Plan (WAP) activities.	S	S	S
				The QA programs and technical programs were adequate, satisfactorily implemented, and effective.		
LANL	A-02-16	2/25-28/02	Selected technical activities related to the LANL TRU waste characterization and certification programs for debris wastes. Audit included the evaluation of two new NDA systems: the Combined Thermal-Epithermal Neutron (CTEN) system and a portable tomographic gamma scanner (P-TGS).	S	S	S
				The LANL technical processes for the CTEN system were adequate, satisfactorily implemented, and effective. The technical activities related to the P-TGS were judged to be indeterminate. The QA program continues to be adequate, satisfactorily implemented, and effective.		
LANL	A-02-30	8/26-30/02	LANL TWCP, including QA and WIPP HWFP activities. Audit conducted to evaluate Summary Category Group S5000, contact-handled and newly generated heterogeneous debris waste.	S	S	S
				The LANL technical and QA procedures continue to be adequate. The LANL technical processes were satisfactorily implemented and effective. The LANL process for manual headspace gas sampling of S5000 waste was concluded to be indeterminate, due to a limited operational time and lack of analytical batch data reports.		
LANL	A-03-07	10/29-31/02	Obtaining manual samples of headspace gas (HSG) in Summa® canisters and utilizing the Idaho National Engineering and Environmental Laboratory (INEEL) for analytical services.	S	S	S
				The LANL process for obtaining manual HSG samples was adequate. The LANL technical processes were satisfactorily implemented and effective.		
LANL	S-03-07	12/17-20/02	Loading of high-wattage waste at LANL and shipment of the waste to WIPP. Receipt and venting of the inner containment vessel (ICV) at WIPP.	S	S	S
				The LANL team displayed excellent job control and conduct of operations techniques during TRUPACT-II operations. LANL management, the Transportation Certification Official, QA personnel, Radiological Control personnel, and the DOE-National Nuclear Security Administration-Los Alamos Site Office Program Management and Facility Representatives were supportive and actively involved in all phases of TRUPACT-II operations.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-2. Los Alamos National Laboratory – Carlsbad Operations Office (LANL-CO) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
LANL-CO	A-03-12	12/17-19/02	LANL-CO QA program in accordance with CBFO Quality Assurance Program Description (QAPD) for performing quality-affecting work including the Actinide Chemistry program for the WIPP. LANL-CO implementation of the Sandia National Laboratories (SNL) QA program as detailed in the SNL and LANL Memorandum of Agreement (MOA) dated 8/2/02 and revised MOA dated 12/06/02 for performing work on the Transuranic Waste Baseline Inventory Report (TWBIR) in supporting the Performance Assessment (PA) for SNL and the WIPP.	S	I	I
				The status of LANL-CO QA program is adequate with one exception concerning nonconformances. The TWBIR program implementation performed by LANL-CO in accordance with SNL procedures was considered indeterminate. See S-03-11 for follow-up.		
LANL-CO	S-03-11	1/23/03	Implementation of the LANL-CO corrective action for Corrective Action Report (CAR) W-03-02 issued for conditions adverse to quality identified in conducting TWBIR activities.	S	S	S
				The corrective actions identified in CAR W-03-02, issued during audit A-03-01, were completed with the exception of the agreed upon LANL-CO surveillance of the TWBIR program activities, which was scheduled for the last week in February. The actions implemented for CAR W-03-02 are considered satisfactory.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-3. Nevada Test Site (NTS) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
Nevada Test Site (NTS)	A-99-01	11/2-6/98	The NTS TRU waste characterization and certification activities.	S	S	S
				Overall the adequacy, implementation, and effectiveness were satisfactory; however, two areas (integration process with mobile service contractor and data reconciliation) were concluded to be indeterminate.		
Audit of TRUtech, Inc. at NTS	A-99-02	12/7-11/98	The technical and QA programs related to TRUtech TRU waste characterization and certification activities.	S	S	S
				The adequacy, implementation, and effectiveness of the TRUtech QA program were satisfactory.		
Audit of Mobile Characterization Systems (MCS) at NTS	A-99-03	11/2-6/98	The technical and QA programs related to MCS TRU waste characterization and certification activities.	S	S	S
				MCS's technical and QA programs were adequate, satisfactorily implemented, and effective; however, improvements were needed in the areas of drum filter procurements, software configuration management, and the collection of field duplicates for HSG analysis.		
NTS	A-99-20	6/7-11/99	The NTS TRU waste characterization and certification activities including the AK process and the mobile services contractor interface.	S	S/M	S/M
				The adequacy of QA programs was satisfactory. However, the technical program was only marginally implemented and marginally effective. Corrective actions in the marginal areas were implemented and verified.		
NTS using the Central Characterization Project (CCP)	A-02-15	9/23-27/02	The CCP TRU waste characterization and certification activities related to Summary Category Group S5000 (debris waste) contracted to Bechtel-Nevada.	S	S	S
				The CCP technical and QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD, the WAP of the WIPP HWFP, and the WIPP Waste Acceptance Criteria (WAC). The assessed activities were being satisfactorily implemented and the QA program was determined to be effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) – Indeterminate

Table AUD-4. Hanford Site Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
Hanford	A-99-05	7/12-17/99	The TRU waste characterization, certification, and transportation programs.	S	S/M	S/M
				The QA program's adequacy, implementation, and effectiveness were satisfactory. Technical processes were marginally implemented and marginally effective.		
Hanford	S-00-04	3/28-30/00	Technical processes related to NDA systems. Also, the verification of corrective actions implemented for issues identified in Carlsbad Field Office (CBFO) Audits A-99-05 and A-00-05.	S	S	S
				Overall, the Hanford Site technical and QA programs were determined to be adequate in accordance with the CBFO QAPD. The audit team also concluded that Hanford procedures were being satisfactorily implemented and that the evaluated processes were effective.		
Hanford	A-00-05	1/24-28/00	The technical and QA processes related to Hanford TRU waste characterization and transportation activities.	S	S	S
				The QA program was satisfactory and implemented as required. Technical processes evaluated were determined to also be adequate, effective and satisfactorily implemented.		
Hanford	A-01-03	6/11-15/01	The Hanford TRU waste characterization activities for contact-handled debris waste.	S	S	S
				Hanford technical and QA programs continue to meet requirements. The audit team concluded that the defined QA and technical processes for the audited activities continue to be implemented in accordance with the Hanford Quality requirements and implementing procedures and that the processes were effective.		
Hanford	S-01-04	1/16/01	The Hanford Site QA program as it relates to the Hanford organization.	S	S	S
				The Hanford activities evaluated relating to QA were adequate, satisfactorily implemented, and effective.		
Hanford	A-01-16	6/11-15/01	The applicable technical and QA activities related to the TRU waste characterization activities performed at the Plutonium Finishing Plant (PFP). Hanford procedures and processes for assay, visual examination, and repackaging of waste at the PFP as applied to retrievably stored debris were examined during this audit.	S	S	S
				The Hanford technical and QA procedures for the PFP were adequate relative to the migration of requirements from the CBFO QAPD, the WAP, and the WAC. The Hanford procedures were being satisfactorily implemented and the evaluated processes were effective.		

Table AUD-4. Hanford Site Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
Hanford	S-01-33	8/8-9/01	The Hanford Site TWCP QA and technical program, as related to the Document Control program and TRU waste characterization activities.	S	S	S
				The QA program requirements related to the activities evaluated during the surveillance were adequate, satisfactorily implemented, and effective.		
Hanford	S-02-04	12/18-19/01	The technical activities related to the Hanford Site TRU waste characterization activities performed at the PFP. Hanford procedures and processes for assay, visual examination, and repackaging of waste at the PFP as applied to retrievably stored debris (S5000) and homogenous solid (S3000) waste were examined during this surveillance.	S	S	S
				The Hanford technical procedures are adequate relative to the flow down of requirements from the CBFO QAPD, and the WAC. The Hanford QA program satisfactorily met the requirements of the QAPD and WAC and is being satisfactorily implemented. The Hanford QA program was verified and documented during recertification Audit A-01-03. The Hanford technical processes evaluated for PFP are satisfactorily implemented, and effective.		
Hanford	A-02-23	6/24-28/02	Re-evaluation of the Hanford Site TRU waste characterization, transportation, and certification activities.	S	S	S
				The Hanford QA program continues to satisfactorily meet the requirements of the QAPD, WAP, contact-handled (CH) WAC, and TRUPACT-II Authorized Methods for Payload Control (TRAMPAC). The QA program is satisfactorily implemented and effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) – Indeterminate

Table AUD-5. Rocky Flats Environmental Technology Site (RFETS) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RFETS	A-99-07	2/23-25/99	The technical and QA processes related to the RFETS TRU waste characterization, certification, and transportation activities.	S	S/M	S
				The RFETS QA program was adequate, satisfactorily implemented, and effective. Document control was found to be marginally implemented, but effective.		
RFETS	A-99-09	3/8-12/99	The RFETS TRU waste characterization activities associated with Salt Stabilization and LECO® Crucible Repackaging.	S	S/M	S/M
				The QA program was adequate, effective, and satisfactorily implemented. The implementation and effectiveness of the technical processes were marginal.		
RFETS	A-99-13	3/24-25/99	The software QA program as evaluated by RFETS and implemented by Canberra, relative to the TRU waste characterization program.	S	S	S
				The software QA program was adequate, effective, and satisfactorily implemented for the QA program and technical processes.		
RFETS	A-99-16	4/27-29/99	The technical and QA processes related to RFETS TRU waste characterization and certification activities associated with Salt Residue Stabilization and LECO® Crucible Repackaging processes.	S	S	S
				The QA and technical processes evaluated were adequate, satisfactorily implemented, and effective.		
RFETS	A-99-17	9/13-17/99	The technical and QA processes related to RFETS TRU waste characterization and certification activities associated with Salt Residue Repack, Dry Residue Repack, Ash Repack, and Combustible Residue Repack.	S	S	S
				The audit team concluded that the adequacy, implementation, and effectiveness of the technical and QA programs were satisfactory in meeting requirements.		
RFETS	A-00-02	11/16-17/00	The technical and QA processes related to the RFETS TRU waste characterization and certification activities associated with Segmented Gamma Scanner (SGS) Drum Counter, SGS Can Counters, and mobile TGS, AK, and Field Sample QC Data Collections.	S	S	S
				All activities assessed were adequate, satisfactorily implemented, and effective.		

Table AUD-5. Rocky Flats Environmental Technology Site (RFETS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RFETS	A-00-07	1/29-2/1/00	The TRU waste characterization activities relative to the requirements detailed in the WIPP HWFP and the CBFO QAPD.	S	S	S
				The RFETS technical and QA programs were adequate. The defined QA and technical programs for these activities were being satisfactorily implemented in accordance with the RFETS QA documents and the processes were effective.		
RFETS	A-00-08	12/13-17/99 and 1/18-20/00	The RFETS TRU waste characterization activities for debris waste.	S	S	S
				The RFETS technical and QA programs were adequate. The defined QA and technical programs for these activities were being implemented in accordance with the RFETS Quality Assurance Project Plan (QAPP) and the implementing procedures and processes were effective.		
RFETS	A-00-10	3/6-8/00	Proper maintenance of the RFETS QA program since the last certification audit in March 1999. Recertification audit.	S	S	S
				All activities assessed were adequate, satisfactorily implemented, and effective.		
RFETS	A-00-12	9/18-22/00 and 11/1-2/00	The RFETS TRU waste activities as they relate to the HWFP for homogenous solid waste.	S	S	S
				All activities assessed were adequate, satisfactorily implemented, and effective.		
RFETS	A-01-05	3/26-28/01	Evaluate two additional waste streams and the indeterminate actions of CBFO audit A-00-12, with the exception of the on-line HSG unit that the RFETS no longer intends to use.	S	S	S
				The adequacy of the RFETS technical and Quality Assurance (QA) programs was satisfactory. All activities assessed were satisfactorily implemented and effective.		
RFETS	A-01-07	1/29-2/1/01	The RFETS TRU waste activities related to HWFP and QA elements.	S	S	S
				All activities assessed were adequate, satisfactorily implemented, and effective.		
RFETS	A-01-12	5/14-18/01	The RFETS TRU waste activities as they related to three new NDA systems, radiography, visual examination, and the Waste and Environmental Management System (WEMS)- WIPP Waste Information System (WWIS) interface.	S	S	S
				The RFETS technical and QA programs were determined to be adequate, satisfactorily implemented, and effective.		

Table AUD-5. Rocky Flats Environmental Technology Site (RFETS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RFETS	S-01-30	7/11-12/01	Evaluate the RFETS QA and technical program, as related to the document control program and TRU waste characterization activities.	S	S	S
				The QA program was adequate, satisfactorily implemented, and effective.		
RFETS	S-01-39	9/25-27/01	The RFETS automated procurement system.	S	S	S
				The automated procurement system was adequate, satisfactorily implemented, and effective.		
RFETS	A-02-05	11/27-30/01	The RFETS TRU waste characterization activities for debris waste, particularly newly generated debris waste.	S	S	S
				The overall adequacy of the RFETS technical and QA programs was satisfactory in meeting requirements. The defined QA and technical programs for these activities were being satisfactorily implemented and the processes were effective.		
RFETS	A-02-07	2/4-8/02	The RFETS TRU waste characterization activities for debris and solid waste.	S	S	S
				The adequacy of the RFETS technical and QA programs was satisfactory and the defined QA and technical processes were being satisfactorily implemented and were effective.		
RFETS	A-02-19	6/4-6/02	The RFETS TRU waste characterization activities for debris waste. A new mobile real-time radiography (RTR) unit and a new multipurpose crate counter (MPCC) were also evaluated.	S	S	S
				The overall adequacy of the RFETS technical and QA programs was satisfactory and the defined QA and technical programs for these activities were being satisfactorily implemented and are effective.		
RFETS	A-03-02	11/19-20/02	The audit scope included Summary Category Groups S5000 debris and S3000 solid wastes. The audit evaluated a new VE facility (in Building 371) to confirm RTR, and polychlorinated biphenyl (PCB) analysis. In addition, the Building 440 gas generation testing program (GGTP) was evaluated.	S	S	S
				The overall adequacy of the RFETS technical and QA programs was satisfactory in meeting requirements. The audit team also concluded that the defined QA and technical programs for these activities (except PCB analysis and GGTP) were being implemented in accordance with the RFETS QAPP and the applicable implementing procedures and processes were effective. The audit team found that the adequacy, implementation, and effectiveness of the PCB analysis and GGTP activities were indeterminate.		

Table AUD-5. Rocky Flats Environmental Technology Site (RFETS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RFETS	A-03-03	3/4-7/03	The RFETS TRU waste characterization activities relative to the requirements detailed in the WIPP HWFP and the CBFO QAPD. Three new activities were evaluated during the audit: the Building 440 GGTP, Building 371 HSG Sampling Using an Automated Manifold, and Building 664 Mobile RTR (for lead-lined drums).	S	S	S
				Overall, the RFETS technical and QA programs were satisfactory in meeting requirements. The defined QA and technical programs for these activities were being implemented in accordance with the RFETS QAPP and its implementing procedures, and the processes were effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) – Indeterminate

Table AUD-6. Idaho National Engineering and Environmental Laboratory (INEEL) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
Idaho National Engineering and Environmental Laboratory (INEEL)	A-99-08	5/17-20/99	The INEEL TRU waste characterization, transportation, and certification activities.	M	M	M
				The QA program was marginally adequate. Technical areas were also marginally implemented and marginally effective.		
INEEL	S-99-10	5/3-4/99	The INEEL software QA program as it relates to the Transuranic Reporting, Inventory and Processing System (TRIPS).	S	M	S
				The activities evaluated relating to QA were adequate and marginally implemented. The technical activities were determined to be effective.		
INEEL	A-00-06	4/24-28/00	The INEEL TRU waste characterization, transportation, and certification activities.	S	S	S
				The defined QA program was adequate and effectively implemented in accordance with the INEEL quality and implementing procedures. Also, except for the visual examination process, the INEEL technical areas were satisfactorily implemented and effective.		
INEEL	A-00-07	4/24-28/00	The INEEL TRU waste characterization, transportation, and certification activities for retrievably stored debris waste.	S	S	S
				The technical and QA procedures were adequate and the QA and technical programs were effectively implemented except for visual examination, which was marginally acceptable.		

Table AUD-6. Idaho National Engineering and Environmental Laboratory (INEEL) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
INEEL	A-01-02	12/5-8/01 and 1/18/01	The INEEL TRU waste characterization, transportation, and certification activities associated with solid wastes.	S	S	S
				All activities assessed were adequate, satisfactorily implemented, and effective.		
INEEL	S-01-06	5/1/01	The INEEL QA program as it relates to the organization. Also evaluation of the trailer mounted RTR unit, analysis of gas samples for hydrogen and methane, new gas chromatography/flame ionization detector equipment, and the TRUPACT loading and unloading operations.	S	S	S
				The QA activities were adequate, satisfactorily implemented, and effective. The audit team also concluded that the RTR and TRUPACT operations procedures were adequate, implemented, and effective.		
INEEL	A-01-14	7/30-8/3/01	The INEEL TRU waste characterization, transportation, and certification activities for retrievably stored debris waste.	S	S	S
				The INEEL technical and QA procedures continue to be adequate relative to the CBFO QAPD, WAP, WAC, and TRAMPAC. Also, the procedures were adequate, satisfactorily implemented, and effective.		
INEEL	S-01-29	7/2-3/01 and 7/25-26/01	The INEEL process for use of the Waste Assay Gamma Ray Spectrometer (WAGS).	S	S	S
				The WAGS procedure was adequate. The surveillance team determined that the activities evaluated relating to WAGS process were adequate, satisfactorily implemented, and effective.		
INEEL	S-02-03	10/30/01	Evaluate new analytical equipment and the process of reducing data from composited HSG analysis results at the INEEL.	S	S	S
				The new equipment was identical to existing equipment and the process for data reduction is acceptable.		

Table AUD-6. Idaho National Engineering and Environmental Laboratory (INEEL) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
INEEL	A-02-21	4/9-11/02	Evaluate the NDA of summary category groups S3000 solid waste and S5000 heterogeneous debris waste using the WAGS and the Stored Waste Examination Pilot Plant (SWEPP) Gamma Ray Spectrometer (SGRS) Systems in absolute mode. The audit also evaluated the NDA assay of category groups S3000 homogeneous solidified organic waste streams using the Passive-Active Neutron (PAN) system in combination with the WAGS system and in combination with the SGRS system. Concurrent with the evaluation of the new NDA systems, an evaluation was conducted of the Data Review Expert System (DRXS) for NDA validation and INEEL's software QA program as they are implemented for the NDA platforms in use at INEEL.	S	S	S
				Overall, the INEEL technical and QA procedures were adequate relative to the requirements of the CBFO QAPD and WAC. The defined software QA program implemented for the NDA platforms, the SGRS and WAGS Absolute Systems, the PAN/WAGS and PAN/SGRS systems, and the DRXS were satisfactorily implemented and effective.		
INEEL	S-02-17	5/21-22/02	The INEEL recovery option of standard waste box (SWB) blending activities as applied to the payload assembly, certification, and loading process, and the TRIPS and WIPP Waste Information System (WWIS) Interface for this option.	S	S	S
				The blending methods and payload assembly, certification, and loading processes utilized were adequate, satisfactory implemented, and effective.		
INEEL	A-02-27	8/5-9/02	The INEEL Transuranic Waste Characterization, Certification, and Transportation Programs, including the following activities: Transportation, HSG sampling and analysis, VE, RTR, NDA of CH-TRU debris and organic and inorganic homogeneous solid waste, and overpacking activities associated with the SWBs.	S	S	S
				The INEEL technical and QA procedures continue to be adequate relative to the flow down of requirements from the CBFO QAPD, WIPP WAP, WAC, and TRAMPAC. The defined QA Program continued to be satisfactorily implemented in accordance with the INEEL QAPP and implementing procedures. The INEEL technical areas evaluated continue to be satisfactorily implemented and remain effective.		

Table AUD-6. Idaho National Engineering and Environmental Laboratory (INEEL) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
INEEL	S-03-01	1/28-29/03	The INEEL characterization and certification activities for the period between audit A-02-27 (August 5-9, 2002) and the last shipment of TRU waste to WIPP (October 21, 2002), 3100 m^3 project closeout activities including records disposition and turnover activities, preparation and turnover of applicable software programs for continued access and use, and the disposition and turnover of acceptable knowledge records for waste that is to be transferred to the Advanced Mixed Waste Treatment Project (AMWTP).	S	S	S
				All activities evaluated are adequate, satisfactorily implemented, and effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-7. Washington TRU Solutions (WTS) Audits

NOTE: The M&OC had three different names during this time period. Up to January 2001, the M&OC was Westinghouse Waste Isolation Division (WID). From January 2001 through January 2003, the M&OC was Westinghouse TRU Solutions (WTS). From January 2003 to present, the M&OC has been Washington TRU Solutions (WTS). These names are reflected, as appropriate, in this table.

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
Westinghouse Waste Isolation Division (WID)	A-99-14	6/28-7/2/99	Evaluate the WID QA and technical programs.	S	S	S
				The audit team concluded that the technical and QA processes were adequate, satisfactorily implemented, and effective.		
WID	A-99-11	2/15-19/99	Evaluate the WID Self-Assessment Program.	S	S	S
				The WTS Self-Assessment Program was adequate, satisfactorily implemented, and effective.		
WID	S-00-03	3/13-15/00	The WID procedures and work processes related to the WWIS and WID compliance with the recently issued HWFP.	S	S	M
				The WID procedures related to the WWIS were adequate and implemented. The effectiveness of the WID QA program elements associated with the WWIS were rated as marginal due to inconsistencies identified during the surveillance.		
WID	A-00-14	8/7-8/00	The WTS QA program activities.	S	S	S
				The QA programs were adequate, satisfactorily implemented, and effective.		
Westinghouse TRU Solutions (WTS)	S-01-07	2/12-13/01	The WTS WIPP Coring Operations procedure.	S	S	S
				Current programmatic and procedural requirements relative to core storage, handling, and distribution processes were adequate, satisfactorily implemented, and effective.		
WTS	S-01-08	3/5/01	The WTS WIPP groundwater level measurement program.	S	S	S
				The procedures were adequate, satisfactorily implemented, and effective.		
WTS	S-01-12	3/19-21/01	Software used for Intranet security purposes and the process used for posting CBFO controlled documents on the Intranet and Internet.	S	S	S
				With one exception, the purchase and control of software was adequate, satisfactorily implemented, and effective.		

Table AUD-7. Washington TRU Solutions (WTS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
WTS	A-01-13	5/7-11/01	Verify continued implementation of the QA requirements in CBFO and WTS QAPDs – Sections 1 and 2, and applicable NQA-1 elements and implementing procedures.	M	M	M
				The WTS QA procedures were marginally adequate relative to the flow down of requirements from the CBFO QAPD. The audit team also concluded that the CBFO quality requirements contained within the CBFO QAPD Sections 1 and 2 were being marginally implemented through the WTS QAPD and WTS implementing procedures and the processes were marginally effective.		
WTS	S-01-14	8/13-16/01	The WIPP site's compliance with the requirements of the National Pollutant Discharge Elimination System (NPDES) Multi-Sector General Permit (MSGP).	S	S	S
				The design, operation, and maintenance of the WIPP storm water management system at the facility was outstanding and the Best Management Practices (BMPs) were satisfactorily implemented and effective.		
WTS	A-01-18	7/30-8/2/01	The QA requirements in the CBFO and WTS QAPDs – Sections 3 and 4, applicable NQA-1 elements and implementing procedures.	M	M	M
				The WTS QA procedures were marginally adequate relative to the CBFO QAPD. The CBFO quality requirements contained within the CBFO QAPD Sections 3 and 4 were being marginally implemented through the WTS QAPD and the WTS implementing procedures. The processes were marginally effective.		
WTS	A-02-08	10/1-10/01	The WTS conduct of operations program.	S	S	S
				Overall, the conduct of operations program was adequate in accordance with the applicable WTS implementing procedures. The WTS conduct of operations were satisfactorily implemented and effective.		
WTS	A-02-02	11/27-30/01	Continued implementation of the software QA requirements defined in the CBFO and WTS QAPDs, Section 6, and the applicable WTS implementing procedures.	M	S	S
				The WTS software QA procedures are marginally adequate relative to the flow-down of requirements from the CBFO QAPD. The CBFO quality requirements contained within the CBFO QAPD Section 6 are being satisfactorily implemented through the WTS QAPD and WTS implementing procedures. The processes are effective.		

Table AUD-7. Washington TRU Solutions (WTS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation		Effectiveness
S (Centralized Procurement Program)	A-02-10	11/6-8/01	The WTS QAPD pertaining to the Centralized Procurement Program. (Joint audit by INEEL and Hanford site auditors.)	Supplier Evaluation	S	S	I
				CBFO Supplemental Audit	M	M	I
				Verification of CAR 01-028	S	S	S
				See specific area above (Supplier Evaluation, CBFO Supplemental Audit, and Verification of CAR 01-028).			
WTS	S-02-19	3/26/02	Verify corrective actions and assess the adequacy of the WTS implementing procedures and updated WTS QA Procedures Matrix for compliance with the applicable portions of the CBFO QAPD. (Closeout of open items from Audits A-01-13, A-01-18, and A-02-02.)	S	N/A		N/A
				The procedures currently implemented by WTS and the updated WTS Matrix adequately address and meet applicable elements of the CBFO QAPD.			
WTS	A-02-24	5/20-21/02	The WTS QAPD requirements in accordance with the CBFO QAPD and ASME/NQA-1, 1989, Criteria 1, 2 and 3. (Included Sections 1.1, 1.2, 1.3, 2.2, 3.1 and 3.2 and the associated implementing procedures.)	S	S		S
				Overall, the WTS QA program is adequate relative to the flow-down of requirements from the CBFO QAPD and ASME/NQA-1 Criteria 1, 2, and 3. Implementation is satisfactory and the program is effective. Corrective action continues to be effective for CARs previously identified.			
WTS	A-02-25	7/9-12/02	The WTS QAPD requirements in accordance with the CBFO QAPD and ASME NQA-1, Criteria 4, 5, 7, 8, 9, and 13. Sections 2.1 and 2.3 of the WTS QAPD were also evaluated.	S	S		S
				Overall, the WTS QA program is adequate relative to the flow-down of requirements from the CBFO QAPD and NQA-1 Criteria. The implementing procedures are satisfactorily implemented and are effective. The corrective actions continue to be effective for CARs previously generated.			
WTS	S-02-23	7/23-24/02	The WTS software configuration management, software change control, software life cycle documentation, and data entry for container overpacking activities for the WWIS.	S	S		S
				All audited processes are adequate, satisfactorily implemented, and effective.			

Table AUD-7. Washington TRU Solutions (WTS) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
WTS	A-03-06	11/12-15/02	The WTS QAPD requirements in accordance with the CBFO QAPD and NQA-1, Criteria 10, 11, 12, 14, and QAPD Section 4. Sections 2.4.1, 2.4.2, 2.4.3, and 2.1.3.B.5 were also evaluated.	S	S	S
				Overall, the WTS QA program is adequate relative to the flow-down of requirements from the CBFO QAPD. The implementing procedures are satisfactorily implemented and are effective. The corrective actions continue to be effective for CARs previously generated.		
Washington TRU Solutions (WTS)	A-03-10	1/13-16/03	The WTS QAPD requirements in accordance with NQA-1, Criteria 6, 15, 16, 17, and 18, the CBFO QAPD, and TRAMPAC (WTS QAPD Sections 1.3, 1.4, 1.5, 3, and 6).	S	S	S
				Overall, the WTS QA program is adequate relative to the flow-down of requirements from the CBFO QAPD to the WTS QAPD and implementing procedures. The implementing procedures are satisfactorily implemented and are effective. Corrective actions continue to be effective for previously generated CARs, except in the area of nonconforming items.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-8. Sandia National Laboratories (SNL) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
Sandia National Laboratories (SNL)	S-99-07	2/23-25/99	The SNL document control program.	S	S	S
				The document control program was adequate, satisfactorily implemented, and effective.		
SNL	A-00-01	11/8-11/00	The SNL QA program requirements implementation.	S	S	S
				The SNL QA program was adequate, satisfactorily implemented, and effective.		
SNL	A-01-04	11/27-12/1/00	The SNL technical and QA activities.	S	M	M
				The QA program was adequate; however, implementation and effectiveness were marginal. The areas of performance assessment, parameters, and sensitivity analysis were determined to be marginal. Software QA was inadequate and the implementation and effectiveness unsatisfactory.		
SNL	A-02-01	10/29-11/2/01	The SNL QA program for WIPP activities in accordance with the CBFO QAPD, Revision 3. Scope included a technical review of performance assessment (PA), sensitivity analysis, parameters, software QA activities, and an evaluation of the effectiveness of corrective actions implemented for conditions adverse to quality identified during the previous audit (A-00-01).	S	M	S
				The SNL QA program for WIPP remains adequate and effective; however, implementation was considered to be marginal.		
SNL-C	S-02-11	3/19-20/02	The SNL-WIPP Geologic Core management activities, including evaluation of controls for the SNL-WIPP Geologic Core stored in the WIPP underground located in Q Room Access Drift (W700), and geologic cores transferred and maintained at SNL's analytical laboratories in Carlsbad.	S	S	S
				Current procedures relative to core identification, storage, handling, custody, distribution, and records controls are adequately defined, satisfactorily implemented, and effective.		
SNL-C	A-03-11	11/4-7/02	The SNL Nuclear Waste Management Program (NWMP) QA Program for the WIPP. Evaluation included a technical review of PA, sensitivity analysis, parameters, and software QA activities.	S	S	S
				The SNL QA program for the WIPP remains adequate, satisfactorily implemented, and effective.		

Table AUD-8. Sandia National Laboratories (SNL) Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
SNL-C	S-03-09	2/4-5/03	The Compliance Recertification Application (CRA) activities of SNL, Carlsbad, New Mexico.	S	S	S
				SNL's activities pertaining to the CRA activities are adequate, satisfactorily implemented, and effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-9. Savannah River Site (SRS) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
Savannah River Site (SRS)	S-01-32	7/19-20/01	The SRS QA and technical program related to the Document Control program and TRU waste characterization activities.	S	S	S
				The QA program requirements related to the activities evaluated were adequate, satisfactorily implemented, and effective.		
SRS	A-02-06	12/10-14/01	The SRS TRU waste characterization activities relative to the requirements detailed in the WIPP HWFP and the CBFO QAPD.	S	S	S
				The overall adequacy of the SRS technical and QA programs, as applicable to audited activities, was satisfactory in meeting requirements, and the procedures and processes were satisfactorily implemented and effective.		
SRS	A-02-20	3/13-14/02	The TRU waste characterization activities for new HSG sampling and analysis systems and processes.	S	S	S
				The overall SRS technical and QA programs, as applicable to compositing with the currently certified HSG analysis equipment and the new canister cleaning station, were adequate and satisfactory in meeting requirements, and the procedures and processes were satisfactorily implemented and effective.		
SRS	S-02-20	7/1/02	The Acceptable Knowledge (AK) process at the SRS. Examined the characterization of contact-handled debris waste (Summary Category Group S5000) training, AK reporting, control of discrepancies and confirmation.	S	S	S
				SRS AK process is adequate and satisfactorily implementing procedural requirements and the AK process continues to be satisfactorily implemented and effective.		
SRS (CCP)	A-02-09	10/15-19/01	The Central Characterization Program (CCP) characterization and certification activities; technical and QA related to Summary Category Group S5000 (debris waste).	S	S	S
				The CCP technical and QA procedures were adequate relative to the CBFO QAPD, the WAP of the WIPP HWFP, and the WAC of the WIPP. Assessed activities were being implemented in accordance with the CCP QAPP and implementing procedures. The established technical processes and the QA program were effective.		
SRS (CCP)	A-03-01	10/22-25/02	The TRU waste characterization activities performed by the CCP.	S	S	S
				The evaluation procedures and programs were adequate and met requirements. The defined QA and technical programs for these activities were being satisfactorily implemented, and the implementing procedures and processes were effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) – Indeterminate

Table AUD-10. Carlsbad Field Office (CBFO) Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
DOE Carlsbad Field Office (CBFO)	A-00-04	4/24-28/00	Internal QA audit by DOE/Headquarters of CBFO.	S	S	S
				The QA program was adequate, satisfactorily implemented, and effective.		
CBFO	A-01-15	4/30-5/4/01	Internal QA audit of CBFO by DOE/Headquarters.	S	S	S
				The CBFO implementation of DOE 414.1A into the QA program was adequate, satisfactorily implemented, and effective.		
CBFO	S-01-20	7/24-25/01	The CBFO observation process.	M	M	S
				The observation process was effective, but marginally implemented and marginally adequate. Corrective action reports have all been completed and closed.		
CBFO	S-03-08	2/10-13/03	Activities within the Office of Program Support.	S	U	U
				The QA program was adequate but it was not being satisfactorily implemented and was not effective. Corrective action is being taken through the CAR system.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Table AUD-11. Carlsbad Field Office (CBFO) Supplier Audits

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
Carlsbad Field Office Technical Assistance Contractor (CTAC) (Portage Environmental)	A-02-11	1/21-24/02 and 1/29-31/02	The WIPP Performance Demonstration Program (PDP) activities. Verify compliance to the requirements detailed in the WIPP HWFP and the QAPD.	S	S	S
				The QA and technical activities of the PDP were adequate, satisfactorily implemented, and effective. Programmatic direction and oversight activities by the DOE/CBFO and CTAC, as specified in the PDP plans and implementing procedures, were adequate, satisfactorily implemented, and effective.		
Carlsbad Field Office Technical Assistance Contractor (CTAC) (Portage Environmental)	A-02-22	4/16, 17/02 and 4/29/02	The WIPP Performance Demonstration Program (PDP) for Nondestructive Assay. Verify compliance to the requirements detailed in the WIPP HWFP and the QAPD for drummed and boxed waste.	S	S	S
				The PDP NDA activities evaluated from PDP NDA Cycles 6 through 8 were adequate, satisfactorily implemented, and effective.		
Argonne National Laboratory East (ANL-E)	S-01-15	7/10-11/01	The Argonne National Laboratory (ANL-E) technical support activities for the preparation of samples needed to support the WIPP HSG PDP.	S	S	S
				The HSG PDP activities were adequate, satisfactorily implemented, and effective. The implementing procedures and activities for sample preparation, verification, and distribution were also adequate, satisfactorily implemented, and effective.		
ANL-E/CCP	A-02-03 and A-03-13	9/9-13/02 and 2/10-13/03	The ANL-E/CCP TRU waste characterization and certification activities related to Summary Category Groups S5000 (debris waste) and S3000 (homogeneous solid waste). Previous audit assessed the technical and QA activities and the characterization of homogeneous solid waste activities.	S	S	S
				The ANL-E/CCP technical and QA programs met the requirements contained in the HWFP. The deficiencies identified in previous CARs have been corrected. The QA and technical processes are adequate and are being implemented in accordance with the CCP Transuranic Waste QAPP and the associated implementing procedures. The processes were also found to be effective.		
Battelle Columbus Lab (BCL)	A-99-15	5/6-7/99	The BCL Decommissioning Project (BCLDP) TRU Waste AK activities.	N/A	U	U
				The procedures related to AK were not implemented and the evaluated processes were ineffective.		
BCL	S-01-37	7/28-30/01	Assess the implementation of the BCLDP AK program as it applies to selected waste attributes.	S	S	S
				Battelle has established a program that can quantify these waste attributes.		

Table AUD-11. Carlsbad Field Office (CBFO) Supplier Audits — Continued

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessment	Adequacy	Implementation	Effectiveness
Mobile Characterization Services, LLC (MCS)	A-99-18	6/7-11/99	The QA processes related to the MCS TRU waste characterization and certification activities.	S	S	S
				The QA and technical programs were adequate, satisfactorily implemented, and effective.		
Carlsbad Environmental Monitoring and Research Center (CEMRC)	A-03-09	12/10-13/02	Audit A-03-09 was conducted to qualify the Carlsbad Environmental Monitoring and Research Center (CEMRC) QA program for quality-affecting activities for the WIPP. CEMRC may provide actinide chemistry support in the future.	M	M	M
				The CEMRC QA program for quality-affecting activities for the WIPP was marginally inadequate, implemented, and effective.		

(S) - Satisfactory; (M) - Marginal; (U) - Unsatisfactory; (N/A) - Not Applicable; (I) - Indeterminate

Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix BARRIERS

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix BARRIERS

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ACRONYMS AND ABBREVIATIONS

AISC	American Institute of Steel Construction
AISinR	a synthetic brine representative of fluids sampled from the Culebra Member of the Rustler Formation in the WIPP Air Intake Shaft
alumina	Al_2O_3
aq	aqueous
ASTM	American Society for Testing Materials
atm	atmosphere(s)
BLM	Bureau of Land Management
BRAGFLO	Brine and Gas Flow
brucite	$Mg(OH_2)$
ºC	degrees Celsius
calcite	$CaCO_3$
CCA	(WIPP) Compliance Certification Application
CPR	cellulosic, plastic, and rubber (materials)
CRA	(WIPP) Compliance Recertification Application
DI	deionized (water)
DOE	(U.S.) Department of Energy
DRZ	Disturbed Rock Zone
EPA	(U.S.) Environmental Protection Agency
EQ3/6	a geochemical software package for speciation and solubility calculations (EQ3NR) and reaction-path calculations (EQ6)
ERDA-6	Energy Research and Development Administration (WIPP Well) 6, a synthetic brine representative of fluids in Castile-Formation brine reservoirs
f_{CO_2}	fugacity (similar to the partial pressure) of CO_2
FMT	Fracture-Matrix Transport, a geochemical speciation and solubility code
forsterite	Mg_2SiO_4
ft	foot (feet)
g	gaseous or gram(s)
G Seep	a naturally occurring brine collected from G Drift in the WIPP underground
gal	gallon(s)
GWB	Generic Weep Brine, a synthetic brine representative of intergranular Salado-Formation brines
H-17	a synthetic brine representative of brine from the Culebra at the WIPP H-17 Hydropad
halite	NaCl
hydromagnesite	$Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O$ or $Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$
in.	inch(es)
K_d	distribution coefficient
kg	kilogram(s)
km	kilometer(s)
L	liter(s)
lb	pound(s)
lime	CaO
m	meter(s)

M	molar
magnesite	$MgCO_3$
mL	milliliters
mm	millimeter
µm	micrometer(s)
mol	mole(s)
monticellite	$CaMgSiO_4$
MSHA	Mine Safety and Health Administration
nesquehonite	$MgCO_3 \cdot 3H_2O$
nm	nanometer(s)
PA	performance assessment
PAVT	(WIPP) Performance Assessment Verification Test
periclase	pure, crystalline magnesium oxide, the primary constituent of the WIPP engineered barrier
pH	the negative, common logarithm of the activity of hydrogen ion
portlandite	$Ca(OH)_2$
RCRA	Resource Conservation and Recovery Act
RH	relative humidity or remote-handled (TRU waste)
s	second(s)
silica	SiO_2
SMC	Salado Mass Concrete
SPC	Salado Primary Constituents, a synthetic brine similar to Brine A
spinel	$MgAl_2O_4$
SWB	standard waste box
TDOP	ten-drum overpack
TRU	transuranic (waste)
ulvöspinel	$Ti(Fe,Mg)_2O_4$
WIPP	(U.S. DOE) Waste Isolation Pilot Plant
wt	weight
WTS	Westinghouse TRU Solutions
VOC	volatile organic compound
XRD	X-ray diffraction

BARRIERS-1.0 INTRODUCTION

BARRIERS-1.1 Purpose and Objectives

Appendix BARRIERS to the Waste Isolation Pilot Plant (WIPP) Compliance Recertification Application (2004) consolidates the information pertaining to engineered and disposal system barriers related to the WIPP repository. In the initial Compliance Certification Application (CCA) (DOE 1996a), this information was contained in Appendices BACK, EBS, PCS, and SEAL.

This appendix documents how the WIPP satisfies the Environmental Protection Agency (EPA) assurance requirement to provide different types of barriers to isolate the waste from the accessible environment as required by Title 40 Code of Federal Regulations (CFR) § 191.14(d) (EPA 1993). The EPA's Certification Criteria also required the Department of Energy (DOE) to conduct a benefit and detriment study (40 CFR § 194.44) when considering engineered barrier alternatives. The CCA documented this study in Appendix EBS and is included by reference.

BARRIERS-1.2 Background

To address the requirements of 40 CFR 194.44, the DOE performed an Engineered Alternatives Cost/Benefit Study (see CCA Appendix EBS) to examine the benefits and detriments associated with an array of engineered barrier alternatives. Based on the results of these studies and the existing repository design, the DOE proposed four engineered barriers in the CCA: shaft seals, panel closures, magnesium oxide (MgO), and borehole plugs.

In Docket A-93-02 Item V-B-2, Compliance Application Review Document No. 44, the EPA states:

> "EPA reviewed the information contained in the CCA and agreed that the emplacement of MgO in waste panels of the WIPP may be expected to substantially delay the movement of water or radionuclides…For compliance with this requirement, EPA did not evaluate panel seals, shaft seals or borehole plugs. EPA considered these items to be features of the disposal system design and evaluated them in that context."

In the final certification decision for WIPP (63 FR 27397) (EPA 1998a) the EPA concluded:

> "The EPA finds that DOE complies with § 194.44. The EPA found that DOE conducted the requisite analysis of engineered barriers and selected an engineered barrier designed to prevent or substantially delay the movement of water or radionuclides toward the accessible environment. The DOE provided sufficient documentation to show that MgO can effectively reduce actinide solubility in the disposal system. The DOE proposed to emplace a large amount of MgO around waste drums in order to provide additional factor of safety and thus account for uncertainties in the geochemical conditions that would affect CO_2 generation and MgO reactions."

The EPA determined that MgO met the regulatory definition of an engineered barrier. The other three systems proposed as engineered barriers by the DOE were viewed by the EPA as part of the disposal system design. For completeness, this appendix describes both the MgO engineered barrier and the other barriers used by the DOE in the repository design which are not considered to meet the regulatory assurance requirement.

BARRIERS-2.0 ENGINEERED BARRIER

BARRIERS-2.1 Introduction

The DOE is emplacing MgO in the disposal system. The effect of MgO in the disposal system will be to decrease the solubilities of the actinide elements in transuranic (TRU) waste in any brine present in the repository after closure. MgO will decrease actinide solubilities by consuming essentially all carbon dioxide (CO_2) that would be produced by microbial activity-should all cellulosic, plastic, and rubber (CPR) materials in TRU waste and the waste containers be consumed. Although MgO will consume essentially all CO_2, minute quantities (relative to the quantity that would be produced by microbial consumption of all CPR materials) will persist in the aqueous and gaseous phases. The residual quantity will be so small relative to the initial quantity that the adverb "essentially" is omitted hereafter in this appendix. Consumption of CO_2 will prevent the acidification of brine or the production of significant quantities of carbonate ion (CO_3^{2-}), which could increase actinide solubilities.

The effects of MgO carbonation (consumption of CO_2) were included in the CCA performance assessment (PA) and the recertification PA by assuming there is no CO_2 in the disposal system. This assumption is included in PA by (1) removing CO_2 from the gaseous phase in Brine and Gas Flow (BRAGFLO) calculations, thereby reducing somewhat the predicted pressurization of the repository (see Appendix PA, Section PA-4.2); and (2) using the values of f_{CO_2} and pH established by reactions among MgO, brine, and aqueous or gaseous CO_2 to calculate actinide solubilities (see Appendix PA, Attachment SOTERM).

Although the hydration of MgO will remove water (H_2O) from the repository, MgO hydration is not included in PA. Not including MgO hydration in PA is considered a conservative assumption.

In this appendix, "MgO" refers to the bulk, granular material being emplaced in the WIPP to serve as the engineered barrier. MgO comprises periclase (pure, crystalline MgO - the main, reactive constituent of the WIPP engineered barrier) and various impurities (see Section 2.5.1 of this appendix). Pure, crystalline MgO is always referred to as periclase in this appendix. The term "periclase" and other mineral names used herein are, strictly speaking, restricted to naturally occurring forms of the materials that meet all other requirements of the definition of a mineral (see, for example, Bates and Jackson 1984). However, mineral names are used for convenience in this appendix.

BARRIERS-2.2 Description of the Waste Isolation Pilot Plant Engineered-Barrier System

The DOE is emplacing MgO in polypropylene "supersacks" on top of the stacks of three seven-packs of 55-gal (208-L) drums, three standard waste boxes (SWBs), or various combinations of these and other waste containers. Other such containers include ten-drum overpacks (TDOPs), four-packs of 85-gal (321-L) drums, and three-packs of 100-gal (379-L) drums (see Appendix DATA, Attachment H). Each supersack contains 4200 ± 50 lb (1905 ± 23 kg) of MgO (WTS 2003).

Emplacement of MgO in supersacks: (1) facilitates handling and emplacement of MgO; (2) minimizes potential worker exposure to dust; and (3) minimizes the exposure of periclase, the main, reactive constituent of MgO, to atmospheric CO_2 and H_2O during handling and emplacement, and prior to panel closure. WTS (2003) provides detailed specifications for the supersacks. In particular, WTS (2003) specifies that the supersacks "shall provide a barrier to atmospheric moisture and carbon dioxide (CO_2) … equivalent to or better than that provided by a standard commercial cement bag" and "must be able to retain [their] contents for a period of two years after emplacement without rupturing from [their] own weight." The specifications also require a certificate of compliance with all requirements of WTS (2003) for every shipment of MgO (see next paragraph), and a certified chemical analysis of each new lot of MgO. The supersacks are subject to random receipt inspection at the WIPP to ensure compliance with the dimensions and labeling specified by WTS (2003), and to identify any shipping damage.

The supersacks contain dry, granular MgO, of which less than 0.5 percent can exceed 3/8 in. (9.5 mm) in diameter (WTS 2003). Emplacement of granular MgO instead of powder (1) results in a bulk density high enough that sufficient MgO can be emplaced without causing major operational difficulties, (2) reduces the likelihood of formation and release of dust in the event of premature rupture of a supersack, and (3) ensures that the permeability of the material is high enough to promote complete reaction with aqueous or gaseous CO_2.

Creep closure of WIPP disposal rooms will rupture the supersacks and disperse the MgO among and within the ruptured waste containers. This will in turn expose the MgO to the room atmosphere, to any CO_2 produced by microbial consumption of CPR materials, and to H_2O vapor and any brine present.

BARRIERS-2.2.1 Changes in MgO Emplacement since the CCA

Two changes have occurred in MgO emplacement since the CCA, a new supplier was needed for the bulk MgO and operational concerns necessitated the elimination of the minisacks.

National Magnesia Chemicals provided the MgO emplaced in the WIPP from 1999 through 2000. After National Magnesia Chemicals stopped producing MgO, Premier Chemicals in Gabbs, Nevada, was selected as the supplier. Premier MgO was selected based on cost and a technical evaluation verifying its suitability as the engineered barrier (Papenguth 1999). The technical evaluation included a reactivity test developed by Krumhansl et al. (1997). Premier Chemicals has supplied MgO since 2000.

Initially, MgO was emplaced in both supersacks and minisacks. The 25-pound minisacks were emplaced among the waste containers and between the waste containers and the ribs (sides) of the disposal rooms (see CCA Chapter 3). In 2000, however, the DOE requested EPA approval of the elimination of the minisacks (see Triay 2000); the EPA approved this request in 2001 (EPA 2001a).

BARRIERS-2.3 Backfill Conceptual Model

The function of backfill is included in the chemical conditions conceptual model. MgO will create conditions in the repository that decrease actinide solubilities. These lower solubilities are

a result of the consumption of CO_2 produced by microbial consumption of CPR materials and by buffering $f_{CO_2}$and pH in the disposal system. In the model, MgO will initially hydrate by reacting with any brine present in the repository to form brucite:

$$MgO + H_2O(aq \text{ or } g) \rightleftharpoons Mg(OH)_2. \quad (1)$$

Brucite dissolution is expected to buffer brine by:

$$Mg(OH)_2 \rightleftharpoons Mg^{2+} + 2OH^-, \quad (2)$$

CO_2 in the system will initially react with brucite to form metastable phases including hydrogagnesite:

$$5Mg(OH)_2 + 4CO_2(aq \text{ or } g) \rightleftharpoons Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O, \quad (3)$$

or:

$$4Mg(OH)_2 + 3CO_2(aq \text{ or } g) \rightleftharpoons Mg_4(CO_3)_3(OH)_2{\cdot}3H_2O, \quad (4)$$

and nesquehonite:

$$Mg(OH) + 2H_2O + CO_2(aq \text{ or } g) \rightleftharpoons MgCO_3\ 3H_2O, \quad (5)$$

The DOE believes that hydromagnesite, the most likely metastable phase, and nesquehonite, another possible metastable phase, will dehydrate to form magnesite (MgCO3), the stable carbonate, in the event of microbial activity:

$$Mg_5(CO_3)_4(OH)_2\ 4H_2O + CO_2(aq \text{ or } g) \rightleftharpoons 5MgCO_3 + 5H_2O, \quad (6)$$

EPA summarized the chemical conditions conceptual model in their TSD for 194.24 (Docket A-93-02, V-B-17; EPA 1998d):

> "Based on the above discussion, the sequence of events resulting from brine infiltration and reaction with the MgO backfill in the repository may be conceptualized by the following reactions, in order:
>
> 1. Rapid reaction (hours to days) between the brine and MgO to produce brucite.
> 2. Rapid carbonation (hours to days) of the brucite to produce nesquehonite and possibly hydromagnesite.
> 3. Rapid conversion (days to weeks) of the nesquehonite to hydromagnesite.
> 4. Slow conversion (hundreds to thousands of years) of the hydromagnesite to magnesite.

> The available rate data indicate that some portion, perhaps all, of the hydromagnesite will be converted to magnesite over the 10,000-year period for repository performance. The exact time required for complete conversion has not been established for all chemical conditions. However, the available laboratory and field data clearly indicate that magnesite formation takes from few hundred to, perhaps, a few thousand years. Thus, the early repository conditions can be best represented by the equilibrium between brucite and hydromagnesite. These conditions will eventually evolve to equilibrium between brucite and magnesite."

For the 2004 Compliance Recertification Application (CRA-2004), DOE has adopted the approach EPA used in the 1997 Performance Assessment Verification Test (PAVT). The DOE assumes for its actinide-solubility calculations that the metastable brucite-hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) carbonation reaction will buffer f_{CO_2}. However, in the long-term, the brucite-magnesite carbonation reaction will buffer f_{CO_2}.

BARRIERS-2.4 Predictions of the Effects of Magnesium Oxide

The following sections discuss the effects of MgO on the disposal system. The predicted effects used in the CCA and the effects now included in the CRA are discussed.

BARRIERS-2.4.1 Previous Predictions of the Effects of Magnesium Oxide

Novak et al. (1996) and CCA Appendix BACK concluded that magnesite will be the dominant Mg carbonate in the repository during the 10,000-year regulatory period, and that the brucite-magnesite carbonation reaction,

$$Mg(OH)_2 + CO_2(\text{aq or g}) \rightleftharpoons MgCO_3 + H_2O(\text{aq or g}), \qquad (7)$$

will buffer f_{CO_2} in the WIPP whether or not significant microbial CO_2 production occurs. Novak et al. (1996) calculated actinide solubilities for the CCA PA. They did not report f_{CO_2}, but the EPA (1998d, Tables 4-6 and 4-7) reported a value of $10^{-6.89}$ atm for both Salado Primary Constituents (SPC[1]) and Energy Research and Development Administration (WIPP Well) 6 (ERDA-6[2]) brines in equilibrium with brucite and magnesite. This value of f_{CO_2} was used for the actinide-speciation and -solubility calculations for all CCA PA vectors (both with and without microbial activity). (Other minerals, such as halite and anhydrite, were also present.) Novak et al. (1996) used the brucite dissolution reaction (see Reaction (2), above) to buffer the pH in their actinide-solubility calculations, but did not report their results. The EPA (EPA 1998d, Tables 4-6 and 4-7) reported pH values of 8.69 and 9.24 for SPC and ERDA-6, respectively, in equilibrium with the mineral assemblages provided above. These values of pH were used for the solubility calculations for all CCA PA vectors.

1 SPC is similar to Brine A, another synthetic fluid that has been used to represent intergranular Salado brines (molecke 1983).
2 ERDA-6 is a synthetic brine representative of fluids in brine reservoirs in the Castile Formation (Popielak et al. 1983)

For the 1997 PAVT, the EPA specified that the brucite-hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) carbonation reaction (see Reaction (3), above) will buffer f_{CO_2} in the WIPP whether or not significant microbial CO_2 production occurs. The EPA (1998b, Tables 4.10-3 and 4.10-4; 1998d, Tables 4-8 and 4-9) reported a value of $10^{-5.50}$ atm for both SPC and ERDA-6 in equilibrium with brucite and hydromagnesite. This value of f_{CO_2} was used for the actinide-solubility calculations for all 1997 PAVT vectors (both with and without microbial activity; other minerals, such as halite and anhydrite, were also present). The EPA (1998b, Tables 4.10-3 and 4.10-4; 1998d, Tables 4-8 and 4-9) reported pH values of 8.69 and 9.24 for SPC and ERDA-6, respectively, in equilibrium with the mineral assemblages provided above. These pH values were used for the solubility calculations for all 1997 PAVT vectors.

*BARRIERS-2.4.2 Current Predictions of the Effects of Magnesium Oxid*e

The following sections describe the implementation of the chemical conditions conceptual model in the CRA-2004 PA. Specifically, the effects of MgO hydration and carbonation are discussed along with discussions of MgO's buffering ability and potential impacts on other significant chemical processes included in the CRA-2004 PA.

BARRIERS-2.4.2.1 Effects of Magnesium Oxide Hydration and Carbonation

The most important effect of MgO modeled in PA is its ability to sequester CO_2 and buffer f_{CO_2}. The PA includes the impacts of MgO on two elements relating to gas generation and actinide solubilities. With respect to gas generation, PA assumes there is no CO_2 in the disposal system for vectors with microbial activity. For MgO's effect on actinide solubilities, the CRA-2004 PA, Brush and Xiong (2003b) determined the log f_{CO_2} and pH for use in PA solubility calculations. Table BARRIERS-2 compares the values of log f_{CO_2} and pH calculated for the CRA-2004 PA solubility calculations by Brush and Xiong (2003b) with those calculated for the CCA PA and the 1997 PAVT. Table BARRIERS-2 shows that, despite modest differences in the predicted values of log f_{CO_2} and pH, reactions among brine, CO_2, and MgO will consume essentially all CO_2 that could be produced in the repository, buffer f_{CO_2} within a range of about 10^{-5} to 10^{-6} atm (or about 10^{-7} atm if significant quantities of magnesite form), and buffer the pH at about 9.

Table BARRIERS-1. Comparison of Log f_{CO_2} and pH Calculated for the CRA-2004 PA, the 1997 PAVT, and the CCA PA[1,2,3]

Property and Brine	CRA,[1] Microbial Vectors	CRA,[1] Nonmicrobial Vectors	1997 PAVT,[3] All Vectors	CCA,[2] All Vectors
Log f_{CO_2}, Salado Brine	-5.50	-5.48	-5.50	-6.9
Log f_{CO_2}, Castile Brine	-5.50	-6.15	-5.50	-6.9
pH, Salado Brine	8.69	8.69	8.69	8.69
pH, Castile Brine	9.02	8.99	9.24	9.24

[1] From Brush and Xiong (2003b). See text for details.
[2] From Novak et al. (1996) and EPA (1998c). See text for details.
[3] From EPA (1998b, 1998c). See text for details.

These values of f_{CO_2} are significantly lower than those anticipated in the absence of MgO (see CCA Appendix SOTERM, Figures SOTERM-1 and SOTERM-2).

BARRIERS-2.4.2.2 Effects of Magnesium Oxide in the Event of Significant Microbial Activity

The DOE is emplacing significantly more MgO than would be required to sequester the CO_2 that could be produced by microbial consumption of all CPR materials in the WIPP (see Section 2.6 of this appendix). Therefore, both brucite and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$), or brucite, a Mg-Cl-OH-H_2O phase, and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$), will be present in the repository even if all CPR materials are consumed; and these solids will buffer f_{CO_2} (see Reaction (2), above). In this and other reactions used for thermodynamic calculations, it has been assumed that the effects of possible substitution of Fe(II) for Mg in Mg-bearing solids such as brucite and hydromagnesite are insignificant. Brush and Xiong (2003a, 2003b) used equilibria among Generic Weep Brine (GWB[3]), brucite, $Mg_2Cl(OH)_3{\cdot}4H_2O$, and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$), or among ERDA-6, brucite, and hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$), to buffer f_{CO_2} for the actinide-speciation and -solubility calculations for the CRA-2004 PA vectors with microbial activity. Brush and Xiong (2003b, Table 6) reported a value of $10^{-5.50}$ atm for f_{CO_2} for both GWB and ERDA-6 and the mineral assemblages provided above. Other minerals, such as halite (NaCl) and anhydrite ($CaSO_4$), were also present in these mineral assemblages, but are not reactants or products of the carbonation reaction(s) that buffer f_{CO_2}.

The brucite dissolution reaction (see Reaction (2) above), will buffer pH in the WIPP in the event of significant microbial activity. Brush and Xiong (2003b, Table 6) reported a pH value of 8.69 for GWB and 9.02 for ERDA-6.

These values of f_{CO_2} and pH were used for the actinide-speciation and -solubility calculations for the CRA-2004 PA vectors with significant microbial activity (see Appendix PA, Attachment SOTERM, Section SOTERM-3.0).

BARRIERS-2.4.2.3 Effects of Magnesium Oxide in the Absence of Significant Microbial Activity

Brush and Xiong (2003a) redefined the reaction that will buffer f_{CO_2} for those PA vectors without microbial activity. Brush and Xiong (2003b) evaluated the effects of this change on f_{CO_2} and pH, and on the speciation and solubilities of thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), and americium (Am). Brush and Xiong (2003b) demonstrated that redefining the reaction that will buffer f_{CO_2} does not change f_{CO_2}, pH, or actinide solubilities significantly. However,

3 GWB is a synthetic brine typical of intergranular (grain-boundary) fluids from the Salado Formation at or near the stratigraphic horizon of the repository (Snider 2003b)

implementation of this change in the CRA-2004 PA has made the actinide solubilities used in these calculations consistent with the conceptual model for microbial activity in the WIPP (see above).

Calcite ($CaCO_3$) is more stable under expected WIPP conditions than magnesite, hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$ or $Mg_4(CO_3)_3(OH)_2 \cdot 4H_2O$) or nesquehonite. Furthermore, calcite precipitates readily under the low-temperature conditions expected in the WIPP. Formation of calcite from the carbonation of lime (CaO) and/or portlandite ($Ca(OH)_2$)(has been observed in as little as 16 days in GWB, and by 50 days in ERDA-6, in the carbonation experiments described above. Therefore, Brush and Xiong (2003a, 2003b) suppressed (prevented the formation of) calcite (and magnesite) by "disabling" it in their input files, thereby allowing the formation of hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$), the third-most-stable carbonate mineral under expected WIPP conditions. This was appropriate for the vectors with microbial activity because the large quantities of CO_2 produced in these vectors would overwhelm the capacity of dissolved calcium (Ca^{2+}) to precipitate CO_2 as calcite, thus leaving most of the microbial CO_2 to react with periclase, brucite, or $Mg_2Cl(OH)_3 \cdot 4H_2O$ and produce hydromagnesite or (initially) nesquehonite. However, in the absence of microbial CO_2 production, the quantity of Ca^{2+} present would be sufficient to precipitate any CO_2 present as calcite without formation of metastable Mg carbonates. Therefore, for the vectors without microbial activity, Brush and Xiong (2003a, 2003b) allowed calcite to precipitate. The reaction that will buffer f_{CO_2} in the absence of microbial activity is:

$$Mg(OH)_2 + Ca^{2+} + CO_2(\text{aq or g}) \rightleftharpoons CaCO_3 + Mg^{2+} + H_2O(\text{aq or g}). \qquad (8)$$

Unlike the brucite-hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) carbonation reaction (see Reaction (2), above), which buffers f_{CO_2} at a unique value of $10^{-5.50}$ atm, the value of f_{CO_2} maintained by the brucite-calcite carbonation reaction (Reaction (4)) depends on the ratio of the activities of Mg^{2+} and Ca^{2+}, which in turn depends on the composition of the brine after equilibration with MgO. Brush and Xiong (2003b, Table 6) reported a value of $10^{-5.48}$ atm for GWB, brucite, and calcite, and $10^{-6.15}$ atm for ERDA-6, brucite, and calcite. (Other minerals, such as halite and anhydrite, were also present.)

The brucite dissolution reaction (see Reaction (3), above) would also buffer pH in the WIPP in the absence of significant microbial activity. Brush and Xiong (2003b, Table 6) reported pH values of 8.69 for GWB and 8.99 for ERDA-6.

These values of f_{CO_2} and pH were used for the actinide-speciation and -solubility calculations for the CRA-2004 PA vectors without microbial activity (see Appendix PA, Attachment SOTERM, Section SOTERM-3.0).

BARRIERS-2.4.2.4 <u>Effects of Magnesium Oxide on Colloidal Actinide Concentrations</u>

Colloids could affect the long-term performance of the WIPP because of their potential ability to bind cationic metals such as the actinide elements in TRU waste and because of their potential mobility under expected repository conditions (Choppin 1988). Colloids are typically defined as phases intermediate in size between dissolved ionic or molecular species and suspended particles

large enough to settle by gravity. The size range of colloids is typically on the order of 1 nm to 1 μm.

Humic substances, microbes, and mineral fragments could bind actinides in the WIPP. Under some conditions, actinides could also form intrinsic colloids without binding to humics, microbes, or minerals. Even if one or more of these four types of colloids form(s) in the WIPP, they would not transport actinides out of the repository unless they remain suspended in brine. If coagulation occurs, any actinides bound to these colloids would be immobile, at least with respect to direct brine releases or injection of brine into the Culebra Member of the Rustler Formation.

Chemical conditions in the repository will affect the colloidal actinide source term. For example, the pH of any brine present will affect the concentration(s) of intrinsic colloids. Studies carried out to quantify the colloidal source term included experiments under conditions that will be established by MgO (see Appendix PA, Attachment SOTERM, Section SOTERM-6.0).

BARRIERS 2.5 Experimental Activities and Modeling Investigations Since the CCA

The Scientific Advisor (SA) has investigated MgO efficacy through various experiments to test key functions. Specifically the SA has characterized MgO samples from suppliers and performed hydration and carbonation experiments. The following sections discuss the experiments and implications on the chemical conditions conceptual models.

BARRIERS-2.5.1 Characterization of Premier Magnesium Oxide

As stated in Section 2.2.1, Premier Chemicals manufactures the MgO currently being emplaced in the WIPP by mining ore from a sedimentary magnesite deposit and calcining it to expel all CO_2 from magnesite, thereby producing periclase. Calcination of accessory calcite produces small quantities of lime. Calcination of other accessory minerals in the ore creates minor quantities of oxide and silicate minerals such as spinel ($MgAl_2O_4$), ulvöspinel ($Ti(Fe,Mg)_2O_4$), forsterite (Mg_2SiO_4), and monticellite ($CaMgSiO_4$). Calcination also drives off all H_2O in the ore.

Bryan and Snider (2001a) reported that a typical chemical analysis of Premier MgO yields about 91 wt percent MgO, 1 wt percent alumina (Al_2O_3), 3 wt percent silica (SiO_2), 4 wt percent calcium oxide (CaO), and 1 wt percent iron(III) (Fe(III)) oxide (Fe_2O_3). Most of the MgO and some of the CaO occur as periclase and lime, respectively, in Premier MgO. However, some of the MgO and CaO, and most – if not all – Al_2O_3, SiO_2, and Fe(III) oxide are present in the accessory oxide and silicate minerals described above.

Snider (2003a) used inductively coupled plasma-optical emission spectroscopy, gravimetric analysis, and XRD analysis to quantify the mineralogical composition of one of the lots of Premier MgO used for the experiments described below. Based on the assumption that the silicate in this MgO is forsterite, this lot of MgO contains 86.86 wt percent periclase, 2.386 wt percent lime, 2.071 wt percent spinel, and 5.02 wt percent forsterite. If the silicate is monticellite, this lot contains 88.73 wt percent periclase, 1.273 wt percent lime, 2.071 wt percent spinel, and 5.756 wt percent monticellite. Given the

uncertainties inherent in quantifying the mineralogical composition of materials such as Premier MgO, it is reasonable to conclude that this material contains about 90 wt percent reactive phases (periclase + lime) and 10 wt percent nonreactive phases (oxides and silicates).

After the WIPP is filled and sealed, periclase will react with H_2O in the gaseous phase to form brucite ($Mg(OH_2)$), or with H_2O in brine to form brucite or amorphous or crystalline Mg-Cl-OH-H_2O-bearing solids such as $Mg_3Cl(OH)_5{\cdot}4H_2O$ or $Mg_2Cl(OH)_3{\cdot}4H_2O$. Periclase, brucite, and the Mg-Cl-OH-H_2O phases will react with aqueous or gaseous CO_2 to form solids such as hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ or perhaps $Mg_4(CO_3)_3(OH)_2{\cdot}3H_2O$), nesquehonite ($MgCO_3{\cdot}3H_2O$), and perhaps magnesite. Lime will react with aqueous or gaseous H_2O to form portlandite, and lime and portlandite will react with aqueous or gaseous CO_2 to form calcite. Oxides other than periclase and lime, and silicates will not react with H_2O and CO_2 to a significant extent during the 10,000-year regulatory period. Therefore, oxides other than periclase and lime, and silicates are not included in the calculation of the CO_2 consumption capacity used to calculate the MgO safety factor (see Section 2.6 of this appendix). Furthermore, these oxides and silicates will not affect chemical conditions in the repository significantly.

Bryan and Snider (2001a) carried out particle-size analysis of two of the batches of MgO used for their experiments. Table BARRIERS-1 provides the results of this analysis.

Table BARRIERS-2. Particle-Size Distribution of Two Batches of Premier MgO

(Bryan and Snider 2001a)

Size Range (mm)	Batch 1	Batch 2
< 0.15	30.95%	9.89%
0.15 to 0.30	8.36%	29.37%
0.30 to 0.50	4.59%	29.72%
0.50 to 0.71	3.50%	14.98%
0.71 to 2.00	14.16%	14.51%
> 2.00	37.41%	1.53%

BARRIERS-2.5.2 Hydration of Magnesium Oxide

The SA investigated MgO hydration, including experiments under conditions similar to those expected in the repository. Bryan and Snider (2001a, 2001b) and Snider (2002, 2003a) studied the hydration of Premier MgO, the material currently being emplaced in the WIPP, under humid and inundated conditions. Humid experiments have been carried out with 3 g of uncrushed Premier MgO at a relative humidity (RH) of 35, 50, 75, or 95 percent and temperatures of 25, 40,

60, or 80 ºC for up to 460 days (Snider 2003a); inundated experiments have been conducted with 5 g of uncrushed Premier MgO in 100 mL of deionized (DI) H_2O, 4.00-M sodium chloride (NaCl), ERDA-6, or GWB at temperatures of 25, 50, 70, and 90 °C for up to 360 days (Snider 2003a).

Reaction (1)(see above) is the only hydration reaction observed to date in the humid experiments. Reaction (1) is also the only hydration reaction observed so far in the inundated runs with ERDA-6 (Snider 2003a). In inundated experiments with GWB, hydration has produced both brucite and an amorphous or crystalline Mg-Cl-OH-H_2O phase (Snider 2003a). In most of the runs with GWB, the Mg-Cl-OH-H_2O phase is amorphous and its exact composition has not been determined. In a few experiments at 25 ºC, however, a crystalline phase with the composition $Mg_3Cl(OH)_5{\cdot}4H_2O$ has been identified by X-ray diffraction (XRD) analysis. The thermodynamic speciation and solubility code Fracture-Matrix Transport (FMT) (Babb and Novak 1997 and addenda, Wang 1998) also predicts that both brucite and $Mg_2Cl(OH)_3{\cdot}4H_2O$ are stable in GWB. However, long-term experiments with GWB suggest that brucite may be replacing the amorphous Mg-Cl-OH-H_2O phase.

BARRIERS-2.5.3 Carbonation of Magnesium Oxide

The SA investigated MgO carbonation and intermediate hydrous phases. Bryan and Snider (2001a, 2001b), Snider (2002), Snider and Xiong (2002), and Xiong and Snider (2003) have studied the carbonation of Premier MgO, the material currently being emplaced in the WIPP, and reagent-grade materials under inundated conditions. Inundated experiments have been carried out with 5 g of uncrushed Premier MgO in 100 mL of DI H_2O, 4.00-M NaCl, ERDA-6, or GWB under an atmosphere consisting of compressed, ambient, laboratory air at room temperature for up to 327 days (Snider and Xiong 2002); inundated experiments have also been conducted with uncrushed Premier MgO; crushed, prehydrated Premier MgO; Fisher reagent-grade periclase; or prehydrated Fisher periclase in 100 mL of ERDA-6 or GWB under an atmosphere containing 5 percent CO_2 for periods up to 91 days (Snider and Xiong, 2002). Humid experiments have been performed with 2.5 g of prehydrated Fisher periclase in an atmosphere consisting of compressed, ambient, laboratory air at an RH of 33, 58, 75, or 95 percent at room temperature and 40 ºC.

In experiments with ERDA-6 and atmospheric CO_2, Snider and Xiong (2002) have detected hydromagnesite with the composition $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ by XRD analysis. No other Mg carbonates have been detected in runs with ERDA-6 and atmospheric CO_2. Snider and Xiong (2002) have detected both hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) and nesquehonite by XRD analysis in the experiments with ERDA-6 and 5 percent CO_2, but hydromagnesite is clearly replacing nesquehonite as these experiments proceed. In experiments with GWB, hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) is the only Mg carbonate that has been detected by XRD analysis (Snider and Xiong 2002). Therefore, consistent with the chemical conditions conceptual model, there is strong evidence that hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) will be the dominant Mg carbonate for at least part of the 10,000-year regulatory period. The duration of these experiments supports the conclusion that an intermediate phase will occur early in the disposal system where magnesite formation is not expected for hundreds of years.

Additionally, thermodynamic calculations with EQ3/6 (Daveler and Wolery 1992, Wolery 1992a, 1992b, Wolery and Daveler 1992) and FMT imply the magnesite is stable with respect to

both hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$ or $Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O$) and nesquehonite under expected WIPP conditions (see Brush and Xiong 2003a). Furthermore, magnesite is commonly observed in the Salado (Lang 1939; Adams 1944; Lowenstein 1983, 1988; Stein 1985) and in other formations in the Delaware Basin (Garber et al. 1990). Lowenstein (1988, p. 598) describes the siliciclastic-carbonate mudstone, in which magnesite is most abundant, as a "non-evaporitic sediment" and attributes its origin to subaqueous "settling of fine-grained, suspended material in the center of the Salado basin where the energy of inflow waters had largely dissipated." Therefore, the magnesite observed in the Salado did not necessarily form in situ. However, Garber et al. (1990), who reported that magnesite "occurs pervasively" throughout an 82-m (270-ft) interval of core recovered from a stratigraphic test well located along the subsurface trend of the Capitan Reef 27 km (17 miles) northeast of Carlsbad, concluded that "the most likely origin for the magnesite in the core is the downward movement of dense fluids from the Ochoan Series, Salado Formation into the underlying, and [at the time] shallowly buried Tansil and Yates formations." Clearly, magnesite either formed or persisted for long periods in the Delaware Basin. Therefore, consistent with the chemical conditions conceptual model, the possibility that significant quantities of magnesite could form from carbonation of MgO during the 10,000-year regulatory period cannot be ruled out.

BARRIERS-2.5.4 Effects of Magnesium Oxide on Gas Generation

The two gas-producing processes included in PA are anoxic corrosion of steels and other Fe-base alloys, which produces H_2, and microbial consumption of CPR materials, which produces mainly CO_2 and methane (CH_4).

BARRIERS-2.5.4.1 Potential MgO Impacts on Gas Generation from Anoxic Corrosion of Steels and Other Iron-Base Alloys

Telander and Westerman (1993, 1997) studied anoxic corrosion of various metals and concomitant H_2 production under expected WIPP conditions. Wang and Brush (1996a, 1996c) used results from three types of experiments carried out by Telander and Westerman (1993, 1997) to establish ranges and probability distributions of H_2-production rates for the CCA PA: (1) experiments with low-carbon (C) steels in or above Brine A under atmospheres consisting of initially pure CO_2, nitrogen (N_2), or hydrogen sulfide (H_2S) in inert (noncorroding), metallic containers at low-to-intermediate pressures (about 1 to 20 atm); (2) experiments with low-C steels in Brine A under H_2, CO_2, or N_2 in autoclaves at high pressures (35 to 127 atm); and (3) runs with low-C steels in ERDA-6 at pH values of 2.8 to 10.6 under N_2. All these experiments were conducted at 30 ± 5 ºC. Brine A and ERDA-6 are described above (see Section 2.4.1 of this appendix).

Anoxic corrosion of low-C steels in Brine A under initially pure N_2 resulted in a pH of 8.3, 8.3, and 8.4 after 6, 12, and 24 months, respectively (see Telander and Westerman 1993, Table 6-3, Test Containers 10, 17, and 25). Wang and Brush (1996a, 1996c) used the 12-to-24-month data from these experiments to establish a range and probability distribution of inundated, anoxic-corrosion rates of steels and other Fe-base alloys of 0 to 0.5 μm/year for the CCA PA. This is equivalent to a range of 0 to 1.59×10^{-14} m/s. Data on the effects of pH on corrosion rates (Telander and Westerman 1997, Table 6-5) have demonstrated that rates obtained at a pH of 8.3 or 8.4 are somewhat higher than those at a pH of 8.69, 8.99, or 9.02, the values expected for the

brucite dissolution reaction (see Reaction (3), above). Therefore, the anoxic-corrosion rates established by Brush and Wang (1996a, 1996c) for the CCA incorporated the effects of MgO on pH.

For the 1997 PAVT, the EPA specified that the upper limit of the range of the inundated anoxic-corrosion rate be increased from 1.59×10^{-14} m/s to 3.17×10^{-14} m/s (Trovato 1997a, Enclosure 2; EPA 1998c, Table ES-4, Section 5.15, and Tables 6.3 and 6.4; Hansen and Leigh 2003). A range of 0 to 3.17×10^{-14} m/s was also used for the CRA-2004 PA (see Appendix PA, Section PA-5.2).

BARRIERS-2.5.4.2 <u>Microbial Gas Generation</u>

Francis and Gillow (1994, 2000), Francis et al. (1997), and Gillow and Francis (2001a, 2001b, 2002a, 2002b) did not include MgO or the effects of pH in their study of microbial gas generation under expected WIPP conditions. Instead, they included bentonite in about half of their experiments because a backfill consisting of 70 wt percent crushed salt and 30 wt percent bentonite had been proposed as an alternative to a backfill consisting entirely of crushed salt, the design-basis backfill in January 1992 when these microbial gas-generation experiments were started. No microbial experiments have been carried out with MgO since the use of this material was proposed in 1996 to consume CO_2 and control f_{CO_2} and pH in the WIPP.

The brucite dissolution reaction (see Reaction (3), above) will buffer the pH of any brines present at about 9 whether or not significant microbial activity occurs in the WIPP. This mildly basic value is somewhat higher than the mildly acidic values of pH produced by dissolution of microbial CO_2 in the experiments described by Francis and Gillow (1994, 2000), Francis et al. (1997), and Gillow and Francis (2001a, 2001b, 2002a, 2002b). However, emplacement of MgO in the WIPP and a consequent, mildly basic pH of 9 will not in and of itself preclude significant microbial activity in the repository. This conclusion is based on the common observation of viable alkalohalophilic microbes in alkaline lakes with pH values of 9 to 10. Such alkaline lakes occur frequently in arid and semiarid environments, such as southeastern New Mexico and adjacent areas of west Texas, and could be one of the sources of the halophilic microbes observed in the WIPP.

However, several investigators have reported that MgO and compounds derived from MgO possess inhibitory or even biocidal properties (Asghari and Farrah 1993, Chapman et al. 1995; Koper et al. 2002; Sawai 2003; Sawai et al. 1995a, 1995b, 1996, 2000a, 2000b; Stoimenov et al. 2002; Yamamoto et al. 1998). Some of the results of these studies may be applicable to the WIPP.

First, the inhibitory or biocidal effects of MgO probably result from the presence of brucite, not periclase (Sawai et al. 1995a), because most of the experiments cited above were conducted in aqueous solutions or in growth media that contained H_2O, and most of these experiments were long enough for significant nucleation and growth of brucite on periclase surfaces exposed to these solutions or media.

Second, the inhibitory or biocidal effects of MgO do not seem to be caused by the mildly basic pH that results from the presence of brucite in aqueous solutions or growth media. Sawai et al.

(1997) reported that the survival of Escherichia coli (E. coli) was unaffected by a MgO-free, alkaline growth medium at pH values of 10, 10.25, and 10.5, but that E. coli survival decreased significantly in the same medium at pH values of 10.75 and 11. This result agrees with the conclusion that a mildly basic pH of about 9 caused by the brucite dissolution reaction (see Reaction (3), above) will not by itself preclude microbial activity in the WIPP.

Third, the presence of solid Mg peroxide (MgO_2) (Asghari and Farrah 1993) and/or the anionic dioxygenyl radical ($O_2^{\bullet-}$) (Sawai et al. 1995b) along with periclase may be largely responsible for the inhibitory or biocidal effects of MgO. MgO_2 could be produced by reactions between dissolved hydrogen peroxide (H_2O_2), which will be produced by α radiolysis of H_2O in WIPP brines, and periclase, brucite, or perhaps other Mg-bearing solids. Radiolysis will also produce anionic $O_2^{\bullet-}$.

Fourth, inhibition of microbial activity seems to require contact between MgO particles and microbes (Sawai et al. 2000a). This conclusion is based on the observation that increased shaking speed of an MgO-bearing slurry increased the mortality of E. coli in the slurry.

Fifth, the inhibitory effect is inversely proportional to the size of the MgO particles (Sawai et al. 1996; Koper et al. 2002; Stoimenov et al. 2002) and the temperature at which the MgO was prepared (Sawai et al. 1996).

Application of these results to microbial activity in the WIPP is difficult in the absence of long-term experiments under expected repository conditions. Biocides are often used for sterilization of solid materials, but become ineffective as the volume of the material(s) to be sterilized increases. This is because it becomes progressively more difficult to ensure uniform distribution of the biocide throughout these materials, and hence to ensure contact between the biocide and the microbes, as the volume increases. Therefore, sterilization methods such as autoclaving and radiation are used for materials with large volumes. In the case of MgO, Sawai et al. (2000a) reported that inhibition of microbial activity seems to require contact between MgO particles and microbes. Although room closure will rupture the supersacks and disperse the MgO into the interstices among and within the ruptured waste containers, this will not ensure contact between MgO particles and microbes. Furthermore, survival of microbes in samples subjected to treatment with an inhibitory or biocidal agent such as MgO, especially those that have had some contact with particulate MgO, would probably result in the development of increased resistance to MgO.

Nevertheless, the results described above suggest that MgO might reduce the rate of microbial gas generation in the WIPP. In the absence of repository-specific experiments, however, it is not possible to reduce the microbial gas-production rates used in PA. Therefore, the rates and probability distributions used for the CRA-2004 PA are identical to those used for the CCA PA and the 1997 PAVT.

BARRIERS-2.5.5 Effects of Magnesium Oxide on Room Closure

In the CCA PA, the 1997 PAVT, and the CRA-2004 PA calculations, room closure initially proceeded as if the rooms were open. The free air space was eliminated early in the calculations by unmitigated creep closure. Eventually, the salt contacted the waste and deformed it according

to the waste response model. At the same time, corrosion and gas production pressurized the rooms. The coupled processes involved compression owing to the superincumbent rock counterbalanced by gas production, which was obtained from sampled parameters. Thus, room closure was due to salt creep modified by the structural response of the waste and by gas production. MgO had no effect on room closure.

BARRIERS-2.5.6 Effects of Magnesium Oxide on Far-Field Actinide Transport

MgO could affect the matrix distribution coefficients (K_ds) used to predict transport of dissolved Th, U, Pu, and Am through the Culebra (see Brush 1996 or Brush and Storz 1996 for a definition of matrix K_ds). For the CCA PA, data from an empirical sorption study, a mechanistic sorption study, and a column-transport study were used to establish ranges and probability distributions of K_ds for Th, U, Pu, and Am.

Most of these K_ds were obtained from six-week, empirical sorption experiments carried out with 1 g of dolomite-rich rock crushed to a size range of 75 to 500 μm; 20 mL of Brine A, ERDA-6, AISinR, or H-17 with dissolved Th(IV), U(VI), Np(V), Pu(V), or Am(III); and a controlled atmosphere containing 0.24, 1.4, or 4.1 percent CO_2 to simulate the expected range of f_{CO_2} in the Culebra, about $10^{-3.5}$ to $10^{-1.50}$ atm (see Brush 1996; Brush and Storz 1996). Brine A and ERDA-6 are described above (see Section 2.4.1 of this appendix); AISinR is a synthetic brine representative of fluids sampled from the Culebra in the WIPP Air Intake Shaft; and H-17 simulates Culebra brine from the H-17 Hydropad.

Brush (1996) and Brush and Storz (1996) extended the empirical K_ds obtained with Brine A and ERDA-6 to a pH of about 9 or 10 with data from a mechanistic sorption study that quantified the effects of f_{CO_2}, pH and ionic strength on the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by well-characterized, pure dolomite. Therefore, the K_ds for Brine A and ERDA-6 used for the CCA PA included the effects of MgO on pH. The K_ds for the Culebra brines, however, did not include the effects of MgO on pH because it was assumed that, if mixing is sufficient to produce fluids with compositions similar to those of Culebra brines, the pH of these mixtures will also be similar to those of Culebra brines (Brush 1996; Brush and Storz 1996).

For the 1997 PAVT, the EPA specified that the probability distributions for the K_ds be changed from uniform to log uniform (Trovato 1997b, Enclosure 2; EPA 1998c, Tables ES-3 and ES-4, Sections 5.34 to 5.38 and Tables 6.3 and 6.4; Hansen and Leigh 2003). However, the EPA did not change any of the K_ds.

Brush and Storz (1996) corrected some of the ranges of K_ds established by Brush (1996) for the CCA PA. These corrections were too late for the far-field transport calculations for the CCA PA, and were not included in the far-field transport calculations for the 1997 PAVT. Hansen and Leigh (2003), however, incorporated them in the PA database, and the CRA-2004 PA used the corrected K_ds along with the log-uniform probability distributions specified by the EPA (see Appendix PA, Section PA-5.2). The K_ds for Brine A and ERDA-6 used for the CRA-2004 PA included the effects of MgO on pH (Reaction (8) in Section 2.4.2.3 of this appendix), but the K_ds for the Culebra brines do not (see above).

BARRIERS-2.6 Magnesium Oxide Safety Factor

The MgO safety factor was first established in a request for additional information during the first WIPP certification (DOE 1997, see also Section 2.3). EPA requested information that demonstrated that the excess MgO volume proposed could actually be emplaced in the space above the waste. Documentation developed during the minisack-elimination proposal (Triay 2000 and EPA 2001a) detail the method used to determine the amount needed to ensure the chemical conditions assumptions used in PA. Actual waste emplacement information is used to determine emplaced and projected amounts of MgO that will be emplaced. The excess MgO above that needed was termed the safety factor. More specifically, the MgO safety factor is defined as the quantity of MgO to be emplaced in the WIPP divided by the quantity required to consume all CO_2 that would be produced by microbial consumption of all CPR materials in the repository. The amount of CO_2 was conservatively determined by assuming a one-to-one mole conversion of organic C in the waste to CO_2, the highest amount that could possibly be produced. The safety factor was determined to be 1.95 (DOE 1997). However, this value was later reduced to 1.67 as specified by EPA during their acceptance of DOE's request to eliminate the MgO minisacks (EPA 2001a). Therefore, the DOE MgO emplacement scheme maintains the specified 1.67 safety factor in each panel.

BARRIERS-2.6.1 Calculation of Magnesium Oxide Safety Factor

As stated above, the MgO safety factor must be maintained at or above 1.67 times the amount necessary to ensure the related assumptions in PA are maintained. The amount needed is that which will sequester the maximum amount of CO_2 that could be produced in the repository. This method conservatively assumes no other reactions that will sequester CO_2 such as reactions with the waste (i.e., reactions with cementitious materials and iron) or the natural environment (i.e., precipitation of calcite by Ca^{2+} from dissolution of SO42—bearing minerals such as anhydrite) occur. The amount of CO_2 produced by microbial consumption of CPR materials assumes a 1:1 molar ratio for the conversion of organic C in the waste to CO_2. Emplaced-waste information and projected waste information are used to determine the amounts of CPR materials in the disposal system. The amount of CPR materials stated in the CCA did not account for CPR materials contained in remote handled (RH) waste or the emplacement materials used to aid the disposal process. The current process includes these materials and therefore is more representative of actual materials in the repository.

The amount of MgO that would be emplaced in the repository was originally determined in the CCA to be 85,600 tons (later reduced to account for minisack elimination). This was the amount believed to fit in the space above the waste stacks. Current waste-emplacement data are available to better quantify the amount of MgO that has been and will be emplaced. The current safety-factor calculations use the emplacement information and not the amount assumed in the CCA.

As stated above, the 1.67 safety factor will be maintained by adding additional MgO if necessary to account for locally higher concentrations of CPR materials in the repository. The default MgO emplacement configuration of one supersack per stack of waste will continue to be maintained throughout the disposal rooms. The safety factor calculation used in EPA's approval of the elimination of minisacks (EPA 2001a) in CRA-2004 can be expressed as:

$$S_F^{MgO} = \frac{\left(M_{emp}^{MgO}\right)}{M_{req}^{MgO}} \tag{9}$$

where

M_{emp}^{MgO} = moles MgO emplaced

M_{req}^{MgO} = moles MgO required to consume CO_2 produced

Each of these terms is discussed below.

MOLES MgO EMPLACED

The mass of MgO emplaced will be tracked by the DOE as each room is filled. The conversion from mass to moles is as follows:

$$M_{emp}^{MgO} = m_{emp}^{MgO}\left(\frac{\text{kg}}{2.2046\ \text{lbs}}\right)\left(\frac{1000\text{g}}{\text{kg}}\right)\left(\frac{\text{mole}}{40.3\text{g}}\right) \tag{10}$$

Where

M_{emp}^{MgO} **= moles MgO emplaced**

m_{emp}^{MgO} **= mass of MgO emplaced in pounds**

MOLES MgO REQUIRED TO CONSUME CO_2 PRODUCED

Calculation of the moles of MgO required to consume CO_2 is based on the assumption that one mole of MgO is required to sequester one mole of CO_2 as was done for the safety factor calculation used in the EPA's approval of the elimination of minisacks (EPA 2001a). CO_2 will be produced through the metabolic utilization of CPR materials by microbes in the repository.

The moles of organic C in the repository are derived from the mass of CPR materials. The total moles of organic C can be expressed as:

$$M_T^{OC} = \gamma_{CH}^{OC} \bullet M_{CH} \tag{11}$$

Where

M_T^{OC} = total moles of organic carbon

γ_{CE}^{OC} = moles of organic carbon per mole of cellulose

M_{CE} = moles of cellulose equivalent

Wang and Brush (1996a) concluded that $\gamma_{CE}^{OC} = 6$

The moles of cellulose equivalent are given in Equation 12 (Wang and Brush 1996a). An adjustment is made to account for higher densities of C in plastic materials.

$$M_{CE} = \frac{m_C + m_R + 1.7 \bullet m_P}{MW_{CE}} \tag{12}$$

where

M_{CE} = moles of cellulose equivalent

MW_{CE} = molecular weight of cellulose = 162 g/mole

m_C = mass of cellulose

m_R = mass of rubber

m_P = mass of plastic

Equation (9) determines the safety factor. Operational controls track CPR materials emplaced in the repository and the amount of MgO emplaced. As waste is emplaced, the safety factor will be periodically calculated to determine if additional MgO is necessary to maintain the safety factor.

BARRIERS.2.6.2 Microbial Investigations since the CCA

The SA has continued to investigate microbial gas generation and its impact on long-term repository performance. The MgO engineered barrier will consume CO_2 produced by microbial consumption of CPR materials in the repository. Gas generation from anoxic corrosion of steel and microbial consumption of CPR materials is modeled in PA as described in CRA Chapter 6, Section 6.4.3.3. Microbial consumption of CPR materials is expected to progress via a sequence of processes based on the availability of electron acceptors in the disposal system. The conceptual model of sequential use of electron acceptors is based on the well-known observations that: (1) microbes use the electron acceptor (oxidant) that yields the most free energy per mole of organic C consumed; (2) after depletion of the best available electron acceptor, these microbes – or other microbes – begin to consume the next best electron acceptor; and (3) this process continues until all substrate (CPR materials in the case of the WIPP) is consumed, an essential nutrient is consumed, or some other limiting condition is attained. Sequential use of electron acceptors has been observed in a diverse array of natural environments, such as lacustrine, riverine, estuarine, and oceanic sediments; soils; and in anthropogenic environments, such as landfills. In these environments, the order of use observed is oxygen (O_2) (referred to as aerobic respiration), NO_3^- (denitrification), manganese(IV) (Mn(IV)) oxides and hydroxides (Mn reduction), Fe(III) oxides and hydroxides (Fe reduction), SO_4^{2-} (SO_4^{2--} reduction), and CO_2 (fermentation and methanogenesis) (Froelich et al. 1979;

Berner 1980; Criddle et al. 1991; Chapelle 1993; Wang and Van Cappellen 1996; Schlesinger 1997; Hunter et al. 1998; Fenchel et al. 2000). (In the following discussion, fermentation and methanogenesis are usually referred to as "methanogenesis" for simplicity.) The sequential reactions used to represent possible denitrification, sulfate (SO_4^{2--}) reduction, and methanogenesis in the WIPP (Wang and Brush 1996a) are:

$$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow 7.4H_2O + 6CO_2 + 2.4N_2; \quad (13)$$

$$C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S; \quad (14)$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2. \quad (15)$$

For these reactions, the CO_2 yields are 1 mole of CO_2 per mole of organic C consumed from denitrification and SO_4^{2--} reduction, and 0.5 moles of CO_2 per mole of C from methanogenesis**.**

Results of the long-term study of microbial gas generation now confirm that methanogenesis is a likely respiratory pathway in the repository if significant microbial activity occurs. By the time that Wang and Brush (1996a, 1996b) established the model and parameters for microbial gas generation for the CCA PA, Francis and Gillow (1994) and Francis et al. (1997) had observed aerobic respiration and denitrification - but not methanogenesis - in their experiments, which had been carried out for up to 1,228 days (3.36 years). Therefore, there was no experimental evidence at the time of the CCA that methanogenesis would actually occur in the WIPP, that the quantity of CPR materials consumed by methanogenesis in the WIPP would greatly exceed those consumed by denitrification and SO_4^{2--} reduction, or that the overall CO_2 yield in the repository would be close to 0.50 mol per mol of organic C consumed. At the time of the CCA, a possible explanation for the absence of methanogenesis was that no viable fermentative and/or methanogenic microbes were present in these experiments. There were two reasons why viable fermenters and/or methanogens might not have been present: (1) none were present in the materials used to inoculate these experiments (laboratory dust, brine, and mud from the salt lakes in Nash Draw, and G Seep brine collected from G Drift - a drift located in the northern end of the WIPP underground workings and used previously for in-situ experiments); and (2) communities of halophilic, fermentative, and methanogenic microbes capable of metabolizing complex, organic substrates, such as cellulosic materials under expected WIPP conditions, do not exist.

Since the CCA PA, however, methanogenesis has been observed in numerous experiments carried out under several combinations of conditions (Francis and Gillow 2000, pp. 2, 3, and 10; Gillow and Francis 2001, pp. 3-4 and 3-5; Gillow and Francis 2002a, pp. 2.1 - 12 to 2.1 – 14; and Gillow and Francis 2002b, pp. 3.1 - 5 to 3.1 - 6). Several definitive conclusions can be drawn from these results.

It is now clear that the absence of experimental evidence for methanogenesis at the time of CCA PA was because microbial activity in the initially aerobic experiments had not progressed through aerobic resp/iration, denitrification, and SO_4^{2--} reduction to methanogenesis; and that microbial activity in the initially anaerobic experiments had not progressed through denitrification and SO_4^{2--} reduction to methanogenesis. The requirement that these steps be completed prior to the onset of methanogenesis is a consequence of the conceptual model of

sequential use of electron acceptors (see above), according to which methanogenesis does not start until any and all NO_3^- and SO_4^{2--} are depleted, or until some other process renders the environment unsuitable for denitrification and SO_4^{2--} reduction. Although methanogenesis had not been observed by the time of the CCA PA in experiments carried out for up to 1,228 days (3.36 years), it was later observed in inundated experiments after 2,718 days (7.44 years) and in humid experiments after 2,653 days (7.26 years).

Therefore, it is also clear now that: (1) there exist communities of halophilic, fermentative, and methanogenic microbes capable of metabolizing complex organic substrates, such as cellulosic materials, under expected WIPP conditions; (2) such microbes are present – and viable – in one or more of the materials used to inoculate these experiments; and (3) these microbes are capable of surviving exposure to O_2. Methanogens are obligate anaerobes and, as such, are extremely sensitive to exposure to O_2. The fact that they produced CH_4 after exposure to O_2 implies that they are capable of producing resistant forms that can survive initially oxic conditions in these experiments.

Furthermore, results from the microbial gas-generation study have confirmed that viable halophilic fermenters and methanogens capable of metabolizing cellulosic materials under expected near-field conditions are present in the WIPP underground workings. Francis and Gillow (2000, pp. 2 and 10) detected CH_4 in initially oxic, unamended, and uninoculated experiments, and in initially anoxic, unamended, and uninoculated experiments. The most likely explanation for microbial gas production in these uninoculated experiments is that G Seep, the brine used for these inundated experiments, was collected from the WIPP underground workings. This brine contained a small but viable microflora, including methanogens, and was not sterilized prior to use. The fact that these microbes produced CH_4 after exposure to O_2 in the air used to ventilate G Drift and in initially oxic experiments implies that they are capable of producing resistant forms that can withstand initially oxic conditions in the repository.

However, the presence of viable halophilic fermenters and methanogens in the WIPP does not preclude the possibility that similar communities of microbes are also present in the other materials used to inoculate these experiments, especially brine and mud from the salt lakes in Nash Draw. It is quite possible that methanogens in these lakes are also capable of producing resistant forms that can survive the oxic conditions encountered during eolian transport from Nash Draw to the WIPP Air Intake Shaft, and initially oxic conditions in the repository. Therefore, the presence of viable methanogens in the WIPP does not depend on the claim that microbes have survived in the Salado since the Permian Period (Vreeland et al. 2000), a claim that is controversial (see, for example, Hazen and Roedder 2001; Powers et al. 2001).

Finally, exclusive use of Reaction (16) (gas-producing methanogenesis) to represent methanogenesis in PA (the current implementation of this respiratory pathway) is probably conservative because Reaction (16) produces an equimolar mixture of CH_4 and CO_2. However, another methanogenic reaction,

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O, \qquad (17)$$

which actually consumes CO_2 and H_2, is likely in the WIPP because it is energetically favored with respect to Reaction (16) (see, for example, Madigan et al. 2003, pp. 454-455). Reaction

(17) has been simplified somewhat inasmuch as microbes that use this respiratory pathway typically use acetate ($CH_3CO_2^+$) or other organic acids along with H_2 to reduce CO_2 to CH_4. (Reactions (14), (15), and (16) have also been simplified somewhat, as is typically the case when used for geochemical applications such as predicting the CO_2 yield from microbial consumption of CPR materials in the WIPP.) Nevertheless, if CO_2 and H_2 (and acetate) are present, Reaction (17) (gas-consuming methanogenesis, or – strictly speaking – gas-consuming acetotrophic methanogenesis) will probably proceed instead of Reaction (16). Alternatively, Reaction (17) could probably proceed along with Reaction (16). In either case, Reaction (17) could consume significant quantities of CO_2.

In the event of significant microbial activity in the WIPP, CO_2 and H_2 (and acetate) will be present because: (1) consumption of CPR via Reaction (14), (15), or (16) will produce CO_2, (2) anoxic corrosion of steels and other Fe-base alloys in waste containers and in the waste will produce H_2 (if brine is present), and (3) acetic acid and sodium acetate are present in the TRU waste to be emplaced in the WIPP (see Appendix DATA, Attachment F) and will dissolve in any brines that enter the repository, possibly reaching a concentration of 3.57×10^{-3} M (Brush and Xiong 2003c).

BARRIERS-3.0 DISPOSAL SYSTEM BARRIERS

BARRIERS-3.1 Definition of a Disposal System Barrier

Disposal system barriers are included as an integral part of the disposal system design. These disposal system barriers are designed to delay the migration of radionuclides to the accessible environment. Frequently, these disposal system barriers are designed to mitigate impacts to the natural strata and block pathways created in the construction and operational phases of the WIPP facility. As such, they are a necessary part of the overall disposal system design.

BARRIERS-3.2 Description of Waste Isolation Pilot Plant Disposal System Barriers

The DOE incorporated three types of disposal system barriers into the design of the disposal system: panel closures, shaft seals, and borehole plugs.

BARRIERS-3.2.1 Panel Closures

In the CCA, the DOE described four possible panel closure designs to be used depending upon ground conditions and potential for gas generation. CCA Appendix PCS was a design report prepared and signed by a professional engineer certified by the state of New Mexico.

In the final certification decision for WIPP (63 FR 27405) (EPA 1998a), EPA specified four conditions that apply to the certification. Condition 1 details the panel closure system to be used as Option D with Salado Mass Concrete (SMC)**:**

> Condition 1: § 194.14(b), Disposal system design, panel closure system. The Department shall implement the panel seal design designated as Option D in Docket A-93-02, Item II-G-1 (October 29, 1996, Compliance Certification Application submitted to the Agency). The Option D design shall be implemented as described in [CCA] Appendix PCS of Docket A-93-02, Item II-G-1, with the exception that the Department shall use Salado mass concrete (consistent with that proposed

for the shaft seal system, and as described in CCA Appendix SEAL of Docket A-93-02, Item II-g-1) instead of fresh water concrete.

Panel closures are included for Resource Conservation and Recovery Act (RCRA) disposal unit closure to prevent potentially unacceptable levels of volatile organic compound (VOC) release during waste management operations, and to protect against the effects of a postulated deflagration in a closed panel. While the panel closures provide a solid structure within the drifts, they were not intended to support long-term repository performance. Of the four options proposed in the CCA, the EPA specified that one of these, Option D, should be used. This Option consists of a concrete barrier emplaced after removing the disturbed rock zone (DRZ), and an explosion wall. EPA also specified that SMC be used for the barrier (EPA 1998a), which was a potential alternative to ordinary portland cement noted in the CCA.

Characteristics of the Option D design are incorporated into the PA grid and computational methodologies for the recertification calculations (Appendix PA, Section PA-4.2.8). However, the DOE believes that a redesign of the panel closure system is warranted. In a letter to the EPA dated October 7, 2002 (DOE 2002-0205715), the DOE requested approval of a proposed change to the EPA 40 CFR Part 194 Certification of the Waste Isolation Pilot Plant with regard to the design of the panel closure system. The DOE believes that the redesigned panel closure is a simpler design concept that provides equivalent or improved performance.

The EPA responded in a letter dated November 15, 2002 that concluded that the panel closure system design change request would require a rulemaking. Because the rulemaking likely would not be completed before this application would be submitted, the EPA deferred review of the proposal until after the recertification decision. The EPA did agree to construction of the explosion wall and a delay in construction of the Option D concrete monolith after completion of waste emplacement in Panel 1 until a regulatory decision was made on the proposed new panel closure design (Docket A-98-49, II-B-3, Item 44). Until a design change is approved by the EPA and the State of New Mexico, the regulatory baseline includes the modified Option D Panel Closure System.

A description of the Option D Panel Closure System, initially provided in CCA Appendix PCS, is discussed in Sections 3.2.1.1 through 3.2.1.5 of this appendix.

BARRIERS-3.2.1.1 <u>Overview</u>

The panel closure system provides assurance that the RCRA limit for the migration of potential VOCs will be met at the point of compliance, the WIPP site boundary. The panel closure system will be located in the air-intake and air-exhaust drifts to each panel, as shown in Figure BARRIERS-1. The design process commenced with the evaluation of the performance requirements of the panel closure; and the system components have been designed to maintain their intended functional requirements under loads generated from salt creep, internal pressure, and a postulated methane explosion.

BARRIERS-3.2.1.2 Design

The mandated panel closure system is an enlarged tapered concrete barrier that will be grouted along the interface and an explosion-isolation wall. Figure BARRIERS-2 illustrates this design. The design concept for the enlarged concrete barrier incorporates:

- A concrete barrier that is tapered to promote the rapid stress buildup on the host rock. The stiffness was selected to provide rapid buildup of compressive stress and reduction in shear stress in the host rock.

- The enlarged barrier requires DRZ removal to keep the tapered shape approximately spherical. DRZ removal limits potential VOC flow through the panel closure system.

- The design of the panel closure system includes an explosion-isolation wall designed to provide strength and deformational serviceability during the operational period. The length was selected to assure that uniform compression develops over a substantial portion of the structure and that end-shear loading that might result in fracturing of salt into the back is reduced. While no requirements for barricading waste areas exist under the MSHA, the intent of the regulations is to safely isolate abandoned areas from active workings using barricades of "substantial construction." The CCA examined the potential issue of methane gas generation from TRU waste in closed areas. The principal concern is the postulated occurrence of an explosive mixture of methane and an ignition source, which would result in deflagration. An explosion-isolation wall has been designed of sufficient thickness to resist dynamic loads from such a deflagration and creep loads from closure of the salt around the wall.

The CRA-2004 PA calculations implement a conceptual design consistent with Option D, as described above. As noted above, the DOE has reevaluated this panel closure design and believes that a modification is warranted.

BARRIERS-3.2.1.3 Design Components

The following subsections present system and components design features.

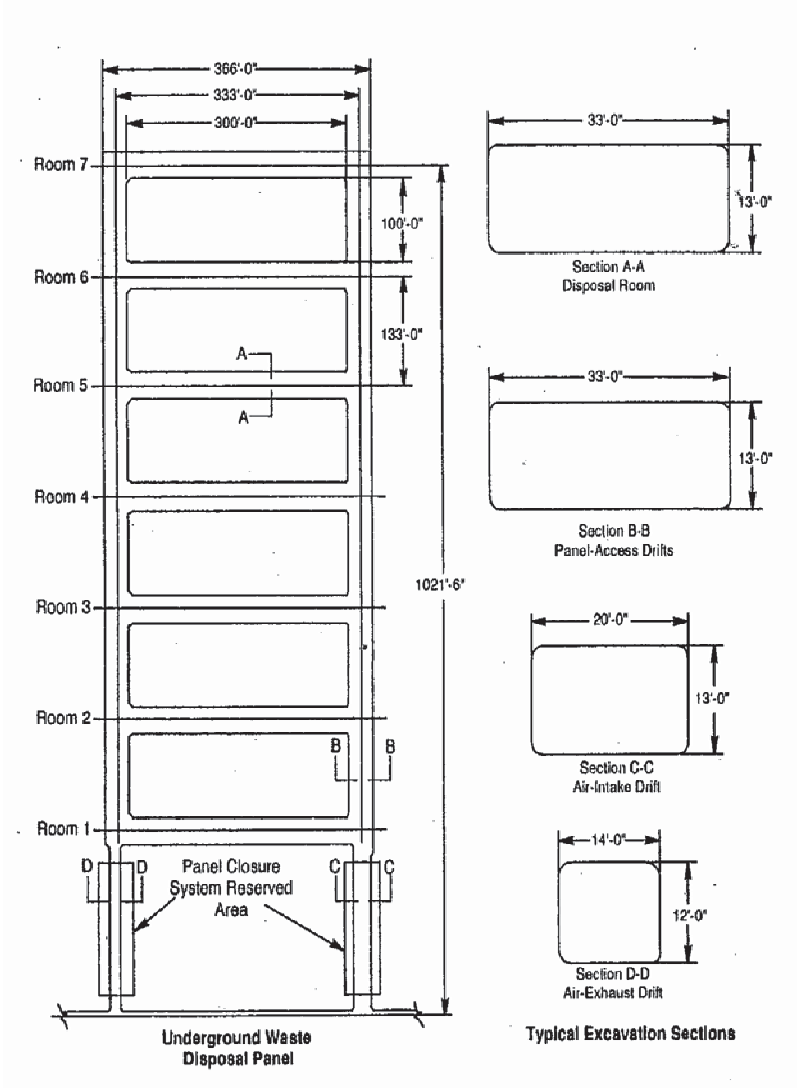

Figure BARRIERS-1. Typical Facilities--Typical Disposal Panel After Westinghouse (1996c)
(Note: Figure is not to Scale. All Dimensions Shown are Nominal)

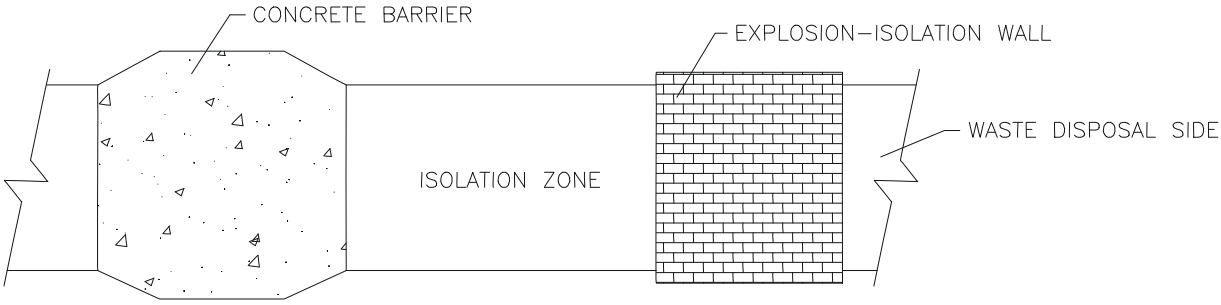

Figure BARRIERS-2. Option D. Explosion-Isolation Wall and Concrete Barrier with DRZ Removed

BARRIERS-3.2.1.3.1 Concrete Barrier

The enlarged concrete barrier consists of SMC, with sufficient unconfined compressive strength and with an approximately circular cross-section excavated into the salt over the central portion of the barrier. The enlarged concrete barrier will be located at the optimum locations in the air-intake and air-exhaust drifts, with the central portion extending just beyond Clay G and MB 139.

The enlarged concrete barrier will be placed in four cells, with construction joints perpendicular to the direction of potential air flow. The concrete strength will be selected according to the standards specified by the latest edition of the ACI code for plain concrete. The concrete will be placed through 6-in- (15-cm)-diameter steel pipes and vibrated from outside the formwork. The formwork is designed to withstand the hydrostatic loads during construction, with minimal bracing onto exposed salt surfaces. This will be accomplished by placing a series of steel plates that are stiffened by angle iron, with load reactions carried by spacer rods. The spacer rods will be staggered to reduce potential flow along the rod surfaces through the barrier. Some exterior bracing will be required when the first cell is poured. All structural steel will be American Society for Testing Materials (ASTM) A36, with detailing, fabrication, and erection of structural steel in conformance with the latest edition of the AISC steel manual (AISC 1989). After concrete placement, the formwork will be left in place.

BARRIERS-3.2.1.3.2 Explosion Wall

An explosion-isolation wall, consisting of concrete blocks, will mitigate the effects of a postulated methane explosion. The concrete block wall design complies with MSHA requirements (MSHA 1987) because it uses incombustible materials of substantial construction.

The explosion-isolation wall in the Panel 1 access drift consists of a structure constructed across the entire cross-section of each drift. Each wall is 12 ft (3.65 m) long and is created from solid concrete blocks mortared together and set in a 0.5-ft (0.15-m) deep keyway cut around the full perimeter of the drifts (Figure BARRIERS-3). The explosion-isolation walls were constructed to the specifications the CCA Appendix PCS, except as noted below.

The revised design, in which the walls are 30 ft (9.1 m) long, uses identical construction techniques, but specifies materials of higher strengths. In summary, the following changes were specified:

- The mortar shall conform to ASTM C 270 type M, using the property specification 3000 psi (20.88 MPa) at 28 days, as a minimum requirement. (The wording of the specification was changed slightly, but the compressive strength requirement is unchanged.)

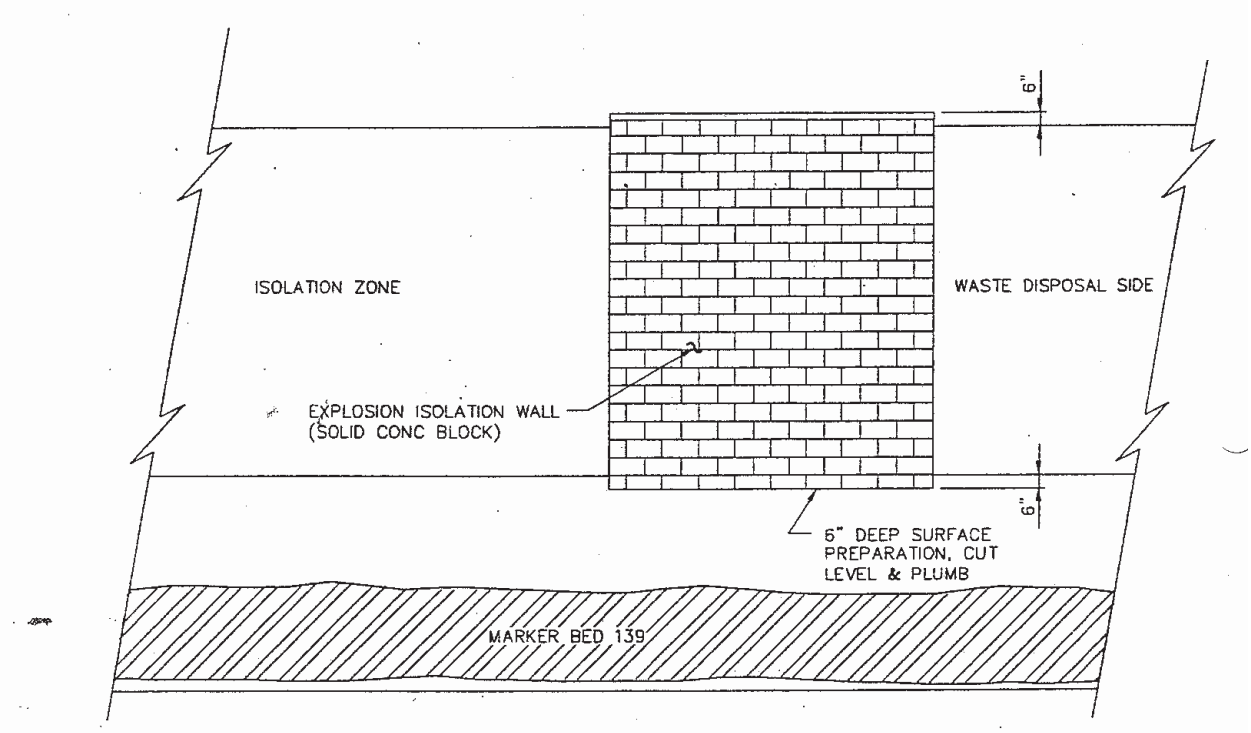

Figure BARRIERS-3. Explosion-Isolation Wall (not to scale)

- The concrete masonry units shall be solid (no cavities or cores), load-bearing, high-strength individual units, having a minimum compressive strength of 5500 psi (37.92 MPa) (average of three units) or 5000 psi (34.47 MPa) for individual unit. (Compressive strength increased from 3500 psi (average of three units) and 3000 psi for individual units.)

- The compressive strength of masonry in each masonry unit shall exceed 5000 psi. (The HWFP specifications do not include this test, which must be performed for each 2000 ft^3 (56.63 m^3) of masonry structure.)

The result of these changes is that materials meeting the specifications of the revised design are consistent with the specification outlined in CCA Appendix PCS. The explosion-isolation wall in Panel 1 was constructed soon after waste emplacement was completed.

BARRIERS-3.2.1.3.3 Interface Grouting

After construction of the main concrete barrier, the interface between the main concrete barrier and the salt will be grouted through a series of grout-supply and air-return lines that will terminate in grout distribution collection boxes. The openings in these boxes will be protected during concrete placement (Figure BARRIERS-4). The grout boxes will be mounted near the top of the barrier. The grout will be injected through one distribution system, with air and return grout flowing through a second distribution system.

BARRIERS-3.2.1.4 Panel-Closure System Construction

The design uses common construction practices according to existing standards. The proposed construction sequence follows completion of the waste-emplacement activities in each panel: (1) perform subsurface exploration to determine the optimum location for the panel closure system, (2) prepare surfaces for the explosion-isolation walls, (3) install these walls, (4) excavate for the enlarged concrete barrier, (5) install concrete formwork, (6) emplace concrete for the first cell, (7) grout the completed cell, and (8) install subsequent formwork, concrete, and grout until completion of the enlarged concrete barrier.

The explosion-isolation walls will be located at some distance from the main concrete barrier. The host rock will be excavated 6 in (15 cm) around the entire perimeter prior to installing the explosion-isolation wall. The surface preparation will produce a level surface for placing the first layer of concrete blocks. Excavation may be performed by either mechanical or manual means.

Excavation for the enlarged concrete barrier will be performed using mechanical means, such as a cutting head on a suitable boom. The existing roadheader at the main barrier location in each drift is capable of excavating the back and the portions of the ribs above the floor level. Some manual excavation may be required in this situation as well. If mechanical means are not available, drilling boreholes and an expansive agent can be used to fragment the rock (Fernandez et al. 1989). Excavation will follow the lines and grades established for the design. The tolerances for the enlarged concrete-barrier excavation are +6 to 0 inches (+15 to 0 cm). In addition, loose or spalling rock from the excavation surface will be removed to provide an appropriate surface abutting the enlarged concrete barrier. The excavations will be performed according to approved ground control plans.

Following completion of the roof excavation for the enlarged barrier, the floor will be excavated. If mechanical means are not available, drilling boreholes and using an expansive agent to fragment the rock (Fernandez et al. 1989) is a method that can be used. Expansive agents would load the rock salt and anhydrite, producing localized tensile fracturing in a controlled manner to produce a sound surface.

A batch plant at the surface or underground will be utilized for batching, mixing, and delivering the concrete to the underground in sufficient quantity to complete placement of the concrete within one form cell.

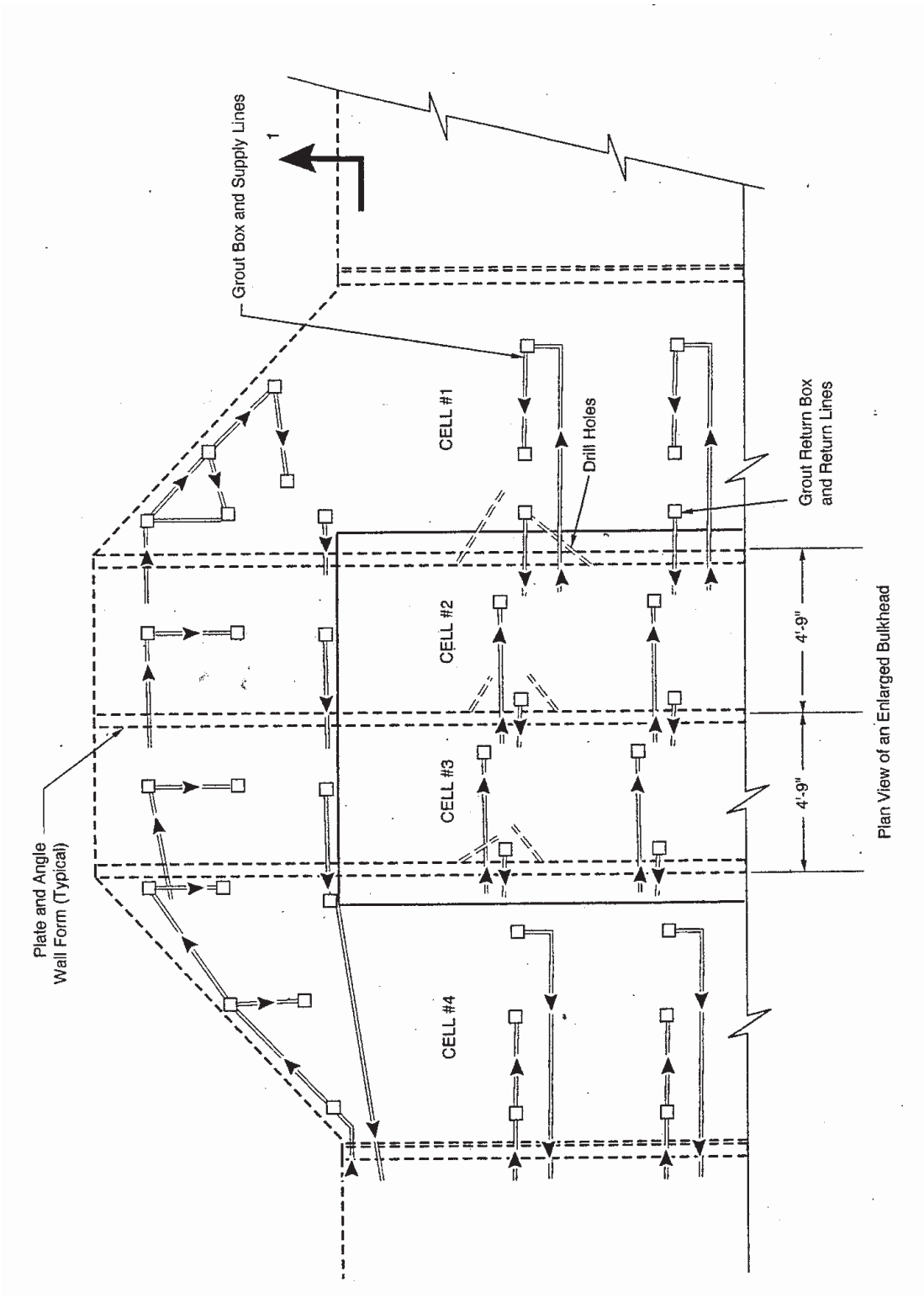

Figure BARRIERS-4. Grouting Details

Pumping equipment suitable for placing the concrete into the forms will be provided at the main concrete barrier location. After transporting, and prior to pumping, the concrete will be remixed to compensate for segregation of aggregate during transport. Batch concrete will be checked at the surface at the time of mixing and again at the point of transfer to the pump for slump and temperature. Admixtures may be added at the remix stage in accordance with the batch design.

BARRIERS-3.2.1.5 Conclusion

A design basis, including the operational requirements, structural and material requirements, and construction requirements, was developed that addresses the governing regulations for the panel closure system. The panel closure system design incorporates mitigative measures to address the treatment in the rock around the openings after fracture and therefore counter the potential migration of VOCs. Several alternatives were evaluated for the treatment of fractures. These included excavation and emplacement of a fully enlarged barrier with removal of the DRZ, excavation of the roof and emplacement of a partially enlarged barrier, and emplacement of a standard barrier with formation grouting. In its final ruling on the CCA, the EPA required, in condition 1, that the Option D design be implemented. This design requires the excavation and emplacement of a fully enlarged barrier. Until resolution is reached on the DOE's proposed design change, the design remains as required by EPA.

To investigate several key design issues and to implement the design, design evaluations were performed. These design evaluations can be divided into evaluations satisfying the operational requirements of the system and evaluations satisfying the structural and materials requirements of the system. The conclusions reached from the evaluations addressing the operational requirements are as follows:

- Based on an air-flow model used to predict the mass flow rate of carbon tetrachloride through the panel-closure system for the alternatives, the air-flow analysis suggests that the fully enlarged barrier is protective for restricting potential VOCs during the operational period of 35 years.

- Interface grouting would be performed at the upper boundary of the concrete barrier.

- The results of the transverse plane-strain models show that high stresses could form in nearby brittle marker beds following excavation, but that after installation of the panel closure system, an increase in barrier-confining stress and a reduction in shear stress would result. The concrete barrier would provide substantial uniform confining stresses as the barrier is subjected to secondary salt creep.

- The removal of the fractured salt prior to installation of the main concrete barrier would reduce the potential for flexure.

The conclusions reached from the design evaluations addressing the structural and material requirements of the panel closure system are as follows:

- Existing information on the heat of hydration of the concrete supports placing concrete with a low cement content to reduce the temperature rise associated with hydration.

Plasticizers might be used to achieve the required slump at the required strength. A thermal analysis, coupled with a salt creep analysis, suggests installation of the enlarged barrier at or below ambient temperatures to adequately control hydration temperatures.

- The trace amounts of brine from the salt at the repository horizon will not degrade the main concrete barrier for at least 35 years.

- In 20 years, the open passage above the waste stack in the rooms would be reduced in size. Furthermore, rooms with bulkheads at each end would be isolated in the panel. It is unlikely that a long passage with an open geometry would exist; therefore, the dynamic analysis considered a deflagration with a peak explosive pressure of 240 psi (1.7 MPa).

- The heat-transfer analysis shows that elevated temperatures would occur within the salt and the explosion-isolation wall; however, the elevated temperatures will be isolated by the panel closure system. Temperature gradients will not significantly affect the stability of the wall.

- The fractures in the roof and floor could be affected by expanding gas products reaching pressures on the order of 240 psi (1.7 MPa). Because the peak internal pressure from the deflagration is only one fifth of the pressure, fractures could not propagate beyond the barrier.

BARRIERS-3.2.2 Shaft Seals

There have been no changes to the shaft seals since the CCA. A description of the shaft seals, initially provided in CCA Appendix SEAL, is discussed in Sections 3.2.2.1 through 3.2.2.4 of this appendix. The representation of the shaft seals in PA has been simplified; see Appendix PA, Section PA-4.2.7 for details.

BARRIERS-3.2.2.1 Overview

The WIPP underground facilities are accessed by four shafts commonly referred to as the waste, air intake, exhaust, and salt handling shafts. These shafts were constructed between 1981 and 1988. Each of the four shafts from the surface to the underground repository must be sealed to limit hazardous material release to the accessible environment and to limit groundwater flow into the repository. Although the seals will be permanent, the regulatory period applicable to the repository system analyses is 10,000 years.

BARRIERS-3.2.2.2 Seal Components

The shaft sealing system comprises 13 elements that completely fill the shaft with engineered materials possessing high density and low permeability (Figure BARRIERS-5). Salado components provide the primary regulatory barrier by limiting fluid transport along the shaft

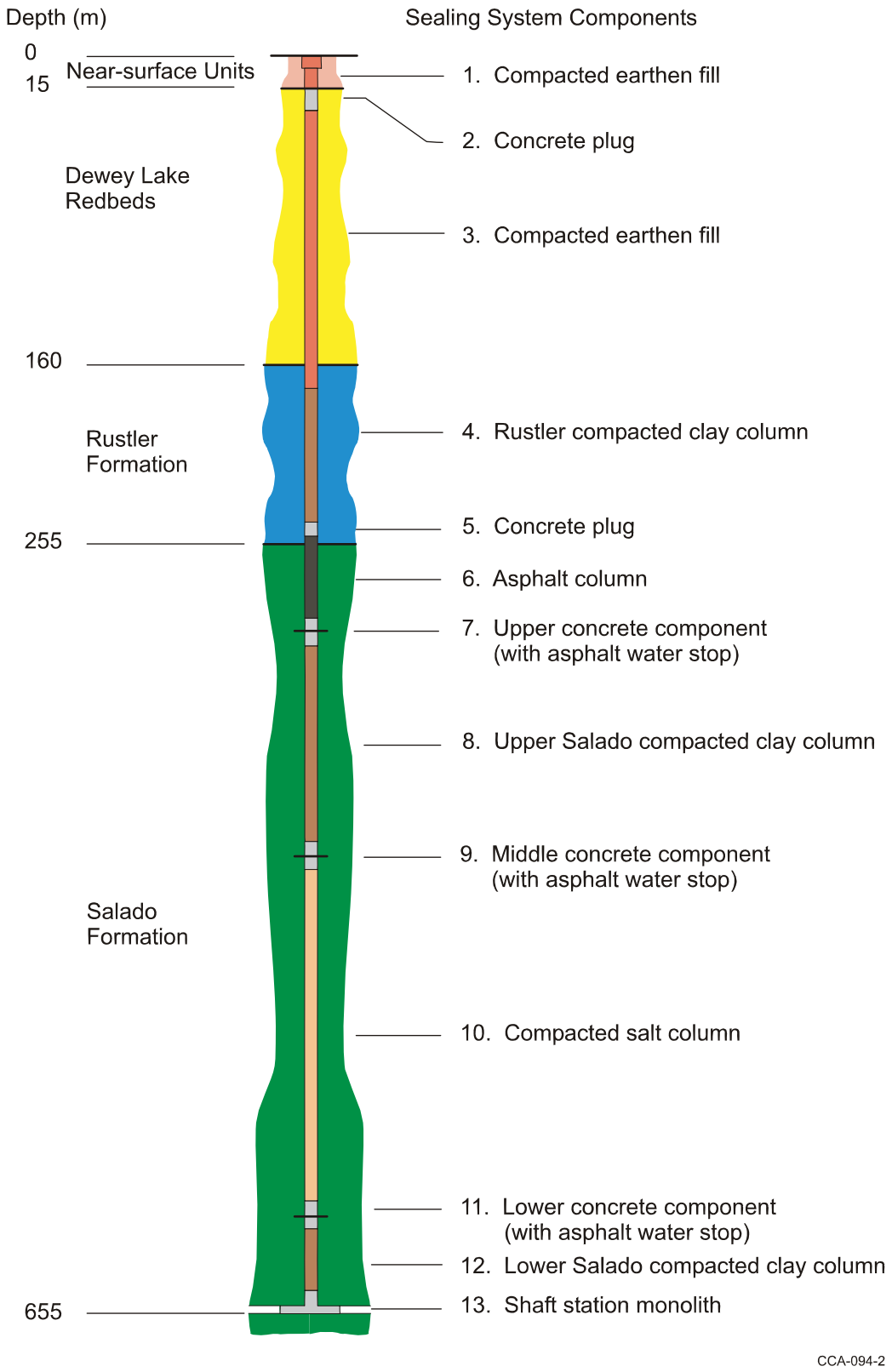

Figure BARRIERS-5. Shaft Sealing System Components

during and beyond the 10,000-year regulatory period. Components within the Rustler Formation limit commingling between brine-bearing members, as required by state regulations. Components from the Rustler Formation to the surface fill the shaft with common materials of high density, consistent with good engineering practice. A synopsis of each component is given below.

BARRIERS-3.2.2.2.1 Shaft Station Monolith

At the bottom of each shaft a salt-saturated concrete monolith supports the local roof. A salt-saturated concrete, called SMC, is specific and is placed using a conventional slickline construction procedure where the concrete is batched at the surface.

SMC has been tailored to match site conditions. The salt-handling shaft and the waste-handling shaft have sumps which will also be filled with salt-saturated concrete as part of the monolith. The monoliths function to support the shaft wall and adjacent drift roof, thus preventing damage to the seal system as the access drift closes from natural processes.

BARRIERS-3.2.2.2.2 Clay Columns

A sodium bentonite is used for three compacted clay components in the Salado and Rustler Formations. Although alternative construction specifications are viable, labor-intensive placement of compressed blocks is specified because of proven performance. Clay columns effectively limit brine movement from the time they are placed to beyond the 10,000-year regulatory period. The upper clay column ranges in length from 102 to 107 m (335 to 351 ft), and the lower clay column ranges in length from 29 to 33 m (94 to 107 ft) in the four shafts. The locations for the upper and lower clay columns were selected based on the need to limit fluid migration into the compacting salt column. The lower clay column stiffness is sufficient to promote healing of fractures in the surrounding rock salt near the bottom of the shafts, thus removing the proximal DRZ as a potential pathway (CCA Appendix SEAL, Appendix D, Section 5.2.1). The Rustler clay column limits brine communication between the Magenta and Culebra Members of the Rustler Formation.

A commercial well-sealing-grade sodium bentonite will be used to construct the Rustler compacted clay column, which will effectively limit fluid movement from the time of placement and provide an effective barrier to fluid migration throughout the 10,000-year regulatory period and thereafter. Design length of the Rustler clay column is about 71 m (234 to 235 ft) in the four shafts.

BARRIERS-3.2.2.2.3 Concrete-Asphalt Waterstop Components

The upper, middle, and lower concrete-asphalt waterstops are identical and are composed of three elements: an upper concrete plug, a central asphalt waterstop, and a lower concrete plug. The concrete specified is SMC. In all cases, the component's overall design length is 15 m (50 ft).

The upper and lower concrete plugs of the concrete-asphalt waterstop are identical. They fill the shaft cross-section and have design length of 7 m (23 ft). The plugs are keyed into the shaft wall to provide positive support for the plug and overlying sealing materials. The interface between

the concrete plugs and the surrounding formation will be pressure grouted. The upper plug in each component will support dynamic compaction of the overlying sealing material if compaction is specified. Dynamic compaction of the salt column is discussed in CCA Appendix SEAL (Section 6).

The asphalt waterstop is located between the upper and lower concrete plugs. In all cases, a kerf extending one shaft radius beyond the shaft wall is cut in the surrounding salt to contain the waterstop. The kerf is 0.3 m (1 ft) high at its edge and 0.6 m (2 ft) high at the shaft wall. The kerf, which cuts through the existing shaft DRZ, will result in the formation of a new DRZ along its perimeter. This new DRZ will heal shortly after construction of the waterstop, and thereafter the waterstop will provide a very low permeability barrier to fluid migration through the DRZ. The formation and healing of the DRZ around the waterstop is discussed in CCA Appendix SEAL (Section 7.6.1). The asphalt fill for the waterstop extends two feet above the top of the kerf to assure complete filling of the kerf. The construction procedure used assures that shrinkage of the asphalt from cooling will not result in the creation of voids within the kerf and will minimize the size of any void below the upper plug.

Concrete-asphalt waterstops are placed at the top of the upper clay column, the top of the compacted salt column, and the top of the lower clay column. The concrete-asphalt waterstops provide independent seals of the shaft cross-section and the DRZ. The SMC plugs (and grout) will fill irregularities in the shaft wall, bond to the shaft wall, and seal the interface. Salt creep against the rigid concrete components will place a compressive load on the salt and promote early healing of the salt DRZ surrounding the SMC plugs. The asphalt waterstop will seal the shaft cross-section and the DRZ.

The position of the concrete components was first determined by the location of the salt and clay columns. The components were then moved upward or downward from their initial design location to assure the components were located in regions where halite was predominant. This positioning, coupled with variations in stratigraphy, is responsible for the variations in the lengths of the salt and clay columns.

BARRIERS-3.2.2.2.4 Compacted Salt Column

Each shaft seal includes a column of compacted WIPP salt with 1.5 percent weight water added to the natural material. The compacted salt column will be constructed of crushed salt taken from the Salado. The length of the salt column varies from 170 to 172 m (556 to 567 ft) in the four shafts. The compacted salt column is sized to allow the column and concrete-asphalt waterstops at either end to be placed between the Vaca Triste Unit and MB 136. The salt will be placed and compacted to a density approaching 90 percent of the average density of intact Salado salt. The effects of creep closure will cause this density to increase with time, further reducing permeability. The salt column will offer limited resistance to fluid migration immediately after emplacement, but it will become less permeable as creep closure further compacts the salt. Salt creep increases rapidly with depth; therefore, at any time, creep closure of the shaft will be greater at greater depth. The location and initial compaction density of the compacted salt column were chosen to assure consolidation of the compacted slat column in the 100 years following repository closure. The state of salt consolidation, results of analyses predicting the creep closure of the shaft, consolidation and healing of the compacted salt, and healing of the

DRZ surrounding the compacted salt columns can be found in CCA Appendix SEAL (Sections 7.5 and 8.4). The location of the compacted salt column near the bottom of the shaft assures the fastest achievable consolidation of the compacted salt column after closure of the repository. Analyses indicate that the salt column becomes an effective long-term barrier in under 100 years.

BARRIERS-3.2.2.2.5 Asphalt Column

An asphalt-aggregate mixture is specified for the asphalt column. This column is 42 to 44 m (138 to 143 ft) in length in the four shafts. The asphalt column is located above the upper concrete-asphalt waterstop; it extends approximately 5 m (16 ft) above the Rustler/Salado interface. A 6-m (20-ft) long concrete plug (part of the Rustler seals) is located just above the asphalt column.

The existing shaft linings will be removed from a point well above the top of the asphalt column to the top of the shaft keys. The concrete shaft keys will be removed to a point just below the lowest chemical seal ring in each key. The asphalt column is located at the top of the Salado and provides an essentially impermeable seal for the shaft cross section and along the shaft wall interface. The length of the asphalt column will decrease slightly as the column cools. The procedure for placing the flowable asphalt-aggregate mixture is described in CCA Appendix SEAL (Section 6).

BARRIERS-3.2.2.2.6 Concrete Plugs

The Rustler concrete plug is constructed of SMC. The plug is 6 m (20 ft) long and will fill the shaft cross-section. The plug is placed directly on top of the asphalt column of the Salado seals. The plug will be keyed into the surrounding rock and grouted. The plug permits work to begin on the overlying clay column before the asphalt has completely cooled. The option of constructing the overlying clay columns using dynamic compaction (present planning calls for construction using compressed clay blocks) is also maintained by keying the plug into the surrounding rock. Current plans call for an SMC near-surface concrete plug (Component 2, Figure BARRIERS-5). However, freshwater concrete may be used if found to be desirable at a future time. The plug extends 12 m (40 ft) downward from the top of the Dewey Lake Redbeds. It is placed inside the existing shaft lining, and the interface is grouted.

BARRIERS-3.2.2.2.7 Earthen Fill

The upper shaft is filled with locally available earthen fill. The near-surface upper compacted earthen fill (Component 1 in Figure BARRIERS-5) will be compacted to a density near that of the surrounding material to inhibit the migration of surface waters into the shaft cross-section. The length of this column varies from 17 to 28 m (56 to 92 ft) in the four shafts. In all cases, this portion of the WIPP sealing system may be modified as required to facilitate decommissioning of the WIPP surface facilities. The near-surface lower compacted earthen fill (Component 3 in Figure BARRIERS-5) will be constructed using locally available fill, which will be placed using dynamic compaction (the same method used to construct the salt column). The fill will be compacted to a density equal to or greater than the surrounding materials to inhibit the migration of surface waters into the shaft cross-section. The length of this column varies from 136 to 148 m (447 to 486 ft) in the four shafts.

BARRIERS-3.2.2.3 Material

The four shafts will be entirely filled with dense materials possessing low permeability and other desirable engineering and economic attributes. Seal materials include concrete, clay, asphalt, and compacted salt. Other construction and fill materials include cementitious grout and earthen fill. Concrete, clay, and asphalt are common construction materials used extensively in sealing applications. Their descriptions, drawn from literature and site-specific references, are given in CCA Appendix SEAL (Appendix A). Compaction and natural reconsolidation of crushed salt are uniquely applied here. Therefore, crushed salt specification includes discussion of constitutive behavior and sealing performance, specific to WIPP applications. Cementitious grout is also specified in some detail.

Seal system components are materials possessing high durability and compatibility with the host rock. The system contains functional redundancy and uses differing materials to reduce uncertainty in performance. All materials used in the shaft seal system are expected to maintain their integrity for very long periods. Some sealing components reduce fluid flow soon after placement, while other components are designed to function well beyond the regulatory period.

A major environmental advantage of the WIPP locale is an overall lack of groundwater to seal against. Even though very little regional water is present in the geologic setting, the seal system reflects great concern for groundwater's potential influence on the shaft seal system. If the hydrologic system sustained considerable fluid flow, brine geochemistry could impact engineered materials. Brine would not chemically change the compacted salt column, but mechanical effects of pore pressure are of concern to reconsolidation. The geochemical setting will have little influence on concrete, asphalt, and clay shaft seal materials. Each material is durable because the potential for degradation or alteration is very low.

Materials used to form the shaft seals are the same as those identified in the scientific and engineering literature as appropriate for sealing deep geologic repositories for radioactive wastes. Durability or longevity of seal components is a primary concern for any long-term isolation system. Issues of possible degradation have been studied throughout the international community and within waste isolation programs in the USA. Specific degradation studies are not detailed in this document because longevity is one of the over-riding attributes of the materials selected and degradation is not perceived to be likely. However, it is acknowledged here that microbial degradation, seal material interaction, mineral transformation, such as silicification of bentonite, and effects of a thermal pulse from asphalt or hydrating concrete are areas of continuing investigation.

Among longevity concerns, degradation of concrete is the most recognized. At this stage of the design, it is established that only small volumes of brine ever reach the concrete elements (CCA Appendix SEAL, Appendix C, Section C4). Further analysis concerned with borehole plugging using cementitious materials shows that at least 100 pore volumes of brine in an open system would be needed to begin degradation processes. In a closed system, such as the hydrologic setting in the WIPP shafts, phase transformations create a degradation product of increased volume. Net volume increase owing to phase transformation in the absence of mass transport would decrease rather than increase permeability of concrete seal elements.

Asphalt has existed for thousands of years as natural seeps. Longevity studies specific to DOE's Hanford site have utilized asphalt artifacts buried in ancient ceremonies to assess long-term stability (Wing and Gee 1994). Asphalt used as a seal component deep in the shaft will inhabit a benign environment, devoid of ultraviolet light or an oxidizing atmosphere. Additional assurance against possible microbial degradation in asphalt elements is provided with addition of characteristics well beyond the regulatory period.

Natural bentonite is a stable material that generally will not change significantly over a period of 10,000 years. Bentonitic clays have been widely used in field and laboratory experiments concerned with radioactive waste disposal. As noted by Gray (1993), three internal mechanisms, illitization, silicification, and charge change, could affect sealing properties of bentonite. Illitization and silicification are thermally driven processes and, following discussion by Gray (1993), are not possible in the environment or time frame of concern at the WIPP. The naturally occurring Wyoming bentonite, which is the specified material for the WIPP shaft seal, is well over a million years old. It is, therefore, highly unlikely that the metamorphism of bentonite enters as a design concern.

BARRIERS-3.2.2.4 Conclusion

The principal conclusion is that an effective, implementable shaft seal system has been designed for the WIPP. Design guidance is addressed by limiting any transport of fluids within the shaft, thereby limiting transport of hazardous material to regulatory boundaries. The application or adaptation of existing technologies for placement of seal components combined with the use of available, common materials provide confidence that the design can be constructed. The structural setting for seal elements is compressive, with shear stresses well below the strength of seal materials. Because of the favorable hydrologic regime coupled with the low intrinsic permeability of seal materials, long-term stability of the shaft seal system is expected. Credibility of these conclusions is bolstered by the basic design approach of using multiple components to perform each sealing function and by using extensive lengths within the shafts to effect a sealing system. The shaft seal system adequately meets design requirements and can be constructed.

BARRIERS-3.2.3 Borehole Plugs

BARRIERS-3.2.3.1 Overview

Exploration drilling has been in progress in the vicinity of the WIPP since 1928 (nine township area). This drilling is done primarily for oil, gas, and potash exploration, although several water wells have been drilled. The drilling and abandonment practices for oil and gas wells or potash exploration holes are regulated by either the Bureau of Land Management (BLM) for federal land or the State of New Mexico for State and private land. The WIPP site has no control over the plugging and abandonment (P&A) of oil and gas wells in the vicinity of the site. See Section 3.2.3.3 of this appendix for a description of the regulations that apply to these oil and gas wells.

The New Mexico State Engineers Office has regulatory authority over the P&A of groundwater production and monitoring wells in the state. The State of New Mexico has several groundwater basins, with each basin having its own district office providing oversight of groundwater issues.

The WIPP area is under the jurisdiction of the Roswell, New Mexico branch of the State Engineers Office. The Roswell office will be the principal regulatory body to approve the WIPP plans for well P&A. In all cases, the permit process will be carried out through the appropriate regulatory agency. This will be the State of New Mexico, State Engineers Office for P&A of all water wells (DOE 1999).

Sealing and plugging of boreholes and monitoring wells associated with underground waste repositories has been an important issue for many years. To develop the most effective methods to limit the potential for fluids to migrate between formations within a sealed borehole, the DOE has conducted extensive research on plugging and sealing materials and emplacement technologies. In some cases, previous P&A research and regulatory compliance documents have recommended or committed to plugging test wells and boreholes following specific guidelines and techniques. In the CCA, the DOE committed to plugging WIPP's shallow boreholes within the controlled area in accordance with applicable state or federal regulations. The WIPP's deep boreholes within the controlled area will be plugged in accordance with OCD, Order R-111P (NM 1988). The WIPP Final Environmental Impact Statement (DOE 1980) states that all boreholes will be plugged with materials that are physically and chemically compatible with the surrounding rock, resistant to groundwater attack, and will securely bond to surrounding geologic materials.

BARRIERS-3.2.3.2 Monitoring Wells

As of the date of this compliance application, the DOE has 92 operational monitoring wells within the vicinity of WIPP. Of these, 17 have been drilled and put into use since submittal of the CCA (see Appendix DATA, Attachment G for a description of the groundwater monitoring wells applicable to this compliance application). Also since the CCA, 10 monitoring wells have been plugged to the surface with cement. Two new shallow wells (54 ft. and 19 ft.) were drilled and plugged with drill cuttings and bentonite gel (Appendix DATA, Attachment G).

Existing boreholes within the controlled area are identified in Figure BARRIERS-6. Of these boreholes, four exceed the depth of the repository and the rest are shallow boreholes that do not reach the repository horizon.

When no longer needed, the four deep wells, DOE 1, ERDA 9, WIPP 12, and WIPP 13 will be plugged according to the State of New Mexico, Oil and Conservation Division, Order R-111-P. See Figures BARRIERS-6 and BARRIERS-7.

The key provisions of Order No. R-111-P are as follows:

- A salt protection string of casing must be installed at least 100 feet (30 meters) below and not more than 600 ft (183 m) below the base of the salt section. Cementing requirements for both shallow wells (above 5,000 ft [1,524 m]) and deep wells (below 5,000 ft [1,524 m]) above or below the Delaware Mountain Group are specified.

- All oil and gas wells drilled within the potash area must provide a solid cement plug through the salt section and any water bearing horizon and prevent liquids or gases from entering the hole above or below the salt section.

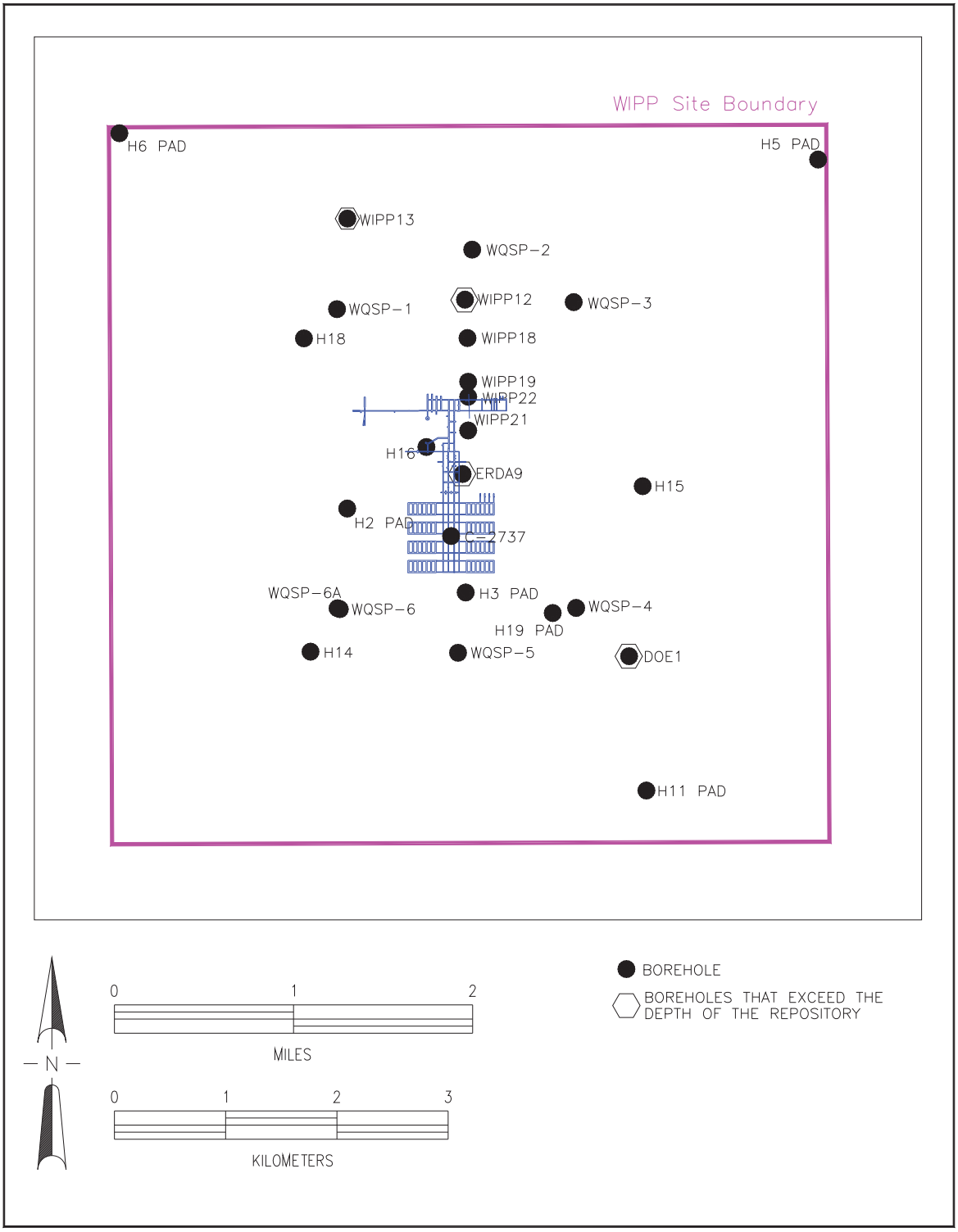

Figure BARRIERS-6. Approximate Locations of Unplugged Boreholes

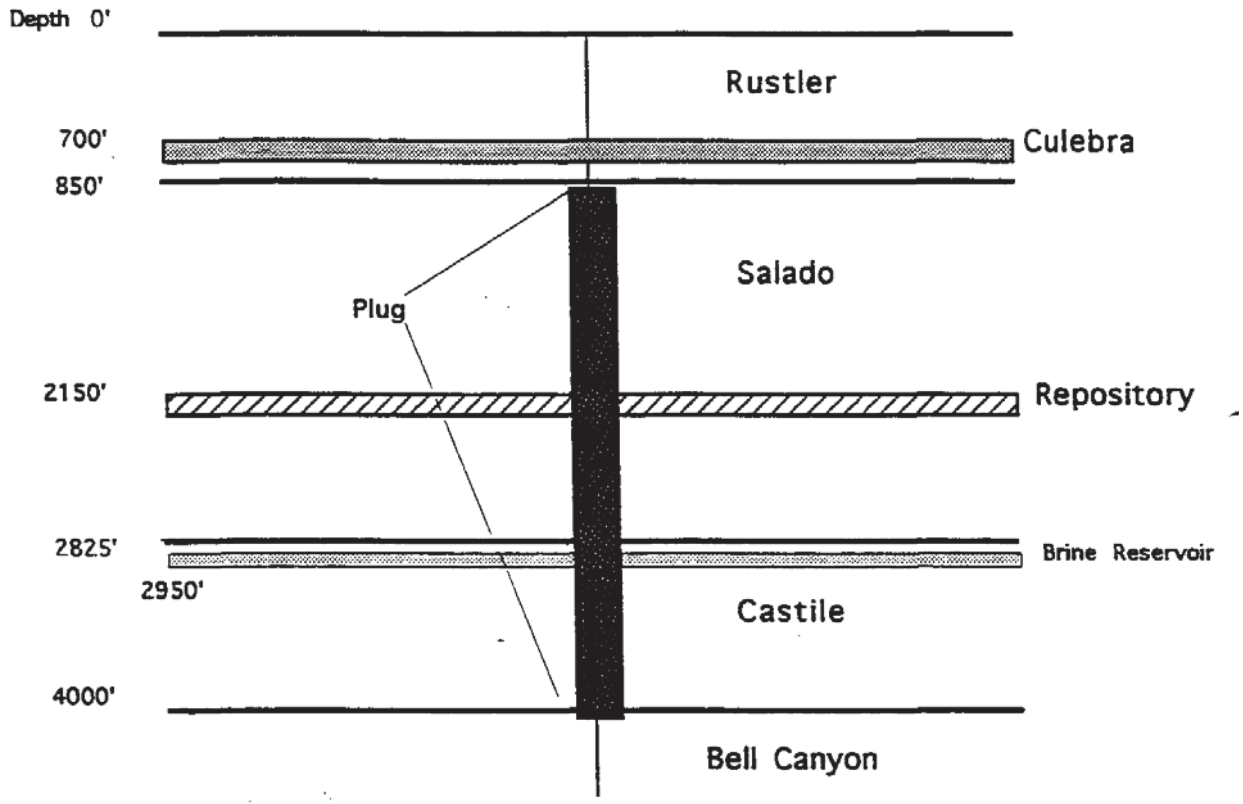

Figure BARRIERS-7. Schematic Diagram for a Continuous Plug

- The fluid used to mix the (plugging) cement must be saturated with salts common to the salt section penetrated but not more than three percent of calcium chloride by weight of cement wherever possible.

As mentioned above, WIPP has been plugging monitoring wells with cement plugs from the bottom to the top of the borehole.

The boreholes not being used for monitoring will be plugged at decommissioning. These boreholes will be plugged to limit the volume of water that could be introduced to the repository from the overlying water-bearing zones and the volume of contaminated brine that could be released from the repository to the accessible environment.

BARRIERS-3.2.3.3 <u>Well Plugging and Abandonment Practices</u>

A description of the plugging and abandonment practices in the area around the WIPP, initially provided in CCA Appendix DEL, is discussed in Sections 3.2.3.3.5 through 3.2.3.4 of this appendix. The representation of borehole plugs in PA is presented in Chapter 6.0, Section 6.4.7.2.

BARRIERS-3.2.3.3.1 BLM Oil and Gas Plugging and Abandonment

The BLM regulations on oil and gas plugging and abandonment in 43 CFR § 3162.3-4 and Oil and Gas Order No. 2 are discussed in detail in CCA Appendix DEL, Section DEL.4.1.2.2. This section serves as a summary of that discussion.

BARRIERS-3.2.3.3.1.1 Oil and Gas Well Plugging Sequence

The first step in plugging and abandoning a well is the submission of the Sundry Notice (Form 3160-5, Attachment 2) that informs the BLM of the operator's intent to abandon the well. This form must include a plan by the operator detailing how the well will be plugged. BLM inspectors will review and approve the plan as presented or make modifications that the operator must follow.

The operator must provide a 24-hour notice to the BLM before beginning abandonment operations in order to allow BLM personnel an opportunity to witness the operation. BLM does not consider the plugging and abandonment procedure completed until a surface cap has been welded on the opening to the casing, a 4-in (10 cm)-diameter pipe, 10 ft (3 m) long, has been embedded in cement and extended 4 feet (1 m) above ground level, and the cellars have been filled to the surface. When all phases of the abandonment are complete and have been inspected, the well plugging bond may be released (see CCA Appendix DEL, Section DEL.6.1.5).

Plugging operations are typically carried out using a pulling unit (a truck with a large mounted derrick). The pulling unit sets up over the wellbore and is used to complete the plug and abandonment operation. The first step in the plugging process is to set the required cast iron bridge plug at the depth shown in the plugging plan approved by the BLM. The point of placement for the bridge plug is just above the uppermost production perforations in the casing. Once the bridge plug is in place, the pulling unit operator will tag the bridge plug (touch the top of the plug with the tubing) to make certain that it is set at the correct depth as specified on the plugging plan contained in Form 3160-5 (Attachment 2).

When the proper depth is confirmed, a minimum of 25 ft (8 m) of cement is placed on top of the bridge plug. The operator will then fill the borehole with at least nine-lb mud or brine water, filling the borehole to the site of the next plug location. The viscosity of the mud allows the operator to then pump a type C or H cement through the tubing to its correct depth on top of the mud. The mud column will support the weight of the cement until it sets up. The operator, if required by the BLM, will again tag the top of the cement to verify both the position and length of the plug.

While the NMOCD has inspection personnel on site in every instance to verify this process, the BLM elects to witness only selected plugging operations. The process of setting plugs will continue in the same manner until each of the plugs identified on the plugging plan has been properly placed. At this point, plugging operations are complete. The only remaining requirement to complete the plug and abandonment operation is that of returning the drill pad to a near-original state. This process may be completed in only a few days or possibly up to several months after plugging has been completed.

BARRIERS-3.2.3.3.1.2 Plugging of Temporarily Abandoned Wells

Wells may be temporarily abandoned for up to five one-year periods with BLM approval (see CCA Appendix DEL, Section DEL.6.1.2.3). A Sundry Notice must be submitted requesting temporary abandonment (Form 3160-5, Attachment 2). The notice must include a description of the abandonment procedure, a complete wellbore diagram, and the anticipated date the operations will occur. As with plugging and abandonment, this plan must be reviewed and approved by BLM inspectors. Once approved, a 48-hour notice must be given to BLM to allow an opportunity for the plugging inspection. Operators must install a bridge plug or a cement plug 50 to 100 ft (15 to 30 m) above the perforations. If a cement plug is chosen, it must be tagged to make certain it is at the proper depth. Bridge plugs are set using a wireline with the proper depth being verified before the plug is set.

The integrity of the casing must be also be verified. If testing indicates problems with the casing, repairs must be made before the well may be temporarily abandoned.

BARRIERS-3.2.3.3.1.3 Plugging in the Potash Resource Area

BLM requirements for plugging and abandonment in the potash areas are the same as in non-potash areas. Although the BLM has not overseen the plugging of any oil or gas wells in the potash area in a number of years, the requirements of the New Mexico Oil Conservation Commission (NMOCC) Order R-111-P (see CCA Appendix DEL, Section DEL.6.2.4) will be considered at the appropriate time (Personal Communication 1996a). According to the Secretary of the Interior Order of October 28, 1986 (51 FR 39425) on oil, gas, and potash leasing, the BLM will cooperate with the NMOCD in implementing state rules and regulations although the BLM will make the final decision.

BARRIERS-3.2.3.3.1.4 Most Common Technical Violations for Oil and Gas Well Plugging

Large national oil companies and large independent companies normally comply strictly with the oil and gas well plugging requirements. Large businesses, which have the necessary resources to properly plug and abandon their wells, typically contract with other large businesses to perform their plugging operations. It has been BLM's experience that these companies follow sound business practices and wish to remain in good standing with the BLM. Smaller, independent operators are more likely to lack resources to respond as quickly to the BLM and may not plug a well with the same expertise that a larger established company might have. The BLM is aware of situations that pose a potential for improper plugging. If the agency has a concern regarding a contractor's methods, BLM personnel are present during the entire plugging operation (Personal Communication 1996b).

Plugging bonds are required to ensure that wells are plugged and abandoned properly and within a reasonable time frame (see CCA Appendix DEL, Sections DEL.6.1.5 and DEL.6.2.1). Both NMOCD and BLM have experienced higher rates recently of what they refer to as "orphan wells." These are wells that should be plugged and abandoned, but the owners of these wells cannot be located. When this occurs, plugging of these wells becomes the responsibility of the agency upon whose land they are located. Both agencies have orphan-well-plugging funds that are funded partially through plugging bonds that have not been returned and money from their

operating budgets. These orphan wells are a matter of concern to both agencies, and they are working to conserve financial resources for plugging.

BARRIERS-3.2.3.3.2 State of New Mexico Oil and Gas Plugging and Abandonment

The NMOCD regulations on well plugging and abandonment are discussed in CCA Appendix DEL, Sections DEL.6.2.2 and DEL.6.2.3. They are similar in many respects to the BLM requirements.

BARRIERS-3.2.3.3.2.1 Plugging Outside the Potash Resource Area

The major distinction between NMOCD and BLM practices is that NMOCD witnesses every well plugging and abandonment operation on state and private land, whereas the BLM is only able to witness approximately 50 percent of the plugging operations on federal leases. Both agencies require sundry notices to be filed with an abandonment plan and both agencies review and approve or modify those plans.

BARRIERS-3.2.3.3.2.2 Plugging Within the Potash Resource Area (R-111-P)

Operators must follow the same procedures within the potash enclave as they do in other areas, with the exception that the NMOCD requires the operator to run a solid cement plug through the entire salt section and water bearing zones in addition to installing a bridge plug above the perforations. Installing a solid cement plug through the salt provides additional assurance that no fluids or gases escape through the casing into potash mining areas or fresh water formations (see CCA Appendix DEL, Section DEL.6.2.3 on NMOCC Order R-111-P).

BARRIERS-3.2.3.3.2.3 Most Common Technical Violations for State of New Mexico Oil and Gas Well Plugging

Because NMOCD inspectors are able to witness 100 percent of the plugging and abandonment operations, technical violations are very rare. NMOCD inspectors are present for each step in the plugging operation. Operators are informed that plugging operations are not to begin before NMOCD inspectors are on site. If NMOCD inspectors are not present when plugging operations begin, the operator may be required to remove everything from the well and start over. The NMOCD also requires plugging bonds to be secured by the operator before plugging and abandonment are carried out (see CCA Appendix DEL, Section DEL.6.2.1). The bond is not released until all requirements for plug and abandonment have been properly completed (Personal Communication 1996c).

BARRIERS-3.2.3.3.3 Plugging of Oil and Gas Service Wells

Oil and gas operators are required to follow NMOCD Rule 705 on commencement, discontinuance, and abandonment of injection operations when plugging an injection well. This rule requires operators to file a Notice of Discontinuance when a decision has been made to cease injection operations. The rule forbids temporary abandonment of service wells. Plugging requirements are the same as when plugging oil and gas wells or dry holes.

BARRIERS-3.2.3.3.4 Plugging of Potash Coreholes

In June 1975, the land that is now the WIPP land withdrawal area became part of the Carlsbad Underground Water Basin. This placed potash coreholes under the jurisdiction of the State Engineer. A review of the records maintained by BLM on commercial potash coreholes indicates that, since 1975, 155 coreholes have been drilled and plugged in the New Mexico portion of the Delaware Basin. Of the 155 coreholes, 151 were plugged from bottom to top with solid cement while four were plugged with a mixture of mud and cement. As indicated by this review, the current plugging practice is to fill potash coreholes with a cement slurry from the bottom of the hole to the surface.

BARRIERS-3.2.3.3.5 Plugging of Water Wells

The State Engineer has authority for all water wells. The State Engineer must be notified when a well is to be plugged and then designates how it is to be plugged. The method typically used in the Carlsbad Underground Water Basin is to remove all casing from the hole, clean the hole to the bottom using a sand pump or a cable tool drilling rig with a bailer, and fill the hole with red clay. The red clay is compacted as the hole is filled. Another method of filling the hole is to circulate the hole full of cement. This method is more expensive and is not typically used.

BARRIERS-3.2.3.4 Conclusion

The WIPP is surrounded by land where oil and gas drilling is taking place. Plugging and abandonment of these oil and gas wells is regulated by either the BLM or the State of New Mexico, depending on the ownership of the land. Water wells also exist in the vicinity of WIPP and are regulated by the State of New Mexico. WIPP has no control over the plugging and abandonment of these wells.

WIPP has drilled monitoring wells to sample for constituents. These wells are regulated by the State of Mexico and will be plugged and abandoned according to the regulations when they are no longer needed for monitoring.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix DATA

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix DATA

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ATTACHMENTS

Attachment A: Delaware Basin Drilling Surveillance Data
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DATA 1.0 INTRODUCTION

Appendix DATA provides the data used to develop the 2004 Compliance Recertification Application (CRA). Interpretation and analysis of that data is provided in the appropriate sections of CRA-2004.

Title 40 of the Code of Federal Regulations (CFR) paragraph 194.15, Content of Recertification Applications (Sections 194.15 (a) (1), (2), (3), and (5)), requires that the U.S. Department of Energy (DOE) provide information gained since the Compliance Certification Application (CCA) related to site geology, hydrology, meteorology, and emplaced waste. Additional monitoring results and the results of laboratory investigations completed after the CCA must also be provided, as well as information regarding the waste emplaced in the disposal system.

In the initial U.S. Environmental Protection Agency (EPA) certification of compliance for the WIPP (63 FR 27354), the EPA agreed that 10 compliance monitoring parameters (COMPs) would be monitored during the operational period of the project. Of the 10, subsidence does not have to be monitored during the operational period, but is done to gage the behavior of the disposal system. This document provides monitoring data related to these COMPs. The locations, in this appendix, of the data for the COMPS are listed below:

COMP	Location of Relevant Data
Culebra groundwater composition	Sections 5, 10, 11, and Attachment C
Change in Culebra groundwater flow	Sections 5, 10, 11, and Attachment B
Probability of encountering a Castile brine reservoir	Sections 2, 10, and Attachment A
Drilling rate	Sections 2, 10, and Attachment A
Subsidence measurement	Sections 3 and 10
Waste activity	Sections 7, 10, and Attachments D-F
Creep closure and stresses	Sections 4 and 10
Extent of brittle deformation	Sections 4, 9, and 10
Initiation of brittle deformation	Sections 4 and 10
Displacement of deformation features	Sections 4 and 10

Monitoring is performed to detect substantial deviations from the assumptions used in the CCA. The above COMPs are being monitored during the pre-closure period.

DATA 2.0 DELAWARE BASIN DRILLING SURVEILLANCE PROGRAM (DBDSP)

The Delaware Basin Drilling Surveillance Program monitors drilling activities in the vicinity of WIPP. This section provides a brief discussion of that program and identifies the relevant data reports.

DATA 2.1 Program Overview

The EPA requires the DOE to demonstrate the expected containment performance of the disposal system using a performance assessment (PA). The PA documented in the CCA demonstrated that the WIPP complies with the EPA's containment standards for undisturbed and human intrusion scenarios.

The EPA required the use of historic drilling information to derive the drilling rate for PA intrusion scenarios. The DBDSP monitoring data is used to determine the drilling rate and continues to monitor drilling related activities to ensure the assumptions and scenarios used in PA remain valid. These monitoring activities will continue until the DOE and EPA agree that no benefit can be gained by further monitoring.

DATA 2.2 Reported Data

Relevant data generated through the Delaware Basin Monitoring Program are provided in Attachment A, as well as the following reports.

- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 0, September 1999.
- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 1, September 2000.
- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 2, September 2001.
- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 3, September 2002.

DATA 3.0 SUBSIDENCE MONITORING PROGRAM (SMP)

Subsidence monitoring is the measurement of vertical movement of the land surface relative to a reference location, using state-of-the-art leveling equipment. This section provides a brief discussion of this program and identifies the relevant data reports.

DATA 3.1 Program Overview

The subsidence monitoring program uses a leveling survey to measure the relative vertical height differences between benchmarks placed a known distance apart. Usually, one reference benchmark is the standard and the relative movement of the other benchmarks is measured to detect vertical height differences. Land surface movement is determined by comparing more recent survey data with survey results from earlier surveys. Subsidence measurements would detect substantial deviations from expected subsidence.

DATA 3.2 Reported Data

Data generated through the Subsidence Monitoring Program are provided in the following reports. Each report is inclusive of previous data collection activities.

- WIPP Subsidence Monument Leveling Surveys 1986, 1997, DOE/WIPP 98-2293, June 1998.
- WIPP Subsidence Monument Leveling Surveys 1998, DOE/WIPP 99-2293, October 1998.
- WIPP Subsidence Monument Leveling Surveys 1999, DOE/WIPP 00-2293, October 1999.
- WIPP Subsidence Monument Leveling Surveys 2000, DOE/WIPP 01-2293, October 2000.
- WIPP Subsidence Monument Leveling Surveys 2001, DOE/WIPP 02-2293, October 2001.
- WIPP Subsidence Monument Leveling Surveys 2002, DOE/WIPP 03-2293, October 2002.

DATA 4.0 GEOTECHNICAL MONITORING PROGRAM (GMP)

The geotechnical monitoring program measures in-situ geotechnical data in the WIPP repository. This section provides a brief discussion of the geotechnical monitoring program and identifies the relevant data reports.

DATA 4.1 Program Overview

The geotechnical monitoring program obtains in-situ data to support the continuous assessment of underground facilities. A detailed description of the geotechnical programs and procedures is presented in WP07-1, Geotechnical Engineering Program Plan. Specifically, the program provides for:

- early detection of conditions that could affect operational safety;
- guidance for design modifications and remedial actions; and
- data for interpreting the behavior of underground openings in comparison with established design criteria.

The geotechnical programs generate instrumentation data and observations, confirm the understanding of site characteristics, and aid in the assessment of the stability and performance of the underground facility. Associated programs include the Geosciences Program, the Geomechanics Program, and the Rock Mechanics Program. They are described in the following paragraphs.

The Geosciences Program serves to confirm site suitability through surface and underground field investigations. These activities generate data used in monitoring the repository and in rock mechanics studies. Information from the Geosciences Program is used to document the existing geologic conditions and characteristics and to monitor excavation response. Activities associated with this program include geologic and fracture mapping of the excavation surface, core logging, and borehole observations.

The Geomechanics Program monitors the geomechancial response of the underground openings after mining using instrumentation installed in the shafts and drifts of the facility. Geotechnical instrumentation installed underground in the shafts and drifts include tape extensometer points, convergence meters, borehole extensometers, piezometers, strain gages, load cells, and crack meters. The instrumentation is sensitive enough to detect small changes in rock displacements and stresses.

In order to determine significant deviations from expected conditions, the Rock Mechanics Program assesses the performance of the WIPP for long-term safety and excavation stability of the underground openings during the operational phase. The results from these assessments allow the identification of areas of potential instability and the application of remedial actions, if necessary. Field data are used to compare the actual mechanical performance of the excavations to expected results. Analytical methods, such as numerical modeling, are used to determine the potential effects of mining new excavations, excavation sequence, and long-term behavior of the

repository. The time-dependent properties of the salt are of significance. Extensive experimental work and observations have established an appropriate, constitutive relationship for salt that is used to predict its in-situ mechanical performance. These assessments rely heavily on the in-situ instrumentation data and field observations from the geosciences and geomechanics programs.

DATA 4.2 Reported Data

Data generated through the geotechnical monitoring program are reported annually in the Geotechnical Analysis Report. References for these reports prepared since the development of the CCA are provided below. Each report is inclusive of previous data collection activities.

- Westinghouse Electric Corporation, 1997, Geotechnical Analysis Report for July 1995 – June 1996, Carlsbad, NM.
- Westinghouse Electric Corporation, 1998, Geotechnical Analysis Report for July 1996 – June 1997, DOE/WIPP 98-3118, Carlsbad, NM.
- Westinghouse Electric Corporation, 1999, Geotechnical Analysis Report for July 1997 – June 1998, DOE/WIPP 99-2300, Carlsbad, NM.
- Westinghouse TRU Solutions, LLC, 2000, Geotechnical Analysis Report for July 1998 – June 1999, DOE/WIPP 00-3177, Carlsbad, NM.
- Westinghouse TRU Solutions, LLC, 2001, Geotechnical Analysis Report for July1999 – June 2000, DOE/WIPP 01-3177, Carlsbad, NM.
- Westinghouse TRU Solutions, LLC, 2002, Geotechnical Analysis Report for July2000 – June 2001, DOE/WIPP 02-3177, Carlsbad, NM.
- Washington TRU Solutions, LLC, 2003, Geotechnical Analysis Report for July 2001 – June 2002, DOE/WIPP 03-3177, Carlsbad, NM.

DATA 5.0 GROUNDWATER MONITORING PROGRAM (GWMP)

The Groundwater Monitoring Program collects and analyzes groundwater from various wells at or near the WIPP Site. This section briefly describes the GWMP and identifies relevant reports.

DATA 5.1 Program Overview

The GWMP is designed to ensure compliance with the WIPP Compliance Certification mandated by 40 CFR 191 Subparts B and C. One function of the GWMP most relevant to compliance with 40 CFR 191 Subparts B and C and 40 CFR 194 is the collection of Culebra groundwater data such as water levels and water quality from numerous wells located at and near the facility. The Culebra was selected as the focus of the GWMP. It has been extensively studied during past hydrologic characterization programs and was found to be the most likely hydrologic pathway to the accessible environment for any potential human-intrusion-caused release scenario. Data obtained through this program are used to generate the Culebra groundwater composition and the Culebra groundwater flow COMP parameters. Details on how the program is implemented are provided in Appendix MON-2004.

DATA 5.2 Reported Data

Attachment B provides a summary of water levels during the recertification time frame. Attachment C shows the water quality data for the Water Quality Sampling Program (WQSP) wells. The annual Site Environmental Reports listed below provide data relevant to the GWMP.

- Westinghouse Electric Corporation, 1996, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1995, DOE/WIPP 96-2182, Carlsbad, NM.
- Westinghouse Electric Corporation, 1997, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1996, DOE/WIPP 97-2225, Carlsbad, NM.
- Westinghouse Electric Corporation, 1998, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1997, DOE/WIPP 98-2225, Carlsbad, NM.
- Westinghouse Electric Corporation, 1999, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1998, DOE/WIPP 99-2225, Carlsbad, NM.
- Environmental Science & Research Foundation, 2000, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1999, DOE/WIPP 00-2225, Carlsbad, NM.
- Environmental Science & Research Foundation, 2001, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 2000, DOE/WIPP 01-2225, Carlsbad, NM.
- Westinghouse TRU Solutions, 2002, Waste Isolation Pilot Plant 2001 Site Environmental Report, DOE/WIPP 02-2225, Carlsbad, NM.
- Washington Regulatory & Environmental Services, 2003, Waste Isolation Pilot Plant Site Environmental Report Calendar Year 2002, DOE/WIPP 03-2225, Carlsbad, NM.

DATA 6.0 METEOROLOGICAL MONITORING PROGRAM

The meteorological monitoring program measures atmospheric data for the WIPP Site. This section provides a brief description of the program and a list of relevant reports.

DATA 6.1 Program Description

The primary WIPP meteorological station is located 600.5 m (1,970 ft) northeast of the Waste Handling Building. The main function of the station is to provide data for atmospheric modeling. The station measures and records wind speed, wind direction, and temperature at elevations of 2, 10, and 50 m (6.5, 33, and 165 ft). The station records ground-level measurements of barometric pressure, relative humidity, precipitation, and solar radiation.

DATA 6.2 Reported Data

The annual Site Environmental Reports listed in Section 5.2 provide data relevant to the Meteorological Monitoring Program. CCA Appendix CLI provides information on past (long-term) climatic conditions and possible future expectations at the WIPP site.

DATA 7.0 WASTE INFORMATION

Two types of information related to waste characteristics are collected: (1) information regarding the waste that has been emplaced in the WIPP underground repository; and (2) information regarding the future inventory that will be emplaced in the WIPP underground repository during the entire lifetime of the project. This section provides a brief description of the programs and a list of relevant reports.

DATA 7.1 Program Overview

Information concerning waste that has been emplaced in the repository is tracked and recorded using the WIPP Waste Information System (WWIS), as described in Chapter 4 of this document. Information concerning future wastes is developed through periodic updates of the Transuranic Waste Baseline Inventory Report (BIR) of DOE (1996). To capture changes in the TRU waste inventory since the CCA, each TRU waste site reviewed data submitted to the 1996 CCA and made revisions as appropriate. The TRU Waste Inventory Update Report (2003) information is based on estimations of existing waste volumes, as well as estimations of waste volumes to be generated by future activities.

DATA 7.2 Reported Data

Attachment D provides summary information based on the emplaced waste data in the WWIS as of 9/30/2002. Attachment E is the WWIS summary data for radionuclides as of 9/30/2002.

The TRU Waste Inventory Update Report, 2003, Attachment F, provides information regarding future inventories planned for emplacement in the WIPP.

DATA 8.0 WIPP BOREHOLES

Information regarding WIPP monitoring wells is identified in this section and relevant data are provided.

DATA 8.1 Program Overview

Information provided in this section was reported in DOE/WIPP 95-2092, Rev. 1, Waste Isolation Pilot Plant Borehole Data Report (CCA Appendix BH). The purpose of CCA Appendix BH was to serve as a central document providing data on boreholes. The report contained a comprehensive database on wells drilled in support of the WIPP and boreholes that were located within the 16-section Land Withdrawal Area.

DATA 8.2 Reported Data

Attachment G provides updates on all of the monitoring wells used in Appendix BH and the new monitoring wells drilled since the initial certification. The attachment also adds the wells that were in use but inadvertently omitted from CCA Appendix BH.

DATA 9.0 REPOSITORY INVESTIGATIONS

The WIPP repository investigations program conducts research activities to confirm assumptions, reduce uncertainty and resolve issues regarding the conceptual models and parameters used in performance assessment. The program is briefly described in this section and references to relevant reports are provided.

DATA 9.1 Program Overview

The DOE has implemented and/or continued several experimental activities that were designed to address specific issues/needs of the WIPP repository. In addition, other investigations have been initiated to examine impacts of planned changes. The general areas covered under these investigations include:

- geochemistry,
- engineered barriers, and
- rock mechanics.

DATA 9.2 Reported Data

Data acquired by the DOE from the repository investigations are available in the following reports published since the initial certification:

- Los Alamos National Laboratory, The Actinide Source-Term Waste Test Program (STTP) Final Report, Volume I, LA-UR-01-6822, Summer 2001.
- Sandia National Laboratories, 2001a, “Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.4, Repository Investigations, Milestone RI010, January 31, 2001,” ERMS 516749, Sandia WIPP Records Center, Carlsbad, NM.
- Sandia National Laboratories, 2001b, “Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.4, Repository Investigations, Milestone RI020, July 31, 2001,” ERMS 518970, Sandia WIPP Records Center, Carlsbad, NM.
- Sandia National Laboratories, 2002a, “Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI110, January 31, 2002,” ERMS 520467, Sandia WIPP Records Center, Carlsbad, NM.
- Sandia National Laboratories, 2002b, “Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI130, July 31, 2002,” ERMS 523189, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2003, “Sandia National Laboratories Technical Baseline Report, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI 03-210, January 31, 2003,” ERMS 526049, Sandia WIPP Records Center, Carlsbad, NM

DATA 10.0 COMPLIANCE MONITORING PROGRAM (CMP)

Annually, the CMP extracts data from the repository investigations and five of the monitoring programs described above (DBDSP, SMP, GMP, GWMP, and WWIS) to derive values for the ten COMPs described in Section DATA 1.0 and to evaluate if significant changes in the parameters have occurred. The CMP activities are briefly described in this section. Data generated under the CMP are also identified.

DATA 10.1 Program Overview

The objective of the CMP is to provide assurance that any deviations from the expected long-term performance of the repository are identified at the earliest possible time. The CMP is implemented in accordance with DOE/WIPP-99-3119, 40 CFR Parts 191 and 194 Compliance Monitoring Implementation Plan. Annual evaluations of the compliance parameters follow the requirements found in Sandia Analysis Plan AP-069, An Analysis Plan for Annually Deriving Compliance Monitoring Parameters and their Assessment Against Performance Expectations to Meet the Requirements of 40 CFR § 194.42.

DATA 10.2 Reported Data

The data and the results of the annual COMPs assessments performed in accordance with the requirements of the CMP are provided in the four reports cited below.

- Sandia National Laboratories, 2000a, “Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment (for Year 1998), WBS 1.2.10.09.01.02, Pkg. No. 510062, July,” Carlsbad, NM.

- Sandia National Laboratories, 2000b, “Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment (for Year 1999), WBS 1.2.10.09.01.02, Pkg. No. 510062, October,” Carlsbad, NM.

- Sandia National Laboratories, 2001, “Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment Report (for Year 2001), WBS 1.3.5.3.1, Pkg. No. 510062, October,” Carlsbad, NM.

- Sandia National Laboratories, 2002, “Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment (for Year 2002), WBS 1.3.5.3.1, 191/194 Compliance Monitoring, November,” Carlsbad, NM.

DATA 11.0 HYDROLOGIC INVESTIGATIONS

The Exhaust Shaft Hydraulic Assessment was initiated in September 1996 to investigate the source and extent of water seepage into the exhaust shaft at the WIPP, and an investigation of rising water levels in the Culebra member was initiated in 1999. These hydrologic investigations are briefly described in this section. Sources of data generated from the investigations are also identified.

DATA 11.1 Program Overview

DATA 11.1.1 Exhaust Shaft Hydraulic Assessment

Investigations led to the observation of a shallow perched groundwater horizon in a saturated layer within the lower Santa Rosa Formation and the upper Dewey Lake Formation, about 15 m (49 ft) below ground surface. During the original drilling of the shaft, no water was encountered at that horizon, indicating that the presence of water may be related to site activities subsequent to shaft drilling. Three wells and 12 piezometers were installed over an 80-acre area between September 1996 and July 1997. Water level and water quality parameters have been monitored and reported on a regular basis since installation.

DATA 11.1.2 Culebra Water-Level Rise Investigation

During the 1999 annual COMPs assessment, Culebra water levels in many of the WIPP monitoring wells exceeded the ranges of uncertainty established for equilibrium freshwater heads used in the CCA to calibrate transmissivity fields needed for Culebra flow and transport calculations. Culebra water-level rises had also been observed at the time of the CCA submittal in 1996, but were attributed to natural recovery of water levels following years of hydraulic well testing at the WIPP site and grouting of the WIPP shafts to prevent observed leakage. Subsequent to the 1999 COMPs assessment, Culebra water levels showed a continued rise even though water levels at the WIPP site were thought to have fully recovered from hydraulic testing and shaft grouting. In response to this observation, the DOE initiated an investigation into the cause of the water-level rise and the impact of the rise on the long-term performance of the WIPP.

DATA 11.2 Reported Data

Data acquired from the two hydrologic investigations are provided in the reports cited below under separate headings for the exhaust shaft hydraulic assessment and the Culebra water-level rise investigation.

DATA 11.2.1 Exhaust Shaft Hydraulic Assessment

The Geotechnical Analysis Reports listed in Section 4.2 provide data relevant to the exhaust shaft hydraulic assessment.

- INTERA, 1997, “Exhaust Shaft Hydraulic Assessment Data Report,” DOE-WIPP 97-2219, Carlsbad, NM, Waste Isolation Pilot Plant.

- U.S. Department of Energy, 1997, "Exhaust Shaft: Phase 2 Hydraulic Assessment Data Report Involving Drilling, Installation, Water-Quality Sampling and Testing of Piezometers 1 – 12," DOE-WIPP 97-2278, Carlsbad, NM, Waste Isolation Pilot Plant.

- U.S. Department of Energy, 2000, "Exhaust Shaft: Phase III Hydraulic Assessment Data Report, October 1997 – October 1998," DOE-WIPP 99-2302, Carlsbad, NM, Waste Isolation Pilot Plant.

DATA 11.2.2 Culebra Water-Level Rise Investigation

- Beauheim, R.L, 2002, "Analysis Plan for Evaluation of the Effects of Head Changes on Calibration of Culebra Transmissivity Fields, AP-088, Rev. 1," ERMS 524785, Carlsbad, NM, Sandia National Laboratories.

- Chace, D.A., 2003a, "Testing of Wells at the WIPP Site, Test Plan TP 03-01, Rev. 0," ERMS 525667, Carlsbad, NM, Sandia National Laboratories.

- Chace, D.A., 2003b, "Compliance Monitoring Program: Recompletion and Testing of Wells for Evaluation of Monitoring Data from the Magenta Member of the Rustler Formation at the WIPP Site, Test Plan TP 00-03, Rev. 1," ERMS 525860, Carlsbad, NM, Sandia National Laboratories.

- Holt, R.M., 2002, "Analysis Report Task 2 of AP-088 Estimating Base Transmissivity Fields," ERMS 523889, Carlsbad, NM, Sandia National Laboratories.

- Holt, R.M., 2003a, "Addendum to Analysis Report Task 2 of AP-088 Estimating Base Transmissivity Fields," ERMS 527601, Carlsbad, NM, Sandia National Laboratories.

- Holt, R.M., 2003b, "Addendum 2 to Analysis Report Task 2 of AP-088 Estimating Base Transmissivity Fields," ERMS 529416, Carlsbad, NM, Sandia National Laboratories.

- Jepsen, R.A., 2000, "Test Plan, TP 99-10 Groundwater Monitoring Activities: Troll Measurements, Bell Canyon Injection Well Monitoring Near H-9, and Meteorological Monitoring at H-9, Rev. 0," ERMS 509869, Carlsbad, NM, Sandia National Laboratories.

- Lowry, T.S., 2003. "Analysis Report Task 5 of AP-088 Evaluation of Mining Scenarios," ERMS 531138, Carlsbad, NM, Sandia National Laboratories.

- McKenna, S.A., and D. Hart, 2003a, "Analysis Report Task 3 of AP-088 Conditioning of Base T Fields to Steady-State Heads," ERMS 529633, Carlsbad, NM, Sandia National Laboratories.

- McKenna, S.A., and D. Hart, 2003b, "Analysis Report Task 4 of AP-088 Conditioning of Base T Fields to Transient Heads," ERMS 531124, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., 2001, "Examining Culebra Water Levels, TP 01-01, Rev. 0," ERMS 518995, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., 2002a, "Analysis Report Task 1 of AP-088 Construction of Geologic Contour Maps," ERMS 522086, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., 2002b, "Addendum to Analysis Report Task 1 of AP-088 Construction of Geologic Contour Maps," ERMS 523886, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., 2003a, "Addendum 2 to Analysis Report Task 1 of AP-088 Construction of Geologic Contour Maps," ERMS 525199, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., 2003b, "Test Plan for Geohydrological Conceptual Model for the Dewey Lake Formation in the Vicinity of the Waste Isolation Pilot Plant (WIPP), TP 02-05, Rev. 0," ERMS 526493, Carlsbad, NM, Sandia National Laboratories.

- Powers, D.W., Holt, R.M., Beauheim, R.L., and McKenna, S.A. (2003 in press). "Geological factors related to the transmissivity of the Culebra Dolomite Member, Permian Rustler Formation, Delaware Basin, southeastern New Mexico," in Johnson, K.S., and Neal, J.T., eds., Evaporite Karst and Engineering/Environmental Problems in the United States: Oklahoma Geological Survey Circular 109.

- Sandia National Laboratories, 2001a, "Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.4, Repository Investigations, Milestone RI010, January 31, 2001," ERMS 516749, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2001b, "Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.4, Repository Investigations, Milestone RI020, July 31, 2001," ERMS 518970, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2002a, "Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI110, January 31, 2002," ERMS 520467, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2002b, "Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI130, July 31, 2002," ERMS 523189, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2003a, "Sandia National Laboratories Technical Baseline Report, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI 03-210, January 31, 2003," ERMS 526049, Sandia WIPP Records Center, Carlsbad, NM.

- Sandia National Laboratories, 2003b. "Program Plan WIPP Integrated Groundwater Hydrology Program, FY03-FY09, Revision 0, March 14, 2003." ERMS 526671, Sandia WIPP Records Center, Carlsbad, NM.

- U.S. Department of Energy, 2003, Strategic Plan for Groundwater Monitoring at the Waste Isolation Pilot Plant. DOE/WIPP-03-3220, February 2003, Carlsbad, NM.

DATA 12.0 WASTE CONTAINERS AND EMPLACEMENT

Information regarding WIPP waste emplacement containers and underground waste emplacement layouts are provided in this section. Approved containers that are inside other containers, such as pipe overpacks, will not be discussed.

DATA 12.1 Program Overview

Information provided in this section was compiled from several sources to serve as a central document describing both waste emplacement containers and waste emplacement layouts. Both Contact Handled- (CH-) and Remote Handled- (RH-) waste containers are described along with CH- and RH-waste emplacement layouts in a typical panel in the underground repository. Only containers approved for storage in the repository will be discussed.

DATA 12.2 Reported Data

Attachment H provides the detailed information on the various waste containers and their emplacement in the underground repository.

APPENDIX DATA

ATTACHMENT A: DELAWARE BASIN DRILLING SURVEILLANCE DATA

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DATA-A-1.0 DELAWARE BASIN DRILLING SURVEILLANCE PROGRAM

The Delaware Basin Drilling Surveillance Program (DBDSP) is designed to monitor drilling activities in the vicinity of the Waste Isolation Pilot Plant (WIPP). The Environmental Protection Agency (EPA) requires the Department of Energy (DOE) to demonstrate the expected performance of the disposal system using a probabilistic risk assessment or performance assessment (PA). The PA must show that the expected repository performance will not release radioactive material above limits set by the EPA's standard and must consider inadvertent drilling into the repository horizon at some future time. The EPA regulations also state that current drilling practice, which is monitored by the DBDSP, should be assumed for future inadvertent intrusions.

The DOE continues to provide surveillance of the drilling activity in the Delaware Basin in accordance with the criteria established in 40 CFR § 194.33. This activity will continue until the DOE and the EPA mutually agree that no benefit can be gained from continued surveillance. The results of the ongoing surveillance activity will be used to determine if a significant change has occurred which would be detrimental to the performance of the disposal system.

DATA-A-2.0 QUALITY ASSURANCE

Because the DBDSP collects information only, the program's Quality Assurance (QA) process is not required to comply with Nuclear Quality Assurance (NQA) standards. Information collected from the various agencies and commercial sources is on an "as is" basis. However, QA is maintained by ensuring that the information collected is verified between the various sources for accuracy, to the extent possible. Also, any discrepancies noted are verified against the extant records at the state offices. As each well is completed, a copy of the drilling report is made from the records submitted to state offices in New Mexico and kept on file by the DBDSP. Before changes are made to any of the records in the databases, a paper copy is used to verify the change being made.

DATA-A-3.0 COLLECTION TIME PERIOD

The DBDSP collects the drilling-related information to be used for future PA calculations. The information collected during the first recertification monitoring period (July 1995 through September 2002) was added to the existing information maintained by the DBDSP. The information is collected weekly from Internet sites provided by the New Mexico Oil Conservation Division (OCD) for the entire state and from a commercial source for Southeastern New Mexico and Texas Railroad Commission, Oil and Gas Division, District 8. This information is then reviewed to determine which wells are within the Delaware Basin and need to be added to the databases. Other sources of information include the Bureau of Land Management (BLM) and the New Mexico Institute of Mining and Technology. The drilling-related activities monitored during the first recertification period by the DBDSP include:

- Drilling-related parameters/data, such as drilling rate, drill bit diameter, drill collar diameter and length, surface casing diameter, drill pipe diameter, speed of drill string rotation, penetration rate through the Salado Formation, type and characteristics (e.g.,

density, viscosity, etc.) of drilling mud, quantity of drilling fluid used, and occurrences of air drilling;

- Castile brine-related parameters/data, such as number of encounters of pressurized brine within the Castile Formation, Castile brine reservoir pressure and volume, and shortest and longest time until well shut-in occurs after a pressure encounter;

- Borehole plug-related parameters/data, such as pattern of plugs, plug materials and lengths; total number, location, and depth of abandoned boreholes; and type of steel alloy in the well casing;

- Enhanced recovery data, including occurrences of fluid injection (water flood) within the nine-township area, carbon dioxide (CO_2) miscible flooding, salt water disposal within the nine-township area, and volume (barrels) of fluid injected near WIPP within the nine-township area;

- Gas storage data, including occurrences of gas storage (cavern and/or reservoir) near WIPP;

- Solution mining data, including occurrences of solution mining within the Delaware Basin;

- Potash mining data, including changes in existing leases within the nine-township area; and

- Seismic data including history of relevant events, e.g., earthquake (natural or human induced) activity, relation of epicenters with geologic structures, geologic setting, etc.

DATA-A-4.0 COMPLIANCE MONITORING PARAMETERS

Two of the ten parameters monitored by the DBDSP are the drilling rate and the probability of encountering a Castile brine reservoir. Both parameters will continue to be monitored during postclosure.

Performance assessment is required by regulation to consider disturbed case scenarios that include intrusions into the repository by inadvertent and intermittent drilling for resources. The probability of these intrusions was based on a future drilling rate of 46.8 boreholes as used in the Compliance Certification Application (CCA) per square kilometer per 10,000 years. This rate is based on consideration of the past record of drilling events in the Delaware Basin.

Two different types of boreholes are considered: those that penetrate a pressurized brine reservoir in the underlying the Castile Formation and those that do not. While the presence of pressurized brine under the repository is speculative, it cannot be completely ruled out based on available information. The primary consequence of contacting pressurized brine is the introduction of an additional source of brine beyond that which is assumed to be released into the repository from the Salado. The human intrusion scenario models are based on extensive field data sets collected by the DOE.

The basis for the drilling rate to be used in PA for this Compliance Recertification Application (CRA) is shown in Table DATA-A-1. The drilling rate is calculated using wells that are deeper than 655 m (2,150 ft) below the surface since a well drilled to that depth would breach the repository horizon.

Table DATA-A-1. Wells in the Delaware Basin Deeper Than 655 m (2,150 ft)

Data collected from 1903 through September 2002

Well Type	Texas	New Mexico	Totals
Core Hole	5	0	5
Dry Hole	2,173	841	3,014
Gas Well	832	611	1,443
Injection Well	248	71	319
Junked and Abandoned Well	56	15	71
Oil Well	3,821	1,805	5,626
Oil and Gas Well	92	5	97
Plugged Gas Well	176	127	303
Plugged Injection Well	0	20	20
Plugged Oil Well	508	278	786
Plugged Oil and Gas Well	36	0	36
Plugged Brine Well	0	1	1
Plugged Salt Water Disposal Well	0	7	7
Drilling or Waiting on Paperwork	20	8	28
Brine Well	5	0	5
Salt Water Disposal Well	5	103	108
Service Well	101	3	104
Stratigraphic Test Hole	43	2	45
Sulfur Core Hole	85	0	85
Potash Core Hole	0	19	19
WIPP Core Hole	0	11	11
Other (Mine Shafts, Gnome Project Wells)	0	6	6
Totals	8,206	3,933	12,139

The drilling rate is calculated as follows: number of deep holes (12,139) × 10,000 years/ Delaware Basin surface area (23,102.1 km^2 [8921.7 mi^2])/100 years. The drilling rate is 52.5 boreholes per square kilometer over 10,000 years. This is an increase from the 46.8 boreholes per square kilometer reported in the CCA. This number is anticipated to rise for quite a few years before it begins to drop. This is because of the 100-year time frame used for drilling results. As new wells are added to the count, wells older than 100 years are dropped. It will be 2011 before any wells are dropped from the count while a number of new wells are expected to be added due to increased oil and gas activity, thus driving up the count.

Castile brine encounters are shown in Table DATA-A-2. The table shows the original encounters used in the CCA and the new brine encounters that occurred from July 1995 through September 2002.

Table DATA-A-2. Castile Brine Encounters

#	Location	Well Name	Spud Date	Status	Well Information
Original CCA-related Castile Brine Encounters – 1896 Through June 1995					
1	21S-31E-26	Federal #1	10/31/1979	P&A	Identified as encountering Castile Brine.
2	21S-31E-35	ERDA-6	06/13/1975	P&A	Identified as encountering Castile Brine.
3	21S-31E-35	Federal “FI” #1	09/25/1981	P&A	Identified as encountering Castile Brine.
4	21S-31E-36	Lost Tank “AIS” State #1	12/07/1991	Oil Well	Identified as encountering Castile Brine.
5	21S-31E-36	Lost Tank “AIS” State #4	11/19/1991	Oil Well	Identified as encountering Castile Brine.
6	21S-32E-31	Lost Tank SWD #1	11/12/1991	SWD	Identified as encountering Castile Brine.
7	22S-29E-09	Danford Permit #1	05/18/1937	P&A	Identified as encountering Castile Brine.
8	22S-31E-01	Unocal “AHU” Federal #1	04/02/1991	Oil Well	Identified as encountering Castile Brine.
9	22S-31E-01	Molly State #1	09/25/1991	Oil Well	Identified as encountering Castile Brine.
10	22S-31E-01	Molly State #3	10/20/1991	Oil Well	Identified as encountering Castile Brine.
11	22S-31E-02	State “2” #3	11/28/1991	Oil Well	Identified as encountering Castile Brine.
12	22S-31E-11	Martha “AIK” Federal #3	05/06/1991	Oil Well	Identified as encountering Castile Brine.
13	22S-31E-11	Martha “AIK” Federal #4	09/02/1991	Oil Well	Identified as encountering Castile Brine.
14	22S-31E-12	Federal “12” #8	03/28/1992	Oil Well	Identified as encountering Castile Brine.
15	22S-31E-13	Neff “13” Federal #5	02/04/1991	Oil Well	Identified as encountering Castile Brine.
16	22S-31E-17	WIPP-12	11/17/1978	Monitoring	Identified as encountering Castile Brine.
17	22S-32E-05	Bilbrey “5” Federal #1	11/26/1981	Oil Well	Identified as encountering Castile Brine.
18	22S-32E-15	Lechuza Federal #4	12/29/1992	Oil Well	Identified as encountering Castile Brine.
19	22S-32E-16	Kiwi “AKX” State #1	04/28/1992	Oil Well	Identified as encountering Castile Brine.
20	22S-32E-25	Covington “A” Federal #1	02/07/1975	Oil Well	Identified as encountering Castile Brine.
21	22S-32E-26	Culberson #1	12/15/1944	P&A	Identified as encountering Castile Brine.
22	22S-32E-34	Red Tank “34” Federal #1	09/23/1992	Oil Well	Identified as encountering Castile Brine.
23	22S-32E-36	Richardson State #1	07/20/1962	P&A	Identified as encountering Castile Brine.
24	22S-32E-36	Shell State #1	02/22/1964	Oil Well	Identified as encountering Castile Brine.
25	22S-33E-20	Cloyd Permit #1	09/07/1937	P&A	Identified as encountering Castile Brine.
26	22S-33E-20	Cloyd Permit #2	06/22/1938	P&A	Identified as encountering Castile Brine.
27	23S-30E-01	Hudson Federal #1	02/25/1974	SWD	Identified as encountering Castile Brine.
New CRA-related Castile Brine Encounters – July 1995 Through September 2002					
1	21S-31E-35	Lost Tank “35” State #4	09/11/2000	Oil Well	Estimated several hundred barrels per hour. Continued drilling.
2	21S-31E-35	Lost Tank “35” State #16	02/06/2002	Oil Well	At 2,705 ft, encountered 1,000 B/H. Shut-in to get room in reserve pit with pressure of 180 psi. Shut in next day with pressure at 100 psi and waterflow of 450 B/H. Two days later no water flow and full returns.
3	22S-31E-02	Graham “AKB” State #8	04/12/2002	Oil Well	Estimated 105 barrels per hour. Continued drilling.
4	23S-30E-01	James Ranch Unit #63	12/23/1999	Oil Well	Sulfur water encountered at 2,900 ft. 35 PPM was reported but quickly dissipated to 3 PPM in a matter of minutes. Continued drilling.
5	23S-30E-01	Hudson “1” Federal #7	01/06/2001	Oil Well	Estimated initial flow at 400 to 500 barrels per hour with a total volume of 600-800 barrels. Continued drilling.

No official documentation of New Mexico state records exists for the five new Castile brine encounters. Four were reported by WIPP site personnel during discussions with area drillers,

while the fifth was reported by one of the operators on the Annual Survey performed by the DBDSP. The Annual Survey is sent to regional area operators requesting information that is not available through other means.

All five wells were drilled in areas where Castile brine was previously encountered during the drilling process. Three wells were drilled in the vicinity of Well #ERDA-6 and the other two were southwest of the WIPP site. All were located in the nine-township area. During this time period, 345 wells were drilled in the nine-township area.

DATA-A-5.0 SUMMARY OF INFORMATION

DATA-A-5.1 Drilling-Related Parameters/Data

Tables DATA-A-3 through DATA-A-6 provide these drilling-related parameters/data: drill bit diameter, drill collar diameter and length, surface casing diameter, drill pipe diameter, speed of drill string rotation, penetration rate through the Salado, type and characteristics (density, viscosity, etc.) of drilling mud, quantity of drilling fluid used, and occurrences of air drilling.

Table DATA-A-3 lists drill bit sizes for the various wells drilled in the nine-township area during the recertification monitoring period. Currently, an 11” bit would be used to drill the same depth as the repository but in the CCA a 12 ¼” bit was modeled.

Table DATA-A-3. Nine-Township Area Bit Sizes

Three-String Hole

Bit Size	Surface Hole	Intermediate Hole	Production Hole	Totals
17 ½"	79	0	0	79
14 ¾"	25	0	0	25
14"	1	0	0	1
12 ¼"	0	16	0	16
11"	0	77	0	77
9 ⅞"	0	12	0	12
8 ⅞"	0	0	1	1
8 ¾"	0	0	3	3
7 ⅞"	0	0	89	89
6 ¾"	0	0	12	12
Totals	105	105	105	315

Note: Bit size information was available on 114 holes out of 345 that were spudded in the nine-township area from July 1995 through September 2002. Of the 114 holes completed, 105 were drilled using a three-string setup.

Two-String Hole

Bit Size	Surface Hole	Production Hole	Totals
12 ¼"	4	0	4
11"	5	0	5
7 ⅞"	0	9	9
Totals	9	9	18

Note: Of the 114 holes with available bit size information, nine holes were completed using a two-string setup.

Table DATA-A-4 lists the different casing sizes for wells drilled in the nine-township area during the recertification monitoring period. Information for casing sizes is acquired from

commercial sources and thus is readily available while drill bit size is acquired from state records which are not available until several months after a well has been completed.

Table DATA-A-4. Nine-Township Area Casing Sizes

Three-String Hole

Casing Size	Surface Casing	Intermediate Casing	Production Casing	Totals
20"	1	0	0	1
13 ⅜"	203	1	0	204
11 ¾"	44	0	0	44
10 ¾"	54	0	0	54
9 ⅞"	0	1	0	1
9 ⅝"	3	12	1	16
8 ⅝"	0	236	0	236
7 ⅞"	0	2	0	2
7 ⅝"	0	50	1	51
7"	0	3	6	9
5 ½"	0	0	235	235
4 ½"	0	0	62	62
Totals	305	305	305	915

Note: There were 345 wells drilled in the nine-township area from July 1995 through September 2002. Casing size information was available on 305 wells which used a three-string casing assembly to complete the well.

Two-String Hole

Casing Size	Surface Casing	Production Casing	Totals
10 ¾"	1	0	1
9 ⅝"	1	0	1
8 ⅝"	17	0	17
7"	0	1	1
5 ½"	0	18	18
Totals	19	19	38

Note: There were 19 wells completed as a two-string assembly out of the 345 wells drilled in the nine-township area during the recertification monitoring period.

Table DATA-A-5 lists these drilling related parameters: drill collar diameter and length, drill pipe diameter, speed of drill string rotation, penetration rate through the Salado, type and characteristics (density, viscosity, etc.) of drilling mud, and quantity of drilling fluid. This information was acquired from the annual surveys of area well operators performed each year during the recertification monitoring period.

Table DATA-A-5. Nine-Township Drilling Survey Information

#	Well Name and No.	Drill Pipe	Rotation Speed	Penetration Rate	Mud Density	Mud Viscosity	Mud Yield	Collar Diameter	Collar Length	Number of Collars
1	Lucy “ALC” State #3	4 ½"	75-85 RPM	35.4 ft/HR	10 PPG	28 SEC/QT	No Report	S=8 1/16 I=7 ½ P=6 ½	No Report	S=25 I=27 P=27
2	Jacque “AQJ” State #5	4 ½"	75-90 RPM	60 ft/HR	10 PPG	28 SEC/QT	No Report	S=7 15/16 I=7 ½ P=6 ⅝	No Report	S=16 I=27 P=27
3	Graham “AKB” State #5	4 ½"	40-90 RPM	68.7 ft/HR	10 PPG	28 SEC/QT	No Report	S=7 11/16 I=8 P=6	No Report	S=18 I=33 P=33
4	Graham “AKB” State #8	4 ½"	50-80 RPM	68 ft/HR	9.9-10.2 PPG	28 SEC/QT	No Report	S=8 I=8 P=6	No Report	S=18 I=33 P=33
5	Flora “AKF” State #3	4 ½"	60-105 RPM	65 ft/HR	10 PPG	28 SEC/QT	No Report	S=7 ⅞ I=7 ⅞ P=6	No Report	S=18 I=33 P=33
6	Remuda Basin State #9	4 ½"	No Report	91.6 ft/HR	8.3 PPG	38 SEC/QT	No Report	S=8	S=30 ft	No Report
7	Remuda Basin State #10	4 ½"	No Report	105 ft/HR	8.7 PPG	29 SEC/QT	No Report	S=8	S=30 ft	No Report
8	Remuda Basin State #11A	4 ½"	No Report	37.9 ft/HR	8.3 PPG	38 SEC/QT	No Report	S=8	S=30 ft	No Report
9	Barclay Federal #15	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=14 I=14 P=26
10	Barclay Federal #10	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=14 I=14 P=26
11	Barclay Federal #21	4 ½"	115 RPM	28 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=813 ft I=781 ft P=782 ft	No Report
12	Barclay Federal #18	4 ½"	120 RPM	28 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=812 ft I=780 ft P=783 ft	No Report

Table DATA-A-5. CRA Nine-Township Drilling Survey Information — Continued

#	Well Name and No.	Drill Pipe	Rotation Speed	Penetration Rate	Mud Density	Mud Viscosity	Mud Yield	Collar Diameter	Collar Length	Number of Collars
13	Barclay Federal #20	4 ½"	115 RPM	28 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=813 ft I=780 ft P=782 ft	No Report
14	Barclay Federal #27		120 RPM	20 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=810 ft I=785 ft P=780 ft	No Report
15	Barclay Federal #28	4 ½"	115 RPM	28 ft/HR	No Report	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=812 ft I=784 ft P=782 ft	No Report
16	Barclay State #7	4 ½"	120 RPM	28 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=810 ft I=781 ft P=780 ft	No Report
17	Barclay State #9	4 ½"	115 RPM		8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=815 ft I=785 ft P=786 ft	No Report
18	Barclay Federal #8	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=13 I=27 P=26
19	Barclay Federal #11	4 ½"	115 RPM	28 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=810 ft I=780 ft P=784 ft	No Report
20	Barclay Federal #13	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=13 I=27 P=26
21	Barclay Federal #17	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=13 I=27 P=26
22	Barclay Federal #19	4 ½"	110 RPM	No Report	10 PPG	29 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=6	S=31 ft I=31 ft P=31 ft	S=13 I=27 P=26
23	Barclay Federal #25	4 ½"	118 RPM	29 ft/HR	8.6 PPG	33 SEC/QT	No Report	S=8 and 6 I=8 and 6 P=8 and 6	S=815 ft I=784 ft P=782 ft	No Report

Note: Under the columns for Collars, the "S" indicates surface string, the "I" indicates intermediate string, and the "P" indicates production string. Also, under the Collar Diameter the production string on some wells indicates 8- and 6-in. collars. This is obviously an error since the hole diameter for that portion of the well is 7 ⅞ inches.

Table DATA-A-6 lists the known instances of air drilling that have occurred in the New Mexico portion of the Delaware Basin since hydrocarbon drilling has been performed. During the 100 years of drilling used for the CCA, there were 15 suspected cases where air may have been used to drill some portion of a well. During the recertification monitoring period, there was one proven incidence of air drilling, although not through the salt section, which occurred near the airport in Carlsbad 40.23 km (25 mi) west of the WIPP site.

Table DATA-A-6. Air-Drilled Wells

#	Location	Well Name and No.	Spud Date	Status	Well Information
Wells Drilled Prior to Submittal of the CCA With Some Portion Drilled by Air					
1	21S-28E-33	Richardson & Bass #1	07/27/1961	P&A	Air drilled through the salt. Between 2,545 and 2,685 encountered water and changed from air to mud based drilling.
2	21S-32E-26	Lincoln Federal Unit #1	04/01/1991	P&A	Lost circulation at 1290. Hole was dry drilled to 1,792. Supposedly air drilled from 2,984 to 4,725.
3	23S-26E-17	Exxon “17” Federal #1	08/01/1989	Gas Well	Air drilled through the salt from 575 to 2,707.
4	23S-28E-11	CP Pardue #1	10/28/1958	P&A	Air drilled through the salt from 390 to 2,620.
5	23S-28E-11	Amoco Federal #1	08/04/1979	Oil Well	Air drilled from 475 to 9,700.
6	23S-28E-11	Amoco Federal #3	02/28/1980	Oil Well	Air drilled from 6271 to 9,692.
7	23S-28E-23	South Culebra Bluff Unit #3	01/21/1979	Oil Well	Air drilled from 6345 to 8,000.
8	23S-28E-23	South Culebra Bluff Unit #4	08/09/1979	Oil Well	Air drilled from 450 to 9,802.
9	24S-31E-03	Lilly “ALY” Federal #2	05/01/1994	Oil Well	Air drilled conductor hole to 40.
10	24S-31E-03	Lilly “ALY” Federal #4	05/16/1994	Oil Well	Air drilled conductor hole to 40.
11	24S-34E-04	Antelope Ridge Unit #2	09/13/1962	Gas Well	Attempted to drill with gas. Had to convert to water at 1,035. Tried again several times at different depths.
12	24S-34E-09	Federal “9” Com #1	12/3/1963	Gas Well	Hit water while gas drilling at 4,865.
13	24S-34E-13	Federal Johnson #1	06/23/1958	P&A	Proposed to drill with air but no information in the records indicate air drilling.
14	26S-32E-20	Russell Federal #1	03/16/1966	Oil Well	Drilled with air to 1,330.
15	26S-32E-36	North El Mar Unit #44	02/19/1959	Oil Well	Proposed to drill with air but no information in the records indicate air drilling.
Wells Drilled After Supplemental Information Provided to the Docket					
1	22S-26E-28	Sheep Draw “28” Federal #13	07/01/1997	Oil Well	Air drilled the first 358 ft.

Note: The research on “air drilling” is a continuous effort since every new well drilled is checked to determine if any portion of the well was drilled by air. A copy of all completion reports are on file for all wells completed within the New Mexico portion of the Delaware Basin.

DATA-A-5.2 Borehole Plug-Related Parameters/Data

Borehole plug-related parameters/data including pattern of plugs; plug materials and lengths; total number, location, and depth of abandoned boreholes; and type of well casing steel alloy are shown in Table DATA-A-7.

Table DATA-A-7. Plugged Wells in the Nine-Township Area of the Delaware Basin – July 1995 Through September 2002

#	Location	Well Name and No.	Plug Date	R-111-P	Depth	No. Plugs	Plug Length	No. Sacks	Cement	Steel Alloy
1	21S-30E-33	Kaleidoscope "AKO" #1	03/13/1996	Yes	7,340	5	35 ft 50ft 100 ft 227 ft 264 ft	35 ft 10 Sacks 25 Sacks 25 Sacks 80 Sacks	Class C	S=J-55 I=J-55 P=J-55
2	21S-30E-34	Julia "AJL" Federal #4	03/19/1996	Yes	7,455	6	35 ft 100 ft 100 ft 185 ft No Report 50 ft	35 ft 25 Sacks 25 Sacks 25 Sacks 65 Sacks 5 Sacks	Class C	S=J-55 I=J-55 P=J-55
3	21S-32E-22	Bilbrey North "22" Federal #1	07/29/1998	Yes	15,020	5	330 ft 180 ft 150 ft 2,150 ft 50 ft	35 Sacks 180 ft 150 ft 750 Sacks 5 Sacks	No Report	S=J-55 I=N-80 P=P-110
4	21S-32E-31	Luke Federal #2	04/26/1998	Yes	8,585	4	No Report 100 ft 424 ft 50 ft	6 Sacks 11 Sacks 362 Sacks 50 Sacks	Class C	S=H-40 I=K-55 P=K-55
5	21S-32E-35	Anderson #1	07/27/1995	No	8,763	5	40 ft No Report 297 ft 197 ft 50 ft	40 ft 15 Sacks 70 Sacks 50 Sacks 10 Sacks	Class C	S=K-55 I=J-55 P=J-55
6	22S-32E-14	Prohibition Federal #5	05/24/1996	No	8,914	6	No Report 192 ft 336 ft 154 ft 125 ft 60 ft	25 Sacks 20 Sacks 50 Sacks 40 Sacks 65 Sacks 40 Sacks	Unknown Unknown Unknown Class C Class C Class C	S=J-55 I=J-55 P=J-55/N-80
7	22S-32E-22	Cercion Federal #8	03/25/1998	No	8,900	6	200 ft 100 ft 100 ft 100 ft 100 ft 20 ft	70 Sacks 50 Sacks 100 Sacks 35 Sacks 35 Sacks 20 Sacks	Class H Class H Class C Class C Class C Class C	No Report

Table DATA-A-7. Plugged Wells in the Nine-Township Area of the Delaware Basin – July 1995 Through September 2002 — Continued

#	Location	Well Name and No.	Plug Date	R-111-P	Depth	No. Plugs	Plug Length	No. Sacks	Cement	Steel Alloy
8	23S-32E-09	Aracanga Federal #2	02/04/1998	No	8,985	4	No Report 100 ft 100 ft 430 ft	35 Sacks 25 Sacks 25 Sacks 112 Sacks	No Report	S=H-40 I=J-55 P=J-55
9	23S-32E-12	Pronghorn Federal “12” #1	02/18/1999	No	9,200	7	50 ft 100 ft 100 ft 150 ft 100 ft 100 ft 50 ft	50 ft 50 Sacks 40 Sacks 60 Sacks 35 Sacks 35 Sacks 15 Sacks	Class H Class C Class C Class C Class C Class C Class C	No Report
10	23S-32E-15	Codorniz Federal #2	12/31/1996	No	9,039	5	100 ft 100 ft 100 ft 100 ft 60 ft	50 Sacks 50 Sacks 50 Sacks 50 Sacks 20 Sacks	Class H	S=H-40 I=J-55/S-80 P=K-55
11	23S-32E-18	Sand “18” Federal #2	05/24/1996	No	8,800	4	200 ft 265 ft 141 ft 75 ft	55 Sacks 180 Sacks 45 Sacks 57 Sacks	Class H	S=WC-40 I=WC-50 P=K-55/L-80
12	23S-32E-24	Red Deer “24” Federal #1	05/27/1997	No	9,101	4	216 ft 115 ft 180 ft 730 ft	50 Sacks 25 Sacks 35 Sacks 140 Sacks	Class C	S=K-55 I=K-55
13	23S-32E-35	Red Ruby “35” Federal #1	08/17/1997	No	9,100	6	202 ft 101 ft 125 ft 110 ft 110 ft 15 ft	60 Sacks 45 Sacks 70 Sacks 30 Sacks 30 Sacks 15 Sacks	No Report	S=J-55 I=NS-80

Note: Under the column for Steel Alloy the “S” indicates surface casing, the “I” indicates intermediate casing, and the “P” indicates production casing. The plugging regulations in New Mexico have not changed since the 1996 CCA.

DATA-A-5.3 Enhanced Recovery Data

Enhanced recovery data, including occurrences of fluid injection (water flood) within the nine-township area; CO_2 miscible flooding; salt water disposal within the nine-township area; and volume (barrels) of fluid injected near WIPP within the nine-township area are shown in the following Figure DATA-A-1 and Table DATA-A-8.

DATA-A-5.3.1 CO_2 Flooding

There are no secondary or tertiary recovery projects in the vicinity of the WIPP site utilizing carbon dioxide flooding as a means to recover oil. The nearest operation of this type is located 40.23 km (25 mi) to the south in Loving County, Texas.

There are no CO_2 pipelines to any of the oil fields in the New Mexico portion of the Delaware Basin where secondary recovery is ongoing. The one field near the WIPP site (El Mar) where secondary recovery is ongoing is located approximately 40.23 km (25 mi) from the CO_2 flooding operation in Loving County, Texas.

DATA-A-5.4 Gas Storage Data

Gas storage data including occurrences of gas storage (cavern and/or reservoir) near WIPP are shown in Table DATA-A-9.

A common underground gas storage facility is a cavern solution mined from the salt formations underlying the surface. They are made by dissolving the salt with fresh water and then pumping the brine to the surface, leaving a cavity that can be used for storage of hydrocarbons while a depleted reservoir storage system utilizes a reservoir from which most or all economically recoverable hydrocarbons have been produced.

In 1992, there were six gas storage facilities permitted in the state of New Mexico. Five were located in Southeast New Mexico, with one being inside the boundaries of the Delaware Basin and of interest to the WIPP site. The Washington Ranch Storage Project, located in the Delaware Basin about 79.03 km (46 mi) to the southwest of the WIPP site, is a multiwell system in a depleted gas reservoir, storing produced natural gas at a depth of approximately 1981.2 to 2133.6 m (6,500 to 7,000 ft). It is still in operation at this time, although at a much reduced level than in 1992.

Of the five facilities located in southeast New Mexico, only three are cavern-type facilities solution mined from the salt. All three store liquefied petroleum gas and are between 53.1 and 56.33 km (33 and 35 mi) from the WIPP site. The two that store produced natural gas do so in a depleted gas reservoir with the nearest facility located 32.19 km (20 mi) from the WIPP site, leaving the Washington Ranch Storage Project the furthest from the site at 79.03 km (46 mi).

At this time, there are no known underground gas storage facilities in the Texas portion of the Delaware Basin.

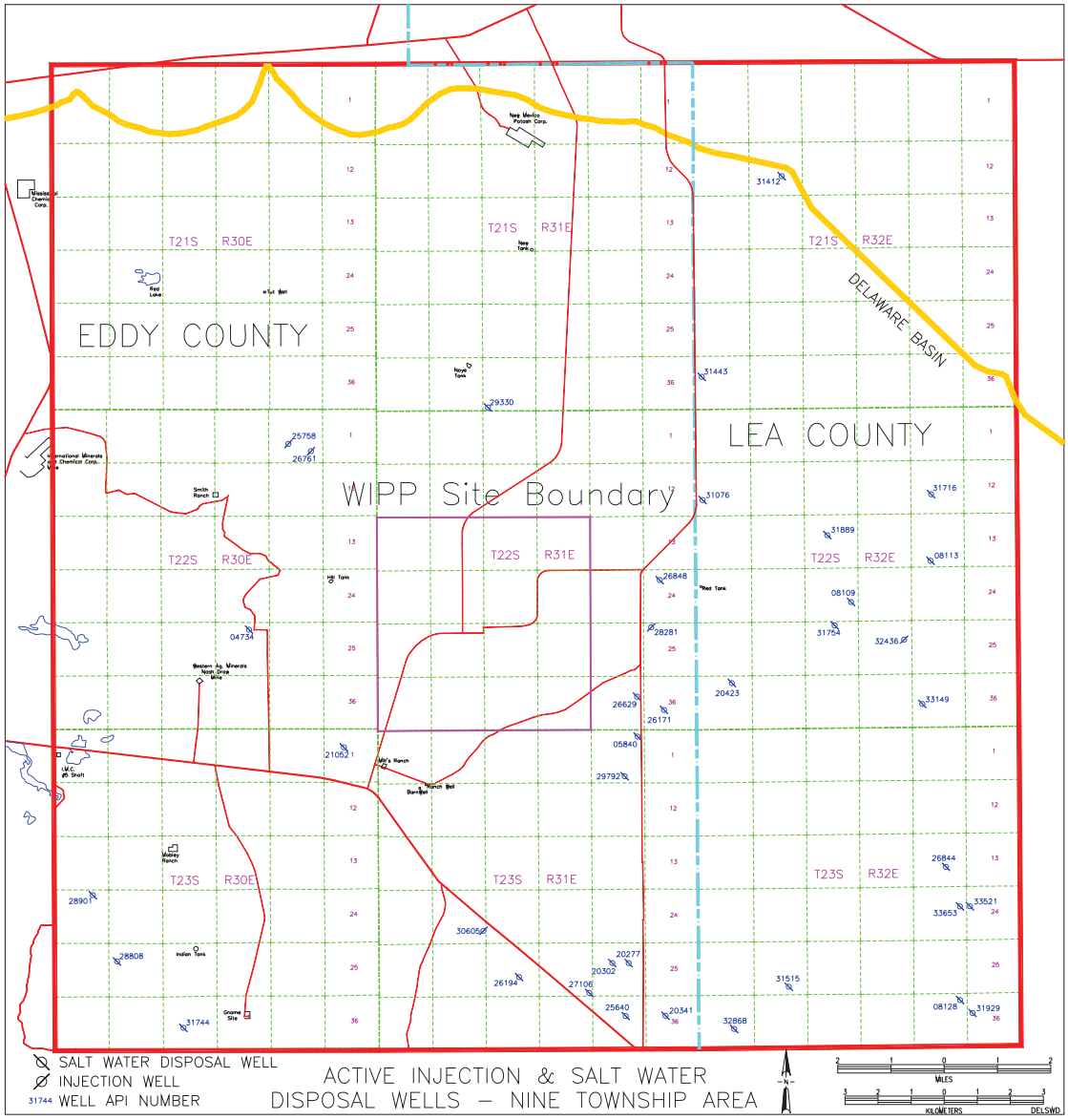

Figure DATA-A-1. Active Injection and Salt Water Disposal Wells

Table DATA-A-8. Nine-Township Injection and Salt Water Disposal (SWD) Well Information

No.	Location	Well Name and No.	Well Status	Injection Zone	1st Inj	Latest Inj	Inj Press	Cumulative Barrels
Wells Completed Prior to the Initial Certification								
1	21S-32E-08	Union “AJS” Federal #1	Salt Water Disposal	4826-5978	1991	June-2002	700 psi	4,784,288 Barrels
2	21S-32E-31	Lost Tank SWD #1	Salt Water Disposal	4618-6012	1992	June-2002	20 psi	157,463 Barrels
3	22S-30E-02	James “A” #3	Injection	7200-7264	1993	June-2002	855 psi	6,376,961 Barrels
4	22S-30E-02	James “A” #12	Injection	5600-7400	1991	June-2002	776 psi	6,758,551 Barrels
5	22S-30E-27	RH Legg Federal #1	Salt Water Disposal	3820-3915	1981	June-2002	760 psi	1,947,467 Barrels
6	22S-31E-24	Getty “24” Federal #5	Salt Water Disposal	4519-5110	1991	June-2002	No Report	4,694,840 Barrels
7	22S-31E-25	Neff Federal #3	Injection	7050-7068	1995	June-2002	600 psi	3,069,445 Barrels
8	22S-31E-35	David Ross “AIT” Federal #1	Salt Water Disposal	4500-5670	1991	June-2002	700 psi	7,791,690 Barrels
9	22S-32E-07	Flamenco Federal #1	Salt Water Disposal	4676-5814	1991	June-2002	300 psi	5,014,465 Barrels
10	22S-32E-11	Prohibition Federal #2	Salt Water Disposal	5200-8706	1994	June-2002	450 psi	915,747 Barrels
11	22S-32E-14	Red Tank “BT” Federal #2	Salt Water Disposal	4900-6080	1994	May-2002	No Report	2,564,127 Barrels
12	22S-32E-16	Kiwi “AKX” State #8	Salt Water Disposal	5240-8710	1995	June-2002	700 psi	4,750,431 Barrels
13	22S-32E-21	Gilmore Federal #1	Salt Water Disposal	4755-5110	1992	June-2002	550 psi	1,847,930 Barrels
14	22S-32E-28	Red Tank “28” Federal #3	Salt Water Disposal	4690-5800	1993	June-2002	300 psi	397,081 Barrels
15	22S-32E-31	Proximity “31” Federal #4	Salt Water Disposal	4662-5915	1993	June-2002	550 psi	2,976,033 Barrels
16	22S-32E-35	Red Tank “35” Federal #3	Salt Water Disposal	4950-6252	1995	June-2002	400 psi	2,025,597 Barrels
17	23S-30E-29	Charger “29” Federal #1	Salt Water Disposal	5479-7220	1996	June-2002	375 psi	1,587,535 Barrels
18	23S-31E-26	Todd Federal “26” #2	Salt Water Disposal	4460-5134	1992	June-2002	900 psi	3,231,147 Barrels
19	23S-31E-26	Todd Federal “26” #3	Salt Water Disposal	4390-6048	1971	June-2002	900 psi	4,460,450 Barrels
20	23S-31E-28	Sand Dunes “28” Federal #1	Salt Water Disposal	4295-5570	1993	June-2002	440 psi	2,944,921 Barrels
21	23S-31E-35	Cal-Mon #5	Salt Water Disposal	4484-5780	1993	June-2002	732 psi	2,347,175 Barrels
22	23S-31E-36	Todd “36” State #1	Salt Water Disposal	5980-6560	1994	June-2002	700 psi	6,836,860 Barrels
23	23S-32E-14	Cuervo Federal #1	Salt Water Disposal	5496-6014	1991	June-2002	550 psi	1,071,613 Barrels
24	23S-32E-29	James Federal #1	Salt Water Disposal	4844-4944	1992	June-2002	650 psi	2,882,040 Barrels
25	23S-32E-31	SDE “31” Federal #9	Salt Water Disposal	5150-5700	1996	June-2002	No Report	629,554 Barrels
26	23S-32E-35	James Federal #1A	Salt Water Disposal	5062-5100	1969	March-2002	850 psi	142,681 Barrels
27	23S-32E-36	Triste Draw “36” State #1	Salt Water Disposal	5364-6138	1995	May-2002	No Report	1,035,920 Barrels

Table DATA-A-8. Nine-Township Injection and Salt Water Disposal (SWD) Well Information — Continued

No.	Location	Well Name and No.	Well Status	Injection Zone	1st Inj	Latest Inj	Inj Press	Cumulative Barrels
Wells Completed Since the Initial Certification								
28	21S-31E-33	Lost Tank “33” Federal #2	Salt Water Disposal	4166-5160	1998	June-2002	360 psi	1,383,513 Barrels
29	22S-31E-36	Medano State Commercial #1	Salt Water Disposal	4500-5700	1998	Sept-2001	950 psi	2,500,628 Barrels
30	22S-32E-27	Prize Federal #4	Injection	6831-8388	1998	April-1999	No Report	No Report
31	23S-30E-01	Hudson Federal #1	Salt Water Disposal	4040-4825	2001	June-2002	800 psi	561,873 Barrels
32	23S-30E-19	Remuda Basin “19” Federal #2	Salt Water Disposal	3402-4609	1997	No Report	No Report	No Report
33	23S-30E-33	Poker Lake Unit #170	Salt Water Disposal	4546-6760	2002	No Report	No Report	No Report
34	23S-31E-02	Conoco State AA-2 #1	Salt Water Disposal	4489-5670	1997	Sept-2001	1010 psi	3,726,488 Barrels
35	23S-31E-02	Barclay State #4	Salt Water Disposal	4500-5850	1998	Sept-2001	1030 psi	2,908,070 Barrels
36	23S-31E-20	Pure Gold “B” Federal #20	Injection	7740-7774	2001	Dec-2001	No Report	244,642 Barrels
37	23S-31E-27	Todd “27” Federal	Salt Water Disposal	4694-5284	1998	No Report	No Report	No Report
38	23S-32E-23	Diamondtail “23” Federal #2	Salt Water Disposal	5954-6064	?	May-2001	420 psi	911,167 Barrels
39	23S-32E-24	Diamondtail “24” Federal #1	Salt Water Disposal	5925-6042	?	June-2002	No Report	732,490 Barrels

Note: Information collected from OCD offices in Artesia and Hobbs. Also, Cumulative Barrels information is collected from the New Mexico Oil & Gas Engineering Committee, Inc. and is valid through June 2002.

Table DATA-A-9. Underground Gas Storage Facilities in the Vicinity of the WIPP Site

Facility/Operator	Type of Facility	Location	Delaware Basin	Capacity	Material Stored
Washington Ranch Storage Project El Paso Natural Gas Company	Multiwell system utilizing a depleted gas reservoir found at a depth of 6,500 to 7,000 ft.	25S-24E 26S-24E Eddy County	Yes	67,253 MMCF	Produced Natural Gas
Loco Hills Arrow Gas Company	Three-well system interconnected by a cavity in the salt section at a depth of 500 to 600 ft.	17S-29E-22 Eddy County	No	235,000 to 238,000 barrels	Liquified Petroleum Gas
LPG Storage Well No. 1 Warren Petroleum Company	One-well storage facility in the salt section at a depth of 1,892 ft.	20S-36E-01 Lea County	No	168,000 barrels	Liquified Petroleum Gas
LPG Storage Well No. 2 Warren Petroleum Company	One-well storage facility in the salt section at a depth of 1,469 ft.	19S-36E-36 Lea County	No	245,000 barrels	Liquified Petroleum Gas
Grama Ridge Morrow Unit Llano, Inc.	Four-well storage facility (two injectors, two withdrawal wells) in a portion of the Grama Ridge Gas Pool at a depth of 12,700 to 13,200 ft.	21S-34E-34 22S-34E-03 Lea County	No	13,000 MMCF	Produced Natural Gas

DATA-A-5.5 Solution Mining

This section discusses occurrences of solution mining within the Delaware Basin. The discussion addresses the following four categories:

- Potash solution mining,
- Sulfur solution mining,
- Brine wells, and
- Naturally occurring radioactive materials (NORM) facilities.

DATA-A-5.5.1 Potash Solution Mining

No solution mining for potash has occurred at any of the mines located within the Delaware Basin in the vicinity of the WIPP site. The DOE is not aware of any plans being considered by any mining companies to use potash solution mining in the Delaware Basin. However, this process has occurred outside the Delaware Basin in the Carlsbad Mining District, which comprises all of the potash mines in the area. Potash can be found in the Mcnutt

The first solution mining attempt was in the late 1960s. Conoco Minerals installed a pilot scale in-situ solution mine on the AMAX lease in 19S-30E-12. This solution cavity was mapped in 1974 from the surface using radar. The cavern created was 213.36 m (700 ft) in diameter and approximately 3.04 m (10 ft) high. There were four boreholes drilled to create this cavity — one injection well and three withdrawal wells. This project was designed to test solution mining of potassium minerals, but the potash ore zone was deemed too thin to make this method economically viable. This occurred approximately 22 miles north of the WIPP Site.

The second potash solution mining endeavor is still in the initial phases and solution mining activities have not yet commenced. In May 1997, Mississippi Chemical filed a notice of intent to proceed with solution mining of potash in the Clayton Basin just to the north of the Delaware Basin. The next step in the process is for a detailed plan to be submitted to the Bureau of Land Management (BLM) for further evaluation. This plan was not submitted until March 2002. BLM approved the test plan in May 2002 for the pilot project. After the pilot phase is completed, an Environmental Impact Statement will be required before work can proceed. Currently, Mississippi Chemical has put the plan on hold due to a lack of funding. Talks with the BLM have indicated that the plan is still of a proprietary nature and the BLM will not allow anyone to review the plan without approval from Mississippi Chemical. However, BLM personnel did indicate that the facility would be located at the old Eddy Potash mine, which is located outside of the Delaware Basin and north-northwest of the WIPP site approximately 30.68 km (19 mi). The proposed plan is to pump water down the shaft into a section of the mine that has been previously mined out, circulating the water around pillars until it becomes saturated with potash, and then pumping the saturated fluid to the surface where it would be dumped into a two- to three-acre evaporation pond. The residue would then be refined. This information was acquired in a phone conversation with BLM personnel on 3/13/02.

DATA-A-5.5.2 Sulfur Solution Mining

Solution mining for sulfur has occurred in the Delaware Basin. Currently, there are no active sulfur solution mining projects within the Delaware Basin. Past activity was at the sulfur mine located west of Orla, Texas, in Culberson County. This facility utilized a number of Class III injection wells to remove sulfur from underground mineral deposits. This mine was closed in June 1999.

DATA-A-5.5.3 Brine Wells

Brine wells are classified as Class II injection wells. In the Delaware Basin, the process involves injecting fresh water through the wells into a salt formation to create a saturated brine solution, which is then extracted and utilized as a drilling agent when drilling a new well. These wells are tracked by the DBDSP on a continuing basis. Supplemental information provided to the EPA in 1997 showed 11 brine wells in the Delaware Basin. Further research showed there to be 15 brine wells. Four of these are plugged and abandoned with 11 being active (see Table DATA-A-10). One new well has been permitted in the Delaware Basin since submittal of the initial certification application (Quito West Unit #207). One well has yet to be verified and is not listed in the table below. Records indicate it has been permitted, but there are no records to indicate whether it was drilled. If records are found to verify when the well was drilled, it will be added to the databases maintained by the DBDSP and classified as a brine well.

Table DATA-A-10. Delaware Basin Brine Well Status

County	Location	API No.	Well Name and No.	Operator	Status
Eddy	22S-26E-36	3001521842	City of Carlsbad #WS-1	Key Energy Services	Brine Well
Eddy	22S-27E-03	3001520331	Tracy #3	Ray Westall	Plugged Brine Well
Eddy	22S-27E-17	3001522574	Eugenie #WS-1	I & W Inc	Brine Well
Eddy	22S-27E-17	3001523031	Eugenie #WS-2	I & W Inc	Plugged Brine Well
Loving	Blk 29-03	4230110142	Lineberry Brine Station #1	Chance Properties	Brine Well
Loving	Blk 01-82	4230130680	Chapman Ford #BR1	Herricks & Son Co.	Plugged Brine Well
Loving	Blk 33-80	4230180318	Mentone Brine Station #1D	Basic Energy Services	Brine Well
Loving	Blk 29-28	4230180319	East Mentone Brine Station #1	Permian Brine Sales, Inc.	Plugged Brine Well
Loving	Blk 01-83	4230180320	North Mentone #1	Chance Properties	Brine Well
Reeves	Blk 56-30	4238900408	Orla Brine Station #1D	Mesquite SWD Inc.	Brine Well
Reeves	Blk 04-08	4238920100	North Pecos Brine Station #WD-1	Chance Properties	Brine Well
Reeves	Blk 07-21	4238980476	Coyanosa Brine Station #1	Chance Properties	Brine Well
Ward	Blk 17-20	4247531742	Pyote Brine Station #WD-1	Chance Properties	Brine Well
Ward	Blk 01-13	4247534514	Quito West Unit #207	Seaboard Oil Co.	Brine Well
Ward	Blk 34-174	4247582265	Barstow Brine Station #1	Chance Properties	Brine Well

DATA-A-5.5.4 Naturally Occurring Radioactive Materials Facilities

NORM facilities are considered because they may be created in salt formations by solution mining to dispose of NORM wastes. According to conversations with the NORM Director for the Texas Railroad Commission, there are four permitted NORM sites in the state of Texas. Three are located in the Permian Basin but well outside of the Delaware Basin. The Andrews facility, approximately 96.56 km (60 mi) east of the WIPP Site, is operated by Lotus LLC and will eventually have a capacity of 570,000 barrels. Another facility is located near Fort Stockton by NES Permian and will have a capacity of 1,000,000 barrels. The third facility is also operated by NES Permian near Big Spring and is considerably smaller. All of these facilities are located in salt formations and were solution mined to facilitate the reinjection of NORM wastes by the oil companies. This information is tracked by the DBDSP. There is no requirement to track NORM facilities outside of the Delaware Basin, but the DBDSP does so for possible future impacts to activities within the Delaware Basin.

DATA-A-5.6 Potash Mining Data

Potash mining data include a map of current potash leases (Figure DATA-A-2) and changes in existing leases within the nine-township area (see Table DATA-A-11). A full-sized copy of Figure DATA-A-2 can be found in a pocket at the end of this volume.

DATA-A-5.7 Seismic Data

Seismic data include a history of relevant events, e.g., earthquake (natural or human induced) activity, relation of epicenters with geologic structures, geologic setting, etc. This information is provided in Figure DATA-A-3 and Table DATA-A-12. A full-sized copy of Figure DATA-A-3 can be found in a pocket at the end of this volume.

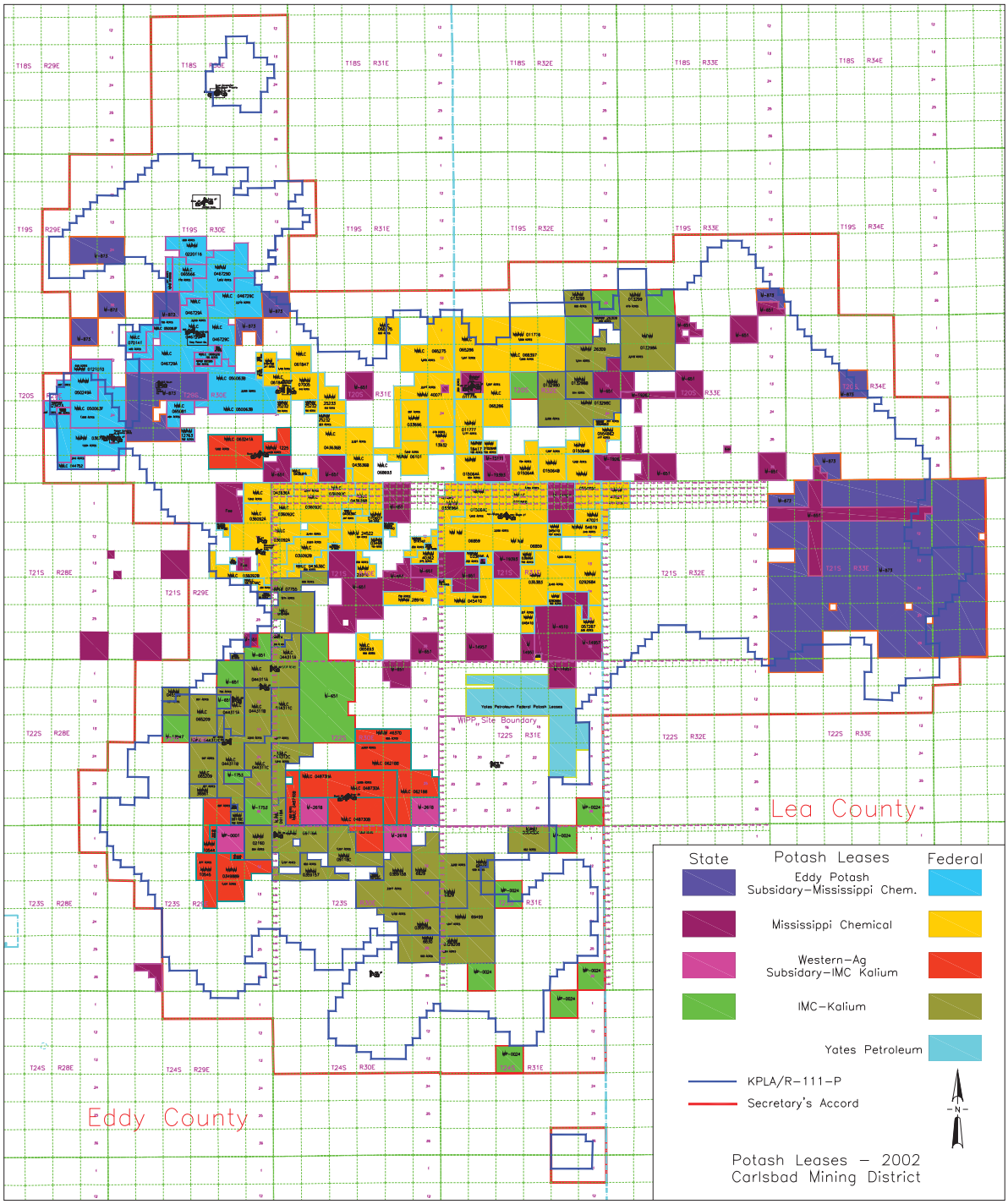

Figure DATA-A-2. Current Potash Leases

Table DATA-A-11. Potash Leases in the Vicinity of the WIPP Site

Company	1995	2002	Federal Leases	Acreage	Lease Eff. Date	State Leases	Acreage	Lease Eff. Date
Horizon Corp	Yes	No	Cancelled			Cancelled		
Eddy Potash (Subsidiary of Mississippi Chemical)	Yes	Yes	NMLC-044752 NMLC-046729A NMLC-046729C NMLC-046729D NMLC-050063B NMLC-050063F NMLC-065081-01 NMLC-065566-01 NMLC-066026-01 NMLC-070141-01 NMNM-023623-01 NMNM-036791 NMNM-050249A NMNM-088285 NMNM-0121810-01 NMNM-0135065 NMNM-0220116 NMNM-13933 NMNM-12763	240.00 2,558.76 2,279.95 1,840.00 2,560.00 2,358.36 480.00 720.00 200.00 438.91 400.00 1,840.00 880.00 120.00 640.00 200.00 800.00 80.00 160.00	09/01/1956 01/18/1933 01/18/1933 01/18/1933 040/1/1939 04/01/1939 12/06/1950 09/28/1951 09/01/1955 01/01/1959 02/01/1962 10/01/1957 09/01/1963 080/1/1960 01/01/1965 06/01/1961 12/01/1961 10/01/1971 06/01/1971	M-873	37,850.28	Unknown
Western-Ag Minerals (Subsidiary of IMC Kalium)	Yes	Yes	NMLC-048730A NMLC-048730B NMLC-062188 NMLC-063241A NMNM-0349889-01 NMNM-1225 NMNM-10544 NMNM-10545 NMNM-46370 NMNM-84935 NMNM-86720	2,560.00 2,556.40 2,520.00 1,600.00 1,400.00 480.00 240.09 800.00 640.00 160.03 640.00	08/21/1952 08/21/1952 12/01/1959 11/30/1949 11/01/1967 06/20/1932 11/01/1969 11/01/1969 02/01/1982 04/01/1991 03/01/1993	MP-001 M-2618	642.97 1,951.18	Unknown Unknown
Harroun	Yes	No	Cancelled			None		
National Potash Company	Yes	No	Owned by Mississippi			None		
New Mexico Potash	Yes	No	Owned by Mississippi			Mississippi		
IMC Global/Noranda	Yes	No	Owned by IMC Kalium			IMC Kalium		

Table DATA-A-11. Potash Leases in the Vicinity of the WIPP Site — Continued

Company	1995	2002	Federal Leases	Acreage	Lease Eff. Date	State Leases	Acreage	Lease Eff. Date
Yates Petroleum/Pogo Producing Co	Yes	Yes		5,184.72	1992	None		
IMC Kalium	Yes	Yes	NMLC-044311A	2,550.33	10/26/1938	M-13947	637.05	Unknown
			NMLC-044311B	2,560.00	10/26/1938	M-1753	921.33	Unknown
			NMLC-044311C	2,563.28	10/26/1938	M-651	5,734.52	Unknown
			NMLC-044312A	302.37	11/15/1946	MP-0024	4,472.90	Unknown
			NMLC-044312B	40.00	11/15/1946	Unknown	2,517.63	Unknown
			NMLC-044312C	1,400.29	11/15/1946			
			NMLC-065209	1,920.00	11/01/1949			
			NMLC-065484-01	1,331.76	01/5/1953			
			NMNM-02160-01	798.78	11/01/1956			
			NMNM-07755-01	665.65	060/1/1957			
			NMNM-09118A	1,766.71	07/02/1951			
			NMNM-09118C	1,400.60	07/02/1951			
			NMNM-045326-01	640.00	05/01/1958			
			NMNM-0329208-01	1,287.00	03/01/1967			
			NMNM-0359157-01	960.20	11/01/1967			
			NMNM-0359158-01	2,520.00	11/01/1967			
			NMNM-0359159-01	1,160.00	02/01/1968			
			NMNM-0384584-01	957.69	11/01/1967			
			NMNM-6829	2,211.12	11/01/1967			
			NMNM-6830	960.00	11/01/1967			
			NMNM-36861	320.00	01/01/1981			
			NMNM-69499	1,926.40	03/01/1967			
			NMNM-68500	640.00	03/01/1967			
			NMNM-013298A	2,564.33	02/24/1953			
			NMNM-013298B	640.00	02/24/1953			
			NMNM-013298C	2,360.00	02/24/1953			
			NMNM-013299	1,277.80	02/24/1953			
			NMNM-26309	1,438.80	02/24/1953			

Table DATA-A-11. Potash Leases in the Vicinity of the WIPP Site — Continued

Company	1995	2002	Federal Leases	Acreage	Lease Eff. Date	State Leases	Acreage	Lease Eff. Date
Mississippi Potash	Yes	Yes	NMLC-036092A	2,436.85	11/21/1929	M-651	19,973.52	Unknown
			NMLC-036092B	2,025.59	11/21/1929	M-19262	1,512.52	Unknown
			NMLC-036092C	2,559.15	11/21/1929	M-14957	2,632.51	Unknown
			NMLC-043636A	1,044.03	06/20/1932	M-15171	121.13	Unknown
			NMLC-043636B	2,311.66	06/20/1932	M-19393	1,084.16	Unknown
			NMLC-043636C	920.00	06/20/1932	M-4510	2,270.97	Unknown
			NMLC-061847-01	1,115.24	07/01/1951			
			NMLC-065693-01	560.00	02/01/1958			
			NMLC-065275-01	2,550.56	01/09/1952			
			NMLC-068397	1,920.00	01/09/1952			
			NMLC-065286-01	2,553.87	01/09/1952			
			NMLC-071868-01	1,938.24	09/01/1955			
			NMNM-06101-01	1,040.00	02/01/1958			
			NMNM-03468	160.00	07/01/1958			
			NMNM-07005	636.28	01/02/1952			
			NMNM-016540-01	120.00	04/04/1960			
			NMNM-033696	960.00	03/01/1958			
			NMNM-063880	120.00	07/01/1959			
			NMNM-070607	551.70	02/01/1960			
			NMNM-0184149	80.00	01/01/1955			
			NMNM-0184150	240.00	11/30/1949			
			NMNM-13932	640.00	11/01/1974			
			NMNM-24522	800.00	03/01/1982			
			NMNM-25232	640.00	07/06/1951			
			NMNM-25233	640.00	01/02/1952			
			NMNM-25234	80.00	11/30/1949			
			NMNM-28916	880.00	08/01/1963			
			NMNM-011776	2,559.06	01/09/1952			
			NMNM-011777	1,117.64	01/09/1952			
			NMNM-40071	2,080.00	05/01/1980			
			NMNM-06859-01	2,554.24	10/26/1953			
			NMNM-014742-01	640.00	08/01/1963			
			NMNM-033696A	1,240.62	03/01/1958			
			NMNM-035383	2,400.00	01/01/1958			
			NMNM-045410	2,438.30	06/01/1958			
			NMNM-057287-01	560.00	01/01/1964			

Table DATA-A-11. Potash Leases in the Vicinity of the WIPP Site — Concluded

Company	1995	2002	Federal Leases	Acreage	Lease Eff. Date	State Leases	Acreage	Lease Eff. Date
Mississippi Potash (continued)	Yes	Yes	NMNM-015064A	1,599.76	10/26/1953			
			NMNM-015064B	1,280.00	10/26/1953			
			NMNM-015064C	1,049.40	10/25/1953			
			NMNM-0292684-01	1,720.00	12/01/1966			
			NMNM-0554862	480.00	02/24/1953			
			NMNM-0554863	200.00	02/24/1953			
			NMNM-0554864	1,250.04	02/24/1953			
			NMNM-18417	160.00	01/09/1952			
			NMNM-28915	117.94	06/01/1958			
			NMNM-40362	280.00	12/01/1980			
			NMNM-41639	120.00	07/01/1981			
			NMNM-47021	1,104.26	07/01/1982			
			NMNM-54619	565.88	03/01/1983			
			NMNM-80707	2,520.00	08/01/1963			

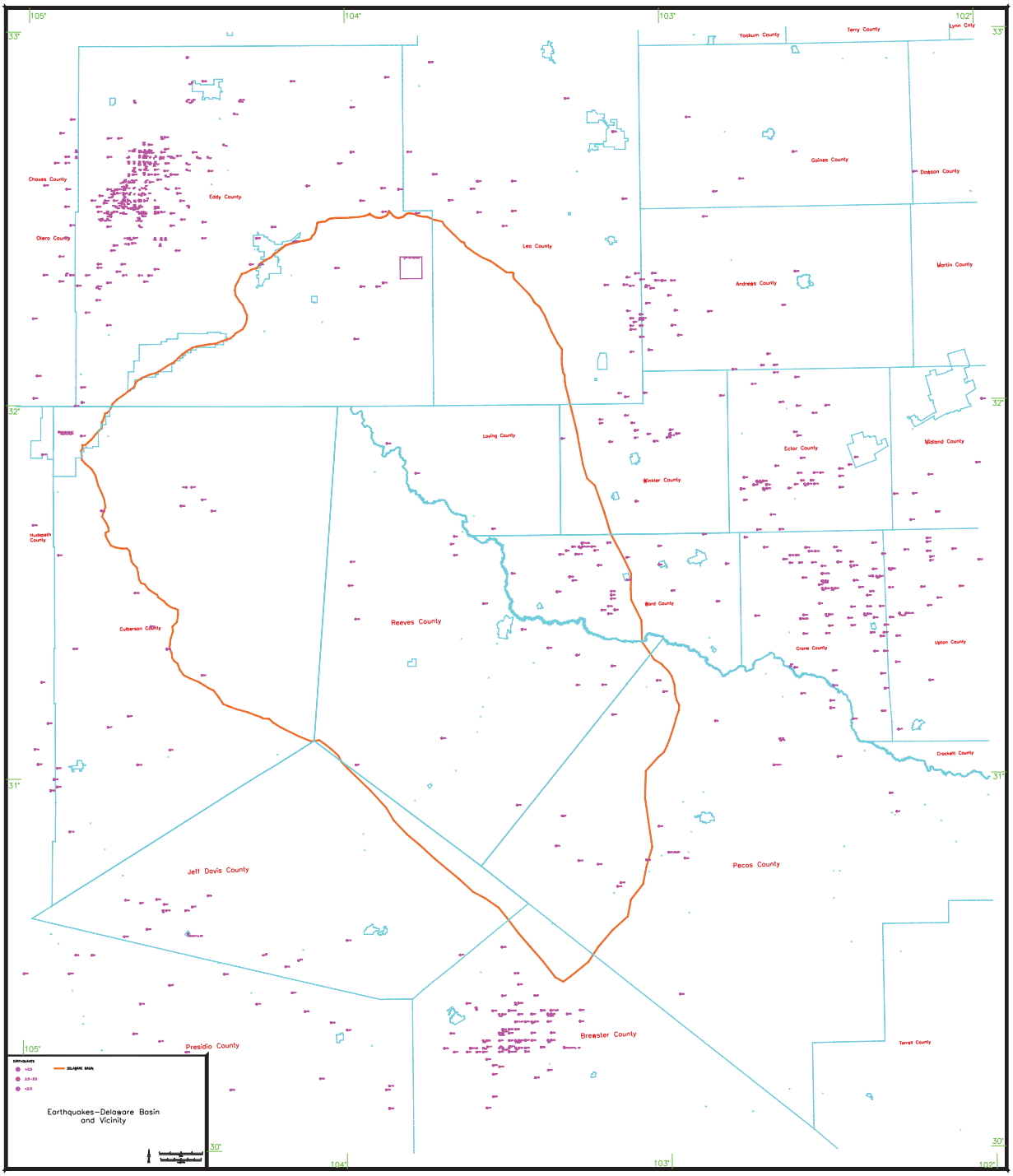

Figure DATA-A-3. Seismic Activity in the Delaware Basin

Table DATA-A-12. Earthquake Events in the Delaware Basin

County	No. of Events	Earliest Event	Latest Event	Smallest Magnitude	Largest Magnitude
Culberson	6	12/30/1997	08/04/2002	1	1.9
Eddy	5	04/24/1983	12/03/1998	1.1	3.5
Loving	3	02/04/1976	04/28/1997	1.1	1.3
Pecos	10	04/03/1977	12/22/1998	1	2.2
Reeves	16	08/03/1975	05/25/2002	1	2.5
Ward	26	09/24/1971	08/18/1984	0.8	3
Winkler	1	04/30/1976	04/30/1976	1.5	1.5
Totals	67	09/24/1971	08/04/2002	0.8	3.5

Key:

Magnitude	
Less than 2	Very seldom ever felt
2.0 to 3.4	Barely felt
3.5 to 4.2	Felt as a rumble
4.3 to 4.9	Shakes furniture; can break dishes
5.0 to 5.9	Dislodges heavy objects; cracks walls
6.0 to 6.9	Considerable damage to buildings
7.0 to 7.3	Major damage to buildings; breaks underground pipe
7.4 to 7.9	Great damage; destroys masonry and frame buildings
Above 8.0	Complete destruction; ground moves in waves

Note: Three of the five earthquake events in Eddy County can be directly attributed to mining activities. The other two remain unexplained. Most of the seismic events recorded in the vicinity of the Delaware Basin can be attributed to oil and gas activities—such as the number of events that continue to occur in the Dagger Draw or Cass Ranch area of Central Eddy County—where a large number of oil and gas activities are being conducted.

The table includes only reported data.

APPENDIX DATA

ATTACHMENT B: HISTORICAL WATER LEVEL DATA

Historical Water Level Data

Groundwater monitoring activities during the 2004 Compliance Recertification Application monitoring period (mid 1995 through September 30, 2002) included groundwater level measurements to support performance assessment. An array of 75 wells are used to acquire data on water levels in seven different water-bearing zones. The two zones of primary interest are the Culebra and Magenta members of the Rustler Formation.

The Groundwater Monitoring Program (GWMP) measures water levels on a monthly basis in at least one accessible well bore at each well site for each available formation. Redundant well bores at each well site are measured on a quarterly basis. Some of the wells were completed at multiple depths and by using packers, these well bores may be monitored in more than one formation.

Water levels are reported in elevation (feet above mean sea level). This is accomplished by measuring from the top of the well casing (a surveyed elevation point) to the top of the water level and subtracting the measured number from the known elevation. Due to the high concentration of total dissolved solids (TDS) in WIPP groundwater, density must be taken into account to accurately determine relative water levels between wells. Measured water levels are adjusted to equivalent fresh-water head values, considering fluid density differences between measuring points.

An activity that affects the ability to take water level measurements is well maintenance. Maintenance is performed to prepare wells for future experiments, repair nonfunctioning wells, recomplete wells to monitor additional zones of interest, and plugging and abandonment of wells that are no longer useful. Well maintenance is an ongoing process and as the following tables and charts show, not all wells have reported water levels at regular intervals. Wells with missing data may have been taken out of service for any of the above reasons.

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Table 1 - Well No. AEC-7 Culebra

January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3036.43	3059.22
02/14/95	3036.45	3059.24
03/13/95	3036.35	3059.13
04/12/95	3036.09	3058.85
05/08/95	3036.54	3059.34
06/05/95	3036.54	3059.34
07/19/95	3036.44	3059.23
08/16/95	3036.60	3059.41
09/08/95	3036.36	3059.14
10/18/95	3036.45	3059.24
11/08/95	3036.35	3059.13
12/06/95	3036.40	3059.19
01/10/96	3036.43	3059.22
02/07/96	3036.43	3059.22
03/13/96	3036.53	3059.33
04/17/96	3036.52	3059.32
05/15/96	3036.48	3059.27
06/12/96	3036.72	3059.54
07/17/96	3036.69	3059.50
08/14/96	3036.91	3059.74
09/05/96	3038.25	3061.20
10/16/96	3037.43	3060.31
11/13/96	3036.95	3059.79
12/11/96	3037.08	3059.93
01/14/97	3036.98	3059.82
02/12/97	3036.87	3059.70
03/12/97	3036.83	3059.66
04/16/97	3036.91	3059.74
05/14/97	3037.16	3060.02
06/12/97	3037.04	3059.88
07/16/97	3037.15	3060.00
08/13/97	3036.95	3059.79
09/17/97	3037.51	3060.40
10/16/97	3037.68	3060.58
11/12/97	3038.42	3061.39
12/10/97	3037.62	3060.52

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3037.81	3060.72
02/11/98	3037.83	3060.75
03/11/98	3038.40	3061.37
04/15/98	3039.19	3062.23
05/13/98	3039.34	3062.39
06/11/98	3039.29	3062.34
07/15/98	3039.22	3062.26
08/12/98	3039.01	3062.03
09/10/98	3038.99	3062.01
10/14/98	3039.10	3062.13
11/11/98	3038.69	3061.68
12/07/98	3038.91	3061.92
01/13/99	3038.71	3061.71
02/08/99	3038.74	3061.74
03/10/99	3038.79	3061.79
04/14/99	3038.74	3061.74
05/12/99	3038.60	3061.59
06/10/99	3038.67	3061.66
07/21/99	3038.46	3061.43
08/11/99	3038.66	3061.65
09/09/99	3038.55	3061.53
10/06/99	3038.50	3061.48
11/10/99	3038.58	3061.56
12/08/99	3038.70	3061.69
01/19/00	3038.44	3061.41
02/16/00	3038.44	3061.41
03/08/00	3038.62	3061.61
04/19/00	3038.63	3061.62
05/15/00	3038.52	3061.50
06/05/00	3038.47	3061.44
07/11/00	3038.62	3061.61
08/16/00	3038.37	3061.33
09/13/00	3038.35	3061.31
10/11/00	3038.30	3061.26
11/06/00	3038.61	3061.60
12/07/00	3038.22	3061.17

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3038.29	3061.25
02/06/01	3038.22	3061.17
03/06/01	3038.33	3061.29
04/04/01	3038.48	3061.45
05/08/01	3038.22	3061.17
06/07/01	3038.36	3061.32
07/10/01	3038.26	3061.21
08/08/01	3038.12	3061.06
09/07/01	3038.50	3061.48
10/08/01	3038.23	3061.18
11/13/01	3038.29	3061.25
12/04/01	3038.29	3061.25
01/15/02	3038.09	3061.03
02/06/02	3038.11	3061.05
03/12/02	3038.17	3061.12
04/09/02	3038.10	3061.04
05/08/02	3038.30	3061.26
06/12/02	3038.24	3061.19
07/15/02	3038.09	3061.03
08/13/02	3038.33	3061.29
09/09/02	3038.21	3061.16

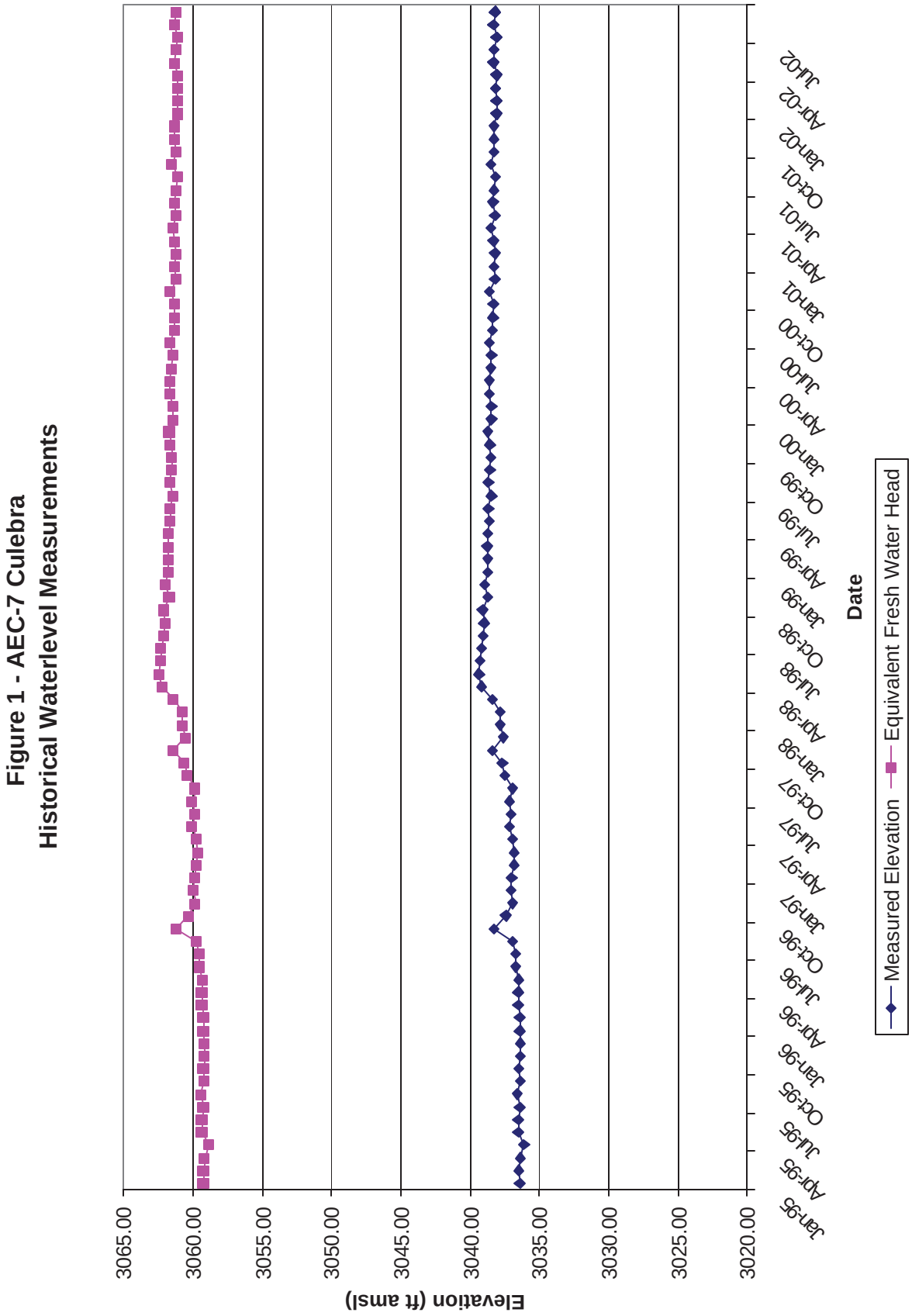
Figure 1 - AEC-7 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3065.00
3060.00
3055.00
3050.00
3045.00
3040.00
3035.00
3030.00
3025.00
3020.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 2 - Well No. AEC-8 Bell Canyon
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	2959.19	N/A
02/14/95	2959.51	N/A
03/13/95	2959.86	N/A
04/12/95	2959.99	N/A
05/08/95	2960.75	N/A
06/05/95	2961.31	N/A
07/19/95	2961.99	N/A
08/16/95	2962.49	N/A
09/08/95	2962.67	N/A
10/18/95	2963.59	N/A
11/08/95	2963.78	N/A
12/06/95	2964.37	N/A
01/10/96	2964.62	N/A
02/07/96	2965.62	N/A
03/13/96	2965.69	N/A
04/17/96	2966.32	N/A
05/15/96	2966.87	N/A
06/12/96	2967.67	N/A
07/17/96	2968.42	N/A
08/14/96	2968.99	N/A
09/05/96	2969.59	N/A
10/16/96	2970.54	N/A
11/13/96	2971.15	N/A
12/11/96	2971.82	N/A
01/14/97	2972.68	N/A
02/12/97	2973.30	N/A
03/13/97	2974.13	N/A
04/16/97	2975.24	N/A
05/14/97	2976.10	N/A
06/12/97	2976.96	N/A
07/16/97	2977.96	N/A
08/13/97	2978.80	N/A
09/17/97	2979.86	N/A
10/16/97	2980.90	N/A
11/12/97	2981.69	N/A
12/10/97	2982.53	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2983.80	N/A
02/11/98	2984.90	N/A
03/11/98	2985.89	N/A
04/15/98	2987.16	N/A
05/13/98	2988.15	N/A
06/11/98	2989.19	N/A
07/15/98	2990.44	N/A
08/12/98	2991.48	N/A
09/10/98	2992.56	N/A
10/14/98	2993.83	N/A
11/09/98	2994.82	N/A
12/07/98	2996.36	N/A
01/13/99	2997.40	N/A
02/08/99	2998.49	N/A
03/08/99	2999.52	N/A
04/14/99	3000.99	N/A
05/10/99	3002.04	N/A
06/04/99	3001.69	N/A
07/21/99	3004.83	N/A
08/11/99	3005.52	N/A
09/09/99	3006.67	N/A
10/06/99	3007.79	N/A
11/10/99	3009.20	N/A
12/08/99	3010.37	N/A
01/19/00	3012.08	N/A
02/16/00	3013.35	N/A
03/08/00	3014.26	N/A
04/19/00	3016.07	N/A
05/15/00	3017.21	N/A
06/05/00	3018.12	N/A
07/11/00	3019.73	N/A
08/16/00	3021.24	N/A
09/13/00	3022.43	N/A
10/11/00	3023.79	N/A
11/06/00	3024.75	N/A
12/07/00	3026.09	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3026.52	N/A
02/06/01	3028.72	N/A
03/06/01	3030.18	N/A
04/04/01	3031.04	N/A
05/08/01	3032.97	N/A
06/07/01	3034.57	N/A
07/10/01	3036.28	N/A
08/08/01	3037.79	N/A
09/07/01	3039.41	N/A
10/08/01	3040.95	N/A
11/12/01	3042.66	N/A
12/03/01	3043.70	N/A
01/15/02	3045.58	N/A
02/06/02	3046.71	N/A
03/12/02	3048.16	N/A
04/09/02	3049.45	N/A
05/08/02	3050.74	N/A
06/13/02	3052.26	N/A
07/15/02	3054.57	N/A
08/13/02	3056.90	N/A
09/10/02	3058.88	N/A

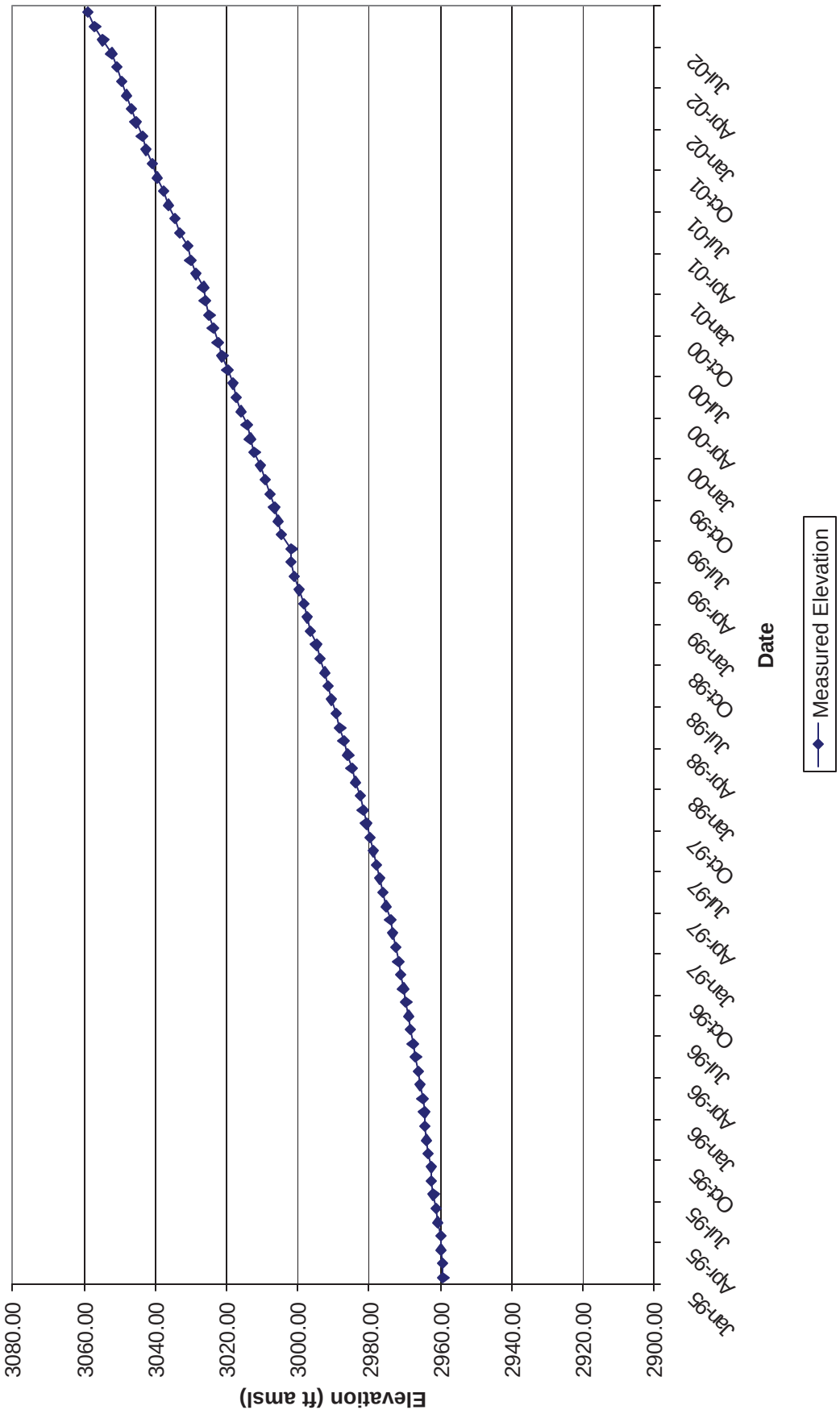
Figure 2 - AEC-8 Bell Canyon
Historical Waterlevel Measurments
Elevation (ft amsl)
3080.00
3060.00
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation

Table 3 - Well No. C-2737 (PIP) Culebra
April 2001 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
04/05/01	3013.98	N/A
05/08/01	3024.01	N/A
06/06/01	3014.11	N/A
07/09/01	3014.23	N/A
08/07/01	3014.30	N/A
09/06/01	3014.63	N/A
10/10/01	3014.62	N/A
11/14/01	3014.50	N/A
12/05/01	3014.27	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/02	3014.44	N/A
02/05/02	3014.55	N/A
03/12/02	3016.05	N/A
04/08/02	3016.32	N/A
05/07/02	3016.37	N/A
06/10/02	3016.72	N/A
07/15/02	3016.70	N/A
08/13/02	3017.01	N/A
09/12/02	3017.04	N/A

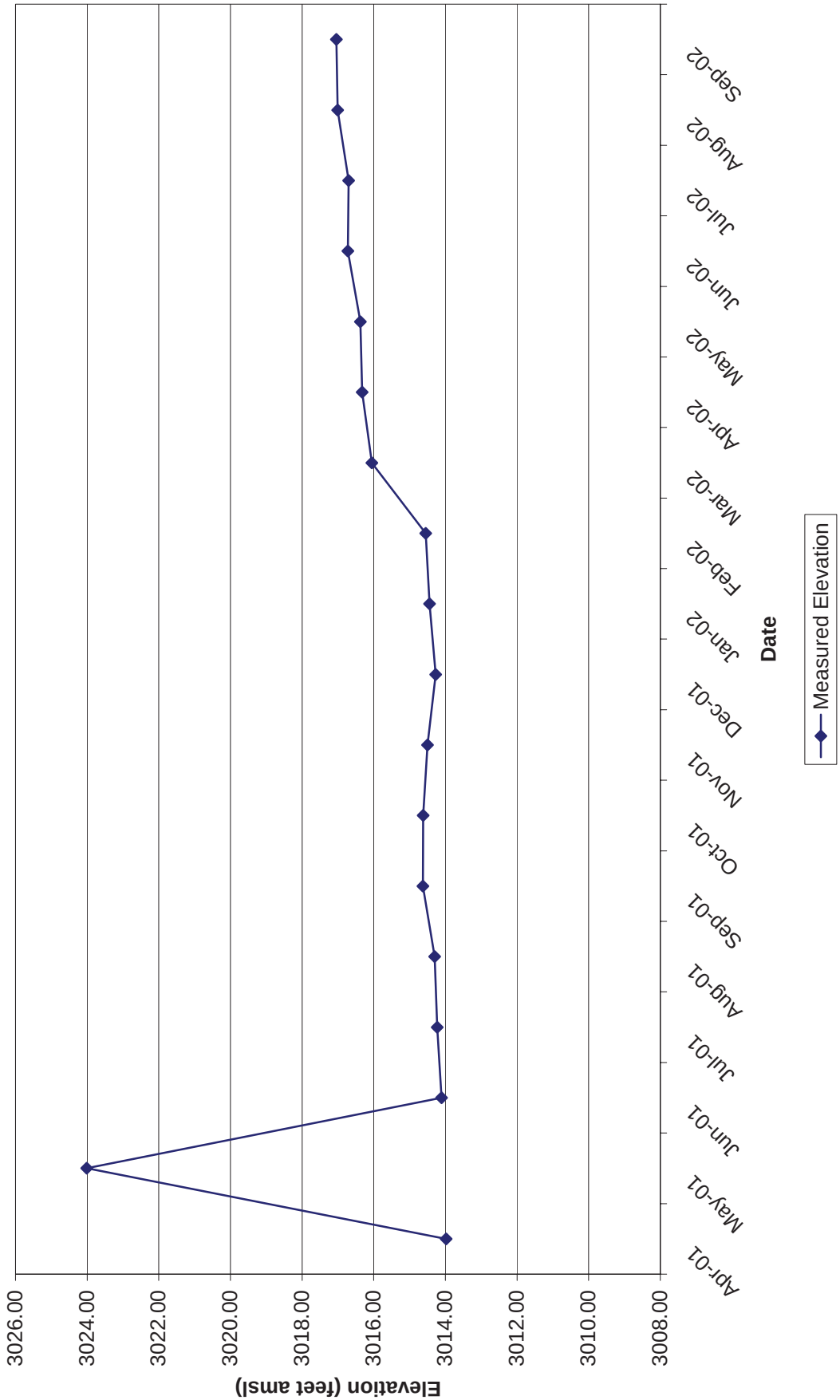
Figure 3 - C-2737 Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3026.00
3024.00
3022.00
3020.00
3018.00
3016.00
3014.00
3012.00
3010.00
3008.00
Apr-01
May-01
Jun-01
Jul-01
Aug-01
Sep-01
Oct-01
Nov-01
Dec-01
Jan-02
Feb-02
Mar-02
Apr-02
May-02
Jun-02
Jul-02
Aug-02
Sep-02
Date
Measured Elevation

Table 4 - Well No. C-2737 (ANNULUS) Magenta
April 2001 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
04/05/01	3141.47	N/A
05/08/01	3145.34	N/A
06/06/01	3145.86	N/A
07/09/01	3145.72	N/A
08/07/01	3145.53	N/A
09/06/01	3145.51	N/A
10/10/01	3145.30	N/A
11/14/01	3144.40	N/A
12/05/01	3144.96	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/02	3144.81	N/A
02/05/02	3144.67	N/A
03/12/02	3144.04	N/A
04/08/02	3143.83	N/A
05/07/02	3143.24	N/A
06/10/02	3142.97	N/A
07/16/02	3142.43	N/A
08/13/02	3142.35	N/A
09/12/02	3142.07	N/A

Figure 4 - C-2737 Magenta
Historical Water level Measurements

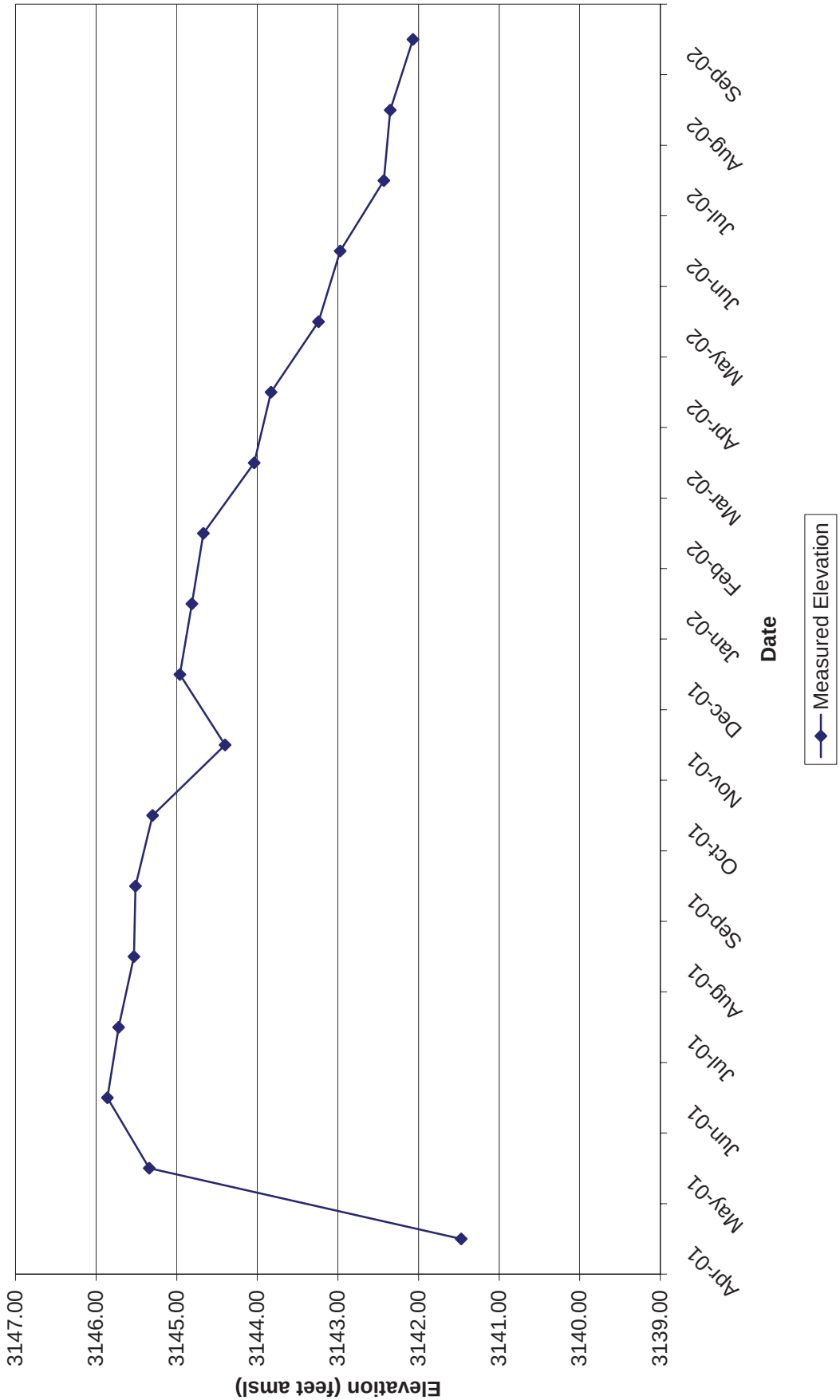

Table 5 - Well No. Cabin Baby-1 Culebra
April 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
04/15/97	2964.46	2967.78
05/14/97	2964.38	2967.70
06/11/97	2964.22	2967.54
07/15/97	2964.11	2967.42
08/12/97	2964.08	2967.39
09/16/97	2964.28	2967.60
10/15/97	2964.38	2967.70
11/11/97	2964.69	2968.02
12/09/97	2964.90	2968.24
01/13/98	2965.31	2968.66
02/10/98	2965.65	2969.01
03/10/98	2965.73	2969.09
04/14/98	2966.21	2969.59
05/12/98	2966.35	2969.73
06/10/98	2966.38	2969.76
07/14/98	2966.41	2969.79
08/11/98	2966.49	2969.88
09/09/98	2966.69	2970.08
10/13/98	2966.83	2970.23
11/10/98	2967.09	2970.4
12/08/98	2967.25	2970.66

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/99	2967.55	2970.97
02/09/99	2967.83	2971.26
03/09/99	2968.11	2971.55
04/13/99	2968.43	2971.88
05/11/99	2968.75	2972.21
06/08/99	2968.93	2972.39
07/20/99	2969.15	2972.62
08/10/99	2969.44	2972.92
09/08/99	3234.71	3246.41
10/05/99	3239.43	3251.28
11/09/99	3241.22	3253.12
12/08/99	3242.45	3254.39
01/08/00	3244.39	3256.39
02/15/00	3237.18	3248.96
03/07/00	3225.76	3237.18
04/18/00	3228.59	3240.10
05/16/00	3233.90	3245.58
06/06/00	3239.19	3251.03
07/11/00	3248.52	3260.65
08/15/00	3250.00	3262.17
09/11/00	3229.12	3240.65
10/11/00	3230.78	3242.36
11/09/00	3244.04	3256.03
12/05/00	3245.85	3257.90

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3244.31	3256.31
02/05/01	3245.41	3257.44
03/07/01	3247.19	3259.28
04/05/01	3251.09	3263.30
05/09/01	3255.92	3268.28
06/06/01	3253.44	3265.72
07/11/01	3252.86	3265.12
08/07/01	3256.52	3268.90
09/05/01	3260.96	3273.47
10/09/01	3266.23	3278.91
11/12/01	3271.28	3284.11
12/03/01	3274.28	3287.21
01/15/02	3280.35	3293.47
02/05/02	3283.14	3296.34
03/13/03	3288.01	3301.36
04/10/02	3291.66	3305.13
06/11/02	2864.73	2864.96
07/16/02	2888.16	2889.12
08/14/02	2905.50	2907.00
09/12/02	2921.53	2923.52

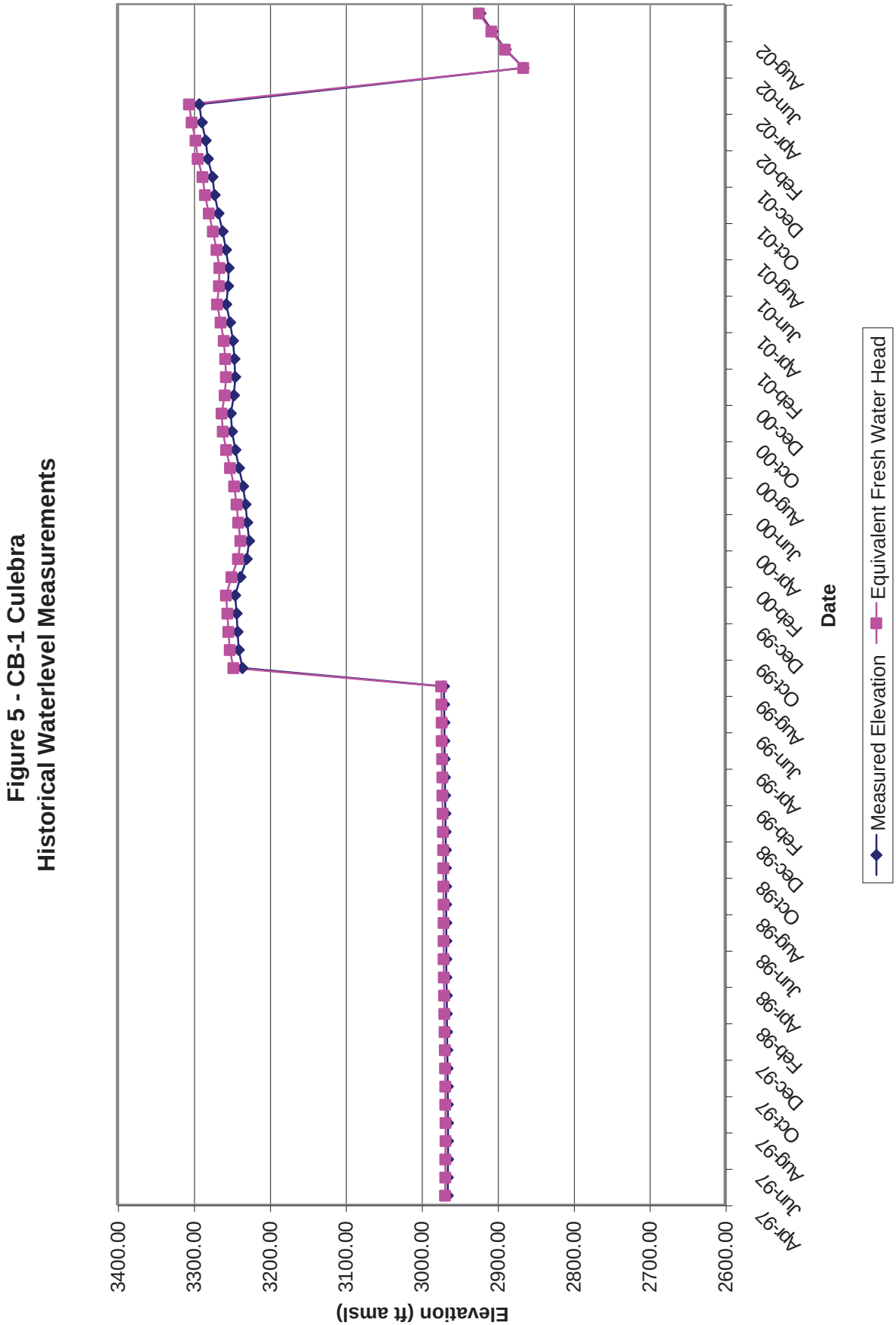
Figure 5 - CB-1 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3400.00
3300.00
3200.00
3100.00
3000.00
2900.00
2800.00
2700.00
2600.00
Date
Apr-97
Jun-97
Aug-97
Oct-97
Dec-97
Feb-98
Apr-98
Jun-98
Aug-98
Oct-98
Dec-98
Feb-99
Apr-99
Jun-99
Aug-99
Oct-99
Dec-99
Feb-00
Apr-00
Jun-00
Aug-00
Oct-00
Dec-00
Feb-01
Apr-01
Jun-01
Aug-01
Oct-01
Dec-01
Feb-02
Apr-02
Jun-02
Aug-02
Measured Elevation
Equivalent Fresh Water Head

Table 6 - Well No. Cabin Baby-1 (PIP) B ell Canyon
September 1999 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
09/08/99	2999.35	N/A
10/05/99	3010.43	N/A
11/09/99	3013.43	N/A
12/08/99	3014.30	N/A
01/18/00	3014.50	N/A
02/15/00	3014.73	N/A
03/07/00	3014.81	N/A
04/18/00	3014.84	N/A
05/16/00	3014.88	N/A
06/06/00	3014.73	N/A
07/11/00	3014.82	N/A
08/15/00	3014.71	N/A
09/11/00	3014.80	N/A
10/11/00	3014.65	N/A
11/09/00	3014.84	N/A
12/05/00	3014.65	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3014.78	N/A
02/05/01	3014.68	N/A
03/07/01	3014.72	N/A
04/05/01	3014.85	N/A
05/09/01	3014.71	N/A
06/06/01	3014.77	N/A
07/11/01	3015.14	N/A
08/07/01	3014.64	N/A
09/05/01	3014.66	N/A
10/09/01	3014.74	N/A
11/12/01	3014.56	N/A
12/03/01	3014.66	N/A
01/15/02	3014.65	N/A
02/05/02	3014.65	N/A
03/13/02	3014.80	N/A
04/10/02	3014.62	N/A
06/11/02	3014.74	N/A
07/16/02	3014.55	N/A
08/14/02	3014.60	N/A
09/12/02	3014.55	N/A

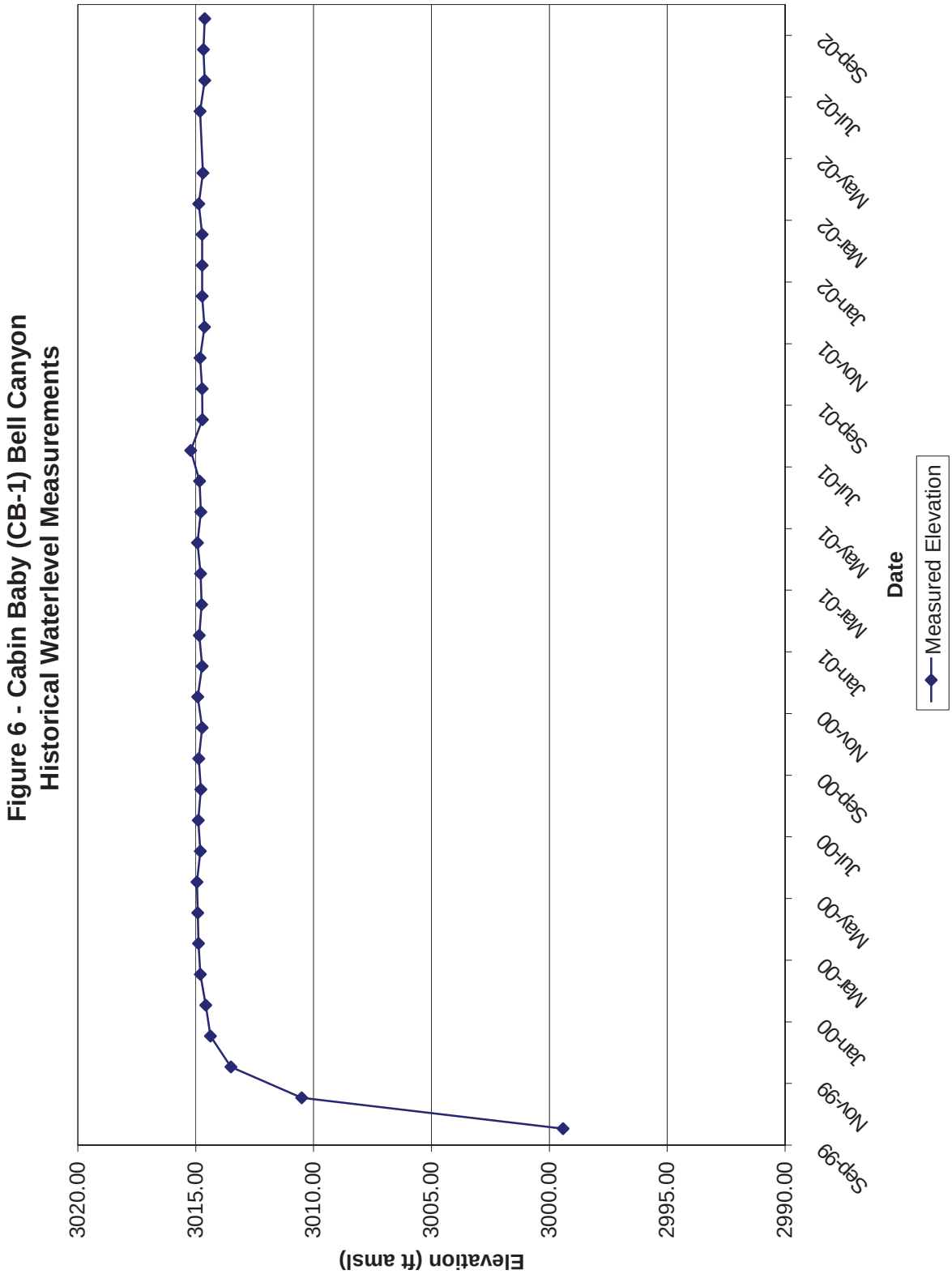
Figure 6 - Cabin Baby (CB-1) Bell Canyon
Historical Waterlevel Measurements
Elevation (ft amsl)
3020.00
3015.00
3010.00
3005.00
3000.00
2995.00
2990.00
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Date
Measured Elevation

Table 7 - Well No. D-268 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3005.89	N/A
02/14/95	3005.35	N/A
03/15/95	3004.94	N/A
04/12/95	3004.85	N/A
05/10/95	3004.90	N/A
06/07/95	3005.14	N/A
07/18/95	3005.35	N/A
08/17/95	3005.42	N/A
09/07/95	3005.25	N/A
10/19/95	3005.37	N/A
11/08/95	3005.28	N/A
12/06/95	3005.38	N/A
01/10/96	3005.41	N/A
02/07/96	3005.44	N/A
03/14/96	3005.47	N/A
04/17/96	3005.44	N/A
05/14/96	3005.40	N/A
06/13/96	3005.35	N/A
07/16/96	3005.36	N/A
08/14/96	3005.31	N/A
09/05/96	3005.61	N/A
10/15/96	3005.81	N/A
11/12/96	3005.46	N/A
12/11/96	3005.70	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/15/97	3005.62	N/A
02/12/97	3005.73	N/A
03/12/97	3005.99	N/A
04/16/97	3005.95	N/A
05/15/97	3006.24	N/A
06/11/97	3006.43	N/A
07/16/97	3006.07	N/A
08/12/97	3006.22	N/A
09/16/97	3006.31	N/A
10/15/97	3006.01	N/A
11/12/97	3006.31	N/A
12/10/97	3006.12	N/A
01/14/98	3006.13	N/A
02/11/98	3006.19	N/A
03/11/98	3005.88	N/A
04/15/98	3006.33	N/A
05/12/98	3006.18	N/A
06/11/98	3005.96	N/A
07/15/98	3005.76	N/A
08/10/98	3005.74	N/A
09/11/98	3005.76	N/A
10/13/98	3005.74	N/A
11/11/98	3005.72	N/A
12/08/98	3005.63	N/A

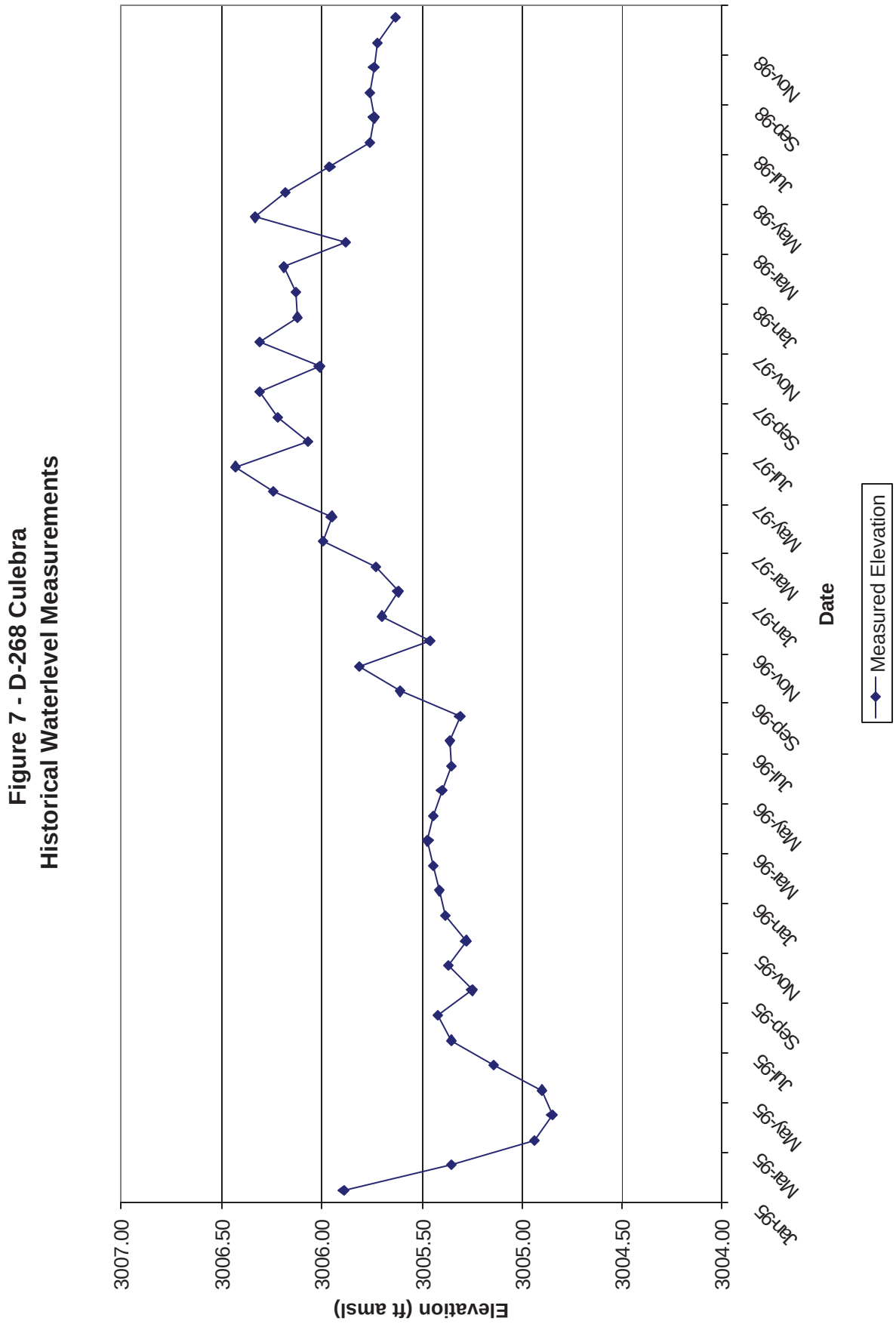
Figure 7 - D-268 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3007.00
3006.50
3006.00
3005.50
3005.00
3004.50
3004.00
Jan-95
Mar-95
May-95
Jul-95
Sep-95
Nov-95
Jan-96
Mar-96
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Date
Measured Elevation

Table 8 - Well No. DOE-1 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2963.19	2991.43
02/14/95	2964.26	2992.59
03/13/95	2965.55	2993.10
04/12/95	2968.49	2996.29
05/09/95	2970.30	2998.25
06/06/95	2969.51	2997.39
07/19/95	2960.60	2987.74
08/14/95	2953.20	2979.73
09/07/95	2958.54	2985.51
10/18/95	2965.68	2993.24
11/07/95	2966.08	2993.68
12/05/95	2967.48	2995.19
01/09/96	2958.88	2985.88
02/06/96	2954.52	2981.16
03/12/96	2937.75	2963.00
04/17/96	2947.70	2973.77
05/14/96	2957.57	2984.46
06/12/96	2961.27	2988.47
07/16/96	2965.73	2993.30
08/13/96	2967.87	2995.62
09/05/96	2968.99	2996.83
10/15/96	2970.02	2997.94
11/12/96	2970.79	2998.78
12/10/96	2971.50	2999.55
01/13/97	2972.13	3000.23
02/11/97	2972.41	3000.53
03/10/97	2972.58	3000.72
04/15/97	2972.44	3000.56
05/14/97	2972.45	3000.58
06/11/97	2972.37	3000.49
07/16/97	2972.15	3000.25
08/12/97	2972.03	3000.12
09/16/97	2972.28	3000.39
10/15/97	2972.67	3000.81
11/11/97	2972.96	3001.13
12/09/97	2973.25	3001.44

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2973.48	3001.69
02/11/98	2974.03	3002.29
03/11/98	2974.05	3002.31
04/15/98	2973.98	3002.23
05/12/98	2973.92	3002.17
06/10/98	2973.72	3001.95
07/15/98	2973.58	3001.80
08/12/98	2973.56	3001.78
09/10/98	2973.32	3001.52
10/13/98	2973.33	3001.53
11/11/98	2973.37	3001.57
12/08/98	2973.65	3001.87
01/12/99	2973.88	3002.12
02/09/99	2974.13	3002.39
03/10/99	2974.41	3002.70
04/12/99	2974.60	3002.90
05/10/99	2974.69	3003.00
06/08/99	2974.78	3003.10
07/20/99	2974.83	3003.15
08/09/99	2974.93	3003.26
09/07/99	2974.96	3003.29
10/05/99	2974.86	3003.19
11/08/99	2974.56	3002.86
12/08/99	2974.68	3002.99
01/18/00	2974.68	3002.99
02/15/00	2974.78	3003.10
03/08/00	2974.84	3003.16
04/18/00	2974.91	3003.24
05/17/00	2975.03	3003.37
06/06/00	2975.05	3003.39
07/10/00	2975.16	3003.51
08/14/00	2974.97	3003.30
09/11/00	2975.17	3003.52
10/11/00	2975.05	3003.39
11/09/00	2975.14	3003.49
12/05/00	2975.04	3003.38

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2975.19	3003.54
02/05/01	2975.25	3003.61
03/08/01	2975.62	3004.01
04/05/01	2975.92	3004.33
05/09/01	2976.09	3004.52
06/06/01	2976.25	3004.69
07/10/01	2976.40	3004.85
08/07/01	2976.64	3005.11
09/07/01	2976.61	3005.08
10/09/01	2976.69	3005.17
11/13/01	2976.65	3005.12
12/05/01	2976.71	3005.19
01/16/02	2976.88	3005.37
02/05/02	2977.09	3005.60
03/13/02	2977.24	3005.76
04/10/02	2976.74	3005.22
05/07/02	2977.22	3005.74
06/11/02	2977.56	3006.11
07/15/02	2977.86	3006.43
08/14/02	2977.98	3006.56
09/11/02	2978.09	3006.68

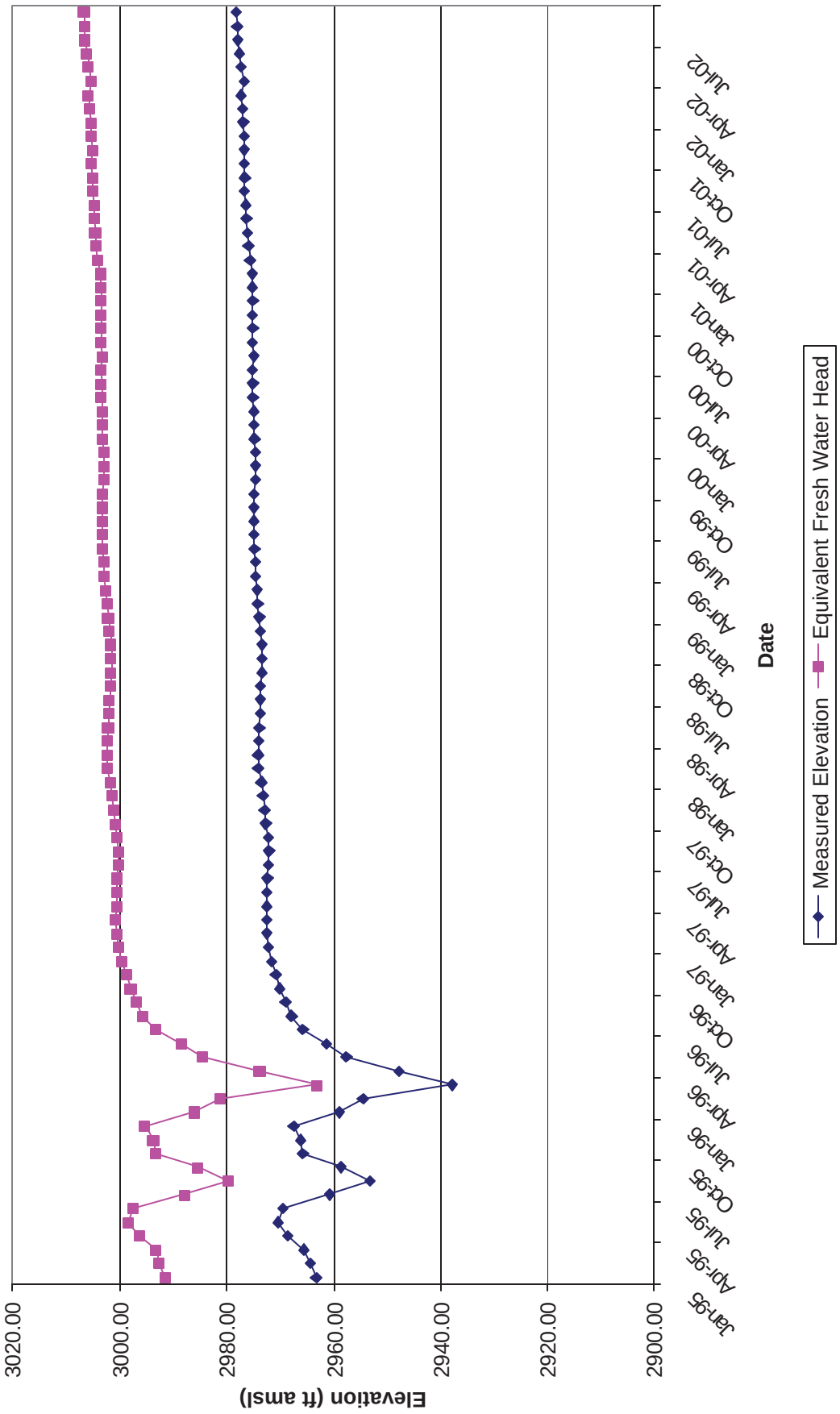
Figure 8 - DOE-1 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 9 - Well No. DOE-2 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3053.92	3067.07
02/13/95	3053.28	3066.41
03/13/95	3053.36	3066.49
04/12/95	3052.88	3066.00
05/08/95	3053.21	3066.34
06/05/95	3053.31	3066.44
07/17/95	3053.22	3066.35
08/14/95	3053.53	3066.67
09/05/95	3052.48	3065.59
10/18/95	3052.94	3066.06
11/08/95	3052.92	3066.04
12/04/95	3053.05	3066.17
01/11/96	3052.90	3066.02
02/07/96	3052.19	3065.29
03/11/96	3052.08	3065.18
04/15/96	3052.21	3065.31
05/13/96	3052.35	3065.45
06/12/96	3052.72	3065.83
07/16/96	3052.89	3066.01
08/14/96	3052.52	3065.63
09/05/96	3052.93	3066.05
10/16/96	3052.97	3066.09
11/13/96	3052.64	3065.75
12/11/96	3052.87	3065.99
01/13/97	3053.11	3066.24
02/10/97	3053.01	3066.13
03/10/97	3053.24	3066.37
04/14/97	3053.56	3066.70
05/14/97	3053.45	3066.58
06/11/97	3053.84	3066.99
07/16/97	3054.33	3067.49
08/12/97	3053.83	3066.98
09/15/97	3053.92	3067.07
10/15/97	3053.64	3066.78
11/12/97	3053.50	3066.64
12/08/97	3052.64	3065.75

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3052.76	3065.88
02/09/98	3055.40	3068.59
03/11/98	3056.54	3069.76
04/15/98	3056.19	3069.40
05/11/98	3055.66	3068.86
06/11/98	3055.21	3068.39
07/15/98	3055.03	3068.21
08/12/98	3055.12	3068.30
09/10/98	3060.89	3074.23
10/14/98	3056.72	3069.95
11/11/98	3055.02	3068.20
12/08/98	3059.31	3072.61
01/11/99	3058.78	3072.06
02/08/99	3058.61	3071.89
03/10/99	3058.42	3071.69
04/12/99	3058.17	3071.44
05/10/99	3058.16	3071.43
06/07/99	3058.05	3071.31
07/20/99	3057.79	3071.05
08/09/99	3057.66	3070.91
09/07/99	3057.47	3070.72
10/04/99	3057.38	3070.62
11/08/99	3057.43	3070.68
12/06/99	3057.50	3070.75
01/17/00	3057.60	3070.85
02/14/00	3057.72	3070.97
03/06/00	3057.76	3071.02
04/17/00	3057.81	3071.07
05/15/00	3057.27	3070.51
06/05/00	3041.95	3054.76
07/10/00	3041.14	3053.93
08/14/00	3040.94	3053.72
09/12/00	3040.98	3053.77
10/09/00	3040.79	3053.57
11/06/00	3041.01	3053.80
12/07/00	3040.80	3053.58

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3040.85	3053.63
02/06/01	3040.74	3053.52
03/06/01	3040.78	3053.56

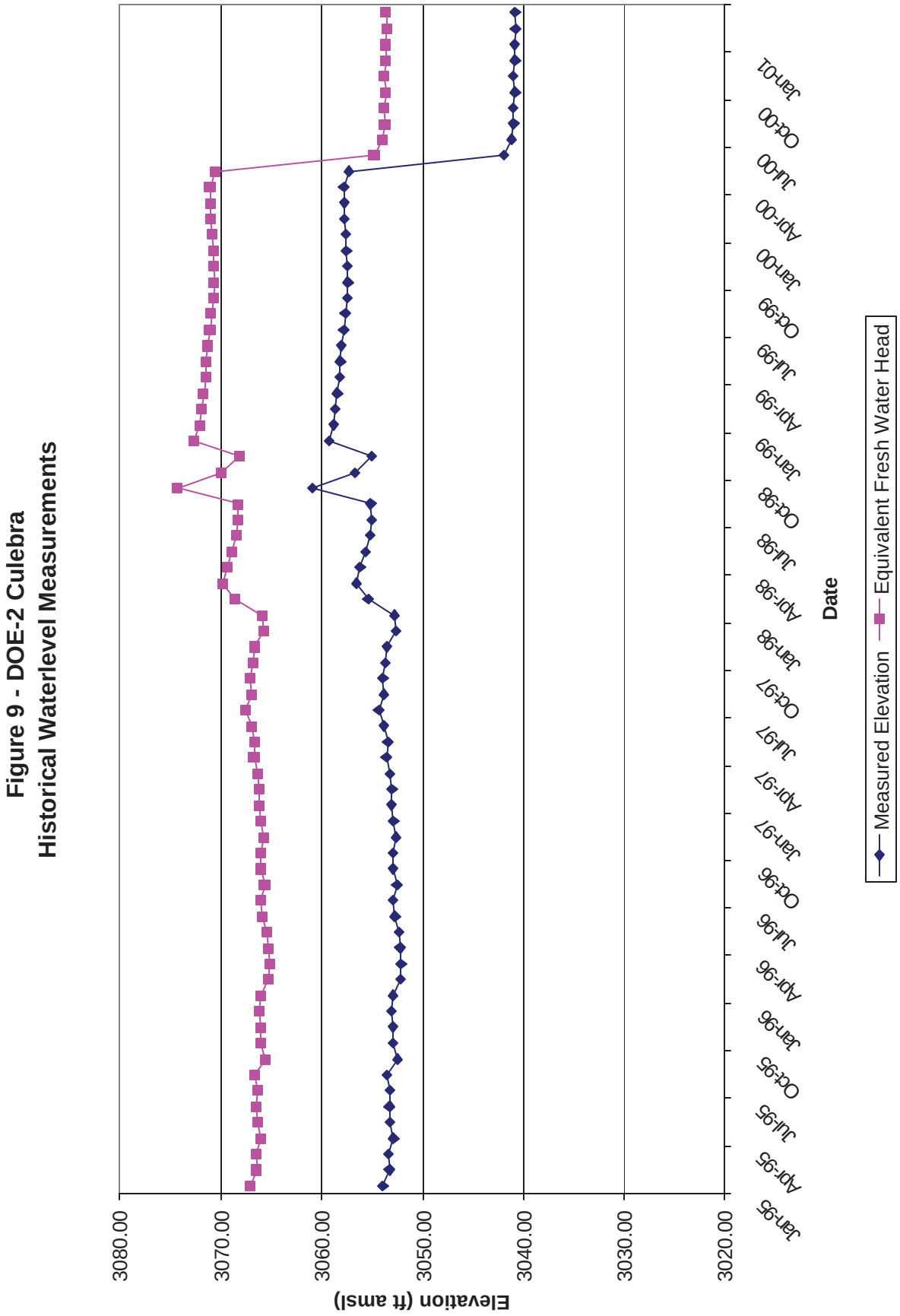
Figure 9 - DOE-2 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3080.00
3070.00
3060.00
3050.00
3040.00
3030.00
3020.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Date
Measured Elevation
Equivalent Fresh Water Head

Table 10 - Well No. DOE-2 Magenta
April 2001 through January 2002

Date	Measured Elevation	Equivalent Fresh Water Head
04/04/01	2942.34	N/A
05/08/01	3047.58	N/A
06/05/01	3048.44	N/A
07/09/01	3049.24	N/A
09/12/01	3053.11	N/A
10/23/01	3056.55	N/A
11/12/01	3057.19	N/A
12/03/01	3058.12	N/A
01/09/02	3059.80	N/A

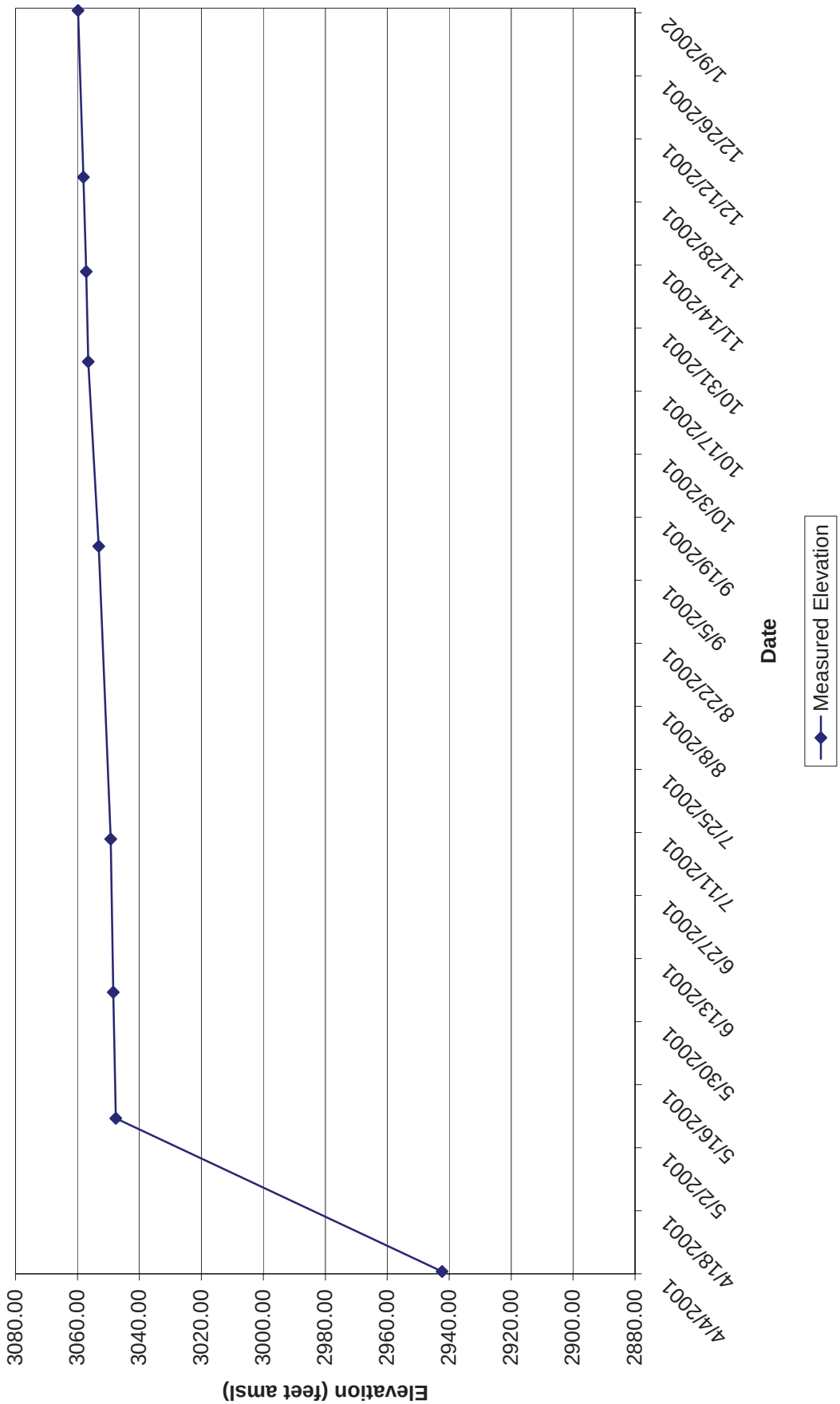
Figure 10 - DOE-2 Magenta
Historical Waterlevel Measurements
Elevation (feet amsl)
3080.00
3060.00
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
2880.00
4/4/2001
4/18/2001
5/2/2001
5/16/2001
5/30/2001
6/13/2001
6/27/2001
7/11/2001
7/25/2001
8/8/2001
8/22/2001
9/5/2001
9/19/2001
10/3/2001
10/17/2001
10/31/2001
11/14/2001
11/28/2001
12/12/2001
12/26/2001
1/9/2002
Date
Measured Elevation

Table 11 - Well No. ERDA-9 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3002.33	3017.47
02/15/95	3002.77	3017.93
03/15/95	3001.36	3016.45
04/12/95	3002.00	3017.12
05/10/95	3002.11	3017.24
06/07/95	3000.26	3015.30
07/19/95	2989.37	3003.87
08/17/95	2984.28	2998.54
09/07/95	2986.21	3000.56
10/18/95	2987.55	3001.97
11/09/95	2989.58	3004.09
12/04/95	2991.66	3006.28
01/11/96	2984.07	2998.31
02/07/96	2974.68	2988.46
03/14/96	2968.17	2981.64
04/17/96	2965.89	2979.24
05/15/96	2972.85	2986.55
06/12/96	2979.06	2993.06
07/17/96	2984.98	2999.27
08/13/96	2988.42	3002.88
09/05/96	2990.82	3005.40
10/16/96	2993.41	3008.11
11/13/96	2994.88	3009.65
12/10/96	2996.40	3011.25
01/16/97	2997.53	3012.43
02/11/97	2998.25	3013.19
03/12/97	2999.37	3014.36
04/16/97	3000.44	3015.49
05/14/97	3001.17	3016.25
06/11/97	3001.47	3016.57
07/16/97	3001.75	3016.86
08/13/97	3002.13	3017.26
09/17/97	3002.51	3017.66
10/15/97	3001.64	3016.75
11/12/97	3002.94	3018.11
12/10/97	3003.17	3018.35

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3003.17	3018.35
02/11/98	3003.59	3018.79
03/11/98	3003.94	3019.16
04/15/98	3004.67	3019.92
05/13/98	3004.86	3020.12
06/10/98	3005.05	3020.32
07/15/98	3005.32	3020.61
08/12/98	3005.42	3020.71
09/10/98	3005.64	3020.94
10/14/98	3005.61	3020.91
11/11/98	3005.62	3020.92
12/09/98	3005.74	3021.05
01/13/99	3005.71	3021.02
02/10/99	3006.03	3021.35
03/10/99	3006.26	3021.60
04/12/99	3006.37	3021.71
05/10/99	3006.61	3021.96
06/09/99	3006.82	3022.18
07/20/99	3006.95	3022.32
08/09/99	3007.18	3022.56
09/07/99	3007.35	3022.74
10/05/99	3007.24	3022.62
11/08/99	3006.94	3022.31
12/08/99	3007.08	3022.45
01/19/00	3006.83	3022.19
02/15/00	3006.75	3022.11
03/08/00	3007.09	3022.47
04/18/00	3007.35	3022.74
05/17/00	3007.60	3023.00
06/07/00	3007.56	3022.96
07/10/00	3007.95	3023.37
08/14/00	3008.03	3023.45
09/11/00	3008.17	3023.60
10/11/00	3007.90	3023.31
11/08/00	3007.98	3023.40
12/06/00	3007.53	3022.93

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3007.29	3022.68
02/05/01	3006.65	3022.00
03/07/01	3007.28	3022.66
04/05/01	3007.75	3023.16
05/08/01	3007.89	3023.30
06/06/01	3008.28	3023.71
07/11/01	3008.45	3023.89
08/07/01	3008.59	3024.04
09/06/01	3008.79	3024.25
10/10/01	3008.84	3024.30
11/14/01	3008.70	3024.15
12/05/01	3008.60	3024.05
01/16/02	3008.40	3023.84
02/05/02	3008.46	3023.90
03/12/02	3008.53	3023.98
04/08/02	3008.87	3024.33
05/07/02	3009.13	3024.61
06/10/02	3009.48	3024.97
07/15/02	3009.66	3025.16
08/14/02	3009.87	3025.38
09/10/02	3009.95	3025.47

Figure 11 - ERDA-9 Culebra
Historical Waterlevel Measurements

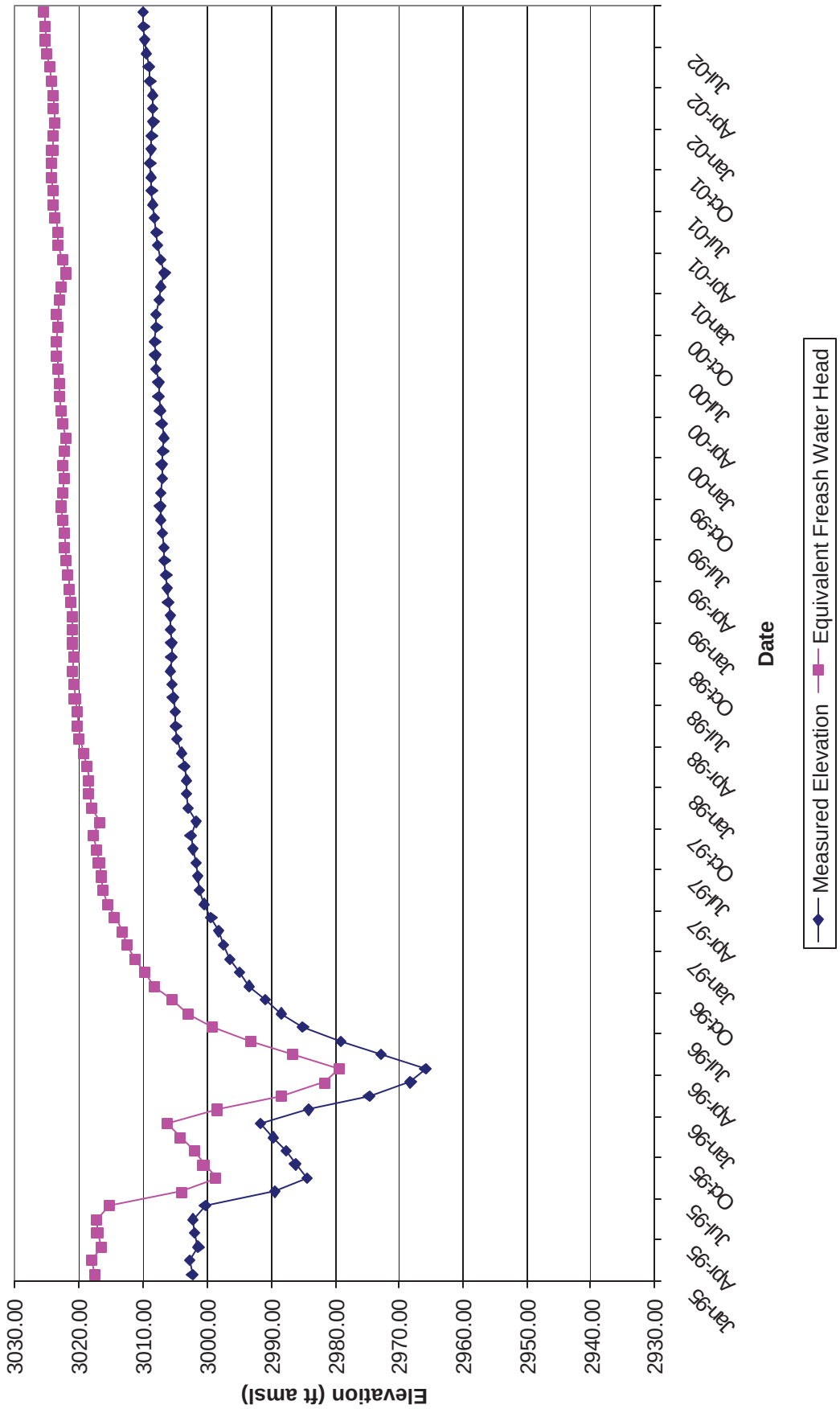

Table 12 - Well No. H-01 (ANNULUS) Magenta
January 1995 through February 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3134.92	N/A
02/14/95	3135.20	N/A
03/15/95	3135.34	N/A
04/12/95	3135.56	N/A
05/10/95	3135.91	N/A
06/07/95	3136.25	N/A
07/19/95	3136.47	N/A
08/17/95	3136.85	N/A
09/07/95	3136.97	N/A
10/18/95	3137.40	N/A
11/09/95	3137.64	N/A
12/06/95	3137.93	N/A
01/11/96	3138.23	N/A
02/07/96	3138.46	N/A
03/14/96	3138.66	N/A
04/17/96	3137.73	N/A
05/15/96	3138.77	N/A
06/12/96	3138.90	N/A
07/17/96	3138.99	N/A
08/13/96	3138.95	N/A
09/05/96	3139.30	N/A
10/16/96	3139.55	N/A
11/13/96	3139.75	N/A
12/10/96	3140.21	N/A
01/16/97	3140.54	N/A
02/11/97	3141.14	N/A
03/12/97	3141.22	N/A
04/16/97	3141.54	N/A
05/14/97	3141.82	N/A
06/11/97	3141.62	N/A
07/16/97	3141.73	N/A
08/13/97	3145.56	N/A
09/17/97	3156.88	N/A
10/15/97	3163.91	N/A
11/12/97	3176.57	N/A
12/10/97	3189.28	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3192.84	N/A
02/11/98	3208.35	N/A
03/11/98	3211.58	N/A
04/15/98	3226.84	N/A
05/13/98	3225.20	N/A
06/10/98	3220.90	N/A
07/15/98	3219.41	N/A
08/12/98	3220.06	N/A
09/10/98	3218.03	N/A
10/12/98	3217.62	N/A
11/09/98	3230.91	N/A
12/09/98	3230.12	N/A
01/13/99	3230.55	N/A
02/08/99	3231.89	N/A
03/10/99	3230.07	N/A
04/13/99	3228.51	N/A
05/10/99	3231.18	N/A
06/09/99	3183.95	N/A
07/21/99	3197.92	N/A
09/09/99	3212.90	N/A
10/05/99	3206.63	N/A
11/10/99	3199.56	N/A
12/08/95	3216.46	N/A
01/19/00	3224.86	N/A
02/16/00	3229.00	N/A
03/08/00	3229.46	N/A
04/18/00	3227.02	N/A
05/17/00	3213.25	N/A
06/07/00	3189.09	N/A
07/10/00	3217.01	N/A
08/14/00	3227.24	N/A
09/11/00	3229.57	N/A
10/11/00	3222.34	N/A
11/08/00	3230.08	N/A
12/06/00	3229.17	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3231.57	N/A
02/05/01	3229.89	N/A

Figure 12 - H-1 Magenta
Historical Waterlevel Measurements

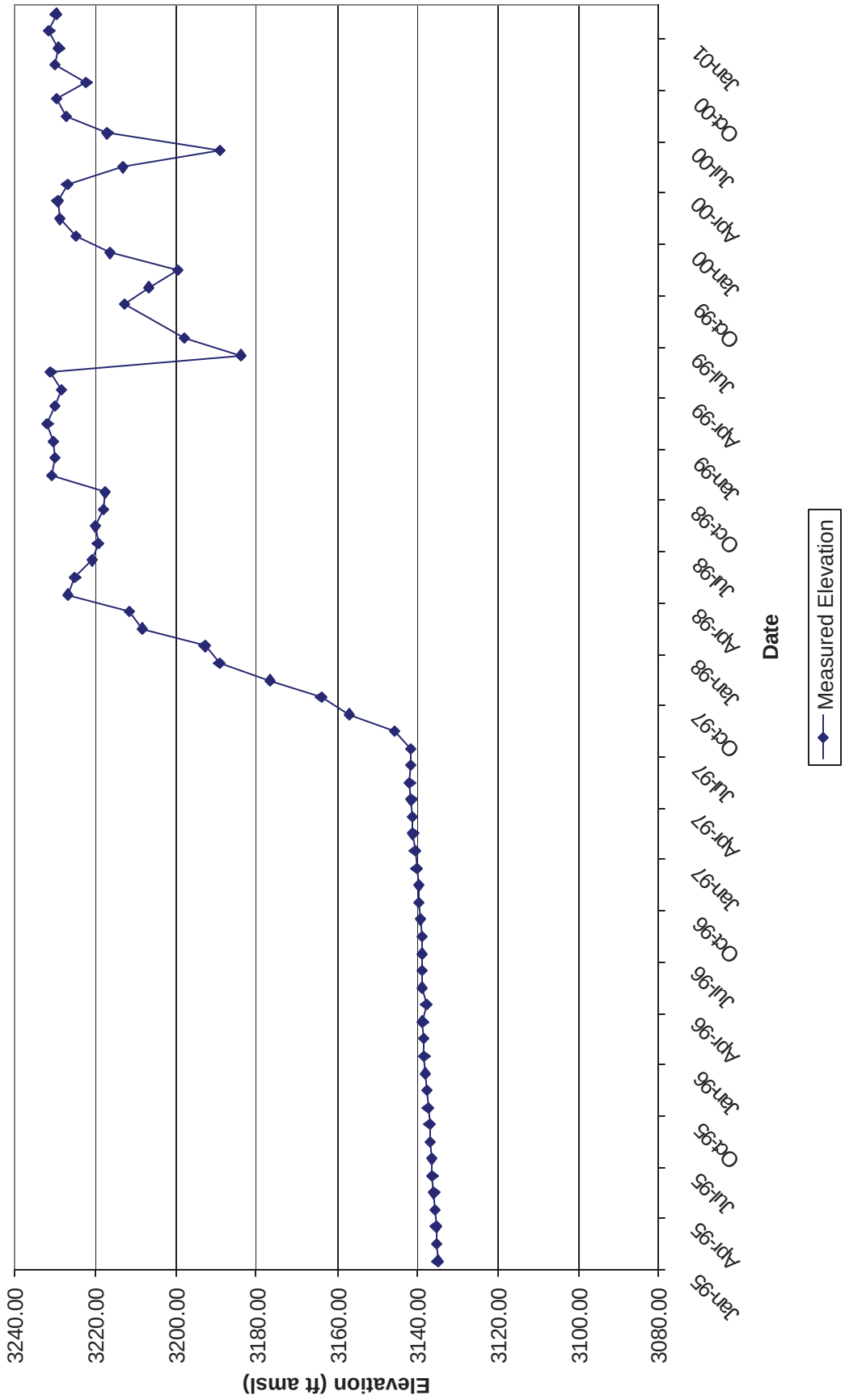

Table 13 - Well No. H-01 (PIP) Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3020.49	3021.11
02/14/95	3021.07	3021.69
03/15/95	3019.85	3020.47
04/12/95	3020.17	3020.79
05/10/95	3020.55	3021.17
06/07/95	3019.48	3020.10
07/19/95	3010.66	3011.26
08/17/95	2998.85	2999.43
09/07/95	3004.54	3005.13
10/18/95	3004.48	3005.07
11/09/95	3006.62	3007.21
12/06/95	3008.26	3008.86
01/11/96	3004.17	3004.76
02/07/96	2994.94	2995.51
03/14/96	2988.37	2988.93
04/17/96	2985.21	2985.76
05/15/96	2989.52	2990.08
06/12/96	2995.30	2995.87
07/17/96	3001.21	3001.79
08/13/96	3004.68	3005.27
09/05/96	3007.34	3007.93
10/16/96	3010.37	3010.97
11/13/96	3011.87	3012.47
12/10/96	3013.70	3014.31

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3021.39	3022.01
02/11/98	3021.67	3022.29
03/11/98	3021.85	3022.47
04/15/98	3022.76	3023.39
05/13/98	3022.98	3023.61
06/10/98	3022.88	3023.51
07/15/98	3023.11	3023.74
08/12/98	3023.26	3023.89
09/10/98	3023.46	3024.09
10/12/98	3023.35	3023.98
11/09/98	3023.47	3024.10
12/09/98	3021.46	3022.08
01/13/99	3021.63	3022.25
02/08/99	3024.29	3024.92
03/10/99	3024.34	3024.97
04/13/99	3024.45	3025.08
05/10/99	3025.17	3025.80
06/09/99	3027.11	3027.74
07/21/99	3027.40	3028.03
08/11/99	3148.39	3148.97
09/09/99	3034.91	3035.26
10/05/99	3037.82	3038.48
11/10/99	3035.58	3036.23
12/08/99	3035.95	3036.60

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3035.50	3036.15
02/05/01	3035.33	3035.98

01/16/97	3014.99	3015.60
02/11/97	3016.16	3016.77
03/12/97	3017.21	3017.82
04/16/97	3018.21	3018.83
05/14/97	3019.03	3019.65
06/11/97	3019.43	3020.05
07/16/97	3019.49	3020.11
08/13/97	3019.77	3020.39
09/17/97	3020.41	3021.03
10/15/97	3020.34	3020.96
11/12/97	3020.95	3021.57
12/10/97	3021.10	3021.72

01/19/00	3034.94	3035.59
02/16/00	3034.93	3035.58
03/08/00	3034.91	3035.56
04/18/00	3036.27	3036.92
05/17/00	3036.26	3036.91
06/07/00	3035.45	3036.10
07/10/00	3035.27	3035.92
08/14/00	3036.16	3036.81
09/11/00	3035.95	3036.60
10/11/00	3035.81	3036.46
11/08/00	3035.78	3036.43
12/06/00	3035.57	3036.22

Figure 13 - H-1 Culebra
Historical Waterlevel Measurements

Table 14 - Well No. H-02a Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/15/95	3028.57	3031.99
06/07/95	3030.22	3033.66
09/07/95	3030.86	3034.30
12/06/95	3030.56	3034.00
03/14/96	3030.06	3033.50
06/12/96	3028.73	3032.15
09/05/96	3027.87	3031.28
12/10/96	3027.85	3031.26
03/12/97	3028.32	3031.73
06/12/97	3029.22	3032.65
09/17/97	3030.27	3033.71
12/10/97	3030.98	3034.43

Date	Measured Elevation	Equivalent Fresh Water Head
03/11/98	3031.68	3035.13
06/10/98	3032.50	3035.96
09/10/98	3033.06	3036.53
12/09/98	3033.56	3037.04
03/10/99	3034.09	3037.57
06/09/99	3034.57	3038.06
09/09/99	3035.04	3038.54
12/09/99	3035.40	3038.90
03/08/00	3035.69	3039.19
06/07/00	3036.10	3039.61
09/11/00	3036.50	3040.01
12/06/00	3036.78	3040.30

Date	Measured Elevation	Equivalent Fresh Water Head
03/08/01	3037.06	3040.58
06/06/01	3037.34	3040.86
09/06/01	3037.59	3041.12
12/05/01	3037.77	3041.30
03/13/02	3038.08	3041.61
06/11/02	3038.30	3041.83
09/10/02	3038.52	3042.06

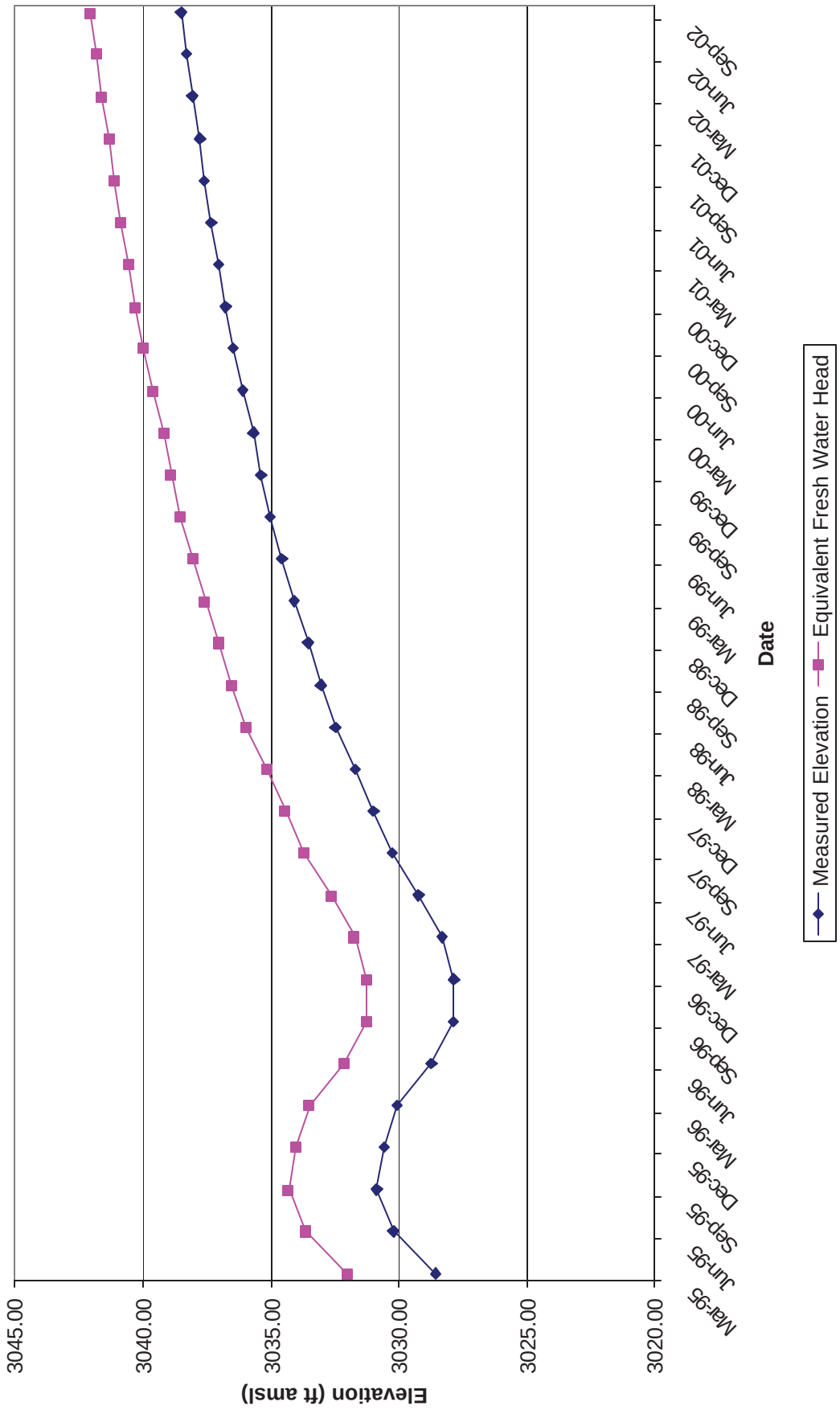
Figure 14 - H-2a Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3045.00
3040.00
3035.00
3030.00
3025.00
3020.00
Mar-95
Jun-95
Sep-95
Dec-95
Mar-96
Jun-96
Sep-96
Dec-96
Mar-97
Jun-97
Sep-97
Dec-97
Mar-98
Jun-98
Sep-98
Dec-98
Mar-99
Jun-99
Sep-99
Dec-99
Mar-00
Jun-00
Sep-00
Dec-00
Mar-01
Jun-01
Sep-01
Dec-01
Mar-02
Jun-02
Sep-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 15 - Well No. H2b1 Magenta

January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3128.91	N/A
02/15/95	3129.30	N/A
03/15/95	3129.62	N/A
04/12/95	3129.84	N/A
05/10/95	3130.25	N/A
06/07/95	3130.61	N/A
07/19/95	3131.01	N/A
08/17/95	3131.26	N/A
09/07/95	3131.42	N/A
10/19/95	3131.76	N/A
11/08/95	3131.88	N/A
12/06/95	3132.13	N/A
01/10/96	3132.38	N/A
02/07/96	3132.61	N/A
03/14/96	3132.88	N/A
04/17/96	3133.15	N/A
05/15/96	3133.37	N/A
06/12/96	3133.62	N/A
07/17/96	3133.85	N/A
08/13/96	3134.00	N/A
09/05/96	3134.15	N/A
10/15/96	3134.42	N/A
11/13/96	3134.59	N/A
12/10/96	3134.71	N/A
01/16/97	3134.87	N/A
02/12/97	3134.96	N/A
03/12/97	3135.14	N/A
04/16/97	3135.30	N/A
05/14/97	3135.47	N/A
06/12/97	3135.58	N/A
07/16/97	3135.68	N/A
08/13/97	3135.73	N/A
09/17/97	3135.78	N/A
10/15/97	3135.85	N/A
11/12/97	3135.91	N/A
12/10/97	3135.99	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3136.10	N/A
02/11/98	3136.20	N/A
03/11/98	3136.34	N/A
04/15/98	3136.58	N/A
05/13/98	3136.82	N/A
06/10/98	3137.09	N/A
07/15/98	3137.46	N/A
08/12/98	3137.84	N/A
09/10/98	3138.24	N/A
10/14/98	3138.73	N/A
11/11/98	3139.14	N/A
12/09/98	3139.57	N/A
01/13/99	3140.12	N/A
02/10/99	3140.65	N/A
03/10/99	3141.13	N/A
04/13/99	3141.71	N/A
05/11/99	3142.02	N/A
06/09/99	3142.37	N/A
07/21/99	3142.85	N/A
08/11/99	3143.15	N/A
09/09/99	3143.49	N/A
10/06/99	3143.79	N/A
11/10/99	3144.16	N/A
12/09/99	3144.47	N/A
01/20/00	3144.76	N/A
02/16/00	3144.93	N/A
03/08/00	3145.07	N/A
04/19/00	3145.35	N/A
05/17/00	3145.52	N/A
06/07/00	3145.66	N/A
07/10/00	3145.88	N/A
08/15/00	3146.09	N/A
09/11/00	3146.22	N/A
10/11/00	3146.31	N/A
11/06/00	3146.43	N/A
12/06/00	3146.54	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3146.56	N/A
02/06/01	3146.48	N/A
03/08/01	3146.58	N/A
04/05/01	3146.72	N/A
05/08/01	3146.85	N/A
06/06/01	3146.95	N/A
07/11/01	3147.04	N/A
08/07/01	3147.12	N/A
09/06/01	3147.23	N/A
10/10/01	3147.23	N/A
11/14/01	3147.20	N/A
12/05/01	3147.19	N/A
01/16/02	3147.15	N/A
02/05/02	3147.17	N/A
03/13/02	3147.15	N/A
04/08/02	3147.21	N/A
05/08/02	3147.17	N/A
06/11/02	3147.14	N/A
07/16/02	3147.09	N/A
08/13/02	3147.01	N/A
09/10/02	3146.96	N/A

Figure 15 - H-2b1 Magenta
Historical Waterlevel Measurements

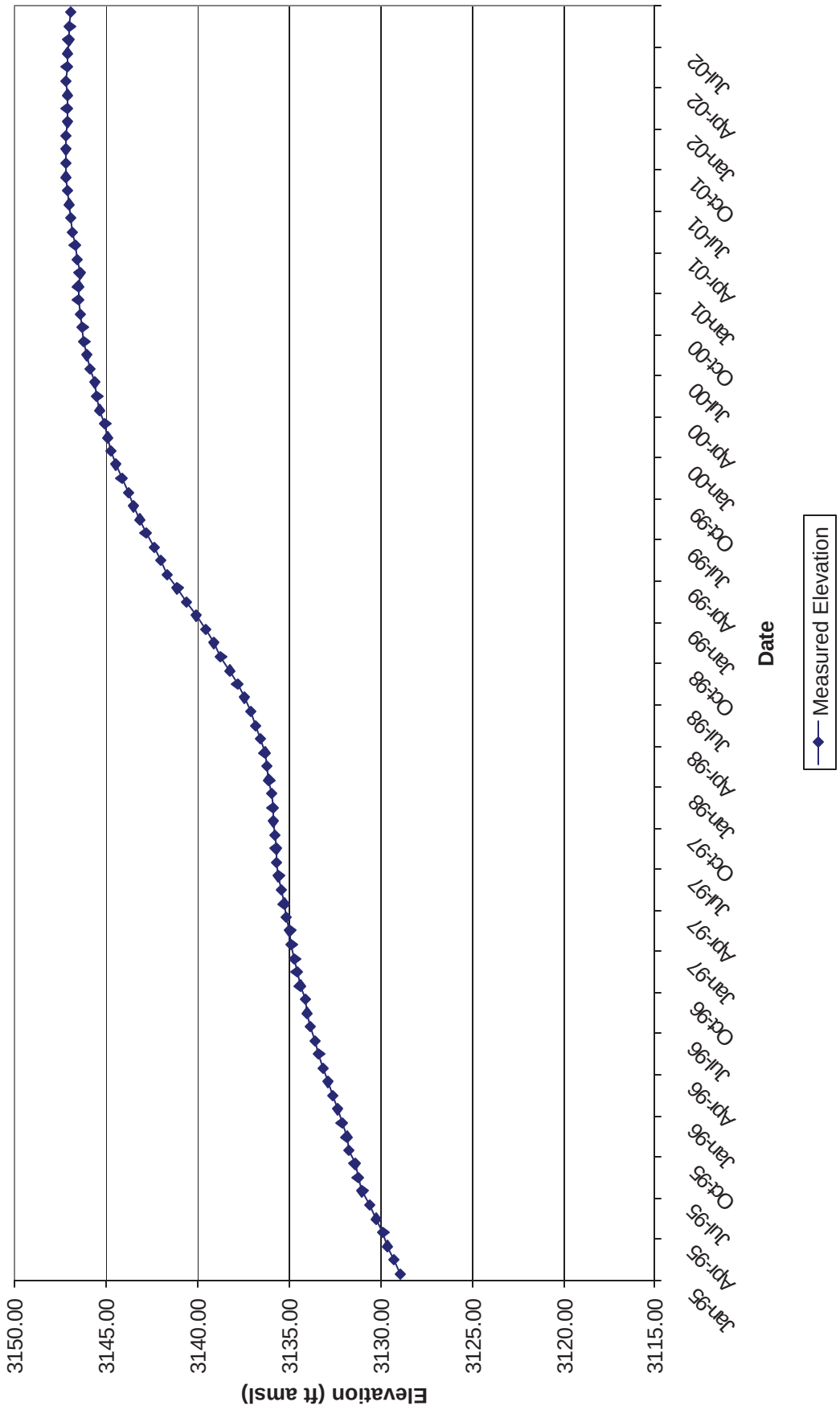

Table 16 - Well No. H2b2 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3031.50	3033.80
02/15/95	3031.92	3034.23
03/15/95	3031.91	3034.22
04/12/95	3031.92	3034.23
05/10/95	3032.26	3034.57
06/07/95	3032.62	3034.93
07/19/95	3031.68	3033.98
08/17/95	3029.83	3032.12
09/07/95	3028.71	3030.99
10/19/95	3027.83	3030.10
11/08/95	3027.53	3029.80
12/06/95	3027.88	3030.15
01/10/96	3028.17	3030.45
02/07/96	3026.97	3029.24
03/14/96	3024.10	3026.34
04/17/96	3021.62	3023.84
05/15/96	3020.57	3022.79
06/12/96	3020.98	3023.20
07/17/96	3022.24	3024.47
08/13/96	3023.34	3025.58
09/05/96	3024.58	3026.83
10/15/96	3026.23	3028.49
11/13/96	3027.01	3029.28
12/10/96	3028.04	3030.32
01/16/97	3028.76	3031.04
02/12/97	3029.59	3031.88
03/12/97	3030.31	3032.60
04/16/97	3030.87	3033.17
05/14/97	3031.52	3033.82
06/12/97	3031.91	3034.22
07/16/97	3032.01	3034.32
08/13/97	3032.29	3034.60
09/17/97	3032.80	3035.11
10/15/97	3032.78	3035.09
11/12/97	3033.25	3035.57
12/10/97	3033.36	3035.68

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3033.54	3035.86
02/11/98	3033.66	3035.98
03/11/98	3033.70	3036.02
04/15/98	3034.52	3036.85
05/13/98	3034.71	3037.04
06/10/98	3034.70	3037.03
07/15/98	3034.67	3037.00
08/12/98	3034.75	3037.08
09/10/98	3034.98	3037.31
10/14/98	3035.21	3037.54
11/11/98	3035.01	3037.34
12/09/98	3035.35	3037.38
01/13/99	3035.26	3037.59
02/10/99	3035.50	3037.84
03/10/99	3035.61	3037.95
04/13/99	3035.81	3038.15
05/11/99	3036.06	3038.40
06/09/99	3035.88	3038.22
07/21/99	3035.93	3038.27
08/11/99	3036.11	3038.45
09/09/99	3036.08	3038.42
10/06/99	3036.18	3038.52
11/10/99	3036.20	3038.54
12/09/99	3036.12	3038.46
01/20/00	3034.12	3036.44
02/16/00	3036.06	3038.40
03/08/00	3036.27	3038.61
04/19/00	3036.55	3038.89
05/17/00	3036.66	3039.00
06/07/00	3036.40	3038.74
07/10/00	3036.69	3039.03
08/15/00	3036.61	3038.95
09/11/00	3036.83	3039.18
10/11/00	3036.73	3039.08
11/06/00	3037.10	3039.45
12/06/00	3036.63	3038.97

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3036.85	3039.20
02/06/01	3036.91	3039.26
03/08/01	3037.12	3039.47
04/05/01	3037.16	3039.51
05/08/01	3036.99	3039.34
06/06/01	3037.28	3039.63
07/11/01	3037.27	3039.62
08/07/01	3037.30	3039.65
09/06/01	3037.61	3039.96
10/10/01	3037.62	3039.97
11/14/01	3037.79	3040.14
12/05/01	3037.60	3039.95
01/16/02	3037.74	3040.09
02/05/02	3037.85	3040.20
03/13/02	3038.18	3040.54
04/08/02	3038.31	3040.67
05/08/02	3038.42	3040.78
06/11/02	3038.45	3040.81
07/16/02	3038.41	3040.77
08/13/02	3038.66	3041.02
09/10/02	3038.65	3041.01

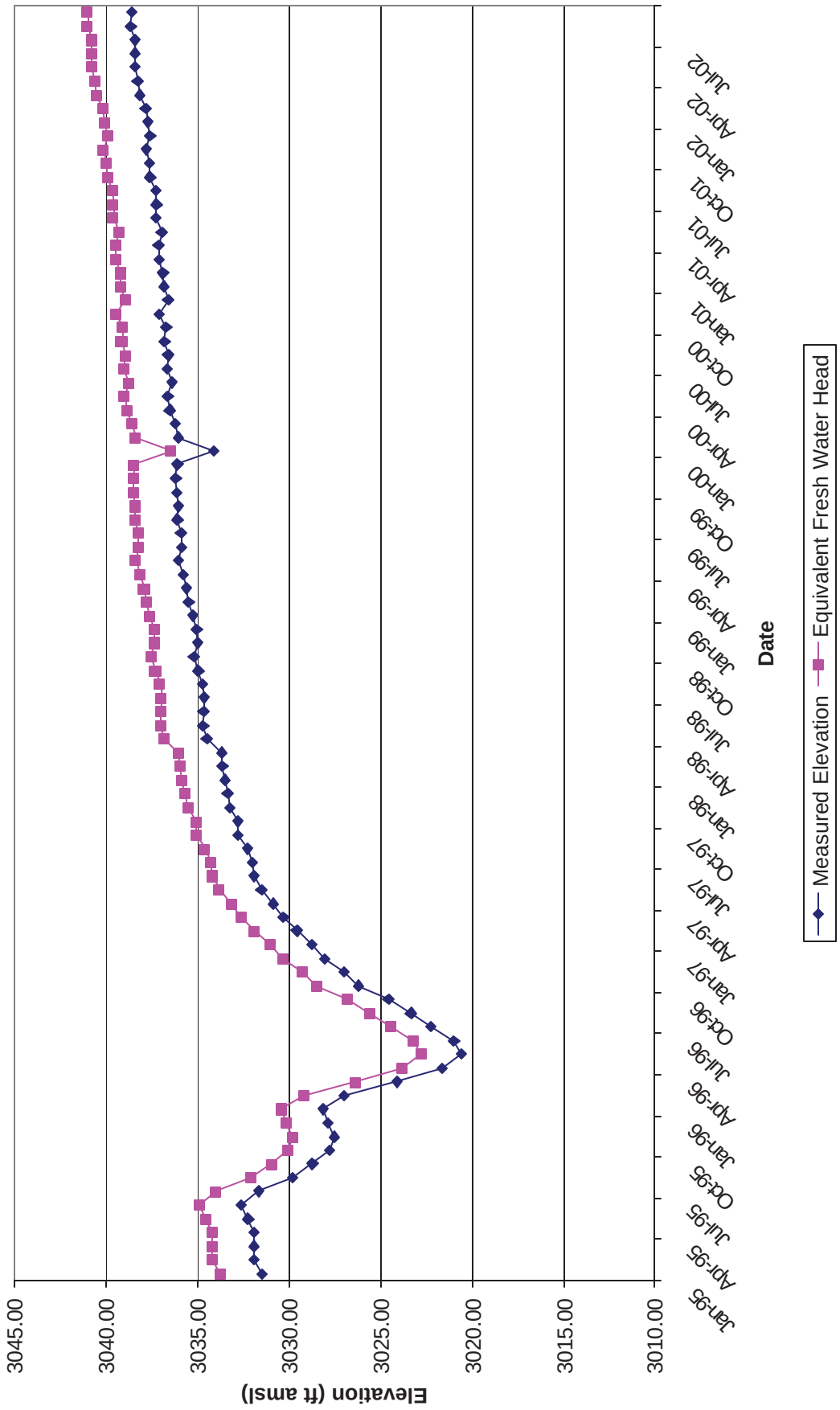
Figure 16 - H-2b2 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3045.00
3040.00
3035.00
3030.00
3025.00
3020.00
3015.00
3010.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 17 - Well No. H-02c Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/15/95	3031.83	3044.51
06/07/95	3032.45	3045.16
09/07/95	3028.67	3041.21
12/06/95	3027.81	3040.31
03/14/96	3024.21	3036.55
06/12/96	3021.05	3033.25
09/05/96	3024.52	3036.88
12/10/96	3027.82	3040.32
03/12/97	3030.13	3042.73
06/12/97	3031.77	3044.45
09/17/97	3032.61	3045.32
12/10/97	3033.27	3046.01
03/11/98	3033.59	3046.35
06/10/98	3034.59	3047.39
09/10/98	3034.81	3047.62
12/09/98	3034.87	3047.68
03/10/99	3035.43	3048.27
06/09/99	3035.78	3048.63
09/09/99	3035.92	3048.78
12/09/99	3036.07	3048.89
03/08/00	3036.47	3049.31
06/07/00	3036.52	3049.36
09/11/00	3036.98	3049.84
12/06/00	3036.78	3049.63
03/08/01	3037.02	3049.88
06/06/01	3037.41	3050.29
09/06/01	3037.64	3050.53
12/05/01	3038.71	3051.65
03/13/02	3038.02	3050.93
06/11/02	3038.41	3051.33
09/10/02	3038.68	3051.62

Figure 17 - H-2c Culebra
Historical Waterlevel Measurements

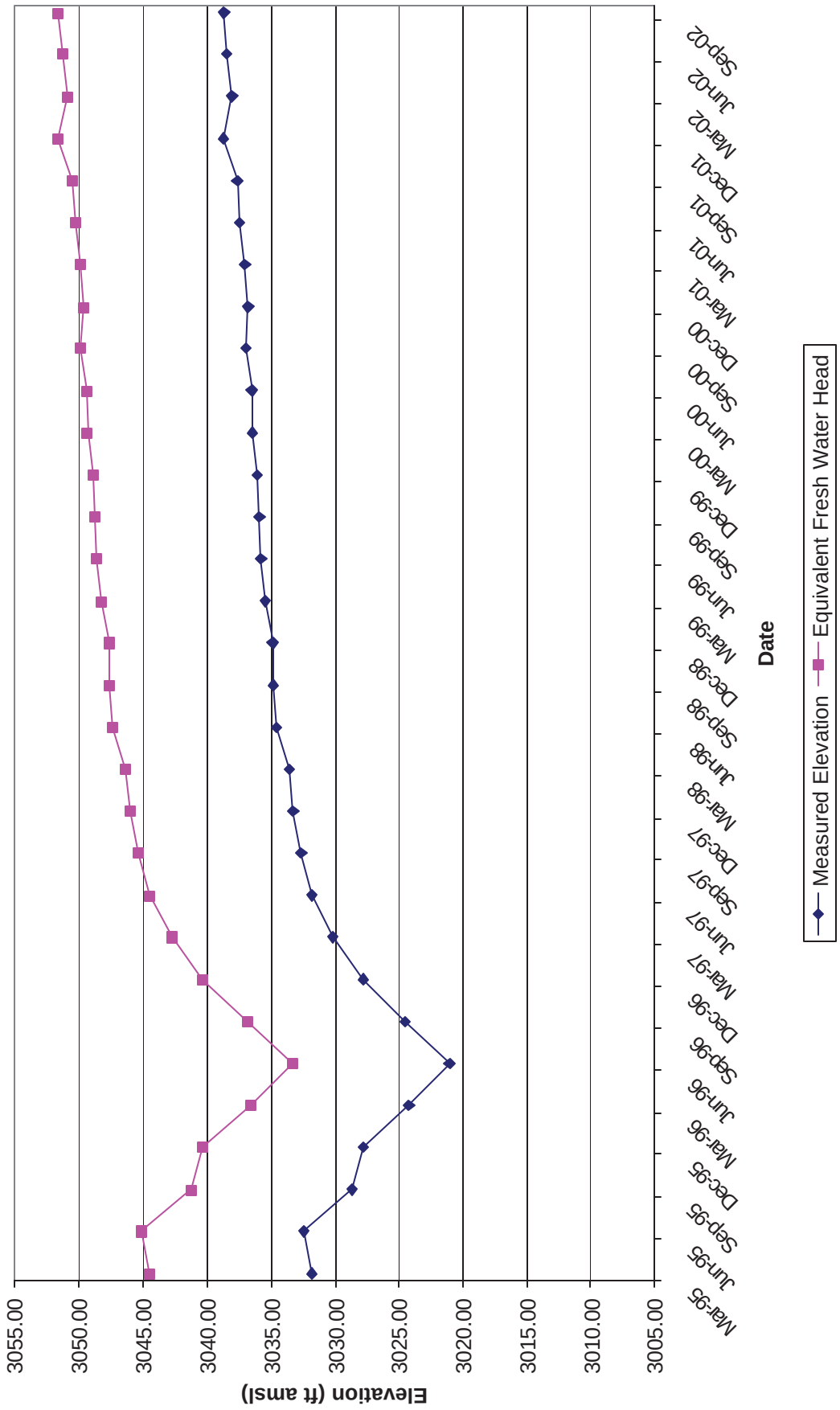

Table 18 - Well No. H-03b1 Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3140.74	N/A
02/15/95	3140.94	N/A
03/14/95	3140.90	N/A
04/12/95	3141.06	N/A
05/10/95	3141.43	N/A
06/07/95	3141.79	N/A
07/20/95	3142.07	N/A
08/17/95	3142.27	N/A
09/07/95	3142.37	N/A
10/18/95	3142.59	N/A
11/08/95	3142.61	N/A
12/06/95	3142.67	N/A
01/10/96	3142.76	N/A
02/07/96	3142.89	N/A
03/13/96	3143.10	N/A
04/17/96	3143.18	N/A
05/15/96	3143.27	N/A
06/12/96	3143.37	N/A
07/17/96	3143.44	N/A
08/13/96	3143.43	N/A
09/05/96	3143.58	N/A
10/17/96	3143.65	N/A
11/13/96	3143.52	N/A
12/10/96	3143.74	N/A
01/16/97	3143.73	N/A
02/12/97	3143.87	N/A
03/12/97	3143.99	N/A
04/16/97	3144.10	N/A
05/14/97	3144.34	N/A
06/12/97	3144.39	N/A
07/16/97	3144.42	N/A
08/13/97	3144.45	N/A
09/17/97	3144.61	N/A
10/15/97	3144.62	N/A
11/12/97	3144.98	N/A
12/10/97	3145.30	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3145.73	N/A
02/11/98	3146.15	N/A
03/11/98	3146.40	N/A
04/15/98	3147.28	N/A
05/13/98	3147.70	N/A
06/10/98	3148.02	N/A
07/15/98	3148.44	N/A
08/12/98	3148.69	N/A
09/10/98	3146.00	N/A
10/14/98	3149.28	N/A
11/11/98	3149.55	N/A
12/09/98	3149.70	N/A
01/13/99	3150.08	N/A
02/10/99	3150.31	N/A
03/16/99	3150.52	N/A
04/13/99	3150.66	N/A
05/11/99	3150.89	N/A
06/09/99	3150.97	N/A
07/21/99	3150.88	N/A
08/11/99	3151.01	N/A
09/09/99	3150.98	N/A
10/05/99	3150.93	N/A
11/10/99	3151.00	N/A
12/08/99	3151.14	N/A
01/19/00	3151.15	N/A
02/15/00	3151.39	N/A
03/08/00	3151.50	N/A
04/18/00	3151.61	N/A
05/17/00	3151.75	N/A
06/07/00	3151.63	N/A
07/10/00	3151.83	N/A
08/14/00	3151.74	N/A
09/11/00	3151.83	N/A
10/11/00	3151.62	N/A
11/08/00	3151.92	N/A
12/06/00	3151.71	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3151.88	N/A
02/06/01	3151.95	N/A
03/08/01	3152.19	N/A
04/05/01	3151.26	N/A
05/09/01	3150.98	N/A
06/06/01	3151.17	N/A
07/10/01	3151.01	N/A
08/07/01	3150.88	N/A
09/06/01	3150.91	N/A
10/10/01	3150.77	N/A
11/14/01	3150.63	N/A
12/05/01	3150.55	N/A
01/16/02	3150.44	N/A
02/05/02	3150.30	N/A
03/18/02	3127.49	N/A
04/09/02	3124.24	N/A
05/08/02	3130.63	N/A
06/10/02	3131.46	N/A
07/17/02	3133.11	N/A
08/14/02	3133.23	N/A
09/10/02	3132.85	N/A

Figure 18 - H-3b1 Magenta
Historical Waterlevel Measurements

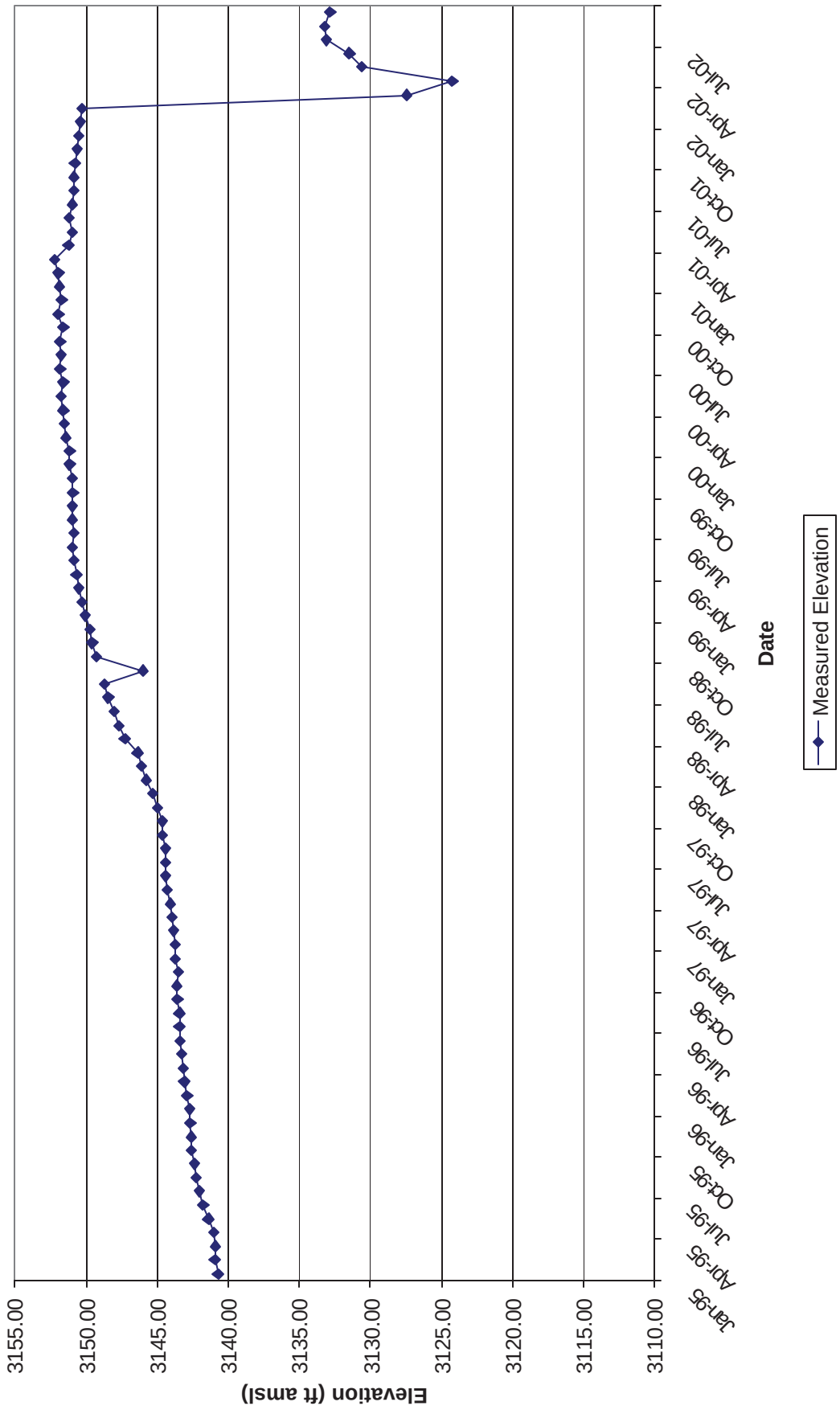

Table 19 - Well No. H-03b2 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2994.87	3006.06
02/15/95	2995.16	3006.36
03/14/95	2992.23	3003.32
04/12/95	2993.53	3004.67
05/10/95	2993.02	3004.14
06/07/95	2982.13	2992.84
07/20/95	2950.69	2960.20
08/17/95	2965.44	2975.51
09/07/95	2961.96	2971.90
10/18/95	2973.67	2984.06
11/08/95	2975.13	2985.57
12/06/95	2977.36	2987.89
01/10/96	2943.94	2953.20
02/07/96	2929.10	2937.79
03/13/96	2927.07	2935.69
04/17/96	2932.67	2941.50
05/15/96	2953.96	2963.60
06/12/96	2962.55	2972.51
07/17/96	2972.18	2982.51
08/13/96	2976.67	2987.17
09/05/96	2979.83	2990.45
10/17/96	2982.34	2993.06
11/13/96	2984.58	2995.38
12/10/96	2986.74	2997.62
01/16/97	2988.17	2999.11
02/12/97	2989.50	3000.49
03/12/97	2990.44	3001.46
04/16/97	2991.07	3002.12
05/14/97	2991.72	3002.79
06/12/97	2991.14	3002.19
07/16/97	2990.87	3001.91
08/13/97	2991.67	3002.74
09/17/97	2991.88	3002.96
10/15/97	2992.00	3003.08
11/12/97	2992.98	3004.10
12/10/97	2993.35	3004.48

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2993.92	3005.08
02/11/98	2994.33	3005.50
03/11/98	2994.38	3005.55
04/15/98	2995.22	3006.43
05/13/98	2994.66	3005.84
06/10/98	2994.73	3005.92
07/15/98	2995.16	3006.36
08/12/98	2995.33	3006.54
09/10/98	2995.65	3006.87
10/14/98	2995.14	3006.34
11/11/98	2995.67	3006.89
12/09/98	2995.93	3007.16
01/13/99	2996.14	3007.38
02/10/99	2996.56	3007.82
03/16/99	2996.83	3008.10
04/13/99	2997.07	3008.35
05/11/99	2996.33	3007.58
06/09/99	2997.02	3008.29
07/21/99	2997.11	3008.39
08/11/99	2997.40	3008.69
09/09/99	2997.53	3008.82
10/05/99	2997.62	3008.92
11/10/99	2996.90	3008.17
12/08/99	2997.61	3008.91
01/19/00	2997.65	3008.95
02/15/00	2997.84	3009.15
03/08/00	2997.82	3009.12
04/18/00	2997.42	3008.71
05/17/00	2997.68	3008.98
06/07/00	2997.75	3009.05
07/10/00	2998.05	3009.36
08/14/00	2998.14	3009.46
09/11/00	2998.26	3009.58
10/11/00	2998.13	3009.45
11/08/00	2997.67	3008.97
12/06/00	2997.81	3009.11

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	2998.23	3009.55
02/06/01	2998.35	3009.67
03/08/01	2998.58	3009.91
04/05/01	2998.67	3010.01
05/09/01	2997.89	3009.20
06/06/01	2998.63	3009.97
07/10/01	2998.88	3010.22
08/07/01	2998.88	3010.22
09/06/01	2999.29	3010.65
10/10/01	2999.24	3010.60
11/14/01	2998.85	3010.19
12/05/01	2998.94	3010.29
01/16/02	2999.35	3010.71
02/05/02	2999.43	3010.80
03/18/02	2999.15	3010.50
04/09/02	2999.15	3010.50
05/07/02	2999.07	3010.42
06/10/02	2999.74	3011.12
07/17/02	2999.72	3011.10
08/14/02	3000.02	3011.41
09/10/02	3000.05	3011.44

Figure 19 - H-3b2 Culebra
Historical Waterlevel Measurements

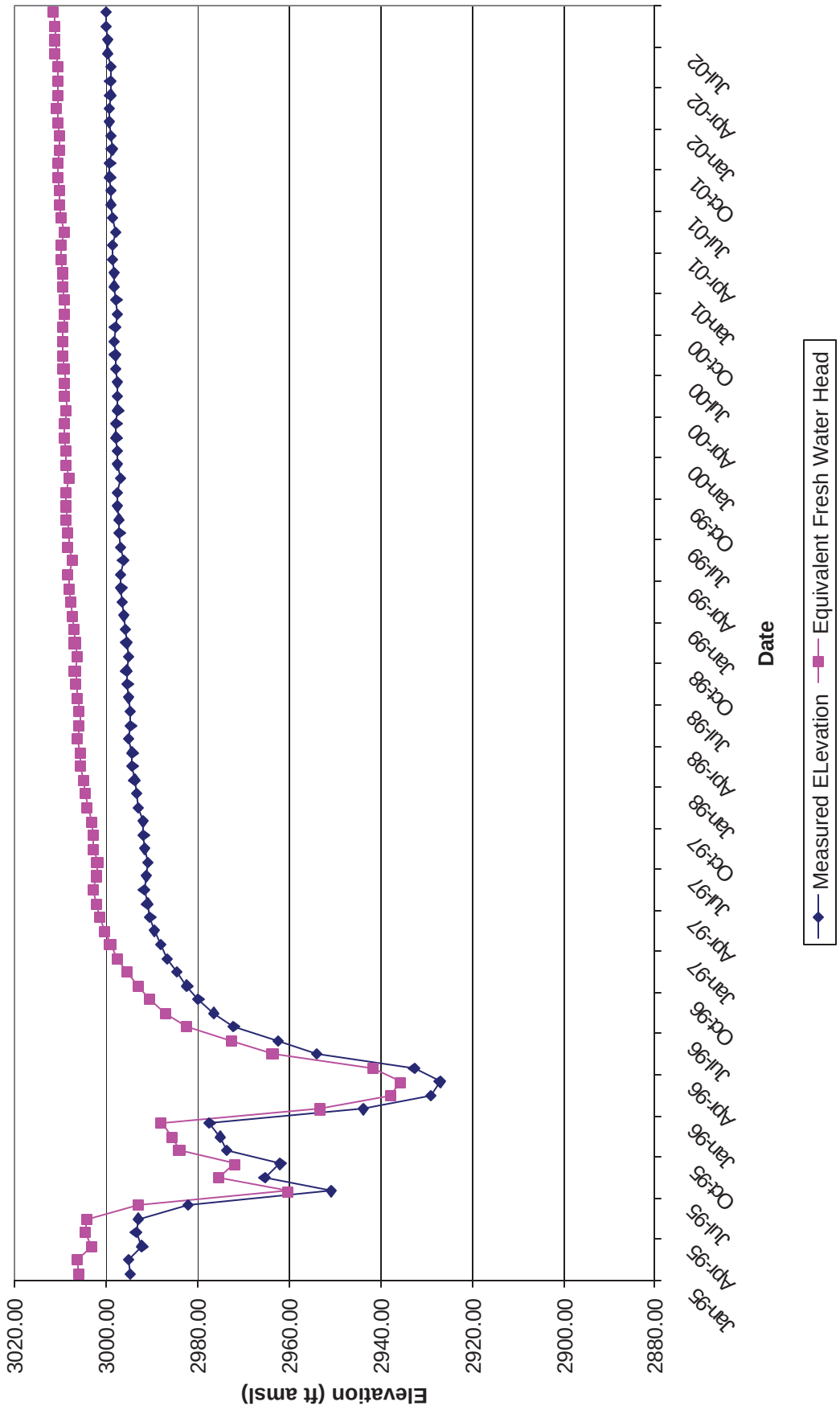

Table 20 - Well No. H-03b3 Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2992.38	3001.87
06/07/95	2982.25	2991.40
09/07/95	2961.99	2970.47
12/06/95	2977.81	2986.82
03/13/96	2927.18	2934.51
06/12/96	2962.77	2971.28
09/05/96	2979.85	2988.92
12/10/96	2986.98	2996.29
03/12/97	2990.67	3000.10
06/12/97	2991.24	3000.69
09/17/97	2992.16	3001.64
12/10/97	2993.55	3003.07

Date	Measured Elevation	Equivalent Fresh Water Head
03/11/98	2994.55	3004.11
06/10/98	2994.78	3004.35
09/10/98	2995.70	3005.30
12/09/98	2996.09	3005.70
03/16/99	2997.05	3006.69
06/09/99	2997.02	3006.66
09/09/99	2997.74	3007.40
12/08/99	2997.79	3007.45
03/08/00	2997.91	3007.58
06/07/00	2997.93	3007.60
09/11/00	2998.43	3008.12
12/06/00	2997.98	3007.65

Date	Measured Elevation	Equivalent Fresh Water Head
03/08/01	2998.33	3008.01
06/06/01	2998.82	3008.52
09/06/01	2999.47	3009.19
12/05/01	2999.00	3008.70
03/18/02	3003.45	3013.30
06/10/02	3004.04	3013.91
09/10/02	3004.41	3014.29

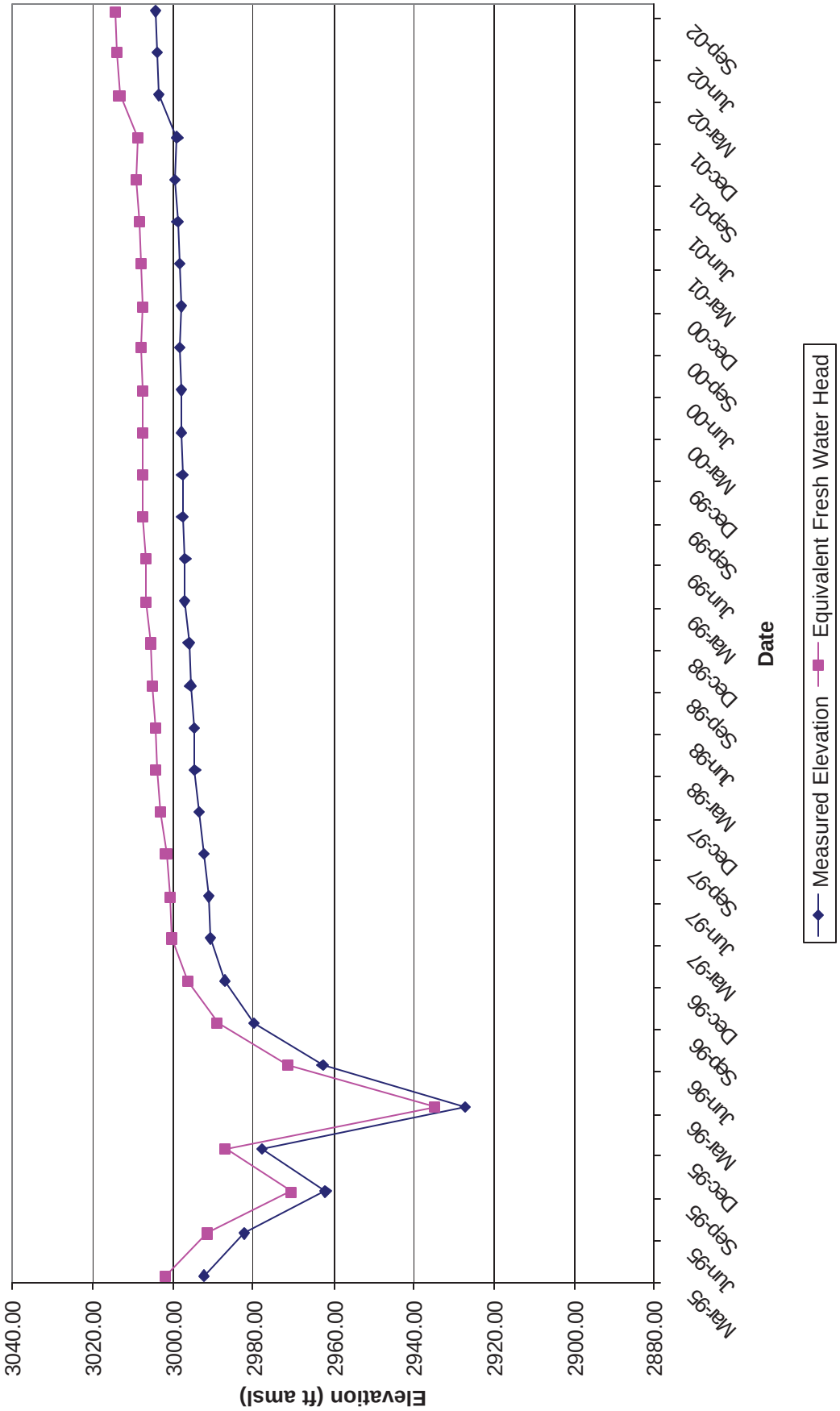
Figure 20 - H-3b3 Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
2880.00
Mar-95
Jun-95
Sep-95
Dec-95
Mar-96
Jun-96
Sep-96
Dec-96
Mar-97
Jun-97
Sep-97
Dec-97
Mar-98
Jun-98
Sep-98
Dec-98
Mar-99
Jun-99
Sep-99
Dec-99
Mar-00
Jun-00
Sep-00
Dec-00
Mar-01
Jun-01
Sep-01
Dec-01
Mar-02
Jun-02
Sep-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 21 - Well No. H-03d/49 (PIP) 49er
January 1995 through February 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3081.68	N/A
02/15/95	3081.74	N/A
03/14/95	3081.83	N/A
04/12/95	3081.84	N/A
05/10/95	3082.02	N/A
06/07/95	3082.17	N/A
07/20/95	3082.38	N/A
08/17/95	3082.47	N/A
09/07/95	3082.42	N/A
10/18/95	3082.77	N/A
11/08/95	3082.81	N/A
12/06/95	3082.79	N/A
01/10/96	3082.91	N/A
02/07/96	3082.98	N/A
03/13/96	3083.38	N/A
04/17/96	3083.26	N/A
05/15/96	3083.34	N/A
06/12/96	3083.43	N/A
07/17/96	3083.46	N/A
08/13/96	3083.52	N/A
09/05/96	3083.63	N/A
10/17/96	3083.71	N/A
11/13/96	3083.70	N/A
12/10/96	3083.79	N/A
01/16/97	3083.84	N/A
02/12/97	3083.93	N/A
03/12/97	3084.07	N/A
04/16/97	3084.26	N/A
05/14/97	3084.44	N/A
06/12/97	3084.49	N/A
07/16/97	3084.52	N/A
08/13/97	3084.61	N/A
09/17/97	3084.56	N/A
10/15/97	3084.73	N/A
11/12/97	3084.82	N/A
12/10/97	3084.89	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3085.10	N/A
02/11/98	3085.26	N/A
03/11/98	3085.39	N/A
04/15/98	3085.54	N/A
05/13/98	3085.56	N/A
06/10/98	3085.52	N/A
07/15/98	3085.46	N/A
08/12/98	3085.59	N/A
09/10/98	3085.63	N/A
10/14/98	3085.65	N/A
11/11/98	3085.85	N/A
12/09/98	3085.95	N/A
01/13/99	3086.08	N/A
02/10/99	3086.20	N/A
03/16/99	3086.37	N/A
04/13/99	3086.48	N/A
05/11/99	3086.68	N/A
06/09/99	3086.69	N/A
07/21/99	3086.84	N/A
08/11/99	3086.79	N/A
09/09/99	3086.79	N/A
10/05/99	3086.94	N/A
11/10/99	3087.03	N/A
12/08/99	3087.12	N/A
01/19/00	3087.31	N/A
02/15/00	3087.48	N/A
03/08/00	3087.62	N/A
04/18/00	3087.91	N/A
05/17/00	3088.12	N/A
06/07/00	3088.22	N/A
07/10/00	3088.70	N/A
08/14/00	3088.84	N/A
09/11/00	3088.97	N/A
10/11/00	3089.04	N/A
11/08/00	3089.38	N/A
12/06/00	3089.45	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3089.71	N/A
02/06/01	3089.86	N/A
03/08/01	3090.18	N/A
04/05/01	3090.42	N/A
05/09/01	3090.73	N/A
06/06/01	3090.89	N/A
07/10/01	3091.00	N/A
08/07/01	3090.97	N/A
09/06/01	3091.23	N/A
10/10/01	3091.39	N/A
11/14/01	3091.61	N/A
12/05/01	3091.64	N/A
01/16/02	3091.95	N/A
02/05/02	3092.15	N/A

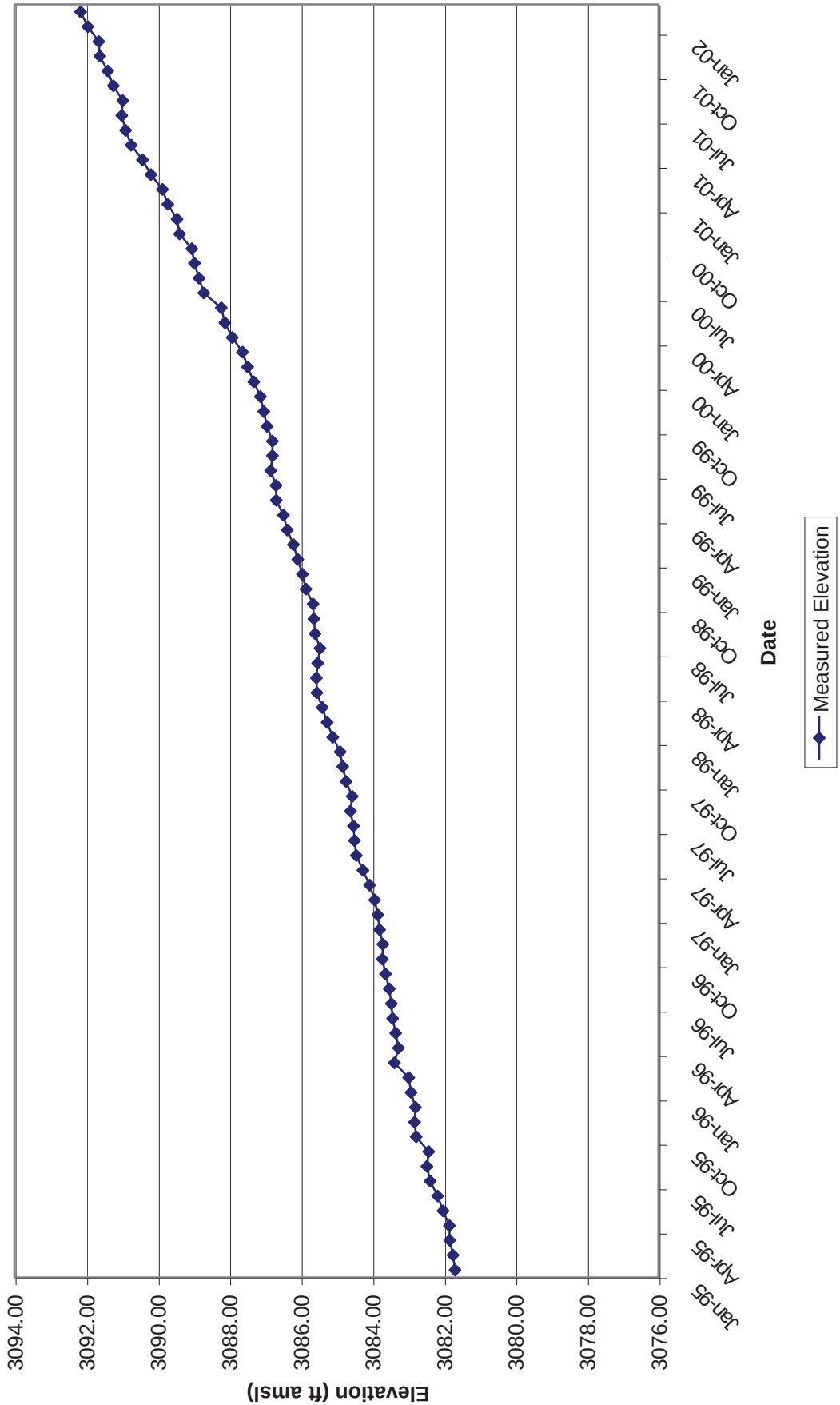
Figure 21 - H-3d 49er
Historical Waterlevel Measurements
Elevation (ft amsl)
3094.00
3092.00
3090.00
3088.00
3086.00
3084.00
3082.00
3080.00
3078.00
3076.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Date
Measured Elevation

Table 22 - Well No. H-03d (PVC) Dewey Lake
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3074.91	N/A
02/15/95	3074.79	N/A
03/14/95	3074.67	N/A
04/12/95	3074.43	N/A
05/10/95	3074.44	N/A
06/07/95	3074.41	N/A
07/20/95	3074.23	N/A
08/17/95	3074.16	N/A
09/07/95	3074.00	N/A
10/18/95	3073.86	N/A
11/08/95	3073.78	N/A
12/06/95	3073.78	N/A
01/10/96	3073.65	N/A
02/07/96	3073.44	N/A
03/13/96	3073.38	N/A
04/17/96	3073.29	N/A
05/15/96	3073.23	N/A
06/12/96	3073.25	N/A
07/17/96	3073.13	N/A
08/13/96	3073.07	N/A
09/05/96	3073.00	N/A
10/17/96	3072.92	N/A
11/13/96	3072.87	N/A
12/10/96	3072.82	N/A
01/16/97	3072.73	N/A
02/12/97	3072.65	N/A
03/12/97	3072.63	N/A
04/16/97	3072.63	N/A
05/14/97	3072.62	N/A
06/12/97	3072.60	N/A
07/16/97	3072.35	N/A
08/13/97	3072.54	N/A
09/17/97	3072.51	N/A
10/15/97	3072.49	N/A
11/12/97	3072.44	N/A
12/10/97	3072.43	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3072.41	N/A
02/11/98	3072.45	N/A
03/11/98	3072.45	N/A
04/15/98	3072.44	N/A
05/13/98	3072.45	N/A
06/10/98	3072.45	N/A
07/15/98	3072.35	N/A
08/12/98	3072.43	N/A
09/10/98	3072.43	N/A
10/14/98	3072.35	N/A
11/11/98	3072.39	N/A
12/09/98	3072.32	N/A
01/13/99	3072.31	N/A
02/10/99	3072.32	N/A
03/16/99	3072.39	N/A
04/13/99	3072.41	N/A
05/11/99	3072.43	N/A
06/09/99	3072.45	N/A
07/21/99	3072.45	N/A
08/11/99	3072.50	N/A
09/09/99	3072.51	N/A
10/05/99	3072.52	N/A
11/10/99	3072.52	N/A
12/08/99	3072.52	N/A
01/19/00	3072.49	N/A
02/15/00	3072.51	N/A
03/08/00	3072.52	N/A
04/18/00	3072.58	N/A
05/17/00	3072.61	N/A
06/07/00	3072.64	N/A
07/10/00	3072.71	N/A
08/14/00	3072.78	N/A
09/11/00	3072.82	N/A
10/11/00	3072.88	N/A
11/08/00	3072.94	N/A
12/06/00	3073.01	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3073.10	N/A
02/06/01	3073.09	N/A
03/08/01	3073.25	N/A
04/05/01	3073.32	N/A
05/09/01	3073.46	N/A
06/06/01	3073.53	N/A
07/10/01	3073.65	N/A
08/07/01	3073.70	N/A
09/04/01	3073.79	N/A
10/10/01	3073.86	N/A
11/14/01	3073.94	N/A
12/05/01	3073.96	N/A
01/16/02	3074.10	N/A
02/05/02	3074.21	N/A
03/18/02	3074.14	N/A
04/09/02	3074.21	N/A
05/07/02	3074.33	N/A
06/10/02	3074.44	N/A
07/17/02	3074.51	N/A
08/14/02	3074.60	N/A
09/10/02	3074.68	N/A

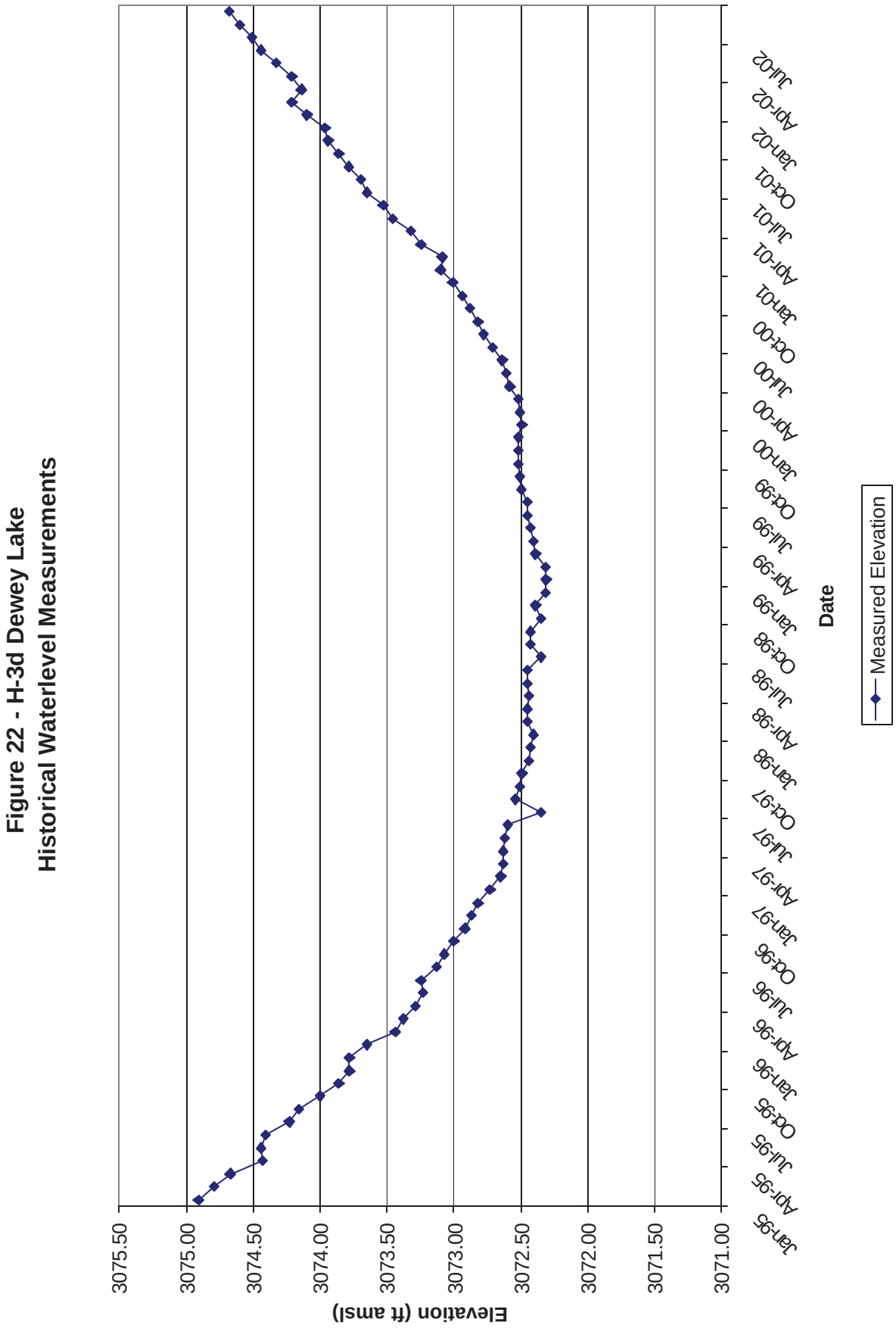
Figure 22 - H-3d Dewey Lake
Historical Waterlevel Measurements
Elevation (ft amsl)
3075.50
3075.00
3074.50
3074.00
3073.50
3073.00
3072.50
3072.00
3071.50
3071.00
Date
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Measured Elevation

Table 23 - Well No. H-04b Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	2999.48	3003.03
02/15/95	2999.76	3003.32
03/14/95	2999.67	3003.23
04/12/95	2999.73	3003.29
05/10/95	3000.01	3003.57
06/07/95	3000.30	3003.87
07/19/95	3000.15	3003.72
08/17/95	3000.12	3003.69
09/07/95	2999.66	3003.22
10/18/95	2999.56	3003.11
11/08/95	2999.35	3002.90
12/06/95	2999.47	3003.02
01/10/96	2999.50	3003.05
02/07/96	2999.48	3003.03
03/14/96	2999.01	3002.55
04/17/96	2998.44	3001.97
05/15/96	2998.70	3002.24
06/12/96	2999.05	3002.59
07/17/96	2999.32	3002.87
08/13/96	2999.75	3003.31
09/05/96	2999.93	3003.49
10/16/96	3000.09	3003.65
11/13/96	2999.93	3003.49
12/11/96	3000.24	3003.81
01/14/97	3000.21	3003.78
02/12/97	3000.14	3003.71
03/12/97	2999.57	3003.12
04/16/97	2998.79	3002.33
05/14/97	2998.70	3002.24
06/12/97	2998.47	3002.00
07/16/97	2998.05	3001.57
08/13/97	2998.00	3001.52
09/16/97	2998.44	3001.97
10/15/97	2998.36	3001.89
11/12/97	2998.77	3002.31
12/10/97	2998.89	3002.43

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2999.14	3002.68
02/11/98	2999.29	3002.84
03/11/98	2999.21	3002.76
04/15/98	2999.73	3003.29
05/12/98	2999.56	3003.11
06/10/98	2999.28	3002.83
07/15/98	2999.20	3002.75
08/12/98	2999.15	3002.69
09/10/98	2999.27	3002.82
10/14/98	2999.33	3002.88
11/11/98	2999.36	3002.91
12/09/98	2999.36	3002.91
01/12/99	2999.73	3003.29
02/10/99	2999.78	3003.34
03/10/99	3000.02	3003.58
04/13/99	3000.17	3003.74
05/11/99	3000.27	3003.84
06/09/99	3000.45	3004.02
07/21/99	3000.27	3003.84
08/11/99	3000.42	3003.99
09/09/99	3000.39	3003.96
10/05/99	3000.19	3003.76
11/10/99	3000.13	3003.70
12/08/99	3000.27	3003.84
01/19/00	3000.13	3003.70
02/15/00	3000.19	3003.76
03/08/00	3002.66	3006.28
04/17/00	3000.34	3003.91
05/17/00	3000.61	3004.19
06/07/00	3000.36	3003.93
07/12/00	3000.45	3004.02
08/14/00	3001.30	3004.89
09/11/00	3000.49	3004.06
10/10/00	3000.26	3003.83
11/09/00	3000.55	3004.12
12/06/00	3000.30	3003.87

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3000.50	3004.07
02/07/01	3000.75	3004.33
03/08/01	3000.95	3004.53
04/05/01	3001.06	3004.64
05/09/01	3001.10	3004.69
06/06/01	3001.38	3004.97
07/11/01	3001.16	3004.75
08/07/01	3000.99	3004.57
09/06/01	3001.11	3004.70
10/10/01	3001.04	3004.62
11/14/01	3001.17	3004.76
12/05/01	3001.07	3004.66
01/16/02	3001.24	3004.83
02/05/02	3001.31	3004.90
03/13/02	3001.66	3005.26
04/09/02	3001.52	3005.11
05/08/02	3001.86	3005.46
06/10/02	3002.01	3005.61
07/16/02	3001.81	3005.41
08/12/02	3001.92	3005.52
09/11/02	3001.73	3005.33

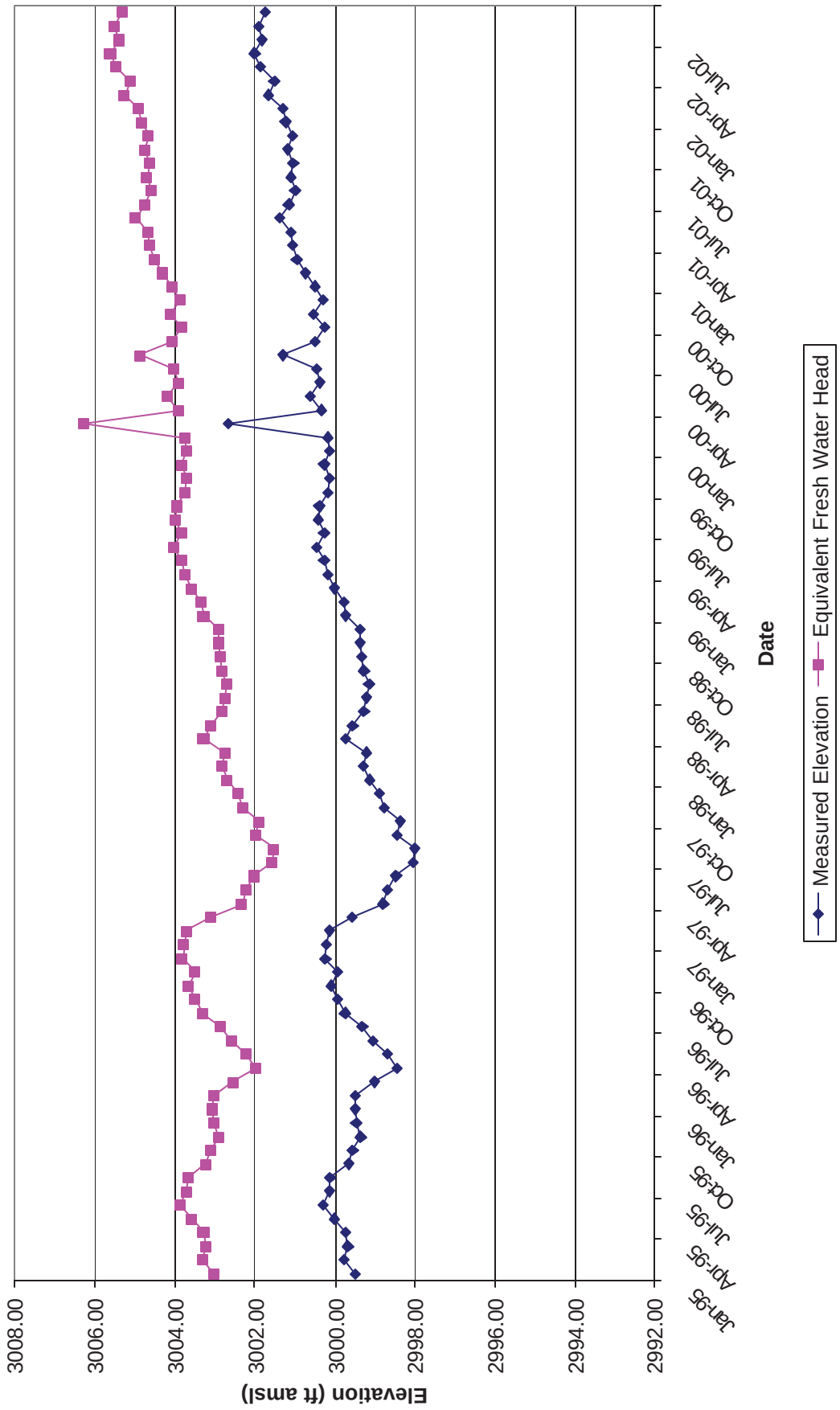
Figure 23 - H-4b Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3008.00
3006.00
3004.00
3002.00
3000.00
2998.00
2996.00
2994.00
2992.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 24 - Well No. H-04c Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3141.97	N/A
02/15/95	3142.01	N/A
03/14/95	3141.92	N/A
04/12/95	3141.94	N/A
05/10/95	3142.04	N/A
06/07/95	3142.16	N/A
07/19/95	3142.19	N/A
08/17/95	3142.13	N/A
09/07/95	3142.02	N/A
10/18/95	3142.18	N/A
11/08/95	3142.09	N/A
12/06/95	3142.10	N/A
01/10/96	3142.08	N/A
02/07/96	3142.12	N/A
03/14/96	3142.26	N/A
04/17/96	3142.35	N/A
05/15/96	3142.35	N/A
06/12/96	3142.36	N/A
07/17/96	3142.50	N/A
08/13/96	3142.38	N/A
09/05/96	3142.57	N/A
10/16/96	3142.45	N/A
11/13/96	3142.34	N/A
12/11/96	3142.48	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3142.84	N/A
02/11/98	3142.89	N/A
03/11/98	3142.93	N/A
04/15/98	3143.00	N/A
05/12/98	3143.01	N/A
06/10/98	3142.91	N/A
07/15/98	3142.89	N/A
08/12/98	3142.96	N/A
09/10/98	3142.93	N/A
10/14/98	3142.96	N/A
11/11/98	3143.11	N/A
12/09/98	3143.02	N/A
01/12/99	3143.05	N/A
02/10/99	3143.16	N/A
03/10/99	3143.22	N/A
04/13/99	3143.22	N/A
05/11/99	3143.33	N/A
06/09/99	3143.40	N/A
07/21/99	3143.15	N/A
08/11/99	3143.27	N/A
09/09/99	3143.25	N/A
10/05/99	3143.19	N/A
11/10/99	3143.19	N/A
12/08/99	3143.28	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3143.98	N/A
02/07/01	3144.04	N/A
03/08/01	3144.16	N/A
04/05/01	3144.30	N/A
05/09/01	3144.18	N/A
06/06/01	3144.32	N/A
07/11/01	3144.19	N/A
08/07/01	3144.19	N/A
09/06/01	3144.33	N/A
10/10/01	3144.28	N/A
11/14/01	3144.22	N/A
12/05/01	3144.33	N/A
01/16/02	3144.31	N/A
02/05/02	3144.31	N/A
03/13/02	3144.44	N/A
04/08/02	3144.58	N/A
05/08/02	3144.60	N/A
06/10/02	3144.57	N/A
07/16/02	3144.53	N/A
08/12/02	3144.52	N/A
09/11/02	3144.39	N/A

01/14/97	3142.41	N/A
02/12/97	3142.44	N/A
03/12/97	3142.56	N/A
04/16/97	3142.57	N/A
05/14/97	3142.70	N/A
06/12/97	3142.69	N/A
07/16/97	3142.75	N/A
08/13/97	3142.69	N/A
09/16/97	3142.69	N/A
10/15/97	3142.67	N/A
11/12/97	3142.73	N/A
12/10/97	3142.79	N/A

01/19/00	3143.20	N/A
02/15/00	3143.32	N/A
03/08/00	3152.87	N/A
04/17/00	3144.60	N/A
05/17/00	3144.19	N/A
06/07/00	3144.01	N/A
07/12/00	3144.19	N/A
08/14/00	3145.24	N/A
09/11/00	3144.28	N/A
10/10/00	3143.90	N/A
11/09/00	3144.13	N/A
12/06/00	3143.93	N/A

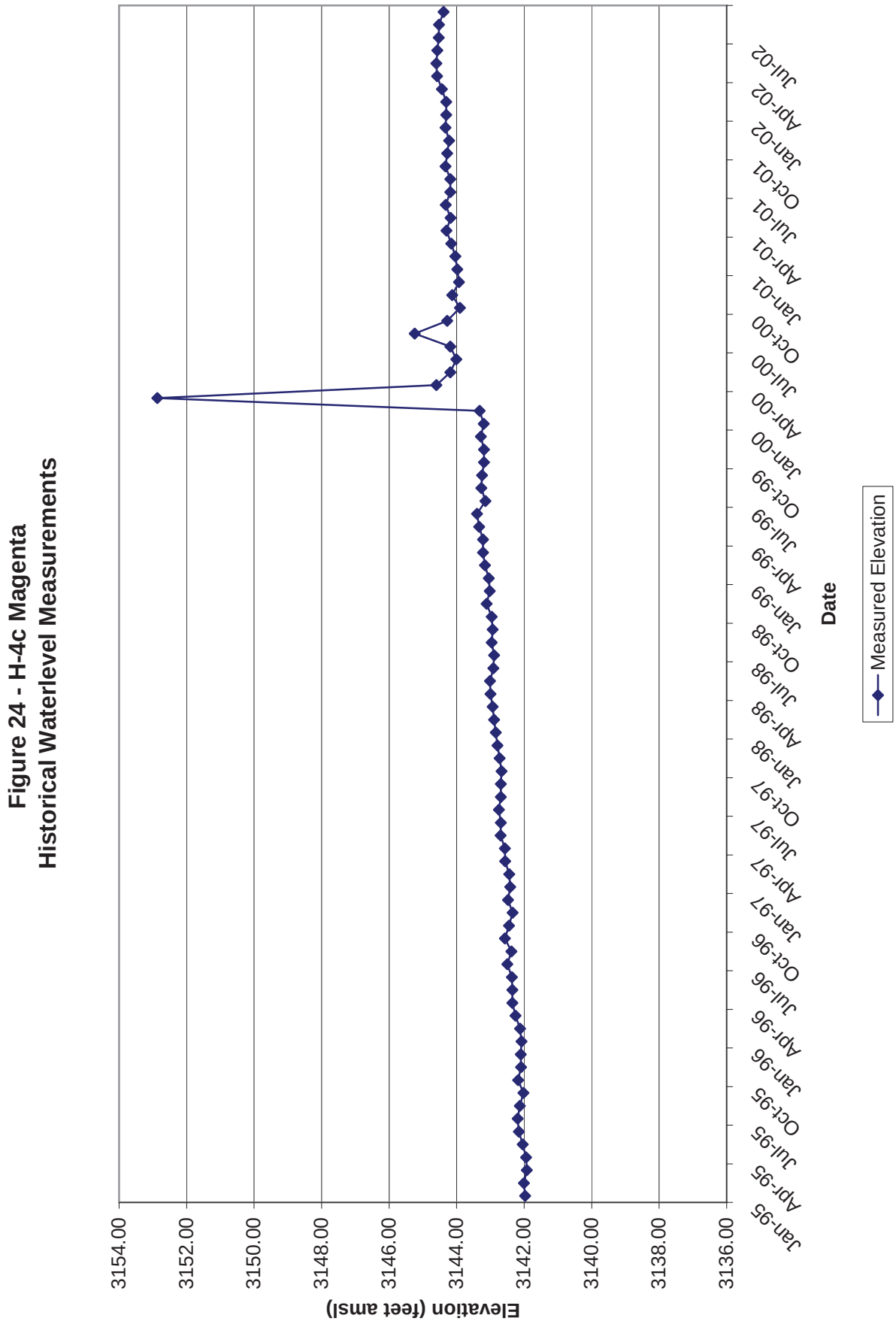
Figure 24 - H-4c Magenta
Historical Waterlevel Measurements
Elevation (feet amsl)
3154.00
3152.00
3150.00
3148.00
3146.00
3144.00
3142.00
3140.00
3138.00
3136.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation

Table 25 - Well No. H-05a Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/15/95	3028.81	3068.53
06/07/95	3029.12	3068.87
09/07/95	3029.14	3068.89
12/06/95	3028.93	3068.66
03/13/96	3029.63	3069.43
06/12/96	3029.72	3069.52
09/05/96	3029.30	3069.07
12/11/96	3029.83	3069.64
03/12/97	3029.29	3069.06
06/12/97	3029.93	3069.75
09/17/97	3029.88	3069.70
12/10/97	3030.06	3069.90

Date	Measured Elevation	Equivalent Fresh Water Head
03/11/98	3030.01	3069.84
06/10/98	3030.28	3070.14
09/10/98	3030.37	3070.23
12/07/98	3030.48	3070.35
03/10/99	3030.64	3070.53
06/09/99	3030.73	3070.63
09/09/99	3030.70	3070.60
12/08/99	3030.89	3070.80
03/08/00	3030.88	3070.79
06/05/00	3030.86	3070.77
09/12/00	3031.04	3070.97
12/07/00	3031.05	3070.98

Date	Measured Elevation	Equivalent Fresh Water Head
03/07/01	3031.15	3071.09
06/07/01	3031.19	3071.13
09/10/01	3031.01	3070.93
12/04/01	3031.30	3071.25
03/12/02	3031.34	3071.29
06/12/02	3031.50	3071.47
09/10/02	3031.41	3071.37

Figure 25 - H-5a Culebra
Historical Waterlevel Measrurements

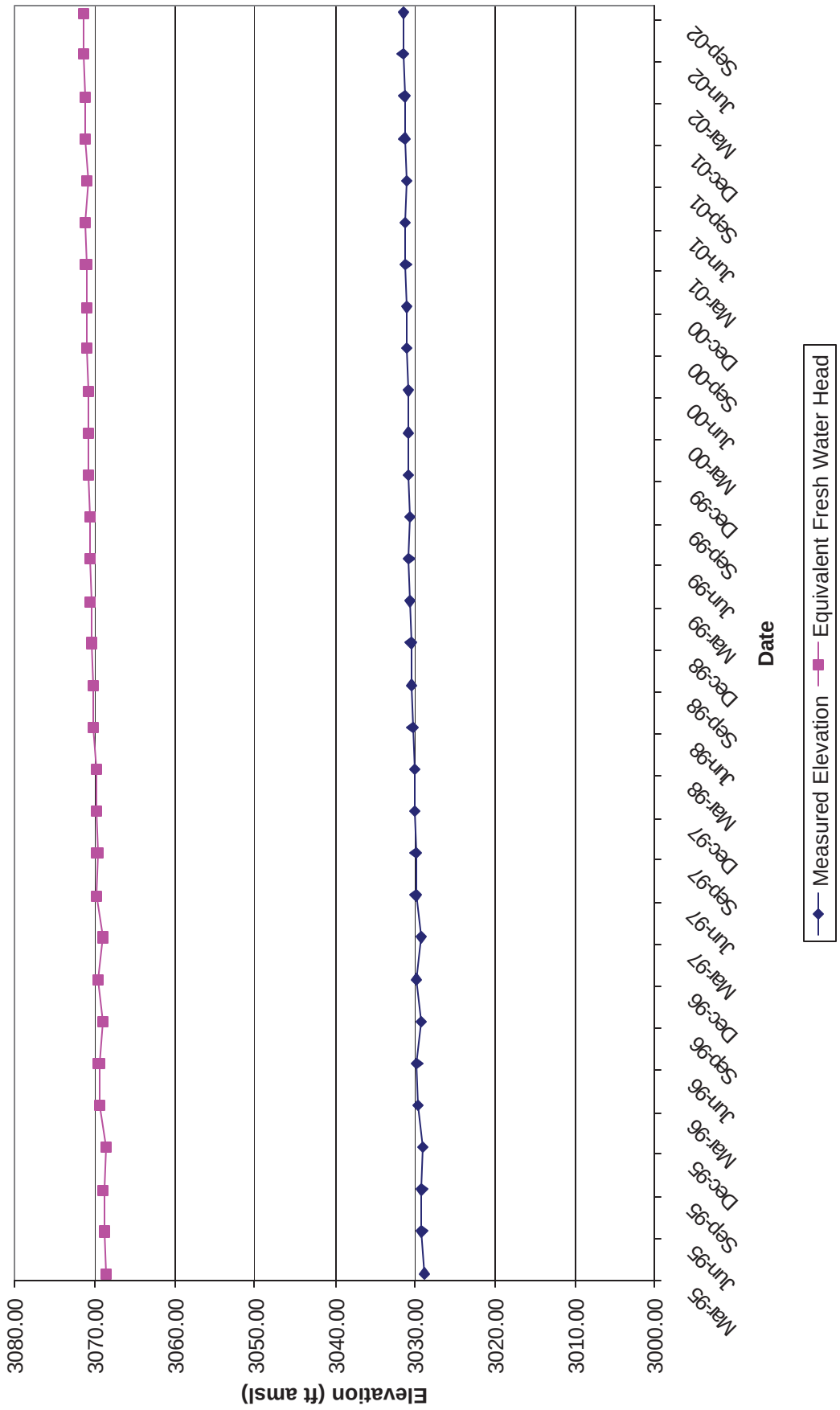

Table 26 - Well No. H-05b Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3026.03	3070.66
02/14/95	3026.08	3070.72
03/13/95	3026.11	3070.75
04/12/95	3025.92	3070.54
05/08/95	3026.35	3071.01
06/05/95	3026.37	3071.04
07/19/95	3026.46	3071.14
08/16/95	3026.56	3071.25
09/08/95	3026.39	3071.06
10/18/95	3026.59	3071.28
11/08/95	3026.50	3071.18
12/06/95	3026.61	3071.30
01/10/96	3026.64	3071.34
02/07/96	3026.68	3071.38
03/13/96	3026.90	3071.62
04/17/96	3026.89	3071.61
05/15/96	3026.90	3071.62
06/12/96	3027.04	3071.78
07/17/96	3026.46	3071.14
08/14/96	3026.93	3071.66
09/05/96	3027.04	3071.78
10/16/96	3027.04	3071.78
11/13/96	3026.83	3071.54
12/11/96	3027.06	3071.80
01/14/97	3026.93	3071.66
02/12/97	3026.96	3071.69
03/12/97	3027.00	3071.73
04/16/97	3027.09	3071.83
05/14/97	3027.51	3072.30
06/12/97	3027.22	3071.98
07/16/97	3027.08	3071.82
08/13/97	3027.08	3071.82
09/17/97	3027.18	3071.93
10/16/97	3027.12	3071.86
11/12/97	3027.35	3072.12
12/10/97	3027.36	3072.13

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3027.38	3072.15
02/11/98	3027.49	3072.27
03/11/98	3027.32	3072.09
04/15/98	3027.69	3072.49
05/13/98	3027.70	3072.51
06/10/98	3027.62	3072.42
07/15/98	3027.65	3072.45
08/12/98	3027.62	3072.42
09/10/98	3027.70	3072.51
10/14/98	3027.70	3072.51
11/11/98	3027.66	3072.46
12/07/98	3027.80	3072.62
01/13/99	3027.80	3072.62
02/08/99	3027.83	3072.65
03/10/99	3027.93	3072.76
04/13/99	3027.95	3072.78
05/12/99	3027.96	3072.79
06/09/99	3028.06	3072.90
07/21/99	3027.92	3072.75
08/11/99	3028.09	3072.94
09/09/99	3028.03	3072.87
10/06/99	3027.99	3072.83
11/10/99	3028.02	3072.86
12/08/99	3028.14	3072.99
01/19/00	3028.07	3072.91
02/16/00	3028.11	3072.96
03/08/00	3028.21	3073.07
04/19/00	3028.30	3073.17
05/15/00	3028.20	3073.06
06/05/00	3028.20	3073.06
07/11/00	3028.47	3073.36
08/15/00	3028.34	3073.21
09/12/00	3028.43	3073.31
10/11/00	3028.23	3073.09
11/06/00	3028.57	3073.47
12/07/00	3028.30	3073.17

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3028.37	3073.24
02/06/01	3028.33	3073.20
03/07/01	3028.45	3073.33
04/04/01	3028.64	3073.54
05/08/01	3028.42	3073.30
06/07/01	3028.54	3073.43
07/10/01	3028.48	3073.37
08/08/01	3028.44	3073.32
09/10/01	3028.42	3073.30
10/10/01	3028.55	3073.44
11/13/01	3028.49	3073.38
12/04/01	3028.57	3073.47
01/16/02	3028.53	3073.42
02/06/02	3028.58	3073.48
03/12/02	3028.65	3073.55
04/09/02	3028.74	3073.65
05/08/02	3028.85	3073.77
06/12/02	3028.84	3073.76
07/15/02	3028.79	3073.71
08/13/02	3028.86	3073.79
09/10/02	3028.77	3073.69

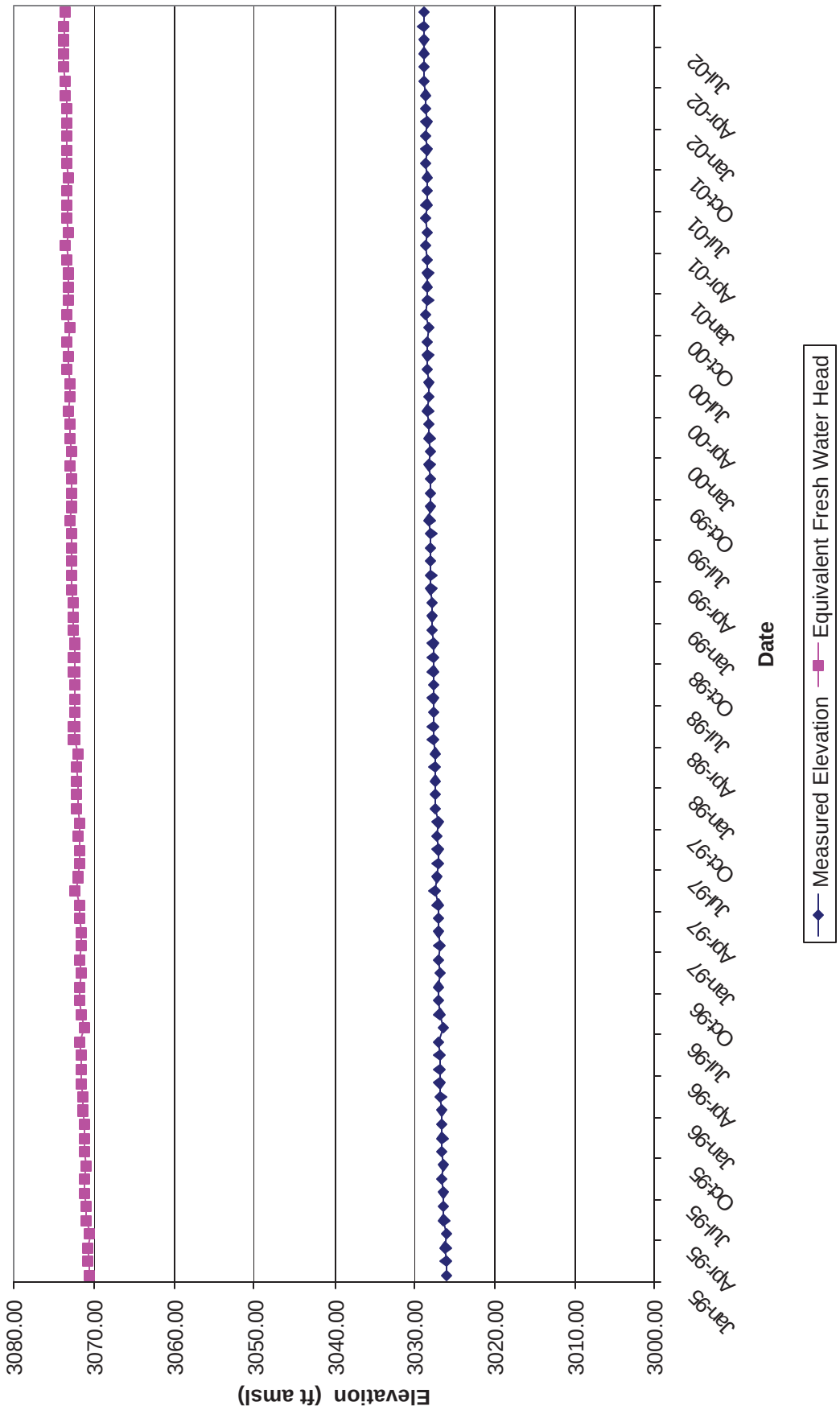
Figure 26 - H-5b Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
3080.00
3070.00
3060.00
3050.00
3040.00
3030.00
3020.00
3010.00
3000.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 27 - Well No. H-05c Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3156.04	N/A
02/14/95	3155.96	N/A
03/13/95	3155.93	N/A
04/12/95	3155.76	N/A
05/08/95	3156.03	N/A
06/05/95	3156.01	N/A
07/19/95	3155.92	N/A
08/16/95	3156.00	N/A
09/08/95	3155.86	N/A
10/18/95	3155.93	N/A
11/08/95	3155.86	N/A
12/06/95	3155.92	N/A
01/10/96	3155.98	N/A
02/07/96	3155.91	N/A
03/13/96	3156.10	N/A
04/17/96	3156.08	N/A
05/15/96	3156.08	N/A
06/12/96	3156.13	N/A
07/17/96	3156.08	N/A
08/14/96	3156.02	N/A
09/05/96	3156.21	N/A
10/16/96	3156.14	N/A
11/13/96	3155.93	N/A
12/11/96	3156.13	N/A
01/14/97	3156.01	N/A
02/12/97	3156.00	N/A
03/12/97	3156.06	N/A
04/16/97	3156.08	N/A
05/14/97	3156.26	N/A
06/12/97	3156.29	N/A
07/16/97	3156.06	N/A
08/13/97	3156.03	N/A
09/17/97	3156.12	N/A
10/16/97	3156.13	N/A
11/12/97	3156.25	N/A
12/10/97	3156.25	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3156.23	N/A
02/11/98	3156.29	N/A
03/11/98	3156.13	N/A
04/15/98	3156.52	N/A
05/13/98	3156.41	N/A
06/10/98	3156.28	N/A
07/15/98	3156.23	N/A
08/12/98	3156.15	N/A
09/10/98	3156.22	N/A
10/14/98	3156.19	N/A
11/11/98	3156.18	N/A
12/07/98	3156.29	N/A
01/13/99	3156.29	N/A
02/08/99	3156.34	N/A
03/10/99	3156.59	N/A
04/13/99	3156.42	N/A
05/12/99	3156.48	N/A
06/09/99	3156.52	N/A
07/21/99	3156.38	N/A
08/11/99	3156.70	N/A
09/09/99	3156.49	N/A
10/06/99	3156.45	N/A
11/10/99	3156.50	N/A
12/08/99	3156.62	N/A
01/19/00	3156.59	N/A
02/16/00	3156.63	N/A
03/08/00	3156.72	N/A
04/19/00	3156.79	N/A
05/15/00	3156.74	N/A
06/05/00	3156.74	N/A
07/11/00	3156.95	N/A
08/15/00	3156.89	N/A
09/12/00	3156.92	N/A
10/11/00	3156.80	N/A
11/06/00	3157.19	N/A
12/07/00	3156.91	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3156.96	N/A
02/06/01	3157.04	N/A
03/07/01	3157.09	N/A
04/04/01	3157.33	N/A
05/08/01	3157.12	N/A
06/07/01	3157.39	N/A
07/10/01	3157.21	N/A
08/08/01	3157.20	N/A
09/10/01	3157.15	N/A
10/10/01	3157.29	N/A
11/13/01	3157.19	N/A
12/04/01	3157.29	N/A
01/16/02	3157.18	N/A
02/06/02	3157.24	N/A
03/12/02	3157.25	N/A
04/09/02	3157.27	N/A
05/08/02	3157.37	N/A
06/12/02	3157.30	N/A
07/15/02	3157.19	N/A
08/13/02	3157.22	N/A
09/10/02	3157.05	N/A

Figure 27 - H-5c Magenta
Historical Waterlevel Measurements

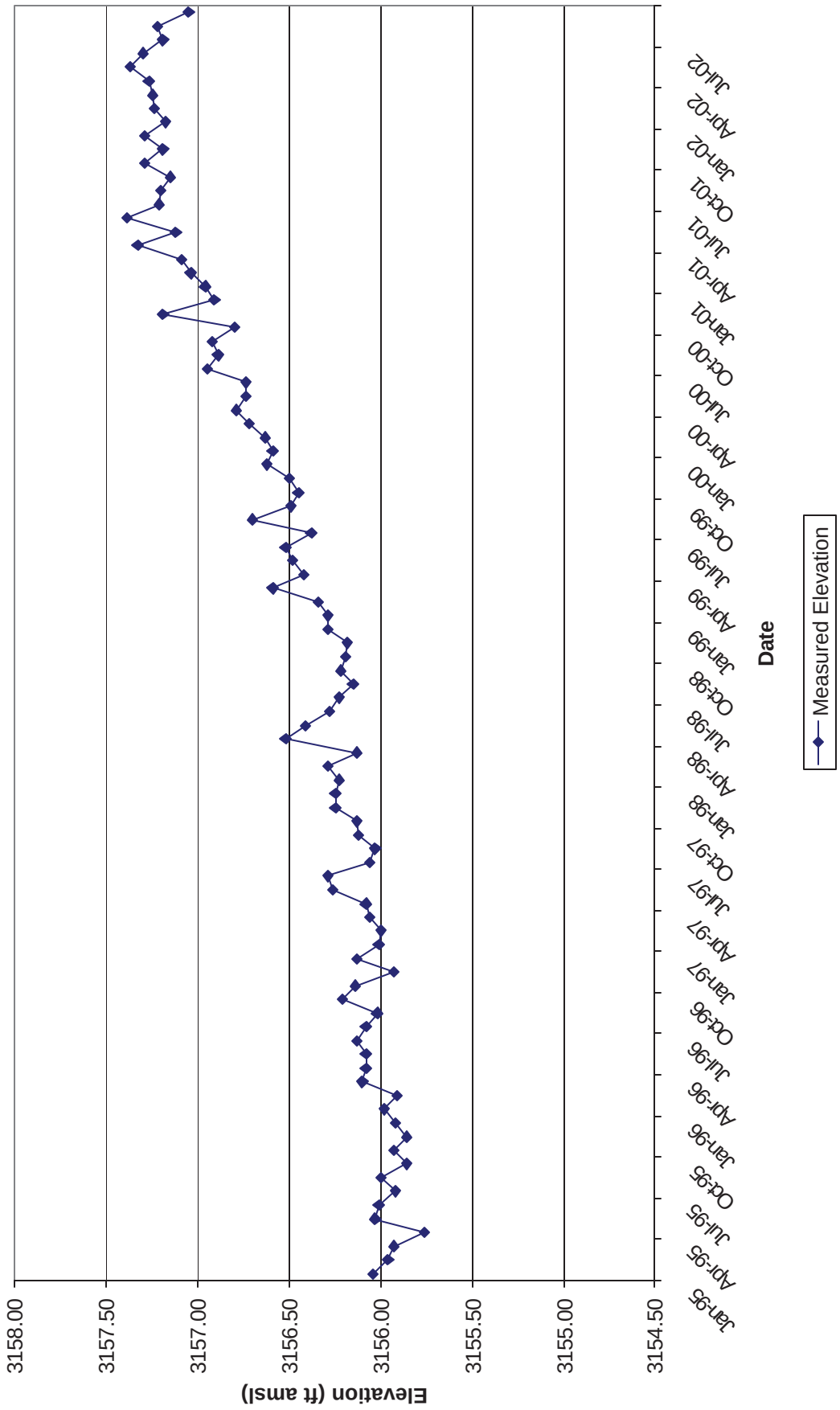

Table 28 - Well No. H-06a Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/13/95	3049.75	3061.83
06/05/95	3050.06	3062.16
09/05/95	3049.95	3062.04
12/04/95	3050.52	3062.63
03/11/96	3050.10	3062.20
06/10/96	3050.68	3062.80
09/03/96	3051.06	3063.19
12/09/96	3050.78	3062.90
03/10/97	3051.00	3063.13
06/09/97	3051.32	3063.46
09/15/97	3051.16	3063.30
12/08/97	3050.43	3062.54

Date	Measured Elevation	Equivalent Fresh Water Head
03/11/98	3051.63	3063.79
06/11/98	3051.01	3063.14
09/10/98	3050.82	3062.94
12/07/98	3050.63	3062.75
03/10/99	3051.17	3063.31
06/07/99	3051.23	3063.37
09/08/99	3050.98	3063.11
12/09/99	3051.86	3064.02
03/06/00	3052.41	3064.59
06/05/00	3052.00	3064.17
09/12/00	3052.17	3064.35
12/07/00	3052.32	3064.50

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/01	3052.57	3064.76
06/05/01	3052.95	3065.16
09/04/01	3053.01	3065.22
12/04/01	3053.14	3065.35
03/11/02	3053.99	3066.23
06/10/02	3054.46	3066.72
09/09/02	3054.72	3066.99

Figure 28 - H-6a Culebra
Historical Waterlevel Measurements

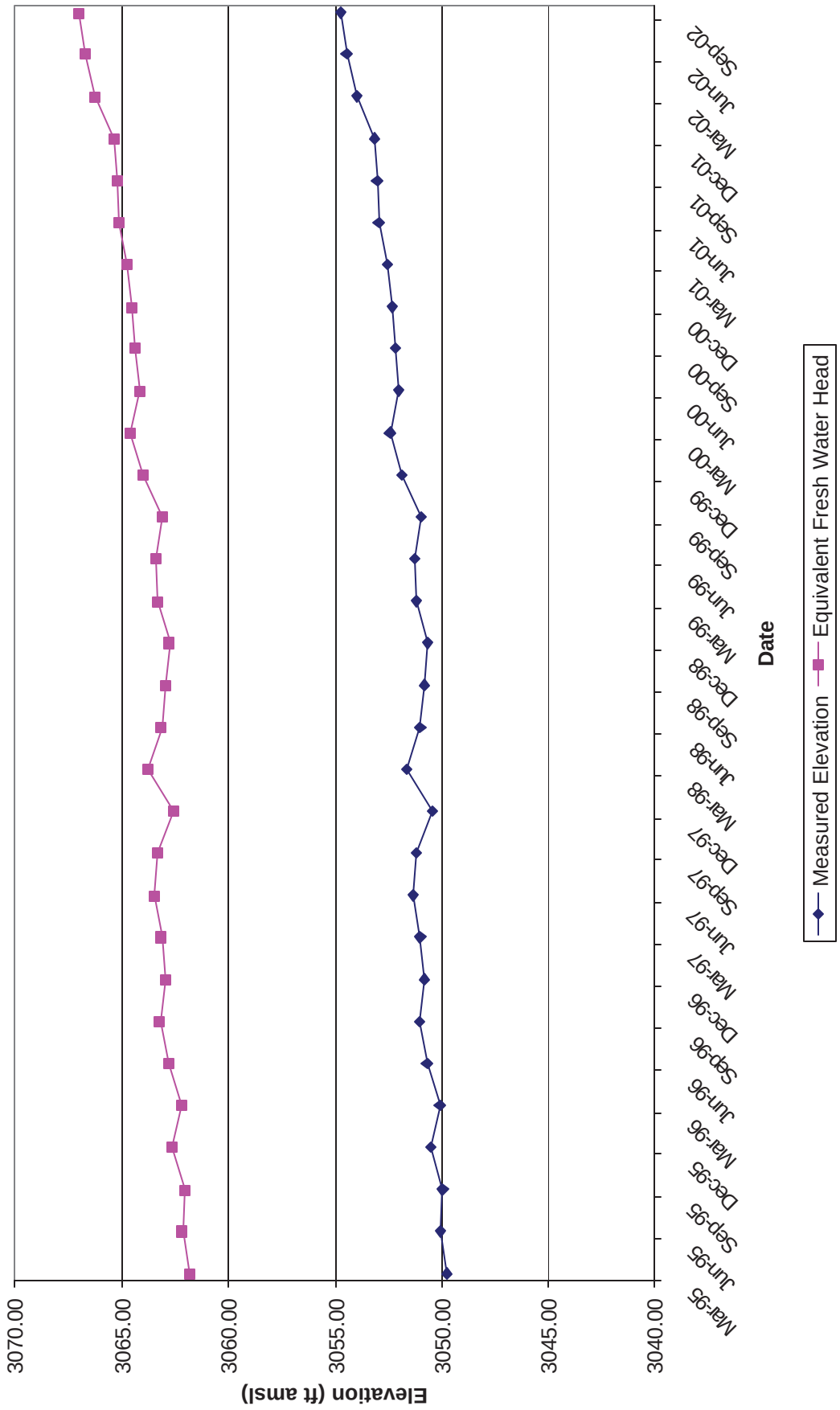

Table 29 - Well No. H-06b Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3049.30	3061.35
02/13/95	3049.23	3061.28
03/13/95	3049.20	3061.25
04/10/95	3049.20	3061.25
05/08/95	3049.40	3061.46
06/05/95	3049.48	3061.54
07/17/95	3049.68	3061.75
08/14/95	3049.89	3061.97
09/05/95	3049.38	3061.44
10/16/95	3049.81	3061.88
11/06/95	3049.97	3062.05
12/04/95	3049.82	3061.89
01/08/96	3049.80	3061.87
02/05/96	3049.34	3061.40
03/11/96	3049.62	3061.69
04/15/96	3049.40	3061.46
05/13/96	3049.75	3061.82
06/10/96	3049.98	3062.06
07/15/96	3050.00	3062.08
08/12/96	3049.88	3061.96
09/03/96	3050.34	3062.43
10/14/96	3050.24	3062.33
11/11/96	3049.98	3062.06
12/09/96	3050.07	3062.15
01/13/97	3050.06	3062.14
02/10/97	3050.12	3062.21
03/10/97	3050.27	3062.36
04/14/97	3050.45	3062.55
05/13/97	3050.59	3062.69
06/09/97	3050.62	3062.72
07/16/97	3050.74	3062.85
08/11/97	3050.64	3062.75
09/15/97	3050.48	3062.58
10/13/97	3050.12	3062.21
11/10/97	3050.03	3062.11
12/08/97	3049.76	3061.83

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3049.73	3061.80
02/09/98	3051.05	3063.17
03/11/98	3051.13	3063.25
04/15/98	3051.33	3063.46
05/11/98	3051.00	3063.12
06/11/98	3050.73	3062.84
07/15/98	3050.69	3062.80
08/12/98	3050.67	3062.78
09/10/98	3050.64	3062.75
10/14/98	3050.63	3062.74
11/11/98	3050.41	3062.51
12/07/98	3050.46	3062.56
01/11/99	3050.67	3062.78
02/09/99	3050.95	3063.07
03/10/99	3051.01	3063.13
04/12/99	3050.83	3062.94
05/10/99	3051.22	3063.35
06/07/99	3051.05	3063.17
07/19/99	3050.76	3062.87
08/09/99	3050.68	3062.79
09/08/99	3050.75	3062.86
10/04/99	3050.65	3062.76
11/08/99	3051.14	3063.26
12/09/99	3051.30	3063.43
01/19/00	3051.86	3064.01
02/14/00	3051.74	3063.89
03/06/00	3051.89	3064.04
04/17/00	3051.73	3063.88
05/15/00	3051.74	3063.89
06/05/00	3051.46	3063.60
07/11/00	3051.74	3063.89
08/15/00	3051.45	3063.59
09/12/00	3051.59	3063.73
10/09/00	3051.29	3063.42
11/06/00	3051.90	3064.05
12/07/00	3051.70	3063.85

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3051.80	3063.95
02/06/01	3051.93	3064.08
03/06/01	3051.92	3064.07
04/04/01	3052.21	3064.38
05/08/01	3052.00	3064.16
06/05/01	3052.28	3064.45
07/09/01	3052.31	3064.48
08/07/01	3052.26	3064.43
09/04/01	3052.37	3064.54
10/10/01	3052.42	3064.59
11/14/01	3052.63	3064.81
12/05/01	3052.50	3064.68
01/16/02	3052.86	3065.05
02/05/02	3052.99	3065.18
03/11/02	3053.26	3065.47
04/08/02	3053.49	3065.70
05/06/02	3053.55	3065.77
06/10/02	3053.71	3065.93
07/15/02	3053.88	3066.11
08/12/02	3054.00	3066.23
09/09/02	3053.94	3066.17

Figure 29 - H-6b Culebra
Historical Waterlevel Measurements

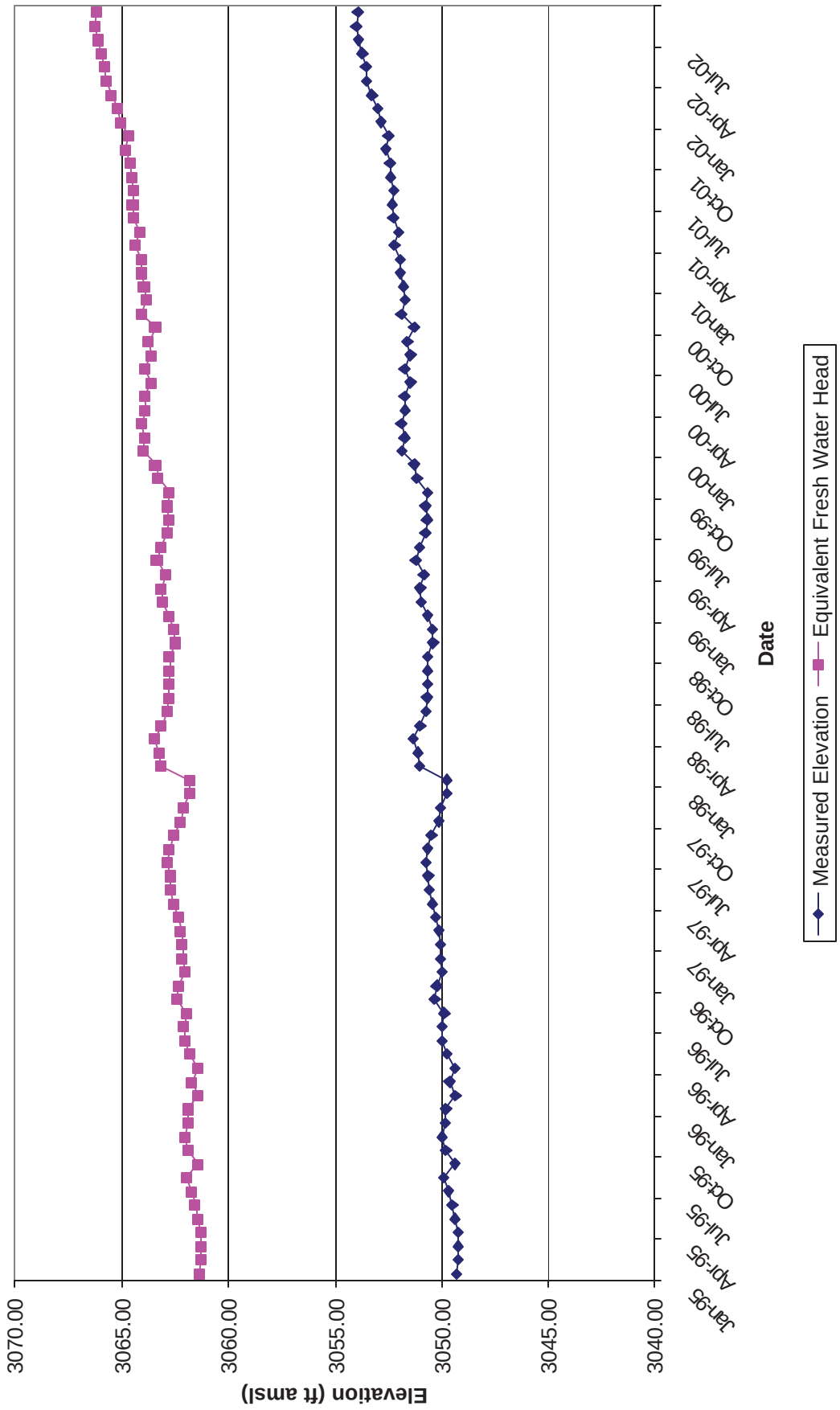

Table 30 - Well No. H-06c Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3061.65	N/A
02/13/95	3061.50	N/A
03/13/95	3061.50	N/A
04/10/95	3061.61	N/A
05/08/95	3061.71	N/A
06/05/95	3061.71	N/A
07/17/95	3061.65	N/A
08/14/95	3061.79	N/A
09/05/95	3061.58	N/A
10/16/95	3061.77	N/A
11/06/95	3061.90	N/A
12/04/95	3061.81	N/A
01/08/96	3061.80	N/A
02/05/96	3061.83	N/A
03/11/96	3061.94	N/A
04/15/96	3061.94	N/A
05/13/96	3062.16	N/A
06/10/96	3062.28	N/A
07/15/96	3062.22	N/A
08/12/96	3062.29	N/A
09/03/96	3062.46	N/A
10/14/96	3062.46	N/A
11/11/96	3062.43	N/A
12/09/96	3062.48	N/A
01/13/97	3062.31	N/A
02/10/97	3062.42	N/A
03/10/97	3062.59	N/A
04/14/97	3062.72	N/A
05/13/97	3062.96	N/A
06/09/97	3062.92	N/A
07/16/97	3062.89	N/A
08/11/97	3062.93	N/A
09/15/97	3062.99	N/A
10/13/97	3062.99	N/A
11/10/97	3062.99	N/A
12/08/97	3063.26	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3063.31	N/A
02/09/98	3063.42	N/A
03/11/98	3063.15	N/A
04/15/98	3063.54	N/A
05/11/98	3063.48	N/A
06/11/98	3063.45	N/A
07/15/98	363.35	N/A
08/12/98	3063.30	N/A
09/10/98	3063.38	N/A
10/14/98	3063.46	N/A
11/11/98	3063.37	N/A
12/07/98	3063.49	N/A
01/11/99	3063.42	N/A
02/09/99	3063.59	N/A
03/10/99	3063.71	N/A
04/12/99	3063.60	N/A
05/10/99	3063.83	N/A
06/07/99	3063.73	N/A
07/19/99	3063.70	N/A
08/09/99	3063.82	N/A
09/08/99	3063.82	N/A
10/04/99	3063.69	N/A
11/08/99	3063.79	N/A
12/09/99	3063.82	N/A
01/19/00	3062.63	N/A
02/14/00	3063.94	N/A
03/06/00	3064.04	N/A
04/17/00	3064.03	N/A
05/15/00	3064.08	N/A
06/05/00	3063.95	N/A
07/11/00	3064.35	N/A
08/15/00	3064.15	N/A
09/12/00	3064.33	N/A
10/09/00	3063.94	N/A
11/06/00	3064.60	N/A
12/07/00	3064.40	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3064.43	N/A
02/06/01	3064.54	N/A
03/06/01	3064.54	N/A
04/04/01	3064.75	N/A
05/08/01	3064.50	N/A
06/05/01	3064.81	N/A
07/09/01	3064.69	N/A
08/07/01	3064.67	N/A
09/04/01	3064.76	N/A
10/10/01	3064.83	N/A
11/14/01	3064.92	N/A
12/05/01	3064.84	N/A
01/16/02	3064.95	N/A
02/05/02	3065.02	N/A
03/11/02	3065.20	N/A
04/08/02	3065.43	N/A
05/06/02	3065.32	N/A
06/10/02	3065.42	N/A
07/15/02	3065.32	N/A
08/12/02	3065.39	N/A
09/09/02	3065.29	N/A

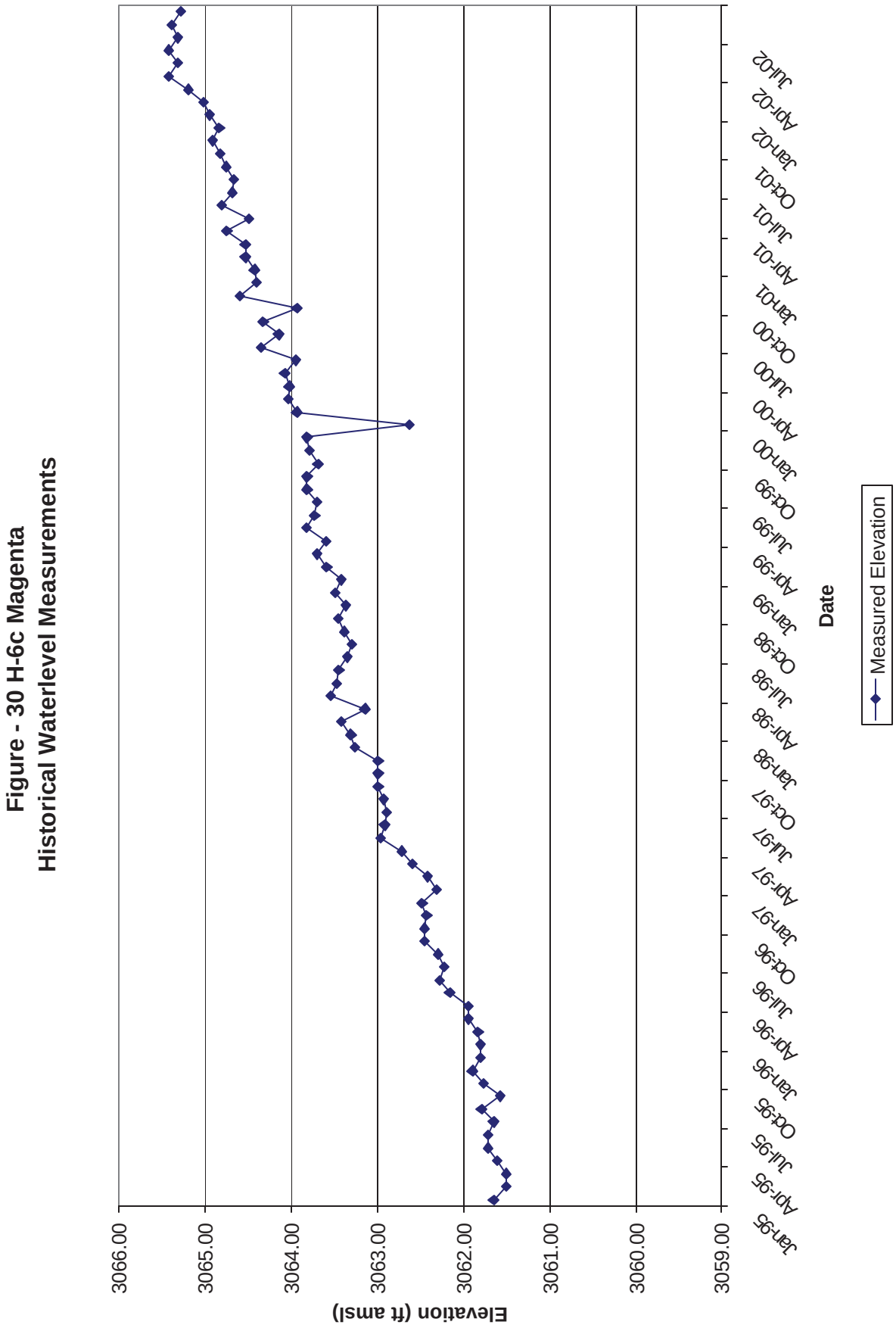
Figure - 30 H-6c Magenta
Historical Waterlevel Measurements
Elevation (ft amsl)
3066.00
3065.00
3064.00
3063.00
3062.00
3061.00
3060.00
3059.00
Date
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Measured Elevation

Table 31 - Well No. H-07b1 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head	Date	Measured Elevation	Equivalent Fresh Water Head	Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2995.90	2996.34	01/13/98	2996.89	2997.33	03/05/01	2997.87	2998.32
02/14/95	2995.97	2996.41	02/10/98	2997.05	2997.49	06/04/01	2998.18	2998.63
03/14/95	2995.78	2996.22	03/10/98	2996.59	2997.03	09/05/01	2997.73	2998.18
04/11/95	2995.76	2996.20	04/14/98	2997.11	2997.56	12/03/01	2997.69	2998.14
05/09/95	2995.92	2996.36	05/12/98	2997.13	2997.58			
06/06/95	2996.13	2996.57	06/09/98	2996.94	2997.38			
07/18/95	2995.99	2996.43	07/14/98	2996.82	2997.26			
08/15/95	2996.17	2996.61	09/09/98	2996.79	2997.23			
09/06/95	2996.12	2996.56	12/08/98	2996.47	2996.91			
10/17/95	2996.34	2996.78						
11/07/95	2996.23	2996.67						
12/05/95	2996.44	2996.88						
01/09/96	2996.40	2996.84	03/09/99	2996.85	2997.29	03/11/02	2997.97	2998.42
02/06/96	2996.36	2996.80	06/08/99	2996.90	2997.34	06/12/02	2997.88	2998.33
03/12/96	2996.60	2997.04	09/08/99	2997.13	2997.58	09/11/02	2997.60	2998.05
04/16/96	2996.43	2996.87	12/07/99	2997.28	2997.73			
05/14/96	2996.60	2997.04						
06/11/96	2996.52	2996.96						
07/16/96	2996.51	2996.95						
08/13/96	2996.45	2996.89						
09/04/96	2996.62	2997.06						
10/15/96	2996.76	2997.20						
11/12/96	2996.47	2996.91						
12/10/96	2996.75	2997.19						
01/15/97	2996.65	2997.09	03/07/00	2997.47	2997.92			
02/11/97	2996.70	2997.14	06/06/00	2997.01	2997.45			
03/11/97	2996.65	2997.09	09/13/00	2997.84	2998.29			
04/15/97	2996.28	2996.72	12/05/00	2997.78	2998.23			
05/13/97	2996.69	2997.13						
06/10/97	2996.56	2997.00						
07/15/97	2996.44	2996.88						
08/12/97	2996.58	2997.02						
09/16/97	2996.83	2997.27						
10/14/97	2996.46	2996.90						
11/11/97	2996.90	2997.34						
12/11/97	2996.62	2997.06						

Figure 31 - H-7b1 Culebra
Historical Waterlevel Measurements

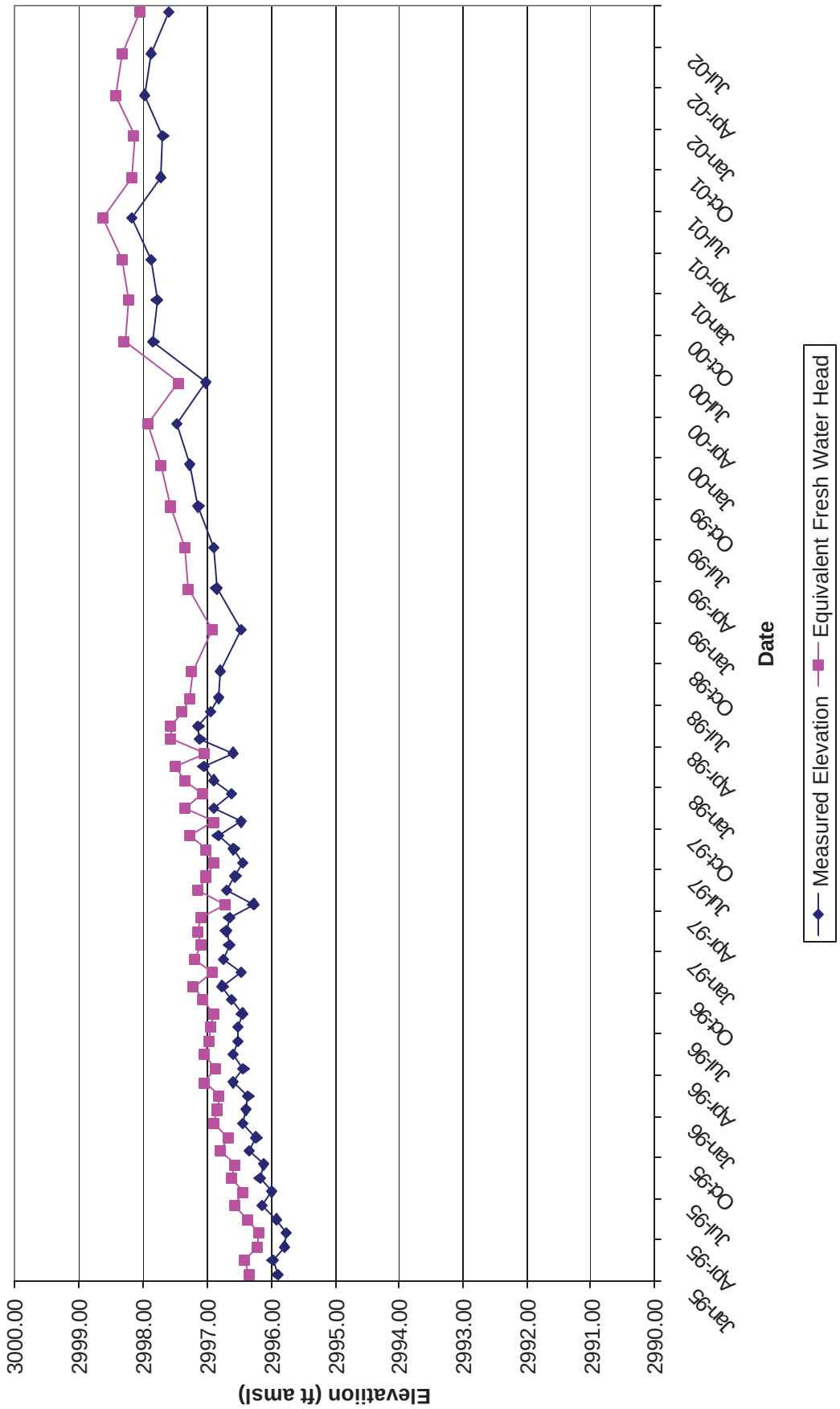

Table 32 - Well No. H-07b2 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2995.60	2995.51
06/06/95	2995.66	2995.57
09/06/95	2995.95	2995.86
12/05/95	2996.25	2996.16
03/12/96	2996.40	2996.31
06/11/96	2996.35	2996.26
09/04/96	2996.45	2996.36
12/10/96	2996.57	2996.48
03/11/97	2996.46	2996.37
06/10/97	2996.37	2996.28
09/16/97	2996.63	2996.54
12/11/97	2996.42	2996.33

Date	Measured Elevation	Equivalent Fresh Water Head
03/10/98	2996.39	2996.30
06/09/98	2996.73	2996.64
08/11/98	2996.55	2996.46
09/09/98	2996.58	2996.49
10/13/98	2996.40	2996.31
11/10/98	2996.41	2996.32
12/08/98	2996.25	2996.16
01/12/99	2996.77	2996.68
02/09/99	2996.57	2996.48
03/09/99	2996.64	2996.55
04/13/99	2996.78	2996.69
05/11/99	2996.78	2996.69
06/08/99	2996.68	2996.59
07/20/99	2996.77	2996.68
08/10/99	2996.93	2996.84
09/08/99	2996.91	2996.82
10/05/99	2996.80	2996.71
11/09/99	2997.01	2996.92
12/07/99	2997.08	2996.99
01/18/00	2996.94	2996.85
02/14/00	2997.11	2997.02
03/07/00	2997.24	2997.15
04/18/00	2997.06	2996.97
05/16/00	2997.09	2997.00
06/06/00	2996.79	2996.70
07/11/00	2997.45	2997.36
08/15/00	2997.56	2997.47
09/13/00	2997.65	2997.56
10/10/00	2997.58	2997.49
11/07/00	2997.91	2997.82
12/05/00	2997.56	2997.47

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2997.92	2997.83
02/07/01	2998.02	2997.93
03/05/01	2997.61	2997.52
04/03/01	2998.00	2997.91
05/07/01	2997.74	2997.65
06/04/01	2998.04	2997.95
07/09/01	2997.72	2997.63
08/06/01	2997.56	2997.47
09/05/01	2997.60	2997.51
10/08/01	2997.60	2997.51
11/12/01	2997.60	2997.51
12/03/01	2997.54	2997.45
01/14/02	2997.48	2997.39
02/06/02	2997.55	2997.46
03/11/02	2997.81	2997.72
04/10/02	2997.52	2997.43
06/12/02	2997.63	2997.54
07/16/02	2996.77	2996.68
08/12/02	2997.50	2997.41
09/11/02	2997.34	2997.25

Figure 32 - H-7b2 Culebra
Historical Waterlevel Measurements

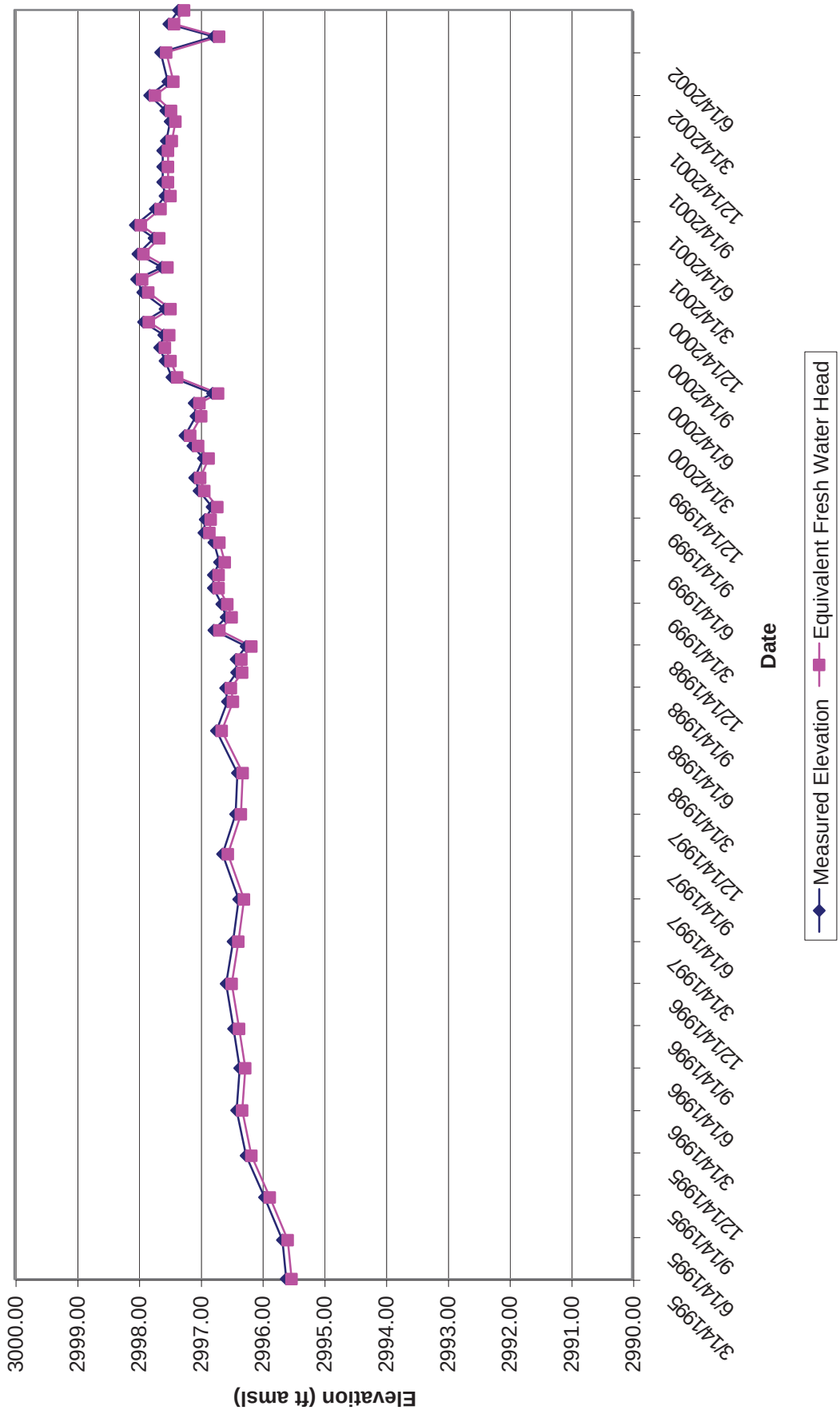

Table 33 - Well No. H-08a Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3027.56	N/A
02/14/95	3027.57	N/A
03/14/95	3027.56	N/A
04/11/95	3027.36	N/A
05/09/95	3027.60	N/A
06/06/95	3027.68	N/A
07/18/95	3027.66	N/A
08/15/95	3027.72	N/A
09/06/95	3027.64	N/A
10/17/95	3027.67	N/A
11/07/95	3027.67	N/A
12/05/95	3027.64	N/A
01/09/96	3027.63	N/A
02/06/96	3027.63	N/A
03/12/96	3027.68	N/A
04/16/96	3027.73	N/A
05/14/96	3027.77	N/A
06/11/96	3027.92	N/A
07/16/96	3027.84	N/A
08/14/96	3027.78	N/A
09/04/96	3027.79	N/A
10/15/96	3027.78	N/A
11/12/96	3027.75	N/A
12/10/96	3027.74	N/A
01/15/97	3027.70	N/A
02/11/97	3027.61	N/A
03/11/97	3027.65	N/A
04/15/97	3027.72	N/A
05/13/97	3027.74	N/A
06/10/97	3027.81	N/A
07/15/97	3027.72	N/A
08/12/97	3027.67	N/A
09/16/97	3027.63	N/A
10/14/97	3027.65	N/A
11/11/97	3027.62	N/A
12/09/97	3027.56	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	3027.59	N/A
02/10/98	3027.67	N/A
03/10/98	3027.68	N/A
04/14/98	3027.70	N/A
05/12/98	3027.67	N/A
06/09/98	3027.62	N/A
07/14/98	3027.53	N/A
08/11/98	3027.49	N/A
09/09/98	3027.42	N/A
10/13/98	3027.40	N/A
11/10/98	3027.37	N/A
12/08/98	3027.35	N/A
01/12/99	3027.32	N/A
02/09/99	3027.33	N/A
03/09/99	3027.40	N/A
04/13/99	3027.42	N/A
05/11/99	3027.48	N/A
06/08/99	3027.46	N/A
07/20/99	3027.39	N/A
08/10/99	3027.43	N/A
09/08/99	3027.36	N/A
10/05/99	3027.28	N/A
11/09/99	3027.21	N/A
12/07/99	3027.20	N/A
01/18/00	3027.15	N/A
02/15/00	3027.13	N/A
03/07/00	3027.14	N/A
04/18/00	3027.17	N/A
05/16/00	3027.19	N/A
06/06/00	3027.19	N/A
07/11/00	3027.24	N/A
08/15/00	3027.21	N/A
09/13/00	3027.19	N/A
10/10/00	3027.08	N/A
11/08/00	3027.10	N/A
12/05/00	3027.07	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3027.04	N/A
02/07/01	3026.94	N/A
03/05/01	3027.09	N/A
04/03/01	3027.11	N/A
05/07/01	3027.11	N/A
06/07/01	3027.10	N/A
07/10/01	3027.03	N/A
08/06/01	3027.00	N/A
09/05/01	3026.95	N/A
10/09/01	3026.88	N/A
11/13/01	3026.84	N/A
12/04/01	3026.83	N/A
01/15/02	3026.76	N/A
02/06/02	3026.87	N/A
03/13/02	3026.90	N/A
04/10/02	3026.96	N/A
05/06/02	3027.01	N/A
06/11/02	3027.03	N/A
07/16/02	3026.89	N/A
08/13/02	3026.98	N/A
09/11/02	3026.97	N/A

Figure 33 - H-8a Magenta
Historical Waterlevel Measurements

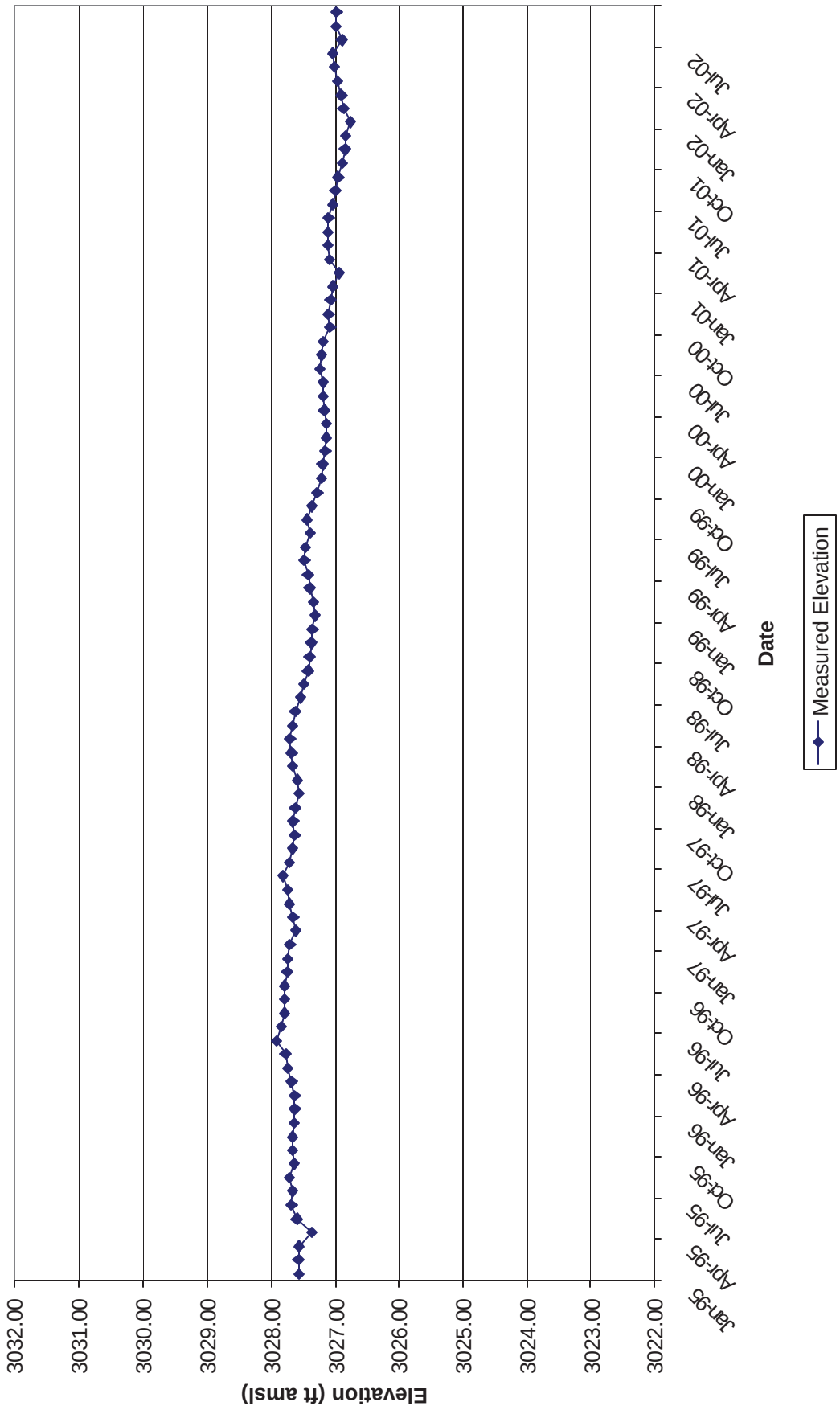

Table 34 - Well No. H-08c Rustler/Salado
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2979.34	N/A
02/14/95	2979.39	N/A
03/14/95	2979.37	N/A
04/11/95	2979.08	N/A
05/09/95	2979.35	N/A
06/06/95	2979.37	N/A
07/18/95	2979.39	N/A
08/15/95	2979.46	N/A
09/06/95	2979.37	N/A
10/17/95	2979.52	N/A
11/07/95	2979.37	N/A
12/05/95	2979.37	N/A
01/09/96	2979.38	N/A
02/06/96	2979.35	N/A
03/12/96	2979.39	N/A
04/16/96	2979.39	N/A
05/14/96	2979.43	N/A
06/11/96	2979.62	N/A
07/16/96	2979.58	N/A
08/14/96	2979.55	N/A
09/04/96	2979.58	N/A
10/15/96	2979.56	N/A
11/12/96	2979.55	N/A
12/10/96	2979.56	N/A
01/15/97	2979.33	N/A
02/11/97	2979.43	N/A
03/11/97	2979.46	N/A
04/15/97	2979.56	N/A
05/13/97	2979.57	N/A
06/10/97	2979.62	N/A
07/15/97	2979.58	N/A
08/12/97	2979.62	N/A
09/16/97	2979.60	N/A
10/14/97	2979.61	N/A
11/11/97	2979.57	N/A
12/09/97	2979.50	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2979.51	N/A
02/10/98	2979.58	N/A
03/10/98	2979.57	N/A
04/14/98	2979.56	N/A
05/12/98	2979.55	N/A
06/09/98	2979.61	N/A
07/14/98	2979.57	N/A
08/11/98	2979.34	N/A
09/09/98	2979.50	N/A
10/13/98	2979.46	N/A
11/10/98	2979.37	N/A
12/08/98	2979.35	N/A
01/12/99	2979.29	N/A
02/09/99	2979.25	N/A
03/09/99	2979.36	N/A
04/13/99	2979.38	N/A
05/11/99	2979.41	N/A
06/08/99	2979.42	N/A
07/20/99	2979.38	N/A
08/10/99	2979.42	N/A
09/08/99	2979.39	N/A
10/05/99	2979.31	N/A
11/09/99	2979.24	N/A
12/07/99	2979.20	N/A
01/18/00	2979.12	N/A
02/15/00	2979.10	N/A
03/07/00	2979.09	N/A
04/18/00	2979.11	N/A
05/16/00	2979.15	N/A
06/06/00	2979.14	N/A
07/11/00	2979.19	N/A
08/15/00	2979.18	N/A
09/13/00	2979.18	N/A
10/10/00	2979.11	N/A
11/07/00	2979.10	N/A
12/05/00	2979.12	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2979.11	N/A
02/07/01	2979.02	N/A
03/05/01	2979.17	N/A
04/03/01	2979.11	N/A
05/07/01	2979.25	N/A
06/07/01	2979.28	N/A
07/10/01	2979.30	N/A
08/06/01	2979.29	N/A
09/05/01	2979.25	N/A
10/09/01	2979.35	N/A
11/13/01	2979.23	N/A
12/04/01	2979.22	N/A
01/15/02	2979.18	N/A
02/06/02	2979.34	N/A
03/13/02	2979.38	N/A
04/10/02	2979.45	N/A
05/06/02	2979.53	N/A
06/11/02	2979.60	N/A
07/16/02	2979.66	N/A
08/13/02	2979.67	N/A
09/11/02	2979.71	N/A

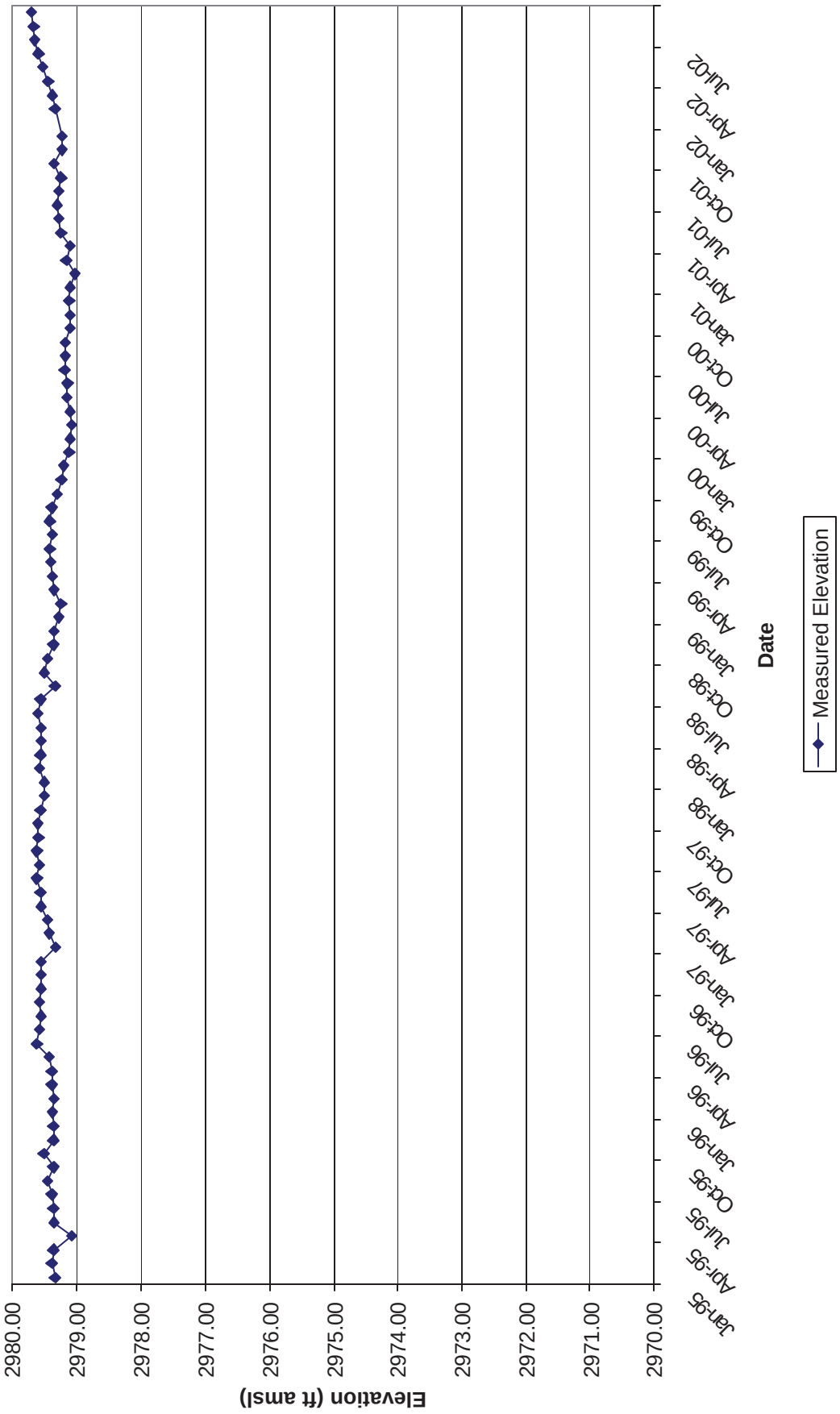
Figure 34 - H-8c Magenta
Historical Waterlevel Measurements
Elevation (ft amsl)
2980.00
2979.00
2978.00
2977.00
2976.00
2975.00
2974.00
2973.00
2972.00
2971.00
2970.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation

Table 35 - Well No. H-09a Culebra
March 1995 through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2990.97	2991.22
06/06/95	2993.10	2993.35
09/06/95	2992.10	2992.35
12/05/95	2992.48	2992.73
03/12/96	2993.10	2993.35
06/11/96	2993.91	2994.16
09/04/96	2993.97	2994.22
12/10/96	2993.53	2993.78
03/11/97	2985.81	2986.05
06/10/97	2984.92	2985.16
09/16/97	2987.80	2988.04
12/09/97	2988.86	2989.10

Date	Measured Elevation	Equivalent Fresh Water Head
03/10/98	2989.46	2989.71
06/09/98	2987.59	2987.83
09/09/98	2988.78	2989.02
12/08/98	2989.19	2989.44
03/09/99	2991.18	2991.43
06/08/99	2991.84	2992.09
09/08/99	2990.64	2990.35
12/07/99	2990.42	2990.67
03/07/00	2991.02	2991.27
06/06/00	2990.74	2990.99
09/13/00	2989.27	2989.52
12/05/00	2989.91	2990.16

Date	Measured Elevation	Equivalent Fresh Water Head
03/05/01	2991.87	2992.12
06/06/01	2992.49	2992.74
09/05/01	2991.14	2991.39
12/04/01	2992.45	2992.70

Figure 35 - H-9a Culebra Historical Waterlevel Measurements

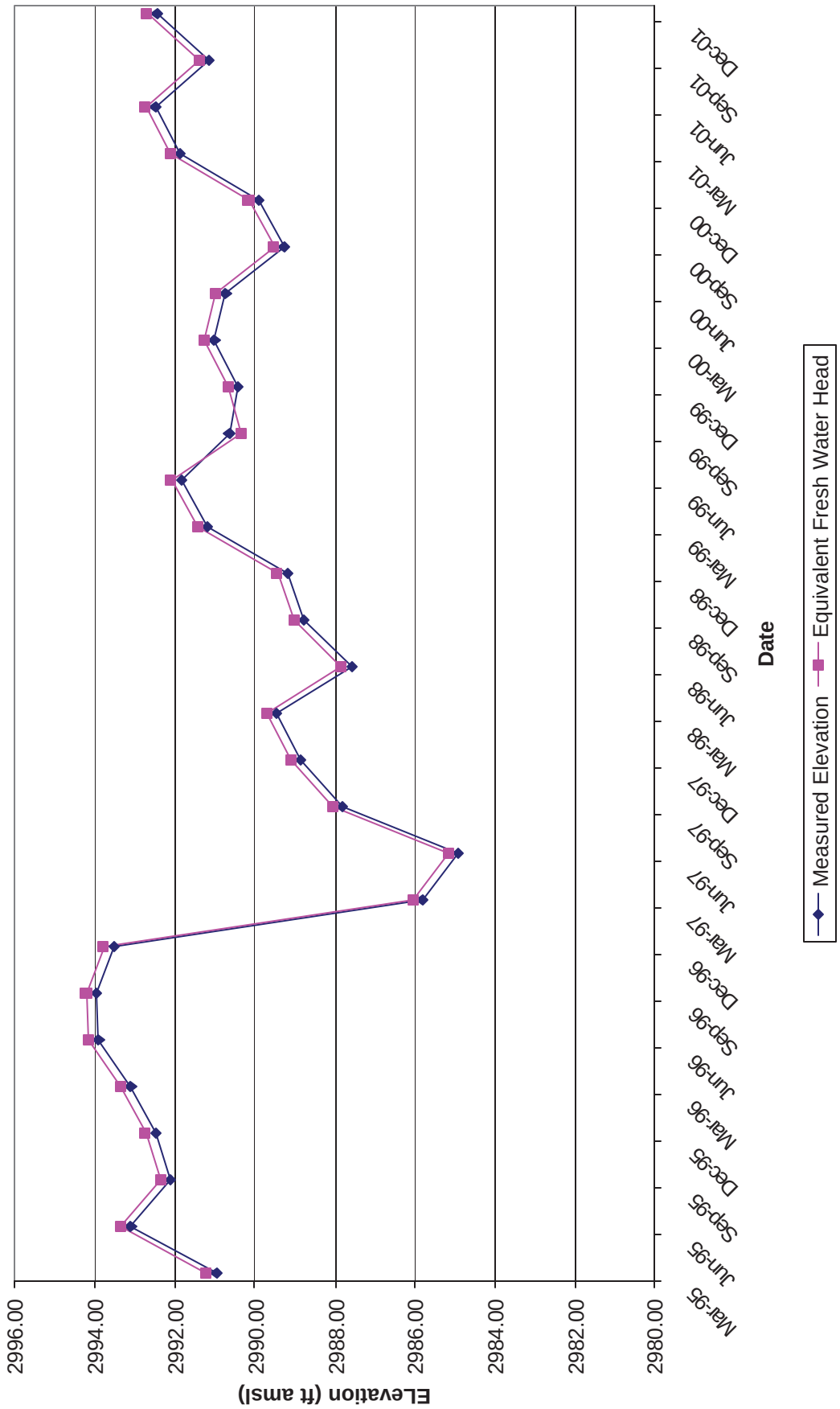

Table 36 - Well No. H-09b Culebra
January 1995 through April 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2990.48	2990.73
02/14/95	2991.16	2991.41
03/14/95	2991.09	2991.34
04/11/95	2991.89	2992.14
05/09/95	2992.69	2992.94
06/06/95	2993.25	2993.50
07/18/95	2993.15	2993.40
08/15/95	2993.09	2993.34
09/06/95	2992.21	2992.46
10/17/95	2991.82	2992.07
11/07/95	2992.42	2992.67
12/05/95	2992.62	2992.87
01/09/96	2992.96	2993.21
02/06/96	2992.93	2993.18
03/12/96	2993.24	2993.49
04/16/96	2993.06	2993.31
05/14/96	2993.94	2994.19
06/11/96	2994.05	2994.30
07/16/96	2994.04	2994.29
08/14/96	2994.13	2994.38
09/04/96	2994.11	2994.36
10/15/96	2994.22	2994.47
11/12/96	2993.58	2993.83
12/10/96	2993.65	2993.90
01/15/97	2993.44	2993.69
02/11/97	2989.97	2990.22
03/11/97	2985.92	2986.16
04/15/97	2985.79	2986.03
05/13/97	2985.46	2985.70
06/10/97	2985.02	2985.26
07/15/97	2984.84	2985.08
08/12/97	2986.42	2986.66
09/16/97	2987.91	2988.15
10/14/97	2987.21	2987.45
11/11/97	2988.40	2988.64
12/09/97	2988.92	2989.17

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2989.48	2989.73
02/10/98	2989.92	2990.17
03/10/98	2989.54	2989.79
04/14/98	2989.51	2989.76
05/12/98	2988.08	2988.32
06/09/98	2987.66	2987.90
07/14/98	2988.46	2988.70
08/11/98	2988.66	2988.91
09/09/98	2988.90	2989.15
10/13/98	2989.39	2989.64
11/10/98	2989.66	2989.91
12/08/98	2989.28	2989.53
01/12/99	2990.50	2990.75
02/09/99	2990.71	2990.96
03/09/99	2991.25	2991.50
04/13/99	2991.84	2992.09
05/11/99	2992.04	2992.29
06/08/99	2991.90	2992.15
07/20/99	2991.80	2992.05
08/10/99	2991.71	2991.96
09/08/99	2990.94	2991.73
10/05/99	2990.68	2990.93
11/09/99	2990.68	2990.93
12/07/99	2990.71	2990.96
01/18/00	2990.44	2990.69
02/15/00	2990.85	2991.10
03/07/00	2991.33	2991.58
04/18/00	2991.77	2992.02
05/16/00	2991.69	2991.94
06/06/00	2991.06	2991.31
07/11/00	2990.78	2991.03
08/15/00	2989.45	2989.70
09/13/00	2989.56	2989.81
10/10/00	2989.93	2990.18
11/08/00	2990.23	2990.48
12/05/00	2990.20	2990.45

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2990.90	2991.15
02/07/01	2991.81	2992.06
03/05/01	2992.19	2992.44
04/03/01	2992.95	2993.20
05/07/01	2992.99	2993.24
06/06/01	2992.82	2993.07
07/10/01	2991.39	2991.64
08/06/01	2991.11	2991.36
09/05/01	2991.47	2991.72
10/09/01	2992.03	2992.28
11/13/01	2990.59	2990.84
12/04/01	2991.31	2991.56
01/15/02	2991.84	2992.09
02/06/02	2992.67	2992.92
03/13/02	3140.35	3140.75
04/10/02	2864.06	2864.18

Figure 36 - H-9b Culebra
Historical Waterlevel Measurements

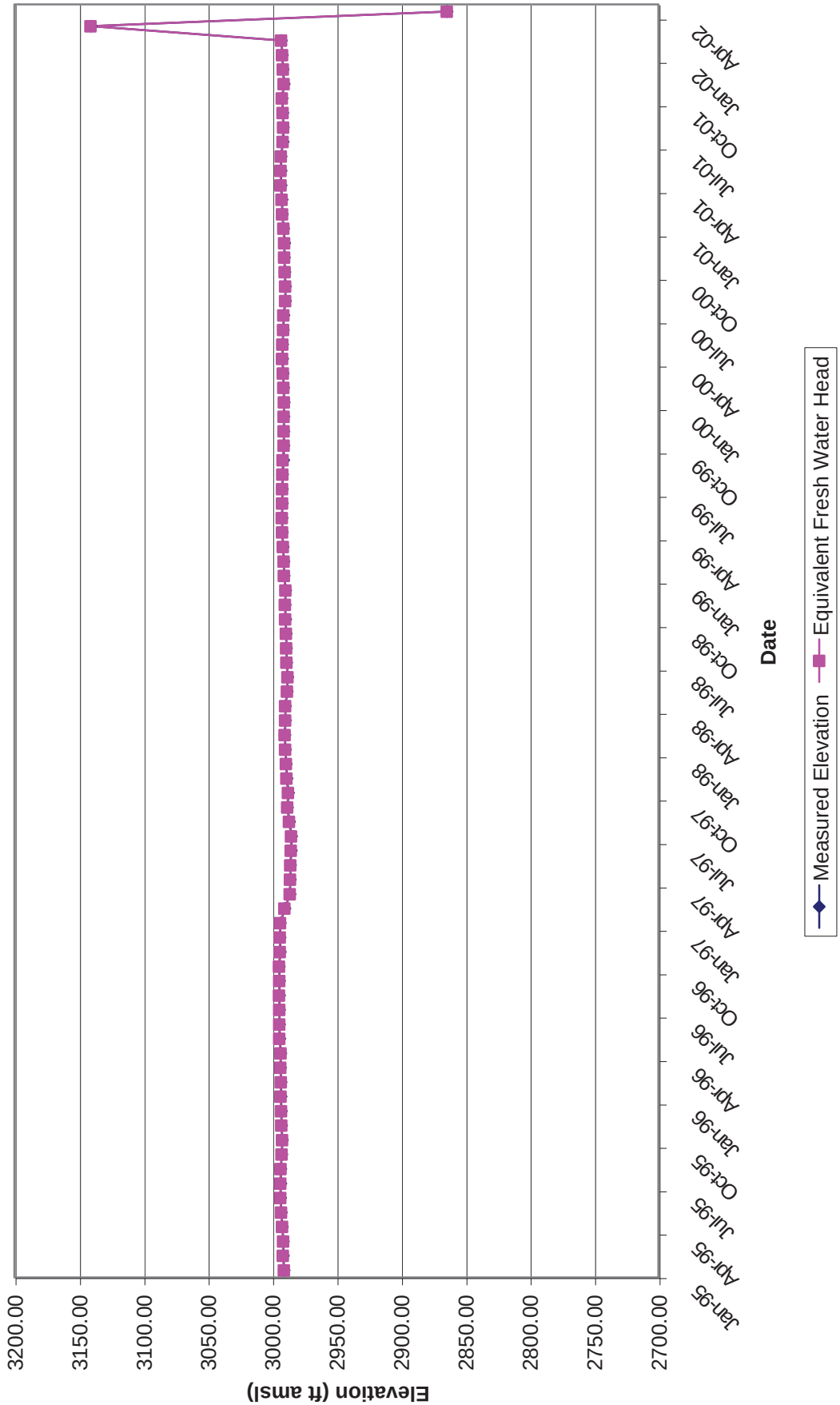

Table 37 - Well No. H-09c Culebra
March 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2991.02	2991.27
06/06/95	2993.18	2993.43
09/06/95	2992.16	2992.41
12/05/95	2992.56	2992.81
03/12/96	2993.21	2993.46
06/11/96	2994.00	2994.25
09/04/96	2994.05	2994.30
12/10/96	2993.60	2993.85
03/11/97	2985.86	2986.10
06/10/97	2984.92	2985.16
09/16/97	2987.88	2988.12
12/09/97	2987.85	2988.09

Date	Measured Elevation	Equivalent Fresh Water Head
03/10/98	2989.46	2989.70
06/09/98	2987.59	2987.83
09/09/98	2988.82	2989.06
12/08/98	2989.18	2989.42
03/09/99	2991.20	2991.45
06/08/99	2991.82	2992.07
09/08/99	2991.47	2991.72
12/07/99	2990.24	2990.49
03/07/00	2990.87	2991.12
06/06/00	2990.59	2990.84
09/13/00	2989.09	2989.33
12/05/00	2989.75	2990.00

Date	Measured Elevation	Equivalent Fresh Water Head
03/05/01	2991.73	2991.98
06/06/01	2992.34	2992.59
09/05/01	2991.00	2991.25
12/04/01	2992.38	2992.63

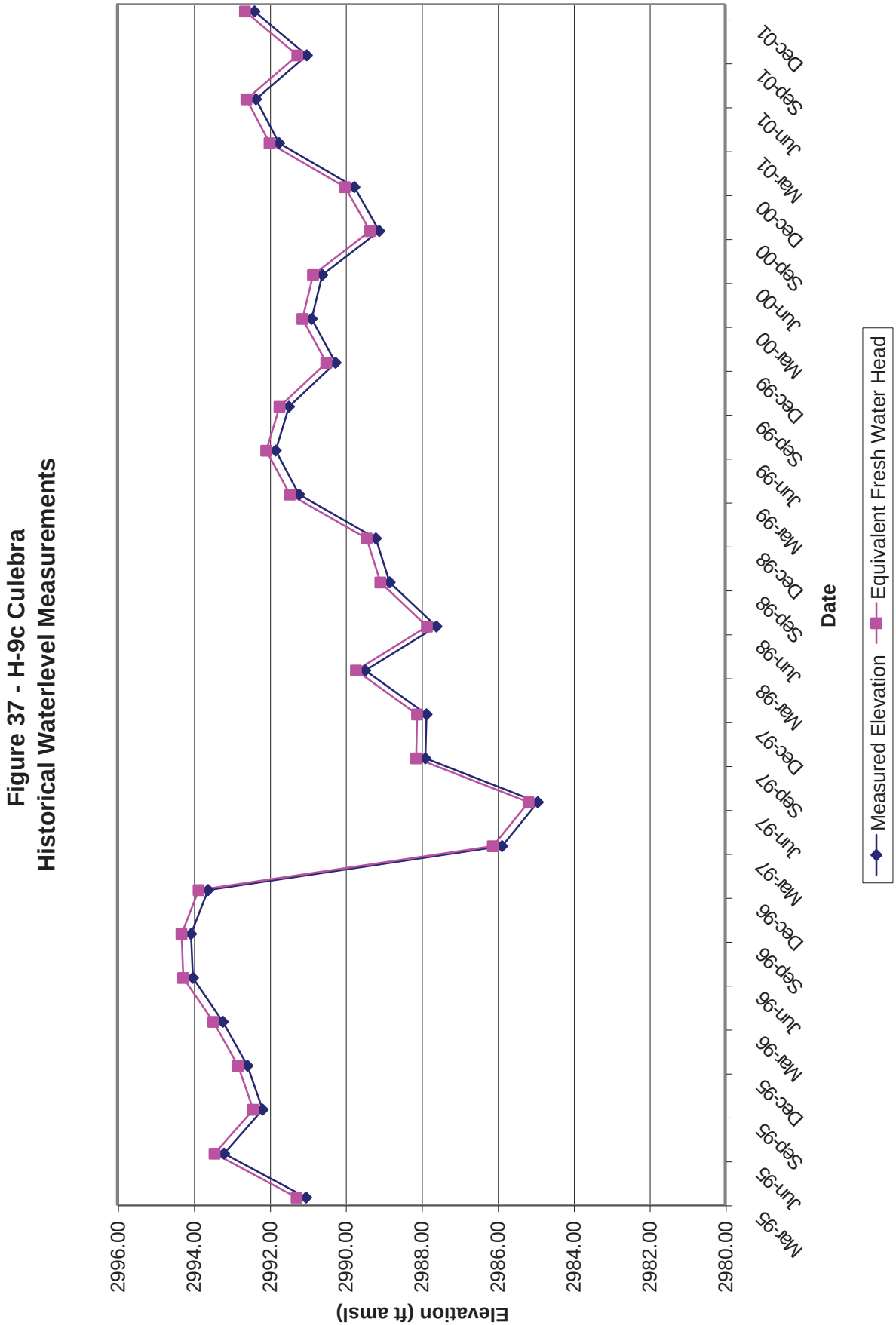
Figure 37 - H-9c Culebra
Historical Waterlevel Measurements
Elevation (ft amsl)
2996.00
2994.00
2992.00
2990.00
2988.00
2986.00
2984.00
2982.00
2980.00
Mar-95
Jun-95
Sep-95
Dec-95
Mar-96
Jun-96
Sep-96
Dec-96
Mar-97
Jun-97
Sep-97
Dec-97
Mar-98
Jun-98
Sep-98
Dec-98
Mar-99
Jun-99
Sep-99
Dec-99
Mar-00
Jun-00
Sep-00
Dec-00
Mar-01
Jun-01
Sep-01
Dec-01
Date
Measured Elevation
Equivalent Fresh Water Head

Table 38 - Well No. H-10a Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3159.77	N/A
02/14/95	3159.73	N/A
03/14/95	3159.70	N/A
04/11/95	3159.44	N/A
05/09/95	3159.73	N/A
06/06/95	3159.69	N/A
07/18/95	3159.59	N/A
08/15/95	3159.60	N/A
09/06/95	3159.43	N/A
10/17/95	3159.42	N/A
11/07/95	3159.37	N/A
12/05/95	3159.32	N/A
01/09/96	3159.25	N/A
02/06/96	3159.26	N/A
03/12/96	3159.29	N/A
04/16/96	3159.34	N/A
05/14/96	3159.31	N/A
06/11/96	3159.40	N/A
07/16/96	3159.28	N/A
08/14/96	3159.23	N/A
09/04/96	3159.35	N/A
10/15/96	3159.41	N/A
11/12/96	3159.31	N/A
12/10/96	3159.36	N/A
01/15/97	3159.36	N/A
02/11/97	3159.26	N/A
03/11/97	3159.35	N/A
04/15/97	3159.63	N/A
05/13/97	3159.63	N/A
06/11/97	3159.59	N/A
07/15/97	3159.56	N/A
08/12/97	3159.48	N/A
09/16/97	3159.50	N/A
10/14/97	3159.57	N/A
11/11/97	3159.61	N/A
12/09/97	3159.62	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	3159.65	N/A
02/10/98	3159.82	N/A
03/10/98	3159.82	N/A
04/14/98	3159.84	N/A
05/12/98	3159.82	N/A
06/09/98	3159.77	N/A
07/14/98	3159.70	N/A
08/11/98	3159.65	N/A
09/09/98	3159.65	N/A
10/13/98	3159.64	N/A
11/10/98	3159.60	N/A
12/08/98	3159.64	N/A
01/12/99	3159.66	N/A
02/09/99	3159.71	N/A
03/09/99	3159.86	N/A
04/13/99	3159.91	N/A
05/11/99	3159.97	N/A
06/08/99	3159.96	N/A
07/20/99	3159.89	N/A
08/10/99	3159.95	N/A
09/08/99	3159.98	N/A
10/05/99	3159.96	N/A
11/09/99	3159.92	N/A
12/07/99	3159.97	N/A
01/18/00	3159.97	N/A
02/15/00	3160.04	N/A
03/07/00	3160.08	N/A
04/18/00	3160.15	N/A
05/16/00	3160.18	N/A
06/06/00	3160.16	N/A
07/11/00	3160.29	N/A
08/15/00	3160.20	N/A
09/13/00	3160.20	N/A
10/10/00	3160.07	N/A
11/08/00	3160.24	N/A
12/05/00	3160.18	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3160.28	N/A
02/07/01	3160.26	N/A
03/07/01	3160.59	N/A
04/04/01	3160.75	N/A
05/07/01	3160.82	N/A
06/06/01	3161.18	N/A
07/11/01	3161.76	N/A
08/06/01	3162.04	N/A
09/05/01	3162.13	N/A
10/09/01	3162.16	N/A
11/13/01	3162.08	N/A
12/04/01	3162.18	N/A
01/15/02	3162.08	N/A
02/06/02	3204.00	N/A
03/13/02	3219.79	N/A
04/10/02	3220.33	N/A
05/06/02	3220.32	N/A
06/11/02	3220.20	N/A
07/16/02	3219.99	N/A
08/13/02	3219.97	N/A
09/11/02	3219.92	N/A

Figure 38 - H-10a Magenta
Historical Waterlevel Measurements

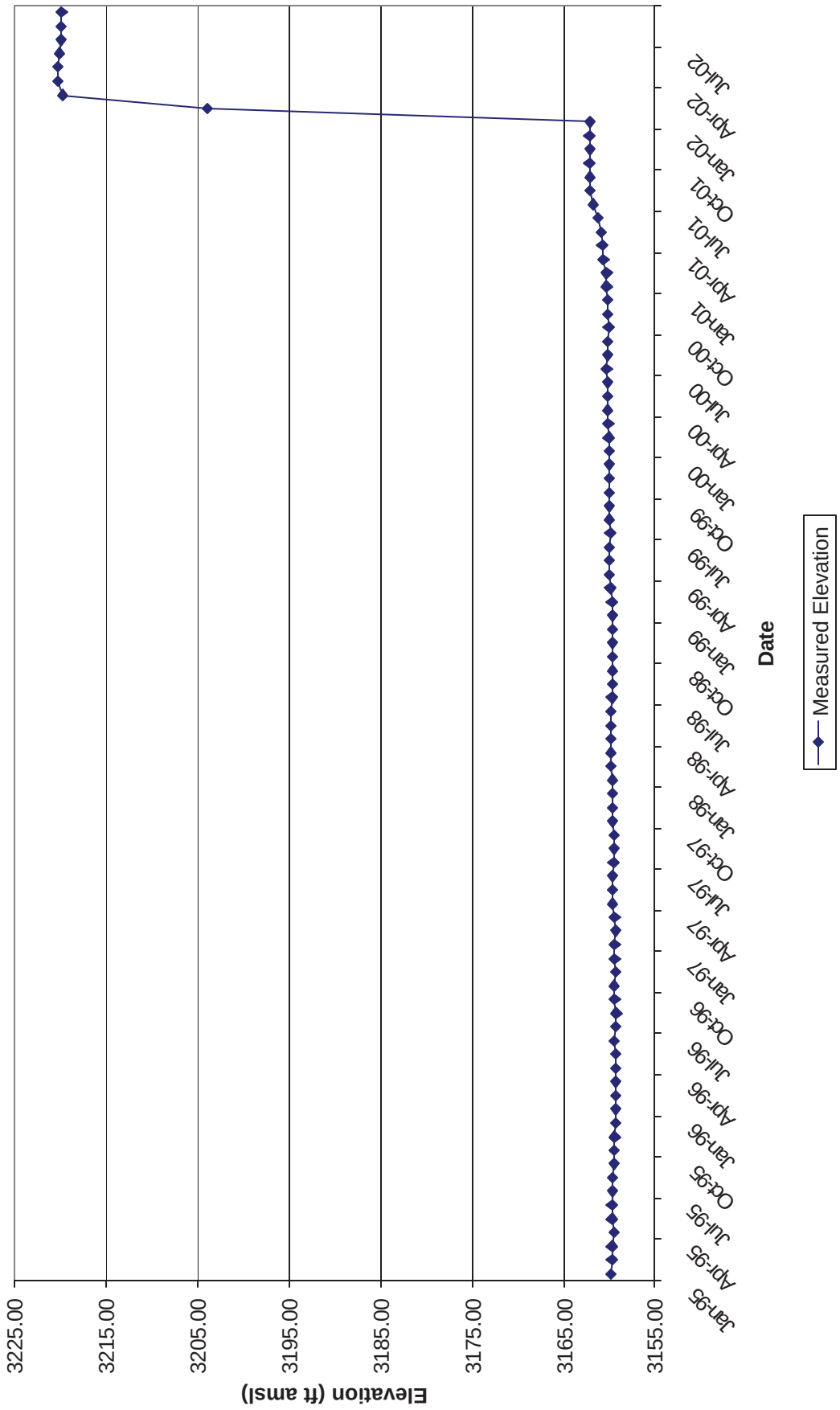

Table 39 - Well No. H-10b Culebra
January 1995 through January 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2992.12	3024.11
02/14/95	2992.15	3024.14
03/14/95	2992.08	3024.07
04/11/95	2992.01	3023.99
05/09/95	2992.39	3024.39
06/06/95	2992.45	3024.45
07/18/95	2992.42	3024.42
08/15/95	2992.67	3024.68
09/06/95	2992.48	3024.49
10/17/95	2992.74	3024.76
11/07/95	2992.75	3024.77
12/05/95	2992.83	3024.85
01/09/96	2992.79	3024.81
02/06/96	2992.76	3024.78
03/12/96	2992.96	3024.99
04/16/96	2992.96	3024.99
05/14/96	2993.15	3025.19
06/11/96	2993.47	3025.52
07/16/96	2993.57	3025.63
08/14/96	2993.53	3025.58
09/04/96	2993.74	3025.80
10/15/96	2993.81	3025.88
11/12/96	2993.73	3025.79
12/10/96	2993.88	3025.95
01/15/97	2993.91	3025.98
02/11/97	2993.77	3025.84
03/11/97	2993.87	3025.94
04/15/97	2994.12	3026.20
05/13/97	2994.25	3026.34
06/11/97	2994.28	3026.37
07/15/97	2994.31	3026.40
08/12/97	2994.40	3026.50
09/16/97	2994.61	3026.72
10/14/97	2994.60	3026.71
11/11/97	2994.78	3026.89
12/09/97	2994.94	3027.06

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2994.86	3026.98
02/10/98	2994.98	3027.10
03/10/98	2994.61	3026.72
04/14/98	2994.80	3026.91
05/12/98	2994.76	3026.87
06/09/98	2994.58	3026.68
07/14/98	2994.38	3026.47
08/11/98	2994.26	3026.35
09/09/98	2994.30	3026.39
10/13/98	2994.18	3026.27
11/10/98	2994.27	3026.36
12/08/98	2994.19	3026.28
01/12/99	2994.26	3026.35
02/09/99	2994.15	3026.23
03/09/99	2994.22	3026.31
04/13/99	2994.12	3026.20
05/11/99	2994.18	3026.27
06/08/99	2994.04	3026.12
07/20/99	2993.81	3025.88
08/10/99	2993.93	3026.00
09/08/99	2993.87	3025.94
10/05/99	2993.66	3025.72
11/09/99	2993.76	3025.83
12/07/99	2993.79	3025.86
01/18/00	2993.62	3025.68
02/15/00	2993.68	3025.74
03/07/00	2993.76	3025.83
04/18/00	2993.74	3025.80
05/16/00	2993.76	3025.83
06/06/00	2993.63	3025.69
07/11/00	2993.98	3026.06
08/15/00	2994.18	3026.27
09/13/00	2994.30	3026.39
10/10/00	2994.05	3026.13
11/08/00	2994.50	3026.60
12/05/00	2994.49	3026.59

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2994.87	3026.99
02/07/01	2994.90	3027.02
03/07/01	2994.83	3026.95
04/04/01	2994.98	3027.10
05/07/01	2995.03	3027.16
06/06/01	2995.40	3027.54
07/11/01	2995.25	3027.39
08/06/01	2995.17	3027.30
09/05/01	2995.01	3027.13
10/09/01	2994.87	3026.99
11/13/01	2994.67	3026.78
12/04/01	2994.70	3026.81
01/15/02	2994.44	3026.54

Figure 39 - H-10b Culebra
Historical Waterlevel Meausrements

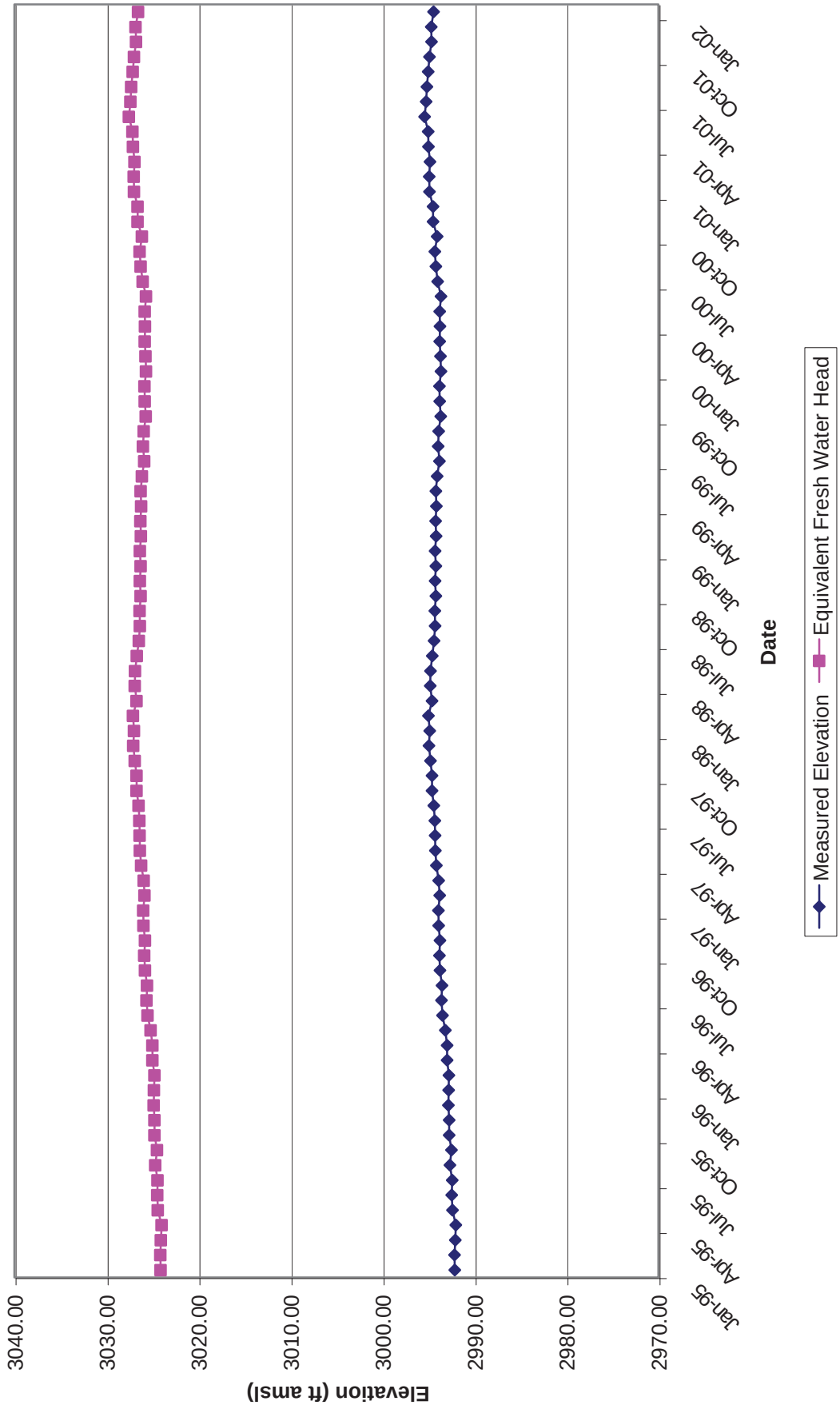

Table 40 - Well No. H-10c Culebra
June 2002 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/02	3026.95	N/A
07/16/02	3026.34	N/A
08/13/02	3026.08	N/A
09/11/02	3026.32	N/A

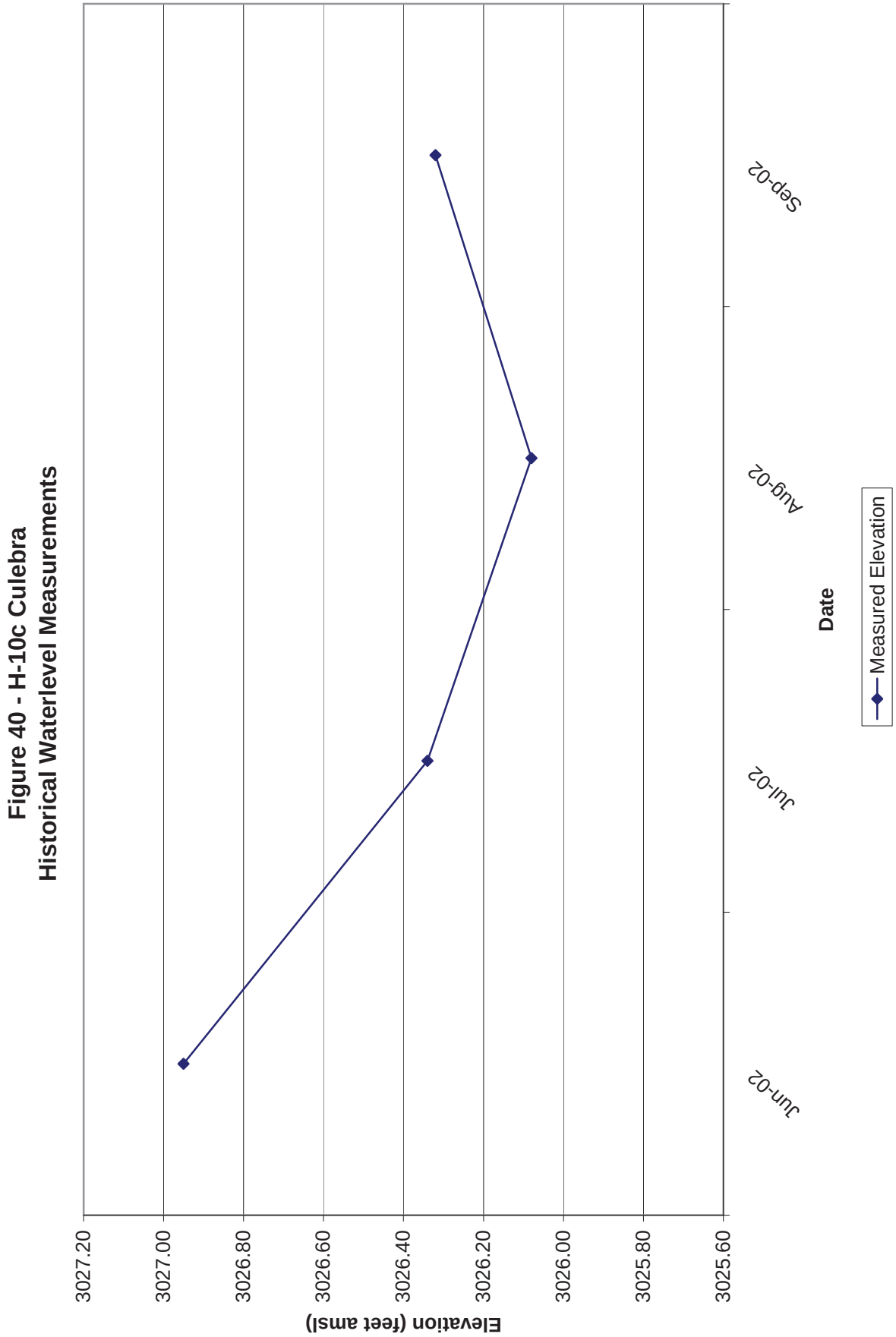
Figure 40 - H-10c Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3027.20
3027.00
3026.80
3026.60
3026.40
3026.20
3026.00
3025.80
3025.60
Jun-02
Jul-02
Aug-02
Sep-02
Date
Measured Elevation

Table 41 - Well No. H-11b1 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2978.88	3001.89
06/06/95	2978.88	3001.89
12/05/95	2975.87	2998.65
03/12/96	2901.78	2919.08
06/11/96	2970.45	2992.83
09/04/96	2975.77	2998.54
12/10/96	2977.74	3000.66
03/11/97	2977.86	3000.79
06/11/97	2976.78	2999.63
09/16/97	2977.01	2999.88
12/09/97	2977.94	3000.88

Date	Measured Elevation	Equivalent Fresh Water Head
03/10/98	2978.55	3001.53
06/09/98	2978.50	3001.48
09/09/98	2978.69	3001.68
12/08/98	2978.77	3001.77
03/09/99	2979.43	3002.48
06/08/99	2979.45	3002.50
09/08/99	2979.37	3002.41
12/07/99	2979.74	3002.81
03/07/00	2979.64	3002.70
06/06/00	2980.13	3003.23
09/13/00	2980.05	3003.14
12/05/00	2980.08	3003.17

Date	Measured Elevation	Equivalent Fresh Water Head
03/07/01	2980.57	3003.70
06/06/01	2981.20	3004.38
09/05/01	2981.32	3004.50
12/03/01	2981.23	3004.41
06/11/02	2992.41	3016.42
09/12/02	2992.59	3016.61

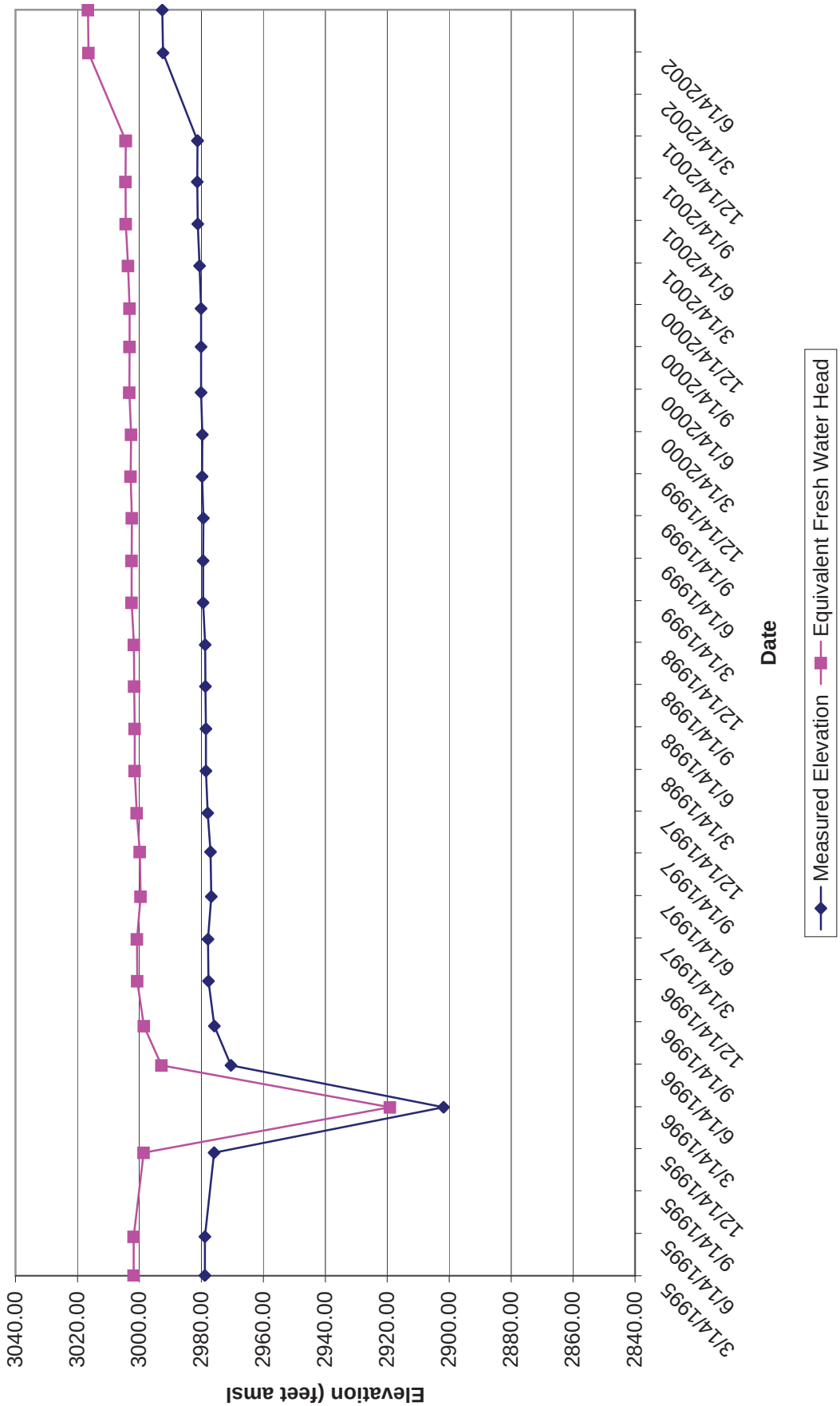
Figure 41 - H-11b1 Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
2880.00
2860.00
2840.00
3/14/1995
6/14/1995
9/14/1995
12/14/1995
3/14/1996
6/14/1996
9/14/1996
12/14/1996
3/14/1997
6/14/1997
9/14/1997
12/14/1997
3/14/1998
6/14/1998
9/14/1998
12/14/1998
3/14/1999
6/14/1999
9/14/1999
12/14/1999
3/14/2000
6/14/2000
9/14/2000
12/14/2000
3/14/2001
6/14/2001
9/14/2001
12/14/2001
3/14/2002
6/14/2002
Date
Measured Elevation
Equivalent Fresh Water Head

Table 42 - Well No. H-11b2 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2978.83	3002.59
02/14/95	2979.16	3002.94
03/14/95	2978.43	3002.16
04/11/95	2978.79	3002.55
05/09/95	2978.95	3002.72
06/06/95	2977.76	3001.44
07/19/95	2971.80	2995.03
08/16/95	2955.96	2977.98
09/07/95	2968.80	2991.80
10/18/95	2973.64	2997.01
11/07/95	2974.26	2997.67
12/05/95	2975.26	2998.75
01/08/96	2965.94	2988.72
02/01/96	2966.66	2989.49
03/12/96	2941.58	2962.51
04/16/96	2959.87	2982.19
05/14/96	2967.55	2990.45
06/11/96	2971.03	2994.20
07/16/96	2973.56	2996.92
08/13/96	2975.27	2998.76
09/04/96	2976.07	2999.62
10/16/96	2976.91	3000.52
11/12/96	2977.21	3000.85
12/10/96	2977.91	3001.60
01/15/97	2978.34	3002.06
02/11/97	2978.46	3002.19
03/11/97	2977.96	3001.65
04/15/97	2977.40	3001.05
05/14/97	2977.27	3000.91
06/11/97	2976.97	3000.59
07/15/97	2976.43	3000.01
08/12/97	2976.65	3000.24
09/16/97	2977.03	3000.65
10/15/97	2977.06	3000.69
11/11/97	2977.69	3001.36
12/09/97	2978.01	3001.71

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2978.16	3001.87
02/10/98	2978.57	3002.31
03/10/98	2978.47	3002.20
04/14/98	2979.42	3003.22
05/12/98	2978.74	3002.49
06/09/98	2978.44	3002.17
07/14/98	2978.48	3002.21
08/11/98	2978.57	3002.31
09/09/98	2978.68	3002.43
10/13/98	2978.62	3002.36
11/10/98	2978.82	3002.58
12/08/98	2978.81	3002.57
03/09/99	2979.41	3003.21
06/08/99	2979.93	3003.77
09/08/99	2980.14	3004.00
12/07/99	2980.13	3003.99
03/07/00	2980.02	3003.87
06/06/00	2979.93	3003.77
09/13/00	2980.02	3003.87
12/05/00	2980.09	3003.94
03/05/01	2980.05	3003.90

Figure 42 - H-11b2 Culebra
Historical Waterlevel Measurements

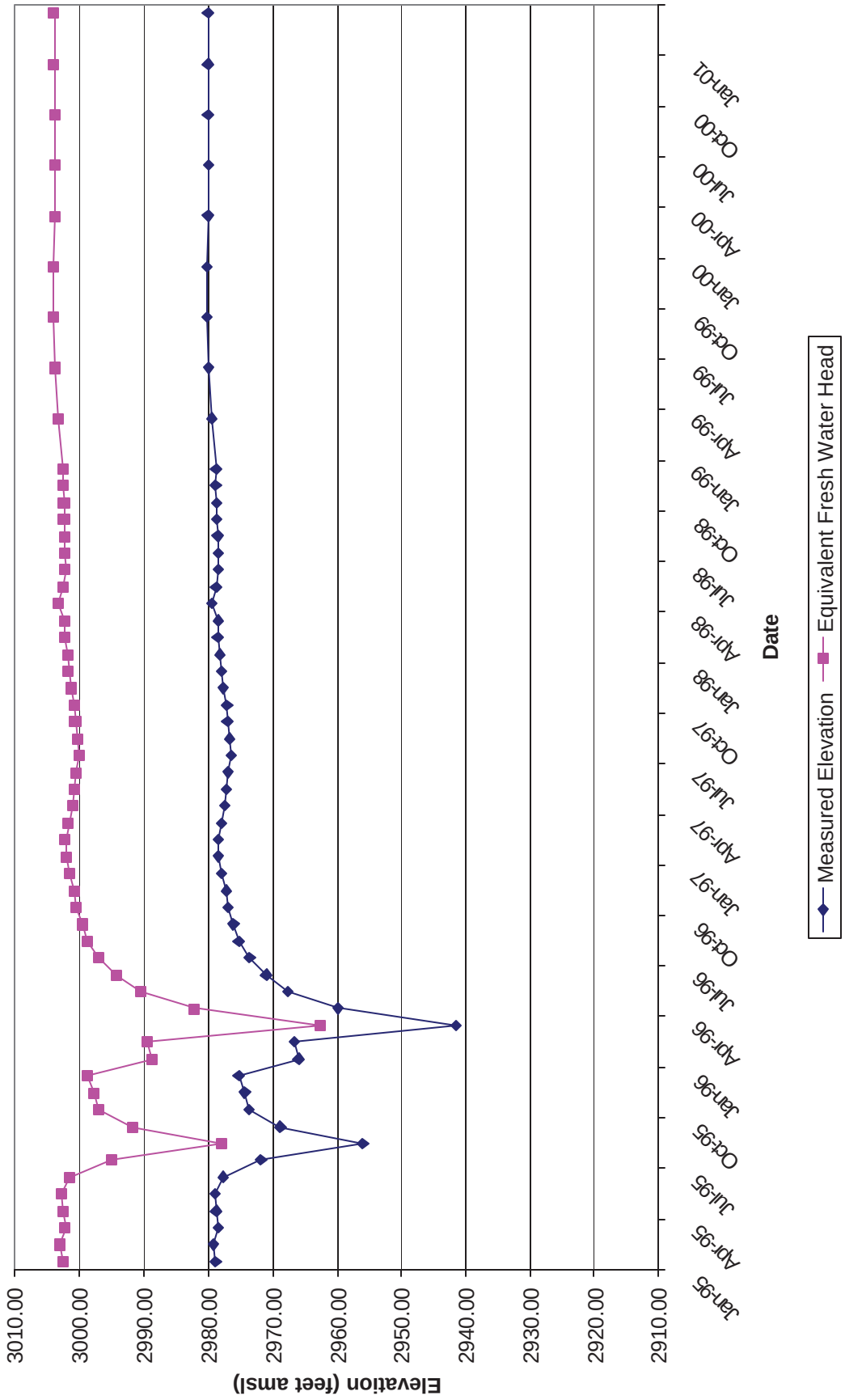

Table 43 - Well No. H-11b2 Magenta
June 2001 through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
06/06/01	3127.40	N/A
07/10/01	3127.48	N/A
09/11/01	3127.34	N/A
10/03/01	3127.52	N/A
11/12/01	3127.48	N/A
12/03/01	3127.59	N/A

Figure 43 - H-11b2 Magenta
Historical Waterlevel Measurements

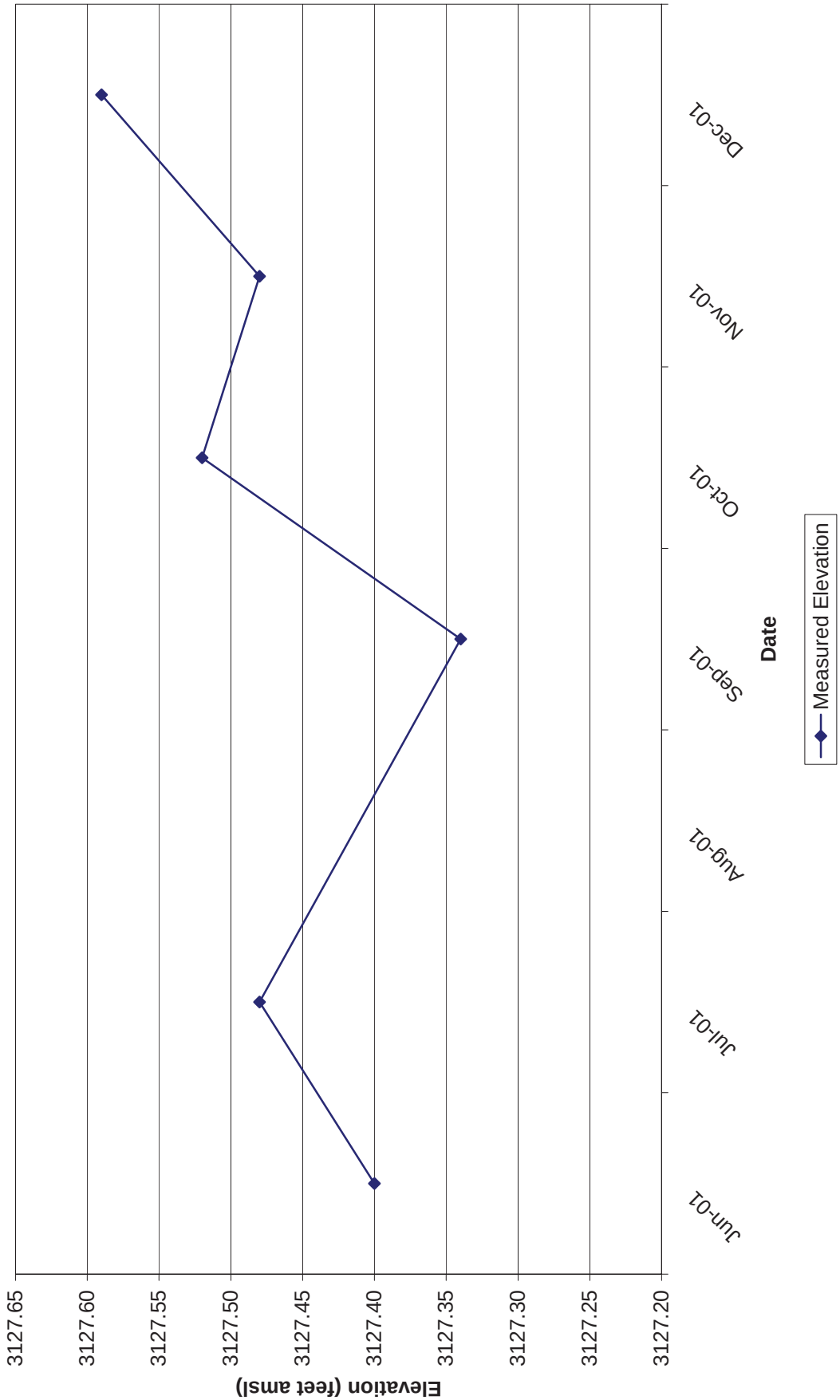

Table 44 - Well No. H-11b3 Culebra
March 1995 through March 2002

Date	Measured Elevation	Equivalent Fresh Water Head
03/14/95	2978.76	3003.51
06/06/95	2978.11	3002.81
09/07/95	2968.58	2992.52
12/05/95	2975.46	2999.95
03/12/96	2941.43	2963.23
06/11/96	2970.61	2994.71
09/04/96	2975.71	3000.22
12/10/96	2977.60	3002.26
03/11/97	2977.66	3002.32
06/11/97	2976.54	3001.11
09/16/97	2976.67	3001.25
12/09/97	2977.77	3002.44

Date	Measured Elevation	Equivalent Fresh Water Head
03/10/98	2978.24	3002.95
06/09/98	2978.21	3002.91
09/09/98	2978.42	3003.14
12/08/98	2978.58	3003.31
03/09/99	2979.37	3004.16
06/08/99	2979.86	3004.69
09/08/99	2979.83	3004.66
12/07/99	2979.86	3004.69
03/07/00	2979.81	3004.64
06/06/00	2979.90	3004.73
09/13/00	2979.80	3004.63
12/05/00	2979.88	3004.71

Date	Measured Elevation	Equivalent Fresh Water Head
03/07/01	2980.21	3005.07
06/06/01	2980.86	3005.77
09/05/01	2980.69	3005.59
12/03/01	2980.87	3005.78
03/13/02	2980.52	3005.40

Figure 44 - H-11b3 Culebra
Historical Waterlevel Measurements

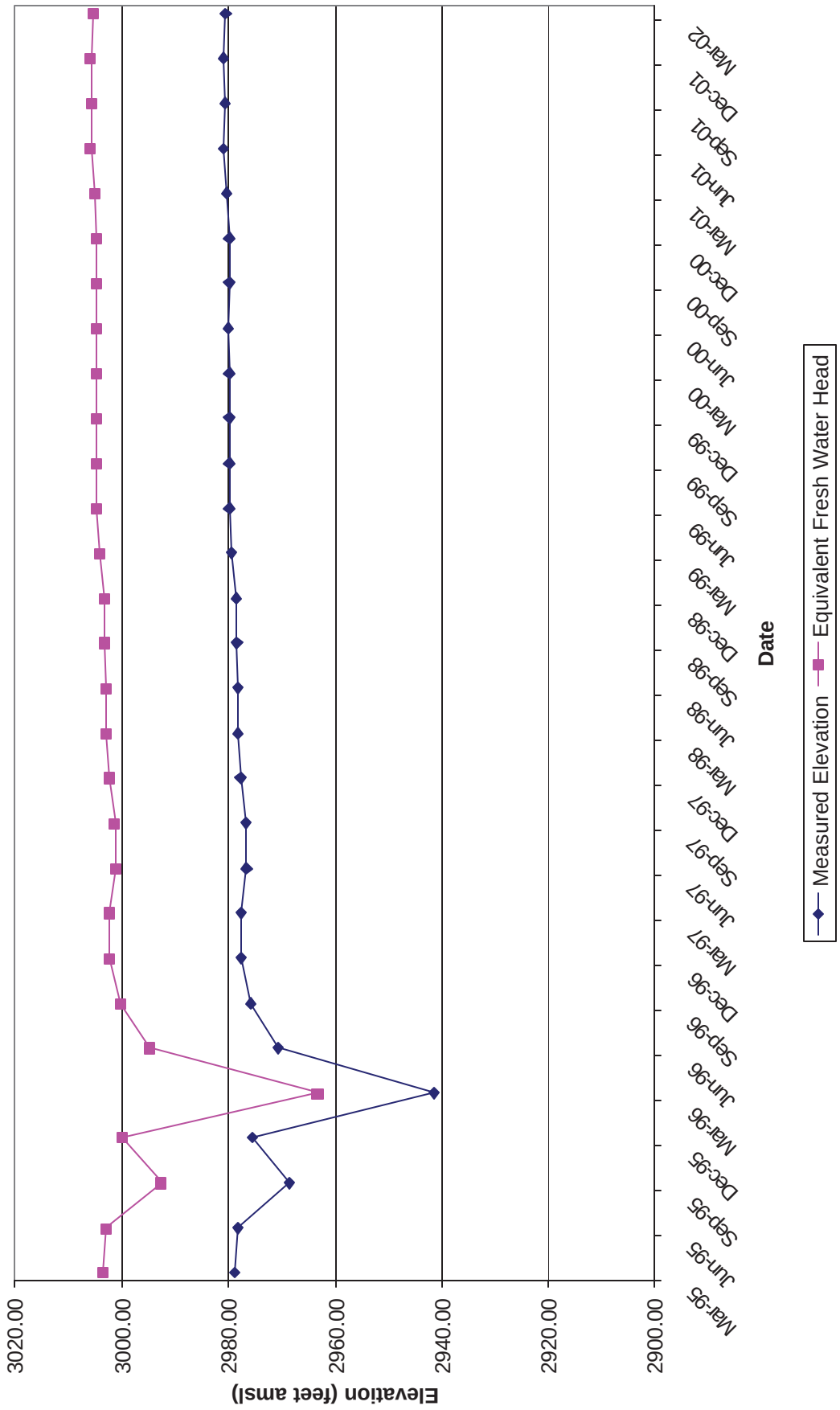

Table 45 - Well No. H-11b4 Culebra
August 1998 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
08/11/98	2981.88	3001.80
09/09/98	2982.06	3002.00
10/13/98	2982.04	3001.97
11/10/98	2982.23	3002.18
12/08/98	2982.23	3002.18
01/11/99	2982.74	3002.72
02/09/99	2982.70	3002.68
03/09/99	2983.01	3003.01
04/13/99	2983.30	3003.32
05/11/99	2983.28	3003.30
06/08/99	2983.53	3003.56
07/20/99	2983.49	3003.52
08/10/99	2983.66	3003.70
09/08/99	2983.58	3003.61
10/05/99	2983.42	3003.44
11/09/99	2983.42	3003.44
12/07/99	2983.57	3003.60
01/18/00	2983.22	3003.23
02/15/00	2983.40	3003.42
03/07/00	2983.50	3003.53
04/18/00	2983.53	3003.56
05/16/00	2983.72	3003.76
06/06/00	2983.51	3003.54
07/11/00	2983.77	3003.82
08/15/00	2983.59	3003.63
09/13/00	2983.53	3003.56
10/11/00	2982.99	3002.99
11/09/00	2983.61	3003.65
12/05/00	2983.61	3003.65

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2983.77	3003.82
02/05/01	2983.82	3003.87
03/07/01	2983.98	3004.04
04/05/01	2984.33	3004.41
05/09/01	2984.43	3004.52
06/06/01	2984.64	3004.74
07/10/01	2984.67	3004.78
08/07/01	2984.39	3004.48
09/05/01	2984.47	3004.56
10/09/01	2984.64	3004.74
11/12/01	2984.48	3004.57
12/03/01	2984.65	3004.75
01/15/02	2984.54	3004.64
02/05/02	2984.70	3004.81
03/13/02	2976.57	2996.15
04/10/02	2982.96	3002.95
05/06/02	2983.46	3003.49
06/11/02	2983.84	3003.89
07/16/02	2983.91	3003.97
08/14/02	2984.05	3004.12
09/12/02	2984.09	3004.16

Figure 45 - H-11b4 Culebra
Historical Waterlevel Measurements

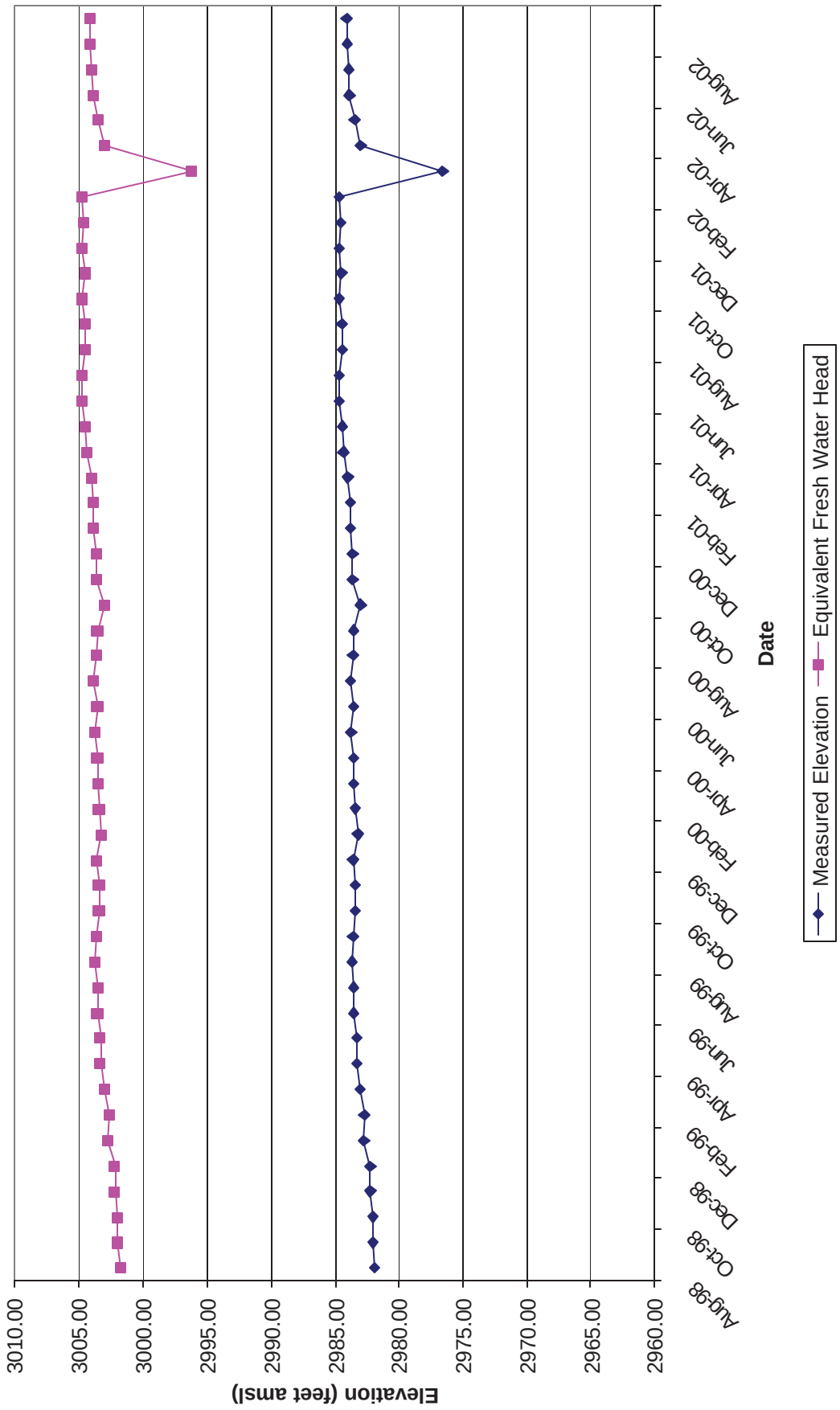

Table 46 - Well No. H-12 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2969.58	3006.83
02/14/95	2969.54	3006.79
03/14/95	2969.64	3006.90
04/11/95	2969.34	3006.57
05/09/95	2969.70	3006.96
06/06/95	2969.83	3007.10
07/18/95	2969.70	3006.96
08/16/95	2969.84	3007.12
09/06/95	2969.62	3006.87
10/17/95	2969.58	3006.83
11/07/95	2969.86	3007.14
12/05/95	2969.54	3006.79
01/09/96	2969.41	3006.64
02/06/96	2969.37	3006.60
03/11/96	2969.40	3006.63
04/16/96	2969.07	3006.27
05/14/96	2969.08	3006.28
06/11/96	2969.41	3006.64
07/16/96	2969.29	3006.51
08/14/96	2969.44	3006.68
09/04/96	2969.60	3006.85
10/15/96	2969.70	3006.96
11/12/96	2969.76	3007.03
12/10/96	2969.85	3007.13
01/15/97	2969.86	3007.14
02/11/97	2969.82	3007.09
03/11/97	2969.84	3007.12
04/15/97	2969.73	3006.99
05/13/97	2969.64	3006.90
06/11/97	2969.57	3006.82
07/15/97	2969.01	3006.20
08/12/97	2968.99	3006.18
09/16/97	2968.85	3006.03
10/14/97	2968.70	3005.86
11/11/97	2968.87	3006.05
12/09/97	2969.05	3006.25

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2969.00	3006.19
02/10/98	2969.30	3006.52
03/10/98	2969.05	3006.25
04/14/98	2969.48	3006.72
05/12/98	2969.54	3006.79
06/09/98	2969.47	3006.71
07/14/98	2969.36	3006.59
08/11/98	2969.30	3006.52
09/09/98	2969.40	3006.63
10/13/98	2969.32	3006.54
11/10/98	2969.44	3006.68
12/08/98	2969.37	3006.60
01/12/99	2969.60	3006.85
02/09/99	2969.67	3006.93
03/09/99	2969.80	3007.07
04/13/99	2969.86	3007.14
05/11/99	2969.99	3007.28
06/08/99	2969.90	3007.18
07/20/99	2969.82	3007.09
08/10/99	2970.08	3007.38
09/08/99	2969.86	3007.14
10/05/99	2969.66	3006.92
11/09/99	2969.60	3006.85
12/07/99	2969.58	3006.83
01/18/00	2969.44	3006.68
02/15/00	2969.48	3006.72
03/07/00	2969.53	3006.77
04/18/00	2969.42	3006.65
05/16/00	2969.45	3006.69
06/06/00	2969.35	3006.58
07/11/00	2969.44	3006.68
08/15/00	2969.31	3006.53
09/13/00	2969.31	3006.53
10/10/00	2969.00	3006.19
11/08/00	2969.24	3006.46
12/05/00	2968.94	3006.13

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2969.14	3006.35
02/07/01	2969.16	3006.37
03/07/01	2969.17	3006.38
04/04/01	2969.39	3006.62
05/07/01	2969.38	3006.61
06/06/01	2969.63	3006.88
07/10/01	2969.56	3006.81
08/07/01	2969.49	3006.73
09/05/01	2970.55	3007.89
10/09/01	2969.58	3006.83
11/13/01	2969.55	3006.80
12/04/01	2969.63	3006.88
01/15/02	2969.62	3006.87
02/06/02	2969.69	3006.95
03/13/02	2970.07	3007.37
04/10/02	2969.93	3007.21
05/06/02	2970.19	3007.50
06/11/02	2970.38	3007.71
07/16/02	2970.29	3007.61
08/13/02	2970.78	3008.15
09/11/02	2970.50	3007.84

Figure 46 - H-12 Culebra
Historical Waterlevel Measurements

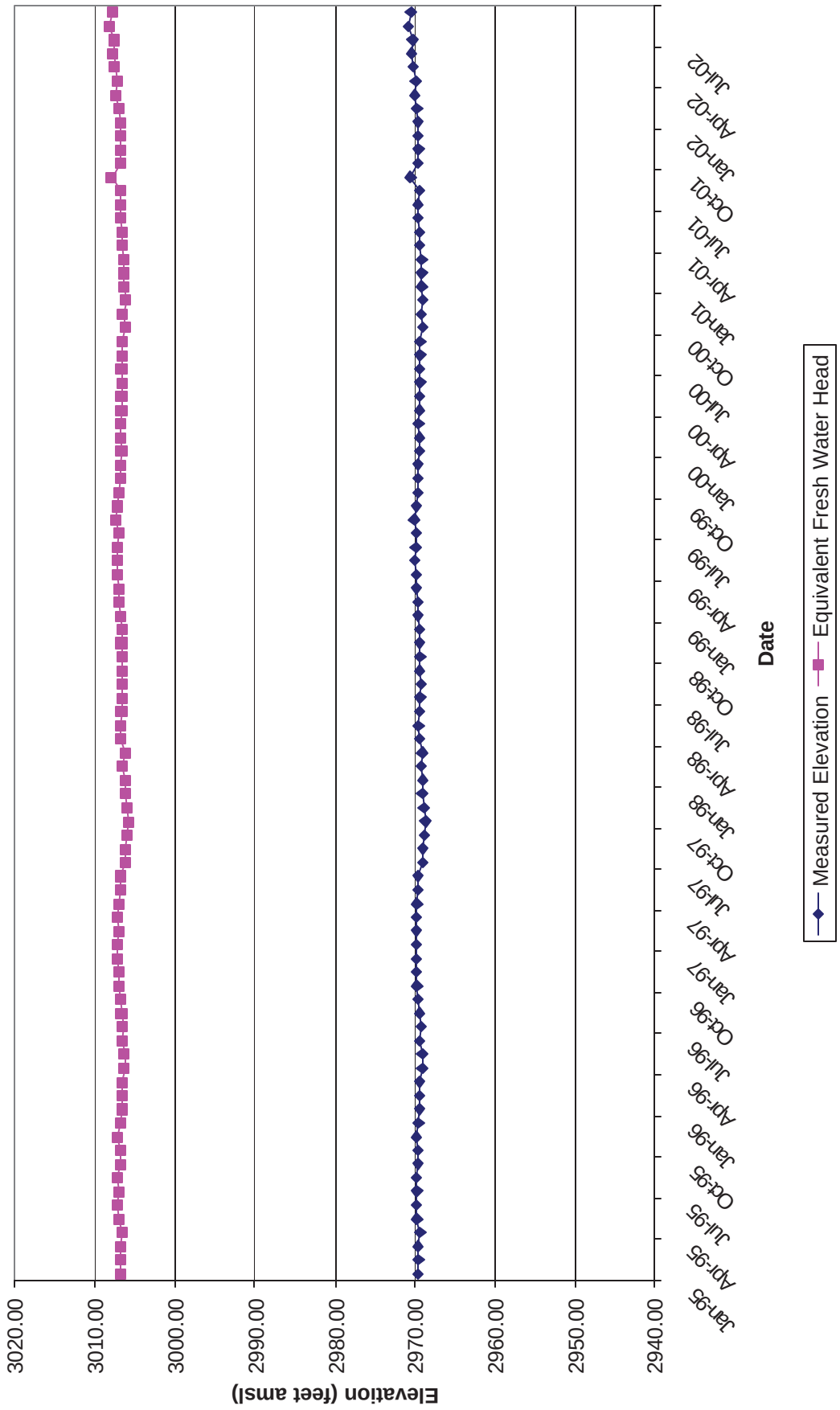

Table 47 - Well No. H14 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3009.19	3012.07
02/15/95	3009.51	3012.39
03/14/95	3009.42	3012.30
04/11/95	3009.36	3012.24
05/09/95	3009.63	3012.51
06/07/95	3009.71	3012.59
07/19/95	3008.44	3011.31
08/17/95	3007.78	3010.64
09/07/95	3006.89	3009.74
10/19/95	2999.41	3002.16
11/08/95	3004.20	3007.01
12/06/95	3004.78	3007.60
01/10/96	3004.46	3007.27
02/07/96	3003.99	3006.80
03/14/96	3000.27	3003.03
04/17/96	2998.79	3001.53
05/14/96	2998.05	3000.78
06/12/96	2998.13	3000.86
07/16/96	2997.21	2999.93
08/14/96	2998.83	3001.57
09/04/96	2999.93	3002.69
10/15/96	3000.31	3003.07
11/13/96	3001.37	3004.14
12/10/96	3002.69	3005.48
01/15/97	3003.69	3006.49
02/11/97	3004.31	3007.12
03/12/97	3004.95	3007.77
04/14/97	3004.33	3007.14
05/14/97	3005.50	3008.33
06/11/97	3005.84	3008.67
07/16/97	3005.00	3007.82
08/12/97	3005.66	3008.49
09/16/97	3006.14	3008.98
10/15/97	3006.14	3008.98
11/12/97	3006.61	3009.45
12/10/97	3006.75	3009.59

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3007.03	3009.88
02/11/98	3007.28	3010.13
03/12/98	3007.15	3010.00
04/16/98	3007.75	3010.61
05/12/98	3007.91	3010.77
06/11/98	3006.90	3009.75
07/14/98	3006.44	3009.28
08/12/98	3007.66	3010.52
09/10/98	3007.83	3010.69
10/13/98	3007.91	3010.77
11/13/98	3007.31	3010.16
12/09/98	3007.68	3010.54
01/12/99	3008.20	3011.06
02/10/99	3008.31	3011.17
03/10/99	3008.55	3011.42
04/13/99	3008.73	3011.60
05/10/99	3008.91	3011.78
06/09/99	3008.37	3011.23
07/21/99	3008.63	3011.50
08/11/99	3008.93	3011.80
09/08/99	3009.01	3011.88
10/04/99	3008.99	3011.86
11/10/99	3008.45	3011.32
12/08/99	3008.98	3011.85
01/19/00	3009.20	3012.08
02/15/00	3009.31	3012.19
03/06/00	3009.42	3012.30
04/17/00	3009.44	3012.32
05/17/00	3008.93	3011.80
06/07/00	3008.96	3011.83
07/12/00	3009.48	3012.36
08/14/00	3009.52	3012.40
09/11/00	3009.68	3012.56
10/10/00	3009.48	3012.36
11/08/00	3009.79	3012.67
12/06/00	3008.98	3011.85

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3009.53	3012.41
02/05/01	3009.40	3012.28
03/08/01	3009.63	3012.51

Figure 47 - H-14 Culebra
Historical Waterlevel Measurements

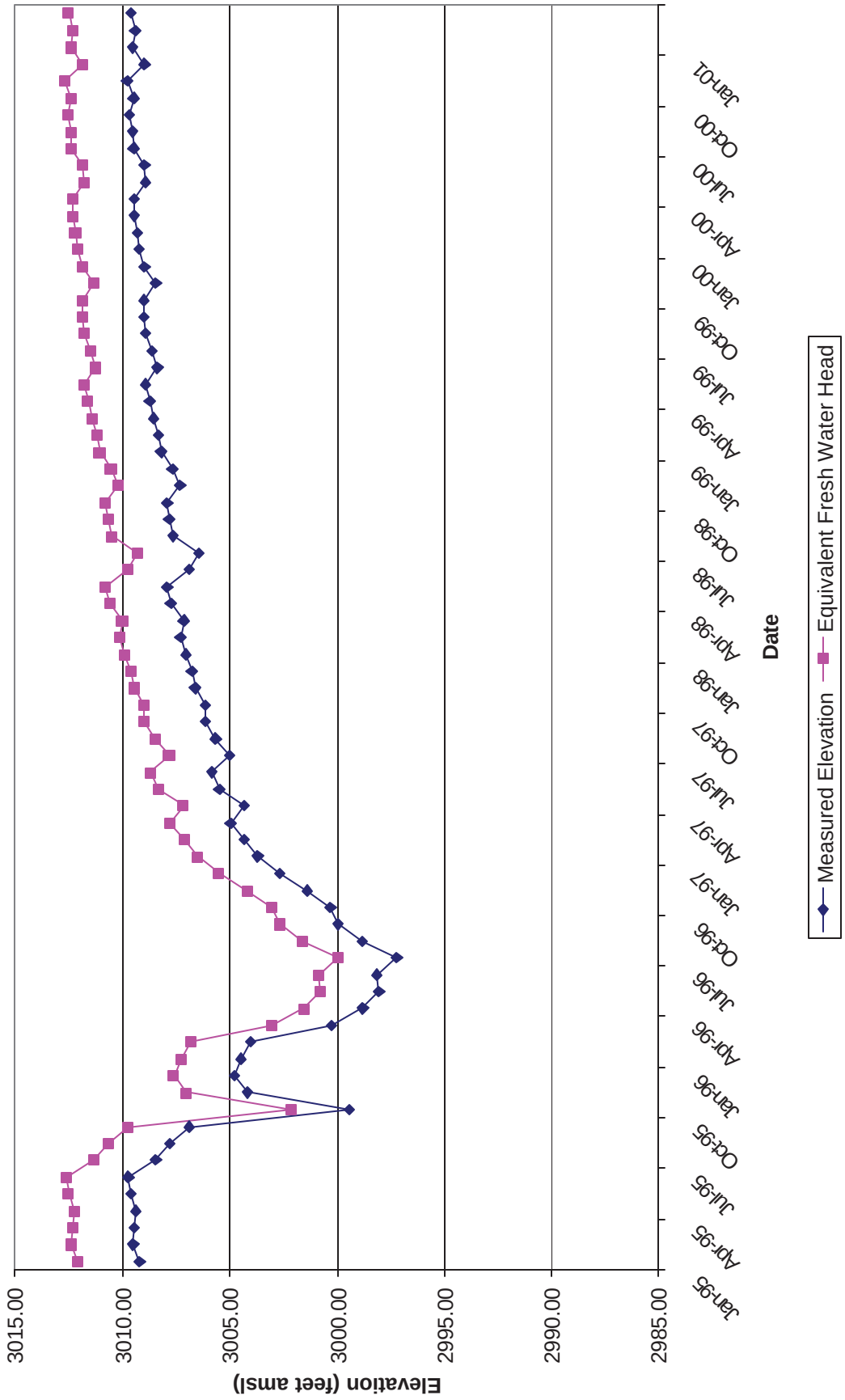

Table 48 - Well No. H-14 Magenta
April 2001through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
04/05/01	3106.99	N/A
05/09/01	3035.07	N/A
06/06/01	3049.31	N/A
07/11/01	3065.32	N/A
09/12/01	3090.39	N/A
10/03/01	3096.00	N/A
11/12/01	3101.86	N/A
12/03/01	3102.47	N/A

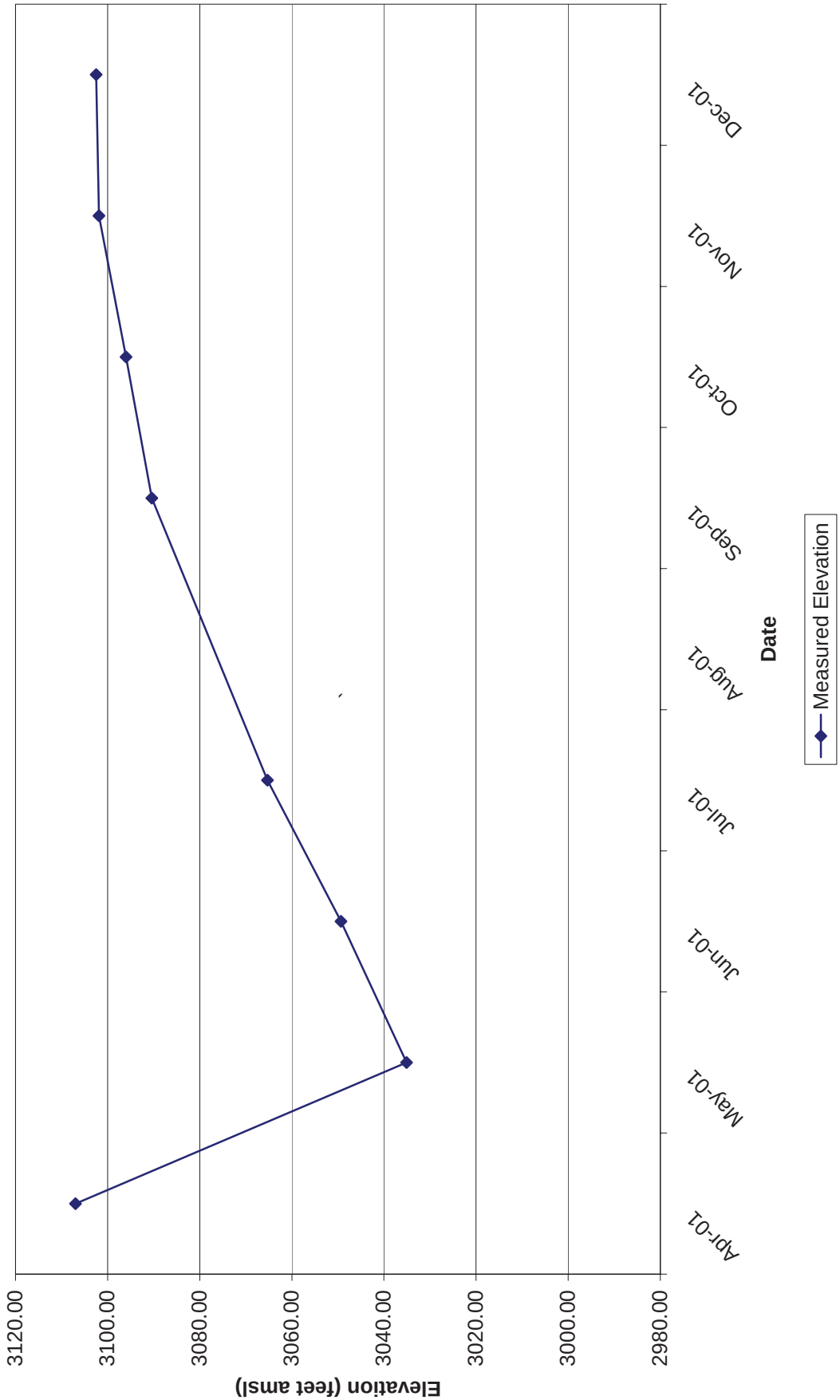
Figure 48 - H-14 Magenta
Historical Waterlevel Measurements
Elevation (feet amsl)
3120.00
3100.00
3080.00
3060.00
3040.00
3020.00
3000.00
2980.00
Apr-01
May-01
Jun-01
Jul-01
Aug-01
Sep-01
Oct-01
Nov-01
Dec-01
Date
Measured Elevation

Table 49 - Well No. H-15 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	2959.70	3012.57
02/15/95	2959.92	3012.82
03/13/95	2959.26	3012.06
04/11/95	2959.18	3011.97
05/09/95	2959.73	3012.60
06/07/95	2959.29	3012.09
07/19/95	2953.98	3005.98
08/17/95	2949.50	3000.82
09/05/95	2945.94	2996.73
10/18/95	2947.36	2998.36
11/08/95	2949.85	3001.23
12/04/95	2951.30	3002.90
01/09/96	2949.09	3000.35
02/05/96	2943.71	2994.16
03/11/96	2932.70	2981.49
04/15/96	2928.45	2976.60
05/15/96	2934.49	2983.55
06/10/96	2939.32	2989.11
07/16/96	2944.10	2994.61
08/12/96	2946.92	2997.86
09/04/96	2948.96	3000.20
10/16/96	2951.26	3002.85
11/13/96	2952.42	3004.19
12/10/96	2953.72	3005.68
01/13/97	2954.75	3006.87
02/12/97	2955.62	3007.87
03/12/97	2956.23	3008.57
04/16/97	2956.70	3009.11
05/14/97	2957.01	3009.47
06/12/97	2957.10	3009.57
07/16/97	2957.03	3009.49
08/13/97	2957.11	3009.58
09/16/97	2957.50	3010.03
10/15/97	2957.60	3010.15
11/12/97	2957.95	3010.55
12/10/97	2958.25	3010.90

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2958.63	3011.33
02/12/98	2959.02	3011.78
03/12/98	2959.06	3011.83
04/16/98	2959.65	3012.51
05/13/98	2959.74	3012.61
06/11/98	2959.64	3012.50
07/15/98	2959.67	3012.53
08/12/98	2959.72	3012.59
09/10/98	2959.92	3012.82
10/14/98	2959.97	3012.88
11/13/98	2960.01	3012.92
12/09/98	2960.15	3013.08
01/13/99	2960.44	3013.42
02/10/99	2960.58	3013.58
03/10/99	2960.88	3013.92
04/13/99	2961.03	3014.10
05/11/99	2961.20	3014.29
06/09/99	2961.26	3014.36
07/21/99	2961.31	3014.42
08/11/99	2961.55	3014.69
09/08/99	2961.60	3014.75
10/04/99	2961.59	3014.74
11/10/99	2961.51	3014.65
12/08/99	2961.62	3014.78
01/19/00	2961.59	3014.74
02/15/00	2961.70	3014.87
03/08/00	2961.77	3014.95
04/18/00	2961.83	3015.02
05/17/00	2961.90	3015.10
06/07/00	2961.79	3014.97
07/10/00	2962.00	3015.21
08/14/00	2961.98	3015.19
09/11/00	2962.10	3015.33
10/11/00	2961.88	3015.07
11/08/00	2962.05	3015.27
12/06/00	2961.86	3015.05

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	2962.01	3015.22
02/05/01	2961.90	3015.10
03/05/01	2962.22	3015.47

Figure 49 - H-15 Culebra
Historical Waterlevel Measurements

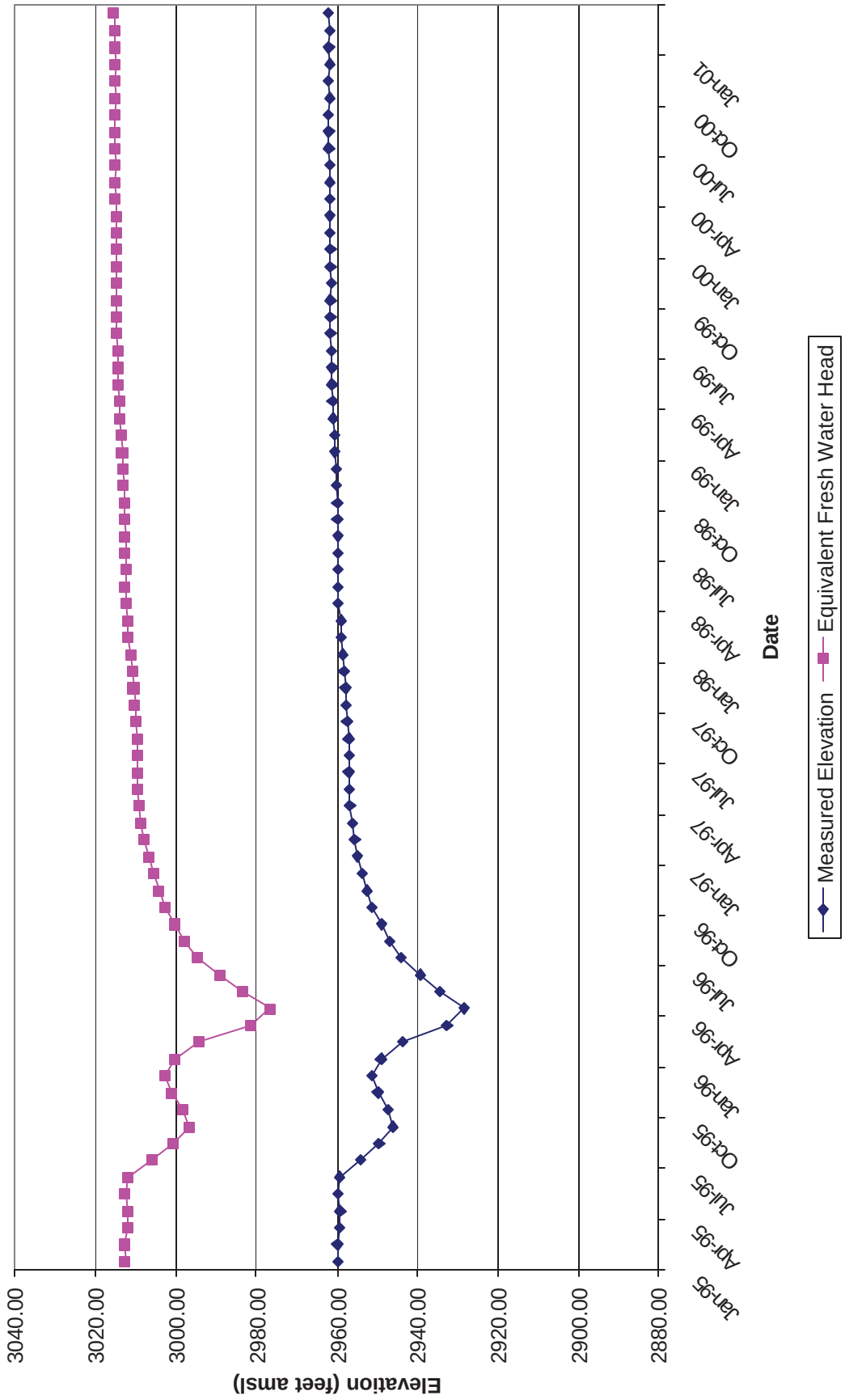

Table 50 - Well No. H-15 Magenta
April 2001through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
04/06/01	3098.69	N/A
05/08/01	3112.21	N/A
06/07/01	3112.59	N/A
07/11/01	3113.04	N/A
09/12/01	3112.86	N/A
10/03/01	3113.53	N/A
11/12/01	3112.95	N/A
12/03/01	3113.00	N/A

Figure 50 - H-15 Magenta
Historical Waterlevel Measurements

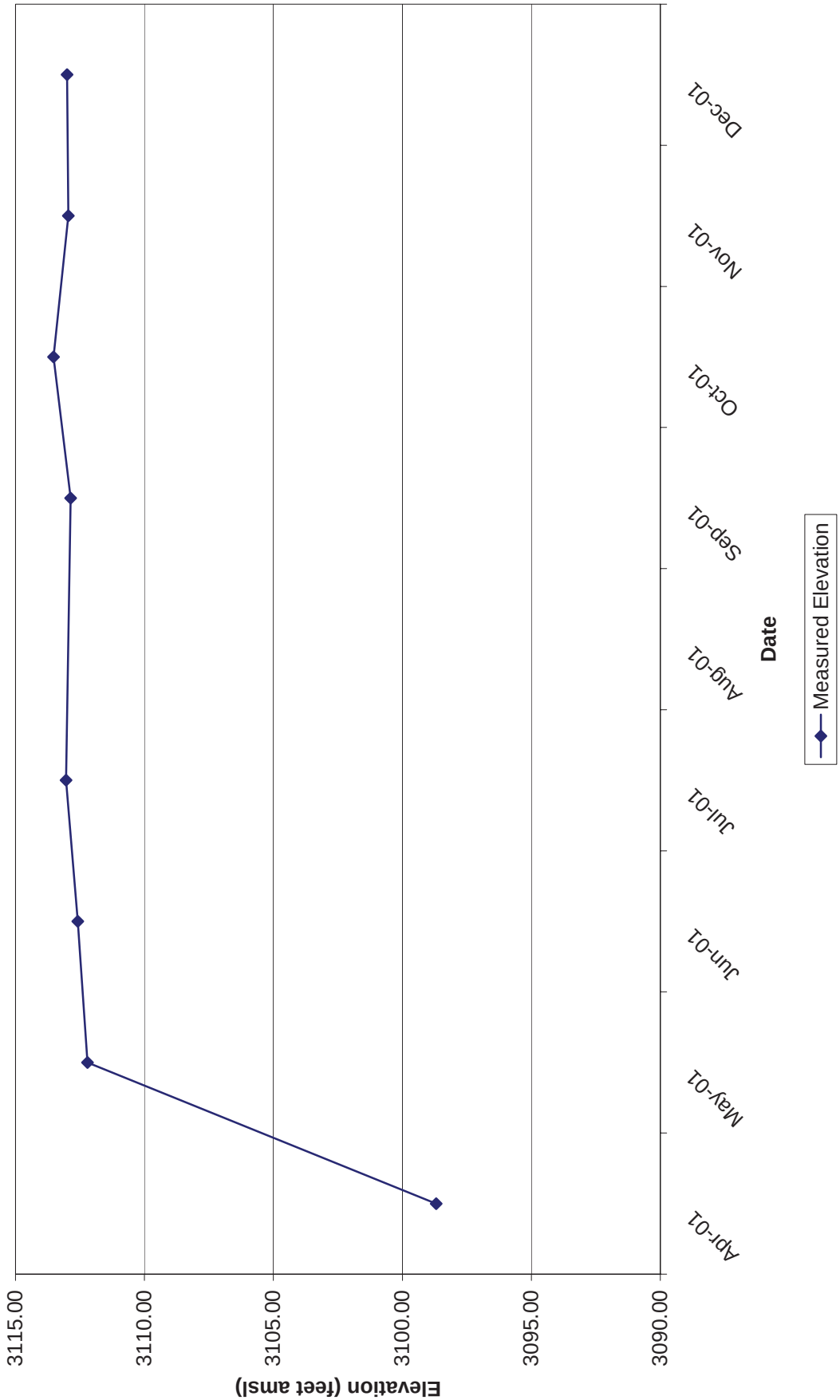

Table 51 - Well No. H-16 (PVC) Los Medanos Member
January 1995 through July 2000

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3050.51	N/A
02/15/95	3050.42	N/A
03/15/95	3050.04	N/A
04/12/95	3049.42	N/A
05/10/95	3049.06	N/A
06/07/95	3048.61	N/A
07/20/95	3048.12	N/A
08/17/95	3047.98	N/A
09/08/95	3047.93	N/A
10/19/95	3048.47	N/A
11/09/95	3048.56	N/A
12/06/95	3048.57	N/A
01/11/96	3048.07	N/A
02/07/96	3047.46	N/A
03/14/96	3046.26	N/A
04/18/96	3044.88	N/A
05/15/96	3044.09	N/A
06/13/96	3043.66	N/A
07/17/96	3043.21	N/A
08/15/96	3043.15	N/A
09/06/96	3043.26	N/A
10/17/96	3045.16	N/A
11/13/96	3046.57	N/A
12/11/96	3047.67	N/A
01/16/97	3048.25	N/A
02/12/97	3048.15	N/A
03/13/97	3047.76	N/A
04/16/97	3047.05	N/A
05/15/97	3046.35	N/A
06/12/97	3045.78	N/A
07/16/97	3045.35	N/A
08/14/97	3045.25	N/A
09/17/97	3045.47	N/A
10/16/97	3046.01	N/A
11/13/97	3046.43	N/A
12/11/97	3046.63	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/15/98	3046.57	N/A
02/12/98	3046.29	N/A
03/12/98	3045.64	N/A
04/16/98	3044.59	N/A
05/13/98	3043.77	N/A
06/11/98	3042.97	N/A
07/15/98	3042.49	N/A
08/12/98	3042.31	N/A
09/11/98	3042.01	N/A
10/15/98	3043.03	N/A
11/13/98	3043.60	N/A
12/09/98	3043.98	N/A
01/13/99	3004.10	N/A
02/10/99	3044.06	N/A
03/10/99	3043.72	N/A
04/14/99	3042.85	N/A
05/12/99	3042.14	N/A
06/10/99	3041.43	N/A
07/21/99	3041.59	N/A
08/11/99	3041.71	N/A
09/09/99	3042.63	N/A
10/06/99	3043.49	N/A
11/10/99	3044.21	N/A
12/09/99	3045.14	N/A
01/20/00	3045.50	N/A
02/16/00	3045.42	N/A
03/08/00	3045.23	N/A
04/19/00	3043.82	N/A
05/17/00	3043.38	N/A
06/08/00	3043.23	N/A
07/12/00	3044.71	N/A

Figure 51 - H-16 Los Medanos Member Historical Waterlevel Measurements

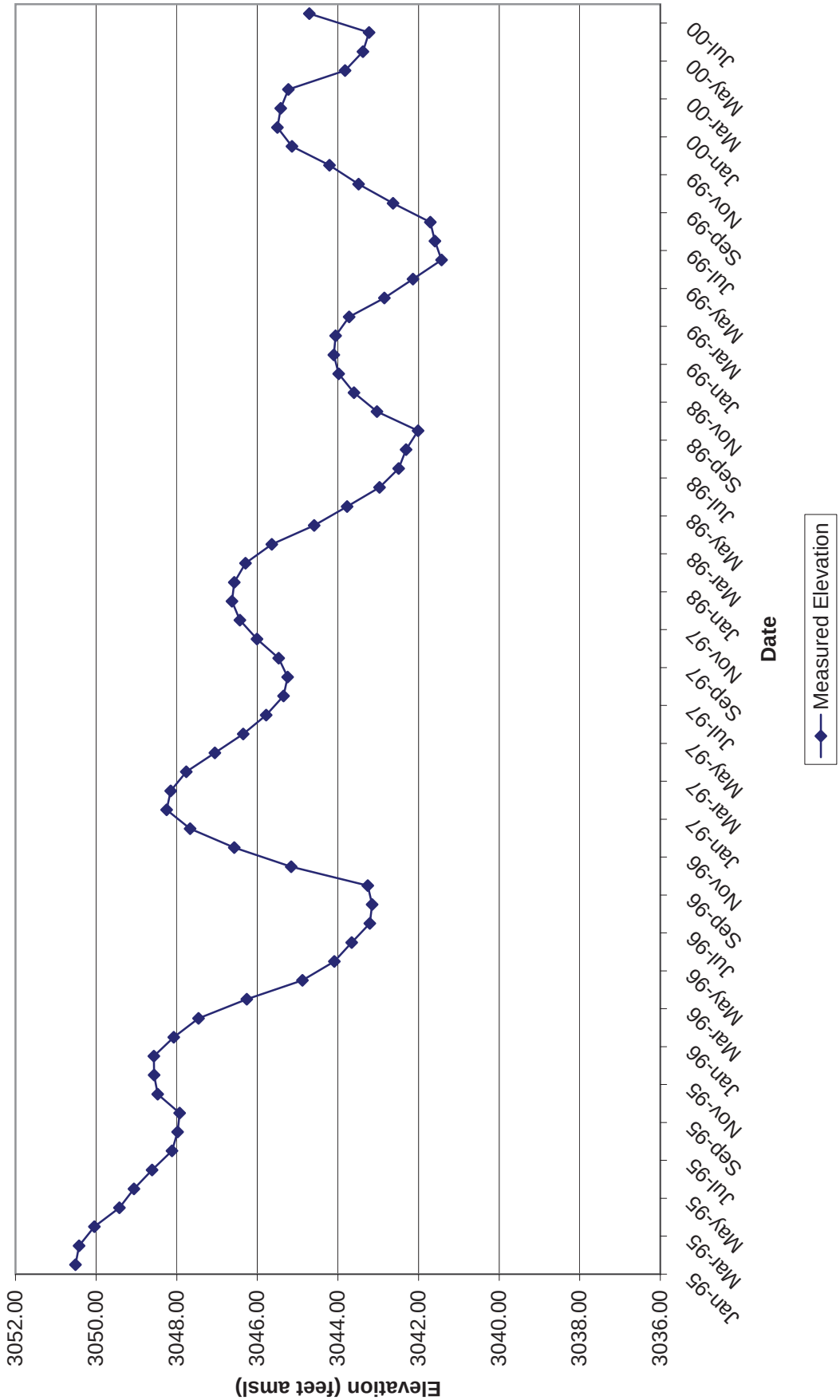

Table 52 - Well No. H-16 (PVC) Dewey Lake
January 1995 through July 2000

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3352.32	N/A
02/15/95	3351.33	N/A
03/15/95	3350.28	N/A
04/12/95	3349.27	N/A
05/10/95	3348.34	N/A
06/07/95	3347.37	N/A
07/20/95	3345.76	N/A
08/17/95	3344.77	N/A
09/08/95	3343.98	N/A
10/19/95	3342.52	N/A
11/09/95	3341.77	N/A
12/06/95	3340.69	N/A
01/11/96	3339.45	N/A
02/07/96	3338.52	N/A
03/14/96	3337.20	N/A
04/18/96	3336.00	N/A
05/15/96	3335.11	N/A
06/13/96	3334.05	N/A
07/17/96	3332.62	N/A
08/15/96	3331.78	N/A
09/06/96	3331.14	N/A
10/17/96	3329.61	N/A
11/13/96	3328.77	N/A
12/11/96	3327.91	N/A
01/16/97	3326.66	N/A
02/12/97	3325.76	N/A
03/13/97	3324.76	N/A
04/16/97	3323.65	N/A
05/15/97	3322.74	N/A
06/12/97	3321.86	N/A
07/16/97	3320.73	N/A
08/14/97	3320.06	N/A
09/17/97	3318.67	N/A
10/16/97	3317.74	N/A
11/13/97	3316.62	N/A
12/11/97	3315.94	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/15/98	3314.85	N/A
02/12/98	3313.95	N/A
03/12/98	3313.05	N/A
04/16/98	3311.94	N/A
05/13/98	3311.10	N/A
06/11/98	3310.18	N/A
07/15/98	3309.07	N/A
08/12/98	3308.07	N/A
09/11/98	3307.14	N/A
10/15/98	3306.13	N/A
11/13/98	3305.22	N/A
12/09/98	3304.45	N/A
01/13/99	3303.43	N/A
02/10/99	3302.61	N/A
03/10/99	3301.84	N/A
04/14/99	3300.91	N/A
05/12/99	3300.11	N/A
06/10/99	3299.58	N/A
07/21/99	3332.85	N/A
08/11/99	3332.33	N/A
09/09/99	3331.42	N/A
10/06/99	3330.59	N/A
11/10/99	3329.50	N/A
12/09/99	3328.61	N/A
01/20/00	3327.31	N/A
02/16/00	3326.49	N/A
03/08/00	3325.84	N/A
04/19/00	3324.55	N/A
05/17/00	3322.77	N/A
06/08/00	3323.03	N/A
07/12/00	3405.95	N/A

Figure 52 - H-16 Dewey Lake Historical Waterlevel Measurements

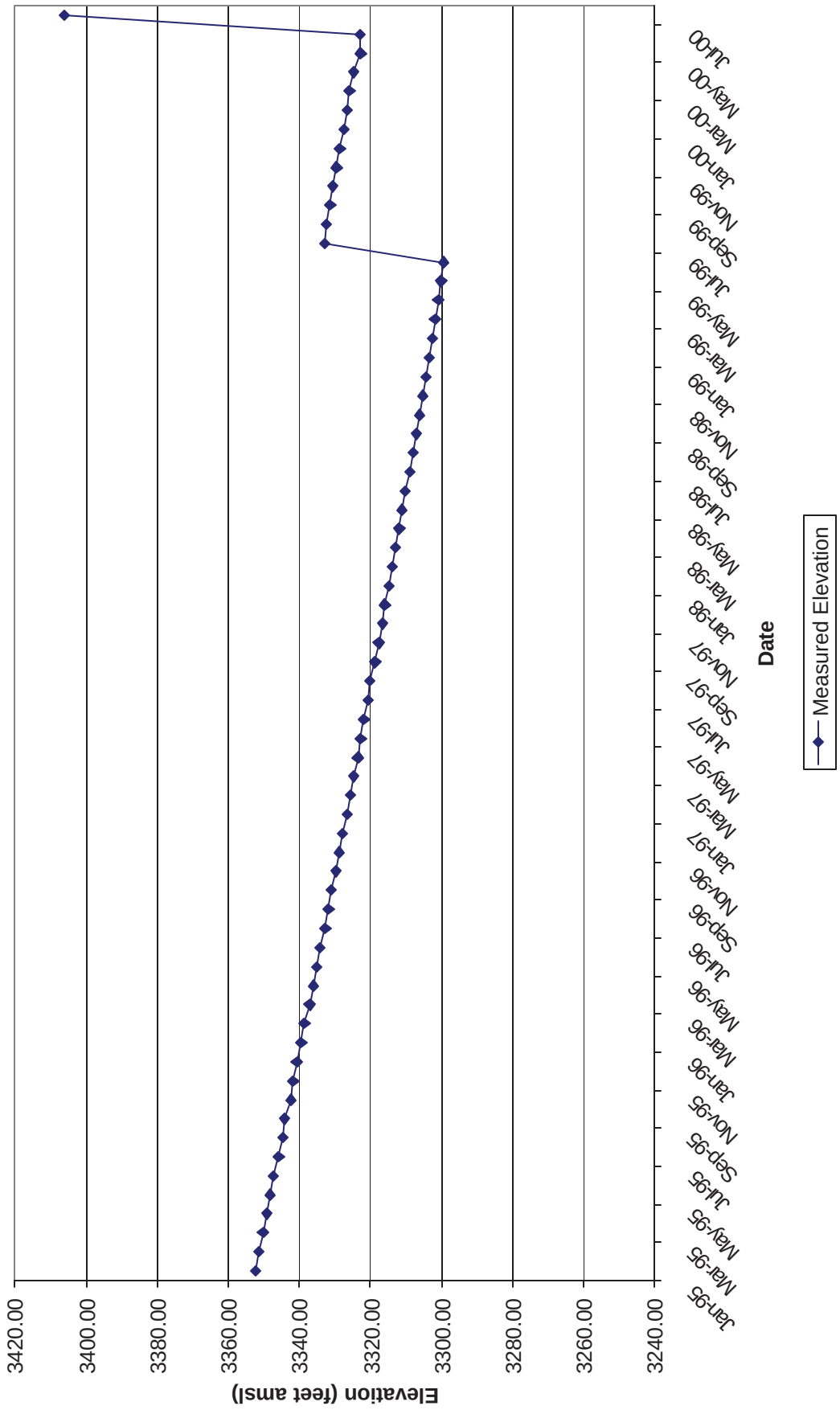

Table 53 - Well No. H-17 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2956.74	3005.00
02/14/95	2956.96	3005.26
03/14/95	2956.90	3005.19
04/11/95	2957.00	3005.30
05/09/95	2957.48	3005.86
06/06/95	2957.61	3006.02
07/19/95	2956.58	3004.81
08/16/95	2955.80	3003.91
09/07/95	2953.77	3001.54
10/18/95	2955.41	3003.45
11/07/95	2955.69	3003.78
12/05/95	2956.08	3004.23
01/09/96	2955.47	3003.52
02/06/96	2954.60	3002.51
03/12/96	2950.18	2997.35
04/16/96	2949.30	2996.33
05/14/96	2952.14	2999.64
06/11/96	2954.02	3001.83
07/16/96	2955.41	3003.45
08/13/96	2956.38	3004.58
09/04/96	2956.84	3005.12
10/16/96	2957.36	3005.72
11/12/96	2957.58	3005.98
12/10/96	2957.98	3006.45
01/15/97	2958.24	3006.75
02/11/97	2958.27	3006.79
03/11/97	2958.08	3006.56
04/15/97	2957.58	3005.98
05/14/97	2957.40	3005.77
06/11/97	2957.14	3005.47
07/15/97	2956.84	3005.12
08/12/97	2956.82	3005.09
09/16/97	2957.10	3005.42
10/15/97	2957.20	3005.54
11/11/97	2957.53	3005.92
12/09/97	2957.88	3006.33

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2958.10	3006.59
02/10/98	2958.47	3007.02
03/10/98	2958.45	3007.00
04/14/98	2958.91	3007.53
05/12/98	2958.97	3007.60
06/10/98	2958.74	3007.33
07/14/98	2958.68	3007.26
08/11/98	2958.71	3007.30
09/09/98	2958.86	3007.47
10/13/98	2958.89	3007.51
11/10/98	2959.08	3007.73
12/08/98	2959.08	3007.73
01/12/99	2959.34	3008.13
02/09/99	2959.48	3008.29
03/09/99	2959.76	3008.62
04/13/99	2959.93	3008.82
05/11/99	2960.17	3009.10
06/08/99	2960.26	3009.20
07/20/99	2960.28	3009.23
08/10/99	2960.45	3009.42
09/08/99	2960.50	3009.48
10/05/99	2960.33	3009.29
11/09/99	2960.31	3009.26
12/07/99	2960.39	3009.36
01/18/00	2960.24	3009.18
02/15/00	2960.41	3009.38
03/07/00	2960.52	3009.51
04/18/00	2960.58	3009.58
05/16/00	2960.71	3009.73
06/06/00	2960.66	3009.67
07/11/00	2960.82	3009.86
08/15/00	2960.72	3009.74
09/13/00	2960.71	3009.73
10/11/00	2960.53	3009.52
11/09/00	2960.82	3009.86
12/05/00	2960.56	3009.55

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2960.85	3009.89
02/05/01	2960.79	3009.82
03/07/01	2961.12	3010.21
04/05/01	2961.46	3010.60
05/09/01	2961.52	3010.67
06/06/01	2961.90	3011.12
07/11/01	2961.90	3011.12
08/07/01	2961.74	3010.93
09/05/01	2961.77	3010.96
10/09/01	2961.72	3010.91
11/13/01	2961.87	3011.08
12/04/01	2961.97	3011.20
01/15/02	2962.03	3011.27
02/05/02	2962.11	3011.36
03/13/02	2962.62	3011.96
04/10/02	2962.36	3011.65
05/07/02	2962.71	3012.06
06/11/02	2962.99	3012.39
07/16/02	2962.95	3012.34
08/14/02	2963.12	3012.54
09/12/02	2963.07	3012.48

Figure 53 - H-17 Culebra
Historical Waterlevel Measurements

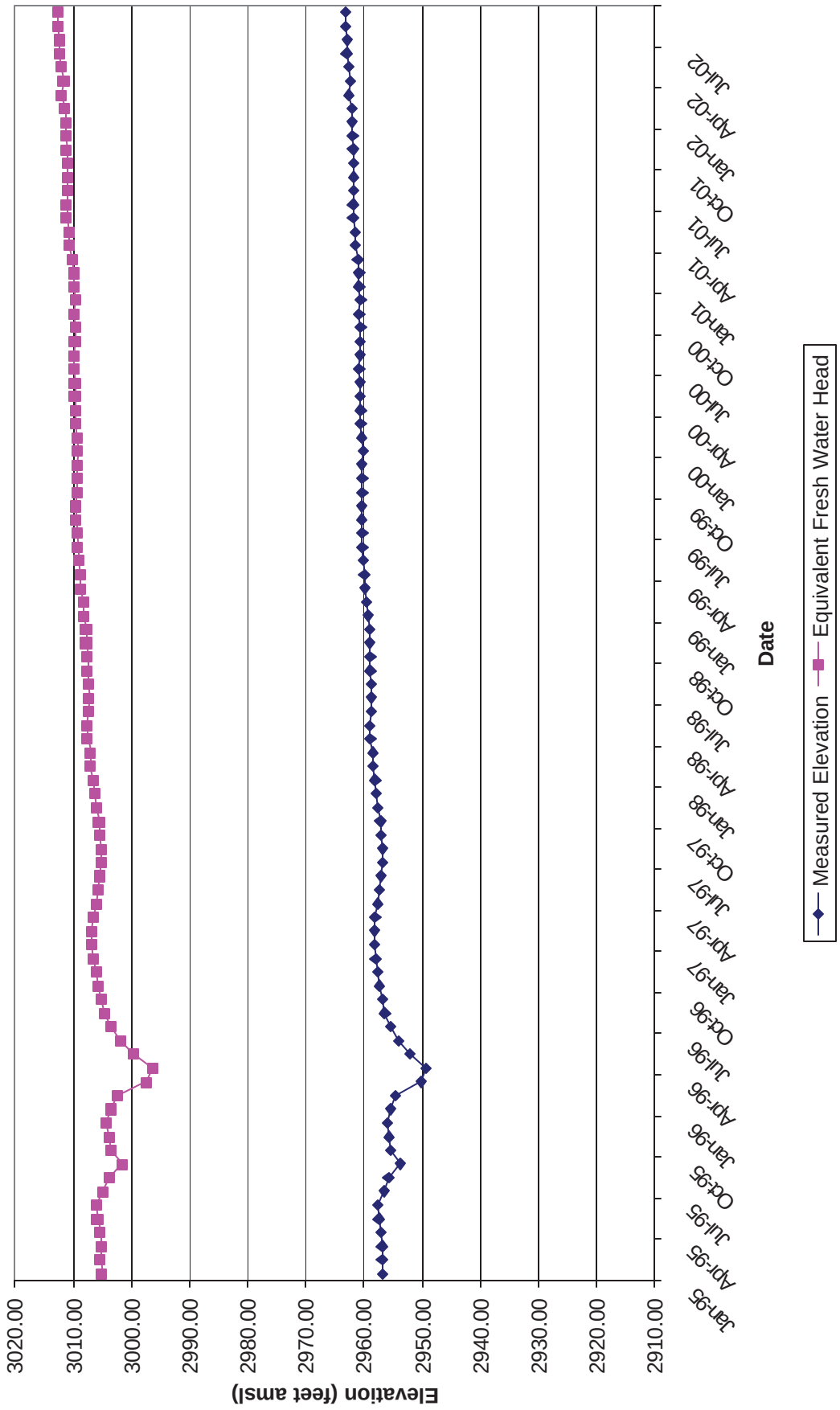

Table 54 - Well No. H18 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3055.91	3071.07
02/13/95	3055.85	3071.01
03/13/95	3055.86	3071.02
04/10/95	3053.81	3068.88
05/08/95	3056.41	3071.59
06/05/95	3056.66	3071.85
07/17/95	3056.80	3072.00
08/14/95	3056.99	3072.20
09/05/95	3056.22	3071.39
10/16/95	3056.83	3072.03
11/06/95	3057.26	3072.48
12/04/95	3057.16	3072.38
01/08/96	3057.11	3072.32
02/05/96	3055.86	3071.02
03/11/96	3056.23	3071.40
04/15/96	3056.11	3071.28
05/13/96	3056.70	3071.89
06/10/96	3057.00	3072.21
07/15/96	3057.16	3072.38
08/12/96	3056.91	3072.11
09/03/96	3057.38	3072.60
10/14/96	3057.52	3072.75
11/11/96	3057.18	3072.40
12/09/96	3057.47	3072.70
01/13/97	3057.53	3072.76
02/10/97	3057.63	3072.87
03/10/97	3057.85	3073.10
04/14/97	3058.12	3073.38
05/13/97	3058.14	3073.40
06/09/97	3058.44	3073.71
07/16/97	3058.68	3073.96
08/11/97	3058.58	3073.86
09/15/97	3058.59	3073.87
10/13/97	3058.27	3073.53
11/10/97	3058.18	3073.44
12/08/97	3057.74	3072.98

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3057.70	3072.94
02/09/98	3059.82	3075.15
03/09/98	3060.43	3075.79
04/15/98	3060.59	3075.96
05/11/98	3060.11	3075.46
06/10/98	3059.64	3074.96
07/15/98	3059.13	3074.43
08/11/98	3059.41	3074.72
09/10/98	3059.25	3074.56
10/14/98	3059.06	3074.36
11/11/98	3058.88	3074.17
12/07/98	3058.81	3074.10
01/11/99	3058.90	3074.13
02/09/99	3059.24	3074.49
03/09/99	3059.25	3074.50
04/12/99	3059.19	3074.44
05/10/99	3058.53	3073.79
06/07/99	3059.42	3074.68
07/19/99	3059.23	3074.48
08/09/99	3059.27	3074.52
09/08/99	3059.11	3074.35
10/04/99	3059.12	3074.36
11/08/99	3059.44	3074.70
12/09/99	3059.51	3074.77
01/19/00	3059.90	3075.18
02/14/00	3059.93	3075.21
03/06/00	3060.00	3075.28
04/17/00	3059.91	3075.19
05/15/00	3059.89	3075.17
06/05/00	3059.65	3074.92
07/10/00	3059.81	3075.08
08/14/00	3059.74	3075.01
09/12/00	3059.61	3074.88
10/09/00	3059.25	3074.50
11/06/00	3059.92	3075.20
12/07/00	3059.60	3074.87

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3059.66	3074.93
02/05/01	3059.70	3074.97
03/06/01	3059.61	3074.88

Figure 54 - H-18 Culebra
Historical Waterlevel Measurements

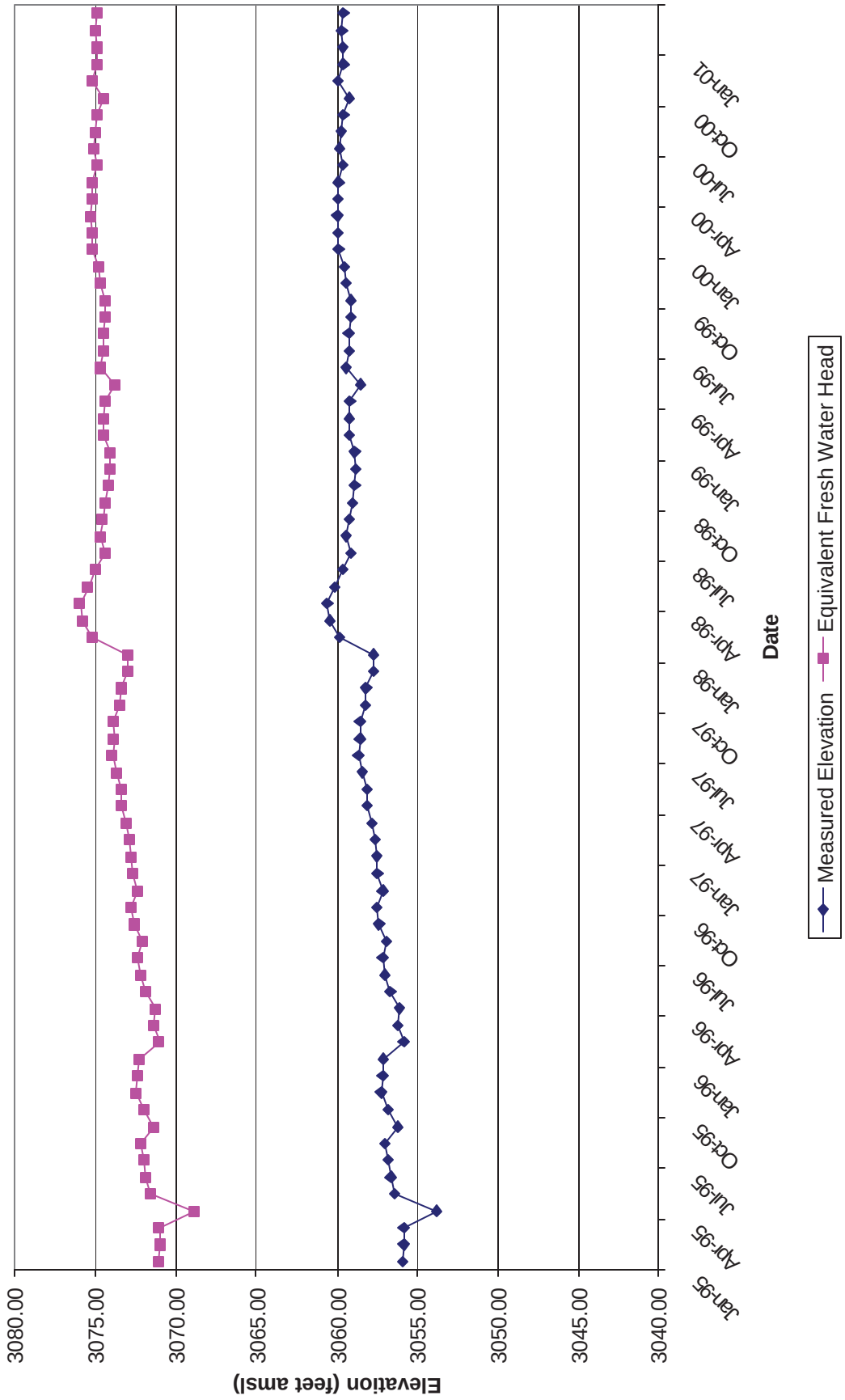

Table 55 - Well No. H-18 Magenta
April 2001through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
04/04/01	2939.73	N/A
05/08/01	3078.59	N/A
06/05/01	3078.42	N/A
07/09/01	3078.12	N/A
09/12/01	3077.34	N/A
10/03/01	3077.36	N/A
11/12/01	3077.17	N/A
12/03/01	3077.25	N/A

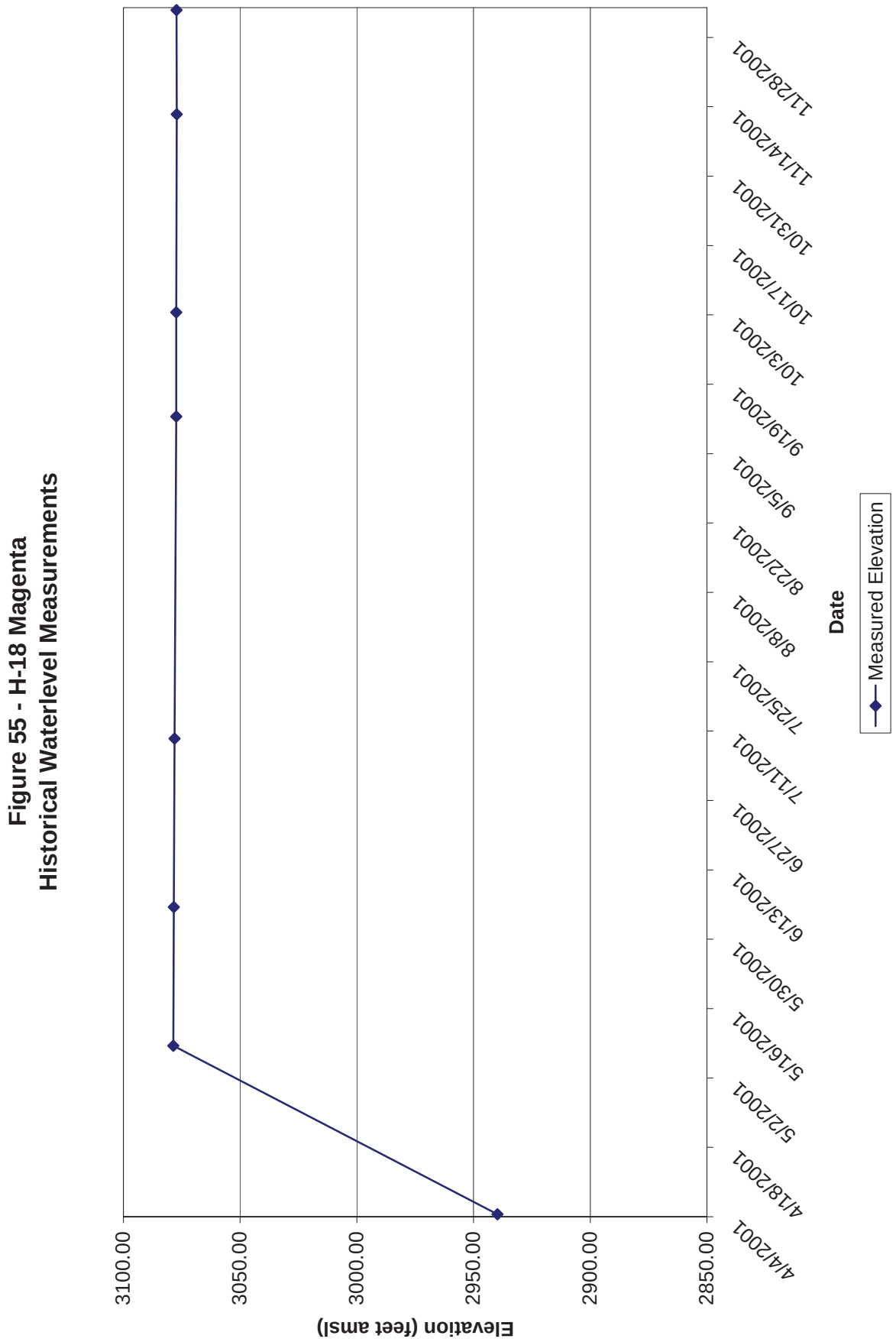
Figure 55 - H-18 Magenta
Historical Waterlevel Measurements
Elevation (feet amsl)
3100.00
3050.00
3000.00
2950.00
2900.00
2850.00
4/4/2001
4/18/2001
5/2/2001
5/16/2001
5/30/2001
6/13/2001
6/27/2001
7/11/2001
7/25/2001
8/8/2001
8/22/2001
9/5/2001
9/19/2001
10/3/2001
10/17/2001
10/31/2001
11/14/2001
11/28/2001
Date
Measured Elevation

Table 56 - Well No. H-19b0 Culebra
April 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
04/15/97	2982.92	3004.23
05/14/97	2983.32	3004.66
06/11/97	2982.22	3003.48
07/15/97	2982.58	3003.87
08/13/97	2983.11	3004.43
09/17/97	2983.20	3004.53
10/16/97	2983.57	3004.92
11/12/97	2984.33	3005.74
12/10/97	2984.61	3006.03
01/13/98	2985.16	3006.62
02/11/98	2985.54	3007.03
03/12/98	2985.67	3007.16
04/15/98	2986.38	3007.92
05/12/98	2985.58	3007.07
06/10/98	2985.91	3007.42
07/14/98	2986.26	3007.79
08/11/98	2986.43	3007.98
09/10/98	2985.31	3006.78
10/14/98	2986.33	3007.87
11/11/98	2986.62	3008.18
12/09/98	2986.85	3008.42
01/12/99	2987.31	3008.91
02/09/99	2987.32	3008.93
03/09/99	2987.66	3009.29
04/12/99	2987.68	3009.31
05/11/99	2987.49	3009.11
06/08/99	2987.93	3009.58
07/19/99	2988.10	3009.76
08/09/99	2988.27	3009.94
09/08/99	2988.40	3010.08
10/04/99	2988.29	3009.96
11/08/99	2987.89	3009.53
12/08/99	2988.42	3010.10

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/00	2988.42	3010.10
02/14/00	2988.57	3010.26
03/06/00	2988.67	3010.37
04/17/00	2987.94	3009.59
05/17/00	2988.62	3010.31
06/07/00	2988.58	3010.27
07/10/00	2988.88	3010.59
08/14/00	2988.91	3010.62
09/11/00	2989.01	3010.73
10/11/00	2988.88	3010.59
11/09/00	2988.66	3010.36
12/06/00	2988.52	3010.21
01/10/01	2989.00	3010.72
02/06/01	2989.03	3010.75
03/08/01	2989.34	3011.08
04/05/01	2989.40	3011.14
05/09/01	2988.98	3010.70
06/06/01	2989.48	3011.23
07/11/01	2989.71	3011.48
08/07/01	2989.74	3011.51
09/07/01	2990.05	3011.84
10/09/01	2990.08	3011.87
11/13/01	2989.72	3011.49
12/05/01	2989.73	3011.50
01/16/02	2990.08	3011.87
02/05/02	2990.19	3011.99
03/13/02	2990.36	3012.17
04/09/02	2990.08	3011.87
05/07/02	2990.32	3012.13
06/11/02	2990.78	3012.62
07/15/02	2990.84	3012.68
08/14/02	2990.98	3012.83
09/10/02	2990.99	3012.84

Figure 56 - H-19b0 Culebra
Historical Waterlevel Measurements

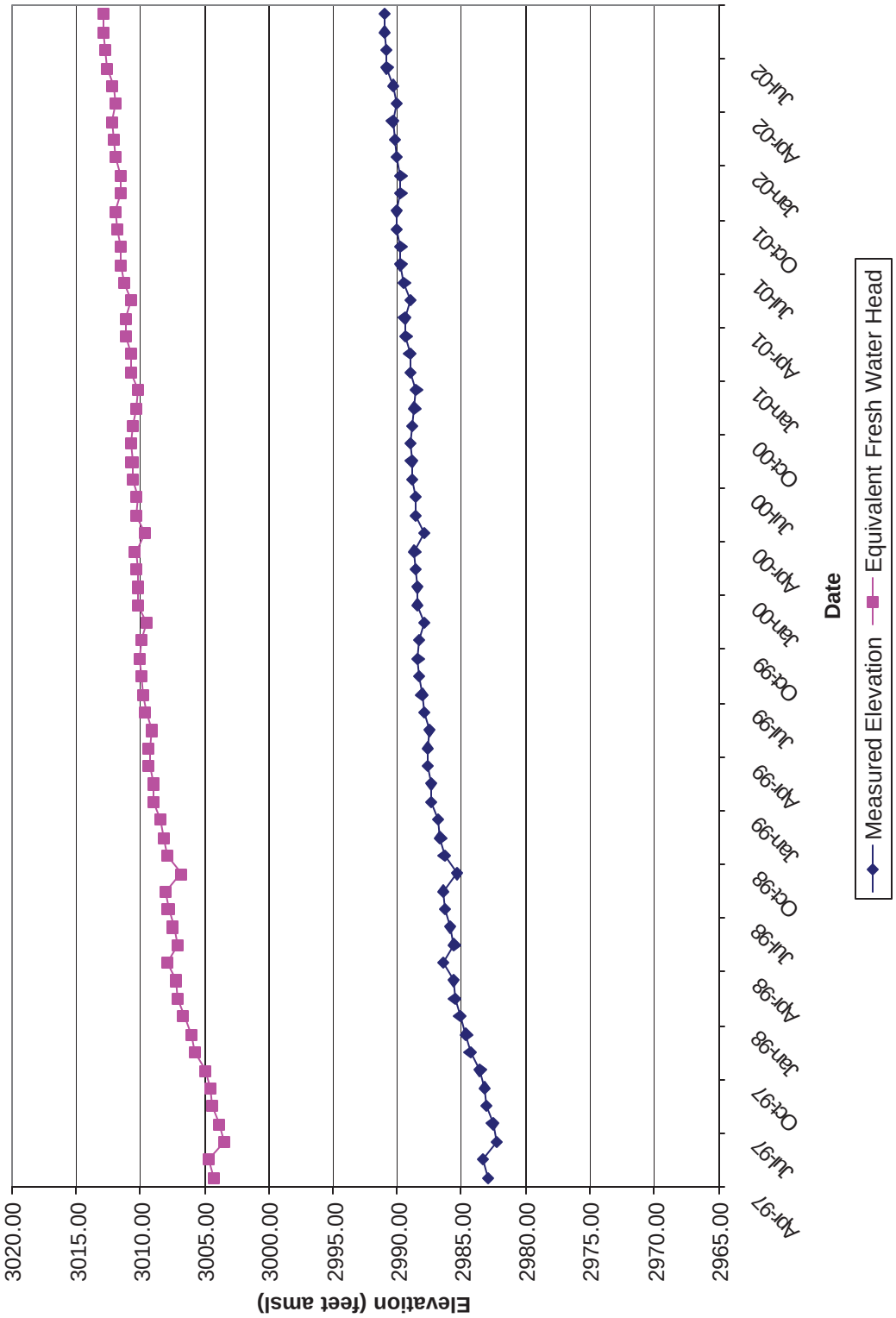

Table 57 - Well No. H-19b2 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2981.60	3002.93
09/17/97	2982.54	3003.93
12/10/97	2984.01	3005.50
03/12/98	2984.98	3006.53
06/10/98	2985.27	3006.84
09/10/98	2987.21	3008.91
12/09/98	2986.21	3007.84
03/09/99	2987.01	3008.70
06/08/99	2987.29	3009.00
09/08/99	2987.76	3009.50
12/08/99	2987.75	3009.49

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2988.02	3009.78
06/07/00	2987.92	3009.67
09/11/00	2988.33	3010.11
12/06/00	2987.86	3009.61
03/08/01	2988.68	3010.48
06/06/01	2988.78	3010.59
09/07/01	2989.38	3011.23
12/05/01	2989.08	3010.91
03/13/02	2989.68	3011.55
06/11/02	2990.09	3011.98
09/10/02	2990.30	3012.21

Figure 57 - H-19b2 Culebra
Historical Waterlevel Measurements

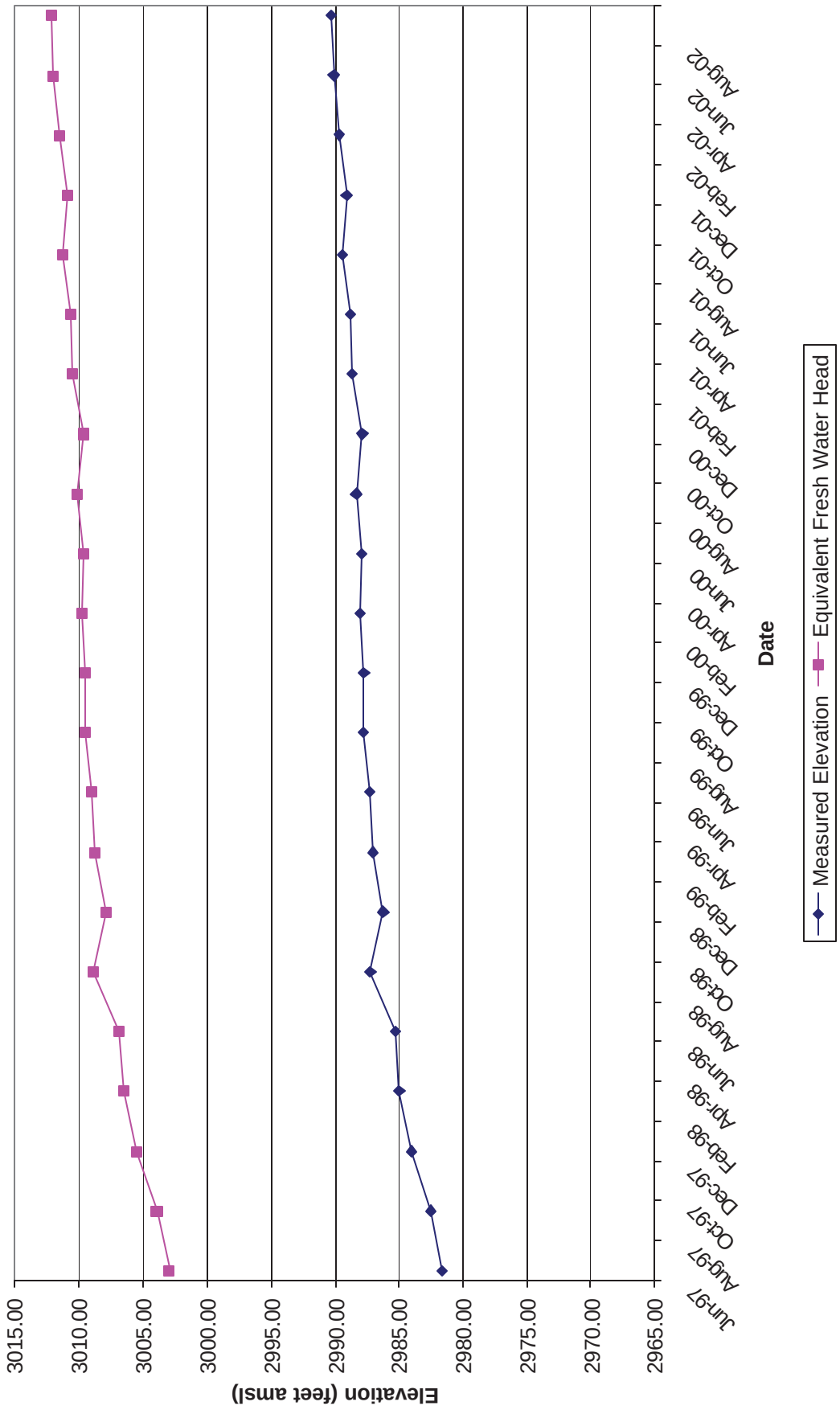

Table 58 - Well No. H-19b3 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2981.45	3002.67
09/17/97	2982.39	3003.67
12/10/97	2983.85	3005.23
03/12/98	2984.84	3006.28
06/10/98	2985.12	3006.58
09/10/98	2985.79	3007.30
12/09/98	2986.05	3007.57
03/09/99	2986.85	3008.43
06/08/99	2987.16	3008.76
09/08/99	2987.60	3009.23
12/08/99	2987.60	3009.23

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2987.87	3009.52
06/07/00	2987.79	3009.43
09/11/00	2988.19	3009.86
12/06/00	2987.73	3009.37
03/08/01	2988.54	3010.23
06/06/01	2988.71	3010.41
09/07/01	2989.26	3011.00
12/05/01	2988.95	3010.67
03/13/02	2989.54	3011.30
06/11/02	2989.95	3011.74
09/10/02	2990.18	3011.98

Figure 58 - H-19b3 Culebra
Historical Waterlevel Measurements

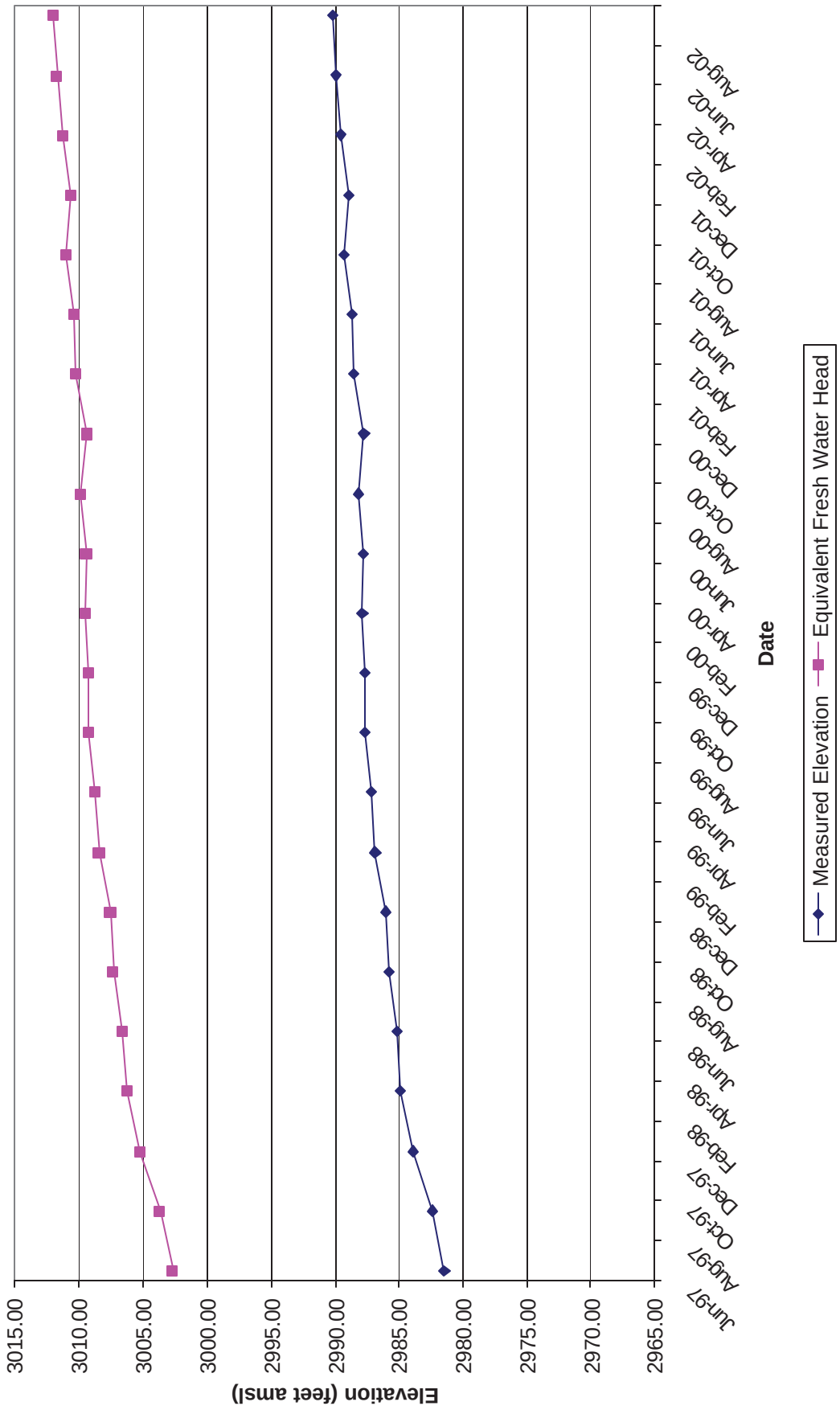

Table 59 - Well No. H-19b4 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2982.12	3003.23
09/17/97	2983.05	3004.22
12/10/97	2984.54	3005.81
03/12/98	2985.53	3006.87
06/10/98	2985.80	3007.16
09/10/98	2986.48	3007.88
12/09/98	2986.75	3009.16
03/09/99	2987.54	3009.01
06/08/99	2987.87	3009.36
09/08/99	2989.28	3010.87
12/08/99	2988.29	3009.81

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2988.58	3010.12
06/07/00	2988.49	3010.03
09/11/00	2988.87	3010.43
12/06/00	2988.41	3009.94
03/08/01	2989.25	3010.84
06/06/01	2989.63	3011.24
09/07/01	2989.95	3011.58
12/05/01	2989.54	3011.15
03/13/02	2990.24	3011.89
06/11/02	2990.65	3012.33
09/10/02	2990.89	3012.59

Figure 59 - H-19b4 Culebra Historical Waterlevel Measurements

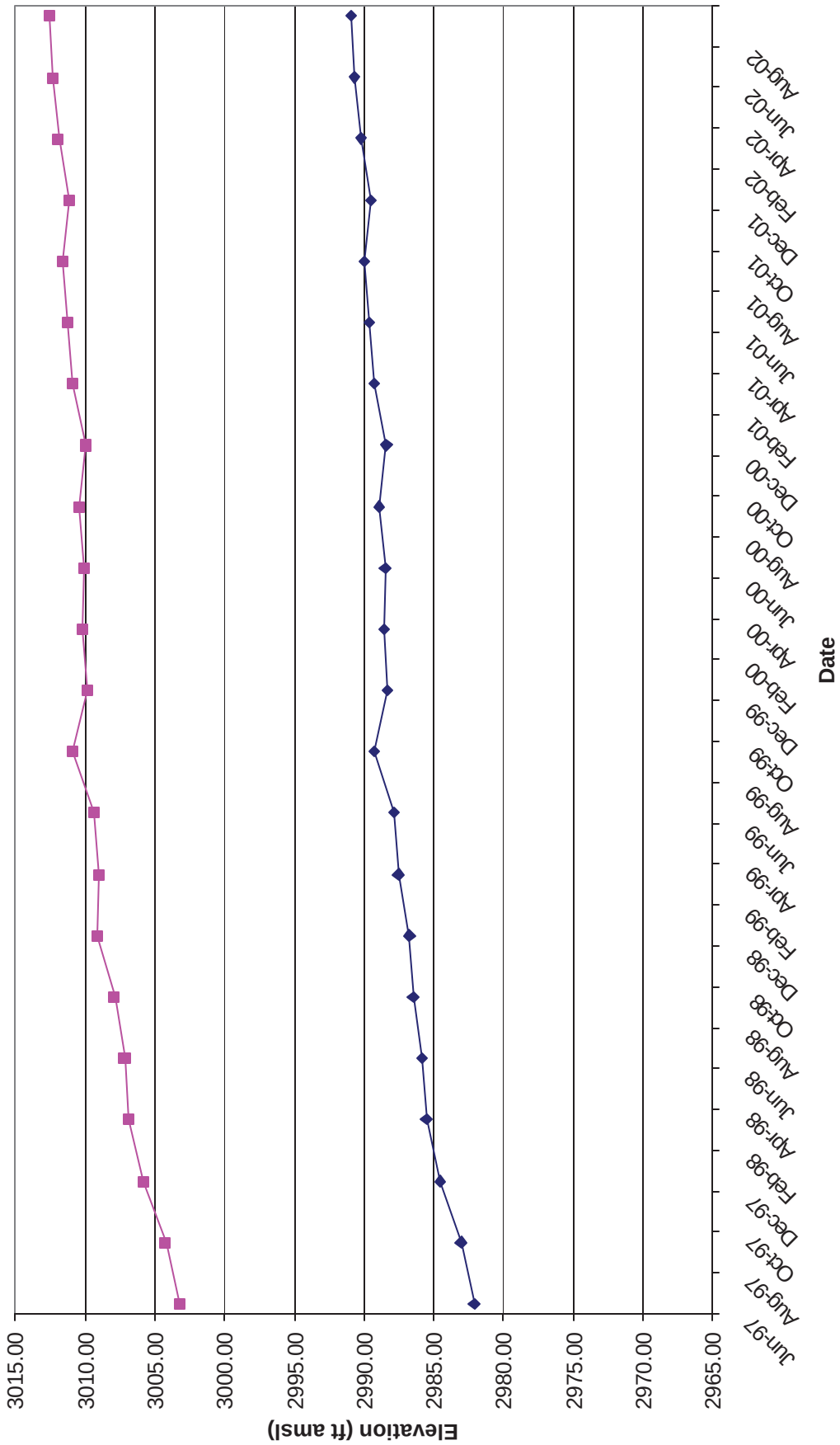

Table 60 - Well No. H-19b5 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2981.03	3002.01
09/17/97	2982.45	3003.52
12/10/97	2983.90	3005.07
03/12/98	2984.92	3006.16
06/10/98	2985.20	3006.46
09/10/98	2985.87	3007.17
12/09/98	2986.19	3007.51
03/09/99	2986.95	3008.32
06/08/99	2987.25	3008.64
09/08/99	2988.73	3010.22
12/08/99	2987.73	3009.16

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2988.02	3009.46
07/07/00	2987.02	3009.36
09/11/00	2988.36	3009.83
12/06/00	2987.88	3009.32
03/08/01	2988.69	3010.18
06/06/01	2988.88	3010.38
09/07/01	2989.39	3010.93
12/05/01	2989.12	3010.64
03/13/02	2989.73	3011.29
06/11/02	2990.14	3011.73
09/10/02	2990.36	3011.96

Figure 60 - H-19b5 Culebra
Historical Waterlevel Measurements

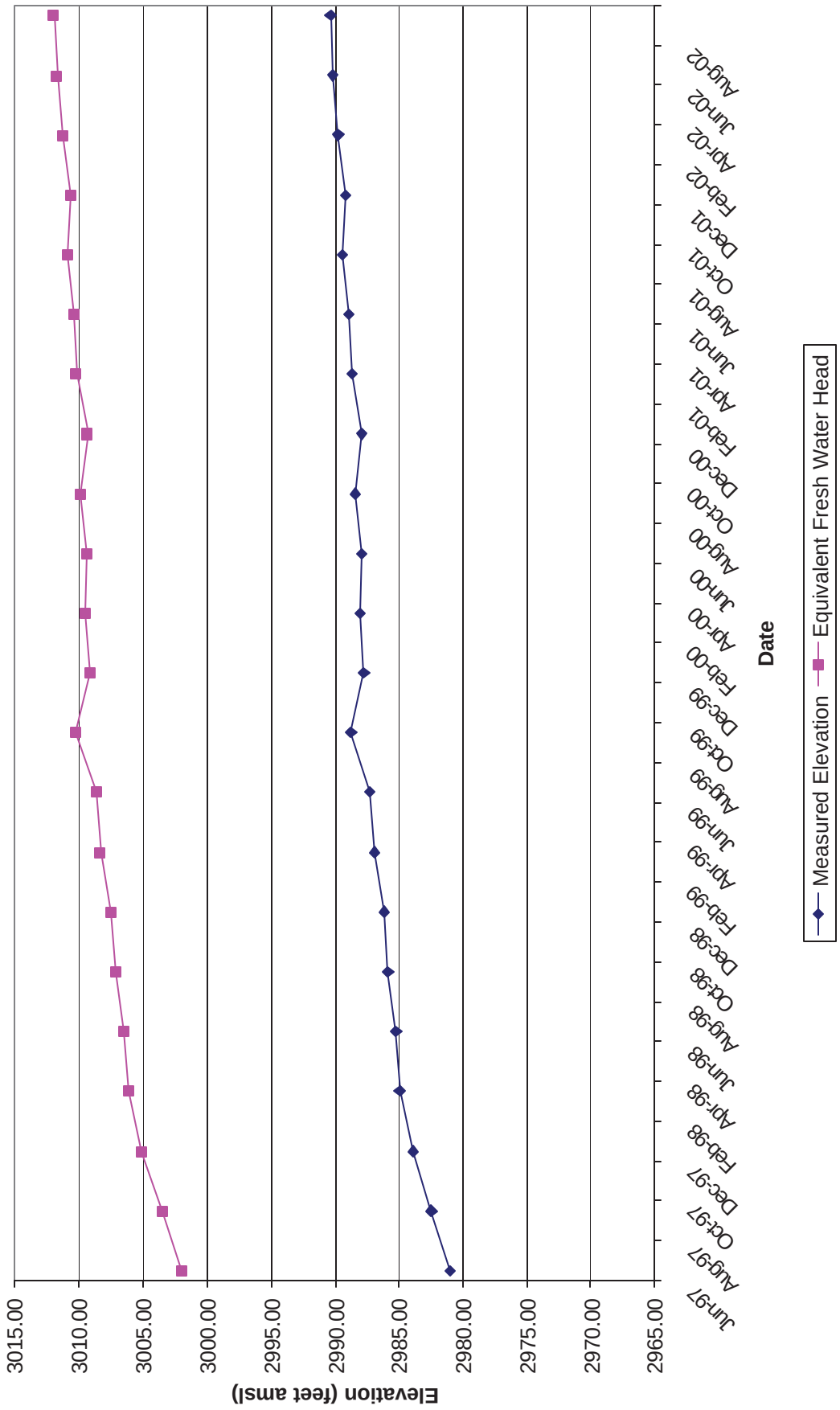

Table 61 - Well No. H-19b6 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2981.62	3002.78
09/17/97	2982.57	3003.79
12/10/97	2984.02	3005.34
03/12/98	2985.01	3006.40
06/10/98	2985.27	3006.67
09/10/98	2985.94	3007.39
12/09/98	2986.19	3007.66
03/09/99	2986.99	3008.51
06/08/99	2987.29	3008.83
09/08/99	2987.68	3009.25
12/08/99	2987.68	3009.25

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2987.97	3009.56
06/07/00	2987.87	3009.45
09/11/00	2988.27	3009.88
12/06/00	2987.81	3009.38
03/08/01	2988.64	3010.27
06/06/01	2988.78	3010.42
09/07/01	2989.36	3011.04
12/05/01	2989.03	3010.69
03/13/02	2989.62	3011.32
06/11/02	2990.03	3011.75
09/10/02	2990.26	3012.00

Figure 61 - H-19b6 Culebra
Historical Waterlevel Measurements

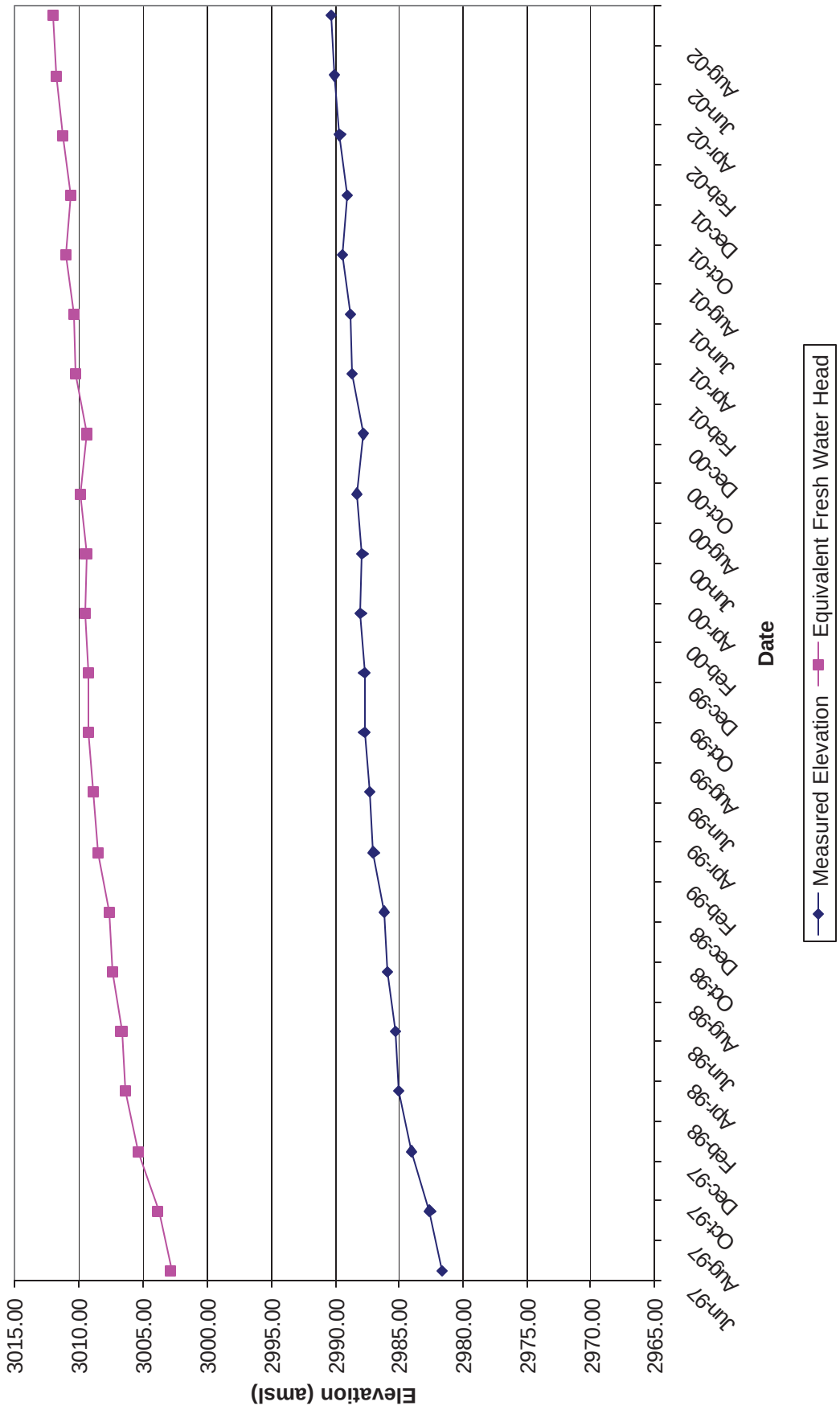

Table 62 - Well No. H-19b7 Culebra
June 1997 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/11/97	2981.27	3002.45
09/17/97	2982.22	3003.46
12/10/97	2983.69	3005.03
03/12/98	2984.68	3006.09
06/10/98	2984.97	3006.40
09/10/98	2985.63	3007.10
12/09/98	2985.90	3007.39
03/09/99	2986.71	3008.25
06/08/99	2987.01	3008.57
09/08/99	2987.45	3009.04
12/08/99	2987.46	3009.05

Date	Measured Elevation	Equivalent Fresh Water Head
03/06/00	2987.73	3009.34
06/07/00	2987.65	3009.26
09/11/00	2988.05	3009.68
12/06/00	2988.59	3010.26
03/08/01	2988.42	3010.08
06/06/01	2988.57	3010.24
09/07/01	2989.10	3010.80
12/05/01	2988.81	3010.50
03/13/02	2989.40	3011.12
06/11/02	2989.83	3011.58
09/10/02	2990.04	3011.81

Figure 62 - H-19b7 Culebra
Historical Waterlevel Measurements

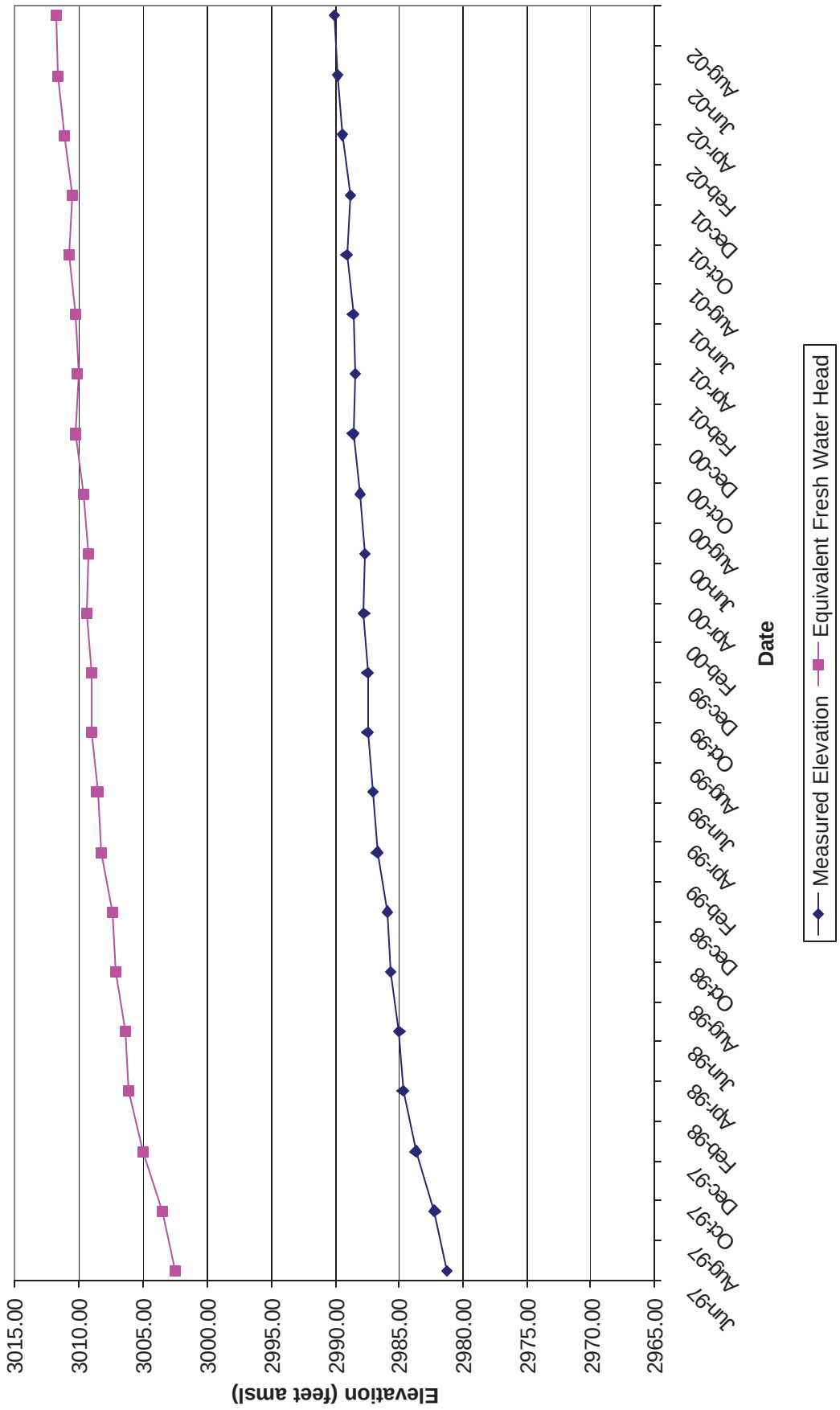

Table 63 - Well No. P-15 Culebra
January 1995 through January 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3012.35	3013.11
02/15/95	3012.41	3013.17
03/15/95	3012.13	3012.89
04/10/95	3012.40	3013.16
05/10/95	3012.39	3013.15
06/07/95	3012.58	3013.34
07/19/95	3012.47	3013.23
08/17/95	3012.49	3013.25
09/07/95	3012.44	3013.20
10/19/95	3012.42	3013.18
11/08/95	3012.28	3013.04
12/06/95	3012.33	3013.09
01/10/96	3012.30	3013.06
02/06/96	3012.26	3013.02
03/14/96	3012.47	3013.23
04/16/96	3012.26	3013.02
05/14/96	3012.15	3012.91
06/12/96	3012.22	3012.98
07/16/96	3012.21	3012.97
08/14/96	3012.33	3013.09
09/04/96	3012.55	3013.31
10/15/96	3012.70	3013.46
11/12/96	3012.75	3013.51
12/11/96	3012.24	3013.00
01/15/97	3013.32	3014.09
02/12/97	3013.38	3014.15
03/12/97	3013.42	3014.19
04/16/97	3013.16	3013.92
05/14/97	3013.20	3013.96
06/11/97	3012.91	3013.67
07/16/97	3012.68	3013.44
08/12/97	3012.55	3013.31
09/16/97	3012.51	3013.27
10/15/97	3012.23	3012.99
11/12/97	3012.54	3013.30
12/10/97	3012.48	3013.24

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3012.52	3013.28
02/11/98	3012.55	3013.31
03/11/98	3012.37	3013.13
04/14/98	3012.85	3013.61
05/12/98	3012.87	3013.63
06/09/98	3012.76	3013.52
07/15/98	3012.73	3013.49
08/10/98	3012.65	3013.41
09/08/98	3012.68	3013.44
10/13/98	3012.58	3013.34
11/11/98	3012.59	3013.35
12/08/98	3012.52	3013.28
01/11/99	3012.61	3013.37
02/09/99	3012.80	3013.56
03/09/99	3012.89	3013.65
04/12/99	3012.86	3013.62
05/10/99	3013.16	3013.92
06/08/99	3013.18	3013.94
07/20/99	3013.14	3013.90
08/10/99	3013.26	3014.02
09/08/99	3013.34	3014.11
10/05/99	3013.16	3013.92
11/10/99	3013.18	3013.94
12/08/99	3013.39	3014.16
01/19/00	3013.31	3014.08
02/14/00	3013.80	3014.57
03/08/00	3013.98	3014.75
04/18/00	3014.18	3014.95
05/17/00	3014.54	3015.31
06/07/00	3014.32	3015.09
07/12/00	3015.17	3015.95
08/15/00	3015.31	3016.09
09/11/00	3016.08	3016.86
10/10/00	3016.10	3016.88
11/09/00	3016.26	3017.04
12/04/00	3015.89	3016.67

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3015.83	3016.61
02/05/01	3015.58	3016.36
03/08/01	3016.03	3016.81
04/05/01	3015.82	3016.60
05/08/01	3015.59	3016.37
06/04/01	3015.93	3016.71
07/11/01	3015.69	3016.47
08/07/01	3015.61	3016.39
09/05/01	3015.60	3016.38
10/08/01	3015.60	3016.38
11/12/01	3015.48	3016.26
12/05/01	3015.60	3016.38
01/16/02	3015.07	3015.85

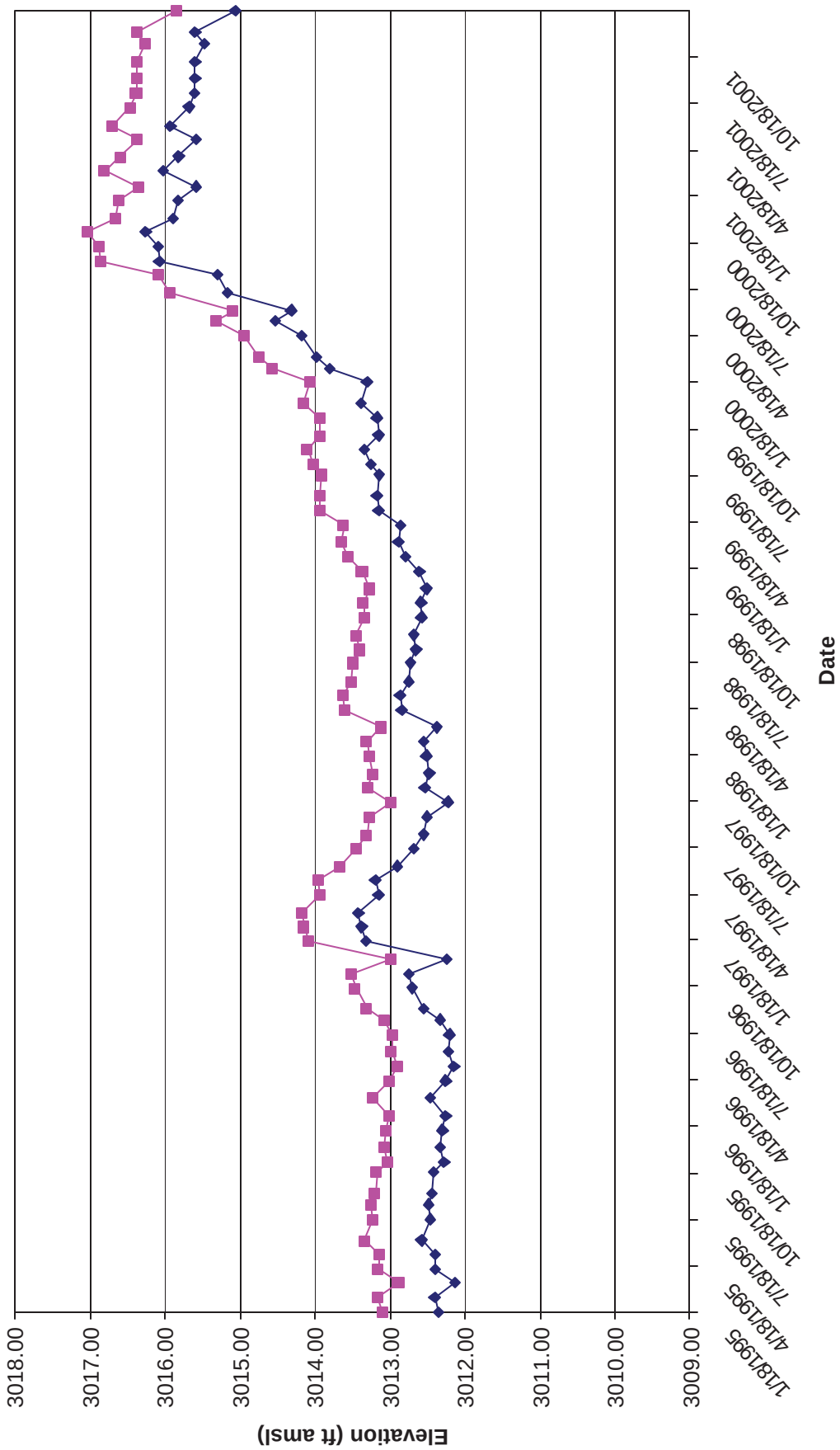

Figure 63 - P-15 Culebra
Historical Waterlevel Measurements

Table 64 - Well No. P-17 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	2983.75	2997.95
02/14/95	2983.88	2998.09
03/14/95	2983.76	2997.96
04/11/95	2983.77	2997.97
05/09/95	2984.13	2998.36
06/06/95	2984.40	2998.64
07/19/95	2984.02	2998.24
08/16/95	2983.68	2997.88
09/07/95	2982.83	2996.97
10/18/95	2982.58	2996.71
11/07/95	2982.54	2996.66
12/05/95	2982.72	2996.85
01/09/96	2982.63	2996.76
02/06/96	2982.32	2996.43
03/12/96	2981.06	2995.09
04/16/96	2979.30	2993.21
05/14/96	2979.80	2993.74
06/11/96	2980.60	2994.60
07/16/96	2981.31	2995.35
08/13/96	2982.03	2996.12
09/04/96	2982.42	2996.53
10/16/96	2982.83	2996.97
11/12/96	2982.82	2996.96
12/10/96	2983.22	2997.39
01/15/97	2983.35	2997.53
02/11/97	2983.38	2997.56
03/11/97	2983.11	2997.27
04/15/97	2982.48	2996.60
05/14/97	2982.21	2996.31
06/11/97	2981.81	2995.89
07/15/97	2981.38	2995.43
08/12/97	2981.20	2995.24
09/16/97	2981.39	2995.44
10/15/97	2981.29	2995.33
11/11/97	2981.64	2995.70
12/09/97	2981.85	2995.93

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	2981.92	2996.00
02/10/98	2982.18	2996.28
03/10/98	2982.00	2996.09
04/14/98	2982.50	2996.62
05/12/98	2982.47	2996.59
06/09/98	2982.19	2996.29
07/14/98	2982.06	2996.15
08/11/98	2981.97	2996.06
09/09/98	2982.02	2996.11
10/13/98	2981.92	2996.00
11/10/98	2982.00	2996.09
12/08/98	2981.90	2995.98
01/12/99	2982.27	2996.38
02/09/99	2982.25	2996.35
03/09/99	2982.43	2996.55
04/13/99	2982.65	2996.78
05/11/99	2982.72	2996.85
06/08/99	2982.83	2996.97
07/20/99	2982.83	2996.97
08/10/99	2982.98	2997.13
09/08/99	2983.15	2997.31
10/05/99	2982.88	2997.02
11/09/99	2982.85	2996.99
12/08/99	2982.82	2996.96
01/18/00	2982.55	2996.67
02/15/00	2982.61	2996.74
03/07/00	2982.67	2996.80
04/18/00	2982.72	2996.85
05/16/00	2982.84	2996.98
06/06/00	2982.71	2996.84
07/11/00	2982.83	2996.97
08/15/00	2982.69	2996.82
09/11/00	2982.78	2996.92
10/11/00	2982.18	2996.28
11/09/00	2982.76	2996.90
12/05/00	2983.47	2997.65

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2982.72	2996.85
02/05/01	2982.60	2996.73
03/07/01	2982.84	2996.98
04/05/01	2983.10	2997.26
05/09/01	2983.17	2997.33
06/06/01	2983.46	2997.64
07/11/01	2983.47	2997.65
08/07/01	2983.30	2997.47
09/05/01	2983.24	2997.41
10/09/01	2983.31	2997.48
11/12/01	2983.25	2997.42
12/03/01	2983.35	2997.53
01/15/02	2983.47	2997.65
02/05/02	2983.53	2997.72
03/13/02	2983.94	2998.15
04/10/02	2983.79	2997.99
05/07/02	2984.09	2998.31
06/11/02	2984.32	2998.56
07/16/02	2984.24	2998.47
08/14/02	2984.37	2998.61
09/12/02	2984.34	2998.58

Figure 64 - P-17 Culebra
Historical Waterlevel Measurements

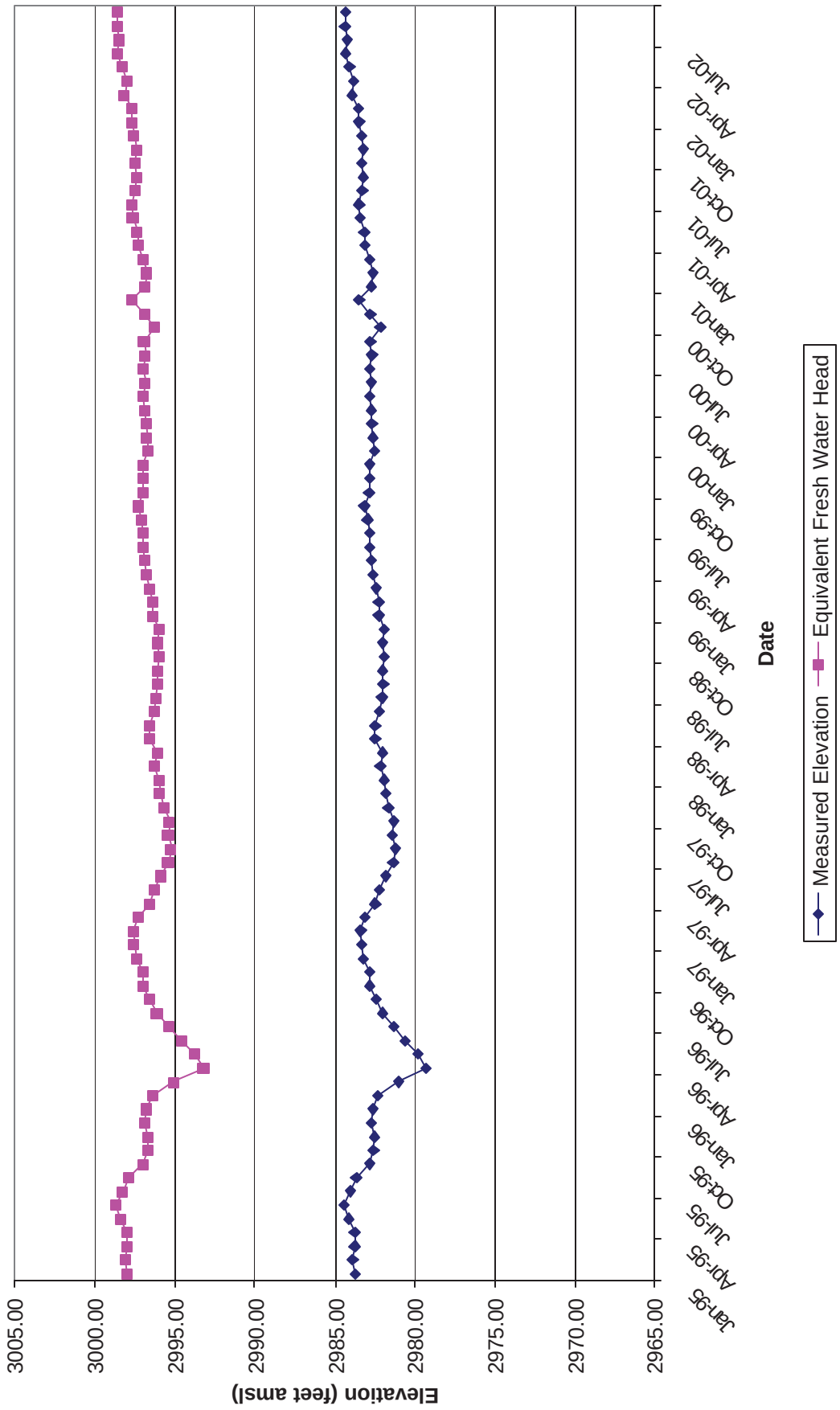

Table 65 - Well No. P-18 Culebra
January 1995 through February 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/17/95	3122.04	3188.82
02/14/95	3122.92	3189.80
03/14/95	3123.92	3190.92
04/11/95	3124.66	3191.74
05/09/95	3125.64	3192.84
06/06/95	3126.52	3193.82
07/18/95	3127.78	3195.23
08/16/95	3128.88	3196.46
09/06/95	3129.89	3197.59
10/17/95	3131.57	3199.46
11/07/95	3132.34	3200.32
12/05/95	3133.34	3201.44
01/09/96	3134.51	3202.75
02/06/96	3135.51	3203.86
03/12/96	3136.63	3205.11
04/16/96	3137.72	3206.33
05/14/96	3138.63	3207.35
06/11/96	3139.54	3208.36
07/16/96	3140.63	3209.58
08/14/96	3141.31	3210.34
09/04/96	3141.83	3210.92
10/15/96	3142.77	3211.97
11/12/96	3143.37	3212.64
12/10/96	3144.06	3213.41
01/15/97	3144.90	3214.35
02/11/97	3145.48	3215.00
03/11/97	3146.08	3215.67
04/15/97	3146.86	3216.54
05/13/97	3147.40	3217.14
06/11/97	3147.97	3217.78
07/15/97	3148.60	3218.48
08/12/97	3149.04	3218.98
09/16/97	3149.72	3219.74
10/14/97	3150.67	3220.24
11/11/97	3150.67	3220.80
12/09/97	3151.07	3221.24

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/98	3151.53	3221.76
02/10/98	3152.06	3222.35
03/10/98	3152.48	3222.82
04/14/98	3153.04	3223.44
05/12/98	3153.49	3223.95
06/09/98	3153.87	3224.37
07/14/98	3154.37	3224.93
08/11/98	3154.73	3225.33
09/09/98	3155.15	3225.80
10/13/98	3155.64	3226.35
11/10/98	3156.01	3226.76
12/08/98	3156.37	3227.16
01/12/99	3156.84	3227.69
02/09/99	3157.21	3228.10
03/09/99	3157.61	3228.55
04/13/99	3158.05	3229.04
05/11/99	3158.37	3229.40
06/08/99	3158.71	3229.78
07/20/99	3159.16	3230.28
08/10/99	3159.43	3230.58
09/08/99	3159.75	3230.94
10/05/99	3160.00	3231.22
11/09/99	3160.34	3231.60
12/07/99	3160.60	3231.89
01/18/00	3160.98	3232.31
02/15/00	3161.26	3232.63
03/07/00	3161.45	3232.84
04/18/00	3161.82	3233.25
05/16/00	3162.06	3233.52
06/06/00	3162.13	3233.60
07/11/00	3162.13	3233.60
08/15/00	3162.16	3233.63
09/13/00	3162.25	3233.73
10/10/00	3162.28	3233.76
11/09/00	3162.35	3233.84
12/05/00	3162.44	3233.94

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3162.62	3234.14
02/07/01	3162.73	3234.27
03/07/01	3162.93	3234.49
04/04/01	3163.08	3234.66
05/07/01	3163.24	3234.84
06/06/01	3163.38	3234.99
07/10/01	3163.50	3235.13
08/07/01	3163.58	3235.22
09/05/01	3163.72	3235.37
10/09/01	3163.82	3235.48
11/13/01	3163.95	3235.63
12/04/01	3164.05	3235.74
01/15/02	3164.17	3235.88
02/06/02	3163.79	3235.45

Figure 65 - P-18 Culebra
Historical Waterlevel Measurements

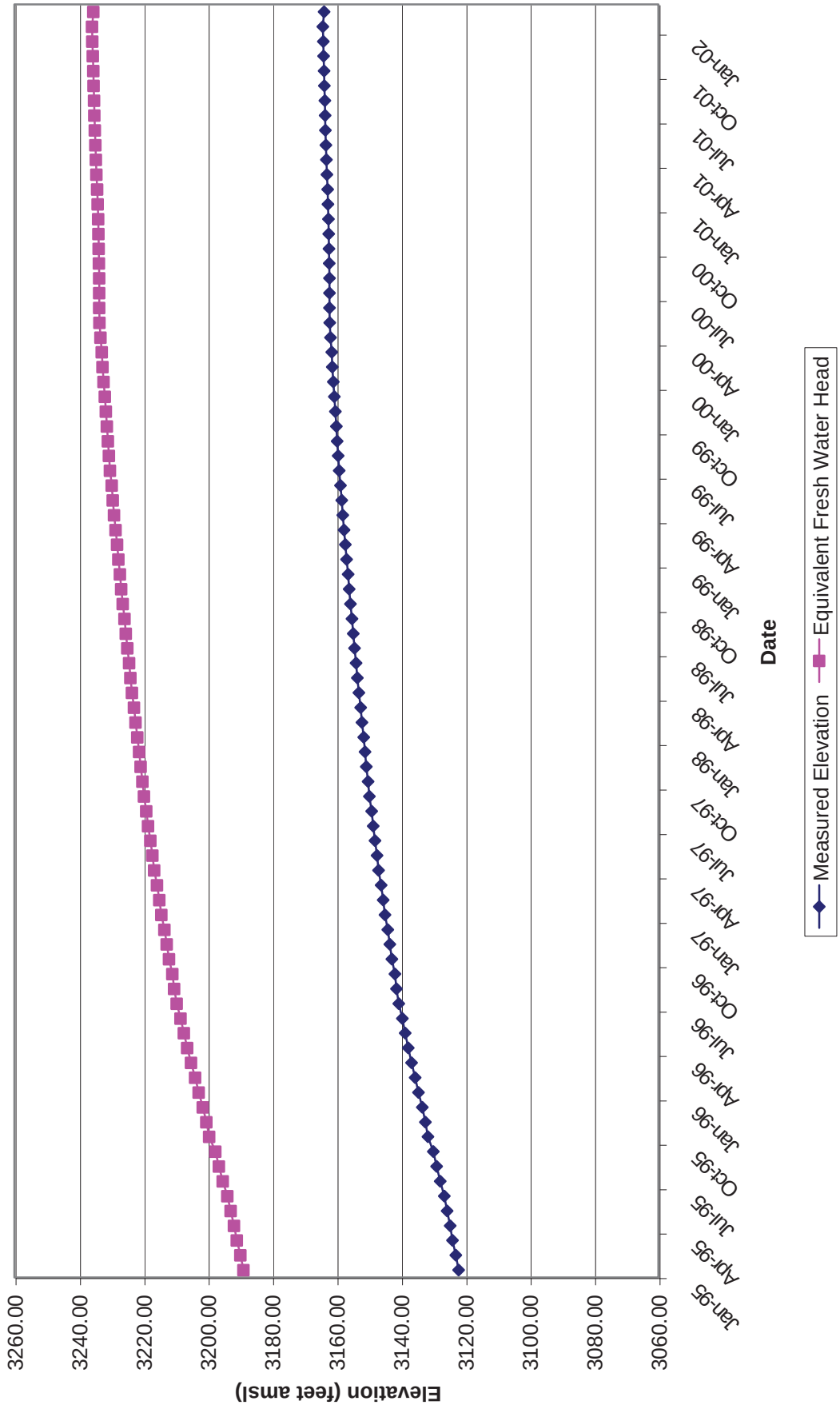

Table 66 - Well No. WIPP-12 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3030.02	3066.62
02/15/95	3030.20	3066.81
03/13/95	3030.24	3066.86
04/10/95	3030.06	3066.66
05/09/95	3030.28	3066.90
06/05/95	3030.08	3066.68
07/17/95	3030.34	3066.97
08/14/95	3030.56	3067.21
09/05/95	3030.02	3066.62
10/16/95	3029.93	3066.52
11/07/95	3029.98	3066.57
12/04/95	3030.12	3066.73
01/08/96	3030.21	3066.83
02/05/96	3029.91	3066.50
03/14/96	3028.43	3064.87
04/15/96	3029.37	3065.90
05/13/96	3029.13	3065.64
06/10/96	3029.31	3065.84
07/15/96	3029.54	3066.09
08/12/96	3029.38	3065.92
09/03/96	3029.61	3066.17
10/14/96	3029.96	3066.55
11/11/96	3030.02	3066.62
12/09/96	3030.10	3066.70
01/13/97	3030.40	3067.03
02/10/97	3030.40	3067.03
03/10/97	3030.61	3067.26
04/14/97	3030.85	3067.53
05/12/97	3030.73	3067.40
06/09/97	3030.98	3067.67
07/14/97	3031.26	3067.98
08/11/97	3031.26	3067.98
09/15/97	3031.25	3067.97
10/13/97	3031.25	3067.97
11/10/97	3031.10	3067.80
12/08/97	3030.75	3067.42

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3030.49	3067.13
02/09/98	3031.25	3067.97
03/12/98	3032.76	3069.62
04/13/98	3033.09	3069.98
05/11/98	3032.83	3069.70
06/08/98	3032.45	3069.28
07/13/98	3031.96	3068.74
08/10/98	3031.76	3068.52
09/08/98	3031.81	3068.58
10/12/98	3031.63	3068.38
11/09/98	3031.45	3068.18
12/07/98	3031.43	3068.16
01/11/99	3031.34	3068.06
02/08/99	3031.54	3068.28
03/08/99	3031.74	3068.50
04/12/99	3031.65	3068.40
05/10/99	3031.77	3068.54
06/07/99	3031.75	3068.51
07/19/99	3031.67	3068.43
08/09/99	3031.71	3068.47
09/07/99	3031.61	3068.36
10/04/99	3031.59	3068.34
11/08/99	3031.60	3068.35
12/06/99	3031.76	3068.52
01/19/00	3031.90	3068.68
02/14/00	3032.08	3068.87
03/06/00	3032.15	3068.95
04/17/00	3032.06	3068.85
05/15/00	3032.06	3068.85
06/05/00	3031.93	3068.71
07/10/00	3031.98	3068.77
08/14/00	3031.76	3068.52
09/11/00	3031.79	3068.56
10/09/00	3031.53	3068.27
11/08/00	3031.63	3068.38
12/06/00	3031.51	3068.25

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3031.59	3068.34
02/05/01	3031.53	3068.27
03/07/01	3031.69	3068.45
04/05/01	3031.84	3068.61
05/08/01	3031.76	3068.52
06/05/01	3032.09	3068.89
07/11/01	3032.01	3068.80
08/08/01	3031.98	3068.77
09/06/01	3031.93	3068.71
10/10/01	3031.97	3068.75
11/14/01	3031.93	3068.71
12/05/01	3032.15	3068.95
01/16/02	3032.24	3069.05
02/05/02	3032.38	3069.20
03/12/02	3032.59	3069.43
04/08/02	3032.83	3069.70
05/07/02	3032.96	3069.84
06/10/02	3033.11	3070.00
07/15/02	3033.16	3070.06
08/13/02	3033.22	3070.12
09/10/02	3033.21	3070.11

Figure 66 - WIPP-12 Culebra
Historical Waterlevel Measurements

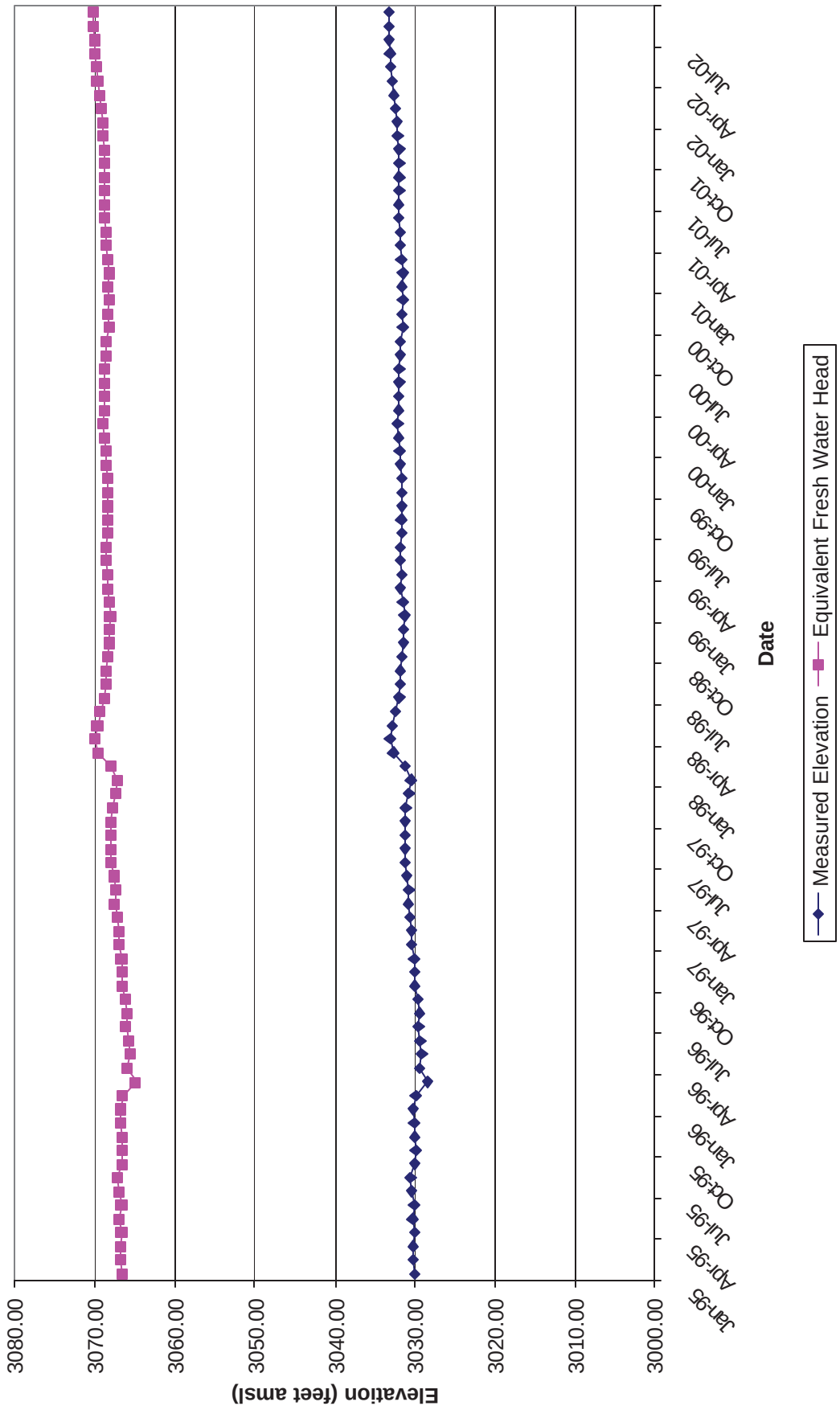

Table 67 - Well No. WIPP-13 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3057.33	3067.90
02/13/95	3057.24	3067.81
03/13/95	3057.13	3067.69
04/10/95	3056.50	3067.05
05/08/95	3057.35	3067.92
06/05/95	3057.52	3068.10
07/17/95	3057.56	3068.14
08/14/95	3057.64	3068.22
09/05/95	3056.95	3067.51
10/16/95	3057.66	3068.24
11/07/95	3057.64	3068.22
12/04/95	3057.73	3068.31
01/08/96	3057.70	3068.28
02/05/96	3056.76	3067.31
03/11/96	3057.06	3067.62
04/15/96	3056.80	3067.35
05/13/96	3057.26	3067.83
06/10/96	3057.57	3068.15
07/15/96	3057.71	3068.29
08/14/96	3057.48	3068.05
09/03/96	3057.94	3068.53
10/14/96	3057.93	3068.52
11/11/96	3057.65	3068.23
12/09/96	3057.78	3068.36
01/13/97	3057.88	3068.47
02/10/97	3057.81	3068.39
03/10/97	3058.01	3068.60
04/14/97	3058.36	3068.96
05/12/97	3058.13	3068.72
06/09/97	3058.53	3069.13
07/14/97	3058.84	3069.45
08/11/97	3058.58	3069.19
09/15/97	3058.44	3069.04
10/13/97	3058.08	3068.67
11/10/97	3058.06	3068.65
12/08/97	3057.40	3067.97

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3057.48	3068.05
02/09/98	3060.42	3071.08
03/09/98	3060.82	3071.49
04/13/98	3060.12	3070.77
05/11/98	3059.73	3070.37
06/08/98	3059.30	3069.93
07/13/98	3058.60	3069.21
08/10/98	3058.86	3069.47
09/08/98	3058.80	3069.41
10/12/98	3058.23	3068.83
11/09/98	3058.80	3069.41
12/07/98	3058.14	3068.73
01/11/99	3058.40	3069.00
02/08/99	3058.75	3069.36
03/08/99	3058.62	3069.23
04/12/99	3058.47	3069.07
05/10/99	3058.79	3069.40
06/07/99	3058.62	3069.23
07/19/99	3058.37	3068.97
08/09/99	3058.21	3068.81
09/07/99	3058.19	3068.78
10/04/99	3058.04	3068.63
11/08/99	3058.38	3068.98
12/06/99	3058.43	3069.03
01/17/00	3058.45	3069.05
02/14/00	3058.57	3069.18
03/06/00	3058.89	3069.50
04/17/00	3058.38	3068.98
05/15/00	3058.24	3068.84
06/05/00	3058.01	3068.60
07/10/00	3058.02	3068.61
08/14/00	3057.91	3068.50
09/12/00	3057.72	3068.30
10/09/00	3057.36	3067.93
11/06/00	3057.88	3068.47
12/07/00	3057.57	3068.15

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3057.50	3068.07
02/05/01	3057.54	3068.12
03/06/01	3057.46	3068.03
04/04/01	3057.33	3067.90
05/07/01	3057.43	3068.00
06/05/01	3057.62	3068.20
07/09/01	3057.48	3068.05
08/08/01	3057.31	3067.88
09/04/01	3057.04	3067.60
10/10/01	3057.19	3067.76
11/14/01	3057.26	3067.83
12/05/01	3057.08	3067.64
01/15/02	3057.26	3067.83
02/05/02	3057.25	3067.82
03/11/02	3057.49	3068.06
04/08/02	3057.64	3068.22
05/06/02	3057.67	3068.25
06/11/02	3057.91	3068.50
07/15/02	3057.84	3068.42
08/13/02	3057.90	3068.49
09/09/02	3057.79	3068.37

Figure 67 - WIPP-13 Culebra
Historical Waterlevel Measurements

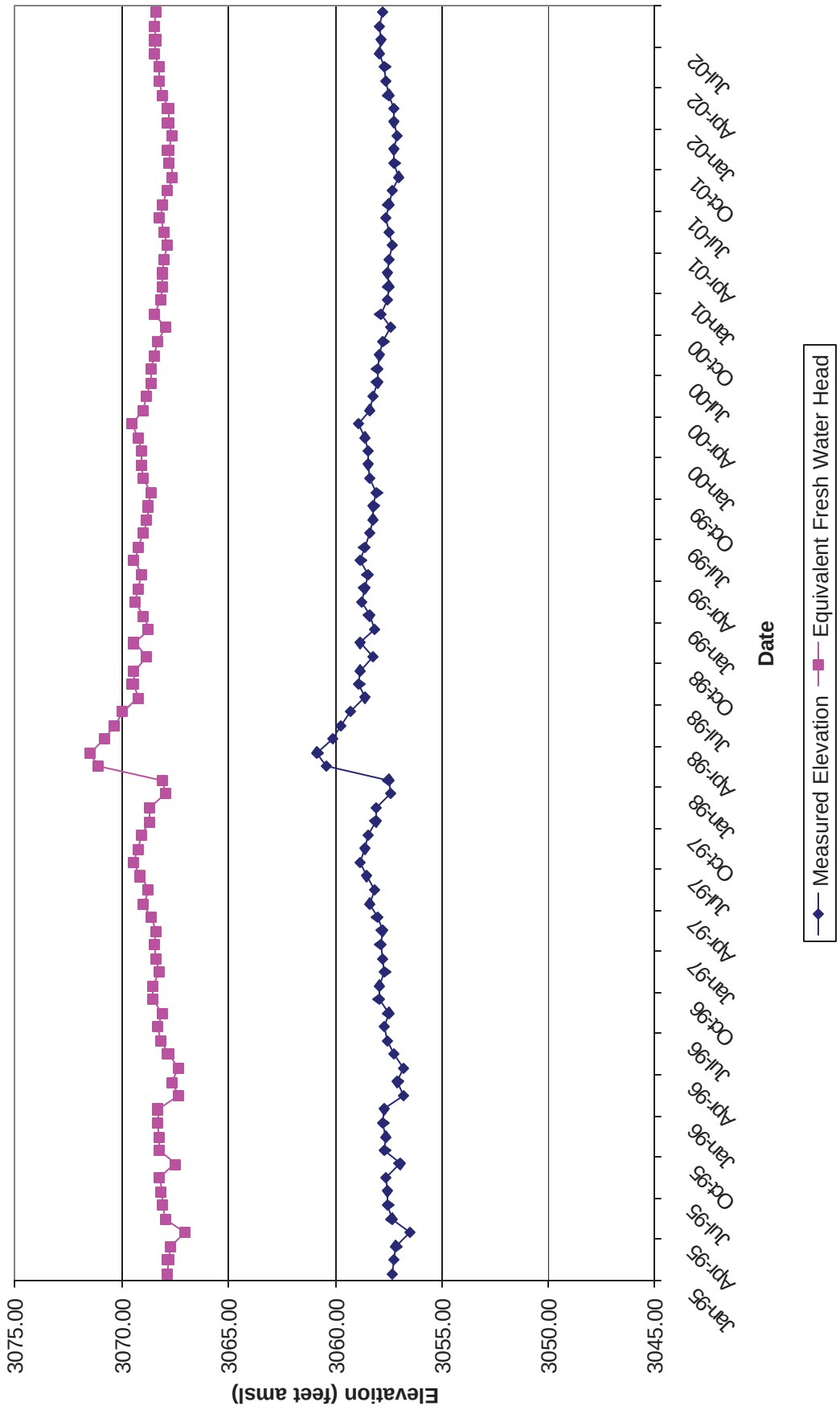

Table 68 - Well No. WIPP-18 Culebra
January 1995 through March 2001

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3027.92	3064.82
02/15/95	3028.27	3065.21
03/13/95	3028.32	3065.26
04/10/95	3028.34	3065.28
05/09/95	3025.95	3062.65
06/05/95	3027.94	3064.84
07/17/95	3028.47	3065.43
08/14/95	3028.50	3065.46
09/05/95	3027.85	3064.74
10/16/95	3027.34	3064.18
11/07/95	3027.48	3064.34
12/04/95	3027.76	3064.64
01/08/96	3027.99	3064.90
02/05/96	3027.28	3064.12
03/14/96	3026.67	3063.45
04/15/96	3026.22	3062.95
05/13/96	3026.16	3062.88
06/10/96	3026.18	3062.91
07/15/96	3026.66	3063.43
08/12/96	3026.95	3063.75
09/03/96	3027.39	3064.24
10/14/96	3027.91	3064.81
11/11/96	3028.13	3065.05
12/09/96	3028.53	3065.49
01/13/97	3028.85	3064.90
02/10/97	3029.09	3064.12
03/10/97	3029.42	3063.45
04/14/97	3029.87	3062.95
05/12/97	3030.00	3062.88
06/09/97	3030.25	3062.91
07/14/97	3030.68	3063.43
08/11/97	3030.78	3063.75
09/15/97	3030.75	3064.24
10/13/97	3030.82	3064.81
11/10/97	3030.86	3065.05
12/08/97	3030.80	3065.49

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3031.67	3068.95
02/09/98	3031.57	3068.84
03/09/98	3032.41	3069.76
04/13/98	3033.06	3070.47
05/11/98	3032.80	3070.19
06/08/98	3032.64	3070.01
07/13/98	3032.49	3069.85
08/10/98	3032.50	3069.86
09/08/98	3032.43	3069.78
10/12/98	3032.12	3069.44
11/09/98	3032.35	3069.69
12/07/98	3032.27	3069.61
01/11/99	3032.20	3069.53
02/08/99	3032.56	3069.92
03/08/99	3032.75	3070.13
04/12/99	3032.46	3069.81
05/10/99	3032.81	3070.20
06/07/99	3032.82	3070.21
07/19/99	3032.83	3070.22
08/09/99	3032.87	3070.27
09/07/99	3032.94	3070.34
10/04/99	3032.87	3070.27
11/08/99	3033.00	3070.41
12/06/99	3033.16	3070.58
01/19/00	3033.45	3070.90
02/14/00	3033.61	3071.08
03/06/00	3033.68	3071.16
04/17/00	3033.60	3071.07
05/15/00	3033.62	3071.09
06/05/00	3033.60	3071.07
07/10/00	3033.79	3071.28
08/14/00	3033.74	3071.22
09/11/00	3033.79	3071.28
10/09/00	3033.37	3070.82
11/08/00	3033.67	3071.15
12/06/00	3033.55	3071.01

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3033.65	3071.12
02/05/01	3033.53	3070.99
03/05/01	3033.69	3071.17

Figure 68 - WIPP-18 Culebra Historical Waterlevel Measurements

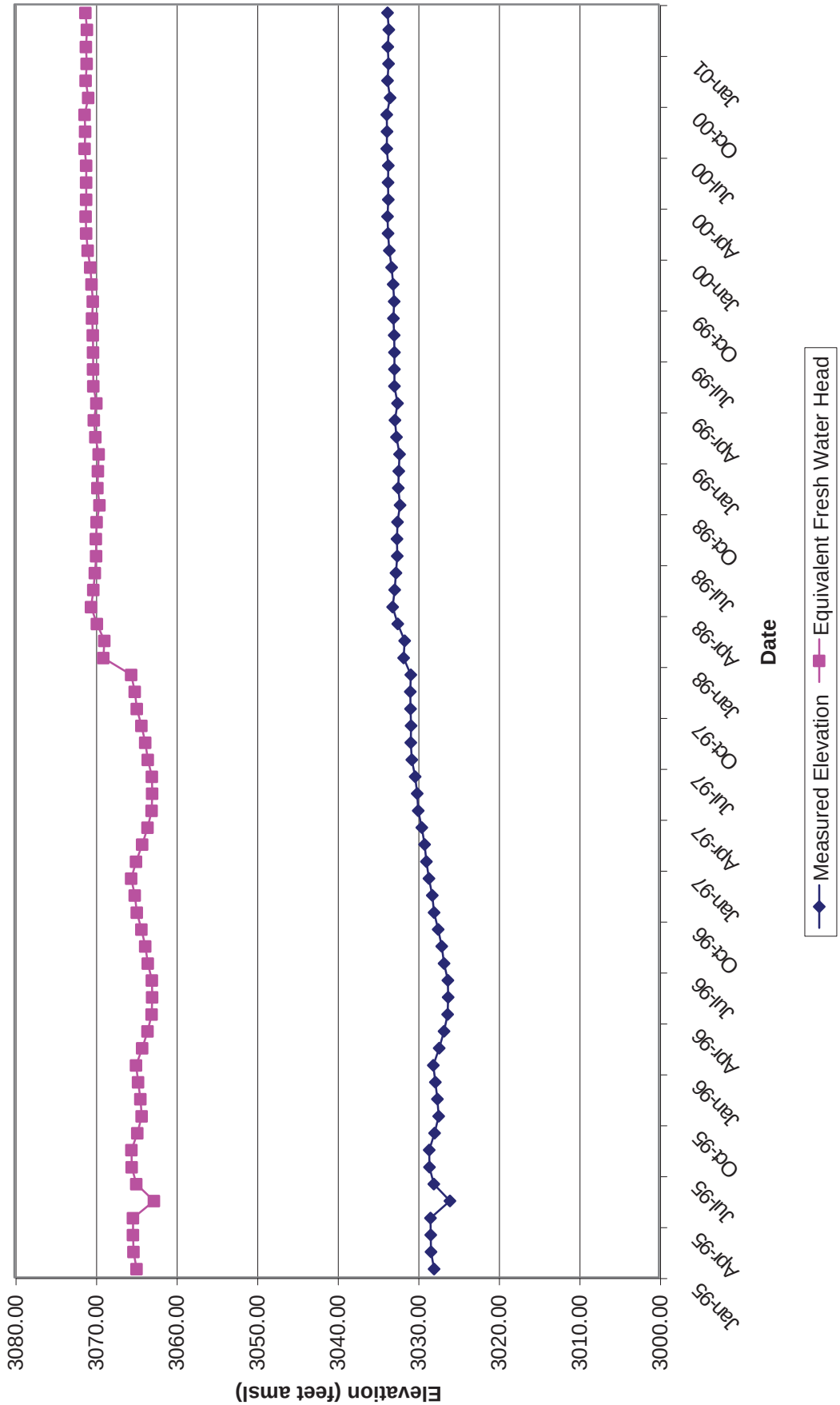

Table 69 - Well No. WIPP-18 Magenta
April 2001 through December 2001

Date	Measured Elevation	Equivalent Fresh Water Head
04/05/01	2936.11	N/A
05/08/01	3139.57	N/A
06/05/01	3140.68	N/A
07/11/01	3140.15	N/A
09/12/01	3132.14	N/A
10/03/01	3125.88	N/A
11/12/01	3116.43	N/A
12/03/01	3112.86	N/A

Figure 69 - WIPP-18 Magenta
Historical Waterlevel Measurements

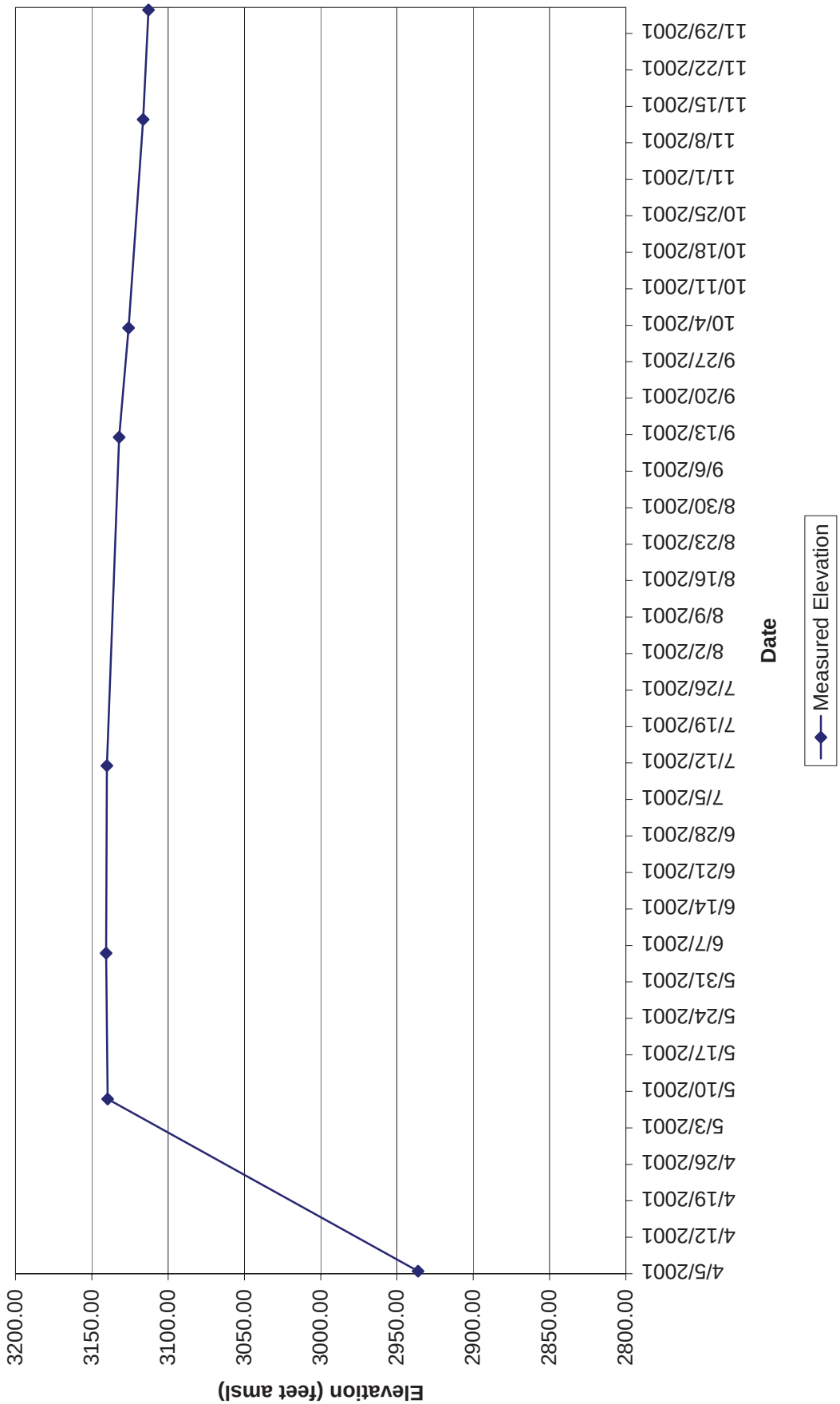

Table 70 - Well No. WIPP-19 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3035.22	3072.55
02/15/95	3035.61	3072.98
03/13/95	3035.52	3072.88
04/10/95	3035.58	3072.94
05/09/95	3027.91	3064.50
06/05/95	3034.60	3071.87
07/17/95	3034.65	3071.92
08/14/95	3033.63	3070.80
09/05/95	3032.89	3069.98
10/16/95	3032.54	3069.60
11/07/95	3032.67	3069.74
12/04/95	3033.11	3070.23
01/08/96	3033.23	3070.36
02/05/96	3031.47	3068.42
03/11/96	3029.42	3066.16
04/15/96	3028.14	3064.75
05/13/96	3028.46	3065.11
06/10/96	3029.07	3065.78
07/15/96	3030.19	3067.01
08/12/96	3031.10	3068.01
09/03/96	3031.89	3068.88
10/14/96	3032.88	3069.97
11/11/96	3033.27	3070.40
12/09/96	3033.88	3071.07
01/13/97	3034.25	3071.48
02/10/97	3034.69	3071.97
03/10/97	3035.03	3072.34
04/14/97	3035.55	3072.91
05/12/97	3035.84	3073.23
06/09/97	3036.28	3073.72
07/14/97	3036.46	3073.91
08/11/97	3036.71	3074.19
09/15/97	3036.77	3074.26
10/13/97	3036.72	3074.20
11/10/97	3036.79	3074.28
12/08/97	3036.90	3074.40

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3036.68	3074.16
02/09/98	3037.31	3074.85
03/09/98	3037.94	3075.54
04/13/98	3038.63	3076.30
05/11/98	3038.65	3076.33
06/08/98	3038.50	3076.16
07/13/98	3038.39	3076.04
08/10/98	3038.40	3076.05
09/08/98	3038.46	3076.12
10/12/98	3038.10	3075.72
11/09/98	3038.43	3076.08
12/07/98	3038.16	3075.79
01/11/99	3038.07	3075.69
02/08/99	3038.33	3075.97
03/08/99	3038.52	3076.18
04/12/99	3038.35	3075.99
05/10/99	3038.68	3076.36
06/07/99	3038.61	3076.28
07/19/99	3038.63	3076.30
08/09/99	3038.72	3076.40
09/07/99	3038.75	3076.44
10/04/99	3038.55	3076.21
11/08/99	3038.78	3076.47
12/06/99	3038.85	3076.55
01/19/00	3039.04	3076.75
02/14/00	3039.07	3076.79
03/06/00	3039.16	3076.89
04/17/00	3039.15	3076.88
05/15/00	3039.13	3076.85
06/05/00	3039.08	3076.80
07/10/00	3039.30	3077.04
08/14/00	3039.27	3077.01
09/11/00	3039.32	3077.06
10/09/00	3038.86	3076.56
11/08/00	3039.15	3076.88
12/06/00	3038.93	3076.63

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3038.99	3076.70
02/05/01	3038.82	3076.51
03/07/01	3038.98	3076.69
04/05/01	3039.13	3076.85
05/08/01	3039.04	3076.75
06/05/01	3039.45	3077.21
07/11/01	3039.56	3077.33
08/08/01	3039.63	3077.40
09/06/01	3039.74	3077.53
10/10/01	3039.84	3077.64
11/14/01	3039.96	3077.77
12/05/01	3039.83	3077.62
01/16/02	3040.01	3077.82
02/05/02	3040.13	3077.95
03/12/02	3040.24	3078.08
04/08/02	3040.52	3078.38
05/07/02	3040.64	3078.52
06/10/02	3040.90	3078.80
07/15/02	3040.88	3078.78
08/13/02	3041.09	3079.01
09/10/02	3041.06	3078.98

Figure 70 -WIPP-19 Culebra
Historical Waterlevel Measurements

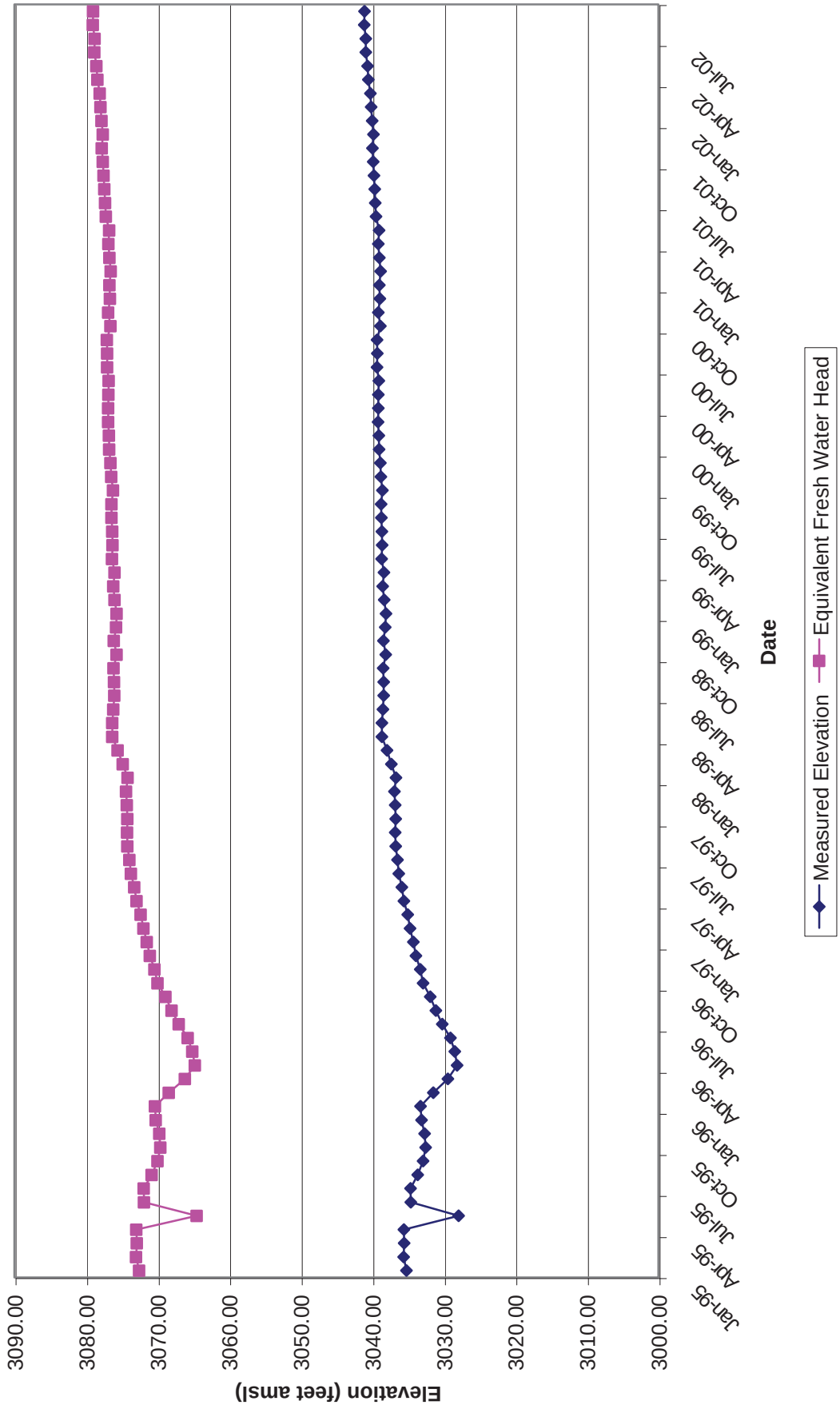

Table 71 - Well No. WIPP-21 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3010.06	3033.78
02/15/95	3010.54	3034.29
03/13/95	3009.78	3033.48
04/10/95	3010.26	3033.99
05/09/95	3008.75	3032.38
06/05/95	3008.98	3032.62
07/17/95	3003.47	3026.72
08/14/95	3000.19	3023.21
09/05/95	3000.55	3023.59
10/16/95	3000.99	3024.06
11/07/95	3002.25	3025.41
12/04/95	3003.19	3026.42
01/08/96	3000.23	3023.25
02/05/96	2993.77	3016.33
03/11/96	2988.73	3010.93
04/15/96	2990.24	3012.55
05/13/96	2990.03	3012.33
06/10/96	2993.96	3016.54
07/15/96	2997.86	3020.71
08/12/96	3000.37	3023.40
09/03/96	3002.09	3025.24
10/14/96	3004.03	3027.32
11/11/96	3005.16	3028.53
12/09/96	3005.99	3029.42
01/13/97	3006.76	3030.24
02/10/97	3007.32	3030.84
03/10/97	3008.27	3031.86
04/14/97	3009.29	3032.95
05/12/97	3009.90	3033.61
06/09/97	3010.37	3034.11
07/14/97	3010.70	3034.46
08/11/97	3011.05	3034.84
09/15/97	3011.29	3035.10
10/13/97	3011.47	3035.29
11/10/97	3011.47	3035.29
12/08/97	3011.68	3035.51

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3011.47	3035.29
02/09/98	3011.91	3035.76
03/09/98	3012.36	3036.24
04/13/98	3013.14	3037.08
05/11/98	3013.35	3037.30
06/08/98	3013.52	3037.48
07/13/98	3013.63	3037.60
08/10/98	3013.67	3037.64
09/08/98	3013.83	3037.82
10/12/98	3013.68	3037.66
11/09/98	3013.82	3037.81
12/07/98	3013.82	3037.81
01/11/99	3013.53	3037.49
02/08/99	3013.90	3037.89
03/08/99	3014.18	3038.19
04/12/99	3014.18	3038.19
05/10/99	3014.47	3038.50
06/07/99	3014.60	3038.64
07/19/99	3014.71	3038.76
08/09/99	3014.90	3038.96
09/07/99	3015.04	3039.11
10/04/99	3014.86	3038.92
11/08/99	3014.74	3038.79
12/06/99	3014.94	3039.00
01/19/00	3014.71	3038.76
02/14/00	3014.76	3038.81
03/06/00	3014.98	3039.05
04/17/00	3015.15	3039.23
05/15/00	3015.32	3039.41
06/05/00	3015.40	3039.50
07/10/00	3015.38	3039.48
08/14/00	3015.71	3039.83
09/11/00	3015.82	3039.95
10/09/00	3015.33	3039.42
11/08/00	3015.58	3039.69
12/06/00	3015.17	3039.25

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3014.93	3038.99
02/05/01	3014.43	3038.46
03/07/01	3014.88	3038.94
04/05/01	3015.32	3039.41
05/08/01	3015.42	3039.52
06/05/01	3015.93	3040.07
07/11/01	3016.05	3040.19
08/08/01	3016.16	3040.31
09/06/01	3016.27	3040.43
10/10/01	3016.36	3040.53
11/14/01	3016.31	3040.47
12/05/01	3016.10	3040.25
01/16/02	3015.97	3040.11
02/05/02	3016.08	3040.23
03/12/02	3016.16	3040.31
04/08/02	3016.57	3040.75
05/07/02	3016.80	3041.00
06/10/02	3017.13	3041.35
07/15/02	3017.25	3041.48
08/13/02	3017.46	3041.70
09/10/02	3017.76	3042.02

Figure 71 - WIPP-21 Culebra
Historical Waterlevel Measurements

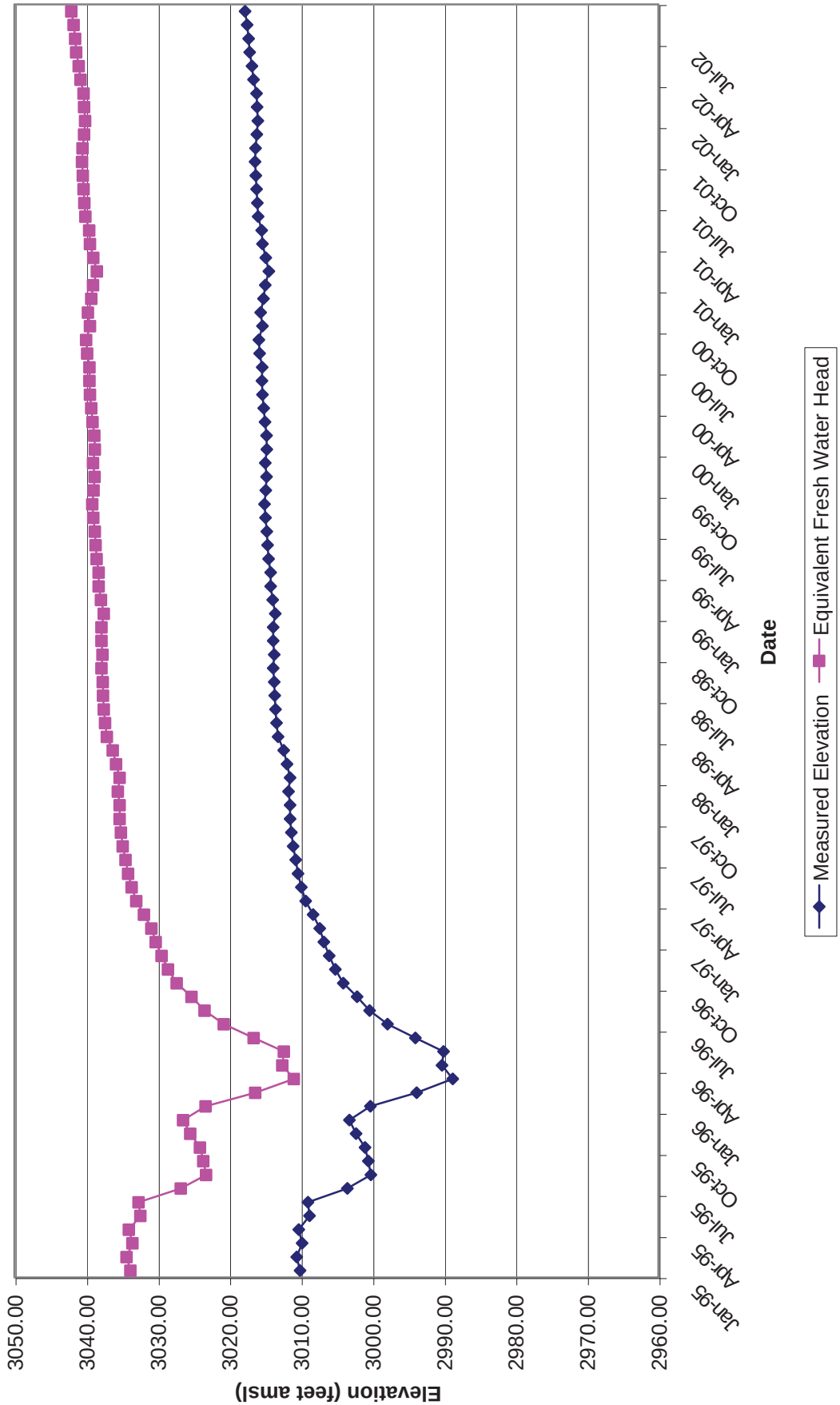

Table 72 - Well No. WIPP-22 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/18/95	3023.56	3054.06
02/15/95	3023.98	3054.52
03/13/95	3023.86	3054.38
04/10/95	3023.97	3054.50
05/09/95	3017.44	3047.41
06/05/95	3022.90	3053.34
07/17/95	3021.87	3052.22
08/14/95	3019.93	3050.11
09/05/95	3019.48	3049.62
10/16/95	3019.18	3049.30
11/07/95	3019.71	3049.87
12/04/95	3020.25	3050.46
01/08/96	3020.00	3050.19
02/05/96	3017.12	3047.06
03/11/96	3013.94	3043.60
04/15/96	3012.67	3042.22
05/13/96	3012.91	3042.48
06/10/96	3014.66	3044.38
07/15/96	3016.64	3046.54
08/12/96	3018.07	3048.09
09/03/96	3019.20	3049.32
10/14/96	3020.50	3050.73
11/11/96	3021.24	3051.54
12/09/96	3021.96	3052.32
01/13/97	3022.51	3052.92
02/10/97	3022.84	3053.28
03/10/97	3023.48	3053.97
04/14/97	3024.24	3054.80
05/12/97	3024.67	3055.27
06/09/97	3025.10	3055.73
07/14/97	3025.45	3056.11
08/11/97	3025.67	3056.35
09/15/97	3025.89	3056.59
10/13/97	3025.98	3056.69
11/10/97	3026.01	3056.72
12/08/97	3026.14	3056.86

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3025.98	3056.69
02/09/98	3026.44	3057.19
03/09/98	3027.05	3057.85
04/13/98	3027.83	3058.70
05/11/98	3027.96	3058.84
06/08/98	3027.93	3058.81
07/13/98	3027.90	3058.78
08/10/98	3027.90	3058.78
09/08/98	3028.01	3058.90
10/12/98	3027.80	3058.67
11/09/98	3027.96	3058.84
12/07/98	3027.88	3058.75
01/11/99	3027.71	3058.57
02/08/99	3028.02	3058.91
03/08/99	3028.26	3059.17
04/12/99	3028.16	3059.06
05/10/99	3028.47	3059.40
06/07/99	3028.47	3059.40
07/19/99	3028.53	3059.46
08/09/99	3028.71	3059.66
09/07/99	3028.79	3059.74
10/04/99	3028.64	3059.58
11/08/99	3028.70	3059.65
12/06/99	3028.76	3059.71
01/19/00	3028.87	3059.83
02/14/00	3029.00	3059.97
03/06/00	3029.10	3060.08
04/17/00	3029.17	3060.16
05/15/00	3029.19	3060.18
06/05/00	3029.20	3060.19
07/10/00	3029.44	3060.45
08/14/00	3029.43	3060.44
09/11/00	3029.51	3060.53
10/09/00	3029.10	3060.08
11/08/00	3029.41	3060.42
12/06/00	3029.15	3060.14

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3029.13	3060.11
02/05/01	3028.84	3059.80
03/07/01	3029.08	3060.06
04/05/01	3029.32	3060.32
05/08/01	3029.32	3060.32
06/05/01	3029.77	3060.81
07/11/01	3029.85	3060.90
08/08/01	3029.92	3060.97
09/06/01	3030.05	3061.11
10/10/01	3030.16	3061.23
11/14/01	3030.22	3061.30
12/05/01	3030.12	3061.19
01/16/02	3030.17	3061.24
02/05/02	3030.26	3061.34
03/12/02	3030.39	3061.48
04/08/02	3030.73	3061.85
05/07/02	3030.84	3061.97
06/10/02	3031.13	3062.29
07/15/02	3031.89	3063.11
08/13/02	3031.37	3062.55
09/10/02	3031.37	3062.55

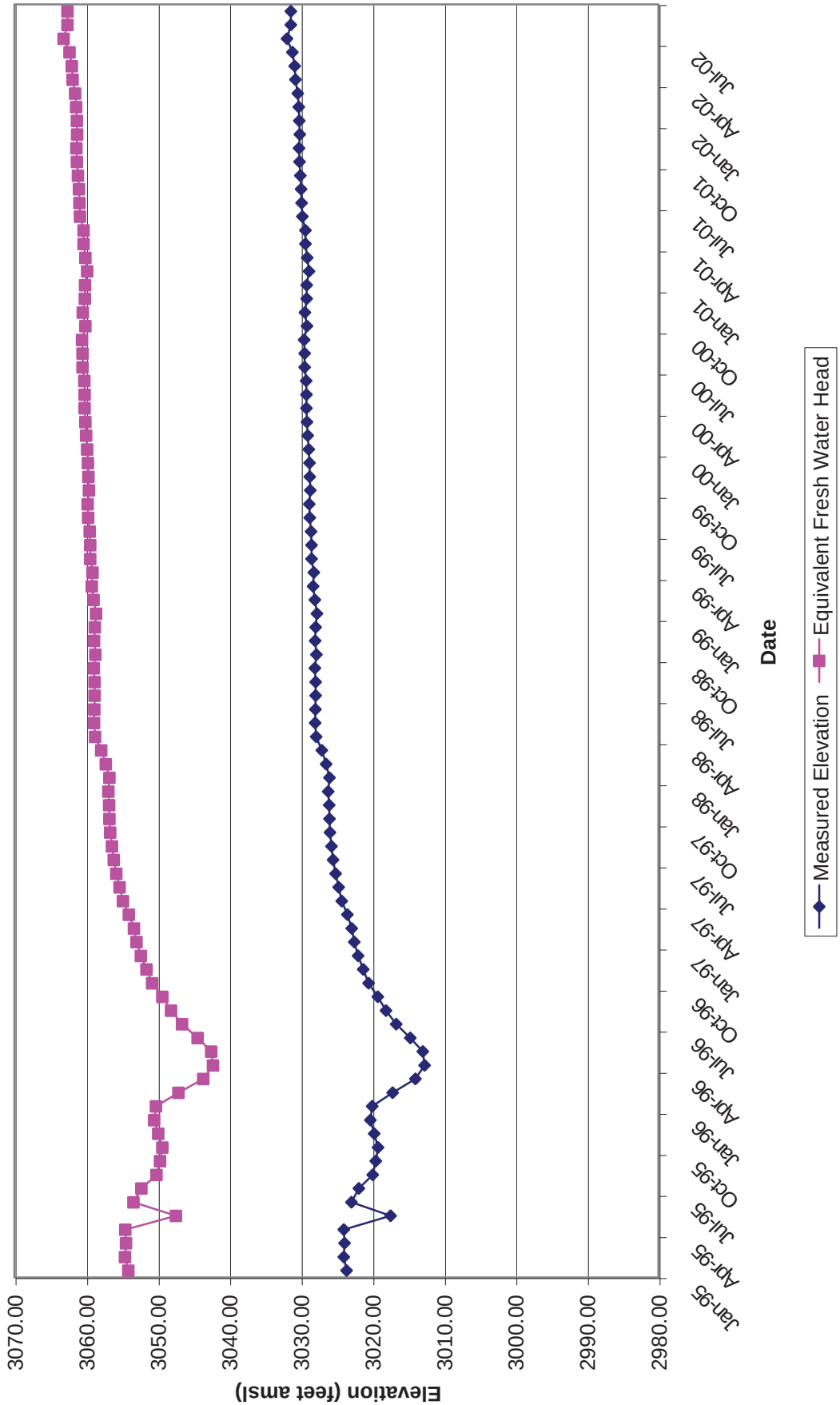

Figure 72 - WIPP-22 Culebra Historical Waterlevel Measurements

Table 73 - Well No. WIPP-25 (ANNULUS) Magenta
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3056.23	N/A
02/13/95	3056.45	N/A
03/13/95	3056.59	N/A
04/10/95	3056.61	N/A
05/08/95	3056.79	N/A
06/05/95	3056.90	N/A
07/17/95	3057.03	N/A
08/14/95	3056.82	N/A
09/05/95	3057.24	N/A
10/16/95	3057.43	N/A
11/06/95	3057.47	N/A
12/04/95	3057.52	N/A
01/08/96	3057.58	N/A
02/05/96	3057.61	N/A
03/11/96	3057.67	N/A
04/15/96	3057.72	N/A
05/13/96	3057.76	N/A
06/10/96	3057.84	N/A
07/15/96	3057.88	N/A
08/12/96	3057.92	N/A
09/03/96	3057.55	N/A
10/14/96	3058.09	N/A
11/11/96	3058.08	N/A
12/09/96	3058.01	N/A
01/13/97	3057.99	N/A
02/10/97	3057.97	N/A
03/10/97	3057.99	N/A
04/14/97	3057.99	N/A
05/13/97	3058.04	N/A
06/09/97	3058.05	N/A
07/14/97	3058.05	N/A
08/11/97	3058.06	N/A
09/15/97	3057.66	N/A
10/13/97	3058.02	N/A
11/10/97	3057.98	N/A
12/08/97	3057.89	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3057.78	N/A
02/09/98	3057.68	N/A
03/09/98	3057.64	N/A
04/13/98	3057.58	N/A
05/11/98	3057.55	N/A
06/08/98	3057.51	N/A
07/13/98	3057.46	N/A
08/10/98	3057.49	N/A
09/08/98	3057.49	N/A
10/12/98	3057.49	N/A
11/09/98	3057.49	N/A
12/07/98	3057.46	N/A
01/11/99	3057.50	N/A
02/08/99	3057.61	N/A
03/08/99	3057.51	N/A
04/12/99	3057.81	N/A
05/10/99	3057.86	N/A
06/07/99	3057.83	N/A
07/19/99	3058.03	N/A
08/09/99	3058.08	N/A
09/07/99	3058.06	N/A
10/04/99	3058.08	N/A
11/08/99	3058.17	N/A
12/06/99	3058.29	N/A
01/17/00	3058.13	N/A
09/12/00	3046.23	N/A
10/10/00	3047.01	N/A
11/06/00	3047.63	N/A
12/07/00	3048.23	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3048.77	N/A
02/05/01	3048.70	N/A
03/06/01	3049.60	N/A
04/03/01	3050.02	N/A
05/07/01	3050.28	N/A
06/05/01	3050.52	N/A
07/09/01	3050.69	N/A
08/08/01	3050.79	N/A
09/04/01	3050.85	N/A
10/08/01	3050.77	N/A
11/13/01	3050.55	N/A
12/04/01	3050.54	N/A
01/14/02	3050.61	N/A
02/06/02	3050.80	N/A
03/11/02	3050.55	N/A
04/09/02	3051.22	N/A
05/06/02	3051.35	N/A
06/10/02	3051.42	N/A
07/16/02	3051.67	N/A
08/12/02	3051.77	N/A
09/11/02	3051.83	N/A

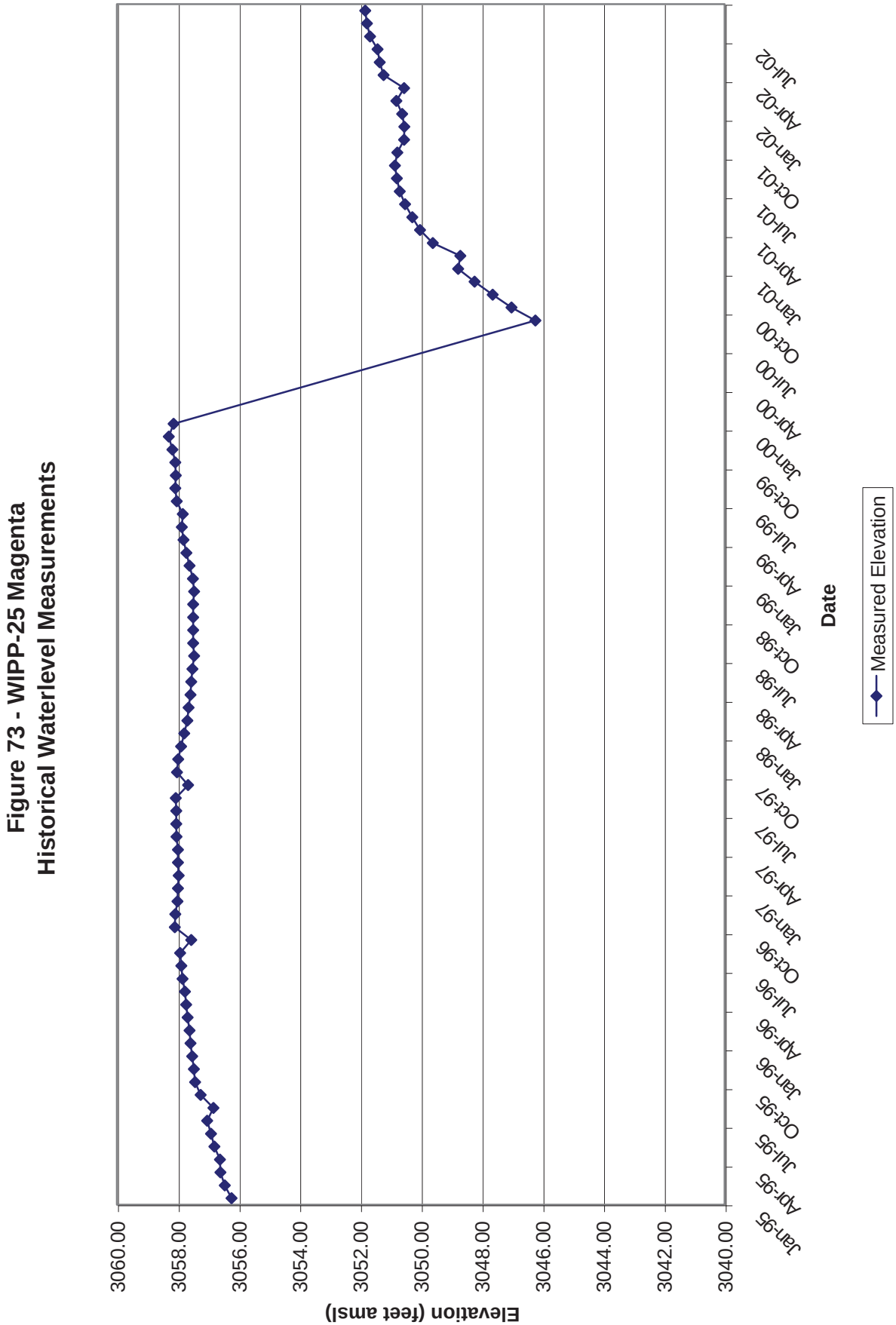
Figure 73 - WIPP-25 Magenta
Historical Waterlevel Measurements
Elevation (feet amsl)
3060.00
3058.00
3056.00
3054.00
3052.00
3050.00
3048.00
3046.00
3044.00
3042.00
3040.00
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Date
Measured Elevation

Table 74 - Well No. WIPP-25 (PIP) Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3056.31	3053.28
02/13/95	3056.72	3053.68
03/13/95	3057.79	3054.74
04/10/95	3056.83	3053.79
05/08/95	3056.71	3053.67
06/05/95	3056.84	3053.80
07/17/95	3057.37	3054.33
08/14/95	3057.53	3054.48
09/05/95	3057.45	3054.41
10/16/95	3057.38	3054.34
11/06/95	3057.36	3054.32
12/04/95	3057.26	3054.22
01/08/96	3057.30	3054.26
02/05/96	3057.43	3054.39
03/11/96	3057.66	3054.61
04/15/96	3057.59	3054.44
05/13/96	3057.71	3054.66
06/10/96	3057.77	3054.72
07/15/96	3057.83	3054.78
08/12/96	3057.93	3054.88
09/03/96	3058.81	3055.45
10/14/96	3057.92	3054.87
11/11/96	3057.69	3054.64
12/09/96	3057.76	3054.71
01/13/97	3057.75	3054.70
02/10/97	3057.93	3054.88
03/10/97	3058.09	3055.04
04/14/97	3058.13	3055.08
05/13/97	3058.25	3055.20
06/09/97	3058.08	3055.03
07/14/97	3058.40	3055.35
08/11/97	3058.13	3055.08
09/15/97	3057.92	3054.87
10/13/97	3057.62	3054.57
11/10/97	3057.11	3054.07
12/08/97	3056.82	3053.78

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3056.91	3053.87
02/09/98	3057.18	3054.14
03/09/98	3057.09	3054.05
04/13/98	3056.74	3053.70
05/11/98	3057.47	3054.42
06/08/98	3057.43	3054.39
07/13/98	3057.46	3054.42
08/10/98	3057.68	3054.63
09/08/98	3057.75	3054.70
10/12/98	3057.40	3054.36
11/09/98	3057.94	3054.89
12/07/98	3057.81	3054.76
01/11/99	3058.37	3055.32
02/08/99	3058.40	3055.35
03/08/99	3058.47	3055.41
04/12/99	3058.32	3055.27
05/10/99	3058.46	3055.41
06/07/99	3058.61	3055.55
07/19/99	3058.14	3055.09
08/09/99	3057.71	3054.66
09/07/99	3058.02	3054.97
10/04/99	3058.10	3055.05
11/08/99	3058.47	3055.41
12/06/99	3059.02	3055.96
01/17/00	3059.59	3056.52
02/14/00	3059.61	3056.54
03/06/00	3059.72	3056.65
04/17/00	3059.70	3056.63
05/15/00	3059.66	3056.59
06/06/00	3059.53	3056.46
07/11/00	3060.05	3056.98
08/14/00	3059.65	3056.58
09/12/00	3053.17	3050.17
10/10/00	3055.38	3052.36
11/06/00	3056.67	3053.63
12/07/00	3057.46	3054.42

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3058.06	3055.01
02/05/01	3058.63	3055.57
03/06/01	3058.96	3055.90
04/03/01	3059.37	3056.31
05/07/01	3059.46	3056.40
06/05/01	3059.60	3056.53
07/09/01	3059.85	3056.78
08/08/01	3059.91	3056.84
09/04/01	3059.86	3056.79
10/08/01	3060.02	3056.95
11/13/01	3060.11	3057.04
12/04/01	3060.43	3057.36
01/14/02	3060.61	3057.53
02/06/02	3060.90	3057.82
03/11/02	3061.19	3058.11
04/09/02	3061.25	3058.17
05/06/02	3061.55	3058.46
06/10/02	3061.64	3058.55
07/16/02	3061.97	3058.88
08/12/02	3062.16	3059.07
09/11/02	3062.10	3059.01

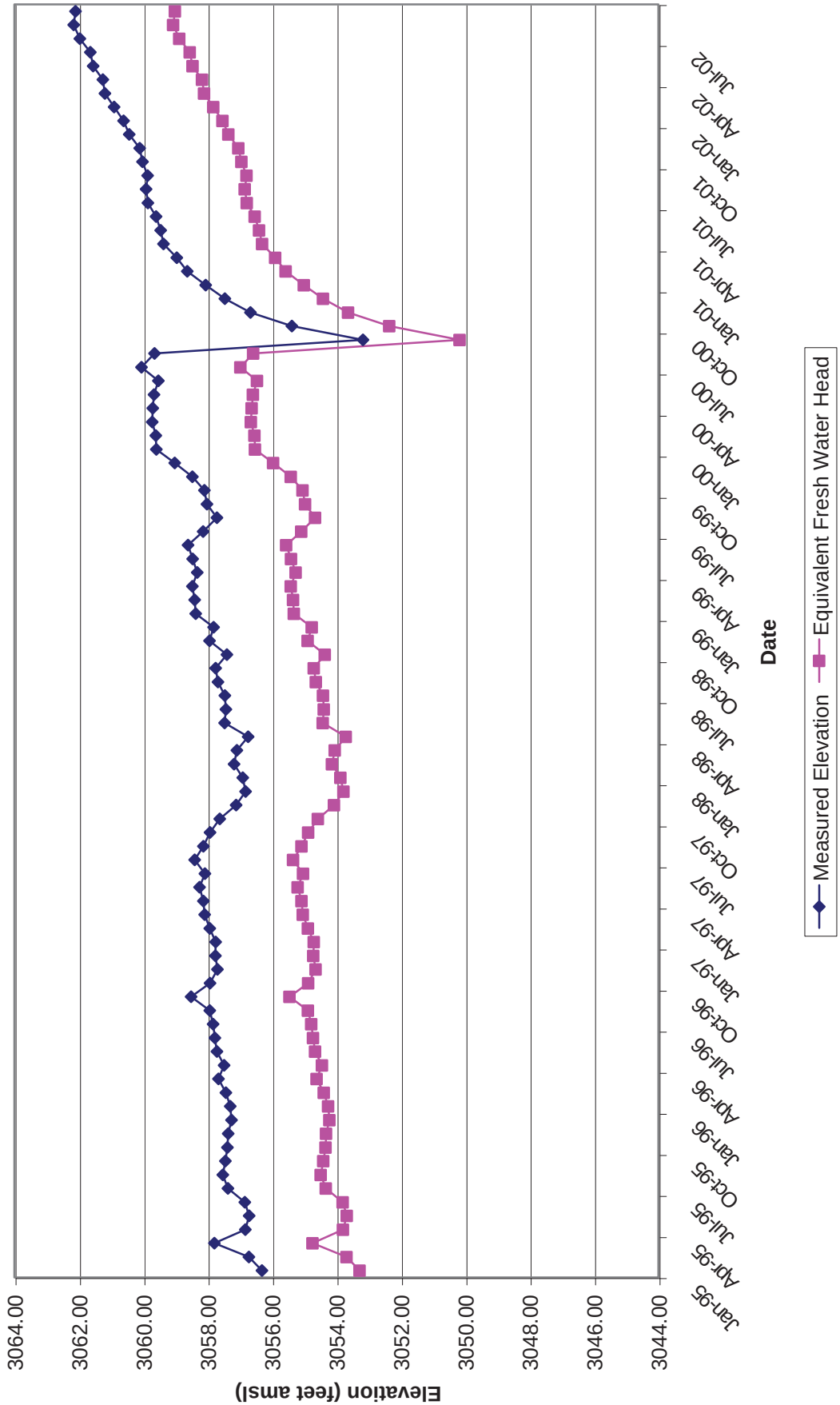

Figure 74 - WIPP-25 Culebra Historical Waterlevel Measurements

Table 75 - Well No. WIPP-26 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3018.25	3018.38
02/13/95	3018.27	3018.40
03/13/95	3018.31	3018.44
04/10/95	3018.26	3018.39
05/08/95	3018.29	3018.42
06/05/95	3018.53	3018.66
07/18/95	3019.14	3019.27
08/14/95	3019.02	3019.15
09/05/95	3018.91	3019.04
10/17/95	3019.12	3019.25
11/07/95	3019.08	3019.21
12/04/95	3019.25	3019.38
01/08/96	3019.25	3019.38
02/05/96	3019.25	3019.38
03/11/96	3019.48	3019.61
04/15/96	3019.23	3019.36
05/13/96	3019.26	3019.39
06/11/96	3019.17	3019.30
07/15/96	3019.40	3019.53
08/13/96	3019.50	3019.63
09/03/96	3020.12	3020.25
10/14/96	3020.44	3020.57
11/11/96	3020.28	3020.41
12/09/96	3020.25	3020.38
01/13/97	3019.96	3020.09
02/10/97	3020.02	3020.15
03/10/97	3020.15	3020.28
04/14/97	3020.06	3020.19
05/12/97	3020.15	3020.28
06/09/97	3019.63	3019.76
07/14/97	3020.14	3020.27
08/11/97	3020.25	3020.38
09/15/97	3020.25	3020.38
10/15/97	3020.25	3020.38
11/13/97	3020.24	3020.37
12/08/97	3020.19	3020.32

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3020.30	3020.43
02/09/98	3020.41	3020.54
03/10/98	3020.05	3020.18
04/13/98	3020.23	3020.36
05/11/98	3020.15	3020.28
06/08/98	3019.98	3020.11
07/13/98	3019.57	3019.70
08/10/98	3019.88	3020.01
09/08/98	3020.00	3020.13
10/12/98	3019.66	3019.79
11/09/98	3020.10	3020.23
12/07/98	3019.78	3019.91
01/11/99	3019.96	3020.09
02/08/99	3020.14	3020.27
03/08/99	3020.11	3020.24
04/12/99	3019.94	3020.07
05/10/99	3020.03	3020.16
06/07/99	3020.07	3020.20
07/19/99	3020.10	3020.23
08/09/99	3020.22	3020.35
09/07/99	3020.07	3020.20
10/04/99	3020.12	3020.25
11/08/99	3020.35	3020.48
12/06/99	3020.41	3020.54
01/19/00	3020.67	3020.80
02/14/00	3020.71	3020.84
03/06/00	3020.87	3021.00
04/17/00	3020.89	3021.02
05/15/00	3020.87	3021.00
06/07/00	3020.71	3020.84
07/11/00	3022.42	3022.56
08/14/00	3021.92	3022.06
09/12/00	3021.64	3021.77
10/10/00	3021.40	3021.53
11/06/00	3021.65	3021.78
12/04/00	3021.71	3021.84

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3021.75	3021.89
02/07/01	3021.83	3021.97
03/06/01	3021.64	3021.77
04/03/01	3022.05	3022.19
05/07/01	3021.95	3022.09
06/04/01	3021.20	3021.33
07/09/01	3021.79	3021.93
08/06/01	3021.40	3021.53
09/05/01	3020.57	3020.70
10/08/01	3021.41	3021.54
11/13/01	3022.14	3022.28
12/05/01	3021.40	3021.53
01/15/02	3021.72	3021.85
02/06/02	3021.82	3021.96
03/11/02	3021.84	3021.98
04/09/02	3021.95	3022.09
05/06/02	3022.14	3022.28
06/12/02	3021.93	3022.07
07/16/02	3022.43	3022.57
08/12/02	3022.39	3022.53
09/11/02	3021.86	3022.00

Figure 75 - WIPP-26 Culebra Historical Waterlevel Measruements

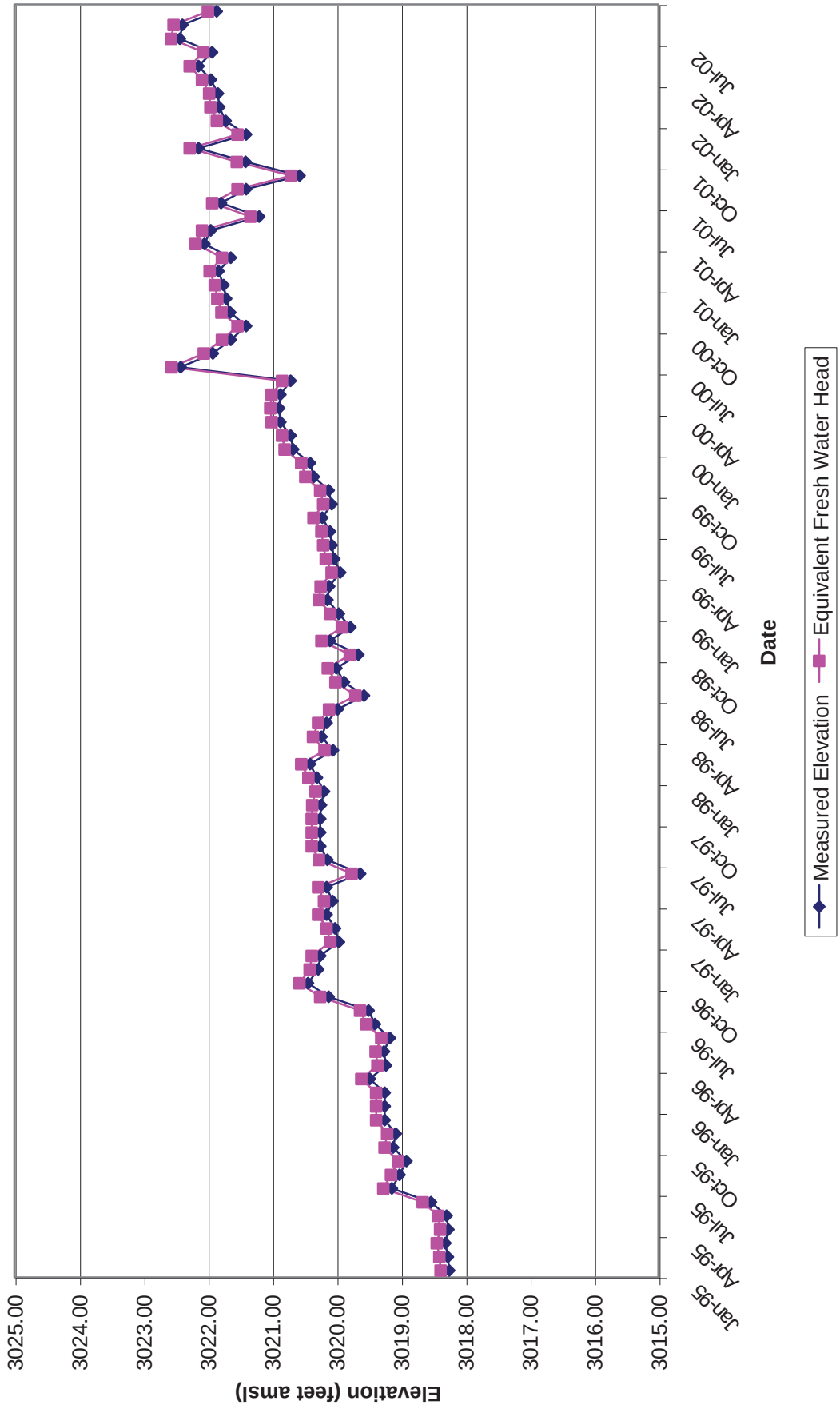

Table 76 - Well No. WIPP-27 (ANNULUS) Magenta
January 1995 through September 1997

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3073.33	N/A
02/13/95	3072.85	N/A
03/13/95	3072.24	N/A
04/10/95	3072.00	N/A
05/08/95	3072.54	N/A
06/05/95	3072.78	N/A
07/17/95	3073.08	N/A
08/14/95	3072.89	N/A
09/05/95	3072.76	N/A
10/16/95	3072.95	N/A
11/06/95	3072.99	N/A
12/04/95	3073.11	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/96	3073.27	N/A
02/05/96	3073.16	N/A
03/11/96	3073.06	N/A
04/15/96	3072.98	N/A
05/13/96	3072.91	N/A
06/10/96	3072.85	N/A
07/15/96	3072.47	N/A
08/12/96	3072.07	N/A
09/03/96	3071.61	N/A
10/14/96	3072.10	N/A
11/11/96	3072.63	N/A
12/09/96	3072.79	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/97	3072.62	N/A
02/10/97	3072.77	N/A
03/10/97	3072.73	N/A
04/14/97	3072.72	N/A
05/12/97	3072.57	N/A
06/09/97	3072.24	N/A
07/14/97	3071.94	N/A
08/11/97	3071.81	N/A
09/15/97	3071.40	N/A

Figure 76 - WIPP-27 Magenta Historical Waterlevel Measurements

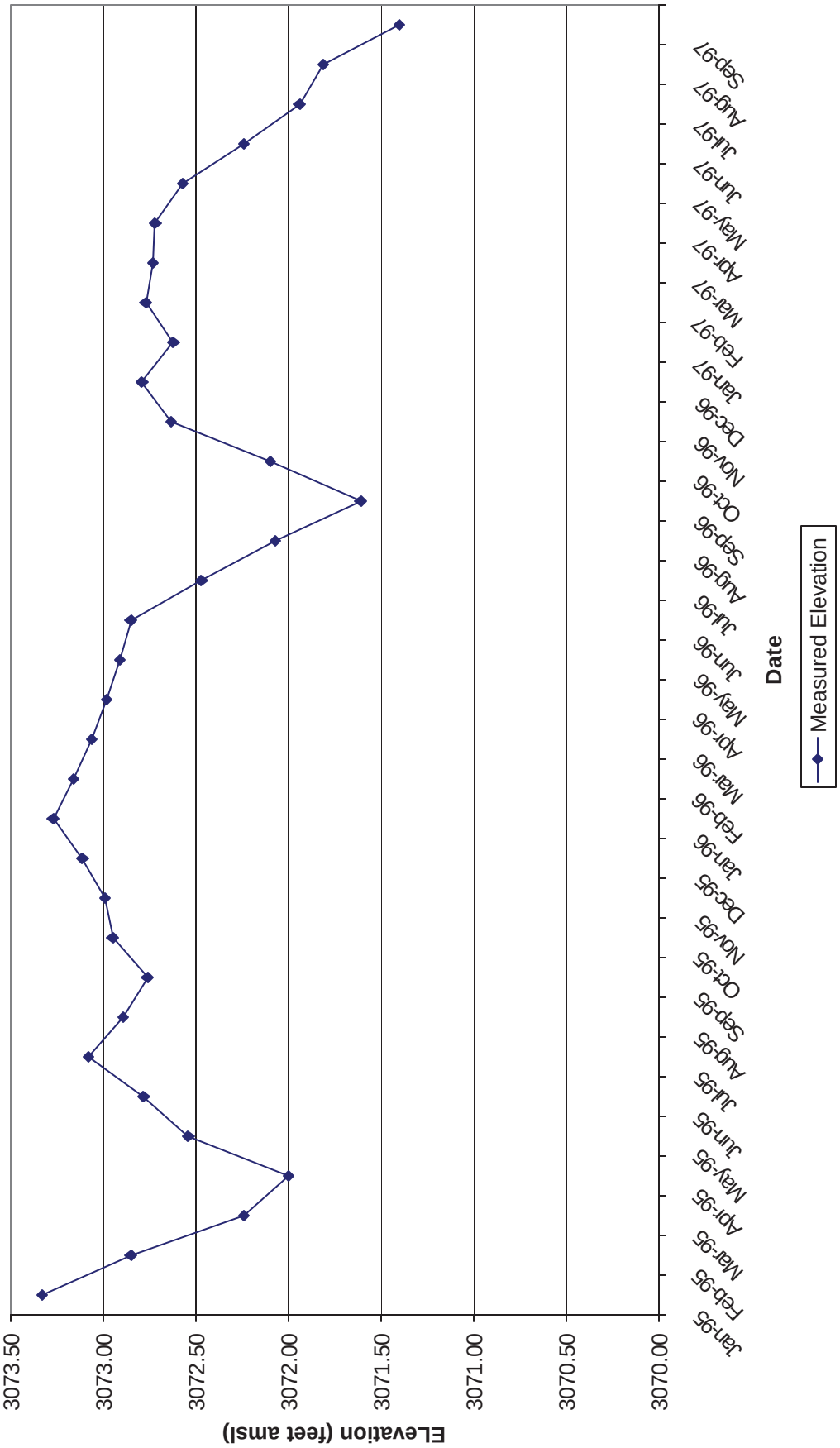

Table 77 - Well No. WIPP-27 (PIP)Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3080.85	3086.90
02/13/95	3079.84	3085.86
03/13/95	3078.96	3084.96
04/10/95	3078.67	3084.66
05/08/95	3079.28	3085.29
06/05/95	3079.46	3085.47
07/17/95	3080.23	3086.26
08/14/95	3080.01	3086.04
09/05/95	3079.71	3085.73
10/16/95	3079.95	3085.98
11/06/95	3080.02	3086.05
12/04/95	3080.24	3086.27
01/08/96	3080.50	3086.54
02/05/96	3080.40	3086.44
03/11/96	3080.27	3086.31
04/15/96	3080.15	3086.18
05/13/96	3080.16	3086.19
06/10/96	3080.15	3086.18
07/15/96	3079.80	3085.82
08/12/96	3079.33	3085.34
09/03/96	3079.22	3085.22
10/14/96	3079.41	3085.42
11/11/96	3079.90	3085.92
12/09/96	3080.29	3086.33
01/13/97	3080.12	3086.15
02/10/97	3080.26	3086.29
03/10/97	3080.18	3086.21
04/14/97	3080.22	3086.25
05/12/97	3080.04	3086.07
06/09/97	3079.68	3085.70
07/14/97	3079.29	3085.30
08/11/97	3079.19	3085.19
09/15/97	3079.22	3085.22
10/13/97	3079.11	3085.11
11/10/97	3079.15	3085.15
12/08/97	3079.18	3085.18

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3079.17	3085.17
02/09/98	3079.31	3085.32
03/09/98	3079.41	3085.42
04/13/98	3078.50	3084.48
05/11/98	3079.25	3085.26
06/08/98	3079.17	3085.17
07/13/98	3079.19	3085.19
08/10/98	3079.49	3085.50
09/08/98	3079.79	3085.81
10/12/98	3079.79	3085.81
11/09/98	3080.09	3086.12
12/07/98	3081.37	3087.44
01/11/99	3080.84	3086.89
02/08/99	3080.81	3086.86
03/08/99	3080.40	3086.44
04/12/99	3080.30	3086.34
05/10/99	3080.32	3086.36
06/07/99	3080.54	3086.58
07/19/99	3080.75	3086.80
08/09/99	3080.71	3086.76
09/07/99	3080.70	3086.75
10/04/99	3080.59	3086.63
11/08/99	3080.69	3086.74
12/06/99	3080.73	3086.78
01/17/00	3080.91	3086.96
02/14/00	3081.07	3087.13
03/06/00	3081.20	3087.26
04/17/00	3081.07	3087.13
05/15/00	3080.87	3086.92
06/05/00	3080.77	3086.82
07/10/00	3081.22	3087.28
09/12/00	3080.98	3087.04
10/09/00	3080.93	3086.98
11/06/00	3081.09	3087.15
12/04/00	3081.22	3087.28

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3081.14	3087.20
02/06/01	3081.02	3087.08
03/06/01	3080.87	3086.92
04/03/01	3080.83	3086.88
05/07/01	3080.65	3086.70
06/04/01	3080.80	3086.85
07/09/01	3080.44	3086.48
08/06/01	3080.13	3086.16
09/04/01	3080.17	3086.20
10/08/01	3080.81	3086.86
11/13/01	3081.45	3087.52
12/04/01	3082.10	3088.19
01/14/02	3082.55	3088.65
02/06/02	3082.65	3088.75
03/11/02	3082.79	3088.90
04/09/02	3082.60	3088.70
05/06/02	3082.62	3088.72
06/10/02	3082.30	3088.39
07/16/02	3081.96	3088.04
08/12/02	3081.86	3087.94
09/10/02	3081.68	3087.76

Figure 77 - WIPP-27 Culebra Historical Waterlevel Measurements

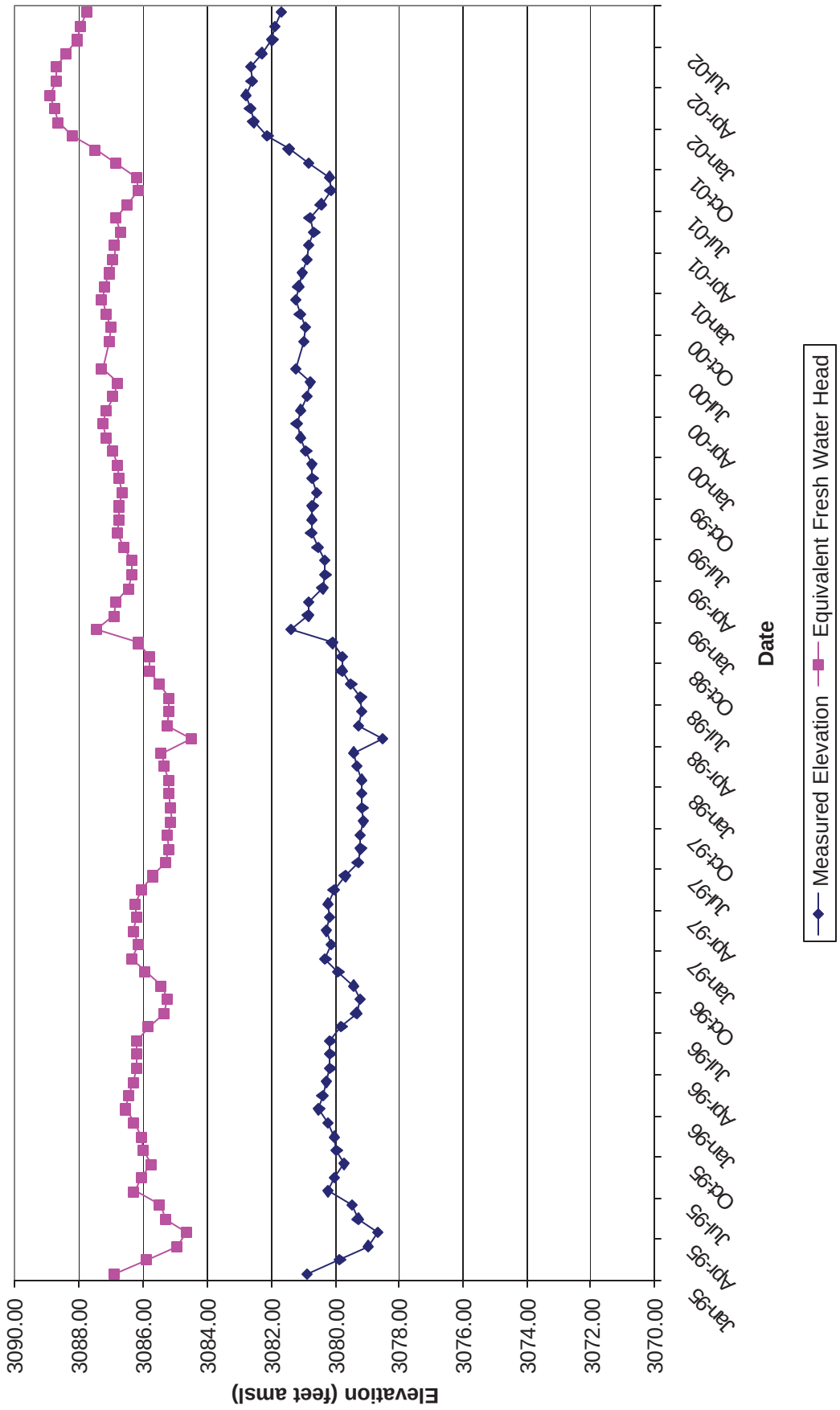

Table 78 - Well No. WIPP-28 (PIP) Rustler/Salado
January 1995 through December 1998

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3052.97	N/A
02/13/95	3052.63	N/A
03/13/95	3052.43	N/A
04/10/95	3052.50	N/A
05/08/95	3052.39	N/A
06/05/95	3052.11	N/A
07/17/95	3051.63	N/A
08/14/95	3051.75	N/A
09/05/95	3051.47	N/A
10/16/95	3051.34	N/A
11/06/95	3051.47	N/A
12/04/95	3051.11	N/A
01/08/96	3050.82	N/A
02/05/96	3050.82	N/A
03/11/96	3051.17	N/A
04/15/96	3050.68	N/A
05/13/96	3050.98	N/A
06/10/96	3050.53	N/A
07/15/96	3050.59	N/A
08/12/96	3050.45	N/A
09/03/96	3050.53	N/A
10/14/96	3050.43	N/A
11/11/96	3050.26	N/A
12/09/96	3050.21	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/13/97	3049.76	N/A
02/10/97	3049.78	N/A
03/10/97	3049.83	N/A
04/14/97	3050.02	N/A
05/13/97	3050.20	N/A
06/09/97	3050.27	N/A
07/14/97	3050.25	N/A
08/11/97	3050.21	N/A
09/15/97	3050.05	N/A
10/13/97	3049.87	N/A
11/10/97	3049.77	N/A
12/08/97	3050.15	N/A
01/12/98	3050.09	N/A
02/09/98	3050.19	N/A
03/09/98	3049.77	N/A
04/13/98	3049.35	N/A
05/11/98	3050.02	N/A
06/08/98	3049.99	N/A
07/13/98	3049.81	N/A
08/10/98	3049.66	N/A
09/08/98	3049.80	N/A
10/12/98	3049.59	N/A
11/09/98	3049.92	N/A
12/07/98	3049.65	N/A

Figure 78 - WIPP-28 Rustler/Salado Historical Waterlevel Measurements

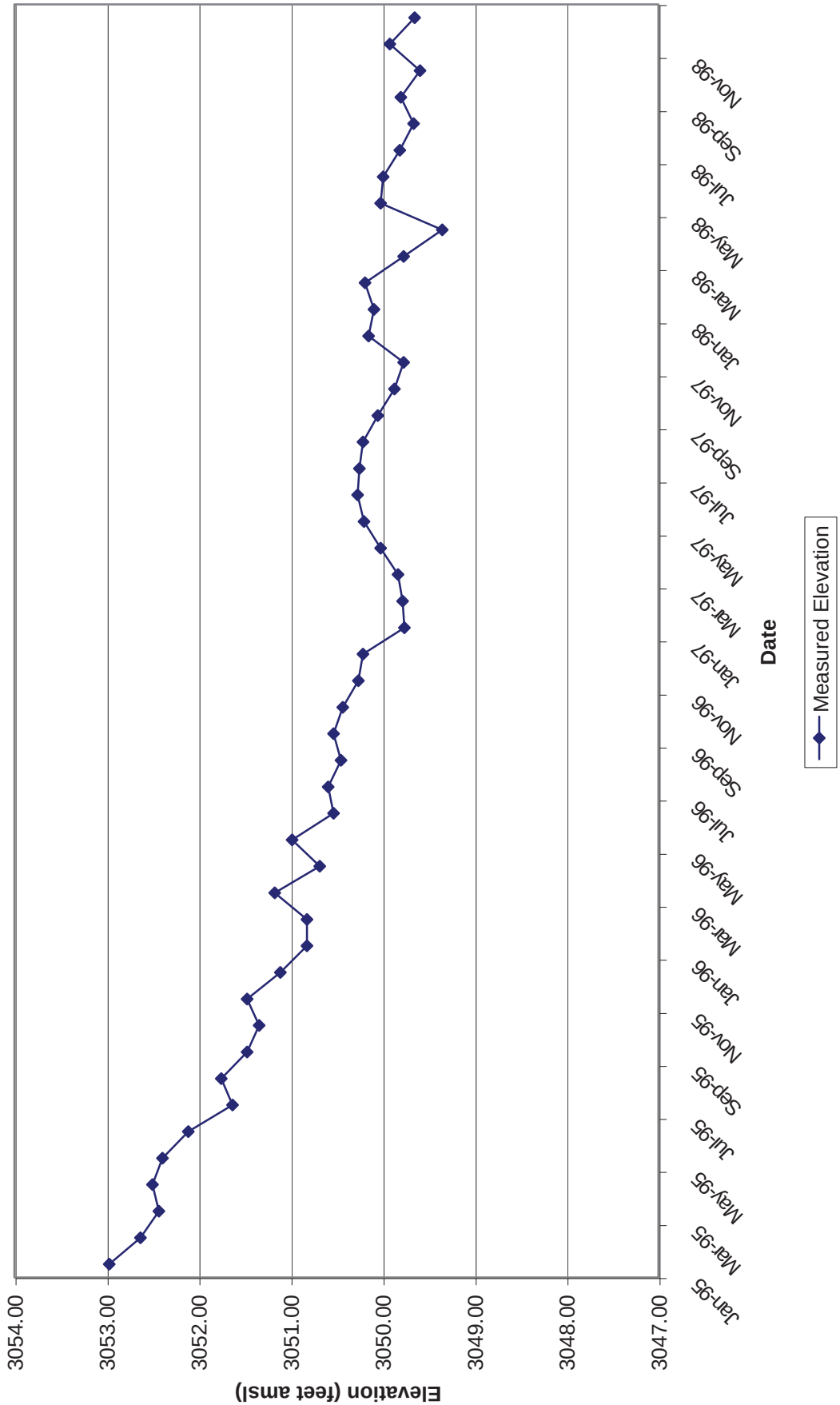

Table 79 - Well No. WIPP-29 Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	2966.84	2969.96
02/14/95	2966.90	2970.04
03/14/95	2966.91	2970.05
04/10/95	2966.93	2970.07
05/09/95	2966.87	2970.00
06/05/95	2966.85	2969.98
07/18/95	2966.95	2970.10
08/14/95	2966.64	2969.73
09/05/95	2966.81	2969.93
10/17/95	2966.89	2970.02
11/07/95	2966.75	2969.86
12/04/95	2966.60	2969.68
01/08/96	2966.66	2969.75
02/05/96	2966.55	2969.62
03/11/96	2966.34	2969.37
04/15/96	2966.70	2969.80
05/14/96	2966.67	2969.76
06/11/96	2966.50	2969.56
07/15/96	2966.66	2969.75
08/13/96	2966.61	2969.69
09/03/96	2967.16	2970.34
10/14/96	2966.64	2969.73
11/11/96	2966.48	2969.54
12/09/96	2966.53	2969.60
01/13/97	2966.51	2969.57
02/10/97	2966.52	2969.59
03/10/97	2966.98	2970.13
04/14/97	2966.95	2970.10
05/12/97	2967.02	2970.18
06/09/97	2967.24	2970.44
07/14/97	2967.36	2970.58
08/11/97	2966.99	2970.14
09/15/97	2966.97	2970.12
10/15/97	2967.39	2970.62
11/10/97	2967.00	2970.15
12/08/97	2967.10	2970.27

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	2967.42	2970.65
02/09/98	2967.33	2970.55
03/10/98	2967.14	2970.32
04/13/98	2967.24	2970.44
05/11/98	2967.14	2970.32
06/08/98	2966.94	2970.08
07/13/98	2967.06	2970.23
08/10/98	2966.98	2970.13
09/08/98	2966.77	2969.88
10/12/98	2967.01	2970.17
11/09/98	2967.22	2970.41
12/07/98	2966.73	2969.83
01/11/99	2966.78	2969.89
02/08/99	2966.93	2970.07
03/08/99	2966.84	2969.96
04/12/99	2966.76	2969.87
05/10/99	2966.85	2969.98
06/07/99	2966.99	2970.14
07/19/99	2967.04	2970.20
08/09/99	2966.94	2970.08
09/07/99	2967.03	2970.19
10/04/99	2966.87	2970.00
11/08/99	2966.68	2969.78
12/06/99	2966.62	2969.70
01/18/00	2966.76	2969.87
02/14/00	2966.82	2969.94
03/06/00	2966.83	2969.95
04/17/00	2966.92	2970.06
05/15/00	2966.77	2969.88
06/07/00	2967.11	2970.28
07/11/00	2967.74	2971.03
08/14/00	2967.17	2970.36
09/12/00	2967.24	2970.44
10/10/00	2967.16	2970.34
11/06/00	2967.66	2970.94
12/04/00	2967.37	2970.59

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	2967.17	2970.36
02/07/01	2967.26	2970.46
03/06/01	2967.23	2970.43
04/04/01	2967.11	2970.28
05/07/01	2967.06	2970.23
06/04/01	2966.91	2970.05
07/09/01	2966.60	2969.68
08/06/01	2967.01	2970.17
09/04/01	2966.86	2969.99
10/08/01	2966.93	2970.07
11/13/01	2966.75	2969.86
12/04/01	2967.06	2970.23
01/14/02	2966.84	2969.96
02/06/02	2967.15	2970.33
03/11/02	2967.00	2970.15
04/09/02	2967.25	2970.45
05/06/02	2967.29	2970.50
06/12/02	2967.07	2970.24
07/16/02	2967.10	2970.27
08/12/02	2967.16	2970.34
09/11/02	2967.07	2970.24

Figure 79 - WIPP-29 Culebra Historical Waterlevel Measurements

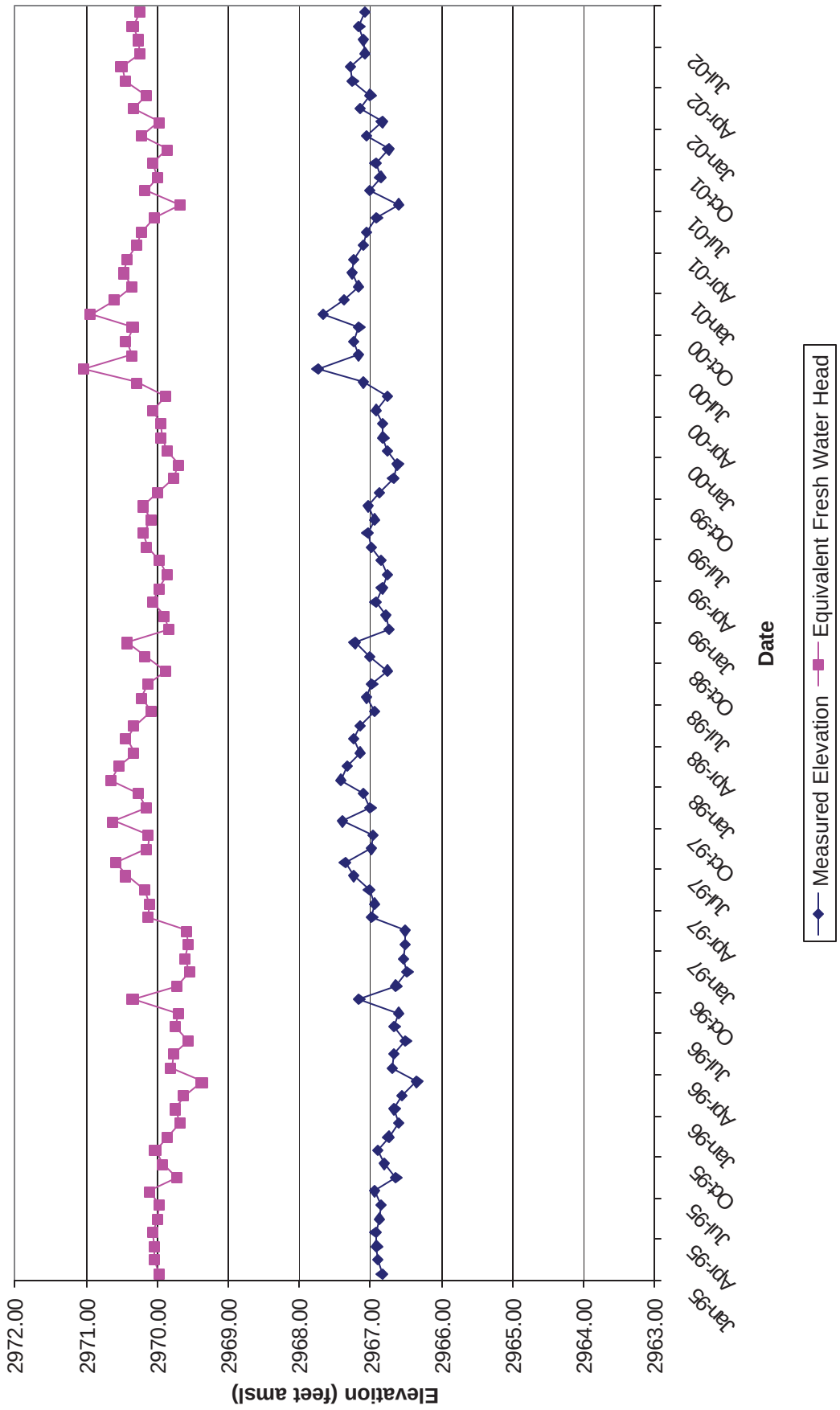

Table 80 - Well No. WIPP-30 (ANNULUS) Magenta
August 2000 through March 2002

Date	Measured Elevation	Equivalent Fresh Water Head
09/12/00	3128.43	N/A
10/09/00	3093.56	N/A
11/06/00	3091.75	N/A
12/07/00	3092.94	N/A
01/08/01	3095.29	N/A
02/06/01	3097.69	N/A
03/06/01	3099.43	N/A
04/04/01	3100.33	N/A
05/08/01	3102.10	N/A
06/05/01	3104.27	N/A
07/10/01	3106.28	N/A
08/08/01	3107.15	N/A
09/04/01	3107.50	N/A
10/10/01	3108.40	N/A
11/12/01	3109.14	N/A
12/03/01	3110.68	N/A
01/15/02	3111.36	N/A
02/06/02	3111.47	N/A
02/06/02	3111.47	N/A
02/06/02	3111.47	N/A
03/11/02	3110.55	N/A

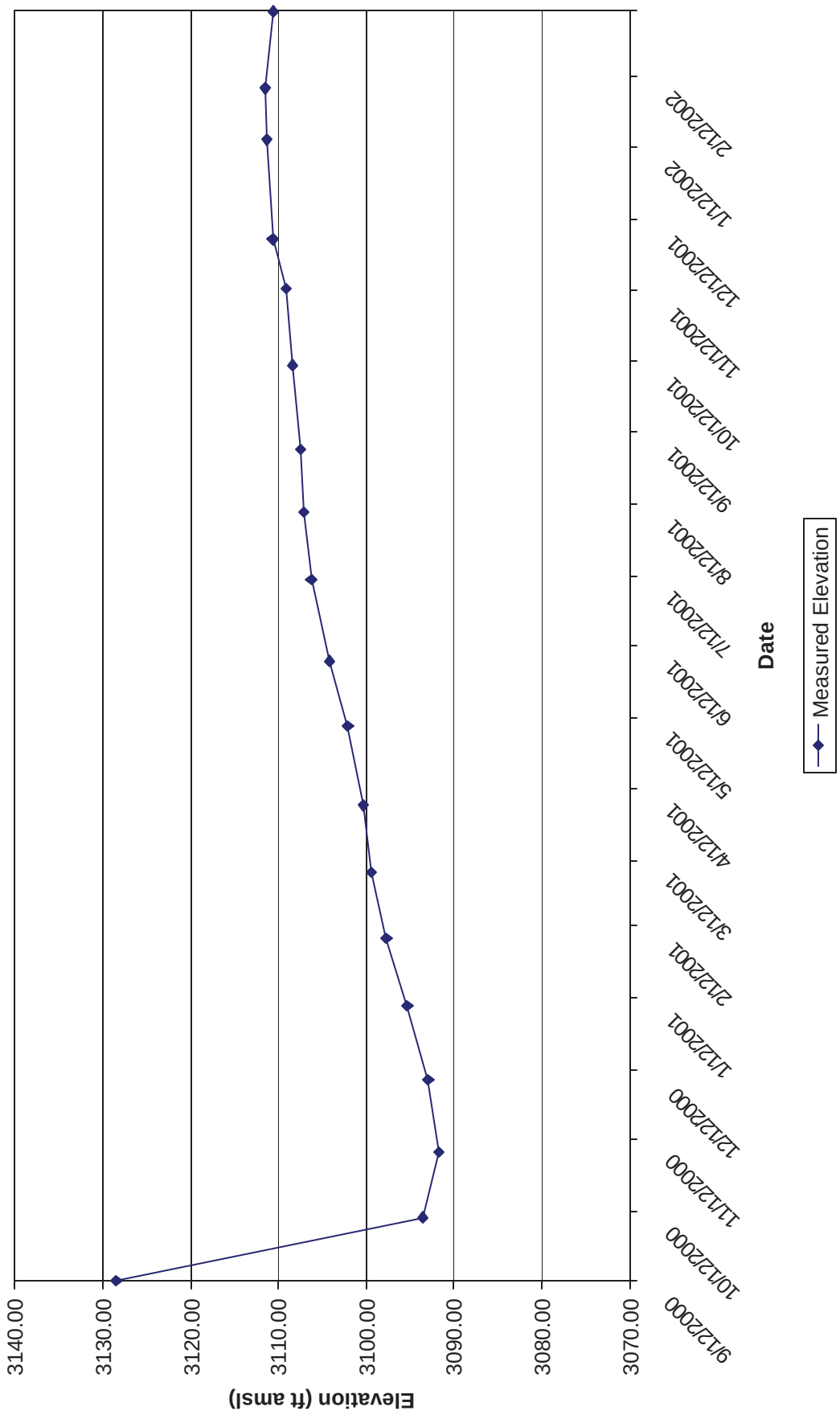
Figure 80 - WIPP-30 Magenta
Historical Waterlevel Measurements
Elevation (ft amsl)
3140.00
3130.00
3120.00
3110.00
3100.00
3090.00
3080.00
3070.00
9/12/2000
10/12/2000
11/12/2000
12/12/2000
1/12/2001
2/12/2001
3/12/2001
4/12/2001
5/12/2001
6/12/2001
7/12/2001
8/12/2001
9/12/2001
10/12/2001
11/12/2001
12/12/2001
1/12/2002
2/12/2002
Date
Measured Elevation

Table 81 - Well No. WIPP-30 (PIP) Culebra
January 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
01/16/95	3064.64	3071.62
02/13/95	3064.50	3071.48
03/13/95	3064.45	3071.42
04/10/95	3064.50	3071.48
05/08/95	3064.64	3071.62
06/05/95	3064.74	3071.72
07/17/95	3064.69	3071.67
08/14/95	3064.97	3071.96
09/05/95	3064.67	3071.65
10/16/95	3064.72	3071.70
11/06/95	3065.01	3072.00
12/04/95	3062.52	3069.45
01/08/96	3064.83	3071.81
02/05/96	3064.58	3071.56
03/11/96	3064.62	3071.60
04/15/96	3064.61	3071.59
05/13/96	3064.64	3071.62
06/10/96	3064.90	3071.89
07/15/96	3065.16	3072.15
08/12/96	3065.08	3072.07
09/03/96	3065.18	3072.17
10/14/96	3065.14	3072.13
11/11/96	3065.09	3072.08
12/09/96	3065.09	3072.08
01/13/97	3065.11	3072.10
02/10/97	3065.15	3072.14
03/10/97	3065.32	3072.32
04/14/97	3065.53	3072.53
05/12/97	3065.59	3072.59
06/09/97	3065.93	3072.94
07/14/97	3066.21	3073.23
08/11/97	3066.14	3073.16
09/15/97	3065.99	3073.00
10/13/97	3065.65	3072.65
11/10/97	3065.48	3072.48
12/08/97	3064.95	3071.94

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3065.05	3072.04
02/09/98	3068.89	3075.98
03/09/98	3069.76	3076.87
04/13/98	3068.72	3075.80
05/11/98	3068.27	3075.34
06/08/98	3067.70	3074.76
07/13/98	3067.40	3074.45
08/10/98	3069.46	3076.56
09/08/98	3067.05	3074.09
10/12/98	3066.34	3073.36
11/09/98	3066.55	3073.58
12/07/98	3066.11	3073.13
01/11/99	3066.23	3073.25
02/08/99	3066.71	3073.74
03/08/99	3066.72	3073.75
04/12/99	3066.55	3073.58
05/10/99	3066.92	3073.96
06/07/99	3066.71	3073.74
07/19/99	3066.51	3073.54
08/09/99	3066.43	3073.45
09/07/99	3066.49	3073.52
10/04/99	3066.46	3073.48
11/08/99	3066.64	3073.67
12/06/99	3066.73	3073.76
01/17/00	3066.72	3073.75
02/16/00	3066.86	3073.89
03/06/00	3067.00	3074.04
04/17/00	3066.79	3073.82
05/15/00	3066.73	3073.76
06/05/00	3066.50	3073.53
07/10/00	3066.54	3073.57
08/14/00	3066.41	3073.43
09/12/00	3064.56	3071.54
10/09/00	3060.69	3067.57
11/06/00	3060.98	3067.87
12/07/00	3061.22	3068.11

Date	Measured Elevation	Equivalent Fresh Water Head
01/08/01	3061.98	3068.89
02/06/01	3062.98	3069.92
03/06/01	3063.93	3070.89
04/04/01	3064.94	3071.93
05/08/01	3065.72	3072.73
06/05/01	3066.59	3073.62
07/10/01	3066.76	3073.79
08/08/01	3066.62	3073.65
09/04/01	3067.12	3074.16
10/10/01	3067.41	3074.46
11/12/01	3067.57	3074.62
12/03/01	3067.85	3074.91
01/15/02	3068.26	3075.33
02/06/02	3068.41	3075.48
03/11/02	3069.00	3076.09
04/09/02	3069.16	3076.25
05/08/02	3069.70	3076.81
06/12/02	3069.94	3077.05
07/15/02	3070.02	3077.13
08/13/02	3070.23	3077.35
09/09/02	3070.19	3077.31

Figure 81 - WIPP-30 Culebra Historical Waterlevel Measurements

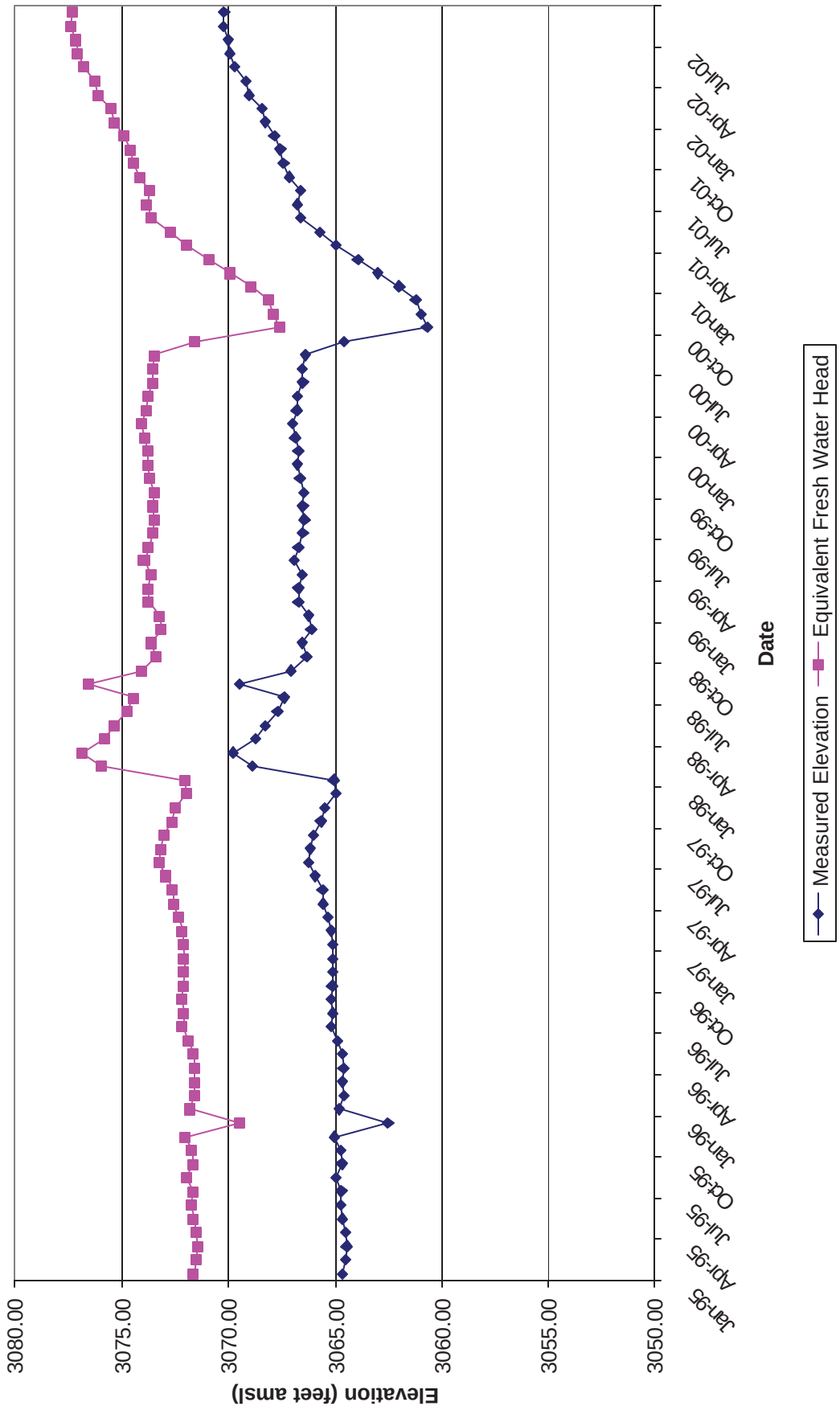

Table 82 - Well No. WQSP-1 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/05/95	3051.58	3068.16
07/17/95	3051.61	3068.19
08/07/95	3051.63	3068.22
09/05/95	3050.68	3067.22
10/16/95	3051.40	3067.97
11/06/95	3051.81	3068.40
12/04/95	3051.68	3068.27
01/10/96	3051.85	3067.59
02/08/96	3051.03	3067.59
03/11/96	3051.00	3067.56
04/15/96	3050.79	3067.34
05/13/96	3051.24	3067.81
06/10/96	3051.68	3068.27
07/15/96	3051.75	3068.34
08/12/96	3051.39	3067.96
09/03/96	3051.95	3068.55
10/14/96	3051.97	3068.57
11/11/96	3051.63	3068.22
12/09/96	3051.87	3068.47
01/13/97	3051.99	3068.59
02/10/97	3051.87	3068.47
03/10/97	3052.12	3068.73
04/14/97	3052.49	3069.12
05/13/97	3052.51	3069.14
06/09/97	3052.76	3069.40
07/15/97	3053.13	3069.79
08/11/97	3052.79	3069.43
09/15/97	3052.67	3069.31
10/13/97	3052.30	3068.92
11/10/97	3052.30	3068.92
12/08/97	3051.65	3068.24

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3051.75	3068.34
02/09/98	3054.69	3071.42
03/09/98	3055.03	3071.78
04/13/98	3054.51	3071.23
05/11/98	3054.09	3070.79
06/08/98	3053.65	3070.33
07/13/98	3053.32	3069.99
08/10/98	3053.31	3069.98
09/08/98	3053.22	3069.88
10/12/98	3052.68	3069.32
11/13/98	3052.75	3069.39
12/07/98	3052.60	3069.23
01/11/99	3052.86	3069.50
02/08/99	3053.24	3069.90
03/08/99	3053.15	3069.81
04/12/99	3053.03	3069.68
05/10/99	3053.35	3070.02
06/07/99	3053.21	3069.87
07/19/99	3052.95	3069.60
08/09/99	3052.84	3069.48
09/07/99	3052.88	3069.53
10/04/99	3052.72	3069.36
11/08/99	3053.10	3069.76
12/06/99	3053.31	3069.98
01/18/00	3053.49	3070.16
02/14/00	3053.45	3070.12
03/06/00	3053.82	3070.51
04/17/00	3053.38	3070.05
05/15/00	3053.36	3070.03
06/05/00	3053.06	3069.71
07/10/00	3053.20	3069.86
08/14/00	3053.16	3069.82
09/12/00	3052.95	3069.60
10/09/00	3052.71	3069.35
11/06/00	3053.31	3069.98
12/07/00	3053.00	3069.65

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3053.00	3069.65
02/06/01	3053.09	3069.75
03/06/01	3053.10	3069.76
04/05/01	3053.09	3069.75
05/08/01	3053.41	3070.08
06/05/01	3053.68	3070.36
07/09/01	3053.65	3070.33
08/07/01	3053.48	3070.15
09/04/01	3053.54	3070.22
10/10/01	3053.58	3070.26
11/14/01	3053.81	3070.50
12/05/01	3053.61	3070.29
01/16/02	3053.89	3070.58
02/05/02	3054.02	3070.72
03/11/02	3054.37	3071.09
04/08/02	3054.62	3071.35
05/06/02	3054.74	3071.47
06/10/02	3054.96	3071.71
07/15/02	3054.97	3071.72
08/12/02	3055.13	3071.88
09/09/02	3055.02	3071.77

Figure 82 - WQSP-1 Culebra
Historical Waterlevel Measurements

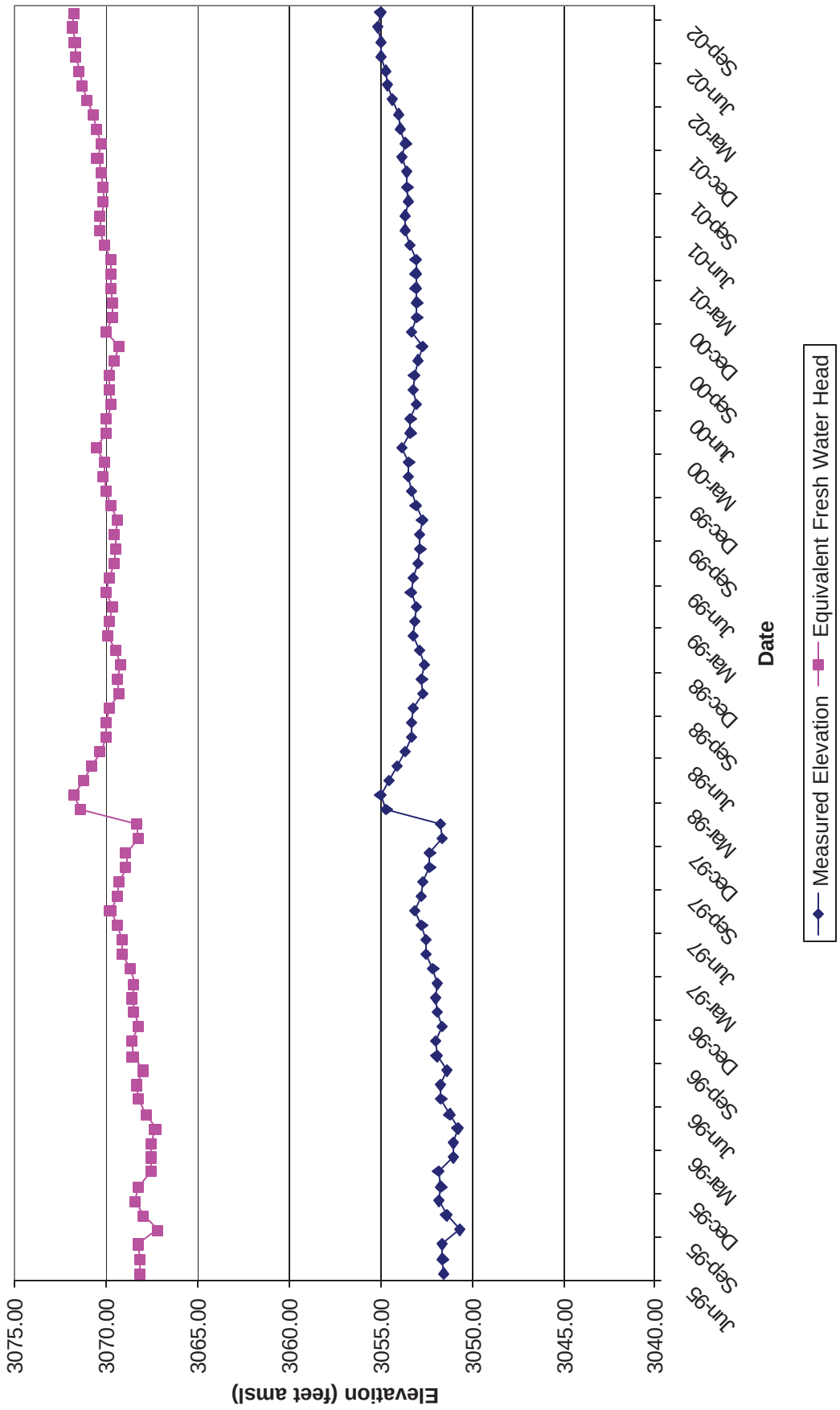

Table 83 - Well No. WQSP-2 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/05/95	3057.26	3076.90
07/19/95	3058.39	3078.08
08/16/95	3055.89	3075.47
09/08/95	3054.09	3073.58
10/18/95	3055.80	3075.37
11/08/95	3056.51	3076.11
12/06/95	3057.65	3077.31
01/10/96	3058.86	3078.46
02/08/96	3058.75	3078.46
03/11/96	3057.16	3076.79
04/15/96	3058.23	3077.92
05/13/96	3056.37	3075.97
06/10/96	3057.90	3077.57
07/15/96	3058.99	3078.71
08/12/96	3056.48	3076.08
09/03/96	3057.97	3077.64
10/14/96	3059.18	3078.91
11/11/96	3059.18	3078.91
12/09/96	3060.12	3079.89
01/14/97	3060.77	3080.57
02/10/97	3060.82	3080.63
03/10/97	3061.46	3081.30
04/14/97	3062.30	3082.18
05/14/97	3058.98	3078.70
06/11/97	3060.29	3080.07
07/15/97	3061.59	3081.43
08/13/97	3059.34	3079.08
09/17/97	3060.59	3080.39
10/16/97	3060.86	3080.67
11/10/97	3061.34	3081.17
12/08/97	3060.88	3080.69

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3061.28	3081.11
02/09/98	3064.57	3084.55
03/09/98	3065.11	3085.12
04/13/98	3061.66	3081.51
05/11/98	3060.91	3080.72
06/08/98	3061.08	3080.90
07/13/98	3061.48	3081.32
08/10/98	3062.00	3081.86
09/08/98	3060.01	3079.78
10/12/98	3060.16	3079.94
11/13/98	3060.80	3080.61
12/07/98	3060.96	3080.77
01/11/99	3061.72	3081.57
02/08/99	3062.24	3082.11
03/08/99	3059.93	3079.69
04/12/99	3059.93	3079.69
05/10/99	3060.76	3080.56
06/07/99	3061.16	3080.98
07/19/99	3061.41	3081.24
08/09/99	3061.52	3081.36
09/07/99	3061.73	3081.58
10/04/99	3058.05	3077.73
11/08/99	3058.96	3078.68
12/06/99	3059.44	3079.18
01/17/00	3059.95	3079.72
02/14/00	3060.42	3080.21
03/06/00	3061.02	3080.84
04/17/00	3059.16	3078.89
05/15/00	3059.41	3079.15
06/05/00	3059.43	3079.17
07/10/00	3059.85	3079.61
08/14/00	3060.08	3079.85
09/12/00	3060.25	3080.03
10/09/00	3058.22	3077.90
11/06/00	3059.13	3078.86
12/07/00	3059.11	3078.84

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3059.47	3079.21
02/06/01	3059.73	3079.49
03/07/01	3059.97	3079.74
04/04/01	3058.68	3078.39
05/08/01	3058.92	3078.64
06/05/01	3059.69	3079.44
07/09/01	3059.90	3079.66
08/08/01	3060.00	3079.77
09/06/01	3060.16	3079.94
10/10/01	3059.01	3078.73
11/14/01	3059.42	3079.16
12/05/01	3059.45	3079.19
01/16/02	3060.01	3079.78
02/05/02	3060.23	3080.01
03/12/02	3060.75	3080.55
04/08/02	3060.01	3079.78
05/06/02	3060.28	3080.06
06/10/02	3060.71	3080.51
07/15/02	3060.83	3080.64
08/12/02	3061.17	3080.99
09/09/02	3061.22	3081.05

Figure 83 - WQSP-2 Culebra
Historical Waterlevel Measurements

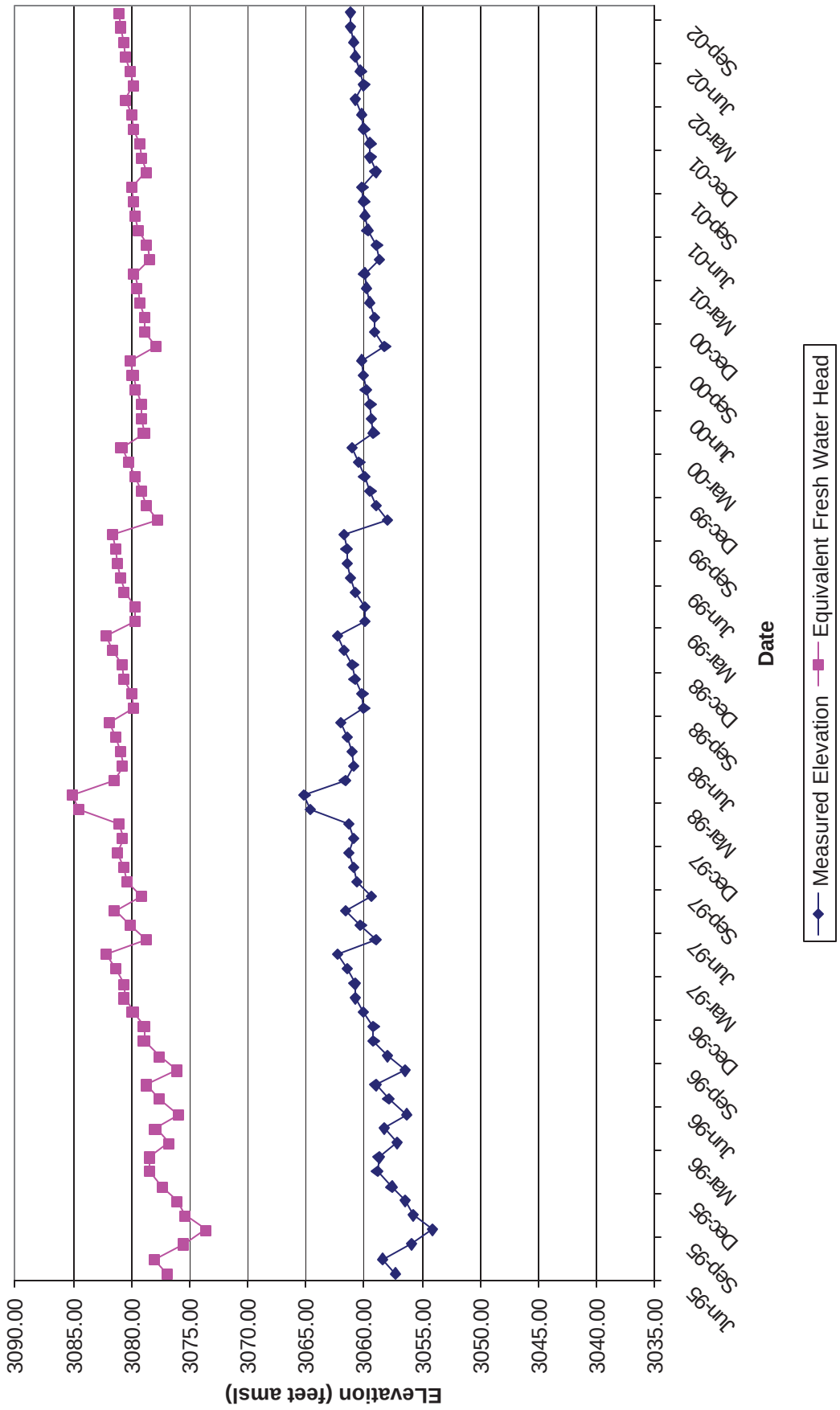

Table 84 - Well No. WQSP-3 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/05/95	3037.27	3098.12
07/19/95	3039.43	3100.59
08/17/95	3038.24	3099.23
09/05/95	3038.58	3099.62
10/16/95	3007.56	3064.07
11/08/95	3010.90	3067.90
12/04/95	3013.43	3070.80
01/10/96	3016.19	3076.00
02/05/96	3017.97	3076.00
03/11/96	3019.42	3077.66
04/15/96	3021.27	3079.78
05/15/96	2999.80	3055.18
06/10/96	3008.24	3064.85
07/17/96	3010.77	3067.75
08/12/96	3012.49	3069.72
09/05/96	3005.51	3061.72
10/14/96	3009.38	3066.16
11/11/96	3011.29	3068.35
12/09/96	3013.00	3070.31
01/13/97	3014.85	3072.43
02/10/97	3016.25	3074.03
03/10/97	3017.73	3075.73
04/14/97	3019.40	3077.64
05/12/97	3020.51	3078.91
06/09/97	3009.34	3066.11
07/15/97	3011.91	3069.06
08/13/97	3008.92	3065.63
09/15/97	3009.04	3065.77
10/16/97	3010.63	3067.59
11/10/97	3011.48	3068.56
12/08/97	3012.24	3069.43

Date	Measured Elevation	Equivalent Fresh Water Head
01/12/98	3012.92	3070.21
02/09/98	3014.13	3071.60
03/12/98	3015.68	3073.38
04/13/98	3016.98	3074.87
05/11/98	3010.44	3067.37
06/11/98	3011.96	3069.11
07/15/98	3012.73	3070.00
08/10/98	3013.30	3070.65
09/08/98	3008.94	3065.65
10/12/98	3010.82	3067.81
11/13/98	3011.60	3068.70
12/07/98	3012.19	3069.38
01/11/99	3012.62	3069.87
02/08/99	3013.28	3070.63
03/08/99	3013.81	3071.23
04/12/99	3003.45	3059.36
05/10/99	3010.33	3067.25
06/07/99	3011.12	3068.15
07/19/99	3011.76	3068.88
08/09/99	3012.10	3069.27
09/07/99	3012.41	3069.63
10/20/99	3009.96	3066.82
11/08/99	3012.13	3069.31
12/06/99	3011.75	3068.87
01/17/00	3012.42	3069.64
02/14/00	3012.89	3070.18
03/06/00	3013.14	3070.47
04/17/00	3010.87	3067.86
05/15/00	3011.66	3068.77
06/05/00	3011.89	3069.03
07/10/00	3012.44	3069.66
08/14/00	3012.60	3069.85
09/11/00	3012.82	3070.10
10/09/00	3004.86	3060.98
11/08/00	3010.83	3067.82
12/06/00	3011.21	3068.25

Date	Measured Elevation	Equivalent Fresh Water Head
01/09/01	3010.35	3067.27
02/05/01	3010.78	3067.76
03/07/01	3011.38	3068.45
04/05/01	3007.35	3063.83
05/08/01	3010.52	3067.46
06/05/01	3011.30	3068.36
07/11/01	3011.58	3068.68
08/08/01	3011.83	3068.96
09/06/01	3012.06	3069.23
10/10/01	3007.59	3064.11
11/14/01	3011.18	3068.22
12/05/01	3011.42	3068.49
01/16/02	3011.98	3069.14
02/05/02	3012.22	3069.41
03/12/02	3012.62	3069.87
04/08/02	3008.24	3064.85
05/07/02	3012.05	3069.22
06/10/02	3012.70	3069.96
07/15/02	3012.90	3070.19
08/12/02	3013.13	3070.45
09/09/02	3013.24	3070.58

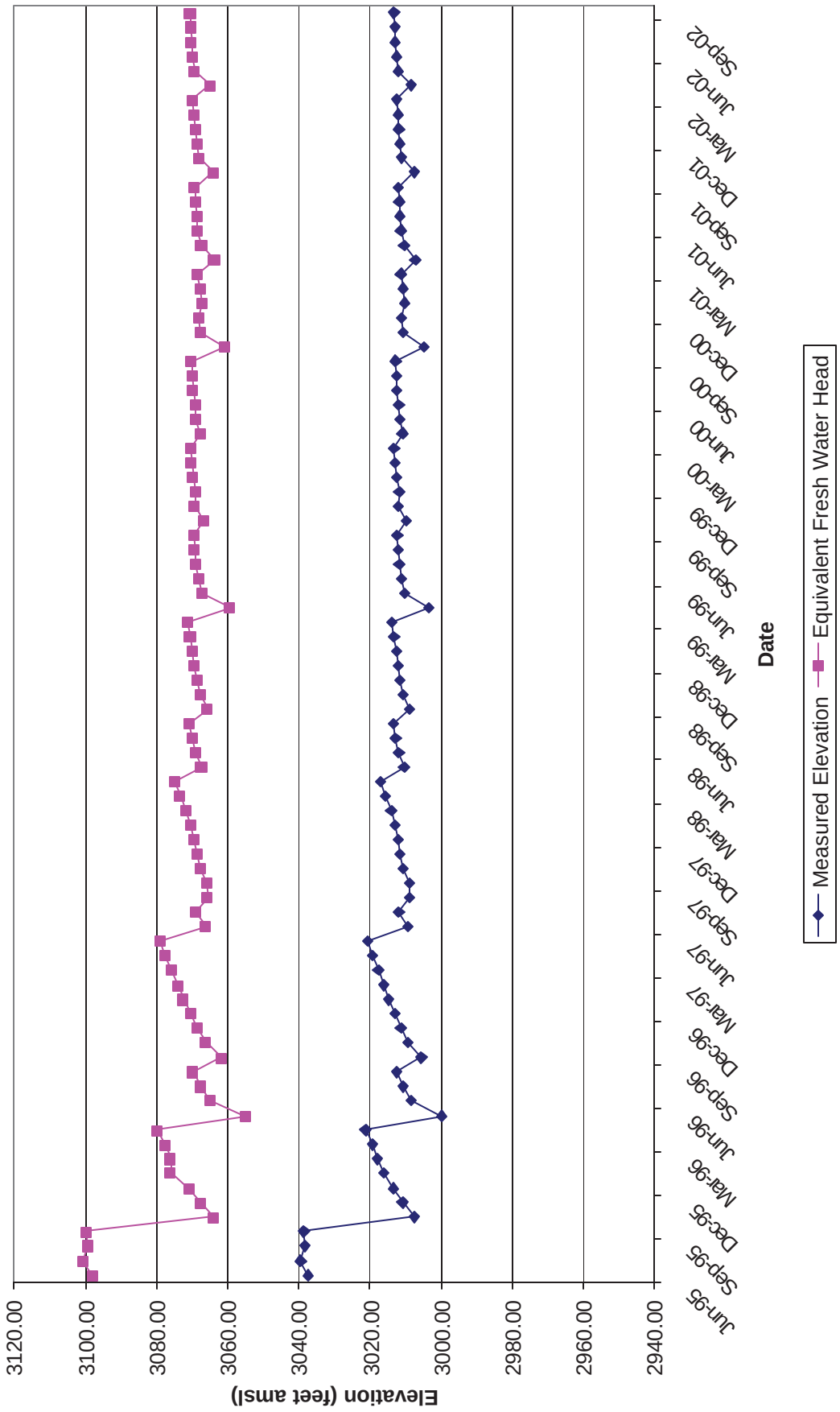
Figure 84 - WQSP-3 Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3120.00
3100.00
3080.00
3060.00
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
Jun-95
Sep-95
Dec-95
Mar-96
Jun-96
Sep-96
Dec-96
Mar-97
Jun-97
Sep-97
Dec-97
Mar-98
Jun-98
Sep-98
Dec-98
Mar-99
Jun-99
Sep-99
Dec-99
Mar-00
Jun-00
Sep-00
Dec-00
Mar-01
Jun-01
Sep-01
Dec-01
Mar-02
Jun-02
Sep-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 85 - Well No. WQSP-4 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/07/95	2962.46	2985.74
07/19/95	2927.58	2948.14
08/17/95	2956.06	2978.86
09/08/95	2951.31	2973.76
11/07/95	2965.45	2988.96
12/04/95	2969.09	2992.87
01/10/96	2918.78	2926.01
02/07/96	2906.89	2926.01
03/12/96	2909.46	2928.77
04/17/96	2926.78	2947.39
05/15/96	2948.24	2970.46
06/12/96	2956.52	2979.36
07/17/96	2964.61	2988.06
08/13/96	2968.62	2992.37
09/05/96	2970.92	2994.84
10/16/96	2973.40	2997.51
11/13/96	2975.24	2999.48
12/10/96	2976.99	3001.36
01/13/97	2978.17	3002.63
02/10/97	2979.06	3003.59
03/10/97	2979.91	3004.50
04/15/97	2980.56	3005.20
05/14/97	2980.92	3005.59
06/11/97	2979.81	3004.40
07/15/97	2980.21	3004.83
08/13/97	2980.66	3005.31
09/16/97	2980.64	3005.29
10/16/97	2981.14	3005.83
11/12/97	2981.86	3006.60
12/10/97	2982.17	3006.93

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2982.70	3007.50
02/11/98	2983.10	3007.93
03/12/98	2983.22	3008.06
04/16/98	2983.84	3008.73
05/12/98	2983.12	3007.95
06/11/98	2983.38	3008.23
07/15/98	2983.72	3008.60
08/12/98	2983.87	3008.76
09/10/98	2984.10	3009.01
10/14/98	2983.85	3008.74
11/13/98	2984.05	3008.95
12/09/98	2984.34	3009.27
01/12/99	2984.79	3009.73
02/10/99	2984.93	3009.88
03/10/99	2985.22	3010.19
04/12/99	2985.17	3010.14
05/11/99	2984.96	3009.91
06/09/99	2985.47	3010.46
07/19/99	2985.62	3010.62
08/09/99	2985.78	3010.79
09/07/99	2985.92	3010.94
10/04/99	2985.74	3010.75
11/08/99	2985.38	3010.36
12/08/99	2985.83	3010.84
01/18/00	2985.91	3010.93
02/14/00	2986.01	3011.04
03/06/00	2986.10	3011.14
04/17/00	2985.38	3010.36
05/17/00	2986.05	3011.08
06/07/00	2986.01	3011.04
07/10/00	2986.28	3011.33
08/14/00	2986.29	3011.34
09/11/00	2986.34	3011.39
10/11/00	2986.48	3011.54
11/09/00	2986.06	3011.09
12/05/00	2986.23	3011.27

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	2986.43	3011.49
02/06/01	2985.50	3010.49
03/08/01	2986.74	3011.82
04/05/01	2986.73	3011.81
05/09/01	2986.45	3011.51
06/06/01	2986.92	3011.83
07/11/01	2987.13	3012.05
08/07/01	2987.16	3012.09
09/07/01	2987.45	3012.40
10/09/01	2987.48	3012.43
11/13/01	2987.21	3012.14
12/05/01	2987.17	3012.10
01/16/02	2987.46	3012.41
02/05/02	2987.58	3012.54
03/13/02	2987.74	3012.71
04/09/02	2987.46	3012.41
05/07/02	2987.69	3012.66
06/10/02	2988.11	3013.11
07/15/02	2988.22	3013.23
08/12/02	2988.47	3013.50
09/09/02	2988.45	3013.47

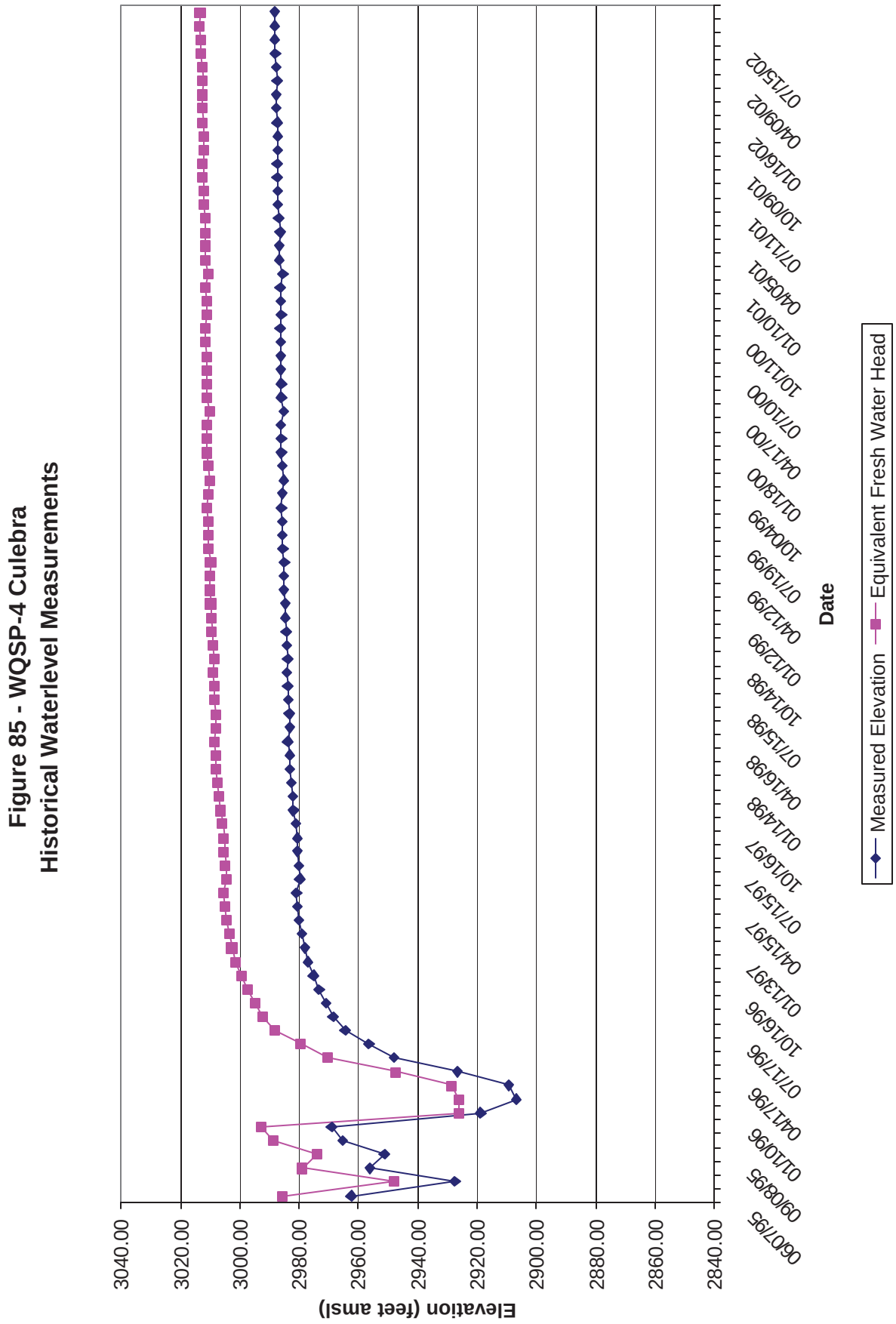
Figure 85 - WQSP-4 Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3040.00
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
2880.00
2860.00
2840.00
06/07/95
09/08/95
01/10/96
04/17/96
07/17/96
10/16/96
01/13/97
04/15/97
07/15/97
10/16/97
01/14/98
04/16/98
07/15/98
10/14/98
01/12/99
04/12/99
07/19/99
10/04/99
01/18/00
04/17/00
07/10/00
10/13/00
01/10/01
04/05/01
07/11/01
10/09/01
01/16/02
04/09/02
07/15/02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 86 - Well No. WQSP-5 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/07/95	2994.44	3001.29
07/19/95	2970.42	2976.67
08/17/95	2974.85	2981.21
09/07/95	2974.25	2980.59
10/18/95	2981.93	2988.46
11/03/95	2982.65	2989.20
12/06/95	2978.95	2985.41
01/10/96	2961.71	2953.07
02/07/96	2947.40	2953.07
03/12/96	2942.21	2947.75
04/17/96	2942.93	2948.49
05/15/96	2960.20	2966.19
06/12/96	2964.35	2970.44
07/17/96	2975.64	2982.02
08/13/96	2980.85	2987.36
09/05/96	2984.33	2990.92
10/16/96	2985.50	2992.12
11/13/96	2988.43	2995.13
12/10/96	2991.08	2997.84
01/14/97	2993.36	3000.18
02/10/97	2994.50	3001.35
03/12/97	2996.02	3002.91
04/15/97	2997.10	3004.01
05/14/97	2997.81	3004.74
06/09/97	2997.50	3004.42
07/15/97	2995.01	3001.87
08/13/97	2996.11	3003.00
09/16/97	2996.65	3003.55
10/16/97	2996.15	3003.04
11/12/97	2997.20	3004.12
12/10/97	2997.67	3004.60

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	2998.30	3005.24
02/11/98	2998.73	3005.68
03/12/98	2998.91	3005.87
04/16/98	2999.68	3006.66
05/12/98	2999.43	3006.40
06/11/98	2998.59	3005.54
07/15/98	2999.13	3006.09
08/12/98	2999.37	3006.34
09/10/98	2999.64	3006.62
10/14/98	2998.70	3005.65
11/13/98	2999.41	3006.38
12/09/98	2999.76	3006.74
01/12/99	3000.36	3007.35
02/10/99	3000.57	3007.57
03/10/99	3000.86	3007.87
04/12/99	3000.84	3007.85
05/11/99	2999.72	3006.70
06/09/99	3000.85	3007.86
07/19/99	3001.10	3008.11
08/09/99	3001.28	3008.30
09/07/99	3001.54	3008.56
10/04/99	3001.13	3008.14
11/08/99	3000.44	3007.44
12/08/99	3001.23	3008.25
01/18/00	3001.34	3008.36
02/14/00	3001.54	3008.56
03/06/00	3001.64	3008.67
04/17/00	3001.31	3008.33
05/17/00	3001.42	3008.44
06/07/00	3001.41	3008.43
07/10/00	3001.76	3008.79
08/14/00	3001.87	3008.90
09/11/00	3001.98	3009.01
10/11/00	3001.94	3008.97
11/09/00	3001.15	3008.16
12/05/00	3001.69	3008.72

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3001.97	3009.00
02/07/01	3002.09	3009.13
03/08/01	3002.36	3009.40
04/05/01	3002.37	3009.41
05/09/01	3001.19	3008.20
06/06/01	3001.25	3008.27
07/11/01	3002.52	3009.57
08/07/01	3002.61	3009.66
09/07/01	3003.02	3010.08
10/09/01	3003.04	3010.10
11/14/01	3002.40	3009.45
12/05/01	3002.59	3009.64
01/16/02	3002.97	3010.03
02/05/02	3003.11	3010.17
03/13/02	3003.10	3010.16
04/09/02	3003.12	3010.18
05/08/02	3002.94	3010.00
06/10/02	3003.63	3010.71
07/15/02	3003.72	3010.80
08/12/02	3004.00	3011.09
09/09/02	3004.04	3011.13

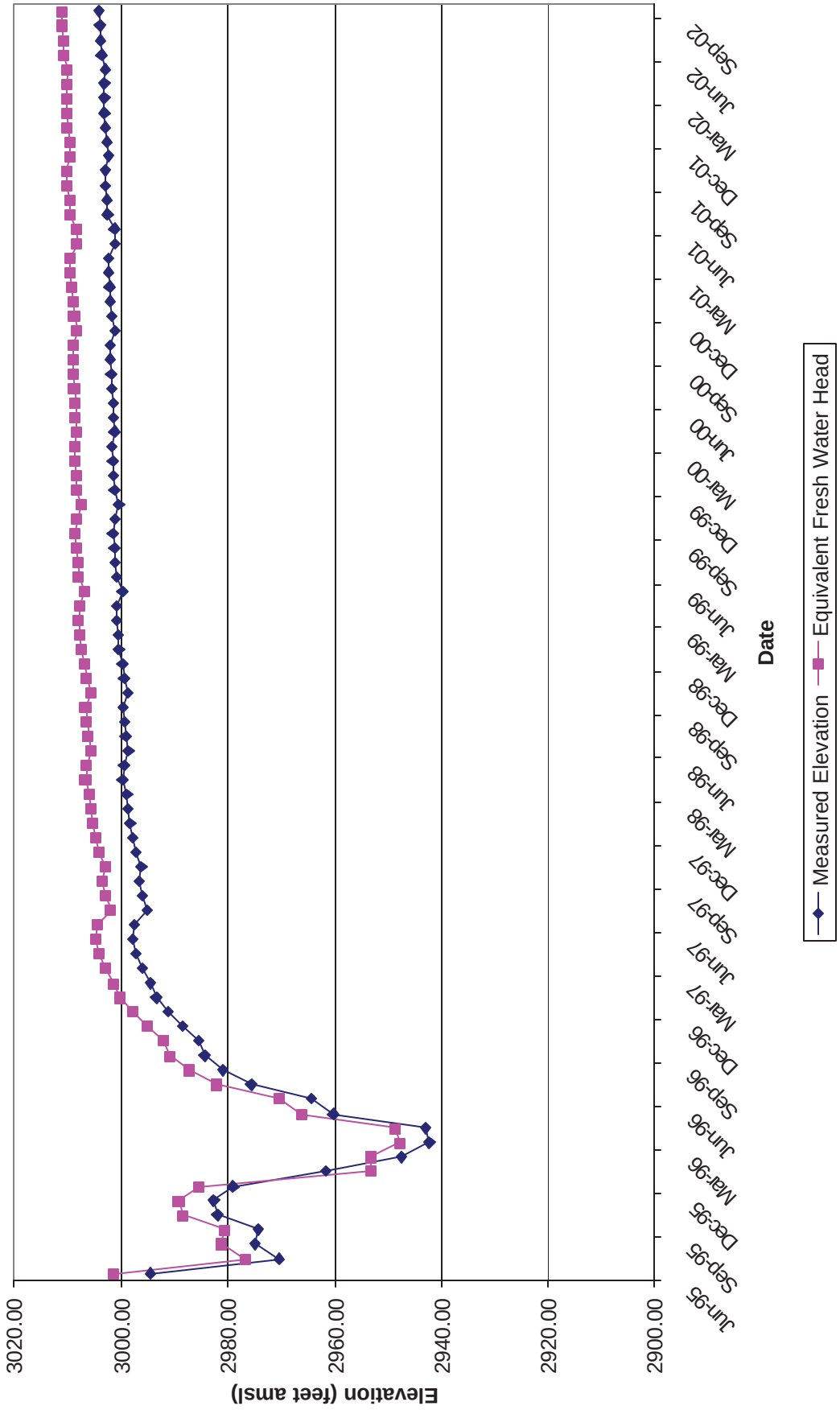
Figure 86 - WQSP-5 Culebra
Historical Waterlevel Measurements
Elevation (feet amsl)
3020.00
3000.00
2980.00
2960.00
2940.00
2920.00
2900.00
Jun-95
Sep-95
Dec-95
Mar-96
Jun-96
Sep-96
Dec-96
Mar-97
Jun-97
Sep-97
Dec-97
Mar-98
Jun-98
Sep-98
Dec-98
Mar-99
Jun-99
Sep-99
Dec-99
Mar-00
Jun-00
Sep-00
Dec-00
Mar-01
Jun-01
Sep-01
Dec-01
Mar-02
Jun-02
Sep-02
Date
Measured Elevation
Equivalent Fresh Water Head

Table 87 - Well No. WQSP-6 Culebra
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/07/95	3005.12	3008.69
07/19/95	3002.11	3005.63
08/17/95	2999.17	3002.65
09/07/95	2998.24	3001.70
10/18/95	2983.78	2987.03
11/08/95	3000.45	3003.95
12/06/95	3002.09	3005.61
01/10/96	3002.06	3003.34
02/07/96	2999.85	3003.34
03/14/96	2974.25	2977.35
04/17/96	2991.96	2995.33
05/15/96	2991.97	2995.34
06/12/96	2993.39	2996.78
07/17/96	2993.39	2996.78
08/13/96	2996.65	3000.09
09/05/96	2998.66	3002.13
10/16/96	2995.43	2998.85
11/13/96	3001.37	3004.88
12/10/96	3003.33	3006.87
01/14/97	3004.76	3008.32
02/10/97	3005.58	3009.15
03/12/97	3006.68	3010.27
04/15/97	3005.17	3008.74
05/14/97	3007.94	3011.55
06/11/97	3008.61	3012.23
07/15/97	3007.24	3010.84
08/13/97	3008.65	3012.27
09/16/97	3009.50	3013.13
10/16/97	3009.57	3013.20
11/12/97	3010.18	3013.82
12/10/97	3010.37	3014.02

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3010.84	3014.49
02/11/98	3011.10	3014.76
03/12/98	3011.15	3014.81
04/16/98	3011.82	3015.49
05/12/98	3012.04	3015.71
06/11/98	3008.56	3012.18
07/15/98	3011.62	3015.28
08/12/98	3011.99	3015.66
09/10/98	3012.28	3015.95
10/14/98	3012.55	3016.23
11/13/98	3011.62	3015.28
12/09/98	3012.45	3016.13
01/12/99	3013.07	3016.76
02/10/99	3013.29	3016.98
03/10/99	3013.51	3017.20
04/12/99	3013.55	3017.24
05/11/99	3013.84	3017.54
06/09/99	3012.81	3016.49
07/19/99	3013.68	3017.38
08/09/99	3013.98	3017.68
09/07/99	3014.21	3017.91
10/04/99	3013.93	3017.63
11/08/99	3010.96	3013.80
12/08/99	3014.19	3017.89
01/18/00	3014.39	3018.10
02/14/00	3014.65	3018.36
03/06/00	3014.81	3018.52
04/17/00	3014.85	3018.56
05/17/00	3012.02	3015.69
06/07/00	3014.23	3017.93
07/10/00	3014.99	3018.71
08/14/00	3015.15	3018.87
09/11/00	3015.36	3019.08
10/11/00	3015.27	3018.99
11/09/00	3015.54	3019.26
12/06/00	3014.19	3017.89

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3015.26	3018.98
02/07/01	3015.51	3019.23
03/08/01	3015.74	3019.47
04/05/01	3015.82	3019.55
05/09/01	3015.73	3019.46
06/06/01	3014.80	3018.51
07/11/01	3015.60	3019.32
08/07/01	3015.76	3019.49
09/07/01	3016.22	3019.95
10/10/01	3016.22	3019.95
11/14/01	3013.34	3017.03
12/05/01	3015.51	3019.23
01/16/02	3016.19	3019.92
02/05/02	3016.33	3020.07
03/13/02	3016.73	3020.47
04/09/02	3016.60	3020.34
05/08/02	3016.97	3020.72
06/10/02	3016.37	3020.11
07/15/02	3016.74	3020.48
08/12/02	3017.01	3020.76
09/09/02	3017.09	3020.84

Figure 87 - WQSP-6 Culebra
Historical Waterlevel Measurements

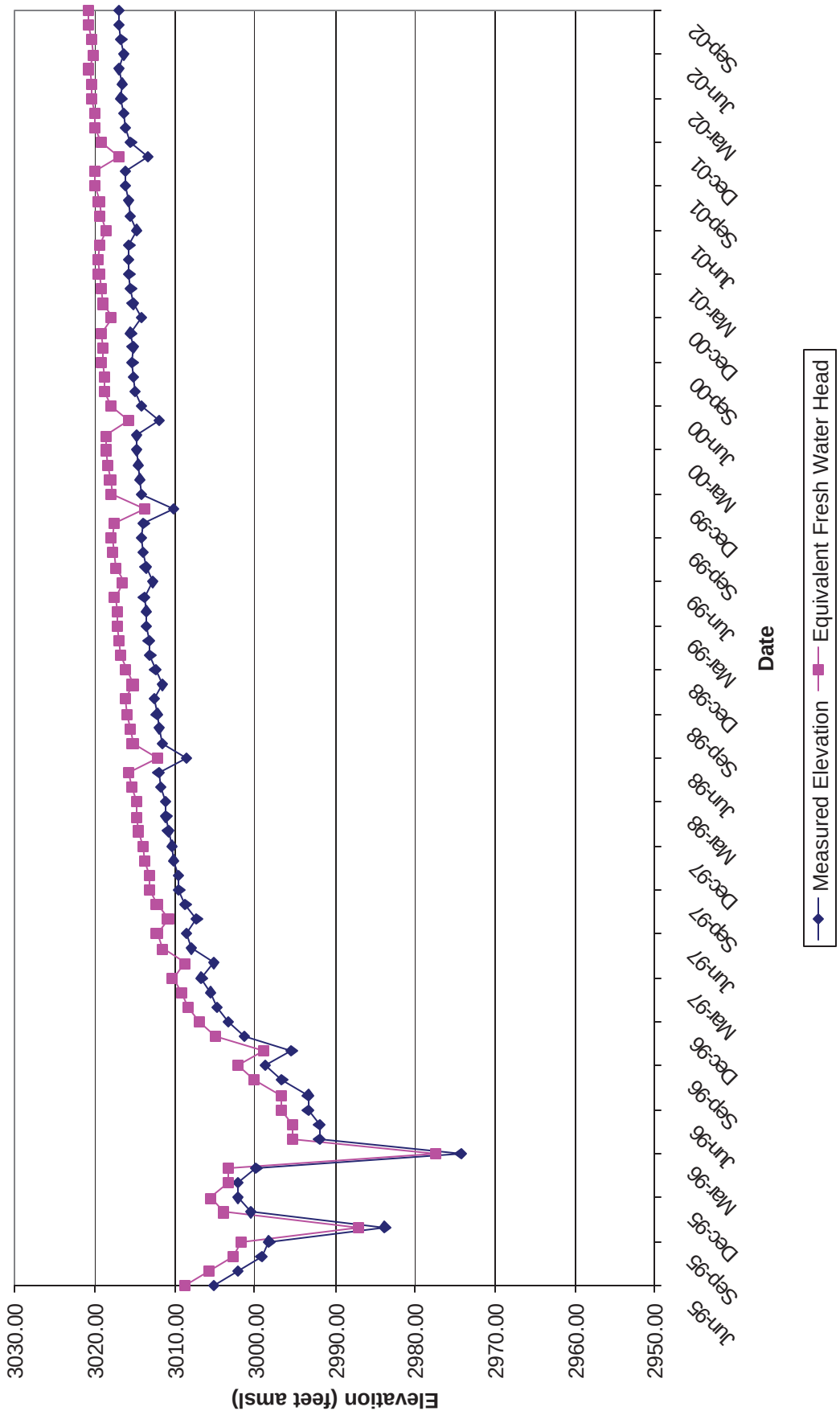

Table 88 - Well No. WQSP-6a Dewey Lake
June 1995 through September 2002

Date	Measured Elevation	Equivalent Fresh Water Head
06/07/95	3199.29	N/A
07/19/95	3199.14	N/A
08/17/95	3199.16	N/A
09/07/95	3199.10	N/A
10/18/95	3198.95	N/A
11/08/95	3198.99	N/A
12/06/95	3199.17	N/A
01/04/96	3196.64	N/A
02/07/96	3199.24	N/A
03/14/96	3199.36	N/A
04/17/96	3199.25	N/A
05/15/96	3199.23	N/A
06/12/96	3199.17	N/A
07/17/96	3199.11	N/A
08/13/96	3199.05	N/A
09/05/96	3199.18	N/A
10/16/96	3199.29	N/A
11/13/96	3198.91	N/A
12/10/96	3199.24	N/A
01/14/97	3199.11	N/A
02/10/97	3198.94	N/A
03/12/97	3199.10	N/A
04/15/97	3199.03	N/A
05/14/97	3199.25	N/A
06/11/97	3199.13	N/A
07/15/97	3198.95	N/A
08/13/97	3198.93	N/A
09/16/97	3199.11	N/A
10/16/97	3198.72	N/A
11/12/97	3199.16	N/A
12/10/97	3198.89	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/14/98	3198.88	N/A
02/11/98	3198.89	N/A
03/12/98	3199.62	N/A
04/16/98	3198.98	N/A
05/12/98	3199.03	N/A
06/11/98	3198.80	N/A
07/15/98	3198.86	N/A
08/12/98	3198.79	N/A
09/10/98	3198.87	N/A
10/14/98	3198.96	N/A
11/13/98	3198.72	N/A
12/09/98	3198.78	N/A
01/12/99	3199.16	N/A
02/10/99	3199.07	N/A
03/10/99	3199.02	N/A
04/12/99	3198.74	N/A
05/11/99	3198.84	N/A
06/09/99	3198.93	N/A
07/19/99	3198.77	N/A
08/09/99	3198.91	N/A
09/07/99	3198.97	N/A
10/04/99	3198.66	N/A
11/08/99	3198.80	N/A
12/08/99	3199.06	N/A
01/18/00	3198.83	N/A
02/14/00	3198.82	N/A
03/06/00	3198.86	N/A
04/17/00	3198.63	N/A
05/17/00	3198.87	N/A
06/07/00	3198.50	N/A
07/10/00	3198.56	N/A
08/14/00	3198.51	N/A
09/11/00	3198.54	N/A
10/11/00	3198.51	N/A
11/09/00	3198.57	N/A
12/06/00	3198.25	N/A

Date	Measured Elevation	Equivalent Fresh Water Head
01/10/01	3198.60	N/A
02/07/01	3198.63	N/A
03/08/01	3198.57	N/A
04/05/01	3198.34	N/A
05/09/01	3198.24	N/A
06/04/01	3198.51	N/A
07/11/01	3198.33	N/A
08/07/01	3198.16	N/A
09/07/01	3198.45	N/A
10/10/01	3198.31	N/A
11/12/01	3198.26	N/A
12/05/01	3198.11	N/A
01/16/02	3198.26	N/A
02/05/02	3198.24	N/A
03/13/02	3198.48	N/A
04/09/02	3198.03	N/A
05/08/02	3198.39	N/A
06/10/02	3198.37	N/A
07/15/02	3198.21	N/A
08/12/02	3198.27	N/A
09/09/02	3198.10	N/A

Figure 88 - WQSP-6a Dewey Lake Historical Waterlevel Measurements

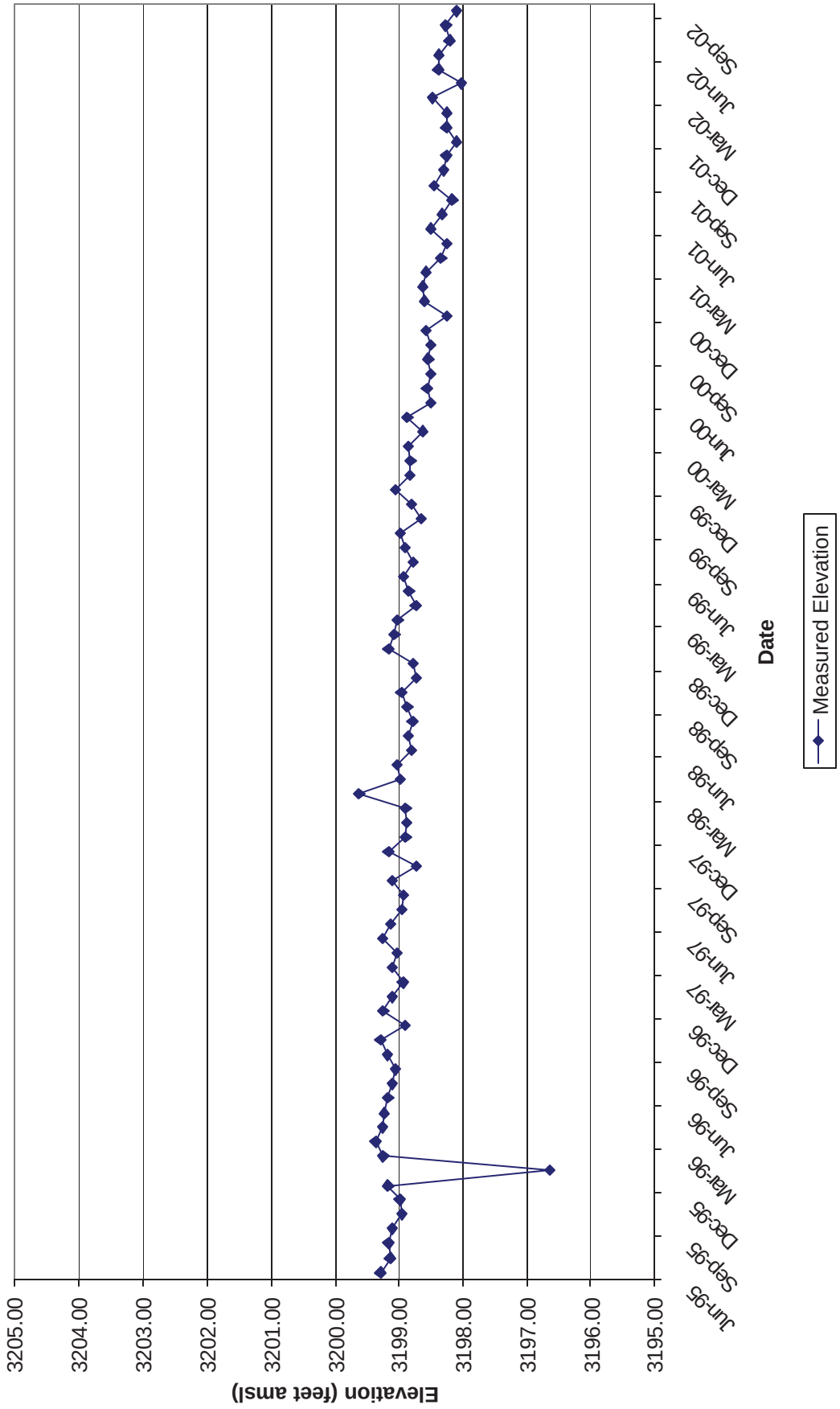

APPENDIX DATA

ATTACHMENT C: WATER QUALITY SAMPLING DATA

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Groundwater Quality Data

Groundwater monitoring activities during the 2004 Compliance Recertification Application monitoring period (mid 1995 through September 30, 2002) included groundwater quality sampling to support performance assessment. Groundwater quality data were gathered from six wells (WQSP-1 through WQSP-6) in the Culebra member of the Rustler Formation and one well (WQSP-6A) in the Dewey Lake Formation.

The Groundwater Monitoring Program (GWMP) is required to sample for groundwater quality twice a year, from March through May and, again, from September through November. Each sampling period is called a round.

There are seven constituents sampled and analyzed by the GWMP for performance assessment. Of the seven, five have a Chemical Abstract Service (CAS) registry number applied to them. CAS number refers to a unique, identifying number applied to each distinct chemical substance in the CAS Chemical Registry System. Governmental agencies (EPA being one) have found CAS numbers ideal for keeping track of substances because the numbers are unique, can be validated quickly and reliably, and are internationally recognized. Of the monitored substances, Alkalinity and Sulfate do not have CAS numbers associated with them since they are not distinct substances.

In the following tables and charts, either the 95th upper tolerance limit value (UTLV) or the 95th percentile value is presented, depending on the type of distribution exhibited by the parameter. Both values represent the value beneath which 95 percent of the values in a population are expected to occur.

WQSP-1 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		1700.0		1670.0	mg/L	2.0	2087.0			<	0.2	1	08/28/95	08/17/95
7440-70-2	CALCIUM		1710.0		1690.0	mg/L	2.0	2087.0	<	0.2	<	0.2	2	05/07/96	04/11/96
7440-70-2	CALCIUM		1740.0		1670.0	mg/L	2.0	2087.0	<	0.2	<	0.2	3	07/30/96	07/25/96
7440-70-2	CALCIUM		1410.0		1510.0	mg/L	2.0	2087.0	<	0.2	<	0.2	4	05/02/97	04/24/97
7440-70-2	CALCIUM		1720.0		1700.0	mg/L	2.0	2087.0	<	0.2	<	0.2	5	08/15/97	07/24/97
7440-70-2	CALCIUM		1610.0		1660.0	mg/L	2.0	2087.0			<	0.2	6	03/19/98	03/05/98
7440-70-2	CALCIUM		1710.0		1570.0	mg/L	0.5	2087.0			<	0.5	7	08/17/98	07/15/98
7440-70-2	CALCIUM		1770.0	<	0.5	mg/L	0.5	2087.0			<	0.5	8	03/15/99	03/03/99
7440-70-2	CALCIUM		1710.0		1726.0	mg/L	0.5	2087.0			<	0.5	9	09/16/99	09/01/99
7440-70-2	CALCIUM		1800.0		1780.0	mg/L	5.0	2087.0				0.1	10	03/06/00	03/02/00
7440-70-2	CALCIUM		2030.0		2160.0	mg/L	5.0	2087.0					10	06/19/00	06/19/00
7440-70-2	CALCIUM		1760.0		1680.0	mg/L	2.0	2087.0			<	1.0	11	10/11/00	09/07/00
7440-70-2	CALCIUM		1854.0		1794.0	mg/L	0.5	2087.0			<	0.5	12	05/10/01	03/01/01
7440-70-2	CALCIUM		1828.0		1795.0	mg/L	0.2	2087.0			<	0.2	13	10/02/01	09/06/01
7440-70-2	CALCIUM		1630.0		1580.0	mg/L	0.2	2087.0			<	0.6	14	03/18/02	03/06/02

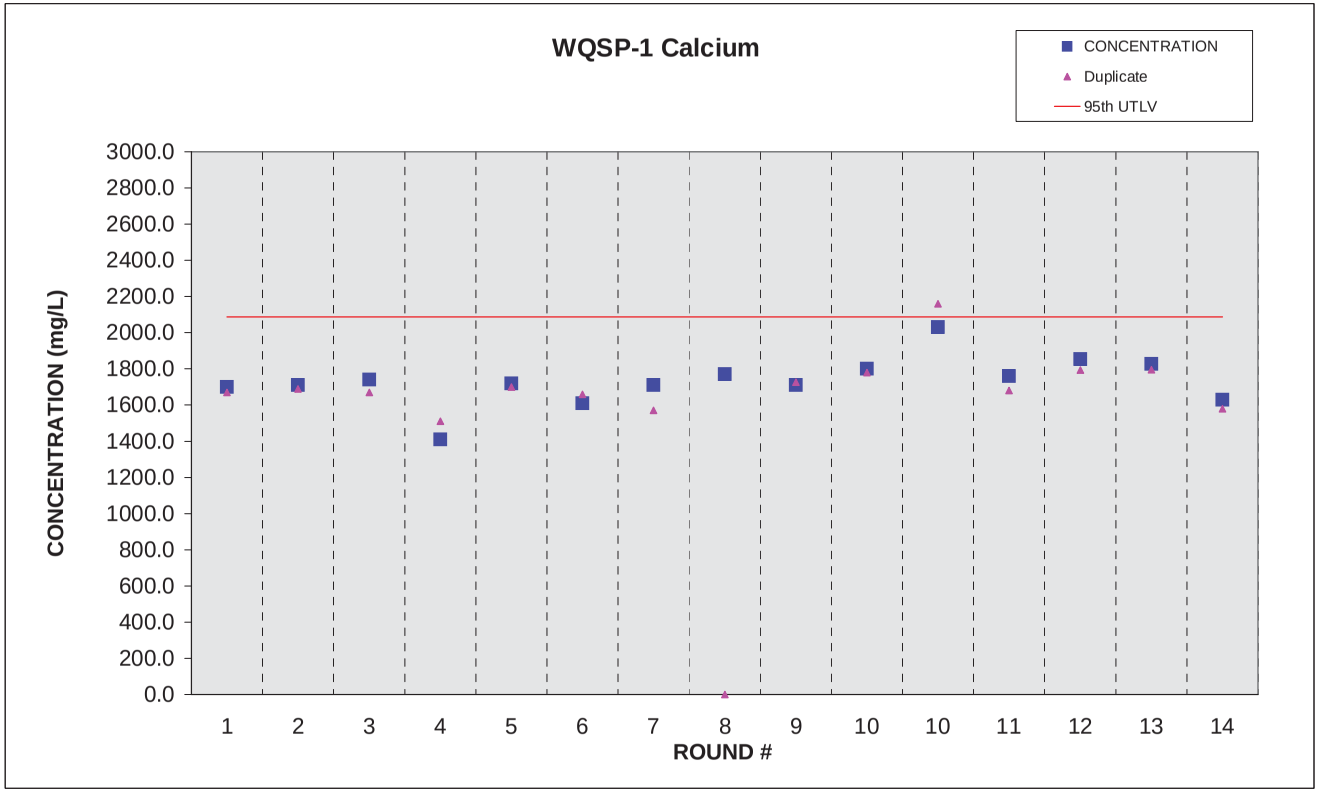

WQSP-1 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		497.0		474.0	mg/L	0.2	799.0			<	0.2	1	08/28/95	08/17/95
7440-09-7	POTASSIUM		476.0		465.0	mg/L	10.0	799.0	<	0.2	<	0.2	2	04/25/96	04/11/96
7440-09-7	POTASSIUM		471.0		451.0	mg/L	2.0	799.0	<	0.2	<	0.2	3	07/30/96	07/25/96
7440-09-7	POTASSIUM		443.0		468.0	mg/L	2.0	799.0	<	0.2	<	0.2	4	05/01/97	04/24/97
7440-09-7	POTASSIUM		499.0		476.0	mg/L	2.0	799.0	<	0.2	<	0.2	5	07/29/97	07/24/97
7440-09-7	POTASSIUM		467.0		487.0	mg/L	2.0	799.0			<	0.2	6	03/19/98	03/05/98
7440-09-7	POTASSIUM		710.0		640.0	mg/L	0.5	799.0			<	0.5	7	08/17/98	07/15/98
7440-09-7	POTASSIUM		661.0	<	1.0	mg/L	1.0	799.0			<	1.0	8	03/15/99	03/03/99
7440-09-7	POTASSIUM		700.0		728.0	mg/L	0.5	799.0			<	0.5	9	09/16/99	09/01/99
7440-09-7	POTASSIUM		442.0		441.0	mg/L	5.0	799.0				0.0	10	03/06/00	03/02/00
7440-09-7	POTASSIUM		717.0		687.0	mg/L	2.0	799.0				0.3	11	10/11/00	09/07/00
7440-09-7	POTASSIUM		767.0		745.0	mg/L	0.5	799.0				0.5	12	05/10/01	03/01/01
7440-09-7	POTASSIUM		896.0		871.0	mg/L	0.2	799.0			<	0.3	13	10/02/01	09/06/01
7440-09-7	POTASSIUM		695.0		721.0	mg/L	0.2	799.0			<	0.6	14	04/24/02	03/06/02

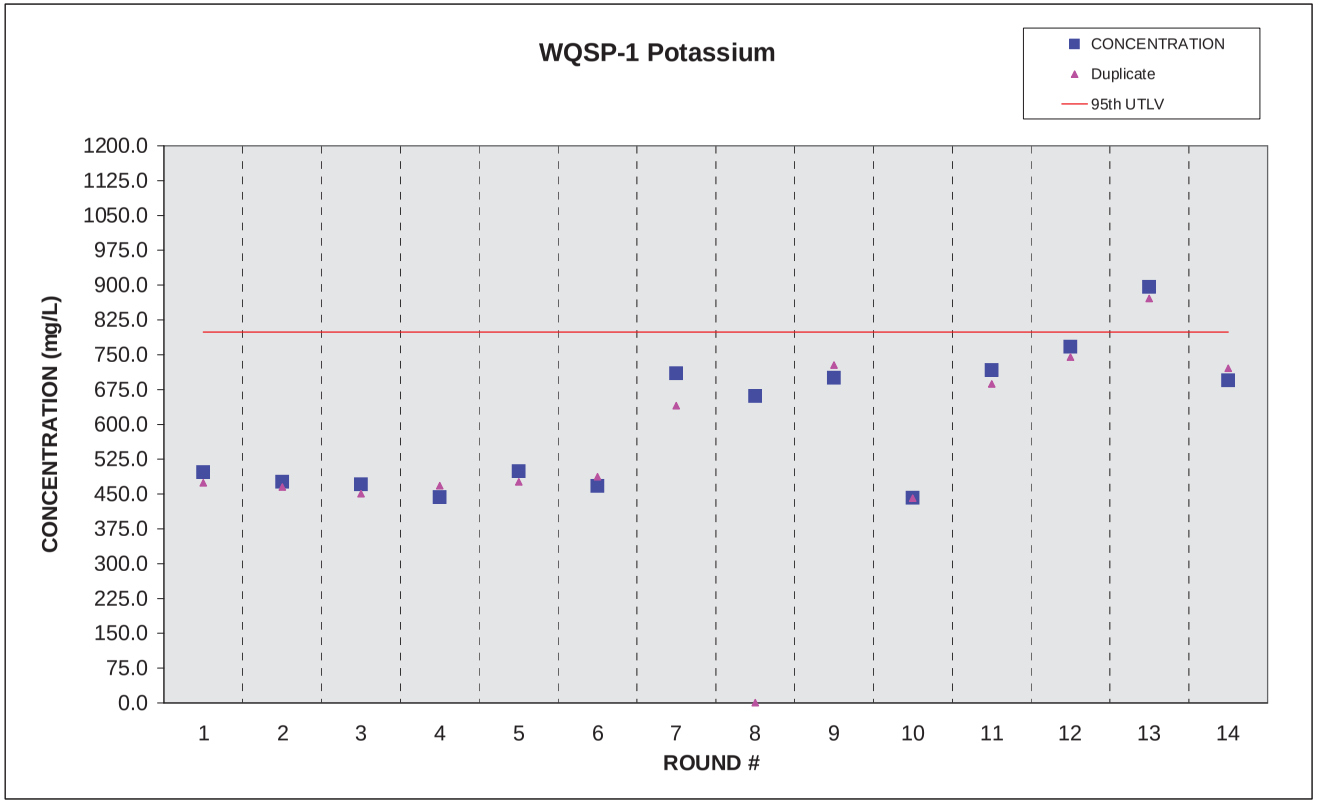

WQSP-1 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		1110.0		1080.0	mg/L	1.0	1247.0			<	0.1	1	08/28/95	08/17/95
7439-95-4	MAGNESIUM		1050.0		1040.0	mg/L	0.5	1247.0	<	0.1	<	0.1	2	05/07/96	04/11/96
7439-95-4	MAGNESIUM		1020.0		982.0	mg/L	0.5	1247.0	<	0.1	<	0.1	3	07/30/96	07/25/96
7439-95-4	MAGNESIUM		928.0		1000.0	mg/L	1.0	1247.0	<	0.1	<	0.1	4	05/02/97	04/24/97
7439-95-4	MAGNESIUM		1180.0		1170.0	mg/L	0.5	1247.0	<	0.1	<	0.1	5	08/15/97	07/24/97
7439-95-4	MAGNESIUM		1160.0		1130.0	mg/L	0.5	1247.0			<	0.1	6	03/19/98	03/05/98
7439-95-4	MAGNESIUM		1140.0		1060.0	mg/L	0.5	1247.0			<	0.5	7	08/17/98	07/15/98
7439-95-4	MAGNESIUM		993.0	<	1.0	mg/L	0.5	1247.0			<	0.5	8	03/15/99	03/03/99
7439-95-4	MAGNESIUM		1100.0		1120.0	mg/L	0.5	1247.0			<	0.5	9	09/16/99	09/01/99
7439-95-4	MAGNESIUM		1112.0		1100.0	mg/L	5.0	1247.0			<	5.0	10	03/06/00	03/02/00
7439-95-4	MAGNESIUM		1200.0		1120.0	mg/L	2.0	1247.0				0.0	11	10/11/00	09/07/00
7439-95-4	MAGNESIUM		1255.0		1180.0	mg/L	0.5	1247.0			<	0.5	12	05/10/01	03/01/01
7439-95-4	MAGNESIUM		1262.0		1270.0	mg/L	0.2	1247.0			<	0.2	13	10/02/01	09/06/01
7439-95-4	MAGNESIUM		1240.0		1220.0	mg/L	0.2	1247.0			<	0.6	14	03/18/02	03/06/02

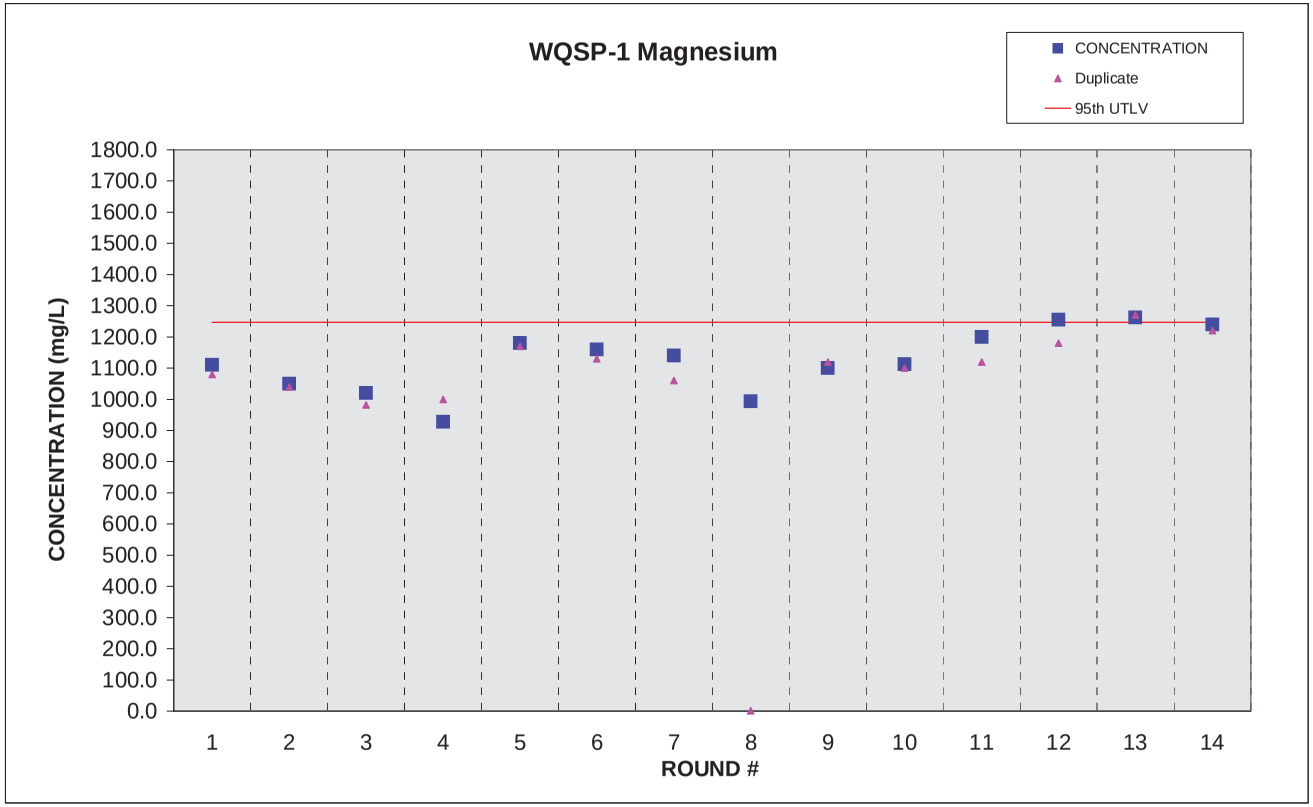

WQSP-1 Sodium

CAS #	PARAMETER		Concentration		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		20100.0		19800.0	mg/L	5.0	22090.0			<	0.5	1	08/28/95	08/17/95
7440-23-5	SODIUM		18500.0		18200.0	mg/L	25.0	22090.0	<	0.5	<	0.5	2	04/25/96	04/11/96
7440-23-5	SODIUM		18900.0		18400.0	mg/L	25.0	22090.0	<	0.5	<	0.5	3	07/30/96	07/25/96
7440-23-5	SODIUM		17700.0		19600.0	mg/L	10.0	22090.0	<	0.5	<	0.2	4	05/01/97	04/24/97
7440-23-5	SODIUM		19400.0		17500.0	mg/L	10.0	22090.0	<	0.2	<	0.2	5	07/29/97	07/24/97
7440-23-5	SODIUM		19800.0		20000.0	mg/L	4.0	22090.0			<	0.2	6	03/19/98	03/05/98
7440-23-5	SODIUM		17550.0		16500.0	mg/L	0.5	22090.0			<	0.5	7	08/17/98	07/15/98
7440-23-5	SODIUM		19700.0	<	1.0	mg/L	1.0	22090.0			<	1.0	8	03/15/99	03/03/99
7440-23-5	SODIUM		16446.0		16234.0	mg/L	5.0	22090.0			<	5.0	10	03/06/00	03/02/00
7440-23-5	SODIUM		19000.0		18600.0	mg/L	2.0	22090.0				0.5	11	10/11/00	09/07/00
7440-23-5	SODIUM		19170.0		17460.0	mg/L	0.5	22090.0				0.7	12	05/10/01	03/01/01
7440-23-5	SODIUM		18450.0		17430.0	mg/L	0.2	22090.0				0.4	13	10/03/01	09/06/01
7440-23-5	SODIUM		18400.0		19600.0	mg/L	0.2	22090.0			<	0.6	14	03/18/02	03/06/02

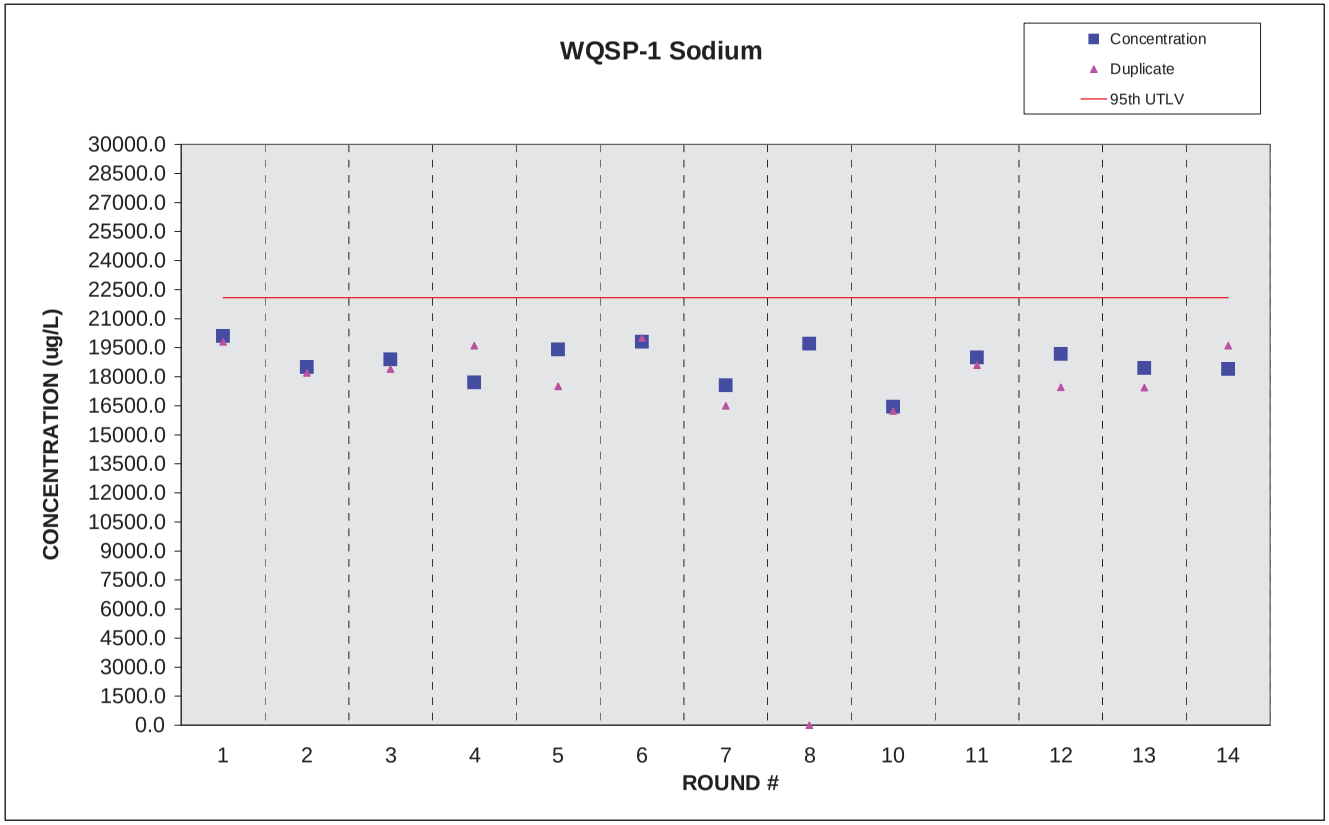

WQSP-1 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
==========	==========	===	==========	==	==========	======	==========	==========	===	==========	===	==========	=======	==========	==========
	ALKALINITY		46.5		47.5	mg/L	5.0	55.7			<	5.0	1	08/29/95	08/17/95
	ALKALINITY		53.0		52.0	mg/L	5.0	55.7			<	5.0	2	04/25/96	04/11/96
	ALKALINITY		50.1		50.1	mg/L	5.0	55.7			<	5.0	3	08/06/96	07/25/96
	ALKALINITY		51.2		50.8	mg/L	5.0	55.7			<	5.0	4	04/30/97	04/24/97
	ALKALINITY		50.0		50.0	mg/L	5.0	55.7			<	5.0	5	08/26/97	07/24/97
	ALKALINITY		50.0		50.0	mg/L	1.0	55.7			<	1.0	7	07/29/98	07/15/98
	ALKALINITY		55.0		50.0	mg/L	4.0	55.7			<	4.0	8	03/05/99	03/03/99
	ALKALINITY		46.0		46.0	mg/L	4.0	55.7			<	4.0	9	09/08/99	09/01/99
	ALKALINITY		49.0		49.0	mg/L	4.0	55.7			<	4.0	10	03/15/00	03/02/00
	ALKALINITY		50.0		52.0	mg/L	6.0	55.7			<	6.0	11	09/07/00	09/07/00
	ALKALINITY		51.0		52.0	mg/L	4.0	55.7			<	4.0	12	03/01/01	03/01/01
	ALKALINITY		50.0		52.0	mg/L	4.0	55.7					13	09/12/01	09/06/01
	ALKALINITY		50.0		48.0	mg/L	4.0	55.7					14	03/12/02	03/06/02

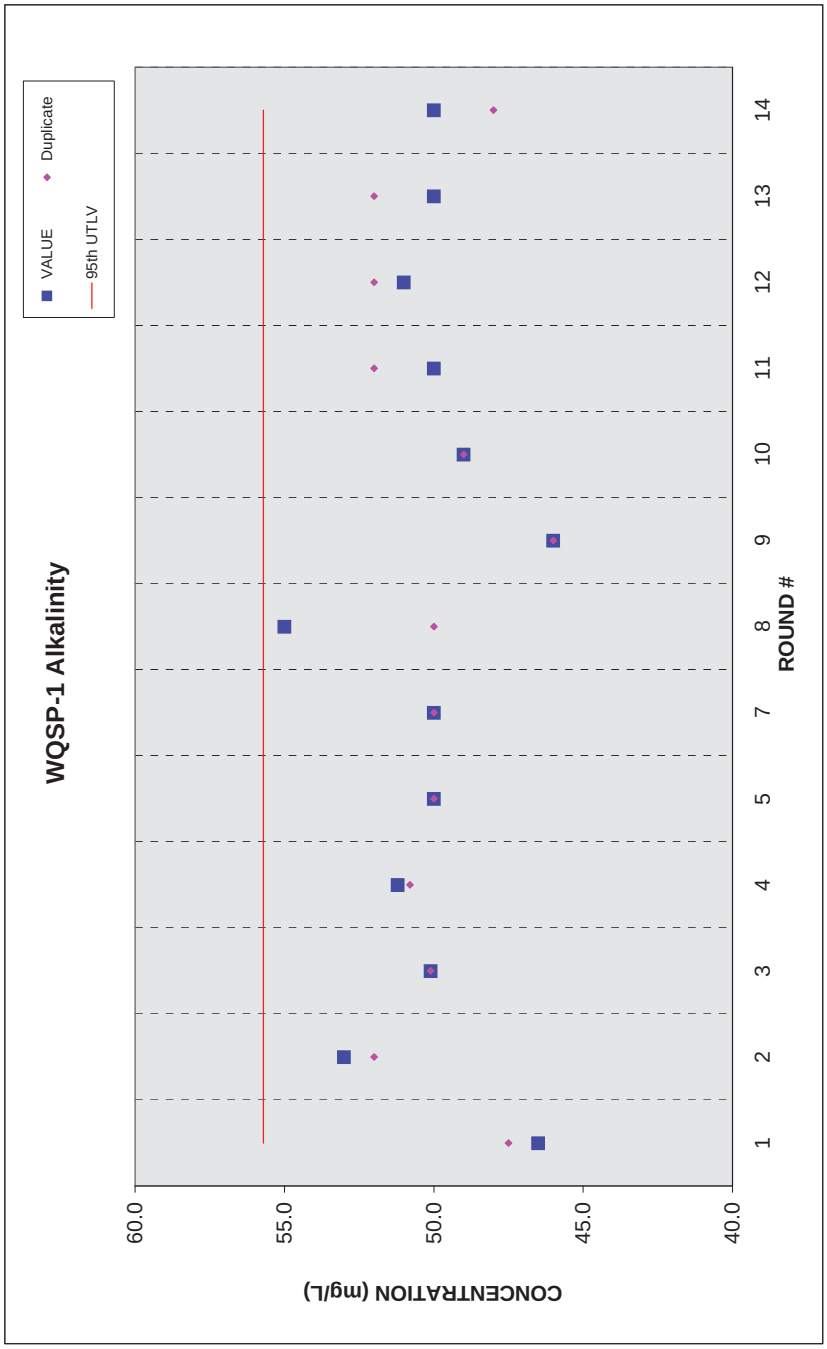

WQSP-1 Chloride

CAS #	PARAMETER		VALUE		VALUE DUPLICATE	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		34500.0		35000.0	mg/L	5.0	40472.0			<	5.0	1	08/23/95	08/17/95
7782-50-5	CHLORIDE		33000.0		33500.0	mg/L	5000.0	40472.0			<	5.0	2	04/22/96	04/11/96
7782-50-5	CHLORIDE		37200.0		37000.0	mg/L	5.0	40472.0			<	5.0	3	08/06/96	07/25/96
7782-50-5	CHLORIDE		34200.0		34200.0	mg/L	250.0	40472.0			<	5.0	4	05/01/97	04/24/97
7782-50-5	CHLORIDE		35700.0		35500.0	mg/L	2500.0	40472.0			<	5.0	5	08/29/97	07/24/97
7782-50-5	CHLORIDE		37600.0		34500.0	mg/L	2500.0	40472.0					6	03/19/98	03/05/98
7782-50-5	CHLORIDE		34000.0		33000.0	mg/L	0.5	40472.0				1.0	7	07/26/98	07/15/98
7782-50-5	CHLORIDE		33000.0		33000.0	mg/L	0.5	40472.0			<	0.5	8	03/03/99	03/03/99
7782-50-5	CHLORIDE		40000.0		40000.0	mg/L	0.5	40472.0			<	0.5	9	09/07/99	09/01/99
7782-50-5	CHLORIDE		36000.0		36000.0	mg/L	0.5	40472.0			<	0.5	10	03/06/00	03/02/00
7782-50-5	CHLORIDE		36000.0		34000.0	mg/L	2.0	40472.0			<	2.0	11	09/21/00	09/07/00
7782-50-5	CHLORIDE		37000.0		36000.0	mg/L	0.5	40472.0			<	0.5	12	03/01/01	03/01/01
7782-50-5	CHLORIDE		35900.0		36100.0	mg/L	0.5	40472.0					13	10/19/01	09/06/01
7782-50-5	CHLORIDE		36600.0		32300.0	mg/L	0.5	40472.0					14	03/08/02	03/06/02

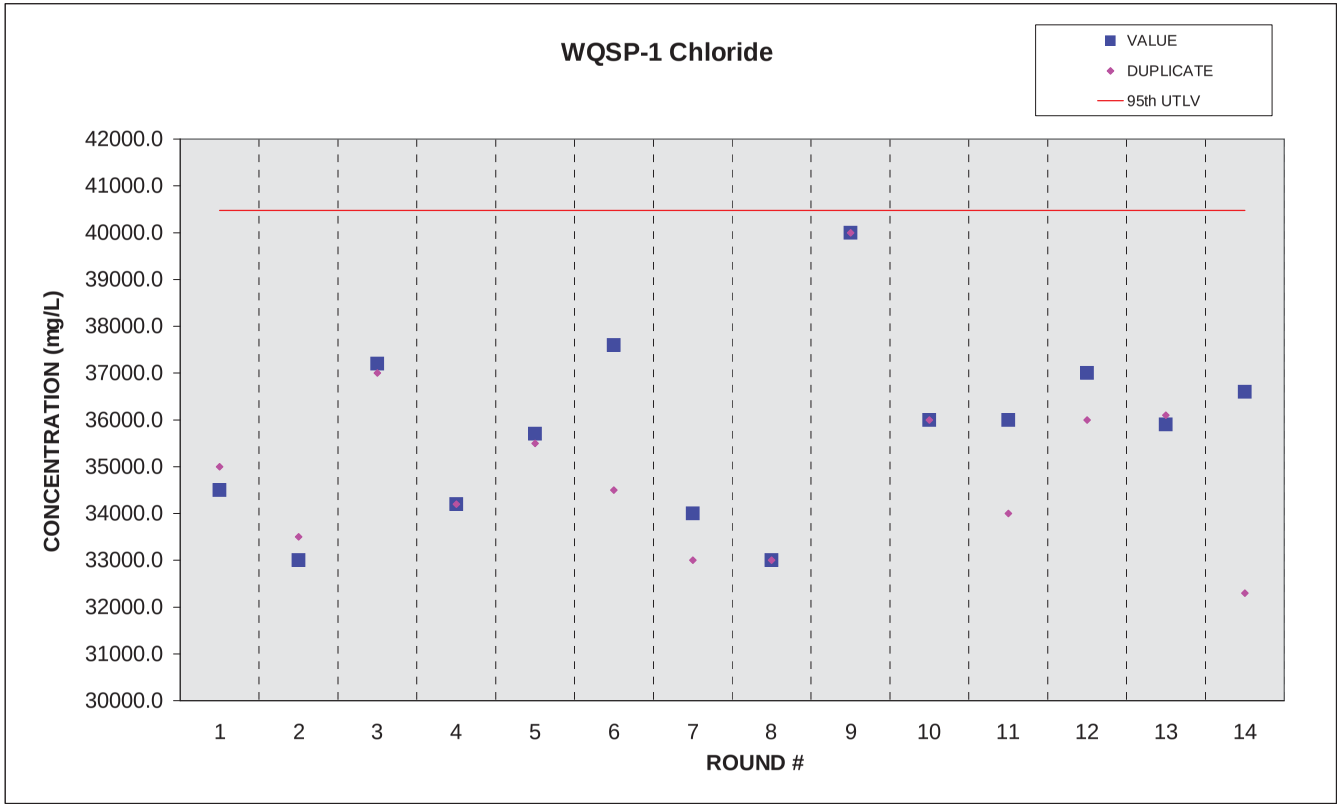

WQSP-1 Sulfate

CASE #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		5230.0		5490.0	mg/L	10.0	5757.0			<	10.0	1	08/29/95	08/17/95
	SULFATE		5480.0		5600.0	mg/L	2500.0	5757.0			<	10.0	2	04/25/96	04/11/96
	SULFATE		4920.0		4950.0	mg/L	1000.0	5757.0			<	10.0	3	08/21/96	07/25/96
	SULFATE		4760.0		4700.0	mg/L	10.0	5757.0			<	10.0	4	05/01/97	04/24/97
	SULFATE		4260.0		4460.0	mg/L	2500.0	5757.0			<	10.0	5	09/03/97	07/24/97
	SULFATE		4400.0		4350.0	mg/L	1000.0	5757.0			<	10.0	6	03/11/98	03/05/98
	SULFATE		4900.0		4400.0	mg/L	0.5	5757.0			<	0.5	7	07/26/98	07/15/98
	SULFATE		4600.0		4900.0	mg/L	0.5	5757.0			<	0.5	8	03/03/99	03/03/99
	SULFATE		5000.0		4700.0	mg/L	0.5	5757.0			<	0.5	9	09/07/99	09/01/99
	SULFATE		4800.0		4700.0	mg/L	0.5	5757.0			<	0.5	10	03/06/00	03/02/00
	SULFATE		4800.0		4700.0	mg/L	0.5	5757.0			<	0.5	11	09/07/00	09/07/00
	SULFATE		4900.0		4800.0	mg/L	0.5	5757.0			<	0.5	12	03/01/01	03/01/01
	SULFATE		4730.0		4720.0	mg/L	0.5	5757.0					13	09/27/01	09/06/01
	SULFATE		4270.0		4010.0	mg/L	0.5	5757.0					14	03/18/02	03/06/02

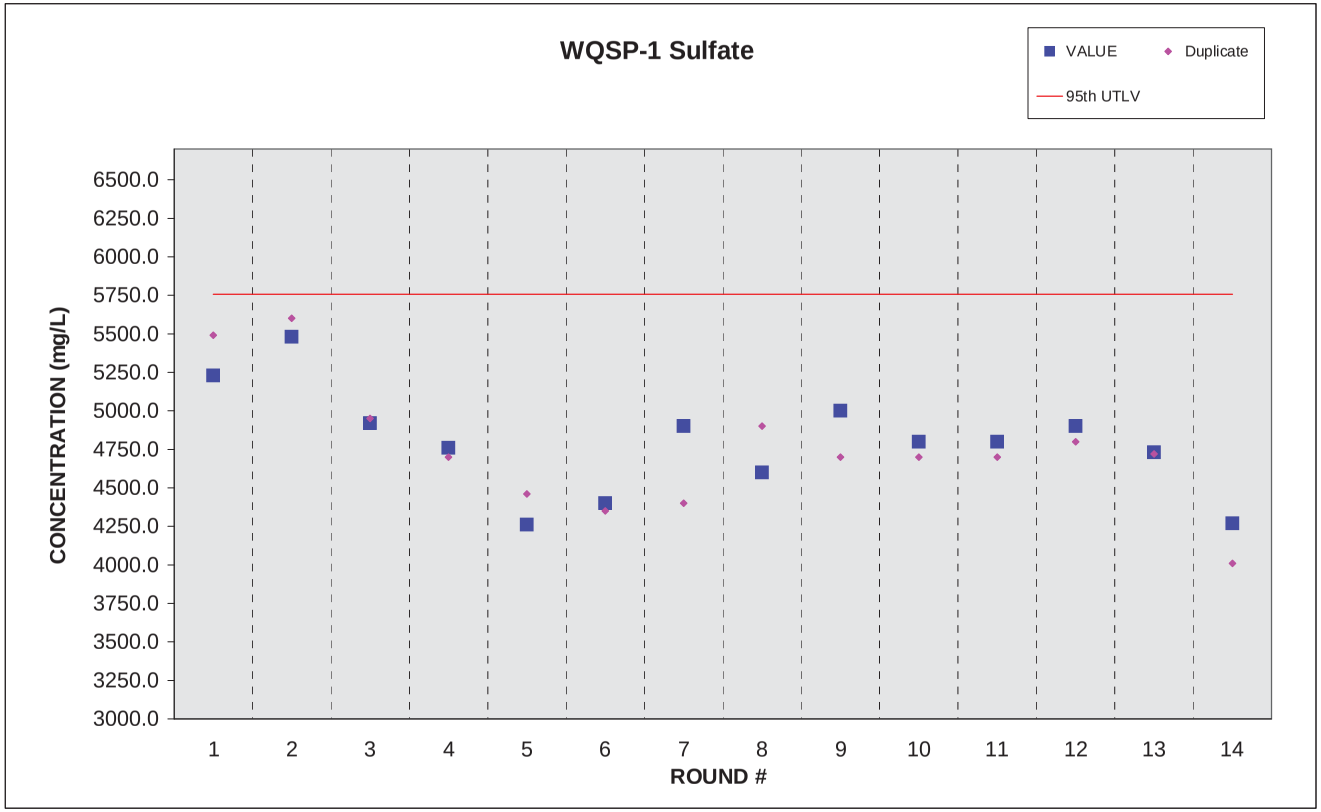

WQSP-2 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		1460.0		1450.0	mg/L	2.0	1827.0			<	0.2	1	09/12/95	08/31/95
7440-70-2	CALCIUM		1480.0		1410.0	mg/L	2.0	1827.0	<	0.2	<	0.2	2	05/10/96	04/25/96
7440-70-2	CALCIUM		1440.0		1400.0	mg/L	2.0	1827.0	<	0.2	<	0.2	3	08/21/96	08/08/96
7440-70-2	CALCIUM		1320.0		1290.0	mg/L	2.0	1827.0	<	0.2	<	0.2	4	05/21/97	05/08/97
7440-70-2	CALCIUM		1540.0		1460.0	mg/L	2.0	1827.0	<	0.2	<	0.2	5	08/15/97	08/07/97
7440-70-2	CALCIUM		1540.0		1505.0	mg/L	12.0	1827.0			<	12.0	6	05/05/98	04/15/98
7440-70-2	CALCIUM		1380.0		1460.0	mg/L	2.0	1827.0	<	0.2	<	5.0	7	09/16/98	08/12/98
7440-70-2	CALCIUM		1510.0		1470.0	mg/L	0.5	1827.0			<	0.5	8	03/19/99	03/17/99
7440-70-2	CALCIUM		1509.0		1428.0	mg/L	0.5	1827.0			<	0.5	9	09/16/99	09/15/99
7440-70-2	CALCIUM		1619.0		1742.0	mg/L	5.0	1827.0					10	03/16/00	03/15/00
7440-70-2	CALCIUM		1840.0		1730.0	mg/L	5.0	1827.0					10	06/19/00	06/19/00
7440-70-2	CALCIUM		1460.0		1530.0	mg/L	1.0	1827.0			<	1.0	11	10/26/00	09/20/00
7440-70-2	CALCIUM		1651.0		1715.0	mg/L	0.5	1827.0			<	0.5	12	05/10/01	03/14/01
7440-70-2	CALCIUM		1689.0		1676.0	mg/L	0.2	1827.0					13	11/09/01	09/19/01
7440-70-2	CALCIUM		1662.0		1624.0	mg/L	0.5	1827.0			<	0.5	14	03/25/02	03/20/02

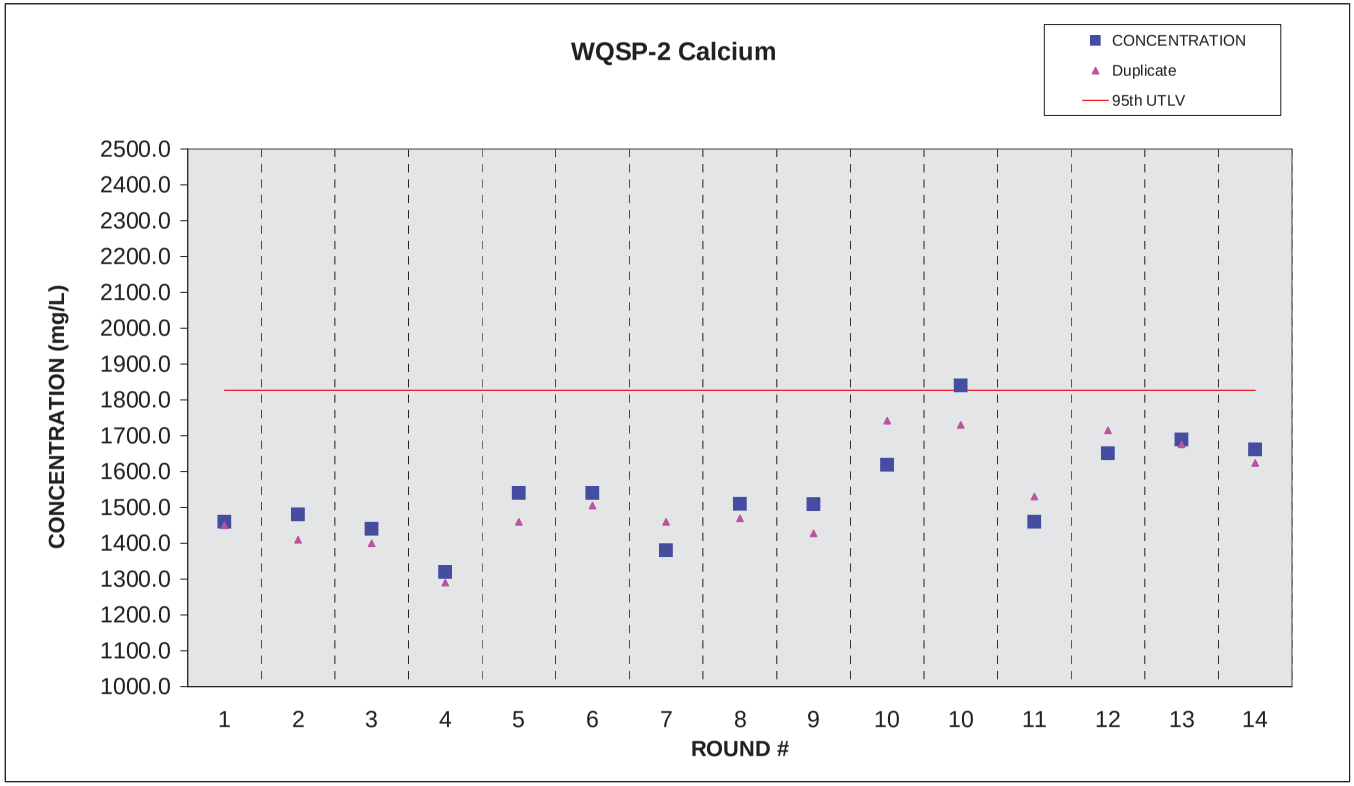

WQSP-2 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		1110.0		1080.0	mg/L	1.0	1244.0			<	0.1	1	08/28/95	08/17/95
7439-95-4	MAGNESIUM		1050.0		1040.0	mg/L	0.5	1244.0	<	0.1	<	0.1	2	05/07/96	04/11/96
7439-95-4	MAGNESIUM		1020.0		982.0	mg/L	0.5	1244.0	<	0.1	<	0.1	3	07/30/96	07/25/96
7439-95-4	MAGNESIUM		928.0		1000.0	mg/L	1.0	1244.0	<	0.1	<	0.1	4	05/02/97	04/24/97
7439-95-4	MAGNESIUM		1180.0		1170.0	mg/L	0.5	1244.0	<	0.1	<	0.1	5	08/15/97	07/24/97
7439-95-4	MAGNESIUM		1160.0		1130.0	mg/L	0.5	1244.0			<	0.1	6	03/19/98	03/05/98
7439-95-4	MAGNESIUM		1140.0		1060.0	mg/L	0.5	1244.0			<	0.5	7	08/17/98	07/15/98
7439-95-4	MAGNESIUM		993.0	<	1.0	mg/L	0.5	1244.0			<	0.5	8	03/15/99	03/03/99
7439-95-4	MAGNESIUM		1100.0		1120.0	mg/L	0.5	1244.0			<	0.5	9	09/16/99	09/01/99
7439-95-4	MAGNESIUM		1033.0		1107.0	mg/L	5.0	1244.0					10	03/16/00	03/15/00
7439-95-4	MAGNESIUM		982.0		1040.0	mg/L	1.0	1244.0			<	1.0	11	10/26/00	09/20/00
7439-95-4	MAGNESIUM		1199.0		1188.0	mg/L	0.5	1244.0			<	0.5	12	05/10/01	03/14/01
7439-95-4	MAGNESIUM		1175.0		1193.0	mg/L	0.2	1244.0					13	11/09/01	09/19/01
7439-95-4	MAGNESIUM		1093.0		1074.0	mg/L	0.5	1244.0			<	0.5	14	03/25/02	03/20/02

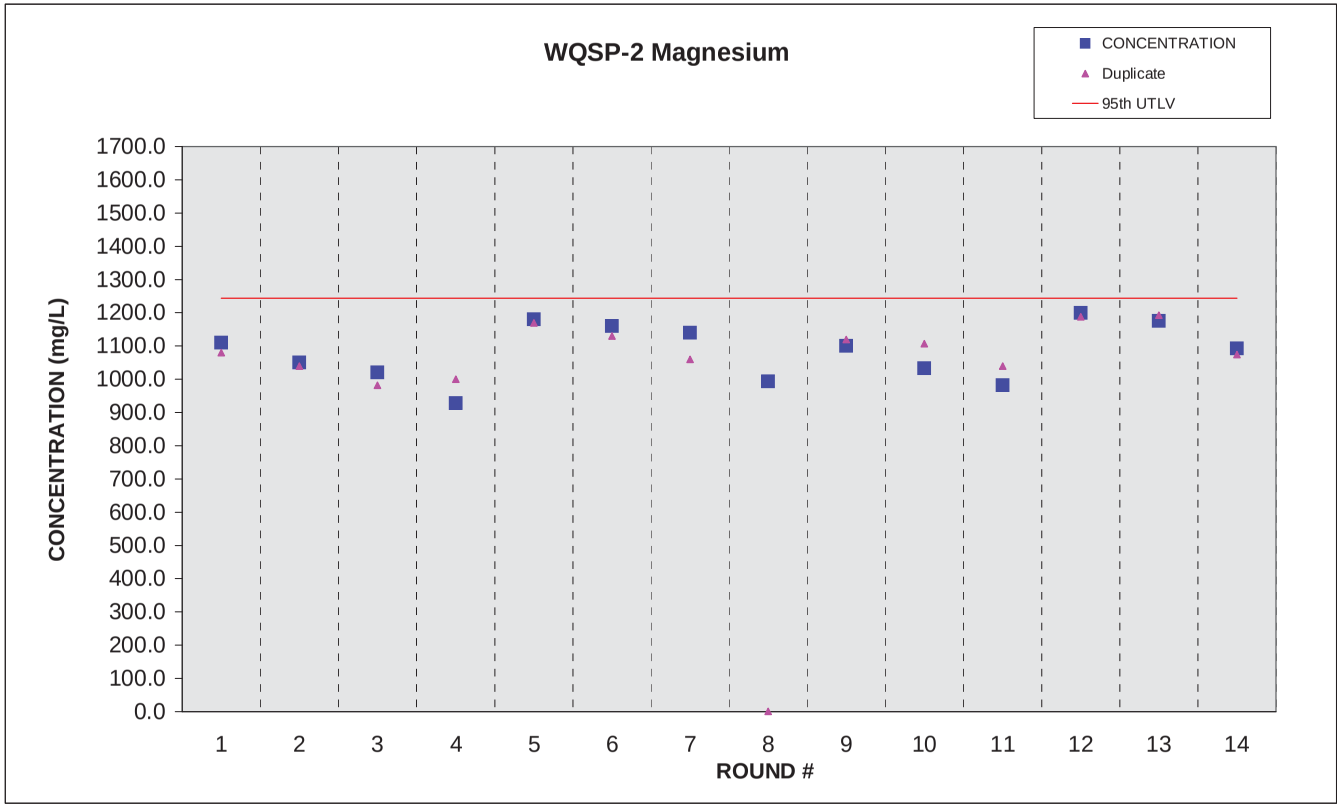

WQSP-2 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		497.0		474.0	mg/L	0.2	845.0			<	0.2	1	08/28/95	08/17/95
7440-09-7	POTASSIUM		476.0		465.0	mg/L	10.0	845.0	<	0.2	<	0.2	2	04/25/96	04/11/96
7440-09-7	POTASSIUM		471.0		451.0	mg/L	2.0	845.0	<	0.2	<	0.2	3	07/30/96	07/25/96
7440-09-7	POTASSIUM		443.0		468.0	mg/L	2.0	845.0	<	0.2	<	0.2	4	05/01/97	04/24/97
7440-09-7	POTASSIUM		499.0		476.0	mg/L	2.0	845.0	<	0.2	<	0.2	5	07/29/97	07/24/97
7440-09-7	POTASSIUM		467.0		487.0	mg/L	2.0	845.0			<	0.2	6	03/19/98	03/05/98
7440-09-7	POTASSIUM		710.0		640.0	mg/L	0.5	845.0			<	0.5	7	08/17/98	07/15/98
7440-09-7	POTASSIUM		661.0	<	1.0	mg/L	0.5	845.0			<	0.5	8	03/15/99	03/03/99
7440-09-7	POTASSIUM		700.0		728.0	mg/L	0.5	845.0			<	0.5	9	09/16/99	09/01/99
7440-09-7	POTASSIUM		333.0		380.0	mg/L	0.0	845.0					10	03/16/00	03/15/00
7440-09-7	POTASSIUM		815.0		823.0	mg/L	1.0	845.0				10.1	11	10/26/00	09/20/00
7440-09-7	POTASSIUM		706.0		768.0	mg/L	0.5	845.0			<	0.5	12	05/10/01	03/14/01
7440-09-7	POTASSIUM		841.0		856.0	mg/L	0.2	845.0					13	11/09/01	09/19/01
7440-09-7	POTASSIUM		759.0		797.0	mg/L	0.5	845.0			<	0.5	14	03/25/02	03/20/02

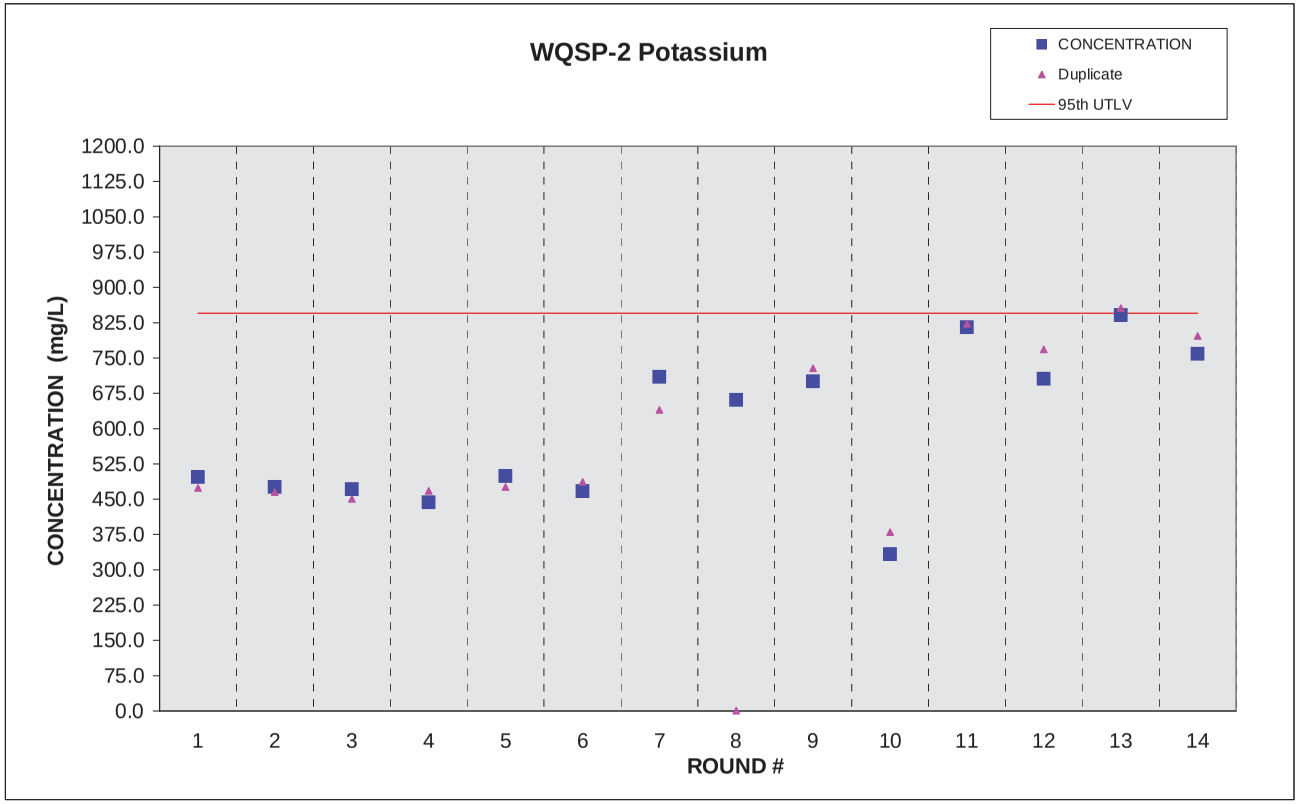

WQSP-2 Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		20100.0		19800.0	mg/L	5.0	21900.0			<	0.5	1	08/28/95	08/17/95
7440-23-5	SODIUM		18500.0		18200.0	mg/L	25.0	21900.0	<	0.5	<	0.5	2	04/25/96	04/11/96
7440-23-5	SODIUM		18900.0		18400.0	mg/L	25.0	21900.0	<	0.5	<	0.5	3	07/30/96	07/25/96
7440-23-5	SODIUM		17700.0		19600.0	mg/L	10.0	21900.0	<	0.5	<	0.2	4	05/01/97	04/24/97
7440-23-5	SODIUM		19400.0		17500.0	mg/L	10.0	21900.0	<	0.2	<	0.2	5	07/29/97	07/24/97
7440-23-5	SODIUM		19800.0		20000.0	mg/L	4.0	21900.0			<	0.2	6	03/19/98	03/05/98
7440-23-5	SODIUM		17550.0		16500.0	mg/L	0.5	21900.0			<	0.5	7	08/17/98	07/15/98
7440-23-5	SODIUM		19700.0	<	1.0	mg/L	1.0	21900.0			<	1.0	8	03/15/99	03/03/99
7440-23-5	SODIUM		15374.0		16396.0	mg/L	5.0	21900.0					10	03/16/00	03/15/00
7440-23-5	SODIUM		19800.0		20300.0	mg/L	1.0	21900.0				22.0	11	10/26/00	09/20/00
7440-23-5	SODIUM		19790.0		21340.0	mg/L	0.5	21900.0			<	0.5	12	05/10/01	03/14/01
7440-23-5	SODIUM		20910.0		21060.0	mg/L	0.2	21900.0					13	11/09/01	09/19/01
7440-23-5	SODIUM		20240.0		20490.0	mg/L	0.5	21900.0			<	0.5	14	03/25/02	03/20/02

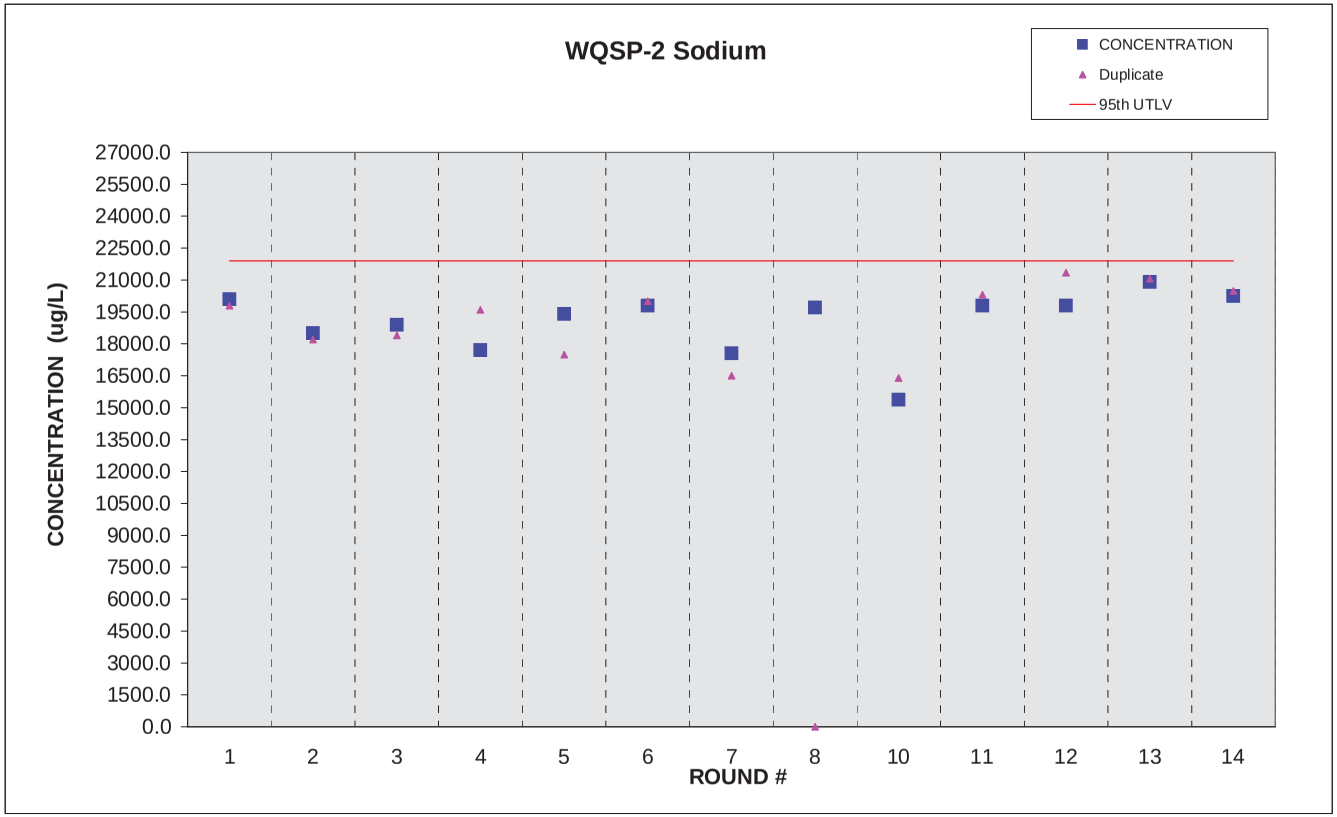

WQSP-2 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		52.5		5.3	mg/L	5.0	70.3			<	5.0	1	09/07/95	08/31/95
	ALKALINITY		48.1		48.1	mg/L	5.0	70.3		0.0	<	5.0	2	05/08/96	04/25/96
	ALKALINITY		48.1		48.1	mg/L	5.0	70.3		0.0	<	5.0	3	08/15/96	08/08/96
	ALKALINITY		50.1		50.1	mg/L	5.0	70.3			<	5.0	4	05/14/97	05/08/97
	ALKALINITY		46.0		47.0	mg/L	5.0	70.3			<	5.0	5	08/26/97	08/07/97
	ALKALINITY		43.0		48.0	mg/L	5.0	70.3					6	04/16/98	04/15/98
	ALKALINITY		46.0		48.0	mg/L	5.0	70.3			<	1.0	7	08/18/98	08/12/98
	ALKALINITY		47.0		49.0	mg/L	5.0	70.3					8	03/18/99	03/17/99
	ALKALINITY		44.0		46.0	mg/L	5.0	70.3					10	03/17/00	03/15/00
	ALKALINITY		51.0		48.0	mg/L	6.0	70.3			<	6.0	11	09/22/00	09/20/00
	ALKALINITY		48.0		50.0	mg/L	4.0	70.3					12	03/20/01	03/14/01
	ALKALINITY		46.0		48.0	mg/L	4.0	70.3					13	09/25/01	09/19/01
	ALKALINITY		48.0		46.0	mg/L	4.0	70.3					14	03/26/02	03/20/02

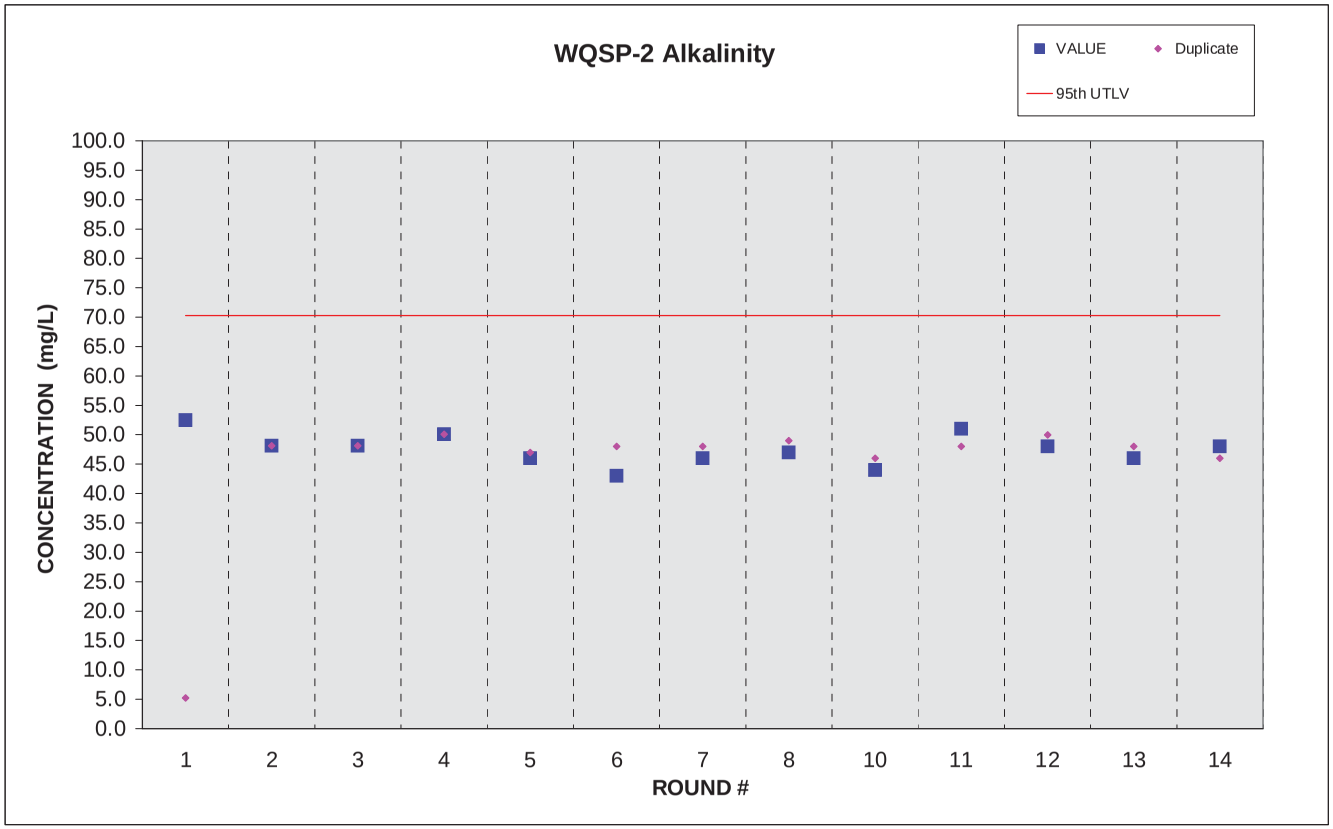

WQSP-2 Chloride

CAS #	PARAMETER		VALUE		VALUE DUPLICATE	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		38500.0		38500.0	mg/L	5.0	39670.0			<	5.0	1	09/08/95	08/31/95
7782-50-5	CHLORIDE		34200.0		36000.0	mg/L	2500.0	39670.0		0.0	<	5.0	2	05/01/96	04/25/96
7782-50-5	CHLORIDE		36000.0		36000.0	mg/L	2500.0	39670.0		0.0	<	5.0	3	08/20/96	08/08/96
7782-50-5	CHLORIDE		33000.0		32700.0	mg/L	2500.0	39670.0			<	5.0	4	05/17/97	05/08/97
7782-50-5	CHLORIDE		32500.0		33000.0	mg/L	2500.0	39670.0			<	5.0	5	08/29/97	08/07/97
7782-50-5	CHLORIDE		35500.0		35300.0	mg/L	0.2	39670.0				0.0	6	04/16/98	04/15/98
7782-50-5	CHLORIDE		37000.0		35000.0	mg/L	2500.0	39670.0				1.7	7	08/17/98	08/12/98
7782-50-5	CHLORIDE		34000.0		34000.0	mg/L	0.5	39670.0			<	0.5	8	03/19/99	03/17/99
7782-50-5	CHLORIDE		36000.0		36000.0	mg/L	0.5	39670.0			<	0.5	9	09/15/99	09/15/99
7782-50-5	CHLORIDE		37000.0		37000.0	mg/L	0.5	39670.0			<	0.5	10	03/21/00	03/15/00
7782-50-5	CHLORIDE		37000.0		36000.0	mg/L	2.0	39670.0			<	0.5	11	09/21/00	09/20/00
7782-50-5	CHLORIDE		35000.0		36000.0	mg/L	0.5	39670.0					12	03/19/01	03/14/01
7782-50-5	CHLORIDE		34900.0		34800.0	mg/L	2.0	39670.0					13	10/08/01	09/19/01
7782-50-5	CHLORIDE		34500.0		33900.0	mg/L	2.0	39670.0					14	03/26/02	03/20/02

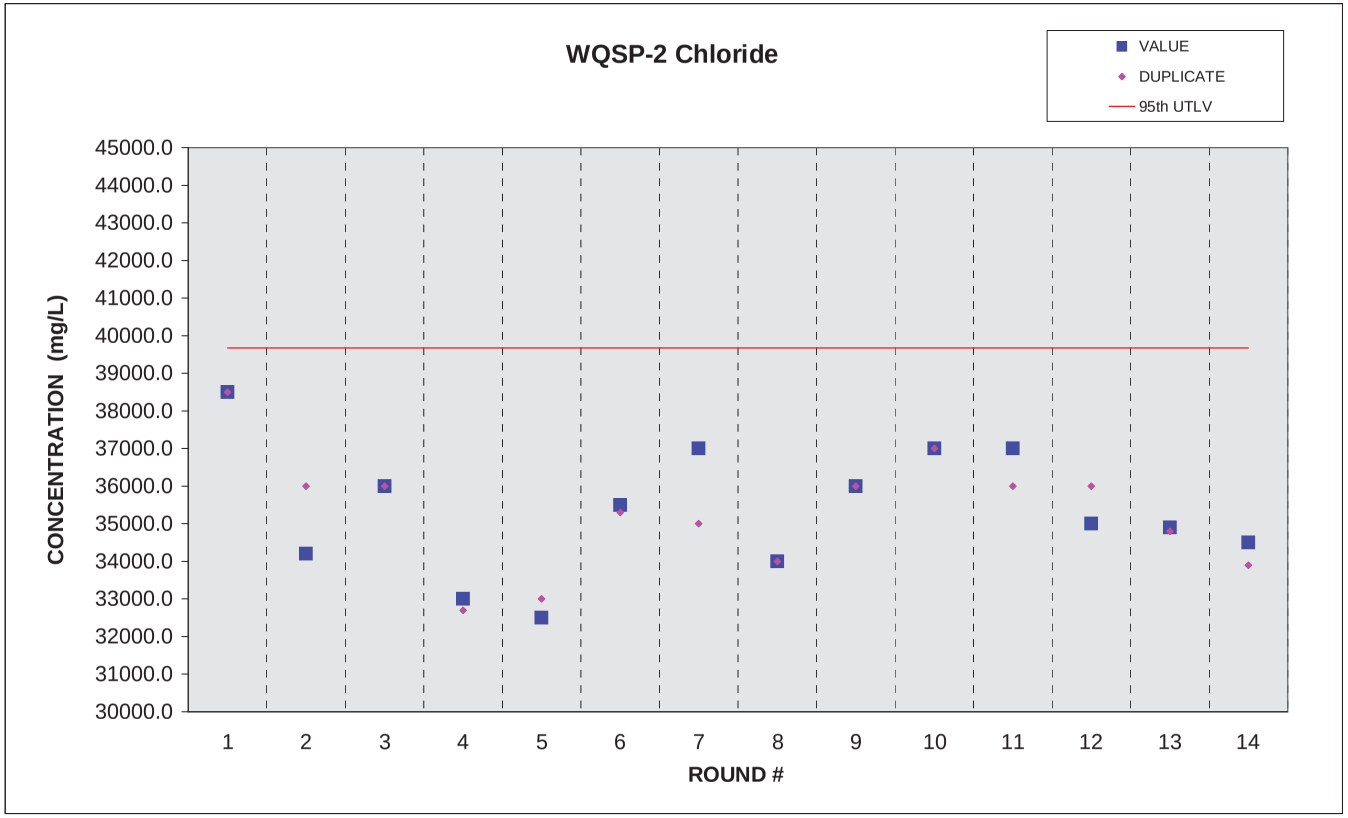

WQSP-2 Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		5540.0		5470.0	mg/L	10.0	6590.0			<	10.0	1	09/06/95	08/31/95
	SULFATE		5610.0		5640.0	mg/L	2500.0	6590.0			<	10.0	2	05/08/96	04/25/96
	SULFATE		5700.0		5710.0	mg/L	1000.0	6590.0			<	10.0	3	08/21/96	08/08/96
	SULFATE		6360.0		6020.0	mg/L	2500.0	6590.0			<	10.0	4	05/19/97	05/08/97
	SULFATE		4990.0		4900.0	mg/L	2500.0	6590.0			<	10.0	5	09/03/97	08/07/97
	SULFATE		5280.0		5260.0	mg/L	0.2	6590.0			<	0.2	6	04/16/98	04/15/98
	SULFATE		5400.0		5000.0	mg/L	2500.0	6590.0			<	0.5	7	08/18/98	08/12/98
	SULFATE		5000.0		4600.0	mg/L	0.5	6590.0			<	0.5	8	03/22/99	03/17/99
	SULFATE		5900.0		6000.0	mg/L	0.5	6590.0			<	0.5	10	03/15/00	03/15/00
	SULFATE		5800.0		5600.0	mg/L	0.5	6590.0			<	0.5	11	09/21/00	09/20/00
	SULFATE		5200.0		5600.0	mg/L	0.5	6590.0					12	03/19/01	03/14/01
	SULFATE		5160.0		5060.0	mg/L	2.0	6590.0					13	10/08/01	09/19/01
	SULFATE		5570.0		5650.0	mg/L	2.0	6590.0					14	03/26/02	03/20/02

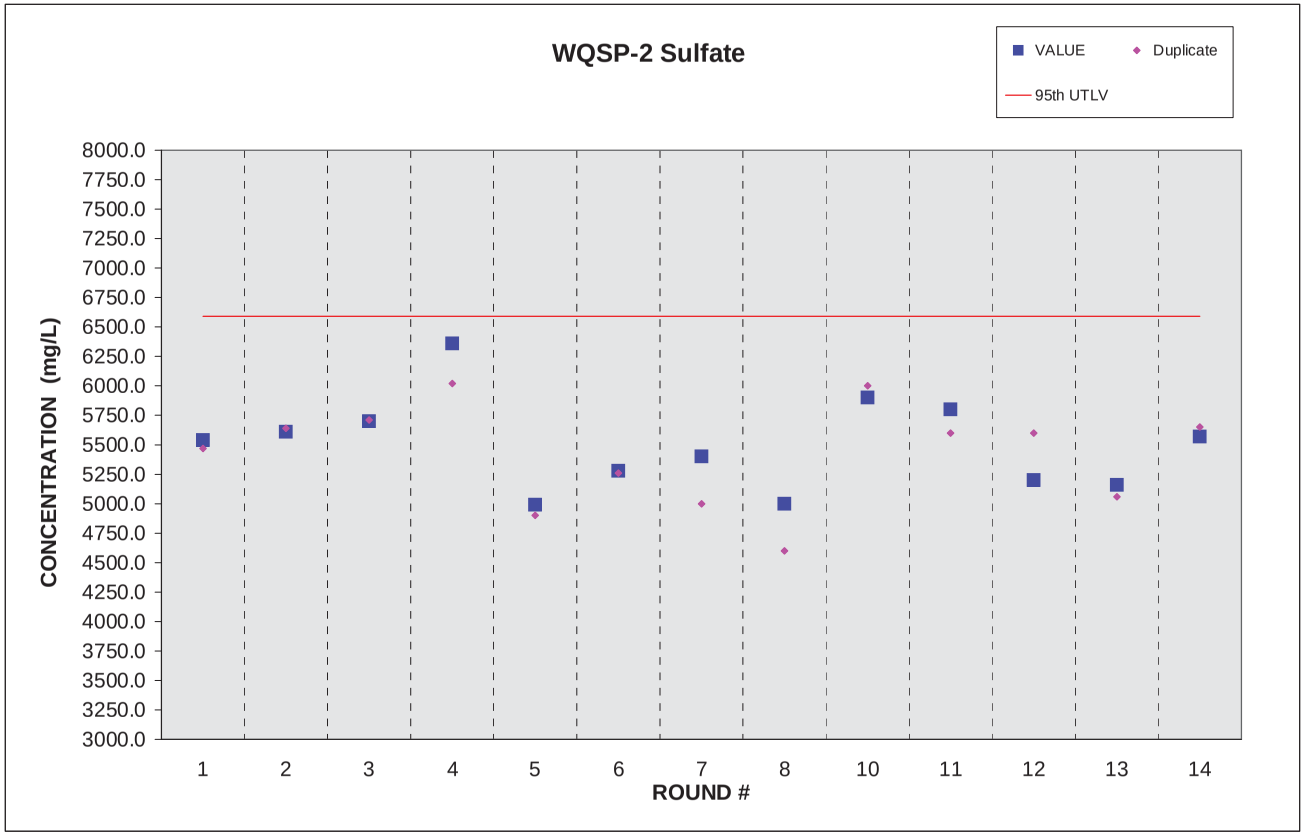

WQSP-3 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		1420.0		1350.0	mg/L	8.0	1680.0			<	0.2	1	10/20/95	09/19/95
7440-70-2	CALCIUM		1480.0		1450.0	mg/L	2.0	1680.0	<	0.2	<	0.2	2	06/03/96	05/09/96
7440-70-2	CALCIUM		1300.0		1260.0	mg/L	2.0	1680.0	<	0.2	<	0.2	3	08/29/96	08/22/96
7440-70-2	CALCIUM		1100.0		1200.0	mg/L	2.0	1680.0	<	0.2	<	0.2	4	06/13/97	05/22/97
7440-70-2	CALCIUM		1210.0		1120.0	mg/L	2.0	1680.0	<	0.2	<	0.2	5	09/05/97	08/21/97
7440-70-2	CALCIUM		1380.0		1409.4	mg/L	0.0	1680.0			<	0.0	6	04/24/98	04/22/98
7440-70-2	CALCIUM		1200.0		1500.0	mg/L	0.1	1680.0			<	0.1	7	09/29/98	08/26/98
7440-70-2	CALCIUM		1400.0		1530.0	mg/L	1.0	1680.0			<	1.0	8	04/15/99	04/08/99
7440-70-2	CALCIUM		1500.0		1500.0	mg/L	1.0	1680.0			<	1.0	9	11/25/99	10/06/99
7440-70-2	CALCIUM		1390.0		1440.0	mg/L	5.0	1680.0				0.1	10	04/06/00	03/23/00
7440-70-2	CALCIUM		1410.0		1420.0	mg/L	1.0	1680.0			<	1.0	11	10/24/00	10/05/00
7440-70-2	CALCIUM		1310.0		1300.0	mg/L	0.5	1680.0			<	0.5	12	06/25/01	03/29/01
7440-70-2	CALCIUM		1537.0		1430.0	mg/L	0.2	1680.0					13	10/17/01	10/04/01
7440-70-2	CALCIUM		1500.0		1560.0	mg/L	0.5	1680.0					14	04/15/02	04/04/02

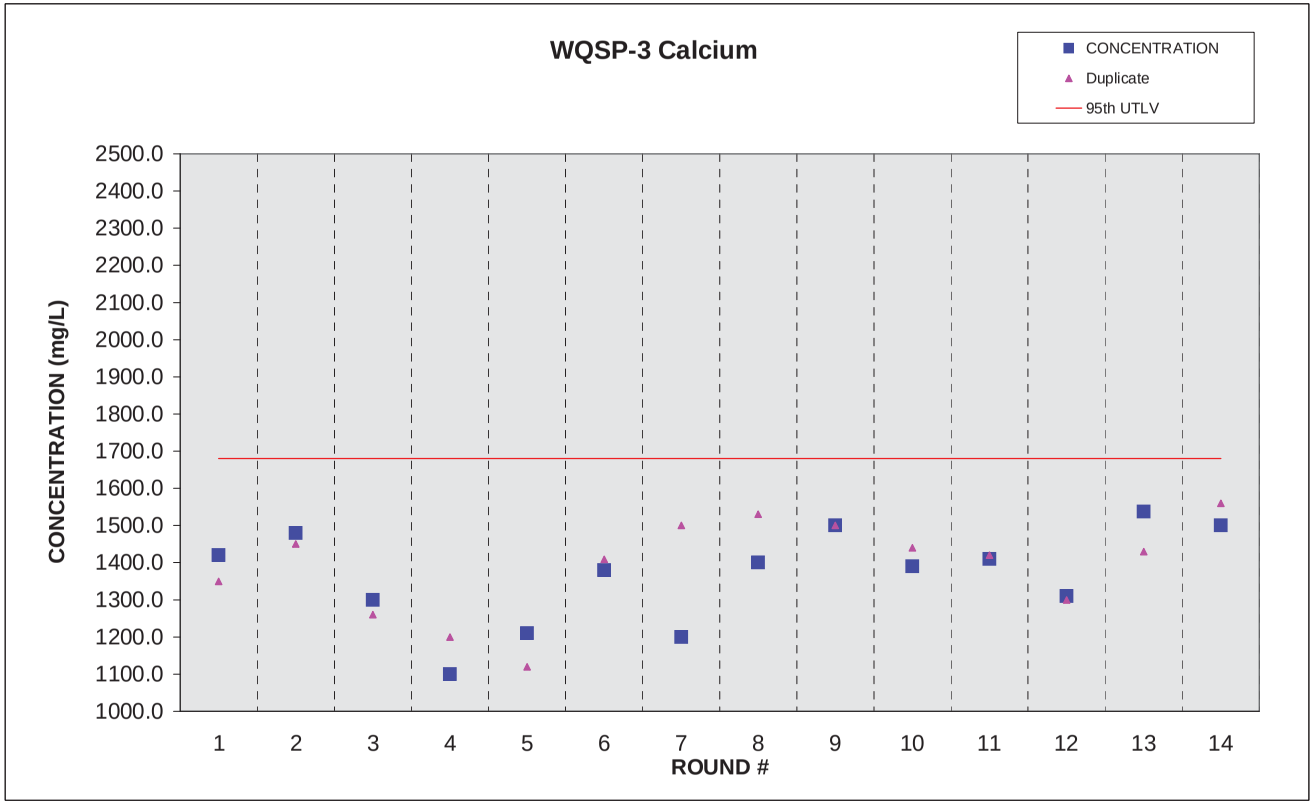

WQSP-3 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		2210.0		2110.0	mg/L	4.0	2625.0			<	0.1	1	10/20/95	09/19/95
7439-95-4	MAGNESIUM		2000.0		1970.0	mg/L	0.5	2625.0	<	0.1	<	0.1	2	06/03/96	05/09/96
7439-95-4	MAGNESIUM		1960.0		1890.0	mg/L	0.5	2625.0	<	0.1	<	0.1	3	08/29/96	08/22/96
7439-95-4	MAGNESIUM		1890.0		2050.0	mg/L	1.0	2625.0	<	0.1	<	0.1	4	06/13/97	05/22/97
7439-95-4	MAGNESIUM		1910.0		1770.0	mg/L	1.0	2625.0	<	0.1	<	0.1	5	09/05/97	08/21/97
7439-95-4	MAGNESIUM		2340.0		2404.0	mg/L	0.1	2625.0			<	0.1	6	04/24/98	04/22/98
7439-95-4	MAGNESIUM		2100.0		2500.0	mg/L	0.1	2625.0			<	0.0	7	09/29/98	08/26/98
7439-95-4	MAGNESIUM		2070.0		2290.0	mg/L	1.0	2625.0			<	1.0	8	04/15/99	04/08/99
7439-95-4	MAGNESIUM		2290.0		2310.0	mg/L	0.5	2625.0			<	0.5	9	11/25/99	10/06/99
7439-95-4	MAGNESIUM		2110.0		2140.0	mg/L	5.0	2625.0				0.1	10	04/06/00	03/23/00
7439-95-4	MAGNESIUM		2120.0		2140.0	mg/L	1.0	2625.0			<	1.0	11	10/24/00	10/05/00
7439-95-4	MAGNESIUM		2120.0		2040.0	mg/L	0.5	2625.0			<	0.5	12	06/25/01	03/29/01
7439-95-4	MAGNESIUM		2455.0		2312.0	mg/L	0.2	2625.0					13	10/17/01	10/04/01
7439-95-4	MAGNESIUM		2270.0		2400.0	mg/L	0.5	2625.0					14	04/15/02	04/04/02

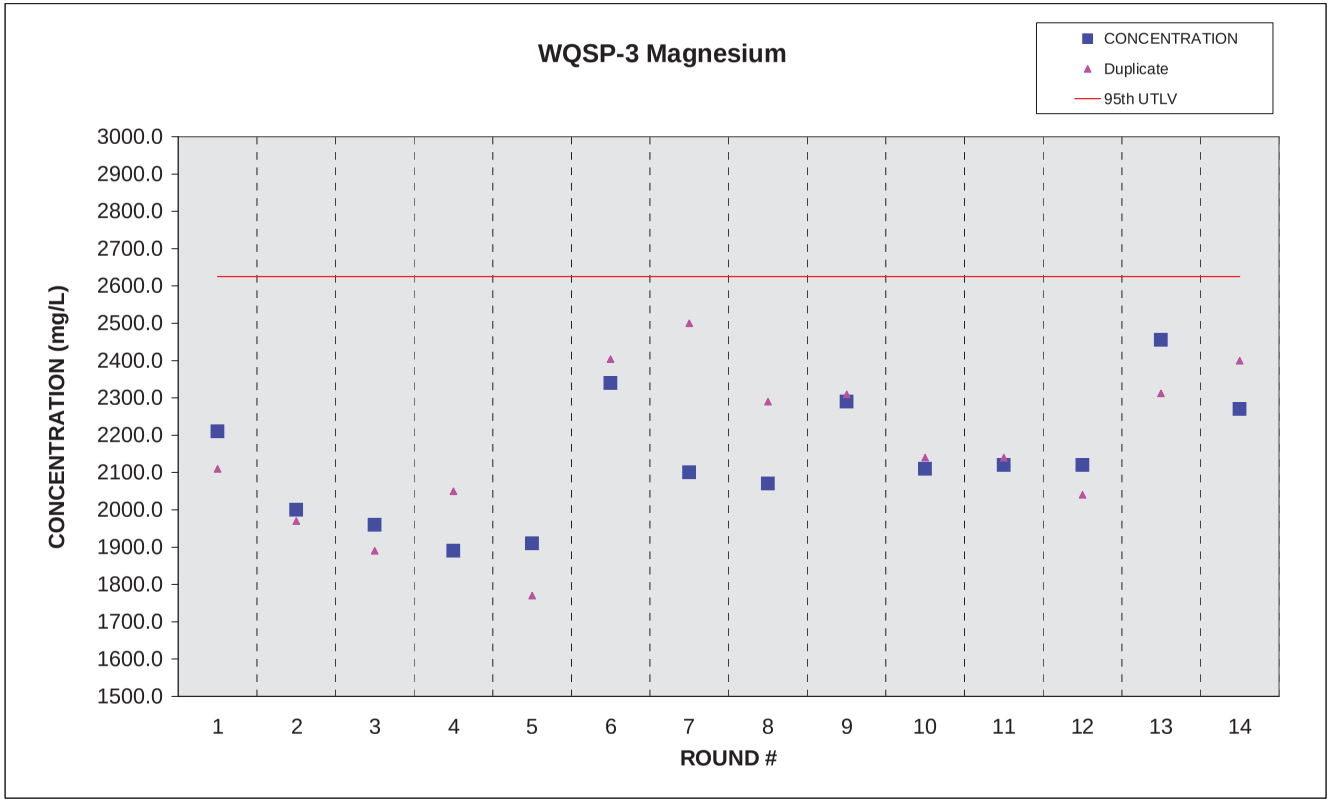

WQSP-3 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		1380.0		1310.0	mg/L	8.0	3438.0			<	0.2	1	10/20/95	09/19/95
7440-09-7	POTASSIUM		1710.0		1710.0	mg/L	0.2	3438.0	<	0.2	<	0.2	2	05/29/96	05/09/96
7440-09-7	POTASSIUM		1360.0		1450.0	mg/L	2.0	3438.0	<	0.2	<	0.2	3	08/29/96	08/22/96
7440-09-7	POTASSIUM		1370.0		1480.0	mg/L	2.0	3438.0	<	0.2	<	0.2	4	05/29/97	05/22/97
7440-09-7	POTASSIUM		1530.0		1400.0	mg/L	2.0	3438.0	<	0.2	<	0.2	5	08/28/97	08/21/97
7440-09-7	POTASSIUM		1460.0		1502.0	mg/L	0.1	3438.0			<	0.1	6	04/24/98	04/22/98
7440-09-7	POTASSIUM		1300.0		1600.0	mg/L	0.1	3438.0			<	0.1	7	09/29/98	08/26/98
7440-09-7	POTASSIUM		2140.0		2440.0	mg/L	1.0	3438.0			<	1.0	8	04/15/99	04/08/99
7440-09-7	POTASSIUM		2870.0		2800.0	mg/L	0.5	3438.0			<	0.5	9	11/25/99	10/07/99
7440-09-7	POTASSIUM		2700.0		2700.0	mg/L	5.0	3438.0				0.1	10	04/06/00	03/23/00
7440-09-7	POTASSIUM		2880.0		3030.0	mg/L	1.0	3438.0				0.2	11	10/24/00	10/05/00
7440-09-7	POTASSIUM		2180.0		2190.0	mg/L	0.5	3438.0			<	0.5	12	06/25/01	03/29/01
7440-09-7	POTASSIUM		3035.0		2862.0	mg/L	0.2	3438.0					13	10/17/01	10/04/01
7440-09-7	POTASSIUM		1960.0		1950.0	mg/L	0.5	3438.0					14	05/06/02	04/04/02

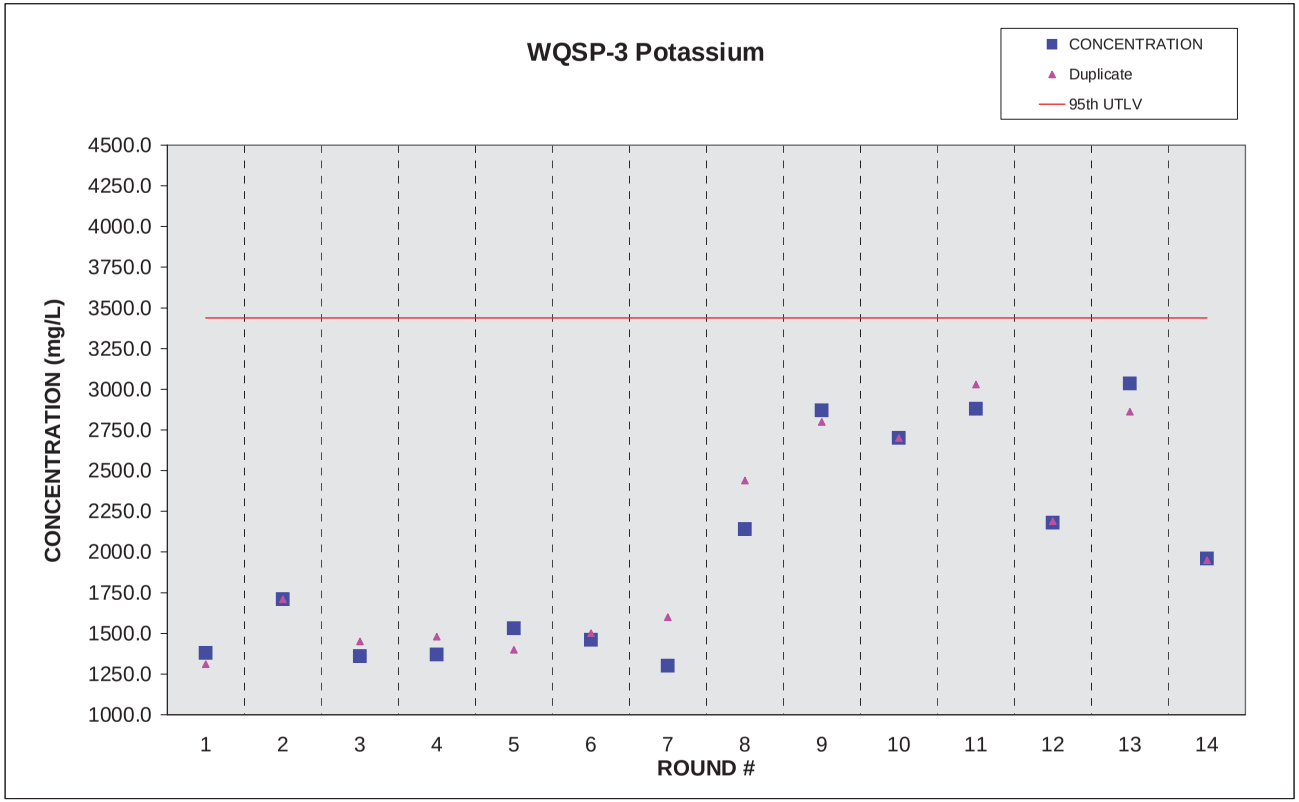

WQSP-3 Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		79100.0		76700.0	mg/L	100.0	140400.0			<	0.5	1	10/20/95	09/19/95
7440-23-5	SODIUM		74200.0		73700.0	mg/L	50.0	140400.0	<	0.5	<	0.5	2	05/29/96	05/09/96
7440-23-5	SODIUM		76700.0		68200.0	mg/L	50.0	140400.0	<	0.5	<	0.5	3	08/29/96	08/22/96
7440-23-5	SODIUM		71200.0		71800.0	mg/L	25.0	140400.0	<	0.5	<	0.5	4	05/29/97	05/22/97
7440-23-5	SODIUM		75700.0		74200.0	mg/L	25.0	140400.0	<	0.5	<	0.5	5	08/28/97	08/21/97
7440-23-5	SODIUM		74900.0		77660.0	mg/L	0.0	140400.0			<	0.0	6	04/24/98	04/22/98
7440-23-5	SODIUM		58000.0		71000.0	mg/L	0.1	140400.0			<	0.1	7	09/29/98	08/26/98
7440-23-5	SODIUM		146800.0		134000.0	mg/L	1.0	140400.0			<	1.0	8	04/15/99	04/08/99
7440-23-5	SODIUM		66600.0		68300.0	mg/L	1.0	140400.0			<	1.0	9	11/25/99	10/06/99
7440-23-5	SODIUM		75200.0		75200.0	mg/L	5.0	140400.0				0.2	10	04/06/00	03/23/00
7440-23-5	SODIUM		77900.0		77800.0	mg/L	5.0	140400.0				0.4	11	12/22/00	10/05/00
7440-23-5	SODIUM		68300.0		71100.0	mg/L	0.5	140400.0			<	0.5	12	06/25/01	03/29/01
7440-23-5	SODIUM		81600.0		74400.0	mg/L	0.2	140400.0					13	10/16/01	10/04/01
7440-23-5	SODIUM		73200.0		75100.0	mg/L	0.5	140400.0					14	04/15/02	04/04/02

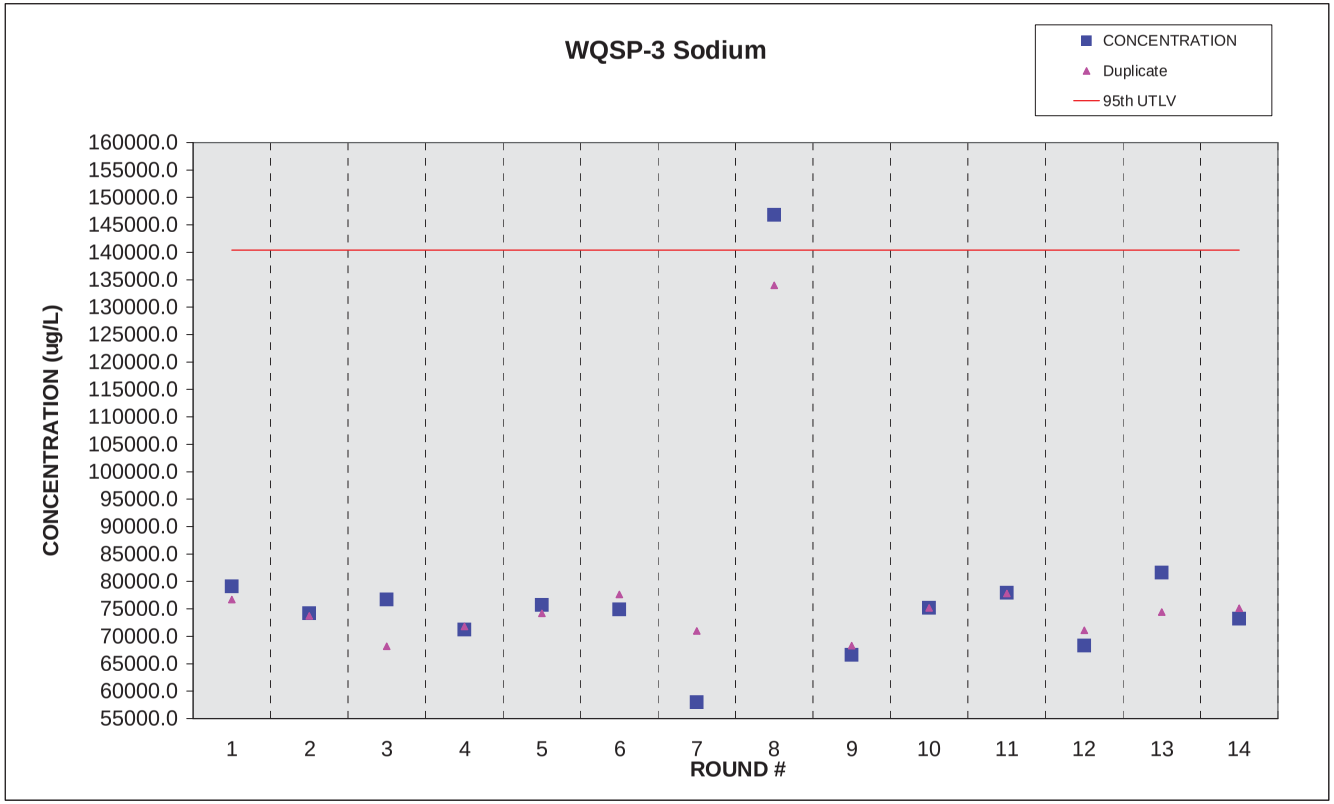

WQSP-3 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		44.0		44.0	mg/L	5.0	54.5			<	5.0	1	10/02/95	09/19/95
	ALKALINITY		35.0		35.0	mg/L	5.0	54.5			<	5.0	2	05/15/96	05/09/96
	ALKALINITY		36.1		35.1	mg/L	5.0	54.5			<	5.0	3	09/12/96	08/22/96
	ALKALINITY		33.0		33.0	mg/L	5.0	54.5			<	5.0	4	06/09/97	05/22/97
	ALKALINITY		32.0		33.0	mg/L	5.0	54.5			<	5.0	5	08/26/97	08/21/97
	ALKALINITY		33.0		33.0	mg/L	5.0	54.5					6	04/24/98	4/22/98
	ALKALINITY		31.0		31.0	mg/L	1.0	54.5			<	1.0	7	09/09/98	08/26/98
	ALKALINITY		31.0		33.0	mg/L	3.0	54.5			<	3.0	8	04/11/99	04/08/99
	ALKALINITY		36.0		37.0	mg/L	3.0	54.5					9	10/12/99	10/06/99
	ALKALINITY		55.0		54.0	mg/L	3.0	54.5					10	03/30/00	03/23/00
	ALKALINITY		35.0		36.0	mg/L	6.0	54.5			<	4.0	11	10/11/00	10/05/00
	ALKALINITY		34.0		32.0	mg/L	4.0	54.5					12	04/04/01	03/29/01
	ALKALINITY		32.0		34.0	mg/L	4.0	54.5					13	10/11/01	10/04/01
	ALKALINITY		36.0		38.0	mg/L	4.0	54.5					14	04/04/02	04/04/02

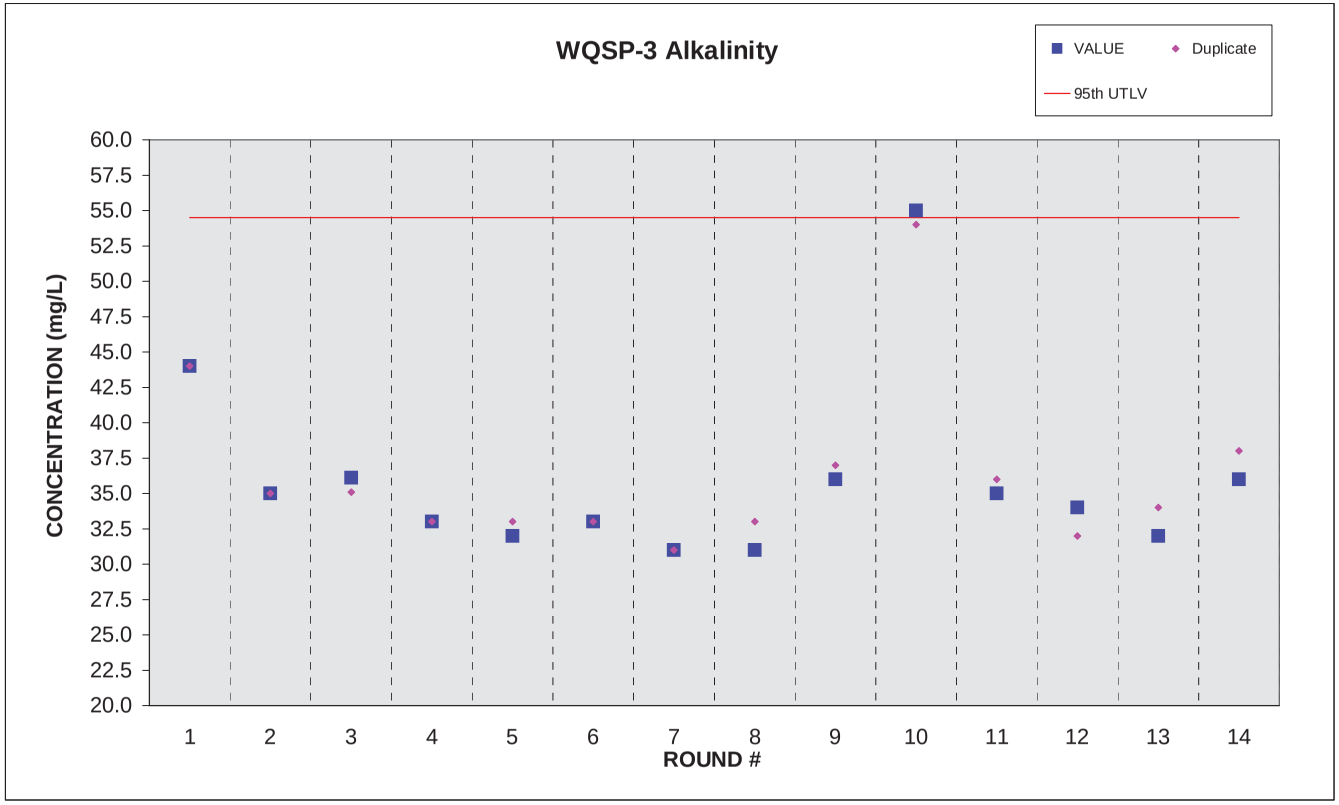

WQSP-3 Chloride

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
7782-50-5	CHLORIDE		130000.0		138000.0	mg/L	5.0	149100.0			<	5.0	1	09/22/95	09/19/95
7782-50-5	CHLORIDE		144000.0		145000.0	mg/L	5000.0	149100.0		0.0	<	5.0	2	05/16/96	05/09/96
7782-50-5	CHLORIDE		129000.0		128000.0	mg/L	5000.0	149100.0		0.0	<	5.0	3	09/18/96	08/22/96
7782-50-5	CHLORIDE		128000.0		129000.0	mg/L	5000.0	149100.0			<	5.0	4	06/04/97	05/22/97
7782-50-5	CHLORIDE		121000.0		123000.0	mg/L	5000.0	149100.0			<	5.0	5	08/29/97	08/21/97
7782-50-5	CHLORIDE		125000.0		125000.0	mg/L	0.0	149100.0				0.0	6	04/24/98	04/22/98
7782-50-5	CHLORIDE		120000.0		130000.0	mg/L	0.5	149100.0				1.7	7	09/03/98	08/26/98
7782-50-5	CHLORIDE		120000.0		130000.0	mg/L	0.5	149100.0			<	0.5	8	04/09/99	04/08/99
7782-50-5	CHLORIDE		140000.0		140000.0	mg/L	0.5	149100.0			<	0.5	9	10/06/99	10/06/99
7782-50-5	CHLORIDE		123000.0		123000.0	mg/L	0.5	149100.0			<	0.5	10	03/24/00	03/23/00
7782-50-5	CHLORIDE		130000.0		130000.0	mg/L	0.5	149100.0			<	0.5	11	10/11/00	10/05/00
7782-50-5	CHLORIDE		130000.0		130000.0	mg/L	0.5	149100.0					12	04/04/01	03/29/01
7782-50-5	CHLORIDE		131000.0		129000.0	mg/L	2.0	149100.0					13	10/12/01	10/04/01
7782-50-5	CHLORIDE		125000.0		126000.0	mg/L	2.0	149100.0					14	04/04/02	04/04/02

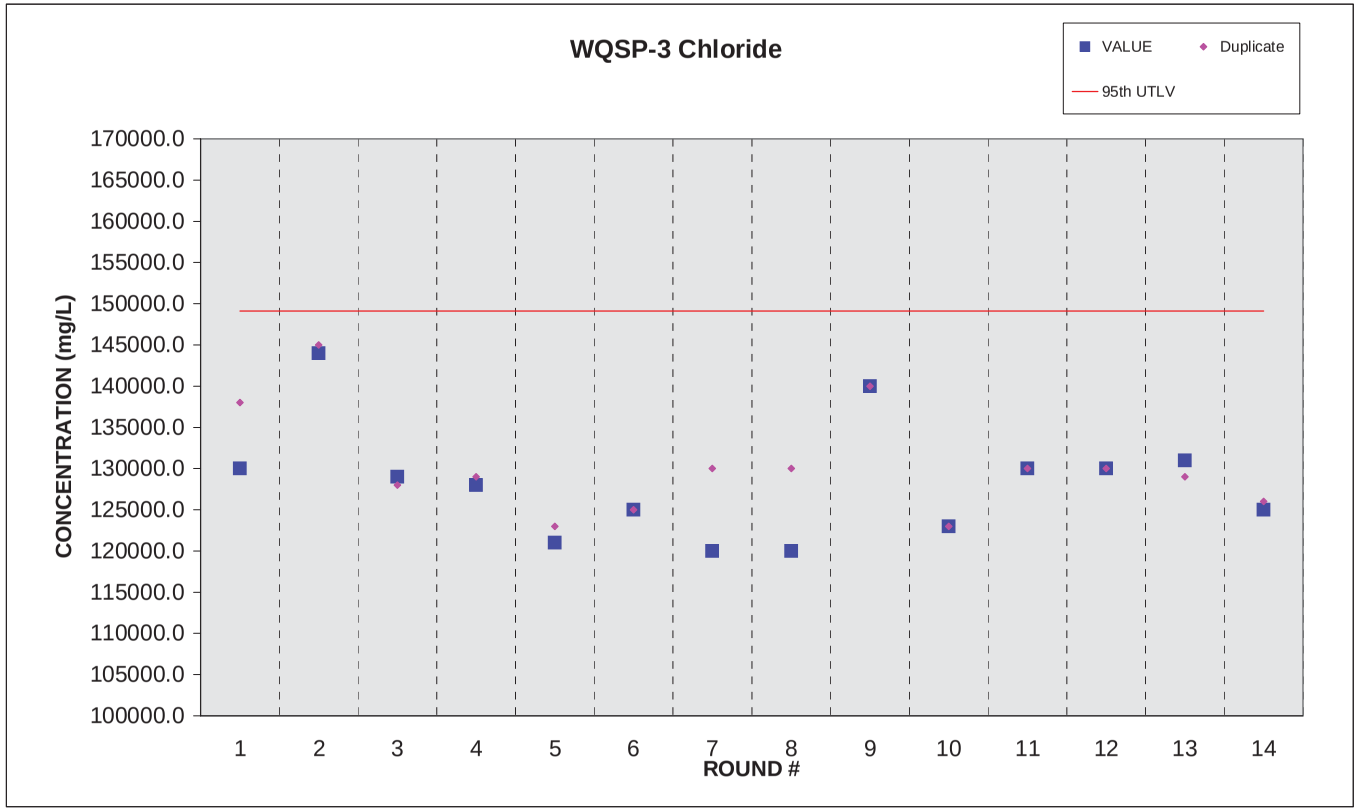

WQSP-3 Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		6710.0		6700.0	mg/L	10.0	8015.0			<	10.0	1	08/29/95	08/17/95
	SULFATE		6760.0		6840.0	mg/L	2.5	8015.0			<	10.0	2	04/25/96	04/11/96
	SULFATE		7650.0		7650.0	mg/L	2.5	8015.0			<	10.0	3	08/21/96	07/25/96
	SULFATE		7230.0		7260.0	mg/L	2.5	8015.0			<	10.0	4	05/01/97	04/24/97
	SULFATE		7400.0		6400.0	mg/L	2.5	8015.0			<	10.0	5	09/03/97	07/24/97
	SULFATE		6770.0		6769.4	mg/L	0.0	8015.0			<	0.0	6	03/11/98	03/05/98
	SULFATE		7400.0		7200.0	mg/L	0.5	8015.0					7	07/26/98	07/15/98
	SULFATE		7300.0		7300.0	mg/L	0.5	8015.0			<	0.5	8	03/03/99	03/03/99
	SULFATE		7500.0		7400.0	mg/L	0.5	8015.0			<	0.5	9	09/07/99	09/01/99
	SULFATE		7500.0		7200.0	mg/L	0.5	8015.0			<	0.5	10	03/24/00	03/23/00
	SULFATE		7000.0		6800.0	mg/L	0.5	8015.0			<	0.5	11	10/09/00	10/05/00
	SULFATE		7200.0		7200.0	mg/L	0.5	8015.0					12	04/04/01	03/29/01
	SULFATE		7460.0		7190.0	mg/L	2.0	8015.0					13	10/12/01	10/04/01
	SULFATE		7540.0		7150.0	mg/L	2.0	8015.0					14	04/04/02	04/04/02

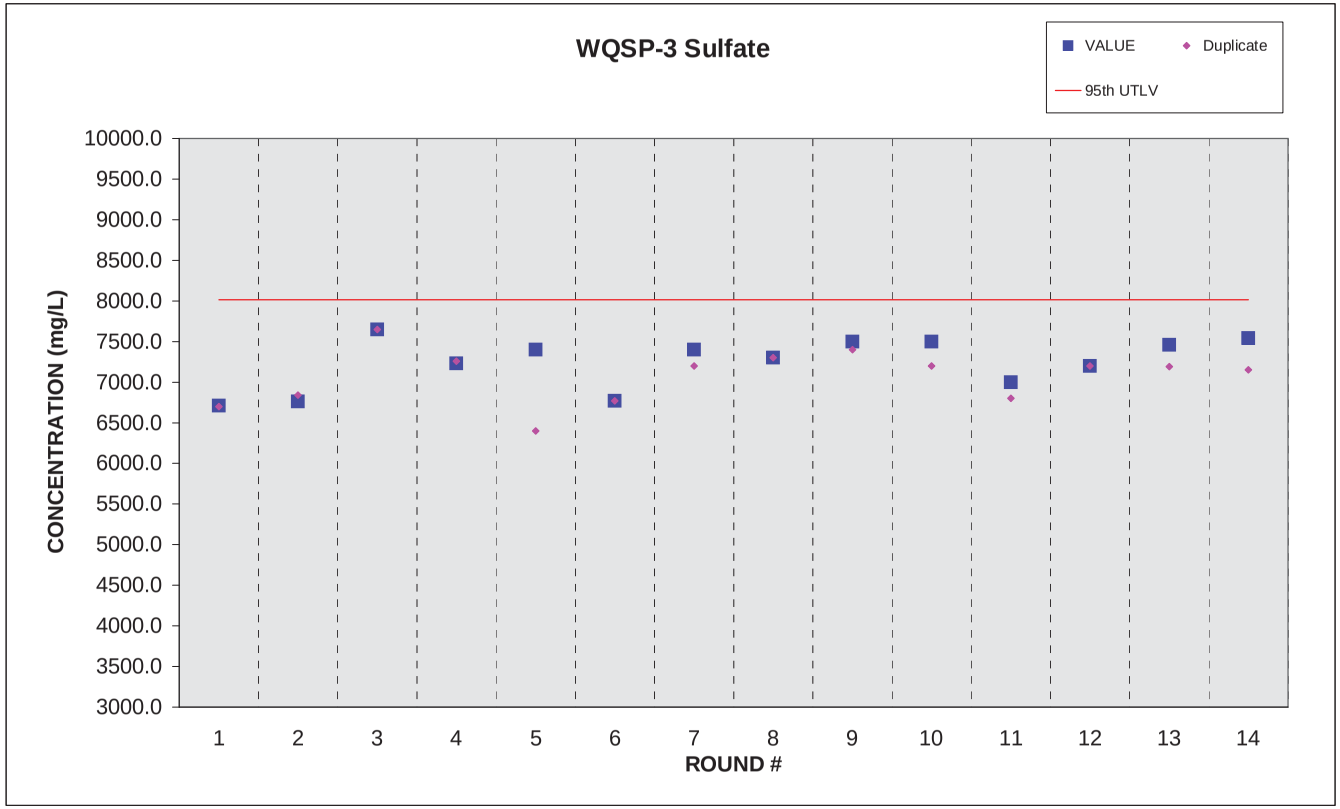

WQSP-4 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		1710.0		1650.0	mg/L	40.0	1834.0			<	0.2	1	10/20/95	09/28/95
7440-70-2	CALCIUM		1570.0		1550.0	mg/L	2.0	1834.0	<	0.2	<	0.2	2	06/18/96	05/23/96
7440-70-2	CALCIUM		1590.0		1600.0	mg/L	2.0	1834.0	<	0.2	<	0.2	3	09/18/96	09/12/96
7440-70-2	CALCIUM		1490.0		1470.0	mg/L	2.0	1834.0	<	0.2	<	0.2	4	06/17/97	06/05/97
7440-70-2	CALCIUM		1480.0		1550.0	mg/L	2.0	1834.0	<	0.2	<	0.2	5	09/30/97	09/11/97
7440-70-2	CALCIUM		1600.0		1600.0	mg/L	0.0	1834.0				0.0	6	05/12/98	05/06/98
7440-70-2	CALCIUM		1560.0		1740.0	mg/L	0.5	1834.0			<	0.5	7	09/28/98	09/23/98
7440-70-2	CALCIUM		1480.0		1670.0	mg/L	1.0	1834.0			<	1.0	8	04/27/99	04/21/99
7440-70-2	CALCIUM		1640.0		1824.0	mg/L	0.1	1834.0			<	0.1	9	12/01/99	11/25/99
7440-70-2	CALCIUM		1610.0		1670.0	mg/L	0.1	1834.0			<	0.1	10	04/24/00	04/12/00
7440-70-2	CALCIUM		1560.0		1550.0	mg/L	5.0	1834.0			<	5.0	11	10/26/00	10/26/00
7440-70-2	CALCIUM		1520.0		1650.0	mg/L	0.5	1834.0			<	0.5	12	06/25/01	04/18/01
7440-70-2	CALCIUM		1470.0		1505.0	mg/L	0.2	1834.0					13	10/29/01	10/17/01
7440-70-2	CALCIUM		1610.0		1590.0	mg/L	0.5	1834.0					14	04/24/02	04/17/02

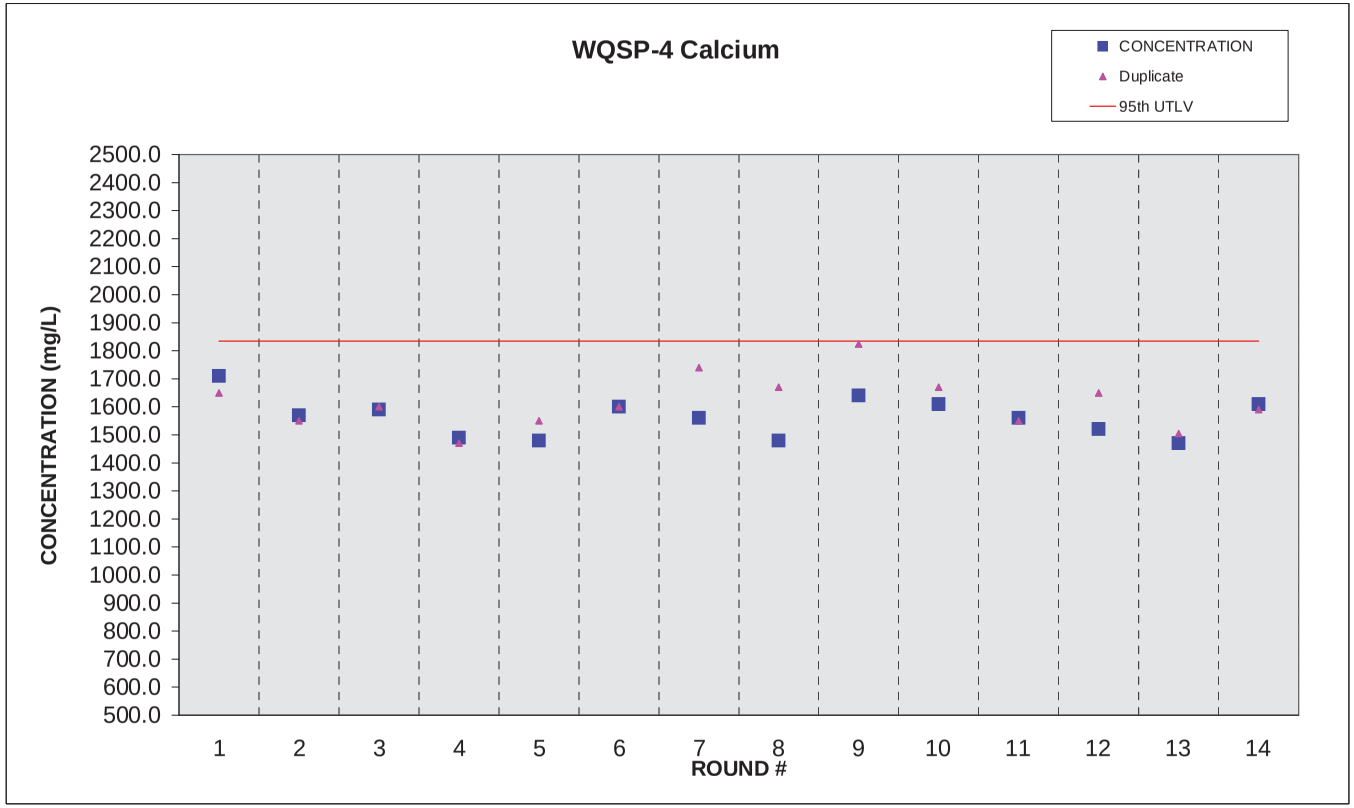

WQSP-4 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		1270.0		1230.0	mg/L	4.0	1472.0			<	0.1	1	10/20/95	09/28/95
7439-95-4	MAGNESIUM		1100.0		1070.0	mg/L	0.5	1472.0	<	0.1	<	0.1	2	06/18/96	05/23/96
7439-95-4	MAGNESIUM		1140.0		1150.0	mg/L	0.5	1472.0	<	0.1	<	0.1	3	09/18/96	09/12/96
7439-95-4	MAGNESIUM		1040.0		1040.0	mg/L	1.0	1472.0	<	0.1	<	0.1	4	06/17/97	06/05/97
7439-95-4	MAGNESIUM		1130.0		1180.0	mg/L	1.0	1472.0	<	0.1	<	0.1	5	09/30/97	09/11/97
7439-95-4	MAGNESIUM		1280.0		1280.0	mg/L	0.1	1472.0				0.1	6	05/12/98	05/06/98
7439-95-4	MAGNESIUM		1230.0		1420.0	mg/L	0.5	1472.0			<	0.5	7	09/28/98	09/23/98
7439-95-4	MAGNESIUM		1040.0		1180.0	mg/L	1.0	1472.0			<	1.0	8	04/27/99	04/21/99
7439-95-4	MAGNESIUM		1249.0		1397.0	mg/L	0.5	1472.0			<	0.5	9	12/01/99	10/13/99
7439-95-4	MAGNESIUM		1180.0		1210.0	mg/L	0.1	1472.0			<	0.5	10	04/24/00	04/12/00
7439-95-4	MAGNESIUM		1190.0		1180.0	mg/L	5.0	1472.0			<	5.0	11	10/26/00	10/18/00
7439-95-4	MAGNESIUM		1050.0		1060.0	mg/L	0.5	1472.0			<	0.5	12	06/25/01	04/18/01
7439-95-4	MAGNESIUM		1093.0		1134.0	mg/L	0.2	1472.0					13	10/29/01	10/17/01
7439-95-4	MAGNESIUM		1260.0		1200.0	mg/L	0.5	1472.0					14	04/24/02	04/17/02

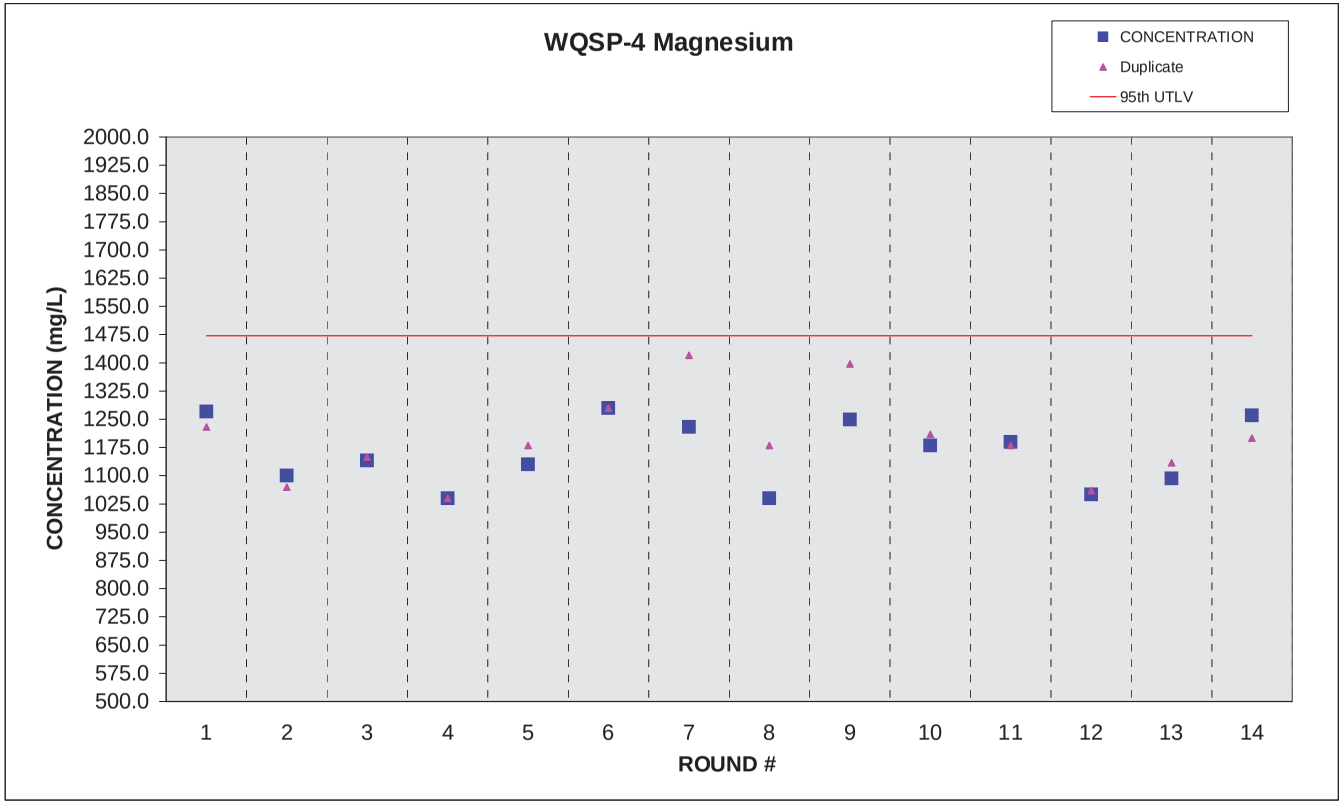

WQSP-4 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		764.0		732.0	mg/L	40.0	1648.0			<	0.2	1	10/20/95	09/28/95
7440-09-7	POTASSIUM		700.0		691.0	mg/L	2.0	1648.0	<	0.2	<	0.2	2	05/29/96	05/23/96
7440-09-7	POTASSIUM		733.0		782.0	mg/L	2.0	1648.0	<	0.2	<	0.2	3	09/20/96	09/12/96
7440-09-7	POTASSIUM		672.0		654.0	mg/L	2.0	1648.0	<	0.2	<	0.2	4	06/13/97	06/05/97
7440-09-7	POTASSIUM		681.0		664.0	mg/L	2.0	1648.0	<	0.2	<	0.2	5	09/19/97	09/11/97
7440-09-7	POTASSIUM		760.0		760.0	mg/L	0.1	1648.0			<	0.1	6	05/12/98	05/06/98
7440-09-7	POTASSIUM		1370.0		1440.0	mg/L	0.5	1648.0			<	0.5	7	09/28/98	09/23/98
7440-09-7	POTASSIUM		935.0		1060.0	mg/L	1.0	1648.0			<	1.0	8	04/27/99	04/21/99
7440-09-7	POTASSIUM		980.0		1049.0	mg/L	0.5	1648.0			<	0.5	9	12/01/99	10/13/99
7440-09-7	POTASSIUM		1180.0		1217.0	mg/L	0.1	1648.0			<	0.5	10	04/24/00	04/12/00
7440-09-7	POTASSIUM		1350.0		1350.0	mg/L	1.0	1648.0					10	06/19/00	same
7440-09-7	POTASSIUM		1320.0		1320.0	mg/L	5.0	1648.0			<	0.2	11	10/26/00	10/18/00
7440-09-7	POTASSIUM		1020.0		1090.0	mg/L	0.5	1648.0			<	0.5	12	06/25/01	04/18/01
7440-09-7	POTASSIUM		1221.0		1245.0	mg/L	0.2	1648.0					13	10/29/01	10/17/01
7440-09-7	POTASSIUM		1220.0		1230.0	mg/L	0.5	1648.0					14	04/24/02	04/17/02

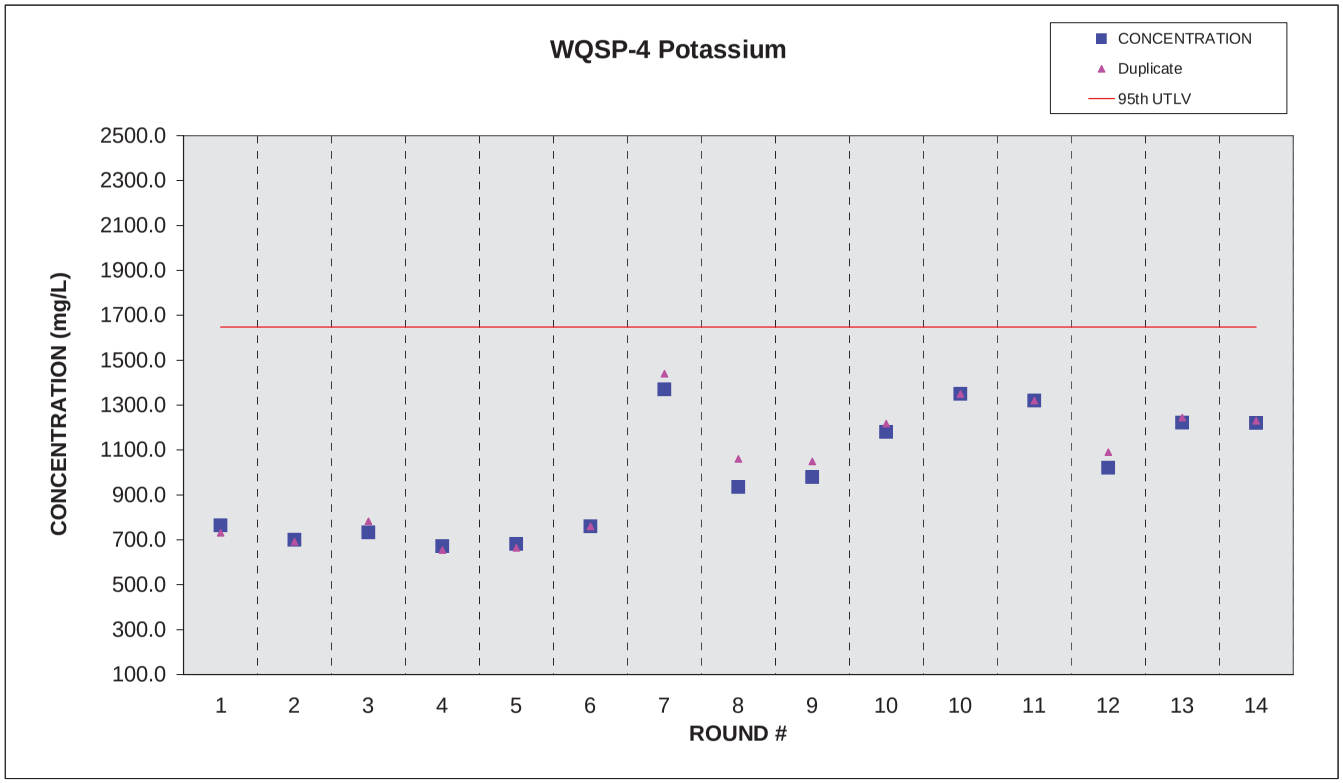

WQSP-4 Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		35900.0		34400.0	mg/L	100.0	38790.0			<	0.5	1	10/20/95	09/28/95
7440-23-5	SODIUM		33600.0		32400.0	mg/L	25.0	38790.0	<	0.5	<	0.5	2	05/29/96	05/23/96
7440-23-5	SODIUM		33300.0		32900.0	mg/L	5.0	38790.0	<	0.5	<	0.5	3	09/20/96	09/12/96
7440-23-5	SODIUM		30800.0		31300.0	mg/L	25.0	38790.0	<	0.5	<	0.5	4	06/13/97	06/05/97
7440-23-5	SODIUM		32600.0		31200.0	mg/L	25.0	38790.0	<	0.5	<	0.5	5	09/19/97	09/11/97
7440-23-5	SODIUM		37300.0		37300.0	mg/L	0.0	38790.0				0.1	6	05/12/98	05/06/98
7440-23-5	SODIUM		31700.0		26900.0	mg/L	0.5	38790.0			<	0.5	7	09/28/98	09/23/98
7440-23-5	SODIUM		32900.0		32500.0	mg/L	1.0	38790.0			<	1.0	8	04/27/99	04/21/99
7440-23-5	SODIUM		30310.0		33250.0	mg/L	0.5	38790.0			<	0.5	9	12/01/99	10/13/99
7440-23-5	SODIUM		34000.0		35200.0	mg/L	0.1	38790.0			<	0.5	10	04/24/00	04/12/00
7440-23-5	SODIUM		30700.0		26100.0	mg/L	5.0	38790.0				0.4	11	10/28/00	10/18/00
7440-23-5	SODIUM		35000.0		34200.0	mg/L	0.5	38790.0			<	0.5	12	06/25/01	04/18/01
7440-23-5	SODIUM		34100.0		33170.0	mg/L	0.2	38790.0					13	10/29/01	10/17/01
7440-23-5	SODIUM		27200.0		31600.0	mg/L	0.5	38790.0					14	04/24/02	04/17/02

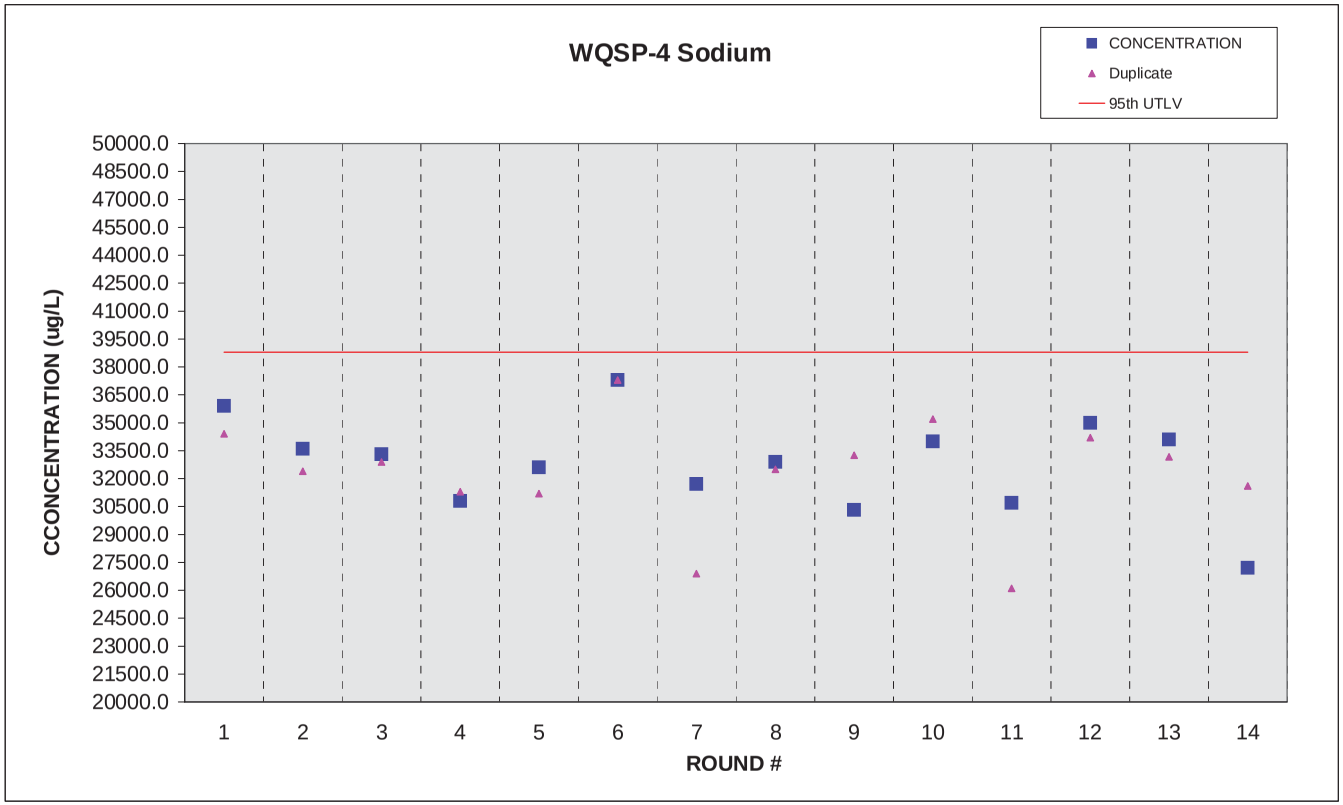

WQSP-4 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		40.0		42.0	mg/L	5.0	47.1			<	5.0	1	10/02/95	09/28/95
	ALKALINITY		29.0		30.0	mg/L	5.0	47.1		0.0	<	5.0	2	05/31/96	05/23/96
	ALKALINITY		39.0		40.1	mg/L	5.0	47.1		0.0	<	5.0	3	09/26/96	09/12/96
	ALKALINITY		38.0		36.0	mg/L	5.0	47.1			<	5.0	4	06/09/97	06/05/97
	ALKALINITY		41.0		40.0	mg/L	5.0	47.1		0.0	<	5.0	5	09/26/97	09/11/97
	ALKALINITY		38.0		38.0	mg/L	5.0	47.1					6	05/12/98	05/06/98
	ALKALINITY		44.0		42.0	mg/L	1.0	47.1			<	1.0	7	09/30/98	09/23/98
	ALKALINITY		39.0		39.0	mg/L	4.0	47.1			<	4.0	8	04/22/99	04/21/99
	ALKALINITY		38.0		36.0	mg/L	4.0	47.1					9	10/22/99	10/13/99
	ALKALINITY		41.0		39.0	mg/L	4.0	47.1					10	04/17/00	04/12/00
	ALKALINITY		36.0		40.0	mg/L	4.0	47.1			<	4.0	11	10/31/00	10/18/00
	ALKALINITY		40.0		38.0	mg/L	4.0	47.1					12	04/25/01	04/18/01
	ALKALINITY		36.0		34.0	mg/L	4.0	47.1					13	10/23/01	10/17/01
	ALKALINITY		42.0		40.0	mg/L	4.0	47.1					14	04/18/02	04/17/02

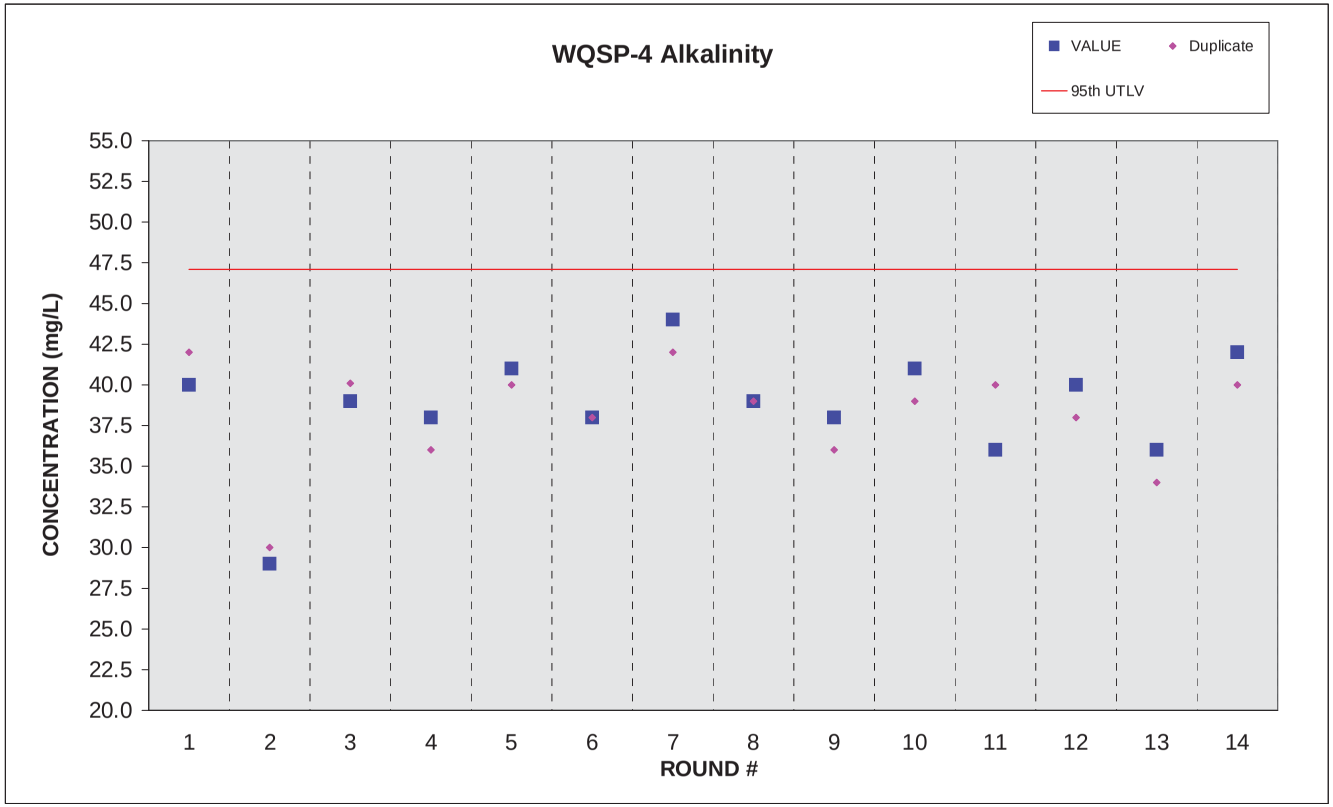

WQSP-4 Chloride

CAS #	PARAMETER		VALUE		VALUE DUPLICATE	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		61200.0		60700.0	mg/L	5.0	63960.0			<	5.0	1	10/13/95	09/28/95
7782-50-5	CHLORIDE		61500.0		61200.0	mg/L	2500.0	63960.0			<	5.0	2	05/29/96	05/23/96
7782-50-5	CHLORIDE		59700.0		57000.0	mg/L	2500.0	63960.0			<	5.0	3	09/18/96	09/12/96
7782-50-5	CHLORIDE		59500.0		59500.0	mg/L	5000.0	63960.0			<	5.0	4	06/18/97	06/05/97
7782-50-5	CHLORIDE		58700.0		58200.0	mg/L	5000.0	63960.0			<	5.0	5	09/26/97	09/11/97
7782-50-5	CHLORIDE		57100.0		55800.0	mg/L	0.0	63960.0				0.0	6	05/12/98	05/06/98
7782-50-5	CHLORIDE		53000.0		55000.0	mg/L	0.5	63960.0				2.0	7	09/28/98	09/23/98
7782-50-5	CHLORIDE		57000.0		57000.0	mg/L	0.5	63960.0			<	0.5	8	04/22/99	04/21/99
7782-50-5	CHLORIDE		57000.0		55000.0	mg/L	0.5	63960.0			<	0.5	9	10/13/99	10/13/99
7782-50-5	CHLORIDE		59000.0		61000.0	mg/L	0.5	63960.0			<	0.5	10	04/18/00	04/12/00
7782-50-5	CHLORIDE		60000.0		54000.0	mg/L	0.5	63960.0			<	0.5	11	11/15/00	10/18/00
7782-50-5	CHLORIDE		54900.0		52100.0	mg/L	0.5	63960.0					12	04/19/01	04/18/01
7782-50-5	CHLORIDE		55300.0		55000.0	mg/L	2.0	63960.0					13	10/23/01	10/17/01
7782-50-5	CHLORIDE		49700.0		50500.0	mg/L	2.0	63960.0					14	04/22/02	04/17/02

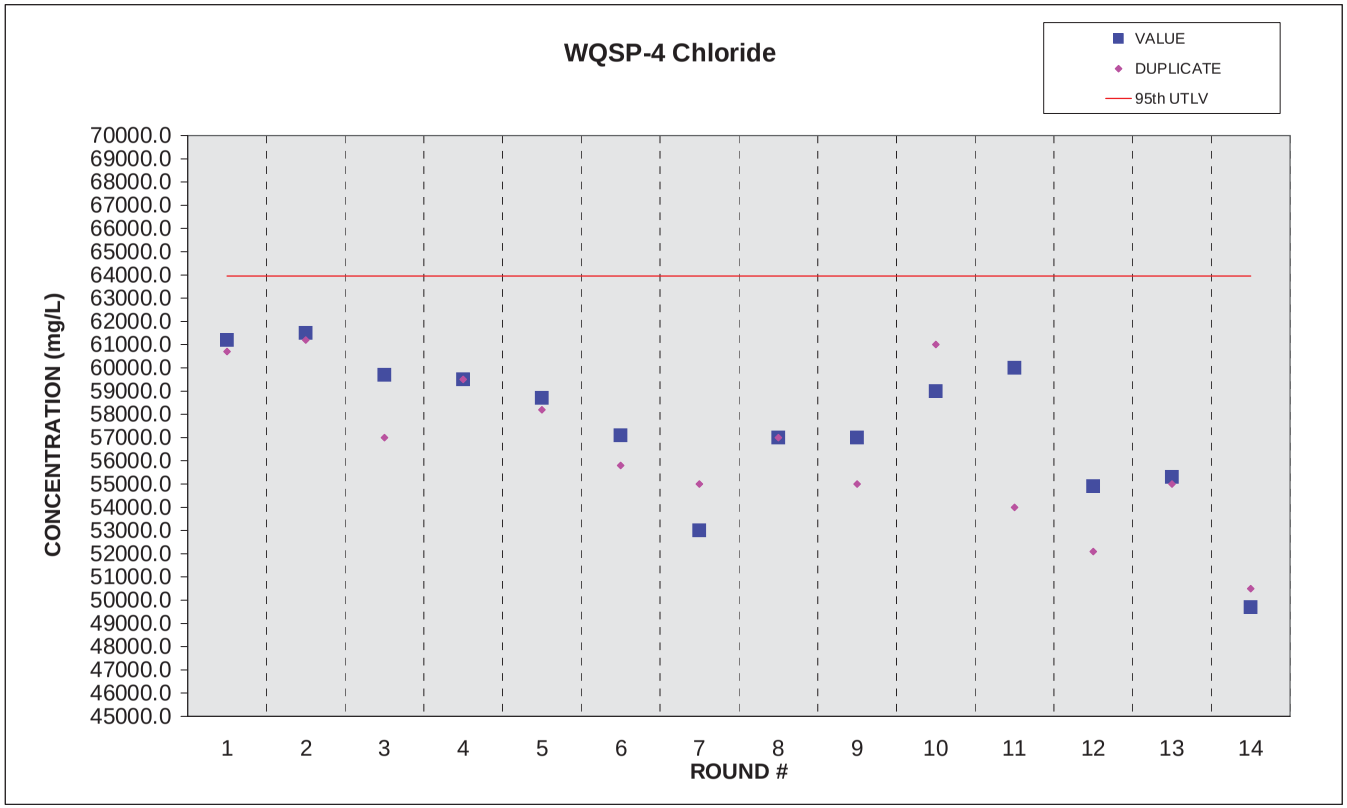

WQSP-4 Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		7100.0		7050.0	mg/L	10.0	7927.0			<	10.0	1	10/13/95	09/28/95
	SULFATE		6520.0		5960.0	mg/L	2500.0	7927.0			<	10.0	2	05/29/96	05/23/96
	SULFATE		6860.0		7660.0	mg/L	2500.0	7927.0			<	10.0	3	09/18/96	09/12/96
	SULFATE		7040.0		7380.0	mg/L	2500.0	7927.0			<	10.0	4	06/18/97	06/05/97
	SULFATE		6940.0		6880.0	mg/L	2500.0	7927.0			<	10.0	5	09/30/97	09/11/97
	SULFATE		6020.0		5820.0	mg/L	0.0	7927.0				0.1	6	05/12/98	05/06/98
	SULFATE		6000.0		6100.0	mg/L	0.5	7927.0					7	10/01/98	09/23/98
	SULFATE		6800.0		6600.0	mg/L	0.5	7927.0			<	0.5	8	04/22/99	04/21/99
	SULFATE		6500.0		6200.0	mg/L	0.5	7927.0			<	0.5	9	10/13/99	10/13/99
	SULFATE		6700.0		7300.0	mg/L	0.5	7927.0			<	0.5	10	04/18/00	04/12/00
	SULFATE		6700.0		6300.0	mg/L	0.5	7927.0			<	0.5	11	11/15/00	10/18/00
	SULFATE		6470.0		6380.0	mg/L	0.5	7927.0					12	04/19/01	04/18/01
	SULFATE		6300.0		6130.0	mg/L	2.0	7927.0					13	10/22/01	10/17/01
	SULFATE		6560.0		6400.0	mg/L	2.0	7927.0					14	04/22/02	04/17/02

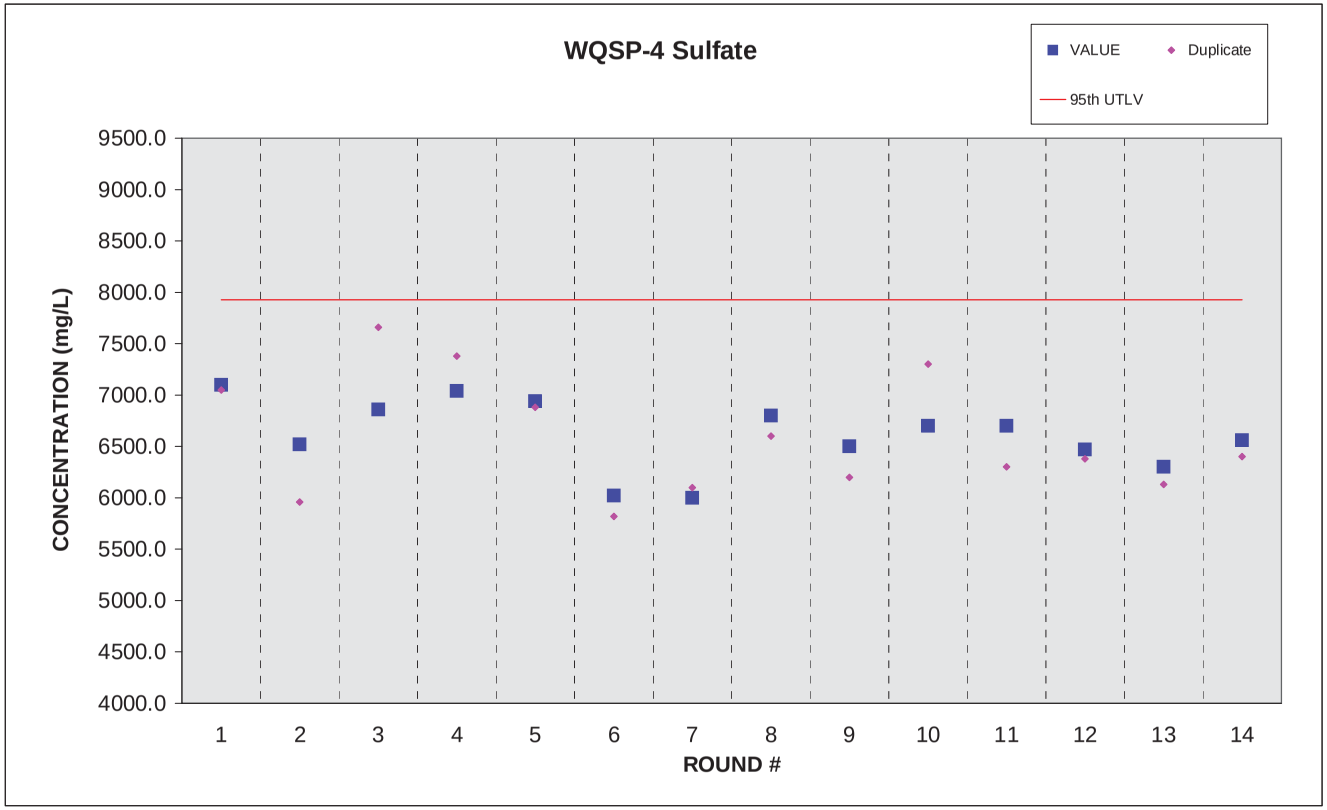

WQSP-5 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		987.0		982.0	mg/L	2.0	1303.0	<	0.2	<	0.2	1	12/15/95	11/20/95
7440-70-2	CALCIUM		1020.0		1020.0	mg/L	2.0	1303.0	<	0.2	<	0.2	2	06/18/96	06/06/96
7440-70-2	CALCIUM		1010.0		1030.0	mg/L	2.0	1303.0	<	0.2	<	0.2	3	10/01/96	09/26/96
7440-70-2	CALCIUM		980.0		982.0	mg/L	2.0	1303.0	<	0.2	<	0.2	4	06/26/97	06/19/97
7440-70-2	CALCIUM		986.0		945.0	mg/L	2.0	1303.0	<	0.2	<	0.2	5	10/27/97	09/25/97
7440-70-2	CALCIUM		1040.0		992.2	mg/L	0.0	1303.0			<	0.0	6	05/22/98	05/20/98
7440-70-2	CALCIUM		1100.0		1030.0	mg/L	0.5	1303.0				0.1	7	11/27/98	10/07/98
7440-70-2	CALCIUM		1090.0		1220.0	mg/L	1.0	1303.0			<	1.0	8	05/12/99	05/05/99
7440-70-2	CALCIUM		1071.0		1126.0	mg/L	0.1	1303.0			<	0.1	9	12/01/99	10/27/99
7440-70-2	CALCIUM		1410.0		991.0	mg/L	5.0	1303.0				0.3	10	05/24/00	04/26/00
7440-70-2	CALCIUM		1170.0		1070.0	mg/L	5.0	1303.0					10	06/19/00	06/19/00
7440-70-2	CALCIUM		1020.0		1010.0	mg/L	5.0	1303.0				0.0	11	11/24/00	11/01/00
7440-70-2	CALCIUM		1011.0		1029.0	mg/L	5.0	1303.0					12	06/25/01	05/02/01
7440-70-2	CALCIUM		1090.0		1080.0	mg/L	0.2	1303.0					13	11/05/01	10/31/01
7440-70-2	CALCIUM		1010.0		1080.0	mg/L	0.5	1303.0					14	05/06/02	05/01/02

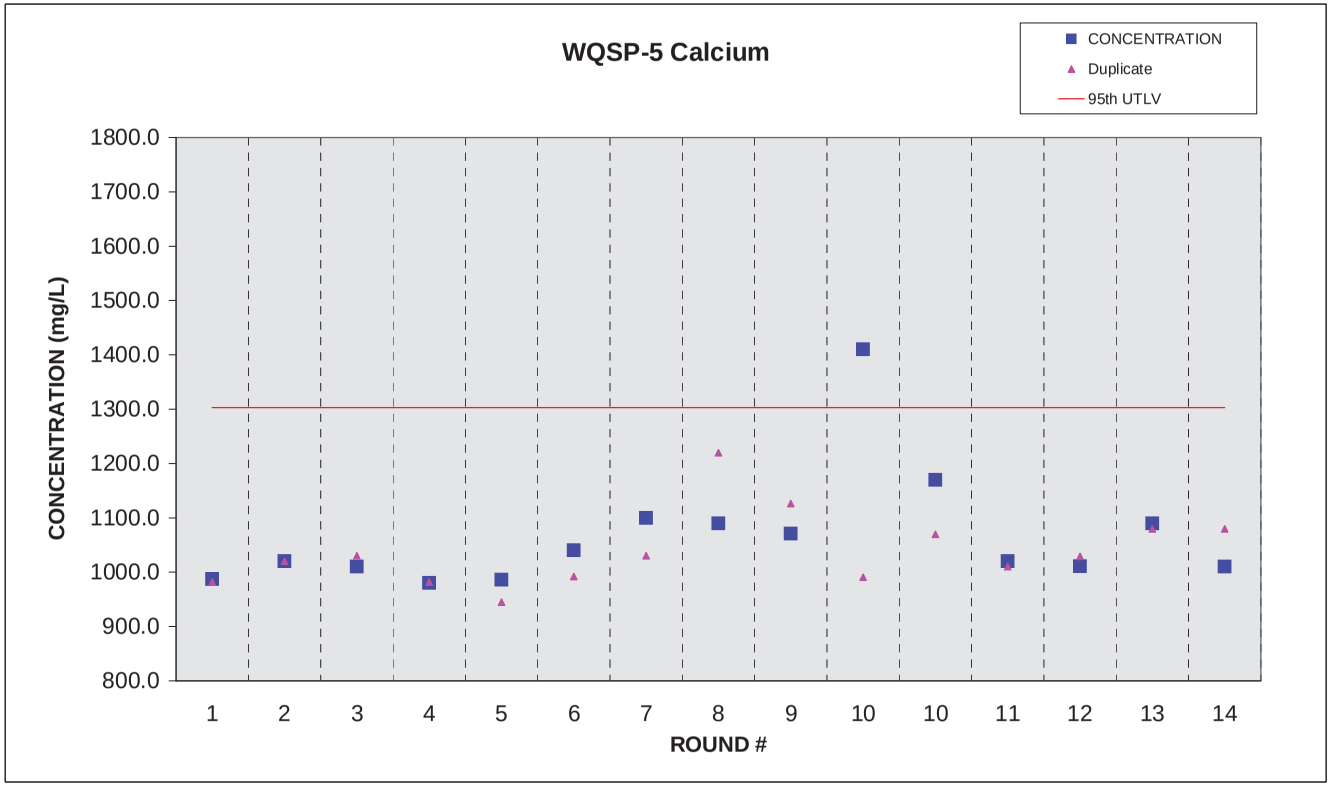

WQSP-5 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		434.0		432.0	mg/L	1.0	547.0	<	0.1	<	0.1	1	12/15/95	11/20/95
7439-95-4	MAGNESIUM		427.0		417.0	mg/L	0.5	547.0	<	0.1	<	0.1	2	06/18/96	06/06/96
7439-95-4	MAGNESIUM		421.0		427.0	mg/L	0.5	547.0	<	0.1	<	0.1	3	10/01/96	09/26/96
7439-95-4	MAGNESIUM		452.0		454.0	mg/L	1.0	547.0	<	0.1	<	0.1	4	06/26/97	06/19/97
7439-95-4	MAGNESIUM		441.0		425.0	mg/L	0.5	547.0	<	0.1	<	0.1	5	10/27/97	09/25/97
7439-95-4	MAGNESIUM		485.0		468.4	mg/L	0.1	547.0			<	0.1	6	05/22/98	05/20/98
7439-95-4	MAGNESIUM		508.0		484.0	mg/L	0.5	547.0			<	0.1	7	11/27/98	10/07/98
7439-95-4	MAGNESIUM		474.0		547.0	mg/L	1.0	547.0			<	1.0	8	05/12/99	05/05/99
7439-95-4	MAGNESIUM		484.0		515.0	mg/L	0.5	547.0			<	0.5	9	12/01/99	10/27/99
7439-95-4	MAGNESIUM		850.0		431.0	mg/L	5.0	547.0				0.2	10	05/24/00	04/26/00
7439-95-4	MAGNESIUM		500.0		450.0	mg/L	5.0	547.0					10	06/19/00	same
7439-95-4	MAGNESIUM		454.0		462.0	mg/L	5.0	547.0				0.1	11	11/24/00	11/01/00
7439-95-4	MAGNESIUM		425.0		437.0	mg/L	5.0	547.0					12	06/25/01	05/02/01
7439-95-4	MAGNESIUM		545.0		545.0	mg/L	0.2	547.0					13	11/05/01	10/31/01
7439-95-4	MAGNESIUM		451.0		457.0	mg/L	0.5	547.0					14	05/06/02	05/01/02

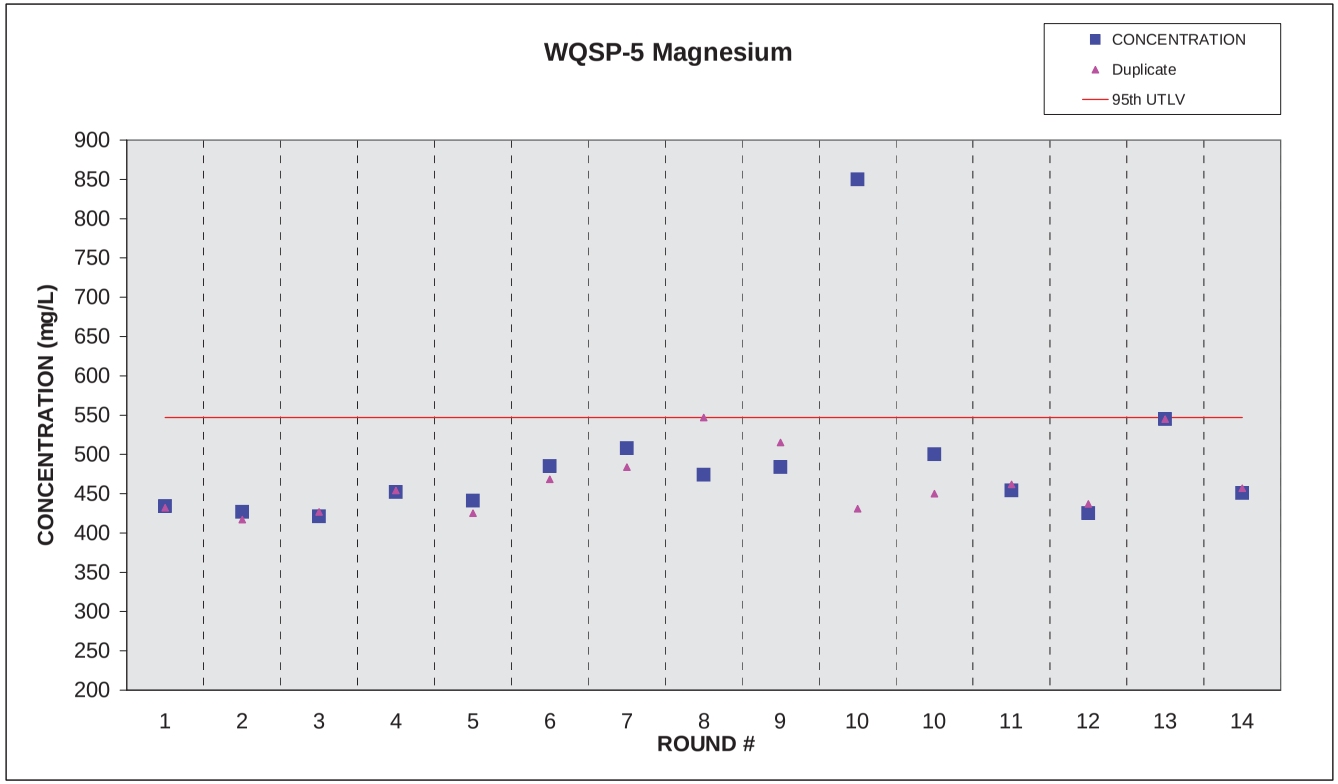

WQSP-5 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		286.0		286.0	mg/L	2.0	622.0	<	0.2	<	0.2	1	12/15/95	11/20/95
7440-09-7	POTASSIUM		290.0		288.0	mg/L	2.0	622.0	<	0.2	<	0.2	2	06/13/96	06/06/96
7440-09-7	POTASSIUM		292.0		291.0	mg/L	2.0	622.0	<	0.2	<	0.2	3	10/02/96	09/26/96
7440-09-7	POTASSIUM		284.0		281.0	mg/L	2.0	622.0	<	0.2	<	0.2	4	06/25/97	06/19/97
7440-09-7	POTASSIUM		282.0		290.0	mg/L	2.0	622.0	<	0.2	<	0.2	5	10/21/97	09/25/97
7440-09-7	POTASSIUM		304.0		301.3	mg/L	0.1	622.0			<	0.1	6	05/22/98	05/20/98
7440-09-7	POTASSIUM		360.0		340.0	mg/L	0.5	622.0			<	0.1	7	11/27/98	10/07/98
7440-09-7	POTASSIUM		527.0		582.0	mg/L	1.0	622.0			<	1.0	8	05/12/99	05/05/99
7440-09-7	POTASSIUM		385.0		416.0	mg/L	0.5	622.0			<	0.5	9	12/01/99	10/27/99
7440-09-7	POTASSIUM		594.0		254.0	mg/L	5.0	622.0				0.2	10	05/24/00	04/23/00
7440-09-7	POTASSIUM		450.0		400.0	mg/L	5.0	622.0					10	06/19/00	06/19/00
7440-09-7	POTASSIUM		395.0		410.0	mg/L	5.0	622.0					11	11/24/00	11/01/00
7440-09-7	POTASSIUM		474.0		505.0	mg/L	5.0	622.0					12	06/25/01	05/02/01
7440-09-7	POTASSIUM		452.0		454.0	mg/L	0.2	622.0					13	11/05/01	10/31/01
7440-09-7	POTASSIUM		398.0		422.0	mg/L	0.5	622.0					14	05/06/02	05/01/02

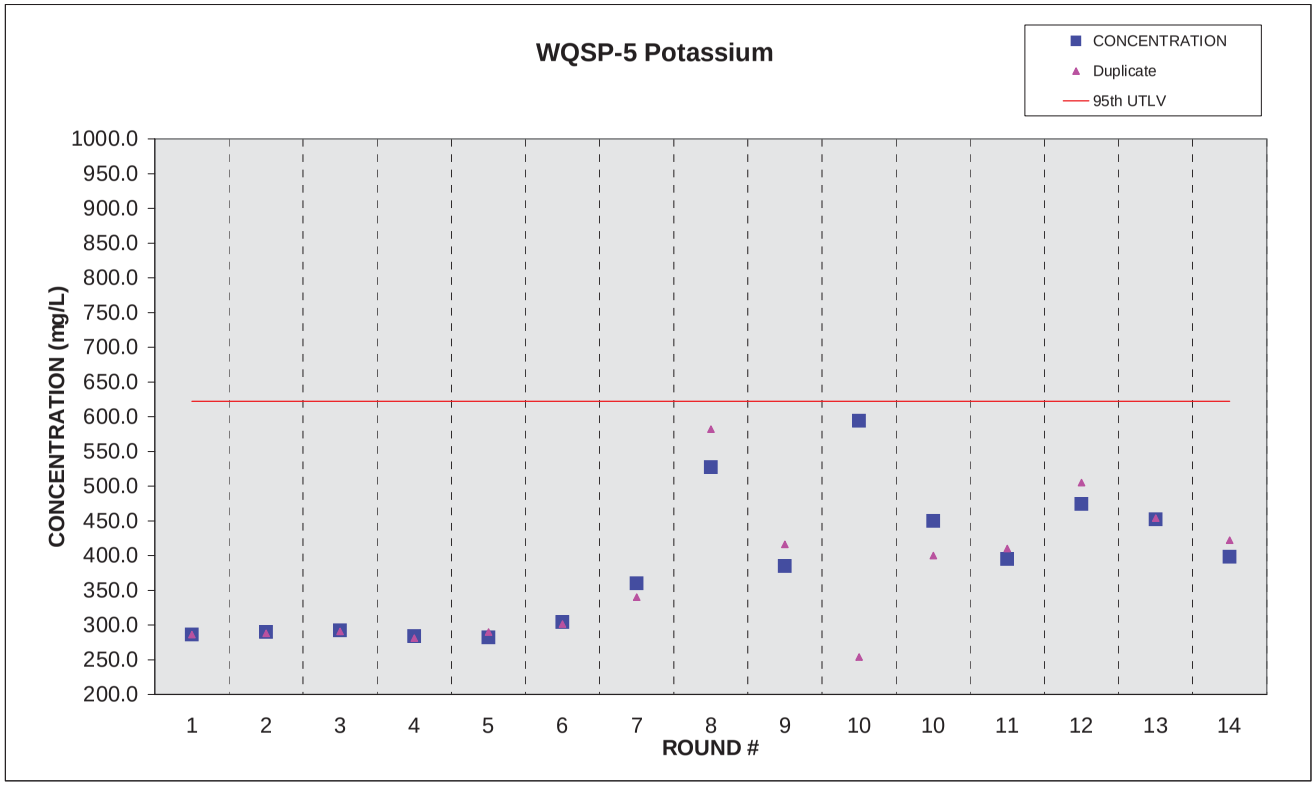

WQSP-5 Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		8880.0		8900.0	mg/L	5.0	11190.0	<	0.5	<	0.5	1	12/15/95	11/20/95
7440-23-5	SODIUM		9580.0		9420.0	mg/L	25.0	11190.0	<	0.5	<	0.5	2	06/13/96	06/06/96
7440-23-5	SODIUM		9400.0		8870.0	mg/L	25.0	11190.0	<	0.5	<	0.5	3	10/02/96	09/26/96
7440-23-5	SODIUM		9220.0		6230.0	mg/L	25.0	11190.0	<	0.5	<	0.5	4	06/25/97	06/19/97
7440-23-5	SODIUM		9160.0		9390.0	mg/L	10.0	11190.0	<	0.2	<	0.2	5	10/21/97	09/25/97
7440-23-5	SODIUM		10500.0		10078.4	mg/L	0.0	11190.0				0.0	6	05/22/98	05/20/98
7440-23-5	SODIUM		9560.0		9140.0	mg/L	0.5	11190.0			<	0.1	7	11/27/98	10/07/98
7440-23-5	SODIUM		9675.0		9545.0	mg/L	1.0	11190.0			<	1.0	8	05/12/99	05/05/99
7440-23-5	SODIUM		8380.0		8739.0	mg/L	0.5	11190.0			<	0.5	9	12/01/99	10/27/99
7440-23-5	SODIUM		8470.0		7860.0	mg/L	0.0	11190.0				0.2	10	05/24/00	04/26/00
7440-23-5	SODIUM		9040.0		8750.0	mg/L	5.0	11190.0				0.2	11	12/22/00	11/01/00
7440-23-5	SODIUM		9756.0		9712.0	mg/L	5.0	11190.0					12	06/25/01	05/02/01
7440-23-5	SODIUM		10600.0		10200.0	mg/L	0.2	11190.0					13	11/05/02	10/31/01
7440-23-5	SODIUM		8740.0		7750.0	mg/L	0.5	11190.0					14	05/06/02	05/01/02

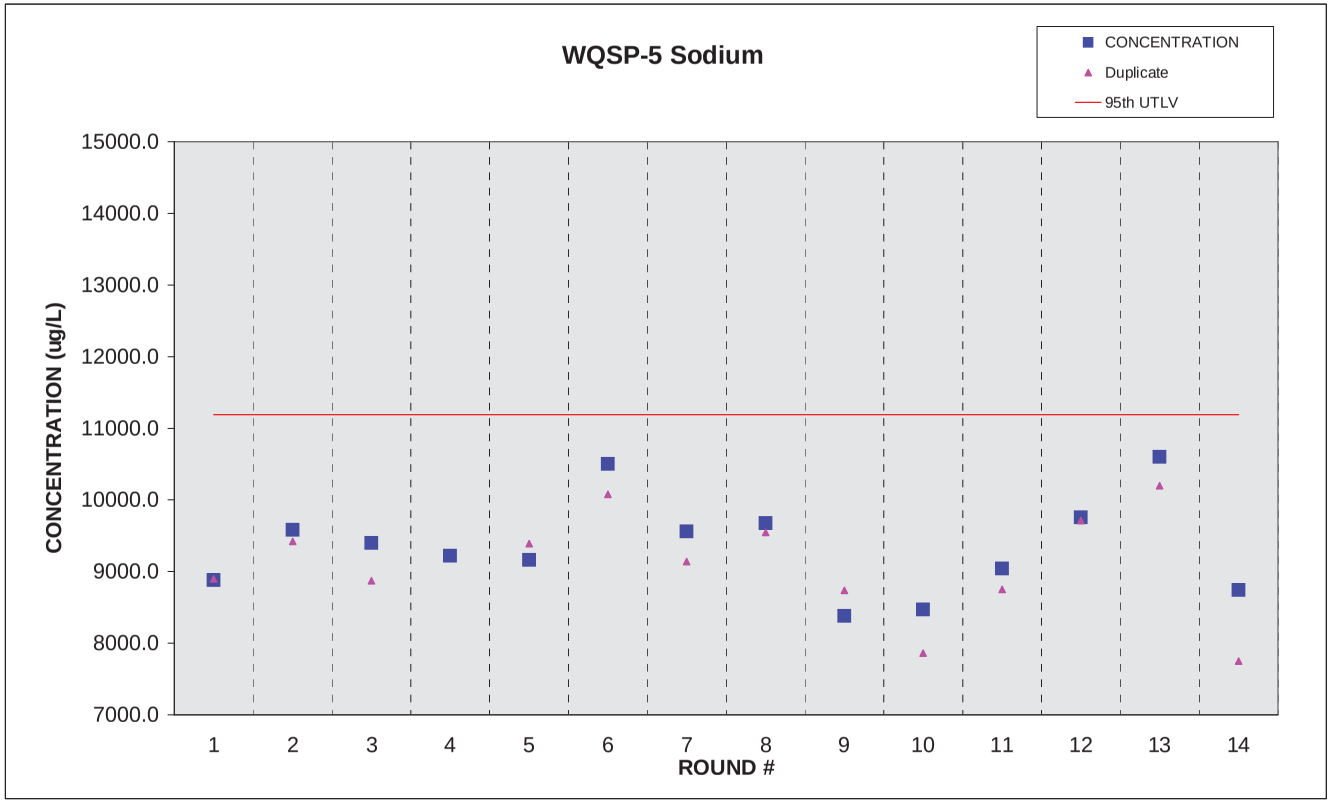

WQSP-5 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		52.0		50.0	mg/L	5.0	56.0			<	5.0	1	11/27/95	11/20/95
	ALKALINITY		41.1		42.1	mg/L	5.0	56.0			<	5.0	2	06/11/96	06/06/96
	ALKALINITY		49.1		51.1	mg/L	5.0	56.0			<	5.0	3	10/03/96	09/26/96
	ALKALINITY		52.0		51.0	mg/L	5.0	56.0			<	5.0	4	06/27/97	06/19/97
	ALKALINITY		49.0		49.0	mg/L	5.0	56.0			<	5.0	5	09/26/97	09/25/97
	ALKALINITY		48.0		48.0	mg/L		56.0					6	05/22/98	05/20/98
	ALKALINITY		48.0		50.0	mg/L	1.0	56.0			<	1.0	7	10/09/98	10/07/98
	ALKALINITY		50.0		46.0	mg/L	1.0	56.0			<	1.0	8	05/11/99	05/05/99
	ALKALINITY		44.0		46.0	mg/L		56.0			<	1.0	9	11/02/99	10/27/99
	ALKALINITY		48.0		46.0	mg/L		56.0			<	1.0	10	05/02/00	04/26/00
	ALKALINITY		46.0		48.0	mg/L	4.0	56.0			<	4.0	11	11/17/00	11/01/00
	ALKALINITY		46.0		46.0	mg/L	4.0	56.0					12	05/08/01	05/02/01
	ALKALINITY		46.0		44.0	mg/L	4.0	56.0					13	11/13/01	10/31/01
	ALKALINITY		46.0		48.0	mg/L	4.0	56.0					14	05/03/02	05/01/02

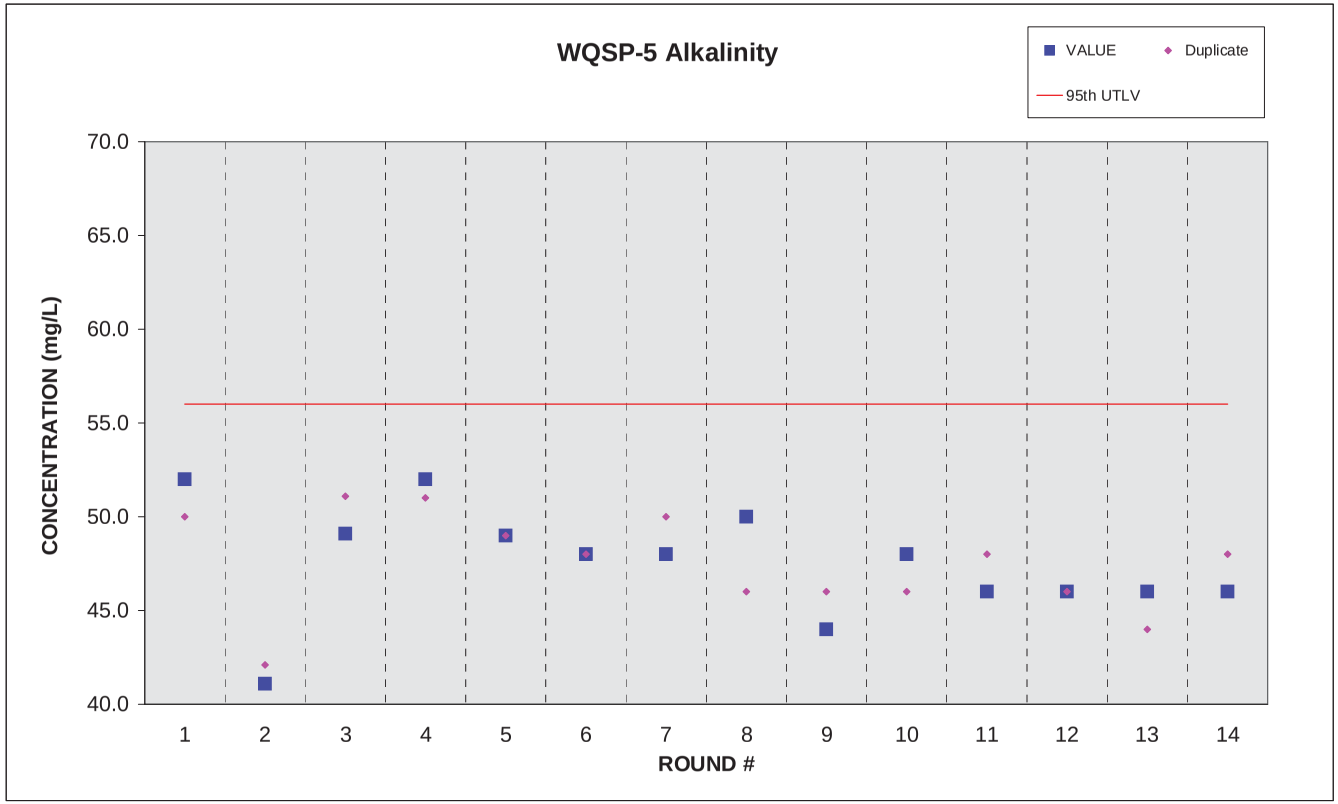

WQSP-5 Chloride

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		15000.0		14800.0	mg/L	5.0	18100.0			<	5.0	1	11/27/95	11/20/95
7782-50-5	CHLORIDE		15700.0		16000.0	mg/L	2500.0	18100.0			<	5.0	2	06/28/96	06/06/96
7782-50-5	CHLORIDE		15700.0		16200.0	mg/L	2500.0	18100.0			<	5.0	3	10/15/96	09/26/96
7782-50-5	CHLORIDE		14500.0		14500.0	mg/L	5000.0	18100.0			<	5.0	4	07/07/97	06/19/97
7782-50-5	CHLORIDE		15300.0		15100.0	mg/L	1000.0	18100.0			<	5.0	5	10/13/97	09/25/97
7782-50-5	CHLORIDE		15300.0		13591.0	mg/L	0.0	18100.0				0.0	6	05/22/98	05/20/98
7782-50-5	CHLORIDE		19000.0		16000.0	mg/L	0.5	18100.0			<	0.5	7	10/13/98	10/07/98
7782-50-5	CHLORIDE		15000.0		16000.0	mg/L	0.5	18100.0			<	0.5	8	05/05/99	05/05/99
7782-50-5	CHLORIDE		15000.0		15000.0	mg/L	0.5	18100.0			<	0.5	9	10/28/99	10/27/99
7782-50-5	CHLORIDE		16000.0		16000.0	mg/L	0.5	18100.0			<	0.5	10	05/04/00	04/26/00
7782-50-5	CHLORIDE		16000.0		16000.0	mg/L	0.5	18100.0			<	0.5	11	11/02/00	11/01/00
7782-50-5	CHLORIDE		16100.0		15700.0	mg/L	0.5	18100.0					12	05/03/01	05/02/01
7782-50-5	CHLORIDE		15600.0		14800.0	mg/L	2.0	18100.0					13	11/15/01	10/31/01
7782-50-5	CHLORIDE		15900.0		15200.0	mg/L	2.0	18100.0					14	05/07/02	05/01/02

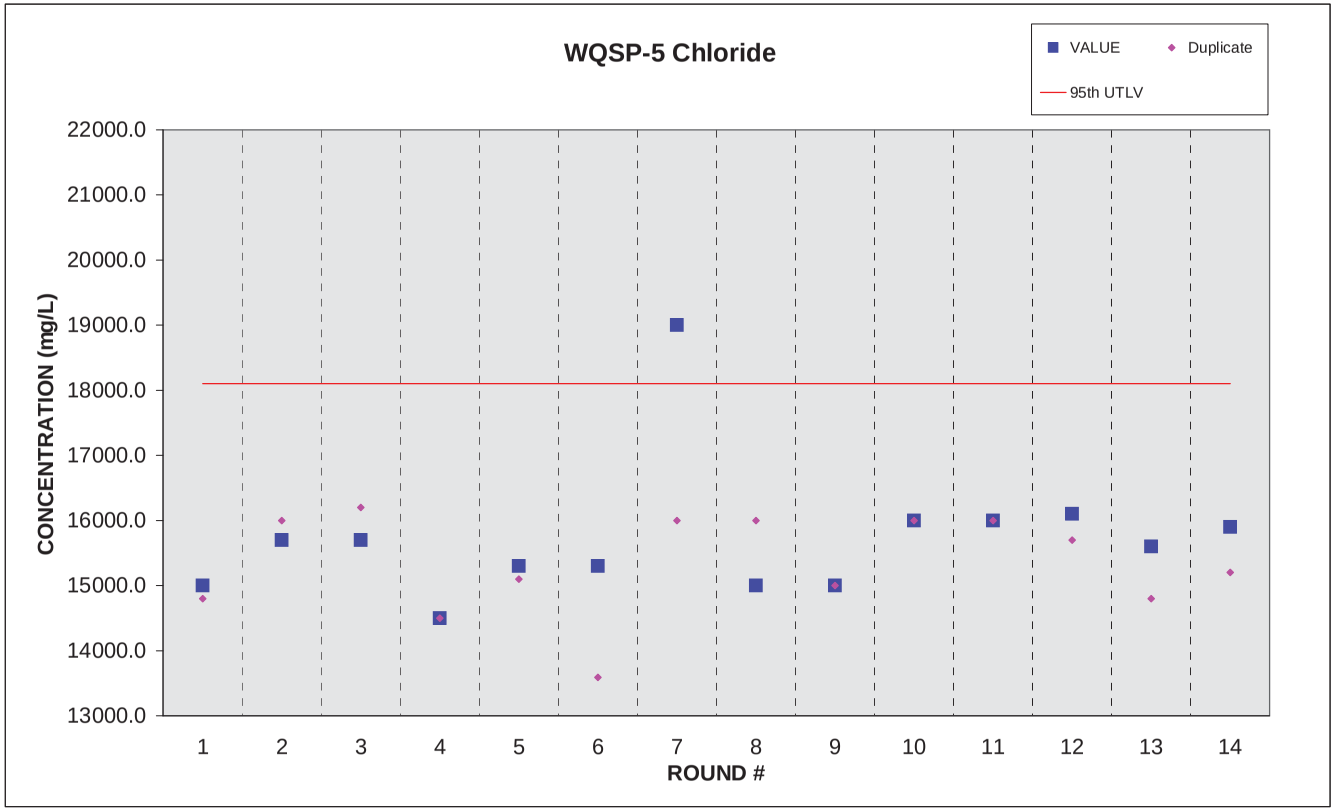

WQSP-5 Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		5370.0		5380.0	mg/L	10.0	6129.0			<	10.0	1	11/27/95	11/20/95
	SULFATE		5730.0		5900.0	mg/L	2500.0	6129.0			<	10.0	2	06/10/96	06/06/96
	SULFATE		5240.0		4940.0	mg/L	2500.0	6129.0			<	10.0	3	10/01/96	09/26/96
	SULFATE		4460.0		4460.0	mg/L	2500.0	6129.0			<	10.0	4	07/07/97	06/19/97
	SULFATE		4900.0		4640.0	mg/L	2500.0	6129.0			<	10.0	5	09/30/97	09/25/97
	SULFATE		4970.0		4370.6	mg/L	0.0	6129.0			<	0.1	6	05/22/98	05/20/98
	SULFATE		5400.0		5000.0	mg/L	0.5	6129.0			<	0.5	7	10/13/98	10/07/98
	SULFATE		4900.0		5200.0	mg/L	0.5	6129.0			<	0.5	8	05/05/99	05/05/99
	SULFATE		4300.0		4300.0	mg/L	0.5	6129.0			<	0.5	9	10/28/99	10/27/99
	SULFATE		5400.0		5200.0	mg/L	0.5	6129.0			<	0.5	10	05/02/00	04/26/00
	SULFATE		5200.0		4800.0	mg/L	0.5	6129.0			<	0.5	11	11/15/00	11/01/00
	SULFATE		4890.0		4800.0	mg/L	0.5	6129.0					12	05/03/01	05/02/01
	SULFATE		4690.0		4470.0	mg/L	2.0	6129.0					13	11/15/01	10/31/01
	SULFATE		5230.0		5250.0	mg/L	2.0	6129.0					14	05/07/02	05/01/02

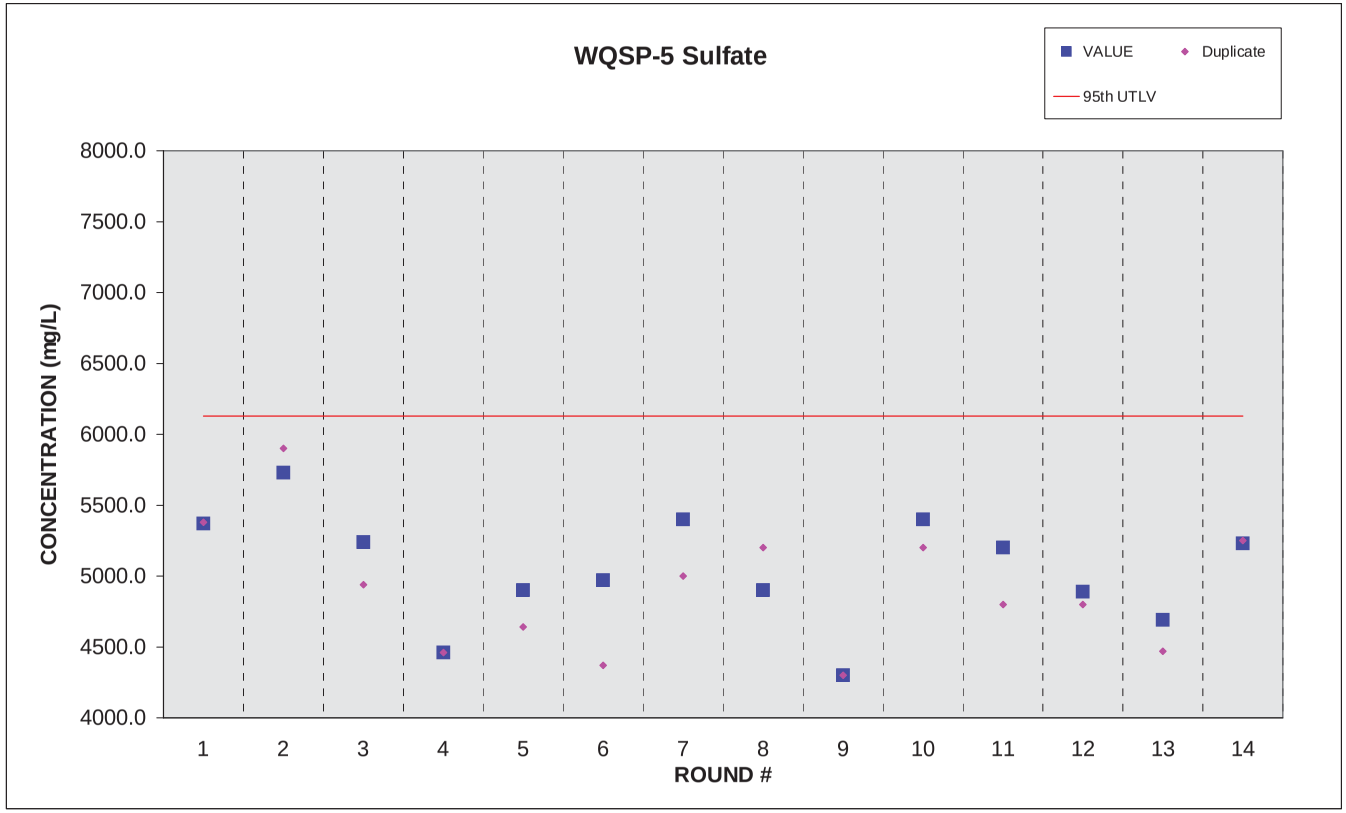

WQSP-6 Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		719.0		731.0	mg/L	2.0	796.0			<	0.2	1	10/25/95	10/16/95
7440-70-2	CALCIUM		663.0		659.0	mg/L	0.5	796.0	<	0.2	<	0.2	2	03/27/96	03/12/96
7440-70-2	CALCIUM		696.0		709.0	mg/L	2.0	796.0	<	0.2	<	0.2	3	07/26/96	06/27/96
7440-70-2	CALCIUM		662.0		657.0	mg/L	2.0	796.0	<	0.2	<	0.2	4	04/11/97	04/03/97
7440-70-2	CALCIUM		572.0		584.0	mg/L	2.0	796.0	<	0.2	<	0.2	5	07/11/97	06/25/97
7440-70-2	CALCIUM		714.0		703.6	mg/L	0.0	796.0				0.0	6	06/05/98	06/03/98
7440-70-2	CALCIUM		680.0		633.0	mg/L	0.5	796.0			<	0.5	7	11/27/98	10/21/98
7440-70-2	CALCIUM		675.0		728.0	mg/L	1.0	796.0			<	1.0	8	05/29/99	05/19/99
7440-70-2	CALCIUM		677.0		690.0	mg/L	1.0	796.0			<	1.0	9	12/09/99	11/03/99
7440-70-2	CALCIUM		707.0		774.0	mg/L	50.0	796.0			<	0.0	10	06/20/00	05/10/00
7440-70-2	CALCIUM		747.0		766.0	mg/L	5.0	796.0			<	5.0	11	11/24/00	11/15/00
7440-70-2	CALCIUM		663.0		667.0	mg/L	0.5	796.0					12	06/15/01	05/16/01
7440-70-2	CALCIUM		672.0		688.0	mg/L	0.2	796.0					13	11/20/01	11/07/01
7440-70-2	CALCIUM		738.0		735.0	mg/L	0.5	796.0					14	05/31/02	05/15/02

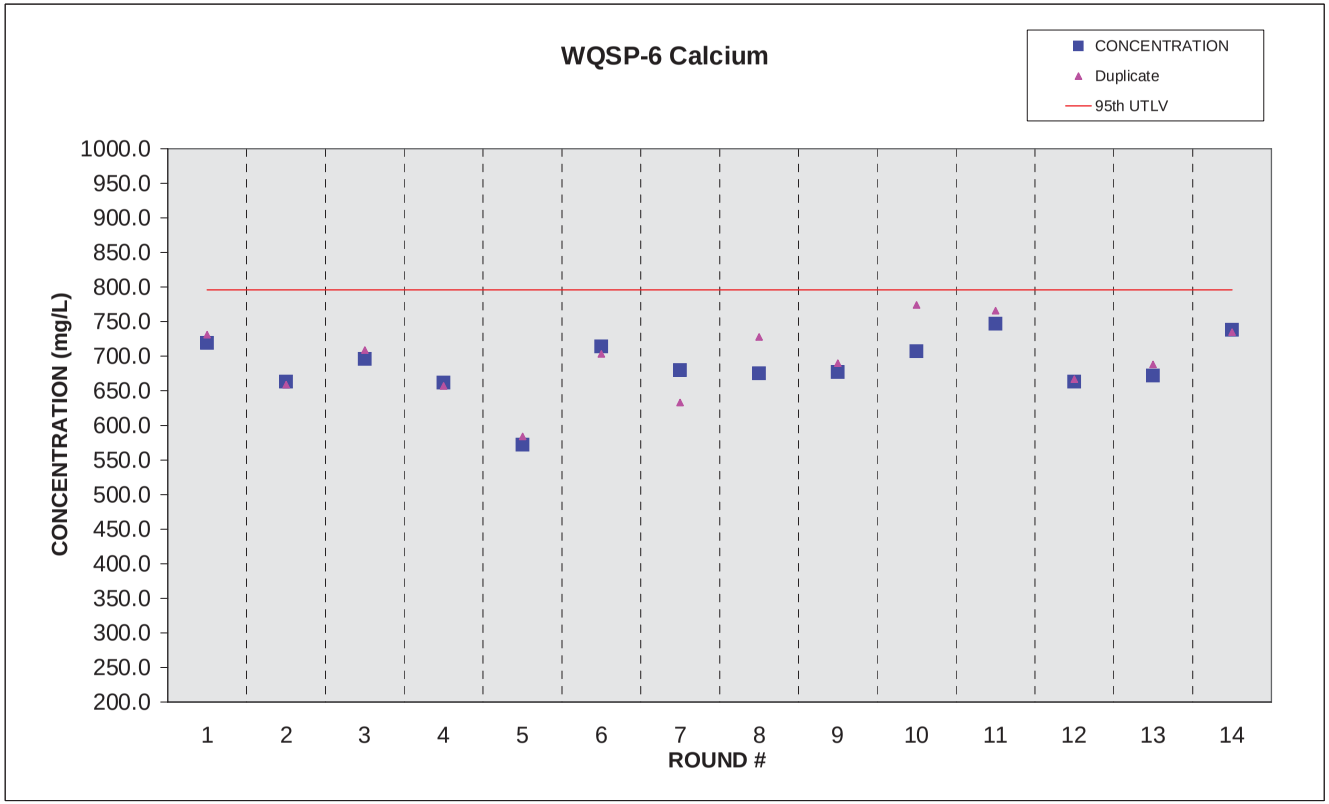

WQSP-6 Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		250.0		253.0	mg/L	1.0	255.0			<	0.1	1	10/25/95	10/16/95
7439-95-4	MAGNESIUM		214.0		213.0	mg/L	0.1	255.0	<	0.1	<	0.1	2	03/27/96	03/12/96
7439-95-4	MAGNESIUM		199.0		202.0	mg/L	0.5	255.0	<	0.1	<	0.1	3	07/26/96	06/27/96
7439-95-4	MAGNESIUM		203.0		201.0	mg/L	1.0	255.0	<	0.1	<	0.1	4	04/11/97	04/03/97
7439-95-4	MAGNESIUM		210.0		212.0	mg/L	1.0	255.0	<	0.1	<	0.1	5	07/11/97	06/25/97
7439-95-4	MAGNESIUM		219.0		219.0	mg/L	0.1	255.0				0.1	6	06/05/98	06/03/98
7439-95-4	MAGNESIUM		200.0		194.0	mg/L	0.5	255.0			<	0.5	7	11/27/98	10/21/98
7439-95-4	MAGNESIUM		201.0		210.0	mg/L	1.0	255.0			<	1.0	8	05/29/99	05/19/99
7439-95-4	MAGNESIUM		214.0		218.0	mg/L	1.0	255.0			<	1.0	9	12/09/99	11/03/99
7439-95-4	MAGNESIUM		222.0		240.0	mg/L	0.5	255.0			<	0.5	10	06/20/00	05/10/00
7439-95-4	MAGNESIUM		226.0		236.0	mg/L	5.0	255.0			<	5.0	11	11/24/00	11/15/00
7439-95-4	MAGNESIUM		212.0		231.0	mg/L	0.5	255.0					12	06/15/01	05/16/01
7439-95-4	MAGNESIUM		234.0		236.0	mg/L	0.2	255.0					13	11/20/01	11/07/01
7439-95-4	MAGNESIUM		238.0		238.0	mg/L	0.5	255.0					14	05/31/02	05/15/02

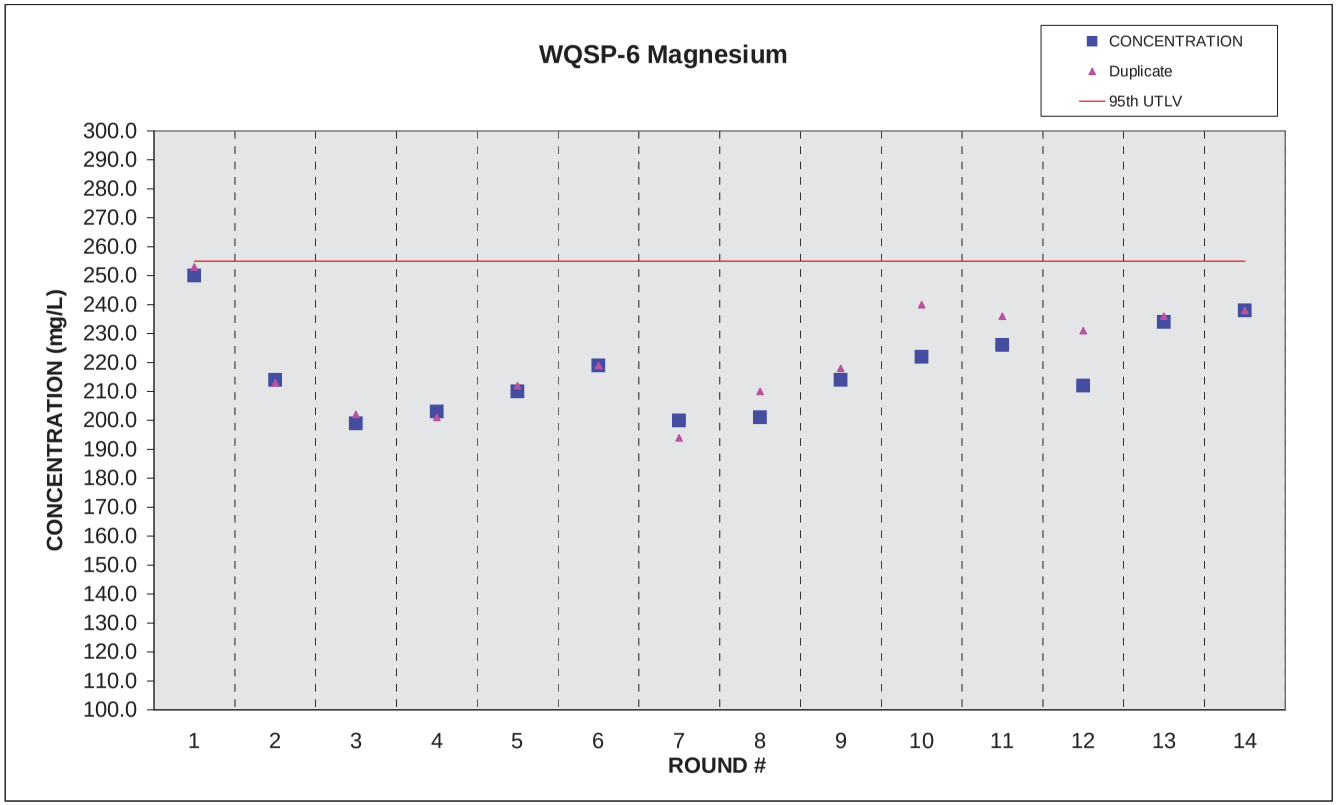

WQSP-6 Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		182.0		184.0	mg/L	0.2	270.0			<	0.2	1	10/25/95	10/16/95
7440-09-7	POTASSIUM		199.0		190.0	mg/L	5.0	270.0	<	0.2	<	0.2	2	03/27/96	03/12/96
7440-09-7	POTASSIUM		152.0		151.0	mg/L	2.0	270.0		0.2	<	0.2	3	07/29/96	06/27/96
7440-09-7	POTASSIUM		150.0		148.0	mg/L	2.0	270.0	<	0.2	<	0.2	4	04/11/97	04/03/97
7440-09-7	POTASSIUM		148.0		157.0	mg/L	2.0	270.0	<	0.2	<	0.2	5	07/10/97	06/25/97
7440-09-7	POTASSIUM		161.0		169.8	mg/L	0.1	270.0				0.1	6	06/05/98	06/03/98
7440-09-7	POTASSIUM		144.0		137.0	mg/L	0.5	270.0			<	0.5	7	11/27/98	10/21/98
7440-09-7	POTASSIUM		215.0		226.0	mg/L	1.0	270.0			<	1.0	8	05/29/99	05/19/99
7440-09-7	POTASSIUM		239.0		244.0	mg/L	1.0	270.0			<	1.0	9	12/09/99	11/25/99
7440-09-7	POTASSIUM		184.0		200.0	mg/L	0.5	270.0			<	0.5	10	06/20/00	05/10/00
7440-09-7	POTASSIUM		224.0		227.0	mg/L	5.0	270.0				0.0	11	11/24/00	11/15/00
7440-09-7	POTASSIUM		208.0		204.0	mg/L	0.5	270.0					12	06/15/01	05/16/01
7440-09-7	POTASSIUM		278.0		282.0	mg/L	0.2	270.0					13	11/20/01	11/07/01
7440-09-7	POTASSIUM		221.0		223.0	mg/L	0.5	270.0					14	05/31/02	05/15/02

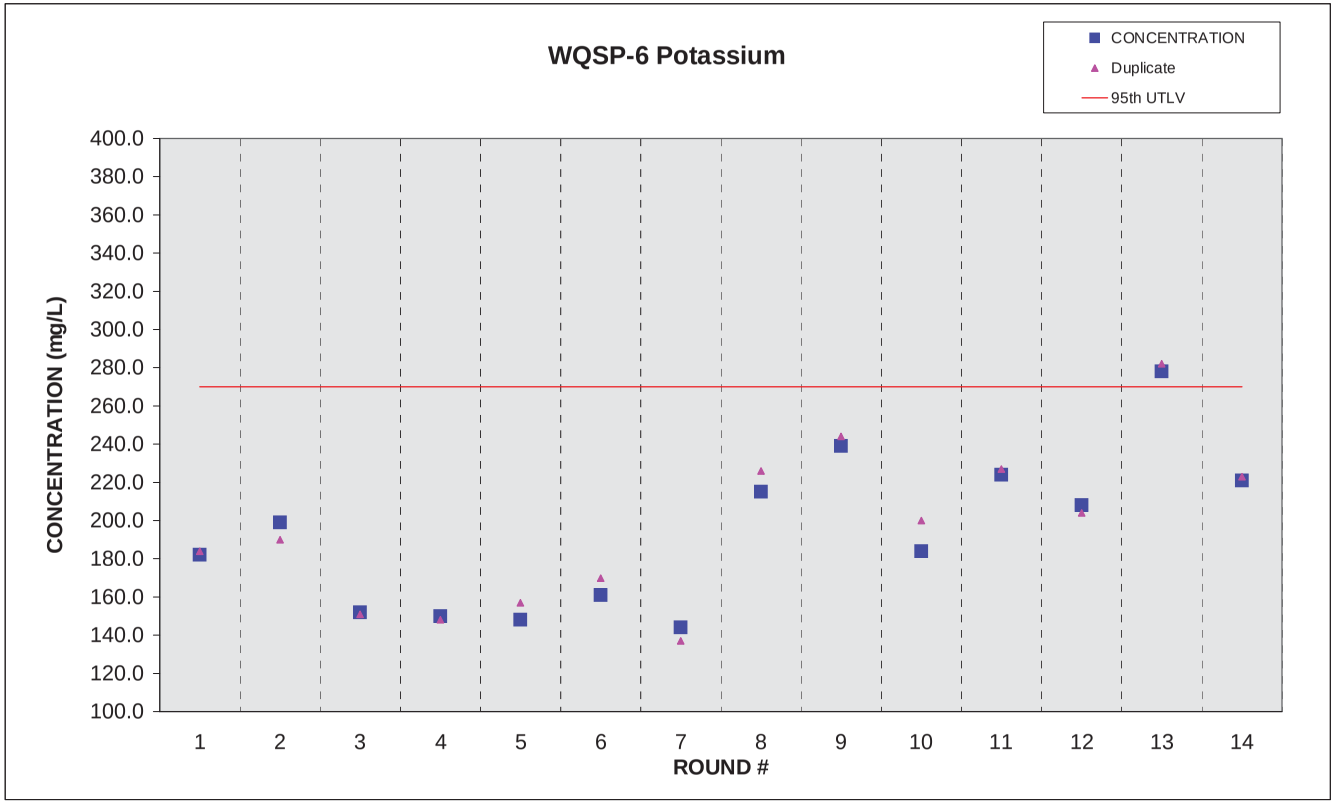

WQSP-6 Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		6070.0		6050.0	mg/L	5.0	6290.0			<	0.5	1	10/25/95	10/16/95
7440-23-5	SODIUM		5540.0		5370.0	mg/L	13.0	6290.0	<	0.5	<	0.5	2	03/27/96	03/12/96
7440-23-5	SODIUM		4470.0		4450.0	mg/L	5.0	6290.0	<	0.5	<	0.5	3	07/29/96	06/27/96
7440-23-5	SODIUM		4280.0		4230.0	mg/L	5.0	6290.0	<	0.5	<	0.5	4	04/11/97	04/03/97
7440-23-5	SODIUM		4210.0		4430.0	mg/L	2.0	6290.0	<	0.5	<	0.5	5	07/10/97	06/25/97
7440-23-5	SODIUM		4890.0		4834.7	mg/L	0.0	6290.0				0.0	6	06/05/98	06/03/98
7440-23-5	SODIUM		4460.0		4090.0	mg/L	1.0	6290.0			<	1.0	8	06/11/99	05/19/99
7440-23-5	SODIUM		4350.0		4470.0	mg/L	1.0	6290.0			<	1.0	9	12/09/99	11/03/99
7440-23-5	SODIUM		4280.0		4740.0	mg/L	0.5	6290.0			<	0.5	10	06/20/00	05/10/00
7440-22-5	SODIUM		4120.0		4280.0	mg/L	5.0	6290.0				0.0	11	11/24/00	11/15/00
7440-22-5	SODIUM		4320.0		4330.0	mg/L	0.5	6290.0					12	06/15/01	05/16/01
7440-22-5	SODIUM		4090.0		4230.0	mg/L	0.2	6290.0					13	11/20/01	11/07/01
7440-22-5	SODIUM		3870.0		3860.0	mg/L	0.5	6290.0					14	05/31/02	05/15/02

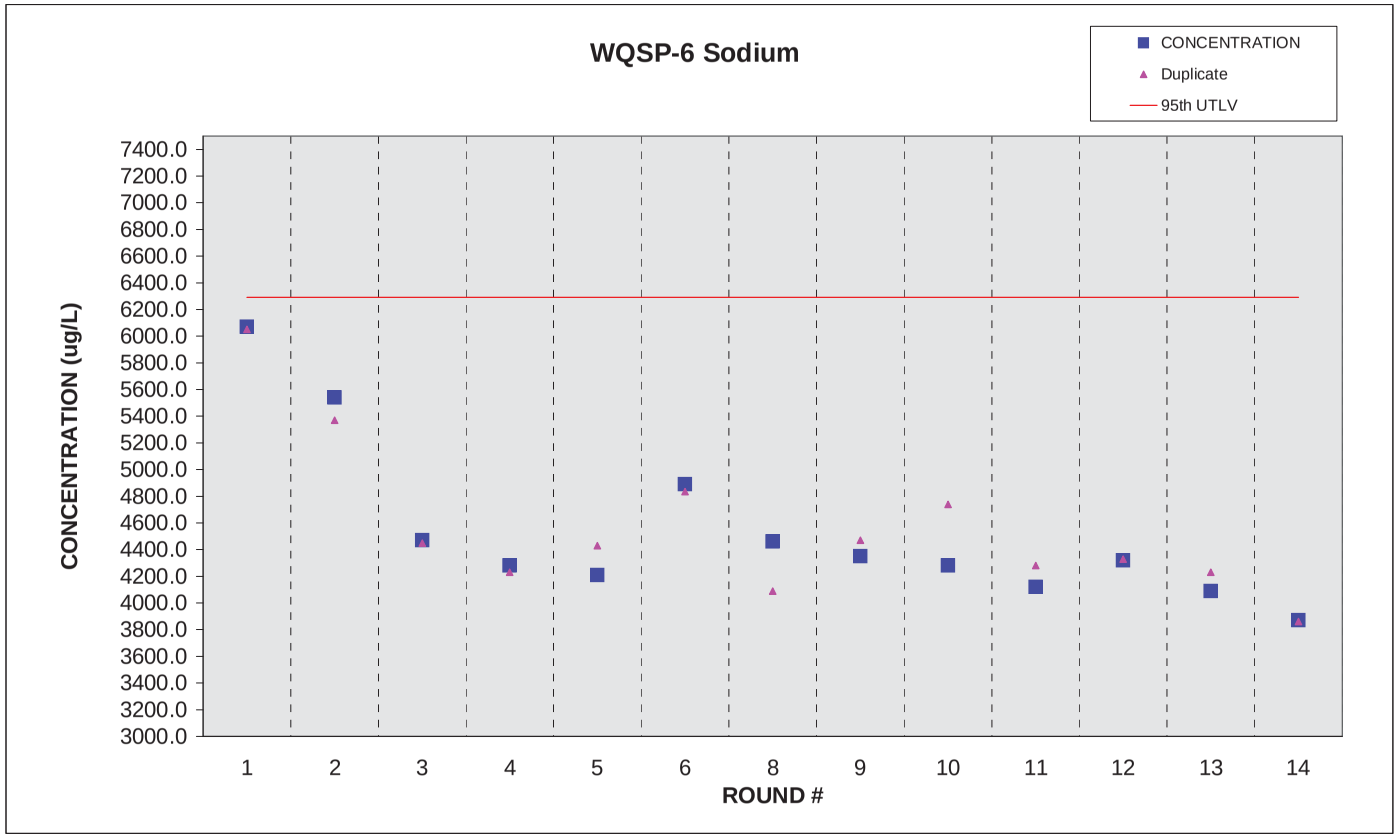

WQSP-6 Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		52.5		52.5	mg/L	5.0	55.8			<	5.0	1	10/18/95	10/16/95
	ALKALINITY		54.0		49.0	mg/L	5.0	55.8			<	5.0	2	03/22/96	03/12/96
	ALKALINITY		48.1		47.1	mg/L	5.0	55.8					3	07/10/96	06/27/96
	ALKALINITY		53.2		51.1	mg/L	5.0	55.8			<	5.0	4	04/16/97	04/03/97
	ALKALINITY		47.0		48.0	mg/L	5.0	55.8			<	5.0	5	06/27/97	06/25/97
	ALKALINITY		43.0		43.0	mg/L	1.0	55.8					6	06/05/98	06/03/98
	ALKALINITY		46.0		48.0	mg/L	1.0	55.8			<	4.0	7	11/02/98	10/21/98
	ALKALINITY		46.0		47.0	mg/L	0.1	55.8			<	4.0	8	05/21/99	05/19/99
	ALKALINITY		44.0		46.0	mg/L	1.0	55.8					9	11/12/99	11/03/99
	ALKALINITY		45.0		45.0	mg/L	4.0	55.8					10	05/19/00	05/10/00
	ALKALINITY		48.0		50.0	mg/L	4.0	55.8			<	4.0	11	11/21/00	11/15/00
	ALKALINITY		42.0		42.0	mg/L	4.0	55.8					12	05/24/01	05/16/01
	ALKALINITY		46.0		44.0	mg/L	4.0	55.8					13	11/19/01	11/07/01
	ALKALINITY		46.0		46.0	mg/L	4.0	55.8					14	05/21/02	05/15/02

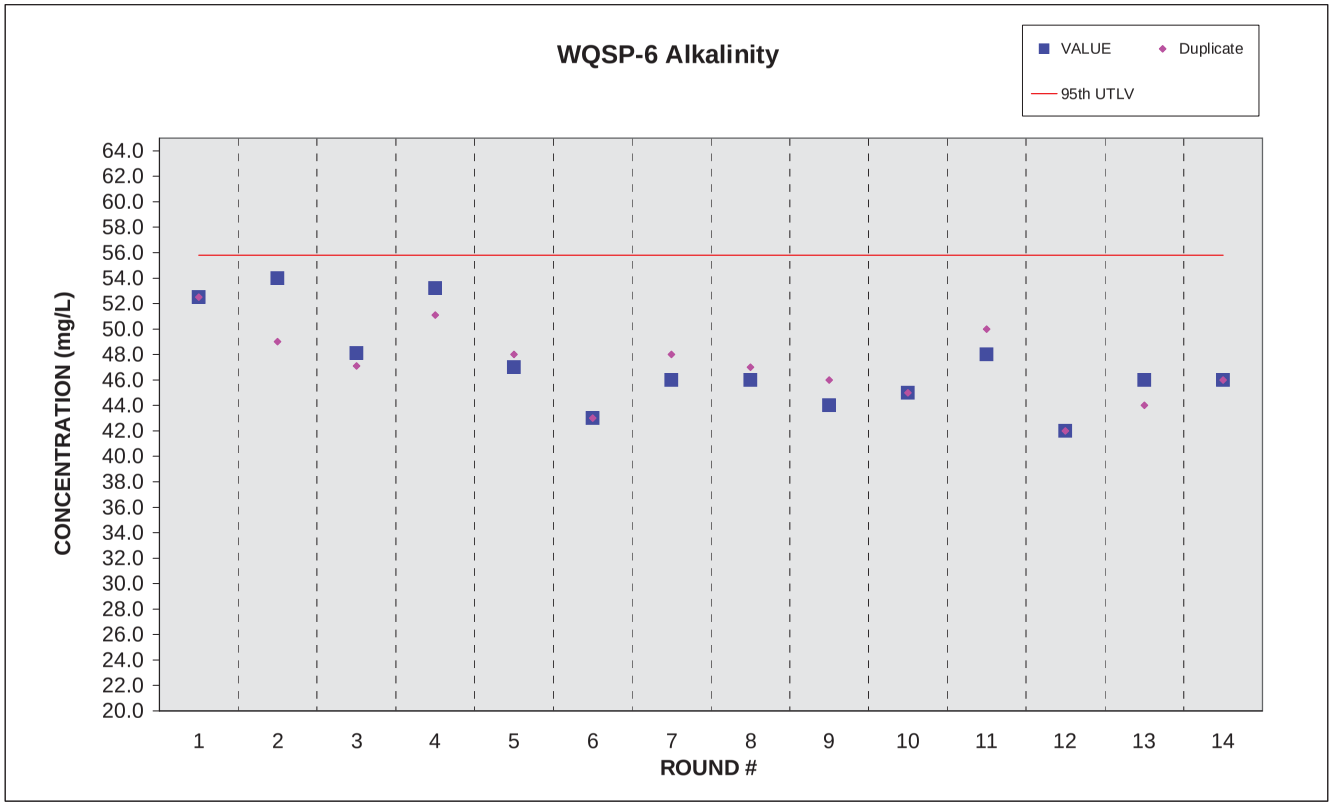

WQSP-6 Chloride

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		15800.0		15800.0	mg/L	5.0	6200.0			<	5.0	1	10/19/95	10/16/95
7782-50-5	CHLORIDE		6200.0		6200.0	mg/L	1000.0	6200.0			<	5.0	2	03/21/96	03/12/96
7782-50-5	CHLORIDE		6198.0		6098.0	mg/L	500.0	6200.0			<	5.0	3	07/10/96	06/27/96
7782-50-5	CHLORIDE		5973.0		5923.0	mg/L	250.0	6200.0			<	5.0	4	04/14/97	04/03/97
7782-50-5	CHLORIDE		5500.0		5750.0	mg/L	5000.0	6200.0			<	5.0	5	07/07/97	06/25/97
7782-50-5	CHLORIDE		6070.0		6053.3	mg/L	0.0	6200.0				0.1	6	06/05/98	06/03/98
7782-50-5	CHLORIDE		6000.0		6000.0	mg/L	0.5	6200.0				1.7	7	10/22/98	10/21/98
7782-50-5	CHLORIDE		5900.0		6000.0	mg/L	0.5	6200.0			<	0.5	8	05/20/99	05/19/99
7782-50-5	CHLORIDE		6000.0		5700.0	mg/L	0.5	6200.0			<	0.5	9	11/03/99	11/03/99
7782-50-5	CHLORIDE		5600.0		5500.0	mg/L	0.5	6200.0			<	0.5	10	05/19/00	05/10/00
7782-50-5	CHLORIDE		5500.0		5500.0	mg/L	2.0	6200.0			<	0.5	11	11/16/00	11/15/00
7782-50-5	CHLORIDE		5140.0		5170.0	mg/L	0.5	6200.0					12	05/23/01	05/16/01
7782-50-5	CHLORIDE		4970.0		4820.0	mg/L	2.0	6200.0					13	11/27/01	11/07/01
7782-50-5	CHLORIDE		4990.0		4950.0	mg/L	2.0	6200.0					14	05/23/02	05/15/02

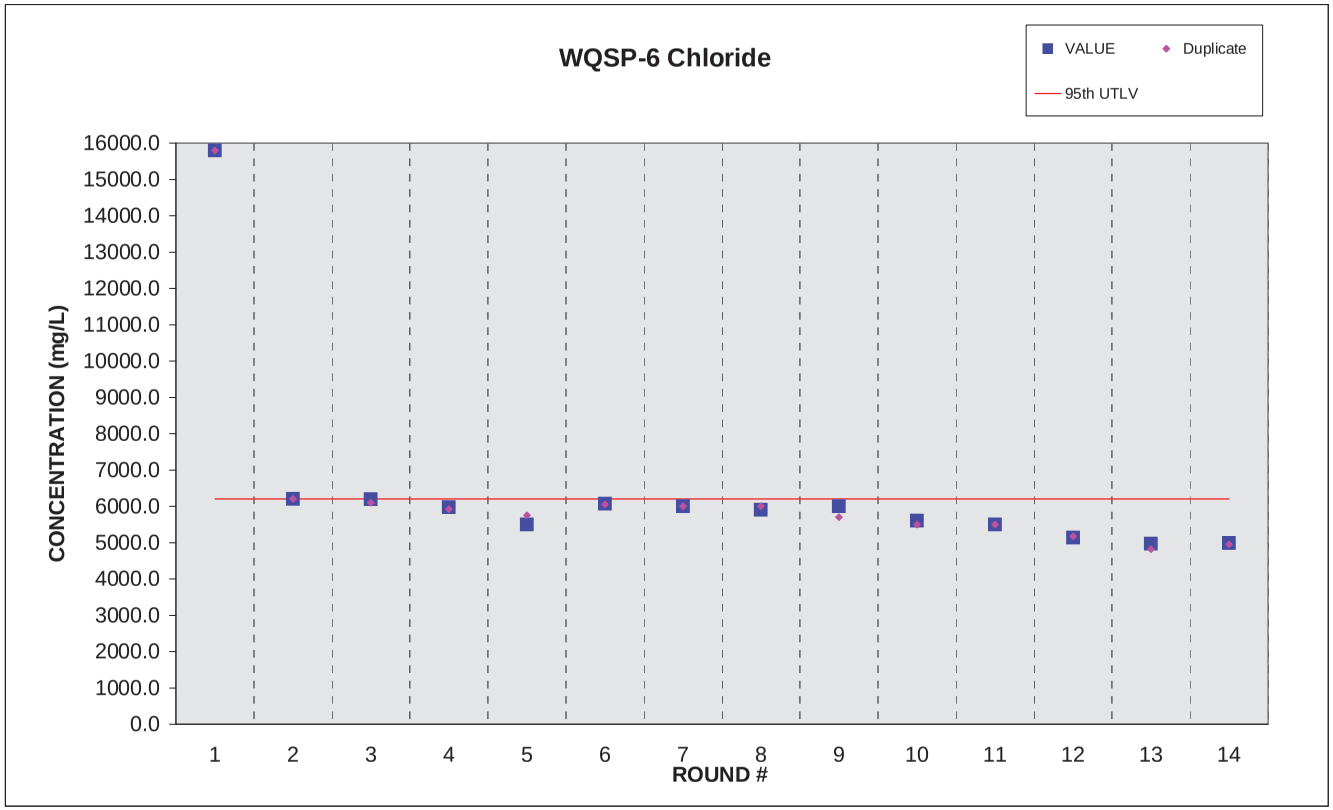

WQSP-6 Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		5590.0		5340.0	mg/L	10.0	5557.0			<	10.0	1	10/19/95	10/16/95
	SULFATE		4730.0		4670.0	mg/L	1000.0	5557.0			<	10.0	2	03/21/96	03/12/96
	SULFATE		4523.0		4337.0	mg/L	1000.0	5557.0			<	10.0	3	07/10/96	06/27/96
	SULFATE		4670.0		4650.0	mg/L	10.0	5557.0			<	10.0	4	04/15/97	04/03/97
	SULFATE		5100.0		4670.0	mg/L	2500.0	5557.0			<	10.0	5	07/07/97	06/25/97
	SULFATE		4660.0		4613.8	mg/L	0.0	5557.0				0.0	6	06/05/98	06/03/98
	SULFATE		4800.0		4900.0	mg/L	0.5	5557.0			<	0.5	7	10/22/98	10/21/98
	SULFATE		4400.0		4200.0	mg/L	0.5	5557.0			<	0.5	8	05/20/99	05/19/99
	SULFATE		5000.0		4800.0	mg/L	0.5	5557.0			<	0.5	9	11/03/99	11/03/99
	SULFATE		4700.0		4600.0	mg/L	0.5	5557.0			<	0.5	10	05/18/00	05/10/00
	SULFATE		4800.0		4700.0	mg/L	0.5	5557.0			<	0.5	11	11/16/00	11/15/00
	SULFATE		4600.0		4720.0	mg/L	0.5	5557.0					12	05/23/01	05/16/01
	SULFATE		4500.0		4510.0	mg/L	2.0	5557.0					13	11/27/01	11/07/01
	SULFATE		4640.0		4600.0	mg/L	2.0	5557.0					14	05/21/02	05/15/02

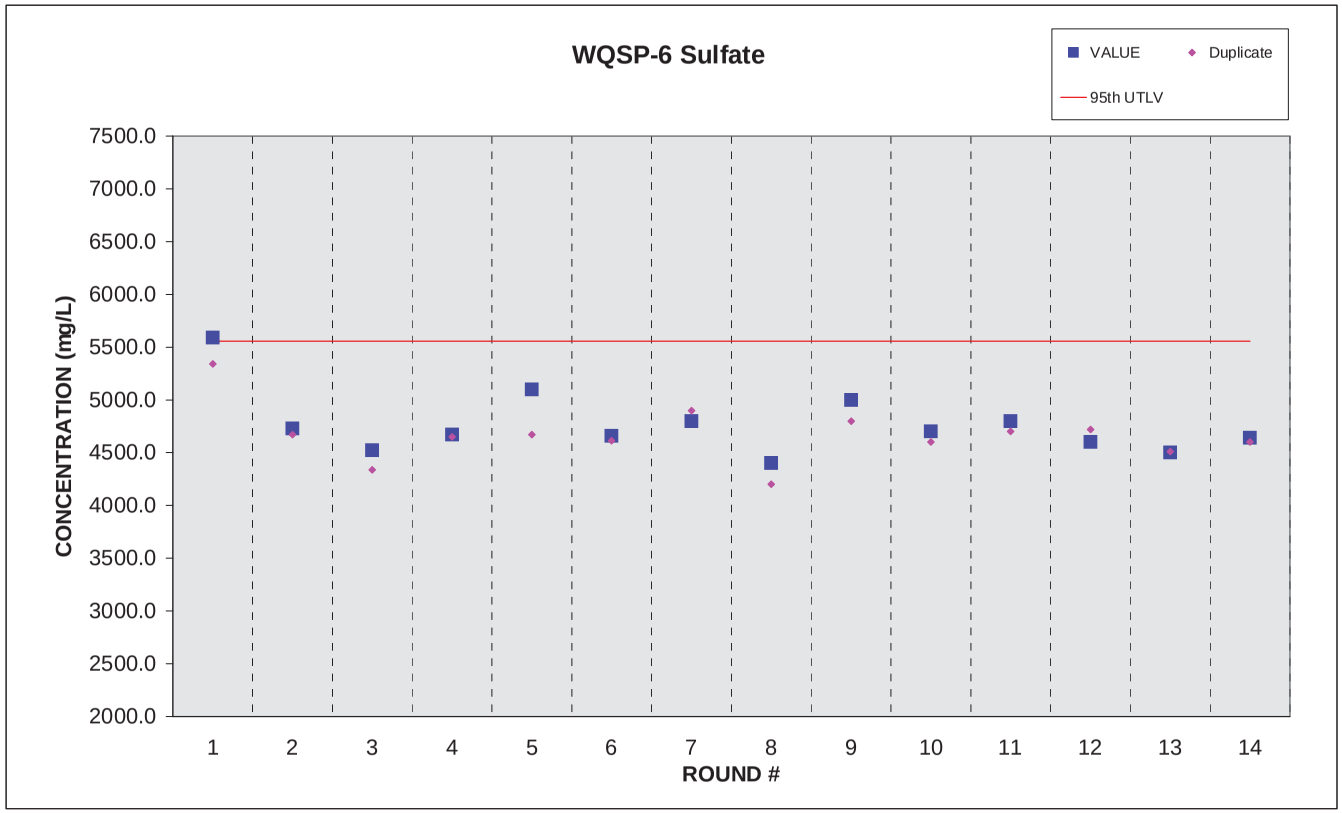

WQSP-6A Calcium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-70-2	CALCIUM		681.0		681.0	mg/L	0.8	733.0	<	0.2	<	0.2	1	07/18/95	07/13/95
7440-70-2	CALCIUM		564.0		568.0	mg/L	0.5	733.0	<	0.2	<	0.2	2	04/05/96	03/28/96
7440-70-2	CALCIUM		645.0		648.0	mg/L	2.0	733.0	<	0.2	<	0.2	3	07/30/96	07/11/96
7440-70-2	CALCIUM		563.0		573.0	mg/L	0.5	733.0	<	0.2	<	0.2	4	04/17/97	04/10/97
7440-70-2	CALCIUM		675.0		631.0	mg/L	2.0	733.0	<	0.2	<	0.2	5	07/17/97	07/10/97
7440-70-2	CALCIUM		649.0		661.0	mg/L	0.0	733.0				0.0	6	06/15/98	06/10/98
7440-70-2	CALCIUM		646.0		674.0	mg/L	0.5	733.0			<	0.5	7	12/15/98	11/03/98
7440-70-2	CALCIUM		654.0		637.0	mg/L	1.0	733.0			<	1.0	8	05/29/99	05/26/99
7440-70-2	CALCIUM		613.0		606.0	mg/L	0.5	733.0			<	0.5	9	12/10/99	11/10/99
7440-70-2	CALCIUM		681.0		664.0	mg/L	0.5	733.0			<	0.5	10	06/20/00	05/24/00
7440-70-2	CALCIUM		655.0		658.0	mg/L	5.0	733.0				1.6	11	12/11/00	11/30/00
7440-70-2	CALCIUM		570.0		540.0	mg/L	0.5	733.0			<	0.5	12	06/25/01	06/06/01
7440-70-2	CALCIUM		622.0		620.0	mg/L	0.5	733.0			<	0.5	13	02/13/02	11/14/01
7440-70-2	CALCIUM		573.0		552.0	mg/L	0.5	733.0			<	0.5	14	06/05/02	05/22/02

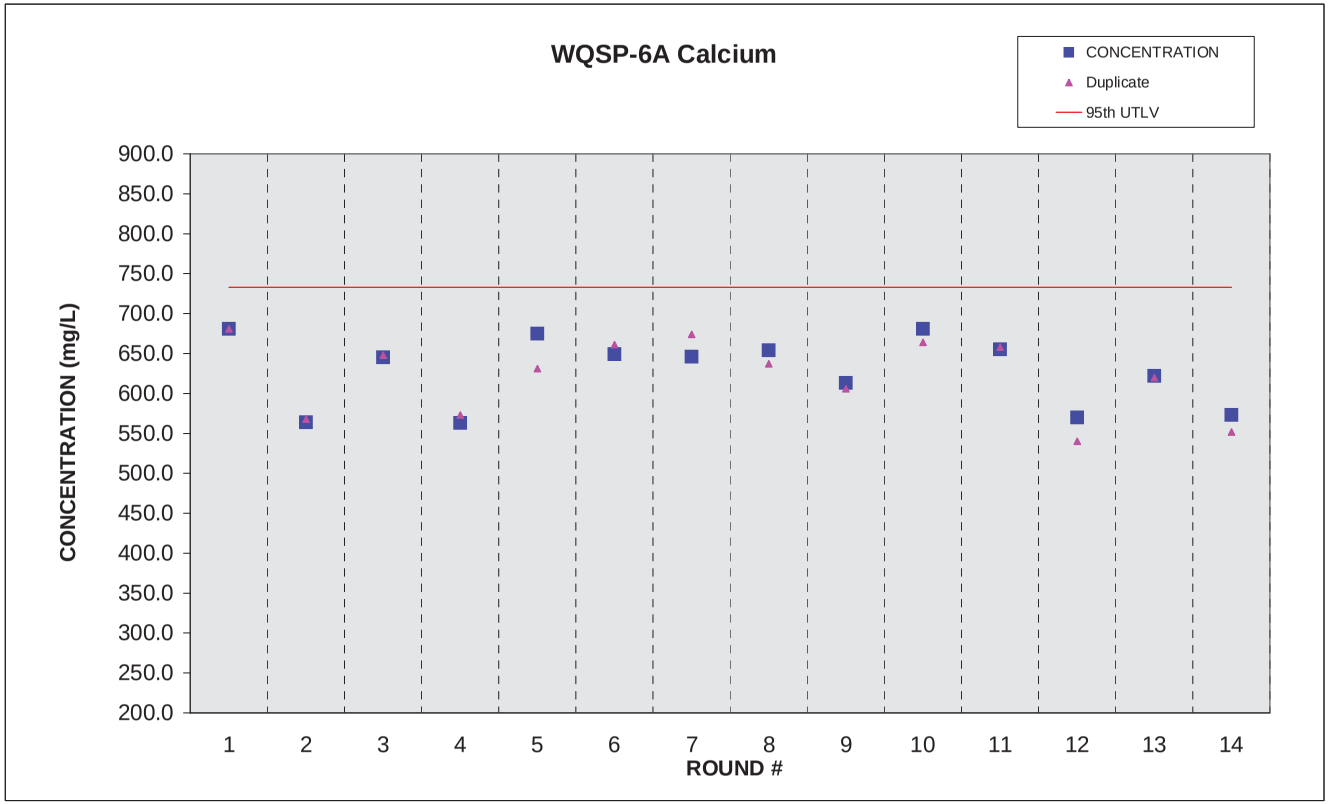

WQSP-6A Magnesium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7439-95-4	MAGNESIUM		181.0		181.0	mg/L	0.4	188.0	<	0.1	<	0.1	1	07/18/95	07/13/95
7439-95-4	MAGNESIUM		155.0		156.0	mg/L	0.1	188.0	<	0.1	<	0.1	2	04/05/96	03/28/96
7439-95-4	MAGNESIUM		155.0		156.0	mg/L	0.5	188.0	<	0.1	<	0.1	3	07/30/96	07/11/96
7439-95-4	MAGNESIUM		150.0		147.0	mg/L	0.1	188.0	<	0.1	<	0.1	4	04/17/97	04/10/97
7439-95-4	MAGNESIUM		173.0		161.0	mg/L	1.0	188.0	<	0.1	<	0.1	5	07/17/97	07/10/97
7439-95-4	MAGNESIUM		173.0		174.0	mg/L	0.1	188.0				0.2	6	06/15/98	06/10/98
7439-95-4	MAGNESIUM		166.0		173.0	mg/L	0.5	188.0			<	0.5	7	12/15/98	11/03/98
7439-95-4	MAGNESIUM		172.0		168.0	mg/L	1.0	188.0			<	1.0	8	05/29/99	05/26/99
7439-95-4	MAGNESIUM		167.0		166.0	mg/L	0.5	188.0			<	0.5	9	12/09/99	11/10/99
7439-95-4	MAGNESIUM		167.0		162.0	mg/L	0.5	188.0			<	0.5	10	06/20/00	05/24/00
7439-95-4	MAGNESIUM		187.0		179.0	mg/L	5.0	188.0				3.7	11	12/11/00	11/30/00
7439-95-4	MAGNESIUM		150.0		146.0	mg/L	0.5	188.0			<	0.5	12	06/25/01	06/06/01
7439-95-4	MAGNESIUM		186.0		169.0	mg/L	0.5	188.0			<	0.5	13	02/13/02	11/14/01
7439-95-4	MAGNESIUM		151.0		154.0	mg/L	0.5	188.0			<	0.5	14	06/05/02	05/22/02

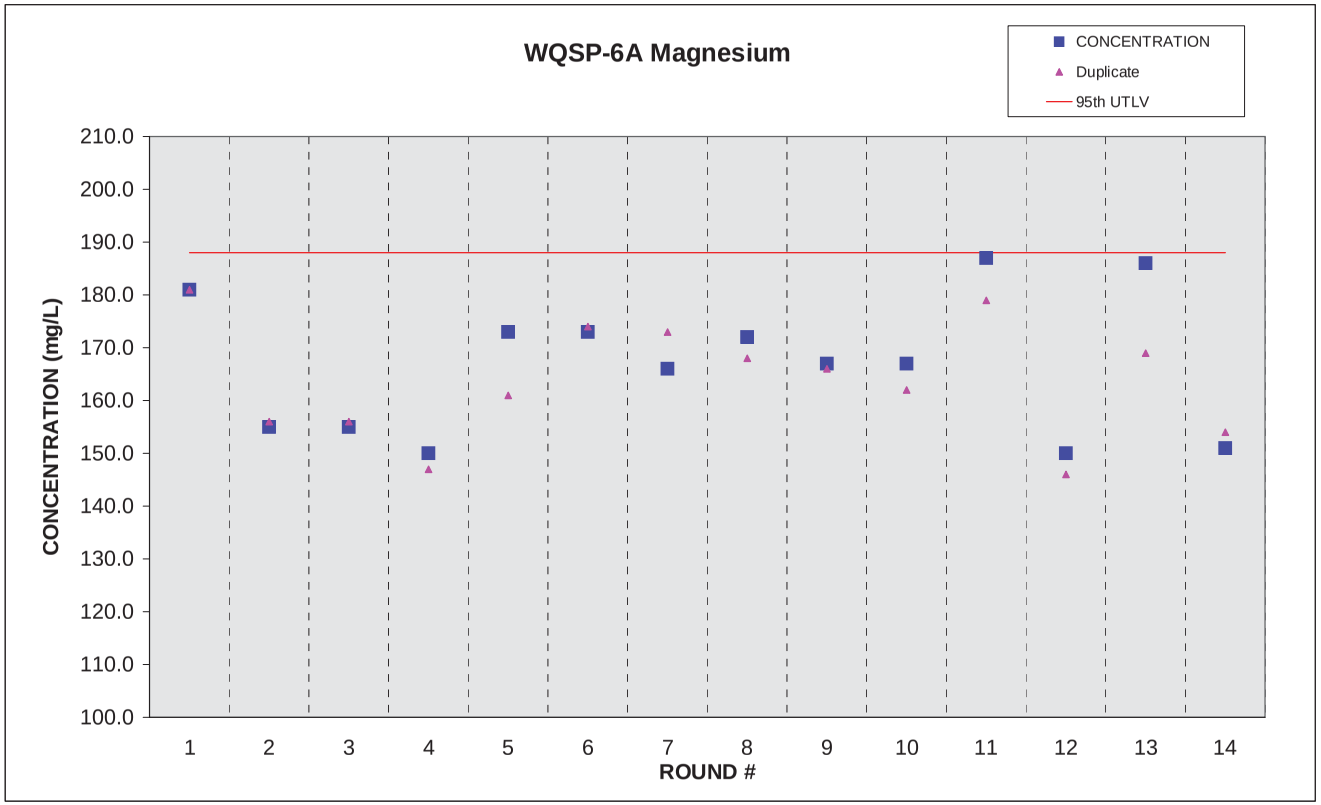

WQSP-6A Potassium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-09-7	POTASSIUM		4.8		4.8	mg/L	0.8	10.1	<	0.2	<	0.2	1	07/18/95	07/13/95
7440-09-7	POTASSIUM		3.9		3.8	mg/L	0.5	10.1	<	0.2	<	0.2	2	04/05/96	03/28/96
7440-09-7	POTASSIUM		5.0		5.1	mg/L	2.0	10.1	<	0.2	<	0.2	3	07/30/96	07/11/96
7440-09-7	POTASSIUM		4.2		4.1	mg/L	0.5	10.1	<	0.2	<	0.2	4	04/17/97	04/10/97
7440-09-7	POTASSIUM		4.5		4.2	mg/L	2.0	10.1	<	0.2	<	0.2	5	07/18/97	07/10/97
7440-09-7	POTASSIUM		4.5		4.4	mg/L	0.0	10.1				0.0	6	06/15/98	06/10/98
7440-09-7	POTASSIUM		7.5		7.5	mg/L	0.5	10.1			<	0.5	7	12/15/98	11/03/98
7440-09-7	POTASSIUM		10.0		9.4	mg/L	1.0	10.1			<	1.0	8	05/29/99	05/26/99
7440-09-7	POTASSIUM	<	10.0	<	10.0	mg/L	1.0	10.1			<	1.0	9	12/09/99	11/10/99
7440-09-7	POTASSIUM		5.2		5.4	mg/L	1.0	10.1			<	1.0	10	06/20/00	05/24/00
7440-09-7	POTASSIUM		3.3		3.0	mg/L	5.0	10.1				0.5	11	12/11/00	11/30/00
7440-09-7	POTASSIUM		7.2		7.5	mg/L	0.5	10.1			<	0.5	12	06/25/01	06/06/01
7440-09-7	POTASSIUM		7.6		7.6	mg/L	0.5	10.1			<	0.5	13	02/13/02	11/14/01
7440-09-7	POTASSIUM		7.3		7.5	mg/L	0.5	10.1			<	0.5	14	06/05/02	05/22/02

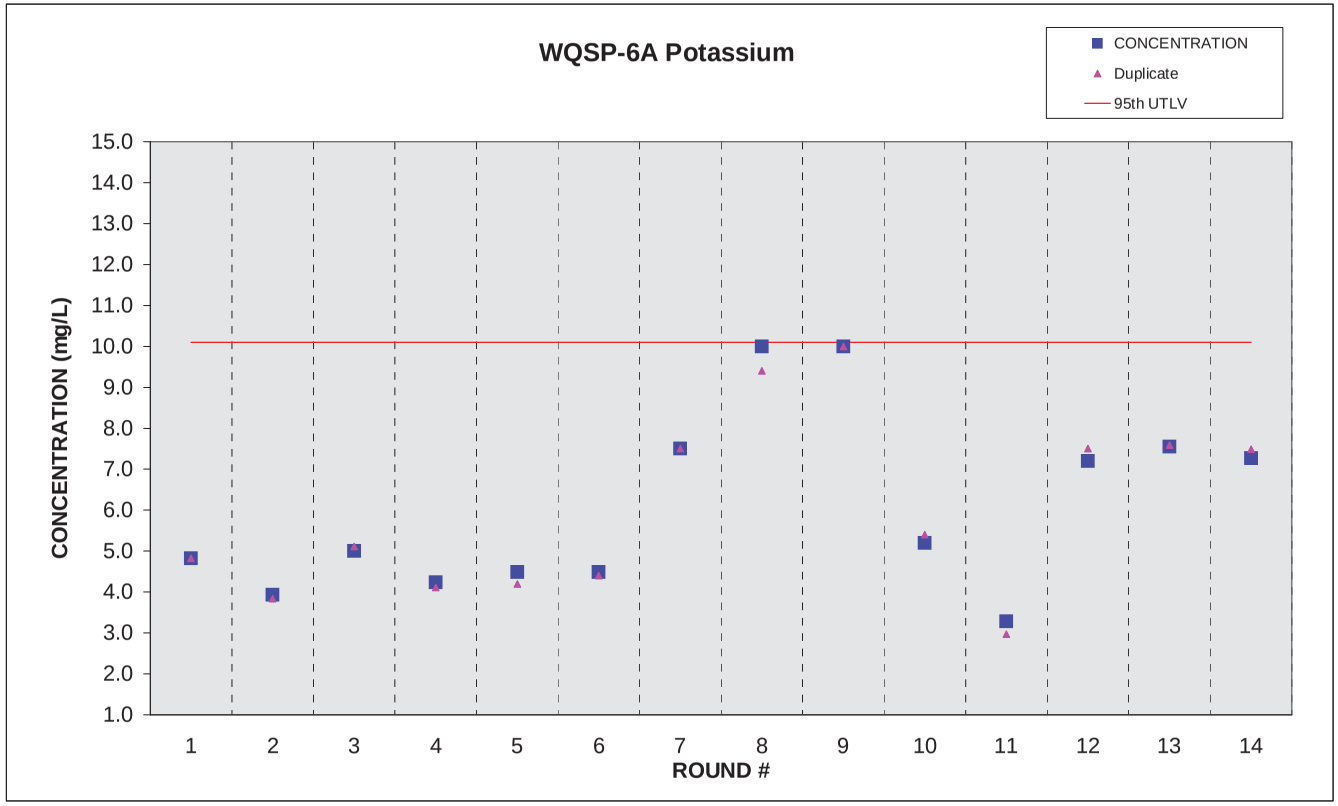

WQSP-6A Sodium

CAS #	PARAMETER		CONCENTRATION		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7440-23-5	SODIUM		347.0		347.0	mg/L	2.0	369.0		0.5		0.5	1	07/18/95	07/13/95
7440-23-5	SODIUM		282.0		282.0	mg/L	1.3	369.0	<	0.5	<	0.5	2	04/05/96	03/28/96
7440-23-5	SODIUM		314.0		314.0	mg/L	5.0	369.0	<	0.5	<	0.5	3	07/30/96	07/11/96
7440-23-5	SODIUM		292.0		284.0	mg/L	1.3	369.0	<	0.5	<	0.5	4	04/17/97	04/10/97
7440-23-5	SODIUM		311.0		290.0	mg/L	5.0	369.0	<	0.5	<	0.5	5	07/18/97	07/10/97
7440-23-5	SODIUM		335.0		334.0	mg/L	0.1	369.0				0.1	6	06/15/98	06/10/98
7440-23-5	SODIUM		313.0		334.0	mg/L	0.5	369.0			<	0.5	7	12/15/98	11/03/98
7440-23-5	SODIUM		291.0		299.0	mg/L	1.0	369.0			<	1.0	8	06/11/99	05/26/99
7440-23-5	SODIUM		269.0		267.0	mg/L	0.5	369.0			<	0.5	9	12/10/99	11/10/99
7440-23-5	SODIUM		279.0		291.0	mg/L	0.5	369.0			<	0.5	10	06/20/00	05/24/00
7440-23-5	SODIUM		258.0		250.0	mg/L	5.0	369.0				0.8	11	12/11/00	11/30/00
7440-25-5	SODIUM		260.0		255.0	mg/L	0.5	369.0			<	0.5	12	06/25/01	06/06/01
7440-25-5	SODIUM		302.0		267.0	mg/L	0.5	369.0			<	0.5	13	02/13/02	11/14/01
7440-25-5	SODIUM		253.0		254.0	mg/L	0.5	369.0			<	0.5	14	06/05/02	05/22/02

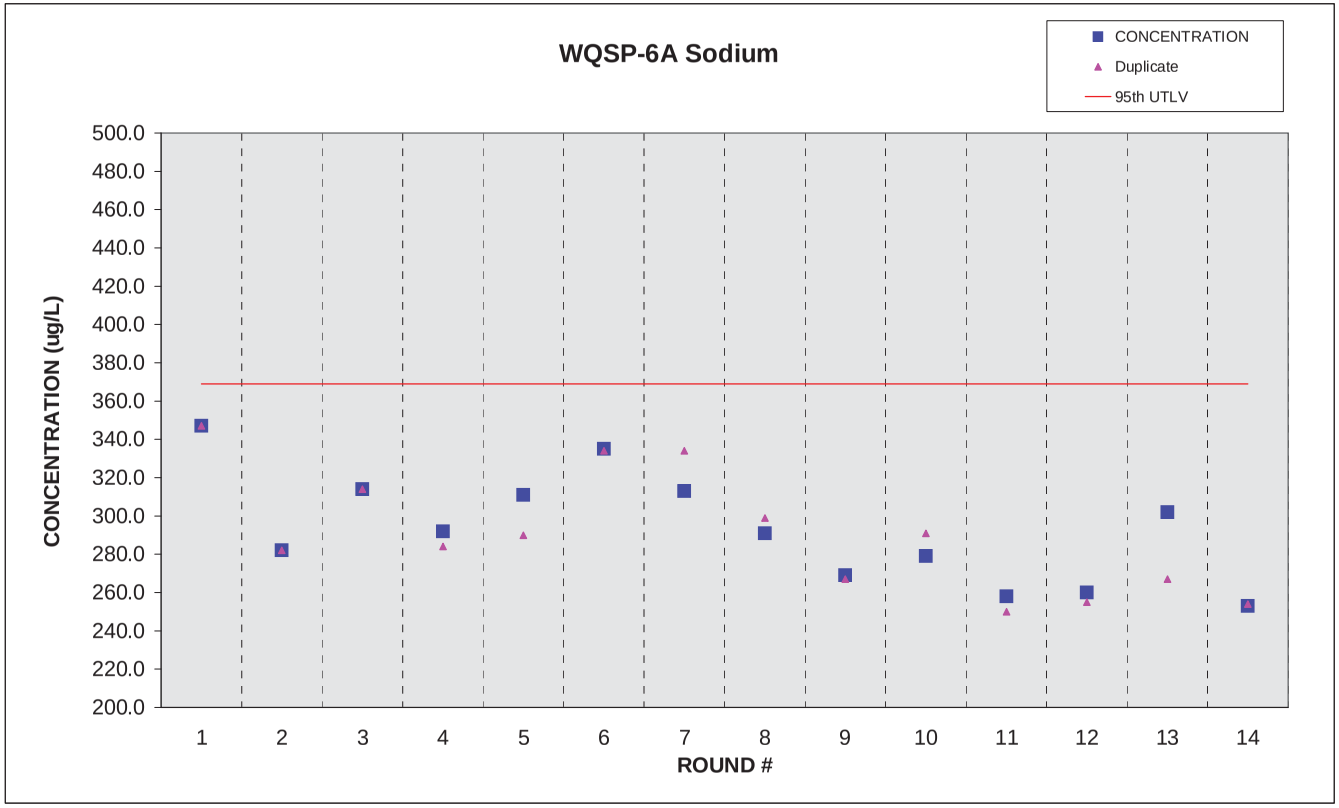

WQSP-6A Alkalinity

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	ALKALINITY		111.0		111.0	mg/L	5.0	113.0			<	5.0	1	07/25/95	07/13/95
	ALKALINITY		101.0		102.0	mg/L	5.0	113.0			<	5.0	2	04/09/96	03/28/96
	ALKALINITY		104.2		105.2	mg/L	5.0	113.0			<	5.0	3	07/25/96	07/11/96
	ALKALINITY		106.0		109.0	mg/L	5.0	113.0			<	5.0	4	04/16/97	04/10/97
	ALKALINITY		102.0		102.0	mg/L	5.0	113.0			<	5.0	5	07/24/97	07/10/97
	ALKALINITY		103.0		103.0	mg/L	5.0	113.0					6	06/13/98	06/10/98
	ALKALINITY		100.0		100.0	mg/L	5.0	113.0			<	5.0	7	11/17/98	11/03/98
	ALKALINITY		102.0		106.0	mg/L	4.0	113.0				4.0	8	05/27/99	05/26/99
	ALKALINITY		100.0		102.0	mg/L	4.0	113.0					9	11/12/99	11/10/99
	ALKALINITY		108.0		103.0	mg/L	6.0	113.0			<	6.0	10	05/30/00	05/24/00
	ALKALINITY		108.0		102.0	mg/L	4.0	113.0					11	11/30/00	12/05/00
	ALKALINITY		104.0		106.0	mg/L	4.0	113.0					12	06/12/01	06/06/01
	ALKALINITY		102.0		102.0	mg/L	4.0	113.0					13	11/27/01	11/14/01
	ALKALINITY		106.0		104.0	mg/L	4.0	113.0					14	05/30/02	05/22/02

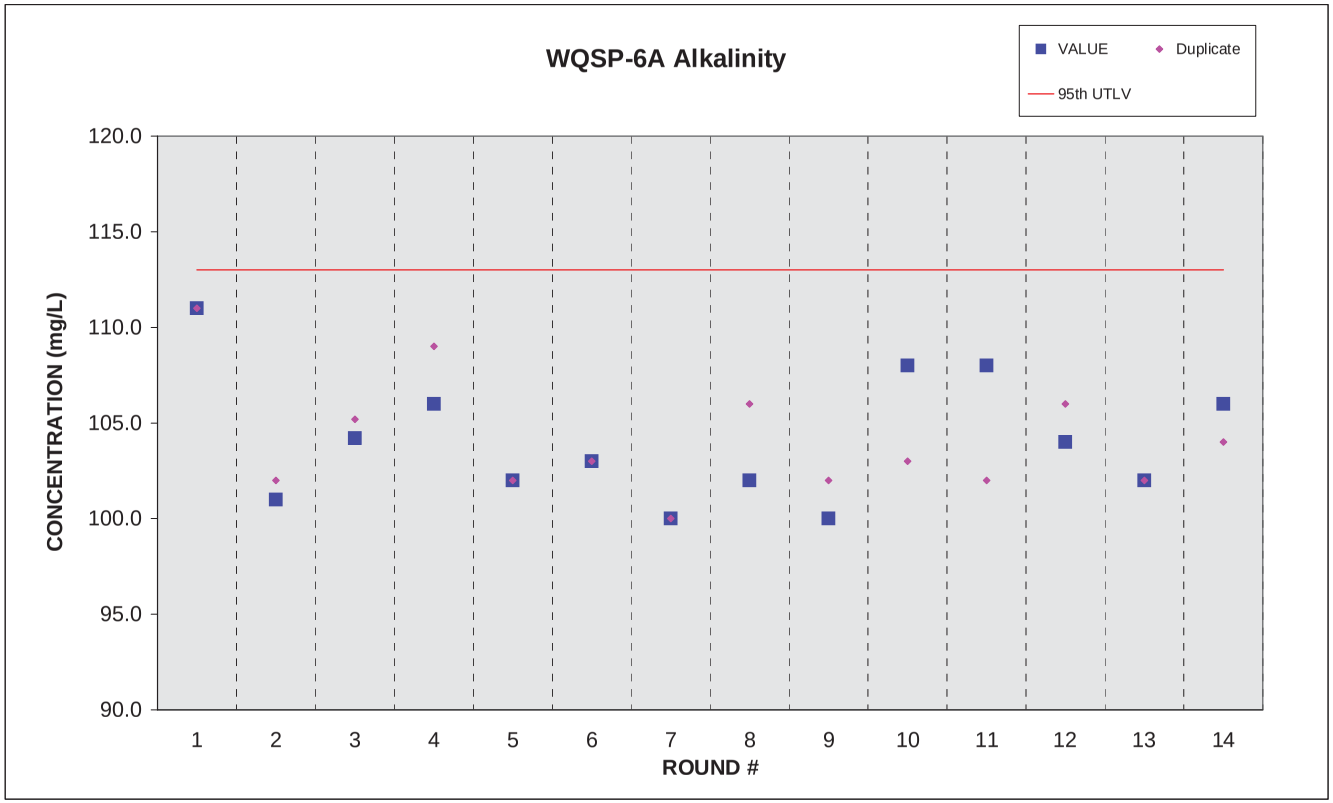

WQSP-6A Chloride

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
7782-50-5	CHLORIDE		1040.0		1040.0	mg/L	5.0	1040.0			<	5.0	1	07/25/95	07/13/95
7782-50-5	CHLORIDE		507.0		515.0	mg/L	50.0	1040.0			<	5.0	2	04/10/96	03/28/96
7782-50-5	CHLORIDE		6748.0		6698.0	mg/L	5.0	1040.0			<	5.0	3	07/17/96	07/11/96
7782-50-5	CHLORIDE		675.0		665.0	mg/L	250.0	1040.0			<	5.0	4	04/14/97	04/10/97
7782-50-5	CHLORIDE		660.0		665.0	mg/L	50.0	1040.0			<	5.0	5	08/29/97	07/10/97
7782-50-5	CHLORIDE		644.0		624.0	mg/L	0.0	1040.0					6	06/13/98	06/10/98
7782-50-5	CHLORIDE		770.0		680.0	mg/L	0.5	1040.0				1.1	7	11/05/98	11/03/98
7782-50-5	CHLORIDE		540.0		510.0	mg/L	0.5	1040.0			<	0.5	8	05/28/99	05/26/99
7782-50-5	CHLORIDE		540.0		540.0	mg/L	0.5	1040.0			<	0.5	9	11/11/99	11/10/99
7782-50-5	CHLORIDE		530.0		510.0	mg/L	0.5	1040.0			<	0.5	10	05/24/00	05/24/00
7782-50-5	CHLORIDE		480.0		480.0	mg/L	0.5	1040.0					11	11/30/00	11/30/00
7782-50-5	CHLORIDE		536.0		505.0	mg/L	0.5	1040.0					12	06/07/01	06/06/01
7782-50-5	CHLORIDE		414.0		411.0	mg/L	2.0	1040.0					13	11/27/01	11/14/01
7782-50-5	CHLORIDE		487.0		400.0	mg/L	2.0	1040.0					14	05/23/02	05/22/02

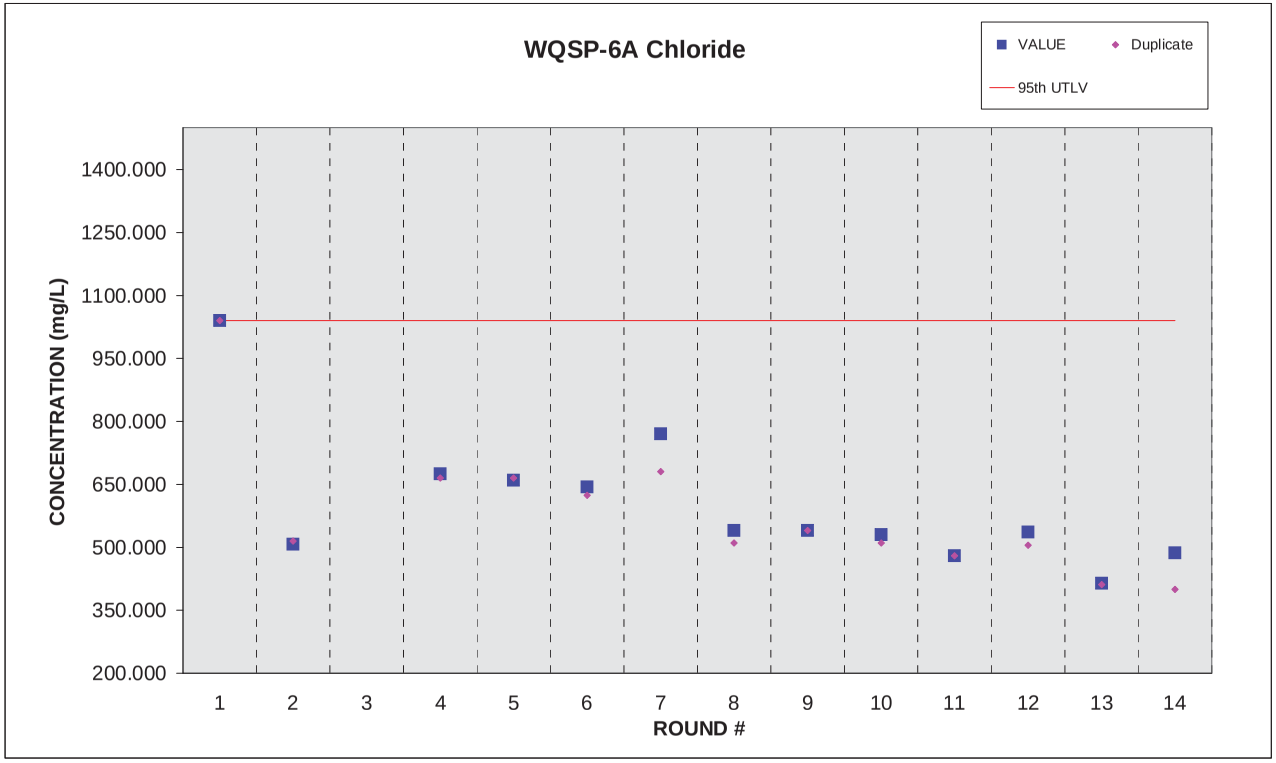

WQSP-6A Sulfate

CAS #	PARAMETER		VALUE		VALUE Duplicate	UNITS	MINIMUM DETECTION LIMIT	95th UTLV		ACID BLANK (AVERAGE)		WATER BLANK (AVERAGE)	ROUND #	DATE ANALYZED	DATE SAMPLED
	SULFATE		1905.0		1905.0	mg/L	10.0	2543.0			<	10.0	1	07/22/95	07/13/95
	SULFATE		1810.0		1790.0	mg/L	10.0	2543.0			<	10.0	2	04/15/96	03/28/96
	SULFATE		1970.5		1989.5	mg/L	10.0	2543.0			<	10.0	3	07/22/96	07/11/96
	SULFATE		2240.0		2240.0	mg/L	10.0	2543.0			<	10.0	4	04/15/97	04/10/97
	SULFATE		2560.0		2480.0	mg/L	10.0	2543.0			<	10.0	5	09/03/97	07/10/97
	SULFATE		1950.0		1890.0	mg/L	0.0	2543.0					6	06/13/98	06/10/98
	SULFATE		2100.0		1900.0	mg/L	0.5	2543.0			<	5.0	7	11/05/98	11/03/98
	SULFATE		1900.0		1900.0	mg/L	0.5	2543.0			<	0.5	8	05/28/99	05/26/99
	SULFATE		1900.0		2000.0	mg/L	0.5	2543.0			<	0.5	9	11/11/99	11/10/99
	SULFATE		2100.0		2000.0	mg/L	0.5	2543.0			<	0.5	10	05/24/00	05/24/00
	SULFATE		1900.0		1900.0	mg/L	0.5	2543.0					11	11/30/00	11/30/00
	SULFATE		1900.0		1830.0	mg/L	0.5	2543.0					12	06/07/01	06/06/01
	SULFATE		1900.0		1870.0	mg/L	2.0	2543.0					13	11/27/01	11/14/01
	SULFATE		1930.0		1940.0	mg/L	2.0	2543.0					14	05/23/02	05/22/02

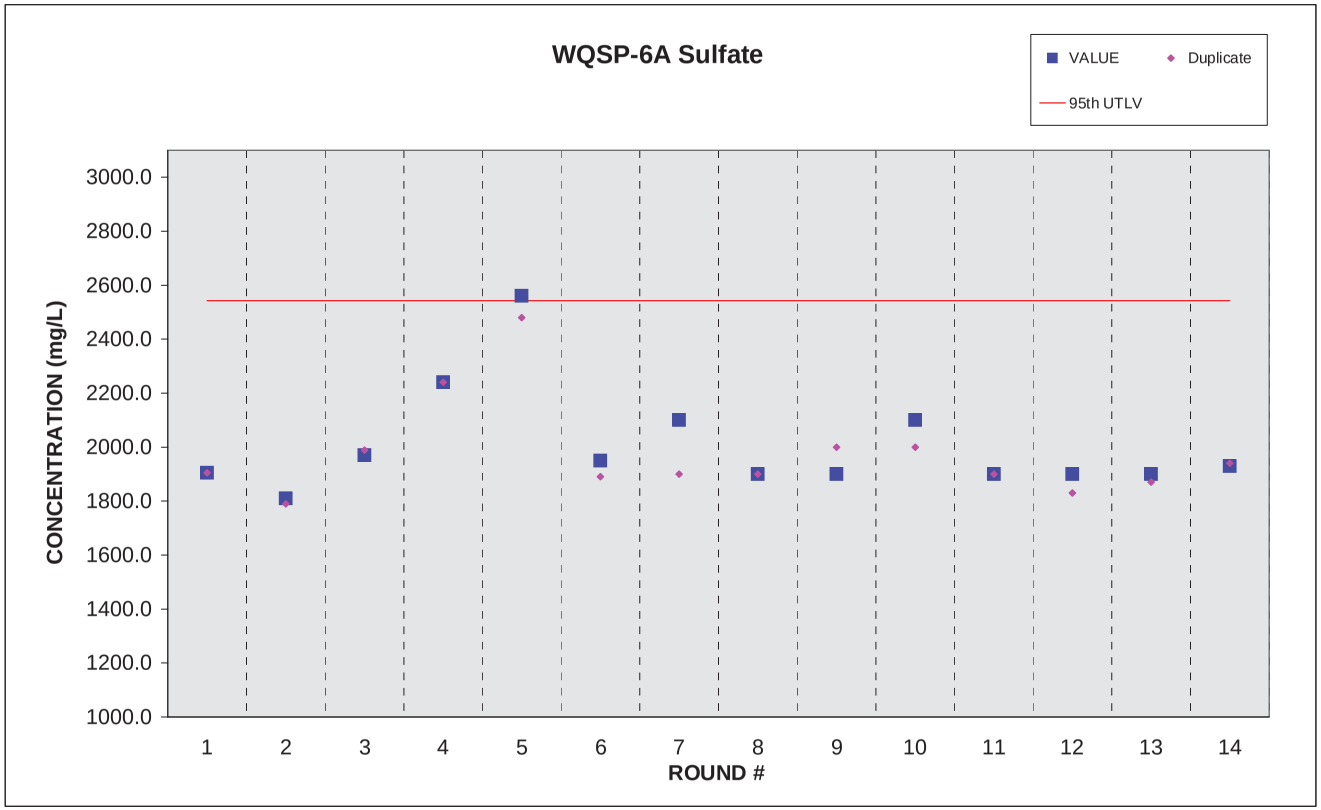

APPENDIX DATA

ATTACHMENT D: INVENTORY AND EMPLACED WASTE DATA

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List of Tables

Table DATA-D1. Nuclide Inventory (Totals) 1
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Table DATA-D4. Compliance Certification Application Relevant Parameters (March 1, 1999 to September 30, 2002) 2

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Waste Inventory as of September 2002

This attachment identifies the total amounts of certain categories of materials used in performance assessment (PA) activities that are emplaced in the repository as of September 30, 2002. The information is derived from reports generated by the WIPP Waste Information System (WWIS). The WWIS database is a computerized data management system used by the WIPP to gather, store, and process information pertaining to contact-handled (CH) transuranic (TRU) waste destined for or disposed of at the WIPP.

Table DATA-D1. Nuclide Inventory (Totals)

Nuclide	Curies	Kilograms
^{227}Ac	3.6430E-04	5.0000E-09
^{241}Am	1.1743E+05	3.3843E+01
^{243}Am	4.8047E-03	2.3856E-05
^{60}Co	3.4700E-07	0.0000E+00
^{137}Cs	3.4124E-04	5.0000E-09
^{40}K	2.8697E-05	5.0809E-03
^{22}Na	5.3430E-06	0.0000E+00
^{237}Np	4.0009E-01	5.6115E-01
^{231}Pa	5.0402E-04	1.0432E-05
^{238}Pu	5.6437E+03	3.2628E-01
^{239}Pu	1.3760E+05	2.1876E+03
^{240}Pu	3.0994E+04	1.3476E+02
^{241}Pu	4.3677E+05	4.2006E+00
^{242}Pu	2.9546E+00	7.4437E-01
^{226}Ra	7.8780E-06	8.0000E-09
^{90}Sr	0.0000E+00	0.0000E+00
^{230}Th	2.4100E-05	1.1800E-06
^{232}Th	2.6070E-06	2.3646E-02
^{233}U	2.7269E-01	2.7939E-02
^{234}U	1.2636E+00	1.9993E-01
^{235}U	1.2202E-01	5.5718E+01
^{238}U	6.5298E+00	1.9204E+04
Total:	7.2845E+05	2.1622E+04

Table DATA-D2. Materials Inventory – CPR

Waste Material	Kilograms
Cellulose	618,821.60
Plastic	306,345.40
Rubber	2,450.31
Total:	927,617.31

Table DATA-D3. Materials Inventory – Metals

Metal	Kilograms
Ferrous	2,487,932.00
Non-Ferrous	31,059.28
Total:	2,518,991.28

Table DATA-D4. Compliance Certification Application Relevant Parameters (March 1, 1999 to September 30, 2002)[1]

Site	Shipments	Container Type	Containers	Weight (kg)	Volume (m3)
EMPLACED WASTE CONTAINERS:					
Savannah River	16	55-Gallon Drum	672	39142.40	141.12
Idaho	509	55-Gallon Drum	13661	2388941.34	2868.81
Idaho	3	Standard Waste Box - Used to overpack four, 55-gallon drums in good condition	8	9106.78	15.04
Los Alamos	1	55-Gallon Drum	28	1535.00	5.88
Los Alamos	25	Standard Waste Box	141	57194.00	265.08
Rocky Flats	101	55-Gallon Drum	3072	202452.34	645.12
Rocky Flats	569	55-Gallon Pipe Overpack - 12 Inch Pipe Overpack	15680	2482536.14	3292.80
Rocky Flats	30	Standard Waste Box	172	135262.98	323.36
Rocky Flats	12	55-Gallon Drum	467	32289.60	98.07
Savannah River	7	55-Gallon Drum	294	17412.40	61.74
		Totals:	34195	5365872.98	7717.02
EMPLACED DUNNAGE[2] CONTAINERS:					
Idaho	226	55-Gallon Drum	516	14964.00	108.36
Rocky Flats	15	55-Gallon Drum	36	1044.00	7.56
Richland	1	55-Gallon Drum	2	58.00	0.42
		Totals:	554	16066.00	116.34

[1] Total Inventory as of 9/30/2002 Containers, Volumes, and Weights by Generator Site and Container type for emplaced waste only.
[2] Dunnage containers are empty containers used to complete a shipping configuration, such as the seven-pack, if too few containers are available that meet transportation requirements. Dunnage containers must clearly be marked “Empty.”

APPENDIX DATA

ATTACHMENT E: WWIS NUCLIDE REPORT

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Panel One Nuclide Inventory by Room

This attachment identifies the total amounts of radionuclides by nuclide emplaced in each room of Panel 1 as of September 30, 2002. The information is derived from reports generated by the WIPP Waste Information System (WWIS). The WWIS database is a computerized data management system used by the WIPP to gather, store, and process information pertaining to contact-handled (CH) transuranic (TRU) waste destined for or disposed of at the WIPP.

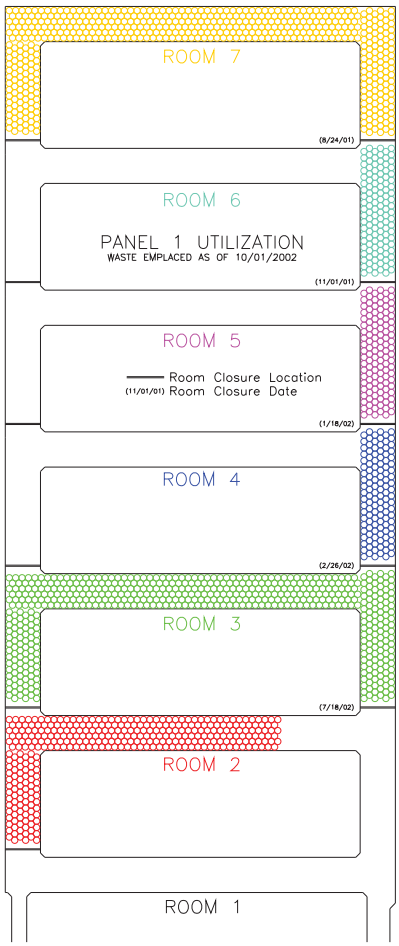

Figure DATA-E1. Panel 1 Waste Emplacement

Table DATA-E1. Panel 1 – Room 2

Radionuclide	Activity (Curies)	Mass (Grams)
^{241}Am – Americium 241	9.2850E+03	2.6758E+03
^{243}Am – Americium 243	9.9560E-04	4.9289E-03
^{137}Cs – Cesium 137	8.0278E-05	9.1225E-07
^{40}K – Potassium 40	8.4940E-06	1.5047E+00
^{237}Np – Neptunium 237	1.4797E-02	2.0754E+01
^{238}Pu – Plutonium 238	5.0904E+02	2.9424E+01
^{239}Pu – Plutonium 239	1.4237E+04	2.2634E+05
^{240}Pu – Plutonium 240	3.2407E+03	1.4090E+04
^{241}Pu – Plutonium 241	5.0010E+04	4.8087E+02
^{242}Pu – Plutonium 242	3.1581E-01	7.9550E+01
^{90}Sr – Strontium 90	0.0000E+00	0.0000E+00
^{233}U – Uranium 233	1.0058E-01	1.0305E+01
^{234}U – Uranium 234	4.7176E-01	7.4619E+01
^{235}U – Uranium 235	4.0517E-02	1.8501E+04
^{238}U – Uranium 238	2.8812E+00	8.4742E+06
Totals	7.7285E+04	8.7365E+06

Table DATA-E2. Panel 1 – Room 3

Radionuclide	Activity (Curies)	Mass (Grams)
^{241}Am – Americium 241	4.8984E+04	1.4116E+04
^{137}Cs – Cesium 137	1.2539E-05	1.4248E-07
^{237}Np – Neptunium 237	1.5878E-01	2.2269E+02
^{238}Pu – Plutonium 238	2.1564E+03	1.2465E+02
^{239}Pu – Plutonium 239	5.5875E+04	8.8832E+05
^{240}Pu – Plutonium 240	1.2569E+04	5.4648E+04
^{241}Pu – Plutonium 241	1.7815E+05	1.7129E+03
^{242}Pu – Plutonium 242	1.1899E+00	2.9973E+02
^{226}Ra – Radium 226	7.8785E-06	7.8785E-06
^{90}Sr – Strontium 90	0.0000E+00	0.0000E+00
^{233}U – Uranium 233	2.8513E-02	2.9214E+00
^{234}U – Uranium 234	4.3515E-01	6.8854E+01
^{235}U – Uranium 235	4.7486E-02	2.1683E+04
^{238}U – Uranium 238	2.3434E+00	6.8923E+06
Totals	2.9774E+05	7.8735E+06

Table DATA-E3. Panel 1 – Room 4

Radionuclide	Activity (Curies)	Mass (Grams)
^{241}Am – Americium 241	5.6147E+03	1.6181E+03
^{237}Np – Neptunium 237	1.6499E-02	2.3141E+01
^{238}Pu – Plutonium 238	7.1070E+02	4.1081E+01
^{239}Pu – Plutonium 239	1.5038E+04	2.3908E+05
^{240}Pu – Plutonium 240	3.3797E+03	1.4694E+04
^{241}Pu – Plutonium 241	5.7280E+04	5.5077E+02
^{242}Pu – Plutonium 242	3.2172E-01	8.1037E+01
^{234}U – Uranium 234	1.0038E-01	1.5883E+01
^{235}U – Uranium 235	9.3989E-03	4.2917E+03
^{238}U – Uranium 238	4.3477E-01	1.2787E+06
Totals	8.2025E+04	1.5391E+06

Table DATA-E4. Panel 1 – Room 5

Radionuclide	Activity (Curies)	Mass (Grams)
^{241}Am – Americium 241	1.1232E+04	3.2369E+03
^{237}Np – Neptunium 237	4.1192E-02	5.7773E+01
^{238}Pu – Plutonium 238	4.9307E+02	2.8501E+01
^{239}Pu – Plutonium 239	1.2341E+04	1.9620E+05
^{240}Pu – Plutonium 240	2.7427E+03	1.1925E+04
^{241}Pu – Plutonium 241	3.8036E+04	3.6573E+02
^{242}Pu – Plutonium 242	2.3423E-01	5.9000E+01
^{233}U – Uranium 233	5.2969E-03	5.4272E-01
^{234}U – Uranium 234	6.4339E-02	1.0180E+01
^{235}U – Uranium 235	8.3825E-03	3.8276E+03
^{238}U – Uranium 238	2.6287E-01	7.7313E+05
Totals	6.4845E+04	9.8885E+05

Table DATA-E5. Panel 1 – Room 6

Radionuclide	Activity (Curies)	Mass (Grams)
^{227}Ac – Actinium	3.6430E-04	4.9741E-06
^{241}Am – Americium 241	1.4472E+04	4.1705E+03
^{243}Am – Americium 243	1.5729E-03	7.7878E-03
^{137}Cs – Cesium 137	7.2349E-06	7.6137E-07
^{40}K – Potassium 40	1.6160E-06	2.8610E-01
^{237}Np – Neptunium 237	7.5073E-02	1.0530E+02

Table DATA-E5. Panel 1 – Room 6 — Continued

Radionuclide	Activity (Curies)	Mass (Grams)
^{231}Pa – Protactinium 231	4.9790E-04	1.0419E-02
^{238}Pu – Plutonium 238	3.3829E+02	1.9554E+01
^{239}Pu – Plutonium 239	1.2851E+04	2.0432E+05
^{240}Pu – Plutonium 240	2.8699E+03	1.2478E+04
^{241}Pu – Plutonium 241	2.6727E+04	2.5699E+02
^{242}Pu – Plutonium 242	2.1064E-01	5.3054E+01
^{230}Th – Thorium	2.4100E-05	1.1800E-03
^{233}U – Uranium 233	4.3707E-03	4.4782E-01
^{234}U – Uranium 234	2.8120E-02	4.4512E+00
^{235}U – Uranium 235	2.5512E-03	1.1650E+03
^{238}U – Uranium 238	1.2067E-01	3.5492E+05
Totals	5.7259E+04	5.7749E+05

Table DATA-E6. Panel 1 – Room 7

Radionuclide	Activity (Curies)	Mass (Grams)
^{241}Am – Americium 241	2.7844E+04	8.0252E+03
^{243}Am – Americium 243	2.2362E-03	1.1140E-02
^{60}Co – Cobalt 60	3.4696E-07	3.0400E-10
^{137}Cs – Cesium 137	2.4119E-04	2.7401E-06
^{40}K – Potassium 40	1.8587E-05	3.2901E+00
^{22}Na – Sodium 22 (NA-22)	5.3435E-06	8.4500E-10
^{237}Np – Neptunium 237	9.3755E-02	1.3149E+02
^{231}Pa – Protactinium 231	6.1146E-06	1.3003E-05
^{238}Pu – Plutonium 238	1.4362E+03	8.3073E+01
^{239}Pu – Plutonium 239	2.7257E+04	4.3332E+05
^{240}Pu – Plutonium 240	6.1924E+03	2.6925E+04
^{241}Pu – Plutonium 241	8.6568E+04	8.3333E+02
^{242}Pu – Plutonium 242	6.8228E-01	1.7200E+02
^{230}Th – Thorium	2.6073E-06	2.3646E+01
^{233}U – Uranium 233	1.3393E-01	1.3722E+01
^{234}U – Uranium 234	1.6387E-01	2.5948E+01
^{235}U – Uranium 235	1.3687E-02	6.2499E+03
^{238}U – Uranium 238	4.8689E-01	1.4312E+06
Totals	1.4930E+05	1.9070E+06

Panel 1 – Room Totals	7.2845E+05	2.1622E+07

ATTACHMENT F: TRANSURANIC WASTE INVENTORY UPDATE REPORT, 2003
TO
APPENDIX DATA

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ACRONYMS AND ABBREVIATIONS

AE	Argonne National Laboratory – East site identifier
ANL-E	Argonne National Laboratory East
ANL-W	Argonne National Laboratory West
AL	Ames Laboratory site identifier
AM	ARCO Medical Products Company site identifier
AW	Argonne National Laboratory - West Side identifier
BC	Battelle Columbus Laboratory site identifier
BAPL	Bettis Atomic Power Laboratory
BCL	Battelle Columbus Laboratory
BL	Babcock and Wilcox Lynchberg site identifier
BLIP	Brookhaven Linear Isotope Production
BT	Bettis Atomic Power Laboratory site identifier
C&C Agreement	Agreement for Consultation and Cooperation between the Department of Energy and the State of New Mexico on the Waste Isolation Pilot Plant
Ca	Calcium
CAO	Carlsbad Area Office
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CFR	Code of Federal Regulations
CH	Contact-handled
CPR	Cellulosic, Plastic, and Rubber Materials
CRA-2004	Compliance Recertification Application
CY	Calendar Year
D&D	Decontamination and Decommissioning
DOE	U.S. Department of Energy
DOR	Direct Oxide Reduction
EDTA	ethylenediaminetetraacetic acid
EPA	U.S. Environmental Protection Agency
ER	Environmental restoration or electro-refining (salts)
ERMS	Electronic Records Management System
ET	Energy Technology Engineering Center site identifier
FFCAct	Federal Facilities Compliance Act
ft^3	Cubic feet
FR	Framatome (Richland) site identifier
GE	General Electric Vallecitos Nuclear Center site identifier
HEPA	High Efficiency Particulate Air
IDB	Integrated Database
IDC	Item Description Code
IN	Idaho National Engineering and Environmental Laboratory site identifier
INEEL	Idaho National Engineering and Environmental Laboratory
IT	Inhalation Toxicology Research Institute (now known as Lovelace Respiratory Research Institute, LRRI) site identifier
JASPER	Joint Actinide Shock Physics Experimental Research
K	Potassium
KA	Knolls Atomic Power Laboratory-Schenectady site identifier

KAPL	Knolls Atomic Power Laboratory
kg	Kilograms
KN	Knolls Atomic Power Laboratory – Nuclear Fuels Service site identifier
LA	Los Alamos National Laboratory site identifier
LANL	Los Alamos National Laboratory
LANL-CO	Los Alamos National Laboratory – Carlsbad Operations
LB	Lawrence Berkeley National Laboratory site identifier
LBNL	Lawrence Berkeley National Laboratory
LECO	Trade name for manufacture of crucibles, furnaces and analytical instrumentation
LL	Lawrence Livermore National Laboratory site identifier
LLNL	Lawrence Livermore National Laboratory
LRRI	Lovelace Respiratory Research Institute
LWA	Land Withdrawal Act
m^3	cubic meters
MC	U.S. Army Material Command site identifier
MgO	Magnesium Oxide
mrem	Millirem
MSE	Molten Salt Extraction
MU	University of Missouri Research Reactor site identifier
MURR	University of Missouri Research Reactor
NT	Nevada Test Site site identifier
NTS	Nevada Test Site
NWMP	Nuclear Waste Management Program
OP	Overpack
OR	Oak Ridge National Laboratory site identifier
ORIGEN2	Oak Ridge Isotope Generation and Depletion Code
ORNL	Oak Ridge National Laboratory
OSR	Offsite Source Recovery
ORP	Office of River Protection
PA	Performance Assessment
PA	Paducah Gaseous Diffusion Plant site identifier (in waste profiles only)
PCB	Polychlorinated Biphenyls
PE	Polyethylene
PGDP	Paducah Gaseous Diffusion Plant
POC	Pipe Overpack Component
Pu	Plutonium
PX	Pantex Plant site identifier
QA	Quality Assurance
RCRA	Resource Conservation and Recovery Act
RF	Rocky Flats Environmental Technology site identifier
RFETS	Rocky Flats Environmental Technology Site
RH	Remote-handled
RL	Hanford (Richland Operations Office) site identifier
RP	Hanford (Office of River Protection) site identifier
SA	Sandia National Laboratories site identifier

SBW	Sodium-bearing waste
SNL	Sandia National Laboratories
SP	Separations Process Research Unit site identifier
SPRU	Separations Process Research Unit
SQAP	Software Quality Assurance Plan
SR	Savannah River Site site identifier
SRS	Savannah River Site
STTP	Source Term Test Program
SWB	Standard Waste Box
TDOP	Ten Drum Overpack
TOC	Total Organic Carbon
TRU	Transuranic
TRUPACT II	Transuranic Package Transporter – II
TWBID	Transuranic Waste Baseline Inventory Database, Rev. 2.1
TWBIR	Transuranic Waste Baseline Inventory Report
TWIUR	Transuranic Waste Inventory Update Report
USAMC	U.S. Army Material Command
WAC	Waste Acceptance Criteria
WHO	Waste Handling Operations
WIPP	Waste Isolation Pilot Plant
WIR	Waste Incidental to Reprocessing
WM	Waste Material
WMC	Waste Matrix Code
WMP	Waste Material Parameter
WP	WIPP repository site identifier
WTWBIR	WIPP Transuranic Waste Baseline Inventory Report
WV	West Valley Demonstration Project site identifier
WWIS	WIPP Waste Information System
Zn	Zinc
Zn-Mg	Zinc-Magnesium (metal alloy)

ABBREVIATED NAMES

TWBIR Revision 3	Transuranic Waste Baseline Inventory Report, Revision 3 (DOE 1996a)
TWBIR Revision 2	Transuranic Waste Baseline Inventory Report, Revision 2 (DOE 1995b)
TWBID Revision 2.1	Transuranic Waste Baseline Inventory Database (LANL 2003a)
2003 Update Report	Transuranic Waste Inventory Update Report – 2003 (this document)
Computational Methodology	Transuranic Waste Inventory Update Report – 2003 Computational methodology (LANL 2003b)

PREFACE

The information in this report summarizes the U.S. Department of Energy's (DOE's) transuranic (TRU) waste inventory, projections, and characteristics, and reports emplaced waste. Revision 0 of the Waste Isolation Pilot Plant (WIPP) Transuranic Waste Baseline Inventory Report (WTWBIR) published in June 1994 (DOE 1994), was the first attempt ever made by the DOE complex to report all of its TRU waste at the waste stream level. The waste data reported in Revision 0 were considered preliminary until the DOE TRU waste generator/storage sites completed quality checks of the data. Data changes resulting from the site reviews were contained in Revision 1 of the WTWBIR (DOE 1995a). Subsequently, two additional baseline reports, Transuranic Waste Baseline Inventory Report (TWBIR) Revisions 2 and 3 (DOE 1995b and DOE 1996a), were published in 1995 and 1996 to include WIPP and non-WIPP wastes and other additional characteristic information.

This document, the Transuranic Waste Inventory Update Report, 2003, is the first update report to these baselines primarily focused on support of performance assessment (PA) in support of the Compliance Recertification Application (CRA-2004) and U.S. Environmental Protection Agency (EPA) concerns related to repository operation. The primary differences between previous data submittals and this update are:

- This report accounts for the Idaho National Engineering and Environmental Laboratory (INEEL) Advanced Mixed Waste Treatment Facility process by which 55-gallon drums are compacted and put into 100-gallon drums and disregards those calculations related to future waste incineration described in the TWBIR Revision 3 (DOE 1996a) that never went into operation.

- This report includes 7,095 m^3 (250,595 ft^3) of stored Hanford tank waste that was added to the inventory in December 2002.

- This report also addresses the waste that has been emplaced since the WIPP opened in 1999.

Finally, this report includes updates to all site Waste Stream Profiles that were reported in TWBIR Revision 2 (DOE 1995b). The TRU waste sites provided updated Waste Stream Profiles which contain parameters that are important to the PA. The updated Waste Stream Profiles for non-WIPP, WIPP, and emplaced waste streams are given in Annexes I, J, and K, respectively. The information contained in these profiles is considered the best estimate as of the inventory date, September 30, 2002, because more TRU waste characterization data are now available. However, a caveat to the profile information is warranted because the profiles contain the TRU waste site's best estimates of their TRU waste inventory. Due to the nature of the information, some inconsistencies remain in the profiles. A thorough review of the profiles was conducted during the CRA-2004 review, resulting in identification of specific inconsistencies in the waste stream information. All inconsistencies that were identified by the CRA-2004 reviewers are anticipated to have no significant impact on the PA calculations. The TRU Waste Baseline Inventory Waste Profile forms only reflect the data as reported by the TRU Waste Sites. During the process of generating the TRU Waste Baseline Inventory Report for the CRA, priority was given to developing data on those parameters considered important to performance

assessment (PA). Work is now in progress to correct noted inconsistencies in the forms. SNL will evaluate whether any of the individual or cumulative corrections of the reported inconsistencies have an impact on PA.

DATA-F-1.0 INTRODUCTION

DATA-F-1.1 Background

The U.S. Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) opened on March 26, 1999, becoming the nation's first deep geologic repository for the permanent disposal of defense-generated TRU waste. This waste is currently retrievably stored at 27 sites across the country (see Figure DATA-F-1). From the WIPP's opening through the inventory date (September 30, 2002), 1255 shipments of TRU waste were safely characterized, transported, and disposed in the WIPP.

TRU waste is defined as "…waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years…" (U.S. Congress 1996). TRU wastes are classified as either contact-handled- (CH-) waste or remote-handled- (RH-) waste, depending on the dose rate at the surface of the waste container. CH-TRU wastes are packaged TRU wastes with an external surface dose rate less than 200 millirem (mrem) per hour, while RH-TRU wastes are packaged TRU wastes with an external surface dose rate of 200 mrem or greater per hour (Pub. L. No. 102-579, 110 Stat. 2422 (1992), as amended by 104-201 (1996)). Unless otherwise indicated, for the purpose of this attachment, all references to TRU waste include TRU waste and mixed TRU waste (waste that contains both radioactive and hazardous components, as defined by the Atomic Energy Act [U.S. Congress 1954] and the Resource Conservation and Recovery Act [RCRA] as codified in Title 40 Code of Federal Regulations [CFR] Part 261.3 [EPA 1980]).

The DOE is committed to demonstrating compliance with all applicable regulations for the permanent disposal of TRU defense wastes in the WIPP repository. These regulations are the environmental standards for management and disposal of TRU defense wastes as mandated in 40 CFR Part 191 (EPA 1993) and Part 194 (EPA 1996), and the RCRA regulations. Compliance demonstration through PA calculations for CRA-2004 will be based on the inventory of existing and currently projected waste streams compiled in this document.

The purpose of the WIPP TRU Waste Baseline Inventory Report (WTWBIR) Revision 0 (DOE 1994) and Revision 1 (DOE 1995a) was to provide data to be included in the PA processes for the WIPP. The Transuranic Waste Baseline Inventory Report, Revision 2 (hereafter referred to as TWBIR Revision 2) (DOE 1995b) expanded the original purpose of Revisions 0 and 1 to include support for the WIPP Land Withdrawal Act (LWA) (Pub. L. No. 102-579, 110 Stat. 2422 (1992), as amended by 104-201 (1996)) by providing the total DOE TRU waste inventory. The TWBIR Revision 2 included a chapter and an appendix that discussed the total DOE TRU waste inventory, including nondefense, commercial, polychlorinated biphenyl (PCB)-contaminated, and buried (predominately pre-1970) TRU wastes that were not planned at the time for disposal in WIPP.

The Transuranic Waste Baseline Inventory Report, Revision 3 (hereafter referred to as TWBIR Revision 3) (DOE 1996a) was based on the TWBIR Revision 2 data, which were supplemented by data in several memoranda issued during early calendar year (CY) 1996. These memoranda summarize additional data requested by the DOE to support PA modeling.

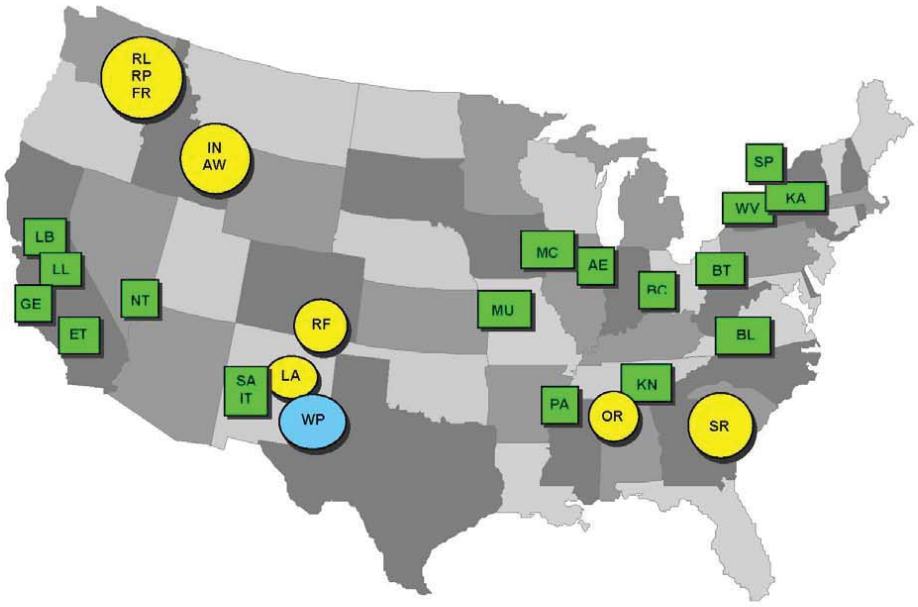

AE	Argonne National Laboratory-East
AW	Argonne National Laboratory-West
BC	Battelle Columbus Laboratories
BT	Bettis Atomic Power Laboratory
BL	Babcock & Wilcox-Lynchburg
ET	Energy Technology Engineering Center
FR	Framatome
GE	General Electric Vallecitos Nuclear Center
IN	Idaho National Engineering and Environmental Laboratory
IT	Inhalation Toxicology Research Institute (known as Lovelace Respiratory Research Institute)
KA	Knolls Atomic Power Laboratory
KN	Knolls Atomic Power Laboratory-Nuclear Fuels Services
LA	Los Alamos National Laboratory
LB	Lawrence Berkeley Laboratory
LL	Lawrence Livermore National Laboratory
MC	U.S. Army Material Command
MU	University of Missouri Research Reactor
NT	Nevada Test Site
OR	Oak Ridge National Laboratory
PA	Paducah Gaseous Diffusion Plant
RF	Rocky Flats Environmental Technology Site
RL	Hanford Site (Richland Operations Office)
RP	Hanford Site (Office of River Protection)
SA	Sandia National Laboratories
SP	Separations Process Research Unit
SR	Savannah River Site
WV	West Valley Demonstration Project
WP	Waste Isolation Pilot Plant

Figure DATA-F-1. U.S. Department of Energy TRU Waste Sites.

The primary purpose of TWBIR Revision 3 was to provide the summary data from TWBIR Revision 2) and the supplemental information used in the PA for the development of the Compliance Certification Application (CCA) (DOE 1996b) that was delivered to the Environmental Protection Agency (EPA), and to support the LWA. The supplemental information was generated from specific data requests to the TRU waste sites since the publication of the TWBIR Revision 2. These supplemental data included: radionuclides, data estimates for complexing agents, oxyanions, and cement content in solidified waste.

DATA-F-1.2 Purpose and Objectives

The purpose of this Transuranic Waste Inventory Update Report – 2003 (hereafter referred to as the 2003 Update Report) is to document the total inventory of DOE TRU waste as defined by the DOE TRU waste sites. The primary purpose of this document is to provide the summary data and the supplemental information required for the PA in support of the CRA-2004 which is to be delivered to the EPA for the five-year recertification as required by the LWA (Pub. L. No. 102-579, 110 Stat. 2422 (1992), as amended by 104-201 (1996)). Knowing that the WIPP waste inventory numbers have changed as a result of characterization activities and improved estimation processes, the EPA has requested that an update to the CCA inventory be included in the CRA-2004. In a letter from the EPA dated August 6, 2002 (EPA 2002), one of the items requested was "Waste inventory (actual inventory to date plus revisions to the estimated inventory as expressed in the Baseline Inventory Report)." This inventory update provides these changes.

The TWBIR Revision 2 (DOE 1995b) contained the waste profiles for all waste streams reported by the generator sites at that time, including some TRU waste streams that are unacceptable for disposal at WIPP. The waste stream profiles resided in two appendices in TWBIR Revision 2: Appendix O reported the "Non-WIPP" waste streams and Appendix P reported the "WIPP" waste streams. For the 2003 Update Report, Annex I reports the Non-WIPP waste streams and Annex J reports the WIPP waste streams, and Annex K reports the "emplaced waste." Although all TRU waste streams currently reported by the sites are accounted for in the current database and are reported in the 2003 Update Report, the non-WIPP waste streams do not contribute to the volume and scaling calculations. Hence, the non-WIPP waste streams will not contribute to inventory for the CRA-2004 PA calculations.

The objectives of the 2003 Update Report are to:

1. Define the DOE TRU waste inventory;

2. Provide the required information and data for use in the calculations for the CRA-2004; and

3. Maintain a consistent DOE complex-wide methodology for tracking TRU waste. A consistent methodology in support of the CRA-2004 provides a common frame of reference for discussion of TRU waste issues with regulatory organizations.

DATA-F-1.3 Sources of Transuranic Waste Information

The TRU waste inventory is taken from existing information about the waste, which has been provided by the TRU waste sites. In addition, information obtained from site Acceptable Knowledge Summary Reports has been incorporated to provide the most up to date data on waste streams that are currently being shipped to WIPP. Particular focus on data collection involved discussion with TRU waste sites about changes to the inventory since the certification of WIPP. Sites visits and onsite interviews facilitated data collection and ensured data were accurately represented. At the conclusion of data collection, each site was asked to provide information concerning what had changed since the baseline data collection and why the changes took place.

The information found in the TWBIR Revision 2 (DOE 1995b) has not been updated since the publication of that document. The TWBIR Revision 3 (DOE 1996a) used the same data plus other supplemental data that were needed for PA calculations. In addition, the WIPP has been open and receiving waste since March 1999. Therefore, data from the emplaced waste through September 30, 2002, are included in this report as obtained from the WIPP Waste Information System (WWIS).

The changes to the inventory since 1996 were requested from and provided by the TRU waste sites. Each site has verified the data that were entered into the database and has been asked to explain what the changes are in their current inventory when compared to TWBIR Revision 2 and 3 and why the inventory changed.

DATA-F-1.4 Document Organization

The 2003 Update Report (Appendix DATA, Attachment F) is organized into sections of text, figures, tables, and supporting annexes that are consistent with the TWBIR Revision 3 (DOE 1996a). The contents of remaining sections in this document are summarized below:

- Section DATA-F-2.0 presents the approach and methods used for gathering and compiling the WIPP waste disposal inventory information including the quality assurance program applied to the inventory project activities. A description of the TWBID Revision 2.1 database, analysis methods, and records used to document data and analysis results are also included in this chapter.

- Section DATA-F-3.0 presents summaries of inventory information including the waste volumes, waste material parameters (WMPs), packaging materials, chemical components, radiological components, discussion regarding the non-WIPP and future potential TRU waste, and discussion regarding the materials used to emplace the waste in the WIPP.

- Section DATA-F-4.0 provides the references used in the preparation of this document.

DATA-F-2.0 METHODS AND APPROACH

This 2003 Update Report provides the information needed for the PA calculations to be generated as part of the completion of the WIPP CRA-2004. The work was performed by Los Alamos National Laboratory—Carlsbad Operations (LANL-CO) and Sandia National

Laboratories (SNL). The role of SNL was to perform the PA calculations and provide documented results for the CRA-2004. The role of LANL-CO was to provide the updated inventory in support of the CRA-2004 PA. The technical work performed and documentation produced was under the controls provided by the SNL Quality Assurance (QA) Program developed for the SNL Nuclear Waste Management Program (NWMP). Inventory personnel:

1. collected TRU waste stream information from the TRU waste sites via site visits and additional communication, as needed;

2. compiled the data into a qualified electronic database;

3. performed analyses of the data in support of the CRA-2004 PA; and

4. published the results as official NWMP records acceptable for use in WIPP PA calculations.

The process is illustrated in Figure DATA-F-2 along with the controlling aspects of the SNL QA program. Figure DATA-F-2 also illustrates the governing SNL QA program procedures implemented in each step of the process.

The sections below describe the four basic process steps leading to the issuance of this report. Section DATA-F-2.1 discusses data collection, compilation and verification. Section DATA-F-2.2 discusses the development of the qualified electronic database, the Transuranic Waste Baseline Inventory Database Revision 2.1 [hereafter referred to as TWBID Revision 2.1] (LANL 2003a), that contains the TRU waste inventory data as of September 30, 2002. Section DATA-F-2.3 discusses the analyses performed in support of the CRA-2004 PA, and Section DATA-F-2.4 discusses the process of documentation in the SNL WIPP Records Center.

DATA-F-2.1 Data Collection, Compilation and Verification

The sections that follow describe the process of data collection, entry, and verification used to ensure data quality was maintained throughout the TRU waste inventory process. The data requirements found in Section DATA-F-2.1.1 were specifically called out by SNL to address the PA data needs. The data were then collected from the TRU waste sites, entered into the TWBID Revision 2.1 (LANL 2003a), and independently reviewed and verified by data entry personnel and the sites themselves. The process by which data were gathered, entered, reviewed, and verified is described in Sections DATA-F-2.2.2 through DATA-F-2.2.4.

All of the activities described in this section were governed by SNL procedure SP 9-6 Baseline Inventory Report (BIR) Change Report Data Collection and Entry (SNL 2003b). A collection of the documents compiled for each site is provided in Table DATA-F-1 including their respective Electronic Records Management System number (ERMS #).

DATA-F-2.1.1 Data Requirements

The data requirements for the 2003 Update Report were called out in a series of communications shown in Annexes G and H.

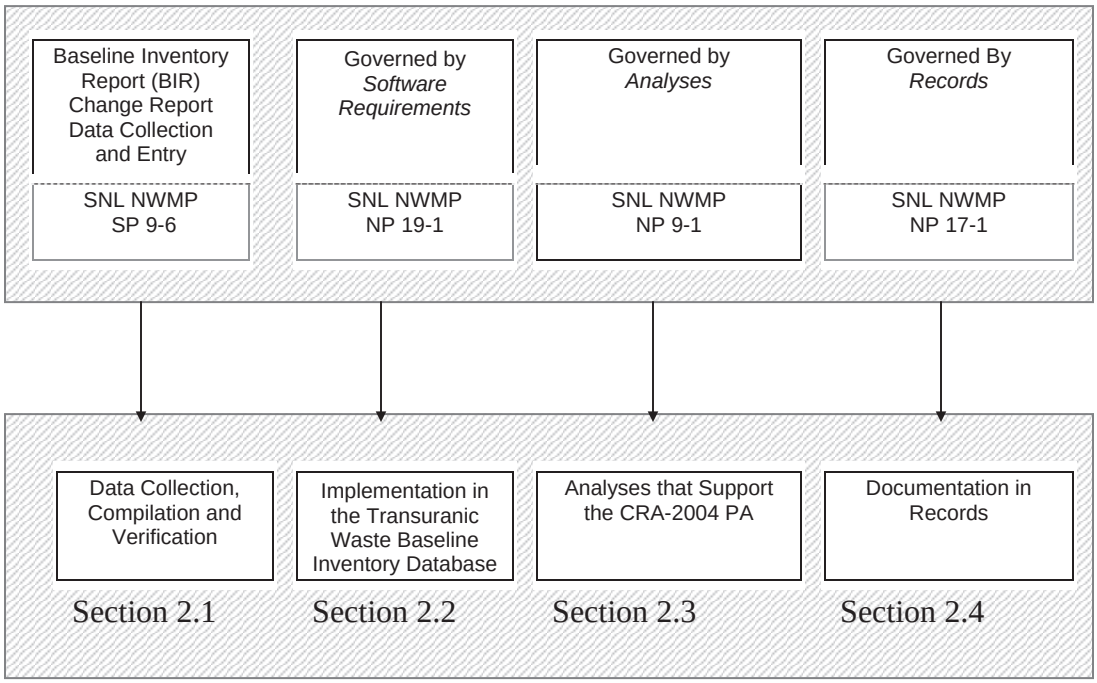

Figure DATA-F-2. Quality Methods for Generating the Transuranic Waste Inventory Update Report – 2003

Specifically, the data requirements for PA were given in Giambalvo (2002) and include the following:

- Waste stream volumes;
- Inventory of radionuclides on a waste stream basis for both CH- and RH-TRU waste and that the radionuclides reported be decayed to a common base year;
- Inventory of all non-radioactive waste material parameters that were previously tracked in the TWBIR Revision 3 (DOE 1996a). In addition, identify whether waste streams contain pyrochemical salts;
- Inventory of any other non-radioactive waste materials that are discovered to account for a significant portion of a waste stream as a result of changes to the inventory;
- Inventory of cellulosic, plastic, and rubber (CPR) materials, and other biodegradable materials used to facilitate emplacement of waste and MgO in the WIPP;
- Inventory of organic complexing agents and oxyanions (sulfate, nitrate, and phosphate; and
- Waste stream level inventories of radionuclides and non-radioactive waste material parameters for waste currently emplaced in the WIPP.

In addition to the seven data requirements listed above, the following was requested:

- A breakdown of the volume of the waste in the inventory into categories of stored, projected, and anticipated.

DATA-F-2.1.2 Collection Method

The EPA is mainly concerned with what has changed in the TRU waste inventory since the CCA (DOE 1996b) that resulted in the certification of the WIPP. To appropriately capture these changes, each TRU waste site was sent a copy of their data (in the form of waste profiles from the TWBIR Revision 2 (DOE 1995b) that they had submitted in 1995 for the CCA (DOE 1996b). With this transmittal to the site, guidance was provided delineating what the sites needed to address. The sites were requested to mark the changes on these profiles. The data were provided, followed by discussions focused on clarifying questions to ensure the data were correct. The data were entered into the electronic database, the TWBID Revision 2.1 (LANL 2003a), and qualified under SNL NP 19-1, Software Requirements (SNL 2002a). Upon completion of data entry, each site was provided with a signature sheet requesting that the DOE site representative responsible for TRU waste verify the data.

The methodology used to collect data and enter data into the TWBID Revision 2.1 (LANL 2003a) from DOE TRU waste sites is captured in procedure SP-9-6, Baseline Inventory Report (BIR) Change Report Data Collection and Entry (SNL 2003b). The process described in this procedure was initiated by a data call based on a request for modification of waste profile information that was included in the TWBIR Revision 2 (DOE 1995b). This data call was followed by a second data call specifically requesting data required by SNL (Giambalvo 2002). During the time these data calls were issued, LANL-CO visited sites to facilitate data collection and worked with the sites to assist with questions and issues as they came up.

DATA-F-2.1.3 Implementation in the Transuranic Waste Baseline Inventory Database, Revision 2.1

Preliminary data collected from the sites included database disks, notes from discussions with waste management personnel, email correspondence, site literature, and data spreadsheets. After data were gathered, they were submitted to the SNL WIPP Records Center.

These data were used to update the TWBID Revision 2.1 (LANL 2003a) by deletion of waste streams that were no longer maintained, modification of waste streams, and addition of new waste streams. Waste stream profile information was modified for sites that either had additional information or had modified TWBIR Revision 2 (DOE 1995b) waste streams. When data discrepancies were found or sites requested changes to data after preliminary data were entered into the database, change information was collected on forms found in procedure SP-9-6, Baseline Inventory Report (BIR) Change Report Data Collection and Entry (SNL 2003b). The database was changed to reflect this new information, accordingly.

DATA-F-2.1.4 Validation and Verification of Data

Upon completion of data entry, an independent review of all changes that were made to the database was conducted. This review was documented in the database. When all changes were completed, the database record was sent back to the sites for final verification and authentication

by the site DOE representative. The verified results were entered into the SNL WIPP Records Center, as were the signed forms from each of the DOE TRU waste sites.

Additional records were collected from the DOE TRU waste sites after the inventory was verified and authenticated by DOE site representatives. Records were received from each site explaining changes that had occurred with their inventory since the baseline data collection was performed in 1995. These records were also entered into the SNL WIPP Records Center.

DATA-F-2.2 Transuranic Waste Baseline Inventory Database

Data tables included in this report were generated by a Microsoft Access 2000 database application known as the TWBID Revision 2.1 (LANL 2003a). TWBID Revision 2.1 was used to manage, maintain, and perform calculations on inventory data.

The sections that follow describe the database and its development. Section DATA-F-2.2.1 describes the origins of the database. Section DATA-F-2.2.2 describes the database in general terms. Section DATA-F-2.2.3 describes configuration control.

All of the activities described in this section were governed by the SNL QA procedure, NP 19-1 Software Requirements (SNL 2002a).

DATA-F-2.2.1 Origins of the Transuranic Waste Baseline Inventory Database

The database used to generate TWBIR Revision 3 (DOE 1996a) (TWBIR.mdb, dated 1/29/1996) was used as a baseline for TWBID Revision 2.1 (LANL 2003a). The database was originally provided in Microsoft® Access 2.0 format, and was subsequently converted to Microsoft® Access 2000 format. Structural changes were then made to the new version to accommodate new requirements. These changes were captured in Microsoft® Visual Source Safe (see Section DATA-F-2.2.3, below).

Development of the TWBID Revision 2.1 (LANL 2003a) was governed by the SNL QA procedure, NP 19-1 Software Requirements (SNL 2002a). NP 19-1 outlines a process whereby a software QA plan (the SQAP) is written for the software product. Following the SQAP, the requirements for the product are defined and documented, the design of the product is created and documented, the product is implemented and its implementation is documented, a plan for testing the product is written, the product is tested and its verification and validation is documented, and the installation of the product is documented. The product and its documentation are reviewed at each step in this process by a technical, QA, and management reviewer.

Each of these steps was completed for the TWBID Revision 2.1 (LANL 2003a). Table DATA-F-3 provides references and ERMS identifiers for the QA documents for the TWBID Revision 2.1 (LANL 2003a).

DATA-F-2.2.2 Database Description

The TWBID Revision 2.1 (LANL 2003a) consists of two main interface database files that link to a third, common data file. The first interface file, TWBID.mdb, contains the interface forms

that data entry personnel use to browse, add, modify, or delete waste streams and related information. Users must log in to this interface in order to gain access to modify the data. A central file, TWBID.mdw, which contains username, password, and permission information, manages authentication. The second interface file, REPORTS.mdb, contains the database objects (tables, queries, reports, macros, and modules) required to generate the tables and reports used within the 2003 Update Report. The third file, TWBID_Data.mdb, contains the raw data used by both the TWBID.mdb and REPORTS.mdb databases. This data file is "linked" to the other two by using the table-linking feature intrinsic to Microsoft® Access 2000. By utilizing linked tables, a multiple-user, client-server environment was established for the TWBID Revision 2.1.

The Microsoft® Access Database files are hosted on a Windows NT 4.0 Server, and are protected by a Windows NT File System permission structure, allowing only approved database users to have access to the files. In addition, there are database-level access controls established using the Workgroup security function inherent in Microsoft® Access.

The tables in the database have no predefined relationships using primary and foreign key values to automatically associate data existing in separate tables. All functionality that relates and manipulates data across tables is established through table joins specified within the database queries themselves.

DATA-F-2.2.3 Configuration Management

The TWBID Revision 2.1 (LANL 2003a) software was placed under configuration control on November 17, 2002 as version 3.01. TWBID Revision 2.1 has undergone several iterative revisions and has been under strict configuration control since that date. The current version of the TWBID Revision 2.1 software is 3.12 (at the point of the publication of this document).

In addition, the data used by the TWBID is also under strict configuration control. Versions of the data were captured at designated points throughout the data entry process. At the point of publication of this document, the current data version was D.4.09.

The tool used to maintain configuration control of the TWBID Revision 2.1 is Microsoft® Visual SourceSafe Version 6.0. The Visual SourceSafe database maintains an archive of all revisions to the TWBID Revision 2.1 software, and allows for easy retrieval of any revision throughout the development and data entry processes. All changes to the TWBID Revision 2.1 database software (not the source code) were approved per procedure NP 19-1, Software Requirements (SNL 2002a). A hardcopy printout of the data from the database was generated for each version update and entered in the SNL WIPP Records Center.

DATA-F-2.3 Analysis Methods

In addition to collecting and processing data from the TRU waste sites and securing the site data in a qualified database for future use, analyses were performed on the data to support the CRA-2004 PA. For example, in preparation of this report, volume data from waste streams was rolled up into stored, projected, and anticipated categories; WMPs were rolled up to provide average

waste material densities in the repository; radionuclides were decay-corrected to the end of calendar year 2001; and radionuclide activities were scaled for the full repository.

All of the analyses performed in support of the CRA-2004 PA were governed by SNL procedure NP 9-1 Analyses (SNL 2001). NP 9-1 requires that an analysis plan governing the work is written. The analysis plan governing the analysis in support of the CRA-2004 PA is AP-092, Analysis Plan for Transuranic Waste Inventory Update Report, 2003 (SNL 2002b). AP-092 specifies that the first step in the analyses in support of the CRA-2004 PA is documentation of the computational methods that will be used to perform the required analyses. Those methods were documented in Transuranic Waste Inventory Update Report, 2003 Computational Methodology [hereafter referred to as the Computational Methodology] (LANL 2003b).

The sections that follow describe the radionuclide decay calculations (Section DATA-F-2.3.1), the roll-up and scaling calculations (Section DATA-F-2.3.2), and calculations of chemical components in the repository (Section DATA-F-2.3.3).

DATA-F-2.3.1 Radionuclide Decay Calculations

One of the data requirements for the radionuclide inventory (see Section DATA-F-2.1.1) for the PA is that all radionuclides reported by waste stream in TWBID Revision 2.1 (LANL 2003a) will be decayed to a common base year. However, the site-provided data consisted of radionuclide activity concentrations at the date of assay for the waste stream (if the waste stream was assayed) or at the date that the site calculated the activity concentrations. Therefore, the radionuclide activity concentration data reported by the sites was exported from the TWBID Revision 2.1 into an external application that performed the radionuclide decay calculations and then imported back into the TWBID Revision 2.1 for storage.

The process of exporting the data from TWBID Revision 2.1 so that it can be decayed and importing the decayed data back into TWBID Revision 2.2 was governed by SNL procedure NP 9-1 Analyses: Appendix C, Routine Calculations (SNL 2001). Documentation of that calculation is provided in Unit Conversion and Data Transfer Between the TWBID Revision 2.1 Version 3.12 and ORIGEN2, Version 2.2 for the Transuranic Waste Inventory Update Report, 2003 (LANL 2003c).

The external application used for the radionuclide decay calculations was ORIGEN 2.2. The software code, ORIGEN 2.2 (Croff 1983; Croff 1980) is an isotope generation and depletion code that uses the matrix exponential solution method. The software was developed and is distributed by the Radiation Safety Information Computational Center at the Oak Ridge National Laboratory (ORNL).

The software was acquired to calculate the inventory of radionuclides decayed to the common base year, December 31, 2001. Qualification of ORIGEN 2.2 in support of these analyses was performed under SNL procedure, NP 19-1 Software Requirements (SNL 2002a). The steps involved in qualification of software under NP 19-1 were described in Section DATA-F-2.2.1. Each of the steps was completed for ORIGEN 2.2. Table DATA-F-4 gives the reader references and ERMS identifiers for the QA documents for ORIGEN 2.2. While the ORIGEN 2.2 software

has many capabilities, the qualification of ORIGEN 2.2 (Croff 1983; Croff 1980) under the SNL QA program is limited to radionuclide buildup and decay calculations.

DATA-F-2.3.2 Roll-up and Scaling Calculations

The roll-up and scaling calculations performed in support of this report were performed within the TWBID Revision 2.1 (LANL 2003a). As discussed in Section DATA-F-2.2.2, TWBID Revision 2.1 was qualified as software under SNL procedure NP 19-1, Software Requirements. That qualification included the qualification of the queries and reports designed to produce the roll-up and scaled information specified in Giambalvo (2002).

The computational methods that apply to the roll-up and scaling calculations were defined in the Computational Methodology (LANL 2003b). This document was used as the basis for drafting the design documentation required for software qualification of TWBID Revision 2.1. The queries that have been qualified for use in TWBID Revision 2.1 produce the data that are tabulated throughout this report and documented in records submitted to the SNL WIPP Records Center.

DATA-F-2.3.3 Chemical Component Calculations

A final requirement set forth in Giambalvo (2002) is that this report supply information about the chemical components of the waste like that supplied in support of the CCA PA in the TWBIR Revision 3 (DOE 1996a). This includes a calculation of the mass of organic ligands (complexing agents), the mass of oxyanions (nitrate, sulfate, and phosphate), and the mass of cement expected in the disposal volume for WIPP.

The calculation of the mass of organic ligands, oxyanions, and cement in the disposal volume for WIPP was governed by SNL procedure NP 9-1, Analyses. Each of these masses was calculated by hand following the processes outlined in NP 9-1 and each is documented in reports that were reviewed by three reviewers (technical, management, and QA), and then submitted to the SNL WIPP Records Center. The reports are discussed briefly in Sections DATA-F-3.2.3.1, DATA-F-3.2.3.2, and DATA-F-3.2.3.3. Appendix DATA, Attachment F, Annex A contains the results of an analysis of the inventory for pyrochemical salts.

Table DATA-F-5 gives the reader ERMS identifiers for the reports on organic ligands, oxyanions, and cement.

DATA-F-2.4 Records

The entire process of data collection, database development, and analysis leading up to the publication of this report has been documented in the SNL WIPP Records Center. The following sections give the reader a roadmap for the official records that support this body of work. All records have been submitted to the SNL WIPP Records Center in accordance with SNL procedure NP 17-1, Records (SNL 2003a).

DATA-F-2.4.1 Records Related to Data

The most extensive set of records pertaining to this body of work are the records related to the data collected from the sites. These data were collected as described in Section DATA-F-2.1, with the initial data call being issued to the sites by CBFO (Gist 2002). This initial data call is stored in the SNL WIPP Records Center under identifiers listed in Table DATA-F-1. The site responses were collected and reviewed to ensure the data were authenticated by signature and date prior to submittal to the SNL WIPP Records Center with the ERMS numbers shown in Table DATA-F--1.

A technical review of these records and a subsequent accuracy check to make sure that the data had been entered correctly into the TWBID Revision 2.1 (LANL 2003a) were then performed. Any modifications made at the time of this review were documented in the site data records listed in Table DATA-F-1.

Upon completion of the technical review that determined that site data had been entered correctly in the TWBID Revision 2.1, a final series of checks was performed to ascertain the completeness and consistency of the data. The methods applied for the completeness and consistency checks were based on a number of database queries documented in the corrections packages listed in Table DATA-F-2. The corrections for completeness and consistency were made incrementally in a series of three steps. Before each step, the proposed changes were reviewed. Then they were implemented. Verification of the changes was printed and submitted as authenticated records to the SNL WIPP Records Center as shown in Table DATA-F-1.

Finally when the accuracy and completeness checks on the database were complete, an electronic file of the data from the TWBID Revision 2.1 was sent to the sites for final verification and authentication. Their concurrence with the data in the TWBID Revision 2.1 was also submitted to records.

DATA-F-2.4.2 Records Related to Software Qualification

The records related to the qualification of the TWBID Revision 2.1 (LANL 2003a) are listed in Table DATA-F-3. The records related to qualification of ORIGEN 2.2 are listed in Table DATA-F-4.

DATA-F-2.4.3 Records Related to Analyses

The records related to analyses have been discussed individually in Section 2.3 of this attachment and are listed for the reader’s convenience in Table DATA-F-5.

DATA-F-3.0 TRANSURANIC WASTE INVENTORY

This section presents the TRU waste inventory that was collected on behalf of the DOE in support of CRA-2004. The data are stored in an electronic database, the TWBID Revision 2.1 Version 3.12 (LANL 2003a), which has been qualified for use in PA calculations as discussed in Section 2 of this attachment.

Table DATA-F-1. Records Related to Data Collection and Processing for the Transuranic Waste Inventory Update Report 2003

Document	ERMS#
Initial Memorandum for Data Call-Gist 2002	525955, 525962, 526065, 526077, 526094, 526113, 526167, 526410, 526598, 526526, 526540, 526558, 526568, 526592, 526609, 526679, 526698, 526739, 526768, 526782, 526428, 526447, 525956, 526054
Data Package For Ames	525948
Data Package For ARCO	526059
Data Package For Mound	525953 and 525958
Data Package For Pantex	525937
Data Package For Teledyne Brown	525934
Data Package For MURR	526555
Data Package For AW	526407 and 528082
Data Package For BC	526424
Data Package For BT	526164 and 528084
Data Package For BL	526051
Data Package For ET	526444 and 528054
Data Package For FR	525983
Data Package For IN	526765 (CH), 526179 (RH) and 528085
Data Package For KA	526087
Data Package For KN	525960 and 526104
Data Package For LA	526504 and 528065
Data Package For LB	526523
Data Package For LL	526536
Data Package For MC	525940
Data Package For NT (Jasper)	526576
Data Package For NT	526565
Data Package For OR	526589 and 528046
Data Package For PA	526074
Data Package For RF	526779 and 528074
Data Package For RL	526736
Data Package For RP	526473
Data Package For SA/IT	526606 and 526799
Data Package For SP	526063
Data Package For SR	526680
Data Package For GE	526463
Data Package For WV	526695
Data Package For WP	528118

Table DATA-F-2. Records Related to Computational Methods

Document Type	ERMS #
Transuranic Waste Inventory Update Report, 2003 Computational Methodology Revision 2	527821
Data Corrections in the TWBID Revision 2.1 Database – Data Screening Package	528538
Data Corrections in the TWBID Revision 2.1 Databases – Volume Package	528542
Data Corrections in the TWBID Revision 2.1 Databases – Waste Material Parameter Package	529603 and 529596
Data Corrections in the TWBID Revision 2.1 Databases – Radionuclide Package	528543

Table DATA-F-3. QA Documents for the TWBID Revision 2.1 (Records Package 526290)

Document Type	ERMS #
Software QA Plan	526292
Requirements Document	526293
Design Document	530621
Implementation Document	530621
Verification and Validation Plan	530623
Validation Document	530623
User's Manual	530622

Table DATA-F-4. QA Documents for ORIGEN2 Version 2.2 (Records Package 525783)

Document Type	ERMS #
Access Control Memorandum	528200
Requirements Document	525785
Code Classification of ORIGEN2, Version 2.2	525790
Implementation Document	525788
Verification and Validation Plan	525786
Validation Document	525786

Table DATA-F-5. Records Related to Inventory Analyses in Support of the CRA-2004 PA (Records Package 525272)

Document Type	ERMS #
Analysis Plan Governing Work	525797
Documentation of Waste Material Parameter Roll-up	530767
Documentation of Radionuclide Inventory Roll-up	530992
Calculation of Organic Ligand Masses	531319
Calculation of Oxyanion Masses	530984
Calculation of Cement Masses	531562

This presentation of the TRU waste inventory for CRA-2004 consists of summaries of the inventory information collected from the generator sites and the information calculated from the data submitted by the sites in support of the PA calculations for CRA-2004. Section DATA-F-3.1 presents the volume information provided by the sites for CH- and RH-TRU waste and the volume roll-ups to the WIPP repository capacity needed for PA. Section DATA-F-3.2 presents the non-radiological waste inventory as reported by the sites and as needed for PA. This includes roll-ups of the waste materials (Section DATA-F-3.2.1), roll-ups of the packaging materials (Section DATA-F-3.2.2), and information about the chemical components of the waste (Section DATA-F-3.2.3). Section DATA-F-3.3 presents the radionuclide inventory reported by the sites and WIPP-level roll-ups of the radionuclide data needed for PA.

Section DATA-F-3.4 presents a discussion of the non-WIPP and future potential waste, and provides the total volumes of the non-WIPP wastes, with the exception of the pre-1970 buried waste. Waste profiles are provided for these waste streams in Appendix DATA, Attachment F, Annex I. Appendix DATA, Attachment F, Section DATA-F-3.5 provides data for the materials used to facilitate waste emplacement at the WIPP. The material in Appendix DATA, Attachment F, Sections DATA-F-3.4 and DATA-F-3.5 is provided for completeness but is not used to support the WIPP PA.

In addition to the summary information presented in this section, a complete TRU waste inventory for all waste streams at all of the sites has been prepared in support of the CRA. That inventory is presented in Appendix DATA, Attachment F, Annexes I, J, and K. Appendix DATA, Attachment F, Annex I presents individual waste stream profiles for all of the waste streams that have been designated as Non-WIPP waste streams, as discussed in Appendix DATA, Attachment F, Section DATA-F-3.4. Annex J presents individual waste stream profiles for all WIPP waste streams planned for emplacement in the WIPP. Appendix DATA, Attachment F, Annex K presents individual waste stream profiles for all WIPP waste streams that were emplaced in the WIPP as of September 30, 2002.

Annex B presents the comparisons of 2003 volume, WMP, and radionuclide data to TWBIR Revision 3 data. Appendix DATA, Attachment F, Annex C presents the crosswalk of waste streams between TWBIR Revision 2 and the 2003 Update Report, and explanations for these changes. Appendix DATA, Attachment F, Annex D presents the packaging materials.

DATA-F-3.1 Transuranic Waste Volume Inventory

The volume information requested from the sites was broken down as follows:

- stored waste – waste that currently exists at the site, regardless of whether it is in its final form, and
- projected waste – waste that will be generated in the future.

Data for emplaced wastes were obtained from the WWIS. The total waste stream volume collected from the sites included stored (v_s) and projected (v_p) components as applicable for each TRU waste stream. The sites also reported both "As Generated" and "Final Form" waste volumes for their waste streams (see Glossary for definitions). This "Final Form" volume accounts for the entire waste container (the volume the waste container occupies in the repository). Since PA only considers the waste volume that will be disposed in the WIPP, only the "Final Form" volumes were used in the calculation of actual (reported by the site) and scaled (used in PA) waste volumes.

Table DATA-F-6 presents the CH-TRU waste anticipated inventory volumes reported by the sites. Table DATA-F-7 presents the RH-TRU waste anticipated inventory volume reported by the sites. The data presented in Tables DATA-F-6 and DATA-F-7 were derived by summing the waste-stream-level data into a site-level roll-up. For each site, all stored waste stream volumes (v_s) were summed to arrive at the total stored volume for the site, V_s. All projected waste stream volumes (v_p) were summed to arrive at the total projected volume for the site, V_p. The sum of the total stored volume and the total projected volume is the anticipated volume, V_a.

$$V_s + V_p = V_a, \qquad (1)$$

where

V_a is the total anticipated volume at the site
V_s is the total stored volume at the site
V_p is the total projected volume at the site.

DATA-F-3.1.1 Waste Isolation Pilot Plant-Level Roll-Up of Waste Inventory for Performance Assessment

Performance assessments conducted in support of the WIPP have been predicated on the assumption that the WIPP repository will be filled to its design capacity at the time of closure. The design capacity for WIPP is 175,564 m^3 (6,200,000 ft^3) (U.S. Congress 1996) with a limit of 7079 m^3 (250,000 ft^3) for RH-TRU waste as imposed by the Consultation and Cooperation Agreement (DOE and State of New Mexico 1981). The volume of anticipated plus emplaced (CH-TRU and RH-TRU) waste reported by the sites in support of the CRA-2004 is less than and more than, respectively, the design capacity for WIPP. Therefore, scaling the CH- and RH-TRU waste volumes (up and down, respectively) to the design capacity for each in the WIPP is necessary for PA. The scaled inventory for PA is referred to as the disposal volume

Table DATA-F-6. WIPP CH-TRU Waste Anticipated Inventory By Site

TRU Waste Site	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
Argonne National Laboratory - East	1.1×10^2	7.9×10^1	1.9×10^2
Argonne National Laboratory - West	6.0×10^0	3.8×10^1	4.4×10^1
Battelle Columbus Laboratories	5.2×10^0	0.0×10^0	5.2×10^0
Bettis Atomic Power Laboratory	1.9×10^1	0.0×10^0	1.9×10^1
Energy Technology Engineering Center	2.3×10^0	0.0×10^0	2.3×10^0
Hanford (Richland-RL)	1.3×10^4	1.3×10^4	2.5×10^4
Hanford (River Protection-RP)	3.9×10^3	0.0×10^0	3.9×10^3
Idaho National Engineering & Environmental Laboratory	6.1×10^4	1.2×10^2	6.1×10^4
Knolls Atomic Power Laboratory - Nuclear Fuel Services	5.5×10^1	1.7×10^2	2.3×10^2
Lawrence Livermore National Laboratory	3.5×10^2	2.1×10^3	2.4×10^3
Los Alamos National Laboratory	1.2×10^4	3.3×10^3	1.5×10^4
Nevada Test Site	6.2×10^2	4.6×10^2	1.1×10^3
Oak Ridge National Laboratory	0.0×10^0	4.5×10^2	4.5×10^2
Paducah Gaseous Diffusion Plant	5.7×10^0	5.7×10^0	1.1×10^1
Rocky Flats Environmental Technology Site	5.4×10^3	2.7×10^3	8.1×10^3
Sandia National Laboratories - Albuquerque	2.4×10^1	0.0×10^0	2.4×10^1
Savannah River Site (SRS)	1.3×10^4	2.4×10^3	1.5×10^4
U.S. Army Material Command	2.5×10^0	0.0×10^0	2.5×10^0
University of Missouri Research Reactor	1.5×10^0	0.0×10^0	1.5×10^0
Totals	1.1×10^5	2.5×10^4	1.3×10^5
Emplaced Volume			
Waste Isolation Pilot Plant	7.7×10^3	0.0×10^0	7.7×10^3
Grand Totals	1.2×10^5	2.5×10^4	1.4×10^5

as described in the Glossary. The CH-TRU waste was scaled up since the anticipated volume is less than the allowable capacity. The RH-TRU waste was scaled down because the anticipated volume of RH-TRU waste exceeded the allowable limit. Scaling is performed only on projected waste.

Table DATA-F-8 presents the volume scaling factors. The following sections discuss the calculation of the WIPP-level roll-up for CH- and RH-TRU waste.

DATA-F-3.1.1.1 Calculation of Waste Isolation Pilot Plant-Level Roll-Up for Contact-Handled- Transuranic Waste

The WIPP disposal limit for CH-TRU waste is 168,485 m^3 (5,950,000 ft^3). Since the total reported volume of CH-TRU waste is less than the WIPP limit, the projected volume was scaled so the total volume equaled the CH-TRU waste disposal limit for WIPP. The scaling

Table DATA-F-7. WIPP RH-TRU Waste Anticipated Inventory By Site

TRU Waste Site	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
Argonne National Laboratory – East	1.5×10^1	1.0×10^2	1.2×10^2
Argonne National Laboratory - West	2.4×10^1	6.9×10^1	9.3×10^1
Battelle Columbus Laboratories	4.4×10^1	1.8×10^0	4.6×10^1
Bettis Atomic Power Laboratory	2.0×10^0	0.0×10^0	2.0×10^0
Energy Technology Engineering Center	5.0×10^0	0.0×10^0	5.0×10^0
Hanford (Richland-RL)	3.8×10^2	9.4×10^3	9.8×10^3
Hanford (River Protection-RP)	4.5×10^3	0.0×10^0	4.5×10^3
Idaho National Engineering & Environmental Laboratory	2.2×10^2	0.0×10^0	2.2×10^2
Knolls Atomic Power Laboratory - Schenectady	0.0×10^0	1.4×10^2	1.4×10^2
Los Alamos National Laboratory	1.2×10^2	0.0×10^0	1.2×10^2
Oak Ridge National Laboratory	0.0×10^0	6.6×10^2	6.6×10^2
Sandia National Laboratories - Albuquerque	4.6×10^0	0.0×10^0	4.6×10^0
Savannah River Site	0.0×10^0	2.3×10^1	2.3×10^1
Totals	5.3×10^3	1.0×10^4	1.6×10^4

factor for CH-TRU waste was calculated using the following equation applied to WIPP waste streams .

The CH-TRU waste volume scaling factor was calculated as follows:

$$SF_{CH} = (\text{CH-TRU Design Capacity in } m^3 - V_s - V_e)/ V_p, \quad (2)$$

where

SF_{CH} is the scaling factor for the CH-TRU waste volume
V_s is the total stored volume over all waste streams and all sites for CH-TRU waste
V_p is the total projected volume over all waste streams and all sites for CH-TRU waste
V_e is the total emplaced volume for CH-TRU waste over all waste streams and all sites as of September 30, 2002.

The disposal inventory for a single CH-TRU waste stream was obtained by multiplying the CH-TRU waste projected volume by the appropriate scaling factor and adding that value to the stored and emplaced volumes for each waste stream.

$$v_{CH\text{-}Disposal} = SF_{CH}\,(v_p) + v_s + v_e, \quad (3)$$

where

$v_{CH\text{-}Disposal}$ is the disposal volume for CH-TRU waste for a single waste stream
SF_{CH} is the scaling factor for the CH-TRU waste volume
v_p is the projected inventory volume for a single CH-TRU waste stream before scaling
v_s is the stored inventory volume for a single CH-TRU waste stream before scaling
v_e is the emplaced inventory volume for a CH-TRU single waste stream before scaling.

Table DATA-F-8 shows the calculation for the CH-TRU waste scaling factor and the CH-TRU waste volumes. The total CH-TRU waste disposal inventory, $V_{CH\text{-}Disposal}$, is the sum of the scaled CH-TRU waste stream volumes. The scaled waste stream volumes for the CH-TRU waste streams included in the estimate of volume for PA are given in Appendix DATA, Attachment F, Annex E, Table DATA-F-E-1. All volume and scaling calculated results were derived from the data and information that were reported in the updated TWBID Revision 2.1 (LANL 2003a) for each CH-TRU waste stream. The volume rollups and scaling calculations were performed under the SNL QA program as described in the Computational Methodology (LANL 2003b).

DATA-F-3.1.1.2 <u>Calculation of Waste Isolation Pilot Plant-level Roll-up for Remote-Handled Transuranic Waste</u>

The WIPP disposal limit for RH-TRU waste is 7,079 m^3 (250,000 ft^3) (U.S. DOE and State of New Mexico 1981). The reported volume of stored RH-TRU waste is less than the disposal limit but the sum of the stored and projected volumes is greater than the disposal limit. Since the total reported volume of RH-TRU waste is greater than the WIPP limit, the projected volume was scaled down so the total volume for PA equaled the RH-TRU waste disposal limit for WIPP. The scaling factor for RH-TRU waste was obtained after RH-TRU waste streams designated as Non-WIPP waste streams were removed for WIPP waste streams.

The scaling factor for RH-TRU waste was calculated using the following equation:

$$SF_{RH} = (\text{RH-TRU Design Capacity in } m^3 - V_s - V_e)/ V_p, \qquad (4)$$

where

SF_{RH} is the scaling factor for the RH-TRU waste volume
V_s is the total stored volume over all waste streams and all sites for RH-TRU waste
V_e is the total emplaced volume over all waste streams and all sites for RH-TRU waste
V_p is the total projected volume over all waste streams and all sites for RH waste.

There is currently no RH-TRU waste emplaced in the WIPP, so the total RH-TRU waste emplaced volume, V_e, is zero.

The disposal inventory for a single RH-TRU waste stream was then obtained by multiplying the RH-TRU waste projected volume by the appropriate scaling factor and adding that value to the stored and emplaced volumes for each waste stream.

$$v_{RH\text{-}Disposal} = SF_{RH}\,(v_p) + v_s + v_e, \qquad (5)$$

where

$v_{RH\text{-}Disposal}$	is the disposal volume for RH-TRU waste for a single waste stream
SF_{RH}	is the scaling factor for the RH-TRU waste volume
v_s	is the stored inventory volume for a single RH-TRU waste stream before scaling
v_e	is the emplaced inventory volume for a single RH-TRU waste stream before scaling
v_p	is the projected inventory volume for a single RH-TRU waste stream before scaling

Table DATA-F-8 shows the calculation for the RH-TRU waste scaling factor and the RH-TRU waste volumes. The total RH-TRU waste disposal inventory, $V_{RH\text{-}Disposal}$, is the sum of the scaled RH-TRU waste stream inventories. The scaled waste stream volumes for the RH-TRU waste streams included in the estimate of volume for PA is given in Appendix DATA, Attachment F, Annex E, Table DATA-F-E-2. All volume and scaling calculated results were derived from the data and information that were reported in the updated TWBID Revision 2.1 (LANL 2003a) for each RH-TRU waste stream. The volume rollups and scaling calculations were performed under the SNL QA program as described in the Computational Methodology (LANL 2003b).

The total disposal inventory for the WIPP repository is the sum of the disposal volumes for CH- and RH-TRU wastes for all waste streams after scaling ($V_{CH\text{-}Disposal}$ and $V_{RH\text{-}Disposal}$).

DATA-F-3.2 Non-Radiological Transuranic Waste Inventory

This section presents the non-radiological TRU waste inventory that was collected on behalf of the DOE in support of the CRA. Section DATA-F-3.2.1 presents the inventory of waste materials. Section DATA-F-3.2.2 presents the inventory of packaging materials, and DATA-F-3.2.3 presents the inventory of chemical components.

The DOE has many reasons for obtaining and tracking non-radiological information about the TRU waste inventory destined for WIPP. For example, the DOE tracks the waste materials that go into the repository (i.e., CPR materials) because they may affect gas generation in the repository. As another example, the DOE tracks the chemical components of the waste going into the repository because they affect the solubility of actinides in the waste. The DOE needs to know the non-radiological properties of the waste not only for PA but also to support safe and economical transportation of the waste and operation of the facility.

Table DATA-F-8. Volume Scaling Factors

CH-WASTE	
WIPP capacity for waste	1.68×10^5 m^3
Total stored volume	1.09×10^5 m^3
Total projected volume	2.48×10^4 m^3
Total emplaced volume	7.72×10^3 m^3
Volume scaling factor (SF_{CH})	2.11×10^0
Note: $\frac{(1.68\times10^5)-((1.09\times10^5)+(7.72\times10^3))}{(2.48\times10^4)} = 2.11\times10^0$	
RH-WASTE	
WIPP capacity for waste	7.08×10^3 m^3
Total stored volume	5.29×10^3 m^3
Total projected volume	1.04×10^4 m^3
Total emplaced volume	0.00×10^0 m^3
Volume scaling factor (SF_{RH})	1.72×10^{-1}
Note: $\frac{(7.08\times10^3)-((5.29\times10^3)+(0.00\times10^0))}{(1.04\times10^4)} = 1.72\times10^{-1}$	

The DOE has established a system of tracking the non-radiological waste inventory destined for WIPP. It involves a description of the waste streams in terms of their waste matrix codes (WMCs), their WMPs, and their final waste forms.

The WMPs, final waste forms, and WMCs are defined in the Glossary, and were previously described in the TWBIR Revision 2 (DOE 1995b). The final waste forms and WMCs are also described in detail in the DOE Waste Treatability Group Guidance (DOE 1995c).

The following WMP descriptions were excerpted from the TWBIR Revision 2 and are operative in this document:

- Iron-base metal/alloys – This designation is meant to include iron and steel alloys in the waste and does not include the waste container materials. This also includes an iron-base metallic phase associated with any vitrification process, if applicable;

- Aluminum-base metal/alloys – Aluminum or aluminum-base alloys in the waste materials;

- Other metal/alloys – All other metals found in the waste materials (e.g., copper, lead, zirconium, tantalum, etc.). The lead portion of lead rubber gloves/aprons is also included in this category;

- Other inorganic material – Includes inorganic non-metal waste materials such as concrete, glass, firebrick, ceramics, graphite, sand, and inorganic sorbents;

- Vitrified material – This refers to waste that has been melted or fused at high temperatures with glass forming additives such as soil or silica in appropriate proportions to result in a homogeneous glass-like matrix. (Note that any unoxidized metallic phases, if present, are included in the iron-base metal/alloys waste material parameter.);

- Cellulosic material – Includes those materials generally derived from high polymer plant carbohydrates. Examples are paper, cardboard, kimwipes, wood, cellophane, cloth, etc;

- Rubber material – Includes natural or manmade elastic latex materials. Examples are Hypalon®, neoprene, surgeons' gloves, leaded-rubber gloves (rubber part only), etc;

- Plastic material – Includes generally manmade materials, often derived from petroleum feedstock. Examples are polyethylene, polyvinylchloride, Lucite®, Teflon®, etc;

- Solidified inorganic material – Includes any homogeneous materials consisting of sludge or aqueous-base liquids that are solidified with cement, Envirostone®, or other solidification agents. Examples are wastewater treatment sludge, cemented aqueous liquids, and inorganic particulates, etc. If a TRU waste site has not reported cement used as part of the solidification process in the cement (solidified) waste material parameter, the density of the cement is included in this field;

- Solidified organic material – Includes cemented organic resins, solidified organic liquids, and sludges;

- Cement (solidified) – Includes the cement used in solidifying liquids, particulates, and sludges. If for a solidified final waste form this field is left blank, it means that either cement is not the solidifying agent or that the cement is included in the solidified inorganic material waste material parameter, and

- Soil – Generally consists of naturally occurring soils that have been contaminated with inorganic radioactive waste materials.

Packaging material parameters are described in further detail in Section DATA-F-3.2.2 and in Annex D. Packaging material parameters were reported from the material parameter descriptions described in the TWBIR Revision 2. These parameters were determined by weights defined as follows:

- Steel – The weight of the steel part of the packaging from container information provided by the TRU waste generator/storage sites. Any necessary overpacking is included in the weight;

- Plastic – The weight of any plastic packaging submitted by the TRU waste sites. When weight of a rigid liner is not given, a 90-mil high density polyethylene (HDPE) liner is assumed; and

- Lead – The weight of the lead shielding in a RH-TRU canister is assumed if not provided by the TRU waste generator/storage sites.

Final waste form refers to the expected physical and chemical form of that waste stream after it is ready for disposal (i.e., once the waste has been processed, treated, or repackaged as necessary). Each final waste form consists of one or more WMCs that are grouped together. The WMCs associated with each of the final waste forms listed below are included in the TWBIR Revision 3 (DOE 1996a, Table 1-2). The purpose of the final waste form is to group waste streams that are expected to have similar physical and chemical properties at the time of disposal. A final waste form was assigned to all reported WIPP waste streams by each of the sites. The final waste forms are:

- Solidified inorganic material,
- Salt,
- Solidified organic material,
- Soil,
- Uncategorized metal (metal waste other than lead and/or cadmium) ,
- Lead/cadmium metal,
- Inorganic non-metal,
- Combustible material,
- Graphite,
- Heterogeneous debris,
- Filter material,
- Excluded waste streams (excluded from disposal at WIPP), and
- Unknown (excluded from disposal at WIPP).

The purpose of the WMCs is to aid in categorizing mixed waste streams into groups based on their different physical and chemical characteristics. The sites assign the WMCs for all of their mixed waste streams and generally assign them for their non-mixed waste streams, as well. The WMC system description and terminology used by the sites and the DOE is detailed in the DOE Waste Treatability Group Guidance. The WMCs are numerous, and are therefore not all listed here. However, the summary category groups (referred to as matrix parameter categories in the DOE Waste Treatability Group Guidance) are debris (S5000), homogeneous solids (S3000), and soil/gravel (S4000).

There are several WMCs in each of these summary category groups. For example, within the debris (S5000) summary category group, there are inorganic debris (S5100), organic debris (S5300), heterogeneous debris (S5400), and unknown/other debris (S5900). Within the inorganic debris group (S5100), there are metal debris (S5110), inorganic nonmetal debris

(S5120), and unknown/other inorganic debris (S5190). Within the metal debris (S5110) group, there are metal debris without lead or cadmium (S5111) and so on. These are detailed in the DOE Waste Treatability Group Guidance document.

DATA-F-3.2.1 Waste Materials

As part of the data call for this 2003 Update Report, the sites were asked to provide information about the materials contained in the waste. For each waste stream they were asked to designate a final waste form and to provide the density of each of the WMPs in the waste stream. The sites were asked to provide minimum, maximum, and average values for the WMPs in each waste stream. In some cases the sites provided all of the information required; in other cases, they did not.

For those waste streams where the site did not provide information regarding WMPs, the WMPs were estimated using the methods described in the Computational Methodology (LANL 2003b) and in the WMP corrections packages as identified in Table DATA-F-2. In summary, when partial information was provided (i.e., the minimum value or maximum value but not the average), it was used to calculate the average WMPs density (which was needed for PA). When no WMPs density information was given for a waste stream, the average density was inferred by identifying an analogous waste stream, and mapping the WMP from that waste stream into the waste stream that lacked WMPs.

For example, when information for a waste stream at a site was missing, the other waste streams from that site were reviewed to identify waste streams with similar final waste forms, WMCs, and waste stream descriptions. If a similar waste stream was identified, the WMPs from that waste stream (source) were attributed to the waste stream that lacked WMPs (destination waste stream). If there were no similar waste streams reported by that site, the other sites were examined to identify an appropriate similar waste regardless of its site of origin. Then the WMPs from the similar waste stream were copied (source to destination waste stream). In both cases, the packaging material parameters were edited using the waste packaging densities discussed in Section DATA-F-3.2.2 as appropriate for the type of container(s) in the destination waste stream.

In some cases, more than one similar waste stream was identified. In these instances, an average of the WMPs from similar streams was calculated and used. It was not necessary to calculate an average set of WMPs based on final waste form, as discussed in the Computational Methodology (LANL 2003b).

Waste streams were sometimes comprised of more than one container type (for example, 55-gallon drums and standard waste boxes (SWBs)). In these instances, when the site provided only one set of WMPs, those WMPs were used for both container types; except for the packaging material parameters which were corrected for the container type using the waste packaging densities given in Section DATA-F-3.2.2. The TWBID Revision 2.1 contains the WMPs list for every container type in a waste stream. However, the waste profiles in Annexes I and J (non-WIPP and WIPP waste streams, respectively) have a weighted average of the WMPs for all container types used in a waste stream. If the site provided a WMPs list for each container type,

those lists were maintained in the TWBID Revision 2.1 and a weighted average of the WMPs for all container types was used in the waste profiles.

In some cases, the sites provided incomplete WMP data from which the needed data could be inferred. Specifically, the WMP average densities were inferred from minimum and maximum WMP data. However, the minimum and maximum values will not be used for CRA PA and therefore were not reported. There are three cases in which WMP data were inferred. If maximum and minimum WMP values were reported, but no average density was reported, the average density was calculated as one half the sum of the maximum and minimum WMPs. If only a minimum WMP was reported, the minimum was assigned as the average density. If only a maximum WMP was reported, the average was calculated as one half the maximum WMP value, and assumed that the minimum was zero.

DATA-F-3.2.1.1 Roll-Up of Final Waste Form Volumes

Table DATA-F-9 presents a roll-up of the final waste form volumes for CH- and RH-TRU waste. Every WIPP waste stream in the TWBID Revision 2.1 (LANL 2003a) has been assigned a final waste form. The total volume for each of the final waste form categories is calculated by summing the actual (not scaled) waste stream volume components (emplaced, stored, and projected) with the same final waste form designation for all waste streams destined for WIPP.

DATA-F-3.2.1.2 Waste Material Parameter average Densities for Each Final Waste Form

Tables DATA-F-10 through DATA-F-29 present the WMP average densities for each final waste form in CH- and RH-TRU waste. Tables DATA-F-10 through DATA-F-20 are for CH-TRU waste. Tables DATA-F-21 through DATA-F-29 are for RH-TRU waste. These tables include the rolled up WMP average densities for each final waste form and the rolled up waste volumes by site that contributed to the total final waste form volume. These volumes are broken out into stored and projected volumes, and the total volume of waste by site for each final waste form. The emplaced volume is given by site, with the WIPP being the only applicable site. The final waste forms that have an emplaced waste CH-TRU waste volume are combustible, filter, heterogeneous, inorganic non-metal, lead/cadmium metal, salt, solidified inorganics, and uncategorized metal. There is no RH-TRU waste emplaced at this time.

For example, Table DATA-F-10 presents the WMP average densities for all CH-TRU waste streams with the combustible final waste form designation. The table shows roll-ups for stored, projected, and emplaced CH-TRU waste with the combustible final waste form designation for each site. This information is derived by summing the component volumes for each CH-TRU waste stream in the combustible category at each site.

Calculation of the WMP average densities in a final waste form requires combining data from the individual waste streams with the same final waste form designation as follows:

$$
\begin{aligned}
{}^{WM}m_i^j &= {}^{WM}p_i^j \times v_i^j \\
{}^{WM}M^j &= \sum {}^{WM}m_i^j \qquad (6) \\
{}^{WM}P^j &= {}^{WM}M^j \,/\, V^j,
\end{aligned}
$$

where

${}^{WM}m_i^j$	is the mass of the waste material (WM) in waste stream i with a final waste form designation j
${}^{WM}p_i^j$	is the average density of the WM in waste stream i with a final form designation j
v_i^j	is the volume of waste stream i (stored + projected + emplaced) with a final form designation of j
${}^{WM}M^j$	is the total mass of WM in all waste streams with a final form designation of j
V^j	is the total volume of all waste streams with a final form designation of j
${}^{WM}P^j$	is the average density of the WM in all waste streams the final form designation j.

Portions of some waste streams have been shipped to the WIPP and emplaced and others have yet to be characterized and shipped. If there was no emplaced waste for a waste stream as of the inventory date, then the emplaced volume in the equation above for that waste stream was zero. If there was no emplaced waste for any of the waste streams within the final waste forms considered, the total emplaced volume for the final waste form was also zero.

There are several notable differences in the WMP average densities for the roll-ups by final waste form when compared to the TWBIR Revision 3 (DOE 1996a). These changes are tabulated and discussed in Appendix DATA, Attachment F, and Annex B.2.

DATA-F-3.2.1.3 Waste Isolation Pilot Plant-Scale Waste Material Parameter Densities

Performance assessments conducted in support of the WIPP have been predicated on the assumption that waste materials are distributed homogeneously throughout the repository. As a result, a WIPP-scale average value for waste material densities is needed for PA. The WIPP-scale WMP average densities for CH- and RH-TRU wastes in support of the CRA are presented in Tables DATA-A-30 and DATA-F-31, respectively. These are equivalent to TWBIR Revision 3 (DOE 1996a) Tables 2-2 and 2-3, respectively. Note also that the TWBIR Revision 3 Tables 2-2 and 2-3 are the same as TWBIR Revision 2 (DOE 1995b, Tables 3-2 and 3-3, respectively). Although these tables in TWBIR Revisions 2 and 3 contain the minimum, maximum, and average densities for the WMP, this report contains only the average densities of the waste because only average values are used in PA.

WMPs were combined, or “rolled up,” for the whole repository according to the Computational Methodology (LANL 2003b). Specifically, the roll-up of WMP average densities required combining data from all of the WIPP waste streams reported by the sites. A weighted average value for the WMP based on the individual waste stream volumes in the total inventory was calculated from the WMP average densities provided by the sites as shown below:

$$
\begin{aligned}
{}^{WM}m_i &= {}^{WM}p_i \times v_i \\
{}^{WM}M &= \sum {}^{WM}m_i \qquad (7) \\
{}^{WM}P &= {}^{WM}M \,/\, V,
\end{aligned}
$$

where

${}^{WM}m_i$	is the mass of the WM in waste stream i
${}^{WM}p_i$	is the average density of the WM in waste stream i
v_i	is the actual (not-scaled) volume of waste stream i (stored + projected + emplaced)
${}^{WM}M$	is the total mass of WM in all waste streams
V	is the actual (not-scaled) volume of all waste streams
${}^{WM}P$	is the average density of the WM in all waste streams.

DATA-F-3.2.1.4 Additional Information Received After Transuranic Waste Baseline Inventory Database, Revision 2.1, Version 3.12, Data Version 4.09

After the TWBID, Revision 2.1 was configured for PA calculations, a typographical error was discovered in six of LANL's waste streams. The final form of these waste streams was listed as "solidified organic material" but should have been "solidified inorganic material" to match the waste matrix code. Therefore, the solidified organic material reported in Table DATA-F-9 and the volume identified for LANL in Table DATA-F-19 would decrease by 3,827 m^3. The solidified inorganic material reported in Table DATA-F-9 and the volume identified for LANL in Table DATA-F-18 would increase by 3,827 m^3. Volumes will also be affected in Tables DATA-F-B-12 and DATA-F-B-13 as well as the analyses for solidified inorganic material and solidified organic material in Appendix DATA, Attachment F, Annex B, Section DATA-F-B-1.4.

Table DATA-F-9. Transuranic Waste Inventory By Final Waste Form For WIPP

Final Waste Forms	Stored Waste	Projected Waste	Emplaced Waste	Total Waste
Contact Handled Waste Volumes (m^3)				
Combustible Material	4.3×10^3	1.9×10^3	6.1×10^2	6.8×10^3
Filter Material	9.9×10^2	5.9×10^2	3.4×10^2	1.9×10^3
Graphite	1.2×10^2	1.3×10^0	0.0×10^0	1.3×10^2
Heterogeneous Debris	4.9×10^4	9.7×10^3	5.7×10^2	5.9×10^4
Inorganic Non-Metal	1.1×10^4	6.8×10^1	9.7×10^2	1.2×10^4
Lead/Cadmium Metal	1.4×10^2	3.2×10^1	8.1×10^1	2.6×10^2
Salt	1.5×10^2	1.9×10^2	1.5×10^3	1.8×10^3
Soil	3.0×10^2	6.0×10^3	0.0×10^0	6.3×10^3
Solidified Inorganic Material [1]	3.5×10^4	7.3×10^2	3.3×10^3	3.9×10^4
Solidified Organic Material [1]	5.2×10^3	3.8×10^2	0.0×10^0	5.5×10^3
Uncategorized Metal	2.4×10^3	5.1×10^3	3.6×10^2	7.9×10^3
Total CH-TRU Waste Volumes	1.1×10^5	2.5×10^4	7.7×10^3	1.4×10^5
Remote-Handled Waste Volumes (m^3)				
Combustible Material	1.8×10^1	8.9×10^{-1}	0.0×10^0	1.9×10^1
Filter Material	8.9×10^0	8.9×10^0	0.0×10^0	1.8×10^1
Heterogeneous Debris	6.1×10^2	3.8×10^3	0.0×10^0	4.4×10^3
Inorganic Non-Metal	4.3×10^1	4.4×10^1	0.0×10^0	8.6×10^1
Lead/Cadmium Metal	1.2×10^1	7.1×10^0	0.0×10^0	1.9×10^1
Soil	0.0×10^0	2.0×10^2	0.0×10^0	2.0×10^2
Solidified Inorganic Material	4.5×10^3	3.3×10^2	0.0×10^0	4.8×10^3
Solidified Organic Material	9.5×10^0	0.0×10^0	0.0×10^0	9.5×10^0
Uncategorized Metal	8.4×10^1	6.1×10^3	0.0×10^0	6.1×10^3
Total RH-TRU Waste Volumes	5.3×10^3	1.0×10^4	0.0×10^0	1.6×10^4
Total TRU Waste Volumes (m^3)	1.1×10^5	3.5×10^4	7.7×10^3	1.6×10^5

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09
[1]See Section DATA-F-3.2.1.4 for additional information.

Table DATA-F-10. WIPP CH-TRU Waste Profiles – Combustible Material

Final Waste Form: **Combustible Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory – East	9.0×10^1	6.6×10^1	1.6×10^2
Argonne National Laboratory - West	5.4×10^0	4.4×10^0	9.8×10^0
Battelle Columbus Laboratories	5.2×10^0	0.0×10^0	5.2×10^0
Hanford (Richland-RL)	9.8×10^1	0.0×10^0	9.8×10^1
Los Alamos National Laboratory	2.9×10^3	1.4×10^3	4.3×10^3
Rocky Flats Environmental Technology Site	1.2×10^3	4.5×10^2	1.6×10^3
TRU Waste Site Total	4.3×10^3	1.9×10^3	6.2×10^3
Emplaced Waste Volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	6.1×10^2	0.0×10^0	6.1×10^2
Emplaced Waste Total	6.1×10^2	0.0×10^0	6.1×10^2
Total Waste Volume (m^3)	4.9×10^3	1.9×10^3	6.8×10^3
Waste Material Parameters	Average Density (kg/m^3)		
Iron-Base Metal/Alloys	1.5×10^1		
Aluminum-Base Metal/Alloys	8.4×10^{-1}		
Other Metal/Alloys	7.9×10^0		
Other Inorganic Material	1.0×10^1		
Cellulosic Material	2.0×10^1		
Rubber Material	1.3×10^1		
Plastic Material	4.9×10^1		
Solidified Inorganic Material	9.4×10^{-1}		
Cement (Solidified)	4.8×10^{-2}		
Vitrified Material	0.0×10^0		
Solidified Organic Material	1.2×10^1		
Soil	8.8×10^{-1}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-11. WIPP Contact-Handled Waste Profiles – Filter Material

Final Waste Form: **Filter Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	2.2×10^1	0.0×10^0	2.2×10^1
Lawrence Livermore National Laboratory	1.9×10^2	4.5×10^2	6.4×10^2
Los Alamos National Laboratory	3.3×10^2	0.0×10^0	3.3×10^2
Rocky Flats Environmental Technology Site	4.5×10^2	1.4×10^2	5.8×10^2
TRU Waste Site Total	9.9×10^2	5.9×10^2	1.6×10^3
Emplaced Waste volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	3.4×10^2	0.0×10^0	3.4×10^2
Emplaced Waste Total	3.4×10^2	0.0×10^0	3.4×10^2
Total Waste Volume (m^3)	1.3×10^3	5.9×10^2	1.9×10^3
Waste Material Parameters	Average Density (kg/m^3)		
Iron-Base Metal/Alloys	4.5×10^1		
Aluminum-Base Metal/Alloys	1.8×10^1		
Other Metal/Alloys	5.7×10^0		
Other Inorganic Material	1.6×10^1		
Cellulosic Material	4.6×10^1		
Rubber Material	6.2×10^0		
Plastic Material	1.6×10^1		
Solidified Inorganic Material	6.0×10^{-1}		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	3.5×10^{-1}		
Soil	4.8×10^0		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-12. WIPP CH-TRU Waste Profiles – Graphite

Final Waste Form: **Graphite**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Rocky Flats Environmental Technology Site	1.2×10^2	1.3×10^0	1.3×10^2
TRU Waste Site Total	1.2×10^2	1.3×10^0	1.3×10^2
Total Waste Volume (m^3)	1.2×10^2	1.3×10^0	1.3×10^2

Waste Material Parameters	**Average Density (kg/m^3)**
Iron-Base Metal/Alloys	1.9×10^1
Aluminum-Base Metal/Alloys	0.0×10^0
Other Metal/Alloys	0.0×10^0
Other Inorganic Material	1.7×10^2
Cellulosic Material	8.6×10^1
Rubber Material	0.0×10^0
Plastic Material	2.3×10^1
Solidified Inorganic Material	7.1×10^0
Cement (Solidified)	0.0×10^0
Vitrified Material	0.0×10^0
Solidified Organic Material	0.0×10^0
Soil	0.0×10^0

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-13. WIPP CH-TRU Waste Profiles – Heterogeneous Debris

Final Waste Form: **Heterogeneous Debris**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory - West	6.2×10^{-1}	3.4×10^{1}	3.4×10^{1}
Bettis Atomic Power Laboratory	1.9×10^{1}	0.0×10^{0}	1.9×10^{1}
Energy Technology Engineering Center	1.5×10^{0}	0.0×10^{0}	1.5×10^{0}
Hanford (Richland-RL)	1.2×10^{4}	2.1×10^{3}	1.4×10^{4}
Idaho National Engineering & Environmental Laboratory	2.0×10^{4}	2.3×10^{1}	2.0×10^{4}
Knolls Atomic Power Laboratory - Nuclear Fuel Services	5.5×10^{1}	1.7×10^{2}	2.3×10^{2}
Lawrence Livermore National Laboratory	1.3×10^{2}	1.4×10^{3}	1.6×10^{3}
Los Alamos National Laboratory	2.1×10^{3}	1.4×10^{3}	3.5×10^{3}
Nevada Test Site	6.1×10^{2}	4.6×10^{2}	1.1×10^{3}
Oak Ridge National Laboratory	0.0×10^{0}	4.5×10^{2}	4.5×10^{2}
Rocky Flats Environmental Technology Site	1.0×10^{3}	1.2×10^{3}	2.2×10^{3}
Sandia National Laboratories - Albuquerque	2.4×10^{1}	0.0×10^{0}	2.4×10^{1}
Savannah River Site	1.3×10^{4}	2.4×10^{3}	1.5×10^{4}
U.S. Army Material Command	2.5×10^{0}	0.0×10^{0}	2.5×10^{0}
University of Missouri Research Reactor	1.5×10^{0}	0.0×10^{0}	1.5×10^{0}
TRU Waste Site Total	4.9×10^{4}	9.7×10^{3}	5.9×10^{4}
Emplaced Waste Volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	5.7×10^{2}	0.0×10^{0}	5.7×10^{2}
Emplaced Waste Total	5.7×10^{2}	0.0×10^{0}	5.7×10^{2}
Total Waste Volume (m^3)	4.9×10^{4}	9.7×10^{3}	5.9×10^{4}
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	2.4×10^{2}		
Aluminum-Base Metal/Alloys	3.3×10^{1}		
Other Metal/Alloys	5.7×10^{1}		
Other Inorganic Material	5.6×10^{1}		
Cellulosic Material	1.2×10^{2}		
Rubber Material	3.2×10^{1}		
Plastic Material	9.0×10^{1}		
Solidified Inorganic Material	3.6×10^{0}		
Cement (Solidified)	0.0×10^{0}		
Vitrified Material	0.0×10^{0}		
Solidified Organic Material	1.8×10^{0}		
Soil	4.2×10^{0}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-14. WIPP CH-TRU Waste Profiles – Inorganic Non-Metal

Final Waste Form: **Inorganic Non-Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	1.1×10^1	3.0×10^1	4.2×10^1
Idaho National Engineering & Environmental Laboratory	1.1×10^4	0.0×10^0	1.1×10^4
Paducah Gaseous Diffusion Plant	5.7×10^0	5.7×10^0	1.1×10^1
Rocky Flats Environmental Technology Site	6.5×10^2	3.2×10^1	6.8×10^2
TRU Waste Site Total	1.1×10^4	6.8×10^1	1.1×10^4
Emplaced Waste Volumes (m^3)			
Site	Stored (m^3)	Projected (m^3)	Total (m^3)
Waste Isolation Pilot Plant	9.7×10^2	0.0×10^0	9.7×10^2
Emplaced Waste Total	9.7×10^2	0.0×10^0	9.7×10^2
Total Waste Volume (m^3)	1.2×10^4	6.8×10^1	1.2×10^4
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	4.2×10^0		
Aluminum-Base Metal/Alloys	1.2×10^{-2}		
Other Metal/Alloys	5.0×10^0		
Other Inorganic Material	5.5×10^1		
Cellulosic Material	1.9×10^1		
Rubber Material	1.1×10^{-1}		
Plastic Material	2.7×10^0		
Solidified Inorganic Material	9.0×10^{-1}		
Cement (Solidified)	0.0×10^0		
Vitrified Material	7.1×10^1		
Solidified Organic Material	2.7×10^{-5}		
Soil	1.8×10^{-3}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-15. WIPP CH-TRU Waste Profiles – Lead/Cadmium Metal

Final Waste Form: **Lead/Cadmium Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	1.7×10^1	1.4×10^1	3.1×10^1
Los Alamos National Laboratory	3.7×10^0	0.0×10^0	3.7×10^0
Rocky Flats Environmental Technology Site	1.2×10^2	1.8×10^1	1.4×10^2
TRU Waste Site Total	1.4×10^2	3.2×10^1	1.8×10^2
Emplaced Waste Volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	8.1×10^1	0.0×10^0	8.1×10^1
Emplaced Waste Total	8.1×10^1	0.0×10^0	8.1×10^1
Total Waste Volume (m^3)	2.2×10^2	3.2×10^1	2.6×10^2
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	9.2×10^2		
Aluminum-Base Metal/Alloys	1.8×10^1		
Other Metal/Alloys	1.5×10^2		
Other Inorganic Material	1.8×10^1		
Cellulosic Material	5.0×10^0		
Rubber Material	3.3×10^0		
Plastic Material	9.3×10^0		
Solidified Inorganic Material	8.2×10^{-1}		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	1.1×10^{-2}		
Soil	1.6×10^{-1}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-16. WIPP CH-TRU Waste Profiles – Salt

Final Waste Form: **Salt**

TRU Waste Site Volumes (m3)			
Site	Stored	Projected	Total
Lawrence Livermore National Laboratory	1.2×10^{0}	1.5×10^{1}	1.6×10^{1}
Los Alamos National Laboratory	1.3×10^{2}	1.7×10^{2}	3.0×10^{2}
Rocky Flats Environmental Technology Site	2.5×10^{1}	0.0×10^{0}	2.5×10^{1}
TRU Waste Site Total	1.5×10^{2}	1.9×10^{2}	3.4×10^{2}
Emplaced Waste Volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	1.5×10^{3}	0.0×10^{0}	1.5×10^{3}
Emplaced Waste Total	1.5×10^{3}	0.0×10^{0}	1.5×10^{3}
Total Waste Volume (m^3)	1.6×10^{3}	1.9×10^{2}	1.8×10^{3}
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	9.3×10^{0}		
Aluminum-Base Metal/Alloys	5.7×10^{-2}		
Other Metal/Alloys	3.1×10^{0}		
Other Inorganic Material	2.1×10^{2}		
Cellulosic Material	1.4×10^{2}		
Rubber Material	4.1×10^{-2}		
Plastic Material	8.9×10^{-1}		
Solidified Inorganic Material	1.3×10^{1}		
Cement (Solidified)	0.0×10^{0}		
Vitrified Material	0.0×10^{0}		
Solidified Organic Material	1.2×10^{1}		
Soil	1.5×10^{0}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-17. WIPP CH-TRU Waste Profiles – Soil

Final Waste Form: **Soil**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	1.1×10^2	5.9×10^3	6.0×10^3
Idaho National Engineering & Environmental Laboratory	0.0×10^0	9.7×10^1	9.7×10^1
Los Alamos National Laboratory	1.9×10^2	0.0×10^0	1.9×10^2
TRU Waste Site Total	3.0×10^2	6.0×10^3	6.3×10^3
Total Waste Volume (m^3)	3.0×10^2	6.0×10^3	6.3×10^3

Waste Material Parameters	**Average Density (kg/m^3)**
Iron-Base Metal/Alloys	2.4×10^{-2}
Aluminum-Base Metal/Alloys	9.1×10^{-3}
Other Metal/Alloys	6.4×10^{-2}
Other Inorganic Material	9.1×10^{-1}
Cellulosic Material	1.5×10^{-1}
Rubber Material	2.7×10^{-2}
Plastic Material	1.4×10^{-1}
Solidified Inorganic Material	1.8×10^0
Cement (Solidified)	1.8×10^0
Vitrified Material	0.0×10^0
Solidified Organic Material	5.0×10^0
Soil	3.2×10^2

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-18. WIPP CH-TRU Waste Profiles – Solidified Inorganic Material[1]

Final Waste Form: **Solidified Inorganic Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory - East	2.4×10^1	1.3×10^1	3.7×10^1
Hanford (Richland-RL)	1.9×10^2	3.0×10^1	2.2×10^2
Hanford (River Protection-RP)	3.9×10^3	0.0×10^0	3.9×10^3
Idaho National Engineering & Environmental Laboratory	2.9×10^4	0.0×10^0	2.9×10^4
Lawrence Livermore National Laboratory	1.4×10^1	1.8×10^2	1.9×10^2
Los Alamos National Laboratory	6.5×10^2	2.4×10^2	8.9×10^2
Nevada Test Site	5.7×10^0	0.0×10^0	5.7×10^0
Rocky Flats Environmental Technology Site	8.1×10^2	2.7×10^2	1.1×10^3
Savannah River Site	2.4×10^1	0.0×10^0	2.4×10^1
TRU Waste Site Total	3.5×10^4	7.3×10^2	3.6×10^4
Emplaced Waste Volumes (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	3.3×10^3	0.0×10^0	3.3×10^3
Emplaced Waste Total	3.3×10^3	0.0×10^0	3.3×10^3
Total Waste Volume (m^3)	3.8×10^4	7.3×10^2	3.9×10^4
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	9.5×10^{-1}		
Aluminum-Base Metal/Alloys	2.9×10^{-2}		
Other Metal/Alloys	1.4×10^0		
Other Inorganic Material	3.3×10^1		
Cellulosic Material	7.6×10^0		
Rubber Material	1.3×10^{-2}		
Plastic Material	3.8×10^0		
Solidified Inorganic Material	2.5×10^2		
Cement (Solidified)	9.8×10^1		
Vitrified Material	4.6×10^{-2}		
Solidified Organic Material	2.7×10^0		
Soil	4.2×10^0		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09
[1]See Section DATA-F-3.2.1.4 for additional information.

Table DATA-F-19. WIPP CH-TRU Waste Profiles – Solidified Organic Material[1]

Final Waste Form: **Solidified Organic Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Energy Technology Engineering Center	8.4×10^{-1}	0.0×10^{0}	8.4×10^{-1}
Hanford (Richland-RL)	2.3×10^{0}	3.4×10^{2}	3.4×10^{2}
Idaho National Engineering & Environmental Laboratory	1.1×10^{3}	0.0×10^{0}	1.1×10^{3}
Lawrence Livermore National Laboratory	8.1×10^{0}	4.8×10^{0}	1.3×10^{1}
Los Alamos National Laboratory	3.9×10^{3}	2.7×10^{1}	3.9×10^{3}
Rocky Flats Environmental Technology Site	1.4×10^{2}	4.4×10^{0}	1.4×10^{2}
TRU Waste Site Total	5.2×10^{3}	3.8×10^{2}	5.5×10^{3}
Total Waste Volume (m^3)	5.2×10^{3}	3.8×10^{2}	5.5×10^{3}
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	3.9×10^{-1}		
Aluminum-Base Metal/Alloys	1.9×10^{-1}		
Other Metal/Alloys	2.8×10^{-1}		
Other Inorganic Material	2.7×10^{1}		
Cellulosic Material	3.7×10^{-1}		
Rubber Material	2.5×10^{-1}		
Plastic Material	7.1×10^{0}		
Solidified Inorganic Material	1.4×10^{2}		
Cement (Solidified)	3.8×10^{1}		
Vitrified Material	0.0×10^{0}		
Solidified Organic Material	3.3×10^{2}		
Soil	3.6×10^{1}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09
[1]See Section DATA-F-3.2.1.4 for additional information.

Table DATA-F-20. WIPP CH-TRU Waste Profiles – Uncategorized Metal

Final Waste Form: **Uncategorized Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	1.1×10^2	4.4×10^3	4.5×10^3
Idaho National Engineering & Environmental Laboratory	9.4×10^0	0.0×10^0	9.4×10^0
Los Alamos National Laboratory	1.5×10^3	3.2×10^1	1.5×10^3
Rocky Flats Environmental Technology Site	7.9×10^2	6.7×10^2	1.5×10^3
TRU Waste Site Total	2.4×10^3	5.1×10^3	7.5×10^3
Emplaced Waste Volume (m^3)			
Site	Stored	Projected	Total
Waste Isolation Pilot Plant	3.6×10^2	0.0×10^0	3.6×10^2
Emplaced Waste Total	3.6×10^2	0.0×10^0	3.6×10^2
Total Waste Volume (m^3)	2.8×10^3	5.1×10^3	7.9×10^3
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	8.8×10^1		
Aluminum-Base Metal/Alloys	5.3×10^0		
Other Metal/Alloys	8.5×10^1		
Other Inorganic Material	1.2×10^0		
Cellulosic Material	2.3×10^0		
Rubber Material	1.5×10^0		
Plastic Material	7.5×10^0		
Solidified Inorganic Material	7.7×10^0		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	6.7×10^{-1}		
Soil	6.1×10^{-2}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-21. WIPP RH-TRU Waste Profiles – Combustible Material

Final Waste Form: **Combustible Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Battelle Columbus Laboratories	1.7×10^{1}	8.9×10^{-1}	1.8×10^{1}
Hanford (Richland-RL)	8.9×10^{-1}	0.0×10^{0}	8.9×10^{-1}
TRU Waste Site Total	1.8×10^{1}	8.9×10^{-1}	1.9×10^{1}
Total Waste Volume (m^3)	1.8×10^{1}	8.9×10^{-1}	1.9×10^{1}
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	8.7×10^{0}		
Aluminum-Base Metal/Alloys	7.6×10^{0}		
Other Metal/Alloys	6.3×10^{0}		
Other Inorganic Material	9.2×10^{0}		
Cellulosic Material	3.9×10^{1}		
Rubber Material	2.3×10^{1}		
Plastic Material	9.2×10^{1}		
Solidified Inorganic Material	0.0×10^{0}		
Cement (Solidified)	1.7×10^{1}		
Vitrified Material	0.0×10^{0}		
Solidified Organic Material	1.5×1^{0}		
Soil	1.4×10^{0}		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-22. WIPP RH-TRU Waste Profiles – Filter Material

Final Waste Form: **Filter Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory - West	1.8×10^0	8.9×10^0	1.1×10^1
Battelle Columbus Laboratories	5.3×10^0	0.0×10^0	5.3×10^0
Hanford (Richland-RL)	1.8×10^0	0.0×10^0	1.8×10^0
TRU Waste Site Total	8.9×10^0	8.9×10^0	1.8×10^1
Total Waste Volume (m^3)	8.9×10^0	8.9×10^0	1.8×10^1

Waste Material Parameters	**Average Density (kg/m^3)**
Iron-Base Metal/Alloys	3.3×10^1
Aluminum-Base Metal/Alloys	1.7×10^1
Other Metal/Alloys	4.3×10^1
Other Inorganic Material	1.1×10^2
Cellulosic Material	7.3×10^1
Rubber Material	1.9×10^1
Plastic Material	6.3×10^0
Solidified Inorganic Material	0.0×10^0
Cement (Solidified)	7.7×10^0
Vitrified Material	0.0×10^0
Solidified Organic Material	1.2×10^1
Soil	0.0×10^0

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-23. WIPP RH-TRU Waste Profiles – Heterogeneous Debris

Final Waste Form: **Heterogeneous Debris**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory - East	1.5×10^1	1.0×10^2	1.2×10^2
Argonne National Laboratory - West	6.2×10^0	3.6×10^1	4.3×10^1
Bettis Atomic Power Laboratory	2.0×10^0	0.0×10^0	2.0×10^0
Energy Technology Engineering Center	8.9×10^{-1}	0.0×10^0	8.9×10^{-1}
Hanford (Richland-RL)	2.6×10^2	3.2×10^3	3.5×10^3
Idaho National Engineering & Environmental Laboratory	2.0×10^2	0.0×10^0	2.0×10^2
Knolls Atomic Power Laboratory - Schenectady	0.0×10^0	1.4×10^2	1.4×10^2
Los Alamos National Laboratory	1.2×10^2	0.0×10^0	1.2×10^2
Oak Ridge National Laboratory	0.0×10^0	2.7×10^2	2.7×10^2
Sandia National Laboratories - Albuquerque	4.6×10^0	0.0×10^0	4.6×10^0
Savannah River Site	0.0×10^0	2.3×10^1	2.3×10^1
TRU Waste Site Total	6.1×10^2	3.8×10^3	4.4×10^3
Total Waste Volume (m^3)	6.1×10^2	3.8×10^3	4.4×10^3
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	1.2×10^2		
Aluminum-Base Metal/Alloys	8.0×10^0		
Other Metal/Alloys	3.5×10^1		
Other Inorganic Material	4.7×10^1		
Cellulosic Material	1.6×10^1		
Rubber Material	1.1×10^1		
Plastic Material	1.6×10^1		
Solidified Inorganic Material	3.6×10^1		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	1.4×10^1		
Soil	3.5×10^1		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-24. WIPP RH-TRU Waste Profiles – Inorganic Non-Metal

Final Waste Form: **Inorganic Non-Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Battelle Columbus Laboratories	1.4×10^1	8.9×10^{-1}	1.5×10^1
Hanford (Richland-RL)	2.8×10^1	4.3×10^1	7.1×10^1
TRU Waste Site Total	4.3×10^1	4.4×10^1	8.6×10^1
Total Waste Volume (m^3)	4.3×10^1	4.4×10^1	8.6×10^1
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	1.6×10^2		
Aluminum-Base Metal/Alloys	2.1×10^1		
Other Metal/Alloys	4.8×10^1		
Other Inorganic Material	9.9×10^2		
Cellulosic Material	3.9×10^0		
Rubber Material	1.8×10^0		
Plastic Material	2.4×10^1		
Solidified Inorganic Material	1.5×10^1		
Cement (Solidified)	3.1×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	2.8×10^{-1}		
Soil	7.1×10^0		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-25. WIPP RH-TRU Waste Profiles – Lead/Cadmium Metal

Final Waste Form: **Lead/Cadmium Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Hanford (Richland-RL)	1.2×10^1	7.1×10^0	1.9×10^1
TRU Waste Site Total	1.2×10^1	7.1×10^0	1.9×10^1
Total Waste Volume (m^3)	1.2×10^1	7.1×10^0	1.9×10^1
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	5.4×10^3		
Aluminum-Base Metal/Alloys	0.0×10^0		
Other Metal/Alloys	7.4×10^1		
Other Inorganic Material	0.0×10^0		
Cellulosic Material	0.0×10^0		
Rubber Material	0.0×10^0		
Plastic Material	0.0×10^0		
Solidified Inorganic Material	0.0×10^0		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	0.0×10^0		
Soil	0.0×10^0		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-26. WIPP RH-TRU Waste Profiles – Soil

Final Waste Form: **Soil**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Oak Ridge National Laboratory	0.0×10^0	2.0×10^2	2.0×10^2
TRU Waste Site Total	0.0×10^0	2.0×10^2	2.0×10^2
Total Waste Volume (m^3)	0.0×10^0	2.0×10^2	2.0×10^2
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	0.0×10^0		
Aluminum-Base Metal/Alloys	0.0×10^0		
Other Metal/Alloys	0.0×10^0		
Other Inorganic Material	0.0×10^0		
Cellulosic Material	0.0×10^0		
Rubber Material	0.0×10^0		
Plastic Material	0.0×10^0		
Solidified Inorganic Material	0.0×10^0		
Cement (Solidified)	0.0×10^0		
Vitrified Material	0.0×10^0		
Solidified Organic Material	0.0×10^0		
Soil	1.3×10^3		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-27. WIPP RH-TRU Waste Profiles – Solidified Inorganic Material

Final Waste Form: **Solidified Inorganic Material**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Argonne National Laboratory - West	1.6×10^1	2.3×10^1	3.9×10^1
Battelle Columbus Laboratories	1.8×10^0	0.0×10^0	1.8×10^0
Hanford (Richland-RL)	1.5×10^1	1.2×10^2	1.3×10^2
Hanford (River Protection-RP)	4.5×10^3	0.0×10^0	4.5×10^3
Idaho National Engineering & Environmental Laboratory	8.9×10^{-1}	0.0×10^0	8.9×10^{-1}
Oak Ridge National Laboratory	0.0×10^0	1.9×10^2	1.9×10^2
TRU Waste Site Total	4.5×10^3	3.3×10^2	4.8×10^3
Total Waste Volume (m^3)	4.5×10^3	3.3×10^2	4.8×10^3

Waste Material Parameters	**Average Density (kg/m^3)**
Iron-Base Metal/Alloys	6.8×10^0
Aluminum-Base Metal/Alloys	0.0×10^0
Other Metal/Alloys	3.4×10^{-2}
Other Inorganic Material	6.9×10^{-1}
Cellulosic Material	3.5×10^{-3}
Rubber Material	0.0×10^0
Plastic Material	1.6×10^{-2}
Solidified Inorganic Material	9.2×10^1
Cement (Solidified)	2.4×10^0
Vitrified Material	1.8×10^{-1}
Solidified Organic Material	3.1×10^{-2}
Soil	4.1×10^{-3}

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-28. WIPP RH-TRU Waste Profiles – Solidified Organic Material

Final Waste Form: **Solidified Organic Material**

TRU Waste Site Volumes ($m^{3)}$			
Site	Stored	Projected	Total
Battelle Columbus Laboratories	5.3×10^0	0.0×10^0	5.3×10^0
Energy Technology Engineering Center	4.1×10^0	0.0×10^0	4.1×10^0
TRU Waste Site Total	9.5×10^0	0.0×10^0	9.5×10^0
Total Waste Volume (m^3)	9.5×10^0	0.0×10^0	9.5×10^0
Waste Material Parameters	**Average Density (kg/m^3)**		
Iron-Base Metal/Alloys	4.9×10^1		
Aluminum-Base Metal/Alloys	0.0×10^0		
Other Metal/Alloys	0.0×10^0		
Other Inorganic Material	1.2×10^1		
Cellulosic Material	2.0×10^1		
Rubber Material	4.2×10^0		
Plastic Material	2.0×10^1		
Solidified Inorganic Material	0.0×10^0		
Cement (Solidified)	1.4×10^2		
Vitrified Material	0.0×10^0		
Solidified Organic Material	1.7×10^2		
Soil	0.0×10^0		

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-29. WIPP RH-TRU Waste Profiles – Uncategorized Metal

Final Waste Form: **Uncategorized Metal**

TRU Waste Site Volumes (m^3)			
Site	Stored	Projected	Total
Battelle Columbus Laboratories	8.9×10^{-1}	0.0×10^{0}	8.9×10^{-1}
Hanford (Richland-RL)	6.1×10^{1}	6.1×10^{3}	6.1×10^{3}
Idaho National Engineering & Environmental Laboratory	2.2×10^{1}	0.0×10^{0}	2.2×10^{1}
TRU Waste Site Total	8.4×10^{1}	6.1×10^{3}	6.1×10^{3}
Total Waste Volume (m^3)	8.4×10^{1}	6.1×10^{3}	6.1×10^{3}

Waste Material Parameters	**Average Density (kg/m^3)**
Iron-Base Metal/Alloys	1.8×10^{2}
Aluminum-Base Metal/Alloys	4.5×10^{-1}
Other Metal/Alloys	5.6×10^{1}
Other Inorganic Material	4.0×10^{1}
Cellulosic Material	7.5×10^{-2}
Rubber Material	5.2×10^{-2}
Plastic Material	7.8×10^{-2}
Solidified Inorganic Material	3.1×10^{-3}
Cement (Solidified)	0.0×10^{0}
Vitrified Material	0.0×10^{0}
Solidified Organic Material	0.0×10^{0}
Soil	6.2×10^{-2}

Table DATA-F-30. WIPP CH-TRU Waste Material Parameter Disposal Inventory

Waste Material Parameters	Average Density (kg/m^3)
Iron-Base Metal/Alloys	1.1×10^2
Aluminum-Base Metal/Alloys	1.4×10^1
Other Metal/Alloys	3.0×10^1
Other Inorganic Material	4.2×10^1
Cellulosic Material	5.8×10^1
Rubber Material	1.4×10^1
Plastic Material	4.2×10^1
Solidified Inorganic Material	7.7×10^1
Cement (Solidified)	2.9×10^1
Vitrified Material	6.2×10^0
Solidified Organic Material	1.6×10^1
Soil	1.9×10^1
Container Materials	
Steel	1.7×10^2
Plastic	1.6×10^1
Lead	1.4×10^{-2}

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

Table DATA-F-31. WIPP RH-TRU Waste Material Parameter Disposal Inventory

Waste Material Parameters	Average Density (kg/m^3)
Iron-Base Metal/Alloys	1.1×10^2
Aluminum-Base Metal/Alloys	2.5×10^0
Other Metal/Alloys	3.2×10^1
Other Inorganic Material	3.5×10^1
Cellulosic Material	4.5×10^0
Rubber Material	3.1×10^0
Plastic Material	4.9×10^0
Solidified Inorganic Material	3.9×10^1
Cement (Solidified)	8.7×10^{-1}
Vitrified Material	5.7×10^{-2}
Solidified Organic Material	4.0×10^0
Soil	2.6×10^1
Container Materials	
Steel	4.8×10^2
Plastic	1.4×10^0
Lead	4.4×10^2

Source: TWBID Revision 2.1, Version 3.12, Data Version 4.09

DATA-F-3.2.2 Packaging Materials

The PA assumption that materials are distributed homogeneously throughout the repository also applies to packaging materials. As a result, a WIPP-scale average value for packaging material densities is needed for PA. The WIPP-scale packaging (container) material average densities for CH- and RH-TRU wastes in support of the CRA are presented in Tables DATA-F-30 and DATA-F-31, respectively. These are equivalent to the TWBIR Revision 3 (DOE 1996a), Tables 2-2 and 2-3, respectively. Note also that the TWBIR Revision 3 Tables 2-2 and 2-3 are the same as TWBIR Revision 2 (DOE 1995b), Tables 3-2 and 3-3, respectively.

Analysis of the packaging material data submitted by the sites identified inconsistencies in reporting among the sites. Therefore, adjustments were made at the waste stream level to achieve consistency among the waste streams. In particular, a consistent set of densities for packaging materials for different types of containers was used unless otherwise noted by the site. Table 1-3 of the TWBIR Revision 2 identified the packaging materials and packaging material densities for the waste containers that were being used at that time. These values were used in this 2003 Update Report as well. Since the time of the TWBIR Revision 2, the sites have begun using ten-drum overpacks (TDOPs) for packaging waste. The calculated packaging material densities for TDOPs are presented in Appendix DATA, Attachment F, Annex D, Packaging Materials.

In addition, sites are also reporting that they use 85 and 100-gallon drums. This is possible because Section 2.1 in the pending update to the TRAMPAC document (DOE 2002b) has been revised to add the 85-gallon drum as an authorized payload container for shipment in the TRUPACT II (the 85-gallon drum is currently authorized for shipment in the Half PACT), and to add the 100-gallon drum as an authorized payload container in the Half PACT (the 100-gallon drum is currently authorized for shipment in the TRUPACT II). This section of the TRAMPAC document has also been revised to specify a range of sizes (75 to 88 gallons) for a container identified as an “85-gallon drum.”

Table DATA-F-32 is a summary of the assumed waste packaging material densities for some common final form container types reported by the sites. The packaging material densities in Table DATA-F-32 for 55-, 85-, and 100-gallon drums, SWBs, RH-TRU canisters, and TDOPs are calculated as shown in Appendix DATA, Attachment F, Annex D.

DATA-F-3.2.3 Chemical Components in Solidified Transuranic Waste

As part of the data call for this 2003 Update Report, the sites were asked to provide information about the chemical components of the waste. The sites were asked about complexing agents (acetate, citrate, oxylate, EDTA), oxyanions (nitrate, sulfate, and phosphate), cement, and pyrochemical salts.

Table DATA-F-32. Assumed Packaging Material Densities[1]

Container Configuration	Steel (kg/m^3)	Plastic (kg/m^3)	Lead (kg/m^3)	Volume (m^3)[2]
55-gallon drum	131	37	0	0.208
SWB (direct load)	154	1.2	0	1.89
SWB (overpack 4 55-gal. drums)	211	16	0	1.89
RH-TRU Waste Canister (direct load)	434	0	464	0.89
RH-TRU Waste Canister (overpack 3 55-gal. drums)	526	26	464	0.89
85-gallon drum	114	0	0	0.322
100-gallon drum	114	81	0	0.379
Ten-Drum Overpacks	218	16	0	4.79

[1] This table was used when sites did not report container volumes.
[2] Container volumes differ from WWIS container volumes.

This section presents the summary of the chemical components that are present in the solidified TRU waste inventory in support of the CRA. Specifically, complexing agents, oxyanions, and cement are calculated as the sum of the constituents found in anticipated waste scheduled for delivery to WIPP and any waste that has already been placed in the repository. The information provided is based on input from the TWBIR Revision 3 (DOE 1996a) and updates received from Rocky Flats Environmental Technology Site (RFETS), Los Alamos National Laboratory (LANL), Idaho National Engineering and Environmental Laboratory (INEEL), Hanford-Richland Operations (Hanford RL) and Hanford-Office of River Protection (Hanford RP). The methods used to estimate the masses of cement, complexing agents, and oxyanions are discussed in Leigh and Lott (2003), Crawford and Leigh (2003), and Leigh and Sparks-Roybal (2003), respectively. A brief discussion of pyrochemical salts is presented in Appendix DATA, Attachment F, Annex A.

DATA-F-3.2.3.1 Cement Content in Solidified Transuranic Waste

The PA for the CRA requires an estimate of the mass of cement in waste expected for disposal in the repository. An estimate of the cement mass for the CCA was given in Appendix B-7 of the TWBIR Revision 3 (DOE 1996a). While the waste stream volumes reported by the generator sites in the 2003 Update Report have changed when compared to the TWBIR Revision 3 volumes, the waste streams identified by the sites at the time of the TWBIR Revision 3 as containing cement have not changed. On the whole, the TRU waste generator sites did not report any new information about cement in this 2003 Update Report. As a result, the mass of cement in the repository was calculated for the PA in support of the CRA as the sum of the mass of cement reported in the TWBIR Revision 3 adjusting for the new waste stream volumes from this update.

The total estimated mass of cement in the scaled solidified waste streams for this 2003 Update Report is 1.20×10^7 kg (2.65×10^7 lb). This estimate of cement mass in the WIPP repository is larger than the estimate made for the CCA (8.54×10^6 kg [1.88×10^7 lb]). The increase in

cement mass is primarily because of larger volumes projected for existing waste streams. The calculations for cement masses are given in Leigh and Lott (2003).

DATA-F-3.2.3.2 Complexing Agents in Solidified Transuranic Waste

The DOE tracks the mass of complexing agents going into the repository because of their impact on solubility of actinides in the waste. In the latest request by DOE for data from the sites, none of the sites updated or modified their estimates of complexing agents in the waste streams that had been reported previously in the TWBIR Revision 3 (DOE 1996a). When applicable, the sites did report the expected masses of complexing agents in waste streams added to their inventory since publication of the TWBIR Revision 3. As a result, the mass of complexing agents in the repository was calculated for the PA in support of the CRA as the sum of the mass of complexing agents reported in the TWBIR Revision 3 plus the mass of complexing agents reported by the sites for their new waste streams.

The TWBIR Revision 3 contained information on complexing agents that was used in the PA in support of the CCA. TWBIR Revision 3 presented two estimates for complexing agents in the WIPP repository; one assuming reduction of complexing agents due to thermal treatment and one without the thermal treatment assumption. Since publication of the TWBIR Revision 3, the DOE's strategy for wastes at the INEEL has changed, and incineration operations for INEEL TRU waste did not occur as planned. Therefore, the data reported in Appendix B-4 of the TWBIR Revision 3 without the thermal treatment assumption is used in the current calculation of mass of complexing agents.

Only two sites reported complexing agents in new waste streams; RFETS and Hanford RP. For their new waste streams, RFETS reported that ethylenediaminetetraacetic acid (EDTA) might be present at trace levels (< 1 wt%) in their waste. Hanford RP identified sodium acetate and sodium oxalate in their new waste streams. The total mass of acetic acid, sodium acetate, citric acid, sodium citrate, oxalic acid, sodium oxalate, and sodium EDTA estimated for the WIPP repository are reported in Table DATA-F-33.

Table DATA-F-33. Mass of Potential Complexing Agents in the WIPP Repository

Compound	RFETS (kg)	LANL(kg)	Hanford RP (kg)	Total (kg)
Acetic Acid	132	10	---	142
Sodium Acetate	1,110	---	7,400	8,510
Citric Acid	90	1,100.5	---	1,190.5
Sodium Citrate	400	---	---	400
Oxalic Acid	90	13,706	---	13,796
Sodium Oxalate	---	---	33,940	33,940
EDTA	25.6	---	---	25.6

Source: Crawford and Leigh (2003)

Only a slight increase in EDTA was reported with this updated information over that reported in 1996 (DOE 1996a). The increase comes from one waste stream at RFETS that reported trace amounts of EDTA present in the waste and is reported as the upper limit of expected

concentration. Waste from Hanford RP waste tanks is included in Table DATA-F-33 as well, and represents a significant increase in sodium acetate and sodium oxalate that had not been reported for the TRU inventory in 1996 (DOE 1996a).

DATA-F-3.2.3.3 Mass of Oxyanions in Solidified Transuranic Waste

The PA for the CRA requires an estimate of the mass of nitrate, sulfate, and phosphate in waste expected for disposal in the repository. An estimate of the oxyanion masses for the CCA was given in Appendix B-6 of the TWBIR Revision 3 (DOE 1996a). The TRU waste sites did not report any new information about oxyanions for this 2003 Update Report with the exception of new waste streams reported by Hanford RP and LANL and revised values for a waste stream at RFETS. Therefore, the mass of nitrate, sulfate, and phosphate in the repository was calculated for the PA in support of the CRA as the sum of the mass of nitrate, sulfate, and phosphate in the TWBIR Revision 3 adjusting for the new waste stream volumes from this update plus the mass of nitrate, sulfate, and phosphate reported by the sites for their new waste streams. Table DATA-F-34 presents the mass of nitrate, sulfate, and phosphate in the WIPP repository for the CRA. The calculations for oxyanion masses are given in Leigh and Sparks-Roybal (2003).

The estimate of nitrate mass in the WIPP repository (2.51×10^6 kg [5.53×10^6 lb]) is larger than the estimate made for the CCA which was 1.62×10^6 kg (3.57×10^6 lb). The increase in nitrate mass is due primarily to larger volumes projected for existing waste streams and the added waste streams from Hanford RP. The estimate of sulfate mass in the WIPP repository (4.21×10^5 kg [9.28×10^5 lb]) is less than the estimate made for the CCA which was 6.33×10^5 kg (1.39×10^6 lb).

The estimate of phosphate mass in the WIPP repository (1.05×10^5 kg [2.31×105 lb]) is significant when compared to the CCA. There was no phosphate of reportable quantity given by the generator sites in the TWBIR Revision 3. The primary source of phosphate in the current estimate is the tank waste from Hanford RP which is now a waste stream to be disposed at WIPP.

Table DATA-F-34. Mass of Oxyanions and Cement In the WIPP Disposal Inventory

Chemical Component	Mass Contained in the Disposal Inventory (kg)
Nitrate	2.51×10^6
Sulfate	4.21×10^5
Phosphate	1.05×10^5
Cement	1.20×10^7

Sources: Leigh and Lott (2003); Leigh and Sparks-Roybal (2003)

DATA-F-3.2.3.4 Pyrochemical Salts in Waste Isolation Pilot Plant Transuranic Waste

Five waste streams at LANL, one waste stream at Lawrence Livermore National Laboratory (LLNL), and seven waste streams at RFETS have been identified as containing pyrochemical salts. Direct oxide reduction (DOR) salts have been identified in two waste streams at LANL (LA-TA-55-39 and LA-TA-55-53), the LLNL waste stream (LL-T004) and in two RFETS waste

streams (RF-TT454X and RF-TT433X). The pyrochemical salt waste streams are given in Appendix DATA, Attachment F, Annex A.

DATA-F-3.3 Transuranic Waste Radionuclide Inventory

As part of the data call for this 2003 Update Report, the sites were asked to provide information about the radiological components in the waste they intend to ship to WIPP. For each waste stream they were asked to specify the radionuclide activity concentrations (in Ci/m^3), to provide the generation or last assay date for each waste stream. In some cases, the sites provided all of the information required; in other cases, they did not.

For those waste streams where the site did not provide adequate information regarding the radiological components of the waste, radionuclide activities were estimated using the methods described in the Computational Methodology (LANL 2003b) and in the radionuclide correction package as identified in Table DATA-F-2. Radionuclide data for comparable waste streams at the same site were mapped into waste streams with missing data. For 73 waste streams without data, this mapping was accomplished by first matching to the site, the handling (RH or CH), and the WMC. Then, if there were no matches, the waste description was used to find a comparable waste stream. In this way, a waste stream requiring radionuclide data was matched to a waste stream that was generated by the same or very similar process. Seven waste streams without data were matched to waste streams with WMCs that were identical through the first two digits. Three waste streams without data were soil waste at Hanford and were matched to another Hanford soil waste stream. Two waste streams, from LANL, were found to have no similar waste stream in the present inventory but were reported in the TWBIR Revision 2 (DOE 1995b) inventory. Data from the TWBIR Revision 2 were used to fill out the radionuclide data for these two waste streams.

All of the radionuclide data were decayed to a common base year of CY 2001 (December 31, 2001) using Oak Ridge National Laboratory Isotope Generation and Depletion Code, Version 2.2 (hereafter referred to as ORIGEN 2.2) (Croff 1983; Croff 1980). ORIGEN 2.2 is a computer code that calculates the buildup and decay of radionuclides. ORIGEN 2.2 was qualified according to SNL procedure, NP 19-1, Software Requirements (SNL 2002a) for the decay calculations that were done for the TRU waste radionuclide inventory. ORIGEN 2.2 uses a matrix exponential method to solve a large system of coupled, linear, first-order ordinary differential equations with constant coefficients.

The ORIGEN 2.2 half-life data are contained within libraries that remain unchanged since their use (via ORIGEN 2.1; ORNL 2002) for the TWBIR Revision 3 (DOE 1996a) in 1996. The results obtained for data in 1996 using ORIGEN 2.1 and those that would be obtained using the current version of ORIGEN 2.2 for 1996 data would be identical. Therefore, the only differences expected between the data obtained in 1996 using ORIGEN 2.1 and those reported for the 2003 Update Report using ORIGEN 2.2 are those related to time.

Updated waste stream volumes were used to calculate waste stream radionuclide activity from the decayed ORIGEN 2.2 radionuclide activity concentrations as shown in the following equation:

$$a(RN)_{Disposal} = \alpha(RN) \cdot v_{Disposal}, \quad (8)$$

where

$a(RN)_{Disposal}$	is the activity of the radionuclide RN in the scaled waste stream volume,
$\alpha(RN)$	is the decayed radionuclide activity in Ci/m^3 from ORIGEN 2.2 for radionuclide RN, and
$v_{Disposal}$	is the waste stream disposal volume for CH-TRU or RH-TRU waste.

More information on how $v_{Disposal}$ was calculated can be found in Section DATA-F-3.1.

The WIPP-scale radionuclide activities were calculated as shown in the following equations for both CH- and RH-TRU wastes. In the first step, the activities of each radionuclide in the scaled waste stream volumes ($a(RN)_{Disposal}$) are summed for all waste streams to give the total activity for each radionuclide in CH-TRU and RH-TRU waste in the repository. In the second step, the total activity for each radionuclide in CH-TRU and RH-TRU waste in the repository is divided by the volume limit (168,485 m^3 [5,950,000 ft^3]for CH-TRU waste and 7,079 m^3 [250,000 ft^3] for RH-TRU waste) to give the activity concentration for a radionuclide in CH-TRU or RH-TRU waste in the repository.

$$A(RN) = \Sigma\, a(RN)_{Disposal}$$

$$\hat{A}(RN) = A(RN)/Limit, \quad (9)$$

where

$A(RN)$	is the total activity (Ci) for a radionuclide in CH-TRU or RH-TRU waste in the repository (after scaling)
$\hat{A}(RN)$	is the activity concentration for a radionuclide in CH-TRU or RH-TRU waste in the repository (Ci/m^3)
$a(RN)_{Disposal}$	is the activity (Ci) of the radionuclide RN in the scaled waste stream volume,
Limit	is 168,485 m^3 (5,950,000 ft^3) for CH-waste and 7,079 m^3 (250,000 ft^3) for RH-TRU waste.

DATA-F-3.3.1 Site-Level Roll-up of Radionuclide Activities

Tables DATA-F-35 and DATA-F-36 provide the site-specific radionuclide inventory estimates in total curies decayed through 2001 for CH-TRU and RH-TRU waste, respectively. The data shown in Tables DATA-F-35 and DATA-F-36 are the radionuclide inventories as the sum of the actual stored and projected volumes (not scaled) reported by the site.

DATA-F-3.3.2 Waste-Stream-Level Radionuclide Activities

The radionuclide activities in the scaled waste stream volumes for the CH-TRU waste streams included in the estimate of volume for PA are given in Appendix DATA, Attachment F, Annex E, Table DATA-F-E-1. The radionuclide activities in the scaled waste stream volumes for the

RH-TRU waste streams included in the estimate of volume for PA are given in Appendix DATA, Attachment F, Annex E, Table DATA-F-E-2.

DATA-F-3.3.3 Waste Isolation Pilot Plant-Level Roll-up of Radionuclide Activities

Table DATA-F-37 presents the WIPP-level roll-up of radionuclide activities for the disposal inventory (scaled for a full WIPP repository) in Ci/$m^3$and total Ci decayed through 2001 for both CH-TRU and RH-TRU waste. Table DATA-F-37 corresponds to Table 3-1, TWBIR Revision 3 (DOE 1996a). The waste-stream-level radionuclide activities provide the decayed (through December 31, 2001) radionuclide inventory by waste stream for all the waste streams included in Appendix DATA, Attachment F, Annex J.

A comparison of TWBIR Revision 3, Table 3-1 data to the data reported in Table DATA-F-37 can be found in Appendix DATA, Attachment F, Annex B Table DATA-F-B-27 for CH-TRU waste and Table DATA-F-B-28 for RH-TRU waste. A review of the results for CH-TRU waste indicates that although there is a substantial change in some radionuclides from 1995 to 2001, with the exception of ^{239}Pu and ^{240}Pu the activities for the dominant five radionuclides (^{241}Am, ^{238}Pu,^{239}Pu, ^{240}Pu, and ^{241}Pu) have decreased. The overall activity for all radionuclides has decreased by 17 percent. The results for RH-TRU waste show substantial variations in individual radionuclide activity. An overall increase in activity of 30 percent was observed with this update. Five radionuclides made up 99.0 percent of the CH-TRU waste curies in the TWBIR Revision 3 and the same five make up 97.2 percent of the total CH-TRU waste curies in this report. The five most abundant RH-TRU waste isotopes in the TWBIR Revision 3 (^{137m}Ba, ^{137}Cs, ^{241}Pu, ^{90}Sr, and ^{90}Y) are still the most abundant in the 2003 Update Report. These five radionuclides made up 96.1 percent of the RH-TRU waste curies in the TWBIR Revision 3 and make up 97.6 percent of the total RH-TRU waste curies in the 2003 Update Report.

DATA-F-3.4 Non-Waste Isolation Pilot Plant and Future Potential Waste

This section identifies waste streams not included in the WIPP inventory used for PA. The waste permitted to come to WIPP is restricted by radionuclide activity limits, volume, and waste generated only from defense activities. Non-WIPP waste streams in Appendix DATA, Attachment F, Annex I are summarized in Section DATA-F-3.4.1.

Other restrictions to the waste result from how the waste has been managed at the TRU waste sites. There are some materials that have not been declared TRU waste by the DOE TRU waste sites at this time that may become TRU waste in the future. Some waste has been identified in the TRU inventory but the option for processing has not been determined at this time. These possible future waste streams may ultimately become eligible for shipment to WIPP and are discussed in Section DATA-F-3.4.2.

Table DATA-F-35. CH-TRU Waste Curies on a Site-by-Site Basis [1]

Radionuclide	AE	AW	MC	BC	BT	ET	IN	KN	LA	LL	MU	NT	OR	PA	RF	RL	RP	SA	SR	WP	Total Of Curies
^{225}Ac	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.8×10^{-5}	1.3×10^{0}
^{227}Ac	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.1×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.9×10^{-6}	---	---	8.3×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{228}Ac	4.9×10^{-5}	---	---	---	---	3.8×10^{-18}	4.8×10^{0}	---	9.4×10^{-7}	---	---	1.9×10^{-15}	1.1×10^{-3}	---	5.4×10^{-13}	---	---	3.7×10^{-3}	9.1×10^{-13}	8.8×10^{-7}	4.8×10^{0}
^{109m}Ag	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.3×10^{-4}	---	---	1.3×10^{-4}
^{110}Ag	---	---	---	---	---	---	---	---	---	---	---	---	2.1×10^{-11}	---	---	---	---	---	---	---	2.1×10^{-11}
^{110m}Ag	---	---	---	---	---	---	---	---	---	---	---	---	1.6×10^{-9}	---	---	---	---	---	---	---	1.6×10^{-9}
^{241}Am	6.1×10^{1}	1.0×10^{-1}	1.6×10^{-1}	6.5×10^{0}	8.4×10^{-3}	2.3×10^{-1}	1.6×10^{5}	7.8×10^{1}	6.8×10^{3}	2.5×10^{3}	2.2×10^{0}	3.7×10^{2}	2.5×10^{3}	---	2.6×10^{4}	3.3×10^{4}	5.2×10^{2}	9.0×10^{0}	8.7×10^{3}	1.2×10^{5}	3.6×10^{5}
^{242}Am	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	4.7×10^{-2}	---	---	4.7×10^{-2}
^{242m}Am	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	4.8×10^{-2}	---	---	4.8×10^{-2}
^{243}Am	---	---	---	---	4.0×10^{-5}	---	6.4×10^{-3}	---	3.8×10^{-3}	---	---	1.2×10^{0}	9.4×10^{0}	---	---	---	---	1.4×10^{-2}	---	4.8×10^{-3}	1.1×10^{1}
^{245}Am	---	---	---	---	---	---	---	---	2.0×10^{-13}	---	---	---	6.2×10^{-11}	---	---	---	---	---	---	---	6.2×10^{-11}
^{217}At	1.6×10^{4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.9×10^{-5}	1.3×10^{0}
^{137m}Ba	3.4×10^{0}	2.8×10^{-1}	---	---	2.0×10^{1}	1.5×10^{-2}	---	---	1.1×10^{-2}	---	---	2.6×10^{-2}	3.4×10^{3}	---	1.5×10^{-2}	3.4×10^{2}	1.3×10^{3}	7.3×10^{1}	---	3.6×10^{-4}	5.2×10^{3}
^{210}Bi	6.2×10^{-10}	1.7×10^{-14}	---	---	---	9.3×10^{-12}	2.7×10^{-8}	---	1.0×10^{-6}	---	---	9.8×10^{-2}	1.2×10^{0}	5.5×10^{-5}	2.6×10^{-8}	---	---	1.1×10^{-2}	5.2×10^{-6}	2.4×10^{-7}	1.3×10^{0}
^{211}Bi	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.0×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.8×10^{-6}	---	---	8.2×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{212}Bi	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.2×10^{0}	---	1.7×10^{-6}	---	---	1.6×10^{-2}	5.0×10^{-1}	---	3.1×10^{-13}	---	---	8.5×10^{-3}	8.7×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{213}Bi	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.8×10^{-5}	1.3×10^{0}
^{214}Bi	4.3×10^{-9}	1.8×10^{-12}	---	---	---	7.6×10^{-11}	2.9×10^{-7}	---	2.3×10^{-6}	---	2.7×10^{-20}	2.5×10^{-1}	2.8×10^{0}	3.1×10^{-4}	2.3×10^{-7}	---	---	5.0×10^{-2}	2.8×10^{-5}	7.8×10^{-6}	3.1×10^{0}
^{249}Bk	---	---	---	---	---	---	---	---	1.4×10^{-8}	---	---	---	4.3×10^{-6}	---	---	---	---	---	---	---	4.3×10^{-6}
^{250}Bk	---	---	---	---	---	---	---	---	---	---	---	---	1.7×10^{-12}	---	---	---	---	---	---	---	1.7×10^{-12}
^{14}C	---	---	---	---	5.3×10^{-4}	---	---	---	---	---	---	2.5×10^{-4}	2.1×10^{-4}	---	---	1.1×10^{0}	9.9×10^{-2}	---	---	---	1.2×10^{0}
^{109}Cd	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.3×10^{-4}	---	---	1.3×10^{-4}
^{144}Ce	---	---	---	---	---	---	---	---	---	---	---	---	1.2×10^{-7}	---	---	---	---	3.6×10^{-4}	---	---	3.6×10^{-4}
^{249}Cf	---	---	---	---	7.6×10^{-13}	---	---	---	1.2×10^{-4}	---	---	1.1×10^{-2}	3.1×10^{-2}	---	---	---	---	---	---	---	4.2×10^{-2}
^{250}Cf	---	---	---	---	---	---	---	---	---	---	---	1.4×10^{-1}	1.9×10^{-2}	---	---	---	---	---	---	---	1.6×10^{-1}
^{251}Cf	---	---	---	---	3.6×10^{-14}	---	---	---	---	---	---	---	1.7×10^{-4}	---	---	---	---	---	---	---	1.7×10^{-4}
^{252}Cf	---	---	---	---	---	---	3.0×10^{-3}	---	---	---	---	8.3×10^{-2}	5.7×10^{-2}	---	---	---	---	---	---	---	1.4×10^{-1}
^{242}Cm	---	---	---	---	---	---	---	---	---	---	---	---	4.3×10^{-10}	---	---	---	---	3.9×10^{-2}	---	---	3.9×10^{-2}
^{243}Cm	---	---	---	---	4.5×10^{-5}	---	---	---	---	---	---	4.6×10^{-4}	---	---	---	---	---	4.0×10^{-1}	---	---	4.0×10^{-1}
^{244}Cm	---	---	---	---	2.5×10^{-3}	---	---	---	3.3×10^{3}	2.6×10^{3}	---	2.3×10^{0}	1.7×10^{3}	---	---	---	---	4.8×10^{0}	---	---	7.6×10^{3}
^{245}Cm	---	---	---	---	2.7×10^{-7}	---	---	---	2.5×10^{-7}	---	---	1.5×10^{-5}	4.0×10^{-3}	---	---	---	---	---	---	---	4.0×10^{-3}

Table DATA-F-35. CH-TRU Waste Curies on a Site-by-Site Basis [1] — Continued

Radionuclide	AE	AW	MC	BC	BT	ET	IN	KN	LA	LL	MU	NT	OR	PA	RF	RL	RP	SA	SR	WP	Total Of Curies
^{246}Cm	---	---	---	---	4.6×10^{-8}	---	---	---	---	---	---	5.2×10^{-4}	7.4×10^{-1}	---	---	---	---	---	---	---	7.4×10^{-1}
^{247}Cm	---	---	---	---	1.1×10^{-13}	---	---	---	---	---	---	---	1.3×10^{-10}	---	---	---	---	---	---	---	1.3×10^{-10}
^{248}Cm	---	---	---	---	1.9×10^{-13}	---	6.8×10^{-7}	---	---	---	---	4.1×10^{-5}	4.3×10^{-2}	---	---	---	---	---	---	---	4.3×10^{-2}
^{250}Cm	---	---	---	---	---	---	---	---	---	---	---	---	3.2×10^{-11}	---	---	---	---	---	---	---	3.2×10^{-11}
^{60}Co	---	---	---	---	9.3×10^{-1}	---	---	---	8.1×10^{-8}	---	---	---	3.5×10^{-3}	---	---	---	---	4.8×10^{-2}	---	1.5×10^{-7}	9.8×10^{-1}
^{134}Cs	---	---	---	---	---	---	---	---	2.2×10^{-10}	---	---	---	8.1×10^{-4}	---	---	---	---	1.9×10^{-2}	---	---	2.0×10^{-2}
^{137}Cs	3.6×10^{0}	3.0×10^{-1}	---	---	2.1×10^{1}	1.6×10^{-2}	---	---	1.1×10^{-2}	---	---	2.8×10^{-2}	3.7×10^{3}	---	1.6×10^{-2}	3.5×10^{2}	1.4×10^{3}	7.8×10^{1}	---	3.9×10^{-4}	5.5×10^{3}
^{152}Eu	---	---	---	---	9.3×10^{-1}	---	---	---	6.8×10^{-8}	---	---	9.2×10^{-1}	4.1×10^{-2}	---	---	---	---	---	---	---	1.9×10^{0}
^{154}Eu	---	---	---	---	9.3×10^{-1}	---	---	---	3.0×10^{-7}	---	---	3.4×10^{-1}	1.2×10^{-1}	---	---	---	---	1.3×10^{-1}	---	---	1.5×10^{0}
^{155}Eu	---	---	---	---	---	---	---	---	2.7×10^{-5}	---	---	---	3.1×10^{-2}	---	---	---	---	1.8×10^{-3}	---	---	3.3×10^{-2}
^{221}Fr	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.8×10^{-5}	1.3×10^{0}
^{223}Fr	2.9×10^{-9}	3.3×10^{-13}	4.4×10^{-17}	---	---	7.3×10^{-16}	5.6×10^{-8}	---	1.7×10^{-5}	---	4.9×10^{-18}	2.8×10^{-6}	3.3×10^{-3}	8.2×10^{-16}	5.3×10^{-8}	---	---	1.1×10^{-5}	3.3×10^{-9}	5.1×10^{-6}	3.3×10^{-3}
^{152}Gd	---	---	---	---	---	---	---	---	4.1×10^{-21}	---	---	3.9×10^{-14}	1.9×10^{-15}	---	---	---	---	---	---	---	4.1×10^{-14}
^{3}H	---	---	---	---	---	---	---	---	2.1×10^{2}	---	---	5.2×10^{-2}	---	---	---	3.4×10^{0}	---	1.8×10^{-2}	---	---	2.2×10^{2}
^{129}I	---	---	---	---	7.0×10^{-6}	---	---	---	---	---	---	---	---	---	---	---	5.0×10^{-4}	---	---	---	5.1×10^{-4}
^{85}Kr	---	---	---	---	---	---	---	---	---	---	---	1.4×10^{-1}	---	---	---	---	---	3.2×10^{-1}	---	---	4.6×10^{-1}
^{22}Na	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	3.9×10^{-7}	3.9×10^{-7}
^{59}Ni	---	---	---	---	7.6×10^{-2}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	7.6×10^{-2}
^{63}Ni	---	---	---	---	3.7×10^{0}	---	---	---	---	---	---	---	1.2×10^{-4}	---	---	---	---	---	---	---	3.7×10^{0}
^{237}Np	6.9×10^{-1}	3.3×10^{-8}	4.0×10^{-7}	---	5.6×10^{-5}	9.9×10^{-7}	8.8×10^{-1}	---	4.0×10^{-2}	---	4.7×10^{-4}	6.5×10^{-3}	8.0×10^{-1}	4.1×10^{-2}	2.5×10^{-1}	---	3.2×10^{-3}	1.4×10^{-1}	4.8×10^{-2}	5.4×10^{-1}	3.4×10^{0}
^{238}Np	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	2.4×10^{-4}	---	---	2.4×10^{-4}
^{239}Np	---	---	---	---	---	---	6.3×10^{-3}	---	3.7×10^{-3}	---	---	1.2×10^{0}	9.2×10^{0}	---	---	---	---	1.4×10^{-2}	---	4.8×10^{-3}	1.0×10^{1}
^{240m}Np	---	---	---	---	---	---	5.1×10^{-14}	---	1.8×10^{-7}	---	---	1.0×10^{-6}	5.7×10^{-9}	---	---	---	---	---	---	---	1.2×10^{-6}
^{231}Pa	9.9×10^{-7}	1.6×10^{-9}	4.0×10^{-14}	---	---	4.1×10^{-13}	2.2×10^{-5}	---	2.9×10^{-6}	---	8.8×10^{-15}	5.1×10^{-4}	5.7×10^{-1}	4.8×10^{-13}	2.3×10^{-5}	---	---	5.6×10^{-3}	1.0×10^{-6}	5.0×10^{-4}	5.8×10^{-1}
^{233}Pa	6.9×10^{-1}	3.3×10^{-8}	4.0×10^{-7}	---	---	9.8×10^{-7}	8.7×10^{-1}	---	4.0×10^{-2}	---	4.7×10^{-4}	6.4×10^{-3}	7.9×10^{-1}	4.1×10^{-2}	2.5×10^{-1}	---	---	1.4×10^{-1}	4.8×10^{-2}	5.3×10^{-1}	3.4×10^{0}

Table DATA-F-35. CH-TRU Waste Curies on a Site-by-Site Basis [1] — Continued

Radionuclide	AE	AW	MC	BC	BT	ET	IN	KN	LA	LL	MU	NT	OR	PA	RF	RL	RP	SA	SR	WP	Total Of Curies
^{234}Pa	6.7×10^{-5}	3.5×10^{-10}	---	---	---	5.4×10^{-18}	3.0×10^{-5}	---	2.7×10^{-4}	---	3.1×10^{-10}	2.0×10^{-7}	8.7×10^{-5}	---	2.3×10^{-4}	---	---	1.2×10^{-5}	---	8.4×10^{-3}	9.1×10^{-3}
^{234m}Pa	5.2×10^{-2}	2.7×10^{-7}	---	---	---	4.1×10^{-15}	2.3×10^{-2}	---	2.0×10^{-1}	---	2.4×10^{-7}	1.5×10^{-4}	6.7×10^{-2}	---	1.8×10^{-1}	---	---	8.9×10^{-3}	---	6.5×10^{0}	7.0×10^{0}
^{209}Pb	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.8×10^{-5}	1.3×10^{0}
^{210}Pb	6.3×10^{-10}	1.7×10^{-14}	---	---	---	9.4×10^{-12}	2.7×10^{-8}	---	1.0×10^{-6}	---	---	9.9×10^{-2}	1.2×10^{0}	5.5×10^{-5}	2.6×10^{-8}	---	---	1.1×10^{-2}	5.3×10^{-6}	2.4×10^{-7}	1.3×10^{0}
^{211}Pb	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.0×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.8×10^{-6}	---	---	8.2×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{212}Pb	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.1×10^{0}	---	1.7×10^{-6}	---	---	1.6×10^{-2}	4.9×10^{-1}	---	3.1×10^{-13}	---	---	8.5×10^{-3}	8.7×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{214}Pb	4.3×10^{-9}	1.8×10^{-12}	---	---	---	7.7×10^{-11}	2.9×10^{-7}	---	2.3×10^{-6}	---	2.7×10^{-20}	2.5×10^{-1}	2.8×10^{0}	3.1×10^{-4}	2.3×10^{-7}	---	---	5.0×10^{-2}	2.8×10^{-5}	7.8×10^{-6}	3.1×10^{0}
^{147}Pm	---	---	---	---	9.3×10^{-1}	---	---	---	---	---	---	---	9.5×10^{-2}	---	---	---	---	6.9×10^{-1}	---	---	1.7×10^{0}
^{210}Po	6.3×10^{-10}	5.5×10^{-15}	---	---	---	9.4×10^{-12}	2.7×10^{-8}	---	1.0×10^{-6}	---	---	9.9×10^{-2}	1.2×10^{0}	5.5×10^{-5}	2.6×10^{-8}	---	---	1.1×10^{-2}	5.3×10^{-6}	1.3×10^{-7}	1.3×10^{0}
^{211}Po	6.4×10^{-10}	7.4×10^{-14}	9.7×10^{-18}	---	---	1.6×10^{-16}	1.2×10^{-8}	---	3.8×10^{-6}	---	1.1×10^{-18}	6.1×10^{-7}	7.2×10^{-4}	1.8×10^{-16}	1.2×10^{-8}	---	---	2.5×10^{-6}	7.2×10^{-10}	1.1×10^{-6}	7.3×10^{-4}
^{212}Po	2.7×10^{-1}	---	---	---	---	1.5×10^{-18}	2.6×10^{0}	---	1.1×10^{-6}	---	---	1.0×10^{-2}	3.2×10^{-1}	---	2.0×10^{-13}	---	---	5.4×10^{-3}	5.6×10^{-13}	2.8×10^{-7}	3.2×10^{0}
^{213}Po	1.6×10^{-4}	9.8×10^{-10}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.3×10^{-9}	---	---	1.1×10^{-6}	1.8×10^{-9}	9.6×10^{-5}	1.3×10^{0}
^{214}Po	4.3×10^{-9}	1.8×10^{-12}	---	---	---	7.7×10^{-11}	2.9×10^{-7}	---	2.3×10^{-6}	---	2.7×10^{-20}	2.5×10^{-1}	2.8×10^{0}	3.1×10^{-4}	2.3×10^{-7}	---	---	5.0×10^{-2}	2.8×10^{-5}	7.8×10^{-6}	3.1×10^{0}
^{215}Po	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.0×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.8×10^{-6}	---	---	8.2×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{216}Po	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.1×10^{0}	---	1.7×10^{-6}	---	---	1.6×10^{-2}	4.9×10^{-1}	---	3.1×10^{-13}	---	---	8.5×10^{-3}	8.7×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{218}Po	4.2×10^{-9}	1.7×10^{-12}	---	---	---	7.5×10^{-11}	2.8×10^{-7}	---	2.3×10^{-6}	---	2.7×10^{-20}	2.5×10^{-1}	2.8×10^{0}	3.0×10^{-4}	2.3×10^{-7}	---	---	4.9×10^{-2}	2.7×10^{-5}	7.7×10^{-6}	3.1×10^{0}
^{144}Pr	---	---	---	---	---	---	---	---	---	---	---	---	1.1×10^{-7}	---	---	---	---	3.5×10^{-4}	---	---	3.5×10^{-4}
^{236}Pu	2.1×10^{-7}	---	---	---	---	---	4.4×10^{-4}	---	---	---	---	---	---	---	---	---	---	---	---	---	4.4×10^{-4}
^{238}Pu	1.4×10^{1}	1.5×10^{2}	---	1.8×10^{3}	9.3×10^{-1}	1.2×10^{-2}	6.9×10^{4}	1.3×10^{1}	9.9×10^{4}	5.5×10^{2}	---	1.6×10^{2}	5.3×10^{3}	---	2.7×10^{3}	1.1×10^{5}	2.2×10^{1}	1.7×10^{0}	1.0×10^{6}	5.4×10^{3}	1.3×10^{6}
^{239}Pu	1.9×10^{2}	1.2×10^{2}	6.1×10^{-2}	2.9×10^{1}	7.3×10^{-4}	2.1×10^{-1}	5.7×10^{4}	1.6×10^{2}	1.1×10^{4}	3.1×10^{3}	5.3×10^{-2}	2.9×10^{3}	1.3×10^{3}	2.7×10^{-1}	7.4×10^{4}	7.2×10^{4}	3.2×10^{3}	4.6×10^{0}	2.0×10^{5}	1.4×10^{5}	5.6×10^{5}
^{240}Pu	1.0×10^{2}	7.0×10^{-1}	---	7.5×10^{0}	1.5×10^{-3}	8.1×10^{-2}	7.6×10^{3}	5.3×10^{1}	3.7×10^{3}	1.4×10^{3}	---	6.3×10^{1}	1.3×10^{3}	---	1.7×10^{4}	1.9×10^{4}	2.7×10^{2}	5.0×10^{-1}	4.9×10^{3}	3.1×10^{4}	8.6×10^{4}
^{241}Pu	2.6×10^{2}	6.2×10^{-1}	1.9×10^{-1}	3.6×10^{2}	1.6×10^{-1}	8.9×10^{-1}	5.1×10^{4}	2.8×10^{2}	3.1×10^{4}	4.3×10^{4}	---	1.4×10^{3}	4.3×10^{4}	---	1.8×10^{5}	1.1×10^{6}	5.4×10^{2}	6.7×10^{0}	9.7×10^{4}	3.4×10^{5}	1.9×10^{6}
^{242}Pu	6.9×10^{-2}	8.8×10^{-6}	---	1.2×10^{-3}	1.2×10^{-5}	2.0×10^{-6}	1.2×10^{1}	4.1×10^{-4}	8.2×10^{-1}	---	---	8.9×10^{-2}	3.8×10^{-1}	---	1.7×10^{0}	4.0×10^{0}	7.7×10^{-3}	7.7×10^{-8}	---	3.0×10^{0}	2.2×10^{1}
^{243}Pu	---	---	---	---	--	---	---	---	---	---	---	---	1.3×10^{-10}	---	---	---	---	---	---	---	1.3×10^{-10}
^{244}Pu	---	---	---	---	6.6×10^{-13}	---	5.0×10^{-14}	---	1.8×10^{-7}	---	---	1.0×10^{-6}	5.7×10^{-9}	---	---	---	---	---	---	---	1.2×10^{-6}

Table DATA-F-35. CH-TRU Waste Curies on a Site-by-Site Basis [1] — Continued

Radionuclide	AE	AW	MC	BC	BT	ET	IN	KN	LA	LL	MU	NT	OR	PA	RF	RL	RP	SA	SR	WP	Total Of Curies
^{223}Ra	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.1×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.9×10^{-6}	---	---	8.3×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{224}Ra	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.1×10	---	1.7×10^{-6}	---	---	1.6×10^{-2}	4.9×10^{-1}	---	3.1×10^{-13}	---	---	8.5×10^{-3}	8.7×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{225}Ra	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.2×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.9×10^{-5}	1.3×10^{0}
^{226}Ra	4.3×10^{-9}	1.8×10^{-12}	---	---	---	7.7×10^{-11}	2.9×10^{-7}	---	2.3×10^{-6}	---	2.8×10^{-20}	2.5×10^{-1}	2.9×10^{0}	3.1×10^{-4}	2.3×10^{-7}	---	---	5.1×10^{-2}	2.8×10^{-5}	7.9×10^{-6}	3.2×10^{0}
^{228}Ra	5.8×10^{-5}	---	---	---	---	4.4×10^{-18}	5.7×10^{0}	---	1.1×10^{-6}	---	---	2.2×10^{-15}	1.3×10^{-3}	---	6.4×10^{-13}	---	---	4.3×10^{-3}	1.1×10^{-12}	1.0×10^{-6}	5.7×10^{0}
^{106}Rh	---	---	---	---	---	---	---	---	8.5×10^{-11}	---	---	---	2.4×10^{-5}	---	---	---	---	1.1×10^{-4}	---	---	1.3×10^{-4}
^{219}Rn	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.0×10^{-6}	---	1.3×10^{-3}	---	3.6×10^{-16}	2.0×10^{-4}	2.4×10^{-1}	6.0×10^{-14}	3.8×10^{-6}	---	---	8.2×10^{-4}	2.4×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{220}Rn	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.1×10^{0}	---	1.7×10^{-6}	---	---	1.6×10^{-2}	4.9×10^{-1}	---	3.1×10^{-13}	---	---	8.5×10^{-3}	8.7×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{222}Rn	4.3×10^{-9}	1.8×10^{-12}	---	---	---	7.7×10^{-11}	2.9×10^{-7}	---	2.3×10^{-6}	---	2.7×10^{-20}	2.5×10^{-1}	2.8×10^{0}	3.1×10^{-4}	2.3×10^{-7}	---	---	5.0×10^{-2}	2.8×10^{-5}	7.8×10^{-6}	3.1×10^{0}
^{106}Ru	---	---	---	---	---	---	---	---	8.6×10^{-11}	---	---	---	2.4×10^{-5}	---	---	---	---	1.1×10^{-4}	---	---	1.3×10^{-4}
^{125}Sb	---	---	---	---	---	---	---	---	2.9×10^{-6}	---	---	---	2.4×10^{-3}	---	---	---	---	---	---	---	2.4×10^{-3}
^{79}Se	---	---	---	---	1.3×10^{-4}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.3×10^{-4}
^{147}Sm	---	---	---	---	---	---	---	---	---	---	---	---	2.0×10^{-10}	---	---	---	---	4.6×10^{-11}	---	---	2.5×10^{-10}
^{151}Sm	---	---	---	---	1.0×10^{-1}	---	---	---	---	---	---	---	---	---	---	---	5.6×10^{1}	2.7×10^{-1}	---	---	5.7×10^{1}
^{90}Sr	2.6×10^{0}	1.5×10^{0}	---	---	2.1×10^{1}	1.2×10^{-2}	---	---	---	---	---	9.5×10^{-5}	2.2×10^{3}	---	---	1.4×10^{2}	5.3×10^{4}	7.4×10^{1}	---	---	5.5×10^{4}
^{99}Tc	5.8×10^{0}	---	---	---	4.7×10^{-3}	---	---	2.5×10^{-2}	---	---	---	---	3.1×10^{1}	2.9×10^{0}	---	4.1×10^{-3}	8.9×10^{1}	1.6×10^{-3}	---	---	1.3×10^{2}
^{123}Te	---	---	---	---	---	---	---	---	---	---	---	---	3.2×10^{-5}	---	---	---	---	---	---	---	3.2×10^{-5}
^{123m}Te	---	---	---	---	---	---	---	---	---	---	---	---	2.4×10^{-19}	---	---	---	---	---	---	---	2.4×10^{-19}
^{125m}Te	---	---	---	---	---	---	---	---	7.1×10^{-7}	---	---	---	5.8×10^{-4}	---	---	---	---	---	---	---	5.8×10^{-4}
^{227}Th	2.1×10^{-7}	2.4×10^{-11}	3.1×10^{-15}	---	---	5.2×10^{-14}	4.0×10^{-6}	---	1.2×10^{-3}	---	3.5×10^{-16}	2.0×10^{-4}	2.3×10^{-1}	5.9×10^{-14}	3.8×10^{-6}	---	---	8.1×10^{-4}	2.3×10^{-7}	3.6×10^{-4}	2.4×10^{-1}
^{228}Th	4.2×10^{-1}	---	---	---	---	2.3×10^{-18}	4.2×10^{0}	1.7×10^{-4}	1.7×10^{-6}	---	---	1.6×10^{-2}	5.0×10^{-1}	---	3.2×10^{-13}	---	---	8.5×10^{-3}	8.8×10^{-13}	4.4×10^{-7}	5.1×10^{0}
^{229}Th	1.6×10^{-4}	1.0×10^{-9}	1.7×10^{-15}	---	---	1.2×10^{-14}	1.1×10^{0}	---	1.4×10^{-3}	---	1.5×10^{-12}	2.7×10^{-3}	2.3×10^{-1}	1.4×10^{-9}	5.4×10^{-9}	---	---	1.1×10^{-6}	1.9×10^{-9}	9.9×10^{-5}	1.3×10^{0}
^{230}Th	1.3×10^{-6}	8.9×10^{-9}	---	---	---	2.8×10^{-8}	1.6×10^{-4}	---	5.6×10^{-5}	---	4.8×10^{-17}	1.2×10^{-6}	3.2×10^{-3}	5.6×10^{-2}	9.1×10^{-5}	---	---	8.5×10^{-6}	7.0×10^{-3}	4.9×10^{-5}	6.6×10^{-2}
^{231}Th	2.9×10^{-3}	7.3×10^{-5}	4.7×10^{-10}	---	---	2.8×10^{-9}	8.1×10^{-2}	---	5.8×10^{-3}	---	2.1×10^{-10}	1.5×10^{-4}	1.0×10^{-2}	3.5×10^{-9}	9.0×10^{-2}	---	---	1.2×10^{-2}	3.9×10^{-3}	1.2×10^{-1}	3.3×10^{-1}
^{232}Th	6.2×10^{-5}	5.1×10^{-19}	---	---	5.6×10^{-14}	1.1×10^{-17}	6.6×10^{0}	2.9×10^{-5}	1.1×10^{-6}	---	---	4.9×10^{-15}	1.3×10^{-3}	---	1.8×10^{-12}	4.4×10^{-2}	---	3.9×10^{-3}	1.8×10^{-12}	2.6×10^{-6}	6.6×10^{0}

Table DATA-F-35. CH-TRU Waste Curies on a Site-by-Site Basis [1] — Continued

Radionuclide	AE	AW	MC	BC	BT	ET	IN	KN	LA	LL	MU	NT	OR	PA	RF	RL	RP	SA	SR	WP	Total Of Curies
^{234}Th	5.2×10^{-2}	2.7×10^{-7}	---	---	---	4.1×10^{-15}	2.3×10^{-2}	---	2.1×10^{-1}	---	2.4×10^{-7}	1.5×10^{-4}	6.7×10^{-2}	---	1.8×10^{-1}	---	---	8.9×10^{-3}	---	6.5×10^{0}	7.0×10^{0}
^{207}Tl	2.1×10^{-7}	2.4×10^{-11}	3.2×10^{-15}	---	---	5.3×10^{-14}	4.0×10^{-6}	---	1.3×10^{-3}	---	3.5×10^{-16}	2.0×10^{-4}	2.3×10^{-1}	5.9×10^{-14}	3.8×10^{-6}	---	---	8.1×10^{-4}	2.3×10^{-7}	3.7×10^{-4}	2.4×10^{-1}
^{208}Tl	1.5×10^{-1}	---	---	---	---	8.2×10^{-19}	1.5×10^{0}	---	6.1×10^{-7}	---	---	5.7×10^{-3}	1.8×10^{-1}	---	1.1×10^{-13}	---	---	3.1×10^{-3}	3.1×10^{-13}	1.6×10^{-7}	1.8×10^{0}
^{209}Tl	3.5×10^{-6}	2.2×10^{-11}	3.8×10^{-17}	---	---	2.7×10^{-16}	2.4×10^{-2}	---	3.1×10^{-5}	---	3.3×10^{-14}	6.0×10^{-5}	4.9×10^{-3}	3.1×10^{-11}	1.2×10^{-10}	---	---	2.4×10^{-8}	4.1×10^{-11}	2.2×10^{-6}	2.9×10^{-2}
^{232}U	4.1×10^{-1}	---	---	---	1.3×10^{-5}	---	3.6×10^{-4}	1.7×10^{-4}	7.3×10^{-7}	---	---	1.6×10^{-2}	4.9×10^{-1}	---	---	---	---	---	---	---	9.1×10^{-1}
^{233}U	1.1×10^{-1}	1.1×10^{-5}	6.9×10^{-12}	---	---	2.9×10^{-11}	8.8×10^{2}	1.5×10^{-2}	5.7×10^{-1}	---	8.0×10^{-9}	1.8×10^{0}	1.4×10^{2}	2.3×10^{-6}	1.0×10^{-5}	5.3×10^{1}	1.1×10^{-5}	2.4×10^{-3}	2.3×10^{-6}	2.7×10^{-1}	1.1×10^{3}
^{234}U	9.1×10^{-3}	1.2×10^{-3}	---	---	2.0×10^{-3}	2.4×10^{-4}	2.6×10^{0}	1.1×10^{-3}	7.6×10^{-1}	---	2.7×10^{-12}	1.2×10^{-2}	2.1×10^{1}	---	8.9×10^{-1}	3.3×10^{1}	1.3×10^{1}	1.9×10^{-1}	6.3×10^{1}	1.3×10^{0}	1.3×10^{2}
^{235}U	2.9×10^{-3}	7.4×10^{-5}	4.8×10^{-10}	---	2.6×10^{-5}	2.8×10^{-9}	8.2×10^{-2}	5.1×10^{-5}	5.8×10^{-3}	---	2.1×10^{-10}	1.5×10^{-4}	1.0×10^{-2}	3.5×10^{-9}	9.1×10^{-2}	3.9×10^{-1}	5.8×10^{-1}	1.2×10^{-2}	4.0×10^{-3}	1.2×10^{-1}	1.3×10^{0}
^{236}U	6.7×10^{-5}	2.1×10^{-8}	---	---	3.0×10^{-4}	3.3×10^{-8}	2.9×10^{-3}	---	2.6×10^{-3}	---	---	1.2×10^{-5}	8.1×10^{-4}	---	6.0×10^{-3}	1.6×10^{-5}	1.0×10^{-1}	7.4×10^{-8}	3.0×10^{-3}	4.5×10^{-3}	1.3×10^{-1}
^{237}U	6.3×10^{-3}	1.5×10^{-5}	4.6×10^{-6}	---	---	2.2×10^{-5}	1.3×10^{0}	---	7.5×10^{-1}	---	---	6.0×10^{-3}	1.1×10^{0}	---	4.3×10^{0}	---	---	1.6×10^{-4}	2.4×10^{0}	8.5×10^{0}	1.8×10^{1}
^{238}U	5.2×10^{-2}	2.7×10^{-7}	---	---	1.2×10^{-7}	4.2×10^{-15}	2.3×10^{-2}	4.0×10^{-3}	2.1×10^{-1}	---	2.4×10^{-7}	1.6×10^{-4}	6.8×10^{-2}	---	1.8×10^{-1}	4.0×10^{0}	1.3×10^{1}	9.0×10^{-3}	---	6.5×10^{0}	2.4×10^{1}
^{240}U	---	---	---	---	---	---	5.0×10^{-14}	---	1.8×10^{-7}	---	---	1.0×10^{-6}	5.6×10^{-9}	---	---	---	---	---	---	---	1.2×10^{-6}
^{90}Y	2.6×10^{0}	1.5×10^{0}	---	---	2.1×10^{1}	1.1×10^{-2}	---	---	---	---	---	9.4×10^{-5}	2.2×10^{3}	---	---	1.4×10^{2}	5.3×10^{4}	7.3×10^{1}	---	---	5.5×10^{4}
^{65}Zn	---	---	---	---	---	---	---	---	---	---	---	---	1.1×10^{-10}	---	---	---	---	---	---	---	1.1×10^{-10}
^{93}Zr	---	---	---	---	1.1×10^{-3}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.1×10^{-3}
Total:	6.5×10^{2}	2.7×10^{2}	4.0×10^{-1}	2.2×10^{3}	9.3×10^{1}	1.5×10	3.5×10^{5}	5.8×10^{2}	1.6×10^{5}	5.3×10^{4}	2.22×10^{0}	4.86×10^{3}	6.68×10^{4}	3.36×10^{0}	2.96×10^{5}	1.33×10^{6}	1.13×10^{5}	3.27×10^{2}	1.33×10^{6}	6.38×10^{5}	4.34×10^{6}

[1] Decayed through December 31, 2001

Table DATA-F-36. RH-TRU Waste Curies on a Site-by-Site Basis [1]

Radionuclide	AE	AW	BC	BT	ET	IN	KA	LA	OR	RL	RP	SA	SR	Total Of Curies
^{225}Ac	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{227}Ac	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.9×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.3 \text{ X } 10^{-5}$	---	---	$4.4 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{228}Ac	1.1×10^{-15}	1.2×10^{-14}	---	---	9.2×10^{-18}	2.4×10^{-16}	3.5×10^{-11}	$1.0 \text{ X } 10^{-16}$	$8.3 \text{ X } 10^{-1}$	---	---	$1.2 \text{ X } 10^{-18}$	---	$8.3 \text{ X } 10^{-1}$
^{110}Ag	---	---	---	---	---	---	---	---	$1.1 \text{ X } 10^{-10}$	---	---	---	---	$1.1 \text{ X } 10^{-10}$
^{110m}Ag	---	---	---	---	---	---	---	---	$8.5 \text{ X } 10^{-9}$	---	---	---	---	$8.5 \text{ X } 10^{-9}$
^{241}Am	1.0×10^{1}	1.2×10^{1}	8.6×10^{1}	2.5×10^{0}	6.5×10^{-1}	3.0×10^{1}	3.0×10^{-2}	$2.5 \text{ X } 10^{-2}$	$3.2 \text{ X } 10^{2}$	$4.5 \text{ X } 10^{3}$	$1.1 \text{ X } 10^{4}$	$2.1 \text{ X } 10^{1}$	---	$1.6 \text{ X } 10^{4}$
^{242}Am	---	5.0×10^{-3}	---	---	---	---	---	---	---	---	---	---	---	$5.0 \text{ X } 10^{-3}$
^{242m}Am	---	5.0×10^{-3}	2.0×10^{-1}	---	---	---	---	---	---	---	---	---	---	$2.1 \text{ X } 10^{-1}$
^{243}Am	3.2×10^{-5}	5.4×10^{-4}	6.7×10^{-1}	1.2×10^{-2}	---	---	5.3×10^{-5}	---	$3.3 \text{ X } 10^{-1}$	---	---	---	$4.1 \text{ X } 10^{-2}$	$1.0 \text{ X } 10^{0}$
^{217}At	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{137m}Ba	4.3×10^{1}	1.6×10^{3}	---	6.2×10^{3}	9.2×10^{0}	1.9×10^{2}	7.2×10^{1}	$1.5 \text{ X } 10^{1}$	$1.5 \text{ X } 10^{4}$	$2.6 \text{ X } 10^{5}$	$1.2 \text{ X } 10^{5}$	$4.6 \text{ X } 10^{2}$	$5.8 \text{ X } 10^{1}$	$4.0 \text{ X } 10^{5}$
^{210}Bi	7.0×10^{-11}	4.3×10^{-11}	---	---	9.8×10^{-16}	9.2×10^{-11}	2.5×10^{-9}	$9.1 \text{ X } 10^{-12}$	$1.2 \text{ X } 10^{-6}$	---	---	$1.8 \text{ X } 10^{-11}$	$2.1 \text{ X } 10^{-13}$	$1.2 \text{ X } 10^{-6}$
^{211}Bi	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.8×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{212}Bi	1.1×10^{-15}	5.6×10^{-15}	---	---	5.4×10^{-18}	9.8×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{213}Bi	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{214}Bi	3.8×10^{-10}	7.2×10^{-10}	---	---	1.7×10^{-14}	1.8×10^{-9}	9.5×10^{-9}	$3.6 \text{ X } 10^{-11}$	$7.9 \text{ X } 10^{-6}$	---	---	$3.5 \text{ X } 10^{-10}$	$3.5 \text{ X } 10^{-12}$	$7.9 \text{ X } 10^{-6}$
^{14}C	---	---	---	1.6×10^{-1}	---	---	1.9×10^{-3}	---	$4.8 \text{ X } 10^{-4}$	$4.9 \text{ X } 10^{0}$	$1.0 \text{ X } 10^{0}$	---	---	$6.1 \text{ X } 10^{0}$
^{113m}Cd	5.9×10^{-1}	---	---	---	---	---	---	---	---	---	---	---	---	$5.9 \text{ X } 10^{-1}$
^{141}Ce	---	4.3×10^{-19}	---	---	---	---	---	---	---	---	---	---	---	$4.3 \text{ X } 10^{-19}$
^{144}Ce	2.0×10^{-9}	7.3×10^{0}	---	---	---	---	---	---	$6.2 \text{ X } 10^{-7}$	---	---	---	---	$7.3 \text{ X } 10^{0}$
^{249}Cf	---	---	---	2.3×10^{-10}	---	---	4.0×10^{-12}	---	$4.9 \text{ X } 10^{-3}$	---	---	---	---	$4.9 \text{ X } 10^{-3}$
^{250}Cf	---	---	---	---	---	---	---	---	$8.7 \text{ X } 10^{-2}$	---	---	---	---	$8.7 \text{ X } 10^{-2}$
^{251}Cf	---	---	---	1.1×10^{-11}	---	---	5.0×10^{-14}	---	$9.3 \text{ X } 10^{-4}$	---	---	---	---	$9.3 \text{ X } 10^{-4}$
^{252}Cf	---	---	---	---	---	---	1.9×10^{-15}	---	$1.0 \text{ X } 10^{-1}$	---	---	---	---	$1.0 \text{ X } 10^{-1}$
^{242}Cm	1.5×10^{-21}	4.2×10^{-3}	---	---	---	---	---	---	$8.9 \text{ X } 10^{-12}$	---	---	---	---	$4.2 \text{ X } 10^{-3}$
^{243}Cm	---	1.4×10^{-4}	4.6×10^{-1}	1.3×10^{-2}	---	---	1.5×10^{-5}	---	$3.1 \text{ X } 10^{-7}$	---	---	$3.8 \text{ X } 10^{-2}$	---	$5.1 \text{ X } 10^{-1}$

Table DATA-F-36. RH-TRU Waste Curies on a Site-by-Site Basis [1]— Continued

Radionuclide	AE	AW	BC	BT	ET	IN	KA	LA	OR	RL	RP	SA	SR	Total Of Curies
^{244}Cm	1.9×10^{-1}	4.4×10^{-3}	6.8×10^{1}	7.6×10^{-1}	---	---	1.5×10^{-3}	---	$1.2 \text{ X } 10^{3}$	---	---	$4.2 \text{ X } 10^{-1}$	---	$1.3 \text{ X } 10^{3}$
^{245}Cm	---	---	1.1×10^{-2}	8.1×10^{-5}	---	---	4.9×10^{-7}	---	$6.9 \text{ X } 10^{-6}$	---	---	---	---	$1.1 \text{ X } 10^{-2}$
^{246}Cm	---	---	1.6×10^{-4}	1.4×10^{-5}	---	---	6.3×10^{-8}	---	$3.9 \text{ X } 10^{0}$	---	---	---	---	$3.9 \text{ X } 10^{0}$
^{247}Cm	---	---	---	3.2×10^{-11}	---	---	1.5×10^{-13}	---	$7.1 \text{ X } 10^{-10}$	---	---	---	$5.5 \text{ X } 10^{1}$	$5.5 \text{ X } 10^{1}$
^{248}Cm	---	---	---	5.8×10^{-11}	---	---	3.0×10^{-13}	---	$1.1 \text{ X } 10^{-2}$	---	---	---	---	$1.1 \text{ X } 10^{-2}$
^{60}Co	2.2×10^{-1}	1.7×10^{1}	5.0×10^{2}	2.8×10^{2}	---	---	---	---	$1.7 \text{ X } 10^{2}$	$8.8 \text{ X } 10^{2}$	---	$3.3 \text{ X } 10^{-2}$	---	$1.8 \text{ X } 10^{3}$
^{134}Cs	8.8×10^{-5}	2.5×10^{1}	2.7×10^{-4}	---	---	---	---	---	$4.5 \text{ X } 10^{-3}$	---	---	$1.6 \text{ X } 10^{1}$	---	$4.2 \text{ X } 10^{1}$
^{135}Cs	---	---	---	---	---	---	4.0×10^{-4}	---	---	---	---	---	---	$4.0 \text{ X } 10^{-4}$
^{137}Cs	4.5×10^{1}	1.7×10^{3}	2.3×10^{3}	6.4×10^{3}	9.8×10^{0}	2.0×10^{2}	7.7×10^{1}	$1.6 \text{ X } 10^{1}$	$1.6 \text{ X } 10^{4}$	$2.8 \text{ X } 10^{5}$	$1.2 \text{ X } 10^{5}$	$4.9 \text{ X } 10^{2}$	$6.2 \text{ X } 10^{1}$	$4.3 \text{ X } 10^{5}$
^{152}Eu	1.7×10^{-4}	---	1.4×10^{-2}	2.8×10^{2}	---	---	---	---	$2.4 \text{ X } 10^{3}$	---	---	---	---	$2.7 \text{ X } 10^{3}$
^{154}Eu	8.2×10^{-3}	3.6×10^{0}	3.8×10^{-1}	2.8×10^{2}	---	---	---	---	$8.2 \text{ X } 10^{2}$	---	---	$1.3 \text{ X } 10^{0}$	---	$1.1 \text{ X } 10^{3}$
^{155}Eu	1.0×10^{-2}	2.2×10^{1}	---	---	---	---	---	$7.9 \text{ X } 10^{-3}$	$8.2 \text{ X } 10^{1}$	---	---	---	---	$1.0 \text{ X } 10^{2}$
^{55}Fe	1.5×10^{-1}	---	---	---	---	---	---	---	---	---	---	---	---	$1.5 \text{ X } 10^{-1}$
^{221}Fr	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{223}Fr	4.0×10^{-10}	4.5×10^{-10}	---	---	2.4×10^{-10}	2.9×10^{-10}	6.6×10^{-10}	$3.3 \text{ X } 10^{-10}$	$3.1 \text{ X } 10^{-7}$	---	---	$6.0 \text{ X } 10^{-11}$	---	$3.1 \text{ X } 10^{-7}$
^{152}Gd	1.7×10^{-17}	---	---	---	---	---	---	---	$1.1 \text{ X } 10^{-10}$	---	---	---	---	$1.1 \text{ X } 10^{-10}$
^{3}H	---	6.8×10^{-4}	---	---	---	---	---	---	$2.6 \text{ X } 10^{-1}$	$6.4 \text{ X } 10^{0}$	---	---	---	$6.7 \text{ X } 10^{0}$
^{129}I	---	---	---	2.1×10^{-3}	---	---	3.7×10^{-5}	---	---	$1.9 \text{ X } 10^{-3}$	$8.0 \text{ X } 10^{-2}$	---	---	$8.4 \text{ X } 10^{-2}$
^{85}Kr	4.1×10^{-1}	---	---	---	---	---	---	---	---	---	---	---	---	$4.1 \text{ X } 10^{-1}$
^{54}Mn	2.5×10^{-9}	2.1×10^{0}	---	---	---	---	---	---	---	---	---	---	---	$2.1 \text{ X } 10^{0}$
^{22}Na	---	3.3×10^{-1}	---	---	---	---	---	---	---	---	---	---	---	$3.3 \text{ X } 10^{-1}$
^{93m}Nb	9.2×10^{-4}	---	---	---	---	---	1.2×10^{-4}	---	---	---	---	---	---	$1.0 \text{ X } 10^{-3}$
^{95}Nb	---	2.4×10^{-13}	---	---	---	---	---	---	---	---	---	---	---	$2.4 \text{ X } 10^{-13}$
^{95m}Nb	---	8.1×10^{-16}	---	---	---	---	---	---	---	---	---	---	---	$8.1 \text{ X } 10^{-16}$
^{59}Ni	---	---	---	2.3×10^{1}	---	---	1.7×10^{-4}	---	---	---	---	---	---	$2.3 \text{ X } 10^{1}$
^{63}Ni	---	---	---	1.1×10^{3}	---	---	1.9×10^{-2}	---	---	---	---	---	---	$1.1 \text{ X } 10^{3}$
^{237}Np	1.7×10^{-3}	1.9×10^{-3}	1.2×10^{-2}	1.7×10^{-2}	2.6×10^{-6}	6.8×10^{-5}	8.5×10^{-4}	$1.6 \text{ X } 10^{-7}$	$1.8 \text{ X } 10^{-3}$	$2.6 \text{ X } 10^{-6}$	$6.4 \text{ X } 10^{-1}$	$9.0 \text{ X } 10^{-4}$	---	$6.7 \text{ X } 10^{-1}$

Table DATA-F-36. RH-TRU Waste Curies on a Site-by-Site Basis [1]— Continued

Radionuclide	AE	AW	BC	BT	ET	IN	KA	LA	OR	RL	RP	SA	SR	Total Of Curies
^{238}Np	---	2.5×10^{-5}	---	---	---	---	---	---	---	---	---	---	---	$2.5 \text{ X } 10^{-5}$
^{239}Np	3.1×10^{-5}	5.3×10^{-4}	---	---	---	---	5.2×10^{-5}	---	$3.2 \text{ X } 10^{-1}$	---	---	---	$4.1 \text{ X } 10^{-2}$	$3.7 \text{ X } 10^{-1}$
^{240m}Np	---	---	---	---	---	---	1.7×10^{-12}	---	$6.5 \text{ X } 10^{-3}$	---	---	---	---	$6.5 \text{ X } 10^{-3}$
^{231}Pa	8.9×10^{-8}	3.7×10^{-7}	---	---	1.5×10^{-7}	2.0×10^{-7}	9.7×10^{-8}	$6.6 \text{ X } 10^{-8}$	$9.9 \text{ X } 10^{-5}$	---	---	$5.8 \text{ X } 10^{-8}$	$5.3 \text{ X } 10^{-19}$	$1.0 \text{ X } 10^{-4}$
^{233}Pa	1.6×10^{-3}	1.9×10^{-3}	---	---	2.6×10^{-6}	6.7×10^{-5}	8.4×10^{-4}	$1.6 \text{ X } 10^{-7}$	$1.8 \text{ X } 10^{-3}$	---	---	$9.0 \text{ X } 10^{-4}$	---	$7.1 \text{ X } 10^{-3}$
^{234}Pa	7.8×10^{-8}	5.9×10^{-7}	---	---	2.9×10^{-6}	1.4×10^{-15}	4.1×10^{-10}	$5.7 \text{ X } 10^{-10}$	$1.6 \text{ X } 10^{-2}$	---	---	$2.4 \text{ X } 10^{-7}$	---	$1.6 \text{ X } 10^{-2}$
^{234m}Pa	6.0×10^{-5}	4.6×10^{-4}	---	---	2.2×10^{-3}	1.1×10^{-12}	3.1×10^{-7}	$4.3 \text{ X } 10^{-7}$	$1.3 \text{ X } 10^{1}$	---	---	$1.8 \text{ X } 10^{-4}$	---	$1.3 \text{ X } 10^{1}$
^{209}Pb	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{210}Pb	7.0×10^{-11}	4.3×10^{-11}	---	---	9.9×10^{-16}	9.3×10^{-11}	2.5×10^{-9}	$9.2 \text{ X } 10^{-12}$	$1.2 \text{ X } 10^{-6}$	---	---	$1.8 \text{ X } 10^{-11}$	$2.1 \text{ X } 10^{-13}$	$1.2 \text{ X } 10^{-6}$
^{211}Pb	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.8×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{212}Pb	1.1×10^{-15}	5.6×10^{-15}	---	---	5.4×10^{-18}	9.8×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{214}Pb	3.9×10^{-10}	7.2×10^{-10}	---	---	1.7×10^{-14}	1.8×10^{-9}	9.5×10^{-9}	$3.6 \text{ X } 10^{-11}$	$7.9 \text{ X } 10^{-6}$	---	---	$3.5 \text{ X } 10^{-10}$	$3.5 \text{ X } 10^{-12}$	$7.9 \text{ X } 10^{-6}$
^{107}Pd	---	---	---	---	---	---	1.7×10^{-5}	---	---	---	---	---	---	$1.7 \text{ X } 10^{-5}$
^{147}Pm	3.0×10^{-2}	3.7×10^{2}	---	2.8×10^{2}	---	---	5.9×10^{-2}	---	---	---	---	$7.0 \text{ X } 10^{0}$	$2.2 \text{ X } 10^{0}$	$6.6 \text{ X } 10^{2}$
^{210}Po	7.0×10^{-11}	4.3×10^{-11}	---	---	9.9×10^{-16}	9.3×10^{-11}	2.0×10^{-9}	$9.2 \text{ X } 10^{-12}$	$1.2 \text{ X } 10^{-6}$	---	---	$1.8 \text{ X } 10^{-11}$	$2.1 \text{ X } 10^{-13}$	$1.2 \text{ X } 10^{-6}$
^{211}Po	8.8×10^{-11}	1.0×10^{-10}	---	---	5.4×10^{-11}	6.3×10^{-11}	1.5×10^{-10}	$7.2 \text{ X } 10^{-11}$	$6.8 \text{ X } 10^{-8}$	---	---	$1.3 \text{ X } 10^{-11}$	---	$6.9 \text{ X } 10^{-8}$
^{212}Po	6.8×10^{-16}	3.5×10^{-15}	---	---	3.5×10^{-18}	6.3×10^{-17}	6.6×10^{-6}	$6.6 \text{ X } 10^{-17}$	$1.0 \text{ X } 10^{1}$	---	---	$2.1 \text{ X } 10^{-19}$	---	$1.0 \text{ X } 10^{1}$
^{213}Po	4.5×10^{-7}	1.1×10^{-4}	---	---	3.1×10^{-14}	2.2×10^{-13}	9.4×10^{-10}	$6.0 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.5 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{214}Po	3.9×10^{-10}	7.2×10^{-10}	---	---	1.7×10^{-14}	1.8×10^{-9}	9.5×10^{-9}	$3.6 \text{ X } 10^{-11}$	$7.9 \text{ X } 10^{-6}$	---	---	$3.5 \text{ X } 10^{-10}$	$3.5 \text{ X } 10^{-12}$	$7.9 \text{ X } 10^{-6}$
^{215}Po	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.8×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{216}Po	1.1×10^{-15}	5.5×10^{-15}	---	---	5.4×10^{-18}	9.8×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{218}Po	3.8×10^{-10}	7.1×10^{-10}	---	---	1.6×10^{-14}	1.7×10^{-9}	9.3×10^{-9}	$3.5 \text{ X } 10^{-11}$	$7.8 \text{ X } 10^{-6}$	---	---	$3.5 \text{ X } 10^{-10}$	$3.5 \text{ X } 10^{-12}$	$7.8 \text{ X } 10^{-6}$
^{144}Pr	2.0×10^{-9}	7.1×10^{0}	---	---	---	---	---	---	$6.1 \text{ X } 10^{-7}$	---	---	---	---	$7.1 \text{ X } 10^{0}$
^{238}Pu	9.2×10^{0}	1.2×10^{0}	7.8×10^{1}	2.8×10^{2}	1.5×10^{-2}	2.7×10^{3}	2.8×10^{0}	$1.3 \text{ X } 10^{-2}$	$2.5 \text{ X } 10^{2}$	$1.1 \text{ X } 10^{3}$	$1.0 \text{ X } 10^{1}$	$4.2 \text{ X } 10^{0}$	$3.6 \text{ X } 10^{0}$	$4.5 \text{ X } 10^{3}$
^{239}Pu	1.8×10^{1}	4.2×10^{1}	1.0×10^{1}	2.2×10^{-1}	1.1×10^{0}	3.5×10^{1}	7.6×10^{-3}	$2.5 \text{ X } 10^{0}$	$1.4 \text{ X } 10^{2}$	$2.3 \text{ X } 10^{3}$	$4.2 \text{ X } 10^{3}$	$2.8 \text{ X } 10^{0}$	$4.8 \text{ X } 10^{-6}$	$6.8 \text{ X } 10^{3}$
^{240}Pu	3.8×10^{0}	2.3×10^{1}	1.6×10^{1}	4.5×10^{-1}	2.7×10^{-1}	3.3×10^{1}	1.9×10^{-3}	$2.7 \text{ X } 10^{-2}$	$3.4 \text{ X } 10^{1}$	$1.3 \text{ X } 10^{3}$	$1.0 \text{ X } 10^{3}$	$4.3 \text{ X } 10^{-1}$	---	$2.4 \text{ X } 10^{3}$
^{241}Pu	3.0×10^{1}	7.2×10^{2}	1.3×10^{3}	4.8×10^{1}	2.2×10^{0}	6.6×10^{1}	2.7×10^{-1}	$2.2 \text{ X } 10^{-1}$	$1.5 \text{ X } 10^{2}$	$1.4 \text{ X } 10^{5}$	$1.8 \text{ X } 10^{4}$	$2.5 \text{ X } 10^{-2}$	---	$1.6 \text{ X } 10^{5}$

Table DATA-F-36. RH-TRU Waste Curies on a Site-by-Site Basis [1]— Continued

Radionuclide	AE	AW	BC	BT	ET	IN	KA	LA	OR	RL	RP	SA	SR	Total Of Curies
^{242}Pu	---	5.5×10^{-4}	4.8×10^{-2}	3.5×10^{-3}	---	1.0×10^{-3}	7.2×10^{-6}	$1.6 \text{ X } 10^{-5}$	$7.1 \text{ X } 10^{-2}$	$4.4 \text{ X } 10^{-1}$	$2.2 \text{ X } 10^{-1}$	---	---	$7.8 \text{ X } 10^{-1}$
^{243}Pu	---	---	---	---	---	---	1.5×10^{-13}	---	$7.0 \text{ X } 10^{-10}$	---	---	---	$5.4 \text{ X } 10^{1}$	$5.4 \text{ X } 10^{1}$
^{244}Pu	---	---	---	2.0×10^{-10}	---	---	1.7×10^{-12}	---	$6.4 \text{ X } 10^{-3}$	---	---	---	---	$6.4 \text{ X } 10^{-3}$
^{223}Ra	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.9×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.3 \text{ X } 10^{-5}$	---	---	$4.4 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{224}Ra	1.1×10^{-15}	5.5×10^{-15}	---	---	5.4×10^{-18}	9.8×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{225}Ra	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$
^{226}Ra	3.9×10^{-10}	7.3×10^{-10}	---	---	1.7×10^{-14}	1.8×10^{-9}	9.6×10^{-9}	$3.6 \text{ X } 10^{-11}$	$8.0 \text{ X } 10^{-6}$	---	---	$3.6 \text{ X } 10^{-10}$	$3.6 \text{ X } 10^{-12}$	$8.0 \text{ X } 10^{-6}$
^{228}Ra	1.3×10^{-15}	1.4×10^{-14}	---	---	1.1×10^{-17}	2.8×10^{-16}	4.1×10^{-11}	$1.2 \text{ X } 10^{-16}$	$9.8 \text{ X } 10^{-1}$	---	---	$1.4 \text{ X } 10^{-18}$	---	$9.8 \text{ X } 10^{-1}$
^{106}Rh	3.6×10^{-7}	---	---	---	---	---	---	$1.3 \text{ X } 10^{-10}$	$2.2 \text{ X } 10^{-3}$	$3.9 \text{ X } 10^{-1}$	---	---	---	$4.0 \text{ X } 10^{-1}$
^{219}Rn	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.8×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.3 \text{ X } 10^{-5}$
^{220}Rn	1.1×10^{-15}	5.6×10^{-15}	---	---	5.4×10^{-18}	9.8×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{222}Rn	3.9×10^{-10}	7.2×10^{-10}	---	---	1.7×10^{-14}	1.8×10^{-9}	9.5×10^{-9}	$3.6 \text{ X } 10^{-11}$	$7.9 \text{ X } 10^{-6}$	---	---	$3.5 \text{ X } 10^{-10}$	$3.5 \text{ X } 10^{-12}$	$7.9 \text{ X } 10^{-6}$
^{106}Ru	3.6×10^{-7}	---	---	---	---	---	---	$1.3 \text{ X } 10^{-10}$	$2.3 \text{ X } 10^{-3}$	$3.9 \text{ X } 10^{-1}$	---	---	---	$4.0 \text{ X } 10^{-1}$
^{125}Sb	3.7×10^{-3}	5.0×10^{0}	2.8×10^{-3}	---	---	---	---	$5.5 \text{ X } 10^{-4}$	$1.3 \text{ X } 10^{-2}$	---	---	---	---	$5.0 \text{ X } 10^{0}$
^{126}Sb	1.2×10^{-4}	---	---	---	---	---	4.7×10^{-5}	---	---	---	---	---	---	$1.7 \text{ X } 10^{-4}$
^{126m}Sb	8.7×10^{-4}	---	---	---	---	---	3.4×10^{-4}	---	---	---	---	---	---	$1.2 \text{ X } 10^{-3}$
^{79}Se	---	---	---	4.0×10^{-2}	---	---	1.0×10^{-4}	---	---	$2.8 \text{ X } 10^{-2}$	---	---	---	$6.7 \text{ X } 10^{-2}$
^{147}Sm	9.3×10^{-10}	3.5×10^{-8}	---	---	---	---	4.4×10^{-13}	---	---	---	---	$4.7 \text{ X } 10^{-10}$	$4.0 \text{ X } 10^{-10}$	$3.7 \text{ X } 10^{-8}$
^{151}Sm	2.0×10^{0}	3.5×10^{1}	---	3.1×10^{1}	---	---	1.2×10^{0}	---	---	$3.5 \text{ X } 10^{2}$	$2.4 \text{ X } 10^{2}$	---	---	$6.6 \text{ X } 10^{2}$
^{121m}Sn	---	---	---	---	---	---	3.0×10^{-3}	---	---	---	---	---	---	$3.0 \text{ X } 10^{-3}$
^{126}Sn	8.7×10^{-4}	---	---	---	---	---	3.4×10^{-4}	---	---	---	---	---	---	$1.2 \text{ X } 10^{-3}$
^{90}Sr	2.6×10^{1}	1.3×10^{3}	1.5×10^{3}	6.4×10^{3}	9.5×10^{0}	---	7.3×10^{1}	---	$5.6 \text{ X } 10^{4}$	$1.9 \text{ X } 10^{5}$	$7.5 \text{ X } 10^{4}$	$4.9 \text{ X } 10^{2}$	$5.8 \text{ X } 10^{1}$	$3.3 \text{ X } 10^{5}$
^{99}Tc	1.1×10^{-2}	---	4.4×10^{-1}	1.4×10^{0}	---	---	2.1×10^{-2}	---	$6.5 \text{ X } 10^{-9}$	$6.6 \text{ X } 10^{-3}$	$1.6 \text{ X } 10^{2}$	---	---	$1.6 \text{ X } 10^{2}$
^{125m}Te	8.9×10^{-4}	1.2×10^{0}	---	---	---	---	---	$1.3 \text{ X } 10^{-4}$	$3.1 \text{ X } 10^{-3}$	---	---	---	---	$1.2 \text{ X } 10^{0}$
^{227}Th	2.8×10^{-8}	3.2×10^{-8}	---	---	1.7×10^{-8}	2.0×10^{-8}	4.7×10^{-8}	$2.3 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.2 \text{ X } 10^{-5}$
^{228}Th	1.1×10^{-15}	5.6×10^{-15}	---	---	5.5×10^{-18}	9.9×10^{-17}	1.0×10^{-5}	$1.0 \text{ X } 10^{-16}$	$1.6 \text{ X } 10^{1}$	---	---	$3.2 \text{ X } 10^{-19}$	---	$1.6 \text{ X } 10^{1}$
^{229}Th	4.6×10^{-7}	1.2×10^{-4}	---	---	3.2×10^{-14}	2.2×10^{-13}	9.6×10^{-10}	$6.1 \text{ X } 10^{-15}$	$2.1 \text{ X } 10^{-1}$	---	---	$4.6 \text{ X } 10^{-12}$	---	$2.1 \text{ X } 10^{-1}$

Table DATA-F-36. RH-TRU Waste Curies on a Site-by-Site Basis [1]— Continued

Radionuclide	AE	AW	BC	BT	ET	IN	KA	LA	OR	RL	RP	SA	SR	Total Of Curies
^{230}Th	9.8×10^{-8}	5.6×10^{-7}	---	---	1.4×10^{-11}	1.8×10^{-6}	1.4×10^{-6}	$5.5 \text{ X } 10^{-9}$	$2.2 \text{ X } 10^{-3}$	---	---	$3.3 \text{ X } 10^{-7}$	$3.1 \text{ X } 10^{-9}$	$2.2 \text{ X } 10^{-3}$
^{231}Th	1.5×10^{-4}	2.9×10^{-3}	---	---	8.9×10^{-4}	1.3×10^{-3}	7.1×10^{-5}	$9.9 \text{ X } 10^{-5}$	$2.7 \text{ X } 10^{-1}$	---	---	$5.4 \text{ X } 10^{-4}$	$1.2 \text{ X } 10^{-14}$	$2.8 \text{ X } 10^{-1}$
^{232}Th	2.0×10^{-15}	4.7×10^{-14}	---	1.7×10^{-11}	2.9×10^{-17}	1.2×10^{-15}	4.1×10^{-11}	$1.5 \text{ X } 10^{-16}$	$1.0 \text{ X } 10^{0}$	$4.3 \text{ X } 10^{-2}$	---	$7.8 \text{ X } 10^{-18}$	---	$1.1 \text{ X } 10^{0}$
^{234}Th	6.0×10^{-5}	4.6×10^{-4}	---	---	2.2×10^{-3}	1.1×10^{-12}	3.1×10^{-7}	$4.4 \text{ X } 10^{-7}$	$1.3 \text{ X } 10^{1}$	---	---	$1.8 \text{ X } 10^{-4}$	---	$1.3 \text{ X } 10^{1}$
^{207}Tl	2.9×10^{-8}	3.3×10^{-8}	---	---	1.8×10^{-8}	2.1×10^{-8}	4.8×10^{-8}	$2.4 \text{ X } 10^{-8}$	$2.2 \text{ X } 10^{-5}$	---	---	$4.3 \text{ X } 10^{-9}$	---	$2.2 \text{ X } 10^{-5}$
^{208}Tl	3.8×10^{-16}	2.0×10^{-15}	2.3×10^{-3}	---	2.0×10^{-18}	3.5×10^{-17}	3.7×10^{-6}	$3.7 \text{ X } 10^{-17}$	$5.6 \text{ X } 10^{0}$	---	---	$1.2 \text{ X } 10^{-19}$	---	$5.6 \text{ X } 10^{0}$
^{209}Tl	1.0×10^{-8}	2.6×10^{-6}	---	---	7.1×10^{-16}	4.9×10^{-15}	2.1×10^{-11}	$1.3 \text{ X } 10^{-16}$	$4.7 \text{ X } 10^{-3}$	---	---	$1.0 \text{ X } 10^{-13}$	---	$4.7 \text{ X } 10^{-3}$
^{232}U	---	---	7.3×10^{-4}	4.0×10^{-3}	---	---	3.4×10^{-5}	---	$1.5 \text{ X } 10^{1}$	---	---	---	---	$1.5 \text{ X } 10^{1}$
^{233}U	1.8×10^{-4}	2.1×10^{-1}	1.3×10^{-6}	---	7.6×10^{-11}	1.0×10^{-9}	3.9×10^{-7}	$7.9 \text{ X } 10^{-12}$	$1.3 \text{ X } 10^{2}$	$8.5 \text{ X } 10^{0}$	$2.3 \text{ X } 10^{0}$	$1.9 \text{ X } 10^{-8}$	---	$1.5 \text{ X } 10^{2}$
^{234}U	7.8×10^{-4}	1.0×10^{-2}	2.8×10^{-2}	6.0×10^{-1}	4.0×10^{-7}	5.5×10^{-2}	4.8×10^{-3}	$2.0 \text{ X } 10^{-5}$	$1.4 \text{ X } 10^{1}$	$9.2 \text{ X } 10^{0}$	$1.5 \text{ X } 10^{1}$	$7.4 \text{ X } 10^{-3}$	$8.4 \text{ X } 10^{-5}$	$3.9 \text{ X } 10^{1}$
^{235}U	1.6×10^{-4}	2.9×10^{-3}	4.1×10^{-4}	7.8×10^{-3}	9.0×10^{-4}	1.4×10^{-3}	7.2×10^{-5}	$1.0 \text{ X } 10^{-4}$	$2.8 \text{ X } 10^{-1}$	$5.3 \text{ X } 10^{-1}$	$5.6 \text{ X } 10^{-1}$	$5.5 \text{ X } 10^{-4}$	$1.3 \text{ X } 10^{-14}$	$1.4 \text{ X } 10^{0}$
^{236}U	3.1×10^{-6}	1.6×10^{-4}	5.4×10^{-3}	8.9×10^{-2}	9.4×10^{-8}	6.8×10^{-6}	6.8×10^{-4}	$1.1 \text{ X } 10^{-7}$	$4.9 \text{ X } 10^{-2}$	$8.3 \text{ X } 10^{-1}$	$1.2 \text{ X } 10^{0}$	$6.3 \text{ X } 10^{-8}$	---	$2.2 \text{ X } 10^{0}$
^{237}U	7.3×10^{-4}	1.8×10^{-2}	---	---	5.4×10^{-5}	1.6×10^{-3}	6.6×10^{-6}	$5.5 \text{ X } 10^{-6}$	$3.7 \text{ X } 10^{-3}$	---	---	$6.1 \text{ X } 10^{-7}$	---	$2.4 \text{ X } 10^{-2}$
^{238}U	6.1×10^{-5}	4.6×10^{-4}	8.0×10^{-3}	3.6×10^{-5}	2.2×10^{-3}	1.1×10^{-12}	3.2×10^{-7}	$4.4 \text{ X } 10^{-7}$	$1.3 \text{ X } 10^{1}$	$4.5 \text{ X } 10^{0}$	$1.3 \text{ X } 10^{2}$	$1.8 \text{ X } 10^{-4}$	---	$1.4 \text{ X } 10^{2}$
^{240}U	---	---	---	---	---	---	1.7×10^{-12}	---	$6.4 \text{ X } 10^{-3}$	---	---	---	---	$6.4 \text{ X } 10^{-3}$
^{90}Y	2.5×10^{1}	1.3×10^{3}	---	6.4×10^{3}	9.4×10^{0}	---	7.2×10^{1}	---	$5.5 \text{ X } 10^{4}$	$1.8 \text{ X } 10^{5}$	$7.5 \text{ X } 10^{4}$	$4.8 \text{ X } 10^{2}$	$5.7 \text{ X } 10^{1}$	$3.2 \text{ X } 10^{5}$
^{91}Y	---	4.7×10^{-12}	---	---	---	---	---	---	---	---	---	---	---	$4.7 \text{ X } 10^{-12}$
^{93}Zr	1.3×10^{-3}	---	---	3.4×10^{-1}	---	---	2.6×10^{-3}	---	---	---	---	---	---	$3.4 \text{ X } 10^{-1}$
^{95}Zr	---	1.1×10^{-13}	---	---	---	---	---	---	---	---	---	---	---	$1.1 \text{ X } 10^{-13}$
Total:	2.1×10^{2}	7.2×10^{3}	5.8×10^{3}	2.8×10^{4}	4.2×10^{1}	3.3×10^{3}	3.0×10^{2}	$3.3 \text{ X } 10^{1}$	$1.5 \text{ X } 10^{5}$	$1.1 \text{ X } 10^{6}$	$4.3 \text{ X } 10^{5}$	$2.0 \text{ X } 10^{3}$	$3.5 \text{ X } 10^{2}$	$1.7 \text{ X } 10^{6}$

[1] Decayed through December 31, 2001

Table DATA-F-37. WIPP Disposal Radionuclide Inventory for the CRA[1, 2]

Radionuclide	CH Concentration (Ci/m^3)	RH Concentration (Ci/m^3)	CH-TRU Curies	RH-TRU Curies
^{225}Ac	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{227}Ac	3.0×10^{-6}	5.7×10^{-10}	5.1×10^{-1}	4.0×10^{-6}
^{228}Ac	2.8×10^{-5}	2.0×10^{-5}	4.8×10^{0}	1.4×10^{-1}
^{109m}Ag	7.5×10^{-10}	NR	1.3×10^{-4}	NR
^{110}Ag	2.6×10^{-16}	2.7×10^{-15}	4.4×10^{-11}	1.9×10^{-11}
^{110m}Ag	2.0×10^{-14}	2.1×10^{-13}	3.3×10^{-9}	1.5×10^{-9}
^{241}Am	2.4×10^{0}	1.9×10^{0}	4.0×10^{5}	1.4×10^{4}
^{242}Am	2.8×10^{-7}	1.2×10^{-7}	4.7×10^{-2}	8.5×10^{-4}
^{242m}Am	2.8×10^{-7}	2.8×10^{-5}	4.8×10^{-2}	2.0×10^{-1}
^{243}Am	1.3×10^{-4}	1.0×10^{-4}	2.1×10^{1}	7.2×10^{-1}
^{245}Am	7.8×10^{-16}	NR	1.3×10^{-10}	NR
^{217}At	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{137m}Ba	5.4×10^{-2}	4.7×10^{1}	9.1×10^{3}	3.4×10^{5}
^{210}Bi	1.5×10^{-5}	3.0×10^{-11}	2.6×10^{0}	2.1×10^{-7}
^{211}Bi	3.0×10^{-6}	5.6×10^{-10}	5.0×10^{-1}	4.0×10^{-6}
^{212}Bi	3.5×10^{-5}	3.8×10^{-4}	5.8×10^{0}	2.7×10^{0}
^{213}Bi	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{214}Bi	3.7×10^{-5}	1.9×10^{-10}	6.3×10^{0}	1.4×10^{-6}
^{249}Bk	5.4×10^{-11}	NR	9.1×10^{-6}	NR
^{250}Bk	2.2×10^{-17}	NR	3.7×10^{-12}	NR
^{14}C	7.2×10^{-6}	2.9×10^{-4}	1.2×10^{0}	2.1×10^{0}
^{109}Cd	7.6×10^{-10}	NR	1.3×10^{-4}	NR
^{113m}Cd	NR	2.3×10^{-5}	NR	1.6×10^{-1}
^{141}Ce	NR	5.3×10^{-23}	NR	3.8×10^{-19}
^{144}Ce	2.1×10^{-9}	2.6×10^{-4}	3.6×10^{-4}	1.8×10^{0}
^{249}Cf	4.5×10^{-7}	1.2×10^{-7}	7.6×10^{-2}	8.4×10^{-4}
^{250}Cf	1.1×10^{-6}	2.1×10^{-6}	1.8×10^{-1}	1.5×10^{-2}
^{251}Cf	2.2×10^{-9}	2.3×10^{-8}	3.6×10^{-4}	1.6×10^{-4}
^{252}Cf	1.2×10^{-6}	2.5×10^{-6}	2.1×10^{-1}	1.8×10^{-2}
^{242}Cm	2.3×10^{-7}	1.0×10^{-7}	3.9×10^{-2}	7.2×10^{-4}
^{243}Cm	2.4×10^{-6}	6.9×10^{-5}	4.0×10^{-1}	4.9×10^{-1}
^{244}Cm	6.9×10^{-2}	3.8×10^{-2}	1.2×10^{4}	2.7×10^{2}
^{245}Cm	5.0×10^{-8}	1.5×10^{-6}	8.4×10^{-3}	1.1×10^{-2}
^{246}Cm	9.2×10^{-6}	9.5×10^{-5}	1.6×10^{0}	6.7×10^{-1}
^{247}Cm	1.7×10^{-15}	1.3×10^{-3}	2.8×10^{-10}	9.4×10^{0}
^{248}Cm	5.4×10^{-7}	2.6×10^{-7}	9.1×10^{-2}	1.8×10^{-3}

Table DATA-F-37. WIPP Disposal Radionuclide Inventory for the CRA[1, 2]—Continued

Radionuclide	CH Concentration (Ci/m^3)	RH Concentration (Ci/m^3)	CH-TRU Curies	RH-TRU Curies
^{250}Cm	3.9×10^{-16}	NR	6.6×10^{-11}	NR
^{60}Co	5.9×10^{-6}	2.4×10^{-1}	9.9×10^{-1}	1.7×10^{3}
^{134}Cs	1.2×10^{-7}	4.8×10^{-3}	2.1×10^{-2}	3.4×10^{1}
^{135}Cs	NR	9.8×10^{-9}	NR	6.9×10^{-5}
^{137}Cs	5.7×10^{-2}	5.2×10^{1}	9.7×10^{3}	3.7×10^{5}
^{152}Eu	1.2×10^{-5}	9.8×10^{-2}	2.0×10^{0}	7.0×10^{2}
^{154}Eu	9.8×10^{-6}	6.0×10^{-2}	1.7×10^{0}	4.2×10^{2}
^{155}Eu	4.0×10^{-7}	2.6×10^{-3}	6.7×10^{-2}	1.9×10^{1}
^{55}Fe	NR	5.9×10^{-6}	NR	4.2×10^{-2}
^{221}Fr	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{223}Fr	4.1×10^{-8}	7.7×10^{-12}	6.9×10^{-3}	5.5×10^{-8}
^{152}Gd	2.6×10^{-19}	2.8×10^{-15}	4.4×10^{-14}	2.0×10^{-11}
^{3}H	1.3×10^{-3}	1.6×10^{-4}	2.2×10^{2}	1.2×10^{0}
^{129}I	3.0×10^{-9}	1.2×10^{-5}	5.1×10^{-4}	8.2×10^{-2}
^{85}Kr	2.7×10^{-6}	1.6×10^{-5}	4.6×10^{-1}	1.1×10^{-1}
^{54}Mn	NR	2.6×10^{-4}	NR	1.8×10^{0}
^{22}Na	2.3×10^{-12}	4.2×10^{-5}	3.9×10^{-7}	3.0×10^{-1}
^{93m}Nb	NR	3.9×10^{-8}	NR	2.8×10^{-4}
^{95}Nb	NR	1.1×10^{-17}	NR	7.5×10^{-14}
^{95m}Nb	NR	3.6×10^{-20}	NR	2.5×10^{-16}
^{59}Ni	4.5×10^{-7}	3.3×10^{-3}	7.6×10^{-2}	2.3×10^{1}
^{63}Ni	2.2×10^{-5}	1.6×10^{-1}	3.7×10^{0}	1.1×10^{3}
^{237}Np	2.8×10^{-5}	9.4×10^{-5}	4.8×10^{0}	6.7×10^{-1}
^{238}Np	1.4×10^{-9}	6.1×10^{-10}	2.4×10^{-4}	4.3×10^{-6}
^{239}Np	1.2×10^{-4}	8.9×10^{-6}	2.1×10^{1}	6.3×10^{-2}
^{240m}Np	7.8×10^{-12}	1.6×10^{-7}	1.3×10^{-6}	1.1×10^{-3}
^{231}Pa	7.2×10^{-6}	2.5×10^{-9}	1.2×10^{0}	1.8×10^{-5}
^{233}Pa	2.8×10^{-5}	3.3×10^{-7}	4.8×10^{0}	2.3×10^{-3}
^{234}Pa	5.5×10^{-8}	4.0×10^{-7}	9.3×10^{-3}	2.8×10^{-3}
^{234m}Pa	4.2×10^{-5}	3.1×10^{-4}	7.1×10^{0}	2.2×10^{0}
^{209}Pb	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{210}Pb	1.6×10^{-5}	3.0×10^{-11}	2.6×10^{0}	2.1×10^{-7}
^{211}Pb	3.0×10^{-6}	5.6×10^{-10}	5.0×10^{-1}	4.0×10^{-6}
^{212}Pb	3.5×10^{-5}	3.8×10^{-4}	5.8×10^{0}	2.7×10^{0}
^{214}Pb	3.7×10^{-5}	1.9×10^{-10}	6.3×10^{0}	1.4×10^{-6}
^{107}Pd	NR	4.1×10^{-10}	NR	2.9×10^{-6}
^{147}Pm	1.1×10^{-5}	5.0×10^{-2}	1.8×10^{0}	3.5×10^{2}

Table DATA-F-37. WIPP Disposal Radionuclide Inventory for the CRA[1, 2]—Continued

Radionuclide	CH Concentration (Ci/m^3)	RH Concentration (Ci/m^3)	CH-TRU Curies	RH-TRU Curies
^{210}Po	1.6×10^{-5}	3.0×10^{-11}	2.6×10^{0}	2.1×10^{-7}
^{211}Po	9.1×10^{-9}	1.7×10^{-12}	1.5×10^{-3}	1.2×10^{-8}
^{212}Po	2.2×10^{-5}	2.4×10^{-4}	3.7×10^{0}	1.7×10^{0}
^{213}Po	9.0×10^{-6}	5.1×10^{-6}	1.5×10^{0}	3.6×10^{-2}
^{214}Po	3.7×10^{-5}	1.9×10^{-10}	6.3×10^{0}	1.4×10^{-6}
^{215}Po	3.0×10^{-6}	5.6×10^{-10}	5.0×10^{-1}	4.0×10^{-6}
^{216}Po	3.5×10^{-5}	3.8×10^{-4}	5.8×10^{0}	2.7×10^{0}
^{218}Po	3.7×10^{-5}	1.9×10^{-10}	6.2×10^{0}	1.3×10^{-6}
^{144}Pr	2.1×10^{-9}	2.5×10^{-4}	3.5×10^{-4}	1.8×10^{0}
^{236}Pu	2.6×10^{-9}	NR	4.4×10^{-4}	NR
^{238}Pu	9.6×10^{0}	5.1×10^{-1}	1.6×10^{6}	3.6×10^{3}
^{239}Pu	3.9×10^{0}	7.6×10^{-1}	6.6×10^{5}	5.4×10^{3}
^{240}Pu	6.4×10^{-1}	2.4×10^{-1}	1.1×10^{5}	1.7×10^{3}
^{241}Pu	1.4×10^{1}	1.6×10^{1}	2.4×10^{6}	1.1×10^{5}
^{242}Pu	1.6×10^{-4}	6.7×10^{-5}	2.7×10^{1}	4.7×10^{-1}
^{243}Pu	1.6×10^{-15}	1.3×10^{-3}	2.7×10^{-10}	9.3×10^{0}
^{244}Pu	7.7×10^{-12}	1.6×10^{-7}	1.3×10^{-6}	1.1×10^{-3}
^{223}Ra	3.0×10^{-6}	5.6×10^{-10}	5.1×10^{-1}	4.0×10^{-6}
^{224}Ra	3.5×10^{-5}	3.8×10^{-4}	5.8×10^{0}	2.7×10^{0}
^{225}Ra	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{226}Ra	3.8×10^{-5}	2.0×10^{-10}	6.4×10^{0}	1.4×10^{-6}
^{228}Ra	3.4×10^{-5}	2.4×10^{-5}	5.7×10^{0}	1.7×10^{-1}
^{106}Rh	9.4×10^{-10}	9.6×10^{-6}	1.6×10^{-4}	6.8×10^{-2}
^{219}Rn	3.0×10^{-6}	5.6×10^{-10}	5.0×10^{-1}	4.0×10^{-6}
^{220}Rn	3.5×10^{-5}	3.8×10^{-4}	5.8×10^{0}	2.7×10^{0}
^{222}Rn	3.7×10^{-5}	1.9×10^{-10}	6.3×10^{0}	1.4×10^{-6}
^{106}Ru	9.5×10^{-10}	9.6×10^{-6}	1.6×10^{-4}	6.8×10^{-2}
^{125}Sb	3.0×10^{-8}	6.2×10^{-4}	5.0×10^{-3}	4.4×10^{0}
^{126}Sb	NR	5.9×10^{-9}	NR	4.2×10^{-5}
^{126m}Sb	NR	4.2×10^{-8}	NR	3.0×10^{-4}
^{79}Se	7.8×10^{-10}	6.3×10^{-6}	1.3×10^{-4}	4.5×10^{-2}
^{147}Sm	2.8×10^{-15}	9.7×10^{-13}	4.8×10^{-10}	6.9×10^{-9}
^{151}Sm	3.4×10^{-4}	8.2×10^{-2}	5.7×10^{1}	5.8×10^{2}
^{121m}Sn	NR	7.3×10^{-8}	NR	5.2×10^{-4}
^{126}Sn	NR	4.2×10^{-8}	NR	3.0×10^{-4}
^{90}Sr	3.4×10^{-1}	3.5×10^{1}	5.8×10^{4}	2.5×10^{5}
^{99}Tc	9.9×10^{-4}	2.3×10^{-2}	1.7×10^{2}	1.6×10^{2}

Table DATA-F-37. WIPP Disposal Radionuclide Inventory for the CRA[1, 2]—Continued

Radionuclide	CH Concentration (Ci/m^3)	RH Concentration (Ci/m^3)	CH-TRU Curies	RH-TRU Curies
^{123}Te	4.0×10^{-10}	NR	6.8×10^{-5}	NR
^{123m}Te	3.0×10^{-24}	NR	5.0×10^{-19}	NR
^{125m}Te	7.2×10^{-9}	1.5×10^{-4}	1.2×10^{-3}	1.1×10^{0}
^{227}Th	2.9×10^{-6}	5.5×10^{-10}	4.9×10^{-1}	3.9×10^{-6}
^{228}Th	3.5×10^{-5}	3.9×10^{-4}	5.9×10^{0}	2.7×10^{0}
^{229}Th	9.2×10^{-6}	5.2×10^{-6}	1.6×10^{0}	3.7×10^{-2}
^{230}Th	6.0×10^{-7}	5.3×10^{-8}	1.0×10^{-1}	3.8×10^{-4}
^{231}Th	2.1×10^{-6}	7.4×10^{-6}	3.5×10^{-1}	5.2×10^{-2}
^{232}Th	3.9×10^{-5}	3.1×10^{-5}	6.6×10^{0}	2.2×10^{-1}
^{234}Th	4.2×10^{-5}	3.1×10^{-4}	7.1×10^{0}	2.2×10^{0}
^{207}Tl	3.0×10^{-6}	5.6×10^{-10}	5.0×10^{-1}	3.9×10^{-6}
^{208}Tl	1.2×10^{-5}	1.4×10^{-4}	2.1×10^{0}	9.7×10^{-1}
^{209}Tl	2.0×10^{-7}	1.1×10^{-7}	3.4×10^{-2}	8.1×10^{-4}
^{232}U	9.8×10^{-6}	3.6×10^{-4}	1.6×10^{0}	2.5×10^{0}
^{233}U	7.3×10^{-3}	4.8×10^{-3}	1.2×10^{3}	3.4×10^{1}
^{234}U	1.0×10^{-3}	3.1×10^{-3}	1.7×10^{2}	2.2×10^{1}
^{235}U	7.8×10^{-6}	1.3×10^{-4}	1.3×10^{0}	9.4×10^{-1}
^{236}U	7.7×10^{-7}	2.0×10^{-4}	1.3×10^{-1}	1.4×10^{0}
^{237}U	1.3×10^{-4}	2.5×10^{-6}	2.2×10^{1}	1.8×10^{-2}
^{238}U	1.5×10^{-4}	1.8×10^{-2}	2.4×10^{1}	1.3×10^{2}
^{240}U	7.6×10^{-12}	1.5×10^{-7}	1.3×10^{-6}	1.1×10^{-3}
^{90}Y	3.4×10^{-1}	3.4×10^{1}	5.7×10^{4}	2.4×10^{5}
^{91}Y	NR	1.2×10^{-16}	NR	8.1×10^{-13}
^{65}Zn	1.4×10^{-15}	NR	2.3×10^{-10}	NR
^{93}Zr	6.7×10^{-9}	4.8×10^{-5}	1.1×10^{-3}	3.4×10^{-1}
^{95}Zr	NR	4.8×10^{-18}	NR	3.4×10^{-14}
Total:	3.2×10^{1}	1.9×10^{2}	5.3×10^{6}	1.3×10^{6}

NR=Not Reported

[1] Decayed through 2001

[2] Total curies estimated by assuming 168,485 m^3 for CH-TRU Waste and 7,079 m^3 for RH-TRU Waste

DATA-F-3.4.1 Non-Defense TRU Waste-Waste Isolation Pilot Plant Future Potential Waste

The DOE has several categories of waste that are currently not acceptable for disposal in WIPP. These are summarized below:

- Non-Defense Waste—The National Security Programs (Public Law 96-164, 1980, National Security and Military Applications of Nuclear Energy Authorization Act of

1980, 93 Stat. 1259), which authorized the construction of the WIPP, states that the WIPP is to be a defense waste repository. Therefore, those wastes that are identified as non-defense are not currently allowed to be disposed in the WIPP. Waste streams from sites for which a defense determination has not been made are identified in Table DATA-F-38 and in Table DATA-F-39.

Table DATA-F-38. Non-Defense TRU Waste (Final Waste Form)

Waste Stream ID	Waste Stream Name	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
Non-defense TRU Waste				
FM-MOX-MT0	Framatome MOX Fuel Plant D&D Mixed TRU Waste	4.2×10^{-1}	0.0×10^{0}	4.2×10^{-1}
FM-MOX-T01	Framatome MOX Fuel Plant D&D TRU Waste	6.9×10^{0}	0.0×10^{0}	6.9×10^{0}
LA-OS-00-02	Isotopic sources waiting determination of eligibility for WIPP disposal	0.0×10^{0}	1.6×10^{2}	1.6×10^{2}
LA-TA-00-06	Containers waiting assignment to waste streams	4.5×10^{1}	0.0×10^{0}	4.5×10^{1}
LB-T001	LBL -Waste	6.2×10^{-1}	1.0×10^{0}	1.7×10^{0}
RL-W684	327 TRU RH heterogeneous S5420 Non-mixed	8.9×10^{-1}	0.0×10^{0}	8.9×10^{-1}
VN-CHT001		0.0×10^{0}	2.0×10^{1}	2.0×10^{1}
VN-RHT001		0.0×10^{0}	1.2×10^{1}	1.2×10^{1}
	Totals	5.3×10^{1}	1.9×10^{2}	2.4×10^{2}

Table DATA-F-39. Possible Future Waste for WIPP

Waste Stream ID	Waste Stream Name	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
BL-001	Reactor Fuel Test Specimens	4.5×10^{1}	0.0×10^{0}	4.5×10^{1}
LA-TA-00-01	Containers waiting assignment to waste streams	7.7×10^{1}	0.0×10^{0}	7.7×10^{1}
LA-TA-00-02	Containers waiting assignment to waste streams	1.1×10^{2}	0.0×10^{0}	1.1×10^{2}
LA-TA-00-03	Containers waiting assignment to waste streams	7.7×10^{0}	0.0×10^{0}	7.7×10^{0}
LA-TA-00-04	Containers waiting assignment to waste streams	2.1×10^{2}	0.0×10^{0}	2.1×10^{2}
LA-TA-00-05	Containers waiting assignment to waste streams	4.2×10^{2}	0.0×10^{0}	4.2×10^{2}
LA-TA-00-06	Containers waiting assignment to waste streams	4.5×10^{1}	0.0×10^{0}	4.5×10^{1}
LA-TA-00-07	Containers waiting assignment to waste streams	1.8×10^{1}	0.0×10^{0}	1.8×10^{1}
PA-B015	Transuranic and Technetium Wastes - Liquid	2.5×10^{0}	0.0×10^{0}	2.5×10^{0}
PA-W014	Transuranic Waste Liquid	4.2×10^{-1}	0.0×10^{0}	4.2×10^{-1}
RF-MT0503		1.7×10^{0}	0.0×10^{0}	1.7×10^{0}
RF-MT0505		2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RF-MT0529		2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RF-MT0533		3.1×10^{0}	0.0×10^{0}	3.1×10^{0}
RF-MT0535		6.3×10^{-1}	0.0×10^{0}	6.3×10^{-1}
RF-TT0533		8.3×10^{-1}	0.0×10^{0}	8.3×10^{-1}
RL-W284	201C Unknown form CH RCRA MTRU w/ met	4.2×10^{-1}	0.0×10^{0}	4.2×10^{-1}
RL-W332	2345Z Unknown form CH St MTRU	1.9×10^{0}	0.0×10^{0}	1.9×10^{0}

Table DATA-F-39. Possible Future Waste for WIPP — Continued

Waste Stream ID	Waste Stream Name	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
RL-W357	KAPL Unknown form CH/r TRU	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W366	202A Unknown form CH TRU	1.5×10^{0}	8.3×10^{-1}	2.3×10^{0}
RL-W382	2345Z Unknown form CH TRU	1.9×10^{1}	6.1×10^{1}	8.0×10^{1}
RL-W391	308 Combustible unknown form CH TRU	4.2×10^{-1}	0.0×10^{0}	4.2×10^{-1}
RL-W471	202A MTRU CH unknown forms S9000 Mixed RCRA w/ org, met, Hg	1.9×10^{0}	0.0×10^{0}	1.9×10^{0}
RL-W472	202A MTRU CH unknown forms S9000 Mixed RCRA w/ met	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W556	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ org, met, Hg	4.2×10^{-1}	0.0×10^{0}	4.2×10^{-1}
RL-W557	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ org, ign	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W558	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ org	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W559	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ met, ign	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W560	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ met	4.0×10^{0}	0.0×10^{0}	4.0×10^{0}
RL-W561	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ met, Hg, cor	2.1×10^{-1}	$0.0 \text{ x } 10^{0}$	2.1×10^{-1}
RL-W562	2345Z MTRU CH unknown forms S9000 Mixed RCRA w/ met, Hg	1.0×10^{0}	0.0×10^{0}	1.0×10^{0}
RL-W577	2345Z TRU RH unknown forms S9000 Non-mixed	2.7×10^{0}	0.0×10^{0}	2.7×10^{0}
RL-W578	2345Z TRU RH unknown forms U9999 Non-mixed	5.3×10^{0}	0.0×10^{0}	5.3×10^{0}
RL-W609	324 MTRU CH unknown forms S9000 Mixed RCRA w/org, met, Hg	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W650	325 TRU CH unknown forms S9000 Non-mixed	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
RL-W651	325 MTRU CH unknown forms S9000 Mixed RCRA w/org, met	1.0×10^{0}	0.0×10^{0}	1.0×10^{0}
RL-W652	325 MTRU CH unknown forms S9000 Mixed RCRA w/org	3.8×10^{0}	0.0×10^{0}	3.8×10^{0}
RL-W667	325 TRU RH unknown forms S9000 Non-mixed	8.9×10^{-1}	0.0×10^{0}	8.9×10^{-1}
RL-W722	MCGEE TRU CH unknown forms S9000 Non-mixed	2.1×10^{-1}	0.0×10^{0}	2.1×10^{-1}
SR-T001-WSB-3	Unknown	0.0×10^{0}	1.4×10^{2}	1.4×10^{2}
VN-CHT001		0.0×10^{0}	2.0×10^{1}	2.0×10^{1}
VN-RHT001		0.0×10^{0}	1.2×10^{1}	1.2×10^{1}

Table DATA-F-39. Possible Future Waste for WIPP — Continued

Waste Stream ID	Waste Stream Name	Stored Volumes (m^3)	Projected Volumes (m^3)	Anticipated Volumes (m^3)
WV-M007	TRU General Waste	1.1×10^1	0.0×10^0	1.1×10^1
WV-T004	Fissile Material - Other	6.2×10^{-1}	0.0×10^0	6.2×10^{-1}
WV-T020	PPC/XC2 PPE and DAW	0.0×10^0	2.3×10^2	2.3×10^2
	Totals	1.2×10^3	6.7×10^2	1.9×10^3
WV-M005	TRU Filters	6.0×10^1	4.6×10^1	1.1×10^2
WV-M008	TRU Concrete	2.1×10^{-1}	0.0×10^0	2.1×10^{-1}
WV-M010	TRU Spent Absorbents	8.3×10^{-1}	0.0×10^0	8.3×10^{-1}
WV-M013	Sweeping Compound	1.9×10^0	0.0×10^0	1.9×10^0
WV-M015	Chemical Process Cell General Waste	6.0×10^0	0.0×10^0	6.0×10^0
WV-T001	Fissile Material -Solids	3.7×10^1	0.0×10^0	3.7×10^1
WV-T006	TRU General Waste	1.0×10^1	1.0×10^1	2.1×10^1
WV-T009	TRU General Laboratory Waste	1.0×10^1	2.1×10^1	3.1×10^1
WV-T011	TRU Glove Boxes	1.0×10^1	0.0×10^0	1.0×10^1
WV-T014	Chemical Process Cell Vessels	1.1×10^1	0.0×10^0	1.1×10^1
WV-T016	Chemical Process Cell Miscellaneous Equipment	8.5×10^0	0.0×10^0	8.5×10^0
WV-T017	Spent Filter Media	2.5×10^0	0.0×10^0	2.5×10^0
WV-T018	Head End Cell Debris	5.4×10^1	2.6×10^1	8.0×10^1
WV-T019	FRS Pool Filters	0.0×10^0	2.1×10^1	2.1×10^1
WV-T021	RHWF Process	0.0×10^0	8.1×10^1	8.1×10^1
WV-W024	TRU Lead	1.9×10^1	0.0×10^0	1.9×10^1
	Totals	1.2×10^3	6.7×10^2	1.9×10^3

- Pre-1970 buried TRU Waste—Several sites (i.e., LANL, SRS, SNL, Hanford Site, INEEL, Oak Ridge National Laboratory, and West Valley Demonstration Project) have TRU wastes that were buried prior to 1970. The final disposition of the buried pre-1970 TRU waste at DOE sites is still undecided.

- Classified Waste—Some classified TRU waste is now acceptable to be disposed of at WIPP. TRU-contaminated classified materials are materials used in weapons production. These materials are classified for security and national defense purposes due to their physical shape or form. TRU-contaminated classified materials include graphite shapes, metal shapes, tooling, and plastic shapes. The same characterization and associated QA activities, as currently required under the WIPP program, will be implemented for the characterization of classified materials in waste. The primary change associated with the proposed acceptance at WIPP of classified materials in waste is the security qualifications of the responsible parties implementing the waste characterization requirements and the associated QA requirements. Due to national security requirements, responsible parties

for waste characterization and related QA activities will possess a DOE "Q" clearance. Site and CBFO personnel will accomplish waste characterization and related QA activities in accordance with currently approved requirements.

- Polychlorinated Biphenyls (PCBs) —The U.S. Environmental Protection Agency, Region 6, Dallas, Texas office approved the disposal of non-liquid polychlorinated biphenyl-contaminated TRU waste (PCB/TRU waste) and PCB/TRU waste mixed with hazardous waste (PCB/TRU mixed waste) at the WIPP in May 2003. However, at the time the inventory data was prepared for the PA, this approval had not been received, therefore PCB-contaminated TRU waste > 50ppm was not included in this updated inventory data.

- RH-TRU waste that exceeds 23,000 Curies/m3 (650 Curies/ft3)—This limit is from the LWA (Pub. L. No. 102-579, 110 Stat. 2422 (1992), as amended by 104-201 (1996)).

- Waste streams that have unknown waste matrices —There are waste streams at the TRU waste sites that have not been characterized and therefore the determination cannot be made regarding the make up of the waste stream. These wastes are assigned unknown WMCs or final forms and have no known WMPs or radionuclide content.

DATA-F-3.4.2 Other Possible Future Waste Isolation Pilot Plant Waste

There are several other categories of material that eventually may become waste acceptable at WIPP. These include the following wastes.

- One category of potential future waste may come from waste streams that have been currently declared "unknown." These waste streams are summarized in Table DATA-F-39. These wastes have not been characterized adequately to determine the final waste form and/or other significant parameters. If these wastes are characterized, and if they meet the WAC (DOE 2002a), they will be included in the WIPP inventory in the future.

- Babcock and Wilcox in Lynchburg, Virginia, currently has approximately 45 m^3 (1,590 ft^3) of TRU waste that requires a defense determination, in on-site storage silos of which a portion may be possible future TRU waste. Virtually all of the material was generated from the Light Water Reactor Extended Burn-up Program. That program was responsible for sending test elements of reactor fuel to various hot cells, including the one at Lynchburg. The waste consists mostly of cellulosic material, rubber material, and lead-lined gloves.

- Another potential TRU waste site is the Brookhaven National Laboratory (BNL). BNL has identified an existing legacy 17,500-lb concrete vault stored at the Hazardous Waste Management Facility as TRU waste based on recalculation of ^{239}Pu curie content. The vault holds five plutonium foils (TRU waste) and other non-TRU waste constituents including Brookhaven Linear Isotope Production (BLIP) waste and cesium and cobalt sources embedded in concrete. The vault must now be managed as TRU waste.

- There are four waste streams at the SRS that were not listed in Table DATA-F-39. These waste streams will account for nearly 9.6×10^3 m^3 (3.3×10^5 ft^3) of possible future TRU

waste for WIPP. These waste streams will come from proposed facilities at SRS. Those waste streams are SR-T001-WSB-1, SR-T001-WSB-2, SR-W026-PDCF-1, and SR-W026-MFFF-1.

- Sodium-Bearing Waste (SBW) at INEEL requires a declaration that it is waste incidental to reprocessing (WIR). Several treatment options are being considered with the final treatment option to be selected in the near future. For this update, the SBW is included in the Non-WIPP TRU waste and has been entered using the bounding case for RH-TRU waste. That is, the case in which RH-TRU waste is generated from the calcine process.

- Beryllium Block Waste from the INEEL is a waste stream that includes beryllium blocks and outer shim control cylinders from the Advanced Test Reactor. The radionuclide concentrations are too great to be considered in this update but may considered in the future.

DATA-F-3.5 Emplacement Materials

The inventory of CPR materials used by WIPP Waste Handling Operations (WHO) to facilitate waste emplacement was estimated to support the CRA-2004 PA. Other materials that were not accounted for by the sites in their waste/ packaging material parameter data submissions were also estimated. Finally, the mass of magnesium oxide (MgO) used as backfill was estimated for the full repository. The results of these estimations were summarized in a letter to SNL (Crawford 2003a).

The estimates for CPR materials, other emplacement materials, and MgO are based on the number and type of waste containers emplaced in the WIPP as of the inventory date, September 30, 2002.

The TRUPACT-II Authorized Methods for Payload Control (TRAMPAC), Revision 19c (NMED 2002) allows certain container types to be transported in the Transuranic Package Transporter-II (TRUPACT-II). These are 55-gallon drums, 100-gallon drums, SWB, and ten-drum overpacks (TDOP).

The WIPP was designed to receive both CH- and RH-TRU waste. CH-TRU waste that has been emplaced in the WIPP since the repository opened is in seven-packs of 55-gallon drums and/or pipe overpack components (POCs), SWBs, and TDOPs. RH-TRU waste has not been shipped to the WIPP to date.

WIPP WHO uses several materials to facilitate the emplacement of TRU waste, and MgO is used as barrier. Plastic and cellulosic materials are used to emplace CH-TRU waste. The MgO is placed on top of the containers and comes in a woven plastic bag called a “supersack.” RH-TRU waste will be emplaced in boreholes in the salt and then a shield plug, which consists of concrete (cement), steel, and plastic, will be installed to seal the canister into the borehole and provide shielding. There are no rubber materials used for waste emplacement.

The materials used to emplace CH-TRU waste are:

- Polyethylene (PE) slip-sheets for the seven-packs of 55-gallon drums and/or POCs and the MgO supersacks (plastics);
- Fiberboard slip-sheet for the SWB and TDOP (cellulosic material);
- Woven polypropylene supersacks containing MgO (plastic material/MgO);
- Cardboard stabilizers for the supersacks (cellulosic material); and
- Stretch wrap for the seven-packs (plastic material).

The materials that will be used to emplace RH-TRU waste are:

- Shield plug (cement components);
- Shield plug (steel components); and
- Shield plug (plastic components).

Data on the MgO and other emplacement materials were obtained from WIPP WHO drawings and procedures, from WWIS personnel, from the WIPP CH-TRU Waste Safety Analysis Report, and from the internet. These sources are referenced in a letter to SNL (Crawford 2003a).

For CH-TRU waste, the total mass of each of the emplacement materials (plastic, cellulosic, and MgO) as of the inventory date was calculated. These total masses were then divided by the total volume of the emplaced waste (as of the inventory date September 30, 2002) to obtain the density of these materials in the WIPP as of the inventory date. These densities were then scaled to a full repository based on the volume limit for CH-TRU waste of 168,485 m^3 (5,950,000 ft^3).

The total masses of the emplacement materials (cement, steel, and plastic) that will be used for RH-TRU waste emplaced in the WIPP in the future were calculated. This was done by first determining the total number of RH-TRU waste shield plugs that will be used in the repository. The total mass of each shield plug component for the repository was then calculated by determining the mass of each component for each shield plug and multiplying that mass by the number of plugs to be used.

The estimates for CPR and MgO, as well as for the steel and cement used in the RH-TRU waste shield plug, are provided in Table DATA-F-40.

Table DATA-F-40. Estimates of Materials Used to Facilitate Emplacement of Waste in the WIPP

Material Parameter	Mass used for CH Waste (kg) [1]	Density used for CH Waste (kg/m^3) [1]	CH Mass-Scaled to CH Limit[2] (kg)	RH Mass-for the WIPP (kg)	Total (CH+RH) WIPP Mass (kg)
Cellulosic Material (fibreboard slip-sheets)	2.03×10^3	2.63×10^{-1}	4.44×10^4	N/A	4.44×10^4
Cellulosic Material (cardboard stabilizers)	7.02×10^3	9.09×10^{-1}	1.53×10^5	N/A	1.53×10^5
Total Cellulosic Material	9.06×10^3	1.17×10^0	1.98×10^5	N/A	1.98×10^5
Plastic (slip-sheets)	1.02×10^5	1.33×10^1	2.23×10^6	N/A	2.23×10^6
Plastic (poly bag)	6.24×10^3	8.08×10^{-1}	1.36×10^5	N/A	1.36×10^5
Plastic (shrink wrap)	3.56×10^3	4.62×10^{-1}	7.78×10^4	N/A	7.78×10^4
Plastic (RH shield plug)				1.73×10^5	1.73×10^5
Total Plastic Material	1.12×10^5	1.45×10^1	2.45×10^6	1.73×10^5	2.62×10^6
Rubber Material	N/A	N/A	N/A	N/A	N/A
Cement (RH-TRU Waste shield plug)	N/A	N/A	N/A	6.33×10^6	6.33×10^6
Steel (RH-TRU Waste shield plug)	N/A	N/A	N/A	7.95×10^4	7.95×10^4
Magnesium Oxide	3.20×10^6	4.14×10^2	6.98×10^7	N/A	6.98×10^7

[1] These are the masses and densities of the materials that were used to facilitate emplacement of waste in the WIPP as of September 30, 2002. There was no RH-TRU waste emplaced as of that date.

[2] The CH-TRU waste limit is 1.68×10^5 m^3.

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APPENDIX DATA

ATTACHMENT G: WIPP BOREHOLE UPDATE

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WIPP BOREHOLES

The Department of Energy (DOE) prepared DOE/WIPP 95-2092, Rev. 1, Waste Isolation Pilot Plant Borehole Data Report (CCA Appendix BH) to serve as a central document providing data on boreholes used in characterizing the site. The report contained a comprehensive database on wells drilled in support of the WIPP and boreholes that were located within the 16-section Land Withdrawal Area.

This report was categorized into seven groups of boreholes: commercially drilled boreholes, DOE wells, geologic exploration boreholes, hydrologic test boreholes, potash boreholes, subsurface exploration boreholes, and Water Quality Sampling Program boreholes. There were 179 boreholes in the report. At the time of the CCA, 80 of those boreholes were being used as monitoring wells. The rest of the boreholes were plugged and abandoned after being drilled for their specific purpose, i.e., potash information, hydrocarbon information, or WIPP site characterization information.

This report updates all of the monitoring wells identified in CCA Appendix BH and adds the new monitoring wells drilled since the initial certification. This report also adds the wells that were in use but inadvertently omitted from CCA Appendix BH.

Table DATA-G-1. Monitoring Well Status

Well Name	CCA Monitoring Status	CRA Monitoring Status	Depth	Year Drilled	Year Plugged
AEC-7	Culebra	Culebra	4734 ft	1974	N/A
AEC-8	Bell Canyon	Bell Canyon	4922 ft	1974	N/A
B-1	Observation	Observation	58 ft	1978	N/A
B-1A	Observation	Observation	13 ft	1978	N/A
B-4	Observation	Observation	39 ft	1978	N/A
B-4A	Observation	Observation	14 ft	1978	N/A
B-13	Observation	Observation	28 ft	1978	N/A
B-16	Observation	Observation	31 ft	1978	N/A
B-18	Observation	Observation	33 ft	1978	N/A
B-20	Observation	Observation	14 ft	1978	N/A
B-20A	Observation	Observation	34 ft	1978	N/A
B-38	Observation	Observation	50 ft	1979	N/A
B-54	Observation	Observation	210 ft	1979	N/A
D-268	Culebra	Rancher’s Water Well	1411 ft	1984	1999
DOE-1	Culebra	Culebra	4057 ft	1982	N/A
DOE-2	Culebra	Magenta	4325 ft	1984	N/A
ERDA-9	Culebra	Culebra	2886 ft	1976	N/A
H-1	Culebra/Magenta	Plugged	856 ft	1976	2001
H-2A	Culebra	Culebra	672 ft	1977	N/A
H-2B1	Magenta	Magenta	661 ft	1977	N/A

1

Table DATA-G-1. Monitoring Well Status — Continued

Well Name	CCA Monitoring Status	CRA Monitoring Status	Depth	Year Drilled	Year Plugged
H-2B2	Culebra	Culebra	660 ft	1984	N/A
H-2C	Magenta	Culebra	795 ft	1977	N/A
H-3B1	Magenta	Magenta	902 ft	1976	N/A
H-3B2	Culebra	Culebra	725 ft	1983	N/A
H-3B3	Magenta	Culebra	730 ft	1983	N/A
H-3D	Dewey Lake	Dewey Lake	554 ft	1987	N/A
H-4A	not in use	Plugged	532 ft	1978	2000
H-4B	Culebra	Culebra	529 ft	1978	N/A
H-4C	Magenta	Magenta	661 ft	1978	N/A
H-5A	Culebra	Culebra	930 ft	1978	N/A
H-5B	Culebra	Culebra	925 ft	1978	N/A
H-5C	Magenta	Magenta	1076 ft	1978	N/A
H-6A	Culebra	Culebra	637 ft	1978	N/A
H-6B	Culebra	Culebra	640 ft	1978	N/A
H-6C	Culebra	Culebra	741 ft	1978	N/A
H-7A	not in use	Plugged	154 ft	1979	2000
H-7B1	Culebra	Culebra	286 ft	1979	N/A
H-7B2	Culebra	Culebra	295 ft	1983	N/A
H-7C	not in use	not in use	420 ft	1979	N/A
H-8A	Magenta	Magenta	505 ft	1979	N/A
H-8B	not in use	Rancher’s Water Well	624 ft	1979	1987
H-8C	Rustler	Rustler	808 ft	1979	N/A
H-9A	Culebra	Plugged	692 ft	1979	2002
H-9B	Culebra	Culebra	708 ft	1979	N/A
H-9C	Culebra	Magenta	816 ft	1979	N/A
H-10A	Magenta	Magenta	1318 ft	1979	N/A
H-10B	Magenta	Plugged	1398 ft	1979	2002
H-10C	not in use	Culebra	1550 ft	1979	N/A
H-11B1	Culebra	Culebra	785 ft	1983	N/A
H-11B2	Culebra	Magenta	776 ft	1983	N/A
H-11B3	Culebra	Plugged	789 ft	1983	2002
H-11B4	not in use	Culebra	765 ft	1988	N/A
H-12	Culebra	Culebra	1001 ft	1983	N/A
H-14	Culebra	Magenta	589 ft	1986	N/A
H-15	Culebra	Magenta	900 ft	1986	N/A
H-16	Dewey Lake	not in use	851 ft	1987	N/A

Table DATA-G-1. Monitoring Well Status — Continued

Well Name	CCA Monitoring Status	CRA Monitoring Status	Depth	Year Drilled	Year Plugged
H-17	Culebra	Culebra	880 ft	1987	N/A
H-18	Culebra	Magenta	840 ft	1987	N/A
H-19B0	not in use	Culebra	779 ft	1995	N/A
H-19B2	not in use	Culebra	785 ft	1995	N/A
H-19B3	not in use	Culebra	785 ft	1995	N/A
H-19B4	not in use	Culebra	782 ft	1995	N/A
H-19B5	not in use	Culebra	786 ft	1995	N/A
H-19B6	not in use	Culebra	788 ft	1995	N/A
H-19B7	not in use	Culebra	785 ft	1995	N/A
P-14	Culebra	Plugged	1545 ft	1976	1999
P-15	Culebra	Plugged	1465 ft	1976	2002
P-17	Culebra	Culebra	1660 ft	1976	N/A
P-18	Culebra	Plugged	1998 ft	1976	2002
WIPP-12	Culebra	Culebra	3928 ft	1978	N/A
WIPP-13	Culebra	Culebra	3856 ft	1978	N/A
WIPP -18	Culebra	Magenta	1060 ft	1978	N/A
WIPP-19	Culebra	Culebra	1038 ft	1978	N/A
WIPP-21	Culebra	Culebra	1045 ft	1978	N/A
WIPP-22	Culebra	Culebra	1450 ft	1978	N/A
WIPP-25	Culebra/Magenta	Culebra/Magenta	650 ft	1978	N/A
WIPP-26	Culebra	Culebra	503 ft	1978	N/A
WIPP-27	Culebra/Magenta	Culebra	592 ft	1978	N/A
WIPP-28	Rustler	Plugged	801 ft	1978	1999
WIPP-29	Culebra	Culebra	377 ft	1978	N/A
WIPP-30	Culebra/Magenta	Culebra/Magenta	913 ft	1978	N/A
WQSP-1	Culebra	Culebra	737 ft	1994	N/A
WQSP-2	Culebra	Culebra	846 ft	1994	N/A
WQSP-3	Culebra	Culebra	879 ft	1994	N/A
WQSP-4	Culebra	Culebra	800 ft	1994	N/A
WQSP-5	Culebra	Culebra	681 ft	1994	N/A
WQSP-6	Culebra	Culebra	617 ft	1994	N/A
WQSP-6A	Dewey Lake	Dewey Lake	225 ft	1994	N/A
Wells Inadvertently Omitted From Appendix BH of the CCA					
CB-1	Culebra	Culebra/Bell Canyon	4291 ft	1974	N/A
D-207	Potash/plugged	Plugged	1613 ft	1958	1958
H-19B	Not in Use/Capped	not in use/capped	40 ft	1995	N/A
H-19B1	plugged	Plugged	733 ft	1995	1995

Table DATA-G-1. Monitoring Well Status — Continued

Well Name	CCA Monitoring Status	CRA Monitoring Status	Depth	Year Drilled	Year Plugged
I-457	Potash/plugged	Plugged	1885 ft	1976	1976
New Monitoring Wells Drilled During the First CRA Time Period					
C-2505	N/A	Santa Rosa/Dewey Lake	97 ft	1996	N/A
C-2506	N/A	Santa Rosa/Dewey Lake	69 ft	1996	N/A
C-2507	N/A	Santa Rosa/Dewey Lake	73 ft	1996	N/A
C-2737	N/A	Culebra/Magenta	710 ft	2001	N/A
C-2811	N/A	Santa Rosa/Dewey Lake	80 ft	2001	N/A
ES-001	N/A	Plugged	54 ft	1996	1996
ES-002	N/A	Plugged	19 ft	1996	1996
PZ-1	N/A	Santa Rosa	68 ft	1997	N/A
PZ-2	N/A	Santa Rosa	65 ft	1997	N/A
PZ-3	N/A	Santa Rosa	71 ft	1997	N/A
PZ-4	N/A	Santa Rosa	65 ft	1997	N/A
PZ-5	N/A	Santa Rosa	72 ft	1997	N/A
PZ-6	N/A	Santa Rosa	66 ft	1997	N/A
PZ-7	N/A	Santa Rosa	72 ft	1997	N/A
PZ-8	N/A	Santa Rosa	68 ft	1997	N/A
PZ-9	N/A	Santa Rosa	82 ft	1997	N/A
PZ-10	N/A	Santa Rosa	57 ft	1997	N/A
PZ-11	N/A	Santa Rosa	82 ft	1997	N/A
PZ-12	N/A	Santa Rosa	72 ft	1997	N/A

Individual Well Reports

This section provides data on the plugged wells and the new wells drilled during the CRA monitoring period (July 1995 through September 2002).

C-2505

Location: T22S-R31E-20 Spud Date: 09/23/1996 Total Depth: 97 ft
Status: Monitoring Well Completed: 09/24/1996 Elevation: 3413 ft
Hole Size: 0-97 ft = 7 7/8" Stratigraphy: 0-9 = Holocene Deposits
Casing Size: 0-65 ft = 4 ½" PVC 9-12 = Mescalero Caliche Formation
12-49 = Gatuña Formation
49-54 = Santa Rosa Formation Sandstone
54-65 = Dewey Lake Formation Redbeds

C-2506

Location: T22S-R31E-20 Spud Date: 09/25/1996 Total Depth: 69 ft
Status: Monitoring Well Completed: 09/25/1996 Elevation: 3413 ft
Hole Size: 0-69 ft = 7 7/8" Stratigraphy: 0-10 = Holocene Deposits
Casing Size: 0-65 ft = 4 ½" PVC 10-48 = Gatuña Formation
48-54 = Santa Rosa Formation Sandstone
54-65 = Dewey Lake Formation Redbeds

C-2507

Location: T22S-R31E-20 Spud Date: 10/01/1996 Total Depth: 73 ft
Status: Monitoring Well Completed: 10/02/1996 Elevation: 3410 ft
Hole Size: 0-73 ft = 7 7/8" Stratigraphy: 0-10 = Holocene Deposits
Casing Size: 0-69 ft = 4 ½" PVC 10-40 = Gatuña Formation
40-54 = Santa Rosa Formation Sandstone
54-69 = Dewey Lake Formation Redbeds

C-2737

Location: T22S-R31E-29 Spud Date: 02/14/2001 Total Depth: 710 ft
Status: Monitoring Well Completed: 03/09/2001 Elevation: 3397 ft
Hole Size: 0-710 ft = 12 ¼" Stratigraphy: 35-40 = Santa Rosa Formation Sandstone
Casing Size: 0-700 ft = 7" Fiberglass 40-505 = Dewey Lake Formation Redbeds
505-561 = Forty-niner Member
561-584 = Magenta Dolomite Member
584-675 = Tamarisk Member
675-698 = Culebra Dolomite Member
698-710 = Los Medaños Member

C-2811

Location: T22S-R31E-29 Spud Date: 03/12/2001 Total Depth: 80 ft
Status: Monitoring Well Completed: 03/12/2001 Elevation: 3399 ft
Hole Size: No Report Stratigraphy: 0-10 = Holocene Deposits
Casing Size: 0-80 ft = 2" PVC 10-48 = Gatuña Formation
48-54 = Santa Rosa Formation Sandstone
54-65 = Dewey Lake Formation Redbeds

CB-1

Location: T23S-R31E-05 Spud Date: 05/31/1974 Total Depth: 4299 ft
Status: Monitoring Well Completed: 02/08/1975 Elevation: 3320 ft
Casing Size: 0-650 ft = 13 3/8"
Notes: Originally drilled as a hydrocarbon exploration well. Before the operator plugged and abandoned the well, it was turned over to DOE to be utilized as a monitoring well. Currently used to monitor the Culebra Dolomite Member and Bell Canyon Formation.

D-207
Location: T22S-R31E-19 Spud Date: 06/15/1958 Total Depth: 1613 ft
Status: Plugged Completed: 07/03/1958 Elevation: No Report
Plug Date: 07/03/1958
Notes: Potash core hole located on the Land Withdrawal Area. Hole was filled with cement and brine water from total depth to 560 ft. From that depth to the surface, it was filled with cuttings and soil.

D-268
Location: T22S-R30E-35 Spud Date: 07/10/1984 Total Depth: 1411 ft
Status: Rancher's Water Well Completed: 07/26/1984 Elevation: No Report
Hole Size: No Report Stratigraphy: No Report
Casing Size: 0-528 ft = 8 5/8"
Notes: Originally drilled as a potash core test, it was converted to a monitoring well in 1988. Plugged back to 493 ft and converted to a water well for livestock use in 1999. Ownership transferred.

ES-001
Location: T22S-R31E-20 Spud Date: 10/02/1996 Total Depth: 54 ft
Status: Plugged Completed: 10/02/1996 Elevation: 3413 ft
Plug Date: 10/02/1996
Notes: Backfilled to land surface. Drill cuttings and bentonite gel used to plug well.

ES-002
Location: T22S-R31E-20 Spud Date: 10/03/1996 Total Depth: 19 ft
Status: Plugged Completed: 10/03/1996 Elevation: 3413 ft
Plug Date: 10/03/1996
Notes: Backfilled to land surface with drill cuttings and bentonite gel used to plug well.

H-1
Location: T22S-R31E-29 Spud Date: 05/20/1976 Total Depth: 856 ft
Status: Plugged Completed: 06/10/1976 Elevation: 3400 ft
Plug Date: 02/19/2001
Casing Size: 0-848 ft = 7"
Notes: Plugged to surface with cement.

H-4A
Location: T22S-R31E-05 Spud Date: 04/30/1978 Total Depth: 532 ft
Status: Plugged Completed: 05/23/1978 Elevation: 3333 ft
Plug Date: 10/25/2000
Casing Size: 0-364 ft = 5 1/2"
Notes: Plugged to surface with cement.

H-7A
Location: T23S-R30E-14 Spud Date: 09/18/1979 Total Depth: 154 ft
Status: Plugged Completed: 10/18/1979 Elevation: 3164 ft
Plug Date: 06/23/2000
Casing Size: 0-109 ft = 7"
Notes: Plugged to surface with cement.

H-8B
Location: T24S-R30E-23 Spud Date: 08/06/1979 Total Depth: 624 ft
Status: Rancher's Water Well Completed: 08/12/1979 Elevation: 3434 ft
Casing Size: 0-574 ft = 7"
Notes: Turned over to rancher for livestock use in 1987.

H-9A
Location: T24S-R31E-04 Spud Date: 07/09/1979 Total Depth: 692 ft
Status: Plugged Completed: 09/05/1979 Elevation: 3407 ft
Plug Date: 02/11/2002
Casing Size: 0-570 ft = 7"
Notes: Plugged to surface with cement.

H-10B
Location: T23S-R32E-20 Spud Date: 10/07/1979 Total Depth: 1398 ft
Status: Plugged Completed: 10/13/1979 Elevation: 3689 ft
Plug Date: 01/31/2002
Casing Size: 0-1346 ft = 7"
Notes: Well bore was plugged with cement from the bottom to the surface.

H-11B3
Location: T22S-R31E-33 Spud Date: 12/01/1983 Total Depth: 789 ft
Status: Plugged Completed: 01/04/1984 Elevation: 3412 ft
Plug Date: 08/28/2002
Casing Size: 0-733 ft = 5 1/2"
Notes: Well was plugged with cement from the bottom to the surface.

H-19B
Location: T22S-R31E-28 Spud Date: xx/xx/1995 Total Depth: 40 ft
Status: Capped Completed: xx/xx/1995 Elevation: 3417 ft
Casing Size: 0-38 ft = 20"
Notes: Cap welded on surface casing.

H-19B1
Location: T22S-R31E-28 Spud Date: 02/14/1995 Total Depth: 733 ft
Status: Plugged Completed: 03/19/1995 Elevation: 3417 ft
Plug Date: 03/19/1995
Notes: Well was plugged and abandoned because drilling tools stuck in the hole were not retrievable.

I-457
Location: T22S-R31E-27 Spud Date: 07/08/1976 Total Depth: 1885 ft
Status: Plugged Completed: 07/22/1976 Elevation: 3460 ft
Plug Date: 07/22/1976
Notes: Potash core hole, plugged with cement and all casings recovered.

P-14
Location: T22S-R30E-24 Spud Date: 09/24/1976 Total Depth: 1545 ft
Status: Plugged Completed: 10/04/1976 Elevation: 3358 ft
Plug Date: 08/26/1999
Casing Size: 0-775 ft = 4 1/2"
Notes: Hole was plugged back from 1545 ft to 775 ft with cement and converted to monitoring well in 1979. Plugged in 1999 with 200 ft^3 of cement from 775 ft to the surface.

P-15
Location: T22S-R31E-31 Spud Date: 10/04/1976 Total Depth: 1465 ft
Status: Plugged Completed: 10/15/1976 Elevation: 3310 ft
Plug Date: 02/11/2002
Casing Size: 0-635 ft = 4 1/2"
Notes: In 1977, well was plugged back to 620 ft. and converted to monitoring well. Plugged in 2002 with cement from the bottom to the surface, leaving 210 ft of casing in hole.

P-18
Location: T22S-R31E-26 Spud Date: 10/19/1976 Total Depth: 1998 ft
Status: Plugged Completed: 11/06/1976 Elevation: 3479 ft
Plug Date: 02/28/2002
Casing Size: 0-1138 ft = 4 1/2"
Notes: Converted to monitoring well in 1977 by plugging back well to 1125 ft. Abandoned and plugged in 2002 with cement from the well bottom to the surface.

PZ-1
Location: T22S-R31E-20 Spud Date: 06/23/1997 Total Depth: 68 ft
Status: Monitoring Well Completed: 07/10/1997 Elevation: 3413 ft
Hole Size: 0-68 ft = 6 5/8" Stratigraphy: 40-56 = Santa Rosa Sandstone
Casing Size: 0-62 ft = 2" PVC 56-68 = Dewey Lake Redbeds

PZ-2

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 65 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3413 ft
Hole Size: 0-65 ft = 6 5/8" | Stratigraphy: 0-9 = Holocene Deposits
Casing Size: 0-62 ft = 2" PVC | 9-12 = Mescalero Caliche Formation
12-39 = Gatuña Formation
39-57 = Santa Rosa Formation Sandstone
57-65 = Dewey Lake Formation Redbeds

PZ-3

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 71 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3416 ft
Hole Size: 0-71 ft = 6 5/8" | Stratigraphy: 0-8 = Holocene Deposits
Casing Size: 0-65 ft = 2" PVC | 8-10 = Mescalero Caliche Formation
10-38 = Gatuña Formation
38-63 = Santa Rosa Formation Sandstone
63-71 = Dewey Lake Formation Redbeds

PZ-4

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 65 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3412 ft
Hole Size: 0-65 ft = 6 5/8" | Stratigraphy: 0-9 = Holocene Deposits
Casing Size: 0-60 ft = 2" PVC | 9-12 = Mescalero Caliche Formation
12-31 = Gatuña Formation
31-57 = Santa Rosa Formation Sandstone
57-65 = Dewey Lake Formation Redbeds

PZ-5

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 72 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3415 ft
Hole Size: 0-72 ft = 6 5/8" | Stratigraphy: 0-7 = Holocene Deposits
Casing Size: 0-65 ft = 2" PVC | 7-9 = Mescalero Caliche Formation
9-36 = Gatuña Formation
36-63 = Santa Rosa Formation Sandstone
63-72 = Dewey Lake Formation Redbeds

PZ-6

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 66 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3413 ft
Hole Size: 0-66 ft = 6 5/8" | Stratigraphy: 0-7 = Holocene Deposits
Casing Size: 0-62 ft = 2" PVC | 7-9 = Mescalero Caliche Formation
9-32 = Gatuña Formation
32-55 = Santa Rosa Formation Sandstone
55-66 = Dewey Lake Formation Redbeds

PZ-7

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 72 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3414 ft
Hole Size: 0-72 ft = 6 5/8" | Stratigraphy: 0-8 = Holocene Deposits
Casing Size: 0-71 ft = 2" PVC | 8-10 = Mescalero Caliche Formation
10-30 = Gatuña Formation
30-69 = Santa Rosa Formation Sandstone
69-72 = Dewey Lake Formation Redbeds

PZ-8

Location: T22S-R31E-21 | Spud Date: 06/23/1997 | Total Depth: 68 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3418 ft
Hole Size: 0-68 ft = 6 5/8" | Stratigraphy: 0-7 = Holocene Deposits
Casing Size: 0-68 ft = 2" PVC | 7-9 = Mescalero Caliche Formation
9-31 = Gatuña Formation
31-60 = Santa Rosa Formation Sandstone
60-68 = Dewey Lake Formation Redbeds

PZ-9

Location: T22S-R31E-21 | Spud Date: 06/23/1997 | Total Depth: 82 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3421 ft
Hole Size: 0-82 ft = 6 5/8" | Stratigraphy: 0-8 = Holocene Deposits
Casing Size: 0-75 ft = 2" PVC | 8-11 = Mescalero Caliche Formation
11-36 = Gatuña Formation
36-75 = Santa Rosa Formation Sandstone
75-82 = Dewey Lake Formation Redbeds

PZ-10

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 57 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3406 ft
Hole Size: 0-57 ft = 6 5/8" | Stratigraphy: 0-6 = Holocene Deposits
Casing Size: 0-54 ft = 2" PVC | 6-9 = Mescalero Caliche Formation
9-28 = Gatuña Formation
28-46 = Santa Rosa Formation Sandstone
46-57 = Dewey Lake Formation Redbeds

PZ-11

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 82 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3419 ft
Hole Size: 0-82 ft = 6 5/8" | Stratigraphy: 0-10 = Holocene Deposits
Casing Size: 0-71 ft = 2" PVC | 10-13 = Mescalero Caliche Formation
13-34 = Gatuña Formation
34-71 = Santa Rosa Formation Sandstone
71-82 = Dewey Lake Formation Redbeds

PZ-12

Location: T22S-R31E-20 | Spud Date: 06/23/1997 | Total Depth: 72 ft
Status: Monitoring Well | Completed: 07/10/1997 | Elevation: 3409 ft
Hole Size: 0-72 ft = 6 5/8" | Stratigraphy: 0-6 = Holocene Deposits
Casing Size: 0-64 ft = 2" PVC | 6-8 = Mescalero Caliche Formation
8-39 = Gatuña Formation
39-62 = Santa Rosa Formation Sandstone
62-72 = Dewey Lake Formation Redbeds

WIPP-28

Location: T21S-R31E-18 | Spud Date: 08/07/1978 | Total Depth: 801 ft
Status: Plugged | Completed: 08/28/1978 | Elevation: 3349 ft
Plug Date: 11/29/1999
Notes: All casing was removed and hole was plugged with cement.

APPENDIX DATA

ATTACHMENT H: WIPP WASTE CONTAINERS AND EMPLACEMENT

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DATA-H-1.0 AUTHORIZED WASTE EMPLACEMENT CONTAINERS

DATA-H-1.1 Container Descriptions

The Compliance Certification Application (CCA) to the Environmental Protection Agency (EPA) identified the following containers as outer containment vessels for waste emplacement in the repository:

- 208-L (55-g) Drum
- 322-L (85-g) Drum (Short)
- 322-L (85-g) Drum (Tall)
- 379-L (100-g) Drum
- Standard Waste Box (SWB)
- 10-Drum Overpack (TDOP)
- RH-TRU Waste Canister

DATA-H-1.2 Dunnage Containers

Dunnage containers are empty containers used to complete a shipping configuration, such as the seven-pack, if too few containers are available that meet transportation requirements. Dunnage containers must clearly be marked “Empty.” The TDOP and the RH-TRU Waste Canister are not used as dunnage containers for shipping purposes. For emplacement purposes in the repository, the 208-, 322-, and 379-L (55-, 85-, and 100-g) drums can be used as dunnage containers and only if they arrive in a shrink-wrapped package assembly such as the seven-pack, four-pack, or three-pack. To date, only 208-L (55-g) drums have been emplaced in the repository as dunnage containers.

The 208-L (55-g) drum is shipped in a seven-pack configuration and is normally emplaced in the repository in the same configuration, but can be emplaced as an individual unit should the need arise. A single drum can be used for collecting and storing site-derived waste. An illustration of the 55-gallon drum components and emplacement configuration are provided in Figure DATA-H-1. The drum's specifications are provided in Table DATA-H-1.

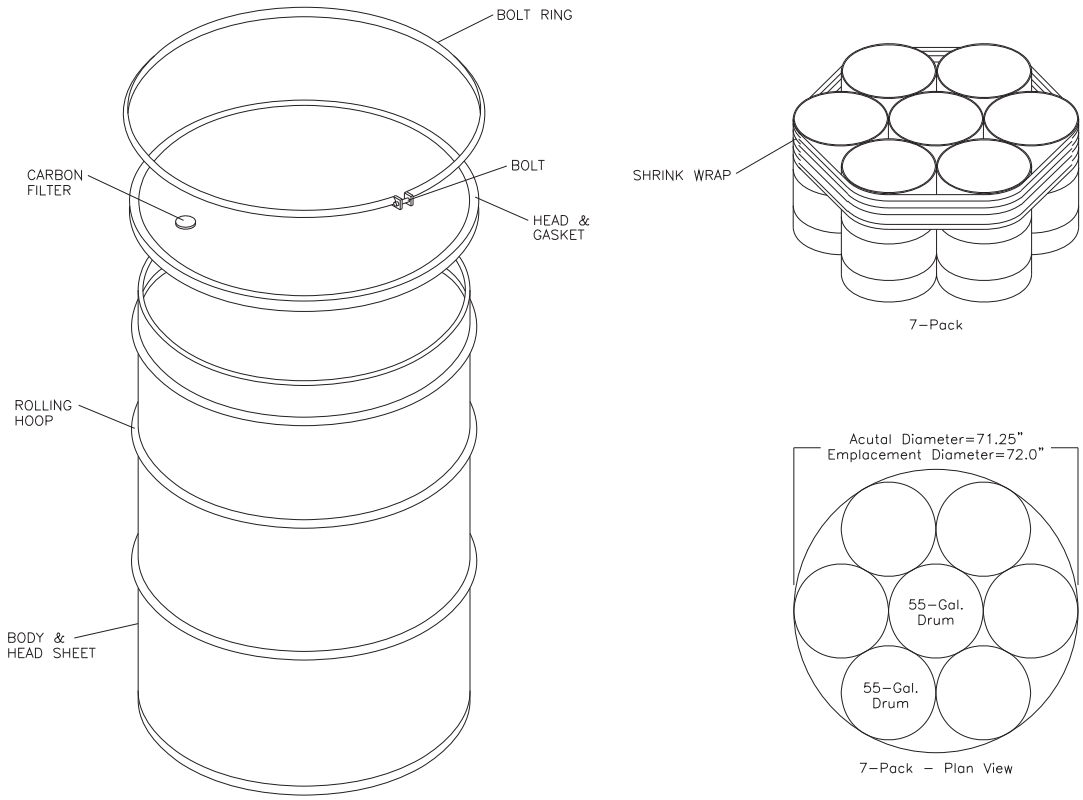

Figure DATA-H-1. 55-Gallon Drum Components and Emplacement Configuration.

Table DATA-H-1. 55-Gallon Drum Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	32 ⅝	34 ¼	830	870	Gallons	55
Diameter	22 ½	23 ¾	572	603	Liters	208
					Cubic Feet	7.35
					Cubic Meters	0.208

The 322-L (85-g) drum is shipped in a four-pack configuration and will be emplaced in the repository in the same configuration but can be emplaced as an individual unit should the need arise. A single drum can be used for collecting and storing site-derived waste. An illustration of the 85-gallon drum (short) components and emplacement configuration are provided in Figure DATA-H-2. The drum's specifications are provided in Table DATA-H-2.

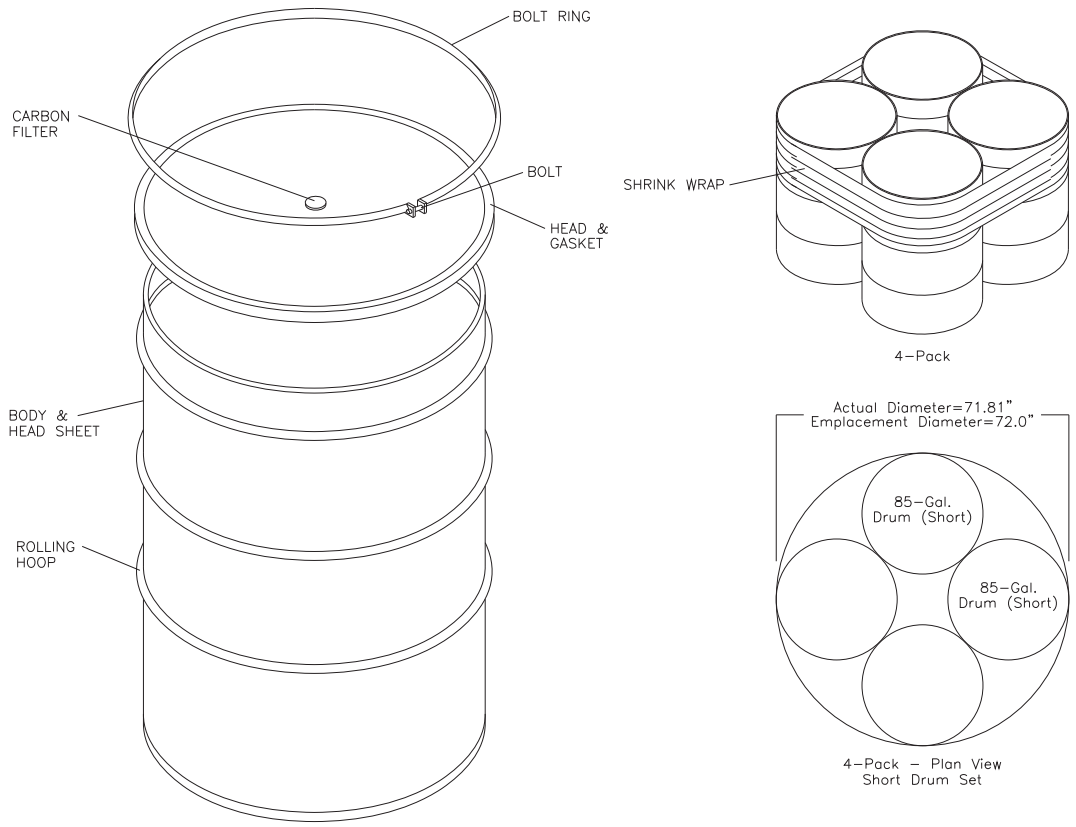

Figure DATA-H-2. 85-Gallon Drum (Short) Components and Emplacement Configuration.

Table DATA-H-2. 85-Gallon Drum (Short) Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	33 ¼	35	845	889	Gallons	85
Diameter	27 ⅛	29 ¾	689	756	Liters	322
					Cubic Feet	11.3
					Cubic Meters	0.32

The 322-L (85-g) drum is shipped in a four-pack configuration and will be emplaced in the repository in the same configuration. It is also used for overpacking 208-L (55-g) drums that are individually emplaced in the repository. A single drum can be used for collecting and storing site-derived waste. An illustration of the 85-gallon drum (tall) components and emplacement configuration are provided in Figure DATA-H-3. The drum's specifications are provided in Table DATA-H-3.

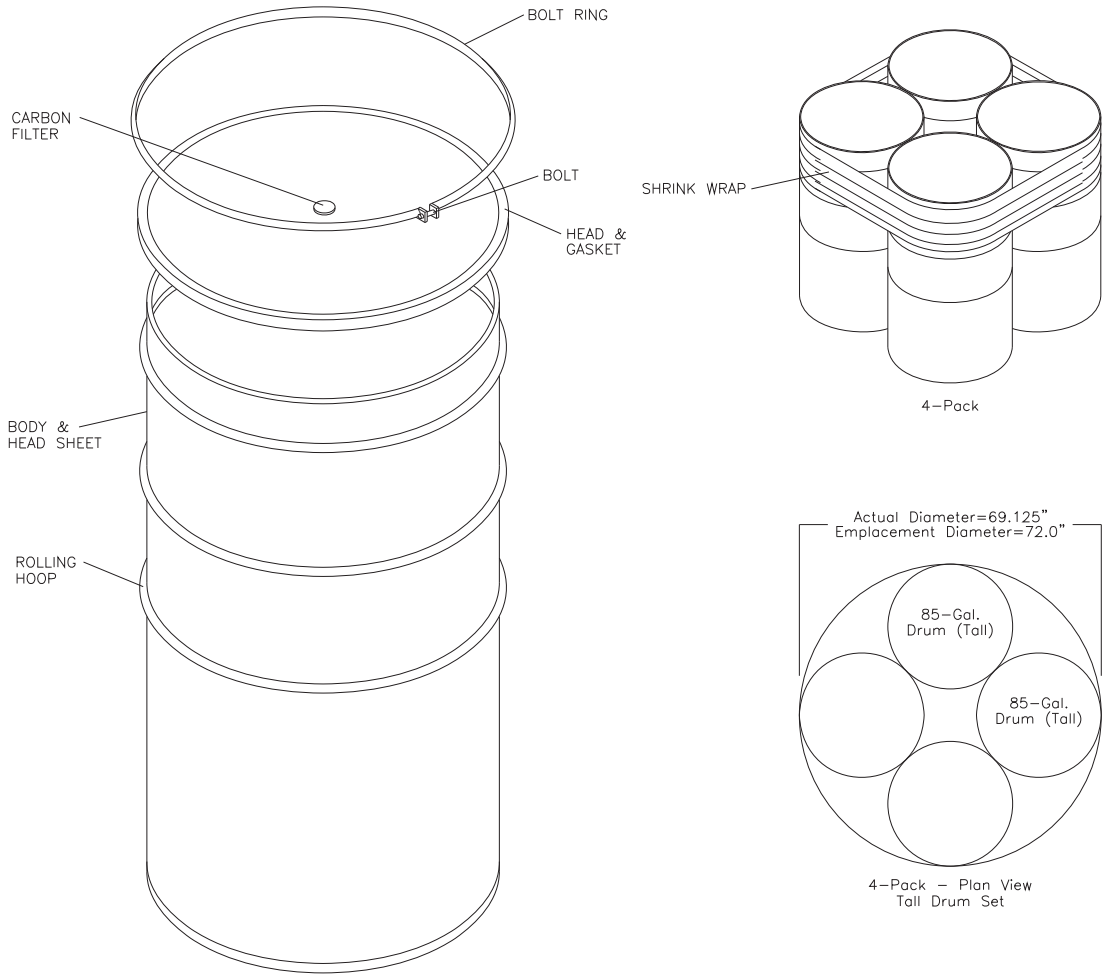

Figure DATA-H-3. 85-Gallon Drum (Tall) Components and Emplacement Configuration.

Table DATA-H-3. 85-Gallon Drum (Tall) Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	38 ¼	40 ¼	972	1,022	Gallons	85
Diameter	26	28 ⅝	660	728	Liters	322
					Cubic Feet	11.3
					Cubic Meters	0.32

The 379-L (100-g) drum is shipped in a three-pack configuration and will be emplaced in the repository in the same configuration. The 379-L (100-g) drum can be emplaced as an individual unit should the need arise. An illustration of the 100-gallon drum components and emplacement configuration are provided in Figure DATA-H-4. The drum's specifications are provided in Table DATA-H-4.

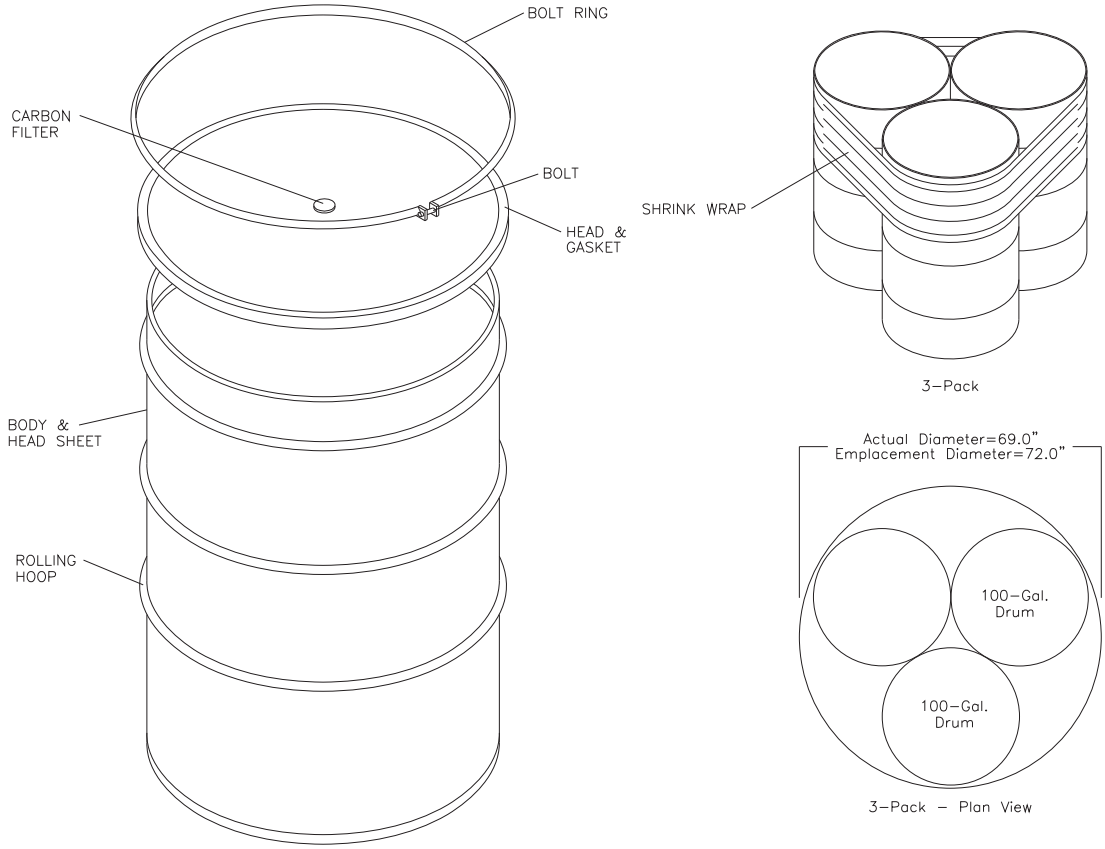

Figure DATA-H-4. 100-Gallon Drum Components and Emplacement Configuration.

Table DATA-H-4. 100-Gallon Drum Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	33	35	838	889	Gallons	100
Diameter	30	32	762	813	Liters	379
					Cubic Feet	13.4
					Cubic Meters	0.38

The SWB is shipped and emplaced as an individual unit. Normally, two SWBs are shipped in a TRUPACT-II shipping container. An illustration of the SWB is provided in Figure DATA-H-5. The box's specifications are provided in Table DATA-H-5.

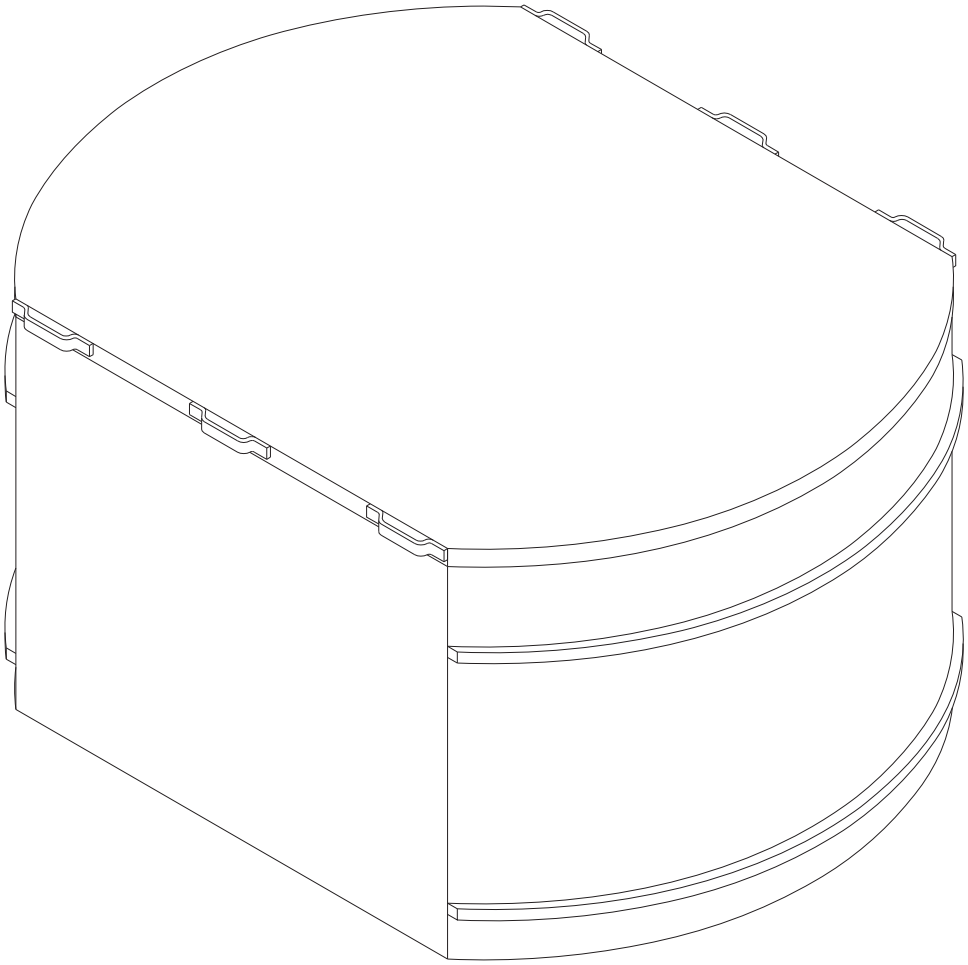

Figure DATA-H-5. Illustration of a Standard Waste Box.

Table DATA-H-5. SWB Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	36 ¾	37	933	940	Gallons	496
Length	68 ¾	71	1,746	1,803	Liters	1,877
Width	51 ⅞	54	1,318	1,372	Cubic Feet	66.3
					Cubic Meters	1.88

The TDOP is shipped as an individual unit and emplaced as an individual unit. An illustration of the TDOP's components is provided in Figure DATA-H-6. The overpack's specifications are provided in Table DATA-H-6.

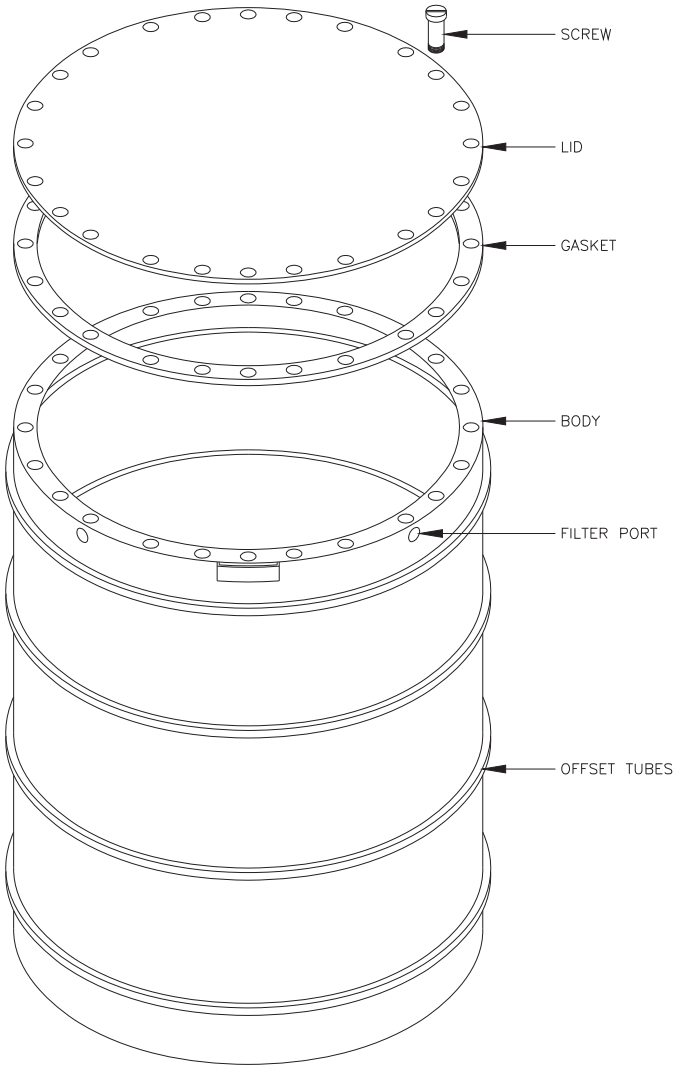

Figure DATA-H-6. TDOP Components.

Table DATA-H-6. TDOP Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	70 ½	73	1791	1,854	Gallons	1,197
Diameter	71 ½	72	1,816	1,829	Liters	4,531
					Cubic Feet	160
					Cubic Meters	4.5

The RH-TRU Waste Canister is shipped as a single unit and emplaced as a single unit. Illustrations of the canister's components are provided in Figure DATA-H-7. The canister's specifications are provided in Table DATA-H-7.

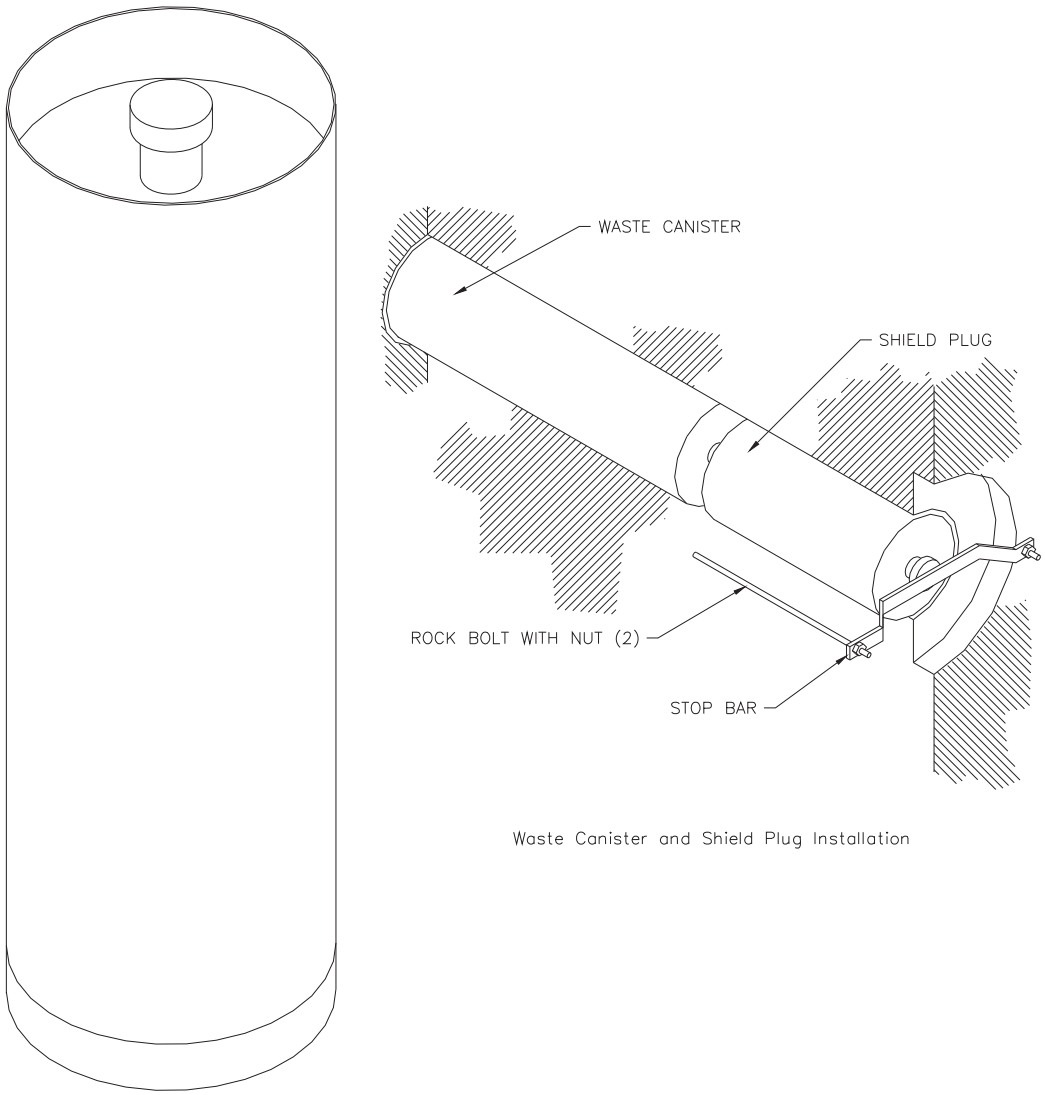

Figure DATA-H-7. RH-TRU Waste Canister Components.

Table DATA-H-7. RH-TRU Waste Canister Specifications

Dimension	Approximate Measurement				Approximate Volume	
	I.D. (inches)	O.D. (inches)	I.D. (mm)	O.D. (mm)		
Height	108	121	2,743	3,073	Gallons	235
Diameter	25 ½	26	648	660	Liters	890
					Cubic Feet	31.44
					Cubic Meters	0.89

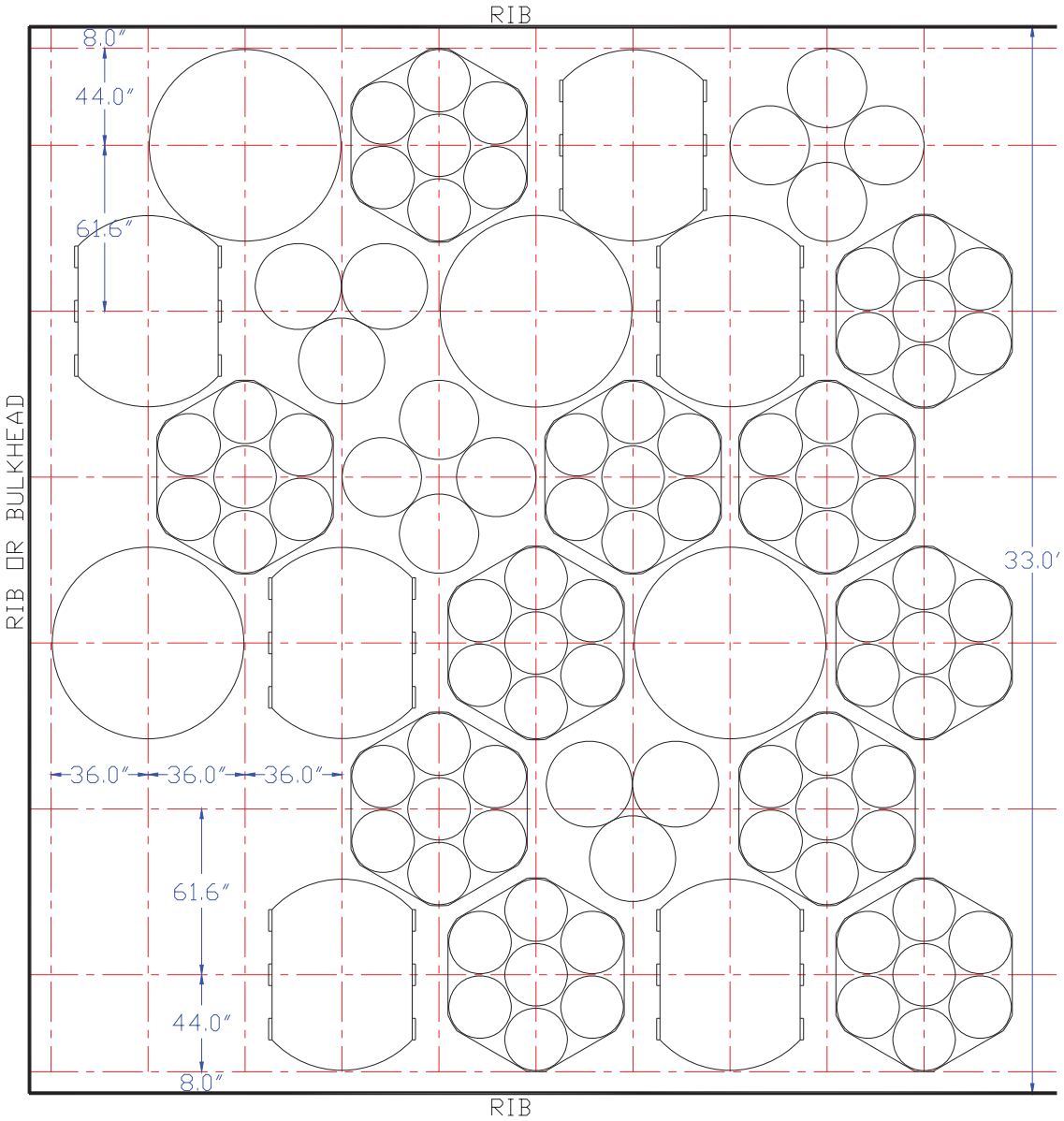

Figure DATA-H-8. CH-TRU Waste Emplacement Layout.

Shown above in Figure DATA-H-8 is the typical position for waste emplacement containers in a room of a panel. TDOPs are only emplaced on the bottom position with another assembly stacked on top. All of the other assemblies can be stacked three high before the MgO supersack is emplaced on the top of the stack. CH-TRU waste emplacement within the repository panels is shown in Figure DATA-H-9. The planned RH-TRU waste emplacement is shown in Figure DATA-H-10.

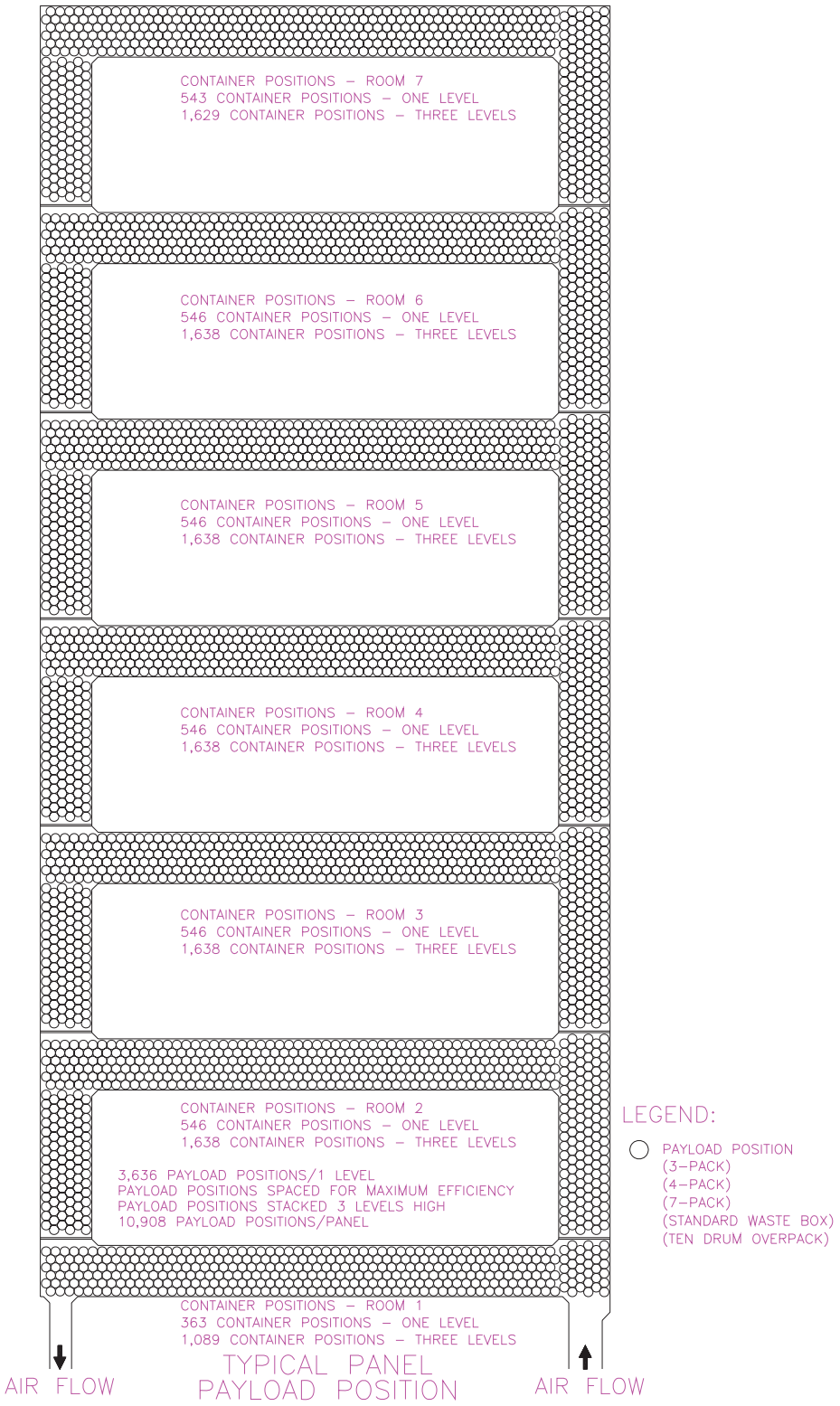

Figure DATA-H-9. CH-TRU Waste Emplacement.

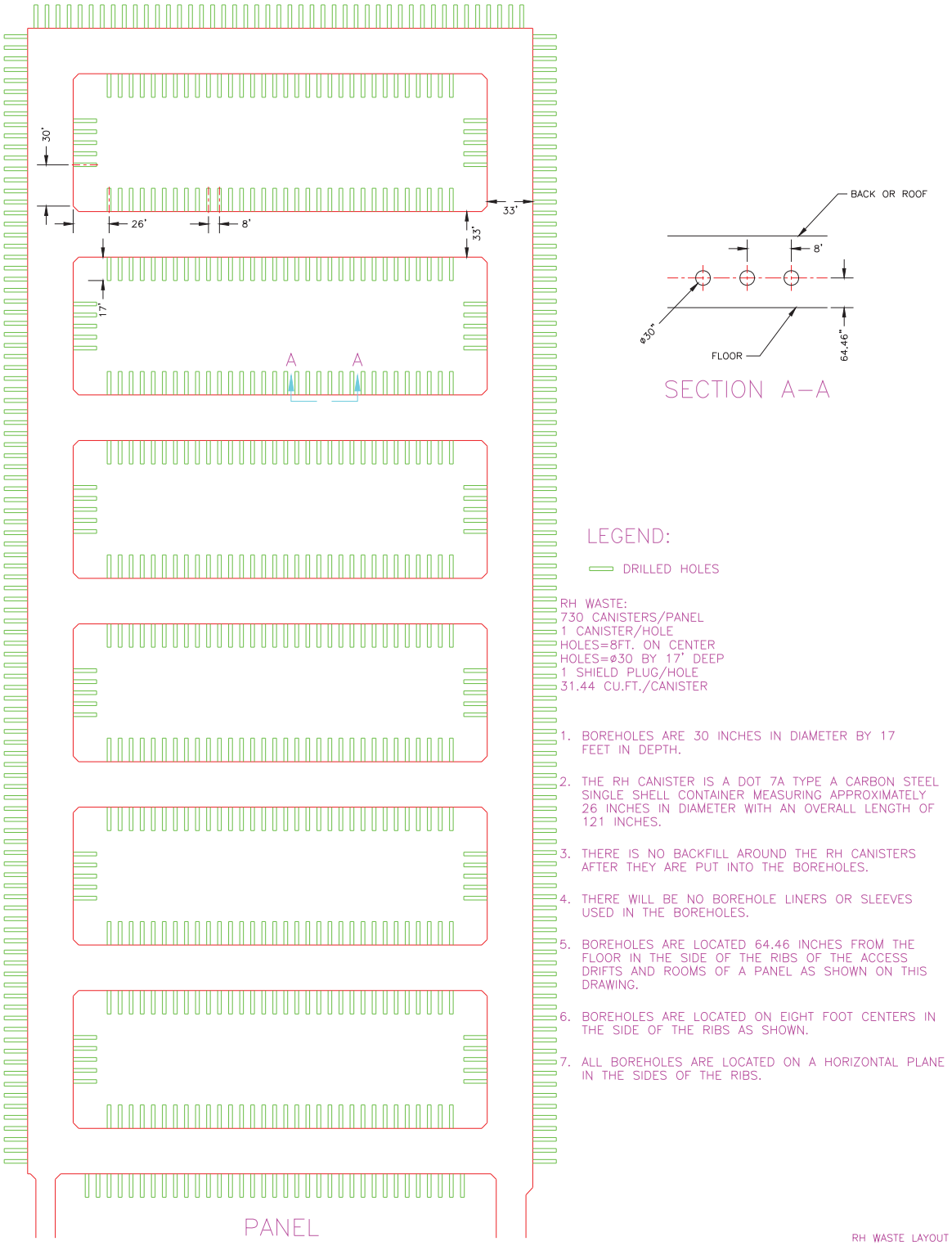

Figure DATA-H-10. Planned RH-TRU Waste Emplacement.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix MON 2004

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Preclosure and Postclosure Compliance Monitoring

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ACRONYMS AND ABBREVIATIONS

ACR	Annual Charge Report
ASER	Annual Site Environmental Report
CARD	Compliance Application Review Document
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CMP	Compliance Monitoring Program
COMPs	Compliance Monitoring Parameters
CRA	Compliance Recertification Application
DBDSP	Delaware Basin Drilling Surveillance Program
DOE	Department of Energy
DRZ	disturbed rock zone
EPA	Environmental Protection Agency
FEP	feature, event, or process
GWMP	Groundwater Monitoring Program
M&OC	Management and Operating Contractor
M&TE	measuring and test equipment
PA	performance assessment
QA	Quality Assurance
QAPD	Quality Assurance Program Document
SA	Scientific Advisor
SMP	Subsidence Monitoring Program
SNL	Sandia National Laboratory
WIPP	Waste Isolation Pilot Plant
WQSP	Water Quality Sampling Program
WWIS	WIPP Waste Information System

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MON-1.0 INTRODUCTION

This Appendix to the Compliance Recertification Application (CRA) is a new document and it replaces the October 1996, version submitted with the Compliance Certification Application (CCA) (DOE 1996). This appendix describes a specific monitoring program that was developed to meet commitments contained in the DOE's application to the Environmental Protection Agency (EPA) which demonstrated compliance with radioactive waste disposal regulations 40 CFR 191 Subparts B and C and 40 CFR Part 194. This appendix does not address monitoring activities intended to demonstrate compliance with 40 CFR Part 191 Subpart A. The monitoring activities described are performed as assurance measures to ensure that deviations from the expected long-term radioactive containment performance of the repository are identified at the earliest possible time. The EPA requires a monitoring program to detect substantial deviations from expected performance. This program is to consist of a preclosure and postclosure monitoring program that uses monitoring techniques that do not jeopardize the isolation of the waste and must be conducted until there are no significant concerns to be addressed by further monitoring. The long-term performance expectations for the disposal system are to be derived from conceptual models, scenarios, and assumptions developed for the Waste Isolation Pilot Plant (WIPP) performance assessment (PA).

On January 3, 2002, the DOE Carlsbad Field Office (CBFO) submitted a letter to the EPA. This letter requested EPA approval to delete CCA Appendices BECR, LMP, and VCMP from the compliance certification because they are not needed to demonstrate compliance with 40 CFR § 191.14(b). The letter also requested CCA Appendices SER and DEL be changed to references, Appendices EMP, GWMP, GTMP, SMP, and DMP be deleted, and that Appendix MON be rewritten to incorporate the portions of those plans required to demonstrate compliance with 40 CFR § 191.14(b) in accordance with the criteria established by 40 CFR § 194.42. The EPA approved these requests in a letter to CBFO on March 15, 2002.

The activities performed for the overall monitoring programs at WIPP comprehensively address the range of regulatory requirements at departmental, state, and federal levels. This appendix addresses those activities relevant to long-term monitoring of the disposal system. This document provides an overview of the Compliance Monitoring Program (CMP) and specifically describes how information and data are extracted from the various WIPP monitoring and sampling programs, how the compliance monitoring parameters are derived from the data, how the assessments are made against repository performance expectations, and how the results are reported to the EPA. The descriptions provided in this appendix are specific to the CMP and thus the requirements of 191.14(b) and 194.42.

MON-1.1 Compliance Monitoring Program

This appendix describes the compliance monitoring program for the WIPP. Compliance monitoring concentrates on the following areas:

- Geotechnical Engineering Program Plan,
- Groundwater Monitoring Program (GWMP),

- Delaware Basin Drilling Surveillance Program (DBDSP),
- Subsidence Monitoring Program (SMP), and
- WIPP Waste Tracking and Control.

The data and information collected since the issuance of the CCA for the above listed programs are recorded or referenced in Appendix DATA.

MON-1.2 Preclosure and Postclosure Monitoring

The requirements of 40 CFR § 191.14, 40 CFR § 194.42, and the initial EPA certification serve as the regulatory basis for compliance monitoring. These requirements specify that disposal systems be monitored after waste disposal to detect substantial deviation from expected disposal system performance.

MON-1.3 Monitoring Assessment

The DOE was required by 40 CFR § 194.42(a) to perform an analysis to determine effects of parameters on the performance of the disposal system and to use the results in preclosure and postclosure monitoring plans. The results identified 10 monitoring parameters, listed in Section 2.1 of this appendix, to be monitored and assessed within the CMP. The discussion of preclosure monitoring activities for these 10 parameters in this appendix includes the following:

- identifying activities required to comply with the monitoring requirements of the EPA's certification of compliance with 40 CFR Part 191 Subparts B and C during the preclosure phase of the project (more commonly referred to as the "operational" or "disposal" phase);
- identifying the organizations that generate the monitoring data, the organizations that convert the data to monitoring parameters and assess the results against expected results, and the organization that reports the results of the assessments to the EPA;
- identifying the compliance monitoring schedule; and
- providing an overview of quality assurance (QA) requirements applicable to the compliance monitoring program.

MON-1.4 Appendix Summary

Section 2.0 of this Appendix identifies the monitoring requirements of 40 CFR 191 Subparts B and C and 40 CFR 194. Section 3.0 describes the preclosure monitoring program associated with each monitoring parameter, the monitoring schedules, and program outputs. Section 4.0 describes the planned postclosure monitoring. Section 5.0 describes the QA requirements applicable to the Compliance Monitoring Program.

MON-2.0 COMPLIANCE MONITORING PROGRAM REQUIREMENTS

The DOE's preclosure CMP assesses the performance of specific aspects of the disposal system. The relevant monitoring requirements are identified in:

- 40 CFR § 191.14(b),
- 40 CFR § 194.42, and
- the EPA's initial certification of the WIPP (EPA 1998).

MON-2.1 Compliance Certification

The original approach used to develop the CMP was based on the results of the parameter analysis documented in CCA Chapter 7, and Appendix MON, Attachment MONPAR. The EPA documented its approval of the DOE monitoring approach in the compliance certification (EPA 1998) and Certification Application Review Document (CARD) Number 42 (EPA 1998a). The current CMP description is contained in Chapter 7, and this Appendix. Sandia National Laboratory (SNL) conducted an assessment of the CCA Attachment MONPAR and determined the original conclusions and monitoring parameters identified in MONPAR remain valid and unchanged (Wagner and Kirkes 2003). The EPA-approved monitoring approach recognizes that DOE will monitor 10 parameters. These parameters are:

1. creep closure and stresses,
2. extent of brittle deformation,
3. initiation of brittle deformation,
4. displacement of deformation features,
5. Culebra groundwater composition,
6. change in Culebra groundwater flow,
7. drilling rate,
8. probability of encountering a Castile brine reservoir,
9. subsidence, and
10. waste activity.

All of the above parameters are being monitored during the preclosure period.

The CCA describes DOE's plans for postclosure monitoring and this description has been brought forward as Attachment A. DOE will revisit this plan for postclosure monitoring before the end of facility operations, expected some 35 years in the future.

The 10 parameters listed are called "compliance monitoring parameters (COMPs)." As discussed previously, the DOE determined that during the WIPP certification activities, these parameters met regulatory requirements.

The data used to generate the 10 separate monitoring parameters of the CMP are generated by five separate monitoring programs (described in Sections 3.1 through 3.5). Each of the monitoring programs focuses on the collection of direct field measurements related to CCA requirements and other information relating to the site. Each program that generates or evaluates the data is described in Section 6.0. Results from each monitoring program are documented individually in annual reports (see Appendix DATA) while the results of the assessment of the 10 parameters are documented and reported annually in a compliance monitoring parameter assessment report which is provided annually to the EPA in the Annual Change Report (ACR). The monitoring parameters which have related PA parameters include:

- drilling rate,
- probability of encountering Castile brine,
- Culebra water-level,
- Culebra groundwater composition, and
- waste activity.

The other monitoring parameters are related to screening decisions for repository features, events or processes (FEPs). Table MON-1 provides a description of the related PA parameters and the major FEP screening decisions. The 10 monitoring parameters will be evaluated to determine if there is an impact on the PA-related parameters, conceptual models, or FEP screening decisions. All Scientific Advisor (SA) processes and procedures used in the parameter analysis and reporting are governed by their QA and document control procedures.

As stated earlier, if any of the data, parameters, or observations are not consistent with the CCA PA expectations, the SA again will report its evaluations and recommendations to the DOE. If needed, the CMP process will be modified to address concerns or recommendations identified by unexpected results.

Results from monitoring programs will be generated on an ongoing basis throughout the operational period of the repository. Compliance monitoring data are provided to the cognizant individuals and organizations within the project, evaluated for their significance, and evaluation results and data summaries are reported to the EPA on an annual basis. Section 6.0 describes the process of communicating and reporting CMP results and evaluations.

Table MON-1. Monitoring Parameters

Monitoring Parameter	Monitoring Program	Frequency of Data Collection and Reporting	Related Performance Assessment Parameter	Related FEPs Evaluation Cycle	Evaluation of Data
Creep Closure and Stresses	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data are reported annually.	Not directly related to a PA parameter. May provide a short-term (operational) observation of the geomechanical response of repository excavation. Can provide confidence in the creep closure model.	Salt creep, excavation-induced stress changes, changes in stress field, pressurization. Consolidation of waste/backfill.	Data from this monitoring program are evaluated annually and during recertification.
Extent of Brittle Deformation	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data reported annually.	Not directly related to a PA parameter. Can provide confidence in the long-term behavior of the disturbed rock zone (DRZ) as modeled. Intrinsic shaft DRZ permeability and effective shaft seal permeabilities calculated from this parameter.	DRZ, roof falls, consolidation of seals.	Data are evaluated annually and during recertification.
Initiation of Brittle Deformation	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data reported annually.	Not directly related to a PA parameter. Can provide confidence in the anhydrite fracture model implemented in the BRAGFLO code. May provide related repository observation data on initiation or displacement of major brittle deformation features in the roof or surrounding rock.	Disruption due to gas effects.	Data are evaluated annually and during recertification.
Displacement of Deformation Features	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data reported annually.	Not directly related to a PA parameter. Provides related repository operational data on initiation or displacement of major brittle deformation features in the roof or surrounding rock.	Stability of open panel.	Data are evaluated annually and during recertification.
Culebra Groundwater Composition	Groundwater Monitoring Program	Data are collected semiannually and reported annually.	Average Culebra brines composition and matrix distribution coefficient for U(IV, VI), Pu(III, IV), Th(IV), Am(III). Matrix distribution coefficient is not a sensitive PA parameter.	Groundwater geochemistry, actinide sorption.	Data are evaluated annually and during recertification.

Table MON-1. Monitoring Parameters — Continued

Monitoring Parameter	Monitoring Program	Frequency of Data Collection and Reporting	Related Performance Assessment Parameter	Related FEPs Evaluation Cycle	Evaluation of Data
Change in Culebra Groundwater Flow (Water Level)	Groundwater Monitoring Program	Data collected monthly and reported annually.	Culebra transmissivity, fracture and matrix porosity, fracture spacing, dispersivity, and climate index. Changes in Culebra groundwater flow are moderately significant to performance and incorporated into the PA.	Groundwater flow and recharge/discharge. Infiltration. Precipitation.	Data are evaluated annually and during recertification.
Drilling Rate	Delaware Basin Drilling Surveillance Program	As well records are received (weekly and monthly basis). Data are reported annually.	Drilling rate per unit area. The number of holes is used to calculate a frequency of potential future intrusions into the repository.	Drilling.	Data are evaluated annually and during recertification.
Probability of Encountering a Castile Brine Reservoir	Delaware Basin Drilling Surveillance Program	As drilling records are received. Data are reported annually.	Probability of encountering a Castile brine reservoir, reservoir pressure, and volume. The probability of encountering a brine reservoir is significant to long-term repository performance.	Drilling fluid flow, drilling fluid loss, blowouts, brine reservoirs.	Data are evaluated annually and during recertification.
Subsidence	Subsidence Monitoring Program	Annually or as determined necessary by the DOE. Data are reported annually or as determined necessary by the DOE.	Not directly related to a PA parameter. Can provide spatial information on surface subsidence (if any) over the influence area of the underground openings during operations.	Changes to groundwater flow due to mining effects; subsidence baseline.	Data are evaluated annually or as determined necessary by the DOE.
Waste Activity	WIPP Waste Tracking and Control	Continually updated as waste is approved for shipment to WIPP. Data are reported annually.	Radionuclide inventory. Material parameter weights.	Waste radiological characteristics.	Data are evaluated annually and during recertification.

MON-3.0 PRECLOSURE COMPLIANCE MONITORING

This section provides a general description of the preclosure CMP and the resulting data. The 10 parameters, associated monitoring program for each, frequency of data collection and reporting, related PA parameters, and related screening decisions used to support the PA are listed in Table MON-1. WIPP Waste Tracking and Control is listed as a monitoring program because waste-related data are extracted from reports it generates.

MON-3.1 Geotechnical Engineering Program Plan

The WIPP Geotechnical Engineering Program Plan (WIPP 2002) defines the field programs and investigations carried out by the Geotechnical Engineering group within the M&OC (Management and Operating Contractor). The geotechnical engineering activities are designed to provide geologic information related to geotechnical characteristics and to assess the stability and performance of the underground facility. The activities within this plan that collect data related to PA parameters are Geomechanical Monitoring and Geosciences.

MON-3.1.1 Geomechanical Monitoring Activities

The purpose of the geomechanical monitoring activities is to determine the geomechanical performance of the underground by monitoring the geomechanical response of the underground openings after excavation. It also monitors geotechnical instruments installed in the shafts and drifts of the WIPP facility. This activity generates data related to the four following parameters:

1. creep closure and stresses,
2. extent of brittle deformation,
3. initiation of brittle deformation, and
4. displacement of deformation features.

MON-3.1.1.1 Scope

The instrumentation system for geomechanical monitoring activities provides data on the WIPP design for routine evaluation of safety and stability of excavations, and for collecting data on the behavior of underground openings. From an operational point of view, data related to identifying areas of potential instability allow corrective action to be taken in a timely manner. For underground opening behavior, in-situ data are used to model long-term disposal system performance.

MON-3.1.1.2 Instrumentation

Geomechanical instruments installed in the shafts and along drifts within the WIPP facility monitor the geotechnical parameters. Instrumentation in the shafts and the underground repository presently include tape extensometer stations, convergence meters, borehole extensometers, piezometers, embedment strain gauges, stress gauges, inclinometers, load cells, and crack meters.

Geomechanical instruments installation and monitoring are governed by approved procedures. Instruments in the underground are either monitored remotely by a surface data logger or read manually.

MON-3.1.1.3 Data Acquisition

Geomechanical data are acquired either remotely by the geomechanical data logging system or manually by geotechnical engineering technicians. Manually acquired data are collected on a quarterly basis and remotely acquired data are collected on a monthly basis, as a minimum.

MON-3.1.1.4 Data Analysis and Dissemination

The frequency of data analysis on geomechanical data is based upon the requirements established in the WIPP Safety Analysis Report (DOE 1995). Data analysis is performed on an annual basis and published. The results of the analyses are published annually in the Geotechnical Analysis Report (DOE 2002).

An assessment of convergence measurements and geotechnical observations is made after each round of data collection. The results of each assessment are distributed to affected underground operations, engineering, and safety managers.

MON-3.1.2 Geosciences Activities

The purpose of the Geosciences activities is to document existing geologic conditions and characteristics and to monitor for changes resulting from the excavations. This activity generates data related to the following four parameters:

- creep closure and stresses,
- extent of brittle deformation,
- initiation of brittle deformation, and
- displacement of deformation features.

MON-3.1.2.1 Scope

Changes resulting from excavations are monitored by routine inspections of selected borehole arrays to detect and quantify the occurrences of discontinuities such as fractures and bed separations. The data collected from these inspections further the understanding of fracture development within the Salado Formation that occurs around the excavations. Geosciences activities also provide geologic and fracture mapping, geologic sampling, and seismic monitoring.

MON-3.1.3 Schedule

The following activities are performed on the indicated schedule:

- Geomechanical Monitoring – This program consists of monitoring using instrumentation located in the shafts and drifts, including tape extensometer stations, convergence meters, borehole extensometers, piezometers, embedment strain gauges, stress gauges, inclinometers, load cells, and crack meters. Instruments are read monthly (remotely read instruments) or quarterly (manually read instruments) as a minimum;

- Seismic Monitoring – Regional seismic monitoring and evaluation are conducted by the New Mexico Institute of Mining and Technology. The network is operated continuously and monitoring results are reported quarterly; and

- Geologic Mapping – Geologic mapping is conducted in newly excavated areas and in other areas when deemed necessary by the cognizant engineer or Geotechnical Engineering Manager.

At a minimum, a complete analysis of geotechnical data is performed annually. The geotechnical activities will be ongoing throughout the operations period.

MON-3.2 Groundwater Monitoring Program

The purpose of the Groundwater Monitoring Program (GWMP) is to collect groundwater data from numerous wells located near the facility. Groundwater monitoring at the WIPP is carried out under the WIPP GWMP (WIPP 2003).

The Culebra Dolomite Member remains the focus of the GWMP. It has been extensively studied during past hydrologic characterization programs and was found to be the most likely hydrologic pathway to the accessible environment or compliance point for any potential human-intrusion-caused release scenario.

Data obtained through this program are used to generate the Culebra groundwater composition and the Culebra groundwater flow parameters. Details on how the program is implemented are provided in the GWMP (WIPP 2003) and Strategic Plan for Groundwater Monitoring at the Waste Isolation Pilot Plant (DOE 2003).

MON-3.2.1 Scope

The GWMP addresses requirements for sample collection, groundwater surface elevation monitoring, groundwater flow direction, data management, and reporting of groundwater monitoring data. It also identifies analytical parameters selected to assess groundwater quality.

Seven wells were drilled as part of the WIPP GWMP (see Figure 2-2 in Chapter 2). They are as follows: six wells, WQSP-1 through WQSP-6, completed to the Culebra Member of the Rustler Formation, and one other well, WQSP-6a, completed to the Dewey Lake Formation. Water samples are collected from these wells and analyzed for certain chemical and physical parameters. This activity generates data in support of the Culebra Groundwater Composition Parameter. This parameter calls for the analysis of the following:

- Ca^{2+},

- Cl^-,
- HCO_3^{2-},
- K^+,
- Mg^{2+},
- Na^+, and
- SO_4^{2-}.

Water level data are collected to assess changes in Culebra groundwater flow. Water level measurements are tracked over time using Water Quality Sampling Program (WQSP) wells and other wells that are widely distributed across the WIPP area to monitor the area's potentiometric surface and groundwater flow directions. If changes in water level or water levels occur, the cause is investigated and any potential impact on the long-term performance of the repository is assessed.

MON-3.2.1.1 Sampling and Reporting for Water Quality

Sampling for water quality is performed at seven groundwater monitoring wells. The Culebra is monitored using wells WQSP-1 through WQSP-6 and the Dewey Lake is monitored using well WQSP-6a. Two types of water samples are collected in accordance with approved procedures maintained by M&OC: serial samples and final samples.

Serial samples are taken at regular intervals and analyzed for various physical and chemical parameters (called field indicator parameters) in a mobile field laboratory positioned at the wellhead. The serial sample data are used to determine when the borehole effects are minimized so a representative sample of the formation water can be taken. The field indicator parameters are chloride, divalent cations, alkalinity, total iron, pH, Eh, temperature, specific conductance, and specific gravity. Interpretation of the serial sampling data determines when conditions representative of undisturbed groundwater are attained in the pumped groundwater.

When the field indicator parameters have stabilized, indicating that the sample is representative of formation groundwater, final samples are collected in the appropriate type of container for the specific analysis to be performed to meet state and federal requirements. The final samples are submitted to laboratories for chemical analysis. Section 3.2.1 lists the analytes needed to support the PA parameter.

The sample tracking system at WIPP uses uniquely numbered Chain of Custody Forms and Request for Analysis Forms. The primary consideration for storage or transportation is that samples must be analyzed within the prescribed holding times for the parameters of interest. Procedures for sample tracking and preservation are generated, approved, and maintained by the M&OC.

MON-3.2.1.2 Sampling and Reporting for Water Level Fluctuations

Water level measurements are taken in the seven groundwater monitoring wells (WQSP-1 through WQSP-6a) and other available WIPP wells in the monitoring network (see Figure 2-2 in Chapter 2). The objective of water level monitoring is to identify water level fluctuations.

In addition to the water level measurements, pressure density surveys are conducted to determine the specific gravity of the water in the wells. These surveys allow the water level measurements to be converted to equivalent freshwater heads that can be used to develop potentiometric surface maps. Specific procedures regarding water level monitoring activities are generated, approved, and maintained by the M&OC.

MON-3.2.2 Schedule

Background water quality in both the upgradient and downgradient monitoring wells has been established for the WIPP. Therefore, the seven WQSP monitoring wells constructed for the GWMP are sampled on a semiannual basis to confirm the existing baseline water quality.

The groundwater level is measured by monitoring the wells on a monthly basis. Groundwater level measurements are monitored and collected for other WIPP wells, as well as for the WQSP wells. The water levels are determined in at least one accessible completed interval at each available well pad and quarterly in redundant wells at well pads with two or more wells completed in the same interval. Groundwater level measurements are made primarily to examine changes in groundwater flow rate and direction to identify any changes pertinent to compliance. These groundwater data supplement the area water level database.

The characteristics of the GWMP, such as the frequency of sampling and the location of the sampled wells, will be reevaluated if significant changes are observed in the groundwater flow direction or gradient. Monitoring frequencies are listed in Table MON-2.

Table MON-2. WIPP Groundwater Monitoring Program Sample Collection and Water Level Measurement Frequency

Type of Well	Frequency
Water Quality Sampling	
WQSP wells (7)	Semiannually
Other WIPP wells	On special request only
Water Level Monitoring	
WQSP wells (7)	Monthly and before sampling events
Other WIPP wells	Monthly

Note: These frequencies are subject to change as WIPP permits are modified and updated.

MON-3.2.3 Program Outputs

The groundwater samples are analyzed to quantify the following Culebra Groundwater Composition parameters and water quality parameters such as pH and density:

- Ca^{2+},
- Cl^{-},
- HCO_3^{2-},
- K^{+},
- Mg^{2+},
- Na^{+}, and
- SO_4^{2-}.

The GWMP also generates Culebra water level data. The data and results of the GWMP are summarized and published on an annual basis in the WIPP Annual Site Environmental Report (ASER) (DOE 2002a).

MON-3.3 Delaware Basin Drilling Surveillance Program

The Delaware Basin Drilling Surveillance Program (DBDSP) is described in the Delaware Basin Drilling Surveillance Plan (WIPP 1997). This plan provides for the surveillance of drilling activities within the Delaware Basin, with specific emphasis on the nine-township area surrounding the WIPP site. The DBDSP collects information related to the following two parameters:

1. probability of encountering a Castile brine reservoir, and
2. drilling rate.

In addition to the parameters listed above, the DBDSP collects information on the following activities:

- borehole plugging,
- enhanced recovery,
- gas storage,
- solution mining,
- potash mining, and
- seismic events.

The WIPP PA includes the impacts of drilling on the performance of the repository. The number of deep boreholes drilled per square kilometer is a parameter used in PA calculations for WIPP

inadvertent intrusion scenarios. They are based on actual drilling rates within the Delaware Basin over the last 100 years as required by 40 CFR § 194.33.

The results of the DBDSP continue to build on the existing database. The purpose of this program is to update these data to detect any substantial deviations from the assumptions used in the previous PA (see Table MON-3 below). The collection of additional information about resource exploration and exploitation activities and practices in the Delaware Basin provides information to determine whether the drilling scenarios, assumptions, and probabilities used in the PA continue to be valid for each five-year recertification of the WIPP.

Drilling information for the study area is obtained through commercially available electronic databases and from the records of government agencies. The electronic database is updated and reviewed weekly to reflect drilling activities in the Delaware Basin.

MON-3.3.1 Schedule

Table MON-3. DBDSP Data Collection Schedule

Information Collected	Frequency
Borehole plugging	Weekly
Enhanced recovery	Monthly
Gas storage	Annually
Solution mining	Annually
Potash mining	Annually
Seismic events	Quarterly
Drilling-related	Weekly
Probability of encountering a Castile brine reservoir	Weekly
Drilling rate calculations	Quarterly

MON-3.3.2 Program Outputs

The DBDSP updates and maintains a database of drilling activities and related practices in the Delaware Basin. Maps of the Delaware Basin are published on request. For the nine-township area surrounding the WIPP, the DBDSP updates and maintains a database containing the following information:

- plugging and abandonment activities including descriptions of plugging configurations;
- determination of the fraction of plugged and abandoned boreholes that are sealed;
- well conversion activities (injection, disposal, water);
- injection well operation (disposal and secondary recovery);

- drilling activities including borehole depths, diameters, and type and amount of drilling fluid;
- identification of ownership of all state and federal minerals and hydrocarbon leases within the area; and
- occurrences of pressurized brine within the Castile.

Data collected and recorded by the DBDSP are reported annually in the Delaware Basin Monitoring Annual Program Report (DOE 2002b).

MON-3.4 Subsidence Monitoring Program

The Subsidence Monitoring Program (SMP) is described in detail in the WIPP Underground and Surface Surveying Program (WIPP 2003a). Subsidence monitoring is the measurement of vertical movement of the land surface relative to a reference location, using state-of-the-art leveling equipment. The technique used to monitor subsidence measures the vertical height difference between two or more markers placed on a surface a known distance away from each other using a leveling survey. A reference benchmark is used as the standard and the relative movement of the other benchmark(s) is measured to detect vertical movement over time. Subsidence measurements are relative because the reference is fixed only with respect to the subsidence markers.

The activities associated with the SMP are designed to:

- provide time-related spatial information on surface subsidence within 152.4 m (500 ft) surrounding the waste shaft during the operational phase of the repository;
- provide time-related spatial information on surface subsidence over the influence area of the underground openings for comparison with subsidence predictions; and
- maintain a database of subsidence data.

With current technology, vertical elevation can be measured at a precision of 0.0305 cm (0.001 ft). Subsidence monitoring was chosen by the DOE as a long-term monitoring tool because it effectively meets the requirements in 40 CFR § 191.14(b) for long-term monitoring. Subsidence monitoring is conducted to detect substantial deviations from expected repository performance by allowing a comparison of actual subsidence to that calculated previously.

Subsidence data are currently being compiled and will be compared to subsidence predictions. In addition, monitoring subsidence during the operational phase generates data to establish a baseline against which long-term subsidence data and information may be evaluated.

MON-3.4.1 Schedule

Subsidence surveys are performed throughout the operations period as deemed necessary. After closure of the repository, subsidence surveys will be performed at 10-year intervals for at least 100 years or until no further useful information may be obtained through continued monitoring.

MON-3.4.2 Program Outputs

The SMP generates annual surface subsidence data for 32.19 km (20 mi) of leveling loops through approximately 50 monuments. Results are reported annually in the WIPP Subsidence Monument Leveling Survey (DOE 2002c).

MON-3.5 WIPP Waste Information System

Information on the waste activity parameter is measured or estimated by generator sites through waste characterization activities. Sites are required to report certain information in the WIPP Waste Information System (WWIS). Reports are generated by Waste Tracking and Control to provide tabulations of key waste parameters. The waste activity parameter includes tracking the total material parameter weights and curie content of 10 radionuclides, listed in Section 3.5.2.

MON-3.5.1 Schedule

Radionuclide inventory data and material parameter weights for every container of waste placed in the WIPP underground are submitted to the WWIS database. A current collection of radionuclide inventory data and material parameter weights for the WIPP is maintained within the WWIS.

MON-3.5.2 Program Outputs

The curie content of the radionuclides americium-241, plutonium-238, plutonium-239, plutonium-240, plutonium-242, uranium-233, uranium-234, uranium-238, strontium-90, and cesium-137 and the material parameter weights (cellulose, plastics and rubber (CPR) materials, free liquids, and metals) for the waste emplaced in the WIPP underground are reported in November of each year to the EPA in the annual 40 CFR § 194.4(b)(4) report (DOE 2002d).

MON-4.0 POSTCLOSURE (LONG-TERM) MONITORING

The final Postclosure Monitoring Plan will be developed prior to final facility closure (sealing of the shafts), but will not be implemented until after facility closure. This plan will include a review of CCA Appendix MON, sections MON.6 through MON.7, which are brought forward as Attachment A of this Appendix. Attachment A is as written in the CCA and any references in Attachment A are to the CCA. When the final Postclosure Monitoring Plan is written, any proposed changes to the commitments made in Attachment A will only be made after review and approval by the appropriate regulatory authorities.

MON-5.0 MONITORING PROGRAMS QUALITY ASSURANCE REQUIREMENTS

The quality of the work performed under the DOE CMP is controlled by the application of the CBFO Quality Assurance Program Document (QAPD) (DOE 2003a) and existing QA procedures employed by the CBFO. Waste information is controlled by implementation of the QAPD at generator sites.

In addition to the management requirements, such as document and record control established in the QAPD, requirements related to sampling and monitoring activities are specified. In particular, the following two sections of the QAPD are directly related to the performance of monitoring work and the control of samples:

- **Section 2.4 – Inspection and Testing**
  - qualification of personnel,
  - inspection,
  - test requirements,
  - monitoring, measuring, testing, and data collection,
  - use and control of measuring and test equipment (M&TE), and
  - calibration.
- **Section 4.0 – Sample Control Requirements**
  - sample control,
  - sample identification,
  - handling, storing, and shipping samples, and
  - disposition of nonconforming samples.

Sampling and monitoring activities follow properly documented and implemented quality assurance/quality control procedures. WIPP monitoring programs are subject to EPA inspections in accordance with 40 CFR § 194.21.

The CMP relies on the individual monitoring plans' QA programs to ensure compliance with DOE WIPP requirements for data quality assessments, objectives, and analyses. Each sampling and monitoring program is implemented through individual implementation plans, which include the QA descriptions, objectives, and references to the applicable governing QA documents.

MON-6.0 REPORTING AND ASSESSMENT

Information flow is controlled to ensure important monitoring results are communicated to the appropriate individuals and groups.

MON-6.1 Monitoring Data Reporting

The monitoring programs that generate the data used in the CMP are implemented by the M&OC. The reporting of the data for the 10 compliance monitoring parameters is coordinated through the M&OC.

It is the responsibility of the M&OC to ensure that the DOE is fully informed regarding any occurrence of anomalous CMP results and evaluations. The M&OC communicates important monitoring results to the SA. The SA communicate to the M&OC, via the DOE, any information generated that may impact the M&OC monitoring activities during their assessment.

MON-6.1.1 Assessing Compliance Monitoring Parameters

The SA is responsible for assessing compliance monitoring parameters against PA expectations and will report results through an annual compliance assessment report to the DOE.

It is the responsibility of the SA to ensure that the DOE is fully informed in the event that the SA's activities generate information that changes current understanding of data, parameter values, or conceptual models that are important to the assessment of the performance of the repository. In this role, the SA integrates the information generated through the various SA activities and presents a single position to the DOE. When unexpected or anomalous results are generated, the SA recommends to the DOE actions appropriate to mitigate or respond to the unexpected result. The SA also serves the information-exchange function described above by communicating to the M&OC any results that may impact the M&OC monitoring activities. The SA develops the compliance monitoring parameter assessment annually. This report is sent to the EPA as part of the annual reporting requirement of 40 CFR § 194.4(b)(4).

MON-6.1.2 Reporting and Assessment Point of Contact

In its role as the centralized point of contact for monitoring activities, the DOE is responsible for the following activities:

- Review monitoring results – CMP results may indicate two general cases:

  (1) normal or expected conditions in which results are generally consistent with existing data, parameter values, and conceptual models; or

  (2) anomalous conditions that are inconsistent with existing data, parameter values, or conceptual models. It is the responsibility of the DOE to review recommendations provided by the M&OC and the SA generated through the monitoring programs to determine whether these results are consistent or inconsistent with expected

conditions modeled in PA or screening decisions used to support the compliance determination.

- Definition of responsive actions or changes – Anomalous results may warrant changes in the monitoring programs, research activities, PA assumptions, or some other aspect of the overall compliance program. In addition, occasions may arise when it is appropriate to modify existing monitoring programs for modifications that may be required by regulators or are initiated from within the project.

MON-6.1.3 External Reporting

The DOE will review the recommendations of the M&OC and the SA to evaluate their significance. Significance will be determined based on consideration of the following criteria:

- containment requirements established pursuant to 40 CFR § 191.13 are, or are expected to be, exceeded;

- releases from waste already emplaced lead to committed effective doses that are, or are expected to be, in excess of those established pursuant to 40 CFR § 191.15 (not including emissions from operations covered pursuant to Subpart A of 40 CFR Part 191); or

- releases have caused, or are expected to cause, concentrations of radionuclides (or estimated doses due to radionuclides in underground sources of drinking water in the accessible environment) to exceed the limits established pursuant to 40 CFR 191, Subpart C.

If monitoring results meet any of these criteria, the results will be considered to be significant. Monitoring results determined by the CBFO to be significant will be promptly reported to the EPA. The report will be accompanied by a recommended course of action, including the appropriate external reporting. If the monitoring results indicate an exceedance or possible exceedance of containment requirements or release as specified in 40 CFR § 194.4(b)(3)(ii), the CBFO will immediately cease emplacement of waste in the WIPP and notify the EPA within 24 hours.

If monitoring results are significant but do not indicate an immediate or imminent exceedance or release as described in 40 CFR § 194.4(b)(3)(ii), the CBFO will prepare a written report of its findings. The CBFO Manager provides this report to the EPA within 10 days.

For normal conditions where monitoring results are within expectations, the compliance monitoring parameter assessment will document this condition annually. As stated previously, this report is sent to the EPA as part of the annual reporting requirement of 40 CFR § 194.4(b)(4).

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ATTACHMENT A
TO
APPENDIX MON 2004

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ACRONYMS

BEAR	Backfill Engineering Analysis Report
DOE	Department of Energy
DOI	Department of Interior
FEIS	Final Environmental Impact Statement
FSAR	Final Safety Analysis Report
NGS	National Geodetic Survey
QAPD	Quality Assurance Program Description
SNL	Sandia National Laboratories
S-Caps	Subsidence Monuments
WEC	Westinghouse Electric Corporation
WIPP	Waste Isolation Pilot Plant

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POSTCLOSURE MONITORING

MON-A-6. REVIEW OF POSTCLOSURE MONITORING TECHNOLOGIES

Each of the technologies listed below are discussed, defining the monitoring technology and describing the past, current, and future work using this technology as related to performance monitoring. Also defined are the advantages, disadvantages, and proposed uses of the technologies in postclosure monitoring of the repository.

- Subsidence
- Seismic reflection and refraction
- Gravitational
- Electromagnetic
- Resistivity
- Direct repository monitoring

MON-A-6.1 Subsidence

Subsidence is defined as vertical movement of the land surface anywhere in the subsidence basin. Subsidence monitoring is defined as the measurement of *relative vertical movement* of the land surface. This movement can be up (uplift) or down (subsidence) and is relative to a fixed reference. This reference is assumed fixed, even though it is subjected to the same factors that cause the surface movement and is moving also. Subsidence monitoring is used to determine the measurable vertical movement of a land mass. The techniques used to monitor subsidence measure the vertical height difference between two or more markers placed on the surface a known distance away from each other and is done with a leveling survey. Usually, one reference benchmark is used as the standard and the relative movement of other stations or benchmarks is measured to detect vertical movement over time. All subsidence measurements are relative because the reference is not fixed.

The error of the survey is determined by the equipment and distances between the stations. A first order survey has an error of one part in 100,000 and a second order survey has an error of one part in 20,000. With current technology, several thousandths of an inch vertical movement can be measured to the stated accuracy.

Subsidence can be caused by a variety of factors. Mining, hydrocarbon extraction, water injection and extraction, geological tilt, and dissolutioning are major subsidence causing factors all of which may be applicable to the WIPP over the long term.

MON-A-6.1.1 Advantages of Subsidence Monitoring

Subsidence monitoring is advantageous because it is a passive monitoring technique that is relatively simple to perform and uses well established technologies. The cost of the survey is

low compared to other technologies. This technique requires little system maintenance or monitoring and has no power requirement. The benchmarks are not affected by weather and can last for hundreds of years. Benchmarks can be replaced if required and the data can be offset to account for the change without affecting data quality.

MON-A-6.1.2 Disadvantages of Subsidence Monitoring

The disadvantages associated with subsidence monitoring are in the benchmark placement. The benchmark should be left undisturbed. Existing benchmarks may be destroyed or moved if new construction occurs over the benchmarks. The permanent markers design calls for large earthen berms around the facility after closure. The placement of the berm may cover some of the existing benchmarks and may preclude the necessary line-of-sight measurements between existing benchmarks. The benchmarks are also not currently protected, and could be destroyed during land use by ranchers, drillers, or developers. This necessitates replacing markers and incorporating new markers on the berm to maintain a line-of-sight reference with the benchmarks. Future advancements in global positioning systems may eliminate the need for line-of-sight placement of the benchmarks.

MON-A-6.1.3 Past Subsidence Work

During the initial site selection process, 195 miles (314 kilometers) of first order, Class 1 leveling survey was performed in 1977 by the National Geodetic Survey (NGS). Later, new survey lines were established that connected the previous first order benchmarks through Carlsbad to second order survey lines through Eunice and Hobbs. Benchmarks were placed over the Nash Draw from the north end to the Remuda Basin, over potash mines, the WIPP site, and the San Simon Sink (Powers 1993). Independent of the NGS benchmarks, an additional 52 benchmarks were installed over the WIPP site and surrounding area.

The NGS network was resurveyed in 1981 and the relative movement between Carlsbad and the WIPP site was measured to be about 0.8 inches (2 centimeters). The relationships between subsidence and potash mining in the WIPP vicinity are discussed in Powers (1993). From data in this report, potash mining was shown to have caused significant subsidence at mines close to the WIPP. Two benchmarks over the Mississippi Chemical Corporation mine measured relative to Carlsbad show 10- and 40-inch (25.4- and 102.7-centimeter) movement downward from 1977 to 1981. Powers (1993) also discusses mining effects on surface subsidence at other mines and correlated a relationship between mining and the surface area effects. This effect is of importance to WIPP monitoring in that estimations of area mining and WIPP mining can be calculated into the subsidence predictions. From Powers (1993), "In May, 1982, the NGS placed and leveled 15 additional high-quality benchmarks along a north-south line across the position of WIPP 12 (1 mile [1.6 kilometers] north of WIPP surface facilities) and the underlying brine reservoirs in the Castile Formation." After testing and fluid production of approximately 27,058 barrels of brine from the brine reservoir, the NGS resurveyed these benchmarks in January, 1983. According to Powers (1993), "The major difference in elevation across these 15 benchmarks from May, 1982 to January, 1983, is about 6 to 7 millimeters between the north end of the line and the approximate position of the WIPP."

MON-A-6.1.4 Subsidence Predictions

Subsidence predictions as a result of mining can also be calculated empirically. Techniques such as mass conservation, National Coal Board, and profile and influence functions can be used to calculate subsidence caused by mining. The influence function technique can estimate subsidence from room and pillar type mining, which is the type of mining used at the WIPP (Sutherland and Munson 1983). Four studies have been performed that have calculated subsidence predictions, the results are found in the *Final Environmental Impact Statement* (FEIS) (DOE 1980), the *Final Safety Analysis Report (FSAR)* (DOE 1990), Sandia National Laboratories' (SNL's) 1991 comparison with 40 CFR Part 191 (WIPP Performance Assessment Division 1991), and the *Backfill Engineering Analysis Report (BEAR)* (WEC 1994b). The following details each report's maximum subsidence predictions:

MAXIMUM SUBSIDENCE PREDICTIONS

FEIS

70-percent backfill density	1-foot (0.3-meter) subsidence
50-percent backfill density	1.6-foot (0.5-meter) subsidence
No backfill	3.28-foot (1.0-meter) subsidence

FSAR

Shaft pillar area	1- to 1.2-foot (0.3- to 0.38-meter) subsidence

(backfill type and amount not specified)

SNL

35E angle	0.3-foot (0.09-meter) subsidence
25E angle	0.4-foot (0.13-meter) subsidence

BEAR

No backfill	1.3- to 2-foot (0.40- to 0.60-meter) subsidence
Highly compacted backfill	1- to 1.7-foot (0.30- to 0.52-meter) subsidence

MON-A.6.1.5 Current Work in Subsidence Monitoring

Current subsidence work includes annual monitoring, a proposed NGS, and a satellite positioning survey. The WIPP Subsidence Monitoring Program is performed annually allowing for a comparison of the data, development of a database, and analysis of subsidence characteristics at the WIPP site. The program includes surface subsidence monitoring involving twenty miles of leveling loops through approximately fifty monuments (S-Caps). Subsidence monitoring surveys include Global Positioning Satellite and surveys of the S-Caps. Figure SMP-1 (see Appendix SMP) identifies approximately 50 benchmarks (those designated "S" and "PT") distributed throughout the area of influence of the repository and excavated support regions. The annual survey is completed so as to achieve closures that exceed a minimum standard of Second Order Class II for vertical control surveys. State of the art digital leveling technology is employed for all subsidence surveys. From 1996 onward, the survey is being performed to yet higher standards to allow for upgrading the precision of measurements.

Maintenance and calibration of equipment used for monitoring is addressed in Section 2.4.4 of the Westinghouse Waste Isolation Division Quality Assurance Program Description, (see Appendix QAPD). For subsidence measurements, maintenance and calibration are performed by the equipment vendor in accordance with national standards. Equipment is only procured from, maintained, and calibrated by vendors on the WIPP approved Qualified Supplier's List.

Data, plots, graphics, and reports generated as a result of the subsidence surveys are reviewed by cognizant technical engineering personnel to ensure their adequacy and accuracy in accordance with DOE and DOE/WIPP Quality Assurance Review procedures.

The WIPP currently monitors the existing benchmarks as indicated in Figure SMP-1 (see Appendix SMP) on an annual basis (drawing by John West Engineering Co., 1-11-93).

MON-A-6.1.6 Future Work on Subsidence Monitoring

A NGS survey was performed in 1996 however the final report has not yet been published. The current plan is to resurvey about every 10 years. The last NGS survey was performed in 1982.

MON-A-6.1.7 Define Use of Subsidence Surveys for Postclosure Monitoring

This report assumes that substantial work will be performed during the operational phase to gather subsidence information and data. This data will be used to relate expected subsidence over time for various scenarios of repository performance. The effects of petroleum production, mining, and geological subsidence must be accounted for in these scenarios. These estimates would be compared to actual measurements.

During the operational phase, the current benchmarks and new benchmark network will be used to gather baseline data. After the operational phase, however, decommissioning of the surface facilities and erection of active and passive controls will eliminate some of this network. For this reason, during the decommissioning, damaged or lost stations should be replaced. Additional stations may be necessary to compensate for line-of-sight losses incurred as a result of the proposed passive permanent markers. It is expected that analysis may have determined subsidence estimates at specific locations; these locations should be included in the benchmark network.

After decommissioning and adjustment of the benchmark network, a Class 1 leveling survey will be performed to determine baseline data. The network will be monitored after closure and until monitoring is determined to be no longer necessary. The monitoring frequency is to be every third year for the first 15 years. During this time, the data will be compared to the previous trends and if no important anomalies are found, the monitoring frequencies will be adjusted to 10-year intervals.

MON-A-6.2 Seismic Reflection and Refraction Surveys

Seismic reflection and refraction surveys are used to determine the depth, thickness, composition, and physical properties of geologic layers. Data from the survey can locate specific horizons such as water tables, clay layers, and bedrock. This technology can be used to map the

geological structures of large areas at great depths. Survey results are often used by geologists to locate specific geologies that may contain hydrocarbon reserves.

This method uses seismic wave transmissions to determine geologic structure depth and composition. Seismic waves travel at different velocities depending on the soil and rock type. Hard and dense rock has higher wave velocities than soft and less dense rock. Seismic waves can travel through, reflect, or refract off of geological structures. Some of the wave energy will travel along the layers. This phenomenon is used to determine depth and composition of the strata by measuring the return time of an induced wave generated at the surface and reflected and refracted back from the underlying strata.

This technique measures wave travel times through a sensor array called geophones placed over the area of interest. A seismic wave is generated by dropping a weight (anything from a hand sledge to truck-mounted ram), or by using high explosives. A seismograph is used to amplify and record the data. By using various seismic wave input energies, sensor array spacings and numbers, specific depths can be mapped. The map corresponds to a geological profile along the line surveyed. Figure MON-A.6 details the basic seismic surveying technique.

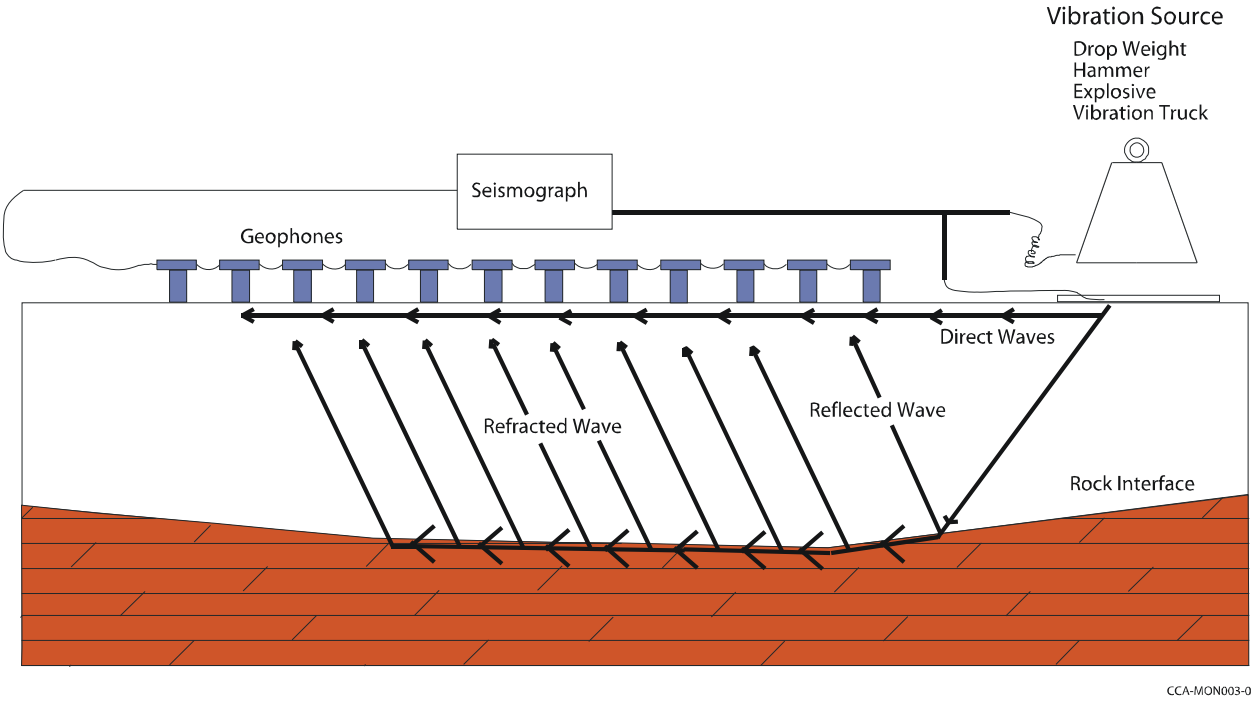

Figure MON-A.6. Seismic Reflection and Refraction Survey Concept

MON-A-6.2.1 Advantages of Seismic Reflection and Refraction Surveys

One advantage of this technique is the abundance of existing data. Numerous petroleum companies have performed seismic surveys in the WIPP area and several other surveys were performed during site selection (Powers et al. 1978; included in this compliance application as Appendix GCR). This data can be used as a reference to detect changes by comparison with new

data. The quality of the data is good for lower structures but is not as useful above the 3,000-foot (914-meter) level (Appendix GCR).

Seismic surveys are nonintrusive and require no permanent devices to be installed at the site. Seismic surveys are relatively inexpensive.

MON-A-6.2.2 Disadvantages of Seismic Reflection and Refraction Surveys

Basic disadvantages of this technique include data quality and interpretation. This technique is sensitive to noise and equipment set-up. The data must be electronically processed, conditioned, and interpreted by an experienced geologist. Interpretation is an art form and no two interpretations are the same (Griswold 1977). This can create repeatability errors if the surveys are repeated on the same geology. The results are usually compared to core samples to verify the interpretation and validate the results.

Seismic surveys use equipment that allows for many variations in how data are collected. For comparison reasons, surveys must be performed using similar equipment set-ups, that is, array spacings, line locations, and data conditioning. Any variations in the technique and equipment must be accounted for in the interpretation of the data to ensure that changes caused when different equipment is used for repeated surveys are not interpreted as geological changes. Relatively thin strata and layers of similar densities cannot be distinguished. Because the technique is based on wave velocities, layers of material that may have different chemical and geological characteristics, but similar velocity components, cannot be differentiated.

MON-A-6.2.3 Past Seismic Reflection and Refraction Survey Work

During the siting process for the WIPP, several geophysical techniques were used to gather geological data that would identify a suitable site location.

From 1976 to 1978, SNL conducted three surveys totaling 79 line miles (127 kilometers) of data, of which 72 line miles (116 kilometers) were over or near the WIPP site (Hern et al. 1978). The first survey consisted of three lines totaling 24.98 line miles (40.47 kilometers) of conventional petroleum style data and was collected from petroleum companies. The other two surveys were conducted using short geophone spacing and high signal frequency for better shallow field resolution above 4,000 feet (1,220 meters) (Appendix GCR). One of these surveys totaled 47.04 line miles (67.65 kilometers) involving 13 lines. The third survey included 7.5 line miles (12 kilometers) of profiling run along crossing lines through the site (Griswold 1977; Hern et al. 1978).

Approximately 189 line miles (304 kilometers) of older (1950s to 1960s) seismic surveys performed by Shell Oil Co. were purchased from a brokerage firm (G.J. Long Associates 1976). Exxon allowed 196 line miles (315 kilometers) of their data to be viewed at their office, Amoco allowed 513 line miles (825 kilometers) of data to be viewed (G.J. Long Associates 1976). This data were considered proprietary and could not be distributed to other sources. All of the listed data were gathered and interpreted during 1976 (Griswold 1977). Results of the data were used to map the geological layers around the WIPP site. These maps are found in WP 02-9, FSAR Section 2.7 (DOE 1990).

In 1976, attempts were made to perform a high-resolution shallow survey using weight drop techniques. This survey produced data that was not interpretable when compared to known geological information (Hern et al. 1978).

In 1979, an extensive seismic survey was performed that profiled lines directly over the WIPP site boundaries in north-south and east-west patterns. The north-south lines were spaced at 0.25-mile (0.4-kilometer) intervals and the east-west lines were spaced 0.5-mile (0.8-kilometer) apart in Zone 2. In the areas between Zones 2 and 3, the lines were spaced farther apart. The north-south lines were separated by 0.5-miles (0.8-kilometers) and the east-west lines were spaced at one mile (1.62 kilometers). This survey used the same basic parameters as the original Sandia National Laboratories (SNL) survey with closer line spacing. The intent was to improve the accuracy of the data above the Salado.

MON-A-6.2.4 Current Seismic Reflection and Refraction Work

No seismic surveys are being performed.

MON-A-6.2.5 Define Uses for Seismic Reflection and Refraction Surveys in Postclosure Monitoring

The seismic method determines the difference in geology by measuring the velocity of a wave through the rock. Any physical change in the rock is accompanied by a corresponding change in its velocity. Seismic surveys can be used to map the repository at various times. The specific depths and densities of various formations can be mapped and compared to data generated in the future to evaluate the repository performance. Changes in the strata, such as changes in aquifer depth and strata density changes, can be determined.

After the repository is sealed and the facility is decommissioned, a seismic survey could be performed over the repository and surrounding area. This survey could be performed to provide good resolution above and below the repository. The survey results and raw data could be documented and all interpretations of the data could be documented. The results and data could be archived so baseline data can be used for comparison to future seismic data if the need arises. The baseline data will help identify changes in the geology surrounding the facility that could help determine if the repository performance is acceptable. The survey could be performed after closure and will not be resurveyed unless new data are required.

The following are requirements for seismic monitoring uses in postclosure monitoring.

- Archive data in at least two permanent formats,
- Line surveys will be referenced to benchmarks in the subsidence network,
- All data reduction programs will be included in the archive data,
- The exact location for the survey will be in accordance with the recommendation of an experienced geologist, and

- Research will be conducted to identify methods to improve repeatability in geophone placement.

MON-A-6.3 Gravitational Surveys

The gravity survey method maps small variations in the earth's gravitational field. These variations result from mass and density difference in the subsurface lithography of the earth's crust. Interpretation of the data from a gravity survey can detect structural displacement in the strata (Barrows et al. 1983). The survey is performed by using a gravimeter. The instrument measures the gravity intensity at a point. The data is expressed in milligal, where a gal is an acceleration of 1 centimeter per square second. Standard equipment is accurate to within a tenth of a milligal.

MON-A-6.3.1 Advantages of Gravitational Surveys

This technology is helpful in determining the depth and area of various geological anomalies. In itself, gravity surveys are not concise, but aid the researcher in determining areas (anomalies) that should be explored using other geophysical techniques to determine the specifics of the anomaly. The gravity survey is nonintrusive and relatively inexpensive when compared to other geophysical monitoring techniques.

MON-A-6.3.2 Disadvantages of Gravitational Surveys

Gravity surveys do not provide the type of information that allows a geologist to determine the exact geological description and location of the strata surveyed.

This technique is very dependent on placement of the gravimeter. Placement errors can cause variability in results if the survey is repeated. For repeatability, exact placement of the gravimeter must be recorded and verified. This variation is not as pronounced when the results are mapped over a large area.

The data from the gravimeter is sensitive to surface structure, elevation, geographic latitude, and solar and lunar tides (Barrows et al. 1983). Corrections must be made for the terrain and usually cause an error of ± 0.3 milligal (DOE U.S. Department of the Interior [DOI] 1981). Surveying data point position and altitude is half the effort of the gravity survey. This method is prone to human error because manual recording is used. The data is often edited by reviewing the data and deleting any suspected transcription errors.

MON-A-6.3.3 Past Gravitational Survey Work

During the siting phase a regional gravity control was purchased in 1976, from a geophysical company (Griswold 1977, DOE 1983). Over 3,000 miles (4,800 kilometers) of gravity data were collected in the area as part of various hydrocarbon exploration surveys (Westinghouse Electric Corporation [WEC] 1990, *Final Safety Analysis Report [FSAR]* 2.7-27). Also, two gravity surveys, the main site and the reconnaissance profiles, were conducted by SNL. Three smaller areas within the main site survey were resurveyed in greater detail to provide information on suspected anomalies.

The main site survey covered approximately 8.5 square miles (13.7 square kilometers). The lines were spaced 0.6 miles (0.27 kilometers) apart and ran north-south with the stations spaced at 0.18-mile (0.09-kilometer) intervals (Barrows et al. 1983). During this survey, an anomaly was discovered and a borehole was drilled in that area. This area was surveyed in greater detail and covered an area 1,164 feet by 679 feet (355 meters by 207 meters). The stations were spaced in a grid 97 feet (30 meters) apart. Two other smaller areas were resurveyed to provide enhanced detail.

These data were used to detect anomalies in the strata and develop an interpretation of the disturbed zone. However, the disturbed zone data was inconclusive (Barrows et al. 1983). Areas surveyed detected some karst development. A gravity contour map of the WIPP site areas surveyed is found in Barrows et al. (1983).

MON-A-6.3.4 Current Gravitational Survey Work

No gravitational survey work is currently being performed by the DOE.

MON-A-6.3.5 Define Uses of Gravitational Surveys for Postclosure Monitoring

Gravity survey data could be included in the baseline database. All past surveys could be included along with extensive documentation defining the equipment, procedures, and data collection and processing techniques used. Surveys could be performed over the repository after closure and decommissioning, to provide baseline data for the repository. The original gravity survey data will not include the influence of over 6 million cubic feet (170 thousand cubic meters) of waste, so a new survey would be needed to provide a baseline after closure.

MON-A-6.4 Electromagnetic Conductivity Surveys

The term electromagnetic conductivity is used by many geological companies to describe various geophysical equipment. For this report, the term is defined as a method that measures subsurface conductivity by low-frequency electromagnetic induction. This method uses a coil placed on the surface that transmits electromagnetic pulses that induce eddy current loops in the layered strata below the transmitting loop. The induced loop currents are in theory directly proportional to the resistance of the strata. The induced current produces a secondary field current that can be sensed by a receiving coil placed a fixed distance from the transmitting coil. The reading is a bulk measurement of conductivity of the strata directly below the transmitting loop to the effective depth of the instrument. The instruments effective depth is related to the distance between the transmitting and receiving coils. The electromagnetic system usually measures conductivity of the materials in millimhos per meter and is easily converted to resistivity. Conductivity is the reciprocal of resistivity.

The electromagnetic system determines the conductivity of the strata that is related to the soil and rock geophysical and geochemical properties. Properties such as porosity, permeability, concentrations of colloids and dissolved electrolytes in the pores, and conductive minerals all influence conductivity, but the most influential factor is water content. Because water is the main factor, aquifers and brine pockets can be detected. Pipes, waste containers, metallic debris, and wire lines can also be detected.

Electromagnetic systems can be used to profile and map strata. Both stationary and mobile systems are available. Mobile systems are capable of taking continuous readings. A diagram of the basic system configuration is shown in Figure MON-A.7.

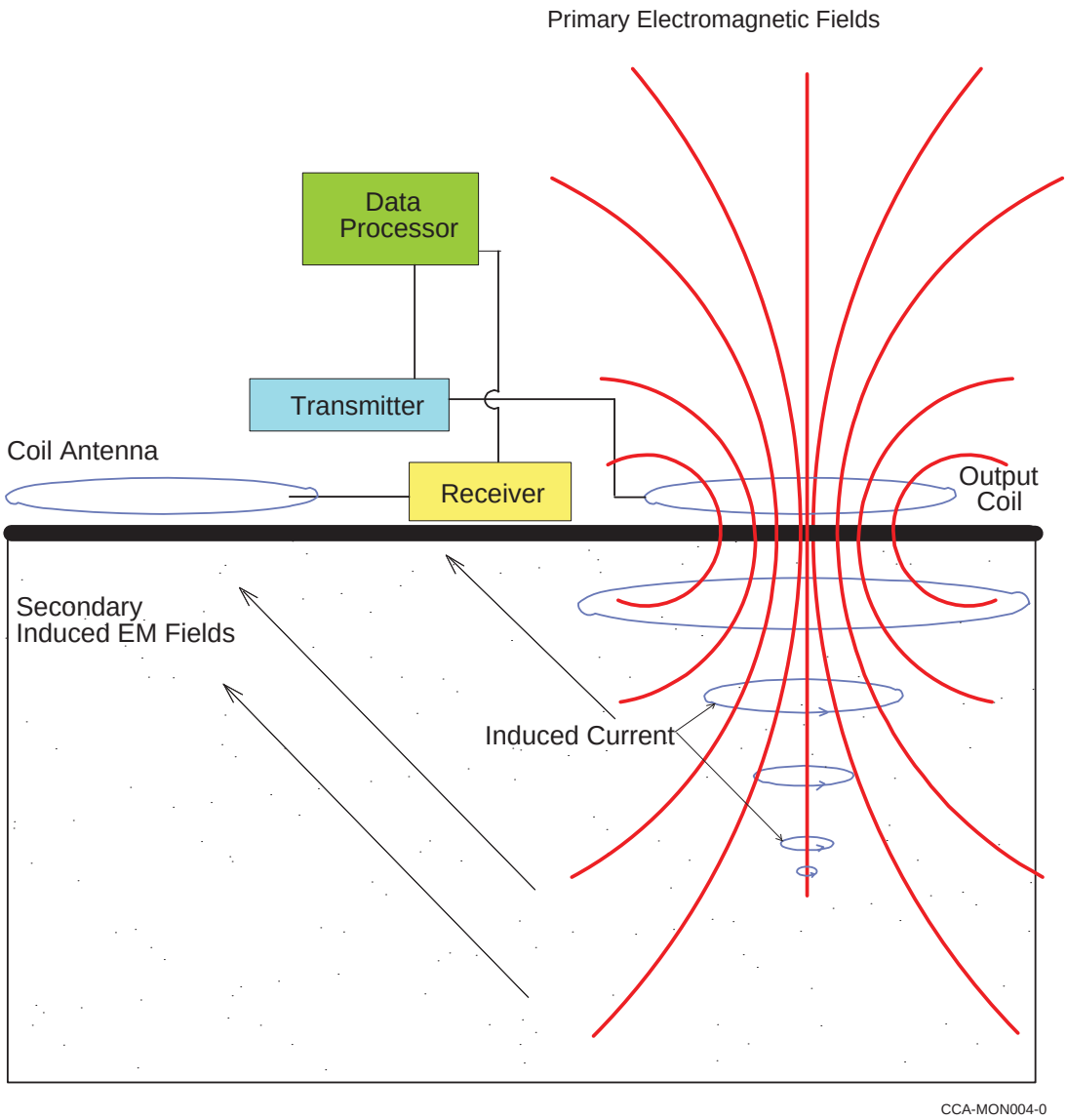

Figure MON-A.7. Electromagnetic Survey Technique

MON-A-6.4.1 Advantages of Electromagnetic Conductivity Surveys

The electromagnetic method is nonintrusive and can detect brine occurrences, strata layers with differing physical properties, and aquifers. Mapping of an area can be compared to subsequently acquired data to determine changes such as brine movements. The depth and area of brine pockets can be determined which can then be used to estimate the volumes of the pockets. Electromagnetic surveys may be used to locate waste after placement.

The electromagnetic method does not require ground contact and the measurements can be taken continuously. Methods of this nature have good repeatability. Measurements can be made at ground level or from aerial surveys.

MON-A-6.4.2 Disadvantages of Electromagnetic Conductivity Surveys

Electromagnetic technology falls short in data interpretation when a highly resistive layer is sandwiched between two highly conductive layers. Strata can have the same relative conductivity but be entirely different geologically. This method is not concise enough to be a stand-alone method, but can be used along with other geophysical techniques to interpret the strata.

The results can vary with ground moisture content. Results after substantial rains are significantly different than those performed after prolonged droughts. Interpretation of the data must account for these variations.

MON-A-6.4.3 Past Electromagnetic Conductivity Survey Work

Several electromagnetic type surveys were performed by SNL. One survey was initiated to map brine occurrences in the strata above and below the repository. The survey measured 36 locations in a 0.9- by 0.6-mile (1.5- by 1.0-kilometer) grid directly over the repository. Two other measurements were made, one at the WIPP-12 borehole and the other at the DOE-1 borehole. A calibration measurement was made at ERDA-9. The final interpretation of the survey data details brine occurrences. These results correlated well with the depths of the brine occurrences found at WIPP-12 and ERDA-9 (Earth Technology Corporation 1988).

When comparing the results of electromagnetic survey data with borehole logs, the accuracy of determining the depth to brine is better than 246 feet (75 meters) at depths between 3,280 to 4,920 feet (1,000 to 1,500 meters).

Aeromagnetic survey maps are available from the U.S. Geological Survey (Map GP-861, Carlsbad/West Texas) and Aero Service Library (No. 43-6, Carlsbad/West Texas) (Elliot Geophysical Co. 1976).

MON-A-6.4.4 Current Electromagnetic Conductivity Survey Work

No electromagnetic work is currently being performed.

MON-A-6.4.5 Define Uses of Electromagnetic Conductivity Surveys for Postclosure Monitoring

Electromagnetic surveying is capable of detecting water or brine occurrences, and can differentiate layers with varying physical properties. This technique could be used to monitor the facility after closure to determine if brine has migrated into the shafts, boreholes and/or repository.

The performance of the shaft, borehole seals, and boreholes could be monitored to determine if they are maintaining the isolation between the aquifers in the Rustler Formation. The repository

could be mapped directly after the repository is sealed and included in the baseline data to be used for comparison at a later date.

MON-A-6.5 Resistivity Surveys

The resistivity method is similar in nature to the electromagnetic method. Resistivity measures the resistance of the rock and electromagnetic measures the conductance. Resistance is the reciprocal of conductance. The resistivity of the rock and soil is influenced by the same factors listed in the previous section for conductivity. By varying the electrode spacing geometries and currents, different parameters can be measured. Two specific methods used during WIPP siting are called Schlumberger sounding and gradient array profiling.

The resistivity method uses four sets of electrodes on the surface, spaced in a specific geometry. Two electrodes are energized to create a current through the strata between the electrodes. The second pair of electrodes measures the potential produced from the first pair. The strata's resistivity can be calculated from the potential and electrode geometry and spacing.

As with the other types of geophysical monitoring methods, resistivity measurements can be used to perform sounding and profiling. Profiling maps the changes in the subsurface resistivity horizontally. Sounding can detect vertical changes in subsurface resistivity. The interpretation of the results can be used to determine the depth and thickness of geologic layers of different resistivity. This method can detect soil thickness and depth to aquifers or brine layers. A diagram describing the basic system configuration is shown in Figure MON-A.8.

MON-A-6.5.1 Advantages of Resistivity Surveys

The gradient array method is a relatively simple method. The electrodes are separated at large distances which enables economical mapping of large areas. The advantages of this method are identical to the electromagnetic method.

MON-A-6.5.2 Disadvantages of Resistivity Surveys

Variations in placement will give differing results if the survey is repeated in the same area. The resistivity surveys require direct ground contact and cannot be performed continuously. The condition of the surface layer can affect the results because variation in the soils moisture content can be detected. Measurements performed shortly after rains will be significantly different than measurements taken after prolonged droughts. However, this can be accounted for in the interpretation of the results. Resistivity also has the same disadvantages as the electromagnetic method.

MON-A-6.5.3 Past Resistivity Survey Work

Extensive resistivity surveys were conducted during the siting of the WIPP from 1976 to 1978. Areas around suspected breccia pipes and sinks (off-site) were surveyed to determine if resistivity surveys could be used to detect these structures within the WIPP site. All zones of the WIPP site were surveyed. Mining Geophysical Surveys, Inc. performed 53 Schlumberger array soundings and approximately 391 line miles (629 kilometers) of gradient array profiling (9,880 measurements) (Elliot Geophysical Co. 1977).

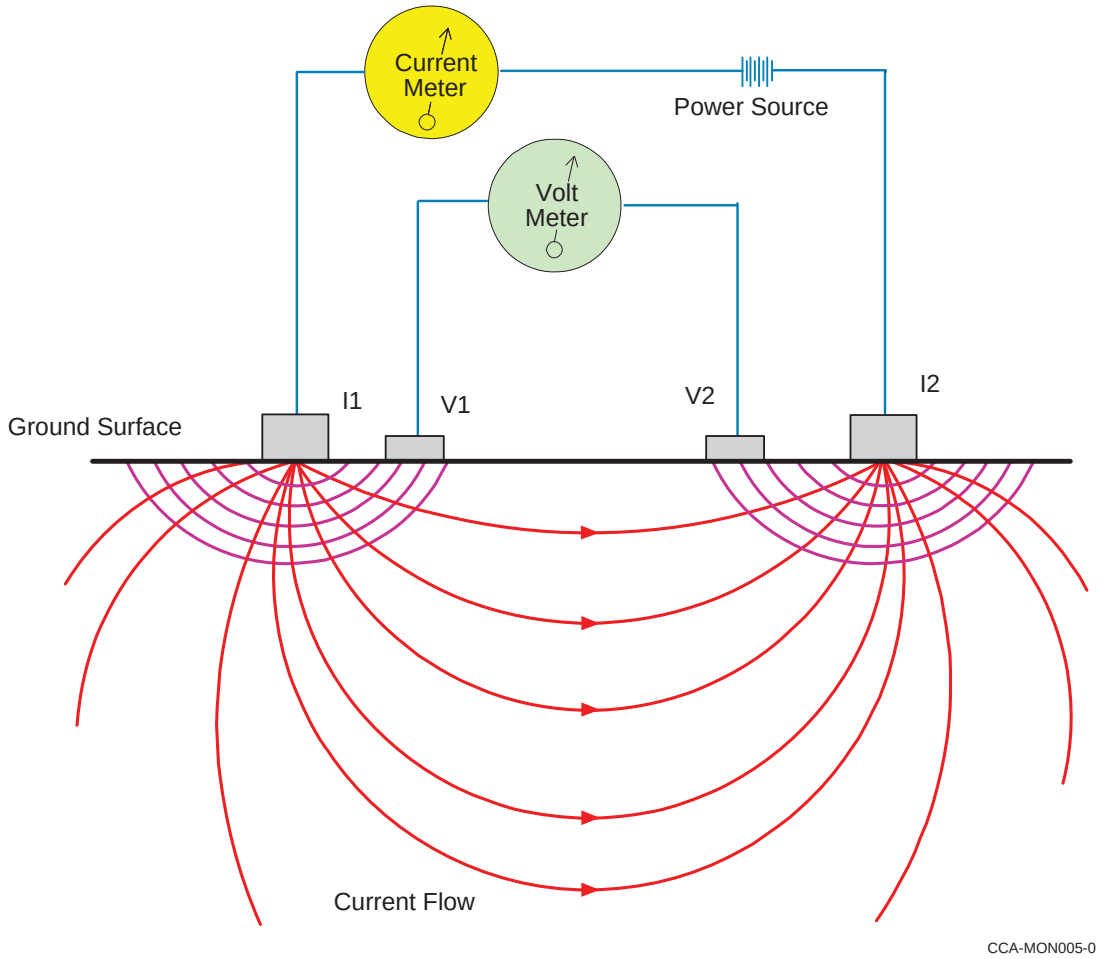

Figure MON-A.8. Resistivity Survey Content

MON-A-6.5.4 Current Resistivity Survey Work

No resistivity work is currently being performed.

MON-A-6.5.5 Define Uses of Resistivity Surveys for Postclosure Monitoring

This technology can be used along with electromagnetic techniques to gather data immediately after the repository is sealed. Both profiling and sounding would be performed to produce geological maps of the strata's resistivity. When the surveys are made, the exact locations and methods used could be carefully documented. If possible, research could be required to develop a system for electrode placement to ensure good repeatability in the surveys. This data would be documented in the baseline database for future comparison.

MON-A-6.6 Environmental Monitoring

Environmental monitoring of the WIPP repository will be performed during the operational and decontamination-and-decommissioning periods. The C&C between the state of New Mexico and the DOE requires radiological environmental monitoring for at least five years after final facility closure. This agreement specifies that the environmental monitoring program in place

during the operational phase must be continued after closure and decommissioning for at least two years, and that an abbreviated program with a limited number of radiological air, soil, water, and background samples be continued for the following three years.

The postclosure environmental monitoring program is required to include the following (DOE 1994a):

- Radiological Environmental Monitoring (first two years after decontamination and decommissioning)

  - Airborne particulate
    lo-vol sampling, eight stations

  - Vegetation
    four sites

  - Beef
    annual muscle samples if available

  - Game animals
    annual muscle samples of rabbits and quail.

  - Soil samples
    annual, multiple samples at multiple depths at six locations.

  - Surface and drinking water
    annual surface water samples from 12 major bodies of surface water in the vicinity of the site (drinking water will not exist after decontamination and decommissioning)

  - Groundwater
    annually, one sample from eight of the wells within the 16 sections boundary taken from the Culebra Dolomite.

  - Aquatic foodstuffs
    samples of catfish taken from the Pecos River and Brantley Lake and analysis annually.

  - Sediment sampling
    annual samples taken from the Hill and Indian tank and the Pecos River near Artesia and Malaga, New Mexico.

- Abbreviated radiological environmental monitoring (three, four, and five years after decontamination and decommissioning).

  - Airborne particulate
    intermittent operation of the state-operated high-volume air sampling stations.

- Soil
  four annual soil surface samples.

- Water
  four annual well water samples.

Only the radiological environmental monitoring techniques that apply after final closure are included. Items such as effluent monitoring at the exhaust shaft were not included because they do not apply after final facility closure.

Environmental monitoring has been an ongoing program since the WIPP's inception. Baseline environmental data were gathered and reported in annual reports and an environmental monitoring plan was created. The current operational environmental monitoring plan is detailed in the *Waste Isolation Pilot Plant Environmental Monitoring Plan*, WIPP/DOE 94-024 (DOE 1994a) and the *Waste Isolation Pilot Plant Site Environmental Report for the Calendar Year 1993*, DOE/WIPP 94-2033 (DOE 1994b).

MON-A-6.7 Direct Repository Monitoring

From earlier discussions, no proposed postclosure monitoring techniques include technologies to directly monitor the repository. This is due to the inherent difficulties imposed by the noninvasive requirement. No wiring or boreholes will be used to connect monitoring equipment in the repository to the surface.

The U.S. Bureau of Mines and commercial companies throughout the world are currently researching techniques to communicate through the strata to mine working areas using very-low frequency and ultra-low frequency electromagnetic radiation. Several companies have developed mine paging systems that use very-low frequency to warn workers within the mine using a system placed on the surface. One system can transmit messages with up to 32 characters to mobile mine pagers. This technology shows promise in remote instrumentation communication that could directly monitor the repository. It has been demonstrated in other salt mines that communication from the surface to the depth of the WIPP repository is possible.

Recently, researchers have started to investigate methods to remotely monitor the sealed rooms and panels. This work uses very-low frequency technology to link sensors and equipment in sealed rooms to the data recorder without a hardwired link. Current work is focused on communication from where the link between the transmitter and receiver is only 10 to 33 feet (3 to 10 meters).

Very-low frequency could be used to transmit data from the surface to equipment located in the repository but the problem lies in communicating the sensor data to the surface. The power required to transmit between the surface and the underground using the current technology is related to the strata conductivity, the output power at the transmitter, and the antenna design. Tests performed in actual mines used large loop antennas on the surface to transmit the signal. Tests have shown that loop diameter is more important in transmission efficiency than output power. Antennas ranging from 98 feet to over 328 feet (30 meters to over 100 meters) in diameter have been used (DOI 1991).

There are many problems that must be overcome to directly monitor the repository after closure. Some of these problems are listed below.

- Future sensor and transducer calibration would not be possible,
- Sensor longevity in the repository environment is not likely,
- Data collection and transmission power requirements could be problematic, and
- Antenna locations and sizes could pose issues with regard to other surface structures and activities.

MON-A-6.7.1 Sensor Calibration

Over time, most sensors, such as pressure, gas analyzer, and extensometer sensor and transducer, experience some change in resolution or drift. Any type of sensor and transducer used would need to operate for 100 years without recalibration. To overcome this problem, redundant sensors, sensor drift calculations, and accessible sensors as standards could be used to limit the induced errors. However, this would not ensure accuracy over the required time frame.

MON-A-6.7.2 Sensor Longevity

The sensors used for postclosure monitoring would be required to operate in a salt/brine environment for over 100 years. This imposes the biggest obstacle in direct repository monitoring. Corrosion, oxidation, and various chemical reactions would easily limit the life span to less than 50 years.

MON-A-6.7.3 Data Collection and Transmission Power Requirements

A power source that could operate for the time required is not currently available. Battery systems have limited shelf lives and capacities. Lithium-type batteries have the longest shelf life of the common battery types. Standard shelf lives of five to 10 years at their rated capacity is standard with some manufacturer's claiming 80-percent capacity after 15 years. Because the capacity requirements are dependent on the equipment load, the highest current requirement would occur during data transmittal. From experimental work, an estimate of at least 350 watts may be required to transmit to the surface. This can be accomplished with standard power sources for the short-term, but other currently unavailable methods of power generation would be required for the long-term.

One potential method is power transmission and retention. Power could be transmitted from the surface using ultra-low frequency energy and an antenna would intercept this energy and store it in capacitors or a special battery. Because the system could be charged for long periods of time between data transmissions, only a small amount of surface transmitted power is required. The problem with this approach is power storage.

The chemical nature of rechargeable batteries limits their life span. The effects of oxidation, outgasing, and heat damage will cause a battery to fail. The life span of most common rechargeable (lead acid, gel, and nickel cadmium) batteries is dependent on the number of

recharge cycles, the rate of discharge, and charge rates. Under favorable conditions, most rechargeable batteries can last up to 10 years.

The capacitor is a device that stores energy on two plates separated by an insulator. Capacitors can be designed for this application that would last the required time frame. The problem associated with capacitors is related to power storage capability and size. In comparison, a capacitor and a battery with the same approximate volume do not have the same energy storage capacity. For example, a one-microfarad capacitor charged to 1,000 volts has 0.5 Joules of energy storage, a 500-mAh nickel cadmium (1.2 volts) of similar volume has 2,160 Joules of energy storage. A capacitor that has this energy storage potential would be extremely large (4,320 times larger).

Satellite power sources use nuclear energy to generate power. The systems are not considered off-the-shelf technology. However, work is progressing on a nuclear heat power source using (almost) off-the-shelf technology. One experimental study calls this type of power source a Powerstick (Chmielewski and Ewell 1994). This theoretical device would use a nuclear heat source and a thermopile to generate an electrical potential. The heat source is a common satellite product used to heat instrumentation. The power source is capable of producing 42 milliwatts at 15 volts initially and would degrade to 37 milliwatts at 14 volts in 10 years. These power sources could be used to slowly charge batteries and/or capacitors that would then be used for a short duration, high-demand data transmission cycle or in parallel for a higher current source.

The regulatory issues associated with nuclear power sources have not been researched. If the remotely-handled waste could supply an adequate heat source and WIPP receives remotely-handled waste, the regulatory issues may be overcome.

The nuclear and thermopile power source technology has not been proven and there is no prototype as yet. Advances in battery design and the development of this nuclear power source could eventually allow this technology to power a direct repository monitor.

MON-A-6.7.4 Antenna Location and Size

The size of the antenna may pose a problem in the mine setting. If the antenna is placed inside a room, diameters are limited to a maximum of approximately 328 feet (100 meters). If the antenna can be wrapped around a pillar, the antenna would have a radius of approximately 164 feet (50 meters) but diameters between 32.8 feet and 328 feet (10 meters and 100 meters) would require special provisions. Also, the effects of the metal in the room will increase the power requirement. These problems can be overcome and experimentation would be needed to verify the effectiveness of the antenna design.

From current technology, no known system is currently available that could be used to directly transmit data to the surface without a hardwired link. Extensive research and development is needed to develop such a system; however, the systems longevity will be suspect, since actual long-term testing could not be accomplished and new technologies are rarely foolproof. For this reason, direct repository monitoring is not recommended at this time for postclosure monitoring.

MON-A-6.8 Conclusion

There is no single geophysical technical exploratory technique that can determine the condition of the surveyed strata. Several techniques are used to gather data to assess the geological structure that is being examined because interpretation of one technique often uses data from another. For this reason, no single technique could be used to fully assess the repository's condition. One technique can be used as an identifier to alert that a condition may exist and other techniques can be used in unison to assess and validate the condition.

From the review of geophysical survey techniques, the best current monitoring technology that can be used for a postclosure monitoring identifier is subsidence. This method is the most practical because it is a simple, repeatable, low-cost, low-maintenance, low-technology approach to monitoring the repository. This method should be used as a primary monitor technique for determining that a possible repository performance problem exists. Other techniques can then be utilized to determine the cause of the problem.

A combination of seismic, electromagnetic, resistivity, and gravitational surveys can be used to assess repository performance. However, it is not practical to perform these on a regular basis. These techniques are also not needed if there is good confidence that a performance-related event will not occur. For this reason, an initial collection of surveys could be compiled and used as a standard to assess future data and perform subsidence monitoring to forewarn of changing conditions that may significantly affect repository performance.

MON-A-7. POSTCLOSURE MONITORING PROGRAM SUMMARY

Physical, chemical, economical, and technical factors have been included in the conceptual approach to designing a practical, yet effective, postclosure monitoring system. The needed information can be obtained from a monitoring system composed of a subsidence network, a monitoring program, a baseline database, a closure review study, and a subsidence data study.

The following summarizes the postclosure monitoring program.

- The DOE will create a baseline database that includes data from developmental and operational phase activities.
- The DOE will perform a subsidence data study.
- The DOE will compile subsidence predictions and include any performance assessment-developed scenarios of repository performance which fall outside the baseline subsidence predictions. The DOE will develop proper benchmark locations over the repository. The subsidence predictions will be developed from the information available in the *Backfill Engineering Analysis Report (BEAR)* (WEC 1994b) and from any additional information provided by the performance assessment.
- The DOE will create a subsidence network over and around the facility.
- The DOE will perform a closure review study.

- The DOE will perform the following surveys to establish baseline data for the baseline database.
  - Seismic survey over the waste panels after final facility closure (one time).
  - Resistivity survey over the waste panels after final facility closure (one time).
  - Electromagnetic survey over the waste panels after closure (one time).
  - Gravitational survey after final facility closure (one time).
  - Subsidence survey (throughout the program lifetime).
  - Obtain and archive core samples from previous core work (one time).
- The DOE will initiate the monitoring program after closure. The DOE will perform periodic leveling surveys of the subsidence network and develop a schedule for future surveys. The DOE will perform the radiological environmental monitoring program for two years and the abbreviated program for an additional three years.
- The DOE will compare leveling survey data to expected results.
- The DOE will perform periodic reviews at least every two years during the monitoring program to evaluate the monitoring schedule.
- The DOE will perform maintenance on RCRA wells, replacing casings as required or every 25 years until monitoring ceases. The DOE will monitor in accordance with the postclosure monitoring schedule and postclosure monitoring plan requirements.
- The DOE will perform maintenance on subsidence network as required (determined during the leveling surveys).

This monitoring concept is based on current technologies and data for monitoring repository performance. Future monitoring during the repository development and operational phases may provide data that lead to the conclusion that postclosure monitoring will not be relevant or may identify new parameters that must be monitored.

The monitoring techniques specified in this report can be used to meet the requirements in the current regulations governing the facility and to monitor performance of the facility. This concept provides for a reliable database against which future monitoring results can be compared.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix PA

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix PA

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ACRONYMS AND ABBREVIATIONS

AMG	algebraic multi-grid solver
CDF	cumulative distribution function
CCDF	complementary cumulative distribution function
CFR	Code of Federal Regulations
CH-TRU	contact-handled transuranic (waste)
DBR	direct brine release
DOE	United States Department of Energy
DDZ	drilling damaged zone
DRZ	disturbed rock zone
EPA	United States Environmental Protection Agency
FEP	feature, event, or process
LHS	Latin Hypercube Sample
LMG	Link- algebraic multi-grid solver
LWB	Land Withdrawal Boundary
MB	Marker Bed
PA	performance assessment
PAVT	Performance Assessment Verification Test
PCS	panel closure system
PDF	probability density function
PDE	partial differential equations
PRCC	partial rank correlation coefficient
RH-TRU	remote-handled transuranic (waste)
SMC	Salado Mass Concrete
SOR	successive over-relaxation
TRU	transuranic (waste)
TVD	Total Variation Diminishing
WIPP	Waste Isolation Pilot Plan

PA-1.0 INTRODUCTION

This appendix presents the mathematical models used to evaluate performance of the Waste Isolation Pilot Plant (WIPP) and the results of these models for the CRA-2004 Performance Assessment (PA). This appendix supplements information presented in Chapter 6 of this application.

This appendix is organized as follows. Section PA-2.0 describes the overall conceptual structure of the CRA-2004 PA. As described in Section 6.1, the WIPP PA is designed to answer the requirements of Title 40 Code of Federal Regulations (CFR) Part 191, and thus involves three basic entities: (1) A probabilistic characterization of different futures that could occur at the WIPP site over the next 10,000 years, (2) Models for the physical processes that take place at the WIPP site and for the estimation of potential radionuclide releases that may be associated with these processes, and (3) A probabilistic characterization of the uncertainty in the models and parameters that underlie the WIPP PA. Section PA-2.0 is supplemented by Attachment SCR, which documents the results of the screening process for features, events, and processes (FEPs) that are retained in the conceptual models of repository performance.

Section PA-3.0 describes the probabilistic characterization of different futures. This characterization plays an important role in the construction of the complementary cumulative distribution function (CCDF) specified in 40 CFR § 191.13. Regulatory guidance and extensive review of the WIPP site resulted in identification of exploratory drilling for natural resources and the mining of potash as the only significant disruptions at the WIPP site with the potential to affect radionuclide releases to the accessible environment (Section 6.2.5). Section PA-3.0 summarizes the stochastic variables that represent future drilling and mining events in the PA.

Section PA-4.0 presents the mathematical models for the physical processes that take place at the WIPP and for the estimation of potential radionuclide releases. The mathematical models implement the conceptual models described in Section 6.4, and permit the construction of the CCDF specified in 40 CFR § 191.13. Models presented in Section PA-4.0 include: two-phase (i.e., gas and brine) flow in the vicinity of the repository; radionuclide transport in the Salado; releases to the surface at the time of a drilling intrusion due to cuttings, cavings, spallings, and direct releases of brine; brine flow in the Culebra Dolomite Formation; and radionuclide transport in the Culebra Dolomite. Section PA-4.0 is supplemented by Attachments MASS, TFIELD, and PORSURF. Attachment MASS discusses the modeling assumptions used in the WIPP PA. Attachment TFIELD discusses the generation of the transmissivity fields used to model fluid flow in the Culebra. Attachment PORSURF presents results of modeling the effects of excavated region closure, waste consolidation, and gas generation in the repository.

Section PA-5.0 discusses the probabilistic characterization of parameter uncertainty, and summarizes the uncertain variables incorporated into the 2004 PA, the distributions assigned to these variables, and the correlations between variables. Section PA-5.0 is supplemented by Attachments PAR and SOTERM. Attachment PAR catalogs the full set of parameters used in the CRA-2004 PA. Attachment SOTERM describes the actinide source term for the WIPP performance calculations, including calculation of the mobile concentrations of actinides that may be released from the repository in brine.

Section PA-6.0 summarizes the computational procedures used in the CRA-2004 PA, including: sampling techniques (i.e., random and Latin hypercube sampling); sample size; statistical confidence for mean CCDF; generation of Latin hypercube samples (LHSs); generation of individual futures; construction of CCDFs; calculations performed with the models discussed in Section PA-4.0; construction of releases for each future; and the sensitivity analysis techniques in use.

Section PA-7.0 presents the results of the PA for an undisturbed repository. Releases from the undisturbed repository are determined by radionuclide transport in brine flowing from the repository to the land withdrawal boundary (LWB) through the marker beds (MBs) or shafts (Section 6.3.1. Releases in the undisturbed scenario are used to demonstrate compliance with the individual and groundwater protection requirements in 40 CFR Part 191 (Chapter 8).

Section PA-8.0 presents PA results for a disturbed repository. As discussed in Section 6.2.3, the only future events and processes in the analysis of disturbed performance are those associated with mining and deep drilling. Release mechanisms include direct releases at the time of the intrusion via cuttings, cavings, spallings, and direct release of brine; and radionuclide transport up abandoned boreholes to the Culebra and thence to the land withdrawal boundary. Section PA-8.0 presents results for the most significant output variables from the PA models, accompanied by sensitivity analyses to determine which subjectively uncertain parameters are most influential in the uncertainty of PA results.

Section PA-9.0 presents the set of CCDFs resulting from the CRA-2004 PA. This material supplements Section 6.5, which demonstrates compliance with the containment requirements of 40 CFR § 191.13. Section PA.9.0 includes sensitivity analyses that identify which uncertain parameters are most significant in the calculation of releases.

This appendix follows the approach used by Helton et al. (1998) to document the mathematical models used in the CCA PA and the results of that analysis. Much of the content of this appendix derives from Helton et al. (1998); these authors' contributions are gratefully acknowledged.

PA-2.0 CONCEPTUAL STRUCTURE OF THE PERFORMANCE ASSESSMENT

The conceptual structure of the CRA-2004 PA is unchanged from the CCA PA. Section 6.1 provides a general, less technical overview of the PA conceptual structure. This section of Appendix PA presents the conceptual basis for the CRA-2004 PA in a more formal manner. A corresponding presentation for the CCA PA is provided in Helton et al. (1998).

PA-2.1 Regulatory Requirements

The conceptual structure of the CRA-2004 PA derives from the regulatory requirements imposed on this facility. The primary regulation determining this structure is the Environmental Protection Agency's (EPA's) standard for the geologic disposal of radioactive waste, Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR Part 191) (EPA 1985, 1993), which is divided into three subparts. Subpart A applies to a disposal facility prior to decommissioning and limits the annual radiation doses members of the public can be exposed to from waste management and storage operations. Subpart B applies after decommissioning and sets probabilistic limits on cumulative releases of radionuclides to the accessible environment for 10,000 years (40 CFR § 191.13) and assurance requirements to provide confidence that 40 CFR Section 191.13 will be met (40 CFR Section 191.14). Subpart B also sets limits on radiation doses to members of the public in the accessible environment for 10,000 years of undisturbed performance (40 CFR § 191.15). Subpart C limits radioactive contamination of groundwater for 10,000 years after disposal (40 CFR § 191.24). The Department of Energy (DOE) must demonstrate a reasonable expectation that the WIPP will continue to comply with the requirements of Subparts B and C of 40 CFR Part 191.

The following is the central requirement in 40 CFR Part 191, Subpart B, and the primary determinant of the conceptual structure of the CRA-2004 PA (p. 38086, EPA 1985):

> § 191.13 Containment requirements:
>
> (a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:
>
> (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and
>
> (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).
>
> (b) Performance assessments need not provide complete assurance that the requirements of 191.13(a) will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with 191.13(a) will be achieved.

Section 191.13(a) refers to "quantities calculated according to Table 1 (Appendix A)," which means a normalized radionuclide release to the accessible environment based on the type of waste being disposed of, the initial waste inventory, and the size of release that may occur (EPA 1985, Appendix A). Table 1 of Appendix A specifies allowable releases (i.e., release limits) for individual radionuclides and is reproduced as Table PA-1 of this appendix. The WIPP is a repository to transuranic (TRU) waste, which is defined as "waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years, per gram of waste" (p. 38084, EPA 1985). The normalized release R for transuranic waste is defined by

$$R = \sum_i \left(\frac{Q_i}{L_i}\right)\left(1 \times 10^6\ Ci/C\right) \tag{1}$$

where Q_i is the cumulative release of radionuclide i to the accessible environment during the 10,000-year period following closure of the repository (curies), L_i is the release limit for radionuclide i given in Table PA-1 (curies), and C is the amount of TRU waste emplaced in the repository (curies). In the CRA-2004 PA, $C = 2.48 \times 10^6$ curies (Appendix TRU WASTE, Section TRU WASTE-2.3.1). Further, accessible environment means (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all of the lithosphere that is beyond the controlled area; and controlled area means (1) a surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system and (2) the subsurface underlying such a surface location (40 CFR § 191.13).

To help clarify the intent of 40 CFR Part 191, the EPA promulgated 40 CFR Part 194, Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance With the 40 CFR Part 191 Disposal Regulations. There, the following elaboration on the intent of 40 CFR § 191.13 set out.

> § 194.34 Results of performance assessments.
>
> (a) The results of performance assessments shall be assembled into "complementary, cumulative distributions functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events.
>
> (b) Probability distributions for uncertain disposal system parameter values used in performance assessments shall be developed and documented in any compliance application.
>
> (c) Computational techniques, which draw random samples from across the entire range of the probability distributions developed pursuant to paragraph (b) of this section, shall be used in generating CCDFs and shall be documented in any compliance application.
>
> (d) The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability.

Table PA-1. Release Limits for the Containment Requirements (EPA 1985, Appendix A, Table 1)

Radionuclide	Release Limit L_i per 1000 MTHM[1] or other unit of waste[2]
Americium (Am)-241 or –243	100
Carbon 14	100
Cesium-135 or -137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium (Pu)-238, -239, -240, or -242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium (Th)-230 or -232	10
Tin-126	1,000
Uranium (U)-233, -234, -235, -236, or -238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1,000

[1] Metric tons of heavy metal exposed to a burnup between 25,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM

[2] An amount of transuranic wastes containing one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years

(e) Any compliance application shall display the full range of CCDFs generated.

(f) Any compliance application shall provide information which demonstrates that there is at least a 95 percent level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 of this chapter.

Three basic entities (EN1, EN2, EN3) underlie the results required by Sections 191.13 and § 194.34 and ultimately determine the conceptual and computational structure of the CRA-2004 PA:

EN1 - a probabilistic characterization of the likelihood of different futures occurring at the WIPP site over the next 10,000 years,

EN2 - a procedure for estimating the radionuclide releases to the accessible environment associated with each of the possible futures that could occur at the WIPP site over the next 10,000 years,

EN3 - a probabilistic characterization of the uncertainty in the parameters used in the definition of EN1 and EN2.

The preceding entities arise from an attempt to answer three questions about the WIPP:

Q1 - What events could occur at the WIPP site over the next 10,000 years?

Q2 - How likely are the different futures that could take place at the WIPP site over the next 10,000 years?

Q3 - What are the consequences of the different occurrences that could take place at the WIPP site over the next 10,000 years?

and one question about the PA:

Q4 - How much confidence can be placed in answers to these questions?

In the WIPP PA, EN1 provides answers to Q1 and Q2, EN2 provides an answer to Q3, and EN3 provides an answer to Q4. Together, EN1 and EN2 give rise to the CCDF specified in Section 191.13(a), and EN3 corresponds to the distributions specified by Section 194.34(b). The nature of EN1, EN2 and EN3, the role that they play in the CRA-2004 PA, and the method for constructing CCDFs are elaborated on in the next three sections.

PA-2.2 EN1: Probabilistic Characterization of Different Futures

The entity EN1 results from the scenario development process for the WIPP outlined in Section 6.3. The EN1 entity provides a probabilistic characterization of the likelihood of different futures that could occur at the WIPP site over the 10,000-year period specified in 40 CFR Part 191. Formally, EN1 is defined by a probability space $\left(\boldsymbol{X_{st}, S_{st}, p_{st}}\right)$, with the sample space X_{st} given by Equation (2).

$$\boldsymbol{X_{st}} = \left\{\boldsymbol{x_{st}} : \boldsymbol{x_{st}} \textit{ is a possible 10,000-year sequence of occurrences at the WIPP}\right\} \qquad (2)$$

The subscript st refers to stochastic (i.e., aleatory) uncertainty and is used because $\left(\boldsymbol{X_{st}, S_{st}, p_{st}}\right)$ is providing a probabilistic characterization of occurrences that may take place in the future (Helton 1997). Incorporation of stochastic uncertainty is fundamental to the DOE's methodology for performance assessment Section 6.1.2. It is this stochastic uncertainty that gives rise to the distribution of releases evident in a CCDF.

A probability space $\left(\boldsymbol{X, S, p}\right)$ consists of three components: a set X that contains everything that could occur for the particular "universe" under consideration, a suitably restricted set S of subsets of X and a function p defined for elements of S that actually defines probability (Feller 1971). In the terminology of probability theory, X is the sample space, the elements of X are elementary events, the subsets of X contained in S are events, and p is a probability measure. In most applied problems, the function p defined on S is replaced by a probability density function (PDF) d (e.g., d_{st} in Figure PA-1).

In the CCA PA, the scenario development process for the WIPP identified exploratory drilling for natural resources as the only disruption with sufficient likelihood and consequence for

inclusion in the definition of EN1 (CCA Appendix SCR [DOE 1996]). Reexamination of the FEPs and the scenario development process for the CRA-2004 PA did not change this conclusion (Section 6.2.6). In addition, 40 CFR Part 194 specifies that the occurrence of mining within the land withdrawal boundary must be included in the PA. As a result, the elements $\boldsymbol{x}_{st}$ of X_{st} are vectors of the form

$$\boldsymbol{x}_{st} = [\underbrace{t_1, e_1, l_1, b_1, p_1, \mathbf{a}_1}_{1^{st}\ intrusion}, \underbrace{t_2, e_2, l_2, b_2, p_2, \mathbf{a}_2}_{2^{nd}\ intrusion}, \ldots, \underbrace{t_n, e_n, l_n, b_n, p_n, \mathbf{a}_n}_{n^{th}\ intrusion}, t_{min}] , \qquad (3)$$

where n is the number of drilling intrusions, t_i is the time (year) of the ith $_{intrusion}$, l_i designates the location of the ith intrusion, e_i designates the penetration of an excavated or nonexcavated area by the ith intrusion, b_i designates whether or not the ith intrusion penetrates pressurized brine in the Castile Formation, p_i designates the plugging procedure used with the ith intrusion (i.e., continuous plug, two discrete plugs, three discrete plugs), $\mathbf{a}_i$ designates the type of waste penetrated by the ith intrusion (i.e., no waste, contact-handled (CH-TRU) waste, remote-handled (RH-TRU) waste), and t_{min} is the time at which potash mining occurs within the land withdrawal boundary.

In the development of $(\boldsymbol{X}_{st}, \boldsymbol{S}_{st}, \boldsymbol{p}_{st})$, the probabilistic characterization of n, t_i, l_i and e_i is based on the assumption that drilling intrusions will occur randomly in time and space (i.e., follow a Poisson process), the probabilistic characterization of b_i derives from assessed properties of brine pockets, the probabilistic characterization of $\mathbf{a}_i$ derives from the properties of the waste emplaced in the WIPP, and the probabilistic characterization of p_i derives from current drilling practices in the sedimentary basin (i.e., the Delaware Basin) in which the WIPP is located. A vector notation is used for $\mathbf{a}_i$ because it is possible for a given drilling intrusion to penetrate several different types of waste. Further, the probabilistic characterization for t_{min} follows from the guidance in 40 CFR Part 194 that the occurrence of potash mining within the land withdrawal boundary should be assumed to occur randomly in time (i.e., follow a Poisson process with a rate constant of $\lambda_m = 10^{-4}$ yr^{-1}), with all commercially viable potash reserves within the land withdrawal boundary being extracted at time t_{min}.

With respect to the three fundamental questions discussed about, X_{st} provides an answer to Q1, while S_{st} and p_{st} provide an answer to Q2. In practice, Q2 will be answered by specifying distributions for n , t_i , e_i , l_i , b_i , p_i , $\mathbf{a}_i$, and t_{min} , which in turn lead to definitions for S_{st} and p_{st} . The CCDF in 40 CFR Part 191 will be obtained by evaluating an integral involving $(\boldsymbol{X}_{st}, \boldsymbol{S}_{st}, \boldsymbol{p}_{st})$ (Figure PA-1). The definition of $(\boldsymbol{X}_{st}, \boldsymbol{S}_{st}, \boldsymbol{p}_{st})$ is discussed in more detail in Section PA-3.0.

PA-2.3 EN2: Estimation of Releases

The entity EN2 is the outcome of the model development process for the WIPP and provides a way to estimate radionuclide releases to the accessible environment for the different futures (i.e.,

elements $\mathbf{x}_{st}$ of X_{st}) that could occur at the WIPP. Estimation of environmental releases corresponds to evaluation of the function f in Figure PA-1. Release mechanisms associated with f include direct transport of material to the surface at the time of a drilling intrusion (i.e., cuttings, spallings, brine flow) and release subsequent to a drilling intrusion due to brine flow up a borehole with a degraded plug (i.e., groundwater transport).

The function f in Figure PA-1 is evaluated by a series of computational models shown in Figure PA-2. These computational models implement the conceptual models representing the repository system as described in Section 6.4, and the mathematical models for physical processes that are presented in Section PA-4.0. Most of the computational models involve the numerical solution of partial differential equations used to represent processes such as material deformation, fluid flow and radionuclide transport.

The models in Figure PA-2 are too complex to permit a closed form evaluation of the integral in Figure PA-1 that defines the CCDF specified in 40 CFR Part 191. Rather, a Monte Carlo procedure is used in the CRA-2004 PA. Specifically, elements $\mathbf{x}_{st,i}$, i = 1, 2, …, nS are randomly sampled from X_{st} in consistency with the definition of $\left(X_{st}, S_{st}, p_{st}\right)$. Then, the integral in Figure PA-1, and hence the associated CCDF, is approximated by

$$prob\left(Rel > R\right) = \int_{S_{st}} \delta_R\left[f\left(\mathbf{x}_{st}\right)\right] d_{st}\left(\mathbf{x}_{st}\right) dV_{st} = \sum_{i=1}^{nS} \delta_R\left[f\left(\mathbf{x}_{st,i}\right)\right] / nS\,, \qquad (4)$$

where $\delta_R\left[f\left(\mathbf{x}_{st}\right)\right] = 1$ if $f\left(\mathbf{x}_{st}\right) > R$ and $\delta_R\left[f\left(\mathbf{x}_{st}\right)\right] = 0$ if $f\left(\mathbf{x}_{st}\right) \le R$ (Helton and Shiver 1996). However, the models in Figure PA-2 are also too computationally intensive to permit their evaluation for every element $\mathbf{x}_{st,i}$ of X_{st} in Equation (4). Due to this constraint, the models in Figure PA-2 are evaluated for representative elements of X_{st} and the results of these evaluations are used to construct values of f for the large number of $\mathbf{x}_{st,i}$ (e.g., nS = 10,000) in Equation (4). The representative elements are the scenarios E0, E1, E2, and E1E2 defined in Section PA-3.9; the procedure for constructing a CCDF from these scenarios is described in Section PA-6.0.

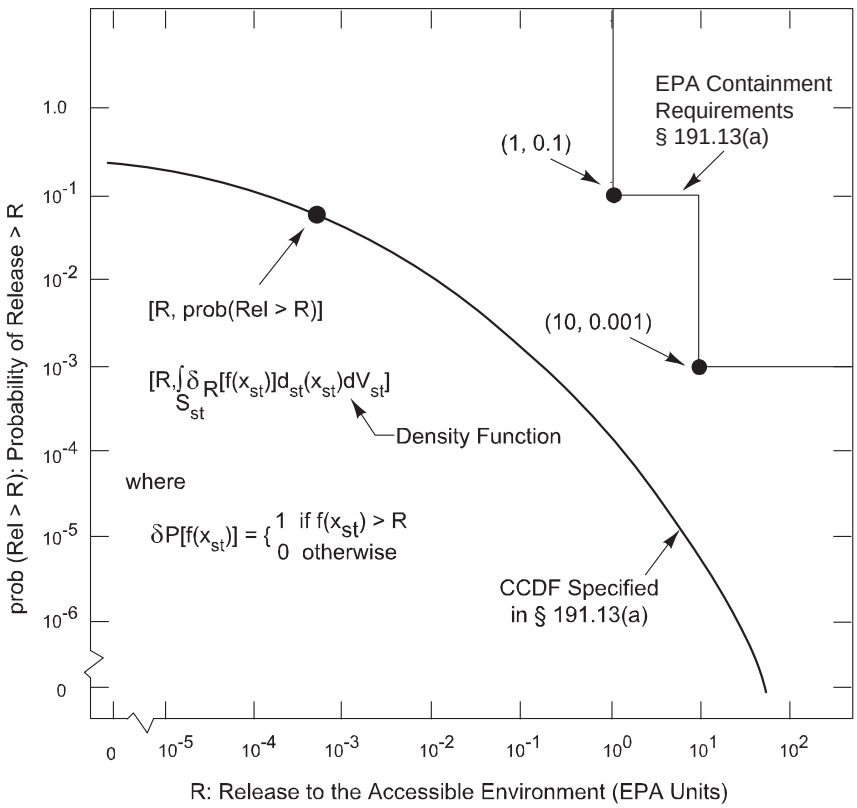

Figure PA-1. Construction of the CCDF Specified in 40 CFR Part 191, Subpart B.

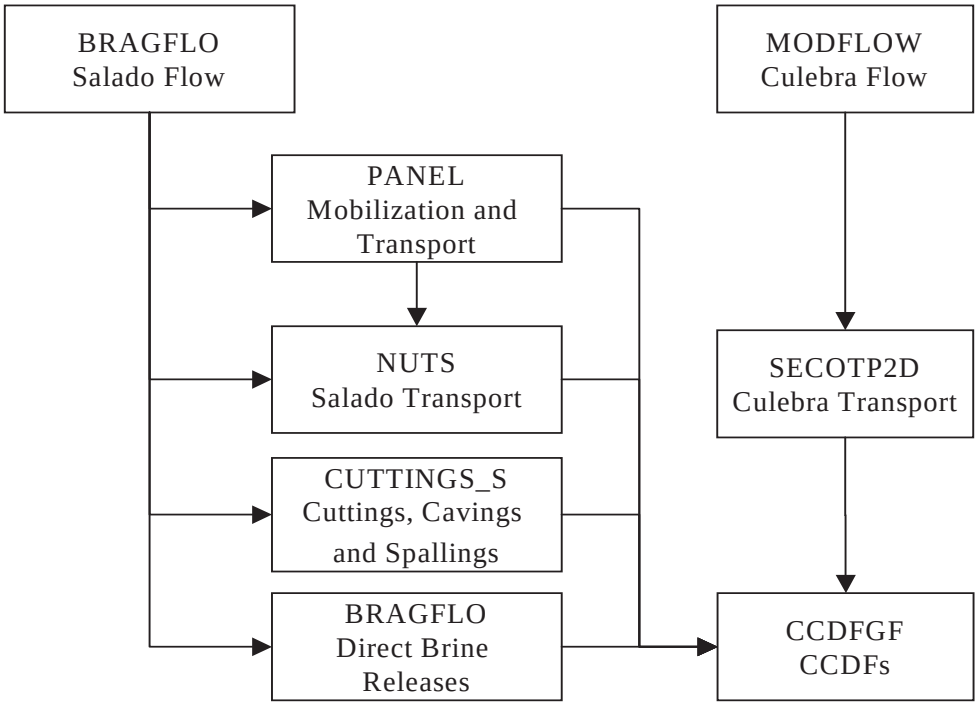

Figure PA-2. Computational Models Used in the CRA-2004 PA.

PA-2.4 EN3: Probabilistic Characterization of Parameter Uncertainty

The entity EN3 is the outcome of the data development effort for the WIPP (summarized in Chapter 2) and provides a probabilistic characterization of the uncertainty in the parameters that underlie the CRA-2004 PA. When viewed formally, EN3 is defined by a probability space $\left(X_{su}, S_{su}, p_{su}\right)$, with the sample space X_{su} given by Equation (5).

$$X_{su} = \left\{ \mathbf{x}_{su} : \mathbf{x}_{su} \textit{ is a possible vector of parameter values for the WIPP PA models} \right\} \tag{5}$$

The subscript su refers to subjective (i.e., epistemic) uncertainty and is used because $\left(X_{su}, S_{su}, p_{su}\right)$ is providing a probabilistic characterization of the possible inputs to the WIPP PA (Helton 1997). In practice, some elements of $\mathbf{x}_{su}$ could affect the definition of $\left(X_{st}, S_{st}, p_{st}\right)$ (e.g., the rate constant λ used to define the Poisson process for drilling intrusions) and other elements could relate to the models in Figure PA-2 that determine the function f in Figure PA-1 (e.g., radionuclide solubilities in Castile brine). Incorporation of subjective uncertainty is fundamental to the DOE's methodology for PA (Section 6.1.2).

If the value for $\mathbf{x}_{su}$ was precisely known, the CCDF in Figure PA-1 could be determined with certainty and compared with the boundary line specified in 40 CFR Part 191. However, given the complexity of the WIPP site and the 10,000-year time period under consideration, $\mathbf{x}_{su}$ can never be known with certainty. Rather, uncertainty in $\mathbf{x}_{su}$ as characterized by $\left(X_{su}, S_{su}, p_{su}\right)$ will lead to a distribution of CCDFs (Figure PA-3), with a different CCDF resulting for each possible value that $\mathbf{x}_{su}$ can take on. The proximity of this distribution to the boundary line in Figure PA-1 provides an indication of the confidence with which 40 CFR Part 191 will be met.

The distribution of CCDFs in Figure PA-3 can be summarized by distributions of exceedance probabilities conditional on individual release values (Figure PA-4). For a given release value R, this distribution is defined by a double integral over X_{su} and X_{st} (Helton 1996, 1997). In practice, this integral is too complex to permit a closed-form evaluation. Instead, the WIPP PA uses Latin hypercube sampling (McKay et al. 1979) to evaluate the integral over S_{su} and, as indicated in Equation (4), simple random sampling to evaluate the integral over X_{st}.

Specifically, a LHS $\mathbf{x}_{su,k}$, k = 1, 2, …, nLHS, is generated from S_{su} in consistency with the definition of $\left(X_{su}, S_{su}, p_{su}\right)$ and a random sample $\mathbf{x}_{st,i}$, i = 1, 2, …, nS, is generated from X_{st} in consistency with the definition of $\left(X_{st}, S_{st}, p_{st}\right)$. The probability $prob\left(p \le P \middle| R\right)$ is approximated by

$$prob\left(p \le P \mid R\right) \cong 1 - \sum_{k=1}^{nLHS} \delta_P \left[\sum_{i=1}^{nS} \delta_R \left[f\left(\mathbf{x}_{st,i}, \mathbf{x}_{su,k}\right)\right] / nS \right] / nLHS \tag{6}$$

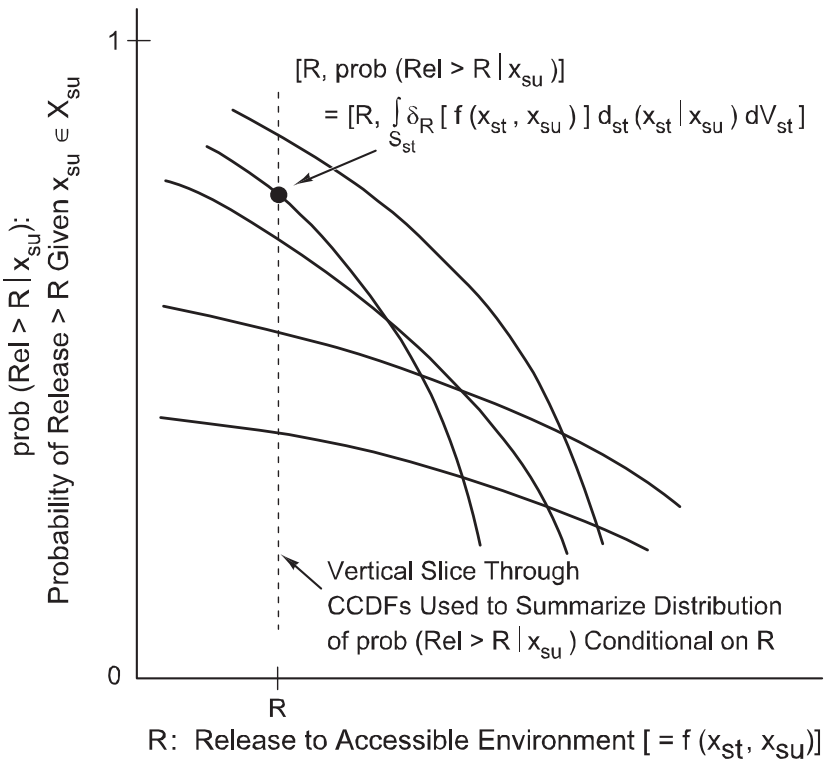

Figure PA-3. Distribution of CCDFs Resulting from Possible Values for $x_{su} \in X_{su}$.

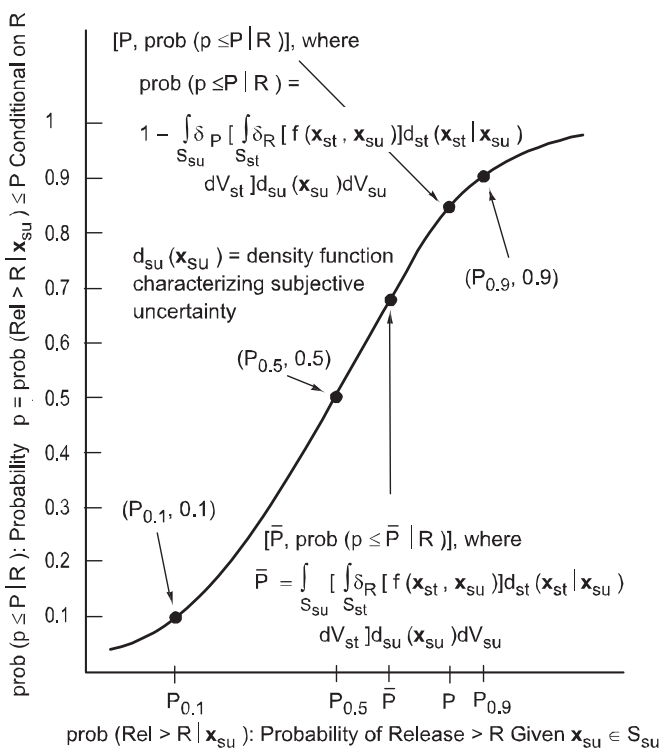

Figure PA-4. Distribution of Exceedance Probabilities Due to Subjective Uncertainty.

The result of the preceding calculation is typically displayed by plotting percentile values (e.g., $P_{0.1}$, $P_{0.5}$, $P_{0.9}$ in Figure PA-4) and also mean values for exceedance probabilities above the corresponding release values (i.e., R) and then connecting these points to form continuous curves (Figure PA-5). The proximity of these curves to the indicated boundary line provides an indication of the confidence with which 40 CFR Part 191 will be met.

With respect to the previously indicated questions, $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$ and results derived from $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$ (e.g., the distributions in Figure PA-3 and Figure PA-5) provide an answer to Q4. The definition of $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$ is discussed in more detail in Section PA-5.0.

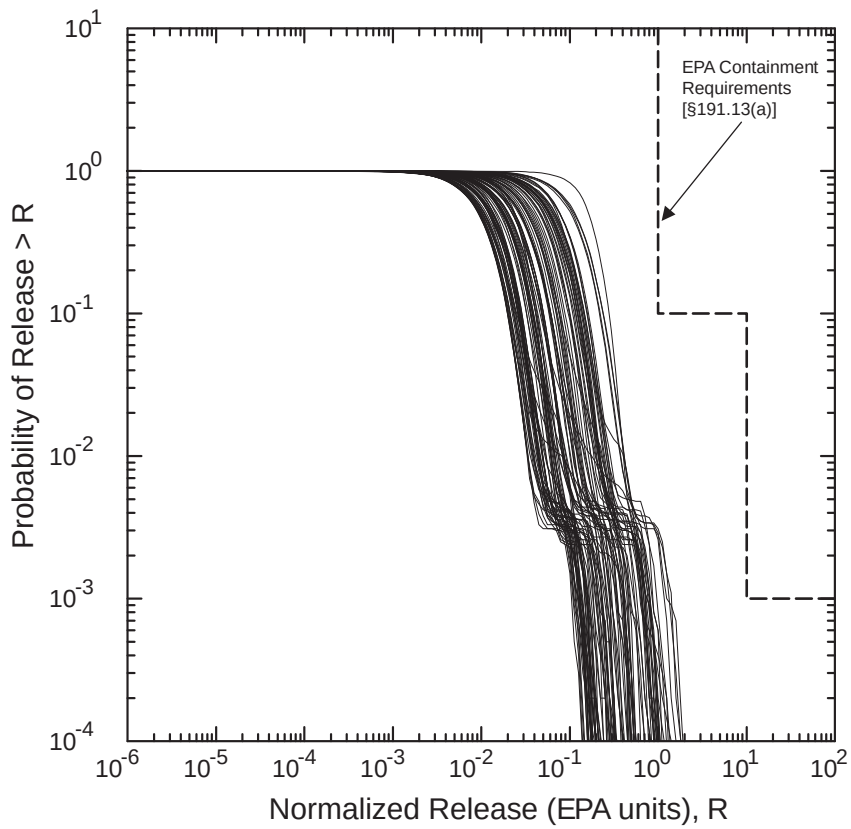

Figure PA-5. Example CCDF Distribution From CRA-2004 PA.

PA-3.0 PROBABILISTIC CHARACTERIZATION OF FUTURES

This section describes how stochastic uncertainty is implemented in PA. Screening analyses of possible future events concluded that the only significant events with potential to affect radionuclide releases to the accessible environment are drilling and mining within the land withdrawal boundary (Section 6.2.6). Consequently, modeling the future states of the repository focuses on representing the occurrences and effects of these two events.

PA-3.1 Probability Space

The first entity that underlies the CRA-2004 PA is a probabilistic characterization of the likelihood of different futures occurring at the WIPP site over the next 10,000 years. As discussed in Section PA-2.2, this entity is defined by a probability space $\left(X_{st}, S_{st}, p_{st}\right)$ that characterizes stochastic uncertainty. The individual elements x_{st} of X_{st} are vectors of the form shown in Equation (3). Sections PA-3.2 through PA-3.8 describe the individual components t_i, e_i, l_i, b_i, p_i, a_i, and t_{min} of x_{st}, and their associated probability distributions. These components and their associated distributions give rise to the probability space $\left(X_{st}, S_{st}, p_{st}\right)$ for stochastic uncertainty. The concept of a scenario as a subset of the sample space X_{st} for stochastic uncertainty is discussed in Section PA-3.9. Further, the procedure used to sample the individual elements $x_{st,i}$ of X_{st} indicated in Equation (4) is described in Section PA-6.5.

PA-3.2 Drilling Intrusion

As described in Section 6.3.2, drilling intrusions in the CRA-2004 PA are assumed to occur randomly in time and space (i.e., follow a Poisson process). Specifically, the drilling rate considered within the area marked by a berm as part of the system for passive institutional controls (Figure PA-6) is 5.25×10^{-3} intrusions per km $^{-2}$ yr $^{-1}$ (Section 6.4.12.2). Active institutional controls are assumed to prevent any drilling intrusions for the first 100 years after the decommissioning of the WIPP (Section 7.1). Unlike in the CCA PA, passive institutional controls are not assumed to reduce the drilling rate after decommissioning (Section 7.3).

For the computational implementation of the CRA-2004 PA, it is convenient to represent the Poisson process for drilling intrusions by its corresponding rate term $\lambda_d\left(t\right)$ for intrusions into the area marked by the berm. Specifically,

$$\lambda_d\left(t\right) = \begin{cases} 0 & 0 \le t \le 100\,yr \\ (0.6285\ km^2)(52.5\ km^{-2}\,10^{-4}\,yr) = 3.3 \times 10^{-3}\ yr^{-1} & 100 \le t \le 10{,}000\,yr \end{cases} \tag{7}$$

where 0.6285 km^2 is the area of the berm Attachment PAR, Table PAR-45 and t is elapsed time since decommissioning of the WIPP.

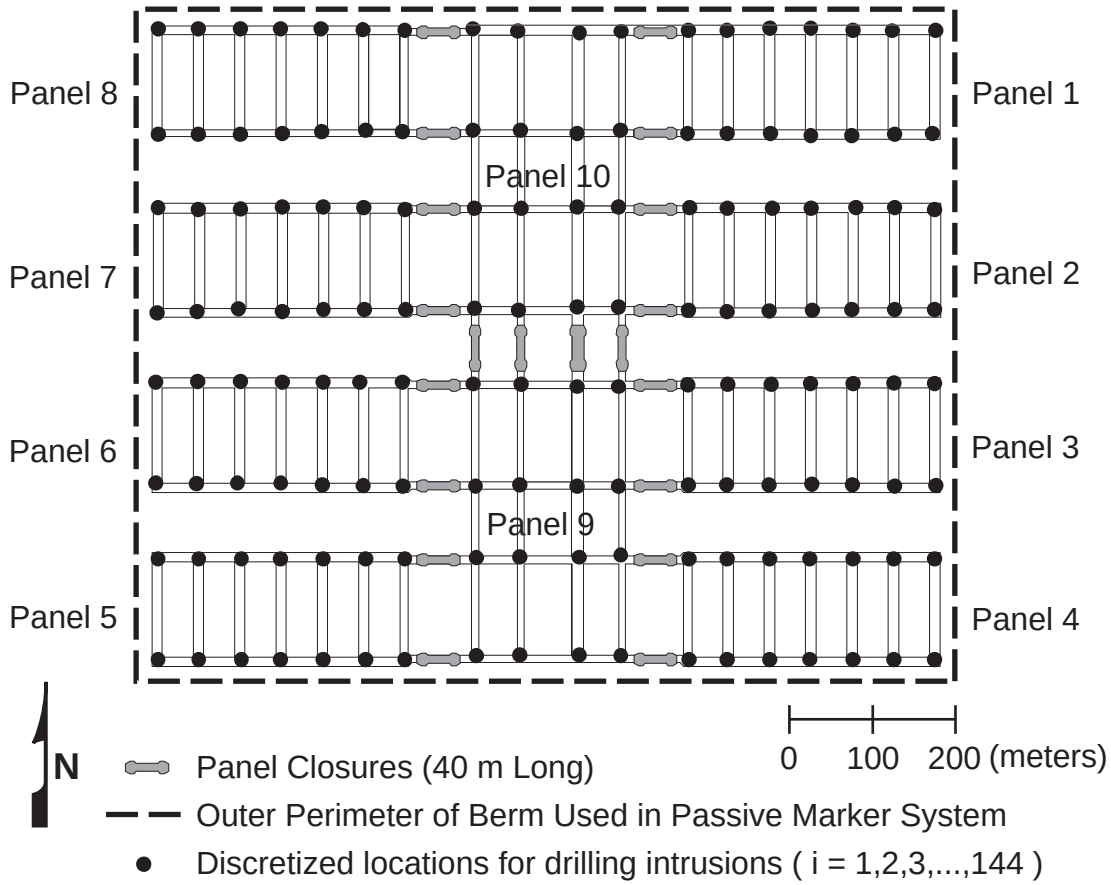

Figure PA-6. Location of Berm Used in Passive Marker System.

The function $\lambda_d(t)$ defines the part of the probability space (X_{st}, S_{st}, p_{st}) in Section PA-2.2 that corresponds to t_i . In the computational implementation of the analysis, $\lambda_d(t)$ is used to define the distribution of time between drilling intrusions (Figure PA-7). As a reminder, the occurrence of one event in a Poisson process has no effect on the occurrence of the next event. Thus, the cumulative distributions in Figure PA-7 can be used to define the time from one drilling event to the next (Section PA-6.5). Due to the 10,000-year regulatory period specified in 40 CFR § 191.13, t_i is assumed to be bounded above by 10,000 years in the definition of X_{st}. Further, t_i is bounded below by 100 years as defined in Equation (7).

The function $\lambda_d(t)$ also determines the probability $prob(nBH = n \| [a,b])$ that a future will have exactly n drilling intrusions in the time interval [a, b] (Helton 1993), where

$$prob(nBH = n \,|\, [a,b]) = \left[\left(\int_a^b \lambda_d(t)dt \right)^n / n! \right] \exp\left(-\int_a^b \lambda_d(t)dt \right). \tag{8}$$

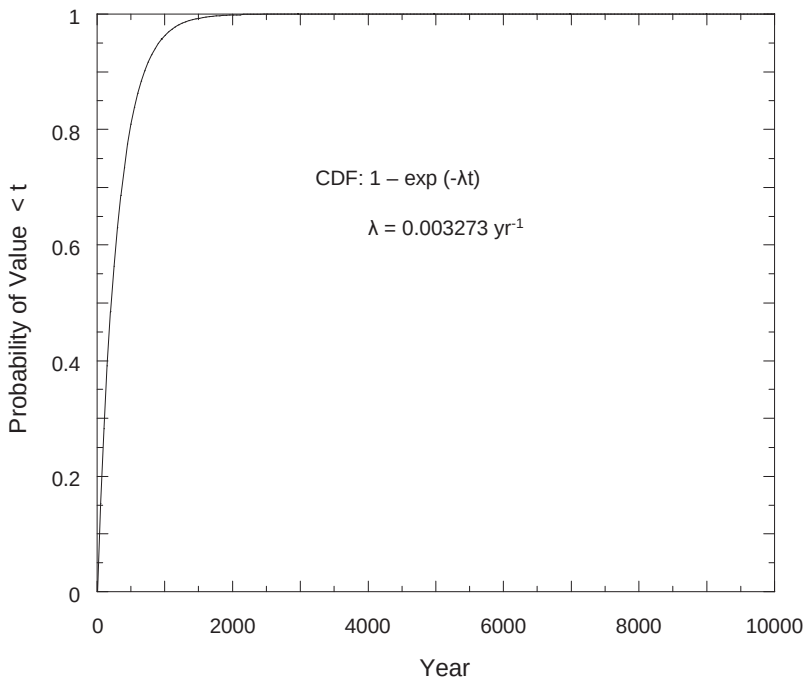

Figure PA-7. Cumulative Distribution Function (CDF) for Time Between Drilling Intrusions.

Further, the probability $prob\left(nBH \geq n \middle| [a,b]\right)$ that a future will have greater than or equal to n drilling intrusions in the time interval [a, b] is given by

$$prob(nBH \geq n \,|\, [a,b]) = \begin{cases} 1 & n = 0 \\ 1 - \sum_{m=0}^{n-1} prob(nBH = m \,|\, [a,b]) & n > 0 \end{cases} \tag{9}$$

PA-3.3 Penetration of Excavated/Nonexcavated Area

The variable e_i is a designator for whether or not the ith drilling intrusion penetrates an excavated, waste-filled area of the repository (i.e., e_i = 0, 1 implies penetration of nonexcavated, excavated area, respectively). The corresponding probabilities pE_0 and pE_1 for e_i = 0 and e_i = 1 are

$$pE_1 = 0.1273\ km^2 / 0.6285\ km^2 = 0.203 \tag{10}$$

$$pE_0 = 1 - pE_1 = 0.797\ , \tag{11}$$

where 0.1273 km^2 and 0.6285 km^2 are the excavated area of the repository filled with waste and the area of the berm, respectively (Attachment PAR, Table PAR-45). The probabilities pE_0 and pE_1 define the part of $\left(X_{st}, S_{st}, p_{st}\right)$ in Section PA.2.2 associated with e_i.

PA-3.4 Drilling Location

Locations of drilling intrusions through the excavated, waste-filled area of the repository are discretized to the 144 locations in Figure PA-6. Assuming that a drilling intrusion occurs within the excavated area, it is assumed to be equally likely to occur at each of these 144 locations. Thus, the (conditional) probability pL_j that drilling intrusion i will occur at location L_j, j = 1, 2, …, 144, in Figure PA-6 is

$$pL_j = 1/144 = 6.94 \times 10^{-3}. \tag{12}$$

The probabilities pL_j define the part of $\left(X_{st}, S_{st}, p_{st}\right)$ in Section PA.2.2 associated with l_i.

PA-3.5 Penetration of Pressurized Brine

The conceptual models for the Castile Formation include the possibility that pressurized brine reservoirs underlie the repository (Section 6.4.8). The variable b_i is a designator for whether or not the ith drilling intrusion penetrates pressurized brine, where $b_i = 0$ signifies nonpenetration and $b_i = 1$ signifies penetration of pressurized brine. In the CCA PA, the probabilities pB_0 and pB_1 for $b_i = 0$ and $b_i = 1$ were 0.92 and 0.08, respectively (see CCA Section 6.4.12.6). In the CRA-2004 PA, the probability pB_1 is sampled from a uniform distribution ranging from 0.01 to 0.60 (Section 6.4.12.6; see also PBRINE in Table PA-17). The probabilities pB_0 and pB_1 define the part of $\left(X_{st}, S_{st}, p_{st}\right)$ in Section PA-2.2 that corresponds to b_i.

PA-3.6 Plugging Pattern

As presented in Section 6.4.7.2, three borehole plugging patterns are considered in the 2004 PA: (1) p_1, a full concrete plug through Salado Formation to the Bell Canyon Formation, (2) p_2, a two plug configuration with concrete plugs at Rustler/Salado interface and Castile/Bell Canyon interface, and (3) p_3, a three plug configuration with concrete plugs at the Rustler/Salado, Salado/Castile and Castile/Bell Canyon interfaces. The probability that a given drilling intrusion will be sealed with plugging pattern p_j, j = 1, 2, 3, is given by pPL_j, where $pPL_1 = 0.015$, $pPL_2 = 0.696$ and $pPL_3 = 0.289$ (Section 6.4.12.7). The probabilities pPL_j define the part of $\left(X_{st}, S_{st}, p_{st}\right)$ in Section PA-2.2 that corresponds to p_i.

PA-3.7 Activity Level

The waste intended for disposal at the WIPP is represented by 779 distinct waste streams with 693 of these waste streams designated as CH-TRU waste and 86 designated as RH-TRU waste. For the CRA-2004 PA, the 86 separate RH-TRU waste streams are represented by a single, combined RH-TRU waste stream. The activity levels for the waste streams are given in Attachment PAR, Table PAR-50. Each waste container emplaced in the repository contains waste from a single CH-TRU waste stream. Waste packaged in 55-gallon drums is stacked three drums high within the repository. Although waste in other packages (e.g., standard waste boxes, 10 drum overpacks, etc.) may not be stacked three high, the CRA-2004 PA assumes that each

drilling intrusion into CH-TRU waste might intersect three different waste streams. In contrast, all RH-TRU waste is represented by a single waste stream, and so each drilling intrusion through RH-TRU waste is assumed to intersect this single waste stream. Attachment MASS (Section MASS.21) examines the sensitivity of PA results to the assumption that three waste streams are intersected by each drilling intrusion into CH-TRU waste.

The vector $\boldsymbol{a_i}$ characterizes the type of waste penetrated by the ith drilling intrusion. Specifically,

$$\boldsymbol{a_i} = 0 \text{ if } e_i = 0 \tag{13}$$

(i.e., if the ith drilling intrusion does not penetrate an excavated area of the repository);

$$\boldsymbol{a_i} = 1 \text{ if } e_i = 1 \text{ and RH-TRU is penetrated;} \tag{14}$$

and

$$\boldsymbol{a_i} = [iCH_{i1}, CH_{i2}, iCH_{i3}] \text{ if } e_i = 1 \text{ and CH-TRU is penetrated ,} \tag{15}$$

where iCH_{i1}, iCH_{i2} and iCH_{i3} are integer designators for the CH-TRU waste streams intersected by the ith drilling intrusion (i.e., each of iCH_{i1}, iCH_{i2} and iCH_{i3} is an integer between 1 and 693).

Whether the ith intrusion penetrates a nonexcavated or excavated area is determined by the probabilities pE_0 and pE_1 discussed in Section PA-3.4. The type of waste penetrated is determined by the probabilities pCH and pRH. The excavated area used for disposal of CH-TRU waste is 1.115×105 m^2 and the area used for disposal of RH-TRU waste is 1.576×10^4 m^2 (Attachment PAR, Table PAR-43), for a total disposal area of aEX = aCH + aRH = 1.273×10^5 m^2. Given that the ith intrusion penetrates an excavated area, the probabilities pCH and pRH of penetrating CH- and RH-TRU waste are given by

$$\boldsymbol{pCH = aCH / aEX = \left(1.115 \times 10^5\ m^2\right) / \left(1.273 \times 10^5\ m^2\right) = 0.876} \tag{16}$$

$$\boldsymbol{pCH = aCH / aEX = \left(1.576 \times 10^4\ m^2\right) / \left(1.273 \times 10^5\ m^2\right) = 0.124\ .} \tag{17}$$

As indicated in this section, the probabilistic characterization of $\boldsymbol{a_i}$ in $\left(\boldsymbol{X_{st}, S_{st}, p_{st}}\right)$ depends on a number of individual probabilities. Specifically, pE_0 and pE_1 determine whether a nonexcavated or excavated area is penetrated (Section PA-3.4); pCH and pRH determine whether CH- or RH-TRU waste is encountered given penetration of an excavated area; and the individual waste stream probabilities in Attachment PAR, Table PAR-50 determine the specific waste streams iCH_{i1} , iCH_{i2} , and iCH_{i3} encountered given a penetration of CH-TRU waste.

PA-3.8 Mining Time

As presented in Section 6.2.5.2, full mining of known potash reserves within the land withdrawal boundary is assumed to occur at time t_{min}. The occurrence of mining within the land withdrawal boundary in the absence of institutional controls is specified as following a Poisson process with a rate of $\lambda_m = 1 \times 10^{-4}$ yr^{-1}. However, this rate can be reduced by active and passive institutional controls. Specifically, active institutional controls are assumed to result in no possibility of mining for the first 100 years after decommissioning of the WIPP (Section 7.1.4). In the CCA PA, passive institutional controls were assumed to reduce the base mining rate by two orders of magnitude between 100 and 700 years after decommissioning (CCA Section 7.3.4). In the CRA-2004 PA, passive institutional controls do not affect the mining rate (Section 7.3.4). Thus, the mining rate $\lambda_m(t)$ is:

$$\lambda_m(t) = 0 \ yr^{-1} \quad for\ 0 \le t \le 100\ yrs \tag{18}$$

$$\lambda_m(t) = 1 \times 10^{-4}\ yr^{-1} \quad for\ 100 \le t \le 10{,}000\ yrs\ , \tag{19}$$

where t is elapsed time since decommissioning of the WIPP. The function $\lambda_m(t)$ defines the part of (X_{st}, S_{st}, p_{st}) that corresponds to t_{min}.

In the computational implementation of the analysis, $\lambda_m(t)$ is used to define the distribution of time to mining. The use of $\lambda_m(t)$ to characterize t_{min} is analogous to the use of λ_d to characterize the t_i except that only one mining event is assumed to occur (i.e., x_{st} contains only one value for t_{min}) in consistency with guidance given in 40 CFR Part 194 that mining within the land withdrawal boundary should be assumed to remove all economically viable potash reserves. Due to the 10,000-year regulatory period specified in 40 CFR § 191.13, t_{min} is assumed to be bounded above by 10,000 years in the definition of X_{st}.

PA-3.9 Scenarios and Scenario Probabilities

A scenario is a subset $\mathcal{S}$ of the sample space X_{st} for stochastic uncertainty. More specifically, a scenario is an element $\mathcal{S}$ of the set S_{st} in the probability space (X_{st}, S_{st}, p_{st}) for stochastic uncertainty, and the probability of $\mathcal{S}$ is given by $p_{st}(\mathcal{S})$. Thus, a scenario is what is called an event in the usual terminology of probability theory.

Given the complexity of the elements x_{st} of X_{st} (see Equation (3)), many different scenarios can be defined. The computational complexity of the function f in Figure PA-1 limits evaluation to only a few scenarios. As presented in Section 6.3, the CRA-2004 PA considers four fundamental scenarios:

E0 = { x_{st} : x_{st} involves no drilling intrusion through an excavated area of the repository (i.e., n = 0 or e_i = 0 in Equation (3) for i = 1, 2, …, n > 0)};

E1 = { $\boldsymbol{x}_{st} : \boldsymbol{x}_{st}$ involves one drilling intrusion through an excavated area of the repository with this intrusion penetrating pressurized brine in the Castile Formation (i.e., n > 0 in Equation (3) and there exists exactly one integer i such that $1 \le i \le n$, $e_i = 1$, $b_i = 1$, and $e_j = 0$ for $j \ne i$ and $1 \le j \le n$)};

E2 = { $\boldsymbol{x}_{st} : \boldsymbol{x}_{st}$ involves one drilling intrusion through an excavated area of the repository, with this intrusion not penetrating pressurized brine in the Castile Formation (i.e., n > 0 in Equation (3) and there exists exactly one integer i such that $1 \le i \le n$, $e_i = 1$, $b_i = 0$, and $e_j = 0$ for $j \ne i$ and $1 \le j \le n$)};

E1E2 = { $\boldsymbol{x}_{st} : \boldsymbol{x}_{st}$ involves two drilling intrusions through excavated areas of the repository, with the first intrusion not penetrating pressurized brine and the second intrusion penetrating pressurized brine (i.e., $n \ge 2$ in Equation (3) and there exist two integers i, j such that $1 \le i < j \le n$, $e_i = 1$, $b_i = 0$, $e_j = 1$, $b_j = 1$, and $e_k = 0$ for $k \ne i, j$ and $1 \le k \le n$)}.

The definitions of the preceding four scenarios are quite simple. In general, scenarios can be defined on the basis of any possible characterization of the properties of the individual elements of $\boldsymbol{x}_{st}$, which can lead to very complex scenario definitions.

The scenarios E0, E1, E2, and E1E2 are elements of S_{st}, and their probabilities are formally represented by $p_{st}(E0)$, $p_{st}(E1)$, $p_{st}(E2)$, and $p_{st}(E1E2)$, with these probabilities deriving from the probability distributions assigned to the individual elements of $\boldsymbol{x}_{st}$. For example, assume that pB_1 takes on its mean value of 0.305 (see Section PA-3.5), the probabilities of the first three scenarios can be calculated exactly:

$$p_{st}(E0) = \exp\left(-\int_a^b pE_1 \lambda_d(t)\,dt\right) = 1.3 \times 10^{-3} \tag{20}$$

$$p_{st}(E1) = \left[\left(\int_a^b pE_1 \lambda_d(t)\,dt\right)^1 \Big/ 1!\right]\left[\exp\left(-\int_a^b pE_1 \lambda_d(t)\,dt\right)\right]\left[pB_1\right] = 2.6 \times 10^{-3} \tag{21}$$

$$p_{st}(E2) = \left[\left(\int_a^b pE_1 \lambda_d(t)\,dt\right)^1 \Big/ 1!\right]\left[\exp\left(-\int_a^b pE_1 \lambda_d(t)\,dt\right)\right]\left[pB_0\right] = 6.0 \times 10^{-3}, \tag{22}$$

where $[a,b] = [100,\ 10{,}000\ yrs]$, $pE_1 = 0.203$ (see Section PA-3.4), $\lambda_d(t)$ is defined in Equation (7), and the probabilities in Equation (21) and Equation (22) are based on the relationship in Equation (8).

The expressions defining $p_{st}(E0)$, $p_{st}(E1)$, and $p_{st}(E2)$ are relatively simple because the scenarios E0, E1, and E2 are relatively simple. The scenario E1E2 is more complex and, as a

result, $p_{st}(E1E2)$ is also more complex. Closed-form formulas for the probabilities of quite complex scenarios can be derived but they are very complicated and involve large numbers of iterated integrals (Helton 1993). Thus, p_{st} can be defined in concept but does not have a simple form that can be easily displayed.

The fundamental scenarios E0, E1, E2, and E1E2 have infinitely many elements because the drilling intrusions and mining events can occur throughout the regulatory period. However, scenarios involving drilling intrusions that occur at specific times will have a probability of zero. For example, the scenario

$$\mathcal{S} = \left\{ x_{st} : x_{st} = \left[t_1 = 350\,yr,\ e_1 = 1,\ l_1,\ b_1 = 1,\ p_1 = 2,\ a_1,\ t_{min} \right] \right\}, \tag{23}$$

where e_1, a_1 and t_{min} are arbitrary, contains infinitely many futures (i.e., infinitely many x_{st} meet the criteria to belong to $\mathcal{S}$ due to the infinite number of values that l_1, a_1, and t_{min} can assume) and also has a probability of zero (i.e., $p_{st}(\mathcal{S}) = 0$) because t_1 is restricted to a single value. Sets that contain single elements of X_{st} are also scenarios, but such scenarios will typically have a probability of zero; the only single element scenario that has a nonzero probability contains the future that has no drilling intrusions and no mining.

Releases from the repository are calculated (i.e. the function f in Figure PA-1 is evaluated) for a small number of elements belonging to each of the four fundamental scenarios (Sections PA-6.7 and PA-6.8). Releases for an arbitrary element x_{st} of X_{st} are estimated from the results of the fundamental scenarios (Section PA-6.8); these releases are used to construct CCDFs by Equation (4).

PA-3.10 Historical Review of CCDF Construction

The 1991 and 1992 WIPP PAs used an approach to the construction of the CCDF specified in 40 CFR § 191.13 based on the exhaustive division of X_{st} into a collection of mutually exclusive scenarios $S_{st,i}$, i = 1, 2, …, nS (Helton and Iuzzolino 1993). A probability $p_{st}(S_{st,i})$ and a normalized release R_i were then calculated for each scenario $S_{st,i}$ and used to construct the CCDF specified in 40 CFR § 191.13. Due to the complexity of the elements x_{st} of X_{st} (see Equation (3)), this approach was not used in the CCA PA. In particular, the decomposition of X_{st} into a suitable and defensible collection of scenarios $S_{st,i}$, i = 1, 2, …, nS, is quite difficult. Further, once these scenarios are defined, it is necessary to calculate their probabilities $p_{st}(S_{st,i})$, which is also not easy. Although the calculation of the probabilities $p_{st}(S_{st,i})$ is difficult, the development of an appropriate and acceptable decomposition of X_{st} into the scenarios $S_{st,i}$ posed a great challenge. Accordingly, the CCA PA used the Monte Carlo approach to CCDF construction indicated in Equation (4), thus avoiding the difficulties associated with decomposing X_{st} into a collection of mutually exclusive scenarios and then

calculating the probabilities of these scenarios. The CRA-2004 PA uses the same approach as used in the CCA PA.

PA-4.0 ESTIMATION OF RELEASES

This section describes how releases to the accessible environment are estimated for a particular future in the CRA-2004 PA.

PA-4.1 Results for Specific Futures

The function $f\left(x_{st}\right)$ (Figure PA-1) estimates the radionuclide releases to the accessible environment associated with each of the possible futures x_{st} that could occur at the WIPP site over the next 10,000 years. In practice, f is quite complex and is constructed by the models implemented in computer programs used to simulate important processes and releases at the WIPP. In the context of these models, f has the form

$$\begin{aligned} f\left(x_{st}\right) = {} & f_C\left(x_{st}\right) + f_{SP}\left[x_{st}, f_B\left(x_{st}\right)\right] + f_{DBR}\left[x_{st}, f_B\left(x_{st}\right)\right] \\ & + f_{MB}\left[x_{st}, f_B\left(x_{st}\right)\right] + f_{DL}\left[x_{st}, f_B\left(x_{st}\right)\right] + f_S\left[x_{st}, f_B\left(x_{st}\right)\right], \\ & + f_{ST}\left[x_{st,0}, f_{MF}\left(x_{st}\right), f_{NP}\left[x_{st}, f_B\left(x_{st}\right)\right]\right] \end{aligned} \tag{24}$$

where

x_{st} ~ particular future under consideration,

$x_{st,0}$ ~ future involving no drilling intrusions but a mining event at the same time t_{min} as in x_{st},

$f_C\left(x_{st}\right)$ ~ cuttings and cavings release to accessible environment for x_{st} calculated with CUTTINGS_S,

$f_B\left(x_{st}\right)$ ~ two-phase flow in and around the repository calculated for x_{st} with BRAGFLO; in practice, $f_B\left(x_{st}\right)$ is a vector containing a large amount of information, including pressure and brine saturation in various geologic members,

$f_{SP}\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ spallings release to accessible environment for x_{st} calculated with the spallings model contained in CUTTINGS_S; this calculation requires repository conditions calculated by $f_B\left(x_{st}\right)$ as input,

$f_{DBR}\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ direct brine release to accessible environment for x_{st} also calculated with BRAGFLO; this calculation requires repository conditions calculated by $f_B\left(x_{st}\right)$ as input,

$f_{MB}\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ release through anhydrite marker beds to accessible environment for x_{st} calculated with NUTS; this calculation requires flows in and around the repository calculated by $f_B\left(x_{st}\right)$ as input,

$f_{DL}\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ release through Dewey Lake Red Beds to accessible environment for x_{st} calculated with NUTS; this calculation requires flows in and around the repository calculated by $f_B\left(x_{st}\right)$ as input,

$f_S\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ release to land surface due to brine flow up a plugged borehole for x_{st} calculated with NUTS or PANEL; this calculation requires flows in and around the repository calculated by $f_B\left(x_{st}\right)$ as input,

$f_{MF}\left(x_{st,0}\right)$ ~ flow field in the Culebra calculated for $x_{st,0}$ with MODFLOW,

$f_{NP}\left[x_{st}, f_B\left(x_{st}\right)\right]$ ~ release to Culebra for x_{st} calculated with NUTS or PANEL as appropriate; this calculation requires flows in and around the repository calculated by $f_B\left(x_{st}\right)$ as input, and

$f_{ST}\left[x_{st,0}, f_{MF}\left(x_{st,0}\right), f_{NP}\left[x_{st}, f_B\left(x_{st}\right)\right]\right]$ ~ groundwater transport release through Culebra to accessible environment calculated with SECOTP2D.This calculation requires MODFLOW results (i.e., $f_{MF}\left(x_{st,0}\right)$) and NUTS or PANEL results (i.e., $f_{NP}\left[x_{st}, f_B\left(x_{st}\right)\right]$ as input; $x_{st,0}$ is used as an argument to f_{ST} because drilling intrusions are assumed to cause no perturbations to the flow field in the Culebra.

The remainder of this section describes the mathematical structure of the mechanistic models that underlie the component functions of f in Equation (24).

The Monte Carlo CCDF construction procedure, implemented in the code CCDFGF (WIPP PA 2003a), uses a sample of size nS = 10,000 in the CRA-2004 PA. The individual programs that estimate releases do not run fast enough to allow this number of evaluations of f. As a result, a two-step procedure is being used to evaluate f in the calculation of the integral in Equation (4). First, f and its component functions are evaluated with the procedures (i.e., models) described in this section for a group of preselected futures. Second, values of $f\left(x_{st,i}\right)$ for the randomly

selected futures $\mathbf{x}_{st,i}$ used in the numerical evaluation of the integral in Equation (4) are then constructed from results obtained in the first step. These constructions are described in Sections PA-6.7 and PA-6.8, and produce the evaluations of f that are actually used in Equation (4).

For notational simplicity, the functions on the right hand side of Equation (24) will typically be written with only $\mathbf{x}_{st}$ as an argument (e.g., $f_{SP}\left(\mathbf{x}_{st}\right)$ will be used instead of $f_{SP}\left[\mathbf{x}_{st}, f_B\left(\mathbf{x}_{st}\right)\right]$). However, the underlying dependency on the other arguments will still be present.

The major topics considered in this chapter are two-phase flow in the vicinity of the repository as modeled by BRAGFLO (i.e., f_B) (Section PA-4.2), radionuclide transport in the vicinity of the repository as modeled by NUTS (i.e., f_{MB}, f_{DL}, f_S, f_{NP}) (Section PA-4.3), radionuclide transport in the vicinity of the repository as modeled by PANEL (i.e., f_S, f_{NP}) (Section PA-4.4), cuttings and cavings releases to the surface as modeled by CUTTINGS_S (i.e., f_C) (Section PA-4.5), spallings releases to the surface as modeled by DRSPALL and CUTTINGS_S (i.e., f_{SP}) (Section PA-4.6), direct brine releases to the surface as modeled by BRAGFLO (i.e., f_{DBR}) (Section PA-4.7), brine flow in the Culebra as modeled by MODFLOW (i.e., f_{MF}) (Section PA-4.8), and radionuclide transport in the Culebra as modeled by SECOTP2D (i.e., f_{ST}) (Section PA-4.9).

PA-4.2 Two-Phase Flow: BRAGFLO

Quantification of the effects of gas and brine flow on radionuclide transport from the repository requires use of a two-phase (brine and gas) flow code. For the CRA-2004 PA, the DOE uses the two-phase flow code BRAGFLO to simulate gas and brine flow in and around the repository (WIPP PA 2003b). Additionally, the BRAGFLO code incorporates the effects of disposal room consolidation and closure, gas generation, and rock fracturing in response to gas pressure. This section describes the mathematical models on which BRAGFLO is based, the representation of the repository in the model, and the numerical techniques employed in the solution.

PA-4.2.1 Mathematical Description

Two-phase flow in the vicinity of the repository is represented by the following system of two conservation equations, two constraint equations, and three equations of state:

Gas Conservation

$$\nabla \bullet \left[\frac{\alpha \rho_g \mathbf{K}_g k_{rg}}{\mu_g} \left(\nabla p_g + \rho_g g \nabla h \right) \right] + \alpha q_{wg} + \alpha q_{rg} = \alpha \frac{\partial \left(\phi \rho_g S_g \right)}{\partial t}, \tag{25a}$$

Brine Conservation

$$\nabla \bullet \left[\frac{\alpha \rho_b \mathbf{K}_b k_{rb}}{\mu_b} \left(\nabla p_b + \rho_b g \nabla h \right) \right] + \alpha q_{wb} + \alpha q_{rb} = \alpha \frac{\partial \left(\phi \rho_b S_b \right)}{\partial t}, \tag{25b}$$

Saturation Constraint

$$S_g + S_b = 1, \tag{25c}$$

Capillary Pressure Constraint

$$p_C = p_g - p_b = f\left(S_b\right), \tag{25d}$$

Gas Density

ρ_g (determined by Redlich-Kwong-Soave equation of state; see Equation (46)), (25e)

Brine Density

$$\rho_b = \rho_0 \exp\left[\beta_b\left(\rho_b - \rho_{b0}\right)\right], \text{ and} \tag{25f}$$

Formation Porosity

$$\phi_b = \phi_0 \exp\left[\beta_f\left(\rho_b - \rho_{b0}\right)\right], \tag{25g}$$

where

g = acceleration due to gravity (m/s^2)

h = vertical distance from a reference location (m)

K_l = permeability tensor (m^2) for fluid l (l = g ~ gas, l = b ~ brine)

k_{rl} = relative permeability (dimensionless) to fluid l

p_C = capillary pressure (Pa)

p_l = pressure of fluid l (Pa)

q_{rl} = rate of production (or consumption, if negative) of fluid l due to chemical reaction (kg/m^3 s)

q_{wl} = rate of injection (or removal, if negative) of fluid l (kg/m^3 s)

S_l = saturation of fluid l (dimensionless)

t = time (s)

α = geometry factor (m)

ρ_l = density of fluid l (kg/m^3)

μ_l = viscosity of fluid l (Pa s)

ϕ = porosity (dimensionless)

ϕ_0 = reference (i.e., initial) porosity (dimensionless)

p_{b0} = reference (i.e., initial) brine pressure (Pa), constant in Equation (25f) and spatially variable in Equation (25g)

ρ_0 = reference (i.e., initial) brine density (kg/m^3)

β_f = pore compressibility (Pa^{-1})

β_b = brine compressibility (Pa^{-1}).

The conservation equations are valid in one (i.e., $\nabla = [\partial/\partial \boldsymbol{x}]$), two (i.e., $\nabla = [\partial/\partial \boldsymbol{x}, \partial/\partial \boldsymbol{y}]$) and three (i.e., $\nabla = [\partial/\partial \boldsymbol{x}, \partial/\partial \boldsymbol{y}, \partial/\partial \boldsymbol{z}]$) dimensions. In the CRA-2004 PA, the preceding system of equations is used to model two-phase fluid flow within the two-dimensional region shown in Figure PA-8. The details of this system are now discussed.

The α term in Equation (25a) and Equation (25b) is a dimension-dependent geometry factor and is specified by

α = area normal to flow direction in one-dimensional flow (i.e., $\Delta y \Delta z$; units = m^2),

= thickness normal to flow plane in two-dimensional flow (i.e., Δz; units = m),

= 1 in three-dimensional flow (dimensionless). (26)

The CRA-2004 PA uses a two-dimensional geometry for computation of two-phase flow in the vicinity of the repository, and as a result, α is the thickness of the modeled region (i.e., Δz) normal to the flow plane (Figure PA-8). Due to the use of the two-dimensional grid in Figure PA-8, α is spatially dependent, with the values used for α defined in the column labeled "Δz ." Specifically, α increases with distance away from the repository edge in both directions to incorporate the increasing pore volume through which fluid flow occurs. The method used in the CRA-2004 PA, called rectangular flaring, is illustrated in Figure PA-9 and ensures that the total volume surrounding the repository is conserved in the numerical grid. The equations and

method used to determine α for the grid shown in Figure PA-8 are described in detail by Stein (2002a).

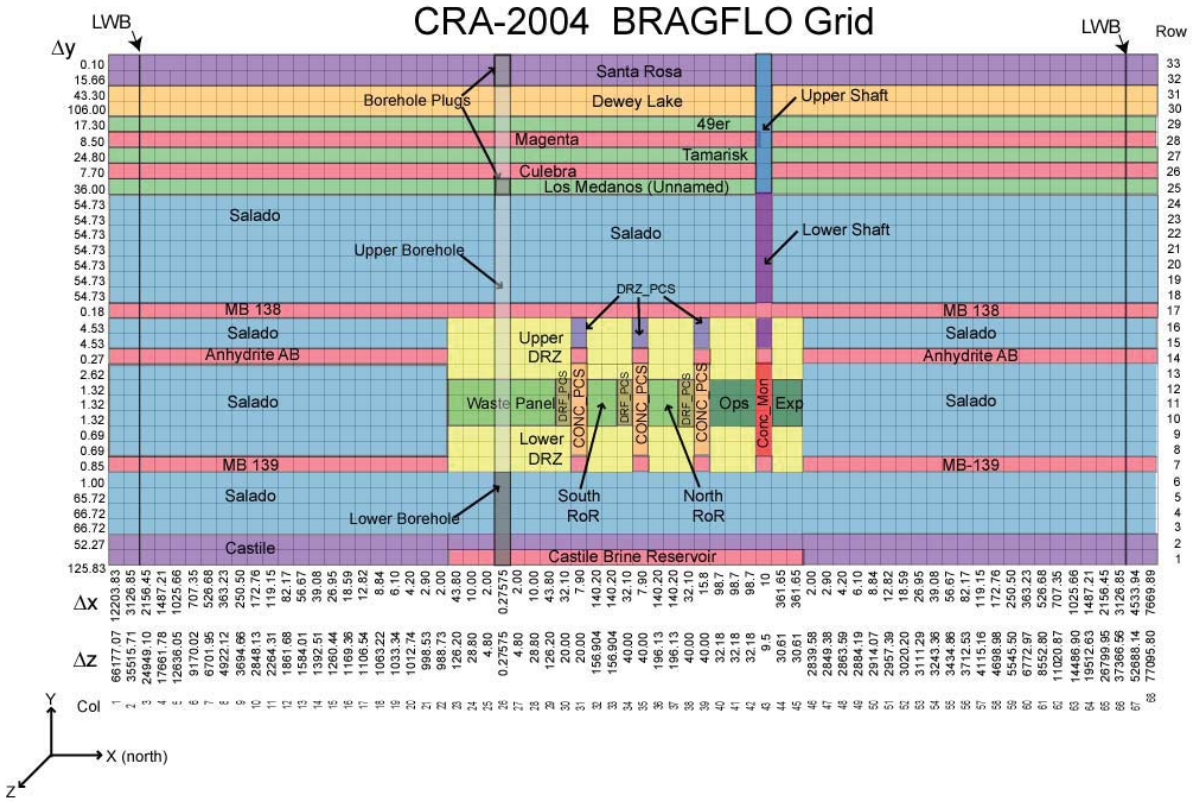

Figure PA-8. Computational Grid Used in BRAGFLO in the CRA-2004 PA.

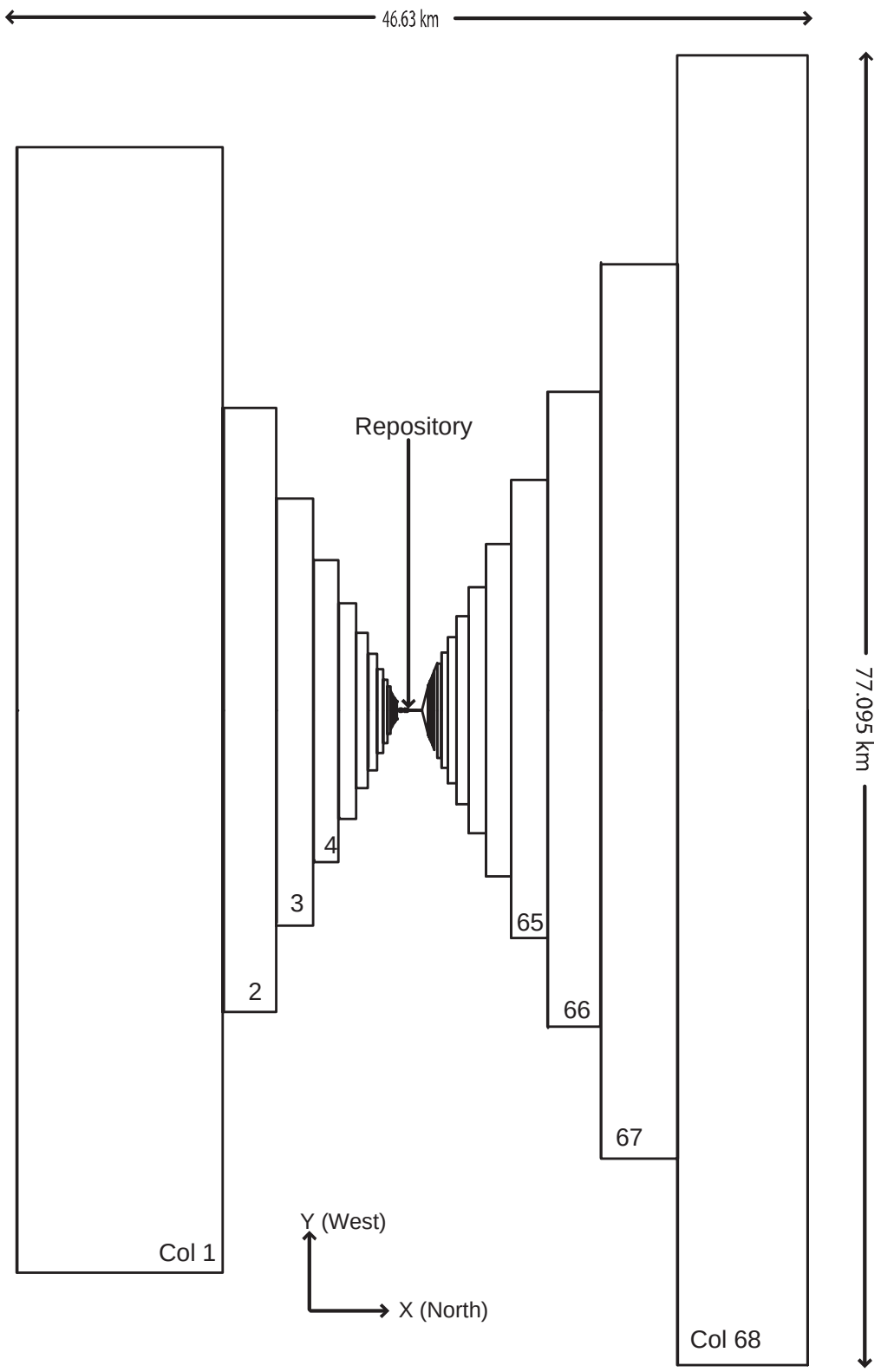

Figure PA-9. Definition of Element Depth in BRAGFLO Grid in the CRA-2004 PA.

The h term in Equation (25a) and Equation (25b) defines vertical distance from a reference point. In the CRA-2004 PA, this reference point is taken to be the center of MB 139 at the location of the shaft (i.e., $\left(x_{ref}, y_{ref}\right) = \left(23664.9\ m,\ 378.685\ m\right)$, which is the center of cell 1266 in Figure PA-10). Specifically, h is defined by

$$h\left(x, y\right) = \left(x - x_{ref}\right)\sin\theta + \left(y - y_{ref}\right)\cos\theta, \tag{27}$$

where θ is the inclination of the formation in which the point $\left(x, y\right)$ is located. In the CRA-2004 PA, the Salado Formation is modeled as having an inclination of 1° from north to south, and all other formations are modeled as being horizontal. Thus, θ = 1° for points within the Salado, and θ = 0° otherwise. Treating the Salado as an inclined formation and treating the Castile Formation, Castile brine reservoir, Rustler Formation, and overlying units as horizontal creates discontinuities in the grid at the lower and upper boundaries of the Salado. However, this treatment does not create a computational problem, since the Salado is isolated from vertical flow; its upper boundary adjoins the impermeable Los Medaños Member (formerly referred to as the Unnamed Member) at the base of the Rustler Formation, and its lower boundary adjoins the impermeable Castile Formation.

In the solution of Equation (25), S_b and S_g are functions of location and time. Thus, p_C, k_{rb} and k_{rg} are functions of the form $p_C\left(x, y, t\right)$, $k_{rb}\left(x, y, t\right)$, and $k_{rg}\left(x, y, t\right)$. In the computational implementation of the solution of the preceding equations, flow of phase l out of a computational cell (Figure PA-10) cannot occur when $S_l\left(x, y, t\right) \le S_{lr}\left(x, y, t\right)$, where S_{lr} denotes the residual saturation for phase l. The values used for S_{lr}, l = b, g are summarized in Table PA-2.

Values for ϕ_0 and β_f (Equation (25g)) are also given in Table PA-2. Initial porosity ϕ_0 for the DRZ is a function of the uncertain parameter for initial halite porosity ϕ_{0H} (HALPOR; see Table PA-17) and is given by Martell (1996a, Chapter 4; Bean et al. 1996)

$$\phi_0 = \phi_{0H} + 0.0029\ . \tag{28}$$

This representation is used because the DRZ and halite porosities are correlated, with the high, low, and median porosity values for the DRZ being 0.0029 higher than the corresponding undisturbed halite values. Initial porosity ϕ_0 of the Castile brine reservoir is correlated to the uncertain sampled parameter for bulk compressibility (BPCOMP; see Table PA-17), according to the following relationship:

$$\phi_0 = \frac{BPCOMP}{1.0823 \times 10^{-10}}, \tag{29}$$

where 1.0860×10^{-10} is a scaling constant that ensures that the productivity ratio, PR, remains constant at 2.0×10^{-3} m^3/Pa. The productivity ratio PR is computed by

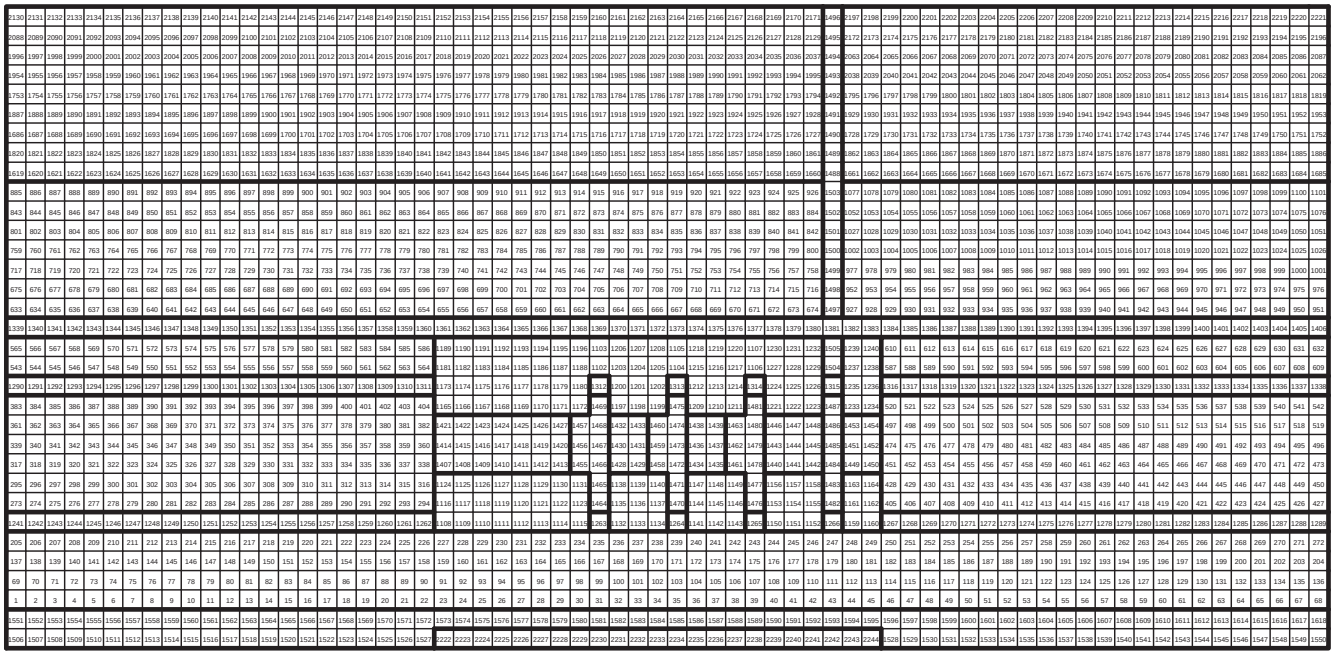

Figure PA-10. Identification of Individual Cells in BRAGFLO Grid in the CRA-2004 PA.

Table PA-2. Parameter Values Used in Representation of Two Phase Flow

Region	Material	Material Description	Brooks-Corey Pore Distribution λ	Threshold Pressure Linear Parameter a	Threshold Pressure Exponential Parameter η	Residual Brine Saturation S_{br}	Residual Gas Saturation S_{gr}	Porosity ϕ_0	Pore Compressibility β_f	Intrinsic Permeability k, m2
Salado	S_HALITE	Undisturbed halite	0.7	0.56	–0.346	0.3	0.2	HALPOR1	f(HALCOMP1)3	10x, x = HALPRM1
Upper DRZ	DRZ_0	Disturbed rock zone, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMP1)3	9.999999 × 10–18
	DRZ_1	Disturbed rock zone, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMP1)3	10x, x = DRZPRM1
Lower DRZ	DRZ_0	Disturbed rock zone, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMP1)3	9.999999 × 10–18
	DRZ_1	Disturbed rock zone, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMP1)3	10x, x = DRZPRM1
MB 138	S_MB138	Anhydrite marker bed in Salado Formation	ANHBCEXP1	0.26	–0.348	ANRBSAT1	ANRGSSAT1	0.011	f(ANHCOMP1)3	10x, x = ANHPRM1
Anhydrite AB	S_ANH_AB	Anhydrite layers a and b in Salado Formation	ANHBCEXP1	0.26	–0.348	ANRBSAT1	ANRGSSAT1	0.011	f(ANHCOMP1)3	10x, x = ANHPRM1
MB 139	S_MB139	Anhydrite marker bed in Salado Formation	ANHBCEXP1	0.26	–0.348	ANRBSAT1	ANRGSSAT1	0.011	f(ANHCOMP1)3	10x, x = ANHPRM1
Waste Panel	CAVITY_1	Single waste panel, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	WAS_AREA	Single waste panel, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT1	WRGSSAT1	0.8485	0.0	2.4 × 10–13
South RoR	CAVITY_2	Rest of repository, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	REPOSIT	Rest of repository, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT1	WRGSSAT1	0.848 5	0.0	2.4 × 10–13
North RoR	CAVITY_2	Rest of repository, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	REPOSIT	Rest of repository, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT1	WRGSSAT1	0.848 5	0.0	2.4 × 10–13
Ops	CAVITY_3	Operations area, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	OPS_AREA	Operations area, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	0.18	0.0	1.0 × 10–11

Table PA-2. Parameter Values Used in Representation of Two Phase Flow — Continued

Region	Material	Material Description	Brooks-Corey Pore Distribution λ	Threshold Pressure Linear Parameter a	Threshold Pressure Exponential Parameter η	Residual Brine Saturation S_{br}	Residual Gas Saturation S_{gr}	Porosity ϕ_0	Pore Compressibility β_f	Intrinsic Permeability k, m2
Exp	CAVITY_3	Experimental area, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	EXP_AREA	Experimental area, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	0.18	0.0	1.0 × 10–11
Castile	IMPERM_Z	Castile Formation	0.7	0.0	0.0	0.0	0.0	0.005	0.0	9.999999 × 10–36
Castile Brine Reservoir	CASTILER	Brine Reservoir in Castile Formation	0.7	0.56	–0.346	0.2	0.2	f(BPCOMP 1)4	f(BPCOMP 1)3	10x, x = BPPRM1
Culebra	CULEBRA	Culebra Member of Rustler Formation	0.6436	0.26	–0.348	0.08363	0.07711	0.151	6.622517 × 10–10	2.098938 × 10–14
Magenta	MAGENTA	Magenta Member of Rustler Formation	0.6436	0.26	–0.348	0.08363	0.07711	0.138	1.915942 × 10–9	6.309576 × 10–16
Dewey Lake	DEWYLAKE	Dewey Lake Redbeds	0.6436	0.0	0.0	0.08363	0.07711	0.143	6.993007 × 10–8	5.011881 × 10–17
Santa Rosa	SANTAROS	Santa Rosa Formation	0.6436	0.0	0.0	0.08363	0.07711	0.175	5.714286 × 10–8	1.0 × 10–10
Los Medanos	UNNAMED	Los Medaños Member of Rustler Formation	0.7	0.0	0.0	0.2	0.2	0.181	0.0	9.999999 × 10–36
Tamarisk	TAMARISK	Tamarisk Member of Rustler Formation	0.7	0.0	0.0	0.2	0.2	0.064	0.0	9.999999 × 10–36
49er	FORTYNIN	Fortyniner Member of Rustler Formation	0.7	0.0	0.0	0.2	0.2	0.082	0.0	9.999999 × 10–36
DRZ_PCS	DRZ_0	Disturbed rock zone, -5 to 0 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMP1)3	9.999999 × 10–18
DRZ_PCS	DRZ_PCS	DRZ above the panel closures, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR1)2	f(HALCOMPa)c	10x, x = DRZPCPRM1
CONC_PCS	CAVITY_4	Concrete portion of panel closures, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10
	CONC_PCS	Concrete portion of panel closures, 0 to 10,000 years	0.9193	0.0	0.0	CONBRSAT1	CONGSSAT1	0.005	1.2 × 10–9	10x, x = CONPRM1
DRF_PCS	CAVITY_4	Drift adjacent to panel closures, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0 × 10–10

Table PA-2. Parameter Values Used in Representation of Two Phase Flow — Continued

Region	Material	Material Description	Brooks-Corey Pore Distribution λ	Threshold Pressure Linear Parameter a	Threshold Pressure Exponential Parameter η	Residual Brine Saturation S_{br}	Residual Gas Saturation S_{gr}	Porosity ϕ_0	Pore Compressibility β_f	Intrinsic Permeability k, m2
	DRF_PCS	Drift adjacent to panel closures, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT1	WRGSSAT1	0.848	0.0	2.4×10^{-13}
CONC_MON	CAVITY_4	Concrete monolith portion of shaft seals, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0×10^{-10}
	CONC_MON	Concrete monolith portion of shaft seals, 0 to 10,000 years	0.94	0.0	0.0	SHURBRN1	SHURGAS1	0.05	1.2×10^{-9}	1.0×10^{-14}
Upper Shaft	CAVITY_4	Upper portion of shaft seals, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0×10^{-10}
	SHFTU	Upper portion of shaft seals, 0 to 10,000 years	0.9193	0.0	0.0	SHURBRN1	SHURGAS1	0.005	2.05×10^{-8}	10x, x = SHUPRM 1
Lower Shaft	CAVITY_4	Lower portion of shaft seals, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	1.0	0.0	1.0×10^{-10}
	SHFTL_T1	Lower portion of shaft seals, 0 - 200 years	0.9193	0.0	0.0	SHURBRN1	SHURGAS1	0.005	4.28×10^{-9}	10x, x = SHLPRM11
	SHFTL_T2	Lower portion of shaft seals, 200 - 10,000 years	0.9193	0.0	0.0	SHURBRN1	SHURGAS1	0.005	4.28×10^{-9}	10x, x = SHLPRM21
Borehole plugs	CONC_PLG	Concrete borehole plug, before plug degradation	0.94	0.0	0.0	0.0	0.0	0.32	0.0	10x, x = PLGPRM1
	BH_SAND	Borehole after plug degradation, 200 years after intrusion	0.94	0.0	0.0	0.0	0.0	0.32	0.0	10x, x = BHPRM1
Upper Borehole	BH_OPEN	Borehole above repository before plug degradation	0.7	0.0	0.0	0.0	0.0	0.32	0.0	1.0×10^{-9}
	BH_SAND	Borehole after plug degradation, 200 years after intrusion	0.94	0.0	0.0	0.0	0.0	0.32	0.0	10x, x = BHPRM1
Lower Borehole	BH_OPEN	Borehole below repository before creep closure	0.7	0.0	0.0	0.0	0.0	0.32	0.0	1.0×10^{-9}

Table PA-2. Parameter Values Used in Representation of Two Phase Flow — Continued

Region	Material	Material Description	Brooks-Corey Pore Distribution λ	Threshold Pressure Linear Parameter a	Threshold Pressure Exponential Parameter η	Residual Brine Saturation S_{br}	Residual Gas Saturation S_{gr}	Porosity ϕ_0	Pore Compressibility β_f	Intrinsic Permeability k, m2
	BH_CREEP	Borehole below repository after creep closure, 1,000 years after intrusion	0.94	0.0	0.0	0.0	0.0	0.32	0.0	10x/10, x = BHPRM1

[1] Uncertain variable, see Table PA-17.
[2] See Equation (28).
[3] See Equation (31); ϕ_0 can also be defined by an uncertain variable.
[4] See Equation (29).
[5] Initial value of porosity ϕ_0; porosity changes dynamically to account for creep closure (see Section PA-4.2.3).

$$PR = V \frac{BPCOMP}{\phi_0}, \tag{30}$$

where V is the volume of the grid block representing the Castile brine reservoir in Figure PA-8. The effect of this relationship is that the initial porosity of the brine reservoir ranges from 0.1842 to 0.9208. This range of porosity is not meant to represent an actual reservoir, but rather allows a reservoir to supply a volume of brine to the repository in the event of an E1 intrusion consistent with observed brine flows in the Delaware Basin.

The compressibility β_f in Equation (25f) and Table PA-2 is pore compressibility. Compressibility is treated as uncertain for Salado anhydrite, Salado halite, and regions of pressurized brine in the Castile Formation. However, the sampled value for each of these variables corresponds to bulk compressibility rather than to the pore compressibility actually used in the calculation. The conversion from bulk compressibility β_{fB} to pore compressibility β_f is approximated by

$$\beta_f = \beta_{fB} / \phi_0 , \tag{31}$$

where ϕ_0 is the initial porosity in the region under consideration.

The primary model used in the CRA-2004 PA for capillary pressure p_C and relative permeability k_{rl} is a modification of the Brooks-Corey model (Brooks and Corey 1964). In this model, p_C, k_{rb} and k_{rg} are defined by

$$p_C = p_t(k) / S_{e2}^{1/\lambda} \tag{32a}$$

$$k_{rb} = S_{e1}^{(2+3\lambda)/\lambda} \tag{32b}$$

$$k_{rg} = \left(1 - S_{e2}\right)^2 \left(1 - S_{e2}^{(2+\lambda)/\lambda}\right), \tag{32c}$$

where

λ = pore distribution parameter (dimensionless)

$p_t(k)$ = capillary threshold pressure (Pa) as a function of intrinsic permeability k (Webb 1992)

$$= ak^{\eta} \tag{33}$$

S_{e1} = effective brine saturation (dimensionless) without correction for residual gas saturation

$$= \left(S_b - S_{br}\right) / \left(1 - S_{br}\right) \tag{34}$$

S_{e2} = effective brine saturation (dimensionless) with correction for

residual gas saturation

$$= \left(S_b - S_{br}\right) \Big/ \left(1 - S_{gr} - S_{br}\right) \ . \tag{35}$$

The values used for λ, a, η, S_{br}, S_{gr}, and k are summarized in Table PA-2. The statement that the Brooks-Corey model is in use means that p_C , k_{rb}, and k_{rg} are defined by Equation (32). The Brooks-Corey model is used for all materials with the two exceptions, as identified in Table PA-3. In the anhydrite MBs, either the Brooks-Corey model or the van Genuchten-Parker model is used as determined by the subjectively uncertain parameter ANHBCVGP (see Table PA-17). A linear model is used in the representation of two-phase flow in an open borehole (i.e., for the first 200 years after a drilling intrusion for boreholes with two-plug or three-plug configurations (Section 6.4.7.2)). Each of these alternatives to the Brooks-Corey model is now discussed.

Table PA-3. Models for Relative Permeability and Capillary Pressure for Two-Phase Flow

Material	Relative Permeability[1]	Capillary Pressure[2]	Material	Relative Permeability[1]	Capillary Pressure[2]
S_HALITE	4	2	WAS_AREA	4	1
DRZ_0	4	1	DRZ_1	4	1
S_MB139	ANHBCVGP[3]	2	DRZ_PCS	4	1
S_ANH_AB	ANHBCVGP[3]	2	CONC_PCS	4	1
S_MB138	ANHBCVGP[3]	2	UNNAMED	4	1
CAVITY_1	4	1	TAMARISK	4	1
CAVITY_2	4	1	FORTYNIN	4	1
CAVITY_3	4	1	DRF_PCS	4	1
CAVITY_4	4	1	REPOSIT	4	1
IMPERM_Z	4	1	CONC_MON	4	1
CASTILER	4	2	SHFTU	4	1
OPS_AREA	4	1	SHFTL_T1	4	1
EXP_AREA	4	1	SHFTL_T2	4	1
CULEBRA	4	2	CONC_PLG	4	1
MAGENTA	4	2	BH_OPEN	5	1
DEWYLAKE	4	1	BH_SAND	4	1
SANTAROS	4	1	BH_CREEP	4	1

[1] Relative permeability model, where 4 ~ Brooks-Corey model (Equation (32)), 5 ~ linear model (Equation (37)), and ANHBCVGP ~ use of Brooks-Corey or van Genuchten-Parker model treated as a subjective uncertainty.

[2] Capillary pressure model, where 1 ~ p_C = 0 Pa, 2 ~ p_C bounded above by 1×10^8 Pa as S_b approaches S_{br}.

[3] See ANHBCVGP in Table PA-17.

In the van Genuchten-Parker model, p_C, k_{rb}, and k_{rg} are defined by (van Genuchten 1978):

$$p_C = p_{VGP}\left(S_{e2}^{-1/m} - 1\right)^{1-m} \tag{36a}$$

$$k_{rb} = S_{e1}^{1/2}\left[1-\left(1-S_{e1}^{1/m}\right)^{m}\right]^{2} \tag{36b}$$

$$k_{rg} = \left(1-S_{e2}\right)^{1/2}\left(1-S_{e2}^{1/m}\right)^{2m}, \tag{36c}$$

where $m = \lambda/(1+\lambda)$ and the capillary pressure parameter p_{VGP} is determined by requiring that the capillary pressures defined in Equation (32a) and Equation (36a) are equal at an effective brine saturation of $S_{e2} = 0.5$ (Webb 1992). The van Genuchten-Parker model is only used for the anhydrite MBs in the Salado and uses the same values for λ , S_{br}, and S_{gr} as the Brooks-Corey model (Table PA-2).

In the linear model, p_C , k_{rb}, and k_{rg} are defined by:

$$p_C = 0,\ k_{rb} = S_{e1},\ k_{rg} = 1 - S_{e1}. \tag{37}$$

Capillary pressure p_C for both the van Genuchten-Parker and Brooks-Corey models becomes unbounded as brine saturation S_b approaches the residual brine saturation, S_{br} . To avoid unbounded values, p_C is capped at 1×10^8 Pa in selected regions (Table PA-3).

The saturation and capillary pressure constraints (i.e., Equation (25c) and Equation (25d)) permit a reduction of the number of equations to be solved from four to two. In particular, the constraint equations are used to reformulate Equation (25a) and Equation (25b) so that the unknown functions are gas saturation S_g and brine pressure p_b . Specifically, the saturation constraint in Equation (25c) allows S_b to be expressed as

$$S_b = 1 - S_g, \tag{38}$$

and thus allows S_{e1} and S_{e2} in Equation (34) and Equation (35) to be reformulated as

$$S_{e1} = \left(1 - S_g - S_{br}\right)/\left(1 - S_{br}\right) \tag{39}$$

$$S_{e1} = \left(1 - S_g - S_{br}\right)/\left(1 - S_{gr} - S_{br}\right). \tag{40}$$

Further, the capillary pressure constraint in Equation (25d) allows p_g to be expressed as

$$p_g = p_b + p_C$$

$$= p_b + p_t(k)/S_{e2}^{1/2} \quad \text{for Brooks-Corey model, Equation (32a)} \tag{41a}$$

$$= p_b + p_{VGP}\left(S_{e2}^{-1/m} - 1\right)^{1-m} \tag{41b}$$

for van Genuchten-Parker model, Equation (36a)

$= p_b$ for linear model, Equation (37). (41c)

The equalities in Equation (39), Equation (40), and Equation (41) allow the transformation of Equation (25a) and Equation (25b) into two equations whose unknown functions are S_g and p_b, which are the equations that are actually solved in BRAGFLO:

$$\nabla \bullet \left[\frac{\alpha \rho_g K_g k_{rg}}{\mu_g} \left(\nabla p_g + \rho_g g \nabla h \right) \right] + \alpha q_{wg} + \alpha q_{rg} = \alpha \frac{\partial \left(\phi \rho_g S_g \right)}{\partial t} \tag{42a}$$

$$\nabla \bullet \left[\frac{\alpha \rho_b K_b k_{rb}}{\mu_b} \left(\nabla p_b + \rho_b g \nabla h \right) \right] + \alpha q_{wb} + \alpha q_{rb} = \alpha \frac{\partial \left(\phi \rho_b S_b \right)}{\partial t}. \tag{42b}$$

Once S_g and p_b are known, S_b and p_g can be obtained from Equation (38) and from Equation (41), respectively.

All materials are assumed to be isotropic (Howarth and Christian-Frear 1997). Thus, the tensor K_l in Equation (25) has the form

$$\mathbf{K}_l = \begin{bmatrix} k_l & 0 \\ 0 & k_l \end{bmatrix}, \tag{43}$$

where k_l is the permeability to fluid l for the particular material under consideration. For brine (i.e., fluid l = b), the permeability k_b is the same as the intrinsic permeability k in Table PA-2. For gas (i.e., fluid l = g), the permeability k_g is obtained by modifying the intrinsic permeability k to account for the Klinkenberg effect (Klinkenberg 1941). Specifically,

$$k_g = k \left(\frac{1 + b k^a}{p_g} \right), \tag{44}$$

where $a = a_{klink}$ and $b = b_{klink}$ are gas- and formation-dependent constants. Values of $a_{klink} = -0.3410$ and $b_{klink} = 0.2710$ were determined from data obtained for MB 139 (Christian-Frear 1996), with these values used for all regions in Figure PA-8. A pressure-dependent modification of k is used in the anhydrite MBs and in the DRZ in the presence of pressure-induced fracturing (see Section PA-4.2.4).

Gas density is computed using the Redlich-Kwong-Soave (RKS) equation of state, with the gas assumed to be pure hydrogen. For a pure gas, the RKS equation of state has the form (pp. 43-54, Walas 1985)

$$p_g = \frac{RT}{V - b} - \frac{a\alpha}{V(V + b)}, \tag{45}$$

where

R = gas constant = 8.31451 J mol^{-1} K^{-1},

T = temperature (K) = 300.15 K (= 30° C),

V = molar volume (m^3 mol^{-1}),

a = $0.42747\ R^2 T_c^2 / P_c$,

b = $0.08664\ RT_c / P_c$,

α = $\left[1+\left(0.48508+1.55171\omega-0.15613\omega^2\right)\left(1-T_r^{0.5}\right)\right]^2$

≈ $1.202\exp\left(-0.30288T_r\right)$ for hydrogen (Graboski and Daubert 1979),

T_c = critical temperature (K),

P_c = critical pressure (Pa),

T_r = T / T_c = reduced temperature,

ω = acentric factor
= 0 for hydrogen (Graboski and Daubert 1979).

For hydrogen, pseudo-critical temperature and pressure values of T_c = 43.6 °K and $P_c = 2.047 \times 10^6$ Pa are used instead of the true values of these properties (Prausnitz 1969). Equation (45) is solved for molar volume V. The gas density ρ_g then is given by

$$\rho_g = \frac{M_{w,H_2}}{V}, \tag{46}$$

where M_{w,H_2} is the molecular weight of hydrogen (i.e., 2.01588×10^{-3} kg/mol; see p. B-26, Weast 1969).

Brine density ρ_b is defined by Equation (25f), with ρ_0 = 1230.0 kg/m^3 at a pressure of p_{b0} = 1.0132×10^5 Pa and $\beta_b = 2.5 \times 10^{-10}$ Pa^{-1} (Roberts 1996). Porosity, ϕ, is used as defined by Equation (25g) with two exceptions: in the repository (see Section PA-4.2.3) and in the MBs subsequent to fracturing (see Section PA-4.2.4). The values of ϕ_0 and β_f used in conjunction with Equation (25g) are listed in Table PA-2. The reference pressure p_{b0} in Equation (25g) is spatially-variable and corresponds to the initial pressures $p_b\left(x, y, -5\right)$ (see Section PA-4.2.2).

The gas and brine viscosities μ_l, l = g, b in Equation (25a) and Equation (25b) were assumed to have values of $\mu_g = 8.92 \times 10^{-6}$ Pa s (Vargaftik 1975) and $\mu_b = 2.1 \times 10^{-3}$ Pa s (McTigue 1993).

The terms q_{wg}, q_{rg}, q_{wb}, and q_{rb} in Equation (25a) and Equation (25b) relate to well injection or removal (i.e., q_{wg} , q_{wb}) and reaction production or consumption (i.e., q_{rg} , q_{rb}) of gas and brine, with positive signs corresponding to injection or production and negative signs corresponding to removal or consumption. No injection or removal of gas or brine is assumed to take place within the region in Figure PA-8. Thus, q_{wg} and q_{wb} are equal to zero. Further, no gas consumption occurs (see below), and gas production has the potential to occur (due to corrosion of steel or microbial degradation of cellulosic, plastic, or rubber (CPR) materials) only in the waste disposal regions of the repository (i.e., Waste Panel, South RoR, and North RoR in Figure PA-8). Thus,

$$\begin{aligned} q_{rg} &\geq 0 \quad \text{in waste disposal regions of Figure PA-8} \\ &= 0 \quad \text{elsewhere.} \end{aligned} \tag{47}$$

In actuality, some gas consumption does occur due to the reaction of CO_2 with the MgO in the waste panels. This gas consumption is not modeled explicitly and is accounted for by reducing the gas generation rate q_{rg}, as discussed in Section PA-4.2.5. Finally, no brine production occurs, and brine consumption has the potential to occur (due to the consumption of brine during the corrosion of steel) only in the waste disposal regions of the repository. Thus,

$$\begin{aligned} q_{rb} &\leq 0 \quad \text{in waste disposal regions of Figure PA-8} \\ &= 0 \quad \text{elsewhere.} \end{aligned} \tag{48}$$

More detail on the definition of q_{rg} and q_{rb} is provided in Section PA-4.2.5.

PA-4.2.2 Initial Conditions

In each two-phase flow simulation, a short period of time representing disposal operations is simulated. This period of time is called the start-up period and covers five years from t = –5 years to 0 years, corresponding to the amount of time a typical panel is expected to be open during disposal operations. All grid locations require initial brine pressure and gas saturation at the beginning of the simulation (t = –5 years).

The Rustler Formation and overlying units (except in the shaft) are modeled as horizontal with spatially constant initial pressure in each layer (see Figure PA-8). Table PA-4 lists the initial brine pressure p_b and gas saturation S_g for the Rustler Formation.

Table PA-4. Initial Conditions in the Rustler Formation

Name	Mesh Row (Figure PA-8)	$p_b(x, y, -5)$, Pa	$S_g(x, y, -5)$
Santa Rosa Formation	33	1.013250×10^5	1 – Sbr = 0.916

Santa Rosa Formation	32	1.013250×10^5	1 – Sbr = 0.916
Dewey Lake	31	1.013250×10^5	1 – Sbr = 0.916
Dewey Lake	30	7.355092×10^5	1 – Sbr = 0.916
49er	29	1.473284×10^6	0
Magenta	28	9.170000×10^5	0
Tamarisk	27	1.827087×10^6	0
Culebra	26	8.220000×10^5	0
Los Medaños Unnamed	25	2.274809×10^6	0

The Salado Formation (mesh rows 3 – 24 in Figure PA-8) is assumed to dip uniformly θ = 1° downward from north to south (right to left in Figure PA-8). Except in the repository excavations and in the shaft, brine is assumed initially (i.e., at –5 years) to be in hydrostatic equilibrium relative to an uncertain initial pressure $p_{b,ref}$ (SALPRES, see Table PA-17) at a reference point located at center of shaft at the elevation of the midpoint of MB139, which is the center of cell 1266 in Figure PA-10). This gives rise to the condition

$$p_b\left(x, y, -5\right) = p_{b0} + \left(\frac{1}{\beta_b}\right) \ln\left[\frac{\rho_b\left(x, y, -5\right)}{\rho_{b0}}\right], \tag{49}$$

where

$$\rho_b\left(x, y, -5\right) = \frac{1}{g\,\beta_b\left[y_e - \Phi\left(x_{ref}, y_{ref}, -5\right) + \dfrac{1}{g\,\beta_b\,\rho_{b0}}\right]}$$

$$\Phi\left(x_{ref}, y_{ref}, -5\right) = y_{ref} + \frac{1}{g\,\beta_b}\left[\frac{1}{\rho_{b0}} - \frac{1}{\rho_b\left(x_{ref}, y_{ref}, -5\right)}\right]$$

$$\rho_b\left(x_{ref}, y_{ref}, -5\right) = \rho_{b0} \exp\left[-\beta_b\left(p_{b,ref} - p_{b0}\right)\right]$$

$$y_e = y_{ref} + h(x, y) = y_{ref} + \left(x - x_{ref}\right)\sin\theta + \left(y - y_{ref}\right)\cos\theta \quad \text{(see Equation (27))}$$

and ρ_{b0} = 1220 kg/m^3, $\beta_b = 3.1 \times 10^{-10}$ Pa^{-1}, g = 9.80665 m/s^2, and $p_{b0} = 1.01325 \times 10^5$ Pa. In the Salado Formation, initial gas saturation $S_g\left(x, y, -5\right) = 0$.

The Castile Formation (mesh rows 1 and 2) is modeled as horizontal, and initial brine pressure is spatially constant within each layer, except that the brine reservoir is treated as a different

material from rest of Castile and has a different initial pressure. Specifically, outside the brine reservoir,

$$p_b(x, y, -5) = \begin{cases} 1.54445 \times 10^7 \ Pa & \text{in mesh row 2} \\ 1.65151 \times 10^7 \ Pa & \text{in mesh row 1} \end{cases}. \tag{50}$$

Within the reservoir, $p_b(x, y, -5) = BPINTPRS$, the uncertain initial pressure in the reservoir (see Table PA-17). Initial gas saturation $S_g(x, y, -5) = 0$.

Within the shaft (areas Upper Shaft, Lower Shaft, and CONC_MON) and panel closures (areas CONC_PCS and DRF_PCS), $p_b(x, y, -5) = 1.01325 \times 10^5$ Pa and $S_g(x, y, -5) = 1 \times 10^{-7}$. Within the excavated areas (Waste Panel, South RoR, and North RoR, Ops and Exp), $p_b(x, y, -5) = 1.01325 \times 10^5$ Pa and $S_g(x, y, -5) = 0$.

At the end of the initial five-year start-up period and the beginning of the regulatory period (t = 0 years), brine pressure and gas saturation are reset in the shaft, panel closures, and excavated areas. In the shaft (areas Upper Shaft, Lower Shaft, and CONC_MON) and panel closures (areas CONC_PCS and DRF_PCS), $p_b(x, y, 0) = 1.01325 \times 10^5$ Pa and $S_g(x, y, 0) = 1 \times 10^{-7}$. In the waste disposal regions (areas Waste Panel, South RoR, and North RoR), $p_b(x, y, 0) = 1.01325 \times 10^5$ Pa and $S_g(x, y, 0) = 0.985$. In the other excavated areas, $p_b(x, y, 0) = 1.01325 \times 10^5$ Pa and $S_g(x, y, 0) = 1.0$.

PA-4.2.3 Creep Closure of Repository

The porosity of the waste disposal regions and neighboring access drifts (i.e., Waste Panel, South RoR, North RoR, and DRF_PCS in Figure PA-8) is assumed to change through time due to creep closure of the halite surrounding the excavations. The equations on which BRAGFLO is based do not incorporate this type of deformation. Therefore, the changes in repository porosity due to halite deformation are modeled in a separate analysis with the geomechanical program SANTOS, which implements a quasi-static, large-deformation, finite-element procedure (Stone 1997). Interpolation procedures are then used with the SANTOS results to define ϕ within the repository as a function of time, pressure, and gas generation rate.

For more information on the generation of the porosity surface for BRAGFLO for the CRA-2004 PA, see Appendix PA, Attachment PORSURF.

PA-4.2.4 Fracturing of Marker Beds and Disturbed Rock Zone

Fracturing within the anhydrite MBs (i.e., regions MB 138, Anhydrite AB, and MB 139 in Figure PA-8) and in the DRZ (region DRZ in Figure PA-8) is assumed to occur at pressures slightly below lithostatic pressure and is implemented through a pressure-dependent

compressibility $\beta_f\left(p_b\right)$ (Mendenhall and Gerstle 1995). Specifically, fracturing of the MBs begins at a brine pressure of

$$p_{bi} = p_{b0} + \Delta p_i \ , \tag{51}$$

where p_{bi} and p_{b0} are spatially dependent (i.e., $p_{b0} = p_b\left(x, y, 0\right)$ as in Section PA-4.2.2) and $\Delta p_i = 2 \times 10^5$ Pa.

Fracturing ceases at a pressure of

$$p_{ba} = p_{b0} + \Delta p_a \tag{52}$$

and a fully-fractured porosity of

$$\phi\left(p_{ba}\right) = \phi_a = \phi_0 + \Delta\phi_a \ , \tag{53}$$

where $\Delta p_a = 3.8 \times 10^6$ Pa, ϕ_0 is spatially dependent (Table PA-2), and $\Delta\phi_a$ = 0.04, 0.24, and 0.04 for anhydrite materials S_MB138, S_ANH_AB and S_MB139, respectively.

Compressibility β_f is a linear function

$$\beta_f\left(p_b\right) = \beta_f + \left(\frac{p_b - p_{bi}}{p_{ba} - p_{bi}}\right)\left(\beta_{fa} - \beta_f\right) \tag{54}$$

of brine pressure for $p_{bi} \le p_b \le p_{ba}$, with β_{fa} defined so that the solution ϕ of

$$\frac{d\phi}{dp_b} = \beta_{fa}(p_b)\phi, \quad where \ \ \phi(p_{bi}) = \phi_0 \exp\left[\beta_f(p_{bi} - p_{b0})\right] \tag{55}$$

satisfies $\phi\left(p_{ba}\right) = \phi_a$; specifically, β_{fa} is given by

$$\beta_{fa} = \beta_f\left[1 - \frac{2\left(p_{ba} - p_{b0}\right)}{p_{ba} - p_{bi}}\right] + \left[\frac{2}{p_{ba} - p_{bi}}\right]\ln\left(\frac{\phi_a}{\phi_0}\right) \ . \tag{56}$$

The permeability $k_f\left(p_b\right)$ of fractured material at brine pressure p_b is related to the permeability of unfractured material at brine pressure p_{bi} by

$$k_f(p_b) = \left[\frac{\phi(p_b)}{\phi(p_{bi})}\right]^n k \ , \tag{57}$$

where k is the permeability of unfractured material (i.e., at p_{bi}) and n is defined so that $k_f(p_b) = 1 \times 10^{-9}\ m^2$ (i.e., n is a function of k, which is an uncertain input to the analysis; see ANHPRM in Table PA-17). When fracturing occurs, $k_f(p_b)$ is used instead of k in the definition of the permeability tensor K_l in Equation (43) for the fractured areas of the anhydrite MBs.

Fracturing is also modeled in the DRZ. The implementation of the fracture model is the same as for the anhydrite materials. In this case, fracturing would be in halite rather than anhydrite, but because of the limited extent of the DRZ and the proximity of the nearby interbeds, this representation was deemed acceptable by the Salado Flow Peer Review panel (Caporuscio et al. 2003).

PA-4.2.5 Gas Generation

Gas production is assumed to result from anoxic corrosion of steel and microbial degradation of CPR materials. Thus, the gas generation rate q_{rg} in Equation (25a) is of the form

$$q_{rg} = q_{rgc} + q_{rgm}\,, \tag{58}$$

where q_{rgc} is the rate of gas production per unit volume of waste (kg/m^3/s) due to anoxic corrosion of Fe-base metals and q_{rgm} is the rate of gas production per unit volume of waste (kg/m^3/s) due to microbial degradation of CPR materials. Furthermore, q_{rb} in Equation (25b) is used to describe the consumption of brine during the corrosion process.

Gas generation takes place only within the waste disposal regions (i.e., Waste Panel, South RoR, and North RoR in Figure PA-8) and all the generated gas is assumed to have the same properties as H_2 (see discussion in Attachment MASS, Section MASS-3.2). In the CCA PA and the CRA-2004 PA, the consumable materials are assumed to be homogeneously distributed throughout the waste disposal regions (i.e., the concentration of Fe-base metals and of CPR materials in the waste is a constant; see Appendix TRU WASTE, Table TRU WASTE-1). A separate analysis examined the potential effects on PA results of spatially-varying concentrations of Fe-base metals and CPR materials, and concluded that PA results are not affected by representing these materials with spatially-varying concentrations (see Attachment MASS, Section MASS.21).

The rates q_{rgc}, q_{rb} and q_{rgm} are defined by

$$q_{rgc} = \left(R_{ci}S_{b,eff} + R_{ch}S_g^*\right)D_s\rho_{Fe}X_c\left(H_2|Fe\right)M_{H_2} \tag{59}$$

$$q_{rb} = \left(q_{rgc}/M_{H_2}\right)X_c\left(H_2O|H_2\right)M_{H_2O} \tag{60}$$

$$q_{rgm} = \left(R_{mi}S_{b,eff} + R_{mh}S_g^*\right)D_c y\left(H_2|C\right)M_{H_2}\,, \tag{61}$$

where

D_s = surface area concentration of steel in the repository ((m^2 surface area steel)/(m^3 disposal volume)),

D_c = mass concentration of cellulosics in the repository ((kg biodegradable material)/(m^3 of disposal volume)),

M_{H_2} = molecular weight of H_2 (kg H_2/mol H_2),

M_{H_2O} = molecular weight of H_2O (kg H_2O/mol H_2O),

R_{ci} = corrosion rate under inundated conditions (m/s),

R_{ch} = corrosion rate under humid conditions (m/s),

R_{mi} = rate of cellulose biodegradation under inundated conditions (mol $C_6H_{10}O_5$/kg $C_6H_{10}O_5$/s),

R_{mh} = rate of cellulose biodegradation under humid conditions (mol $C_6H_{10}O_5$/kg $C_6H_{10}O_5$/s),

$S_{b,eff}$ = effective brine saturation due to capillary action in the waste materials (see Equation (78) in Section PA-4.2.6),

$$S_g^* = \begin{cases} 1 - S_{b,eff} & \text{if } S_{b,eff} > 0 \\ 0 & \text{if } S_{b,eff} = 0 \end{cases},$$

$X_c(H_2|Fe)$ = stoichiometric coefficient for gas generation due to corrosion of steel, i.e., moles of H_2 produced by the corrosion of 1 mole of Fe (mol H_2 / mol Fe),

$X_c(H_2O|H_2)$ = stoichiometric coefficient for brine consumption due to corrosion of steel, i.e., moles of H_2O consumed per mole of H_2 generated by corrosion (mol H_2O / mol H_2),

$y(H_2|C)$ = average stoichiometric factor for microbial degradation of cellulose, i.e., the moles of H_2 generated per mole of carbon consumed by microbial action (mol H_2 / mol $C_6H_{10}O_5$), and

ρ_{Fe} = molar density of steel (mol/m^3).

The products $R_{ci}\ D_s\ \rho_{Fe}\ X_c$, $R_{ch}\ D_s\ \rho_{Fe}\ X_c$, $R_{mi}\ D_c\ y$, and $R_{mh}\ D_c\ y$ in Equation (59) and Equation (61) define constant rates of gas generation (mol/m^3/s) that continue until the associated substrate (i.e. steel or cellulose) is exhausted (i.e., zero order kinetics). The terms $S_{b,eff}$ and S_g^* in Equation (59) and Equation (61), which are functions of location and time, correct for the amount of substrate that is exposed to inundated and humid conditions, respectively. All the corrosion and microbial action is assumed to cease when no brine is present, which is the reason that 0 replaces $S_g = 1$ in the definition of S_g^*. In the CRA-2004 PA, $R_{ch} = 0$ and R_{ci}, R_{mh}, and R_{mi} are defined by uncertain variables (see WGRCOR, WGRMICH, WGRMICI in Table PA-17). Further, $M_{H_2} = 2.02 \times 10^{-3}$ kg/mol (pp. 1-7, 1-8, Lide 1991), $M_{H_2O} = 1.80 \times 10^{-2}$ kg/mol (pp. 1-7, 1-8, Lide 1991), $\rho_{Fe} = 1.41 \times 10^5$ mol/m^3 (Telander and Westerman 1993), and D_s , D_c , $X_c\left(H_2O \middle| H_2\right)$, $X_c\left(H_2 \middle| Fe\right)$ and $y\left(H_2 \middle| C\right)$ are discussed below.

The concentration D_s in Equation (59) is defined by

$$D_s = A_d n_d / V_R , \tag{62}$$

where

A_d = surface area of steel associated with a waste disposal drum (m^2/drum),

V_R = initial volume of the repository (m^3), and

n_d = number of waste drums required to hold all the waste emplaced in the repository (drums).

In the CRA-2004 PA, $A_d = 6$ m^2/drum (Vol. 3, WIPP PA 1991-1992), $V_R = 438{,}406$ m^3 (Stein 2002b), and $n_d = 818{,}498$ drums ($n_d = V_R \times$ DROOM / VROOM, where DROOM is the number of drums per room {6804 drums} and VROOM is the volume of each room {3644 m^3}).

The biodegradable materials to be disposed of at the WIPP consist of cellulosic materials, rubbers, and both waste plastics and container plastics. Cellulosics have been demonstrated experimentally to be the most biodegradable among these materials (Francis et al. 1997). The occurrence of significant microbial gas generation in the repository will depend on: (1) whether microbes capable of consuming the emplaced organic materials will be present and active; (2) whether sufficient electron acceptors will be present and available; and (3) whether enough nutrients will be present and available. Given the uncertainties in these factors, a probability of 0.5 is assigned to the occurrence of microbial gas generation (see WMICDFLG in Table PA-17). Furthermore, two factors may increase the biodegradability of plastics and rubbers: long time scale and cometabolism. Over a time scale of 10,000 years, the chemical properties of plastics and rubbers may change, increasing their biodegradability. Cometabolism means that microbes

may degrade organic compounds, but do not use them as a source of energy, which is derived from other substrates. Both of these factors are highly uncertain and therefore a probability of 0.5 is assigned to biodegradation of plastics and rubbers conditional on the occurrence of biodegradation of cellulosic materials(see WMICDFLG in Table PA-17). In cases where biodegradation of rubbers and plastics occur, rubbers and plastics are converted to an equivalent quantity of cellulosics based on their carbon equivalence (Wang and Brush 1996a). This produces the density calculation

$$D_c = \begin{cases} m_{cel} / V_R & \text{for biodegradation of cellulosics only} \\ \left(m_{cel} + m_r + 1.7 m_p\right) / V_R & \text{for biodegradation of CPR materials,} \end{cases} \tag{63}$$

where m_{cel} is mass of cellulosics (kg), m_r is the mass of rubbers (kg), and m_p is the mass of plastics (kg). The factor of 1.7 converts all plastics to an equivalent quantity of cellulosics based on carbon equivalence. In the CRA-2004 PA,

$$m_{cel} = [(58.0 \text{ kg/ m}^3 \times 168{,}485 \text{ m}^3) + (4.5 \text{ kg/ m}^3 \times 7{,}079 \text{ m}^3)] = 9.8 \times 10^6 \text{ kg},$$

$$m_r = [(14.0 \text{ kg/ m}^3 \times 168{,}485 \text{ m}^3) + (3.1 \text{ kg/m3} \times 7{,}079 \text{ m}^3)] = 2.4 \times 10^6 \text{ kg}$$

$$m_p = [(58.0 \text{ kg/m3} \times 168{,}485 \text{ m}^3) + (6.3 \text{ kg/m3} \times 7{,}079 \text{ m}^3)] = 9.8 \times 10^6 \text{ kg}.$$

Values for the density for CPR materials can be found in Appendix DATA, Attachment F.

The most plausible corrosion reactions after closure of the WIPP are believed to be (Wang and Brush 1996a)

$$Fe + 2H_2O = Fe(OH)_2 + H_2 \tag{64}$$

and

$$3Fe + 4H_2O = Fe_3O_4 + 4H_2. \tag{65}$$

When linearly weighted by the factors x and $1 - x$ $\left(0 \le x \le 1\right)$, the two preceding reactions become

$$Fe + \left(\frac{4 + 2x}{3}\right) H_2O = \left(\frac{4 - x}{3}\right) H_2 + xFe(OH)_2 + \left(\frac{1 - x}{3}\right) Fe_3O_4 , \tag{66}$$

where x and $1 - x$ are the fractions of iron consumed in the reactions in Reaction (64) and Reaction (65), respectively. Although magnetite (Fe_3O_4) has been observed to form on iron as a corrosion product in low-Mg anoxic brines at elevated temperatures (Telander and Westerman 1997) and in oxic brine (Haberman and Frydrych 1988), there is no evidence that it will form at WIPP repository temperatures. If Fe_3O_4 were to form, H_2 would be produced (on a molar basis)

in excess of the amount of Fe consumed. However, anoxic corrosion experiments (Telander and Westerman 1993) did not indicate the production of H_2 in excess of the amount of Fe consumed. Therefore, the stoichiometric factor x in Reaction (66) is set to 1.0 (i.e., x = 1), which implies that Reaction (64) represents corrosion. Thus, the stoichiometric factor for corrosion is

$$X_c\left(H_2 \middle| Fe\right) = \left(4 - x\right)/3 = 1\ mol/mol\ , \tag{67}$$

which implies that one mole of H_2 is produced for each mole of iron consumed, and the stoichiometric factor for brine consumption is

$$X_c\left(H_2O \middle| H_2\right) = \left(4 + 2x\right)/3 = 2\ mol/mol\ , \tag{68}$$

which implies that two moles of H_2O are consumed for each mole of H_2 produced. The most plausible biodegradation reactions after closure of the WIPP are believed to be (Wang and Brush 1996a)

Denitrification: $$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- = 7.4H_2O + 6CO_2 + 2.4N_2\ , \tag{69a}$$

Sulfate reduction: $$C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} = 5H_2O + 6CO_2 + 3H_2S\ , \tag{69b}$$

Methanogenesis: $$C_6H_{10}O_5 + H_2O = 3CH_4 + 3CO_2\ . \tag{69c}$$

Accumulation of CO_2 produced by the above reactions could decrease pH and thus increase actinide solubility in the repository (Wang and Brush 1996b). To improve WIPP performance, a sufficient amount of MgO will be added to the repository to remove CO_2 (Bynum et al. 1997). The consumption of CO_2 by MgO in the repository takes place by the reactions outlined in Section 6.4.3.4. The removal of CO_2 by MgO is not explicitly represented in the BRAGFLO code. Rather, the effect of CO_2 consumption is accounted for by modifying the stoichiometry of Reaction (69) to remove the CO_2 from the mass of gas produced by microbial action.

The average stoichiometry of Reaction (69), is

$$C_6H_{10}O_5 + unknowns = 6\,y\ (mol)\ gas + \ unknowns\ , \tag{70}$$

where the average stoichiometric factor y in Reaction (70) represents the number of moles of gas produced and retained in the repository from each mole of carbon consumed. This factor y depends on the extent of the individual biodegradation pathways in Reaction (69), and the consumption of CO_2 by MgO. An range of values for y is estimated by considering the maximum mass of gas that can be produced from consumption of cellulosics (M_{cel}) and Fe-base metals (M_{Fe}), and is derived as follows (Wang and Brush 1996b).

Estimates of the maximum quantities M_{cel} and M_{Fe} (mol) of cellulosics (i.e., $C_6H_{10}O_5$) and steels that can be potentially consumed in 10,000 years are given by

$$M_{cel} = \min\left\{\frac{6000 m_{cel}}{162},\ 3.2 \times 10^{11} R_m m_{cel}\right\} \tag{71}$$

$$M_{Fe} = \min\left\{\frac{1000 m_{Fe}}{56},\ 4.4 \times 10^{16} R_{ci} A_d n_d\right\}, \tag{72}$$

where m_{cel} and m_{Fe} are the masses (kg) of cellulosics (see Equation (63) for definition) and steels initially present in the repository. The mass of cellulosics that can be consumed is determined by the uncertain parameter WMICDFLG (see Table PA-17). The mass of steels, $m_{Fe} = 5.15 \times 10^7$ kg; this value is calculated as:

$$V_{CH}\left(\rho_{WCH} + \rho_{CCH}\right) + V_{RH}\left(\rho_{WRH} + \rho_{CRH}\right), \tag{73}$$

where V_{CH} and V_{RH} are the volumes of CH- and RH-TRU waste, ρ_{WCH} and ρ_{WRH} are the iron densities in CH- and RH-TRU waste, and ρ_{CCH} and ρ_{CRH} are the iron densities of the containers of CH- and RH-TRU waste (Appendix DATA, Attachment F). The terms 6000 m_{cel}/162 and 1000 m_{Fe}/56 in Equation (71) and Equation (72) equal the inventories in moles of cellulosics and steel, respectively. The terms 3.2×10^{11} $R_m m_{cel}$ and 4.4×10^{16} $R_{ci} A_d n_d$ equal the maximum amounts of cellulosics and steel that could be consumed over 10,000 years. In Equation (71), $R_m = \max\left\{R_{mh}, R_{mi}\right\}$, where R_{mh} and R_{mi} are defined by uncertain variables (see WGRMICH and WGRMICI in Table PA-17, respectively), and $3.2 \times 10^{11} = (3.15569 \times 10^7$ s/yr) (10^4 yr). In Equation (72), $A_d n_d$ is the total surface area of all drums (m^2) and the factor $4.4 \times 10^{16} = (3.15569 \times 10^7$ s/yr) (10^4 yr) (1.41×10^5 mol/ m^3), where $\rho_{Fe} = 1.41 \times 10^5$ mol/m^3 (see Equation (59)) (Telander and Westerman 1993), converts the corrosion rate from m/s to mol/m^2/s.

A range of possible values for the average stoichiometric factor y in Reaction (70) can be obtained by considering individual biodegradation pathways involving M_{cel} and accounting for the removal of CO_2 by the MgO. Two extreme cases corresponding to the maximum and minimum values of y exist: (1) there is no reaction of microbially produced H_2S with ferrous metals and metal corrosion products, and (2) there is a complete reaction of microbially produced H_2S with ferrous metals and metal corrosion products. If no H_2S is consumed by reactions with Fe and Fe-corrosion products, the maximum quantity of microbial gas will be retained in the repository and therefore the maximum value for y results. Thus, the maximum value of y can be estimated by averaging the gas yields for all reaction pathways to produce

$$y_{max} = \frac{\dfrac{2.4 M_{NO_3}}{4.8} + \dfrac{3 M_{SO_4}}{3} + 0.5\left(M_{cel} - \dfrac{6 M_{NO_3}}{4.8} - \dfrac{6 M_{SO_4}}{3}\right)}{M_{cel}}, \tag{74}$$

where M_{NO_3} and M_{SO_4} are the quantities of NO_3^- and SO_4^{2-} (in moles) initially present in the repository. Specifically, M_{NO_3} = 2.51 × 10^7 mol and M_{SO_4} = 4.21 × 10^5 mol (Appendix DATA, Attachment F, Table DATA-F-35).

If H_2S reacts with Fe and Fe- corrosion products, a significant quantity or perhaps all of the microbially produced H_2S would be consumed to produce FeS, which would result in the minimum value of y. Specifically,

$$y_{min} = \frac{\frac{2.4 M_{NO_3}}{4.8} + \frac{3 M_{SO_4}}{3} + 0.5\left(M_{cel} - \frac{6 M_{NO_3}}{4.8} - \frac{6 M_{SO_4}}{3} \right) - G}{M_{cel}} = y_{max} - \frac{G}{M_{cel}}, \quad (75)$$

where

$$G = \min\left\{ \frac{3 M_{SO_4}}{3}, M_{Fe} \right\}. \quad (76)$$

The stoichiometric factor y value is believed to be located within the interval $\left[y_{min}, y_{max} \right]$. That is,

$$y = y_{min} + \beta\left(y_{max} - y_{min} \right), \quad 0 \le \beta \le 1. \quad (77)$$

The variable β in the preceding equation is treated as an uncertain quantity in the CRA-2004 PA (see WFBETCEL in Table PA-17).

PA-4.2.6 Capillary Action in the Waste

Capillary action (wicking) refers to the ability of a material to carry a fluid by capillary forces above the level it would normally seek in response to gravity. In the current analysis, this phenomena is accounted for by defining an effective saturation given by

$$S_{b,eff} = \begin{cases} S_b + S_{wick} & \text{if } 0 < S_b < 1 - S_{wick} \\ 0 & \text{if } S_b = 0 \\ 1 & \text{if } S_b > 1 - S_{wick} \end{cases}, \quad (78)$$

where

$S_{b,eff}$ = effective brine saturation,

S_b = brine saturation,

S_{wick} = wicking saturation.

The effective saturation is used on a grid block basis within all waste regions (Waste Panel, South RoR, and North RoR in Figure PA-8). The wicking saturation, S_{wick}, is treated as an uncertain variable (see WASTWICK in Table PA-17). The effective brine saturation $S_{b,eff}$ is only used in the calculation of the corrosion of steel (Equation (59)) and the microbial degradation of cellulose (Equation (61)) and does not directly affect the two-phase flow calculations indicated.

PA-4.2.7 Shaft Treatment

The WIPP excavation includes four shafts that connect the repository region to the surface: the air intake shaft, salt handing shaft, waste handling shaft, and exhaust shaft. In both the CCA PA and the CRA-2004 PA, these four shafts are modeled as a single shaft. The rationale for this modeling treatment is set forth in WIPP PA 1992-1993 (Section 2.3, Vol. 5).

A shaft seal model is included in the CRA-2004 grid (column 43 in Figure PA-8), but it is implemented in a simpler fashion than for the CCA PA. A detailed description of the new implementation and its parameters are discussed in AP-094 (James and Stein 2002) and the resulting analysis report (James and Stein 2003). The final version of the shaft seal model used in the CRA-2004 PA is described by Stein and Zelinski (2003a); this model was approved by the Salado Flow Peer Review panel (Caporuscio et al. 2003).

The planned design of the shaft seals involves numerous materials including earth, crushed salt, clay, asphalt, and Salado Mass Concrete (SMC) (CCA Appendix SEAL). The design is intended to control both short-term and long-term fluid flow through the Salado portion of the shafts. For the CCA PA, each material in the shaft seal was represented in the BRAGFLO grid. Analysis of the flow results from the CCA PA and subsequent 1997 Performance Assessment Verification Test (PAVT) (SNL 1997) indicated that no significant flows of brine or gas occurred in the shaft during the 10,000-year regulatory period. As a result of these analyses, a simplified shaft seal model was developed for the CRA-2004 PA.

A conceptual representation of the simplified shaft seal system used in CRA-2004 PA is shown in Figure PA-11. The simplified model divides the shaft into three sections: an upper section (shaft seal above the Salado), a lower section (within the Salado), and a concrete monolith section within the repository horizon. A detailed discussion on how the material properties were assigned for the simplified shaft seal model is included in James and Stein (2003). The permeability value used to represent the upper and lower sections is defined as the harmonic mean of the permeability of the component materials in the detailed shaft seal model (including permeability adjustments made for the DRZ assumed to surround the lower shaft seal section within the Salado). Porosity is defined as the thickness-weighted mean porosity of the component materials. Other material properties are described in James and Stein (2003).

The lower section of the shaft experiences a change in material properties at 200 years. This change simulates the consolidation of the seal materials within the Salado and results in a significant decrease in permeability. This time was chosen as a conservative overestimate of the amount of time expected for this section of the shaft to become consolidated. The concrete monolith section of the shaft is unchanged from the CCA PA and is represented as being highly permeable for 10,000 years to ensure that fluids can access the north end (operations and

experimental areas) in the model. In three thin regions at the stratigraphic position of the anhydrite MBs, the shaft seal is modeled as MB material (Figure PA-11). This model feature is included so that fluids flowing in the DRZ and MB fractures can access the interbeds to the north of the repository "around" the shaft seals. Because these layers are so thin, they have virtually no effect on the effective permeability of the shaft seal itself.

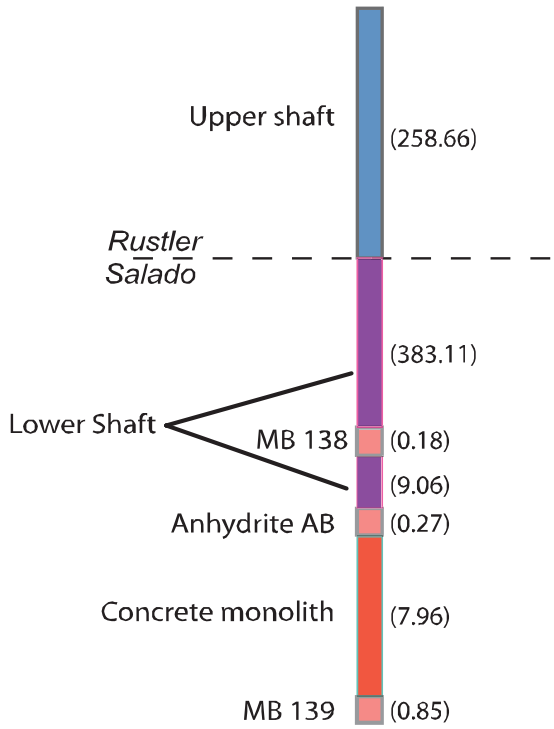

Figure PA-11. Schematic View of the Simplified Shaft Model.

The simplified shaft model was tested in the AP-106 analysis (Stein and Zelinski 2003a), which supported the Salado Flow Peer Review. The results of the AP-106 analysis demonstrated that vertical brine flow through the simplified shaft model was comparable to brine flows seen through the detailed shaft model used in the CCA PA and subsequent PAVT calculations.

PA-4.2.8 Option D Panel Closures

The CRA-2004 PA includes panel closures models that represent the Option D panel closure design (Section 6.4.3). Option D closures (Figure PA-12) are designed to allow minimal fluid flow between panels. The CRA-2004 PA explicitly represents selected Option D panel closures in the computational grid using a model that was approved by the Salado Flow Peer Review Panel (Caporuscio et al. 2003). The Option D panel closure design has several components: an SMC monolith, which extends into the DRZ in all directions, an empty drift section, and a block and mortar explosion wall (Figure PA-13). Each set of panel closures are represented in the BRAGFLO grid by four materials in 13 grid cells:

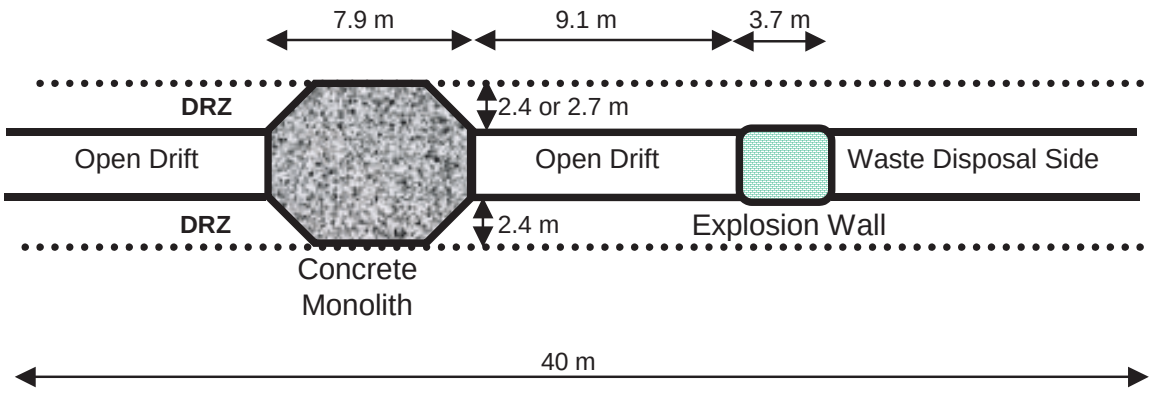

Figure PA-12. Schematic Side View of Option D Panel Closure.

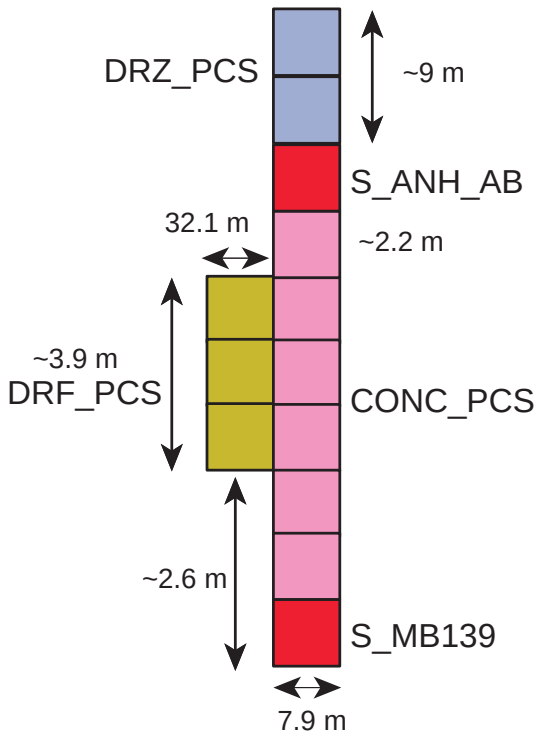

Figure PA-13. Representation of Option D Panel Closures in the BRAGFLO Grid.

- Six cells of panel closure concrete (area CONC_PCS, material CONC_PCS),
- One cell above and one cell below the concrete material consisting of MB anhydrite (areas MB 139 and Anhydrite AB, materials S_MB139 and S_ANH_AB, respectively),
- Two cells of healed DRZ above Anhydrite AB above the panel closure system (PCS) (area DRZ_PCS, material DRZ_PCS), and
- Three cells of empty drift and explosion wall (area DRF_PCS, material DRF_PCS).

Properties for the materials comprising the panel closure system are listed in Table PA-2.

PA-4.2.8.1 Panel Closure Concrete

The Option D panel closure design requires the use of a salt-saturated concrete, identified as SMC, as specified for the shaft seal system. The design of the shaft seal system and the properties of SMC are described in Hurtado et al. (1997). The BRAGFLO grid incorporates the material, CONC_PCS, which is assigned the material properties of undegraded SMC and is used to represent the concrete portion of the Option D panel closure system (Figure PA-8). A double-thick concrete segment is used to represent the northernmost set of panel closures (between the north rest of repository and the operations area). This feature is meant to represent the two sets of panel closures in series that will be emplaced between the waste filled repository and the shaft.

PA-4.2.8.2 Panel Closure Abutment with Marker Beds

In the BRAGFLO grid, regions where the Option D panel closures intersect the MBs are represented as blocks of MB material (Figure PA-8). This representation is warranted for two reasons:

1. The MB material has a very similar permeability distribution (10^{-21} to $10^{-17.1}$ m^2) as the concrete portion of the Option D panel closures ($10^{-20.699}$ to 10^{-17} m^2), and thus, assigning this material as anhydrite MB in the model has essentially the same effect as calling it concrete, as long as pressures are below the fracture initiation pressure.

2. In the case of high pressures, it is expected that fracturing may occur in the anhydrite MBs and flow could go “around” the panel closures out of the two-dimensional plane considered in the model grid. In this case, the flow would be through the MB material, which incorporates a fracture model, as described above.

PA-4.2.8.3 Disturbed Rock Zone Above the Panel Closure

After construction of the concrete portion of the panel closure, the salt surrounding the monolith will be subjected to compressive stresses, which will facilitate the rapid healing of disturbed halite. The rounded configuration of the monolith creates a situation very favorable for concrete durability: high compressive stresses and low stress differences. In turn, the compressive stresses developed within the salt will quickly heal any damage caused by construction excavation, thereby eliminating the DRZ along the length of this portion of the panel closure. The permeability of the salt immediately above and below the rigid concrete monolith component of Option D will approach the intrinsic permeability of the undisturbed Salado halite.

To represent the DRZ above the monoliths, the CRA-2004 PA uses the material, DRZ_PCS, in the BRAGFLO grid (Figure PA-8). The values assigned to DRZ_PCS are the same as those values used for the DRZ above the excavated areas (material DRZ_1, see Table PA-2), except for the properties PRMX_LOG, PRMY_LOG, and PRMZ_LOG, the logarithm of permeability in the x, y, and z directions, respectively. These permeability values are assigned the same distributions used for the material CONC_PCS. In this instance, the values are based on the

nature of the model set-up, and not directly on experimental data (although the general range of the distribution agrees with experimental observations of healed salt). The use of these permeabilities ensures that any fluid flow is equally probable through or around the Option D panel closures and represents the range of uncertainty that exists in the performance of the panel closure system.

PA-4.2.8.4 Empty Drift and Explosion Wall Materials

The DRF_PCS is the material representing the empty drift and explosion wall. For simplicity, this material is assumed to have hydrologic properties equivalent to the material representing the waste panel and is used for the three sets of panel closures represented in the grid (Figure PA-8). The creep closure model is applied to this material to be consistent with the neighboring materials. The assignment of a high permeability to this region containing the explosion wall is justified because the explosion wall is not designed to withstand the stresses imposed by creep closure and will be highly permeable following rapid room closure.

PA-4.2.9 Borehole Model

The major disruptive event in the CRA-2004 PA is the penetration of the repository by a drilling intrusion. In the undisturbed scenario (scenario S1; see Section PA-6.7.1), these blocks have the material properties of the neighboring stratigraphic or excavated modeling unit, and there is no designation in the grid of a borehole except for the reduced lateral dimensions of this particular column of grid blocks.

In the scenarios simulating drilling disturbance, these cells start out with the same material properties as in the undisturbed scenario, but at the time of intrusion the borehole grid blocks are reassigned to borehole material properties. The drilling intrusion is modeled by modifying the permeability of the grid blocks in column 26 of Figure PA-8 (values listed in Table PA-5). Further, the drilling intrusion is assumed to produce a borehole with a diameter of 12.25 in. (0.31 m) (Vaughn 1996; Howard 1996); borehole fill is assumed to be incompressible; capillary effects are ignored; residual gas and brine saturations are set to zero; and porosity is set to 0.32 (see materials CONC_PLG, BH_OPEN, BH_SAND and BH_CREEP in Table PA-2). When a borehole that penetrates pressurized brine in the Castile Formation is simulated (i.e., an E1 intrusion), the permeability modifications indicated in Table PA-5 extend from the land surface (i.e., grid cell 2155 in Figure PA-10) to the base of the pressurized brine (i.e., grid cell 2225 in Figure PA-10). When a borehole that does not penetrate pressurized brine in the Castile Formation is under consideration (i.e., an E2 intrusion), the permeability modifications indicated in Table PA-5 stop at the bottom of the lower DRZ (i.e., grid cell 1111 in Figure PA-10).

Table PA-5. Permeabilities for Drilling Intrusions Through the Repository

Time After Intrusion	Assigned Permeabilities
0 - 200 years	Concrete plugs are assumed to be emplaced at the Santa Rosa Formation (i.e., a surface plug with a length of 15.76 m; corresponds to grid cells 2113, 2155 in Figure PA-10) and the Los Medanõs Member of the Rustler Formation (i.e., a plug at top of Salado with a length of 36 m; corresponds to grid cell 1644 in Figure PA-10). Concrete plugs are assumed to have a permeability of $k = 5 \times 10^{-17}$ m^2; open potions of the borehole are assumed to have a permeability of 1×10^{-9} m^2. See material CONC_PLG in Table PA-3.
200 - 1200 years	Concrete plugs are assumed to fail after 200 years (DOE 1995) an entire borehole is assigned a permeability typical of silty sand, i.e., $k = 10^x$ m^2, x = BHPRM, where BHPRM is an uncertain input to the analysis (see Table PA-17). See material BH_SAND in Table PA-3.
> 1200 years	Permeability reduced by one order of magnitude in Salado Formation beneath repository due to creep closure of borehole (Thompson et al. 1996) (i.e., $k = 10^x/10$, x = BHPRM, in grid cells 2225, 1576, 26, 94, 162, 230, 1111, 1119, 1127 of Figure PA-10). No changes are made within and above the lower DRZ. See material BH_CREEP in Table PA-3.

PA-4.2.10 Numerical Solution

Determination of gas and brine flow in the vicinity of the repository requires the numerical solution of the two nonlinear partial differential equations in Equation (42) on the computational domain in Figure PA-8 together with evaluation of appropriate auxiliary conditions (Equation (25f), Equation (25g), and Equation (41)). The actual unknown functions in this solution are p_b and S_g, although the constraint conditions also give rise to values for p_g and S_b. As two dimensions in space and one dimension in time are in use, p_b, p_g, S_b and S_g are functions of the form $p_b(x,y,t)$, $p_g(x,y,t)$, $S_b(x,y,t)$ and $S_g(x,y,t)$.

The solution of Equation (42) requires both initial value and boundary value conditions for p_b and S_g . The initial value conditions for p_b and S_g are given in Section PA.4.2.2. As indicated there, the calculation starts at time t = –5 years, with a possible resetting of values at t = 0 years, which corresponds to final waste emplacement and sealing of the repository. The boundary conditions are such that no brine or gas moves across the exterior grid boundary (Table PA-6). This Neumann-type boundary condition is maintained for all time. Further, BRAGFLO allows the user to specify pressure and/or saturation at any grid block. This feature is used to specify Dirichlet-type conditions at the surface grid blocks (i = 1, 2, …, 68, j = 33, Figure PA-8) and at the far field locations in the Culebra and Magenta Formations (i = 1, 68, j = 26 and i = 1, 68, j = 28, Figure PA-8). These auxiliary conditions are summarized in Table PA-7).

Table PA-6. Boundary Value Conditions for p_g and p_b

Boundaries below (y = 0 m) and above (y = 1039 m) system for 0 ≤ x ≤ 46630 m and –5 yr ≤ t	
$\left(\nabla p_g + \rho_g g \nabla h\right)\Big\|_{(x,y,t)} \cdot j = 0 \ Pa/m$	no gas flow condition
$\left(\nabla p_b + \rho_b g \nabla h\right)\Big\|_{(x,y,t)} \cdot j = 0 \ Pa/m$	no brine flow condition
Boundaries at left (x = 0 m) and right (x = 46630 m) of system for 0 ≤ y ≤ 1039 m and –5 yr ≤ t	
$\left(\nabla p_g + \rho_g g \nabla h\right)\Big\|_{(x,y,t)} \cdot i = 0 \ Pa/m$	no gas flow condition
$\left(\nabla p_b + \rho_b g \nabla h\right)\Big\|_{(x,y,t)} \cdot i = 0 \ Pa/m$	no brine flow condition

Table PA-7. Auxiliary Dirichlet Conditions for p_b and S_g

Surface Grid Blocks	
$S_g(i,j,t)$ = 0.08363	i = 1, 2, …, 68, j = 33, –5 yr ≤ t
$p_b(i,j,t)$ = 1.01×10^5 Pa	i = 1, 2, …, 68, j = 33, –5 yr ≤ t
Culebra and Magenta Far Field	
$p_b(i,26,t)$ = 8.22×10^5 Pa	i = 1 and 68, j = 26, –5 yr ≤ t (Culebra)
$p_b(i,28,t)$ = 9.17×10^5 Pa	i = 1 and 68, j = 28, –5 yr ≤ t (Magenta)

A fully implicit finite difference procedure is used to solve Equation (42). The associated discretization of the gas mass balance equation is given by

$$\frac{1}{\Delta x_i}\left\{\frac{1}{x_{i+1}-x_i}\left[\frac{\alpha\rho_g k_x k_{rg}}{\mu_g}\right]^{n+1}_{i+1/2,j}\left(\Phi^{x-}_{g_{i+1,j}}-\Phi^{x+}_{g_{i,j}}\right)^{n+1}\right.$$

$$\left.-\frac{1}{x_i-x_{i-1}}\left[\frac{\alpha\rho_g k_x k_{rg}}{\mu_g}\right]^{n+1}_{i-1/2,j}\left(\Phi^{x-}_{g_{i,j}}-\Phi^{x+}_{g_{i-1,j}}\right)^{n+1}\right\}$$

$$+\frac{1}{\Delta y_j}\left\{\frac{1}{y_{j+1}-y_j}\left[\frac{\alpha\rho_g k_y k_{rg}}{\mu_g}\right]^{n+1}_{i,j+1/2}\left(\Phi^{y-}_{g_{i,j+1}}-\Phi^{y+}_{g_{i,j}}\right)^{n+1}\right.$$

$$-\frac{1}{y_j - y_{j-1}}\left[\frac{\alpha\rho_g k_y k_{rg}}{\mu_g}\right]_{i,j-1/2}^{n+1}\left(\Phi_{g_{i,j}}^{y-} - \Phi_{g_{i,j-1}}^{y+}\right)^{n+1}\Bigg\}$$

$$+\alpha_{i,j}q_{wg_{i,j}}^{n+1} + \alpha_{i,j}q_{rg_{i,j}}^{n+1} - \frac{\left(\alpha\phi\rho_g S_g\right)_{i,j}^{n+1} - \left(\alpha\phi\rho_g S_g\right)_{i,j}^{n}}{\Delta t} = 0\,, \tag{79}$$

where Φ represents the phase potentials given by

$$\Phi_{gi,j}^{x+} = p_{gi,j} + \rho_{gi+1/2,j}gh_{i,j}, \quad \Phi_{gi,j}^{x-} = p_{gi,j} + \rho_{gi-1/2\,j}gh_{i,j}$$

and

$$\Phi_{gi,j}^{y+} = p_{gi,j} + \rho_{gi,j+1/2}gh_{i,j}, \quad \Phi_{gi,j}^{y-} = p_{gi,j} + \rho_{gi,j-1/2}gh_{i,j}\,,$$

and the subscripts are defined by

i = x-direction grid index

j = y-direction grid index

$i \pm 1/2$ = x-direction grid block interface

$j \pm 1/2$ = y-direction grid block interface

x_i = grid block center in the x-coordinate direction (m)

y_j = grid block center in the y-coordinate direction (m)

Δx_i = grid block length in the x-coordinate direction (m)

Δy_j = grid block length in the y-coordinate direction (m),

the superscripts are defined by

n= index in the time discretization, known solution time level

n+1= index in the time discretization, unknown solution time level,

and the interblock densities are defined by

$$\rho_{gi+1/2,j} = \frac{\Delta x_{i+1,j}}{\Delta x_{i,j} + \Delta x_{i+1,j}}\rho_{gi,j} + \frac{\Delta x_{i,j}}{\Delta x_{i,j} + \Delta x_{i+1,j}}\rho_{gi+1,j}\,,$$

$$\rho_{gi-1/2,j} = \frac{\Delta x_{i,j}}{\Delta x_{i-1,j} + \Delta x_{i,j}} \rho_{g,i-1,j} + \frac{\Delta x_{i-1,j}}{\Delta x_{i-1,j} + \Delta x_{i,j}} \rho_{gi,j} ,$$

$$\rho_{gi,j+1/2} = \frac{\Delta y_{i,j+1}}{\Delta y_{i,j} + \Delta y_{i,j+1}} \rho_{gi,j} + \frac{\Delta y_{i,j}}{\Delta y_{i,j} + \Delta y_{i,j+1}} \rho_{gi,j+1} ,$$

$$\rho_{gi,j-1/2} = \frac{\Delta y_{i,j}}{\Delta y_{i,j-1} + \Delta y_{i,j}} \rho_{gi,j-1} + \frac{\Delta y_{i,j-1}}{\Delta y_{i,j-1} + \Delta y_{i,j}} \rho_{gi,j} .$$

The interface values of k_{rg} in Equation (79) are evaluated using upstream weighted values (i.e., the relative permeabilities at each grid block interface are defined to be the relative permeabilities at the center of the adjacent grid block that has the highest potential). Further, interface values for $\alpha \rho_g k_x / \mu_g$ and $\alpha \rho_g k_y / \mu_g$ are obtained by harmonic averaging of adjacent grid block values for these expressions.

The discretization of the brine mass balance equation is obtained by replacing the subscript for gas, g, by the subscript for brine, b. As a reminder, p_g and S_b are replaced in the numerical implementation with the substitutions indicated by Equation (25d) and Equation (25c), respectively. For the CRA-2004 PA, wells are not used in the conceptual model. Thus, the terms q_{wg} and q_{wb} are zero. For this analysis, the wellbore is not treated by a well model, but rather is explicitly modeled within the grid as a distinct material region (i.e., Upper Borehole and Lower Borehole in Figure PA-8).

The resultant coupled system of nonlinear brine and gas mass balance equations is integrated in time using the Newton-Raphson method with upstream weighting of the relative permeabilities as previously indicated. The primary unknowns at each computational cell center are brine pressure and gas saturation.

PA-4.2.11 Gas and Brine Flow across Specified Boundaries

The Darcy velocity vectors $\mathbf{v}_g(x, y, t)$ and $\mathbf{v}_b(x, y, t)$ for gas and brine flow ($(m^3/m^2)/s = m/s$) are defined by the expressions

$$\mathbf{v}_g(x,y,t) = \mathbf{K}_g k_{rg} \left(\nabla p_g + \rho_g g \nabla h \right) / \mu_g \tag{80}$$

and

$$\mathbf{v}_b(x,y,t) = \mathbf{K}_b k_{rb} \left(\nabla p_b + \rho_b g \nabla h \right) / \mu_b . \tag{81}$$

Values for $\mathbf{v}_g$ and $\mathbf{v}_b$ are obtained and saved as the numerical solution of Equation (42) is carried out. Cumulative flows of gas, $C_g(t,\mathcal{B})$, and brine, $C_b(t,\mathcal{B})$, from time 0 to time t across an arbitrary boundary $\mathcal{B}$ in the domain of (Figure PA-8) is then given by

$$C_l(t,\mathcal{B}) = \int_0^t \left[\int_{\mathcal{B}} \alpha(x,y)\, \mathbf{v}_l(x,y,t) \cdot \mathbf{n}(x,y)\, ds \right] dt \tag{82}$$

for l = g, b, where $\alpha(x,y)$ is the geometry factor defined in Figure PA-9, $\mathbf{n}(x,y)$ is an outward pointing unit normal vector, and $\int_{\mathcal{B}} ds$ denotes a line integral. As an example, $\mathcal{B}$ could correspond to the boundary of the waste disposal regions in Figure PA-8. The integrals defining $C_g(t,\mathcal{B})$ and $C_b(t,\mathcal{B})$ are evaluated using the Darcy velocities defined by Equation (80) and Equation (81). Due to the dependence of gas volume on pressure, $C_g(t,\mathcal{B})$ is typically calculated in moles or in m^3 at standard temperature and pressure, which requires an appropriate change of units for $\mathbf{v}_g$ in Equation (82).

PA-4.2.12 Additional Information

Additional information on BRAGFLO and its use in the CRA-2004 PA can be found in the BRAGFLO User's Manual (WIPP PA 2003c) and in the analysis package for the Salado flow calculations for the CRA-2004 PA (Stein and Zelinski 2003b).

PA-4.3 Radionuclide Transport in the Salado: NUTS

This section describes the model used to compute transport of radionuclides in the Salado for E0, E1 and E2 scenarios (defined in Section 6.3). The model for transport in the E1E2 scenario is described in Section PA-4.4.

PA-4.3.1 Mathematical Description

The following system of partial differential equations is used to model radionuclide transport in the Salado:

$$-\nabla \cdot \alpha \mathbf{v}_b C_{bl} + \alpha S_l = \alpha \frac{\partial}{\partial t}\left(\phi S_b C_{bl}\right) + \left(\alpha \phi S_b C_{bl}\right)\lambda_l - \alpha \phi S_b \sum_{p \in P(l)} C_{bp}\lambda_p \tag{83a}$$

$$-S_l = \frac{\partial}{\partial t}\left(C_{sl}\right) + C_{sl}\lambda_l - \sum_{p \in P(l)} C_{sp}\lambda_p \tag{83b}$$

for l = 1, 2, …, nR, where

$\mathbf{v}_b$ = Darcy velocity vector ((m^3/m^2)/s = m/s) for brine (supplied by BRAGFLO from solution of Equation (81)),

C_{bl} = concentration (kg/m^3) of radionuclide l in brine,

C_{sl} = concentration (kg/m^3) of radionuclide l in solid phase (i.e., not in brine), with concentration defined with respect to total (i.e., bulk) formation volume (only used in repository; see Figure PA-8),

S_l = linkage term ((kg/m^3)/s) due to dissolution/precipitation between radionuclide l in brine and in solid phase (see Equation (84)),

ϕ = porosity (supplied by BRAGFLO from solution of Equation (25)),

S_b = brine saturation (supplied by BRAGFLO from solution of Equations (25)),

λ_l = decay constant (s^{-1}) for radionuclide l,

$P(l)$ = {p: radionuclide p is a parent of radionuclide l},

nR = number of radionuclides,

and α is the dimension dependent geometry factor in Equation (26). The CRA-2004 PA uses a two-dimensional representation for fluid flow and radionuclide transport in the vicinity of the repository with α defined by the element depths in Figure PA-8 . Although omitted from the notation for brevity, the terms α, $\boldsymbol{v_b}$, C_{bl}, C_{sl}, S_l, ϕ and S_b are functions $\boldsymbol{\alpha(x,y)}$, $\boldsymbol{v_b(x,y,t)}$, $\boldsymbol{C_{bl}(x,y,t)}$, $\boldsymbol{C_{sl}(x,y,t)}$, $\boldsymbol{S_l(x,y,t)}$, $\boldsymbol{\phi(x,y,t)}$, and $\boldsymbol{S_b(x,y,t)}$ of time t and the spatial variables x, y. Equation (83) is defined and solved on the same computational grid used with BRAGFLO for the solution of Equation (25) (Figure PA-8).

Radionuclides are assumed to be present in both brine (Equation (83a)) and in an immobile solid phase (Equation (83b)). Radionuclide transport takes place only by brine flow (Equation (83a)). A maximum radionuclide concentration in brine is assumed for each element (Section PA-4.3.2). Then, each individual radionuclide equilibrates between the brine and solid phases on the basis of the maximum concentration of its associated element and the mole fractions of other isotopes of this element that are included in the calculation. The linkage between the brine and solid phases in Equation (83) accomplished by the term S_l, where

$$\boldsymbol{S_l} = \begin{cases} \boldsymbol{\delta(\tau - t)\, Dif\left(S_T, C_{b,El(l)}\right) MF_{sl}} & \boldsymbol{if\ \ 0 \le Dif\left(S_T, C_{b,El(l)}\right) \le C_{s,El(l)} / (\phi S_b),\ 0 < S_b} \\ \boldsymbol{\delta(\tau - t)\left[C_{s,El(l)} / (\phi S_b)\right] MF_{sl}} & \boldsymbol{if\ \ 0 \le C_{s,El(l)} / (\phi S_b) < Dif\left(S_T, C_{b,El(l)}\right),\ 0 < S_b} \\ \boldsymbol{\delta(\tau - t)\, Dif\left(S_T, C_{b,El(l)}\right) MF_{bl}} & \boldsymbol{if\ \ Dif\left(S_T, C_{b,El(l)}\right) < 0,\ 0 < S_b} \\ \boldsymbol{0} & \boldsymbol{otherwise} \end{cases} \quad (84)$$

with

$S_T\left[Br(t), Ox(l), Mi, El(l)\right]$ = maximum concentration (kg/m^3) of element $El(l)$ in oxidation state $Ox(l)$ in brine type $Br(t)$, where $El(l)$ denotes the element of which radionuclide l is an isotope, $Ox(l)$ denotes the oxidation state in which element $El(l)$ is present, Mi indicates whether microbial activity is present, and $Br(t)$ denotes the type of brine present in the repository at time t (see Section PA-4.3.2 for definition of $S_T\left(Br, Ox, Mi, El\right)$.

$C_{p,El(l)}$ = concentration (kg/m^3) of element $El(l)$ in brine (p = b) or solid (p = s) (i.e., sum of concentrations of radionuclides that are isotopes of same element as radionuclide l, where $k \in El(l)$ only if k is an isotope of element $El(l)$)

$$= \sum_{k \in El(l)} C_{pk} \tag{85}$$

$Dif\left(S_T, C_{b,El(l)}\right)$ = difference (kg/m^3) between maximum concentration of element $El(l)$ in brine and existing concentration of element $El(l)$ in brine

$$= S_T\left[Br(t), Ox(l), Mi, El(l)\right] - C_{b,El(l)} \tag{86}$$

MF_{pl} = mole fraction of radionuclide l in phase p, where p = b ~ brine and p = s ~ solids

$$= C_{pl}CM_l \Big/ \sum_{k \in El(l)} C_{pk}CM_k \tag{87}$$

CM_l = conversion factor (mole/kg) from kilograms to moles for radionuclide l

$\delta(\tau - t)$ = Dirac delta function (s^{-1})(i.e., $\delta(\tau - t) = 0 \;\; if \;\; \tau \neq t \;\; and \;\; \int_{-\infty}^{\infty} \delta(\tau - t)\, d\tau = 1$).

Although omitted for brevity, the terms S_l, $C_{p,El(l)}$, MF_{pl}, ϕ and S_b are functions of time t and spatial variables x, y. The Dirac delta function, $\delta(t - \tau)$, appears in Equation (84) to indicate that the adjustments to concentration are implemented instantaneously within the numerical solution of Equation (83) whenever a concentration imbalance is observed.

The velocity vector v_b in Equation (83) is defined in Equation (81) and is obtained from the numerical solution of Equation (25). If $\mathcal{B}$ denotes an arbitrary boundary (e.g., the land withdrawal boundary) in the domain of Equation (83) (i.e., Figure PA-8), then the cumulative transport of $C_l(t, \mathcal{B})$ of radionuclide l from time 0 to time t across $\mathcal{B}$ is given by

$$C_l(t,\mathcal{B}) = \int_0^t \left[\int_{\mathcal{B}} \mathbf{v}_b(x,y,t) C_l(x,y,t) \alpha(x,y) \cdot \mathbf{n}(x,y) ds \right] dt \ , \tag{88}$$

where $\mathbf{n}(x,y)$ is an outward pointing unit normal vector and $\int_{\mathcal{B}} ds$ denotes a line integral over $\mathcal{B}$.

Equation (83) models advective radionuclide transport due to the velocity vector $\mathbf{v}_b$. Although the effects of solubility limits are considered, no chemical or physical retardation is included in the model. Also, molecular diffusion is not included in the model, with this omission having little effect as the radionuclides under consideration have molecular diffusion coefficients on the order of 10^{-10} m^2/s and thus can be expected to move approximately 10 m over 10,000 years due to molecular diffusion. Mechanical dispersion is also not included, with this omission having little effect on the final results due to the uniform initial radionuclide concentrations assumed within the repository and the use of time-integrated releases in assessing compliance with 40 CFR § 191.13.

PA-4.3.2 Calculation of Maximum Concentration $S_T(Br,Ox,Mi,El)$

A maximum concentration $S_T(Br,Ox,Mi,El)$ S_T(Br, Ox, Mi, El) (mol/l) is calculated for each brine type (Br ~ Salado, Castile), oxidation state (Ox ~ +3, +4, +5, +6), presence of microbial action (present or not) and element (El ~ Am, Pu, U, and Th). The maximum concentration is given by

$$S_T(Br,Ox,Mi,El) = S_D(Br,Ox,Mi,El) + S_C(Br,Ox,Mi,El), \tag{89}$$

where $S_D(Br,Ox,Mi,El)$ is the dissolved solubility (mol/l) and $S_C(Br,Ox,Mi,El)$ is the concentration (mol/l) of the element sorbed to colloids.

The dissolved solubility $S_D(Br,Ox,Mi,El)$ is given by

$$S_D(Br,Ox,Mi,El) = S_{FMT}(Br,Ox,Mi) \times 10^{UF(Br,Ox,El)} \tag{90}$$

where

$S_{FMT}(Br,Ox,Mi)$ = dissolved solubility (mol/l) calculated by FMT model (WIPP PA 1998a) for brine type Br, oxidation state Ox, and presence of microbial action Mi,

$UF(Br,Ox,El)$ = logarithm (base 10) of uncertainty factor for solubilities calculated by FMT expressed as a function of brine type Br, oxidation state Ox and element El.

Table PA-8 lists the calculated values of $S_{FMT}(Br,Ox,Mi)$; details of the calculation are provided in Attachment SOTERM. The values of Mi are determined by the uncertain parameter

WMICDFLG; see Table PA-17. The uncertainty factors $UF(Br, Ox, El)$ are determined by the uncertain parameters listed in Table PA-9; definition of each uncertain parameter is provided in Table PA-17.

Table PA-8. Calculated Values for Dissolved Solubility

Brine/Microbial action	Oxidation State			
	+3	+4	+5	+6
Salado/No microbial gas generation	3.07×10^{-7}	1.24×10^{-8}	9.72×10^{-7}	8.7×10^{-6}
Castile/No microbial gas generation	1.77×10^{-7}	5.84×10^{-9}	2.13×10^{-5}	8.8×10^{-6}
Salado/With microbial gas generation	3.07×10^{-7}	1.19×10^{-8}	1.02×10^{-6}	8.7×10^{-6}
Castile/With microbial gas generation	1.69×10^{-7}	2.47×10^{-8}	5.08×10^{-6}	8.8×10^{-6}

Table PA-9. Uncertainty Factors for Dissolved Solubility

Brine	Oxidation State, Element					
	+3, Am	+3, Pu	+4, Pu	+4, U	+6, U	+4, Th
Salado	WSOLAM3S	WSOLPU3S	WSOLPU4S	WSOLU4S	WSOLU6S	WSOLTH4S
Castile	WSOLAM3C	WSOLPU3C	WSOLPU4C	WSOLU4C	WSOLU6C	WSOLTH4C

The concentration (mol/l) of the element sorbed to colloids $S_C(Br, Ox, Mi, El)$ is given by

$$S_C(Br, Ox, Mi, El) = S_{Hum}(Br, Ox, Mi, El) + S_{Mic}(Br, Ox, Mi, El) + S_{Act}(El) + S_{Mn}, \quad (91)$$

where

$S_{Hum}(Br, Ox, Mi, El)$ = solubility (i.e., concentration expressed in mol/l) in brine type Br of element El in oxidation state Ox with or without microbial action (Mi) resulting from formation of humic colloids

$$= \min\left\{SF_{Hum}(Br, Ox, El) \times S_D(Br, Ox, Mi, El), UB_{Hum}\right\}$$

$SF_{Hum}(Br, Ox, El)$ = scale factor used as a multiplier on $S_D(Br, Ox, Mi, El)$ in definition of $S_{Hum}(Br, Ox, Mi, El)$ (see Table PA-10),

Table PA-10. Scale Factor $SF_{Hum}(Br, Ox, El)$ Used in Definition of $S_{Hum}(Br, Ox, Mi, El)$

Brine	Oxidation state, Element					
	+3, Am	+3, Pu	+4, Pu	+4, U	+6, U	+4, Th
Salado	0.19	0.19	6.3	6.3	0.12	6.3
Castile	WPHUMOX3[1]	WPHUMOX3[1]	6.3	6.3	0.51	6.3

[1] See Table PA-17.

UB_{Hum} = upper bound on solubility (i.e., concentration expressed in mol/l) of individual actinide elements resulting from formation of humic colloids

= 1.1×10^{-5} mol/l,

$S_{Mic}(Br, Ox, Mi, El)$ = solubility (i.e., concentration expressed in mol/l) in brine type Br of element El in oxidation state Ox with or without microbial action (Mi) resulting from formation of microbial colloids

$$= \min\left\{SF_{Mic}(Ox, Mi, El) \times S_D(Br, Ox, Mi, El), UB_{Mic}(Ox, El)\right\},$$

$SF_{Mic}(Ox, Mi, El)$ = scale factor used as multiplier on $S_D(Br, Ox, Mi, El)$ in definition of $S_{Mic}(Br, Ox, Mi, El)$ (see Table PA-11),

$UB_{Mic}(Ox, El)$ = upper bound on solubility (i.e., concentration expressed in mol/l) of element El in oxidation state Ox resulting from formation of microbial colloids (see Table PA-11),

Table PA-11. Scale Factor $SF_{Mic}(Ox, Mi, El)$ and Upper Bound $UB_{Mic}(Ox, Mi, El)$ (mol/l) Used in Definition of $S_{Mic}(Br, Ox, Mi, El)$

	Oxidation state, Element					
	+3, Am	+3, Pu	+4, Pu	+4, U	+6, U	+4, Th
No Microbial Action						
$SF_{Mic}(Ox, Mi, El)$	0.0	0.0	0.0	0.0	0.0	0.0
$UB_{Mic}(Ox, Mi, El)$	0.0	0.0	0.0	0.0	0.0	0.0
Microbial Action						
$SF_{Mic}(Ox, Mi, El)$	3.6	0.3	0.3	2.1×10^{-3}	2.1×10^{-3}	3.1
$UB_{Mic}(Ox, Mi, El)$	1	6.8×10^{-5}	6.8×10^{-5}	2.1×10^{-3}	2.1×10^{-3}	1.9×10^{-3}

$S_{Act}(El)$ = solubility (i.e., concentration expressed in mol/l) of element El resulting from formation of actinide intrinsic colloids

$$= \begin{cases} 1 \times 10^{-9} \text{ mol/l} & \text{if } El = \text{plutonium} \\ 0 \text{ mol/l} & \text{otherwise} \end{cases},$$

S_{Mn} = solubility (i.e., concentration expressed in mol/l) of individual actinide element resulting from formation of mineral fragment colloids

= 2.6 × 10–8 mol/l.

PA-4.3.3 Radionuclides Transported

Appendix TRU WASTE (Table TRU WASTE-9) lists the radionuclides included in the transport calculations. With the exceptions of ^{137}Cs, ^{147}Pm, and ^{90}Sr, the radionuclides in Table TRU WASTE-9 belong to the following decay chains:

$$^{242}U \rightarrow \begin{matrix} ^{238}Pu \\ \Downarrow \\ ^{238}U \end{matrix} \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \tag{92a}$$

$$\begin{matrix} ^{243}Cm \\ \Downarrow \\ ^{243}Am \end{matrix} \rightarrow {}^{239}Pu \rightarrow {}^{235}U \rightarrow {}^{231}Pa \tag{92b}$$

$$^{252}Cf \rightarrow {}^{248}Cm \rightarrow {}^{244}Pu \rightarrow {}^{240}Pu \rightarrow {}^{236}U \rightarrow {}^{232}Th \rightarrow {}^{228}Ra \tag{92c}$$

$$^{245}Cm \rightarrow {}^{241}Pu \rightarrow {}^{241}Am \rightarrow {}^{237}Np \rightarrow {}^{233}U \rightarrow {}^{229}Th\,. \tag{92d}$$

Since the solution of Equation (83) for this many radionuclides and decay chains would be very time-consuming, the number of radionuclides for direct inclusion in the analysis was reduced using the algorithm shown in Appendix TRU WASTE (Figure TRU WASTE-5); the rationale for each radionuclide excluded from transport is presented in Table TRU WASTE-10. The CRA-2004 PA uses the same reduction algorithm as was used in the CCA PA (see CCA Appendix WCA); the algorithm was found to be acceptable in the review of the CCA (EPA 1998, Section 4.6.1.1).

After the reduction of radionuclides summarized in Table TRU WASTE-10, the following 10 radionuclides remained from the decay chains shown above:

$$^{242}Pu \text{ and } {}^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \tag{93a}$$

$$^{239}Pu \tag{93b}$$

$$^{240}Pu \tag{93b}$$

$$^{241}Pu \rightarrow {}^{241}Am \rightarrow {}^{233}U \rightarrow {}^{229}Th\,. \tag{93d}$$

Next, ^{238}Pu was eliminated from transport calculations due to its short half-life (87.8 years). The remaining nine radionuclides were then further reduced by combining radionuclides that have similar decay and transport properties. In particular, ^{234}U, ^{230}Th, and ^{239}Pu were used as surrogates for the groups {^{234}U, ^{233}U}, {^{230}Th, ^{229}Th}, and {^{242}Pu, ^{239}Pu, ^{240}Pu}, with the initial inventories of ^{234}U, ^{230}Th and ^{239}Pu being redefined to account for the additional radionuclide(s) in each group. In redefining the initial inventories, the individual radionuclides were combined on either a mole or curie basis (i.e., moles added and then converted back to curies or curies added directly). In each case, the method that maximized the combined inventory was used, i.e.: ^{233}U was added to ^{234}U by curies; ^{240}Pu was added to ^{239}Pu by curies; ^{242}Pu was added to ^{239}Pu by moles; and ^{229}Th was added to ^{230}Th by curies. In addition, ^{241}Pu was added to ^{241}Am by moles because ^{241}Pu has a half life of 14 years and will quickly decay to ^{241}Am, and neglect of this ingrowth would underestimate the ^{241}Am inventory by about four percent (Table PA-12). The outcome of this process was the following five radionuclides and three simplified decay chains:

$$^{241}Am, \quad ^{238}Pu \rightarrow {}^{234}U \rightarrow {}^{230}Th, \quad ^{239}Pu, \tag{94}$$

which were then used with Equation (83) for transport in the vicinity of the repository and also for transport in the Culebra Dolomite (Section PA-4.9). These radionuclides account for 99 percent of the EPA units in the waste after 2,000 years (Appendix TRU WASTE, Table TRU WASTE-9), and hence will dominate any releases by transport.

Table PA-12. Combination of Radionuclides for Transport

Combination	Isotope Initial Values	Combination Procedure	Combined Inventory
$^{233}U \rightarrow {}^{234}U$	1.27×10^3 Ci ^{233}U 3.19×10^2 Ci ^{234}U	1.27×10^3 Ci ^{233}U $\rightarrow 1.27 \times 10^3$ Ci ^{234}U	1.59×10^3 Ci ^{234}U
$^{242}Pu \rightarrow {}^{239}Pu$ $^{240}Pu \rightarrow {}^{239}Pu$	2.71×10^1 Ci ^{242}Pu 1.08×10^5 Ci ^{240}Pu 6.65×10^5 Ci ^{239}Pu	2.71×10^1 Ci ^{242}Pu $= 2.82 \times 10^1$ moles ^{242}Pu $\rightarrow 2.82 \times 10^1$ moles ^{239}Pu $= 4.24 \times 10^2$ Ci ^{239}Pu 1.08×10^5 Ci ^{240}Pu $\rightarrow 1.08 \times 10^5$ Ci ^{239}Pu	7.73×10^5 Ci ^{239}Pu
$^{229}Th \rightarrow {}^{230}Th$	5.39×10^0 Ci ^{229}Th 1.76×10^{-1} Ci ^{230}Th	5.39×10^0 Ci ^{229}Th $\rightarrow 5.39 \times 10^0$ Ci ^{230}Th	5.57×10^0 Ci ^{230}Th
$^{241}Pu \rightarrow {}^{241}Am$	5.38×10^5 Ci ^{241}Pu 4.58×10^5 Ci ^{241}Am	5.38×10^5 Ci ^{241}Pu $= 2.15 \times 10^1$ moles ^{241}Pu $\rightarrow 2.15 \times 10^1$ moles ^{241}Am $= 1.80 \times 10^4$ Ci ^{241}Am	4.60×10^5 Ci ^{241}Am

PA-4.3.4 Numerical Solution

Equation (83) is numerically solved by the NUTS program (WIPP PA 1997a) on the same computational grid (Figure PA-8) used by BRAGFLO in the solution of Equation (25). In the solution procedure, Equation (83a) is numerically solved with $S_l = 0$ for each time step, with the instantaneous updating of concentrations indicated in Equation (84) and the appropriate modification to C_{sl} in Equation (83b) taking place after the time step. The solution is carried out for the five radionuclides indicated in Equation (94).

The initial value and boundary value conditions used with Equation (83) are given in Table PA-13. At time t = 0 (i.e., year 2033), the total inventory of each radionuclide is assumed to be in brine; the solubility constraints associated with Equation (84) then immediately adjust the values for $C_{bl}(x, y, t)$ and $C_{sl}(x, y, t)$ for consistency with the constraints imposed by $S_T\,[Br(t), Ox(l), Mi, El(l)]$ and available radionuclide inventory.

Table PA-13. Initial and Boundary Conditions for $C_{bl}(x, y, t)$ and $C_{sl}(x, y, t)$

Initial Conditions for $C_{bl}(x, y, t)$ and $C_{sl}(x, y, t)$	
$C_{bl}(x, y, t)$	= $A_l(0)/V_b(0)$ if x, y is a point in the repository (i.e., areas Waste Panel, South RoR and North RoR, in Figure PA-8), where $A_l(0)$ is the amount (kg) of radionuclide l present at time t = 0 (Table PA-12) and $V_b(0)$ is the amount (m^3) of brine in repository at time t = 0 (from solution of Equation (25) with BRAGFLO) for all x, y.
	= 0 otherwise.
$C_{sl}(x, y, t)$	= 0 if x, y is a point in the repository.
Boundary Conditions for $C_{bl}(x, y, t)$	
$f_l(\mathcal{B}, t)$	= $\int_{\mathcal{B}} v_b(x, y, t)\, C_{bl}(x, y, t)\, \alpha(x, y)\, n(x, y)\, ds$, where $\mathcal{B}$ is any subset of the outer boundary of the computational grid in Figure PA-8, $f_l(\mathcal{B}, t)$ is the flux (kg/s) at time t of radionuclide l across $\mathcal{B}$, $v_b(x, y, t)$ is the Darcy velocity ((m^3/m^2)/s) of brine at (x, y) on $\mathcal{B}$ and is obtained from the solution of Equation (25) by BRAGFLO, $n(x, y)$ denotes an outward-pointing unit normal vector, and $\int_{\mathcal{B}} ds$ denotes a line integral along $\mathcal{B}$.

The nR partial differential equations in Equation (83a) are discretized in two dimensions and then developed into a linear system of algebraic equations for numerical implementation. The following conventions are used in the representation of each discretized equation:

- the subscript b is dropped from C_{bl}, with the result that the unknown function is represented by C_l,

- a superscript n denotes time (t_n), with the assumption that the solution C_l is known at time t_n and is to be advanced (i.e., computed) at time t_{n+1},

- the grid indices are i in the x-direction, j in the y-direction, and are identical with the BRAGFLO grid indices; fractional indices refer to quantities evaluated at grid block interfaces, and

- each time step by NUTS is equal to 20 BRAGFLO time steps, which results because BRAGFLO reported (i.e., stored) results (i.e., $\boldsymbol{v}_b$, ϕ, S_b) every 20 time steps.

The following finite difference discretization is used for the lth equation in each grid block i, j:

$$q_{b,i+1/2,j}^{n+1} C_{l,i+1/2,j}^{n+1} - q_{b,i-1/2,j}^{n+1} C_{l,i-1/2,j}^{n+1} + q_{b,i,j+1/2}^{n+1} C_{l,i,j+1/2}^{n+1} - q_{b,i,j-1/2}^{n+1} C_{l,i,j-1/2}^{n+1} =$$

$$\frac{V_{R,i,j}}{\Delta t}\left[\left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n+1} - \left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n}\right] \qquad (95)$$

$$+ V_{R,i,j}\left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n+1} \lambda_l - V_{R,i,j}\left(\phi_{i,j} S_{b_{i,j}}\right)^{n+1} \sum_{p \in P(l)} C_{p,i,j}^{n+1} \lambda_p$$

where q_b is the grid block interfacial brine flow rate (m^3/s) and V_R is the grid block volume (m^3). The quantity q_b is based on $\boldsymbol{v}_b$ and α in Equation (83a), and the quantity V_R is based on grid block dimensions (Figure PA-8) and α .

The interfacial values of concentration in Equation (95) are discretized using the one-point upstream weighting method (Aziz and Settari 1979), which results in

$$q_{b,i+1/2,j}^{n+1}\left(\omega_{i+1} C_{l,i,j}^{n+1} + \left(1-\omega_{i+1}\right) C_{l,i+1,j}^{n+1}\right) - q_{b,i-1/2,j}^{n+1}\left(\omega_i C_{l,i-1,j}^{n+1} + \left(1-\omega_i\right) C_{l,i,j}^{n+1}\right)$$
$$+ q_{b,i,j+1/2}^{n+1}\left(\omega_{j+1} C_{l,i,j}^{n+1} + \left(1-\omega_{j+1}\right) C_{l,i,j+1}^{n+1}\right) - q_{b,i,j-1/2}^{n+1}\left(\omega_j C_{b,i,j-1}^{n+1} + \left(1-\omega_j\right) C_{l,i,j}^{n+1}\right) =$$

$$\frac{V_{R,i,j}}{\Delta t}\left[\left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n+1} - \left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n}\right] + V_{R,i,j}\left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n+1} \lambda_l \qquad (96)$$

$$- V_{R,i,j}\left(\phi_{i,j} S_{b_{i,j}}\right)^{n+1} \sum_{p \in P(l)} C_{p,i,j}^{n+1} \lambda_p$$

where ω derives from the upstream weighting for flow between adjacent grid blocks and is defined by

$$\omega_i = \begin{cases} 1 & \textit{if flow is from grid block } i-1, j \textit{ to grid block } i, j \\ 0 & \textit{otherwise} \end{cases}$$

$$\omega_j = \begin{cases} 1 & \textit{if flow is from grid block } i, j-1 \textit{ to grid block } i, j \\ 0 & \textit{otherwise.} \end{cases}$$

By collecting similar terms, Equation (96) can be represented by the linear equation

$$AC_{l,i,j-1}^{n+1} + BC_{l,i-1,j}^{n+1} - j + DC_{l,i,j}^{n+1} + EC_{l,i+1,j}^{n+1} + FC_{l,i,j+1}^{n+1} = R_{l,i,j}, \tag{97}$$

where

$$A = -\omega_j q_{b,i,j-1/2}^{n+1} \qquad B = -\omega_j q_{b,i-1/2,j}^{n+1}$$
$$E = \left(1-\omega_{i+1}\right) q_{b,i+1/2,j}^{n+1} \qquad F = \left(1-\omega_{j+1}\right) q_{b,i,j+1/2}^{n+1}$$

$$D = -\left(1-\omega_j\right) q_{b,i,j-1/2}^{n+1} - \left(1-\omega_i\right) q_{b,i-1/2,j}^{n+1} + \omega_{j+1} q_{b,i,j+1/2}^{n+1} + \omega_{i+1} q_{b,i+1/2,j}^{n+1}$$
$$-\left(\frac{V_{R,i,j}}{\Delta t} - V_{R,i,j}\lambda_l\right)\left\{\phi_{i,j} S_{b_{i,j}}\right\}^{n+1}$$

$$R_{l,i,j} = -\frac{V_{R,i,j}}{\Delta t}\left\{\phi_{i,j} S_{b_{i,j}} C_{l,i,j}\right\}^{n} - V_{R,i,j}\left(\phi_{i,j} S_{b_{i,j}}\right)^{n+1} \sum_{p \in P(l)} C_{p,i,j}^{n+1} \lambda_p \, .$$

Given the form of Equation (97), the solution of Equation (83a) has now been reduced to the solution of nR × nG linear algebraic equations in nR × nG unknowns, where nR is the number of equations for each grid block (i.e., the number of radionuclides) and nG is the number of grid blocks into which the spatial domain is discretized (Figure PA-8).

The system of partial differential equations in Equation (83a) is strongly coupled because of the contribution from parental decay to the equation governing the immediate daughter. Consequently, a sequential method is used to solve the system in which radionuclide concentrations are solved for by starting at the top of a decay chain and working down from parent to daughter. This implies that when solving Equation (97) for the lth isotope concentration, all parent concentrations occurring in the right hand side term R are known. The resulting system of equations is then linear in the concentrations of the lth isotope. As a result, solution of Equation (83a) is reduced from the solution of one algebraic equation at each time step with nR × nG unknowns to the solution of nR algebraic equations each with nG unknowns at each time step, which can result in a significant computational savings.

The matrix resulting from one-point upstream weighting has the following structural form for a 3 × 3 system of grid blocks and a similar structure for a larger number of grid blocks:

	1	2	3	4	5	6	7	8	9
1	X	X	0	X					
2	X	X	X	0	X				
3	0	X	X	0	0	X			
4	X	0	0	X	X	0	X		
5		X	0	X	X	X	0	X	
6			X	0	X	X	0	0	X
7				X	0	0	X	X	0
8					X	0	X	X	X
9						X	0	X	X

,

where X designates possible nonzero matrix entries, and 0 designates zero entries. Entries outside of the banded structure are zero. Because of this structure, a banded direct elimination solver (Aziz and Settari 1979, Section 8.2.1) is used to solve the linear system for each radionuclide. The bandwidth is minimized by indexing equations first in the coordinate direction having the minimum number of grid blocks. The coefficient matrix is stored in this banded structure and all infill coefficients calculated during the elimination procedure are contained within the band structure. Therefore, for the matrix system in two dimensions, a pentadiagonal matrix of dimension IBW × nG is inverted instead of a full nG × nG matrix, where IBW is the band width.

The numerical implementation of Equation (83b) enters the solution process through an updating of the radionuclide concentrations in Equation (96) between each time step as indicated in Equation (84). The numerical solution of Equation (83) also generates the concentrations required for the numerical evaluation of the integral that defines $C_l(t,B)$ in Equation (88).

PA-4.3.5 Additional Information

Additional information on NUTS and its use in WIPP PA can be found in the NUTS users manual (WIPP PA 1997a) and in the analysis package for Salado transport calculations for the CRA-2004 PA (Lowry 2003). Furthermore, additional information on dissolved and colloidal actinides is given in Attachment SOTERM.

PA-4.4 Radionuclide Transport in the Salado: PANEL

This section describes the model used to compute transport of radionuclides in the Salado for E1E2 scenario. The model for transport in E0, E1, and E2 scenarios is described in Section PA-4.3.

PA-4.4.1 Mathematical Description

A relatively simple mixed-cell model is used for radionuclide transport in the vicinity of the repository when connecting flow between two drilling intrusions into the same waste panel is assumed to take place (i.e., an E1E2 intrusion). With this model, the amount of radionuclide l contained in a waste panel is represented by

$$\frac{dA_l}{dt} = -r_b C_{bl} - \lambda_l A_l + \sum_{p \in P(l)} \lambda_p A_p \,, \tag{98}$$

where

$A_l(t)$ = amount (mol) of radionuclide l in waste panel at time t,

$C_{bl}(t)$ = concentration (mol/m^3) of radionuclide l in brine in waste panel at time t (Equation (99)),

$r_b(t)$ = rate (m^3/s) at which brine flows out of the repository at time t (supplied by BRAGFLO from solution of Equation (81), and λ_l and $P(l)$ are defined in conjunction with Equation (84).

The brine concentration C_{bl} in Equation (98) is defined by

$$C_{bl}(t) = S_T\left[Br(t), Ox(l), Mi, El(l)\right] MF_l(t) \quad \text{if} \quad S_T\left[Br(t), Ox(l), Mi, El(l)\right] \le \sum_{k \in El(l)} A_k(t)/V_b(t) \tag{99a}$$

$$= A_l(t)/V_b(t) \quad \text{if} \quad \sum_{k \in El(l)} A_k(t)/V_b(t) < S_T\left[Br(l), Ox(l), Mi, El(l)\right], \tag{99b}$$

where

$MF_l(t)$ = mole fraction of radionuclide l in waste panel at time t

$$= \frac{A_l(t)}{\sum_{k \in El(l)} A_k(t)} \tag{100}$$

$V_b(t)$ = volume (m^3) of brine in waste panel at time t (supplied by BRAGFLO from solution of Equation (25)), and $S_T\left[Br(l), Ox(l), Mi, El(l)\right]$ and $E(l)$ are by Equation (89).

For use in Equation (99), $S_T\left[Br(l), Ox(l), Mi, El(l)\right]$ must be expressed in units of mol/l. In words, $C_{bl}(t)$ is defined to be the maximum concentration (S_T in Equation (89)) if there is sufficient radionuclide inventory in the waste panel to generate this concentration (Equation (99a)); otherwise, $C_{bl}(t)$ is defined by the concentration that results when all the relevant element in the waste panel is placed in solution (Equation (99b)).

Given r_b and C_{bl}, evaluation of the integral

$$v_i(x,y) = \left[u_i(x,y), v_i(x,y)\right] = SFC\left[K_i(x,y)\nabla h_i(x,y)\right]^T \tag{101}$$

provides the cumulative release $R_l(t)$ of radionuclide l from the waste panel through time t.

PA-4.4.2 Numerical Solution

Equation (98) is numerically evaluated by the PANEL model (WIPP PA 1998b).

A discretization based on 50-year or smaller time steps is used by PANEL. Specifically, Equation (98) is evaluated with the approximation

$$A_l(t_{n+1}) = A_l(t_n) - \left[\int_{t_n}^{t_{n+1}} r_b(\tau)\,d\tau\right] C_{bl}(t_n) - A_l(t_n)\exp(-\lambda_l \Delta t) + G_l(t_n, t_{n+1}), \tag{102}$$

where

$G_l(t_n, t_{n+1})$ = gain in radionuclide l due to the decay of precursor radionuclides between t_n and t_{n+1} (see Equation (103)),

$\Delta t = t_{n+1} - t_n = 50\ yr$.

As the solution progresses, values for $C_{bl}(t_n)$ are updated in consistency with Equation (99) and the products $r_b(t_n)C_{bl}(t_n)$ are accumulated to provide an approximation to R_l in Equation (101).

The term $G_l(t_n, t_{n+1})$ in Equation (102) is evaluated with the Bateman equations (Bateman 1910), with PANEL programmed to handle up to four succeeding generations of a given radionuclide (i.e., decay chains of length 5). As a single example, if radionuclide l is the third radionuclide in a decay chain (i.e., l = 3) and the two preceding radionuclides in the decay chain are designated by l = 1 and l = 2, then

$$
\begin{aligned}
G_3(t_n, t_{n+1}) = {} & \lambda_2 A_2(t_n)\left[\exp(-\lambda_2 \Delta t) - \exp(-\lambda_3 \Delta t)\right] / (\lambda_3 - \lambda_2) \\
& + \lambda_1 \lambda_2 A_2(t_n)\Big\{\left[\exp(-\lambda_1 \Delta t)\right] / \left[(\lambda_2 \lambda_1)(\lambda_3 \lambda_1)\right] \\
& \quad + \left[\exp(-\lambda_2 \Delta t)\right] / \left[(\lambda_3 - \lambda_2)(\lambda_1 - \lambda_2)\right] \\
& \quad + \left[\exp(-\lambda_3 \Delta t)\right] / \left[(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)\right]\Big\}
\end{aligned}
\tag{103}
$$

in Equation (102).

PA-4.4.3 Implementation in Performance Assessment

The preceding model was used in two ways in the CRA-2004 PA. First, Equation (101) was used to estimate releases to the Culebra associated with E1E2 intrusions (scenario S6; see Section PA-6.7). Second, with r_b set to a very small number and V_b set to a fixed value, Equation (98) and Equation (99) were used to estimate radionuclide concentrations in brine for use in the estimation of direct brine releases (see Section PA-6.8.5).

For E1E2 intrusions, the initial amount A_l of radionuclide l is the inventory of the isotope decayed to at the time of the E1 intrusion. Isotopes considered in the PANEL calculations for release to the Culebra are listed in Appendix TRU WASTE (Table TRU WASTE-9). PANEL calculates the inventory of each radionuclide throughout the regulatory period. The initial concentration C_{bl} of radionuclide l is computed by Equation (98) and Equation (99). For use as part of the direct brine release calculations, the initial amount Al of radionuclide l is the inventory of the isotope at the time of repository closure; isotopes considered in the PANEL calculations for direct brine releases are listed in Appendix TRU WASTE (Table TRU WASTE-9).

PA-4.4.4 Additional Information

Additional information on PANEL and its use in the CRA-2004 PA calculations can be found in the PANEL user's manual (WIPP PA 2003d) and the analysis package for PANEL calculations (Garner 2003).

PA-4.5 Cuttings and Cavings to Surface: CUTTINGS_S

Cuttings are waste solids contained in the cylindrical volume created by the cutting action of the drill bit passing through the waste. Cavings are additional waste solids eroded from the borehole by the upward-flowing drilling fluid within the borehole. The releases associated with these processes are computed within the CUTTINGS_S code (WIPP PA 2003e). The mathematical representations used for the first two processes, cuttings and cavings, are described in this section.

PA-4.5.1 Cuttings

The uncompacted volume of cuttings removed and transported to the surface in the drilling mud, V_{cut}, is given by

$$V_{cut} = AH_i = \pi D^2 H_i / 4 , \tag{104}$$

where H_i is the initial (i.e., uncompacted) repository height (m), A is the drill bit area (m^2), and D is the drill-bit diameter (m). In the CRA-2004 PA, D = 12.25 in. = 0.31115 m and H_i = 3.96 m (Attachment PAR, Table PAR-13). For drilling intrusions through RH-TRU waste, H_i = 0.509 m is used (Attachment PAR, Table PAR-45).

PA-4.5.2 Cavings

The cavings component of the direct surface release is caused by the shearing action of the drilling fluid (mud) on the waste as the mud flows up the borehole annulus. As for the cuttings release, the cavings release is assumed to be independent of the conditions that exist in the repository at the time of a drilling intrusion.

The final diameter of the borehole will depend on the diameter of the drillbit and on the extent to which the actual borehole diameter exceeds the drill-bit diameter. Although a number of factors affect erosion within a borehole (Broc 1982), the most important factor is believed to be the fluid shear stress on the borehole wall (i.e., the shearing force per unit area, (kg m/s^2/m^2)) resulting from circulating drilling fluids (Darley 1969; Walker and Holman 1971). As a result, the CRA-2004 PA estimates cavings removal with a model based on the effect of shear stress on the borehole diameter. In particular, the borehole diameter is assumed to grow until the shear stress on the borehole wall is equal to the shear strength of the waste (i.e., the limiting shear stress below which the erosion of the waste ceases).

The final eroded diameter D_f (m) of the borehole through the waste determines the volume V (m^3) of uncompacted waste that will be removed to the surface by circulating drilling fluid. Specifically,

$$V = V_{cut} + V_{cav} = \pi D_f^2 H_i / 4 , \tag{105}$$

where V_{cav} is the volume (m^3) of waste removed as cavings.

Most borehole erosion is believed to occur in the vicinity of the drill collar (Figure PA-14) because of decreased flow area and consequent increased mud velocity (Rechard et al. 1990, Letters 1a and 1b, App. A). An important determinant of the extent of this erosion is whether the flow of the drilling fluid in the vicinity of the collar is laminar or turbulent. The CRA-2004 PA uses Reynolds numbers to distinguish between the occurrence of laminar flow and turbulent flow. The Reynolds number is the ratio between inertial and viscous (i.e., shear) forces in a fluid and can be expressed as (Fox and McDonald 1985):

$$R_e = \frac{\rho_f \|\mathbf{v}\| D_e}{\eta} , \tag{106}$$

where R_e is the Reynolds number (dimensionless), ρ_f is the fluid density (kg m^{-3}), D_e is the equivalent diameter (m), v is the fluid velocity (m s^{-1}), and η is the fluid viscosity (kg m^{-1} s^{-1}).

Typically, ρ, v and η are averages over a control volume with an equivalent diameter of D_e. In the CRA-2004 PA, $\rho f = 1.21 \times 10^3$ kg m^{-3} (Attachment PAR, Table PAR-13), $\|\boldsymbol{v}\| = 0.7089$ m s^{-1} (based on 40 gallons/min per inch of drill diameter) (Berglund 1992), and $D_e = 2\,(R - R_i)$, as shown in Figure PA-14. The diameter of the drill collar (i.e., $2R_i$ in Figure PA-14) is 8.0 in = 0.2032 m (Dunagan 2003b). The determination of η is discussed below. Reynolds numbers less than 2100 are assumed to be associated with laminar flow, while Reynolds numbers greater than 2100 are assumed to be associated with turbulent flow (Walker 1976).

Drilling fluids are modeled as non-Newtonian, which means that the viscosity η is a function of the shear rate within the fluid (i.e., the rate at which the fluid velocity changes normal to the flow direction, ((m/s)/m). The CRA-2004 PA uses a model proposed by Oldroyd (1958) to estimate the viscosity of drilling fluids. As discussed by Broc (1982), the Oldroyd model leads to the following expression for the Reynolds number associated with the helical flow of a drilling fluid within an annulus:

$$R_e = \frac{0.8165\,\rho_f\,\|\boldsymbol{v}\|\,D_e}{\eta_\infty}, \tag{107}$$

where ρ_f, $\|\boldsymbol{v}\|$ and D_e are defined as in Equation (106), and η_∞ is the asymptotic value for the derivative of the shear stress (τ, kg m^{-1} s^{-2}) with respect to the shear rate (Γ, s^{-1}) obtained as the shear rate increases (i.e., $\eta_\infty = d\tau/d\Gamma \;\; as\; \Gamma \to \infty$). The CRA-2004 PA uses Equation (107) to obtain the Reynolds numbers that are used to determine whether drilling fluids in the area of the drill collar are undergoing laminar or turbulent flow.

The Oldroyd model assumes that the shear stress τ is related to the shear rate Γ by the relationship

$$\tau = \eta_0 \left(\frac{1 + \sigma_2 \Gamma^2}{1 + \sigma_1 \Gamma^2} \right) \Gamma, \tag{108}$$

where η_0 is the asymptotic value of the viscosity (kg m^{-1} s^{-1}) that results as the shear rate Γ approaches zero, and σ_1, σ_2 are constants (s^2). The expression leads to

$$\eta_\infty = \eta_0 \left(\frac{\sigma_2}{\sigma_1} \right). \tag{109}$$

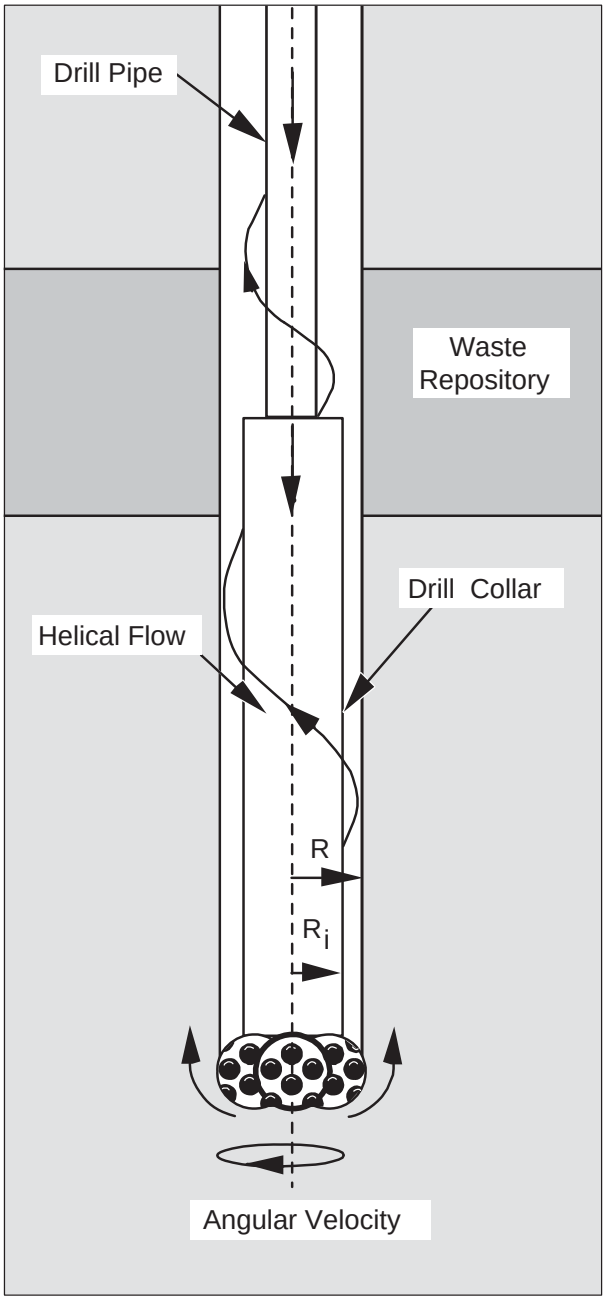

Figure PA-14. Detail of Rotary Drill String Adjacent to Drill Bit.

The CRA-2004 PA uses values of $\eta_0 = 1.834 \times 10^{-2}$ kg m^{-1} s^{-1}, $\sigma_1 = 1.082 \times 10^{-6}$ s^2 and $\sigma_2 = 5.410 \times 10^{-7}$ s^2 (Berglund 1996), and a resultant value of $\eta_\infty = 9.17 \times 10^{-3}$ kg m^{-1} s^{-1}. The quantity η_∞ is comparable to the plastic viscosity of the fluid (Broc 1982).

As previously indicated, different models are used to determine the eroded diameter D_f of a borehole depending on whether flow in the vicinity of the drill collar is laminar or turbulent. The model for borehole erosion in the presence of laminar flow is described next, and is then followed by a description of the model for borehole erosion in the presence of turbulent flow.

PA-4.5.2.1 Laminar Flow Model

As shown by Savins and Wallick (1966), the shear stresses associated with the laminar helical flow of a non-Newtonian fluid can be expressed as

$$\tau(R,r) = \left\{ \left[\frac{C}{r^2} \right]^2 + \left[\frac{RJ}{2} \left(\frac{r^2 - \lambda^2}{r} \right) \right]^2 \right\}^{1/2} \tag{110}$$

for $R_i / R \le r \le 1$, where R_i and R are the inner and outer radii within which the flow occurs as indicated in Figure PA-14; $\tau(R,\rho)$ is the shear stress (kg m^{-1} s^{-2}) at a radial distance ΔR beyond the inner boundary (i.e., at $r = (R_i + \Delta R)/R$); and the quantities C, J, and λ are functions of R that satisfy conditions indicated below. The shear stress at the outer boundary (i.e., R) is given by

$$\tau(R,1) = \left\{ C^2 + \left[\frac{RJ}{2} \left(1 - \lambda^2 \right) \right]^2 \right\}^{1/2} . \tag{111}$$

As previously indicated, the borehole radius R is assumed to increase as a result of erosional processes until a value of R is reached at which $\tau(R,1)$ is equal to the shear strength of the waste. In the CRA-2004 PA, the shear strength of the waste is treated as an uncertain parameter (see WTAUFAIL in Table PA-17). Computationally, determination of the eroded borehole diameter R associated with a particular value for waste shear strength requires repeated evaluation of $\tau(R,1)$, as indicated in Equation (111), until a value of R is determined for which $\tau(R,1)$ equals that shear strength.

The quantities C, J, and λ must satisfy the following three conditions (Savins and Wallick 1966) for the expression in Equation (111) to be valid:

$$0 = \int_{R_i/R}^{1} \left(\frac{\rho^2 - \lambda^2}{\rho \eta} \right) d\rho \tag{112a}$$

$$0 = C \int_{R_i / R}^{1} \left(\frac{1}{\rho^3 \eta} \right) d\rho - \Delta\Omega \tag{112b}$$

and

$$0 = \frac{4Q}{\pi R^3} + 2RJ \int_{R_i / R}^{1} \left(\frac{\left(R_i / R\right)^2 - \rho^2}{\rho\eta} \right) \left(\frac{\rho^2 - \lambda^2}{\rho\eta} \right) d\rho , \tag{112c}$$

where η is the drilling fluid viscosity (kg m^{-1} s^{-1}) and is a function of R and ρ, $\Delta\Omega$ is the drill string angular velocity (rad s^{-1}), and Q is the drilling fluid flow rate (m^3 s^{-1}).

The viscosity η in Equation (112) is introduced into the analysis through the assumption that the drilling fluid follows the Oldroyd model for shear stress in Equation (108). In particular, because

$$\tau = \eta\Gamma \tag{113}$$

as a result of the definition of the viscosity η and

$$\Gamma^2 = \frac{\left(\eta - \eta_0\right)}{\left(\eta_0\sigma_2 - \eta\sigma_1\right)} \tag{114}$$

from Equation (108), the expression in Equation (110) can be reformulated as

$$\frac{\eta^2 \left(\eta - \eta_0\right)^2}{\left(\eta_0\sigma_2 - \eta\sigma_1\right)^2} = \left[\frac{C}{\rho^2} \right]^2 + \left[\frac{RJ}{2} \left(\frac{\rho^2 - \lambda^2}{\rho} \right) \right]^2 . \tag{115}$$

As discussed by Savins and Wallick (1966) and also by Berglund (1992), the expressions in Equation (112) and Equation (114) can be numerically evaluated to obtain C, J, and λ for use in Equation (110) and Equation (111). In the CRA-2004 PA, the drill string angular velocity $\Delta\Omega$ is treated as an uncertain parameter (see DOMEGA in Table PA-17), and

$$Q = \|\mathbf{v}\| \left(\pi R^2 - \pi R_i^2 \right), \tag{116}$$

where $\|\mathbf{v}\|$ = 0.7089 m s^{-1} as used in Equation (106), and η_0, σ_1, and σ_2 are defined by Equation (109).

PA-4.5.2.2 <u>Turbulent Flow Model</u>

The model for borehole erosion in the presence of turbulent flow is now described. Unlike the theoretically derived relationship for erosion in the presence of laminar flow, the model for borehole erosion in the presence of turbulent flow is empirically based. In particular, pressure

loss for axial flow in an annulus under turbulent flow conditions can be approximated by (Broc 1982)

$$\Delta P = \frac{2 f L \rho_f \|\mathbf{v}\|^2}{0.8165 D_e} \tag{117}$$

where ΔP is the pressure change (Pa), L is distance (m) over which pressure change ΔP occurs, f is the Fanning friction factor (dimensionless), and ρ_f, $\|\mathbf{v}\|$ and D_e are defined in Equation (106).

For pipe flow, f is empirically related to the Reynolds number R_e and a roughness term ε by (Whittaker 1985)

$$\frac{1}{\sqrt{f}} = -4 \log_{10}\left(\frac{\varepsilon}{3.72 D} + \frac{1.255}{R_e \sqrt{f}}\right), \tag{118}$$

where D is the inside diameter (m) of the pipe and ε is the average depth (m) of pipe wall irregularities. In the absence of a similar equation for flow in an annulus, Equation (118) is used in the CRA-2004 PA to define f for use in Equation (117), with D replaced by the effective diameter $D_e = 2\left(R - R_i\right)$ and ε equal to the average depth of irregularities in the waste-borehole interface. In the present analysis, ε = 0.025 m (Attachment PAR, Table PAR-34), which exceeds the value often chosen for use in calculations involving very rough concrete or riveted steel piping (Streeter 1958). Further, the Reynolds number R_e is defined in Equation (107).

The pressure change ΔP in Equation (117) and the corresponding shear stress τ at the walls of the annulus are approximately related by

$$\Delta P\left[\pi\left(R^2 - R_i^2\right)\right] = \tau\left[2\pi L\left(R + R_i\right)\right] \tag{119}$$

where $\pi\left(R^2 - R_i^2\right)$ is the cross-sectional area of the annulus (see Figure PA-14) and $2\pi L\left(R + R_i\right)$ is the total (i.e., interior and exterior) surface area of the annulus. Rearrangement of Equation (117) and use of the relationship in Equation (113) yields

$$\tau = \frac{f \rho_f \|\mathbf{v}\|^2}{2(0.8165)}, \tag{120}$$

which was used in the 1991 and 1992 WIPP PAs to define the shear stress at the surface of a borehole of radius R. As a reminder, R enters into Equation (112a) through the use of $D = 2\left(R - R_i\right)$ in the definition of f in Equation (118). As in the case for laminar flow, the borehole radius R is assumed to increase until a value of τ (actually, $\tau\left(R\right)$) is reached that equals

the sample value for the shear strength of the waste (i.e., the uncertain parameter WTAUFAIL in Table PA-17). Computationally, the eroded borehole diameter is determined by solving Equation (120) for R under the assumption that τ equals the assumed shear strength of the waste.

In the CRA-2004 PA, a slight modification to the definition of τ in Equation (120) was made to account for drill string rotation when fluid flow in the vicinity of the drill collars is turbulent (Abdul Khader and Rao 1974; Bilgen et al. 1973). Specifically, an axial flow velocity correction factor (i.e., a rotation factor), F_r, was introduced into the definition of τ. The correction factor F_r is defined by

$$F_r = \|\mathbf{v}_{2100}\| / \|\mathbf{v}\|, \tag{121}$$

where $\|\mathbf{v}_{2100}\|$ is the norm of the flow velocity required for the eroded diameters to be the same for turbulent and laminar flow at a Reynolds number of $R_e = 2100$ and is obtained by solving

$$\tau_{fail} = \frac{f \rho_f \|\mathbf{v}_{2100}\|^2}{2(0.8165)} \tag{122}$$

for $\|\mathbf{v}_{2100}\|$ with D in the definition of f in Equation (118) assigned the final diameter value that results for laminar flow at a Reynolds number of $R_e = 2100$ (i.e., the D in $D_e = 2(R - R_i) = D - 2R_i$ obtained from Equation (107) with $R_e = 2100$). The modified definition of τ is

$$\tau = \frac{f \rho_f \left(F_r \|\mathbf{v}\|\right)^2}{2(0.8165)}, \tag{123}$$

and results in turbulent and laminar flow having the same eroded diameter at a Reynolds number of 2100, which is the Reynolds number at which a transition between turbulent and laminar flow is assumed to take place.

PA-4.5.2.3 <u>Calculation of R_f</u>

The following algorithm was used to determine the final eroded radius R_f of a borehole and incorporates the possible occurrence of a transition from turbulent to laminar fluid flow within a borehole.

Step 1. Use Equation (107) to determine an initial Reynolds number R_e, with R set to the drill-bit radius, $R_0 = 12.25$ in (Attachment PAR, Table PAR-13).

Step 2. If $R_e < 2100$, the flow is laminar and the procedure in Section PA-4.5.2.1 is used to determine R_f. Because any increase in the borehole diameter will cause the Reynolds number to decrease, the flow will remain laminar and there is no need to consider the

possibility of turbulent flow as the borehole diameter increases, with the result that R_f determined in this step is the final eroded radius of the borehole.

Step 3. If $R_e \geq 2100$, then the flow is turbulent and the procedure discussed in Section PA-4.5.2.2 is used to determine R_f. Once R_f is determined, the associated Reynolds number R_e is calculated with Equation (107) and $R = R_f$. If $R_e > 2100$, then a transition from turbulent to laminar flow cannot take place, and the final eroded radius is R_f determined in this step.

Step 4. If the Reynolds number R_e determined in Step 3 satisfies the inequality $R_e \leq 2100$, then a transition from turbulent to laminar flow is assumed to have taken place. In this case, the calculation of R_f is redone for laminar flow, with the outer borehole radius R initially defined to be the radius at which the transition from turbulent to laminar flow occurs (i.e., the radius associated with $R_e = 2100$). In particular, the initial value for R is given by

$$R = R_i + \frac{2100\eta_\infty}{2(0.8165)\|v\|\rho}, \tag{124}$$

which is obtained from Equation (107) by solving for R with $R_e = 2100$. A new value for R_f is then calculated with the procedure discussed in Section PA-4.5.2.1 for laminar flow, with this value of R_f replacing the value from Step 3 as the final eroded diameter of the borehole.

Step 5. Once R_f is known, the amount of waste removed to the surface is determined by Equation (105) with $D_f = 2R_f$.

PA-4.5.3 Additional Information

Additional information on CUTTINGS_S and its use in the CRA-2004 PA to determine cuttings and cavings releases can be found in the CUTTINGS_S user's manual (WIPP PA 2003e) and in the analysis package for cuttings and cavings releases (Dunagan 2003a).

PA-4.6 Spallings to Surface: DRSPALL and CUTTINGS_S

Spallings are waste solids introduced into a borehole by the movement of waste-generated gas towards the lower-pressure borehole. In engineering literature, the term "spalling" is used to describe the phenomenon of dynamic fracture of a solid material such as rock or metal (Antoun et al. 2003). In WIPP PA, the model for spallings describes a series of processes including tensile failure of solid waste, fluidization of failed material, entrainment into the wellbore flow, and transport up the wellbore to the land surface. Spallings releases could occur when pressure differences between the repository and the wellbore are sufficient to cause solid stresses in the waste exceeding the waste material strength and gas velocities sufficient to mobilize failed waste material.

The spallings model is described in the following sections. Presented first are the primary modeling assumptions used to build the conceptual model. Next, the mathematical model and its numerical implementation in the FORTRAN code DRSPALL (for Direct Release Spall) are described. Finally, implementation of the spallings model in WIPP PA by means of the code CUTTINGS_S.

PA-4.6.1 Summary of Assumptions

Assumptions underlying the spallings model include the future state of the waste, specifications of drilling equipment, and the driller's actions at the time of intrusion. Consistent with the other PA models, the spallings model assumes massive degradation of the emplaced waste through mechanical compaction, corrosion, and biodegradation. Waste is modeled as a homogeneous, isotropic, weakly-consolidated material with uniform particle size and shape. The rationale for selection of the spallings model material properties is addressed in detail in reports by Hansen et al. (1997, 2003).

Drilling equipment specifications, such as bit diameter and drilling mud density, are based on surveys of drillers in the Delaware Basin (Hansen et al. 2003). Assumptions about the driller's actions during the intrusion are conservative. Typically, the drilling mud density is controlled to maintain a slightly "overbalanced" condition so that the mud pressure is always slightly higher that the fluid pressures in the formation. If the borehole suddenly passes through a high-pressure zone, the well can quickly become "underbalanced," with a resulting fluid pressure gradient driving formation fluids into the wellbore. This situation is known as a "kick," and is of great concern to drillers because a violent kick can lead to a blowout of mud, gas, and oil from the wellbore, leading to equipment damage and worker injury. Standard drilling practice is to watch diligently for kicks. The first indicator of a kick is typically an increase in mud return rate leading to an increase in mud pit volume (Frigaard and Humphries 1997). Down-hole monitors detect whether the kick is air, H_2S, or brine. If the kick fluid is air, the standard procedure is to stop drilling and continue pumping mud in order to circulate the air pocket out. If the mud return rate continues to grow after drilling has stopped and the driller believes that the kick is sufficiently large to cause damage, the well may be shut in by closing the blowout preventer. Once shut in, the well pressure may be bled off slowly and mud weight eventually increased and circulated to offset the higher formation pressure before drilling continues. The spallings model simulates an underbalanced system in which a gas kick is assured, and the kick proceeds with no intervention from the drill operation. Therefore, drilling and pumping continue during the entire blowout event.

PA-4.6.2 Conceptual Model

The spallings model calculates transient repository and wellbore fluid flow before, during, and after the drilling intrusion. To simplify the calculations, both the wellbore and the repository are modeled by one-dimensional geometries. The wellbore assumes a compressible Newtonian fluid consisting of a mixture of mud, gas, salt and waste solids; viscosity of the mixture varies with the fraction of waste solids in the flow. In the repository, flow is viscous, isothermal, compressible single-phase (gas) flow in a porous medium.

The wellbore and repository flows are coupled by a cylinder of porous media before penetration, and by a cavity representing the bottom of the borehole after penetration. Schematic diagrams of the flow geometry prior to and after penetration are shown in Figure PA-15 and Figure PA-16, respectively. The drill bit moves downward as a function of time, removing salt or waste material. After penetration, waste solids freed by drilling, tensile failure, and associated fluidization may enter the wellbore flow stream at the cavity forming the repository-wellbore boundary.

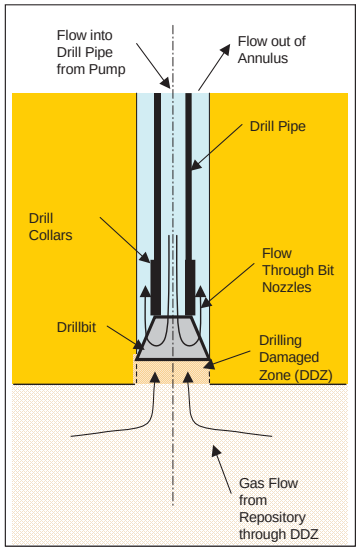

Figure PA-15. Schematic Diagram of the Flow Geometry Prior to Repository Penetration.

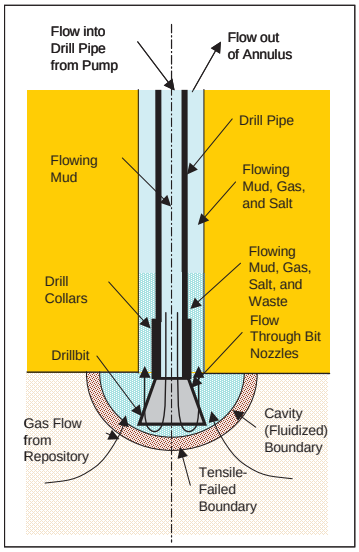

Figure PA-16. Schematic Diagram of the Flow Geometry After Repository Penetration.

PA-4.6.2.1 Wellbore Flow Model

Flow in the well is modeled as one-dimensional pipe flow with cross-sectional areas corresponding to the appropriate flow area at a given position in the well, as shown in Figure PA-17 and Figure PA-18. In concept, this model is similar to that proposed by Podio and Yang (1986) and now in use in the oil and gas industry. Drilling mud is added at the wellbore entrance by the pump. Flow through the drill bit is treated as a choke with cross-sectional area appropriate for the bit nozzle area. At the annulus output to the surface, mixture ejection is to a constant atmospheric pressure. The gravitational body force acts in its appropriate direction based on position before or after the bit.

Prior to drill bit penetration into the repository, gas from the repository can flow through drilling-damaged salt into the well. After penetration, the cavity at the bottom of the wellbore couples the wellbore flow and the repository flow models; gas and waste material can exit the repository domain into the cavity. The cavity radius increases as waste materials are moved into the wellbore.

The system of equations representing flow in the wellbore includes: four equations for mass conservation, one for each phase (salt, waste, mud and gas); one equation for conservation of total momentum; two equations relating gas and mud density to pressure; the definition of density for the fluid mixture; and one constraint imposed by the fixed volume of the wellbore. The conservation of mass and momentum are described by:

$$\frac{\partial}{\partial t}\left(\rho_q V_q\right) + \frac{\partial}{\partial z}\left(\rho_q V_q u\right) = S_q \tag{125a}$$

$$\frac{\partial}{\partial t}\left(\rho V u\right) + \frac{\partial}{\partial z}\left(\rho V u^2\right) = -V\left(\frac{\partial P}{\partial z} - \rho g + F\right) + S_{mom}\,, \tag{125b}$$

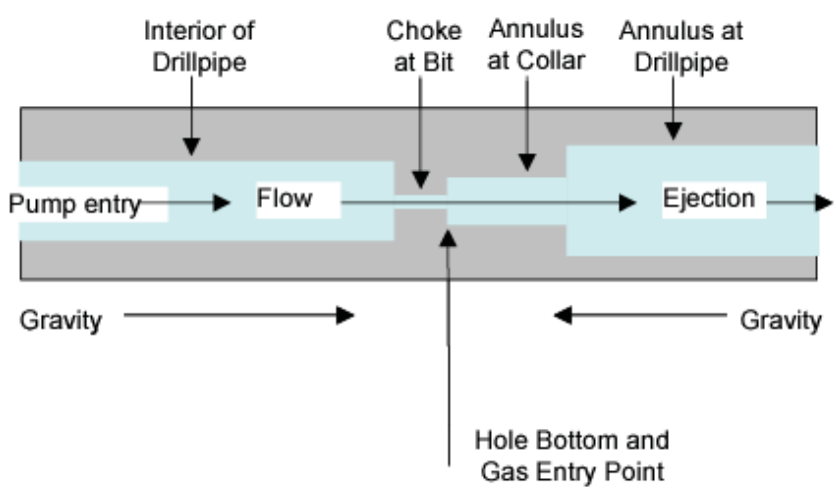

Figure PA-17. Effective Wellbore Flow Geometry Before Bit Penetration.

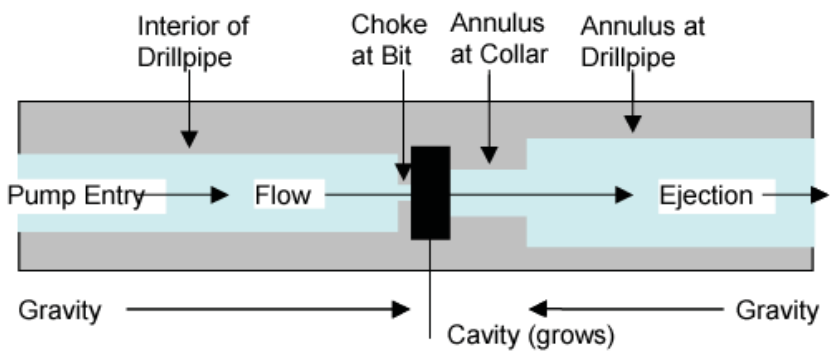

Figure PA-18. Effective Wellbore Flow Geometry After Bit Penetration.

where

q = phase (w for waste, s for salt, m for mud, and g for gas),

V_q = volume (m^3) of phase q,

V = total volume (m^3) ,

ρ_q = density (kg/m^3) of phase q, constant for salt and waste (2180 and 2650 kg/m^3, respectively) and pressure-dependent for gas and mud (see Equation (126) and Equation (127)),

ρ = density of fluid mixture (kg/m^3) determined by Equation (128),

u = velocity (m/s) of fluid mixture in wellbore ,

t = time (s),

z = distance (m) from inlet at top of well ,

S_q = rate of mass (kg/s) of phase q entering and exiting wellbore domain at position z (Equation (138)),

S_{mom} = rate of momentum (kg m / s^2) entering and exiting wellbore domain at position z (Equation (141)),

P = pressure (Pa) at position z ,

g = gravity constant (9.8067 kg/m s^2),

F = friction loss using pipe flow model ($kg/m^2\ s^2$) determined by Equation (130).

Gas is treated as isothermal and ideal, so

$$\frac{\rho}{\rho_{g,0}} = \frac{P}{P_{atm}}, \tag{126}$$

where $\rho_{g,0}$ is the density of the gas at atmospheric pressure (8.24182×10^{-2} kg/m^3 in the CRA-2004 PA).

The mud is assumed to be a compressible liquid, so

$$\rho_m = \rho_{m,0}\left[1 + c_m\left(P - P_{atm}\right)\right], \tag{127}$$

where $\rho_{m,0}$ is the density of the mud at atmospheric pressure (1210 kg/m^3 in the CRA-2004 PA) and c_m is the compressibility of the mud (3.1×10^{-10} Pa^{-1} in the CRA-2004 PA).

The density of the fluid mixture is determined from the densities and volumes occupied by the phases:

$$\rho = \frac{\rho_g V_g + \rho_m V_m + \rho_s V_s + \rho_w V_w}{V}. \tag{128}$$

The volume of each phase is constrained by the fixed volume of the wellbore:

$$V = V_g + V_m + V_s + V_w. \tag{129}$$

The friction loss is a standard formulation for pipe flow (Fox and McDonald 1985), where the head loss per unit length is given as:

$$F = f\frac{\rho}{d_h}\frac{u^2}{2}. \tag{130}$$

The hydraulic diameter d_h is given by

$$d_h = \frac{4A}{\pi\left(D_i + D_o\right)}. \tag{131}$$

In the CRA-2004 PA, D_o = 0.31115 m throughout the domain. From the bit to the top of the collar, D_i = 0.2032 m; above the collar, D_i = 0.1143 m. The area A is calculated as the area of the annulus between the outer and inner radii. Thus, d_h = 0.108 m from the bit to the top of the collar, and d_h = 0.197 m above the collar.

The friction factor f is determined by method of Colebrook (Fox and MacDonald 1985). In the laminar regime (Re < 2100)

$$f = \frac{64}{\mathbf{Re}}, \tag{132}$$

and in the turbulent regime (Re > 2100)

$$\frac{1}{\sqrt{f}} = 1.0 \log\left(\frac{\varepsilon/d_h}{3.7} + \frac{2.51}{\mathbf{Re}\sqrt{f}}\right), \tag{133}$$

where $\mathbf{Re} = \frac{u\rho d_h}{\eta}$ is the Reynolds number of the mixture, and η is the viscosity calculated by Equation (134). As the wellbore mixture becomes particle-laden, the viscosity of the mixture is determined from an empirical relationship developed for proppant slurry flows in channels for the oil and gas industry (Barree and Conway 1995). Viscosity is computed by an approximate slurry formula based on the volume fraction of waste solids:

$$\eta = \eta_0 \left(1 - \frac{w}{w_{max}}\right)^s, \tag{134}$$

where η_0 is a base mixture viscosity (9.17×10^{-3} Pa sec in the CRA-2004 PA), $w = V_w / V$ is the current volume fraction of waste solids, w_{max} is an empirically determined maximal volume fraction above which flow is choked (0.615 in the CRA-2004 PA), and s is an empirically determined constant (–1.5 in the CRA-2004 PA) (Hansen et al. 2003).

PA.-4.6.2.1.1 Wellbore initial conditions

Initial conditions in the wellbore approximate mixture flow conditions just prior to penetration into the waste. The wellbore is assumed to contain only mud and salt. Initial conditions for the pressure, fluid density, volume fractions of mud and salt, and the mixture velocity are set by the following algorithm.

Step 1. Set pressure in the wellbore to hydrostatic: $P(z) = P_{atm} + \rho_{m,0} g z$.

Step 2. Set mud density using Equation (127).

Step 3. Set mixture velocity: $u(z) = \frac{R_m}{A(z)}$, where R_m is the volume flow rate of the pump (0.0202 m^3/s in the CRA-2004 PA), and $A(z)$ is the cross-sectional area of the wellbore.

Step 4. Set volume of salt in each cell: $V_{s,i} = R_{drill} A_{bit} \frac{\Delta z_i}{u_i}$, where R_{drill} is the rate of drilling (0.004445 m/s in the CRA-2004 PA), $A_{bit} = \frac{\pi d_{bit}^2}{4}$ is the area of the bottom of the wellbore and d_{bit} is the diameter of the bit (0.31115 m in the CRA-2004 PA).

Step 5. Set volume fraction of mud in each cell: $V_{m,i} = V_i - V_{s,i}$.

Step 6. Recalculate mixture density using Equation (128), assuming no waste or gas in the wellbore.

The initial conditions set by this algorithm approximate a solution to the wellbore flow (Equation (125)) for constant flow of mud and salt in the well. The approximation rapidly converges to a solution for wellbore flow if steady-state conditions are maintained (WIPP PA 2003f).

PA-4.6.2.1.2 Wellbore boundary conditions

For simplicity, the CRA-2004 PA does not model flow of mud down the pipe to the bit. Mass can enter the wellbore below the drill bit, and can exit at the wellbore outlet. Below the bit, mud, salt, gas, and waste can enter the wellbore. The CRA-2004 PA assumes a constant volume of mud flow down the drilling pipe; therefore, the source term for mud, $S_{m,\,in}$, is set by the volume flow rate of the pump R_m (0.0202 m^3/s in the CRA-2004 PA) and the density of the mud at the bottom of the wellbore:

$$S_{m,in} = \rho_m R_m \,. \tag{135}$$

Until the drill bit penetrates the repository, salt enters the wellbore at a constant rate:

$$S_{s,in} = \rho_s R_{drill} A_{bit} \,. \tag{136}$$

Additional mass enters the wellbore by gas flow from the repository ($S_{gas,in}$) or by drilling or spalling of waste material ($S_{w,in}$); these mass sources are discussed in Section PA-4.6.2.3. The outlet of the wellbore is set to atmospheric pressure. Mass exiting the wellbore is determined from the mixture velocity, the area of the outlet A_{out} (0.066 m^2 in the CRA-2004 PA), and the density and volume fraction of each phase at the outlet of the wellbore:

$$S_{q,out} = \rho u_{out} A_{out} \frac{V_q}{V} \,. \tag{137}$$

Finally, the net change in mass for phase q is

$$S_q = S_{q,in} - S_{q,out} \,. \tag{138}$$

$$S_{mom,in} = \frac{\rho_{0,m}}{A_p} R_{mudpump} \cdot \tag{139}$$

The outlet of the wellbore is set to atmospheric pressure. Momentum exiting the wellbore is determined from the fluid velocity and the area of the outlet A_{out} (0.066 m^2 in the CRA-2004 PA):

$$S_{mom,out} = -\rho A_{out} u_{out}^2 \cdot \tag{140}$$

No momentum is added by mass flow into the wellbore from the repository, thus:

$$S_{mom} = S_{mom,in} - S_{mom,out} \cdot \tag{141}$$

PA-4.6.2.2 Repository Flow Model

The repository is modeled as a radially-symmetric domain. A spherical coordinate system is used for this presentation and for most DRSPALL calculations in the CRA-2004 PA. In a few circumstances, cylindrical coordinates are used in CRA-2004 PA calculations, where spall volumes are large enough that spherical coordinates are not representative of the physical process (Lord et al. 2003). Cylindrical coordinates are also available; the Design Document for DRSPALL (WIPP PA 2003g) provides details on the implementation of the repository flow model in cylindrical coordinates.

Flow in the repository is transient, compressible, viscous, and single phase (gas) flow in a porous medium. Gas is treated as isothermal and ideal. The equations governing flow in the repository are the equation of state for gas, conservation of mass, and Darcy's law with the Forchheimer correction (Aronson 1986; Whitaker 1996):

$$\frac{\rho_g}{\rho_{g,0}} = \frac{P}{P_{atm}}, \tag{142a}$$

$$\phi \frac{\partial \rho_g}{\partial t} + \nabla \cdot \left(\rho_g u \right) = 0, \tag{142b}$$

$$\nabla P = -\frac{\eta_g}{k} \left(1 + F \right) u, \tag{142c}$$

where

P = pressure in pore space (Pa),

ρ_g = density of gas (kg/m^3),

u = velocity of gas in pore space (m/s),

ϕ = porosity of the solid (unitless),

η_g = gas viscosity (8.934×10^{-6} Pa s),

k = permeability of waste solid (m^2),

F = Forchheimer coefficient (unitless).

The Forchheimer correction is included to account for inertia in the flowing gas, which becomes important at high gas velocities (Ruth and Ma 1992). When the Forchheimer coefficient is zero, Equation (142c) reduces to Darcy's Law. A derivation of Equation (142c) from the Navier-Stokes equations is given by Whitaker (1996); the derivation suggests that F is a linear function of gas velocity for a wide range of Reynolds numbers.

In the CRA-2004 PA, the Forchheimer coefficient takes the form

$$F = \beta_{nd} \rho u \,, \tag{143}$$

where β_{nd} is the non-Darcy coefficient, which depends on material properties such as the tortuosity and area of internal flow channels, and is empirically determined (Belhaj et al. 2003). The CRA-2004 PA uses a value from a study by Li et al. (2001) that measured high-velocity nitrogen flow through porous sandstone wafers, giving the result

$$\beta_{nd} = \frac{1.15 \times 10^{-6}}{k\phi} \,. \tag{144}$$

Equation (142) combines into a single equation for pressure in the porous solid:

$$\frac{\partial P}{\partial t} = \frac{k'}{2\phi\eta_g} \nabla^2 P^2 + \frac{1}{2\phi\eta_g} \nabla P^2 \cdot \nabla k' \,, \tag{145}$$

where

$$k' = \frac{k}{1+F} = \frac{k}{1+\beta_{nd}\rho u} \,, \tag{146}$$

and the operator in a radially-symmetric coordinate system is given by

$$\nabla^2 = \frac{1}{r^{n-1}} \frac{\partial}{\partial r}\left(r^{n-1} \frac{\partial}{\partial r} \right) \,, \tag{147}$$

where n = 2 and n = 3 for cylindrical and spherical coordinates, respectively.

In the CRA-2004 PA, the permeability of the waste solid is a subjectively uncertain parameter that is constant for waste material that has not failed and fluidized. In a region of waste that has

failed, the permeability increases as the waste fluidizes by a factor of $1 + F_f$, where F_f is the fraction of failed material that has fluidized and is based on the fluidization relaxation time. This approximately accounts for the bulking of material as it fluidizes.

Initial pressure in the repository is set to a constant value P_{ff}. A no-flow boundary condition is imposed at the outer boundary (r = R):

$$\nabla \boldsymbol{P}(\boldsymbol{R}) = \boldsymbol{0}\,. \tag{148}$$

At the inner boundary ($r = r_{cav}$), the pressure is specified as $\boldsymbol{P}(\boldsymbol{r_{cav}}, \boldsymbol{t}) = \boldsymbol{P_{cav}}(\boldsymbol{t})$, where $\boldsymbol{P_{cav}}(\boldsymbol{t})$ is defined in the next section. The cavity radius r_{cav} increases as drilling progresses and as waste material fails and moves into the wellbore; calculation of r_{cav} is described in Section PA-4.6.2.3.3.

PA-4.6.2.3 <u>Wellbore to Repository Coupling</u>

Prior to penetration, a cylinder of altered-permeability salt material with diameter equal to the drill bit is assumed to connect the bottom of the wellbore to the repository. At the junction of the repository and this cylinder of salt, a small, artificial cavity is used to determine the boundary pressure for repository flow. After penetration, the cavity merges with the bottom of the wellbore to connect the wellbore to the repository.

PA-4.6.2.3.1 Flow Prior to Penetration

The cylinder of salt connecting the wellbore to the repository is referred to as the Drilling Damaged Zone (DDZ) in Figure PA-15. The permeability of the DDZ, k_{DDZ}, is 1×10^{-14} (m^2) in the CRA-2004 PA. The spall model starts with the bit 0.15 m above the repository; the bit advances at a rate of $R_{drill} = 0.004445$ (m/s).

To couple the repository to the DDZ, the model uses an artificial pseudo-cavity in the small hemispherical region of the repository below the wellbore, with the same surface area as the bottom of the wellbore (Figure PA-18). The pseudo-cavity is a numerical device that smoothes the discontinuities in pressure and flow that would otherwise occur upon bit penetration of the repository. The pseudo-cavity contains only gas and is initially at repository pressure. The mass of gas in the cavity m_{cav} is given by:

$$\frac{d\boldsymbol{m_{cav}}}{d\boldsymbol{t}} = \boldsymbol{S_{rep}} - \boldsymbol{S_{g,in}}\,, \tag{149}$$

where

S_{rep} = gas flow from repository into pseudo-cavity (kg/s); see Equation (150),

$S_{g,\,in}$ = gas flow from pseudo-cavity through DDZ into wellbore (kg/s); see Equation (151).

Flow from the repository into the pseudo-cavity is given by

$$S_{rep} = \rho_{g,rep} u_{rep} \phi A_{cav}, \tag{150}$$

where

$\rho_{g,rep}$ = gas density in repository at cavity surface (kg/m^3) = $\rho_g\left(r_{cav}\right)$,

u_{rep} = gas velocity (m/s) in repository at cavity surface = $u\left(r_{cav}\right)$,

ϕ = porosity of waste (unitless),

A_{cav} = surface area of hemispherical part of the cavity (m^2),

= $\frac{\pi}{4} d_{bit}^2$, where d_{bit} is the diameter of the bit (m).

Flow out of the pseudo-cavity through the DDZ and into the wellbore is modeled as steady-state using Darcy's Law:

$$S_{g,in} = \frac{k_{DDZ}\pi\left(\frac{d_{bit}}{2}\right)^2}{2\eta_g R_0 T L}\left(P_{cav}^2 - P_{BH}^2\right), \tag{151}$$

where

η_g = gas viscosity (8.934×10^{-6} Pa s),

R_0 = ideal gas constant for hydrogen (4116 J / kg °K),

T = repository temperature (constant at 300 °K),

L = length (m) of DDZ (from bottom of borehole to top of repository)

P_{cav} = pressure in pseudo-cavity (Pa),

P_{BH} = pressure at bottom of wellbore (Pa).

A justification for the use of this steady-state equation is provided in the Design Document for DRSPALL (WIPP PA 2003g). The pseudo-cavity is initially filled with gas at a pressure of P_{ff}. The boundary pressure on the well side (P_{BH}) is the pressure immediately below the bit, determined by Equation (125). The pressure in the pseudo-cavity (P_{cav}) is determined by the ideal gas law:

$$P_{cav} = \frac{m_{cav} R_0 T}{V_{cav}}, \tag{152}$$

where the volume of the cavity V_{cav} is given by

$$V_{cav} = \left(\frac{\pi}{24\sqrt{2}} \right) d_{bit}^3 . \tag{153}$$

In the CRA-2004 PA the drilling rate is constant at 0.004445 (m/s) thus $L = L_i - 0.004445t$ until $L = 0$, at which time the bit penetrates the waste. The term L_i is the distance from the bit to the waste at the start of calculation (0.15 m in the CRA-2004 PA).

PA-4.6.2.3.2 Flow After Penetration

After penetration of the waste, the bottom of the wellbore is modeled as a hemispherical cavity in the repository, the radius of which grows as drilling progresses and as material fails and moves into the cavity. Gas, drilling mud, and waste are assumed to thoroughly mix in this cavity; the resulting mixture flows around the drill collars and then up the annulus between the wellbore and the drill string. Gas flow from the repository into the cavity is given by Equation (150); however, A_{cav} is now dependent on the increasing radius of the cavity (see Section PA-4.6.2.3.3). Mudflow into the cavity from the wellbore is given by Equation (135). Waste flow into the cavity is possible if the waste fails and fluidizes; these mechanisms are discussed in Sections PA-4.6.2.3.4 and PA-4.6.2.3.5. Pressure in the cavity is equal to the pressure at the bottom of the wellbore and is computed by Equation (152).

PA-4.6.2.3.3 Cavity Volume After Penetration

The cylindrical cavity of increasing depth created by drilling is mapped to a hemispherical volume at the bottom of the wellbore to form the cavity. This mapping maintains equal surface areas in order to preserve the gas flux from the repository to the wellbore. The cavity radius from drilling is thus

$$r_{drill} = \sqrt{\frac{d_{bit}^2 + 4 d_{bit} \Delta H}{8}}, \tag{154}$$

where ΔH is the depth of the drilled cylinder. In the CRA-2004 PA, the drilling rate is constant at 0.004445 (m/s) thus $\Delta H = 0.004445t$ until $\Delta H = H$, the height of compacted waste (m). Since the initial height of the repository is 3.96 m, H is computed from the porosity ϕ by $H = 3.96 \times \frac{1-\phi_0}{1-\phi}$, where ϕ is the initial porosity of a waste-filled room.

The cavity radius r_{cav} is increased by the radius of failed and fluidized material r_{fluid}, which is the depth to which fluidization has occurred beyond the drilled radius. That is,

$$r_{cav} = r_{drill} + r_{fluid} \cdot \tag{155}$$

PA-4.6.2.3.4 Waste Failure

Gas flow from the waste creates a pressure gradient within the waste, which induces elastic stresses in addition to the far-field confining stress. These stresses may lead to tensile failure of the waste material, assumed to be prerequisite to spallings releases. While the fluid calculations using Equation (142) are fully transient, the elastic stress calculations are assumed to be quasi-static (i.e., sound-speed phenomena in the solid are ignored). Elastic effective stresses are (Timoshenko and Goodier 1970):

$$\sigma_r(r) = \sigma_{sr}(r) + \sigma_{ff}\left(1 - \left(\frac{r_{cav}}{r}\right)^3\right) + P(r_{cav})\left(\frac{r_{cav}}{r}\right)^3 - \beta P(r), \tag{156}$$

$$\sigma_\theta(r) = \sigma_{s\theta}(r) + \sigma_{ff}\left[1 + \frac{1}{2}\left(\frac{r_{cav}}{r}\right)^2\right] - \frac{P(r_{cav})}{2}\left(\frac{r_{cav}}{r}\right)^3 - \beta P(r), \tag{157}$$

where β is Biot's constant (1.0 in the CRA-2004 PA) and σ_{ff} is the confining far-field stress (assumed constant at 14.9 MPa in the CRA-2004 PA).

The flow-related radial and tangential stresses (σ_{sr} and $\sigma_{s\theta}$, respectively) are computed by equations analogous to differential thermal expansion (Timoshenko and Goodier 1970):

$$\sigma_{sr}(r) = 2\beta\left(\frac{1-2\upsilon}{1-\upsilon}\right)\frac{1}{r^3}\int_{r_{cav}}^{r}\left(P(s) - P_{ff}\right)s^2 ds, \tag{158}$$

$$\sigma_{s\theta}(r) = -\beta\left(\frac{1-2\upsilon}{1-\upsilon}\right)\left(\frac{1}{r^3}\int_{r_{cav}}^{r}\left(P(s) - P_{ff}\right)s^2 ds - \left(P(r) - P_{ff}\right)\right), \tag{159}$$

where P_{ff} is the initial repository pressure and υ is Poisson's ratio (0.38 in the CRA-2004 PA).

Since stresses are calculated as quasi-static, an initial stress reduction caused by an instantaneous pressure drop at the cavity face propagates instantaneously through the waste. The result of calculating Equation (156) can be an instantaneous early-time tensile failure of the entire repository if the boundary pressure is allowed to change suddenly. This is non-physical and merely a result of the quasi-static stress assumption combined with the true transient pore pressure and flow-related stress equations. To prevent this non-physical behavior, tensile failure propagation is limited by a tensile failure velocity (1000 m/s in the CRA-2004 PA; see Hansen et al. 1997). This limit has no quantitative effect on results other than to prevent non-physical tensile failure.

At the cavity face, Equation (156) and Equation (158) evaluate to zero, consistent with the quasi-static stress assumption. This implies that the waste immediately at the cavity face cannot experience tensile failure; however, tensile failure may occur at some distance into the waste material. Consequently, the radial effective stress σ_r is averaged from the cavity boundary into the waste over a characteristic length L_t (0.02 m in the CRA-2004 PA). If this average radial stress $\bar{\sigma}_r$ is tensile and its magnitude exceeds the material tensile strength ($|\bar{\sigma}_r| > \boldsymbol{TENSLSTR}$), the waste is no longer capable of supporting radial stress and fails, permitting fluidization. The waste tensile strength is an uncertain parameter in the analysis (see TENSLSTR in Table PA-14).

Equation (157) and (159) evaluate shear stresses in the waste. The CRA-2004 PA does not use the shear stresses in the waste in the calculation of waste failure for spall releases. These stresses are included in this discussion for completeness.

PA-4.6.2.3.5 Waste Fluidization

Failed waste material is assumed to be disaggregated, but not in motion; it remains as a porous, bedded material lining the cavity face, and is treated as a continuous part of the repository from the perspective of the porous flow calculations. The bedded material may be mobilized and may enter the wellbore if the gas velocity in the failed material (see Equation (142c)) exceeds a minimum fluidization velocity, U_f. The minimum fluidization velocity is determined by solving the following quadratic equation (Cherimisinoff and Cherimisinoff 1984; Ergun 1952):

$$\frac{1.75}{a\phi^3}\left(\frac{d_p U_f \rho_g}{\eta_g}\right)^2 + 150\left(\frac{1-\phi}{a^2\phi^3}\right)\left(\frac{d_p U_f \rho_g}{\eta_g}\right) = \frac{d_p^3 \rho_g \left(\rho_w - \rho_g\right) g}{\eta_g^2}, \qquad (160)$$

where

a = particle shape factor (unitless),

d_p = particle diameter (m).

Fluidization occurs in the failed material to the depth at which gas velocity does not exceed the fluidization velocity; this depth is denoted by r_{fluid} and is used to determine cavity radius (Section PA-4.6.2.3.3). If fluidization occurs, the gas and waste particles mix into the cavity at the bottom of the wellbore. To account for the fact that this mixing cannot be instantaneous, which would be non-physical (much as allowing instantaneous tensile failure propagation would be non-physical), a small artificial relaxation time, equal to the cavity radius r_{cav} divided by the superficial gas velocity $u\left(r_{cav}\right)$, is imposed upon the mixing phenomenon. The fluidized material is released into the cavity uniformly over the relaxation time.

PA-4.6.3 Numerical Model

The numerical model implements the conceptual and mathematical models described above. Both the wellbore and the repository domain calculations use time-marching finite differences.

These are part of a single computational loop and therefore use the same time step. The differencing schemes for the wellbore and repository calculations are similar, but not identical.

PA-4.6.3.1 Numerical Method – Wellbore

The wellbore is zoned for finite differencing as shown in Figure PA-19. This shows zones, zone indices, grid boundaries, volumes, and interface areas. The method is Eulerian; i.e., zone boundaries are fixed, and fluid flows across the interfaces by advection. Quantities are zone-centered and integration is explicit in time.

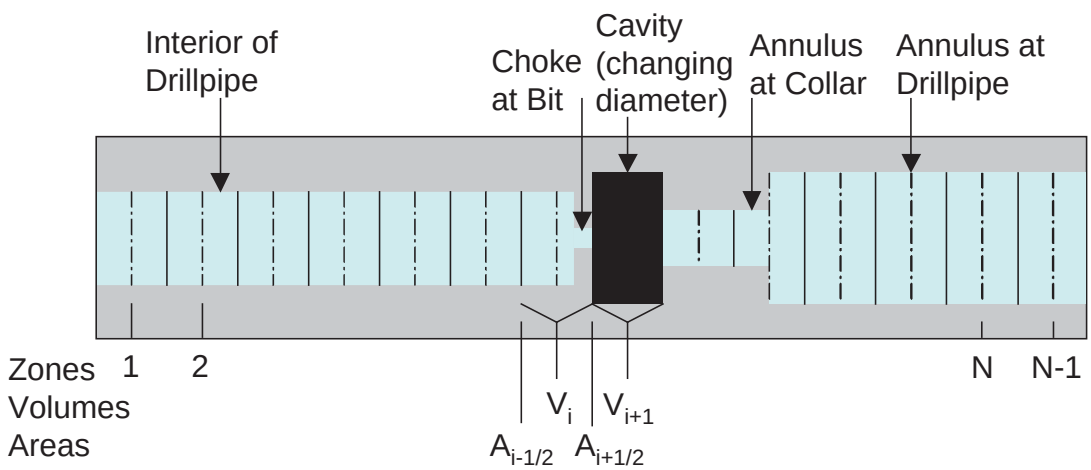

Figure PA-19. Finite Difference Zoning for Wellbore.

To reduce computation time, an iterative scheme is employed to update the wellbore flow solution. The finite difference scheme first solves Equation (125) for the mass of each phase in each grid cell and the momentum in each grid cell.

The updated solution to Equation (125) is then used to compute the volume of each phase, the pressure, and the mixture velocity in each grid cell.

All of the materials (mud, salt, gas, and waste) are assumed to move together as a mixture. Since fluid moves through the cell boundaries, the calculation requires values for the flow through cell boundaries during a timestep. These values are obtained by averaging the fluid velocities at the zone centers, given by:

$$u_{i+1/2} = \frac{1}{2}\left(u_{i+1}^{n-1} + u_i^{n-1}\right). \tag{161}$$

The mass transport equation, prior to any volume change, becomes

$$V_i\ \rho_i^* = V_i\ \rho_i^{n-1} - \Delta t\left(A_{i+1/2}\rho_{i+1/2}^{n-1}u_{i+1/2} - A_{i-1/2}\rho_{i-1/2}^{n-1}u_{i-1/2}\right) + \Delta t S_{m,i}\,. \tag{162}$$

Here, the source terms $\left(S_{m,i}\right)$ are set to correspond to material entering or exiting at the pump, cavity, and surface. The "upwind" zone centered densities are used for the interfaces values, $\rho_{i+1/2}^{n-1}$ and $\rho_{i-1/2}^{n-1}$.

Finally any changed volumes are incorporated and numerical mass diffusion is added for stability:

$$V_i \rho_i^n = V_i \rho_i^* + \Delta z_i \sum_{q=w,m,s,g} \zeta_q D_{i,q}, \tag{163}$$

where

$$D_{i,q} = \left[A_{i+1/2}\left(\left(\rho f_q\right)_{i+1}^{n-1} - \left(\rho f_q\right)_i^{n-1}\right) - A_{i-1/2}\left(\left(\rho f_q\right)_i^{n-1} - \left(\rho f_q\right)_{i-1}^{n-1}\right)\right]$$

and ζ_q is the diffusion coefficient for phase q. The density ρf_q for the phase q being diffused is calculated from the mixture density, ρ, and the mass fraction, f_q, of the phase q in the referenced cell ($f_q = \rho V_{q,i} / \rho V_i$). The numerical diffusion coefficient ζ_q is chosen empirically for stability. Separate diffusion coefficients could be used for the different materials (mud, gas, etc.). However, sufficient stability is obtained by only diffusing mud and salt using the same coefficient ($\zeta_m = \zeta_s = 0.0001$ and $\zeta_w = \zeta_g = 0$ in the CRA-2004 PA).

Momentum is differenced as:

$$\begin{aligned} V_i \ (\rho u)_i^* = V_i \ (\rho u)_i^{n-1} - \Delta t\left(A_{i+1/2}(\rho u)_{i+1/2}^{n-1} u_{i+1/2} - A_{i-1/2}(\rho u)_{i-1/2}^{n-1} u_{i-1/2}\right) \\ - V_i \ \Delta t\left(\frac{P_{i+1}^{n-1} - P_{i-1}^{n-1}}{2\Delta z} - \rho_i^{n-1} g + F_i^{n-1}\right) + \Delta t S_{mom,i}, \end{aligned} \tag{164}$$

where the dissipation term F_i^{n-1} is obtained from Equation (130) and is constrained by:

$$\left|F_i^{n-1}\right| \le \left|\frac{P_{i+1}^{n-1} - P_{i-1}^{n-1}}{2\Delta z} - \rho_i^{n-1} g\right|, \qquad 165)$$

and the sign of F_i^{n-1} is chosen to oppose flow. Finally, numerical momentum diffusion is added without distinguishing between phases in the mixture (ρ is the mixture density).

$$V_i \ (\rho u)_i^n = V_i \ (\rho u)_i^* - \zeta_p \Delta x_i \left[A_{i+1/2}\left((\rho u)_{i+1}^{n-1} - (\rho u)_i^{n-1}\right) - A_{i-1/2}\left((\rho u)_i^{n-1} - (\rho u)_{i-1}^{n-1}\right)\right]. \tag{166}$$

In the CRA-2004 PA, $\zeta_p = 0.01$.

Equation (127), Equation (128), and Equation (129) comprise a simultaneous system of equations for the volumes of gas and mud, and the pressure in the wellbore. The volumes of salt and waste will be known, since they are considered incompressible. Equation (127) and Equation (128) combine into a quadratic equation for gas volume

$$aV_g^2 + bV_g - c = 0\,, \tag{167}$$

where

$$\begin{aligned} a &= 1 - c_m P_{atm}\,, \\ b &= c_m P_{atm} V_{g,0} - aV^* + V_{m,0}\,, \\ c &= V^* c_m P_{atm} V_{g,0}\,, \\ V_{g,0} &= m_g / \rho_{g,0}\,, \\ V_{m,0} &= m_m / \rho_{m,0}\,, \end{aligned}$$

and

$$V^* = V_m + V_g = V - V_s - V_w$$

The volume of the mud phase follows from Equation (127) and the pressure from Equation (126). Once mixture density in each cell (ρ_i) is updated by Equation (128), mixture velocity in each cell (u_i) is computed by

$$u_i = \frac{(\rho u)_i}{\rho_i}\,,$$

where the quantity ρ u is determined by Equation (166).

PA-4.6.3.2 <u>Numerical Method – Repository</u>

The time integration method for the repository flow is implicit, with spatial derivatives determined after the time increment. This method requires the inversion of a matrix for the entire repository, which is usually straightforward. The implicit scheme is unconditionally stable. However, it is still necessary to use small time steps to ensure gradient accuracy.

The numerical method follows Press et al. (1989). For simplicity, the equations are presented for constant zone size, although DRSPALL implements difference equations that allow for a variable zone size. Near the cavity, a small, constant zone size is used, and then zones are allowed to grow geometrically as the outer boundary is approached. This procedure greatly increases computational efficiency without sacrificing accuracy in the region of interest.

For an isothermal ideal gas, the pseudopressure is defined as

$$\psi = \frac{P^2}{\eta} \quad \text{or} \quad P = \sqrt{\eta\psi}\,. \tag{168}$$

Using Equation (168), Equation (145) is expanded to

$$\frac{\partial\psi}{\partial t} = D(\psi)\left[\frac{\partial^2\psi}{\partial r^2} + \frac{(m-1)}{r}\frac{\partial\psi}{\partial r} + \frac{1}{k'}\frac{\partial k'}{\partial r}\frac{\partial\psi}{\partial r}\right], \tag{169}$$

where $D(\psi) = \frac{k'}{\phi}\sqrt{\frac{\psi}{\eta}} = \frac{k'P}{\phi\eta}$; Equation (169) is then converted to a difference equation by treating $D(\psi)$ as constant over a zone, using its zone-centered value at the current time D_j^n:

$$\frac{\psi_j^{n+1} - \psi_j^n}{\Delta t} = \frac{D_j^n}{\Delta r}\left[\frac{\psi_{j+1}^{n+1} - 2\psi_j^{n+1} + \psi_{j-1}^{n+1}}{\Delta r} + \frac{(m-1)\left(\psi_{j+1}^{n+1} - \psi_{j-1}^{n+1}\right)}{2r_j} + \frac{\left(k'^{\,n+1}_{j+1} - k'^{\,n+1}_{j-1}\right)\left(\psi_{j+1}^{n+1} - \psi_{j-1}^{n+1}\right)}{4k'\Delta r}\right]. \tag{170}$$

Collecting similar terms in ψ leads to a tridiagonal system:

$$-\alpha 1\psi_{j-1}^{n+1} + (1 + 2\alpha\alpha)_j^{n+1} - \alpha 2\psi_{j+1}^{n+1} = \psi_j^n - \alpha_1\Psi_{j-1}^{n+1} + (1 + 2\alpha \quad j = 1,2\ldots, \tag{171}$$

where

$$\alpha = \frac{D_j^n \Delta t}{(\Delta r)^2},$$

$$\alpha_1 = \left(\frac{D_j^n}{\Delta r}\right)\left(\frac{1}{\Delta r} - \frac{(m-1)}{2r_j} - \frac{k'^{\,n+1}_{i+1} - k'^{\,n+1}_{i-1}}{4k'\Delta r}\right)\Delta t\,,$$

$$\alpha_2 = \left(\frac{D_j^n}{\Delta r}\right)\left(\frac{1}{\Delta r} + \frac{(m-1)}{2r_j} + \frac{k'^{\,n+1}_{i+1} - k'^{\,n+1}_{i-1}}{4k'\Delta r}\right)\Delta t\,.$$

Equation (171) may be solved by simplified LU decomposition as presented in Press et al. (1989).

The boundary condition at the inner radius is implemented by noting that for i = 1 (the first intact or non-fluidized cell), ψ_{i-1} is the cavity pseudopressure, which is known, and therefore can be moved to the right hand side of Equation (171):

$$\left(1+2\alpha\right)\psi_1^{n+1} - \alpha_2\psi_2^{n+1} = \psi_1^n + \alpha_1\psi_{cav}^{n+1}. \tag{172}$$

The far field boundary condition is a zero gradient, which is implemented by setting $\psi_{j+1}^{n+1} = \psi_j^{n+1}$ in Equation (172), recognizing that $1+2\alpha = 1+\alpha_1+\alpha_2$ and rearranging, which gives

$$-\alpha_1\psi_{j-1}^{n+1} + \left(1+\alpha_1\right)\psi_j^{n+1} = \psi_j^n, \tag{173}$$

where j is the index of the last computational cell.

PA-4.6.3.3 Numerical Method – Wellbore to Repository Coupling

The term u_{rep}, appearing in Equation (150), is the gas velocity in the repository at the waste-cavity interface and is determined from the pressure gradient inside the waste. The CRA-2004 PA uses the pressure (P_1) at the center of the first numerical zone in the waste to determine u_{rep} :

$$u_{rep} = \frac{k\left(P_1 - P_{cav}\right)}{\Delta r\,\eta_g\phi}. \tag{174}$$

PA-4.6.4 Implementation

During development of the spallings model, a total of five parameters were determined to be both uncertain and potentially significant to model results (Hansen et al. 2003; Lord and Rudeen 2003). All five parameters relate to the repository conditions or the state of the waste at the time of intrusion. Table PA-14 lists the uncertain parameters in the DRSPALL calculations.

The computational requirements of DRSPALL prohibit calculation of spall volumes for all possible combinations of initial conditions and parameter values. Since repository pressure is a time-dependent value computed by the BRAGFLO model (see Section PA-4.2), DRSPALL calculations were performed for a small number of pressures. Sensitivity studies showed that spall does not occur at pressures below 10 MPa; this value was used as the lower bound on

Table PA-14. Uncertain Parameters in the DRSPALL Calculations

Parameter	Variable	Implementation
Repository Pressure	REPIPRES	Initial repository pressure (Pa); spall calculated for values of 10, 12, 14, and 14.8 MPa. Defines initial repository pressure in Equation (145) (see Section PA-4.6.2.2) and Pff in Equation (158).
Repository Permeability	REPIPERM	Permeability (m^2) of waste, implemented by parameter SPALLMOD/REPIPERM. Loguniform distribution from 2.4×10^{-14} to 2.4×10^{-12}. Defines k in Equation (142c).
Repository Porosity	REPIPOR	Porosity (dimensionless) of waste, implemented by parameter SPALLMOD/REPIPOR. Uniform distribution from 0.35 to 0.66. Defines ϕ in Equation (142b).
Particle Diameter	PARTDIAM	Particle diameter of waste (m) after tensile failure, implemented by parameter SPALLMOD/PARTDIAM. Loguniform distribution from 0.001 to 0.1 (m). Defines d_p in Equation (160).
Tensile Strength	TENSLSTR	Tensile strength of waste (Pa), implemented by parameter SPALLMOD/TENSLSTR. Uniform distribution from 0.12 MPa to 0.17 MPa. Defines $\overline{\sigma}_r$ in Section PA-4.6.2.3.5.

pressure. In DRSPALL, the repository pressure cannot exceed the far-field confining stress (14.9 MPa in the CRA-2004 PA); consequently, 14.8 MPa was used as the upper bound on pressure. Computations were also performed for intermediate pressures of 12 and 14 MPa.

The remaining four parameters listed in Table PA-14 were treated as subjectively uncertain. The uncertainty represented by these parameters pertains to the future state of the waste, which is modeled in PA as a homogeneous material with uncertain properties. In order to ensure that sampled values are independent and that the extremes of each parameter's range are represented in the results, the CRA-2004 PA uses Latin hypercube sampling to generate a sample of 50 elements. The LHS generated for DRSPALL calculations is independent of the LHS generated for the general PA calculations. Spall volumes are computed for each combination of initial pressure and sample element, for a total of $4 \times 50 = 200$ model runs. Although repository porosity could be treated as an initial condition (using the time-dependent value computed by BRAGFLO), to reduce the number of computational cases, and to ensure that extreme porosity values were represented, repository porosity was included as a sampled parameter. The LHS for DRSPALL and the results of the DRSPALL calculations are presented in Lord et al. (2003).

The spallings submodel of the code CUTTINGS_S uses the DRSPALL results to compute the spall volume for a given initial pressure P. An uncertain parameter SPALLMOD/RNDSPALL is included in the LHS for performance assessment (see Section PA-5.2) and is sampled from a uniform distribution on $[0,1]$. This parameter selects a sample element from the LHS for DRSPALL. The DRSPALL results for the selected sample element are used to construct the spall volume. If $P < 10$ MPa or $P > 14.8$ MPa, the spall volume is the value computed for REPIPRESS = 10 MPa or REPIPRESS = 14.8 MPa, respectively. If P falls between 10 and 14.8 MPa, the spall volume is constructed by linear interpolation between the DRSPALL results for pressures which bracket P.

PA-4.6.5 Additional Information

Additional information on DRSPALL and its use in the CRA-2004 PA to determine spallings releases can be found in the User's Manual for DRSPALL (WIPP PA 2003h) and in the analysis package for spallings releases (Lord et al. 2003). Additional information on the construction of spall volumes by the code CUTTINGS_S can be found in the CUTTINGS_S Design Document (WIPP PA 2003i).

PA-4.7 Direct Brine Release to Surface: BRAGFLO

This section describes the model for direct brine release (DBR) volumes, which are volumes of brine released to the surface at the time of a drilling intrusion. DBR volumes are calculated by the code BRAGFLO, the same code used to compute two-phase flow in and around the repository (see Section PA-4.2).

PA-4.7.1 Overview of Conceptual Model

DBRs could occur if the pressure in the repository at the time of a drilling intrusion exceeds 8 MPa, which is the pressure exerted by a column of brine-saturated drilling fluid at the depth of the repository (Stoelzel and O'Brien 1996). For repository pressures less than 8 MPa, no DBRs are assumed to occur. However, even if the repository pressure exceeds 8 MPa at the time of a drilling intrusion, a DBR is not assured, as there might not be sufficient mobile brine in the repository to result in movement towards the borehole.

DBRs are estimated for the following cases: (1) an initial intrusion into the repository into either a lower (down-dip), middle, or upper (up-dip) panel, (2) an intrusion into a waste panel that has been preceded by an E1 intrusion into either the same waste panel, an adjacent panel, or a non-adjacent panel, and (3) an intrusion into a waste panel that has been preceded by an E2 intrusion into either the same waste panel, an adjacent panel, or a non-adjacent panel (see Section PA-6.7). To determine releases for the above cases, the DBR calculations use a computational grid that explicitly includes all 10 waste panels (Figure PA-20).

The DBRs are assumed to take place over a relatively short period of time (i.e., 3 to 11 days) following the drilling intrusion. The initial value conditions for determining DBR volumes are obtained by mapping solutions of Equation (25) obtained from BRAGFLO with the computational grid in Figure PA-8 onto the grid in Figure PA-20.

In concept, the DBR for a drilling intrusion has the form

$$\boldsymbol{DBR} = \int_0^{t_e} \boldsymbol{rDBR}(t)\,dt\,, \tag{175}$$

where

DBR = direct brine release volume (m^3) for drilling intrusion,

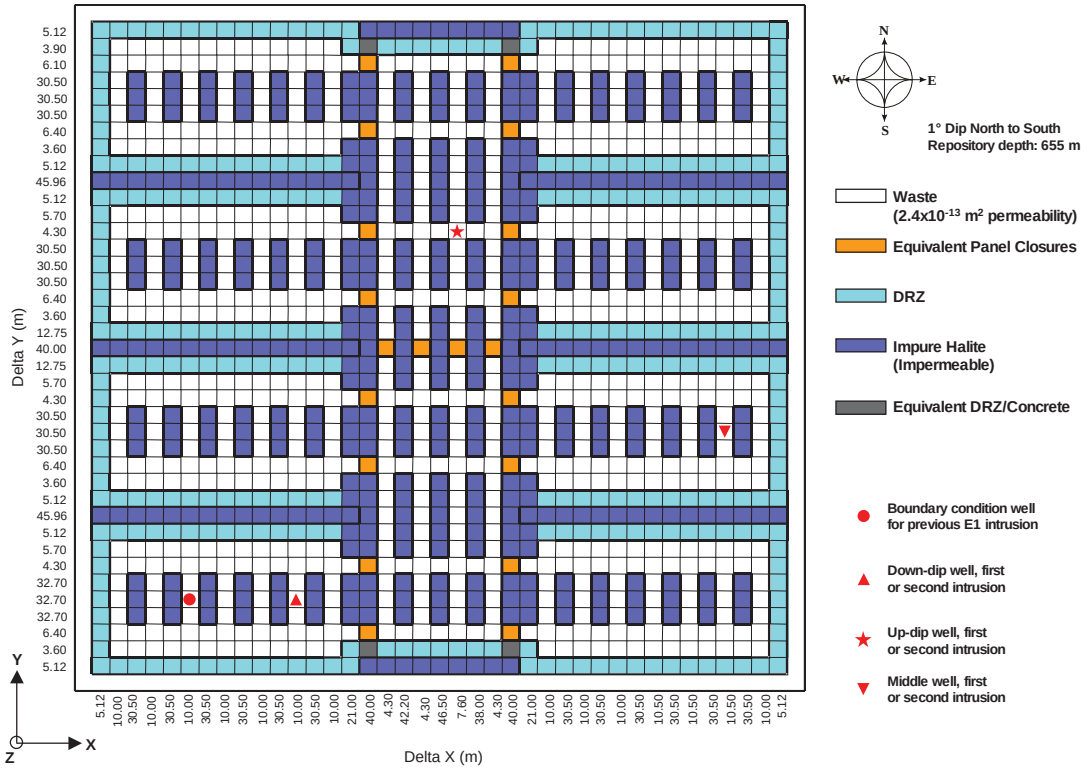

Note: Model cells are not to scale. The actual dimensions of the grid blocks are indicated along the edge of the diagram.

Figure PA-20. DBR Logical Mesh.

$rDBR(t)$ = rate (m^3) at time t at which brine flows up intruding borehole,

t = elapsed time (s) since drilling intrusion,

t_e = time (s) at which direct brine release ends.

The definition of $rDBR(t)$ is discussed in the following sections and is based on the two-phase flow relationships in Equation (25) and use of the Poettmann-Carpenter correlation (Poettmann and Carpenter 1952) to determine a boundary pressure at the connection between the intruding borehole and the repository. The time t_e is based on current drilling practices in the Delaware Basin (Section PA-4.7.8).

PA-4.7.2 Linkage to Two-Phase Flow Calculation

The mesh in Figure PA-20 was linked to the mesh in Figure PA-8 by subdividing the waste disposal area in the mesh in Figure PA-8 into three regions (Figure PA-21). Region 1 represents the northern rest of repository North RoR area in Figure PA-8. Region 2 represents the southern rest of repository South RoR area in Figure PA-8. Region 3 represents the farthest down-dip repository area Waste Panel in Figure PA-8 that contained waste and thus corresponds to the single down-dip waste panel. The linkage between the solutions to

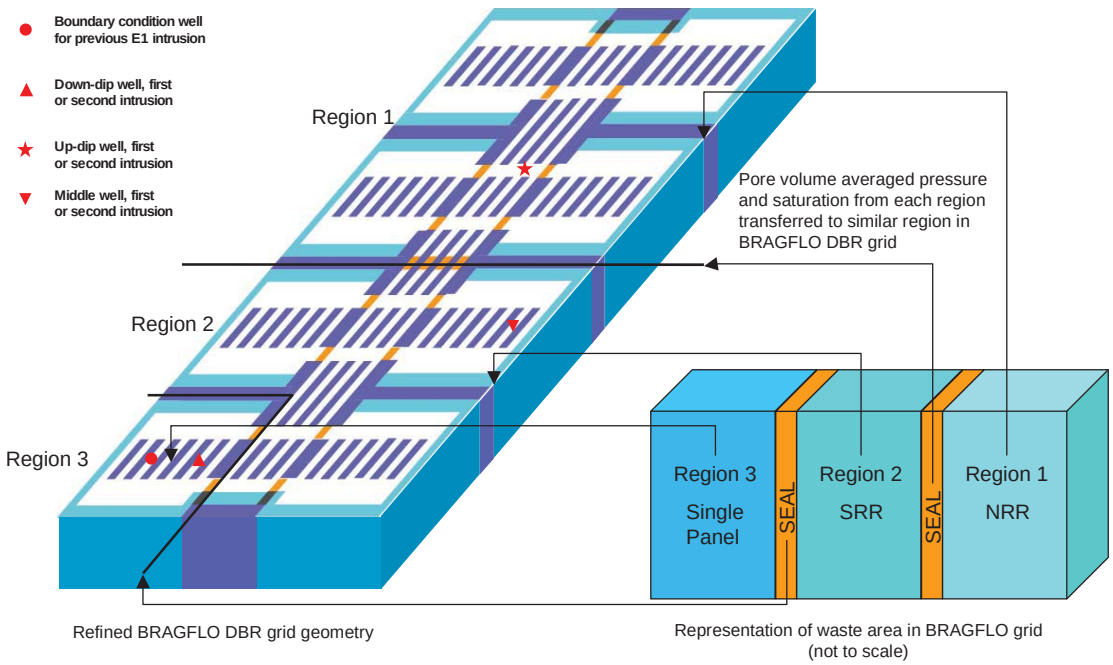

Figure PA-21. Assignment of Initial Conditions for DBR Calculation at Each Intrusion Time.

Equation (25) and the DBR calculations was made by assigning quantities calculated by BRAGFLO for each region in Figure PA-8 to the corresponding waste region in Figure PA-20.

The height of the grid in Figure PA-20 was assigned a value that corresponded to the crushed height h (m) of the waste as predicted by the solution of Equation (25). Specifically,

$$h = h_i \frac{1-\phi_i}{1-\phi}, \tag{176}$$

where h_i and ϕ_i are the initial height (m) and porosity of the waste and ϕ is the volume-averaged porosity of the waste at the particular time under consideration (Section PA-4.2.3). The areas designated equivalent panel closures, DRZ, and impure halite in Figure PA-20 were assigned the same pressures and saturations as the corresponding grid blocks in the 10,000 year BRAGFLO calculations. The area designated equivalent DRZ/concrete (Figure PA-20) was assigned the same pressures and saturations as the DRZ. These areas were assigned porosities that resulted in a conservation of the initial pore volumes used for these areas in the solution of Equation (25) on the grid in Figure PA-8. Specifically, the pore volumes associated with the panel closures, DRZ, and impure halite do not change with time, with this constancy implemented by the definitions of $\varphi(x,y,0)$ in Table PA-15.

The initial brine pressure $p_b(x,y,0)$ and gas saturation $S_g(x,y,0)$ in the grid in Figure PA-20 are assigned by:

$$p_b(x,y,0) = \int_R \tilde{p}_b(\tilde{x},\tilde{y},t_{int})dV / \int_R dV \,, \tag{177}$$

$$S_g(x,y,0) = \int_R \tilde{S}_g(\tilde{x},\tilde{y},t_{int})dV / \int_R dV \,, \tag{178}$$

where (x,y) designates a point in the grid in Figure PA-20, $\tilde{p}_b$ and $\tilde{S}_g$ denote solutions to Equation (25), $\tilde{x}$ and $\tilde{y}$ denote the variables of integration, tint is the time at which the drilling intrusion occurs, and R corresponds to the region in the computational grid for BRAGFLO (Figure PA-8) that is mapped into the region in the computational grid for BRAGFLO for DBR (Figure PA-20) that contains the point (x,y) (Figure PA-21). Note that t_{int} defines a time in the solution of Equation (25); t = 0 defines the start time for the DBR calculation and corresponds to t_{int} in the solution of Equation (25).

The initial porosity $\phi(x,y,0)$ in the grid in Figure PA-20 is set by the equations listed in Table PA-15. In Table PA-15, hi is initial height of waste panels (3.96 m), $\phi_{WP,i}$ is initial porosity of waste panels (0.848), $h(t_{int})$ is height of repository at time of intrusion (typically 1 to 1.5 m; corresponds to h in Equation (25)), $h_{DRZ,i}$ is initial height for DRZ (43.60 m) that results in DRZ in Figure PA-20 having the same pore volume as the initial pore volume of the DRZ in Figure PA-8, A_{DRZ} is area associated with DRZ in Figure PA-20, and $\phi_{DRZ,i}$ is initial porosity of DRZ (see Table PA-2). The quantity $h_{DRZ,i} \times A_{DRZ} \times \phi_{DRZ,i}$ is equal to pore volume of DRZ above and below the waste filled regions in Figure PA-8. In Table PA-15, the term ϕ_C is the porosity of the panel closure concrete material (CONC_PCS; see Table PA-2), d_1 is the length of the drift/explosion wall portion of the panel closure (32.1 m; see Figure PA-13), and d_2 is the length of the concrete portion of the panel closure (7.9 m; see Figure PA-13). The porosity of the panel closure and the equivalent DRZ/concrete materials are defined as the volume-weighted mean porosity of the component materials; this definition results in the same brine volume within the pore space in each set of panel closures in Figure PA-8 and Figure PA-20. In Table PA-15, $h_{H,i}$ is initial height of undisturbed halite in Figure PA-20, which is arbitrarily taken to be 8.98 m. However, this value is unimportant because of the extremely low permeability of the undisturbed halite (~3.16×10^{-23} m^2); any brine in the halite could not flow into the waste over the short time period of the DBR calculation, so no effort was made to preserve halite pore volume when mapping from the computational grid in Figure PA-8 to the computational grid in Figure PA-20. The quantity $\phi_{H,i}$ is initial porosity of halite (HALPOR, see Table PA-17).

PA-4.7.3 Conceptual Representation for Flow Rate rDBR(t)

The driving force that would give rise to the DBR is a difference between waste panel pressure, p_w (Pa), and the flowing bottomhole pressure in the borehole, p_{wf} (Pa) at the time of the intrusion. The flowing bottomhole pressure p_{wf}, defined as the dynamic pressure at the

Table PA-15. Initial Porosity in the DBR Calculation

Grid region	Initial Porosity $\varphi(x, y, 0)$
Waste	$1 - h_i \dfrac{1 - \phi_{WP,i}}{h(t_{\mathrm{int}})}$
Panel Closures	$\dfrac{\phi_C d_2 + d_1 \left[1 - h_i \left(1 - \phi_{WP,i} \right) / h(t_{int}) \right]}{d_1 + d_2}$
DRZ	$\dfrac{h_{DRZ,i} \phi_{DRZ,i}}{h(t_{int})}$
Impure Halite	$\dfrac{h_{H,i} \phi_{H,i}}{h(t_{int})}$
Equivalent DRZ/Concrete	$\dfrac{\phi_C d_1 + \phi_{DRZ,i} d_2}{d_1 + d_2}$

inlet of the intruding borehole to the waste panel, is less than the static pressure p_w due to elevation, friction and acceleration effects. The rate at which brine and gas are transported up the intruding borehole is determined by the difference $p_w - p_{wf}$ and a productivity index J_p for the intruded waste panel (Mattax and Dalton 1990, p. 79):

$$q_p(t) = J_p \left[p_w(t) - p_{wf} \right], \tag{179}$$

where

$q_p(t)$ = flow rate (m^3/s) at time t for phase p (p = b ~ brine, p = g ~ gas),

J_p = productivity index ($m^3/Pa \cdot s$) for phase p

and p_w and p_{wf} are defined above. As indicated by the inclusion/exclusion of a dependence on t, the terms J_p and p_{wf} are constant during the determination of $q_p(t)$ for a particular drilling intrusion in the present analysis, and $p_w(t)$ changes as a function of time. In concept, the DBR is given by

$$DBR = \int_0^{t_e} rDBR(t)\,dt = \int_0^{t_e} J_b \left[p_w(t) - p_{wf} \right] dt, \tag{180}$$

once J_p, p_w and p_{wf} are determined. Section PA-4.7.4 discusses the determination of J_p; Section PA-4.7.5 presents the numerical determination of p_w and DBR; and the determination of

p_{wf} is discussed in Section PA-4.7.6. The associated gas release is given by the corresponding integral with J_g rather than J_b. In the computational implementation of the analysis, DBR is determined as part of the numerical solution of the system of partial differential equations that defines p_w (Section PA-4.7.5).

PA-4.7.4 Determination of Productivity Index J_p

In a radial drainage area with uniform saturation, which is assumed to be valid throughout the DBR, the following representation for J_p can be determined from Darcy's law (Mattax and Dalton 1990, p. 79; Williamson and Chappelear 1981; Chappelear and Williamson 1981):

$$J_p = \frac{2\pi\pi k_{rp} h}{\mu_p \left[\ln(r_e / r_w) + s + c \right]}, \tag{181}$$

where

k = absolute permeability (assumed to be constant through time at 2.4×10^{-13} m^2),

k_{rp} = relative permeability to phase p (calculated with modified Brooks-Corey model in Equation (32) and brine and gas saturations, S_b and S_g, obtained by mapping solutions of Equation (25) obtained with grid in Figure PA-8 onto grid in Figure PA-20),

h = crushed panel height (Equation (176)),

μ_p = viscosity of fluid phase (assumed to be constant through time with $\mu_b = 1.8 \times 10^{-3}$ Pa·s, and $\mu_g = 8.92 \times 10^{-6}$ Pa·s (Kaufmann 1960)),

r_e = external drainage radius (for use with the rectangular grid-blocks in Figure PA-20, r_e is taken to be the equivalent areal radius; see Equation (182)),

r_w = wellbore radius (assumed to be constant through time at 0.1556 m (Table 14.7, Gatlin 1960)),

c = –0.50 for pseudo steady-state flow,

s = skin factor, which is used to incorporate flow stimulation caused by spallings release (see Equation (183)).

In the present analysis,

$$r_e = \sqrt{(\Delta\Delta x)(\Delta y)/}, \tag{182}$$

where Δx is the x-dimension (m) and Δy is the y-dimension (m) of the grid block containing the down-dip well in Figure PA-20 (Δx = 10 m and Δy = 32.7 m).

The skin factor s is derived from the spallings release through the following petroleum engineering well testing relationship (pp. 5-7, Lee 1982):

$$s = \left(\frac{k}{k_s} - 1\right) \ln\left(\frac{r_s}{r_w}\right), \tag{183}$$

where

k_s = permeability (m^2) of an open channel as a result of spallings releases (assumed to be infinite),

r_s = effective radius (m) of the wellbore with the spalled volume removed.

In the CCA PA, the effective radius r_s was obtained by converting the spalled volume release V_i into a cylinder of equal volume, then computing the radius of the cylinder. The area of the cylinder A_i is

$$A_i = \frac{V_i}{h_i}. \tag{184}$$

Then,

$$r_s = \sqrt{A_i / \pi} \tag{185}$$

and substitution of r_s into Equation (183) with $k_s = \infty$ yields

$$s = -\ln\left[\frac{\sqrt{A_i / \pi}}{r_w}\right]. \tag{186}$$

For the CRA-2004 PA, calculation of the skin factor was simplified by assuming that the spalled volume, V_i, would be equal to 4 m^3 for all intrusions. This assumption was made only for the calculation of the skin factor to determine DBRs. This assumption is conservative since it will overestimate the well productivity index and consequently overestimate DBRs for all intrusions where the spalled volume is less than 4 m^3.

PA-4.7.5 Determination of Waste Panel Pressure $p_w(t)$ and Direct Brine Release

The repository pressure $p_w(t)$ in Equation (180) after a drilling intrusion is determined with the same system of nonlinear partial differential equations discussed in Section PA-4.2. These equations are solved numerically by the code BRAGFLO used with the computational grid in

Figure PA-20 and assumptions (i.e., parameter values, initial value conditions, and boundary value conditions) that are appropriate for representing brine flow to an intruding borehole over a relatively short time period immediately after the intrusion (i.e., 3 – 11 days). Due to the short time periods under consideration, the model for DBR does not include gas generation due to either corrosion or microbial action and also does not include changes in repository height due to creep closure. Furthermore, to stabilize the calculation and thus allow longer time steps in the numerical solution, the capillary pressure was assigned a value of 0 Pa in all modeled regions (Figure PA-20); in the analysis of the full system in Section PA-4.2, capillary pressure had a value of 0 Pa in the waste regions and the DRZ but a nonzero value in the panel closures (Table PA-3). Use of a capillary pressure of 0 Pa results in the brine pressure $p_b(x,y,t)$ and the gas pressure $p_g(x,y,t)$ being equal, with the pressure $p_w(t)$ in Equation (180) given by

$$p_w(t) = p_b(x,y,t). \tag{187}$$

Although the determination of DBR can be conceptually represented by the integral in Equation (175), in the numerical implementation of the analysis, DBR is determined within the numerical solution of the system of partial differential equations that defines $p_b(x,y,t)$.

With the specific assumptions for DBR, Equation (25) becomes:

Gas Conservation
$$\nabla \bullet \left[\frac{\alpha \rho_g K_g k_{rg}}{\mu_g} \left(\nabla p_g + \rho_g g \nabla h \right) \right] = \alpha \frac{\partial \left(\phi \rho_g S_g \right)}{\partial t}, \tag{188a}$$

Brine Conservation
$$\nabla \bullet \left[\frac{\alpha \rho_b K_b k_{rb}}{\mu_b} \left(\nabla p_b + \rho_b g \nabla h \right) \right] = \alpha \frac{\partial \left(\phi \rho_b S_b \right)}{\partial t}, \tag{188b}$$

Saturation Constraint
$$S_g + S_b = 1, \tag{188c}$$

Capillary Pressure Constraint
$$p_g - p_b = 0, \tag{188d}$$

Gas Density ρ_g determined by Redlich-Kwong-Soave equation of state (Equation (45)) (188e)

Brine Density
$$\rho_b = \rho_0 \exp\left[\beta_b \left(p_b - p_{b0} \right) \right], \tag{188f}$$

Formation Porosity
$$\phi = \phi_0 \exp\left[\beta_f \left(p_b - p_{b0} \right) \right], \tag{188g}$$

with all symbols having the same definitions as in Equation (25).

The primary differences between the BRAGFLO calculations described in Section PA-4.2 and the BRAGFLO calculations described in this section are in the computational meshes used (Figure PA-20 and Figure PA-8), the initial values used (Table PA-2 and Section PA-4.7.2), and the boundary conditions used (Table PA-16). In particular, brine and gas flow associated with

intruding boreholes in the DBR calculations are incorporated by the appropriate assignment of boundary conditions. Specifically, brine flow up an intruding borehole is incorporated into Equation (188) by using the Poettmann-Carpenter wellbore model to determine the pressure at the outflow point in a waste panel (Figure PA-20), with this pressure entering the calculation as a boundary value condition (Table PA-16). The details of this determination are discussed in Section PA-4.7.6. Further, for calculations that assume a prior E1 intrusion, the effects of this intrusion are also incorporated into the analysis by specifying a pressure specified as a boundary condition (Table PA-16). The determination of this pressure is discussed in Section PA-4.7.6.

Table PA-16. Boundary Conditions for p_b and S_g in DBR Calculations

(x, y) on Upper (Northern) or Lower (Southern) Boundary in Figure PA-20, $0 \le t$	
$\left(\nabla p_g + \rho_g g \nabla h\right)\Big\vert_{(x,y,t)} \cdot j = 0 \;\; Pa/m$	no gas flow condition
$\left(\nabla p_b + \rho_b g \nabla h\right)\Big\vert_{(x,y,t)} \cdot j = 0 \;\; Pa/m$	no brine flow condition
(x, y) on Right (Eastern) or Left (Western) Boundary in Figure PA-20, $0 \le t$	
$\left(\nabla p_g + \rho_g g \nabla h\right)\Big\vert_{(x,y,t)} \cdot i = 0 \;\; Pa/m$	no gas flow condition
$\left(\nabla p_b + \rho_b g \nabla h\right)\Big\vert_{(x,y,t)} \cdot i = 0 \;\; Pa/m$	no brine flow condition
(x, y) at Location of Drilling Intrusion under Consideration (see indicated points in Figure PA-20), $0 \le t$	
$P_b(x, y, t) = P_{wf}$ (see Section PA.4.7.6)	constant pressure condition
(x, y) at Location of Prior Drilling Intrusion into Pressurized Brine (see indicated point in Figure PA-20), $0 \le t$	
$P_b(x, y, t) = P_{wE1}$ (see Section PA.4.7.7)	constant pressure condition

For perspective, the following provides a quick comparison of the assumptions that underlie the solution of Equation (25) on the mesh in Figure PA-8 (i.e., the BRAGFLO mesh) and the solution of Equation (188) on the mesh in Figure PA-20 (i.e., the BRAGFLO mesh for DBR):

1. The BRAGFLO mesh for DBR is defined in the areal plane with the z-dimension (height) one element thick; the BRAGFLO mesh is defined as a cross-section, with multiple layers in height and the thickness (y-dimension) one element thick.

2. The BRAGFLO mesh for DBR uses constant thickness, while BRAGFLO uses rectangular flaring to account for three-dimensional volumes in a two-dimensional grid (Figure PA-9).

3. The BRAGFLO mesh for DBR represents flow only in the waste area. The BRAGFLO model includes the surrounding geology as well as the entire WIPP excavation (including operations, experimental, and shaft regions).

4. Local scale heterogeneities are included in the BRAGFLO mesh for DBR, including the salt pillars, rooms, panel closures, and passageways that contain waste. These are not fully represented in the BRAGFLO mesh.

5. The DRZ is included in both models, but exists above and below the excavated regions in the BRAGFLO model, whereas the DRZ surrounds the waste rooms on the sides of the BRAGFLO mesh for DBR.

6. Both models include a one-degree formation dip through the excavated regions (Equation (27)).

PA-4.7.6 Boundary Value Pressure p_{wf}

The boundary value pressure p_{wf} at the inlet of the intruding borehole is defined by a system of equations of the following form:

$$\frac{dp}{dh} = G\left(q_b\left[p(0)\right], q_g\left[p(0)\right], p(h), h\right), \quad 0 \le h \le 655m\,, \tag{189a}$$

$$p(655) = 1.013 \times 10^5 \ Pa\,, \tag{189b}$$

$$q_b\left[p(0)\right] = J_b\left[p_w - p(0)\right], \tag{189c}$$

$$q_g\left[p(0)\right] = J_g\left[p_w - p(0)\right], \tag{189d}$$

where $p(h)$ is pressure (Pa) at elevation h (m) in the borehole with h = 0 m corresponding to the entry point of the borehole into the waste panel and h = 655 m corresponding to the land surface (Figure PA-22), G is a function (Pa/m) characterizing the change of pressure with elevation in the borehole, $p(655)$ is an initial value condition requiring that pressure at the land surface (i.e., the outlet point of the borehole) be equal to atmospheric pressure, $q_b\left[p(0)\right]$ and $q_b\left[p(0)\right]$ define brine and gas flow rates (m^3/s) into the borehole, J_b and J_g are productivity indexes (m^3/Pa s) (see Equation (181)), and p_w is the pressure (Pa) in the repository at the time of the drilling intrusion.

The boundary value pressure p_{wf} is defined by

$$p_{wf} = p(0)\,. \tag{190}$$

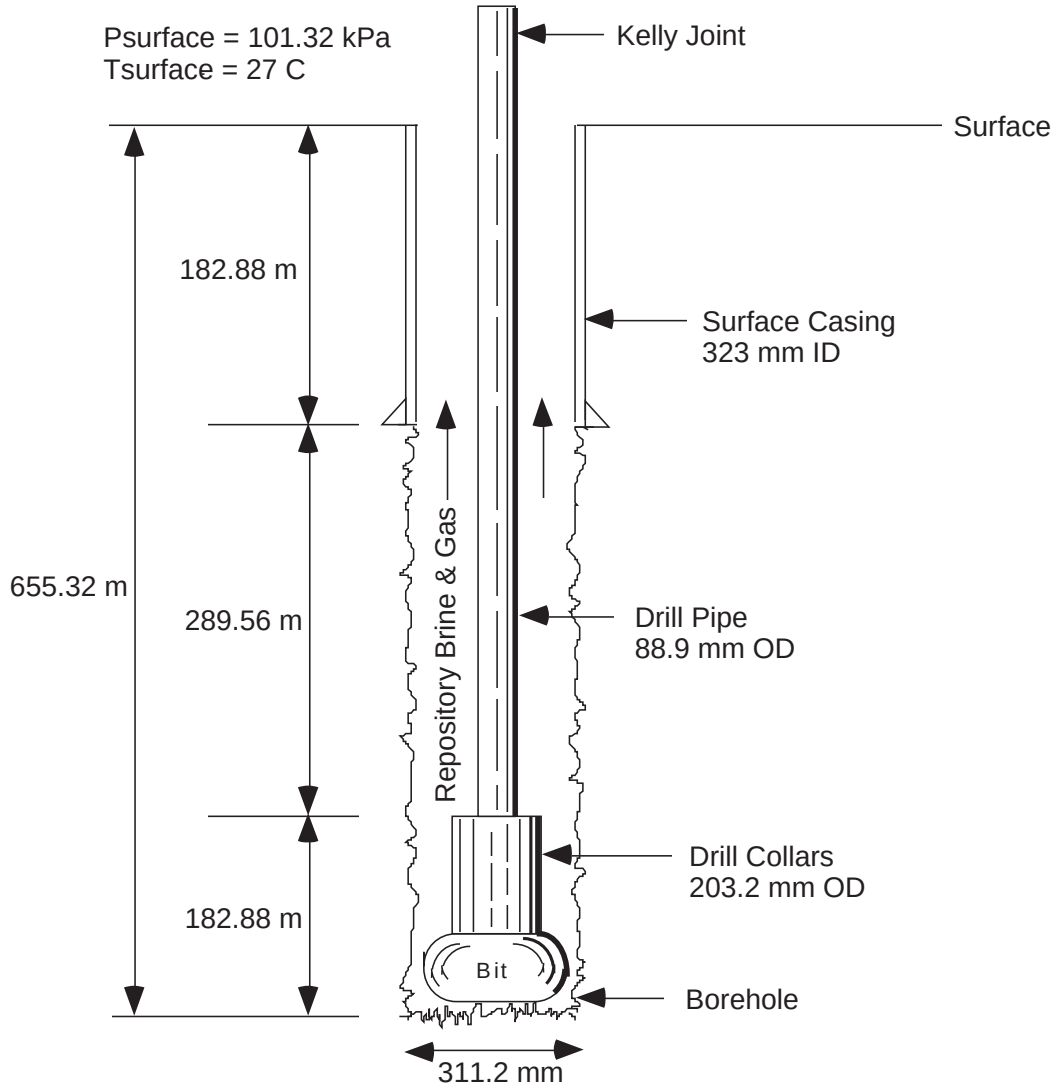

Figure PA-22. Borehole Representation Used for Poettmann-Carpenter Correlation.

Thus, p_{wf} is determined by the numerical solution of Equation (189a) for $\boldsymbol{p}(\boldsymbol{0})$ subject to the constraints in Equation (189b), Equation (189c) and Equation (189d).

The pressure p_w corresponds to the pressure $\boldsymbol{p_w}(\boldsymbol{0})$ in Equation (187) and is obtained from the solution of Equation (25) with the computational grid in Figure PA-8 (see Section PA-4.7.2). The production indexes J_b and J_g are defined in Equation (181). Thus, the only quantity remaining to be specified in Equation (189) is the function G.

Brine and gas flow up a borehole is governed by complex physics dependent on frictional effects and two-phase fluid properties. This phenomenon has been widely studied in the petroleum industry and many modeling procedures have been developed to predict flow rates and pressures in vertical two-phase pipe flow (i.e., to define G in Equation (189a)) (Brill and Beggs 1986). For this analysis, the Poettmann-Carpenter model (Poettmann and Carpenter 1952, Welchon et al.

1962) was used to define G because it accounts for multiphase frictional effects based on empirical (i.e., field) data from flowing wells, is one of the few modeling approaches that included annular flow data in its development, and is relatively easy to implement. Specifically, the Poettmann-Carpenter model defines G by:

$$G\left(q_b\left[p(0)\right], q_g\left[p(0)\right], p(h), h\right) = gm(h) + f'\left(m(h), D(h), q_b\left[p(0)\right]\right) gm(h) F^2(h) / D^5(h), \quad (191)$$

where

g = acceleration due to gravity (9.8 m/s^2),

m(h) = density (kg/m^3) of fluids (i.e., gas and brine) in wellbore at elevation h (Note: ***m(h)*** is a function of $q_b\left[p(0)\right]$ and $q_g\left[p(0)\right]$; see Equation (192), below),

$f'\left\{m(h), D(h) q_b\left[p(0)\right]\right\}$ = empirically defined scale factor (m/s^2) (Note: f' is the scale factor in the Poettmann-Carpenter model for fluid flow in a wellbore [Poettmann and Carpenter 1952]; see discussion below),

$F(h)$ = flow rate (m^3/s) of fluids (i.e., gas and brine) in wellbore at elevation h (Note: $F(h)$ is a function of $q_b\left[p(0)\right]$ and $q_g\left[p(0)\right]$; see Equation (193), below),

$D(h)$ = effective diameter (m) of wellbore (see Equation (196), below).

The first term, $gm(h)$, in Equation (191) results from the contribution of elevation to pressure; the second term results from frictional effects (Poettmann and Carpenter 1952). The fluid density $m(h)$ at elevation h is given by

$$m(h) = \frac{q_b\left[p(0)\right]\rho_b\left[p(0)\right] + q_g\left[p(0)\right]\rho_g\left[p(0)\right]}{F(h)}, \quad (192)$$

where

$$F(h) = q_b\left[p(0)\right] + \frac{z(h)\,p(h)}{p(0)} q_g\left[p(0)\right], \quad (193)$$

and

$\rho_b\left[p(0)\right]$ = density (kg/m^3) of brine at pressure $p(0)$ and temperature 300.1°K, which is fixed at 1230 kg/m^3,

$\rho_g\,[p(0)]$ = density (kg/m^3) of H_2 at pressure $p(0)$ and temperature 300.1°K (see Equation (194), below),

$z(h)$ = z-factor for compressibility of H_2 at elevation h (Note: $z(h)$ is a function of $p(h)$; see Equation (195), below), and $q_g\,[p(0)]$ and $q_g\,[p(0)]$ are defined in Equation (189).

The gas density in Equation (192) is obtained from the universal gas law, PV = nRT, by

$$\rho_g\,[p(0)] = C_{m,\,kg}\,\frac{n}{V} = C_{m,\,kg}\,\frac{P}{RT}, \tag{194}$$

where n is the amount of gas (mol) in a volume V, $C_{m,kg}$ is the conversion factor from moles to kilograms for H_2 (i.e., 2.02×10^{-3} kg/mol), $P = p(0)$, R = 8.3145 kg m^2/mol°K s^2, and T = 300.1°K. The z-factor is given by

$$z(h) = 1 + (8.54 \times 10^{-8}\ Pa^{-1})\,p(h), \tag{195}$$

and was obtained from calculations performed with the SUPERTRAPP program (Ely and Huber 1992) for pure H_2 and a temperature of 300.1°K (Stoelzel and O'Brien 1996, Figure 4.7.4). The preceding approximation to $z(h)$ was obtained by fitting a straight line between the results for pressures of 0 psi and 3000 psi and a hydrogen mole fraction of 1 in Stoelzel and O'Brien (1996, Figure 4.7.4); the actual calculations used the more complex, but numerically similar, regression model given in Stoelzel and O'Brien (1996, Figure 4.7.4). The numerator and denominator in Equation (192) involve rates, with the time units canceling to give $m(h)$ in units of kg/m^3.

The effective diameter $D(h)$ in Equation (191) is defined with the hydraulic radius concept. Specifically,

$$D^5(h) = [D_0(h) + D_i(h)]^2\,[D_0(h) - Di/(h)]^3, \tag{196}$$

where $D_i(h)$ and $D_0(h)$ are the inner and outer diameters (m) of the wellbore at elevation $h(m)$ (see Figure PA-22). The factor f' in Equation (191) is a function of $m(h)$, $D(h)$ and $q_g\,[p(0)]$.

In the original development by Poettmann and Carpenter (1952, Figure 4), f' is defined in terms of quantities commonly used to measure production from oil and gas wells. The result is that f' is expressed in quantities that are unfamiliar outside of the oil and gas industry. For clarity, Equation (191) and the quantities contained in it are expressed in SI units. However, to allow use of the original correlations developed by Poettmann and Carpenter to define f', the calculations within the CCA PA (Stoelzel and O'Brien 1996) were performed in the same oilfield units originally used by Poettmann and Carpenter (1952).

Subsequent to submittal of the CCA PA, it was discovered that the factor of 2π was omitted from Equation (181). This error was determined to be of no consequence to the conclusions of the CCA PA (Hadgu et al. 1999) and has been corrected in the CRA-2004 PA. As a consequence of the error correction, the regression models used to determine the boundary pressure p_{wf} were recalculated (Hadgu et al. 1999). The corrected regression models are reported in this appendix.

The following iterative procedure based on bisection method was used to approximate solutions to Equation (189).

Step 1. Estimate $p(0)$ using a bisection algorithm. (Initial guess for $p(0)$ is the midpoint $\frac{1}{2}p_w$ of interval $[0, p_w]$, where p_w is the pressure in the repository at the time of the drilling intrusion used in Equation (189)). Next guess for $p(0)$ is at the midpoint of either $\left[0, \frac{1}{2}p_w\right]$ or $\left[\frac{1}{2}p_w, p_w\right]$ depending on whether resultant approximation to $p(655)$ is above or below atmospheric pressure. Subsequent guesses for $p(0)$ are made in a similar manner.

Step 2. Use $p(0)$, known values for J_b, J_g and p_w, and Equation (189) to determine $q_b[p(0)]$ and $q_g[p(0)]$.

Step 3. Use the bisection method with Δh = 25 ft = 7.62 m and appropriate changes in annular diameter (Figure PA-22) to determine $p(655)$ (i.e., $p(h+\Delta h) = p(h) + G\left(q_b[p(0)], q_g[p(0)], p(h), h\right)\Delta h$).

Step 4. Stop if $p(655)$ is within 0.07% of atmospheric pressure (i.e., if $\left|1.013\times 10^5\ Pa - p(655)\right| \le 70\ Pa$). Otherwise, return to Step 1 and repeat process.

The preceding procedure is continued until the specified error tolerance (i.e., 0.07percent) has been met. The computational design of the PA has the potential to require more than 23,000 separate DBR calculations (3 replicates × 5 scenarios × 3 drilling locations × 100 vectors × 5 to 6 intrusion times per scenario). In concept, each of these cases requires the solution of Equation (189) with the iterative procedure just presented to obtain the boundary value condition $p_{wf} = p(0)$ (Table PA-16). To help hold computational costs down, $p(0)$ was calculated for approximately 2000 randomly generated vectors of the form

$$v = \left[p_w, h, S_{br}, S_{gr}, S_b, A_i\right], \tag{197}$$

where p_w is the repository pressure (used in definition of $q_b\left[p(0)\right]$ and $q_g\left[p(0)\right]$ in Equation (189)), h is the crushed height of the repository (used in definition of J_p in Equation (181)), S_{br} and S_{gr} are the residual saturations for gas and brine in the repository (used in definition of k_{rp} in Equation (181)), S_b is the saturation of brine in the repository (used in definition of k_{rp} in Equation (181)), and A_i is the equivalent area of material removed by spallings (used in definition of skin factor s in Equation (186)). The outcomes of these calculations were divided into three cases:

1. mobile brine only (i.e., $k_{rg} = 0$ in Equation (188a))
2. brine-dominated flow (i.e., $k_{rb} > k_{rg}$), and
3. gas-dominated flow (i.e., $k_{rg} > k_{rb}$).

Then, regression procedures were used to fit algebraic models that can be used to estimate $p(0)$. These regression models were then used to determine $p(0)$, and hence p_{wf}. The resulting three regression models (or curve fit equations) for flowing bottomhole pressure (p_{wf}) are as follows.

1. For a system with only mobile brine (i.e., $k_{rg} = 0$)

$$p_{wf} = a + bx + cy + dx^2 + ey^2 + fxy + gx^3 + hy^3 + ixy^2 + jx^2y\,, \qquad (198a)$$

where $x = \mathbf{log}\left(J_b\right)$ and $y = p_w$ (= repository pressure). The coefficients in Equation (198a) were determined to be:

$$\begin{aligned}
a &= 3.2279346 \times 10^{11},\\
b &= 9.4816648 \times 10^{10},\\
c &= -6.2002715 \times 10^{3},\\
d &= 9.2450601 \times 10^{9},\\
e &= 4.1464475 \times 10^{-6},\\
f &= -1.2886068 \times 10^{3},\\
g &= 2.9905582 \times 10^{8},\\
h &= 1.0857041 \times 10^{-14},\\
i &= 4.7119798 \times 10^{-7},\\
j &= -6.690712 \times 10^{-1},
\end{aligned}$$

with resulting coefficient of determination $R^2 = 0.974$.

2. For brine dominated flow ($k_{rb} > k_{rg}$):

$$Pwf = \frac{a + bx + cx^2 + dy}{1 + ex + fx^2 + gx^3 + hy}, \tag{198b}$$

where $x = \log\left(\frac{k_{rg}}{k_{rb}}\right)$ and $y = p_w$ (= repository pressure). The coefficients in Equation (198b) were determined to be:

a = 1.6065077×10^{6},
b = 2.6243397×10^{6},
c = 2.4768899×10^{6},
d = $-5.3635476 \times 10^{-2}$,
e = 7.0815693×10^{-1},
f = 3.8012696×10^{-1},
g = 4.1916956×10^{-3},
h = $-2.4887085 \times 10^{-8}$,

with resulting coefficient of determination $R^2 = 0.997$.

3. For gas dominated flow ($k_{rg} > k_{rb}$):

$$p_{wf} = a + b\frac{1}{x} + cy + d\frac{1}{x^2} + ey^2 + f\frac{x}{y} + g\frac{1}{x^3} + hy^3 + i\frac{y^2}{x} + j\frac{y}{x^2}, \tag{198c}$$

where $x = \log\left(J_g\right)$ and $y = p_w$ (= repository pressure). The coefficients in Equation (198c) were determined to be:

a = -1.0098405×10^{9},
b = $-2.3044622 \times 10^{10}$,
c = 9.8039146,
d = $-1.7426466 \times 10^{11}$,
e = 1.8309137×10^{-7},
f = 1.7497064×10^{2},
g = $-4.3698224 \times 10^{11}$,
h = $-1.4891198 \times 10^{-16}$,
i = 1.3006196×10^{-6},
j = 7.5744833×10^{2},

with resulting coefficient of determination $R^2 = 0.949$.

PA-4.7.7 Boundary Value Pressure p_{wE1}

Some of the calculations for DBR are for a drilling intrusion that has been preceded by an E1 intrusion in either the same waste panel, an adjacent waste panel, or a nonadjacent waste panel (Section PA-6.7.5). The effects of these prior E1 intrusions are incorporated into the solution of Equation (188), and hence into the DBR, by the specification of a boundary pressure p_{wE1} at the location of the E1 intrusion into the repository (Table PA-16).

Two cases are considered for the definition of p_{wE1}: (1) an open borehole between the brine pocket and the repository, and (2) a borehole between the brine pocket and the repository filled with material with properties similar to silty sand. The first case corresponds to the situation in which the drilling intrusion under consideration has occurred within 200 years of a prior drilling intrusion that penetrated the pressurized brine pocket, and the second case corresponds to the situation in which the drilling intrusion under consideration has occurred more than 200 years after a prior drilling intrusion that penetrated the pressurized brine pocket.

PA-4.7.7.1 Solution for Open Borehole

In this case, p_{wE1} is set equal to the flowing well pressure p_{wfBP} of an open borehole between the brine pocket and the repository and is given by:

$$Q = f_1\left(p_{BP}, p_{wfBP}\right), \tag{199a}$$

$$Q = f_2\left(p_{wfBP}, p_{wfBI}\right), \tag{199b}$$

$$Q = f_3\left(p_{wfBI}, p_{wfBO}\right), \tag{199c}$$

where

pB = pressure (Pa) in brine pocket,

p_{wfBP} = flowing well pressure (Pa) at outlet from brine pocket,

p_{wfBI} = flowing well pressure (Pa) at inlet to repository from brine pocket,

p_{wfBO} = flowing well pressure (Pa) at outlet from repository due to intruding borehole (Note: The boreholes associated with p_{wfBI} and p_{wfBO} arise from different drilling intrusions and hence are at different locations; see Figure PA-20),

Q = brine flow rate (m^3/s) from brine pocket to repository, through repository, and then to surface,

and f_1, f_2 and f_3 are linear functions of their arguments. In the development, p_{BP} and p_{wfBO} are assumed to be known, with the result that Equation (199) constitutes a system of three linear

equations in three unknowns (i.e., p_{wfBP}, p_{wfBI}, Q) that can be solved to obtain p_{wfBI}. In the determination of $p_{wfBI} = p_{wE1}$ for use in a particular solution of Equation (188), p_{BP} is the pressure in the brine pocket at the time of the intrusion obtained from the solution of Equation (25) with BRAGFLO, and p_{wfBO} is the flowing well pressure obtained from conditions at the time of the intrusion (from the solution of Equation (25)) and the solutions of the Poettmann-Carpenter model embodied in Equation (198) (i.e., given pressure, k_{rg} and k_{rb} at the time of the intrusion from the solution of Equation (25) with BRAGFLO and J_b from both the solution of Equation (25) with BRAGFLO and the evaluation of the spallings release (assumed to be a constant of 4 m^3), p_{wfBO} is determined from the regression models indicated in Equation (198).

The definition of Equation (199) is now discussed. Equation (199a) characterizes flow out of the brine pocket into an open borehole and has the form (Williamson and Chappelear 1981, Chappelear and Williamson 1981):

$$Q = \left(\frac{2\pi k_{BP} h_{BP}}{\mu \left[\ln\left(r_{eBP} / r_w \right) - 0.5 \right]} \right) \left(p_{BP} - p_{wfBP} \right), \tag{200}$$

where

k_{BP} = brine pocket permeability (m^2),

h_{BP} = effective brine pocket height (m),

r_{eBP} = effective brine pocket radius (m),

r_w = wellbore radius (m),

μ = brine viscosity (Pa s).

In the present analysis, k_{BP} is an uncertain analysis input (see BHPRM in Table PA-17), h_{BP} = 125.83 m, r_{eBP} = 114 m (Stoelzel and O'Brien 1996), which corresponds to the size of the largest brine pocket that could fit under one waste panel, r_w = (8.921 in.) / 2 = 0.1133 m, which is the inside radius of a 9 5/8 in. outside diameter casing (Gatlin 1960, Table 14.7), $\mu = 1.8 \times 10^{-3}$ Pa s, and p_{BP} is determined from the solution of Equation (25) as previously indicated.

Equation (199b) characterizes flow up an open borehole from the brine pocket to the repository and is based on Poiseuille's Law (Prasuhn 1980, Eqs. 7-21, 7-22). Specifically, Equation (199b) has the form

$$Q = \left[\frac{\pi D^4}{128\mu \left(y_{BP} - y_{rep} \right)} \right] \left[\left(p_{wfBP} - p_{wfBI} \right) + g\rho \left(y_{rep} - y_{BP} \right) \right], \tag{201}$$

where

D = wellbore diameter (m),

y_{rep} = elevation of repository (m) measured from surface,

y_{BP} = elevation of brine pocket (m) measured from surface,

g = acceleration due to gravity (9.8 m/s^2),

ρ = density of brine (kg/m^3),

and the remaining symbols have already been defined.

In the present analysis, $D = 2r_w = 0.2266$ m, $\rho = 1230$ kg/m^3, and $y_{rep} - y_{BP} = 247$ m. With the preceding values,

$$128\mu\left(y_{BP} - y_{rep}\right)\Big/\pi D^4 = 6.87 \times 10^3 \ \ Pa\ s/m^3 \ , \tag{202}$$

$$g\rho\left(y_{rep} - y_{BP}\right) == 2.98 \times 10^6 \ \ Pa \ . \tag{203}$$

Thus,

$$p_{wfBI} = p_{wfBP} - 2.98 \times 10^6 \ \ Pa \ . \tag{204}$$

when Q is small (≤ 0.1 m^3/s). When appropriate, this approximation can be used to simplify the construction of solutions to Equation (199).

Equation (199c) characterizes flow through the repository from the lower borehole to the bottom of the borehole associated with the drilling intrusion under consideration and has the same form as Equation (200). Specifically,

$$Q = \left(\frac{2\pi k_{rep} h_{rep}}{\mu\left[\ln\left(r_{e,rep}/r_w\right) - 0.5\right]}\right)\left(p_{wfBI} - p_{wfBO}\right), \tag{205}$$

where

k_{rep} = repository permeability (m^2),

h_{rep} = repository height (m),

$r_{e,rep}$ = effective repository radius (m),

and the remaining symbols have already been defined. In the present analysis, $k_{rep} = 2.4 \times 10^{-13}\, m^2$; h_{rep} at the time of the drilling intrusion under consideration is obtained from the solution of Equation (25) (see Equation (176)); and $r_{e,rep}$ is the same as the radius r_e defined in Equation (182). As previously indicated, p_{wfBO} is obtained from the solutions to the Poettmann-Carpenter model summarized in Equation (198).

Three equations (i.e., Equation (200), Equation (201) and Equation (205)) in three unknowns (i.e., p_{wfBP}, p_{wfBI} and Q) have now been developed. The solution for p_{wfBI} defines the initial value p_{wE1} in Table PA-16. When the simplification in Equation (204) is used, the resultant solution for p_{wfBI} is

$$p_{wfBI} = \frac{p_{wfBO} + \left(p_{BP} - 2.98 \times 10^6\right) K_1}{1 + K_1}, \tag{206}$$

where

$$K_1 = \frac{k_{BP} h_{BP} \left[\ln\left(\frac{r_{e,rep}}{r_w} \right) - \frac{1}{2} \right]}{k_{rep} h_{rep} \left[\ln\left(\frac{r_{eBP}}{r_w} \right) - \frac{1}{2} \right]}, \tag{207}$$

and -2.98×10^6 comes from Equation (203). The expression in Equation (207) was used to define p_{wE1} in the CCA PA in the determination of DBRs for a drilling intrusion that occurred within 200 years of a preceding E1 intrusion (see Table PA-5). The same approach was used for the CRA-2004 PA.

PA-4.7.7.2 Solution for Sand-Filled Borehole

The determination of the pressure p_{wfBI} with the assumption that a borehole filled with material with properties similar to silty sand connects the brine pocket and the repository is now considered. The approach is similar to that used for the open borehole except that Equation (199a) and Equation (199b) are replaced by a single equation based on Darcy's Law. Specifically, flow from the brine pocket to the repository is represented by

$$Q = \frac{k_{BH} A_{BH} \left[\left(p_{wfBP} - p_{wfBI} \right) + g\rho \right]}{\mu \left(y_{BP} - y_{rep} \right)}, \tag{208}$$

where

k_{BH} = borehole permeability (m^2),

A_{BH} = borehole cross-sectional area (m^2),

and the remaining symbols have been defined previously. In the present analysis, k_{BH} is an uncertain input (see BHPRM in Table PA-17) and A_{BH} is defined by the assumption that the borehole diameter is the same as the drill bit diameter (i.e., 12.25 in. = 0.311 m).

The representation for flow from the brine pocket inlet point to the repository to the outlet point associated with the drilling intrusion under consideration remains as defined in Equation (205). Thus, two equations (i.e., Equation (208) and Equation (205)) and two unknowns (i.e., p_{wfBI} and Q) are under consideration. Solution for p_{wfBI} and yields

$$p_{wfBI} = \frac{p_{wfBO} + K_2 p_{BP} - 2.98 \times 10^6 K_2}{1 + K_2} \tag{209}$$

where

$$K_2 = \frac{\pi k_{BH} r_w^2 \left[\ln\left(\frac{r_{eBP}}{r_w} \right) - \frac{1}{2} \right]}{2\pi h_{rep} k_{rep} \left(y_{BP} - y_{rep} \right)} \tag{210}$$

and -2.98×10^6 comes from Equation (203). The expression in Equation (209) was used to define p_{wE1} in the determination of DBRs for a drilling intrusion that occurred more than 200 years after a preceding E1 intrusion (see Table PA-5).

PA-4.7.8 End of Direct Brine Release

The CRA-2004 PA has 23,400 cases that potentially required solution of Equation (188) to obtain the DBR volume (See Section PA-6.7.5). However, the DBR was set to zero without solution of Equation (188) when there was no possibility of a release (i.e., the intruded waste panel at the time of the intrusion had either a pressure less than 8 MPa or a brine saturation below the residual brine saturation S_{br}).

For the remaining cases, Equation (188) was solved for a time period of 50 days, although the value used for t_e was always less than 50 days. The minimum value used for t_e was three days, which is an estimate of the time required to drill from the repository through the Castile Formation and then cement the intermediate casing. If there is little or no gas flow associated with brine inflow into the borehole during drilling in the Salado Formation, current industry practice is to allow the brine to “seep” into the drilling mud and be discharged to the mud pits until the salt section is cased.

If there is a significant amount of gas flow, then it is possible that the driller will lose control of the well. In such cases, DBRs will take place until the gas flow is brought under control. Two possibilities exist: (1) the driller will regain control of the well when the gas flow drops to a manageable level, and (2) aggressive measures will be taken to shut off the gas flow before it

drops to a manageable level. In the CCA PA, the driller was assumed to be able to regain control of the well when the gas flow dropped to a "cut-off" rate of 1×10^5 standard cubic feet per day (SCF/d in commonly used oil field units). Experience at the South Culebra Bluff Unit #1, which blew out in January 1978, suggests that approximately 11 days may be needed to bring a well under control before the gas flow drops to a manageable level (i.e., 1×10^5 SCF/d) (DOE 1996, Appendix MASS Attachment MASS 16-2). In particular, it took 11 days to assemble the equipment and personnel needed to bring that well under control.

Given the preceding, t_e is defined by

$$t_e = \begin{cases} \max\left\{3\ d, t_f\right\} & \text{if } t_f \le 11\ d \\ 11\ d & \text{if } t_f > 11\ d \end{cases} \tag{211}$$

in the CRA-2004 PA, where t_f is the time at which the gas flow out of the well drops below 1×10^5 SCF/d. As a reminder, gas flow out of the repository in the intruding borehole, and hence t_e, is determined as part of the solution to Equation (188).

PA.-4.7.9 Numerical Solution

As previously indicated, the BRAGFLO program is used to solve Equation (188) with the computational grid in Figure PA-20, the initial value conditions in Section PA-4.7.2, the boundary value conditions in Table PA-16, and parameter values appropriate for modeling DBRs. Thus, the numerical procedures in use for Equation (188) are the same as those described in Section PA-4.2.10 for the solution of Equation (25).

In this solution, the boundary value conditions associated with drilling intrusions (i.e., p_{wf} and pwE1 in Table PA-16) are implemented through the specification of fluid withdrawal terms (i.e., q_{wg} and q_{wb} in Equation (25)) rather than as defined boundary value conditions. With this implementation, the representations in Equation (188a) and Equation (188b) for gas and brine conservation become

$$\nabla \cdot \left[\frac{\alpha \rho_g K_g k_{rg}}{\mu_g} \left(\nabla p_g + \rho_g g \nabla h \right) \right] + \alpha q_{wg} = \alpha \frac{\partial \left(\phi \rho_g S_g \right)}{\partial t} \tag{212a}$$

$$\nabla \cdot \left[\frac{\alpha \rho_b K_b k_{rb}}{\mu_b} \left(\nabla p_b + \rho_b g \nabla h \right) \right] + \alpha q_{wb} = \alpha \frac{\partial \left(\phi \rho_b S_b \right)}{\partial t}, \tag{212b}$$

and the constraints in Equation (188) remain unchanged. As used in Equation (212), q_{wg} and q_{wb} are independent of the computational grid in use (Figure PA-20). In practice, q_{wg} and q_{wb} are defined with a productivity index (see Equation (181)) that is a function of the specific computational grid in use, with the result that these definitions are only meaningful in the context of the computational grid that they are intended to be used with. This specificity results because

q_{wg} and q_{wb} as used in Equation (212) are defined on a much smaller scale than can typically be implemented with a reasonable-sized computational grid. As a result, the values used for q_{wg} and q_{wb} in the numerical solution of Equation (212) must incorporate the actual size of the grid in use.

In the solution of Equation (212) with the computational grid in Figure PA-20, q_{wg} is used to incorporate gas flow out of the repository and q_{wb} is used to incorporate both brine inflow to the repository from a pressurized brine pocket and brine flow out of the repository. For gas flow out of the repository,

$$q_{wg}(x,y,t) = \frac{kk_{rg}(x,y,t)[p_g(x,y,t) - p_{wf}]}{\mu_g[\ln(r_e/r_w) + s + c]}, \tag{213}$$

if (x,y) is at the center of the grid cell containing the drilling intrusion (Figure PA-20) and $q_{wg}(x,y,t)$ = 0 (kg/m^3)/s otherwise, where k, k_{rg}, μ_g, r_e, r_w, s and c are defined in conjunction with Equation (181), p_g is gas pressure, and p_{wf} is the flowing well pressure at the outlet borehole (i.e., the boundary value condition in Table PA-16). The factor h in Equation (181) is the crushed height of the repository as indicated in Equation (176) and defines the factor α in Equation (212). In the numerical solution, $q_{wg}(x,y,t)$ defines $q^{n+1}_{wgi,j}$ in Equation (79), with $q^{n+1}_{wgi,j}$ having a nonzero value only when i, j correspond to the grid cell containing the borehole through which gas outflow is taking place (i.e., the grid cells containing the down-dip and up-dip wells in Figure PA-20).

For brine flow,

$$q_{wb}(x,y,t) = \frac{kk_{rb}(x,y,t)[p_b(x,y,t) - p_{wf}]}{\mu_b[\ln(r_e/r_w) + s + c]}, \tag{214}$$

if (x,y) is at the center of the grid cell containing the drilling intrusion through which brine outflow from the repository is taking place (Figure PA-20);

$$q_{wb}(x,y,t) = \frac{kk_{rb}(x,y,t)[p_{wE1} - p_b(x,y,t)]}{\mu_b[\ln(r_e/r_w) + c]}, \tag{215}$$

if (x,y) is at the center of the grid cell containing a prior drilling intrusion into a pressurized brine pocket (Figure PA-20), where p_{wE1} is the boundary value condition defined in Table PA-16; and $q_{wb}(x,y,t)$ = 0 otherwise. In the numerical solution of Equation (212a), $q_{wb}(x,y,t)$ defines $q^{n+1}_{wbi,j}$ in a discretization for Equation (212b) that is equivalent to the discretization for Equation (212a) shown in Equation (79), with $q^{n+1}_{wbi,j}$ having a nonzero value only when i, j

correspond to the grid cell containing the borehole through which brine outflow is taking place (i.e., the grid cells containing the down-dip and up-dip wells in Figure PA-20, in which case, Equation (214) defines $q_{wbi,j}^{n+1}$ or to the grid cell containing the borehole through which brine inflow to the repository from a pressurized brine pocket is taking place (i.e., the grid cell containing the E1 intrusion in Figure PA-20; in which case, Equation (215) defines $q_{wbi,j}^{n+1}$.

PA-4.7.10 Additional Information

Additional information on BRAGFLO and its use in the CRA-2004 PA to determine DBRs can be found in the analysis package for DBR (Stein 2003) and in the BRAGFLO User's Manual (WIPP PA 2003c).

PA-4.8 Brine Flow in Culebra: MODFLOW

This section describes the model for the calculation of brine flow in the Culebra.

PA-4.8.1 Mathematical Description

Groundwater flow in the Culebra Dolomite is represented by the partial differential equation

$$S\left(\frac{\partial h}{\partial t}\right) = \nabla\cdot\left(bK\nabla h\right) - Q\,, \tag{216}$$

where

S = medium storativity (dimensionless),

h = hydraulic head (m),

t = time (s),

b = aquifer thickness (m),

K = hydraulic conductivity tensor (m/s),

Q = source/sink term expressed as the volumetric flux per unit area ($(m^3/m^2)/s = m/s$).

Further, the Culebra is assumed to be isotropic, and as a result, K is defined by

$$K(x,y) = k(x,y)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \tag{217}$$

where $k(x,y)$ is the hydraulic conductivity (m/s) at the point (x,y). The following simplifying assumptions are also made: fluid flow in the Culebra is at steady state (i.e., $\partial h/\partial t = 0$), and

source and sink effects arising from borehole intrusions and infiltration are negligible (i.e., Q = 0). Given these assumptions, Equation (216) simplifies to

$$\nabla \cdot \left(\boldsymbol{bK} \nabla \boldsymbol{h} \right) = \boldsymbol{0} \,, \tag{218}$$

which is the equation actually solved to obtain fluid flow (i.e., $\boldsymbol{K} \nabla \boldsymbol{h}$) in the Culebra. In the CRA-2004 PA, b = 7.75 m, and $\boldsymbol{k}\left(\boldsymbol{x}, \boldsymbol{y}\right)$ in Equation (217) is a function of an imprecisely known transmissivity field, as discussed in Section PA-4.8.2.

PA-4.8.2 Implementation

The first step in the analysis of fluid flow in the Culebra is to generate transmissivity fields ***t(x, y)*** (m^2/s) for the Culebra and to characterize the uncertainty in these fields. This was accomplished by generating a large number of plausible transmissivity fields. A description of the method used to construct these transmissivity fields is included in Attachment TFIELD. Below, a brief outline of the method is presented.

The transmissivity fields used for the CRA-2004 PA are based on several types of information, including a regression model developed on WIPP-site geologic data, measured head levels in the Culebra for the year 2000, and well drawdown test results. The following steps led to the final transmissivity fields used in this analysis:

Geologic data including: (1) depth to the top of the Culebra, (2) reduction in thickness of the upper Salado Formation by dissolution, and (3) the spatial distribution of halite in the Rustler Formation below and above the Culebra were used to define a geologic regression model that relates transmissivity at any location to a set of geologically defined parameters.

Base transmissivity fields are defined for a modeling domain measuring 22.4 km east-west by 30.7 km north-south using a method of stochastic simulation. The base transmissivity fields were constructed from information on the depth to the Culebra, indicator functions defining the location of Salado dissolution, halite occurrence, and high transmissivity zones.

Seed transmissivity fields are defined by conditioning base transmissivity fields to measured values of transmissivity. This conditioning is performed with a Gaussian geostatistical simulation algorithm.

The seed transmissivity fields are calibrated to transient water level data from the year 2000 in 37 wells across the region using parameter estimation program PEST (Doherty 2002). The PEST program iteratively changes the seed transmissivity field values to minimize an objective function, using MODFLOW to rerun the flow solution between each iteration. The objective function minimized by PEST is a combination of the weighted sum of the squared residuals between the measured and modeled head data and a second weighted sum of the squared differences in the estimated transmissivity between pairs of pilot points. The second weighted sum is designed to keep the transmissivity field as homogeneous as possible and to provide numerical stability when estimating more parameters than there are data.

The calibrated transmissivity fields produced by PEST and MODFLOW are screened according to specific acceptance criteria. Calibrated transmissivity fields that meet the acceptance criteria are modified for the partial and full mining scenarios. This modification increases transmissivity by a random factor between 1 and 1000 in areas identified as containing potash reserves, as described below. Steady-state flow simulations are then run using the mining-modified transmissivity fields.

The transport code SECOTP2D uses a grid with uniform cells of 50 × 50 m. Thus as a final step, MODFLOW runs with a 50 × 50 m grid to calculate the flow fields required for the transport code. The hydraulic conductivities for the finer grid are obtained by dividing each 100 × 100 m cell into four 50 × 50 m cells. The conductivity assigned to each of the four cells is equal to the conductivity of the larger cell (Leigh et al. 2003).

The hydraulic conductivity $\boldsymbol{k}(\boldsymbol{x},\boldsymbol{y})$ in Equation (217) is defined in terms of the transmissivity fields $\boldsymbol{t}(\boldsymbol{x},\boldsymbol{y})$ by

$$\boldsymbol{k}(\boldsymbol{x},\boldsymbol{y}) = \boldsymbol{t}(\boldsymbol{x},\boldsymbol{y})/\boldsymbol{b}\,. \tag{219}$$

Fluid flow (i.e., $\boldsymbol{K}\nabla\boldsymbol{h}$) is determined by solving Equation (218) for two different cases: (1) a partial mining case (mining of potash deposits outside the land withdrawal boundary), and (2) a full mining case (mining of potash deposits inside and outside the land withdrawal boundary) (Figure PA-23). As specified by guidance in 40 CFR Part 194 (p. 5229, EPA 1996), potash mining increases the hydraulic conductivity in the Culebra in the vicinity of such mining by an uncertain factor with a value between 1 and 1000. As specified in 40 CFR § 194.32 and described in Section PA-3.8, economic potash reserves outside the land withdrawal boundary are assumed to have been fully mined by the end of the 100 year-period of active institutional controls, after which the occurrence of potash mining within the land withdrawal boundary follows a Poisson process with a rate constant of $\lambda_m = 1 \times 10^{-4}$ yr^{-1}.

In the partial mining case, the hydraulic conductivity $\boldsymbol{k_{PM}}(\boldsymbol{x},\boldsymbol{y})$ is defined by Equation (219) inside the WIPP boundary and by $\boldsymbol{k_{PM}}(\boldsymbol{x},\boldsymbol{y}) = \boldsymbol{k}(\boldsymbol{x},\boldsymbol{y}) \times \boldsymbol{MF}$ outside the WIPP boundary, where MF is determined by the uncertain parameter CTRANSFM (see Table PA-17). In the full mining case, the hydraulic conductivity $\boldsymbol{k_{FM}}(\boldsymbol{x},\boldsymbol{y}) = \boldsymbol{k}(\boldsymbol{x},\boldsymbol{y}) \times \boldsymbol{MF}$ in all areas of the modeling domain.

In turn, $\boldsymbol{k_{PM}}(\boldsymbol{x},\boldsymbol{y})$ and $\boldsymbol{k_{FM}}(\boldsymbol{x},\boldsymbol{y})$ result in the following definition for the hydraulic conductivity tensor K:

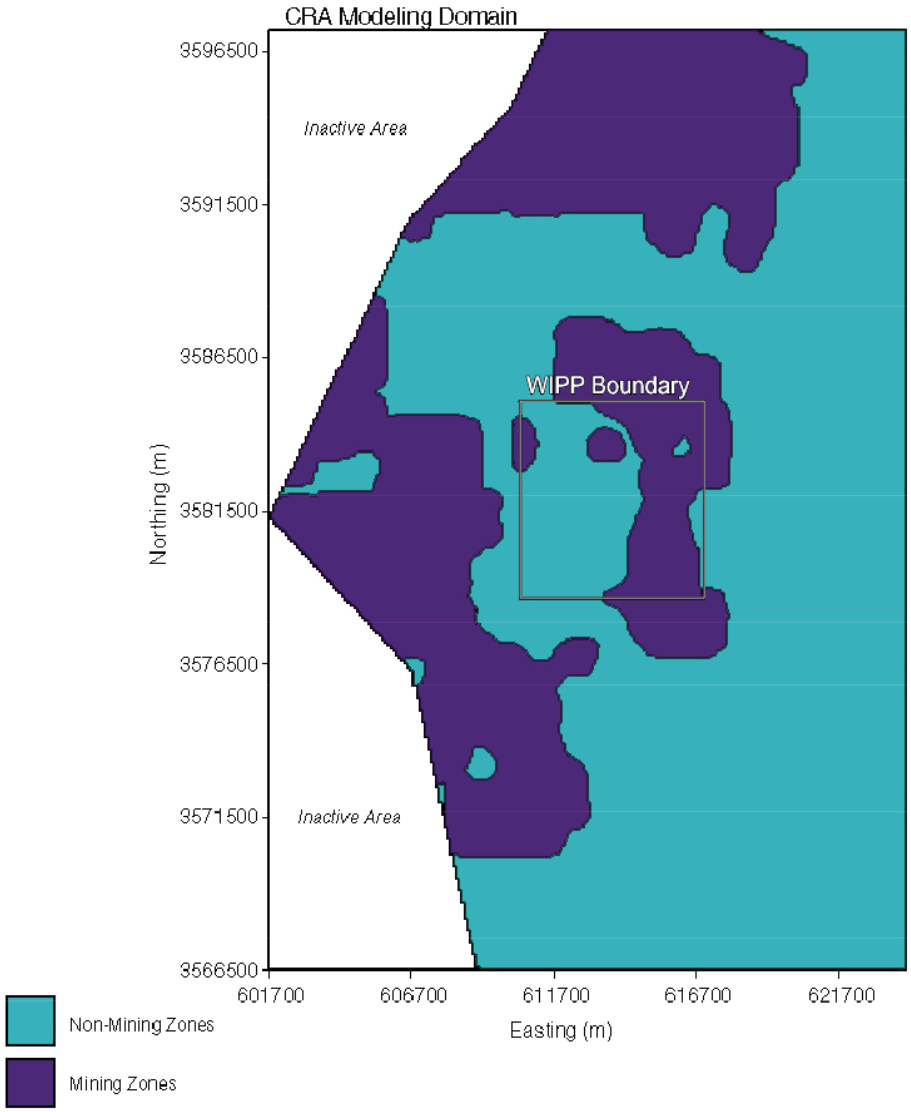

Figure PA-23. Areas of Potash Mining in the McNutt Potash Zone.

$$K_i(x,y) = k_i(x,y)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad i = PM, FM \ . \tag{220}$$

In the analysis, Equation (218) is solved with each of the preceding definitions of K_i to obtain characterizations of fluid flow in the Culebra for partially-mined conditions (i.e., $K_{PM}\nabla h$) and fully-mined conditions (i.e., $K_{FM}\nabla h$).

The determination of fluid flow in the Culebra through the solution of Equation (218) does not incorporate the potential effects of climate change on fluid flow. Such effects are incorporated into the analysis by an uncertain scale factor to introduce the potential effects of climate change

into the analysis (Corbet and Swift 1996a, 1996b). Specifically, the Darcy fluid velocity $\boldsymbol{v_i}(x,y)$ actually used in the radionuclide transport calculations is given by

$$\boldsymbol{v_i}(x,y) = \left[u_i(x,y), v_i(x,y)\right] = SFC\left[\boldsymbol{K_i}(x,y)\nabla h_i(x,y)\right]^T, \tag{221}$$

where $u_i(x,y)$ and $v_i(x,y)$ represent Darcy fluid velocities (m/s) at the point (x,y) in the x and y directions, respectively, $\nabla h_i(x,y)$ is obtained from Equation (218) with $\boldsymbol{K} = \boldsymbol{K_i}$, and SFC is a scale factor used to incorporate the uncertainty that results from possible climate changes. The scale factor SFC is determined by the uncertain parameter CCLIMSF (see Table PA-17).

PA-4.8.3 Computational Grids and Boundary Value Conditions

The representation for fluid flow in the Culebra in Equation (218) is evaluated on a numerical grid 22.4 km east-west by 30.7 km north-south, aligned with the compass directions (Figure PA-24). The modeling domain is discretized into 68,768 uniform 100-m × 100-m cells. The northern model boundary is slightly north of the northern end of Nash Draw, 12 km north of the northern WIPP site boundary, and about 1 km north of Mississippi Potash Incorporated's east tailings pile. The eastern boundary lies in a low-T region that contributes little flow to the modeling domain. The southern boundary lies 12.2 km south of the southern WIPP site boundary, 1.7 km south of WIPP's southernmost well (H-9), and far enough from the WIPP site to have little effect on transport rates on the site. The western model boundary passes through the IMC tailings pond (Laguna Uno; see Hunter (1985)) due west of the WIPP site in Nash Draw.

Two types of boundary conditions are specified: constant-head and no-flow (Figure PA-25). Constant-head conditions are assigned along the eastern boundary of the model domain, and along the central and eastern portions of the northern and southern boundaries. Values of these heads are obtained from the kriged initial head field. The western model boundary passes through the IMC tailings pond (Laguna Uno) due west of the WIPP site in Nash Draw. A no-flow boundary (a flow line) is specified in the model from this tailings pond up the axis of Nash Draw to the northeast, reflecting the concept that groundwater flows down the axis of Nash Draw, forming a groundwater divide. Similarly, another no-flow boundary is specified from the tailings pond down the axis of the southeastern arm of Nash Draw to the southern model boundary, coinciding with a flow line in the regional modeling of Corbet and Knupp (1996). Thus, the northwestern and southwestern corners of the modeling domain are specified as inactive cells in MODFLOW.

PA-4.8.4 Numerical Solution

The flow model in Equation (218) is evaluated with a second-order difference procedure (McDonald and Harbaugh 1988, p. 126) on the computational grid described in Section PA.4.8.3. Specifically, the discretized form of Equation (218) is

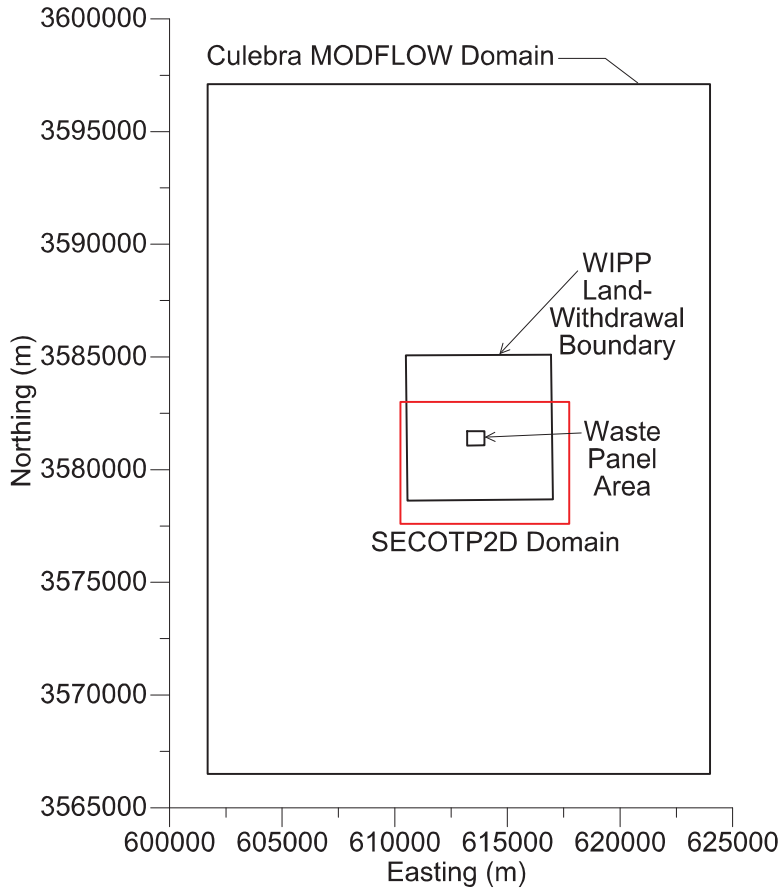

Figure PA-24. Modeling Domain for Groundwater Flow (MODFLOW) and Transport (SECOTP2D) in the Culebra.

$$0 = CR_{i,j-1/2}\left(h_{i,j-1} - h_{i,j}\right) + CR_{i,j+1/2}\left(h_{i,j+1} - h_{i,j}\right)$$

$$+ CC_{i-1/2,j}\left(h_{i-1,j} - h_{i,j}\right) + CC_{i+1/2,j}\left(h_{i+1,j} - h_{i,j}\right) , \qquad (222)$$

where CR and CC are the row and column hydraulic conductances at the cell interface between node i, j and a neighboring node (m^2/s). Since the grid is uniform, the hydraulic conductance is simply the harmonic mean of the hydraulic conductivity in the two neighboring cells multiplied by the aquifer thickness. For example, the hydraulic conductance between cells (i, j) and $(i, j-1)$ is given by $CR_{i,j-1/2}$ and the hydraulic conductance between cells (i, j) and $(i+1, j)$ is given by $CC_{i+1/2,j}$:

$$CR_{i,j-1/2} = \frac{2k_{i,j}k_{i,j-1}}{k_{i,j} + k_{i,j-1}} \times b \quad \text{and} \quad CC_{i+1/2,j} = \frac{2k_{i,j}k_{i+1,j}}{k_{i,j} + k_{i+1,j}} \times b ,$$

where $k_{i,j}$ is the hydraulic conductivity in cell i, j (m/s) and b is the aquifer thickness (m).

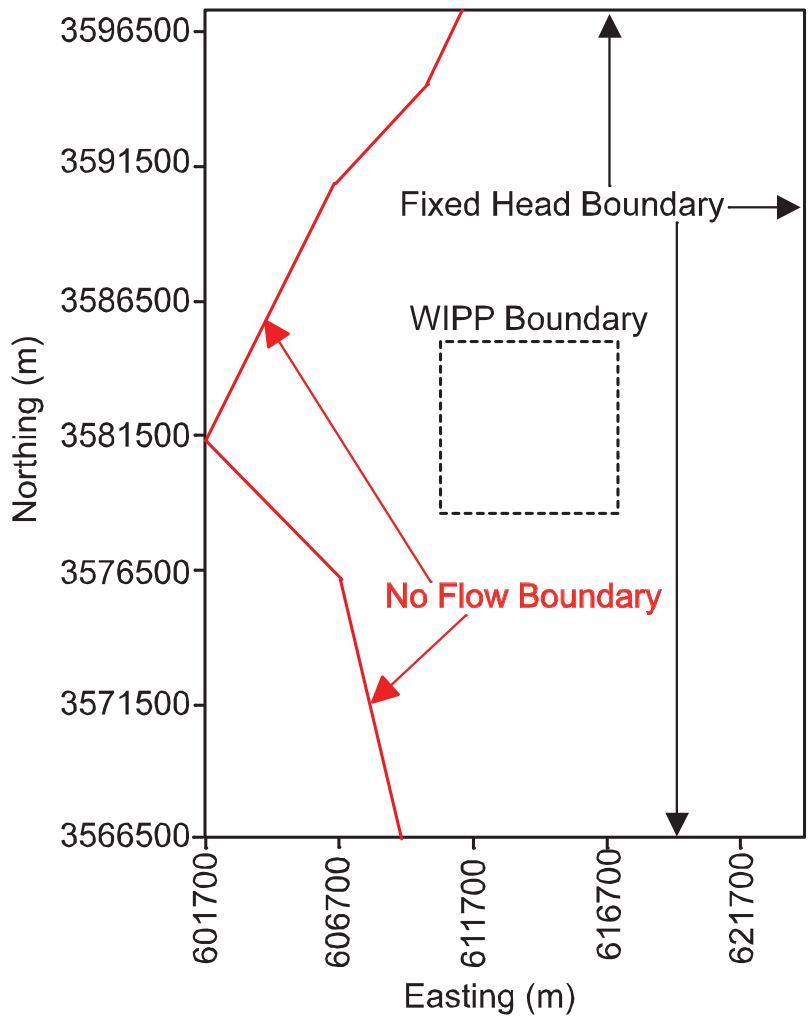

Figure PA-25. Boundary Conditions Used for Simulations of Brine Flow in the Culebra.

Figure PA-26 illustrates the cell numbering convention used in the finite difference grid for MODFLOW. The determination of h is then completed by the solution of the linear system of equations in Equation (222) for the unknown heads $h_{i,j}$. The solution is accomplished using the algebraic multigrid solver (AMG) (Ruge and Stuben 1987) that is part of the Link-AMG (LMG) package within MODFLOW (Mehl and Hill 2001). The AMG method solves Equation (222) with the successive over-relaxation (SOR) iterative method (Roache 1972) on different grids that are coarser than the original grid. The coarser grid solutions provide the initial condition to the next finer solution until a solution based on the original grid size is obtained. The advantage of the AMG method is that the larger grid solutions reduce the large frequency oscillations in the numerical solution much faster than if solved on a finer grid. The finer grid solutions are then able to remove the small frequency oscillations to obtain the final solution. While memory intensive, the AMG method produces solutions faster than ordinary iterative methods (Mehl and Hill 2001). Brine fluxes at cell interfaces are calculated from the values for $h_{i,j}$ internally in MODFLOW.

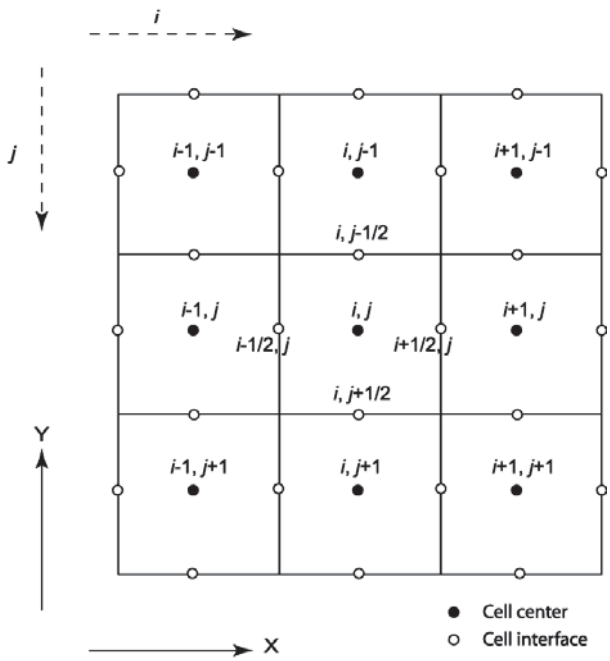

Figure PA-26. Finite Difference Grid Showing Cell Index Numbering Convention Used by MODFLOW.

PA-4.8.5 Additional Information

Additional information on MODFLOW and its use in the CRA-2004 PA to determine fluid flow in the Culebra can be found in the MODFLOW-2000 User's Manual (Harbaugh et al. 2000) and in McKenna and Hart (2003) and Lowry (2003). The flow fields computed for the CRA-2004 PA are presented in Attachment TFIELD.

PA-4.9 Radionuclide Transport in Culebra: SECOTP2D

Radionuclide transport in the Culebra formation is computed using the SECOTP2D computer code. The mathematical equations solved by the code SECOTP2D and the numerical methods used are described in the following sections.

PA-4.9.1 Mathematical Description

Radionuclide transport in the Culebra Dolomite is described by a parallel plate dual porosity model (Meigs and McCord 1996). The parallel plate dual porosity conceptualization assumes that the numerous fractures within the formation are aligned in a parallel fashion and treats the fractured porous media as two overlapping continua: one representing the fractures and the other representing the surrounding porous rock matrix (See Figure PA-27). In this model, one system of partial differential equations (PDEs) is used to represent advective transport in fractures within the Culebra Dolomite and another PDE system is used to represent diffusive transport and sorption in the matrix that surrounds the fractures.

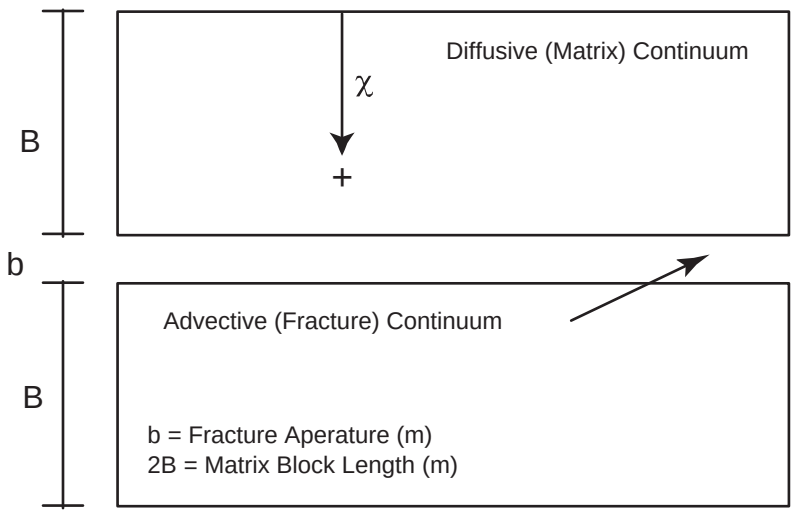

Figure PA-27. Parallel Plate Dual Porosity Conceptualization.

PA-4.9.1.1 Advective Transport in Fractures

The PDE system used to represent advective transport in fractures is given by (WIPP PA 1997b)

$$\nabla \bullet \left[\phi D_k \nabla C_k - v C_k \right] = \phi R_k \left(\frac{\partial C_k}{\partial t} \right) + \phi R_k \lambda_k C_k - \phi R_{k-1} \lambda_{k-1} C_{k-1} - Q_k - \Gamma_k , \qquad (223)$$

for $k = 1, 2, \ldots, nR$, where

nR = number of radionuclides under consideration,

C_k = concentration of radionuclide k in brine (kg/m^3),

D_k = hydrodynamic dispersion tensor (m^2/s),

v = Darcy velocity (i.e., specific discharge) of brine ($m/s = (m^3/m^2)/s$),

ϕ = advective (i.e., fracture) porosity (dimensionless),

R_k = advective retardation coefficient (dimensionless),

λ_k = decay constant for radionuclide k (s^{-1}),

Q_k = injection rate of radionuclide k per unit bulk volume of formation ($(kg/s)/m^3$) (Note: $Q_k > 0$ corresponds to injection into the fractures),

$\boldsymbol{\Gamma_k}$ = mass transfer rate of radionuclide k per unit bulk volume of formation due to diffusion between fractures and surrounding matrix ((kg/s)/m^3) (Note: $\boldsymbol{\Gamma_k} > 0$ corresponds to diffusion into fractures).

The Darcy velocity $\boldsymbol{v}$ is obtained from the solution of Equation (218); specifically, $\boldsymbol{v}$ is defined by the relationship in Equation (221). The advective porosity ϕ, defined as the ratio of the interconnected fracture pore volume to the total volume, is determined by an uncertain parameter (see CFRCPOR in Table PA-17).

The hydrodynamic dispersion tensor is defined by (WIPP PA 1997b; Bear 1972)

$$\boldsymbol{D_k} = \frac{1}{\|\boldsymbol{v}\|\phi}\begin{bmatrix} u & -v \\ v & u \end{bmatrix}\begin{bmatrix} \alpha_L & 0 \\ 0 & \alpha_T \end{bmatrix}\begin{bmatrix} u & v \\ -v & u \end{bmatrix} + \tau D_k^* \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \tag{224}$$

where α_L and α_T are the longitudinal and transverse dispersivities (m); u and v are the x and y components of $\boldsymbol{v}$ (i.e., $\boldsymbol{v} = [u, v]$); D_k^* is the free water molecular diffusion coefficient (m^2 s^{-1}) for radionuclide k; and τ is the advective tortuosity, defined as the ratio of the true length of the flow path of a fluid particle to the straight-line distance between the starting and finishing points of the particle's motion. As in the CCA PA (Helton et al. 1998), the CRA-2004 PA uses $\alpha_L = \alpha_T = 0$ m and $\tau = 1$. Thus, the definition of $\boldsymbol{D_k}$ used in the CRA-2004 PA reduces to

$$\boldsymbol{D_k} = D_k^* \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{225}$$

The diffusion coefficient D_k^* equals 3×10^{-10} m^2/s for radionuclides in the +3 oxidation state (i.e., Am(III), Pu(III)), 1.53×10^{-10} m^2/s for radionuclides in the +4 oxidation state (i.e., Pu(IV), Th(IV), U(IV)), and 4.26×10^{-10} m^2/s for radionuclides in the +6 oxidation state (i.e., U(VI)) (Attachment PAR, Table PAR-35). The existence of Pu in the +3 or +4 oxidation state (i.e., as Pu(III) or Pu(IV)) and the existence of U in the +4 or +6 oxidation state (i.e., as U(IV) or U(VI)) is determined by an uncertain parameter (see WOXSTAT in Table PA-17).

The advective retardation coefficient R_k is defined by

$$\boldsymbol{R_k} = 1 + (1 - \phi)\rho_A K_{Ak} / \phi, \tag{226}$$

where

ρ_A = surface area density of fractures in Culebra (m^2/m^3 = 1/m) (i.e., surface area of fractures (m^2) divided by volume of fractures (m^3)),

K_{Ak} = surface area distribution coefficient ((kg/m^2)/(kg/m^3) = m) (i.e., concentration of radionuclide k sorbed on fracture surfaces (kg/m^2) divided by concentration of radionuclide k dissolved in brine within fractures (kg/m^3)).

Following the logic of the CCA PA (Helton et al. 1998), $K_{Ak} = 0$ and thus $R_k = 1$ in the 2004 PA.

In concept, the term Q_k in Equation (223) provides the link between the releases to the Culebra calculated with NUTS and PANEL (Section PA-6.7) and transport within the Culebra. In the computational implementation of the CRA-2004 PA, radionuclide transport calculations in the Culebra were performed for unit radionuclide releases to the Culebra and then the outcomes of these calculations were used to construct the release to the accessible environment associated with time-dependent releases into the Culebra derived from NUTS and PANEL calculations (Section PA-6.8.7). The definition of Q_k is discussed in more detail in Section PA-4.9.1.4.

The initial condition for Equation (223) is

$$C_k(x, y, 0) = 0 \text{ kg / m}^3. \tag{227}$$

Furthermore, the boundary value conditions for Equation (223) are defined at individual points on the boundary of the grid in Figure (PA-24) on the basis of whether the flow vector $\mathbf{V} = [u, v]$ defines a flow entering the grid or leaving the grid. The following Neumann boundary value condition is imposed at points (x, y) where flow leaves the grid:

$$\nabla C_k(x, y, t) \cdot n(x, y) = 0 \text{ (kg/m}^3\text{)/m}, \tag{228}$$

where $n(x, y)$ is an outward-pointing unit normal vector defined at (x, y). The following Dirichlet boundary value condition is imposed at points (x, y) where flow enters the grid:

$$C_k(x, y, t) = 0 \text{ kg/m}^3. \tag{229}$$

PA-4.9.1.2 <u>Diffusive Transport in the Matrix</u>

The system of PDEs used to represent diffusive transport in the matrix surrounding the fractures is given by (WIPP PA 1997b)

$$\frac{\partial}{\partial \chi}\left(\phi'_k D'_k \frac{\partial C'_k}{\partial \chi}\right) = \phi' R'_k \left(\frac{\partial C'_k}{\partial t}\right) + \phi' R'_k \lambda_k C'_k - \phi' R'_{k-1} \lambda_{k-1} C'_{k-1} \ , \tag{230}$$

where χ is the spatial coordinate in Figure PA-27, D'_k is the matrix diffusion coefficient (m^2/s) for radionuclide k defined by $D'_k = D^*_k \tau'$, and τ' is the matrix tortuosity. The remaining terms have the same meaning as those in Equation (223) except that the prime denotes properties of the matrix surrounding the fractures. A constant value ($\tau' = 0.11$) for the matrix (i.e., diffusive)

tortuosity is used in the CRA-2004 PA (Meigs 1996). The matrix (i.e., diffusive) porosity φ' is an uncertain input to the analysis (see CMTRXPOR in Table PA-17). The matrix retardation R'_k is defined by

$$R'_k = 1 + \left(1 - \phi'\right)\rho_s K_{dk} / \phi' , \tag{231}$$

where ρ_s is the particle density (kg/m^3) of the matrix and K_{dk} is the distribution coefficient ((Ci/kg)/(Ci/m^3) = m^3/kg) for radionuclide k in the matrix. The density ρ_s is assigned a value of 2.82×10^3 kg/m^3 (Martell 1996b). The distribution coefficients K_{dk} are uncertain inputs to the analysis and dependent on the uncertain oxidation state of the relevant element (see CMKDAM3, CMKDPU3, CMKDPU4, CMKDTH4, CMKDU4, CMKDU6, and WOXSTAT in Table PA-17).

The initial and boundary value conditions used in the formulation of Equation (230) are

$$C'_k\left(x, y, \chi, 0\right) = 0 \ kg / m^3 , \tag{232}$$

$$\partial C'_k\left(x, y, 0, t\right) / \partial z = 0 \ \ kg / m^2 , \tag{233}$$

$$C'_k\left(x, y, B, t\right) = C_k(x, y, t), \tag{234}$$

where $\left(x, y\right)$ corresponds to a point in the domain on which Equation (223) is solved and B is the matrix half block length (m) in Figure PA-27 (i.e., 2B is the thickness of the matrix between two fractures). The initial condition in Equation (232) means that no radionuclide is present in the matrix at the beginning of the calculation. The boundary value condition in Equation (233) implies that no radionuclide movement can take place across the centerline of a matrix block separating two fractures. The boundary value condition in Equation (234) ensures that the dissolved radionuclide concentration in the matrix at the boundary with the fracture is the same as the dissolved radionuclide concentration within the fracture. The matrix half block length B is an uncertain input to the analysis (see CFRCSP in Table PA-17).

PA-4.9.1.3 Coupling Between Fracture and Matrix Equations

The linkage between Equation (223) and Equation (230) is accomplished through the term Γ_k, defining the rate at which radionuclide k diffuses across the boundary between a fracture and the adjacent matrix (see Figure PA-27). Specifically,

$$\Gamma_k = -\frac{2\phi}{b}\left(\phi' D'_k \left.\frac{\partial C'_k}{\partial \chi}\right|_{z=\chi}\right), \tag{235}$$

where b is the fracture aperture (m) defined by

$$b = \phi B\left(1 - \phi\right). \tag{236}$$

PA-4.9.1.4 Source Term

As already indicated, Equation (223) and Equation (230) are solved for unit radionuclide releases to the Culebra. Specifically, a release of 1 kg of each radionuclide under consideration was assumed to take place over a time interval from 0 to 50 years, with this release taking place into the computational cell WPAc , located at the center of the Waste Panel Area in Figure PA-24, that has dimensions of 50 m × 50 m. The volume of this cell is given by

$$V = (50m)(50m)(4m) = 1 \times 10^4 \ m^3 , \tag{237}$$

where 4 m is the assumed thickness of the Culebra Dolomite (Meigs and McCord 1996). As a result, $Q_k(x, y, t)$ has the form

$$Q_k(x, y, t) = \frac{1 \ kg}{(1 \times 10^4 \ m^3)(50 \ yr)(3.16 \times 10^7 \ s / yr)} = 6.33 \times 10^{-14} \ kg / m^3 / s \tag{238}$$

for $0 \le t \le 50$ yr and (x, y) is in cell WPAC and $Q_k(x, y, t) = 0$ (kg/m^3/s) otherwise.

PA-4.9.1.5 Cumulative Releases

If $\mathcal{B}$ denotes an arbitrary boundary (e.g., the land withdrawal boundary) in the domain of Equation (223) (i.e., Figure PA-24), then the cumulative transport of $C_k(t, \mathcal{B})$ of radionuclide k from time 0 to time t across $\mathcal{B}$ is given by

$$C_k(t, \mathcal{B}) = \int_0^t \left[\int_{\mathcal{B}} \left\{ \mathbf{v}(x, y) C_k(x, y, \tau) - \phi \mathbf{D}_k(x, y, t) \nabla C_k(x, y, \tau) \right\} \mathbf{b} \bullet \mathbf{n}(x, y) ds \right] d\tau , \tag{239}$$

where h is the thickness of the Culebra (4 m), ϕ is the advective porosity in Equation (223), $\mathbf{n}(x, y)$ is an outward pointing unit normal vector, and $\int_{\mathcal{B}} ds$ denotes a line integral over $\mathcal{B}$.

PA-4.9.2 Numerical Solution

The numerical solution to the coupled PDE system represented by Equation (223), and Equation (230) is computed using SECOTP2D, an implicit finite volume code for the simulation of multispecies reactive transport. A high-level description of the numerical procedures implemented in SECOTP2D follows, with more detail available in WIPP PA (1997b).

PA-4.9.2.1 Discretization of Fracture Domain

The fracture domain is discretized in space using the block centered finite difference method indicated in Figure PA-28. In this formulation, cell concentrations are defined at grid block centers while the velocity components $[u, v]$ are defined on grid cell faces. A uniform mesh with 50 m × 50 m cells is used for the spatial discretization. Ghost cells are placed outside the

problem domain for the purpose of implementing boundary conditions. The temporal discretization is accomplished using variable time step sizes.

The dispersive term, $\nabla\cdot\left(\phi D_k \nabla C_k\right)$, in Equation (223) is approximated using a second-order central difference formula (Fletcher 1988).

The advective term, $\nabla\cdot v C_k$, is approximated using the Total Variation Diminishing (TVD) method (Sweby 1984). The TVD method provides a way of accurately resolving advection dominated transport problems without the occurrence of nonphysical oscillations commonly present in second-order solutions. This method invokes a weighted upstream differencing scheme that locally adjusts the weighting to prevent oscillatory behavior and maximize solution accuracy. The weighting parameters are known as the TVD flux limiters $\Phi\left(x, y, r\right)$, where r is a function of the concentration gradient and direction of flow. PA uses the van Leer TVD limiter (Sweby 1984, p. 1005), which is defined as

$$\Phi\left(x, y, r\right) = \max\left\{0, \min\left\{2r, \frac{r+|r|}{1+|r|}\right\}\right\}. \tag{240}$$

At locations where u (i.e., the Darcy velocity in the x direction) is positive, r is defined at the j–1/2, k interface by

$$r_{j-1/2,k} = \frac{\partial C/\partial x\big|_{j-3/2,k}}{\partial C/\partial x\big|_{j-1/2,k}}, \tag{241}$$

and at locations where u is negative, r is defined by

$$r_{j-1/2,k} = \frac{\partial C/\partial x\big|_{j+1/2,k}}{\partial C/\partial x\big|_{j-1/2,k}}. \tag{242}$$

Similar definitions are made for r at the j, k–1/2 interface in the y-direction with v (i.e., the Darcy velocity in the y direction) used instead of u.

Because Φ_k is a function of C_k, the discretized set of equations is nonlinear. This nonlinearity is addressed by treating the flux limiters explicitly (i.e., time lagged). Explicit treatment of the limiter functions, however, can lead to oscillatory and sometimes unstable solutions when the Courant number exceeds unity (Cr > 1), where Cr is defined by

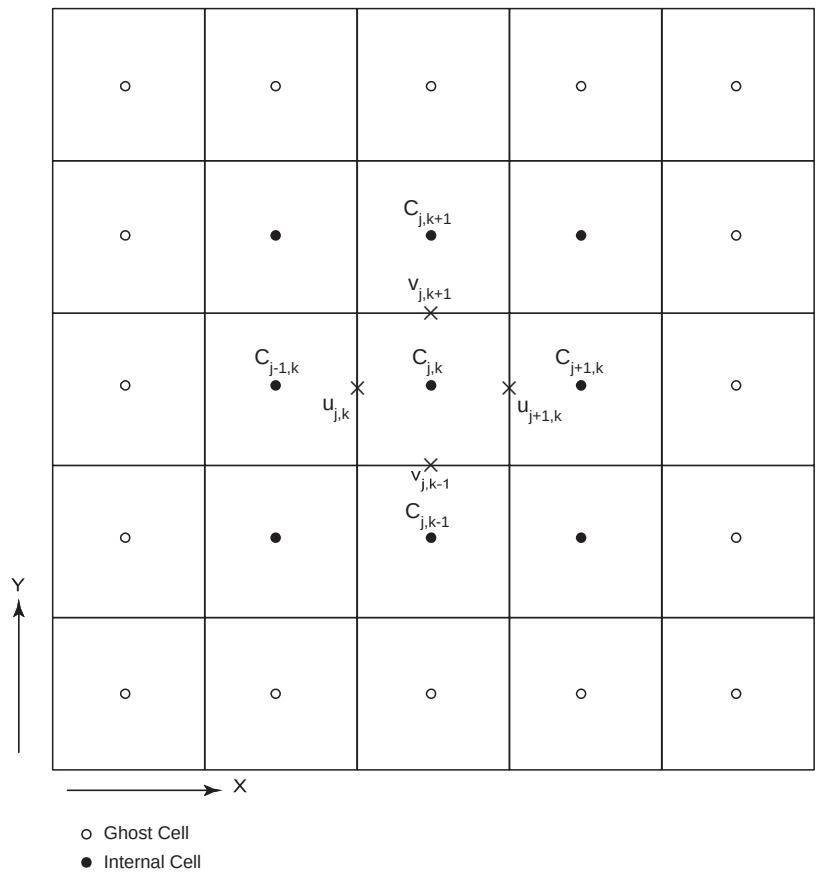

Figure PA-28. Schematic of Finite Volume Staggered Mesh Showing Internal and Ghost Cells.

$$Cr = \max\left\{Cr_x, Cr_y\right\}, \ \textit{where } Cr_x = |u|\Delta t/\phi\Delta x \ \textit{ and } \ Cr_y = |v|\Delta t/\phi\Delta y. \tag{243}$$

To avoid this behavior, the application of the TVD method is restricted to regions in which the Courant numbers are less than one. In regions where Cr > 1, a first order full upwinding scheme is invoked, which is unconditionally stable and nonoscillatory.

The discretized form of Equation (223) can be expressed in a delta formulation as

$$\left(\boldsymbol{I} + \boldsymbol{L_{xx}} + \boldsymbol{L_{yy}} + \boldsymbol{S}\right)\Delta \boldsymbol{C^{n+1}} = \boldsymbol{RHS^n}, \tag{244}$$

where $\boldsymbol{I}$ is the identity matrix, $\boldsymbol{L_{xx}}$ and $\boldsymbol{L_{yy}}$ are finite difference operators in the x and y directions, $\boldsymbol{S}$ is an implicit source term that accounts for decay and mass transfer between the matrix and the fracture, $\boldsymbol{RHS}$ consists of the right hand side known values at time level n, and $\Delta \boldsymbol{C_{n+1}} = \boldsymbol{C_{n+1}} - \boldsymbol{C_n}$. Direct inversion of Equation (244) for a typical Culebra transport problem is very computationally intensive, requiring large amounts of memory and time. To reduce these requirements, the operator in Equation (244) is factored as follows:

$$\left(\boldsymbol{I}+\boldsymbol{L}_{xx}+\alpha_x\boldsymbol{S}\right)\left(\boldsymbol{I}+\boldsymbol{L}_{yy}+\alpha_y\boldsymbol{S}\right)\Delta\boldsymbol{C}^{n+1}=\boldsymbol{RHS}^n, \tag{245}$$

where α_x and α_y are constants that must sum to one (i.e., $\alpha_x + \alpha_y = 1$). The left hand sides in Equation (244) and Equation (245) are not equivalent, with the result that the factorization of Equation (244) in Equation (245) is referred to as an approximate factorization (Fletcher 1988). The advantage of approximately factoring Equation (244) is that the resulting equation consists of the product of two finite difference operators that are easily inverted independently using a tridiagonal solver. Hence, the solution to the original problem is obtained by solving a sequence of problems in the following order:

$$\left(\boldsymbol{I}+\boldsymbol{L}_{xx}+\alpha_x\boldsymbol{S}\right)\Delta\overline{\boldsymbol{C}}=\boldsymbol{RHS}^n, \tag{246}$$

$$\left(\boldsymbol{I}+\boldsymbol{L}_{yy}+\alpha_y\boldsymbol{S}\right)\Delta\boldsymbol{C}^{n+1}=\Delta\overline{\boldsymbol{C}}, \tag{247}$$

$$\boldsymbol{C}^{n+1}=\boldsymbol{C}^n+\Delta\boldsymbol{C}^{n+1}. \tag{248}$$

PA-4.9.2.2 Discretization of Matrix Equation

The nonuniform mesh used to discretize the matrix equation is shown in Figure PA-29. Straightforward application of standard finite difference or finite volume discretizations on nonuniform meshes results in truncation error terms which are proportional to the mesh spacing variation (Hirsch 1988). For nonuniform meshes, the discretization can be performed after a transformation from the Cartesian physical space (χ) to a stretched Cartesian computational space (ξ). The transformation is chosen so that the nonuniform grid spacing in physical space is transformed to a uniform spacing of unit length in computational space (the computational space is thus a one-dimensional domain with a uniform mesh). The transformed equations contain metric coefficients that must be discretized, introducing the mesh size influence into the difference formulas. Then standard unweighted differencing schemes can then be applied to the governing equations in the computational space.

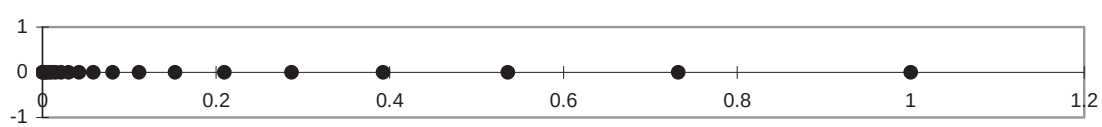

Figure PA-29. Illustration of Stretched Grid Used for Discretization of Matrix Domain.

The SECOTP2D code applies such a coordinate transformation to the nonuniform diffusion domain mesh, solving the transformed system of equations in the uniform computational space. The transformed matrix equation is written as:

$$\phi' R'_k \frac{\partial \hat{C}'_k}{\partial t} - \frac{\partial \hat{F}'_v}{\partial \xi'} = -\phi' R'_k \lambda_k \hat{C}'_k + \phi' R'_{k-1} \lambda_{k-1} \hat{C}'_{k-1}, \tag{249}$$

where

$$\hat{C}'_k = \frac{C'_k}{J}, \tag{250}$$

$$\hat{F}'_v = D' \xi'_x \frac{\partial C'_k}{\partial \xi'}. \tag{251}$$

In the uniform computational space, a first-order backwards difference formula is used to approximate the temporal derivative while a second-order accurate central difference is used to approximate spatial derivatives.

PA-4.9.2.3 Fracture-Matrix Coupling

The equations for the fracture and the matrix are coupled through the mass transfer term Γ_k. In the numerical solution, these equations are coupled in a fully implicit manner and solved simultaneously. A procedure outlined in (Huyakorn et al. 1983) was adapted and redeveloped for an approximate factorization algorithm with the delta formulation and a finite volume grid. The coupling procedure consists of three steps.

Step 1. Write the mass transfer term Γ_k in a delta (Δ) form.

Step 2. Evaluate Δ terms that are added to the implicit part of the fracture equation. This is accomplished using the inversion process (LU factorization) in the solution of the matrix equation. After the construction of the lower tridiagonal matrix L and the intermediate solution, there is enough information to evaluate the Δ terms. This new information is fed into the fracture equation that subsequently is solved for concentrations in the fracture at the new time level (n+1).

Step 3. Construct the boundary condition for the matrix equation at the fracture-matrix interface using fracture concentrations at the (n+1) time level. Matrix concentrations are then obtained using the upper tridiagonal matrix U by back substitution. A detailed description of this technique and its implementation is given in the SECOTP2D User's Manual (WIPP PA 1997b).

PA-4.9.2.4 Cumulative Releases

The cumulative transport $C_k(t, \mathcal{B})$ of individual radionuclides across specified boundaries indicated in Equation (239) is also accumulated during the numerical solution of Equation (223) and Equation (230).

PA-4.9.3 Additional Information

Additional information on SECOTP2D and its use in the CRA-2004 PA to determine radionuclide transport in the Culebra Dolomite can be found in the SECOTP2D User's Manual (WIPP PA 1997b) and in the analysis package for radionuclide transport in the Culebra Dolomite (Kanney 2003).

PA-5.0 PROBABILISTIC CHARACTERIZATION OF SUBJECTIVE UNCERTAINTY

This section summarizes the uncertain parameters in the CRA-2004 PA that constitute the space for subjective uncertainty defined in Section PA-2.4.

PA-5.1 Probability Space

As discussed in Section PA-2.4, the third entity (EN3) that underlies the CRA-2004 PA is a probabilistic characterization of the uncertainty in important variables used as input to the analysis. This entity is defined by a probability space $\left(X_{su}, S_{su}, p_{su}\right)$ that characterizes subjective uncertainty. The individual elements of S_{su} are vectors x_{su} of the form

$$x_{su} = \left[x_1, x_2, \ldots x_{nV}\right], \tag{252}$$

where each x_j is an imprecisely-known input to the analysis and nV is the number of such inputs.

The uncertainty in the x_j, and hence in x_{su}, is characterized by developing a distribution

$$D_j, \;\; j = 1, 2, \ldots, nV \;, \tag{253}$$

for each x_j. Each distribution is based on all available knowledge about the corresponding variable and describes a degree of belief as to where the appropriate value to use for this variable is located. This degree of belief is conditional on the numerical, spatial, and temporal resolution of the models selected for use in the CRA-2004 PA (Chapter PA-4.0). When appropriate, correlations between imprecisely-known variables are also possible, with such correlations indicating a dependency in the knowledge about the correlated variables. It is the distributions in Equation (253) and any associated correlations between the x_j that define $\left(X_{su}, S_{su}, p_{su}\right)$.

The uncertain variables (i.e., x_j) incorporated into the CRA-2004 PA are discussed in Section PA-5.2. Then, the distributions and correlations assigned to these variables are described in Section PA-5.3 and Section PA-5.4. Finally, a discussion of the concept of a scenario is given in Section PA-5.5.

PA-5.2 Variables Included For Subjective Uncertainty

The CRA-2004 PA selected nV = 64 imprecisely-known variables for inclusion in the analysis (Table PA-17). The individual variables in Table PA-17 correspond to the elements x_j of the vector x_{su} in Equation (252). Most variables listed in Table PA-17 were also treated as uncertain in the CCA PA (CCA Appendix PAR). Table PA-18 lists the differences between the set of subjectively uncertain variables in the CCA PA and the CRA-2004 PA. Most differences result from the inclusion of additional uncertain variables from the 1997 PAVT. All subjectively uncertain variables incorporated into the CRA-2004 PA are used as input to the models discussed in Section PA-2.3 and Chapter 4.0.

PA-5.3 Variable Distributions

Each uncertain variable is assigned a distribution that characterizes the subjective uncertainty in that variable. Distributions for each parameter are described in Attachment PAR. Attachment PAR contains documentation for each of the 64 parameters that were sampled by the LHS code during the PA.

PA-5.4 Correlations

Most of the variables in Table PA-17 are assumed to be uncorrelated. However, the pairs (ANHCOMP, ANHPRM), (HALCOMP, HALPRM), and (BPCOMP, BPPRM) are assumed to have rank correlations of –0.99, –0.99, and –0.75, respectively (Figure PA-30, Figure PA-31, and Figure PA-32). These correlations result form a belief that the underlying physics implies that a large value for one variable in a pair should be associated with a small value for the other variable in the pair. The scatterplots in Figure PA-29, Figure PA-30, and Figure PA-31 result from the LHSs described in Section PA-6.4, with the rank correlations within the pairs (ANHCOMP, ANHPRM), (HALCOMP, HALPRM), and (BPCOMP, BPPRM) induced with the Iman and Conover (1982) restricted pairing technique.

The distributions and associated correlations indicated in Table PA-17 and Figure PA-29, Figure PA-30, and Figure PA-31 define the probability space $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$ for subjective uncertainty in Section PA.2.4. The vector $\boldsymbol{x_{su}}$ in Equation (252) has the form

$$\boldsymbol{x_{su}} = \left[\boldsymbol{ANHBCEXP, ANHBCVGP, ..., WTAUFAIL}\right], \tag{254}$$

where the individual elements of $\boldsymbol{x_{su}}$ are the subjectively uncertain variables described in Table PA-17.

PA-5.5 Separation of Stochastic and Subjective Uncertainty

The CRA-2004 PA uses the term “scenario” to refer to subsets E_{st} of the sample space, S_{st} for stochastic uncertainty, with scenario probabilities $\boldsymbol{p_{st}}\left(\boldsymbol{E_{st}}\right)$ being defined by the function p_{st} associated with the probability space $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$ (Section PA-3.9). This definition is consistent with the concept that a scenario is something that could happen in the future. Subsets E_{su} of the sample space for subjective uncertainty S_{su} are not referred to as scenarios to maintain the important distinction between the two sample spaces. In particular, a scenario E_{st} contains vectors $\boldsymbol{x_{st}}$ of the form defined in Equation (3), and the probability $\boldsymbol{p_{st}}\left(\boldsymbol{E_{st}}\right)$ for E_{st} characterizes the likelihood that a vector $\boldsymbol{x_{st}}$ in E_{st} will match the occurrences that will take place at the WIPP over the next 10,000 years. In contrast, a subset E_{su} from the space of subjective uncertainty X_{su} contains vectors $\boldsymbol{x_{su}}$ of the form defined in Equation (252) and the probability $\boldsymbol{p_{su}}\left(\boldsymbol{E_{su}}\right)$ characterizes a degree of belief that a vector $\boldsymbol{x_{su}}$ in E_{su} contains the appropriate values for the 64 uncertain variables in Table PA-17.

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA

Sample Position	Variable Name	Material Name	Property Name	Description
1	WGRCOR	STEEL	CORRMCO2	Rate of anoxic steel corrosion (m/s) under brine inundated conditions and with no CO_2 present. Defines R_{ci} in Equation (59) for areas Waste Panel, South RoR, and North RoR in Figure PA-8.
2	WMICDFLG	WAS_AREA	PROBDEG	Index for model of microbial degradation of CPR materials (dimensionless). Used in areas Waste Panel, South RoR, and North RoR in Figure PA-8.
3	WGRMICI	WAS_AREA	GRATMICI	Rate of CPR biodegradation (mol $C_6H_{10}O_5$ / kg $C_6H_{10}O_5$ / s) under anaerobic, brine-inundated conditions. Defines R_{mi} in Equation (61) for areas Waste Panel, South RoR, and North RoR, in Figure PA-8.
4	WGRMICH	WAS_AREA	GRATMICH	Rate of CPR biodegradation (mol $C_6H_{10}O_5$ / kg $C_6H_{10}O_5$ / s) under anaerobic, humid conditions. Defines R_{mh} in Equation (61) for areas Waste Panel, South RoR, and North RoR, in Figure PA-8.
5	WFBETCEL	CELLULS	FBETA	Scale factor used in definition of stoichiometric coefficient for microbial gas generation (dimensionless). Defines β in Equation (77) for areas Waste Panel, South RoR, and North RoR, in Figure PA-8.
6	WRGSSAT	WAS_AREA	SAT_RGAS	Residual gas saturation in waste (dimensionless). Defines S_{gr} in Equation (35) for areas Waste Panel, South RoR, and North RoR in Figure PA-8; also used in waste material in Figure PA-20 for calculation of DBR; see Section PA-4.7.
7	WRBRNSAT	WAS_AREA	SAT_RBRN	Residual brine saturation in waste (dimensionless). Defines S_{br} in Equation (34) for areas Waste Panel, South RoR, and North RoR, in Figure PA-8; also used in waste material in Figure PA-20 for calculation of DBR; see Section PA-4.7.
8	WASTWICK	WAS_AREA	SAT_WICK	Increase in brine saturation of waste due to capillary forces (dimensionless). Defines S_{wick} in Equation (78) for areas Waste Panel, South RoR, and North RoR, in Figure PA-8.

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA — Continued

Sample Position	Variable Name	Material Name	Property Name	Description
9	DRZPCPRM	DRZ_PCS	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the DRZ immediately above the panel closure concrete (Section PA-4.2.8.3). Used in region DRZ_PCS in Figure PA-8.
10	CONPRM	CONC_PCS	PRMX_LOG	Logarithm of intrinsic permeability (m^2) for the concrete portion of the panel closure. (Section PA-4.2.8.1). Used in region CONC_PCS in Figure PA-8.
11	WSOLU4C	SOLU4	SOLCIM	Uncertainty factor (dimensionless) for solubility of U in the +IV oxidation state in Castile brine. Defines UF(Castile, +4, U) in Equation (90).
12	WSOLTH4C	SOLTH4	SOLCIM	Uncertainty factor (dimensionless) for solubility of Th in the +IV oxidation state in Castile brine. Defines UF(Castile, +4, Th) in Equation (90).
14	CONGSSAT	CONC_PCS	SAT_RGAS	Residual gas saturation (dimensionless) in panel closure concrete (Section PA-4.2.8.1). Defines S_{gr} in Equation (35) for area CONC_PCS in Figure PA-8.
15	CONBRSAT	CONC_PCS	SAT_RBRN	Residual brine saturation (dimensionless) in panel closure concrete (Section PA-4.2.8.1). Defines S_{br} in Equation (35) for use in region CONC_PCS in Figure PA-8.
16	CONBCEXP	CONC_PCS	PORE_DIS	Brooks-Corey pore distribution parameter (dimensionless) for panel closure concrete (Section PA-4.2.8.1). Defines λ in Equation (32) for region CONC_PCS of Figure PA-8 for use with Brooks-Corey model; defines λ in $m = \lambda/(1 + \lambda)$ in Equation (36) for use with van Genuchten-Parker model in region CONC_PCS.
17	HALPOR	S_HALITE	POROSITY	Halite porosity (dimensionless). Defines ϕ_0 in Equation (25g) for region Salado in Figure PA-8.
18	HALPRM	S_HALITE	PRMX_LOG	Logarithm of intrinsic halite permeability (m^2). Used in region Salado in Figure PA-8.
19	HALCOMP	S_HALITE	COMP_RCK	Bulk compressibility of halite (Pa^{-1}). Defines β_{fB} in Equation (31) for region Salado of Figure PA-8.
20	ANHPRM	S_MB139	PRMX_LOG	Logarithm of intrinsic anhydrite permeability (m^2). Used in regions MB 138, Anhydrite AB, and MB 139 in Figure PA-8.
21	ANHCOMP	S_MB139	COMP_RCK	Bulk compressibility of anhydrite (Pa^{-1}). Defines β_{fB} in Equation (31) for regions MB 138, Anhydrite AB and MB 139 in Figure PA-8.

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA — Continued

Sample Position	Variable Name	Material Name	Property Name	Description
22	ANHBCVGP	S_MB139	RELP_MOD	Indicator for relative permeability model (dimensionless) for regions MB 138, Anhydrite AB and MB 139 in Figure PA-8. See Table PA-3.
23	ANRBRSAT	S_MB139	SAT_RBRN	Residual brine saturation in anhydrite (dimensionless). Defines S_{br} in Equation (35) for regions MB 138, Anhydrite AB, and MB 139 in Figure PA-8.
24	ANRGSSAT	S_MB139	SAT_RGAS	Residual gas saturation in anhydrite (dimensionless). Defines S_{gr} in Equation (34) for regions MB 138, Anhydrite AB, and MB 139 in Figure PA-8.
25	ANHBCEXP	S_MB139	PORE_DIS	Brooks-Corey pore distribution parameter for anhydrite (dimensionless). Defines λ in Equation (32) for regions MB 138, Anhydrite AB, and MB 139 of Figure PA-8 for use with Brooks-Corey model; defines λ in $m = \lambda/(1 + \lambda)$ in Equations (36) for use with van Genuchten-Parker model in the same regions.
26	SALPRES	S_HALITE	PRESSURE	Initial brine pore pressure (Pa) in the Salado halite, applied at an elevation consistent with the intersection of MB 139. Defines $p_{b,ref}$ for Equation (49) for region Salado in Figure PA-8.
27	BPINTPRS	CASTILER	PRESSURE	Initial brine pore pressure in the Castile brine reservoir. Defines $Pb(x, y, -5)$ in Equation (50) for region CASTILER in Figure PA-8.
28	BPPRM	CASTILER	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the Castile brine reservoir. Used in region CASTILER in Figure PA-8.
29	BPCOMP	CASTILER	COMP_RCK	Bulk compressibility (Pa^{-1}) of Castile brine reservoir. Defines β_{fB} in Equation (29) for region CASTILER of Figure PA-8
30	BHPERM	BH_SAND	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the silty sand-filled borehole (Table PA-5). Used in regions Upper Borehole and Lower Borehole in Figure PA-8.
31	DRZPRM	DRZ_1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the DRZ. Used in regions Upper DRZ and Lower DRZ in Figure PA-8.
32	PLGPRM	CONC_PLG	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the concrete borehole plugs (Table PA-5). Used in region Borehole Plugs in Figure PA-8.
34	WSOLAM3S	SOLAM3	SOLSIM	Uncertainty factor (dimensionless) for solubility of Am in the +III oxidation state in Salado brine. Defines UF(Salado, +3, Am) in Equation (90).

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA — Continued

Sample Position	Variable Name	Material Name	Property Name	Description
35	WSOLAM3C	SOLAM3	SOLCIM	Uncertainty factor (dimensionless) for solubility of Am in the +III oxidation state in Castile brine. Defines UF(Castile, +3, Am) in Equation (90).
36	WSOLPU3S	SOLPU3	SOLSIM	Uncertainty factor (dimensionless) for solubility of Pu in the +III oxidation state in Salado brine. Defines UF(Salado, +3, Pu) in Equation (90).
37	WSOLPU3C	SOLPU3	SOLCIM	Uncertainty factor (dimensionless) for solubility of Pu in the +III oxidation state in Castile brine. Defines UF(Castile, +3, Pu) in Equation (90).
38	WSOLPU4S	SOLPU4	SOLSIM	Uncertainty factor (dimensionless) for solubility of Pu in the +IV oxidation state in Salado brine. Defines UF(Salado, +4, Pu) in Equation (90).
39	WSOLPU4C	SOLPU4	SOLCIM	Uncertainty factor (dimensionless) for solubility of Pu in the +IV oxidation state in Castile brine. Defines UF(Castile, +4, Pu) in Equation (90).
40	WSOLU4S	SOLU4	SOLSIM	Uncertainty factor (dimensionless) for solubility of U in the +IV oxidation state in Salado brine. Defines UF(Salado, +4, U) in Equation (90).
41	WSOLU6S	SOLU6	SOLSIM	Uncertainty factor (dimensionless) for solubility of U in the +VI oxidation state in Salado brine. Defines UF(Salado, +6, U) in Equation (90).
42	WSOLU6C	SOLU6	SOLCIM	Uncertainty factor (dimensionless) for solubility of U in the +VI oxidation state in Castile brine. Defines UF(Castile, +6, U) in Equation (90).
43	WSOLTH4S	SOLTH4	SOLSIM	Uncertainty factor (dimensionless) for solubility of Th in the +IV oxidation state in Salado brine. Defines UF(Salado, +4, Th) in Equation (90).
44	WPHUMOX3	PHUMOX3	PHUMCIM	Ratio (dimensionless) of concentration of actinides attached to humic colloids to dissolved concentration of actinides for oxidation state +III in Castile brine. Defines SF_{Hum}(Castile, +3, Am) and SF_{Hum}(Castile, +3, Pu) for Equation (90).
45	WOXSTAT	GLOBAL	OXSTAT	Indicator variable for elemental oxidation states (dimensionless). WOXSTAT = 0 indicates use of CMKDPU3, CMKDU4, WSOLPU3C, WSOLPUS, , WSOLU4C, and WSOLU4S. WOXSTAT = 1 implies use of CMKDPU4, CMKDU6, WSOLPU4C, WSOLPU4S, WSOLU6C, and WSOLU6S.

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA — Continued

Sample Position	Variable Name	Material Name	Property Name	Description
46	CTRANSFM	CULEBRA	MINP_FAC	Multiplier (dimensionless) applied to transmissivity of the Culebra within the land withdrawal boundary after mining of potash reserves. Defines MF in Equation (216) (See section PA-4.8.2).
47	CTRAN	GLOBAL	TRANSIDX	Indicator variable for selecting transmissivity field. See Section PA-4.8.2.
48	CCLIMSF	GLOBAL	CLIMTIDX	Climate scale factor (dimensionless) for Culebra flow field. Defines SFC in Equation (221).
49	CFRACSP	CULEBRA	HMBLKLT	Culebra fracture spacing (m). Equal to half the distance between fractures (i.e., the Culebra half matrix block length). Defines B in Equation (236) and Figure PA-26.
50	CFRACPOR	CULEBRA	APOROS	Culebra fracture (i.e., advective) porosity (dimensionless). Defines ϕ in Equation (223).
51	CMTRXPOR	CULEBRA	DPOROS	Culebra matrix (i.e., diffusive) porosity (dimensionless). Defines ϕ' in Equation (230).
52	CMKDU6	U+6	MKD_U	Matrix distribution coefficient (m^3/kg) for U in +6 oxidation state. Defines K_{dk} in Equation (231).
53	CMKDU4	U+4	MKD_U	Matrix distribution coefficient (m^3/kg) for U in +4 oxidation state. Defines K_{dk} in Equation (231).
54	CMKDPU3	PU+3	MKD_PU	Matrix distribution coefficient (m^3/kg) for Pu in +3 oxidation state. Defines K_{dk} in Equation (231).
55	CMKDPU4	PU+4	MKD_PU	Matrix distribution coefficient (m^3/kg) for Pu in +4 oxidation state. Defines K_{dk} in Equation (231).
56	CMKDTH4	TH+4	MKD_TH	Matrix distribution coefficient (m^3/kg) for Th in +4 oxidation state. Defines K_{dk} in Equation (231).
57	CMKDAM3	AM+3	MKD_AM	Matrix distribution coefficient (m^3/kg) for Am in +3 oxidation state. Defines K_{dk} in Equation (231).
58	WTAUFAIL	BOREHOLE	TAUFAIL	Shear strength of waste (Pa). Defines $r(R,1)$ in Equation (111).
60	PBRINE	GLOBAL	PBRINE	Probability that a drilling intrusion penetrates pressurized brine in the Castile Formation. Defines p_{B1}; see Section PA-3.5.

Table PA-17. Variables Representing Subjective Uncertainty in the CRA-2004 PA — Continued

Sample Position	Variable Name	Material Name	Property Name	Description
61	DOMEGA	BOREHOLE	DOMEGA	Drill string angular velocity (rad/s). Defines $\Delta\Omega$ in Equation (112b).
62	SHURBRN	SHFTU	SAT_RBRN	Residual brine saturation in upper shaft seal materials (dimensionless). Defines S_{br} in Equation (35) for region Upper Shaft in Figure PA-8.
63	SHURGAS	SHFTU	SAT_RGAS	Residual gas saturation in upper shaft seal materials (dimensionless). Defines S_{gr} in Equation (34) for region Upper Shaft in Figure PA-8.
64	SHUPRM	SHFTU	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of upper shaft seal materials. Used in region Upper Shaft in Figure PA-8.
65	SHLPRM1	SHFTL_T1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of lower shaft seal materials for the first 200 years after closure. Used in region Lower Shaft in Figure PA-8.
66	SHLPRM2	SHFTL_T2	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of lower shaft seal materials from 200 years to 10,000 years after closure. Used in region Lower Shaft in Figure PA-8.
75	RNDSPALL	SPALLMOD	RNDSPALL	Indicator variable for selecting element from the LHS for DRSPALL. See Section PA-4.6.4.

Table PA-18. Differences in Uncertain Parameters in the CCA PA and CRA-2004 PA

Material Name	Property Name	Description	When Used	Reason for Removal or Addition
DRZ_PCS	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the DRZ immediately above the panel closure concrete.	2003	Added due to the addition of the Option D panel closures.
CONC_PCS	PRMX_LOG	Logarithm of intrinsic permeability (m^2) for the concrete portion of the panel closure.	2003	Added due to the addition of the Option D panel closures.
SOLU4	SOLCIM	Uncertainty factor (dimensionless) for solubility of U in the +IV oxidation state in Castile brine.	2003	Added for completeness.
SOLTH4	SOLCIM	Uncertainty factor (dimensionless) for solubility of Th in the +IV oxidation state in Castile brine.	2003	Added for completeness.
DRZ_1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the DRZ.	2003	Added from 1997 PAVT (Hansen and Leigh 2003).
CONC_PLG	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of the concrete borehole plugs.	2003	Added from 1997 PAVT (Hansen and Leigh 2003).
GLOBAL	PBRINE	Probability that a drilling intrusion penetrates pressurized brine in the Castile Formation.	2003	Added due to change in Castile Brine pocket modeling (Section 6.12.4.6).
BOREHOLE	DOMEGA	Drill string angular velocity (rad/s).	2003	Added from 1997 PAVT (Hansen and Leigh 2003).
SHFTU	SAT_RBRN	Residual brine saturation in upper shaft seal materials (dimensionless).	2003	Added due to the simplified shaft model.
SHFTU	SAT_RGAS	Residual gas saturation in upper shaft seal materials (dimensionless).	2003	Added due to the simplified shaft model.
SHFTU	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of upper shaft seal materials.	2003	Added due to the simplified shaft model.
SHFTL_T1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of lower shaft seal materials for the first 200 years after closure.	2003	Added due to the simplified shaft model.
SHFTL_T2	PRMX_LOG	Logarithm of permeability of lower shaft seal materials (m^2) from 200 years to 10,000 years after closure.	2003	Added due to the simplified shaft model.
SPALLMOD	RNDSPALL	Indicator variable for selecting element from the LHS for DRSPALL.	2003	Use of DRSPALL to calculate spall volumes.

Table PA-18. Differences in Uncertain Parameters in the CCA PA and CRA-2004 PA — Continued

Material Name	Property Name	Description	When Used	Reason for Removal or Addition
CL_L_T1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) for clay components of shaft.	1996	Removed due to the simplified shaft model.
CONC_T1	PRMX_LOG	Logarithm of intrinsic permeability (m^2) for concrete component of shaft seal for 0 to 400 years.	1996	Removed due to the simplified shaft model.
ASPHALT	PRMX_LOG	Logarithm of intrinsic permeability (m^2) for clay components of shaft seal (m^2).	1996	Removed due to the simplified shaft model.
SHFT_DRZ	PRMX_LOG	Logarithm of intrinsic permeability (m^2) of DRZ surrounding shaft.	1996	Removed due to the simplified shaft model.
SALT_T1	CUMPROB	Pointer variable used to select intrinsic permeability in crushed salt component of shaft seal at different times.	1996	Removed due to the simplified shaft model.
CASTILER	GRIDFLO	Pointer variable for selection of brine pocket volume.	1996	Removed due to changes in Castile Brine pocket modeling (Section 6.12.4.6).
BLOWOUT	PARTDIA	Waste particle diameter (m).	1996	Removed due to replacement of spall model.

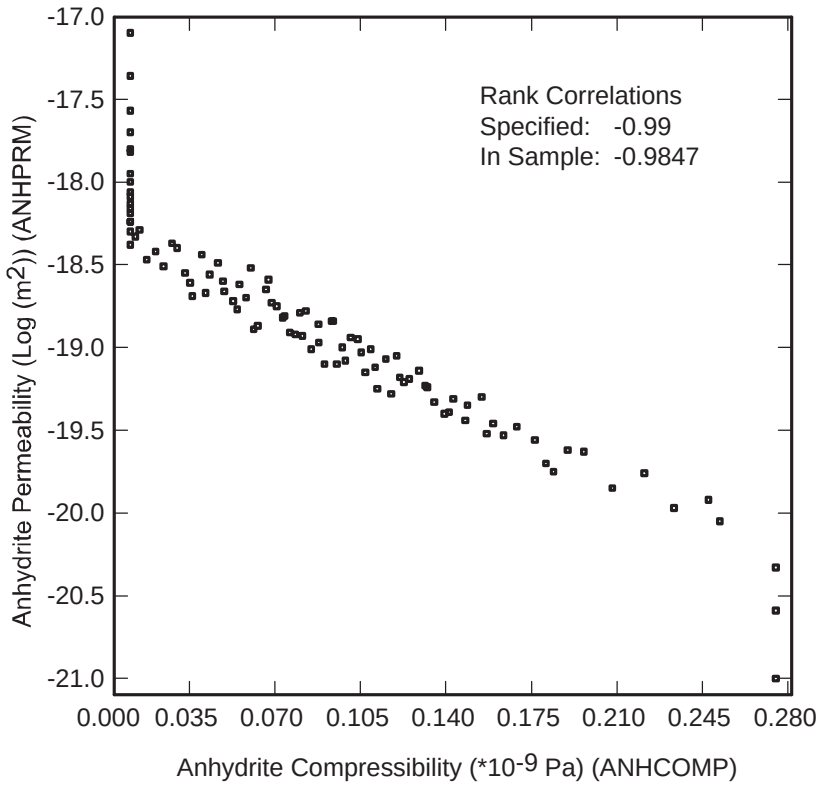

Figure PA-30. Correlation Between ANHCOMP and ANHPRM.

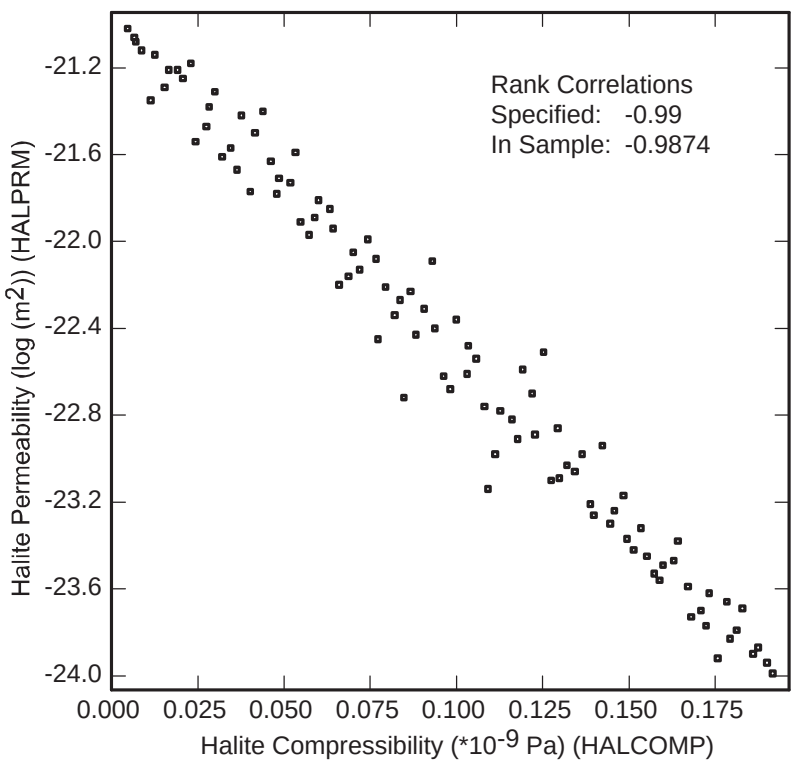

Figure PA-31. Correlation Between HALCOMP and HALPRM.

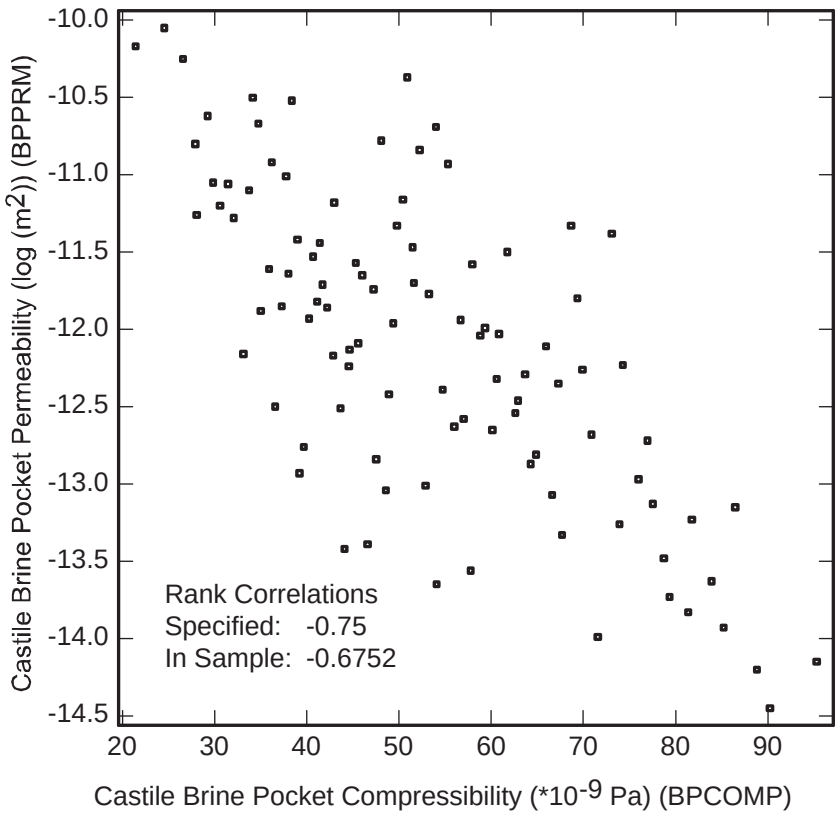

Figure PA-32. Correlation between BPCOMP and BPPRM.

PA-6.0 COMPUTATIONAL PROCEDURES

This section outlines the computational procedures used to execute the CRA-2004 PA. First, this section outlines the sampling procedures applied to evaluate performance accounting for subjective and stochastic uncertainty. The mechanistic calculations used to evaluate the function f in Equation (24) are tabulated, followed by a description of the algorithms used to compute releases. This section concludes with a discussion of sensitivity analysis techniques used to identify which uncertain parameters are primary contributors to the uncertainty in the PA results.

PA-6.1 Sampling Procedures

Extensive use is made of sampling procedures in the CRA-2004 PA. In particular, random sampling is used in the generation of individual CCDFs (i.e., for integration over the probability space $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$ for stochastic uncertainty; see Section PA-2.3) and Latin hypercube sampling is used for the assessment of the effects of imprecisely known analysis inputs (i.e., for integration over the probability space $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$ for subjective uncertainty; see Section PA-2.4).

In random sampling, sometimes also called simple random sampling, the observations

$$\boldsymbol{x_k} = \left[\boldsymbol{x_{k1}}, \boldsymbol{x_{k2}}, \ldots, \boldsymbol{x_{knV}}\right], \text{ k = 1, 2, ..., nR,} \tag{255}$$

where nR is the sample size, are selected according to the joint probability distribution for the elements of x as defined by $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$. In practice, $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$ is defined by specifying a distribution D_j for each element x_j of $\boldsymbol{x}$. Points from different regions of the sample space S_{st}, occur in direct relationship to the probability of occurrence of these regions. Furthermore, each sample element is selected independently of all other sample elements. The random sampling provides unbiased estimates for means, variances, and distributions of the elements x that comprise $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$.

The random sampling to integrate over the probability space for $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$ for stochastic uncertainty is implemented in the WIPP PA code CCDFGF. The code CCDFGF is capable of generating and evaluating thousands of possible futures; the CRA-2004 PA uses a sample size nS = 10,000 from the space $\left(\boldsymbol{X_{st}}, \boldsymbol{S_{st}}, \boldsymbol{p_{st}}\right)$ to estimate repository releases. This sample size is sufficient to estimate the 0.999 quantile of the distribution of releases to the accessible environment.

Latin hypercube sampling is used to integrate over the space for subjective uncertainty $\left(\boldsymbol{X_{su}}, \boldsymbol{S_{su}}, \boldsymbol{p_{su}}\right)$. This technique was first introduced by McKay et al (1979). In Latin hypercube sampling, the range of each variable (i.e., the x_j) is divided into nLHS intervals of equal probability and one value is selected at random from each interval. The nLHS values thus obtained for x_1 are paired at random without replacement with the nLHS values obtained for x_2. These nLHS pairs are combined in a random manner without replacement with the nLHS values

of x_3 to form nLHS triples. This process is continued until a set of nLHS nV-tuples is formed. These nV-tuples are of the form

$$\boldsymbol{x_k} = \left[x_{k1}, x_{k2}, \ldots, x_{knV} \right], \text{ k = 1, ..., nLHS,} \tag{256}$$

and constitute the Latin hypercube sample. The individual x_j must be independent for the preceding construction procedure to work; a method for generating Latin hypercube and random samples from correlated variables was developed by Iman and Conover (1982) and is used in WIPP PA. For more information about Latin hypercube sampling and a comparison with other sampling techniques, see Helton and Davis (2003).

Latin hypercube sampling provides unbiased estimates for means and distribution functions and dense stratification across the range of each sampled variable (McKay et al. 1979), ensuring that the sampled values cover the full range of each uncertain element x_j of $\boldsymbol{x}$. In particular, uncertainty and sensitivity analysis results obtained with Latin hypercube sampling are robust even when relatively small samples (i.e., nLHS = 50 to 200) are used (Iman and Helton 1988, 1991; Helton et al. 1995).

PA-6.2 Sample Size for Incorporation of Subjective Uncertainty

Section 194.34(d) states that "The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability." For an LHS of size nLHS, the preceding guidance is equivalent to the inequality

$$1 - 0.99^{nLHS} > 0.95, \tag{257}$$

which results in a minimum value of 298 for nLHS. The CRA-2004 PA uses a total sample size of 300 to integrate over the probability space $\left(X_{su}, S_{su}, p_{su} \right)$ for subjective uncertainty. As discussed in the next section, however, in order to demonstrate convergence of the mean for the population of CCDFs, the total sample of 300 is created by means of three replicated samples of size 100 each.

PA-6.3 Statistical Confidence on Mean CCDF

Section 194.34(f) states that "Any compliance assessment shall provide information which demonstrates that there is at least a 95 percent level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 of this chapter." Given that Latin hypercube sampling is used, the confidence intervals required by Section 194.34(f) are obtained with a replicated sampling technique proposed by Iman (1982). In this technique, the sampling in Equation (256) is repeated nR times with different random seeds. These samples lead to a sequence $\bar{P}_r(R),\ r = 1, 2, \ldots, nR,$ of estimated mean exceedance probabilities, where $\bar{P}_r(R)$ defines the mean CCDF obtained for sample r (i.e., $\bar{P}_r(R)$ is the mean probability that a normalized release of size R will be exceeded; see Section PA-2.4) and nR is the number of independent samples generated with different random seeds. Then,

$$\bar{P}(R) = \sum_{r=1}^{nR} \bar{P}_r(R) / nR \tag{258}$$

and

$$SE(R) = \left\{ \sum_{r=1}^{nR} \left[\bar{P}_r(R) - \bar{P}(R) \right]^2 / nR(nR-1) \right\}^{1/2} \tag{259}$$

provide an additional estimate of the mean CCDF and an estimate of the standard error associated with the mean exceedance probabilities. The t-distribution with nR–1 degrees of freedom can be used to place confidence intervals around the mean exceedance probabilities for individual R values (i.e., around $\bar{P}(R)$). Specifically, the 1–α confidence interval is given by $\bar{P}_r(R) \pm t_{1-\alpha/2} SE(R)$, where $t_{1-\alpha/2}$ is the $1-\alpha/2$ quantile of the t-distribution with nR–1 degrees of freedom (e.g., $t_1 - \alpha/2 = 4.303$ for α = 0.05 and nR = 3). The same procedure can also be used to place pointwise confidence intervals around percentile curves.

PA-6.4 Generation of LHSs

The LHS program (WIPP PA 1996) is used to produce three independently generated LHSs of size nLHS = 100 each, for a total of 300 sample elements. Each individual replicate is an LHS of the form

$$x_{su,k} = \left[x_{k1}, x_{k2}, \ldots, x_{knV} \right], \text{ k = 1, 2, …, nLHS = 100.} \tag{260}$$

In the context of the replicated sampling procedure described in Section PA-6.2, nR = 3 replicates of 100 are used. For notational convenience, the replicates are designated by R1, R2, and R3.

The restricted pairing technique described in Section PA-6.2 is used to induce requested correlations and also to assure that uncorrelated variables have correlations close to zero. The variable pairs (ANHCOMP, ANHPRM), (HALCOMP, HALPRM), and (BPCOMP, BPPRM) are assigned rank correlations of –0.99, –0.99, and –0.75, respectively (Section PA-5.4). All other variable pairs are assigned rank correlations of zero. The restricted pairing technique is very successful in producing these correlations (Table PA-19). Specifically, the correlated variables have correlations that are close to their specified values and uncorrelated variables have correlations that are close to zero.

Table PA-19. Example Correlations in Replicate R1

	WGRCOR	WMICDFLG	WGRMICI	WGRMICH	WFBETCEL	WRGSSAT	WRBRNSAT	WASTWICK
WGRCOR	1.0000							
WMICDFLG	-0.0993	1.0000						
WGRMICI	0.0152	0.0495	1.0000					
WGRMICH	0.0191	-0.0098	0.0150	1.0000				
WFBETCEL	0.0113	-0.0139	-0.0273	0.0033	1.0000			
WRGSSAT	0.0004	0.0712	-0.0451	-0.0058	-0.0517	1.0000		
WRBRNSAT	0.0192	0.0244	-0.0558	0.0321	-0.0128	-0.0260	1.0000	
WASTWICK	-0.0096	0.0955	-0.0099	0.0043	0.0057	-0.0147	0.0076	1.0000

PA-6.5 Generation of Individual Futures

Random sampling (Section PA-6.1) is used to generate elements $\boldsymbol{x_{st}}$ of S_{st} for CCDF construction. Table PA-20 outlines the algorithm used to generate a single future $\boldsymbol{x_{st}}$ in the CRA-2004 PA. For each LHS element $\boldsymbol{x_{su,k}}$, k = 1, 2, …, 300, a total of nS = 10,000 individual futures of the form

$$\boldsymbol{x_{st,i}} = \left[t_{i1}, e_{i1}, l_{i1}, b_{i1}, p_{i1}, a_{i1}, t_{i2}, e_{i2}, l_{i2}, b_{i2}, p_{i2}, a_{i2}, \ldots, t_{in}, e_{in}, l_{in}, b_{in}, p_{in}, a_{in}, t_{i,min} \right], \quad i = 1, 2, \ldots, nS = 10{,}000 \tag{261}$$

are generated in the construction of all CCDFs for that LHS element. A different random seed is used to initiate the sampling of $\boldsymbol{x_{st}}$ for each LHS element, with the result that each LHS element uses different values for $\boldsymbol{x_{st}}$ in CCDF construction. As 300 LHS elements are used in the analysis and 10,000 futures are sampled for each LHS element, the total number of futures $\boldsymbol{x_{st}}$ used in the analysis in CCDF construction is 3×10^6.

The drilling rate λ_d is used to generate the times at which drilling intrusions occur. For a Poisson process with a constant λ_d (i.e., a stationary process), the CDF for the time Δt between the successive events is given by (Ross 1987, p. 113)

$$prob\left(t \le \Delta t\right) = 1 - \exp\left(-\lambda_d \Delta t\right). \tag{262}$$

A uniformly distributed random number is selected from [0, 1]. Then, solution of

$$r_1 = 1 - \exp\left(-\lambda_d\, t_1\right) \tag{263}$$

Table PA-20. Algorithm to Generate a Single Future x_{st} from S_{st}

1. Sample t_1 with a time dependent λ_d given by $\lambda_d(t) = \begin{cases} 0 & \text{if } 0 \le t \le tA \\ \lambda_d & \text{if } t > tA \end{cases}$, where tA = 100 yr (i.e., time at which administrative control ends) and $\lambda_d = 3.30 \times 10^{-3}\ \text{yr}^{-1}$ (see Section PA-3.2).
2. Sample e_1 with a probability of $pE_0 = 0.797$ that the intrusion will be in an unexcavated area and a probability of $pE_1 = 0.203$ that the intrusion will be in an excavated area (see Section PA-3.3).
3. Sample l_1 with a probability of $pL_j = 6.74 \times 10^{-3}$ for each of the j = 1, 2, …, 144 nodes in Figure PA-6 (see Section PA-3.4).
4. Sample b_1 with a probability of $pB_1 = p(x_{su})$ that the intrusion will penetrate pressurized brine (see Section PA-3.5).
5. Sample p_1 with probabilities of $pPL_1 = 0.015$, $pPL_2 = 0.696$, and $pPL_3 = 0.289$ that plugging pattern 1, 2, or 3, respectively, will be used (see Section PA-3.6).
6. Sample a_1 (see Section PA-3.7). 6.1 Penetration of nonexcavated area (i.e., $e_1 = 0$): $a_i = a_1 = 0$. 6.2 Penetration of excavated area (i.e., $e_1 = 1$): Sample to determine if intrusion penetrates RH-TRU or CH-TRU waste with probabilities of pRH = 0.124 and pCH = 0.876 of penetrating RH-TRU and CH-TRU waste, respectively. 6.3 Penetration of RH-TRU waste: $a_i = a_1 = 1$. 6.4 Penetration of CH-TRU waste: Use probabilities pCH_j of intersecting waste stream j, j = 1, 2, …, 693, (see Attachment PAR, Table PAR-50) to independently sample three intersected waste streams iCH_{11}, iCH_{12}, iCH_{13} (i.e., each of iCH_{11}, iCH_{12}, iCH_{13} is an integer between 1 and 693). Then, a_1 = [2, iCH_{11}, iCH_{12}, iCH_{13}].
7. Repeat steps 1 - 6 to determine properties (i.e., t_i, e_i, l_i, b_i, p_i, a_i) of the ith drilling intrusion.
8. Continue until $t_{n+1} > 10{,}000$ yr; the n intrusions thusly generated define the drilling intrusions associated with x_{st}.
9. Sample t_{min} with a time dependent λ_m given by $\lambda_m(t) = \begin{cases} 0 & \text{if } 0 \le t \le tA \\ \lambda_m & \text{if } t > tA \end{cases}$ where tA = 100 yr and $\lambda_m = 1 \times 10^{-4}\ \text{yr}^{-1}$ (see Section PA-3.8).

for t_1 gives the time of the first drilling intrusion. An initial period of 100 years of administrative control is assumed, thus 100 years is added to the t_1 obtained in Equation (263) to obtain the time of the first drilling intrusion. Selection of a second random number r_2 and solution of

$$r_2 = 1 - \exp\left(-\lambda_d \, \Delta t_1\right) \tag{264}$$

for Δt_1 gives the time interval between the first and second drilling intrusions, with the outcome that $t_2 = t_1 + \Delta t_1$. This process is continued until t_{n+1} exceeds 10,000 yr. The times $t_1, t_2, \ldots, t_n$ then constitute the drilling times in x_{st} in Equation (261).

The mining time t_{min} is sampled in a manner similar to sampling the drilling times. Additional uniformly distributed random numbers from $[0,1]$ are used to generate the elements e_i, l_i, b_i, p_i, a_i of x_{st} from their assigned distributions (see Section PA-3.0).

PA-6.6 Construction of CCDFs

In the CRA-2004 PA, the sampling of individual futures (Section PA-6.5) and associated CCDF construction is carried out by the CCDFGF program (WIPP PA 2003d). The sampled futures $x_{st,i}$ in Equation (261) are used to construct CCDFs for many different quantities (e.g., cuttings and cavings releases, spallings releases, direct brine releases, etc.). The construction process is the same for each quantity. For notational convenience, assume that the particular quantity under consideration can be represented by a function $f\left(x_{st,i}\right)$, with the result that 10,000 values

$$f\left(x_{st,i}\right),\ i = 1, 2, \ldots, 10{,}000 \tag{265}$$

are available for use in CCDF construction. Formally, the resultant CCDF is defined by the expression in Equation (4). In practice, the indicator function δ_R is not directly used and the desired CCDF is obtained after an appropriate ordering of the $f\left(x_{st,i}\right)$ (i.e., from smallest to largest or largest to smallest) as described below.

The CRA-2004 PA uses a binning procedure in CCDF construction to simplify sorting the individual $f\left(x_{st,i}\right)$ and to reduce the number of plot points. Specifically, the range of f is divided into intervals (i.e., bins) by the specified points

$$f_{min} = b_0 < b_1 < b_2 < \ldots < b_n = f_{max}, \tag{266}$$

where f_{min} is the minimum value of f to be plotted (typically 10^{-6} or 10^{-5} when an EPA normalized release is under consideration), f_{max} is the maximum value of f to be plotted (typically 100 when an EPA normalized release is under consideration), n is the number of bins in use, and the b_i are typically loguniformly placed with 20 values per order of magnitude. A counter nB_j is used for each interval $\left[b_{j-1}, b_j\right]$. All counters are initially set to zero. Then, as individual values $f\left(x_{st,i}\right)$ are generated, the counter nB_j is incremented by 1 when the inequality

$$b_{j-1} < f\left(x_{st,i}\right) \le b_j \tag{267}$$

is satisfied. When necessary, f_{max} is increased in value so that the inequality $f\left(x_{st,i}\right) < f_{max}$ will always be satisfied. Once the 10,000 values for $f\left(x_{st,i}\right)$ have been generated, a value of nB_j exists for each interval $\left[b_{j-1}, b_j\right]$. The quotient

$$pB_j = nB_j / 10{,}000 \tag{268}$$

provides an approximation to the probability that $f\left(x_{st}\right)$ will have a value that falls in the interval $\left[b_{j-1}, b_j\right]$. The resultant CCDF is then defined by the points

$$\left(b_j,\ prob\left(value > b_j\right)\right) = \left(b_j,\ \sum_{k=j+1}^{n} pB_k\right) \tag{269}$$

for j = 0, 1, 2, …, n–1, where $prob\left(value > b_j\right)$ is the probability that a value greater than b_j will occur.

The binning technique produces histograms that are difficult to read when multiple CCDFs appear in a single plot. As the number of futures is increased and the bins are refined, the histogram CCDF should converge to a continuous CCDF as additional points (i.e., elements x_{st} of S_{st}) are used in its construction. The continuous CCDF is approximated by drawing diagonal lines from the left end of one bin to the left end of the next bin.

When multiple CCDFs appear in a single plot, the bottom of the plot becomes very congested as the individual CCDFs drop to zero on the abscissa. For this reason, each CCDF stops at the largest observed consequence value among the 10,000 values calculated for that CCDF. Stopping at the largest consequence value rather than the left bin boundary of the bin that contains this value permits the CCDF to explicitly show the largest observed consequence. Due to the use of a sample size of 10,000 in the generation of CCDFs for comparison with the EPA release limits, the last nonzero exceedance probability in the resultant CCDFs is typically 10^{-4}; Figure PA-5 shows an example of CCDFs from the 2004 PA.

PA-6.7 Mechanistic Calculations

For the CRA-2004 PA, calculations were performed with the models described in Chapter PA-4.0 for selected elements of S_{st} (see Section PA-3.9) and the results were used to determine the releases to the accessible environment for the large number (i.e., 10,000) of randomly sampled futures used in the estimation of individual CCDFs. The same set of mechanistic calculations was performed for each LHS element. This section summarizes the calculations performed with each of the models described in Chapter PA-4.0; Section PA-6.8 outlines the algorithms used to construct releases for the randomly sampled elements $x_{st,i}$ of S_{st} from the results of the

mechanistic calculations. Long (2003) documents execution of the calculations and archiving of calculation results.

PA-6.7.1 BRAGFLO Calculations

The BRAGFLO code (Section PA-4.2) computes two-phase (brine and gas) flow in and around the repository. BRAGFLO results are used as initial conditions in the models for Salado Transport (implemented in NUTS and PANEL), spallings (implemented in CUTTINGS_S) and DBR (also calculated by BRAGFLO). Thus, the BRAGFLO scenarios are used to define scenarios for other codes.

The four fundamental scenarios for the CRA-2004 PA (Section PA-3.9) define four categories of calculations to be performed with BRAGFLO (i.e., E0, E1, E2, and E1E2). These four fundamental scenarios were expanded into six general scenarios by specifying the time of drilling intrusions. Table PA-21 summarizes the specific scenarios used in the CRA-2004 PA. A total of 6 scenarios × nR × nLHS = 6 × 3 × 100 = 1800 BRAGFLO calculations were conducted for the CRA-2004 PA.

Table PA-21. BRAGFLO Scenarios in the CRA-2004 PA

Fundamental Scenario (Section PA-3.9)	*Specific Scenario*	*Time of drilling intrusion(s)*
E0: no drilling intrusions	S1	N/A
E1: single intrusion into excavated area (e_1 = 1), pressurized brine is penetrated (b_1 = 1), and plugging pattern 2 is used (p_1 = 2).	S2	350 years
	S3	1,000 years
E2: single intrusion into excavated area (e_1 = 1), pressurized brine is penetrated (b_1 = 1) and plugging pattern 3 is used (p_1 = 3), or pressurized brine is not penetrated (b_1 = 0).	S4	350 years
	S5	1,000 years
E1E2: two intrusions into the same waste panel (e_1 = e_2 = 1), the first being an E2 intrusion and the second being an E1 intrusion.	S6	800 years for E2 intrusion 2,000 years for E1 intrusion

Values for the activity level a_1 and for mining time t_{min} are not needed for the mechanistic calculations; these values are used in the construction of the releases from the results of the mechanistic calculations (Section PA-6.8). Although a value for drilling location l_1 is not specified, a drilling location is required for the BRAGFLO calculations. If equivalent grids were used in the definition of x_{st} (Figure PA-6) and in the numerical solution of the partial differential equations on which BRAGFLO is based (Figure PA-8), the location of the drilling intrusion used in the BRAGFLO calculations could be specified as a specific value for l_1, which in turn would correspond to one of the 144 locations in Figure PA-6 that are designated by l in the definition of x_{st}. However, as these grids are not the same, a unique pairing between a value for l_1 and the location of the drilling intrusion used in the computational grid employed with BRAGFLO is not possible. The BRAGFLO computational grid divides the repository into

a lower waste panel (area Waste Panel), a middle group of four waste panels (area South RoR), and an upper group of five waste panels (area North RoR), with the drilling intrusion taking place through the center of the lower panel (Figure PA-8). Thus, in the context of the locations in Figure PA-6 potentially indexed by l_1, the drilling intrusions in Scenario S2, Scenario S3, Scenario S4 and Scenario S5 occur at a location in Panel 5. In Scenario S6, both intrusions occur at a location in Panel 5, with the effects of flow between the two boreholes implemented through assumptions involving the time-dependent behavior of borehole permeability (Table PA-5).

PA-6.7.2 NUTS Calculations

Transport through the Salado is computed by the code NUTS (Section PA-4.3) using the flow fields computed by BRAGFLO. Two types of calculations are performed with NUTS. First, a set of screening calculations identifies elements of the sample from S_{su} for which radionuclide transport is possible through the Salado to the LWB or to the Culebra. The screening calculations identify a subset of the sample from S_{st} for which transport is possible and for which releases calculations are performed. Screening calculations are performed for all BRAGFLO cases, for a total of 1500 screening calculations with NUTS (Table PA-21). Table PA-22 summarizes the NUTS release calculations for the CRA-2004 PA. Based on the screening calculations, a total of 1402 release calculations are performed for the CRA-2004 PA. For each vector that is retained (based on the screening calculations), release calculations are performed for a set of intrusion times.

Table PA-22. NUTS Release Calculations in the CRA-2004 PA

NUTS Scenario	Number of vectors (all replicates)	Flow field	Intrusion time (t_1)
S1	1 + 0 + 0 = 1	BRAGFLO S1 scenario	N/A
S2	60 + 64 + 61 = 185	BRAGFLO S2 scenario	E1 intrusion at 100 and 350 years
S3	49 + 55 + 51 = 155	BRAGFLO S3 scenario	E1 intrusion at 1,000, 3,000, 5,000, 7,000 and 9,000 years
S4	13 + 14 + 11 = 38	BRAGFLO S4 scenario	E2 intrusion at 100, 350 years
S5	12 + 13 + 11 = 36	BRAGFLO S5 scenario	E2 intrusion at 1,000, 3,000, 5,000, 7,000 and 9,000 years

Table PA-22 lists five scenarios for release calculations corresponding to the five BRAGFLO scenarios. Each NUTS scenario uses the flow field computed for the corresponding BRAGFLO scenario. The intrusion times for the NUTS scenarios are accommodated by shifting the BRAGFLO flow fields in time so that the NUTS and BRAGFLO intrusions coincide. For example, the NUTS S3 scenario with an intrusion at 3,000 years requires a flow field for the time interval between (3,000 yr, 10,000 yr); this scenario uses the BRAGFLO S3 flow field for the time interval between (1,000 yr, 8,000 yr).

Values for the variables indicating intrusion into excavated area (e_1), penetration of pressurized brine (b_1), plugging pattern (p_1) and drilling location (l_1) are the same as in the corresponding

BRAGFLO scenario. Values for the activity level a_i and for mining time t_{min} are not specified for the NUTS scenarios.

PA-6.7.3 PANEL Calculations

As outlined in Section PA-4.4, the code PANEL is used to estimate releases to the Culebra associated with E1E2 scenarios and to estimate radionuclide concentrations in brine for use in the estimation of direct brine releases. An E1E2 scenario assumes two drilling intrusions into the same waste panel: the first intrusion being an E2 intrusion (Table PA-22) occurring at time t1 and the second intrusion being an E1 intrusion (Table PA-22) occurring at time t_2. PANEL calculations are performed for t_2 = 100, 350, 1,000, 2,000, 4,000, 6,000 and 9,000 years using the flow field produced by the single BRAGFLO calculation for Scenario S6, for a total of 7 × nR × nLHS = 7 × 3 × 100 = 2100 PANEL calculations. The BRAGFLO flow field is shifted forward or backward in time as appropriate so that the time of the second intrusion (t_2) coincides. The shifting of the BRAGFLO flow field results in values for the time (t_1) of the first intrusion (E2) for the PANEL calculations given by

$$t_1 = \max\left\{100\,yr,\ t_2 - 1200\,yr\right\}, \tag{270}$$

where the restriction that t_1 cannot be less than 100 years results from the definition of x_{st}, which does not allow negative intrusion times, and from the assumption of 100 years of administrative control during which there is no drilling (i.e., $\lambda_d(t)$ = 0 yr^{-1} for $0 \le t \le 100$ yr; see Equation (7)). Under this convention, what is specified in concept by the definition of Scenario S6 for the BRAGFLO calculations differs from what is actually done computationally because t_1 does not always precede t_2 by 1200 yr in the PANEL calculation. Values for the other variables defining the element x_{st} of S_{st} for the PANEL E1E2 scenarios are the same as in the BRAGFLO S6 scenario.

Calculation of radionuclide concentration are not specific to any BRAGFLO scenario. The concentration calculations compute the mobilized activity in two different brines (Castile and Salado) and are performed at 100, 125, 175, 350, 1,000, 3,000, 5,000, 7,500 and 10,000 years for a total of 2 × 9 × nR = 54 calculations.

PA-6.7.4 CUTTINGS_S Calculations

The code CUTTINGS_S computes the volumes of solids removed from the repository by cuttings and cavings (see Section PA-4.5) and spallings (see Section PA-4.6). Table PA-23 lists the CUTTINGS_S calculations performed for the CRA-2004 PA, totaling 78 × nR × nLHS = 78 × 3 × 100 = 23,400 CUTTINGS_S calculations.

Table PA-23. CUTTINGS_S Scenarios in the CRA-2004 PA

Scenario	Description
S1	Intrusion into lower, middle, and upper waste panel in undisturbed (i.e., E0 conditions) repository at 100, 350, 1,000, 3,000, 5,000, and 10,000 years = 18 combinations.
S2	Initial E1 intrusion at 350 years followed by a second intrusion into the same, adjacent, and nonadjacent waste panel at 550, 750, 2,000, 4,000 or 10,000 years = 15 combinations.
S3	Initial E1 intrusion at 1000 years followed by a second intrusion into the same, adjacent, and nonadjacent waste panel at 1200, 1,400, 3,000, 5,000 or 10,000 years = 15 combinations.
S4	Initial E2 intrusion at 350 years followed by a second intrusion into the same, adjacent, and nonadjacent waste panel at 550, 750, 2,000, 4,000 or 10,000 years = 15 combinations.
S5	Initial E2 intrusion at 1000 years followed by a second intrusion into the same, adjacent, and nonadjacent waste panel at 1,200, 1,400, 3,000, 5,000 or 10,000 years = 15 combinations.

The CUTTINGS_S S1 scenario computes volumes of solid material released from the initial intrusion in the repository. Initial conditions for the CUTTINGS_S S1 scenario are taken from the results of the BRAGFLO S1 scenario at the time of the intrusion for areas Waste Panel, South RoR, and North RoR in Figure PA-8, corresponding to the lower, middle, and upper waste panels. In this scenario, the excavated area is penetrated ($e_1 = 1$) and the drilling location (l_1) is defined as one of the nodes (Figure PA-6) in the appropriate panel of Figure PA-20. The actual locations at which the intrusions are assumed to occur correspond to the points in Figure PA-20 designated “Down-dip well,” “Middle well,” and “Up-Dip Well” for the lower, middle, and upper waste panel, respectively. Values for the variables indicating penetration of pressurized brine (b_1), plugging pattern (p_1), activity level ($\boldsymbol{a_1}$), and for mining time (t_{min}) are not specified for the CUTTINGS_S S1 scenario.

The other CUTTINGS_S scenarios (Scenario S2, Scenario S3, Scenario S4, and Scenario S5) compute volumes of solids released by a second or subsequent intrusion. Initial conditions are taken from the results of the corresponding BRAGFLO scenario at the time of the second intrusion. As in the BRAGFLO scenarios, the first intrusion occurs in the lower waste panel (area Waste Panel in Figure PA-8) so the drilling location (l_1) is defined as one of the nodes in Panel 5 (Figure PA-6). The second intrusion occurs in the same waste panel as the first intrusion (area Waste Panel in Figure PA-8), an adjacent waste panel (area South RoR in Figure PA-8), or a nonadjacent waste panel (area North RoR in Figure PA-8). Hence the drilling location (l_2) is defined as one of the nodes (Figure PA-6) in the appropriate panel of Figure PA-20.

The activity level for the first intrusion $\boldsymbol{a_1}$ takes a value that indicates penetration of CH-TRU waste (i.e., $\boldsymbol{a_1}$ = [2, CH_{11}, CH_{12}, CH_{13}]) but the specific waste streams penetrated (i.e. CH_{11}, CH_{12}, CH_{13}) are not specified. For the second intrusion, the excavated area is penetrated

(e_2 = 1) and the drilling location (l_2) is defined as one of the nodes (Figure PA-6) in the appropriate panel, as described above. The actual locations at which the intrusions are assumed to occur correspond to the point in Figure PA-20 designated "Down-dip well" for the first intrusion for Category (1) intrusions and "Up-dip well, first or second intrusion" for Category (2) intrusions. As for the first intrusion, the activity level a_2 only indicates penetration of CH-TRU waste. Values for the other variables defining the first intrusion (e_1, b_1, and p_1) are the same as in the corresponding BRAGFLO scenario. Values for the other variables defining the second intrusion (b_2 and p_2) and the mining time t_{min} are not specified for the CUTTINGS_S scenarios.

PA-6.7.5 BRAGFLO Calculations for Direct Brine Release Volumes

Volumes of brine released to the surface at the time of an intrusion are calculated using BRAGFLO as described in Section PA-4.7. Calculations of DBR volumes were conducted for the same scenarios as for CUTTINGS_S (Table PA-23). Thus, the elements of S_{st} described in Section PA-6.7.4 also characterize the elements of S_{st} for which DBR volumes are computed; a total of 23,400 BRAGFLO calculations were performed.

PA-6.7.6 MODFLOW Calculations

As described in Section PA-4.8, the MODFLOW calculations produce flow fields in the Culebra for two categories of conditions: partially-mined conditions in the vicinity of the repository and fully-mined conditions in the vicinity of the repository (Figure PA-23). As specified in 40 CFR § 194.32(b), partially-mined conditions are assumed to exist by the end of the period of administrative control (i.e., at 100 years after closure). After the time that mining occurs within the LWB (t_{min}; see Section PA-3.8), fully-mined conditions are assumed for the remainder of the 10,000 regulatory period. The flow fields for partially-mined conditions are calculated by MODFLOW using the t-fields for partially-mined conditions (see Section PA-4.8.2). Additional MODFLOW calculations determine the flow fields for fully-mined conditions and are performed using the t-fields for fully-mined conditions. Thus a total of 2 × nR × nLHS = 2 × 3 × 100 = 600 MODFLOW calculations were performed. The element CTRAN of x_{su} (see Table PA-17) specifies the association between the uncertain transmissivity fields and the calculation of flow fields by MODFLOW.

Table PA-24. MODFLOW Scenarios in the CRA-2004 PA

MODFLOW: 600 Flow-Field Calculations
PM: Partially mined conditions in vicinity of repository
FM: Fully mined conditions in vicinity of repository
Total calculations = 2 nR nLHS = 2 × 3 × 100 = 600
Note: Only 100 unique transmissivity fields were constructed with MODFLOW for use in the analysis. The transmissivity fields are an input to the calculation of flow-fields. In each replicate, the transmissivity field used for a particular flow field was assigned using an index value (CTRAN, see Table PA-17) included in the LHS.

PA-6.7.7 SECOTP2D Calculations

The SECOTP2D calculations are performed for the same elements $x_{st,0}$ and $x_{st,m}$ of S_{st} defined in Section PA-6.7.6 for the MODFLOW calculations for a total of $2 \times nR \times nLHS = 2 \times 3 \times 100 = 600$ SECOTP2D calculations.

Table PA-25. SECOTP2D Scenarios in the CRA-2004 PA

SECOTP2D: 600 Calculations
PM: Partially mined conditions in vicinity of repository
FM: Fully mined conditions in vicinity of repository
Total calculations = 2 nR nLHS = $2 \times 3 \times 100 = 600$
Note: Each calculation includes a unit release of each of four radionuclides: ^{241}Am, ^{239}Pu, ^{230}Th, ^{234}U.

PA-6.8 Computation of Releases

The mechanistic computations outlined in Section PA-6.7 are used to compute releases for each sampled element x_{st} of S_{st}. Releases from the repository can be partitioned into three categories: undisturbed releases, which may occur in futures without drilling intrusions; direct releases, which occur at the time of a drilling event; and long-term releases, which occur as a consequence of a history of drilling intrusions. For a given future (x_{st} of S_{st} in Equation (261)) other than undisturbed conditions ($x_{st,0}$) the direct and long-term releases are computed by the code CCDFGF (WIPP PA 2003a) from the results of the mechanistic calculations summarized in Section PA-6.7, performed with the models presented in Chapter PA-4.0. Releases from an undisturbed repository are computed from the results of the NUTS S1 scenario (Section PA-6.7.2).

PA-6.8.1 Undisturbed Releases

Releases from the repository for the futures ($x_{st,0}$) in which no drilling intrusions occur are computed by the NUTS release calculations for E0 conditions (Table PA-22). The NUTS model computes the activity of each radionuclide that reaches the accessible environment during the regulatory period via transport through the MBs and through the Dewey Lake Red Beds. These releases are represented as $f_{MB}\left[x_{st,0}, f_B\left(x_{st,0}\right)\right]$ and $f_{DL}\left[x_{st,0}, f_B\left(x_{st,0}\right)\right]$ in Equation (24).

PA-6.8.2 Direct Releases

Direct releases include cuttings, cavings, spallings, and DBRs. The model for each component of direct releases computes a volume (solids or liquid) released to directly to the surface for each drilling intrusion. These volumes are combined with an appropriate concentration of activity in the released waste.

PA-6.8.3 Construction of Cuttings and Cavings Releases

Each drilling intrusion encountering waste is assumed to release a volume of solid material as cuttings as described in Section PA-4.5.2. The uncompacted volume of waste removed by cuttings (V_{cut}) is computed by Equation (104). In addition, drilling intrusions that encounter CH-TRU waste may release additional solid material as cavings, as described in Section PA-4.5.2. The uncompacted volume of material removed by cuttings and cavings combined ($\boldsymbol{V} = \boldsymbol{V_{cut}} + \boldsymbol{V_{cav}}$) is computed by Equation (105). For a drilling intrusion that encounter RH-TRU waste, the final eroded diameter D_f in Equation (105) is equal to the bit diameter in Equation (104). In the CRA-2004 PA, all drilling intrusions assume a drill bit diameter of 12.25 in (Attachment PAR, Table PAR-13).

The uncompacted volume of material removed is not composed entirely of waste material; rather, the uncompacted volume includes MgO and any void space initially present around the waste containers. The volume of waste removed (V_w) is determined by multiplying the uncompacted volume by the fraction of excavated volume (FVW) of the repository that is occupied by waste. In the CRA-2004 PA, FVW = 0.386 for CH-TRU waste and FVW = 1.0 for RH-TRU waste (Attachment PAR, Table PAR-45), thus

$$\boldsymbol{V_w} = \boldsymbol{V} \times \boldsymbol{FVW} \ . \tag{271}$$

The activity in the material released by cuttings and cavings is determined by stochastically selecting a subset of the set of all waste streams. The vector ($\boldsymbol{a_i}$) described in Section PA-3.7 determines which type of waste (CH-TRU or RH-TRU) and which waste streams are selected. The activity per m^3 of waste stream volume is computed for each waste stream at a discrete set of times by the code EPAUNI (Fox 2003), the results of the EPAUNI calculations are presented in Attachment PAR, Tables PAR-50 through PAR-61. Activities at other times are determined by linear interpolation. The cuttings and cavings release $\boldsymbol{f_C}\left(\boldsymbol{x_{st}}\right)$ is the product of the average activity per m^3 (C_r, computed as the average activity over the waste streams comprising the selected subset with the assumption that each waste stream contributes an equal volume to the release) and the volume of waste released (Equation (272)).

$$\boldsymbol{f_C}\left(\boldsymbol{x_{st}}\right) = \boldsymbol{V_w} \times \boldsymbol{C_r} \ . \tag{272}$$

PA-6.8.4 Determining Initial Conditions for Direct and Transport Releases

A sequence of intrusions into the repository can change the conditions in and around the repository and hence affect releases from subsequent intrusions. This section describes how panel and repository conditions are determined for a given intrusion.

PA-6.8.4.1 Determining Repository and Panel Conditions

Direct releases by DBR and spallings, and subsequent releases by radionuclide transport require a determination of the conditions in the intruded panel and in the repository at the time of the intrusion. One of three conditions is assigned to the repository:

E0 the repository is undisturbed by drilling,

E1 the repository has at least one E1 intrusion, or

E2 the repository has one or more E2 intrusions but no E1 intrusions.

In addition, each panel is assigned one of four conditions:

E0 the excavated regions of the panel have not been intruded by drilling,

E1 the panel has one previous E1 intrusions (intersects a brine reservoir in the Castile),

E2 the panel has one or more previous E2 intrusions (none intersect brine reservoirs), or

E1E2 the panel has at least two previous intrusions, at least one of which is an E1 intrusion.

Repository conditions are used to determine direct releases for each intrusion by DBRs and spallings. Panel conditions are used to determine releases by transport through the Culebra.

When an intrusion into CH-TRU waste occurs, the stochastic variables in Table PA-20 are used in the algorithm shown in Figure PA-33 to determine the type of the intrusion (E1 or E2). The type of the intrusion is used to update the conditions for the intruded panel and the repository before stepping forward in time to the next intrusion.

PA-6.8.4.2 Determining Distance from Previous Intrusions

Direct releases by DBR and spallings require a determination of the distance between the panel hit by the current intrusion and the panels hit by previous intrusions. In the CRA-2004 PA, the 10 panels are divided into three groups: lower, consisting of only panel 5; middle, including of panels 3, 4, 6, and 9; and upper, including of panels 1, 2, 7, 8, and 10, as shown in Figure PA-21. These divisions are consistent with the representation of the repository in the BRAGFLO model for Salado flow (Section PA-4.2) and for DBRs (Section PA-4.7).

Although the initial intrusion can occur in any of the 10 actual waste panels, direct releases for the initial intrusion are modeled as if the initial intrusion occurred in a lower waste panel (panel 4 or 5; see Figure PA-6), by using initial conditions for direct releases from the waste panel in the BRAGFLO grid (Figure PA-8), which are mapped to the lower panel in Figure PA-21. This treatment is the same as in the CCA PA and is conservative, since the waste panel typically has higher brine saturation than do the panels in the rest of repository areas (see Sections PA-7.1.2 and PA-8.3.2). Initial conditions for direct releases from subsequent intrusions are modeled by one of three cases: lower, middle, and upper, corresponding to the three panel groups shown in Figure PA-21 and listed in Table PA-24. The lower case represents a second intrusion into a previously intruded panel. The middle case represents an intrusion into an undisturbed

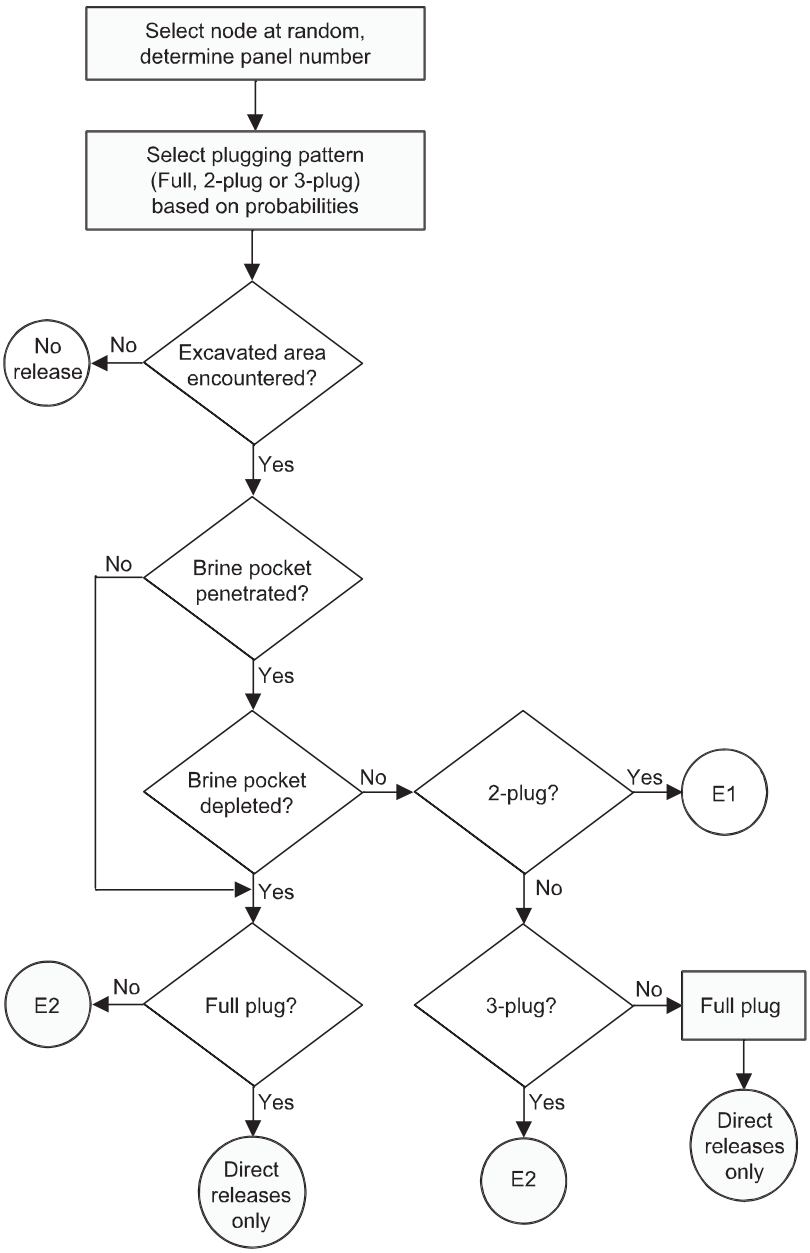

Figure PA-33. The Determination of the Type of Intrusion.

panel that is adjacent to a previously disturbed panel. The upper case represents an intrusion into an undisturbed panel that is not adjacent to a previously disturbed panel. Adjacent panels share one side in common and nonadjacent panels share no sides in common.

Selection of the time and location of the previous intrusion used to determine distance from the current intrusion depends on the repository condition. The repository condition is determined by the intrusion of greatest consequence across all panels prior to the current intrusion. E1 intrusions are assumed to be of the greater consequence than E2 intrusions. The previous intrusion is selected by finding the closest panel (same, adjacent, nonadjacent) whose intrusion condition, excluding the current intrusion, is equal to the repository condition. The time of the

previous intrusion is the time of the most recent intrusion having the greatest consequence and closest distance. Likewise, the condition of each panel is equal to the intrusion of greatest consequence into the panel prior to the current intrusion.

PA-6.8.5 Construction of Direct Brine Releases

DBRs (also termed blowout releases) are calculated for all intrusions that encounter CH-TRU waste. DBRs $f_{DBR}(x_{st})$ are constructed from volume of brine released (V_{DBR}) to the surface (Equation (175)) and radionuclide concentrations in brine (C_{bl}, see Equation (85)). Brine volume released to the surface is computed by BRAGFLO (Section PA-4.7.3) for the times listed in Table PA-23; brine volumes released for intrusions at other times are computed by linear interpolation (WIPP PA 2003d).

Calculation of DBR volumes distinguishes between the first intrusion and subsequent intrusions. The release volumes for the initial intrusion (E0 repository conditions) are further distinguished by the panel group (upper, middle, and lower). As shown in Table PA-23, BRAGFLO computes release volumes for the initial intrusion at each of a series of intrusion times; the release volume for the initial intrusion at other times is computed by linear interpolation (WIPP PA 2003a). Release volumes for subsequent intrusions are distinguished by the current state of the repository (E1 or E2) and the relative distance between the panel intruded by the current borehole and the panel of the initial intrusion (same, adjacent, non-adjacent). The algorithms for determining repository conditions and distance between intrusions are described in Section PA-6.8.4.

As indicated in Table PA-23, DBR volumes for a second intrusion are computed by BRAGFLO for a set of combinations of repository condition, distance between intrusions, and time between intrusions. Brine release volumes for other combinations of condition, distance, and time are computed by linear interpolation (WIPP PA 2003a). Brine releases from third and subsequent intrusions are computed as if the current intrusion was the second intrusion into the repository.

Radionuclide concentrations in brine (C_{bl}) are calculated by PANEL (Section PA-6.7.3) for the times listed in Table PA-22; concentrations at other times are computed by linear interpolation (WIPP PA 2003a). The type of intrusion (E1 or E2) determines the brine (Salado or Castile brine) selected for the concentration calculation; for E1 intrusions, Castile brine is used, and Salado brine is used for E2 intrusions.

The direct brine release is computed as the product of the release concentration and the volume, V_{DBR}, i.e.

$$f_{DBR}(x_{st}) = V_{DBR} \times C_{bl} \tag{273}$$

PA-6.8.6 Construction of Spallings Releases

Spallings releases are calculated for all intrusions that encounter CH-TRU waste. The construction of the spallings release $f_{SP}(x_{st})$ is nearly identical to that described in Section PA-6.8.5 for the calculation of DBRs except that volumes of solid material released will be used rather than volumes of brine. These solid releases are calculated with the spallings submodel of

the CUTTINGS_S program for the combinations of repository condition, distance from previous intrusions, and time between intrusions listed in Table PA-23. Linear interpolation determines the releases for other combinations of repository condition, distance, and time between intrusions (WIPP PA 2003a).

The concentration of radionuclides in the spallings release volume is computed as the average activity per m^3 in the CH-TRU waste at the time of intrusion. Activities in each waste stream are computed at a discrete set of times by the code EPAUNI (Fox 2003); activities at other times are determined by linear interpolation.

PA-6.8.7 Radionuclide Transport Through the Culebra

One potential path for radionuclide transport from the repository is up through boreholes to the Culebra, then through the Culebra to the LWB (Section 6.4.6). As indicated in Table PA-22, the NUTS and PANEL models are used to estimate radionuclide transport through boreholes to the Culebra $f_{NP}(x_{st})$ for a fixed set of intrusion times; releases to the Culebra for intrusions at other times are determined by linear interpolation (WIPP PA 2003a). NUTS computes the release to the Culebra over time for E1 and E2 boreholes; PANEL computes the release to the Culebra for an E1E2 borehole.

Each borehole may create a pathway for releases to the Culebra. The first E1 or E2 borehole in each panel creates a release path, with the radionuclide release taken from the appropriate NUTS data. Subsequent E2 boreholes into a panel with only E2 boreholes do not cause additional releases; WIPP PA assumes that a subsequent E2 borehole into a panel having only earlier E2 intrusions does not provide a significant source of additional brine, and thus does not release additional radionuclides to the Culebra.

An E1E2 borehole results from the combination of two or more intrusions into the same panel, at least one of which is an E1 intrusion. A subsequent E1 borehole changes the panel's condition to E1E2, as does an E2 borehole into a panel that has an earlier E1 intrusion. Once E1E2 conditions exist in a panel, they persist throughout the regulatory period. However, releases from a panel with E1E2 conditions are restarted for each subsequent E1 intrusion into that panel, since additional E1 intrusions may introduce new volumes of brine to the panel.

Releases to the Culebra are summed across all release pathways to the Culebra to obtain total releases to the Culebra $r_k(t)$ for the kth radionuclide at each time t. Releases to the Culebra include both dissolved radionuclides and radionuclides sorbed to colloids. The WIPP PA assumes that radionuclides sorbed to humic colloids disassociate and transport as do dissolved radionuclides; other colloid species do not transport in the Culebra (see Attachment SOTERM). The release to the Culebra is partitioned into dissolved and colloid species by multiplying $r_k(t)$ by radionuclide-specific factors for the fraction dissolved and the fraction on colloids (see Table 4.3.1). Dissolved radionuclides are transported through the Culebra.

Radionuclide transport through the Culebra is computed by the code SECOTP2D (Section PA-4.9) for partially-mined and fully-mined conditions (Section 6.4.6.2.3) as indicated in Table PA-25. These computations assume a 1 kg source of each radionuclide placed in the Culebra

between 0 and 50 years, and result in the fraction of each source $f_{m,k}(t)$, where m is the mining condition and k is the index for the radionuclide) reaching the LWB at each subsequent time t. For convenience, the time-ordering of the data from SECOTP2D is reversed so that the fraction $f_{m,k}(t)$ associated with year t = 200, for example, represents the release at the boundary at year 10,000 for a release occurring between 150 and 200 years.

The total release through the Culebra $R_{Cul,k}$ is calculated for the kth radionuclide by

$$R_{Cul,k} = \sum_{t_i \le t_m} r_k(t_i)\, f_{PM,k}(t_i) + \sum_{t_i > t_m} r_k(t_i)\, f_{FM,k}(t_i), \tag{274}$$

where $r_k(t_i)$ is the release of the kth radionuclide to the Culebra in kg at time t_i and $f_{PM,k}(t_i)$ and $f_{FM,k}(t_i)$ are the fractions of a unit source placed in the Culebra in the interval (t_{i-1}, t_i) that reaches the LWB by the end of the 10,000-year regulatory period, for partial mined and fully mined conditions within the LWB, respectively. The function $f_{m,k}(t)$ changes when mining is assumed to occur within the LWB; hence the sum in the equation above is evaluated in two parts, where t_{min} is the time that mining occurs. The total releases through the Culebra $f_{ST}(x_{st})$ is computed by converting the release of each radionuclide $R_{Cul,k}$ from kg to EPA units, then summing over all radionuclides.

PA-6.8.8 CCDF Construction

For each vector $x_{su,k}$ in the space of subjective uncertainty, the code CCDFGF samples a sequence $x_{st,i}$, i = 1, 2, …, nS of futures. In the CRA-2004 PA, nS = 10,000; this number of futures is sufficient to generate an adequate estimate of the mean CCDF for total releases for comparison with the boundary line specified in 40 CFR § 191.13, as demonstrated in Section PA-9.1. A release $f(x_{st,i})$ for each future is then constructed as described in Sections PA-6.8.1 through PA-6.8.7. Once the $f(x_{st,i})$ are evaluated, the CCDF can be approximated as indicated in Equation (275).

$$prob(Rel > R) = \int_{S_{St}} \delta_R\left[f(x_{st})\right] d_{st}(x_{st})\, dV_{st} \cong \sum_{i=1}^{nS} \delta_R\left[f(x_{st,i})\right] / nS \tag{275}$$

A binning technique is used to construct the desired CCDF (i.e., the consequence axis is divided into a sequence of bins and the number of values for $f(x_{st,i})$ falling in each bin is accumulated). In addition, all values for $f(x_{st,i})$ are saved and subsequently ordered to provide an alternative method for constructing the CCDFs. In addition to the total CCDF for all releases, it will be possible to obtain CCDFs for individual release modes (e.g., cuttings,

spallings, direct brine releases, to Culebra, through MBs, through Culebra). The logic for the production of the CCDFs is diagrammed in Figure PA-34.

The CCDF construction indicated in this section is for a single sample element $\boldsymbol{x}_{su,k}$ of the form indicated in conjunction with Equation (260). Repeated generation of CCDFs for individual sample elements $\boldsymbol{x}_{su,k}$, i.e. for the vectors representing epistemic uncertainty in the model results, will lead to the distribution of complete CCDFs.

PA-6.9 Sensitivity Analysis

Evaluation of one or more of the models discussed in Chapter PA-4.0 with the LHS in Equation (260) creates a mapping

$$\left\{\boldsymbol{x}_{su,k}, \boldsymbol{y}_{su,k}\right\}, \text{ k = 1, 2, …, nLHS} \tag{276}$$

from analysis inputs (i.e., $\boldsymbol{x}_{su,k}$) to analysis results (i.e., $\boldsymbol{y}\left(\boldsymbol{x}_{su,k}\right)$), where $\boldsymbol{y}_{su,k}$ denotes the results obtained with the model or models under consideration. A vector notation is used for y because, in general, a large number of predicted results are produced by each of the models used in the CRA-2004 PA. In addition, $\boldsymbol{y}\left(\boldsymbol{x}_{su,k}\right)$ could also correspond to a CCDF for normalized release constructed from model results associated with $\boldsymbol{x}_{su,k}$. Sensitivity analysis explores the mapping in Equation (276) to determine how the uncertainty in individual elements of $\boldsymbol{x}_{su}$ affects the uncertainty in individual elements of $\boldsymbol{y}\left(\boldsymbol{x}_{su}\right)$. Understanding how uncertainty in analysis inputs affects analysis results aids in understanding the current PA, and aids in improving the models for future PAs.

The presentation of results from each major model in the WIPP PA is accompanied by sensitivity analyses of the most important output of each major model. Where practical, sensitivity analysis results are based on a pooling of the results obtained for the three replicated LHSs (i.e., R1, R2, R3) discussed in Section PA-6.4. In other cases, the sensitivity analysis is based on the results for the first replicate (i.e., R1), and statistics are compared across the three replicates.

Three principle techniques are used in the sensitivity analysis: scatterplots; regression analyses to determine standardized regression coefficients and partial correlation coefficients; and stepwise regression analyses. Each technique is briefly discussed. A discussion of sensitivity analyses conducted for the CCA PA is provided in Helton et al. (1998).

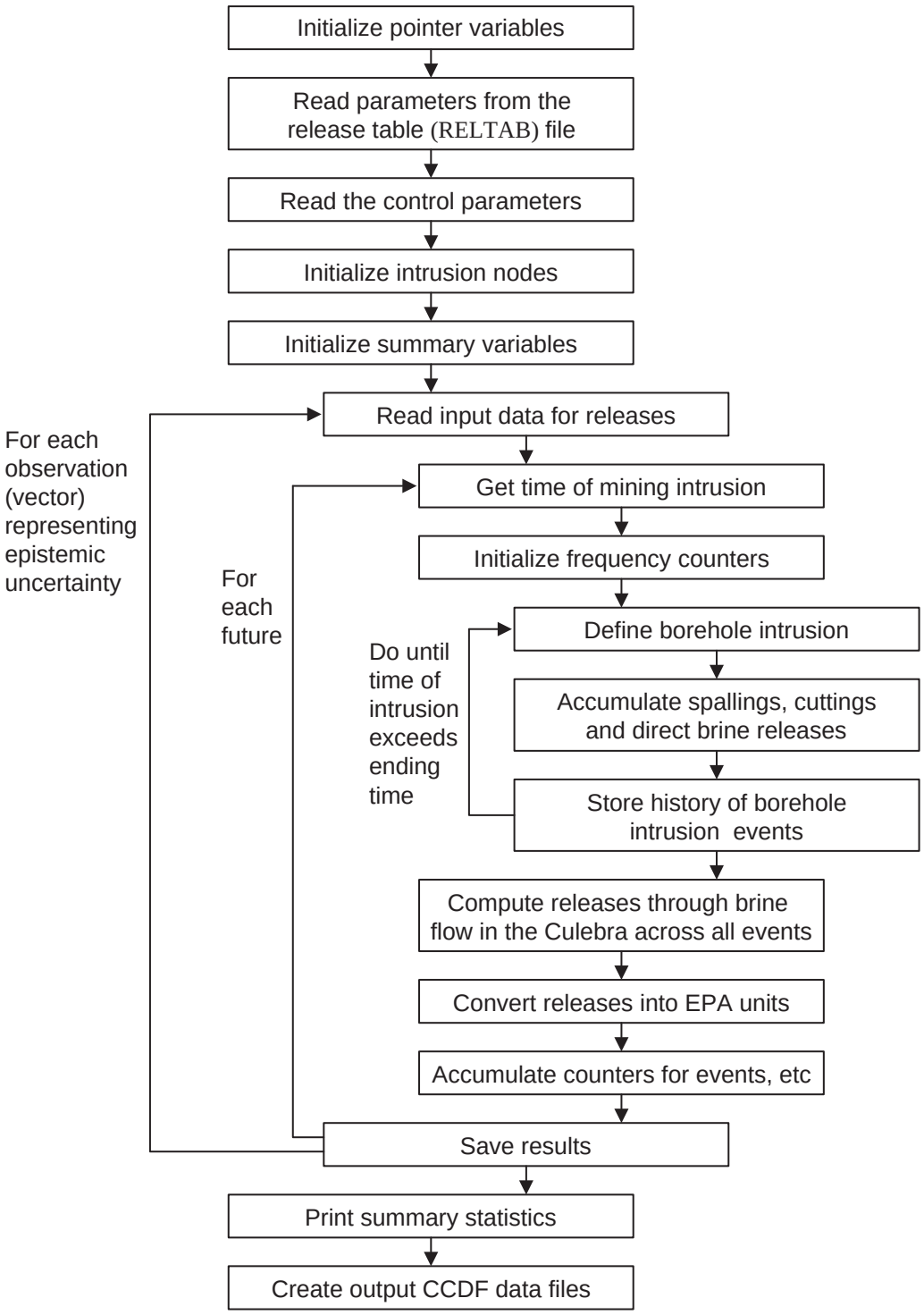

Figure PA-34. Processing of Input Data to Produce CCDFs.

PA-6.9.1 Scatterplots

Scatterplots are the simplest sensitivity analysis technique, performed by plotting the points

$$\left(x_{kj}, y_k\right), \text{ k = 1, 2, …, nLHS} \tag{277}$$

for each element x_j of x. The resulting plots can reveal relationships between y and the elements of x (i.e., the x_j). Scatterplots can be effective at revealing nonlinear relationships or threshold values, and at screening the elements of x for further investigation. The examination of such plots when Latin hypercube sampling is used can be particularly revealing due to the full stratification over the range of each input variable. Iman and Helton (1988) provide an example where the examination of scatterplots revealed a rather complex pattern of variable interactions.

PA-6.9.2 Regression Analysis

A more formal investigation of the mapping in Equation (276) can be based on regression analysis. In this approach, a model of the form

$$y = b_0 + \sum_{j=1}^{n} b_j x_j \tag{278}$$

is developed from the mapping between analysis inputs and analysis results shown in Equation (276), where the x_j are the input variables under consideration and the b_j are coefficients that must be determined. The coefficients b_j and other aspects of the construction of the regression model in Equation (278) can be used to indicate the importance of the individual variables x_j with respect to the uncertainty in y. The CRA-2004 PA employs the method of least squares to determine the coefficients b_j (Myers 1986).

Often the regression in Equation (278) is performed after the input and output variables are normalized to mean zero and standard deviation one. The resulting coefficients b_j are called standardized regression coefficients (SRCs). When the x_j are independent, the absolute value of the SRCs can be used to provide a measure of variable importance. Specifically, the coefficients provide a measure of importance based on the effect of moving each variable away from its expected value by a fixed fraction of its standard deviation while retaining all other variables at their expected values.

Partial correlation coefficients (PCCs) can also provide a measure of the linear relationships between the output variable y and the individual input variables. The PCC between y and an individual variable x_p is obtained from the use of a sequence of regression models. First, the following two regression models are constructed:

$$\hat{y} = b_0 + \sum_{\substack{j=1 \\ j \neq p}}^{n} b_j x_j \text{ and } \hat{x}_p = c_0 + \sum_{\substack{j=1 \\ j \neq p}}^{n} c_j x_j \ , \tag{279}$$

Then, the results of the two preceding regressions are used to define the new variables $y - \hat{y}$ and $x_p - \hat{x}_p$. By definition, the PCC between y and x_p is the correlation coefficient between $y - \hat{y}$

and $x_p - \hat{x}_p$. Thus, the PCC provides a measure of the linear relationship between y and x_p with the linear effects of the other variables removed.

Regression and correlation analyses often perform poorly when the relationships between the input and output variables are nonlinear. This is not surprising since such analyses are based on the assumption of linear relationships between variables. The problems associated with poor linear fits to nonlinear data can be avoided by use of the rank transformation (Iman and Conover 1979). The rank transformation is a simple concept: data are replaced with their corresponding ranks and then the usual regression and correlation procedures are performed on these ranks. Specifically, the smallest value of each variable is assigned the rank 1, the next largest value is assigned the rank 2, and so on up to the largest value, which is assigned the rank m, where m denotes the number of observations. The analysis is then performed with these ranks being used as the values for the input and output variables. A formal development of PCCs and the relationships between PCCs and SRCs is provided by Iman et al. (1985).

PA-6.9.3 Stepwise Regression Analysis

Stepwise regression analysis provides an alternative to constructing a regression model containing all the input variables. With this approach, a sequence of regression models is constructed. The first regression model contains the single input variable that has the largest impact on the uncertainty in the output variable (i.e., the input variable that has the largest correlation with the output variable y). The second regression model contains the two input variables that have the largest impact on the output variable: the input variable from the first step plus whichever of the remaining variables has the largest impact on the uncertainty not accounted for by the first variable (i.e., the input variable that has the largest correlation with the uncertainty in y that cannot be accounted for by the first variable). Additional models in the sequence are defined in the same manner until a point is reached at which further models are unable to meaningfully increase the amount of the uncertainty in the output variable that can be accounted for.

Stepwise regression analysis can provide insights on the importance of the individual variables. First, the order in which the variables are selected in the stepwise procedure provides an indication of their importance, with the most important variable being selected first, the next most important variable being selected second, and so on. Second, the R^2 values at successive steps of the analysis also provide a measure of variable importance by indicating how much of the uncertainty in the dependent variable can be accounted for by all variables selected through each step. When the input variables are uncorrelated, the differences in the R^2 values for the regression models constructed at successive steps equals the fraction of the total uncertainty in the output variable that can be accounted for by the individual input variables being added at each step. Third, the absolute values of the SRCs in the individual regression models provide an indication of variable importance. Further, the sign of an SRC indicates whether the input and output variable tend to increase and decrease together (a positive coefficient) or tend to move in opposite directions (a negative coefficient).

PA-7.0 RESULTS FOR THE UNDISTURBED REPOSITORY

The PA tabulates releases from the repository for undisturbed conditions. Releases to the accessible environment from the undisturbed repository fall under two sets of protection requirements. The first, as set forth 40 CFR § 191.15, protects individuals from radiological exposure; the second, in 40 CFR Part 191, Subpart C, protects groundwater resources from contamination. Chapter 8 describes how WIPP complies with these two requirements. This section supplements Chapter 8 by presenting flow (BRAGFLO) and transport (NUTS) results from modeling the undisturbed repository.

PA-7.1 Salado Flow

Flow in the Salado is computed by BRAGFLO (see Section PA-4.2). This section summarizes the Salado flow calculation results for the undisturbed scenario (S1). Pressure in the repository, brine saturation in the waste, and brine flow out of the repository are presented, along with sensitivity analyses that identify the uncertain parameters to which these results are most sensitive. The analysis package for Salado Flow (Stein and Zelinski 2003b) contains a detailed presentation on the BRAGFLO model, calculation results, and further sensitivity analyses.

PA-7.1.1 Pressure in the Repository

In undisturbed conditions, pressure strongly influences the extent to which contaminated brine might migrate from the repository to the accessible environment. In addition, pressure developed under undisturbed conditions is an initial condition for the models for spallings and DBR (Section PA-4.6 and Section PA-4.7, respectively).

The Salado flow model represents the repository as five regions in the numerical grid: three waste-filled regions (the Waste Panel, South RoR, and North RoR in Figure PA-8) and two excavated regions with no waste (Ops and Exp in Figure PA-8), which are combined in this analysis into the single nonwaste region. Figure PA-35 shows pressure in each region for the 100 realizations in Replicate R1. Pressures within the three waste-filled areas are very similar, because gas generation occurs in each region simultaneously. The pressure in the nonwaste region tends to be lower than in the waste-filled regions due to the intervening panel closures (CONC_PCS in Figure PA-8).

During the first 1,000 years, repository pressure may increase rapidly due to several factors: rapid initial creep closure of rooms (see Attachment PORSURF); initial inflow of brine causes gas generation due to corrosion; and availability of CPR material to produce gas by microbial degradation. Pressure generally approaches a steady-state value after 1,000 years as room closure ceases, brine inflow slows (thereby reducing gas generation by corrosion), and CPR materials are consumed.

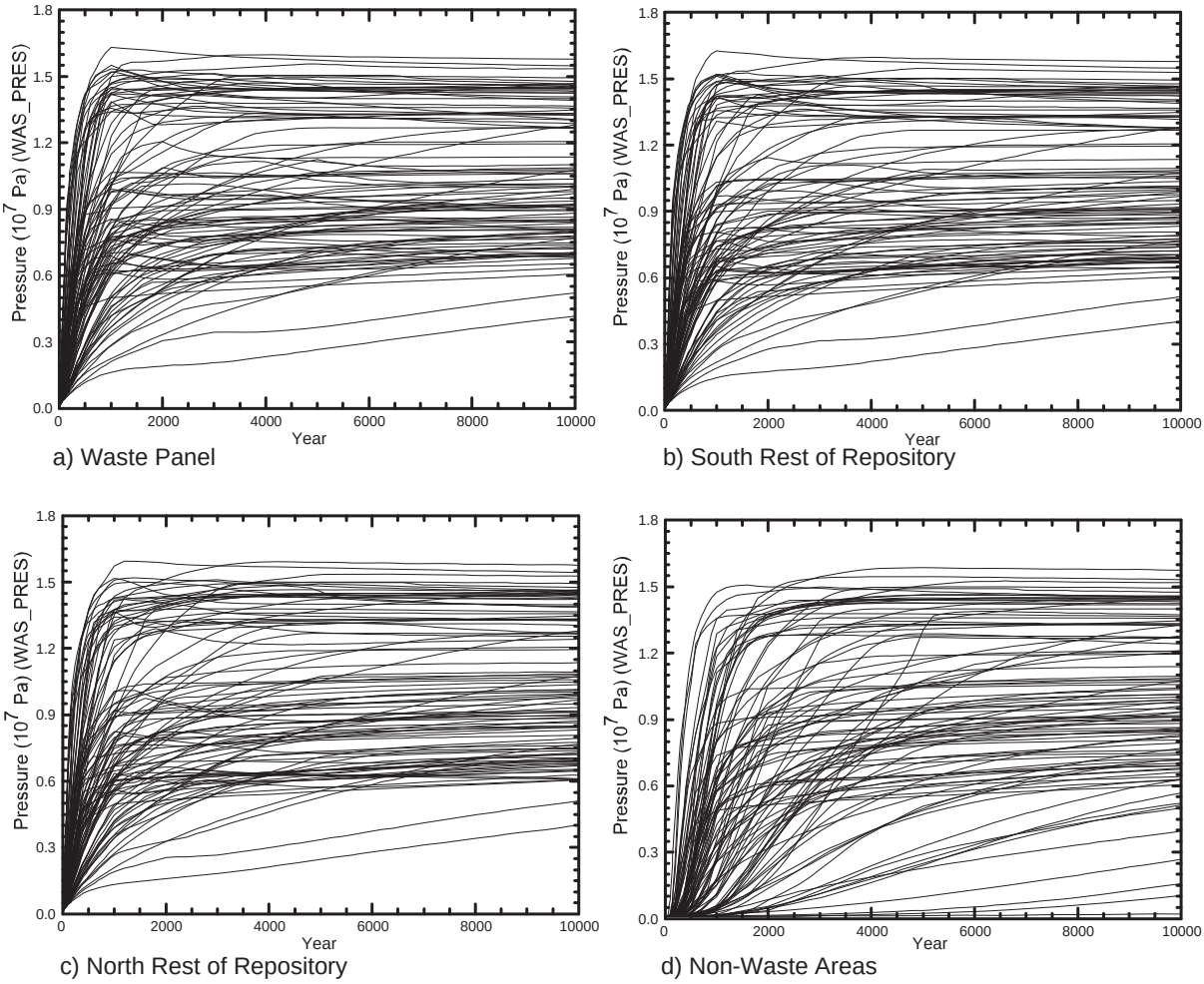

Figure PA-35. Pressure in the Excavated Areas, Replicate R1, Scenario S1.

Figure PA-36 shows the mean and 90th percentile values for pressure in each region. There is a consistent pattern of declining pressure from the waste panel through South RoR (SRR_PRES) and North RoR (NRR_PRES) to the nonwaste region (NWA_PRES). The differences in pressure reflect the slow migration of gas from waste-filled regions to the nonwaste regions where no gas is being produced. The 90th percentile pressures level off between 14 and 15 MPa indicating equilibrium between gas generation, which increases pressure, and pressure relief processes (e.g., fracturing, outward migration of fluids, and increased porosity of the excavated areas).

Sensitivity analyses are used to determine the importance of parameter uncertainty to the uncertainty in model results. Figure PA-37 shows partial rank correlation coefficients (PRCCs) resulting from regression between pressure in the waste panel (WAS_PRES) and the uncertain variables in the LHS (Section PA-5.0). The figure shows that uncertainty in the pressure in the waste panel is primarily determined by the sampled input parameter, WMICDFLG, which indicates whether microbial gas generation is active and what materials,

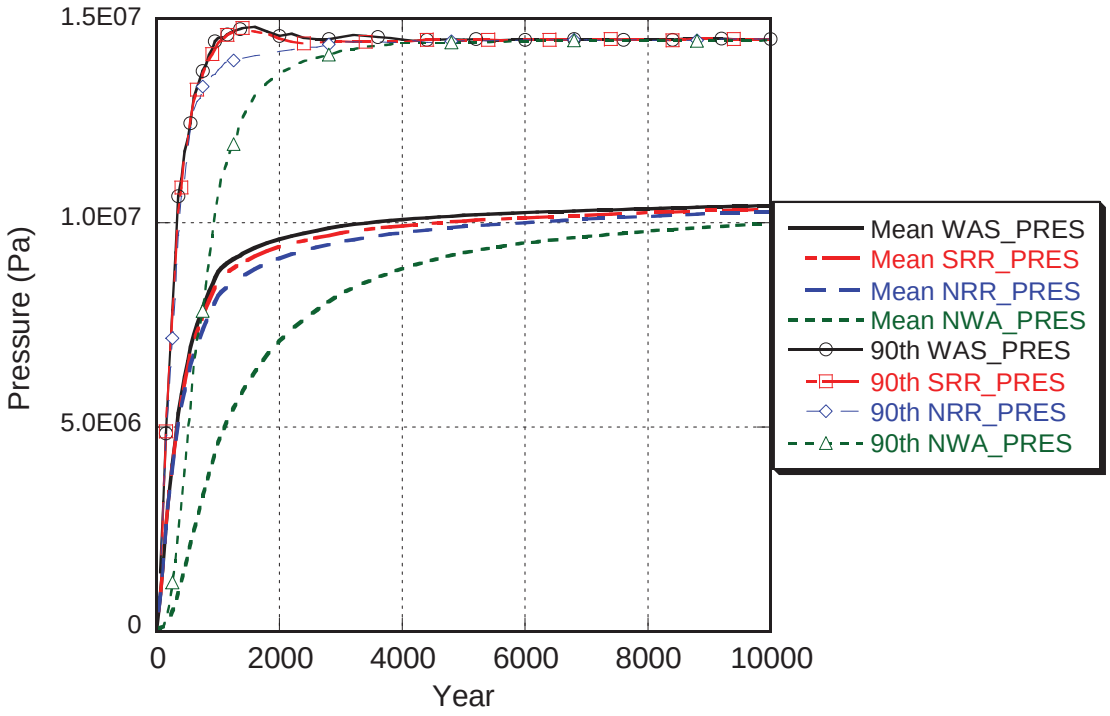

Figure PA-36. Mean and 90th Percentile Values for Pressure in Excavated Areas, Replicate R1, Scenario S1.

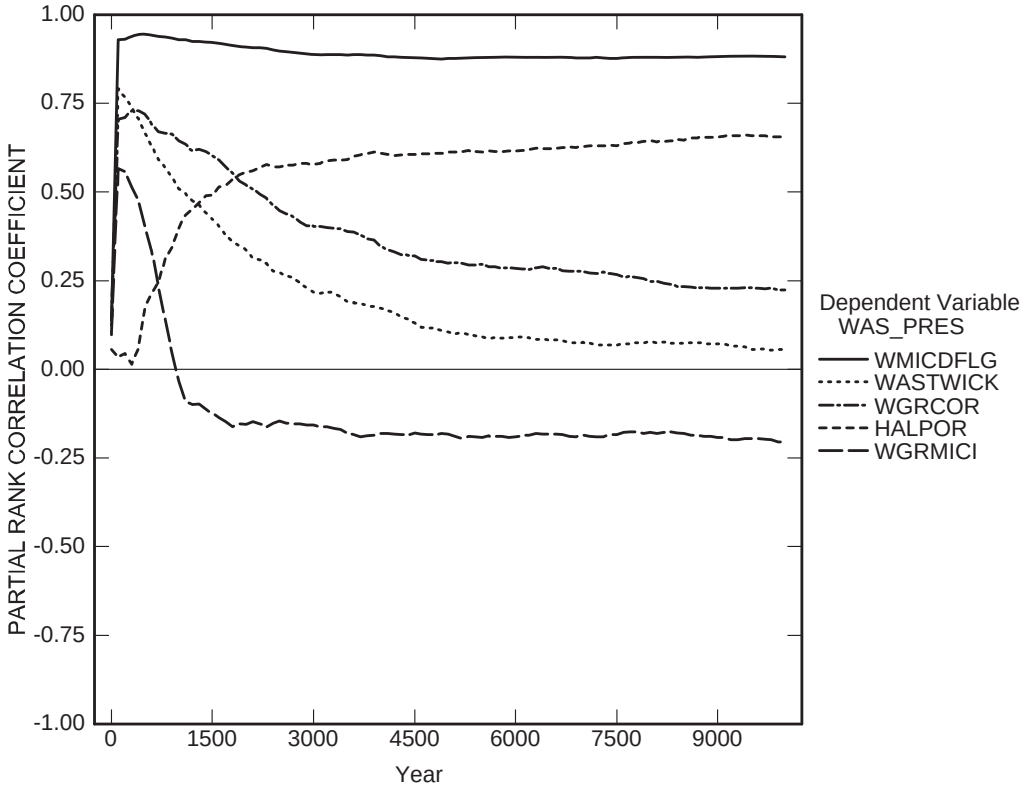

Figure PA-37. Primary Correlations of Pressure in the Waste Panel with Uncertain Parameters, Replicate R1, Scenario S1.

if any, are consumed. The positive correlation indicates that higher pressures result from higher values of WMICDFLG, which represent larger amounts of material available for gas production by microbial activity. The PRCC for WMICDFLG is approximately 0.85 throughout the 10,000-year calculation time, indicating that uncertainty in this parameter explains the variability in the waste panel pressure. Consequently, uncertainties in other parameters are not very significant; the other PRCCs in Figure PA-37 indicate that halite porosity (HALPOR), the inundated microbial gas generation rate (WGRMICI), the corrosion rate for steel (WGRCOR), and the waste wicking parameter (WASTWICK) determine the remaining variability in waste panel pressure.

Figure PA-38 compares statistics for pressure in the waste panel among the three replicates and shows that results for the three replicates are very similar. Mean pressures are nearly coincident; small differences between replicates are observable among the replicates at very high or very low pressures.

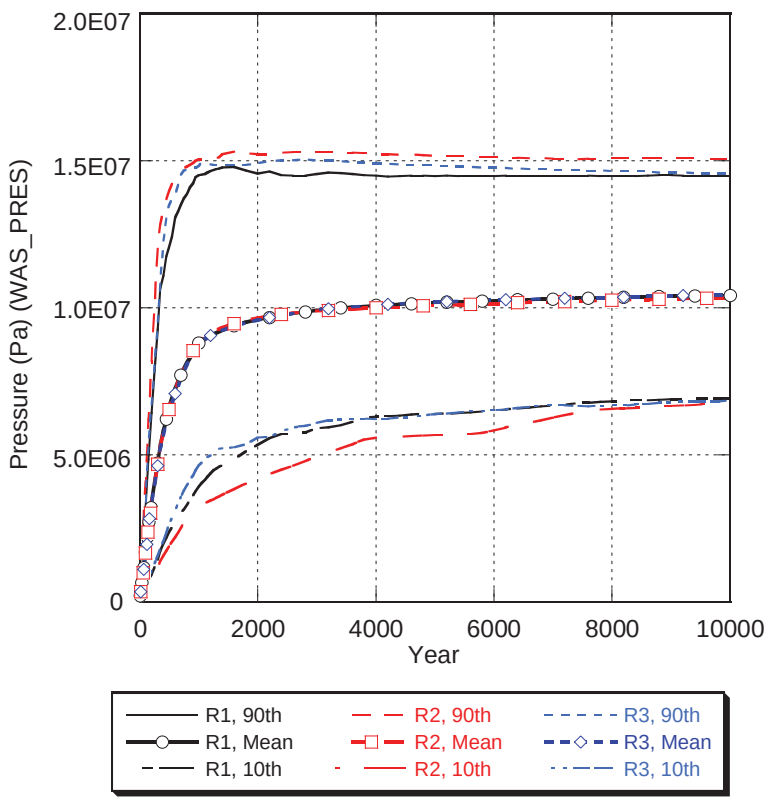

Figure PA-38. Comparison of Pressure in the Waste Panel Between All Replicates, Scenario S1.

PA-7.1.2 Brine Saturation in the Waste

Brine saturation is an important result of the model for Salado Flow, because gas generation processes, which tend to increase pressure, require brine. Brine saturation is also an initial condition in the model for DBR (Section PA-4.7).

Figure PA-39 shows brine saturation in the various excavated areas of the repository for the 100 realizations of Replicate 1. Brine saturation in the waste-filled areas is set initially to 0.015. Saturation increases very rapidly (in the first 100 years) in all excavated areas as brine flows toward the excavations, primarily from the DRZ above the excavation. Initially there is a large pressure differential between the DRZ and the excavated regions, and the relatively high permeability of the DRZ, compared to undisturbed halite, permits the rapid influx of brine. Brine inflow slows as the pressures equalize and as brine saturation in the DRZ decreases. Brine saturation in the waste decreases over time as brine is consumed by corrosion. Brine may also be driven out of the repository by high pressure.

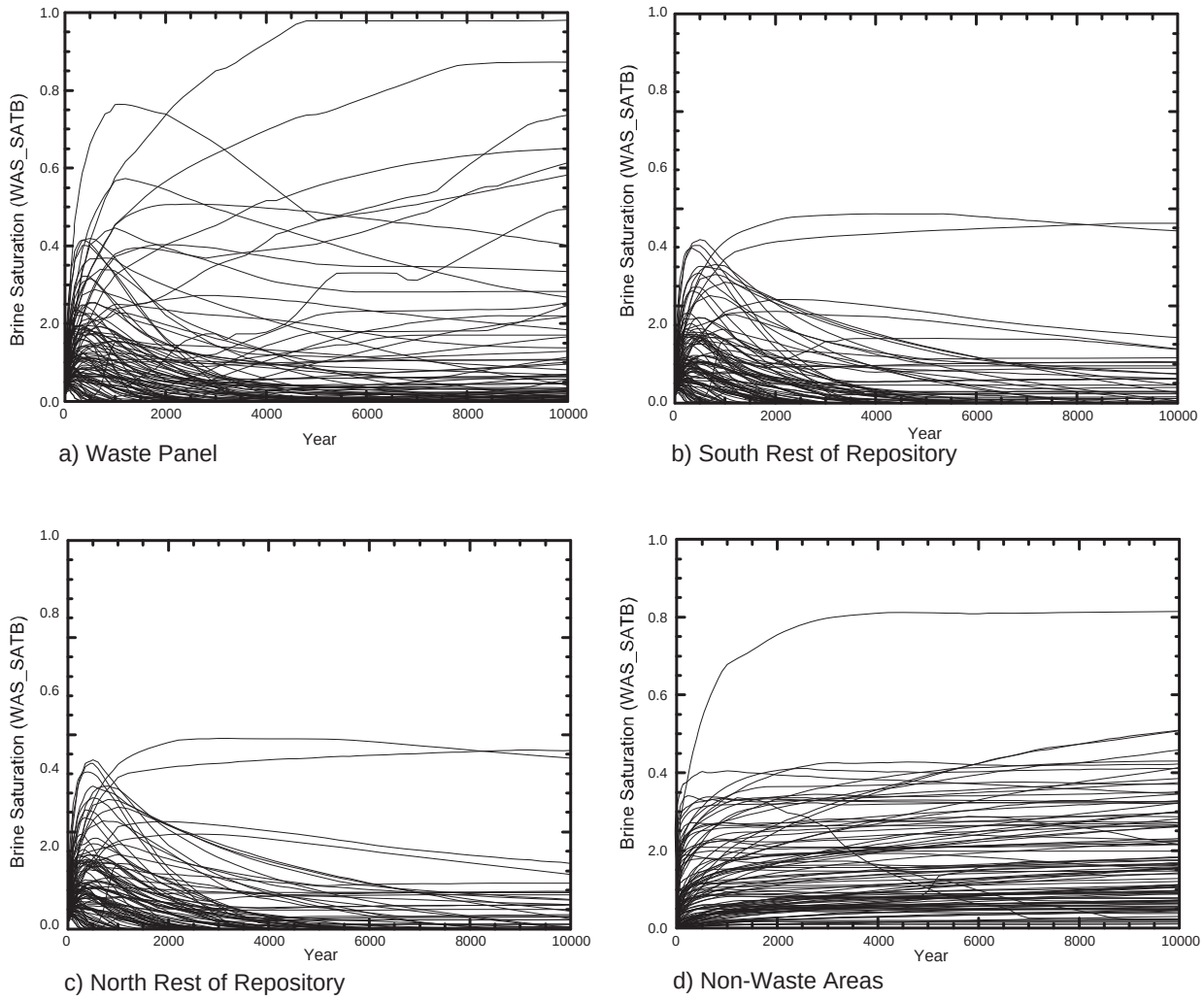

Figure PA-39. Brine Saturation in the Excavated Areas, Replicate R1, Scenario S1.

Figure PA-40 compares statistics for brine saturation between the different regions of the repository. Brine saturation in the waste panel (WAS_SATB) tends to be greater than in the rest of repository regions (SRR_SATB and NRR_SATB) due to the artificial two-dimensional modeling of the Salado; in the modeling grid (Figure PA-8), the waste panel has direct contact with the anhydrite MBs while the rest of repository regions do not. Brine saturation in the

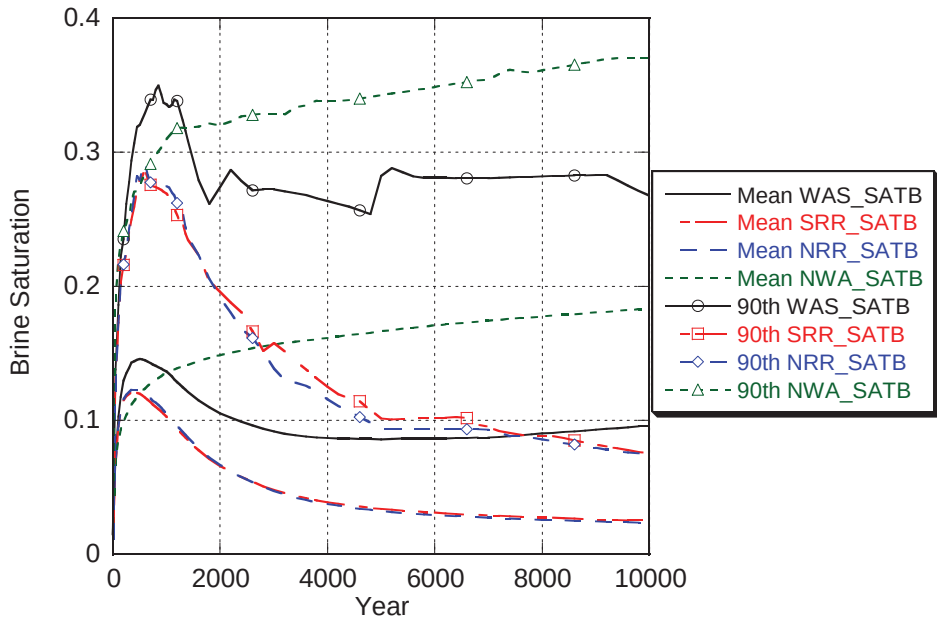

Figure PA-40. Mean and 90th Percentile Values for Brine Saturation in Excavated Areas, Replicate R1, Scenario S1.

non-waste region (NWA_SATB) is higher than in the waste-filled regions due to brine consumption in the waste regions, but also due to the panel closures. Brine that enters the experimental area flows down the stratigraphic gradient into the operations area, then ponds up against the panel closure separating the operations area from the waste filled regions.

Regression between the brine saturation in the waste panel (WAS_SATB) and the uncertain parameters in the LHS identifies a number of parameters that contribute to the uncertainty in brine saturation. The relative importance of these parameters varies over the 10,000-year modeling period, and none of the parameters is clearly dominant. Figure PA-41 shows positive correlations with halite porosity (HALPOR) and DRZ permeability (DRZPRM). Increases in halite porosity increase the volume of brine available in the material overlying the waste; increases in DRZ permeability accelerate drainage into the waste. Negative correlations are found between brine saturation and the corrosion rate (WGRCOR) and the wicking factor (WASTWICK) because increases in these two variables increase the rate at which brine is consumed by corrosion, thus decreasing saturation. The negative correlation between brine saturation and WMICDFLG, which becomes significant near the end of the simulation, indicates that increasing total gas generated (by adding microbial degradation of CPR material) eventually leads to less brine inflow and consequently lower saturation.

Figure PA-42 compares brine saturation statistics for the three replicates. The plots of the mean brine saturation are nearly coincident. Significant differences between replicates are evident at the high end of the saturation scale because there are only a few vectors in each replicate with high saturations.

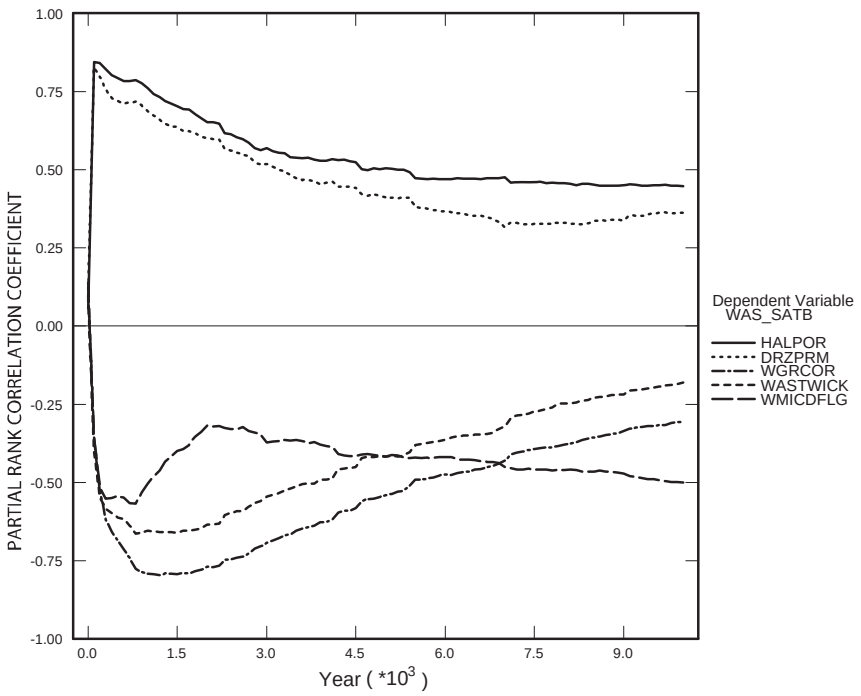

Figure PA-41. Primary Correlations of Brine Saturation in the Waste Panel with Uncertain Parameters, Replicate R1, Scenario S1.

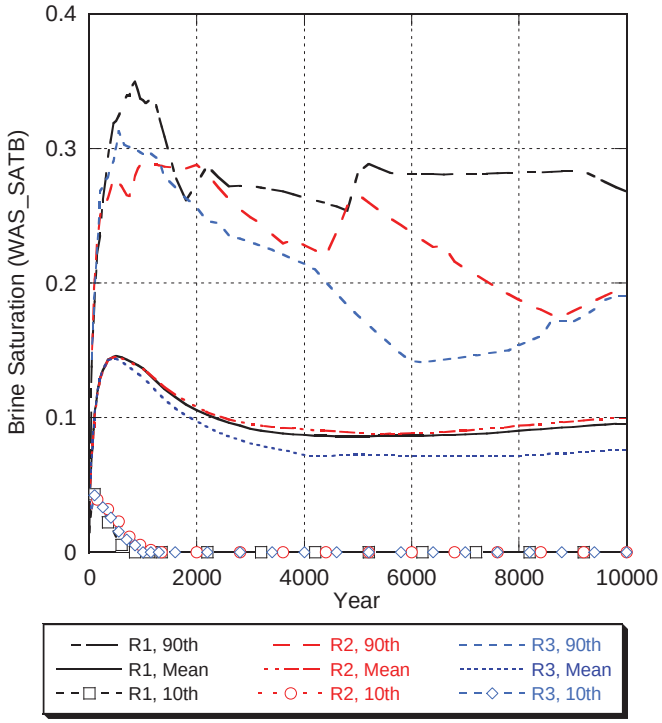

Figure PA-42. Comparison of Brine Saturation in the Waste Panel Between Replicates, Scenario S1.

PA-7.1.3 Brine Flow Out of the Repository

The anhydrite MBs and the shafts provide possible pathways for brine flow away from the repository in the undisturbed scenario (S1). The Salado flow model only tabulates the volume of brine crossing boundaries within the model grid; it does not identify whether the brine contains radionuclides from the waste. Transport is calculated separately from the flow and is discussed in Section PA-7.2.

Figure PA-43 shows cumulative brine outflow from the excavated regions of the repository (BRNREPOC). Brine flow out of the DRZ into the MBs is shown in Figure PA-44, and flow up the shaft to the bottom of the Culebra is shown in Figure PA-45. Comparison of total cumulative brine outflow into all MBs (BRAALOC, Figure PA-44) to total outflow (Figure PA-43) confirms that the primary path for brine outflow is along the MBs.

The distribution of brine flow among the potential pathways varies somewhat between vectors, but typically outflow along MB 139 to the south accounts for most of the total brine outflow. The dominance of MB 139 to the south as the primary conduit for brine outflow is illustrated in Table PA-26, which tabulates maximum brine outflow along each potential pathway for any vector in replicate R1. MB 139 is down the stratigraphic dip, and, being the lowest outflow pathway, it is most frequently saturated.

Figure PA-46 shows the volumes of brine that cross the LWB through the MBs. The largest outflow across the LWB is 433 m^3. Table PA-26 shows that a smaller volume of brine (50 m^3) may reach the Culebra through the shaft. Brine crossing the LWB or moving up the shaft does not necessarily indicate releases from the repository, since the brine may not have been in contact with the waste; the brine may have been present in the MBs at the start of the regulatory period. Section PA-7.2 presents the results of the transport calculations that determine the amount of radionuclides that be released by transport in brine.

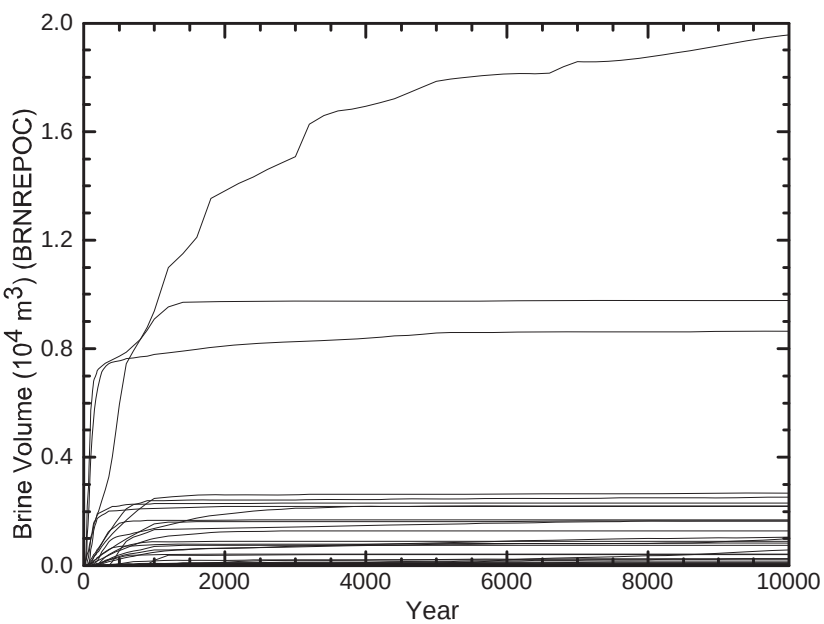

Figure PA-43. Brine Flow Away from the Repository, Replicate R1, Scenario S1.

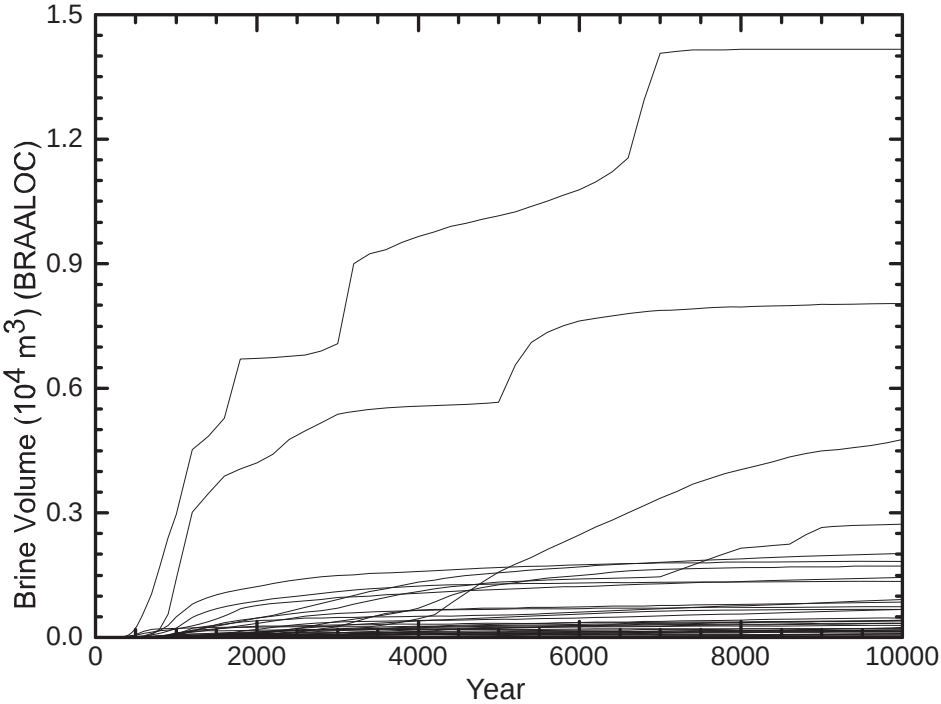

Figure PA-44. Brine Flow Away from the Repository Via All Marker Beds, Replicate R1, Scenario S1.

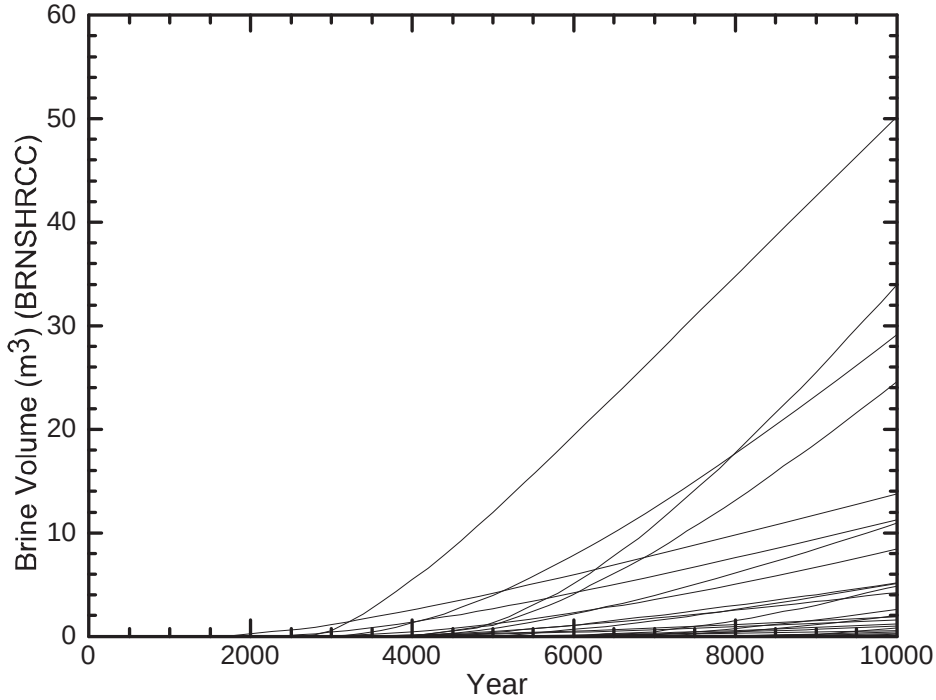

Figure PA-45. Brine Outflow Up the Shaft, Replicate R1, Scenario S1.

Table PA-26. Volume of Brine Outflow by Various Potential Pathways

Pathway for Brine Outflow	Maximum (m^3)
MB 138 North	432
MB 138 South	1,567
Anhydrite AB North	0
Anhydrite AB South	5
MB 139 North	1,832
MB 139 South	12,828
Shaft (to base of Culebra)	50

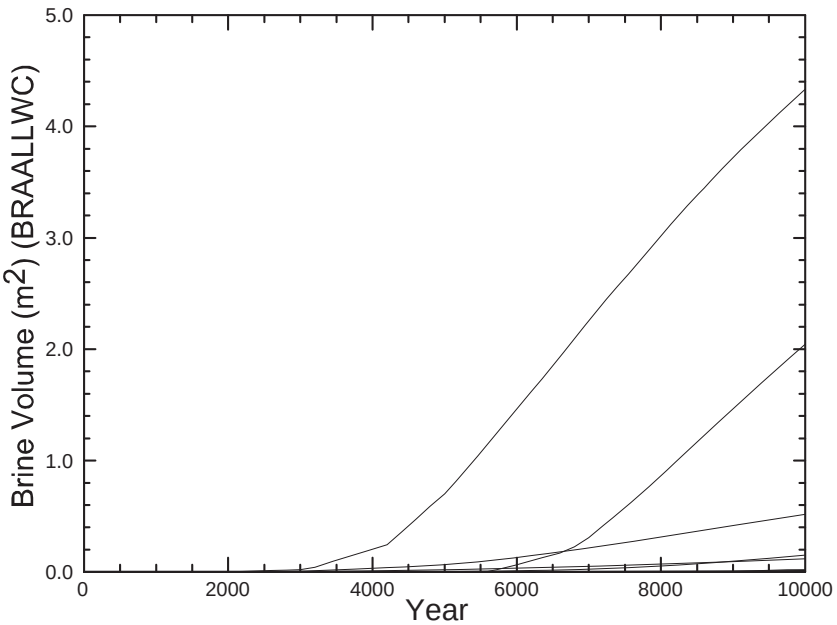

Figure PA-46. Brine Flow Via All MBs Across The LWBs, Replicate R1, Scenario S1.

Regression between total cumulative brine flow into the MBs (BRAALOC) and the uncertain parameters in the LHS (Figure PA-47) shows that uncertainty in brine outflow into the MBs is primarily determined by WMICDFLG, which indicates whether microbial gas generation is modeled and what materials, if any, are consumed. The positive correlation of WMICDFLG with BRAALOC is comparable to the correlation of WMICDFLG with pressure in the waste panel (WAS_PRES) indicating that increasing pressure correlates with increasing brine flow into the marker beds. The PRCC for WMICDFLG is approximately 0.85 throughout the 10,000-year calculation time, indicating that uncertainty in this parameter explains roughly 85% of the variability in BRAALOC. The porosity of halite (HALPOR) accounts for most of the remaining uncertainty. Increasing HALPOR means that more brine is available in the DRZ for inflow into the repository, and brine inflow is a necessary precursor to outflow. The influence of the other three parameters listed in Figure PA-47 is negligible.

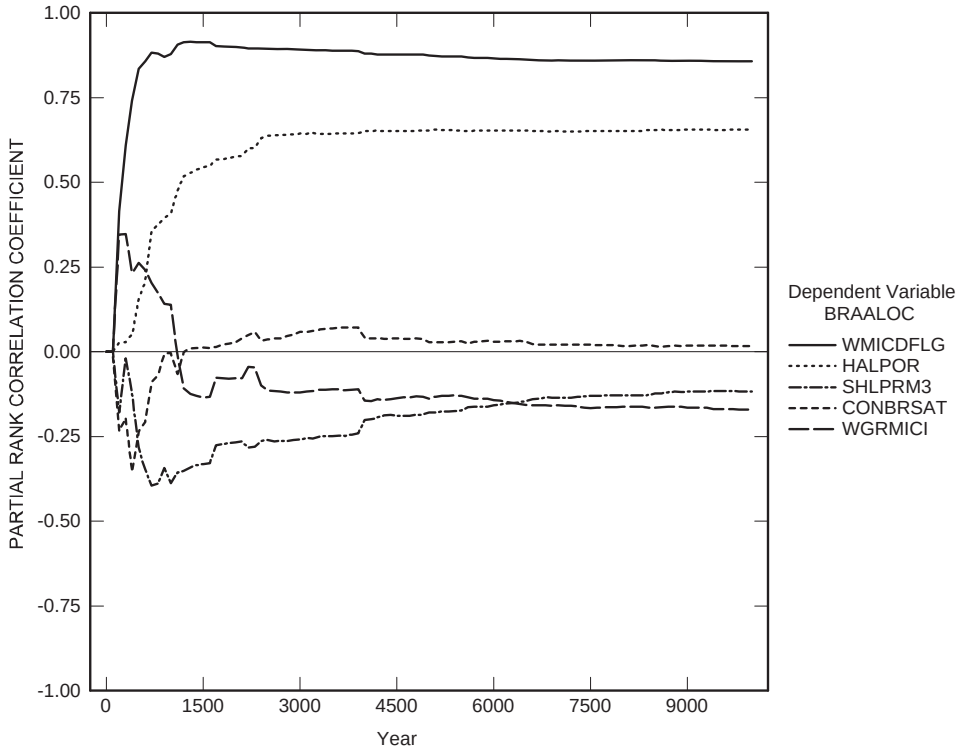

Figure PA-47. Primary Correlations of Total Cumulative Brine Flow Away from the Repository Through All MBs with Uncertain Parameters, Replicate R1, Scenario S1.

Figure PA-48 compares statistics of brine outflow from the repository for the three replicates, and shows that all three replicates produce similar results. The BRNREPOC provides a more valid basis for comparison among the replicates than the other outflow variables, because it has fewer vectors with zero values.

PA-7.2 Radionuclide Transport

Radionuclide transport in the undisturbed scenario is calculated by the code NUTS. Screening runs are used to determine which vectors have the potential to transport radionuclides to the accessible environment (see Section PA-6.7.2). Full transport simulations are run for all vectors that are screened in. This section summarizes the transport results for the undisturbed repository, both up the shaft to the Culebra, and through the Salado to the LWB. Lowry (2003) presents a detailed analysis of NUTS results for the CRA-2004 PA.

PA-7.2.1 Transport to the Culebra

No vectors showed any amount of radionuclide transported to the Culebra through the shafts from the undisturbed repository. Consequently, no radionuclides can transport through the Culebra to the LWB in undisturbed conditions.

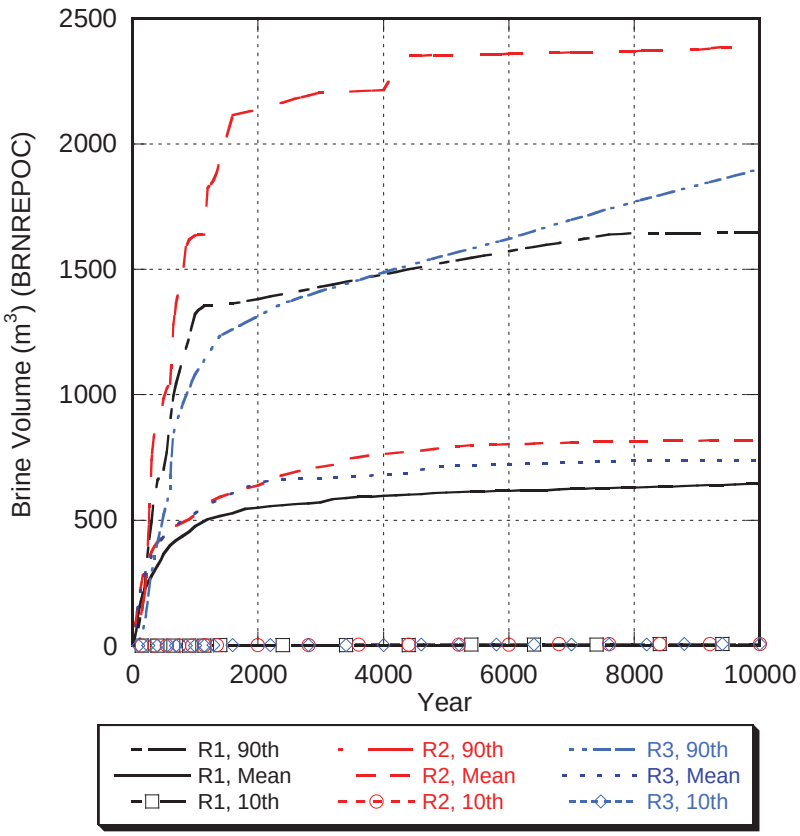

Figure PA-48. Comparison of Brine Flow Away from the Repository between Replicates, Scenario S1.

PA-7.2.2 Transport to the Land Withdrawal Boundary

In all three replicates (300 vectors) of the CRA-2004 PA, only one vector displayed non-zero releases across the LWB from the undisturbed repository. Vector 82 of Replicate R1 released a total of 2.89×10^{-15} EPA units out the southern anhydrite MB 139 over 10,000 years. The release is predominately ^{239}Pu. In this vector, quantities of all of the isotopes move through the MB about 677 m. However, at 984 m from the edge of the repository the concentration of ^{239}Pu decreases to less than 1×10^{-7} EPA units. The total distance from the repository edge to the LWB is 2,400 m. Thus, the non-zero release in this vector is indicative of numerical dispersion resulting from the coarse grid spacing between the repository and the LWB, rather than a probable transport of radionuclides.

The releases from the undisturbed scenario are insignificant when compared to releases from drilling intrusions (see Section PA-9.0). Consequently, releases in the undisturbed scenario are omitted from the calculation of total releases from the repository (see Section PA-9.0) to satisfy the containment requirements of 40 CPR Part 194. Chapter 8.0 demonstrates that WIPP complies with the individual protection requirements of 40 CFR § 191.15 and the groundwater protection requirements of 40 CFR Part 191, Subpart C.

PA-8.0 RESULTS FOR A DISTURBED REPOSITORY

The WIPP repository might be disturbed by exploratory drilling for natural resources during the 10,000-year regulatory period. Drilling could create additional pathways for radionuclide transport, especially in the Culebra, and could release material directly to the surface. In addition, mining for potash within the LWB might alter flow in the overlying geologic units and may accelerate transport through the Culebra. The disturbed scenarios used in PA modeling capture the range of possible releases resulting from drilling and mining.

As outlined in Section PA-6.8, total releases are computed by the code CCDFGF, which evaluates the function f in Equation (24) for each stochastically generated future of the repository. Total releases comprise transport releases and direct releases. Transport releases generally involve movement of radionuclides up an abandoned borehole into the Culebra, then through the Culebra to the LWB. Transport of radionuclides to the Culebra is computed using the codes NUTS and PANEL (see Section PA-4.3 and Section PA-4.4, respectively) using the brine flows computed by BRAGFLO. Transport through the Culebra is computed by the code SECOTP2D (see Section PA-4.9) using flow fields calculated by MODFLOW (see Section PA-4.8).

Direct releases occur at the time of a drilling intrusion and include releases of solids (cuttings, cavings, and spallings) computed using the code CUTTINGS_S (see Section PA-4.5 and Section PA-4.6) and direct releases of brine computed using BRAGFLO (see Section PA-4.7). Pressure and brine saturation within the waste are initial conditions to the models for direct releases. Results from the undisturbed repository (see Section PA-7.0) are used as the initial conditions for the first intrusion. To calculate initial conditions for subsequent intrusions, and to compute the source of radionuclides for transport in the Culebra, a set of drilling scenarios are used to calculate conditions within the repository after an intrusion, using BRAGFLO (Section PA-6.7.1).

This section first summarizes the scenarios used to represent drilling intrusions and the resulting repository conditions calculated by BRAGFLO. Next, transport releases are presented, followed by cuttings and cavings, spallings, and DBRs. Finally, total releases from the repository are summarized.

PA-8.1 Drilling Scenarios

As described in Section PA-3.9, the PA considers two types of drilling intrusions, E1 and E2. The E1 scenario represents the possibility that a borehole connects the repository with a pressurized brine reservoir located within the underlying Castile formation. The E2 scenario represents a borehole that does not connect the repository with an underlying brine reservoir. Repository conditions are calculated for the E1 scenario at 350 and 1,000 years, referred to as the BRAGFLO S2 and S3 scenarios, respectively. The BRAGFLO scenarios S4 and S5 represent E2 drilling events that occur at 350 and 1,000 years, respectively. An additional BRAGFLO scenario, S6, simulates the effects of an E2 intrusion at 800 years followed by an E1 intrusion 1,200 years later into the same panel. For more details on the BRAGFLO scenarios, see Section PA-6.7.1.

PA-8.2 Mining Scenarios

Long-term releases within the Culebra could be influenced by future mining activities that remove all the known potash reserves within the LWB and cause the transmissivity within the overlying Culebra to change. As outlined in Section PA-3.8, full mining of known potash reserves within the LWB in the absence of active and passive controls occurs with a probability specified as a Poisson process with a rate of 10^{-4} yr^{-1}. For any particular future $\boldsymbol{x}_{st}$ in S_{st}, this rate is used to define a time t_{min} at which full mining has occurred. As described in Section PA-6.8.7, flow fields are calculated for the Culebra for two conditions: partial mining, which assumes that all potash as been mined from reserves outside the LWB; and full mining, which assumes all reserves have been mined both inside and outside the LWB. Transport through the Culebra uses the partial mining flow fields prior to t_{min}, and the full mining flow fields after t_{min}.

PA-8.3 Salado Flow

This section summarizes the results of the Salado flow calculations for the disturbed scenarios. Stein and Zelinski (2003b) provide a detailed presentation on the BRAGFLO model, calculation results, and further sensitivity analyses

PA-8.3.1 Pressure in the Repository

Figure PA-49 shows pressure in the waste panel (WAS_PRES for area Waste Panel of Figure PA-8) for the 100 vectors of replicate R1 for each BRAGFLO scenario (Table PA-21). Scenario S1 represents undisturbed repository conditions; the pressure in the waste panel in scenario S1 (Figure PA-49a) is analyzed in Section PA-7.1. Before the drilling intrusions at 350 or 1,000 years, repository pressure increases as described in Section PA-7.1.

After the intrusion, pressure exhibits patterns that vary depending on the type of intrusion and upon sampled input variables related to the intrusion.

Scenarios S2 and S3 represent E1 intrusions at 350 and 1,000 years, respectively (Table PA-21). At the time of the intrusion, brine flow from the Castile brine reservoir leads to an increase in pressure (Figure PA-49b and c). However, pressure drops sharply 200 years after the intrusion when the borehole plugs above the repository fail (Table PA-5) and the permeability of the borehole generally increases. However, in vectors with low borehole permeability after plug failure, pressure does not change noticeably as a result of the borehole plug failure. Twelve hundred years after the drilling intrusion, the permeability of the borehole connecting the repository to the Castile is reduced by an order of magnitude because of creep closure (Table PA-5). This material change reduces pressure slightly in some vectors, but does not appear to have a significant effect on the pressure in most vectors.

Scenarios S4 and S5 represent E2 intrusions at 350 years and 1,000 years, respectively. The borehole plugs effectively prevent any change in repository pressure from the time of the intrusion until the borehole plugs fail (Figure PA-49d and e). As in the scenarios for E1 intrusions, pressure generally drops sharply when the plugs fail, except for vectors with low borehole permeability after plug failure.

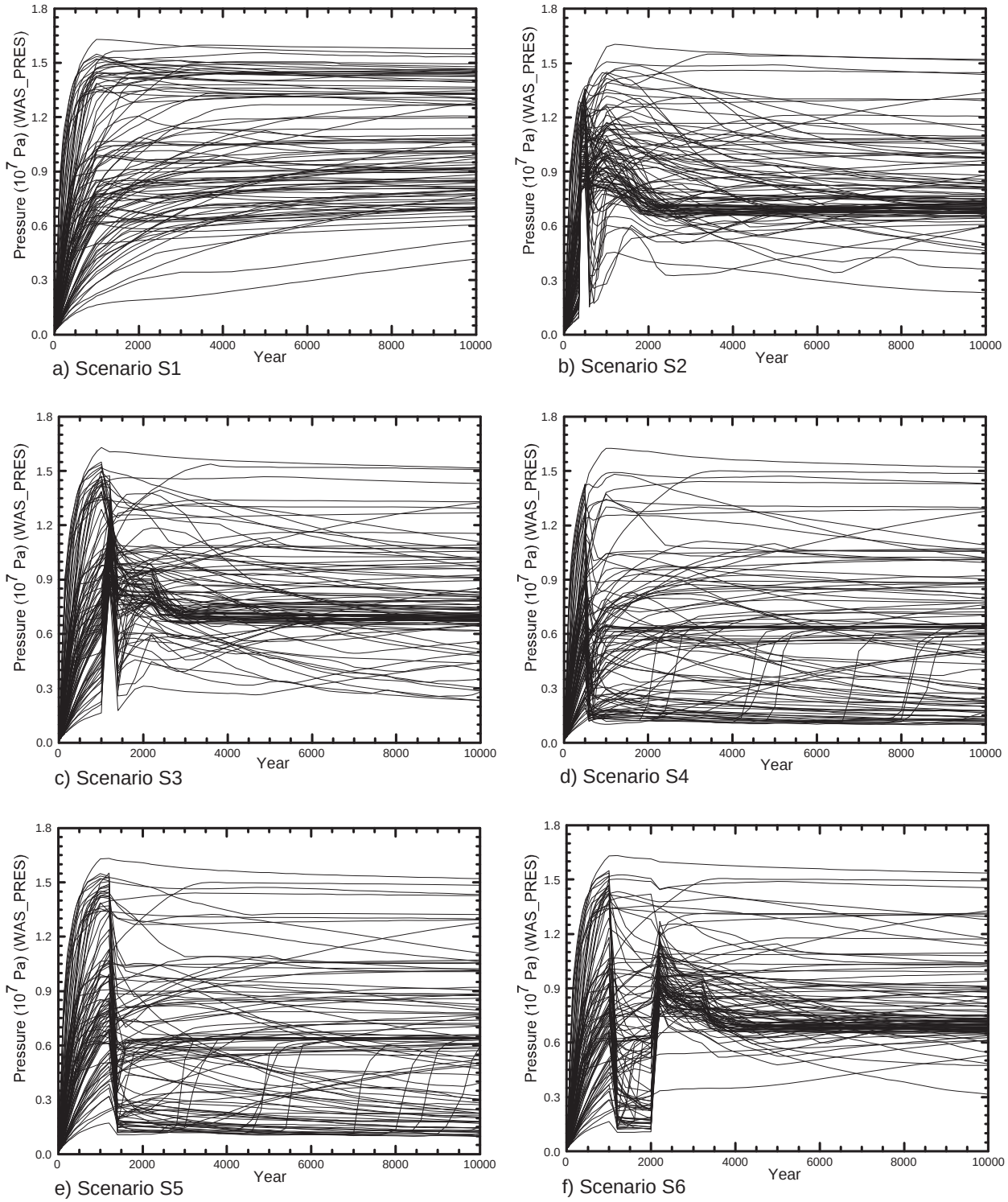

Figure PA-49. Pressure in the Waste Panel for All Scenarios, Replicate R1.

Scenario S6 represents two intrusions into the same panel: an E2 intrusion at 800 years followed by an E1 intrusion at 2000 years. Figure PA-49f shows pressure in the panel for the S6 scenario. The changes in pressure after the first intrusion are nearly identical to that observed in Scenario S5 (Figure PA-49e). In most vectors, the pressure decreases so much that there is a sharp increase in pressure at the time of the second intrusion, which connects the waste panel to the Castile brine reservoir. The changes in pressure after the second intrusion are very similar to those predicted after an E1 intrusion (Scenario S3, Figure PA-49c).

Figure PA-50 shows pressure in the rest of repository areas (SRR_PRES for area South RoR and NRR_PRES for area North RoR in Figure PA-8) and in the nonwaste areas (NWA_PRES averaged over areas Ops and Exp in Figure PA-8) for Scenarios S2 and S5, which represent E1 and E2 drilling intrusions into the waste panel at 350 and 1,000 years, respectively. In general, pressure in the rest of repository and nonwaste areas is not immediately affected by the intrusion. The presence of the Option D panel closures (see Section PA-4.2.8) inhibits flow of gas and brine between the intruded panel and adjoining areas, moderating the effects of the intrusion.

Figure PA-51 compares mean pressure in the waste panel among the scenarios. Pressure in the disturbed scenarios tends to be lower after the intrusion than pressure in the undisturbed scenario due to the borehole connection to the surface. By 2,000 years after the intrusion, the mean pressure after an E1 intrusion (Scenarios S2, S3, and S6) is about 80 percent of the mean pressure in undisturbed conditions (Scenario S1), and the mean pressure after an E2 intrusion (scenarios S4 and S5) is 60 percent of the mean pressure in undisturbed conditions.

Figure PA-52 illustrates the differences in pressure among the various excavated regions after an E1 intrusion at 350 years (Scenario S2). Following the intrusion, mean pressure in the waste panel (WAS_PRES) is temporarily higher than in the other repository regions. About 1,500 years after the intrusion, mean pressure in the South RoR (SRR_PRES) and North RoR (NRR_PRES) is approximately equal to mean pressure in the waste panel. Mean pressure in the nonwaste regions (NWA_PRES) is lower than pressure in the waste-filled regions until about 4,000 years after the intrusion. The delay in pressure equalization between different repository regions is due to the panel closures, which tend to prevent rapid exchange of brine and gas between regions (Hansen et al. 2002) unless pressure exceeds the fracture initiation pressure (approximately 12-14 MPa) after which pressure can rapidly equalize among the regions.

Regression between pressure in the waste panel for an E1 intrusion at 350 years (Scenario S2) and the uncertain parameters in the analysis (Section PA-5.2) shows that the uncertainty in the permeability of the borehole (BHPERM) is largely responsible for the uncertainty in pressure after the borehole plugs fail (Figure PA-53). Before the borehole plugs fail, pressure is most sensitive to variations in the initial pressure in the Castile (BPINTPRS) and the indicator for microbial gas generation (WMICDFLG). Increases in BPINTRS can increase brine flow from the Castile to the repository; larger values of WMICDFLG indicate the potential to generate additional gas as a consequence of the additional brine flowing into the

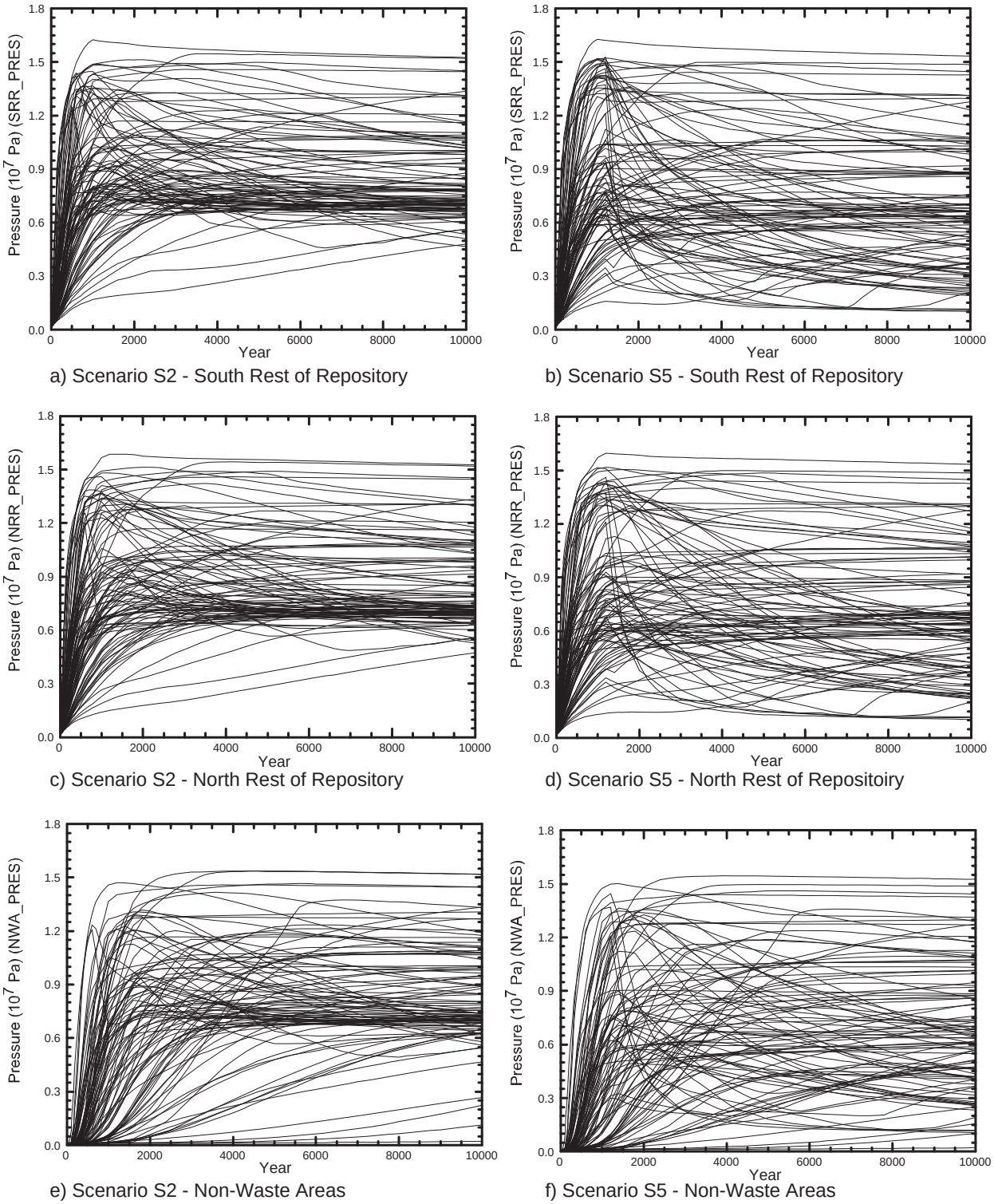

Figure PA-50. Pressure in Various Regions, Replicate R1, Scenarios S2 And S5.

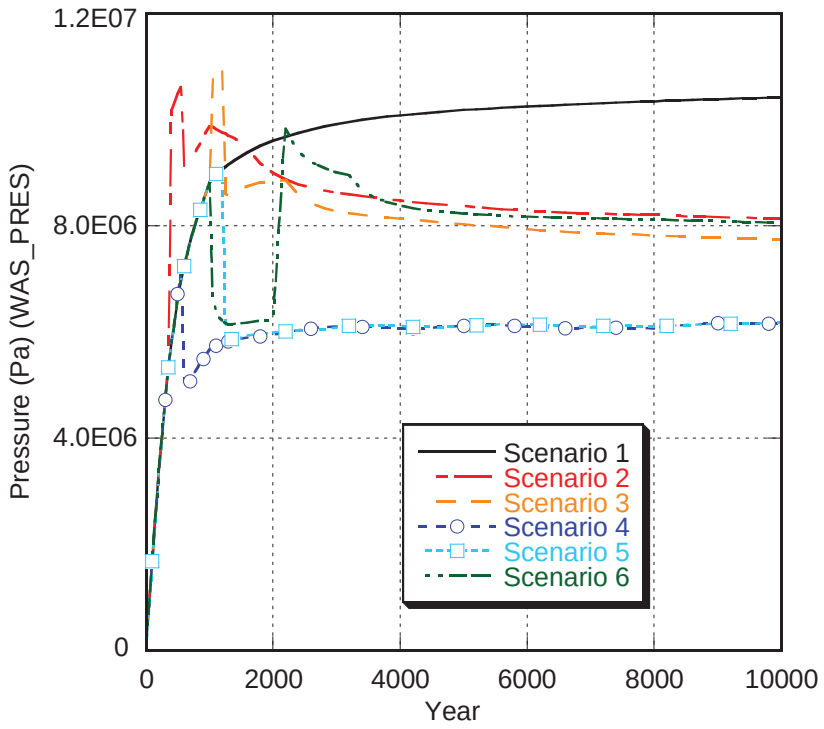

Figure PA-51. Mean Pressure in the Waste Panel for All Scenarios, Replicate R1

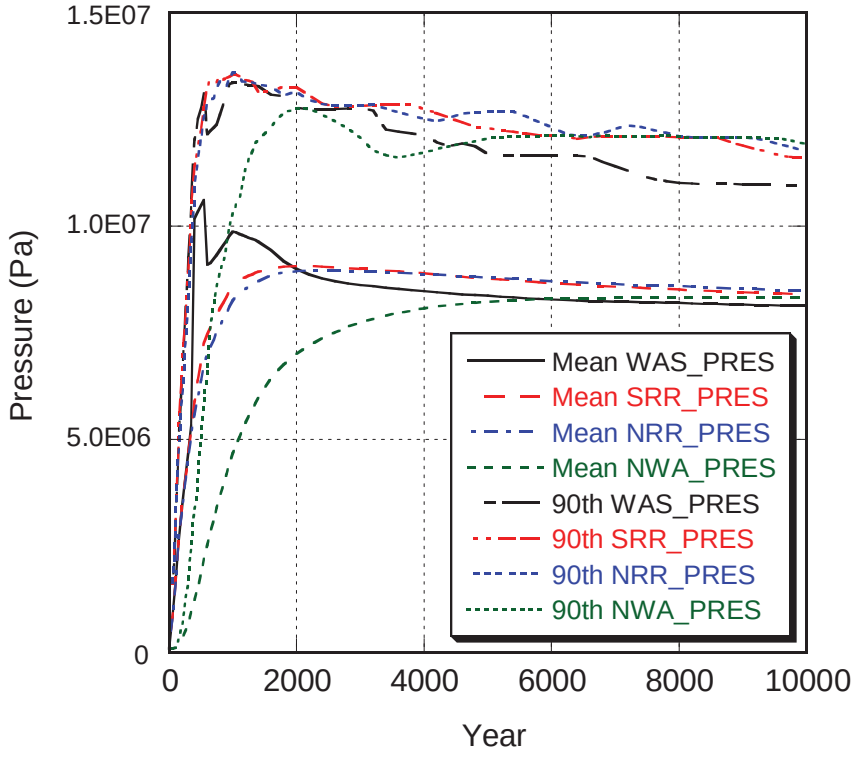

Figure PA-52. Mean And 90th Percentile Values For Pressure In The Excavated Regions Of The Repository, Replicate R1, Scenario S2.

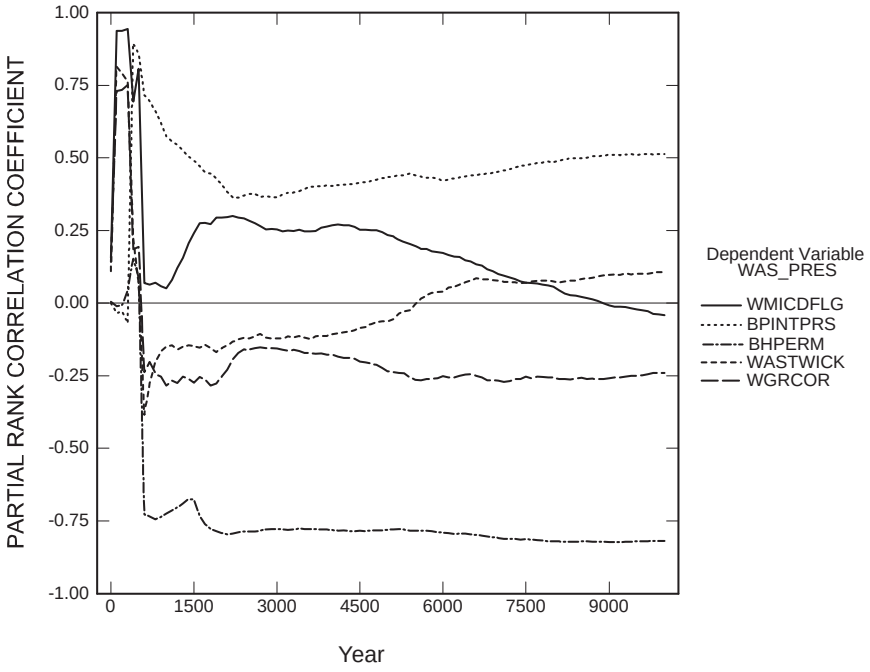

Figure PA-53. Primary Correlations For Pressure In The Waste Panel With Uncertain Parameters, Replicate R1, Scenario S2.

repository. Figure PA-54 shows the regression analysis results for an E2 intrusion at 1,000 years (Scenario S5). As in the analysis of Scenario S2, before the intrusion, the uncertainty in the indicator for microbial gas generation (WMICDFLG) is most important; after the borehole plugs fail, uncertainty in the permeability of borehole fill (BHPERM) is most important. Regression analyses for an E1 intrusion at 1,000 years and for an E2 intrusion at 350 years lead to similar conclusions (Stein and Zelinski, 2003b).

Figure PA-55 compares statistics for pressure in the waste panel for scenario S2 among the three replicates, and show that the three replicates produced statistically similar results.

PA-8.3.2 Brine Saturation

Brine saturation tends to increase after a drilling intrusion. Figure PA-56 shows brine saturation in the waste panel (WAS_SATB for area Waste Panel in Figure PA-8) for replicate R1 of each BRAGFLO scenario. In many vectors, the intruded panel becomes saturated after an E1 intrusion (Scenarios S2, S3, and S6). Depending on the borehole permeability and pressures in the repository and in the brine reservoir, quantities of brine can flow from the reservoir into the intruded panel, possibly filling the panel. In contrast, after an E2 intrusion (Scenarios S4 and S5) saturation increases for only a few vectors. An E2 intrusion tends to reduce the pressure in the intruded panel by releasing fluids (mainly gas) up the borehole (Figure PA-49). The reduced pressure in the waste permits an increase in brine inflow from the DRZ and the MBs. In addition, in some vectors brine can flow down the borehole from the Culebra into the intruded panel, depending on the permeability of the borehole.

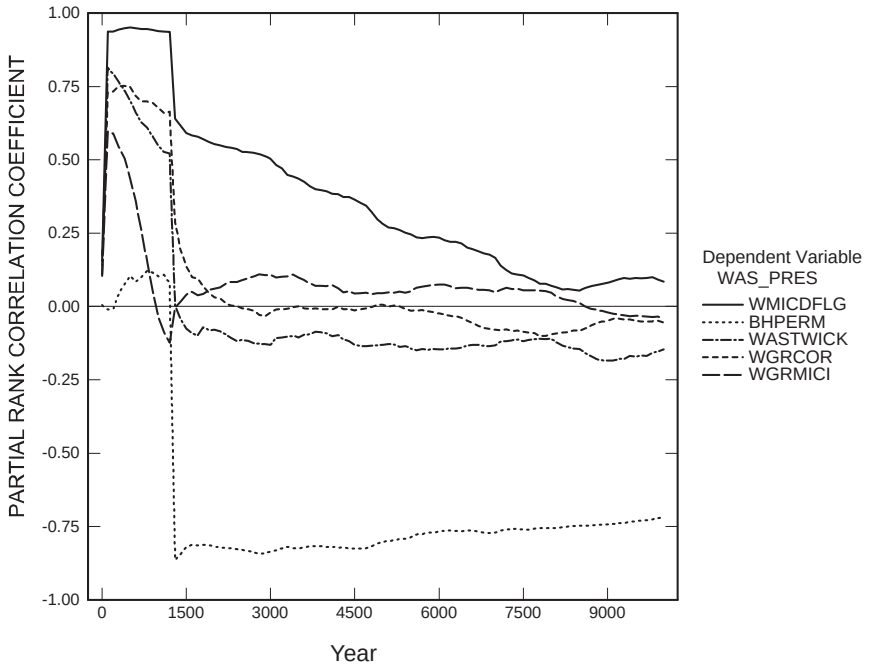

Figure PA-54. Primary Correlations For Pressure In The Waste Panel With Uncertain Parameters, Replicate R1, Scenario S5.

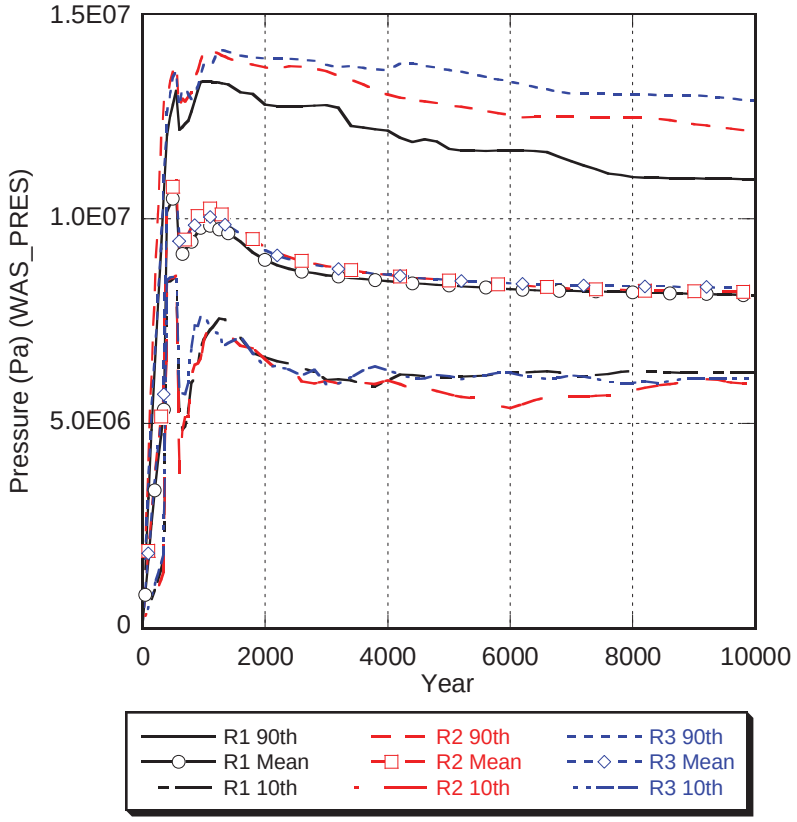

Figure PA-55. Statistics For Pressure in the Waste Panel For All Replicates, Scenario S2.

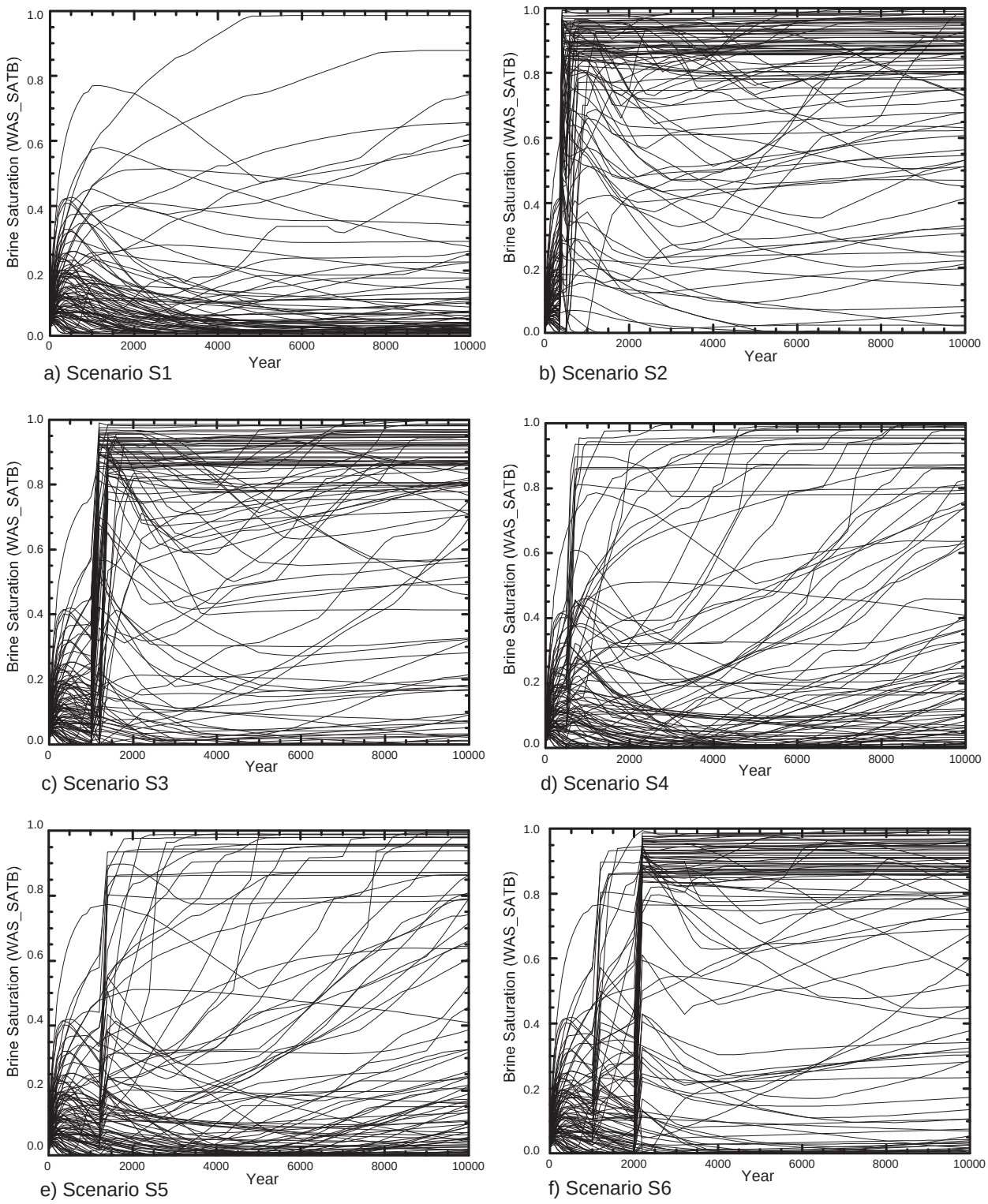

Figure PA-56. Brine Saturation in the Waste Panel for All Scenarios, Replicate R1.

Figure PA-57 compares the mean values for brine saturation in the waste panel (WAS_SATB) for each scenario. Brine saturation is highest after E1 intrusions (Scenarios S2, S3, and S6), but also increases somewhat after an E2 intrusion (Scenarios S4 and S5). However, saturation in other excavated areas is not generally increased. Figure PA-58 shows brine saturation in the rest of repository (SRR_SATB for area South RoR and NRR_SATB for area North RoR in Figure PA-8) and in the nonwaste areas (NWA_SATB averaged over areas Ops and Exp in Figure PA-8) for the Scenarios S2 and S5. Comparison of Figure PA-57 with Figure PA-39, which shows brine saturation in undisturbed conditions, reveals that brine saturation in unintruded regions is generally unaffected by the intrusion. The panel closures separating the intruded panel from these regions effectively prevent brine flow between excavated areas. In addition, the intruded panel is modeled as one of the panels at the southern end of the repository, and hence is down the stratigraphic dip from the other excavated regions.

Figure PA-58 also shows that brine saturation in the nonwaste areas (areas Ops and Exp in Figure PA-8) is somewhat higher than in the rest of repository areas (areas South RoR and North RoR in Figure PA-8). Brine saturation in the nonwaste areas is higher because of the lack of brine consuming corrosion processes in these areas and their position adjacent to the northern marker beds, which supply brine to the excavated area. The rest of repository areas have the lowest saturations because they are not connected to the brine reservoir, corrosion consumes brine in these regions, and their internal position in the two-dimensional grid (Figure PA-8) prevents direct flow of brine from the MBs.

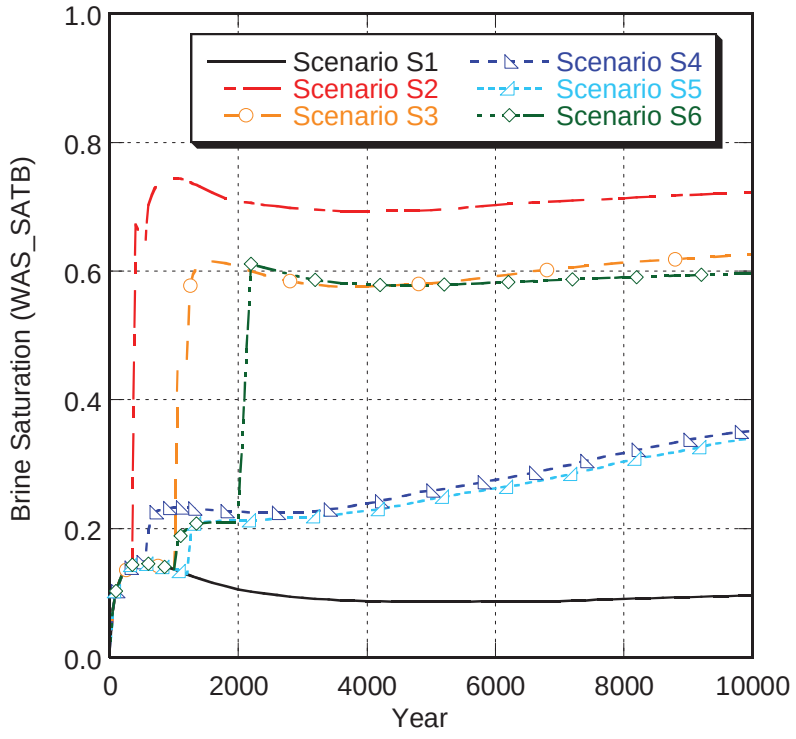

Figure PA-57. Mean Values for Brine Saturation in the Waste Panel for All Scenarios, Replicate R1.

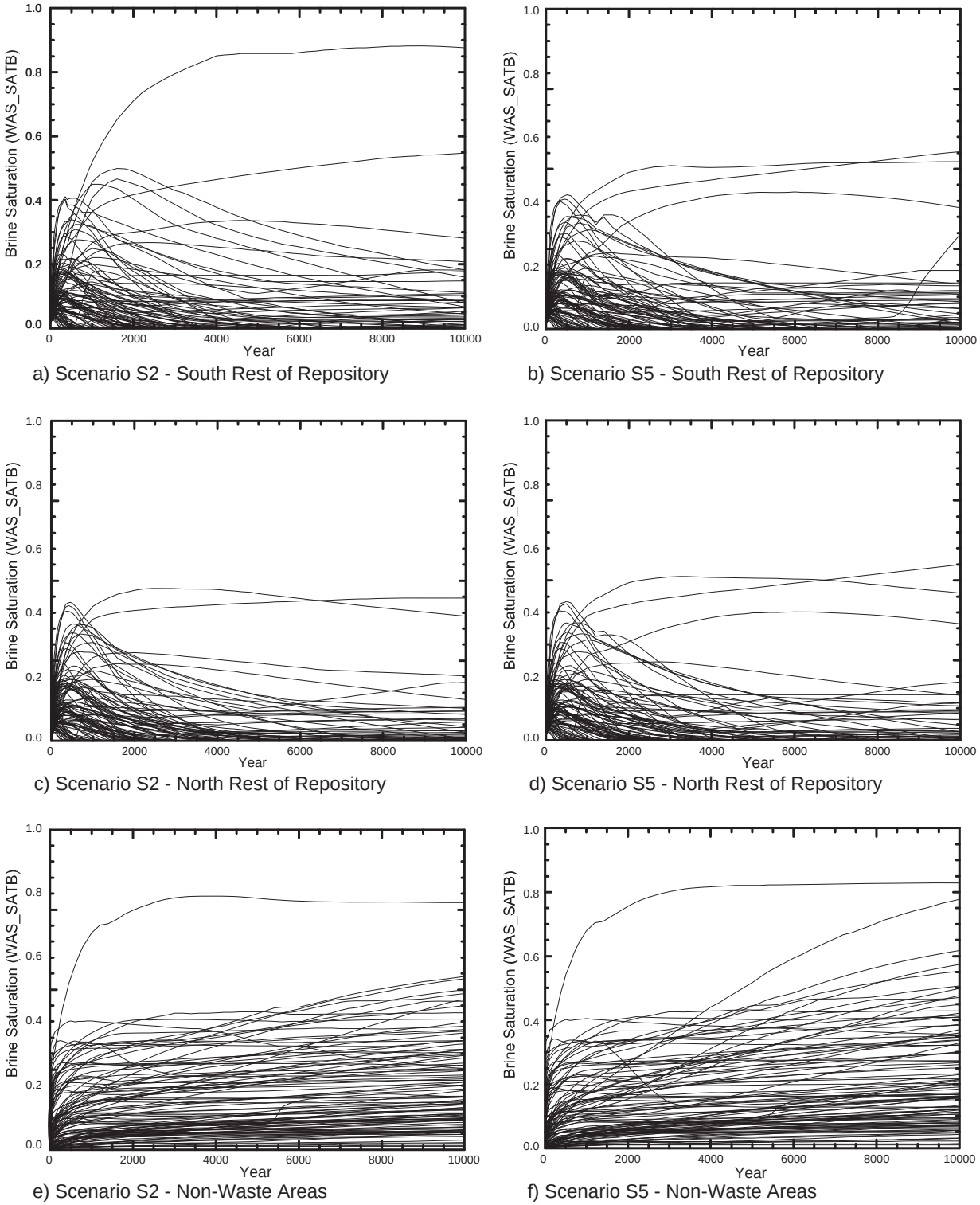

Figure PA-58. Brine Saturation in Excavated Areas, Replicate R1, Scenarios S2 and S5.

Figure PA-59 compares mean and 90th percentile brine saturations among the excavated areas for an E1 intrusion at 350 years (Scenario S2). Brine saturations in the waste panel are the highest due to the connection with the brine reservoir. Comparison of Figure PA-59 to Figure PA-40, which shows mean pressure for undisturbed conditions, indicates that brine saturation outside of the waste panel is very similar to the undisturbed Scenario S1.

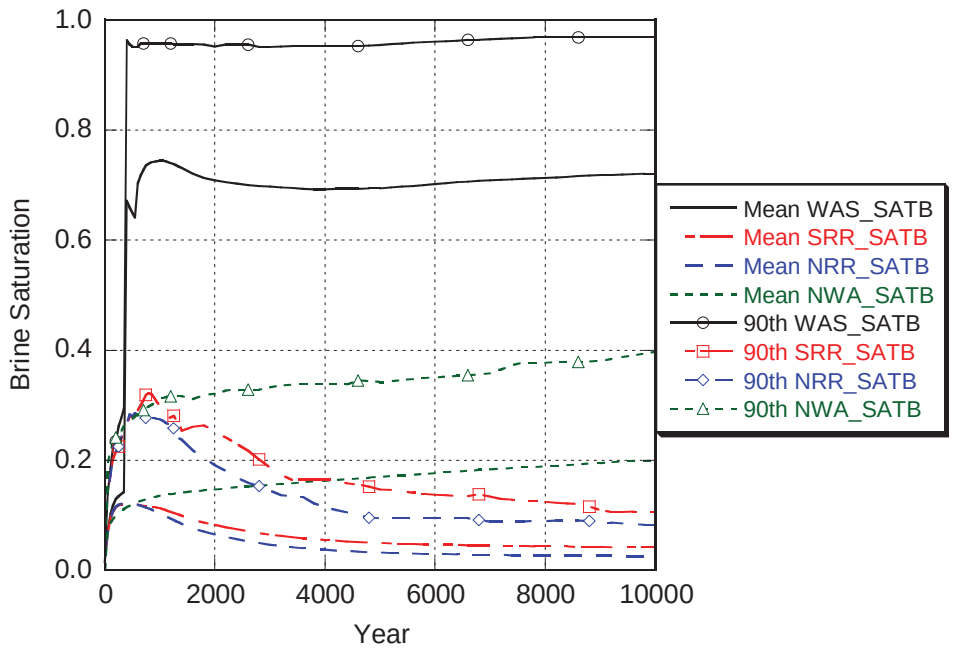

Figure PA-59. Statistics For Brine Saturation in Excavated Areas, Replicate R1, Scenario S2.

Figure PA-60 shows the results of the regression analysis between brine saturation in the waste panel (WAS_SATB) for the S2 scenario and the uncertain parameters in the analysis (Section PA-5.2). For most of the time after the intrusion, uncertainty in borehole permeability (BHPERM) is primarily responsible for the uncertainty in brine saturation, with increases in borehole permeability leading to increases in brine saturation. The indicator for microbial degradation (WMICDFLG), which has a negative correlation with the brine saturation in the waste panel, also has a significant influence throughout the 10,000-year modeling period. Because the S2 scenario models an intrusion at 350 years, much of the CPR material is still present in the waste. Additional brine entering the waste panel would saturate more of the waste and accelerate the degradation of the CPR material, increasing gas pressure, and in turn retarding brine inflow. Thus, the negative correlation between the indicator for microbial degradation and brine saturation is quite strong immediately after the intrusion, but decreases in importance at later times. Uncertainty in the other parameters in Figure PA-60 (HALPOR, DRZPRM, and WGRCOR, defined in Table PA-17), have relatively little influence on brine saturation. Regression analysis of waste saturation for the S3 scenario yields a similar result (Stein and Zelinski 2003b).

Figure PA-61 shows the results of the regression analysis between brine saturation in the waste panel (WAS_SATB) for the S5 scenario and the uncertain parameters in the analysis (Section PA-5.2). As with the S2 scenario, borehole permeability is the primary factor

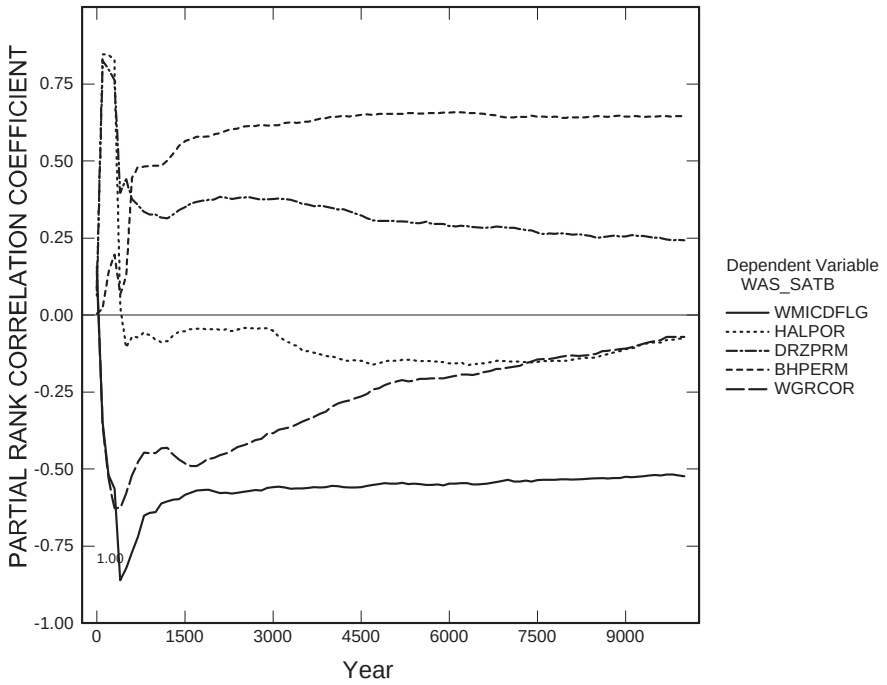

Figure PA-60. Primary Correlations for Brine Saturation in the Waste Panel with Uncertain Parameters, Replicate R1, Scenario S2.

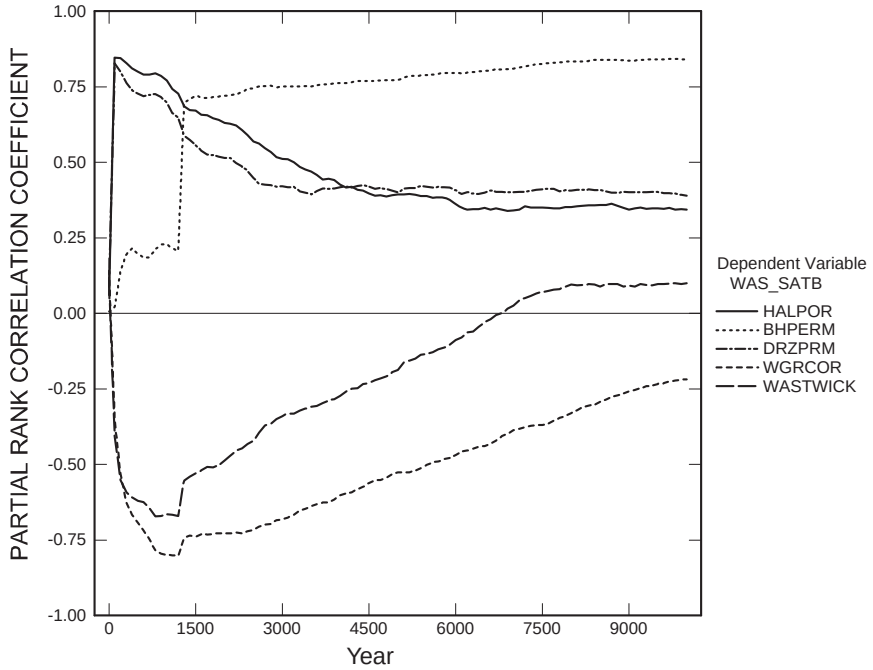

Figure PA-61. Primary Correlations of Brine Saturation in the Waste Panel with Uncertain Parameters, Replicate R1, Scenario S5.

influencing brine saturation in the waste panel (WAS_SATB) after the borehole plugs fail. Regression analysis of waste saturation for the S4 scenario yields a similar result (Stein and Zelinski 2003b).

Figure PA-62 compares statistics for brine saturation for the three replicates of the S2 scenario, and shows that the replicates produced similar results.

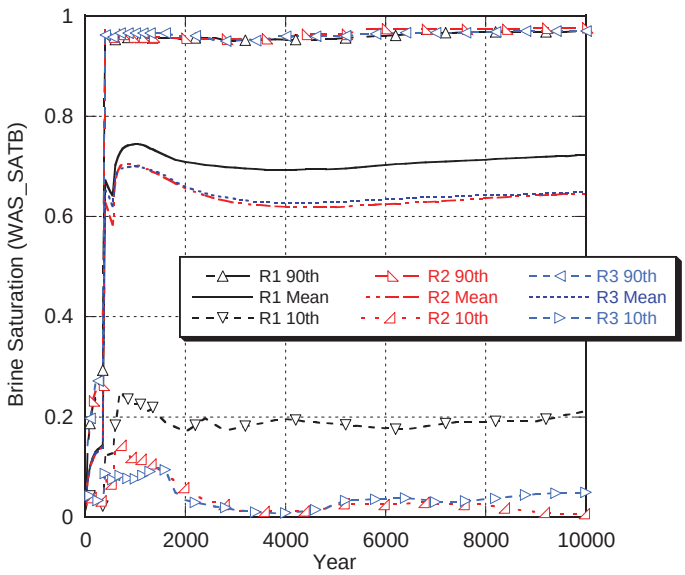

Figure PA-62. Statistics for Brine Saturation in the Waste Panel For All Replicates, Scenario S2.

PA-8.3.3 Brine Flow Out of the Repository

This section describes the flow of brine up a borehole to the Culebra. Brine flow to the Culebra is an important input to the calculations of long-term releases in the Culebra, described in Section PA-8.4.3. Direct brine flow up the borehole to the surface at the time of drilling is modeled separately in the DBR calculations, presented in Section PA-8.5.3.

Figure PA-63 shows cumulative brine flow out of the repository (BRNREPOC) and brine flow up a borehole to the Culebra (BRNBHRCC) for the five BRAGFLO scenarios that model drilling intrusions. The largest volumes of brine flow from the repository after E1 intrusions (Scenarios S2, S3, and S6), which is consistent with the higher brine saturation in the intruded panel (Figures PA-56b, PA-56c, and PA-56f, respectively). The similarity between the plots of BRNREPOC and BRNBHRCC indicate that nearly all the brine leaving the repository after an intrusion flows up the borehole to the Culebra. The few vectors that show brine flow out of the repository before the drilling intrusion generally have either very high pressures or very high DRZ permeability, allowing brine to flow from the repository into the MBs before the intrusion occurs. At 1,200 years after an E1 intrusion, the permeability of the borehole between the repository and the Castile is reduced by an order of magnitude because of creep closure (see Table PA-5), reducing brine flowing into the repository and causing a corresponding decrease in brine out of the repository.

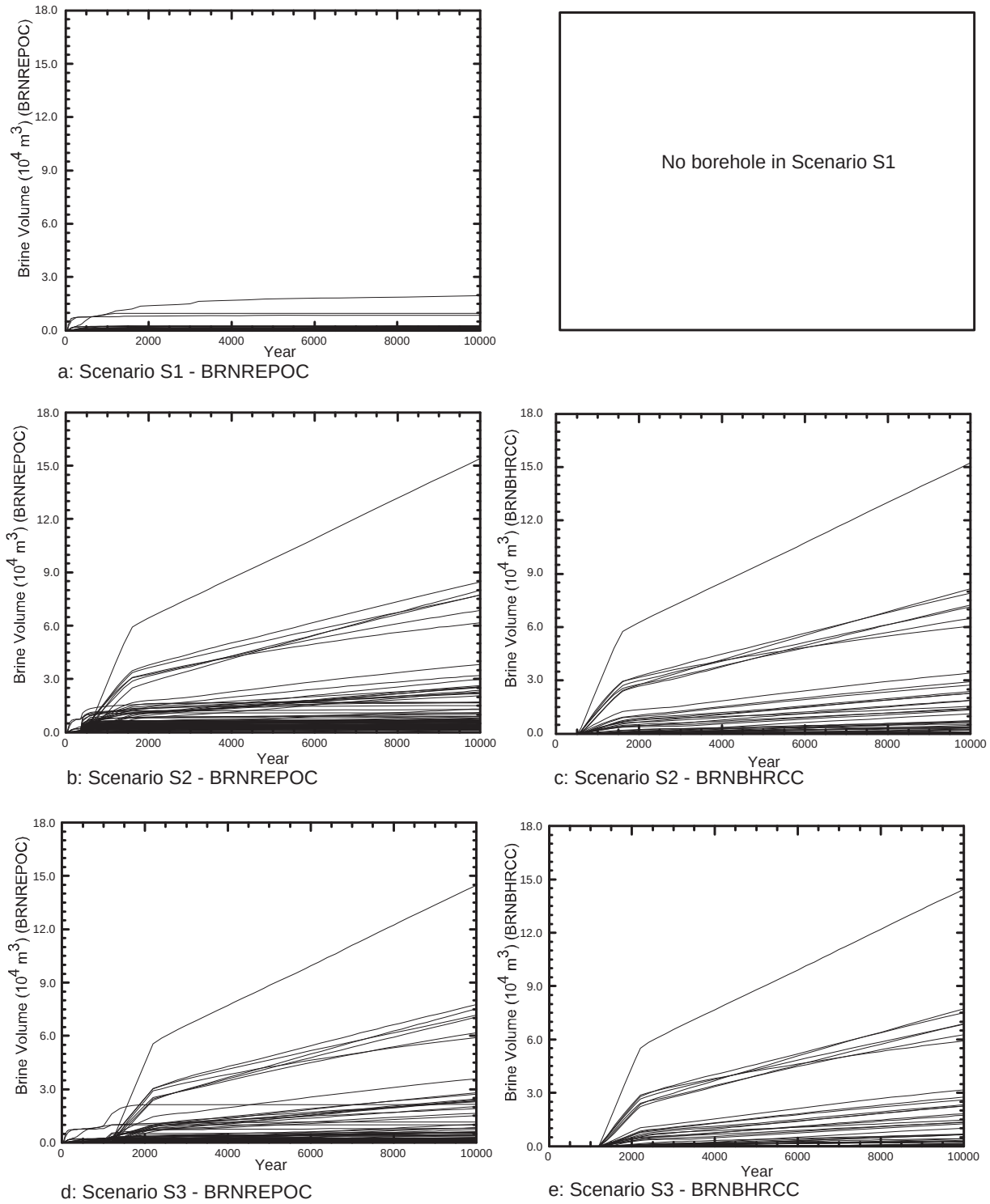

Figure PA-63. Total Cumulative Brine Outflow and Brine Flow Up the Borehole in All Scenarios, Replicate R1.

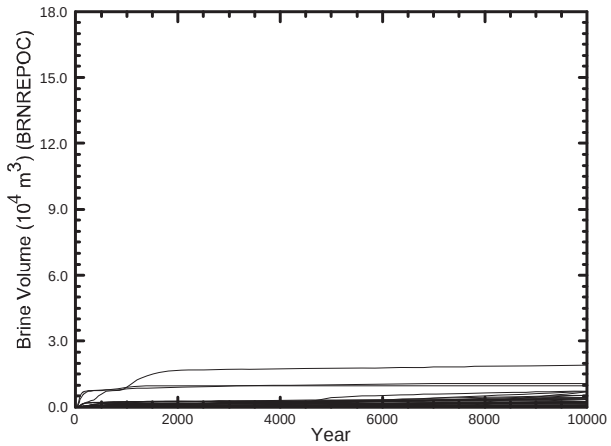

f) Scenario S4 - BRNREPOC

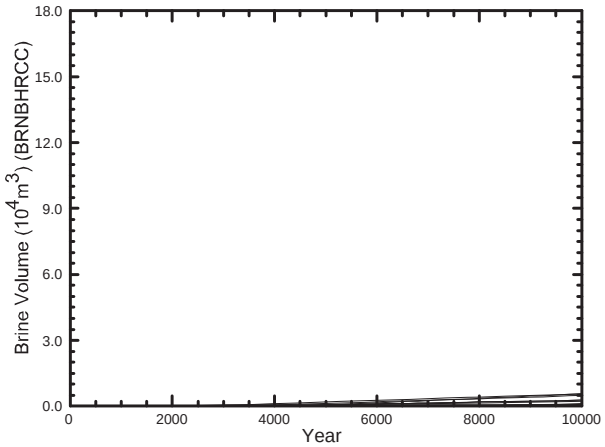

g) Scenario S4 - BRNBHRCC

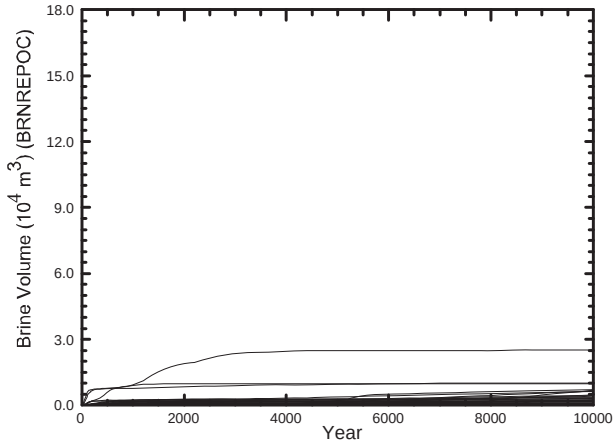

h) Scenario S5 - BRNREPOC

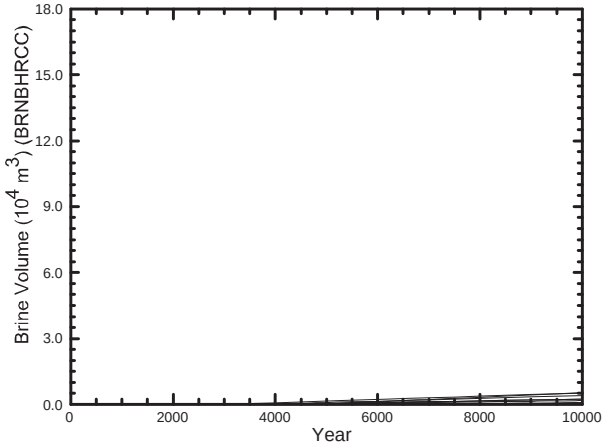

i) Scenario S5 - BRNBHRCC

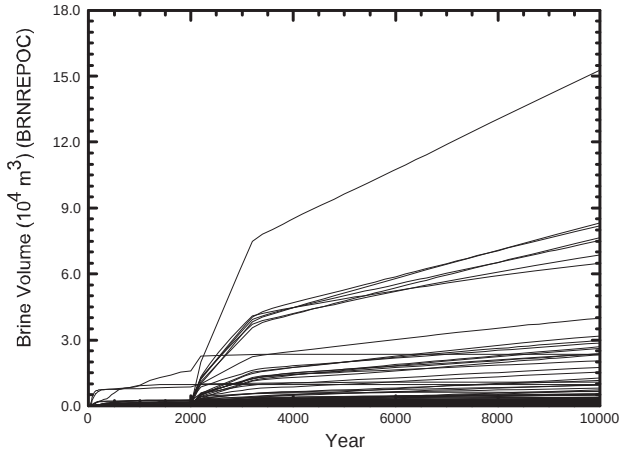

j) Scenario S6 - BRNREPOC

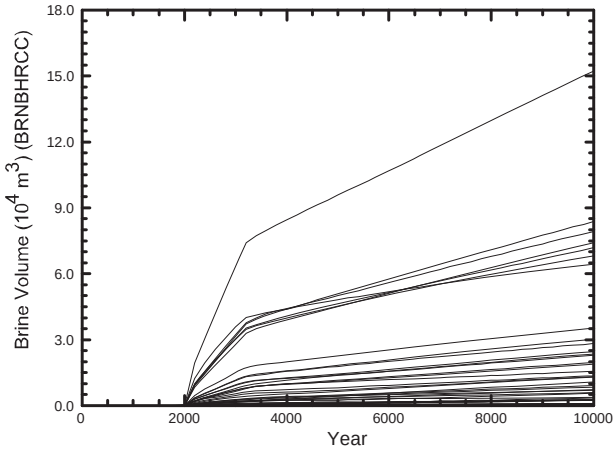

k) Scenario S6 - BRNBHRCC

Figure PA-63(cont). Total Cumulative Brine Outflow and Brine Flow Up the Borehole in All Scenarios, Replicate R1

Figure PA-64 shows the results of regression analysis between the brine flow up the borehole to the Culebra (BRNBHRCC) and the uncertain parameters in the analysis (Section PA-5.2). Before the intrusion, non-zero values of BRNBHRCC result from numerical error in the calculation; these values do not exceed 10^{-18} m^3 and thus the correlation to uncertainty in shaft permeability (SHUPRM) is not meaningful. Immediately after the intrusion, uncertainty in the permeability of the undegraded borehole plugs (PLGPRM) contributes most of the uncertainty in brine flow volumes. After the borehole plugs degrade (200 years after the intrusion), uncertainty in the permeability of the borehole (BHPERM) almost exclusively determines the uncertainty in brine volumes reaching the Culebra. The indicator for microbial degradation (WMICDFLG) is weakly correlated with the small amount of uncertainty that is not explained by the uncertainty in borehole permeability.

Figure PA-65 compares statistics for brine flow out of the repository for the three replicates of Scenario S2. The figure shows that brine flow results are very similar among replicates.

PA-8.4 Radionuclide Transport

In the disturbed scenarios, radionuclide transport in the Salado is calculated by the code NUTS (see Section PA-4.3). Transport from the Salado to the Culebra is calculated by NUTS and PANEL (see Section PA-4.3 and Section PA-4.4). Transport within the Culebra is calculated by SECOTP2D (see Section PA-4.9). For all transport calculations, mobilized concentrations of radionuclides in Salado and Castile brines are computed by the code PANEL (see Section PA-4.4).

This section summarizes the transport results for the disturbed scenarios. Detailed analysis of the NUTS results is presented in Lowry (2003). Garner (2003) provides analysis of the PANEL results; Kanney (2003) presents analysis of the SECOPT2D results.

PA-8.4.1 Radionuclide Source Term

The code PANEL calculates the source term for transport, which is the time-varying concentration of radioactivity mobilized in brine, either as dissolved isotopes or as isotopes sorbed to mobile colloids. Two different brines are considered: the interstitial brine present in the Salado Formation, which is magnesium rich; and the brine in the Castile Formation, which is sodium rich. Radionuclide solubility in the two brines can be considerably different. Before an E1 intrusion, performance assessment assumes that the brine in the repository is Salado brine. After an E1 intrusion, brine in the repository is assumed to be from the Castile.

Figure PA-66 and Figure PA-67 show the source term in Salado and Castile brines, respectively, as a function of time for all vectors in replicate R1. Concentrations are expressed as EPA units/m^3 to combine the radioactivity in different isotopes. Short-lived radionuclides, such as ^{238}Pu, decay rapidly in the first few years. After this initial decay, the source term is dominated by Am (Garner 2003); the concentration of Am is limited by its solubility until all the inventory of Am is in solution. After all Am is in solution, the total radionuclide concentration generally decreases as the Am decays, until the source term becomes dominated by Pu (Garner 2003). The horizontal lines in the figures indicate periods of time when the

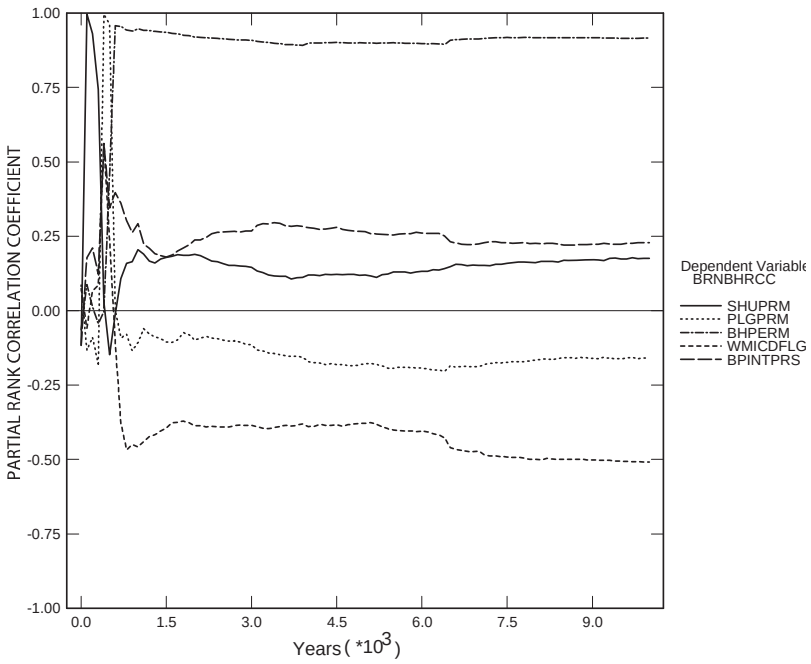

Figure PA-64. Primary Correlations for Cumulative Brine Flow Up the Borehole with Uncertain Parameters, Replicate R1, Scenario S2.

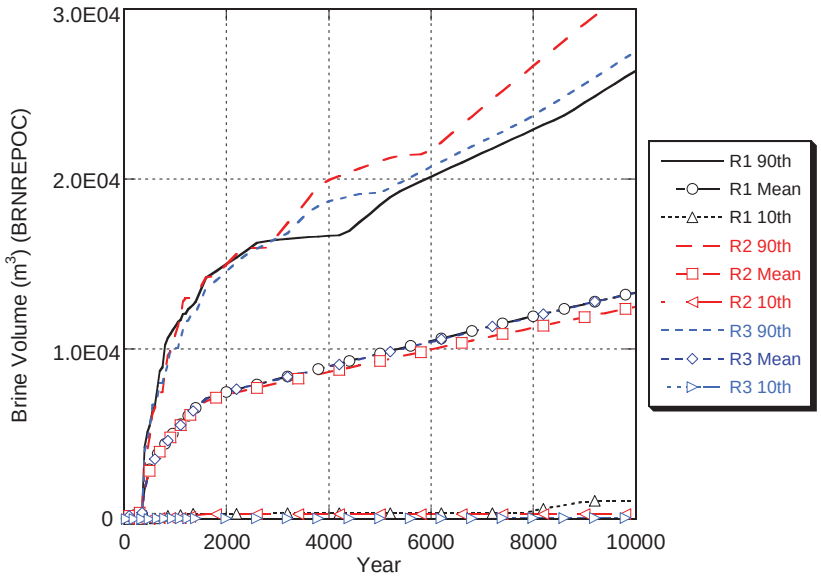

Figure PA-65. Statistics for Cumulative Brine Outflow in All Replicates, Scenario S2.

total radionuclide concentration is limited by the solubility of Am (before about 3,000 years) or Pu (after about 6,000 years). Thus, the uncertainty in total radionuclide concentration is determined by the uncertainty factors used in the calculation of solubilities for Am and Pu (see Table PA-9).

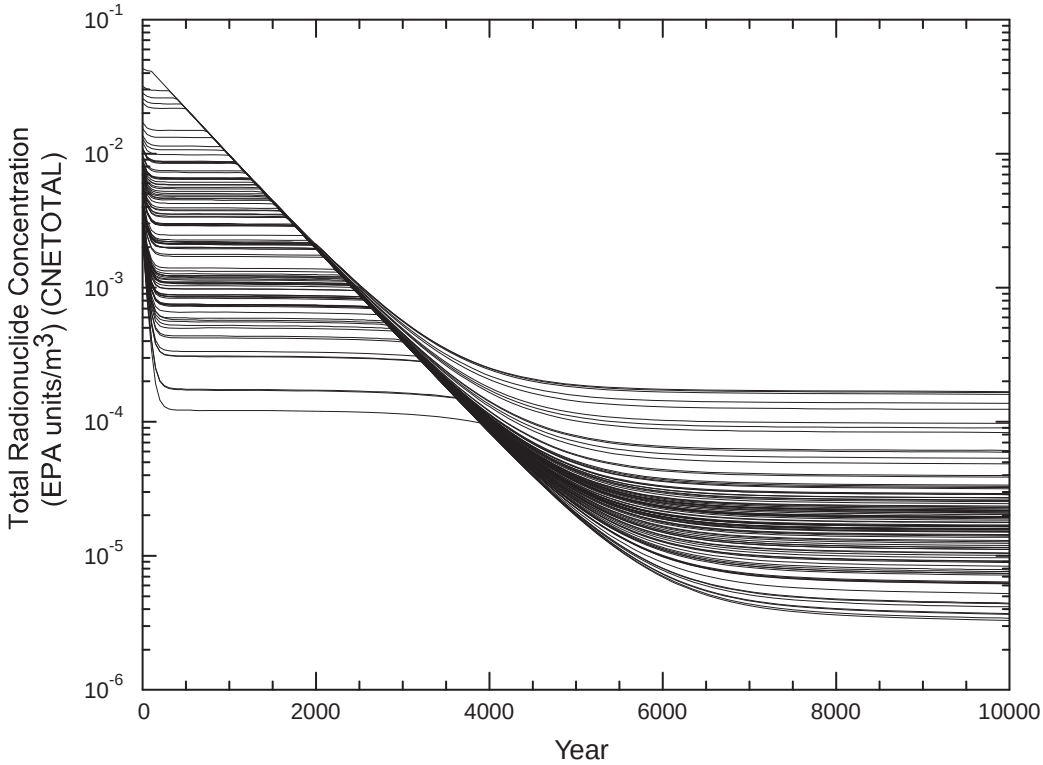

Figure PA-66. Total Mobilized Concentrations in Salado Brine.

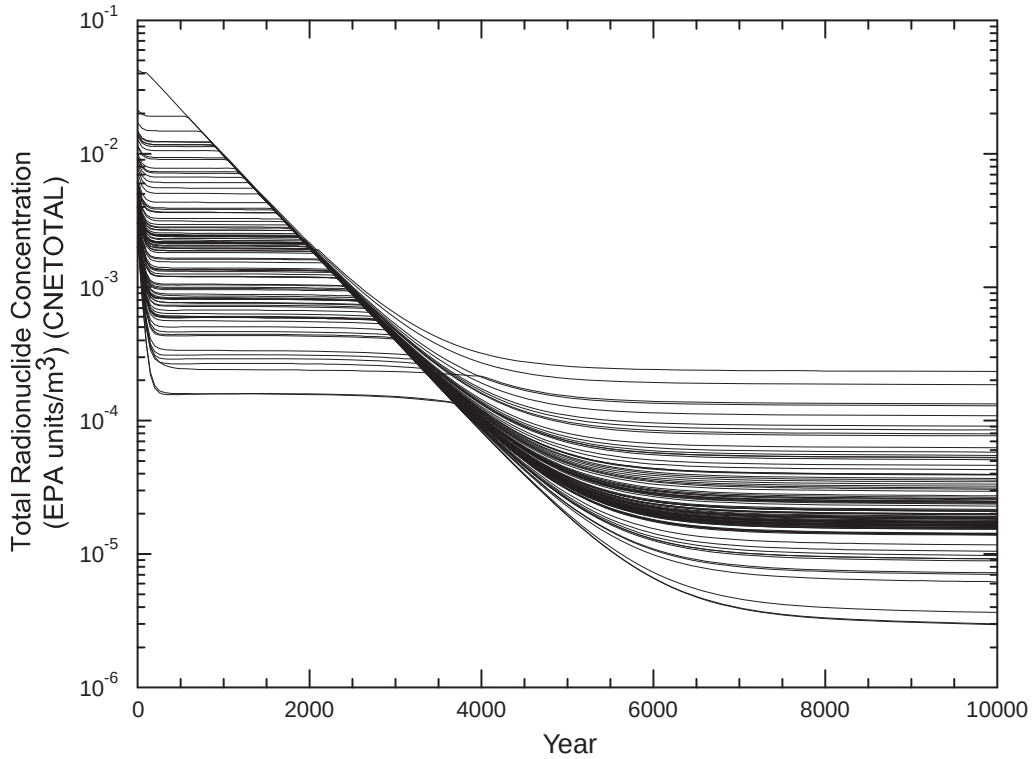

Figure PA-67. Total Mobilized Concentrations in Castile Brine.

PA-8.4.2 Transport through Marker Beds and Shaft

In the disturbed scenarios, none of the 300 realizations resulted in transport of radionuclides through the MBs and across the LWB (Lowry 2003). In addition, no realization showed transport of radionuclides through the shaft to the Culebra.

PA-8.4.3 Transport to the Culebra

In four of the disturbed scenarios (S2, S3, S4, and S5), transport to the Culebra is modeled with the code NUTS. In the multiple intrusion scenario (S6), the code PANEL is used to calculate transport to the Culebra. Figures PA-68 through PA-71 show cumulative radioactivity transported up the borehole to the Culebra. Transport to the Culebra is larger and occurs for more vectors in the S2 and S3 scenarios (E1 intrusions) than in the S4 or S5 scenarios (E2 intrusions). For most vectors that show significant transport, most of the transport occurs over a relatively short period of time, immediately after the borehole plugs fail.

Figure PA-72 shows total EPA units transported to the Culebra via the borehole in the S6 scenario. Almost no radionuclides are released after the E2 intrusion at 800 years; most transport occurs immediately following the E1 intrusion at 2,000 years.

Figure PA-73 and Figure PA-74 compare mean values among all three replicates for cumulative normalized releases up the borehole to the Culebra for scenarios S3 and S6, respectively. These figures show that the results from each replicate are very similar.

Sensitivity analysis of total radionuclides transported to the Culebra identified a strong linear relationship between the uncertainty in the total release to the Culebra and the uncertainty in the brine flow up the borehole (calculated by BRAGFLO; see Section PA-8.3.3). Figure PA-75 shows the relationship between total releases to the Culebra (EPATBHRC, calculated by NUTS; see Section PA-4.3) and brine flow up the borehole (BRNBHRCC, calculated by BRAGFLO; see Section PA-8.3.3) at 10,000 years after an E1 intrusion at 1,000 years (Scenario S3). Figure PA-76 shows the relationship between total releases to the Culebra (LDETOTAL, calculated by PANEL; see Section PA-4.4) and brine flow up the borehole (BRNBHRCC, calculated by BRAGFLO; see Section PA-8.3.3) at 10,000 years after the combination of an E2 intrusion at 800 years followed by an E1 intrusion in the same panel at 2,000 years (Scenario S6).

Sensitivity analysis (Section PA-8.3.3) identified borehole permeability (BHPERM) as the most important parameter contributing to the uncertainty in flow up the borehole (BRNBHRCC). Separate stepwise regression analyses (Lowry 2003; Garner 2003) confirmed the correlation between uncertainty in borehole permeability and releases to the Culebra. These analyses also identified the initial pressure in the brine pocket (BPINTPRS), indicator for microbial action (WMICDFLG), and steel corrosion rate (WGRCOR) as contributing to uncertainty in releases to the Culebra although the importance of these parameters is much less than that of borehole permeability.

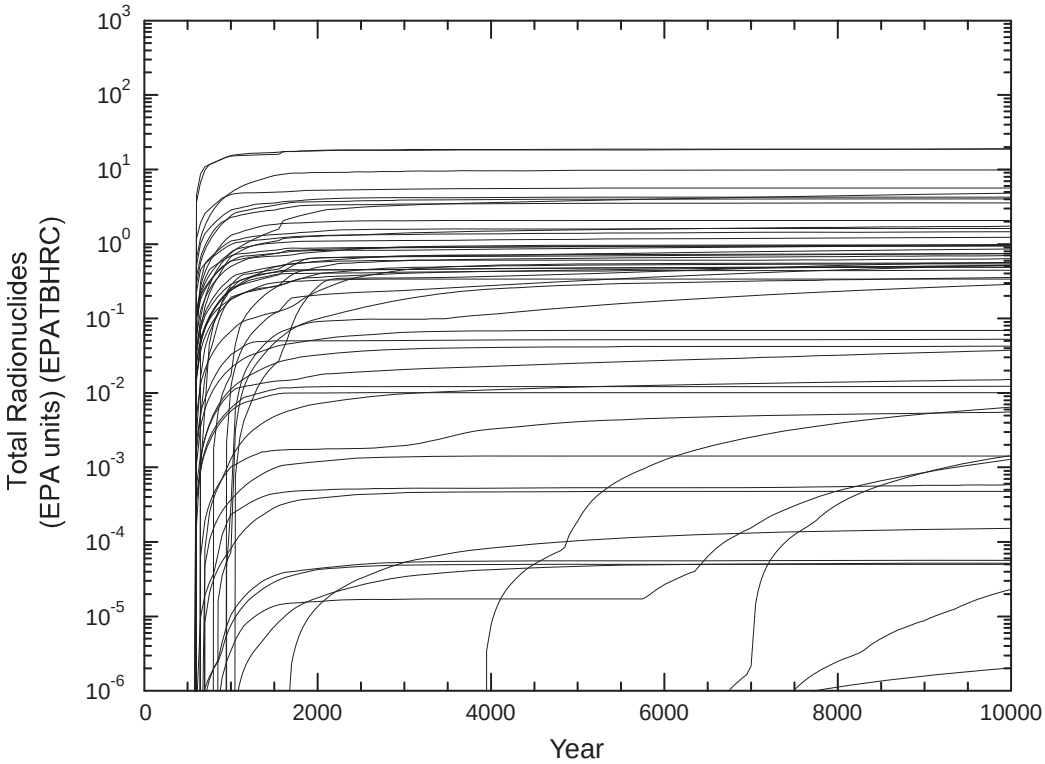

Figure PA-68. Cumulative Normalized Release Up the Borehole, Replicate R1, Scenario S2.

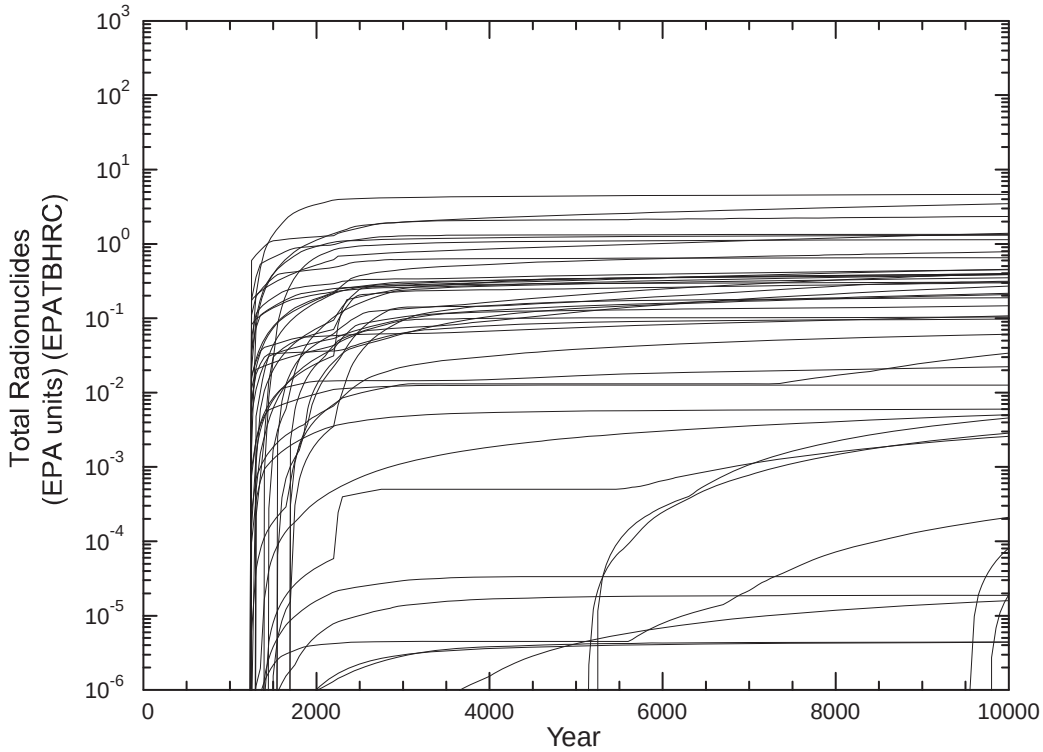

Figure PA-69. Cumulative Normalized Release Up the Borehole, Replicate R1, Scenario S3.

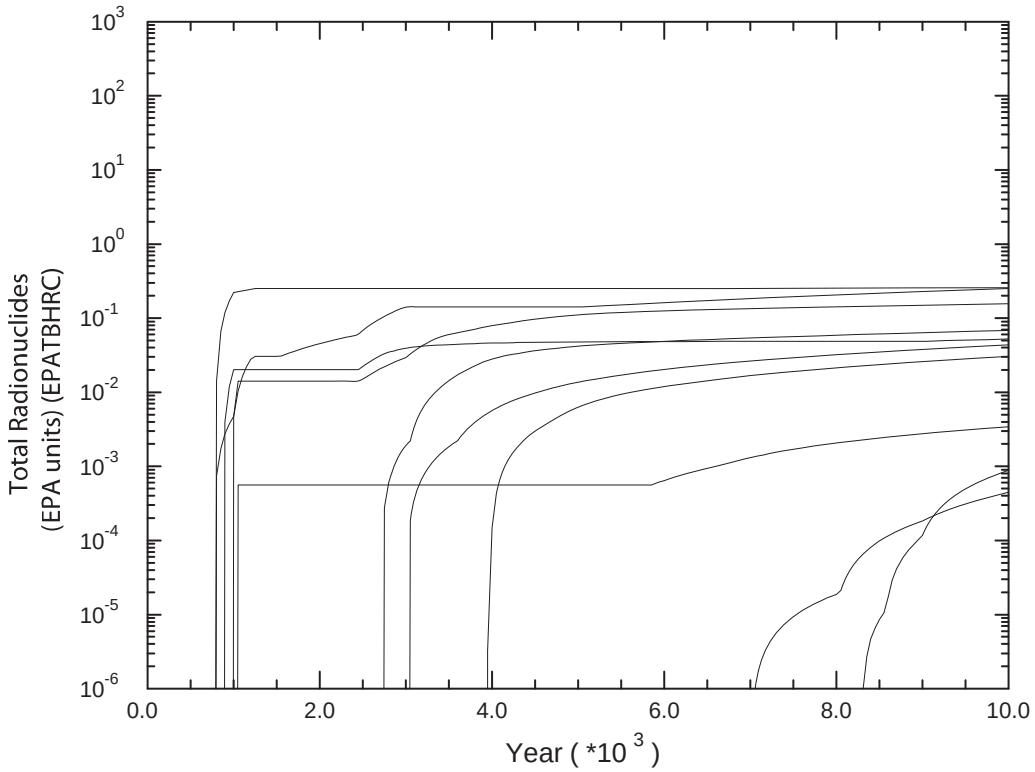

Figure PA-70. Cumulative Normalized Release Up the Borehole, Replicate R1, Scenario S4.

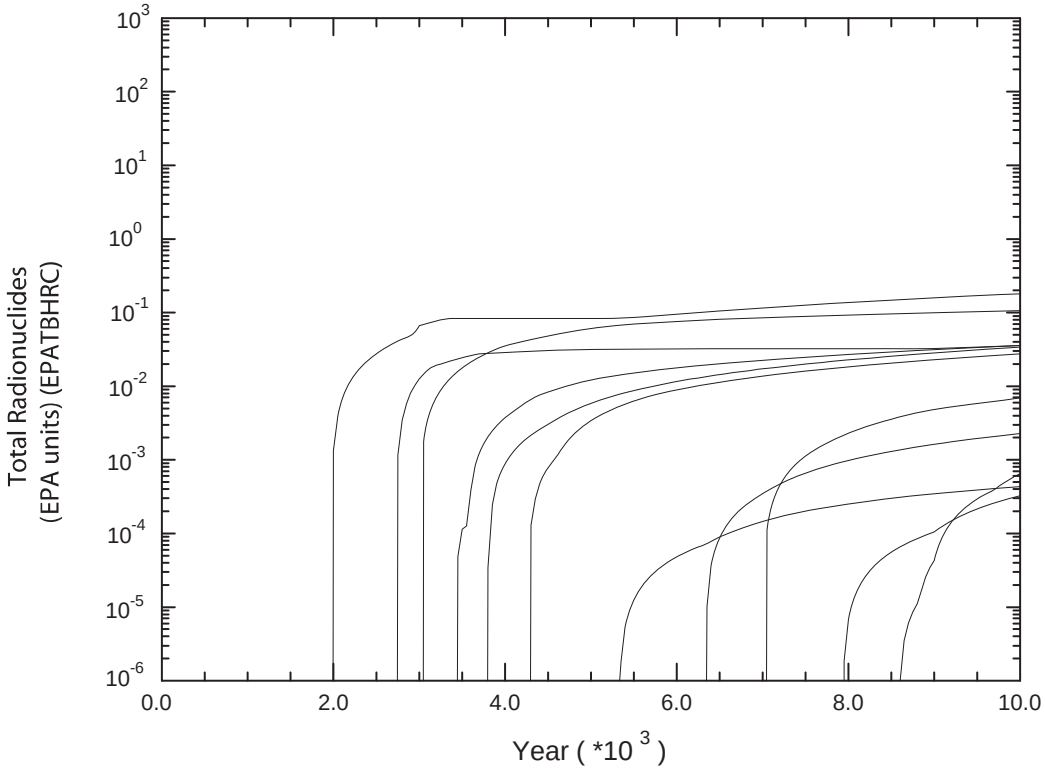

Figure PA-71. Cumulative Normalized Release Up the Borehole, Replicate R1, Scenario S5.

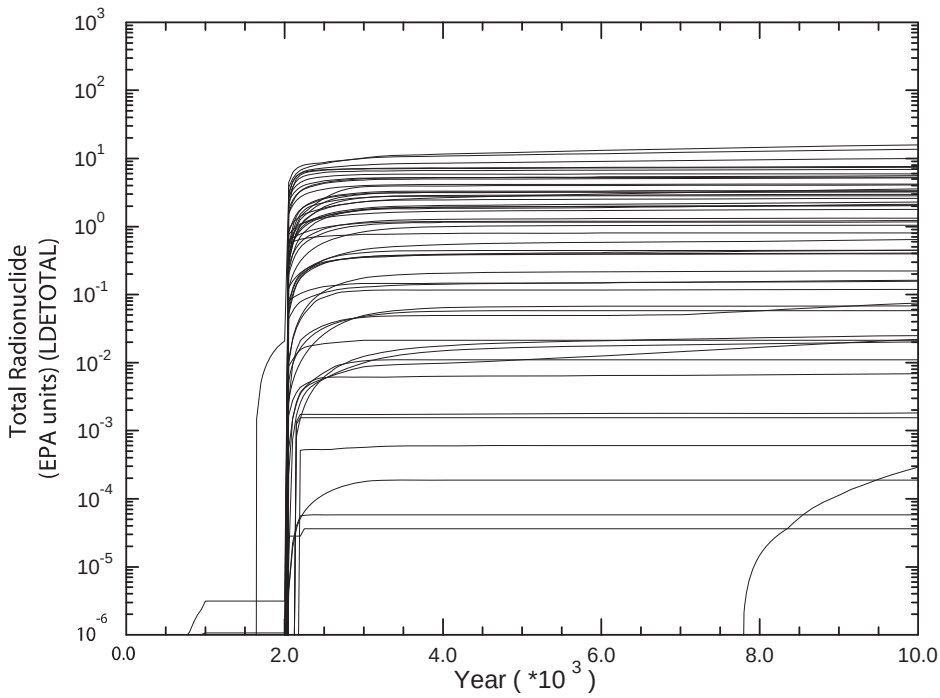

Figure PA-72. Cumulative Normalized Release Up the Borehole, Replicate R1, Scenario S6.

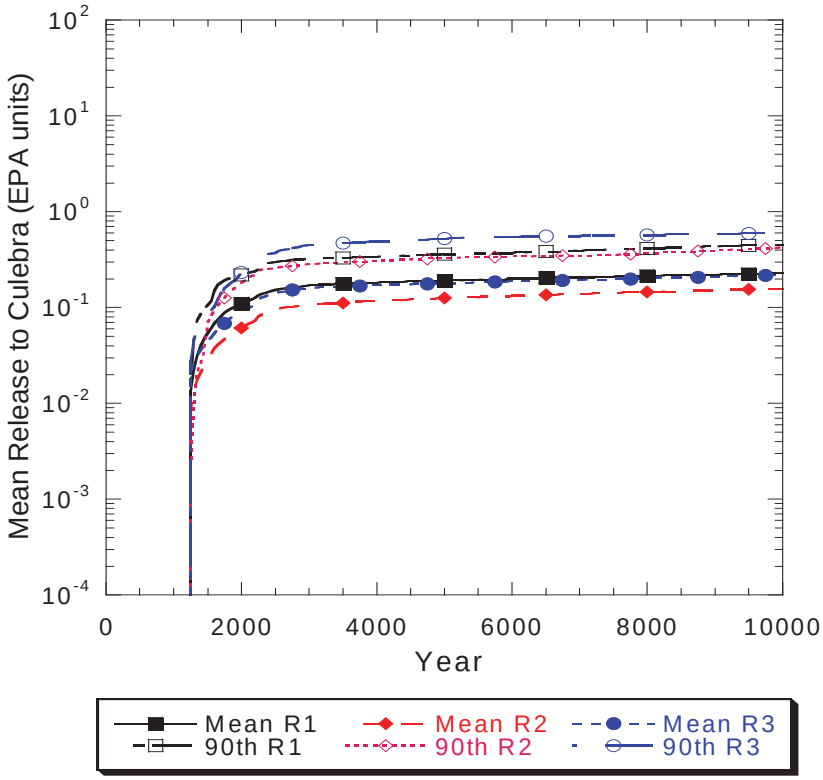

Figure PA-73. Mean Values for Cumulative Normalized Release Up the Borehole for All Replicates, Scenario S3.

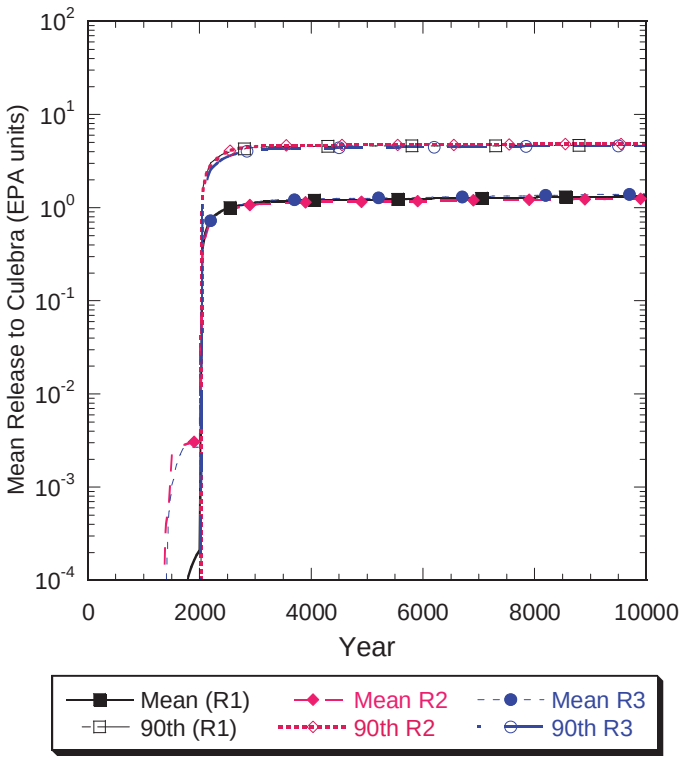

Figure PA-74. Mean Values for Cumulative Normalized Release Up Borehole for All Replicates, Scenario S6.

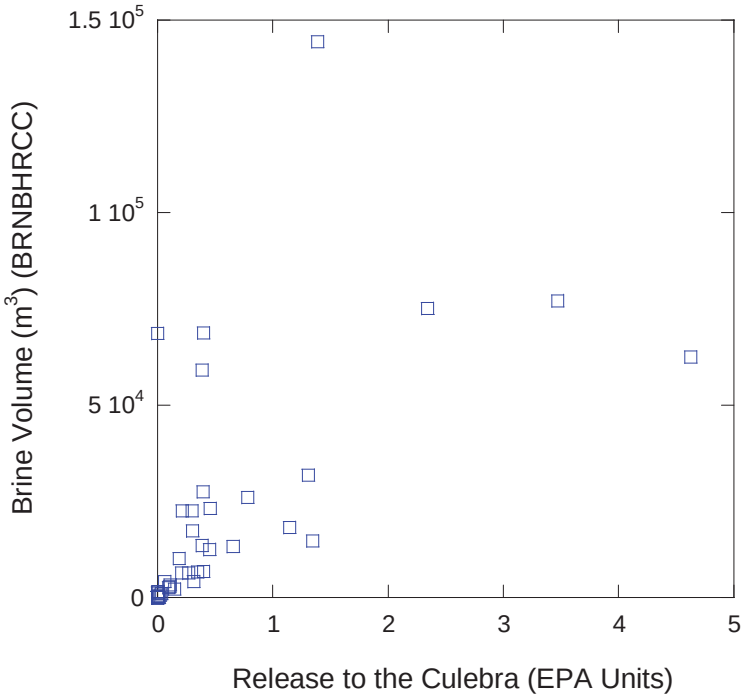

Figure PA-75. Comparison of Total Release to Culebra with Flow Up Borehole, Replicate 1 Scenario S3.

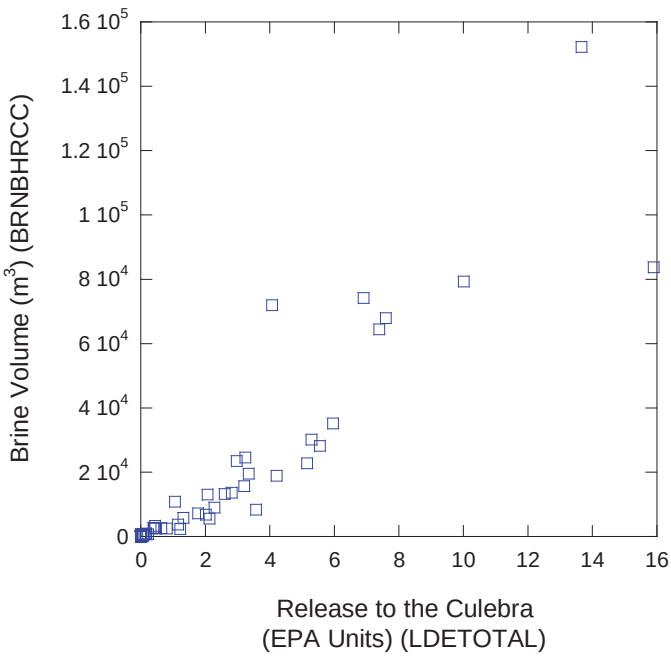

Figure PA-76. Comparison of Total Release to Culebra with Flow Up Borehole, Replicate 1 Scenario S3.

PA-8.4.4 Transport through the Culebra

Releases through the Culebra are calculated with the code SECOTP2D (see Section PA-4.9). As explained in Section PA-6.8.7, transport through the Culebra is calculated for a release of 1 kg of each of four radionuclides (^{241}Am, ^{234}U, ^{230}Th, and ^{239}Pu). Am is present as Am(III) and Th as Th(IV). Uranium may be present as either U(IV) or U(VI); plutonium may be present as Pu(III) or Pu(IV). The oxidation state of uranium and plutonium is an uncertain parameter (see WOXSTAT in Table PA-17). The total release of radionuclides across the LWB at the Culebra is calculated by the code CCDFGF by convoluting the SECOTP2D results with the transport to the Culebra calculated by NUTS and PANEL. This section discusses the SECOTP2D results; releases through the Culebra are presented in Section PA-9.5.

Transport calculations were performed for both partial-mining and full-mining scenarios. The partial-mining scenario assumes the extraction of all potash reserves outside the LWB while full mining assumes that all potash reserves both inside and outside the LWB are exploited. Flow fields in the Culebra are computed separately for each mining scenario by the code MODFLOW (see Section PA-4.8).

All SECOTP2D results, regardless of magnitude, are included in the calculation of releases through the Culebra. In practice, most non-zero releases computed by SECOTP2D are vanishingly small and result from numerical error (Kanney 2003). Consequently, the analysis of SECOTP2D results focused on realizations in which at least one billionth (10^{-9}) of the 1 kg source was transported to the land withdrawal boundary.

PA-8.4.4.1 Partial Mining Results

Under partial-mining conditions, only the ^{234}U species was transported beyond the LWB in any significant amount during the course of the 10,000-year simulation (Kanney 2003). Table PA-27 shows the eight vectors that resulted in releases greater than one billionth of the 1 kg source. Sensitivity analysis indicates that releases of ^{234}U are associated with the (VI) oxidation state. This result is reasonable because the matrix distribution coefficients for uranium in the (IV) state are much lower than for the (VI) state (see Section PA-5.2 and Attachment PAR, Table PAR-35).

Table PA-27. Releases of ^{234}U at LWB in Partial Mining Conditions

Replicate	Vector	^{234}U Release at LWB (fraction of 1 kg source)
3	54	0.479
3	84	0.177
3	38	0.0815
2	10	0.0711
1	58	0.0541
3	23	1.40×10^{-3}
1	8	2.36×10^{-4}
3	71	7.12×10^{-8}

PA-8.4.4.2 Full Mining Results

Under full-mining conditions, only the ^{234}U species was transported beyond the LWB in significant amounts during the course of the 10,000-year simulation. Table PA-28 shows the 18 vectors that resulted in releases greater than one billionth of the source of 1 kg. Sensitivity analysis indicates that releases of ^{234}U in the full mining conditions are also associated with the U(VI) oxidation state.

Two vectors showed releases of ^{239}Pu greater 1×10^{-9} kg. Replicate 2, vector 71 computed a release of 6.15×10^{-6} kg; replicate R1, vector 92 showed a release of 2.03×10^{-9} kg. No releases of ^{230}Th or ^{241}Am exceeded 1×10^{-9} kg.

PA-8.4.4.3 Additional Information

More detailed information on the results of the Culebra transport calculations can be found in the Analysis Package for the Culebra Transport Calculations: Compliance Recertification Application (Kanney 2003).

Table PA-28. Releases of ^{234}U at LWB in Full-Mining Conditions

Replicate	Vector	^{234}U Release at LWB (fraction of 1 kg source)
2	15	0.987
3	38	0.987
1	58	0.889
1	65	0.766
3	54	0.712
2	10	0.209
3	27	0.0269
1	90	0.0127
2	30	0.0123
1	31	6.18×10^{-3}
3	65	4.72×10^{-3}
3	66	1.80×10^{-4}
2	53	1.66×10^{-5}
3	67	1.59×10^{-7}
1	67	1.03×10^{-8}
3	42	4.53×10^{-9}
2	33	1.98×10^{-9}
2	24	1.61×10^{-9}

PA-8.5 Direct Releases

Direct releases occur at the time of a drilling intrusion, and include cuttings and cavings; spallings; and DBRs. This section presents analysis of the volume released by each mechanism.

PA-8.5.1 Cuttings and Cavings Volumes

Cuttings and cavings releases are solid waste material that is removed from the repository by the cutting of the drill bit and additional material that is sheared off the borehole wall by the circulation of the drilling fluid. Figure PA-77 shows the CCDFs for the total volume removed to the surface from cuttings and cavings for replicate R1. Figure PA-78 compares statistics for the CCDFs for cuttings and cavings volume for each replicate, and shows that the three replicates produced very similar results.

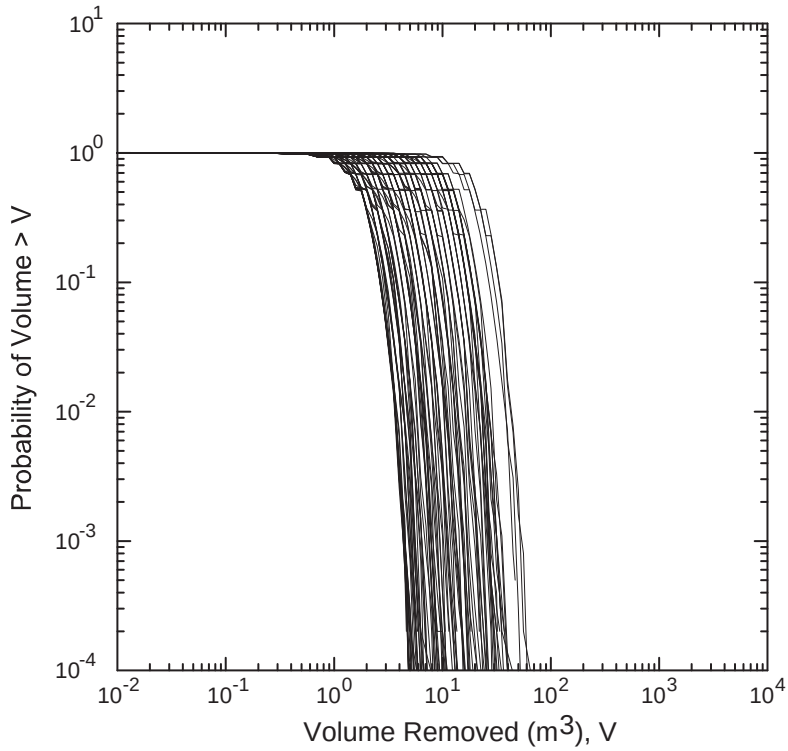

Figure PA-77. Total Volume Removed by Cuttings and Cavings, Replicate R1.

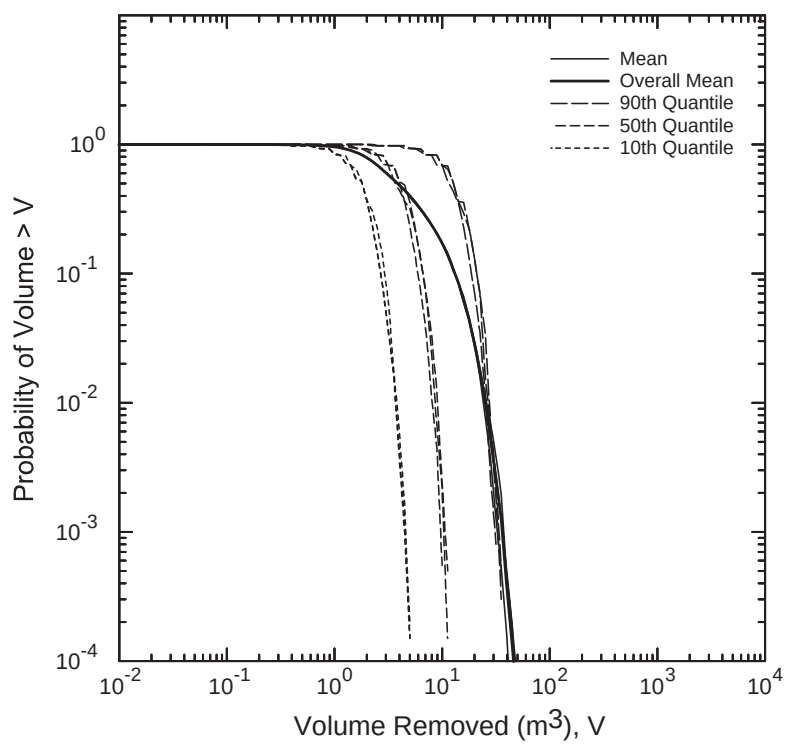

Figure PA-78. Statistics for Volumes Removed by Cuttings and Cavings, All Replicates.

Figure PA-79 shows that the uncertainty in cuttings and cavings volume arises primarily from the uncertainty in the shear strength of the waste (WTAUFAIL, see Table PA-17). The uncertainty in drill string angular velocity (DOMEGA) affects the calculation of cavings volume (Section PA-4.5), but is much less significant (Dunagan 2003a).

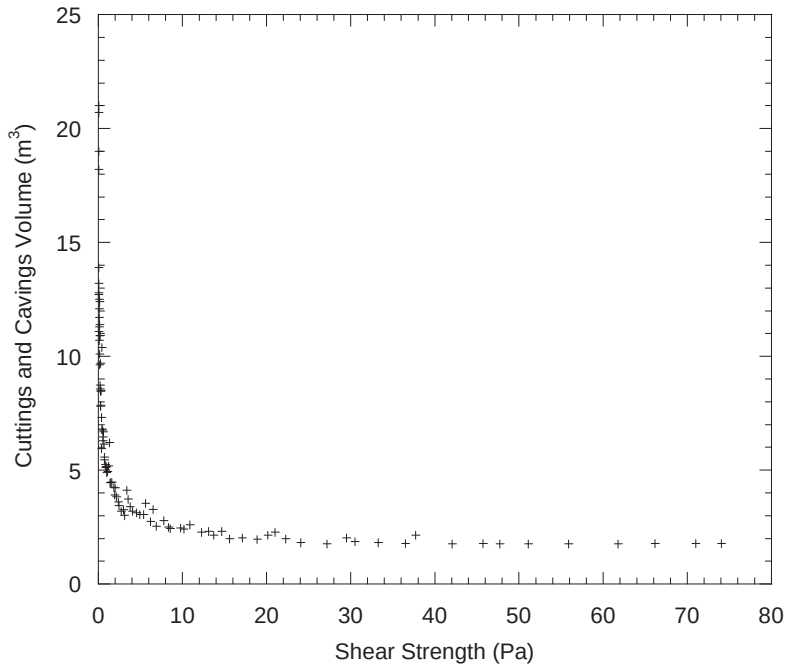

Figure PA-79. Sensitivity of Mean Cuttings and Cavings Volume to Waste Shear Strength.

PA-8.5.2 Spall Volumes

The volume of solid waste material released to the surface due to the spallings mechanism is calculated with the code DRSPALL. As outlined in Section PA-4.6.4, the code was run for each of 50 vectors in an LHS for DRSPALL, and for four values of repository pressure (10, 12, 14, and 14.8 MPa). Figure PA-80 shows the distribution of spall volumes for each value of repository pressure, ordered by increasing spall volume at 14.8 MPa. The maximum volume is 12.062 m^3 occurring at repository pressure of 14.8 MPa. At repository pressure at or below 10 MPa, no spallings occurred.

The distributions presented in Figure PA-80 are the volumes that could be removed by a single intrusion. As outlined in Section PA-4.6.4, the uncertainty in these volumes arises from four variables that are uncertain in the DRSPALL calculations: waste permeability; waste porosity; waste tensile strength; and waste particle diameter. Figure PA-81 and Figure PA-82 show the relationship between the spall volumes (SPALVOL) for the scenario with initial pressure of 14.8 MPa and the particle diameter (PARTDIAM) and the ratio of waste permeability to waste porosity (PERMPOR, from the term k'/ϕ in Equation (145)). Figure PA-81 and Figure PA-82 show that large spall volumes result from combinations of low values of particle diameter and low values for the ratio of waste permeability to waste porosity, and that uncertainty in these two parameters dominates the uncertainty in the spall volume from a single intrusion.

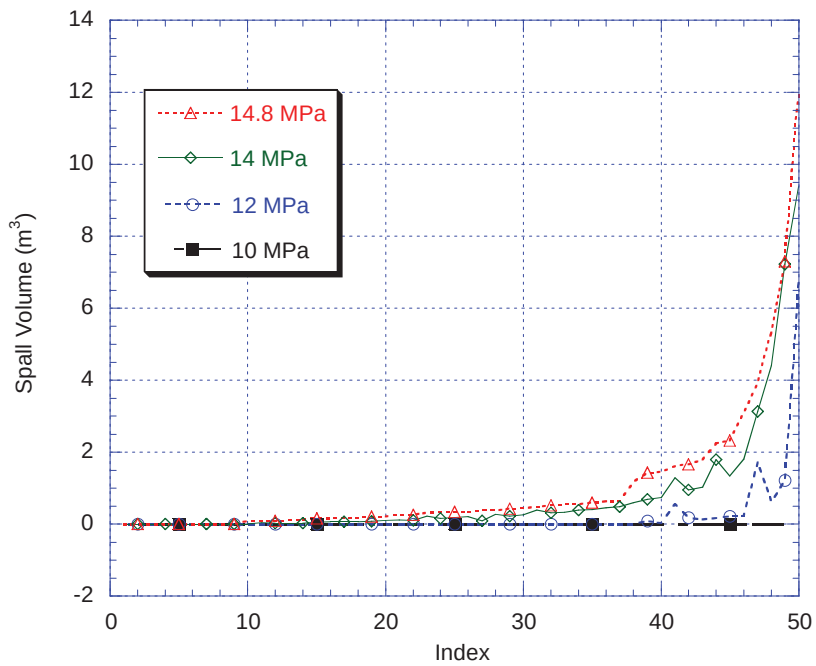

Figure PA-80. Spall Volume for a Single Intrusion (Ranked by Increasing Volume in the 14.8 MPa Scenario).

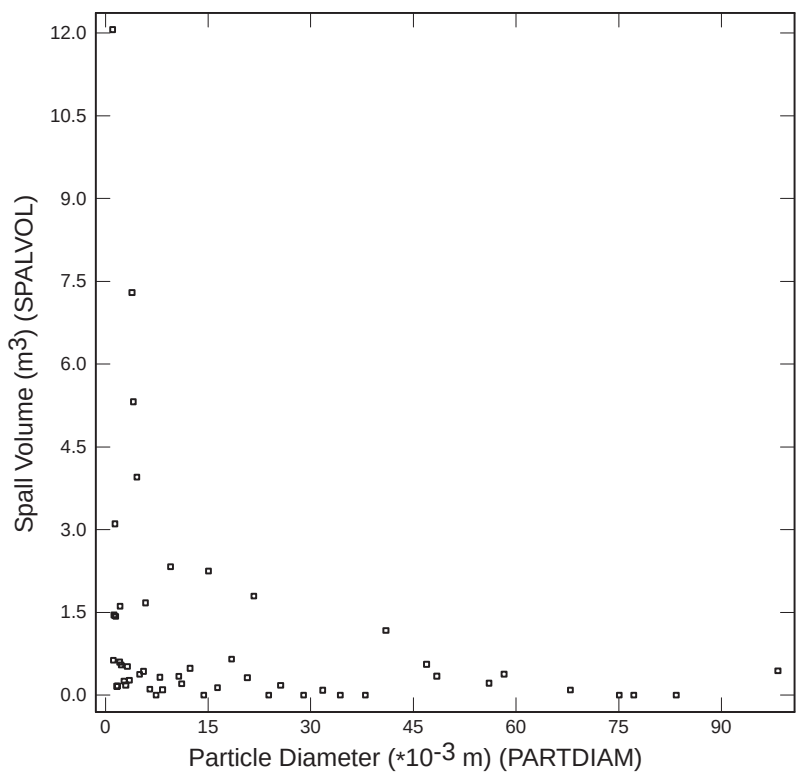

Figure PA-81. Sensitivity of Spall Volume for a Single Intrusion to Particle Diameter, 14.8 MPa Scenario.

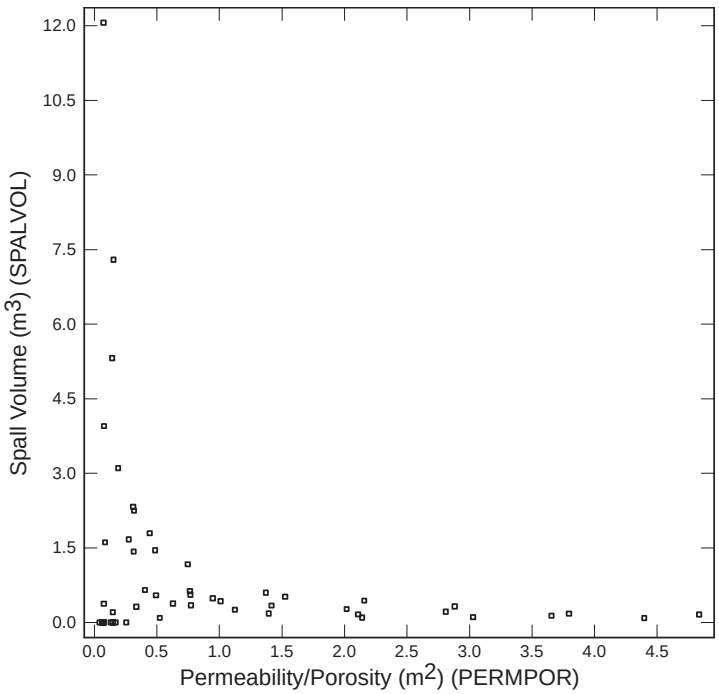

Figure PA-82. Sensitivity of Spall Volume for a Single Intrusion to *Waste Permeability / Waste Porosity* , 14.8 MPa Scenario.

The code CCDFGF stochastically generates futures for the repository and constructs the distribution of total volume removed by spallings for all intrusions (see Section PA-6.5 and Section PA-6.8). Figure PA-83 shows the CCDFs for the volume of material released (m^3) by spallings for replicate R1. Figure PA-84 compares statistics for the distribution of CCDFs for spall volume among the three replicates, and shows that the three replicates produce similar results. The median (50th quantile) and 10th quantile CCDFs do not plot on the scale of Figure PA-84 due to the large number of observations with spall volumes less than 0.01 m^3.

The distribution of spall volumes arises from the uncertain parameters used in the calculation of repository pressure (see Section PA-4.2) and the uncertain volume removed by a single intrusion (Figure PA-80). Section PA-7.1.1 and Section PA-8.3.1 identified three uncertain variables in the space for subjective uncertainty S_{su} that are primarily responsible for the uncertainty in repository pressure: borehole permeability (BHPERM); the indicator for microbial action (WMICDFLG); and the initial pressure in the Castile brine reservoir (BPINTPRS). Thus, these three variables may correlate to uncertainty in the total volume released by spalling.

In addition, the variable RNDSPALL (Table PA-17) in the LHS for the CRA-2004 PA (Equation (254)) assigns vectors from the LHS for DRSPALL (Section PA-4.6.4) to vectors in the LHS for the CRA-2004 PA. The variable RNDSPALL creates a mapping between the uncertain spall volumes in Figure PA-80 and the CCDFs in Figure PA-83. Thus, the spall volume (SPALVOL) for the 14.8 MPa scenario can be included in the sensitivity analysis for total spall volumes.

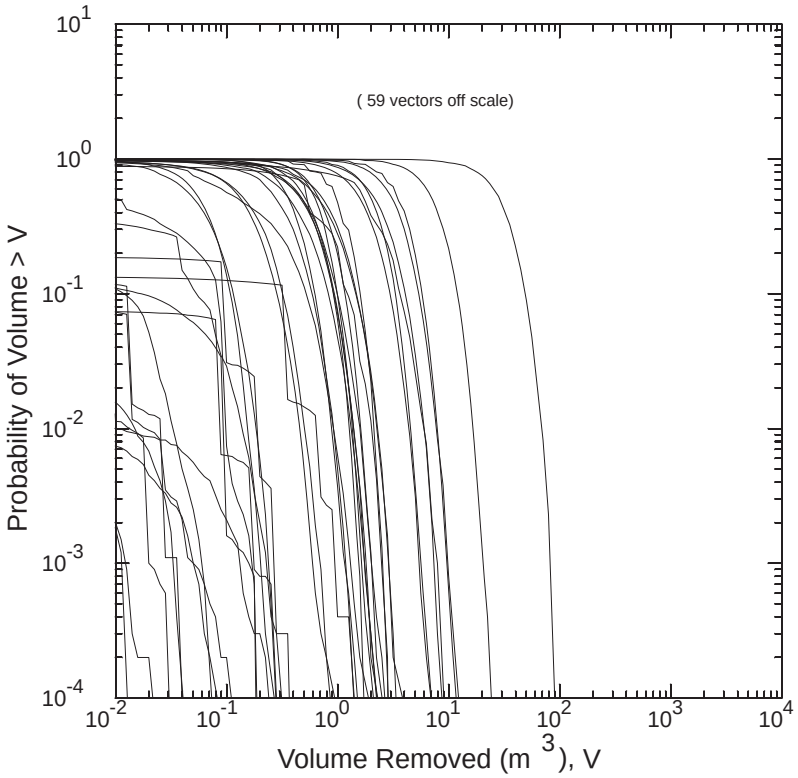

Figure PA-83. Total Volume Removed by Spallings, Replicate R1.

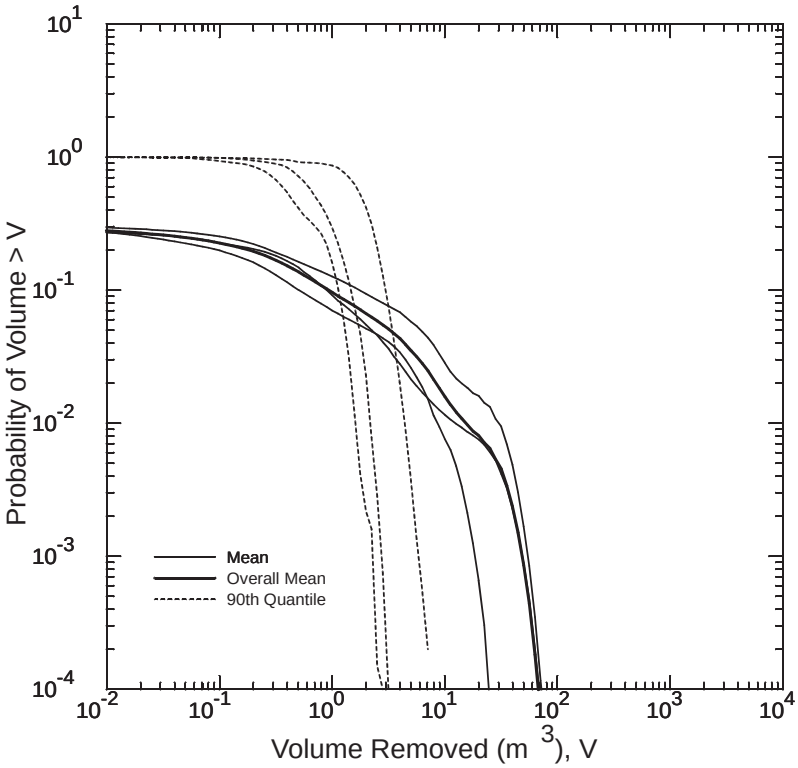

Figure PA-84. Statistics for Total Spall Volume, All Replicates.

Figure PA-85 demonstrates that the uncertainty in mean total spall volume arises primarily from the uncertainty in the indicator for microbial action (WMICDFLG) and the uncertainty in the spall volume from a single intrusion (SPALVOL). The indicator for microbial action (WMICDFLG) partitions the vectors into two sets of equal size: a set of vectors where microbial action occurs (WMICDFLG = 1 or 2) and a set where no microbial action is present (WMICDFLG = 0). Figure PA-80 shows that no spall releases are possible unless pressure exceeds 10 MPa. Figure PA-85 shows that when no microbial action is present, no spallings releases occur even when the spall volume from a single intrusion could be non-zero. Therefore, when no microbial action is present, repository pressure does not exceed the threshold for spall releases. In contrast, when microbial action is present (WMICDFLG = 1 or 2), Figure PA-85 shows that the uncertainty in total mean spall releases arises primarily from the uncertainty in the spall volume from a single release (SPALVOL).

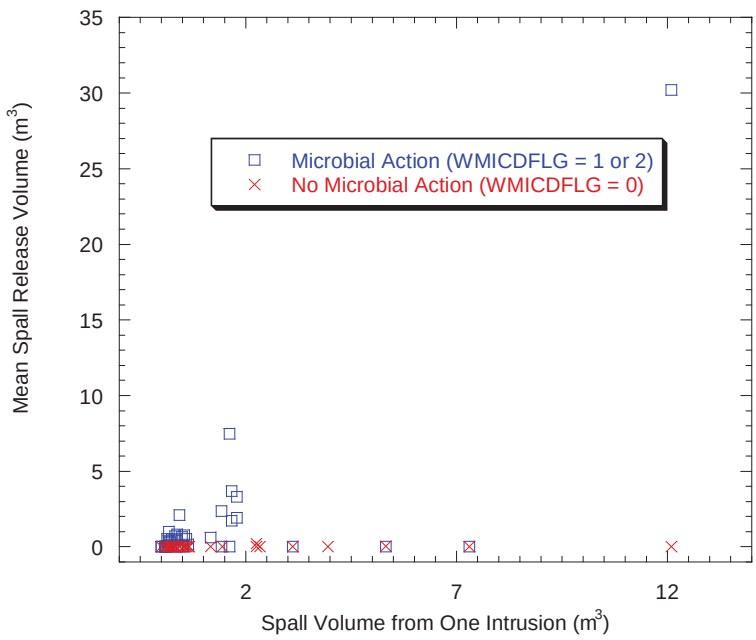

Figure PA-85. Sensitivity of Mean Total Spall Volume, Replicate R1.

PA-8.5.3 Direct Brine Release Volumes

DBRs to the surface can occur during or shortly after a drilling intrusion. For each element of the LHS, the code BRAGFLO (Section PA-4.7) calculates volumes of brine released for a total of 78 combinations of intrusion time, intrusion location, and initial conditions (Section PA-6.7.5) Initial conditions for the DBR calculations are computed by BRAGFLO for five scenarios (S1 through S5; see Section PA-6.7) Results from the S1 scenario represent undisturbed repository conditions; results from the S2 through S5 scenarios represent repository conditions that result after a drilling intrusion.

For replicate R1, only about eight percent of the 7,800 DBR calculations (100 vectors × 78 combinations) resulted in direct brine flow to the surface. The maximum DBR release is approximately 115 m^3. Only intrusions into a lower panel (see Section PA-4.7.1) resulted in

significant brine volume releases. In the S1 scenario, the lower panel represents an undisturbed panel at the south end of the repository. In the S2 and S3 scenarios, the lower panel represents any panel that has a previous E1 intrusion; in the S4 and S5 scenarios, the lower panel has a previous E2 intrusion.

Figure PA-86 shows probability plots of DBR volumes for Scenarios S1 through S5, lower intrusion, at the discrete times for which DBR is calculated. A probability plot displays the percentage of the vectors on the x-axis where release volumes are less than the value on the y-axis. Figure PA-86a shows DBR volumes for scenario S1 representing the initial intrusion at various times. Figure PA-86b and Figure PA-86c show DBR volumes for Scenarios S2 and S3, which represent a subsequent intrusion (at various times) into a panel that had an E1 intrusion at 350 years and 1,000 years, respectively. Figure PA-86d and Figure PA-86e show DBR volumes for Scenarios S4 and S5, which represent a subsequent intrusion (at various times) into a panel that had an E2 intrusion at 350 years and 1,000 years, respectively. Release volumes are larger and occur more frequently in the S2 and S3 scenarios, because the lower panel has much higher saturations after an E1 intrusion (Section PA-8.3.2).

Sensitivity analysis determined that DBR volume from a single intrusion is most sensitive to the initial pressure and brine saturation in the intruded panel (Stein 2003). The analysis is illustrated below for scenario S2; similar conclusions follow from analysis of the other scenarios. The initial pressure and brine saturation in the DBRs calculations are transferred from the Salado Flow calculations as described in Section PA-4.7.2. Thus, the uncertain parameters that are most influential to the uncertainty in pressure and brine saturation in the Salado Flow calculations (see Section PA-7.1 and Section PA-8.3) are also most influential in the uncertainty in DBR volumes.

The combination of relatively high pressure and brine saturation in the intruded panel is required for direct brine release to the surface. Figure PA-87 shows a scatter plot of pressure in the waste panel vs. DBR volumes for Scenario S2, lower intrusion with symbols indicating the value of the mobile brine saturation (defined as brine saturation S_b from the solution of Equation (25) minus residual brine saturation S_{br} in the waste (see Table PA-2)). The figure clearly shows that there are no releases until pressures exceed 8 MPa as indicated by the vertical line. Above 8 MPa, a significant number of vectors have zero releases, but these vectors have mobile brine saturations less than zero and thus no brine is available to be released. When mobile brine saturation approaches 1, relative permeability to gas becomes small enough that no gas flows into the well, and in these circumstances DBR releases end after three days (Equation (211)). Thus, in vectors with high mobile brine saturations, DBR releases increase proportionally with increases in pressure, as evidenced by the linear relationship between DBR volume and pressure for mobile brine saturation between 0.8 and 1.0. For vectors with mobile saturations between 0.2 and 0.8, both gas and brine can flow in the well, and the rate of gas flow can be high enough that the ending time of DBR releases may be as long as 11 days. Although brine may be flowing at slower rates in these vectors than in vectors with high mobile saturations, brine flow may continue longer and thus result in larger DBR volumes.

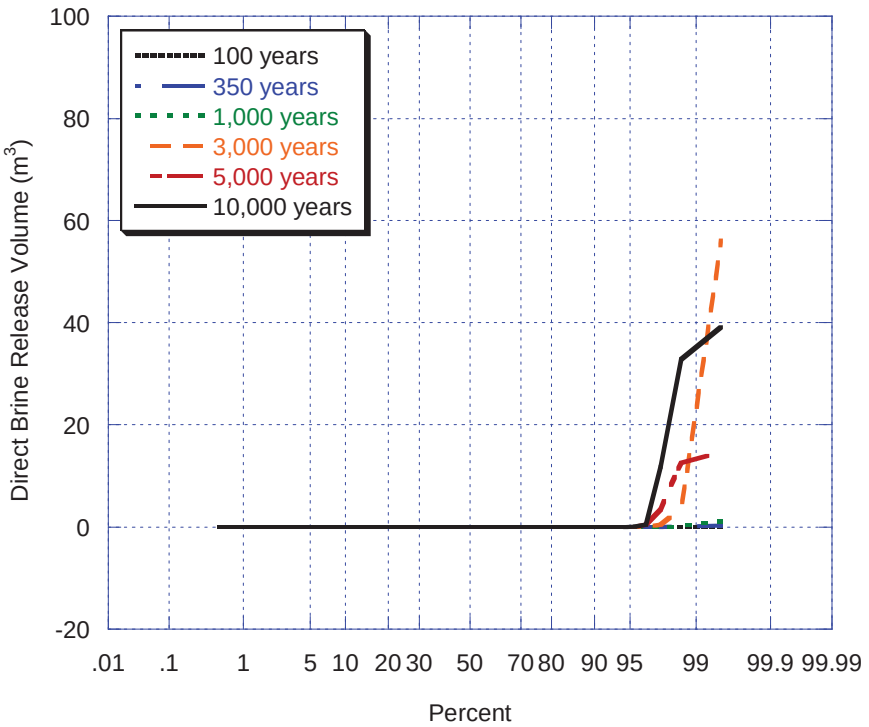

Figure PA-86a. DBRs for Initial Intrusions into Lower Panel (Scenario S1), Replicate R1.

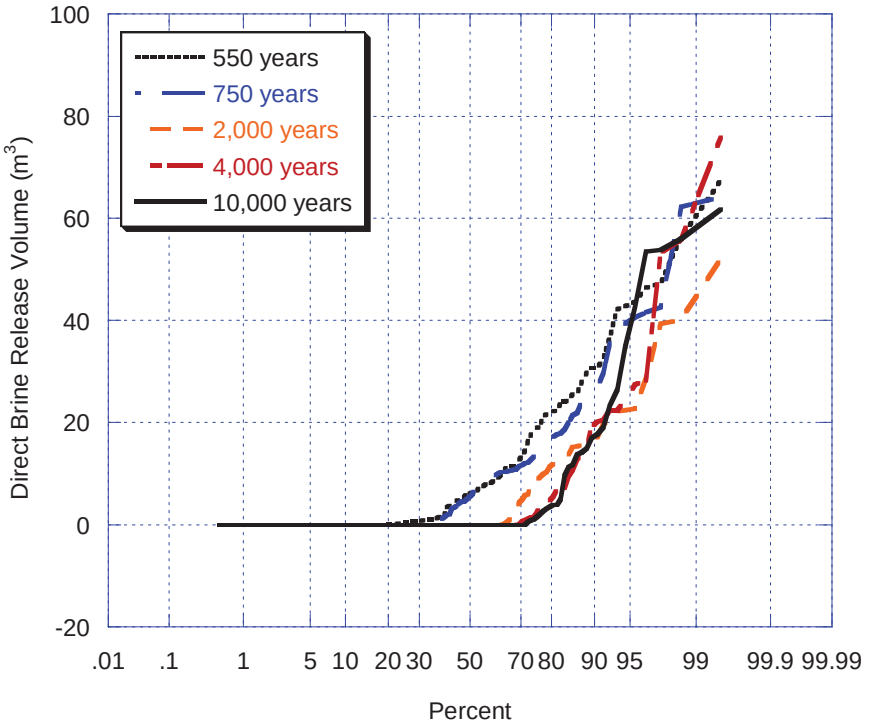

Figure PA-86b. DBRs for Subsequent Intrusions into Lower Panel After an E1 Intrusion at 350 Years (Scenario S2), Replicate R1.

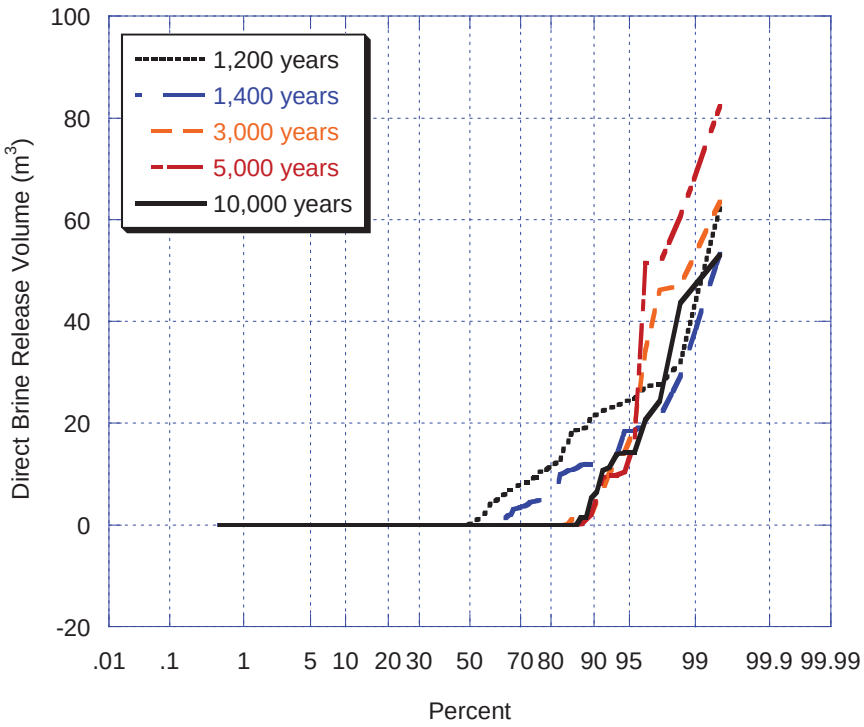

Figure PA-86c. DBRs for Subsequent Intrusions into Lower Panel After an E1 Intrusion at 1,000 Years (Scenario S3), Replicate R1.

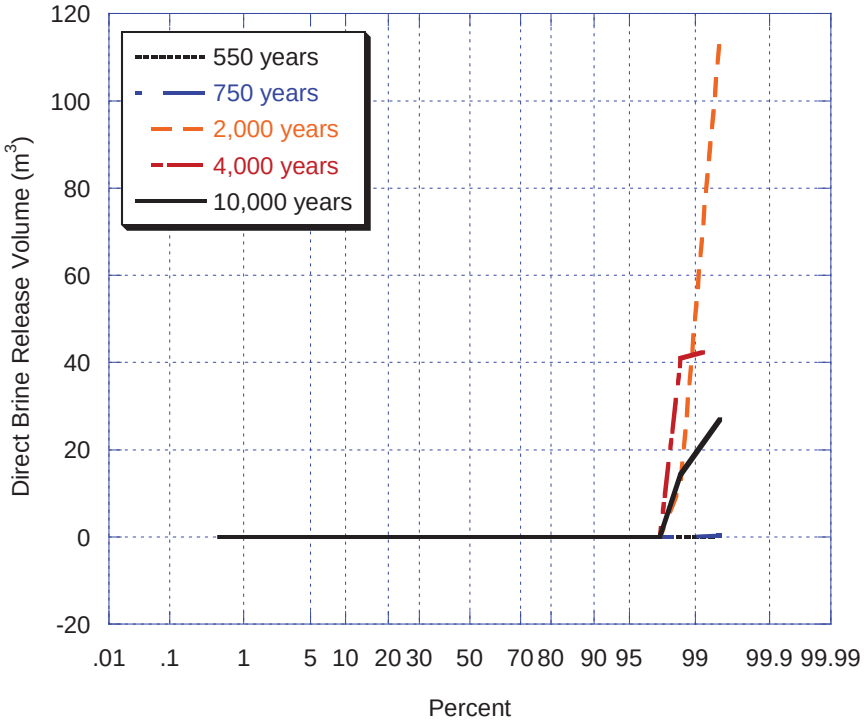

Figure PA-86d. DBRs for Subsequent Intrusions into Lower Panel After an E2 Intrusion at 350 Years (Scenario S4), Replicate R1.

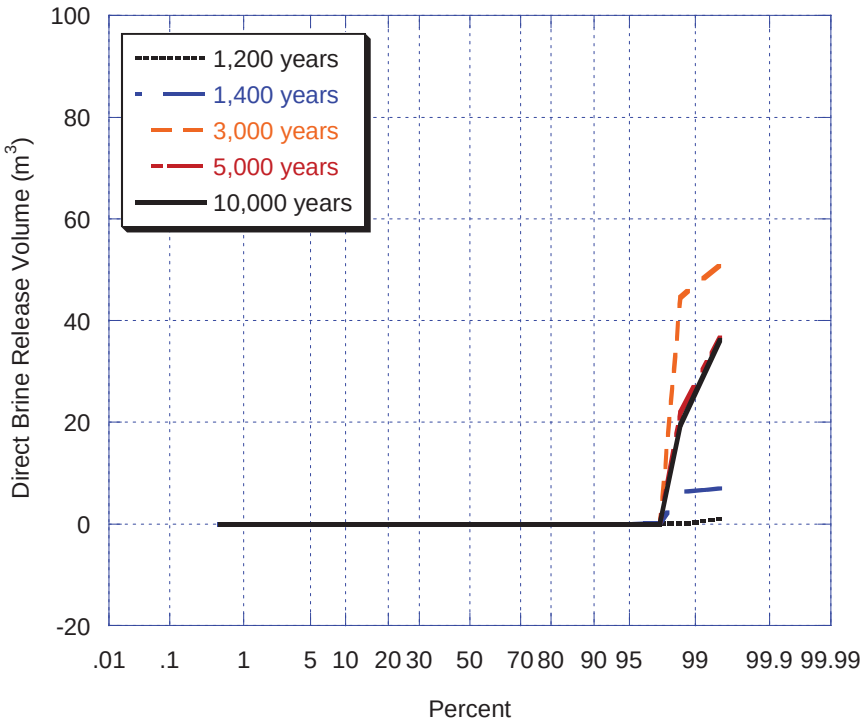

Figure PA-86e. DBRs for Subsequent Intrusions into Lower Panel After an E2 Intrusion at 1,000 Years (Scenario S5), Replicate R1.

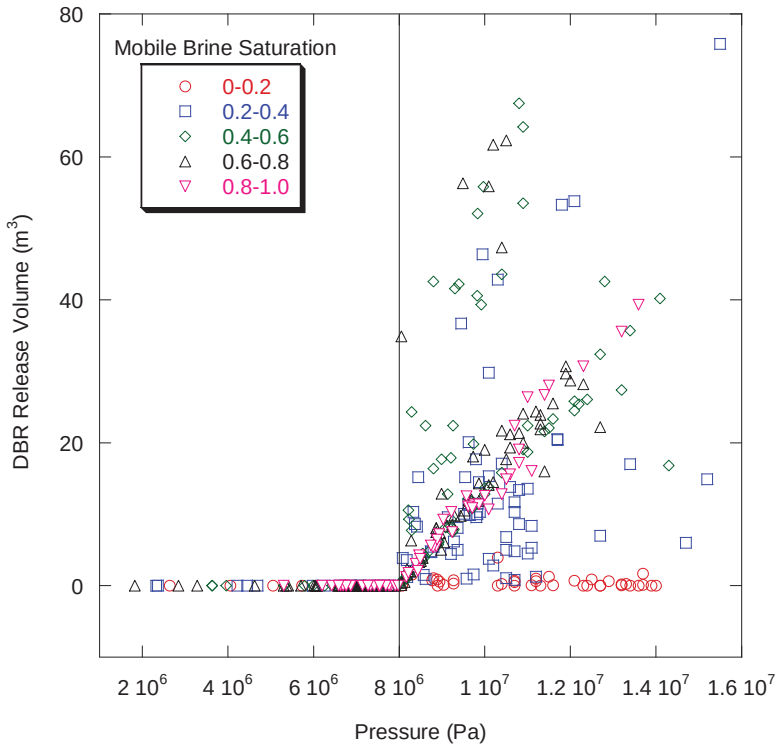

Figure PA-87. Sensitivity of DBR Volumes to Pressure, Replicate R1, Scenario S2, Lower Panel.

Figure PA-88 plots pressure against mobile brine saturation for the S2 scenario for all intrusion times with symbols indicating the range of DBR volumes. It is clear from Figure PA-88 that not all the variability in DBRs can be explained by pressure and saturation alone.

Borehole permeability can also be an important parameter controlling the volume of direct brine released. Borehole permeability is not a direct input to the DBR calculations, but this parameter affects conditions in the repository as modeled in the 10,000-year BRAGFLO calculations, which are used as initial conditions of the DBR model. Figure PA-89 shows a scatter plot of the log of borehole permeability against DBR volume for Scenario S2, lower intrusion with symbols indicating intrusion times. As borehole permeability decreases direct brine releases tend to increase, especially at late intrusion times (4,000 and 10,000 years). Helton et al. (1998) identified this same relationship in analysis of the CCA PA. Low values of borehole permeability tend to result in higher pressures following an E1 intrusion (Figure PA-53), which in turn lead to higher DBRs from subsequent intrusions.

The distributions presented in Figure PA-86 are for volumes of brine that could be released by a single intrusion. The code CCDFGF stochastically generates futures for the repository, specifying drilling times and locations, and constructs the distribution of total brine volume released (see Section PA-6.5 and Section PA-6.8). Figure PA-90 shows the CCDFs for the total brine volume released for replicate R1. Figure PA-91 compares the statistics for the CCDFs for total brine volume released among the three replicates, and shows that the three replicates produced similar results. Due to the number of observations which do not plot on the scale of Figure PA-90, the 10th quantiles do not appear on Figure PA-91.

Table PA-29 summarizes a stepwise regression analysis for mean total DBR volume. The uncertain parameters most important to uncertainty in total DBR volumes are those related to repository pressure (the indicator for microbial action (WMICDFLG) and the rate of steel corrosion (WGRCOR)) and brine saturation (the probability of an intrusion into the Castile brine reservoir (PBRINE), the pressure in the Castile brine reservoir (BPINTPRS), the permeability of the DRZ around the panel closures (DRZPCPRM), and the residual brine saturation in the waste (WRBRNSAT)). The linear regression model is not very effective at explaining the uncertainty in the total DBRs. The lack of resolution is due to the large number of vectors in which no direct brine releases occur; this conclusion was reached after analysis of the CCA PA (Helton et al. 1998).

PA-8.5.4 Additional Information

Dunagan (2003b) provides additional information about the cuttings and cavings releases calculated for the CRA-2004 PA. Additional information about the spallings releases is found in Lord et al. (2003) and Lord and Rudeen (2003). Stein (2003) provides detailed analysis of direct brine releases in the CRA-2004 PA.

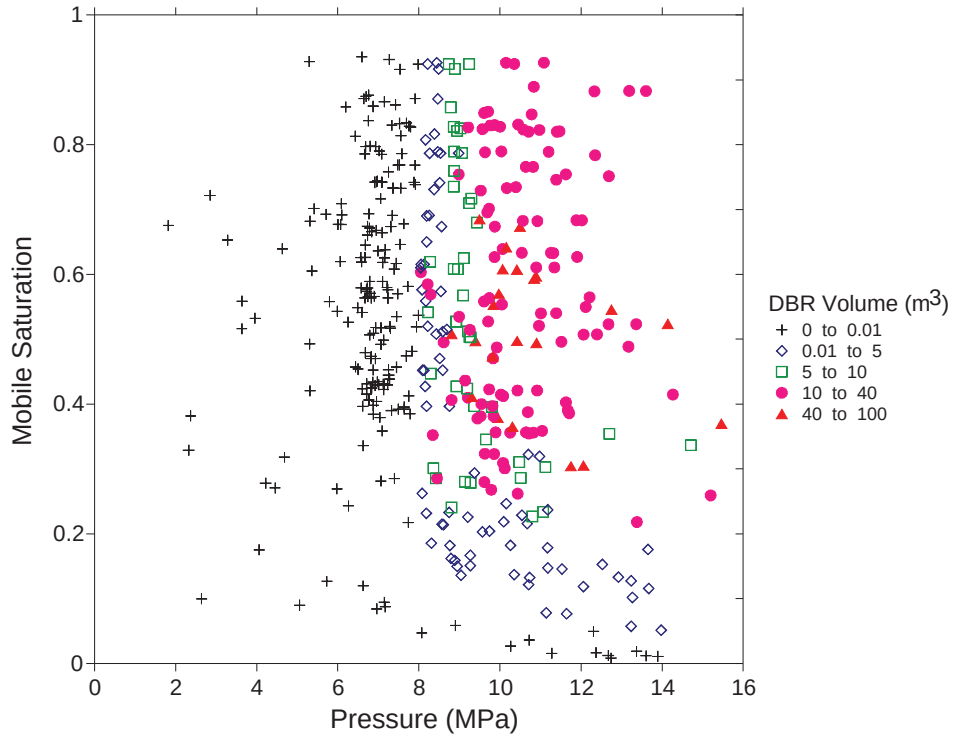

Figure PA-88. Sensitivity of DBR **Volumes to Pressure and Mobile Brine Saturation, Replicate R1, Scenario S2, Lower Panel.**

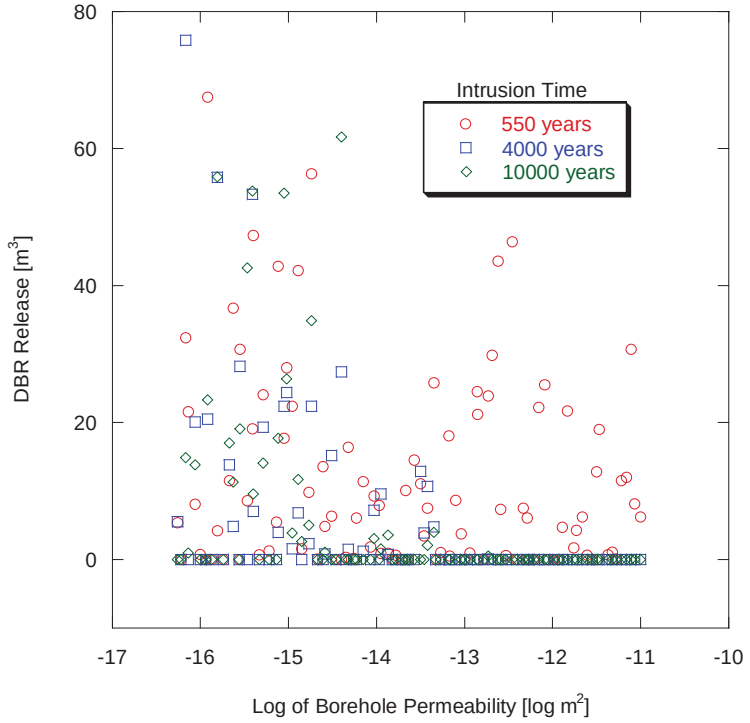

Figure PA-89. Sensitivity of DBR Volumes to Borehole Permeability, Replicate R1, Scenario S2, Lower Panel.

Table PA-29. Stepwise Regression Analysis for Mean Total DBR **Volume**

Step[1]	Expected Normalized Release		
	Variable[2]	SRRC[3]	R^2 [4]
1	WMICDFLG	–0.583	0.239
2	PBRINE	–0.385	0.378
3	BPINTPRS	0.389	0.515
4	WGRCOR	–0.190	0.553
5	DRZPCPRM	0.176	0.585
6	WRBRNSAT	–0.168	0.613

[1] Steps in stepwise regression analysis

[2] Variables listed in order of selection in regression analysis

[3] Standardized Rank Regression Coefficient in final regression model

[4] Cumulative R^2 value with entry of each variable into regression model

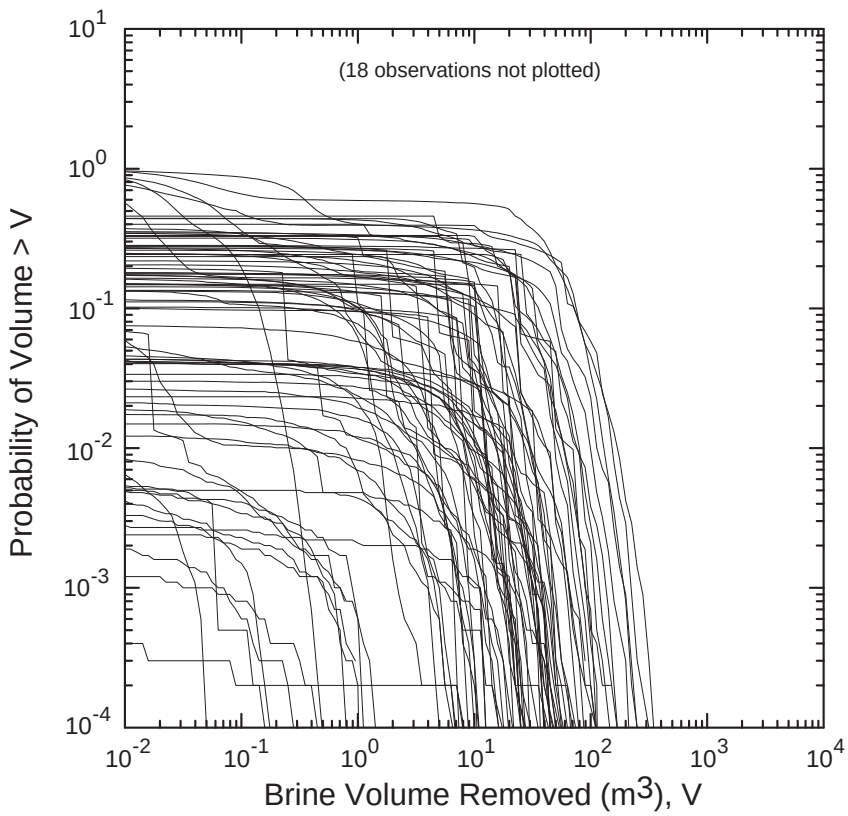

Figure PA-90. Total DBRs Volumes, Replicate R1.

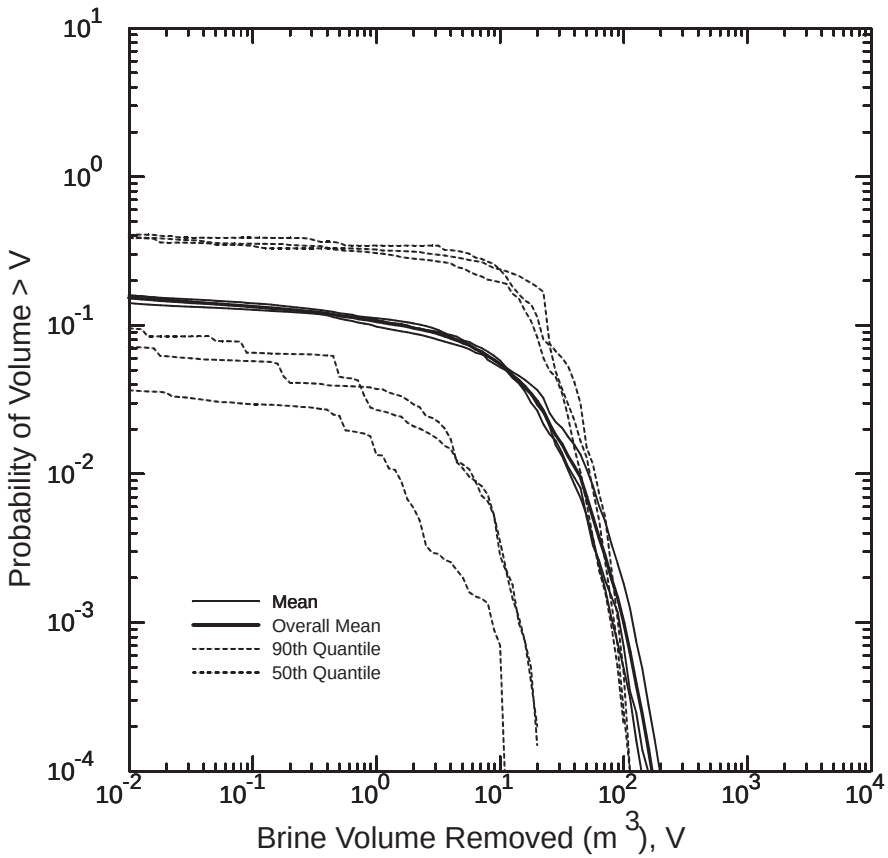

Figure PA-91. Statistics for Total DBR Volumes, All Replicates.

PA-9.0 NORMALIZED RELEASES

This section presents total normalized releases, followed by discussion of each of the four categories of releases that constitute the total release: cuttings and cavings; spallings; DBRs; and transport releases. Finally, this section concludes with a discussion of the sensitivity of total releases to uncertainty in parameter values.

PA-9.1 Total Releases

Figures PA-92, PA-93, and PA-94 show the CCDFs for total releases for replicates R1, R2, and R3 of the CRA-2004 PA. Each CCDF lies below and to the left of the limits specified in 40 CFR § 191.13(a). Thus, the WIPP continues to comply with the containment requirements of 40 CFR Part 191. The consistent increase in total releases at a probability of approximately 0.003 results from unlikely cuttings and cavings releases, as discussed in Section PA-9.6.1.

To compare the distributions of CCDFs among replicates and to demonstrate sufficiency of the sample size, mean and quantile CCDFs are computed. At each value for normalized release R on the abscissa, the CCDFs for a single replicate define 100 values for probability. The arithmetic mean of these 100 probabilities is the mean probability that release exceeds R; the curve defined by the mean probabilities for each value of R is the mean CCDF. The quantile CCDFs are defined analogously.

Figure PA-95 compares the mean, median, 90th and 10th quantiles for each replicate's distribution of CCDFs for total releases. Figure PA-95 shows that each replicate's distribution is quite similar, and shows qualitatively that the sample size of 100 in each replicate is sufficient to generate a stable distribution of outcomes.

Each of the mean and quantiles CCDFs in Figure PA-95 is an estimate of the true mean CCDF of the population of CCDFs. The overall mean CCDF is computed as the arithmetic mean of the three mean CCDFs from each replicate, and is an estimate of the true mean CCDF. To quantitatively determine the sufficiency of the sample size, a confidence interval is computed about the overall mean CCDF using Student's t-distribution. Figure PA-96 shows 95 percent confidence intervals about the overall mean, and provides quantitative confirmation of the sufficiency of the sample size, by displaying the overall mean together with the 0.95 confidence interval of the Student's t-distribution estimated from the individual means of the three independent replicates.

Figure PA-97, Figure PA-98, and Figure PA-99 show the mean CCDFs for each component of total releases, for replicates R1, R2, and R3, respectively. In each replicate, the location of the mean CCDF for total releases is dominated by the cuttings and cavings releases. The mean predicted released from spallings and direct brine are an order of magnitude less than mean releases for cuttings and cavings; therefore, these categories of releases make relatively little contribution to the location of the mean CCDF for total releases. Release by subsurface transport in the Salado or Culebra make essentially no contribution to total releases.

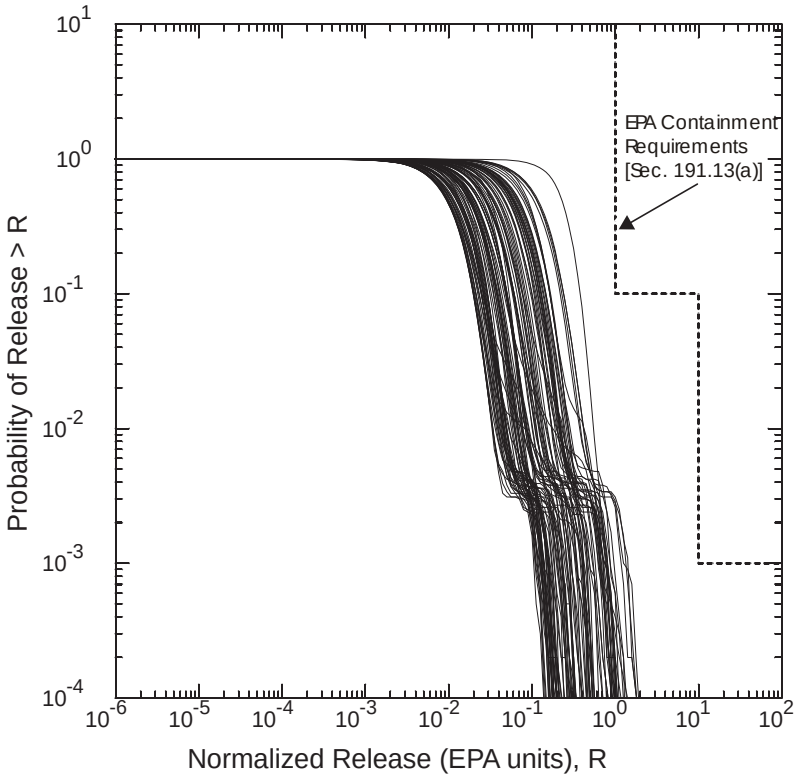

Figure PA-92. Total Normalized Releases, Replicate R1.

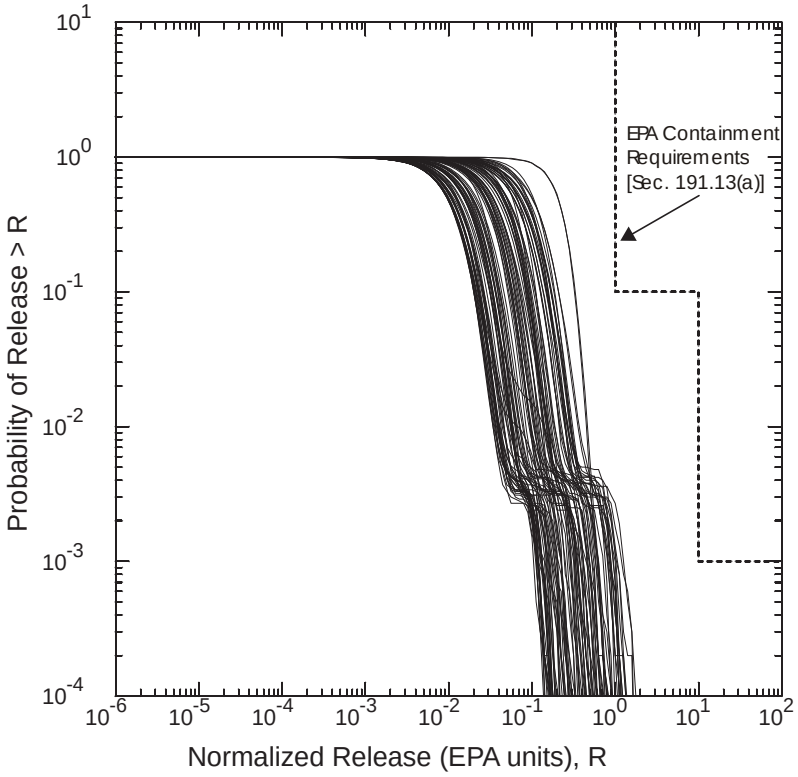

Figure PA-93. Total Normalized Releases, Replicate R2.

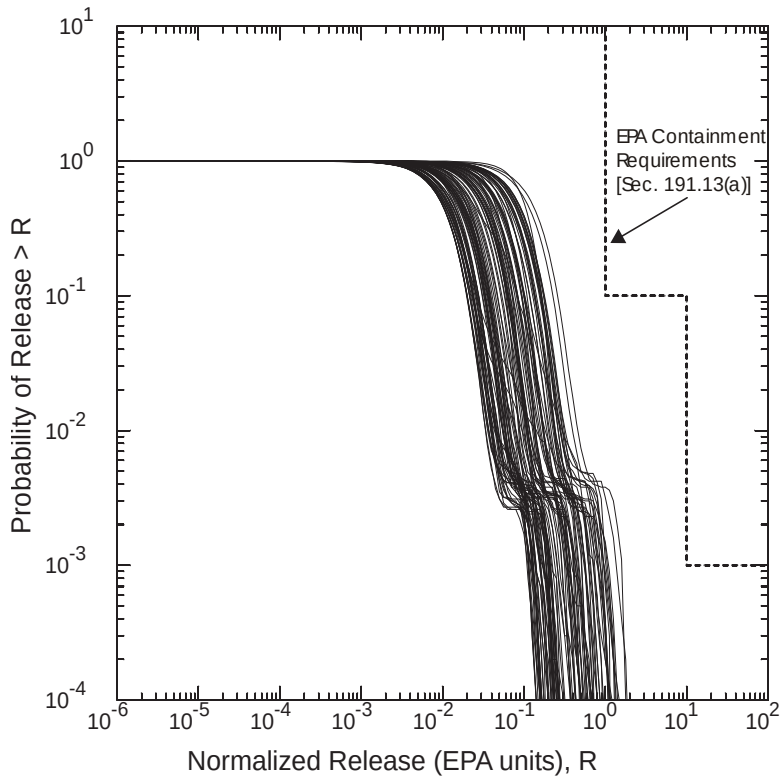

Figure PA-94. Total Normalized Releases, Replicate R3.

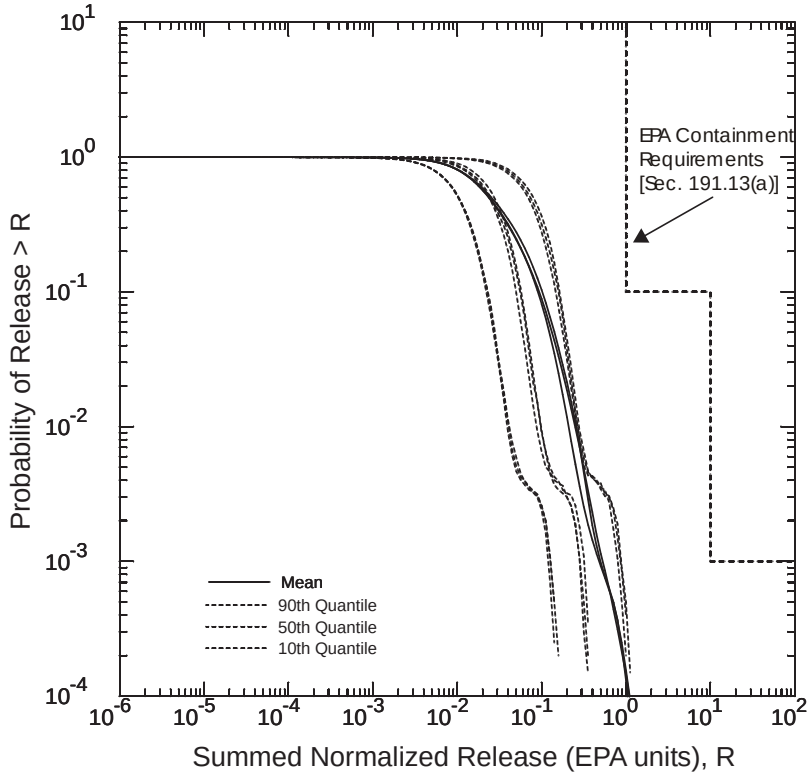

Figure PA-95. Mean and Quantiles CCDFs for Total Normalized Releases, All Replicates.

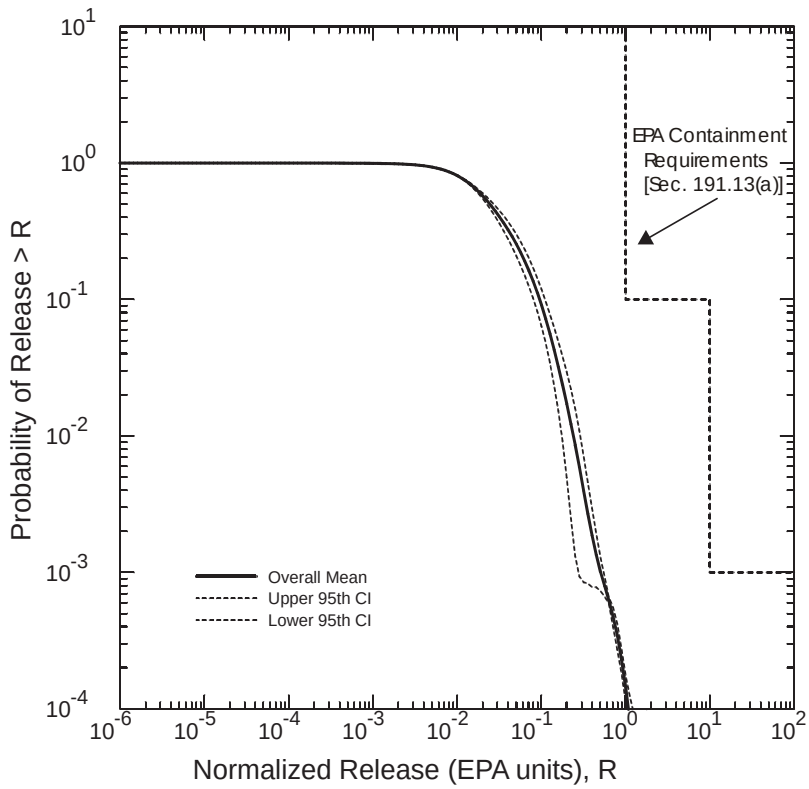

Figure PA-96. Confidence Interval on Overall Mean CCDF for Total Normalized Releases.

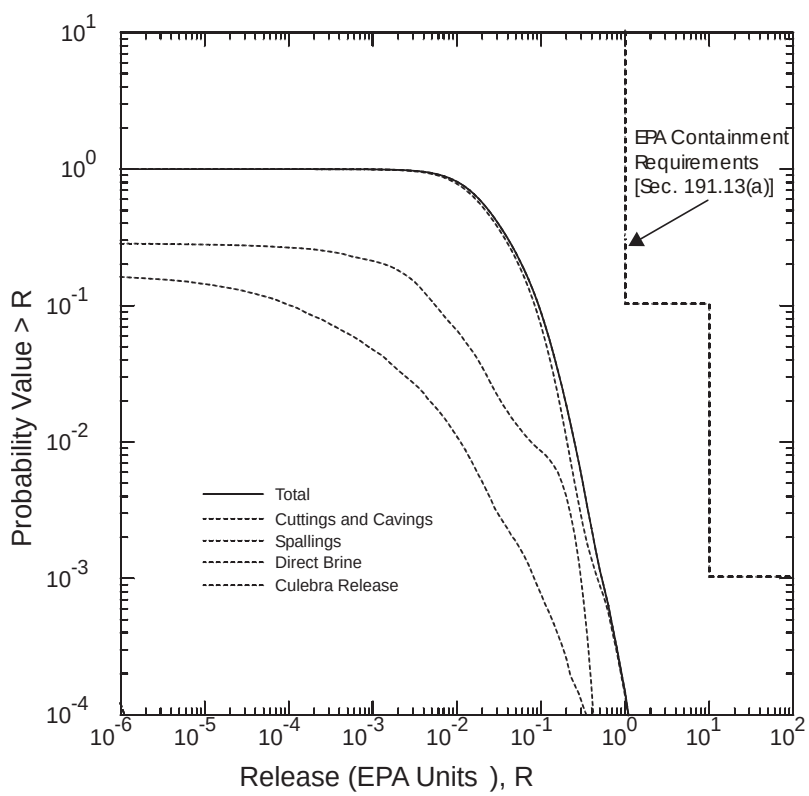

Figure PA-97. Mean CCDFs for Components of Total Normalized Releases, Replicate R1.

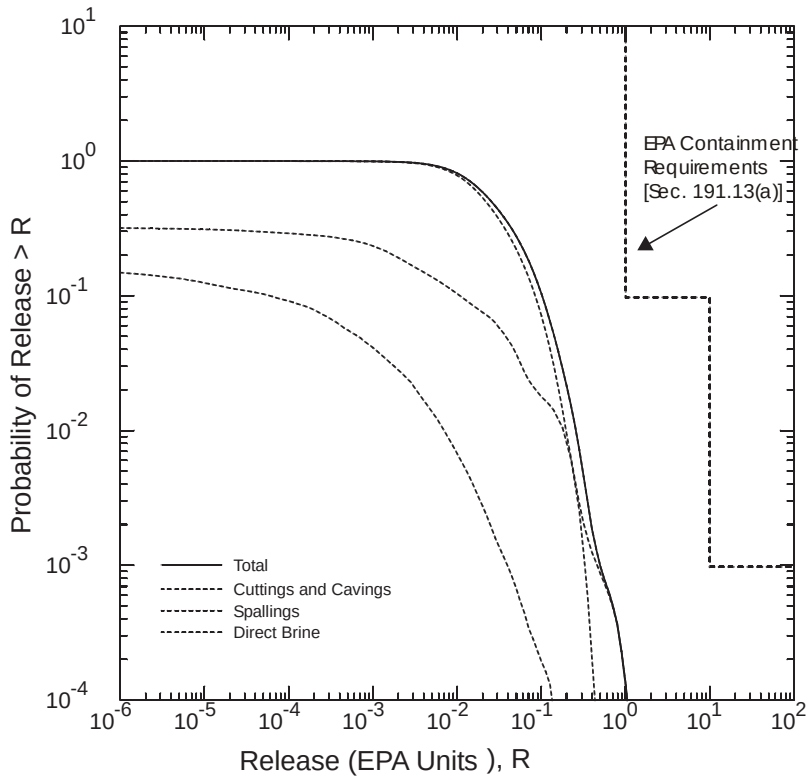

Figure PA-98. Mean CCDFs for Components of Total Normalized Releases, Replicate R2.

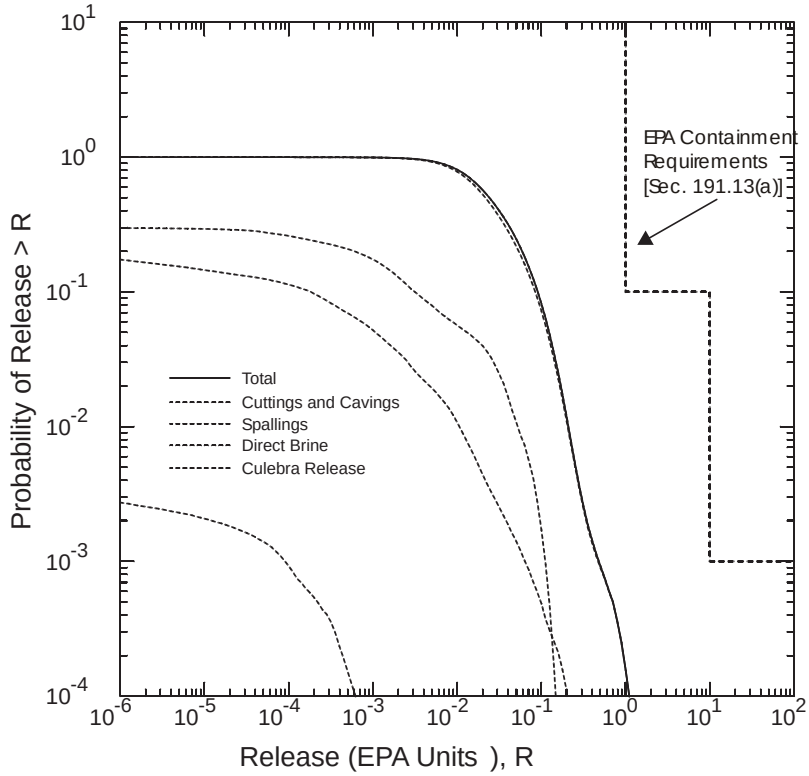

Figure PA-99. Mean CCDFs for Components of Total Normalized Releases, Replicate R3.

PA-9.2 Cuttings and Cavings Normalized Releases

Figures PA-100, PA-101, and PA-102 show the CCDFs for normalized releases due to cuttings and cavings for replicates R1, R2, and R3. The releases in each replicate are very similar; Figure PA-103 compares the mean and quantile CCDFs for cuttings and cavings releases for each replicate.

The increase in cuttings and cavings releases at a probability of 0.003 in each replicate is due to a few waste streams with very high radioactivity that are present in the updated inventory (Appendix DATA, Attachment F). These waste streams maintain significant radioactivity during the 10,000-year period. For example, a single waste stream (LA-TA-55-48, oil/vermiculate waste from ^{238}Pu heat source fabrication) has a concentration of radioactivity of 4.05 EPA units/m^3 at 100 years after repository closure, decaying to 1.95 EPA units/m^3 by 10,000 years (Fox 2003). This waste stream maintains high radioactivity concentration over time because it contains high quantities of longer-lived radioisotopes, principally ^{239}Pu and ^{240}Pu. The radioactivity concentrations in this waste stream can lead to cuttings and cavings releases exceeding 1 EPA unit for a single intrusion.

The volume of the LA-TA-55-48 waste stream (31 m^3) implies a probability of 31/168,500 = 0.00018 that this waste stream is selected as one of the three waste streams contributing to the cuttings and cavings release for a single intrusion at the probability of 10^2, which is below the EPA containment requirement. However, in any future of the repository, roughly six intrusions are expected (Dunagan 2003b), implying that 18 waste streams are selected for cuttings and cavings releases. The mean probability that the LA-TA-58-48 waste stream is selected at least once for cuttings and cavings releases is estimated to be

$$1-\left(1-0.00018\right)^{18}=0.0033\,;$$

thus, the increase in releases at a probability of about 0.003 in Figure PA-100, Figure PA-101, and Figure PA-102.

Figure PA-103 compares the mean, median, 90th, and 10th quantiles for each replicate's distribution of CCDFs for cuttings and cavings releases. The statistical measures of each replicate's distribution of CCDFs are quite similar, indicating that the sample size of 100 elements in each replicate is sufficient to estimate the distribution of CCDFs. Figure PA-104 shows the 95 percent confidence interval about the overall mean of the CCDFs for cuttings and cavings releases. The upper and lower confidence intervals nearly coincide with the overall mean, showing that the overall mean is estimated quite accurately.

Section PA-8.5.1 presents a sensitivity analysis for cuttings and cavings release volumes, and shows that the uncertainty in total cuttings and cavings volumes arises almost entirely from the uncertainty in waste shear strength (WTAUFAIL; see Table PA-17). Cuttings and cavings releases are computed by multiplying the volume released by the average concentration of radioactivity in the three selected CH-TRU waste streams (see Section PA-3.7). However, the uncertainty in the radioactivity in the cuttings and cavings materials is stochastic uncertainty, and is thus represented by the shape of the individual CCDFs in Figures PA-100, PA-101, and

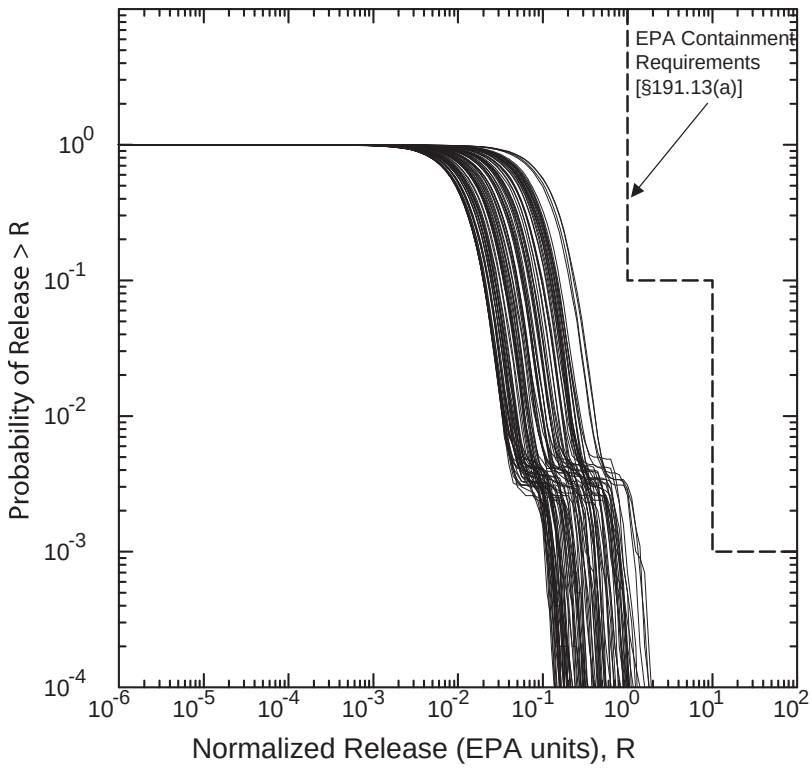

Figure PA-100. Cuttings and Cavings Releases, Replicate R1.

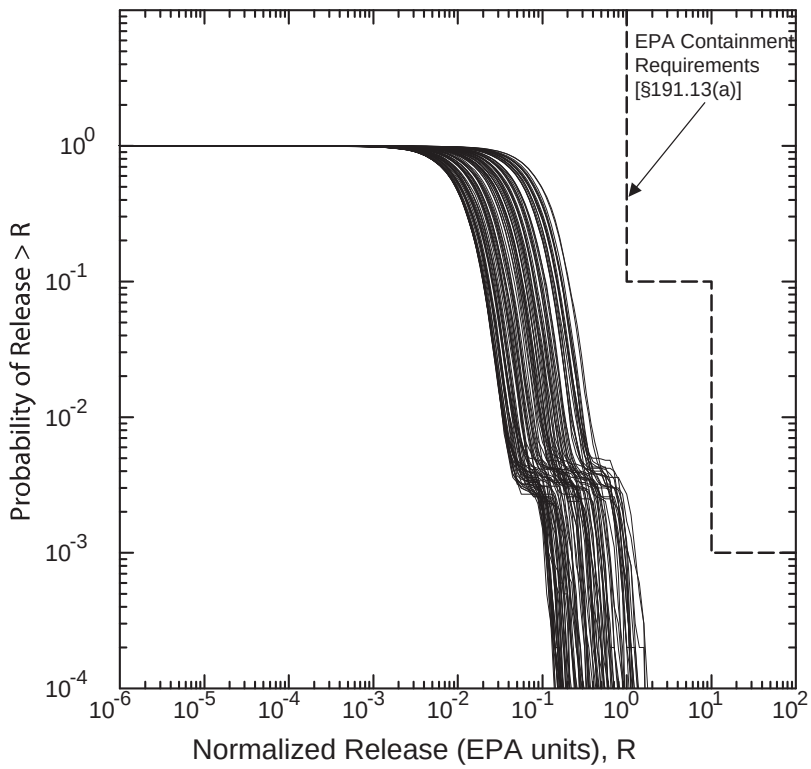

Figure PA-101. Cuttings and Cavings Releases, Replicate R2.

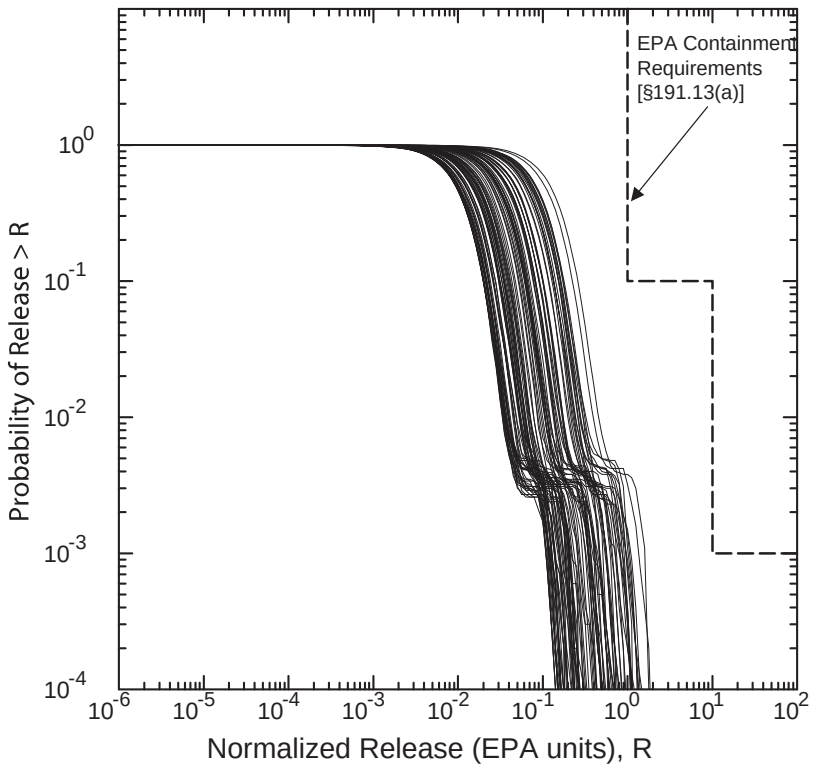

Figure PA-102. Cuttings and Cavings Releases, Replicate R3.

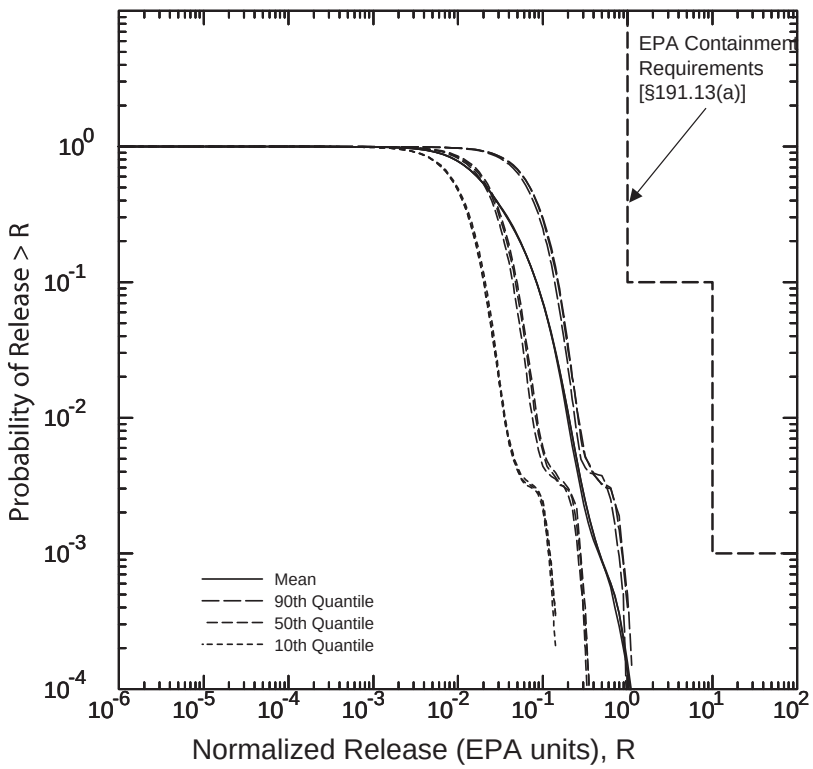

Figure PA-103. Mean and Quantile CCDFs for Cuttings and Cavings Releases, All Replicates.

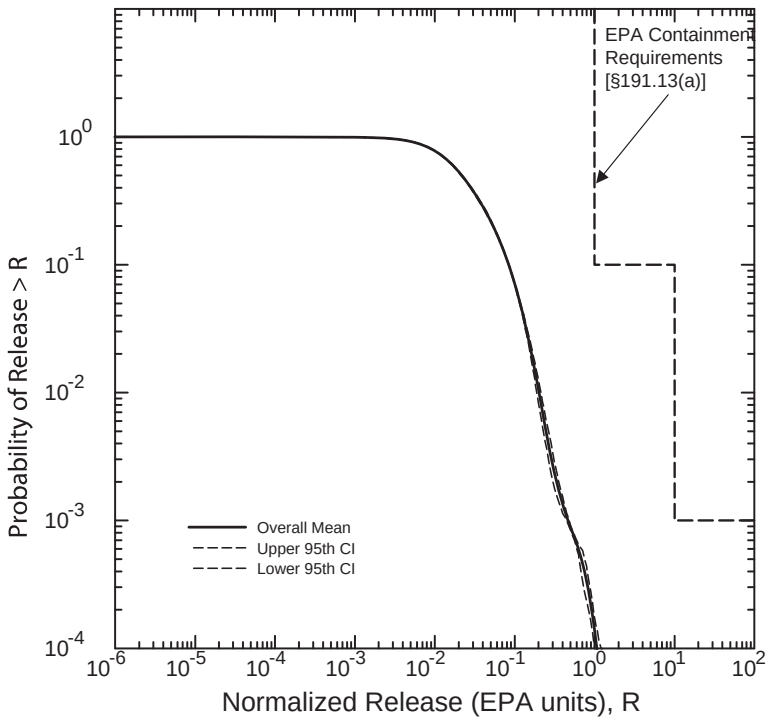

Figure PA-104. Confidence Interval on Overall Mean CCDF for Cuttings and Cavings Releases.

PA-102. Consequently, the uncertainty in mean cuttings and cavings releases is due to the subjective uncertain in the cuttings and cavings volume, as demonstrated in Figure PA-105, which demonstrates the high correlation between mean cuttings and cavings releases and the uncertainty in waste shear strength.

PA-9.3 Spallings Normalized Releases

Figures PA-106, PA-107, and PA-108 show the CCDFs for normalized releases due to spallings for replicates R1, R2, and R3. The releases for each replicate are very similar; Figure PA-109 compares the mean and quantile CCDFs for spallings releases for each replicate and indicates that the distribution of spallings releases are similar in each replicate. Figure PA-110 shows the 95 percent confidence interval about the overall mean of the CCDFs for spallings releases. Although the confidence interval for spallings releases is broader than that shown in Figure PA-104 for cuttings and cavings releases, the overall mean is quite similar to the upper confidence interval, particularly at low probabilities. This result provides confidence that the true mean CCDF for spallings releases does not lie far to the right of the overall mean computed from the three replicates, and thus remains far below the release limits.

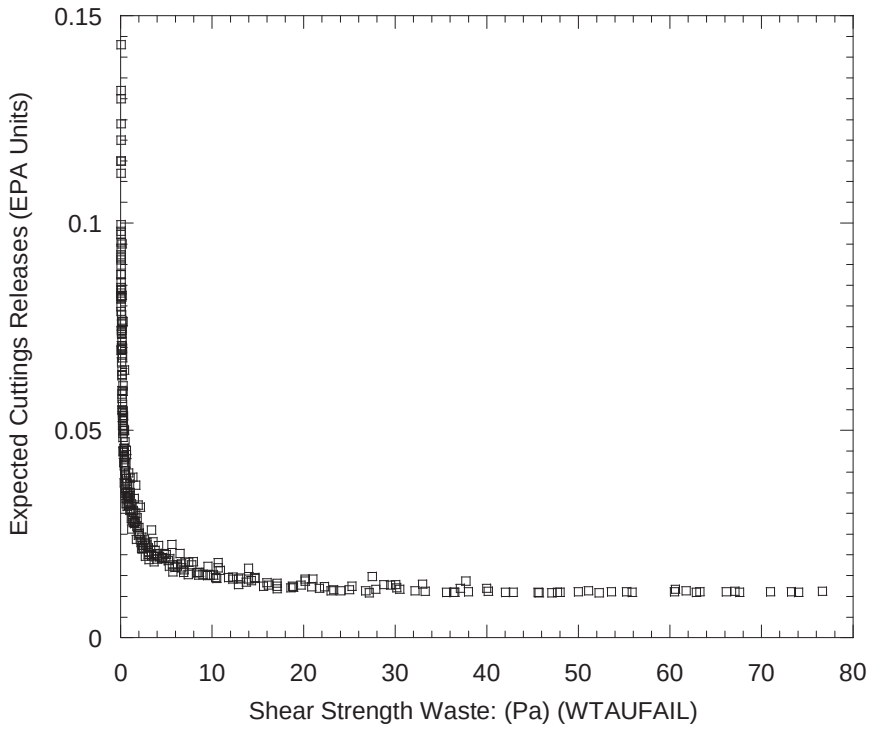

Figure PA-105. Uncertainty in Cuttings and Cavings Releases Due to Waste Shear Strength, All Replicates.

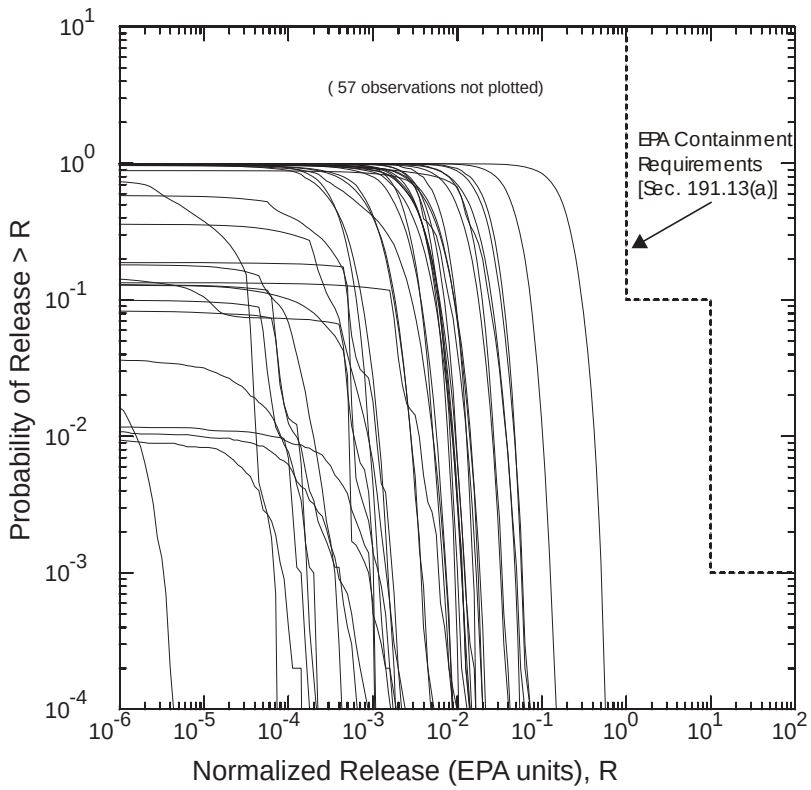

Figure PA-106. Spallings Releases, Replicate R1.

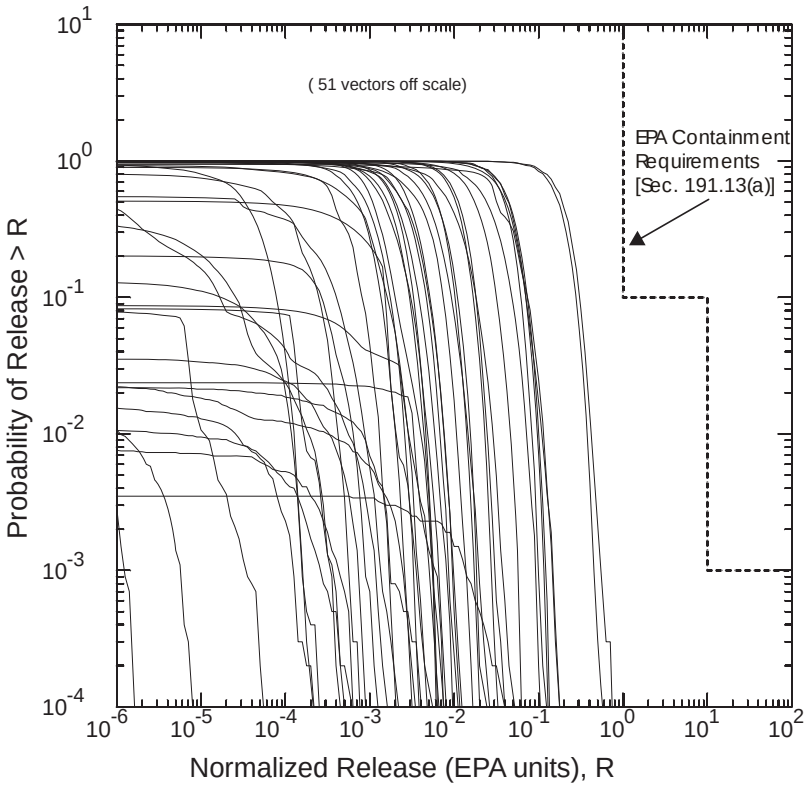

Figure PA-107. Spallings Releases, Replicate R2.

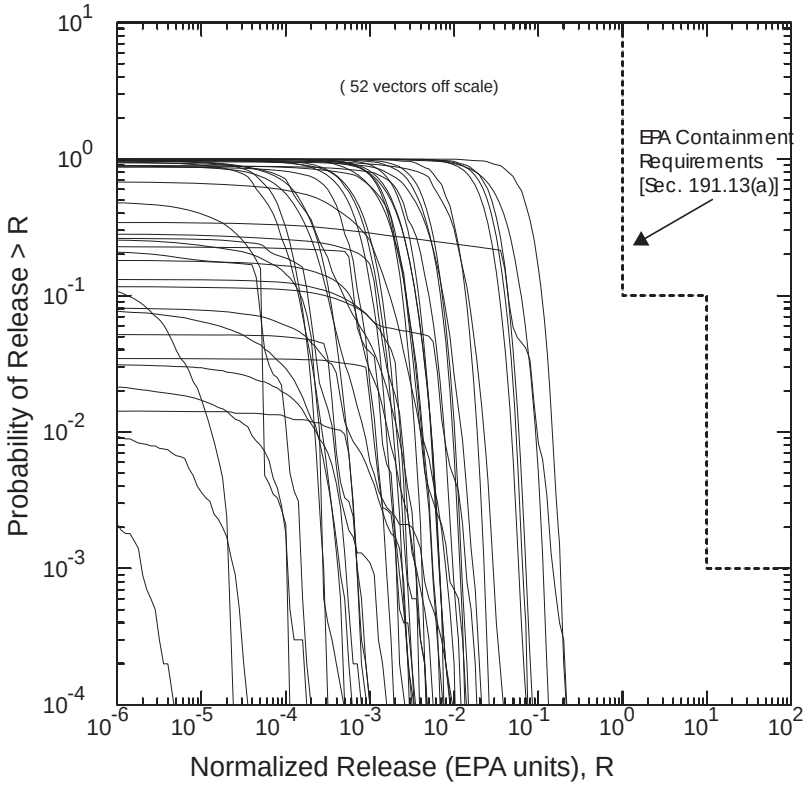

Figure PA-108. Spallings Releases, Replicate R3.

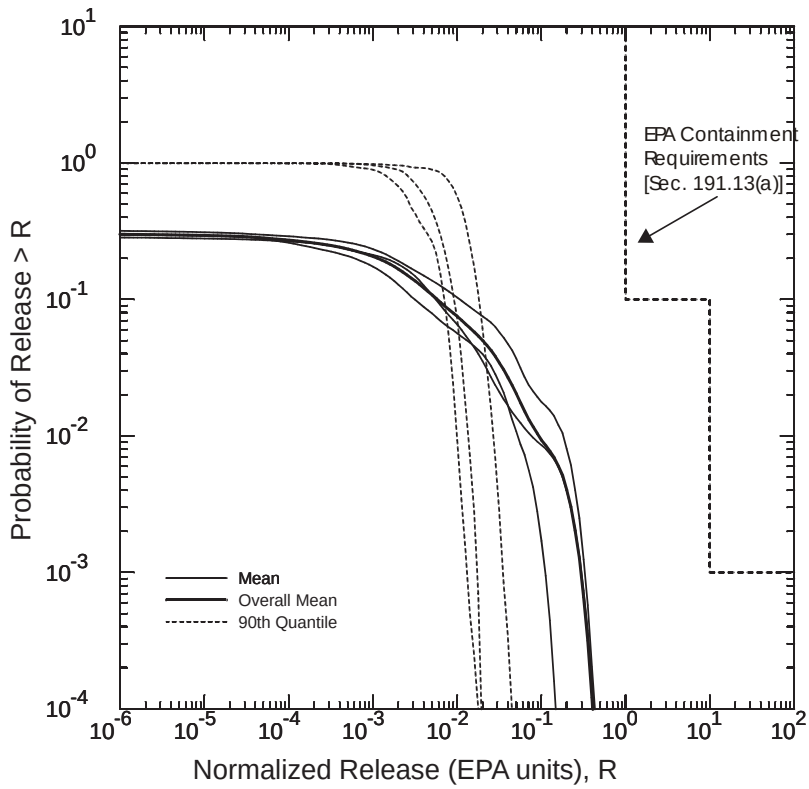

Figure PA-109. Mean and Quantile CCDFs for Spallings Releases, All Replicates.

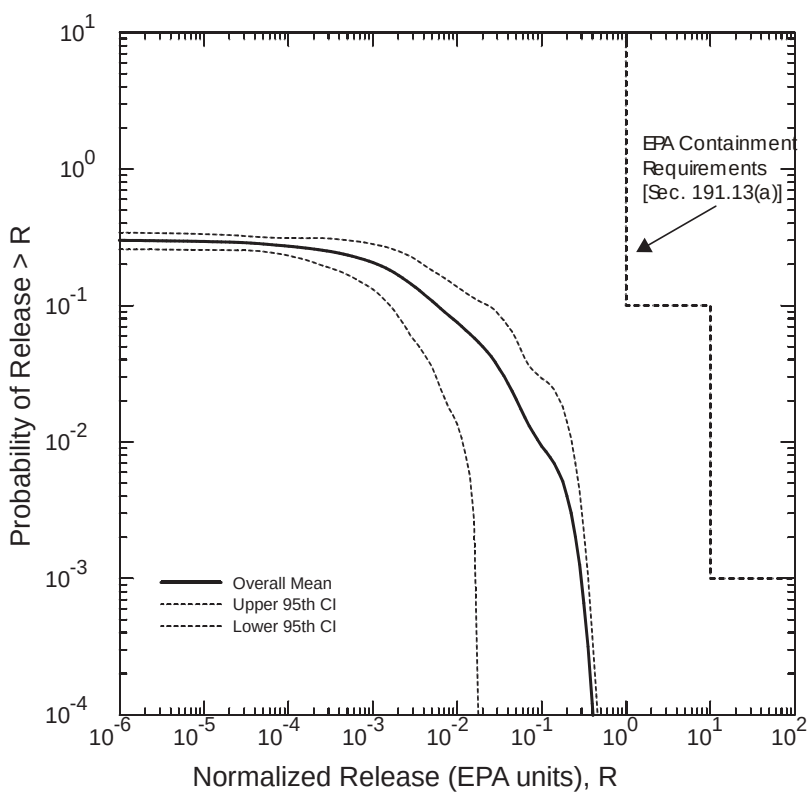

Figure PA-110. Confidence Interval on Overall Mean CCDF for Spallings Releases.

Section PA-8.5.2 presents a sensitivity analysis for spallings release volumes, and shows that the uncertainty in total spall volumes arises from the uncertainty in microbial action (WMICDFLG; see Table PA-17) and the uncertain spall volume from a single intrusion (see RNDSPALL in Table PA-17 and the discussion in Section PA-8.5.2). Since spall releases are computed by multiplying the volume released by the average concentration of radioactivity in the CH-TRU waste at the time of intrusion, the uncertainty in spalling releases is due to the same parameters that contribute to uncertainty in total spall volumes.

PA-9.4 Normalized Direct Brine Releases

Figures PA-111, PA-112, and PA-113 show the CCDFs for normalized direct brine releases for replicates R1, R2, and R3. The releases for each replicate are very similar; Figure PA-114 compares the mean and quantile CCDFs for each replicate; the 10th quantile for normalized DBRs does not plot on the scale of Figure PA-114. Figure PA-115 shows the 95 percent confidence interval about the overall mean of the CCDFs for DBRs, and shows that the overall mean is estimated reasonably well.

Section PA-8.5.3 provides an analysis identifying the sensitivity of the volume of brine released from a single intrusion to the uncertain parameters in the analysis. The sensitivity analysis showed that direct brine release volumes are most sensitive to uncertainty in pressure and brine saturation in the waste, which in turn, are most sensitive to microbial action in the waste (WMICDFLG; see Table PA-17) and borehole permeability (BHPERM).

As described in Section PA-6.8.5, DBRs are computed by multiplying the volume of brine released by the concentration of radionuclides in the brine. A stepwise regression analysis (summarized in Table PA-30) determined that the uncertainty in mean DBR is dominated by the parameters that influence the DBR volumes (WMIDFLG, the indicator for microbial action; BPINTPRS, the pressure in the Castile brine reservoir; PBRINE, the probability of an intrusion hitting the Castile brine reservoir; and WRBRNSAT, the residual brine saturation in the waste). The uncertainty in radionuclide concentration has a lesser influence on mean direct brine release, as only a single related parameter entered the analysis (WSOLAM3C, the uncertainty in the solubility of Am(III) in Castile brine). Figure PA-116 illustrates the sensitivity of mean DBR to DBR volume and to the most influential uncertain parameter, the indicator for microbial action (WMICDFLG). The figure shows that the mean DBRs is roughly proportional to the mean DBR volume among subsets of vectors with or without microbial action.

PA-9.5 Transport Normalized Releases

Figures PA-117 and PA-118 show the CCDFs for normalized releases due to transport through the Culebra for replicates R1 and R3. No transport releases larger than 10^{-6} EPA units occurred in replicate R2. Since the transport releases are small and statistically rare, no confidence intervals or sensitivity analyses are provided.

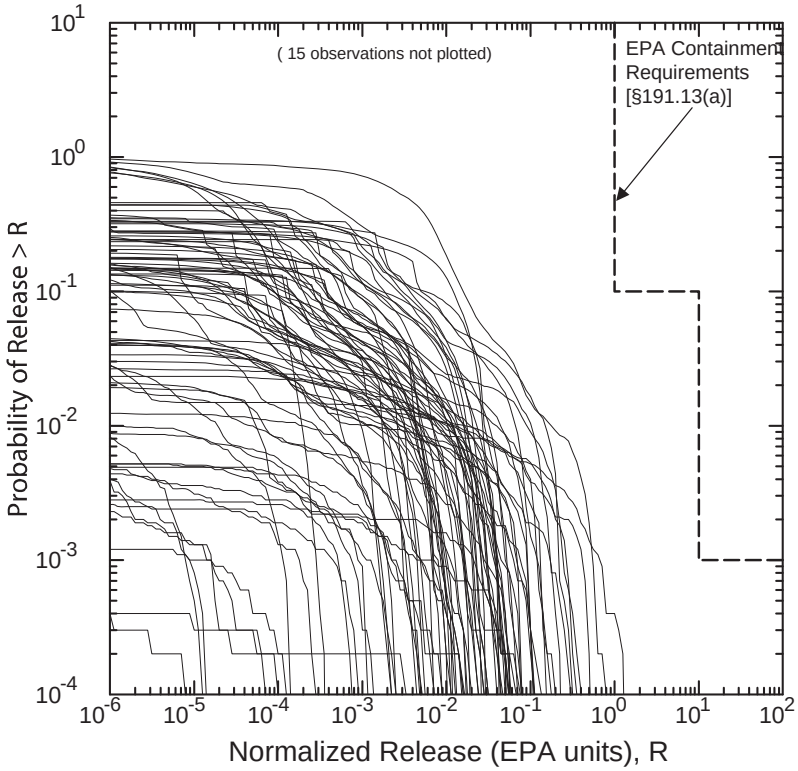

Figure PA-111. DBRs, Replicate R1.

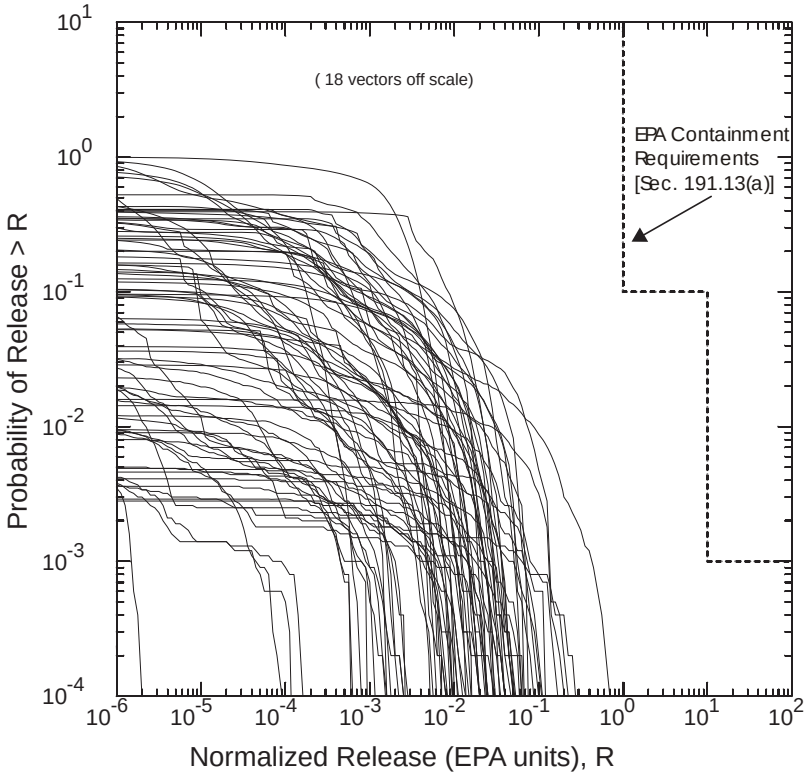

Figure PA-112. DBRs, Replicate R2.

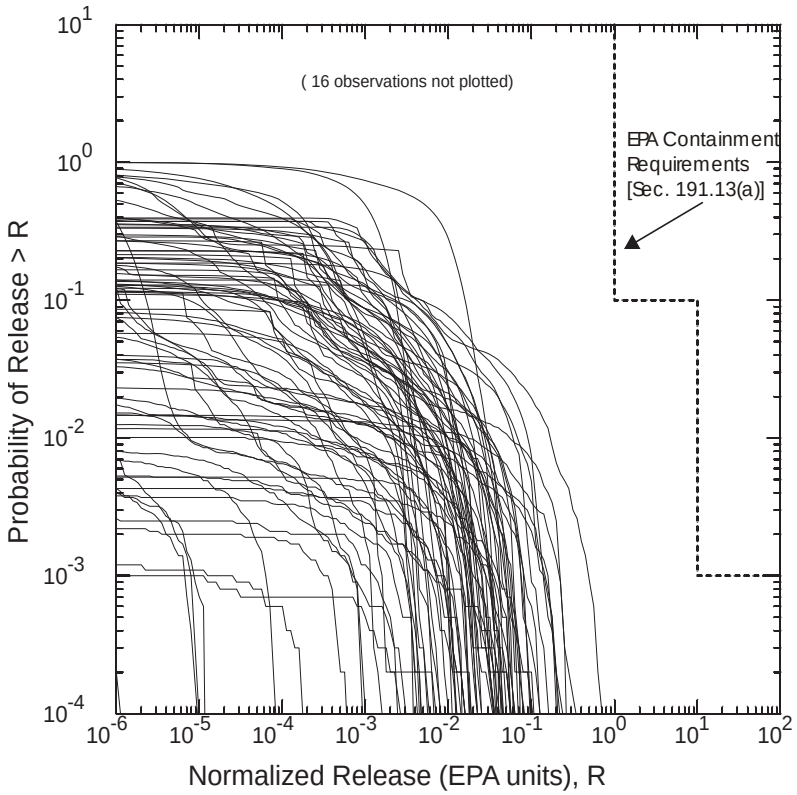

Figure PA-113. DBRs, Replicate R3.

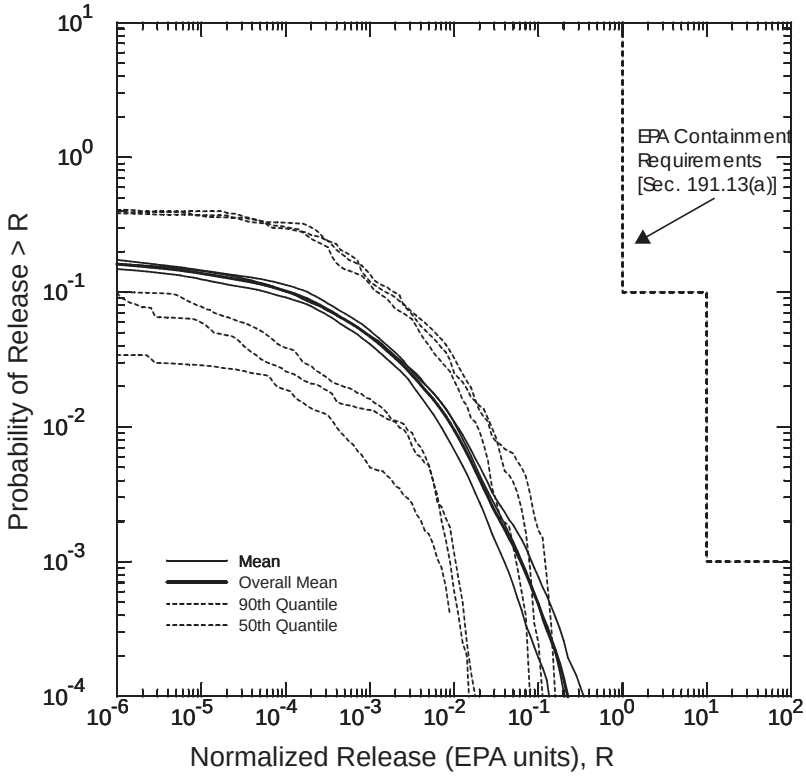

Figure PA-114. Mean and Quantile CCDFs for DBRs, All Replicates.

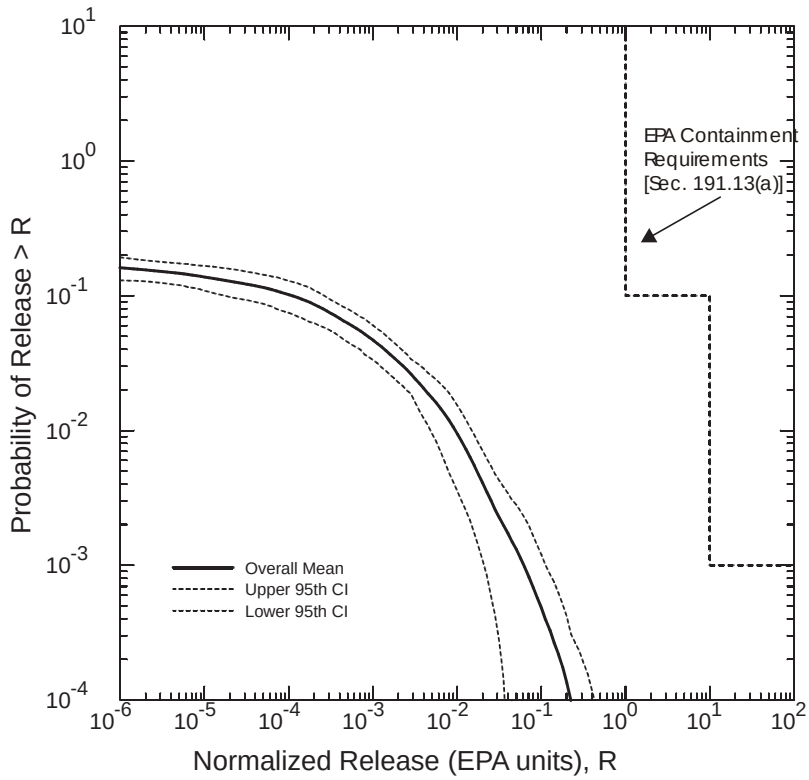

Figure PA-115. Confidence Interval on Overall Mean CCDF for DBRs.

Table PA-30. Stepwise Regression Analysis for Mean Total DBRs

	Expected Normalized Release		
Step[a]	Variable[b]	SRRC[c]	R^{2d}
1	WMICDFLG	-0.46784	0.15776
2	BPINTPRS	0.48223	0.34337
3	PBRINE	0.36000	0.47058
4	WSOLAM3C	0.29070	0.51608
5	WRBRNSAT	-0.15397	0.55481
6	CONGSSAT	-0.22426	0.57556
7	REPIPERM	-0.21496	0.60771
8	WGRCOR	-0.16265	0.63011
9	TENSLSTR	-0.14810	0.64990

[a] Steps in stepwise regression analysis

[b] Variables listed in order of selection in regression analysis

[c] Standardized Rank Regression Coefficient in final regression model

[d] Cumulative R^2 value with entry of each variable into regression model

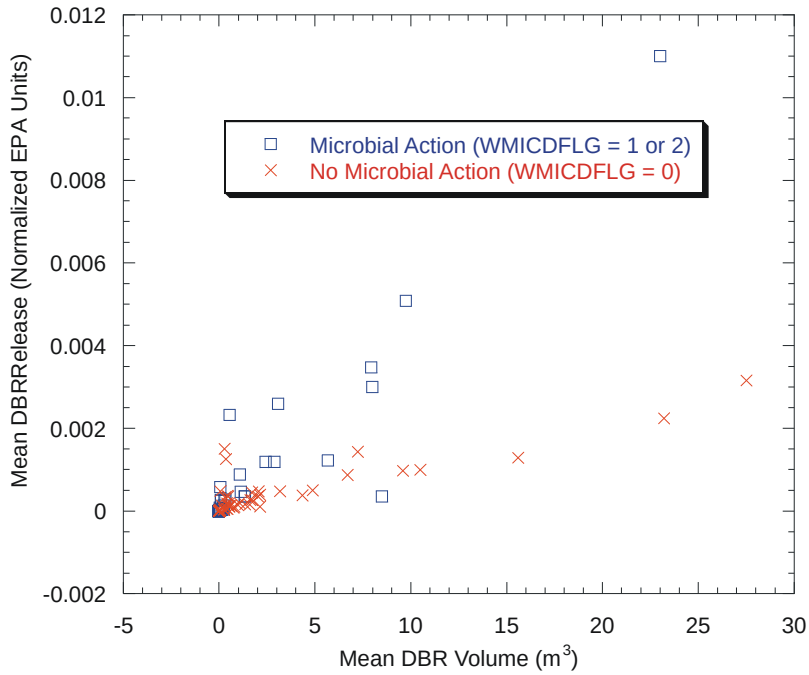

Figure PA-116. Sensitivity of DBRs.

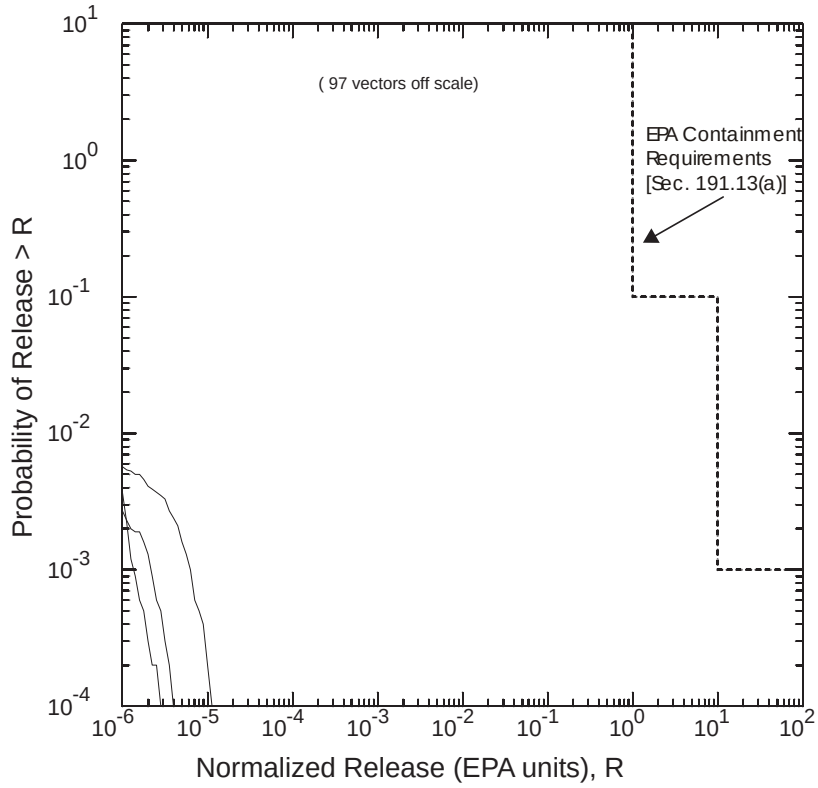

Figure PA-117. Transport Releases Through the Culebra, Replicate R1.

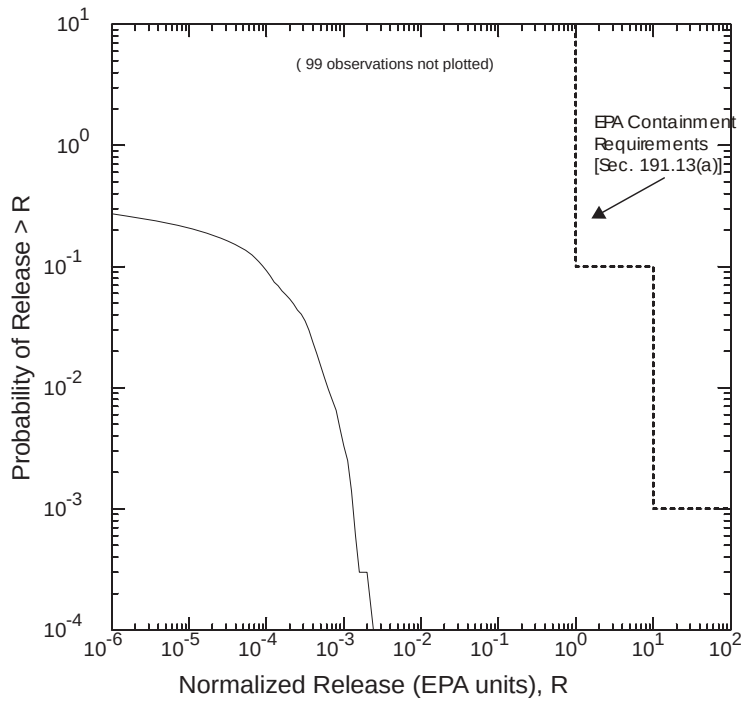

Figure PA-118. Transport Releases Through the Culebra, Replicate R3.

PA-9.6 Sensitivity Analysis for Total Normalized Releases

Uncertainty in total normalized releases is largely due to uncertainty in waste shear strength (WTAUFAIL; see Table PA-17). Table PA-31 lists the results of a stepwise regression between mean total normalized releases and the uncertain parameters in the analysis; waste shear strength (WTAUFAIL) is highly correlated with the uncertainty in mean total normalized releases. Figure PA-119 shows the relationship between the uncertainty in total releases and the uncertainty in WTAUFAIL for all replicates.

Table PA-31. Stepwise Regression Analysis for Mean Total Normalized Releases

	Expected Normalized Release		
Step[a]	Variable[b]	SRRC[c]	R^{2d}
1	WTAUFAIL	-0.95137	0.91345
2	WMICDFLG	0.11538	0.92727
3	DOMEGA	0.10735	0.93639
4	SPALLVOL	0.08003	0.94139
5	BPINTPRS	0.06271	0.94475
6	PLGPRM	0.05841	0.94802
7	SHLPRM3	-0.04728	0.95022

[a] Steps in stepwise regression analysis

[b] Variables listed in order of selection in regression analysis

[c] Standardized Rank Regression Coefficient in final regression model

[d] Cumulative R^2 value with entry of each variable into regression model

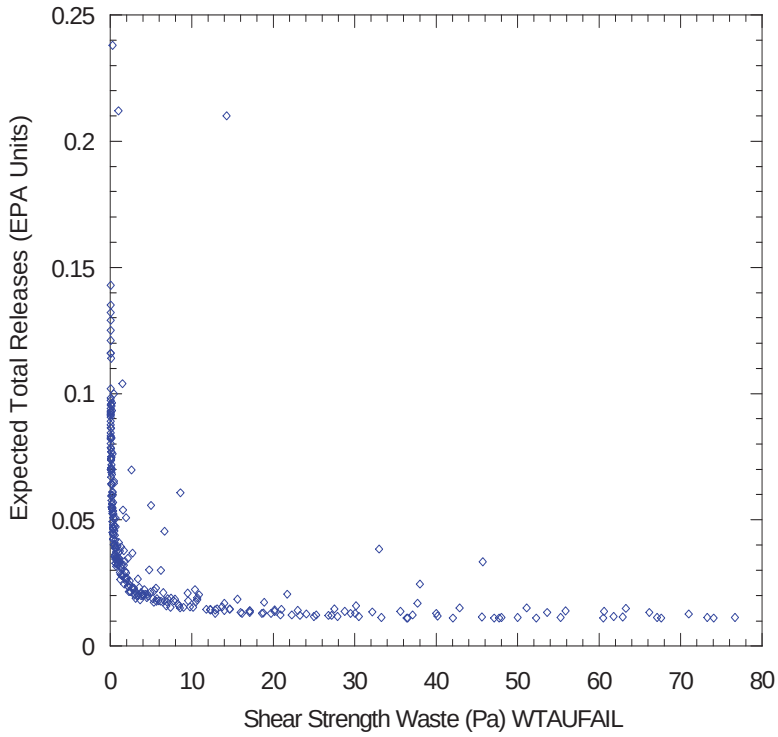

Figure PA-119. Uncertainty in Mean Total Releases Due to Waste Shear Strength, All Replicates.

As shown in Section PA-9.1, cuttings and cavings releases constitute most of the total releases from the repository. As shown in Section PA-8.5.1, most of the uncertainty in cuttings and cavings releases arises from uncertainty in waste shear strength (WTAUFAIL). Thus, uncertainty in WTAUFAIL dominates uncertainty in total releases.

The remaining uncertainty in total releases is primarily due to uncertainty in the spallings releases. Figure PA-120 compares total releases and cuttings and cavings releases for replicate R1, and shows that almost all of the total releases are due to cuttings and cavings. For replicate R1, Figure PA-121 shows the uncertainty in total releases that is not due to uncertainty in cuttings and cavings, and demonstrates that most of the remaining uncertainty arises from uncertainty in spallings releases. This figure shows that spallings releases account for almost all of the variability in the difference between the total releases and cuttings and cavings releases. The small amount of uncertainty in total releases that is not due to cuttings and cavings or spallings arises from uncertainty in the other components of total releases (i.e. DBR and transport releases). Since the three replicates are statistically similar (Figure PA-95), these conclusions hold for all replicates.

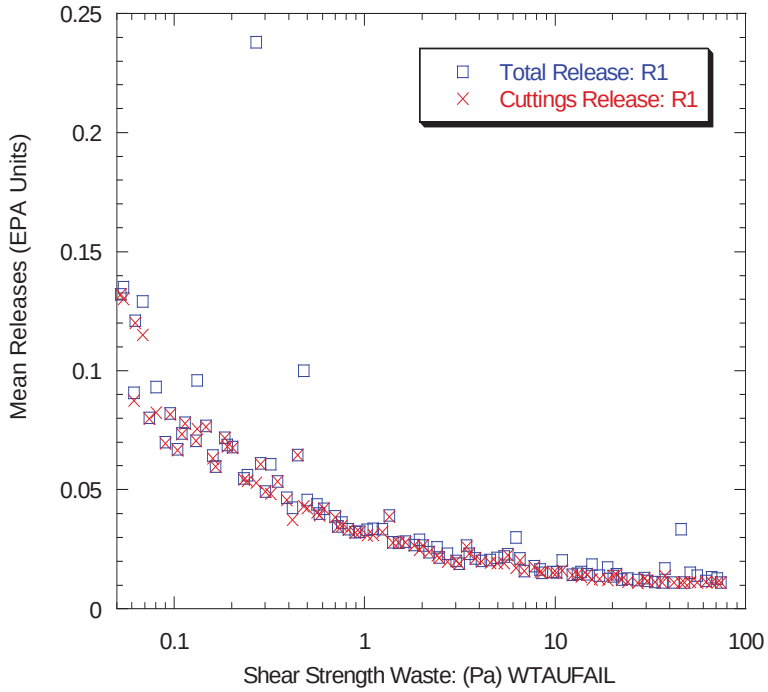

Figure PA-120. Comparison of Mean Total Releases to Mean Cuttings and Cavings Releases, Replicate R1.

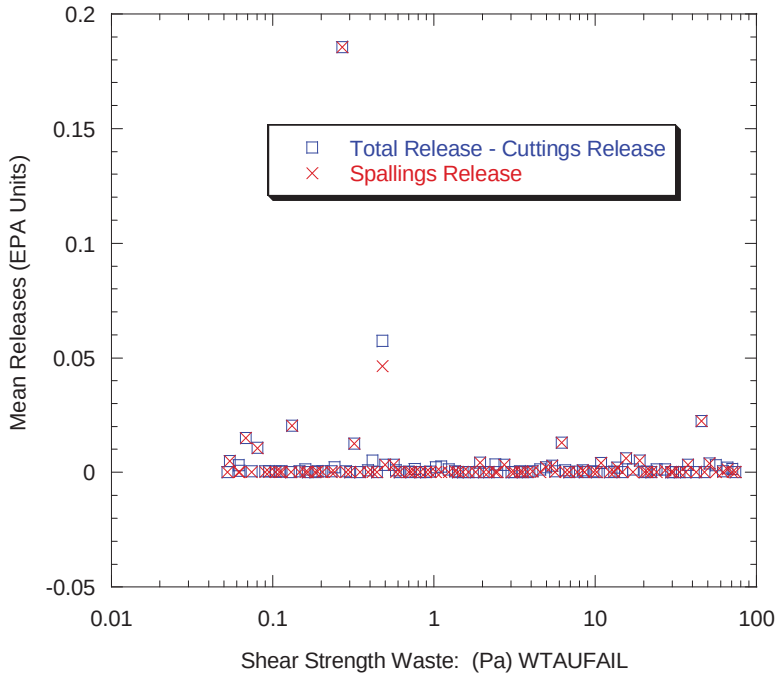

Figure PA-121. Comparison of Mean Total Releases Minus Mean Cuttings Releases to Spall Releases, Replicate R1.

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Appendix PA

Attachment MASS

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ACRONYMS AND ABBREVIATIONS

An	actinide
ASTP	Actinide Source Term Program
BSEP	Brine Sampling and Evaluation Program
CCDF	complementary cumulative distribution function
CH	contact-handled
CCA	Compliance Certification Application
CPR	cellulosic, plastic, and rubber
CRA	Compliance Recertification Application
DCCA	Draft Compliance Certification Application
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
DSEIS	Draft Supplement, Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
FEIS	Final Environmental Impact Statement
FEPs	features, events, and processes
FMT	Fracture-Matrix Transport
FSEIS	Final Supplemental Environmental Impact Statement
LANL	Los Alamos National Laboratory
LEFM	linear elastic fracture mechanics
LLNL	Lawrence Livermore National Laboratory
MB	marker bed
PA	performance assessment
PAVT	Performance Assessment Verification Test
QA	quality assurance
RH	remote-handled
RoR	Rest of Repository
SMC	Salado Mass Concrete
SNL	Sandia National Laboratories
SSBI	Small-Scale Brine Inflow
SWCF	Sandia National Laboratories WIPP Central Files
TDEM	Time Domain ElectroMagnetic
TRU	transuranic
WIPP	Waste Isolation Pilot Plant
WQSP	Water Quality Sampling Program

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MASS-1.0 INTRODUCTION

This attachment presents supplementary information to Appendix PA regarding the assumptions, simplifications, or approximations used in the models of the first recertification performance assessment (PA) of the Waste Isolation Pilot Plant (WIPP). Within this attachment, relevant issues in the formulation or development of the various types of models (for example, conceptual, mathematical, numerical, or computer code) used for the topic are discussed, and references to relevant historical information are included where appropriate.

Section MASS-2.0 contains a summary of changes in the PA since the Compliance Certification Application (CCA). Section MASS-3.0 includes a discussion of general modeling assumptions applicable to the disposal system as a whole, including a table of assumptions made in PA models, with cross-references. The remainder of this attachment discusses assumptions specific to the first recertification PA conceptual models. Historical development of the WIPP conceptual models that led to the PA used in the CCA is documented in CCA Appendix MASS-2.0.

MASS-2.0 SUMMARY OF CHANGES IN PERFORMANCE ASSESSMENT

Since the CCA, several concepts about the processes important to the performance of the WIPP have changed. Additionally, ongoing confirmatory experiments, monitoring results, and operational practices have generated information relevant to the conceptual models for the WIPP PA and provide additional support to the conceptual basis of the PA.

Changes that have occurred since the 1996 PA and new information that may be important to PA are as follows:

1. Features, events and processes (FEPs) assessment
   A. Inclusion of organic ligands in solubility calculations

2. Monitoring
   A. Changes resulting from Culebra water level investigations
   B. Drilling rate parameter change
   C. Changes in Borehole plugging configuration probabilities

3. Experimental Activities
   A. Magnesium-oxide investigations
   B. Changes resulting from actinide investigations

4. PA Models and Systems
   A. Administrative hardware and software updates
   B. Conceptual model changes
      i. Panels closures
      ii. Simplification of shafts
      iii. Grid refinements
      iv. North and South Rest of Repository (RoR)
   C. Spallings

D. Recalculation of Culebra T-fields
E. Performance Assessment Verification Test (PAVT) Baseline

5. Operational Considerations
   A. WIPP horizon moved up to Clay Seam G
   B. Waste inventory update
   C. Evaluation of waste structural impacts, emplacement, and homogeneity

A summary of each change is presented in this section. References to appropriate sections of this attachment are provided for those changes that impact modeling assumptions. Additional references are provided to other areas of the Compliance Recertification Application (CRA) discussing change implementation.

MASS-2.1 Features, Events, and Processes Assessment

Based on the PA methodology for WIPP (see Section 6.2), FEPs are important elements to help develop the conceptual models and modeling assumptions represented in PAs. The process used to develop and screen FEPs is outlined in Section 6.2. The results of the CCA FEPs screening was documented in CCA Appendix SCR. For the CRA, a reassessment of the baseline PA FEPs was conducted to determine if changes in WIPP activities and conditions changed the original FEPs descriptions, basis, or screening decisions. This assessment also determined if additional FEPs should be included in the CRA baseline. The reassessment results are documented in SNL (2003a) and have been used to develop Appendix PA, Attachment SCR. Changes to the FEPs' baseline include combining similar FEPs and deleting redundant or inclusive FEPs, separating general FEPs into more descriptive FEPs, and FEP screening decision changes.

MASS-2.2 Monitoring

Monitoring activities have continued since the certification of WIPP. These activities are used to validate assumptions and PA parameters, and also to detect substantial and detrimental deviation from expected repository performance. Monitoring, as discussed here, applies to the assurance requirement of 40 CFR §191.14(b) and the monitoring criteria at 40 CFR §194.42. Appendix MON details the monitoring program that meets these requirements. The monitoring program has led to three changes:

- Culebra water levels at some wells have exceeded the ranges used in the CCA steady-state T-field calibrations,
- The drilling rate for deep boreholes has increased since 1996, and
- The probabilities for borehole plug configurations have changed slightly since 1996.

The impacts and implementation of the new Culebra data are discussed in Section 2.2.1.4.1.2. and Appendix PA, Attachment TFIELD (see also MASS-2.4.2).

In the 2004 PA, two parameters have changed; the drilling rate and the probabilities for borehole plugging. The drilling rate for boreholes is discussed in Sections 6.0.2.3, 6.2.5.2; and Appendix DATA (Section DATA-2.0 and Attachment A). The probability for borehole plugging

configurations is discussed in Section 6.4.7.2. No changes are necessary to modeling assumptions to account for these parameter changes.

MASS-2.3 Experimental Activities

The EPA requires the recertification documentation to include an update of "additional analyses and results of laboratory experiments conducted by the Department or its contractors as part of the WIPP program" (40 CFR 194.15(a)(3)). The following discusses analyses and experiments conducted to support compliance determinations. Only the analyses with conclusions relevant to this recertification are discussed here; all ongoing and supportive experiments are presented in biannual reports previously submitted to Environmental Protection Agency (EPA) (SNL 2001a, 2001b; SNL 2002a, 2002b; and SNL 2003b).

MASS-2.3.1 Magnesium-Oxide Investigations

Experiments have been preformed to support implementation of magnesium oxide (MgO) as an engineered barrier. These experiments investigate hydration and carbonization of MgO to confirm its ability to sequester carbon dioxide (CO_2), buffer brine pH, and subsequently reduce actinide solubilities in the repository. The conclusions drawn from these activities are described in Appendix BARRIERS. Specifically, the incorporation of MgO in PA has not changed from the 1996 PA.

MASS-2.3.2 Actinide Investigations

An Actinide Source Term Program (ASTP) has continued to investigate actinide (An) speciation and solubilities since the certification of WIPP. These investigations include work relating to organic ligands and colloid effects on solubilities, and the appropriateness of the use of the oxidation state analogy. These activities are described in SNL (2001a, 2001b; SNL 2002a, 2002b; and SNL 2003b). The conclusions drawn from these activities and the changes to the 2004 PA are described in Appendix PA, Attachment SOTERM. Specifically, organic ligands are considered in the 2004 PA through the solubility calculations.

MASS-2.4 Performance Assessment Models and Systems

Changes have been made to the systems that are used to perform PAs. The PA hardware, operating systems, and parameter database were updated since the 1996 PA. These changes were necessary to replace obsolete hardware and operating systems and to increase PA capabilities. These changes were implemented and approved under applicable quality assurance (QA) requirements.

Additionally, conceptual model changes were necessary to implement new or different representations of physical systems in PA. Changes to conceptual models led to revised or replacement codes, which implement the conceptual models in PA. The following discusses these changes.

MASS-2.4.1 Administrative Hardware and Software Updates

The computer systems and operating systems have been upgraded since the 1996 PA because of increasing obsolescence of the operating system and hardware. New hardware is being used along with a newer operating system for the 2004 PA. All changes to these systems are performed under the appropriate QA program, and include testing, validation, and verification to ensure that there is no impact on PA implementation. A synopsis of the changes and references to the QA documentation are found in Long (2003).

MASS-2.4.2 Conceptual Model Changes

The certification decision by the EPA (1998a) included several conditions that the U.S. Department of Energy (DOE) was required to meet. In the first of these conditions, the EPA required the DOE to implement a specific design for the panel closure system (referred to as "Option D") and using Salado Mass Concrete (SMC). The DOE had included in the CCA four Options (A-D) for the panel closure design. The Option D design consisted of two components, a large concrete monolith and an explosion wall constructed of concrete blocks. The 1996 PA generically represented the closures in BRAGFLO and did not model a specific closure. The representation of the Option D closure has been incorporated into the BRAGFLO grid. The Option D closure modeling assumptions are discussed in Section MASS-19.0 and MASS-4.2. Panel closure implementation in PA is discussed in Appendix PA, Section PA-4.2.8.

To account for this design in PA, the conceptual model for Repository Fluid Flow, Disturbed Rock Zone (DRZ), and the Disposal System Geometry were revised and peer reviewed. Chapter 9 and Appendix PEER contain information on the conceptual model peer review. These conceptual models are implemented in BRAGFLO. See Section MASS-2.5.2 and MASS-4.2 for information on modeling assumptions and implementation of these conceptual models. Implementation of these conceptual model changes led to the following changes in BRAGFLO.

1. Implementation of Option D panel closures,
2. Simplification of the shaft seal model,
3. Refinement of grid outside the excavated area to improve computational accuracy and efficiency,
4. Increased Segmentation in the North RoR and South RoR.

MASS-2.4.3 Spallings Model

An EPA guidance letter on recertification requested the DOE implement a new spallings conceptual model (EPA 2002). The original conceptual model for spallings was peer reviewed during the first certification, but was deemed inadequate by the peer review panel. The DOE later derived a method to represent spallings that was deemed conservative by the peer reviewers and was used by DOE in the 1996 PA. Since the CCA, however, a more appropriate and representative spallings model has been developed, peer reviewed, and implemented in the 2004 PA. Results of the peer review are found in Chapter 9 and Appendix PEER. Modeling

assumptions concerning the Spallings model are detailed in Section MASS-16.1. Implementation of the spallings model is described in Appendix PA, Section PA-4.6.

No other conceptual models were revised for this recertification application.

MASS-2.4.4 Recalculation of Culebra T-fields

Water level rises in the Culebra have continued over recent years and the observed heads have exceeded the ranges of uncertainty established for the steady-state heads in many of the 32 wells used in the calibration of the transmissivity fields described in the CCA (SNL 2002b). Therefore, the DOE has recalculated T-Fields for the CRA using new Culebra data and geologic information (see Appendix PA, Attachment TFIELD; and Section 2.0). The DOE has implemented a program to identify other potential causes for the water-level rises (SNL 2003c).

MASS-2.4.5 Performance Assessment Verification Test Baseline

The EPA's PAVT parameters were incorporated into the 2004 PA parameter baseline (EPA 1998b, V-B-14). These parameters and a cross-reference of discussions concerning their incorporation into the 2004 PA are shown in Table 6-1.

MASS-2.5 Operational Considerations

Operational considerations are impacts to PA from changes to WIPP operations that the DOE has requested and the EPA has approved, or changes that have been mandated by the EPA.

MASS-2.5.1 Waste Isolation Pilot Plant Horizon Moved up to Clay Seam G

Operational changes to the repository design since the CCA include mining the repository horizon in the southern half of the waste panels at a different location than the northern half. Specifically, panels 3, 4, 5, 6, and 9 will be excavated at an elevation approximately 2.4 m above the level of panels 1, 2, 7, 8, and 10, and the operations and experimental areas. This change in horizon will bring the roof of the raised rooms to the level of the Clay Seam G. The change is expected to improve roof conditions and enhance operations and mine safety. The DOE submitted a planned change request to the EPA that described the change and presented an argument that the change would have minimal impact on long-term repository performance (DOE 2000). The EPA responded to the change request in a letter (EPA 2000) in which they agreed with DOE that the effects to long-term performance would be minimal. Further investigations led DOE to determine that no changes to the 2004 PA models were necessary to account for this change. Section MASS-20.0 discusses the justification for this determination.

MASS-2.5.2 Waste Inventory Update

The waste inventory used in the CCA was based on information contained in the TWBIR (CCA Appendix BIR). No waste had been emplaced in the repository at that time. Since 1996, waste has been emplaced in the repository and better estimates have been made of the existing and projected waste streams at the generator sites. The new waste information has been updated in the 2004 PA to include the emplaced, currently stored, and projected waste streams. This information was collected in the TWBID, Rev 2, with specific WIPP information detailed in

Appendix DATA, Attachment F. Inclusion of waste information in the 2004 PA is discussed in Appendix TRU WASTE.

MASS-2.5.3 Evaluation of Waste Structural Impacts, Emplacement, and Homogeneity

During the development of the CCA PA, the DOE choose to assume random placement of transuranic (TRU) waste in the WIPP, and developed conceptual and numerical models accordingly. The EPA reviewed these models and their results, and determined that DOE had modeled accurately random placement of waste in the disposal system. Since the time of the CCA, additional information about the waste and its emplacement has emerged and requires waste-related assumptions to be reevaluated. This evaluation is discussed in Section MASS-21.0.

MASS-3.0 GENERAL ASSUMPTIONS IN PERFORMANCE ASSESSMENT MODELS

Several assumptions are applied generally to the disposal system through the conceptual and mathematical models implemented in the major computer codes used in this PA. Several major assumptions are discussed here. A table of general assumptions is also presented in Section MASS-3.4.

MASS-3.1 Darcy's Law Applied to Fluid Flow Calculated by BRAGFLO, MODFLOW-2000, and SECOTP2D

A mathematical relationship expressing the flux of fluid as a function of hydraulic head gradients applied, commonly known as Darcy's Law, is applied to geologic media for all fluid-flow calculations. For details about the specific formulation of Darcy's Law used, refer to Appendix PA, Section PA-4.2 for the disposal system and Section PA-4.8 for the Culebra. Darcy's Law is not applied for flow up a borehole that is being drilled (see Section MASS-16.2; and Section 6.4.7.1.1 for more discussion of this topic).

Darcy's Law generally applies for flow models if certain conditions are satisfied: (1) the flow occurs in a porous medium with interconnected porosity, (2) flow velocities are low enough that viscous forces dominate inertial forces, and (3) a threshold hydraulic gradient is exceeded. In CCA Appendix MASS, these conditions were shown to be valid for the WIPP PA.

Darcy's Law assumes laminar flow, that is, there is no motion of the fluid at the fluid/solid interface. For liquids, it is reasonable to assume laminar flow under most conditions. For gases at low pressure, however, gas molecules near the solid interface may not have intimate contact with the solid and may have finite velocity, not necessarily zero. This effect, which results in additional flux of gas above that predicted by application of Darcy's Law, is known as the slip phenomenon, or Klinkenberg effect (Bear 1972, 128). A correction to Darcy's Law for the Klinkenberg effect is incorporated into the BRAGFLO model (see Appendix PA, Section PA-4.2).

Darcy flow for one and two phases implies that values for certain parameters must be specified. Some principal parameters relate to the properties of the fluid, others to the rock. Fluid properties in the Darcy flow model used for the WIPP are its density, viscosity, and compressibility. Rock properties in Darcy flow models are porosity, permeability, and

compressibility (pore, bulk, or rock). In BRAGFLO, other parameters are required to describe the interactions or interference between the two phases present in the model, gas and brine, because they can occupy the same pore space. In the WIPP application of Darcy flow models, compressibility of both the liquid and rock are related to porosity through a dependence on pressure. Fluid density, viscosity, and compressibility are functions of fluid composition, pressure, and temperature. In BRAGFLO, fluid viscosity is a function of pressure, but its density and compressibility are held constant. Fluid composition for the purposes of modeling flow and transport is assumed to be constant.

MASS-3.2 Hydrogen Gas as Surrogate for Waste-Generated Gas Physical Properties in BRAGFLO and DRSPALL

Hydrogen gas is produced by the corrosion of steel in the repository by water or brine. As in the CCA, the gas phase in the BRAGFLO model is assigned the properties of hydrogen because hydrogen will, under most conditions reasonable for the WIPP, be the dominant component of the gas phase. The model for spallings, DRSPALL, also assigns physical properties of hydrogen to the gas phase. In the CCA, the effect of assuming flow of pure H_2 instead of a mixture of gases (including H_2, CO_2, H_2S, and CH_4), was shown to be minor relative to the permeability variations in the surrounding formations.

Other gases may be produced by processes occurring in the repository. If microbial degradation occurs, a significant amount of carbon dioxide (CO_2) and methane (CH_4) will be generated by microbial degradation of cellulosics, and, perhaps, plastics and rubbers in the waste. The CO_2 produced, however, will react with the magnesium-oxide (MgO) engineered barrier and cementitious materials to form brucite ($Mg(OH_2)$), hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$), and calcite ($CaCO_3$) thus resulting in very low CO_2 fugacity in the repository. Although other gases exist in the disposal system, for BRAGFLO calculations it is assumed these gases are insignificant and are not included in the model.

With the average stoichiometry gas generation model, the total number of moles of gas generated will be the same whether the gas is considered to be pure H_2 or a mixture of several gases, because the generation of other gases is accounted for by specifying the stoichiometric factor y. Therefore, considering the moles of gas generated alone, the pressure buildup in the repository will be approximately the same, because the expected gases behave similarly to an ideal gas, even up to lithostatic pressures.

The effect of assuming pure H_2 instead of a mixture of gases (including H_2, CO_2, H_2S and CH_4) on flow behavior, and its resulting impact on the WIPP repository pressure is presented as follows:

Radial flow of a 100 percent saturated rock with nonideal gas is described by Darcy's Law (Amyx et al. 1960):

$$q_b = 1.988_10^{-5}\left[\frac{T_b z_b}{P_b}\frac{kh\left(P_e^2 - P_w^2\right)}{\mu_{avg} z_{avg} \ln\left(\frac{r_e}{r_w}\right)}\right], \qquad (2)$$

which can be rewritten:

$$P_e^2 - P_w^2 = \frac{q_b}{1.988_10^{-5}}\left[\frac{P_b}{T_b z_b}\frac{\mu_{avg} z_{avg} \ln\left(\frac{r_e}{r_w}\right)}{kh}\right], \qquad (3)$$

where:

q = gas flow rate, cubic feet per day at base (reference) conditions
T = temperature, K
P = pressure, pounds per square inch atmosphere
k = permeability, millidarcys
h = height, feet
μ = viscosity, centipoises
z = gas compressibility factor (a function of gas pressure and temperature)
r = radius, consistent units
e = external boundary (repository)
w = internal boundary (wellbore)
b = base or reference conditions for gas (temperature, pressure, compressibility factor)
avg = average properties between external and internal boundaries because u and z are functions of pressure which change with time.

This expression is very useful for looking at the relationships of gas properties (specifically μ and z [which is a function of the gas temperature and pressure]) and rock properties (namely k) on defining q and P.

In order to evaluate the effect of gas composition on q and P, a computer program developed by the National Institute of Standards and Technology (NIST) entitled SUPERTRAPP was used (NIST 1992). This computer program allows calculations of gas properties for 116 pure fluids and mixtures of up to 20 components for temperatures to 1,000 K and pressures to 300 megapascals. The computer program currently can evaluate hydrogen, CO_2, and water but does not have the capacity to evaluate brine (Friend and Huber 1994). Because such small quantities of H_2S are anticipated at the WIPP, its impact will be neglected.

Figure MASS-1 shows the relationship between gas viscosity H_2-CO_2 mixtures for various mole fractions of H_2 at pressures of 7 megapascals and 15 megapascals as determined from SUPERTRAPP. The viscosity at 50 percent mole fraction H_2 is 2.3 times greater than for 100 percent mole fraction H_2. As shown in Equation (2), viscosity has an inverse relationship to flow rate and, as shown in Equation (3), a direct relationship to the square of the repository pressure.

Hence viscosity differences that would result if gas properties other than those of hydrogen were incorporated would result in a decrease in flow rate and potentially higher pressures.

As shown in Figure MASS-2, the gas compressibility at 50 percent mole fraction H_2 is about 0.9 times that at 100 percent mole fraction H_2. Like viscosity, the gas compressibility factor is inversely related to flow rate and directly related to the square of the repository pressure. Hence changing composition from 100 percent to 50 percent H_2 would result in a slight increase in flow rate and a decrease in pressure. Therefore, the impact of variation in gas compressibility caused by composition is considered minor and so is neglected.

The viscosity and compressibility calculations described above for H_2-CO_2 mixtures were repeated for H_2-CH_4 mixtures for various mole fractions of H_2 at pressures of 7 MPa and 15 MPa (Kanney 2003). The variability of viscosity with the composition for the H_2-CH_4 mixtures is smaller than that observed for the H_2-CO_2 mixtures. For example, the gas viscosity of H_2-CH_4 at 50 percent mole fraction is only 1.6 times greater than that for 100 percent mole fraction H_2 at 15 MPa. The H_2-CH_4 mixtures are only slightly less compressible than the H_2-CO_2 mixtures. For example, the gas compressibility of H_2-CH_4 at 50 percent mole fraction is about 0.94 times that for 100 percent mole fraction H_2 at 15 MPa.

The absolute permeability of the surrounding formation plays a significant part with respect to both flow rate and pressure determinations. Because marker bed permeabilities range over four orders of magnitude (see Appendix PAR, Tables PAR-30 to PAR-32), these primary flow pathways will have a greater influence on pressure and flow rate determinations compared to either uncertainty in viscosity or gas compressibility effects.

It should also be noted that the BRAGFLO code includes a pressure-induced fracture model that will limit pressure increases in the repository (Schreiber 1997). For example, at high repository pressures, the factor of 2.3 pressure increase calculated here using the simplified Darcy's Law model is unlikely to be seen in the BRAGFLO results, since fracturing will lead to increased permeability, effectively limiting pressure increases.

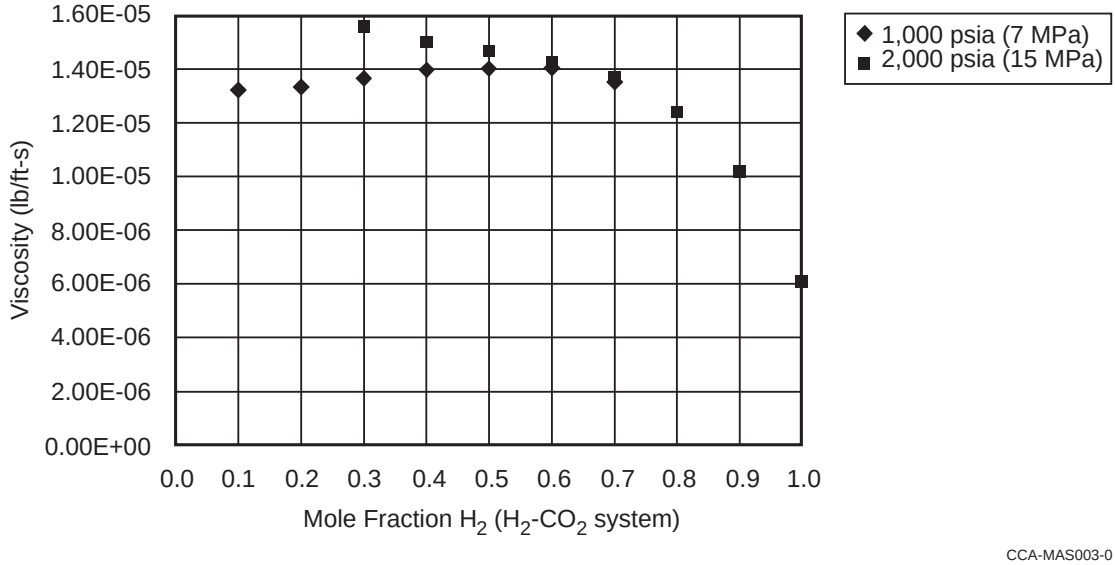

Figure MASS-1. Gas Viscosity as a Function of Mole Fraction H_2 at 7 Megapascals and 15 Megapascals Pressure

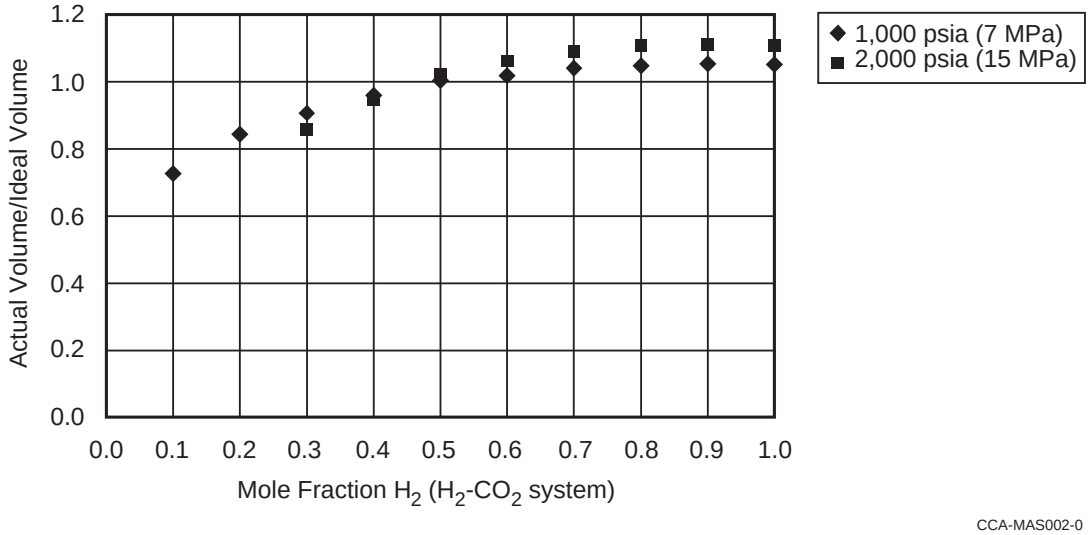

Figure MASS-2. Gas Compressibility as a Function of Mole Fraction H_2

MASS-3.3 Salado Brine as Surrogate for Liquid Phase Physical Properties in BRAGFLO

BRAGFLO models physical properties for all liquids as Salado brine properties. However, liquid in the modeled region may consist of (1) brine originally in the Salado, (2) liquid introduced in the excavation during construction, maintenance, and ventilation during the operational phase, (3) a very small amount of liquid introduced as a component of the waste, (4) liquid from overlying units, and (5) liquid from the Castile brine reservoir. However, for

BRAGFLO modeling it is assumed that the properties of all of these liquids are similar enough to Salado brine properties that the effect of variation in properties that may occur from liquids mixing is negligible. The variations in chemical properties of brine are accounted for as discussed in Section 6.4.3.4, and 6.4.3.5; and Appendix PA, Attachment SOTERM.

MASS-3.4 Table of General Modeling Assumptions

This section presents Table MASS-1, which lists modeling assumptions used in the PA. Table MASS-1 is a guide to general modeling assumptions used and provides some guidance for integrating the assumptions made with (a) the chapters or appendices in which they are discussed and (b) the code(s) that implement these assumptions.

The FEPs discussed in Appendix PA, Attachment SCR that are relevant to the assumptions are also indicated. The final column in the table indicates whether the DOE considers the assumption described to be reasonable or conservative. As discussed in Section 6.5, the DOE has not attempted to bias the overall results of the performance assessment toward a conservative outcome. However, where data or models are infeasible to obtain, or where effects on performance are not expected to be significant enough to justify development of a more complicated model, the DOE has chosen to use conservative assumptions. The designator R (reasonable) in the final column indicates that the DOE considers the assumption to be reasonable based on WIPP-specific data or information, data and information considered analogous to the WIPP disposal system, expert judgment, or other reasoning. The designator C (conservative) indicates the DOE considers the assumption made may overestimate a process or effect that may contribute to releases to the accessible environment. The regulatory designator (Reg) indicates that the assumption is based on regulations in 40 CFR Part 191, criteria in 40 CFR Part 194, or other regulatory guidance.

MASS-4.0 MODEL GEOMETRIES

This section presents supplementary information on the disposal system geometry.

MASS-4.1 Disposal System Geometry as Modeled in BRAGFLO

Overall, the conceptual model of the geometry of the disposal system is that the spatial effects of process interactions can be represented in two dimensions. The geometry used to represent the processes of long-term fluid flow in the Salado, flow between a borehole and overlying units, and flow within the repository (where processes coupled to fluid flow occur, such as creep closure and gas generation), is a vertical cross-section through the repository on a north-south axis. The dimension of this geometry in the direction perpendicular to the plane of the cross-section varies so that spatial effects of certain processes can be better represented, as discussed below.

Table MASS-1. General Modeling Assumptions

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
MASS-3.0 Some General Assumptions in Performance Assessment Models					
MASS-3.1 Darcy's Law Applied for Fluid Flow calculated by BRAGFLO, MODFLOW-2000, and SECOTP2D					
	1	BRAGFLO MODFLOW-2000	Flow is governed by mass conservation and Darcy's Law in porous media. Flow is laminar and fluids are Newtonian.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24) Brine inflow (W40)	R
	2	BRAGFLO	Two-phase flow in the porous media is by simultaneous immiscible displacement.	Fluid flow caused by gas production (W42)	R
	3	BRAGFLO	The Brooks-Corey or Van Genuchten/Parker equations represent interaction between brine and gas.	Fluid flow caused by gas production (W42)	R
	4	BRAGFLO	The Klinkenberg effect is included for flow of gases at low pressures.	Fluid flow caused by gas production (W42)	R
	5	BRAGFLO	Threshold displacement pressure for flow of gas into brine is constant.	Fluid flow caused by gas production (W42)	R
	6	BRAGFLO MODFLOW-2000 SECOTP2D	Fluid composition and compressibility are constant.	Saturated groundwater flow (N23) Fluid flow caused by gas production (W42)	R
MASS-3.2 Hydrogen Gas as Surrogate for Waste-Generated Gas Physical Properties in BRAGFLO					
	7	BRAGFLO DRSPALL	The gas phase is assigned the density and viscosity properties of hydrogen.	Fluid flow caused by gas production (W42)	R
MASS-3.3 Salado Brine as Surrogate for Liquid Phase Physical Properties in BRAGFLO					
	8	BRAGFLO	All liquid physical properties are assigned the properties of Salado brine.	Saturated groundwater flow (N23)	R
6.4.2 Model Geometries MASS-4.0 Model Geometries					
6.4.2.1 Disposal System Geometry MASS.4.1 Disposal System Geometry as Modeled in BRAGFLO					
		BRAGFLO	The disposal system is represented by a two-dimensional, north-south, vertical cross section.	Stratigraphy (N1) Physiography (N39)	R
		BRAGFLO	Flow in the disposal system is radially convergent or divergent centered on the repository, shaft, and borehole for disturbed performance.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24)	R
		BRAGFLO	Variable dip in the Salado is approximated by a 1 degree dip to the south.	Stratigraphy (N1)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
		BRAGFLO	Stratigraphical layers are parallel.	Stratigraphy (N1)	R
		BRAGFLO	The stratigraphy consists of units above the Dewey Lake, the Dewey Lake, the Forty niner, the Magenta, the Tamarisk, the Culebra, the Los Medaños, and the Salado (comprising impure halite, MB 138, anhydrites a and b [lumped together], and MB139). The dimensions of these units are constant. A Castile brine reservoir is included in all scenarios.	Stratigraphy (N1)	R
6.4.2.2 Culebra Geometry MASS-4.3 Historical Context of Culebra Geometries as Modeled in MODFLOW-2000 and SECOTP2D					
		MODFLOW-2000 SECOTP2D	The Culebra is represented by a two-dimensional, horizontal geometry for groundwater flow and radionuclide transport simulation.	Stratigraphy (N1)	R
		MODFLOW 2000 PEST	Transmissivity varies spatially. There is no vertical flow to or from the Culebra.	Groundwater recharge (N54) Groundwater discharge (N53)	R
		SECOTP2D	The regional flow field provides boundary conditions for local transport calculations.	Advection (W90)	R
6.4.3 The Repository MASS.5 BRAGFLO Geometry of the Repository					
		BRAGFLO	The repository comprises five regions separated by panel closures: the waste panel, a north RoR, a south RoR and the access drifts (separated by panel closures), the operations region, and the experimental region. Also, a single shaft region is modeled, and a borehole region is included for a borehole that intersects the separate waste panel. The dimensions of these regions are constant (see Figure 6-14).	Disposal geometry (W1)	R-C
		BRAGFLO	Long-term flow up plugged and abandoned boreholes is modeled as if all intrusions occur into a downdip (southern) panel.	Disposal geometry (W1)	C
		BRAGFLO	For each repository region the model geometry preserves design volume.	Disposal geometry (W1)	R
		BRAGFLO	Pillars individual drifts and rooms are not modeled for long-term performance, and containers provide	Disposal geometry (W1)	C

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			no barrier to fluid flow.		
		BRAGFLO	Long-term flow is radial to and from the borehole that intersects the waste disposal panel during disturbed performance.	Waste-induced borehole flow (H32)	R
		BRAGFLO	DRZ provides a pathway to Marker Beds		R
		BRAGFLO	Grid and material properties are consistent with the Option D design		R
6.4.3.1 Creep Closure MASS-6.0 Creep Closure Appendix PORSURF					
		SANTOS	Creep closure is modeled using a two-dimensional model of a single room. Room interactions are insignificant.	Salt creep (W20) Changes in the stress field Excavation-induced changes in stress (W19)	R
		SANTOS	Creep closure causes a decrease in room volume, which decreases waste porosity. The amount of creep closure is a function of time, gas pressure, and waste matrix strength.	Salt creep (W20) Changes in the stress field (W21) Consolidation of waste (W32) Pressurization (W26)	R
		BRAGFLO	Porosity of operations and experimental areas is fixed at a value representative of consolidated material.	Salt creep (W20)	R
6.4.3.2 Repository Fluid Flow MASS-7.0 Repository Fluid Flow					
		BRAGFLO	General assumptions 1 to 8.		See above
		BRAGFLO	The waste disposal region is assigned a constant permeability representative of average consolidated waste without backfill.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24)	R
MASS-7.1 Flow Interactions with the Creep Closure Model					
		BRAGFLO	The experimental and operations regions are assigned a constant permeability representative of unconsolidated material and a constant porosity representative of consolidated material.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24) Salt creep (N20)	R
MASS-7.2 Flow Interactions with the Gas Generation Model					
		BRAGFLO	For gas generation calculations, the effects of wicking are accounted for by assuming that brine in the	Wicking (W41)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			repository contacts waste to an extent greater than that calculated by the Darcy flow model used.		
6.4.3.3 Gas Generation MASS-8.0 Gas Generation Appendix TRU WASTE					
		BRAGFLO	Gas generation occurs by anoxic corrosion of steel containers, and Fe and Fe-base alloys in the waste, giving H_2, and microbial consumption of cellulosics and, perhaps, plastics and rubbers, giving mainly CO_2 and CH_4. Radiolysis, oxic reactions, and other gas generation mechanisms are insignificant. Gas generation is calculated using the average - stoichiometry model, and is dependent on brine availability.	Container material inventory (W5) Waste inventory (W2) Degradation Consumption of (W44) Gases from metal corrosion (W49)	R
		BRAGFLO	The anoxic corrosion rate is dependent on liquid saturation. Anoxic corrosion of steel continues until all the steel is consumed. Steel corrosion will not be passivated by microbially-generated gases CO_2 or H_2S. Brine is consumed by the corrosion reaction.	Brine inflow (W40) Gases from metal corrosion (W49) Consumption of organic material (W44)	R
		BRAGFLO	Laboratory-scale experimental measurements of gas generation rates at expected room temperatures are used to account for the effects of biofilms and chemical reactions.	Effects of biofilms on microbial gas generation (W48) Effects of temperature on microbial gas generation (W45) Chemical effects of corrosion (W51)	R
		BRAGFLO	The rate of microbial gas production is dependent on the amount of liquid present. It is assumed that microbial activity neither produces nor consumes water. Significant microbial activity occurs in half the simulations. In half of the simulations with microbial activity, microbes consume all of the cellulosics but none of the plastics and rubbers. In the other half of the simulations with microbial activity, microbes consume all of the cellulosics and all of the plastics and rubbers. Microbial production will	Brine inflow (W40) Consumption of CPR (W44) Waste inventory (W2)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			continue until all biodegradable CPR materials are consumed if brine is present. The MgO backfill will react with all of the CO_2 and remove it from the gaseous phase.		
		BRAGFLO	Gas dissolution in brine is of negligible consequence.	Fluid flow caused by gas production (W42)	R
		BRAGFLO	The gaseous phase is assigned the properties of hydrogen (general assumption 8).	Fluid flow caused by gas production (W42)	See above
6.4.3.4 Chemical Conditions in the Repository SOTERM-2.0 Conceptual Framework of Chemical Conditions					
		NUTS PANEL	Chemical conditions in the repository will be constant. Chemical equilibrium is assumed for all reactions that occur between brine in the repository, waste, and abundant minerals, with the exceptions of gas generation and redox reactions.	Speciation (W56) Redox kinetics (W66)	R
		NUTS PANEL	Brine and waste in the repository will contain a uniform mixture of dissolved and solid-state species. All actinides have instant access to all repository brine.	Heterogeneity of waste forms (W3) Speciation (W56)	C
		NUTS PANEL	No microenvironments that influence the overall chemical environment will persist.	Speciation (W56)	R
		NUTS PANEL	For the undisturbed performance and E2 scenarios, brine in the waste panels has the composition of Salado brine. For E1 and E1E2 scenarios, all brine in the waste panel intersected by the borehole has the composition of Castile brine.	Speciation (W56)	R
		NUTS PANEL	Chemical conditions in the waste panels will be reducing. However, a condition of redox disequilibrium will exist between the possible oxidation states of the actinide elements.	Redox kinetics (W56) Speciation (W56) Effects of metal corrosion (W64)	R
		NUTS PANEL	The pH and f_{CO2} in the waste panels will be controlled by the equilibrium between brucite and hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) (A result of this assumption is low f_{CO2} and mildly basic conditions).	Speciation (W56) Backfill chemical composition (W10)	R
6.4.3.5 Dissolved Actinide Source Term					

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
SOTERM-3.3 The FMT Computer Code					
		NUTS PANEL	Radionuclide dissolution to solubility limits is instantaneous.	Dissolution of waste (W58)	C
		NUTS PANEL	Six actinides (Th, U, Np, Pu, Am, and Cm) are considered in PANEL for calculations of radionuclide transport of brine (up a borehole). Four actinides (Th, U, Pu, and Am) are considered in NUTS for calculations of radionuclide transport in brine (porous materials) (Leigh 2003). Choice of radionuclides is discussed in Appendix TRU WASTE, Table TRU WASTE-9.	Waste inventory (W2)	R
		NUTS PANEL	The reducing conditions in the repository will eliminate significant concentrations of Np(VI), Pu(V), Pu(VI), and Am(V)species. Am and Cm will exist predominantly in the +III oxidation state, Th in the +IV oxidation state. It is assumed that the solubilities and K_ds of U, Np, and Pu will be dominated by one of the remaining oxidation states: U(IV) or U(VI), Np(IV or Np(V), and Pu(III) or Pu(IV).	Speciation (W56) Redox kinetics (W66)	R
		NUTS PANEL	For a given oxidation state, the different actinides exhibit similar chemical behavior and thus have similar solubilities.	Speciation (W56)	R
		NUTS PANEL	For undisturbed performance and for all aspects of disturbed performance except for cuttings and cavings releases, radionuclide-bearing compounds are distributed evenly throughout the disposal panel.	Waste inventory (W2) Heterogeneity of waste forms (W3)	R
		NUTS PANEL	Mobilization of actinides in the gas phase is negligible.	Dissolution of waste (W58)	R
		NUTS PANEL	Actinide concentrations in the repository will be inventory limited when the mass of an actinide becomes depleted such that the predicted solubilities cannot be achieved.	Dissolution of waste (W58)	R
6.4.3.6 Source Term for Colloidal Actinides					
		NUTS PANEL	Four types of colloids constitute the source term for colloidal actinides; microbes, humic substances, intrinsic	Colloid formation and stability (W79) Humic and fulvic acids	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			colloids, and mineral fragments.	(W70)	
		NUTS PANEL	The only intrinsic colloids that will form are those of the plutonium Pu(IV) polymer.	Colloid formation and stability (W79)	R
		NUTS PANEL	Concentrations of intrinsic colloids and mineral-fragment colloids are modeled as constants that were based on experimental observations. Humic and microbial colloidal actinide concentrations are modeled as proportional to dissolved actinide concentrations.	Colloid formation and stability (W79)	R
		NUTS PANEL	The maximum concentration of each actinide associated with each colloid type is constant.	Actinide sorption (W61)	R
6.4.4 Shafts and Shaft Seals MASS-12.0 Shafts and Shaft Seals					
		BRAGFLO	General Assumptions 1 to 8.		See above
		BRAGFLO	The four shafts connecting the repository to the surface are represented by a single shaft with a cross-section and volume equal to the total volume of the four real shafts and separated from the waste by less than the distance of the nearest real shaft.	Disposal geometry (W1)	R
		BRAGFLO	The seal system is represented by an upper and lower shaft region representing a composite of the actual materials in those regions.	Seal geometry (W6) Seal physical properties (W7)	R
		BRAGFLO	The shaft is surrounded by a DRZ which heals with time. The DRZ is represented through the composite permeabilities of the shaft system itself, rather than as a discrete zone. The effective permeability of shaft materials are adjusted at 200 years after closure to reflect consolidation and possible degradation. Permeabilities are constant for the shaft seal materials through the Rustler formation.	Salt creep (W20) Consolidation of seals (W36) DRZ (W18) Microbial growth on concrete (W76) Chemical degradation of seals (W74) Mechanical degradation of seals (W37)	R
		BRAGFLO	Concrete shaft components of the lower shaft are modeled as if they degrade after emplacement.	Mechanical degradation of seals	C
		NUTS	Radionuclides are not retarded by the	Actinide sorption (W61)	C

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			seals.	Speciation (W56)	
6.4.5 The Salado MASS-13.0 Salado					
		BRAGFLO	General Assumptions 1 to 8.		See above
6.4.5.1 Impure Halite MASS-13.1 High Threshold Pressure for Halite-Rich Salado Rock Units					
		BRAGFLO	Rock and hydrologic properties are constant.	Stratigraphy (N1)	R
6.4.5.2 Salado Interbeds MASS-13.3 The Fracture Model					
		BRAGFLO	Interbeds have a fracture-initiation pressure above which local fracturing and changes in porosity and permeability occur in response to changes in pore pressure. A power function relates the permeability increase to the porosity increase. A pressure is specified above which porosity and permeability do not change.	Disruption caused by gas effects (W25)	R
		BRAGFLO	Interbeds have identical physical properties; they differ only in position, thickness, and some fracture parameters.	Saturated groundwater flow (N23)	R
6.4.5.3 Disturbed Rock Zone MASS-13.4 Flow in the Disturbed Rock Zone					
		BRAGFLO	The permeability of the DRZ is sampled with the low value similar to intact halite and a high value representing a fractured material. The DRZ porosity is equal to the porosity of impure halite to plus 0.29 percent.	Disturbed rock zone (W18) Roof falls (W22) Gas explosions (W27) Seismic activity (N12) Underground boreholes (W39)	C-R
6.4.5.4 Actinide Transport in the Salado MASS-13.5 Actinide Transport in the Salado					
		NUTS	Dissolved actinides and colloidal actinides are transported by advection in the Salado. Diffusion and dispersion are assumed negligible.	Advection (W90) Diffusion (W91) Matrix diffusion (W92)	R
		NUTS	Sorption of actinides in the anhydrite interbeds, colloid retardation, colloid transport at higher than average velocities, co-precipitation of minerals containing actinides, channeled flow, and viscous fingering are not	Actinide sorption (W61) Colloid transport (W78) Colloid filtration (W80) Colloid sorption (W81) Fluid flow caused by gas production (W42)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			modeled.	Fracture flow (N25)	
		NUTS	Radionuclides having the same elemental form are grouped as discussed in Appendix TRU WASTE.	Radioactive decay and ingrowth (W12)	R
		NUTS	Sorption of actinides in the borehole is not modeled.	Actinide sorption (W61)	C
6.4.6 Units Above the Salado MASS-14.0 Geologic Units above the Salado					
		SECOTP2D	Above the Salado, lateral actinide transport to the accessible environment can occur only through the Culebra.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24) Solute transport (W77)	R
6.4.6.1 Los Medaños					
		MODFLOW-2000 BRAGFLO	The Los Medaños member of the Rustler Formation, Tamarisk, and Forty-niner are assumed to be impermeable.	Saturated groundwater flow (N23)	C
6.4.6.2 The Culebra MASS-15.0 Culebra Attachment TFIELD					
		MODFLOW-2000 SECOTP2D	General Assumptions 1, 6, and 8 (see first page of this table).		See above
		MODFLOW-2000 SECOTP2D	For fluid flow the Culebra is modeled as a uniform (single-porosity) porous medium. For radionuclide transport a double-porosity model is used (advection in high permeability features and diffusion and sorption in low-permeability features).	Saturated groundwater flow (N23) Fracture flow (N25) Advection (W90) Diffusion (W91)	R
		MODFLOW-2000	The Culebra flow field is determined from the observed hydraulic conditions and estimates of the effects of climate change and potash mining outside the controlled area, and does not change with time unless mining is predicted to occur in the disposal system in the future.	Saturated groundwater flow (N23) Climate change (N61) Precipitation (for example, rainfall) (N59) Temperature (N60) Changes in groundwater flow caused by mining (H37)	R
		BRAGFLO	The Culebra is assigned a single permeability to calculate brine flow into the unit from an intrusion borehole.	Natural borehole fluid flow (H31) Waste-induced borehole flow (H32)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
		MODFLOW-2000	Gas flow in the Culebra is not modeled. Gas from the repository does not affect fluid flow in the Culebra.	Saturated groundwater flow (N23) Fluid flow caused by gas production (W42)	R
		BRAGFLO MODFLOW-2000 SECOTP2D	Different thickness of the Culebra are assumed for BRAGFLO, MODFLOW-2000, and SECOTP2D calculations, although the transmissivities are consistent.	Effects of preferential pathways (N27)	R
		PEST	Uncertainty in the spatial variability of the Culebra transmissivity is accounted for by statistically generating many T-fields.	Saturated groundwater flow (N23) Fracture flow (N25) Shallow dissolution (N16)	R
		MODFLOW-2000 BRAGFLO	Potentiometric heads are set on the edges of the regional grid to represent flow in a portion of a much larger hydrologic system.	Groundwater recharge (N54) Groundwater discharge (N53) Changes in groundwater recharge and discharge (N56) Infiltration (N55)	R
6.4.6.2.1 Transport of Dissolved Actinides in the Culebra MASS-15.2 Dissolved Actinide Transport and Retardation in the Culebra					
		SECOTP2D	Dissolved actinides are transported by advection in high-permeability features and diffusion in low permeability features.	Solute transport (W77) Advection (W90) Diffusion (W91) Matrix diffusion (W92)	R
		SECOTP2D	Sorption occurs on dolomite in the matrix. Sorption on clays present in the Culebra is not modeled.	Actinide sorption (W61) Changes in sorptive surfaces (W63)	C
		SECOTP2D	Sorption is represented using a linear isotherm model.	Actinide sorption (W61) Kinetics of sorption (W62)	R
		SECOTP2D	The possible effects on sorption of the injection of brines from the Castile and Salado into the Culebra are accounted for in the distribution of actinide K_ds.	Actinide sorption (W61) Groundwater geochemistry (N36, N37) Natural borehole fluid flow (H31)	R
		SECOTP2D	Hydraulically-significant fractures are assumed to be present everywhere in the Culebra.	Advection (W90)	C
6.4.6.2.2 Transport of Colloidal Actinides in the Culebra MASS-15.3 Colloidal Actinide Transport and Retardation in the Culebra					

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
		SECOTP2D	Humic actinides are chemically retarded identically to dissolved actinides and are treated as dissolved actinides.	Advection (W90) Diffusion (W91) Colloid transport (W78) Microbial transport (W87)	R
		SECOTP2D	The concentration of intrinsic colloids is sufficiently low to justify elimination from PA transport calculations.		R
		SECOTP2D	Microbial colloids and mineral fragments are too large to undergo matrix diffusion. Filtration of these colloids occurs in high permeability features (which is modeled using a decay approach). Attenuation is so effective that associated actinides are assumed to be retained within the disposal system and are not transported in SECOTP2D.	Microbial transport (W87) Colloid sorption (W81)	R
6.4.6.2.3 Subsidence Due to Potash Mining MASS-15.4 Subsidence Caused by Potash Mining in the Culebra					
		MODFLOW-2000	The effect of potash mining is to increase the hydraulic conductivity in the Culebra by a factor from 1 to 1,000.	Potash mining (H13) Changes in groundwater flow caused by mining (H37)	Reg.
6.4.6.3 The Tamarisk					
		MODFLOW-2000 BRAGFLO	The Tamarisk is assumed to be impermeable.	Saturated groundwater flow (N23)	R
6.4.6.4 The Magenta					
		BRAGFLO	General Assumptions 1 to 8 (see first page of this table).		See above
		BRAGFLO	The Magenta permeability is set to the lowest value measured near to the center of the WIPP site. This increases the flow into the Culebra.	Saturated groundwater flow (N23)	R
		NUTS	No radionuclides entering the Magenta will reach the accessible environment. However, the volumes of brine and actinides entering and stored in the Magenta are modeled.	Solute transport (W77)	R
6.4.6.5 The Forty-niner					
		BRAGFLO	The Forty-niner is assumed to be impermeable.	Saturated groundwater flow (N23)	R
6.4.6.6 Dewey Lake					

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
		BRAGFLO	General Assumptions 1 to 8 (see first page of this table).		See above
		NUTS	The sorptive capacity of the Dewey Lake is sufficiently large to prevent any release over 10,000 years.	Saturated groundwater flow (N23) Actinide sorption (W61)	R
6.4.6.7 Supra-Dewey Lake Units					
		BRAGFLO	General Assumptions 1 to 8 (see first page of this table).		See above
		BRAGFLO	The units above the Dewey Lake are a single hydrostratigraphic unit.	Stratigraphy (N1)	R
		BRAGFLO	The units are thin and predominantly unsaturated.	Unsaturated groundwater flow (N24) Saturated groundwater flow (N23)	R
6.4.7 The Intrusion Borehole MASS-16.0 Intrusion Borehole					
6.4.7.1 Releases During Drilling					
		CUTTINGS_S BRAGFLO DRSPALL	Any actinides that enter the borehole are assumed to reach the surface.	—	C
MASS-16.1 Cuttings, Cavings, and Spall Releases during Drilling					
		BRAGFLO PANEL CUTTINGS_S DRSPALL	Future drilling practices will be the same as they are at present.	Oil and gas exploration (H1) Potash exploration (H2) Oil and gas exploitation (H4) Other resources (H8) Enhanced oil and gas recovery (H9)	Reg.
		CUTTINGS_S DRSPALL	Releases of particulate waste material are modeled (cuttings, cavings, and spallings). Releases are corrected for radioactive decay until the time of intrusion.	Drilling fluid flow (H21) Suspension of particles (W82) Cuttings (W84) Cavings (W85) Spallings (W86)	R
		CUTTINGS_S	Degraded waste properties are based on properties of marine clays, considered a worst case	Cavings (W85)	C
		DRSPALL	A hemispherical geometry with one-dimensional spherical symmetry defines the flow field and cavity in the waste	Spallings (W86)	**C**
		DRSPALL	Tensile strength, based on completely degraded waste surrogates, is felt to	Spallings (W86)	**C**

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			represent extreme, low-end tensile strengths because it does not account for several strengthening mechanisms		
		DRSPALL	Shape factor is 0.1, corresponding to particles that are easier to fluidize and entrain in the flow	Spallings (W86)	**C**
6.4.7.1.1 Direct Brine Release During Drilling MASS-16.2 Direct Brine Releases during Drilling					
		BRAGFLO PANEL	Brine containing actinides may flow to the surface during drilling. Direct brine release will have negligible effect on the long-term pressure and saturation in the waste panel.	Blowouts (W23)	R
		BRAGFLO	A two-dimensional grid (one degree dip) on the scale of the waste disposal region is used for direct brine release calculations.	Blowouts (H23)	R
		BRAGFLO CCDFGF	Calculation of direct brine release from several different locations provides reference results for the variation in release associated with location.	Blowouts (H23)	R
6.4.7.2 Long-Term Releases Following Drilling MASS-16.3 Long-Term Properties of the Abandoned Intrusion Borehole					
		BRAGFLO CCDFGF	Plugging and abandonment of future boreholes are assumed to be consistent with practices in the Delaware Basin.	Natural borehole fluid flow (H31) Waste-induced borehole flow (H32)	Reg.
6.4.7.2.1 Continuous Concrete Plug through the Salado and Castile					
		BRAGFLO CCDFGF	A continuous concrete plug is assumed to exist throughout the Salado and Castile. Long-term releases through a continuous plug are analogous to releases through a sealed shaft.	Natural borehole fluid flow (H31) Waste-induced borehole flow (H32)	Reg-R
6.4.7.2.2 The Two-Plug Configuration					
		BRAGFLO	A lower plug is located between the Castile brine reservoir and underlying formations. A second plug is located immediately above the Salado. The brine reservoir and waste panel are in direct communication though an open cased hole.	Natural borehole fluid flow (H31) Waste-induced borehole flow (H32)	Reg.-R
		BRAGFLO	The casing and upper concrete plug	Natural borehole fluid	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			are assumed to fail after 200 years, and the borehole is assumed to be filled with silty-sand like material. At 1,200 years after abandonment the permeability of the borehole below the waste panel is decreased by one order of magnitude as a result of salt creep.	flow (H31) Waste-induced borehole flow (H32)	
6.4.7.2.3 The Three-Plug Configuration					
		BRAGFLO	In addition to the two plug configuration, a third plug is placed within the Castile above the brine reservoir. The third plug is assumed not to fail over the regulatory time period.	Natural borehole fluid flow (H31) Waste-induced borehole flow (H32)	Reg.-R
6.4.8 Castile Brine Reservoir MASS-18.0 Castile Brine Reservoir					
		BRAGFLO	The Castile region is assigned a low permeability, which inhibits fluid flow. Brine occurrences in the Castile are bounded systems. Brine reservoirs under the waste panels are assumed to have limited extent and interconnectivity, with effective radii on the order of several hundred meters.	Brine reservoirs (N2)	R
6.4.9 Climate Change MASS-17.0 Climate Change					
		SECOTP2D	Climate-related factors are treated through recharge. A parameter called the Climate Index is used to scale the Culebra flux field.	Climate change (N61) Temperature (N60) Precipitation (for example, rainfall) (N59)	R
6.4.10 Initial and Boundary Conditions for Disposal System Modeling					
6.4.10.1 Disposal System Flow and Transport Modeling (BRAGFLO and NUTS)					
		BRAGFLO	There are no gradients for flow in the far-field of the Salado, and pressures are above hydrostatic, but below lithostatic. Excavation and waste emplacement result in partial drainage of the DRZ.	Saturated groundwater flow (N23) Brine inflow (W40)	R
		BRAGFLO	An initial water-table surface is set in the Dewey Lake at an elevation of 3,215 ft (980 m) above mean sea level. The initial pressures in the Salado are extrapolated from a sampled pressure in MB139 at the	Saturated groundwater flow (N23)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			shaft and are in hydrostatic equilibrium. The excavated region is assigned an initial pressure of one atmosphere. The liquid saturation of the waste-disposal region is consistent with the liquid saturation of emplaced waste. Other excavated regions are assigned zero liquid saturation, except the shaft which is fully saturated.		
		NUTS	Molecular transport boundary conditions are no diffusion or dispersion in the normal direction across far-field boundaries. Initial actinide concentrations are zero everywhere except in the waste.	Radionuclide decay and ingrowth (W12) Solute transport (W77)	R
6.4.10.2 Culebra Flow and Transport Modeling (MODFLOW-2000, SECOTP2D)					
		MODFLOW-2000	Constant head and no flow boundary conditions are set on the far-field boundaries of the flow model.	Saturated groundwater flow (N23)	R
		MODFLOW-2000	Initial actinide concentrations in the Culebra are zero.	Solute transport (W77)	R
6.4.10.3 Initial and Boundary Conditions for Other Computational Models					
		NUTS PANEL BRAGFLO (direct brine release) CUTTINGS_S	Initial and boundary conditions interpolated from previously executed BRAGFLO calculation.		R
6.4.12 Sequences of Future Events					
		CCDFGF	Each 10,000 year future (random sequence of future events) is generated by randomly and repeatedly sampling: the time between drilling events; the location of drilling events; the activity level of the waste penetrated by each drilling intrusion; the plug configuration of the borehole, and the penetration of a Castile brine reservoir, and by randomly sampling the occurrence of mining in the disposal system.	Oil and gas exploration (H1) Potash exploration (H2) Oil and gas exploitation (H4) Other resources (H8) Enhanced oil and gas recovery (H9) Natural borehole fluid flow (N31) Waste-induced borehole flow (H32)	Reg.-R
6.4.12.1 Active and Passive Institutional Controls in Performance Assessment Chapter 7.0					
		CCDFGF	Active institutional controls are effective for 100 years and completely eliminate possibility of		Reg.-R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
			incompatible activities. No credit is taken for passive institutional controls.		
6.4.12.2 Number and Time of Drilling Intrusions					
		CCDFGF	Drilling may occur after 100 years according to a Poisson process.	Loss of records (H57) Oil and gas exploration (H1) Potash exploration (H2) Oil and gas exploitation (H4) Other resources (H8)	Reg.-R
6.4.12.3 Location of Intrusion Boreholes					
		CCDFGF	The waste disposal region is discretized with 144 regions with the probability of each region being intersected equal. A borehole can penetrate only one region.	Disposal geometry (W1)	R
6.4.12.4 Activity of the Intersected Waste Appendix TRU WASTE					
		CCDFGF	693 waste streams identified for contact-handled (CH)-TRU and all 86 remote-handled (RH)-TRU waste streams were grouped (binned) together into one equivalent or average (WIPP-scale) RH-TRU waste stream.	Heterogeneity of waste form (W3)	R
6.4.12.5 Diameter of the Intrusion Borehole CCA Appendix DEL					
		CUTTINGS_S	The diameter of the intrusion borehole is constant at 12.25 in. (31.12 cm).		Reg.-R
6.4.12.6 Probability of Intersecting a Brine Reservoir					
		CCDFGF	One brine reservoir is assumed to exist below the waste panels. The probability that a deep borehole intersects a brine reservoir below the waste panels is sampled uniformly from 0.01 to 0.60.	Brine reservoirs (N2)	R
6.4.12.7 Plug Configuration in the Abandoned Intrusion Borehole					
		CCDFGF	The two-plug configuration has a probability of 0.698. The three-plug configuration has a probability of 0.289. The continuous concrete plug has a probability of 0.015.		Reg.-R
6.4.12.8 Probability of Mining Occurring in the Land Withdrawal Area					

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
		CCDFGF	Mining in the disposal system occurs a maximum of once in 10,000 years (a 10^{-4} probability per year).		Reg.-R
6.4.13 Construction of a Single CCDF					
		CCDFGF	Deterministic calculations are executed with BRAGFLO, NUTS, MODFLOW-2000, SECOTP2D, CUTTINGS_S, and PANEL to generate reference conditions. These reference conditions are used to estimate the consequences associated with random sequences of future events. These are in turn used to develop CCDFs.		R
		CCDFGF	10,000 random sequences of future events are generated for each CCDF plotted.		R
6.4.13.1 Constructing Consequences of the Undisturbed Performance Scenario					
		CCDFGF	A BRAGFLO and NUTS calculation with undisturbed conditions is sufficient for estimating the consequences of the undisturbed performance scenario.		R
6.4.13.2 Scaling Methodology for Disturbed Performance Scenarios					
		CCDFGF	Consequences for random sequences of future events are constructed by scaling the consequences associated with deterministic calculations (reference conditions) to other times, generally by interpolation but sometimes by assuming either similarity or no consequence.		R
6.4.13.3 Estimating Long-Term Releases from the E1 Scenario					
		CCDFGF NUTS	Reference conditions are calculated or estimated for intrusions at 100, 350, 1,000, 3,000, 5,000, 7,000, and 9,000 years.	Waste-induced borehole flow (H32)	R
6.4.13.4 Estimating Long-Term Releases from the E2 Scenario					
		CCDFGF NUTS SECOTP2D	The methodology is similar to the methodology for the E1 scenario. For multiple E1 intrusions into the same panel, the additional source term to the Culebra for the second and subsequent intrusions is assumed to be negligible.	Waste-induced borehole flow (H32) Waste inventory (W2)	R

Table MASS-1. General Modeling Assumptions — Continued

CRA Section and Appendix		Code	Modeling Assumption	Related FEP in Attachment SCR	Assumption Considered*
6.4.13.5 Estimating Long-Term Releases from the E1E2 Scenario					
		CCDFGF PANEL	The concentration of actinides in liquid moving up the borehole assumes homogeneous mixing within the panel.	Waste-induced borehole flow (H32)	C
		PANEL	Any actinides that enter the borehole reach the Culebra.	Waste-induced borehole flow (H32)	C
		CCDFGF PANEL	Reference conditions are calculated or estimated for intrusion at 100, 300, 1,000, 2,000, 4,000, 6,000 and 9,000 years.	Oil and Gas Exploration (H1)	
6.4.13.6 Multiple Scenario Occurrences					
		CCDFGF PANEL	The panels are assumed not to be interconnected for long term brine flow.	Saturated groundwater flow (N23) Unsaturated groundwater flow (N24)	R
6.4.13.7 Estimating Releases During Drilling for All Scenarios					
		CCDFGF PANEL NUTS	Repository conditions will be dominated by Castile brine if any borehole connects to a brine reservoir.	Brine reservoirs (N2) Natural borehole fluid flow (H31)	R
		CUTTINGS_S PANEL CCDFGF	Depletion of actinides in parts of the repository that have been penetrated by boreholes is not accounted for in calculating the releases from subsequent intrusions at such locations.	Waste-induced borehole flow (N32) Waste inventory (W2)	C
6.4.13.8 Estimating Releases in the Culebra and the Impact of the Mining Scenario					
		CCDFGF MODFLOW-2000 SECOTP2D	Releases from intrusions at random times in the future are scaled from releases calculated at 100 years with a unit source of radionuclides in the Culebra.		R
		CCDFGF	Actinides in transit in the Culebra when mining occurs are transported in the flow field used for the undisturbed case. Actinides introduced subsequent to mining are transported in the flow field used for the disturbed case (that is, mined case).		R

* R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

Three other two-dimensional model geometries are used in performance assessment. For fluid flow and transport modeling in the Culebra, the geometry is a horizontal two-dimensional plane (see Sections 6.4.2 and 6.4.6.2). For modeling brine flow from the intruded panel to the borehole during drilling, the geometry is a two-dimensional, horizontal representation of a waste panel (see Section 6.4.7). For modeling brine flow that might occur between an E-type borehole and other boreholes penetrating the repository, the geometry used is a two-dimensional, horizontal representation of the entire repository (see Section 6.4.2). These geometries are mentioned here but not discussed in detail because they are components of other conceptual models requiring geometric assumptions.

The two-dimensional geometry developed for the Salado is based on the assumption that brine and gas flow will converge upon and diverge from the repository horizon. The impact of this conceptual model and its implementation in a two-dimensional grid has been compared to a model that does not make the assumption of convergent and divergent flow (see Attachment 4-1 for additional information). The conceptual model for the Salado includes the slight and variable dip of beds in the vicinity of the repository, which might affect fluid flow.

Above and below the repository, it is assumed that any flow between the borehole or shaft (see Section 6.4.3) and surrounding materials will converge or diverge. With respect to flow in units overlying the Salado, the only purpose of this conceptual model is to determine the quantity (flux) of fluid leaving or entering the borehole or shaft. Fluid movement through the units above the Salado is treated in a different conceptual model (see Section 6.4.6). Below the repository, the possible presence of a brine reservoir is considered to be important, so a hydrostratigraphic layer representing the Castile and a possible brine reservoir in it is included (see CCA Appendix MASS, Section MASS.4.2 for the disposal system geometry historical context prior to the CCA).

MASS-4.2 Change to Disposal System Geometry Since the CCA

Changes have been made to the disposal system geometry since the first WIPP certification. The disposal system geometry is specifically represented in BRAGFLO. This section describes the methodology used to create the two-dimensional BRAGFLO computational grid used for the 2004 PA calculations. The CRA-2004 grid is similar to that used for the CCA and PAVT, except for the differences that are described below.

The most important changes with respect to the CRA BRAGFLO grid are the implementation of the Option D panel closures and a simplified shaft seal model. Additional grid refinements have also been implemented to increase numerical accuracy and computational efficiency and to reduce numerical dispersion, but these refinements do not entail any changes to conceptual models. All conceptual model changes were approved by the Salado Flow Peer Review Panel in February 2003 (Caporuscio et al. 2003). For completeness, all changes from the CCA/PAVT grid are described here.

MASS-4.2.1 Baseline Grid Changes

The baseline grid used in the CCA and PAVT had (NX, NY) dimensions of (33, 31). The grid used for the CRA-2004 calculations has dimensions (68, 33). The specific changes that have been implemented in the CRA-2004 grid are listed below and then discussed in more detail in the

following sections. Logical grids for the CCA/PAVT and CRA are shown in Figures MASS-3 and MASS-4.

Changes implemented in the CRA-2004 Grid:

1. A simplified shaft seal model is implemented,
2. Option D type panel closures are implemented,
3. Segmentation of the waste regions is increased,
4. A grid flaring method is redefined and simplified,
5. X spacing of the grid beyond the repository to the north and south is refined, and
6. Layers above and below MB 139 have been made relatively thin (~1 m thick), and Y-spacing in Salado has been changed.

MASS-4.2.2 Simplified Shaft Seal Model

A shaft seal model is included in the CRA-2004 grid, but it is implemented in a simpler fashion than was used for the CCA and PAVT. A detailed description of the parameters used to define the simplified model is discussed in AP-094 (James and Stein 2002) and the resulting

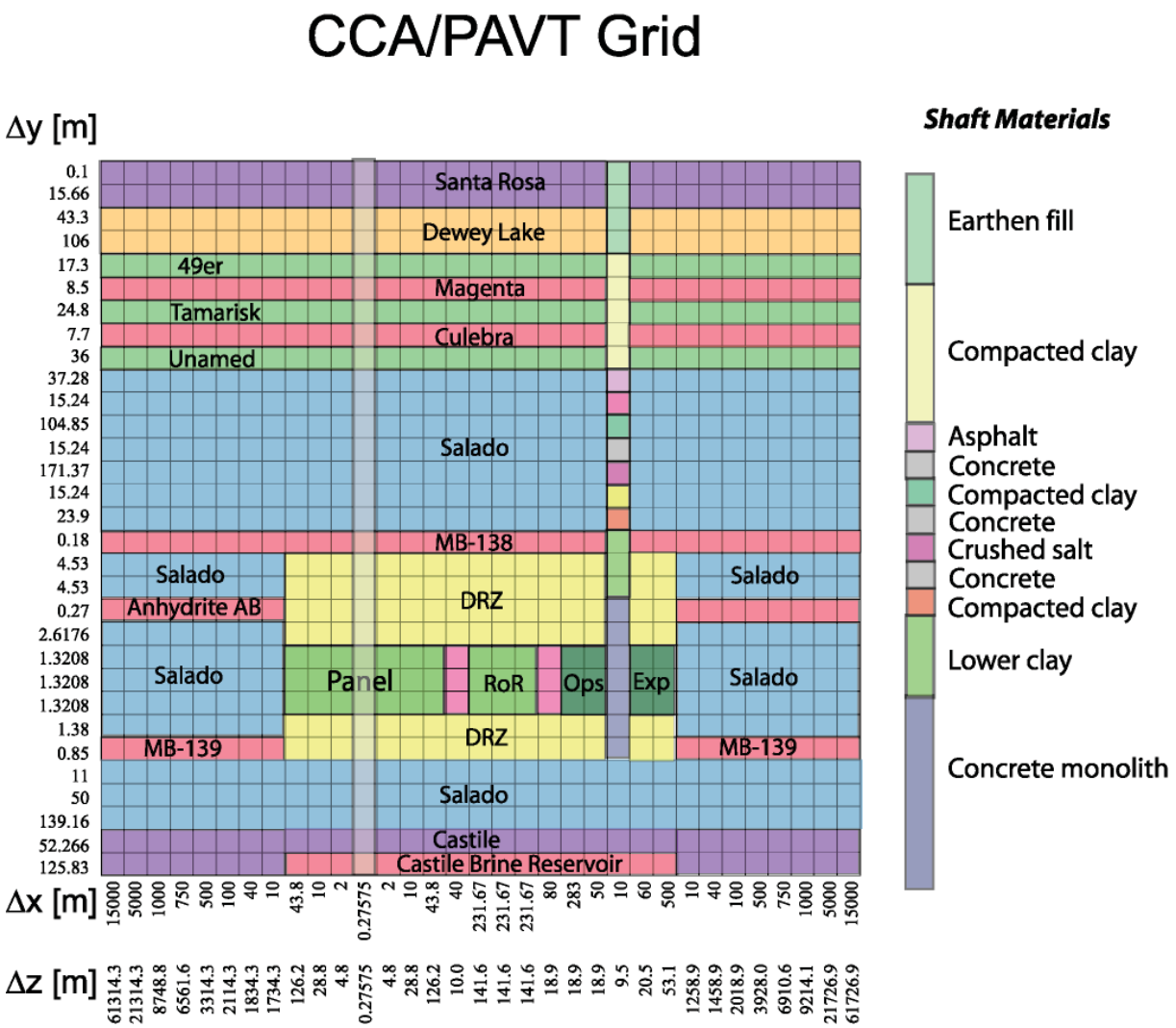

Figure MASS-3. Logical Grid Used for the 1996 WIPP PA BRAGFLO Calculations

analysis report (James and Stein 2003). The model that is used in the 2004 PA is described by Stein and Zelinski (2003a; 2003b), and was approved by the Salado Flow Peer Review panel (Caporuscio et al. 2003).

The new model does not alter the conceptual model of the shaft seal components as described in the CCA. Rather, it represents the behavior of seal components in the repository system model. Specifically, the original 11 separate material layers that defined the shaft model for the CCA were reduced to two layers each with properties equivalent to the composite effect of the original materials combined in series. Additionally, the six time intervals that were used to represent the evolution of the shaft seal materials over time were reduced to two intervals. The CRA and CCA shaft models are graphically compared in Figure MASS-5. The simplified shaft model was tested in the AP-106 calculations (Stein and Zelinski 2003a; 2003b), which supported the Salado Flow Peer Review. The results of this analysis demonstrated that brine flow through the simplified shaft model was comparable to brine flows seen through the

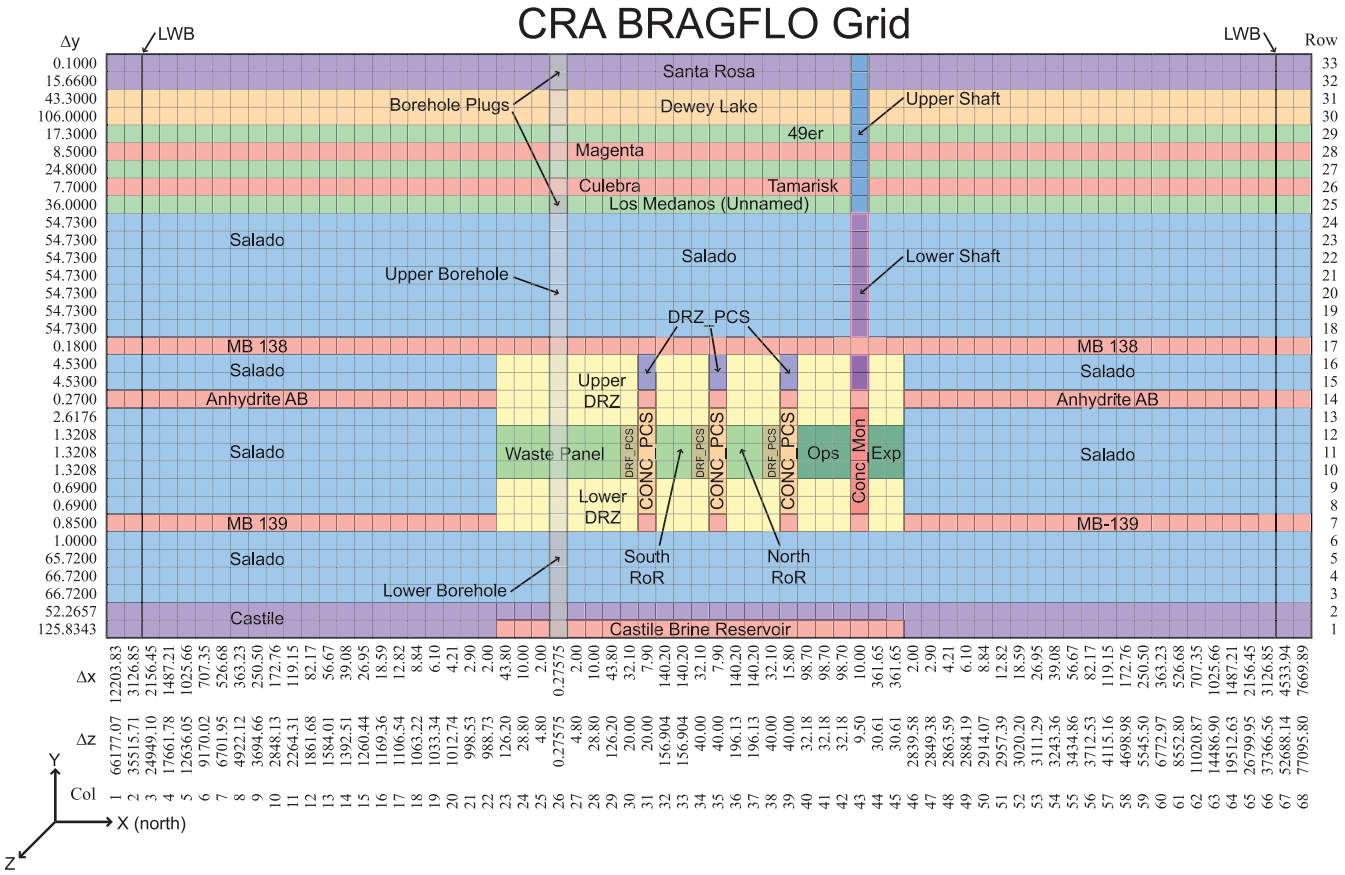

Figure MASS-4. Logical Grid Used for the 2004 PA BRAGFLO Calculations

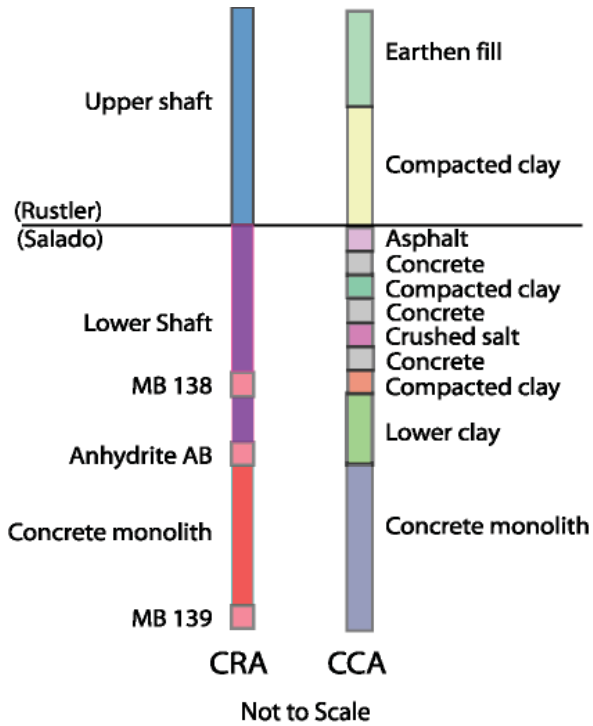

Figure MASS-5. Comparison of the Simplified Shaft (CRA-2004) and the Detailed Shaft (CCA) Models

detailed shaft model in the 1997 PAVT calculations. The conclusion remains that the shaft seals are very effective barriers to flow throughout the 10,000-year regulatory period.

MASS-4.2.3 Implementation of Option D Type Panel Closure

In the CCA, the DOE presented four options for panel closure designs (A through D). Upon reviewing the CCA, the EPA mandated the implementation of the Option D design. For CRA-2004, the true cross-sectional area of the Option D panel closures is represented in the flow model. In addition, to appropriately represent the effect of Option D geometry on repository fluid flow, the segmentation of the waste regions was increased in the grid. This change is described fully in MASS-4.2.4.

For CRA-2004, three sets of panel closures are included in the model domain. The southernmost set of closures represents a pair of closures separating a single waste panel from the other waste areas. The middle set of closures represents four panel closures that will be emplaced between the southern and northern extended panels. The northernmost set of panel closures represents two sets of four panel closures that will be emplaced between the waste regions and the shaft seals.

Each set of panel closures is represented in the CRA-2004 grid with four materials. Refer to Figure MASS-6.

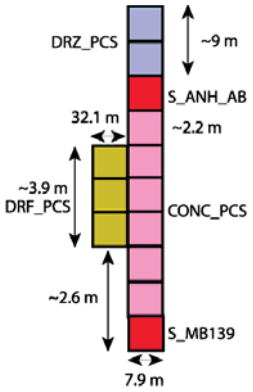

Figure MASS-6. Logical Grid Representation of the Option D Panel Closures for the CRA.

1. CONC_PCS: This material represents the concrete monolith, which has properties of SMC.

2. DRZ_PCS: This material represents the DRZ immediately above the concrete monolith that is expected to heal after the emplacement of the monolith.

3. DRF_PCS: This material represents the empty drift and explosion wall portion of the panel closure. This material has the same properties as WAS_AREA (including creep closure).

4. Marker bed materials: These materials are the same as those used to represent the anhydrite marker beds in other parts of the grid. Marker bed materials were used because they have permeability ranges very close to the material CONC_PCS and in the case when pressures near the panel closures exceed the fracture initiation pressure of the marker beds, fractures could extend around the concrete monolith out of the 2-D plane represented by the numerical grid. By using marker bed materials to represent the parts of the panel closures that intersect marker beds, both the permeability of the closure and the potential fracture behavior of marker bed material near the closures are represented.

Figure MASS-7 is a schematic diagram comparing the panel closure implementation in the CCA and CRA-2004 grids. Permeability ranges are indicated for all materials. Figure MASS-6 shows the 13 grid cells used to represent each set of Option D panel closures in the CRA-2004 BRAGFLO grid.

MASS-4.2.4 Increased Segmentation of Waste Regions in Grid

The CCA/PAVT grid divided the waste regions into two regions; a single panel in the southern end of the repository referred to as the Waste Panel, and a larger region containing the other nine panels referred to as the RoR. The Waste Panel is intersected by an intrusion borehole and is used to represent conditions in any panel that is intersected by a borehole. It is assumed that the Option D panel closures are effective at impeding flow between panels. Therefore, it was considered necessary to divide the RoR into northern and southern blocks

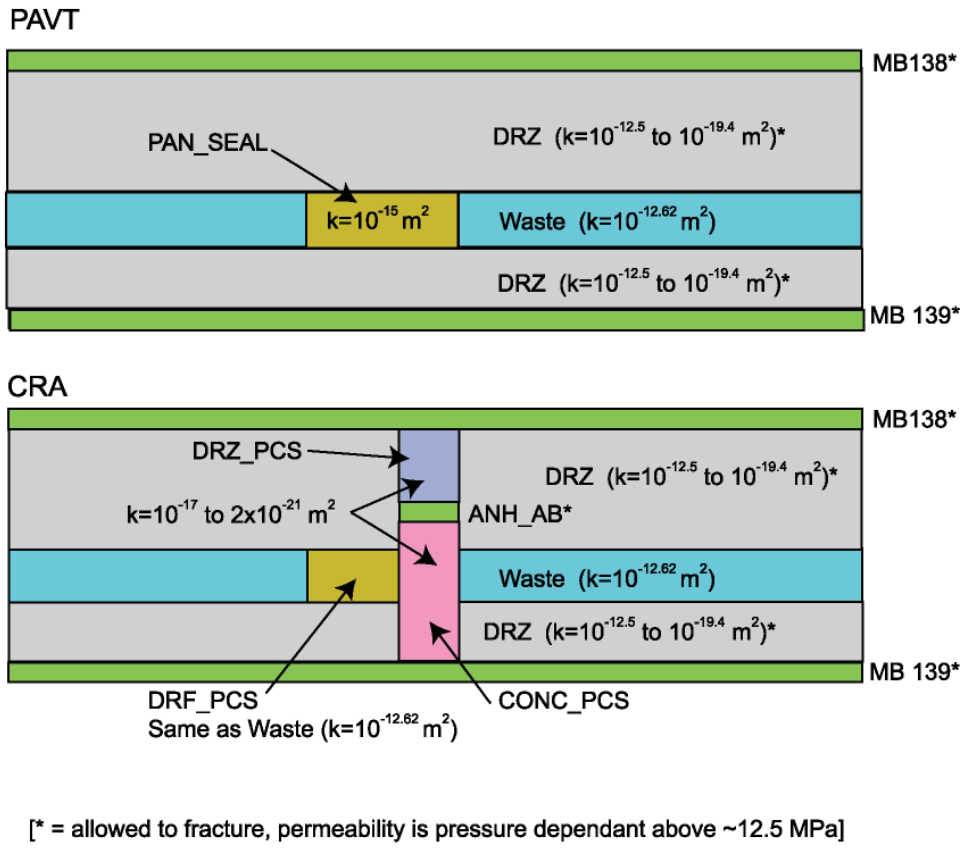

[* = allowed to fracture, permeability is pressure dependant above ~12.5 MPa]

Figure MASS-7. Schematic Comparison of the Representation of Panel Closures in the PAVT and CRA-2004.

separated by a set of panel closures. The south RoR block represents conditions in a panel directly adjacent to an intruded panel. The north RoR block represents conditions in a nonadjacent panel far from the intruded panel (has at least two panel closures between it and the intruded panel). This representation assumes that the effects of drilling intrusions will be damped in nonintruded panels and the degree of damping will depend on the proximity of the drilling intrusion and the number of panel closures separating the intruded panel from other regions of the repository. The delta Z dimensions of the RoR blocks were chosen so that the volume of the southern and northern RoR blocks were equivalent to four and five panels, respectively.

It should be noted that the total volume of the waste-filled areas represented in the CCA/PAVT grid (approximately 4.36×10^5 m^3) was found to be approximately 0.5 percent less than the designed volume (approximately 4.38×10^5 m^3) (Stein 2002). For CRA-2004, the larger correct volume has been used.

MASS-4.2.5 Redefined and Simplified Grid Flaring Method

Grid flaring is a method to represent 3-D volumes in a 2-D grid. Flaring is used when flows can be represented as divergent and convergent from the center of flaring. The CCA/PAVT grid used flaring at two different scales: locally around the borehole and shaft, and regionally to the north

and south of the excavated regions (around a point in the northern end of the RoR). For CRA-2004, the local flaring around the borehole is the same as in the CCA/PAVT grid. The local flaring around the shaft has been eliminated because it has been demonstrated not to be a release pathway. Likewise, the manner in which the regional flaring is calculated has been simplified.

The regional rectangular flaring occurs only for the grid blocks to the north and south of the excavated region. The CRA flaring is very similar to what was done for the CCA/PAVT grid; however the CRA flaring methodology is easier to implement. To define the flaring, it is assumed that looking from the top of the grid (x-z plane), the excavated regions of the grid can be approximated by a rectangle with length equal to the distance between the southern edge of the Waste Panel and the northern edge of the Experimental Area in the grid (x = 1830 m) and width, defined so that the area of the rectangle is equal to the total area of the excavated regions of the grid in the x-z plane (z = 80 m). In order to calculate the rectangular flaring for the grid cells outside the excavated regions, a centerline is defined to divides the flaring on the north and south. Because the waste panels are located in the southern part of the excavated area, the centerline is chosen to be the "center of waste" as the middle of the panel closure that separates the northern RoR from the southern RoR. The position of this center of the waste is described as the distances from the north and south edges of the gridded repository, DN and DS, respectively DN = 1378 m, DS = 452 m, DN + DS = 1830 m. Each flared grid block has length, Dx, and width, Dz. The block can be thought of as wrapped around the excavated area like half a rectangular onion, with the center at the center of waste (Figure MASS-8). Each Dz can be calculated from the preceding Dxs as follows.

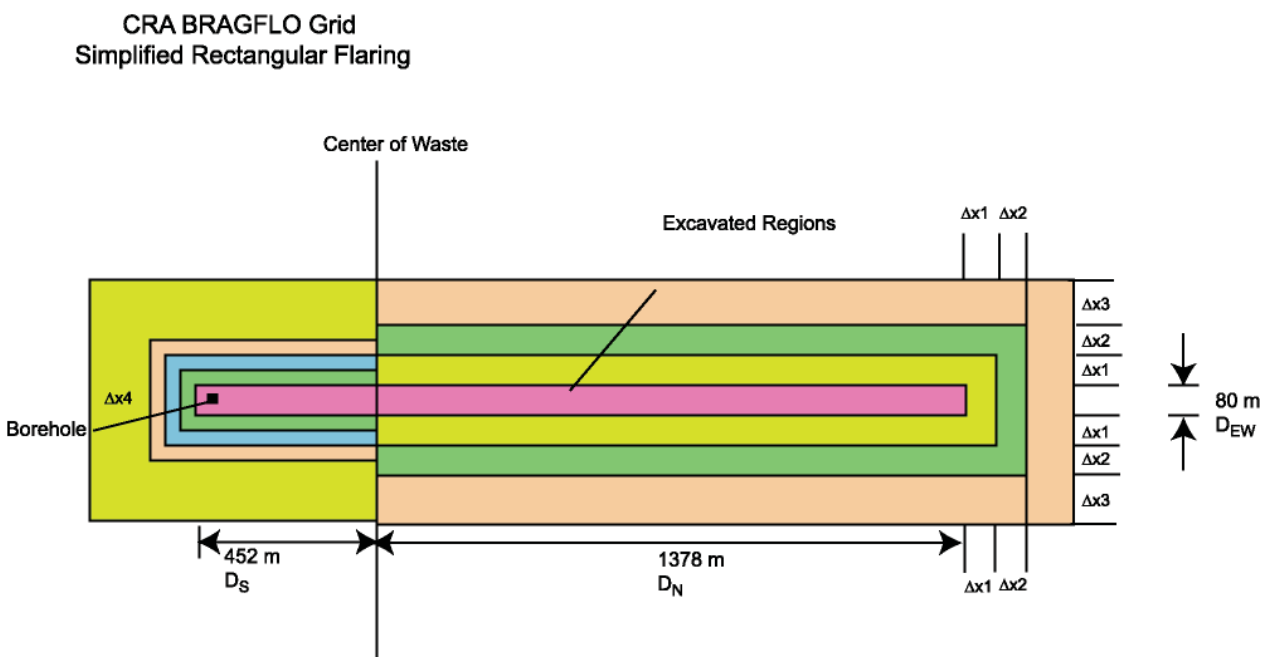

Figure MASS-8. CRA Flaring

For the northern end:

$$\Delta z_1 = 2D_N + D_{EW} + 2\Delta x_1$$

$$\Delta z_2 = 2D_N + D_{EW} + 4\Delta x_1 + 2\Delta x_2$$
$$\Delta z_3 = 2D_N + D_{EW} + 4\Delta x_1 + 4\Delta x_2 + 2\Delta x_3$$

Flaring for blocks wrapped around the southern end is the same with D_S substituted for D_N.

This method of rectangular flaring ensures that the grid accounts for all the volume surrounding the repository.

MASS-4.2.6 Refinement of the X-Spacing Outside the Repository

The grid blocks to the north and south of the excavated region will be refined in the x-direction from the baseline grid. The x-dimension of the grid cells immediately to the north and south of the repository start at 2 m and increases by a factor of 1.45. Exceptions to this are

$$\Delta z_n = 2D_N + D_{EW} + 4\sum_{i=1}^{n-1} \Delta x_i + 2\Delta x_n$$

made to ensure that the location of the Land Withdrawal Boundary (LWB) and the total extent of the grid matches that in the baseline grid. This refinement factor was chosen to reduce numerical dispersion caused by rapid increases in cell dimensions (Anderson and Woessner 1992; Wang and Anderson 1982).

MASS-4.2.7 Refinement of the Y-Spacing

In the y-direction, the grid spacing within layers representing the Salado has been changed from the CCA/PAVT. The CCA grid spacing in the Salado was dictated by the thickness of different shaft seal materials. Since the shaft is no longer represented in the model domain, the y spacing in the Salado is now uniform. In addition, two layers were added immediately above and below MB 139 to refine the grid spacing and reduce numerical dispersion. These changes result in a total of 33 y-divisions for the grid, and will increase the numerical accuracy of flow and transport calculations.

MASS-5.0 BRAGFLO GEOMETRY OF THE REPOSITORY

The repository geometry conceptual model is represented using the BRAGFLO code. As with the geometry of the disposal system discussed in Section 6.4.2.1 and earlier in this section, the principal process considered in setting up the repository geometry is fluid flow. Several features considered to be important in fluid flow are included in the conceptual model. The first is the overall dimension of the repository along the north-south trend of the cross section, as well as the major divisions within the repository (waste disposal region, operations region, and experimental region). The second is the volume of a single panel, because fluid flow to a borehole penetrating the repository can potentially access only the volume in a waste panel directly and other regions of the repository only by flow through or around a panel closure. The third is the physical dimensions of panel closures separating the single panel and the other major divisions of the repository.

Notably absent from the conceptual model for the long-term performance of the repository are pillars and individual drifts and rooms. These are excluded from the model for simplicity, and it is assumed that they have either negligible impact on fluid flow processes or, alternatively, that including them in the conceptual model would be beneficial to long-term performance because their presence could make flow paths more tortuous and decrease fluxes. This assumption includes lumping four and five of the 10 panels into the south RoR and north RoR regions respectively (see MASS-4.2.4).

The BRAGFLO model of the WIPP disposal system is a two-dimensional array of three-dimensional grid blocks. Each grid block has a finite length, width, height, volume, and surface area for its boundaries with neighboring grid blocks. The BRAGFLO two-dimensional grid is similar to any other two-dimensional grid used to treat flows, except that the grid-block dimension in the direction perpendicular (z-direction) to the plane of the grid varies from block to block as a function of the lateral direction (x-direction; see MASS-4.2.5). This allows the BRAGFLO grid to treat important geometric aspects of the WIPP disposal system, such as the very small intrusion borehole, the moderate-size shaft, and the larger controlled areas. The grid configurations used in the 1996 CCA PA and 1997 PAVT are shown in Figure MASS-3 while the 2004 PA grid is shown in Figure MASS-4.

MASS-5.1 Historical Context of the Repository Model

Several early models of repository fluid-flow behavior (models of radionuclide migration pathways, gas flow from the disposal area to the shaft, Salado brine flow through panel to borehole, effects of anhydrite layers on Salado brine flow through a panel, and flow from a brine reservoir through a disposal room) are summarized in a 1990 report (Rechard et al. 1990). In the preliminary performance assessment of 1992, all waste was lumped into a single region (WIPP Performance Assessment Department 1993). Because human intrusion boreholes were treated in detail for the 1996 performance assessment, it was necessary to model a single waste panel with a borehole surrounded by two-dimensional radial-flaring gridblocks. This approach is continued for the 2004 PA. The 1996 PA treated the remainder of the waste area as a single RoR. For the 2004 PA, the RoR is divided into two areas separated by a panel closure system. This change was made to more adequately simulate the effects of the Option D closure in impeding fluid flow between panels.

MASS-6.0 CREEP CLOSURE

The model used for creep closure of the repository is discussed in Appendix PA, Attachment PORSURF.4.11. Historical information is contained in CCA Appendix PORSURF.

MASS-7.0 REPOSITORY FLUID FLOW

This model represents the long-term flow behavior of liquid and gas in the repository and its interaction with other regions in which fluid flow may occur, such as the Salado, shafts, or intrusion borehole. This model is not used to represent the interaction of fluids in the repository with a borehole during drilling. Historical information on alternative conceptual models for brine inflow to the repository is contained in CCA Appendix MASS, Section MASS.7.

The third conceptual model for flow, the clay consolidation model, arises from observations made as part of the BSEP. On the basis of observations recorded during more than nine years of

The first principle in the conceptual model for fluid flow in the repository is that gas and brine can be both present and mobile (two-phase flow), governed by conservation of energy and mass and by Darcy's Law for their fluxes (see Appendix PA, Section PA-4.2). Consistent with typical concepts of two-phase flow, the phases can affect each other by impeding flow caused by partial saturation (relative permeability effects) and by affecting pressure caused by capillary forces (capillary pressure effects).

The flow of brine and gas in the repository is assumed to behave as two-phase, immiscible, Darcy flow (see Appendix PA, Section PA-4.2). BRAGFLO is used to simulate brine and gas flow in the repository and to incorporate the effects of disposal room closure and gas generation. Fluid flow in the repository is affected by the following factors:

- the geometrical association of pillars, rooms, and drifts; panel closure caused by creep; and possible borehole locations;
- the varied properties of the waste areas resulting from creep closure and heterogeneous contents;
- flow interactions with other parts of the disposal system; and
- reactions that generate gas.

The geometry of the panel around the intrusion borehole is consistent with the assumption that fluid flow there will occur directly toward or directly away from the borehole. The geometry represents a semi-circular volume north of the borehole and a semi-circular volume south of the borehole (representing the assumption of radial flow in a subregion of a two-dimensional representation of the repository.

Approximating convergent and divergent flow around the intrusion borehole creates a narrow neck in the otherwise fairly uniform width grid in the region representing the repository. In the undisturbed performance scenario and under certain conditions in other scenarios, flow in the repository may pass laterally through this neck. In reality, this neck does not exist. The presence in the model is expected to have a negligible or conservative impact on model predictions compared to predictions that would result from use of a more realistic model geometry. The time scale involved and the permeability contrast between the repository and surrounding rock are sufficient that lateral flow that may occur in the repository is restricted by the rate at which liquid gets into or out of the repository, rather than the rate at which it flows through the repository.

Gas generation is affected by the quantity of liquid in contact with metal. However, the distribution of fluid in the repository can be only approximated. For example, capillary action can create wicking that would increase the overall region in which gas generation occurs, but this cannot be modeled at the necessary resolution to fundamentally stimulate processes without undesirable effects on the duration of the model simulations. Therefore, as a bounding measure

for gas generation purposes, brine in the repository is distributed to an extent greater than actually estimated by the Darcy flow models used and values of parameters chosen.

Option D panel closures and the surrounding rocks are represented by a group of materials, which include:

1. SMC,
2. a material representing the empty drift and explosion wall,
3. a material representing healed DRZ, and
4. Marker beds.

SMC and healed DRZ materials are assigned permeability values that are sampled independently from a distribution ranging from 2×10^{-21} to 1×10^{-17} m^2. This value range is considered reasonable because the shape of the Option D closure assumes a compressive state and concrete permeability range similar to the tighter end of the 1997 PAVT permeability. This range captures the uncertainty in the long-term performance of the Option D panel closure design.

Modeling of flow within the repository is based on homogenizing the room contents into relatively large computational volumes. The approach ignores heterogeneities in disposal room contents that may influence gas and brine behavior in the room by causing fluid flow among channels or preferential paths in the waste, bypassing entire regions. Isolated regions could exist for several reasons:

- they may be isolated by low-permeability regions of waste that serve as barriers,
- connectivity with the interbeds may occur only at particular locations within the repository, or
- the repository dip may promote preferential gas flow in the upper regions of the waste.

For the CCA, the adequacy of the repository homogeneity assumption was examined in screening analyses DR-1 (Webb 1995) and DR-6 (Vaughn et al. 1995a). The analyses used an additional parameter in BRAGFLO to specify the minimum active (mobile) brine flow saturation (pseudo-residual brine saturation). Above this saturation, the normal descriptions of two-phase flow apply (that is, either the Brooks and Corey or van Genuchten and Parker relative permeability models). Below this minimum, brine is immobile, although it is available for reaction and may still be consumed during gas-generation reactions. The assumption of a minimum saturation limit was justified based on the presumed heterogeneity of the waste and the slight dip in the repository. The minimum active brine saturation was treated as an uncertain parameter and sampled uniformly between values 0.1 and 0.8 during the analysis. This saturation limit was applied uniformly throughout the disposal room to bound the impact of heterogeneities on flow (Webb 1995; Vaughn et al. 1995a). Results of this analysis showed that releases to the accessible environment in the baseline case (homogenization) are consistently higher.

The experimental and operations regions were represented in performance assessment (for the CCA) by a fixed porosity of 18.0 percent and a permeability of 10^{-11} m^2. The combination of low porosity and high permeability conservatively overestimated fluid flow through these regions and limit the capacity of these regions to store fluids, thus potentially overestimating releases to the environment. This conclusion was based on a screening analysis (Vaughn et al. 1995b) that examined the importance of permeability varying with porosity in closure regions (waste disposal region, experimental region, and operations region). To perform this analysis, a model for estimating the change in permeability with porosity in the closure regions was implemented in BRAGFLO. A series of BRAGFLO simulations was performed to determine whether permeability varying with porosity in the closure regions could enhance contaminant migration to the accessible environment. Two basic scenarios were considered in the screening analysis, undisturbed performance and disturbed performance. To assess the sensitivity of system performance on dynamic permeability in the closure regions, CCDFs of normalized contaminated brine releases were constructed and compared with the corresponding baseline conditional CCDFs. The baseline model treated permeabilities in the closure regions as fixed values. Results of this analysis showed that the inclusion of dynamic closure of the waste disposal region, experimental region, and operations region in BRAGFLO resulted in computed releases to the accessible environment that are essentially equivalent to the baseline case.

A separate analysis (Park and Hansen 2003) examined the possible effects of heterogeneity in waste container and waste material strength on room closure. The analysis of room closure found that the room porosity may vary widely depending on the type of waste container and on the emplacement of waste in the repository. However, analysis of a separate PA (Hansen et al. 2003a) found that PA results are relatively insensitive to the uncertainty in room closure and room porosity. The conclusions of the separate PA are summarized in Section MASS-21.0.

MASS-7.1 Flow Interactions with the Creep Closure Model

The dynamic effect of halite creep and room consolidation on room porosity is modeled only in the waste disposal region. Other parts of the repository, such as the experimental region and the operations region, are modeled assuming fixed (invariant with time) properties. In these regions, the permeability is held at a fixed high value representative of unconsolidated material, while the porosity is maintained at relatively low values associated with highly consolidated material. It is assumed that this combination of low porosity and high permeability conservatively overestimates flow through these regions and minimizes the capacity of this material to store fluids, thus maximizing the release to the environment. To examine the acceptability of this assumption, a screening analysis (Vaughn et al. 1995c) evaluated the effect of including closure of the experimental region and operations region. In this analysis, consolidation of the experimental region and operations region was implemented in BRAGFLO by relating pressure and time to porosity using a porosity-surface method. The porosity surface for the experimental region and operations region differs from the one used for consolidation of the disposal room and is based on an empty excavation (see Appendix PA, Attachment PORSURF). Results of the screening analysis showed that disregarding dynamic closure of the experimental region is acceptable because it is conservative: lower releases occur when closure of the experimental region and operations region is computed compared to simulations with time-invariant high permeability and low porosity.

MASS-7.2 Flow Interactions with the Gas Generation Model

Gas generation affects repository pressure, which in turn is an important parameter in other processes such as two-phase flow, creep closure, and fracturing of the interbeds and DRZ. Gas generation processes considered in performance assessment calculations include anoxic corrosion and microbial degradation. Radiolysis is excluded from performance assessment calculations on the basis of laboratory experiments and a screening analysis (Vaughn et al. 1995d) that concluded that radiolysis does not significantly affect repository performance.

In modeling gas generation, the effective liquid in a computational cell is the computed liquid in that cell plus an adjustment to account for the uncertainty associated with wicking by the waste (see Appendix PA, Section PA-4.2). Capillary action (wicking) is the ability of a material to carry a fluid by capillary forces above the level it would normally seek in response to gravity. Because the current gas-generation model computes substantially different gas-generation rates depending on whether the waste is wet or merely surrounded by water vapor, the physical extent of wetting could be important. A screening analysis (Vaughn et al. 1995e) examined wicking and concluded that it should be included in performance assessment calculations. The baseline gas-generation model in BRAGFLO accounts for corrosion of iron and microbial degradation of cellulosics. The net reaction rate of these processes depends directly on brine saturation: an increase in brine saturation will increase the net reaction rate by weighting the inundated portion more heavily and the slower humid portion less heavily. To simulate the effect of wicking on the net reaction rate, an effective brine saturation, which includes a wicking saturation contribution, is used to calculate reaction rates rather than the actual brine saturation. To account for uncertainty in the wicking saturation contribution, this contribution was sampled from a uniform distribution that ranged from 0.0 to 1.0 for each BRAGFLO simulation in the analysis.

MASS-8.0 GAS GENERATION

This model represents the possible generation of gas in the repository by corrosion of steel and microbial degradation of cellulosic, plastic, and rubber (CPR) materials. Additional discussion of this topic may be found in Appendix PA, Section PA-4.2.5 and Attachment SCR (FEPs W44 through W48, W53, and N71) and Section 6.4.3.3.

Gas will be produced in the repository by a variety of chemical reactions, principally those between brine, metals, microbes, CPR materials and by liberation of dissolved gases to the gaseous phase. The processes assumed for long-term performance are anoxic corrosion of steel waste containers and Fe-base metals in the waste and possible microbial consumption of CPR materials in the waste (a significant quantity of plastic is also present as drum liners). Anoxic-corrosion reactions between brine and steel are expected to occur and produce H_2; they are included in the conceptual model. Microbial consumption of cellulosics, plastics and rubbers, might occur. If it does, it may produce various gases, primarily CH_4 and CO_2. However, by reaction with the MgO backfill that will be emplaced to control the chemistry of the repository, CO_2 produced by microbial activity will be rapidly removed from the gaseous phase (see Appendix PA, Attachment SOTERM, Section SOTERM-2.2.2; and Section 6.4.3.4). Other gases such as N_2 and H_2S produced by microbial activity are insignificant in quantity (see CCA Appendix MASS, Attachment 8-1). Thus the conceptual model for gas generation assumes that

anoxic corrosion of steel will produce H_2; microbial consumption of CPR materials might occur and produce CH_4, CO_2, and other gases, but any CO_2 produced will be rapidly removed by reaction with MgO.

In the conceptual model, the rate of gas production in the repository by anoxic corrosion can be limited by several factors. Anoxic corrosion cannot occur unless brine (water) is present and in contact with steel. The corrosion rate is assumed to be dependent on brine saturation. Because anoxic corrosion consumes steel, the rate of gas production can be limited by the quantity of steel left in the repository. Because corrosion is a surface reaction, it proceeds at quantifiable rates per unit surface area of steel. In addition, anoxic corrosion consumes water. Because of these factors, the rate of gas generation in the repository can vary through time as conditions change. It is assumed that anoxic corrosion can occur in the repository as soon as the shafts are sealed.

Microbial consumption of CPR materials is limited by several factors, chiefly the long-term viability of microbes in the repository. Whether microbes consume plastics and rubbers is also important. The rate of microbial production is dependent on brine saturation. Because of uncertainty, however, it is assumed that there is no effect of microbial activity on brine (water) content in the repository.

A limited quantity of O_2 will be trapped in the panels after repository closure. However, this O_2 will be consumed quickly by both oxic corrosion and aerobic microbial activity, and reducing conditions will dominate in the repository over 10,000 years. The contribution of oxic corrosion and aerobic microbial activity to overall gas production is negligible. Thus, oxic reactions are not considered in the conceptual model for gas generation.

Addition of an MgO engineered barrier significantly reduces the impact of microbial production of CO_2 (see Appendix PA, Attachment SOTERM). As discussed in Section 6.4.3.4, the MgO backfill will react with carbon dioxide produced by microbial degradation and remove it from the gaseous phase.

Because the conceptual model comprises the general processes and interactions assumed to occur without direct reference to the mathematical equations used, no parameters are defined by this conceptual model. The mathematical model used to implement it, the average-stoichiometry model, is discussed in Section 6.4.3.3. The most important parameter in the average-stoichiometry model is the rate at which gas production occurs with brine and steel present, because this is the principal control on the total quantity of gas generated. The assumptions made about the principal reactions and their stoichiometries are also important, however, because they affect the quantity of gas created per unit quantity of steel and water reacted.

The feedback between the gas generation conceptual model and the repository fluid flow conceptual model is important to understand. Gas production cannot continue for long with the low initial quantity of liquid present in the waste, as specified by waste-acceptance criteria. For gas production to occur, brine must flow into the repository; for gas production to be sustained, brine consumed by gas production must be replenished. Gas production, however, tends to increase repository pressure and keep brine from flowing into it. Thus the rates at which various processes proceed are important in determining the conditions of the repository. There is

important feedback as well between the gas-generation model and other conceptual models through pressure effects, such as those calculating creep closure (Section 6.4.3.1), interbed fracturing (Section 6.4.5.2), two-phase flow (Section 6.4.3.2), and the radionuclide release associated with spalling and direct brine release during an inadvertent drilling intrusion (Section 6.4.7).

Single-process laboratory studies of anoxic corrosion of steels and Al-based materials by R. E. Westerman and his colleagues at Pacific Northwest National Laboratory (PNNL) from November 1989 through September 1995 have shown that the factor with the greatest effect on the rate of H_2 generation by anoxic corrosion is the quantity of brine in WIPP disposal rooms (see also CCA Appendix MASS, Attachment 8-2). This is because anoxic corrosion occurs rapidly under inundated conditions, but not at all under humid conditions. The pressure difference between WIPP disposal rooms and the far field and the porosity of the room contents also affect the extent of brine inflow and outflow and, hence, the anoxic-corrosion rate. Because the average-stoichiometry model is incorporated in BRAGFLO, gas production is coupled with brine and gas inflow and outflow. Moreover, because BRAGFLO uses a porosity surface to simulate room closure (Butcher and Mendenhall 1993), it also couples gas production to room closure. Telander and Westerman (1993, 1997) and subsequent studies of anoxic corrosion at PNNL have shown that pH, pressure, and the composition of the gaseous phase also affect the H_2 production rate.

The greatest uncertainty in modeling gas generation in WIPP disposal rooms is whether microbial gas generation will occur and, if so, to what extent it will occur and what its effects will be. The following sources of microbial uncertainty have been described:

- whether microorganisms capable of carrying out the potentially significant respiratory pathways identified by Brush (1990) (denitrification sulfate (SO_4^{2-}) reduction, and methanogenesis) will be present when the repository is filled and sealed,
- whether these microbes will survive for a significant fraction of the 10,000-year period of performance of the repository,
- whether sufficient H_2O will be present in the waste or brine,
- whether sufficient electron acceptors (oxidants) will be present and available,
- whether enough nutrients, especially N and P, will be present and available,
- whether microbes will consume significant quantities of plastics and rubbers during the 10,000-year period of performance of the repository, and
- the stoichiometry of the overall reaction for each significant respiratory pathway, especially the number of moles of electron acceptors, nutrients, gases, and H_2O consumed or produced per mole of substrate consumed.

With regard to the first five of these uncertainties, it has been concluded that, although significant microbial gas production is possible, it is by no means certain. To incorporate this uncertainty in PA, it is assumed that there is a probability of 0.50 for significant microbial

activity. In the event of significant microbial activity, microbes would consume 100 percent of the cellulosics in the repository. Furthermore, there is a probability of 0.50 that microbes would consume all of the plastics and rubbers after consuming all of the cellulosics. Thus, there is microbial consumption of all of the cellulosics, but no plastics or rubbers, in about 25 percent of the PA realizations (vectors); microbial consumption of all of the CPR materials in 25 percent of the vectors; and no microbial activity at all in the remaining 50 percent of the vectors (see CCA Appendix MASS, Attachment 8-3).

Single-process laboratory studies of microbial consumption of cellulosics by A.J. Francis and his colleagues at Brookhaven National Laboratory from May 1991 through September 2003 showed that if significant microbial activity occurs, the factor with the greatest effect on the microbial gas-generation rate is the quantity of brine in the repository (see Francis and Gillow 1994, 2000; Francis et al. 1997; Gillow and Francis 2001a, 2001b, 2002a, 2002b; CCA Appendix MASS, Attachment 8-2). This is because microbial gas production occurs rapidly under inundated conditions, but at much lower rates under humid conditions. These studies also found that inoculation with halophilic microbes from the WIPP site and nearby lakes, amendment with NO_3^- (an electron acceptor), amendment with nutrients, and addition of bentonite (a previously proposed backfill material) affect the rate or extent of microbial gas generation. Other factors that could affect the rate or extent of microbial gas generation, but which these studies did not quantify, are the pH; the dissolved or suspended concentrations of actinides or other heavy metals, which could inhibit or preclude microbial activity; and the concentrations of microbial byproducts, which could inhibit or preclude additional microbial activity. High pressure will not preclude or even inhibit microbial activity significantly, even when it increases to 150 atmospheres (lithostatic pressure at the depth of the repository).

Data summarized by Molecke (1979) imply that radiolysis of CPR materials will not be a significant, long-term gas-generation process in WIPP disposal rooms. (Radiolysis here refers to α radiolysis, the breaking of chemical bonds by α particles emitted during the radioactive decay of the actinide elements in TRU waste. Because molecular dissociation caused by other types of radiation will be insignificant in a TRU-waste repository such as the WIPP, this discussion considers only α radiolysis.) Based on calculations using the results of laboratory studies of brine radiolysis carried out for the WIPP by Reed et al. (1993) on estimates of the quantities of brine that could be present in the repository after filling and sealing, and on estimates of the solubilities of Pu, Am, Np, Th, and U summarized by Trauth et al. (1992), it was concluded that radiolysis of H_2O will not significantly affect the overall gas or H_2O content of the repository (see Appendix PA, Attachment SCR, FEP W52,).

Gas generation models are implemented in BRAGFLO with the assumption that the substrates (CPR materials and Fe-base metals) are homogeneously distributed throughout the waste. A separate PA (Hansen et al. 2003a) examined the possible effects of heterogeneity in substrate concentrations on PA results, and found that PA results are insensitive to the heterogeneity in substrate concentrations. The conclusions of the separate PA are summarized in Section MASS-21.0.

MASS-8.1 Historical Context of Gas Generation Modeling

See CCA Appendix MASS, Section MASS.8.1 for historical information that led to the CCA gas generation conceptual model.

MASS-9.0 CHEMICAL CONDITIONS

The models used for chemical conditions in the repository are discussed in Appendix BARRIERS and Appendix PA, Attachment SOTERM and Section 6.4.3.4.

MASS-10.0 DISSOLVED ACTINIDE SOURCE TERM

The models used for the dissolved actinide source term in the repository are discussed in Appendix PA, Attachments SOTERM and SCR and Section 6.4.3.5)

MASS-11.0 COLLOIDAL ACTINIDE SOURCE TERM

The models used for the colloidal actinide source term are discussed in Appendix PA, Attachment SOTERM (Section SOTERM.6) and Section 6.4.3.6.

MASS-12.0 SHAFTS AND SHAFT SEALS

The conceptual model for the shafts and shaft seals used in the performance assessment has been chosen to provide a reasonable and realistic basis for simulating long-term fluid flow through the shaft seal system and to allow evaluation of the effect that uncertainty about the long-term properties of the shaft seal system may have on cumulative radionuclide releases from the disposal system. The conceptual model and seal system design are also discussed in Section 6.4.4 and CCA Appendix SEAL (Section 2).

The conceptual model of the seals is based on results of detailed numerical models of the shaft seal system design. These models were developed to evaluate the performance of the shaft seal system under a range of conditions. Both fluid flow and structural response of the system have been evaluated. The principal uncertainties associated with the detailed models follow:

- reconsolidation of the crushed salt component,
- construction, permeability, and gas threshold pressure of the clay components, and
- damage, permeability, healing, and character of the Salado disturbed rock zones.

These uncertainties are also present in the performance assessment model and have been accounted for in the values specified for seal parameters. The consequences of uncertainty in seal component performance were a primary motivation in the development of the proposed seal system design. Although there is uncertainty in many of the materials and models, the shaft will be completely filled with high density, low permeability materials. The use of multiple materials

and components for each sealing function results in a robust system. Time dependency of the performance of seal components is incorporated directly into the model through temporal variation in seal properties.

The processes that can affect the performance of the shaft seals—structural, hydraulic, and coupled structural and hydrological—are discussed in some detail in CCA Appendix SEAL, Sections 7 and 8. Evaluation of these issues required the use of existing structural and both single-and two-phase flow codes. In addition, development of conceptual and numerical models for crushed salt reconsolidation, the disturbed rock zone, and the shaft seal system was required. These models have been reviewed by independent, qualified experts, are well documented, and have been developed within an accepted quality assurance program. Codes used in the analyses include SPECTROM-32 (structural) (Callahan 1994), SWIFT II (single-phase flow) (Reeves et al. 1986), and TOUGH2 (multi-phase flow) (Pruess 1991). These codes were selected for their capability to simulate the processes thought to affect seal performance. They are also well-documented, accepted, and widely used within the scientific community. The codes were modified to implement the conceptual models specific to the seals, and these modifications were made within a program that establishes criteria for assuring software quality.

The BRAGFLO model of the shaft seal system requires consistency with parameters associated with the surrounding system. The BRAGFLO shaft seal model implemented for the 2004 PA calculations grouped several shaft seal materials into two composite materials having properties derived from the combination of grouped materials in series. For example, the permeability of the material used to represent the lower portion of the shaft seal that lies in the Salado formation is derived from the permeability and thickness of the asphalt, concrete crushed salt, and clay layers of the seal in this horizon. This permeability changes after 200 years to incorporate the combined effects of the consolidation of these materials. The effects of the halite DRZ surrounding the shafts is included in the derivation of the composite properties used in the BRAGFLO model. A detailed description of the shaft model used in the 2004 PA BRAGFLO calculations can be found in James and Stein (2002 and 2003).

MASS-12.1 Historical Development of the Shaft Seals

The four shafts into the repository will be sealed after completion of disposal activities at the WIPP. The shaft seal system design has evolved over time (Stormont 1988; Nowak et al. 1990; DOE 1995). The Initial Reference Seal System Design proposed a two-component design to achieve a sealing strategy with two phases: concrete and clay seals formed a short-term seal, and a crushed salt seal formed long-term protection. The use of native rock (that is, crushed salt) as a permanent sealing material is considered the most effective means to eliminate the shafts as a preferred pathway for migration of hazardous constituents. Because some interim period must pass for the crushed salt to reconsolidate to sufficiently high densities, short-term seals were proposed as a means to prevent fluid migration during the interim. Estimates of this interim period ranged from 100 to 200 years.

Seal design changes and refinements have been incorporated into the conceptual model of the seals used by the DOE (Bertram-Howery et al. 1990; WIPP Performance Assessment Department 1991; Sandia WIPP Project 1992). Performance assessments conducted prior to 1992 addressed general sealing issues but did not include specific seal components.

Results of the scoping calculations using the DCCA model demonstrated that low-permeability materials were required for the shaft seals (DOE 1995, Appendix D). However, the simplicity of the conceptual model limited the applicability of results to the detailed seal system design.

The shaft seal design for the WIPP is presented in CCA Appendix SEAL (Sections 4 and 5).

MASS-13.0 SALADO

The purpose of this model is to reasonably represent the effects of fluid flow in the Salado on long-term performance of the disposal system. The conceptual model is also discussed in Section 6.4.5.

Fluid flow in the Salado is considered in the conceptual model of long-term disposal system performance for several reasons. First, some liquid could move from the Salado to the repository because of the considerable gradients that can form for liquid flow inward to the repository. This possibility is important because such fluid can interact with creep closure, gas generation, actinide solubilities, and other processes occurring in the repository. Second, gas generated in the repository is thought to be capable of fracturing the Salado interbeds under certain conditions, creating increased permeability channels that could be pathways for lateral transport. The pathway of lateral transport in intact Salado is also modeled, but it is considered unlikely to result in any significant radionuclide transport to the accessible environment boundary.

The fundamental principle in the conceptual model for fluid flow in the Salado is that it is a porous medium within which gas and brine can be both present and mobile (two-phase flow), governed by conservation of energy and mass, and by Darcy's Law for their fluxes (see Appendix PA, Sections PA-4.2). Consistent with typical concepts of two-phase flow, each phase can affect the other by impeding flow because of partial saturation (relative permeability effects) and by affecting pressure by capillary forces (capillary pressure effects). It is assumed that no waste-generated gas is present initially. Future states are modeled as producing gas by corrosion and microbial activities. Should high pressure develop over the regulatory period, it is allowed to access marker beds in the Salado.

Some variability in composition exists between different horizons of the Salado. The largest differences occur between the anhydrite-rich layers called interbeds and those dominated by halite. Within horizons dominated by halite, composition varies from nearly pure halite to halite plus several percent other minerals, in some instances including clay (see Chapter 2.0, Section 2.1.3.4). The Salado is modeled as impure halite except for those interbeds that intersect the DRZ near the repository. This conceptual model and an alternative model that explicitly represented all stratigraphically distinct layers of the Salado near the repository (Christian-Frear and Webb 1996) produced similar results.

From other modeling and theoretical considerations, flow between the Salado and the repository is expected to occur primarily through interbeds that intersect the DRZ. Because of the large surface areas between the interbeds and surrounding halite, the interbeds serve as conduits for the flow of brine in two directions: from halite to interbeds to the repository, or, for brine flowing out of the repository, from the repository into interbeds and then into halite. Because the repository is modeled as a relatively porous and permeable region, brine is considered most

likely (but not constrained) to leave the repository through MB139 below the repository because of the effect of gravity. If repository pressures become sufficiently high, gas is modeled to exit the repository via the marker beds in the proximity of the disposal room.

The effect of gravity may also be important in the Salado because of the slight and variable natural stratigraphic dip. For long-term performance modeling, the dip in the Salado within the domain is taken to be constant and 1 degree from the north to south.

Fluid flow in the Salado is conceptualized as occurring either convergently upon the repository, or divergently from it, as discussed in detail in Section 6.4.2.1. Because the repository is not conceptualized as homogeneous, implementing a geometry for the conceptual model of convergent or divergent flow in the Salado is somewhat complicated and is discussed in Section 6.4.2.1.

The conceptual model for Salado fluid flow has primary interactions with three other conceptual models. The interbed fracture conceptual model allows porosity and permeability of the interbeds to increase as a function of pressure. The repository fluid flow model is directly coupled to the Salado fluid flow model by the governing equations of flow in BRAGFLO (in the governing equations of the mathematical model, they cannot be distinguished), and it differs only in the region modeled and the parameters assigned to materials. The Salado model for actinide transport is directly coupled to the conceptual model for flow in the Salado through the process of advection.

MASS-13.1 High Threshold Pressure for Halite-Rich Salado Rock Units

A parameter used to describe the effects of two-phase flow is threshold pressure. The threshold pressure is important because it helps determine the ease with which gas can enter a liquid-saturated rock unit. For a brine-saturated rock, the threshold pressure is defined as “equal to the capillary pressure at which the relative permeability to the gas phase begins to rise from its zero value, corresponding to the incipient development of interconnected gas flow paths through the pore network” (Davies 1991, p. 9).

The threshold pressure, as well as other parameters used to describe two-phase characteristics, has not been measured for halite-rich rocks of the Salado. The Salado, however, is thought to be similar in pore structure to rocks for which threshold pressures have been measured (Davies 1991). Based on this observation, Davies (1991) postulated that the threshold pressure of the halite-rich rocks in the Salado could be estimated if an empirical correlation exists between rocks postulated to have similar pore structure.

Davies developed a correlation between threshold pressure and intrinsic permeability applicable to the Salado halites. (A similar correlation was developed for Salado anhydrites; subsequent testing confirmed that the correlation predicted threshold pressures accurately.) The correlation developed by Davies predicts threshold pressures in intact Salado halites on the order of 20 megapascals or greater (Davies 1991). This threshold pressure predicted by correlation is so high that for all practical and predictive purposes, no gas will flow into intact Salado halites (see Section 6.4.5.1).

Because threshold pressure helps control the flow of gas, and because the greatest volume of rock in the Salado is rich in halite, a high threshold pressure effectively limits the volume of gas that can be accommodated in the pore spaces of the host formation. Thus high threshold pressure is considered conservative as well as realistic, because if gas could flow into the pore spaces of Salado halite, repository pressures could be reduced dramatically.

MASS-13.2 Historical Context of the Salado Conceptual Model

See CRA Appendix MASS, Section MASS.13.2 for the historical information relating to the CCA Salado conceptual model. The Salado conceptual model is unchanged for CRA-2004.

MASS-13.3 The Fracture Model

The purpose of this model is to alter the porosity and permeability of the anhydrite interbeds and the DRZ if their pressure approaches lithostatic, simulating some of the hydraulic effects of fractures with the intent that unrealistically high pressures (in excess of lithostatic) do not occur in the repository or disposal system. The conceptual model is also discussed in Section 6.4.5.2.

In the 1992 preliminary performance assessment, repository pressures were shown to greatly exceed lithostatic pressure if a large quantity of gas was generated. Pressures within the waste repository and surrounding regions were predicted to be roughly 20 to 25 megapascals. It was expected that fracturing within the anhydrite marker beds would occur at pressures slightly below lithostatic pressure. An expert panel on fractures was convened to develop the conceptual bases for the fracturing within the anhydrite marker beds.

The porosity and permeability increases are conceptualized as occurring vertically throughout the affected interbed; in other words, throughout the porous medium as a whole rather than on discrete portions. This simplification facilitates numerical implementation and execution.

Two parametric behaviors must be quantified in the conceptual model. First, the change of porosity with pressure in the anhydrite marker beds must be specified. This is done with a relatively simple equation, described in Appendix PA, Section PA-4.2, that relates porosity change to pressure change using an assumption that the fracturing can be thought of as increasing the compressibility of interbeds. Parameters in the model are treated as fitting parameters and have little relation to physical behavior except that they affect the porosity change. The second parametric behavior is the change of permeability with pressure, which is incorporated by a functional dependence on the porosity change. It is assumed that a power function is appropriate for relating the magnitude of permeability increase to the magnitude of porosity increase. The parameter in this power function, an exponent, is also treated as a fitting parameter and can be set so that the behavior of permeability increase with porosity increase fits the desired behavior.

The fracture enhancement model assumes fracture propagation is uniform in the lateral direction to flow within the marker beds in the absence of dip. The 1-degree dip modeled in BRAGFLO may affect fracture propagation direction. That is, within the accuracy of the finite difference grid, a fracture will develop radially outward. This would not account for fracture fingering or a preferential fracturing direction; however, no existing evidence supports heterogeneous anhydrite

properties that would contribute to preferential fracture propagation. This evidence is discussed in CCA Appendix MASS, Attachment 13-2).

The maximum enhanced fracture porosity controls the storativity within the fracture. The extent of the migration of the gas front into the marker bed is sensitive to this storativity. The additional storativity caused by porosity enhancement will mitigate gas migration within the marker bed. The enhancement of permeability by marker-bed fracturing will make the gas more mobile and will contribute to longer gas-migration distances. Thus the effects of porosity enhancement at least partially counteract the effects of permeability enhancement in affecting the gas-migration distances.

Because intact anhydrite is partially fractured, the pressure at which porosity or permeability changes are initiated is close to the initial pressure within the anhydrite. The fracture treatment within the marker beds will not contribute to early brine drainage from the marker bed, because the pressures at these times are below the fracture initiation pressure.

The input data to the interbed fracture model (see Appendix PA, Attachment PAR) were chosen deterministically to produce the appropriate pressure and porosity response as predicted by a linear elastic fracture mechanics (LEFM) model, as discussed in Mendenhall and Gerstle (1993).

MASS-13.4 Flow in the Disturbed Rock Zone

The conceptual model for the DRZ around the waste disposal, operations, and experimental regions has been chosen to provide a reasonably conservative estimate of fluid flow between the repository and the intact halite and anhydrite marker beds. The conceptual model is also discussed in Section 6.4.5.3 of this application.

The conceptual model implemented in the performance assessment uses values for the permeability and porosity of the DRZ that do not vary with time. A screening analysis examined an alternative conceptual model for the DRZ in which permeability and porosity changed dynamically in response to changes in pressure (Vaughn et al. 1995). This analysis implemented a fracturing model in BRAGFLO for the DRZ. This fracturing model is identical to the existing anhydrite interbed alteration model. In this model, formation permeability and porosity depend on brine pressure as described by Freeze et al. (1995, 2-16 to 2-19) and Appendix PA, Section PA-4.2.1. This model permits the representation of two important formation alteration effects. First, pressure build-up caused by gas generation and creep closure within the waste will slightly increase porosity within the DRZ and offer additional fluid storage with lower pressures. Second, the accompanying increase in formation permeability will enhance fluid flow away from the DRZ. Because an increase in porosity tends to reduce outflow into the far field, parameter values for this analysis were selected so that the DRZ alteration model greatly increases permeability while only modestly increasing porosity.

Two basic scenarios were considered in the screening analysis by Vaughn et al. (1995), undisturbed performance and disturbed performance. Both scenarios included a 1-degree formation dip downward to the south. Intrusion event E1 is considered in the disturbed scenario and consists of a borehole that penetrates the repository and pressurized brine in the underlying Castile. Two variations of intrusion event E1 were examined, E1 updip and E1 downdip. In the

E1 updip event, the intruded panel region was located on the updip (north) end of the waste disposal region, whereas in the E1 downdip event, the intruded panel region is located on the downdip (south) end of the disposal region. These two different geometries permitted evaluation of the possibility of increased brine flow into the panel region caused by higher brine saturations downdip from the borehole and the potential for subsequent impacts on contaminant migration. To incorporate the effects of uncertainty in each case (E1 updip, E1 downdip, and undisturbed), a Latin hypercube sample size of 20 was used, for a total of 60 simulations. To assess the sensitivity of system performance on formation alteration of the DRZ, conditional CCDFs of normalized contaminated brine releases were constructed and compared with the corresponding baseline model conditional CCDFs that were computed with constant DRZ permeability and porosity values. Based on comparisons between conditional CCDFs, computed releases to the accessible environment were determined to be essentially equivalent between the two treatments.

Preliminary performance assessments considered alternative conceptual models that allowed for some lateral extent of the DRZ into the halite surrounding the waste disposal region and for the development of a transition zone between anhydrites a and b and MB 138 (SNL 1993, Figures 4.1-2 and 5.1.2; Davies et al. 1993; Gorham et al. 1992). The transition zone was envisioned as a region that had experienced some hydraulic depressurization and perhaps some elastic stress relief because of the excavation, but probably no irreversible rock damage and no large permeability changes. Modeling results indicated that including the lateral extent of the DRZ had no significant effect on fluid flow. Communication vertically to MB 138 was thought to be a potentially important process, however, and the model adopted for the performance assessment assumes that the DRZ extends upward to MB 138 and permeability is sampled over the same range used in the 1997 PAVT.

MASS-13.5 Actinide Transport in the Salado

The purpose of this model is to represent the transport of actinides in the Salado. The model for actinide transport in the Salado is implemented in the code NUTS. This model is also discussed in Section 6.4.5.4 and Appendix PA, Section PA-4.3.

Actinide transport in the Salado is conceptualized as occurring only by advection through the porous medium described in the Salado hydrology conceptual model. Advection is the movement of material with the bulk flow of fluid. Other processes that might disperse actinides, such as diffusion, hydrodynamic dispersion, and channeling in discrete fractures, are not included in the conceptual model.

Advection is a direct function of fluid flow, which is discussed in the conceptual model for Salado fluid flow.

This application of NUTS treats the transport of radionuclides within all the regions for which BRAGFLO computes brine and gas flow. The brine must pass through some part of the repository at some period in its history to become contaminated. While there, it is assumed to acquire radioactive constituents, which it then transports by advection to other regions outside the repository. NUTS uses BRAGFLO's velocity field, pressures, porosities, saturations, and other model parameters (including geometrical grid, residual saturation, material map, brine compressibility, and time step) averaged over a given number of time steps (20 for this

performance assessment calculation), which it takes as input for its transport calculations. Consequently, the results of NUTS are subject to all the uncertainties associated with BRAGFLO's conceptual model and parameterization, which will not be repeated here. Details of the source term are discussed in Appendix PA, Attachment SOTERM.

This application of NUTS disregards sorptive and other retarding effects throughout the entire flow region, even though retardation must occur at some level within the repository, the marker beds, and the anhydrite interbeds, and especially in zones with clay layers or clay as accessory minerals.

This application of NUTS neglects molecular dispersion, which leads to uncertainty. For materials of interest in the WIPP repository system, molecular diffusion coefficients are at a maximum on the order of 4×10^{-10} m^2 per second. Thus, the simplest scaling argument using a time scale of 10,000 years leads to a molecular diffusion (that is, mixing) length scale of approximately 33 ft (10 m), which is negligible compared to the lateral advection length scale of roughly 7,874 ft (2,400 m) (the lateral distance from the repository to the accessible environment).

This application of NUTS also neglects mechanical dispersion, which leads to additional uncertainty (see Section 6.4.5.4.2). Dispersion is quantified by dispersivities, which are empirical (tensor) factors that are proportional to flow velocity (to within geometrical factors related to flow direction). They account for both the downstream and cross-stream spreading of local extreme values in concentration of dissolved constituents. Physically, the spreading is caused by the fact that both the particle paths and velocity histories of once-neighboring particles can be vastly different because of material heterogeneities characterized by permeability variations. These variations arise from the irregular cross-sectional areas and tortuous nonhomogeneous, nonisotropic connectivity between pores. Because of its velocity dependence, the transverse component of mechanical dispersivity tends to transport dissolved constituents from regions of relatively rapid flow (where mechanical dispersion has a larger effect) to regions of slower flow (where mechanical dispersion has a smaller effect). In the downstream direction, dispersivity merely spreads constituents in the flow direction. Conceptually, ignoring lateral spreading assures that dissolved constituents will remain in the rapid part of the flow field, which assures their transport toward the boundary. Similarly, ignoring longitudinal dispersivity ignores the elongation of a feature in the flow direction, which ignores foreshortening (or lengthening) of arrival times. However, because the EPA release limits are time-integrated measures, the exact times of arrival are unimportant for constituents that arrive at the accessible environment within the assessment period (10,000 years).

Advection is therefore the only transport mechanism considered important, which underscores NUTS' reliance on BRAGFLO. Because the Darcy flows are given to NUTS as input, the maximum solubility limits for combined dissolved and colloidal components are the most important NUTS parameters. These components are described in Appendix PA, Attachment SOTERM.

MASS-14.0 GEOLOGIC UNITS ABOVE THE SALADO

The model for geologic units above the Salado was developed to provide a reasonable and realistic basis for simulations of fluid flow within the disposal system and detailed simulations of groundwater flow and radionuclide transport in the Culebra. The conceptual model for these units is also discussed in Section 6.4.6 of this application.

The conceptual model used in PA for the geologic units above the Salado is based on the overall concept of a groundwater basin, as introduced in Chapter 2.0 (Section 2.2.1.1) of this recertification application, and developed further in CCA Appendix MASS, Section MASS.14.2. The computer code SECOFL3D was used to evaluate the effect on regional-scale fluid flow by recharge and rock properties in the groundwater basin above the Salado (CCA Appendix MASS, Attachment 17-2). However, simpler models for this region are implemented in codes used in performance assessment. For example, in the BRAGFLO model, layer thicknesses, important material properties including porosity and permeability, and hydrologic properties such as pressure and initial fluid saturation are specified, but the model geometry and boundary conditions are not suited to groundwater basin modeling (nor is the BRAGFLO model used to make inferences about groundwater flow in the units above the Salado). In PA the Culebra is the only subsurface pathway modeled for radionuclide transport above the Salado, although the groundwater basin conceptual model includes other flow interactions. The Culebra model implemented in PA includes spatial variability in hydraulic conductivity and uncertainty and variability in physical and chemical transport processes. Thus, the geometries and properties of units in the different models applied to the units above the Salado by the DOE are chosen to be consistent with the purpose of the model.

The MODFLOW-2000 and SECOTP2D codes are used directly in PA to model fluid flow and transport in the Culebra. The assumptions made in these codes are discussed in Section 6.4.6.2 and Section MASS-15.0.

With respect to the units above the Salado, the BRAGFLO model is used only for determination of fluid fluxes between the shaft or intrusion borehole and hydrostratigraphic units. For this purpose, it does not need to resolve regional or local flow characteristics.

The basic stratigraphy and hydrology of the units above the Salado are described in Sections 2.1.3.5 through 2.1.3.10, and Section 2.2.1.4, respectively. Additional supporting information is contained in CCA Appendices GCR, HYDRO, and SUM. Details of the conceptual model for each unit are described in Sections 6.4.6.1 through 6.4.6.7.

MASS-14.1 Historical Context of the Units above the Salado Model

See CCA Appendix MASS, Section MASS.14.1 for historical information relating to the conceptual models for units above the Salado for the CCA. The conceptual models for the units above the Salado are unchanged for CRA-2004. However, CRA-2004 uses MODFLOW-2000 in place of SECOFL2D to model fluid flow in the Culebra.

MASS-14.2 Groundwater-Basin Conceptual Model

For a discussion on the groundwater-basin conceptual model, see CCA Appendix MASS, Section MASS.14.2.

MASS-15.0 CULEBRA

The conceptual model for groundwater flow in the Culebra (a) provides a reasonable and realistic basis for simulating radionuclide transport in the Culebra and (b) allows evaluation of the extent to which uncertainty about groundwater flow in the Culebra may contribute to uncertainty in the estimate of cumulative radionuclide releases from the disposal system. See Section 6.4.6.2 for additional references to other relevant discussions on this conceptual model.

The conceptual model used in performance assessment for groundwater flow in the Culebra treats the Culebra as a confined two-dimensional aquifer with constant thickness and spatially varying transmissivity (see CCA Appendix MASS, Attachment 15-7). Flow is modeled as single-phase (liquid) Darcy flow in a porous medium.

Basic stratigraphy and hydrology of the units above the Salado are described in Chapter 2.0, Sections 2.1 and 2.2. Additional supporting information is contained in CCA Appendices GCR, HYDRO, and SUM.

The conceptual model for flow in the Culebra is discussed in Section 6.4.6.2. Details of the calibration of the T-fields, based on available field data, are given in Appendix PA, Attachment TFIELD, Section TFIELD-4. Initial and boundary conditions used in the model are given in Section 6.4.10.2. A discussion of the adequacy of the two-dimensional assumption for PA calculations is included as Attachment 15-7 to CCA Appendix MASS.

The principal parameter used in the PA to characterize flow in the Culebra is an index parameter (the transmissivity index) used to select a single T-field for each Latin hypercube sample element from a set of calibrated fields, each of which is consistent with available data (see Appendix PAR).

MASS-15.1 Historical Context of the Culebra Model

Since the FEIS in 1980, the model used to describe flow and transport within the Culebra has changed significantly. In the FEIS, the Culebra and Magenta were combined and modeled as one layer referred to as the Rustler aquifers. In the modeling, the Rustler aquifers were assumed to be an isotropic porous medium with a uniform porosity of 0.10 (Lappin et al. 1989, Table K-2, K-18). A uniform T-field was assumed across the model domain except in Nash Draw. Regional flow was assumed to be toward the southwest discharging at Malaga Bend on the Pecos River. (There was no regulatory framework or boundary defined at this time.) Numerical modeling was not able to consider the possible effect of variations in brine density within the Rustler, so modeling used an equivalent freshwater head. Steady-state flow directions and rates were assumed. As for physical-transport characteristics, the Culebra was incorporated into the Rustler aquifers and assumed to be an isotropic, homogeneous porous medium.

Haug et al. (1987) calibrated a flow model to the H-3 pumping test (Beauheim 1987a) and the effects from the excavation of the shafts. Data from numerous new boreholes installed and tested since the 1980 study were included in this model. The boundaries of the model were not much larger than the extent of the WIPP site. Brine densities were also used as a calibration target. The brine densities were assigned at the boundaries and subsequently modified to match the observed fluid densities. Vertical leakage was included in an attempt to calibrate the brine densities. This attempt led to the recommendation that future modeling studies treat the Culebra as a leaky-confined aquifer. The T-field was estimated by kriging and modified by the addition of pilot points, which were located by trial and error. In this model, single- and double-porosity effects on the flow field were investigated. At the regional scale, the use of a double-porosity vs. single-porosity (matrix-only) conceptual model had little effect on the flow field.

A modeling study (LaVenue et al. 1990) conducted to support the DSEIS only slightly modified the conceptual model used by Haug et al. (1987). The differences in the conceptual model were the assumptions that brine density varied spatially but was held constant through time, and vertical leakage was not included. It was assumed that the brine concentrations could be considered to have changed little over the period of time modeled. The boundaries of the 1989 study were much larger than those of the 1987 study, extending approximately 18.6 mi (30 km) north and south and 12.4 mi (20 km) in east and west. The model grid was centered on the WIPP site. The boundaries were selected to include the region for which head data were available and to minimize the boundary effects during transient simulation of the H-3, WIPP-13, and H-11 pumping tests. Fixed heads were assigned around all four boundaries based upon the regional head values. Transmissivities were estimated by kriging and ranged over seven orders of magnitude in this study. Pilot points were added to modify the T-field during steady-state and transient calibration. Pilot-point locations were selected using an adjoint sensitivity analysis technique. The Culebra T-field were calibrated on the basis of 41 test locations. Transmissivity was recognized to vary by approximately three orders of magnitude within the WIPP site. Modern flow in Culebra was recognized as being predominantly north to south on the WIPP site, and strongly affected by a high-transmissivity zone in the southeastern portion of the WIPP site. Flow was calculated on the basis of a fully confined Culebra and boundary conditions applied at the WIPP site scale. As discussed in Lappin et al. (1989), local flow and transport behavior were affected by fracturing where the transmissivity is greater than approximately 10^{-6} m^2 per second. For physical transport, a double-porosity (matrix-diffusion) transport model for off-site transport from waste panels was assumed. Transport parameters were based on best estimates from nonsorbing tracer tests at three locations (Jones et al. 1992). It was assumed that the effective thickness was equal to the total thickness. Contaminant-transport calculations were one-dimensional.

The initial conditions for the Culebra flow field have been taken from the hydrographs of the WIPP boreholes. Prior to excavation of the salt handling shaft, the hydrographs showed little evidence of head change over the ten years preceding the shaft excavations. Head values were selected for each borehole with a hydrograph that preceded shaft excavation or that was located far from the shaft effects on the flow field. These data provided an estimate of the undisturbed head field and were subsequently used as initial conditions for the Culebra model's transient simulation.

In modeling the hydrologic characteristics of the Culebra, SNL (1992-1993) generated multiple T-field conditioned on hydraulic test data (point transmissivity data and transient head data) and then sampled those fields. This procedure addressed uncertainties in the location-specific values of the Culebra transmissivity. The geologic conceptual model was further revised to indicate that the degree of fracture flow was related to the degree of gypsum cement in the fractures. Contaminant-transport calculations were two-dimensional. The effective thickness of the Culebra was taken to be equal to the total thickness. A range of physical-transport parameters was used, as opposed to best estimates, to address the variability of physical-transport properties within the Culebra. The maximum fracture spacing was assumed to be equal to the total thickness of the Culebra (approximately 26 ft [8 m]). The fracture spacing used in modeling was a convenient modeling simplification based on the concept of through-going parallel fractures. Representing fracturing in terms of fracture spacing is a mechanism to ensure that the proper surface-to-volume ratios are used in estimating the role of matrix diffusion. Calculations considered the possibility of both single-porosity (fracture-flow-only) and double-porosity (matrix diffusion) behavior.

The main differences between the 1989 and 1992 models were the model boundary locations, boundary conditions, and the geostatistical approach used to develop and modify the T-field (LaVenue and RamaRao 1992). The 1992 model boundaries were rotated 38 degrees east to align with the axis of Nash Draw. This permitted the specification of a no-flow boundary condition along a portion of the western boundary, which was selected to coincide with the axis of Nash Draw. In addition, the northeastern corner of the model was treated as a no-flow boundary because of the low transmissivities in the area and the lack of any nearby regional heads to provide boundary head estimates. Transmissivities were simulated by conditional simulation. Pilot points were automatically located and assigned transmissivity values using an optimization routine during steady-state and transient-state calibration.

By 1994, the model of the Culebra's hydrologic characteristics was unchanged from that of December 1992. For the physical-transport characteristics, double-porosity transport was assumed, but the base case had large fracture spacing, effectively the same as the Culebra thickness. A single block size was assumed in each realization. Calculations still assumed an effective thickness equal to the total thickness.

For the 1996 CCA, the model of the Culebra's regional hydrologic characteristics had not changed from the 1994 model, although additional large-scale information from pumping at H-19 and small-scale information at Water Quality Sampling Program (WQSP) wells was incorporated into the calibration. Existing borehole-transmissivity interpretations were refined. The model of the physical-transport characteristics were changed on the basis of analysis of new data from H-19 and H-11 and reanalysis of previous tests of H-3, H-11, H-6. The Culebra was conceived of as a fractured porous medium with inherent local variability in the degree and scale of fracturing. Examination of core and shaft exposures revealed that there are multiple scales of porosity within the Culebra including fractures from microscale to large, vuggy zones, and inter-particle and inter-crystalline porosity. This variability leads to both lateral and vertical variations in permeability. Advection is believed to occur largely through fractures; however, in some areas it may also occur through vugs connected by small fractures and interparticle porosity. Diffusion occurs into all connected porosity. PA, rather than conceiving of transport in terms of fracture and matrix porosities, conceives the Culebra as being composed of advective and

diffusive porosities. Matrix diffusion is still believed to be effective and significant. The effective transport thickness is thought to be less than the total stratigraphic thickness. The available data suggest that the permeability of the upper portion of the Culebra is relatively low. Therefore the DOE has concluded that the Culebra is adequately represented by a double-porosity continuum model on the scale of PA calculations, and it is not necessary to use a discrete-fracture model on this scale.

For the 2004 PA, the method of defining the initial (pre-calibration) distribution of T within the Culebra has been revised to explicitly include the geologically zoned distribution of T first developed for the basin-scale model. Three zones are identified: an eastern zone in which halite is present in the Rustler members immediately above and/or below the Culebra and the Culebra transmissivity is consistently low (log T [m^2/s] < -5.4), a western zone in which dissolution of the upper Salado has occurred and the Culebra T is consistently high (log T [m^2/s] > -5.4), and an intermediate transition zone that includes most of the WIPP site. Areas of high T are distributed stochastically within 27.8 percent of the intermediate transition zone to represent the current uncertainty in their locations. Within each of the three zones, T is inversely correlated to the thickness of overburden above the Culebra.

The flow code used for the CRA T-fields was MODFLOW-2000 (Harbaugh et al. 2000). The model domain for CRA-2004 is similar in size (22.4 km [13.9 mi] wide by 30.7 km [19.1 mi] long) to that used for the CCA (approximately 22 km [13.7 mi] wide by 30 km [18.6 mi] long), but is oriented with the long axis extending north to south. The model domain was discretized into uniform 100-m [328-ft] by 100-m [328-ft] grid blocks. Constant-head conditions were prescribed for the eastern boundary of the model, as well as for the eastern portions of the northern and southern boundaries. Flow lines (no-flow boundaries) were prescribed from northeast to southwest down the axis of the northern part of Nash Draw, and from northwest to southeast down the southern arm of Nash Draw. Model cells in the northwest and southwest portions of the model domain beyond the flow lines were treated as inactive by MODFLOW-2000.

Implementation of the pilot-point method for T-field calibration was also revised for the CRA-2004 T-fields. Instead of using an adjoint-sensitivity approach to optimize the locations of the same number of pilot points as there were well locations, 100 pilot points were located to provide a relatively uniform distribution of wells and pilot points within the intermediate transition zone and near the borders of the other two zones. The regularization technique described by Doherty (2003) was used to prevent the large number of pilot points from causing numerical instability. PEST v. 5.5 (Doherty 2002) was used instead of GRASP to optimize T at pilot-point locations during the model-calibration process. The calibration process involved matching to heads measured in late 2000 and to transient heads at 40 wells resulting from seven major pumping tests.

Additional information on the T-field modeling performed for the 2004 PA is given in Chapter 6 and Appendix PA, Attachment TFIELD. Transport modeling for CRA-2004 was performed in the same manner as for the CCA.

MASS-15.2 Dissolved Actinide Transport and Retardation in the Culebra

The purpose of this model is to represent the effects of advective transport, physical retardation, and chemical retardation on the movement of actinides in the Culebra. This conceptual model is also discussed in Section 6.4.6.2.1.

The properties of the Culebra have been characterized by direct observation in outcrop, boreholes, and shafts (Holt and Powers 1984, 1986, 1988, 1990), field hydraulic testing and analysis (Beauheim 1987b), field tracer testing and analysis (Attachment 15-6; Jones et al. 1992; Mercer and Orr 1979), and laboratory testing and analysis (Papenguth and Behl 1996a, 1996b). The conceptual model for dissolved actinide transport in the Culebra is based on these observations, tests, and analyses. Because testing and analysis of the Culebra suggest that its upper portion does not play a significant role in transport, transport is modeled only for the lower portion of the Culebra.

The conceptual model for actinide transport in the Culebra has three principal components: advective transport, physical retardation, and chemical retardation. Two types of porosity are present—porosity in which advective transport occurs, and porosity that is relatively inactive in advective transport. This type of behavior is typically referred to as double porosity

Advective transport refers to the transport of actinides in those pores of the Culebra where the principal fluid flow occurs. This flow primarily occurs in fractures, but may also occur in microfractures connecting vugs in vuggy regions or other portions of the porosity of the Culebra that contain large pore-throat apertures (that is, high permeability regions). This mechanism includes the effects of diffusion and dispersion in advective porosity as well as the movement of actinides with the bulk fluid flow. Advective transport is thought to be controlled by hydraulic gradient, hydraulic conductivity, formation thickness, and advective porosity.

Physical retardation refers to the process of diffusion from advective porosity into diffusive porosity, that is, those portions of the porosity of the Culebra that are relatively inactive in advective transport. Once in the diffusive porosity, the transport of actinides is controlled by diffusion and sorption. Diffusion can be an important process for effectively retarding solutes by transferring mass from the porosity where advection (flow) is the dominant process into other portions of the rock. The properties that control the diffusion of actinides into the diffusive porosity are the surface-area-to-volume ratio of the matrix blocks, the tortuosity of the diffusive porosity, and actinide free-water diffusion coefficients (see CCA Appendix MASS, Attachment 15-3).

Chemical retardation refers to the sorption of actinides on minerals present in the Culebra. Sorption is thought to occur on dolomite grains, but will also occur on clay or other minerals. In the conceptual model, chemical retardation occurs only in the diffusive porosity, and adds to the effects of the physical retardation. The governing properties for sorption are described in a parametric expression of the degree to which dissolved actinides tend to sorb or remain in solution (in the mathematical model, a K_d or a linear isotherm is used), which requires the concentration of actinides in solution and the abundance of minerals on which sorption can occur (see CCA Appendix MASS, Attachment 15-1).

Advective porosity is thought to be a small percentage of the total volume of the Culebra. This porosity is interconnected and contains high-permeability features such as fractures or vuggy pore structures. In this advective porosity, little actual rock material is considered to exist (in other words, it is the fracture apertures and pore volumes without surrounding rock). In contrast, diffusive porosity makes up the major portion of the Culebra pore volume. It comprises lower-permeability features and most of the rock material. The rate at which diffusion removes solutes from advective porosity is a function of the surface area-to-volume ratio of the matrix blocks. For a given geometry of advective porosity assumed in a model (for example, parallel-plate fractures), this surface area-to-volume ratio can be expressed as a characteristic length, which is known as the matrix block length (for example, the thickness of a matrix slab between two parallel-plate fractures).

In summary, the conceptual model for dissolved actinide transport in the Culebra includes two types of porosity: advective porosity associated with high-permeability features of the Culebra, and diffusive porosity associated with lower-permeability features. These two types of porosity are distributed throughout the Culebra and are intertwined on a small scale; hence, mapping their regional extent or boundaries between them is not feasible. Advection, diffusion, and dispersion of dissolved actinides occur within the advective porosity. Diffusion (physical retardation) and sorption (chemical retardation) occur within the diffusive porosity. Advective porosity makes up a small portion of the overall pore volume of the Culebra; diffusion is an important process for transferring actinides into other portions of the rock in which there is a larger surface area for sorption. Because the upper portion of the Culebra has been observed to be relatively inactive in solute transport in tests, it is assumed to be unimportant and is not included in the conceptual model. Attachment 15-6 of CCA Appendix MASS contains additional information on the transport properties of the Culebra.

Several parameters are referred to or implied in the conceptual model as discussed in Section 6.4.6.2. For transport in advective porosity, the principal parameter is the porosity of the network, but because of links to the Culebra fluid flow model, the hydraulic gradient and hydraulic conductivity largely control the specific discharge calculated by MODFLOW-2000. Within diffusive porosity, the porosity, tortuosity, and diffusion coefficients for various actinides are important because of their effect on the rate of diffusion. A parameter called matrix block length, a measure of the surface area between the advective and diffusive porosities, is also important. The density of sorbing minerals and their sorption properties, expressed by K_d, are important in chemical retardation.

It is commonly assumed that there should be a relationship between the conductivity of advective porosity and its porosity and distribution, that is, that the fracture permeability, porosity, and aperture or spacing should be correlated. Data collected and analyzed at the WIPP do not support this assumption. There are no meaningful trends among these parameters for the data that have been collected. Therefore, values of these parameters are not correlated in the PA (see CCA Appendix MASS, Attachment 15-6, page 14 and Attachment 15-10).

Transport of actinides in the Culebra is coupled to several other conceptual models. An important coupling is to models for features that can introduce actinides to the Culebra, for example, the exploratory borehole, shafts and shaft seals, and dissolved actinide source term. The most important coupling is to the model for flow in the Culebra. Because transport in the

Culebra is one of the last processes to occur along this pathway prior to release, it does not feed back to other conceptual models in any significant manner. This conceptual model falls at the downstream end of the overall disposal system model, and thus has little or no impact on models that come before it.

MASS-15.2.1 Current Studies of Sorption in the Culebra

Several factors affect the sorption of Pu, Am, U, Th, and Np, the elements for which K_d values are required in PA for Culebra transport calculations (Ramsey 1996) including:

- the properties of the sorbents (solids) that will sorb actinides from solution,
- the composition of solutions that currently exist in the Culebra or could enter the Culebra after human intrusion into WIPP disposal rooms,
- the oxidation state of the sorbate (actinide elements) in the Culebra,
- dissolved actinide concentration,
- equilibration time, and
- direction of reaction (sorption versus desorption).

The two most important sorbents in the Culebra are dolomite, a carbonate mineral that constitutes most of the Culebra, and corrensite, an ordered mixture of chlorite and saponite associated with fracture surfaces and dispersed in the matrix (intact rock between the fractures) of the Culebra. Dolomite is important because it is by far the most abundant mineral in the Culebra. Corrensite is important because, although a minor constituent, it sorbs actinide elements more strongly than dolomite. The work of Sewards (1991) and Sewards et al. (1991, 1992) indicates that corrensite is associated with fracture surfaces and dispersed in the matrix at concentrations high enough to increase the retardation of Pu, Am, U, Th, and Np relative to that observed in laboratory studies with dolomite-rich rock. (Np was not transported in the 1996, the 2004 PA, or the 1997 PAVT, but K_ds were also determined for this element for completeness.) However, the DOE does not include K_ds for clay minerals in the ranges and probability distributions for the matrix K_ds used in PA calculations because laboratory data for clay-rich rock under expected Culebra conditions are insufficient at this time. Furthermore, the DOE does not take any credit for sorption by clay minerals associated with fracture surfaces. Omitting K_ds for clays is conservative.

The experimental basis for the ranges and probabilities of matrix distribution coefficients is documented in CCA MASS Attachment 15-1.

MASS-15.2.2 Historical Studies of Sorption in the Culebra

See CCA Appendix MASS, Section MASS.15.2.2 for historical information relating to the CCA Culebra conceptual model.

MASS-15.3 Colloidal Actinide Transport and Retardation in the Culebra

The purpose of this model is to represent the effects of colloidal actinide transport in the Culebra. This model is also discussed in Section 6.4.6.2.2 and Attachments 15-2, 15-8, and 15-9.

A particle is referred to as being in the colloidal state when the particle size lies roughly in the range between 1 nanometer and 1 micron. These particles are generally much larger than simple ions, and as a result, the transport behavior of colloids in groundwater systems can be quite different from that of dissolved species. In a groundwater system, colloids are essentially a third phase consisting of a mobile solid that can associate with or contain actinides and potentially increase transport rates slightly relative to the average groundwater velocity.

In the WIPP disposal system, for instance, colloids are often too large to pass through the small pore throats of diffusive porosity. Such colloids will be restricted to the advective portion of the flow system. Colloids may also be less reactive than dissolved actinides with the host rock. Therefore, even though a colloid is small enough to penetrate the diffusive porosity, the retardation coefficient associated with the colloid will in some cases be smaller than the retardation coefficient of the actinide associated with the colloid.

Colloid-facilitated actinide transport has not been included in the 1996 PA, the 2004 PA calculations, or the 1997 PAVT because of a lack of adequate information to model this phenomenon and demonstrate its impact on compliance (see, for example, SNL, 1992-1993, Vol. 1, 4-12, line 29). Transport of actinides by colloidal particles has been recognized only relatively recently as a phenomenon of potential importance to the performance of nuclear waste repositories (Jacquier 1991; Avogadro and de Marsily 1984). In fact, the study of colloid-facilitated contaminant transport is a relatively new topic to the geosciences in general. Nyhan et al. (1985) was one of the first investigations to demonstrate the potential importance of colloid-facilitated radionuclide transport. Since then, a number of researchers have investigated colloids as a potential transport mechanism (for example, McCarthy and Zachara 1989; Corapcioglu and Jiang 1993; Grindrod 1993; Ibaraki and Sudicky 1995). Grindrod (1993) and Ibaraki and Sudicky (1995) addressed the topic of colloid-facilitated transport through fractured porous media. Consequently, their work is most applicable to the colloid-transport problem in the Culebra.

Among the most sophisticated and rigorous numerical models developed are those by van der Lee et al. (1993, 1994) and Bennett et al. (1993). Many of the colloid-transport numerical models described in the literature focus on simulating solute transport through fractured media with double-porosity flow characteristics, and they have been generalized to include unique features of colloid transport (for example, Hwang et al. 1989; Grindrod and Worth 1990; Light et al. 1990; Smith and Delgueldre 1993; Harmand and Sardin 1994). Some numerical models, such as the population-balance model by Travis and Nuttall (1985), assume equilibrium colloid concentrations. That is, the loss of colloidal particles by attachment to the medium wall is compensated by the generation of new colloidal particles by various mechanisms such as condensation and entrainment. The modeling approach developed by Travis and Nuttall (1985) is similar to the double-porosity transport model.

MASS-15.3.1 Experimental Results

As discussed in Section 6.4.6.2.2, the four types of colloids and colloidal sized particles modeled to be introduced to the Culebra are microbes, mineral fragments, humic substances, and actinide intrinsic colloids. To investigate the impact of these four colloid types on radionuclide transport in the Culebra, an experimental program was developed and implemented at SNL with significant contributions from Lawrence Livermore National Laboratory (LLNL), Battelle National Laboratory, Los Alamos National Laboratory (LANL), and Florida State University. The intent of this experimental program was to develop parameter ranges and distributions for the conceptual models discussed above. With the exception of the Pu (IV) polymer, the experimental results indicated that colloid-facilitated actinide transport is not a viable mechanism for actinide transport in the Culebra. Furthermore, the potential amount of Pu (IV) polymer that could be introduced to the Culebra was found to be insignificant with respect to the EPA normalized release limit. Consequently, colloid-facilitated actinide transport was not simulated in the PA.

The experimental results and implications for PA modeling are summarized as follows:

- Mineral fragments and microbes are attenuated so effectively it was deemed unnecessary to include them in the transport calculations (see CCA Appendix MASS, Attachments 15-8 and 15-9).

- The total potential amount of Pu (IV) polymer introduced to the Culebra was found to be insignificant with respect to the EPA normalized release limit (Attachment 15-8). Therefore, the contribution of Pu (IV) polymer to the integrated discharge was disregarded in the PA.

- Under neutral to slightly basic brine conditions, the presence of humic substances in the brine did not influence the sorption behavior of dissolved actinides. Results indicate that at these geochemical conditions, humic substances were not effective complexants in the presence of dolomite (Attachment 15-8). Therefore, actinides associated with humic substances are assumed to disassociate upon entering the Culebra.

MASS-15.3.2 Indigenous Colloidal Transport

In an intrusion scenario at the WIPP, as dissolved actinide elements are introduced to the Culebra, it is possible that those dissolved actinides could sorb onto a separate population of indigenous mineral fragments, microbes, and humic substances. The physical and chemical behavior of these newly formed actinide-bearing colloidal particles will be nearly identical to the behavior of colloids introduced from the repository. Microbes and mineral fragments will be rapidly filtered out of the advective flow domain; hence, disregarding the interaction between dissolved actinides and these types of colloids is considered to be a conservative approach. Experimental results indicate that humic substances do not interact with dissolved actinides under the expected Culebra geochemical conditions. Consequently, the quantity of newly formed actinide-bearing humics will be insignificant.

MASS-15.3.3 Alternative Approaches Considered

As discussed above, results of experimental studies show that colloidal actinides are strongly attenuated or present in negligible concentrations, making it unnecessary to include them in PA simulations. The following section describes the three alternative transport conceptual models considered prior to the completion of these experimental results.

After the introduction of colloidal actinides and dissolved actinides into the Culebra, realistically a new equilibrium condition will be established, with the stipulation that the total concentration of actinide must be preserved. As in the repository, quantifying an equilibrium assemblage is not practicable.

Three approaches were considered to quantify colloid-facilitated actinide transport at the WIPP. First, the transport of one or more types of actinide-bearing colloidal particles in the Culebra could be assumed to be instantaneous. In other words, as actinides associated with that type of colloidal particle migrate to the Culebra from the repository, or are generated within the Culebra, the mass of actinides associated with those colloidal particles becomes part of the integrated release of actinides at the accessible environment boundary. This approach can be useful if the concentrations of actinides associated with one or more types of colloidal particles are very low. Treating colloid-facilitated actinide transport as instantaneous, however, is a significant shortcoming, because of the potentially large expected retardation effects of colloidal particles.

Second, SECOTP2D and supporting codes could be used to simulate the effects of one or more of the colloid retardation phenomena (Ramsey 1996). The double-porosity advection and diffusion equation solved by SECOTP2D can simulate colloid sorption in the matrix and to the fracture walls. The code can also model colloid filtration using the decay term of the governing equation. For colloids considered too large to diffuse into the matrix, matrix diffusion can be disabled by setting the matrix tortuosity to zero. This approach was used for some calculations completed in 1994. Specifically, microbes, because of their relatively large size, were excluded from matrix diffusion and limited to advective flow in fractures. Humic substances were allowed to diffuse into intercrystalline pores, but at a reduced rate relative to dissolved actinide species.

This approach requires a number of simplifying assumptions under the presumption they are conservative with respect to the integrated release of radionuclides. The first assumption is that the dissolved concentration will be greatest at the source point and therefore, the concentration of radionuclides associated with colloids will be greatest at the source as well. Second, a radionuclide associated with a colloid is assumed to remain fixed to that colloid throughout the simulation. Given these assumptions, the colloidal actinide concentration is no longer a function of the dissolved actinide concentration, and it is not necessary to solve the dissolved species transport problem and the colloid transport problem simultaneously. As a result, the standard advection-diffusion transport equation can be used to predict colloid transport and compute integrated colloid releases. Given the initial concentration of radionuclides sorbed to each specific type of colloid, the integrated colloid release can be converted to an integrated radionuclide release by postprocessing the colloid transport results. Radionuclide decay can also be accounted for in postprocessing.

The third assumption is that colloid-facilitated actinide transport could be quantified by a rigorous numerical modeling code developed for the WIPP. Such a rigorous transport model would address all physical and chemical processes that could affect the movement and fate of the four colloidal particle types, including colloid generation; interactions with solutes, the dispersant, and rock; advection; dispersion; diffusion; filtration; gravitational settling; attachment and detachment; adsorption and desorption; coagulation; flocculation; and peptization. Ideally, permeability reduction caused by pore clogging by colloids, which would affect solute transport as well, would also be considered. Currently available models do not include all of these processes (see CCA Appendix MASS, Attachments 15-2, 15-8, and 15-9).

The most practical approach to evaluating the transport of colloidal actinides is the second option presented above, using the SECOTP2D code. Where possible, the DOE considered reducing the number of phenomena treated in the transport code and address them in the source term. For example, the effect of ionic strength on colloid stability would have been included in the colloid source term. Retardation of colloidal particles was to be quantified using a retardation factor, and filtration was to be quantified through the decay term.

MASS-15.4 Subsidence Caused by Potash Mining in the Culebra

This model incorporates the effects of potash mining in the McNutt on disposal system performance (see Appendix PA, Attachment SCR, FEPs H13, H37, and H38). 40 CFR Part 194 provides a conceptual model and parts of a mathematical model for these effects. The DOE has implemented the EPA conceptual model to be consistent with EPA criteria and guidance. It is described in Section 6.4.6.2.3 of this recertification application. Additional information on the implementation of the mining subsidence model is available in Appendix PA, Attachment TFIELD, Section TFIELD-9.0; CCA Appendix MASS, Attachments 15-4 and 15-7; and Wallace (1996).

The principal parameter in this model is the range assigned to a factor by which hydraulic conductivity in the Culebra is increased (CCA Appendix MASS, Attachment 15-4). As allowed in supplementary information to 40 CFR Part 194, it is the only parameter changed to account for the effects of mining.

Mining in the McNutt has been considered in the performance of the WIPP since the original siting activities. Siting criteria for both the site abandoned in 1975 and the current site included setbacks from active mines. (See, for example, Section MASS-2.0.) The 1980 FEIS for the WIPP (DOE 1980) considered the possibility of an indirect dose arising from the effects of solution mining for potash or halite; it concluded that direct access of waste by solution mining for potash was not likely because of the methods that would be used to control the flow of solvent through the formation. See Appendix PA, Attachment SCR (FEPs H58 and H59).

Mining has been included in scenario development for the WIPP since the earliest work on this topic (for example, Hunter 1989; Marietta et al. 1989; Guzowski 1990; Tierney 1991; and WIPP Performance Assessment Division 1991). These early scenario developments considered both solution and room-and-pillar mining. The focus was generally on effects of mining outside the disposal system. The two primary effects of mining considered were changes in the hydraulic conductivity of the Culebra or other units and changes in recharge as a result of surface

subsidence. These mining effects were not formally incorporated into quantitative assessment of repository performance in preliminary PAs.

The inclusion of mining in PA satisfies the criteria of 40 CFR Part 194 to consider the effects of this activity on the disposal system.

MASS-16.0 INTRUSION BOREHOLE

The inclusion of intrusion boreholes in PA adds to the number of release pathways for radionuclides from the disposal system. Direct releases to the surface may occur during drilling as particulate material from cuttings, cavings, and spall are carried to the surface. Also, dissolved actinides may be carried to the surface in brine during drilling. Once abandoned, the borehole presents a possible long-term pathway for fluid flow, such as might occur between a hypothetical Castile brine reservoir, the repository, and overlying units. This topic is also addressed in Chapter 6.0, (Section 6.4.7) and Appendix PA Attachment SCR (FEPs H1 and H21).

MASS-16.1 Cuttings, Cavings, and Spall Releases during Drilling

These models estimate the quantity of actinides released as solids directly to the surface during drilling through the repository by three mechanisms: the drillbit boring through the waste (cuttings), the drilling fluid eroding the walls of the borehole (cavings), and high repository gas pressure causing solid material failure and entrainment into the drilling fluid in the wellbore (spallings). See Section 6.4.7.1 and references to other appendices cited in that section for additional information. Stochastic uncertainty with respect to parameters relevant to these release mechanisms is addressed in Section 6.4.12. The conceptual model for cuttings, cavings, and spallings is discussed in three parts because of the differing process by which the three types of material are produced.

Cuttings are materials removed to the surface through drilling mud by the direct mechanical action of the drill bit. The volume of waste removed to the surface is a function of the repository height and the drill bit area. The cuttings model has as a principal parameter the diameter of the drill bit (see Appendix DATA, Attachment A).

Cavings are materials introduced into the drilling mud by the erosive action of circulating drilling fluid on the waste in the walls of the borehole annulus. Erosion is driven solely by the shearing action of the drilling fluid (or mud) as it moves up the borehole annulus. Shearing may be caused by either laminar or turbulent flow. Repository-pressure effects on cavings, which are negligible, are covered by the spall process. The principal parameters in the cavings model are the properties of the drilling mud, drilling rates, the drill string angular velocity, and the shear resistance of the waste. See Appendix PA, Attachment PAR (Tables PAR-13 and PAR-18) for details on the sampled parameters used in the cavings model, the drill string angular velocity, and the effective shear resistance to erosion.

Spallings are solids introduced into the wellbore by the fluid pressure difference between the repository and the bottom of the wellbore. If the repository pressure is sufficiently high (~ >12 MPa) relative to the well bottom hole pressure (~8 MPa), the stress state in the repository may cause repository solids to fail in the vicinity of the wellbore. In turn, these solids may become

entrained in the gas flowing toward the well, ultimately to be carried up to the land surface, constituting a release. The principal parameters in the spallings model are the gas pressure in the repository when it is penetrated and properties of the waste such as permeability, tensile strength, and particle diameter. Because the release associated with spalling is sensitive to gas pressure in the repository, it is strongly coupled to the BRAGFLO-calculated conditions in the repository at the time of penetration.

MASS-16.1.1 Historical Context of Cuttings, Cavings and Spallings Models

Cuttings and cavings releases are straightforward. The analytical equations governing erosion (cavings) based on laminar and turbulent flow (Appendix PA, Section PA-4.5) have been implemented in the code CUTTINGS_S. Using selected input based on assumed physical properties of the waste and other drilling parameters, this code calculates the final caved diameter of the borehole that intersects the waste.

The various approaches used for spallings up to the CCA PA are documented in CCA Appendix MASS.16.1.1. Since the CCA PA, the spallings model has been extensively revised and has changed fundamentally from an end-state erosional model to a mechanically based coupled material failure and transport model (WIPP PA 2003a). This model is implemented in a new code, DRSPALL. The following discussion traces the historical steps from the CCA erosional model to DRSPALL.

According to the WIPP Conceptual Models Peer Review Report (CCA Section 9.3.1.2.7), the three primary objections to the erosional spallings model were; (1) channel flow scenario needed additional validation, (2) waste erosion resistance process and parameters had not been adequately evaluated, and (3) assumptions concerning waste degradation and strength. Though the strength value used, 1 lb/in^2, was consistent with the strength of soils, salt and clay mixtures, and similar mixtures with MgO (see CCA Appendix PEER, Section 2.6 for Berglund 1996), the peer review panel was not convinced of the applicability of this value in the model (Wilson et al. 1996b). Hansen et al. (1997) decided to revise the approach to estimating spall release and embarked on a two-part effort that sought to (1) derive mechanical strength estimates from laboratory measurements on surrogate WIPP wastes, and (2) develop a new mechanically-based model for spall that attempts to encompass the entire system response from bit penetration to near steady state rather than just the end state, as done in the erosional model. The results of the model development efforts were implemented in the code GASOUT (Hansen et al. 1997, Appendix C).

MASS-16.1.2 Waste Mechanistic Properties

The spalling event can occur only in cases that combine high pressure with highly degraded waste. A systematic approach was implemented to characterize the waste after compaction, corrosion, and microbial consumption through the used of waste surrogate materials. The primary emphasis of the waste surrogate testing was devoted to quantifying tensile strength, although many other characteristics, such as particle size, permeability, and heterogeneity, will greatly influence potential spall release. Utilizing a projected inventory of waste materials placed in the repository and assuming extensive degradation, recipes (mixtures) for surrogate products were determined. Surrogate recipes derived from corrosion of 50 percent and 100 percent of the

Fe-based inventory were fabricated and mechanically tested using standard laboratory procedures (Hansen et al. 1997).

Degraded waste strength was recognized as a key parameter in a WIPP spallings model (Wilson et al. 1996a, 1996b). Lacking, however, were compelling data to validate the value of tensile strength T_o = 1 lb/in^2 used in the CCA erosional model. In an attempt to build an understanding of the mechanical properties of degraded WIPP wastes, Hansen et al. (1997) developed a test methodology to construct and examine surrogate wastes. They scanned the inventory of WIPP wastes and prepared recipes for various surrogate wastes. A wide variety of materials were cut, shred, compressed, and aged in the laboratory to create specimens appropriate for standard laboratory measurements such as tensile and compression tests. Overall, results from 38 specimens were reported in Hansen et al. (1997) quantifying properties including tensile strength, cohesion, friction angle, Poisson's ratio, and Biot's constant. These data helped to make the case that the T_o = 1 lb/in^2 value used in the CCA was indeed conservative.

Subsurface processes leading to extensive degradation are based on several contributing conditions including ample brine availability, extensive microbial activity, corrosion, and the absence of cementation and salt encapsulation effects. Property values from these surrogate materials are selected to represent the worst-case response to the process being investigated (Hansen et al. 2003b). In terms of the degraded waste properties, the model is highly conservative.

MASS-16.1.3 New Mechanistic Model for Spall

In addition to the work on waste degradation, Hansen's team also laid the groundwork for a new approach to modeling the WIPP spallings process. Instead of focusing on the end state after penetration, as is done in the erosional model, the new effort sought to capture the system behavior from just before penetration through to the end state. In doing so, many more phenomena were included in the model. Considered in this new conceptual model was unsteady, convergent gas flow from the repository toward the wellbore that caused mechanical stress and potential failure of solids near the face of the wellbore. Pressure in the cavity at the point of penetration was balanced by the mud column in the wellbore and the repository pressure. This represented a more complex modeling approach, and was developed sufficiently to satisfy the peer review panel that convened in April, 1997 that the spallings release values used in the CCA were conservative (Wilson et al. 1997).

The new spall model, DRSPALL (WIPP PA 2003a) is based on a predecessor code called GASOUT (Hansen et al. 1997, Appendix C). DRSPALL builds upon GASOUT by:

1. Adding a wellbore flow model that transports mud, repository gas, and waste solids from repository level to the land surface; and

2. Adding a fluidized bed model that evaluates the potential for failed particulate waste to fluidize and become entrained in the wellbore flow.

The wellbore flow model in DRSPALL utilizes one-dimensional geometry with a compressible, viscous, isothermal, homogeneous mixture of mud, gas, and solids. Standard mass and momentum balance, friction loss, and slurry viscosity equations are used. Wellbore flow model

results were successfully verified against those from an independent commercial code for several test problems (WIPP PA 2003b).

DRSPALL applies the fluidized bed theory to determine the mobilization of failed material to the flow stream in the wellbore. If the escaping gas velocity exceeds the minimum fluidization velocity, failed material is fluidized and entrained for transport at the land surface. If gas velocity is too low to fluidize the bedded material, however, the cavity size is allowed to stabilize The spall volumes predicted by DRSPALL are based on conservative assumptions for material properties and for the flow geometry within the repository.

- The particle size distribution for spallings is based on a detailed analysis (Wang 1997) of data from an expert elicitation (DOE 1997). This analysis considered several limiting cases in developing a conservative distribution for mean particle size ranging from 1 mm to 10 cm (Hansen et al. 2003b).

- The shape factor for fluidization of particles has a potential range from 0 to 1.0. Smaller values of the shape factor denote particles that are less spherical, and therefore more easily fluidized and transported in the flow. The shape factor is conservatively set to a value of 0.1 for CRA-2004 (Lord 2003).

- The tensile strength of the waste assigned for the spalling process is uncertain, ranging from 0.12 MPa to 0.17 MPa (Hansen et al. 2003b). Tensile strength data was measured in laboratory experiments on surrogate materials that were chosen to conservatively represent highly degraded residuals from typical wastes. The given range is felt to represent extreme, low-end tensile strengths because it does not account for several strengthening mechanisms, such as MgO hydration and halite precipitation/cementation (Hansen et al. 1997).

- DRSPALL uses a hemispherical geometry (one-dimensional spherical symmetry) for the flow field and cavity in the waste. This conceptual model is appropriate when the drill bit first penetrates the repository. But as the drill bit passes completely through the compacted waste, the flow field will transition toward a cylindrically symmetric geometry. This transition is important because the largest spall release volumes are predicted to occur at late times, well after the drillbit has penetrated through the waste, and because the spall volumes predicted for a cylindrical geometry are less than for the hemispherical geometry (Lord et al. 2003).

In spite of this transition, the hemispherical geometry is used for the CRA-2004 spallings release calculations because it produces conservative results. Fifty calculations performed with DRSPALL in both the hemispherical and cylindrical flow geometries demonstrated that the spall volumes predicted with the hemispherical geometry are always larger than those for the cylindrical geometry (Lord and Rudeen 2003, Section 3.3 Sensitivity Analysis Report Part 2). In fact, the spall volumes are zero for all 50 realizations with a cylindrical geometry, which indicates that the likelihood of spalling is quite small in this geometry. It follows that the hemispherical geometry results in spall volumes that are conservative relative to the cylindrical geometry.

There is no consensus about how the driller will act as the drill approaches the waste horizon; that is, whether he or she will be able anticipate the presence of the gas-filled repository, or if he or she can or will control the drilling process once penetration occurs. For the WIPP intrusion scenarios, the conceptual model assumes the worst possible limiting situation, in which the borehole is driven through the waste by a driller without any knowledge of the existence of the repository, and the driller is unable or unwilling to control the subsequent gas release.

In summary, the conservative assumptions for waste properties, the waste flow geometry and the driller's actions provide very conservative spalling release volumes for CRA-2004 (see also Appendix PA, Section PA-4.6 for a description of the spallings model and Section 9.3.1.3.5.5 for the results of the new spallings model peer review).

MASS-16.1.4 Calculation of Cuttings, Cavings, and Spall Releases

As detailed in Appendix PA, Section PA-6.7, cuttings and cavings releases for intrusions into contact handled (CH)-TRU waste are computed by multiplying the volume released (calculated by the code CUTTINGS_S) with the radioactivity in three independently-selected waste streams, consistent with the conceptual assumption that waste is randomly placed within the repository. The effect of this assumption on PA results was examined in a separate PA (Hansen et al. 2003a) in which cuttings and cavings releases were computed by assuming that each intrusion encounters only a single waste stream. The differences in repository performance (determined by comparing the mean CCDFs for releases) were determined to be minor. For more details on the analysis, see Section MASS-21.0.

Because spallings may releases a relatively large volume of material (exceeding 4 m^3), spallings releases for intrusions into CH-TRU waste are computed by multiplying the volume of spalled material with the average concentration of radioactivity in the waste at the time of the intrusion. A separate PA (Hansen et al. 2003a) compared spallings releases computed using the average concentration of radioactivity in the waste to spallings releases computed by using the radioactivity of a single, randomly selected single waste stream. The analysis determined that the assumption had only a minor effect on the mean CCDF for releases. For more details on the analysis, see Section MASS-21.0.

MASS-16.2 Direct Brine Releases during Drilling

This model provides a series of calculations to estimate the quantity of brine released directly to the surface during drilling. Direct brine releases (DBRs) may occur when a driller penetrates the WIPP and unknowingly brings contaminated brine to the surface during drilling (these releases are not accounted for in the cuttings, cavings and spallings calculations, which model only the solids removed during drilling). Appendix PA, Section PA-4.7 described the DBR model used for the 2004 PA. CCA Appendix MASS, Attachment 16-2 describes the direct brine release model used for the 1996 PA. The conceptual model for DBRs is discussed in Section 6.4.7.1.1.

Uncertainty in the BRAGFLO direct-brine-release calculations is captured in the 10,000-year BRAGFLO calculations from which the initial and boundary conditions are derived. The model parameters that have the most influence on the direct brine releases are repository pressure and brine saturation at time of intrusion. Brine saturation is influenced by many factors, including

Salado and marker bed permeability and gas-generation rates (for undisturbed calculations). For E1 and E2 intrusions, Castile brine-reservoir pressure and volume and abandoned borehole permeabilities influence conditions for the second and subsequent intrusions. Dip in the repository (hence the location of intrusions), two-phase flow parameters (residual brine and gas saturation), time of intrusion, and duration of flow have lesser impacts on brine releases.

To account for changes in the BRAGFLO model (see Section MASS-2.0), the implementation of the DBR model has been adjusted for the CRA 2004-PA. Figure MASS-9 shows the DBR

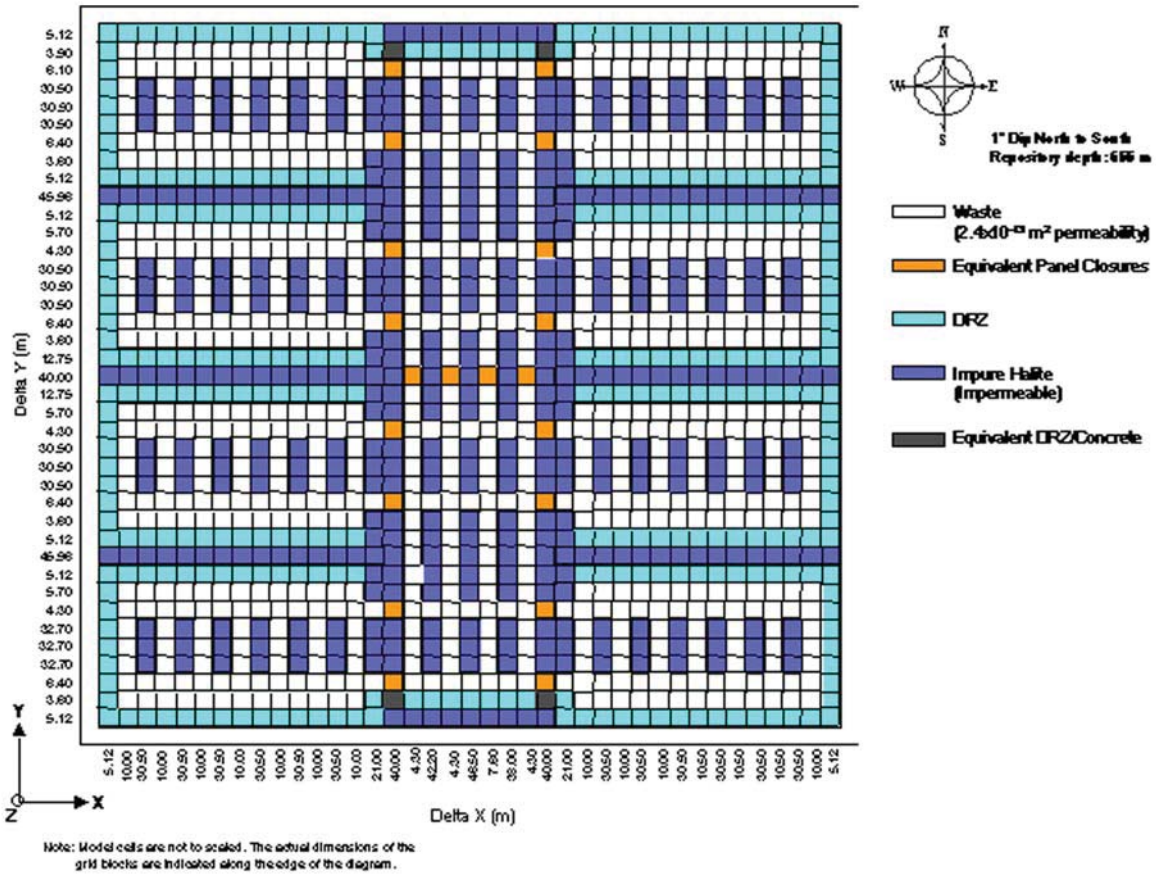

Figure MASS-9. Repository-Scale Horizontal BRAGFLO Mesh Used for Direct Brine Release Calculations

grid used in the 2004 PA. The grid dimensions and resolution are the same as in the CCA PA, but the material parameters assigned to the panel closures have been changed to be more consistent with the conceptual model for the Option D panel closures. In addition, the material parameters assigned to the DRZ have been changed to more consistently represent the DRZ. In the CCA PA, the pillars between rooms and the halite separating panels were assigned properties consistent with the DRZ material in the BRAGFLO grid. The DRZ permeability used in the CCA (10^{-15} m^2) was low enough that brine did not flow between panels during the 11-day DBR calculations. When the permeability of the DRZ was changed in the PAVT (from a constant value of 10^{-15} m^2 to a sampled value between $10^{-19.4}$ m^2 and $10^{-12.5}$ m^2), realizations with high

DRZ permeability allowed brine flow between panels during the 11-day period for DBR calculations. It is not reasonable to model the halite between panels as DRZ, since the DRZ would extend only a few meters into the 60-m thick ribs. Consequently, the material parameters assigned to cells separating panels were changed to be representative of undisturbed halite, rather than DRZ. Stein (2003b) provides details on the material parameters used in the DBR calculation and the rationale for the parameter values.

MASS-16.3 Long-Term Properties of the Abandoned Intrusion Borehole

The purpose of the model for the long-term properties of the intrusion borehole is to provide in BRAGFLO the physical properties relevant to fluid flow through a plugged and abandoned borehole that intersects the repository. The model includes several possible plugging and configuration patterns based on current practice in the Delaware Basin (CCA Appendix MASS, Attachment 16-1). Because plugging practice is closely controlled by state regulations, only the New Mexico portion of the Delaware Basin is considered. Section 6.4.7.2 of this application describes the properties assigned to the boreholes and the types of plug configurations considered in performance assessment.

The conceptual model for long-term flow up a plugged and abandoned borehole addresses the principal parameters in the intrusion borehole model for long-term flow: permeability, porosity, compressibility, and two-phase properties. Because these properties may change with time as the borehole plugs degrade, some types of boreholes have several defined stages for the evolution of borehole properties. No retardation of actinides or other transport-limiting effects in the borehole are assumed. This is considered a conservative assumption (see Table MASS-1).

Permeability, the most important borehole property, changes according to the stage of borehole degradation. The values assigned to other parameters are held constant for all stages and are set consistent with a borehole fill referred to as silty sand, consisting of the material that would naturally slough off the walls of the borehole or the remains of degraded plugs. The porosity of the plugged and abandoned borehole is set at a low value within the porosities expected of materials that will be in the borehole; the low value was chosen because smaller void volume in the borehole reduces storage in the borehole and slightly increases the total flux of fluids that may pass through it.

Predictions of the time-dependent permeability of plugged boreholes are based on three configurations for borehole plugs and two concepts of how the plug materials will be altered by fluids. The concepts include steel corrosion and concrete degradation. From the outside inward, the conceptual model for borehole plugs envisions concentric circles of ordinary portland cement as grout attaching the casing to the rock, low carbon steel (the casing), and a central disc of ordinary portland cement (the concrete plug). The bulk of the data used to predict the service lives of borehole plugs comes from the open literature on corrosion of low carbon steel and ordinary portland cement and from tabulated thermodynamic data bases.

Predictions of plug performance derived from the conceptual models are sensitive to both chemical and physical parameters. Key areas of uncertainty include the following:

- opened or closed nature of the physical and chemical systems,

- degree to which performance data from generic materials apply to WIPP-specific materials and conditions,
- conditions at the precise locations where WIPP plugs are emplaced, and
- physical dimensions of the plugs.

The conceptual models for predicting the time-dependent permeability of plugged boreholes recognize two types of systems: open and closed. Open systems are ones in which chemical components can be added or subtracted freely, whereas closed systems are ones in which the identity and amount of chemical components available for reaction are constant. In physical models, a closed system maintains a constant volume, while in open systems volume is unconstrained. The principal area of uncertainty in the conceptual models is the definition of the boundary between open and closed space. This boundary is significant because real systems are somewhere between totally open or closed, and open and closed systems result in very different expected performance lives for plugged boreholes.

In chemical systems, a very small addition or release of reacting components is insignificant, but a substantial change can have large effects: in open systems reactions proceed until the supply of reactants is exhausted. In open systems, equilibrium considerations may have little or no significance; hence treatment by equilibrium thermodynamics may be unenlightening. Similarly, in physical systems, a small amount of system expansion will have little effect on internal stresses, but unlimited expansion may cause the system to fail in tension.

MASS-16.3.1 Corrosion

There are many low-carbon-steel alloys, and not all corrode at the same rate in a given environment. However, because of the aggressive corrosion rate selected for the model, steel composition is not thought to introduce significant uncertainty about the rate. Corrosion of the casing steel has been modeled thermodynamically for plugged boreholes. Hydrogen is a common byproduct of corrosion. An equilibrium hydrogen pressure has been calculated for a number of potential reactions, using metallic iron to represent steel and pure water to represent brines. Attainment of equilibrium hydrogen pressure is taken to indicate cessation of corrosion. To reach equilibrium, the system must contain the hydrogen that is generated. The hydrostatic pressure of the brine column has been assumed to confine hydrogen when the pressure exceeds the equilibrium hydrogen pressure calculated for the corrosion reaction of interest.

Reactions most representative of corrosion of steel casing produce iron hydroxide corrosion products. Equilibrium hydrogen pressures for these reactions are exceeded by hydrostatic pressures at depths greater than about 1,100 ft (335 m). Corrosion of casing above this depth is treated as open; the casing corrodes until the supply of metallic iron is exhausted and the casing disintegrates. Without axial support supplied by the casing, the concrete plug also fails. In contrast, corrosion is assumed to take place in a closed system at depths greater than 1,100 ft (335 m). Hydrogen is not free to nucleate as a gas and leave the system. Although local perforations in the casing are expected, the casing does not disintegrate. It supports the concrete plugs, and permeability changes in the plugs are attributed to alteration of cement phases by the brine that flows through them.

The greatest uncertainty associated with composition is likely to arise from the thermodynamic calculations used in the model. Pure phases (Fe for steel and H_2O for brine) have been assumed so that hand calculations may be more readily performed. Various reactions and environments have been modeled without directly considering complexities in the chemical system (other than volatiles). Qualitatively, the added complexities are likely to have no substantial consequence on the ability of the brines to dissolve a pathway through the casing. However, system complexities might decrease the equilibrium hydrogen pressures calculated for the corrosion reactions or lead to unexpected reaction products.

Data supporting low-carbon-steel corrosion models come primarily from the literature. The empirical data support the assumption that general corrosion is the dominant mechanism for corrosion under oxic conditions and that pitting will occur under low oxygen (and high pH) or elevated carbon dioxide and hydrogen disulfide conditions. Corrosion rates are a function of the conditions under which corrosion occurs. Published data include rates as rapid as 3 mm per year, which is the value assumed in the model. Such rapid rates are not inconsistent with reports in the Delaware Basin of casing failures occurring from corrosion within months to years (CCA Appendix MASS, Attachment 16-3, B-17). Data from corrosion of steel enshrouded in concrete come from the literature on marine construction and the data base on reinforcing steels. These data support the assumption that steel encased in concrete cannot be assumed to corrode more slowly than exposed steel. This subject area is discussed in detail in CCA Appendix MASS, Attachment 16-3 (Section 3.2 and Appendix B).

MASS-16.3.2 Portland Cement Concrete

The cementitious materials used in hydrocarbon exploration are variable. The degree to which oil-field materials might perform differently from the cement mixtures investigated and reported in the literature is unknown. There is no standard mix formulation that specifies plugging cements precisely; the use of generic data is reasonable, because the vagaries of cement composition are implicitly included. The published empirical studies of concrete degradation include a large body of data for reacting solutions ranging from pure water to marine brines. Waters with higher chloride and magnesium contents cause greater reaction. This level of detail has not been factored into the model directly; rather, alteration by brines has been the favored source when extracting information on degradation.

Chemical alteration of cement phases by brine produces new solids with greater molar volumes than the unaltered, hardened cement phase. In a closed physical system, the alteration will lead to decreased internal porosity and consequent decrease in permeability. In an open physical system, alteration will lead to increased internal pore pressures that will eventually exceed the tensile strength of the concrete plug. The result is often seen on concrete sidewalks or other unreinforced concrete structures: without something to restrain expansion, the concrete cracks, increasing its porosity and permeability.

Current plugging practices create configurations that favor each model. Plugs installed to respond to the New Mexico Oil Conservation Division regulation R-111-P approach 2,000 ft (610 m) in length (State of New Mexico 1988). These plugs are judged to be long enough that they are self-confining. As a result, alteration of R-111-P plugs produces a situation in which performance is indistinguishable from the undisturbed rock. In contrast, plugs emplaced in

response to regulations of the U.S. Bureau of Land Management have a mean length near 40 m. This length is judged to be too short to provide self-confinement; alteration of the concrete results in fracturing and increased porosity and permeability in the plug. The plug length that changes the physical system from open to closed is undetermined. For both chemical and physical model elements, a closed system enhances performance.

Simulation of concrete plug degradation follows a model proposed by Berner (1990), in which the matrix degrades after dissolution and removal of soluble materials such as alkali salts. The model is grounded in empirical observations that concrete alteration sequentially removes excess alkalis, portlandite, and tobermorite or calcium-silicate-hydrate (CSH). Decreased strength attends removal of portlandite.

A critical amount of flow must occur before this degradation threshold is crossed. A volume equivalent to 100 pore volumes has been taken as the critical flow volume, based on values for common compositions of ordinary portland cement concrete (Berner 1990). Also following Berner, the model tracks the amount of flow as pore volumes, reasoning that flow occurs only through pores and that alteration is therefore limited to the solids that surround the pores. The model does not explicitly account for the strength of the concrete but instead makes the conservative assumption that physical failure occurs suddenly at the onset of chemical attack on CSH, that is, at approximately 100 pore volumes. As a result, initial porosity of the hardened concrete is a key parameter for timing plug degradation.

The initial permeability of hardened cement is directly related to the connected porosity that permits flow to occur. Initial permeability of ordinary portland cement is a strong function of the water:cement ratio of the mix. Higher water contents produce higher porosity and permeability. To simplify the analysis, the CCA used an initial plug permeability of 5×10^{-17} m^2. This value lies in the upper range of permeabilities reported for ordinary portland cement and is verified by field measurements made during a single field test of borehole plugging conducted for the DOE (CCA Appendix MASS, Attachment 16-3, C-4). In their review of the CCA, the EPA required the DOE to treat this parameter as uncertain (EPA 1998b, Section 5.17). DOE implemented log-uniform distribution of values ranging from 10^{-19} to 10^{-17} m^2. This distribution is used for the 2004 PA calculations.

The initial permeability of the concrete plug is an important parameter because water must penetrate and flow through the structure before it can alter the hardened plug. The lower the permeability, the longer it takes for 100 pore volumes to pass through the plug. Somewhat paradoxically, the lower the porosity, the smaller the volume of water needed before attack of the CSH begins, because the model decouples the relationship between porosity and permeability by holding permeability constant. In the real world, cement formulations with low water:cement ratios generally produce fewer alkalis and have both lower porosities and lower permeabilities. Less water must pass through the concrete body before onset of CSH degradation, but the lower permeabilities lead to a longer life. The simplified model is conservative: it holds the permeability constant at the upper end of the established range while allowing porosity to vary over the full range commonly encountered in ordinary portland cement. This accommodation reflects better knowledge of permeabilities than porosities in as-emplaced borehole plugs. The range in porosity modeled (5 to 40 percent) can create an order-of-magnitude spread in predicted performance life.

Data supporting the concrete degradation model come primarily from two sources: the international repository literature and journals on concrete construction (for example, dams or bridges). The international literature on repositories contains both models and empirical studies confirming that alteration of concrete will result in decreased porosities and permeabilities in closed systems. Experience for dams confirms this conclusion and confirms the diffusion-driven concrete alteration rates used in the model. The general concrete literature confirms the values of initial permeability and porosity of hardened concrete used in the model.

Observations made on cores recovered from potash mines near the WIPP confirm that alteration of concrete plugs is not extensive after decades of service. Qualitative data have been produced by recovery, microscopic inspection, and leach testing of concrete cores recovered from nearby potash mines. These data establish that plugs placed in boreholes will have low initial permeabilities and that plugs placed in the Salado will form tight interfaces at the borehole-rock interface and will not degrade substantially by contact with formation brines in the amounts and compositions that might reasonably be expected. See CCA Appendix MASS, Attachment 16-3 for the historical discussions of concrete plug alteration and creep closure of boreholes.

MASS-16.3.3 Borehole Configurations

The conceptual models for borehole plugs examine three basic possibilities: a continuous plug through the evaporite sequence, a plug below the brine reservoir horizon coupled with a plug between the repository and the Rustler, and three or more plugs with at least one intermediate plug between the brine reservoir and the repository and another between the repository and the Rustler. These possibilities represent simplifications of the plugging schemes documented in a 1996 survey during the 1996 CCA and verified by the Delaware Basin Drilling Surveillance Program (see Appendix DATA, Attachment A; and Sections 6.4.7.2.1 through 6.4.7.2.3). Since the CCA, plugging data show these three plug configurations continue to represent plugging patterns employed within the WIPP vicinity (WRES 2003, Attachment C).

As stated, the basis for these assumptions is a detailed survey of plugging practices in the Delaware Basin. The survey examined the lengths, locations, and intervals plugged, as well as the materials used for construction. The locations of plugs are determined partly by stratigraphic changes and partly by operational considerations during exploration and recovery. Variations in plug length and location affect pressure regimes and flow rates through plugs. The 120-ft (40-m) length of the plugs is the approximate mean value of approximately 188 plugs in the survey. Minimum lengths prescribed by regulations are 50 ft (15 m) above plus 50 ft (15 m) below casing transitions or recovery points. Additional plug lengths sometimes occur for unspecified reasons. When all else is equal, performance life is proportional to plug length. For conservatism, the model does not consider the longer plugs. In the conceptual model, all plugs are taken to be 120 ft (40 m) long. See CCA Appendix MASS, Attachment 16-3 (Section 5.0), for a more detailed discussion of plug performance.

The borehole permeability model was assembled beginning in February 1996. Initially, the model considered only the plug configuration stipulated by Oil Conservation Division regulations, but it was subsequently expanded to consider all regulations and practices documented in the New Mexico portion of the Delaware Basin, without specific consideration of their applicability to the WIPP in the future. The model was developed to be straightforward and

easy to understand. Use of hand calculations was favored over the use of complex computer codes. As a result, no detailed evaluation of potentially applicable codes was undertaken, and no screening of codes was performed.

CCA Appendix MASS, Attachment 16-3 describes the model and its predictions contains about 40 references with data that support the model. In general, these references support the plug configurations, steel corrosion mechanisms and rates, and concrete alteration processes that underpin the model. Additionally, the Delaware Basin Drilling Surveillance Program continuously monitors plugging practices in the WIPP vicinity (WRES 2003).

MASS-17.0 CLIMATE CHANGE

The purpose of this model is to allow quantitative consideration of the extent to which uncertainty about future climate may contribute to uncertainty in estimates of cumulative radionuclide releases from the disposal system. Consideration is limited to conditions that could result from reasonably possible natural climatic changes. The model is not intended to provide a quantitative prediction of future climate, nor is it intended to address uncertainty in system properties other than estimated cumulative radionuclide releases that may be affected by climate change. This model is also discussed in Section 6.4.9.

As discussed in CCA Appendix CLI, paleoclimatic data from the literature form the basis for reconstructing the climatic variability in southeastern New Mexico since late Pleistocene time, spanning the transition from full glacial conditions in North America (ice sheets as far south as the Northern Great Plains) to the present interglacial period. The wettest and coolest climate at the WIPP corresponded to periods of continental glaciation. During Holocene time (the past 10,000 years), the climate has been predominantly dry, like that of the present, with several wetter episodes.

Future climate at the WIPP may differ in the next 10,000 years from that of the present, but it should be bounded by the extremes of the late Pleistocene glaciation. For the purposes of performance assessment, the DOE assumes that uncertainty about future climate is adequately captured by considering two possible patterns: one in which the Holocene pattern of predominantly dry conditions alternating with wetter conditions continues; and one in which the climate becomes continuously wetter.

Effects of climatic change on the WIPP are limited in the performance assessment model to effects on groundwater flow in the Culebra. Flow (that is, specific discharge in the MODFLOW-2000 model) is increased from its present calibrated value by a sampled factor that ranges from 1.0 to 2.25 to simulate effects of wetter climates. Possible decreases in flow during drier climates are not considered. Justification for limiting the effects of climate change to flow in the Culebra is based on regional three-dimensional modeling that estimates the extent to which changes in recharge will alter the altitude of the water table and in turn affect flow in the Culebra and other units. Maximum recharge rates considered in the analysis result in a simulated water-table altitude at or near the ground surface throughout the region. Other effects of climatic change, including changes in temperature, wind, evapotranspiration, and vegetation, are not

modeled explicitly but are qualitatively included in this analysis through the consideration of the effects of varying recharge.

The climate change model is implemented through the use of a single parameter, the Climate Index. This parameter is a dimensionless factor by which the specific discharge in each grid block of the MODFLOW-2000domain is multiplied. It is a sampled parameter in the PA, with a bimodal distribution ranging from 1.00 to 1.25 and from 1.50 to 2.25. See Corbet (1995) and CCA Appendix MASS, Attachment 17-1 for a discussion of this distribution.

The climate change model used for performance assessment is predicated on the assumption that climate will change during the next 10,000 years. The extent of this change is uncertain, but it should be bounded by the changes that occurred in the past during the peaks of Pleistocene glaciation. Other conceptual models for climate change are not consistent with present scientific understanding of the Earth's climate or with the EPA's guidance to consider natural processes of climatic change (EPA 1996, pp. 5227-5228). For example, climate could be assumed to remain constant for 10,000 years, but this would be inconsistent with scientific understanding of climate. Alternatively, climate could be assumed to change to conditions unlike any known from the Pleistocene; however, no natural processes are known that could result in such change within 10,000 years.

As discussed in Corbet (1995) and CCA Appendix MASS, Attachment 17-1, the implementation of climate change in the performance assessment incorporates uncertainty about future climates within the range known from the Pleistocene. Alternative approaches to treating climate change in the performance assessment (that is, varying boundary conditions rather than specific discharge) are discussed in the following section. Past analyses performed using a different approach as part of the 1991 and 1992 preliminary performance assessments suggest that disposal system performance is not sensitive to climate change (Swift et al. 1994, p. 12).

MASS-17.1 Historical Context of the Climate Change Model

See CCA Appendix MASS, Section MASS.17.1 for historical information on the Climate Change model. This Climate Change model is unchanged for the 2004 PA.

MASS-18.0 CASTILE BRINE RESERVOIR

The conceptual model for the hypothetical brine reservoir is included in the performance assessment to estimate the extent to which uncertainty about the existence of a brine reservoir under the waste disposal region may contribute to uncertainty in the estimate of cumulative radionuclide releases from the disposal system. The conceptual model is not intended to provide a realistic approximation of an actual brine reservoir under the waste disposal region: data are insufficient to determine whether such a brine reservoir exists.

The Castile is treated as an impermeable unit in PA and plays no role in the analysis except to separate the Salado from the modeled brine reservoir in the BRAGFLO grid. In human-intrusion scenarios, the hypothetical brine reservoir can be penetrated by an intrusion borehole connecting it to the repository. The amount of brine that can enter the repository from the brine reservoir is

important to PA because brine is required for gas generation reactions to proceed and can transport radionuclides in solution, contributing to potential releases.

The properties of the hypothetical brine reservoir defined for PA include: permeability, porosity, pore volume, initial pressure, and various two-phase flow parameters. Values assigned for these properties were chosen to either be consistent with the available data from and analyses of borehole penetrations of brine reservoirs in the region, or to provide a reasonable response in the BRAGFLO model.

The treatment of the brine reservoir for the 2004 PA is different than that used in the 1996 CCA PA. The major changes to the brine reservoir representation were made by the EPA in their 1997 PAVT (EPA 1998b, V-B-14). In the 1997 PAVT, EPA defined new parameter ranges for bulk compressibility and total pore volume. The range of bulk compressibility was based on a reevaluation of field test data from the WIPP-12 borehole following the CCA (Beauheim 1997). Since the total volume of the grid cells used to represent the brine reservoir in BRAGFLO is fixed, the range of total pore volume was set by defining a range of "effective" porosity (pore volume = grid volume × effective porosity). This range of porosity values is not representative of the actual host rock rather it was chosen to produce a reasonable response in the BRAGFLO model by providing a predefined range of total pore volumes based on the field tests at WIPP-12.

For the 2003 WIPP PA, DOE has implemented this approach by assuming that the productivity ratio (PR) remains constant (2.0051×10^{-3} m^3/Pa). The productivity ratio is defined as:

$$PR = V \frac{C_r}{\phi},$$

where V is the grid volume of the brine reservoir (18,462,514 m^3), C_r is the bulk compressibility (2×10^{-11} to 1×10^{-10} Pa^{-1}), and φ is the effective porosity (0.1842 to 0.9208). The porosity range used in the CRA-2003 PA is slightly modified from that used by the EPA because the fixed-grid volume increased slightly from the volume assumed in the CCA BRAGFLO grid. In this approach, bulk compressibility and effective porosity are directly proportional (Stein 2003a). See Appendix PA, Section PA-4.2, for the details on the implementation in PA.

Basic geologic information about the Castile is given in Section 2.1.3.3. The hydrology of the known brine reservoirs is discussed in Section 2.2.1.2.2. The treatment of the hypothetical brine reservoir in the PA is discussed in Section 6.4.8, which also points to supplementary information included in this recertification application.

MASS-18.1 Historical Context of the Castile Brine Reservoir Model

See CCA Appendix MASS, Section MASS.18.1 for historical information on the Castile Brine Reservoir model.

MASS-19.0 OPTION D PANEL CLOSURES

The certification decision by the EPA (1998a) included several conditions that the DOE was required to meet. In the first of these conditions, the EPA required the DOE to implement a specific design for the panel closure system referred to as Option D and required the concrete monolith to be constructed using SMC. The DOE had included in the CCA four Options (A-D) for the panel closure design. The Option D design consisted of two components; a large monolith constructed of SMC and keyed into the surrounding DRZ, and an explosion wall constructed of concrete blocks, which is not keyed into the DRZ.

The PA calculations that supported the CCA and the subsequent 1997 PAVT calculations included generic panel closures in the BRAGFLO grid. These generic closures were not representative of the Option D design. Specifically, the Option D panel closures are designed to impede fluid flow (brine and gas) between panels over long-time scales. The generic panel closures included in the 1996 CCA and 1997 PAVT calculations were relatively permeable and allowed gas to flow freely between panels. In the 1996 CCA and 1997 PAVT PA calculations, a drilling intrusion into a single panel generally caused pressures in the entire repository to decrease.

Following the certification of the repository, the DOE updated the modeling of the panel closures in PA so that the mandated Option D design was adequately represented. A new panel closure representation was developed and presented to the Salado Flow Peer Review Panel in May 2002 and again in February 2003. The peer review panel approved the new conceptual models, which included the implementation of the Option D panel closures in the grid (Caporuscio et al. 2003).

In the CCA/PAVT BRAGFLO grid, only two panel closures were represented. For the 2004 PA, however, DOE included an additional set of panel closures. Preliminary tests of the Option D panel closure representation (Hansen et al. 2002) concluded that Option D panel closures were effective at impeding fluid flow between panels on the order of thousands of years, but that given enough time, pressures slowly equilibrated. These results suggest that the effect of a single intrusion event on pressures in other panels depends on the number of panel closures that lie between the intruded panel and the other panels. Therefore, DOE decided to divide the RoR region into two regions separated by a panel closure. This panel closure represents a set of four panel closures to be located between the northern and southern internal extended panels. The south RoR represents panels directly adjacent to an intruded panel and the north RoR represents panels that are farther away from the intruded panel (two sets of panel closures lie in between).

The DOE assumes that the effect of the Option D panel closures will be to impede fluid flow through and around the closures. Only the concrete monolith portion of the closure system is assumed to remain effective over the 10,000-year regulatory period. The explosion wall is assumed to effective only for a brief period during the operational period. The explosion wall and the open drift adjacent to the monolith are represented in the BRAGFLO grid by a column of grid cells with the properties of the waste area (e.g., high permeability) and include creep closure effects. The monolith is represented in the BRAGFLO grid by an adjacent column of grid cells with a length equal to the length of the monolith (7.9 m) multiplied by the number of panel closures in series and a width equal to the width of the monolith (10 m) multiplied by the number of panel closures in parallel. For instance, in Figure MASS-6, the southern panel closure in the

BRAGFLO grid represents a single set of two panel closures (in parallel) that separate a single external panel from the one of the two internal extended panels (9 and 10). The middle panel closure in the BRAGFLO grid represents a single set of four panel closures (in parallel) that separate the internal extended panels from one another. The northern panel closure in the BRAGFLO grid represents two sets (in series) of four panel closures (in parallel) that lie between the northern edge of the waste region and the shafts.

It is assumed in the modeling that the DRZ above the concrete monolith will heal and quickly attain a state of relatively low permeability. However, it is also assumed that if pressures exceed the fracture initiation pressure (~12.5 MPa), DRZ and anhydrite marker bed materials that intersect the waste room can fracture and allow gas or brine to circumvent the panel closures by flowing around the concrete monolith. This possibility is included in the implementation of the panel closures in the BRAGFLO by replacing the concrete monolith material with marker bed material everywhere the monolith intersects and cuts through the marker beds. This implementation is appropriate even at low pressures because the permeability range of the concrete and the marker beds is nearly equivalent. And at high pressures, fracturing is considered in these grid elements allowing fluids to flow, thus simulating the consequence of fractures extending around the monolith.

Additional information on panel closure effects on repository performances can be seen in the BRAGFLO Analysis package (SNL 2003c).

MASS-20.0 SUMMARY OF CLAY SEAM G MODELING ASSUMPTIONS

One of the changes to the repository design since the CCA is the raising of the repository horizon in the southern half of the waste panels. Specifically, Panels 3, 4, 5, 6, and 9 will be excavated at an elevation approximately 2.4 m above the level of Panels 1, 2, 7, 8, and 10, and the operations and experimental areas. This change in horizon will bring the roof of the raised rooms to the level of the Clay Seam G. The change is expected to improve roof conditions and enhance operations and mine safety. The DOE submitted a planned change request to EPA that described the change and presented an argument that the change would have minimal impact on long-term repository performance (DOE 2000). The EPA responded to the change request in a letter (EPA 2000) in which they agreed with the DOE that the effects to long-term performance would be minimal.

As part of the Salado Flow Peer Review in February 2003, the DOE did an impact assessment on the possible effects of the horizon change to PA to better demonstrate the minimal impact of this change on long-term performance. Two possible effects of this change on the results of PA were considered in this assessment.

First, it was considered that the horizon change might influence the creep-closure porosity surface calculated by the code SANTOS and used by BRAGFLO to determine the porosity of the waste rooms. This possibility was considered by simulating creep closure around a WIPP disposal room raised to Clay Seam G (Park 2002). The resulting Clay G porosity surface was then compared with the original porosity surface, which was used in the CCA. The differences

were shown to be so minor that long-term PA would not be significantly altered (Park and Holland 2003).

The second effect that was considered was the possibility that the thickness of the upper and lower DRZ, as represented in the BRAGFLO grid, might change due to the horizon change. Specifically, in the raised part of the repository, the lower DRZ might become thicker since the distance from the floor of the rooms to MB 139 will be greater than in the unraised part of the repository. A similar decrease in the thickness of the upper DRZ might occur as the roof of the rooms would be nearer to MB 138. Since the DRZ is assumed to be an important source of brine in BRAGFLO, these potential changes to the thickness of the DRZ might affect the amount of brine available to the waste in the raised panels. To assess whether such a change would affect long-term performance, DOE ran a single replicate of 100 undisturbed BRAGFLO vectors in which the total pore volume in the DRZ was adjusted to account for the thickness changes (Stein and Zelinski 2003a). Pressure and saturation results within the waste regions were compared to results assuming the original DRZ thicknesses. It was concluded from these comparisons that the effects of the DRZ thickness changes were very minor and not at all significant for long-term repository performance (Stein and Zelinski 2003b).

The results of the impact assessment were presented to the Salado Flow Peer Review panel in February 2003. The panel accepted the position that the repository horizon change was adequately represented by the impact assessment and need not be implemented explicitly in the BRAGFLO grid for PA calculations (Yew et al. 2003). Based on the results of this impact assessment and the acceptance of the Salado Flow Peer Review, the DOE has determined that it is not warranted to include the change in the repository horizon to Clay Seam G explicitly in the BRAGFLO grid.

MASS-21.0 EVALUATION OF WASTE STRUCTURAL IMPACTS, EMPLACEMENT AND HOMOGENEITY

During the development of the CCA PA, the DOE choose to assume random placement of TRU waste in the WIPP, and developed conceptual and numerical models accordingly. The EPA reviewed these models and their results, and determined that DOE had modeled accurately random placement of waste in the disposal system. Since the time of the CCA, additional information about the waste and its emplacement has emerged, and requires the assumption of random placement to be reevaluated. The waste inventory estimates have been updated since the CCA PA (see Appendix TRU WASTE), resulting in different estimates of important waste components, such as CPR materials. Additionally, the CCA PA assumed that all waste could be modeled as if the waste was emplaced in 55-gallon drums. However, the DOE is emplacing waste using several different types of waste containers, including standard waste boxes (SWBs) and pipe overpacks (Section 4.1). Waste has been shipped to WIPP in campaigns from the generator sites, resulting in waste emplacement that appears inconsistent with the representation of the waste as a homogeneous material. Finally, DOE plans to emplace waste types, such as supercompacted waste, that were not considered in the CCA inventory (DOE 2002). As a result of this new information and these proposed changes, DOE performed a separate analysis (Hansen et al. 2003a) to determine if the modeling assumptions used in PA continue to adequately represent the waste.

Many important waste characteristics, such as the radionuclide content and the mass of CPR materials, are directly incorporated in PA by means of waste material parameters. These parameters have been updated consistent with the inventory update (see Appendix TRU WASTE) and thus are represented in the 2004 PA. However, PA does not account for heterogeneity in waste materials or in waste containers. At the Idaho National Engineering and Environmental Laboratory, for instance, debris waste will be volume-reduced by supercompaction, resulting in a very dense waste form containing a high concentration of CPR material. In addition, the Pu residues from the Rocky Flats Environmental Technology Site have been packaged in pipe overpacks, which are more rigid than the typical 55-gallon drum assumed in the CCA. Additionally, PA assumes that waste is emplaced in a random or homogeneous manner. Actual waste emplacement is determined by the availability of waste at generator sites and the shipping schedules. Pipe overpacks occupy about 43 percent of the containers emplaced in Panel 1, suggesting that actual emplacement will not be statistically random.

The analysis reported in Hansen et al. (2003a) focused on potential effects of supercompacted waste and of waste in pipe overpacks on repository performance. Both waste types are structurally stiffer than the generic waste model used in the CCA PA, and the supercompacted waste in particular has high concentrations of CPR materials. The analysis began with a systematic reevaluation the baseline FEPs to identify specific components of PA that could be affected by supercompacted waste. The reassessment concluded that the FEPs “screened in” were adequate to represent the variety of waste types and containers, and that none of the “screened out” FEPs should be reconsidered for implementation. The FEPs assessment concluded that creep closure of the repository, chemical conditions of the waste, gas generation models, and waste mechanical properties could be affected by heterogeneities in the waste materials and waste containers. In addition, DOE determined that the assumption of random waste emplacement should be reevaluated.

Analysis of creep closure of waste-filled rooms, accounting for several types of waste materials and packaging, indicated that a wider range of long-term porosities could occur relative to that established in the CCA, given the uncertainties about the structural integrity of waste packages and their spatial arrangement in the repository (Park and Hansen 2003). For this reason, the analysis in Hansen et al. (2003a) treated creep closure as an uncertain variable. Sensitivity analysis showed that this additional uncertainty did not affect the results of PA in a significant way.

Chemical conditions also were reexamined under a range of possible waste arrangements. The assessment found that regardless of actual waste emplacement, the MgO would still be sufficient to maintain desired chemical conditions. Moreover, the constituents of supercompacted waste would not alter the reactions that determine chemical equilibrium and, consequently, no changes to actinide solubilities or to the gas generation models were warranted.

Supercompacted waste contains elevated amounts of CPR materials relative to other waste streams, and the future arrangement of this waste in the WIPP repository is uncertain. Thus, the analysis treated the spatial distribution of CPR materials as uncertain. However, sensitivity analysis demonstrated that uncertainty in the spatial distribution of CPR materials had little effect on PA results.

The representation of the waste properties also was considered; however, it was determined that no changes to permeability, shear strength, or tensile strength were warranted. Based on this evaluation, no changes to the models for direct releases were necessary.

Direct releases as a consequence of a drilling intrusion are calculated with the assumption of random waste emplacement in the repository. In addition, releases by spallings, DBR, and long-term radionuclide transport assume that radionuclides are homogeneously distributed throughout the waste. A sensitivity analysis determined that PA results are not greatly affected by the assumption of random waste emplacement or by the assumption that radionuclides are homogeneously distributed.

Based on the analysis reported in Hansen et al. (2003a), DOE concluded that:

1. Explicit representation of the specific features of supercompacted waste and of waste in pipe overpacks, such as structural rigidity, was not warranted in modeling, since PA results were relatively insensitive to the effects of such features.

2. PA results were not affected significantly by the assumption of nonrandom waste emplacement and the representation of these waste types as a homogeneous material.

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APPENDIX PA

ATTACHMENT PAR

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ACRONYMS AND ABBREVIATIONS

AIS	Air Intake Shaft
AMM	Asphalt mastic mix
CCA	Compliance Certification Application
CCDF	Complementary cumulative distribution function
CDF	Cumulative distribution function
CH	Contact-handled
DOE	Department of Energy
DRZ	Disturbed rock zone
EPA	Environmental Protection Agency
ERMS	Electronic Records Management System
FMT	Fracture matrix transport
GTFM	Graph Theoretic Field Model
ID	Identification number
LANL	Los Alamos National Laboratory
LHS	Latin hypercube sample
MB	Marker bed
MU	Map unit
PAVT	Performance Assessment Verification Test
PDF	Probability distribution function
PNL	Pacific Northwest Laboratory
QA	Quality Assurance
QAP	Quality Assurance Procedure
RH	Remote-handled
SMC	Salado Mass Concrete
SNL	Sandia National Laboratories
SSSPT	Small Scale Seal Performance Tests
SWCF	Sandia WIPP Central Files
TRU	Transuranic
TWBIR	Transuranic Waste Baseline Inventory Report
WES	Waterways Experiment Station
WIPP	Waste Isolation Pilot Plant

PAR 1.0 INTRODUCTION

This attachment contains information for the parameters used by performance assessment (PA) codes. Documentation, in the form of parameter sheets, is provided for the 64 parameters sampled by the Latin hypercube sample (LHS) code during the PA (see also Section 6.1.5 for discussion on probabilistic analyses and Section 6.1.5.2 for discussion on LHS). In addition, this attachment includes a listing of the sampled values for LHS sampled parameters (see Tables PAR-8 through PAR-11), four parameters sampled by LHS for the Spall model (see Tables PAR-12), the fixed-value parameters used in the PA codes (see Tables PAR-13 through PAR-49) and the parameters relating to the TRU waste inventory (see Tables PAR-50 through PAR-61). Additional information relevant to the use of these parameters in the PA is contained in Appendix PA; Appendix TRU WASTE provides details on the waste inventory.

Although the parameter development terminology used in this attachment is not the same as in Appendix PAR of the CCA, it is equivalent. Differences in terminology include; NP 9-2 rather than QAP 9-2, Parameter Data Entry Forms rather than Form 464's, material:property for identification rather than ID numbers, slightly different definintions for mean, median, and mode, and justification documents rather than parameter record package.

For additional information regarding all parameters, readers are referred to the parameter supporting information packages, which are contained in the Sandia National Laboratories (SNL) Waste Isolation Pilot Plant (WIPP) Records Center located at the SNL office in Carlsbad, New Mexico.

PAR 2.0 PARAMETER DEVELOPMENT PROCESS

The development of parameter values is controlled by the application of Nuclear Waste Management Program Procedure (NP) Parameters (NP 9-2). The process includes documentation of parameter development by those responsible for completion of a particular experimental investigation, development of a system design, or by staff involved in the PA modeling process. All of the references pertaining to parameter selection are contained within the three levels of parameter and data documentation: **(**1) Parameter Data Entry Form NP-9-2-1, (2) Analysis records packages, and (3) supporting data records packages.

The Parameter Data Entry Form is the highest-level record documenting parameter development that includes application of statistics and interpretations. The Parameter Data Entry Formsinclude a justification section, which is a pointer to supporting information including, where applicable, the Analysis plan and source document. All values provided in this attachment were derived from the WIPP PA parameter database. The numbers from the WIPP PA parameter database may differ slightly from those contained in the Parameter Data Entry Forms because of rounding.

The parameter supporting information package includes references to related information, such as Analysis Plans, SAND reports, test plans, and related ERMS file codes, and, where applicable, a summary on the experimental data collection (that is, method used, assumptions made in testing, and interpretation). The parameter supporting information packages point to the data records packages contain information such as the raw data, analysis, and data interpretation.

Each Parameter Data Entry Form, and parameter supporting information package are assigned unique Electronic Records Management System (ERMS) numbers. Copies of the Parameter Data Entry Forms, and parameter supporting information packages are maintained in the SNL WIPP Records Center.

PAR 3.0 PARAMETER DISTRIBUTIONS

Probability distributions are used to characterize the uncertainty concerning the value of a parameter. Numbers that characterize a particular distribution include the range, the mean, median, and mode (only for triangular distributions).

- Range. The range of a distribution can be denoted by (a,b), a pair of numbers in which a and b are minimum and maximum values of the parameter, respectively.

- Mean. The expectation of a random variable: i.e., the sum (or intergral) of the product of the variable and the PDF over the range of the variable. There is sample mean and mean: The mean, μ, of a distribution is one measure of the central tendency of a distribution, analogous to the arithmetic average of a series of numbers. The sample mean, $\bar{x}$, is the arithmetic average of value in an empirical data set.

- Median. The value of a random variable at which its CDF takes the value 0.5; i.e., the 50th percentile point.

- Mode. The value of a random variable at which its PDF takes its maximum value. The mode of a set of data is the value in the set that occurs most often.

PAR 3.1 Distribution Types And Applications

Distributions used to characterize uncertainty in parameters of the PA include: uniform, cumulative, triangular, Student's-t, delta, normal, log uniform, log cumulative, lognormal, and constant.

PAR 3.1.1 Uniform Distribution

Density Function: $$f(x) = \frac{1}{B - A} \qquad A \le x \le B \tag{1}$$

Distribution Function: $$F(x) = \frac{x - A}{B - A} \qquad A \le x \le B \tag{2}$$

Expected Value and Variance: $$E(X) = \frac{A + B}{2} \qquad V(X) = \frac{(B - A)^2}{12} \tag{3}$$

Median: $$X_{0.5} = \text{mean}$$

Use of the uniform distribution is appropriate when all that is known about a parameter is its range (a,b); the uniform distribution is the Maximum Entropy distribution under these circumstances (Tierney 1990).

PAR 3.1.2 Cumulative Distribution

A cumulative distribution (also called a constructed distribution) is described by a set of N ordered pairs:

$$(x_1 0), (x_2, P_2), (x_3, P_3), \ldots, (x_N, 1) \{\text{i.e., } P_1 = 0 \text{ and } P_N = 1 \text{ always}\} \tag{4}$$

where $x_1 < x_2 < x_3 < \ldots < x_N$ and $0 < P_2 < P_3 < \ldots < P_{N-1} < 1$

Because of the nature of the data, the PDF for this distribution takes the form:

$$P(\xi) = \begin{cases} 0 & \text{if } \xi < x1 \\ \dfrac{P_n - P_{n-1}}{x_n - x_{n-1}} & \text{if } x_{n-1} \le \xi \le x_n, n = 2,3,_, N \\ 0 & \text{if } \xi \ge x_N \end{cases} \tag{5}$$

and so the cumulative distribution function (CDF) takes the form:

$$P_r[X \le \xi] \approx II(\xi) = \begin{cases} 0 & \text{if } \xi < x_1 \\ P_{n-1} + \dfrac{(P_n - P_{n-1})(\xi - x_{n-1})}{(x_n - x_{n-1})} & \text{if } x_{n-1} \le \xi \le x_x \\ 1 & \text{if } \xi > x_N \end{cases} \quad n = 2,3,_, N \tag{6}$$

Expected Value:

$$E(X) = \sum_{n=2}^{N} (P_n - P_{n-1}) \frac{(x_n + x_{n-1})}{2} \tag{7}$$

Variance:

$$V(X) = \sum_{n=2}^{N} (P_n - P_{n-1}) \frac{(x_n^2 + x_n x_n - 1 + x_{n-1}^2)}{3} - \{E(X)\} \tag{8}$$

Median:

$$x_{0.50} = x_{m-1} + (x_m - x_{m-1}) \frac{(0.50 - P_{m-1})}{(P_m - P_{m-1})} \text{ where } P_{m-1} \le 0.50 < P_m \cdot \tag{9}$$

The cumulative distribution takes its name from the fact that it closely resembles the empirical CDF obtained by plotting the empirical percentiles of the data set (x_1,x_2,x_3, ..., x_N) (Blom 1989, p. 216). The cumulative distribution used here is the result of plotting the subjectively determined percentile points (x_1,P_1), (x_2,P_2), (x_3,P_3) ... , that arise in a formal elicitation of expert opinion concerning the form of the distribution of the parameter in question. A simple form of the cumulative distribution is used when the range (a,c) of the parameter is known and the analyst believes that his or her best estimate value, b, is also the median (or 50th percentile) of the

unknown distribution. In this case, the subjectively determined percentile points take the form: (a, 0.0), (b, 0.5), (c, 1.0) (Tierney 1990).

The cumulative distribution is the Maximum Entropy distribution associated with a set of percentile points (x_1,P_1), (x_2,P_2), ..., (x_N, P_N), no matter how that set of percentile points is obtained (that is, independent of whether the points are empirically or subjectively derived) (Tierney 1990).

PAR 3.1.3 Triangular Distribution

Density Function:

$$f(x) = \frac{2(x-a)}{(c-a)(b-a)} \qquad a \le x \le b$$

$$= \frac{2(c-x)}{(c-a)(c-b)} \qquad b \le x \le c \qquad (10)$$

Distribution Function:

$$F(x) = \frac{(x-a)^2}{(c-a)(b-a)} \qquad a \le x \le b$$

$$= \frac{(b-a)}{(c-a)} - \frac{(x+b-2c)(x-b)}{(c-a)(c-b)} \qquad b \le x \le c \qquad (11)$$

Expected Value:

$$E(X) = \frac{a+b+c}{3} \qquad (12)$$

Variance:

$$V(X) = \frac{a(a-b)+b(b-c)+c(c-a)}{18} \qquad (13)$$

Median:

$$X_{0.5} = a + \sqrt{\frac{(c-a)(b-a)}{2}} \quad \text{if } b \ge \frac{a+c}{2}$$

$$= c - \sqrt{\frac{(c-b)(c-a)}{2}} \quad \text{if } b \le \frac{a+c}{2} \qquad (14)$$

The triangular distribution is defined on the range (a,c) and has mode b. The mode can equal either of the two boundary values, which may simplify the computations above (Iman and Shortencarier 1984).

Use of the triangular distribution is appropriate when the range, (a,c), of the parameter is known and the analyst believes that his or her best estimate value, b, is also the mode (or most probable value) of the unknown distribution.

PAR 3.1.4 Student's-t Distribution

A Student's-t distribution is a Bayesian distribution for the unknown mean value of a parameter. Its use is appropriate when one has measured values of the parameter available (in contrast to values obtained subjectively through elicitation of professional opinion). If N denotes the number of measurements available, and $X_1, X_2, X_3, \ldots, X_N$ denote the values of the measurements, then the expected value or mean of the Student's-t distribution is the sample standard deviation divided by $\sqrt{N}$; the median value is equal to the mean value.

The Student's-t distribution applies when there are few measurements, say $3<N<10$. For large N, say $N>20$, there is little difference between the t-distribution and a normal distribution (see below) with the same mean and standard deviation.

In WIPP PA data characterized by Student's-t distribution are equally weighted. In other words, each measured value X_i is assigned a weight of 1/N, where N is the number of measurements.

PAR 3.1.5 Delta Distribution

The delta distribution is used to assign probabilities to the elements of some set of objects. For example, if the set consists of four alternative mathematical models of some phenomena and each model is labeled with one of the integers {1,2,3,4}, in other words,

$$M_1, M_2, M_3, M_4$$

then we might assign the vector of probabilities (p_1, p_2, p_3, p_4), where each p_i is a number between 0 and 1 and

$$p_1 + p_2 + p_3 + p_4 = 1. \tag{15}$$

The CDF associated with this delta distribution can be symbolically expressed by

$$F(x) = \sum_{n=1}^{4} p_n u(x-n). \tag{16}$$

The graph of this CDF can be visualized as an ascending staircase starting at zero level for x less than one, and having steps of height p_n at the points x = 1, 2, 3, 4.

The notion of mean value and variance still apply to a delta distribution, but the meanings of these quantities may require careful interpretation. If the M_n represents four different functions (say, discharge as a function of pressure), then it makes sense to talk about mean and variance functions. For the example of the four alternative mathematical models, the mean mathematical model is the linear combination

$$\overline{M} = \sum_{n=1}^{4} p_n M_n \tag{17}$$

and the variance of the models is similarly defined:

$$\Sigma^2 = \sum_{n=1}^{4} P_n \left(\overline{M} - M_n\right)^2 \tag{18}$$

The notion of median value is meaningless for a delta distribution.

PAR 3.1.6 Normal Distribution

Density function:

$$f\left(x\right) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{\frac{-x-\mu^2}{2\sigma^2}\right\} -\infty < x < \infty \tag{19}$$

Distribution function:

$$F\left(x\right) = \int_{-\infty}^{x} f\left(t\right) dt \; -\infty < x < \infty \tag{20}$$

Expected value and variance: $E\left(X\right) = \mu$ and $V\left(X\right) = \sigma^2$. (21)

The WIPP PA Program employs a truncated normal distribution where data are concentrated within an interval (lowrange, hirange) (Iman and Shortencarier 1984). The parameters of the truncated distribution can be expressed as follows:

$$E\left(X\right) = \mu = \frac{\left(\text{lowrange} + \text{hirange}\right)}{2} \quad V\left(X\right) = \sigma^2 = \left(\frac{\left(\text{lowrange} - \text{hirange}\right)}{6.18}\right)^2 \tag{22}$$

Median = mean (μ) and lowrange = 0.01 quantile, hirange = 0.99 quantile. The range of the random variable is arbitrarily set to (lowrange, hirange). Alternatively, the expected value μ and the standard deviation σ can be specified by the user of this distribution; in this case, the random variable takes on the range $\left(-\infty, \infty\right)$ and will need to be truncated to a finite interval and renormalized.

Use of the normal distribution is appropriate when it is known that the parameter is the sum of independent, identically-distributed random variables (this is seldom the case in practice) and there are a sufficient number of measurements of the parameter (N > 10) to make accurate, unbiased estimates of the mean (μ) and variance (σ^2) (Sandia WIPP Project 1992; Tierney 1990).

PAR 3.1.7 Log uniform Distribution

If X has a log uniform distribution on the interval from A to B where B > A > 0, then Y = $\log_{10}$ X has a uniform distribution from $\log_{10}$ A to $\log_{10}$ B (Iman and Shortencarier 1984).

Density Function:

$$f\left(x\right) = \frac{1}{x}\left(\ln B - \ln A\right) \qquad A < x < B \tag{23}$$

Distribution Function: $$F(x) = \frac{\ln x - \ln A}{\ln B - \ln A} \quad A < x < B \tag{24}$$

Expected Value: $$E(X) = \frac{B - A}{\ln B - \ln A} \tag{25}$$

Variance: $$V(X) = (B - A)\left[\frac{(\ln B - \ln A)(B + A) - 2(B - A)}{2(\ln B - \ln A)^2}\right] \tag{26}$$

Median: $$X_{0.5} = \sqrt{AB} \tag{27}$$

Use of the log uniform distribution is appropriate when all that is known about a parameter is its range (a,b) and B/A » 10; that is, the range (a,b) spans many orders of magnitude.

PAR 3.1.8 Log Cumulative Distribution

In this case, the independent variable is Y, where Y = log X. As with the cumulative distribution, this distribution is described by a set of N ordered pairs:

$$(y_p\, 0), (y_2, P_2), (y_3, P_3), \ldots, (y_N, 1) \; \{\text{that is}, P_1 = 0 \text{ and } P_N = 1 \text{ always}\} \tag{28}$$

where $y_1 < y_2 < y_3 < \ldots < y_N$ *and* $0 < P_2 < P_3 < \ldots < P_{N-1} < 1$

Because of the nature of the data, the PDF for this distribution takes the form:

$$P(\xi) = \begin{cases} 0 & \text{if } \xi < x1 \\ \dfrac{P_n - P_{n-1}}{\ln x_n - \ln x_{n-1}} \dfrac{1}{\xi} & \text{if } x_{n-1} \le \xi \le x_n, n = 2,3,_,N \\ 0 & \text{if } \xi \ge x_N \end{cases} \tag{29}$$

and so the CDF takes the form:

$$P_r X \le \xi = \begin{cases} 0 & \text{if } \xi < x_1 \\ P_{n-1} + \dfrac{(P_n - P_{n-1})(\ln\xi - \ln xn - 1)}{\ln x_{n-1} n x_{n-1}} & \text{if } \dfrac{x_{n-1} \le \xi \le x_x}{n - 2,3,_,N} \\ 1 & \text{if } \xi > x_N \end{cases} \tag{30}$$

Expected Value: $$E(X) = \sum_{n=2}^{N} (P_n - P_{nl}) \frac{(x_n - x_{n-1})}{\ln x_n - \ln x_{n-1}} \tag{31}$$

Variance: $$V(X) = \sum_{n=2}^{N} \frac{1}{2}(P_n - P_{n-1}) \frac{x_n^2 - x_{n-1}^2}{\ln x_n - \ln x_{n-1}} - \{E(X)\}^2 \quad (32)$$

Median:

$$X_{0.5} = 10^{**}\left\{x_{m-1} + (x_m - x_{m-1})\frac{(0.50 - P_{m-1})}{P_m - P_{m-1}}\right\} \text{ where } P_{m-1} \le 0.50 \le P_m . \quad (33)$$

PAR 3.1.9 Lognormal Distribution

If X ~ normal distribution with mean, μ, and variance, σ^2, and $Y = e^X$, the Y has a lognormal distribution. (34)

Density function: $$f(y) = \frac{1}{y\sigma\sqrt{2\pi}} \exp\left\{\frac{-(\ln y - \mu)}{2\sigma^2}\right\} \quad y > 0 \quad (35)$$

Distribution function: $$F(x) = \int_0^y f(t)\,dt \quad y > 0 \quad (36)$$

Expected value and variance:

$$E(Y) = \exp\left(\mu + \frac{\sigma^2}{2}\right) \quad V(Y) = \exp(2\mu + \sigma)\,[\exp(\sigma^2) - 1] \quad (37)$$

Median: $$X_{0.5} = e^{\mu} \quad (38)$$

As with the normal distribution, the lognormal distribution requires lowrange and hirange values. These values are in logarithmic form and are utilized in a normal distribution to determine a mean (μ) and a variance (σ^2), which in turn are used to identify the expected value and variance for the lognormal distribution (Iman and Shortencarier 1984).

PAR 3.1.10 Constants

Parameters may also be assigned a constant value in the PA parameter database. These parameters are tabulated at the end of the appendix.

PAR 4.0 PARAMETER CORRELATION

Parameter correlations used in PA are exclusively in LHS. Consequently, parameter correlations affect only sampled parameters described in the attached parameter sheets. Two types of parameter correlations are used. They are defined as explicit parameter correlation and induced parameter correlation. This section addresses the following criteria concerning parameter correlations, as specified in 40 CFR § 194.23(c)(6):

> (c) Documentation of all models and computer codes included, as part of any compliance application performance assessment calculation shall be provided. Such documentation shall include, but shall not be limited to:
>
> (6) An explanation of the manner in which models and computer codes incorporate the effects of parameter correlation.

Explicit parameter correlations are introduced or prohibited in LHS by the restricted pairing technique of Iman and Conover (1982). Three parameter correlations are specified in this PA through this technique. These correlations are all related to rock compressibility and permeability. In the Marker Bed (MB) 139 material region in BRAGFLO, rock compressibility (S_MB139:COMP_RCK) and intrinsic permeability (S_MB139:PRMX_LOG) are inverse-correlated with a correlation coefficient of -0.99. In the Salado Formation impure halite material region in BRAGFLO, rock compressibility (S_Halite:COMP_RCK) and intrinsic permeability (S_Halite:PRMX_LOG) are inverse correlated with a correlation coefficient of -0.99. In the Castile brine reservoir material region in BRAGFLO, rock compressibility (Castiler:COMP_RCK) and intrinsic permeability (Castiler:PRMX_LOG) are inverse correlated with a correlation coefficient of -0.75. Explicit parameter correlation is not used to correlate other sampled parameters.

Rock compressibilities and intrinsic permeabilities are correlated to be most consistent with interpretations of the hydraulic tests that have been performed in these units. In hydraulic testing, hydraulic diffusivity (the ratio of permeability to compressibility) is determined more precisely than either permeability or compressibility alone. Introducing the correlation of the permeability and compressibility parameters in PA better represents the knowledge of the formation gained from hydraulic testing than specifying no correlation whatsoever.

An induced correlation in PA is created when a parameter sampled in LHS (the underlying variable) is used to define the values of other parameters (defined variables). This is a prevalent method of correlation in this PA. For example, uncertainty in dissolved actinide oxidation states is represented in LHS by sampling the OXSTAT parameter (Global:OXSTAT). The results of this sampling are used in part to determine actinide solubilities (NUTS and PANEL), colloidal actinide concentrations (NUTS and PANEL), and K_D values (SECOTP2D) used for a particular vector. Selected examples of other induced parameter correlations include:

- the underlying variable x-direction permeability and the defined variables y- and z-direction permeabilities in many materials (BRAGFLO),
- the underlying variable x-direction permeability and defined variable threshold pressure in many materials (BRAGFLO),
- the underlying variable Lower Salado Clay permeability and the defined variable permeabilities of other clay members of the shaft seal system (BRAGFLO), and
- the underlying variable residual gas saturation (or other two-phase flow parameters) in many materials and the defined variable residual gas saturation (or other two-phase flow parameters) in other materials (BRAGFLO).

- the underlying variable americium properties and the defined variable curium properties (NUTS, PANEL, and SECOTP2D).

Where relevant, parameter sheets in this attachment contain information related to parameter correlation.

No correlations were used in this PA for certain parameters used to describe transport in the Culebra for which the possibility of correlation might be suspected. The treatment in PA is most consistent with available information, because, as discussed in CCA Appendix MASS (Attachments MASS 15-10 and 15-6, 14), correlation of well-to-well transmissivity versus well-to-well advective porosity and matrix block length is not evident in existing data, nor is the correlation between advective porosity and matrix block length.

There are four additional ways in which parameter correlations may be considered to be used in this PA, although they are not typically discussed as correlations per se. In a given LHS sample element, there is a correlation of 1 (100 percent) between the single observation of subjective uncertainty (the LHS sample for a complementary cumulative distribution function (CCDF)) with all of the sequences of random future events (scenarios) used to construct a CCDF. This is discussed in Section 6.1.

A correlation is made between the scenario being considered and the chemical properties (chemical composition) of brine in the repository (the physical properties viscosity and density are assumed to be the same for all scenarios). Brine composition affects actinide solubility. For undisturbed performance and E2 scenarios, brine composition is considered to be that of Salado brine. For the E1 and E1E2 scenarios, the brine composition is considered to be that of Castile brine. This is discussed in Section 6.4.3.4.

There are some correlations made in the construction of a CCDF regarding the similarity of events in a sequence of random future events. For example, the direct releases resulting from a third or later intrusion are determined from the calculated conditions following the second intrusion. This is discussed in Section 6.4.13.

Finally, there are also correlations among model parameters developed explicitly by the governing equations of computational models used. For example, the porosity of nodal blocks in BRAGFLO is a function of the initial porosity, pressure change, and compressibility. These types of relationships among parameters are documented in the Appendix PA.

PAR 5.0 KEY TO PARAMETER SHEETS

The parameter sheets included in this attachment contain a variety of information, some of which is extracted from the WIPP PA parameter database. Parameters are listed in the order in which they are retrieved from the WIPP PA parameter database. Eleven of the parameters retrieved from the database are dummy parameters and are not actually utilized by the code. Those parameters are therefore not are not listed or discussed in this section. Breaks in the numerical sequence of the parameters are due to dummy parameters.

Information presented in the parameter sheets is grouped into boxes labeled as follows:

PAR 5.1 Parameter(s)

The name of the parameter and the disposal system feature with which it is associated.

PAR 5.2 Parameter Description

The Parameter Description box defines the parameter and, where appropriate, explains the role of the parameter in the modeling.

PAR 5.3 Material and Property Name(s)

This box provides a link to the PA parameter database. The parameter label listed first is taken from the PA model parameter database and identifies the type of material in the disposal system being modeled (for example, S_MB139 means Salado MB139). The second label describes the PA model parameter name for the property of the material physical or operational meaning for the parameter (for example, SAT_RBRN means residual brine saturation).

PAR 5.4 Computational Code(s)

A list of the current computational models used by the PA Department that use this parameter.

PAR 5.5 Parameter Statistics

This box identifies the minimum and maximum for uniform distributions, the mode, minimum and maximum for Triangular distributions, the probability and the value associated with that probability for cumulative and delta distributions, and the measured values for the student's-t distribution. All values provided in this attachment were derived from the WIPP PA parameter database. These numbers may differ slightly from those contained in the Parameter Data Entry Forms because of rounding.

PAR 5.6 Units

The physical units of the parameters (usually expressed in metric units).

PAR 5.7 Distribution Type

This box identifies the type of parameter distribution (see PAR 3.1).

Data: The basis for the parameter values or parameter distribution is provided in this section. All values provided in this attachment were derived from the WIPP PA parameter database. These numbers may differ slightly from those contained in the Parameter Data Entry Forms because of rounding. The parameters are derived from the following kinds of data and information:

- Site-specific or waste-specific experimental data. These data includes information obtained from in situ experiments and research conducted at off-site laboratories (for example, permeability data, microbial gas generation). This category also includes

simulated waste experiments and may indicate correlations made with other material regions based on professional judgment.

- Waste-specific observational data. This category includes data obtained through observation or empirical analysis, such as semi-quantitative and qualitative visual characterization or acceptable knowledge of transuranic (TRU) waste (for example, waste components).

- Professional judgment. This category of information may involve the use of experimental or observational data from other non-WIPP contexts; interpreting information obtained from the general literature; or may be based on general engineering knowledge (see below).

- General Literature Data. This category of information includes that obtained from reports, journal articles, or handbooks relevant to systems or processes being modeled in the PA. It is often employed in conjunction with professional judgment.

- General Engineering Knowledge. This category of information identifies parameter values obtained from knowledge of standard engineering principles.

Readers are referred to justification documents and associated data packages maintained in the SNL WIPP Records Center for additional information.

PAR 5.8 Discussion

This box identifies the source(s) of parameter value(s) and the rationale for the parameter distribution and may clarify use of a particular parameter. Other relevant background information is also included in this section, where clarification is appropriate.

PAR 5.9 References

This box contains the references pertaining to parameter selection. The references are contained within the three levels of parameter and data documentation: (1) Parameter Data Entry Form, and (2) parameter supporting information packages. Selected references cited in the parameter supporting information packages are included in the parameter sheets to establish data quality.

PAR 6.0 EPAUNI OUTPUT DATA

Tables PAR-50 – 61 represent output files from the code EPAUNI Version 1.15A (for more information regarding EPAUNI output files, see Fox [2003]).

Table PAR-50 contains data from the EPAUNI output files EPU_CRA1_CH_UNIT2.OUT and EPU_CRA1_RH_UNIT2.OUT. The table contains waste stream volume and EPA units per m^3 for each of the CH-TRU and RH-TRU waste streams over each of the 10 time periods after closure (0, 100, 125, 175, 350, 1000, 3000, 5000, 7500, and 10,000 years). It also contains the probability of hitting each waste stream during a drilling intrusion at each of the 10 time periods after closure.

Tables PAR-51 – 60 contains data from the EPAUNI output file EPU_CRA1_CH_ ACTIVITY.DIA. The table contains activity information for each of the seven isotopes of concern for EPA unit calculations (^{241}Am, ^{244}Cm, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{234}U), the total activity used to calculate EPA units (called Total EPA Curies), and the EPA units for each CH-TRU waste stream. The code calculates these activities for each of the 10 time periods after closure (0, 100, 125, 175, 350, 1000, 3000, 5000, 7500, and 10,000 years) based on build-up and decay.

Table PAR-61 contains data from the EPAUNI output file EPU_CRA1_RH_ACTIVITY.DIA. The table contains activity information for each of the nine isotopes of concern for EPA unit calculations (^{241}Am, ^{244}Cm, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{234}U, ^{137}Cs, and ^{90}Sr), the total activity used to calculate EPA units (called Total EPA Curies), and the EPA units for each RH-TRU waste stream. The code calculates these activities for each of the 10 time periods after closure (0, 100, 125, 175, 350, 1000, 3000, 5000, 7500, and 10,000 years) based on build-up and decay.

PAR 7.0 PARAMETER SHEETS

Index of LHS Sampled Parameters:

Parameter #	Material Name	Property Name
Parameter 1	STEEL	CORRMCO2
Parameter 2	WAS_AREA	PROBDEG
Parameter 3	WAS_AREA	GRATMICI
Parameter 4	WAS_AREA	GRATMICH
Parameter 5	CELLULS	FBETA
Parameter 6	WAS_AREA	SAT_RGAS
Parameter 7	WAS_AREA	SAT_RBRN
Parameter 8	WAS_AREA	SAT_WICK
Parameter 9	DRZ_PCS	PRMX_LOG
Parameter 10	CONC_PCS	PRMX_LOG
Parameter 11	SOLU4	SOLCIM
Parameter 12	SOLTH4	SOLCIM
Parameter 14	CONC_PCS	SAT_RGAS
Parameter 15	CONC_PCS	SAT_RBRN
Parameter 16	CONC_PCS	PORE_DIS
Parameter 17	S_HALITE	POROSITY
Parameter 18	S_HALITE	PRMX_LOG
Parameter 19	S_HALITE	COMP_RCK
Parameter 20	S_MB139	PRMX_LOG
Parameter 21	S_MB139	COMP_RCK
Parameter 22	S_MB139	RELP_MOD
Parameter 23	S_MB139	SAT_RBRN
Parameter 24	S_MB139	SAT_RGAS
Parameter 25	S_MB139	PORE_DIS
Parameter 26	S_HALITE	PRESSURE
Parameter 27	CASTILER	PRESSURE
Parameter 28	CASTILER	PRMX_LOG
Parameter 29	CASTILER	COMP_RCK
Parameter 30	BH_SAND	PRMX_LOG
Parameter 31	DRZ_1	PRMX_LOG
Parameter 32	CONC_PLG	PRMX_LOG
Parameter 34	SOLAM3	SOLSIM
Parameter 35	SOLAM3	SOLCIM
Parameter 36	SOLPU3	SOLSIM
Parameter 37	SOLPU3	SOLCIM
Parameter 38	SOLPU4	SOLSIM

Index of LHS Sampled Parameters (continued):

Parameter #	Material Name	Property Name
Parameter 39	SOLPU4	SOLCIM
Parameter 40	SOLU4	SOLSIM
Parameter 41	SOLU6	SOLSIM
Parameter 42	SOLU6	SOLCIM
Parameter 43	SOLTH4	SOLSIM
Parameter 44	PHUMOX3	PHUMCIM
Parameter 45	GLOBAL	OXSTAT
Parameter 46	CULEBRA	MINP_FAC
Parameter 47	GLOBAL	TRANSIDX
Parameter 48	GLOBAL	CLIMTIDX
Parameter 49	CULEBRA	HMBLKLT
Parameter 50	CULEBRA	APOROS
Parameter 51	CULEBRA	DPOROS
Parameter 52	U+6	MKD_U
Parameter 53	U+4	MKD_U
Parameter 54	PU+3	MKD_PU
Parameter 55	PU+4	MKD_PU
Parameter 56	TH+4	MKD_TH
Parameter 57	AM+3	MKD_AM
Parameter 58	BOREHOLE	TAUFAIL
Parameter 60	GLOBAL	PBRINE
Parameter 61	BOREHOLE	DOMEGA
Parameter 62	SHFTU	SAT_RBRN
Parameter 63	SHFTU	SAT_RGAS
Parameter 64	SHFTU	PRMX_LOG
Parameter 65	SHFTL_T1	PRMX_LOG
Parameter 66	SHFTL_T2	PRMX_LOG
Parameter 75	SPALLMOD	RNDSPALL

Index of DRSPALL Sampled Parameters:

Material Name	Property Name
SPALLMOD	REPIPORE
SPALLMOD	REPIPERM
SPALLMOD	TENSLSTR
SPALLMOD	PARTDIAM

Refer to Table PAR-12 for the LHS Sampled Values for the Spall Model.

Parameter 1: Inundated Corrosion Rate for Steel Without CO_2 Present

Parameter Description:

This parameter is used to describe the rate of anoxic steel corrosion under brine-inundated conditions and with no CO_2 present (Appendix PA, Section PA-4.2).

Material and Property Name(s):

STEEL CORRMCO2

Computational Code: BRAGFLO

minimum	maximum
0.0	3.17×10^{-14}

Units: Meters/second

Distribution Type: Uniform

Data: Site- Specific Experimental Data

A discussion of the data associated with this parameter for the initial application may be found in Appendix PAR (DOE 1996). Justification for the change of this parameter for CRA may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the PA Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

Based on experimental results (Telander and Westerman 1993; 1997), steel is expected to corrode in the repository via the following reaction (Wang and Brush, 1996a, 1996b):

$$Fe^0 + 2H_2O \rightarrow Fe(OH)_2 + H_2$$

The rate of this reaction under a brine-inundated condition (no CO_2 present at all) is estimated to be 0 - 0.5 μm/year (0 - 1.59×10^{-14} m/s). This steel corrosion rate was estimated by DOE based on long-term anoxic steel corrosion experiments. Because of its uncertainty, this parameter was treated as a sampled variable in the CCA with a uniform distribution ranging from 0.0 to 1.59×10^{-14} m/s (see CCA Appendix PAR).

Subsequent to the CCA, the EPA questioned both the upper and lower bounds on DOE's assigned range of values for CORRMCO2. After evaluating the values DOE assigned to the steel corrosion rate, the EPA carefully examined experimental results. In all cases, except for the case of high pressure, the EPA, like the DOE, concluded that the steel corrosion rate used in the CCA was appropriate.

However, the EPA questioned the upper bound for the steel corrosion rate in the case of high pressures in the repository. Some experiments of six months duration conducted on steel immersed in brine under a hydrogen atmosphere indicated that the steel corrosion rate first

decreased at pressures from 2 to 70 atm and then increased at pressures from 70 to 127 atm (Telander and Westerman 1993). Because the repository may approach or exceed lithostatic pressure and because of the increase in the experimental corrosion rates at higher pressures, the EPA requested that DOE double the upper bound of the inundated corrosion rate to 3.17×10^{-14} m/s (EPA 1998). DOE has adopted this revised range for the rate of anoxic steel corrosion (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS 528582

Telander M. R. and Westerman, R.E. 1993. Hydrogen Generation by Metal Corrosion in Simulated Waste Isolation Pilot Plant Environments: Progress Report for the Period November 1989 through December 1992. SAND92-7347. Sandia National Laboratories. Albuquerque, NM.

Telander M. R. and Westerman, R.E. 1997. Hydrogen Generation by Metal Corrosion in Simulated Waste Isolation Pilot Plant Environments. SAND96-2538. Sandia National Laboratories. Albuquerque, NM.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Vols 1-XXI.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C. ERMS 525158.

Wang Y., and Brush L. H. 1996a. “Estimates Of Gas-Generation Parameters For The Long-Term WIPP PA” Memorandum to M. Tierney, 1/26/1996.. Sandia National Labs. Albuquerque, NM. ERMS 231943

Wang Y., and Brush L. H. 1996b. “Modify The Stoichiometric Factor Y In The BRAGFLO To Include The Effect Of MgO Added To WIPP Repository As A Backfill”. Memorandum to M. Tierney, 2/23/1996. Sandia National Labs. Albuquerque, NM. ERMS 232286.

Parameter 2: Probability of Microbial Degradation of Plastics and Rubbers in the Waste in the Event of Significant Microbial Gas Generation

Parameter Description:

This parameter is used to index alternative models of microbial degradation of plastics and rubbers in the waste in the repository in the event of significant microbial gas generation. It is a sampled parameter for the waste emplacement area and the waste, and the values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA PROBDEG)

Computational Code: BRAGFLO

Value	0	1.0	2.0
Percentiles	.50	.25	.25

Units: None

Distribution Type: Delta (see Figure PAR-1 for values.)

Data: General Engineering Knowledge - Professional Judgment

A discussion of the data associated with this parameter may be found in Tierney (1996) and the following parameter records package: Estimates of Gas Generation Parameters Required for BRAGFLO (ERMS #230819).

Discussion:

Cellulosics, plastics, and rubbers have been identified as the major organic materials to be emplaced in the WIPP repository (Appendix TRU WASTE) and could be degraded by microbes in 10,000 years. The occurrence of significant microbial gas generation in the repository will depend on: (1) whether microbes capable of consuming the emplaced organic materials will be present and active; (2) whether sufficient electron acceptors will be present and available; and (3) whether enough nutrients will be present and available. Considering uncertainties in evaluation of these factors and also in order to bracket all possible effects of gas generation on the WIPP PA, a probability of 50 percent is assigned to the occurrence of significant microbial gas generation (Wang and Brush 1996).

There are two factors that may potentially increase the biodegradability of these materials: long time scale and cometabolism. Over a time scale of 10,000 years, plastics and rubbers may change their chemical properties and therefore their biodegradability.

Cometabolism means that microbes degrade an organic compound, but do not use it or its constituent elements as a source of energy; these are derived from other substrates (Alexander 1994). In the WIPP repository, plastics and rubbers, which are resistant to biodegradation, may still be cometabolized with cellulosics and other more biodegradable organic compounds.

Because of these uncertainties, a probability of 50 percent is assigned to the biodegradation of plastics and rubbers in the event of significant microbial gas generation (Wang and Brush 1996).

The distribution for PROBDEG parameter is illustrated in Figure PAR-1. The parameter value ranges over the integers from 0 (no significant microbial gas generation) to 2 (significant microbial gas generation with degradation of plastics and rubbers); the third choice, a parameter value of 1, represents significant microbial gas generation without degradation of plastics and rubbers.

Parameter Data Entry Form ERMS: #234881

References:

Alexander, M. 1994. Biodegradation and Bioremediation. Academic Press, N.Y.

DOE/CAO. 1996. Transuranic Waste Baseline Inventory Report (Rev. 2). DOE/CAO-95-1121.

Tierney, M. 1996. Memorandum to File, Re: Reasons for choice of the PROBDEG parameter (id nos. 2824 and 2823) on February 22, 1996, March 29, 1996 (contained in ERMS 234881).

Wang, Y., and Brush, L. 1996. Memorandum to Martin Tierney, Re: Estimates of Gas-Generation Parameters for the Long-Term WIPP Performance Assessment, January 26, 1996. ERMS 231943.

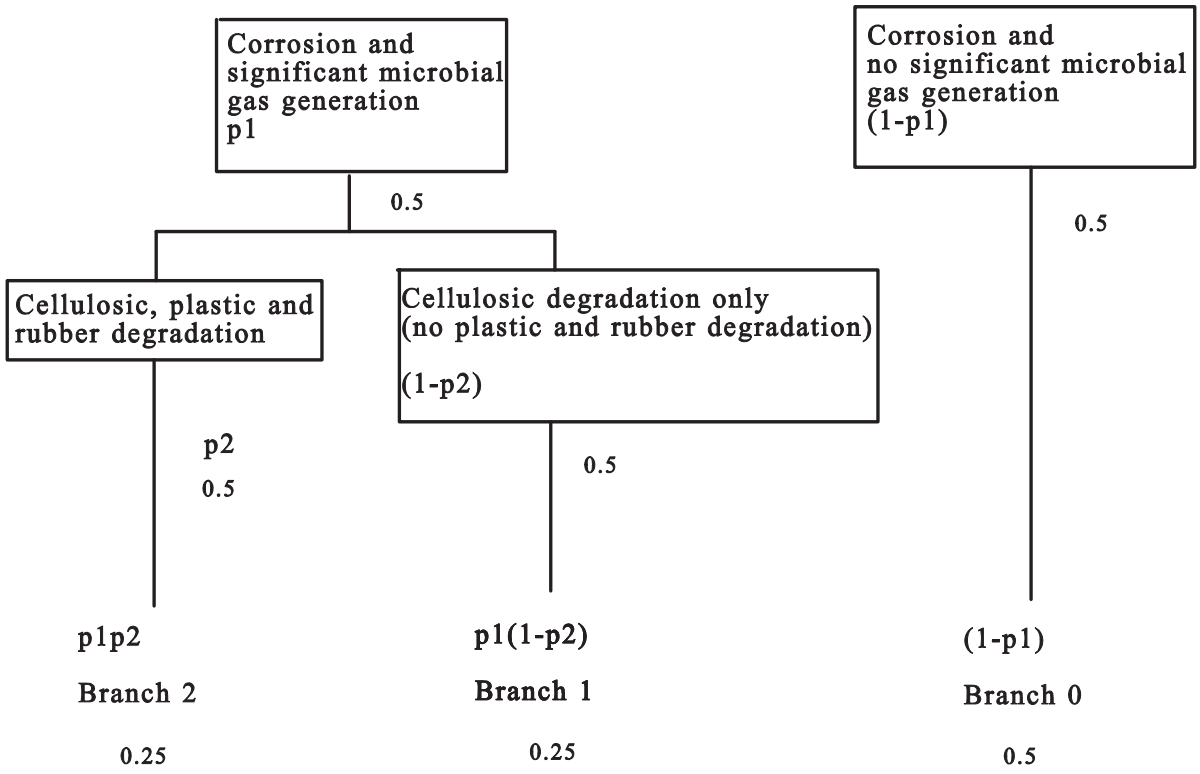

p1 = probability of occurrence of significant microbial gas generation (=50 percent)

p2 = probability of occurrence of plastics and rubber biodegradation in the event of significant gas generation (=50 percent)

Figure PAR-1. Logic Diagram for Possible Outcomes and Probabilities for the Parameter PROBDEG (modified from Tierney 1996)

Parameter 3: Biodegradation Rate of Cellulosics Under Brine-Inundated Conditions

Parameter Description:

This parameter is used to describe the rate of cellulosics biodegradation under anaerobic, brine-inundated conditions (see Appendix PA, Section PA-4.2). It is a sampled parameter for the waste emplacement area and the waste, and the values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA GRATMICI

Computational Code: BRAGFLO

minimum	maximum
3.171×10^{-10}	9.5129×10^{-9}

Units: Moles/(kilograms*second)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the parameter records package: Estimates of Gas Generation Required for BRAGFLO (ERMS #230819).

Discussion:

The maximum rate is estimated using the data obtained from both NO_3 - and nutrients-amended experiments, whereas the minimum rate is derived using the data obtained from the inoculated-only experiments without any nutrient and NO_3 amendment. The rates were calculated from the initial linear part of the experimental curve of CO_2 vs. time by assuming that cellulosics biodegradations in those experiments were nitrate- or nutrient-limited (Wang and Brush 1996).

Parameter Data Entry Form ERMS: #234928

References:

Wang, Y. and Brush, L. 1996. Memorandum to Martin Tierney, Re: Estimates of Gas-Generation Parameters for the Long-Term WIPP Performance Assessment, January 26, 1996. ERMS 231943.

Parameter 4: Biodegradation Rate of Cellulosics Under Humid Conditions

Parameter Description:

This parameter is used to describe the rate of cellulosics biodegradation under anaerobic, humid conditions (see Appendix PA, Section PA-4.2). It is a sampled parameter for the waste emplacement area and the waste, and the values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA GRATMICH

Computational Code: BRAGFLO

minimum	maximum
0.0	1.2684×10^{-9}

Units: Moles/(kilograms*second)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the parameter records package: Estimates of Gas Generation Required for BRAGFLO (ERMS #230819).

Discussion:

The maximum rate was estimated from cellulosics biodegradation experiments under anaerobic, humid conditions. The minimum rate is set to zero, corresponding to the cases where microbes become inactive because of water or nutrient stresses (Wang and Brush 1996).

Parameter Data Entry Form ERMS: #234923

References:

Wang, Y. and Brush, L. 1996. Memorandum to Martin Tierney, Re: Estimates of Gas-Generation Parameters for the Long-Term WIPP Performance Assessment, January 26, 1996. ERMS 231943.

Parameter 5: Factor β for Microbial Reaction Rates

Parameter Description:

Factor β is an index that characterizes the stoichiometry used to calculate the microbially generated gas, accounting for interaction with gases reacting with steel and steel corrosion products (see Appendix PA, Section PA-4.2).

Material and Property Name(s):

CELLULS FBETA)

Computational Code: BRAGFLO

minimum	maximum
0.0	1.0

Units: None

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the parameter records package: Estimates of Gas Generation Required for BRAGFLO (ERMS #230819).

Discussion:

Microbially generated gases CO_2 and H_2S may react with steel and steel corrosion products. Factor β characterizes the extent of CO_2 and H_2S consumption by those reactions: see Equation (18) in Wang and Brush 1996.

Parameter Data Entry Form ERMS: #231826

References:

Wang, Y. and Brush, L. 1996. Memorandum to Martin Tierney, Re: Estimates of Gas-Generation Parameters for the Long-Term WIPP Performance Assessment, January 26, 1996. ERMS #231943.

Parameter 6: Residual Gas Saturation - Repository

Parameter Description:

The residual (critical) gas saturation (S_{gr}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves. S_{gr} corresponds to the degree of waste-generated gas saturation necessary to create an incipient interconnected pathway in porous material, a condition required for porous rock to be permeable to gas. Below values of the S_{gr}, gas is immobile. It is a sampled parameter for the waste emplacement area and the waste. The values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA SAT_RGAS

Computational Code: BRAGFLO

minimum	maximum
0	0.15

Units: None

Distribution Type: Uniform

Data: General Literature and Professional Judgment

The parameter values are based on a November 15, 1995 Solutions Engineering letter report to D.M. Stoelzel of Sandia National Laboratories entitled “Critical (residual) Gas Saturation Recommendations for WIPP.”

Discussion:

Under conditions of chemical and biochemical gas generation and repository closure, gas saturation may increase to a level where the pore network in repository material regions becomes connected and gas permeability begins to increase. The lowest gas saturation at which continuous gas flow will occur is the residual (critical) gas saturation (S_{gr}). In a review of studies involving S_{gr}, Solutions Engineering (1996) reports values ranging from 0 to 27 percent. The assigned range for S_{gr} between 0 to 15 percent is consistent with recommendations in the Solutions Engineering report.

Parameter Data Entry Form ERMS: #234905

References:

Solutions Engineering. 1996. “Critical Gas Saturation Recommendations for WIPP.” Letter Report to D.M. Stoelzel, Sandia National Laboratories, November 15, 1995, Albuquerque, New Mexico. ERMS # 238769.

Parameter 7: Residual Brine Saturation – Waste Area

Parameter Description:

The residual brine saturation (S_{br}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves. Referred to also as S_{wr} (wetting phase) or S_{lr} (liquid phase), residual brine saturation is the point reached under high gas saturation conditions when brine is no longer continuous throughout the pore network and relative brine permeability becomes zero. Below the value of the S_{br}, brine is immobile. It is a sampled parameter for the waste emplacement area and the waste, and the values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA SAT_RBRN

Computational Code: BRAGFLO

minimum	maximum
0	0.55

Units: None

Distribution Type: Uniform

Data: General Literature and Professional Judgment

Two-phase flow parameters have not been measured for materials representing a collapsed empty, back-filled, or waste-filled room. Therefore, the parameter values are based on literature values for unconsolidated materials.

Discussion:

Brooks and Corey evaluated their two-phase characteristic equations against capillary pressure and relative permeability data obtained in laboratory experiments (Brooks and Corey 1964). Mualem (1976) proposed a modified procedure to that of Brooks and Corey for determining the wetting phase (S_{wr}) permeability curve by adding the constraint that the extrapolated curve should pass through the highest capillary pressure data point. Although their wetting phase relative permeability predictions are similar to each other and to the data, the Mualem procedure, in some cases, results in S_{wr} values less than those predicted by the Brooks and Corey model. Consequently, Table PAR-1 lists the Mualem (1976) residual wetting phase saturations to ensure that the potential for brine mobility is not underestimated. As indicated in Table PAR-1, single-phase liquid permeabilities of the Brooks and Corey materials are of the same order of magnitude as those assigned to waste disposal regions (10^{-13} m^2).

Table PAR-1. Brooks and Corey (1964) Materials Parameters - Unconsolidated Media[a]

Material	Permeability (m^2)[b]	Porosity	S_{wr}[c]
Volcanic Sand	1.1×10^{-11}	0.365	0.137
Fine Sand	2.85×10^{-12}	0.360	0.140
Glass Beads	1.05×10^{-11}	0.383	0.0783
Fragmented Mixture	1.50×10^{-11}	0.441	0.275
Fragmented Fox Hill Sandstone	1.61×10^{-11}	0.503	0.318
Touchet Silt Loam	5.00×10^{-13}	0.469	0.277
Poudre River Sand	2.26×10^{-11}	0.364	0.0824
Amarillo Silty Clay Loam	2.34×10^{-12}	0.455	0.242
Consolidated Berea Sandstone	4.81×10^{-13}	0.206	0.243
Consolidated Hygiene Sandstone	1.78×10^{-13}	0.250	0.560

a - Consolidated materials are identified in the material column
b - Single-phase liquid permeability
c - Mualem S_{wr} corrected for comparison to Brooks and Corey (1964)
S_{wr} - Wetting phase residual saturation

Parameter Data Entry Form ERMS: #234902

References:

Brooks, R.H., and Corey, A.T. 1964. Hydraulic Properties of Porous Media. Hydrology Paper No. 3. Fort Collins, CO: Colorado State University. NWM Library.

Mualem, Y. 1976. A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media. Water Resources Research. Vol. 12, no. 3, 513-522.

Vaughn, Palmer. 1996. Memo to Martin Tierney. RE: WAS_AREA and REPOSIT/SAT_RBRN Distribution, February 13, 1996. ERMS 234902.

Parameter 8: Wicking Saturation – Waste Area

Parameter Description:

The wicking saturation in the waste is used in the gas generation model (see Appendix PA, Section PA-4.2). It is a sampled parameter for the waste emplacement area and the waste, and the values are then applied to the repository regions outside of the panel region.

Material and Property Name(s):

WAS_AREA SAT_WICK

Computational Code: BRAGFLO

minimum	maximum
0.0	1.0

Units: None

Distribution Type: Uniform

Data: Professional Judgment

The wicking parameter value varies from 0 (0 percent saturation) to 1.0 (100 percent saturation) and the parameter is assumed to be uniformly distributed.

Discussion:

Wicking is the ability of a material to carry a fluid by capillary action above the level it would normally seek in response to gravity. The use of a two-phase Darcy flow model in BRAGFLO includes possible effects of capillary action, but uncertainty remains about the extent to which the assumed homogeneous properties of the waste adequately characterize wicking. Because estimated rates of gas generation are higher for waste that is in direct contact with brine, brine saturation in the repository is adjusted in BRAGFLO to account for the possibility of wicking in the waste.

The adjustment is done as follows:

$$S_{b,eff} = S_b + S_w,$$

and

$$S_{b,eff} \leq 1.0,$$

where S_b is the brine saturation in the waste calculated by BRAGFLO, S_w is the wicking saturation that describes the additional amount of brine that may be present and in contact with the waste because of wicking, and $S_{b,eff}$ is the effective brine saturation used to determine the gas generation rates used in the analysis.

Parameter Data Entry Form ERMS: #234908

References:

N/A

Parameter 9: Log of Intrinsic Permeability – DRZ directly above the concrete portion of the panel closure

Parameter Description:

This parameter describes the permeability of cells immediately above the concrete part of the panel closures in the upper DRZ (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions. The permeability of these cells will be sampled to reflect the range expected for healed DRZ. This will capture the effect of rigid panel closures that include excavation of the DRZ immediately surrounding the concrete monolith that is emplaced quickly to prevent the further local development of DRZ, and healing of the DRZ due to compressive stresses imposed by creep closure around the rigid structure. In this way the panel closures are modeled as effective seals, including healing effects, in accordance with their design.

Material and Property Name(s):

DRZ_PCS PRMX_LOG
DRZ_PCS PRMY_LOG
DRZ_PCS PRMZ_LOG

Computational Code: BRAGFLO

mode	minimum	maximum
-18.75	-20.70	-17.0

Units: Log (meters squared)

Distribution Type: Triangular

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: Analysis Reports Relating to Analysis Plan AP-086 (ERMS 520523) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

Option D panel closures are designed to remove the DRZ above and below the panel entry drifts. Loose salt in the roof would also be taken down just prior to construction of the concrete monolith. The remaining salt surrounding the panel closure concrete would be subjected to compressive stresses, which would tighten any disturbed zones. Owing to the rounded configuration of Option D, the compressive stress state creates a situation very favorable for concrete: high compressive stresses and low stress differences. In turn, the compressive stresses developed within the salt will quickly heal any damage caused by construction excavation, thereby effectively eliminating the DRZ along the length of the panel closure. The volume of salt immediately above and below the rigid concrete monolith will likely approach the intrinsic permeability of Salado salt.

Undisturbed Salado salt is essentially impermeable. A low-end permeability would be immeasurably low (10^{-23} m^2, for example). The salt above and below the rigid monolith would assume relatively impermeable conditions. Permeability values employed are the same range as described for the concrete (2×10^{-21} to 10^{-17} m^2) (Stein 2002). The reason this range was selected rather than using the range approved for use with the intact halite is twofold. First, because the healed DRZ zone is relatively thin (9.06-m-thick in the model) small-scale heterogeneities including thin clay seams introduce uncertainties to how well this DRZ will impede flow. Second, the Panel Closure System will perform as a composite system that includes the healed DRZ, the concrete monolith, and the surrounding marker beds. In this system any flow will be focused through the highest permeability component of the system. In order that the PA calculations represent the uncertainties of exactly where any flow will occur during the regulatory period, we set the permeability range of the healed DRZ equal to the concrete so that there will be an equal probability of potential flow in either material. The permeability distributions can be implemented in PA by fitting a triangular distribution to the log of the permeability values described for concrete.

Parameter Data Entry Form ERMS: #520524

References:

Stein, J. 2002. Analysis Plan for Calculations of Salado Flow: Technical Baseline Migration (TBM), AP-086, February 13, 2002, ERMS #520612.

Parameter 10: Log of Intrinsic Permeability– Concrete portion of PCS

Parameter Description:

Log of the vertical and horizontal intrinsic permeability for the concrete portion of the Option D panel closure (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

CONC_PCS PRMX_LOG
CONC_PCS PRMY_LOG
CONC_PCS PRMZ_LOG

Computational Code: BRAGFLO

mode	minimum	maximum
-18.75	-20.70	-17.0

Units: Log (meters squared)

Distribution Type: Triangular

Data: Site- Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The distribution of permeability values for the concrete portion of the Option D panel closure is the same as were used for the concrete portion of the shaft seal in the original CCA (DOE 1996) shaft seal model (Stein 2002). The following justification is provided for permeability values used for the shaft seal concrete (see material CONC_T1, Appendix PAR in DOE 1996)

As reported by Repository Isolation Systems Department (1996), traditional freshwater concrete has been widely used for hydraulic applications such as water storage tanks, water and sewer systems, and massive dams because it has exceptionally low permeability (less than 10^{-20} m^2 upon hydration). Salado Mass Concrete (SMC) is a specially-designed, salt-saturated concrete mix (Wakeley et al. 1994; Wakeley et al. 1995).

Pfeifle, et al. (1996) performed two permeability tests on concrete specimens prepared from cores recovered from the WIPP SSSPT field experiments and one test on an SMC specimen prepared from a sample batched by the Waterways Experiment Station (WES). The specimens were tested as received with no attempts made to dry the specimens or to determine their moisture contents. Each test was performed using nitrogen gas as the permeant, flowmeters to measure gas flow, and fluid pressure gradients of 0.3, 0.6, or 0.75 megapascals. Attempts were made to apply Klinkenberg corrections to measured values of permeability, but

the range in pressure gradients used in the testing was not large enough to establish any particular trend when the permeability data were plotted as a function of reciprocal mean fluid pressure.

A total of 18 permeability measurements were made on the three specimens. Measured permeabilities of the specimens were all very low with a range from 2.1×10^{-21} m^2 to 7.51×10^{-21} m^2 with an average of 4.71×10^{-21} m^2. Knowles and Howard (1996) presented results of field permeability tests performed in the WIPP SSSPT boreholes during 1985-1987 and 1993-1995. Although individual seal system component material permeabilities for concrete, DRZ salt, and salt were not determined, overall seal system permeabilities were determined and ranged from 1.0×10^{-20} m^2 to 1.0×10^{-17} m^2 and from 1.0×10^{-23} m^2 to 1.0×10^{-19} m^2 for the 1985–1987 tests and the 1993-1995 tests, respectively. These ranges encompass the laboratory values measured by Pfeifle, et al. (1996).

The data described above were derived from gas permeability measurements in which no Klinkenberg corrections were applied to the measured values. The Klinkenberg corrections were expected to be small because of the low mean pressure gradients used in the tests.

The interface between the Salado salt and the SMC components may provide a flow path around the SMC components. This flow path is possible if a small aperture develops as the concrete is curing or if the interface degrades because of corrosive brines. If such a flow path occurs, the effective permeability of the SMC will increase. Because of this uncertainty, the upper bound permeability was assigned to a value of -17, which corresponds to a permeability of 1.0×10^{-17} m^2. This value was selected after an effective permeability calculation was performed. In this calculation, the interface zone was assumed to have a permeability of 1.0×10^{-14} m^2 and concrete permeabilities were varied from 1.0×10^{-23} to 1.0×10^{-19} m^2. Assuming the interface zone had a thickness of 0.001 times the shaft radius or smaller, the effective permeability of the concrete was about 1.0×10^{-17} m^2 regardless of the value selected for the permeability of the SMC seal.

Parameter Data Entry Form ERMS: #520524

References:

Knowles, M.K. and Howard, C.L. 1996. “Field and Laboratory Testing of Seal Materials Proposed for the Waste Isolation Pilot Plant,” Proceedings of the Waste Management 1996 Symposium. Tucson, AZ, February 25-29, 1996. SAND95-2082C. Albuquerque, NM: Sandia National Laboratories. ERMS #230945.

Pfeifle, T.W., Hansen, F.D., and Knowles, M.K. 1996. “Salt-Saturated Concrete Strength and Permeability,” Proceedings of the ASCE Fourth Materials Engineering Conference, Washington, DC, November 1996 (accepted for publication).

Repository Isolation Systems Department. 1996. Waste Isolation Pilot Plant Shaft Sealing System Compliance Submittal Design Report. SAND96-1326. Sandia National Laboratories. Albuquerque, NM. August 1996.

Stein, J. 2002. Analysis Plan for Calculations of Salado Flow: Technical Baseline Migration

(TBM), AP-086, February 13, 2002, ERMS #520612.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Vols 1-XXI.

Wakeley, L.D., Poole, T.S. and Burkes, J.P. 1994. Durability of Concrete Materials in High-Magnesium Brine. SAND93-7073. Albuquerque, NM: Sandia National Laboratories. WPO 10674.

Wakeley, L.D., Harrington, P.T., and Hansen, F.D. 1995. Variability in Properties of Salado Mass Concrete. SAND94-1495. Albuquerque, NM: Sandia National Laboratories. WPO 22744.

Parameter 11: Log of the Distribution of Solubility of U(IV) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for uranium in the +IV oxidation state in Castile brine.

Material and Property Name(s):

SOLU4 SOLCIM

Computational Code: PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: General Literature Data

For the CCA, solubilities were calculated using the Fracture Matrix Transport (FMT) code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of U(IV) in Castile brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Attachment SOTERM.

Parameter Data Entry Form ERMS: #529447

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 12: Log of the Distribution of Solubility of Th(IV) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for thorium in the +IV oxidation state in Castile brine.

Material and Property Name(s):

SOLTH4 SOLCIM

Computational Code: PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: General Literature Data

For the CCA, solubilities were calculated using the Fracture Matrix Transport (FMT) code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Th(IV) in Castile brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #529448

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 14: Residual Gas Saturation – Concrete Portion of PCS

Parameter Description:

The residual (critical) gas saturation (S_{gr}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves (see CCA Appendix PA, Figure 4.2.1). S_{gr} corresponds to the degree of waste-generated gas saturation necessary to create an incipient interconnected pathway in porous material, a condition required for porous rock to be permeable to gas.

Material and Property Name(s):

CONC_PCS SAT_RGAS

Computational Code: BRAGFLO

minimum	maximum
0	0.40

Units: None

Distribution Type: Uniform

Data: General Literature Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

This distribution is the same as were used in the original CCA shaft seal model. The initial gas saturation in the simplified shaft is a volume-weighted average of the initial gas saturations in the original shaft's subcomponents (James and Stein 2002; 2003). The following justification is provided for gas saturation values used for the CCA shaft seal subcomponents (see material SALT_T1, in Appendix PAR) DOE (1996).

A literature search was conducted to obtain residual saturation values for consolidated geologic materials, concrete, and asphalt in support of the CCA.

A single value of 0.18 was found for normal concrete (Mayer et al. 1992). Based on this value, a distribution was assumed for the seal components. The recommended value was 0.2, and the recommended range was 0.0 to 0.4 with a uniform distribution for all shaft seal materials.

Parameter Data Entry Form ERMS: #520524

References:

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Mayer, G., Jacobs, F., and Wittmann, F.H. 1992. "Experimental Determination and Numerical Simulation of the Permeability of Cementitious Materials," Nuclear Engineering and Design. Vol. 138, no. 2, 171-177.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

Parameter 15: Residual Brine Saturation – Concrete Portion of PCS

Parameter Description:

The residual brine saturation (S_{br}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves (see CCA Appendix PA, Figure 4.2.1). Referred to also as S_{wr} (wetting phase) or S_{lr} (liquid phase), residual brine saturation is the point reached under high gas saturation conditions when brine is no longer continuous throughout the pore network and relative brine permeability becomes zero.

Material and Property Name(s):

CONC_PCS SAT_RBRN

Computational Code: BRAGFLO

Value	0.0	0.20	0.60
Percentiles	0	0.50	1

Units: None

Distribution Type: Cumulative

Data: General Literature Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

This distribution is the same as were used for the original 1996 CCA shaft seal model. Recall that the initial brine saturation in the simplified shaft is a volume-weighted average of the initial brine saturations in the original shaft's subcomponents (James and Stein 2002, 2003). The following justification is provided for the residual brine saturation used for the CCA shaft components (see Material SALT_T1, CCA Appendix PAR in DOE [1996]).

A literature search was conducted to obtain residual liquid saturation values for consolidated geologic materials, concrete, and asphalt in support of the CCA. Residual liquid saturations for geologic materials were found in four references (Brooks and Corey 1964; Lappala et al. 1987; Parker et al. 1987; and Rawls et al. 1982). Brooks and Corey (1964) determined residual saturations for five unconsolidated samples based on measured values of liquid saturation as a function of capillary pressure. Lappala et al. (1987) determined residual moisture content for 11 soils by obtaining best fits to measured moisture content versus pressure head data using three models. The residual moisture contents determined for each soil using the three models were averaged and divided by the reported porosity to obtain a residual liquid saturation for each soil. Parker et al. (1987) fit their saturation-pressure relationship to observed data to obtain residual saturations for a sandy and clayey porous

media. Residual water contents reported by Rawls et al. (1982) for 11 soil texture classes were divided by the reported porosity to obtain residual saturations.

Mayer et al. (1992) reported a residual liquid saturation for normal concrete of 0.30. Data regarding residual liquid saturations in asphalt materials were not found in the literature.

The literature values of residual liquid saturation for geologic materials and concrete fall within the range of 0.0 to 0.6 with all but two values falling within the range of 0.0 to 0.4. It was recommended that a value of 0.2 be used for the residual liquid saturation of all seal components.

Parameter Data Entry Form ERMS: #520524

References:

Brooks, R.H., and Corey, A.T. 1964. Hydraulic Properties of Porous Media. Hydrology Paper No. 3. Fort Collins, CO: Colorado State University.

Lappala, E.G., Healy, R.W., and Weeks, E.P. 1987. Documentation of Computer Program VS2D to Solve the Equations of Fluid Flow in Variably Saturated Porous Media. Water-Resources Investigations Report 83-4099. Denver, CO: U.S. Geological Survey. Tech Library books collection: PC173.4.P67L31987.

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Mayer, G., Jacobs, F., and Wittmann, F.H. 1992. "Experimental Determination and Numerical Simulation of the Permeability of Cementitious Materials," Nuclear Engineering and Design. Vol. 138, no. 2, 171-177.

Parker, J.C., Lenhard, R.J., and Kuppusamy, T. 1987. "A Parametric Model for Constitutive Properties Governing Multiphase Flow in Porous Media," Water Resources Research. Vol. 23, no. 4, 618-624.

Rawls, W.J., Brakensiek, D.L., and Saxton, K.E. 1982. "Estimation of Soil Water Properties," Transactions of the ASAE. St. Joseph, MI: American Society of Agricultural Engineers. 1316-1328.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Vols 1-XXI.

Parameter 16: Pore Distribution Parameter in the Concrete portion of PCS

Parameter Description:

The Brooks-Corey pore size distribution parameter (λ) is used to calculate capillary pressure and relative permeabilities for gas and brine flow in the two-phase flow model (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter.

Material and Property Name(s):

CONC_PCS PORE_DIS

Computational Code: BRAGFLO

Value	0.11	0.94	8.1
Percentiles	0	0.50	1

Units: None

Distribution Type: Cumulative

Data: General Literature Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

This distribution of pore size values for the concrete portion of the Option D panel closure is the same as were used for the concrete portion of the shaft seal in the original 1996 CCA shaft seal model. (Stein, 2002) The following justification is provided for pore size distribution values used for the shaft seal (see material SALT_T1, CCA Appendix PAR)

A literature search was conducted to find pore distribution (that is, lambda) values for geologic materials and concrete. For geologic materials, 81 lambda values were found in 5 references (Brooks and Corey 1964; Mualem 1976; Rawls et al. 1982; Haverkamp and Parlange 1986; and Lappala et al. 1987). In addition, 38 lambda values were calculated from values of the van Genuchten parameter n found in 6 references (van Genuchten 1980; van Genuchten and Nielsen 1985; Hopmans and Overmars 1986; Parker et al. 1987; Stephens et al. 1988; and Wösten and van Genuchten 1988).

The total number of lambda values found in the literature or calculated from n values found in the literature was 119. In a few cases, different literature sources reported different values of lambda and/or n for the same materials. For this situation, the different lambda values were arithmetically averaged to obtain a single value for the material. This procedure yielded lambda values for a total of 85 different geologic materials.

The lambda values range from 0.11 to 11.67 and have a median of 0.94. Based on the shape of the histogram and CDF, it appears that the lambda values are log normally distributed. The Lilliefors test for normality (Iman and Conover 1983) was applied to the data to verify that the logarithm of the lambda values can be described by a normal distribution. The mean of the log lambda values was found to be -0.064 with a standard deviation of 1.08. The Lilliefors bounds represent the region within which 95 percent of normally distributed values will fall.

For concrete, a literature search yielded only one reference (Mayer et al. 1992). This reference indicates that the Corey (1954) relationships are appropriate for describing the two-phase characteristic curves for the normal concretes they tested. For asphalt materials, data regarding lambda values were not found in the literature.

Both a lognormal and cumulative distribution for this parameter was recommended for the seal components constructed from granular earth materials (that is, earthen fill, compacted clay, and reconsolidated crushed salt). A cumulative distribution is appropriate when the range (a, c) of the parameter is known and the best estimate value, b, is the median. The value recommended was 0.94, which is the median of the literature values for geologic materials. The recommended range for the distribution was 0.11 to 8.1. Consequently, a cumulative distribution is assigned. In the absence of literature data, the same lambda distribution type, value, and range were also recommended for the concrete and asphalt seal components.

Parameter Data Entry Form ERMS: #520524

References:

Brooks, R.H., and Corey, A.T. 1964. Hydraulic Properties of Porous Media. Hydrology Paper No. 3. Fort Collins, CO: Colorado State University.

Corey, A.T. 1954. “The Interrelation Between Gas and Oil Relative Permeabilities,” Producer's Monthly. Vol. XIX, no. 1, 38-41.

Haverkamp, R., and Parlange, J.Y. 1986. “Predicting the Water-Retention Curve From Particle-Size Distribution: 1. Sandy Soils Without Organic Matter,” Soil Science. Vol. 142, no. 6, 325-339.

Hopmans, J.W., and Overmars, B. 1986. “Presentation and Application of an Analytical Model to Describe Soil Hydraulic Properties,” Journal of Hydrology. Vol. 87, no. 1-2. 135-143.

Iman, R.L., and Conover, W.J. 1983. Modern Business Statistics. New York, NY: John Wiley & Sons, Inc.

Lappala, E.G., Healy, R.W., and Weeks, E.P. 1987. Documentation of Computer Program VS2D to Solve the Equations of Fluid Flow in Variably Saturated Porous Media. Water-Resources Investigations Report 83-4099. Denver, CO: U.S. Geological Survey.

Mayer, G., Jacobs, F., and Wittmann, F.H. 1992. “Experimental Determination and Numerical Simulation of the Permeability of Cementitious Materials,” Nuclear Engineering

and Design. Vol. 138, no. 2, 171-177.

Mualem, Y. 1976. "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media," Water Resources Research. Vol.12, no. 3, 513-522.

Parker, J.C., Lenhard, R.J., and Kuppusamy, T. 1987. "A Parametric Model for Constitutive Properties Governing Multiphase Flow in Porous Media," Water Resources Research. Vol. 23, no. 4, 618-624.

Rawls, W.J., Brakensiek, D.L., and Saxton, K.E. 1982. "Estimation of Soil Water Properties," Transactions of the ASAE. St. Joseph, MI: American Society of Agricultural Engineers. 1316-1328.

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

Stephens, D.B., Unruh, M., Havlena, J., Knowlton, R.G., Jr., Mattson, E., and Cox, W. 1988. "Vadose Zone Characterization of Low-Permeability Sediments Using Field Permeameters," Ground Water Monitoring Review. Vol. 8, no. 2, 59-66.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Vols 1-XXI.

van Genuchten, M. Th. 1980. "A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils," Soil Science Society of America Journal. Vol. 44, no. 5, 892-898.

van Genuchten, M. Th., and Nielsen, D.R. 1985. "On Describing and Predicting the Hydraulic Properties of Unsaturated Soils," Annales Geophysicae. Vol. 3, no. 5, 615-628.

Wösten, J.H.M., and van Genuchten, M. Th. 1988. "Using Texture and Other Soil Properties to Predict the Unsaturated Soil Hydraulic Functions," Soil Science Society of America Journal. Vol. 52, no. 6, 1762-1770.

Parameter 17: Effective Porosity - Halite

Parameter Description:

The effective porosity of Salado Formation halite and polyhalite refers to the ratio of the interconnected pore volume to the bulk volume.

Material and Property Name(s):

S_HALITE POROSITY

Computational Code: BRAGFLO

Value	1.0×10^{-3}	0.01	0.03
Percentiles	0	0.50	1

Units: None

Distribution Type: Cumulative

Data: Site-Specific Experimental Data

The effective porosity distribution of Salado halite is supported by three separate porosity calculations: (1) Skokan et al. (1989; p. 15) determined from electromagnetic and DC resistivity experiments, (2) drying experiments described in Powers et al. (1978; p. 7-30), and (3) drying experiments reported in Deal et al. (1993). The parameter records package associated with this parameter is: Halite Porosity (ERMS #230601).

Discussion:

The high value (0.03) for the range of porosity is suggested in Skokan et al. (1989; p.6,13), based on the low end (10 ohm) of the DC resistivity measurements registered in the underground repository. The low value (0.001) is suggested in Powers et al. (1978) based on drying experiments. The median value of 0.01 is suggested in Skokan et al. (1989; p.15). Deal et al. (1993) found an average value of 0.016 for total porosity from a different series of drying experiments.

Parameter Data Entry Form ERMS: #234387

References:

Deal, D.E., Abitz, R.J., Myers, J., Martin, M.L., Millgan, D.J., Sobocinski, R.W., Lipponer, P.P.J., and Belski, D.S. 1993. Brine Sampling and Evaluation Program, 1991 Report. DOE-WIPP-93-026. Carlsbad, NM: Westinghouse Electric Corporation, Waste Isolation Division.

Powers, D.W., Lambert, S.J., Shaffer, S.E., Hill, L.R., and Weart, W.D., eds. 1978. Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico. SAND78-1596. Albuquerque, NM: Sandia National Laboratories. Vols. 1-2.

V. 1 - ERMS #205448; V.2 - ERMS #226829 – #226830, original photos - ERMS #226859.

Skokan, C.K., Pfeifer, M.C., Keller, G.V., and Andersen, H.T. 1989. Studies of Electrical and Electromagnetic Methods for Characterizing Salt Properties at the WIPP Site, New Mexico. SAND87-7174. Albuquerque, NM: Sandia National Laboratories. ERMS #224033.

Parameter 18: Log of Intrinsic Permeability - Halite

Parameter Description:

The Salado Formation halite is assigned an intrinsic permeability intended to reflect the stratigraphic variability of Salado halite and far-field hydraulic conditions (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

S_HALITE PRMX_LOG
S_HALITE PRMY_LOG
S_HALITE PRMZ_LOG

Computational Code: BRAGFLO

minimum	maximum
-24.0	-21.0

Units: Log (m^2)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

The reported permeability range of undisturbed impure halite is based on four selected in situ hydraulic tests: three flow tests believed representative of far-field permeability and one flow test that measured permeability in a zone which included a range of halite lithologies. Computer-derived permeabilities based upon brine inflow data from Room Q fall within the range derived from flow tests. The reader is referred to the relevant parameter record package for more detail: Halite Permeability (ERMS #231218) Salado Halite Permeability from Room Q Analysis (ERMS #230721).

Discussion:

Impure halite denotes a broad range of lithologic types ranging from pure halite to lithologies with various degrees of impurities, including polyhalite, argillaceous and anhydrite halite. Far-field tests of the pure halite exist; however, far-field hydraulic tests data do not exist for relatively impure halites, which tend to show higher permeabilities in the near-field. Thus a range of permeability is specified, bounded by rounded low and high permeability values determined from the testing program.

Three hydraulic tests believed representative of far-field pure halite permeability were conducted in the present location of Room Q in map units with relatively low impurities: a halite with less than 0.5 percent impurity, a halite containing approximately one percent impurity and a halite and polyhalite zone with a one to two percent impurity. These tests are believed to represent the lower end of the permeability range for Salado halite (see Table

PAR-2). These units were tested before the large-scale brine inflow excavation was mined and at stratigraphic intervals located over 20 m (66 ft) from the excavation.

Although probably located within the influence of the DRZ, one flow test (C2H01-BGZ) was performed within map units 0-4. This permeability value in conjunction with Room Q model analysis determination of far-field permeability are used to bound the maximum permeability of Salado halite containing relatively high impurities.

A summary of selected interpretative results of these four flow and pressure tests is compiled in the attached table. A schematic representation of Salado map units near the disposal area horizon, adapted from Deal et. al. (1989), is attached for information purposes (see Figure PAR-2).

Parameter Data Entry Form ERMS: #234397

References:

Beauheim, R.L., Saulnier, G.J., Jr., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #226033.

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Albuquerque, NM: Sandia National Laboratories. ERMS #223378.

Davies, Peter and Rick Beauheim. 1996. Memo to Martin Tierney. RE: Changes to the parameter records package and form #464 for far-field permeability of Salado halites (id#s: 547, 548, and 549; idmtrl: S_HALITE; idpram: PRMX_LOG, PRMY_LOG, and PRMZ_LOG, respectively). March 7, 1996. ERMS #236772.

Deal, D.E., Abitz, R.J., Belski, D.S., and Case, J.B. 1989. Brine Sampling and Evaluation Program, 1988 Report. DOE-WIPP-89-015. Carlsbad, NM: Westinghouse Electric Corporation.

Jensen, A.L., Howard, C.L., Jones, R.L., and Peterson, T.P. 1993. Room Q Data Report: Test Borehole Data from April 1989 through November 1991. SAND92-1172. Albuquerque, NM: Sandia National Laboratories. ERMS #223548.

Saulnier, G.J., Jr., Domski, P.S., Palmer, J.B., Roberts, R.M., Stensrud, W.A., and Jensen, A.L. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Albuquerque, NM: Sandia National Laboratories. ERMS #225746

Stensrud, W.A., Dale, T.F., Domski, P.S., Palmer, J.B., Roberts, R.M., Fort, M.D., Saulnier, G.J., Jr., and Jensen, A.L. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Albuquerque, NM: Sandia National Laboratories. ERMS #226432.

Table PAR-2. Summary of Permeability Test-Interpretations Results from In Situ Permeability Tests Representing Undisturbed Impure Halite

Test Interval (meters from excavation)	Hole	Map unit(s)	Analysis Method	Permeability k (m^2)
20.13-21.03	QPPO5	MU 6	GTFM6.0	1.12×10^{-24}
23.35-24.20	QPP12	H3	GTFM6.0	2.69×10^{-22}
20.19-21.09	QPP15	MU O - MU PH-4	GTFM6.0	5.5×10^{-24}
4.50-5.58	C2H01-BGZ	MU O - MU 4	GTFM6.0	1.38×10^{-21}

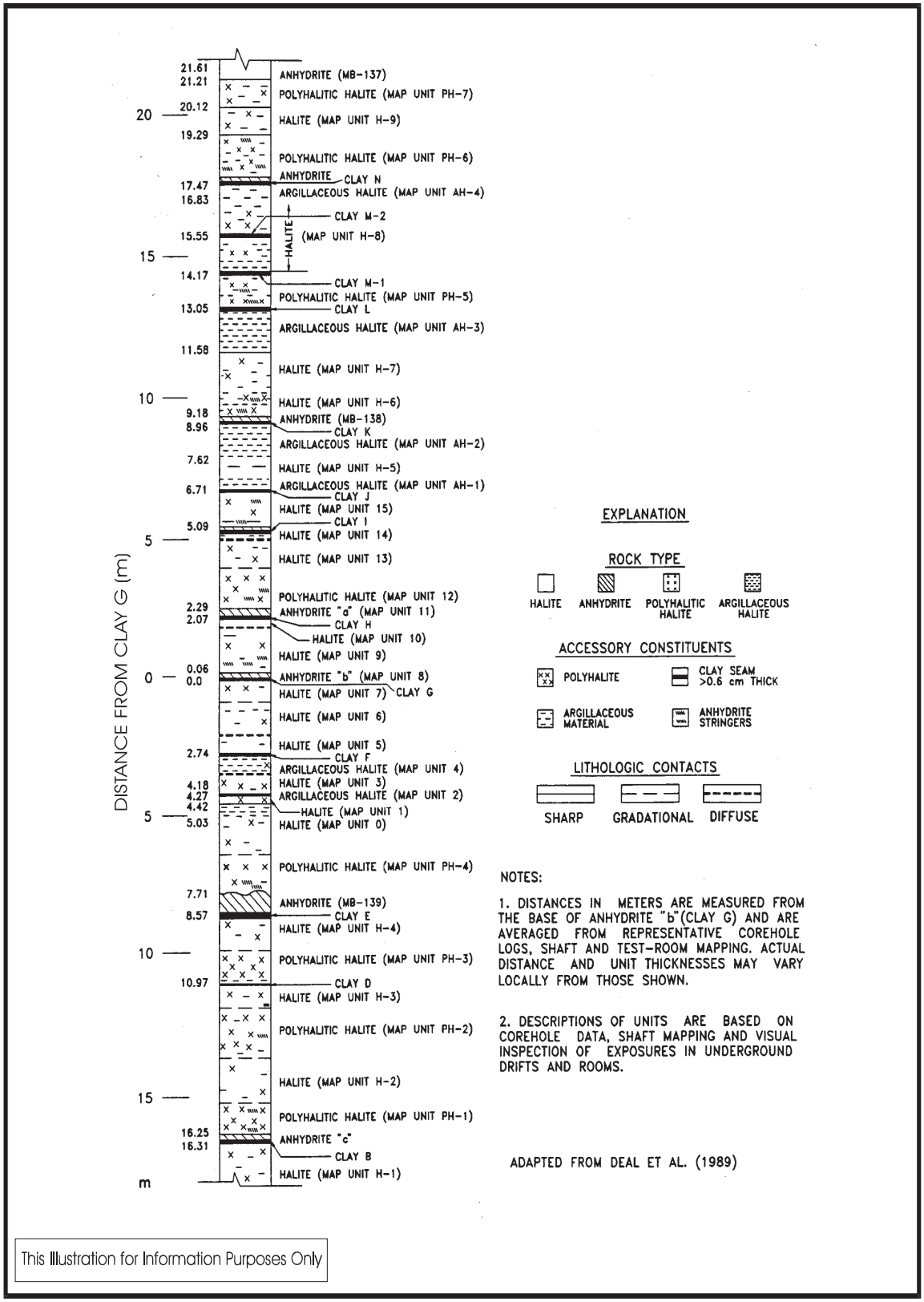

NMVP-6342-164-0

Figure PAR-2. Salado Map Units Near the Disposal Area Horizon

Parameter 19: Rock Compressibility - Halite

Parameter Description:

The rock (or bulk) compressibility of the Salado Formation halite is used to calculate the pore compressibility that is used in BRAGFLO. Pore compressibility is used to predict the effect of material compressibility on porosity and mass storage in the equation of state for flow through porous media as follows:

$$\varphi = \varphi_o \exp\left(c_p(p-p_o)\right)$$

where,

φ = porosity of solid matrix (cubic meters/cubic meters)
φ_o = porosity at reference pressure p_o
c_p = pore compressibility (pascals^{-1})
p = pore pressure (pascals)
p_o = reference pore pressure (pascals)

The rock compressibility is divided by effective porosity to calculate pore compressibility.

Material and Property Name(s):

S_HALITE COMP_RCK

Computational Code: BRAGFLO

minimum	maximum
2.94×10^{-12}	1.92×10^{-10}

Units: Pascals^{-1}

Distribution Type: Uniform

Data: Site-Specific Experimental Data

The parameter distribution for halite rock compressibility is based upon data from two hydraulic tests in Room Q: QPP05 and QPP15. Another data point calculated from sensitivity studies using brine inflow data from Room Q is within the range driven from the hydraulic tests. Parameter records packages associated with this parameter are: Halite Rock Compressibility (ERMS #231220) and Salado Halite Rock Compressibility from Room Q ANALYSIS (ERMS #230598).

The two in-situ hydraulic tests were conducted in the location of Room Q before the large-scale brine inflow excavation was mined (see Table PAR-3). Test intervals were located over 20 m (65 ft) from the excavation. Map units (MU) represented included MU 6 (halite) and MU 0 (halite)/MU PH-4 (polyhalite) within a radius of about 1 m (3.3 ft) of each borehole. Raw data included pressure, fluid volume, temperature, axial test-tool movement, and radial borehole closure.

Interpretation of all flow tests in the WIPP facility is based on the assumption that Darcy flow and borehole closure are the only forms of pressure/flow transmission during hydraulic tests. References related to data collection and interpretation are listed in the references section.

Parameter Data Entry Form ERMS: #234210

References:

Beauheim, R.L., Saulnier, G.J., Jr., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Watts Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #226003.

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Albuquerque, NM: Sandia National Laboratories. ERMS #223378.

Jensen, A.L., Howard, C.L., Jones, R.L., and Peterson, T.P. 1993. Room Q Data Report: Test Borehole Data from April 1989 through November 1991. SAND92-1172. Albuquerque, NM: Sandia National Laboratories. ERMS #223548

Saulnier, G.J., Jr., Domski, P.S., Palmer, J.B., Roberts, R.M., Stensrud, W.A., and Jensen, A.L. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Albuquerque, NM: Sandia National Laboratories. ERMS #225746

Stensrud, W.A., Dale, T.F., Domski, P.S., Palmer, J.B., Roberts, R.M., Fort, M.D., Saulnier, G.J., Jr., and Jensen, A.L. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Albuquerque, NM: Sandia National Laboratories. ERMS #226432.

Table PAR-3. Summary of Rock Compressibility Test-Interpretations Results from In Situ Permeability Tests for Undisturbed Halite and Polyhalite Map Units

Test Interval (meters from excavation)	Hole	Zone	Map Unit(s)	Analysis Method	Rock Compressibility C_r (1/pascal)	Formation Pore Pressure (megapascal)[1]
20.13-21.03 down	QPPO5 Room Q	undisturbed	MU 6	GTFM6.0	2.94×10^{-12}	13.89
20.19-21.09 down	QPP15 Room Q	undisturbed	MU 0 MU PH-4	GTFM6.0	1.92×10^{-10}	11.04

[1] Mean

Note: See Record Parameter Package for additional detail.

Parameter 20: Log of Intrinsic Permeability - Marker Bed 139

Parameter Description:

This parameter represents the intrinsic permeabilities for MB139.

Material and Property Name(s):

S_MB139 PRMX_LOG
S_MB139 PRMY_LOG
S_MB139 PRMZ_LOG

Computational Code: BRAGFLO

Measured Values:	-21.0	-19.2	-19.1	-18.8	-18.1	-17.1

Units: Log (meters squared)

Distribution Type: Student's-t

Data: Site-Specific Experimental Data and Laboratory-Measured Data

The reported parameter range of undisturbed Salado anhydrite permeabilities is based upon selected data collected from the following in situ hydraulic tests and measurements conducted in the laboratory: (1) five hydraulic tests conducted in the underground experimental area; and (2) 31 Klinkenberg-corrected gas permeabilities measured in the laboratory on specimens collected from MB139 core samples. Summary data tables are attached for both in situ and laboratory tests (see Table PAR-4 and Table PAR-5). Parameter records packages associated with this parameter are Anhydrite Permeability (x,y,z) (ERMS #231217); Salado Anhydrite Permeability in the X-Direction (ERMS #230603); Salado Anhydrite Permeability in the Y-Direction (ERMS 2 #30605); Salado Anhydrite Permeability in the Z-Direction (ERMS #230606).

Out of 15 borehole and field permeability tests conducted in MB140, MB139, MB138 and anhydrites a and b, 5 in situ hydraulic tests are considered representative of undisturbed anhydrite permeability. Located from about 10 to 24 m (33 to 79 ft) from the excavation, the test intervals for these five boreholes were outside of the DRZ. The radius of visibility ranged from 4 to 25 m (13 to 82 ft). The five successful tests are summarized as follows:

Borehole	Location	Map Unit	Testing Period
QPP03	Room Q	Anhydrite b	4/89 11/91
QPP13	Room Q	MB 139	4/89 11/91
C2H02	Room C2	MB 139	4/89 12/89
L4P51-C1	Room L4	MB 140	4/92 6/94
SCP01-A	Core Storage	MB 139	4/90 10/90

Klinkenberg-corrected gas permeability measured in the laboratory can be used as an equivalent measure of liquid permeability. Klinkenberg-corrected test specimen data exist

from six whole cores taken from MB139 in the northern experimental area: E1X07, E1X08, E1X10, E1X11 (E140 Drift), P3X10, and P3X11 (Room L3).

For purposes of parameterization, in situ test data are treated differently than laboratory-derived data. Uncertainty exists in regards to the spatial representativeness of the core samples. In situ hydraulic tests are considered representative of expected permeability conditions on the scale of the grid system used in the BRAGFLO mesh. Consequently, for the parameter distribution above, laboratory data from the 6 megapascals net effective stress are averaged as one data point, whereas each of the five hydraulic tests is considered an individual data point.

Parameter Data Entry Form ERMS: #234865

References:

Beauheim, R.L., Saulnier, G.J., Jr., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #2 26003.

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Albuquerque, NM; Sandia National Laboratories. ERMS #223378.

Howarth S.M., and Christian-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. Albuquerque, NM: Sandia National Laboratories. ERMS #238019

Jensen, A.L., Howard, C.L., Jones, R.L., and Peterson, T.P. 1993. Room Q Data Report: Test Borehole Data from April 1989 through November 1991. SAND92-1172. Albuquerque, NM: Sandia National Laboratories. ERMS #223548.

Saulnier, G.J., Jr., Domski, P.S., Palmer, J.B., Roberts, R.M., Stensrud, W.A., and Jensen, A.L. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Albuquerque, NM: Sandia National Laboratories. ERMS #225746.

Stensrud, W.A., T.F. Dale, P.S. Domski, J.B. Palmer, R.M. Roberts, M.D. Fort, G.J. Saulnier, Jr., and A.L. Jensen. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Albuquerque, NM: Sandia National Laboratories. ERMS #226432.

Table PAR-4. Summary of Test-Interpretations Results from In Situ Permeability Tests for Undisturbed Anhydrite Map Units

Test Interval (meters from excavation)	Hole	Zone	Map Unit	Analysis Method	Permeability k (m^2)	Formation Pore Pressure (megapascals)[1]
10.68-14.78 down	SCP01-A	undisturbed	MB139	GTFM6.0	1.4×10^{-19}	12.27
9.47-10.86 down	C2H02	undisturbed	MB139	GTFM6.0	1.0×10^{-21}	11.11
20.50-21.40 up	QPPO3	undisturbed	anhydrite b	GTFM6.0	7.6×10^{-20}	12.9
20.62-21.52 down	QPP13	undisturbed	MB139	GTFM6.0	6.0×10^{-20}	12.43
17.44-22.20 down	L4P51-C1	undisturbed	MB140	GTFM6.0	8.7×10^{-18}	9.38

[1] Mean

Note: See Record Parameter Package for additional detail.

Table PAR-5. Summary of MB139 Permeability Laboratory Test Results

	Permeability (pressure values are net effective stress)					
	Gas (Klinkenberg Corrected)			Log of Permeability		
	3.4 megapascals (m^2)	6 megapascals (m^2)	10 megapascals (m^2)	2 megapascals (m^2)	6 megapascals (m^2)	10 megapascals (m^2)
Minimum	1.5E-19	5.9E-20	5.0E-20	-18.84	-19.23	-19.30
Maximum	8.3E-16	3.0E-16	1.5E-16	-15.08	-15.52	-15.82
Sum	9.0E-16	3.4E-16	1.8E-16	-552.29	-524.43	-402.17
Points	31	29	22	31	29	22
Mean	2.9E-17	1.2E-17	8.0E-18	-17.82	-18.08	-18.28
Median	1.3E-18	5.7E-19	3.1E-19	-17.89	-18.24	-18.51
Std Deviation	1.5E-16	5.6E-17	3.2E-17	0.67	0.69	0.83
Variance	2.2E-32	3.2E-33	1.1E-33	0.45	0.48	0.69

Parameter 21: Rock Compressibility - Marker Bed 139

Parameter Description:

The rock (or bulk) compressibility of the Salado Formation Anhydrite Layers a and b MB139 is used to calculate the pore compressibility that is used in BRAGFLO. Pore compressibility is used to predict the effect of material compressibility on porosity and mass storage in the equation of state for flow through porous media as follows:

$$\varphi = \varphi_o \exp\left(c_p(p-p_o)\right)$$

where,

φ = porosity of solid matrix (cubic meters/cubic meters)
φ_o = porosity at reference pressure p_o
c_p = pore compressibility (pascals^{-1})
p = pore pressure (pascals)
p_o = reference pore pressure (pascals)

The rock compressibility is divided by effective porosity to calculate pore compressibility. It is a sampled parameter for MB139 and the values are then applied to MB138 and Anhydrite Layers a and b.

Material and Property Name(s):

S_MB139 COMP_RCK

Computational Code: BRAGFLO

Measured Values:	1.09×10^{-11}	1.09×10^{-11}	3.37×10^{-11}	2.75×10^{-10}

Units: Pascals^{-1}

Distribution Type: Student's-t

Data: Site-Specific Experimental Data

The parameter distribution for anhydrite rock compressibility is based upon data from four hydraulic tests in the underground WIPP facility (see Table PAR-6). The boreholes and map units tested include: C2H02 (MB139); QPP03 (Anhydrite b); QPP13 (MB139); and SCP01 (MB139). The parameter records package associated with this parameter is located at: WIPP: 1.2.07.1:PDD: QA:SALADO:PKG 19:Rock Compressibility (ERMS #231186).

The four successful tests include:

Borehole	Location	Start Date of Testing	End Date of Testing
QPP03	Room Q	4/89	11/91
QPP13	Room Q	4/89	11/91
C2H02	Room C2	4/89	11/89
SCP01-A	Core Storage	4/90	10/90

Raw data collected during hydraulic tests include pressure, fluid volume, temperature, axial test-tool movement, and radial borehole closure. Pressure/flow transmission during hydraulic tests is assumed to be a result of Darcy flow and borehole closure. The reader is referred to the anhydrite rock compressibility parameter record package for more detail.

Parameter Data Entry Form ERMS: #234574

References:

Beauheim, R.L., Saulnier, Jr., G.J., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #226003.

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Albuquerque, NM: Sandia National Laboratories. ERMS #223378.

Jensen, A.L., Howard, C.L., Jones, R.L., and Peterson, T.P. 1993. Room Q Data Report: Test Borehole Data from April 1989 through November 1991. SAND92-1172. Albuquerque, NM: Sandia National Laboratories. ERMS #223548.

Saulnier, Jr., G.J., Domski, P.S., Palmer, J.B., Roberts, R.M., Stensrud, W.A., and Jensen, A.L. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Albuquerque, NM: Sandia National Laboratories. ERMS #225746.

Stensrud, W.A., Dale, T.F., Domski, P.S., Palmer, J.B., Roberts, R.M., Fort, M.D., Saulnier, G.J., Jr., and Jensen, A.L. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Albuquerque, NM: Sandia National Laboratories. ERMS #226432.

Table PAR-6. Summary of Rock Compressibility Test-Interpretations Results from In Situ Permeability Tests for Undisturbed Anhydrite Marker Beds

Test Interval (meters from excavation)	Hole and Location	Zone	Map Unit(s)	Analysis Method	Rock Compressibility C_r (1/pascals)	Formation Pore Pressure (megapascals)[1]
9.47-10.86 down	C2H02	undisturbed	MB 139	GTFM6.0	1.09×10^{-11}	11.11
20.62-21.52 down	QPP13	undisturbed	MB 139	GTFM6.0	3.37×10^{-11}	12.43
10.68-14.78 down	SCP01	undisturbed	MB 139	GTFM6.0	1.09×10^{-11}	12.27
20.50-21.40 up	QPP03	undisturbed	Anhydrite b	GTFM6.0	2.75×10^{-10}	12.94

[1] Mean

Note: See Record Parameter Package for additional detail.

Parameter 22: Relative Permeability – Marker Bed 139

Parameter Description:

The relative permeability model number parameter is the flag used to select two-phase flow model for use in BRAGFLO. It is a sampled parameter for MB139 (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

S_MB139 RELP_MOD

Computational Code: BRAGFLO

Value	1.0	2.0	3.0	4.0
Percentiles	.50	0	0	.50

Units: None

Distribution Type: Delta

Data: Site-Specific Experimental Data

Site-specific experimental data was collected from whole core taken from six underground boreholes at the WIPP. The specimens first underwent permeability and porosity testing, then subsequent capillary pressure tests. Test data from MB 139 was applied to MB 138 and Anhydrite Layers a and b. All other material regions use the second modified Brooks-Corey two-phase flow model.

Assumptions made during testing were:

1) Cores were 100 percent saturated at initiation of capillary pressure tests.
2) Use of a 140° contact angle was appropriate for correcting mercury-air data to brine-air repository conditions.
3) Although tests were conducted at ambient conditions (no stress), the data are adequate to describe two-phase conditions at stress.

The following parameter records package is associated with the tests: Anhydrite Two-Phase Parameters, Appendix E for SAND94-0472 (ERMS #230643).

There are several two-phase relative permeability models described in Appendix BRAGFLO (DOE 1996), including the van Genuchten-Parker and the second modified Brooks-Corey. Interpretation of the experimental test results showed that either the second modified Brooks-Corey or the van Genuchten-Parker two-phase flow models could be used to describe the data.

Parameter Data Entry Form ERMS: #234500

References:

Howarth S.M., and Christian-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. Albuquerque, NM: Sandia National Laboratories. (ERMS #238019).

Webb, S.W. 1991. "Sensitivity Studies for Gas Release from the Waste Isolation Pilot Plant," Chapter 4.0 in Waste-Generated Gas at the Waste Isolation Pilot Plant: Papers Presented at the Nuclear Energy Agency Workshop on Gas Generation and Release from the Radioactive Waste Repositories, P.B. Davies et al., eds., SAND91-2378, November 1991. Albuquerque, NM: Sandia National Laboratories. (ERMS #228772).

Parameter 23: Residual Brine Saturation - Marker Bed 139

Parameter Description:

The residual brine saturation (S_{br}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves. Referred to also as S_{wr} (wetting phase) or S_{lr} (liquid phase), residual brine saturation is the point reached under high gas saturation conditions when brine is no longer continuous throughout the pore network and relative brine permeability becomes zero. It is a sampled parameter for MB139 (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

S_MB139 SAT_RBRN

Computational Code: BRAGFLO

Measured Values:	7.78×10^{-3}	0.069	0.070	0.073	0.109	0.174

Units: None

Distribution Type: Student's-t

Data: Site-Specific Experimental Data

Residual brine saturation parameter values for the marker beds are based on curve fit parameter values predicted from laboratory measurements of capillary pressure. The parameter records package associated with this parameter is: Anhydrite Two-Phase Parameters, Appendix E for SAND94-0472 (ERMS #230643).

Discussion:

Parameter values are based on curve fit capillary pressure data measured using a mercury injection technique. The two-phase flow program reports the results of curve-fitted measurements of capillary pressure on six MB samples (Howarth and Christian-Frear 1996). Specimens were collected from intact MB139 core samples taken from the experimental area of the repository.

Parameter Data Entry Form ERMS: #234506

References:

Howarth S.M., and Christian-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. Albuquerque, NM: Sandia National Laboratories. (ERMS #238019).

Parameter 24: Residual Gas Saturation - Marker Bed 139

Parameter Description:

The residual (critical) gas saturation (S_{gr}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves. S_{gr} corresponds to the degree of waste-generated gas saturation necessary to create an incipient interconnected pathway in porous material, a condition required for porous rock to be permeable to gas. It is a sampled parameter for MB139 (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

S_MB139 SAT_RGAS

Computational Code: BRAGFLO

Measured Values:	0.014	0.025	0.032	0.078	0.116	0.197

Units: None

Distribution: Student's-t

Data: Site-Specific Experimental Data

Residual gas saturation parameter values for the marker beds are based on curve-fitted laboratory measurements of capillary pressure. The parameter records package is associated with this parameter is: Anhydrite Two-Phase Parameters, Appendix E for SAND 94-0472 (ERMS #230643).

Discussion:

The two-phase flow program reports the results of curve-fitted measurements of capillary pressure on six marker bed samples tested using mercury injection (Howarth and Christian-Frear 1996). The samples were taken from intact MB139 core samples collected from the northern experimental area of the repository. The measurements were conducted at ambient conditions (no stress) and were assumed to be 100 percent saturated at the initiation of capillary pressure tests.

Parameter Data Entry Form ERMS: #234508

References:

Howarth S.M., and Christian-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. Albuquerque, NM: Sandia National Laboratories. ERMS #238019.

Parameter 25: Pore Distribution - Marker Bed 139

Parameter(s) Description:

The Brooks-Corey pore size distribution parameter (λ) is used to calculate capillary pressure and relative permeabilities for gas and brine flow in the two-phase flow model. It is a sampled parameter for MB139 (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

S_MB139 PORE_DIS

Computational Code: BRAGFLO

Measured Values:	0.491	0.558	0.652	0.655	0.665	0.842

Units: None

Distribution Type: Student's-t

Data: Site-Specific Experimental Data

Pore size distribution parameter values for all anhydrite units are based on curve fit values predicted from laboratory measurements of capillary pressure. The parameter records package associated with this parameter is retained in Anhydrite Two-Phase Parameters, Appendix E for SAND94-0472 (ERMS #230643).

Discussion:

Curve fit parameter values are derived from six specimens cut from intact MB139 core samples collected from the northern experimental area of the repository. Reported data and parameters are based on mercury injection capillary pressure tests (Howarth and Christian-Frear 1996).

Parameter Data Entry Form ERMS: #234859

References:

Howarth S.M., and Christian-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. Albuquerque, NM: Sandia National Laboratories. (ERMS #238019).

Parameter 26: Initial Pressure - Salado Halite

Parameter Description:

The initial brine far-field (undisturbed) pore pressure in the Salado halite is applied at an elevation consistent with the intersection of MB139 (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

S_HALITE PRESSURE

Computational Code: BRAGFLO

minimum	maximum
1.10×10^7	1.39×10^7

Units: Pascals

Distribution Type: Uniform

Data: Site-Specific Experimental Data

Two hydraulic tests were performed in boreholes in undisturbed halite in the underground WIPP repository. Both tests were performed in the area where Room Q would later be mined. The tests were undertaken in April-July, 1989. Pressure, fluid volume, temperature, axial test-tool movement, and radial borehole closure were measured during the hydraulic tests in undisturbed rock. The following parameter records package is associated with the tests: Halite Pressure (ERMS #231221).

Discussion:

It was assumed that Darcy flow and borehole closure were the only forms of pressure/flow transmission during the hydraulic tests in undisturbed halite. The uncertainty associated with the estimated parameter values is high. The distribution is based on the two data points provided in the data package and the calculated median is 1.247×10^7 pascals.

Parameter Data Entry Form ERMS: #234394

References:

Beauheim, R.L., Saulnier, G.J., Jr., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #226003.

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Albuquerque, NM: Sandia National Laboratories.

ERMS #223378.

Jensen, A.L., Howard, C.L., Jones, R.L., and Peterson, T.P. 1993. Room Q Data Report: Test Borehole Data from April 1989 through November 1991. SAND92-1172. Albuquerque, NM: Sandia National Laboratories. ERMS #223548.

Saulnier, G.J., Jr., Domski, P.S., Palmer, J.B., Roberts, R.M., Stensrud, W.A., and Jensen, A.L. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Albuquerque, NM: Sandia National Laboratories. ERMS #225746.

Stensrud, W.A., Dale, T.F., Domski, P.S., Palmer, J.B., Roberts, R.M., Fort, M.D., and Saulnier, G.J., Jr. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Albuquerque, NM: Sandia National Laboratories. ERMS #226432.

Parameter 27: Initial Pressure - Castile Brine Reservoir

Parameter Description:

Initial brine pore pressure in the Castile brine reservoir (see CCA Appendix PA, Figure 4.2.1).

Material and Property Name(s):

CASTILER PRESSURE

Computational Code: BRAGFLO

mode	minimum	maximum
1.27×10^7	1.11×10^7	1.70×10^7

Units: Pascals

Distribution Type: Triangular

Data: Site-Specific Experimental Data and Professional Judgment

The parameter records package associated with this parameter is as follows: Castile Brine Reservoir Pressure (ERMS #231072).

Discussion:

All pressure measurements were adjusted to reflect formation pressure of the WIPP-12 reservoir. Pressure adjustments were made as follows:

$$P_a = P + \rho\, g\, (h - 140)\, 1 \times 10^{-6}$$

where:
- P_a = adjusted pressure (megapascals)
- P = measured/estimated pressure (megapascals)
- ρ = assumed density (kilograms per cubic meter)
- g = gravitational constant (9.8 Newtons per kilogram)
- h = brine reservoir elevation (meters above sea level)

Observed (measured and interpreted) Castile brine reservoir fluid pressures were compared with their corresponding lithostatic pressures; four locations (shown in Table PAR-7) were found to best represent the formation pressure. The measured values in Table PAR-7 are adjusted to reflect formation pressure at the depth of WIPP-12, which is representative of the depth of the BRAGFLO Castile Brine Reservoir. The pressure adjustment requires an assumption about pressure variation with depth in the Castile. Two bounding cases were used, hydrostatic and 85 percent of lithostatic; the adjusted pressure was calculated using the equation provided above. A brine density of 1,240 kg/m^3 (Reeves et al. 1989) was assumed for the hydrostatic variation; an average formation density of 2,040 kg/m^3 (Sandia WIPP Project 1992) was assumed for the lithostatic variation. The best-measured value (that is, the mode) is the brine reservoir pressure reported for WIPP-12 (12.7 megapascals). The maximum

brine reservoir pressure is 85 percent of lithostatic at WIPP-12 depth (17 megapascals). The minimum value is the lowest measured hydrostatic pressure (11.1 megapascals). Freeze and Larson (1996), attached to CCA Appendix MASS, Section 18 , provide more detail.

Parameter Data Entry Form ERMS: #231612

References:

Freeze, Geoff, and Larson, K. 1996. Memorandum to Martin Tierney Re: Initial Pressure in the Castile Brine Reservoir, March 20, 1996. ERMS #237148.

Lappin, A.R., Hunter, R.L., Garber, D.P., and Davies, P.B., eds. 1989. Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico, March 1989. SAND89-0462. Albuquerque, NM: Sandia National Laboratories. ERMS #224125.

Popielak, R.S., Beauheim, R.L., Black, S.R., Coons, W.E., Ellingson, C.T., and Olsen, R.L. 1983. Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico, DOE Report TME-3153.

Reeves, M., Freeze, G.A., Kelley, V.A., Pickens, J.F., Upton, D.T., and Davies, P.B. 1989. Regional Double-Porosity Solute Transport in the Culebra Dolomite under Brine-Reservoir-Breach Release Conditions: An Analysis of Parameter Sensitivity and Importance. SAND89-7069. Albuquerque, NM: Sandia National Laboratories. ERMS #224048.

Sandia WIPP Project. 1992. Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992: Volume 3, Model Parameters. SAND92-0700/3. Albuquerque, NM: Sandia National Laboratories. ERMS #223529.

Table PAR-7. Measured Castile Brine Reservoir Formation Pressures

Location	Pressure at Reservoir Depth (megapascals)	Pressure at WIPP-12 Depth with Hydrostatic Adjustment (megapascals)	Pressure at WIPP-12 Depth with 85% Lithostatic Adjustment (megapascals)
WIPP-12	12.7[(1)]	12.7	12.7
ERDA-6	14.1[(2)]	15.5	16.4
Belco	14.3[(2)]	14.5	14.5
Gulf Covington	13.6[(2)]	12.1	11.1

[(1)] from Reeves et al. 1989, Appendix A
[(2)] from Popielak et al. 1983, Table H.1

Parameter 28: Log of Intrinsic Permeability - Castile Brine Reservoir

Parameter Description:

The log of the intrinsic permeability of the Castile Brine Reservoir. It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

CASTILER PRMX_LOG
CASTILER PRMY_LOG
CASTILER PRMZ_LOG

Computational Code: BRAGFLO

mode	minimum	maximum
-11.80	-14.70	-9.80

Units: Log (meters squared)

Distribution Type: Triangular

Data: Site-Specific Experimental Data and Professional Judgment

Although several shorter flow tests were conducted to measure permeability of Castile brine reservoirs, only one test is considered representative of the long-term behavior of the brine reservoir behavior: the WIPP-12 Flow Test 3 (24,800 bbl produced, nine months recovery). The Graph Theoretic Field Model (GTFM) analysis of WIPP-12 Flow Test 3 (Reeves et al. 1989) is considered better than the Horner analysis because it considers the effects of pre-test borehole pumping history. The GTFM interpreted hydraulic conductivity from WIPP-12 Flow Test 3 therefore provides the basis for the mean permeability for the Castile brine reservoir. The other values from WIPP-12 and ERDA-6 were used to establish the permeability distribution.

Professional judgment was used to better define the data mean and range because of the shortage of directly relevant data points. The parameter records package associated with this parameter is as follows: Castile Brine Reservoir Permeability (ERMS #231070).

The GTFM analysis from WIPP-12 Flow Test 3 consists of a match to pressure response data and a match to flow rate data. The late time match to the pressure data are controlled primarily by the formation pressure and is not very sensitive to the hydraulic conductivity or the specific storage. To match the flow rate data, the GTFM interpreted hydraulic conductivity (K) is strongly correlated with the specified specific storage (S_s), where:

$$S_s = \rho g \, (C_R + \Phi\beta)$$

For Castile brine reservoir properties, specific storage is proportional to the bulk rock compressibility (C_R). The correlation between K and S_s is such that their product is

approximately a constant. For example, if the assumed specific storage (or rock compressibility) in GTFM is reduced by an order of magnitude, the interpreted hydraulic conductivity must increase by an order of magnitude to produce the same flow rate. The new combination of K and S_s will produce a different early-time pressure response, but will not impact the late-time match. For the GTFM analyses of the WIPP-12 Flow Tests, a rock compressibility of 1×10^{-9} pascals^{-1} was assumed. Because the mean rock compressibility for the Castile brine reservoir is 1×10^{-10} pascals^{-1}, the hydraulic conductivity required to reproduce the WIPP-12 flow is approximately 1×10^{-5} m/s (permeability of -11.81 log (square meters)). For all triangular distributions, the mode is the best estimate. GTFM analysis determines a hydraulic conductivity (with units of meters per second) based on pressure change, flow rate, and assumptions about fluid and formation properties. Conversions from meters per second to square meters were based on a conversion factor of 1.7×10^{-7} m^2 per (meters per second). The conversion factor is based on the assumed GTFM fluid properties.

Parameter Data Entry Form ERMS: #231613

References:

Popielak, R.S., Beauheim, R.L., Black, S.R., Coons, W.E., Ellingson, C.T., and Olsen, R.L. 1983. Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico. DOE Report TME-3153.

Reeves, M., Freeze, G.A., Kelley, V.A., Pickens, J.F., Upton, D.T., and Davies, P.B. 1989. Regional Double-Porosity Solute Transport in the Culebra Dolomite under Brine-Reservoir-Breach Release Conditions: An Analysis of Parameter Sensitivity and Importance. SAND89-7069. Albuquerque, NM: Sandia National Laboratories. ERMS #224048.

Parameter 29: Rock Compressibility - Castile Brine Reservoir

Parameter Description:

The rock (or bulk) compressibility of the Castile Brine Reservoir is used to calculate the pore compressibility, which is required for running BRAGFLO (see CCA Appendix PA, Figure 4.2.1). Pore compressibility is used to predict the effect of material compressibility on porosity and mass storage in the equation of state for flow through porous media as follows:

$$\phi = \phi_o \exp\left(c_p\left(p - p_o\right)\right)$$

where,

φ = porosity of solid matrix (cubic meters per cubic meters)
φ_o = porosity at reference pressure p_o
c_p = pore compressibility (pascals^{-1})
p = pore pressure (pascals)
p_o = reference pore pressure (pascals)

The rock compressibility is divided by effective porosity to calculate pore compressibility.

Material and Property Name(s):

CASTILER COMP_RCK

Computational Code: BRAGFLO

mode	minimum	maximum
4.00×10^{-11}	2.00×10^{-11}	1.00×10^{-10}

Units: Pascals^{-1}

Distribution Type: Triangular

Data: Site-Specific Experimental Data and Professional Judgment

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR in DOE (1996), parameter values were based on an analysis of data from WIPP-12. Rock compressibility values were determined by calculating the bulk modulus of anhydrite from the acoustic log of the Castile Anhydrite III unit found in WIPP-12. The DOE chose to use the acoustic log because it measures compressive wave travel time over short distances through relatively intact, undisturbed rock, then uses a correlation

between wave velocity and elastic rock properties to estimate bulk modulus. Various laboratory compression tests on anhydrite from other WIPP locations produced similar results for the bulk modulus (Popielak et al., 1983).

The estimated bulk modulus, K, for the intact Anhydrite III at WIPP-12 was 6.9×10^{10} pascals (10×10^{6} psi). Assuming uniaxial strain, the rock compressibility (C_R) can be estimated from the bulk modulus (K) and the shear modulus (G) of the rock:

$$C_R = \frac{1}{K + 4G/3}$$

No estimates for shear modulus for Anhydrite III were available. Beauheim et al. (1991) reported a value for G that was approximately 1/3 of K for Salado anhydrite. Using this estimate for G, the calculated intact rock compressibility is 1×10^{-11} pascals^{-1}.

The bulk modulus may be 2 to 10 times smaller for fractured rock (Popielak et al. 1983), corresponding to a 2 to 10 times increase in compressibility (assuming G changes accordingly). Beauheim et al. (1991) suggest that fracturing might result in a fourfold increase in rock compressibility. Using these adjustments for fractured rock, the calculated rock compressibility ranges from 2×10^{-11} pascals^{-1} to 1×10^{-10} pascals^{-1}, with an average value of 5×10^{-11} pascals^{-1}.

Hydraulic testing was performed in transition-zone (disturbed) Salado anhydrite and halite. Interpreted rock compressibilities for transition zone anhydrite ranged from 5×10^{-12} pascals^{-1} to 3×10^{-9} pascals^{-1}. Freeze and Cherry (1979) report a range for rock compressibility for fractured or jointed rock of 1×10^{-8} to 1×10^{-10} pascals^{-1} (DOE 1996).

Subsequent to the CCA PA calculations, EPA reviewed the CCA, and supporting information and references, and concluded that the compressibility parameter for the Castile Formation brine reservoir was not consistent with available information (EPA, 1998). Subsequent to the CCA, the field test data for the WIPP-12 borehole was re-examined and arrived at a revised range for rock compressibility. EPA regarded the re-analysis as a better estimate of the rock compressibility parameter than the value used in the CCA.

The Sandia National Laboratories Technical Library and Records Center undertook a key word-based (Castile rock compressibility) literature and records search to identify documentation/research that addresses the brine reservoir rock compressibility. Titles of all recent documents identified by the search were reviewed for relevancy; following this, abstracts and/or complete documents were reviewed to determine if information more recent than that cited in the CCA or PAVT was available. The literature and records search and review did not identify new information that would offer further support of, or otherwise refute the distributions and parameter ranges presented above. Consequently, rock compressibility is treated as a sampled variable having a triangular distribution and a revised range of 2×10^{-11} to 1×10^{-10} Pa^{-1} and a revised mode of 4×10^{-11} Pa^{-1}.

Parameter Data Entry Form ERMS: #522016

References:

Beauheim, R.L., Saulnier, G.J., Jr., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant: First Interim Report. SAND90-0083. Albuquerque, NM: Sandia National Laboratories. ERMS #226003.

Freeze, R.A., and Cherry, J.A. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

Popielak, R.S., Beauheim, R.L., Black, S.R., Coons, W.E., Ellingson, C.T., and Olsen, R.L. 1983. Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico. DOE Report TME-3153.

Reeves, M., Freeze, G.A., Kelley, V.A., Pickens, J.F., Upton, D.T., and Davies, P.B. 1989. Regional Double-Porosity Solute Transport in the Culebra Dolomite Under Brine-Reservoir-Breach Release Conditions: An Analysis of Parameter Sensitivity and Importance. SAND89-7069. Albuquerque, NM: Sandia National Laboratories. ERMS #224048.

U.S. Environmental Protection Agency (EPA). 1998. Response to Comments, Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with 40 CFR 191 Disposal Regulations: Certification Decision. Docket No. A-93-02, V-C-1. U.S. Environmental Protection Agency. Washington D.C.

Parameter 30: Log of Intrinsic Permeability - Intrusion Borehole Filled With Silty Sand

Parameter Description:

This parameter represents the log of the intrinsic permeability of the silty-sand-filled borehole in the human-intrusion scenario (see CCA Appendix PA, Figure 4.2.1). This permeability is representative of degraded concrete or material which may sluff into the borehole or spall from the sides. It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

BH_SAND PRMX_LOG
BH_SAND PRMY_LOG
BH_SAND PRMZ_LOG

Computational Code: BRAGFLO

minimum	maximum
-16.30	-11.00

Units: Log (meters squared)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR, this parameter represented the permeability of the silty-sand-filled borehole in the human-intrusion scenario. The permeability was representative of degraded concrete or material which may sluff into the borehole or spall from the sides. Three plug configurations with different permeabilities were associated with each configuration. Borehole materials and plug configurations were based on a review of regulations and practices, and the permeability predictions are based on models and data for steel corrosion and concrete alteration found in the literature (Thompson et al. 1996). Wherever possible, the predictions were calibrated by comparing predicted behavior to field data (Thompson et al. 1996).

The three plug configurations consisted of: a continuous concrete plug through the Salado and Castile which was assigned a probability of 0.015 (see Section 6.4.7.2.1), a two-plug configuration (a lower plug located between the Castile brine reservoir and underlying formations and an upper plug located in the Rustler immediately above the Salado), which was

assigned a probability of 0.696 (see Section 6.4.7.2.2), and a three-plug configuration (two plugs same as two-plug configuration and third plug located in the Castile above the brine reservoir and below the waste-disposal panel) which was assigned a probability of 0.289 (see Section 6.4.7.2.3).

The plugs were initially expected to have a tight permeability of 5×10^{-17} m^2 (Thompson et al. 1996). The continuous concrete plug was assumed not to degrade and had a permeability of 5×10^{-17} m^2 for the entire regulatory period. For the two-plug configuration, the permeability between the repository and the surface is 5×10^{-17} m^2 for the first 200 years and 10^{-14} to 10^{-11} m^2 after that; the permeability between the Castile and the repository is 10^{-14} to 10^{-11} m^2 up to 1,200 years and 10^{-15} to 10^{-12} m^2 after that. The three-plug configuration had the same material properties as the corresponding regions in the two-plug configuration and the third plug was assumed to behave as the lower plug in the two-plug configuration (DOE 1996).

Subsequent to the CCA PA calculations, EPA questioned the range of borehole sand permeabilities and the assumption that concrete borehole plugs would degrade to a more permeable material. The EPA (1997a) concluded that the lower bound for long-term borehole sand permeability proposed (10^{-14} m^2) should be closer to that of an undegraded borehole plug (5×10^{-17} m^2). The lower value was of interest to EPA because a lower permeability could result in increased gas pressures with consequent increases in brine and spallings releases during a human intrusion event.

The EPA also investigated drilling practices used in the petroleum industry and found literature values for cement permeability ranging from 9×10^{-21} to 1×10^{-16} m^2 (EPA 1997b). The EPA also found that filter cake and compacted, clay-based drilling muds could yield permeabilities of less than 9.9×10^{-22} m^2. In their considerations, the EPA noted that drilling mud used in the Delaware Basin boreholes might not have the permeability of clay-based solids; however, they noted that natural cuttings could contribute to lower borehole permeabilities than those assumed by the DOE. The EPA also postulated that the effective average permeability over an abandoned borehole could remain in the range of 9×10^{-21} to 1×10^{-16} m^2 over a period of hundreds of years or more if complete degradation does not occur throughout a plug configuration or if natural materials or mud were to provide additional layers with sealing properties.

With these findings, the EPA decided that the borehole sand permeabilities assigned in the CCA, while consistent with the broad range of available data, did not adequately represent the total range of permeability conditions that could exist. As a result, lower borehole sand permeabilities values are used. (Hansen and Leigh 2003)

Parameter Data Entry Form ERMS: #522016

References:

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

Thompson, T.W., Coons, W.E., Krumhansl, J.L., and Hansen, F.D. 1996. Inadvertent

Intrusion Borehole Permeability, Final Draft, July 8, 1996.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Vols 1-XXI.

U.S. Environmental Protection Agency (EPA). 1997a. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, III-B-14, U.S. Environmental Protection Agency. Washington D.C.

U.S. Environmental Protection Agency (EPA). 1997b. Compliance Application Review Documents for the Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations: Proposed Certification Decision. Docket No. A-93-02, III-B-2. U.S. Environmental Protection Agency. Washington D.C.

U.S. Environmental Protection Agency (EPA). 1998a. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C. ERMS #525158.

Parameter 31: Log of Intrinsic Permeability - Disturbed Rock Zone

Parameter Description:

This parameter represents the log of the intrinsic permeability of the disturbed rock zone (DRZ), 0-10,000 yrs (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

DRZ_1 PRMX_LOG
DRZ_1 PRMY_LOG
DRZ_1 PRMZ_LOG

Computational Code: BRAGFLO

minimum	maximum
-19.40	-12.50

Units: Log (meters squared)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

The grid used in CCA calculations implemented a DRZ of constant permeability (10^{-15} m^2) over a region 12 m above and 2.23 m below the disposal rooms. The grid was continuous above panel closure systems, such that the same permeability and thickness existed above and below the simulated panel closures. A more realistic representation of the DRZ over disposal rooms would include high permeability near the free surface of rooms, and reduction of permeability as a function of depth into the surrounding rock. Generally speaking, the DRZ extends greater distances above a room than below, and is relatively shallow into the ribs.

Subsequent to the CCA PA calculations, the EPA determined an alternate lower bound for DRZ permeability from measured gas permeability in anhydrite cores from MB139 (Howarth 1996; Beauheim 1996; Howarth and Christain-Frear 1994). The EPA concluded that a value of -19.4 for the log of the permeability was a more appropriate lower bound for the range of likely values. The EPA selected a value of -12.5 as an upper bound on the log of DRZ permeability based upon a sensitivity analysis (EPA 1998). The EPA also assigned a uniform distribution for the range of -19.4 to -12.5 based on the supposition that all the values are

equally likely. The geometric dimensions of the DRZ are the same in the CCA and the PAVT. The DOE has adopted this revised range for the DRZ permeability (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Beauheim, R.L. 1996. "Salado Package #16, (X, Y, Z) DRZ Permeability." Revision 1. Records Package. Sandia National Laboratories. Albuquerque, NM. ERMS #232038.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

Howarth, S.M. 1996. "[Salado Package #13], Salado Anhydrite Permeability in the X-Direction." Records Package. Sandia National Laboratories. Albuquerque, NM. ERMS #230603.

Howarth, S.M., and Christain-Frear, T. 1996. Porosity, Single-Phase Permeability, and Capillary Pressure Data from Preliminary Laboratory Experiments on Selected Samples from Marker Bed 139 at the Waste Isolation Pilot Plant. SAND94-0472 (Draft). Sandia National Laboratories. Albuquerque, NM. ERMS #238367.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 32: Log of Intrinsic Permeability – Concrete Plug

Parameter Description:

This parameter represents the log of the intrinsic permeability of the concrete plug, at the surface of the repository and in the Rustler (see CCA Appendix PA Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

CONC_PLG PRMX_LOG
CONC_PLG PRMY_LOG
CONC_PLG PRMZ_LOG

Computational Code: BRAGFLO

minimum	maximum
-19.00	-17.00

Units: Log (meters squared)

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In preparation for the CCA, DOE developed a set of assumed plug configurations for boreholes drilled and abandoned in the future. Each assumed plug configuration involved several materials with varying degrees of integrity over the lifetime of the repository. One material used in the CCA PA borehole models was a concrete material. The DOE assumed that initially, the concrete plugs would be effective in limiting fluid flow in the borehole. However, for purposes of the CCA PA calculation, some plugs above the repository were assumed to degrade after 200 years of emplacement. From that point on, the borehole was assumed to be filled with a silty, sand-like material containing degraded concrete, corrosion products resulting from degradation of the casing, and material that sloughs off of the walls of the borehole.

In CCA Appendix PAR, borehole concrete permeability was set at a constant 5×10^{-17} m^2, based on results reported by Thompson et al. (1996). This value was directly measured for a concrete borehole plug at the WIPP site (Christensen and Hunter 1980).

Subsequent to the CCA PA calculations, EPA required the DOE to consider a range of values for the borehole concrete permeability (EPA 1998). The lower bound of the range chosen by EPA, – 1×10^{-19} m^2 – is more than two orders of magnitude lower than the lowest value measured for a WIPP borehole plug grout (5×10^{-17} m^2) as reported by Christensen and Hunter (1980). The EPA considered this to be a more conservative lower bound because a less permeable borehole plug may result in higher repository gas pressures and hence greater releases during a human intrusion event. The EPA chose an upper bound, 1×10^{-17} m^2, which was equal to the permeability of the concrete in the shaft seal systems. The EPA specified a uniform distribution over the permeability range (from 10^{-19} to 10^{-17}) (Froehlich 1997). The DOE has adopted this revised range for the borehole concrete permeability. (Hansen and Leigh 2003)

Parameter Data Entry Form ERMS: #522016

References:

Christensen, C.L. and Hunter, T.O. 1980. The Bell Canyon Test Results. SAND80-2414C. Sandia National Laboratories. Albuquerque, New Mexico.

Froehlich, G. 1997. “PAV1 Parameter Values.” Memorandum to C. Lattier. ERMS #246087. Sandia National Laboratories. Albuquerque, NM.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

Thompson, T.W., Coons, W.E., Krumhansl, J.L., and Hansen, F.D. 1996. Inadvertent Intrusion Borehole Permeability. Final Draft. Sandia National Laboratories. Carlsbad, NM.

U.S. Environmental Protection Agency (EPA). 1998a. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C. ERMS #525158.

Parameter 34: Log of the Distribution of Solubility of Am(III) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for americium in the +III oxidation state in Salado brine.

Material and Property Name(s):

SOLAM3 SOLSIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

For the CCA, solubilities were calculated using the Fracture Matrix Transport (FMT) code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Am (+III) in Salado brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237105

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 35: Log of the Distribution of Solubility of Am(III) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for americium in the +III oxidation state in Castile brine.

Material and Property Name(s):

SOLAM3 SOLCIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

For the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Am (+III) in Castile brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237106

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 36: Log of the Distribution of Solubility of Pu(III) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for plutonium in the +III oxidation state in Salado brine.

Material and Property Name(s):

SOLPU3 SOLSIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Pu (+III) in Salado brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: 237109

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 37: Log of the Distribution of Solubility of Pu(III) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for plutonium in the +III oxidation state in Castile brine.

Material and Property Name(s):

SOLPU3 SOLCIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Pu (+III) in Castile brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237108

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 38: Log of the Distribution of Solubility of Pu(IV) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for plutonium in the +IV oxidation state in Salado brine.

Material and Property Name(s):

SOLPU4 SOLSIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Pu(+IV) in Salado brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: 237110

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 39: Log of the Distribution of Solubility of Pu(IV) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for plutonium in the +IV oxidation state in Castile brine.

Material and Property Name(s):

SOLPU4 SOLCIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Pu(+IV) in Castile brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237111

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 40: Log of the Distribution of Solubility of U(IV) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for uranium in the +IV oxidation state in Salado brine.

Material and Property Name(s):

SOLU4 SOLSIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of U(+IV) in Salado brine assuming equilibrium conditions. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: 237112

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996. Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 41: Log of the Distribution of Solubility of U(VI) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for uranium in the +VI oxidation state in Salado brine.

Material and Property Name(s):

SOLU6 SOLSIM)

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

Data on U(+VI) solubility in Salado brine was compiled by Hobart and Moore (1996), both from ongoing WIPP-directed research and from published literature. Project experimental data was from Reed et al. (1996) (see CCA Appendix SOTERM). Published data was from Yamazaki, et al (1992) and Pashalidas et al (1993). Based on these data, Hobart and Moore recommend a value for U(+VI) for use in performance assessment. Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

The solubility of U(+VI) in Salado brine is a function of pH, CO_2 fugacity, and other brine components. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237113

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791

Hobart, D.E., and Moore, R. 1996. Draft Analysis of Uranium (VI) Solubility Data for WIPP Performance Assessment, Sandia National Laboratories, March 28, 1996. ERMS #239856.

Hobart, D.E., and Moore, R. 1996. Analysis of Uranium (VI) Solubility Data for WIPP Performance Assessment: Implementation of Analysis Plan AP-028, Sandia National Laboratories, August 6, 1996. Contained in package ERMS #236488.

Pashalidis, I., Runde, W., Kim, J.I. 1993. "A Study of Solid-Liquid Phase Equilibria of Pu(VI) and U(VI) in Aqueous Carbonate Systems," Radiochim. Acta, 63, 141-146. ERMS #249861.

Reed, D.T., Wygmans, D.G., and Richmann, M.K. 1996. Stability of Pu(VI), Np(VI), and U(VI) in Simulated WIPP Brine, 3/13/96 Interim Report, Argonne National Laboratory Interim Report (personal communication). ERMS #235197.

Yamazaki, H., Lagerman, B., Symeopoulos, V., and Choppin, G. 1992. Solubility of Uranyl in Brine, Proceedings of the Third International High Level Radioactive Waste Management Conference, Las Vegas, NV, April 12-16, 1992, American Nuclear Society, La Grange Park, IL, and American Society of Engineers, New York. Located in: Vol. 2, p. 1607-1611. SAND92-7069C- ERMS #239678.

Parameter 42: Log of the Distribution of Solubility of U(VI) in Castile Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for uranium in the +VI oxidation state in Castile brine.

Material and Property Name(s):

SOLU6 SOLCIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, data on U(+VI) solubility in Castile brine was compiled by Hobart and Moore (1996), both from ongoing WIPP-directed research and from published literature. Project experimental data was from Reed et al. (1996) (see Appendix PA, Attachment SOTERM). Published data was from Yamazaki, et al (1992) and Pashalidas et al (1993). Based on these data, Hobart and Moore recommend a value for U(+VI) for use in PA. Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

The solubility of U(+VI) in Castile brine is a function of pH, CO_2 fugacity, and other brine components. The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237114

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Hobart, D.E., and Moore, R. 1996. Draft Analysis of Uranium (VI) Solubility Data for WIPP Performance Assessment, Sandia National Laboratories, March 28, 1996. ERMS #233703.

Reed, D.T., Wygmans, D.G., and Richmann, M.K. 1996. Stability of Pu(VI), Np(VI), and U(VI) in Simulated WIPP Brine, Argonne National Laboratory Interim Report (personal communication). 3/13/96 Interim Report contained in ERMS #235197.

Yamazaki, H., Lagerman, B., Symeopoulos, V., and Choppin, G. 1992. Solubility of Uranyl in Brine, Proceedings of the Third International High Level Radioactive Waste Management Conference, Las Vegas, NV, April 12-26, 1992, American Nuclear Society, La Grange Park and American Society of Engineers, New York. SAND92-7069C – ERMS #239678.

Parameter 43: Log of the Distribution of Solubility of Th(IV) in Salado Brine

Parameter Description:

This parameter represents the distribution ($\log_{10}$) of the uncertainty about the modeled solubility value for thorium in the +IV oxidation state in Salado brine.

Material and Property Name(s):

SOLTH4 SOLSIM

Computational Code(s): PANEL

Value	-2.0	-1.0	-0.50	-0.25	0	0.25	0.50	1.0	1.40
Percentiles	0	0.04	0.13	0.27	0.63	0.84	0.89	0.99	1.0

Units: None (see PPR-04-2002, ERMS #524651)

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Thermodynamic Calculations

In the CCA, solubilities were calculated using the FMT code (Novak 1996). Bynum (1996) compared 150 modeled and experimentally determined solubilities and provided a distribution of the differences between them. The parameter records package associated with this parameter is located at: Solubility Parameters for Actinide Source Term Look-up Tables (ERMS #235835).

Discussion:

FMT calculates the solubility of Th(+IV) in Salado brine assuming equilibrium conditions The uncertainty in solubilities was determined by Bynum (1996) by comparing modeled solubilities for all oxidation states with the experimentally determined solubilities.

Further information on this parameter is provided in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: 237115

References:

Bynum, R.V. 1996. Memorandum to Martin Tierney and Christine Stockman, Re: Revised Update of Uncertainty Range and Distribution for Actinide Solubility to be used in CCA NUTS Calculations, May 23, 1996. ERMS #237791.

Novak, C.F. 1996.Memorandum to J.T. Holmes Re: Release of FMT Data Base Files HMW_3456_960318.CHEMDAT and HMW_345_960325.CHEMDAT, March 27, 1996. ERMS #235923.

Parameter 44: Humic Proportionality Constant

Parameter Description:

The humic proportionality constant is used to calculate concentrations of actinides associated with mobile humic substances for actinide elements with oxidation state of +III, in the Castile brine.

Material and Property Name(s):

PHUMOX3 PHUMCIM

Computational Code(s): PANEL

Value	0.07	1.37	1.60
Percentiles	0	0.50	1.0

Units: None

Distribution Type: Cumulative

Data: Site-Specific Experimental Data

Experiments were conducted at Florida State University (Greg R. Choppin) and at SNL (Hans W. Papenguth and co-workers). These results, combined with WIPP-specific data on calcium and magnesium concentrations, formed the basis for this parameter distribution. The parameter records package associated with this parameter is located at: Mobile Colloidal Actinide Source Term 3, Humic Substances (ERMS #235855).

Discussion:

Humic substances encompass a broad variety of high-molecular-weight organic compounds that can mobilize actinides. To determine the concentration of actinides associated with humic substances, four pieces of information are required: (1) the concentration of reactive humic substance in the aqueous phase (that is, humic solubility); (2) the binding capacity of the humic substance; (3) actinide uptake (that is, actinide complexation constants); and (4) concentration of actinide ions in the aqueous phase (that is, actinide solubility). Quantification of actinide solubilities is described in Novak and Moore (1996). Collection of the other data, interpretation of that information, and development of parameter values for PA calculations is described in detail in Papenguth and Moore (1996). The humic proportionality constant is a combination of information from (1) and (3) above. This constant is multiplied by (4), the actinide concentration, to obtain the concentrations of actinides mobilized on humic colloids.

Further information on this parameter is found in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237683

References:

Novak, C.F., and Moore, R.C. 1996. Technical Memorandum to Malcolm Siegel, Re: Estimates of Dissolved Concentrations for +III, +IV, +V, and +VI Actinides in a Salado and a Castile Brine under Anticipated Repository Conditions, March 28, 1996. ERMS #236207.

Papenguth, Hans W. 1996. Memo to Christine T. Stockman. RE: Colloidal Actinide Source Term Parameters, Revision 2, April 22, 1996. ERMS #237522.

Papenguth, Hans W., and Moore, R.C. 1996. Mobile - Colloidal- Actinide Source Term, 3. Humic Substances, Sandia National Laboratories (ERMS #235855 Attachment A).

Parameter 45: Oxidation State Distribution Parameter

Parameter Description:

This parameter determines whether the repository environment is more reducing or less reducing for a particular realization.

Material and Property Name(s):

GLOBAL OXSTAT

Computational Code(s): PANEL

minimum	maximum
0	1.0

Units: None

Distribution Type: Uniform

Data: Site-Specific Experimental Data and Literature Research

Experimental results from Los Alamos National Laboratory, Pacific Northwest National Laboratory, and Argonne National Laboratories-East were used, as well as data from an extensive literature search. The parameter records package associated with this parameter is located at: Oxidation State Distribution (ERMS #235194).

Discussion:

The oxidation state distribution parameter is used to designate which oxidation states dominate the solubility. Actinides addressed are thorium, uranium, neptunium, plutonium, americium, and curium. Analysis of literature data demonstrated that certain actinides (that is, americium, thorium, curium) will exist only in one oxidation state given the expected WIPP repository conditions. Therefore, this distribution is not used with the PA for these actinides. Experimental evidence indicated that two oxidation states were possible for plutonium, uranium, and neptunium under the expected WIPP repository conditions. For these actinides, it is assumed that their solubilities and k_ds will be dominated by only one oxidation state, but it is uncertain which of two possible states will dominate. Therefore, in half of the realizations employing this parameter (if >0.5), the higher oxidation state solubilities and k_ds will be used, and in the other half of the realizations (if <0.5), the lower oxidation state solubilities and k_ds will be used (Weiner et al. 1996). Further information on this parameter is found in Appendix PA, Attachment SOTERM.

Parameter Data Entry Form ERMS: #237663

References:

Novak, C.F., and Moore, R.C. 1996. Technical Memorandum to Malcolm Siegel, Re: Estimates of Dissolved Concentrations for +III, +IV, +V, and +VI Actinides in a Salado and a Castile Brine under Anticipated Repository Conditions, March 28, 1996. ERMS #236207.

Stockman, Christine. 1996. Memo to Martin Tierney. RE: Implementation of Chemistry Parameters in PA. April 16, 1996. ERMS #237536.

Weiner, Ruth F., Hobart, D.E., Tait, C.D., and Clark, D.L. 1996. Analysis of Actinide Oxidation States in the WIPP. Contained in package ERMS #235194.

Parameter 46: Mining Transmissivity Multiplier

Parameter Description:

This parameter is a multiplier, which applies to the transmissivity in areas of the Culebra, which are located above areas of present and future potash mining.

Material and Property Name(s):

CULEBRA MINP_FAC

Computational Code: Routine Calculation

minimum	maximum
1.0	1000.0

Units: None

Distribution Type: Uniform

Data: Regulatory Basis

Data for the Mining Transmissivity Multiplier comes directly from the Preamble published in 40 CFR Part 194 (61 FR 5229). Based on its review of the literature, the EPA determined that mining can increase the conductivity of overlying formations by a factor of much as 1,000. Since the EPA does not specify a distribution for the multiplier, the DOE has assigned it a uniform distribution from 1 to 1,000 with a median value of 500.5. A discussion of the data associated with this parameter may be found in the following parameter records package: Mining Transmissivity Multiplier (ERMS #236489).

Discussion:

EPA's 40 CFR Part 194 requires that the DOE evaluate the consequences of mining in the McNutt on the performance of the WIPP (Larson 1996). The impacts of mining are taken into account by using a multiplier, which varies from 1 to 1,000 with a uniform distribution. The multiplier applies only to the transmissivity in the Culebra and it applies to areas that qualify under a range of criteria, including both mined areas and areas to be mined (Howard 1996).

In the PA, two cases are considered: (1) the partial mining case which includes all mining outside of the controlled area and (2) the full mining case which includes mining outside and inside of the controlled area. Everywhere that the Culebra is underlain by economical quantities of potash (see Section 2.3.1.1), the transmissivity is multiplied by the multiplier. The multiplier is applied uniformly over the entire mined area for a particular Tfield; however, the value of the multiplier changes for different Tfields. The partial mining case applies to all transmissivity vectors in the PA analysis. Starting from that initial condition, the full mining case has a 1 in 100 probability of occurring in any century over the 10,000 year regulatory

time frame (for any given Tfield).

Parameter Data Entry Form ERMS: #237666

References:

Howard, B. A. 1996. Memo from B. A. Howard to Mel Marietta, April 3, 1996, RE: Future Mining Events in the Performance Assessment. Attachment: Extent of Mining Position Paper, Revision 1. ERMS #238571.

Larson, Kurt. 1996. Memo to Mike Wallace, "Mining Transmissivity Multiplier—Area to be mined." April 25, 1996. ERMS #237455.

Wallace, M. 1996. Memo to M. Tierney, "Distribution for Non-Salado Parameter for SECOFL2D: Mining Transmissivity Multiplier," April 18, 1996. ERMS #239355.

Parameter 47: Culebra Transmissivity Field Index

Parameter Description:

This parameter is intended to incorporate uncertainty in the transmissivity field within the Culebra Dolomite Member of the Rustler Formation.

Material and Property Name(s):

GLOBAL TRANSIDX

Computational Code(s): SCMS Script

minimum	maximum
0.0	1.0

Units: None

Distribution Type: Uniform

Data: Professional Judgment - General Engineering Knowledge

No experimental data are associated with the transmissivity field index. The parameter is an index for selecting 1 of 100 transmissivity fields produced by PEST and MODFLOW. It varies uniformly from 0 to 1.

Discussion:

Using an approach known as conditioning, or making realizations of random fields coherent with measured information such as hydraulic head values, 100 equally likely Culebra transmissivity fields were generated (employing PEST and MODFLOW). After incorporating changes requested by EPA to account for future potash mining. Each realization was then converted to a flow field, using MODFLOW, assuming uniform Culebra thickness of 8 m and 16 percent effective porosity. TRANSDIX was used to sample on the interval (0,1). The result was mapped onto the integers 1-100 (the number of transmissivity fields) and the resulting integer was used to select a transmissivity field (Ruskauff 1996; Sandia WIPP Project 1992).

Parameter Data Entry Form ERMS: #233055

References:

Ruskauff, Greg. 1996. Memorandum to Martin Tierney, Re: Culebra Transmissivity Field Index, March 13, 1996. ERMS #235193

Sandia WIPP Project. 1992. Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992, Vol.3: Model Parameters. SAND92-0700/3. Albuquerque, NM: Sandia National Laboratories. ERMS #223529.

Parameter 48: Climate Index

Parameter Description:

A change in climate over the next 10,000 years could alter flow rates in the Culebra, thereby impacting radionuclide transport. The Climate Index is a multiplication factor to enhance the magnitude of flow in each realization of the Culebra flow field caused by changes in future climate.

Material and Property Name(s):

GLOBAL CLIMTIDX

Computational Code(s): PRESECOTP

Value	1	1.25	1.50	2.25
Percentiles	0	0.75	0.75	1

Units: None

Distribution Type: Cumulative

Data: General Literature and Professional Judgment

The parameter distribution was obtained by first surveying the available literature to obtain information that can be used to infer the annual precipitation rate since the end of the Pleistocene and for the next 10,000 years. Next, numerical simulations were performed to see how various assumed rates and temporal patterns of recharge would impact groundwater flow velocities in the Culebra within the WIPP site. The parameter records package associated with this parameter is located at: Climate Index (ERMS #236425).

Discussion:

The following main assumptions were used in the numerical simulations:

1. the groundwater basin conceptual model is applicable,
2. the lateral boundaries are flow divides (that is, no-flow boundaries) during the period simulated,
3. flow in the unsaturated zone can be neglected, and
4. the flow system was equilibrated to a recharge rate sufficient to maintain the water table near the land surface at the start of the simulations.

As described in the Climate Index Record Package (Corbet and Swift 1996), a step recharge function, which represents a radical disruption of the climate pattern of the Holocene, is unlikely and is assigned a 0.25 probability of occurrence and the Holocene recharge pattern is assigned a 0.75 probability of occurrence.

First, simulations were performed using a step recharge function for the pattern of future recharge. The results specify a uniform distribution between 1.5 and 2.25.

Next, six transient simulations using the Holocene pattern of future recharge were performed. The results specify a uniform distribution between 1.0 and 1.25.

Parameter Data Entry Form ERMS: #233031

References:

Corbet, T. and Swift, P. 1996. Memo to M. Tierney. Re: Distribution for Non-Salado Parameter for SECOFL2D: Climate Index, April 12, 1996. ERMS #237465.

Parameter 49: Culebra Half Matrix Block Length

Parameter Description:

This parameter is used to describe the half matrix block length (defined as one-half the thickness of a matrix slab between two parallel plates of fractures) for the Culebra dolomite. It is one of the parameters required in the SECOTP2D code for the double-porosity conceptualization of the Culebra (see also Appendix PA, Section PA-4.9).

Material and Property Name(s):

CULEBRA HMBLKLT

Computational Code(s): SECOTP2D

minimum	maximum
0.05	0.5

Units: Meters

Distribution Type: Uniform

Data: Professional Judgment - General Engineering Knowledge

The half matrix block length distribution is derived from numerical simulations of tracer test data. The data associated with this parameter are located in the following parameter records packages: Culebra Half Matrix Block Length (Culebra Transport Parameter) (ERMS #237225). Supporting data records packages for this parameter include: Tracer Test Interpretations, Simulations for Determination of Adective Porosity and Half Matrix Block Length parameters for CCA Calculations (ERMS #237450); Tracer Test Sample Analyses, H-19 Tracer Tests Conducted June 1995 through July 1995 (ERMS #237468); Tracer Test Sample Analyses, H-19 Tracer Tests Conducted December 1995 through April 1996 (ERMS #237452); and Tracer Test Sample Analyses, H-11 Tracer Tests Conducted February 1996 through March 1996 (ERMS #237467).

Discussion:

The half matrix block length is defined as one-half the thickness of a matrix slab between two parallel plates of fractures. Diffusive processes at the WIPP will cause some fraction of actinides, which are released from the repository, to diffuse from the advective porosity into the diffusive porosity (or matrix), thereby delaying and attenuating discharges at the site boundary. The larger the half matrix block length (smaller surface area for diffusion), the larger the release because there will be less diffusion and in turn less access to surface area for sorption (Meigs and McCord 1996; see CCA Appendix MASS).

The distribution of values for the half matrix block length is uniform, with values ranging from 0.05 to 0.5 m (that is, full matrix block length values from 0.1 to 1.0 m). This distribution

is based on numerical simulations of tracer test data from the H-3, H-11, and H-19 hydropads (Meigs and McCord 1996). Multiwell convergent flow tracer tests have been performed previously at H-3 and H-11 (Stensrud et al. 1989; Hydro Geo Chem, Inc. 1985). Additional tracer tests have been performed at H-11 and at H-19 (Beauheim et al. 1995). The 1995-96 tests at H-11 and H-19 consisted of single-well injection-withdrawal tests and multiwell convergent flow tests.

The matrix block length and the advective porosity are essentially fitting parameters inferred from comparing the results of numerical simulations of the tracer tests to the field data. Numerical simulations were performed with double-porosity models with both homogeneous and heterogeneous hydraulic conductivity fields. For the homogeneous approach, the field data was analyzed using the SWIFT-II transport code, and for the heterogeneous approach, the field data was analyzed using the THEMM code. Both modeling approaches yielded consistent results for each well-to-well path with regard to matrix block length (Meigs and McCord 1996).

Parameter Data Entry Form ERMS: #238356

References:

Beauheim, R. L., Meigs, L.C., Saulnier, G.J., and Stensrud, W.A. 1995. Culebra Transport Program Test Plan: Tracer Testing of the Culebra Dolomite Member of the Rustler Formation at the H-19 and H-11 Hydropads on the WIPP Site. ERMS #230156.

Hydro Geo Chem, Inc. 1985. WIPP Hydrology Program Waste Isolation Pilot Plant, SENM Hydrologic Data Report #1. SAND85-7206. Albuquerque, NM: Sandia National Laboratories. ERMS #228430.

Meigs, Lucy, and McCord, Jim. 1996. Memo to file. RE: Physical Transport in the Culebra Dolomite, July 11, 1996. ERMS #239167.

Stensrud, W.A., Bame, M.A., Lantz, K.D., Palmer, J.B., and Saulnier, G.J., Jr. 1989. WIPP Hydrology Program Waste Isolation Pilot Plant Southeastern New Mexico Hydrologic Data Report #8. SAND89-7056. Albuquerque, NM: Sandia National Laboratories. ERMS #228582.

Parameter 50: Culebra Advective Porosity

Parameter Description:

This parameter is used to describe the advective porosity (typically referred to as the fracture porosity) for the Culebra dolomite. It is one of the parameters required in the SECOTP2D code for the double-porosity conceptualization of the Culebra (see also Section 4.9).

Material and Property Name(s):

CULEBRA APOROS

Computational Code(s): SECOTP2D

minimum	maximum
1.0×10^{-4}	0.01

Units: None

Distribution Type: Log uniform

Data: Professional Judgment - General Engineering Knowledge

This porosity distribution is derived from numerical simulations of tracer test data. The data associated with this parameter are located in the following parameter records packages: Culebra Advective Porosity (Culebra Transport parameter) (ERMS #237227). Supporting data records packages for this parameter include: Tracer Test Interpretations, Simulations for Determination of Adective Porosity and Half Matrix Block Length parameters for CCA Calculations (ERMS #237450); Tracer Test Sample Analyses, H-19 Tracer Tests Conducted December 1995 through April 1996 (ERMS #237452); and Tracer Test Sample Analyses, H-11 Tracer Tests Conducted February 1996 through March 1996 (ERMS #237467).

Discussion:

The Culebra is a fractured dolomite with nonuniform properties and multiple scales of porosity, including fractures ranging from microscale to large, vuggy zones, inter-particle and inter-crystalline porosity. When the permeability contrast is significant between different scales of connected porosity, the total porosity of the system can be modeled by dividing it into the advective porosity (for example, fractures, and to some extent vugs connected by fractures, and interparticle porosity) and the diffusive (or matrix) porosity. The advective porosity refers to porosity through which most of the flow occurs (for example, fractures), while the diffusive porosity includes features such as intercrystalline porosity, and to some extent microfractures, vugs, and interparticle porosity, accessible to solutes only through diffusion. The advective porosity used for the PA simulations has been determined from evaluation of tracer test data (Meigs and McCord 1996). The diffusive porosity has been determined from laboratory measurements of core plugs, which do not contain large fractures

(Meigs and McCord 1996).

The distribution for the advective porosity is based on numerical simulations of tracer test data from the H-3, H-11, and H-19 hydropads (Meigs and McCord 1996). Multiwell convergent flow tests have been performed previously at H-3 and H-11 (Stensrud et al. 1989; Hydro Geo Chem, Inc. 1985). Additional tracer tests have been performed at H-11 and at H-19 (Beauheim et al. 1995). The recent tests at H-11 and H-19 consisted of single-well injection-withdrawal tests and multiwell convergent flow tests.

The advective porosity and the matrix block length are essentially fitting parameters inferred from comparing the results of numerical simulations of the tracer tests to the field data. Numerical simulations were performed with double-porosity models with both homogeneous and heterogeneous hydraulic conductivity fields. For the homogeneous approach, the field data was analyzed using the SWIFT-II transport code, and for the heterogeneous approach, the field data was analyzed using the THEMM code. Both modeling approaches yielded consistent results for each well-to-well path with regard to advective porosity (Meigs and McCord 1996).

Parameter Data Entry Form ERMS: #238358

References:

Beauheim, R. L., Meigs, L.C., Saulnier, G.J., and Stensrud, W.A. 1995. Culebra Transport Program Test Plan: Tracer Testing of the Culebra Dolomite Member of the Rustler Formation at the H-19 and H-11 Hydropads on the WIPP Site. ERMS #230156.

Hydro Geo Chem, Inc. 1985. WIPP Hydrology Program Waste Isolation Pilot Plant, SENM Hydrologic Data Report #1. SAND85-7206. Albuquerque, NM: Sandia National Laboratories. ERMS #228430.

Meigs, Lucy, and McCord, Jim. 1996. Memo to file. RE: Physical Transport in the Culebra Dolomite, July 11, 1996. ERMS #239167.

Stensrud, W.A., Bame, M.A., Lantz, K.D., Palmer, J.B., and Saulnier, G.J., Jr. 1989. WIPP Hydrology Program Waste Isolation Pilot Plant Southeastern New Mexico Hydrologic Data Report #8. SAND89-7056. Albuquerque, NM: Sandia National Laboratories. ERMS #28582.

Parameter 51: Culebra Diffusive Porosity

Parameter Description:

This parameter is used to describe the diffusive porosity (typically referred to as the matrix porosity) for the Culebra dolomite. It is one of the parameters required in the SECOTP2D code for the double-porosity conceptualization of the Culebra (see also Section PA-4.9).

Material and Property Name(s):

CULEBRA DPOROS

Computational Code(s): SECOTP2D

Value	0.10	0.11	0.12	0.16	0.18	0.19	0.25
Percentiles	0	0.10	0.25	0.50	0.75	0.90	1

Units: None

Distribution Type: Cumulative

Data: Site-Specific Experimental Data and Professional Judgment - General Engineering Knowledge

This porosity distribution is derived from laboratory measurements. The data associated with this parameter are located in the following parameter records packages: Culebra Diffusive Porosity (Culebra Transport Parameter) (ERMS #237228). Supporting data records packages for this parameter includes: Non-Salado Core Analyses Performed by Terra Tek (AA-2896) (ERMS #238234).

Discussion:

The Culebra is a fractured dolomite with nonuniform properties and multiple scales of porosity, including fractures ranging from microscale to large, vuggy zones and inter-particle and inter-crystalline porosity. When the permeability contrast is significant between different scales of connected porosity, the total porosity of the system can be modeled by dividing it into the advective (for example, fractures and, to some extent, vugs connected by fractures, and interparticle porosity) porosity and the diffusive (or matrix) porosity. The advective porosity refers to porosity through which most of the flow occurs, while the diffusive porosity includes features such as intercrystalline porosity and, to some extent, microfractures, vugs, and interparticle porosity accessible to solutes only through diffusion. The advective porosity to be used for the PA simulations has been determined from evaluation of tracer test data. The diffusive porosity has been determined from laboratory measurement of core plugs, which do not contain large fractures (Meigs and McCord 1996).

This diffusive porosity distribution is derived from laboratory measurements. Boyle's Law helium porosity measurements have been made from 103 Culebra core plugs from 17 locations as reported in Kelley and Saulnier (1990) as well as additional porosity measurements

completed by Terra Tek (ERMS #238234). The methodology used for porosity measurements are described in Kelley and Saulnier (1990). To account for areal averaging, individual porosity measurements from a borehole and/or hydropad were averaged to yield a borehole/hydropad average porosity. The averaged values were used to construct the distribution (Meigs and McCord 1996).

Parameter Data Entry Form ERMS: #238357

References:

Kelley, V. A., and Saulnier, G. 1990. Core Analyses for Selected Samples from the Culebra Dolomite at the Waste Isolation Pilot Plant Site. SAND90-7011. Albuquerque, NM: Sandia National Laboratories. ERMS #228629.

Meigs, Lucy, and McCord, Jim. 1996. Memo to file. RE: Physical Transport in the Culebra Dolomite, July 11, 1996. ERMS #239167.

Parameter 52: Matrix Distribution Coefficient for U(VI)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for uranium in the +VI oxidation state. K_d is the equilibrium ratio of the mass of U adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

U+6 MKD_U

Computational Code(s): SECOTP2D

minimum	maximum
3×10^{-5}	0.02

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved uranium. The experimental data did not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for uranium in the Culebra was set to zero, which was also conservative (DOE 1996). The laboratory sorption studies supporting the CCA values are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of K_ds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's K_ds are conservative (Brush 1996).

P.V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by samples of pure dolomite from Norway. Although this study did not yield K_ds for actual

samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP air intake shaft (AIS). This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density. Second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997, the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA 1998) than the uniform distribution specified by Brush and Storz (1996). The DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines,

Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 53: Matrix Distribution Coefficient for U(IV)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for uranium in the +IV oxidation state. K_d is the equilibrium ratio of the mass of uranium adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

U+4 MKD_U

Computational Code(s): SECOTP2D

minimum	maximum
0.70	10.0

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved uranium. The experimental data did not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for uranium in the Culebra was set to zero, which was also conservative (DOE 1996). The laboratory sorption studies are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of K_ds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's K_ds are conservative (Brush 1996).

P.V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by

samples of pure dolomite from Norway. Although this study did not yield K_ds for actual samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP AIS. This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density. Second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997, the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA 1998) than the uniform distribution specified by Brush and Storz (1996). The DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 54: Matrix Distribution Coefficient for Pu(III)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for plutonium in the +III oxidation state. K_d is the equilibrium ratio of the mass of plutonium adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

PU+3 MKD_PU

Computational Code(s): SECOTP2D

minimum	maximum
0.02	0.40

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved plutonium. The experimental data did not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for plutonium in the Culebra was set to zero, which was also conservative. (DOE 1996) The laboratory sorption studies are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of Kds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's Kds are conservative (Brush 1996).

P.V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by

samples of pure dolomite from Norway. Although this study did not yield K_ds for actual samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP AIS. This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density. Second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997, the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA 1998) than the uniform distribution specified by Brush and Storz (1996). The DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003)

Parameter Data Entry Form ERMS: #527707

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 55: Matrix Distribution Coefficient for Pu(IV)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for plutonium in the +IV oxidation state. K_d is the equilibrium ratio of the mass of plutonium adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

PU+4 MKD_PU

Computational Code(s): SECOTP2D

minimum	maximum
0.70	10.0

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved plutonium. The experimental data did not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for plutonium in the Culebra was set to zero, which was also conservative (DOE 1996). The laboratory sorption studies are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of K_ds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's K_ds are conservative (Brush 1996).

P. V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by samples of pure dolomite from Norway. Although this study did not yield K_ds for actual

samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP AIS. This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density. Second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997, the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA 1998) than the uniform distribution specified by Brush and Storz (1996). DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23: Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 56: Matrix Distribution Coefficient for Th(IV)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for thorium in the +IV oxidation state. K_d is the equilibrium ratio of the mass of thorium adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

TH+4 MKD_TH

Computational Code(s): SECOTP2D

minimum	maximum
0.70	10.0

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved thorium. The experimental data do not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for thorium in the Culebra was set to zero, which was also conservative (DOE 1996). The laboratory sorption studies are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of K_ds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's K_ds are conservative (Brush 1996).

P.V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by samples of pure dolomite from Norway. Although this study did not yield K_ds for actual

samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP AIS. This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density, and, second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997 the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA, 1998) than the uniform distribution specified by Brush and Storz (1996). The DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 57: Matrix Distribution Coefficient for Am(III)

Parameter Description:

This parameter describes the matrix distribution coefficient (K_d) for americium in the +III oxidation state. K_d is the equilibrium ratio of the mass of americium adsorbed on the solid phase(s) per unit mass of solid divided by the concentration of that element in the aqueous phase.

Material and Property Name(s):

AM+3 MKD_AM

Computational Code(s): SECOTP2D

minimum	maximum
0.02	0.40

Units: Cubic meters/kilogram

Distribution Type: Log uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , Brush (1996) described the laboratory sorption studies used to determine matrix K_ds for dissolved americium. The experimental data did not include K_ds for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. Brush (1996) believed that this was a more conservative approach. Further, the fracture-surface K_d (actually, K_a) for americium in the Culebra was set to zero, which was also conservative (DOE 1996). The laboratory sorption studies are summarized below.

I. Triay at LANL studied the sorption of Th(IV), U(VI), Np(V), Pu(V), and Am(III) by dolomite-rich Culebra rock. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase(s) versus the final dissolved radionuclide concentration, or plots of K_ds versus the final dissolved radionuclide concentration. The samples, which Triay used, contained a lower concentration of clay minerals than the Culebra as a whole and therefore, Triay's K_ds are conservative (Brush 1996).

P.V. Brady at SNL studied the sorption of Nd(III) (a nonradioactive analog of Pu(III) and Am(III)), Th(IV), U(VI), Np(V), Pu(V), and Am(III) from synthetic NaCl solutions by samples of pure dolomite from Norway. Although this study did not yield K_ds for actual

samples of Culebra rock and Culebra fluids, it did yield results useful for interpreting the results of Triay's study and for extending Triay's data to the pH conditions (about 9 to 10) expected from an MgO backfill in WIPP disposal rooms (Brush 1996).

D.A. Lucero at SNL studied actinide transport through intact core samples from the Culebra in the WIPP AIS. This study did not yield K_ds directly. Instead, Lucero calculated retardation factors (Rs) and K_ds. For U(VI) and Np(V), which were eluted from the cores, Lucero was able to calculate discrete K_ds. For Th(IV), Pu(V), and Am(III), which were not eluted during the experiments, Lucero was only able to calculate minimum values of K_ds.

The range and probability distribution of matrix K_ds for deep (Castile and Salado) or Culebra brines that resulted in less retardation for each element or elemental oxidation state was used in the calculations. Since there are uncertainties as to the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the probability distributions of these factors (especially brine type, the partial pressure of CO_2, and the resulting pH) in the Culebra. Therefore, the matrix K_ds were specified as a uniform distribution rather than a Student's-t distribution.

Subsequent to the CCA PA calculations, two errors were found in the procedures used to calculate the matrix K_ds. First, a brine density of 1.00 g/ml was used rather than the measured brine density, and, second, incorrect values for the mass of dolomite were incorporated (Brush and Storz 1996). The erroneous use of these values led to incorrectly calculated distribution coefficients. However, the influence of the changes in these values on the distribution coefficients was believed to be insignificant (Brush and Storz 1996). Brush and Storz (1996) provided the corrected values of these K_ds.

For some isotopes, Brush and Storz (1996) calculated K_ds for both deep (Castile or Salado) and Culebra brines. To remain conservative and consistent with the CCA, the range of K_d values for the brine that has the smaller mean value were used.

In 1997, the EPA's review of experimental K_d data indicated that K_d values appeared to be logarithmically distributed. In addition, since the actinide K_ds ranged over more than an order of magnitude, the EPA felt that a log uniform distribution was more appropriate (EPA 1998) than the uniform distribution specified by Brush and Storz (1996). The DOE has adopted the revised values and distribution for the K_ds (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #527706

References:

Brush, L. H. 1996. Memo to M. S. Tierney, RE: Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA, June 10, 1996. ERMS #238801.

Brush, L.H. and Storz, L. 1996. Memo to M. S. Tierney, RE: Revised Ranges and Probability Distributions of K_ds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA calculations to Support the WIPP CCA, July 24, 1996. ERMS #241561.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.
U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

Parameter 58: Effective Shear Resistance to Erosion

Parameter Description:

This parameter describes the intrusion borehole's effective shear strength for erosion.

Material and Property Name(s):

BOREHOLE TAUFAIL

Computational Code: CUTTINGS_S

minimum	maximum
0.05	77.0

Units: Pascals

Distribution Type: Log uniform

Data: Professional Judgment

WIPP specific experimental data were not available for the effective shear resistance to erosion of the waste. Therefore, at the recommendation of the EPA, an estimation technique based on particle size distributions was used. A discussion of this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

The waste shear resistance was estimated based on particle size distributions as determined by an expert elicitation panel. The estimate used the Shield's parameter, which relies on a measure of the central point of a population of particles of various sizes, to determine the critical shear stress for an erodible, cohesionless sediment bed (Simon and Senturk 1992). With this approach, the calculated critical shear stresses ranged from 0.64 Pa to 77 Pa. For conservatism, the low value for waste shear resistance from the CCA PA was retained for the low value in the PAVT while the high value from the Shield's parameter method was used for the high value in the PAVT. The decision to use 0.05 Pa for the low value was supported by information that indicated that very fine-grained materials are not cohesionless as assumed in the Shield's parameter calculation. The information also showed that a lower bound of the critical shear stress for fine-grained cohesive sediments is on the order of the 0.05 Pa. (Parthenaides and Paaswell 1970) The high end of the range was considered appropriate for cohesionless particles and was retained based on the expert elicitation results. A log uniform distribution for the waste shear resistance was selected for the PAVT to provide equal

weighting over the three orders of magnitude in the range, 0.05 to 77 Pa.

Until additional experimental data becomes available, the range of values selected for the PAVT is certainly inclusive of any reasonable values for the shear strength of the waste. Therefore, DOE has adopted the PAVT values for the shear strength of the waste (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #522016

References:

Simon, D.B. and Senturk, F. 1992. "Sediment Transport Technology Water and Sediment Dynamics." Water Resource Publication.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582.

Parameter 60: Probability of Hitting a Brine Reservoir

Parameter Description:

The parameter represents the probability of hitting a brine reservoir during a drilling intrusion.

Material and Property Name(s):

GLOBAL PBRINE

Computational Code: CCDFGF

minimum	maximum
0.01	0.60

Units: None

Distribution Type: Uniform

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

In CCA Appendix PAR , geophysical methods, geological structure analysis, and geostatistical correlation were performed to determine the probability of intersection of a borehole with both the waste disposal region and a pressurized brine reservoir in the Castile formation. The DOE estimated that there is a 0.08 probability that any random borehole that penetrates waste at the WIPP also would penetrate an underlying brine reservoir (DOE 1996).

During preparation of the CCA, DOE reexamined their time-domain electromagnetic geophysical survey and found that between 10 and 55 percent of the waste panel area may be underlain by relatively conductive units, possibly due to one or more brine reservoirs (Alumbaugh 1996). The data did not support a means to distinguish boundaries between possible brine reservoirs and non-reservoir areas. As a consequence, DOE assumed that only one reservoir existed below the waste panels.

The DOE also mapped the geologic structure of selected units within the Castile and Salado Formations to examine the relationship between identified brine intercepts and evaporite deformation. Studies indicated that many of the observed brine encounters in the Delaware Basin were associated with structural deformation in the Castile Formation (e.g. ERDA-6). The mapping exercise reaffirmed DOE's belief that much of the Castile Formation underlying the WIPP site is generally not deformed (and therefore, the likelihood of a brine reservoir

beneath the waste panels was expected to be low). However, DOE did not consider the results of this geologic structural analysis in quantifying the probability of a drilling intrusion intersecting a brine reservoir.

The DOE then conducted a geostatistical analysis to estimate the probability of drilling into a fractured reservoir in areas overlain by the waste disposal panels. The analysis was based on 354 drill holes and 27 brine reservoir intercepts within the vicinity of the WIPP. Geostatistical techniques were used to estimate the probabilities that a randomly placed drilling intrusion would encounter pressurized brine in the Castile Formation. The overall probability for the waste panel area was determined to be 0.08 (a probability of 0.08 that a drilling intrusion would intersect a waste panel and penetrate into a underlying, pressurized brine reservoir). This value was selected for the parameter PBRINE in the PA calculation.

The EPA reviewed the CCA and supporting documentation and concluded that the parameter PBRINE should be changed from a constant having a value of 0.08 to a uniform distribution represented by a range of 0.01 to 0.60 (median value of 0.305). The EPA believes that this range better reflects the uncertainty in the parameter and is a more appropriate representation of the concept of reasonable expectation than the fixed value of 0.08 used by DOE in the CCA (EPA 1998a).

In reaching its conclusion, EPA considered the possibility that the WIPP-12 brine reservoir may underlie the entire WIPP site and thus the probability of a drilling intrusion encountering the pressurized reservoir could approach certainty (100 percent). This would require the assumption that this reservoir is cylindrical in shape, which EPA considered unlikely because brine resides in vertical or subvertical fractures, and because of the nature of the results from the time domain electromagnetic soundings.

For these reasons, EPA agreed with DOE that there exists a significant uncertainty concerning the magnitude and extent of brine reservoirs beneath the waste panels, but questioned DOE's basis for the probability of encountering such a brine reservoir to be only eight percent, since other DOE-generated information indicated that this probability could be as high as 60 percent (EPA 1998a and 1998b).

EPA found that the most direct information on the presence of brine reservoirs was provided by the time domain electromagnetic information, which could be interpreted to indicate that brine reservoirs underlie as much as 55 percent of the repository. The EPA also found that these same data could be interpreted to mean that brine reservoirs may underlie as little as 10 percent of the repository.

Using the time domain electromagnetic information, EPA developed probability distributions for four cases involving either random or block models to correlate adjacent measurements and assumed either the base of the Castile Formation or the base of the Anhydrite III layer in the Castile Formation was the cutoff point above which brine reservoirs may exist (EPA 1998a and 1998b). EPA found that it made little difference whether the random model or block model was used to characterize correlation between the time domain electromagnetic measurements. However, the simulated probability distributions for encountering brine were highly sensitive to the geologic assumption of whether or not brine reservoirs exist below the bottom of the Anhydrite III layer. Using the base of the Castile Formation Anhydrite Layer III

as the lowermost stratigraphic layer below which no brine reservoirs occur, the simulations showed that the area beneath the WIPP containing brine reservoirs varies from one to six percent. However, if the base of the Castile Formation is the lowermost stratigraphic layer below which no brine reservoirs occur, the area of the excavated repository underlain by reservoirs increases to about 35 to 58 percent.

For these reasons, EPA selected one percent as the lower limit and 60 percent as the upper limit for the fraction of the excavated area underlain by brine reservoirs. The upper limit was slightly larger than the largest estimated value for this parameter, but was less than 100percent because it was unreasonable to assume that brine reservoirs must exist. The lower limit was equal to the smallest estimated value and was greater than zero because it was also unreasonable to assume with absolute certainty that a reservoir does not exist. A uniform distribution was mandated because the range of this parameter spans slightly more than an order of magnitude and the use of a uniform distribution conservatively biased the sampling toward the high end. The DOE has adopted the value for the probability of a drilling intrusion intersecting a brine reservoir in the Castile Formation beneath the WIPP (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #248783

References:

Alumbaugh, D.L. 1996. “Re-analysis of the Time Domain Electromagnetic (TDEM) Data Collected at the WIPP Site.” ERMS #245405. Sandia National Laboratories. Albuquerque, NM.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, NM: United States Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

U.S. Environmental Protection Agency (EPA). 1998a. Technical Support Document for Section 194.23:Parameter Justification Report. Docket No. A-93-02, V-B-14. U.S. Environmental Protection Agency. Washington, D.C.

U.S. Environmental Protection Agency (EPA). 1998b. Response to Comments, Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant’s Compliance with 40 CFR 191 Disposal Regulations: Certification Decision. Docket No. A-93-02, V-C-1. U.S. Environmental Protection Agency. Washington D.C.

Parameter 61: Drill String Angular Velocity

Parameter Description:

This parameter describes the drill string angular velocity. This value is required to calculate the fluid-generated shear stress.

Material and Property Name(s):

BOREHOLE DOMEGA

Computational Code: CUTTINGS_S

Value	4.2	6.3	8.4	10.5	12.6	14.7	16.8	18.8	20.9	23.0
Percentiles	0	0.15	0.65	0.80	0.90	0.95	0.97	0.98	0.99	1.0

Units: Radians/second

Distribution Type: Cumulative

Data: Site-Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records package: Analysis Reports Relating to Analysis Plan AP-086 (ERMS #520523), specifically Summary of parameter changes adopted from the Performance Assessment Verification Test for the Technical Baseline Migration (ERMS #522016).

Discussion:

The quantity of waste brought to the surface due to an inadvertent penetration of the repository by an exploratory drill bit depends upon three physical processes:

- Cuttings - waste contained in the cylindrical volume created by the cutting action of the drill bit passing through the waste.
- Cavings - waste that erodes from the borehole in response to movement of drilling fluid within the annulus between the drill collars and the borehole wall
- Spallings - waste forced into the drilling fluid due to pressurization of the repository by waste-generated gas. This requires a repository gas pressure that exceeds the hydrostatic pressure of the drilling mud.

The cavings component of direct surface release, after a waste disposal room is penetrated, consists of that quantity of waste material that is eroded from the borehole wall by the action of the flowing drilling fluid. The erosion process model describes the shearing action on the waste by the drilling fluid as it moves up the borehole annulus. The amount of material eroded from the borehole wall is dependent upon the magnitude of the fluid-generated shear

stress acting on the wall and the effective shear resistance to erosion of the compacted, decomposed waste. The drill string angular velocity is required to calculate the fluid-generated shear stress.

For the CCA, the DOE had information about the rotational velocities used in current practice when drilling through salt. Using this information, the DOE derived a median value based on a constructed cumulative distribution of the known, applicable rotational velocities for drilling in salt. The derived median value was 7.8 radians/second. The CCA PA calculation assigned a constant value of 7.8 radians/second to the drill string angular velocity.

In its review, the EPA found that the data used to derive the median drill string angular velocity encompassed a rather large range of values, from 4.2 to 23 radians/second. Because of this large range, the EPA questioned whether the PA model showed sensitivity to variations in drill string angular velocity over this range. The EPA performed a sensitivity analysis over the range of drill string angular velocities and observed a 60 percent change in cavings releases. As a result, the EPA determined that a constant value for drill string angular velocity did not sufficiently reflect the uncertainty due to the wide range of possible values. The EPA also found that the potential impact on repository performance was sufficient to warrant use of a range of values and required the DOE to treat the drill string angular velocity as a sampled variable with a constructed cumulative distribution with a minimum of 4.2 radians/second, a maximum of 23 radians/second, and a median of 7.77 radians/second. The data were based on a study of current drilling practices in salt, documented in EPA (1998). DOE has adopted the distribution for the drill angular velocity (Hansen and Leigh 2003).

Parameter Data Entry Form ERMS: #231512

References:

EPA (U.S. Environmental Protection Agency). 1998. Technical Support Document for Section 194.23:Parameter Justification Report.

Hansen, C., Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Carlsbad, NM. Sandia National Laboratories. ERMS #528582

Parameter 62: Residual Brine Saturation – Upper Portion of Simplified Shaft

Parameter Description:

The residual brine saturation (S_{br}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves (see CCA Appendix PA, Figure 4.2.1). Referred to also as S_{wr} (wetting phase) or S_{lr} (liquid phase), residual brine saturation is the point reached under high gas saturation conditions when brine is no longer continuous throughout the pore network and relative brine permeability becomes zero.

Material and Property Name(s):

SHFTU SAT_RBRN

Computational Code: BRAGFLO

Value	0	0.20	0.60
Percentiles	0	.50	1

Units: None

Distribution Type: Cumulative

Data: General Literature Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: CRA Parameter Package (ERMS #526660) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The values sampled for the material SHFTU are assigned to the other shaft seal materials (SHFTL_T1, SHFTL_T2, and CONC_MON). These distributions are the same as were used for the material SALT_T1 in DOE (1996) shaft seal model (James and Stein 2002, 2003).

A literature search was conducted to obtain residual liquid saturation values for consolidated geologic materials, concrete, and asphalt in support of the CCA. Residual liquid saturations for geologic materials were found in four references (Brooks and Corey 1964; Lappala et al. 1987; Parker et al. 1987; and Rawls et al. 1982). Brooks and Corey (1964) determined residual saturations for five unconsolidated samples based on measured values of liquid saturation as a function of capillary pressure. Lappala et al. (1987) determined residual moisture content for 11 soils by obtaining best fits to measured moisture content versus pressure head data using three models. The residual moisture contents determined for each soil using the three models were averaged and divided by the reported porosity to obtain a residual liquid saturation for each soil. Parker et al. (1987) fit their saturation-pressure relationship to observed data to obtain residual saturations for a sandy and clayey porous

media. Residual water contents reported by Rawls et al. (1982) for 11 soil texture classes were divided by the reported porosity to obtain residual saturations.

Mayer et al. (1992) reported a residual liquid saturation for normal concrete of 0.30. Data regarding residual liquid saturations in asphalt materials were not found in the literature.

The literature values of residual liquid saturation for geologic materials and concrete fall within the range of 0.0 to 0.6 with all but two values falling within the range of 0.0 to 0.4. It was recommended that a value of 0.2 be used for the residual liquid saturation of all seal components.

Parameter Data Entry Form ERMS: #527670

References:

Brooks, R.H., and Corey, A.T. 1964. Hydraulic Properties of Porous Media. Hydrology Paper No. 3. Fort Collins, CO: Colorado State University.

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Lappala, E.G., Healy, R.W., and Weeks, E.P. 1987. Documentation of Computer Program VS2D to Solve the Equations of Fluid Flow in Variably Saturated Porous Media. Water-Resources Investigations Report 83-4099. Denver, CO: U.S. Geological Survey. Tech Library books collection: PC173.4.P67L31987.

Mayer, G., Jacobs, F., and Wittmann, F.H. 1992. "Experimental Determination and Numerical Simulation of the Permeability of Cementitious Materials," Nuclear Engineering and Design. Vol. 138, no. 2, 171-177.

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Parameter 63: Residual Gas Saturation – Upper Portion Simplified Shaft

Parameter Description:

The residual (critical) gas saturation (S_{gr}) is required in the two-phase flow model to define the relative permeability and capillary pressure curves (see CCA Appendix PA, Figure 4.2.1). S_{gr} corresponds to the degree of waste-generated gas saturation necessary to create an incipient interconnected pathway in porous material; a condition required for porous rock to be permeable to gas.

Material and Property Name(s):

SHFTU SAT_RGAS

Computational Code: BRAGFLO

minimum	maximum
0	0.40

Units: None

Distribution Type: Uniform

Data: General Literature Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: CRA Parameter Package (ERMS #526660) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The values sampled for the material SHFTU are assigned to the other shaft seal materials (SHFTL_T1, SHFTL_T2, and CONC_MON). These distributions are the same as were used for the material SALT_T1 in DOE (1996) shaft seal model (James and Stein 2002; 2003).

A literature search was conducted to obtain residual saturation values for consolidated geologic materials, concrete, and asphalt in support of the CCA.

A single value of 0.18 was found for normal concrete (Mayer et al. 1992). Based on this value, a distribution was assumed for the seal components. The recommended value was 0.2, and the recommended range was 0.0 to 0.4 with a uniform distribution for all shaft seal materials.

Parameter Data Entry Form ERMS: #527671

References:

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Mayer, G., Jacobs, F., and Wittmann, F.H. 1992. "Experimental Determination and Numerical Simulation of the Permeability of Cementitious Materials," Nuclear Engineering and Design. Vol. 138, no. 2, 171-177.

Parameter 64: Log of Intrinsic Permeability – Upper Portion of Simplified Shaft

Parameter Description:

This parameter describes the permeability distribution for the shaft in the non-Salado formations (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

SHFTU PRMX_LOG

Computational Code: BRAGFLO

Value	-20.5	-20.0	-19.5	-19.0	-18.5	-18.0	-17.5	-17.0	-16.5
Percentiles	0	0.03	0.11	0.24	0.43	0.65	0.89	0.99	1

Units: Log (meters squared)

Distribution Type: Cumulative

Data:

A discussion of the data associated with this parameter may be found in the following parameter records packages: CRA Parameter Package (ERMS #526660) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The simplified shaft seal model (James and Stein 2002; 2003) was developed by combining the effects of the many different materials used in the baseline shaft seal model and representing these effects with fewer materials.

The permeability of the non-Salado portion of the simplified shaft was obtained by calculating the effective permeability of the materials above the Salado in the baseline shaft seal model (EARTH and CLAY_RUS). A cumulative distribution was fit to the resulting equivalent permeability data (James and Stein 2003).

Parameter Data Entry Form ERMS: #527656

References:

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Parameter 65: Log of Intrinsic Permeability – Lower Portion of Simplified Shaft (0-200 yrs)

Parameter Description:

This parameter describes the permeability distributions for the portion of the shaft in the Salado for the first 200 years of operation (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

SHFTL_T1 PRMX_LOG

Computational Code: BRAGFLO

Value	-20.0	-19.5	-19.0	-18.5	-18.0	-17.5	-17.0	-16.5
Percentiles	0	0.01	0.10	0.31	0.64	0.87	0.99	1

Units: Log (meters squared)

Distribution Type: Cumulative

Data: Site- Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: CRA Parameter Package (ERMS #526660) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The simplified shaft seal model (James and Stein 2002; 2003) was developed by combining the effects of the many different materials used in the baseline shaft seal model and representing these effects with fewer materials.

An analysis of the equivalent permeability data from the baseline shaft model used in the CCA indicates that the distributions for 0–10, 10–25, and 25–50 years are nearly identical (with mean equivalent permeabilities decreasing by 5 and 42 percent at 10 and 25 years, respectively). After 50 years, permeability progressively decreases between time intervals 25–50, 50–100, 100–200, and 200–400 years (with mean equivalent permeabilities decreasing by 133 percent, 604 percent, and 2507 percent at 50, 100, and 200 years, respectively). The final change occurs at 400 years and results in a very slight increase in effective permeability (mean equivalent permeability increases by 31 percent) because of increases in concrete permeability assumed for the 400–10,000 year period.

To capture the time-dependent behavior of the Salado composite material, there is a single permeability change at 200 years. A conservative choice for the distribution of the first 200

years is to average the distributions for the 0–10, 10–25, and 25–50 year intervals. Note that the 50–100 and 100–200 year intervals are not used. From 200 to 10,000 years, the distribution is defined as the average of the distributions from the baseline shaft seal model for the 200–400 and 400–10,000 year intervals. Because only the highest permeability data from the first 50 years is used to constrain the model for 200 years, this approach overestimates the permeability during the first 200 years and is thereby conservative. The permeability distributions can be implemented in PA by fitting a cumulative distribution to the data (James and Stein 2003).

Parameter Data Entry Form ERMS: #527672

References:

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Parameter 66: Log of Intrinsic Permeability – Lower Portion of Simplified Shaft (200-10,000 yrs)

Parameter Description:

This parameter describes the permeability distributions for the portion of the shaft in the Salado for the 200 to 10,000 years of operation (see CCA Appendix PA, Figure 4.2.1). It is a sampled parameter for the x-direction and the values are then applied to the y- and z-directions.

Material and Property Name(s):

SHFTL_T2 PRMX_LOG

Computational Code: BRAGFLO

Value	-22.5	-22.0	-21.5	-21.0	-20.5	-20.0	-19.5	-19.0	-18.5	-18.0
Percentiles	0	0.02	0.08	0.17	0.31	0.53	0.70	0.87	0.97	1

Units: Log (meters squared)

Distribution Type: Cumulative

Data: Site- Specific Experimental Data

A discussion of the data associated with this parameter may be found in the following parameter records packages: CRA Parameter Package (ERMS #526660) and Analysis Reports for AP-094 (ERMS #525186).

Discussion:

The simplified shaft seal model (James and Stein 2002; 2003) was developed by combining the effects of the many different materials used in the baseline shaft seal model and representing these effects with fewer materials.

An analysis of the equivalent permeability data from the baseline shaft model used in the CCA indicates that the distributions for 0–10, 10–25, and 25–50 years are nearly identical (with mean equivalent permeabilities decreasing by 5 and 42 percent at 10 and 25 years, respectively). After 50 years, permeability progressively decreases between time intervals 25–50, 50–100, 100–200, and 200–400 years (with mean equivalent permeabilities decreasing by 133, 604, and 2507 percent at 50, 100, and 200 years, respectively). The final change occurs at 400 years and results in a very slight increase in effective permeability (mean equivalent permeability increases by 31 percent) because of increases in concrete permeability assumed for the 400–10,000 year period.

To capture the time-dependent behavior of the Salado composite material from 200 to 10,000 years, the distribution is defined as the average of the distributions from the baseline shaft seal model for the 200–400 and 400–10,000 year intervals. Because only the highest permeability

data from the first 50 years is used to constrain the model for 200 years, this approach overestimates the permeability during the first 200 years and is thereby conservative. The permeability distributions are implemented in PA by fitting a cumulative distribution to the data. (James and Stein 2003)

Parameter Data Entry Form ERMS: #527682

References:

James, S.J., and Stein, J. 2002. Analysis Plan for the Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment. AP-094. Carlsbad, NM: Sandia National Laboratories. ERMS #524958.

James, S.J., Stein, J. 2003. Analysis Report for: Development of a Simplified Shaft Seal Model for the WIPP Performance Assessment, Rev. 1. January 23, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS #525203.

Parameter 75: Index for Selecting Realizations for the SPALL Model

Parameter Description:

The index for selecting realizations in the SPALL model is used by CUTINGS_S to randomly match the 50 LHS elements (vectors) generated for DRSPALL to the 100 LHS elements (vectors) generated for BRAGFLO.

Material and Property Name(s):

SPALLMOD RNDSPALL

Computational Code: CUTTINGS_S

minimum	maximum
0.0	1.0

Units: None.

Distribution Type: Uniform

Data: Professional Judgment

The parameter distribution is uniform because each of the 50 unique sets of property values generated for DRSPALL is deemed equally probable.

Discussion:

Uncertainty in waste property values for DRSPALL is addressed by using LHS to sample on selected input parameters to create 50 equally probable, unique sets of input data (vectors). DRSPALL is then executed 50 times (once per vector) to create an array of 50 equally probable spall volumes for a selected repository pressure. When exercised over several pressures, a “spallings response surface” is thus created.

CUTTINGS_S must use a technique to map BRAGFLO vectors to DRSPALL vectors, since the vectors are created by independent LHS runs. CUTTINGS_S thus reads the RNDSPALL( ) value for a given BRAGFLO vector, multiplies it by 50, and takes the resulting integer value as the “index” of the DRSPALL vector associated with this BRAGFLO vector. Since there are 50 DRSPALL vectors and 100 BRAGFLO vectors, two BRAGFLO vectors will be mapped to one DRSPALL vector.

Parameter Data Entry Form ERMS: # NA

References:

NA

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied)

LHS#	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
1	STEEL	Generic steel in waste	CORRMCO2	Inundated corrosion rate for steel without CO2 present	Uniform	m/s	1.59E-14	1.59E-14	0.00E+00	3.17E-14	9.15E-15
2	WAS_AREA	Waste emplacement area and waste	PROBDEG	Probability of plastics and rubber biodegradation in event of microbial gas generation	Delta	NONE	2.00E+00	2.00E+00	0.00E+00	2.00E+00	0.00E+00
3	WAS_AREA	Waste emplacement area and waste	GRATMICI	Inundated biodegradation rate for cellulose	Uniform	moles/(kg*s)	4.92E-09	4.92E-09	3.17E-10	9.51E-09	2.65E-09
4	WAS_AREA	Waste emplacement area and waste	GRATMICH	Humid biodegredation rate for cellulose	Uniform	moles/(kg*s)	6.34E-10	6.34E-10	0.00E+00	1.27E-09	3.66E-10
5	CELLULS	Cellulose	FBETA	Factor beta for microbial reaction rates	Uniform	NONE	5.00E-01	5.00E-01	0.00E+00	1.00E+00	2.89E-01
6	WAS_AREA	Waste emplacement area and waste	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	7.50E-02	7.50E-02	0.00E+00	1.50E-01	4.33E-02
(6)	DRF_PCS	Drift/Explosion Wall Portion of PCS	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	7.50E-02	7.50E-02	0.00E+00	1.50E-01	4.33E-02
(6)	REPOSIT	Repository regions outside of panel region	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	7.50E-02	7.50E-02	0.00E+00	1.50E-02	4.33E-03
7	WAS_AREA	Waste emplacement area and waste	SAT_RBRN	Residual Brine Saturation	Uniform	NONE	2.76E-01	2.76E-01	0.00E+00	5.52E-01	1.59E-01
(7)	DRF_PCS		SAT_RBRN	Residual Brine Saturation	Uniform	NONE	2.76E-01	2.76E-01	0.00E+00	5.52E-01	1.59E-01
(7)	REPOSIT	Repository regions outside of panel region	SAT_RBRN	Residual Brine Saturation	Uniform	NONE	2.76E-01	2.76E-01	0.00E+00	5.52E-02	1.59E-02
8	WAS_AREA	Waste emplacement area and waste	SAT_WICK	Index for computing wicking	Uniform	NONE	5.00E-01	5.00E-01	0.00E+00	1.00E+00	2.89E-01
9	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	log(m^2)	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01
(9)	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	log(m^2)	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01
(9)	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	log(m^2)	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
10	3525	CONC_PCS	Concrete portion of PCS	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	log(m^2)	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01
(10)		CONC_PCS	Concrete portion of PCS	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	$\log(m^2)$	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01
(10)		CONC_PCS	Concrete portion of PCS	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	$\log(m^2)$	-1.88E+01	-1.87E+01	-2.07E+01	-1.70E+01	7.55E-01
11	3626	SOLU4	Solubility Multiplier for U+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
12	3627	SOLTH4	Solubility Multiplier for Th+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
14	3532	CONC_PCS	Concrete portion of PCS	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01	2.00E-01	0.00E+00	4.00E-01	1.16E-01
15	3531	CONC_PCS	Concrete portion of PCS	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.50E-01	2.00E-01	0.00E+00	6.00E-01	1.76E-01
16	3522	CONC_PCS	Concrete portion of PCS	PORE_DIS	Brooks-Corey pore distribution parameter	Cumulative	NONE	2.52E+00	9.40E-01	1.10E-01	8.10E+00	2.48E+00
17	544	S_HALITE	Salado halite, intact	POROSITY	Effective porosity	Cumulative	NONE	1.28E-02	1.00E-02	1.00E-03	3.00E-02	8.52E-03
18	547	S_HALITE	Salado halite, intact	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$\log(m^2)$	-2.25E+01	-2.25E+01	-2.40E+01	-2.10E+01	8.66E-01
(18)		S_HALITE	Salado halite, intact	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$\log(m^2)$	-2.25E+01	-2.25E+01	-2.40E+01	-2.10E+01	8.66E-01
(18)		S_HALITE	Salado halite, intact	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$\log(m^2)$	-2.25E+01	-2.25E+01	-2.40E+01	-2.10E+01	8.66E-01
19	541	S_HALITE	Salado halite, intact	COMP_RCK	Bulk Compressibility	Uniform	Pa^{-1}	9.75E-11	9.75E-11	2.94E-12	1.92E-10	5.46E-11
20	591	S_MB139	Salado marker bed 139, intact and fractured	PRMX_LOG	Log of intrinsic permeability, X-direction	Student	$\log(m^2)$	-1.89E+01	-1.89E+01	-2.10E+01	-1.71E+01	1.20E+00
(20)		S_MB139	Salado marker bed 139, intact and fractured	PRMY_LOG	Log of intrinsic permeability, Y-direction	Student	$\log(m^2)$	-1.89E+01	-1.89E+01	-2.10E+01	-1.71E+01	1.20E+00
(20)		S_MB139	Salado marker bed 139, intact and fractured	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Student	$\log(m^2)$	-1.89E+01	-1.89E+01	-2.10E+02	-1.71E+02	1.20E+01

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
21	580	S_MB139	Salado marker bed 139, intact and fractured	COMP_RCK	Bulk Compressibility	Student	Pa^{-1}	8.26E-11	8.26E-11	1.09E-11	2.75E-10	1.12E-10
22	596	S_MB139	Salado marker bed 139, intact and fractured	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00	4.00E+00	1.00E+00	4.00E+00	0.00E+00
23	598	S_MB139	Salado marker bed 139, intact and fractured	SAT_RBRN	Residual Brine Saturation	Student	NONE	8.36E-02	8.36E-02	7.78E-03	1.74E-01	5.01E-02
24	599	S_MB139	Salado marker bed 139, intact and fractured	SAT_RGAS	Residual Gas Saturation	Student	NONE	7.71E-02	7.71E-02	1.40E-02	1.97E-01	6.41E-02
25	587	S_MB139	Salado marker bed 139, intact and fractured	PORE_DIS	Brooks-Corey pore distribution parameter	Student	NONE	6.44E-01	6.44E-01	4.91E-01	8.42E-01	1.09E-01
26	546	S_HALITE	Salado halite, intact	PRESSURE	Brine far-field pore pressure	Uniform	Pa	1.25E+07	1.25E+07	1.10E+07	1.39E+07	8.23E+05
27	66	CASTILER	Castile Brine Reservoir	PRESSURE	Brine far-field pore pressure	Triangular	Pa	1.36E+07	1.27E+07	1.11E+07	1.70E+07	1.25E+06
28	67	CASTILER	Castile Brine Reservoir	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	$log(m^2)$	-1.21E+01	-1.18E+01	-1.47E+01	-9.80E+00	1.01E+00
(28)		CASTILER	Castile Brine Reservoir	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	$log(m^2)$	-1.21E+01	-1.18E+01	-1.47E+01	-9.80E+00	1.01E+00
(28)		CASTILER	Castile Brine Reservoir	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	$log(m^2)$	-1.21E+02	-1.18E+02	-1.47E+02	-9.80E+01	1.01E+01
29	61	CASTILER	Castile Brine Reservoir	COMP_RCK	Bulk Compressibility	Triangular	Pa^{-1}	5.30E-11	4.00E-11	2.00E-11	1.00E-10	1.70E-11
30	3184	BH_SAND	Borehole filled with silty sand	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$log(m^2)$	-1.37E+01	-1.37E+01	-1.63E+01	-1.10E+01	1.53E+00
(30)		BH_SAND	Borehole filled with silty sand	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$log(m^2)$	-1.37E+01	-1.37E+01	-1.63E+01	-1.10E+01	1.53E+00
(30)		BH_SAND	Borehole filled with silty sand	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$log(m^2)$	-1.37E+01	-1.37E+01	-1.63E+02	-1.10E+02	1.53E+01
31	198	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$log(m^2)$	-1.60E+01	-1.60E+01	-1.94E+01	-1.25E+01	2.00E+00
(31)		DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$log(m^2)$	-1.60E+01	-1.60E+01	-1.94E+01	-1.25E+01	2.00E+00
(31)		DRZ_2	Disturbed rock zone; time period 0 to 10,000 years	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$log(m^2)$	-1.60E+01	-1.60E+01	-1.94E+02	-1.25E+02	2.00E+01
32	3185	CONC_PLG	Concrete Plug, surface and Rustler	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$log(m^2)$	-1.80E+01	-1.80E+01	-1.90E+01	-1.70E+01	5.80E-01

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
(32)		CONC_PLG	Concrete Plug, surface and Rustler	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	log(m^2)	-1.80E+01	-1.80E+01	-1.90E+01	-1.70E+01	5.80E-01
(32)		CONC_PLG	Concrete Plug, surface and Rustler	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	log(m^2)	-1.80E+01	-1.80E+01	-1.90E+01	-1.70E+01	5.80E-01
34	3262	SOLAM3	Solubility Multiplier for Am+3	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
35	3263	SOLAM3	Solubility Multiplier for Am+3	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
36	3265	SOLPU3	Solubility Multiplier for Pu+3	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
37	3264	SOLPU3	Solubility Multiplier for Pu+3	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
38	3266	SOLPU4	Solubility Multiplier for Pu+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
39	3389	SOLPU4	Solubility Multiplier for Pu+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
40	3390	SOLU4	Solubility Multiplier for U+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
41	3391	SOLU6	Solubility Multiplier for U+6	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
42	3392	SOLU6	Solubility Multiplier for U+6	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
43	3393	SOLTH4	Solubility Multiplier for Th+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	NONE (see PPR-04-2002, ERMS #524651)	1.80E-01	-9.00E-02	-2.00E+00	1.40E+00	3.68E-01
44	3429	PHUMOX3	Proportionality Constant, +3 State, Humic Colloids	PHUMCIM	Proportionality Const., Humic Colloids, Castile Brine, MgO controls pH	Cumulative	NONE	1.10E+00	1.37E+00	6.50E-02	1.60E+00	4.69E-01
45	3417	GLOBAL	Information that applies globally	OXSTAT	Index for the Oxidation State	Uniform	NONE	5.00E-01	5.00E-01	0.00E+00	1.00E+00	2.89E-01
46	3419	CULEBRA	Culebra member of the Rustler formation	MINP_FAC	Mining Transmissivity Multiplier	Uniform	NONE	5.01E+02	5.01E+02	1.00E+00	1.00E+03	2.88E+02
47	225	GLOBAL	Information that applies globally	TRANSIDX	Index for selecting realizations of the Transmissivity Field	Uniform	NONE	5.00E-01	5.00E-01	0.00E+00	1.00E+00	2.89E-01
48	223	GLOBAL	Information that applies globally	CLIMTIDX	Climate Index	Cumulative	NONE	1.31E+00	1.17E+00	1.00E+00	2.25E+00	3.48E-01
49	3485	CULEBRA	Culebra member of the Rustler formation	HMBLKLT	Culebra Half Matrix-Block Length	Uniform	m	2.75E-01	2.75E-01	5.00E-02	5.00E-01	1.30E-01
50	3487	CULEBRA	Culebra member of the Rustler formation	APOROS	Culebra Advective Porosity	Log uniform	NONE	2.10E-03	1.00E-03	1.00E-04	1.00E-02	2.50E-03
51	3486	CULEBRA	Culebra member of the Rustler formation	DPOROS	Diffusive Porosity for Culebra Dolomite	Cumulative	NONE	1.60E-01	1.60E-01	1.00E-01	2.50E-01	3.50E-02
52	3475	U+6	Uranium VI	MKD_U	Matrix Partition Coefficient for Uranium	Log uniform	m^3/kg	3.10E-03	7.70E-04	3.00E-05	2.00E-02	4.60E-03
53	3479	U+4	Uranium IV	MKD_U	Matrix Partition Coefficient for Uranium	Log uniform	m^3/kg	3.50E+00	2.60E+00	7.00E-01	1.00E+01	2.50E+00

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
54	3480	PU+3	Plutonium III	MKD_PU	Matrix Partition Coefficient for Plutonium	Log uniform	m^3/kg	1.30E-01	9.00E-02	2.00E-02	4.00E-01	1.00E-01
55	3481	PU+4	Plutonium IV	MKD_PU	Matrix Partition Coefficient for Plutonium	Log uniform	m^3/kg	3.50E+00	2.60E+00	7.00E-01	1.00E+01	2.50E+00
56	3478	TH+4	Thorium IV	MKD_TH	Matrix Partition Coefficient for Thorium	Log uniform	m^3/kg	3.50E+00	2.60E+00	7.00E-01	1.00E+01	2.50E+00
58	2254	BOREHOLE	Borehole and Fill	TAUFAIL	Effective shear strength for erosion (rfail)	Log uniform	Pa	1.05E+01	1.96E+00	5.00E-02	7.70E+01	1.71E+01
60	3493	GLOBAL	Information that applies globally	PBRINE	Prob. that Drilling Intrusion In Excavated Area Encounters Pressurized Brine	Uniform	NONE	3.05E-01	3.05E-01	1.00E-02	6.00E-01	1.70E-01
61	27	BOREHOLE	Borehole and Fill	DOMEGA	Drill string angular velocity (0)	Cumulative	rad/s	8.63E+00	7.80E+00	4.20E+00	2.30E+01	3.16E+00
62	3560	SHFTU	Upper portion of simplified shaft	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.50E-01	2.00E-01	0.00E+00	6.00E-01	1.76E-01
(62)		CONC_MON	Concrete Monolith	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.50E-01	2.00E-01	0.00E+00	6.00E-01	1.76E-01
(62)		SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.50E-01	2.00E-01	0.00E+00	6.00E-01	1.76E-01
(62)		SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.50E-01	2.00E-01	0.00E+00	6.00E-01	1.76E-01
63	3561	SHFTU	Upper portion of simplified shaft	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01	2.00E-01	0.00E+00	4.00E-01	1.16E-01
(63)		CONC_MON	Concrete Monolith	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01	2.00E-01	0.00E+00	4.00E-01	1.16E-01
(63)		SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01	2.00E-01	0.00E+00	4.00E-01	1.16E-01
(63)		SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01	2.00E-01	0.00E+00	4.00E-01	1.16E-01
64	3557	SHFTU	Upper portion of simplified shaft	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	$log(m^2)$	-1.82E+01	-1.83E+01	-2.05E+01	-1.65E+01	7.94E-01
(64)		SHFTU	Upper portion of simplified shaft	PRMY_LOG	Log of intrinsic permeability, Y direction	Cumulative	$log(m^2)$	-1.82E+01	-1.83E+01	-2.05E+01	-1.65E+01	7.94E-01

Table PAR-8. Parameters Sampled in LHS Code (and parameters to which sampled values were applied) — Continued

LHS#	Id #	Material	Material Description	Property	Property Description	Distribution Type	Units	Mean	Median	Low	High	Standard Deviation
(64)		SHFTU	Upper portion of simplified shaft	PRMZ_LOG	Log of intrinsic permeability, Z direction	Cumulative	log(m^2)	-1.82E+01	-1.83E+01	-2.05E+01	-1.65E+01	7.94E-01
65	3569	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	log(m^2)	-1.80E+01	-1.82E+01	-2.00E+01	-1.65E+01	5.97E-01
(65)		SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PRMY_LOG	Log of intrinsic permeability, Y-direction	Cumulative	log(m^2)	-1.80E+01	-1.82E+01	-2.00E+01	-1.65E+01	5.97E-01
(65)		SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Cumulative	log(m^2)	-1.80E+01	-1.82E+01	-2.00E+01	-1.65E+01	5.97E-01
66	3579	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	log(m^2)	-1.98E+01	-2.01E+01	-2.25E+01	-1.80E+01	9.37E-01
(66)		SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PRMY_LOG	Log of intrinsic permeability, Y-direction	Cumulative	log(m^2)	-1.98E+01	-2.01E+01	-2.25E+01	-1.80E+01	9.37E-01
(66)		SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Cumulative	log(m^2)	-1.98E+01	-2.01E+01	-2.25E+01	-1.80E+01	9.37E-01
75	NA	SPALLMOD	Material developed for DRSPALL	RNDSPALL	Index for selecting realizations of the SPALL model.	Uniform	NONE	0.50E+00	0.50E+00	0.00E+00	1.00E+00	2.89E-01

[1]For parameters with a triangular distribution, the value provided for the median is actually the mode

Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
1	1.09E-14	0.00E+00	8.17E-09	1.11E-10	5.59E-01	1.70E-02	9.33E-02	8.69E-01	-1.95E+01	-1.89E+01	-1.51E+00	5.78E-01	2.80E-01	3.06E-01	9.27E-01	2.33E-02	-2.23E+01	8.37E-11	-1.90E+01	9.76E-11	4.00E+00	1.08E-01	9.60E-02	5.73E-01
2	1.49E-14	2.00E+00	3.54E-09	6.47E-10	6.83E-02	1.48E-01	9.96E-02	7.30E-01	-1.75E+01	-1.73E+01	2.26E-01	-4.71E-01	1.44E-01	1.34E-01	7.95E-01	1.07E-02	-2.35E+01	1.57E-10	-1.86E+01	3.53E-11	1.00E+00	1.09E-01	5.56E-02	6.65E-01
3	1.20E-15	0.00E+00	2.31E-09	1.16E-09	3.07E-01	1.39E-01	1.86E-01	9.48E-01	-2.01E+01	-1.86E+01	-2.60E-01	8.41E-02	1.40E-01	3.83E-01	3.40E+00	5.58E-03	-2.26E+01	1.19E-10	-1.94E+01	1.41E-10	4.00E+00	1.15E-01	1.05E-01	6.62E-01
4	1.97E-14	2.00E+00	7.38E-09	1.15E-09	7.86E-02	6.79E-02	2.44E-01	8.75E-01	-1.93E+01	-1.89E+01	-4.15E-01	-2.73E-01	2.81E-02	7.63E-03	5.57E-01	4.73E-03	-2.35E+01	1.60E-10	-1.89E+01	8.13E-11	1.00E+00	1.23E-02	6.04E-02	7.43E-01
5	2.87E-14	1.00E+00	5.20E-09	9.97E-10	6.91E-01	3.89E-03	2.21E-01	5.80E-01	-1.83E+01	-2.02E+01	-6.54E-02	2.63E-04	4.01E-02	1.45E-03	7.79E+00	8.67E-03	-2.14E+01	4.39E-11	-1.87E+01	5.83E-11	4.00E+00	1.39E-01	7.07E-02	8.26E-01
6	1.89E-14	1.00E+00	1.98E-09	2.08E-10	9.77E-01	1.41E-01	1.16E-01	7.79E-01	-1.87E+01	-1.75E+01	-2.05E-02	2.69E-01	1.17E-01	4.16E-01	4.86E+00	2.54E-02	-2.33E+01	1.45E-10	-2.00E+01	2.33E-10	1.00E+00	9.22E-02	7.15E-02	7.31E-01
7	1.06E-14	0.00E+00	4.58E-09	6.89E-10	5.09E-01	8.61E-02	1.09E-01	4.52E-02	-1.82E+01	-1.92E+01	1.30E-01	-2.00E-01	1.72E-01	5.05E-02	4.65E+00	2.84E-02	-2.16E+01	4.62E-11	-1.83E+01	1.30E-11	4.00E+00	7.24E-02	8.48E-02	6.30E-01
8	2.51E-14	0.00E+00	3.13E-09	6.15E-10	1.39E-01	5.49E-03	3.35E-01	6.12E-01	-1.85E+01	-1.92E+01	1.55E-01	-1.32E-01	3.06E-01	1.85E-01	8.36E-01	1.54E-02	-2.12E+01	1.92E-11	-1.96E+01	1.96E-10	1.00E+00	7.25E-02	4.13E-02	6.83E-01
9	1.57E-14	1.00E+00	9.32E-09	2.58E-10	8.39E-01	1.28E-01	4.42E-01	6.82E-01	-1.99E+01	-2.01E+01	1.04E-01	-7.16E-02	3.91E-01	5.11E-01	5.64E+00	2.79E-02	-2.12E+01	1.66E-11	-1.84E+01	2.12E-11	1.00E+00	3.78E-02	1.29E-01	6.48E-01
10	2.41E-15	2.00E+00	2.78E-09	7.11E-10	4.32E-01	1.13E-01	3.22E-01	5.36E-01	-2.00E+01	-1.91E+01	2.45E-01	-4.41E-01	1.14E-01	1.65E-01	7.55E+00	5.91E-03	-2.34E+01	1.55E-10	-1.92E+01	1.21E-10	1.00E+00	9.86E-02	6.38E-02	5.82E-01
11	2.48E-14	0.00E+00	2.64E-09	8.21E-12	5.00E-01	7.27E-02	5.43E-01	5.85E-01	-1.85E+01	-1.88E+01	-3.44E-01	-2.34E-02	7.47E-02	1.98E-01	5.02E-01	4.49E-03	-2.38E+01	1.81E-10	-1.87E+01	3.63E-11	4.00E+00	8.44E-02	8.39E-02	6.26E-01
12	1.72E-14	1.00E+00	5.56E-09	1.26E-09	1.06E-01	8.71E-02	2.73E-01	3.35E-01	-1.88E+01	-1.84E+01	-6.84E-01	-4.63E-01	1.29E-01	5.62E-01	2.58E+00	2.00E-02	-2.28E+01	1.16E-10	-1.90E+01	8.81E-11	4.00E+00	5.25E-02	1.14E-01	6.60E-01
13	3.02E-14	0.00E+00	8.73E-09	2.03E-10	5.95E-01	8.05E-02	7.81E-02	9.05E-01	-1.89E+01	-1.86E+01	2.80E-01	-1.41E+00	2.12E-01	3.18E-01	3.66E+00	7.96E-03	-2.34E+01	1.49E-10	-1.86E+01	6.64E-11	4.00E+00	7.62E-02	9.41E-02	6.05E-01
14	3.64E-15	2.00E+00	4.90E-09	8.19E-10	3.17E-01	1.06E-01	2.08E-01	3.17E-02	-1.97E+01	-1.83E+01	-1.14E+00	-9.53E-01	2.58E-01	2.65E-01	4.43E+00	6.45E-03	-2.36E+01	1.73E-10	-1.87E+01	6.88E-11	4.00E+00	6.39E-02	1.08E-01	7.38E-01
15	3.16E-14	2.00E+00	6.82E-09	7.72E-10	2.69E-01	6.11E-02	5.19E-01	2.90E-01	-1.87E+01	-1.88E+01	-9.96E-01	2.45E-01	3.22E-01	6.69E-02	6.95E+00	1.43E-02	-2.37E+01	1.71E-10	-1.92E+01	1.23E-10	4.00E+00	7.96E-02	6.85E-02	5.25E-01
16	1.71E-14	1.00E+00	3.04E-09	1.66E-10	8.10E-02	7.56E-02	2.09E-02	9.34E-01	-1.88E+01	-1.87E+01	-1.31E-01	-9.54E-02	3.38E-01	1.06E-02	4.89E-01	9.05E-03	-2.11E+01	1.26E-11	-2.06E+01	2.75E-10	4.00E+00	8.36E-02	1.16E-01	6.16E-01
17	2.83E-14	1.00E+00	4.41E-09	2.67E-10	1.59E-01	1.01E-01	3.80E-01	7.45E-01	-1.87E+01	-1.89E+01	-3.87E-01	-4.89E-02	2.96E-01	2.57E-01	8.89E-01	3.30E-03	-2.25E+01	1.25E-10	-1.77E+01	1.09E-11	1.00E+00	7.83E-02	9.02E-02	5.96E-01
18	6.12E-15	2.00E+00	4.52E-09	1.20E-10	4.30E-02	9.56E-02	4.41E-01	3.54E-01	-1.89E+01	-1.79E+01	3.11E-02	-6.74E-02	2.52E-01	5.53E-01	3.35E+00	2.74E-03	-2.15E+01	2.44E-11	-2.10E+01	2.75E-10	1.00E+00	9.44E-02	1.13E-01	6.65E-01
19	1.37E-14	0.00E+00	5.15E-09	8.26E-10	8.23E-01	6.64E-02	3.60E-01	9.81E-01	-1.94E+01	-1.96E+01	5.41E-01	-3.04E-01	2.21E-01	1.77E-01	1.97E-01	1.23E-02	-2.13E+01	1.54E-11	-1.91E+01	1.29E-10	1.00E+00	1.11E-01	1.01E-01	6.38E-01
20	2.09E-14	0.00E+00	3.70E-09	4.86E-10	7.16E-01	3.15E-02	3.42E-01	9.98E-01	-1.89E+01	-1.83E+01	-1.85E+00	-7.91E-02	3.76E-01	5.72E-01	2.14E+00	2.20E-02	-2.19E+01	5.48E-11	-1.84E+01	1.09E-11	1.00E+00	8.57E-02	2.30E-02	6.55E-01
21	4.71E-16	0.00E+00	7.27E-09	1.08E-09	2.74E-01	1.44E-02	2.39E-01	8.22E-02	-1.84E+01	-1.81E+01	-9.06E-02	-4.91E-01	3.31E-01	3.91E-01	6.91E-01	1.46E-02	-2.15E+01	4.16E-11	-1.88E+01	7.41E-11	1.00E+00	1.01E-01	8.00E-02	5.67E-01
22	2.95E-14	2.00E+00	7.82E-09	1.28E-10	9.37E-01	1.11E-02	6.78E-03	8.23E-01	-1.85E+01	-1.80E+01	9.83E-01	-1.23E-02	2.75E-01	2.90E-01	2.71E+00	2.94E-02	-2.27E+01	1.22E-10	-1.88E+01	8.03E-11	4.00E+00	5.41E-02	8.70E-02	6.40E-01
23	7.20E-15	1.00E+00	3.91E-09	9.41E-11	4.76E-01	4.32E-02	2.54E-01	7.89E-01	-1.81E+01	-1.87E+01	-3.07E-02	3.72E-02	1.89E-01	1.55E-01	2.24E-01	9.37E-03	-2.13E+01	2.99E-11	-1.96E+01	1.90E-10	4.00E+00	8.82E-02	9.13E-02	6.78E-01
24	2.55E-14	0.00E+00	3.24E-09	3.05E-10	7.09E-01	2.49E-02	4.76E-01	4.42E-01	-1.86E+01	-1.95E+01	-5.29E-02	-7.85E-01	2.87E-01	1.00E-01	6.02E+00	3.77E-03	-2.38E+01	1.79E-10	-1.88E+01	9.32E-11	1.00E+00	8.41E-02	3.99E-02	6.18E-01
25	9.22E-16	0.00E+00	2.18E-09	5.57E-10	8.04E-01	6.99E-02	9.40E-02	3.78E-01	-1.87E+01	-1.76E+01	-5.87E-01	-3.98E-01	3.40E-01	7.19E-02	3.39E-01	1.19E-02	-2.32E+01	1.39E-10	-1.84E+01	2.80E-11	1.00E+00	1.33E-01	5.05E-02	6.08E-01
26	1.40E-14	2.00E+00	6.22E-09	6.14E-11	7.50E-01	6.98E-03	2.35E-01	2.93E-01	-1.93E+01	-1.84E+01	-9.76E-02	-2.32E-01	3.19E-01	2.76E-02	3.84E-01	1.09E-02	-2.37E+01	1.78E-10	-1.85E+01	3.33E-11	1.00E+00	8.77E-02	8.15E-02	6.55E-01
27	1.54E-14	2.00E+00	1.41E-09	5.69E-10	2.60E-02	7.13E-02	4.82E-01	4.81E-01	-1.91E+01	-1.84E+01	-7.98E-02	-1.69E-01	3.34E-01	2.96E-01	3.74E+00	1.66E-02	-2.36E+01	1.59E-10	-1.91E+01	9.89E-11	4.00E+00	6.13E-02	1.09E-01	6.96E-01
28	3.66E-17	1.00E+00	7.54E-09	7.40E-10	1.25E-01	1.26E-01	5.56E-02	2.56E-01	-1.83E+01	-1.98E+01	-1.35E-01	-2.27E-01	1.50E-01	4.87E-01	5.65E-01	2.51E-02	-2.24E+01	9.37E-11	-1.85E+01	2.45E-11	4.00E+00	9.83E-02	3.77E-02	5.90E-01
29	2.60E-14	2.00E+00	7.17E-09	8.58E-10	6.89E-01	1.22E-01	5.08E-02	4.56E-01	-1.95E+01	-1.90E+01	6.72E-01	-3.38E-01	4.94E-02	1.07E-01	1.05E+00	2.45E-02	-2.18E+01	4.79E-11	-1.90E+01	8.49E-11	1.00E+00	1.05E-01	1.40E-02	6.43E-01
30	1.44E-14	2.00E+00	9.12E-09	1.11E-09	4.50E-01	5.10E-02	2.78E-01	7.93E-01	-1.79E+01	-1.88E+01	6.05E-01	5.74E-02	6.39E-02	5.86E-02	3.14E+00	1.97E-02	-2.29E+01	1.18E-10	-1.91E+01	9.54E-11	1.00E+00	9.07E-02	1.07E-01	6.04E-01
31	4.92E-15	0.00E+00	8.45E-09	1.00E-09	4.44E-01	6.17E-02	4.64E-01	3.44E-01	-1.79E+01	-1.78E+01	7.47E-01	9.69E-01	3.50E-01	1.84E-02	4.76E+00	1.74E-02	-2.30E+01	1.11E-10	-1.81E+01	1.09E-11	1.00E+00	9.66E-02	5.20E-02	7.01E-01
32	1.03E-14	0.00E+00	7.69E-09	1.17E-09	3.85E-01	3.27E-02	3.92E-01	1.94E-01	-1.90E+01	-1.91E+01	-2.71E-02	-1.66E+00	2.32E-01	1.25E-01	7.04E+00	6.78E-03	-2.17E+01	3.64E-11	-1.97E+01	1.81E-10	4.00E+00	8.98E-02	5.41E-02	6.46E-01
33	1.47E-14	0.00E+00	6.98E-09	1.04E-09	8.48E-01	8.25E-02	4.31E-02	7.07E-01	-1.94E+01	-1.80E+01	-4.33E-01	-1.51E-01	3.88E-02	1.14E-01	7.95E+00	8.34E-03	-2.33E+01	1.53E-10	-1.83E+01	1.09E-11	4.00E+00	3.43E-02	6.73E-02	6.35E-01
34	1.17E-14	1.00E+00	7.58E-10	5.16E-10	3.60E-01	1.03E-01	3.72E-01	7.67E-01	-1.84E+01	-1.90E+01	-5.61E-02	6.53E-01	2.25E-01	4.92E-01	1.70E+00	2.80E-02	-2.26E+01	9.63E-11	-1.88E+01	8.27E-11	4.00E+00	8.29E-02	3.41E-02	6.10E-01
35	2.91E-14	0.00E+00	4.71E-09	1.02E-09	5.76E-01	9.04E-02	3.53E-01	6.42E-01	-1.81E+01	-1.74E+01	7.24E-02	-7.48E-01	1.80E-02	5.84E-01	6.40E+00	2.42E-03	-2.20E+01	7.01E-11	-1.86E+01	6.74E-11	4.00E+00	7.15E-02	6.13E-02	6.52E-01
36	1.75E-14	0.00E+00	6.53E-09	1.25E-09	6.56E-01	1.20E-01	4.75E-01	5.50E-01	-1.83E+01	-1.91E+01	1.10E+00	9.06E-01	1.58E-01	3.54E-01	3.05E+00	1.38E-02	-2.14E+01	2.83E-11	-1.82E+01	1.09E-11	4.00E+00	7.75E-02	1.06E-01	6.44E-01
37	2.06E-14	0.00E+00	4.92E-09	1.48E-10	1.46E-01	4.14E-02	5.35E-01	1.75E-01	-1.75E+01	-2.02E+01	-1.29E-02	-4.06E-03	2.07E-01	1.50E-01	3.24E-01	1.89E-02	-2.31E+01	1.30E-10	-1.91E+01	1.15E-10	1.00E+00	6.78E-02	7.63E-02	6.17E-01

Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
38	2.60E-14	0.00E+00	1.31E-09	9.67E-10	9.42E-01	1.44E-01	4.31E-01	4.27E-01	-1.88E+01	-1.94E+01	-2.13E-01	1.30E-01	1.88E-01	6.03E-02	4.10E+00	5.17E-03	-2.27E+01	9.82E-11	-1.94E+01	1.48E-10	4.00E+00	8.61E-02	8.44E-02	6.21E-01
39	2.17E-15	1.00E+00	3.26E-09	1.49E-11	5.87E-01	2.86E-02	1.12E-01	6.25E-01	-1.93E+01	-1.86E+01	1.44E-01	7.25E-01	2.68E-01	5.40E-02	4.02E+00	2.06E-03	-2.34E+01	1.64E-10	-1.86E+01	4.88E-11	4.00E+00	7.93E-02	9.59E-02	5.82E-01
40	4.45E-15	2.00E+00	8.32E-09	3.93E-10	8.12E-01	1.43E-01	5.20E-01	8.58E-01	-1.98E+01	-1.94E+01	-3.62E-02	-6.44E-01	2.16E-01	2.31E-01	7.25E-01	1.51E-02	-2.15E+01	2.75E-11	-1.80E+01	1.09E-11	1.00E+00	5.53E-02	4.27E-02	6.32E-01
41	1.25E-14	2.00E+00	6.07E-09	3.40E-10	9.03E-01	1.31E-01	5.39E-01	2.28E-01	-1.91E+01	-1.89E+01	4.42E-02	3.96E-01	2.94E-01	1.30E-01	5.29E+00	2.56E-02	-2.25E+01	1.06E-10	-2.01E+01	2.52E-10	4.00E+00	6.05E-02	1.70E-02	6.69E-01
42	1.22E-14	1.00E+00	5.21E-10	4.10E-10	7.83E-01	2.63E-02	4.45E-02	4.67E-01	-1.84E+01	-1.82E+01	-2.16E-01	-8.34E-02	4.74E-03	4.04E-02	4.26E-01	5.40E-03	-2.18E+01	4.02E-11	-1.95E+01	1.64E-10	4.00E+00	5.99E-02	6.27E-02	6.74E-01
43	1.40E-15	1.00E+00	8.60E-09	3.99E-10	4.26E-01	3.86E-02	4.19E-01	6.07E-01	-2.01E+01	-1.79E+01	-1.67E-01	-1.47E-02	2.88E-01	8.12E-02	4.68E-01	2.69E-02	-2.39E+01	1.90E-10	-1.95E+01	1.59E-10	4.00E+00	1.17E-01	9.15E-02	6.98E-01
44	2.77E-14	0.00E+00	8.93E-09	1.12E-09	6.31E-01	3.60E-02	1.95E-01	8.87E-01	-1.86E+01	-1.98E+01	-7.94E-01	7.29E-02	1.71E-01	4.55E-01	5.98E-01	1.64E-03	-2.17E+01	4.85E-11	-1.93E+01	1.43E-10	1.00E+00	1.02E-01	8.22E-02	7.70E-01
45	3.11E-14	2.00E+00	2.15E-09	7.09E-10	5.45E-01	5.43E-02	3.56E-01	1.17E-01	-1.87E+01	-1.83E+01	-3.08E-01	-6.91E-01	2.79E-01	4.08E-01	2.43E-01	2.40E-02	-2.24E+01	1.00E-10	-1.88E+01	5.46E-11	4.00E+00	9.10E-02	1.03E-01	5.93E-01
46	7.84E-15	1.00E+00	5.73E-09	4.58E-10	8.86E-01	4.45E-02	3.19E-01	4.15E-01	-1.85E+01	-1.93E+01	-7.37E-02	-1.26E-01	3.13E-01	3.68E-01	1.29E+00	1.04E-03	-2.27E+01	8.47E-11	-1.89E+01	8.79E-11	4.00E+00	5.01E-02	6.32E-02	7.18E-01
47	2.97E-15	1.00E+00	9.75E-10	1.10E-09	8.97E-01	1.32E-01	5.10E-01	8.44E-01	-1.79E+01	-1.88E+01	-1.78E-01	-1.89E-01	3.09E-01	1.35E-02	8.17E-01	1.84E-02	-2.22E+01	6.87E-11	-1.90E+01	1.09E-10	4.00E+00	4.19E-02	1.74E-01	7.25E-01
48	8.52E-15	0.00E+00	1.08E-09	3.24E-10	9.22E-02	1.15E-01	6.21E-02	7.54E-01	-1.96E+01	-1.87E+01	-4.72E-01	1.17E-01	6.91E-02	4.43E-02	6.27E-01	1.94E-02	-2.25E+01	7.72E-11	-1.71E+01	1.09E-11	4.00E+00	6.50E-02	6.69E-02	6.86E-01
49	8.98E-15	0.00E+00	5.55E-09	1.64E-10	2.23E-01	4.54E-02	3.10E-01	4.73E-01	-1.93E+01	-1.87E+01	-2.35E-01	-5.41E-01	2.38E-03	2.50E-01	6.63E+00	2.08E-02	-2.12E+01	2.30E-11	-1.91E+01	9.03E-11	1.00E+00	1.11E-01	9.35E-02	6.90E-01
50	2.31E-14	0.00E+00	8.04E-09	5.90E-10	1.66E-01	1.07E-01	2.27E-01	1.23E-01	-2.03E+01	-1.91E+01	3.69E-01	-4.22E-02	8.23E-02	3.37E-02	5.89E+00	2.88E-02	-2.21E+01	7.66E-11	-1.94E+01	1.39E-10	4.00E+00	4.49E-02	7.31E-02	6.82E-01
51	1.87E-14	2.00E+00	8.79E-09	2.96E-10	2.18E-01	1.10E-01	1.61E-01	1.34E-01	-1.83E+01	-1.89E+01	-1.87E-01	1.90E-01	2.15E-01	2.07E-01	1.79E-01	1.33E-03	-2.11E+01	7.04E-12	-1.81E+01	1.09E-11	4.00E+00	7.80E-02	8.83E-02	5.70E-01
52	9.60E-15	1.00E+00	6.89E-09	9.47E-10	3.44E-01	8.90E-02	4.06E-01	3.91E-01	-1.85E+01	-1.95E+01	7.75E-01	-2.03E-01	1.66E-01	4.11E-01	2.34E+00	8.39E-03	-2.32E+01	1.48E-10	-1.88E+01	7.33E-11	4.00E+00	8.01E-02	1.63E-01	6.80E-01
53	1.65E-14	1.00E+00	6.15E-09	5.01E-10	7.79E-01	3.55E-02	4.88E-01	9.28E-01	-1.92E+01	-1.80E+01	8.00E-01	1.14E+00	1.32E-01	5.24E-01	4.33E+00	3.45E-03	-2.37E+01	1.83E-10	-1.86E+01	4.34E-11	1.00E+00	7.05E-02	1.40E-02	6.39E-01
54	1.29E-14	0.00E+00	1.21E-09	7.82E-10	7.45E-01	1.00E-01	2.87E-01	3.68E-01	-1.91E+01	-1.88E+01	8.60E-01	-5.71E-01	1.99E-01	4.76E-01	1.92E+00	1.02E-02	-2.39E+01	1.88E-10	-1.84E+01	3.00E-11	4.00E+00	1.68E-01	2.62E-02	6.71E-01
55	2.34E-14	0.00E+00	1.71E-09	7.54E-10	1.90E-02	5.95E-02	4.30E-01	7.12E-01	-1.97E+01	-1.93E+01	-1.40E-01	-3.51E-01	3.56E-01	7.61E-02	7.19E+00	8.16E-03	-2.14E+01	1.14E-11	-1.96E+01	1.76E-10	1.00E+00	5.83E-02	4.86E-02	6.03E-01
56	1.20E-14	0.00E+00	2.81E-09	2.84E-10	7.63E-01	4.83E-02	2.97E-01	5.16E-01	-2.03E+01	-1.97E+01	5.89E-01	-1.07E+00	2.35E-01	1.41E-01	2.92E-01	3.10E-03	-2.35E+01	1.63E-10	-1.89E+01	6.31E-11	1.00E+00	7.38E-02	7.49E-02	6.33E-01
57	6.89E-15	0.00E+00	5.04E-09	9.63E-10	7.39E-01	5.05E-02	3.76E-02	2.08E-01	-1.76E+01	-1.99E+01	9.51E-02	-1.22E-01	2.03E-01	2.09E-01	1.55E+00	1.35E-02	-2.37E+01	1.68E-10	-1.87E+01	4.17E-11	1.00E+00	7.78E-03	7.64E-02	6.29E-01
58	2.46E-14	0.00E+00	4.79E-09	1.07E-09	2.09E-01	1.24E-01	4.62E-01	1.47E-01	-1.96E+01	-1.92E+01	1.48E-02	8.42E-01	1.55E-01	4.62E-01	3.07E-01	4.33E-03	-2.26E+01	1.03E-10	-1.98E+01	1.84E-10	4.00E+00	1.07E-01	6.01E-02	6.23E-01
59	1.92E-14	0.00E+00	4.05E-09	1.18E-09	5.22E-01	2.05E-02	3.98E-01	6.96E-01	-1.74E+01	-1.77E+01	-2.02E-01	4.44E-01	3.61E-01	1.11E-01	5.32E-01	2.65E-02	-2.18E+01	6.33E-11	-1.91E+01	1.11E-10	1.00E+00	4.84E-02	1.21E-01	6.22E-01
60	5.20E-15	0.00E+00	5.36E-09	6.80E-10	3.91E-01	2.18E-03	1.99E-01	6.58E-01	-1.90E+01	-1.85E+01	4.85E-01	2.56E-02	3.88E-01	3.46E-01	5.77E+00	9.59E-03	-2.23E+01	9.06E-11	-1.95E+01	1.69E-10	4.00E+00	1.22E-01	5.44E-02	6.76E-01
61	2.75E-14	0.00E+00	4.19E-09	2.74E-11	9.26E-01	5.75E-02	1.41E-01	2.65E-01	-1.72E+01	-2.00E+01	-1.97E-01	1.62E-02	9.74E-02	4.33E-01	3.92E+00	1.30E-02	-2.31E+01	1.34E-10	-1.93E+01	1.18E-10	1.00E+00	8.94E-02	1.53E-01	7.20E-01
62	1.59E-14	0.00E+00	8.06E-09	1.23E-09	2.51E-01	4.05E-02	2.77E-02	4.40E-01	-1.84E+01	-1.92E+01	6.55E-02	-3.61E-01	3.26E-01	5.52E-01	5.86E-01	6.28E-03	-2.17E+01	5.18E-11	-1.92E+01	1.32E-10	4.00E+00	6.64E-02	2.81E-02	5.99E-01
63	2.16E-14	0.00E+00	4.71E-10	9.88E-10	9.61E-01	7.36E-02	4.95E-01	5.22E-02	-1.78E+01	-1.85E+01	-1.10E-01	-8.60E-01	2.50E-01	8.53E-02	7.72E-01	2.75E-02	-2.29E+01	1.29E-10	-1.98E+01	2.21E-10	1.00E+00	9.51E-02	4.40E-02	6.51E-01
64	1.34E-14	2.00E+00	1.95E-09	5.43E-10	8.76E-01	9.33E-03	5.04E-01	4.04E-01	-1.91E+01	-1.75E+01	1.89E-01	-2.16E-01	5.98E-02	5.35E-01	6.59E-01	7.61E-03	-2.11E+01	6.57E-12	-1.87E+01	5.30E-11	4.00E+00	9.94E-02	7.79E-02	6.62E-01
65	1.63E-14	0.00E+00	2.55E-09	7.29E-10	6.25E-01	8.49E-02	2.68E-01	1.64E-01	-1.95E+01	-1.93E+01	-1.25E-01	-4.16E-02	3.97E-01	5.15E-01	2.44E+00	4.23E-03	-2.14E+01	3.77E-11	-1.93E+01	1.12E-10	1.00E+00	1.05E-01	7.48E-02	7.14E-01
66	2.27E-14	0.00E+00	4.17E-09	8.89E-10	5.20E-01	2.34E-02	4.50E-01	7.39E-01	-1.99E+01	-1.79E+01	9.40E-01	-1.80E-01	3.36E-02	3.73E-01	2.44E-01	2.04E-02	-2.39E+01	1.86E-10	-1.78E+01	1.09E-11	4.00E+00	6.90E-02	1.36E-01	6.57E-01
67	3.25E-15	2.00E+00	6.41E-10	1.06E-09	6.41E-01	1.38E-03	6.99E-02	8.04E-01	-1.81E+01	-2.05E+01	-1.92E-01	-1.13E-01	3.47E-01	1.40E-01	8.41E-01	7.10E-03	-2.33E+01	1.40E-10	-1.85E+01	1.76E-11	4.00E+00	9.61E-02	7.38E-02	6.25E-01
68	5.70E-15	2.00E+00	6.33E-09	4.35E-10	1.16E-01	1.08E-01	2.62E-01	5.07E-01	-1.81E+01	-1.97E+01	1.99E-01	-2.43E-01	2.67E-01	3.25E-01	6.88E-01	8.74E-03	-2.30E+01	1.32E-10	-1.87E+01	7.08E-11	4.00E+00	9.28E-02	6.94E-02	6.94E-01
69	2.63E-14	0.00E+00	6.44E-09	8.43E-10	6.07E-01	1.32E-02	1.28E-01	3.09E-01	-1.89E+01	-1.80E+01	-6.27E-01	-1.79E+00	3.82E-01	4.69E-01	2.88E+00	2.39E-02	-2.22E+01	7.94E-11	-1.85E+01	6.03E-11	1.00E+00	6.40E-02	8.06E-02	7.54E-01
70	2.72E-14	0.00E+00	2.39E-09	8.68E-10	9.31E-03	2.75E-02	1.91E-01	6.76E-01	-1.86E+01	-1.84E+01	-3.12E-03	1.49E-01	1.83E-01	9.69E-02	7.40E+00	2.30E-02	-2.21E+01	7.20E-11	-1.89E+01	1.01E-10	1.00E+00	7.67E-02	3.07E-02	5.53E-01
71	8.72E-15	0.00E+00	9.47E-09	1.80E-10	4.06E-01	1.20E-01	1.71E-01	3.21E-01	-1.73E+01	-1.93E+01	-8.82E-01	-2.38E-01	4.64E-02	5.01E-01	5.09E+00	9.70E-03	-2.23E+01	8.21E-11	-1.89E+01	7.61E-11	4.00E+00	1.04E-01	9.72E-02	6.49E-01
72	1.96E-14	2.00E+00	7.10E-09	1.21E-09	9.53E-01	7.52E-03	1.23E-01	6.04E-02	-1.91E+01	-1.82E+01	-2.24E-01	1.69E-01	1.04E-01	3.43E-01	1.36E-01	4.91E-03	-2.31E+01	1.09E-10	-1.92E+01	1.07E-10	1.00E+00	7.51E-02	8.91E-02	5.02E-01
73	2.00E-14	1.00E+00	8.55E-09	3.52E-10	4.68E-01	2.20E-02	3.65E-01	2.62E-02	-1.98E+01	-1.78E+01	-1.15E-01	4.65E-01	2.61E-01	2.38E-01	7.99E+00	4.00E-03	-2.13E+01	2.07E-11	-1.84E+01	4.02E-11	1.00E+00	1.29E-01	1.32E-01	6.42E-01
74	2.35E-14	0.00E+00	6.00E-09	3.72E-10	2.89E-01	1.18E-01	2.11E-01	5.48E-01	-1.94E+01	-2.01E+01	-4.50E-01	-1.06E-01	2.42E-01	2.06E-02	1.43E+00	9.99E-03	-2.24E+01	8.83E-11	-1.82E+01	1.09E-11	4.00E+00	1.20E-01	8.80E-02	6.68E-01
75	1.30E-14	0.00E+00	9.00E-09	8.00E-10	4.13E-01	4.66E-02	4.99E-01	5.21E-01	-1.80E+01	-1.90E+01	-3.24E-01	-1.57E-01	8.94E-03	1.81E-01	1.74E-01	2.61E-02	-2.34E+01	1.51E-10	-1.93E+01	1.35E-10	4.00E+00	8.21E-02	6.48E-02	5.36E-01
76	2.98E-14	2.00E+00	7.87E-09	6.27E-10	1.91E-01	1.26E-01	1.52E-02	9.19E-01	-1.92E+01	-1.83E+01	1.08E-01	-1.85E-01	3.01E-01	7.34E-02	4.54E-01	2.15E-03	-2.20E+01	5.72E-11	-1.90E+01	1.04E-10	4.00E+00	9.75E-02	1.01E-01	5.88E-01

Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
38	2.60E-14	0.00E+00	1.31E-09	9.67E-10	9.42E-01	1.44E-01	4.31E-01	4.27E-01	-1.88E+01	-1.94E+01	-2.13E-01	1.30E-01	1.88E-01	6.03E-02	4.10E+00	5.17E-03	-2.27E+01	9.82E-11	-1.94E+01	1.48E-10	4.00E+00	8.61E-02	8.44E-02	6.21E-01
39	2.17E-15	1.00E+00	3.26E-09	1.49E-11	5.87E-01	2.86E-02	1.12E-01	6.25E-01	-1.93E+01	-1.86E+01	1.44E-01	7.25E-01	2.68E-01	5.40E-02	4.02E+00	2.06E-03	-2.34E+01	1.64E-10	-1.86E+01	4.88E-11	4.00E+00	7.93E-02	9.59E-02	5.82E-01
40	4.45E-15	2.00E+00	8.32E-09	3.93E-10	8.12E-01	1.43E-01	5.20E-01	8.58E-01	-1.98E+01	-1.94E+01	-3.62E-02	-6.44E-01	2.16E-01	2.31E-01	7.25E-01	1.51E-02	-2.15E+01	2.75E-11	-1.80E+01	1.09E-11	1.00E+00	5.53E-02	4.27E-02	6.32E-01
41	1.25E-14	2.00E+00	6.07E-09	3.40E-10	9.03E-01	1.31E-01	5.39E-01	2.28E-01	-1.91E+01	-1.89E+01	4.42E-02	3.96E-01	2.94E-01	1.30E-01	5.29E+00	2.56E-02	-2.25E+01	1.06E-10	-2.01E+01	2.52E-10	4.00E+00	6.05E-02	1.70E-02	6.69E-01
42	1.22E-14	1.00E+00	5.21E-10	4.10E-10	7.83E-01	2.63E-02	4.45E-02	4.67E-01	-1.84E+01	-1.82E+01	-2.16E-01	-8.34E-02	4.74E-03	4.04E-02	4.26E-01	5.40E-03	-2.18E+01	4.02E-11	-1.95E+01	1.64E-10	4.00E+00	5.99E-02	6.27E-02	6.74E-01
43	1.40E-15	1.00E+00	8.60E-09	3.99E-10	4.26E-01	3.86E-02	4.19E-01	6.07E-01	-2.01E+01	-1.79E+01	-1.67E-01	-1.47E-02	2.88E-01	8.12E-02	4.68E-01	2.69E-02	-2.39E+01	1.90E-10	-1.95E+01	1.59E-10	4.00E+00	1.17E-01	9.15E-02	6.98E-01
44	2.77E-14	0.00E+00	8.93E-09	1.12E-09	6.31E-01	3.60E-02	1.95E-01	8.87E-01	-1.86E+01	-1.98E+01	-7.94E-01	7.29E-02	1.71E-01	4.55E-01	5.98E-01	1.64E-03	-2.17E+01	4.85E-11	-1.93E+01	1.43E-10	1.00E+00	1.02E-01	8.22E-02	7.70E-01
45	3.11E-14	2.00E+00	2.15E-09	7.09E-10	5.45E-01	5.43E-02	3.56E-01	1.17E-01	-1.87E+01	-1.83E+01	-3.08E-01	-6.91E-01	2.79E-01	4.08E-01	2.43E-01	2.40E-02	-2.24E+01	1.00E-10	-1.88E+01	5.46E-11	4.00E+00	9.10E-02	1.03E-01	5.93E-01
77	2.19E-14	1.00E+00	1.67E-09	4.78E-10	3.28E-01	1.42E-01	3.48E-01	9.68E-01	-1.82E+01	-1.87E+01	-8.34E-02	-9.39E-01	1.08E-01	1.57E-01	5.15E-01	2.80E-03	-2.25E+01	1.03E-10	-1.94E+01	1.49E-10	1.00E+00	6.29E-02	7.02E-02	5.43E-01
78	1.82E-14	1.00E+00	8.30E-09	4.10E-11	8.68E-01	1.16E-01	8.60E-02	2.42E-01	-1.82E+01	-1.92E+01	-5.54E-01	-2.95E-01	1.43E-02	1.22E-01	6.76E+00	1.81E-02	-2.20E+01	7.43E-11	-1.92E+01	1.32E-10	1.00E+00	1.15E-01	4.60E-02	5.86E-01
79	2.25E-14	2.00E+00	7.41E-09	9.03E-10	9.88E-01	6.49E-02	3.88E-01	5.68E-01	-1.99E+01	-1.94E+01	-2.47E-01	-1.41E-01	8.97E-02	1.64E-01	4.17E-01	1.27E-02	-2.31E+01	1.27E-10	-1.86E+01	5.56E-11	1.00E+00	1.25E-01	8.28E-02	6.87E-01
80	2.41E-14	0.00E+00	6.58E-09	5.82E-10	5.76E-02	9.63E-02	3.85E-01	1.09E-01	-1.88E+01	-1.71E+01	4.78E-02	-1.63E-01	1.23E-01	3.01E-02	2.64E-01	1.70E-02	-2.28E+01	1.08E-10	-1.90E+01	1.20E-10	1.00E+00	1.03E-01	7.72E-02	6.32E-01
81	4.08E-15	0.00E+00	1.80E-09	2.46E-10	5.62E-01	8.27E-02	1.76E-01	3.81E-01	-1.77E+01	-1.77E+01	1.75E-01	1.97E-01	6.46E-02	1.93E-01	4.02E-01	5.79E-03	-2.11E+01	8.70E-12	-1.83E+01	1.46E-11	4.00E+00	6.86E-02	7.89E-02	7.03E-01
82	9.33E-15	2.00E+00	1.45E-09	1.20E-09	7.27E-01	3.35E-02	3.06E-01	8.20E-01	-1.86E+01	-1.97E+01	-4.91E-01	7.72E-01	2.55E-02	3.94E-01	7.53E-01	2.17E-02	-2.19E+01	6.42E-11	-1.85E+01	4.67E-11	4.00E+00	1.27E-01	5.70E-02	6.07E-01
83	2.68E-14	0.00E+00	9.34E-09	4.30E-10	7.99E-01	1.35E-01	1.52E-01	5.97E-01	-1.76E+01	-1.77E+01	-4.03E-01	3.24E-01	3.92E-01	9.47E-02	9.07E-01	5.13E-03	-2.22E+01	6.60E-11	-1.82E+01	1.09E-11	1.00E+00	6.99E-02	3.64E-02	8.05E-01
84	1.78E-14	0.00E+00	3.82E-09	3.67E-10	3.75E-02	7.66E-02	5.25E-01	7.95E-03	-1.80E+01	-1.99E+01	2.34E-01	-5.64E-02	1.10E-01	1.20E-01	6.17E-01	2.53E-03	-2.32E+01	1.46E-10	-1.78E+01	1.09E-11	1.00E+00	1.12E-01	8.59E-02	6.75E-01
85	3.08E-14	1.00E+00	5.84E-09	9.26E-10	1.83E-01	1.34E-01	1.44E-01	2.79E-01	-1.88E+01	-1.86E+01	-7.46E-01	8.54E-01	1.95E-01	5.79E-01	7.17E-01	1.77E-02	-2.40E+01	1.92E-10	-1.99E+01	2.08E-10	1.00E+00	1.00E-01	5.74E-02	7.07E-01
86	1.80E-15	1.00E+00	9.18E-09	1.14E-09	3.63E-01	6.34E-02	2.50E-01	4.94E-01	-1.90E+01	-1.83E+01	-1.58E-01	2.12E-01	9.44E-02	1.74E-01	3.44E-01	1.46E-03	-2.29E+01	1.42E-10	-1.89E+01	7.85E-11	1.00E+00	5.74E-02	1.40E-02	7.09E-01
87	6.49E-15	1.00E+00	5.75E-09	8.80E-10	2.44E-01	9.22E-02	3.01E-01	8.96E-01	-1.96E+01	-1.96E+01	-2.42E-01	2.37E-01	1.41E-01	3.33E-01	1.98E+00	2.97E-02	-2.19E+01	5.89E-11	-1.80E+01	1.09E-11	1.00E+00	8.49E-02	9.31E-02	5.61E-01
88	4.38E-15	0.00E+00	7.65E-09	6.60E-10	9.10E-01	1.49E-01	1.58E-01	6.65E-01	-1.78E+01	-1.90E+01	1.39E-01	-4.12E-01	3.69E-01	9.17E-02	3.68E-01	7.35E-03	-2.21E+01	9.30E-11	-2.03E+01	2.75E-10	4.00E+00	9.19E-02	7.23E-02	5.77E-01
89	1.12E-14	2.00E+00	1.59E-09	7.92E-10	5.39E-01	7.81E-02	5.48E-01	8.36E-01	-1.86E+01	-1.82E+01	-1.33E+00	-2.53E-01	1.76E-01	1.44E-01	6.12E+00	7.77E-03	-2.16E+01	5.33E-11	-1.76E+01	1.09E-11	4.00E+00	8.89E-02	5.90E-02	6.00E-01
90	9.95E-15	2.00E+00	4.28E-09	1.04E-09	2.92E-01	9.43E-02	1.81E-01	9.53E-01	-1.80E+01	-2.04E+01	-1.73E-01	1.63E-01	1.26E-01	2.79E-01	5.40E+00	3.66E-03	-2.39E+01	1.76E-10	-1.93E+01	1.55E-10	1.00E+00	8.10E-02	1.41E-01	6.45E-01
91	2.11E-14	1.00E+00	8.43E-10	9.21E-10	6.63E-01	1.37E-01	2.84E-01	9.18E-02	-1.90E+01	-1.86E+01	-2.93E-01	-3.45E-02	8.46E-02	2.41E-01	7.88E-01	1.14E-02	-2.10E+01	4.70E-12	-1.81E+01	1.09E-11	1.00E+00	8.67E-02	9.98E-02	6.69E-01
92	3.05E-14	0.00E+00	2.46E-09	1.23E-09	8.52E-01	1.04E-01	7.38E-02	1.66E-02	-2.04E+01	-1.88E+01	-3.63E-01	5.03E-01	3.56E-01	3.86E-02	1.46E-01	7.26E-03	-2.30E+01	1.36E-10	-1.88E+01	9.40E-11	1.00E+00	9.37E-02	1.23E-01	6.28E-01
93	5.74E-15	2.00E+00	3.45E-09	2.37E-10	6.14E-01	1.30E-01	3.26E-01	8.00E-02	-1.90E+01	-1.96E+01	-9.14E-01	1.36E-01	2.46E-01	4.30E-01	6.55E-01	2.13E-02	-2.28E+01	1.13E-10	-1.92E+01	1.25E-10	1.00E+00	5.18E-02	4.78E-02	6.36E-01
94	8.23E-15	0.00E+00	5.38E-09	6.07E-10	9.91E-01	5.39E-02	4.11E-01	3.14E-01	-1.93E+01	-1.85E+01	-1.51E-01	-9.80E-02	5.56E-02	2.21E-01	7.30E+00	1.85E-03	-2.22E+01	8.67E-11	-1.95E+01	1.57E-10	1.00E+00	4.08E-02	9.90E-02	4.91E-01
95	2.81E-14	0.00E+00	3.36E-09	5.27E-10	3.31E-01	1.11E-01	4.55E-01	9.78E-01	-1.89E+01	-1.81E+01	2.06E-01	-3.88E-01	2.40E-01	2.85E-01	8.61E-01	1.58E-02	-2.29E+01	1.23E-10	-1.89E+01	6.14E-11	4.00E+00	1.49E-01	1.12E-01	6.14E-01
96	2.66E-15	0.00E+00	3.72E-09	2.19E-10	4.83E-01	9.84E-02	2.23E-01	2.37E-01	-1.78E+01	-1.82E+01	-4.64E-02	1.00E-01	3.77E-01	4.47E-01	6.38E+00	9.12E-03	-2.36E+01	1.67E-10	-1.82E+01	1.09E-11	1.00E+00	7.41E-02	1.25E-01	5.55E-01
97	2.94E-14	0.00E+00	8.88E-10	4.45E-10	6.74E-01	1.46E-01	2.48E-02	1.88E-01	-1.92E+01	-1.95E+01	4.26E-01	2.26E-01	3.65E-01	1.90E-01	1.11E+00	6.19E-03	-2.16E+01	3.20E-11	-1.74E+01	1.09E-11	4.00E+00	7.54E-02	1.40E-02	6.12E-01
98	7.47E-15	0.00E+00	2.98E-09	7.67E-11	1.80E-01	1.64E-02	1.38E-01	2.14E-01	-2.02E+01	-1.85E+01	-2.85E-01	6.08E-01	2.37E-02	1.68E-01	9.19E-01	6.59E-03	-2.16E+01	3.45E-11	-1.99E+01	2.48E-10	1.00E+00	2.69E-02	6.61E-02	6.59E-01
99	2.43E-14	1.00E+00	6.70E-09	7.50E-11	3.74E-01	1.84E-02	4.23E-01	6.35E-01	-1.97E+01	-2.00E+01	1.19E-03	-2.15E-01	1.60E-01	5.42E-01	1.22E-01	2.25E-02	-2.18E+01	6.00E-11	-1.87E+01	4.94E-11	4.00E+00	6.68E-02	5.16E-02	6.92E-01
100	2.13E-14	1.00E+00	4.08E-10	6.39E-10	2.38E-01	5.70E-02	4.29E-03	1.54E-01	-1.95E+01	-1.94E+01	3.01E-01	6.43E-02	7.67E-02	6.00E-01	5.12E+00	1.62E-02	-2.38E+01	1.72E-10	-1.90E+01	1.05E-10	1.00E+00	8.14E-02	1.17E-01	6.53E-01

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Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector Num.	S_HALITE PRESSURE	CASTILER PRESSURE	CASTILER PRMX_LOG	CASTILER COMP_RCK	BH_SAND PRMX_LOG	DRZ_1 PRMX_LOG	CONC_PLG PRMX_LOG	SOLAM3 SOLSIM	SOLAM3 SOLCIM	SOLPU3 SOLSIM	SOLPU3 SOLCIM	SOLPU4 SOLSIM	SOLPU4 SOLCIM	SOLU4 SOLSIM	SOLU6 SOLSIM	SOLU6 SOLCIM	SOLTH4 SOLSIM	PHUMOX3 PHUMCIM	GLOBAL OXSTAT	CULEBRA MINP_FAC	GLOBAL TRANSIDX	GLOBAL CLIMTIDX	CULEBRA HMBLKLT
1	1.27E+07	1.61E+07	-1.21E+01	6.60E-11	-1.56E+01	-1.53E+01	-1.83E+01	-2.01E-01	-6.30E-01	8.10E-02	-2.59E-01	1.37E-01	-1.94E+00	-4.22E-01	2.02E-01	-3.34E-02	-3.65E-01	1.44E+00	5.60E-01	2.98E+02	1.67E-01	1.23E+00	2.86E-01
2	1.22E+07	1.33E+07	-1.16E+01	5.79E-11	-1.22E+01	-1.80E+01	-1.83E+01	-9.92E-01	1.00E-02	-6.62E-01	4.83E-01	-3.87E-02	8.40E-01	-5.96E-02	-6.76E-02	-1.21E-01	-3.14E-01	1.41E+00	1.86E-01	2.09E+02	3.23E-01	1.75E+00	4.38E-01
3	1.27E+07	1.23E+07	-1.18E+01	5.32E-11	-1.35E+01	-1.42E+01	-1.84E+01	-1.38E-01	-5.31E-01	-1.22E-02	-4.38E-02	-1.46E-01	-4.45E-02	9.30E-01	-2.99E-01	-4.32E-01	-9.85E-02	2.22E-01	7.35E-01	5.39E+02	3.36E-01	1.13E+00	2.51E-01
4	1.32E+07	1.28E+07	-1.42E+01	8.88E-11	-1.24E+01	-1.45E+01	-1.83E+01	-3.15E-01	-4.96E-01	-1.90E-01	1.20E-01	-5.63E-02	-7.06E-01	-5.11E-02	-3.38E-02	6.11E-01	-1.98E+00	1.56E+00	9.76E-01	5.30E+01	1.91E-01	1.12E+00	4.27E-01
5	1.20E+07	1.45E+07	-1.23E+01	6.99E-11	-1.59E+01	-1.44E+01	-1.86E+01	2.38E-01	7.50E-01	-3.97E-02	6.16E-02	-1.65E+00	-1.56E-01	-3.26E-02	1.36E-01	4.60E-02	8.39E-01	1.38E+00	1.25E-01	5.70E+02	7.28E-01	1.65E+00	3.17E-01
6	1.18E+07	1.41E+07	-1.28E+01	6.49E-11	-1.18E+01	-1.50E+01	-1.87E+01	2.97E-01	4.80E-01	-1.28E-04	-7.09E-01	-2.95E-02	1.33E-01	-2.25E-01	-1.29E-01	-6.44E-02	7.86E-01	1.54E+00	4.65E-01	6.91E+02	1.26E-01	1.07E+00	5.75E-02
7	1.19E+07	1.33E+07	-1.18E+01	6.94E-11	-1.12E+01	-1.73E+01	-1.76E+01	-7.43E-02	9.08E-01	5.78E-01	1.73E-01	-1.20E-01	1.49E-01	-1.08E-01	-1.90E+00	1.13E-01	-5.54E-01	1.42E+00	6.22E-02	8.42E+01	6.73E-01	1.23E+00	3.13E-01
8	1.17E+07	1.21E+07	-1.02E+01	2.15E-11	-1.25E+01	-1.75E+01	-1.72E+01	-1.12E-01	-4.14E-01	-1.53E-01	9.37E-01	-3.22E-01	6.37E-02	1.24E+00	5.65E-01	2.05E-01	-1.42E-01	1.53E+00	5.34E-01	2.59E+02	5.56E-01	1.12E+00	1.82E-01
9	1.17E+07	1.51E+07	-1.20E+01	5.93E-11	-1.14E+01	-1.62E+01	-1.90E+01	-1.77E-01	-1.58E-01	-4.65E-01	-1.60E-01	-3.04E-01	-2.91E-01	-1.51E-01	-7.52E-01	-4.00E-03	-9.54E-01	1.53E-01	5.20E-01	1.00E+01	4.78E-01	1.24E+00	5.25E-02
10	1.38E+07	1.26E+07	-1.01E+01	2.46E-11	-1.19E+01	-1.27E+01	-1.76E+01	6.45E-01	-2.26E-01	9.98E-01	-9.46E-01	-1.32E-01	3.28E-01	2.52E-02	-3.89E-02	3.45E-01	-2.86E-01	1.52E+00	7.41E-01	6.43E+02	8.68E-01	1.16E+00	4.77E-01
11	1.14E+07	1.34E+07	-1.12E+01	4.30E-11	-1.37E+01	-1.47E+01	-1.80E+01	2.25E-01	-8.14E-02	-4.05E-01	-2.32E-01	-6.94E-01	-1.29E-01	-7.09E-01	-9.58E-01	9.06E-01	1.70E-01	1.58E+00	9.65E-01	6.61E+01	5.85E-01	1.13E+00	1.39E-01
12	1.28E+07	1.35E+07	-1.12E+01	5.04E-11	-1.36E+01	-1.41E+01	-1.75E+01	-3.69E-02	3.15E-02	-9.71E-02	1.59E-01	6.72E-03	-8.56E-02	-2.13E-01	2.84E-01	-1.36E-01	-4.75E-01	1.51E+00	1.94E-01	1.95E+02	9.56E-01	1.02E+00	1.63E-01
13	1.11E+07	1.29E+07	-1.33E+01	6.77E-11	-1.43E+01	-1.31E+01	-1.88E+01	-2.78E-01	-1.87E+00	-5.73E-02	7.76E-01	6.56E-02	-1.23E-01	-1.80E-01	1.71E-01	-2.44E-01	5.89E-01	9.61E-01	1.75E-01	8.21E+02	9.13E-01	1.17E+00	2.16E-01
14	1.25E+07	1.18E+07	-1.19E+01	4.03E-11	-1.56E+01	-1.32E+01	-1.79E+01	6.99E-02	2.76E-01	-7.76E-01	-3.30E-01	-1.30E+00	7.74E-03	1.68E-01	-1.16E-01	-9.50E-01	1.28E-01	1.58E+00	3.96E-01	9.41E+01	2.91E-01	1.17E+00	9.10E-02
15	1.12E+07	1.16E+07	-1.21E+01	4.56E-11	-1.38E+01	-1.34E+01	-1.81E+01	-4.08E-01	-1.93E-01	7.51E-01	-5.56E-02	1.69E-01	4.21E-01	1.18E-01	1.03E-01	7.04E-01	5.38E-02	1.00E+00	4.86E-02	2.29E+02	9.26E-02	1.05E+00	2.99E-01
16	1.29E+07	1.44E+07	-1.16E+01	4.53E-11	-1.46E+01	-1.39E+01	-1.77E+01	-1.71E-01	6.20E-01	1.40E-01	1.09E-01	3.20E-01	-1.79E-01	-1.34E-02	-2.00E-01	1.12E-02	-6.86E-02	5.73E-01	8.16E-01	4.74E+02	4.37E-01	1.09E+00	4.48E-01
17	1.18E+07	1.43E+07	-1.30E+01	7.60E-11	-1.13E+01	-1.53E+01	-1.89E+01	4.28E-01	-2.29E-01	-5.99E-01	5.38E-01	-9.78E-01	-2.27E-01	-2.41E-01	-6.41E-01	-7.84E-02	2.35E-01	1.57E+00	4.80E-01	9.05E+02	3.16E-01	1.05E+00	3.58E-01
18	1.16E+07	1.41E+07	-1.15E+01	6.18E-11	-1.36E+01	-1.76E+01	-1.71E+01	1.74E-01	-9.58E-02	2.44E-01	-1.09E-01	-3.98E-01	-1.66E+00	4.07E-02	2.03E-01	-5.92E-02	-2.09E-01	1.10E+00	2.18E-01	7.05E+02	2.07E-01	2.03E+00	4.90E-01
19	1.30E+07	1.25E+07	-1.23E+01	6.06E-11	-1.51E+01	-1.66E+01	-1.71E+01	9.65E-01	-3.89E-01	2.99E-01	2.41E-01	-2.67E-01	-3.29E-01	1.24E-01	-8.10E-01	-3.45E-01	-8.19E-01	1.57E+00	2.59E-01	1.19E+02	4.59E-01	1.10E+00	8.04E-02
20	1.37E+07	1.23E+07	-1.11E+01	3.37E-11	-1.13E+01	-1.54E+01	-1.77E+01	-2.93E-01	1.59E-01	-1.35E-01	-3.37E-02	-4.89E-01	2.10E-01	3.49E-01	9.36E-01	-3.86E-01	2.45E-01	1.39E+00	1.60E-02	4.50E+02	7.35E-02	1.96E+00	1.56E-01
21	1.21E+07	1.64E+07	-1.33E+01	7.39E-11	-1.22E+01	-1.65E+01	-1.82E+01	-5.45E-01	1.24E-01	2.18E-01	-5.19E-02	-1.75E+00	8.05E-02	6.12E-02	-3.54E-01	7.44E-02	9.19E-01	1.39E+00	6.29E-01	8.87E+02	1.85E-01	1.01E+00	2.36E-01
22	1.20E+07	1.54E+07	-1.22E+01	4.46E-11	-1.44E+01	-1.47E+01	-1.76E+01	9.19E-01	2.39E-01	1.77E-01	-2.40E-01	-4.66E-02	7.80E-01	7.53E-01	-1.48E-01	-2.86E-01	-3.90E-01	1.46E+00	8.22E-01	5.58E+02	6.44E-03	1.11E+00	4.93E-01
23	1.29E+07	1.32E+07	-1.16E+01	3.59E-11	-1.10E+01	-1.77E+01	-1.79E+01	-1.22E-01	-8.32E-01	-2.05E-01	-4.08E-01	-1.59E-01	-5.70E-02	-1.25E-01	7.91E-02	1.03E-01	-6.01E-01	1.42E+00	5.16E-02	5.08E+02	4.16E-01	1.02E+00	3.36E-01
24	1.30E+07	1.53E+07	-1.17E+01	4.17E-11	-1.52E+01	-1.92E+01	-1.75E+01	-9.12E-02	1.46E-02	-9.47E-01	-3.91E-01	9.48E-02	1.83E-01	8.13E-01	-1.92E-01	-2.00E-01	-4.18E-01	1.50E+00	9.97E-01	2.60E+01	4.66E-01	1.19E+00	6.06E-02
25	1.25E+07	1.28E+07	-1.07E+01	3.48E-11	-1.63E+01	-1.81E+01	-1.80E+01	-1.73E+00	-5.68E-02	4.69E-01	6.43E-01	2.01E-01	1.81E-02	-1.27E+00	-1.82E-01	2.17E-01	-2.34E-01	3.82E-01	6.69E-01	2.50E+02	1.51E-01	1.19E+00	6.48E-02
26	1.32E+07	1.45E+07	-1.13E+01	4.98E-11	-1.57E+01	-1.25E+01	-1.82E+01	-1.09E-01	-3.29E-01	1.07E-01	8.88E-01	2.49E-01	-7.26E-02	1.93E-01	1.86E-02	-7.84E-01	-7.57E-02	1.50E+00	5.00E-01	8.70E+02	7.53E-01	1.90E+00	1.31E-01
27	1.23E+07	1.49E+07	-1.12E+01	3.06E-11	-1.47E+01	-1.42E+01	-1.80E+01	-1.61E-01	-2.25E-02	-8.74E-01	-1.44E-01	9.38E-01	-3.77E-01	-1.65E-01	-1.15E+00	-5.65E-01	-5.61E-02	7.23E-01	5.91E-01	7.41E+02	5.00E-01	1.24E+00	1.52E-01
28	1.36E+07	1.28E+07	-1.34E+01	4.41E-11	-1.40E+01	-1.61E+01	-1.77E+01	7.78E-01	-1.46E-01	1.87E-02	3.42E-02	-1.49E-01	-4.59E-01	1.33E-01	-4.65E-01	2.64E-01	2.76E-01	1.16E+00	3.54E-01	5.14E+02	7.86E-01	1.08E+00	7.46E-02
29	1.37E+07	1.63E+07	-1.23E+01	6.73E-11	-1.59E+01	-1.36E+01	-1.88E+01	-8.92E-01	-6.75E-01	-1.82E-01	-2.25E-01	-9.08E-01	-1.00E-01	2.18E-01	-1.44E-01	-7.14E-02	-2.17E-02	1.53E+00	2.67E-01	7.90E+02	2.71E-01	1.93E+00	9.64E-02
30	1.27E+07	1.24E+07	-1.39E+01	8.52E-11	-1.20E+01	-1.51E+01	-1.78E+01	-1.27E-01	-1.85E-01	1.13E-01	-3.55E-01	2.55E-01	5.74E-01	-3.69E-01	-2.72E-01	-1.88E+00	-4.36E-02	7.77E-01	8.36E-01	4.69E+01	2.47E-01	1.04E+00	1.16E-01
31	1.30E+07	1.36E+07	-1.23E+01	6.37E-11	-1.12E+01	-1.54E+01	-1.78E+01	-3.17E-02	-1.39E+00	1.57E-01	-1.70E-01	1.79E-01	-1.46E-01	-7.62E-02	-2.46E-01	-4.90E-01	-1.92E-01	1.49E+00	9.24E-01	9.61E+02	9.33E-01	1.11E+00	3.81E-01
32	1.32E+07	1.60E+07	-1.28E+01	4.75E-11	-1.29E+01	-1.80E+01	-1.71E+01	-8.80E-02	-3.17E-01	-1.53E-01	4.34E-01	3.66E-01	-1.73E-01	8.60E-02	-2.31E-01	-1.56E-01	-1.59E+00	1.44E+00	2.93E-01	9.98E+02	6.95E-02	1.21E+00	1.89E-01
33	1.28E+07	1.24E+07	-1.05E+01	3.84E-11	-1.17E+01	-1.33E+01	-1.73E+01	1.79E-01	-2.40E-01	8.56E-01	-1.12E-01	5.78E-02	-8.23E-01	-1.14E-01	1.26E-01	-4.58E-02	2.15E-01	8.12E-01	3.85E-01	2.37E+02	8.28E-01	1.20E+00	3.39E-01
34	1.29E+07	1.66E+07	-1.17E+01	4.60E-11	-1.62E+01	-1.28E+01	-1.75E+01	3.33E-01	-2.04E-01	-7.01E-02	-1.75E-01	5.59E-01	9.89E-01	-4.49E-01	-3.24E-01	-5.44E-02	-2.97E-02	1.56E+00	5.03E-01	6.15E+02	7.74E-01	1.24E+00	2.02E-01
35	1.26E+07	1.52E+07	-1.24E+01	5.47E-11	-1.61E+01	-1.89E+01	-1.84E+01	1.33E+00	-1.44E-01	6.13E-01	-1.93E-01	1.15E-01	-4.45E-01	-1.42E-01	2.31E-01	-4.02E-02	-7.06E-01	9.40E-02	2.83E-01	1.45E+02	5.92E-01	1.11E+00	1.72E-01
36	1.33E+07	1.34E+07	-1.06E+01	2.93E-11	-1.61E+01	-1.67E+01	-1.84E+01	-6.61E-02	-3.46E-01	-1.96E+00	-8.79E-02	1.49E-01	8.66E-02	-3.19E-01	6.10E-01	2.02E-02	6.13E-01	1.38E+00	7.82E-01	3.46E+02	5.17E-01	1.15E+00	4.08E-01
37	1.37E+07	1.48E+07	-1.04E+01	5.09E-11	-1.54E+01	-1.44E+01	-1.84E+01	-2.13E-02	-1.31E-01	-5.17E-02	-6.39E-02	-2.47E-01	-5.87E-01	-3.95E-01	8.26E-01	-1.20E+00	3.43E-01	1.49E+00	3.13E-01	3.76E+02	3.92E-01	1.02E+00	4.43E-01
38	1.16E+07	1.48E+07	-1.08E+01	4.81E-11	-1.46E+01	-1.71E+01	-1.85E+01	-1.30E+00	-3.96E-01	6.69E-03	8.39E-02	-5.55E-01	-6.34E-01	2.05E-01	-1.55E+00	-2.19E-01	-1.30E-01	1.06E+00	9.20E-02	4.83E+02	1.01E-02	1.06E+00	4.69E-01
39	1.35E+07	1.17E+07	-1.14E+01	7.31E-11	-1.29E+01	-1.93E+01	-1.73E+01	6.80E-01	-6.11E-01	-3.22E-01	1.91E-01	-4.58E-01	-1.08E-01	-3.45E-01	-2.25E-01	7.99E-01	-7.68E-03	9.09E-01	4.36E-01	7.14E+02	6.61E-01	2.01E+00	2.26E-01
40	1.15E+07	1.39E+07	-1.19E+01	4.22E-11	-1.59E+01	-1.56E+01	-1.70E+01	-1.52E-01	-4.72E-01	2.13E-01	-8.92E-01	-6.11E-01	-3.63E-01	-7.73E-02	6.65E-02	2.01E-01	-1.66E-01	1.48E+00	7.60E-01	7.30E+02	6.26E-01	1.15E+00	3.56E-01
41	1.24E+07	1.14E+07	-1.19E+01	3.73E-11	-1.28E+01	-1.57E+01	-1.79E+01	-8.85E-01	-6.04E-03	-1.72E-01	6.61E-01	2.04E-01	-2.79E-01	-6.10E-01	7.68E-01	-2.31E-01	-4.29E-01	3.18E-01	6.55E-01	8.49E+02	5.60E-01	1.07E+00	1.69E-01
42	1.14E+07	1.22E+07	-1.26E+01	5.70E-11	-1.30E+01	-1.57E+01	-1.83E+01	3.82E-02	-1.75E+00	-1.07E-01	-5.29E-01	7.58E-02	-2.57E-03	-2.07E-01	-9.41E-01	-2.56E-01	-8.53E-02	1.47E+00	1.35E-01	8.39E+02	7.00E-01	1.16E+00	1.05E-01
43	1.19E+07	1.37E+07	-1.22E+01	4.28E-11	-1.25E+01	-1.73E+01	-1.87E+01	2.45E-01	-1.37E-01	-3.51E-01	-2.07E-01	6.57E-01	-2.31E-01	-2.13E-02	-4.09E-01	4.84E-01	5.15E-01	3.68E-01	2.31E-01	1.33E+02	4.23E-01	1.19E+00	4.67E-01
44	1.26E+07	1.44E+07	-1.20E+01	6.09E-11	-1.29E+01	-1.27E+01	-1.72E+01	-2.07E-01	3.83E-01	-3.62E-01	-8.02E-01	8.65E-01	-4.75E-01	-9.95E-01	-5.28E-01	-1.95E-02	-9.27E-02	1.48E+00	2.40E-01	9.72E+02	9.41E-01	2.14E+00	1.42E-01
45	1.36E+07	1.39E+07	-1.10E+01	2.98E-11	-1.16E+01	-1.63E+01	-1.74E+01	-3.67E-01	-9.37E-01	1.88E-01	-6.35E-01	-2.23E-01	-2.14E-01	6.85E-01	-3.08E-01	-1.12E-01	7.14E-01	9.29E-01	8.43E-01	5.75E+02	9.10E-01	1.63E+00	3.94E-01
46	1.24E+07	1.56E+07	-1.36E+01	8.39E-11	-1.11E+01	-1.69E+01	-1.83E+01	-4.14E-01	3.39E-01	1.15E+00	1.40E-01	-3.46E-01	5.22E-01	-2.96E-01	3.69E-01	-1.67E-01	-3.54E-02	1.11E+00	6.05E-01	4.91E+02	8.06E-01	1.12E+00	1.97E-01
47	1.19E+07	1.40E+07	-1.25E+01	6.26E-11	-1.57E+01	-1.31E+01	-1.74E+01	-3.54E-01	4.35E-01	-3.19E-01	9.90E-02	-6.28E-01	-9.57E-02	8.50E-01	5.58E-02	1.86E-01	-1.12E-01	1.43E+00	4.45E-01	3.94E+02	7.45E-01	1.13E+00	2.75E-01
48	1.18E+07	1.52E+07	-1.17E+01	5.16E-11	-1.50E+01	-1.37E+01	-1.71E+01	6.62E-03	-1.67E-02	-5.53E-01	-3.08E-01	1.64E-01	5.48E-02	7.16E-01	-8.53E-02	-4.09E-01	-2.22E-01	1.90E-01	4.18E-01	9.27E+02	1.43E-01	1.01E+00	3.44E-01
49	1.23E+07	1.47E+07	-1.13E+01	2.81E-11	-1.51E+01	-1.71E+01	-1.81E+01	-3.33E-01	-2.69E-01	3.80E-02	-1.58E-01	-4.74E-01	-1.89E-02	-1.92E+00	-5.87E-02	5.96E-01	-3.32E-01	5.50E-01	7.15E-01	4.26E+02	7.16E-01	1.25E+00	3.04E-01
50	1.34E+07	1.25E+07	-1.20E+01	5.88E-11	-1.43E+01	-1.90E+01	-1.77E+01	-5.72E-01	1.72E-01	-1.25E-01	7.99E-03	2.15E-02	-9.43E-01	-3.78E-01	8.86E-01	6.57E-02	9.88E-01	1.53E+00	6.46E-01	7.69E+02	3.77E-01	1.14E+00	1.33E-01
51	1.16E+07	1.40E+07	-1.03E+01	2.66E-11	-1.43E+01	-1.87E+01	-1.86E+01	-4.57E-02	9.91E-02	5.35E-01	-4.25E-01	-2.56E-02	-2.17E-01	9.65E-01	-1.81E-01	-5.42E-01	-5.34E-02	1.37E+00	9.60E-01	9.13E+02	6.49E-01	1.03E+00	7.23E-02
52	1.20E+07	1.38E+07	-1.17E+01	4.72E-11	-1.53E+01	-1.84E+01	-1.75E+01	1.06E-01	-1.18E+00	6.69E-01	-1.52E-01	5.38E-01	3.60E-01	-2.46E-01	-4.23E-01	-2.43E-01	1.01E+00	1.46E+00	2.79E-02	1.60E+02	8.13E-02	1.56E+00	2.83E-01
53	1.35E+07	1.42E+07	-1.15E+01	4.07E-11	-1.51E+01	-1.60E+01	-1.78E+01	-1.94E+00	-8.42E-02	-4.84E-02	-4.62E-01	-3.81E-01	-1.13E-01	5.82E-01	-5.89E-01	-4.54E-01	-1.39E-01	5.28E-01	3.34E-01	3.52E+02	3.48E-01	1.22E+00	2.70E-01

Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector Num.	S_HALITE PRESSURE	CASTILER PRESSURE	CASTILER PRMX_LOG	CASTILER COMP_RCK	BH_SAND PRMX_LOG	DRZ_1 PRMX_LOG	CONC_PLG PRMX_LOG	SOLAM3 SOLSIM	SOLAM3 SOLCIM	SOLPU3 SOLSIM	SOLPU3 SOLCIM	SOLPU4 SOLSIM	SOLPU4 SOLCIM	SOLU4 SOLSIM	SOLU6 SOLSIM	SOLU6 SOLCIM	SOLTH4 SOLSIM	PHUMOX3 PHUMCIM	GLOBAL OXSTAT	CULEBRA MINP_FAC	GLOBAL TRANSIDX	GLOBAL CLIMTIDX	CULEBRA HMBLKLT
54	1.31E+07	1.27E+07	-1.31E+01	7.75E-11	-1.26E+01	-1.46E+01	-1.72E+01	3.09E-02	-1.07E-01	-2.11E-01	-2.12E-01	-2.71E-01	-9.54E-01	-4.29E-01	-9.54E-02	-9.82E-02	4.69E-02	1.40E+00	8.55E-01	4.20E+02	4.97E-02	1.00E+00	3.89E-01
55	1.11E+07	1.37E+07	-1.16E+01	3.80E-11	-1.32E+01	-1.58E+01	-1.86E+01	3.73E-01	-7.73E-01	-2.41E-01	-1.85E-01	-1.23E+00	8.93E-01	-9.21E-01	-7.75E-02	-7.40E-01	2.05E-01	4.91E-01	5.77E-01	2.64E+02	8.87E-01	1.22E+00	3.29E-01
56	1.17E+07	1.43E+07	-1.29E+01	3.92E-11	-1.26E+01	-1.78E+01	-1.88E+01	8.51E-01	9.90E-01	-2.42E-02	1.84E-01	1.40E+00	-1.11E+00	8.22E-02	-2.28E-02	-1.29E-01	8.52E-01	1.01E+00	2.74E-01	8.13E+02	4.10E-01	1.18E+00	3.27E-01
57	1.14E+07	1.35E+07	-1.14E+01	4.14E-11	-1.35E+01	-1.91E+01	-1.89E+01	-2.12E-01	-2.87E-01	-1.18E-01	-1.90E+00	-1.19E-02	-3.08E-01	1.62E-01	3.04E-01	8.46E-01	-2.28E-01	1.41E+00	1.41E-01	5.21E+02	1.71E-01	2.16E+00	4.78E-01
58	1.25E+07	1.38E+07	-1.40E+01	7.16E-11	-1.27E+01	-1.34E+01	-1.76E+01	-1.85E-01	8.75E-01	3.43E-01	-2.91E-01	-8.33E-01	-2.46E-01	-1.68E-01	-2.08E-01	-4.27E-01	1.04E-01	1.55E+00	7.68E-01	3.26E+01	4.81E-01	2.25E+00	4.52E-01
59	1.33E+07	1.32E+07	-1.34E+01	4.66E-11	-1.56E+01	-1.84E+01	-1.74E+01	7.24E-01	8.84E-02	-4.35E-01	-2.84E-01	-2.32E-01	-4.01E-02	-1.56E+00	-1.01E-01	8.68E-01	-5.00E-01	1.47E+00	3.24E-01	9.32E+02	1.35E-01	1.60E+00	2.23E-01
60	1.15E+07	1.29E+07	-1.30E+01	4.86E-11	-1.23E+01	-1.68E+01	-1.81E+01	-7.91E-01	1.36E-01	-6.70E-02	-7.77E-01	-1.85E-01	2.28E-01	-8.16E-01	-3.58E-01	-1.16E-02	-1.72E-01	1.44E+00	8.75E-02	1.30E+02	9.81E-01	1.06E+00	2.05E-01
61	1.33E+07	1.25E+07	-1.19E+01	3.50E-11	-1.58E+01	-1.59E+01	-1.73E+01	-7.09E-01	7.89E-02	9.04E-01	-3.49E-02	1.02E-01	-2.38E-01	-1.02E-01	-4.96E-01	-1.48E-01	-1.49E-01	2.46E-01	9.09E-01	3.84E+02	9.29E-01	1.02E+00	3.24E-01
62	1.13E+07	1.20E+07	-1.07E+01	5.40E-11	-1.41E+01	-1.48E+01	-1.84E+01	-4.57E-01	5.85E-02	-2.17E-01	7.36E-02	9.92E-01	-9.55E-03	-1.68E-02	-4.58E-01	3.94E-01	9.17E-02	1.55E+00	5.88E-01	2.83E+02	2.63E-01	1.17E+00	2.65E-01
63	1.23E+07	1.27E+07	-1.09E+01	5.53E-11	-1.17E+01	-1.50E+01	-1.89E+01	8.37E-01	1.84E-01	-2.25E-01	-1.60E+00	-1.74E-01	-1.83E-01	4.60E-01	-7.82E-03	-3.61E-01	-2.37E-01	7.26E-02	4.81E-01	8.98E+02	8.51E-01	1.24E+00	2.58E-01
64	1.24E+07	1.12E+07	-1.30E+01	5.29E-11	-1.62E+01	-1.40E+01	-1.90E+01	-3.79E-01	-3.84E-02	-7.90E-02	2.02E-01	-1.94E-01	-5.05E-02	1.81E-01	-6.89E-01	1.65E-01	-1.96E-01	1.54E+00	7.96E-01	8.07E+02	3.62E-01	1.83E+00	4.57E-01
65	1.13E+07	1.23E+07	-1.13E+01	6.86E-11	-1.50E+01	-1.78E+01	-1.79E+01	2.13E-01	2.31E-01	-1.18E-01	-5.93E-01	6.16E-01	-2.43E-02	-2.17E-01	5.25E-01	-2.06E-01	-8.11E-02	1.57E+00	8.84E-01	4.33E+02	2.76E-02	1.07E+00	3.08E-01
66	1.23E+07	1.31E+07	-1.09E+01	3.62E-11	-1.15E+01	-1.77E+01	-1.82E+01	-8.03E-02	8.43E-01	2.36E-01	1.09E+00	-7.48E-01	1.29E-01	-7.32E-01	2.50E-01	-3.09E-01	-8.46E-01	8.72E-01	9.39E-01	9.40E+02	1.17E-01	2.05E+00	2.76E-01
67	1.31E+07	1.29E+07	-1.35E+01	7.87E-11	-1.34E+01	-1.38E+01	-1.76E+01	-2.41E-01	-1.19E-01	-2.61E-01	-7.77E-02	-2.06E-01	-5.09E-01	-1.33E-01	1.21E+00	-2.28E-01	1.53E-01	2.75E-01	8.94E-01	1.82E+02	3.53E-01	1.18E+00	2.93E-01
68	1.39E+07	1.37E+07	-1.10E+01	3.78E-11	-1.45E+01	-1.70E+01	-1.90E+01	-8.37E-03	1.07E-01	-1.78E-01	-1.35E-01	-8.41E-01	-2.65E-01	-6.65E-01	6.79E-03	-6.87E-01	-1.45E+00	6.97E-01	6.76E-03	7.38E+02	5.27E-01	1.14E+00	1.92E-01
69	1.35E+07	1.35E+07	-1.20E+01	4.94E-11	-1.32E+01	-1.65E+01	-1.87E+01	-2.16E-01	-8.43E-01	-2.48E-01	-2.47E-01	-5.19E-02	-6.82E-02	-1.11E+00	-8.37E-01	-1.61E-01	1.89E-01	1.27E+00	9.87E-01	5.81E+02	6.06E-01	1.09E+00	4.97E-01
70	1.36E+07	1.31E+07	-1.27E+01	7.09E-11	-1.49E+01	-1.70E+01	-1.84E+01	1.95E-01	7.79E-01	-2.07E-02	3.29E-01	-6.47E-03	-8.47E-01	2.93E-01	-1.48E+00	1.36E-01	1.41E-01	1.04E+00	6.75E-01	3.40E+02	5.46E-01	1.20E+00	1.01E-01
71	1.34E+07	1.19E+07	-1.27E+01	7.70E-11	-1.45E+01	-1.91E+01	-1.71E+01	-5.39E-02	6.68E-02	-1.59E+00	-7.47E-02	-8.12E-02	9.39E-01	1.45E-01	-2.21E-01	-8.42E-01	4.11E-01	7.55E-01	4.29E-01	7.74E+02	6.98E-01	1.86E+00	4.85E-01
72	1.34E+07	1.47E+07	-1.08E+01	5.22E-11	-1.37E+01	-1.30E+01	-1.81E+01	1.25E-01	-4.42E-02	-7.97E-01	4.21E-02	-2.17E-01	-1.91E-01	-3.33E-01	-4.62E-02	1.28E-01	-2.56E-01	6.60E-01	1.60E-01	1.04E+02	7.91E-01	1.04E+00	3.97E-01
73	1.21E+07	1.50E+07	-1.32E+01	8.18E-11	-1.27E+01	-1.29E+01	-1.72E+01	1.99E-02	-1.79E-01	-2.97E-01	-5.89E-03	-1.18E-01	1.91E-01	4.13E-01	1.11E-01	2.43E-01	-1.23E-01	1.28E-01	8.70E-01	6.10E+02	2.60E-01	1.54E+00	2.45E-01
74	1.21E+07	1.22E+07	-1.29E+01	6.43E-11	-1.60E+01	-1.82E+01	-1.89E+01	1.44E-01	-1.17E-02	8.35E-01	-8.42E-01	-9.38E-02	1.20E+00	-2.34E-01	4.32E-01	4.29E-01	-6.65E-01	1.20E+00	4.09E-01	7.55E+02	3.10E-01	1.03E+00	3.64E-01
75	1.12E+07	1.19E+07	-1.15E+01	5.15E-11	-1.33E+01	-1.41E+01	-1.78E+01	1.40E-01	4.23E-02	3.56E-01	-1.29E-01	-2.98E-01	1.06E-01	-1.26E-01	8.34E-02	-8.55E-02	-1.94E-02	4.45E-01	9.11E-01	6.30E+02	3.86E-01	2.19E+00	8.62E-02
76	1.37E+07	1.27E+07	-1.14E+01	3.90E-11	-1.21E+01	-1.44E+01	-1.88E+01	5.04E-02	6.93E-01	-4.47E-01	-1.18E+00	-7.01E-02	2.20E-01	-8.71E-02	2.21E-01	-1.79E-01	-3.40E-01	6.91E-01	6.81E-01	4.60E+02	4.92E-01	1.23E+00	8.43E-02
77	1.28E+07	1.59E+07	-1.36E+01	5.41E-11	-1.33E+01	-1.38E+01	-1.71E+01	-4.90E-01	5.15E-01	9.49E-02	-1.18E-01	-1.06E-01	1.56E-01	-8.62E-01	-5.49E-02	-1.45E-01	3.58E-01	2.71E-01	3.47E-01	4.03E+02	2.24E-01	1.15E+00	4.16E-01
78	1.12E+07	1.41E+07	-1.11E+01	3.15E-11	-1.15E+01	-1.51E+01	-1.75E+01	-2.34E-01	1.51E-01	-1.03E+00	5.23E-02	3.66E-02	-4.05E-01	-4.77E-01	1.62E-01	-1.52E+00	-8.95E-01	1.60E+00	5.64E-01	4.64E+02	1.04E-01	1.22E+00	3.74E-01
79	1.22E+07	1.57E+07	-1.08E+01	2.79E-11	-1.23E+01	-1.84E+01	-1.73E+01	-1.61E-02	5.58E-01	-9.17E-01	8.18E-01	-1.76E-02	4.66E-01	3.54E-01	-1.66E-02	1.12E+00	1.60E-01	1.31E+00	7.44E-02	3.08E+02	9.61E-01	1.05E+00	3.69E-01
80	1.15E+07	1.30E+07	-1.38E+01	8.14E-11	-1.40E+01	-1.88E+01	-1.74E+01	-7.59E-01	-1.70E-01	-4.17E-01	-1.32E+00	-1.99E-01	-7.23E-01	-4.20E-02	7.06E-01	5.93E-02	6.82E-02	8.23E-01	3.64E-01	5.43E+02	8.45E-01	1.09E+00	1.26E-01
81	1.16E+07	1.54E+07	-1.19E+01	5.67E-11	-1.21E+01	-1.61E+01	-1.80E+01	-4.30E-01	-1.97E-01	-1.96E-01	-3.61E-01	4.37E-01	-2.02E-01	6.04E-01	9.76E-01	1.72E-01	6.58E-01	1.41E+00	6.32E-01	1.87E+01	6.36E-01	1.71E+00	1.19E-01
82	1.11E+07	1.46E+07	-1.28E+01	3.97E-11	-1.18E+01	-1.88E+01	-1.87E+01	4.79E-01	-9.84E-01	-6.69E-01	2.31E-01	1.24E-01	-4.27E-01	4.81E-03	1.80E-01	-9.36E-01	-2.76E-01	1.26E+00	7.26E-01	2.15E+02	5.79E-01	1.11E+00	3.72E-01
83	1.31E+07	1.21E+07	-1.22E+01	3.31E-11	-1.49E+01	-1.74E+01	-1.78E+01	5.73E-01	-7.04E-02	-8.63E-02	1.50E-01	-2.42E-01	-1.31E+00	-1.58E-01	-4.43E-01	-2.72E-01	1.34E-02	4.11E-01	1.12E-01	7.36E+01	2.84E-01	1.21E+00	3.87E-01
84	1.25E+07	1.27E+07	-1.25E+01	3.66E-11	-1.19E+01	-1.26E+01	-1.82E+01	-9.74E-02	-2.11E-01	-1.65E-01	-1.47E-02	8.09E-01	1.74E-01	-5.53E-04	-1.60E-01	5.40E-01	-1.08E+00	3.47E-01	3.11E-02	3.17E+02	5.08E-02	1.20E+00	2.41E-01
85	1.27E+07	1.37E+07	-1.25E+01	6.29E-11	-1.38E+01	-1.83E+01	-1.82E+01	1.64E-01	-4.34E-01	1.55E-01	7.25E-01	-3.69E-01	-7.98E-02	2.44E-01	-1.19E-01	9.92E-01	-1.07E-01	1.35E+00	7.71E-01	9.59E+02	5.32E-01	1.04E+00	1.10E-01
86	1.11E+07	1.49E+07	-1.05E+01	3.41E-11	-1.53E+01	-1.55E+01	-1.79E+01	7.28E-02	2.21E-01	-1.04E-01	-2.57E-02	-2.09E-01	6.16E-01	-2.61E-01	-2.41E-01	-1.88E-01	-1.53E-01	1.17E+00	6.95E-01	6.86E+02	7.61E-01	1.04E+00	4.04E-01
87	1.13E+07	1.21E+07	-1.24E+01	4.89E-11	-1.39E+01	-1.62E+01	-1.85E+01	-6.37E-01	1.08E+00	6.00E-02	-4.98E-01	2.92E-02	-4.93E-01	-6.63E-02	-3.91E-01	-1.82E-01	2.84E-02	1.32E+00	6.13E-01	8.61E+02	8.19E-01	1.09E+00	4.60E-01
88	1.21E+07	1.30E+07	-1.31E+01	6.66E-11	-1.48E+01	-1.37E+01	-1.86E+01	5.34E-01	-3.75E-01	-2.84E-01	9.82E-01	-1.73E-01	2.65E-02	-1.83E-01	4.12E-02	-9.53E-02	1.09E-01	6.29E-01	9.47E-01	3.64E+02	7.40E-01	1.82E+00	3.47E-01
89	1.22E+07	1.32E+07	-1.31E+01	8.65E-11	-1.30E+01	-1.94E+01	-1.78E+01	-2.94E-03	-5.28E-02	4.45E-01	2.23E-01	7.81E-01	-1.37E-01	-2.01E-01	-7.15E-02	-4.81E-01	1.05E-02	1.40E+00	3.02E-01	6.60E+02	6.86E-01	1.72E+00	2.90E-01
90	1.31E+07	1.33E+07	-1.13E+01	3.21E-11	-1.16E+01	-1.85E+01	-1.85E+01	-1.09E+00	-2.20E-01	-3.39E-02	-4.32E-01	-1.64E-01	1.18E-01	5.70E-02	-2.61E-01	6.82E-01	1.98E-01	1.51E+00	8.68E-01	9.83E+02	2.14E-01	1.78E+00	1.45E-01
91	1.38E+07	1.31E+07	-1.18E+01	4.11E-11	-1.11E+01	-1.35E+01	-1.86E+01	1.10E-01	-2.48E-01	1.99E-01	5.75E-01	4.78E-01	-3.03E-02	-5.53E-01	1.48E-01	1.44E-01	4.71E-01	1.45E+00	7.06E-01	1.73E+02	3.49E-02	1.15E+00	1.61E-01
92	1.26E+07	1.42E+07	-1.25E+01	4.37E-11	-1.54E+01	-1.91E+01	-1.75E+01	-1.57E-01	-4.48E-01	7.19E-01	-2.16E-01	-1.32E-01	2.60E-01	-2.72E-01	-1.09E-01	-1.45E+00	-2.06E-01	1.51E+00	2.08E-01	5.91E+02	6.17E-01	2.09E+00	2.31E-01
93	1.35E+07	1.55E+07	-1.45E+01	9.02E-11	-1.39E+01	-1.72E+01	-1.89E+01	9.06E-02	-1.66E-01	5.41E-02	2.02E-02	2.31E-01	7.45E-01	5.44E-01	-4.34E-04	3.39E-02	-4.02E-01	1.21E+00	8.04E-01	3.23E+02	8.70E-01	2.12E+00	4.23E-01
94	1.37E+07	1.26E+07	-1.37E+01	7.94E-11	-1.42E+01	-1.64E+01	-1.81E+01	-2.65E-01	2.10E-01	-1.36E+00	-1.95E-01	2.14E-01	4.41E-02	-9.48E-02	-1.35E-01	8.73E-02	7.49E-02	1.43E+00	2.29E-01	8.56E+02	4.49E-01	1.01E+00	2.10E-01
95	1.32E+07	1.45E+07	-1.22E+01	7.43E-11	-1.31E+01	-1.86E+01	-1.88E+01	-4.74E-01	2.02E-01	2.56E-02	-9.36E-02	7.06E-01	-1.63E-01	2.29E-01	4.75E-01	-1.08E-01	-4.49E-01	1.59E+00	4.55E-01	2.72E+02	9.94E-01	1.06E+00	4.29E-01
96	1.15E+07	1.30E+07	-1.36E+01	5.78E-11	-1.55E+01	-1.30E+01	-1.85E+01	-5.58E-02	-2.84E-02	1.28E-01	-1.03E-01	-4.14E-01	-3.49E-01	1.02E-01	6.90E-01	-2.11E-01	-7.23E-01	1.59E+00	1.64E-01	6.52E+02	8.98E-01	1.20E+00	2.21E-01
97	1.19E+07	1.26E+07	-1.26E+01	5.60E-11	-1.23E+01	-1.58E+01	-1.70E+01	-1.88E-01	-1.14E-01	-4.87E-01	-7.75E-03	-9.75E-02	-1.43E-01	-4.88E-01	-2.05E-01	2.27E-01	-1.78E-01	8.99E-01	5.28E-01	7.90E+02	9.74E-01	1.52E+00	4.12E-01
98	1.38E+07	1.36E+07	-1.21E+01	4.46E-11	-1.42E+01	-1.79E+01	-1.87E+01	-1.43E-01	-6.32E-02	-1.44E-01	2.81E-01	-6.30E-02	2.41E-01	-4.15E-02	-1.65E-01	-6.48E-01	-2.19E-03	1.45E+00	3.77E-01	1.63E+02	8.38E-01	1.10E+00	4.33E-01
99	1.28E+07	1.18E+07	-1.41E+01	9.53E-11	-1.33E+01	-1.49E+01	-1.72E+01	-2.44E-01	-2.63E-01	-2.33E-01	-4.82E-01	-8.77E-02	6.82E-01	1.35E-02	-1.73E-01	-2.64E-02	-1.86E-01	4.76E-01	1.08E-01	6.73E+02	2.31E-01	1.08E+00	2.55E-01
100	1.12E+07	1.32E+07	-1.27E+01	6.01E-11	-1.47E+01	-1.67E+01	-1.74E+01	-2.26E-01	-1.01E-01	-3.86E-01	3.99E-01	-4.39E-01	-1.97E-01	-1.89E-01	2.74E-02	-3.24E-01	-2.49E-01	6.02E-01	5.41E-01	6.27E+02	6.54E-01	1.16E+00	1.78E-01

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Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
1	1.14E-03	1.20E-01	3.25E-03	2.06E+00	2.66E-02	1.53E+00	5.20E+00	3.89E-02	1.03E+00	4.85E-01	7.01E+00	3.86E-01	2.05E-01	-1.79E+01	-1.79E+01	-2.08E+01	1.66E-01
2	2.01E-04	1.72E-01	1.31E-02	4.61E+00	5.43E-02	5.02E+00	2.22E+00	2.04E-02	1.09E+01	2.00E-01	1.15E+01	5.10E-01	1.46E-01	-1.87E+01	-1.85E+01	-2.01E+01	3.58E-01
3	1.66E-03	1.41E-01	4.46E-04	2.23E+00	3.93E-02	8.22E+00	6.69E+00	2.64E-02	3.65E+01	3.73E-01	6.30E+00	1.90E-01	3.48E-01	-1.80E+01	-1.70E+01	-2.04E+01	1.71E-01
4	1.03E-04	1.46E-01	1.45E-02	1.88E+00	1.01E-01	2.28E+00	1.26E+00	6.96E-02	5.40E+00	3.24E-01	9.11E+00	3.69E-02	3.30E-01	-1.82E+01	-1.70E+01	-2.02E+01	3.26E-01
5	3.82E-04	1.80E-01	1.84E-03	4.78E+00	6.50E-02	1.50E+00	2.58E+00	1.81E-01	2.42E-01	1.73E-01	7.05E+00	2.54E-01	1.90E-01	-1.77E+01	-1.87E+01	-2.04E+01	5.72E-01
6	2.87E-04	1.45E-01	2.83E-04	6.97E+00	1.16E-01	4.20E+00	1.29E+00	6.56E-02	6.25E-02	3.30E-01	1.25E+01	5.28E-01	1.04E-01	-1.80E+01	-1.72E+01	-2.17E+01	8.18E-01
7	1.87E-04	1.10E-01	1.95E-03	3.77E+00	5.01E-02	2.72E+00	5.87E+00	1.20E-01	8.56E+00	1.26E-02	6.49E+00	2.36E-01	2.14E-01	-1.82E+01	-1.82E+01	-2.01E+01	6.89E-01
8	1.10E-04	1.11E-01	1.07E-04	8.51E-01	5.81E-02	8.05E+00	2.74E+00	2.20E-01	1.30E-01	5.88E-02	7.47E+00	2.75E-01	2.34E-02	-1.89E+01	-1.91E+01	-1.96E+01	3.26E-02
9	2.69E-03	1.85E-01	4.01E-03	2.64E+00	1.85E-01	3.77E+00	1.59E+00	2.36E-01	1.35E+00	1.80E-01	1.84E+01	5.47E-01	2.76E-01	-1.79E+01	-1.83E+01	-1.94E+01	7.45E-01
10	1.19E-03	1.65E-01	3.91E-03	2.57E+00	3.17E-02	8.66E-01	2.34E+00	7.87E-02	5.43E-02	2.09E-01	1.30E+01	2.22E-01	1.31E-01	-1.83E+01	-1.80E+01	-2.05E+01	9.88E-01
11	7.85E-04	1.24E-01	5.59E-05	7.83E+00	2.32E-02	5.39E+00	8.75E+00	5.81E-02	7.41E-02	4.18E-01	5.32E+00	2.84E-02	2.94E-01	-1.87E+01	-1.83E+01	-1.85E+01	8.25E-01
12	3.38E-03	1.90E-01	4.10E-04	8.59E+00	2.27E-01	6.40E+00	6.84E+00	1.02E-01	1.04E-01	4.75E-01	4.65E+00	1.71E-01	2.77E-01	-1.87E+01	-1.94E+01	-1.97E+01	1.57E-01
13	5.83E-03	1.80E-01	1.51E-03	1.47E+00	1.63E-01	1.20E+00	5.45E+00	1.58E-01	3.02E-01	9.01E-02	7.13E+00	8.40E-02	3.98E-01	-2.03E+01	-1.85E+01	-1.99E+01	9.18E-01
14	1.94E-03	1.76E-01	3.03E-04	2.98E+00	4.02E-02	6.56E+00	1.13E+00	8.38E-02	5.11E+01	4.69E-01	7.18E+00	5.97E-01	8.03E-02	-2.00E+01	-1.74E+01	-2.03E+01	5.63E-01
15	6.16E-03	1.81E-01	9.41E-04	4.29E+00	3.39E-01	9.10E-01	2.08E+00	2.50E-02	5.00E-01	3.90E-01	8.22E+00	5.86E-01	5.15E-02	-1.89E+01	-1.75E+01	-1.97E+01	3.82E-01
16	2.79E-03	1.74E-01	1.16E-03	9.95E+00	2.88E-01	1.44E+00	7.25E+00	9.41E-02	4.77E+01	1.09E-01	8.24E+00	3.66E-01	3.53E-01	-1.77E+01	-1.86E+01	-1.95E+01	2.28E-01
17	8.32E-04	1.15E-01	1.45E-04	7.95E-01	2.85E-02	4.98E+00	7.86E-01	2.13E-01	1.82E+00	5.75E-01	8.38E+00	0	1.32E-01	-1.81E+01	-1.92E+01	-1.99E+01	1.95E-01
18	6.56E-04	1.59E-01	8.99E-05	8.92E-01	1.78E-01	2.87E+00	1.36E+00	4.57E-02	5.62E-01	5.70E-01	8.14E+00	3.35E-01	3.05E-01	-1.98E+01	-1.74E+01	-1.99E+01	6.72E-01
19	4.02E-03	1.75E-01	7.07E-04	8.45E+00	1.47E-01	7.04E-01	7.31E-01	2.79E-02	6.90E+00	5.08E-01	6.02E+00	1.27E-01	1.41E-01	-1.83E+01	-1.84E+01	-2.00E+01	4.17E-01
20	1.65E-04	1.67E-01	5.77E-04	3.34E+00	3.33E-02	1.95E+00	7.43E+00	9.03E-02	1.51E+00	5.36E-01	8.19E+00	8.50E-03	3.24E-01	-1.88E+01	-1.81E+01	-1.90E+01	8.82E-01
21	5.78E-04	1.12E-01	2.08E-04	7.35E+00	3.73E-01	4.65E+00	1.37E+00	1.13E-01	3.43E+00	2.64E-01	1.56E+01	8.99E-02	2.53E-02	-2.03E+01	-1.73E+01	-2.07E+01	3.97E-01
22	3.21E-04	1.51E-01	1.10E-03	4.44E+00	3.02E-02	4.81E+00	1.63E+00	8.01E-02	4.80E-01	4.95E-01	7.93E+00	4.04E-01	3.95E-01	-1.84E+01	-1.85E+01	-1.93E+01	7.73E-02
23	4.06E-04	1.66E-01	4.29E-03	8.00E-01	1.95E-01	5.14E+00	1.53E+00	2.53E-01	2.46E+00	9.27E-02	5.57E+00	5.83E-01	1.55E-01	-1.90E+01	-1.84E+01	-2.14E+01	9.26E-01
24	2.22E-03	1.96E-01	1.02E-03	1.15E+00	3.99E-01	2.50E+00	3.56E+00	2.28E-02	6.11E-01	2.34E-01	9.71E+00	1.37E-01	3.59E-01	-1.92E+01	-1.80E+01	-2.07E+01	2.35E-01
25	1.39E-04	1.82E-01	5.15E-05	2.70E+00	2.78E-02	3.18E+00	1.04E+00	3.54E-01	8.20E-01	1.57E-01	6.78E+00	4.65E-01	3.92E-01	-1.91E+01	-1.89E+01	-2.11E+01	5.84E-01
26	4.53E-03	1.65E-01	7.55E-03	4.13E+00	1.69E-01	8.97E+00	9.99E-01	2.74E-02	3.20E-01	3.04E-02	7.37E+00	1.41E-01	4.70E-02	-1.74E+01	-1.75E+01	-2.18E+01	9.08E-01
27	1.06E-03	1.35E-01	2.13E-03	1.96E+00	1.38E-01	2.06E+00	8.21E-01	1.09E-01	1.94E+00	3.17E-01	7.06E+00	4.96E-03	1.02E-01	-1.75E+01	-1.84E+01	-1.98E+01	8.60E-01
28	3.07E-03	2.36E-01	1.48E-03	1.39E+00	9.94E-02	1.66E+00	2.93E+00	6.16E-02	2.03E-01	2.47E-01	1.13E+01	4.77E-01	1.68E-01	-1.78E+01	-1.76E+01	-1.82E+01	6.70E-02
29	3.65E-04	2.28E-01	2.37E-04	7.61E-01	5.90E-02	1.15E+00	3.85E+00	1.00E-01	1.56E+01	4.30E-01	4.98E+00	3.11E-01	5.72E-02	-1.84E+01	-1.88E+01	-1.86E+01	1.04E-01
30	1.16E-04	1.08E-01	3.37E-05	1.21E+00	2.53E-02	2.34E+00	3.39E+00	4.94E-02	6.22E+00	4.14E-01	7.28E+00	1.47E-01	2.19E-01	-1.92E+01	-1.80E+01	-2.05E+01	5.01E-01
31	7.69E-03	2.48E-01	9.54E-04	6.82E+00	4.76E-02	6.81E+00	4.51E+00	3.82E-01	2.95E+01	4.01E-01	1.20E+01	4.63E-01	2.52E-01	-1.88E+01	-1.77E+01	-1.97E+01	9.86E-02
32	3.25E-03	1.07E-01	1.66E-04	2.19E+00	2.92E-02	6.15E+00	1.84E+00	2.54E-02	7.59E-01	4.42E-01	7.53E+00	1.15E-01	3.65E-02	-1.76E+01	-1.83E+01	-2.07E+01	7.87E-01
33	1.95E-04	1.77E-01	9.51E-05	8.70E-01	3.12E-01	3.05E+00	3.16E+00	1.32E-01	4.45E-01	2.85E-01	2.23E+01	3.09E-03	1.86E-01	-1.84E+01	-1.82E+01	-2.13E+01	3.06E-01
34	4.73E-04	1.00E-01	4.04E-05	1.24E+00	2.35E-01	1.98E+00	6.21E+00	3.21E-02	5.59E+01	3.37E-01	1.05E+01	2.96E-01	2.25E-01	-1.85E+01	-1.78E+01	-2.05E+01	4.77E-02
35	1.77E-04	1.70E-01	8.71E-04	9.11E+00	3.44E-02	9.87E+00	4.28E+00	2.43E-01	3.05E+01	6.90E-02	8.01E+00	4.51E-01	4.14E-02	-1.79E+01	-1.81E+01	-1.96E+01	6.34E-01
36	2.13E-03	1.18E-01	8.57E-03	1.82E+00	4.32E-02	7.81E+00	1.90E+00	1.23E-01	8.98E-02	5.51E-01	4.40E+00	4.26E-01	2.66E-01	-1.80E+01	-1.71E+01	-2.12E+01	4.66E-01
37	1.30E-04	2.07E-01	3.23E-03	4.26E+00	1.44E-01	8.48E+00	1.75E+00	1.07E-01	6.62E+01	2.60E-01	1.40E+01	9.45E-02	2.82E-01	-1.94E+01	-1.80E+01	-2.00E+01	4.48E-01
38	1.76E-03	1.63E-01	5.29E-04	9.54E-01	6.17E-02	1.76E+00	7.50E+00	2.83E-01	1.90E-01	3.48E-01	1.03E+01	1.76E-01	6.78E-02	-1.76E+01	-1.83E+01	-2.19E+01	3.77E-01
39	1.46E-03	1.19E-01	2.81E-03	2.92E+00	1.99E-01	4.51E+00	5.05E+00	8.73E-02	2.23E+01	1.82E-01	7.79E+00	3.98E-01	8.59E-02	-1.91E+01	-1.73E+01	-1.90E+01	3.61E-01
40	4.25E-04	1.06E-01	1.63E-03	2.38E+00	9.28E-02	3.68E+00	8.19E+00	2.02E-01	4.57E+01	2.97E-01	8.09E+00	5.66E-01	2.85E-01	-1.86E+01	-1.94E+01	-2.15E+01	7.03E-01
41	2.60E-03	1.13E-01	1.42E-04	2.39E+00	4.13E-02	1.23E+00	1.41E+00	7.54E-02	1.37E+01	2.27E-02	6.52E+00	1.67E-02	7.65E-02	-1.92E+01	-1.81E+01	-1.87E+01	8.88E-02
42	3.88E-03	1.64E-01	6.34E-04	5.19E+00	2.70E-01	6.01E+00	2.29E+00	1.28E-01	2.10E+01	5.97E-01	1.37E+01	1.32E-01	2.03E-01	-1.82E+01	-1.99E+01	-1.98E+01	4.04E-01
43	3.11E-04	1.76E-01	1.84E-02	2.00E+00	3.63E-02	6.97E+00	9.22E+00	3.56E-02	9.52E-02	3.55E-01	7.25E+00	7.55E-02	3.22E-02	-1.93E+01	-1.95E+01	-2.01E+01	2.99E-02
44	3.38E-04	1.12E-01	5.64E-03	1.27E+00	6.37E-02	2.60E+00	1.66E+00	3.50E-02	1.84E-01	7.80E-02	1.10E+01	5.68E-01	2.42E-01	-1.99E+01	-1.76E+01	-1.93E+01	1.38E-01
45	8.17E-04	1.16E-01	2.62E-03	5.03E+00	2.50E-01	1.01E+00	1.19E+00	3.02E-01	1.89E+01	5.25E-01	6.04E+00	2.10E-01	3.45E-01	-1.70E+01	-1.76E+01	-2.24E+01	2.17E-01
46	1.32E-03	1.40E-01	1.35E-02	2.28E+00	2.12E-01	3.58E+00	9.50E-01	2.95E-02	4.17E-01	5.57E-01	4.21E+00	4.11E-01	3.41E-01	-1.74E+01	-1.81E+01	-1.92E+01	2.04E-01
47	6.48E-03	1.69E-01	7.41E-05	7.22E-01	3.76E-02	1.26E+00	7.72E+00	9.71E-02	1.24E+00	1.51E-01	1.01E+01	1.84E-01	3.12E-01	-1.86E+01	-1.77E+01	-1.91E+01	5.32E-01
48	1.58E-04	1.68E-01	1.26E-03	5.90E+00	2.99E-01	9.45E-01	7.04E-01	3.62E-01	6.16E-02	1.44E-01	5.30E+00	2.25E-01	2.60E-01	-1.96E+01	-1.78E+01	-1.89E+01	8.79E-01
49	3.66E-03	1.61E-01	1.29E-04	3.60E+00	1.67E-01	3.40E+00	9.35E-01	7.35E-02	3.90E-01	3.81E-01	7.83E+00	1.23E-01	3.75E-01	-1.97E+01	-1.81E+01	-2.06E+01	1.65E-02
50	5.25E-04	1.31E-01	4.87E-04	6.57E+00	5.32E-02	4.01E+00	1.93E+00	6.65E-02	7.77E+00	5.30E-01	9.95E+00	4.45E-01	3.65E-01	-1.81E+01	-1.90E+01	-2.10E+01	9.94E-01
51	2.33E-04	1.57E-01	4.99E-03	1.36E+00	2.18E-02	1.82E+00	8.76E+00	2.40E-02	6.84E-02	1.13E-01	1.22E+01	4.18E-02	3.39E-01	-1.85E+01	-1.76E+01	-1.93E+01	6.19E-01
52	2.69E-04	1.88E-01	2.73E-04	1.79E+00	2.42E-01	1.31E+00	3.77E+00	3.07E-01	1.65E-01	8.36E-02	6.21E+00	4.54E-02	9.37E-02	-1.77E+01	-1.79E+01	-1.88E+01	2.58E-01
53	4.46E-04	1.21E-01	4.67E-03	3.53E+00	1.27E-01	3.02E+00	8.77E-01	1.40E-01	5.62E+00	2.54E-01	1.62E+01	3.48E-01	2.45E-01	-1.82E+01	-1.93E+01	-1.81E+01	7.58E-01

Table PAR-9. LHS Sampled Values (100 vectors) Replicate 1 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
54	8.44E-03	1.14E-01	1.58E-02	1.12E+00	4.82E-02	1.12E+00	1.12E+00	5.14E-02	3.14E+00	3.86E-02	4.49E+00	1.12E-01	2.88E-01	-1.95E+01	-1.87E+01	-1.92E+01	5.56E-01
55	1.44E-03	1.50E-01	1.68E-02	5.54E+00	3.24E-02	1.06E+00	1.71E+00	5.68E-02	4.21E+01	1.66E-01	6.83E+00	2.80E-01	2.23E-01	-1.88E+01	-1.77E+01	-2.09E+01	2.45E-01
56	1.32E-04	1.58E-01	5.77E-05	9.37E-01	7.58E-02	1.69E+00	7.07E+00	2.18E-01	7.10E+01	2.93E-01	6.88E+00	5.58E-01	3.19E-01	-1.88E+01	-1.79E+01	-2.02E+01	5.50E-01
57	9.99E-03	1.48E-01	3.06E-05	6.16E+00	4.38E-02	2.17E+00	7.73E-01	2.21E-02	1.02E+01	1.61E-01	7.66E+00	1.17E-01	2.98E-01	-1.95E+01	-1.80E+01	-1.94E+01	4.57E-01
58	9.72E-04	1.72E-01	1.78E-04	8.21E+00	7.74E-02	1.60E+00	2.00E+00	2.70E-01	2.03E+00	1.60E-02	9.47E+00	1.05E-01	2.60E-01	-1.95E+01	-1.90E+01	-2.05E+01	2.88E-01
59	7.06E-04	2.12E-01	1.13E-02	1.71E+00	7.41E-02	9.14E-01	3.72E+00	1.99E-01	1.31E+01	2.39E-01	8.45E+00	6.43E-02	2.71E-01	-1.90E+01	-1.83E+01	-2.00E+01	9.57E-01
60	6.14E-04	1.83E-01	6.59E-04	7.10E-01	1.06E-01	3.54E+00	3.22E+00	1.39E-01	9.78E+00	4.28E-01	7.86E+00	1.47E-02	3.70E-01	-1.72E+01	-1.77E+01	-2.03E+01	9.38E-01
61	1.65E-03	1.86E-01	9.73E-03	1.58E+00	2.62E-02	2.25E+00	1.23E+00	4.14E-02	4.55E+00	5.87E-01	8.29E+00	2.58E-01	9.70E-03	-2.01E+01	-1.89E+01	-2.06E+01	6.58E-01
62	3.54E-03	1.55E-01	1.98E-02	7.26E+00	2.21E-02	9.79E-01	2.94E+00	3.21E-01	1.41E+00	5.91E-01	7.48E+00	1.58E-01	1.12E-01	-1.93E+01	-1.78E+01	-2.03E+01	7.66E-01
63	4.89E-04	1.28E-01	2.24E-03	2.47E+00	4.55E-02	4.41E+00	3.96E+00	5.43E-02	7.24E-01	4.39E-01	6.38E+00	1.64E-01	3.79E-01	-1.89E+01	-1.82E+01	-1.94E+01	2.94E-01
64	1.26E-03	1.83E-01	5.28E-03	3.44E+00	2.73E-01	5.59E+00	4.95E+00	1.53E-01	4.96E+00	2.18E-01	8.65E+00	2.02E-01	2.38E-01	-1.83E+01	-1.71E+01	-1.97E+01	4.83E-01
65	1.53E-03	2.24E-01	3.76E-04	1.05E+00	3.19E-01	3.35E+00	1.07E+00	1.76E-01	2.85E-01	2.28E-01	1.18E+01	1.96E-01	2.09E-01	-1.70E+01	-1.90E+01	-2.04E+01	1.46E-01
66	5.00E-03	1.78E-01	7.47E-04	1.18E+00	1.57E-01	8.03E-01	8.39E+00	4.63E-02	1.14E-01	5.01E-01	8.35E+00	3.77E-01	6.38E-02	-1.86E+01	-1.84E+01	-2.17E+01	1.19E-01
67	5.44E-03	1.11E-01	2.18E-04	5.33E+00	8.01E-02	2.80E+00	9.84E+00	2.32E-01	7.00E-01	5.19E-01	9.10E+00	5.34E-01	8.90E-02	-1.76E+01	-1.87E+01	-1.92E+01	5.21E-01
68	2.40E-04	1.30E-01	5.11E-04	8.77E+00	2.24E-01	7.36E-01	9.48E+00	3.24E-02	1.32E-01	5.45E-01	8.94E+00	1.03E-01	1.77E-01	-1.78E+01	-1.82E+01	-2.02E+01	5.10E-01
69	1.67E-04	1.60E-01	3.61E-05	3.12E+00	5.68E-02	8.49E-01	4.75E+00	3.04E-02	3.81E+00	4.25E-02	9.26E+00	4.91E-01	1.57E-02	-1.73E+01	-1.84E+01	-1.86E+01	7.31E-01
70	9.37E-03	1.17E-01	7.84E-04	1.03E+00	1.35E-01	9.63E+00	4.23E+00	6.40E-02	1.60E-01	2.42E-01	6.97E+00	3.38E-01	3.27E-01	-1.89E+01	-1.86E+01	-2.09E+01	8.49E-01
71	2.39E-03	1.15E-01	3.60E-03	8.35E-01	2.15E-01	1.58E+00	2.63E+00	5.36E-02	1.64E+00	1.33E-01	8.76E+00	4.21E-01	3.82E-01	-1.75E+01	-1.92E+01	-2.10E+01	6.26E-01
72	5.58E-04	1.71E-01	1.15E-04	7.42E-01	1.08E-01	6.36E+00	9.02E-01	4.32E-02	8.35E+00	1.39E-01	6.72E+00	1.77E-01	3.12E-01	-1.75E+01	-1.82E+01	-2.02E+01	8.61E-01
73	3.58E-04	1.84E-01	7.79E-05	5.65E+00	8.28E-02	1.43E+00	5.30E+00	6.03E-02	2.41E+01	4.54E-01	5.74E+00	9.62E-02	1.16E-01	-1.84E+01	-1.88E+01	-1.91E+01	9.78E-01
74	2.41E-03	1.03E-01	6.55E-03	1.07E+00	1.12E-01	5.79E+00	2.41E+00	1.60E-01	2.02E+01	2.11E-01	9.87E+00	2.01E-02	3.17E-02	-1.79E+01	-1.82E+01	-1.95E+01	6.61E-01
75	2.91E-04	1.29E-01	5.92E-03	9.82E-01	1.23E-01	1.36E+00	1.09E+00	2.72E-01	1.23E+01	3.61E-01	7.32E+00	5.18E-01	1.77E-02	-1.72E+01	-1.80E+01	-1.89E+01	6.93E-01
76	6.75E-03	1.82E-01	4.51E-05	1.43E+00	5.16E-02	1.83E+00	1.17E+00	3.76E-01	3.33E+01	1.88E-01	7.60E+00	5.74E-02	3.46E-03	-1.94E+01	-1.89E+01	-2.19E+01	5.08E-02
77	8.04E-03	2.20E-01	1.21E-02	1.31E+00	3.07E-02	9.44E+00	4.06E+00	4.85E-02	1.11E+00	2.71E-01	7.95E+00	2.98E-01	6.86E-02	-1.73E+01	-1.81E+01	-1.98E+01	8.37E-01
78	4.36E-03	1.87E-01	1.32E-03	3.99E+00	2.56E-01	7.18E+00	9.70E+00	3.26E-01	1.71E+01	4.11E-01	6.47E+00	7.01E-02	1.38E-01	-1.75E+01	-1.71E+01	-1.89E+01	6.00E-01
79	4.70E-03	1.43E-01	1.70E-03	9.34E+00	2.35E-02	3.24E+00	8.22E-01	1.91E-01	3.77E+01	3.99E-01	1.93E+01	2.43E-02	3.01E-01	-1.81E+01	-1.74E+01	-1.99E+01	2.72E-01
80	2.96E-03	1.16E-01	3.40E-04	3.90E+00	7.13E-02	1.91E+00	2.65E+00	1.73E-01	5.25E-02	2.78E-01	1.29E+01	2.66E-01	2.36E-01	-1.71E+01	-1.77E+01	-1.94E+01	1.21E-01
81	1.02E-03	1.53E-01	1.10E-02	2.13E+00	9.58E-02	7.49E-01	4.79E+00	2.15E-02	6.18E+01	3.02E-01	6.57E+00	3.46E-02	7.50E-03	-1.83E+01	-1.86E+01	-2.14E+01	7.75E-01
82	8.84E-04	1.89E-01	2.52E-04	6.35E+00	1.78E-01	1.18E+00	2.50E+00	3.43E-02	3.49E-01	5.18E-02	1.04E+01	4.97E-01	1.50E-01	-1.90E+01	-1.87E+01	-2.15E+01	9.67E-01
83	5.22E-03	1.02E-01	1.88E-04	4.63E+00	3.55E-01	2.74E+00	2.12E+00	1.65E-01	3.02E+00	3.69E-01	5.80E+00	1.33E-01	1.25E-01	-1.84E+01	-1.72E+01	-2.11E+01	3.45E-01
84	2.20E-04	1.39E-01	9.71E-05	3.71E+00	8.95E-02	1.39E+00	3.45E+00	1.16E-01	1.47E+01	5.81E-01	9.52E+00	4.38E-01	3.85E-01	-1.81E+01	-1.85E+01	-2.03E+01	4.91E-01
85	1.83E-03	1.95E-01	3.86E-04	1.66E+00	6.72E-02	8.38E-01	5.66E+00	3.84E-02	7.41E+01	1.28E-01	6.68E+00	1.85E-01	3.64E-01	-1.78E+01	-1.84E+01	-2.06E+01	7.29E-01
86	8.72E-03	1.22E-01	1.25E-04	3.05E+00	3.33E-01	1.07E+00	7.98E+00	1.46E-01	2.40E+00	3.86E-01	6.64E+00	3.24E-01	1.73E-01	-1.78E+01	-1.88E+01	-2.00E+01	8.06E-01
87	2.53E-04	1.86E-01	3.19E-04	1.48E+00	3.82E-01	7.65E+00	9.66E-01	2.10E-02	2.72E+01	5.16E-01	5.06E+00	6.09E-02	9.80E-02	-1.79E+01	-1.86E+01	-1.96E+01	4.80E-01
88	1.47E-04	1.36E-01	6.58E-05	6.41E+00	1.20E-01	4.33E+00	7.41E-01	4.06E-02	1.47E-01	5.59E-01	1.08E+01	7.99E-02	1.94E-01	-1.77E+01	-1.89E+01	-1.91E+01	9.00E-01
89	2.08E-03	1.89E-01	1.61E-04	2.78E+00	2.09E-02	1.03E+00	8.46E-01	1.88E-01	4.10E+00	3.10E-01	8.02E+00	1.52E-01	1.82E-01	-1.82E+01	-1.82E+01	-2.02E+01	2.66E-01
90	2.09E-04	1.73E-01	8.02E-05	9.56E+00	8.75E-02	9.06E+00	1.78E+00	2.59E-01	2.73E+00	6.89E-02	4.89E+00	1.56E-01	2.28E-01	-1.78E+01	-1.83E+01	-2.01E+01	6.41E-01
91	7.30E-03	1.07E-01	2.87E-03	1.54E+00	2.02E-01	5.47E+00	2.18E+00	4.43E-02	3.55E+00	1.20E-01	1.16E+01	1.64E-01	3.35E-01	-1.85E+01	-1.89E+01	-1.87E+01	4.22E-01
92	6.71E-04	1.18E-01	9.79E-03	2.85E+00	1.31E-01	7.29E+00	6.51E+00	3.09E-02	5.81E-01	4.79E-01	7.69E+00	3.16E-01	1.99E-01	-1.97E+01	-1.85E+01	-1.83E+01	7.96E-01
93	7.58E-04	1.62E-01	2.47E-03	9.93E-01	1.50E-01	4.10E+00	4.45E+00	3.97E-01	8.05E-02	4.92E-01	6.41E+00	4.83E-02	1.16E-01	-1.99E+01	-1.84E+01	-2.10E+01	7.16E-01
94	1.22E-04	1.33E-01	8.81E-03	7.91E+00	2.82E-01	7.99E-01	5.95E+00	8.58E-02	8.92E-01	1.96E-01	6.92E+00	2.45E-01	1.68E-01	-1.85E+01	-1.86E+01	-2.04E+01	3.30E-03
95	1.31E-03	1.05E-01	4.76E-05	3.26E+00	3.55E-01	2.13E+00	3.06E+00	2.96E-01	9.43E-01	4.48E-01	7.42E+00	4.86E-01	7.49E-02	-1.91E+01	-1.78E+01	-1.87E+01	9.42E-01
96	5.14E-04	1.26E-01	7.06E-03	5.83E+00	2.43E-02	2.54E+00	1.44E+00	7.11E-02	2.18E+00	4.98E-02	7.62E+00	1.96E-01	2.55E-01	-1.71E+01	-1.91E+01	-2.12E+01	1.89E-01
97	1.06E-04	2.40E-01	6.54E-05	4.88E+00	6.87E-02	3.93E+00	3.33E+00	2.34E-02	1.09E-01	4.60E-01	6.61E+00	3.68E-01	5.31E-02	-1.87E+01	-1.78E+01	-2.08E+01	3.13E-01
98	5.63E-03	1.79E-01	4.19E-05	1.61E+00	2.03E-02	7.63E-01	1.48E+00	1.26E-01	2.32E-01	3.20E-01	7.19E+00	5.40E-01	1.63E-01	-1.76E+01	-1.79E+01	-1.93E+01	4.31E-01
99	7.24E-03	1.68E-01	3.67E-05	7.52E+00	3.71E-02	8.64E+00	6.15E+00	3.73E-02	2.69E-01	1.00E-01	7.75E+00	5.55E-02	1.59E-01	-1.80E+01	-1.76E+01	-2.21E+01	5.92E-01
100	9.43E-04	1.03E-01	7.27E-03	1.75E+00	8.50E-02	2.39E+00	2.82E+00	3.35E-01	6.52E+00	3.46E-01	1.45E+01	8.22E-02	1.21E-01	-1.77E+01	-1.75E+01	-1.95E+01	3.38E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
1	7.81E-15	1.00E+00	7.04E-09	1.26E-09	3.94E-01	1.46E-02	3.19E-01	2.99E-01	-1.99E+01	-1.86E+01	-4.10E-01	6.99E-02	3.37E-01	8.32E-02	4.08E-01	2.84E-02	-2.31E+01	1.34E-10	-1.75E+01	1.09E-11	4.00E+00	4.16E-02	9.74E-02	5.88E-01
2	1.80E-14	2.00E+00	5.94E-09	8.62E-10	5.39E-01	1.27E-01	2.10E-01	7.62E-01	-1.84E+01	-2.00E+01	-2.93E-01	7.66E-01	1.48E-01	3.12E-01	1.58E+00	2.25E-03	-2.39E+01	1.81E-10	-1.93E+01	1.65E-10	4.00E+00	7.49E-02	1.08E-01	5.43E-01
3	1.84E-14	2.00E+00	7.66E-10	1.63E-10	5.98E-01	8.24E-02	1.13E-01	8.09E-01	-2.02E+01	-2.02E+01	-4.88E-01	-2.83E-01	1.37E-01	7.97E-02	4.28E+00	8.30E-03	-2.39E+01	1.84E-10	-1.85E+01	2.21E-11	4.00E+00	9.27E-02	8.77E-02	6.78E-01
4	1.11E-15	0.00E+00	7.18E-09	8.09E-10	2.35E-02	6.58E-02	5.24E-01	6.13E-01	-1.87E+01	-1.94E+01	-1.16E-01	1.02E+00	3.14E-01	1.29E-01	3.91E+00	2.27E-03	-2.37E+01	1.66E-10	-1.93E+01	1.38E-10	4.00E+00	1.26E-01	8.05E-02	6.45E-01
5	1.61E-14	2.00E+00	9.47E-09	5.32E-10	4.07E-01	9.18E-02	1.51E-01	8.41E-01	-1.90E+01	-1.91E+01	-3.64E-01	1.86E-01	2.72E-02	6.46E-02	7.78E+00	2.23E-02	-2.20E+01	5.29E-11	-1.86E+01	5.60E-11	4.00E+00	8.35E-02	1.13E-01	6.22E-01
6	1.75E-14	0.00E+00	1.46E-09	2.73E-10	4.31E-01	1.23E-01	5.11E-01	9.68E-01	-1.89E+01	-1.88E+01	2.54E-02	-9.70E-02	3.99E-01	3.76E-01	4.00E+00	2.02E-02	-2.29E+01	1.23E-10	-1.99E+01	2.10E-10	4.00E+00	8.15E-02	2.78E-02	6.31E-01
7	2.39E-14	1.00E+00	8.21E-09	2.10E-10	6.64E-01	1.74E-02	1.93E-01	1.65E-01	-1.80E+01	-1.93E+01	-1.65E-02	-1.09E-01	3.32E-01	1.64E-04	5.06E-01	1.50E-02	-2.12E+01	1.80E-11	-1.96E+01	1.62E-10	1.00E+00	6.12E-02	1.14E-01	6.37E-01
8	1.48E-14	0.00E+00	3.25E-09	8.26E-10	3.08E-01	6.42E-02	2.04E-01	7.69E-02	-1.93E+01	-1.90E+01	1.27E-01	-7.69E-01	5.14E-02	5.45E-01	2.79E+00	6.07E-03	-2.30E+01	1.37E-10	-1.97E+01	1.92E-10	4.00E+00	5.72E-02	9.50E-02	5.69E-01
9	2.50E-15	1.00E+00	8.73E-09	6.36E-10	5.13E-01	1.12E-01	3.05E-01	1.34E-01	-1.94E+01	-1.81E+01	-3.38E-01	8.83E-01	2.88E-01	1.60E-01	5.05E+00	4.89E-03	-2.17E+01	4.51E-11	-2.01E+01	2.69E-10	4.00E+00	8.62E-02	9.97E-02	7.05E-01
10	1.50E-15	0.00E+00	5.77E-09	9.66E-10	7.27E-01	3.11E-02	4.38E-01	4.49E-01	-1.79E+01	-1.91E+01	3.69E-01	-2.45E-01	2.58E-01	2.19E-01	7.31E-01	1.01E-02	-2.28E+01	1.18E-10	-1.87E+01	5.92E-11	1.00E+00	1.10E-01	1.40E-02	5.54E-01
11	2.77E-14	1.00E+00	2.11E-09	1.00E-09	8.49E-01	1.97E-03	2.61E-01	4.91E-01	-2.03E+01	-1.94E+01	-6.66E-02	6.43E-01	1.34E-01	5.69E-01	7.49E+00	1.47E-02	-2.14E+01	2.61E-11	-1.91E+01	9.93E-11	4.00E+00	9.43E-02	3.40E-02	6.72E-01
12	1.57E-14	1.00E+00	2.91E-09	1.20E-09	7.43E-01	1.02E-01	3.48E-01	2.04E-01	-1.89E+01	-1.80E+01	-1.38E+00	1.56E-01	3.75E-01	5.11E-01	1.11E+00	1.61E-02	-2.24E+01	1.05E-10	-1.84E+01	2.91E-11	4.00E+00	9.36E-02	5.99E-02	6.95E-01
13	6.99E-15	2.00E+00	5.85E-09	7.10E-10	4.95E-01	6.78E-02	2.30E-01	3.62E-01	-1.85E+01	-1.77E+01	-5.86E-02	5.80E-03	1.26E-01	3.07E-01	1.73E+00	1.10E-02	-2.32E+01	1.41E-10	-1.94E+01	1.35E-10	1.00E+00	5.52E-02	1.01E-01	6.58E-01
14	1.50E-14	0.00E+00	3.78E-09	1.18E-09	7.51E-01	1.94E-02	3.43E-02	4.21E-01	-1.75E+01	-1.96E+01	-1.16E+00	1.16E-01	2.08E-01	4.58E-01	5.58E-01	1.40E-03	-2.23E+01	7.24E-11	-1.83E+01	1.09E-11	1.00E+00	7.78E-03	9.09E-02	6.05E-01
15	1.66E-14	0.00E+00	5.70E-09	5.97E-10	9.73E-01	3.74E-02	4.60E-01	7.19E-01	-1.97E+01	-1.94E+01	-1.96E-01	-9.35E-03	2.09E-01	2.10E-01	3.44E-01	2.54E-02	-2.24E+01	8.22E-11	-1.81E+01	1.09E-11	1.00E+00	9.18E-02	1.31E-01	6.19E-01
16	1.75E-15	2.00E+00	6.59E-09	1.47E-10	7.91E-01	1.02E-01	1.29E-01	6.95E-01	-2.03E+01	-1.77E+01	-2.14E-01	-1.17E+00	4.49E-02	2.42E-01	2.50E+00	7.89E-03	-2.14E+01	2.83E-11	-1.93E+01	1.32E-10	4.00E+00	6.88E-02	3.83E-02	6.88E-01
17	9.22E-15	2.00E+00	9.01E-09	1.16E-10	4.50E-01	5.04E-02	1.97E-01	1.04E-01	-1.86E+01	-1.77E+01	-1.62E-01	-1.89E-01	1.50E-02	4.93E-01	3.84E-01	2.79E-02	-2.23E+01	9.34E-11	-1.90E+01	1.04E-10	4.00E+00	1.04E-01	7.78E-02	6.70E-01
18	2.74E-14	0.00E+00	4.05E-09	8.72E-10	1.94E-01	2.61E-02	1.00E-01	1.74E-01	-1.82E+01	-1.85E+01	5.34E-01	3.89E-01	1.68E-01	5.52E-02	4.27E-01	6.93E-03	-2.38E+01	1.79E-10	-1.90E+01	1.07E-10	1.00E+00	1.42E-01	6.30E-02	6.90E-01
19	3.03E-15	0.00E+00	5.31E-09	1.09E-10	2.26E-01	3.76E-02	7.91E-02	9.41E-01	-1.83E+01	-1.88E+01	3.03E-01	1.21E-01	7.83E-02	3.59E-01	6.66E+00	7.35E-03	-2.17E+01	6.99E-11	-1.88E+01	6.96E-11	1.00E+00	9.71E-02	1.21E-01	5.26E-01
20	2.43E-14	2.00E+00	7.60E-09	4.74E-10	4.61E-01	8.67E-02	3.67E-01	2.35E-01	-1.83E+01	-1.90E+01	-1.91E-01	-4.00E-01	3.43E-01	3.41E-01	4.12E+00	9.58E-03	-2.36E+01	1.75E-10	-2.00E+01	2.50E-10	1.00E+00	5.46E-02	9.80E-02	5.92E-01
21	5.43E-16	0.00E+00	6.42E-09	4.63E-10	5.51E-01	1.33E-01	4.04E-01	6.24E-01	-1.92E+01	-1.85E+01	-7.03E-03	-6.82E-01	2.18E-01	1.41E-01	7.22E-01	2.47E-03	-2.15E+01	3.36E-11	-1.89E+01	1.05E-10	1.00E+00	8.07E-02	7.16E-02	6.28E-01
22	6.63E-15	0.00E+00	3.62E-09	9.40E-10	5.72E-01	1.06E-01	4.24E-01	5.97E-01	-1.96E+01	-1.93E+01	-1.02E-01	-1.84E-01	2.56E-01	1.65E-01	2.37E-01	5.67E-03	-2.38E+01	1.77E-10	-1.87E+01	3.72E-11	4.00E+00	2.78E-02	1.04E-01	6.01E-01
23	1.98E-14	2.00E+00	4.18E-09	3.12E-10	3.57E-01	9.06E-02	5.36E-01	3.72E-02	-1.82E+01	-2.05E+01	-3.85E-01	7.08E-01	2.64E-01	4.55E-01	5.49E+00	9.92E-03	-2.15E+01	4.20E-11	-1.91E+01	1.16E-10	1.00E+00	7.39E-02	1.03E-01	7.08E-01
24	1.71E-14	0.00E+00	4.29E-09	5.58E-10	4.77E-01	5.14E-02	4.98E-01	5.20E-01	-1.91E+01	-1.95E+01	-1.50E-01	-2.19E-01	3.82E-01	1.37E-01	9.04E-01	4.99E-03	-2.31E+01	1.25E-10	-1.88E+01	9.61E-11	4.00E+00	7.75E-02	7.18E-02	7.10E-01
25	2.61E-14	0.00E+00	6.38E-09	5.95E-10	1.33E-01	8.70E-02	2.54E-01	3.14E-01	-1.93E+01	-1.83E+01	8.22E-02	-5.18E-03	6.96E-02	5.29E-01	1.78E-01	1.83E-02	-2.38E+01	1.87E-10	-1.84E+01	1.79E-11	4.00E+00	1.23E-01	1.01E-01	5.95E-01
26	3.17E-14	1.00E+00	5.61E-09	3.69E-10	8.82E-01	1.43E-01	4.30E-01	3.03E-01	-1.88E+01	-1.74E+01	-3.45E-01	-1.24E-01	2.66E-01	1.53E-01	1.38E+00	2.92E-03	-2.18E+01	4.04E-11	-1.83E+01	1.09E-11	1.00E+00	1.19E-01	8.22E-02	6.38E-01
27	9.53E-15	1.00E+00	7.34E-09	1.25E-09	6.57E-01	4.22E-02	1.47E-01	9.16E-01	-1.79E+01	-1.74E+01	1.74E-01	9.85E-01	2.97E-01	9.99E-02	4.45E-01	3.27E-03	-2.26E+01	1.02E-10	-1.96E+01	1.83E-10	4.00E+00	9.95E-02	7.45E-02	6.57E-01
28	1.38E-14	2.00E+00	8.33E-09	3.54E-10	8.92E-01	1.28E-01	3.95E-01	9.37E-01	-2.02E+01	-1.79E+01	1.17E+00	-7.99E-01	3.58E-01	4.08E-01	3.72E-01	9.00E-03	-2.18E+01	4.27E-11	-1.97E+01	1.96E-10	1.00E+00	7.84E-02	1.06E-01	6.43E-01
29	2.66E-14	1.00E+00	3.52E-09	9.96E-10	7.88E-01	1.17E-01	9.87E-02	7.36E-01	-1.86E+01	-1.85E+01	1.54E-01	2.43E-01	2.90E-01	2.24E-01	8.73E-01	1.65E-02	-2.33E+01	1.55E-10	-1.89E+01	7.43E-11	1.00E+00	1.32E-01	5.88E-02	6.29E-01
30	2.47E-14	0.00E+00	3.99E-09	9.38E-11	3.49E-02	6.00E-02	5.32E-01	2.89E-01	-1.92E+01	-2.01E+01	-9.28E-01	5.76E-02	2.95E-01	5.16E-01	3.50E+00	2.17E-02	-2.35E+01	1.56E-10	-1.78E+01	1.09E-11	1.00E+00	7.66E-02	1.45E-02	6.55E-01
31	2.36E-14	1.00E+00	6.07E-09	5.64E-10	9.30E-01	1.43E-03	3.41E-01	4.89E-01	-1.90E+01	-1.98E+01	-3.06E-01	-3.18E-01	2.29E-01	1.01E-01	8.31E-01	1.38E-02	-2.39E+01	1.89E-10	-1.95E+01	1.75E-10	4.00E+00	6.37E-02	9.24E-02	6.82E-01
32	2.27E-14	0.00E+00	2.22E-09	1.24E-09	9.25E-02	8.93E-02	2.89E-01	4.61E-01	-1.98E+01	-1.88E+01	2.13E-01	-6.88E-02	1.32E-01	3.27E-02	3.57E+00	9.80E-03	-2.32E+01	1.39E-10	-1.81E+01	1.09E-11	4.00E+00	8.01E-02	1.07E-01	6.42E-01
33	2.20E-14	0.00E+00	2.53E-09	6.76E-10	6.38E-01	1.04E-01	1.69E-01	5.41E-02	-2.00E+01	-1.96E+01	4.45E-01	-2.55E-01	1.91E-01	4.43E-01	6.80E-01	2.34E-02	-2.19E+01	6.71E-11	-1.95E+01	1.71E-10	1.00E+00	7.90E-02	5.72E-02	6.24E-01
34	2.02E-14	0.00E+00	2.39E-09	4.30E-10	3.32E-01	7.42E-03	2.99E-01	8.63E-02	-1.79E+01	-1.80E+01	-8.72E-02	-3.91E-01	3.07E-01	4.17E-01	2.84E+00	1.06E-03	-2.11E+01	1.23E-11	-1.80E+01	1.09E-11	4.00E+00	6.60E-02	4.80E-02	6.86E-01
35	8.32E-15	0.00E+00	1.40E-09	2.98E-11	4.21E-01	1.08E-01	1.21E-01	5.83E-01	-1.94E+01	-1.76E+01	-2.17E-01	3.03E-02	2.46E-01	1.88E-01	6.24E-01	2.61E-02	-2.18E+01	7.48E-11	-1.88E+01	6.67E-11	1.00E+00	7.61E-02	8.52E-02	6.67E-01
36	1.22E-14	0.00E+00	9.20E-09	1.22E-09	3.29E-01	7.86E-02	2.96E-01	3.49E-01	-1.95E+01	-1.91E+01	-4.58E-01	-2.10E-01	2.32E-01	5.01E-01	7.44E-01	1.72E-02	-2.12E+01	1.25E-11	-1.72E+01	1.09E-11	1.00E+00	8.85E-02	8.35E-02	6.32E-01
37	1.88E-14	0.00E+00	7.57E-09	9.81E-10	2.51E-01	4.03E-02	1.36E-01	6.68E-01	-1.88E+01	-1.93E+01	8.09E-01	-1.62E-01	8.96E-02	5.22E-01	6.50E+00	8.04E-03	-2.19E+01	5.81E-11	-1.87E+01	4.52E-11	4.00E+00	5.19E-02	7.89E-02	7.36E-01
38	2.86E-14	0.00E+00	2.48E-09	2.28E-10	9.82E-01	2.91E-02	3.84E-01	6.05E-01	-1.81E+01	-1.76E+01	4.88E-01	3.03E-01	2.20E-01	3.71E-01	2.14E-01	8.79E-03	-2.24E+01	8.42E-11	-1.86E+01	2.63E-11	1.00E+00	7.18E-02	8.66E-02	6.14E-01
39	1.15E-16	0.00E+00	4.75E-09	6.89E-10	2.88E-01	8.44E-03	3.23E-01	8.68E-01	-2.04E+01	-1.84E+01	-6.65E-01	1.72E-01	1.23E-01	1.48E-01	6.64E-01	7.18E-03	-2.34E+01	1.59E-10	-1.87E+01	4.38E-11	1.00E+00	8.94E-02	5.75E-02	5.73E-01
40	2.95E-14	1.00E+00	1.71E-09	5.11E-10	5.44E-01	9.63E-02	4.88E-01	1.59E-01	-1.92E+01	-1.92E+01	2.94E-01	-1.95E-02	1.59E-01	1.69E-01	8.51E-01	1.98E-02	-2.13E+01	2.11E-11	-2.07E+01	2.75E-10	4.00E+00	7.12E-02	7.64E-02	4.91E-01
41	9.14E-16	0.00E+00	8.25E-09	1.18E-09	3.18E-01	4.62E-02	4.84E-01	7.90E-01	-1.85E+01	-1.81E+01	2.38E-01	1.37E-01	1.07E-01	1.10E-01	3.35E+00	2.50E-02	-2.28E+01	1.26E-10	-1.90E+01	8.46E-11	1.00E+00	9.09E-02	5.57E-02	6.06E-01
42	3.00E-14	1.00E+00	3.32E-09	1.11E-09	3.46E-01	1.23E-01	6.82E-02	2.12E-01	-1.92E+01	-1.82E+01	-7.57E-01	-1.80E+00	4.07E-02	3.45E-01	5.21E+00	1.93E-02	-2.23E+01	9.98E-11	-1.90E+01	9.31E-11	1.00E+00	1.74E-01	6.13E-02	6.18E-01
43	1.42E-14	1.00E+00	9.68E-10	5.77E-10	5.30E-01	8.54E-02	1.14E-02	3.23E-01	-1.88E+01	-1.89E+01	-4.44E-01	5.75E-01	2.00E-02	2.64E-02	3.74E+00	5.30E-03	-2.33E+01	1.51E-10	-1.85E+01	6.18E-11	1.00E+00	8.07E-02	4.59E-02	6.13E-01
44	2.17E-15	0.00E+00	5.13E-09	5.54E-11	5.81E-01	2.01E-02	1.73E-01	1.46E-02	-1.95E+01	-1.81E+01	-1.85E-01	2.82E-01	1.70E-01	2.90E-01	7.08E+00	2.87E-02	-2.29E+01	1.14E-10	-1.88E+01	7.60E-11	1.00E+00	9.78E-02	1.36E-01	7.94E-01
45	2.24E-14	0.00E+00	8.41E-09	5.00E-10	3.75E-01	1.21E-01	1.40E-01	2.64E-01	-1.72E+01	-1.83E+01	-2.34E-02	5.49E-01	6.07E-02	3.33E-01	8.85E-01	1.89E-02	-2.13E+01	1.81E-11	-1.92E+01	1.27E-10	4.00E+00	4.74E-02	6.88E-02	5.78E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
46	2.57E-14	1.00E+00	1.20E-09	6.34E-10	6.14E-01	9.51E-02	4.67E-01	8.23E-01	-1.91E+01	-1.82E+01	1.32E-01	1.82E-02	2.40E-01	2.98E-01	8.19E-01	2.10E-02	-2.20E+01	8.47E-11	-1.86E+01	6.10E-11	1.00E+00	6.21E-02	5.34E-02	6.99E-01
47	6.85E-15	0.00E+00	4.62E-09	7.39E-10	1.16E-01	3.57E-02	4.89E-02	1.73E-03	-1.87E+01	-1.78E+01	-1.34E-01	-2.31E-01	2.49E-01	1.97E-01	4.79E+00	7.67E-03	-2.35E+01	1.65E-10	-1.92E+01	1.24E-10	1.00E+00	1.73E-02	7.37E-02	6.49E-01
48	1.64E-14	2.00E+00	8.08E-09	1.55E-13	7.13E-01	4.91E-02	4.09E-01	1.22E-01	-1.91E+01	-1.93E+01	5.46E-02	-1.73E-01	8.15E-02	1.76E-01	3.17E-01	5.94E-03	-2.24E+01	7.93E-11	-1.91E+01	1.14E-10	1.00E+00	8.29E-02	8.93E-02	7.21E-01
49	1.43E-14	1.00E+00	2.63E-09	1.10E-09	1.84E-01	7.58E-02	1.82E-01	4.57E-01	-1.87E+01	-1.78E+01	2.00E-01	-3.37E-02	3.25E-01	1.89E-01	2.64E-01	2.92E-02	-2.32E+01	1.45E-10	-1.86E+01	6.63E-11	4.00E+00	1.09E-01	9.16E-02	6.63E-01
50	7.31E-15	0.00E+00	4.49E-09	3.64E-10	8.86E-02	1.15E-01	5.51E-01	2.40E-02	-1.77E+01	-1.79E+01	-5.52E-01	-9.15E-01	9.65E-03	3.23E-01	8.03E-01	3.61E-03	-2.38E+01	1.76E-10	-1.85E+01	4.07E-11	1.00E+00	1.18E-01	7.50E-02	5.82E-01
51	1.19E-14	0.00E+00	6.73E-09	6.63E-10	9.17E-01	1.17E-01	5.25E-01	7.53E-01	-1.86E+01	-1.89E+01	6.76E-01	-1.53E-01	2.80E-01	5.87E-01	5.71E-01	1.05E-02	-2.35E+01	1.60E-10	-1.89E+01	8.78E-11	4.00E+00	1.15E-01	6.28E-02	6.69E-01
52	9.14E-15	2.00E+00	2.27E-09	3.37E-10	7.71E-01	5.70E-02	4.76E-01	1.92E-01	-1.82E+01	-1.83E+01	7.48E-01	9.00E-01	1.74E-01	1.34E-01	4.87E+00	5.70E-03	-2.36E+01	1.70E-10	-1.79E+01	1.09E-11	1.00E+00	4.58E-02	5.44E-02	7.27E-01
53	2.47E-14	0.00E+00	9.35E-09	2.38E-11	7.20E-02	1.13E-01	3.12E-01	8.82E-01	-1.96E+01	-1.86E+01	-2.78E-01	-1.41E-01	8.54E-02	4.70E-03	1.85E+00	2.14E-02	-2.30E+01	1.40E-10	-1.83E+01	1.09E-11	4.00E+00	6.69E-02	6.47E-02	7.34E-01
54	1.00E-14	0.00E+00	7.71E-09	9.11E-10	5.65E-01	1.46E-01	2.11E-02	3.76E-01	-1.85E+01	-2.00E+01	-2.26E-01	-4.78E-01	3.18E-01	2.02E-01	5.31E+00	1.22E-02	-2.22E+01	8.92E-11	-1.81E+01	1.09E-11	4.00E+00	1.02E-01	7.81E-02	5.97E-01
55	1.72E-14	1.00E+00	3.37E-09	3.85E-10	2.67E-01	1.30E-01	2.82E-01	2.42E-01	-1.95E+01	-1.95E+01	-2.34E-01	-4.18E-02	3.79E-01	4.76E-01	2.06E+00	1.71E-03	-2.11E+01	3.78E-12	-1.94E+01	1.25E-10	4.00E+00	1.06E-01	8.43E-02	6.83E-01
56	2.78E-15	2.00E+00	1.91E-09	1.16E-09	8.14E-01	1.09E-01	8.83E-02	5.51E-01	-1.88E+01	-1.97E+01	-1.80E-01	-5.89E-01	3.97E-02	1.50E-01	2.50E-01	8.52E-03	-2.20E+01	6.31E-11	-2.02E+01	2.75E-10	1.00E+00	8.42E-02	4.97E-02	6.80E-01
57	3.01E-14	0.00E+00	5.49E-09	1.09E-09	7.65E-01	1.37E-01	2.42E-01	9.65E-02	-1.93E+01	-1.94E+01	2.43E-01	-5.33E-02	3.72E-01	2.63E-01	6.93E+00	2.64E-02	-2.27E+01	9.37E-11	-1.88E+01	7.35E-11	1.00E+00	8.42E-02	1.09E-01	5.48E-01
58	5.96E-15	1.00E+00	5.04E-10	1.13E-09	4.74E-02	4.08E-02	3.63E-01	5.08E-01	-1.84E+01	-1.90E+01	1.29E-02	-8.72E-01	9.94E-02	4.87E-02	4.80E-01	4.03E-03	-2.33E+01	1.44E-10	-1.91E+01	9.73E-11	4.00E+00	1.13E-01	1.44E-01	7.70E-01
59	8.15E-15	0.00E+00	6.48E-10	9.60E-10	1.23E-01	5.71E-02	4.57E-01	7.47E-01	-1.78E+01	-1.87E+01	1.82E-01	-5.53E-01	3.03E-02	2.71E-01	1.65E-01	8.59E-03	-2.10E+01	5.69E-12	-1.86E+01	3.93E-11	4.00E+00	7.01E-02	1.97E-01	6.75E-01
60	1.95E-14	2.00E+00	5.05E-09	1.14E-09	6.07E-01	1.19E-01	5.07E-01	8.30E-01	-1.81E+01	-1.89E+01	8.34E-02	-1.27E-01	1.77E-01	6.01E-02	7.53E+00	2.47E-02	-2.16E+01	7.50E-11	-1.88E+01	5.31E-11	1.00E+00	6.96E-02	3.57E-02	6.73E-01
61	1.07E-14	0.00E+00	7.81E-09	1.15E-09	3.61E-01	1.31E-01	3.33E-01	7.23E-01	-1.86E+01	-1.81E+01	-4.12E-01	-2.01E-01	2.71E-01	1.25E-01	4.63E+00	1.13E-02	-2.25E+01	1.07E-10	-1.93E+01	1.44E-10	1.00E+00	6.00E-02	9.37E-02	7.16E-01
62	5.28E-15	0.00E+00	2.72E-09	9.32E-10	2.19E-01	1.47E-01	3.09E-02	4.71E-02	-1.88E+01	-1.98E+01	5.99E-01	-7.77E-02	3.61E-01	4.25E-01	5.71E+00	1.88E-02	-2.35E+01	1.48E-10	-1.95E+01	1.47E-10	4.00E+00	8.20E-02	4.95E-02	8.12E-01
63	1.28E-14	1.00E+00	1.14E-09	4.86E-10	7.36E-01	1.41E-01	5.44E-01	3.56E-01	-1.84E+01	-1.89E+01	-2.40E-01	1.92E-01	1.48E-01	9.56E-03	7.94E+00	5.49E-03	-2.19E+01	5.04E-11	-1.82E+01	1.09E-11	1.00E+00	4.33E-02	1.11E-01	6.39E-01
64	2.82E-14	0.00E+00	4.70E-09	7.19E-10	9.56E-01	2.55E-02	5.63E-02	6.38E-01	-1.89E+01	-2.02E+01	1.57E-01	-6.08E-02	6.57E-03	1.74E-01	3.23E+00	2.30E-02	-2.21E+01	9.05E-11	-1.98E+01	2.23E-10	1.00E+00	1.06E-01	1.18E-01	6.65E-01
65	1.81E-14	1.00E+00	6.94E-09	4.52E-10	4.46E-01	5.30E-02	1.55E-01	9.09E-01	-1.94E+01	-1.97E+01	9.95E-01	-2.91E-01	9.41E-02	2.84E-01	9.09E-01	3.79E-03	-2.13E+01	2.54E-11	-1.84E+01	3.40E-11	4.00E+00	9.88E-02	4.23E-02	6.55E-01
66	2.66E-14	2.00E+00	7.98E-10	7.90E-10	9.21E-01	9.52E-03	4.97E-01	1.88E-01	-1.85E+01	-1.84E+01	-2.46E-01	-2.27E-01	6.77E-02	2.80E-01	2.98E+00	3.02E-03	-2.26E+01	7.72E-11	-1.92E+01	9.42E-11	4.00E+00	9.02E-02	8.14E-02	5.36E-01
67	1.08E-14	0.00E+00	3.66E-10	1.70E-10	7.02E-01	2.75E-02	2.11E-01	9.97E-01	-1.84E+01	-1.80E+01	-7.12E-01	-3.52E-01	3.48E-01	5.38E-01	6.18E+00	1.43E-02	-2.34E+01	1.53E-10	-1.92E+01	1.54E-10	4.00E+00	3.74E-02	8.58E-02	6.34E-01
68	4.66E-15	2.00E+00	6.26E-09	1.06E-09	9.90E-01	4.69E-02	7.66E-02	4.40E-01	-1.95E+01	-1.84E+01	-4.55E-02	-1.36E-01	3.52E-01	3.93E-01	1.30E+00	1.30E-02	-2.37E+01	1.72E-10	-1.82E+01	1.29E-11	1.00E+00	7.56E-02	2.05E-02	6.53E-01
69	2.52E-14	0.00E+00	5.43E-09	1.03E-09	9.01E-01	6.63E-02	3.26E-01	6.60E-02	-2.01E+01	-1.91E+01	-3.94E-02	-3.58E-01	2.43E-01	4.55E-02	2.53E+00	6.67E-03	-2.25E+01	1.03E-10	-1.85E+01	4.77E-11	4.00E+00	9.65E-02	1.26E-01	6.60E-01
70	2.54E-14	2.00E+00	4.88E-09	1.08E-09	6.24E-02	7.05E-02	3.89E-01	8.10E-01	-1.88E+01	-1.71E+01	-1.74E+00	-4.90E-01	3.03E-01	5.60E-01	4.41E+00	2.06E-02	-2.22E+01	5.42E-11	-1.94E+01	1.40E-10	1.00E+00	5.95E-02	7.94E-02	6.51E-01
71	2.81E-14	0.00E+00	2.86E-09	1.83E-10	2.92E-01	3.22E-02	1.07E-01	1.11E-01	-1.90E+01	-1.88E+01	-8.72E-01	1.44E-01	3.85E-01	2.18E-02	1.37E-01	1.56E-02	-2.25E+01	9.76E-11	-2.10E+01	2.75E-10	1.00E+00	1.24E-01	4.36E-02	6.23E-01
72	3.61E-15	2.00E+00	7.49E-09	1.03E-09	1.46E-01	8.04E-02	5.18E-01	6.86E-01	-1.97E+01	-2.03E+01	-9.79E-01	-2.38E-01	2.14E-01	1.84E-01	4.20E-01	1.17E-02	-2.10E+01	8.27E-12	-1.93E+01	1.57E-10	1.00E+00	1.02E-01	6.58E-02	6.47E-01
73	3.05E-14	0.00E+00	6.87E-09	7.59E-10	5.42E-02	1.25E-01	3.47E-01	5.65E-01	-1.97E+01	-1.79E+01	3.95E-02	6.73E-01	7.27E-02	5.98E-02	6.52E-01	9.32E-03	-2.31E+01	1.19E-10	-1.96E+01	1.78E-10	1.00E+00	7.38E-02	1.40E-02	6.87E-01
74	2.14E-14	1.00E+00	8.86E-09	2.49E-10	8.09E-01	7.72E-02	4.70E-01	8.74E-01	-1.74E+01	-1.96E+01	-1.06E-01	-1.76E-01	2.82E-01	1.23E-01	2.76E-01	1.60E-02	-2.40E+01	1.86E-10	-1.84E+01	1.09E-11	4.00E+00	8.79E-02	4.41E-02	7.45E-01
75	2.92E-14	0.00E+00	8.53E-09	8.20E-10	9.44E-01	8.26E-02	4.44E-01	9.83E-01	-1.83E+01	-1.87E+01	-1.78E+00	-6.25E-01	1.87E-01	1.05E-01	7.83E-01	3.36E-03	-2.36E+01	1.62E-10	-1.98E+01	2.21E-10	4.00E+00	1.00E-01	8.87E-02	6.52E-01
76	2.18E-14	2.00E+00	4.37E-09	7.13E-11	1.54E-01	2.31E-02	4.33E-01	5.39E-01	-1.82E+01	-1.89E+01	-1.42E-01	-2.07E-01	1.17E-01	2.54E-01	6.75E+00	2.94E-02	-2.33E+01	1.49E-10	-1.90E+01	1.02E-10	4.00E+00	1.01E-01	3.93E-02	5.85E-01
77	3.08E-14	2.00E+00	8.90E-09	8.42E-10	2.74E-01	7.48E-02	4.17E-01	3.33E-01	-1.98E+01	-1.85E+01	7.59E-01	-1.50E-01	5.94E-02	4.35E-01	5.37E-01	1.70E-02	-2.30E+01	1.15E-10	-1.78E+01	1.09E-11	4.00E+00	5.24E-02	1.32E-01	6.49E-01
78	1.92E-14	2.00E+00	3.06E-09	6.54E-10	8.44E-04	1.13E-02	6.57E-02	9.26E-01	-1.73E+01	-1.85E+01	-9.05E-02	-9.95E-01	3.55E-01	6.95E-02	7.31E+00	2.26E-02	-2.17E+01	3.77E-11	-1.85E+01	3.19E-11	4.00E+00	1.35E-01	1.16E-01	6.11E-01
79	2.04E-14	0.00E+00	6.81E-09	4.96E-11	2.41E-01	1.10E-01	4.11E-02	7.03E-01	-1.81E+01	-1.98E+01	-1.21E-01	-4.50E-01	3.95E-01	5.59E-01	6.26E-01	2.72E-03	-2.16E+01	4.87E-11	-1.71E+01	1.09E-11	1.00E+00	7.27E-02	5.17E-02	6.61E-01
80	3.13E-14	0.00E+00	9.28E-09	2.57E-10	1.67E-01	9.40E-02	1.85E-01	4.75E-01	-1.89E+01	-1.82E+01	-2.54E-01	7.91E-02	3.30E-01	7.40E-02	4.73E-01	4.18E-03	-2.17E+01	6.88E-11	-1.89E+01	8.23E-11	1.00E+00	6.73E-02	6.95E-02	5.94E-01
81	1.11E-14	2.00E+00	8.04E-09	5.36E-10	6.20E-01	1.25E-02	4.01E-01	8.52E-01	-1.77E+01	-1.96E+01	-2.47E-03	2.17E-01	2.25E-01	9.11E-02	7.13E+00	4.42E-03	-2.11E+01	9.74E-12	-1.89E+01	8.43E-11	1.00E+00	9.49E-02	7.65E-02	6.29E-01
82	8.62E-15	1.00E+00	4.09E-09	6.10E-10	8.30E-01	1.34E-01	2.34E-01	6.51E-01	-1.77E+01	-1.86E+01	9.15E-01	-1.50E+00	1.98E-01	1.60E-01	8.05E+00	1.36E-02	-2.40E+01	1.91E-10	-1.89E+01	9.07E-11	4.00E+00	8.71E-02	9.62E-02	6.26E-01
83	4.32E-15	2.00E+00	2.03E-09	7.33E-10	6.42E-01	1.39E-01	1.26E-01	7.86E-01	-1.80E+01	-1.86E+01	-5.23E-02	9.20E-02	3.23E-01	9.59E-02	1.94E-01	2.69E-02	-2.15E+01	3.68E-11	-1.90E+01	8.82E-11	4.00E+00	8.77E-02	9.46E-02	6.76E-01
84	2.94E-14	1.00E+00	8.63E-09	1.21E-09	4.12E-01	7.16E-02	2.20E-01	9.00E-01	-1.89E+01	-1.87E+01	-6.95E-02	4.35E-02	2.12E-02	5.82E-01	9.25E-01	1.34E-03	-2.26E+01	1.09E-10	-1.86E+01	5.42E-11	4.00E+00	1.08E-01	6.71E-02	7.53E-01
85	2.09E-14	0.00E+00	1.83E-09	7.73E-10	8.52E-01	7.25E-02	3.54E-01	6.70E-01	-1.76E+01	-1.87E+01	-4.81E-01	-2.74E-02	3.49E-02	1.16E-01	2.19E+00	2.98E-02	-2.16E+01	3.17E-11	-1.91E+01	1.22E-10	4.00E+00	4.91E-02	7.29E-02	7.02E-01
86	2.33E-14	2.00E+00	1.66E-09	1.05E-09	4.85E-01	2.13E-02	2.79E-01	2.59E-01	-1.80E+01	-1.88E+01	6.76E-02	-1.66E+00	2.03E-01	1.63E-02	5.96E-01	4.45E-03	-2.22E+01	8.79E-11	-1.91E+01	1.20E-10	4.00E+00	8.55E-02	5.30E-02	6.97E-01
87	3.98E-15	0.00E+00	6.56E-09	4.12E-10	8.73E-01	9.81E-02	4.50E-01	2.77E-01	-1.83E+01	-1.91E+01	-1.58E-01	-8.98E-02	1.50E-03	3.65E-01	6.36E+00	9.23E-03	-2.21E+01	5.73E-11	-1.88E+01	7.88E-11	1.00E+00	1.12E-01	3.13E-02	5.86E-01
88	2.29E-14	0.00E+00	1.53E-09	4.41E-10	2.34E-01	1.44E-01	2.26E-03	9.58E-01	-1.90E+01	-1.89E+01	2.90E-03	1.03E-01	1.92E-01	3.85E-01	1.06E+00	6.28E-03	-2.28E+01	1.29E-10	-1.90E+01	7.95E-11	1.00E+00	6.43E-02	1.24E-01	6.44E-01
89	6.22E-15	1.00E+00	6.14E-09	9.16E-10	2.01E-01	1.42E-01	3.77E-01	2.21E-01	-1.81E+01	-2.04E+01	2.25E-01	-1.14E-01	1.08E-01	1.17E-01	1.44E-01	2.43E-02	-2.19E+01	6.49E-11	-1.94E+01	1.32E-10	4.00E+00	2.98E-02	1.40E-02	5.60E-01
90	3.46E-15	0.00E+00	8.81E-10	7.76E-10	9.66E-01	1.00E-01	1.61E-01	4.04E-01	-1.78E+01	-1.92E+01	-8.31E-01	8.44E-01	1.42E-01	4.67E-01	7.69E-01	2.38E-02	-2.13E+01	2.21E-11	-1.84E+01	2.27E-11	4.00E+00	1.54E-01	9.02E-02	6.41E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
91	1.24E-14	0.00E+00	5.21E-09	4.04E-10	6.94E-01	4.64E-03	2.74E-01	3.96E-01	-1.92E+01	-1.75E+01	6.40E-01	-4.19E-01	3.09E-01	1.34E-02	5.99E+00	4.65E-03	-2.14E+01	2.94E-11	-1.87E+01	6.42E-11	4.00E+00	9.05E-02	2.35E-02	5.67E-01
92	2.72E-14	1.00E+00	3.10E-09	8.79E-10	1.79E-01	6.19E-02	8.99E-02	7.75E-01	-1.99E+01	-1.87E+01	-3.45E-02	4.80E-01	5.39E-02	4.20E-02	5.55E+00	2.06E-03	-2.27E+01	1.11E-10	-1.92E+01	1.11E-10	1.00E+00	5.81E-02	1.40E-02	6.36E-01
93	1.31E-14	2.00E+00	7.24E-09	8.94E-10	6.82E-01	5.50E-02	2.61E-02	3.89E-01	-1.91E+01	-1.92E+01	-1.32E-01	-3.29E-01	3.67E-01	3.91E-02	2.32E+00	2.73E-02	-2.21E+01	4.71E-11	-1.80E+01	1.09E-11	1.00E+00	7.07E-02	6.44E-02	6.09E-01
94	1.52E-14	1.00E+00	3.87E-09	2.40E-10	8.37E-01	5.98E-02	2.68E-01	5.73E-01	-1.93E+01	-1.90E+01	1.03E-01	-9.91E-02	1.62E-01	8.66E-02	3.29E-01	1.77E-02	-2.12E+01	1.52E-11	-1.83E+01	1.45E-11	4.00E+00	9.33E-02	8.25E-02	7.14E-01
95	5.51E-15	2.00E+00	3.72E-09	1.98E-10	6.75E-01	1.35E-01	2.51E-01	4.14E-01	-1.87E+01	-1.84E+01	-2.05E-01	2.14E-01	1.52E-01	2.34E-01	5.79E-01	1.80E-03	-2.27E+01	1.20E-10	-1.87E+01	7.19E-11	1.00E+00	1.05E-01	1.61E-01	6.20E-01
96	1.02E-14	0.00E+00	7.92E-09	2.95E-10	5.00E-01	3.30E-02	5.10E-02	5.43E-01	-1.75E+01	-1.99E+01	-5.96E-01	-4.34E-01	1.04E-01	1.94E-01	3.00E-01	1.27E-02	-2.36E+01	1.68E-10	-1.88E+01	5.05E-11	1.00E+00	7.82E-02	6.10E-02	6.65E-01
97	4.84E-15	0.00E+00	9.07E-09	1.33E-10	8.68E-01	4.44E-02	9.54E-03	1.47E-01	-1.86E+01	-1.83E+01	-1.71E-01	2.28E-01	2.72E-01	4.83E-01	6.98E-01	7.11E-03	-2.32E+01	1.32E-10	-1.90E+01	1.09E-10	4.00E+00	8.52E-02	6.66E-02	6.00E-01
98	2.11E-14	1.00E+00	1.30E-09	3.27E-10	1.51E-02	1.51E-02	2.22E-01	9.70E-01	-1.87E+01	-1.92E+01	-7.83E-02	4.09E-01	1.16E-01	5.99E-01	1.24E-01	2.57E-02	-2.27E+01	9.72E-11	-1.91E+01	1.12E-10	1.00E+00	6.48E-02	7.06E-02	6.16E-01
99	1.33E-14	0.00E+00	4.94E-09	2.92E-10	1.05E-01	3.19E-03	3.74E-01	5.24E-01	-1.97E+01	-1.99E+01	8.93E-01	-7.59E-02	3.91E-01	4.03E-01	5.92E+00	7.57E-03	-2.29E+01	1.31E-10	-1.95E+01	1.50E-10	1.00E+00	1.16E-01	1.56E-01	6.07E-01
100	1.17E-14	0.00E+00	4.43E-10	8.42E-11	3.88E-01	1.49E-01	2.43E-01	6.43E-01	-1.99E+01	-1.86E+01	1.13E-01	-3.99E-02	1.81E-01	2.99E-02	5.18E-01	6.44E-03	-2.21E+01	6.08E-11	-1.77E+01	1.09E-11	4.00E+00	9.55E-02	6.86E-02	5.01E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector Num.	S_HALITE PRESSURE	CASTILER PRESSURE	CASTILER PRMX_LOG	CASTILER COMP_RCK	BH_SAND PRMX_LOG	DRZ_1 PRMX_LOG	CONC_PLG PRMX_LOG	SOLAM3 SOLSIM	SOLAM3 SOLCIM	SOLPU3 SOLSIM	SOLPU3 SOLCIM	SOLPU4 SOLSIM	SOLPU4 SOLCIM	SOLU4 SOLSIM	SOLU6 SOLSIM	SOLU6 SOLCIM	SOLTH4 SOLSIM	PHUMOX3 PHUMCIM	GLOBAL OXSTAT	CULEBRA MINP_FAC	GLOBAL TRANSIDX	GLOBAL CLIMTIDX	CULEBRA HMBLKLT
1	1.20E+07	1.29E+07	-1.15E+01	6.02E-11	-1.33E+01	-1.74E+01	-1.71E+01	-1.01E-01	-4.84E-01	3.55E-01	2.39E-01	1.88E-01	2.12E-01	-4.98E-01	2.49E-01	-1.48E-01	-7.50E-01	1.46E+00	8.42E-01	7.97E+02	5.39E-01	1.01E+00	4.79E-01
2	1.28E+07	1.21E+07	-1.43E+01	6.75E-11	-1.37E+01	-1.62E+01	-1.78E+01	8.79E-01	-1.21E+00	8.65E-01	1.47E-01	-2.34E-03	3.53E-01	-1.95E-01	2.82E-03	1.23E-01	-4.53E-01	1.41E+00	6.50E-01	4.76E+02	8.09E-02	1.06E+00	1.93E-01
3	1.12E+07	1.32E+07	-1.12E+01	3.64E-11	-1.49E+01	-1.48E+01	-1.71E+01	3.64E-01	-4.19E-01	-7.16E-02	-4.14E-01	9.07E-01	-7.40E-01	-2.06E-01	-3.58E-01	-1.24E+00	-1.90E-01	1.41E+00	1.44E-01	9.89E+01	7.78E-01	2.10E+00	3.45E-01
4	1.29E+07	1.52E+07	-1.27E+01	7.45E-11	-1.53E+01	-1.57E+01	-1.73E+01	-2.81E-01	-1.35E-01	-1.23E+00	-1.32E+00	-2.57E-01	-2.34E-01	-9.56E-03	-1.03E-01	-1.73E-01	1.26E-01	1.07E-01	3.58E-01	9.38E+02	4.94E-01	1.06E+00	1.14E-01
5	1.29E+07	1.26E+07	-1.10E+01	2.35E-11	-1.22E+01	-1.83E+01	-1.84E+01	4.07E-01	8.67E-02	-1.80E-01	-1.01E-01	8.78E-02	-1.17E-01	6.41E-01	-4.03E-01	-3.88E-03	-1.67E-01	3.73E-01	1.95E-01	9.89E+02	5.94E-01	1.07E+00	4.30E-01
6	1.19E+07	1.23E+07	-1.24E+01	6.88E-11	-1.36E+01	-1.42E+01	-1.85E+01	-9.67E-01	4.85E-01	-7.99E-01	-2.12E-01	7.49E-01	4.59E-02	-7.74E-01	-2.49E-01	1.53E-01	-9.49E-01	9.88E-01	5.89E-02	8.65E+02	5.85E-01	1.04E+00	3.90E-01
7	1.38E+07	1.57E+07	-1.13E+01	3.17E-11	-1.32E+01	-1.45E+01	-1.77E+01	5.62E-02	-2.35E-01	5.03E-02	8.40E-01	-1.04E-01	1.18E-01	5.24E-02	-1.68E-01	-7.84E-01	-2.70E-01	1.40E+00	6.17E-01	8.19E+02	2.36E-01	1.17E+00	3.09E-01
8	1.34E+07	1.30E+07	-1.07E+01	4.03E-11	-1.52E+01	-1.65E+01	-1.90E+01	1.91E-01	-2.24E-02	-7.75E-01	1.07E+00	-3.54E-02	-2.20E-02	-3.86E-01	9.23E-01	-1.75E-01	-1.56E-02	1.42E+00	3.32E-01	6.53E+02	9.06E-01	1.87E+00	6.32E-02
9	1.28E+07	1.62E+07	-1.16E+01	2.97E-11	-1.11E+01	-1.63E+01	-1.71E+01	-2.54E-01	8.63E-01	7.05E-01	-3.29E-01	-4.19E-02	1.92E-01	-3.20E-03	1.91E-02	9.26E-01	-6.01E-02	1.29E+00	5.40E-01	2.83E+02	5.72E-01	1.15E+00	7.35E-02
10	1.20E+07	1.19E+07	-1.17E+01	3.96E-11	-1.10E+01	-1.81E+01	-1.89E+01	9.39E-01	3.65E-01	-1.01E-01	-4.57E-01	2.43E-01	2.33E-03	-1.06E-01	9.85E-02	4.64E-02	2.49E-01	9.60E-01	8.64E-01	7.29E+02	6.57E-01	1.20E+00	3.73E-01
11	1.33E+07	1.31E+07	-1.18E+01	3.84E-11	-1.29E+01	-1.35E+01	-1.74E+01	-5.40E-02	8.44E-01	1.07E-01	-1.71E-01	-1.86E-01	3.44E-01	1.31E-01	2.63E-02	-2.37E-01	-5.12E-01	1.43E+00	5.62E-01	3.40E+02	5.09E-01	1.17E+00	2.55E-01
12	1.37E+07	1.27E+07	-1.10E+01	2.77E-11	-1.61E+01	-1.77E+01	-1.75E+01	7.76E-01	4.48E-02	1.22E-02	-1.58E-01	-2.74E-01	1.70E-01	-1.91E+00	-3.24E-01	-3.49E-01	-1.84E-01	7.59E-01	5.96E-01	4.88E+02	9.33E-01	1.14E+00	2.45E-01
13	1.23E+07	1.49E+07	-1.33E+01	5.62E-11	-1.57E+01	-1.26E+01	-1.88E+01	-1.51E+00	6.92E-01	1.36E+00	3.28E-02	-1.51E-01	-1.84E-02	-6.64E-01	-7.33E-04	-5.26E-01	4.32E-01	1.44E+00	7.62E-02	6.08E+02	7.42E-01	1.23E+00	3.31E-01
14	1.13E+07	1.23E+07	-1.02E+01	2.65E-11	-1.39E+01	-1.51E+01	-1.72E+01	-2.32E-01	9.41E-01	-2.43E-01	-3.54E-01	-2.43E-01	-1.94E-01	9.97E-01	-4.12E-01	-2.15E-02	-1.20E-01	1.52E+00	4.46E-01	5.15E+02	4.05E-02	1.12E+00	1.23E-01
15	1.28E+07	1.40E+07	-1.40E+01	6.48E-11	-1.44E+01	-1.90E+01	-1.87E+01	-4.06E-01	9.99E-01	-1.54E-02	1.36E-01	-1.98E-02	-4.49E-01	-8.56E-01	-1.32E-01	-2.06E-01	7.88E-01	1.34E+00	9.10E-01	2.41E+02	5.29E-01	1.18E+00	2.20E-01
16	1.39E+07	1.51E+07	-1.10E+01	4.33E-11	-1.48E+01	-1.83E+01	-1.81E+01	-3.41E-01	-6.98E-02	-4.96E-01	-2.64E-01	1.63E-01	-2.05E-01	-7.01E-01	-9.39E-01	-5.92E-02	-8.56E-01	8.60E-01	5.84E-01	3.84E+02	3.16E-01	1.59E+00	3.21E-01
17	1.16E+07	1.14E+07	-1.09E+01	3.43E-11	-1.17E+01	-1.87E+01	-1.90E+01	-2.93E-01	-2.51E-01	-2.51E-01	-1.92E-01	-1.81E+00	5.08E-02	2.17E-01	-9.64E-02	-7.80E-02	-1.90E-05	1.47E+00	8.03E-01	3.29E+01	1.85E-01	1.08E+00	1.55E-01
18	1.19E+07	1.39E+07	-1.05E+01	3.21E-11	-1.28E+01	-1.72E+01	-1.85E+01	-1.44E-01	7.26E-01	-1.54E-03	2.54E-03	-8.20E-02	2.42E-01	-8.56E-02	-2.31E-02	-4.88E-01	1.41E-01	1.54E-01	2.07E-01	3.65E+02	7.95E-01	1.15E+00	2.70E-01
19	1.16E+07	1.20E+07	-1.19E+01	5.49E-11	-1.25E+01	-1.85E+01	-1.76E+01	-2.19E-01	-1.09E-01	1.79E-01	7.12E-01	9.81E-02	-6.93E-01	-9.17E-02	-4.48E-01	-2.01E-01	5.72E-01	5.57E-01	8.87E-01	5.59E+02	9.96E-01	1.53E+00	4.94E-01
20	1.17E+07	1.46E+07	-1.30E+01	4.96E-11	-1.37E+01	-1.60E+01	-1.89E+01	5.12E-03	-2.47E-01	1.17E-02	-8.66E-01	8.03E-01	2.27E-01	2.33E-01	-1.98E-01	1.75E-01	3.13E-01	1.09E+00	6.48E-01	5.92E+02	8.90E-01	1.96E+00	3.16E-01
21	1.14E+07	1.15E+07	-1.25E+01	4.56E-11	-1.32E+01	-1.37E+01	-1.84E+01	-7.16E-02	3.39E-02	8.72E-02	-3.37E-02	9.51E-01	-2.45E-01	-1.59E-01	-1.74E-01	-1.89E+00	-6.40E-01	5.83E-01	4.80E-01	9.52E+02	1.10E-01	1.04E+00	2.36E-01
22	1.25E+07	1.33E+07	-1.21E+01	6.18E-11	-1.16E+01	-1.49E+01	-1.89E+01	-6.73E-02	-3.64E-03	-3.98E-01	-4.07E-01	-4.44E-01	-2.25E-01	4.38E-01	-2.90E-01	1.97E-01	-1.38E-01	1.57E+00	6.72E-01	9.42E+02	8.75E-01	1.21E+00	4.33E-01
23	1.12E+07	1.59E+07	-1.12E+01	3.70E-11	-1.18E+01	-1.88E+01	-1.87E+01	-3.80E-02	-3.43E-01	-3.73E-01	-5.54E-02	-2.12E-01	-1.06E+00	-4.05E-01	2.27E-01	-3.02E-01	-2.92E-01	1.56E+00	6.30E-01	3.45E+02	6.46E-02	1.09E+00	3.56E-01
24	1.38E+07	1.16E+07	-1.20E+01	8.05E-11	-1.13E+01	-1.50E+01	-1.83E+01	-3.76E-01	-1.87E-01	5.59E-01	-2.14E-02	-2.07E-01	-2.19E-01	-1.34E-01	-2.72E-01	-3.77E-01	-1.70E+00	1.25E-01	9.87E-01	2.35E+02	4.74E-01	2.06E+00	1.71E-01
25	1.31E+07	1.53E+07	-1.33E+01	7.59E-11	-1.25E+01	-1.30E+01	-1.88E+01	-2.00E-01	1.84E-01	4.63E-01	-7.25E-01	-6.48E-02	-3.96E-01	-9.38E-01	1.37E-01	-2.85E-01	-1.53E-01	1.40E+00	4.88E-01	1.60E+02	2.97E-01	1.07E+00	2.77E-01
26	1.25E+07	1.19E+07	-1.03E+01	3.81E-11	-1.14E+01	-1.32E+01	-1.80E+01	-1.67E-01	-4.42E-01	-1.07E-01	6.74E-01	-8.64E-01	2.23E-01	-3.10E-01	-8.69E-02	-4.02E-02	3.99E-02	1.05E+00	1.17E-02	7.08E+02	6.00E-01	1.03E+00	4.72E-01
27	1.27E+07	1.34E+07	-1.27E+01	6.56E-11	-1.54E+01	-1.92E+01	-1.78E+01	-5.56E-02	-9.70E-01	-6.35E-01	7.77E-01	-5.56E-02	-6.45E-03	9.60E-02	-8.45E-01	-7.37E-02	-1.75E-01	3.21E-01	4.49E-02	1.30E+02	3.99E-01	1.24E+00	3.75E-01
28	1.30E+07	1.41E+07	-1.06E+01	3.31E-11	-1.60E+01	-1.39E+01	-1.83E+01	7.27E-01	-8.75E-02	2.18E-01	-3.08E-01	1.54E-01	-1.65E+00	3.25E-01	8.86E-01	1.40E-01	-4.88E-01	4.86E-01	2.51E-01	2.22E+02	5.53E-01	1.07E+00	4.25E-01
29	1.36E+07	1.21E+07	-1.32E+01	6.27E-11	-1.35E+01	-1.36E+01	-1.83E+01	-7.59E-01	-1.18E-01	6.72E-01	-6.79E-01	-4.80E-01	-1.38E-01	1.01E+00	-2.95E-02	-6.64E-02	-1.96E+00	1.31E+00	8.10E-01	6.79E+02	6.60E-01	1.19E+00	1.89E-01
30	1.31E+07	1.40E+07	-1.22E+01	4.77E-11	-1.54E+01	-1.87E+01	-1.83E+01	-5.51E-01	1.66E-01	1.70E-01	-1.67E-02	-3.37E-01	1.86E-01	2.02E-02	-1.91E-01	2.28E-02	1.14E-01	1.24E+00	3.15E-03	3.11E+02	1.91E-01	1.20E+00	1.73E-01
31	1.11E+07	1.36E+07	-1.22E+01	6.40E-11	-1.57E+01	-1.41E+01	-1.86E+01	-7.02E-01	4.09E-01	2.60E-02	-3.63E-01	-2.89E-01	-4.41E-01	6.80E-02	-1.20E-01	-3.18E-01	-2.57E-02	2.37E-01	7.32E-01	4.64E+02	7.82E-01	1.03E+00	4.99E-01
32	1.25E+07	1.18E+07	-1.29E+01	5.29E-11	-1.59E+01	-1.71E+01	-1.82E+01	9.12E-02	-9.85E-02	5.37E-01	-2.06E-01	-1.53E-01	-5.20E-01	1.99E-01	-7.55E-02	9.60E-01	1.77E-01	1.49E+00	2.61E-02	5.36E+02	7.54E-01	1.22E+00	3.84E-01
33	1.12E+07	1.28E+07	-1.28E+01	5.14E-11	-1.47E+01	-1.59E+01	-1.70E+01	-1.24E-02	7.95E-02	-2.16E-01	-1.98E-01	-1.30E+00	4.49E-01	1.59E-01	-1.85E-01	7.04E-01	-4.33E-01	6.04E-01	6.39E-01	9.18E+02	8.85E-01	1.22E+00	1.60E-01
34	1.17E+07	1.65E+07	-1.22E+01	4.59E-11	-1.29E+01	-1.89E+01	-1.80E+01	2.31E-01	-4.08E-01	9.51E-01	-2.46E-01	2.31E-01	-8.01E-01	-2.99E-01	-1.08E-01	-1.61E-01	-1.16E-01	4.56E-01	3.00E-01	8.28E+02	3.42E-01	1.03E+00	3.41E-01
35	1.26E+07	1.33E+07	-1.43E+01	9.49E-11	-1.34E+01	-1.66E+01	-1.84E+01	1.65E-01	-8.11E-01	-1.24E-01	-6.40E-01	-5.36E-01	-1.46E-01	8.94E-01	-5.79E-02	-7.06E-01	1.39E+00	1.52E+00	4.07E-01	5.48E+02	3.28E-02	1.10E+00	2.25E-01
36	1.23E+07	1.25E+07	-1.25E+01	5.56E-11	-1.46E+01	-1.54E+01	-1.75E+01	-1.51E-02	-2.95E-02	-1.89E-01	-2.21E-01	1.28E+00	9.51E-01	8.04E-01	-4.20E-02	-1.33E+00	-7.62E-02	8.00E-01	5.51E-01	8.68E+00	2.73E-01	1.81E+00	4.68E-01
37	1.15E+07	1.30E+07	-1.36E+01	7.82E-11	-1.27E+01	-1.58E+01	-1.88E+01	1.51E-01	-2.12E-01	-2.00E+00	-1.24E-01	2.12E-01	6.82E-02	1.85E-01	2.89E-01	-1.67E+00	-5.84E-01	1.06E+00	3.68E-02	8.06E+02	3.33E-01	1.01E+00	1.13E-01
38	1.12E+07	1.42E+07	-1.39E+01	5.82E-11	-1.32E+01	-1.82E+01	-1.78E+01	2.18E-01	9.60E-02	-3.39E-01	-1.30E-01	-1.01E-01	-5.20E-02	-3.39E-01	-5.71E-01	1.57E-01	-9.18E-01	1.17E+00	6.81E-01	1.97E+02	6.94E-01	1.18E+00	3.15E-01
39	1.34E+07	1.60E+07	-1.15E+01	5.91E-11	-1.31E+01	-1.79E+01	-1.81E+01	-1.28E-01	-1.42E-01	-3.47E-02	3.63E-01	3.17E-01	-6.18E-02	1.50E-01	-1.48E-01	3.02E-02	5.34E-01	1.56E+00	2.27E-01	3.80E+02	1.24E-01	1.11E+00	1.33E-01
40	1.14E+07	1.20E+07	-1.01E+01	5.23E-11	-1.63E+01	-1.90E+01	-1.78E+01	-1.98E-03	-1.98E-01	7.97E-01	-2.70E-01	1.58E-02	5.91E-01	-1.83E-01	-2.28E-01	-1.83E-01	2.35E-01	1.20E+00	5.37E-01	4.97E+02	8.37E-01	1.05E+00	7.86E-02
41	1.26E+07	1.31E+07	-1.04E+01	2.89E-11	-1.55E+01	-1.48E+01	-1.77E+01	1.08E+00	-1.49E-01	-7.68E-02	-4.77E-01	-1.58E+00	-2.82E-01	3.87E-02	5.81E-01	-2.13E-01	-2.33E-01	1.55E+00	2.72E-01	4.08E+02	4.42E-01	2.22E+00	4.55E-01
42	1.22E+07	1.44E+07	-1.23E+01	5.31E-11	-1.24E+01	-1.84E+01	-1.77E+01	-1.07E+00	-1.78E-01	6.06E-02	5.22E-01	5.90E-02	-1.89E+00	7.52E-01	-2.50E-01	-2.16E-01	-2.16E-01	1.54E+00	7.45E-01	3.07E+02	9.79E-01	1.02E+00	1.98E-01
43	1.21E+07	1.26E+07	-1.20E+01	5.72E-11	-1.21E+01	-1.43E+01	-1.84E+01	2.44E-01	-1.24E-02	-2.78E-01	-2.40E-01	4.47E-01	1.51E-01	-7.80E-01	1.51E-01	3.09E-01	-3.31E-02	1.54E+00	7.19E-01	7.61E+02	8.46E-01	1.19E+00	4.15E-01
44	1.37E+07	1.22E+07	-1.24E+01	7.76E-11	-1.40E+01	-1.64E+01	-1.81E+01	3.16E-01	1.97E-02	-4.27E-01	-7.93E-01	1.20E-01	-3.76E-02	-2.38E-01	-6.79E-02	7.88E-01	-2.57E-01	1.37E+00	7.67E-01	8.81E+02	6.47E-01	1.70E+00	2.95E-01
45	1.31E+07	1.47E+07	-1.28E+01	7.92E-11	-1.38E+01	-1.43E+01	-1.72E+01	-4.40E-02	5.57E-01	2.08E-01	-2.00E+00	7.63E-02	-6.36E-01	8.55E-02	-2.38E-01	-5.99E-01	-1.27E-01	1.50E+00	4.51E-01	5.79E+02	8.57E-01	1.75E+00	9.82E-02
46	1.32E+07	1.23E+07	-1.18E+01	3.76E-11	-1.24E+01	-1.29E+01	-1.85E+01	1.26E-01	2.25E-01	-2.46E-01	4.74E-01	5.34E-01	-2.99E-01	-1.77E-02	6.70E-02	-1.41E-01	-1.66E-01	1.45E+00	3.25E-01	7.83E+01	1.43E-01	1.79E+00	9.44E-02
47	1.19E+07	1.17E+07	-1.13E+01	3.57E-11	-1.30E+01	-1.55E+01	-1.75E+01	-1.81E+00	-9.25E-01	3.94E-02	-2.87E-01	-1.34E-01	1.23E-01	-4.23E-01	-5.52E-02	-1.21E-01	-2.09E-01	1.46E+00	4.38E-01	1.08E+02	2.22E-01	1.89E+00	3.81E-01
48	1.33E+07	1.28E+07	-1.22E+01	7.18E-11	-1.43E+01	-1.94E+01	-1.71E+01	-2.39E-01	8.00E-01	8.22E-01	8.76E-01	-2.17E-01	-1.40E-01	2.45E-01	6.37E-01	-2.48E-01	-3.49E-01	1.50E+00	1.09E-01	6.94E+02	4.17E-01	1.25E+00	4.63E-01
49	1.27E+07	1.64E+07	-1.16E+01	4.90E-11	-1.51E+01	-1.53E+01	-1.79E+01	-4.22E-01	-1.47E+00	-2.36E-01	7.69E-02	2.67E-01	8.94E-02	9.00E-01	-3.56E-01	-1.10E-01	-1.23E+00	1.53E+00	7.04E-01	8.60E+02	8.16E-01	1.16E+00	4.47E-01
50	1.35E+07	1.29E+07	-1.25E+01	7.29E-11	-1.23E+01	-1.33E+01	-1.72E+01	5.39E-01	6.15E-02	-8.57E-02	1.04E-01	-3.47E-02	-8.95E-02	-7.09E-02	-3.91E-01	-4.36E-01	-4.05E-01	1.44E+00	6.61E-01	7.50E+02	7.17E-01	1.10E+00	2.16E-01
51	1.22E+07	1.35E+07	-1.14E+01	3.03E-11	-1.49E+01	-1.69E+01	-1.70E+01	3.89E-02	-1.57E-01	-5.07E-01	-2.29E-01	-2.27E-01	1.31E-02	-5.82E-01	8.31E-01	-4.64E-01	8.18E-01	1.59E+00	9.44E-01	1.88E+02	5.16E-01	1.09E+00	2.62E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector Num.	S_HALITE PRESSURE	CASTILER PRESSURE	CASTILER PRMX_LOG	CASTILER COMP_RCK	BH_SAND PRMX_LOG	DRZ_1 PRMX_LOG	CONC_PLG PRMX_LOG	SOLAM3 SOLSIM	SOLAM3 SOLCIM	SOLPU3 SOLSIM	SOLPU3 SOLCIM	SOLPU4 SOLSIM	SOLPU4 SOLCIM	SOLU4 SOLSIM	SOLU6 SOLSIM	SOLU6 SOLCIM	SOLTH4 SOLSIM	PHUMOX3 PHUMCIM	GLOBAL OXSTAT	CULEBRA MINP_FAC	GLOBAL TRANSIDX	GLOBAL CLIMTIDX	CULEBRA HMBLKLT
52	1.36E+07	1.24E+07	-1.20E+01	4.39E-11	-1.62E+01	-1.38E+01	-1.78E+01	-7.98E-02	-7.68E-02	-3.89E-01	2.11E-01	-1.80E-01	-2.38E-01	2.63E-01	-1.09E+00	-4.68E-02	7.36E-01	1.44E+00	3.93E-01	8.34E+02	3.78E-01	1.14E+00	4.23E-01
53	1.10E+07	1.37E+07	-1.37E+01	4.64E-11	-1.58E+01	-1.38E+01	-1.80E+01	1.04E-01	2.41E-01	-5.48E-02	4.47E-01	-3.64E-01	5.08E-01	-2.14E-01	4.26E-02	6.50E-01	-8.06E-01	1.02E+00	6.98E-01	4.53E+02	6.77E-01	1.08E+00	1.64E-01
54	1.18E+07	1.56E+07	-1.31E+01	8.38E-11	-1.55E+01	-1.75E+01	-1.82E+01	-1.22E-01	1.36E-01	-9.19E-02	-6.75E-02	-1.18E+00	1.42E-01	-1.43E+00	1.20E-01	2.67E-01	-6.75E-01	7.73E-01	1.14E-01	4.32E+01	7.63E-02	1.17E+00	4.44E-01
55	1.11E+07	1.28E+07	-1.34E+01	6.66E-11	-1.52E+01	-1.62E+01	-1.80E+01	-4.33E-01	1.08E-01	-1.58E+00	-6.59E-03	-8.79E-02	-4.45E-02	3.57E-01	-2.21E-01	1.10E-01	-1.02E-01	1.58E+00	1.70E-01	5.84E+02	9.87E-01	1.65E+00	4.03E-01
56	1.30E+07	1.47E+07	-1.26E+01	5.40E-11	-1.39E+01	-1.86E+01	-1.81E+01	4.88E-01	1.45E-01	1.43E-01	3.59E-02	-6.02E-01	9.40E-01	-1.11E-01	-1.73E+00	-2.56E-01	8.92E-02	9.24E-01	9.94E-02	1.41E+02	4.05E-01	1.24E+00	2.52E-01
57	1.38E+07	1.34E+07	-1.23E+01	4.52E-11	-1.42E+01	-1.78E+01	-1.85E+01	-1.67E-01	-3.04E-01	-2.07E-01	1.51E-02	6.87E-01	-8.67E-01	8.72E-03	5.47E-01	2.40E-01	4.64E-01	8.23E-01	8.21E-01	9.07E+02	1.61E-02	1.73E+00	1.78E-01
58	1.30E+07	1.38E+07	-1.30E+01	4.21E-11	-1.35E+01	-1.76E+01	-1.86E+01	3.01E-02	-4.55E-01	2.26E-01	-4.29E-01	-1.63E-01	-6.85E-02	-2.35E-01	6.72E-01	-2.81E-02	-3.08E-01	1.42E+00	4.30E-01	2.57E+02	9.30E-01	1.05E+00	6.39E-02
59	1.34E+07	1.22E+07	-1.18E+01	3.47E-11	-1.59E+01	-1.85E+01	-1.77E+01	-1.45E+00	1.23E-01	-2.96E-01	-1.08E-02	-9.56E-02	-9.37E-02	-1.62E-01	5.27E-02	6.80E-01	-2.43E-01	8.95E-01	5.71E-01	7.34E+02	2.42E-01	1.13E+00	2.84E-01
60	1.21E+07	1.42E+07	-1.19E+01	6.32E-11	-1.34E+01	-1.74E+01	-1.85E+01	-3.33E-01	-2.39E-01	7.87E-02	1.17E-01	6.10E-01	1.61E-01	-6.71E-02	1.87E-01	-3.95E-01	1.73E-03	2.70E-01	3.78E-01	6.30E+02	7.02E-01	2.18E+00	7.24E-02
61	1.14E+07	1.48E+07	-1.14E+01	4.85E-11	-1.36E+01	-1.41E+01	-1.77E+01	-3.27E-02	-9.63E-02	-9.12E-01	-1.79E-01	-1.73E-01	-1.95E-01	-2.80E-01	1.99E-01	1.89E-01	2.75E-01	1.39E+00	5.25E-01	1.71E+02	7.34E-01	1.01E+00	3.53E-01
62	1.24E+07	1.38E+07	-1.21E+01	6.97E-11	-1.51E+01	-1.46E+01	-1.83E+01	5.64E-01	-1.27E-01	9.15E-01	1.71E-01	-2.47E-01	-4.15E-01	5.70E-01	-1.53E-01	-1.32E-01	8.50E-01	3.38E-01	8.53E-01	7.01E+01	2.84E-01	1.08E+00	4.52E-01
63	1.28E+07	1.43E+07	-1.11E+01	3.88E-11	-1.12E+01	-1.63E+01	-1.82E+01	-2.28E-01	-8.73E-01	2.02E-01	-2.34E-01	-4.53E-01	-1.77E-01	-4.59E-02	3.83E-01	-8.69E-02	-1.97E-01	1.36E+00	2.65E-01	5.11E+01	9.48E-01	1.59E+00	2.80E-01
64	1.34E+07	1.45E+07	-1.26E+01	5.41E-11	-1.15E+01	-1.67E+01	-1.79E+01	-2.14E-02	-1.64E+00	-1.70E-01	-4.87E-01	4.35E-02	8.46E-01	-4.51E-01	-4.88E-01	-4.76E-01	-4.41E-02	1.48E+00	1.84E-01	9.24E+02	6.34E-01	1.02E+00	3.06E-01
65	1.27E+07	1.44E+07	-1.09E+01	4.16E-11	-1.20E+01	-1.27E+01	-1.72E+01	-9.38E-01	-2.04E-01	6.14E-01	-3.84E-01	1.12E-01	-3.06E-02	-2.50E-01	1.56E-01	2.05E-01	5.09E-02	1.53E+00	8.43E-02	9.63E+02	1.10E-01	1.85E+00	4.84E-01
66	1.32E+07	1.36E+07	-1.41E+01	9.26E-11	-1.57E+01	-1.34E+01	-1.80E+01	6.21E-01	-4.62E-02	-1.65E-01	-8.90E-02	-2.01E-01	-3.40E-01	-2.29E-01	-3.14E-01	2.37E-01	-1.50E-01	7.15E-01	1.21E-01	1.19E+02	1.34E-01	1.08E+00	3.97E-01
67	1.30E+07	1.39E+07	-1.25E+01	4.93E-11	-1.15E+01	-1.72E+01	-1.72E+01	5.97E-02	-3.63E-01	-1.33E-01	2.35E-01	-4.96E-01	6.04E-01	7.40E-01	9.56E-01	-7.75E-01	1.95E-01	4.64E-01	4.16E-01	2.75E+02	8.61E-01	1.11E+00	3.51E-01
68	1.13E+07	1.53E+07	-1.24E+01	8.26E-11	-1.17E+01	-1.70E+01	-1.81E+01	1.12E-01	5.08E-02	-2.12E-01	6.34E-01	-1.90E-01	-4.93E-01	-1.45E-01	-1.15E-01	5.06E-01	-1.48E+00	1.47E+00	3.83E-01	7.75E+02	8.29E-01	1.12E+00	5.01E-02
69	1.27E+07	1.47E+07	-1.17E+01	5.10E-11	-1.19E+01	-1.78E+01	-1.89E+01	1.80E-02	6.17E-01	-4.57E-01	-4.66E-02	-1.12E-01	3.18E-02	4.53E-01	-1.00E-02	-1.59E-01	2.24E-01	1.38E+00	2.46E-01	6.61E+02	6.11E-01	2.08E+00	4.41E-01
70	1.16E+07	1.37E+07	-1.34E+01	7.12E-11	-1.18E+01	-1.77E+01	-1.79E+01	-1.77E-01	1.92E-01	4.25E-01	1.20E-01	-2.35E-02	7.63E-02	-1.32E-01	-2.10E-01	2.26E-01	6.17E-01	6.80E-01	8.76E-01	9.97E+02	9.38E-02	1.23E+00	3.26E-01
71	1.24E+07	1.25E+07	-1.13E+01	3.50E-11	-1.22E+01	-1.66E+01	-1.79E+01	2.85E-01	-3.60E-02	-3.26E-01	-8.98E-01	4.61E-01	-1.04E-01	-1.02E-01	3.28E-01	-3.25E-01	6.28E-02	1.43E+00	2.12E-01	8.49E+02	2.45E-02	1.16E+00	4.11E-01
72	1.18E+07	1.24E+07	-1.29E+01	6.82E-11	-1.44E+01	-1.26E+01	-1.88E+01	2.13E-01	-2.83E-01	2.97E-01	6.73E-02	-4.13E-01	-1.24E-01	-5.46E-02	-6.55E-01	-9.28E-02	-6.69E-02	1.57E+00	6.03E-01	7.86E+02	3.28E-01	1.09E+00	1.81E-01
73	1.21E+07	1.38E+07	-1.20E+01	4.44E-11	-1.49E+01	-1.55E+01	-1.75E+01	-2.46E-01	-5.47E-02	-2.29E-01	5.66E-01	3.57E-01	-1.71E-01	-9.58E-01	-4.77E-01	-9.78E-01	7.63E-02	1.58E+00	9.01E-01	4.47E+02	6.22E-01	1.13E+00	2.98E-01
74	1.24E+07	1.30E+07	-1.07E+01	4.47E-11	-1.41E+01	-1.81E+01	-1.86E+01	-1.89E-01	-2.24E-01	3.22E-01	2.82E-01	1.78E-01	7.46E-01	3.32E-02	-3.90E-02	5.54E-02	3.46E-02	1.58E+00	7.78E-01	7.54E+02	6.81E-01	1.52E+00	1.43E-01
75	1.33E+07	1.32E+07	-1.21E+01	5.01E-11	-1.53E+01	-1.69E+01	-1.76E+01	-4.52E-01	-5.44E-01	-1.59E-01	-5.78E-01	-7.05E-01	-3.04E-01	-1.24E-01	-8.13E-02	-1.02E-01	1.54E-01	1.47E+00	3.16E-01	5.67E+02	2.63E-01	2.00E+00	1.39E-01
76	1.35E+07	1.29E+07	-1.23E+01	5.59E-11	-1.20E+01	-1.50E+01	-1.74E+01	-1.50E-01	-1.70E-01	-8.39E-01	1.62E-01	7.07E-02	-1.06E-01	1.24E-01	-1.64E-01	8.19E-01	1.57E-01	6.14E-01	1.54E-01	2.44E+01	4.56E-01	1.04E+00	4.76E-01
77	1.20E+07	1.41E+07	-1.38E+01	8.79E-11	-1.19E+01	-1.60E+01	-1.73E+01	-1.06E-01	-4.64E-01	-6.99E-01	-1.67E+00	-1.40E-01	7.60E-01	-2.50E-01	-5.19E-01	-3.69E-01	1.50E-02	5.35E-01	3.67E-01	4.15E+02	4.30E-01	2.15E+00	1.20E-01
78	1.15E+07	1.44E+07	-1.19E+01	6.00E-11	-1.56E+01	-1.58E+01	-1.79E+01	9.72E-01	1.32E+00	-1.83E-01	-5.94E-02	-7.29E-01	-7.06E-02	-4.69E-01	-1.41E-01	-4.18E-01	-2.27E-01	1.51E+00	5.03E-01	6.50E+02	3.06E-01	2.23E+00	2.40E-01
79	1.39E+07	1.45E+07	-1.17E+01	4.25E-11	-1.60E+01	-1.80E+01	-1.87E+01	1.42E-01	-6.94E-01	-1.29E-01	-5.01E-01	-7.04E-02	9.77E-02	-1.76E-01	-7.52E-01	-1.28E-01	-8.74E-02	1.55E+00	9.30E-01	8.95E+02	9.51E-01	1.19E+00	3.62E-01
80	1.33E+07	1.32E+07	-1.18E+01	4.80E-11	-1.29E+01	-1.73E+01	-1.75E+01	8.23E-01	1.75E-01	-3.13E-01	-3.59E-02	-4.94E-02	-9.09E-01	-2.75E-02	1.69E-01	3.83E-01	-3.86E-01	1.38E+00	5.20E-01	8.68E+01	7.23E-01	1.11E+00	1.50E-01
81	1.35E+07	1.33E+07	-1.31E+01	8.48E-11	-1.40E+01	-1.52E+01	-1.87E+01	-3.15E-01	2.36E-01	1.27E-01	-1.86E-01	2.15E-01	2.82E-01	1.76E-01	-2.01E-02	1.01E-01	-7.76E-02	1.59E+00	7.27E-01	1.69E+01	9.61E-01	1.00E+00	2.30E-01
82	1.23E+07	1.36E+07	-1.16E+01	3.99E-11	-1.27E+01	-1.92E+01	-1.73E+01	-1.58E-01	5.22E-01	-6.53E-02	-7.62E-02	-1.27E-01	-1.26E-01	7.63E-02	-8.16E-01	-2.24E-01	-3.64E-01	1.60E+00	2.33E-01	6.18E+02	2.63E-04	1.03E+00	1.45E-01
83	1.18E+07	1.17E+07	-1.28E+01	7.40E-11	-1.13E+01	-1.91E+01	-1.74E+01	-6.63E-01	-6.04E-02	-2.77E-02	-1.24E+00	5.60E-01	-5.97E-01	-1.62E+00	-4.35E-01	9.07E-02	2.09E-01	1.49E+00	1.37E-01	1.69E+02	5.68E-01	1.22E+00	2.71E-01
84	1.22E+07	1.34E+07	-1.12E+01	4.07E-11	-1.14E+01	-1.46E+01	-1.82E+01	8.23E-02	-2.21E-01	-4.07E-02	-9.57E-02	-3.43E-01	-3.80E-01	-1.68E-01	-9.80E-01	5.51E-01	9.32E-01	7.39E-01	7.80E-01	6.83E+02	4.29E-01	1.21E+00	4.06E-01
85	1.15E+07	1.50E+07	-1.08E+01	4.18E-11	-1.42E+01	-1.28E+01	-1.89E+01	1.83E-01	-1.62E-01	-5.86E-02	-8.04E-02	2.45E-02	-3.34E-01	-6.03E-02	-1.35E+00	-9.31E-03	-4.21E-01	1.12E+00	9.39E-01	2.05E+02	1.51E-01	1.17E+00	1.99E-01
86	1.29E+07	1.42E+07	-1.27E+01	6.98E-11	-1.30E+01	-1.28E+01	-1.72E+01	-1.84E-01	-1.15E-01	-9.48E-01	2.16E-01	7.51E-01	-1.39E-02	2.09E-01	7.82E-01	1.18E+00	6.62E-01	1.52E+00	8.94E-01	3.22E+02	2.14E-01	1.25E+00	2.10E-01
87	1.11E+07	1.55E+07	-1.17E+01	4.08E-11	-1.62E+01	-1.68E+01	-1.73E+01	-2.04E-01	-1.81E+00	-1.17E-01	-1.40E-01	7.79E-03	-8.05E-02	-3.84E-02	7.07E-01	4.92E-01	-9.28E-02	2.86E-01	9.52E-01	6.37E+02	2.50E-01	1.15E+00	3.68E-01
88	1.37E+07	1.31E+07	-1.13E+01	6.39E-11	-1.38E+01	-1.40E+01	-1.76E+01	1.74E-01	2.55E-01	-4.34E-02	9.44E-02	-1.24E-01	1.11E+00	-1.21E+00	2.11E-01	4.32E-01	-1.01E-02	1.40E+00	9.62E-01	3.59E+02	5.66E-02	1.06E+00	3.37E-01
89	1.36E+07	1.52E+07	-1.36E+01	6.14E-11	-1.11E+01	-1.51E+01	-1.76E+01	-1.11E-01	1.16E-02	-4.78E-01	3.33E-01	-8.02E-01	-1.60E-01	-1.46E-01	-2.06E-01	-2.35E-01	-1.41E-01	6.48E-01	1.73E-01	4.35E+02	7.67E-01	1.22E+00	4.88E-01
90	1.25E+07	1.35E+07	-1.19E+01	4.72E-11	-1.45E+01	-1.37E+01	-1.82E+01	-8.01E-01	-2.93E-01	-1.40E-01	1.96E-01	-1.36E-02	-1.56E-01	-4.39E-01	4.84E-01	-1.90E-01	-3.36E-01	1.39E+00	3.01E-01	9.71E+02	3.65E-01	1.94E+00	2.33E-01
91	1.23E+07	1.39E+07	-1.30E+01	5.77E-11	-1.47E+01	-1.44E+01	-1.89E+01	-5.85E-01	-6.09E-01	1.16E-01	-9.60E-01	-9.26E-01	8.68E-01	-3.65E-01	-2.32E-01	-1.11E-01	1.05E-01	1.48E+00	7.91E-01	3.96E+02	1.64E-01	1.12E+00	2.07E-01
92	1.26E+07	1.26E+07	-1.35E+01	7.65E-11	-1.50E+01	-1.93E+01	-1.85E+01	-8.50E-01	-6.51E-02	-4.42E-01	-1.09E-01	-6.38E-01	-9.66E-01	-2.21E-01	1.13E+00	-6.55E-01	-4.72E-01	1.14E+00	9.98E-01	4.22E+02	2.03E-01	1.63E+00	2.90E-01
93	1.36E+07	1.26E+07	-1.14E+01	3.08E-11	-1.45E+01	-1.31E+01	-1.74E+01	-4.89E-01	-1.50E-02	-6.05E-01	-1.14E-01	-9.71E-01	-1.42E+00	-5.01E-01	-1.29E-01	-9.38E-01	9.66E-01	4.19E-01	4.99E-01	7.16E+02	9.12E-01	1.01E+00	5.72E-02
94	1.13E+07	1.25E+07	-1.38E+01	8.84E-11	-1.24E+01	-1.47E+01	-1.71E+01	6.79E-01	-3.35E-01	2.49E-01	1.89E-01	-3.83E-01	-2.55E-01	1.17E-01	4.15E-01	-4.96E-02	3.58E-01	3.83E-01	4.70E-01	8.71E+02	4.62E-01	1.20E+00	8.37E-02
95	1.18E+07	1.50E+07	-1.16E+01	5.19E-11	-1.48E+01	-1.31E+01	-1.82E+01	-4.80E-01	3.39E-01	-1.50E+00	4.89E-02	-2.32E-01	6.64E-01	5.20E-01	1.12E-01	-8.82E-01	-1.06E-01	1.73E-01	9.78E-01	5.01E+02	3.55E-01	1.19E+00	3.95E-01
96	1.32E+07	1.27E+07	-1.15E+01	4.31E-11	-1.59E+01	-1.54E+01	-1.75E+01	-3.60E-01	-1.88E-01	-1.52E-01	-1.34E-01	8.87E-01	-1.82E-01	-8.03E-02	7.29E-02	8.70E-01	-5.51E-02	6.88E-02	3.41E-01	2.97E+02	4.86E-01	1.13E+00	1.27E-01
97	1.14E+07	1.30E+07	-1.32E+01	5.87E-11	-1.43E+01	-1.30E+01	-1.87E+01	-8.88E-02	-6.61E-01	-9.81E-03	9.95E-01	1.94E-01	-2.10E-01	-1.91E-01	8.93E-02	5.99E-02	-3.80E-02	1.50E+00	6.94E-02	2.13E+02	8.10E-01	2.03E+00	1.05E-01
98	1.20E+07	1.55E+07	-1.04E+01	3.33E-11	-1.21E+01	-1.56E+01	-1.87E+01	-9.27E-02	-3.87E-01	1.36E-01	-1.49E-01	-4.00E-01	-4.67E-01	-3.04E-02	2.24E-01	2.15E-04	-2.42E-01	9.31E-01	2.82E-01	5.27E+02	5.46E-01	1.16E+00	2.60E-01
99	1.17E+07	1.28E+07	-1.11E+01	3.69E-11	-1.16E+01	-1.35E+01	-1.73E+01	-2.12E-01	-7.67E-01	-1.96E-01	9.02E-01	-3.17E-01	-3.65E-01	-3.39E-01	-1.84E+00	8.00E-02	-2.07E-01	1.21E+00	8.33E-01	1.45E+02	1.77E-01	1.24E+00	1.02E-01
100	1.17E+07	1.58E+07	-1.08E+01	2.50E-11	-1.26E+01	-1.67E+01	-1.86E+01	-1.36E-01	2.12E-01	1.58E-01	-1.66E-01	1.38E-01	4.67E-01	6.85E-01	-6.92E-01	-1.72E-02	1.89E-01	2.19E-01	7.54E-01	2.64E+02	3.86E-01	1.11E+00	8.70E-02

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
1	1.45E-03	1.89E-01	2.64E-03	2.30E+00	2.61E-02	8.04E-01	2.47E+00	1.12E-01	4.20E+00	3.31E-01	1.20E+01	2.99E-01	2.15E-01	-1.89E+01	-1.83E+01	-1.96E+01	3.99E-01
2	1.31E-03	1.12E-01	1.96E-03	9.56E-01	2.48E-01	1.08E+00	4.44E+00	5.16E-02	2.30E+01	5.23E-02	5.70E+00	9.75E-02	5.30E-02	-1.82E+01	-1.79E+01	-1.91E+01	1.75E-01
3	1.44E-04	1.57E-01	1.28E-03	9.36E-01	1.38E-01	1.74E+00	1.14E+00	3.80E-01	3.59E-01	5.66E-01	6.91E+00	3.20E-01	2.27E-01	-1.77E+01	-1.89E+01	-2.04E+01	3.87E-01
4	2.72E-03	1.61E-01	1.01E-02	1.48E+00	6.93E-02	1.63E+00	1.62E+00	8.31E-02	5.43E-02	5.39E-01	9.59E+00	1.20E-01	1.32E-01	-1.79E+01	-1.89E+01	-1.95E+01	1.61E-02
5	6.07E-03	1.80E-01	1.72E-03	5.24E+00	9.60E-02	7.07E+00	8.54E+00	1.58E-01	1.77E+00	5.85E-01	8.73E+00	3.97E-01	3.24E-01	-2.02E+01	-1.73E+01	-2.02E+01	1.64E-01
6	3.49E-03	1.53E-01	1.14E-04	7.25E-01	1.88E-01	8.39E-01	8.46E+00	2.13E-01	5.53E+01	2.61E-01	8.09E+00	2.73E-01	3.69E-01	-1.86E+01	-1.75E+01	-2.17E+01	1.00E+00
7	2.56E-04	1.84E-01	2.48E-04	1.14E+00	3.77E-01	9.87E-01	1.16E+00	2.80E-02	3.26E-01	5.06E-01	6.15E+00	1.37E-03	2.37E-01	-1.98E+01	-1.91E+01	-2.11E+01	4.53E-01
8	3.32E-04	1.42E-01	2.18E-04	6.46E+00	4.46E-02	1.02E+00	6.52E+00	3.58E-01	3.56E+01	5.49E-01	7.13E+00	2.90E-01	3.86E-01	-1.93E+01	-1.88E+01	-2.01E+01	8.99E-01
9	4.07E-04	1.19E-01	1.89E-03	6.72E+00	4.70E-02	9.58E-01	1.49E+00	7.89E-02	5.71E+00	2.66E-01	4.64E+00	5.56E-01	2.19E-01	-1.96E+01	-1.75E+01	-2.10E+01	8.30E-01
10	1.60E-04	1.87E-01	7.98E-05	8.00E-01	2.01E-01	7.09E+00	8.92E-01	1.29E-01	8.79E-01	3.13E-01	1.26E+01	1.79E-02	1.83E-01	-1.91E+01	-1.86E+01	-1.93E+01	4.69E-01
11	1.48E-04	1.90E-01	4.77E-03	7.65E+00	5.12E-02	8.88E-01	2.28E+00	5.32E-02	2.02E+01	2.42E-02	1.31E+01	1.64E-01	1.95E-01	-1.74E+01	-1.92E+01	-1.91E+01	8.18E-01
12	7.89E-03	1.04E-01	4.09E-03	7.54E-01	3.52E-01	3.97E+00	9.63E-01	3.34E-02	2.75E+01	5.57E-01	2.06E+01	1.66E-01	4.22E-02	-1.76E+01	-1.77E+01	-2.03E+01	4.07E-01
13	4.68E-03	1.82E-01	5.02E-04	7.11E-01	1.23E-01	9.20E+00	2.42E+00	2.98E-02	1.21E-01	4.67E-01	7.50E+00	2.68E-01	2.84E-01	-1.87E+01	-1.83E+01	-1.91E+01	9.45E-01
14	2.41E-03	1.88E-01	2.11E-03	9.09E-01	4.19E-02	8.01E+00	1.59E+00	1.21E-01	2.35E+00	5.08E-02	7.99E+00	6.50E-02	3.73E-01	-1.84E+01	-1.77E+01	-1.99E+01	2.70E-01
15	5.92E-03	1.68E-01	3.09E-05	1.30E+00	2.02E-02	4.49E+00	8.61E-01	2.58E-01	8.43E+00	1.94E-01	7.38E+00	5.96E-01	2.43E-02	-1.83E+01	-1.87E+01	-2.12E+01	5.40E-02
16	9.08E-04	1.70E-01	3.91E-04	1.91E+00	8.99E-02	3.83E+00	1.78E+00	1.46E-01	2.91E+00	8.06E-02	9.08E+00	8.64E-03	1.46E-01	-1.81E+01	-1.85E+01	-2.00E+01	1.43E-01
17	8.68E-04	1.08E-01	5.90E-04	8.27E-01	1.25E-01	1.31E+00	7.82E-01	8.67E-02	4.81E-01	2.78E-01	6.65E+00	1.29E-01	9.74E-02	-1.78E+01	-1.87E+01	-1.97E+01	9.76E-01
18	2.09E-04	2.08E-01	2.32E-04	6.15E+00	3.12E-01	1.97E+00	4.37E+00	6.47E-02	1.86E+01	4.62E-01	5.43E+00	5.42E-02	1.99E-02	-1.81E+01	-1.73E+01	-1.94E+01	7.11E-01
19	2.77E-03	1.13E-01	2.76E-03	3.92E+00	2.46E-01	5.44E+00	6.07E+00	2.77E-01	3.01E+01	1.33E-01	1.30E+01	4.94E-02	3.52E-01	-2.00E+01	-1.87E+01	-1.96E+01	5.48E-01
20	7.97E-03	2.03E-01	3.22E-04	2.85E+00	2.30E-02	1.49E+00	7.15E-01	1.52E-01	6.94E+00	4.30E-01	7.21E+00	2.50E-02	3.63E-01	-1.70E+01	-1.74E+01	-1.92E+01	8.80E-02
21	4.72E-04	1.23E-01	1.45E-02	4.27E+00	3.81E-02	1.23E+00	1.38E+00	5.01E-02	1.19E-01	7.00E-02	6.39E+00	2.18E-01	2.09E-01	-1.87E+01	-1.94E+01	-1.99E+01	6.48E-01
22	1.08E-03	1.38E-01	7.12E-04	1.36E+00	1.60E-01	1.20E+00	5.02E+00	2.15E-02	4.02E+01	5.82E-01	4.84E+00	4.99E-01	8.93E-03	-1.93E+01	-1.81E+01	-1.98E+01	1.31E-01
23	7.75E-04	1.70E-01	9.31E-05	4.39E+00	1.92E-01	3.41E+00	4.65E+00	1.58E-01	1.43E+01	2.78E-02	7.74E+00	3.52E-01	3.14E-01	-1.94E+01	-1.89E+01	-1.94E+01	5.83E-01
24	4.37E-04	1.19E-01	1.63E-03	1.52E+00	2.12E-02	2.78E+00	6.30E+00	3.09E-01	4.08E-01	3.98E-01	7.32E+00	1.03E-01	2.08E-01	-1.90E+01	-1.77E+01	-1.93E+01	6.70E-01
25	2.30E-04	1.68E-01	1.55E-02	1.11E+00	1.49E-01	1.19E+00	4.56E+00	2.20E-01	1.06E-01	3.70E-02	8.63E+00	8.34E-02	2.76E-01	-1.99E+01	-1.70E+01	-1.93E+01	7.16E-02
26	3.70E-03	1.80E-01	5.99E-05	6.31E+00	4.62E-02	8.50E-01	1.77E+00	1.01E-01	7.57E-01	3.63E-01	9.22E+00	1.38E-01	1.12E-01	-1.77E+01	-1.77E+01	-1.90E+01	1.82E-01
27	6.44E-04	1.58E-01	1.69E-04	1.45E+00	2.45E-02	3.09E+00	2.20E+00	1.39E-01	1.29E+01	1.38E-01	4.56E+00	8.95E-02	2.54E-01	-1.81E+01	-1.93E+01	-1.95E+01	7.85E-01
28	1.13E-03	1.83E-01	8.97E-04	2.58E+00	1.35E-01	7.51E+00	5.26E+00	2.23E-02	9.96E-01	1.92E-02	9.91E+00	4.67E-01	9.41E-02	-1.83E+01	-1.88E+01	-1.96E+01	3.63E-01
29	1.58E-03	1.77E-01	4.04E-05	3.81E+00	2.87E-01	2.16E+00	8.85E-01	1.66E-01	1.56E+00	3.77E-01	7.90E+00	5.77E-01	3.99E-01	-1.88E+01	-1.94E+01	-2.02E+01	3.09E-01
30	1.01E-03	1.84E-01	1.13E-02	9.20E+00	3.31E-01	2.28E+00	3.31E+00	6.96E-02	6.70E+00	3.88E-01	9.24E+00	1.25E-02	3.07E-01	-1.84E+01	-1.91E+01	-2.05E+01	1.02E-01
31	1.32E-03	1.10E-01	8.75E-04	9.86E+00	1.42E-01	6.20E+00	1.30E+00	2.27E-01	2.10E+00	1.15E-01	8.52E+00	3.07E-02	3.12E-02	-1.78E+01	-1.79E+01	-2.06E+01	8.53E-01
32	6.04E-04	1.00E-01	3.50E-03	1.65E+00	3.96E-02	9.18E-01	7.26E-01	3.90E-02	8.42E-01	2.03E-01	8.12E+00	1.15E-01	3.17E-01	-1.91E+01	-1.82E+01	-2.03E+01	7.72E-01
33	4.29E-04	1.78E-01	3.53E-04	9.70E-01	3.28E-02	3.86E+00	5.37E+00	3.46E-01	3.66E+00	4.46E-02	4.98E+00	2.39E-02	2.36E-02	-1.97E+01	-1.89E+01	-1.92E+01	2.27E-01
34	8.45E-03	1.34E-01	2.85E-04	1.25E+00	1.44E-01	1.26E+00	1.27E+00	2.69E-01	1.21E+00	1.53E-01	6.96E+00	1.74E-01	2.43E-01	-1.89E+01	-1.81E+01	-1.89E+01	7.07E-01
35	5.60E-03	1.77E-01	8.58E-03	1.09E+00	5.81E-02	1.69E+00	5.52E+00	3.94E-01	7.67E+01	4.55E-01	9.51E+00	1.25E-01	2.48E-01	-1.79E+01	-1.85E+01	-1.88E+01	6.17E-01
36	2.03E-04	1.61E-01	4.25E-04	4.76E+00	3.89E-01	4.57E+00	5.62E+00	1.26E-01	1.05E+01	3.73E-01	6.51E+00	5.09E-01	1.14E-01	-1.79E+01	-1.70E+01	-1.92E+01	9.27E-01
37	2.54E-03	1.42E-01	4.85E-05	2.90E+00	3.70E-02	2.47E+00	1.10E+00	8.89E-02	2.70E-01	2.57E-01	7.42E+00	4.57E-01	1.03E-01	-1.76E+01	-1.78E+01	-1.97E+01	9.71E-02
38	7.31E-03	1.72E-01	6.06E-04	5.66E+00	2.60E-01	1.01E+00	7.84E+00	4.06E-02	6.91E-02	4.01E-01	7.71E+00	1.06E-01	2.70E-01	-1.81E+01	-1.77E+01	-2.08E+01	8.82E-01
39	7.00E-04	1.72E-01	3.65E-05	3.60E+00	2.00E-01	2.84E+00	3.37E+00	5.93E-02	1.81E-01	2.47E-01	6.59E+00	1.35E-01	6.28E-02	-1.82E+01	-1.78E+01	-1.99E+01	8.00E-01
40	1.41E-03	1.90E-01	1.02E-03	2.21E+00	2.64E-01	5.71E+00	2.86E+00	1.18E-01	5.36E-02	2.29E-01	5.55E+00	5.37E-01	8.23E-02	-1.87E+01	-1.81E+01	-2.05E+01	1.99E-01
41	8.16E-04	1.81E-01	1.22E-03	5.14E+00	1.02E-01	1.35E+00	2.05E+00	3.27E-01	1.98E-01	2.40E-01	6.74E+00	2.00E-01	3.58E-01	-1.76E+01	-1.76E+01	-2.20E+01	5.29E-01
42	3.15E-03	1.65E-01	1.66E-02	1.79E+00	3.12E-02	1.39E+00	8.20E+00	2.59E-02	6.08E-01	3.52E-01	4.33E+00	1.18E-01	7.00E-02	-1.75E+01	-1.80E+01	-2.02E+01	4.84E-01
43	1.81E-03	1.55E-01	1.10E-02	8.52E+00	6.24E-02	8.67E+00	4.77E+00	2.93E-02	9.15E-02	2.94E-01	7.05E+00	1.11E-01	1.37E-01	-1.77E+01	-1.97E+01	-1.94E+01	9.58E-01
44	4.40E-03	1.46E-01	7.58E-03	7.81E+00	7.91E-02	2.53E+00	1.08E+00	3.21E-02	7.51E-01	1.77E-01	5.06E+00	1.72E-01	2.97E-01	-1.86E+01	-1.71E+01	-1.87E+01	6.28E-01
45	7.45E-04	1.41E-01	1.43E-03	2.12E+00	6.29E-02	9.13E-01	8.88E+00	2.17E-01	1.09E+00	4.10E-01	1.47E+01	2.55E-01	4.41E-03	-1.77E+01	-1.87E+01	-1.98E+01	8.31E-01
46	7.12E-03	1.73E-01	9.70E-03	3.96E+00	4.00E-02	1.46E+00	1.69E+00	2.93E-01	3.41E+00	5.34E-01	6.44E+00	3.43E-02	2.09E-03	-2.04E+01	-1.83E+01	-2.15E+01	1.15E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
47	2.16E-03	1.18E-01	3.56E-05	7.92E+00	2.64E-02	3.35E+00	7.28E+00	4.34E-02	1.55E-01	4.26E-01	1.35E+01	1.89E-01	8.86E-02	-1.85E+01	-1.81E+01	-2.08E+01	2.60E-01
48	2.66E-04	1.79E-01	4.39E-03	7.88E-01	2.74E-02	3.55E+00	3.21E+00	7.18E-02	2.61E+00	5.41E-01	8.27E+00	1.47E-01	3.77E-01	-1.76E+01	-1.79E+01	-2.00E+01	5.13E-01
49	4.05E-03	1.66E-01	6.78E-04	4.36E+00	5.49E-02	8.49E+00	2.19E+00	2.49E-01	2.17E+00	3.89E-01	1.74E+01	2.47E-01	1.23E-01	-1.92E+01	-1.85E+01	-1.90E+01	9.16E-01
50	9.96E-04	1.75E-01	3.35E-05	5.37E+00	2.92E-01	6.71E+00	1.05E+00	3.32E-02	6.71E+01	1.40E-01	6.78E+00	5.24E-01	2.34E-01	-1.86E+01	-1.88E+01	-1.96E+01	4.26E-01
51	5.47E-03	1.15E-01	2.22E-03	6.69E+00	3.13E-02	3.46E+00	7.22E+00	5.87E-02	2.24E-01	5.92E-01	5.99E+00	6.22E-02	3.93E-01	-1.82E+01	-1.83E+01	-1.84E+01	4.98E-01
52	1.17E-04	1.21E-01	7.34E-05	1.40E+00	4.92E-02	1.87E+00	9.65E+00	1.79E-01	3.64E-01	6.77E-02	5.29E+00	4.83E-01	1.69E-01	-1.77E+01	-1.75E+01	-2.00E+01	5.78E-01
53	3.27E-04	2.31E-01	8.97E-05	1.36E+00	5.70E-02	8.23E+00	7.02E+00	9.49E-02	3.98E+00	5.01E-01	7.94E+00	3.89E-01	1.06E-01	-1.80E+01	-1.86E+01	-1.80E+01	5.62E-01
54	3.76E-04	1.15E-01	5.58E-03	1.01E+00	7.42E-02	4.26E+00	2.96E+00	1.92E-01	6.26E-02	3.22E-01	6.36E+00	4.77E-01	3.02E-01	-2.01E+01	-1.84E+01	-2.00E+01	7.35E-01
55	1.70E-04	1.14E-01	5.27E-05	7.18E+00	2.36E-01	4.14E+00	8.24E-01	6.10E-02	1.63E-01	2.88E-01	9.73E+00	1.50E-01	1.27E-01	-1.98E+01	-1.74E+01	-1.90E+01	2.65E-01
56	8.87E-03	1.50E-01	5.35E-03	5.77E+00	2.19E-01	2.66E+00	4.04E+00	3.19E-01	1.95E+00	2.75E-01	1.57E+01	5.73E-01	1.77E-01	-1.95E+01	-1.80E+01	-1.82E+01	3.47E-01
57	3.58E-04	1.86E-01	7.46E-05	2.55E+00	2.31E-01	2.92E+00	2.59E+00	3.05E-01	9.75E-02	5.19E-01	8.30E+00	3.92E-02	1.31E-02	-1.78E+01	-1.80E+01	-1.88E+01	9.87E-01
58	9.19E-04	1.89E-01	4.17E-05	3.73E+00	8.09E-02	5.33E+00	9.48E+00	3.66E-01	2.80E-01	1.48E-01	1.09E+01	1.86E-01	2.62E-01	-1.73E+01	-1.84E+01	-2.15E+01	4.48E-01
59	2.26E-04	1.74E-01	1.80E-02	2.07E+00	3.24E-01	5.87E+00	1.53E+00	5.55E-02	4.80E+01	4.78E-01	8.17E+00	2.00E-01	1.41E-01	-1.71E+01	-1.82E+01	-2.03E+01	2.15E-01
60	1.83E-04	1.13E-01	3.73E-03	2.16E+00	2.49E-02	7.82E+00	3.62E+00	2.02E-02	7.44E+00	2.17E-01	1.16E+01	2.36E-01	3.40E-01	-1.80E+01	-1.76E+01	-1.85E+01	2.34E-01
61	2.41E-04	2.25E-01	1.41E-02	3.02E+00	4.25E-02	2.63E+00	7.57E-01	2.39E-01	4.56E+01	3.37E-01	7.08E+00	1.82E-01	1.73E-01	-1.88E+01	-1.90E+01	-2.04E+01	7.66E-01
62	5.96E-04	1.63E-01	1.03E-04	2.42E+00	1.16E-01	6.12E+00	3.69E+00	2.07E-02	6.29E+01	3.07E-01	7.30E+00	4.10E-02	2.04E-01	-1.85E+01	-1.84E+01	-2.22E+01	2.09E-01
63	6.91E-04	1.71E-01	4.79E-03	8.81E-01	1.65E-01	6.63E+00	2.08E+00	2.05E-01	6.25E+00	1.83E-01	7.88E+00	4.27E-01	1.51E-01	-1.78E+01	-1.81E+01	-2.01E+01	8.78E-01
64	1.09E-04	1.47E-01	2.95E-03	1.03E+00	8.92E-02	1.88E+00	1.03E+00	9.81E-02	2.79E+01	2.45E-01	7.82E+00	2.80E-01	2.94E-01	-1.82E+01	-1.71E+01	-2.14E+01	5.40E-01
65	9.81E-03	1.16E-01	1.06E-04	5.57E+00	1.19E-01	3.11E+00	1.47E+00	2.86E-01	6.05E+01	5.29E-01	4.44E+00	2.32E-01	1.66E-01	-1.75E+01	-1.83E+01	-1.98E+01	2.47E-01
66	1.52E-04	1.85E-01	7.27E-03	9.51E+00	2.19E-02	5.88E+00	1.01E+00	3.69E-02	3.22E+01	5.98E-01	7.78E+00	3.47E-01	3.33E-01	-1.94E+01	-1.85E+01	-1.99E+01	7.59E-01
67	1.63E-03	1.82E-01	8.06E-04	3.12E+00	9.47E-02	2.40E+00	4.91E+00	2.48E-02	5.89E-02	1.75E-01	6.63E+00	2.09E-01	2.44E-01	-1.96E+01	-1.76E+01	-2.10E+01	3.27E-01
68	1.76E-04	1.17E-01	4.67E-04	1.19E+00	3.38E-01	7.44E+00	2.87E+00	1.35E-01	9.51E+00	5.64E-01	6.84E+00	9.54E-02	2.68E-01	-1.73E+01	-1.80E+01	-2.12E+01	3.54E-01
69	5.01E-03	1.05E-01	3.12E-03	1.22E+00	2.25E-01	7.03E-01	9.80E+00	2.73E-02	5.22E-01	1.17E-01	1.19E+01	4.16E-01	2.82E-01	-1.74E+01	-1.95E+01	-2.01E+01	3.46E-02
70	1.25E-04	1.11E-01	5.90E-03	5.91E+00	3.75E-01	4.73E+00	4.12E+00	3.37E-01	2.08E-01	3.44E-01	6.30E+00	4.92E-01	3.08E-01	-1.72E+01	-1.90E+01	-2.11E+01	3.79E-01
71	2.19E-03	1.08E-01	6.77E-03	1.26E+00	2.22E-02	9.51E+00	7.97E+00	4.67E-02	1.18E+01	4.50E-01	7.47E+00	5.88E-01	1.56E-01	-1.83E+01	-1.85E+01	-2.14E+01	6.61E-01
72	4.25E-03	1.86E-01	1.23E-04	2.51E+00	3.50E-02	1.16E+00	9.13E+00	3.05E-02	6.69E-01	3.03E-01	1.24E+01	4.78E-03	3.31E-01	-1.79E+01	-1.72E+01	-2.19E+01	9.03E-01
73	3.09E-04	1.06E-01	1.95E-04	1.86E+00	1.04E-01	1.56E+00	7.77E-01	1.76E-01	1.06E+00	2.08E-01	1.05E+01	1.53E-01	3.55E-01	-1.94E+01	-1.84E+01	-2.04E+01	1.56E-01
74	3.47E-03	1.28E-01	1.96E-02	8.25E+00	9.91E-02	1.67E+00	1.99E+00	1.87E-01	1.40E+01	1.24E-02	7.60E+00	4.49E-01	4.97E-02	-1.89E+01	-1.83E+01	-2.04E+01	6.37E-01
75	3.00E-04	1.26E-01	4.51E-05	3.24E+00	1.79E-01	3.69E+00	2.56E+00	4.18E-02	5.23E+00	1.66E-01	8.36E+00	7.40E-02	6.00E-02	-1.86E+01	-1.82E+01	-1.87E+01	9.68E-01
76	2.33E-03	1.75E-01	1.58E-04	7.72E-01	7.68E-02	3.25E+00	1.40E+00	7.51E-02	8.44E-02	9.60E-02	1.11E+01	4.46E-01	1.58E-01	-1.80E+01	-1.86E+01	-2.08E+01	2.94E-01
77	6.33E-03	1.57E-01	4.52E-04	1.73E+00	1.12E-01	9.41E+00	3.87E+00	2.32E-02	2.09E+01	1.27E-01	7.23E+00	4.79E-02	3.24E-01	-1.95E+01	-1.92E+01	-2.25E+01	7.95E-01
78	1.70E-03	1.67E-01	6.91E-05	1.95E+00	2.97E-02	7.61E-01	1.90E+00	3.50E-02	1.62E+01	6.03E-02	6.52E+00	1.79E-01	3.95E-02	-1.83E+01	-1.81E+01	-2.02E+01	4.11E-01
79	1.33E-04	1.97E-01	1.11E-03	2.69E+00	3.56E-02	2.06E+00	1.25E+00	4.46E-02	1.31E-01	3.25E-01	6.98E+00	5.31E-01	1.60E-01	-1.85E+01	-1.82E+01	-2.07E+01	8.65E-01
80	2.82E-04	1.03E-01	3.77E-04	7.45E+00	7.05E-02	8.83E+00	5.89E+00	2.46E-01	2.53E+01	1.04E-01	8.95E+00	5.75E-02	3.41E-01	-1.75E+01	-1.72E+01	-2.07E+01	4.88E-02
81	3.26E-03	1.04E-01	2.57E-04	2.01E+00	8.54E-02	5.00E+00	3.83E+00	9.53E-02	1.27E+00	5.71E-01	7.17E+00	7.91E-02	4.51E-02	-1.81E+01	-1.90E+01	-2.05E+01	3.31E-01
82	5.01E-04	1.50E-01	9.95E-04	6.96E+00	4.81E-02	6.49E+00	1.96E+00	4.90E-02	3.01E-01	4.87E-01	2.17E+01	1.93E-01	6.77E-02	-1.90E+01	-1.79E+01	-2.06E+01	7.25E-01
83	1.31E-04	2.49E-01	5.70E-05	8.99E+00	1.69E-01	7.80E-01	5.86E+00	2.69E-02	8.64E+00	3.54E-01	7.67E+00	1.57E-01	2.72E-01	-1.84E+01	-1.84E+01	-1.95E+01	6.28E-02
84	3.90E-04	2.16E-01	1.48E-03	1.07E+00	2.86E-02	4.31E+00	6.66E+00	1.06E-01	1.49E-01	4.45E-01	1.02E+01	4.35E-01	1.36E-01	-1.91E+01	-1.85E+01	-2.16E+01	5.93E-01
85	1.23E-03	1.28E-01	1.34E-04	2.74E+00	1.30E-01	1.11E+00	3.11E+00	5.53E-02	2.39E-01	4.88E-01	6.17E+00	3.72E-01	3.91E-01	-1.78E+01	-1.84E+01	-1.86E+01	2.24E-02
86	1.91E-03	1.65E-01	3.41E-03	8.44E-01	2.09E-01	2.24E+00	2.74E+00	8.14E-02	4.30E-01	1.06E-01	1.13E+01	4.11E-01	3.47E-01	-1.93E+01	-1.74E+01	-1.91E+01	4.31E-01
87	5.05E-04	1.30E-01	1.47E-04	1.63E+00	3.34E-02	7.28E-01	7.52E+00	3.78E-02	5.23E+01	2.85E-01	1.01E+01	3.06E-01	3.40E-02	-1.84E+01	-1.83E+01	-2.13E+01	4.74E-01
88	2.97E-03	1.37E-01	6.37E-05	4.96E+00	6.66E-02	2.95E+00	2.72E+00	1.41E-01	1.39E+00	1.89E-01	1.02E+01	1.41E-01	1.91E-01	-1.72E+01	-1.86E+01	-1.98E+01	6.57E-01
89	1.89E-03	1.33E-01	6.52E-03	9.38E+00	5.24E-02	5.02E+00	1.21E+00	1.15E-01	7.49E-02	2.23E-01	6.69E+00	3.79E-01	1.17E-01	-1.69E+01	-1.78E+01	-2.03E+01	6.82E-01
90	3.83E-03	1.62E-01	3.02E-04	3.43E+00	6.51E-02	9.81E+00	3.03E+00	1.10E-01	5.47E-01	8.52E-02	5.81E+00	6.87E-02	7.73E-02	-1.88E+01	-1.80E+01	-2.10E+01	1.26E-01
91	1.10E-04	1.18E-01	8.63E-03	4.71E+00	1.58E-01	4.81E+00	6.87E+00	1.99E-01	1.70E+01	4.16E-01	8.20E+00	3.23E-01	1.87E-01	-1.90E+01	-1.78E+01	-2.01E+01	6.66E-03
92	9.53E-03	2.36E-01	2.44E-03	3.08E+00	3.61E-01	1.55E+00	9.21E-01	2.45E-02	3.06E+00	4.17E-01	7.59E+00	5.14E-01	2.56E-01	-1.85E+01	-1.73E+01	-2.02E+01	6.02E-01

Table PAR-10. LHS Sampled Values (100 vectors) Replicate 2 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
93	1.18E-03	1.44E-01	7.46E-04	3.46E+00	1.07E-01	2.34E+00	4.18E+00	6.68E-02	3.80E+01	9.03E-02	6.85E+00	3.44E-01	3.67E-01	-1.87E+01	-1.82E+01	-1.87E+01	6.94E-01
94	5.30E-04	1.10E-01	2.03E-04	8.68E+00	2.75E-01	2.00E+00	8.08E-01	9.16E-02	7.83E-02	5.16E-01	1.40E+01	4.05E-01	8.43E-02	-1.84E+01	-1.79E+01	-2.09E+01	9.36E-01
95	1.93E-04	1.32E-01	1.32E-03	1.59E+00	8.33E-02	1.06E+00	1.67E+00	1.69E-01	1.69E+00	4.40E-01	1.14E+01	2.57E-01	2.24E-01	-1.80E+01	-1.78E+01	-2.18E+01	2.85E-01
96	5.11E-03	1.15E-01	1.26E-04	4.16E+00	1.77E-01	7.46E-01	3.54E+00	6.43E-02	5.72E-01	4.94E-01	7.52E+00	3.68E-01	2.90E-01	-1.92E+01	-1.88E+01	-2.07E+01	5.54E-01
97	5.70E-04	2.40E-01	1.27E-02	3.33E+00	6.05E-02	1.40E+00	1.33E+00	7.37E-02	1.07E+01	1.60E-01	1.59E+01	5.47E-01	2.31E-01	-1.76E+01	-1.82E+01	-2.09E+01	3.19E-01
98	1.04E-04	1.01E-01	1.85E-04	1.75E+00	2.90E-02	2.11E+00	1.85E+00	2.39E-02	4.78E+00	4.75E-01	1.05E+01	3.35E-01	7.58E-02	-1.89E+01	-1.81E+01	-1.85E+01	5.01E-01
99	6.86E-03	1.62E-01	1.24E-02	2.32E+00	2.98E-01	5.22E+00	2.33E+00	3.63E-02	2.76E+00	3.65E-01	8.04E+00	5.66E-01	1.99E-01	-1.71E+01	-1.82E+01	-1.95E+01	7.44E-01
100	2.08E-03	1.24E-01	5.50E-04	4.55E+00	2.39E-02	1.79E+00	9.67E-01	4.57E-02	4.59E+00	2.12E-01	8.35E+00	8.74E-02	3.81E-01	-1.80E+01	-1.76E+01	-2.04E+01	8.41E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector Num.	STEEL CORRMCO2	WAS_AREA PROBDEG	WAS_AREA GRATMICI	WAS_AREA GRATMICH	CELLULS FBETA	WAS_AREA SAT_RGAS	WAS_AREA SAT_RBRN	WAS_AREA SAT_WICK	DRZ_PCS PRMX_LOG	CONC_PCS PRMX_LOG	SOLU4 SOLCIM	SOLTH4 SOLCIM	CONC_PCS SAT_RGAS	CONC_PCS SAT_RBRN	CONC_PCS PORE_DIS	S_HALITE POROSITY	S_HALITE PRMX_LOG	S_HALITE COMP_RCK	S_MB139 PRMX_LOG	S_MB139 COMP_RCK	S_MB139 RELP_MOD	S_MB139 SAT_RBRN	S_MB139 SAT_RGAS	S_MB139 PORE_DIS
1	1.50E-15	0.00E+00	3.32E-09	4.55E-10	8.57E-01	9.81E-02	2.56E-01	6.81E-01	-1.75E+01	-1.85E+01	-1.38E-01	2.26E-02	7.95E-02	1.28E-01	1.48E-01	9.34E-03	-2.15E+01	3.76E-11	-1.88E+01	7.45E-11	4.00E+00	7.44E-02	1.40E-02	6.93E-01
2	1.76E-14	0.00E+00	2.90E-09	3.12E-10	7.11E-01	8.22E-02	4.02E-01	4.09E-01	-2.02E+01	-1.93E+01	1.31E-01	-3.43E-01	6.38E-02	1.17E-01	6.59E+00	2.24E-02	-2.27E+01	1.08E-10	-1.94E+01	1.31E-10	4.00E+00	9.81E-02	8.59E-02	6.95E-01
3	2.13E-14	2.00E+00	9.41E-09	1.12E-09	1.33E-01	5.13E-02	9.78E-02	6.32E-01	-1.84E+01	-1.87E+01	-4.24E-02	6.71E-02	1.96E-01	5.93E-01	5.11E-01	4.04E-03	-2.30E+01	1.17E-10	-1.89E+01	7.27E-11	1.00E+00	5.62E-02	8.65E-02	6.75E-01
4	2.54E-14	2.00E+00	5.78E-09	1.25E-09	3.16E-01	1.11E-01	1.90E-01	7.96E-01	-1.88E+01	-1.77E+01	1.17E+00	-1.57E-01	1.31E-01	3.93E-01	7.30E+00	1.14E-02	-2.35E+01	1.68E-10	-1.84E+01	1.09E-11	1.00E+00	9.59E-02	6.68E-02	6.23E-01
5	2.45E-14	0.00E+00	7.65E-09	1.05E-09	3.13E-02	1.29E-01	1.20E-01	5.55E-01	-1.80E+01	-1.77E+01	6.66E-02	-2.71E-01	2.20E-01	1.41E-01	2.74E+00	1.81E-02	-2.22E+01	7.83E-11	-1.81E+01	1.09E-11	4.00E+00	1.17E-01	5.03E-02	6.18E-01
6	4.30E-15	0.00E+00	9.18E-09	3.44E-10	4.73E-01	6.58E-02	1.45E-01	3.80E-01	-1.85E+01	-1.93E+01	9.84E-01	8.37E-01	9.38E-02	6.59E-02	5.56E-01	8.31E-03	-2.17E+01	3.55E-11	-1.95E+01	1.62E-10	4.00E+00	1.03E-01	4.41E-02	6.61E-01
7	1.13E-14	1.00E+00	7.43E-09	4.25E-10	3.22E-01	7.76E-03	3.12E-01	5.68E-02	-1.87E+01	-1.79E+01	7.24E-01	7.85E-01	3.60E-01	1.38E-01	3.38E-01	1.99E-02	-2.26E+01	1.03E-10	-1.87E+01	4.86E-11	4.00E+00	8.64E-02	1.11E-01	6.84E-01
8	7.27E-15	2.00E+00	6.29E-09	1.21E-10	1.80E-01	9.21E-02	4.67E-01	5.81E-01	-1.93E+01	-1.91E+01	-2.44E-01	-2.03E-01	3.30E-01	1.71E-01	6.93E+00	1.28E-02	-2.14E+01	1.80E-11	-1.92E+01	1.08E-10	4.00E+00	1.29E-01	9.64E-02	6.67E-01
9	2.94E-14	1.00E+00	8.46E-09	4.67E-10	2.58E-01	1.35E-01	5.34E-01	1.26E-01	-1.91E+01	-1.86E+01	-1.28E-01	-1.27E-01	3.56E-01	7.09E-02	4.04E-01	1.13E-03	-2.34E+01	1.40E-10	-1.84E+01	3.47E-11	4.00E+00	6.27E-02	6.51E-02	5.82E-01
10	1.29E-14	0.00E+00	3.37E-09	2.06E-10	7.92E-01	3.17E-02	1.73E-01	5.49E-01	-1.85E+01	-1.88E+01	-5.62E-01	-1.06E-01	7.50E-03	3.55E-01	7.68E+00	6.96E-03	-2.34E+01	1.56E-10	-1.96E+01	1.65E-10	1.00E+00	1.06E-01	1.40E-02	6.46E-01
11	2.25E-14	2.00E+00	5.91E-09	2.27E-10	4.84E-01	6.24E-02	4.15E-01	9.14E-02	-1.88E+01	-2.03E+01	-6.04E-02	-3.93E-01	2.69E-01	3.49E-01	3.52E+00	4.43E-03	-2.18E+01	6.23E-11	-1.88E+01	6.72E-11	4.00E+00	8.52E-02	1.18E-01	6.76E-01
12	3.13E-14	2.00E+00	1.17E-09	1.17E-09	6.41E-01	7.06E-02	1.02E-01	7.53E-01	-1.86E+01	-1.93E+01	-9.18E-03	-2.43E-01	1.99E-01	3.02E-01	2.72E-01	3.56E-03	-2.24E+01	7.08E-11	-1.85E+01	3.11E-11	1.00E+00	9.40E-02	6.17E-02	6.39E-01
13	6.29E-16	0.00E+00	5.43E-09	1.09E-09	4.97E-01	1.83E-02	4.86E-01	4.65E-01	-1.98E+01	-2.02E+01	4.41E-01	-3.80E-01	2.12E-01	9.81E-02	1.23E+00	7.95E-03	-2.29E+01	1.30E-10	-1.95E+01	1.68E-10	4.00E+00	4.20E-02	7.41E-02	6.48E-01
14	5.73E-15	0.00E+00	6.56E-09	1.21E-09	9.11E-01	1.07E-01	3.28E-01	4.92E-01	-1.81E+01	-1.96E+01	-2.15E-01	-1.77E-01	3.20E-01	1.16E-01	7.77E-01	1.72E-02	-2.38E+01	1.78E-10	-1.94E+01	1.12E-10	1.00E+00	8.20E-02	1.20E-01	5.46E-01
15	3.16E-14	0.00E+00	7.23E-10	1.12E-09	4.52E-01	4.22E-02	5.21E-01	2.51E-02	-1.81E+01	-1.82E+01	-2.65E-02	-1.13E-01	2.43E-01	2.06E-01	7.58E+00	6.90E-03	-2.27E+01	1.06E-10	-1.89E+01	8.42E-11	4.00E+00	5.80E-02	1.22E-01	5.90E-01
16	2.89E-14	0.00E+00	4.61E-09	3.61E-10	8.39E-01	5.75E-02	2.76E-01	3.01E-01	-1.74E+01	-1.80E+01	-5.43E-01	7.66E-02	2.01E-01	4.95E-02	5.93E+00	1.44E-02	-2.37E+01	1.73E-10	-1.90E+01	8.17E-11	4.00E+00	4.63E-02	4.27E-02	6.59E-01
17	3.09E-14	1.00E+00	5.54E-09	7.81E-10	6.97E-01	1.41E-02	2.26E-01	8.89E-01	-1.88E+01	-1.95E+01	-6.13E-01	5.08E-01	3.87E-01	2.24E-01	7.11E-01	2.01E-02	-2.14E+01	3.42E-11	-1.92E+01	1.56E-10	1.00E+00	1.43E-01	9.51E-02	5.94E-01
18	1.51E-14	0.00E+00	2.85E-09	5.63E-10	4.47E-01	1.06E-01	3.40E-01	1.39E-01	-1.91E+01	-1.86E+01	-1.09E-01	-6.01E-01	3.00E-01	4.89E-01	5.85E-01	7.14E-03	-2.39E+01	1.86E-10	-1.96E+01	1.84E-10	4.00E+00	1.19E-01	5.45E-02	7.06E-01
19	1.62E-14	1.00E+00	2.29E-09	1.19E-09	2.78E-01	1.42E-01	2.97E-02	1.01E-01	-1.88E+01	-1.89E+01	-3.62E-01	-3.81E-02	2.61E-02	8.52E-02	5.26E-01	2.74E-02	-2.23E+01	9.07E-11	-2.01E+01	2.75E-10	1.00E+00	8.91E-02	5.74E-02	6.74E-01
20	2.08E-14	1.00E+00	7.58E-09	8.59E-10	8.60E-01	1.23E-01	1.27E-01	2.09E-01	-1.97E+01	-1.74E+01	-1.66E-01	-1.48E+00	1.55E-01	4.29E-02	8.35E-01	2.28E-03	-2.32E+01	1.39E-10	-1.93E+01	1.36E-10	1.00E+00	7.06E-02	8.77E-02	6.55E-01
21	1.41E-14	0.00E+00	8.72E-09	8.75E-10	5.12E-01	7.93E-02	4.09E-01	3.35E-01	-2.00E+01	-1.94E+01	-1.82E+00	-1.37E-01	1.72E-01	2.10E-01	5.63E-01	2.24E-02	-2.28E+01	1.13E-10	-1.88E+01	7.69E-11	4.00E+00	1.07E-01	4.77E-02	6.72E-01
22	1.44E-14	1.00E+00	5.21E-09	1.16E-09	8.26E-01	2.51E-02	8.22E-02	5.16E-01	-2.03E+01	-1.77E+01	-4.99E-02	-2.54E-01	2.11E-01	4.26E-01	5.58E+00	1.78E-02	-2.13E+01	1.32E-11	-1.78E+01	1.09E-11	4.00E+00	8.42E-02	3.97E-02	6.60E-01
23	4.46E-15	1.00E+00	7.04E-09	5.12E-10	9.31E-01	7.29E-02	4.80E-01	8.31E-01	-1.84E+01	-1.98E+01	-8.07E-02	-2.24E-01	3.08E-01	3.78E-01	6.40E-01	3.88E-03	-2.30E+01	1.30E-10	-1.83E+01	1.94E-11	4.00E+00	5.75E-02	5.66E-02	6.01E-01
24	9.99E-15	0.00E+00	3.93E-09	7.97E-10	5.58E-01	9.01E-02	1.37E-01	4.84E-03	-1.82E+01	-1.92E+01	1.18E-01	-1.87E-02	3.25E-01	2.88E-01	6.49E-01	2.72E-02	-2.31E+01	1.24E-10	-2.06E+01	2.75E-10	4.00E+00	6.35E-02	4.60E-02	6.05E-01
25	1.39E-14	2.00E+00	4.48E-09	6.92E-10	9.86E-01	8.68E-02	5.41E-01	1.50E-02	-2.01E+01	-1.89E+01	2.15E-01	-4.92E-01	1.27E-01	4.96E-01	4.83E-01	9.04E-03	-2.17E+01	5.36E-11	-1.87E+01	5.56E-11	4.00E+00	1.12E-01	7.37E-02	6.27E-01
26	2.11E-14	1.00E+00	8.84E-09	6.51E-10	9.70E-01	7.60E-02	4.97E-01	2.41E-01	-1.86E+01	-1.92E+01	-1.37E+00	-9.98E-02	6.52E-02	5.66E-01	6.16E+00	2.55E-02	-2.19E+01	4.72E-11	-1.83E+01	1.09E-11	1.00E+00	2.11E-02	1.08E-01	6.13E-01
27	3.99E-15	1.00E+00	6.37E-09	8.16E-10	3.85E-01	1.18E-01	4.62E-01	6.67E-01	-1.87E+01	-1.97E+01	5.24E-01	-1.62E-01	4.88E-02	1.97E-01	1.87E+00	3.04E-03	-2.35E+01	1.49E-10	-1.89E+01	9.02E-11	1.00E+00	1.11E-01	6.61E-02	6.58E-01
28	9.15E-15	2.00E+00	5.19E-09	1.06E-09	6.60E-01	9.72E-02	1.79E-01	5.93E-01	-2.04E+01	-1.87E+01	-1.90E-01	-7.36E-01	3.81E-01	4.33E-01	5.46E+00	2.98E-02	-2.29E+01	1.15E-10	-2.00E+01	2.18E-10	1.00E+00	7.35E-02	2.84E-02	6.47E-01
29	7.86E-15	0.00E+00	2.75E-09	5.83E-10	7.77E-01	7.66E-02	4.76E-01	2.15E-01	-1.81E+01	-1.84E+01	-2.98E-02	2.22E-01	2.99E-01	3.86E-02	3.73E+00	2.41E-02	-2.24E+01	1.00E-10	-1.90E+01	9.76E-11	1.00E+00	1.00E-01	7.84E-02	6.09E-01
30	1.28E-16	2.00E+00	1.34E-09	1.03E-09	5.47E-02	1.16E-01	4.16E-02	4.56E-01	-1.96E+01	-1.89E+01	3.09E-01	4.06E-01	1.76E-01	1.55E-01	6.19E-01	3.28E-03	-2.14E+01	2.23E-11	-1.92E+01	1.42E-10	4.00E+00	5.03E-02	7.21E-02	4.91E-01
31	2.95E-14	1.00E+00	4.37E-09	4.90E-10	7.86E-01	5.28E-02	5.93E-02	3.25E-01	-1.98E+01	-2.00E+01	-1.51E-01	1.34E+00	3.91E-01	4.66E-01	2.46E-01	1.01E-02	-2.16E+01	4.22E-11	-1.75E+01	1.09E-11	4.00E+00	9.73E-02	1.09E-01	5.82E-01
32	5.13E-15	0.00E+00	8.98E-10	8.99E-10	4.30E-01	1.00E-01	5.29E-01	6.52E-01	-1.80E+01	-1.86E+01	-7.84E-01	8.62E-01	3.18E-01	3.85E-01	6.59E-01	5.79E-03	-2.37E+01	1.71E-10	-1.87E+01	4.59E-11	1.00E+00	8.46E-02	7.95E-02	7.32E-01
33	2.61E-14	0.00E+00	3.18E-09	1.02E-09	6.20E-01	1.31E-01	1.22E-01	3.12E-01	-1.91E+01	-1.91E+01	4.74E-01	1.24E-01	8.90E-02	1.51E-01	8.45E-01	2.71E-03	-2.20E+01	5.59E-11	-1.94E+01	1.44E-10	1.00E+00	6.45E-02	7.51E-02	7.24E-01
34	2.70E-14	1.00E+00	5.36E-09	2.45E-10	4.26E-02	2.76E-02	3.25E-01	1.54E-01	-1.79E+01	-1.93E+01	-8.67E-01	-4.34E-01	2.20E-01	7.89E-03	3.21E-01	1.58E-03	-2.20E+01	7.26E-11	-1.96E+01	2.30E-10	4.00E+00	6.78E-02	1.72E-02	6.21E-01
35	6.75E-15	0.00E+00	1.53E-09	9.83E-10	5.87E-01	9.57E-02	4.39E-01	9.39E-01	-1.77E+01	-1.84E+01	2.26E-01	-1.77E+00	2.34E-01	5.56E-01	3.65E-01	6.29E-03	-2.12E+01	1.56E-11	-1.93E+01	1.26E-10	1.00E+00	8.00E-02	1.97E-01	7.53E-01
36	1.55E-14	2.00E+00	1.71E-09	8.37E-10	6.83E-01	3.71E-03	1.39E-01	5.27E-01	-1.90E+01	-1.83E+01	-7.11E-01	-1.92E-01	3.67E-01	2.53E-01	6.90E-01	5.02E-03	-2.37E+01	1.81E-10	-1.88E+01	6.91E-11	1.00E+00	1.14E-01	6.03E-02	8.42E-01
37	1.81E-14	0.00E+00	4.87E-09	1.22E-09	9.49E-01	4.07E-02	2.27E-01	9.88E-01	-1.91E+01	-1.96E+01	7.83E-01	-1.72E-01	2.83E-01	1.77E-03	7.50E+00	1.43E-02	-2.38E+01	1.76E-10	-1.87E+01	6.63E-11	1.00E+00	1.02E-01	6.00E-02	7.42E-01
38	2.19E-14	2.00E+00	3.80E-09	6.11E-11	1.89E-02	1.77E-02	3.81E-01	6.28E-01	-1.83E+01	-1.89E+01	2.11E-01	-2.09E-01	1.67E-01	5.93E-02	5.01E+00	2.92E-03	-2.39E+01	1.87E-10	-1.71E+01	1.09E-11	4.00E+00	5.99E-02	6.71E-02	6.51E-01
39	6.40E-15	2.00E+00	3.90E-10	4.13E-10	8.78E-01	1.50E-01	2.98E-01	2.33E-01	-2.00E+01	-1.81E+01	-2.16E-01	-5.84E-02	7.06E-02	4.83E-01	4.30E+00	1.35E-03	-2.29E+01	1.26E-10	-1.93E+01	1.48E-10	1.00E+00	6.59E-02	3.24E-02	6.16E-01
40	2.31E-14	1.00E+00	7.20E-09	6.99E-10	6.70E-01	1.02E-01	3.54E-01	9.72E-01	-1.95E+01	-1.85E+01	-4.90E-01	-7.92E-01	2.85E-01	1.91E-01	2.79E-01	1.75E-02	-2.34E+01	1.64E-10	-1.94E+01	1.28E-10	1.00E+00	7.45E-02	7.60E-02	5.73E-01
41	1.15E-14	1.00E+00	3.85E-09	8.02E-10	3.59E-01	3.40E-02	8.64E-02	7.13E-02	-1.81E+01	-1.82E+01	-7.73E-01	-3.39E-01	2.59E-01	5.42E-02	5.74E+00	1.88E-02	-2.10E+01	4.83E-12	-1.73E+01	1.09E-11	1.00E+00	4.71E-02	9.16E-02	7.14E-01
42	2.99E-14	2.00E+00	2.38E-09	5.00E-10	8.41E-01	1.04E-01	3.92E-01	3.62E-01	-1.89E+01	-1.88E+01	-8.84E-02	6.95E-01	5.74E-02	1.62E-01	1.39E-01	1.50E-02	-2.16E+01	4.44E-11	-1.87E+01	6.23E-11	4.00E+00	2.48E-02	7.69E-02	6.78E-01
43	2.52E-14	0.00E+00	8.19E-09	9.29E-10	9.67E-02	5.88E-02	2.07E-01	1.67E-01	-1.85E+01	-1.94E+01	9.20E-02	-6.80E-01	2.38E-01	1.93E-01	2.98E-01	2.33E-02	-2.31E+01	1.36E-10	-1.91E+01	1.18E-10	1.00E+00	8.81E-02	9.48E-02	7.41E-01
44	2.49E-14	0.00E+00	9.11E-09	1.42E-11	1.55E-01	1.12E-01	1.61E-02	2.77E-01	-1.97E+01	-1.87E+01	-3.13E-01	5.03E-02	3.16E-01	2.58E-01	4.14E+00	1.62E-02	-2.26E+01	9.41E-11	-1.84E+01	1.34E-11	1.00E+00	9.34E-02	4.14E-02	6.92E-01
45	8.42E-16	0.00E+00	8.96E-09	5.41E-10	3.32E-01	5.05E-02	2.04E-01	3.85E-01	-1.92E+01	-1.80E+01	-3.52E-01	7.18E-01	2.50E-01	5.07E-01	9.35E-01	9.77E-03	-2.40E+01	1.91E-10	-1.95E+01	1.78E-10	1.00E+00	8.67E-02	8.39E-02	7.01E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
46	9.68E-15	1.00E+00	3.60E-09	8.26E-10	8.93E-01	2.03E-02	2.35E-01	7.15E-01	-1.95E+01	-1.79E+01	8.12E-01	2.43E-01	2.75E-01	2.01E-02	8.83E-01	5.98E-03	-2.15E+01	2.77E-11	-1.85E+01	5.08E-11	4.00E+00	1.33E-01	8.50E-02	6.50E-01
47	1.34E-14	0.00E+00	8.67E-09	7.36E-10	3.69E-01	6.75E-02	1.61E-01	4.83E-02	-1.89E+01	-2.01E+01	-2.23E-01	5.67E-01	2.39E-02	1.65E-01	6.29E+00	1.90E-02	-2.11E+01	8.40E-12	-1.88E+01	8.94E-11	1.00E+00	7.30E-02	1.13E-01	6.32E-01
48	1.84E-14	0.00E+00	8.33E-09	4.01E-10	5.08E-01	1.02E-01	2.11E-01	1.71E-01	-1.77E+01	-1.86E+01	-4.06E-02	1.19E-01	1.63E-01	5.51E-01	3.11E+00	5.64E-03	-2.25E+01	9.93E-11	-1.86E+01	5.47E-11	1.00E+00	1.26E-01	6.35E-02	5.72E-01
49	2.80E-15	2.00E+00	1.30E-09	2.80E-10	1.05E-01	3.07E-02	7.64E-02	7.85E-01	-1.73E+01	-1.85E+01	-9.08E-01	-2.19E-01	3.46E-01	2.57E-02	8.95E-01	3.49E-03	-2.13E+01	1.94E-11	-1.86E+01	3.61E-11	1.00E+00	9.98E-02	1.03E-01	5.35E-01
50	2.84E-14	0.00E+00	4.77E-09	1.91E-10	2.37E-01	1.09E-01	5.44E-01	4.33E-01	-1.93E+01	-2.05E+01	6.27E-01	-6.60E-01	2.44E-01	2.85E-02	1.91E-01	2.87E-02	-2.25E+01	9.36E-11	-1.84E+01	1.09E-11	1.00E+00	8.55E-02	2.16E-02	7.04E-01
51	9.36E-15	2.00E+00	8.59E-09	2.60E-10	2.05E-01	1.34E-01	3.63E-01	9.52E-01	-1.84E+01	-1.76E+01	-3.33E-01	1.99E-01	1.85E-01	3.18E-01	5.28E+00	2.48E-02	-2.14E+01	2.98E-11	-1.91E+01	9.86E-11	4.00E+00	6.96E-02	7.14E-02	7.86E-01
52	1.07E-14	0.00E+00	5.71E-09	5.01E-11	7.53E-02	3.68E-02	4.49E-01	6.47E-01	-1.95E+01	-2.00E+01	7.25E-02	-4.25E-02	1.36E-02	1.76E-01	4.43E+00	1.54E-02	-2.36E+01	1.45E-10	-1.91E+01	1.24E-10	1.00E+00	1.09E-01	7.88E-02	6.12E-01
53	7.31E-15	0.00E+00	8.08E-09	1.50E-10	8.07E-01	4.46E-02	2.52E-01	1.99E-01	-1.86E+01	-1.89E+01	5.54E-01	1.90E-01	1.72E-01	4.72E-01	7.00E-01	2.17E-02	-2.40E+01	1.88E-10	-1.79E+01	1.09E-11	4.00E+00	5.24E-02	1.36E-01	6.20E-01
54	2.73E-14	0.00E+00	6.42E-09	5.49E-10	9.69E-01	1.25E-01	2.39E-02	5.06E-01	-1.71E+01	-1.94E+01	2.76E-01	-1.97E-01	3.13E-02	3.73E-01	4.01E+00	4.20E-03	-2.16E+01	5.13E-11	-1.89E+01	9.28E-11	1.00E+00	7.83E-02	1.00E-01	6.25E-01
55	8.01E-15	1.00E+00	5.09E-09	3.32E-10	1.40E-01	7.03E-02	2.38E-01	2.69E-01	-1.78E+01	-1.95E+01	-1.96E-01	-4.17E-01	3.41E-01	4.66E-02	7.92E-01	1.22E-02	-2.19E+01	6.36E-11	-1.80E+01	1.09E-11	1.00E+00	8.13E-02	1.40E-02	6.11E-01
56	2.68E-14	0.00E+00	4.91E-10	8.68E-10	3.44E-01	4.66E-02	3.20E-01	9.49E-01	-1.99E+01	-1.97E+01	-1.14E+00	2.29E-01	5.29E-02	3.07E-01	4.10E-01	1.05E-02	-2.12E+01	8.90E-12	-1.85E+01	1.09E-11	1.00E+00	7.74E-02	2.48E-02	6.36E-01
57	1.67E-14	0.00E+00	6.02E-09	1.24E-09	4.68E-01	7.43E-02	2.79E-01	3.14E-02	-1.90E+01	-2.00E+01	-1.77E-01	-1.16E+00	2.30E-01	2.46E-01	1.70E+00	8.17E-03	-2.35E+01	1.66E-10	-1.87E+01	5.88E-11	4.00E+00	9.51E-02	8.91E-02	5.20E-01
58	1.30E-14	2.00E+00	3.53E-09	6.19E-10	9.55E-01	2.96E-02	1.14E-01	7.77E-01	-1.82E+01	-1.81E+01	1.88E-01	-1.87E-01	7.54E-02	1.23E-01	7.73E-01	2.92E-02	-2.33E+01	1.42E-10	-1.88E+01	6.09E-11	4.00E+00	1.58E-01	9.29E-02	5.53E-01
59	2.28E-14	0.00E+00	3.65E-09	6.43E-11	1.70E-01	1.07E-02	1.94E-01	8.46E-01	-1.96E+01	-1.83E+01	9.03E-01	-9.32E-02	3.79E-01	4.15E-01	3.88E-01	2.61E-02	-2.21E+01	6.81E-11	-1.92E+01	1.10E-10	1.00E+00	4.11E-02	7.28E-02	4.91E-01
60	1.23E-14	1.00E+00	2.53E-09	4.81E-10	8.85E-01	6.13E-02	4.70E-02	1.14E-01	-1.82E+01	-1.83E+01	1.57E-01	-3.05E-01	3.90E-02	1.55E-02	9.85E-01	2.58E-02	-2.23E+01	8.18E-11	-1.86E+01	4.46E-11	4.00E+00	6.67E-02	8.28E-02	7.15E-01
61	1.92E-14	2.00E+00	2.23E-09	7.11E-10	2.67E-01	8.73E-02	4.26E-01	4.15E-01	-1.78E+01	-1.99E+01	-6.26E-02	3.42E-01	1.18E-01	4.55E-01	2.99E+00	9.49E-03	-2.39E+01	1.82E-10	-1.80E+01	1.09E-11	4.00E+00	9.68E-02	5.62E-02	6.98E-01
62	5.50E-15	2.00E+00	4.92E-09	3.83E-10	5.26E-01	1.39E-01	5.05E-01	3.44E-01	-1.84E+01	-1.91E+01	-2.83E-01	-1.24E-01	3.57E-01	3.63E-01	7.08E+00	5.44E-03	-2.10E+01	4.63E-12	-1.91E+01	1.04E-10	1.00E+00	9.91E-02	6.81E-02	7.76E-01
63	3.38E-15	1.00E+00	6.10E-09	3.18E-10	5.38E-01	1.13E-01	1.70E-01	7.67E-01	-1.97E+01	-1.85E+01	-3.84E-01	-5.29E-02	1.33E-01	1.87E-01	2.26E-01	6.60E-03	-2.37E+01	1.83E-10	-1.81E+01	1.09E-11	4.00E+00	7.78E-03	1.14E-01	7.21E-01
64	1.04E-14	0.00E+00	6.65E-10	1.10E-09	3.05E-01	1.33E-01	1.78E-02	4.29E-01	-1.89E+01	-1.99E+01	-1.40E-01	6.42E-01	9.75E-02	4.07E-01	3.86E+00	7.32E-03	-2.34E+01	1.59E-10	-1.79E+01	1.09E-11	4.00E+00	1.74E-01	1.00E-01	6.63E-01
65	2.31E-14	1.00E+00	8.26E-09	5.31E-10	5.78E-01	1.27E-01	8.96E-02	9.06E-01	-1.86E+01	-1.88E+01	-4.04E-01	-9.15E-01	1.51E-01	7.42E-02	6.05E-01	1.46E-03	-2.15E+01	3.96E-11	-2.09E+01	2.75E-10	4.00E+00	1.22E-01	9.37E-02	6.44E-01
66	2.42E-14	0.00E+00	1.99E-09	4.37E-10	1.25E-01	9.43E-02	5.49E-01	8.91E-01	-1.93E+01	-1.82E+01	1.99E-01	-3.24E-02	2.63E-01	1.81E-01	1.96E-01	1.19E-02	-2.11E+01	1.11E-11	-1.95E+01	1.49E-10	1.00E+00	9.13E-02	8.83E-02	6.52E-01
67	1.96E-14	1.00E+00	1.48E-09	2.72E-11	2.19E-01	1.21E-01	6.61E-02	1.40E-01	-1.91E+01	-1.81E+01	-4.71E-01	-5.23E-01	2.95E-01	4.47E-01	4.33E-01	2.29E-02	-2.38E+01	1.74E-10	-1.92E+01	1.39E-10	4.00E+00	9.21E-02	8.24E-02	6.01E-01
68	2.40E-14	0.00E+00	4.36E-09	1.08E-09	2.85E-01	6.78E-04	5.01E-01	6.10E-01	-1.99E+01	-1.75E+01	-1.55E+00	-2.45E-02	2.26E-01	1.58E-01	2.24E+00	1.72E-03	-2.33E+01	1.49E-10	-1.97E+01	1.90E-10	4.00E+00	1.08E-01	1.72E-01	6.53E-01
69	1.74E-15	1.00E+00	6.95E-09	9.06E-10	8.35E-02	8.98E-02	4.08E-01	8.71E-01	-1.93E+01	-1.97E+01	-1.18E-01	-4.98E-03	9.51E-04	7.70E-02	7.57E-01	9.90E-03	-2.18E+01	6.07E-11	-1.89E+01	7.85E-11	1.00E+00	1.01E-01	1.51E-01	5.60E-01
70	1.24E-14	0.00E+00	1.09E-09	5.91E-10	1.13E-01	4.63E-02	4.24E-01	9.17E-01	-1.90E+01	-1.74E+01	-1.67E-01	-1.48E-01	1.04E-01	5.77E-01	6.77E+00	2.96E-02	-2.21E+01	6.67E-11	-1.82E+01	2.15E-11	4.00E+00	7.20E-02	5.85E-02	6.04E-01
71	2.18E-14	0.00E+00	6.74E-09	1.19E-09	6.59E-01	1.57E-02	1.06E-01	8.30E-01	-1.85E+01	-1.90E+01	-1.23E-01	3.14E-02	1.04E-01	1.25E-01	7.29E-01	6.09E-03	-2.21E+01	8.32E-11	-1.85E+01	2.80E-11	1.00E+00	6.53E-02	6.38E-02	6.66E-01
72	3.02E-14	0.00E+00	8.68E-10	1.66E-10	2.26E-01	2.36E-02	4.74E-03	9.66E-01	-1.82E+01	-2.02E+01	-2.50E-01	-3.69E-01	3.57E-02	5.35E-01	4.93E+00	8.51E-03	-2.36E+01	1.64E-10	-1.92E+01	1.34E-10	4.00E+00	8.07E-02	1.26E-01	7.09E-01
73	1.57E-14	1.00E+00	6.66E-09	2.32E-10	6.19E-01	5.61E-02	3.03E-01	5.75E-01	-2.05E+01	-1.88E+01	-1.53E-01	-1.00E+00	8.49E-02	1.47E-01	3.29E+00	1.28E-02	-2.13E+01	2.52E-11	-1.76E+01	1.09E-11	1.00E+00	6.97E-02	8.05E-02	6.68E-01
74	3.07E-14	2.00E+00	4.20E-09	1.86E-10	8.11E-01	3.84E-02	3.52E-01	2.29E-01	-1.94E+01	-1.90E+01	8.83E-01	9.89E-01	1.84E-01	3.41E-01	2.41E+00	6.40E-03	-2.15E+01	3.21E-11	-2.02E+01	1.97E-10	1.00E+00	7.16E-02	9.82E-02	6.88E-01
75	2.91E-15	1.00E+00	7.72E-09	1.13E-09	2.11E-02	1.41E-01	3.80E-01	4.79E-01	-1.88E+01	-1.81E+01	-1.01E-01	9.14E-01	2.89E-01	6.30E-02	7.83E+00	7.66E-03	-2.19E+01	4.97E-11	-1.89E+01	7.99E-11	4.00E+00	8.03E-02	7.09E-02	6.41E-01
76	1.69E-14	0.00E+00	5.58E-10	7.48E-10	2.42E-01	1.38E-01	3.34E-01	8.59E-01	-1.90E+01	-1.94E+01	6.78E-01	2.08E-01	3.04E-01	5.22E-01	9.17E-01	4.31E-03	-2.31E+01	1.43E-10	-1.86E+01	6.44E-11	1.00E+00	6.03E-02	6.24E-02	6.40E-01
77	2.04E-14	0.00E+00	3.02E-09	9.13E-10	4.12E-01	1.48E-01	6.84E-02	6.96E-01	-1.80E+01	-1.92E+01	4.79E-02	1.69E-01	3.76E-01	4.58E-01	5.05E-01	2.79E-02	-2.25E+01	9.56E-11	-1.90E+01	1.14E-10	4.00E+00	1.12E-01	1.06E-01	6.86E-01
78	2.59E-14	0.00E+00	1.89E-09	1.64E-10	3.98E-01	4.93E-02	1.51E-01	8.97E-02	-1.86E+01	-1.78E+01	3.55E-01	-2.34E-01	1.41E-01	3.33E-01	6.40E+00	1.39E-02	-2.11E+01	2.15E-11	-1.98E+01	2.06E-10	1.00E+00	8.35E-02	6.87E-02	6.30E-01
79	2.78E-14	0.00E+00	7.30E-09	1.01E-09	2.96E-01	1.23E-01	3.88E-01	9.29E-01	-1.92E+01	-1.90E+01	-2.43E-01	-7.66E-02	1.91E-01	1.88E-02	8.12E-01	2.47E-02	-2.24E+01	1.11E-10	-1.90E+01	9.40E-11	4.00E+00	5.06E-02	1.02E-01	6.33E-01
80	1.61E-14	0.00E+00	1.69E-09	6.74E-10	9.03E-01	6.43E-02	2.68E-01	3.51E-01	-1.94E+01	-1.78E+01	-1.83E-01	2.85E-01	2.05E-01	3.56E-02	6.03E+00	5.19E-03	-2.33E+01	1.61E-10	-1.87E+01	5.17E-11	4.00E+00	9.05E-02	5.40E-02	5.98E-01
81	1.90E-14	2.00E+00	3.13E-09	9.65E-10	6.08E-02	1.05E-02	4.73E-01	6.03E-02	-1.83E+01	-1.72E+01	-9.37E-02	-6.30E-02	1.75E-02	5.70E-01	1.17E-01	8.83E-03	-2.32E+01	1.33E-10	-1.91E+01	1.05E-10	4.00E+00	9.26E-02	7.02E-02	6.07E-01
82	1.73E-14	1.00E+00	6.94E-09	6.06E-10	7.68E-01	8.52E-02	4.53E-01	9.91E-01	-1.79E+01	-1.92E+01	1.43E-01	-6.98E-02	3.93E-01	1.07E-01	8.05E+00	1.67E-02	-2.36E+01	1.50E-10	-1.98E+01	2.48E-10	1.00E+00	3.66E-02	5.12E-02	5.96E-01
83	3.80E-15	0.00E+00	4.04E-09	8.90E-11	9.22E-01	2.16E-02	2.17E-01	4.47E-01	-1.94E+01	-1.91E+01	2.41E-02	1.49E-01	4.07E-02	1.76E-01	8.62E-01	4.87E-03	-2.22E+01	8.59E-11	-1.93E+01	1.53E-10	4.00E+00	7.94E-02	8.97E-02	6.26E-01
84	8.34E-15	0.00E+00	2.52E-09	1.17E-11	7.53E-01	1.44E-01	6.88E-03	7.20E-01	-1.96E+01	-1.90E+01	2.28E-02	-2.95E-01	3.99E-01	2.76E-01	2.66E+00	2.02E-03	-2.29E+01	1.20E-10	-1.91E+01	8.53E-11	4.00E+00	6.14E-02	1.07E-01	5.86E-01
85	2.50E-15	2.00E+00	5.58E-09	1.05E-10	7.33E-01	7.34E-03	2.60E-01	2.82E-01	-1.87E+01	-1.87E+01	1.74E-01	-8.70E-01	2.79E-01	2.81E-01	4.56E+00	7.69E-03	-2.22E+01	7.40E-11	-1.83E+01	2.46E-11	4.00E+00	1.03E-01	9.09E-02	6.90E-01
86	4.90E-15	0.00E+00	6.11E-09	9.43E-10	5.51E-03	6.86E-02	3.61E-02	4.84E-01	-1.95E+01	-1.83E+01	2.42E-01	-1.64E+00	1.59E-01	1.12E-01	4.56E-01	2.08E-02	-2.21E+01	7.98E-11	-1.82E+01	1.09E-11	4.00E+00	8.30E-02	8.40E-02	6.28E-01
87	6.18E-15	2.00E+00	6.85E-09	8.18E-11	5.67E-01	2.68E-02	1.60E-01	8.62E-01	-1.87E+01	-1.96E+01	-4.11E-01	1.37E-01	1.00E-02	5.14E-01	4.71E-01	1.58E-02	-2.27E+01	1.21E-10	-1.90E+01	8.71E-11	1.00E+00	8.75E-02	3.59E-02	5.45E-01
88	2.02E-14	0.00E+00	8.99E-09	2.95E-10	4.35E-01	1.19E-01	2.88E-01	8.16E-01	-1.90E+01	-1.74E+01	1.07E-01	1.17E-02	1.14E-01	1.36E-01	2.91E+00	2.59E-03	-2.27E+01	1.23E-10	-1.85E+01	4.13E-11	1.00E+00	8.85E-02	1.32E-01	6.81E-01
89	2.64E-14	2.00E+00	4.17E-09	2.68E-10	3.74E-01	7.99E-02	3.72E-01	5.39E-01	-1.83E+01	-1.86E+01	-1.76E-02	9.35E-02	1.48E-01	9.48E-02	2.22E+00	1.95E-02	-2.26E+01	1.04E-10	-1.97E+01	2.56E-10	4.00E+00	7.59E-02	1.31E-01	6.56E-01
90	1.19E-14	0.00E+00	7.32E-09	1.27E-09	1.96E-01	1.28E-02	2.86E-01	2.58E-01	-1.89E+01	-1.98E+01	-6.79E-03	-4.60E-01	3.37E-01	5.86E-01	7.16E+00	2.12E-03	-2.12E+01	2.71E-11	-1.88E+01	7.03E-11	4.00E+00	7.80E-02	5.31E-02	6.31E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25
Vector	STEEL	WAS_AREA	WAS_AREA	WAS_AREA	CELLULS	WAS_AREA	WAS_AREA	WAS_AREA	DRZ_PCS	CONC_PCS	SOLU4	SOLTH4	CONC_PCS	CONC_PCS	CONC_PCS	S_HALITE	S_HALITE	S_HALITE	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139	S_MB139
Num.	CORRMCO2	PROBDEG	GRATMICI	GRATMICH	FBETA	SAT_RGAS	SAT_RBRN	SAT_WICK	PRMX_LOG	PRMX_LOG	SOLCIM	SOLCIM	SAT_RGAS	SAT_RBRN	PORE_DIS	POROSITY	PRMX_LOG	COMP_RCK	PRMX_LOG	COMP_RCK	RELP_MOD	SAT_RBRN	SAT_RGAS	PORE_DIS
91	2.82E-14	0.00E+00	7.81E-09	1.32E-10	7.43E-01	5.46E-02	3.06E-01	7.08E-01	-1.76E+01	-1.84E+01	-7.52E-02	-2.47E-01	8.13E-02	2.37E-01	4.70E+00	2.66E-02	-2.18E+01	5.94E-11	-1.90E+01	1.02E-10	4.00E+00	9.45E-02	8.11E-02	5.66E-01
92	2.87E-14	2.00E+00	9.48E-09	6.32E-10	4.01E-01	1.44E-01	4.44E-01	6.18E-01	-1.92E+01	-1.83E+01	1.38E-01	9.71E-02	2.56E-01	2.67E-01	1.57E+00	1.36E-02	-2.31E+01	1.53E-10	-1.91E+01	1.17E-10	1.00E+00	1.16E-01	3.41E-02	5.76E-01
93	1.80E-14	2.00E+00	2.67E-09	3.76E-10	7.24E-01	4.00E-02	5.11E-01	6.70E-01	-1.85E+01	-1.84E+01	1.73E-04	-8.59E-02	1.37E-01	8.22E-02	2.42E-01	1.12E-02	-2.30E+01	1.09E-10	-1.84E+01	3.04E-11	1.00E+00	1.27E-01	3.72E-02	6.64E-01
94	1.01E-15	2.00E+00	1.00E-09	9.56E-10	1.86E-01	4.58E-03	1.85E-01	2.98E-01	-1.79E+01	-1.96E+01	-2.32E-01	4.40E-02	3.71E-01	9.16E-02	2.03E+00	2.81E-02	-2.28E+01	1.33E-10	-1.99E+01	1.74E-10	1.00E+00	7.64E-02	1.16E-01	6.71E-01
95	1.98E-14	1.00E+00	2.09E-09	6.68E-10	5.42E-01	1.46E-01	3.69E-01	1.85E-01	-2.00E+01	-1.88E+01	-9.87E-01	4.57E-01	2.64E-01	1.12E-02	5.10E+00	2.14E-02	-2.32E+01	1.56E-10	-1.82E+01	1.09E-11	1.00E+00	8.99E-02	1.40E-01	5.90E-01
96	1.47E-14	0.00E+00	7.93E-09	9.90E-10	5.91E-01	2.90E-03	2.47E-01	7.39E-01	-1.87E+01	-1.89E+01	-2.06E-01	-1.15E-02	3.33E-01	3.25E-01	3.49E+00	4.66E-03	-2.20E+01	7.59E-11	-1.89E+01	9.58E-11	1.00E+00	7.56E-02	1.40E-02	6.37E-01
97	8.78E-15	0.00E+00	1.83E-09	7.69E-10	6.32E-01	8.37E-02	4.34E-01	5.60E-01	-1.89E+01	-1.79E+01	3.62E-02	1.67E-01	1.10E-01	2.22E-01	1.20E+00	2.05E-02	-2.17E+01	5.55E-11	-1.89E+01	1.08E-10	4.00E+00	5.50E-02	4.87E-02	6.43E-01
98	2.37E-14	0.00E+00	9.27E-09	1.15E-09	7.01E-01	3.56E-02	5.00E-02	8.06E-01	-1.92E+01	-1.87E+01	-2.86E-01	3.58E-01	1.23E-01	1.01E-01	3.59E-01	8.60E-03	-2.25E+01	8.90E-11	-1.93E+01	1.21E-10	1.00E+00	3.29E-02	7.75E-02	6.79E-01
99	1.09E-14	1.00E+00	4.65E-09	7.51E-10	6.06E-01	1.28E-01	5.14E-01	7.41E-01	-1.75E+01	-1.91E+01	-4.43E-01	-4.81E-01	4.53E-02	4.22E-01	1.45E+00	2.38E-02	-2.23E+01	8.70E-11	-1.86E+01	3.92E-11	4.00E+00	6.84E-02	1.04E-01	6.35E-01
100	2.07E-15	0.00E+00	7.96E-09	6.35E-10	9.99E-01	1.14E-01	3.43E-01	3.98E-01	-1.76E+01	-1.80E+01	-4.61E-01	-1.44E-01	3.51E-01	5.39E-01	1.65E-01	9.19E-03	-2.19E+01	4.63E-11	-1.83E+01	1.09E-11	1.00E+00	1.05E-01	9.71E-02	6.17E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector Num.	S_HALITE PRESSURE	CASTILER PRESSURE	CASTILER PRMX_LOG	CASTILER COMP_RCK	BH_SAND PRMX_LOG	DRZ_1 PRMX_LOG	CONC_PLG PRMX_LOG	SOLAM3 SOLSIM	SOLAM3 SOLCIM	SOLPU3 SOLSIM	SOLPU3 SOLCIM	SOLPU4 SOLSIM	SOLPU4 SOLCIM	SOLU4 SOLSIM	SOLU6 SOLSIM	SOLU6 SOLCIM	SOLTH4 SOLSIM	PHUMOX3 PHUMCIM	GLOBAL OXSTAT	CULEBRA MINP_FAC	GLOBAL TRANSIDX	GLOBAL CLIMTIDX	CULEBRA HMBLKLT
1	1.31E+07	1.41E+07	-1.32E+01	4.35E-11	-1.38E+01	-1.51E+01	-1.73E+01	-1.97E+00	1.98E-01	-3.81E-01	-1.94E-02	-1.81E-01	-7.97E-01	6.61E-02	-1.83E-01	-4.80E-01	-4.56E-01	1.40E+00	2.34E-01	1.35E+01	4.49E-01	1.00E+00	1.44E-01
2	1.19E+07	1.41E+07	-1.01E+01	3.45E-11	-1.33E+01	-1.34E+01	-1.88E+01	-2.10E-01	-1.31E-01	6.16E-02	-6.85E-02	9.58E-01	1.11E-01	-4.63E-01	-1.78E+00	-2.12E-01	-1.44E-01	1.45E+00	8.50E-01	2.02E+02	8.04E-01	1.07E+00	4.04E-01
3	1.22E+07	1.34E+07	-1.27E+01	4.20E-11	-1.50E+01	-1.66E+01	-1.86E+01	8.67E-02	5.27E-01	-1.10E-02	-7.58E-02	1.42E-01	-3.97E-01	-3.17E-01	2.42E-01	2.72E-01	-1.28E-01	1.37E+00	4.30E-01	9.36E+02	5.24E-01	1.10E+00	3.71E-01
4	1.24E+07	1.48E+07	-1.35E+01	6.39E-11	-1.54E+01	-1.89E+01	-1.83E+01	-2.21E-01	-9.25E-01	5.33E-02	-5.83E-01	-1.67E-01	-3.29E-01	2.30E-01	-2.60E-01	1.54E-01	-4.23E-01	1.49E+00	4.07E-01	8.57E+01	8.63E-01	1.19E+00	4.40E-01
5	1.27E+07	1.57E+07	-1.25E+01	4.61E-11	-1.17E+01	-1.67E+01	-1.81E+01	3.05E-01	2.87E-02	-4.96E-01	1.95E-01	7.33E-01	-2.45E-01	-1.67E-01	-2.50E-01	-1.15E-01	-2.97E-01	3.89E-01	6.06E-01	3.92E+02	1.57E-03	1.09E+00	1.37E-01
6	1.19E+07	1.44E+07	-1.15E+01	6.13E-11	-1.62E+01	-1.82E+01	-1.70E+01	-1.81E-01	-4.18E-01	2.15E-01	-2.27E-01	-1.08E-01	-5.36E-01	-1.56E+00	-7.90E-02	-1.89E-02	-7.90E-02	1.15E+00	2.55E-01	3.07E+02	3.87E-01	1.03E+00	2.66E-01
7	1.35E+07	1.36E+07	-1.19E+01	4.94E-11	-1.31E+01	-1.26E+01	-1.86E+01	9.55E-01	4.47E-02	1.20E+00	-1.42E-01	-3.57E-01	-2.12E-01	-9.92E-02	9.24E-01	-6.48E-01	3.89E-02	6.23E-01	3.99E-01	4.79E+02	3.24E-02	1.16E+00	2.93E-01
8	1.28E+07	1.27E+07	-1.31E+01	5.67E-11	-1.32E+01	-1.89E+01	-1.79E+01	-5.28E-01	-1.49E-01	4.23E-01	-3.56E-01	2.28E-03	3.79E-01	-6.69E-01	2.27E-01	2.38E-01	-2.40E-01	1.20E+00	2.03E-01	2.17E+02	2.13E-01	1.17E+00	3.67E-01
9	1.25E+07	1.45E+07	-1.03E+01	2.40E-11	-1.46E+01	-1.86E+01	-1.83E+01	-2.48E-01	2.09E-01	-2.03E-01	-6.03E-02	-1.31E-02	-1.46E-01	4.60E-01	-1.64E-01	9.12E-01	1.75E-01	1.50E+00	6.68E-01	7.78E+01	9.33E-02	1.23E+00	1.16E-01
10	1.36E+07	1.24E+07	-1.09E+01	4.74E-11	-1.57E+01	-1.34E+01	-1.78E+01	7.70E-01	-7.47E-02	4.75E-01	-1.16E-01	6.32E-02	-4.28E-01	8.37E-02	2.79E-02	5.45E-01	5.82E-01	1.40E+00	9.72E-01	2.38E+02	8.78E-01	1.15E+00	3.51E-01
11	1.12E+07	1.43E+07	-1.43E+01	7.31E-11	-1.39E+01	-1.29E+01	-1.87E+01	-1.86E-03	5.79E-01	-7.49E-01	-3.08E-01	-2.23E-01	-1.46E+00	9.80E-01	-8.41E-02	-1.72E-01	-2.71E-01	9.82E-01	1.30E-01	7.25E+02	6.34E-01	1.51E+00	2.30E-01
12	1.35E+07	1.44E+07	-1.27E+01	5.24E-11	-1.43E+01	-1.28E+01	-1.81E+01	-1.38E-01	-9.70E-01	8.14E-01	3.85E-02	3.52E-02	6.74E-01	-4.11E-01	6.52E-01	9.71E-02	-2.04E-01	9.62E-01	3.08E-02	6.48E+02	6.85E-01	1.99E+00	9.71E-02
13	1.12E+07	1.34E+07	-1.16E+01	3.15E-11	-1.29E+01	-1.78E+01	-1.84E+01	-4.18E-01	-4.40E-01	6.25E-01	9.31E-02	9.47E-01	5.13E-02	2.80E-01	3.68E-01	-1.93E-01	-8.85E-01	8.65E-01	1.02E-01	9.97E+02	5.41E-01	1.20E+00	3.52E-01
14	1.19E+07	1.53E+07	-1.36E+01	7.46E-11	-1.51E+01	-1.82E+01	-1.73E+01	2.34E-01	8.90E-02	-5.64E-02	5.01E-01	2.39E-01	2.89E-01	5.04E-01	-3.89E-02	1.22E-01	-9.03E-01	1.51E+00	4.73E-01	1.24E+02	7.57E-01	1.11E+00	3.91E-01
15	1.28E+07	1.23E+07	-1.24E+01	7.15E-11	-1.39E+01	-1.39E+01	-1.80E+01	-1.71E-01	8.81E-01	-1.28E+00	2.13E-01	-1.30E-01	-2.97E-01	-4.27E-01	-2.35E-01	9.21E-02	-6.55E-01	1.11E+00	5.76E-01	1.38E+02	5.19E-01	1.01E+00	1.09E-01
16	1.36E+07	1.56E+07	-1.17E+01	5.58E-11	-1.37E+01	-1.87E+01	-1.88E+01	3.50E-01	-2.90E-01	-6.11E-01	-1.48E-01	-9.76E-02	6.05E-02	-2.33E-01	-2.90E-02	-9.61E-01	4.07E-01	1.36E+00	1.23E-01	8.35E+02	1.76E-01	1.24E+00	4.70E-01
17	1.16E+07	1.51E+07	-1.14E+01	4.83E-11	-1.21E+01	-1.43E+01	-1.71E+01	-2.37E-01	-2.03E-01	9.64E-02	-4.76E-01	1.22E-01	-1.22E+00	3.20E-01	-1.36E-01	-7.65E-02	-5.55E-01	2.56E-01	8.28E-01	8.02E+02	5.84E-01	2.02E+00	3.62E-01
18	1.36E+07	1.21E+07	-1.13E+01	3.97E-11	-1.52E+01	-1.35E+01	-1.73E+01	-4.82E-01	6.82E-01	-8.95E-02	1.28E-02	-2.50E-03	-1.59E-01	2.49E-01	-4.60E-02	-2.74E-01	-2.16E-01	1.56E+00	3.76E-01	9.68E+01	9.33E-01	2.25E+00	1.77E-01
19	1.24E+07	1.27E+07	-1.18E+01	5.44E-11	-1.57E+01	-1.49E+01	-1.84E+01	3.25E-02	6.64E-02	5.82E-01	-3.03E-01	-4.97E-01	5.24E-01	1.24E+00	-9.59E-02	9.76E-01	-6.74E-02	3.52E-01	4.89E-01	3.40E+01	7.17E-01	1.04E+00	1.87E-01
20	1.35E+07	1.30E+07	-1.19E+01	4.30E-11	-1.45E+01	-1.69E+01	-1.72E+01	-4.58E-01	-3.32E-01	-2.68E-01	1.11E+00	-2.60E-01	-9.59E-01	-6.08E-01	-4.37E-01	-2.48E-01	7.10E-02	7.01E-01	8.71E-01	8.41E+02	9.06E-01	1.16E+00	5.00E-01
21	1.17E+07	1.38E+07	-1.23E+01	6.42E-11	-1.28E+01	-1.91E+01	-1.87E+01	-2.68E-01	-7.94E-03	-4.02E-02	-5.45E-01	-3.57E-01	-4.61E-01	-9.54E-01	7.79E-01	-1.95E-01	1.24E-01	1.41E+00	9.59E-01	2.48E+01	3.72E-01	1.00E+00	1.67E-01
22	1.20E+07	1.39E+07	-1.18E+01	5.31E-11	-1.28E+01	-1.31E+01	-1.75E+01	7.18E-01	-1.18E-01	-1.88E-01	1.20E-01	-1.83E+00	1.72E-01	-3.16E-02	8.99E-02	4.09E-01	-7.59E-01	1.01E+00	9.66E-01	1.59E+02	1.18E-01	1.25E+00	1.92E-01
23	1.27E+07	1.55E+07	-1.22E+01	4.20E-11	-1.61E+01	-1.59E+01	-1.85E+01	-1.02E-01	-4.87E-01	7.26E-01	4.82E-01	-1.14E-01	6.01E-01	7.71E-02	-3.33E-01	-1.51E+00	-1.12E+00	1.45E+00	9.90E-01	1.46E+02	6.48E-01	1.15E+00	2.22E-01
24	1.32E+07	1.27E+07	-1.21E+01	4.69E-11	-1.36E+01	-1.26E+01	-1.85E+01	6.39E-02	-2.18E-02	2.11E-01	-4.98E-02	-1.79E-01	-2.08E-01	-2.50E-01	-5.53E-01	8.13E-01	-9.02E-02	1.53E+00	1.79E-01	8.27E+02	6.67E-01	1.12E+00	3.43E-01
25	1.15E+07	1.41E+07	-1.24E+01	7.72E-11	-1.59E+01	-1.65E+01	-1.85E+01	-7.05E-02	1.70E-01	-9.30E-01	-6.42E-01	8.89E-02	-1.36E-01	-1.33E-01	-1.07E-01	-4.86E-03	9.74E-01	4.39E-01	1.52E-01	2.61E+02	5.25E-02	1.87E+00	4.77E-01
26	1.35E+07	1.19E+07	-1.12E+01	3.56E-11	-1.15E+01	-1.37E+01	-1.71E+01	-1.39E+00	-9.51E-02	1.89E-01	-2.39E-01	2.51E-01	7.19E-02	1.73E-01	-1.19E-01	-5.37E-01	-1.73E-01	1.39E+00	4.16E-01	2.94E+02	1.60E-02	1.75E+00	2.67E-01
27	1.21E+07	1.22E+07	-1.19E+01	5.12E-11	-1.46E+01	-1.57E+01	-1.86E+01	-4.94E-02	1.33E-01	-8.35E-01	1.79E-01	-2.76E-01	8.39E-01	-2.24E-01	-1.31E-01	-4.53E-01	6.52E-01	1.49E+00	5.60E-01	9.16E+02	1.98E-01	1.09E+00	1.52E-01
28	1.32E+07	1.48E+07	-1.30E+01	9.02E-11	-1.10E+01	-1.63E+01	-1.87E+01	3.77E-02	2.45E-01	2.27E-01	7.44E-01	-8.04E-01	-1.67E+00	-2.13E-01	-2.05E-01	-5.79E-01	-1.49E-01	1.42E+00	3.08E-01	8.61E+02	4.57E-01	1.20E+00	7.78E-02
29	1.34E+07	1.28E+07	-1.11E+01	3.29E-11	-1.16E+01	-1.64E+01	-1.87E+01	6.30E-03	-4.76E-01	-5.07E-01	1.38E-01	6.96E-01	-7.39E-01	-1.18E-01	6.28E-01	6.96E-02	5.07E-02	1.60E+00	6.75E-01	6.25E+02	2.77E-01	2.11E+00	3.04E-01
30	1.31E+07	1.47E+07	-1.28E+01	8.22E-11	-1.27E+01	-1.36E+01	-1.87E+01	-3.85E-01	-9.84E-02	-1.74E-01	-1.75E+00	2.35E-01	-2.36E-01	-7.55E-02	-1.90E-01	2.22E-01	-4.84E-01	1.59E+00	8.82E-01	7.38E+02	1.85E-01	1.17E+00	3.95E-01
31	1.36E+07	1.49E+07	-1.22E+01	6.06E-11	-1.35E+01	-1.48E+01	-1.86E+01	-3.53E-01	-2.01E-01	-6.96E-01	9.78E-01	6.23E-01	-9.39E-02	-7.46E-01	2.09E-01	-3.63E-01	4.95E-01	1.56E+00	2.92E-01	2.42E+02	9.95E-01	1.04E+00	1.26E-01
32	1.21E+07	1.32E+07	-1.17E+01	6.61E-11	-1.22E+01	-1.60E+01	-1.73E+01	-1.90E-01	-2.27E-01	-4.70E-02	-8.17E-01	-8.60E-01	-7.02E-01	-1.85E+00	-1.04E+00	-1.10E-01	-1.22E-01	8.35E-01	6.42E-02	5.49E+02	6.24E-01	2.14E+00	1.83E-01
33	1.13E+07	1.31E+07	-1.29E+01	6.65E-11	-1.21E+01	-1.40E+01	-1.73E+01	-6.90E-01	4.39E-01	-1.11E-01	-2.32E-01	1.99E-01	-1.18E-01	1.42E-01	-3.16E-01	-1.99E+00	1.06E-01	9.38E-01	6.17E-01	3.49E+02	8.37E-01	1.93E+00	3.30E-01
34	1.20E+07	1.38E+07	-1.33E+01	9.10E-11	-1.31E+01	-1.66E+01	-1.78E+01	-6.91E-02	-4.11E-01	7.98E-01	1.69E-01	3.96E-01	-2.74E-01	2.14E-01	-3.99E-01	7.97E-01	1.83E-01	1.47E+00	3.27E-01	2.85E+02	6.11E-01	1.20E+00	1.97E-01
35	1.18E+07	1.30E+07	-1.04E+01	4.28E-11	-1.29E+01	-1.41E+01	-1.90E+01	1.23E-01	-1.20E-01	7.80E-02	1.46E-01	-1.51E-02	-8.16E-02	3.65E-02	-1.05E-03	-2.27E-01	-1.98E-01	1.52E+00	2.80E-01	1.87E+02	7.25E-01	1.01E+00	2.53E-01
36	1.28E+07	1.38E+07	-1.28E+01	8.48E-11	-1.41E+01	-1.92E+01	-1.76E+01	9.83E-02	-1.65E-01	-9.52E-02	6.62E-01	8.44E-01	9.77E-01	-6.18E-02	-2.11E-01	1.40E-02	-4.33E-01	1.38E+00	1.96E-01	1.94E+02	1.66E-01	1.60E+00	1.19E-01
37	1.11E+07	1.23E+07	-1.12E+01	4.16E-11	-1.49E+01	-1.54E+01	-1.77E+01	5.25E-02	2.87E-01	5.50E-01	-4.83E-01	5.09E-01	-2.11E-02	-3.57E-01	-4.12E-01	-1.87E-01	2.04E-01	1.48E+00	4.39E-01	8.94E+02	1.41E-01	1.14E+00	1.74E-01
38	1.18E+07	1.33E+07	-1.20E+01	5.15E-11	-1.54E+01	-1.30E+01	-1.80E+01	-1.14E-01	-1.19E+00	3.09E-01	3.27E-02	-9.11E-01	-4.78E-01	-4.30E-02	-4.86E-02	-3.89E-01	-1.37E-01	5.68E-01	6.93E-01	3.56E+02	4.85E-01	1.04E+00	8.20E-02
39	1.34E+07	1.53E+07	-1.28E+01	5.75E-11	-1.26E+01	-1.45E+01	-1.75E+01	1.13E-01	-8.56E-01	-7.65E-02	2.15E-01	2.37E-02	-3.17E-01	1.22E-01	8.63E-01	-1.19E-01	1.31E-01	7.87E-01	7.47E-02	8.57E+02	7.25E-02	1.06E+00	2.00E-01
40	1.14E+07	1.47E+07	-1.06E+01	4.67E-11	-1.25E+01	-1.28E+01	-1.80E+01	-7.80E-01	3.74E-01	-2.23E-01	-9.69E-01	4.96E-01	-1.75E-01	-8.52E-01	8.39E-01	8.88E-01	-2.48E-01	8.99E-01	8.62E-02	6.72E+02	4.32E-01	1.05E+00	3.98E-01
41	1.14E+07	1.51E+07	-1.15E+01	5.72E-11	-1.55E+01	-1.88E+01	-1.90E+01	-1.72E+00	-1.67E-01	8.57E-02	-2.46E-01	5.12E-02	-8.81E-02	-5.46E-02	-1.07E-02	1.86E-01	-4.81E-02	1.57E+00	4.93E-01	7.43E+02	8.11E-01	1.21E+00	1.49E-01
42	1.14E+07	1.49E+07	-1.24E+01	7.82E-11	-1.49E+01	-1.61E+01	-1.76E+01	-1.08E-01	-7.62E-01	-2.92E-01	-1.36E-02	-8.38E-02	1.07E-01	1.63E-01	-9.66E-01	-4.08E-01	1.62E-01	1.07E+00	7.86E-01	7.07E+02	2.02E-01	1.10E+00	3.39E-01
43	1.38E+07	1.54E+07	-1.10E+01	3.52E-11	-1.24E+01	-1.90E+01	-1.88E+01	-1.24E-01	-5.34E-01	-2.21E-01	-1.30E-01	-2.04E-01	-4.93E-02	-1.63E-01	-9.82E-02	-1.32E-01	-2.16E-02	7.59E-02	8.41E-01	4.29E+02	8.96E-01	1.25E+00	4.34E-01
44	1.11E+07	1.45E+07	-1.19E+01	6.87E-11	-1.44E+01	-1.29E+01	-1.80E+01	-1.80E-01	-4.03E-02	-3.55E-01	5.62E-01	-1.35E-01	2.04E-01	7.59E-01	-4.92E-01	1.72E-01	6.67E-03	1.43E+00	5.43E-02	9.26E+02	7.65E-01	1.18E+00	3.37E-01
45	1.25E+07	1.59E+07	-1.23E+01	4.54E-11	-1.48E+01	-1.33E+01	-1.82E+01	-4.24E-02	-2.36E-01	-1.98E+00	-3.97E-01	1.02E+00	8.50E-01	3.20E-02	1.45E-01	-2.04E-01	-1.16E-01	1.49E-01	4.51E-01	1.68E+02	2.70E-01	1.04E+00	3.82E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector	S_HALITE	CASTILER	CASTILER	CASTILER	BH_SAND	DRZ_1	CONC_PLG	SOLAM3	SOLAM3	SOLPU3	SOLPU3	SOLPU4	SOLPU4	SOLU4	SOLU6	SOLU6	SOLTH4	PHUMOX3	GLOBAL	CULEBRA	GLOBAL	GLOBAL	CULEBRA
Num.	PRESSURE	PRESSURE	PRMX_LOG	COMP_RCK	PRMX_LOG	PRMX_LOG	PRMX_LOG	SOLSIM	SOLCIM	SOLSIM	SOLCIM	SOLSIM	SOLCIM	SOLSIM	SOLSIM	SOLCIM	SOLSIM	PHUMCIM	OXSTAT	MINP_FAC	TRANSIDX	CLIMTIDX	HMBLKLT
46	1.32E+07	1.54E+07	-1.09E+01	3.64E-11	-1.38E+01	-1.68E+01	-1.78E+01	-3.07E-02	7.90E-01	-1.60E-01	1.10E-01	-9.61E-01	9.24E-01	8.57E-01	-4.62E-01	1.99E-01	-2.11E-01	1.40E+00	3.83E-01	7.66E+02	3.17E-01	1.23E+00	4.86E-01
47	1.11E+07	1.24E+07	-1.18E+01	4.47E-11	-1.57E+01	-1.72E+01	-1.75E+01	1.58E-01	6.07E-03	-1.15E-01	7.79E-01	3.03E-01	-2.58E-01	-3.03E-01	9.85E-02	-9.46E-02	-6.04E-01	4.15E-01	9.45E-01	4.82E+02	4.99E-01	1.68E+00	3.12E-01
48	1.18E+07	1.16E+07	-1.14E+01	3.93E-11	-1.47E+01	-1.31E+01	-1.89E+01	-7.70E-01	3.47E-01	1.16E-01	8.02E-01	-4.20E-01	4.87E-01	-1.77E-01	-1.15E-01	-8.67E-01	-1.79E-01	9.03E-01	1.67E-01	4.49E+02	6.91E-01	1.13E+00	4.25E-01
49	1.30E+07	1.31E+07	-1.20E+01	3.80E-11	-1.20E+01	-1.44E+01	-1.81E+01	8.41E-01	9.80E-01	1.44E-01	-9.71E-02	8.69E-01	4.39E-02	-9.24E-01	-7.06E-01	-1.27E-01	2.17E-01	2.45E-01	3.68E-01	5.03E+02	7.34E-01	1.11E+00	2.82E-01
50	1.27E+07	1.32E+07	-1.26E+01	4.40E-11	-1.19E+01	-1.85E+01	-1.85E+01	4.62E-01	-6.02E-02	-2.45E-01	-2.15E-01	-6.62E-02	-1.27E-01	-1.46E-01	-1.70E-01	2.04E-01	-4.77E-01	1.47E+00	2.68E-01	3.27E+02	3.07E-01	1.15E+00	2.35E-01
51	1.13E+07	1.68E+07	-1.12E+01	2.96E-11	-1.20E+01	-1.32E+01	-1.79E+01	8.64E-01	2.24E-01	-1.03E-01	-3.21E-02	-1.65E-01	-6.37E-02	-2.38E-01	-2.27E-01	7.87E-02	-4.05E-03	1.43E+00	8.65E-01	3.74E+02	9.78E-01	1.72E+00	2.41E-01
52	1.39E+07	1.65E+07	-1.26E+01	7.35E-11	-1.34E+01	-1.48E+01	-1.84E+01	-2.84E-01	2.33E-02	-1.29E-01	-1.55E-01	1.48E-01	-4.05E-02	-1.05E-01	-5.78E-02	3.93E-02	-4.09E-01	5.98E-01	4.62E-01	6.52E+02	5.72E-01	2.05E+00	7.00E-02
53	1.37E+07	1.42E+07	-1.13E+01	6.47E-11	-1.19E+01	-1.71E+01	-1.82E+01	-1.97E-01	2.32E-01	9.80E-01	-3.75E-01	-2.19E-01	-6.08E-01	6.50E-01	-2.99E-01	-5.42E-02	-2.29E-01	1.53E+00	9.16E-01	8.17E+02	4.09E-01	1.06E+00	2.20E-01
54	1.26E+07	1.59E+07	-1.18E+01	7.00E-11	-1.13E+01	-1.76E+01	-1.86E+01	9.03E-01	1.30E-01	-2.06E-02	-1.06E-03	4.61E-02	3.42E-01	-2.64E-01	-3.43E-01	-1.80E-01	-1.91E-01	1.24E+00	6.38E-01	5.18E+02	6.75E-02	1.81E+00	2.46E-01
55	1.23E+07	1.28E+07	-1.08E+01	4.07E-11	-1.12E+01	-1.41E+01	-1.70E+01	-9.30E-02	-1.77E-01	-8.26E-01	6.92E-04	-2.01E-01	1.60E-01	1.87E-01	7.05E-02	-1.61E-01	-3.45E-01	1.52E+00	8.19E-01	6.91E+02	3.41E-01	1.24E+00	4.52E-01
56	1.17E+07	1.18E+07	-1.16E+01	3.78E-11	-1.40E+01	-1.50E+01	-1.89E+01	2.24E-01	-3.51E-01	1.67E-01	-2.82E-01	2.23E-01	-4.41E-01	8.10E-01	-2.01E-01	-9.06E-01	-3.84E-01	4.69E-01	6.87E-01	6.70E+02	4.18E-01	1.14E+00	4.60E-01
57	1.12E+07	1.37E+07	-1.31E+01	6.71E-11	-1.11E+01	-1.79E+01	-1.72E+01	5.84E-01	-1.99E+00	-2.01E-01	-1.34E-01	-5.20E-01	2.47E-01	-8.06E-01	-2.84E-01	-2.17E-01	8.40E-02	3.01E-01	8.05E-01	8.85E+02	9.49E-01	1.08E+00	2.86E-01
58	1.26E+07	1.26E+07	-1.30E+01	5.39E-11	-1.45E+01	-1.58E+01	-1.88E+01	-9.30E-01	-2.40E-01	-1.08E+00	-3.22E-01	-2.68E-02	-9.12E-01	5.86E-02	-6.09E-01	-1.32E-02	3.63E-01	1.70E-01	5.28E-01	4.93E+02	5.08E-01	1.21E+00	5.43E-02
59	1.27E+07	1.21E+07	-1.32E+01	6.91E-11	-1.59E+01	-1.58E+01	-1.79E+01	-8.37E-02	-2.60E-01	-3.18E-01	-3.81E-02	7.55E-02	1.94E-01	1.50E-01	1.74E-01	-4.29E-02	3.14E-01	1.27E+00	7.94E-01	3.64E+02	6.58E-01	1.91E+00	4.58E-01
60	1.15E+07	1.35E+07	-1.36E+01	6.22E-11	-1.22E+01	-1.72E+01	-1.81E+01	-2.25E-01	1.61E-01	1.58E-01	-9.77E-02	-2.48E-01	-1.67E-01	-1.03E+00	1.05E+00	-2.43E-01	-1.83E-01	1.29E+00	1.12E-01	5.43E+00	8.56E-01	1.58E+00	4.78E-01
61	1.17E+07	1.35E+07	-1.36E+01	5.83E-11	-1.33E+01	-1.57E+01	-1.82E+01	-1.23E+00	9.83E-02	1.35E-01	-8.28E-02	-1.67E+00	2.37E-01	-1.90E-01	-2.40E-02	6.52E-01	5.47E-01	1.42E+00	5.94E-01	9.67E+02	2.22E-01	1.22E+00	4.28E-01
62	1.38E+07	1.39E+07	-1.40E+01	9.43E-11	-1.48E+01	-1.78E+01	-1.76E+01	-4.38E-01	-5.16E-02	-3.11E-02	-4.38E-01	-8.06E-02	5.84E-01	9.84E-02	-2.16E-01	-2.54E-02	2.47E-01	6.90E-01	9.88E-01	9.74E+02	8.84E-01	1.03E+00	2.99E-01
63	1.22E+07	1.13E+07	-1.30E+01	6.19E-11	-1.23E+01	-1.37E+01	-1.82E+01	1.86E-01	-1.41E-01	-4.76E-01	-4.66E-02	-4.24E-02	2.26E-01	-4.41E-01	-3.71E-01	3.19E-01	-3.61E-01	1.38E-01	6.27E-01	5.76E+02	4.70E-01	2.17E+00	6.28E-02
64	1.29E+07	1.26E+07	-1.17E+01	4.01E-11	-1.14E+01	-1.55E+01	-1.77E+01	-4.93E-01	-6.16E-01	-1.59E-01	5.57E-02	-7.24E-02	-1.86E-01	-1.95E-02	-1.57E-01	1.10E-01	-9.81E-01	1.51E+00	3.17E-01	4.03E+02	3.37E-01	1.07E+00	4.90E-01
65	1.22E+07	1.29E+07	-1.14E+01	3.91E-11	-1.44E+01	-1.51E+01	-1.89E+01	-1.57E-01	-1.52E+00	-4.40E-01	-1.62E-01	-7.44E-01	-3.71E-01	1.13E-01	2.19E-01	-1.11E+00	-1.53E-01	1.55E+00	7.58E-01	7.56E+02	2.42E-02	1.97E+00	5.74E-02
66	1.33E+07	1.28E+07	-1.38E+01	8.31E-11	-1.18E+01	-1.73E+01	-1.81E+01	-8.11E-02	4.88E-01	1.91E-01	8.81E-01	-6.04E-02	1.38E-01	9.32E-03	-6.34E-02	-8.39E-02	-6.09E-02	6.41E-01	7.28E-01	5.98E+02	4.69E-01	1.03E+00	4.11E-01
67	1.21E+07	1.29E+07	-1.39E+01	4.79E-11	-1.41E+01	-1.75E+01	-1.83E+01	1.46E-01	1.54E-01	9.28E-01	-7.34E-01	1.76E-01	-1.08E-01	-2.70E-01	-1.49E+00	-1.29E+00	-1.10E-01	1.41E+00	9.38E-01	3.34E+02	8.90E-02	1.54E+00	4.65E-01
68	1.16E+07	1.42E+07	-1.25E+01	5.54E-11	-1.53E+01	-1.60E+01	-1.79E+01	-3.58E-01	-3.08E-03	3.97E-01	6.11E-01	-1.33E+00	-1.22E-01	-1.24E-01	8.28E-02	3.58E-01	-2.30E-01	1.44E+00	7.15E-01	5.90E+02	4.97E-02	1.12E+00	4.45E-01
69	1.28E+07	1.62E+07	-1.24E+01	5.27E-11	-1.40E+01	-1.39E+01	-1.77E+01	1.37E-01	-2.75E-01	-4.13E-03	2.76E-01	-4.10E-01	-2.20E-01	-1.81E-01	-1.80E-01	-1.48E-01	1.13E+00	1.46E+00	1.47E-01	5.61E+01	8.27E-01	2.08E+00	2.15E-01
70	1.11E+07	1.31E+07	-1.33E+01	8.13E-11	-1.60E+01	-1.92E+01	-1.74E+01	2.07E-01	-2.11E-01	-1.22E-01	1.60E-01	1.05E-01	-1.63E-01	-3.63E-02	-3.79E-01	-2.64E-01	3.32E-02	1.58E+00	4.42E-02	4.63E+02	6.09E-01	1.84E+00	1.62E-01
71	1.38E+07	1.22E+07	-1.22E+01	5.93E-11	-1.63E+01	-1.77E+01	-1.81E+01	-3.24E-01	6.29E-01	-1.67E-01	-1.70E-01	4.05E-01	-2.24E-01	-5.33E-01	5.40E-01	-2.82E-02	-6.97E-02	5.55E-01	9.04E-01	9.02E+02	8.44E-01	2.19E+00	2.77E-01
72	1.32E+07	1.46E+07	-1.22E+01	5.06E-11	-1.13E+01	-1.77E+01	-1.71E+01	-1.62E-01	8.30E-02	-3.32E-01	-2.52E-01	1.86E-01	-1.71E-03	6.18E-01	7.08E-01	-3.61E-02	8.47E-01	1.57E+00	5.82E-01	2.25E+02	4.26E-01	1.07E+00	4.50E-01
73	1.38E+07	1.39E+07	-1.10E+01	2.45E-11	-1.42E+01	-1.54E+01	-1.76E+01	-1.47E-01	-6.70E-01	-7.42E-02	-2.21E-01	-4.70E-01	-1.83E-02	-1.44E-01	-1.49E-01	-6.72E-02	1.43E-01	1.38E+00	1.17E-02	6.15E+02	7.78E-01	1.10E+00	3.85E-01
74	1.12E+07	1.23E+07	-1.11E+01	2.78E-11	-1.12E+01	-1.85E+01	-1.76E+01	-1.39E-02	-3.12E-01	2.30E-02	7.66E-02	-9.26E-02	-7.41E-02	-9.70E-02	1.33E-01	1.31E-01	-2.04E-02	1.19E+00	5.34E-01	4.56E+01	3.66E-01	1.23E+00	7.46E-02
75	1.33E+07	1.17E+07	-1.23E+01	7.64E-11	-1.27E+01	-1.81E+01	-1.88E+01	-3.70E-02	-3.62E-01	-4.03E-01	-8.55E-02	-1.24E-01	-6.22E-02	4.06E-01	9.71E-01	-7.09E-01	-2.54E-01	7.43E-01	3.38E-01	2.77E+02	6.80E-01	1.79E+00	3.76E-01
76	1.21E+07	1.36E+07	-1.17E+01	5.47E-11	-1.53E+01	-1.75E+01	-1.82E+01	-2.33E-01	-6.81E-02	1.28E-01	-1.06E-01	-1.52E-01	-1.44E-01	-4.72E-01	-1.62E-02	-9.90E-02	7.33E-01	3.60E-01	9.22E-01	1.06E+02	1.54E-01	1.23E+00	2.97E-01
77	1.29E+07	1.25E+07	-1.09E+01	3.06E-11	-1.56E+01	-1.81E+01	-1.73E+01	2.44E-01	-8.65E-02	-1.49E-01	3.72E-01	-3.89E-01	-3.83E-01	-6.66E-02	1.96E-01	5.77E-02	8.87E-01	1.33E+00	7.64E-01	9.84E+02	2.51E-01	1.08E+00	1.70E-01
78	1.17E+07	1.61E+07	-1.20E+01	3.65E-11	-1.61E+01	-1.46E+01	-1.71E+01	-3.12E-01	-2.18E-01	-6.44E-02	-1.86E-01	-1.41E-01	-2.91E-02	-1.31E+00	4.20E-01	-2.86E-01	-1.56E+00	1.48E+00	3.52E-01	9.40E+02	3.56E-01	1.09E+00	9.15E-02
79	1.31E+07	1.31E+07	-1.44E+01	8.64E-11	-1.58E+01	-1.26E+01	-1.75E+01	2.04E-02	8.31E-01	-2.31E-01	-8.52E-01	-7.17E-01	4.50E-01	-6.44E-01	3.07E-01	-2.31E-01	-4.15E-02	1.59E+00	6.47E-01	5.62E+02	1.37E-01	1.64E+00	4.21E-01
80	1.16E+07	1.44E+07	-1.27E+01	4.10E-11	-1.17E+01	-1.83E+01	-1.89E+01	-1.45E-01	9.32E-01	1.04E-02	-1.97E-01	-2.42E-01	-2.39E-01	9.02E-01	4.15E-03	1.59E-01	-3.02E-02	2.01E-01	7.32E-01	8.71E+02	9.80E-01	1.12E+00	6.61E-02
81	1.13E+07	1.33E+07	-1.01E+01	2.61E-11	-1.16E+01	-1.80E+01	-1.76E+01	-1.28E-01	-2.97E-02	-2.53E-01	-1.56E+00	-2.84E-02	7.11E-01	-1.13E-02	4.56E-01	-4.99E-01	6.44E-01	1.58E+00	7.01E-01	9.56E+02	9.60E-01	1.15E+00	2.06E-01
82	1.15E+07	1.35E+07	-1.21E+01	4.45E-11	-1.18E+01	-1.47E+01	-1.72E+01	-3.93E-01	-1.50E-02	-2.41E-01	7.05E-02	-1.91E-01	1.89E-02	5.78E-01	5.60E-01	-3.53E-01	9.37E-01	5.25E-01	6.53E-01	1.73E+02	9.23E-01	1.11E+00	2.10E-01
83	1.23E+07	1.15E+07	-1.26E+01	6.27E-11	-1.14E+01	-1.73E+01	-1.80E+01	1.38E+00	-1.91E-01	-4.49E-01	-1.24E-01	-4.33E-01	7.96E-01	-3.58E-01	5.81E-02	6.29E-01	-1.64E-01	1.54E+00	5.64E-01	5.51E+02	9.10E-01	1.13E+00	1.57E-01
84	1.20E+07	1.30E+07	-1.04E+01	3.44E-11	-1.55E+01	-1.93E+01	-1.83E+01	-5.96E-02	5.11E-02	-3.66E-01	-1.09E+00	-1.24E+00	3.55E-02	-3.25E-01	1.15E-01	4.96E-01	-6.67E-01	1.09E+00	5.13E-01	3.12E+02	5.52E-01	1.21E+00	3.26E-01
85	1.23E+07	1.20E+07	-1.41E+01	7.93E-11	-1.51E+01	-1.53E+01	-1.72E+01	2.63E-01	-1.09E-01	-1.43E-01	-2.44E-02	7.78E-01	-1.95E+00	-7.91E-02	1.88E-01	-7.30E-02	2.63E-01	1.44E+00	7.78E-01	7.95E+02	1.24E-01	1.05E+00	2.49E-01
86	1.25E+07	1.21E+07	-1.07E+01	5.03E-11	-1.24E+01	-1.65E+01	-1.71E+01	-8.76E-01	1.89E-01	4.38E-02	2.31E-01	-4.92E-02	9.42E-02	3.80E-01	1.29E-01	-4.45E-01	2.02E-01	2.94E-01	3.45E-01	4.15E+02	2.40E-01	1.12E+00	1.03E-01
87	1.18E+07	1.37E+07	-1.16E+01	4.59E-11	-1.31E+01	-1.94E+01	-1.84E+01	-2.87E-01	1.28E+00	-1.82E-01	9.41E-01	-5.65E-01	-2.01E-01	-1.32E-01	-2.38E-01	-3.38E-01	-3.21E-01	1.39E+00	9.86E-02	6.88E+02	2.95E-01	1.17E+00	3.20E-01
88	1.26E+07	1.26E+07	-1.37E+01	7.08E-11	-1.11E+01	-1.56E+01	-1.77E+01	-2.03E-01	-5.67E-01	-1.37E-01	-1.79E-01	1.62E-01	-8.55E-01	-2.73E-02	-1.65E+00	2.31E-01	-5.53E-02	1.54E+00	4.45E-01	3.85E+02	7.01E-01	1.19E+00	4.10E-01
89	1.34E+07	1.29E+07	-1.13E+01	4.96E-11	-1.49E+01	-1.88E+01	-1.74E+01	1.95E-01	-7.97E-02	-5.38E-02	-4.56E-01	-3.37E-01	-9.86E-02	1.94E-01	-6.17E-01	-7.53E-01	-1.41E+00	1.02E-01	5.50E-03	7.11E+02	7.98E-01	1.14E+00	3.58E-01
90	1.37E+07	1.34E+07	-1.15E+01	3.07E-11	-1.37E+01	-1.69E+01	-1.72E+01	6.26E-01	7.25E-01	-2.13E-01	-1.27E+00	-2.36E-01	6.32E-03	-1.99E-01	-7.79E-01	-4.21E-01	1.67E-02	1.47E+00	2.29E-01	6.50E+01	6.00E-01	1.20E+00	1.08E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	26	27	28	29	30	31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Vector	S_HALITE	CASTILER	CASTILER	CASTILER	BH_SAND	DRZ_1	CONC_PLG	SOLAM3	SOLAM3	SOLPU3	SOLPU3	SOLPU4	SOLPU4	SOLU4	SOLU6	SOLU6	SOLTH4	PHUMOX3	GLOBAL	CULEBRA	GLOBAL	GLOBAL	CULEBRA
Num.	PRESSURE	PRESSURE	PRMX_LOG	COMP_RCK	PRMX_LOG	PRMX_LOG	PRMX_LOG	SOLSIM	SOLCIM	SOLSIM	SOLCIM	SOLSIM	SOLCIM	SOLSIM	SOLSIM	SOLCIM	SOLSIM	PHUMCIM	OXSTAT	MINP_FAC	TRANSIDX	CLIMTIDX	HMBLKLT
91	1.30E+07	1.25E+07	-1.34E+01	7.55E-11	-1.26E+01	-1.43E+01	-1.87E+01	-9.83E-01	-8.06E-01	2.79E-02	-9.44E-01	-2.90E-01	1.30E+00	-2.02E-01	-1.42E-01	5.74E-01	-1.04E-01	4.94E-01	5.04E-01	4.58E+02	3.24E-01	1.08E+00	1.29E-01
92	1.25E+07	1.18E+07	-1.21E+01	4.90E-11	-1.34E+01	-1.71E+01	-1.84E+01	-1.19E-02	-1.57E-01	6.67E-01	1.05E-01	5.91E-01	1.21E-01	-3.84E-01	1.89E-02	-1.56E-01	-3.39E-01	1.58E+00	5.43E-01	6.32E+02	7.83E-01	1.17E+00	3.17E-01
93	1.30E+07	1.37E+07	-1.21E+01	5.98E-11	-1.35E+01	-1.38E+01	-1.75E+01	6.56E-01	-1.36E-01	-1.73E+00	-4.19E-01	-3.11E-01	-4.83E-01	-1.54E-01	1.61E-01	-3.13E-01	-1.97E+00	1.50E+00	9.00E-01	5.35E+02	9.60E-01	1.06E+00	3.07E-01
94	1.23E+07	1.43E+07	-1.18E+01	3.71E-11	-1.50E+01	-1.42E+01	-1.85E+01	-5.64E-01	-1.45E+00	-9.58E-01	4.24E-01	-6.21E-01	1.53E-01	-8.57E-02	-7.40E-01	-1.45E-01	-1.17E-02	1.50E+00	8.33E-01	2.58E+02	1.03E-01	1.22E+00	2.58E-01
95	1.29E+07	1.33E+07	-1.08E+01	3.22E-11	-1.60E+01	-1.62E+01	-1.74E+01	5.18E-01	1.08E-01	2.54E-01	-3.84E-01	1.10E-01	1.89E-01	2.34E-02	-7.33E-02	-7.95E-01	1.10E-01	1.45E+00	2.16E-01	5.26E+02	5.40E-01	1.02E+00	1.34E-01
96	1.24E+07	1.25E+07	-1.13E+01	3.87E-11	-1.30E+01	-1.44E+01	-1.89E+01	1.68E-01	-4.62E-01	-2.65E-02	-2.05E-01	-4.61E-01	-3.55E-01	-2.22E-01	-4.76E-01	2.65E-02	7.52E-01	1.04E+00	2.10E-02	1.12E+02	2.90E-01	1.02E+00	4.92E-01
97	1.33E+07	1.50E+07	-1.05E+01	2.83E-11	-1.23E+01	-1.53E+01	-1.79E+01	-6.55E-01	-4.72E-02	2.48E-01	3.38E-01	2.11E-01	-8.93E-03	-4.85E-01	-8.80E-01	7.34E-01	7.73E-02	8.07E-01	7.46E-01	6.09E+02	2.34E-01	1.19E+00	2.26E-01
98	1.37E+07	1.19E+07	-1.34E+01	5.88E-11	-1.43E+01	-1.84E+01	-1.77E+01	-2.35E-02	-1.84E-01	-4.28E-01	-1.91E-01	-1.56E-01	-4.80E-02	2.19E-01	-9.05E-01	3.45E-03	-9.13E-02	1.55E+00	1.85E-01	7.72E+02	3.92E-01	1.02E+00	8.74E-02
99	1.31E+07	1.27E+07	-1.06E+01	3.35E-11	-1.62E+01	-1.62E+01	-1.78E+01	4.42E-01	-2.47E-01	-5.67E-01	2.38E-01	-3.56E-02	-6.53E-01	-6.57E-03	2.56E-01	1.39E+00	-8.26E-01	7.53E-01	2.85E-01	7.84E+02	5.65E-01	1.18E+00	4.17E-01
100	1.14E+07	1.40E+07	-1.29E+01	6.82E-11	-1.36E+01	-1.50E+01	-1.74E+01	7.31E-02	-3.79E-01	8.72E-01	-7.14E-01	-2.15E-01	-1.90E-01	7.32E-01	4.37E-02	-5.74E-02	2.28E-01	1.23E+00	2.40E-01	4.35E+02	7.42E-01	1.70E+00	2.73E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector Num.	CULEBRA APOROS	CULEBRA DPOROS	U+6 MKD_U	U+4 MKD_U	PU+3 MKD_PU	PU+4 MKD_PU	TH+4 MKD_TH	AM+3 MKD_AM	BOREHOLE TAUFAIL	GLOBAL PBRINE	BOREHOLE DOMEGA	SHFTU SAT_RBRN	SHFTU SAT_RGAS	SHFTU PRMX_LOG	SHFTL_T1 PRMX_LOG	SHFTL_T2 PRMX_LOG	SPALLMOD RNDSPALL
1	9.77E-03	1.53E-01	3.78E-04	1.16E+00	8.85E-02	2.00E+00	7.03E+00	3.78E-01	1.88E+01	3.39E-01	6.77E+00	1.24E-01	1.01E-01	-1.97E+01	-1.86E+01	-2.07E+01	5.98E-02
2	1.72E-04	1.12E-01	3.13E-03	7.50E-01	3.49E-01	3.31E+00	1.49E+00	3.73E-01	1.86E-01	5.73E-01	5.65E+00	1.60E-01	1.60E-01	-1.75E+01	-1.81E+01	-1.93E+01	1.10E-01
3	8.34E-03	1.65E-01	2.26E-04	9.07E+00	2.94E-01	7.13E-01	8.83E+00	2.00E-01	8.53E-02	5.47E-01	7.53E+00	5.14E-01	9.65E-02	-1.80E+01	-1.87E+01	-1.97E+01	1.74E-01
4	1.61E-03	1.85E-01	3.03E-04	3.60E+00	2.09E-02	6.79E+00	2.27E+00	2.96E-01	5.36E+00	5.95E-01	6.10E+00	4.31E-01	1.25E-01	-1.77E+01	-1.73E+01	-2.02E+01	4.04E-02
5	1.61E-04	2.42E-01	1.57E-02	1.45E+00	4.73E-02	4.48E+00	7.70E-01	1.33E-01	1.31E+00	7.67E-02	7.19E+00	3.45E-01	2.94E-01	-1.79E+01	-1.84E+01	-2.00E+01	3.22E-01
6	8.55E-04	1.10E-01	1.32E-02	5.05E+00	5.16E-02	3.88E+00	1.94E+00	1.09E-01	1.66E+00	4.66E-01	1.97E+01	7.67E-02	2.47E-01	-1.74E+01	-1.81E+01	-1.98E+01	6.52E-01
7	1.58E-03	1.85E-01	3.23E-04	8.75E-01	2.04E-01	1.23E+00	6.89E+00	1.78E-01	6.76E+01	2.69E-01	6.90E+00	3.63E-01	3.09E-01	-1.83E+01	-1.78E+01	-1.86E+01	9.08E-01
8	6.74E-03	1.81E-01	2.60E-04	6.61E+00	2.50E-01	5.88E+00	1.76E+00	7.82E-02	4.29E+01	5.07E-01	4.30E+00	1.89E-02	9.05E-02	-1.87E+01	-1.80E+01	-1.86E+01	2.43E-01
9	1.00E-03	1.20E-01	7.93E-04	1.19E+00	5.65E-02	4.55E+00	1.02E+00	5.32E-02	4.50E+00	9.84E-02	7.48E+00	5.01E-01	1.07E-01	-1.99E+01	-1.83E+01	-2.03E+01	4.45E-01
10	6.44E-03	1.86E-01	2.29E-03	2.12E+00	2.59E-01	1.38E+00	1.25E+00	1.71E-01	3.41E+00	1.67E-01	6.17E+00	3.32E-01	2.58E-01	-2.00E+01	-1.82E+01	-2.11E+01	8.71E-01
11	7.83E-03	1.74E-01	3.29E-03	3.24E+00	1.03E-01	2.19E+00	9.11E-01	9.49E-02	2.63E-01	4.43E-02	8.25E+00	1.05E-01	1.69E-01	-1.73E+01	-1.83E+01	-2.02E+01	8.05E-01
12	1.24E-04	1.62E-01	7.17E-03	8.40E-01	3.17E-02	1.52E+00	6.64E+00	7.65E-02	2.51E-01	4.17E-01	7.90E+00	1.85E-01	2.86E-01	-1.87E+01	-1.76E+01	-1.90E+01	2.17E-01
13	1.06E-03	1.58E-01	1.45E-03	1.69E+00	5.24E-02	1.71E+00	8.06E-01	2.88E-02	2.19E-01	5.14E-01	7.17E+00	5.50E-01	3.18E-01	-1.86E+01	-1.72E+01	-1.98E+01	9.84E-01
14	1.22E-03	1.02E-01	6.60E-04	1.48E+00	6.16E-02	8.89E-01	1.57E+00	2.66E-02	2.68E+01	1.29E-01	5.91E+00	1.46E-02	2.91E-01	-1.96E+01	-1.88E+01	-2.08E+01	6.10E-01
15	9.40E-03	1.35E-01	1.09E-02	8.10E+00	2.48E-02	1.81E+00	5.91E+00	4.20E-02	2.88E+01	5.81E-01	1.23E+01	4.03E-01	3.43E-01	-1.87E+01	-1.82E+01	-1.91E+01	6.38E-01
16	3.20E-03	1.87E-01	2.08E-04	1.35E+00	1.68E-01	9.60E-01	3.55E+00	2.28E-02	4.00E+01	2.03E-01	1.35E+01	3.73E-02	1.68E-01	-1.82E+01	-1.80E+01	-1.94E+01	3.57E-02
17	7.90E-04	1.51E-01	1.33E-03	1.84E+00	2.45E-01	3.81E+00	4.32E+00	5.75E-02	3.02E+01	3.60E-01	9.72E+00	0	6.91E-02	-1.88E+01	-1.80E+01	-2.00E+01	8.85E-01
18	3.02E-03	2.22E-01	2.21E-04	5.63E+00	8.24E-02	4.64E+00	5.32E+00	3.63E-02	4.02E+00	2.27E-01	6.52E+00	4.92E-02	3.13E-01	-1.77E+01	-1.78E+01	-1.92E+01	1.85E-01
19	8.13E-03	1.30E-01	2.38E-03	4.38E+00	1.41E-01	1.56E+00	2.87E+00	3.48E-02	1.17E+00	2.49E-01	8.22E+00	2.01E-01	2.20E-01	-1.84E+01	-1.71E+01	-2.08E+01	9.20E-01
20	2.47E-03	1.48E-01	4.07E-03	2.92E+00	3.92E-02	2.32E+00	2.14E+00	1.83E-01	1.59E+01	1.51E-02	7.76E+00	1.41E-01	5.35E-02	-1.79E+01	-1.75E+01	-1.89E+01	9.75E-01
21	1.90E-03	1.17E-01	4.79E-03	7.13E-01	3.39E-02	3.95E+00	5.00E+00	2.74E-02	5.31E-02	3.43E-01	1.61E+01	1.36E-01	3.47E-01	-1.80E+01	-1.85E+01	-2.02E+01	4.92E-01
22	5.09E-04	1.16E-01	7.06E-04	9.93E+00	3.75E-02	4.82E+00	9.64E-01	1.14E-01	4.20E-01	2.73E-01	8.16E+00	1.01E-02	1.72E-01	-1.79E+01	-1.82E+01	-1.88E+01	8.97E-01
23	3.96E-03	1.93E-01	1.30E-03	3.30E+00	2.89E-02	1.94E+00	2.05E+00	1.36E-01	1.07E+01	3.83E-01	1.25E+01	2.71E-01	1.98E-01	-1.81E+01	-1.80E+01	-1.92E+01	9.30E-01
24	1.05E-04	1.37E-01	3.12E-05	1.09E+00	6.44E-02	1.11E+00	1.12E+00	8.74E-02	1.47E+01	4.09E-01	9.37E+00	6.98E-02	2.05E-01	-1.87E+01	-1.88E+01	-1.92E+01	5.54E-01
25	2.58E-04	1.85E-01	7.73E-04	7.45E+00	1.07E-01	9.90E-01	2.66E+00	2.02E-01	1.16E-01	4.90E-01	1.01E+01	1.12E-01	2.13E-01	-2.00E+01	-1.87E+01	-2.17E+01	2.51E-01
26	1.88E-04	1.16E-01	9.60E-04	7.52E+00	1.31E-01	3.20E+00	4.47E+00	9.50E-02	2.89E+00	4.22E-01	8.30E+00	5.35E-01	3.01E-01	-1.70E+01	-1.76E+01	-2.13E+01	7.29E-01
27	2.80E-04	1.10E-01	5.74E-05	3.16E+00	1.15E-01	9.67E+00	2.25E+00	2.39E-02	7.33E+01	5.19E-01	9.93E+00	6.56E-02	2.43E-01	-1.89E+01	-1.76E+01	-1.82E+01	4.55E-01
28	2.72E-03	1.12E-01	1.13E-02	2.14E+00	4.32E-02	1.17E+00	2.62E+00	1.01E-01	5.12E-01	5.60E-01	6.96E+00	2.91E-01	8.75E-02	-2.02E+01	-1.81E+01	-1.97E+01	1.21E-01
29	5.41E-03	1.39E-01	5.65E-04	9.29E-01	2.22E-02	4.90E+00	4.62E+00	3.47E-01	7.92E-02	2.22E-01	7.39E+00	5.64E-02	2.60E-02	-1.85E+01	-1.89E+01	-1.95E+01	9.96E-01
30	4.85E-03	1.88E-01	8.64E-04	7.30E-01	1.24E-01	2.57E+00	4.76E+00	1.31E-01	1.23E+01	5.23E-02	7.98E+00	4.12E-01	3.57E-01	-1.78E+01	-1.89E+01	-2.04E+01	7.97E-01
31	1.78E-03	1.72E-01	2.42E-04	8.73E+00	3.15E-01	7.19E+00	1.28E+00	3.34E-02	5.31E-01	1.18E-01	4.80E+00	4.32E-01	3.07E-01	-1.95E+01	-1.85E+01	-2.01E+01	4.63E-01
32	1.68E-03	1.67E-01	7.45E-05	3.36E+00	2.31E-02	1.43E+00	9.89E-01	3.23E-01	1.97E+01	4.52E-01	7.98E+00	5.38E-01	3.29E-01	-1.97E+01	-1.79E+01	-2.10E+01	6.16E-01
33	1.13E-04	1.64E-01	1.08E-04	5.84E+00	2.77E-01	5.60E+00	8.29E+00	3.90E-01	1.29E+01	6.78E-02	8.06E+00	2.77E-01	3.90E-01	-1.83E+01	-1.89E+01	-1.99E+01	7.07E-01
34	1.16E-04	1.98E-01	5.31E-03	9.53E+00	3.00E-01	2.69E+00	1.32E+00	6.18E-02	3.98E-01	5.36E-01	1.02E+01	3.71E-01	4.03E-02	-1.82E+01	-1.86E+01	-1.89E+01	1.42E-01
35	1.91E-03	1.83E-01	1.79E-03	2.67E+00	1.05E-01	8.99E+00	1.38E+00	4.93E-02	1.40E+01	3.14E-01	1.57E+01	4.56E-01	7.74E-02	-1.78E+01	-1.99E+01	-2.05E+01	4.00E-01
36	2.54E-03	1.42E-01	1.63E-03	1.37E+00	2.12E-01	8.07E+00	1.83E+00	3.64E-01	5.00E+00	2.37E-01	1.05E+01	3.80E-01	1.46E-01	-1.85E+01	-1.78E+01	-2.03E+01	9.41E-01
37	4.06E-03	1.79E-01	4.63E-03	7.00E+00	1.50E-01	1.89E+00	9.07E+00	4.72E-02	7.43E-01	1.77E-02	7.26E+00	9.19E-02	6.72E-02	-1.95E+01	-1.89E+01	-2.01E+01	2.92E-01
38	9.79E-04	1.14E-01	3.73E-05	3.97E+00	6.78E-02	2.27E+00	3.26E+00	2.37E-01	9.94E-02	8.66E-02	7.30E+00	2.14E-02	3.64E-01	-1.92E+01	-1.79E+01	-2.10E+01	4.11E-01
39	1.26E-03	1.40E-01	6.37E-04	2.42E+00	2.36E-01	9.01E+00	3.29E+00	5.96E-02	1.99E-01	2.93E-01	9.10E+00	1.29E-01	1.50E-01	-1.74E+01	-1.82E+01	-1.95E+01	1.94E-01
40	2.40E-04	1.83E-01	9.55E-05	2.53E+00	2.38E-02	4.31E+00	2.47E+00	1.67E-01	4.70E+01	4.79E-02	8.11E+00	1.50E-01	1.86E-01	-1.89E+01	-1.74E+01	-2.06E+01	2.27E-01
41	6.16E-04	2.35E-01	6.01E-03	2.22E+00	1.86E-01	9.70E-01	4.08E+00	1.22E-01	6.33E+01	4.38E-01	8.64E+00	4.80E-03	1.77E-01	-1.76E+01	-1.71E+01	-2.20E+01	6.89E-01
42	5.33E-04	1.04E-01	4.56E-04	9.10E-01	8.66E-02	1.64E+00	7.08E+00	3.17E-02	1.71E+01	5.52E-01	4.45E+00	2.11E-01	3.84E-02	-1.82E+01	-1.76E+01	-2.08E+01	8.68E-01
43	6.63E-04	1.06E-01	3.24E-05	3.92E+00	7.99E-02	3.42E+00	7.40E-01	3.39E-01	3.71E+01	4.98E-01	1.08E+01	1.18E-01	2.25E-01	-1.78E+01	-1.95E+01	-2.01E+01	5.10E-01
44	9.02E-03	1.14E-01	1.14E-04	1.16E+00	2.77E-02	4.24E+00	8.42E+00	5.15E-02	1.73E+00	3.90E-01	5.20E+00	2.62E-01	1.53E-01	-1.70E+01	-1.88E+01	-1.99E+01	5.27E-01
45	1.18E-03	1.73E-01	7.74E-03	7.18E+00	7.24E-02	3.50E+00	5.16E+00	5.47E-02	5.94E+00	5.01E-01	6.74E+00	1.13E-01	1.89E-01	-1.89E+01	-1.83E+01	-1.96E+01	8.14E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector	CULEBRA	CULEBRA	U+6	U+4	PU+3	PU+4	TH+4	AM+3	BOREHOLE	GLOBAL	BOREHOLE	SHFTU	SHFTU	SHFTU	SHFTL_T1	SHFTL_T2	SPALLMOD
Num.	APOROS	DPOROS	MKD_U	MKD_U	MKD_PU	MKD_PU	MKD_TH	MKD_AM	TAUFAIL	PBRINE	DOMEGA	SAT_RBRN	SAT_RGAS	PRMX_LOG	PRMX_LOG	PRMX_LOG	RNDSPALL
46	3.38E-03	1.73E-01	1.72E-04	4.89E+00	3.28E-02	8.28E-01	2.35E+00	8.52E-02	3.47E-01	4.80E-01	8.89E+00	4.68E-01	2.81E-01	-1.84E+01	-1.90E+01	-2.05E+01	1.53E-01
47	4.38E-04	1.89E-01	4.26E-04	1.05E+00	2.79E-02	6.40E+00	2.13E+00	3.10E-01	5.68E+00	1.41E-01	7.31E+00	1.33E-01	2.78E-01	-1.93E+01	-1.77E+01	-1.80E+01	3.82E-03
48	2.72E-04	1.80E-01	4.29E-03	7.93E-01	3.67E-02	1.76E+00	1.19E+00	1.19E-01	5.53E-02	2.60E-01	1.18E+01	3.06E-01	2.33E-02	-1.90E+01	-1.77E+01	-2.18E+01	8.28E-01
49	1.42E-03	1.01E-01	3.02E-03	5.23E+00	5.88E-02	3.12E+00	2.53E+00	6.63E-02	3.11E-01	4.59E-01	7.80E+00	4.65E-02	2.52E-01	-1.80E+01	-1.80E+01	-2.06E+01	6.73E-01
50	7.05E-04	1.59E-01	4.97E-04	6.74E+00	9.89E-02	2.08E+00	7.97E+00	1.91E-01	1.05E-01	1.52E-01	6.31E+00	1.99E-01	4.00E-01	-1.88E+01	-1.76E+01	-1.98E+01	8.36E-01
51	3.32E-04	1.68E-01	8.50E-05	2.60E+00	2.31E-01	2.72E+00	1.64E+00	3.99E-02	6.83E-01	2.15E-01	1.34E+01	5.69E-01	1.19E-01	-2.04E+01	-1.79E+01	-2.04E+01	8.55E-01
52	3.57E-03	1.19E-01	2.01E-03	6.26E+00	4.79E-02	1.51E+00	3.04E+00	4.43E-02	7.97E+00	7.38E-02	1.26E+01	5.89E-01	1.07E-02	-1.71E+01	-1.77E+01	-2.13E+01	2.07E-01
53	2.29E-04	1.60E-01	1.00E-02	9.46E+00	9.73E-02	7.65E+00	4.72E+00	5.57E-02	8.73E-01	2.28E-01	7.64E+00	3.34E-02	1.10E-01	-1.91E+01	-1.87E+01	-1.93E+01	4.34E-01
54	3.69E-03	1.33E-01	1.19E-04	1.79E+00	1.37E-01	9.43E+00	5.48E+00	6.97E-02	9.18E-02	1.97E-01	7.89E+00	3.21E-01	3.70E-01	-1.90E+01	-1.69E+01	-2.09E+01	3.47E-01
55	4.44E-03	1.69E-01	5.68E-03	1.96E+00	1.75E-01	5.10E+00	5.66E+00	2.41E-01	1.83E+00	5.94E-01	1.15E+01	5.63E-01	1.64E-01	-1.84E+01	-1.92E+01	-1.94E+01	3.62E-01
56	5.04E-03	1.11E-01	1.03E-03	8.80E+00	2.99E-02	7.05E+00	1.53E+00	3.00E-02	5.00E+01	1.73E-01	8.47E+00	2.36E-01	5.63E-02	-1.92E+01	-1.84E+01	-2.01E+01	6.54E-02
57	7.25E-03	2.50E-01	6.30E-05	2.81E+00	2.67E-01	1.45E+00	3.69E+00	1.84E-01	9.01E+00	1.38E-01	7.08E+00	2.40E-01	1.21E-01	-1.81E+01	-1.83E+01	-2.15E+01	5.75E-01
58	1.47E-03	1.66E-01	1.60E-04	2.26E+00	3.34E-01	5.28E+00	9.43E-01	4.29E-02	1.51E+00	3.78E-01	1.39E+01	3.88E-01	2.65E-01	-1.76E+01	-1.81E+01	-1.94E+01	9.50E-01
59	1.75E-04	1.32E-01	1.90E-02	1.62E+00	3.54E-02	2.48E+00	1.34E+00	2.56E-01	7.06E+00	1.87E-01	1.07E+01	1.74E-01	1.43E-01	-1.98E+01	-1.77E+01	-2.11E+01	1.12E-01
60	1.94E-04	1.08E-01	6.68E-03	7.80E+00	5.38E-02	2.63E+00	3.53E+00	2.57E-02	2.22E+00	1.08E-01	6.70E+00	5.97E-01	1.29E-02	-1.80E+01	-1.85E+01	-2.01E+01	7.49E-01
61	4.67E-04	1.22E-01	1.50E-02	1.41E+00	4.38E-02	9.75E+00	8.51E-01	3.81E-02	1.04E+01	3.58E-01	6.88E+00	6.25E-02	4.48E-02	-1.83E+01	-1.94E+01	-2.09E+01	7.11E-01
62	1.57E-04	1.77E-01	2.64E-03	4.53E+00	2.15E-02	1.26E+00	2.95E+00	3.08E-02	4.68E-01	2.87E-02	8.35E+00	5.58E-01	3.22E-01	-1.94E+01	-1.82E+01	-1.88E+01	5.45E-01
63	3.86E-04	1.74E-01	1.42E-02	1.59E+00	4.96E-02	7.82E-01	3.75E+00	1.04E-01	1.00E+00	2.76E-01	1.16E+01	2.67E-02	1.81E-01	-1.77E+01	-1.94E+01	-2.03E+01	1.40E-01
64	3.26E-04	1.47E-01	1.92E-04	3.80E+00	2.79E-01	8.09E-01	3.17E+00	4.62E-02	1.73E-01	3.10E-01	2.14E+01	9.23E-02	5.13E-02	-1.92E+01	-1.75E+01	-1.93E+01	3.08E-01
65	3.67E-04	1.13E-01	3.64E-03	8.31E+00	3.11E-02	7.34E-01	1.92E+00	1.62E-01	7.42E+00	5.30E-01	5.41E+00	1.79E-01	2.54E-01	-1.88E+01	-1.84E+01	-2.04E+01	6.64E-01
66	1.14E-03	1.78E-01	4.81E-05	2.48E+00	9.45E-02	1.21E+00	7.63E+00	2.10E-01	2.03E-01	3.00E-01	1.20E+01	1.66E-03	1.38E-01	-1.76E+01	-1.74E+01	-2.05E+01	7.87E-01
67	5.84E-04	2.31E-01	1.43E-04	4.06E+00	5.82E-02	8.19E+00	7.85E+00	2.50E-02	2.06E+00	5.55E-01	8.12E+00	2.20E-01	2.19E-01	-1.89E+01	-1.86E+01	-2.16E+01	7.60E-01
68	2.00E-04	1.44E-01	5.45E-04	9.67E-01	3.62E-01	6.56E+00	7.31E+00	1.50E-01	3.82E-01	2.44E-01	6.48E+00	4.95E-01	3.00E-01	-1.82E+01	-1.88E+01	-2.09E+01	2.74E-01
69	8.18E-04	1.71E-01	2.06E-03	2.79E+00	2.40E-02	7.45E+00	9.93E+00	8.29E-02	2.73E+00	5.27E-01	7.44E+00	1.24E-01	6.11E-02	-1.86E+01	-1.85E+01	-1.97E+01	6.00E-01
70	4.31E-04	1.63E-01	6.92E-05	1.74E+00	1.12E-01	1.66E+00	4.19E+00	7.46E-02	1.08E+00	3.90E-02	1.10E+01	2.81E-01	3.40E-01	-1.78E+01	-1.92E+01	-1.85E+01	9.63E-01
71	4.32E-03	1.65E-01	5.35E-05	1.11E+00	4.10E-02	4.06E+00	3.93E+00	2.40E-02	5.86E-02	5.86E-01	6.99E+00	1.93E-01	3.50E-01	-1.79E+01	-1.90E+01	-2.00E+01	5.89E-01
72	3.61E-04	1.43E-01	1.34E-04	1.24E+00	2.05E-02	8.65E-01	9.14E-01	2.77E-01	4.28E+00	3.32E-01	7.59E+00	8.12E-02	3.87E-01	-1.83E+01	-1.87E+01	-1.95E+01	5.31E-01
73	5.51E-03	1.70E-01	8.06E-03	9.55E-01	3.87E-01	2.21E+00	3.40E+00	1.15E-01	3.30E+01	4.27E-01	1.46E+01	1.54E-01	3.94E-01	-1.99E+01	-1.84E+01	-2.05E+01	3.16E-01
74	6.30E-03	2.05E-01	7.47E-05	8.47E-01	4.23E-02	1.09E+00	1.73E+00	2.21E-02	9.58E+00	1.77E-01	1.12E+01	1.62E-01	3.55E-02	-1.83E+01	-1.84E+01	-2.02E+01	4.88E-01
75	2.36E-04	1.17E-01	8.24E-05	5.95E+00	3.08E-01	3.65E+00	2.03E+00	1.49E-01	3.35E-01	2.57E-01	5.05E+00	8.64E-02	2.01E-01	-1.91E+01	-1.82E+01	-2.19E+01	5.12E-01
76	2.22E-03	1.29E-01	9.07E-03	1.54E+00	3.99E-01	7.65E-01	7.83E-01	1.27E-01	1.24E+00	2.94E-01	5.01E+00	4.81E-01	7.57E-02	-1.78E+01	-1.87E+01	-1.87E+01	7.36E-01
77	8.80E-04	1.79E-01	1.77E-02	3.51E+00	7.67E-02	5.18E+00	6.53E+00	2.28E-01	2.50E+01	2.85E-01	6.44E+00	3.93E-01	2.73E-01	-1.75E+01	-1.75E+01	-2.14E+01	3.78E-01
78	4.06E-04	1.55E-01	1.08E-03	5.51E+00	1.96E-01	3.08E+00	1.15E+00	3.67E-02	6.30E-01	4.46E-01	7.82E+00	4.36E-02	2.63E-01	-1.95E+01	-1.91E+01	-2.14E+01	8.46E-01
79	7.10E-03	1.55E-01	1.26E-04	2.06E+00	3.75E-01	7.70E+00	7.10E-01	1.57E-01	1.46E+00	3.95E-01	9.58E+00	2.53E-01	1.35E-01	-1.81E+01	-1.73E+01	-1.96E+01	3.98E-01
80	1.37E-04	1.15E-01	4.85E-04	1.26E+00	1.57E-01	6.13E+00	5.85E+00	2.65E-01	5.36E+01	4.71E-01	1.01E+01	4.72E-01	3.25E-01	-1.85E+01	-1.84E+01	-1.95E+01	1.65E-01
81	5.79E-03	1.09E-01	6.40E-03	6.48E+00	9.11E-02	2.89E+00	2.39E+00	2.83E-01	7.47E-02	1.26E-01	7.41E+00	1.65E-01	1.31E-01	-1.86E+01	-1.71E+01	-1.87E+01	2.87E-01
82	5.56E-04	1.90E-01	2.69E-03	3.72E+00	1.94E-01	2.10E+00	4.05E+00	9.09E-02	1.41E-01	5.68E-01	9.10E+00	9.87E-02	2.33E-01	-1.76E+01	-1.79E+01	-2.07E+01	4.72E-01
83	3.13E-04	1.82E-01	9.49E-03	4.25E+00	7.00E-02	5.57E+00	1.08E+00	1.43E-01	3.64E+01	4.30E-01	5.78E+00	3.58E-01	3.35E-01	-1.77E+01	-1.81E+01	-2.23E+01	3.39E-01
84	6.47E-04	1.26E-01	4.63E-05	3.10E+00	1.22E-01	6.28E+00	9.40E+00	8.06E-02	1.28E-01	3.24E-01	8.37E+00	3.39E-01	8.38E-02	-1.81E+01	-1.75E+01	-1.91E+01	5.62E-01
85	1.36E-03	1.06E-01	3.46E-05	1.29E+00	4.52E-02	1.13E+00	1.46E+00	2.21E-01	6.65E+00	4.01E-01	7.71E+00	5.80E-01	1.87E-02	-1.84E+01	-1.71E+01	-2.15E+01	7.17E-02
86	9.15E-04	1.76E-01	4.35E-05	1.03E+00	7.45E-02	2.79E+00	1.42E+00	2.06E-02	3.08E+00	3.72E-01	6.60E+00	4.43E-01	1.92E-01	-1.93E+01	-1.86E+01	-2.04E+01	3.54E-01
87	2.98E-04	1.88E-01	1.83E-03	4.73E+00	2.18E-01	8.99E-01	1.16E+00	2.49E-01	2.17E+01	2.09E-01	6.59E+00	1.69E-01	2.69E-01	-1.81E+01	-1.77E+01	-1.91E+01	7.77E-01
88	2.32E-03	1.18E-01	1.22E-02	1.67E+00	2.26E-01	9.36E-01	1.78E+00	2.16E-02	8.82E-01	4.83E-01	7.03E+00	1.92E-01	3.80E-01	-1.93E+01	-1.72E+01	-1.90E+01	6.98E-01
89	4.77E-03	1.61E-01	1.69E-02	8.19E-01	6.38E-02	8.48E+00	1.07E+00	1.05E-01	6.47E-02	1.10E-01	6.39E+00	1.45E-01	2.40E-01	-1.85E+01	-1.90E+01	-2.00E+01	2.64E-01
90	1.27E-04	1.05E-01	3.76E-03	7.59E-01	1.79E-01	1.32E+00	6.31E+00	4.81E-02	2.33E+01	1.02E-01	6.67E+00	7.37E-02	6.83E-03	-1.77E+01	-1.79E+01	-2.06E+01	3.84E-01

Table PAR-11. LHS Sampled Values (100 vectors) Replicate 3 — Continued

Parameter	50	51	52	53	54	55	56	57	58	60	61	62	63	64	65	66	75
Vector	CULEBRA	CULEBRA	U+6	U+4	PU+3	PU+4	TH+4	AM+3	BOREHOLE	GLOBAL	BOREHOLE	SHFTU	SHFTU	SHFTU	SHFTL_T1	SHFTL_T2	SPALLMOD
Num.	APOROS	DPOROS	MKD_U	MKD_U	MKD_PU	MKD_PU	MKD_TH	MKD_AM	TAUFAIL	PBRINE	DOMEGA	SAT_RBRN	SAT_RGAS	PRMX_LOG	PRMX_LOG	PRMX_LOG	RNDSPALL
91	2.08E-03	1.50E-01	9.73E-05	1.89E+00	1.17E-01	1.04E+00	8.65E+00	3.30E-01	2.32E+00	8.90E-02	5.55E+00	4.62E-01	3.03E-02	-1.91E+01	-1.93E+01	-1.84E+01	4.29E-01
92	2.11E-03	1.01E-01	3.86E-04	4.48E+00	1.59E-01	1.33E+00	5.03E+00	6.48E-02	6.05E+01	5.94E-02	1.74E+01	3.13E-01	3.79E-01	-1.71E+01	-1.93E+01	-2.18E+01	8.03E-02
93	1.01E-04	2.16E-01	3.39E-04	9.96E-01	1.65E-01	1.05E+00	2.75E+00	2.08E-02	5.88E-01	3.52E-01	4.63E+00	2.31E-01	1.14E-01	-1.72E+01	-1.80E+01	-2.02E+01	2.30E-01
94	7.45E-04	1.20E-01	1.21E-03	6.05E+00	1.45E-01	2.43E+00	6.07E+00	2.82E-02	1.40E-01	2.20E-02	9.41E+00	5.26E-01	3.64E-01	-1.80E+01	-1.78E+01	-1.99E+01	1.85E-02
95	2.16E-04	1.83E-01	1.79E-04	4.86E+00	2.59E-02	7.43E-01	8.22E-01	2.98E-01	7.98E-01	4.56E-01	7.67E+00	5.09E-01	9.28E-02	-1.75E+01	-1.84E+01	-1.96E+01	6.25E-01
96	4.83E-04	1.76E-01	1.54E-03	5.34E+00	2.69E-02	5.78E+00	2.85E+00	3.96E-02	2.49E+00	1.59E-01	6.34E+00	4.19E-01	3.74E-01	-1.73E+01	-1.81E+01	-1.92E+01	9.38E-01
97	2.82E-03	1.68E-01	5.78E-05	8.05E+00	3.50E-02	1.85E+00	8.89E-01	3.27E-02	2.76E-01	1.85E-01	4.59E+00	3.18E-02	2.28E-01	-1.72E+01	-1.83E+01	-2.12E+01	9.44E-02
98	1.47E-04	2.13E-01	4.07E-05	2.97E+00	7.87E-02	8.72E+00	1.60E+00	2.17E-01	6.88E-02	3.19E-01	8.68E+00	1.80E-01	2.47E-03	-1.89E+01	-1.83E+01	-2.03E+01	6.47E-01
99	1.39E-04	1.27E-01	9.04E-04	2.34E+00	3.41E-01	3.56E+00	9.57E+00	6.38E-02	3.78E+00	3.65E-01	6.81E+00	2.98E-01	2.10E-01	-1.86E+01	-1.85E+01	-1.98E+01	7.63E-01
100	3.11E-03	1.23E-01	2.88E-04	2.02E+00	1.32E-01	2.97E+00	7.32E-01	7.16E-02	1.54E-01	1.49E-01	7.10E+00	1.04E-01	3.54E-01	-1.76E+01	-1.82E+01	-1.88E+01	2.98E-02

Table PAR-12. LHS Sampled Values for the Spall Model (50 vectors) Only 1 Replicate

Vector Num.	Parameter			
	SPALLMOD REPIPORE	SPALLMOD REPIPERM	SPALLMOD TENSLSTR	SPALLMOD PARTDIAM
1	5.17E-01	3.97E-13	1.38E+05	4.69E-02
2	3.77E-01	5.77E-14	1.25E+05	3.88E-03
3	6.24E-01	3.90E-14	1.47E+05	7.72E-02
4	6.41E-01	5.49E-14	1.39E+05	2.13E-03
5	4.91E-01	7.22E-14	1.52E+05	1.11E-02
6	6.32E-01	8.81E-13	1.66E+05	2.96E-03
7	5.69E-01	4.28E-14	1.64E+05	2.39E-02
8	6.04E-01	2.42E-14	1.55E+05	3.80E-02
9	5.33E-01	7.55E-13	1.30E+05	1.07E-02
10	6.12E-01	1.03E-13	1.60E+05	7.51E-02
11	4.85E-01	3.05E-13	1.23E+05	5.82E-02
12	5.38E-01	2.81E-13	1.31E+05	6.79E-02
13	4.52E-01	1.27E-12	1.50E+05	5.60E-02
14	4.70E-01	1.72E-12	1.65E+05	1.64E-02
15	4.96E-01	1.00E-12	1.37E+05	3.51E-03
16	3.59E-01	2.74E-14	1.54E+05	4.60E-03
17	4.61E-01	3.46E-14	1.44E+05	4.98E-03
18	3.51E-01	2.62E-13	1.63E+05	4.10E-02
19	4.46E-01	6.33E-14	1.26E+05	4.06E-03
20	5.85E-01	1.96E-13	1.44E+05	2.08E-02
21	4.36E-01	1.10E-13	1.21E+05	8.34E-02
22	6.02E-01	1.82E-12	1.29E+05	6.48E-03
23	3.73E-01	1.18E-13	1.67E+05	1.50E-02
24	4.62E-01	3.53E-13	1.50E+05	1.16E-03
25	5.88E-01	1.24E-12	1.33E+05	1.76E-03

Vector Num.	Parameter			
	SPALLMOD REPIPORE	SPALLMOD REPIPERM	SPALLMOD TENSLSTR	SPALLMOD PARTDIAM
26	3.97E-01	1.76E-13	1.48E+05	2.17E-02
27	6.18E-01	4.75E-14	1.53E+05	3.43E-02
28	4.37E-01	2.13E-13	1.42E+05	1.24E-03
29	4.77E-01	4.51E-13	1.47E+05	1.23E-02
30	4.02E-01	2.89E-14	1.39E+05	1.04E-03
31	5.20E-01	1.64E-13	1.55E+05	1.51E-03
32	6.51E-01	1.39E-12	1.62E+05	8.34E-03
33	6.38E-01	7.16E-13	1.35E+05	2.73E-03
34	3.68E-01	5.05E-13	1.58E+05	2.06E-03
35	3.85E-01	8.31E-13	1.29E+05	9.83E-02
36	5.11E-01	1.40E-13	1.59E+05	5.84E-03
37	5.45E-01	8.09E-14	1.27E+05	1.44E-02
38	4.21E-01	2.04E-12	1.34E+05	1.64E-03
39	5.94E-01	4.58E-13	1.70E+05	4.84E-02
40	5.63E-01	7.35E-14	1.22E+05	2.89E-02
41	5.26E-01	2.31E-12	1.43E+05	3.17E-02
42	4.30E-01	6.55E-13	1.26E+05	3.18E-03
43	3.92E-01	1.13E-12	1.35E+05	7.96E-03
44	4.08E-01	1.55E-12	1.69E+05	2.56E-02
45	5.51E-01	2.23E-13	1.45E+05	1.84E-02
46	5.79E-01	5.84E-13	1.21E+05	5.57E-03
47	5.03E-01	9.51E-14	1.61E+05	1.40E-03
48	4.14E-01	1.28E-13	1.68E+05	9.49E-03
49	5.58E-01	3.53E-14	1.41E+05	7.40E-03
50	6.57E-01	3.24E-13	1.56E+05	2.32E-03

Table PAR-13. Borehole, Blowout and Drill Mud Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BLOWOUT	Material for direct brine release calculations	GAS_MIN	Gas rate cut-off	Constant	mscf/day	1.00E+02
	BLOWOUT	Material for direct brine release calculations	HREPO	Height of repository at burial time in CUTTINGS model	Constant	m	3.96E+00
	BLOWOUT	Material for direct brine release calculations	MAXFLOW	Maximum blowout flow	Constant	s	9.50E+05
	BLOWOUT	Material for direct brine release calculations	MINFLOW	Minimum blowout flow	Constant	s	2.59E+05
	BLOWOUT	Material for direct brine release calculations	PARTDIA	Waste Particle Diameter in CUTTINGS Model	Log uniform	m	2.80E-03
	BLOWOUT	Material for direct brine release calculations	RE_CAST	External drainage radius for the Castile formation	Constant	m	1.14E+02
	BLOWOUT	Material for direct brine release calculations	RGAS	Gas Constant for Hydrogen	Constant	N*m/kg/K	4.12E+03
	BLOWOUT	Material for direct brine release calculations	RHOS	Waste Particle Density in CUTTINGS_S Model	Constant	kg/m^3	2.65E+03
	BLOWOUT	Material for direct brine release calculations	THCK_CAS	Thickness of the Castile Brine Reservoir	Constant	m	1.26E+02
	BLOWOUT	Material for direct brine release calculations	TREPO	Temperature of repository in CUTTINGS model	Constant	K	3.00E+02
	BOREHOLE	Borehole and Fill	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	BOREHOLE	Borehole and Fill	COLDIA	Drill collar diameter in CUTTINGS model	Constant	m	2.03E-01
	BOREHOLE	Borehole and Fill	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	2.64E-09
	BOREHOLE	Borehole and Fill	DIAMMOD	Modern or current diameter	Constant	m	3.11E-01
	BOREHOLE	Borehole and Fill	DOMEGA	Drill string angular velocity (0)	Cumulative	rad/s	Sampled Value
	BOREHOLE	Borehole and Fill	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	BOREHOLE	Borehole and Fill	L1	Drill collar length in CUTTINGS model	Constant	m	1.83E+02
	BOREHOLE	Borehole and Fill	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	BOREHOLE	Borehole and Fill	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	BOREHOLE	Borehole and Fill	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	BOREHOLE	Borehole and Fill	PIPED	Drill pipe diameter in CUTTINGS model	Constant	m	1.14E-01

Table PAR-13. Borehole, Blowout and Drill Mud Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BOREHOLE	Borehole and Fill	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	BOREHOLE	Borehole and Fill	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	9.40E-01
	BOREHOLE	Borehole and Fill	POROSITY	Effective porosity	Constant	NONE	5.00E-02
	BOREHOLE	Borehole and Fill	PRMX_LOG	Log of intrinsic permeability, X-direction	Normal	$\log(m^2)$	-1.25E+01
	BOREHOLE	Borehole and Fill	PRMY_LOG	Log of intrinsic permeability, Y-direction	Normal	$\log(m^2)$	-1.25E+01
	BOREHOLE	Borehole and Fill	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Normal	$\log(m^2)$	-1.25E+01
	BOREHOLE	Borehole and Fill	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	BOREHOLE	Borehole and Fill	SAT_RBRN	Residual Brine Saturation	Constant	NONE	2.00E-01
	BOREHOLE	Borehole and Fill	SAT_RGAS	Residual Gas Saturation	Constant	NONE	2.00E-01
	BOREHOLE	Borehole and Fill	TAUFAIL	Effective shear strength for erosion (rfail)	Log uniform	Pa	Sampled Value
	BOREHOLE	Borehole and Fill	WUF	Unit of Waste	Constant	Curies	2.48E+00
	DRILLMUD	Drilling Mud	DNSFLUID	Brine Density	Cumulative	kg/m^3	1.21E+03
	DRILLMUD	Drilling Mud	VISCO	Viscosity	Cumulative	Pa*s	9.17E-03
	DRILLMUD	Drilling Mud	YLDSTRSS	Yield Stress Point	Cumulative	Pa	4.40E+00

Table PAR-14. Borehole (Concrete Plug) Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CONC_PLG	Concrete Plug, surface and Rustler	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	3.80E-10
	CONC_PLG	Concrete Plug, surface and Rustler	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CONC_PLG	Concrete Plug, surface and Rustler	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CONC_PLG	Concrete Plug, surface and Rustler	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	9.40E-01
	CONC_PLG	Concrete Plug, surface and Rustler	POROSITY	Effective porosity	Constant	NONE	3.20E-01
	CONC_PLG	Concrete Plug, surface and Rustler	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$\log(m^2)$	-1.80E+01
	CONC_PLG	Concrete Plug, surface and Rustler	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$\log(m^2)$	-1.80E+01
	CONC_PLG	Concrete Plug, surface and Rustler	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	CONC_PLG	Concrete Plug, surface and Rustler	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-15. Borehole (Open) Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BH_OPEN	Borehole Unrestricted	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	BH_OPEN	Borehole Unrestricted	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	BH_OPEN	Borehole Unrestricted	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	BH_OPEN	Borehole Unrestricted	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	BH_OPEN	Borehole Unrestricted	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	BH_OPEN	Borehole Unrestricted	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	BH_OPEN	Borehole Unrestricted	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	BH_OPEN	Borehole Unrestricted	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	BH_OPEN	Borehole Unrestricted	POROSITY	Effective porosity	Constant	NONE	3.20E-01
	BH_OPEN	Borehole Unrestricted	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$log(m^2)$	-9.00E+00
	BH_OPEN	Borehole Unrestricted	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$log(m^2)$	-9.00E+00
	BH_OPEN	Borehole Unrestricted	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$log(m^2)$	-9.00E+00
	BH_OPEN	Borehole Unrestricted	RELP_MOD	Model number, relative permeability model	Constant	NONE	5.00E+00
	BH_OPEN	Borehole Unrestricted	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	BH_OPEN	Borehole Unrestricted	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-16. Borehole (Silty Sand) Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BH_SAND	Borehole filled with silty sand	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	BH_SAND	Borehole filled with silty sand	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	BH_SAND	Borehole filled with silty sand	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	BH_SAND	Borehole filled with silty sand	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	BH_SAND	Borehole filled with silty sand	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	BH_SAND	Borehole filled with silty sand	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	BH_SAND	Borehole filled with silty sand	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	BH_SAND	Borehole filled with silty sand	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	9.40E-01
	BH_SAND	Borehole filled with silty sand	POROSITY	Effective porosity	Constant	NONE	3.20E-01
	BH_SAND	Borehole filled with silty sand	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$log(m^2)$	Sampled Value
	BH_SAND	Borehole filled with silty sand	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$log(m^2)$	Applied Value See BH_SAND PRMX_LOG
	BH_SAND	Borehole filled with silty sand	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$log(m^2)$	Applied Value See BH_SAND PRMX_LOG
	BH_SAND	Borehole filled with silty sand	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	BH_SAND	Borehole filled with silty sand	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	BH_SAND	Borehole filled with silty sand	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-17. Borehole (Creep) Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BH_CREEP	Creep Borehole Fill	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	BH_CREEP	Creep Borehole Fill	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	BH_CREEP	Creep Borehole Fill	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	BH_CREEP	Creep Borehole Fill	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	BH_CREEP	Creep Borehole Fill	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	BH_CREEP	Creep Borehole Fill	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	BH_CREEP	Creep Borehole Fill	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	BH_CREEP	Creep Borehole Fill	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	9.40E-01
	BH_CREEP	Creep Borehole Fill	POROSITY	Effective porosity	Constant	NONE	3.20E-01
	BH_CREEP	Creep Borehole Fill	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$log(m^2)$	-1.35E+01
	BH_CREEP	Creep Borehole Fill	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$log(m^2)$	-1.35E+01
	BH_CREEP	Creep Borehole Fill	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$log(m^2)$	-1.35E+01
	BH_CREEP	Creep Borehole Fill	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	BH_CREEP	Creep Borehole Fill	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	BH_CREEP	Creep Borehole Fill	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-18. DRSPALL Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SPALLMOD	Material developed for DRSPALL	ANNUROUG	Absolute wall roughness of wellbore annulus	Constant	m	5.00E-05
	SPALLMOD	Material developed for DRSPALL	BIOTBETA	Biot's beta for waste	Constant	NONE	1.00E+00
	SPALLMOD	Material developed for DRSPALL	COHESION	Cohesion of waste	Constant	Pa	1.40E+05
	SPALLMOD	Material developed for DRSPALL	DDZPERM	Permeability of drilling-damaged zone (DDZ)	Constant	m2	1.00E-14
	SPALLMOD	Material developed for DRSPALL	DDZTHICK	Thickness of drilling-damaged zone (DDZ)	Constant	m	1.60E-01
	SPALLMOD	Material developed for DRSPALL	DRILRATE	Drill penetration rate through Salado	Constant	m/s	4.45E-03
	SPALLMOD	Material developed for DRSPALL	DRZPERM	DRZ Permeability for DRSPALL	Constant	m^2	1.00E-15
	SPALLMOD	Material developed for DRSPALL	FFSTRESS	Isotropic in-situ stress in waste area	Constant	Pa	1.49E+07
	SPALLMOD	Material developed for DRSPALL	FRICTANG	Friction angle of waste	Constant	deg	4.58E+01
	SPALLMOD	Material developed for DRSPALL	MUDPRATE	Typical volumetric mud pumping rate for drilling in Salado	Constant	(m3)/s	2.02E-02
	SPALLMOD	Material developed for DRSPALL	MUDSOLMX	Solids volume fraction in drill mud that causes choking of flow	Constant	NONE	6.15E-01
	SPALLMOD	Material developed for DRSPALL	MUDSOLVE	Exponent on mud slurry viscosity power law	Constant	NONE	-1.50E+00
	SPALLMOD	Material developed for DRSPALL	PARTDIAM	Particle diameter of disaggregated waste	Loguniform	m	1.00E-02
	SPALLMOD	Material developed for DRSPALL	PIPEID	Inner diameter of drill pipe (where OD = 0.1143 m)	Constant	m	9.72E-02
	SPALLMOD	Material developed for DRSPALL	PIPEROUG	Absolute wall roughness of drill pipe	Constant	m	5.00E-05
	SPALLMOD	Material developed for DRSPALL	POISRAT	Poisson's ratio for waste	Constant	NONE	3.80E-01
	SPALLMOD	Material developed for DRSPALL	REFPRS	Atmospheric pressure at sea level	Constant	Pa	1.02E+05
	SPALLMOD	Material developed for DRSPALL	REPIPERM	Waste permeability to gas local to intrusion borehole	Loguniform	m2	2.40E-13

Table PAR-18. DRSPALL Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SPALLMOD	Material developed for DRSPALL	REPOSTOP	Elevation of roof in excavated area	Constant	m	3.85E+02
	SPALLMOD	Material developed for DRSPALL	SALTDENS	Density of solid cuttings from the Salado	Constant	kg/m3	2.18E+03
	SPALLMOD	Material developed for DRSPALL	SHAPEFAC	Shape factor for disaggregated waste particles	Constant	NONE	1.00E-01
	SPALLMOD	Material developed for DRSPALL	STPDVOLR	Mud ejection rate that turns off drilling	Constant	$(m^3)/s$	1.00E+03
	SPALLMOD	Material developed for DRSPALL	STPPVOLR	Mud ejection rate that turns off mud pump	Constant	$(m^3)/s$	1.00E+03
	SPALLMOD	Material developed for DRSPALL	SURFELEV	Elevation of land surface at WIPP site	Constant	m	1.04E+03
	SPALLMOD	Material developed for DRSPALL	TENSLSTR	Tensile strength of waste	Uniform	Pa	1.45E+05

Table PAR-19. Shaft Material Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CONC_MON	Concrete Monolith	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	CONC_MON	Concrete Monolith	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	6.00E-11
	CONC_MON	Concrete Monolith	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CONC_MON	Concrete Monolith	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CONC_MON	Concrete Monolith	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	CONC_MON	Concrete Monolith	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	CONC_MON	Concrete Monolith	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CONC_MON	Concrete Monolith	PORE_DIS	Brooks-Corey pore distribution parameter	Cumulative	NONE	9.40E-01
	CONC_MON	Concrete Monolith	POROSITY	Effective porosity	Constant	NONE	5.00E-02
	CONC_MON	Concrete Monolith	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$log(m^2)$	-1.40E+01
	CONC_MON	Concrete Monolith	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$log(m^2)$	-1.40E+01
	CONC_MON	Concrete Monolith	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$log(m^2)$	-1.40E+01
	CONC_MON	Concrete Monolith	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CONC_MON	Concrete Monolith	SAT_IBRN	Initial Brine Saturation	Constant	NONE	1.00E+00
	CONC_MON	Concrete Monolith	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	2.00E-01
	CONC_MON	Concrete Monolith	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	COMP_POR	Pore volume compressibility	Constant	Pa^{-1}	4.28E-09
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01

Table PAR-19. Shaft Material Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	POROSITY	Effective porosity	Constant	NONE	1.13E-01
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	$\log(m^2)$	Sampled Value
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	SHFTL_T1	Lower portion of simplified shaft from 0 - 200 years	SAT_IBRN	Initial Brine Saturation	Constant	NONE	5.34E-01
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	COMP_POR	Pore volume compressibility	Constant	Pa^{-1}	4.28E-09
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	POROSITY	Effective porosity	Constant	NONE	1.13E-01
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	$\log(m^2)$	Sampled Value
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	SHFTL_T2	Lower portion of simplified shaft from 200 - 10,000 years	SAT_IBRN	Initial Brine Saturation	Constant	NONE	5.34E-01
	SHFTU	Upper portion of simplified shaft	COMP_POR	Pore volume compressibility	Constant	Pa^{-1}	2.05E-08
	SHFTU	Upper portion of simplified shaft	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	SHFTU	Upper portion of simplified shaft	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	SHFTU	Upper portion of simplified shaft	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01

Table PAR-19. Shaft Material Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SHFTU	Upper portion of simplified shaft	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	SHFTU	Upper portion of simplified shaft	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	SHFTU	Upper portion of simplified shaft	POROSITY	Effective porosity	Constant	NONE	2.91E-01
	SHFTU	Upper portion of simplified shaft	PRMX_LOG	Log of intrinsic permeability, X-direction	Cumulative	$\log(m^2)$	Sampled Value
	SHFTU	Upper portion of simplified shaft	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	SHFTU	Upper portion of simplified shaft	SAT_IBRN	Initial Brine Saturation	Constant	NONE	7.96E-01
	SHFTU	Upper portion of simplified shaft	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	Sampled Value
	SHFTU	Upper portion of simplified shaft	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	Sampled Value

Table PAR-20. Panel Closure Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CONC_PCS	Concrete portion of PCS	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	CONC_PCS	Concrete portion of PCS	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	6.00E-11
	CONC_PCS	Concrete portion of PCS	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CONC_PCS	Concrete portion of PCS	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CONC_PCS	Concrete portion of PCS	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	CONC_PCS	Concrete portion of PCS	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	CONC_PCS	Concrete portion of PCS	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CONC_PCS	Concrete portion of PCS	PORE_DIS	Brooks-Corey pore distribution parameter	Cumulative	NONE	Sampled Value
	CONC_PCS	Concrete portion of PCS	POROSITY	Effective porosity	Constant	NONE	5.00E-02
	CONC_PCS	Concrete portion of PCS	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	$log(m^2)$	Sampled Value
	CONC_PCS	Concrete portion of PCS	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	$log(m^2)$	Applied Value See CONC_PCS PRMX_LOG
	CONC_PCS	Concrete portion of PCS	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	$log(m^2)$	Applied Value See CONC_PCS PRMX_LOG
	CONC_PCS	Concrete portion of PCS	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CONC_PCS	Concrete portion of PCS	SAT_RBRN	Residual Brine Saturation	Cumulative	NONE	Sampled Value
	CONC_PCS	Concrete portion of PCS	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	Sampled Value
	DRZ_PCS	DRZ directly above concrete portion of panel closure	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	DRZ_PCS	DRZ directly above concrete portion of panel closure	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	7.41E-10
	DRZ_PCS	DRZ directly above concrete portion of panel closure	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00

Table PAR-20. Panel Closure Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	DRZ_PCS	DRZ directly above concrete portion of panel closure	POROSITY	Effective porosity	Cumulative	NONE	1.29E-02
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	$\log(m^2)$	Sampled Value
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	$\log(m^2)$	Applied Value See DRZ_PCS PRMX_LOG
	DRZ_PCS	DRZ directly above concrete portion of panel closure	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	$\log(m^2)$	Applied Value See DRZ_PCS PRMX_LOG
	DRZ_PCS	DRZ directly above concrete portion of panel closure	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	DRZ_PCS	DRZ directly above concrete portion of panel closure	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-21. Santa Rosa Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SANTAROS	Santa Rosa Formation	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	SANTAROS	Santa Rosa Formation	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	1.00E-08
	SANTAROS	Santa Rosa Formation	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	SANTAROS	Santa Rosa Formation	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	SANTAROS	Santa Rosa Formation	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	SANTAROS	Santa Rosa Formation	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	SANTAROS	Santa Rosa Formation	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	SANTAROS	Santa Rosa Formation	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	6.44E-01
	SANTAROS	Santa Rosa Formation	POROSITY	Effective porosity	Constant	NONE	1.75E-01
	SANTAROS	Santa Rosa Formation	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	SANTAROS	Santa Rosa Formation	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.00E+01
	SANTAROS	Santa Rosa Formation	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.00E+01
	SANTAROS	Santa Rosa Formation	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.00E+01
	SANTAROS	Santa Rosa Formation	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	SANTAROS	Santa Rosa Formation	SAT_IBRN	Initial Brine Saturation	Constant	NONE	8.36E-02
	SANTAROS	Santa Rosa Formation	SAT_RBRN	Residual Brine Saturation	Constant	NONE	8.36E-02
	SANTAROS	Santa Rosa Formation	SAT_RGAS	Residual Gas Saturation	Constant	NONE	7.71E-02

Table PAR-22. Dewey Lake Formation

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	DEWYLAKE	Dewey Lake Red Beds	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	DEWYLAKE	Dewey Lake Red Beds	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	1.00E-08
	DEWYLAKE	Dewey Lake Red Beds	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	DEWYLAKE	Dewey Lake Red Beds	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	DEWYLAKE	Dewey Lake Red Beds	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	DEWYLAKE	Dewey Lake Red Beds	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	DEWYLAKE	Dewey Lake Red Beds	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	DEWYLAKE	Dewey Lake Red Beds	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	6.44E-01
	DEWYLAKE	Dewey Lake Red Beds	POROSITY	Effective porosity	Student	NONE	1.43E-01
	DEWYLAKE	Dewey Lake Red Beds	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.63E+01
	DEWYLAKE	Dewey Lake Red Beds	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.63E+01
	DEWYLAKE	Dewey Lake Red Beds	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.63E+01
	DEWYLAKE	Dewey Lake Red Beds	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	DEWYLAKE	Dewey Lake Red Beds	SAL_USAT	Average saturation, unsaturated zones	Constant	NONE	8.36E-02
	DEWYLAKE	Dewey Lake Red Beds	SAT_IBRN	Initial Brine Saturation	Constant	NONE	1.00E+00
	DEWYLAKE	Dewey Lake Red Beds	SAT_RBRN	Residual Brine Saturation	Constant	NONE	8.36E-02
	DEWYLAKE	Dewey Lake Red Beds	SAT_RGAS	Residual Gas Saturation	Constant	NONE	7.71E-02

Table PAR-23. Forty-Niner Member of the Rustler Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	FORTYNIN	Forty Niner Member	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	FORTYNIN	Forty Niner Member	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	FORTYNIN	Forty Niner Member	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	FORTYNIN	Forty Niner Member	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	FORTYNIN	Forty Niner Member	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	FORTYNIN	Forty Niner Member	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	FORTYNIN	Forty Niner Member	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	FORTYNIN	Forty Niner Member	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	FORTYNIN	Forty Niner Member	POROSITY	Effective porosity	Student	NONE	8.20E-02
	FORTYNIN	Forty Niner Member	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$log(m^2)$	-3.50E+01
	FORTYNIN	Forty Niner Member	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$log(m^2)$	-3.50E+01
	FORTYNIN	Forty Niner Member	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$log(m^2)$	-3.50E+01
	FORTYNIN	Forty Niner Member	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	FORTYNIN	Forty Niner Member	SAT_RBRN	Residual Brine Saturation	Constant	NONE	2.00E-01
	FORTYNIN	Forty Niner Member	SAT_RGAS	Residual Gas Saturation	Constant	NONE	2.00E-01

Table PAR-24. Magenta Member of the Rustler Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	MAGENTA	Magenta Member	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	MAGENTA	Magenta Member	COMP_RCK	Bulk Compressibility	Student	Pa^{-1}	2.64E-10
	MAGENTA	Magenta Member	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	MAGENTA	Magenta Member	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	MAGENTA	Magenta Member	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	MAGENTA	Magenta Member	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	MAGENTA	Magenta Member	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	MAGENTA	Magenta Member	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	6.44E-01
	MAGENTA	Magenta Member	POROSITY	Effective porosity	Student	NONE	1.38E-01
	MAGENTA	Magenta Member	PRESSURE	Brine far-field pore pressure	Constant	Pa	9.47E+05
	MAGENTA	Magenta Member	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.52E+01
	MAGENTA	Magenta Member	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.52E+01
	MAGENTA	Magenta Member	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.52E+01
	MAGENTA	Magenta Member	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	MAGENTA	Magenta Member	SAT_RBRN	Residual Brine Saturation	Constant	NONE	8.36E-02
	MAGENTA	Magenta Member	SAT_RGAS	Residual Gas Saturation	Constant	NONE	7.71E-02

Table PAR-25. Tamarisk Member of the Rustler Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	TAMARISK	Tamarisk Member	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	TAMARISK	Tamarisk Member	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	TAMARISK	Tamarisk Member	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	TAMARISK	Tamarisk Member	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	TAMARISK	Tamarisk Member	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	TAMARISK	Tamarisk Member	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	TAMARISK	Tamarisk Member	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	TAMARISK	Tamarisk Member	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	TAMARISK	Tamarisk Member	POROSITY	Effective porosity	Student	NONE	6.40E-02
	TAMARISK	Tamarisk Member	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$log(m^2)$	-3.50E+01
	TAMARISK	Tamarisk Member	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$log(m^2)$	-3.50E+01
	TAMARISK	Tamarisk Member	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$log(m^2)$	-3.50E+01
	TAMARISK	Tamarisk Member	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	TAMARISK	Tamarisk Member	SAT_RBRN	Residual Brine Saturation	Constant	NONE	2.00E-01
	TAMARISK	Tamarisk Member	SAT_RGAS	Residual Gas Saturation	Constant	NONE	2.00E-01

Table PAR-26. Culebra Member of the Rustler Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CULEBRA	Culebra member of the Rustler formation	APOROS	Culebra Advective Porosity	Log uniform	NONE	Sampled Value
	CULEBRA	Culebra member of the Rustler formation	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	CULEBRA	Culebra member of the Rustler formation	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	1.00E-10
	CULEBRA	Culebra member of the Rustler formation	DISP_L	Longitudinal dispersivity	Constant	m	0.00E+00
	CULEBRA	Culebra member of the Rustler formation	DISPT_L	Transverse dispersivity	Constant	m	0.00E+00
	CULEBRA	Culebra member of the Rustler formation	DNSGRAIN	Material Grain Density	Constant	kg/m^3	2.82E+03
	CULEBRA	Culebra member of the Rustler formation	DPOROS	Diffusive Porosity for Culebra Dolomite	Cumulative	NONE	Sampled Value
	CULEBRA	Culebra member of the Rustler formation	DTORT	Diffusive Tortuosity	Constant	NONE	1.10E-01
	CULEBRA	Culebra member of the Rustler formation	FTORT	Fracture Tortuosity	Constant	NONE	1.00E+00
	CULEBRA	Culebra member of the Rustler formation	HMBLKLT	Culebra Half Matrix-Block Length	Uniform	m	Sampled Value
	CULEBRA	Culebra member of the Rustler formation	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CULEBRA	Culebra member of the Rustler formation	MINP_FAC	Mining Transmissivity Multiplier	Uniform	NONE	Sampled Value
	CULEBRA	Culebra member of the Rustler formation	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CULEBRA	Culebra member of the Rustler formation	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	CULEBRA	Culebra member of the Rustler formation	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	CULEBRA	Culebra member of the Rustler formation	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CULEBRA	Culebra member of the Rustler formation	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	6.44E-01

Table PAR-26. Culebra Member of the Rustler Formation Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CULEBRA	Culebra member of the Rustler formation	POROSITY	Effective porosity	Constant	NONE	1.51E-01
	CULEBRA	Culebra member of the Rustler formation	PRESSURE	Brine far-field pore pressure	Constant	Pa	9.14E+05
	CULEBRA	Culebra member of the Rustler formation	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.31E+01
	CULEBRA	Culebra member of the Rustler formation	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.31E+01
	CULEBRA	Culebra member of the Rustler formation	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.31E+01
	CULEBRA	Culebra member of the Rustler formation	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CULEBRA	Culebra member of the Rustler formation	SAT_IBRN	Initial Brine Saturation	Constant	NONE	1.00E+00
	CULEBRA	Culebra member of the Rustler formation	SAT_RBRN	Residual Brine Saturation	Constant	NONE	8.36E-02
	CULEBRA	Culebra member of the Rustler formation	SAT_RGAS	Residual Gas Saturation	Constant	NONE	7.71E-02
	CULEBRA	Culebra member of the Rustler formation	SKIN_RES	Skin Resistance	Constant	NONE	0.00E+00

Table PAR-27. Los Medanos (Unnamed Lower) Member of the Rustler Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	UNNAMED	Unnamed Lower Member of Rustler Formation	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	UNNAMED	Unnamed Lower Member of Rustler Formation	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	UNNAMED	Unnamed Lower Member of Rustler Formation	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	UNNAMED	Unnamed Lower Member of Rustler Formation	POROSITY	Effective porosity	Student	NONE	1.81E-01
	UNNAMED	Unnamed Lower Member of Rustler Formation	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-3.50E+01
	UNNAMED	Unnamed Lower Member of Rustler Formation	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-3.50E+01
	UNNAMED	Unnamed Lower Member of Rustler Formation	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-3.50E+01
	UNNAMED	Unnamed Lower Member of Rustler Formation	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	UNNAMED	Unnamed Lower Member of Rustler Formation	SAT_RBRN	Residual Brine Saturation	Constant	NONE	2.00E-01
	UNNAMED	Unnamed Lower Member of Rustler Formation	SAT_RGAS	Residual Gas Saturation	Constant	NONE	2.00E-01

Table PAR-28. Salado Formation – Intact Halite – Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_HALITE	Salado halite, intact	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	S_HALITE	Salado halite, intact	COMP_RCK	Bulk Compressibility	Uniform	Pa^{-1}	Sampled Value
	S_HALITE	Salado halite, intact	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	S_HALITE	Salado halite, intact	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	S_HALITE	Salado halite, intact	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	S_HALITE	Salado halite, intact	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	S_HALITE	Salado halite, intact	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	S_HALITE	Salado halite, intact	PORE_DIS	Brooks-Corey pore distribution parameter	Cumulative	NONE	7.00E-01
	S_HALITE	Salado halite, intact	POROSITY	Effective porosity	Cumulative	NONE	Sampled Value
	S_HALITE	Salado halite, intact	PRESSURE	Brine far-field pore pressure	Uniform	Pa	Sampled Value
	S_HALITE	Salado halite, intact	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$\log(m^2)$	Sampled Value
	S_HALITE	Salado halite, intact	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$\log(m^2)$	Applied Value See S_HALITE PRMX_LOG
	S_HALITE	Salado halite, intact	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$\log(m^2)$	Applied Value See S_HALITE PRMX_LOG
	S_HALITE	Salado halite, intact	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00
	S_HALITE	Salado halite, intact	SAT_RBRN	Residual Brine Saturation	Uniform	NONE	3.00E-01
	S_HALITE	Salado halite, intact	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	2.00E-01

Table PAR-29. Salado Formation – Brine – Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	BRINESAL	Salado Brine	COMPRES	Brine Compressibility	Constant	Pa^{-1}	3.10E-10
	BRINESAL	Salado Brine	DNSFLUID	Brine Density	Constant	kg/m^3	1.22E+03
	BRINESAL	Salado Brine	REF_PRES	Reference pressure for porosity	Constant	Pa	1.01E+05
	BRINESAL	Salado Brine	REF_TEMP	Reference Temperature	Constant	K	3.00E+02
	BRINESAL	Salado Brine	VISCO	Viscosity	Constant	Pa*s	2.10E-03
	BRINESAL	Salado Brine	WTF	Mass fraction of salt in brine	Student	NONE	3.24E-01

Table PAR-30. Salado Formation – Marker Bed 138 – Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_MB138	Salado marker bed 138, intact and fractured	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	COMP_RCK	Bulk Compressibility	Student	Pa^{-1}	8.26E-11
	S_MB138	Salado marker bed 138, intact and fractured	DPHIMAX	Incremental increase in porosity relative to intact conditions	Constant	NONE	3.90E-02
	S_MB138	Salado marker bed 138, intact and fractured	IFRX	Index for fracture perm. enhancement in X-direction	Constant	NONE	1.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	IFRY	Index for fracture perm. enhancement in Y-direction	Constant	NONE	1.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	IFRZ	Index for fracture perm. enhancement in Z-direction	Constant	NONE	0.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	KMAXLOG	Log of Maximum Permeability in Altered Anhydrite Flow Model Anhydrites	Constant	$log(m^2)$	-9.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	S_MB138	Salado marker bed 138, intact and fractured	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	S_MB138	Salado marker bed 138, intact and fractured	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	S_MB138	Salado marker bed 138, intact and fractured	PF_DELTA	Incremental pressure for full fracture development	Constant	Pa	3.80E+06
	S_MB138	Salado marker bed 138, intact and fractured	PI_DELTA	Fracture initiation pressure increment	Constant	Pa	2.00E+05
	S_MB138	Salado marker bed 138, intact and fractured	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	S_MB138	Salado marker bed 138, intact and fractured	PORE_DIS	Brooks-Corey pore distribution parameter	Student	NONE	6.44E-01
	S_MB138	Salado marker bed 138, intact and fractured	POROSITY	Effective porosity	Student	NONE	1.10E-02
	S_MB138	Salado marker bed 138, intact and fractured	PRMX_LOG	Log of intrinsic permeability, X-direction	Student	$log(m^2)$	-1.89E+01
	S_MB138	Salado marker bed 138, intact and fractured	PRMY_LOG	Log of intrinsic permeability, Y-direction	Student	$log(m^2)$	-1.89E+01

Table PAR-30. Salado Formation – Marker Bed 138 – Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_MB138	Salado marker bed 138, intact and fractured	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Student	$\log(m^2)$	-1.89E+01
	S_MB138	Salado marker bed 138, intact and fractured	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00
	S_MB138	Salado marker bed 138, intact and fractured	SAT_RBRN	Residual Brine Saturation	Student	NONE	8.36E-02
	S_MB138	Salado marker bed 138, intact and fractured	SAT_RGAS	Residual Gas Saturation	Student	NONE	7.71E-02
	S_MB139	Salado marker bed 139, intact and fractured	COMP_RCK	Bulk Compressibility	Student	Pa^{-1}	Sampled Value

Table PAR-31. Salado Formation – Marker Bed 139 – Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CONC_PLG	Concrete Plug, surface and Rustler	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	log(m^2)	Sampled Value
	S_MB139	Salado marker bed 139, intact and fractured	BKLINK	Klinkenberg B Correction Parameters for H2 gas	Constant	Pa	2.71E-01
	S_MB139	Salado marker bed 139, intact and fractured	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	DPHIMAX	Incremental increase in porosity relative to intact conditions	Constant	NONE	3.90E-02
	S_MB139	Salado marker bed 139, intact and fractured	EXPKLINK	Klinkenberg b correction parameters for H2 gas	Constant	NONE	-3.41E-01
	S_MB139	Salado marker bed 139, intact and fractured	IFRX	Index for fracture perm. enhancement in X-direction	Constant	NONE	1.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	IFRY	Index for fracture perm. enhancement in Y-direction	Constant	NONE	1.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	IFRZ	Index for fracture perm. enhancement in Z-direction	Constant	NONE	0.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	KMAXLOG	Log of Maximum Permeability in Altered Anhydrite Flow Model Anhydrites	Constant	log(m^2)	-9.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	S_MB139	Salado marker bed 139, intact and fractured	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	S_MB139	Salado marker bed 139, intact and fractured	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	S_MB139	Salado marker bed 139, intact and fractured	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	S_MB139	Salado marker bed 139, intact and fractured	PF_DELTA	Incremental pressure for full fracture development	Constant	Pa	3.80E+06
	S_MB139	Salado marker bed 139, intact and fractured	PI_DELTA	Fracture initiation pressure increment	Constant	Pa	2.00E+05
	S_MB139	Salado marker bed 139, intact and fractured	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	S_MB139	Salado marker bed 139, intact and fractured	PORE_DIS	Brooks-Corey pore distribution parameter	Student	NONE	Sampled Value
	S_MB139	Salado marker bed 139, intact and fractured	POROSITY	Effective porosity	Student	NONE	1.10E-02

Table PAR-31. Salado Formation – Marker Bed 139 – Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_MB139	Salado marker bed 139, intact and fractured	PRMX_LOG	Log of intrinsic permeability, X-direction	Student	$\log(m^2)$	Sampled Value
	S_MB139	Salado marker bed 139, intact and fractured	PRMY_LOG	Log of intrinsic permeability, Y-direction	Student	$\log(m^2)$	-1.89E+01
	S_MB139	Salado marker bed 139, intact and fractured	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Student	$\log(m^2)$	-1.89E+01
	S_MB139	Salado marker bed 139, intact and fractured	RELP_MOD	Model number, relative permeability model	Delta	NONE	Sampled Value
	S_MB139	Salado marker bed 139, intact and fractured	SAT_RBRN	Residual Brine Saturation	Student	NONE	Sampled Value
	S_MB139	Salado marker bed 139, intact and fractured	SAT_RGAS	Residual Gas Saturation	Student	NONE	Sampled Value

Table PAR-32. Salado Formation – Anhydrite a and b, Intact and Fractured – Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	COMP_RCK	Bulk Compressibility	Student	Pa^{-1}	8.26E-11
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	DPHIMAX	Incremental increase in porosity relative to intact conditions	Constant	NONE	2.39E-01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	IFRX	Index for fracture perm. enhancement in X-direction	Constant	NONE	1.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	IFRY	Index for fracture perm. enhancement in Y-direction	Constant	NONE	1.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	IFRZ	Index for fracture perm. enhancement in Z-direction	Constant	NONE	0.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	KMAXLOG	Log of Maximum Permeability in Altered Anhydrite Flow Model Anhydrites	Constant	$log(m^2)$	-9.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	2.60E-01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.48E-01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PF_DELTA	Incremental pressure for full fracture development	Constant	Pa	3.80E+06
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PI_DELTA	Fracture initiation pressure increment	Constant	Pa	2.00E+05
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PORE_DIS	Brooks-Corey pore distribution parameter	Student	NONE	6.44E-01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	POROSITY	Effective porosity	Student	NONE	1.10E-02
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PRMX_LOG	Log of intrinsic permeability, X-direction	Student	$log(m^2)$	-1.89E+01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PRMY_LOG	Log of intrinsic permeability, Y-direction	Student	$log(m^2)$	-1.89E+01

Table PAR-32. Salado Formation – Anhydrite a and b, Intact and Fractured – Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Student	log(m^2)	-1.89E+01
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	SAT_RBRN	Residual Brine Saturation	Student	NONE	8.36E-02
	S_ANH_AB	Salado anhydrite beds A and B, intact and fracture	SAT_RGAS	Residual Gas Saturation	Student	NONE	7.71E-02

Table PAR-33. Disturbed Rock Zone Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	7.41E-10
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	POROSITY	Effective porosity	Cumulative	NONE	1.29E-02
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.70E+01
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.70E+01
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.70E+01
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	DRZ_0	Disturbed rock zone; time period -5 to 0 years	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	7.41E-10
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00

Table PAR-33. Disturbed Rock Zone Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	POROSITY	Effective porosity	Cumulative	NONE	1.29E-02
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PRMX_LOG	Log of intrinsic permeability, X-direction	Uniform	$\log(m^2)$	Sampled Value
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PRMY_LOG	Log of intrinsic permeability, Y-direction	Uniform	$\log(m^2)$	Applied Value See DRZ-1 PRMX_LOG
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Uniform	$\log(m^2)$	Applied Value See DRZ_1 PRMX_LOG
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	RELP_MOD	Model number, relative permeability model	Delta	NONE	4.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	DRZ_1	Disturbed rock zone; time period 0 to 10,000 years	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-34. Waste Area and Waste Material Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	WAS_AREA	Waste emplacement area and waste	ABSROUGH	Absolute roughness of material	Uniform	m	2.50E-02
	WAS_AREA	Waste emplacement area and waste	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	WAS_AREA	Waste emplacement area and waste	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	WAS_AREA	Waste emplacement area and waste	DCELLCHW	Average density of cellulosics in CH waste	Constant	kg/m^3	5.80E+01
	WAS_AREA	Waste emplacement area and waste	DCELLRHW	Average density of cellulosics in RH waste	Constant	kg/m^3	4.50E+00
	WAS_AREA	Waste emplacement area and waste	DIRNCCHW	Bulk density of iron containers, CH waste	Constant	kg/m^3	1.70E+02
	WAS_AREA	Waste emplacement area and waste	DIRNCRHW	Bulk density of iron containers, RH waste	Constant	kg/m^3	4.80E+02
	WAS_AREA	Waste emplacement area and waste	DIRONCHW	Average density of iron-based material in CH waste	Constant	kg/m^3	1.10E+02
	WAS_AREA	Waste emplacement area and waste	DIRONRHW	Average density of iron-based material in RH waste	Constant	kg/m^3	1.10E+02
	WAS_AREA	Waste emplacement area and waste	DPLASCHW	Average density of plastics in CH waste	Constant	kg/m^3	4.20E+01
	WAS_AREA	Waste emplacement area and waste	DPLASRHW	Average density of plastics in CH waste	Constant	kg/m^3	4.90E+00
	WAS_AREA	Waste emplacement area and waste	DPLSCCHW	Bulk density of plastic liners, CH waste	Constant	kg/m^3	1.60E+01
	WAS_AREA	Waste emplacement area and waste	DPLSCRHW	Bulk density of plastic liners, RH waste	Constant	kg/m^3	1.40E+00
	WAS_AREA	Waste emplacement area and waste	DRUBBCHW	Average density of rubber in CH waste	Constant	kg/m^3	1.40E+01
	WAS_AREA	Waste emplacement area and waste	DRUBBRHW	Average density of rubber in RH waste	Constant	kg/m^3	3.10E+00
	WAS_AREA	Waste emplacement area and waste	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	WAS_AREA	Waste emplacement area and waste	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	WAS_AREA	Waste emplacement area and waste	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00

Table PAR-34. Waste Area and Waste Material Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	WAS_AREA	Waste emplacement area and waste	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	WAS_AREA	Waste emplacement area and waste	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	WAS_AREA	Waste emplacement area and waste	PORE_DIS	Brooks-Corey pore distribution parameter	Cumulative	NONE	2.89E+00
	WAS_AREA	Waste emplacement area and waste	POROSITY	Effective porosity	Constant	NONE	8.48E-01
	WAS_AREA	Waste emplacement area and waste	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.26E+01
	WAS_AREA	Waste emplacement area and waste	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.26E+01
	WAS_AREA	Waste emplacement area and waste	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.26E+01
	WAS_AREA	Waste emplacement area and waste	PROBDEG	Probability of plastics and rubber biodegradation in event of microbial gas generation	Delta	NONE	Sampled Value
	WAS_AREA	Waste emplacement area and waste	PTHRESH	Capillary threshold displacement pressure	Constant	Pa	8.00E+06
	WAS_AREA	Waste emplacement area and waste	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	WAS_AREA	Waste emplacement area and waste	SAT_IBRN	Initial Brine Saturation	Constant	NONE	1.50E-02
	WAS_AREA	Waste emplacement area and waste	SAT_RBRN	Residual Brine Saturation	Uniform	NONE	Sampled Value
	WAS_AREA	Waste emplacement area and waste	SAT_RGAS	Residual Gas Saturation	Uniform	NONE	Sampled Value
	WAS_AREA	Waste emplacement area and waste	SAT_WICK	Index for computing wicking	Uniform	NONE	Sampled Value
	WAS_AREA	Waste emplacement area and waste	VOLCHW	BIR total volume of CH waste	Constant	m^3	1.69E+05
	WAS_AREA	Waste emplacement area and waste	VOLRHW	BIR total volume of RH waste	Constant	m^3	7.08E+03

Table PAR-35 Waste Chemistry Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	AM	Americium	CAPMIC	Maximum Concentration of Actinide on Microbe Colloids	Constant	moles/liter	1.00E+00
	AM	Americium	CONCINT	Actinide Concentration with Mobile Actinide Intrinsic Colloids	Constant	moles/liter	0.00E+00
	AM	Americium	CONCMIN	Actinide Concentration with Mobile Mineral Fragment Colloids	Constant	moles/liter	2.60E-08
	AM	Americium	PROPMIC	Moles of Actinide Mobilized on Microbe Colloids per Moles Dissolved	Constant	NONE	3.60E+00
	AM+3	Americium III	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	3.00E-10
	AM+3	Americium III	MKD_AM	Matrix Partition Coefficient for Americium	Log uniform	m^3/kg	Sampled Value
	NP	Neptunium	CAPHUM	Maximum Concentration of Actinide with Mobile Humic Colloids	Constant	moles/liter	1.10E-05
	NP	Neptunium	CAPMIC	Maximum Concentration of Actinide on Microbe Colloids	Constant	moles/liter	2.70E-03
	NP	Neptunium	CONCINT	Actinide Concentration with Mobile Actinide Intrinsic Colloids	Constant	moles/liter	0.00E+00
	NP	Neptunium	CONCMIN	Actinide Concentration with Mobile Mineral Fragment Colloids	Constant	moles/liter	2.60E-08
	NP	Neptunium	PROPMIC	Moles of Actinide Mobilized on Microbe Colloids per Moles Dissolved	Constant	NONE	1.20E+01
	PHUMOX3	Proportionality Constant, +3 State, Humic Colloids	PHUMCIM	Proportionality Const., Humic Colloids, Castile Brine, MgO controls pH	Cumulative	NONE	Sampled Value
	PHUMOX3	Proportionality Constant, +3 State, Humic Colloids	PHUMSIM	Proportionality Const. Of Actinides in Salado Brine w/Humic Colloids, Inorganic	Constant	NONE	1.90E-01
	PHUMOX4	Proportionality constant with humic colloids for a	PHUMCIM	Proportionality Const., Humic Colloids, Castile Brine, MgO controls pH	Constant	NONE	6.30E+00
	PHUMOX4	Proportionality constant with humic colloids for a	PHUMSIM	Proportionality Const. Of Actinides in Salado Brine w/Humic Colloids, Inorganic	Constant	NONE	6.30E+00
	PHUMOX5	Proportionality constant with humic colloids for a	PHUMCIM	Proportionality Const., Humic Colloids, Castile Brine, MgO controls pH	Constant	NONE	7.40E-03

Table PAR-35. Waste Chemistry Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	PHUMOX5	Proportionality constant with humic colloids for a	PHUMSIM	Proportionality Const. Of Actinides in Salado Brine w/Humic Colloids, Inorganic	Constant	NONE	9.10E-04
	PHUMOX6	Proportionality constant with humic colloids for a	PHUMCIM	Proportionality Const., Humic Colloids, Castile Brine, MgO controls pH	Constant	NONE	5.10E-01
	PHUMOX6	Proportionality constant with humic colloids for a	PHUMSIM	Proportionality Const. Of Actinides in Salado Brine w/Humic Colloids, Inorganic	Constant	NONE	1.20E-01
	PU	Plutonium	CAPHUM	Maximum Concentration of Actinide with Mobile Humic Colloids	Constant	moles/liter	1.10E-05
	PU	Plutonium	CAPMIC	Maximum Concentration of Actinide on Microbe Colloids	Constant	moles/liter	6.80E-05
	PU	Plutonium	CONCINT	Actinide Concentration with Mobile Actinide Intrinsic Colloids	Constant	moles/liter	1.00E-09
	PU	Plutonium	CONCMIN	Actinide Concentration with Mobile Mineral Fragment Colloids	Constant	moles/liter	2.60E-08
	PU	Plutonium	PROPMIC	Moles of Actinide Mobilized on Microbe Colloids per Moles Dissolved	Constant	NONE	3.00E-01
	PU+3	Plutonium III	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	3.00E-10
	PU+3	Plutonium III	MKD_PU	Matrix Partition Coefficient for Plutonium	Log uniform	m^3/kg	Sampled Value
	PU+4	Plutonium IV	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	1.53E-10
	PU+4	Plutonium IV	MKD_PU	Matrix Partition Coefficient for Plutonium	Log uniform	m^3/kg	Sampled Value
	SOLAM3	Solubility Multiplier for Am+3	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLAM3	Solubility Multiplier for Am+3	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLMOD3	Oxidation state III model	SOLCOC	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	1.77E-07
	SOLMOD3	Oxidation state III model	SOLCOH	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	1.69E-07

Table PAR-35. Waste Chemistry Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SOLMOD3	Oxidation state III model	SOLSOC	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	3.07E-07
	SOLMOD3	Oxidation state III model	SOLSOH	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	3.07E-07
	SOLMOD4	Oxidation state IV model	SOLCOC	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	5.84E-09
	SOLMOD4	Oxidation state IV model	SOLCOH	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	2.47E-08
	SOLMOD4	Oxidation state IV model	SOLSOC	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	1.24E-08
	SOLMOD4	Oxidation state IV model	SOLSOH	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	1.19E-08
	SOLMOD5	Oxidation state V model	SOLCOC	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	2.13E-05
	SOLMOD5	Oxidation state V model	SOLCOH	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	5.08E-06
	SOLMOD5	Oxidation state V model	SOLSOC	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	9.72E-07
	SOLMOD5	Oxidation state V model	SOLSOH	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	1.02E-06
	SOLMOD6	Oxidation state VI model	SOLCOC	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	8.80E-06
	SOLMOD6	Oxidation state VI model	SOLCOH	Solubility in Castile Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	8.80E-06
	SOLMOD6	Oxidation state VI model	SOLSOC	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/CaCO3	Constant	moles/liter	8.70E-06
	SOLMOD6	Oxidation state VI model	SOLSOH	Solubility in Salado Brine with Organics included Controlled by Mg(OH)2/Hydromagnisite buffer(5424)	Constant	moles/liter	8.70E-06

Table PAR-35. Waste Chemistry Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	SOLPU3	Solubility Multiplier for Pu+3	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLPU3	Solubility Multiplier for Pu+3	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLPU4	Solubility Multiplier for Pu+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLPU4	Solubility Multiplier for Pu+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLTH4	Solubility Multiplier for Th+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLTH4	Solubility Multiplier for Th+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLU4	Solubility Multiplier for U+4	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLU4	Solubility Multiplier for U+4	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLU6	Solubility Multiplier for U+6	SOLCIM	Solubility Mult. in Castile Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value
	SOLU6	Solubility Multiplier for U+6	SOLSIM	Solubility Mult. in Salado Brine, Inorganic Chem Controlled by Mg(OH)2-MgCO3	Cumulative	None (see PPR-04-2002, ERMS #524651)	Sampled Value

Table PAR-35. Waste Chemistry Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	TH	Thorium	CAPHUM	Maximum Concentration of Actinide with Mobile Humic Colloids	Constant	moles/liter	1.10E-05
	TH	Thorium	CAPMIC	Maximum Concentration of Actinide on Microbe Colloids	Constant	moles/liter	1.90E-03
	TH	Thorium	CONCINT	Actinide Concentration with Mobile Actinide Intrinsic Colloids	Constant	moles/liter	0.00E+00
	TH	Thorium	CONCMIN	Actinide Concentration with Mobile Mineral Fragment Colloids	Constant	moles/liter	2.60E-08
	TH	Thorium	PROPMIC	Moles of Actinide Mobilized on Microbe Colloids per Moles Dissolved	Constant	NONE	3.10E+00
	TH+4	Thorium IV	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	1.53E-10
	TH+4	Thorium IV	MKD_TH	Matrix Partition Coefficient for Thorium	Log uniform	m^3/kg	Sampled Value
	U	Uranium	CAPHUM	Maximum Concentration of Actinide with Mobile Humic Colloids	Constant	moles/liter	1.10E-05
	U	Uranium	CAPMIC	Maximum Concentration of Actinide on Microbe Colloids	Constant	moles/liter	2.10E-03
	U	Uranium	CONCINT	Actinide Concentration with Mobile Actinide Intrinsic Colloids	Constant	moles/liter	0.00E+00
	U	Uranium	CONCMIN	Actinide Concentration with Mobile Mineral Fragment Colloids	Constant	moles/liter	2.60E-08
	U	Uranium	PROPMIC	Moles of Actinide Mobilized on Microbe Colloids per Moles Dissolved	Constant	NONE	2.10E-03
	U+4	Uranium IV	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	1.53E-10
	U+4	Uranium IV	MKD_U	Matrix Partition Coefficient for Uranium	Log uniform	m^3/kg	Sampled Value
	U+6	Uranium VI	MD0	Molecular diffusion in pure fluid	Constant	m^2/s	4.26E-10
	U+6	Uranium VI	MKD_U	Matrix Partition Coefficient for Uranium	Log uniform	m^3/kg	Sampled Value

Table PAR-36. Radionuclide Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	AM241	Americium 241	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.41E-01
	AM241	Americium 241	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	AM241	Americium 241	HALFLIFE	Halflife	Constant	s	1.36E+10
	AM243	Americium 243	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.43E-01
	AM243	Americium 243	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	AM243	Americium 243	HALFLIFE	Halflife	Constant	s	2.33E+11
	CF252	Californium 252	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.52E-01
	CF252	Californium 252	EPAREL	EPA Release Limit	Constant	Curies/wuf	0.00E+00
	CF252	Californium 252	HALFLIFE	Halflife	Constant	s	8.33E+07
	CM243	Curium 243	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.43E-01
	CM243	Curium 243	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	CM243	Curium 243	HALFLIFE	Halflife	Constant	s	8.99E+08
	CM244	Curium 244	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.44E-01
	CM244	Curium 244	EPAREL	EPA Release Limit	Constant	Curies/wuf	0.00E+00
	CM244	Curium 244	HALFLIFE	Halflife	Constant	s	5.72E+08
	CM245	Curium 245	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.45E-01
	CM245	Curium 245	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	CM245	Curium 245	HALFLIFE	Halflife	Constant	s	2.68E+11
	CM248	Curium 248	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.48E-01
	CM248	Curium 248	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	CM248	Curium 248	HALFLIFE	Halflife	Constant	s	1.07E+13
	CS137	Cesium 137	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	1.37E-01
	CS137	Cesium 137	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+03
	CS137	Cesium 137	HALFLIFE	Halflife	Constant	s	9.47E+08
	NP237	Neptunium 237	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.37E-01
	NP237	Neptunium 237	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	NP237	Neptunium 237	HALFLIFE	Halflife	Constant	s	6.75E+13
	PA231	Protactinium 231	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.31E-01
	PA231	Protactinium 231	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PA231	Protactinium 231	HALFLIFE	Halflife	Constant	s	1.03E+12
	PB210	Lead 210	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.10E-01
	PB210	Lead 210	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02

Table PAR-36. Radionuclide Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	PB210	Lead 210	HALFLIFE	Halflife	Constant	s	7.04E+08
	PM147	Promethium 147	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	1.47E-01
	PM147	Promethium 147	EPAREL	EPA Release Limit	Constant	Curies/wuf	0.00E+00
	PM147	Promethium 147	HALFLIFE	Halflife	Constant	s	8.28E+07
	PU238	Plutonium 238	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.38E-01
	PU238	Plutonium 238	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PU238	Plutonium 238	HALFLIFE	Halflife	Constant	s	2.77E+09
	PU239	Plutonium 239	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.39E-01
	PU239	Plutonium 239	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PU239	Plutonium 239	HALFLIFE	Halflife	Constant	s	7.59E+11
	PU240	Plutonium 240	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.40E-01
	PU240	Plutonium 240	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PU240	Plutonium 240	HALFLIFE	Halflife	Constant	s	2.06E+11
	PU241	Plutonium 241	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.41E-01
	PU241	Plutonium 241	EPAREL	EPA Release Limit	Constant	Curies/wuf	0.00E+00
	PU241	Plutonium 241	HALFLIFE	Halflife	Constant	s	4.54E+08
	PU242	Plutonium 242	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.42E-01
	PU242	Plutonium 242	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PU242	Plutonium 242	HALFLIFE	Halflife	Constant	s	1.22E+13
	PU244	Plutonium 244	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.44E-01
	PU244	Plutonium 244	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	PU244	Plutonium 244	HALFLIFE	Halflife	Constant	s	2.61E+15
	RA226	Radium 226	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.26E-01
	RA226	Radium 226	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	RA226	Radium 226	HALFLIFE	Halflife	Constant	s	5.05E+10
	RA228	Radium 228	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.28E-01
	RA228	Radium 228	EPAREL	EPA Release Limit	Constant	Curies/wuf	0.00E+00
	RA228	Radium 228	HALFLIFE	Halflife	Constant	s	2.11E+08
	SR90	Strontium 90	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	8.99E-02
	SR90	Strontium 90	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+03
	SR90	Strontium 90	HALFLIFE	Halflife	Constant	s	9.19E+08
	TH229	Thorium 229	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.29E-01
	TH229	Thorium 229	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02

Table PAR-36. Radionuclide Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	TH229	Thorium 229	HALFLIFE	Halflife	Constant	s	2.32E+11
	TH230	Thorium 230	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.30E-01
	TH230	Thorium 230	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+01
	TH230	Thorium 230	HALFLIFE	Halflife	Constant	s	2.43E+12
	TH232	Thorium 232	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.32E-01
	TH232	Thorium 232	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+01
	TH232	Thorium 232	HALFLIFE	Halflife	Constant	s	4.43E+17
	U233	Uranium 233	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.33E-01
	U233	Uranium 233	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	U233	Uranium 233	HALFLIFE	Halflife	Constant	s	5.00E+12
	U234	Uranium 234	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.34E-01
	U234	Uranium 234	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	U234	Uranium 234	HALFLIFE	Halflife	Constant	s	7.72E+12
	U235	Uranium 235	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.35E-01
	U235	Uranium 235	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	U235	Uranium 235	HALFLIFE	Halflife	Constant	s	2.22E+16
	U236	Uranium 236	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.36E-01
	U236	Uranium 236	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	U236	Uranium 236	HALFLIFE	Halflife	Constant	s	7.39E+14
	U238	Uranium 238	ATWEIGHT	Atomic Weight in kg/mole	Constant	kg/mole	2.38E-01
	U238	Uranium 238	EPAREL	EPA Release Limit	Constant	Curies/wuf	1.00E+02
	U238	Uranium 238	HALFLIFE	Halflife	Constant	s	1.41E+17

Table PAR-37. Isotope Inventory

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	AM241	Americium 241	INVCHD	Inventory of Contact Handled Design	Constant	Curies	4.42E+05
	AM241	Americium 241	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.58E+04
	AM241L	Americium 241 Lumped with Plutonium 241	INVCHD	Inventory of Contact Handled Design	Constant	Curies	4.59E+05
	AM241L	Americium 241 Lumped with Plutonium 241	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.66E+04
	AM243	Americium 243	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.10E+01
	AM243	Americium 243	INVRHD	Inventory of Remote Handled Design	Constant	Curies	7.42E-01
	CF252	Californium 252	INVCHD	Inventory of Contact Handled Design	Constant	Curies	4.64E-05
	CF252	Californium 252	INVRHD	Inventory of Remote Handled Design	Constant	Curies	3.95E-06
	CM243	Curium 243	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.82E-01
	CM243	Curium 243	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.25E-01
	CM244	Curium 244	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.43E+03
	CM244	Curium 244	INVRHD	Inventory of Remote Handled Design	Constant	Curies	7.94E+01
	CM245	Curium 245	INVCHD	Inventory of Contact Handled Design	Constant	Curies	8.59E-03
	CM245	Curium 245	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.06E-02
	CM248	Curium 248	INVCHD	Inventory of Contact Handled Design	Constant	Curies	9.14E-02
	CM248	Curium 248	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.83E-03
	CS137	Cesium 137	INVCHD	Inventory of Contact Handled Design	Constant	Curies	4.61E+03
	CS137	Cesium 137	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.74E+05
	NP237	Neptunium 237	INVCHD	Inventory of Contact Handled Design	Constant	Curies	9.25E+00
	NP237	Neptunium 237	INVRHD	Inventory of Remote Handled Design	Constant	Curies	8.22E-01
	PA231	Protactinium 231	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.21E+00
	PA231	Protactinium 231	INVRHD	Inventory of Remote Handled Design	Constant	Curies	6.55E-04
	PB210	Lead 210	INVCHD	Inventory of Contact Handled Design	Constant	Curies	4.94E+00
	PB210	Lead 210	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.42E-05
	PM147	Promethium 147	INVCHD	Inventory of Contact Handled Design	Constant	Curies	3.86E-04
	PM147	Promethium 147	INVRHD	Inventory of Remote Handled Design	Constant	Curies	7.47E-02
	PU238	Plutonium 238	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.25E+06
	PU238	Plutonium 238	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.80E+03
	PU238L	Plutonium 238 Equals Plutonium 238 Inventory	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.25E+06

Table PAR-37. Isotope Inventory — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	PU238L	Plutonium 238 Equals Plutonium 238 Inventory	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.80E+03
	PU239	Plutonium 239	INVCHD	Inventory of Contact Handled Design	Constant	Curies	6.59E+05
	PU239	Plutonium 239	INVRHD	Inventory of Remote Handled Design	Constant	Curies	5.37E+03
	PU239L	Plutonium 239 Lumped with Plutonium 240 and Pluton	INVCHD	Inventory of Contact Handled Design	Constant	Curies	7.66E+05
	PU239L	Plutonium 239 Lumped with Plutonium 240 and Pluton	INVRHD	Inventory of Remote Handled Design	Constant	Curies	7.05E+03
	PU240	Plutonium 240	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.07E+05
	PU240	Plutonium 240	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.67E+03
	PU241	Plutonium 241	INVCHD	Inventory of Contact Handled Design	Constant	Curies	5.14E+05
	PU241	Plutonium 241	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.39E+04
	PU242	Plutonium 242	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.66E+01
	PU242	Plutonium 242	INVRHD	Inventory of Remote Handled Design	Constant	Curies	4.74E-01
	PU244	Plutonium 244	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.32E-06
	PU244	Plutonium 244	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.10E-03
	RA226	Radium 226	INVCHD	Inventory of Contact Handled Design	Constant	Curies	6.28E+00
	RA226	Radium 226	INVRHD	Inventory of Remote Handled Design	Constant	Curies	4.99E-05
	RA228	Radium 228	INVCHD	Inventory of Contact Handled Design	Constant	Curies	7.63E+00
	RA228	Radium 228	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.51E-01
	SR90	Strontium 90	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.68E+04
	SR90	Strontium 90	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.15E+05
	TH229	Thorium 229	INVCHD	Inventory of Contact Handled Design	Constant	Curies	5.25E+00
	TH229	Thorium 229	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.39E-01
	TH230	Thorium 230	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.69E-01
	TH230	Thorium 230	INVRHD	Inventory of Remote Handled Design	Constant	Curies	6.67E-03
	TH230L	Thorium 230 Lumped with Thorium 229	INVCHD	Inventory of Contact Handled Design	Constant	Curies	5.42E+00
	TH230L	Thorium 230 Lumped with Thorium 229	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.46E-01
	TH232	Thorium 232	INVCHD	Inventory of Contact Handled Design	Constant	Curies	6.61E+00
	TH232	Thorium 232	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.18E-01

Table PAR-37. Isotope Inventory — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	U233	Uranium 233	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.24E+03
	U233	Uranium 233	INVRHD	Inventory of Remote Handled Design	Constant	Curies	3.41E+01
	U234	Uranium 234	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.97E+02
	U234	Uranium 234	INVRHD	Inventory of Remote Handled Design	Constant	Curies	2.20E+01
	U234L	Uranium 234 Lumped with Uranium 233	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.54E+03
	U234L	Uranium 234 Lumped with Uranium 233	INVRHD	Inventory of Remote Handled Design	Constant	Curies	5.61E+01
	U235	Uranium 235	INVCHD	Inventory of Contact Handled Design	Constant	Curies	1.34E+00
	U235	Uranium 235	INVRHD	Inventory of Remote Handled Design	Constant	Curies	9.42E-01
	U236	Uranium 236	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.31E-01
	U236	Uranium 236	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.42E+00
	U238	Uranium 238	INVCHD	Inventory of Contact Handled Design	Constant	Curies	2.44E+01
	U238	Uranium 238	INVRHD	Inventory of Remote Handled Design	Constant	Curies	1.30E+02

Table PAR-38. Waste Container Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	REFCON	Reference Constant	ASDRUM	Surface area of corrodible metal per drum	Constant	m^2	6.00E+00
	REFCON	Reference Constant	DRROOM	Number of drums, per room, in ideal packing	Constant	NONE	6.80E+03

Table PAR-39. Stoichiometric Gas Generation Model Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	STEEL	Generic steel in waste	CORRMCO2	Inundated corrosion rate for steel without CO2 present	Uniform	m/s	Sampled Value
	STEEL	Generic steel in waste	HUMCORR	Humid corrosion rate for steel	Constant	m/s	0.00E+00
	STEEL	Generic steel in waste	STOIFX	Stoichiometric factor - X	Constant	NONE	1.00E+00
	SULFATE	Sulfate	QINIT	Initial quantity of material in waste	Constant	moles	6.59E+06
	WAS_AREA	Waste emplacement area and waste	DCELLCHW	Average density of cellulosics in CH waste	Constant	kg/m^3	5.80E+01
	WAS_AREA	Waste emplacement area and waste	DCELLRHW	Average density of cellulosics in RH waste	Constant	kg/m^3	4.50E+00
	WAS_AREA	Waste emplacement area and waste	DIRNCCHW	Bulk density of iron containers, CH waste	Constant	kg/m^3	1.70E+02
	WAS_AREA	Waste emplacement area and waste	DIRNCRHW	Bulk density of iron containers, RH waste	Constant	kg/m^3	4.80E+02
	WAS_AREA	Waste emplacement area and waste	DIRONCHW	Average density of iron-based material in CH waste	Constant	kg/m^3	1.10E+02
	WAS_AREA	Waste emplacement area and waste	DIRONRHW	Average density of iron-based material in RH waste	Constant	kg/m^3	1.10E+02
	WAS_AREA	Waste emplacement area and waste	DPLASCHW	Average density of plastics in CH waste	Constant	kg/m^3	4.20E+01
	WAS_AREA	Waste emplacement area and waste	DPLASRHW	Average density of plastics in RH waste	Constant	kg/m^3	4.90E+00
	WAS_AREA	Waste emplacement area and waste	DPLSCCHW	Bulk density of plastic liners, CH waste	Constant	kg/m^3	1.60E+01
	WAS_AREA	Waste emplacement area and waste	DPLSCRHW	Bulk density of plastic liners, RH waste	Constant	kg/m^3	1.40E+00
	WAS_AREA	Waste emplacement area and waste	DRUBBCHW	Average density of rubber in CH waste	Constant	kg/m^3	1.40E+01
	WAS_AREA	Waste emplacement area and waste	DRUBBRHW	Average density of rubber in RH waste	Constant	kg/m^3	3.10E+00
	WAS_AREA	Waste emplacement area and waste	GRATMICH	Humid biodegredation rate for cellulose	Uniform	moles/(kg*s)	Sampled Value
	WAS_AREA	Waste emplacement area and waste	GRATMICI	Inundated biodegradation rate for cellulose	Uniform	moles/(kg*s)	Sampled Value

Table PAR-40. Predisposal Cavities (Waste Area) Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CAVITY_1	Cavity for Waste Areas	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	CAVITY_1	Cavity for Waste Areas	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	CAVITY_1	Cavity for Waste Areas	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CAVITY_1	Cavity for Waste Areas	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CAVITY_1	Cavity for Waste Areas	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	CAVITY_1	Cavity for Waste Areas	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	CAVITY_1	Cavity for Waste Areas	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CAVITY_1	Cavity for Waste Areas	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	CAVITY_1	Cavity for Waste Areas	POROSITY	Effective porosity	Constant	NONE	1.00E+00
	CAVITY_1	Cavity for Waste Areas	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	CAVITY_1	Cavity for Waste Areas	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_1	Cavity for Waste Areas	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_1	Cavity for Waste Areas	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_1	Cavity for Waste Areas	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CAVITY_1	Cavity for Waste Areas	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_1	Cavity for Waste Areas	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_1	Cavity for Waste Areas	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	CAVITY_2	Cavity for Non-waste Areas	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CAVITY_2	Cavity for Non-waste Areas	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CAVITY_2	Cavity for Non-waste Areas	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	CAVITY_2	Cavity for Non-waste Areas	POROSITY	Effective porosity	Constant	NONE	1.00E+00
	CAVITY_2	Cavity for Non-waste Areas	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05

Table PAR-40. Predisposal Cavities (Waste Area) Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CAVITY_2	Cavity for Non-waste Areas	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_2	Cavity for Non-waste Areas	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_2	Cavity for Non-waste Areas	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_2	Cavity for Non-waste Areas	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CAVITY_2	Cavity for Non-waste Areas	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_2	Cavity for Non-waste Areas	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00
	CAVITY_3	Cavity for Shaft	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	CAVITY_3	Cavity for Shaft	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	CAVITY_3	Cavity for Shaft	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CAVITY_3	Cavity for Shaft	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CAVITY_3	Cavity for Shaft	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	CAVITY_3	Cavity for Shaft	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	CAVITY_3	Cavity for Shaft	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CAVITY_3	Cavity for Shaft	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	CAVITY_3	Cavity for Shaft	POROSITY	Effective porosity	Constant	NONE	1.00E+00
	CAVITY_3	Cavity for Shaft	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	CAVITY_3	Cavity for Shaft	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_3	Cavity for Shaft	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_3	Cavity for Shaft	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_3	Cavity for Shaft	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CAVITY_3	Cavity for Shaft	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_3	Cavity for Shaft	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_3	Cavity for Shaft	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00
	CAVITY_4	Cavity for Borehole	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	CAVITY_4	Cavity for Borehole	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	CAVITY_4	Cavity for Borehole	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CAVITY_4	Cavity for Borehole	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CAVITY_4	Cavity for Borehole	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00

Table PAR-40. Predisposal Cavities (Waste Area) Parameters — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CAVITY_4	Cavity for Borehole	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	CAVITY_4	Cavity for Borehole	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CAVITY_4	Cavity for Borehole	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	CAVITY_4	Cavity for Borehole	POROSITY	Effective porosity	Constant	NONE	1.00E+00
	CAVITY_4	Cavity for Borehole	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	CAVITY_4	Cavity for Borehole	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_4	Cavity for Borehole	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_4	Cavity for Borehole	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.00E+01
	CAVITY_4	Cavity for Borehole	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CAVITY_4	Cavity for Borehole	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_4	Cavity for Borehole	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	CAVITY_4	Cavity for Borehole	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-41. Operations Region Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	OPS_AREA	Operations Region	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	OPS_AREA	Operations Region	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	OPS_AREA	Operations Region	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	OPS_AREA	Operations Region	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	OPS_AREA	Operations Region	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	OPS_AREA	Operations Region	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	OPS_AREA	Operations Region	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	OPS_AREA	Operations Region	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	OPS_AREA	Operations Region	POROSITY	Effective porosity	Constant	NONE	1.80E-01
	OPS_AREA	Operations Region	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	OPS_AREA	Operations Region	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$log(m^2)$	-1.10E+01
	OPS_AREA	Operations Region	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$log(m^2)$	-1.10E+01
	OPS_AREA	Operations Region	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$log(m^2)$	-1.10E+01
	OPS_AREA	Operations Region	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	OPS_AREA	Operations Region	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	OPS_AREA	Operations Region	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	OPS_AREA	Operations Region	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-42. Area Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	EXP_AREA	Experimental Area	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	EXP_AREA	Experimental Area	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	EXP_AREA	Experimental Area	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	EXP_AREA	Experimental Area	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	EXP_AREA	Experimental Area	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	EXP_AREA	Experimental Area	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	EXP_AREA	Experimental Area	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	EXP_AREA	Experimental Area	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	EXP_AREA	Experimental Area	POROSITY	Effective porosity	Constant	NONE	1.80E-01
	EXP_AREA	Experimental Area	PRESSURE	Brine far-field pore pressure	Constant	Pa	1.01E+05
	EXP_AREA	Experimental Area	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-1.10E+01
	EXP_AREA	Experimental Area	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-1.10E+01
	EXP_AREA	Experimental Area	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-1.10E+01
	EXP_AREA	Experimental Area	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	EXP_AREA	Experimental Area	SAT_IBRN	Initial Brine Saturation	Constant	NONE	0.00E+00
	EXP_AREA	Experimental Area	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	EXP_AREA	Experimental Area	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-43. Castile Formation Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	IMPERM_Z	Impermeable Zones	CAP_MOD	Model number, capillary pressure model	Constant	NONE	1.00E+00
	IMPERM_Z	Impermeable Zones	COMP_RCK	Bulk Compressibility	Constant	Pa^{-1}	0.00E+00
	IMPERM_Z	Impermeable Zones	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0
	IMPERM_Z	Impermeable Zones	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	IMPERM_Z	Impermeable Zones	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	0.00E+00
	IMPERM_Z	Impermeable Zones	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	0.00E+00
	IMPERM_Z	Impermeable Zones	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	IMPERM_Z	Impermeable Zones	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	IMPERM_Z	Impermeable Zones	POROSITY	Effective porosity	Constant	NONE	5.00E-03
	IMPERM_Z	Impermeable Zones	PRMX_LOG	Log of intrinsic permeability, X-direction	Constant	$\log(m^2)$	-3.50E+01
	IMPERM_Z	Impermeable Zones	PRMY_LOG	Log of intrinsic permeability, Y-direction	Constant	$\log(m^2)$	-3.50E+01
	IMPERM_Z	Impermeable Zones	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Constant	$\log(m^2)$	-3.50E+01
	IMPERM_Z	Impermeable Zones	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	IMPERM_Z	Impermeable Zones	SAT_RBRN	Residual Brine Saturation	Constant	NONE	0.00E+00
	IMPERM_Z	Impermeable Zones	SAT_RGAS	Residual Gas Saturation	Constant	NONE	0.00E+00

Table PAR-44. Castile Brine Reservoir Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	CASTILER	Castile Brine Reservoir	CAP_MOD	Model number, capillary pressure model	Constant	NONE	2.00E+00
	CASTILER	Castile Brine Reservoir	COMP_RCK	Bulk Compressibility	Triangular	Pa^{-1}	Sampled Value
	CASTILER	Castile Brine Reservoir	KPT	Flag for Permeability Determined Threshold	Constant	NONE	0.00E+00
	CASTILER	Castile Brine Reservoir	PC_MAX	Maximum allowable capillary pressure	Constant	Pa	1.00E+08
	CASTILER	Castile Brine Reservoir	PCT_A	Threshold Pressure Linear Parameter	Constant	Pa	5.60E-01
	CASTILER	Castile Brine Reservoir	PCT_EXP	Threshold pressure exponential parameter	Constant	NONE	-3.46E-01
	CASTILER	Castile Brine Reservoir	PO_MIN	Minimum brine pressure for capillary model KPC=3	Constant	Pa	1.01E+05
	CASTILER	Castile Brine Reservoir	PORE_DIS	Brooks-Corey pore distribution parameter	Constant	NONE	7.00E-01
	CASTILER	Castile Brine Reservoir	POROSITY	Effective porosity	Student	NONE	8.70E-03
	CASTILER	Castile Brine Reservoir	PRESSURE	Brine far-field pore pressure	Triangular	Pa	1.27E+07
	CASTILER	Castile Brine Reservoir	PRMX_LOG	Log of intrinsic permeability, X-direction	Triangular	$\log(m^2)$	-1.18E+01
	CASTILER	Castile Brine Reservoir	PRMY_LOG	Log of intrinsic permeability, Y-direction	Triangular	$\log(m^2)$	-1.18E+01
	CASTILER	Castile Brine Reservoir	PRMZ_LOG	Log of intrinsic permeability, Z-direction	Triangular	$\log(m^2)$	-1.18E+01
	CASTILER	Castile Brine Reservoir	RELP_MOD	Model number, relative permeability model	Constant	NONE	4.00E+00
	CASTILER	Castile Brine Reservoir	SAT_IBRN	Initial Brine Saturation	Constant	NONE	1.00E+00
	CASTILER	Castile Brine Reservoir	SAT_RBRN	Residual Brine Saturation	Constant	NONE	2.00E-01
	CASTILER	Castile Brine Reservoir	SAT_RGAS	Residual Gas Saturation	Constant	NONE	2.00E-01

Table PAR-45. Reference Constants

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	REFCON	Reference Constant	ABERM	Area of Berm Placed Over Waste Panel	Constant	m^2	6.29E+05
	REFCON	Reference Constant	ACF_CH4	Acentric Factors - CH4	Constant	NONE	1.00E-02
	REFCON	Reference Constant	ACF_CO2	Acentric Factors - CO2	Constant	NONE	2.31E-01
	REFCON	Reference Constant	ACF_H2	Acentric Factors - H2	Constant	NONE	0.00E+00
	REFCON	Reference Constant	ACF_H2S	Acentric Factors - H2S	Constant	NONE	1.00E-01
	REFCON	Reference Constant	ACF_N2	Acentric Factors - N2	Constant	NONE	4.50E-02
	REFCON	Reference Constant	ACF_O2	Acentric Factors - O2	Constant	NONE	1.90E-02
	REFCON	Reference Constant	AREA_CH	Area For CH Waste Disposal in CDFGF Model	Constant	m^2	1.12E+05
	REFCON	Reference Constant	AREA_RH	Area For RH Waste Disposal in CDFGF Model	Constant	m^2	1.58E+04
	REFCON	Reference Constant	AREA_ZRO	Area in Waste Panels Not Used For Disposal (CCDFGF Model)	Constant	m^2	4.13E+03
	REFCON	Reference Constant	ATMPA	Conversion from std. atmosphere to Pa	Constant	Pa/atm	1.01E+05
	REFCON	Reference Constant	AVOGADRO	Avogadro's number	Constant	$mole^{-1}$	6.02E+23
	REFCON	Reference Constant	BIP_11	H2:H2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_12	H2:CO2 - Binary Interaction Parameter	Constant	NONE	-3.43E-01
	REFCON	Reference Constant	BIP_13	H2:CH4 - Binary Interaction Parameter	Constant	NONE	-2.22E-02
	REFCON	Reference Constant	BIP_14	H2:N2 - Binary Interaction Parameter	Constant	NONE	9.78E-02
	REFCON	Reference Constant	BIP_15	H2:H2S - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_16	H2:O2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_21	CO2:H2 - Binary Interaction Parameter	Constant	NONE	-3.43E-01
	REFCON	Reference Constant	BIP_22	CO2:CO2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_23	CO2:CH4 - Binary Interaction Parameter	Constant	NONE	9.33E-02
	REFCON	Reference Constant	BIP_24	CO2:N2 - Binary Interaction Parameter	Constant	NONE	-3.15E-02
	REFCON	Reference Constant	BIP_25	CO2:H2S - Binary Interaction Parameter	Constant	NONE	9.89E-02

Table PAR-45. Reference Constants — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	REFCON	Reference Constant	BIP_26	CO2:O2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_31	CH4:H2 - Binary Interaction Parameter	Constant	NONE	-2.22E-02
	REFCON	Reference Constant	BIP_32	CH4:CO2 - Binary Interaction Parameter	Constant	NONE	9.33E-02
	REFCON	Reference Constant	BIP_33	CH4:CH4 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_34	CH4:N2 - Binary Interaction Parameter	Constant	NONE	2.78E-02
	REFCON	Reference Constant	BIP_35	CH4:H2S - Binary Interaction Parameter	Constant	NONE	8.50E-02
	REFCON	Reference Constant	BIP_36	CH4:O2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_41	N2:H2 - Binary Interaction Parameter	Constant	NONE	9.78E-02
	REFCON	Reference Constant	BIP_42	N2:CO2 - Binary Interaction Parameter	Constant	NONE	-3.15E-02
	REFCON	Reference Constant	BIP_43	N2:CH4 - Binary Interaction Parameter	Constant	NONE	2.78E-02
	REFCON	Reference Constant	BIP_44	N2:N2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_45	N2:H2S - Binary Interaction Parameter	Constant	NONE	1.70E-01
	REFCON	Reference Constant	BIP_46	N2:O2 - Binary Interaction Parameter	Constant	NONE	-7.80E-03
	REFCON	Reference Constant	BIP_51	H2S:H2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_52	H2S:CO2 - Binary Interaction Parameter	Constant	NONE	9.89E-02
	REFCON	Reference Constant	BIP_53	H2S:CH4 - Binary Interaction Parameter	Constant	NONE	8.50E-02
	REFCON	Reference Constant	BIP_54	H2S:N2 - Binary Interaction Parameter	Constant	NONE	1.70E-01
	REFCON	Reference Constant	BIP_55	H2S:H2S - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_56	H2S:O2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_61	O2:H2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_62	O2:CO2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_63	O2:CH4 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_64	O2:N2 - Binary Interaction Parameter	Constant	NONE	-7.80E-03
	REFCON	Reference Constant	BIP_65	O2:H2S - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	BIP_66	O2:O2 - Binary Interaction Parameter	Constant	NONE	0.00E+00
	REFCON	Reference Constant	CITOBQ	Curie to Becquerel Conversion	Constant	Bq/Curies	3.70E+10
	REFCON	Reference Constant	DARM2	Conversion from darcy to m^2	Constant	m^2/darcy	9.87E-13

Table PAR-45. Reference Constants — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	REFCON	Reference Constant	DAYSEC	Conversion from days to seconds	Constant	s/day	8.64E+04
	REFCON	Reference Constant	FTM	Conversion from feet to meter	Constant	m/ft	3.05E-01
	REFCON	Reference Constant	FVRW	Fraction of Emplaced RH Volume Occupied by RH Waste in CCDFGF Model	Constant	NONE	1.00E+00
	REFCON	Reference Constant	FVW	Fraction of Repository Volume Occupied By Waste In CCDFGF Model	Constant	NONE	3.86E-01
	REFCON	Reference Constant	GRAVACC	Standard gravitational acceleration	Constant	m/s^2	9.81E+00
	REFCON	Reference Constant	HRH	Emplaced Height of Remote Handled Waste in CCDFGF Model	Constant	m	5.09E-01
	REFCON	Reference Constant	MW_CELL	Carbon Normalized Molecular Weight of Cellulose	Constant	kg/mole	2.70E-02
	REFCON	Reference Constant	MW_CH4	Molecular Weight of CH4	Constant	kg/mole	1.60E-02
	REFCON	Reference Constant	MW_CO2	Molecular Weight of CO2	Constant	kg/mole	4.40E-02
	REFCON	Reference Constant	MW_FE	Molecular Weight - FE	Constant	kg/mole	5.58E-02
	REFCON	Reference Constant	MW_H2	Molecular Weight - H2	Constant	kg/mole	2.02E-03
	REFCON	Reference Constant	MW_H2O	Molecular Weight - H2O	Constant	kg/mole	1.80E-02
	REFCON	Reference Constant	MW_H2S	Molecular Weight of H2S	Constant	kg/mole	3.41E-02
	REFCON	Reference Constant	MW_N2	Molecular Weight of N2	Constant	kg/mole	2.80E-02
	REFCON	Reference Constant	MW_NACL	Molecular Weight of NaCl	Constant	kg/mole	5.84E-02
	REFCON	Reference Constant	MW_O2	Molecular Weight of O2	Constant	kg/mole	3.20E-02
	REFCON	Reference Constant	OMEGAA	Constants for RKS EOS	Constant	NONE	4.27E-01
	REFCON	Reference Constant	OMEGAB	Constants for RDS EOS	Constant	NONE	8.66E-02
	REFCON	Reference Constant	PC_CH4	Critical Pressure of CH4	Constant	Pa	4.62E+06
	REFCON	Reference Constant	PC_CO2	Critical Pressure of CO2	Constant	Pa	7.38E+06
	REFCON	Reference Constant	PC_H2	Critical Pressure of H2	Constant	Pa	2.05E+06
	REFCON	Reference Constant	PC_H2S	Critical Pressure of H2S	Constant	Pa	9.01E+06
	REFCON	Reference Constant	PC_N2	Critical Pressure of N2	Constant	Pa	3.39E+06
	REFCON	Reference Constant	PC_O2	Critical Pressure of O2	Constant	Pa	5.08E+06
	REFCON	Reference Constant	PI	Mathematical constant: PI	Constant	NONE	3.14E+00
	REFCON	Reference Constant	PSIPA	Conversion from psi to pascal	Constant	$Pa*in^2/lb$	6.89E+03
	REFCON	Reference Constant	R	Gas constant R	Constant	J/mole*K	8.31E+00

Table PAR-45. Reference Constants — Continued

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	REFCON	Reference Constant	SECYR	Seconds to years Conversion	Constant	yr/s	3.17E-08
	REFCON	Reference Constant	TC_CH4	Critical temperature: Methane (CH4)	Constant	K	1.91E+02
	REFCON	Reference Constant	TC_CO2	Critical temperature: Carbon Dioxide (CO2)	Constant	K	3.04E+02
	REFCON	Reference Constant	TC_H2	Critical temperature: Hydrogen (H2)	Constant	K	4.36E+01
	REFCON	Reference Constant	TC_H2S	Critical temperature: Hydrogen Sulfide (H2S)	Constant	K	3.74E+02
	REFCON	Reference Constant	TC_N2	Critical temperature: Nitrogen (N2)	Constant	K	1.26E+02
	REFCON	Reference Constant	TC_O2	Critical temperature: Oxygen (O2)	Constant	K	1.55E+02
	REFCON	Reference Constant	VOLWP	Uncompacted Volume of Waste Panels In CCDFGF Model	Constant	m^3	4.36E+05
	REFCON	Reference Constant	VPANLEX	Excavated volume of one panel	Constant	m^3	4.61E+04
	REFCON	Reference Constant	VREPOS	Excavated storage volume of repository	Constant	m^3	4.38E+05
	REFCON	Reference Constant	VROOM	Volume of one room in repository	Constant	m^3	3.64E+03
	REFCON	Reference Constant	YRSEC	Conversion from mean solar or tropical year to seconds	Constant	s/yr	3.16E+07

Table PAR-46. Global Parameters

	Material	Material Description	Property	Property Description	Distribution Type	Units	Value
	GLOBAL	Information that applies globally	FPICD	PIC multiplicative factor for human intrusion by drilling	Constant	NONE	1.00E+00
	GLOBAL	Information that applies globally	FPICM	PIC multiplicative factor for human intrusion by mining	Constant	NONE	1.00E+00
	GLOBAL	Information that applies globally	LAMBDAD	Drilling Rate Per Unit Area	Constant	(km^{-2}) (yr^{-1})	5.25E-03
	GLOBAL	Information that applies globally	MINERT	Mining rate from 40 CFR 194	Constant	yr^{-1}	1.00E-04
	GLOBAL	Information that applies globally	ONEPLG	Probability of having Plug Pattern 1	Constant	NONE	1.50E-02
	GLOBAL	Information that applies globally	PLGPAT	Index for Plugging Pattern After Drilling Intrusion	Delta	NONE	0.00E+00
	GLOBAL	Information that applies globally	TA	Time Active Institutional Controls at WIPP Site Are Effective	Constant	yr	1.00E+02
	GLOBAL	Information that applies globally	THREEPLG	Probability of having Plug Pattern 3	Constant	NONE	2.89E-01
	GLOBAL	Information that applies globally	TPICD	Time over which passive institutional controls reduce rate of drilling	Constant	yr	6.00E+02
	GLOBAL	Information that applies globally	TPICM	Time over which passive institutional controls reduce rate of mining	Constant	yr	6.00E+02
	GLOBAL	Information that applies globally	TWOPLG	Probability of having Plug Pattern 2	Constant	NONE	6.96E-01

Table PAR-47. Listing of Parameters Used in BRAGFLO Which Differ From the PA Parameter Database

Database Material	Database Property	Modeling value used	Distribution type	Database value	Units
REPOSIT	DCELLCHW	5.80E+01	CONSTANT	5.40E+01	kg/m^3
REPOSIT	DCELLRHW	4.50E+00	CONSTANT	1.70E+01	kg/m^3
REPOSIT	DIRNCCHW	1.70E+02	CONSTANT	1.39E+02	kg/m^3
REPOSIT	DIRNCRHW	4.80E+02	CONSTANT	2.59E+03	kg/m^3
REPOSIT	DIRONCHW	1.10E+02	CONSTANT	1.70E+02	kg/m^3
REPOSIT	DIRONRHW	1.10E+02	CONSTANT	1.00E+02	kg/m^3
REPOSIT	DPLASCHW	4.20E+01	CONSTANT	3.40E+01	kg/m^3
REPOSIT	DPLSCCHW	1.60E+01	CONSTANT	2.60E+01	kg/m^3
REPOSIT	DRUBBCHW	1.40E+01	CONSTANT	1.00E+01	kg/m^3
REPOSIT	DRUBBRHW	3.10E+00	CONSTANT	3.30E+00	kg/m^3
SHFTL_T1	PCT_A	0.00E+00	CONSTANT	5.60E-01	Pa
SHFTL_T1	PCT_EXP	0.00E+00	CONSTANT	-3.46E-01	NONE
SHFTL_T1	SAT_IBRN	9.99E-01	CONSTANT	5.34E-01	NONE
SHFTL_T2	PCT_A	0.00E+00	CONSTANT	5.60E-01	Pa
SHFTL_T2	PCT_EXP	0.00E+00	CONSTANT	-3.46E-01	NONE
SHFTL_T2	SAT_IBRN	9.99E-01	CONSTANT	5.34E-01	NONE
SHFTU	PCT_A	0.00E+00	CONSTANT	5.60E-01	Pa
SHFTU	PCT_EXP	0.00E+00	CONSTANT	-3.46E-01	NONE
SHFTU	SAT_IBRN	9.99E-01	CONSTANT	7.96E-01	NONE

Table PAR-48. Listing of Parameters Used in DRSPALL Not in the PA Parameter Database

Database Material	Database Property	Modeling value used	Distribution type
SPALLMOD	CHARLEN	0.02E+00	Constant
SPALLMOD	DRZTCK	0.85E+00	Constant
SPALLMOD	EXITPLEN	0.00E+00	Constant
SPALLMOD	EXITPDIA	20.32E-02	Constant
SPALLMOD	FRCHBETA	1.15E-06	Constant
SPALLMOD	INITBAR	0.15E+00	Constant
SPALLMOD	MAXPPRES	27.50E+06	Constant
SPALLMOD	REPOSTCK	0.00E+00	Constant
SPALLMOD	REPOTRAD	1.92E+01	Constant
SPALLMOD	STPDTIME	1.00E+03	Constant

Table PAR-49. Reference Thicknesses for Hydrostratigraphic Units in BRAGFLO

Hydrostratigraphic Unit	Total Hydrostratigraphic Unit Thickness (meters)	Geologic Units Combined as Units Above Dewey Lake	Geologic Unit Thickness (meters)
Units above Dewey Lake	15.76[1]	Surficial Sediments Mescalero Caliche Gatuña Santa Rosa	0 - 3 0 – 4.6[2] 0 – [2.7 – 9.0][3] 0 – [0.6 – 64.0][4]
Dewey Lake	149.3		
Forty-niner	17.3		
Magenta	8.5		
Tamarisk	24.8		
Culebra	7.7		
Unnamed lower Member	36.0		
Impure Halite	600.3		
Marker Bed 138			
Anhydrite Layers and b	0.27		
Marker Bed 139	0.85		
Castile	78.5		

[1] Thicknesses of supra-Dewey Lake hydrostratigraphic unit relates to the ranges of total thickness of geologic units as determined for the following quadrants of the land withdrawal area:

Northwest – 6.0 m (H-6) – 22 m (WIPP-13)
Southwest – 6.0 m (P-6) – 12 m (H-14)
Southeast – 11.3 m (ERDA-9) – 47 m (H-15)
Northeast – 21 m (WIPP-21) – 67 m (H-5)

Source: Sanchez and McCasland, 1994, Assessment of Solid Waste Management Units: NMED/DOE/AIP-94/1, New Mexico Environment Department, Santa Fe, New Mexico, p. 4-1 – 4-28.

[2] Mescalero caliche engulfs local bedrock; thickness of unit is accounted for in bedrock unit thickness of geologic units above Dewey Lake.

[3] Gatuña thickness is variable; generally thickest on west half of land withdrawal area and absent on east side. Range includes AIS shaft (2.7 m) and H-14 (9.0 m).

[4] Santa Rosa is generally absent on west half of land withdrawal area; thickens to east. Range includes AIS shaft (0.6 m) and H-5 (64 m).

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
AE-T001	2.30E+02	1.36E-03	7.57E-03	7.21E-03	7.13E-03	6.99E-03	6.61E-03	5.82E-03	4.96E-03	4.46E-03	3.94E-03	3.50E-03
AE-T003	5.21E+01	3.09E-04	7.84E-03	7.68E-03	7.63E-03	7.54E-03	7.30E-03	6.76E-03	5.99E-03	5.46E-03	4.89E-03	4.41E-03
AW-N026.82	2.10E-01	1.25E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	1.46E+01	8.68E-05	2.67E-02	1.93E-02	1.82E-02	1.65E-02	1.39E-02	1.28E-02	1.21E-02	1.14E-02	1.06E-02	9.87E-03
AW-T033.1325	5.35E+01	3.17E-04	2.67E-02	1.93E-02	1.82E-02	1.65E-02	1.39E-02	1.28E-02	1.21E-02	1.14E-02	1.06E-02	9.86E-03
AW-W049	1.80E+01	1.07E-04	1.73E-04	1.73E-04	1.73E-04	1.72E-04	1.72E-04	1.68E-04	1.59E-04	1.50E-04	1.40E-04	1.30E-04
BCLCH-MT01	5.24E+00	3.11E-05	1.10E+00	5.23E-01	4.36E-01	3.05E-01	1.03E-01	3.03E-02	2.51E-02	2.30E-02	2.09E-02	1.90E-02
BT-T002	1.86E+01	1.10E-04	1.60E-04	7.45E-05	6.16E-05	4.24E-05	1.25E-05	1.58E-06	9.01E-07	8.23E-07	7.65E-07	7.19E-07
ET-C1-B55	8.40E-01	4.99E-06	7.41E-04	6.88E-04	6.75E-04	6.52E-04	5.92E-04	4.77E-04	3.84E-04	3.46E-04	3.08E-04	2.76E-04
ET-C1-D139	2.10E-01	1.25E-06	4.13E-04	3.83E-04	3.76E-04	3.64E-04	3.30E-04	2.67E-04	2.16E-04	1.94E-04	1.73E-04	1.55E-04
ET-C2-SEFOR	1.25E+00	7.42E-06	1.18E-03	1.10E-03	1.08E-03	1.04E-03	9.24E-04	6.84E-04	5.18E-04	4.70E-04	4.23E-04	3.82E-04
FM-MOX-MT02	4.20E-01	2.49E-06	2.46E-08	2.11E-08	2.01E-08	1.85E-08	1.45E-08	7.76E-09	4.03E-09	3.51E-09	3.09E-09	2.75E-09
FM-MOX-T01	6.86E+00	4.07E-05	2.49E-08	2.13E-08	2.03E-08	1.87E-08	1.46E-08	7.84E-09	4.06E-09	3.54E-09	3.12E-09	2.78E-09
IN-BN-510	1.99E+04	1.18E-01	1.81E-02	1.35E-02	1.28E7-02	1.18E-02	9.95E-03	8.73E-03	7.89E-03	7.37E-03	6.80E-03	6.27E-03
IN-GEM-01	2.05E+02	1.22E-03	2.85E-03	2.58E-03	2.52E-03	2.40E-03	2.07E-03	1.39E-03	9.65E-04	8.78E-04	7.97E-04	7.27E-04
IN-GEM-02	4.87E+01	2.89E-04	2.84E-03	2.58E-03	2.52E-03	2.40E-03	2.07E-03	1.39E-03	9.65E-04	8.78E-04	7.98E-04	7.27E-04
IN-W157.144	7.46E+02	4.43E-03	2.58E-03	2.51E-03	2.48E-03	2.44E-03	2.31E-03	2.04E-03	1.78E-03	1.64E-03	1.49E-03	1.36E-03
IN-W163.1007	1.15E+01	6.81E-05	4.69E-02	4.61E-02	4.58E-02	4.52E-02	4.36E-02	4.01E-02	3.58E-02	3.30E-02	3.00E-02	2.73E-02
IN-W164.153	4.79E+00	2.84E-05	1.07E-03	1.05E-03	1.05E-03	1.03E-03	9.94E-04	9.14E-04	8.16E-04	7.52E-04	6.83E-04	6.23E-04
IN-W167.149	3.83E+02	2.28E-03	2.24E-03	2.19E-03	2.17E-03	2.14E-03	2.05E-03	1.86E-03	1.65E-03	1.52E-03	1.38E-03	1.26E-03
IN-W174.154	4.31E+02	2.56E-03	1.91E-02	8.70E-03	7.15E-03	4.84E-03	1.26E-03	6.68E-05	5.25E-05	4.65E-05	4.04E-05	3.56E-05
IN-W177.156	8.03E+02	4.77E-03	2.17E-02	9.88E-03	8.11E-03	5.47E-03	1.39E-03	2.82E-05	1.95E-05	1.90E-05	1.83E-05	1.77E-05
IN-W179.158	2.00E+03	1.19E-02	8.71E-03	3.96E-03	3.25E-03	2.19E-03	5.53E-04	8.05E-06	4.70E-06	4.65E-06	4.59E-06	4.53E-06
IN-W181.162	8.03E+01	4.77E-04	8.42E-04	8.28E-04	8.22E-04	8.12E-04	7.82E-04	7.19E-04	6.42E-04	5.92E-04	5.38E-04	4.90E-04

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
IN-W188.160	1.49E+02	8.85E-04	3.06E-03	3.01E-03	2.99E-03	2.95E-03	2.84E-03	2.61E-03	2.33E-03	2.15E-03	1.95E-03	1.78E-03
IN-W216.98	1.27E+04	7.57E-02	4.60E-02	3.96E-02	3.81E-02	3.54E-02	2.73E-02	1.12E-02	2.58E-03	2.07E-03	1.87E-03	1.70E-03
IN-W218.909	2.08E+03	1.24E-02	1.69E-03	1.49E-03	1.44E-03	1.36E-03	1.10E-03	5.98E-04	3.12E-04	2.79E-04	2.53E-04	2.31E-04
IN-W219.110	3.95E+00	2.35E-05	7.04E-03	6.92E-03	6.88E-03	6.79E-03	6.54E-03	6.02E-03	5.37E-03	4.95E-03	4.50E-03	4.10E-03
IN-W219.914	1.89E+00	1.12E-05	2.32E-03	2.28E-03	2.27E-03	2.24E-03	2.16E-03	1.99E-03	1.77E-03	1.63E-03	1.48E-03	1.35E-03
IN-W220.114	1.89E+03	1.12E-02	1.19E-02	1.03E-02	9.99E-03	9.32E-03	7.37E-03	3.47E-03	1.34E-03	1.17E-03	1.06E-03	9.65E-04
IN-W221.927	3.92E+01	2.33E-04	4.32E-03	4.25E-03	4.22E-03	4.17E-03	4.02E-03	3.69E-03	3.30E-03	3.04E-03	2.76E-03	2.52E-03
IN-W222.116	2.59E+02	1.54E-03	2.21E-02	2.18E-02	2.16E-02	2.13E-02	2.06E-02	1.89E-02	1.69E-02	1.55E-02	1.41E-02	1.29E-02
IN-W228.101	8.06E+03	4.79E-02	8.50E-04	7.54E-04	7.32E-04	6.90E-04	5.68E-04	3.23E-04	1.82E-04	1.63E-04	1.48E-04	1.35E-04
IN-W240.931	3.97E+02	2.36E-03	6.63E-03	6.44E-03	6.38E-03	6.27E-03	5.95E-03	5.29E-03	4.62E-03	4.26E-03	3.87E-03	3.53E-03
IN-W243.808	7.73E+02	4.59E-03	5.68E-03	5.55E-03	5.51E-03	5.42E-03	5.19E-03	4.69E-03	4.14E-03	3.82E-03	3.47E-03	3.16E-03
IN-W245.301	7.52E+02	4.47E-03	1.09E-02	1.07E-02	1.07E-02	1.05E-02	1.01E-02	9.31E-03	8.30E-03	7.65E-03	6.95E-03	6.34E-03
IN-W247.810	7.62E+02	4.52E-03	5.27E-03	5.18E-03	5.14E-03	5.07E-03	4.89E-03	4.49E-03	4.01E-03	3.70E-03	3.36E-03	3.06E-03
IN-W249.527	6.68E+00	3.97E-05	7.39E-01	3.40E-01	2.80E-01	1.91E-01	5.38E-02	7.91E-03	7.23E-03	6.84E-03	6.39E-03	5.97E-03
IN-W263.520	2.80E+02	1.66E-03	1.95E-03	9.49E-04	8.01E-04	5.80E-04	2.36E-04	1.20E-04	1.12E-04	1.06E-04	9.87E-05	9.19E-05
IN-W267.1005	1.15E+01	6.81E-05	8.48E-02	8.34E-02	8.28E-02	8.18E-02	7.88E-02	7.25E-02	6.47E-02	5.96E-02	5.42E-02	4.94E-02
IN-W309.609	7.73E+03	4.59E-02	2.28E-03	2.22E-03	2.20E-03	2.16E-03	2.05E-03	1.83E-03	1.61E-03	1.48E-03	1.34E-03	1.23E-03
IN-W315.601	3.44E+01	2.04E-04	1.04E-01	8.85E-02	8.51E-02	7.87E-02	5.98E-02	2.21E-02	2.34E-03	1.43E-03	1.27E-03	1.15E-03
IN-W319.584	4.79E+00	2.84E-05	3.12E-02	3.07E-02	3.05E-02	3.01E-02	2.90E-02	2.67E-02	2.38E-02	2.19E-02	1.99E-02	1.82E-02
IN-W321.1023	1.15E+01	6.81E-05	1.13E-01	1.11E-01	1.10E-01	1.09E-01	1.05E-01	9.64E-02	8.60E-02	7.93E-02	7.21E-02	6.57E-02
IN-W322.851	1.89E+00	1.12E-05	2.35E-02	2.34E-02	2.33E-02	2.33E-02	2.31E-02	2.25E-02	2.08E-02	1.92E-02	1.75E-02	1.60E-02
IN-W322.952	1.66E+00	9.85E-06	7.12E-02	7.09E-02	7.08E-02	7.07E-02	7.01E-02	6.83E-02	6.30E-02	5.82E-02	5.30E-02	4.84E-02
IN-W323.562	1.89E+00	1.12E-05	2.73E-03	1.62E-03	1.45E-03	1.19E-03	7.68E-04	5.58E-04	4.90E-04	4.61E-04	4.29E-04	3.99E-04
IN-W323.951	2.10E-01	1.25E-06	7.77E-03	7.58E-03	7.49E-03	7.32E-03	6.86E-03	5.96E-03	5.24E-03	4.93E-03	4.59E-03	4.27E-03
IN-W332.661	4.79E+00	2.84E-05	1.06E-02	4.86E-03	4.01E-03	2.74E-03	7.71E-04	1.15E-04	1.05E-04	9.92E-05	9.27E-05	8.66E-05
IN-W337.673	2.10E-01	1.25E-06	7.04E-02	7.01E-02	7.00E-02	6.99E-02	6.94E-02	6.75E-02	6.23E-02	5.76E-02	5.24E-02	4.79E-02
IN-W337.957	1.89E+00	1.12E-05	2.35E-02	2.34E-02	2.33E-02	2.33E-02	2.31E-02	2.25E-02	2.08E-02	1.92E-02	1.75E-02	1.60E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
IN-W341.671	2.10E-01	1.25E-06	3.74E-02	3.73E-02	3.73E-02	3.72E-02	3.70E-02	3.64E-02	3.43E-02	3.24E-02	3.01E-02	2.81E-02
IN-W341.954	1.89E+00	1.12E-05	1.25E-02	1.25E-02	1.25E-02	1.24E-02	1.24E-02	1.21E-02	1.15E-02	1.08E-02	1.01E-02	9.37E-03
IN-W342.652	1.89E+00	1.12E-05	9.31E-03	7.94E-03	7.63E-03	7.05E-03	5.35E-03	1.94E-03	1.54E-04	7.72E-05	6.91E-05	6.42E-05
IN-W342.953	4.20E-01	2.49E-06	2.80E-02	2.39E-02	2.30E-02	2.12E-02	1.61E-02	5.83E-03	4.62E-04	2.33E-04	2.08E-04	1.93E-04
IN-W347.818	1.54E+02	9.14E-04	6.19E-03	6.13E-03	6.12E-03	6.09E-03	6.00E-03	5.68E-03	4.87E-03	4.21E-03	3.53E-03	3.00E-03
IN-W348.1012	2.29E+01	1.36E-04	9.16E-02	9.03E-02	9.00E-02	8.96E-02	8.86E-02	8.61E-02	7.92E-02	7.32E-02	6.65E-02	6.06E-02
IN-W353.917	2.10E-01	1.25E-06	4.80E-04	4.78E-04	4.78E-04	4.77E-04	4.75E-04	4.66E-04	4.40E-04	4.15E-04	3.86E-04	3.60E-04
IN-W357.1022	4.79E+00	2.84E-05	8.61E-04	8.48E-04	8.46E-04	8.42E-04	8.33E-04	8.09E-04	7.45E-04	6.88E-04	6.25E-04	5.70E-04
IN-W358.854	1.89E+00	1.12E-05	6.61E-01	3.07E-01	2.54E-01	1.75E-01	5.26E-02	1.14E-02	9.61E-03	8.33E-03	7.02E-03	5.99E-03
IN-W358.855	3.33E+00	1.98E-05	2.00E+00	9.28E-01	7.68E-01	5.29E-01	1.59E-01	3.44E-02	2.90E-02	2.51E-02	2.12E-02	1.81E-02
IN-W358.948	2.10E-01	1.25E-06	6.62E+00	3.07E+00	2.54E+00	1.75E+00	5.26E-01	1.14E-01	9.59E-02	8.31E-02	7.02E-02	5.98E-02
IN-W361.1021	1.15E+01	6.81E-05	3.47E-02	3.42E-02	3.41E-02	3.39E-02	3.36E-02	3.26E-02	3.00E-02	2.77E-02	2.52E-02	2.30E-02
IN-W362.1020	4.59E+01	2.72E-04	1.13E-01	1.12E-01	1.11E-01	1.11E-01	1.10E-01	1.06E-01	9.79E-02	9.04E-02	8.22E-02	7.49E-02
IN-W363.1019	4.79E+00	2.84E-05	5.15E-02	5.07E-02	5.06E-02	5.03E-02	4.98E-02	4.83E-02	4.45E-02	4.11E-02	3.73E-02	3.41E-02
IN-W364.1011	4.79E+00	2.84E-05	8.46E-02	8.33E-02	8.31E-02	8.27E-02	8.18E-02	7.94E-02	7.31E-02	6.75E-02	6.14E-02	5.60E-02
IN-W365.1010	1.15E+01	6.81E-05	1.32E-01	1.16E-01	1.13E-01	1.06E-01	8.64E-02	4.72E-02	2.50E-02	2.23E-02	2.03E-02	1.85E-02
IN-W366.841	1.63E+01	9.65E-05	1.70E-02	1.68E-02	1.67E-02	1.66E-02	1.64E-02	1.58E-02	1.45E-02	1.34E-02	1.22E-02	1.11E-02
IN-W372.832	1.89E+00	1.12E-05	9.31E-03	7.94E-03	7.63E-03	7.05E-03	5.35E-03	1.94E-03	1.54E-04	7.72E-05	6.91E-05	6.42E-05
IN-W375.1096	2.00E+02	1.19E-03	5.04E-04	4.97E-04	4.96E-04	4.93E-04	4.88E-04	4.74E-04	4.36E-04	4.03E-04	3.66E-04	3.34E-04
KN-B234TRU	4.14E+02	2.46E-03	5.43E-03	5.13E-03	5.06E-03	4.93E-03	4.59E-03	3.91E-03	3.31E-03	3.02E-03	2.71E-03	2.46E-03
LA-IT-00-01	9.78E+00	5.81E-05	2.50E-03	1.64E-03	1.50E-03	1.28E-03	8.53E-04	4.25E-04	2.33E-04	2.13E-04	1.97E-04	1.83E-04
LA-OS-00-01	6.96E+01	4.13E-04	8.91E+00	4.20E+00	3.49E+00	2.44E+00	7.77E-01	1.34E-01	7.16E-02	6.57E-02	6.13E-02	5.73E-02
LA-PX-00-01	6.20E-01	3.68E-06	8.94E-04	8.56E-04	8.48E-04	8.33E-04	7.95E-04	7.23E-04	6.41E-04	5.91E-04	5.36E-04	4.89E-04
LA-SL-00-01	4.20E-01	2.49E-06	2.73E-03	2.04E-03	1.93E-03	1.78E-03	1.53E-03	1.43E-03	1.35E-03	1.27E-03	1.18E-03	1.10E-03
LA-TA-03-12	2.21E+02	1.31E-03	6.98E-05	3.91E-05	3.44E-05	2.75E-05	1.63E-05	1.10E-05	9.35E-06	8.53E-06	7.67E-06	6.94E-06
LA-TA-03-13	4.64E+01	2.75E-04	9.34E-04	4.73E-04	4.05E-04	3.01E-04	1.39E-04	7.55E-05	6.50E-05	5.98E-05	5.43E-05	4.96E-05
LA-TA-03-19	1.80E+02	1.07E-03	3.73E-04	1.95E-04	1.69E-04	1.29E-04	6.54E-05	3.95E-05	3.39E-05	3.11E-05	2.81E-05	2.55E-05

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
LA-TA-03-20	3.01E+01	1.79E-04	1.06E-03	5.56E-04	4.80E-04	3.66E-04	1.86E-04	1.10E-04	9.30E-05	8.48E-05	7.63E-05	6.89E-05
LA-TA-03-24	3.00E+01	1.78E-04	3.82E-03	1.86E-03	1.57E-03	1.13E-03	4.47E-04	1.97E-04	1.69E-04	1.55E-04	1.40E-04	1.27E-04
LA-TA-03-26	2.43E+01	1.44E-04	6.31E-04	5.30E-04	5.15E-04	4.92E-04	4.54E-04	4.33E-04	4.07E-04	3.84E-04	3.57E-04	3.31E-04
LA-TA-03-28	5.84E+00	3.47E-05	4.32E-04	2.89E-04	2.67E-04	2.35E-04	1.85E-04	1.66E-04	1.56E-04	1.48E-04	1.37E-04	1.28E-04
LA-TA-03-30	8.30E-01	4.93E-06	3.70E-02	3.58E-02	3.55E-02	3.50E-02	3.36E-02	3.10E-02	2.76E-02	2.53E-02	2.29E-02	2.08E-02
LA-TA-03-31	2.10E-01	1.25E-06	4.28E-04	2.86E-04	2.65E-04	2.33E-04	1.84E-04	1.64E-04	1.55E-04	1.46E-04	1.36E-04	1.27E-04
LA-TA-03-40	2.66E+02	1.58E-03	1.15E-06	9.73E-07	9.46E-07	9.06E-07	8.41E-07	8.05E-07	7.60E-07	7.17E-07	6.68E-07	6.21E-07
LA-TA-03-42	3.00E+02	1.78E-03	5.40E-08	4.99E-08	4.93E-08	4.83E-08	4.67E-08	4.52E-08	4.26E-08	4.01E-08	3.73E-08	3.47E-08
LA-TA-21-06	2.26E+02	1.34E-03	1.08E-03	5.02E-04	4.16E-04	2.89E-04	9.06E-05	2.30E-05	2.00E-05	1.84E-05	1.67E-05	1.52E-05
LA-TA-21-12	2.64E+02	1.57E-03	5.50E-03	2.54E-03	2.10E-03	1.44E-03	4.16E-04	7.04E-05	6.07E-05	5.59E-05	5.08E-05	4.63E-05
LA-TA-21-13	1.62E+01	9.63E-05	3.66E-04	3.22E-04	3.12E-04	2.94E-04	2.39E-04	1.30E-04	6.94E-05	6.33E-05	5.88E-05	5.48E-05
LA-TA-21-14	7.90E+00	4.69E-05	5.75E-03	3.85E-03	3.57E-03	3.15E-03	2.49E-03	2.23E-03	2.10E-03	1.98E-03	1.85E-03	1.72E-03
LA-TA-21-15	3.54E+00	2.10E-05	2.00E-03	1.97E-03	1.96E-03	1.94E-03	1.90E-03	1.81E-03	1.65E-03	1.53E-03	1.40E-03	1.28E-03
LA-TA-21-16	7.17E+01	4.25E-04	8.25E-04	8.06E-04	8.01E-04	7.93E-04	7.71E-04	7.22E-04	6.51E-04	6.00E-04	5.44E-04	4.96E-04
LA-TA-21-40	1.02E+03	6.07E-03	5.24E-06	3.09E-06	2.77E-06	2.29E-06	1.55E-06	1.28E-06	1.21E-06	1.14E-06	1.06E-06	9.87E-07
LA-TA-21-41	4.15E+01	2.46E-04	6.88E-05	6.86E-05	6.86E-05	6.85E-05	6.81E-05	6.69E-05	6.31E-05	5.96E-05	5.54E-05	5.16E-05
LA-TA-21-42	6.91E+02	4.10E-03	3.01E-06	1.96E-06	1.80E-06	1.57E-06	1.19E-06	1.01E-06	9.27E-07	8.68E-07	8.02E-07	7.41E-07
LA-TA-21-43	2.53E+03	1.50E-02	1.12E-03	1.09E-03	1.09E-03	1.08E-03	1.05E-03	9.83E-04	8.87E-04	8.17E-04	7.42E-04	6.76E-04
LA-TA-21-44	1.38E+02	8.18E-04	3.45E-03	3.40E-03	3.39E-03	3.38E-03	3.35E-03	3.28E-03	3.09E-03	2.92E-03	2.71E-03	2.53E-03
LA-TA-48-01	6.20E-01	3.68E-06	4.60E-03	4.49E-03	4.45E-03	4.39E-03	4.21E-03	3.76E-03	3.04E-03	2.55E-03	2.07E-03	1.69E-03
LA-TA-49-01	9.62E+01	5.71E-04	3.67E-03	3.58E-03	3.55E-03	3.50E-03	3.35E-03	3.00E-03	2.43E-03	2.04E-03	1.65E-03	1.35E-03
LA-TA-50-10	1.04E+00	6.174E-06	3.37E-04	2.97E-04	2.90E-04	2.78E-04	2.47E-04	1.97E-04	1.64E-04	1.54E-04	1.43E-04	1.33E-04
LA-TA-50-11	8.57E+00	5.087E-05	3.00E-04	2.93E-04	2.91E-04	2.88E-04	2.80E-04	2.62E-04	2.37E-04	2.18E-04	1.99E-04	1.81E-04
LA-TA-50-15	1.59E+02	9.446E-04	5.12E-05	3.02E-05	2.70E-05	2.22E-05	1.45E-05	1.07E-05	9.35E-06	8.61E-06	7.83E-06	7.14E-06
LA-TA-50-17	2.16E+02	1.284E-03	6.80E-04	6.20E-04	6.07E-04	5.84E-04	5.19E-04	3.94E-04	3.14E-04	2.94E-04	2.73E-04	2.54E-04
LA-TA-50-18	9.84E+01	5.842E-04	1.70E-04	1.60E-04	1.58E-04	1.54E-04	1.45E-04	1.27E-04	1.12E-04	1.05E-04	9.80E-05	9.12E-05
LA-TA-50-19	1.18E+03	7.003E-03	2.72E-06	2.42E-06	2.36E-06	2.26E-06	2.00E-06	1.55E-06	1.26E-06	1.18E-06	1.09E-06	1.02E-06

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
LA-TA-50-20	6.20E-01	3.680E-06	1.21E-04	1.12E-04	1.10E-04	1.07E-04	9.57E-05	7.31E-05	5.85E-05	5.48E-05	5.10E-05	4.75E-05
LA-TA-50-40	2.45E+01	1.456E-04	3.48E-06	3.31E-06	3.27E-06	3.19E-06	2.99E-06	2.59E-06	2.20E-06	1.99E-06	1.77E-06	1.59E-06
LA-TA-50-41	3.59E+01	2.132E-04	7.14E-06	7.04E-06	7.00E-06	6.94E-06	6.76E-06	6.35E-06	5.74E-06	5.29E-06	4.80E-06	4.38E-06
LA-TA-55-19	3.24E+03	1.925E-02	5.35E-05	5.14E-05	5.09E-05	4.99E-05	4.74E-05	4.23E-05	3.69E-05	3.39E-05	3.06E-05	2.78E-05
LA-TA-55-20	6.30E+02	3.738E-03	5.95E-03	5.81E-03	5.77E-03	5.69E-03	5.48E-03	5.02E-03	4.47E-03	4.11E-03	3.73E-03	3.40E-03
LA-TA-55-21	9.90E+01	5.876E-04	2.80E-04	2.72E-04	2.69E-04	2.65E-04	2.53E-04	2.28E-04	2.01E-04	1.85E-04	1.68E-04	1.53E-04
LA-TA-55-22	1.42E+01	8.417E-05	6.71E-03	6.46E-03	6.41E-03	6.30E-03	6.04E-03	5.53E-03	4.92E-03	4.54E-03	4.12E-03	3.75E-03
LA-TA-55-23	1.25E+01	7.408E-05	5.56E-03	5.33E-03	5.27E-03	5.17E-03	4.91E-03	4.40E-03	3.87E-03	3.56E-03	3.23E-03	2.94E-03
LA-TA-55-24	1.25E+00	7.420E-06	2.65E-02	2.60E-02	2.58E-02	2.55E-02	2.46E-02	2.25E-02	2.01E-02	1.85E-02	1.68E-02	1.53E-02
LA-TA-55-25	2.26E+01	1.344E-04	7.32E-03	7.17E-03	7.12E-03	7.02E-03	6.75E-03	6.19E-03	5.51E-03	5.07E-03	4.61E-03	4.20E-03
LA-TA-55-28	3.74E+00	2.220E-05	1.40E-02	1.36E-02	1.35E-02	1.33E-02	1.27E-02	1.16E-02	1.03E-02	9.44E-03	8.57E-03	7.81E-03
LA-TA-55-30	3.31E+03	1.966E-02	2.75E-04	2.64E-04	2.62E-04	2.57E-04	2.44E-04	2.18E-04	1.91E-04	1.75E-04	1.59E-04	1.45E-04
LA-TA-55-32	4.78E+00	2.837E-05	3.81E-02	2.53E-02	2.34E-02	2.04E-02	1.55E-02	1.26E-02	1.09E-02	1.00E-02	9.02E-03	8.18E-03
LA-TA-55-33	6.66E+00	3.953E-05	1.55E-03	1.49E-03	1.47E-03	1.44E-03	1.36E-03	1.20E-03	1.04E-03	9.50E-04	8.56E-04	7.76E-04
LA-TA-55-34	2.68E+02	1.591E-03	5.24E-03	5.09E-03	5.05E-03	4.98E-03	4.77E-03	4.34E-03	3.84E-03	3.53E-03	3.20E-03	2.91E-03
LA-TA-55-38	8.48E+02	5.035E-03	9.74E-04	8.73E-04	8.50E-04	8.06E-04	6.80E-04	4.27E-04	2.75E-04	2.48E-04	2.25E-04	2.04E-04
LA-TA-55-39	2.91E+00	1.727E-05	1.50E-01	1.47E-01	1.46E-01	1.44E-01	1.39E-01	1.28E-01	1.14E-01	1.05E-01	9.56E-02	8.72E-02
LA-TA-55-41	4.37E+01	2.594E-04	4.32E-02	3.84E-02	3.72E-02	3.51E-02	2.90E-02	1.68E-02	9.76E-03	8.77E-03	7.95E-03	7.25E-03
LA-TA-55-43	6.49E+01	3.853E-04	1.32E-02	6.00E-03	4.93E-03	3.33E-03	8.52E-04	2.44E-05	1.69E-05	1.59E-05	1.49E-05	1.40E-05
LA-TA-55-44	2.31E+02	1.369E-03	8.81E-03	4.04E-03	3.33E-03	2.27E-03	6.24E-04	6.82E-05	5.64E-05	5.21E-05	4.76E-05	4.36E-05
LA-TA-55-48	3.10E+01	1.841E-04	4.31E+00	4.05E+00	3.99E+00	3.88E+00	3.60E+00	3.09E+00	2.62E+00	2.38E+00	2.14E+00	1.93E+00
LA-TA-55-49	1.83E+01	1.086E-04	5.84E-01	2.72E-01	2.25E-01	1.55E-01	4.71E-02	9.66E-03	7.98E-03	7.33E-03	6.66E-03	6.07E-03
LA-TA-55-53	2.16E+02	1.284E-03	7.70E-03	7.43E-03	7.36E-03	7.24E-03	6.88E-03	6.13E-03	5.36E-03	4.94E-03	4.48E-03	4.09E-03
LA-TA-55-56	9.47E+02	5.622E-03	3.26E-03	2.75E-03	2.67E-03	2.53E-03	2.28E-03	2.03E-03	1.79E-03	1.65E-03	1.49E-03	1.36E-03
LA-TA-55-60	2.11E+02	1.254E-03	3.73E-06	3.11E-06	3.00E-06	2.82E-06	2.44E-06	1.97E-06	1.62E-06	1.48E-06	1.33E-06	1.20E-06
LA-TA-55-61	2.27E+02	1.344E-03	8.17E-06	5.84E-06	5.47E-06	4.91E-06	3.96E-06	3.32E-06	2.89E-06	2.64E-06	2.37E-06	2.15E-06
LA-TA-55-62	7.36E+01	4.368E-04	2.58E-06	2.46E-06	2.43E-06	2.37E-06	2.21E-06	1.91E-06	1.62E-06	1.47E-06	1.30E-06	1.17E-06

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
LA-TA-55-63	5.66E+00	3.360E-05	7.19E-05	7.08E-05	7.05E-05	6.98E-05	6.80E-05	6.40E-05	5.78E-05	5.33E-05	4.84E-05	4.41E-05
LL-M001	3.40E+01	2.018E-04	3.26E-02	2.71E-02	2.60E-02	2.42E-02	2.01E-02	1.42E-02	1.05E-02	9.40E-03	8.38E-03	7.52E-03
LL-T001	3.83E+02	2.273E-03	1.36E-02	1.33E-02	1.31E-02	1.27E-02	1.15E-02	8.96E-03	7.05E-03	6.36E-03	5.67E-03	5.09E-03
LL-T002	2.08E+03	1.235E-02	2.53E-02	2.39E-02	2.35E-02	2.26E-02	2.03E-02	1.57E-02	1.23E-02	1.11E-02	9.95E-03	8.96E-03
LL-T003	1.06E+03	6.303E-03	1.71E-03	1.53E-03	1.48E-03	1.40E-03	1.20E-03	8.46E-04	6.07E-04	5.35E-04	4.67E-04	4.11E-04
LL-T004	3.24E+01	1.922E-04	3.24E-02	3.04E-02	2.97E-02	2.84E-02	2.47E-02	1.76E-02	1.26E-02	1.11E-02	9.70E-03	8.53E-03
LL-T005	1.13E+03	6.691E-03	4.57E-03	4.08E-03	3.95E-03	3.72E-03	3.13E-03	2.07E-03	1.39E-03	1.22E-03	1.06E-03	9.31E-04
LL-W018	2.11E+00	1.253E-05	2.17E-04	2.16E-04	2.12E-04	2.04E-04	1.81E-04	1.31E-04	9.27E-05	7.86E-05	6.53E-05	5.47E-05
LL-W019	1.82E+01	1.080E-04	1.27E-02	1.21E-02	1.19E-02	1.14E-02	9.96E-03	6.99E-03	4.93E-03	4.34E-03	3.77E-03	3.32E-03
LL-W034	2.10E+01	1.245E-04	4.18E-03	3.72E-03	3.60E-03	3.39E-03	2.84E-03	1.88E-03	1.26E-03	1.10E-03	9.59E-04	8.42E-04
MC-W001	2.50E+00	1.484E-05	3.44E-04	3.09E-04	3.01E-04	2.85E-04	2.39E-04	1.45E-04	9.16E-05	8.46E-05	7.87E-05	7.32E-05
MU-W002	1.46E+00	8.667E-06	5.84E-03	5.00E-03	4.80E-03	4.45E-03	3.39E-03	1.29E-03	1.80E-04	1.28E-04	1.17E-04	1.09E-04
NT-JAS-01	9.56E+02	5.676E-03	1.71E-03	1.53E-03	1.49E-03	1.40E-03	1.20E-03	8.47E-04	6.08E-04	5.36E-04	4.68E-04	4.11E-04
NT-W001	6.32E+02	3.753E-03	2.09E-02	2.02E-02	2.01E-02	1.99E-02	1.93E-02	1.82E-02	1.68E-02	1.59E-02	1.47E-02	1.37E-02
NT-W021	5.67E+00	3.366E-05	3.23E-02	3.17E-02	3.15E-02	3.11E-02	3.01E-02	2.78E-02	2.48E-02	2.29E-02	2.08E-02	1.90E-02
OR-W201	1.21E+02	7.183E-04	4.28E-01	3.74E-01	3.60E-01	3.36E-01	2.78E-01	1.82E-01	1.21E-01	1.06E-01	9.15E-02	8.00E-02
OR-W202	5.86E+02	3.480E-03	5.86E-02	3.35E-02	2.96E-02	2.38E-02	1.41E-02	8.48E-03	6.30E-03	5.53E-03	4.78E-03	4.17E-03
OR-W203	2.00E+02	1.189E-03	9.60E-05	8.18E-05	7.88E-05	7.36E-05	6.13E-05	4.15E-05	2.68E-05	2.15E-05	1.66E-05	1.28E-05
OR-W204	3.86E+01	2.290E-04	2.35E-04	1.67E-04	1.56E-04	1.40E-04	1.09E-04	8.04E-05	6.29E-05	5.61E-05	4.93E-05	4.36E-05
PA-A015	1.76E+01	1.046E-04	9.74E-05	9.71E-05	9.71E-05	9.69E-05	9.64E-05	9.46E-05	8.93E-05	8.43E-05	7.85E-05	7.30E-05
RF-MT0001	8.15E+00	4.838E-05	1.05E+00	9.10E-01	8.78E-01	8.19E-01	6.46E-01	3.01E-01	1.13E-01	9.72E-02	8.81E-02	8.03E-02
RF-MT0002	6.30E-01	3.740E-06	1.04E+00	9.05E-01	8.74E-01	8.15E-01	6.43E-01	2.99E-01	1.12E-01	9.69E-02	8.77E-02	8.00E-02
RF-MT0003	1.67E+00	9.913E-06	1.19E-02	1.17E-02	1.16E-02	1.14E-02	1.10E-02	1.01E-02	9.03E-03	8.33E-03	7.56E-03	6.90E-03
RF-MT0007	8.30E-01	4.927E-06	1.05E-02	9.37E-03	9.10E-03	8.59E-03	7.09E-03	4.07E-03	2.33E-03	2.09E-03	1.90E-03	1.73E-03
RF-MT0089	4.20E-01	2.493E-06	4.72E-04	4.63E-04	4.59E-04	4.53E-04	4.37E-04	4.02E-04	3.59E-04	3.31E-04	3.01E-04	2.74E-04
RF-MT0090	2.50E+00	1.484E-05	2.03E-01	1.98E-01	1.97E-01	1.94E-01	1.88E-01	1.73E-01	1.55E-01	1.43E-01	1.30E-01	1.18E-01
RF-MT0091	1.49E+02	8.835E-04	2.27E-01	2.21E-01	2.20E-01	2.17E-01	2.10E-01	1.94E-01	1.74E-01	1.60E-01	1.46E-01	1.33E-01

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-MT0092	2.15E+01	1.274E-04	2.26E-01	2.20E-01	2.19E-01	2.16E-01	2.09E-01	1.93E-01	1.73E-01	1.60E-01	1.45E-01	1.32E-01
RF-MT0093	2.34E+01	1.386E-04	2.28E-01	2.22E-01	2.20E-01	2.18E-01	2.10E-01	1.93E-01	1.72E-01	1.59E-01	1.44E-01	1.31E-01
RF-MT0097	1.46E+00	8.667E-06	1.85E-01	1.80E-01	1.79E-01	1.77E-01	1.71E-01	1.57E-01	1.41E-01	1.30E-01	1.19E-01	1.08E-01
RF-MT0099	6.30E-01	3.740E-06	4.71E-04	4.62E-04	4.59E-04	4.53E-04	4.36E-04	4.02E-04	3.59E-04	3.31E-04	3.00E-04	2.74E-04
RF-MT0290	1.90E+01	1.126E-04	3.88E-02	3.80E-02	3.77E-02	3.72E-02	3.59E-02	3.30E-02	2.95E-02	2.72E-02	2.47E-02	2.25E-02
RF-MT-0292	2.40E+01	1.423E-04	3.88E-02	3.81E-02	3.78E-02	3.73E-02	3.59E-02	3.31E-02	2.95E-02	2.72E-02	2.47E-02	2.26E-02
RF-MT-0299	3.11E+01	1.844E-04	1.13E+00	1.06E+00	1.05E+00	1.01E+00	9.18E-01	7.27E-01	5.87E-01	5.39E-01	4.89E-01	4.46E-01
RF-MT0302	4.20E-01	2.493E-06	2.65E-03	2.57E-03	2.55E-03	2.51E-03	2.38E-03	2.13E-03	1.87E-03	1.72E-03	1.56E-03	1.42E-03
RF-MT0320	7.09E+00	4.209E-05	1.60E-01	1.54E-01	1.53E-01	1.50E-01	1.41E-01	1.24E-01	1.07E-01	9.89E-02	8.99E-02	8.20E-02
RF-MT0321	4.16E+01	2.469E-04	1.03E-02	9.72E-03	9.58E-03	9.32E-03	8.59E-03	7.09E-03	5.90E-03	5.42E-03	4.92E-03	4.49E-03
RF-MT-0328	3.24E+00	1.923E-05	1.25E-02	1.21E-02	1.19E-02	1.17E-02	1.10E-02	9.54E-03	8.23E-03	7.57E-03	6.88E-03	6.28E-03
RF-MT0330	4.88E+00	2.897E-05	1.49E-01	1.45E-01	1.44E-01	1.43E-01	1.37E-01	1.26E-01	1.12E-01	1.03E-01	9.31E-02	8.48E-02
RF-MT-0331	2.46E+01	1.460E-04	1.35E-01	1.31E-01	1.30E-01	1.28E-01	1.22E-01	1.09E-01	9.59E-02	8.84E-02	8.03E-02	7.33E-02
RF-MT0332	1.46E+00	8.667E-06	4.76E-04	4.66E-04	4.63E-04	4.57E-04	4.40E-04	4.05E-04	3.62E-04	3.34E-04	3.03E-04	2.77E-04
RF-MT-0335	8.30E-01	4.927E-06	4.63E-02	4.50E-02	4.45E-02	4.38E-02	4.17E-02	3.74E-02	3.29E-02	3.03E-02	2.75E-02	2.51E-02
RF-MT0336	1.43E+01	8.483E-05	1.91E-01	1.85E-01	1.83E-01	1.80E-01	1.72E-01	1.54E-01	1.35E-01	1.25E-01	1.13E-01	1.03E-01
RF-MT0337	1.40E+01	8.293E-05	1.17E-01	1.14E-01	1.13E-01	1.11E-01	1.06E-01	9.56E-02	8.43E-02	7.77E-02	7.06E-02	6.44E-02
RF-MT0339	2.60E+02	1.544E-03	1.44E-02	1.40E-02	1.38E-02	1.36E-02	1.29E-02	1.14E-02	9.94E-03	9.16E-03	8.32E-03	7.59E-03
RF-MT-0342	4.20E-01	2.493E-06	7.61E-02	7.42E-02	7.36E-02	7.26E-02	6.98E-02	6.38E-02	5.68E-02	5.24E-02	4.76E-02	4.34E-02
RF-MT0371	2.04E+01	1.213E-04	3.39E-01	3.28E-01	3.24E-01	3.18E-01	3.00E-01	2.64E-01	2.29E-01	2.11E-01	1.92E-01	1.75E-01
RF-MT-0372	1.46E+00	8.667E-06	3.03E-02	2.96E-02	2.93E-02	2.89E-02	2.77E-02	2.52E-02	2.23E-02	2.06E-02	1.87E-02	1.71E-02
RF-MT0373	3.96E+00	2.351E-05	2.02E-01	1.98E-01	1.96E-01	1.94E-01	1.87E-01	1.73E-01	1.54E-01	1.42E-01	1.29E-01	1.18E-01
RF-MT0374	6.30E-01	3.740E-06	2.73E-02	2.65E-02	2.63E-02	2.58E-02	2.46E-02	2.19E-02	1.92E-02	1.77E-02	1.61E-02	1.47E-02
RF-MT0376	2.10E-01	1.247E-06	7.85E-02	7.65E-02	7.59E-02	7.48E-02	7.17E-02	6.51E-02	5.76E-02	5.31E-02	4.82E-02	4.40E-02
RF-MT0377	7.44E+01	4.418E-04	1.08E-01	1.05E-01	1.04E-01	1.02E-01	9.69E-02	8.65E-02	7.58E-02	6.98E-02	6.34E-02	5.79E-02
RF-MT0378	6.30E-01	3.740E-06	1.69E-01	1.65E-01	1.64E-01	1.61E-01	1.54E-01	1.40E-01	1.24E-01	1.14E-01	1.03E-01	9.43E-02
RF-MT0419	4.79E+00	2.843E-05	2.33E-02	2.24E-02	2.22E-02	2.17E-02	2.04E-02	1.77E-02	1.52E-02	1.40E-02	1.27E-02	1.16E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-MT0420	8.30E-01	4.927E-06	2.34E-02	2.25E-02	2.22E-02	2.17E-02	2.04E-02	1.77E-02	1.52E-02	1.40E-02	1.27E-02	1.16E-02
RF-MT0423	1.04E+00	6.174E-06	2.40E-01	2.32E-01	2.31E-01	2.27E-01	2.18E-01	1.97E-01	1.74E-01	1.61E-01	1.46E-01	1.33E-01
RF-MT0425	2.10E-01	1.247E-06	2.31E-02	2.22E-02	2.20E-02	2.15E-02	2.02E-02	1.75E-02	1.50E-02	1.38E-02	1.26E-02	1.15E-02
RF-MT-0438	6.30E-01	3.740E-06	1.19E-01	1.16E-01	1.15E-01	1.14E-01	1.09E-01	9.98E-02	8.87E-02	8.18E-02	7.43E-02	6.78E-02
RF-MT0440	2.29E+00	1.359E-05	1.19E-02	1.17E-02	1.16E-02	1.14E-02	1.10E-02	1.00E-02	8.88E-03	8.18E-03	7.43E-03	6.78E-03
RF-MT0442	8.30E-01	4.927E-06	1.15E-02	1.12E-02	1.11E-02	1.09E-02	1.04E-02	9.46E-03	8.37E-03	7.72E-03	7.01E-03	6.40E-03
RF-MT0443	1.94E+01	1.151E-04	7.36E-03	7.20E-03	7.15E-03	7.05E-03	6.79E-03	6.24E-03	5.57E-03	5.13E-03	4.66E-03	4.25E-03
RF-MT0444	4.51E+01	2.675E-04	1.65E-02	1.60E-02	1.59E-02	1.56E-02	1.48E-02	1.32E-02	1.15E-02	1.06E-02	9.66E-03	8.81E-03
RF-MT0480	1.19E+02	7.076E-04	1.76E-02	1.70E-02	1.68E-02	1.65E-02	1.57E-02	1.40E-02	1.23E-02	1.13E-02	1.03E-02	9.36E-03
RF-MT0488	5.25E+02	3.114E-03	6.00E-03	5.81E-03	5.76E-03	5.65E-03	5.35E-03	4.74E-03	4.13E-03	3.81E-03	3.46E-03	3.16E-03
RF-MT0490	1.89E+00	1.122E-05	9.36E-03	9.12E-03	9.04E-03	8.90E-03	8.50E-03	7.68E-03	6.78E-03	6.25E-03	5.68E-03	5.18E-03
RF-MT-0491	6.30E-01	3.740E-06	1.44E-03	1.38E-03	1.36E-03	1.33E-03	1.25E-03	1.08E-03	9.24E-04	8.50E-04	7.73E-04	7.05E-04
RF-MT0523A	1.08E+01	6.435E-05	6.59E-02	6.33E-02	6.26E-02	6.12E-02	5.74E-02	4.95E-02	4.24E-02	3.90E-02	3.55E-02	3.23E-02
RF-MT0523B	1.08E+01	6.435E-05	6.59E-02	6.33E-02	6.26E-02	6.12E-02	5.74E-02	4.95E-02	4.24E-02	3.90E-02	3.55E-02	3.23E-02
RF-MT0523C	1.08E+01	6.435E-05	6.59E-02	6.33E-02	6.26E-02	6.12E-02	5.74E-02	4.95E-02	4.24E-02	3.90E-02	3.55E-02	3.23E-02
RF-MT0523D	1.08E+01	6.435E-05	6.59E-02	6.33E-02	6.26E-02	6.12E-02	5.74E-02	4.95E-02	4.24E-02	3.90E-02	3.55E-02	3.23E-02
RF-MT0523E	1.08E+01	6.435E-05	6.59E-02	6.33E-02	6.26E-02	6.12E-02	5.74E-02	4.95E-02	4.24E-02	3.90E-02	3.55E-02	3.23E-02
RF-MT0531	2.10E-01	1.247E-06	4.71E-04	4.62E-04	4.58E-04	4.52E-04	4.36E-04	4.01E-04	3.58E-04	3.30E-04	3.00E-04	2.74E-04
RF-MT0532E	1.56E+01	9.278E-05	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.38E-02	7.73E-02	6.42E-02	5.90E-02	5.36E-02	4.89E-02
RF-MT0532F	1.56E+01	9.278E-05	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.38E-02	7.73E-02	6.42E-02	5.90E-02	5.36E-02	4.89E-02
RF-MT0541	4.38E+00	2.600E-05	8.77E-03	8.02E-03	7.84E-03	7.50E-03	6.52E-03	4.54E-03	3.28E-03	2.99E-03	2.72E-03	2.48E-03
RF-MT0545	2.10E-01	1.247E-06	4.29E-03	4.21E-03	4.18E-03	4.12E-03	3.97E-03	3.66E-03	3.27E-03	3.01E-03	2.74E-03	2.50E-03
RF-MT0800	6.25E+01	3.709E-04	7.85E-02	6.78E-02	6.53E-02	6.07E-02	4.73E-02	2.04E-02	6.00E-03	5.02E-03	4.54E-03	4.14E-03
RF-MT0801	1.03E+02	6.082E-04	8.77E-03	8.02E-03	7.84E-03	7.50E-03	6.52E-03	4.54E-03	3.28E-03	2.99E-03	2.72E-03	2.48E-03
RF-MT0803	2.29E+00	1.359E-05	8.79E-03	8.04E-03	7.85E-03	7.51E-03	6.53E-03	4.54E-03	3.28E-03	2.99E-03	2.72E-03	2.48E-03
RF-MT0806	2.10E-01	1.247E-06	2.01E-01	1.96E-01	1.95E-01	1.93E-01	1.86E-01	1.72E-01	1.54E-01	1.42E-01	1.29E-01	1.17E-01
RF-MT0807	8.42E+01	4.997E-04	2.69E-03	2.56E-03	2.53E-03	2.47E-03	2.29E-03	1.94E-03	1.64E-03	1.50E-03	1.37E-03	1.25E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-MT0816	4.20E-01	2.493E-06	7.03E-02	6.77E-02	6.69E-02	6.55E-02	6.16E-02	5.35E-02	4.62E-02	4.25E-02	3.86E-02	3.52E-02
RF-MT-0823	2.10E-01	1.247E-06	6.55E-02	6.29E-02	6.22E-02	6.08E-02	5.70E-02	4.91E-02	4.21E-02	3.88E-02	3.52E-02	3.21E-02
RF-MT0827	1.05E+01	6.257E-05	7.08E-02	6.81E-02	6.74E-02	6.60E-02	6.20E-02	5.40E-02	4.65E-02	4.28E-02	3.89E-02	3.55E-02
RF-MT0831	5.99E+01	3.557E-04	3.12E-02	3.03E-02	3.00E-02	2.95E-02	2.81E-02	2.52E-02	2.21E-02	2.04E-02	1.85E-02	1.69E-02
RF-MT0832	1.94E+02	1.153E-03	4.13E-02	3.96E-02	3.92E-02	3.83E-02	3.59E-02	3.10E-02	2.66E-02	2.45E-02	2.22E-02	2.03E-02
RF-MT0833	1.21E+02	7.173E-04	1.95E-02	1.87E-02	1.84E-02	1.80E-02	1.69E-02	1.45E-02	1.24E-02	1.14E-02	1.03E-02	9.42E-03
RF-MT0855	1.67E+00	9.913E-06	5.09E-04	4.99E-04	4.95E-04	4.89E-04	4.71E-04	4.34E-04	3.87E-04	3.57E-04	3.24E-04	2.96E-04
RF-MT0857	2.10E-01	1.247E-06	2.01E-01	1.96E-01	1.95E-01	1.93E-01	1.86E-01	1.71E-01	1.53E-01	1.41E-01	1.28E-01	1.17E-01
RF-MT0H61	7.71E+00	4.577E-05	2.03E-01	1.98E-01	1.97E-01	1.94E-01	1.88E-01	1.73E-01	1.55E-01	1.43E-01	1.30E-01	1.18E-01
RF-MT2116	2.08E+00	1.235E-05	4.12E-02	3.96E-02	3.91E-02	3.83E-02	3.59E-02	3.09E-02	2.65E-02	2.44E-02	2.22E-02	2.02E-02
RF-MT3010	5.58E+01	3.315E-04	1.38E-02	1.34E-02	1.33E-02	1.30E-02	1.24E-02	1.11E-02	9.80E-03	9.03E-03	8.20E-03	7.48E-03
RF-MT3011	5.03E+02	2.987E-03	9.78E-03	9.47E-03	9.37E-03	9.20E-03	8.71E-03	7.71E-03	6.72E-03	6.18E-03	5.62E-03	5.12E-03
RF-MT420P	1.61E+02	9.554E-04	2.32E-01	2.26E-01	2.24E-01	2.21E-01	2.13E-01	1.94E-01	1.72E-01	1.59E-01	1.44E-01	1.32E-01
RF-MT532A	3.86E+01	2.290E-04	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.38E-02	7.73E-02	6.43E-02	5.91E-02	5.37E-02	4.90E-02
RF-MT532B	1.73E+02	1.028E-03	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.38E-02	7.73E-02	6.43E-02	5.91E-02	5.37E-02	4.90E-02
RF-MT532C	3.47E+02	2.061E-03	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.37E-02	7.73E-02	6.43E-02	5.90E-02	5.36E-02	4.89E-02
RF-MT532D	2.19E+00	1.300E-05	1.12E-01	1.07E-01	1.05E-01	1.02E-01	9.40E-02	7.75E-02	6.45E-02	5.92E-02	5.38E-02	4.91E-02
RF-TT0069	2.10E-01	1.247E-06	1.12E-02	1.09E-02	1.07E-02	1.06E-02	1.00E-02	8.89E-03	7.77E-03	7.16E-03	6.50E-03	5.93E-03
RF-TT0200	6.30E-01	3.740E-06	1.58E-01	1.53E-01	1.51E-01	1.48E-01	1.40E-01	1.23E-01	1.06E-01	9.79E-02	8.90E-02	8.11E-02
RF-TT0299	2.10E-01	1.247E-06	1.12E+00	1.06E+00	1.04E+00	1.01E+00	9.11E-01	7.23E-01	5.84E-01	5.35E-01	4.86E-01	4.44E-01
RF-TT0300	4.31E+01	2.557E-04	1.11E-01	1.08E-01	1.08E-01	1.06E-01	1.01E-01	9.19E-02	8.13E-02	7.50E-02	6.81E-02	6.21E-02
RF-TT0301	5.84E+00	3.467E-05	1.12E-01	1.09E-01	1.08E-01	1.06E-01	1.02E-01	9.22E-02	8.16E-02	7.52E-02	6.84E-02	6.23E-02
RF-TT0302	9.91E+00	5.883E-05	2.67E-03	2.60E-03	2.57E-03	2.53E-03	2.40E-03	2.15E-03	1.88E-03	1.73E-03	1.57E-03	1.44E-03
RF-TT0303	1.25E+00	7.420E-06	1.17E-01	1.13E-01	1.12E-01	1.10E-01	1.04E-01	9.19E-02	8.01E-02	7.38E-02	6.71E-02	6.12E-02
RF-TT0310	3.13E+00	1.858E-05	2.00E-01	1.95E-01	1.93E-01	1.90E-01	1.81E-01	1.64E-01	1.45E-01	1.33E-01	1.21E-01	1.10E-01
RF-TT0312	5.80E+01	3.440E-04	2.38E-01	2.31E-01	2.29E-01	2.25E-01	2.15E-01	1.93E-01	1.70E-01	1.56E-01	1.42E-01	1.30E-01
RF-TT0317	2.10E-01	1.247E-06	5.78E-02	5.67E-02	5.63E-02	5.55E-02	5.35E-02	4.92E-02	4.39E-02	4.05E-02	3.68E-02	3.35E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-TT0320	2.80E+01	1.664E-04	1.60E-01	1.54E-01	1.53E-01	1.50E-01	1.41E-01	1.24E-01	1.07E-01	9.89E-02	8.99E-02	8.20E-02
RF-TT0330	1.71E+01	1.014E-04	1.49E-01	1.46E-01	1.45E-01	1.43E-01	1.37E-01	1.26E-01	1.12E-01	1.03E-01	9.33E-02	8.50E-02
RF-TT-0331	7.15E+01	4.244E-04	1.35E-01	1.31E-01	1.30E-01	1.28E-01	1.22E-01	1.09E-01	9.58E-02	8.83E-02	8.02E-02	7.32E-02
RF-TT-0334	4.70E+00	2.790E-05	1.21E+00	1.18E+00	1.17E+00	1.16E+00	1.11E+00	1.02E+00	9.07E-01	8.37E-01	7.60E-01	6.93E-01
RF-TT0335	1.11E+02	6.600E-04	4.61E-02	4.47E-02	4.43E-02	4.36E-02	4.15E-02	3.72E-02	3.27E-02	3.01E-02	2.74E-02	2.49E-02
RF-TT0336	2.38E+01	1.412E-04	1.91E-01	1.85E-01	1.83E-01	1.80E-01	1.72E-01	1.54E-01	1.35E-01	1.25E-01	1.13E-01	1.03E-01
RF-TT0337	4.91E+01	2.915E-04	1.17E-01	1.14E-01	1.13E-01	1.11E-01	1.06E-01	9.56E-02	8.43E-02	7.77E-02	7.06E-02	6.44E-02
RF-TT0338	1.53E+02	9.092E-04	1.49E-01	1.44E-01	1.43E-01	1.40E-01	1.34E-01	1.20E-01	1.05E-01	9.71E-02	8.83E-02	8.05E-02
RF-TT0340	7.30E+00	4.333E-05	3.87E-02	3.80E-02	3.77E-02	3.72E-02	3.59E-02	3.30E-02	2.95E-02	2.72E-02	2.47E-02	2.25E-02
RF-TT0342	2.21E+01	1.312E-04	7.66E-02	7.47E-02	7.41E-02	7.31E-02	7.03E-02	6.43E-02	5.72E-02	5.27E-02	4.79E-02	4.37E-02
RF-TT0360	6.30E-01	3.740E-06	1.33E-01	1.29E-01	1.28E-01	1.25E-01	1.18E-01	1.04E-01	9.05E-02	8.33E-02	7.57E-02	6.90E-02
RF-TT0368	1.25E+01	7.426E-05	1.35E-01	1.30E-01	1.29E-01	1.26E-01	1.19E-01	1.05E-01	9.14E-02	8.42E-02	7.65E-02	6.97E-02
RF-TT0370	1.71E+01	1.014E-04	2.14E-01	2.07E-01	2.05E-01	2.01E-01	1.91E-01	1.70E-01	1.49E-01	1.37E-01	1.25E-01	1.14E-01
RF-TT0371	2.10E-01	1.247E-06	3.36E-01	3.25E-01	3.21E-01	3.15E-01	2.98E-01	2.62E-01	2.27E-01	2.09E-01	1.90E-01	1.73E-01
RF-TT0372	4.20E-01	2.493E-06	3.01E-02	2.93E-02	2.91E-02	2.87E-02	2.75E-02	2.50E-02	2.22E-02	2.04E-02	1.86E-02	1.69E-02
RF-TT0374	1.14E+01	6.749E-05	2.75E-02	2.67E-02	2.65E-02	2.60E-02	2.47E-02	2.21E-02	1.94E-02	1.78E-02	1.62E-02	1.48E-02
RF-TT0375A	3.05E+00	1.811E-05	1.56E-03	1.53E-03	1.52E-03	1.50E-03	1.44E-03	1.33E-03	1.19E-03	1.09E-03	9.93E-04	9.05E-04
RF-TT0375B	3.05E+00	1.811E-05	1.56E-03	1.53E-03	1.52E-03	1.50E-03	1.44E-03	1.33E-03	1.19E-03	1.09E-03	9.93E-04	9.05E-04
RF-TT0376	1.15E+01	6.803E-05	7.92E-02	7.72E-02	7.66E-02	7.54E-02	7.23E-02	6.56E-02	5.81E-02	5.35E-02	4.86E-02	4.43E-02
RF-TT0377	3.86E+00	2.291E-05	1.08E-01	1.05E-01	1.04E-01	1.02E-01	9.68E-02	8.64E-02	7.57E-02	6.98E-02	6.34E-02	5.78E-02
RF-TT0391	4.20E-01	2.493E-06	2.43E-01	2.37E-01	2.35E-01	2.31E-01	2.21E-01	1.99E-01	1.76E-01	1.62E-01	1.47E-01	1.34E-01
RF-TT0392	2.10E-01	1.247E-06	2.41E-01	2.35E-01	2.34E-01	2.31E-01	2.23E-01	2.05E-01	1.84E-01	1.69E-01	1.54E-01	1.40E-01
RF-TT0393	1.11E+01	6.559E-05	2.34E-01	2.27E-01	2.25E-01	2.21E-01	2.09E-01	1.86E-01	1.63E-01	1.50E-01	1.36E-01	1.24E-01
RF-TT0398	4.20E-01	2.493E-06	2.24E-01	2.19E-01	2.17E-01	2.15E-01	2.07E-01	1.92E-01	1.71E-01	1.58E-01	1.44E-01	1.31E-01
RF-TT0409	2.10E-01	1.247E-06	2.49E-01	2.41E-01	2.39E-01	2.35E-01	2.24E-01	2.01E-01	1.77E-01	1.63E-01	1.48E-01	1.35E-01
RF-TT0412	2.10E-01	1.247E-06	2.49E-01	2.41E-01	2.39E-01	2.35E-01	2.24E-01	2.01E-01	1.77E-01	1.63E-01	1.48E-01	1.35E-01
RF-TT0414	6.46E+00	3.835E-05	2.51E-01	2.43E-01	2.40E-01	2.37E-01	2.26E-01	2.03E-01	1.78E-01	1.64E-01	1.49E-01	1.36E-01

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-TT0430	2.10E-01	1.247E-06	3.20E-03	3.14E-03	3.12E-03	3.08E-03	2.96E-03	2.73E-03	2.44E-03	2.25E-03	2.04E-03	1.86E-03
RF-TT0431	2.28E+01	1.355E-04	7.26E-03	7.12E-03	7.06E-03	6.97E-03	6.71E-03	6.18E-03	5.51E-03	5.08E-03	4.62E-03	4.21E-03
RF-TT0438	7.21E+01	4.279E-04	1.20E-01	1.17E-01	1.16E-01	1.14E-01	1.10E-01	1.00E-01	8.90E-02	8.21E-02	7.46E-02	6.80E-02
RF-TT0440	7.17E+01	4.259E-04	1.19E-02	1.16E-02	1.15E-02	1.14E-02	1.09E-02	9.98E-03	8.87E-03	8.17E-03	7.42E-03	6.76E-03
RF-TT0441	1.45E+02	8.605E-04	2.16E-02	2.10E-02	2.08E-02	2.04E-02	1.94E-02	1.73E-02	1.51E-02	1.39E-02	1.27E-02	1.15E-02
RF-TT0442	4.86E+01	2.886E-04	1.14E-02	1.11E-02	1.10E-02	1.09E-02	1.04E-02	9.42E-03	8.34E-03	7.69E-03	6.98E-03	6.37E-03
RF-TT0443	1.97E+00	1.169E-05	7.36E-03	7.20E-03	7.15E-03	7.05E-03	6.79E-03	6.24E-03	5.57E-03	5.13E-03	4.66E-03	4.25E-03
RF-TT0479	1.04E+00	6.174E-06	1.40E-01	1.38E-01	1.37E-01	1.35E-01	1.30E-01	1.20E-01	1.07E-01	9.84E-02	8.94E-02	8.16E-02
RF-TT0480	3.70E+02	2.196E-03	1.76E-02	1.70E-02	1.69E-02	1.66E-02	1.57E-02	1.40E-02	1.23E-02	1.13E-02	1.03E-02	9.38E-03
RF-TT0481	2.10E-01	1.247E-06	1.74E-02	1.69E-02	1.67E-02	1.64E-02	1.56E-02	1.39E-02	1.22E-02	1.12E-02	1.02E-02	9.29E-03
RF-TT0483	8.30E-01	4.927E-06	2.18E-02	2.13E-02	2.12E-02	2.09E-02	2.01E-02	1.85E-02	1.66E-02	1.53E-02	1.39E-02	1.27E-02
RF-TT0484	9.80E+00	5.817E-05	7.91E-03	7.72E-03	7.66E-03	7.54E-03	7.22E-03	6.55E-03	5.80E-03	5.35E-03	4.86E-03	4.43E-03
RF-TT0485	5.42E+00	3.217E-05	9.31E-04	9.03E-04	8.94E-04	8.78E-04	8.33E-04	7.41E-04	6.48E-04	5.97E-04	5.42E-04	4.94E-04
RF-TT0486	1.44E+01	8.536E-05	2.08E-03	2.02E-03	2.00E-03	1.96E-03	1.86E-03	1.66E-03	1.45E-03	1.33E-03	1.21E-03	1.11E-03
RF-TT0487	2.82E+00	1.674E-05	4.12E-02	3.96E-02	3.91E-02	3.83E-02	3.59E-02	3.10E-02	2.65E-02	2.44E-02	2.22E-02	2.02E-02
RF-TT0489	9.38E+00	5.568E-05	4.80E-03	4.66E-03	4.62E-03	4.54E-03	4.32E-03	3.86E-03	3.39E-03	3.12E-03	2.83E-03	2.58E-03
RF-TT0490	3.02E+02	1.790E-03	9.37E-03	9.12E-03	9.05E-03	8.90E-03	8.51E-03	7.69E-03	6.79E-03	6.26E-03	5.68E-03	5.18E-03
RF-TT0491	2.96E+01	1.754E-04	1.44E-03	1.39E-03	1.37E-03	1.34E-03	1.26E-03	1.08E-03	9.29E-04	8.55E-04	7.77E-04	7.08E-04
RF-TT0492	1.89E+00	1.122E-05	1.13E-02	1.10E-02	1.09E-02	1.07E-02	1.02E-02	9.19E-03	8.10E-03	7.46E-03	6.78E-03	6.18E-03
RF-TT0523A	1.46E+00	8.667E-06	6.58E-02	6.32E-02	6.25E-02	6.11E-02	5.72E-02	4.94E-02	4.23E-02	3.89E-02	3.54E-02	3.23E-02
RF-TT0523B	1.46E+00	8.667E-06	6.58E-02	6.32E-02	6.25E-02	6.11E-02	5.72E-02	4.94E-02	4.23E-02	3.89E-02	3.54E-02	3.23E-02
RF-TT0523C	1.46E+00	8.667E-06	6.58E-02	6.32E-02	6.25E-02	6.11E-02	5.72E-02	4.94E-02	4.23E-02	3.89E-02	3.54E-02	3.23E-02
RF-TT0523D	1.46E+00	8.667E-06	6.58E-02	6.32E-02	6.25E-02	6.11E-02	5.72E-02	4.94E-02	4.23E-02	3.89E-02	3.54E-02	3.23E-02
RF-TT0523E	1.46E+00	8.667E-06	6.58E-02	6.32E-02	6.25E-02	6.11E-02	5.72E-02	4.94E-02	4.23E-02	3.89E-02	3.54E-02	3.23E-02
RF-TT0532A	1.66E+01	9.830E-05	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.39E-02	7.74E-02	6.43E-02	5.91E-02	5.37E-02	4.90E-02
RF-TT0532B	1.66E+01	9.830E-05	1.12E-01	1.06E-01	1.05E-01	1.02E-01	9.39E-02	7.74E-02	6.43E-02	5.91E-02	5.37E-02	4.90E-02
RF-TT0541	2.10E-01	1.247E-06	3.85E-02	3.78E-02	3.75E-02	3.70E-02	3.57E-02	3.29E-02	2.93E-02	2.71E-02	2.46E-02	2.24E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-TT0545	4.20E-01	2.493E-06	4.28E-03	4.20E-03	4.17E-03	4.11E-03	3.96E-03	3.65E-03	3.26E-03	3.00E-03	2.73E-03	2.49E-03
RF-TT0601	2.71E+00	1.609E-05	1.35E-01	1.30E-01	1.29E-01	1.26E-01	1.19E-01	1.05E-01	9.14E-02	8.42E-02	7.64E-02	6.97E-02
RF-TT0802	5.71E+01	3.387E-04	5.52E-01	5.28E-01	5.21E-01	5.09E-01	4.74E-01	4.03E-01	3.42E-01	3.15E-01	2.86E-01	2.61E-01
RF-TT0809	4.70E+00	2.790E-05	5.51E-01	5.27E-01	5.20E-01	5.08E-01	4.73E-01	4.03E-01	3.42E-01	3.15E-01	2.86E-01	2.61E-01
RF-TT0821	2.48E+02	1.470E-03	3.57E-02	3.46E-02	3.43E-02	3.38E-02	3.22E-02	2.89E-02	2.55E-02	2.35E-02	2.13E-02	1.94E-02
RF-TT0822	2.60E+02	1.540E-03	2.78E-02	2.67E-02	2.64E-02	2.59E-02	2.43E-02	2.11E-02	1.82E-02	1.68E-02	1.52E-02	1.39E-02
RF-TT0823	2.10E-01	1.247E-06	6.55E-02	6.29E-02	6.22E-02	6.08E-02	5.70E-02	4.91E-02	4.21E-02	3.88E-02	3.52E-02	3.21E-02
RF-TT0824	1.24E+03	7.339E-03	1.48E-02	1.43E-02	1.42E-02	1.40E-02	1.32E-02	1.18E-02	1.03E-02	9.48E-03	8.62E-03	7.86E-03
RF-TT0825	6.34E+02	3.760E-03	2.22E-02	2.15E-02	2.12E-02	2.08E-02	1.97E-02	1.74E-02	1.51E-02	1.39E-02	1.27E-02	1.15E-02
RF-TT0832	2.12E+02	1.257E-03	4.11E-02	3.95E-02	3.90E-02	3.82E-02	3.58E-02	3.09E-02	2.65E-02	2.44E-02	2.21E-02	2.02E-02
RF-TT0854	2.82E+00	1.674E-05	2.24E-03	2.20E-03	2.19E-03	2.16E-03	2.08E-03	1.91E-03	1.71E-03	1.57E-03	1.43E-03	1.30E-03
RF-TT0886	2.10E-01	1.247E-06	4.27E-03	4.19E-03	4.16E-03	4.10E-03	3.95E-03	3.64E-03	3.25E-03	3.00E-03	2.72E-03	2.48E-03
RF-TT2216	3.13E+00	1.858E-05	4.12E-02	3.96E-02	3.91E-02	3.83E-02	3.59E-02	3.10E-02	2.66E-02	2.44E-02	2.22E-02	2.03E-02
RF-TT3010	7.13E+02	4.235E-03	1.38E-02	1.34E-02	1.33E-02	1.30E-02	1.24E-02	1.12E-02	9.81E-03	9.04E-03	8.21E-03	7.49E-03
RF-TT3011	2.18E+03	1.293E-02	9.78E-03	9.47E-03	9.37E-03	9.19E-03	8.71E-03	7.70E-03	6.71E-03	6.18E-03	5.62E-03	5.12E-03
RF-TT301U	1.56E+01	9.278E-05	1.41E-01	1.37E-01	1.36E-01	1.34E-01	1.28E-01	1.15E-01	1.02E-01	9.38E-02	8.52E-02	7.77E-02
RF-TT310P	2.71E+00	1.609E-05	2.64E-01	2.57E-01	2.55E-01	2.51E-01	2.41E-01	2.20E-01	1.95E-01	1.80E-01	1.64E-01	1.50E-01
RF-TT338S	4.20E-01	2.493E-06	5.77E-02	5.66E-02	5.62E-02	5.54E-02	5.34E-02	4.91E-02	4.38E-02	4.04E-02	3.67E-02	3.35E-02
RF-TT390P	4.20E-01	2.493E-06	2.83E-01	2.76E-01	2.74E-01	2.70E-01	2.60E-01	2.37E-01	2.11E-01	1.95E-01	1.77E-01	1.62E-01
RF-TT391P	2.27E+01	1.349E-04	2.45E-01	2.38E-01	2.36E-01	2.33E-01	2.23E-01	2.01E-01	1.77E-01	1.63E-01	1.48E-01	1.35E-01
RF-TT392P	6.52E+01	3.873E-04	2.42E-01	2.37E-01	2.35E-01	2.32E-01	2.24E-01	2.07E-01	1.85E-01	1.70E-01	1.55E-01	1.41E-01
RF-TT393R	1.25E+01	7.426E-05	1.93E-01	1.88E-01	1.87E-01	1.85E-01	1.79E-01	1.65E-01	1.48E-01	1.36E-01	1.24E-01	1.13E-01
RF-TT394P	6.20E-01	3.680E-06	3.19E-01	3.09E-01	3.06E-01	3.02E-01	2.88E-01	2.58E-01	2.27E-01	2.10E-01	1.91E-01	1.74E-01
RF-TT395P	8.30E-01	4.927E-06	3.19E-01	3.09E-01	3.06E-01	3.01E-01	2.87E-01	2.58E-01	2.27E-01	2.10E-01	1.91E-01	1.74E-01
RF-TT396P	2.10E-01	1.247E-06	3.15E-01	3.05E-01	3.02E-01	2.98E-01	2.84E-01	2.55E-01	2.24E-01	2.07E-01	1.88E-01	1.72E-01
RF-TT398P	4.32E+01	2.561E-04	2.26E-01	2.20E-01	2.19E-01	2.16E-01	2.09E-01	1.93E-01	1.73E-01	1.60E-01	1.45E-01	1.32E-01
RF-TT398R	6.98E+01	4.145E-04	3.41E-01	3.18E-01	3.13E-01	3.03E-01	2.74E-01	2.16E-01	1.73E-01	1.59E-01	1.45E-01	1.32E-01

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RF-TT411R	7.71E+00	4.577E-05	2.51E-01	2.43E-01	2.40E-01	2.37E-01	2.26E-01	2.03E-01	1.78E-01	1.64E-01	1.49E-01	1.36E-01
RF-TT429R	2.08E+00	1.235E-05	5.41E-01	4.86E-01	4.73E-01	4.49E-01	3.80E-01	2.39E-01	1.55E-01	1.41E-01	1.28E-01	1.17E-01
RF-TT433X	6.30E-01	3.740E-06	5.44E-01	4.87E-01	4.73E-01	4.49E-01	3.77E-01	2.31E-01	1.46E-01	1.32E-01	1.20E-01	1.10E-01
RF-TT436R	7.09E+00	4.209E-05	4.41E-01	4.03E-01	3.95E-01	3.78E-01	3.30E-01	2.33E-01	1.71E-01	1.56E-01	1.42E-01	1.29E-01
RF-TT454X	4.20E-01	2.493E-06	4.37E-01	4.01E-01	3.92E-01	3.76E-01	3.28E-01	2.32E-01	1.70E-01	1.55E-01	1.41E-01	1.29E-01
RL-T101	5.68E+02	3.371E-03	8.44E-03	8.41E-03	8.36E-03	8.27E-03	8.02E-03	7.46E-03	6.71E-03	6.19E-03	5.63E-03	5.13E-03
RL-T102	2.00E+02	1.188E-03	3.06E-07	3.05E-07	3.03E-07	3.00E-07	2.91E-07	2.71E-07	2.44E-07	2.25E-07	2.04E-07	1.87E-07
RL-T103	9.96E+01	5.914E-04	2.39E-02	2.32E-02	2.30E-02	2.25E-02	2.14E-02	1.90E-02	1.67E-02	1.54E-02	1.40E-02	1.28E-02
RL-T104	4.99E+00	2.962E-05	1.75E-05	1.74E-05	1.73E-05	1.71E-05	1.66E-05	1.55E-05	1.39E-05	1.28E-05	1.16E-05	1.06E-05
RL-T105	8.04E+01	4.773E-04	4.12E-04	4.10E-04	4.08E-04	4.03E-04	3.91E-04	3.64E-04	3.27E-04	3.02E-04	2.74E-04	2.50E-04
RL-T106	8.11E+00	4.814E-05	3.99E-03	3.97E-03	3.95E-03	3.90E-03	3.78E-03	3.52E-03	3.17E-03	2.92E-03	2.66E-03	2.42E-03
RL-T107	6.16E+03	3.654E-02	6.39E-02	3.69E-02	3.28E-02	2.66E-02	1.69E-02	1.29E-02	1.16E-02	1.07E-02	9.69E-03	8.84E-03
RL-T108	1.93E+02	1.143E-03	5.33E-04	3.85E-04	3.62E-04	3.26E-04	2.68E-04	2.34E-04	2.10E-04	1.94E-04	1.76E-04	1.61E-04
RL-T109	1.97E+01	1.171E-04	3.44E-03	3.42E-03	3.40E-03	3.36E-03	3.26E-03	3.03E-03	2.72E-03	2.51E-03	2.28E-03	2.08E-03
RL-T110	4.94E+02	2.933E-03	1.59E-02	1.57E-02	1.56E-02	1.54E-02	1.49E-02	1.39E-02	1.25E-02	1.15E-02	1.04E-02	9.52E-03
RL-T112	1.38E+02	8.176E-04	9.67E-03	9.10E-03	8.96E-03	8.71E-03	8.08E-03	6.94E-03	5.95E-03	5.48E-03	4.98E-03	4.55E-03
RL-T113	4.28E+01	2.541E-04	8.16E-05	7.97E-05	7.91E-05	7.79E-05	7.50E-05	6.97E-05	6.27E-05	5.78E-05	5.26E-05	4.80E-05
RL-T114	1.96E+01	1.162E-04	2.62E-02	2.61E-02	2.59E-02	2.57E-02	2.49E-02	2.32E-02	2.08E-02	1.92E-02	1.75E-02	1.59E-02
RL-T115	1.03E+03	6.087E-03	7.38E-03	7.19E-03	7.12E-03	6.99E-03	6.64E-03	5.95E-03	5.23E-03	4.82E-03	4.38E-03	4.00E-03
RL-T116	1.10E+01	6.542E-05	7.62E-02	7.59E-02	7.54E-02	7.46E-02	7.23E-02	6.73E-02	6.05E-02	5.58E-02	5.08E-02	4.63E-02
RL-T118	2.62E+02	1.555E-03	4.11E-03	3.82E-03	3.75E-03	3.64E-03	3.37E-03	2.94E-03	2.55E-03	2.35E-03	2.13E-03	1.95E-03
RL-T120	1.34E+02	7.943E-04	2.11E-03	2.05E-03	2.03E-03	1.99E-03	1.88E-03	1.67E-03	1.47E-03	1.35E-03	1.23E-03	1.12E-03
RL-T122	2.93E+01	1.739E-04	1.22E-03	1.21E-03	1.21E-03	1.19E-03	1.16E-03	1.10E-03	1.01E-03	9.42E-04	8.73E-04	8.12E-04
RL-T123	6.20E-01	3.680E-06	1.41E-01	1.41E-01	1.40E-01	1.38E-01	1.34E-01	1.25E-01	1.12E-01	1.04E-01	9.41E-02	8.59E-02
RL-T125	1.52E+01	9.011E-05	2.60E-01	2.50E-01	2.44E-01	2.33E-01	2.04E-01	1.52E-01	1.15E-01	1.03E-01	9.18E-02	8.20E-02
RL-T127	2.84E+02	1.683E-03	2.36E-02	2.29E-02	2.26E-02	2.21E-02	2.07E-02	1.79E-02	1.53E-02	1.41E-02	1.28E-02	1.17E-02
RL-T128	4.20E-01	2.493E-06	6.46E-03	5.50E-03	5.29E-03	4.88E-03	3.68E-03	1.30E-03	5.28E-05	2.36E-06	2.49E-07	1.93E-07

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-T129	2.88E+01	1.707E-04	1.66E-02	8.96E-03	7.81E-03	6.08E-03	3.37E-03	2.32E-03	2.08E-03	1.92E-03	1.75E-03	1.59E-03
RL-T130	2.10E-01	1.247E-06	7.60E-04	7.57E-04	7.53E-04	7.45E-04	7.22E-04	6.73E-04	6.05E-04	5.58E-04	5.08E-04	4.63E-04
RL-T131	3.02E+01	1.790E-04	1.16E-03	1.12E-03	1.11E-03	1.09E-03	1.03E-03	9.14E-04	8.01E-04	7.38E-04	6.71E-04	6.13E-04
RL-T132	2.87E+01	1.704E-04	5.36E-01	5.34E-01	5.31E-01	5.25E-01	5.09E-01	4.74E-01	4.26E-01	3.93E-01	3.58E-01	3.26E-01
RL-T133	2.10E-01	1.247E-06	1.24E-03	1.22E-03	1.22E-03	1.20E-03	1.16E-03	1.07E-03	9.56E-04	8.82E-04	8.02E-04	7.31E-04
RL-T134	2.10E-01	1.247E-06	3.16E-03	3.14E-03	3.12E-03	3.09E-03	3.00E-03	2.79E-03	2.51E-03	2.31E-03	2.10E-03	1.92E-03
RL-T135	4.20E-01	2.493E-06	7.43E-03	7.39E-03	7.35E-03	7.27E-03	7.05E-03	6.57E-03	5.91E-03	5.46E-03	4.96E-03	4.53E-03
RL-T137	1.52E+02	9.001E-04	1.79E-01	1.73E-01	1.72E-01	1.68E-01	1.59E-01	1.41E-01	1.24E-01	1.14E-01	1.04E-01	9.47E-02
RL-T140	1.38E+02	8.198E-04	2.02E-01	1.95E-01	1.92E-01	1.88E-01	1.77E-01	1.55E-01	1.35E-01	1.24E-01	1.12E-01	1.02E-01
RL-T143	4.04E+02	2.396E-03	9.15E-04	9.11E-04	9.06E-04	8.96E-04	8.69E-04	8.09E-04	7.28E-04	6.71E-04	6.10E-04	5.57E-04
RL-T145	7.11E+02	4.222E-03	1.48E-03	1.47E-03	1.46E-03	1.45E-03	1.40E-03	1.31E-03	1.18E-03	1.09E-03	9.86E-04	9.00E-04
RL-W407	4.89E+02	2.901E-03	5.11E-03	5.03E-03	4.99E-03	4.93E-03	4.76E-03	4.39E-03	3.92E-03	3.62E-03	3.29E-03	3.00E-03
RL-W408	3.80E+00	2.256E-05	2.65E-06	2.62E-06	2.60E-06	2.57E-06	2.48E-06	2.28E-06	2.04E-06	1.88E-06	1.71E-06	1.56E-06
RL-W415	8.41E+01	4.993E-04	2.65E-06	2.62E-06	2.60E-06	2.57E-06	2.48E-06	2.28E-06	2.04E-06	1.88E-06	1.71E-06	1.56E-06
RL-W418	1.73E+01	1.025E-04	5.55E-05	5.47E-05	5.44E-05	5.37E-05	5.18E-05	4.78E-05	4.27E-05	3.94E-05	3.58E-05	3.26E-05
RL-W437	1.60E+03	9.502E-03	5.10E-03	5.02E-03	4.99E-03	4.93E-03	4.76E-03	4.39E-03	3.92E-03	3.62E-03	3.29E-03	3.00E-03
RL-W438	5.31E+00	3.152E-05	2.65E-06	2.62E-06	2.60E-06	2.57E-06	2.48E-06	2.29E-06	2.04E-06	1.88E-06	1.71E-06	1.56E-06
RL-W439	1.25E+04	7.427E-02	2.39E-02	2.33E-02	2.30E-02	2.26E-02	2.14E-02	1.91E-02	1.67E-02	1.54E-02	1.40E-02	1.28E-02
RL-W443	1.41E+03	8.365E-03	5.11E-03	5.03E-03	5.00E-03	4.94E-03	4.76E-03	4.39E-03	3.93E-03	3.62E-03	3.29E-03	3.00E-03
RL-W444	1.05E+03	6.205E-03	5.11E-03	5.03E-03	5.00E-03	4.94E-03	4.77E-03	4.39E-03	3.93E-03	3.62E-03	3.29E-03	3.00E-03
RL-W447	9.87E+00	5.859E-05	6.09E-05	6.02E-05	5.98E-05	5.90E-05	5.69E-05	5.24E-05	4.68E-05	4.32E-05	3.93E-05	3.58E-05
RL-W448	1.68E+00	9.973E-06	2.65E-06	2.62E-06	2.60E-06	2.57E-06	2.48E-06	2.28E-06	2.04E-06	1.88E-06	1.71E-06	1.56E-06
RL-W449	1.05E+00	6.233E-06	4.78E-03	4.09E-03	3.93E-03	3.64E-03	2.77E-03	1.04E-03	1.31E-04	8.76E-05	7.83E-05	7.14E-05
RL-W450	8.40E-01	4.986E-06	8.01E-05	7.92E-05	7.87E-05	7.77E-05	7.50E-05	6.91E-05	6.17E-05	5.69E-05	5.17E-05	4.72E-05
RL-W451	4.20E-01	2.493E-06	2.28E-05	2.25E-05	2.24E-05	2.21E-05	2.13E-05	1.96E-05	1.75E-05	1.62E-05	1.47E-05	1.34E-05
RL-W452	7.60E+00	4.511E-05	5.55E-05	5.48E-05	5.44E-05	5.37E-05	5.19E-05	4.78E-05	4.27E-05	3.94E-05	3.58E-05	3.27E-05
RL-W453	2.10E-01	1.247E-06	5.77E-04	5.68E-04	5.65E-04	5.58E-04	5.39E-04	4.96E-04	4.44E-04	4.09E-04	3.72E-04	3.40E-04

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W454	2.10E-01	1.247E-06	8.07E-03	7.94E-03	7.89E-03	7.80E-03	7.53E-03	6.94E-03	6.20E-03	5.72E-03	5.20E-03	4.74E-03
RL-W455	2.10E-01	1.247E-06	2.13E-03	2.10E-03	2.09E-03	2.07E-03	1.99E-03	1.84E-03	1.64E-03	1.51E-03	1.38E-03	1.26E-03
RL-W456	9.03E+00	5.360E-05	6.59E-03	6.49E-03	6.45E-03	6.37E-03	6.15E-03	5.67E-03	5.07E-03	4.67E-03	4.25E-03	3.87E-03
RL-W457	6.30E-01	3.740E-06	9.17E-03	9.03E-03	8.97E-03	8.86E-03	8.56E-03	7.89E-03	7.05E-03	6.50E-03	5.91E-03	5.39E-03
RL-W458	2.10E-01	1.247E-06	2.43E-02	2.32E-02	2.26E-02	2.16E-02	1.90E-02	1.42E-02	1.07E-02	9.60E-03	8.50E-03	7.58E-03
RL-W459	6.12E+00	3.633E-05	1.29E-02	1.25E-02	1.23E-02	1.19E-02	1.10E-02	9.30E-03	7.83E-03	7.16E-03	6.46E-03	5.86E-03
RL-W460	2.10E-01	1.247E-06	5.11E-03	5.03E-03	4.99E-03	4.93E-03	4.76E-03	4.39E-03	3.92E-03	3.62E-03	3.29E-03	3.00E-03
RL-W461	4.20E-01	2.493E-06	3.11E-04	2.65E-04	2.55E-04	2.35E-04	1.77E-04	6.26E-05	2.53E-06	1.03E-07	1.86E-09	3.38E-11
RL-W462	2.10E-01	1.247E-06	1.44E-03	1.42E-03	1.42E-03	1.40E-03	1.35E-03	1.24E-03	1.11E-03	1.02E-03	9.31E-04	8.49E-04
RL-W463	4.20E-01	2.493E-06	3.75E-03	3.69E-03	3.67E-03	3.62E-03	3.50E-03	3.23E-03	2.88E-03	2.66E-03	2.42E-03	2.21E-03
RL-W464	4.20E-01	2.493E-06	1.73E-03	1.70E-03	1.69E-03	1.67E-03	1.61E-03	1.49E-03	1.33E-03	1.22E-03	1.11E-03	1.02E-03
RL-W465	8.40E-01	4.986E-06	5.75E-03	5.67E-03	5.63E-03	5.56E-03	5.37E-03	4.95E-03	4.42E-03	4.08E-03	3.71E-03	3.38E-03
RL-W466	1.41E+01	8.352E-05	4.71E-03	4.64E-03	4.61E-03	4.56E-03	4.40E-03	4.05E-03	3.62E-03	3.34E-03	3.04E-03	2.77E-03
RL-W467	1.26E+00	7.480E-06	2.68E-03	2.64E-03	2.62E-03	2.59E-03	2.50E-03	2.31E-03	2.06E-03	1.90E-03	1.73E-03	1.58E-03
RL-W468	2.10E-01	1.247E-06	8.23E-05	8.11E-05	8.06E-05	7.96E-05	7.68E-05	7.08E-05	6.33E-05	5.84E-05	5.30E-05	4.84E-05
RL-W469	1.26E+00	7.480E-06	5.58E-03	5.50E-03	5.46E-03	5.40E-03	5.21E-03	4.80E-03	4.29E-03	3.96E-03	3.60E-03	3.28E-03
RL-W470	2.10E-01	1.247E-06	2.60E-01	2.50E-01	2.44E-01	2.33E-01	2.04E-01	1.52E-01	1.15E-01	1.03E-01	9.17E-02	8.19E-02
RL-W474	1.89E+00	1.122E-05	8.51E-04	6.19E-04	5.79E-04	5.11E-04	3.60E-04	1.46E-04	3.89E-05	3.09E-05	2.68E-05	2.35E-05
RL-W476	4.78E+00	2.837E-05	2.72E-03	2.68E-03	2.66E-03	2.63E-03	2.54E-03	2.35E-03	2.10E-03	1.93E-03	1.76E-03	1.60E-03
RL-W480	4.20E-01	2.493E-06	4.93E-03	4.86E-03	4.82E-03	4.77E-03	4.60E-03	4.24E-03	3.79E-03	3.49E-03	3.18E-03	2.90E-03
RL-W481	6.30E-01	3.740E-06	5.15E-03	5.08E-03	5.05E-03	4.98E-03	4.81E-03	4.43E-03	3.96E-03	3.65E-03	3.32E-03	3.03E-03
RL-W482	2.50E+00	1.484E-05	2.06E-01	1.98E-01	1.90E-01	1.75E-01	1.32E-01	4.65E-02	2.14E-03	3.09E-04	1.98E-04	1.67E-04
RL-W483	1.04E+00	6.174E-06	3.70E-02	3.56E-02	3.42E-02	3.15E-02	2.36E-02	8.34E-03	3.80E-04	5.19E-05	3.24E-05	2.72E-05
RL-W484	8.40E-01	4.986E-06	6.14E-04	5.79E-04	5.70E-04	5.55E-04	5.10E-04	4.18E-04	3.47E-04	3.18E-04	2.89E-04	2.63E-04
RL-W485	2.10E-01	1.247E-06	2.27E-04	2.15E-04	2.12E-04	2.08E-04	1.96E-04	1.73E-04	1.50E-04	1.38E-04	1.25E-04	1.14E-04
RL-W486	2.10E-01	1.247E-06	9.57E-05	9.07E-05	8.96E-05	8.78E-05	8.28E-05	7.28E-05	6.32E-05	5.81E-05	5.27E-05	4.81E-05
RL-W487	2.10E-01	1.247E-06	1.42E-02	1.36E-02	1.35E-02	1.32E-02	1.24E-02	1.08E-02	9.27E-03	8.50E-03	7.69E-03	6.99E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W488	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	2.10E-01	1.247E-06	1.53E-02	1.50E-02	1.49E-02	1.47E-02	1.42E-02	1.30E-02	1.16E-02	1.07E-02	9.72E-03	8.87E-03
RL-W490	1.90E+00	1.128E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	2.10E-01	1.247E-06	2.32E-03	2.16E-03	2.11E-03	2.03E-03	1.82E-03	1.47E-03	1.22E-03	1.12E-03	1.02E-03	9.27E-04
RL-W492	2.10E-01	1.247E-06	3.21E-04	3.16E-04	3.13E-04	3.09E-04	2.97E-04	2.73E-04	2.43E-04	2.24E-04	2.04E-04	1.86E-04
RL-W493	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.75E+01	4.600E-04	5.27E-03	4.68E-03	4.43E-03	3.99E-03	2.88E-03	1.01E-03	6.38E-05	2.31E-05	1.88E-05	1.66E-05
RL-W495	4.20E-01	2.493E-06	1.43E-02	1.41E-02	1.36E-02	1.25E-02	9.36E-03	3.32E-03	1.73E-04	4.18E-05	3.20E-05	2.81E-05
RL-W496	2.10E-01	1.247E-06	1.92E-01	1.86E-01	1.78E-01	1.63E-01	1.22E-01	4.28E-02	1.99E-03	3.14E-04	2.16E-04	1.89E-04
RL-W497	2.10E-01	1.247E-06	2.61E-02	2.41E-02	2.36E-02	2.27E-02	2.05E-02	1.65E-02	1.34E-02	1.21E-02	1.08E-02	9.71E-03
RL-W498	7.14E+02	4.237E-03	7.57E-05	7.47E-05	7.42E-05	7.33E-05	7.07E-05	6.52E-05	5.82E-05	5.37E-05	4.88E-05	4.45E-05
RL-W499	2.10E-01	1.247E-06	2.31E-06	2.28E-06	2.26E-06	2.23E-06	2.16E-06	1.99E-06	1.77E-06	1.64E-06	1.49E-06	1.36E-06
RL-W500	2.10E-01	1.247E-06	1.05E-04	1.02E-04	1.01E-04	9.88E-05	9.34E-05	8.28E-05	7.24E-05	6.67E-05	6.07E-05	5.54E-05
RL-W501	5.44E+01	3.231E-04	1.42E-02	1.37E-02	1.35E-02	1.32E-02	1.24E-02	1.08E-02	9.29E-03	8.52E-03	7.71E-03	7.00E-03
RL-W502	3.15E+00	1.870E-05	8.20E-05	8.09E-05	8.03E-05	7.93E-05	7.66E-05	7.06E-05	6.31E-05	5.82E-05	5.29E-05	4.82E-05
RL-W503	4.20E-01	2.493E-06	2.39E-02	2.32E-02	2.30E-02	2.25E-02	2.13E-02	1.90E-02	1.67E-02	1.54E-02	1.40E-02	1.28E-02
RL-W504	2.10E-01	1.247E-06	1.42E-02	1.36E-02	1.35E-02	1.32E-02	1.24E-02	1.08E-02	9.27E-03	8.50E-03	7.69E-03	6.99E-03
RL-W505	2.10E-01	1.247E-06	1.25E-03	1.24E-03	1.23E-03	1.21E-03	1.17E-03	1.08E-03	9.66E-04	8.91E-04	8.10E-04	7.39E-04
RL-W506	6.30E-01	3.740E-06	1.40E-04	1.37E-04	1.36E-04	1.34E-04	1.29E-04	1.19E-04	1.06E-04	9.76E-05	8.87E-05	8.09E-05
RL-W507	6.30E-01	3.740E-06	1.48E-05	1.46E-05	1.45E-05	1.44E-05	1.39E-05	1.28E-05	1.14E-05	1.05E-05	9.56E-06	8.73E-06
RL-W508	6.30E-01	3.740E-06	1.79E-01	1.73E-01	1.72E-01	1.68E-01	1.59E-01	1.41E-01	1.24E-01	1.14E-01	1.04E-01	9.46E-02
RL-W509	4.83E+00	2.867E-05	2.01E-01	1.94E-01	1.92E-01	1.88E-01	1.76E-01	1.55E-01	1.34E-01	1.23E-01	1.12E-01	1.02E-01
RL-W510	3.36E+00	1.995E-05	2.73E-02	2.65E-02	2.62E-02	2.56E-02	2.42E-02	2.15E-02	1.88E-02	1.73E-02	1.58E-02	1.44E-02
RL-W511	5.29E+01	3.141E-04	2.17E-01	2.12E-01	2.10E-01	2.07E-01	1.98E-01	1.80E-01	1.59E-01	1.47E-01	1.34E-01	1.22E-01
RL-W512	3.13E+01	1.857E-04	2.44E-01	2.35E-01	2.33E-01	2.28E-01	2.16E-01	1.91E-01	1.66E-01	1.53E-01	1.38E-01	1.26E-01
RL-W513	8.79E+03	5.219E-02	3.79E-02	3.30E-02	3.18E-02	2.98E-02	2.49E-02	1.65E-02	1.14E-02	1.02E-02	9.02E-03	8.07E-03
RL-W514	4.20E-01	2.493E-06	9.14E-05	9.00E-05	8.94E-05	8.84E-05	8.53E-05	7.86E-05	7.02E-05	6.48E-05	5.89E-05	5.37E-05

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W515	8.02E+00	4.761E-05	1.86E-04	1.84E-04	1.83E-04	1.80E-04	1.74E-04	1.60E-04	1.43E-04	1.32E-04	1.20E-04	1.10E-04
RL-W516	2.66E+01	1.579E-04	7.78E-05	7.67E-05	7.62E-05	7.53E-05	7.26E-05	6.69E-05	5.98E-05	5.52E-05	5.01E-05	4.57E-05
RL-W517	2.10E-01	1.247E-06	8.76E-11	8.65E-11	8.59E-11	8.48E-11	8.19E-11	7.54E-11	6.74E-11	6.22E-11	5.65E-11	5.16E-11
RL-W518	8.40E-01	4.986E-06	3.65E-02	3.53E-02	3.49E-02	3.41E-02	3.21E-02	2.82E-02	2.45E-02	2.25E-02	2.05E-02	1.86E-02
RL-W519	1.68E+00	9.973E-06	5.57E-03	5.48E-03	5.45E-03	5.38E-03	5.19E-03	4.79E-03	4.28E-03	3.95E-03	3.59E-03	3.27E-03
RL-W520	4.20E-01	2.493E-06	2.44E-03	2.41E-03	2.39E-03	2.36E-03	2.28E-03	2.10E-03	1.88E-03	1.73E-03	1.57E-03	1.44E-03
RL-W521	2.10E-01	1.247E-06	9.10E-05	8.97E-05	8.91E-05	8.80E-05	8.49E-05	7.83E-05	6.99E-05	6.45E-05	5.86E-05	5.35E-05
RL-W522	2.31E+00	1.371E-05	7.55E-02	7.15E-02	7.03E-02	6.82E-02	6.27E-02	5.25E-02	4.40E-02	4.03E-02	3.64E-02	3.30E-02
RL-W523	2.10E-01	1.247E-06	1.36E-01	1.19E-01	1.15E-01	1.07E-01	8.93E-02	5.84E-02	3.92E-02	3.48E-02	3.07E-02	2.73E-02
RL-W524	2.73E+00	1.621E-05	5.60E-02	5.09E-02	4.96E-02	4.73E-02	4.16E-02	3.14E-02	2.43E-02	2.20E-02	1.97E-02	1.78E-02
RL-W525	6.30E-01	3.740E-06	2.31E-02	2.15E-02	2.11E-02	2.03E-02	1.83E-02	1.48E-02	1.20E-02	1.09E-02	9.84E-03	8.90E-03
RL-W526	1.44E+01	8.518E-05	7.38E-03	7.18E-03	7.11E-03	6.98E-03	6.63E-03	5.94E-03	5.23E-03	4.82E-03	4.38E-03	4.00E-03
RL-W527	2.10E-01	1.247E-06	5.47E-02	5.30E-02	5.24E-02	5.14E-02	4.87E-02	4.35E-02	3.82E-02	3.51E-02	3.19E-02	2.91E-02
RL-W528	5.26E+00	3.122E-05	3.07E-01	2.64E-01	2.54E-01	2.37E-01	1.94E-01	1.19E-01	7.33E-02	6.36E-02	5.51E-02	4.81E-02
RL-W529	1.90E+00	1.128E-05	2.12E-03	2.05E-03	2.03E-03	1.99E-03	1.88E-03	1.68E-03	1.47E-03	1.35E-03	1.23E-03	1.12E-03
RL-W530	4.20E-01	2.493E-06	1.10E-01	1.07E-01	1.06E-01	1.03E-01	9.77E-02	8.67E-02	7.59E-02	6.99E-02	6.35E-02	5.80E-02
RL-W531	5.47E+00	3.247E-05	1.73E-01	1.44E-01	1.38E-01	1.27E-01	1.01E-01	5.88E-02	3.45E-02	3.01E-02	2.64E-02	2.33E-02
RL-W532	3.04E+01	1.805E-04	4.55E-04	4.48E-04	4.45E-04	4.40E-04	4.25E-04	3.91E-04	3.50E-04	3.23E-04	2.93E-04	2.67E-04
RL-W533	3.80E+00	2.256E-05	1.15E-03	1.12E-03	1.11E-03	1.09E-03	1.03E-03	9.13E-04	8.00E-04	7.37E-04	6.70E-04	6.12E-04
RL-W534	2.10E-01	1.247E-06	1.84E-06	1.81E-06	1.80E-06	1.78E-06	1.72E-06	1.58E-06	1.41E-06	1.30E-06	1.19E-06	1.08E-06
RL-W535	2.38E+01	1.410E-04	3.21E-02	2.99E-02	2.94E-02	2.83E-02	2.56E-02	2.07E-02	1.70E-02	1.55E-02	1.40E-02	1.27E-02
RL-W536	6.51E+00	3.864E-05	3.15E-03	3.03E-03	2.99E-03	2.92E-03	2.73E-03	2.37E-03	2.04E-03	1.88E-03	1.70E-03	1.55E-03
RL-W537	5.04E+00	2.992E-05	2.18E-01	2.12E-01	2.11E-01	2.08E-01	1.99E-01	1.81E-01	1.60E-01	1.48E-01	1.35E-01	1.23E-01
RL-W538	1.68E+00	9.973E-06	2.92E-06	2.88E-06	2.86E-06	2.82E-06	2.72E-06	2.51E-06	2.24E-06	2.07E-06	1.88E-06	1.72E-06
RL-W539	4.20E-01	2.493E-06	1.29E-03	1.27E-03	1.26E-03	1.25E-03	1.20E-03	1.11E-03	9.91E-04	9.15E-04	8.31E-04	7.58E-04
RL-W540	3.09E+01	1.832E-04	1.14E-02	1.04E-02	1.02E-02	9.72E-03	8.61E-03	6.67E-03	5.28E-03	4.80E-03	4.32E-03	3.90E-03
RL-W541	6.30E-01	3.740E-06	2.49E-03	2.46E-03	2.44E-03	2.41E-03	2.33E-03	2.14E-03	1.92E-03	1.77E-03	1.61E-03	1.47E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W542	3.99E+00	2.369E-05	1.13E-02	1.10E-02	1.08E-02	1.06E-02	1.00E-02	8.84E-03	7.71E-03	7.10E-03	6.44E-03	5.88E-03
RL-W543	4.01E+00	2.380E-05	5.74E-05	5.66E-05	5.62E-05	5.55E-05	5.36E-05	4.94E-05	4.41E-05	4.07E-05	3.70E-05	3.37E-05
RL-W544	2.10E-01	1.247E-06	1.46E-02	1.41E-02	1.40E-02	1.36E-02	1.28E-02	1.13E-02	9.77E-03	8.98E-03	8.14E-03	7.41E-03
RL-W545	3.80E+00	2.256E-05	3.63E-04	3.57E-04	3.55E-04	3.51E-04	3.38E-04	3.12E-04	2.79E-04	2.57E-04	2.34E-04	2.13E-04
RL-W546	8.40E-01	4.986E-06	7.21E-05	7.11E-05	7.06E-05	6.98E-05	6.73E-05	6.21E-05	5.55E-05	5.12E-05	4.65E-05	4.24E-05
RL-W547	5.61E+01	3.333E-04	2.75E-08	2.71E-08	2.69E-08	2.66E-08	2.56E-08	2.36E-08	2.11E-08	1.95E-08	1.77E-08	1.62E-08
RL-W548	4.20E-01	2.493E-06	3.17E-06	3.13E-06	3.11E-06	3.07E-06	2.96E-06	2.73E-06	2.44E-06	2.25E-06	2.04E-06	1.87E-06
RL-W549	4.00E+00	2.374E-05	2.59E-02	2.41E-02	2.37E-02	2.28E-02	2.07E-02	1.69E-02	1.39E-02	1.27E-02	1.15E-02	1.04E-02
RL-W550	4.41E+00	2.618E-05	2.20E-01	2.14E-01	2.13E-01	2.10E-01	2.01E-01	1.83E-01	1.62E-01	1.49E-01	1.36E-01	1.24E-01
RL-W551	1.56E+01	9.248E-05	7.89E-02	7.59E-02	7.51E-02	7.37E-02	6.96E-02	6.11E-02	5.29E-02	4.86E-02	4.40E-02	4.01E-02
RL-W552	8.40E-01	4.986E-06	9.84E-04	9.71E-04	9.64E-04	9.52E-04	9.19E-04	8.47E-04	7.57E-04	6.98E-04	6.35E-04	5.79E-04
RL-W553	4.20E-01	2.493E-06	1.74E-04	1.73E-04	1.72E-04	1.70E-04	1.64E-04	1.51E-04	1.35E-04	1.24E-04	1.13E-04	1.03E-04
RL-W554	9.50E+00	5.639E-05	1.23E-04	1.21E-04	1.20E-04	1.19E-04	1.15E-04	1.06E-04	9.45E-05	8.72E-05	7.92E-05	7.23E-05
RL-W555	1.20E+01	7.141E-05	4.47E-05	4.40E-05	4.38E-05	4.32E-05	4.17E-05	3.84E-05	3.44E-05	3.17E-05	2.88E-05	2.63E-05
RL-W563	2.10E-01	1.247E-06	2.37E-02	2.30E-02	2.27E-02	2.22E-02	2.10E-02	1.87E-02	1.63E-02	1.51E-02	1.37E-02	1.25E-02
RL-W564	1.26E+00	7.480E-06	2.54E-03	2.48E-03	2.45E-03	2.40E-03	2.27E-03	2.01E-03	1.76E-03	1.62E-03	1.47E-03	1.35E-03
RL-W565	2.10E-01	1.247E-06	2.37E-03	2.34E-03	2.32E-03	2.30E-03	2.22E-03	2.04E-03	1.82E-03	1.68E-03	1.53E-03	1.40E-03
RL-W566	2.31E+00	1.371E-05	3.17E-03	3.12E-03	3.10E-03	3.06E-03	2.96E-03	2.72E-03	2.43E-03	2.25E-03	2.04E-03	1.86E-03
RL-W567	2.10E-01	1.247E-06	2.83E-01	2.80E-01	2.69E-01	2.47E-01	1.85E-01	6.59E-02	3.77E-03	1.13E-03	9.00E-04	7.90E-04
RL-W568	3.74E+00	2.220E-05	3.05E-01	3.05E-01	2.93E-01	2.69E-01	2.02E-01	7.31E-02	5.86E-03	2.82E-03	2.37E-03	2.08E-03
RL-W569	2.10E+00	1.247E-05	4.47E-04	4.43E-04	4.24E-04	3.90E-04	2.92E-04	1.03E-04	5.32E-06	1.28E-06	1.03E-06	9.45E-07
RL-W570	4.20E-01	2.493E-06	1.25E-03	1.24E-03	1.23E-03	1.21E-03	1.17E-03	1.08E-03	9.66E-04	8.91E-04	8.10E-04	7.39E-04
RL-W571	1.25E+01	7.408E-05	2.05E-02	1.95E-02	1.88E-02	1.74E-02	1.37E-02	7.00E-03	3.27E-03	2.84E-03	2.52E-03	2.25E-03
RL-W572	2.29E+00	1.359E-05	8.02E-05	7.95E-05	7.65E-05	7.09E-05	5.48E-05	2.38E-05	7.36E-06	6.32E-06	5.84E-06	5.43E-06
RL-W573	1.50E+01	8.892E-05	1.45E-01	1.43E-01	1.37E-01	1.26E-01	9.47E-02	3.39E-02	2.21E-03	8.41E-04	6.91E-04	6.09E-04
RL-W574	8.19E+01	4.861E-04	1.14E-01	1.12E-01	1.08E-01	9.91E-02	7.44E-02	2.65E-02	1.66E-03	5.87E-04	4.79E-04	4.22E-04
RL-W575	2.84E+02	1.687E-03	2.16E-01	2.12E-01	2.03E-01	1.87E-01	1.40E-01	5.03E-02	3.54E-03	1.50E-03	1.26E-03	1.12E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W576	4.11E+01	2.438E-04	1.06E-01	1.05E-01	1.01E-01	9.28E-02	6.96E-02	2.49E-02	1.57E-03	5.67E-04	4.64E-04	4.09E-04
RL-W579	4.20E-01	2.493E-06	1.25E-03	1.10E-03	1.06E-03	9.99E-04	8.10E-04	4.35E-04	2.24E-04	1.99E-04	1.81E-04	1.65E-04
RL-W580	2.11E+00	1.253E-05	3.69E-04	3.67E-04	3.67E-04	3.66E-04	3.64E-04	3.55E-04	3.28E-04	3.05E-04	2.79E-04	2.56E-04
RL-W581	4.20E-01	2.493E-06	1.06E-02	9.01E-03	8.66E-03	7.99E-03	6.04E-03	2.13E-03	8.61E-05	3.49E-06	6.33E-08	1.15E-09
RL-W582	2.10E-01	1.247E-06	3.13E-04	2.82E-04	2.75E-04	2.64E-04	2.32E-04	1.75E-04	1.33E-04	1.20E-04	1.06E-04	9.49E-05
RL-W583	2.10E-01	1.247E-06	8.10E-04	7.98E-04	7.93E-04	7.83E-04	7.56E-04	6.97E-04	6.22E-04	5.74E-04	5.22E-04	4.76E-04
RL-W584	2.10E-01	1.247E-06	7.84E-03	7.14E-03	7.00E-03	6.76E-03	6.18E-03	5.17E-03	4.30E-03	3.88E-03	3.45E-03	3.09E-03
RL-W585	4.20E-01	2.493E-06	2.22E-02	2.10E-02	2.06E-02	2.00E-02	1.83E-02	1.53E-02	1.27E-02	1.14E-02	1.02E-02	9.07E-03
RL-W586	2.10E-01	1.247E-06	1.28E-05	1.26E-05	1.25E-05	1.24E-05	1.19E-05	1.10E-05	9.83E-06	9.07E-06	8.24E-06	7.52E-06
RL-W587	4.20E-01	2.493E-06	1.36E-04	1.34E-04	1.34E-04	1.32E-04	1.27E-04	1.17E-04	1.05E-04	9.67E-05	8.79E-05	8.02E-05
RL-W588	2.10E-01	1.247E-06	6.32E-03	5.77E-03	5.66E-03	5.48E-03	5.04E-03	4.31E-03	3.63E-03	3.28E-03	2.92E-03	2.61E-03
RL-W589	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	6.20E-01	3.680E-06	1.80E-02	1.55E-02	1.46E-02	1.31E-02	9.34E-03	3.31E-03	2.93E-04	1.49E-04	1.22E-04	1.03E-04
RL-W591	2.10E-01	1.247E-06	2.34E-01	2.30E-01	2.20E-01	2.02E-01	1.51E-01	5.32E-02	2.75E-03	6.25E-04	4.55E-04	3.85E-04
RL-W592	2.50E+00	1.484E-05	9.91E-02	9.13E-02	8.69E-02	7.91E-02	5.85E-02	2.17E-02	2.76E-03	1.76E-03	1.48E-03	1.27E-03
RL-W593	6.20E-01	3.680E-06	4.13E-04	4.10E-04	4.09E-04	4.08E-04	4.02E-04	3.83E-04	3.30E-04	2.86E-04	2.41E-04	2.05E-04
RL-W594	2.50E+00	1.484E-05	8.63E-02	7.56E-02	7.25E-02	6.67E-02	5.00E-02	1.77E-02	8.18E-04	1.22E-04	7.89E-05	6.66E-05
RL-W595	6.20E-01	3.680E-06	2.26E-03	1.67E-03	1.55E-03	1.36E-03	9.74E-04	5.44E-04	3.13E-04	2.64E-04	2.21E-04	1.86E-04
RL-W596	9.45E+00	5.610E-05	2.27E-05	1.96E-05	1.85E-05	1.65E-05	1.18E-05	4.20E-06	3.58E-07	1.78E-07	1.44E-07	1.23E-07
RL-W597	3.12E+00	1.852E-05	1.03E-01	9.82E-02	9.40E-02	8.62E-02	6.45E-02	2.34E-02	2.00E-03	9.94E-04	8.09E-04	6.89E-04
RL-W598	8.74E+00	5.188E-05	5.18E-02	4.30E-02	4.04E-02	3.59E-02	2.53E-02	8.95E-03	8.60E-04	4.69E-04	3.88E-04	3.33E-04
RL-W599	2.10E-01	1.247E-06	7.86E-02	7.70E-02	7.37E-02	6.76E-02	5.04E-02	1.78E-02	9.19E-04	2.09E-04	1.52E-04	1.28E-04
RL-W600	8.60E-01	5.105E-06	9.17E-09	9.03E-09	8.97E-09	8.86E-09	8.55E-09	7.88E-09	7.04E-09	6.50E-09	5.90E-09	5.39E-09
RL-W601	1.31E+00	7.776E-06	3.02E-05	3.00E-05	2.98E-05	2.95E-05	2.84E-05	2.62E-05	2.34E-05	2.16E-05	1.96E-05	1.79E-05
RL-W602	2.79E+00	1.656E-05	1.24E-02	1.22E-02	1.21E-02	1.20E-02	1.16E-02	1.07E-02	9.53E-03	8.79E-03	7.99E-03	7.29E-03
RL-W603	7.60E+00	4.511E-05	2.62E-02	2.59E-02	2.57E-02	2.54E-02	2.45E-02	2.26E-02	2.02E-02	1.86E-02	1.69E-02	1.54E-02
RL-W604	2.10E-01	1.247E-06	8.03E-04	7.56E-04	7.43E-04	7.19E-04	6.52E-04	5.25E-04	4.22E-04	3.80E-04	3.38E-04	3.02E-04

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W605	2.10E-01	1.247E-06	5.06E-04	5.03E-04	5.00E-04	4.94E-04	4.76E-04	4.39E-04	3.92E-04	3.62E-04	3.29E-04	3.00E-04
RL-W606	2.10E-01	1.247E-06	2.04E-04	2.03E-04	2.02E-04	1.99E-04	1.92E-04	1.77E-04	1.58E-04	1.46E-04	1.33E-04	1.21E-04
RL-W607	2.10E-01	1.247E-06	1.36E-04	1.28E-04	1.26E-04	1.22E-04	1.10E-04	8.87E-05	7.13E-05	6.42E-05	5.71E-05	5.11E-05
RL-W608	6.12E+00	3.633E-05	3.26E-05	2.67E-05	2.54E-05	2.31E-05	1.76E-05	9.29E-06	4.67E-06	3.96E-06	3.38E-06	2.92E-06
RL-W610	3.80E+00	2.256E-05	4.95E-02	4.88E-02	4.85E-02	4.79E-02	4.62E-02	4.26E-02	3.81E-02	3.51E-02	3.19E-02	2.91E-02
RL-W612	9.89E+00	5.871E-05	4.61E-05	4.54E-05	4.51E-05	4.45E-05	4.30E-05	3.97E-05	3.55E-05	3.28E-05	2.98E-05	2.72E-05
RL-W615	1.89E+00	1.122E-05	7.20E-04	7.18E-04	7.18E-04	7.17E-04	7.13E-04	7.00E-04	6.61E-04	6.24E-04	5.81E-04	5.40E-04
RL-W622	1.89E+00	1.122E-05	3.93E-06	3.87E-06	3.84E-06	3.80E-06	3.66E-06	3.38E-06	3.02E-06	2.79E-06	2.53E-06	2.31E-06
RL-W625	2.10E-01	1.247E-06	4.65E-04	4.27E-04	4.15E-04	3.94E-04	3.47E-04	2.71E-04	2.11E-04	1.86E-04	1.61E-04	1.40E-04
RL-W626	2.10E-01	1.247E-06	1.80E-02	1.62E-02	1.58E-02	1.50E-02	1.30E-02	9.36E-03	6.88E-03	6.14E-03	5.42E-03	4.82E-03
RL-W627	2.10E-01	1.247E-06	3.72E-05	3.61E-05	3.45E-05	3.17E-05	2.36E-05	8.29E-06	3.58E-07	3.52E-08	2.05E-08	1.89E-08
RL-W628	2.10E-01	1.247E-06	1.02E-04	1.01E-04	9.98E-05	9.86E-05	9.52E-05	8.77E-05	7.84E-05	7.23E-05	6.57E-05	6.00E-05
RL-W629	2.10E-01	1.247E-06	6.84E-06	6.76E-06	6.71E-06	6.63E-06	6.40E-06	5.90E-06	5.27E-06	4.86E-06	4.42E-06	4.03E-06
RL-W630	4.20E-01	2.493E-06	4.00E-02	3.93E-02	3.90E-02	3.85E-02	3.72E-02	3.43E-02	3.07E-02	2.83E-02	2.57E-02	2.34E-02
RL-W631	4.20E-01	2.493E-06	6.04E-04	6.00E-04	5.96E-04	5.89E-04	5.68E-04	5.24E-04	4.68E-04	4.32E-04	3.92E-04	3.58E-04
RL-W632	2.10E-01	1.247E-06	2.16E-01	2.13E-01	2.11E-01	2.05E-01	1.90E-01	1.59E-01	1.33E-01	1.21E-01	1.09E-01	9.88E-02
RL-W633	2.10E-01	1.247E-06	2.06E-04	1.86E-04	1.79E-04	1.66E-04	1.31E-04	6.61E-05	2.95E-05	2.50E-05	2.17E-05	1.90E-05
RL-W634	2.10E-01	1.247E-06	1.96E-04	1.95E-04	1.95E-04	1.95E-04	1.94E-04	1.90E-04	1.80E-04	1.69E-04	1.58E-04	1.47E-04
RL-W635	1.54E+01	9.136E-05	2.19E-02	1.78E-02	1.68E-02	1.51E-02	1.11E-02	5.44E-03	2.40E-03	2.00E-03	1.69E-03	1.45E-03
RL-W636	1.05E+00	6.233E-06	2.52E-03	2.27E-03	2.18E-03	2.02E-03	1.60E-03	8.04E-04	3.57E-04	3.03E-04	2.63E-04	2.30E-04
RL-W637	6.30E-01	3.740E-06	2.35E-05	1.88E-05	1.78E-05	1.63E-05	1.31E-05	9.24E-06	6.74E-06	5.90E-06	5.11E-06	4.45E-06
RL-W638	4.01E+00	2.380E-05	7.65E-05	6.65E-05	6.35E-05	5.83E-05	4.52E-05	2.29E-05	1.05E-05	8.95E-06	7.74E-06	6.77E-06
RL-W639	6.30E-01	3.740E-06	1.44E-04	1.42E-04	1.41E-04	1.39E-04	1.34E-04	1.24E-04	1.11E-04	1.02E-04	9.28E-05	8.46E-05
RL-W640	2.10E-01	1.247E-06	1.46E-02	1.43E-02	1.42E-02	1.41E-02	1.36E-02	1.25E-02	1.12E-02	1.03E-02	9.38E-03	8.55E-03
RL-W641	5.46E+00	3.241E-05	6.60E-03	5.42E-03	5.20E-03	4.83E-03	4.05E-03	3.02E-03	2.35E-03	2.12E-03	1.90E-03	1.71E-03
RL-W642	1.68E+00	9.973E-06	2.20E-04	1.98E-04	1.94E-04	1.84E-04	1.57E-04	1.03E-04	7.10E-05	6.59E-05	6.12E-05	5.70E-05
RL-W643	1.68E+00	9.973E-06	6.61E-03	5.43E-03	5.20E-03	4.84E-03	4.06E-03	3.03E-03	2.35E-03	2.12E-03	1.90E-03	1.71E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W644	8.40E-01	4.986E-06	2.63E-04	2.63E-04	2.62E-04	2.62E-04	2.61E-04	2.56E-04	2.42E-04	2.28E-04	2.12E-04	1.97E-04
RL-W645	1.47E+00	8.726E-06	4.28E-04	4.22E-04	4.19E-04	4.13E-04	3.97E-04	3.63E-04	3.23E-04	2.97E-04	2.70E-04	2.46E-04
RL-W646	4.20E-01	2.493E-06	5.81E-04	5.49E-04	5.40E-04	5.23E-04	4.77E-04	3.89E-04	3.16E-04	2.85E-04	2.54E-04	2.27E-04
RL-W647	2.10E-01	1.247E-06	1.21E-02	7.30E-03	6.56E-03	5.44E-03	3.60E-03	2.59E-03	2.19E-03	2.03E-03	1.86E-03	1.70E-03
RL-W648	2.10E-01	1.247E-06	3.47E-05	2.70E-05	2.52E-05	2.21E-05	1.56E-05	7.19E-06	2.88E-06	2.35E-06	1.96E-06	1.66E-06
RL-W649	1.90E+00	1.128E-05	1.41E-05	1.10E-05	1.02E-05	8.99E-06	6.35E-06	2.92E-06	1.17E-06	9.55E-07	7.98E-07	6.74E-07
RL-W653	4.20E-01	2.493E-06	1.30E-05	1.29E-05	1.28E-05	1.26E-05	1.22E-05	1.12E-05	1.00E-05	9.24E-06	8.40E-06	7.66E-06
RL-W654	2.10E-01	1.247E-06	1.44E-04	1.42E-04	1.41E-04	1.39E-04	1.34E-04	1.24E-04	1.10E-04	1.02E-04	9.25E-05	8.44E-05
RL-W655	1.46E+00	8.667E-06	6.54E-01	6.09E-01	5.81E-01	5.30E-01	3.92E-01	1.38E-01	7.07E-03	1.57E-03	1.13E-03	9.47E-04
RL-W656	3.12E+00	1.852E-05	1.13E+00	1.13E+00	1.09E+00	1.01E+00	7.57E-01	2.68E-01	1.19E-02	1.39E-03	8.30E-04	7.17E-04
RL-W657	1.49E+01	8.821E-05	1.27E-01	1.23E-01	1.18E-01	1.09E-01	8.15E-02	2.87E-02	1.31E-03	1.84E-04	1.16E-04	9.76E-05
RL-W659	4.20E-01	2.493E-06	5.67E-01	5.35E-01	5.12E-01	4.69E-01	3.50E-01	1.23E-01	5.78E-03	9.38E-04	6.37E-04	5.49E-04
RL-W660	2.08E+00	1.235E-05	6.77E-01	6.18E-01	5.89E-01	5.36E-01	3.94E-01	1.40E-01	9.25E-03	3.49E-03	2.76E-03	2.34E-03
RL-W661	2.10E-01	1.247E-06	6.07E-02	6.06E-02	5.82E-02	5.36E-02	4.04E-02	1.43E-02	6.35E-04	7.38E-05	4.05E-05	3.19E-05
RL-W662	2.10E-01	1.247E-06	2.07E-03	1.92E-03	1.85E-03	1.70E-03	1.28E-03	4.52E-04	2.27E-05	4.71E-06	3.37E-06	2.85E-06
RL-W665	8.53E+00	5.064E-05	6.95E-01	6.32E-01	6.00E-01	5.42E-01	3.93E-01	1.36E-01	6.70E-03	1.31E-03	9.39E-04	8.12E-04
RL-W666	1.46E+00	8.667E-06	6.31E-02	6.09E-02	5.84E-02	5.38E-02	4.05E-02	1.44E-02	8.28E-04	2.49E-04	1.96E-04	1.70E-04
RL-W668	4.27E+01	2.535E-04	2.47E-04	2.13E-04	2.05E-04	1.91E-04	1.48E-04	6.28E-05	1.72E-05	1.42E-05	1.28E-05	1.16E-05
RL-W669	1.26E+00	7.480E-06	6.60E-03	5.42E-03	5.20E-03	4.83E-03	4.05E-03	3.02E-03	2.35E-03	2.12E-03	1.90E-03	1.71E-03
RL-W670	2.10E-01	1.247E-06	9.28E-04	7.99E-04	7.70E-04	7.15E-04	5.55E-04	2.36E-04	6.48E-05	5.34E-05	4.81E-05	4.36E-05
RL-W671	9.45E+00	5.610E-05	2.99E-03	2.69E-03	2.58E-03	2.37E-03	1.78E-03	6.29E-04	2.88E-05	4.16E-06	2.73E-06	2.37E-06
RL-W672	9.45E+00	5.610E-05	2.03E-02	1.83E-02	1.75E-02	1.61E-02	1.21E-02	4.27E-03	1.96E-04	2.83E-05	1.86E-05	1.61E-05
RL-W673	4.91E+01	2.917E-04	3.77E-03	3.39E-03	3.25E-03	2.99E-03	2.25E-03	7.93E-04	3.64E-05	5.26E-06	3.46E-06	3.00E-06
RL-W674	3.33E+01	1.979E-04	1.39E-03	1.38E-03	1.38E-03	1.38E-03	1.36E-03	1.33E-03	1.25E-03	1.18E-03	1.10E-03	1.02E-03
RL-W675	2.10E-01	1.247E-06	2.15E-02	1.73E-02	1.64E-02	1.49E-02	1.16E-02	6.72E-03	3.99E-03	3.47E-03	3.01E-03	2.64E-03
RL-W676	4.41E+00	2.618E-05	1.58E-04	1.55E-04	1.54E-04	1.52E-04	1.47E-04	1.37E-04	1.25E-04	1.17E-04	1.09E-04	1.01E-04
RL-W677	3.15E+00	1.870E-05	8.32E-02	7.45E-02	7.17E-02	6.66E-02	5.27E-02	2.66E-02	1.20E-02	1.02E-02	8.81E-03	7.73E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W678	4.20E-01	2.493E-06	2.65E-03	2.48E-03	2.40E-03	2.24E-03	1.86E-03	1.20E-03	7.86E-04	6.87E-04	5.97E-04	5.23E-04
RL-W679	3.80E+00	2.256E-05	1.36E-03	1.22E-03	1.17E-03	1.09E-03	8.62E-04	4.34E-04	1.93E-04	1.64E-04	1.42E-04	1.24E-04
RL-W680	2.10E-01	1.247E-06	7.34E-06	5.94E-06	5.58E-06	4.99E-06	3.67E-06	1.79E-06	7.83E-07	6.46E-07	5.42E-07	4.60E-07
RL-W681	2.10E-01	1.247E-06	1.67E-05	1.62E-05	1.60E-05	1.57E-05	1.48E-05	1.33E-05	1.15E-05	1.04E-05	9.24E-06	8.27E-06
RL-W685	1.43E+02	8.484E-04	9.04E-05	8.90E-05	8.84E-05	8.74E-05	8.43E-05	7.77E-05	6.95E-05	6.41E-05	5.83E-05	5.32E-05
RL-W689	2.10E-01	1.247E-06	2.27E-04	1.91E-04	1.83E-04	1.69E-04	1.28E-04	4.95E-05	8.53E-06	6.50E-06	5.99E-06	5.57E-06
RL-W690	4.20E-01	2.493E-06	2.73E-02	2.69E-02	2.67E-02	2.64E-02	2.55E-02	2.35E-02	2.10E-02	1.94E-02	1.77E-02	1.61E-02
RL-W691	2.10E-01	1.247E-06	1.27E-03	1.25E-03	1.24E-03	1.22E-03	1.18E-03	1.09E-03	9.75E-04	8.99E-04	8.17E-04	7.46E-04
RL-W692	4.20E-01	2.493E-06	2.50E-02	2.47E-02	2.45E-02	2.42E-02	2.34E-02	2.16E-02	1.93E-02	1.78E-02	1.62E-02	1.48E-02
RL-W693	6.20E-01	3.680E-06	2.10E-02	2.07E-02	2.05E-02	2.03E-02	1.96E-02	1.81E-02	1.62E-02	1.49E-02	1.36E-02	1.24E-02
RL-W694	2.29E+00	1.359E-05	5.99E-02	5.90E-02	5.86E-02	5.79E-02	5.59E-02	5.16E-02	4.62E-02	4.26E-02	3.87E-02	3.53E-02
RL-W695	8.40E-01	4.986E-06	2.89E-05	2.63E-05	2.57E-05	2.46E-05	2.13E-05	1.46E-05	1.07E-05	9.93E-06	9.24E-06	8.59E-06
RL-W696	2.10E-01	1.247E-06	2.22E-04	2.03E-04	1.97E-04	1.87E-04	1.63E-04	1.22E-04	9.22E-05	8.09E-05	7.00E-05	6.10E-05
RL-W697	2.10E-01	1.247E-06	9.38E-02	5.10E-02	4.44E-02	3.43E-02	1.67E-02	4.43E-03	3.39E-04	1.66E-04	1.48E-04	1.39E-04
RL-W698	2.10E-01	1.247E-06	1.82E-03	1.55E-03	1.49E-03	1.37E-03	1.04E-03	3.67E-04	1.54E-05	1.15E-06	5.19E-07	4.73E-07
RL-W699	4.20E-01	2.493E-06	1.99E-04	1.97E-04	1.90E-04	1.77E-04	1.39E-04	6.34E-05	2.28E-05	1.98E-05	1.81E-05	1.67E-05
RL-W700	1.26E+00	7.480E-06	1.44E-04	1.42E-04	1.41E-04	1.39E-04	1.34E-04	1.24E-04	1.10E-04	1.02E-04	9.25E-05	8.44E-05
RL-W702	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	4.20E-01	2.493E-06	6.60E-03	5.42E-03	5.19E-03	4.83E-03	4.05E-03	3.02E-03	2.34E-03	2.12E-03	1.90E-03	1.71E-03
RL-W705	6.20E-01	3.680E-06	7.63E-05	7.51E-05	7.47E-05	7.38E-05	7.12E-05	6.57E-05	5.88E-05	5.42E-05	4.93E-05	4.50E-05
RL-W706	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	1.87E+00	1.110E-05	9.01E-04	8.88E-04	8.82E-04	8.71E-04	8.41E-04	7.76E-04	6.94E-04	6.40E-04	5.82E-04	5.31E-04
RL-W708	6.20E-01	3.680E-06	4.12E-04	4.06E-04	4.03E-04	3.98E-04	3.85E-04	3.55E-04	3.17E-04	2.93E-04	2.66E-04	2.43E-04
RL-W709	2.10E-01	1.247E-06	4.20E-01	4.14E-01	4.11E-01	4.06E-01	3.92E-01	3.62E-01	3.24E-01	2.98E-01	2.71E-01	2.48E-01
RL-W710	2.10E-01	1.247E-06	2.51E-05	2.47E-05	2.45E-05	2.42E-05	2.34E-05	2.16E-05	1.93E-05	1.78E-05	1.62E-05	1.48E-05
RL-W711	2.10E-01	1.247E-06	7.83E-03	7.71E-03	7.66E-03	7.57E-03	7.31E-03	6.75E-03	6.04E-03	5.57E-03	5.06E-03	4.62E-03

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W712	2.10E-01	1.247E-06	1.01E-02	9.97E-03	9.91E-03	9.79E-03	9.45E-03	8.72E-03	7.80E-03	7.19E-03	6.54E-03	5.97E-03
RL-W713	2.10E-01	1.247E-06	8.73E-03	8.60E-03	8.54E-03	8.44E-03	8.15E-03	7.52E-03	6.72E-03	6.20E-03	5.64E-03	5.14E-03
RL-W714	2.10E-01	1.247E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	4.20E-01	2.493E-06	7.41E-05	7.30E-05	7.25E-05	7.16E-05	6.91E-05	6.37E-05	5.69E-05	5.25E-05	4.77E-05	4.36E-05
RL-W716	8.40E-01	4.986E-06	3.86E-04	3.80E-04	3.78E-04	3.73E-04	3.60E-04	3.32E-04	2.97E-04	2.74E-04	2.49E-04	2.27E-04
RL-W717	2.10E-01	1.247E-06	3.86E-04	3.80E-04	3.78E-04	3.73E-04	3.60E-04	3.32E-04	2.97E-04	2.74E-04	2.49E-04	2.27E-04
RL-W718	4.20E-01	2.493E-06	3.40E-05	3.35E-05	3.33E-05	3.29E-05	3.17E-05	2.92E-05	2.61E-05	2.41E-05	2.19E-05	2.00E-05
RL-W719	4.20E-01	2.493E-06	1.54E-04	1.51E-04	1.50E-04	1.49E-04	1.43E-04	1.32E-04	1.18E-04	1.09E-04	9.91E-05	9.04E-05
RL-W720	2.52E+00	1.496E-05	1.58E-04	1.56E-04	1.55E-04	1.53E-04	1.48E-04	1.36E-04	1.22E-04	1.12E-04	1.02E-04	9.31E-05
RL-W721	2.31E+00	1.371E-05	1.17E-04	1.15E-04	1.14E-04	1.13E-04	1.09E-04	1.01E-04	8.98E-05	8.28E-05	7.53E-05	6.87E-05
RL-W723	6.20E-01	3.680E-06	1.48E-03	1.45E-03	1.44E-03	1.43E-03	1.38E-03	1.27E-03	1.14E-03	1.05E-03	9.54E-04	8.71E-04
RL-W724	3.33E+00	1.977E-05	1.82E-03	1.79E-03	1.78E-03	1.76E-03	1.70E-03	1.57E-03	1.40E-03	1.29E-03	1.17E-03	1.07E-03
RL-W725	1.25E+00	7.420E-06	1.53E-03	1.51E-03	1.50E-03	1.48E-03	1.43E-03	1.32E-03	1.18E-03	1.09E-03	9.91E-04	9.04E-04
RL-W726	1.66E+00	9.854E-06	9.12E-04	8.98E-04	8.92E-04	8.82E-04	8.52E-04	7.86E-04	7.03E-04	6.49E-04	5.90E-04	5.38E-04
RL-W727	6.24E+00	3.704E-05	1.49E-03	1.46E-03	1.45E-03	1.44E-03	1.39E-03	1.28E-03	1.15E-03	1.06E-03	9.60E-04	8.76E-04
RL-W728	8.32E+00	4.939E-05	1.02E-03	1.00E-03	9.96E-04	9.84E-04	9.51E-04	8.78E-04	7.85E-04	7.24E-04	6.58E-04	6.01E-04
RL-W729	2.91E+00	1.727E-05	1.34E-03	1.32E-03	1.31E-03	1.30E-03	1.25E-03	1.16E-03	1.03E-03	9.53E-04	8.66E-04	7.90E-04
RL-W730	1.20E+02	7.100E-04	1.65E-03	1.41E-03	1.35E-03	1.25E-03	9.41E-04	3.32E-04	1.34E-05	5.43E-07	9.86E-09	1.79E-10
RL-W731	2.10E-01	1.247E-06	8.99E-06	8.92E-06	8.90E-06	8.87E-06	8.77E-06	8.50E-06	7.96E-06	7.51E-06	6.99E-06	6.50E-06
RL-W732	6.46E+01	3.835E-04	1.21E-02	1.18E-02	1.17E-02	1.14E-02	1.09E-02	9.73E-03	8.56E-03	7.89E-03	7.18E-03	6.55E-03
RL-W733	6.30E-01	3.740E-06	1.44E-02	1.39E-02	1.37E-02	1.34E-02	1.26E-02	1.12E-02	9.72E-03	8.93E-03	8.10E-03	7.38E-03
RL-W734	4.20E-01	2.493E-06	7.27E-02	7.02E-02	6.94E-02	6.79E-02	6.42E-02	5.72E-02	5.01E-02	4.61E-02	4.18E-02	3.81E-02
RL-W735	2.10E-01	1.247E-06	1.15E-01	1.11E-01	1.09E-01	1.07E-01	1.01E-01	8.98E-02	7.84E-02	7.21E-02	6.53E-02	5.95E-02
RL-W736	2.10E-01	1.247E-06	8.42E-05	8.09E-05	8.00E-05	7.83E-05	7.31E-05	6.20E-05	5.24E-05	4.81E-05	4.35E-05	3.96E-05
RL-W737	8.40E-01	4.986E-06	2.68E-02	2.59E-02	2.56E-02	2.51E-02	2.37E-02	2.12E-02	1.85E-02	1.70E-02	1.55E-02	1.41E-02
RL-W738	2.31E+00	1.371E-05	3.25E-02	3.13E-02	3.09E-02	3.02E-02	2.84E-02	2.50E-02	2.17E-02	2.00E-02	1.81E-02	1.64E-02
RL-W739	2.10E-01	1.247E-06	5.02E-02	4.90E-02	4.86E-02	4.79E-02	4.61E-02	4.24E-02	3.79E-02	3.49E-02	3.17E-02	2.89E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
RL-W740	1.32E+01	7.853E-05	2.25E-02	2.18E-02	2.15E-02	2.11E-02	1.98E-02	1.73E-02	1.50E-02	1.38E-02	1.25E-02	1.13E-02
RL-W741	1.05E+00	6.233E-06	1.74E-01	1.51E-01	1.46E-01	1.37E-01	1.13E-01	7.33E-02	4.83E-02	4.26E-02	3.73E-02	3.30E-02
RL-W742	2.10E-01	1.247E-06	8.97E-02	8.65E-02	8.54E-02	8.34E-02	7.82E-02	6.80E-02	5.87E-02	5.40E-02	4.90E-02	4.47E-02
RL-W743	2.10E-01	1.247E-06	7.53E-05	6.88E-05	6.74E-05	6.47E-05	5.70E-05	4.17E-05	3.22E-05	3.01E-05	2.80E-05	2.60E-05
RL-W744	2.10E-01	1.247E-06	3.21E-03	3.19E-03	3.18E-03	3.17E-03	3.14E-03	3.01E-03	2.66E-03	2.37E-03	2.06E-03	1.81E-03
RL-W745	2.10E-01	1.247E-06	4.72E-04	4.65E-04	4.62E-04	4.56E-04	4.41E-04	4.06E-04	3.63E-04	3.35E-04	3.04E-04	2.78E-04
RL-W746	4.20E-01	2.493E-06	9.07E-04	8.94E-04	8.88E-04	8.77E-04	8.47E-04	7.80E-04	6.97E-04	6.43E-04	5.85E-04	5.33E-04
RL-W747	2.10E-01	1.247E-06	4.91E-03	4.84E-03	4.81E-03	4.75E-03	4.59E-03	4.23E-03	3.78E-03	3.48E-03	3.17E-03	2.89E-03
RL-W748	1.32E+01	7.853E-05	6.58E-02	6.34E-02	6.08E-02	5.59E-02	4.18E-02	1.48E-02	7.87E-04	1.94E-04	1.44E-04	1.23E-04
RL-W749	3.78E+00	2.244E-05	2.36E-03	2.33E-03	2.31E-03	2.28E-03	2.21E-03	2.04E-03	1.82E-03	1.68E-03	1.53E-03	1.39E-03
RL-W750	4.20E-01	2.493E-06	3.18E+00	3.03E+00	2.90E+00	2.67E+00	2.00E+00	7.09E-01	3.83E-02	9.91E-03	7.44E-03	6.33E-03
RL-W751	2.10E-01	1.247E-06	5.74E+00	5.47E+00	5.25E+00	4.82E+00	3.61E+00	1.28E+00	6.92E-02	1.79E-02	1.34E-02	1.14E-02
RL-W752	9.87E+00	5.859E-05	5.31E-02	5.06E-02	4.85E-02	4.46E-02	3.34E-02	1.18E-02	6.40E-04	1.66E-04	1.24E-04	1.06E-04
RL-W753	1.22E+01	7.212E-05	5.80E-01	5.53E-01	5.30E-01	4.87E-01	3.65E-01	1.29E-01	6.99E-03	1.81E-03	1.36E-03	1.16E-03
RP-W754	1.48E+03	8.810E-03	5.71E-03	5.65E-03	5.63E-03	5.61E-03	5.53E-03	5.32E-03	4.94E-03	4.62E-03	4.26E-03	3.93E-03
RP-W755	2.45E+03	1.453E-02	3.21E-03	3.10E-03	3.07E-03	3.02E-03	2.87E-03	2.56E-03	2.26E-03	2.11E-03	1.95E-03	1.80E-03
SA-T001	5.41E+00	3.211E-05	3.02E-03	2.86E-03	2.83E-03	2.77E-03	2.62E-03	2.33E-03	2.09E-03	1.96E-03	1.82E-03	1.70E-03
SA-W134	1.60E+01	9.510E-05	2.52E-03	2.13E-03	2.04E-03	1.90E-03	1.52E-03	8.35E-04	4.55E-04	4.07E-04	3.71E-04	3.39E-04
SA-W134M	2.08E+00	1.235E-05	2.52E-03	2.13E-03	2.05E-03	1.90E-03	1.52E-03	8.36E-04	4.56E-04	4.09E-04	3.72E-04	3.40E-04
T001-221F-HET	2.25E+03	1.338E-02	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.83E-02	4.54E-02	4.22E-02	3.91E-02
T001-221H-HET	4.07E+03	2.415E-02	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.83E-02	4.54E-02	4.22E-02	3.92E-02
T001-235F-HET	2.34E+02	1.389E-03	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.78E-02	5.20E-02	4.83E-02	4.54E-02	4.22E-02	3.91E-02
T001-772F-HET	2.02E+03	1.198E-02	2.76E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.83E-02	4.55E-02	4.22E-02	3.92E-02
T001-773A-CLAS	2.26E+01	1.344E-04	2.76E-01	1.55E-01	1.37E-01	1.10E-01	6.80E-02	5.21E-02	4.84E-02	4.55E-02	4.23E-02	3.92E-02
T001-773A-HET	2.61E+02	1.551E-03	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.78E-02	5.20E-02	4.83E-02	4.54E-02	4.22E-02	3.92E-02
W006-773A-VIT	6.20E-01	3.680E-06	3.49E+00	3.48E+00	3.48E+00	3.47E+00	3.45E+00	3.39E+00	3.20E+00	3.02E+00	2.81E+00	2.62E+00
W026-221F-HET	7.86E+02	4.665E-03	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.81E-02	5.23E-02	4.86E-02	4.57E-02	4.24E-02	3.94E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
W026-221H-HET	5.88E+02	3.488E-03	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.84E-02	4.55E-02	4.22E-02	3.92E-02
W026-235F-HET	9.15E+00	5.432E-05	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.83E-02	4.55E-02	4.22E-02	3.92E-02
W026-772F-HET	2.50E+00	1.484E-05	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.78E-02	5.19E-02	4.82E-02	4.54E-02	4.21E-02	3.91E-02
W026-773A-HET	4.07E+01	2.414E-04	2.75E-01	1.55E-01	1.37E-01	1.10E-01	6.79E-02	5.20E-02	4.83E-02	4.55E-02	4.22E-02	3.92E-02
W027-221F-HET	3.05E+03	1.811E-02	2.47E-01	1.42E-01	1.26E-01	1.03E-01	6.60E-02	5.19E-02	4.83E-02	4.54E-02	4.22E-02	3.92E-02
W027-221H-HET	1.34E+03	7.925E-03	2.46E-01	1.42E-01	1.26E-01	1.03E-01	6.61E-02	5.21E-02	4.84E-02	4.55E-02	4.23E-02	3.92E-02
W027-235F-HET	4.02E+02	2.385E-03	2.46E-01	1.42E-01	1.26E-01	1.03E-01	6.60E-02	5.20E-02	4.83E-02	4.55E-02	4.22E-02	3.92E-02
W027-772F-HET	7.30E+02	4.332E-03	2.46E-01	1.42E-01	1.26E-01	1.03E-01	6.60E-02	5.20E-02	4.83E-02	4.55E-02	4.22E-02	3.92E-02
W027-773A-HET	1.09E+03	6.463E-03	2.46E-01	1.42E-01	1.26E-01	1.03E-01	6.59E-02	5.19E-02	4.82E-02	4.54E-02	4.21E-02	3.91E-02
W027-999-HET	1.24E+03	7.387E-03	2.46E-01	1.42E-01	1.26E-01	1.03E-01	6.60E-02	5.19E-02	4.83E-02	4.54E-02	4.22E-02	3.91E-02
W053-773A-VIT	6.20E-01	3.680E-06	2.59E+00	2.59E+00	2.58E+00	2.58E+00	2.57E+00	2.52E+00	2.38E+00	2.25E+00	2.09E+00	1.94E+00
WP-INW169.001	1.70E+01	1.010E-04	5.53E-03	5.38E-03	5.33E-03	5.25E-03	5.00E-03	4.49E-03	3.95E-03	3.64E-03	3.31E-03	3.02E-03
WP-INW198.001	4.47E+01	2.655E-04	3.58E-03	3.50E-03	3.47E-03	3.43E-03	3.30E-03	3.02E-03	2.68E-03	2.48E-03	2.25E-03	2.05E-03
WP-INW211.001	2.86E+02	1.699E-03	5.34E-02	5.21E-02	5.17E-02	5.09E-02	4.87E-02	4.41E-02	3.89E-02	3.59E-02	3.26E-02	2.98E-02
WP-INW216.001-	8.88E+02	5.273E-03	1.17E-01	1.01E-01	9.73E-02	9.04E-02	7.02E-02	2.98E-02	8.13E-03	6.73E-03	6.08E-03	5.55E-03
WP-INW216.001-	3.09E+02	1.832E-03	9.25E-02	7.98E-02	7.69E-02	7.14E-02	5.54E-02	2.35E-02	6.34E-03	5.24E-03	4.74E-03	4.33E-03
WP-INW218.001-	7.57E+02	4.492E-03	4.13E-03	3.77E-03	3.68E-03	3.52E-03	3.05E-03	2.10E-03	1.50E-03	1.37E-03	1.25E-03	1.14E-03
WP-INW218.001-	2.50E+01	1.483E-04	1.73E-03	1.69E-03	1.67E-03	1.64E-03	1.56E-03	1.40E-03	1.23E-03	1.13E-03	1.03E-03	9.41E-04
WP-INW222.001	3.02E+01	1.795E-04	1.42E-02	1.37E-02	1.36E-02	1.34E-02	1.27E-02	1.13E-02	9.90E-03	9.12E-03	8.29E-03	7.56E-03
WP-INW243.001	6.72E+01	3.989E-04	1.38E-02	1.33E-02	1.32E-02	1.29E-02	1.22E-02	1.08E-02	9.35E-03	8.62E-03	7.83E-03	7.14E-03
WP-INW247.001R	1.08E+02	6.432E-04	1.54E-02	1.49E-02	1.48E-02	1.46E-02	1.39E-02	1.26E-02	1.11E-02	1.03E-02	9.32E-03	8.50E-03
WP-INW276.001	1.03E+01	6.108E-05	1.54E-02	1.50E-02	1.49E-02	1.47E-02	1.42E-02	1.30E-02	1.16E-02	1.07E-02	9.71E-03	8.86E-03
WP-INW276.002	1.62E+01	9.599E-05	1.46E-02	1.42E-02	1.41E-02	1.39E-02	1.34E-02	1.22E-02	1.09E-02	1.00E-02	9.10E-03	8.30E-03
WP-INW276.003	1.86E+02	1.103E-03	4.73E-02	4.60E-02	4.57E-02	4.50E-02	4.32E-02	3.94E-02	3.51E-02	3.23E-02	2.94E-02	2.68E-02
WP-INW276.004	4.66E+01	2.767E-04	4.06E-02	3.94E-02	3.91E-02	3.85E-02	3.68E-02	3.34E-02	2.95E-02	2.72E-02	2.47E-02	2.26E-02
WP-INW296.001-	1.09E+01	6.482E-05	4.67E-02	4.50E-02	4.46E-02	4.37E-02	4.13E-02	3.64E-02	3.17E-02	2.92E-02	2.65E-02	2.42E-02
WP-INW296.001-	8.11E+01	4.812E-04	2.15E-02	2.08E-02	2.06E-02	2.03E-02	1.93E-02	1.72E-02	1.51E-02	1.39E-02	1.26E-02	1.15E-02

Table PAR-50. TRU Waste Stream Volume and EPA Units per m^3 — Continued

TRU Waste Stream ID	Volume (m^3)	Probability of Selection	EPA Unit per m^3 (EPA_U/m^3) Time (years after closure)									
			0	100	125	175	350	1000	3000	5000	7500	10000
WP-LA-TA-55-19	5.88E+00	3.490E-05	3.01E-03	2.74E-03	2.68E-03	2.58E-03	2.33E-03	1.90E-03	1.58E-03	1.45E-03	1.31E-03	1.20E-03
WP-LA-TA-55-19	7.52E+01	4.464E-04	1.84E-02	1.76E-02	1.74E-02	1.71E-02	1.62E-02	1.44E-02	1.25E-02	1.15E-02	1.05E-02	9.53E-03
WP-LA-TA-55-43	1.90E+02	1.127E-03	6.86E-03	3.13E-03	2.57E-03	1.74E-03	4.49E-04	1.72E-05	1.22E-05	1.13E-05	1.05E-05	9.76E-06
WP-RF001.01	4.77E+02	2.832E-03	5.32E-03	5.14E-03	5.10E-03	5.01E-03	4.77E-03	4.28E-03	3.76E-03	3.46E-03	3.15E-03	2.87E-03
WP-RF002.01-A	3.51E+02	2.082E-03	8.18E-03	7.94E-03	7.87E-03	7.73E-03	7.35E-03	6.57E-03	5.77E-03	5.31E-03	4.83E-03	4.40E-03
WP-RF002.01-B	2.10E-01	1.247E-06	1.45E-02	1.41E-02	1.40E-02	1.38E-02	1.31E-02	1.18E-02	1.04E-02	9.59E-03	8.71E-03	7.95E-03
WP-RF003.01	2.32E+02	1.379E-03	2.27E-01	2.21E-01	2.20E-01	2.16E-01	2.07E-01	1.88E-01	1.66E-01	1.53E-01	1.39E-01	1.27E-01
WP-RF004.01	5.67E+00	3.366E-05	5.21E-03	5.09E-03	5.06E-03	4.99E-03	4.80E-03	4.41E-03	3.93E-03	3.62E-03	3.29E-03	3.00E-03
WP-RF005.01	1.21E+02	7.155E-04	3.68E-01	3.41E-01	3.35E-01	3.23E-01	2.88E-01	2.19E-01	1.70E-01	1.56E-01	1.42E-01	1.29E-01
WP-RF005.02	7.83E+01	4.650E-04	4.93E-01	4.46E-01	4.35E-01	4.14E-01	3.54E-01	2.32E-01	1.58E-01	1.43E-01	1.30E-01	1.19E-01
WP-RF006.01	2.21E+02	1.311E-03	2.17E-01	2.10E-01	2.08E-01	2.05E-01	1.96E-01	1.78E-01	1.57E-01	1.45E-01	1.32E-01	1.20E-01
WP-RF008.01	8.00E+01	4.749E-04	1.77E-01	1.72E-01	1.71E-01	1.68E-01	1.60E-01	1.44E-01	1.27E-01	1.17E-01	1.06E-01	9.70E-02
WP-RF009.01	1.30E+03	7.711E-03	3.87E-01	3.58E-01	3.51E-01	3.38E-01	3.01E-01	2.24E-01	1.72E-01	1.58E-01	1.43E-01	1.31E-01
WP-RF010.01	5.55E+01	3.295E-04	8.55E-03	8.33E-03	8.25E-03	8.11E-03	7.72E-03	6.91E-03	6.06E-03	5.58E-03	5.07E-03	4.63E-03
WP-RF029.01-A	4.89E+01	2.902E-04	1.82E-03	1.77E-03	1.75E-03	1.71E-03	1.61E-03	1.40E-03	1.21E-03	1.11E-03	1.01E-03	9.23E-04
WP-RF029.01-B	1.88E+01	1.116E-04	4.58E-03	4.34E-03	4.28E-03	4.15E-03	3.79E-03	3.05E-03	2.50E-03	2.30E-03	2.08E-03	1.90E-03
WP-RF118.01	1.27E+03	7.559E-03	2.45E-01	2.39E-01	2.36E-01	2.32E-01	2.22E-01	2.00E-01	1.76E-01	1.62E-01	1.47E-01	1.35E-01
WP-RLMPDT.001	7.35E+00	4.363E-05	6.87E-03	6.59E-03	6.50E-03	6.35E-03	5.95E-03	5.19E-03	4.48E-03	4.11E-03	3.72E-03	3.39E-03
WP-RLNPDT.002	9.07E+01	5.385E-04	5.79E-03	5.54E-03	5.46E-03	5.32E-03	4.95E-03	4.22E-03	3.59E-03	3.29E-03	2.98E-03	2.71E-03
WP-SR2001.001.	6.17E+01	3.665E-04	6.39E-04	6.15E-04	6.08E-04	5.98E-04	5.72E-04	5.28E-04	4.74E-04	4.38E-04	3.99E-04	3.65E-04
WP-SR-W027-221	1.41E+02	8.377E-04	9.96E-04	9.50E-04	9.37E-04	9.14E-04	8.53E-04	7.39E-04	6.34E-04	5.82E-04	5.27E-04	4.79E-04
CH Total	1.685E+05	1.000E+00										
RH Total	7.078E+03	1.000E+00	3.477E-02	1.475E-02	1.344E-02	1.189E-02	9.480E-03	5.767E-03	3.612E-03	3.248E-03	2.930E-03	2.658E-03

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	8.48E+01	0.00E+00	1.38E+01	2.09E+02	1.24E+02	5.12E+01	1.47E-02	4.31E+02	1.74E+00
AE-T003	1.00E+01	0.00E+00	1.84E+00	6.45E+01	2.49E+01	2.81E+01	3.03E-04	1.01E+02	4.09E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	4.67E-02	0.00E+00	4.88E+01	4.76E+01	2.87E-01	5.47E-02	5.53E-03	9.67E+01	3.90E-01
AW-T033.1325	1.71E-01	0.00E+00	1.79E+02	1.74E+02	1.05E+00	2.00E-01	2.03E-02	3.54E+02	1.43E+00
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.72E-01	0.00E+00	0.00E+00	0.00E+00	7.72E-01	3.11E-03
BCLCH-MT01	1.53E+01	0.00E+00	1.38E+03	2.87E+01	7.51E+00	7.72E+01	1.43E-01	1.43E+03	5.78E+00
BT-T002	1.20E-02	7.43E-04	7.22E-01	7.24E-04	1.48E-03	3.39E-02	2.06E-03	7.39E-01	2.98E-03
ET-C1-B55	5.30E-02	0.00E+00	8.23E-03	6.20E-02	3.09E-02	5.98E-02	2.37E-04	1.54E-01	6.22E-04
ET-C1-D139	7.28E-03	0.00E+00	1.14E-03	8.72E-03	4.35E-03	7.95E-03	1.80E-07	2.15E-02	8.66E-05
ET-C2-SEFOR	1.83E-01	0.00E+00	0.00E+00	1.37E-01	4.59E-02	1.23E-01	0.00E+00	3.66E-01	1.47E-03
FM-MOX-MT02	1.63E-06	0.00E+00	4.60E-07	3.00E-07	1.78E-07	4.27E-06	5.60E-11	2.56E-06	1.03E-08
FM-MOX-T01	2.68E-05	0.00E+00	7.59E-06	4.94E-06	2.94E-06	7.03E-05	9.24E-10	4.23E-05	1.71E-07
IN-BN-510	7.07E+03	0.00E+00	3.91E+04	3.97E+04	3.36E+03	1.68E+01	6.00E+00	8.92E+04	3.60E+02
IN-GEM-01	8.90E+01	0.00E+00	7.76E-01	4.46E+01	1.02E+01	1.19E+01	8.01E-05	1.45E+02	5.83E-01
IN-GEM-02	2.11E+01	0.00E+00	1.85E-01	1.06E+01	2.42E+00	2.81E+00	1.91E-05	3.43E+01	1.38E-01
IN-W157.144	9.87E+01	0.00E+00	7.52E+00	3.03E+02	6.85E+01	2.10E+02	1.15E-03	4.77E+02	1.93E+00
IN-W163.1007	1.59E+01	0.00E+00	2.32E+00	9.39E+01	2.12E+01	6.47E+01	3.56E-04	1.33E+02	5.38E-01
IN-W164.153	1.52E-01	0.00E+00	2.21E-02	8.94E-01	2.02E-01	6.19E-01	3.39E-06	1.27E+00	5.12E-03
IN-W167.149	3.12E+01	0.00E+00	3.60E+00	1.45E+02	3.28E+01	1.00E+02	5.51E-04	2.13E+02	8.57E-01
IN-W174.154	0.00E+00	0.00E+00	2.04E+03	1.95E+00	3.84E+00	0.00E+00	3.12E-01	2.04E+03	8.23E+00
IN-W177.156	2.11E-02	0.00E+00	4.33E+03	1.83E+00	1.12E-02	8.62E-02	6.62E-01	4.33E+03	1.75E+01
IN-W179.158	1.42E-01	0.00E+00	4.31E+03	1.06E-01	5.50E-02	5.79E-01	6.60E-01	4.31E+03	1.74E+01
IN-W181.162	2.02E+00	0.00E+00	2.94E-01	1.18E+01	2.67E+00	8.21E+00	4.50E-05	1.68E+01	6.76E-02
IN-W188.160	1.36E+01	0.00E+00	1.97E+00	7.96E+01	1.79E+01	5.53E+01	3.02E-04	1.13E+02	4.56E-01
IN-W216.98	1.37E+05	0.00E+00	1.61E+02	6.49E+03	1.48E+03	4.52E+03	2.46E-02	1.46E+05	5.87E+02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	6.91E+02	0.00E+00	3.57E+00	1.44E+02	3.26E+01	1.00E+02	5.48E-04	8.71E+02	3.51E+00
IN-W219.110	8.27E-01	0.00E+00	1.20E-01	4.86E+00	1.10E+00	3.36E+00	1.84E-05	6.90E+00	2.78E-02
IN-W219.914	1.30E-01	0.00E+00	1.90E-02	7.66E-01	1.73E-01	5.32E-01	2.90E-06	1.09E+00	4.39E-03
IN-W220.114	4.90E+03	0.00E+00	1.27E+01	5.49E+02	1.21E+02	3.54E+02	1.94E-03	5.58E+03	2.25E+01
IN-W221.927	5.05E+00	0.00E+00	7.34E-01	2.96E+01	6.68E+00	2.06E+01	1.12E-04	4.20E+01	1.70E-01
IN-W222.116	1.72E+02	0.00E+00	2.49E+01	9.99E+02	2.26E+02	6.94E+02	3.81E-03	1.42E+03	5.73E+00
IN-W228.101	1.29E+03	0.00E+00	8.08E+00	3.27E+02	7.38E+01	2.27E+02	1.24E-03	1.70E+03	6.85E+00
IN-W240.931	1.28E+02	0.00E+00	1.03E+01	4.20E+02	9.44E+01	2.87E+02	1.58E-03	6.52E+02	2.63E+00
IN-W243.808	1.73E+02	0.00E+00	1.81E+01	7.32E+02	1.65E+02	5.08E+02	2.77E-03	1.09E+03	4.39E+00
IN-W245.301	2.48E+02	0.00E+00	3.56E+01	1.43E+03	3.24E+02	9.92E+02	5.45E-03	2.04E+03	8.21E+00
IN-W247.810	1.21E+02	0.00E+00	1.73E+01	6.98E+02	1.59E+02	4.84E+02	2.65E-03	9.95E+02	4.01E+00
IN-W249.527	0.00E+00	0.00E+00	1.21E+03	1.24E+01	0.00E+00	0.00E+00	1.86E-01	1.22E+03	4.94E+00
IN-W263.520	3.45E-02	0.00E+00	1.27E+02	8.42E+00	1.34E-02	1.40E-01	1.94E-02	1.35E+02	5.45E-01
IN-W267.1005	2.88E+01	0.00E+00	4.20E+00	1.70E+02	3.84E+01	1.18E+02	6.44E-04	2.41E+02	9.73E-01
IN-W309.609	8.14E+02	0.00E+00	7.04E+01	2.84E+03	6.42E+02	1.97E+03	1.08E-02	4.36E+03	1.76E+01
IN-W315.601	8.69E+02	0.00E+00	2.94E-01	1.19E+01	2.68E+00	8.21E+00	4.51E-05	8.84E+02	3.57E+00
IN-W319.584	4.44E+00	0.00E+00	6.45E-01	2.61E+01	5.91E+00	1.81E+01	9.87E-05	3.71E+01	1.50E-01
IN-W321.1023	3.84E+01	0.00E+00	5.59E+00	2.26E+02	5.10E+01	1.56E+02	8.57E-04	3.21E+02	1.29E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	9.11E+00	1.88E+00	0.00E+00	0.00E+00	1.10E+01	4.43E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.43E+01	5.02E+00	0.00E+00	0.00E+00	2.93E+01	1.18E-01
IN-W323.562	8.20E-02	0.00E+00	9.48E-01	2.49E-01	0.00E+00	3.34E-01	1.45E-04	1.28E+00	5.16E-03
IN-W323.951	9.68E-02	0.00E+00	1.13E-02	2.97E-01	0.00E+00	3.94E-01	1.73E-06	4.05E-01	1.63E-03
IN-W332.661	0.00E+00	0.00E+00	1.24E+01	1.29E-01	0.00E+00	0.00E+00	1.91E-03	1.26E+01	5.06E-02
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	3.04E+00	6.28E-01	0.00E+00	0.00E+00	3.67E+00	1.48E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	9.11E+00	1.88E+00	0.00E+00	0.00E+00	1.10E+01	4.43E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.95E+00	0.00E+00	0.00E+00	0.00E+00	1.95E+00	7.86E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.86E+00	0.00E+00	0.00E+00	0.00E+00	5.86E+00	2.36E-02
IN-W342.652	4.32E+00	0.00E+00	0.00E+00	4.02E-02	1.04E-17	0.00E+00	0.00E+00	4.36E+00	1.76E-02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W342.953	2.89E+00	0.00E+00	0.00E+00	2.69E-02	6.96E-18	0.00E+00	0.00E+00	2.92E+00	1.18E-02
IN-W347.818	2.26E+00	0.00E+00	0.00E+00	8.25E+01	1.52E+02	0.00E+00	1.58E-08	2.36E+02	9.53E-01
IN-W348.1012	1.20E-01	0.00E+00	1.03E+01	4.17E+02	9.43E+01	0.00E+00	1.57E-03	5.21E+02	2.10E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.50E-02	0.00E+00	0.00E+00	0.00E+00	2.50E-02	1.01E-04
IN-W357.1022	0.00E+00	0.00E+00	2.02E-02	8.18E-01	1.84E-01	0.00E+00	3.09E-06	1.02E+00	4.12E-03
IN-W358.854	0.00E+00	0.00E+00	3.04E+02	1.88E+00	3.62E+00	0.00E+00	3.94E-02	3.10E+02	1.25E+00
IN-W358.855	0.00E+00	0.00E+00	1.62E+03	9.99E+00	1.92E+01	0.00E+00	2.10E-01	1.65E+03	6.66E+00
IN-W358.948	0.00E+00	0.00E+00	3.39E+02	2.09E+00	4.01E+00	0.00E+00	4.39E-02	3.45E+02	1.39E+00
IN-W361.1021	3.18E-02	0.00E+00	1.96E+00	7.89E+01	1.78E+01	0.00E+00	3.00E-04	9.88E+01	3.98E-01
IN-W362.1020	0.00E+00	0.00E+00	2.56E+01	1.03E+03	2.34E+02	0.00E+00	3.93E-03	1.29E+03	5.20E+00
IN-W363.1019	0.00E+00	0.00E+00	1.20E+00	4.89E+01	1.11E+01	0.00E+00	1.85E-04	6.11E+01	2.47E-01
IN-W364.1011	0.00E+00	0.00E+00	1.99E+00	8.03E+01	1.81E+01	0.00E+00	3.05E-04	1.01E+02	4.05E-01
IN-W365.1010	2.96E+02	0.00E+00	1.58E+00	6.34E+01	1.44E+01	0.00E+00	2.42E-04	3.76E+02	1.52E+00
IN-W366.841	1.05E+00	0.00E+00	1.34E+00	5.41E+01	1.23E+01	0.00E+00	2.06E-04	6.87E+01	2.77E-01
IN-W372.832	4.32E+00	0.00E+00	0.00E+00	4.02E-02	1.04E-17	0.00E+00	0.00E+00	4.36E+00	1.76E-02
IN-W375.1096	0.00E+00	0.00E+00	4.96E-01	2.00E+01	4.52E+00	0.00E+00	7.59E-05	2.50E+01	1.01E-01
KN-B234TRU	1.50E+02	0.00E+00	1.90E+01	2.91E+02	9.77E+01	1.10E+02	3.91E-03	5.57E+02	2.25E+00
LA-IT-00-01	2.23E+00	4.79E-01	3.23E+00	5.85E-01	1.13E-02	2.11E-08	6.88E-04	6.06E+00	2.44E-02
LA-OS-00-01	4.97E+03	0.00E+00	1.48E+05	1.23E+03	0.00E+00	0.00E+00	1.58E+01	1.54E+05	6.20E+02
LA-PX-00-01	1.95E-02	0.00E+00	6.22E-03	9.04E-02	2.12E-02	3.49E-02	7.82E-07	1.37E-01	5.54E-04
LA-SL-00-01	0.00E+00	0.00E+00	1.31E-01	1.53E-01	0.00E+00	0.00E+00	2.74E-05	2.84E-01	1.15E-03
LA-TA-03-12	2.06E-01	0.00E+00	3.04E+00	4.36E-01	1.52E-01	2.07E-01	6.95E-04	3.83E+00	1.55E-02
LA-TA-03-13	2.66E-01	0.00E+00	9.63E+00	6.80E-01	1.60E-01	2.74E-01	1.53E-03	1.07E+01	4.33E-02
LA-TA-03-19	5.42E-01	0.00E+00	1.44E+01	1.33E+00	3.84E-01	4.24E-01	3.27E-03	1.66E+01	6.70E-02
LA-TA-03-20	2.92E-01	0.00E+00	6.82E+00	5.86E-01	2.06E-01	3.47E-01	1.39E-03	7.90E+00	3.19E-02
LA-TA-03-24	3.95E-01	0.00E+00	2.66E+01	1.09E+00	3.30E-01	3.60E-01	6.15E-03	2.84E+01	1.14E-01
LA-TA-03-26	1.98E-02	0.00E+00	1.10E+00	2.64E+00	4.32E-02	3.15E-02	1.12E-03	3.80E+00	1.53E-02
LA-TA-03-28	0.00E+00	0.00E+00	3.79E-01	2.47E-01	0.00E+00	0.00E+00	8.43E-05	6.26E-01	2.52E-03

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-03-30	8.72E-01	0.00E+00	2.70E-01	5.03E+00	1.46E+00	1.65E+00	5.89E-05	7.62E+00	3.07E-02
LA-TA-03-31	0.00E+00	0.00E+00	1.35E-02	8.79E-03	0.00E+00	0.00E+00	3.01E-06	2.23E-02	9.00E-05
LA-TA-03-40	0.00E+00	0.00E+00	2.14E-02	5.47E-02	0.00E+00	0.00E+00	4.84E-06	7.60E-02	3.07E-04
LA-TA-03-42	2.01E-05	0.00E+00	5.35E-04	3.42E-03	4.50E-05	3.45E-05	1.21E-07	4.02E-03	1.62E-05
LA-TA-21-06	1.98E-01	0.00E+00	5.89E+01	9.56E-01	2.92E-01	3.56E-01	1.31E-02	6.03E+01	2.43E-01
LA-TA-21-12	7.23E-01	0.00E+00	3.55E+02	3.32E+00	9.91E-01	1.22E+00	7.89E-02	3.60E+02	1.45E+00
LA-TA-21-13	1.18E+00	0.00E+00	0.00E+00	2.94E-01	0.00E+00	0.00E+00	0.00E+00	1.47E+00	5.93E-03
LA-TA-21-14	1.76E-04	0.00E+00	6.77E+00	4.49E+00	5.23E-05	4.95E-04	8.77E-04	1.13E+01	4.54E-02
LA-TA-21-15	1.07E-01	0.00E+00	1.86E-02	1.39E+00	2.37E-01	2.01E-01	4.05E-06	1.75E+00	7.06E-03
LA-TA-21-16	1.25E+00	0.00E+00	2.87E-01	1.06E+01	2.53E+00	2.12E+00	6.52E-05	1.47E+01	5.91E-02
LA-TA-21-40	1.65E-04	0.00E+00	9.94E-01	3.33E-01	3.68E-04	8.49E-05	3.54E-04	1.33E+00	5.35E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	7.08E-01	0.00E+00	0.00E+00	0.00E+00	7.08E-01	2.86E-03
LA-TA-21-42	1.71E-02	0.00E+00	3.23E-01	1.64E-01	1.12E-02	2.76E-03	1.30E-04	5.15E-01	2.08E-03
LA-TA-21-43	5.98E+01	0.00E+00	1.07E+01	5.11E+02	1.22E+02	2.19E+01	4.25E-03	7.03E+02	2.83E+00
LA-TA-21-44	2.80E-01	0.00E+00	2.25E+00	1.15E+02	3.06E-01	3.09E-01	6.07E-04	1.18E+02	4.75E-01
LA-TA-48-01	9.31E-02	2.26E+00	8.47E-03	1.18E-01	4.87E-01	2.55E-02	3.06E-06	7.07E-01	2.85E-03
LA-TA-49-01	1.15E+01	2.80E+02	1.04E+00	1.46E+01	6.04E+01	3.15E+00	3.78E-04	8.75E+01	3.53E-01
LA-TA-50-10	3.11E-02	0.00E+00	9.86E-03	4.59E-02	0.00E+00	0.00E+00	1.20E-06	8.68E-02	3.50E-04
LA-TA-50-11	5.84E-02	0.00E+00	1.01E-02	4.66E-01	1.04E-01	2.53E-02	3.52E-06	6.38E-01	2.57E-03
LA-TA-50-15	1.14E-01	0.00E+00	1.49E+00	3.40E-01	7.62E-02	1.00E-01	2.75E-04	2.02E+00	8.15E-03
LA-TA-50-17	1.71E+01	0.00E+00	1.21E+00	1.82E+01	4.29E-04	9.15E-03	5.63E-04	3.65E+01	1.47E-01
LA-TA-50-18	1.02E+00	0.00E+00	1.60E-01	2.97E+00	5.34E-06	2.70E-04	3.63E-05	4.14E+00	1.67E-02
LA-TA-50-19	3.24E-01	0.00E+00	7.13E-02	3.95E-01	4.57E-03	3.34E-03	4.30E-05	7.95E-01	3.21E-03
LA-TA-50-20	8.90E-03	0.00E+00	0.00E+00	9.73E-03	0.00E+00	0.00E+00	0.00E+00	1.86E-02	7.51E-05
LA-TA-50-40	4.64E-03	0.00E+00	9.63E-04	1.06E-02	4.95E-03	1.07E-02	1.93E-07	2.12E-02	8.53E-05
LA-TA-50-41	4.69E-03	0.00E+00	9.71E-04	4.70E-02	1.10E-02	1.91E-02	1.49E-07	6.36E-02	2.56E-04
LA-TA-55-19	7.92E+00	0.00E+00	1.28E+00	2.64E+01	7.45E+00	1.08E+01	1.80E-03	4.30E+01	1.74E-01
LA-TA-55-20	1.24E+02	0.00E+00	1.46E+01	6.37E+02	1.54E+02	2.70E+02	9.64E-02	9.29E+02	3.75E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-21	1.11E+00	6.67E-04	1.68E-01	4.52E+00	1.09E+00	2.23E+00	2.50E-05	6.88E+00	2.78E-02
LA-TA-55-22	3.02E+00	0.00E+00	9.48E-01	1.59E+01	3.73E+00	6.90E+00	1.41E-04	2.36E+01	9.51E-02
LA-TA-55-23	2.84E+00	0.00E+00	7.92E-01	1.09E+01	2.70E+00	6.79E+00	1.15E-04	1.72E+01	6.94E-02
LA-TA-55-24	1.05E+00	0.00E+00	1.24E-01	5.72E+00	1.34E+00	3.24E+00	1.56E-05	8.22E+00	3.32E-02
LA-TA-55-25	5.35E+00	0.00E+00	7.25E-01	2.84E+01	6.65E+00	1.66E+01	9.11E-05	4.11E+01	1.66E-01
LA-TA-55-28	1.83E+00	0.00E+00	4.02E-01	8.71E+00	2.06E+00	5.38E+00	5.20E-05	1.30E+01	5.25E-02
LA-TA-55-30	4.36E+01	6.32E-06	4.81E+00	1.43E+02	3.46E+01	3.94E+01	1.27E-03	2.26E+02	9.11E-01
LA-TA-55-32	3.48E+00	0.00E+00	2.69E+01	1.13E+01	3.50E+00	4.91E+00	6.27E-03	4.51E+01	1.82E-01
LA-TA-55-33	5.22E-01	0.00E+00	6.94E-02	1.49E+00	4.76E-01	6.90E-01	1.36E-05	2.56E+00	1.03E-02
LA-TA-55-34	5.24E+01	0.00E+00	6.42E+00	2.31E+02	5.88E+01	8.32E+01	4.03E-03	3.48E+02	1.41E+00
LA-TA-55-38	1.38E+02	0.00E+00	2.11E+00	5.10E+01	1.38E+01	1.94E+01	2.11E-03	2.05E+02	8.26E-01
LA-TA-55-39	1.35E+01	0.00E+00	1.56E+00	7.60E+01	1.71E+01	3.41E+01	2.20E-04	1.08E+02	4.36E-01
LA-TA-55-41	3.48E+02	0.00E+00	3.23E+00	9.43E+01	2.26E+01	4.29E+01	4.95E-04	4.68E+02	1.89E+00
LA-TA-55-43	1.18E-01	0.00E+00	2.12E+02	1.42E-01	4.98E-02	3.77E-01	2.91E-02	2.12E+02	8.56E-01
LA-TA-55-44	1.10E+00	0.00E+00	4.99E+02	2.63E+00	7.32E-01	1.11E+00	9.97E-02	5.04E+02	2.03E+00
LA-TA-55-48	7.99E+03	0.00E+00	1.97E+03	1.69E+04	6.32E+03	1.16E+04	3.69E-01	3.32E+04	1.34E+02
LA-TA-55-49	1.75E+01	0.00E+00	2.59E+03	3.09E+01	8.70E+00	1.36E+01	5.07E-01	2.65E+03	1.07E+01
LA-TA-55-53	8.20E+01	0.00E+00	5.36E+00	2.64E+02	6.18E+01	7.46E+01	1.01E-03	4.13E+02	1.67E+00
LA-TA-55-56	8.77E+01	0.00E+00	2.00E+02	3.82E+02	9.61E+01	1.73E+02	3.23E-02	7.65E+02	3.09E+00
LA-TA-55-60	4.73E-02	0.00E+00	5.04E-02	7.19E-02	2.56E-02	1.02E-01	9.84E-06	1.95E-01	7.87E-04
LA-TA-55-61	4.03E-02	0.00E+00	2.32E-01	1.39E-01	4.72E-02	9.88E-02	4.34E-05	4.59E-01	1.85E-03
LA-TA-55-62	1.04E-02	0.00E+00	2.21E-03	2.33E-02	1.12E-02	2.66E-02	4.22E-07	4.71E-02	1.90E-04
LA-TA-55-63	7.50E-03	0.00E+00	1.49E-03	7.46E-02	1.73E-02	2.61E-02	2.47E-07	1.01E-01	4.07E-04
LL-M001	1.08E+02	3.03E+01	6.50E+01	6.99E+01	3.16E+01	2.06E+02	6.71E-03	2.75E+02	1.11E+00
LL-T001	5.20E+02	0.00E+00	0.00E+00	5.34E+02	2.41E+02	1.60E+03	0.00E+00	1.30E+03	5.22E+00
LL-T002	5.20E+03	0.00E+00	5.17E+02	5.18E+03	2.13E+03	1.41E+04	5.34E-02	1.30E+04	5.25E+01
LL-T003	2.02E+02	0.00E+00	5.79E+01	1.05E+02	8.49E+01	5.57E+02	5.97E-03	4.49E+02	1.81E+00
LL-T004	1.28E+02	0.00E+00	1.19E+01	6.66E+01	5.35E+01	3.54E+02	1.23E-03	2.60E+02	1.05E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
LL-T005	6.79E+02	1.32E+03	1.40E+02	2.48E+02	2.11E+02	1.31E+03	1.44E-02	1.28E+03	5.15E+00
LL-W018	5.25E-02	0.00E+00	0.00E+00	1.85E-02	4.27E-02	2.68E-01	0.00E+00	1.14E-01	4.58E-04
LL-W019	3.08E+01	0.00E+00	0.00E+00	1.44E+01	1.21E+01	7.84E+01	0.00E+00	5.72E+01	2.31E-01
LL-W034	1.16E+01	2.23E+01	2.45E+00	4.20E+00	3.50E+00	2.23E+01	2.53E-04	2.17E+01	8.77E-02
MC-W001	1.53E-01	0.00E+00	0.00E+00	6.05E-02	0.00E+00	4.03E-02	0.00E+00	2.14E-01	8.61E-04
MU-W002	2.06E+00	0.00E+00	0.00E+00	5.26E-02	0.00E+00	0.00E+00	2.67E-12	2.11E+00	8.52E-03
NT-JAS-01	1.82E+02	0.00E+00	5.21E+01	9.47E+01	7.64E+01	5.02E+02	5.38E-03	4.05E+02	1.63E+00
NT-W001	2.98E+02	6.82E-01	1.04E+02	2.86E+03	1.91E+01	3.51E+01	2.23E-02	3.28E+03	1.32E+01
NT-W021	5.17E+00	0.00E+00	7.46E-01	3.22E+01	7.36E+00	1.80E+01	1.23E-04	4.54E+01	1.83E-01
OR-W201	6.29E+03	4.70E+01	2.24E+03	2.16E+03	2.13E+03	1.88E+04	4.38E+01	1.29E+04	5.18E+01
OR-W202	9.74E+02	9.78E+02	6.45E+03	5.54E+02	5.42E+02	6.04E+02	1.12E+00	8.52E+03	3.44E+01
OR-W203	2.14E+00	3.41E+01	9.24E-01	2.49E-02	1.68E+00	1.53E+00	1.57E-04	4.77E+00	1.92E-02
OR-W204	4.88E-01	1.41E-04	1.05E+00	4.24E-01	2.87E-01	0.00E+00	1.78E-04	2.25E+00	9.06E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.26E-01	0.00E+00	0.00E+00	0.00E+00	4.26E-01	1.72E-03
RF-MT0001	1.87E+03	0.00E+00	6.51E+00	1.96E+02	4.48E+01	1.38E+02	9.71E-04	2.12E+03	8.53E+00
RF-MT0002	1.44E+02	0.00E+00	4.99E-01	1.51E+01	3.44E+00	1.06E+01	7.45E-05	1.63E+02	6.56E-01
RF-MT0003	5.72E-01	0.00E+00	1.14E-01	3.45E+00	7.87E-01	2.42E+00	1.71E-05	4.92E+00	1.98E-02
RF-MT0007	1.64E+00	0.00E+00	0.00E+00	4.30E-01	9.80E-02	2.81E-01	0.00E+00	2.17E+00	8.74E-03
RF-MT0089	5.64E-03	0.00E+00	1.14E-03	3.45E-02	7.86E-03	2.42E-02	1.70E-07	4.91E-02	1.98E-04
RF-MT0090	1.56E+01	0.00E+00	1.62E+00	8.85E+01	2.00E+01	2.42E+01	2.41E-04	1.26E+02	5.07E-01
RF-MT0091	9.49E+02	0.00E+00	1.64E+02	5.92E+03	1.35E+03	2.00E+03	2.75E-02	8.37E+03	3.38E+01
RF-MT0092	1.36E+02	0.00E+00	2.07E+01	8.47E+02	1.96E+02	2.76E+02	3.08E-03	1.20E+03	4.84E+00
RF-MT0093	1.69E+02	0.00E+00	2.13E+01	9.14E+02	2.15E+02	2.36E+02	3.17E-03	1.32E+03	5.32E+00
RF-MT0097	8.44E+00	0.00E+00	9.40E-01	4.78E+01	9.79E+00	1.29E+01	1.40E-04	6.69E+01	2.70E-01
RF-MT0099	8.48E-03	0.00E+00	1.72E-03	5.17E-02	1.18E-02	3.64E-02	2.56E-07	7.36E-02	2.97E-04
RF-MT0290	2.10E+01	0.00E+00	4.25E+00	1.28E+02	2.92E+01	9.02E+01	6.33E-04	1.82E+02	7.35E-01
RF-MT-0292	2.65E+01	0.00E+00	5.37E+00	1.62E+02	3.69E+01	1.14E+02	8.01E-04	2.31E+02	9.30E-01
RF-MT-0299	3.48E+03	0.00E+00	1.38E+02	4.15E+03	9.47E+02	2.94E+03	2.05E-02	8.71E+03	3.51E+01

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0302	5.09E-02	0.00E+00	5.45E-03	1.79E-01	4.10E-02	1.14E-01	1.77E-05	2.76E-01	1.11E-03
RF-MT0320	6.16E+01	0.00E+00	5.65E+00	1.74E+02	3.98E+01	1.15E+02	8.55E-04	2.81E+02	1.13E+00
RF-MT0321	3.55E+01	0.00E+00	1.69E+00	5.60E+01	1.27E+01	3.21E+01	2.66E-03	1.06E+02	4.27E-01
RF-MT-0328	2.39E+00	0.00E+00	2.02E-01	6.08E+00	1.39E+00	4.29E+00	3.69E-04	1.01E+01	4.06E-02
RF-MT0330	2.50E+01	0.00E+00	2.21E+00	1.23E+02	3.03E+01	4.03E+01	3.30E-04	1.80E+02	7.27E-01
RF-MT-0331	1.50E+02	0.00E+00	1.38E+01	5.41E+02	1.21E+02	2.34E+02	2.28E-02	8.25E+02	3.33E+00
RF-MT0332	1.98E-02	0.00E+00	4.01E-03	1.21E-01	2.75E-02	8.51E-02	5.98E-07	1.72E-01	6.94E-04
RF-MT-0335	1.70E+00	0.00E+00	1.84E-01	6.22E+00	1.43E+00	3.47E+00	5.70E-04	9.54E+00	3.85E-02
RF-MT0336	1.22E+02	0.00E+00	1.22E+01	4.42E+02	1.01E+02	2.04E+02	3.64E-03	6.76E+02	2.73E+00
RF-MT0337	6.94E+01	0.00E+00	6.70E+00	2.70E+02	6.05E+01	9.94E+01	4.85E-03	4.06E+02	1.64E+00
RF-MT0339	1.87E+02	0.00E+00	1.83E+01	5.92E+02	1.34E+02	3.60E+02	1.98E-02	9.30E+02	3.75E+00
RF-MT-0342	1.08E+00	0.00E+00	1.53E-01	5.47E+00	1.23E+00	2.64E+00	8.13E-05	7.92E+00	3.20E-02
RF-MT0371	3.70E+02	0.00E+00	3.54E+01	1.07E+03	2.43E+02	7.52E+02	6.58E-03	1.72E+03	6.93E+00
RF-MT-0372	1.57E+00	0.00E+00	2.49E-01	7.45E+00	1.70E+00	4.65E+00	2.77E-04	1.10E+01	4.43E-02
RF-MT0373	2.47E+01	0.00E+00	2.56E+00	1.40E+02	3.17E+01	3.84E+01	3.83E-04	1.99E+02	8.02E-01
RF-MT0374	7.77E-01	0.00E+00	9.16E-02	2.77E+00	6.31E-01	1.94E+00	1.70E-05	4.27E+00	1.72E-02
RF-MT0376	6.20E-01	0.00E+00	7.40E-02	2.76E+00	6.39E-01	1.43E+00	2.61E-05	4.09E+00	1.65E-02
RF-MT0377	3.66E+02	0.00E+00	4.26E+01	1.29E+03	2.93E+02	9.04E+02	1.66E-02	1.99E+03	8.03E+00
RF-MT0378	4.04E+00	0.00E+00	5.90E-01	1.78E+01	4.06E+00	1.25E+01	8.79E-05	2.65E+01	1.07E-01
RF-MT0419	6.77E+00	0.00E+00	5.51E-01	1.66E+01	3.79E+00	1.17E+01	8.21E-05	2.77E+01	1.12E-01
RF-MT0420	1.18E+00	0.00E+00	9.55E-02	2.88E+00	6.58E-01	2.03E+00	1.43E-05	4.81E+00	1.94E-02
RF-MT0423	1.03E+01	0.00E+00	7.77E-01	4.16E+01	9.20E+00	8.06E+00	1.16E-04	6.19E+01	2.49E-01
RF-MT0425	2.95E-01	0.00E+00	2.39E-02	7.20E-01	1.64E-01	5.08E-01	3.57E-06	1.20E+00	4.85E-03
RF-MT-0438	2.66E+00	0.00E+00	3.14E-01	1.28E+01	2.89E+00	5.04E+00	6.00E-05	1.87E+01	7.52E-02
RF-MT0440	9.57E-01	0.00E+00	1.13E-01	4.64E+00	1.08E+00	2.07E+00	1.82E-04	6.78E+00	2.74E-02
RF-MT0442	3.65E-01	0.00E+00	4.87E-02	1.59E+00	3.62E-01	7.69E-01	1.02E-04	2.36E+00	9.53E-03
RF-MT0443	4.26E+00	0.00E+00	8.00E-01	2.47E+01	5.63E+00	1.61E+01	2.78E-04	3.54E+01	1.43E-01
RF-MT0444	3.47E+01	0.00E+00	3.92E+00	1.19E+02	2.70E+01	8.32E+01	6.08E-04	1.85E+02	7.44E-01

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0480	9.77E+01	0.00E+00	1.10E+01	3.34E+02	7.62E+01	2.14E+02	4.11E-03	5.19E+02	2.09E+00
RF-MT0488	1.56E+02	0.00E+00	1.65E+01	4.96E+02	1.13E+02	3.49E+02	3.34E-02	7.81E+02	3.15E+00
RF-MT0490	6.97E-01	0.00E+00	9.55E-02	2.93E+00	6.69E-01	1.93E+00	2.55E-05	4.39E+00	1.77E-02
RF-MT-0491	5.68E-02	0.00E+00	4.37E-03	1.33E-01	3.02E-02	9.02E-02	2.66E-06	2.24E-01	9.04E-04
RF-MT0523A	4.49E+01	0.00E+00	3.47E+00	1.05E+02	2.39E+01	7.35E+01	7.74E-04	1.77E+02	7.15E-01
RF-MT0523B	4.49E+01	0.00E+00	3.47E+00	1.05E+02	2.39E+01	7.35E+01	7.74E-04	1.77E+02	7.15E-01
RF-MT0523C	4.49E+01	0.00E+00	3.47E+00	1.05E+02	2.39E+01	7.35E+01	7.74E-04	1.77E+02	7.15E-01
RF-MT0523D	4.49E+01	0.00E+00	3.47E+00	1.05E+02	2.39E+01	7.35E+01	7.74E-04	1.77E+02	7.15E-01
RF-MT0523E	4.49E+01	0.00E+00	3.47E+00	1.05E+02	2.39E+01	7.35E+01	7.74E-04	1.77E+02	7.15E-01
RF-MT0531	2.82E-03	0.00E+00	5.72E-04	1.72E-02	3.93E-03	1.22E-02	8.53E-08	2.45E-02	9.88E-05
RF-MT0532E	1.46E+02	0.00E+00	7.43E+00	2.29E+02	5.21E+01	1.57E+02	2.22E-03	4.34E+02	1.75E+00
RF-MT0532F	1.46E+02	0.00E+00	7.43E+00	2.29E+02	5.21E+01	1.57E+02	2.22E-03	4.34E+02	1.75E+00
RF-MT0541	5.43E+00	0.00E+00	1.07E-01	3.25E+00	7.40E-01	2.29E+00	1.60E-05	9.52E+00	3.84E-02
RF-MT0545	2.57E-02	0.00E+00	5.19E-03	1.57E-01	3.57E-02	1.10E-01	7.74E-07	2.23E-01	9.01E-04
RF-MT0800	1.12E+03	0.00E+00	2.57E+00	7.74E+01	1.76E+01	5.47E+01	8.67E-04	1.22E+03	4.90E+00
RF-MT0801	1.27E+02	0.00E+00	2.52E+00	7.60E+01	1.73E+01	5.34E+01	3.76E-04	2.23E+02	8.99E-01
RF-MT0803	2.85E+00	0.00E+00	5.63E-02	1.70E+00	3.87E-01	1.20E+00	8.40E-06	4.99E+00	2.01E-02
RF-MT0806	1.29E+00	0.00E+00	1.35E-01	7.38E+00	1.66E+00	2.02E+00	2.02E-05	1.05E+01	4.22E-02
RF-MT0807	1.65E+01	0.00E+00	1.04E+00	3.14E+01	7.17E+00	2.21E+01	1.55E-04	5.61E+01	2.26E-01
RF-MT0816	1.74E+00	0.00E+00	1.47E-01	4.43E+00	1.01E+00	3.13E+00	2.19E-05	7.32E+00	2.95E-02
RF-MT-0823	8.65E-01	0.00E+00	6.68E-02	2.02E+00	4.60E-01	1.41E+00	1.49E-05	3.41E+00	1.38E-02
RF-MT0827	4.38E+01	0.00E+00	3.71E+00	1.12E+02	2.55E+01	7.89E+01	5.54E-04	1.85E+02	7.46E-01
RF-MT0831	8.16E+01	0.00E+00	1.02E+01	3.03E+02	6.92E+01	2.08E+02	1.38E-02	4.64E+02	1.87E+00
RF-MT0832	5.05E+02	0.00E+00	3.69E+01	1.18E+03	2.68E+02	7.42E+02	3.89E-02	1.99E+03	8.02E+00
RF-MT0833	1.54E+02	0.00E+00	1.10E+01	3.41E+02	7.77E+01	2.23E+02	1.08E-02	5.83E+02	2.35E+00
RF-MT0855	2.42E-02	0.00E+00	4.90E-03	1.48E-01	3.37E-02	1.04E-01	7.31E-07	2.11E-01	8.49E-04
RF-MT0857	1.29E+00	0.00E+00	1.34E-01	7.36E+00	1.66E+00	2.02E+00	2.01E-05	1.05E+01	4.22E-02
RF-MT0H61	4.80E+01	0.00E+00	4.99E+00	2.73E+02	6.18E+01	7.48E+01	7.45E-04	3.88E+02	1.56E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT2116	5.42E+00	0.00E+00	3.96E-01	1.26E+01	2.87E+00	7.95E+00	4.17E-04	2.13E+01	8.58E-02
RF-MT3010	3.27E+01	0.00E+00	4.12E+00	1.25E+02	2.87E+01	8.53E+01	1.01E-03	1.90E+02	7.68E-01
RF-MT3011	2.47E+02	0.00E+00	2.56E+01	7.71E+02	1.76E+02	5.44E+02	1.16E-02	1.22E+03	4.92E+00
RF-MT420P	1.35E+03	0.00E+00	1.30E+02	6.34E+03	1.45E+03	1.78E+03	2.94E-02	9.27E+03	3.74E+01
RF-MT532A	3.59E+02	0.00E+00	1.83E+01	5.66E+02	1.29E+02	3.86E+02	5.46E-03	1.07E+03	4.32E+00
RF-MT532B	1.61E+03	0.00E+00	8.23E+01	2.54E+03	5.78E+02	1.74E+03	2.45E-02	4.81E+03	1.94E+01
RF-MT532C	3.23E+03	0.00E+00	1.65E+02	5.09E+03	1.16E+03	3.47E+03	4.93E-02	9.64E+03	3.89E+01
RF-MT532D	2.05E+01	0.00E+00	1.04E+00	3.22E+01	7.32E+00	2.19E+01	3.10E-04	6.10E+01	2.46E-01
RF-TT0069	1.13E-01	0.00E+00	1.24E-02	3.73E-01	8.50E-02	2.64E-01	7.54E-05	5.83E-01	2.35E-03
RF-TT0200	5.43E+00	0.00E+00	4.99E-01	1.53E+01	3.51E+00	1.01E+01	7.55E-05	2.47E+01	9.97E-02
RF-TT0299	2.33E+01	0.00E+00	9.24E-01	2.79E+01	6.36E+00	1.96E+01	1.38E-04	5.85E+01	2.36E-01
RF-TT0300	1.79E+02	0.00E+00	2.63E+01	8.00E+02	1.83E+02	4.78E+02	1.23E-02	1.19E+03	4.80E+00
RF-TT0301	2.42E+01	0.00E+00	3.57E+00	1.09E+02	2.49E+01	6.47E+01	1.67E-03	1.62E+02	6.52E-01
RF-TT0302	1.21E+00	0.00E+00	1.30E-01	4.26E+00	9.73E-01	2.72E+00	4.18E-04	6.57E+00	2.65E-02
RF-TT0303	7.31E+00	0.00E+00	7.58E-01	2.29E+01	5.21E+00	1.61E+01	1.15E-03	3.62E+01	1.46E-01
RF-TT0310	2.47E+01	0.00E+00	3.56E+00	1.03E+02	2.42E+01	5.89E+01	7.16E-04	1.55E+02	6.27E-01
RF-TT0312	6.00E+02	0.00E+00	6.42E+01	2.25E+03	5.08E+02	1.24E+03	1.14E-02	3.42E+03	1.38E+01
RF-TT0317	3.53E-01	0.00E+00	6.98E-02	2.11E+00	4.80E-01	1.48E+00	1.04E-05	3.01E+00	1.21E-02
RF-TT0320	2.44E+02	0.00E+00	2.24E+01	6.87E+02	1.58E+02	4.54E+02	3.39E-03	1.11E+03	4.48E+00
RF-TT0330	8.75E+01	0.00E+00	7.74E+00	4.32E+02	1.06E+02	1.41E+02	1.16E-03	6.32E+02	2.55E+00
RF-TT-0331	4.36E+02	0.00E+00	4.00E+01	1.57E+03	3.51E+02	6.79E+02	6.62E-02	2.40E+03	9.66E+00
RF-TT-0334	1.76E+02	0.00E+00	3.24E+01	9.75E+02	2.22E+02	6.88E+02	4.83E-03	1.41E+03	5.67E+00
RF-TT0335	2.28E+02	0.00E+00	2.45E+01	8.29E+02	1.90E+02	4.63E+02	7.59E-02	1.27E+03	5.13E+00
RF-TT0336	2.04E+02	0.00E+00	2.04E+01	7.34E+02	1.67E+02	3.39E+02	6.06E-03	1.13E+03	4.54E+00
RF-TT0337	2.44E+02	0.00E+00	2.35E+01	9.48E+02	2.12E+02	3.49E+02	1.70E-02	1.43E+03	5.76E+00
RF-TT0338	1.03E+03	0.00E+00	8.54E+01	3.70E+03	8.29E+02	1.56E+03	2.10E-02	5.64E+03	2.28E+01
RF-TT0340	8.08E+00	0.00E+00	1.63E+00	4.92E+01	1.13E+01	3.47E+01	2.43E-04	7.01E+01	2.83E-01
RF-TT0342	5.73E+01	0.00E+00	8.16E+00	2.90E+02	6.49E+01	1.40E+02	4.32E-03	4.20E+02	1.69E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0360	4.44E+00	0.00E+00	4.14E-01	1.30E+01	3.00E+00	8.25E+00	6.81E-05	2.09E+01	8.41E-02
RF-TT0368	8.89E+01	0.00E+00	8.31E+00	2.61E+02	6.01E+01	1.65E+02	1.37E-03	4.18E+02	1.69E+00
RF-TT0370	1.75E+02	0.00E+00	1.79E+01	5.81E+02	1.33E+02	3.51E+02	1.05E-02	9.06E+02	3.65E+00
RF-TT0371	3.78E+00	0.00E+00	3.61E-01	1.09E+01	2.48E+00	7.67E+00	6.71E-05	1.75E+01	7.06E-02
RF-TT0372	4.48E-01	0.00E+00	7.11E-02	2.13E+00	4.86E-01	1.33E+00	7.90E-05	3.13E+00	1.26E-02
RF-TT0374	1.42E+01	0.00E+00	1.67E+00	5.03E+01	1.15E+01	3.54E+01	3.09E-04	7.75E+01	3.13E-01
RF-TT0375A	1.40E-01	0.00E+00	2.75E-02	8.26E-01	1.88E-01	5.83E-01	4.10E-06	1.18E+00	4.77E-03
RF-TT0375B	1.40E-01	0.00E+00	2.75E-02	8.26E-01	1.88E-01	5.83E-01	4.10E-06	1.18E+00	4.77E-03
RF-TT0376	3.41E+01	0.00E+00	4.07E+00	1.52E+02	3.51E+01	7.89E+01	1.44E-03	2.25E+02	9.08E-01
RF-TT0377	1.90E+01	0.00E+00	2.21E+00	6.67E+01	1.53E+01	4.69E+01	8.60E-04	1.03E+02	4.16E-01
RF-TT0391	4.32E+00	0.00E+00	3.11E-01	1.69E+01	3.80E+00	8.21E+00	4.64E-05	2.53E+01	1.02E-01
RF-TT0392	1.53E+00	0.00E+00	1.96E-01	8.82E+00	2.00E+00	2.85E+00	2.94E-05	1.26E+01	5.06E-02
RF-TT0393	1.23E+02	0.00E+00	1.37E+01	4.11E+02	9.38E+01	2.89E+02	2.04E-03	6.41E+02	2.59E+00
RF-TT0398	2.73E+00	0.00E+00	3.60E-01	1.65E+01	3.73E+00	5.38E+00	5.39E-05	2.33E+01	9.40E-02
RF-TT0409	2.36E+00	0.00E+00	1.69E-01	8.51E+00	1.92E+00	2.07E+00	2.58E-05	1.30E+01	5.23E-02
RF-TT0412	2.36E+00	0.00E+00	1.69E-01	8.51E+00	1.92E+00	2.07E+00	2.58E-05	1.30E+01	5.23E-02
RF-TT0414	7.32E+01	0.00E+00	5.21E+00	2.64E+02	5.95E+01	6.41E+01	7.97E-04	4.02E+02	1.62E+00
RF-TT0430	1.92E-02	0.00E+00	3.89E-03	1.17E-01	2.67E-02	8.25E-02	5.81E-07	1.67E-01	6.72E-04
RF-TT0431	4.81E+00	0.00E+00	9.48E-01	2.88E+01	6.57E+00	1.96E+01	3.64E-04	4.11E+01	1.66E-01
RF-TT0438	3.06E+02	0.00E+00	3.61E+01	1.47E+03	3.33E+02	5.81E+02	6.91E-03	2.14E+03	8.64E+00
RF-TT0440	2.99E+01	0.00E+00	3.51E+00	1.45E+02	3.38E+01	6.49E+01	5.69E-03	2.12E+02	8.55E-01
RF-TT0441	1.46E+02	0.00E+00	1.65E+01	5.01E+02	1.15E+02	3.45E+02	7.08E-03	7.78E+02	3.14E+00
RF-TT0442	2.13E+01	0.00E+00	2.84E+00	9.26E+01	2.11E+01	4.50E+01	5.95E-03	1.38E+02	5.56E-01
RF-TT0443	4.33E-01	0.00E+00	8.16E-02	2.51E+00	5.71E-01	1.63E+00	2.82E-05	3.59E+00	1.45E-02
RF-TT0479	4.17E+00	0.00E+00	8.47E-01	2.54E+01	5.80E+00	1.79E+01	1.26E-04	3.62E+01	1.46E-01
RF-TT0480	3.03E+02	0.00E+00	3.42E+01	1.04E+03	2.36E+02	6.67E+02	1.27E-02	1.61E+03	6.50E+00
RF-TT0481	1.71E-01	0.00E+00	1.93E-02	5.84E-01	1.34E-01	3.75E-01	7.18E-06	9.07E-01	3.66E-03
RF-TT0483	5.14E-01	0.00E+00	1.04E-01	3.13E+00	7.15E-01	2.21E+00	1.72E-02	4.48E+00	1.81E-02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0484	2.84E+00	0.00E+00	4.31E-01	1.30E+01	2.97E+00	9.17E+00	1.76E-04	1.92E+01	7.76E-02
RF-TT0485	2.40E-01	0.00E+00	2.66E-02	8.01E-01	1.83E-01	5.66E-01	2.82E-04	1.25E+00	5.05E-03
RF-TT0486	1.42E+00	0.00E+00	1.58E-01	4.76E+00	1.09E+00	3.34E+00	2.51E-04	7.42E+00	2.99E-02
RF-TT0487	7.34E+00	0.00E+00	5.36E-01	1.71E+01	3.89E+00	1.08E+01	5.64E-04	2.88E+01	1.16E-01
RF-TT0489	2.02E+00	0.00E+00	2.41E-01	7.25E+00	1.65E+00	5.12E+00	1.37E-04	1.12E+01	4.50E-02
RF-TT0490	1.11E+02	0.00E+00	1.53E+01	4.68E+02	1.07E+02	3.06E+02	4.07E-03	7.00E+02	2.82E+00
RF-TT0491	2.68E+00	0.00E+00	2.07E-01	6.26E+00	1.43E+00	4.27E+00	1.26E-04	1.06E+01	4.27E-02
RF-TT0492	8.64E-01	0.00E+00	1.17E-01	3.50E+00	7.99E-01	2.46E+00	1.74E-05	5.28E+00	2.13E-02
RF-TT0523A	6.05E+00	0.00E+00	4.68E-01	1.41E+01	3.22E+00	9.90E+00	1.04E-04	2.38E+01	9.60E-02
RF-TT0523B	6.05E+00	0.00E+00	4.68E-01	1.41E+01	3.22E+00	9.90E+00	1.04E-04	2.38E+01	9.60E-02
RF-TT0523C	6.05E+00	0.00E+00	4.68E-01	1.41E+01	3.22E+00	9.90E+00	1.04E-04	2.38E+01	9.60E-02
RF-TT0523D	6.05E+00	0.00E+00	4.68E-01	1.41E+01	3.22E+00	9.90E+00	1.04E-04	2.38E+01	9.60E-02
RF-TT0523E	6.05E+00	0.00E+00	4.68E-01	1.41E+01	3.22E+00	9.90E+00	1.04E-04	2.38E+01	9.60E-02
RF-TT0532A	1.55E+02	0.00E+00	7.84E+00	2.43E+02	5.52E+01	1.66E+02	2.34E-03	4.60E+02	1.86E+00
RF-TT0532B	1.55E+02	0.00E+00	7.84E+00	2.43E+02	5.52E+01	1.66E+02	2.34E-03	4.60E+02	1.86E+00
RF-TT0541	2.30E-01	0.00E+00	4.67E-02	1.41E+00	3.21E-01	9.92E-01	6.97E-06	2.01E+00	8.09E-03
RF-TT0545	5.14E-02	0.00E+00	1.04E-02	3.13E-01	7.15E-02	2.21E-01	1.55E-06	4.46E-01	1.80E-03
RF-TT0601	1.92E+01	0.00E+00	1.79E+00	5.65E+01	1.31E+01	3.58E+01	2.95E-04	9.05E+01	3.65E-01
RF-TT0802	2.19E+03	0.00E+00	1.48E+02	4.46E+03	1.02E+03	3.13E+03	2.20E-02	7.81E+03	3.15E+01
RF-TT0809	1.80E+02	0.00E+00	1.21E+01	3.67E+02	8.33E+01	2.57E+02	1.81E-03	6.42E+02	2.59E+00
RF-TT0821	3.81E+02	0.00E+00	4.40E+01	1.44E+03	3.29E+02	7.65E+02	1.75E-01	2.19E+03	8.84E+00
RF-TT0822	4.27E+02	0.00E+00	3.43E+01	1.08E+03	2.45E+02	6.82E+02	1.88E-01	1.79E+03	7.20E+00
RF-TT0823	8.65E-01	0.00E+00	6.68E-02	2.02E+00	4.60E-01	1.41E+00	1.49E-05	3.41E+00	1.38E-02
RF-TT0824	8.74E+02	0.00E+00	9.40E+01	2.91E+03	6.63E+02	1.93E+03	7.66E-02	4.54E+03	1.83E+01
RF-TT0825	7.36E+02	0.00E+00	6.79E+01	2.19E+03	4.98E+02	1.28E+03	9.12E-02	3.49E+03	1.41E+01
RF-TT0832	5.50E+02	0.00E+00	4.02E+01	1.28E+03	2.92E+02	8.08E+02	4.24E-02	2.16E+03	8.71E+00
RF-TT0854	1.81E-01	0.00E+00	3.67E-02	1.10E+00	2.52E-01	7.78E-01	7.53E-04	1.57E+00	6.33E-03
RF-TT0886	2.57E-02	0.00E+00	5.18E-03	1.56E-01	3.57E-02	1.10E-01	7.73E-07	2.22E-01	8.97E-04

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT2216	8.12E+00	0.00E+00	5.94E-01	1.90E+01	4.31E+00	1.19E+01	6.25E-04	3.20E+01	1.29E-01
RF-TT3010	4.18E+02	0.00E+00	5.26E+01	1.60E+03	3.66E+02	1.09E+03	1.29E-02	2.44E+03	9.82E+00
RF-TT3011	1.07E+03	0.00E+00	1.11E+02	3.34E+03	7.62E+02	2.36E+03	5.03E-02	5.28E+03	2.13E+01
RF-TT301U	8.76E+01	0.00E+00	1.17E+01	3.63E+02	8.41E+01	2.31E+02	1.91E-03	5.46E+02	2.20E+00
RF-TT310P	2.60E+01	0.00E+00	3.05E+00	1.22E+02	2.64E+01	4.84E+01	4.59E-04	1.77E+02	7.15E-01
RF-TT338S	7.05E-01	0.00E+00	1.40E-01	4.21E+00	9.61E-01	2.96E+00	2.09E-05	6.01E+00	2.42E-02
RF-TT390P	4.29E+00	0.00E+00	3.79E-01	2.05E+01	4.30E+00	7.39E+00	8.53E-05	2.94E+01	1.19E-01
RF-TT391P	2.35E+02	0.00E+00	1.70E+01	9.20E+02	2.06E+02	4.48E+02	2.54E-03	1.38E+03	5.56E+00
RF-TT392P	4.77E+02	0.00E+00	6.13E+01	2.76E+03	6.27E+02	8.89E+02	9.19E-03	3.92E+03	1.58E+01
RF-TT393R	7.01E+01	0.00E+00	1.04E+01	4.22E+02	9.65E+01	1.44E+02	1.73E-03	5.99E+02	2.41E+00
RF-TT394P	8.96E+00	0.00E+00	6.44E-01	3.26E+01	6.89E+00	1.04E+01	1.03E-04	4.91E+01	1.98E-01
RF-TT395P	1.20E+01	0.00E+00	8.62E-01	4.36E+01	9.20E+00	1.38E+01	1.38E-04	6.56E+01	2.65E-01
RF-TT396P	2.99E+00	0.00E+00	2.15E-01	1.09E+01	2.30E+00	3.45E+00	3.45E-05	1.64E+01	6.61E-02
RF-TT398P	2.82E+02	0.00E+00	3.73E+01	1.71E+03	3.86E+02	5.55E+02	5.57E-03	2.41E+03	9.73E+00
RF-TT398R	2.45E+03	0.00E+00	6.93E+01	2.76E+03	6.24E+02	1.08E+03	1.03E-02	5.90E+03	2.38E+01
RF-TT411R	8.74E+01	0.00E+00	6.22E+00	3.15E+02	7.11E+01	7.65E+01	9.52E-04	4.79E+02	1.93E+00
RF-TT429R	1.89E+02	0.00E+00	1.34E+00	7.29E+01	1.62E+01	1.34E+01	1.99E-04	2.79E+02	1.13E+00
RF-TT433X	5.94E+01	0.00E+00	3.70E-01	2.10E+01	4.20E+00	5.29E+00	5.52E-05	8.50E+01	3.43E-01
RF-TT436R	4.33E+02	0.00E+00	5.35E+00	2.75E+02	6.19E+01	1.02E+02	7.98E-04	7.75E+02	3.13E+00
RF-TT454X	2.54E+01	0.00E+00	3.15E-01	1.62E+01	3.65E+00	6.02E+00	4.70E-05	4.56E+01	1.84E-01
RL-T101	1.01E+02	0.00E+00	1.91E+01	8.74E+02	1.95E+02	8.51E+02	1.97E-03	1.19E+03	4.80E+00
RL-T102	1.28E-03	0.00E+00	2.43E-04	1.12E-02	2.49E-03	1.08E-02	1.18E-06	1.52E-02	6.13E-05
RL-T103	1.01E+02	0.00E+00	2.31E+01	3.82E+02	8.47E+01	4.52E+02	2.39E-03	5.91E+02	2.38E+00
RL-T104	1.83E-03	0.00E+00	3.47E-04	1.59E-02	3.57E-03	1.55E-02	6.84E-08	2.16E-02	8.72E-05
RL-T105	7.05E-01	0.00E+00	1.31E-01	6.03E+00	1.35E+00	5.85E+00	5.83E-05	8.22E+00	3.31E-02
RL-T106	6.77E-01	0.00E+00	1.29E-01	5.90E+00	1.32E+00	5.72E+00	1.33E-05	8.02E+00	3.23E-02
RL-T107	1.86E+03	0.00E+00	7.57E+04	1.63E+04	3.63E+03	1.57E+04	8.66E+00	9.75E+04	3.93E+02
RL-T108	1.07E+00	0.00E+00	1.31E+01	9.27E+00	2.07E+00	9.00E+00	1.38E-03	2.55E+01	1.03E-01

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T109	1.48E+00	0.00E+00	2.69E-01	1.23E+01	2.75E+00	1.19E+01	2.33E-02	1.68E+01	6.78E-02
RL-T110	1.65E+02	0.00E+00	5.13E+01	1.41E+03	3.16E+02	1.37E+03	1.37E+00	1.94E+03	7.83E+00
RL-T112	7.92E+01	0.00E+00	2.17E+01	1.87E+02	4.18E+01	1.82E+02	7.38E-01	3.30E+02	1.33E+00
RL-T113	7.07E-02	0.00E+00	4.19E-02	6.15E-01	1.38E-01	5.98E-01	4.32E-06	8.66E-01	3.49E-03
RL-T114	1.08E+01	0.00E+00	2.04E+00	9.35E+01	2.09E+01	9.09E+01	2.11E-04	1.27E+02	5.13E-01
RL-T115	3.07E+02	0.00E+00	6.62E+01	1.23E+03	2.75E+02	1.34E+03	4.20E-01	1.88E+03	7.57E+00
RL-T116	1.77E+01	0.00E+00	3.36E+00	1.53E+02	3.43E+01	1.49E+02	5.65E-02	2.08E+02	8.40E-01
RL-T118	5.35E+01	0.00E+00	2.68E+01	1.52E+02	3.40E+01	1.48E+02	8.36E-01	2.67E+02	1.08E+00
RL-T120	1.24E+01	0.00E+00	2.81E+00	4.50E+01	9.97E+00	5.19E+01	2.91E-04	7.01E+01	2.83E-01
RL-T122	6.24E-01	0.00E+00	1.19E-01	5.42E+00	1.22E+00	5.27E+00	1.46E+00	8.83E+00	3.56E-02
RL-T123	1.84E+00	0.00E+00	3.48E-01	1.59E+01	3.57E+00	1.55E+01	5.97E-02	2.17E+01	8.75E-02
RL-T125	3.88E+02	0.00E+00	8.62E+01	3.33E+02	1.71E+02	2.42E+03	8.90E-03	9.79E+02	3.95E+00
RL-T127	4.21E+02	0.00E+00	2.17E+01	9.94E+02	2.22E+02	9.64E+02	8.22E-02	1.66E+03	6.69E+00
RL-T128	6.73E-01	0.00E+00	5.27E-07	2.42E-05	5.39E-06	2.34E-05	5.43E-11	6.73E-01	2.71E-03
RL-T129	1.56E+00	0.00E+00	1.00E+02	1.37E+01	3.04E+00	1.32E+01	1.80E-02	1.19E+02	4.78E-01
RL-T130	3.32E-03	0.00E+00	6.33E-04	2.91E-02	6.49E-03	2.81E-02	8.31E-05	3.96E-02	1.60E-04
RL-T131	1.53E+00	0.00E+00	3.46E-01	5.54E+00	1.23E+00	6.34E+00	8.27E-03	8.64E+00	3.48E-02
RL-T132	3.22E+02	0.00E+00	6.10E+01	2.81E+03	6.27E+02	2.72E+03	2.51E-01	3.82E+03	1.54E+01
RL-T133	7.14E-03	0.00E+00	9.79E-04	4.61E-02	1.03E-02	3.86E-02	1.01E-07	6.44E-02	2.60E-04
RL-T134	1.39E-02	0.00E+00	2.63E-03	1.21E-01	2.69E-02	1.17E-01	2.72E-07	1.64E-01	6.63E-04
RL-T135	6.49E-02	0.00E+00	1.24E-02	5.66E-01	1.27E-01	5.49E-01	4.15E-03	7.74E-01	3.12E-03
RL-T137	1.19E+03	0.00E+00	2.70E+02	4.31E+03	9.57E+02	4.99E+03	3.40E-02	6.72E+03	2.71E+01
RL-T140	1.45E+03	0.00E+00	2.56E+02	4.17E+03	1.03E+03	4.24E+03	2.62E+01	6.92E+03	2.79E+01
RL-T143	7.73E+00	0.00E+00	1.47E+00	6.73E+01	1.51E+01	6.54E+01	3.88E-02	9.16E+01	3.70E-01
RL-T145	2.20E+01	0.00E+00	4.19E+00	1.92E+02	4.28E+01	1.86E+02	9.00E-02	2.61E+02	1.05E+00
RL-W407	7.19E+01	0.00E+00	8.93E+00	4.40E+02	9.83E+01	2.83E+02	9.22E-04	6.19E+02	2.50E+00
RL-W408	2.85E-04	0.00E+00	3.77E-05	1.78E-03	3.98E-04	1.46E-03	3.90E-09	2.50E-03	1.01E-05
RL-W415	6.29E-03	0.00E+00	8.31E-04	3.94E-02	8.79E-03	3.21E-02	8.58E-08	5.53E-02	2.23E-04

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W418	2.75E-02	0.00E+00	3.50E-03	1.69E-01	3.78E-02	1.20E-01	3.62E-07	2.38E-01	9.58E-04
RL-W437	2.36E+02	0.00E+00	2.94E+01	1.44E+03	3.22E+02	9.28E+02	3.03E-03	2.03E+03	8.17E+00
RL-W438	3.99E-04	0.00E+00	5.27E-05	2.49E-03	5.55E-04	2.04E-03	5.44E-09	3.49E-03	1.41E-05
RL-W439	1.27E+04	0.00E+00	2.91E+03	4.80E+04	1.07E+04	5.68E+04	3.00E-01	7.43E+04	2.99E+02
RL-W443	2.08E+02	0.00E+00	2.59E+01	1.27E+03	2.83E+02	8.17E+02	2.67E-03	1.79E+03	7.20E+00
RL-W444	1.54E+02	0.00E+00	1.92E+01	9.41E+02	2.10E+02	6.07E+02	1.98E-03	1.33E+03	5.34E+00
RL-W447	1.71E-02	0.00E+00	2.26E-03	1.06E-01	2.38E-02	8.72E-02	2.33E-07	1.49E-01	6.01E-04
RL-W448	1.26E-04	0.00E+00	1.67E-05	7.86E-04	1.75E-04	6.45E-04	1.72E-09	1.10E-03	4.45E-06
RL-W449	1.22E+00	0.00E+00	6.11E-04	2.25E-02	5.02E-03	1.17E-02	6.31E-08	1.25E+00	5.02E-03
RL-W450	1.90E-03	0.00E+00	2.52E-04	1.19E-02	2.65E-03	9.73E-03	2.60E-08	1.67E-02	6.73E-05
RL-W451	2.71E-04	0.00E+00	3.59E-05	1.69E-03	3.78E-04	1.39E-03	3.70E-09	2.37E-03	9.57E-06
RL-W452	1.21E-02	0.00E+00	1.55E-03	7.44E-02	1.66E-02	5.27E-02	1.60E-07	1.05E-01	4.22E-04
RL-W453	3.49E-03	0.00E+00	4.35E-04	2.14E-02	4.76E-03	1.37E-02	4.49E-08	3.01E-02	1.21E-04
RL-W454	4.88E-02	0.00E+00	6.08E-03	2.99E-01	6.67E-02	1.92E-01	6.28E-07	4.20E-01	1.69E-03
RL-W455	1.29E-02	0.00E+00	1.64E-03	7.90E-02	1.76E-02	5.62E-02	1.69E-07	1.11E-01	4.48E-04
RL-W456	1.71E+00	0.00E+00	2.14E-01	1.05E+01	2.34E+00	6.92E+00	2.21E-05	1.48E+01	5.95E-02
RL-W457	1.66E-01	0.00E+00	2.08E-02	1.02E+00	2.27E-01	6.71E-01	2.15E-06	1.43E+00	5.78E-03
RL-W458	5.06E-01	0.00E+00	1.06E-01	4.19E-01	2.33E-01	2.70E+00	1.10E-05	1.26E+00	5.10E-03
RL-W459	4.83E+00	0.00E+00	1.10E+00	1.04E+01	3.18E+00	2.68E+01	1.13E-04	1.95E+01	7.86E-02
RL-W460	3.09E-02	0.00E+00	3.85E-03	1.89E-01	4.23E-02	1.22E-01	3.98E-07	2.66E-01	1.07E-03
RL-W461	3.24E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.24E-02	1.31E-04
RL-W462	8.64E-03	0.00E+00	1.12E-03	5.35E-02	1.20E-02	3.99E-02	1.15E-07	7.52E-02	3.03E-04
RL-W463	4.53E-02	0.00E+00	5.65E-03	2.78E-01	6.20E-02	1.79E-01	5.84E-07	3.91E-01	1.58E-03
RL-W464	2.10E-02	0.00E+00	2.60E-03	1.28E-01	2.85E-02	8.23E-02	2.69E-07	1.80E-01	7.26E-04
RL-W465	1.38E-01	0.00E+00	1.76E-02	8.51E-01	1.90E-01	5.96E-01	1.82E-06	1.20E+00	4.83E-03
RL-W466	1.90E+00	0.00E+00	2.40E-01	1.17E+01	2.61E+00	7.93E+00	2.48E-05	1.64E+01	6.63E-02
RL-W467	9.63E-02	0.00E+00	1.24E-02	5.96E-01	1.33E-01	4.35E-01	1.27E-06	8.37E-01	3.37E-03
RL-W468	4.92E-04	0.00E+00	6.36E-05	3.05E-03	6.81E-04	2.27E-03	6.57E-09	4.28E-03	1.73E-05

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W469	2.02E-01	0.00E+00	2.56E-02	1.24E+00	2.78E-01	8.36E-01	2.64E-06	1.75E+00	7.04E-03
RL-W470	5.39E+00	0.00E+00	1.19E+00	4.60E+00	2.37E+00	3.36E+01	1.23E-04	1.35E+01	5.46E-02
RL-W474	2.48E-01	0.00E+00	1.31E-01	1.05E-02	8.97E-03	0.00E+00	1.36E-05	3.99E-01	1.61E-03
RL-W476	3.66E-01	0.00E+00	4.72E-02	2.30E+00	5.15E-01	1.52E+00	4.87E-06	3.23E+00	1.30E-02
RL-W480	5.93E-02	0.00E+00	7.56E-03	3.65E-01	8.16E-02	2.59E-01	7.81E-07	5.13E-01	2.07E-03
RL-W481	9.31E-02	0.00E+00	1.19E-02	5.73E-01	1.28E-01	4.07E-01	1.23E-06	8.05E-01	3.25E-03
RL-W482	1.24E+02	0.00E+00	3.95E+00	7.28E-02	1.36E-01	5.40E+02	4.08E-04	1.28E+02	5.15E-01
RL-W483	9.23E+00	0.00E+00	3.07E-01	4.72E-03	9.63E-03	4.03E+01	3.17E-05	9.55E+00	3.85E-02
RL-W484	4.38E-02	0.00E+00	2.47E-03	6.58E-02	1.58E-02	3.34E-02	2.55E-07	1.28E-01	5.15E-04
RL-W485	2.63E-03	0.00E+00	3.50E-04	7.12E-03	1.70E-03	0.00E+00	3.61E-08	1.18E-02	4.76E-05
RL-W486	1.11E-03	0.00E+00	1.48E-04	3.01E-03	7.17E-04	0.00E+00	1.52E-08	4.98E-03	2.01E-05
RL-W487	1.71E-01	0.00E+00	1.90E-02	4.31E-01	1.19E-01	3.11E-01	1.96E-06	7.39E-01	2.98E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	9.31E-02	0.00E+00	1.79E-02	5.58E-01	1.27E-01	5.02E-01	1.84E-06	7.95E-01	3.21E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	3.47E-02	0.00E+00	1.51E-02	5.85E-02	1.29E-02	1.82E-01	1.56E-06	1.21E-01	4.88E-04
RL-W492	2.00E-03	0.00E+00	3.71E-04	1.17E-02	2.64E-03	1.05E-02	3.83E-08	1.67E-02	6.74E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.91E+01	0.00E+00	2.15E+01	2.95E-01	2.52E-01	4.20E+02	2.22E-03	1.01E+02	4.08E-01
RL-W495	1.43E+00	0.00E+00	5.85E-02	2.83E-03	2.25E-03	7.65E+00	6.04E-06	1.49E+00	6.02E-03
RL-W496	9.30E+00	0.00E+00	6.73E-01	9.29E-03	7.47E-03	4.95E+01	6.95E-05	9.99E+00	4.03E-02
RL-W497	4.14E-01	0.00E+00	1.33E-01	5.58E-01	2.53E-01	1.30E+00	1.37E-05	1.36E+00	5.47E-03
RL-W498	1.55E+00	0.00E+00	1.97E-01	9.53E+00	2.13E+00	6.75E+00	2.04E-05	1.34E+01	5.41E-02
RL-W499	1.39E-05	0.00E+00	1.77E-06	8.54E-05	1.91E-05	6.07E-05	1.83E-10	1.20E-04	4.85E-07
RL-W500	9.90E-04	0.00E+00	2.20E-04	3.49E-03	7.75E-04	4.27E-03	2.27E-08	5.47E-03	2.21E-05
RL-W501	4.43E+01	0.00E+00	4.90E+00	1.12E+02	3.07E+01	8.06E+01	5.06E-04	1.92E+02	7.73E-01
RL-W502	7.40E-03	0.00E+00	9.48E-04	4.56E-02	1.02E-02	3.24E-02	9.78E-08	6.41E-02	2.58E-04
RL-W503	4.27E-01	0.00E+00	9.71E-02	1.61E+00	3.57E-01	1.90E+00	1.00E-05	2.49E+00	1.00E-02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W504	1.71E-01	0.00E+00	1.90E-02	4.31E-01	1.19E-01	3.11E-01	1.96E-06	7.39E-01	2.98E-03
RL-W505	7.21E-03	0.00E+00	9.94E-04	4.66E-02	1.04E-02	3.90E-02	1.03E-07	6.51E-02	2.63E-04
RL-W506	2.69E-03	0.00E+00	3.91E-04	1.53E-02	3.42E-03	1.17E-02	4.03E-08	2.18E-02	8.79E-05
RL-W507	2.68E-04	0.00E+00	3.42E-05	1.65E-03	3.68E-04	1.17E-03	3.53E-09	2.32E-03	9.35E-06
RL-W508	4.94E+00	0.00E+00	1.12E+00	1.79E+01	3.98E+00	2.07E+01	1.15E-04	2.79E+01	1.13E-01
RL-W509	5.06E+01	0.00E+00	8.93E+00	1.46E+02	3.58E+01	1.49E+02	9.22E-04	2.41E+02	9.72E-01
RL-W510	4.09E+00	0.00E+00	9.16E-01	1.45E+01	3.22E+00	1.77E+01	9.46E-05	2.27E+01	9.16E-02
RL-W511	4.45E+02	0.00E+00	4.42E+01	1.94E+03	4.25E+02	9.64E+02	4.91E-03	2.85E+03	1.15E+01
RL-W512	4.01E+02	0.00E+00	2.98E+01	1.17E+03	2.91E+02	4.93E+02	3.08E-03	1.89E+03	7.63E+00
RL-W513	4.19E+04	0.00E+00	1.21E+04	1.91E+04	9.49E+03	7.82E+04	1.25E+00	8.26E+04	3.33E+02
RL-W514	1.10E-03	0.00E+00	1.39E-04	6.76E-03	1.52E-03	4.57E-03	1.44E-08	9.52E-03	3.84E-05
RL-W515	4.28E-02	0.00E+00	5.45E-03	2.64E-01	5.88E-02	1.87E-01	5.63E-07	3.71E-01	1.50E-03
RL-W516	5.94E-02	0.00E+00	7.57E-03	3.65E-01	8.16E-02	2.59E-01	7.82E-07	5.13E-01	2.07E-03
RL-W517	5.25E-10	0.00E+00	6.77E-11	3.25E-09	7.25E-10	2.42E-09	6.99E-15	4.56E-09	1.84E-11
RL-W518	1.54E+00	0.00E+00	2.85E-01	4.66E+00	1.13E+00	5.21E+00	2.94E-05	7.61E+00	3.07E-02
RL-W519	2.69E-01	0.00E+00	3.38E-02	1.65E+00	3.68E-01	1.10E+00	3.49E-06	2.32E+00	9.35E-03
RL-W520	2.90E-02	0.00E+00	3.81E-03	1.81E-01	4.04E-02	1.41E-01	3.93E-07	2.54E-01	1.02E-03
RL-W521	5.48E-04	0.00E+00	6.98E-05	3.37E-03	7.53E-04	2.40E-03	7.21E-09	4.74E-03	1.91E-05
RL-W522	1.20E+01	0.00E+00	2.59E+00	2.23E+01	6.39E+00	3.47E+01	2.68E-04	4.32E+01	1.74E-01
RL-W523	3.72E+00	0.00E+00	9.86E-01	1.48E+00	9.00E-01	6.88E+00	1.02E-04	7.09E+00	2.86E-02
RL-W524	1.53E+01	0.00E+00	3.77E+00	1.36E+01	5.27E+00	3.28E+01	3.90E-04	3.79E+01	1.53E-01
RL-W525	1.22E+00	0.00E+00	2.56E-01	1.61E+00	5.33E-01	2.57E+00	2.64E-05	3.61E+00	1.46E-02
RL-W526	4.29E+00	0.00E+00	9.24E-01	1.72E+01	3.85E+00	1.87E+01	9.54E-05	2.63E+01	1.06E-01
RL-W527	4.66E-01	0.00E+00	1.34E-01	1.82E+00	4.33E-01	2.19E+00	1.38E-05	2.85E+00	1.15E-02
RL-W528	2.31E+02	0.00E+00	5.68E+01	5.80E+01	5.56E+01	3.34E+02	5.86E-03	4.01E+02	1.62E+00
RL-W529	1.76E-01	0.00E+00	3.99E-02	6.39E-01	1.42E-01	7.37E-01	4.12E-06	9.97E-01	4.02E-03
RL-W530	2.07E+00	0.00E+00	4.63E-01	7.30E+00	1.62E+00	8.96E+00	4.78E-05	1.15E+01	4.62E-02
RL-W531	1.34E+02	0.00E+00	4.64E+01	3.16E+01	2.28E+01	2.38E+02	4.79E-03	2.34E+02	9.45E-01

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W532	3.95E-01	0.00E+00	5.05E-02	2.44E+00	5.44E-01	1.73E+00	5.21E-06	3.43E+00	1.38E-02
RL-W533	1.92E-01	0.00E+00	4.36E-02	6.97E-01	1.55E-01	7.99E-01	4.50E-06	1.09E+00	4.39E-03
RL-W534	1.10E-05	0.00E+00	1.41E-06	6.80E-05	1.53E-05	4.82E-05	1.45E-10	9.57E-05	3.86E-07
RL-W535	6.15E+01	0.00E+00	1.39E+01	8.72E+01	2.67E+01	1.47E+02	1.44E-03	1.89E+02	7.63E-01
RL-W536	1.19E+00	0.00E+00	1.87E-01	3.03E+00	6.88E-01	3.36E+00	2.25E-05	5.09E+00	2.05E-02
RL-W537	4.12E+01	0.00E+00	4.23E+00	1.86E+02	4.09E+01	9.41E+01	4.63E-04	2.72E+02	1.10E+00
RL-W538	1.40E-04	0.00E+00	1.79E-05	8.64E-04	1.93E-04	6.13E-04	1.84E-09	1.22E-03	4.90E-06
RL-W539	1.54E-02	0.00E+00	2.01E-03	9.55E-02	2.13E-02	7.46E-02	2.08E-07	1.34E-01	5.41E-04
RL-W540	3.24E+01	0.00E+00	8.85E+00	3.44E+01	1.19E+01	7.16E+01	9.14E-04	8.75E+01	3.53E-01
RL-W541	4.46E-02	0.00E+00	5.80E-03	2.77E-01	6.18E-02	2.10E-01	5.99E-07	3.89E-01	1.57E-03
RL-W542	2.11E+00	0.00E+00	4.31E-01	7.00E+00	1.62E+00	8.62E+00	4.45E-05	1.12E+01	4.50E-02
RL-W543	6.59E-03	0.00E+00	8.39E-04	4.06E-02	9.07E-03	2.89E-02	8.66E-08	5.71E-02	2.30E-04
RL-W544	1.51E-01	0.00E+00	3.43E-02	4.62E-01	1.16E-01	5.74E-01	3.54E-06	7.62E-01	3.07E-03
RL-W545	3.95E-02	0.00E+00	5.03E-03	2.43E-01	5.43E-02	1.72E-01	5.19E-07	3.42E-01	1.38E-03
RL-W546	1.73E-03	0.00E+00	2.21E-04	1.07E-02	2.38E-03	7.54E-03	2.28E-08	1.50E-02	6.06E-05
RL-W547	4.42E-05	0.00E+00	5.64E-06	2.72E-04	6.08E-05	1.93E-04	5.82E-10	3.82E-04	1.54E-06
RL-W548	3.80E-05	0.00E+00	4.89E-06	2.35E-04	5.25E-05	1.73E-04	5.05E-10	3.30E-04	1.33E-06
RL-W549	7.98E+00	0.00E+00	1.97E+00	1.21E+01	3.61E+00	2.19E+01	2.03E-04	2.56E+01	1.03E-01
RL-W550	3.67E+01	0.00E+00	3.72E+00	1.64E+02	3.61E+01	8.25E+01	4.03E-04	2.40E+02	9.69E-01
RL-W551	6.74E+01	0.00E+00	5.50E+00	1.85E+02	4.70E+01	8.77E+01	5.68E-04	3.05E+02	1.23E+00
RL-W552	2.35E-02	0.00E+00	3.04E-03	1.46E-01	3.25E-02	1.10E-01	3.14E-07	2.05E-01	8.26E-04
RL-W553	1.94E-03	0.00E+00	2.87E-04	1.30E-02	2.90E-03	1.38E-02	2.97E-08	1.81E-02	7.31E-05
RL-W554	3.34E-02	0.00E+00	4.26E-03	2.06E-01	4.60E-02	1.46E-01	4.40E-07	2.90E-01	1.17E-03
RL-W555	1.54E-02	0.00E+00	1.97E-03	9.48E-02	2.11E-02	6.73E-02	2.03E-07	1.33E-01	5.38E-04
RL-W563	2.23E-01	0.00E+00	4.92E-02	7.86E-01	1.74E-01	9.17E-01	5.07E-06	1.23E+00	4.97E-03
RL-W564	1.41E-01	0.00E+00	3.26E-02	5.09E-01	1.13E-01	7.05E-01	3.37E-06	7.95E-01	3.21E-03
RL-W565	1.42E-02	0.00E+00	1.83E-03	8.78E-02	1.96E-02	6.54E-02	1.89E-07	1.24E-01	4.98E-04
RL-W566	2.09E-01	0.00E+00	2.69E-02	1.29E+00	2.89E-01	9.30E-01	2.77E-06	1.81E+00	7.31E-03

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W567	1.40E+01	0.00E+00	6.87E-01	3.97E-02	3.21E-02	7.89E+01	7.09E-05	1.48E+01	5.95E-02
RL-W568	2.65E+02	0.00E+00	1.45E+01	1.88E+00	1.50E+00	1.63E+03	1.49E-03	2.83E+02	1.14E+00
RL-W569	2.21E-01	0.00E+00	1.09E-02	6.26E-04	5.08E-05	1.25E+00	1.12E-06	2.33E-01	9.39E-04
RL-W570	1.48E-02	0.00E+00	1.90E-03	9.31E-02	2.07E-02	6.15E-02	1.96E-07	1.31E-01	5.27E-04
RL-W571	4.58E+01	0.00E+00	6.46E+00	7.55E+00	3.79E+00	2.49E+02	6.67E-04	6.36E+01	2.56E-01
RL-W572	3.95E-02	0.00E+00	1.93E-03	4.07E-03	9.07E-05	2.23E-01	2.00E-07	4.56E-02	1.84E-04
RL-W573	5.10E+02	0.00E+00	2.48E+01	2.23E+00	1.67E+00	2.83E+03	2.56E-03	5.38E+02	2.17E+00
RL-W574	2.18E+03	0.00E+00	1.07E+02	8.51E+00	6.20E+00	1.23E+04	1.11E-02	2.31E+03	9.30E+00
RL-W575	1.43E+04	0.00E+00	7.22E+02	8.14E+01	4.95E+01	7.74E+04	7.45E-02	1.52E+04	6.12E+01
RL-W576	1.03E+03	0.00E+00	5.04E+01	4.15E+00	2.99E+00	5.81E+03	5.20E-03	1.08E+03	4.37E+00
RL-W579	1.03E-01	0.00E+00	1.33E-03	2.08E-02	4.65E-03	2.05E-02	1.37E-07	1.30E-01	5.24E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.66E-01	2.71E-02	0.00E+00	0.00E+00	1.93E-01	7.78E-04
RL-W581	1.10E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.10E+00	4.44E-03
RL-W582	7.09E-03	0.00E+00	1.13E-03	5.32E-03	2.76E-03	3.32E-03	1.16E-07	1.63E-02	6.57E-05
RL-W583	4.91E-03	0.00E+00	6.12E-04	3.00E-02	6.71E-03	1.93E-02	6.32E-08	4.22E-02	1.70E-04
RL-W584	1.07E-01	0.00E+00	4.02E-02	1.75E-01	8.59E-02	9.71E-02	4.14E-06	4.08E-01	1.65E-03
RL-W585	5.57E-01	0.00E+00	2.14E-01	1.02E+00	5.22E-01	2.96E+00	2.20E-05	2.31E+00	9.32E-03
RL-W586	7.74E-05	0.00E+00	9.63E-06	4.74E-04	1.06E-04	3.04E-04	9.94E-10	6.66E-04	2.69E-06
RL-W587	1.65E-03	0.00E+00	2.08E-04	1.01E-02	2.26E-03	6.84E-03	2.15E-08	1.42E-02	5.73E-05
RL-W588	7.48E-02	0.00E+00	3.39E-02	1.48E-01	7.24E-02	8.17E-02	3.50E-06	3.29E-01	1.33E-03
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	2.01E+00	0.00E+00	7.22E-01	1.14E-02	2.03E-02	1.07E+01	7.45E-05	2.77E+00	1.12E-02
RL-W591	1.14E+01	0.00E+00	8.16E-01	1.41E-02	2.63E-02	6.47E+01	8.42E-05	1.22E+01	4.92E-02
RL-W592	5.10E+01	0.00E+00	8.93E+00	6.53E-01	8.51E-01	2.61E+02	9.22E-04	6.14E+01	2.48E-01
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.36E-02	4.00E-02	0.00E+00	0.00E+00	6.35E-02	2.56E-04
RL-W594	5.18E+01	0.00E+00	1.61E+00	2.92E-02	5.40E-02	6.54E+01	1.66E-04	5.35E+01	2.16E-01
RL-W595	1.21E-01	0.00E+00	1.68E-01	2.00E-02	3.93E-02	6.47E-01	1.73E-05	3.48E-01	1.40E-03
RL-W596	3.95E-02	0.00E+00	1.31E-02	2.06E-04	3.69E-04	1.94E-01	1.35E-06	5.32E-02	2.14E-04

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W597	7.25E+01	0.00E+00	5.74E+00	3.99E-01	6.69E-01	3.62E+02	5.92E-04	7.93E+01	3.20E-01
RL-W598	7.70E+01	0.00E+00	3.39E+01	5.56E-01	8.34E-01	3.75E+02	3.50E-03	1.12E+02	4.52E-01
RL-W599	3.81E+00	0.00E+00	2.73E-01	4.70E-03	8.79E-03	2.16E+01	2.82E-05	4.09E+00	1.65E-02
RL-W600	2.28E-07	0.00E+00	2.84E-08	1.39E-06	3.11E-07	8.96E-07	2.93E-12	1.96E-06	7.89E-09
RL-W601	1.05E-03	0.00E+00	1.55E-04	7.03E-03	1.58E-03	7.50E-03	1.60E-08	9.82E-03	3.96E-05
RL-W602	9.85E-01	0.00E+00	1.27E-01	6.09E+00	1.37E+00	4.54E+00	1.32E-05	8.57E+00	3.46E-02
RL-W603	5.68E+00	0.00E+00	7.35E-01	3.52E+01	7.86E+00	2.61E+01	7.58E-05	4.94E+01	1.99E-01
RL-W604	1.43E-02	0.00E+00	1.93E-03	1.71E-02	8.47E-03	3.11E-02	1.99E-07	4.18E-02	1.69E-04
RL-W605	2.83E-03	0.00E+00	4.19E-04	1.89E-02	4.23E-03	2.02E-02	4.32E-08	2.64E-02	1.06E-04
RL-W606	1.14E-03	0.00E+00	1.69E-04	7.61E-03	1.70E-03	8.14E-03	1.74E-08	1.06E-02	4.29E-05
RL-W607	2.43E-03	0.00E+00	3.26E-04	2.89E-03	1.44E-03	5.25E-03	3.37E-08	7.08E-03	2.85E-05
RL-W608	2.83E-02	0.00E+00	1.27E-02	3.76E-03	4.65E-03	8.06E-02	1.31E-06	4.94E-02	1.99E-04
RL-W610	5.43E+00	0.00E+00	6.77E-01	3.32E+01	7.42E+00	2.14E+01	6.99E-05	4.67E+01	1.88E-01
RL-W612	1.28E-02	0.00E+00	1.64E-03	8.05E-02	1.80E-02	5.06E-02	1.69E-07	1.13E-01	4.56E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.38E-01	0.00E+00	0.00E+00	0.00E+00	3.38E-01	1.36E-03
RL-W622	2.14E-04	0.00E+00	2.67E-05	1.31E-03	2.92E-04	8.42E-04	2.76E-09	1.84E-03	7.42E-06
RL-W625	6.88E-03	0.00E+00	4.06E-03	6.68E-03	6.60E-03	4.57E-02	4.19E-07	2.42E-02	9.77E-05
RL-W626	4.27E-01	0.00E+00	9.24E-02	2.62E-01	1.58E-01	7.97E-01	9.54E-06	9.39E-01	3.78E-03
RL-W627	1.81E-03	0.00E+00	1.24E-04	1.24E-06	0.00E+00	9.47E-03	1.27E-08	1.94E-03	7.82E-06
RL-W628	6.14E-04	0.00E+00	7.76E-05	3.78E-03	8.43E-04	2.55E-03	8.01E-09	5.31E-03	2.14E-05
RL-W629	4.07E-05	0.00E+00	5.34E-06	2.54E-04	5.66E-05	1.98E-04	5.51E-10	3.56E-04	1.44E-06
RL-W630	4.49E-01	0.00E+00	9.94E-02	2.94E+00	6.83E-01	2.14E+00	1.03E-05	4.17E+00	1.68E-02
RL-W631	6.77E-03	0.00E+00	1.00E-03	4.51E-02	1.01E-02	4.82E-02	1.03E-07	6.29E-02	2.54E-04
RL-W632	3.17E+00	0.00E+00	1.35E-01	5.96E+00	1.96E+00	1.60E+01	1.40E-05	1.12E+01	4.53E-02
RL-W633	8.20E-03	0.00E+00	7.84E-04	9.35E-04	8.29E-04	1.97E-02	8.10E-08	1.08E-02	4.33E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	1.02E-02	0.00E+00	0.00E+00	0.00E+00	1.02E-02	4.11E-05
RL-W635	4.62E+01	0.00E+00	2.65E+01	4.34E+00	6.51E+00	1.99E+02	2.73E-03	8.35E+01	3.37E-01
RL-W636	5.00E-01	0.00E+00	5.00E-02	5.67E-02	5.03E-02	1.21E+00	5.16E-06	6.57E-01	2.65E-03

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W637	1.14E-03	0.00E+00	1.27E-03	6.37E-04	6.28E-04	4.35E-03	1.32E-07	3.68E-03	1.48E-05
RL-W638	5.10E-02	0.00E+00	1.30E-02	6.24E-03	5.90E-03	1.62E-01	1.34E-06	7.61E-02	3.07E-04
RL-W639	2.60E-03	0.00E+00	3.32E-04	1.60E-02	3.57E-03	1.13E-02	3.42E-08	2.25E-02	9.06E-05
RL-W640	8.78E-02	0.00E+00	1.10E-02	5.39E-01	1.21E-01	3.64E-01	1.14E-06	7.58E-01	3.06E-03
RL-W641	2.86E+00	0.00E+00	2.42E+00	2.59E+00	1.07E+00	5.85E+00	2.50E-04	8.94E+00	3.60E-02
RL-W642	5.97E-02	0.00E+00	2.52E-04	3.16E-02	1.62E-04	2.53E-03	2.60E-08	9.17E-02	3.70E-04
RL-W643	8.80E-01	0.00E+00	7.46E-01	7.97E-01	3.29E-01	1.80E+00	7.70E-05	2.75E+00	1.11E-02
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.49E-02	0.00E+00	0.00E+00	0.00E+00	5.49E-02	2.21E-04
RL-W645	1.95E-02	0.00E+00	3.36E-03	1.08E-01	2.54E-02	9.84E-02	3.46E-07	1.56E-01	6.30E-04
RL-W646	1.91E-02	0.00E+00	3.00E-03	2.58E-02	1.26E-02	4.78E-02	3.09E-07	6.05E-02	2.44E-04
RL-W647	5.30E-02	0.00E+00	4.48E-01	1.10E-01	1.74E-02	1.60E-01	4.63E-05	6.29E-01	2.53E-03
RL-W648	8.61E-04	0.00E+00	7.66E-04	6.00E-05	1.19E-04	5.12E-03	7.90E-08	1.81E-03	7.28E-06
RL-W649	3.16E-03	0.00E+00	2.82E-03	2.21E-04	4.36E-04	1.88E-02	2.91E-07	6.64E-03	2.68E-05
RL-W653	1.56E-04	0.00E+00	2.02E-05	9.65E-04	2.15E-04	7.18E-04	2.08E-09	1.36E-03	5.47E-06
RL-W654	8.63E-04	0.00E+00	1.10E-04	5.32E-03	1.19E-03	3.77E-03	1.14E-08	7.48E-03	3.01E-05
RL-W655	2.10E+02	0.00E+00	2.61E+01	2.11E-01	4.99E-01	1.01E+03	2.69E-03	2.37E+02	9.54E-01
RL-W656	8.59E+02	0.00E+00	1.17E+01	4.96E-01	5.13E-01	4.80E+03	1.21E-03	8.71E+02	3.51E+00
RL-W657	4.50E+02	0.00E+00	1.73E+01	2.44E-01	4.88E-01	2.12E+03	1.79E-03	4.68E+02	1.89E+00
RL-W659	5.50E+01	0.00E+00	3.91E+00	4.70E-02	5.85E-02	2.40E+02	4.03E-04	5.90E+01	2.38E-01
RL-W660	3.00E+02	0.00E+00	4.70E+01	8.66E-01	1.56E+00	1.37E+03	4.85E-03	3.49E+02	1.41E+00
RL-W661	3.10E+00	0.00E+00	5.88E-02	4.18E-04	3.82E-03	1.66E+01	6.07E-06	3.16E+00	1.28E-02
RL-W662	1.04E-01	0.00E+00	3.50E-03	1.07E-04	1.92E-04	3.41E-01	3.62E-07	1.08E-01	4.34E-04
RL-W665	1.19E+03	0.00E+00	2.80E+02	1.31E+00	1.76E+00	6.77E+03	2.89E-02	1.47E+03	5.93E+00
RL-W666	2.20E+01	0.00E+00	6.87E-01	5.49E-02	5.80E-02	9.79E+01	7.09E-05	2.28E+01	9.21E-02
RL-W668	2.41E+00	0.00E+00	2.16E-02	1.45E-01	4.13E-02	2.31E-01	2.23E-06	2.62E+00	1.06E-02
RL-W669	6.59E-01	0.00E+00	5.60E-01	5.97E-01	2.46E-01	1.35E+00	5.78E-05	2.06E+00	8.32E-03
RL-W670	4.45E-02	0.00E+00	3.98E-04	2.68E-03	7.63E-04	4.29E-03	4.11E-08	4.83E-02	1.95E-04
RL-W671	6.80E+00	0.00E+00	2.04E-01	4.91E-03	5.12E-03	1.41E+01	2.11E-05	7.01E+00	2.83E-02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W672	4.62E+01	0.00E+00	1.39E+00	3.35E-02	3.48E-02	9.56E+01	1.44E-04	4.76E+01	1.92E-01
RL-W673	4.45E+01	0.00E+00	1.34E+00	3.24E-02	3.36E-02	9.22E+01	1.38E-04	4.59E+01	1.85E-01
RL-W674	1.38E-01	0.00E+00	5.97E-02	1.12E+01	9.77E-02	6.43E-01	6.16E-06	1.15E+01	4.63E-02
RL-W675	5.44E-01	0.00E+00	3.30E-01	1.31E-01	1.14E-01	1.57E+00	3.41E-05	1.12E+00	4.51E-03
RL-W676	2.14E-02	0.00E+00	1.98E-03	1.47E-01	2.14E-03	4.65E-02	2.04E-07	1.72E-01	6.95E-04
RL-W677	4.94E+01	0.00E+00	4.91E+00	5.74E+00	5.00E+00	1.12E+02	5.07E-04	6.50E+01	2.62E-01
RL-W678	1.38E-01	0.00E+00	4.10E-02	5.16E-02	4.56E-02	8.79E-01	4.23E-06	2.76E-01	1.11E-03
RL-W679	9.78E-01	0.00E+00	9.16E-02	1.11E-01	9.83E-02	2.25E+00	9.46E-06	1.28E+00	5.16E-03
RL-W680	2.04E-04	0.00E+00	1.29E-04	1.74E-05	3.14E-05	9.67E-04	1.33E-08	3.82E-04	1.54E-06
RL-W681	1.17E-04	0.00E+00	5.23E-05	4.67E-04	2.33E-04	8.04E-04	5.39E-09	8.69E-04	3.51E-06
RL-W685	3.72E-01	0.00E+00	4.64E-02	2.28E+00	5.08E-01	1.47E+00	4.79E-06	3.21E+00	1.29E-02
RL-W689	1.09E-02	0.00E+00	5.58E-04	3.87E-04	0.00E+00	1.41E-03	5.76E-08	1.19E-02	4.78E-05
RL-W690	3.24E-01	0.00E+00	4.10E-02	2.03E+00	4.52E-01	1.28E+00	4.23E-06	2.84E+00	1.15E-02
RL-W691	7.51E-03	0.00E+00	9.55E-04	4.70E-02	1.05E-02	2.96E-02	9.86E-08	6.59E-02	2.66E-04
RL-W692	2.97E-01	0.00E+00	3.78E-02	1.86E+00	4.15E-01	1.17E+00	3.90E-06	2.61E+00	1.05E-02
RL-W693	3.68E-01	0.00E+00	4.67E-02	2.30E+00	5.13E-01	1.44E+00	4.82E-06	3.23E+00	1.30E-02
RL-W694	3.86E+00	0.00E+00	4.90E-01	2.43E+01	5.38E+00	1.52E+01	5.06E-05	3.40E+01	1.37E-01
RL-W695	3.63E-03	0.00E+00	0.00E+00	2.39E-03	0.00E+00	0.00E+00	0.00E+00	6.02E-03	2.43E-05
RL-W696	4.01E-03	0.00E+00	1.79E-03	2.91E-03	2.88E-03	2.09E-02	1.84E-07	1.16E-02	4.67E-05
RL-W697	1.09E+00	0.00E+00	3.78E+00	6.92E-03	9.54E-04	0.00E+00	3.90E-04	4.88E+00	1.97E-02
RL-W698	9.47E-02	0.00E+00	0.00E+00	3.29E-05	0.00E+00	0.00E+00	0.00E+00	9.48E-02	3.82E-04
RL-W699	1.80E-02	0.00E+00	2.52E-04	2.20E-03	2.59E-04	8.77E-02	2.60E-08	2.07E-02	8.37E-05
RL-W700	5.19E-03	0.00E+00	6.60E-04	3.19E-02	7.13E-03	2.27E-02	6.81E-08	4.48E-02	1.81E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	2.20E-01	0.00E+00	1.86E-01	1.99E-01	8.22E-02	4.50E-01	1.92E-05	6.87E-01	2.77E-03
RL-W705	1.33E-03	0.00E+00	1.72E-04	8.35E-03	1.87E-03	5.53E-03	1.77E-08	1.17E-02	4.73E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W707	4.75E-02	0.00E+00	6.10E-03	2.98E-01	6.66E-02	1.97E-01	6.30E-07	4.18E-01	1.69E-03
RL-W708	7.17E-03	0.00E+00	9.24E-04	4.52E-02	1.01E-02	2.98E-02	9.54E-08	6.33E-02	2.55E-04
RL-W709	2.48E+00	0.00E+00	3.18E-01	1.56E+01	3.48E+00	1.03E+01	3.29E-05	2.19E+01	8.82E-02
RL-W710	1.48E-04	0.00E+00	1.90E-05	9.31E-04	2.07E-04	6.15E-04	1.96E-09	1.31E-03	5.26E-06
RL-W711	4.62E-02	0.00E+00	5.94E-03	2.91E-01	6.49E-02	1.92E-01	6.13E-07	4.08E-01	1.64E-03
RL-W712	5.98E-02	0.00E+00	7.69E-03	3.76E-01	8.39E-02	2.49E-01	7.94E-07	5.27E-01	2.13E-03
RL-W713	5.17E-02	0.00E+00	6.64E-03	3.24E-01	7.26E-02	2.14E-01	6.85E-07	4.55E-01	1.83E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	8.97E-04	0.00E+00	1.12E-04	5.49E-03	1.23E-03	3.54E-03	1.15E-08	7.72E-03	3.11E-05
RL-W716	9.35E-03	0.00E+00	1.17E-03	5.72E-02	1.28E-02	3.69E-02	1.20E-07	8.04E-02	3.24E-04
RL-W717	2.33E-03	0.00E+00	2.91E-04	1.43E-02	3.19E-03	9.19E-03	3.01E-08	2.01E-02	8.11E-05
RL-W718	4.12E-04	0.00E+00	5.13E-05	2.52E-03	5.62E-04	1.62E-03	5.30E-09	3.54E-03	1.43E-05
RL-W719	1.86E-03	0.00E+00	2.31E-04	1.14E-02	2.54E-03	7.33E-03	2.39E-08	1.60E-02	6.46E-05
RL-W720	1.15E-02	0.00E+00	1.44E-03	7.03E-02	1.58E-02	4.52E-02	1.48E-07	9.90E-02	3.99E-04
RL-W721	7.79E-03	0.00E+00	9.71E-04	4.76E-02	1.07E-02	3.06E-02	1.00E-07	6.70E-02	2.70E-04
RL-W723	2.58E-02	0.00E+00	3.28E-03	1.62E-01	3.61E-02	1.02E-01	3.38E-07	2.27E-01	9.15E-04
RL-W724	1.72E-01	0.00E+00	2.18E-02	1.07E+00	2.40E-01	6.75E-01	2.25E-06	1.50E+00	6.06E-03
RL-W725	5.42E-02	0.00E+00	6.88E-03	3.39E-01	7.57E-02	2.13E-01	7.10E-07	4.76E-01	1.92E-03
RL-W726	4.27E-02	0.00E+00	5.43E-03	2.68E-01	5.97E-02	1.68E-01	5.60E-07	3.76E-01	1.51E-03
RL-W727	2.62E-01	0.00E+00	3.33E-02	1.64E+00	3.67E-01	1.03E+00	3.44E-06	2.30E+00	9.28E-03
RL-W728	2.38E-01	0.00E+00	3.04E-02	1.50E+00	3.34E-01	9.39E-01	3.13E-06	2.10E+00	8.47E-03
RL-W729	1.10E-01	0.00E+00	1.41E-02	6.89E-01	1.55E-01	4.33E-01	1.45E-06	9.68E-01	3.90E-03
RL-W730	4.89E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.89E+01	1.97E-01
RL-W731	1.58E-05	0.00E+00	0.00E+00	4.51E-04	1.85E-06	0.00E+00	0.00E+00	4.68E-04	1.89E-06
RL-W732	3.08E+01	0.00E+00	8.00E+00	1.27E+02	2.82E+01	1.55E+02	8.26E-04	1.94E+02	7.82E-01
RL-W733	4.16E-01	0.00E+00	1.04E-01	1.38E+00	3.43E-01	1.69E+00	1.07E-05	2.24E+00	9.04E-03
RL-W734	1.31E+00	0.00E+00	3.47E-01	4.76E+00	1.16E+00	5.02E+00	3.58E-05	7.57E+00	3.05E-02
RL-W735	1.08E+00	0.00E+00	2.65E-01	3.71E+00	9.22E-01	3.90E+00	2.73E-05	5.97E+00	2.41E-02

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W736	1.29E-03	0.00E+00	5.65E-07	2.46E-03	6.36E-04	1.19E-03	5.83E-11	4.39E-03	1.77E-05
RL-W737	9.66E-01	0.00E+00	2.42E-01	3.52E+00	8.58E-01	3.36E+00	2.49E-05	5.58E+00	2.25E-02
RL-W738	3.62E+00	0.00E+00	8.31E-01	1.12E+01	2.96E+00	1.22E+01	8.58E-05	1.86E+01	7.50E-02
RL-W739	3.06E-01	0.00E+00	7.33E-02	1.82E+00	4.16E-01	1.11E+00	7.57E-06	2.61E+00	1.05E-02
RL-W740	1.53E+01	0.00E+00	2.69E+00	4.43E+01	1.16E+01	5.59E+01	2.77E-04	7.38E+01	2.98E-01
RL-W741	2.43E+01	0.00E+00	6.32E+00	8.62E+00	6.14E+00	4.20E+01	6.52E-04	4.53E+01	1.83E-01
RL-W742	1.02E+00	0.00E+00	1.90E-01	2.80E+00	6.61E-01	3.60E+00	1.96E-05	4.67E+00	1.88E-02
RL-W743	2.06E-03	0.00E+00	5.17E-05	1.81E-03	0.00E+00	0.00E+00	5.33E-09	3.92E-03	1.58E-05
RL-W744	0.00E+00	0.00E+00	0.00E+00	9.02E-02	7.69E-02	0.00E+00	0.00E+00	1.67E-01	6.74E-04
RL-W745	2.83E-03	0.00E+00	3.61E-04	1.75E-02	3.90E-03	1.24E-02	3.73E-08	2.46E-02	9.91E-05
RL-W746	1.09E-02	0.00E+00	1.39E-03	6.71E-02	1.51E-02	4.76E-02	1.44E-07	9.45E-02	3.81E-04
RL-W747	2.95E-02	0.00E+00	3.77E-03	1.82E-01	4.07E-02	1.29E-01	3.89E-07	2.56E-01	1.03E-03
RL-W748	2.05E+02	0.00E+00	1.06E+01	3.02E-01	4.97E-01	9.71E+02	1.09E-03	2.16E+02	8.71E-01
RL-W749	2.50E-01	0.00E+00	3.23E-02	1.58E+00	3.52E-01	1.04E+00	3.33E-06	2.21E+00	8.92E-03
RL-W750	3.14E+02	0.00E+00	1.60E+01	4.95E-01	8.12E-01	1.37E+03	1.65E-03	3.31E+02	1.33E+00
RL-W751	2.83E+02	0.00E+00	1.45E+01	4.45E-01	7.37E-01	1.24E+03	1.49E-03	2.99E+02	1.21E+00
RL-W752	1.23E+02	0.00E+00	6.28E+00	1.94E-01	3.20E-01	5.38E+02	6.48E-04	1.30E+02	5.24E-01
RL-W753	1.66E+03	0.00E+00	8.47E+01	2.61E+00	4.30E+00	7.24E+03	8.74E-03	1.75E+03	7.05E+00
RP-W754	7.86E+01	0.00E+00	1.07E+01	1.86E+03	1.53E+02	6.69E+01	3.54E-01	2.10E+03	8.47E+00
RP-W755	4.27E+02	0.00E+00	6.42E+00	1.39E+03	1.16E+02	4.99E+01	1.26E+01	1.95E+03	7.86E+00
SA-T001	8.62E-01	1.40E+00	1.54E-01	3.03E+00	1.41E-02	0.00E+00	2.05E-05	4.06E+00	1.64E-02
SA-W134	6.99E+00	5.44E-04	1.05E+00	1.38E+00	4.38E-01	1.27E+00	1.67E-01	1.00E+01	4.04E-02
SA-W134M	9.08E-01	7.05E-05	1.36E-01	1.80E-01	5.68E-02	1.65E-01	2.16E-02	1.30E+00	5.25E-03
T001-221F-HET	1.56E+03	0.00E+00	1.23E+05	2.88E+04	7.12E+02	4.18E+03	1.83E+01	1.54E+05	6.20E+02
T001-221H-HET	2.80E+03	0.00E+00	2.21E+05	5.20E+04	1.29E+03	7.54E+03	3.30E+01	2.77E+05	1.12E+03
T001-235F-HET	1.61E+02	0.00E+00	1.27E+04	2.99E+03	7.39E+01	4.33E+02	1.90E+00	1.60E+04	6.44E+01
T001-772F-HET	1.39E+03	0.00E+00	1.10E+05	2.58E+04	6.37E+02	3.73E+03	1.64E+01	1.38E+05	5.57E+02
T001-773A-CLAS	1.56E+01	0.00E+00	1.24E+03	2.90E+02	7.15E+00	4.20E+01	1.84E-01	1.55E+03	6.24E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
T001-773A-HET	1.80E+02	0.00E+00	1.42E+04	3.34E+03	8.25E+01	4.84E+02	2.12E+00	1.78E+04	7.18E+01
W006-773A-VIT	2.63E-03	0.00E+00	0.00E+00	5.37E+02	0.00E+00	0.00E+00	0.00E+00	5.37E+02	2.16E+00
W026-221F-HET	5.42E+02	0.00E+00	4.28E+04	1.01E+04	2.48E+02	1.46E+03	6.39E+00	5.37E+04	2.17E+02
W026-221H-HET	4.05E+02	0.00E+00	3.20E+04	7.51E+03	1.85E+02	1.09E+03	4.77E+00	4.01E+04	1.62E+02
W026-235F-HET	6.31E+00	0.00E+00	4.99E+02	1.17E+02	2.89E+00	1.70E+01	7.44E-02	6.25E+02	2.52E+00
W026-772F-HET	1.73E+00	0.00E+00	1.36E+02	3.19E+01	7.87E-01	4.63E+00	2.03E-02	1.70E+02	6.87E-01
W026-773A-HET	2.80E+01	0.00E+00	2.21E+03	5.20E+02	1.29E+01	7.52E+01	3.30E-01	2.77E+03	1.12E+01
W027-221F-HET	2.15E+03	0.00E+00	1.45E+05	3.90E+04	9.61E+02	2.38E+03	3.27E+01	1.87E+05	7.52E+02
W027-221H-HET	9.41E+02	0.00E+00	6.31E+04	1.71E+04	4.21E+02	1.04E+03	1.43E+01	8.15E+04	3.29E+02
W027-235F-HET	2.83E+02	0.00E+00	1.90E+04	5.14E+03	1.27E+02	3.13E+02	4.31E+00	2.45E+04	9.88E+01
W027-772F-HET	5.15E+02	0.00E+00	3.45E+04	9.32E+03	2.30E+02	5.68E+02	7.82E+00	4.46E+04	1.80E+02
W027-773A-HET	7.67E+02	0.00E+00	5.14E+04	1.39E+04	3.43E+02	8.49E+02	1.17E+01	6.64E+04	2.68E+02
W027-999-HET	8.77E+02	0.00E+00	5.88E+04	1.59E+04	3.92E+02	9.69E+02	1.33E+01	7.60E+04	3.06E+02
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.99E+02	0.00E+00	0.00E+00	0.00E+00	3.99E+02	1.61E+00
WP-INW169.001	4.16E+00	0.00E+00	3.71E-01	1.54E+01	3.43E+00	8.55E+00	2.03E-04	2.33E+01	9.41E-02
WP-INW198.001	5.38E+00	0.00E+00	6.46E-01	2.76E+01	6.10E+00	1.40E+01	1.49E-04	3.97E+01	1.60E-01
WP-INW211.001	6.05E+02	0.00E+00	6.07E+01	2.56E+03	5.66E+02	1.59E+03	8.24E-03	3.79E+03	1.53E+01
WP-INW216.001-	2.40E+04	0.00E+00	3.49E+01	1.48E+03	3.29E+02	8.79E+02	2.81E-01	2.58E+04	1.04E+02
WP-INW216.001-	6.58E+03	0.00E+00	9.40E+00	4.01E+02	8.87E+01	2.38E+02	2.86E-02	7.08E+03	2.86E+01
WP-INW218.001-	4.53E+02	0.00E+00	6.15E+00	2.58E+02	5.72E+01	1.59E+02	3.87E-01	7.75E+02	3.12E+00
WP-INW218.001-	1.96E+00	0.00E+00	1.69E-01	7.01E+00	1.56E+00	4.50E+00	3.74E-02	1.07E+01	4.33E-02
WP-INW222.001	2.04E+01	0.00E+00	1.83E+00	6.85E+01	1.54E+01	3.82E+01	7.62E-04	1.06E+02	4.28E-01
WP-INW243.001	5.00E+01	0.00E+00	3.94E+00	1.44E+02	3.23E+01	7.72E+01	1.27E-03	2.30E+02	9.28E-01
WP-INW247.001R	6.57E+01	0.00E+00	9.16E+00	2.76E+02	6.28E+01	1.34E+02	1.02E-03	4.13E+02	1.67E+00
WP-INW276.001	4.97E+00	0.00E+00	8.93E-01	2.73E+01	6.22E+00	1.13E+01	1.09E-04	3.94E+01	1.59E-01
WP-INW276.002	7.91E+00	0.00E+00	1.34E+00	4.01E+01	9.33E+00	1.70E+01	1.65E-04	5.87E+01	2.37E-01
WP-INW276.003	3.01E+02	0.00E+00	4.99E+01	1.49E+03	3.40E+02	7.16E+02	5.60E-03	2.18E+03	8.79E+00
WP-INW276.004	7.26E+01	0.00E+00	1.06E+01	3.15E+02	7.18E+01	1.51E+02	1.24E-03	4.70E+02	1.89E+00

Table PAR-51. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 0 years— Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-EPA	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-EPA	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-INW296.001-	2.71E+01	0.00E+00	2.51E+00	7.90E+01	1.79E+01	3.88E+01	2.96E-04	1.27E+02	5.10E-01
WP-INW296.001-	8.09E+01	0.00E+00	8.85E+00	2.80E+02	6.34E+01	1.40E+02	1.27E-03	4.33E+02	1.75E+00
WP-LA-TA-55-19	1.38E+00	0.00E+00	4.12E-01	2.09E+00	5.05E-01	1.39E+00	2.68E-03	4.39E+00	1.77E-02
WP-LA-TA-55-19	6.44E+01	0.00E+00	1.38E+01	2.13E+02	5.20E+01	1.38E+02	8.86E-02	3.43E+02	1.38E+00
WP-LA-TA-55-43	3.46E-01	0.00E+00	3.22E+02	3.23E-01	1.37E-01	1.24E+00	5.98E-02	3.23E+02	1.30E+00
WP-RF001.01	1.15E+02	0.00E+00	1.12E+01	4.10E+02	9.34E+01	1.39E+02	1.05E-02	6.30E+02	2.54E+00
WP-RF002.01-A	1.29E+02	0.00E+00	1.49E+01	4.62E+02	1.06E+02	3.06E+02	1.93E-02	7.11E+02	2.87E+00
WP-RF002.01-B	1.32E-01	0.00E+00	1.03E-02	5.00E-01	1.14E-01	1.93E-01	1.26E-06	7.56E-01	3.05E-03
WP-RF003.01	2.00E+03	0.00E+00	2.40E+02	8.82E+03	2.01E+03	5.06E+03	3.31E-02	1.31E+04	5.27E+01
WP-RF004.01	9.18E-01	0.00E+00	1.61E-01	5.09E+00	1.17E+00	2.89E+00	1.44E-04	7.33E+00	2.96E-02
WP-RF005.01	5.15E+03	0.00E+00	1.22E+02	4.67E+03	1.06E+03	2.01E+03	1.44E-02	1.10E+04	4.43E+01
WP-RF005.02	6.11E+03	0.00E+00	6.30E+01	2.79E+03	6.27E+02	1.03E+03	7.71E-03	9.58E+03	3.87E+01
WP-RF006.01	1.91E+03	0.00E+00	2.29E+02	7.93E+03	1.81E+03	2.61E+03	4.92E-02	1.19E+04	4.79E+01
WP-RF008.01	5.73E+02	0.00E+00	8.16E+01	2.32E+03	5.39E+02	1.73E+03	9.68E-03	3.51E+03	1.42E+01
WP-RF009.01	6.15E+04	0.00E+00	1.00E+03	5.09E+04	1.14E+04	1.98E+04	1.24E-01	1.25E+05	5.03E+02
WP-RF010.01	2.08E+01	0.00E+00	2.54E+00	7.68E+01	1.75E+01	6.11E+01	9.93E-04	1.18E+02	4.75E-01
WP-RF029.01-A	5.03E+00	0.00E+00	4.78E-01	1.35E+01	3.09E+00	1.40E+01	7.79E-04	2.21E+01	8.91E-02
WP-RF029.01-B	7.85E+00	0.00E+00	3.78E-01	1.07E+01	2.44E+00	1.11E+01	2.29E-03	2.14E+01	8.61E-02
WP-RF118.01	1.27E+04	0.00E+00	1.90E+03	5.14E+04	1.15E+04	3.64E+04	4.11E-01	7.74E+04	3.12E+02
WP-RLMPDT.001	2.69E+00	0.00E+00	5.55E-01	7.35E+00	1.91E+00	7.99E+00	5.94E-05	1.25E+01	5.05E-02
WP-RLNPDT.002	3.33E+01	0.00E+00	5.29E+00	7.22E+01	1.94E+01	9.17E+01	5.85E-04	1.30E+02	5.25E-01
WP-SR2001.001.	9.89E-01	0.00E+00	6.08E-01	6.82E+00	1.36E+00	4.99E+00	6.72E-05	9.78E+00	3.94E-02
WP-SR-W027-221	7.82E+00	0.00E+00	1.79E+00	1.96E+01	5.47E+00	2.25E+01	1.86E-01	3.49E+01	1.41E-01
Total	4.42E+05	2.72E+03	1.25E+06	6.60E+05	1.07E+05	5.15E+05	2.97E+02	2.46E+06	9.92E+03

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	7.37E+01	0.00E+00	6.27E+00	2.08E+02	1.22E+02	4.16E-01	1.74E-02	4.11E+02	1.66E+00
AE-T003	9.34E+00	0.00E+00	8.35E-01	6.44E+01	2.47E+01	2.28E-01	6.64E-04	9.92E+01	4.00E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	4.14E-02	0.00E+00	2.21E+01	4.74E+01	2.84E-01	4.44E-04	1.51E-02	6.99E+01	2.82E-01
AW-T033.1325	1.51E-01	0.00E+00	8.11E+01	1.73E+02	1.04E+00	1.62E-03	5.52E-02	2.56E+02	1.03E+00
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.70E-01	0.00E+00	0.00E+00	0.00E+00	7.70E-01	3.11E-03
BCLCH-MT01	1.53E+01	0.00E+00	6.27E+02	2.86E+01	7.44E+00	6.26E-01	4.14E-01	6.79E+02	2.74E+00
BT-T002	1.12E-02	1.62E-05	3.28E-01	7.22E-04	1.47E-03	2.75E-04	2.21E-03	3.43E-01	1.39E-03
ET-C1-B55	4.69E-02	0.00E+00	3.74E-03	6.19E-02	3.06E-02	4.85E-04	2.38E-04	1.43E-01	5.78E-04
ET-C1-D139	6.43E-03	0.00E+00	5.18E-04	8.70E-03	4.30E-03	6.45E-05	4.03E-07	1.99E-02	8.04E-05
ET-C2-SEFOR	1.59E-01	0.00E+00	0.00E+00	1.37E-01	4.55E-02	9.95E-04	0.00E+00	3.41E-01	1.38E-03
FM-MOX-MT02	1.51E-06	0.00E+00	2.09E-07	2.99E-07	1.77E-07	3.46E-08	1.46E-10	2.19E-06	8.84E-09
FM-MOX-T01	2.49E-05	0.00E+00	3.44E-06	4.92E-06	2.91E-06	5.71E-07	2.41E-09	3.62E-05	1.46E-07
IN-BN-510	6.02E+03	0.00E+00	1.78E+04	3.96E+04	3.32E+03	1.36E-01	1.37E+01	6.67E+04	2.69E+02
IN-GEM-01	7.62E+01	0.00E+00	3.52E-01	4.44E+01	1.01E+01	9.62E-02	2.32E-04	1.31E+02	5.28E-01
IN-GEM-02	1.81E+01	0.00E+00	8.39E-02	1.06E+01	2.40E+00	2.28E-02	5.53E-05	3.11E+01	1.26E-01
IN-W157.144	9.02E+01	0.00E+00	3.41E+00	3.02E+02	6.78E+01	1.71E+00	2.63E-03	4.63E+02	1.87E+00
IN-W163.1007	1.54E+01	0.00E+00	1.05E+00	9.36E+01	2.10E+01	5.25E-01	8.11E-04	1.31E+02	5.29E-01
IN-W164.153	1.48E-01	0.00E+00	1.01E-02	8.92E-01	2.00E-01	5.03E-03	7.73E-06	1.25E+00	5.04E-03
IN-W167.149	2.95E+01	0.00E+00	1.63E+00	1.44E+02	3.24E+01	8.14E-01	1.26E-03	2.08E+02	8.39E-01
IN-W174.154	0.00E+00	0.00E+00	9.24E+02	1.94E+00	3.80E+00	0.00E+00	7.11E-01	9.30E+02	3.75E+00
IN-W177.156	2.05E-02	0.00E+00	1.96E+03	1.82E+00	1.10E-02	6.99E-04	1.51E+00	1.97E+03	7.93E+00
IN-W179.158	1.38E-01	0.00E+00	1.96E+03	1.06E-01	5.44E-02	4.70E-03	1.50E+00	1.96E+03	7.90E+00
IN-W181.162	1.96E+00	0.00E+00	1.33E-01	1.18E+01	2.64E+00	6.66E-02	1.03E-04	1.65E+01	6.65E-02
IN-W188.160	1.32E+01	0.00E+00	8.95E-01	7.94E+01	1.78E+01	4.49E-01	6.89E-04	1.11E+02	4.48E-01
IN-W216.98	1.17E+05	0.00E+00	7.30E+01	6.48E+03	1.46E+03	3.67E+01	5.61E-02	1.25E+05	5.05E+02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	5.92E+02	0.00E+00	1.62E+00	1.44E+02	3.23E+01	8.12E-01	1.25E-03	7.69E+02	3.10E+00
IN-W219.110	8.02E-01	0.00E+00	5.46E-02	4.84E+00	1.09E+00	2.73E-02	4.20E-05	6.78E+00	2.74E-02
IN-W219.914	1.27E-01	0.00E+00	8.60E-03	7.64E-01	1.72E-01	4.31E-03	6.62E-06	1.07E+00	4.32E-03
IN-W220.114	4.18E+03	0.00E+00	5.75E+00	5.47E+02	1.19E+02	2.87E+00	4.42E-03	4.85E+03	1.96E+01
IN-W221.927	4.90E+00	0.00E+00	3.33E-01	2.95E+01	6.61E+00	1.67E-01	2.56E-04	4.13E+01	1.67E-01
IN-W222.116	1.67E+02	0.00E+00	1.13E+01	9.96E+02	2.24E+02	5.64E+00	8.67E-03	1.40E+03	5.64E+00
IN-W228.101	1.11E+03	0.00E+00	3.67E+00	3.26E+02	7.30E+01	1.84E+00	2.82E-03	1.51E+03	6.08E+00
IN-W240.931	1.17E+02	0.00E+00	4.69E+00	4.18E+02	9.34E+01	2.33E+00	3.61E-03	6.33E+02	2.55E+00
IN-W243.808	1.62E+02	0.00E+00	8.21E+00	7.30E+02	1.64E+02	4.12E+00	6.32E-03	1.06E+03	4.29E+00
IN-W245.301	2.40E+02	0.00E+00	1.61E+01	1.43E+03	3.21E+02	8.05E+00	1.24E-02	2.00E+03	8.07E+00
IN-W247.810	1.17E+02	0.00E+00	7.86E+00	6.96E+02	1.57E+02	3.93E+00	6.05E-03	9.78E+02	3.94E+00
IN-W249.527	0.00E+00	0.00E+00	5.50E+02	1.24E+01	0.00E+00	0.00E+00	4.23E-01	5.63E+02	2.27E+00
IN-W263.520	3.34E-02	0.00E+00	5.75E+01	8.40E+00	1.32E-02	1.14E-03	4.42E-02	6.60E+01	2.66E-01
IN-W267.1005	2.80E+01	0.00E+00	1.91E+00	1.69E+02	3.80E+01	9.55E-01	1.47E-03	2.37E+02	9.57E-01
IN-W309.609	7.51E+02	0.00E+00	3.20E+01	2.83E+03	6.35E+02	1.60E+01	2.46E-02	4.25E+03	1.71E+01
IN-W315.601	7.41E+02	0.00E+00	1.34E-01	1.19E+01	2.65E+00	6.66E-02	1.03E-04	7.55E+02	3.05E+00
IN-W319.584	4.30E+00	0.00E+00	2.93E-01	2.60E+01	5.85E+00	1.47E-01	2.25E-04	3.65E+01	1.47E-01
IN-W321.1023	3.72E+01	0.00E+00	2.54E+00	2.25E+02	5.05E+01	1.27E+00	1.95E-03	3.15E+02	1.27E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	9.09E+00	1.86E+00	0.00E+00	0.00E+00	1.10E+01	4.42E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.42E+01	4.97E+00	0.00E+00	0.00E+00	2.92E+01	1.18E-01
IN-W323.562	7.96E-02	0.00E+00	4.30E-01	2.48E-01	0.00E+00	2.71E-03	3.31E-04	7.58E-01	3.06E-03
IN-W323.951	9.39E-02	0.00E+00	5.11E-03	2.96E-01	0.00E+00	3.20E-03	3.93E-06	3.95E-01	1.59E-03
IN-W332.661	0.00E+00	0.00E+00	5.64E+00	1.29E-01	0.00E+00	0.00E+00	4.34E-03	5.77E+00	2.33E-02
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	3.03E+00	6.21E-01	0.00E+00	0.00E+00	3.65E+00	1.47E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	9.09E+00	1.86E+00	0.00E+00	0.00E+00	1.10E+01	4.42E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.94E+00	0.00E+00	0.00E+00	0.00E+00	1.94E+00	7.83E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.84E+00	0.00E+00	0.00E+00	0.00E+00	5.84E+00	2.35E-02
IN-W342.652	3.68E+00	0.00E+00	0.00E+00	4.01E-02	1.03E-17	0.00E+00	0.00E+00	3.72E+00	1.50E-02
IN-W342.953	2.46E+00	0.00E+00	0.00E+00	2.68E-02	6.88E-18	0.00E+00	0.00E+00	2.49E+00	1.00E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W347.818	1.93E+00	0.00E+00	0.00E+00	8.23E+01	1.50E+02	0.00E+00	1.58E-08	2.34E+02	9.44E-01
IN-W348.1012	1.02E-01	0.00E+00	4.65E+00	4.15E+02	9.33E+01	0.00E+00	3.58E-03	5.14E+02	2.07E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.49E-02	0.00E+00	0.00E+00	0.00E+00	2.49E-02	1.00E-04
IN-W357.1022	0.00E+00	0.00E+00	9.17E-03	8.16E-01	1.82E-01	0.00E+00	7.05E-06	1.01E+00	4.06E-03
IN-W358.854	0.00E+00	0.00E+00	1.38E+02	1.87E+00	3.58E+00	0.00E+00	9.91E-02	1.44E+02	5.80E-01
IN-W358.855	0.00E+00	0.00E+00	7.37E+02	9.96E+00	1.90E+01	0.00E+00	5.28E-01	7.66E+02	3.09E+00
IN-W358.948	0.00E+00	0.00E+00	1.54E+02	2.08E+00	3.96E+00	0.00E+00	1.10E-01	1.60E+02	6.45E-01
IN-W361.1021	2.71E-02	0.00E+00	8.88E-01	7.87E+01	1.77E+01	0.00E+00	6.83E-04	9.73E+01	3.92E-01
IN-W362.1020	0.00E+00	0.00E+00	1.16E+01	1.03E+03	2.32E+02	0.00E+00	8.95E-03	1.27E+03	5.12E+00
IN-W363.1019	0.00E+00	0.00E+00	5.46E-01	4.87E+01	1.10E+01	0.00E+00	4.20E-04	6.02E+01	2.43E-01
IN-W364.1011	0.00E+00	0.00E+00	9.02E-01	8.01E+01	1.80E+01	0.00E+00	6.94E-04	9.90E+01	3.99E-01
IN-W365.1010	2.53E+02	0.00E+00	7.16E-01	6.33E+01	1.42E+01	0.00E+00	5.50E-04	3.31E+02	1.33E+00
IN-W366.841	8.98E-01	0.00E+00	6.10E-01	5.39E+01	1.21E+01	0.00E+00	4.69E-04	6.75E+01	2.72E-01
IN-W372.832	3.68E+00	0.00E+00	0.00E+00	4.01E-02	1.03E-17	0.00E+00	0.00E+00	3.72E+00	1.50E-02
IN-W375.1096	0.00E+00	0.00E+00	2.25E-01	1.99E+01	4.47E+00	0.00E+00	1.73E-04	2.46E+01	9.93E-02
KN-B234TRU	1.31E+02	0.00E+00	8.60E+00	2.90E+02	9.66E+01	8.92E-01	7.62E-03	5.26E+02	2.12E+00
LA-IT-00-01	1.90E+00	1.04E-02	1.47E+00	5.83E-01	1.25E-02	1.71E-10	1.32E-03	3.97E+00	1.60E-02
LA-OS-00-01	4.23E+03	0.00E+00	6.70E+04	1.23E+03	0.00E+00	0.00E+00	4.47E+01	7.25E+04	2.92E+02
LA-PX-00-01	1.77E-02	0.00E+00	2.82E-03	9.02E-02	2.10E-02	2.84E-04	2.00E-06	1.32E-01	5.31E-04
LA-SL-00-01	0.00E+00	0.00E+00	5.96E-02	1.52E-01	0.00E+00	0.00E+00	5.32E-05	2.12E-01	8.55E-04
LA-TA-03-12	1.81E-01	0.00E+00	1.38E+00	4.34E-01	1.50E-01	1.68E-03	1.29E-03	2.15E+00	8.65E-03
LA-TA-03-13	2.35E-01	0.00E+00	4.37E+00	6.78E-01	1.58E-01	2.23E-03	3.41E-03	5.45E+00	2.20E-02
LA-TA-03-19	4.74E-01	0.00E+00	6.52E+00	1.33E+00	3.80E-01	3.44E-03	6.09E-03	8.71E+00	3.51E-02
LA-TA-03-20	2.59E-01	0.00E+00	3.10E+00	5.84E-01	2.04E-01	2.82E-03	2.73E-03	4.14E+00	1.67E-02
LA-TA-03-24	3.47E-01	0.00E+00	1.21E+01	1.09E+00	3.26E-01	2.92E-03	1.14E-02	1.38E+01	5.58E-02
LA-TA-03-26	1.78E-02	0.00E+00	4.97E-01	2.63E+00	4.27E-02	2.56E-04	1.34E-03	3.19E+00	1.29E-02
LA-TA-03-28	0.00E+00	0.00E+00	1.72E-01	2.46E-01	0.00E+00	0.00E+00	1.59E-04	4.18E-01	1.69E-03
LA-TA-03-30	7.90E-01	0.00E+00	1.23E-01	5.01E+00	1.44E+00	1.34E-02	1.12E-04	7.36E+00	2.97E-02
LA-TA-03-31	0.00E+00	0.00E+00	6.13E-03	8.77E-03	0.00E+00	0.00E+00	5.65E-06	1.49E-02	6.01E-05

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-03-40	0.00E+00	0.00E+00	9.69E-03	5.45E-02	0.00E+00	0.00E+00	9.03E-06	6.42E-02	2.59E-04
LA-TA-03-42	1.82E-05	0.00E+00	2.43E-04	3.41E-03	4.45E-05	2.80E-07	2.26E-07	3.71E-03	1.50E-05
LA-TA-21-06	1.79E-01	0.00E+00	2.67E+01	9.53E-01	2.89E-01	2.89E-03	2.46E-02	2.82E+01	1.14E-01
LA-TA-21-12	6.51E-01	0.00E+00	1.61E+02	3.31E+00	9.80E-01	9.92E-03	1.49E-01	1.66E+02	6.70E-01
LA-TA-21-13	1.00E+00	0.00E+00	0.00E+00	2.93E-01	0.00E+00	0.00E+00	0.00E+00	1.30E+00	5.23E-03
LA-TA-21-14	1.65E-04	0.00E+00	3.07E+00	4.47E+00	5.18E-05	4.02E-06	2.20E-03	7.55E+00	3.04E-02
LA-TA-21-15	9.71E-02	0.00E+00	8.46E-03	1.39E+00	2.35E-01	1.63E-03	7.71E-06	1.73E+00	6.96E-03
LA-TA-21-16	1.13E+00	0.00E+00	1.30E-01	1.06E+01	2.51E+00	1.72E-02	1.21E-04	1.43E+01	5.77E-02
LA-TA-21-40	1.43E-04	0.00E+00	4.51E-01	3.32E-01	3.64E-04	6.89E-07	5.48E-04	7.84E-01	3.16E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	7.06E-01	0.00E+00	0.00E+00	0.00E+00	7.06E-01	2.85E-03
LA-TA-21-42	1.46E-02	0.00E+00	1.47E-01	1.63E-01	1.10E-02	2.24E-05	1.93E-04	3.36E-01	1.35E-03
LA-TA-21-43	5.16E+01	0.00E+00	4.86E+00	5.09E+02	1.20E+02	1.77E-01	6.35E-03	6.86E+02	2.77E+00
LA-TA-21-44	2.47E-01	0.00E+00	1.02E+00	1.15E+02	3.03E-01	2.51E-03	1.05E-03	1.16E+02	4.68E-01
LA-TA-48-01	8.00E-02	4.91E-02	3.84E-03	1.18E-01	4.88E-01	2.07E-04	4.72E-06	6.90E-01	2.78E-03
LA-TA-49-01	9.88E+00	6.10E+00	4.72E-01	1.45E+01	6.05E+01	2.56E-02	5.82E-04	8.54E+01	3.44E-01
LA-TA-50-10	2.65E-02	0.00E+00	4.48E-03	4.57E-02	0.00E+00	0.00E+00	3.13E-06	7.67E-02	3.09E-04
LA-TA-50-11	5.05E-02	0.00E+00	4.58E-03	4.64E-01	1.03E-01	2.05E-04	5.50E-06	6.22E-01	2.51E-03
LA-TA-50-15	9.96E-02	0.00E+00	6.77E-01	3.39E-01	7.54E-02	8.12E-04	5.67E-04	1.19E+00	4.80E-03
LA-TA-50-17	1.46E+01	0.00E+00	5.50E-01	1.81E+01	4.24E-04	7.43E-05	8.00E-04	3.33E+01	1.34E-01
LA-TA-50-18	8.66E-01	0.00E+00	7.26E-02	2.96E+00	5.29E-06	2.19E-06	6.77E-05	3.90E+00	1.57E-02
LA-TA-50-19	2.76E-01	0.00E+00	3.24E-02	3.94E-01	4.53E-03	2.71E-05	5.69E-05	7.07E-01	2.85E-03
LA-TA-50-20	7.58E-03	0.00E+00	0.00E+00	9.70E-03	0.00E+00	0.00E+00	0.00E+00	1.73E-02	6.97E-05
LA-TA-50-40	4.26E-03	0.00E+00	4.37E-04	1.06E-02	4.90E-03	8.70E-05	3.81E-07	2.02E-02	8.13E-05
LA-TA-50-41	4.55E-03	0.00E+00	4.41E-04	4.68E-02	1.09E-02	1.55E-04	3.39E-07	6.27E-02	2.53E-04
LA-TA-55-19	7.06E+00	0.00E+00	5.82E-01	2.63E+01	7.37E+00	8.77E-02	2.05E-03	4.13E+01	1.67E-01
LA-TA-55-20	1.13E+02	0.00E+00	6.63E+00	6.36E+02	1.52E+02	2.19E+00	9.92E-02	9.08E+02	3.66E+00
LA-TA-55-21	1.01E+00	1.45E-05	7.61E-02	4.50E+00	1.08E+00	1.81E-02	5.79E-05	6.67E+00	2.69E-02
LA-TA-55-22	2.77E+00	0.00E+00	4.30E-01	1.58E+01	3.69E+00	5.60E-02	3.27E-04	2.27E+01	9.17E-02
LA-TA-55-23	2.61E+00	0.00E+00	3.60E-01	1.09E+01	2.67E+00	5.52E-02	2.70E-04	1.65E+01	6.66E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-24	9.85E-01	0.00E+00	5.64E-02	5.70E+00	1.32E+00	2.63E-02	4.00E-05	8.06E+00	3.25E-02
LA-TA-55-25	5.04E+00	0.00E+00	3.29E-01	2.83E+01	6.58E+00	1.35E-01	2.33E-04	4.02E+01	1.62E-01
LA-TA-55-28	1.72E+00	0.00E+00	1.82E-01	8.69E+00	2.04E+00	4.37E-02	1.31E-04	1.26E+01	5.09E-02
LA-TA-55-30	3.83E+01	1.38E-07	2.18E+00	1.43E+02	3.42E+01	3.20E-01	2.21E-03	2.17E+02	8.76E-01
LA-TA-55-32	3.11E+00	0.00E+00	1.22E+01	1.13E+01	3.46E+00	3.98E-02	1.15E-02	3.00E+01	1.21E-01
LA-TA-55-33	4.65E-01	0.00E+00	3.15E-02	1.48E+00	4.71E-01	5.60E-03	2.71E-05	2.45E+00	9.89E-03
LA-TA-55-34	4.71E+01	0.00E+00	2.91E+00	2.30E+02	5.82E+01	6.75E-01	5.29E-03	3.38E+02	1.36E+00
LA-TA-55-38	1.18E+02	0.00E+00	9.59E-01	5.08E+01	1.36E+01	1.57E-01	2.52E-03	1.84E+02	7.40E-01
LA-TA-55-39	1.25E+01	0.00E+00	7.09E-01	7.58E+01	1.70E+01	2.77E-01	5.26E-04	1.06E+02	4.27E-01
LA-TA-55-41	2.98E+02	0.00E+00	1.47E+00	9.40E+01	2.24E+01	3.48E-01	1.13E-03	4.16E+02	1.68E+00
LA-TA-55-43	1.12E-01	0.00E+00	9.62E+01	1.42E-01	4.93E-02	3.06E-03	7.07E-02	9.66E+01	3.90E-01
LA-TA-55-44	9.70E-01	0.00E+00	2.27E+02	2.62E+00	7.24E-01	9.05E-03	1.98E-01	2.31E+02	9.32E-01
LA-TA-55-48	7.14E+03	0.00E+00	8.95E+02	1.68E+04	6.25E+03	9.45E+01	7.55E-01	3.11E+04	1.26E+02
LA-TA-55-49	1.53E+01	0.00E+00	1.18E+03	3.08E+01	8.61E+00	1.11E-01	1.02E+00	1.23E+03	4.97E+00
LA-TA-55-53	7.20E+01	0.00E+00	2.43E+00	2.63E+02	6.11E+01	6.05E-01	2.06E-03	3.99E+02	1.61E+00
LA-TA-55-56	7.97E+01	0.00E+00	9.06E+01	3.81E+02	9.51E+01	1.40E+00	7.14E-02	6.46E+02	2.61E+00
LA-TA-55-60	4.32E-02	0.00E+00	2.29E-02	7.17E-02	2.53E-02	8.25E-04	1.97E-05	1.63E-01	6.58E-04
LA-TA-55-61	3.72E-02	0.00E+00	1.05E-01	1.39E-01	4.67E-02	8.02E-04	8.89E-05	3.28E-01	1.32E-03
LA-TA-55-62	9.63E-03	0.00E+00	1.00E-03	2.32E-02	1.10E-02	2.16E-04	8.54E-07	4.49E-02	1.81E-04
LA-TA-55-63	7.15E-03	0.00E+00	6.77E-04	7.44E-02	1.72E-02	2.12E-04	5.39E-07	9.94E-02	4.01E-04
LL-M001	9.81E+01	6.59E-01	2.95E+01	6.97E+01	3.13E+01	1.68E+00	1.94E-02	2.29E+02	9.22E-01
LL-T001	4.90E+02	0.00E+00	0.00E+00	5.32E+02	2.39E+02	1.30E+01	0.00E+00	1.26E+03	5.08E+00
LL-T002	4.84E+03	0.00E+00	2.35E+02	5.16E+03	2.11E+03	1.14E+02	1.55E-01	1.23E+04	4.98E+01
LL-T003	1.88E+02	0.00E+00	2.63E+01	1.05E+02	8.40E+01	4.52E+00	1.73E-02	4.03E+02	1.63E+00
LL-T004	1.20E+02	0.00E+00	5.39E+00	6.65E+01	5.30E+01	2.87E+00	3.55E-03	2.44E+02	9.85E-01
LL-T005	6.17E+02	2.87E+01	6.35E+01	2.47E+02	2.12E+02	1.06E+01	4.18E-02	1.14E+03	4.60E+00
LL-W018	5.25E-02	0.00E+00	0.00E+00	1.84E-02	4.22E-02	2.18E-03	0.00E+00	1.13E-01	4.56E-04
LL-W019	2.85E+01	0.00E+00	0.00E+00	1.44E+01	1.19E+01	6.37E-01	0.00E+00	5.48E+01	2.21E-01
LL-W034	1.05E+01	4.85E-01	1.11E+00	4.18E+00	3.52E+00	1.81E-01	7.32E-04	1.94E+01	7.80E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
MC-W001	1.32E-01	0.00E+00	0.00E+00	6.04E-02	0.00E+00	3.27E-04	0.00E+00	1.92E-01	7.74E-04
MU-W002	1.76E+00	0.00E+00	0.00E+00	5.24E-02	0.00E+00	0.00E+00	2.67E-12	1.81E+00	7.29E-03
NT-JAS-01	1.70E+02	0.00E+00	2.37E+01	9.44E+01	7.56E+01	4.07E+00	1.56E-02	3.63E+02	1.47E+00
NT-W001	2.55E+02	1.48E-02	4.72E+01	2.85E+03	1.89E+01	2.85E-01	4.27E-02	3.17E+03	1.28E+01
NT-W021	4.92E+00	0.00E+00	3.38E-01	3.21E+01	7.28E+00	1.46E-01	2.70E-04	4.46E+01	1.80E-01
OR-W201	5.90E+03	1.02E+00	1.02E+03	2.15E+03	2.11E+03	1.53E+02	4.43E+01	1.12E+04	4.53E+01
OR-W202	8.47E+02	2.13E+01	2.93E+03	5.52E+02	5.39E+02	4.91E+00	2.38E+00	4.87E+03	1.96E+01
OR-W203	1.87E+00	7.42E-01	4.20E-01	2.48E-02	1.76E+00	1.25E-02	3.38E-04	4.07E+00	1.64E-02
OR-W204	4.16E-01	3.08E-06	4.76E-01	4.22E-01	2.84E-01	0.00E+00	3.83E-04	1.60E+00	6.45E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.24E-01	0.00E+00	0.00E+00	0.00E+00	4.24E-01	1.71E-03
RF-MT0001	1.60E+03	0.00E+00	2.95E+00	1.95E+02	4.43E+01	1.12E+00	2.25E-03	1.84E+03	7.41E+00
RF-MT0002	1.23E+02	0.00E+00	2.27E-01	1.50E+01	3.40E+00	8.61E-02	1.72E-04	1.41E+02	5.70E-01
RF-MT0003	5.58E-01	0.00E+00	5.18E-02	3.44E+00	7.79E-01	1.97E-02	3.94E-05	4.83E+00	1.95E-02
RF-MT0007	1.40E+00	0.00E+00	0.00E+00	4.28E-01	9.69E-02	2.28E-03	0.00E+00	1.93E+00	7.78E-03
RF-MT0089	5.51E-03	0.00E+00	5.18E-04	3.44E-02	7.78E-03	1.97E-04	3.94E-07	4.82E-02	1.94E-04
RF-MT0090	1.40E+01	0.00E+00	7.33E-01	8.83E+01	1.98E+01	1.97E-01	5.58E-04	1.23E+02	4.95E-01
RF-MT0091	8.67E+02	0.00E+00	7.44E+01	5.90E+03	1.33E+03	1.62E+01	5.96E-02	8.17E+03	3.29E+01
RF-MT0092	1.24E+02	0.00E+00	9.38E+00	8.45E+02	1.94E+02	2.24E+00	7.13E-03	1.17E+03	4.73E+00
RF-MT0093	1.51E+02	0.00E+00	9.66E+00	9.12E+02	2.13E+02	1.91E+00	7.34E-03	1.29E+03	5.18E+00
RF-MT0097	7.56E+00	0.00E+00	4.27E-01	4.76E+01	9.68E+00	1.05E-01	3.24E-04	6.53E+01	2.63E-01
RF-MT0099	8.28E-03	0.00E+00	7.79E-04	5.15E-02	1.16E-02	2.96E-04	5.92E-07	7.22E-02	2.91E-04
RF-MT0290	2.05E+01	0.00E+00	1.93E+00	1.28E+02	2.89E+01	7.32E-01	1.47E-03	1.79E+02	7.21E-01
RF-MT-0292	2.59E+01	0.00E+00	2.44E+00	1.61E+02	3.65E+01	9.26E-01	1.85E-03	2.26E+02	9.12E-01
RF-MT-0299	3.05E+03	0.00E+00	6.24E+01	4.13E+03	9.37E+02	2.38E+01	4.75E-02	8.19E+03	3.30E+01
RF-MT0302	4.67E-02	0.00E+00	2.48E-03	1.78E-01	4.05E-02	9.26E-04	1.87E-05	2.68E-01	1.08E-03
RF-MT0320	5.58E+01	0.00E+00	2.56E+00	1.73E+02	3.94E+01	9.31E-01	1.96E-03	2.71E+02	1.09E+00
RF-MT0321	3.12E+01	0.00E+00	7.65E-01	5.58E+01	1.25E+01	2.61E-01	2.99E-03	1.00E+02	4.04E-01
RF-MT-0328	2.16E+00	0.00E+00	9.17E-02	6.07E+00	1.37E+00	3.48E-02	4.08E-04	9.69E+00	3.91E-02
RF-MT0330	2.25E+01	0.00E+00	1.01E+00	1.23E+02	3.00E+01	3.27E-01	7.64E-04	1.76E+02	7.10E-01

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT-0331	1.35E+02	0.00E+00	6.24E+00	5.39E+02	1.19E+02	1.90E+00	2.55E-02	7.99E+02	3.22E+00
RF-MT0332	1.93E-02	0.00E+00	1.82E-03	1.21E-01	2.72E-02	6.91E-04	1.38E-06	1.69E-01	6.81E-04
RF-MT-0335	1.55E+00	0.00E+00	8.35E-02	6.21E+00	1.41E+00	2.82E-02	6.06E-04	9.25E+00	3.73E-02
RF-MT0336	1.10E+02	0.00E+00	5.53E+00	4.40E+02	9.96E+01	1.65E+00	6.03E-03	6.55E+02	2.64E+00
RF-MT0337	6.20E+01	0.00E+00	3.04E+00	2.69E+02	5.99E+01	8.07E-01	6.16E-03	3.94E+02	1.59E+00
RF-MT0339	1.70E+02	0.00E+00	8.28E+00	5.90E+02	1.32E+02	2.92E+00	2.34E-02	9.00E+02	3.63E+00
RF-MT-0342	9.97E-01	0.00E+00	6.94E-02	5.45E+00	1.21E+00	2.14E-02	1.11E-04	7.73E+00	3.12E-02
RF-MT0371	3.37E+02	0.00E+00	1.61E+01	1.07E+03	2.41E+02	6.11E+00	1.35E-02	1.66E+03	6.69E+00
RF-MT-0372	1.47E+00	0.00E+00	1.13E-01	7.43E+00	1.69E+00	3.78E-02	3.26E-04	1.07E+01	4.32E-02
RF-MT0373	2.21E+01	0.00E+00	1.16E+00	1.40E+02	3.14E+01	3.11E-01	8.85E-04	1.94E+02	7.83E-01
RF-MT0374	7.19E-01	0.00E+00	4.16E-02	2.76E+00	6.24E-01	1.58E-02	3.50E-05	4.14E+00	1.67E-02
RF-MT0376	5.70E-01	0.00E+00	3.36E-02	2.75E+00	6.32E-01	1.16E-02	4.06E-05	3.99E+00	1.61E-02
RF-MT0377	3.38E+02	0.00E+00	1.94E+01	1.29E+03	2.90E+02	7.34E+00	2.50E-02	1.93E+03	7.79E+00
RF-MT0378	3.80E+00	0.00E+00	2.68E-01	1.77E+01	4.01E+00	1.02E-01	2.03E-04	2.58E+01	1.04E-01
RF-MT0419	6.11E+00	0.00E+00	2.50E-01	1.65E+01	3.75E+00	9.50E-02	1.90E-04	2.66E+01	1.07E-01
RF-MT0420	1.06E+00	0.00E+00	4.34E-02	2.87E+00	6.51E-01	1.65E-02	3.30E-05	4.63E+00	1.87E-02
RF-MT0423	9.03E+00	0.00E+00	3.53E-01	4.14E+01	9.10E+00	6.54E-02	2.68E-04	5.99E+01	2.42E-01
RF-MT0425	2.66E-01	0.00E+00	1.09E-02	7.18E-01	1.63E-01	4.12E-03	8.26E-06	1.16E+00	4.67E-03
RF-MT-0438	2.41E+00	0.00E+00	1.42E-01	1.28E+01	2.86E+00	4.09E-02	1.21E-04	1.82E+01	7.32E-02
RF-MT0440	8.76E-01	0.00E+00	5.11E-02	4.62E+00	1.07E+00	1.68E-02	2.04E-04	6.61E+00	2.67E-02
RF-MT0442	3.33E-01	0.00E+00	2.21E-02	1.58E+00	3.58E-01	6.25E-03	1.12E-04	2.30E+00	9.26E-03
RF-MT0443	4.10E+00	0.00E+00	3.63E-01	2.46E+01	5.57E+00	1.30E-01	4.34E-04	3.46E+01	1.40E-01
RF-MT0444	3.20E+01	0.00E+00	1.78E+00	1.19E+02	2.67E+01	6.75E-01	1.38E-03	1.79E+02	7.22E-01
RF-MT0480	8.95E+01	0.00E+00	5.01E+00	3.33E+02	7.54E+01	1.74E+00	6.27E-03	5.03E+02	2.03E+00
RF-MT0488	1.43E+02	0.00E+00	7.47E+00	4.94E+02	1.11E+02	2.84E+00	3.66E-02	7.56E+02	3.05E+00
RF-MT0490	6.49E-01	0.00E+00	4.34E-02	2.92E+00	6.62E-01	1.57E-02	4.42E-05	4.27E+00	1.72E-02
RF-MT-0491	5.10E-02	0.00E+00	1.98E-03	1.33E-01	2.99E-02	7.32E-04	3.52E-06	2.15E-01	8.68E-04
RF-MT0523A	4.04E+01	0.00E+00	1.58E+00	1.05E+02	2.37E+01	5.97E-01	1.45E-03	1.70E+02	6.86E-01
RF-MT0523B	4.04E+01	0.00E+00	1.58E+00	1.05E+02	2.37E+01	5.97E-01	1.45E-03	1.70E+02	6.86E-01

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0523C	4.04E+01	0.00E+00	1.58E+00	1.05E+02	2.37E+01	5.97E-01	1.45E-03	1.70E+02	6.86E-01
RF-MT0523D	4.04E+01	0.00E+00	1.58E+00	1.05E+02	2.37E+01	5.97E-01	1.45E-03	1.70E+02	6.86E-01
RF-MT0523E	4.04E+01	0.00E+00	1.58E+00	1.05E+02	2.37E+01	5.97E-01	1.45E-03	1.70E+02	6.86E-01
RF-MT0531	2.76E-03	0.00E+00	2.59E-04	1.71E-02	3.89E-03	9.86E-05	1.97E-07	2.40E-02	9.69E-05
RF-MT0532E	1.29E+02	0.00E+00	3.37E+00	2.28E+02	5.16E+01	1.27E+00	3.67E-03	4.12E+02	1.66E+00
RF-MT0532F	1.29E+02	0.00E+00	3.37E+00	2.28E+02	5.16E+01	1.27E+00	3.67E-03	4.12E+02	1.66E+00
RF-MT0541	4.69E+00	0.00E+00	4.86E-02	3.24E+00	7.32E-01	1.86E-02	3.70E-05	8.71E+00	3.51E-02
RF-MT0545	2.51E-02	0.00E+00	2.36E-03	1.56E-01	3.53E-02	8.96E-04	1.79E-06	2.19E-01	8.84E-04
RF-MT0800	9.54E+02	0.00E+00	1.17E+00	7.72E+01	1.75E+01	4.44E-01	1.37E-03	1.05E+03	4.23E+00
RF-MT0801	1.10E+02	0.00E+00	1.14E+00	7.58E+01	1.72E+01	4.33E-01	8.69E-04	2.04E+02	8.22E-01
RF-MT0803	2.46E+00	0.00E+00	2.56E-02	1.69E+00	3.83E-01	9.71E-03	1.94E-05	4.56E+00	1.84E-02
RF-MT0806	1.16E+00	0.00E+00	6.13E-02	7.36E+00	1.65E+00	1.64E-02	4.66E-05	1.02E+01	4.13E-02
RF-MT0807	1.47E+01	0.00E+00	4.72E-01	3.13E+01	7.09E+00	1.79E-01	3.59E-04	5.35E+01	2.16E-01
RF-MT0816	1.57E+00	0.00E+00	6.66E-02	4.41E+00	9.96E-01	2.54E-02	5.07E-05	7.05E+00	2.84E-02
RF-MT-0823	7.78E-01	0.00E+00	3.03E-02	2.01E+00	4.56E-01	1.15E-02	2.80E-05	3.28E+00	1.32E-02
RF-MT0827	3.96E+01	0.00E+00	1.69E+00	1.12E+02	2.52E+01	6.40E-01	1.28E-03	1.78E+02	7.18E-01
RF-MT0831	7.56E+01	0.00E+00	4.62E+00	3.02E+02	6.84E+01	1.69E+00	1.57E-02	4.51E+02	1.82E+00
RF-MT0832	4.52E+02	0.00E+00	1.67E+01	1.18E+03	2.65E+02	6.02E+00	4.61E-02	1.91E+03	7.70E+00
RF-MT0833	1.37E+02	0.00E+00	5.01E+00	3.40E+02	7.69E+01	1.81E+00	1.30E-02	5.59E+02	2.25E+00
RF-MT0855	2.36E-02	0.00E+00	2.22E-03	1.47E-01	3.33E-02	8.46E-04	1.69E-06	2.07E-01	8.33E-04
RF-MT0857	1.16E+00	0.00E+00	6.10E-02	7.34E+00	1.65E+00	1.64E-02	4.64E-05	1.02E+01	4.12E-02
RF-MT0H61	4.31E+01	0.00E+00	2.27E+00	2.72E+02	6.11E+01	6.07E-01	1.72E-03	3.78E+02	1.53E+00
RF-MT2116	4.84E+00	0.00E+00	1.80E-01	1.26E+01	2.84E+00	6.45E-02	4.94E-04	2.04E+01	8.23E-02
RF-MT3010	3.03E+01	0.00E+00	1.87E+00	1.25E+02	2.84E+01	6.92E-01	1.81E-03	1.85E+02	7.47E-01
RF-MT3011	2.26E+02	0.00E+00	1.16E+01	7.69E+02	1.75E+02	4.42E+00	1.66E-02	1.18E+03	4.76E+00
RF-MT420P	1.20E+03	0.00E+00	5.89E+01	6.33E+03	1.43E+03	1.44E+01	5.48E-02	9.02E+03	3.64E+01
RF-MT532A	3.17E+02	0.00E+00	8.32E+00	5.64E+02	1.27E+02	3.13E+00	9.05E-03	1.02E+03	4.10E+00
RF-MT532B	1.42E+03	0.00E+00	3.74E+01	2.53E+03	5.72E+02	1.41E+01	4.06E-02	4.56E+03	1.84E+01
RF-MT532C	2.85E+03	0.00E+00	7.51E+01	5.07E+03	1.14E+03	2.82E+01	8.17E-02	9.14E+03	3.69E+01

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT532D	1.81E+01	0.00E+00	4.72E-01	3.21E+01	7.24E+00	1.77E-01	5.14E-04	5.78E+01	2.33E-01
RF-TT0069	1.04E-01	0.00E+00	5.61E-03	3.72E-01	8.41E-02	2.14E-03	7.78E-05	5.65E-01	2.28E-03
RF-TT0200	4.92E+00	0.00E+00	2.26E-01	1.52E+01	3.47E+00	8.21E-02	1.73E-04	2.39E+01	9.62E-02
RF-TT0299	2.04E+01	0.00E+00	4.20E-01	2.78E+01	6.29E+00	1.59E-01	3.19E-04	5.49E+01	2.22E-01
RF-TT0300	1.66E+02	0.00E+00	1.20E+01	7.98E+02	1.81E+02	3.88E+00	1.74E-02	1.16E+03	4.67E+00
RF-TT0301	2.25E+01	0.00E+00	1.62E+00	1.09E+02	2.47E+01	5.25E-01	2.37E-03	1.57E+02	6.35E-01
RF-TT0302	1.11E+00	0.00E+00	5.89E-02	4.24E+00	9.62E-01	2.21E-02	4.44E-04	6.38E+00	2.57E-02
RF-TT0303	6.69E+00	0.00E+00	3.44E-01	2.28E+01	5.16E+00	1.31E-01	1.30E-03	3.50E+01	1.41E-01
RF-TT0310	2.28E+01	0.00E+00	1.61E+00	1.03E+02	2.40E+01	4.78E-01	1.41E-03	1.51E+02	6.09E-01
RF-TT0312	5.47E+02	0.00E+00	2.92E+01	2.24E+03	5.03E+02	1.01E+01	2.39E-02	3.32E+03	1.34E+01
RF-TT0317	3.44E-01	0.00E+00	3.17E-02	2.10E+00	4.75E-01	1.20E-02	2.41E-05	2.95E+00	1.19E-02
RF-TT0320	2.21E+02	0.00E+00	1.02E+01	6.85E+02	1.56E+02	3.69E+00	7.77E-03	1.07E+03	4.32E+00
RF-TT0330	7.86E+01	0.00E+00	3.51E+00	4.30E+02	1.05E+02	1.15E+00	2.67E-03	6.17E+02	2.49E+00
RF-TT-0331	3.91E+02	0.00E+00	1.82E+01	1.56E+03	3.47E+02	5.52E+00	7.40E-02	2.32E+03	9.36E+00
RF-TT-0334	1.70E+02	0.00E+00	1.47E+01	9.72E+02	2.20E+02	5.58E+00	1.12E-02	1.38E+03	5.55E+00
RF-TT0335	2.07E+02	0.00E+00	1.11E+01	8.27E+02	1.88E+02	3.76E+00	8.07E-02	1.23E+03	4.98E+00
RF-TT0336	1.83E+02	0.00E+00	9.24E+00	7.32E+02	1.66E+02	2.75E+00	1.01E-02	1.09E+03	4.40E+00
RF-TT0337	2.18E+02	0.00E+00	1.07E+01	9.45E+02	2.10E+02	2.84E+00	2.16E-02	1.38E+03	5.58E+00
RF-TT0338	9.24E+02	0.00E+00	3.88E+01	3.69E+03	8.20E+02	1.27E+01	3.78E-02	5.47E+03	2.21E+01
RF-TT0340	7.89E+00	0.00E+00	7.40E-01	4.90E+01	1.11E+01	2.82E-01	5.63E-04	6.88E+01	2.77E-01
RF-TT0342	5.28E+01	0.00E+00	3.70E+00	2.89E+02	6.42E+01	1.13E+00	5.92E-03	4.10E+02	1.65E+00
RF-TT0360	4.03E+00	0.00E+00	1.88E-01	1.30E+01	2.97E+00	6.70E-02	1.49E-04	2.01E+01	8.12E-02
RF-TT0368	8.05E+01	0.00E+00	3.77E+00	2.60E+02	5.95E+01	1.34E+00	2.99E-03	4.04E+02	1.63E+00
RF-TT0370	1.59E+02	0.00E+00	8.14E+00	5.79E+02	1.31E+02	2.85E+00	1.40E-02	8.77E+02	3.54E+00
RF-TT0371	3.44E+00	0.00E+00	1.64E-01	1.09E+01	2.46E+00	6.23E-02	1.38E-04	1.69E+01	6.82E-02
RF-TT0372	4.20E-01	0.00E+00	3.23E-02	2.12E+00	4.81E-01	1.08E-02	9.30E-05	3.06E+00	1.23E-02
RF-TT0374	1.31E+01	0.00E+00	7.58E-01	5.01E+01	1.13E+01	2.87E-01	6.36E-04	7.53E+01	3.04E-01
RF-TT0375A	1.36E-01	0.00E+00	1.25E-02	8.24E-01	1.86E-01	4.73E-03	9.48E-06	1.16E+00	4.67E-03
RF-TT0375B	1.36E-01	0.00E+00	1.25E-02	8.24E-01	1.86E-01	4.73E-03	9.48E-06	1.16E+00	4.67E-03

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0376	3.14E+01	0.00E+00	1.85E+00	1.51E+02	3.47E+01	6.40E-01	2.24E-03	2.19E+02	8.85E-01
RF-TT0377	1.76E+01	0.00E+00	1.01E+00	6.66E+01	1.51E+01	3.81E-01	1.29E-03	1.00E+02	4.04E-01
RF-TT0391	3.92E+00	0.00E+00	1.41E-01	1.68E+01	3.76E+00	6.66E-02	1.08E-04	2.47E+01	9.94E-02
RF-TT0392	1.38E+00	0.00E+00	8.88E-02	8.80E+00	1.98E+00	2.31E-02	6.77E-05	1.23E+01	4.94E-02
RF-TT0393	1.14E+02	0.00E+00	6.20E+00	4.09E+02	9.28E+01	2.35E+00	4.72E-03	6.22E+02	2.51E+00
RF-TT0398	2.48E+00	0.00E+00	1.64E-01	1.64E+01	3.69E+00	4.37E-02	1.25E-04	2.28E+01	9.18E-02
RF-TT0409	2.07E+00	0.00E+00	7.65E-02	8.49E+00	1.90E+00	1.68E-02	5.88E-05	1.25E+01	5.06E-02
RF-TT0412	2.07E+00	0.00E+00	7.65E-02	8.49E+00	1.90E+00	1.68E-02	5.88E-05	1.25E+01	5.06E-02
RF-TT0414	6.42E+01	0.00E+00	2.37E+00	2.63E+02	5.89E+01	5.20E-01	1.82E-03	3.89E+02	1.57E+00
RF-TT0430	1.88E-02	0.00E+00	1.77E-03	1.17E-01	2.64E-02	6.70E-04	1.34E-06	1.64E-01	6.59E-04
RF-TT0431	4.67E+00	0.00E+00	4.30E-01	2.87E+01	6.50E+00	1.59E-01	5.49E-04	4.03E+01	1.62E-01
RF-TT0438	2.78E+02	0.00E+00	1.64E+01	1.46E+03	3.29E+02	4.71E+00	1.40E-02	2.09E+03	8.42E+00
RF-TT0440	2.74E+01	0.00E+00	1.59E+00	1.44E+02	3.34E+01	5.27E-01	6.38E-03	2.07E+02	8.34E-01
RF-TT0441	1.35E+02	0.00E+00	7.47E+00	4.99E+02	1.13E+02	2.80E+00	1.03E-02	7.55E+02	3.04E+00
RF-TT0442	1.94E+01	0.00E+00	1.29E+00	9.24E+01	2.09E+01	3.65E-01	6.51E-03	1.34E+02	5.40E-01
RF-TT0443	4.16E-01	0.00E+00	3.70E-02	2.50E+00	5.65E-01	1.32E-02	4.42E-05	3.52E+00	1.42E-02
RF-TT0479	4.07E+00	0.00E+00	3.84E-01	2.53E+01	5.74E+00	1.45E-01	2.92E-04	3.55E+01	1.43E-01
RF-TT0480	2.78E+02	0.00E+00	1.55E+01	1.04E+03	2.34E+02	5.41E+00	1.94E-02	1.56E+03	6.30E+00
RF-TT0481	1.56E-01	0.00E+00	8.74E-03	5.82E-01	1.32E-01	3.04E-03	1.10E-05	8.79E-01	3.54E-03
RF-TT0483	5.02E-01	0.00E+00	4.72E-02	3.12E+00	7.07E-01	1.79E-02	1.72E-02	4.39E+00	1.77E-02
RF-TT0484	2.69E+00	0.00E+00	1.96E-01	1.30E+01	2.94E+00	7.45E-02	2.60E-04	1.88E+01	7.57E-02
RF-TT0485	2.21E-01	0.00E+00	1.21E-02	7.99E-01	1.81E-01	4.59E-03	2.87E-04	1.21E+00	4.89E-03
RF-TT0486	1.31E+00	0.00E+00	7.16E-02	4.74E+00	1.08E+00	2.71E-02	2.82E-04	7.20E+00	2.90E-02
RF-TT0487	6.56E+00	0.00E+00	2.43E-01	1.70E+01	3.85E+00	8.75E-02	6.69E-04	2.77E+01	1.12E-01
RF-TT0489	1.87E+00	0.00E+00	1.09E-01	7.23E+00	1.64E+00	4.16E-02	1.84E-04	1.09E+01	4.38E-02
RF-TT0490	1.03E+02	0.00E+00	6.94E+00	4.66E+02	1.06E+02	2.49E+00	7.07E-03	6.82E+02	2.75E+00
RF-TT0491	2.41E+00	0.00E+00	9.38E-02	6.25E+00	1.41E+00	3.46E-02	1.67E-04	1.02E+01	4.10E-02
RF-TT0492	8.08E-01	0.00E+00	5.29E-02	3.49E+00	7.91E-01	2.00E-02	4.02E-05	5.14E+00	2.07E-02
RF-TT0523A	5.44E+00	0.00E+00	2.12E-01	1.41E+01	3.19E+00	8.04E-02	1.96E-04	2.29E+01	9.23E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0523B	5.44E+00	0.00E+00	2.12E-01	1.41E+01	3.19E+00	8.04E-02	1.96E-04	2.29E+01	9.23E-02
RF-TT0523C	5.44E+00	0.00E+00	2.12E-01	1.41E+01	3.19E+00	8.04E-02	1.96E-04	2.29E+01	9.23E-02
RF-TT0523D	5.44E+00	0.00E+00	2.12E-01	1.41E+01	3.19E+00	8.04E-02	1.96E-04	2.29E+01	9.23E-02
RF-TT0523E	5.44E+00	0.00E+00	2.12E-01	1.41E+01	3.19E+00	8.04E-02	1.96E-04	2.29E+01	9.23E-02
RF-TT0532A	1.36E+02	0.00E+00	3.56E+00	2.42E+02	5.46E+01	1.35E+00	3.88E-03	4.37E+02	1.76E+00
RF-TT0532B	1.36E+02	0.00E+00	3.56E+00	2.42E+02	5.46E+01	1.35E+00	3.88E-03	4.37E+02	1.76E+00
RF-TT0541	2.25E-01	0.00E+00	2.12E-02	1.41E+00	3.18E-01	8.05E-03	1.61E-05	1.97E+00	7.94E-03
RF-TT0545	5.02E-02	0.00E+00	4.72E-03	3.12E-01	7.07E-02	1.79E-03	3.59E-06	4.37E-01	1.76E-03
RF-TT0601	1.74E+01	0.00E+00	8.14E-01	5.63E+01	1.29E+01	2.91E-01	6.47E-04	8.75E+01	3.53E-01
RF-TT0802	1.95E+03	0.00E+00	6.70E+01	4.44E+03	1.01E+03	2.54E+01	5.09E-02	7.47E+03	3.01E+01
RF-TT0809	1.60E+02	0.00E+00	5.50E+00	3.66E+02	8.24E+01	2.09E+00	4.18E-03	6.14E+02	2.48E+00
RF-TT0821	3.47E+02	0.00E+00	2.00E+01	1.44E+03	3.25E+02	6.21E+00	1.83E-01	2.13E+03	8.58E+00
RF-TT0822	3.84E+02	0.00E+00	1.55E+01	1.08E+03	2.43E+02	5.53E+00	1.94E-01	1.72E+03	6.93E+00
RF-TT0823	7.78E-01	0.00E+00	3.03E-02	2.01E+00	4.56E-01	1.15E-02	2.80E-05	3.28E+00	1.32E-02
RF-TT0824	8.00E+02	0.00E+00	4.27E+01	2.90E+03	6.56E+02	1.56E+01	9.50E-02	4.40E+03	1.77E+01
RF-TT0825	6.64E+02	0.00E+00	3.08E+01	2.18E+03	4.93E+02	1.04E+01	1.05E-01	3.37E+03	1.36E+01
RF-TT0832	4.92E+02	0.00E+00	1.83E+01	1.28E+03	2.89E+02	6.56E+00	5.02E-02	2.07E+03	8.36E+00
RF-TT0854	1.77E-01	0.00E+00	1.66E-02	1.10E+00	2.50E-01	6.32E-03	7.60E-04	1.54E+00	6.21E-03
RF-TT0886	2.51E-02	0.00E+00	2.35E-03	1.55E-01	3.53E-02	8.94E-04	1.79E-06	2.18E-01	8.80E-04
RF-TT2216	7.26E+00	0.00E+00	2.70E-01	1.89E+01	4.26E+00	9.69E-02	7.42E-04	3.07E+01	1.24E-01
RF-TT3010	3.88E+02	0.00E+00	2.39E+01	1.59E+03	3.62E+02	8.86E+00	2.32E-02	2.37E+03	9.55E+00
RF-TT3011	9.79E+02	0.00E+00	5.04E+01	3.33E+03	7.54E+02	1.91E+01	7.20E-02	5.11E+03	2.06E+01
RF-TT301U	8.14E+01	0.00E+00	5.32E+00	3.62E+02	8.32E+01	1.88E+00	4.21E-03	5.32E+02	2.14E+00
RF-TT310P	2.35E+01	0.00E+00	1.39E+00	1.22E+02	2.61E+01	3.93E-01	1.06E-03	1.73E+02	6.96E-01
RF-TT338S	6.87E-01	0.00E+00	6.35E-02	4.19E+00	9.51E-01	2.40E-02	4.82E-05	5.90E+00	2.38E-02
RF-TT390P	3.87E+00	0.00E+00	1.72E-01	2.04E+01	4.25E+00	6.00E-02	1.60E-04	2.87E+01	1.16E-01
RF-TT391P	2.14E+02	0.00E+00	7.72E+00	9.18E+02	2.04E+02	3.64E+00	5.87E-03	1.34E+03	5.42E+00
RF-TT392P	4.32E+02	0.00E+00	2.78E+01	2.75E+03	6.20E+02	7.22E+00	2.12E-02	3.83E+03	1.54E+01
RF-TT393R	6.39E+01	0.00E+00	4.72E+00	4.20E+02	9.55E+01	1.17E+00	3.77E-03	5.85E+02	2.36E+00

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT394P	7.93E+00	0.00E+00	2.92E-01	3.25E+01	6.81E+00	8.40E-02	2.29E-04	4.75E+01	1.92E-01
RF-TT395P	1.06E+01	0.00E+00	3.91E-01	4.34E+01	9.10E+00	1.12E-01	3.07E-04	6.36E+01	2.56E-01
RF-TT396P	2.65E+00	0.00E+00	9.76E-02	1.09E+01	2.28E+00	2.80E-02	7.67E-05	1.59E+01	6.41E-02
RF-TT398P	2.57E+02	0.00E+00	1.69E+01	1.70E+03	3.82E+02	4.51E+00	1.29E-02	2.36E+03	9.51E+00
RF-TT398R	2.12E+03	0.00E+00	3.14E+01	2.75E+03	6.17E+02	8.79E+00	2.39E-02	5.51E+03	2.22E+01
RF-TT411R	7.67E+01	0.00E+00	2.82E+00	3.14E+02	7.03E+01	6.21E-01	2.17E-03	4.64E+02	1.87E+00
RF-TT429R	1.61E+02	0.00E+00	6.06E-01	7.27E+01	1.60E+01	1.08E-01	4.61E-04	2.51E+02	1.01E+00
RF-TT433X	5.08E+01	0.00E+00	1.68E-01	2.09E+01	4.15E+00	4.30E-02	1.28E-04	7.60E+01	3.07E-01
RF-TT436R	3.72E+02	0.00E+00	2.43E+00	2.74E+02	6.12E+01	8.30E-01	1.85E-03	7.09E+02	2.86E+00
RF-TT454X	2.18E+01	0.00E+00	1.43E-01	1.61E+01	3.61E+00	4.89E-02	1.09E-04	4.17E+01	1.68E-01
RL-T101	1.11E+02	0.00E+00	8.67E+00	8.72E+02	1.93E+02	6.91E+00	5.72E-03	1.18E+03	4.78E+00
RL-T102	1.40E-03	0.00E+00	1.10E-04	1.12E-02	2.47E-03	8.77E-05	1.22E-06	1.51E-02	6.10E-05
RL-T103	9.94E+01	0.00E+00	1.05E+01	3.81E+02	8.38E+01	3.67E+00	6.92E-03	5.74E+02	2.32E+00
RL-T104	2.01E-03	0.00E+00	1.58E-04	1.58E-02	3.53E-03	1.26E-04	1.36E-07	2.15E-02	8.68E-05
RL-T105	7.71E-01	0.00E+00	5.96E-02	6.02E+00	1.33E+00	4.75E-02	8.40E-05	8.18E+00	3.30E-02
RL-T106	7.43E-01	0.00E+00	5.85E-02	5.88E+00	1.30E+00	4.65E-02	3.86E-05	7.98E+00	3.22E-02
RL-T107	2.04E+03	0.00E+00	3.44E+04	1.62E+04	3.59E+03	1.28E+02	2.35E+01	5.63E+04	2.27E+02
RL-T108	1.17E+00	0.00E+00	5.92E+00	9.25E+00	2.05E+00	7.31E-02	3.93E-03	1.84E+01	7.42E-02
RL-T109	1.61E+00	0.00E+00	1.22E-01	1.23E+01	2.72E+00	9.69E-02	2.34E-02	1.67E+01	6.75E-02
RL-T110	1.80E+02	0.00E+00	2.33E+01	1.41E+03	3.13E+02	1.11E+01	1.38E+00	1.92E+03	7.75E+00
RL-T112	7.28E+01	0.00E+00	9.84E+00	1.86E+02	4.13E+01	1.47E+00	7.42E-01	3.11E+02	1.25E+00
RL-T113	7.76E-02	0.00E+00	1.90E-02	6.14E-01	1.36E-01	4.85E-03	1.25E-05	8.46E-01	3.41E-03
RL-T114	1.18E+01	0.00E+00	9.27E-01	9.32E+01	2.07E+01	7.38E-01	6.11E-04	1.27E+02	5.11E-01
RL-T115	3.01E+02	0.00E+00	3.00E+01	1.23E+03	2.72E+02	1.09E+01	4.33E-01	1.83E+03	7.37E+00
RL-T116	1.94E+01	0.00E+00	1.52E+00	1.52E+02	3.39E+01	1.21E+00	5.72E-02	2.07E+02	8.36E-01
RL-T118	4.98E+01	0.00E+00	1.22E+01	1.51E+02	3.36E+01	1.20E+00	8.41E-01	2.48E+02	1.00E+00
RL-T120	1.21E+01	0.00E+00	1.28E+00	4.48E+01	9.86E+00	4.21E-01	8.42E-04	6.80E+01	2.74E-01
RL-T122	6.85E-01	0.00E+00	5.39E-02	5.40E+00	1.20E+00	4.28E-02	1.46E+00	8.80E+00	3.55E-02
RL-T123	2.02E+00	0.00E+00	1.58E-01	1.58E+01	3.53E+00	1.26E-01	5.98E-02	2.16E+01	8.71E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T125	4.01E+02	0.00E+00	3.91E+01	3.32E+02	1.70E+02	1.97E+01	2.58E-02	9.42E+02	3.80E+00
RL-T127	3.87E+02	0.00E+00	9.84E+00	9.91E+02	2.20E+02	7.83E+00	8.65E-02	1.61E+03	6.48E+00
RL-T128	5.73E-01	0.00E+00	2.39E-07	2.41E-05	5.34E-06	1.90E-07	1.58E-10	5.73E-01	2.31E-03
RL-T129	1.71E+00	0.00E+00	4.55E+01	1.37E+01	3.01E+00	1.07E-01	3.77E-02	6.39E+01	2.58E-01
RL-T130	3.65E-03	0.00E+00	2.87E-04	2.90E-02	6.42E-03	2.28E-04	8.32E-05	3.94E-02	1.59E-04
RL-T131	1.48E+00	0.00E+00	1.57E-01	5.52E+00	1.21E+00	5.15E-02	8.33E-03	8.38E+00	3.38E-02
RL-T132	3.53E+02	0.00E+00	2.77E+01	2.80E+03	6.20E+02	2.21E+01	2.63E-01	3.80E+03	1.53E+01
RL-T133	7.20E-03	0.00E+00	4.44E-04	4.59E-02	1.02E-02	3.13E-04	2.93E-07	6.37E-02	2.57E-04
RL-T134	1.52E-02	0.00E+00	1.20E-03	1.21E-01	2.66E-02	9.52E-04	7.88E-07	1.64E-01	6.60E-04
RL-T135	7.12E-02	0.00E+00	5.61E-03	5.64E-01	1.25E-01	4.45E-03	4.15E-03	7.70E-01	3.11E-03
RL-T137	1.16E+03	0.00E+00	1.22E+02	4.29E+03	9.47E+02	4.05E+01	8.68E-02	6.52E+03	2.63E+01
RL-T140	1.36E+03	0.00E+00	1.16E+02	4.15E+03	1.02E+03	3.44E+01	2.63E+01	6.67E+03	2.69E+01
RL-T143	8.49E+00	0.00E+00	6.66E-01	6.71E+01	1.49E+01	5.31E-01	3.90E-02	9.12E+01	3.68E-01
RL-T145	2.42E+01	0.00E+00	1.90E+00	1.91E+02	4.23E+01	1.51E+00	9.08E-02	2.60E+02	1.05E+00
RL-W407	6.95E+01	0.00E+00	4.05E+00	4.38E+02	9.72E+01	2.30E+00	2.67E-03	6.09E+02	2.46E+00
RL-W408	2.85E-04	0.00E+00	1.71E-05	1.77E-03	3.94E-04	1.18E-05	1.13E-08	2.47E-03	9.95E-06
RL-W415	6.29E-03	0.00E+00	3.77E-04	3.93E-02	8.70E-03	2.61E-04	2.49E-07	5.46E-02	2.20E-04
RL-W418	2.69E-02	0.00E+00	1.59E-03	1.68E-01	3.74E-02	9.74E-04	1.05E-06	2.34E-01	9.45E-04
RL-W437	2.28E+02	0.00E+00	1.33E+01	1.44E+03	3.19E+02	7.53E+00	8.78E-03	1.99E+03	8.04E+00
RL-W438	3.99E-04	0.00E+00	2.39E-05	2.48E-03	5.49E-04	1.65E-05	1.58E-08	3.45E-03	1.39E-05
RL-W439	1.25E+04	0.00E+00	1.32E+03	4.78E+04	1.06E+04	4.61E+02	8.69E-01	7.22E+04	2.91E+02
RL-W443	2.01E+02	0.00E+00	1.17E+01	1.27E+03	2.80E+02	6.63E+00	7.74E-03	1.76E+03	7.09E+00
RL-W444	1.49E+02	0.00E+00	8.71E+00	9.38E+02	2.08E+02	4.92E+00	5.74E-03	1.30E+03	5.26E+00
RL-W447	1.71E-02	0.00E+00	1.03E-03	1.06E-01	2.36E-02	7.08E-04	6.76E-07	1.47E-01	5.94E-04
RL-W448	1.26E-04	0.00E+00	7.58E-06	7.84E-04	1.74E-04	5.24E-06	5.00E-09	1.09E-03	4.40E-06
RL-W449	1.04E+00	0.00E+00	2.77E-04	2.24E-02	4.97E-03	9.50E-05	1.83E-07	1.07E+00	4.29E-03
RL-W450	1.90E-03	0.00E+00	1.14E-04	1.19E-02	2.62E-03	7.90E-05	7.53E-08	1.65E-02	6.65E-05
RL-W451	2.72E-04	0.00E+00	1.63E-05	1.68E-03	3.74E-04	1.13E-05	1.07E-08	2.35E-03	9.46E-06
RL-W452	1.18E-02	0.00E+00	7.02E-04	7.42E-02	1.65E-02	4.28E-04	4.62E-07	1.03E-01	4.16E-04

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W453	3.37E-03	0.00E+00	1.97E-04	2.13E-02	4.71E-03	1.12E-04	1.30E-07	2.96E-02	1.19E-04
RL-W454	4.71E-02	0.00E+00	2.76E-03	2.98E-01	6.60E-02	1.56E-03	1.82E-06	4.14E-01	1.67E-03
RL-W455	1.26E-02	0.00E+00	7.44E-04	7.88E-02	1.75E-02	4.56E-04	4.90E-07	1.10E-01	4.42E-04
RL-W456	1.66E+00	0.00E+00	9.73E-02	1.05E+01	2.32E+00	5.62E-02	6.41E-05	1.45E+01	5.86E-02
RL-W457	1.61E-01	0.00E+00	9.45E-03	1.02E+00	2.25E-01	5.45E-03	6.23E-06	1.41E+00	5.69E-03
RL-W458	5.09E-01	0.00E+00	4.83E-02	4.17E-01	2.31E-01	2.19E-02	3.18E-05	1.21E+00	4.86E-03
RL-W459	4.90E+00	0.00E+00	4.97E-01	1.04E+01	3.15E+00	2.18E-01	3.28E-04	1.89E+01	7.62E-02
RL-W460	2.99E-02	0.00E+00	1.75E-03	1.88E-01	4.18E-02	9.88E-04	1.15E-06	2.62E-01	1.06E-03
RL-W461	2.76E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.76E-02	1.11E-04
RL-W462	8.52E-03	0.00E+00	5.08E-04	5.33E-02	1.18E-02	3.24E-04	3.35E-07	7.42E-02	2.99E-04
RL-W463	4.38E-02	0.00E+00	2.57E-03	2.77E-01	6.13E-02	1.45E-03	1.69E-06	3.85E-01	1.55E-03
RL-W464	2.02E-02	0.00E+00	1.18E-03	1.28E-01	2.82E-02	6.68E-04	7.78E-07	1.77E-01	7.14E-04
RL-W465	1.35E-01	0.00E+00	8.00E-03	8.49E-01	1.88E-01	4.84E-03	5.27E-06	1.18E+00	4.76E-03
RL-W466	1.85E+00	0.00E+00	1.09E-01	1.17E+01	2.58E+00	6.44E-02	7.18E-05	1.62E+01	6.53E-02
RL-W467	9.47E-02	0.00E+00	5.61E-03	5.94E-01	1.31E-01	3.53E-03	3.69E-06	8.25E-01	3.33E-03
RL-W468	4.85E-04	0.00E+00	2.89E-05	3.04E-03	6.74E-04	1.84E-05	1.90E-08	4.23E-03	1.70E-05
RL-W469	1.97E-01	0.00E+00	1.16E-02	1.24E+00	2.75E-01	6.79E-03	7.64E-06	1.72E+00	6.93E-03
RL-W470	5.57E+00	0.00E+00	5.39E-01	4.58E+00	2.35E+00	2.73E-01	3.55E-04	1.30E+01	5.26E-02
RL-W474	2.11E-01	0.00E+00	5.96E-02	1.05E-02	8.88E-03	0.00E+00	3.93E-05	2.90E-01	1.17E-03
RL-W476	3.56E-01	0.00E+00	2.14E-02	2.29E+00	5.10E-01	1.23E-02	1.41E-05	3.18E+00	1.28E-02
RL-W480	5.80E-02	0.00E+00	3.43E-03	3.64E-01	8.08E-02	2.11E-03	2.26E-06	5.06E-01	2.04E-03
RL-W481	9.12E-02	0.00E+00	5.39E-03	5.71E-01	1.26E-01	3.31E-03	3.55E-06	7.94E-01	3.20E-03
RL-W482	1.21E+02	0.00E+00	1.79E+00	7.26E-02	1.34E-01	4.38E+00	1.18E-03	1.23E+02	4.96E-01
RL-W483	9.04E+00	0.00E+00	1.39E-01	4.70E-03	9.53E-03	3.27E-01	9.18E-05	9.19E+00	3.71E-02
RL-W484	3.83E-02	0.00E+00	1.12E-03	6.57E-02	1.56E-02	2.71E-04	7.39E-07	1.21E-01	4.86E-04
RL-W485	2.24E-03	0.00E+00	1.59E-04	7.10E-03	1.69E-03	0.00E+00	1.05E-07	1.12E-02	4.51E-05
RL-W486	9.47E-04	0.00E+00	6.70E-05	3.00E-03	7.09E-04	0.00E+00	4.41E-08	4.72E-03	1.90E-05
RL-W487	1.55E-01	0.00E+00	8.60E-03	4.29E-01	1.17E-01	2.52E-03	5.67E-06	7.10E-01	2.86E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W489	9.38E-02	0.00E+00	8.11E-03	5.56E-01	1.25E-01	4.07E-03	5.34E-06	7.83E-01	3.16E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	3.48E-02	0.00E+00	6.84E-03	5.83E-02	1.27E-02	1.48E-03	4.51E-06	1.13E-01	4.54E-04
RL-W492	2.01E-03	0.00E+00	1.69E-04	1.17E-02	2.61E-03	8.51E-05	1.11E-07	1.65E-02	6.63E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.96E+01	0.00E+00	9.76E+00	2.94E-01	2.50E-01	3.41E+00	6.44E-03	8.99E+01	3.63E-01
RL-W495	1.44E+00	0.00E+00	2.65E-02	2.82E-03	2.23E-03	6.21E-02	1.75E-05	1.47E+00	5.94E-03
RL-W496	9.36E+00	0.00E+00	3.06E-01	9.27E-03	7.39E-03	4.02E-01	2.01E-04	9.68E+00	3.90E-02
RL-W497	3.90E-01	0.00E+00	6.03E-02	5.56E-01	2.51E-01	1.05E-02	3.97E-05	1.26E+00	5.07E-03
RL-W498	1.51E+00	0.00E+00	8.95E-02	9.50E+00	2.11E+00	5.48E-02	5.90E-05	1.32E+01	5.33E-02
RL-W499	1.36E-05	0.00E+00	8.04E-07	8.52E-05	1.89E-05	4.92E-07	5.30E-10	1.19E-04	4.78E-07
RL-W500	9.67E-04	0.00E+00	9.98E-05	3.48E-03	7.67E-04	3.46E-05	6.58E-08	5.31E-03	2.14E-05
RL-W501	4.01E+01	0.00E+00	2.22E+00	1.12E+02	3.04E+01	6.54E-01	1.47E-03	1.84E+02	7.43E-01
RL-W502	7.25E-03	0.00E+00	4.30E-04	4.54E-02	1.01E-02	2.63E-04	2.83E-07	6.32E-02	2.55E-04
RL-W503	4.19E-01	0.00E+00	4.41E-02	1.60E+00	3.53E-01	1.55E-02	2.90E-05	2.42E+00	9.76E-03
RL-W504	1.55E-01	0.00E+00	8.60E-03	4.29E-01	1.17E-01	2.52E-03	5.67E-06	7.10E-01	2.86E-03
RL-W505	7.27E-03	0.00E+00	4.51E-04	4.64E-02	1.03E-02	3.17E-04	2.97E-07	6.44E-02	2.60E-04
RL-W506	2.63E-03	0.00E+00	1.77E-04	1.52E-02	3.38E-03	9.48E-05	1.17E-07	2.14E-02	8.64E-05
RL-W507	2.62E-04	0.00E+00	1.55E-05	1.64E-03	3.64E-04	9.50E-06	1.02E-08	2.29E-03	9.21E-06
RL-W508	4.81E+00	0.00E+00	5.08E-01	1.78E+01	3.94E+00	1.68E-01	3.35E-04	2.71E+01	1.09E-01
RL-W509	4.74E+01	0.00E+00	4.05E+00	1.45E+02	3.54E+01	1.21E+00	2.67E-03	2.32E+02	9.37E-01
RL-W510	4.00E+00	0.00E+00	4.16E-01	1.44E+01	3.19E+00	1.44E-01	2.74E-04	2.20E+01	8.89E-02
RL-W511	4.07E+02	0.00E+00	2.01E+01	1.93E+03	4.20E+02	7.83E+00	1.36E-02	2.78E+03	1.12E+01
RL-W512	3.56E+02	0.00E+00	1.35E+01	1.17E+03	2.88E+02	4.00E+00	8.92E-03	1.82E+03	7.35E+00
RL-W513	3.80E+04	0.00E+00	5.50E+03	1.90E+04	9.39E+03	6.35E+02	3.62E+00	7.19E+04	2.90E+02
RL-W514	1.07E-03	0.00E+00	6.31E-05	6.74E-03	1.50E-03	3.71E-05	4.16E-08	9.38E-03	3.78E-05
RL-W515	4.19E-02	0.00E+00	2.48E-03	2.63E-01	5.82E-02	1.52E-03	1.63E-06	3.66E-01	1.47E-03
RL-W516	5.81E-02	0.00E+00	3.44E-03	3.64E-01	8.08E-02	2.11E-03	2.27E-06	5.06E-01	2.04E-03
RL-W517	5.18E-10	0.00E+00	3.07E-11	3.24E-09	7.17E-10	1.97E-11	2.03E-14	4.50E-09	1.82E-11

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W518	1.46E+00	0.00E+00	1.29E-01	4.64E+00	1.11E+00	4.23E-02	8.53E-05	7.35E+00	2.96E-02
RL-W519	2.61E-01	0.00E+00	1.53E-02	1.64E+00	3.64E-01	8.92E-03	1.01E-05	2.28E+00	9.21E-03
RL-W520	2.88E-02	0.00E+00	1.73E-03	1.80E-01	3.99E-02	1.15E-03	1.14E-06	2.51E-01	1.01E-03
RL-W521	5.37E-04	0.00E+00	3.17E-05	3.36E-03	7.46E-04	1.95E-05	2.09E-08	4.67E-03	1.88E-05
RL-W522	1.12E+01	0.00E+00	1.18E+00	2.22E+01	6.32E+00	2.82E-01	7.76E-04	4.09E+01	1.65E-01
RL-W523	3.37E+00	0.00E+00	4.48E-01	1.47E+00	8.90E-01	5.58E-02	2.95E-04	6.18E+00	2.49E-02
RL-W524	1.40E+01	0.00E+00	1.71E+00	1.36E+01	5.22E+00	2.66E-01	1.13E-03	3.45E+01	1.39E-01
RL-W525	1.11E+00	0.00E+00	1.16E-01	1.60E+00	5.28E-01	2.09E-02	7.64E-05	3.36E+00	1.35E-02
RL-W526	4.20E+00	0.00E+00	4.20E-01	1.71E+01	3.81E+00	1.52E-01	2.77E-04	2.56E+01	1.03E-01
RL-W527	4.60E-01	0.00E+00	6.06E-02	1.81E+00	4.28E-01	1.77E-02	4.00E-05	2.76E+00	1.11E-02
RL-W528	2.06E+02	0.00E+00	2.58E+01	5.78E+01	5.50E+01	2.71E+00	1.70E-02	3.45E+02	1.39E+00
RL-W529	1.72E-01	0.00E+00	1.81E-02	6.38E-01	1.40E-01	5.98E-03	1.19E-05	9.67E-01	3.90E-03
RL-W530	2.02E+00	0.00E+00	2.10E-01	7.28E+00	1.61E+00	7.27E-02	1.39E-04	1.11E+01	4.48E-02
RL-W531	1.21E+02	0.00E+00	2.11E+01	3.15E+01	2.26E+01	1.93E+00	1.39E-02	1.96E+02	7.90E-01
RL-W532	3.87E-01	0.00E+00	2.29E-02	2.43E+00	5.38E-01	1.40E-02	1.51E-05	3.38E+00	1.36E-02
RL-W533	1.87E-01	0.00E+00	1.98E-02	6.95E-01	1.53E-01	6.49E-03	1.30E-05	1.06E+00	4.26E-03
RL-W534	1.08E-05	0.00E+00	6.38E-07	6.78E-05	1.51E-05	3.91E-07	4.21E-10	9.44E-05	3.81E-07
RL-W535	5.66E+01	0.00E+00	6.31E+00	8.70E+01	2.64E+01	1.19E+00	4.16E-03	1.76E+02	7.11E-01
RL-W536	1.11E+00	0.00E+00	8.50E-02	3.02E+00	6.80E-01	2.73E-02	5.92E-05	4.89E+00	1.97E-02
RL-W537	3.78E+01	0.00E+00	1.92E+00	1.85E+02	4.04E+01	7.64E-01	1.29E-03	2.65E+02	1.07E+00
RL-W538	1.37E-04	0.00E+00	8.11E-06	8.62E-04	1.91E-04	4.98E-06	5.34E-09	1.20E-03	4.83E-06
RL-W539	1.52E-02	0.00E+00	9.13E-04	9.52E-02	2.11E-02	6.05E-04	6.02E-07	1.33E-01	5.34E-04
RL-W540	2.97E+01	0.00E+00	4.02E+00	3.43E+01	1.17E+01	5.81E-01	2.65E-03	7.97E+01	3.21E-01
RL-W541	4.41E-02	0.00E+00	2.63E-03	2.76E-01	6.11E-02	1.71E-03	1.74E-06	3.84E-01	1.55E-03
RL-W542	2.05E+00	0.00E+00	1.96E-01	6.98E+00	1.61E+00	6.99E-02	1.29E-04	1.08E+01	4.37E-02
RL-W543	6.45E-03	0.00E+00	3.81E-04	4.05E-02	8.97E-03	2.35E-04	2.51E-07	5.63E-02	2.27E-04
RL-W544	1.45E-01	0.00E+00	1.55E-02	4.60E-01	1.14E-01	4.66E-03	1.03E-05	7.36E-01	2.97E-03
RL-W545	3.86E-02	0.00E+00	2.28E-03	2.42E-01	5.37E-02	1.40E-03	1.51E-06	3.37E-01	1.36E-03
RL-W546	1.69E-03	0.00E+00	1.00E-04	1.07E-02	2.36E-03	6.12E-05	6.60E-08	1.48E-02	5.97E-05

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W547	4.33E-05	0.00E+00	2.56E-06	2.71E-04	6.02E-05	1.57E-06	1.69E-09	3.77E-04	1.52E-06
RL-W548	3.74E-05	0.00E+00	2.22E-06	2.34E-04	5.20E-05	1.40E-06	1.46E-09	3.26E-04	1.31E-06
RL-W549	7.44E+00	0.00E+00	8.92E-01	1.21E+01	3.57E+00	1.77E-01	5.88E-04	2.40E+01	9.66E-02
RL-W550	3.37E+01	0.00E+00	1.69E+00	1.63E+02	3.57E+01	6.70E-01	1.13E-03	2.35E+02	9.45E-01
RL-W551	5.99E+01	0.00E+00	2.50E+00	1.84E+02	4.65E+01	7.12E-01	1.65E-03	2.93E+02	1.18E+00
RL-W552	2.32E-02	0.00E+00	1.38E-03	1.45E-01	3.22E-02	8.89E-04	9.11E-07	2.02E-01	8.15E-04
RL-W553	2.06E-03	0.00E+00	1.30E-04	1.30E-02	2.87E-03	1.12E-04	8.60E-08	1.80E-02	7.26E-05
RL-W554	3.27E-02	0.00E+00	1.94E-03	2.05E-01	4.56E-02	1.19E-03	1.28E-06	2.85E-01	1.15E-03
RL-W555	1.51E-02	0.00E+00	8.92E-04	9.45E-02	2.09E-02	5.46E-04	5.88E-07	1.31E-01	5.30E-04
RL-W563	2.16E-01	0.00E+00	2.23E-02	7.84E-01	1.73E-01	7.45E-03	1.47E-05	1.20E+00	4.82E-03
RL-W564	1.41E-01	0.00E+00	1.48E-02	5.07E-01	1.11E-01	5.72E-03	9.76E-06	7.74E-01	3.12E-03
RL-W565	1.40E-02	0.00E+00	8.32E-04	8.76E-02	1.94E-02	5.31E-04	5.48E-07	1.22E-01	4.91E-04
RL-W566	2.05E-01	0.00E+00	1.22E-02	1.29E+00	2.86E-01	7.55E-03	8.04E-06	1.79E+00	7.21E-03
RL-W567	1.42E+01	0.00E+00	3.12E-01	3.96E-02	3.18E-02	6.40E-01	2.05E-04	1.46E+01	5.89E-02
RL-W568	2.73E+02	0.00E+00	6.56E+00	1.87E+00	1.48E+00	1.32E+01	4.32E-03	2.83E+02	1.14E+00
RL-W569	2.25E-01	0.00E+00	4.94E-03	6.25E-04	5.03E-05	1.01E-02	3.25E-06	2.31E-01	9.29E-04
RL-W570	1.44E-02	0.00E+00	8.64E-04	9.29E-02	2.05E-02	4.99E-04	5.69E-07	1.29E-01	5.19E-04
RL-W571	4.62E+01	0.00E+00	2.93E+00	7.53E+00	3.75E+00	2.02E+00	1.93E-03	6.04E+01	2.44E-01
RL-W572	4.01E-02	0.00E+00	8.78E-04	4.06E-03	8.97E-05	1.81E-03	5.79E-07	4.51E-02	1.82E-04
RL-W573	5.16E+02	0.00E+00	1.12E+01	2.22E+00	1.66E+00	2.30E+01	7.41E-03	5.31E+02	2.14E+00
RL-W574	2.22E+03	0.00E+00	4.86E+01	8.49E+00	6.13E+00	1.00E+02	3.21E-02	2.28E+03	9.21E+00
RL-W575	1.45E+04	0.00E+00	3.28E+02	8.12E+01	4.90E+01	6.28E+02	2.16E-01	1.49E+04	6.01E+01
RL-W576	1.04E+03	0.00E+00	2.29E+01	4.13E+00	2.96E+00	4.71E+01	1.51E-02	1.07E+03	4.32E+00
RL-W579	8.84E-02	0.00E+00	6.03E-04	2.07E-02	4.61E-03	1.66E-04	3.97E-07	1.14E-01	4.61E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.65E-01	2.68E-02	0.00E+00	0.00E+00	1.92E-01	7.75E-04
RL-W581	9.39E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.39E-01	3.79E-03
RL-W582	6.14E-03	0.00E+00	5.11E-04	5.30E-03	2.73E-03	2.70E-05	3.37E-07	1.47E-02	5.92E-05
RL-W583	4.74E-03	0.00E+00	2.78E-04	2.99E-02	6.64E-03	1.57E-04	1.83E-07	4.15E-02	1.68E-04
RL-W584	9.43E-02	0.00E+00	1.82E-02	1.74E-01	8.50E-02	7.88E-04	1.20E-05	3.72E-01	1.50E-03

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W585	5.60E-01	0.00E+00	9.69E-02	1.02E+00	5.17E-01	2.40E-02	6.39E-05	2.19E+00	8.83E-03
RL-W586	7.48E-05	0.00E+00	4.37E-06	4.72E-04	1.05E-04	2.47E-06	2.88E-09	6.56E-04	2.65E-06
RL-W587	1.60E-03	0.00E+00	9.45E-05	1.01E-02	2.24E-03	5.55E-05	6.23E-08	1.40E-02	5.64E-05
RL-W588	6.61E-02	0.00E+00	1.54E-02	1.47E-01	7.16E-02	6.63E-04	1.01E-05	3.01E-01	1.21E-03
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	2.03E+00	0.00E+00	3.28E-01	1.14E-02	2.01E-02	8.70E-02	2.16E-04	2.39E+00	9.63E-03
RL-W591	1.16E+01	0.00E+00	3.70E-01	1.41E-02	2.60E-02	5.25E-01	2.44E-04	1.20E+01	4.82E-02
RL-W592	5.10E+01	0.00E+00	4.05E+00	6.52E-01	8.42E-01	2.12E+00	2.67E-03	5.66E+01	2.28E-01
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.35E-02	3.95E-02	0.00E+00	0.00E+00	6.31E-02	2.54E-04
RL-W594	4.60E+01	0.00E+00	7.30E-01	2.91E-02	5.35E-02	5.31E-01	4.81E-04	4.69E+01	1.89E-01
RL-W595	1.21E-01	0.00E+00	7.61E-02	1.99E-02	3.89E-02	5.25E-03	5.02E-05	2.56E-01	1.03E-03
RL-W596	3.93E-02	0.00E+00	5.92E-03	2.05E-04	3.65E-04	1.58E-03	3.90E-06	4.58E-02	1.85E-04
RL-W597	7.23E+01	0.00E+00	2.61E+00	3.98E-01	6.62E-01	2.94E+00	1.72E-03	7.59E+01	3.06E-01
RL-W598	7.65E+01	0.00E+00	1.54E+01	5.54E-01	8.25E-01	3.04E+00	1.01E-02	9.32E+01	3.76E-01
RL-W599	3.87E+00	0.00E+00	1.24E-01	4.68E-03	8.70E-03	1.76E-01	8.18E-05	4.01E+00	1.62E-02
RL-W600	2.20E-07	0.00E+00	1.29E-08	1.39E-06	3.08E-07	7.27E-09	8.48E-12	1.93E-06	7.76E-09
RL-W601	1.12E-03	0.00E+00	7.05E-05	7.01E-03	1.56E-03	6.09E-05	4.65E-08	9.76E-03	3.93E-05
RL-W602	9.71E-01	0.00E+00	5.78E-02	6.08E+00	1.35E+00	3.69E-02	3.81E-05	8.46E+00	3.41E-02
RL-W603	5.60E+00	0.00E+00	3.34E-01	3.51E+01	7.78E+00	2.12E-01	2.20E-04	4.88E+01	1.97E-01
RL-W604	1.31E-02	0.00E+00	8.74E-04	1.70E-02	8.38E-03	2.52E-04	5.76E-07	3.94E-02	1.59E-04
RL-W605	3.00E-03	0.00E+00	1.90E-04	1.88E-02	4.18E-03	1.64E-04	1.25E-07	2.62E-02	1.06E-04
RL-W606	1.21E-03	0.00E+00	7.65E-05	7.59E-03	1.69E-03	6.61E-05	5.04E-08	1.06E-02	4.26E-05
RL-W607	2.22E-03	0.00E+00	1.48E-04	2.88E-03	1.42E-03	4.26E-05	9.76E-08	6.67E-03	2.69E-05
RL-W608	2.65E-02	0.00E+00	5.75E-03	3.75E-03	4.61E-03	6.54E-04	3.79E-06	4.06E-02	1.64E-04
RL-W610	5.25E+00	0.00E+00	3.07E-01	3.31E+01	7.34E+00	1.74E-01	2.03E-04	4.60E+01	1.85E-01
RL-W612	1.24E-02	0.00E+00	7.44E-04	8.03E-02	1.79E-02	4.11E-04	4.90E-07	1.11E-01	4.49E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.37E-01	0.00E+00	0.00E+00	0.00E+00	3.37E-01	1.36E-03
RL-W622	2.07E-04	0.00E+00	1.21E-05	1.31E-03	2.89E-04	6.84E-06	7.99E-09	1.81E-03	7.31E-06
RL-W625	7.19E-03	0.00E+00	1.84E-03	6.67E-03	6.53E-03	3.71E-04	1.22E-06	2.22E-02	8.96E-05

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W626	3.87E-01	0.00E+00	4.20E-02	2.61E-01	1.56E-01	6.47E-03	2.77E-05	8.46E-01	3.41E-03
RL-W627	1.82E-03	0.00E+00	5.61E-05	1.24E-06	0.00E+00	7.69E-05	3.69E-08	1.88E-03	7.57E-06
RL-W628	5.97E-04	0.00E+00	3.52E-05	3.77E-03	8.34E-04	2.07E-05	2.32E-08	5.23E-03	2.11E-05
RL-W629	4.04E-05	0.00E+00	2.42E-06	2.53E-04	5.60E-05	1.61E-06	1.60E-09	3.52E-04	1.42E-06
RL-W630	4.45E-01	0.00E+00	4.51E-02	2.93E+00	6.76E-01	1.74E-02	2.97E-05	4.09E+00	1.65E-02
RL-W631	7.17E-03	0.00E+00	4.55E-04	4.49E-02	9.96E-03	3.91E-04	3.00E-07	6.25E-02	2.52E-04
RL-W632	3.17E+00	0.00E+00	6.13E-02	5.94E+00	1.94E+00	1.30E-01	4.04E-05	1.11E+01	4.48E-02
RL-W633	7.56E-03	0.00E+00	3.56E-04	9.32E-04	8.20E-04	1.60E-04	2.35E-07	9.67E-03	3.90E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	1.02E-02	0.00E+00	0.00E+00	0.00E+00	1.02E-02	4.10E-05
RL-W635	4.51E+01	0.00E+00	1.20E+01	4.32E+00	6.44E+00	1.62E+00	7.92E-03	6.79E+01	2.74E-01
RL-W636	4.61E-01	0.00E+00	2.27E-02	5.65E-02	4.98E-02	9.83E-03	1.50E-05	5.90E-01	2.38E-03
RL-W637	1.10E-03	0.00E+00	5.78E-04	6.36E-04	6.21E-04	3.53E-05	3.81E-07	2.93E-03	1.18E-05
RL-W638	4.82E-02	0.00E+00	5.89E-03	6.23E-03	5.84E-03	1.32E-03	3.88E-06	6.61E-02	2.67E-04
RL-W639	2.54E-03	0.00E+00	1.51E-04	1.59E-02	3.53E-03	9.20E-05	9.92E-08	2.22E-02	8.94E-05
RL-W640	8.53E-02	0.00E+00	5.01E-03	5.37E-01	1.19E-01	2.96E-03	3.30E-06	7.47E-01	3.01E-03
RL-W641	2.61E+00	0.00E+00	1.10E+00	2.58E+00	1.06E+00	4.75E-02	7.25E-04	7.34E+00	2.96E-02
RL-W642	5.09E-02	0.00E+00	1.14E-04	3.15E-02	1.60E-04	2.05E-05	7.53E-08	8.27E-02	3.33E-04
RL-W643	8.02E-01	0.00E+00	3.39E-01	7.95E-01	3.25E-01	1.46E-02	2.23E-04	2.26E+00	9.12E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.47E-02	0.00E+00	0.00E+00	0.00E+00	5.47E-02	2.21E-04
RL-W645	1.95E-02	0.00E+00	1.52E-03	1.08E-01	2.52E-02	7.99E-04	1.00E-06	1.54E-01	6.20E-04
RL-W646	1.77E-02	0.00E+00	1.36E-03	2.57E-02	1.24E-02	3.88E-04	8.97E-07	5.72E-02	2.31E-04
RL-W647	4.98E-02	0.00E+00	2.03E-01	1.10E-01	1.73E-02	1.30E-03	1.34E-04	3.80E-01	1.53E-03
RL-W648	8.82E-04	0.00E+00	3.48E-04	5.99E-05	1.17E-04	4.16E-05	2.29E-07	1.41E-03	5.67E-06
RL-W649	3.24E-03	0.00E+00	1.28E-03	2.20E-04	4.31E-04	1.53E-04	8.43E-07	5.17E-03	2.09E-05
RL-W653	1.54E-04	0.00E+00	9.17E-06	9.62E-04	2.13E-04	5.83E-06	6.04E-09	1.34E-03	5.40E-06
RL-W654	8.45E-04	0.00E+00	5.01E-05	5.30E-03	1.17E-03	3.06E-05	3.30E-08	7.37E-03	2.97E-05
RL-W655	2.08E+02	0.00E+00	1.18E+01	2.10E-01	4.94E-01	8.18E+00	7.81E-03	2.21E+02	8.90E-01
RL-W656	8.71E+02	0.00E+00	5.32E+00	4.94E-01	5.08E-01	3.90E+01	3.51E-03	8.77E+02	3.54E+00
RL-W657	4.45E+02	0.00E+00	7.86E+00	2.43E-01	4.83E-01	1.72E+01	5.18E-03	4.54E+02	1.83E+00

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W659	5.38E+01	0.00E+00	1.77E+00	4.68E-02	5.79E-02	1.95E+00	1.17E-03	5.57E+01	2.25E-01
RL-W660	2.95E+02	0.00E+00	2.13E+01	8.64E-01	1.54E+00	1.11E+01	1.41E-02	3.19E+02	1.29E+00
RL-W661	3.12E+00	0.00E+00	2.67E-02	4.16E-04	3.78E-03	1.35E-01	1.76E-05	3.15E+00	1.27E-02
RL-W662	9.83E-02	0.00E+00	1.59E-03	1.07E-04	1.90E-04	2.77E-03	1.05E-06	1.00E-01	4.04E-04
RL-W665	1.21E+03	0.00E+00	1.27E+02	1.31E+00	1.75E+00	5.50E+01	8.39E-02	1.34E+03	5.39E+00
RL-W666	2.16E+01	0.00E+00	3.12E-01	5.47E-02	5.74E-02	7.95E-01	2.05E-04	2.20E+01	8.89E-02
RL-W668	2.06E+00	0.00E+00	9.80E-03	1.44E-01	4.08E-02	1.88E-03	6.46E-06	2.26E+00	9.10E-03
RL-W669	6.01E-01	0.00E+00	2.54E-01	5.96E-01	2.44E-01	1.10E-02	1.68E-04	1.70E+00	6.83E-03
RL-W670	3.80E-02	0.00E+00	1.81E-04	2.67E-03	7.55E-04	3.48E-05	1.19E-07	4.16E-02	1.68E-04
RL-W671	6.20E+00	0.00E+00	9.27E-02	4.89E-03	5.07E-03	1.14E-01	6.11E-05	6.30E+00	2.54E-02
RL-W672	4.21E+01	0.00E+00	6.31E-01	3.34E-02	3.44E-02	7.76E-01	4.16E-04	4.28E+01	1.73E-01
RL-W673	4.06E+01	0.00E+00	6.06E-01	3.23E-02	3.32E-02	7.48E-01	4.00E-04	4.13E+01	1.67E-01
RL-W674	1.36E-01	0.00E+00	2.71E-02	1.12E+01	9.66E-02	5.22E-03	1.79E-05	1.14E+01	4.60E-02
RL-W675	5.09E-01	0.00E+00	1.50E-01	1.31E-01	1.12E-01	1.27E-02	9.87E-05	9.02E-01	3.64E-03
RL-W676	1.96E-02	0.00E+00	8.99E-04	1.46E-01	2.12E-03	3.78E-04	5.92E-07	1.69E-01	6.82E-04
RL-W677	4.53E+01	0.00E+00	2.23E+00	5.72E+00	4.95E+00	9.10E-01	1.47E-03	5.82E+01	2.35E-01
RL-W678	1.43E-01	0.00E+00	1.86E-02	5.14E-02	4.52E-02	7.13E-03	1.23E-05	2.58E-01	1.04E-03
RL-W679	8.98E-01	0.00E+00	4.16E-02	1.11E-01	9.72E-02	1.83E-02	2.74E-05	1.15E+00	4.63E-03
RL-W680	2.02E-04	0.00E+00	5.85E-05	1.73E-05	3.11E-05	7.85E-06	3.86E-08	3.09E-04	1.25E-06
RL-W681	1.23E-04	0.00E+00	2.37E-05	4.65E-04	2.31E-04	6.52E-06	1.56E-08	8.43E-04	3.40E-06
RL-W685	3.60E-01	0.00E+00	2.11E-02	2.27E+00	5.03E-01	1.19E-02	1.39E-05	3.16E+00	1.27E-02
RL-W689	9.33E-03	0.00E+00	2.53E-04	3.86E-04	0.00E+00	1.14E-05	1.67E-07	9.97E-03	4.02E-05
RL-W690	3.13E-01	0.00E+00	1.86E-02	2.02E+00	4.47E-01	1.04E-02	1.23E-05	2.80E+00	1.13E-02
RL-W691	7.26E-03	0.00E+00	4.34E-04	4.68E-02	1.04E-02	2.40E-04	2.86E-07	6.49E-02	2.62E-04
RL-W692	2.87E-01	0.00E+00	1.72E-02	1.85E+00	4.10E-01	9.48E-03	1.13E-05	2.57E+00	1.04E-02
RL-W693	3.55E-01	0.00E+00	2.12E-02	2.29E+00	5.08E-01	1.17E-02	1.40E-05	3.18E+00	1.28E-02
RL-W694	3.73E+00	0.00E+00	2.22E-01	2.42E+01	5.33E+00	1.23E-01	1.47E-04	3.35E+01	1.35E-01
RL-W695	3.09E-03	0.00E+00	0.00E+00	2.38E-03	0.00E+00	0.00E+00	0.00E+00	5.47E-03	2.21E-05
RL-W696	4.02E-03	0.00E+00	8.11E-04	2.90E-03	2.85E-03	1.69E-04	5.34E-07	1.06E-02	4.27E-05

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W697	9.31E-01	0.00E+00	1.72E+00	6.90E-03	9.44E-04	0.00E+00	1.13E-03	2.66E+00	1.07E-02
RL-W698	8.07E-02	0.00E+00	0.00E+00	3.28E-05	0.00E+00	0.00E+00	0.00E+00	8.07E-02	3.26E-04
RL-W699	1.79E-02	0.00E+00	1.14E-04	2.19E-03	2.56E-04	7.12E-04	7.53E-08	2.05E-02	8.26E-05
RL-W700	5.08E-03	0.00E+00	3.00E-04	3.18E-02	7.05E-03	1.84E-04	1.98E-07	4.42E-02	1.78E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	2.00E-01	0.00E+00	8.46E-02	1.98E-01	8.14E-02	3.65E-03	5.58E-05	5.64E-01	2.28E-03
RL-W705	1.29E-03	0.00E+00	7.79E-05	8.33E-03	1.85E-03	4.49E-05	5.13E-08	1.16E-02	4.66E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	4.62E-02	0.00E+00	2.77E-03	2.97E-01	6.59E-02	1.60E-03	1.83E-06	4.12E-01	1.66E-03
RL-W708	6.98E-03	0.00E+00	4.20E-04	4.50E-02	9.96E-03	2.42E-04	2.77E-07	6.24E-02	2.52E-04
RL-W709	2.41E+00	0.00E+00	1.45E-01	1.55E+01	3.44E+00	8.35E-02	9.53E-05	2.15E+01	8.69E-02
RL-W710	1.44E-04	0.00E+00	8.64E-06	9.29E-04	2.05E-04	4.99E-06	5.69E-09	1.29E-03	5.19E-06
RL-W711	4.50E-02	0.00E+00	2.70E-03	2.90E-01	6.42E-02	1.56E-03	1.78E-06	4.02E-01	1.62E-03
RL-W712	5.82E-02	0.00E+00	3.49E-03	3.75E-01	8.30E-02	2.02E-03	2.30E-06	5.19E-01	2.09E-03
RL-W713	5.02E-02	0.00E+00	3.01E-03	3.23E-01	7.18E-02	1.74E-03	1.99E-06	4.48E-01	1.81E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	8.67E-04	0.00E+00	5.08E-05	5.47E-03	1.21E-03	2.87E-05	3.35E-08	7.60E-03	3.06E-05
RL-W716	9.04E-03	0.00E+00	5.29E-04	5.70E-02	1.26E-02	2.99E-04	3.49E-07	7.92E-02	3.19E-04
RL-W717	2.25E-03	0.00E+00	1.32E-04	1.43E-02	3.16E-03	7.46E-05	8.71E-08	1.98E-02	7.98E-05
RL-W718	3.98E-04	0.00E+00	2.33E-05	2.51E-03	5.56E-04	1.32E-05	1.54E-08	3.49E-03	1.41E-05
RL-W719	1.79E-03	0.00E+00	1.05E-04	1.14E-02	2.52E-03	5.95E-05	6.92E-08	1.58E-02	6.36E-05
RL-W720	1.11E-02	0.00E+00	6.52E-04	7.01E-02	1.56E-02	3.67E-04	4.30E-07	9.75E-02	3.93E-04
RL-W721	7.52E-03	0.00E+00	4.41E-04	4.74E-02	1.06E-02	2.49E-04	2.90E-07	6.59E-02	2.66E-04
RL-W723	2.49E-02	0.00E+00	1.49E-03	1.61E-01	3.57E-02	8.25E-04	9.80E-07	2.24E-01	9.01E-04
RL-W724	1.66E-01	0.00E+00	9.91E-03	1.07E+00	2.38E-01	5.48E-03	6.53E-06	1.48E+00	5.97E-03
RL-W725	5.24E-02	0.00E+00	3.12E-03	3.38E-01	7.49E-02	1.73E-03	2.06E-06	4.68E-01	1.89E-03
RL-W726	4.12E-02	0.00E+00	2.46E-03	2.67E-01	5.91E-02	1.36E-03	1.62E-06	3.70E-01	1.49E-03
RL-W727	2.53E-01	0.00E+00	1.51E-02	1.63E+00	3.63E-01	8.37E-03	9.97E-06	2.27E+00	9.13E-03

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W728	2.30E-01	0.00E+00	1.38E-02	1.49E+00	3.30E-01	7.62E-03	9.08E-06	2.07E+00	8.34E-03
RL-W729	1.06E-01	0.00E+00	6.38E-03	6.87E-01	1.53E-01	3.51E-03	4.21E-06	9.53E-01	3.84E-03
RL-W730	4.17E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.17E+01	1.68E-01
RL-W731	1.34E-05	0.00E+00	0.00E+00	4.49E-04	1.83E-06	0.00E+00	0.00E+00	4.65E-04	1.87E-06
RL-W732	3.08E+01	0.00E+00	3.63E+00	1.27E+02	2.79E+01	1.26E+00	2.39E-03	1.89E+02	7.61E-01
RL-W733	4.04E-01	0.00E+00	4.72E-02	1.38E+00	3.39E-01	1.37E-02	3.11E-05	2.17E+00	8.73E-03
RL-W734	1.26E+00	0.00E+00	1.58E-01	4.74E+00	1.14E+00	4.07E-02	1.04E-04	7.31E+00	2.95E-02
RL-W735	1.03E+00	0.00E+00	1.20E-01	3.70E+00	9.12E-01	3.17E-02	7.92E-05	5.76E+00	2.32E-02
RL-W736	1.13E-03	0.00E+00	2.56E-07	2.45E-03	6.29E-04	9.69E-06	1.69E-10	4.21E-03	1.70E-05
RL-W737	9.21E-01	0.00E+00	1.10E-01	3.51E+00	8.49E-01	2.73E-02	7.23E-05	5.39E+00	2.17E-02
RL-W738	3.44E+00	0.00E+00	3.77E-01	1.12E+01	2.93E+00	9.90E-02	2.49E-04	1.79E+01	7.22E-02
RL-W739	2.93E-01	0.00E+00	3.33E-02	1.81E+00	4.11E-01	8.99E-03	2.19E-05	2.55E+00	1.03E-02
RL-W740	1.47E+01	0.00E+00	1.22E+00	4.41E+01	1.14E+01	4.54E-01	8.04E-04	7.14E+01	2.88E-01
RL-W741	2.19E+01	0.00E+00	2.87E+00	8.60E+00	6.07E+00	3.41E-01	1.89E-03	3.94E+01	1.59E-01
RL-W742	9.74E-01	0.00E+00	8.64E-02	2.79E+00	6.54E-01	2.92E-02	5.69E-05	4.50E+00	1.82E-02
RL-W743	1.76E-03	0.00E+00	2.34E-05	1.80E-03	0.00E+00	0.00E+00	1.55E-08	3.58E-03	1.45E-05
RL-W744	0.00E+00	0.00E+00	0.00E+00	9.00E-02	7.61E-02	0.00E+00	0.00E+00	1.66E-01	6.70E-04
RL-W745	2.77E-03	0.00E+00	1.64E-04	1.74E-02	3.86E-03	1.00E-04	1.08E-07	2.42E-02	9.77E-05
RL-W746	1.07E-02	0.00E+00	6.31E-04	6.69E-02	1.49E-02	3.86E-04	4.16E-07	9.31E-02	3.76E-04
RL-W747	2.89E-02	0.00E+00	1.71E-03	1.81E-01	4.02E-02	1.05E-03	1.13E-06	2.52E-01	1.02E-03
RL-W748	2.03E+02	0.00E+00	4.79E+00	3.01E-01	4.92E-01	7.88E+00	3.16E-03	2.08E+02	8.39E-01
RL-W749	2.43E-01	0.00E+00	1.47E-02	1.57E+00	3.48E-01	8.42E-03	9.66E-06	2.18E+00	8.79E-03
RL-W750	3.07E+02	0.00E+00	7.26E+00	4.93E-01	8.04E-01	1.12E+01	4.79E-03	3.16E+02	1.27E+00
RL-W751	2.77E+02	0.00E+00	6.56E+00	4.43E-01	7.29E-01	1.01E+01	4.32E-03	2.85E+02	1.15E+00
RL-W752	1.21E+02	0.00E+00	2.85E+00	1.93E-01	3.17E-01	4.37E+00	1.88E-03	1.24E+02	5.00E-01
RL-W753	1.62E+03	0.00E+00	3.84E+01	2.60E+00	4.25E+00	5.88E+01	2.53E-02	1.67E+03	6.72E+00
RP-W754	6.89E+01	0.00E+00	4.86E+00	1.85E+03	1.51E+02	5.43E-01	3.56E-01	2.08E+03	8.38E+00
RP-W755	3.65E+02	0.00E+00	2.92E+00	1.39E+03	1.14E+02	4.05E-01	1.26E+01	1.88E+03	7.58E+00
SA-T001	7.34E-01	3.06E-02	6.98E-02	3.02E+00	1.77E-02	0.00E+00	5.06E-05	3.84E+00	1.55E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
SA-W134	5.99E+00	1.18E-05	4.76E-01	1.38E+00	4.33E-01	1.03E-02	1.67E-01	8.44E+00	3.40E-02
SA-W134M	7.78E-01	1.54E-06	6.17E-02	1.79E-01	5.62E-02	1.34E-03	2.16E-02	1.10E+00	4.42E-03
T001-221F-HET	1.45E+03	0.00E+00	5.57E+04	2.87E+04	7.04E+02	3.39E+01	4.24E+01	8.66E+04	3.49E+02
T001-221H-HET	2.61E+03	0.00E+00	1.01E+05	5.18E+04	1.27E+03	6.12E+01	7.64E+01	1.56E+05	6.30E+02
T001-235F-HET	1.50E+02	0.00E+00	5.78E+03	2.98E+03	7.31E+01	3.51E+00	4.40E+00	8.99E+03	3.62E+01
T001-772F-HET	1.29E+03	0.00E+00	5.01E+04	2.57E+04	6.30E+02	3.03E+01	3.81E+01	7.77E+04	3.13E+02
T001-773A-CLAS	1.45E+01	0.00E+00	5.61E+02	2.89E+02	7.07E+00	3.41E-01	4.26E-01	8.71E+02	3.51E+00
T001-773A-HET	1.67E+02	0.00E+00	6.45E+03	3.33E+03	8.17E+01	3.93E+00	4.91E+00	1.00E+04	4.05E+01
W006-773A-VIT	2.24E-03	0.00E+00	0.00E+00	5.35E+02	0.00E+00	0.00E+00	0.00E+00	5.35E+02	2.16E+00
W026-221F-HET	5.04E+02	0.00E+00	1.94E+04	1.01E+04	2.46E+02	1.18E+01	1.48E+01	3.03E+04	1.22E+02
W026-221H-HET	3.77E+02	0.00E+00	1.45E+04	7.49E+03	1.83E+02	8.84E+00	1.10E+01	2.26E+04	9.11E+01
W026-235F-HET	5.87E+00	0.00E+00	2.26E+02	1.17E+02	2.86E+00	1.38E-01	1.72E-01	3.52E+02	1.42E+00
W026-772F-HET	1.61E+00	0.00E+00	6.17E+01	3.18E+01	7.79E-01	3.76E-02	4.69E-02	9.59E+01	3.87E-01
W026-773A-HET	2.60E+01	0.00E+00	1.01E+03	5.18E+02	1.27E+01	6.11E-01	7.64E-01	1.56E+03	6.30E+00
W027-221F-HET	1.90E+03	0.00E+00	6.56E+04	3.89E+04	9.51E+02	1.93E+01	6.10E+01	1.07E+05	4.33E+02
W027-221H-HET	8.32E+02	0.00E+00	2.86E+04	1.70E+04	4.16E+02	8.44E+00	2.67E+01	4.69E+04	1.89E+02
W027-235F-HET	2.50E+02	0.00E+00	8.60E+03	5.12E+03	1.25E+02	2.54E+00	8.02E+00	1.41E+04	5.69E+01
W027-772F-HET	4.55E+02	0.00E+00	1.57E+04	9.30E+03	2.28E+02	4.61E+00	1.46E+01	2.56E+04	1.03E+02
W027-773A-HET	6.78E+02	0.00E+00	2.33E+04	1.39E+04	3.39E+02	6.89E+00	2.17E+01	3.82E+04	1.54E+02
W027-999-HET	7.76E+02	0.00E+00	2.67E+04	1.58E+04	3.88E+02	7.86E+00	2.49E+01	4.37E+04	1.76E+02
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.98E+02	0.00E+00	0.00E+00	0.00E+00	3.98E+02	1.60E+00
WP-INW169.001	3.79E+00	0.00E+00	1.68E-01	1.53E+01	3.39E+00	6.94E-02	2.76E-04	2.27E+01	9.15E-02
WP-INW198.001	4.99E+00	0.00E+00	2.93E-01	2.75E+01	6.04E+00	1.14E-01	2.75E-04	3.88E+01	1.57E-01
WP-INW211.001	5.62E+02	0.00E+00	2.75E+01	2.55E+03	5.60E+02	1.29E+01	2.01E-02	3.70E+03	1.49E+01
WP-INW216.001-	2.04E+04	0.00E+00	1.58E+01	1.47E+03	3.25E+02	7.13E+00	2.87E-01	2.22E+04	8.97E+01
WP-INW216.001-	5.62E+03	0.00E+00	4.27E+00	4.00E+02	8.78E+01	1.93E+00	3.04E-02	6.11E+03	2.46E+01
WP-INW218.001-	3.91E+02	0.00E+00	2.79E+00	2.57E+02	5.66E+01	1.29E+00	3.88E-01	7.07E+02	2.85E+00
WP-INW218.001-	1.80E+00	0.00E+00	7.68E-02	6.99E+00	1.54E+00	3.65E-02	3.74E-02	1.04E+01	4.21E-02
WP-INW222.001	1.85E+01	0.00E+00	8.28E-01	6.83E+01	1.52E+01	3.10E-01	1.12E-03	1.03E+02	4.15E-01

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-INW243.001	4.48E+01	0.00E+00	1.79E+00	1.44E+02	3.20E+01	6.26E-01	2.05E-03	2.22E+02	8.95E-01
WP-INW247.001R	5.99E+01	0.00E+00	4.16E+00	2.75E+02	6.21E+01	1.09E+00	2.82E-03	4.01E+02	1.62E+00
WP-INW276.001	4.56E+00	0.00E+00	4.05E-01	2.72E+01	6.15E+00	9.20E-02	2.84E-04	3.83E+01	1.55E-01
WP-INW276.002	7.24E+00	0.00E+00	6.10E-01	4.00E+01	9.23E+00	1.38E-01	4.28E-04	5.70E+01	2.30E-01
WP-INW276.003	2.77E+02	0.00E+00	2.27E+01	1.48E+03	3.36E+02	5.81E+00	1.54E-02	2.12E+03	8.55E+00
WP-INW276.004	6.62E+01	0.00E+00	4.79E+00	3.14E+02	7.10E+01	1.23E+00	3.31E-03	4.56E+02	1.84E+00
WP-INW296.001-	2.42E+01	0.00E+00	1.14E+00	7.88E+01	1.78E+01	3.15E-01	7.88E-04	1.22E+02	4.92E-01
WP-INW296.001-	7.30E+01	0.00E+00	4.02E+00	2.79E+02	6.27E+01	1.13E+00	3.00E-03	4.19E+02	1.69E+00
WP-LA-TA-55-19	1.22E+00	0.00E+00	1.87E-01	2.08E+00	5.00E-01	1.13E-02	2.76E-03	3.99E+00	1.61E-02
WP-LA-TA-55-19	5.89E+01	0.00E+00	6.27E+00	2.12E+02	5.15E+01	1.12E+00	9.13E-02	3.29E+02	1.33E+00
WP-LA-TA-55-43	3.31E-01	0.00E+00	1.46E+02	3.22E-01	1.35E-01	1.00E-02	1.23E-01	1.47E+02	5.94E-01
WP-RF001.01	1.02E+02	0.00E+00	5.08E+00	4.08E+02	9.24E+01	1.13E+00	1.27E-02	6.08E+02	2.45E+00
WP-RF002.01-A	1.19E+02	0.00E+00	6.77E+00	4.60E+02	1.05E+02	2.49E+00	2.23E-02	6.91E+02	2.78E+00
WP-RF002.01-B	1.18E-01	0.00E+00	4.69E-03	4.98E-01	1.12E-01	1.56E-03	3.28E-06	7.33E-01	2.96E-03
WP-RF003.01	1.85E+03	0.00E+00	1.09E+02	8.80E+03	1.99E+03	4.11E+01	8.01E-02	1.27E+04	5.14E+01
WP-RF004.01	8.66E-01	0.00E+00	7.30E-02	5.07E+00	1.15E+00	2.35E-02	1.75E-04	7.16E+00	2.89E-02
WP-RF005.01	4.45E+03	0.00E+00	5.53E+01	4.65E+03	1.05E+03	1.64E+01	3.83E-02	1.02E+04	4.11E+01
WP-RF005.02	5.23E+03	0.00E+00	2.86E+01	2.78E+03	6.20E+02	8.39E+00	2.01E-02	8.66E+03	3.49E+01
WP-RF006.01	1.70E+03	0.00E+00	1.04E+02	7.91E+03	1.80E+03	2.12E+01	9.41E-02	1.15E+04	4.64E+01
WP-RF008.01	5.38E+02	0.00E+00	3.70E+01	2.31E+03	5.34E+02	1.40E+01	2.57E-02	3.42E+03	1.38E+01
WP-RF009.01	5.30E+04	0.00E+00	4.55E+02	5.07E+04	1.12E+04	1.61E+02	3.20E-01	1.15E+05	4.65E+02
WP-RF010.01	1.95E+01	0.00E+00	1.15E+00	7.66E+01	1.74E+01	4.96E-01	1.49E-03	1.15E+02	4.62E-01
WP-RF029.01-A	4.69E+00	0.00E+00	2.17E-01	1.35E+01	3.06E+00	1.14E-01	8.73E-04	2.14E+01	8.63E-02
WP-RF029.01-B	7.01E+00	0.00E+00	1.72E-01	1.07E+01	2.42E+00	8.99E-02	2.36E-03	2.03E+01	8.17E-02
WP-RF118.01	1.19E+04	0.00E+00	8.64E+02	5.12E+04	1.13E+04	2.96E+02	7.84E-01	7.53E+04	3.04E+02
WP-RLMPDT.001	2.53E+00	0.00E+00	2.52E-01	7.33E+00	1.89E+00	6.49E-02	1.68E-04	1.20E+01	4.84E-02
WP-RLNPDT.002	3.10E+01	0.00E+00	2.40E+00	7.20E+01	1.92E+01	7.45E-01	1.62E-03	1.25E+02	5.03E-01
WP-SR2001.001.	9.87E-01	0.00E+00	2.76E-01	6.80E+00	1.34E+00	4.05E-02	1.86E-04	9.41E+00	3.79E-02

Table PAR-52. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 100 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-SR-W027-221	7.32E+00	0.00E+00	8.11E-01	1.95E+01	5.41E+00	1.83E-01	1.87E-01	3.33E+01	1.34E-01
Total	3.92E+05	5.91E+01	5.68E+05	6.58E+05	1.06E+05	4.18E+03	5.42E+02	1.72E+06	6.95E+03

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	7.09E+01	0.00E+00	5.15E+00	2.08E+02	1.22E+02	1.25E-01	1.78E-02	4.06E+02	1.64E+00
AE-T003	8.98E+00	0.00E+00	6.86E-01	6.43E+01	2.46E+01	6.84E-02	7.17E-04	9.86E+01	3.97E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	3.98E-02	0.00E+00	1.82E+01	4.74E+01	2.83E-01	1.33E-04	1.65E-02	6.59E+01	2.66E-01
AW-T033.1325	1.46E-01	0.00E+00	6.65E+01	1.73E+02	1.03E+00	4.87E-04	6.05E-02	2.41E+02	9.72E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.70E-01	0.00E+00	0.00E+00	0.00E+00	7.70E-01	3.10E-03
BCLCH-MT01	1.47E+01	0.00E+00	5.15E+02	2.86E+01	7.42E+00	1.88E-01	4.54E-01	5.66E+02	2.28E+00
BT-T002	1.08E-02	6.22E-06	2.69E-01	7.22E-04	1.46E-03	8.25E-05	2.23E-03	2.84E-01	1.15E-03
ET-C1-B55	4.50E-02	0.00E+00	3.07E-03	6.18E-02	3.05E-02	1.46E-04	2.39E-04	1.41E-01	5.67E-04
ET-C1-D139	6.18E-03	0.00E+00	4.25E-04	8.69E-03	4.29E-03	1.94E-05	4.37E-07	1.96E-02	7.90E-05
ET-C2-SEFOR	1.53E-01	0.00E+00	0.00E+00	1.36E-01	4.53E-02	2.99E-04	0.00E+00	3.35E-01	1.35E-03
FM-MOX-MT02	1.45E-06	0.00E+00	1.71E-07	2.99E-07	1.76E-07	1.04E-08	1.60E-10	2.10E-06	8.45E-09
FM-MOX-T01	2.39E-05	0.00E+00	2.83E-06	4.92E-06	2.90E-06	1.71E-07	2.63E-09	3.46E-05	1.40E-07
IN-BN-510	5.79E+03	0.00E+00	1.46E+04	3.95E+04	3.31E+03	4.09E-02	1.48E+01	6.32E+04	2.55E+02
IN-GEM-01	7.32E+01	0.00E+00	2.89E-01	4.44E+01	1.00E+01	2.89E-02	2.55E-04	1.28E+02	5.16E-01
IN-GEM-02	1.74E+01	0.00E+00	6.89E-02	1.06E+01	2.39E+00	6.84E-03	6.07E-05	3.04E+01	1.23E-01
IN-W157.144	8.67E+01	0.00E+00	2.80E+00	3.02E+02	6.76E+01	5.12E-01	2.84E-03	4.59E+02	1.85E+00
IN-W163.1007	1.48E+01	0.00E+00	8.65E-01	9.36E+01	2.10E+01	1.58E-01	8.78E-04	1.30E+02	5.25E-01
IN-W164.153	1.42E-01	0.00E+00	8.25E-03	8.91E-01	2.00E-01	1.51E-03	8.38E-06	1.24E+00	5.00E-03
IN-W167.149	2.84E+01	0.00E+00	1.34E+00	1.44E+02	3.24E+01	2.44E-01	1.36E-03	2.06E+02	8.32E-01
IN-W174.154	0.00E+00	0.00E+00	7.58E+02	1.94E+00	3.79E+00	0.00E+00	7.70E-01	7.65E+02	3.08E+00
IN-W177.156	1.97E-02	0.00E+00	1.61E+03	1.82E+00	1.10E-02	2.10E-04	1.64E+00	1.62E+03	6.51E+00
IN-W179.158	1.33E-01	0.00E+00	1.61E+03	1.06E-01	5.43E-02	1.41E-03	1.63E+00	1.61E+03	6.48E+00
IN-W181.162	1.88E+00	0.00E+00	1.09E-01	1.18E+01	2.64E+00	2.00E-02	1.11E-04	1.64E+01	6.60E-02
IN-W188.160	1.27E+01	0.00E+00	7.35E-01	7.93E+01	1.77E+01	1.35E-01	7.46E-04	1.10E+02	4.45E-01
IN-W216.98	1.13E+05	0.00E+00	5.99E+01	6.47E+03	1.46E+03	1.10E+01	6.08E-02	1.21E+05	4.86E+02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	5.68E+02	0.00E+00	1.33E+00	1.43E+02	3.22E+01	2.44E-01	1.35E-03	7.45E+02	3.01E+00
IN-W219.110	7.71E-01	0.00E+00	4.49E-02	4.84E+00	1.08E+00	8.20E-03	4.55E-05	6.74E+00	2.72E-02
IN-W219.914	1.22E-01	0.00E+00	7.06E-03	7.64E-01	1.71E-01	1.30E-03	7.17E-06	1.06E+00	4.29E-03
IN-W220.114	4.02E+03	0.00E+00	4.72E+00	5.47E+02	1.19E+02	8.62E-01	4.79E-03	4.69E+03	1.89E+01
IN-W221.927	4.71E+00	0.00E+00	2.73E-01	2.95E+01	6.59E+00	5.01E-02	2.78E-04	4.10E+01	1.66E-01
IN-W222.116	1.60E+02	0.00E+00	9.26E+00	9.96E+02	2.23E+02	1.69E+00	9.40E-03	1.39E+03	5.60E+00
IN-W228.101	1.06E+03	0.00E+00	3.01E+00	3.26E+02	7.28E+01	5.54E-01	3.06E-03	1.46E+03	5.90E+00
IN-W240.931	1.12E+02	0.00E+00	3.85E+00	4.18E+02	9.31E+01	7.00E-01	3.91E-03	6.28E+02	2.53E+00
IN-W243.808	1.56E+02	0.00E+00	6.74E+00	7.30E+02	1.63E+02	1.24E+00	6.85E-03	1.06E+03	4.26E+00
IN-W245.301	2.31E+02	0.00E+00	1.33E+01	1.42E+03	3.20E+02	2.42E+00	1.35E-02	1.99E+03	8.01E+00
IN-W247.810	1.12E+02	0.00E+00	6.45E+00	6.96E+02	1.56E+02	1.18E+00	6.55E-03	9.71E+02	3.92E+00
IN-W249.527	0.00E+00	0.00E+00	4.51E+02	1.23E+01	0.00E+00	0.00E+00	4.58E-01	4.64E+02	1.87E+00
IN-W263.520	3.22E-02	0.00E+00	4.72E+01	8.39E+00	1.32E-02	3.42E-04	4.79E-02	5.57E+01	2.24E-01
IN-W267.1005	2.69E+01	0.00E+00	1.57E+00	1.69E+02	3.79E+01	2.87E-01	1.59E-03	2.36E+02	9.50E-01
IN-W309.609	7.22E+02	0.00E+00	2.62E+01	2.83E+03	6.33E+02	4.79E+00	2.66E-02	4.21E+03	1.70E+01
IN-W315.601	7.12E+02	0.00E+00	1.10E-01	1.19E+01	2.65E+00	2.00E-02	1.11E-04	7.26E+02	2.93E+00
IN-W319.584	4.14E+00	0.00E+00	2.40E-01	2.60E+01	5.83E+00	4.40E-02	2.44E-04	3.62E+01	1.46E-01
IN-W321.1023	3.58E+01	0.00E+00	2.08E+00	2.25E+02	5.04E+01	3.81E-01	2.12E-03	3.13E+02	1.26E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	9.08E+00	1.86E+00	0.00E+00	0.00E+00	1.09E+01	4.41E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.42E+01	4.96E+00	0.00E+00	0.00E+00	2.92E+01	1.18E-01
IN-W323.562	7.65E-02	0.00E+00	3.53E-01	2.48E-01	0.00E+00	8.15E-04	3.59E-04	6.78E-01	2.73E-03
IN-W323.951	9.03E-02	0.00E+00	4.20E-03	2.96E-01	0.00E+00	9.61E-04	4.26E-06	3.90E-01	1.57E-03
IN-W332.661	0.00E+00	0.00E+00	4.63E+00	1.28E-01	0.00E+00	0.00E+00	4.70E-03	4.76E+00	1.92E-02
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	3.03E+00	6.20E-01	0.00E+00	0.00E+00	3.65E+00	1.47E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	9.08E+00	1.86E+00	0.00E+00	0.00E+00	1.09E+01	4.41E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.94E+00	0.00E+00	0.00E+00	0.00E+00	1.94E+00	7.83E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.83E+00	0.00E+00	0.00E+00	0.00E+00	5.83E+00	2.35E-02
IN-W342.652	3.54E+00	0.00E+00	0.00E+00	4.00E-02	1.02E-17	0.00E+00	0.00E+00	3.58E+00	1.44E-02
IN-W342.953	2.36E+00	0.00E+00	0.00E+00	2.68E-02	6.87E-18	0.00E+00	0.00E+00	2.39E+00	9.64E-03

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W347.818	1.85E+00	0.00E+00	0.00E+00	8.22E+01	1.50E+02	0.00E+00	1.58E-08	2.34E+02	9.42E-01
IN-W348.1012	9.80E-02	0.00E+00	3.82E+00	4.15E+02	9.30E+01	0.00E+00	3.88E-03	5.12E+02	2.07E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.49E-02	0.00E+00	0.00E+00	0.00E+00	2.49E-02	1.00E-04
IN-W357.1022	0.00E+00	0.00E+00	7.52E-03	8.15E-01	1.82E-01	0.00E+00	7.64E-06	1.01E+00	4.05E-03
IN-W358.854	0.00E+00	0.00E+00	1.13E+02	1.87E+00	3.57E+00	0.00E+00	1.08E-01	1.19E+02	4.80E-01
IN-W358.855	0.00E+00	0.00E+00	6.05E+02	9.96E+00	1.90E+01	0.00E+00	5.76E-01	6.34E+02	2.56E+00
IN-W358.948	0.00E+00	0.00E+00	1.26E+02	2.08E+00	3.95E+00	0.00E+00	1.20E-01	1.32E+02	5.34E-01
IN-W361.1021	2.60E-02	0.00E+00	7.29E-01	7.86E+01	1.76E+01	0.00E+00	7.40E-04	9.70E+01	3.91E-01
IN-W362.1020	0.00E+00	0.00E+00	9.55E+00	1.03E+03	2.31E+02	0.00E+00	9.69E-03	1.27E+03	5.11E+00
IN-W363.1019	0.00E+00	0.00E+00	4.49E-01	4.87E+01	1.09E+01	0.00E+00	4.56E-04	6.01E+01	2.42E-01
IN-W364.1011	0.00E+00	0.00E+00	7.41E-01	8.00E+01	1.79E+01	0.00E+00	7.52E-04	9.87E+01	3.98E-01
IN-W365.1010	2.43E+02	0.00E+00	5.87E-01	6.32E+01	1.42E+01	0.00E+00	5.96E-04	3.21E+02	1.29E+00
IN-W366.841	8.63E-01	0.00E+00	5.01E-01	5.39E+01	1.21E+01	0.00E+00	5.08E-04	6.73E+01	2.71E-01
IN-W372.832	3.54E+00	0.00E+00	0.00E+00	4.00E-02	1.02E-17	0.00E+00	0.00E+00	3.58E+00	1.44E-02
IN-W375.1096	0.00E+00	0.00E+00	1.85E-01	1.99E+01	4.46E+00	0.00E+00	1.88E-04	2.46E+01	9.90E-02
KN-B234TRU	1.26E+02	0.00E+00	7.06E+00	2.90E+02	9.64E+01	2.68E-01	8.17E-03	5.19E+02	2.09E+00
LA-IT-00-01	1.83E+00	4.00E-03	1.20E+00	5.82E-01	1.25E-02	5.14E-11	1.42E-03	3.63E+00	1.46E-02
LA-OS-00-01	4.07E+03	0.00E+00	5.50E+04	1.22E+03	0.00E+00	0.00E+00	4.90E+01	6.03E+04	2.43E+02
LA-PX-00-01	1.70E-02	0.00E+00	2.32E-03	9.01E-02	2.10E-02	8.51E-05	2.18E-06	1.30E-01	5.26E-04
LA-SL-00-01	0.00E+00	0.00E+00	4.89E-02	1.52E-01	0.00E+00	0.00E+00	5.70E-05	2.01E-01	8.12E-04
LA-TA-03-12	1.74E-01	0.00E+00	1.13E+00	4.34E-01	1.50E-01	5.04E-04	1.38E-03	1.89E+00	7.62E-03
LA-TA-03-13	2.26E-01	0.00E+00	3.59E+00	6.78E-01	1.57E-01	6.68E-04	3.69E-03	4.65E+00	1.88E-02
LA-TA-03-19	4.56E-01	0.00E+00	5.35E+00	1.32E+00	3.79E-01	1.03E-03	6.51E-03	7.52E+00	3.03E-02
LA-TA-03-20	2.49E-01	0.00E+00	2.54E+00	5.83E-01	2.04E-01	8.46E-04	2.93E-03	3.58E+00	1.44E-02
LA-TA-03-24	3.33E-01	0.00E+00	9.90E+00	1.09E+00	3.26E-01	8.77E-04	1.21E-02	1.17E+01	4.70E-02
LA-TA-03-26	1.71E-02	0.00E+00	4.08E-01	2.63E+00	4.26E-02	7.68E-05	1.37E-03	3.10E+00	1.25E-02
LA-TA-03-28	0.00E+00	0.00E+00	1.41E-01	2.46E-01	0.00E+00	0.00E+00	1.70E-04	3.87E-01	1.56E-03
LA-TA-03-30	7.60E-01	0.00E+00	1.01E-01	5.01E+00	1.44E+00	4.02E-03	1.20E-04	7.30E+00	2.95E-02
LA-TA-03-31	0.00E+00	0.00E+00	5.03E-03	8.76E-03	0.00E+00	0.00E+00	6.05E-06	1.38E-02	5.57E-05

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-03-40	0.00E+00	0.00E+00	7.96E-03	5.45E-02	0.00E+00	0.00E+00	9.65E-06	6.24E-02	2.52E-04
LA-TA-03-42	1.75E-05	0.00E+00	1.99E-04	3.41E-03	4.44E-05	8.41E-08	2.42E-07	3.67E-03	1.48E-05
LA-TA-21-06	1.72E-01	0.00E+00	2.19E+01	9.53E-01	2.88E-01	8.67E-04	2.63E-02	2.34E+01	9.42E-02
LA-TA-21-12	6.26E-01	0.00E+00	1.32E+02	3.31E+00	9.78E-01	2.98E-03	1.59E-01	1.37E+02	5.54E-01
LA-TA-21-13	9.64E-01	0.00E+00	0.00E+00	2.93E-01	0.00E+00	0.00E+00	0.00E+00	1.26E+00	5.07E-03
LA-TA-21-14	1.58E-04	0.00E+00	2.52E+00	4.47E+00	5.16E-05	1.21E-06	2.40E-03	7.00E+00	2.82E-02
LA-TA-21-15	9.33E-02	0.00E+00	6.94E-03	1.38E+00	2.34E-01	4.89E-04	8.25E-06	1.72E+00	6.93E-03
LA-TA-21-16	1.08E+00	0.00E+00	1.07E-01	1.06E+01	2.50E+00	5.16E-03	1.30E-04	1.42E+01	5.74E-02
LA-TA-21-40	1.37E-04	0.00E+00	3.70E-01	3.32E-01	3.63E-04	2.07E-07	5.77E-04	7.03E-01	2.83E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	7.06E-01	0.00E+00	0.00E+00	0.00E+00	7.06E-01	2.85E-03
LA-TA-21-42	1.40E-02	0.00E+00	1.20E-01	1.63E-01	1.10E-02	6.74E-06	2.02E-04	3.09E-01	1.25E-03
LA-TA-21-43	4.95E+01	0.00E+00	3.99E+00	5.09E+02	1.20E+02	5.33E-02	6.66E-03	6.82E+02	2.75E+00
LA-TA-21-44	2.38E-01	0.00E+00	8.39E-01	1.15E+02	3.02E-01	7.52E-04	1.11E-03	1.16E+02	4.67E-01
LA-TA-48-01	7.69E-02	1.89E-02	3.15E-03	1.18E-01	4.87E-01	6.21E-05	4.97E-06	6.85E-01	2.76E-03
LA-TA-49-01	9.49E+00	2.34E+00	3.88E-01	1.45E+01	6.03E+01	7.68E-03	6.13E-04	8.47E+01	3.42E-01
LA-TA-50-10	2.54E-02	0.00E+00	3.67E-03	4.57E-02	0.00E+00	0.00E+00	3.42E-06	7.48E-02	3.02E-04
LA-TA-50-11	4.85E-02	0.00E+00	3.76E-03	4.64E-01	1.02E-01	6.16E-05	5.79E-06	6.18E-01	2.49E-03
LA-TA-50-15	9.57E-02	0.00E+00	5.56E-01	3.39E-01	7.52E-02	2.44E-04	6.11E-04	1.07E+00	4.30E-03
LA-TA-50-17	1.40E+01	0.00E+00	4.51E-01	1.81E+01	4.23E-04	2.23E-05	8.36E-04	3.26E+01	1.31E-01
LA-TA-50-18	8.32E-01	0.00E+00	5.96E-02	2.96E+00	5.27E-06	6.58E-07	7.23E-05	3.85E+00	1.55E-02
LA-TA-50-19	2.66E-01	0.00E+00	2.66E-02	3.93E-01	4.51E-03	8.15E-06	5.90E-05	6.90E-01	2.78E-03
LA-TA-50-20	7.28E-03	0.00E+00	0.00E+00	9.70E-03	0.00E+00	0.00E+00	0.00E+00	1.70E-02	6.85E-05
LA-TA-50-40	4.10E-03	0.00E+00	3.59E-04	1.06E-02	4.89E-03	2.61E-05	4.09E-07	1.99E-02	8.02E-05
LA-TA-50-41	4.38E-03	0.00E+00	3.62E-04	4.68E-02	1.08E-02	4.65E-05	3.67E-07	6.23E-02	2.51E-04
LA-TA-55-19	6.78E+00	0.00E+00	4.77E-01	2.63E+01	7.35E+00	2.63E-02	2.09E-03	4.09E+01	1.65E-01
LA-TA-55-20	1.09E+02	0.00E+00	5.44E+00	6.35E+02	1.52E+02	6.58E-01	9.97E-02	9.01E+02	3.63E+00
LA-TA-55-21	9.73E-01	5.58E-06	6.25E-02	4.50E+00	1.07E+00	5.43E-03	6.28E-05	6.61E+00	2.66E-02
LA-TA-55-22	2.67E+00	0.00E+00	3.53E-01	1.58E+01	3.68E+00	1.68E-02	3.55E-04	2.25E+01	9.08E-02
LA-TA-55-23	2.51E+00	0.00E+00	2.95E-01	1.09E+01	2.67E+00	1.66E-02	2.93E-04	1.63E+01	6.58E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-24	9.47E-01	0.00E+00	4.63E-02	5.69E+00	1.32E+00	7.89E-03	4.36E-05	8.01E+00	3.23E-02
LA-TA-55-25	4.85E+00	0.00E+00	2.70E-01	2.83E+01	6.56E+00	4.04E-02	2.54E-04	4.00E+01	1.61E-01
LA-TA-55-28	1.65E+00	0.00E+00	1.50E-01	8.68E+00	2.04E+00	1.31E-02	1.42E-04	1.25E+01	5.05E-02
LA-TA-55-30	3.68E+01	5.28E-08	1.79E+00	1.42E+02	3.41E+01	9.61E-02	2.35E-03	2.15E+02	8.67E-01
LA-TA-55-32	2.98E+00	0.00E+00	1.00E+01	1.13E+01	3.45E+00	1.20E-02	1.23E-02	2.77E+01	1.12E-01
LA-TA-55-33	4.47E-01	0.00E+00	2.58E-02	1.48E+00	4.70E-01	1.68E-03	2.92E-05	2.43E+00	9.78E-03
LA-TA-55-34	4.52E+01	0.00E+00	2.39E+00	2.30E+02	5.80E+01	2.03E-01	5.48E-03	3.36E+02	1.35E+00
LA-TA-55-38	1.14E+02	0.00E+00	7.87E-01	5.08E+01	1.36E+01	4.72E-02	2.58E-03	1.79E+02	7.21E-01
LA-TA-55-39	1.20E+01	0.00E+00	5.82E-01	7.58E+01	1.69E+01	8.30E-02	5.72E-04	1.05E+02	4.24E-01
LA-TA-55-41	2.86E+02	0.00E+00	1.20E+00	9.40E+01	2.23E+01	1.04E-01	1.22E-03	4.04E+02	1.63E+00
LA-TA-55-43	1.07E-01	0.00E+00	7.90E+01	1.41E-01	4.92E-02	9.19E-04	7.68E-02	7.94E+01	3.20E-01
LA-TA-55-44	9.32E-01	0.00E+00	1.86E+02	2.62E+00	7.22E-01	2.72E-03	2.12E-01	1.91E+02	7.68E-01
LA-TA-55-48	6.87E+03	0.00E+00	7.35E+02	1.68E+04	6.24E+03	2.84E+01	8.13E-01	3.07E+04	1.24E+02
LA-TA-55-49	1.47E+01	0.00E+00	9.66E+02	3.08E+01	8.59E+00	3.32E-02	1.09E+00	1.02E+03	4.12E+00
LA-TA-55-53	6.92E+01	0.00E+00	2.00E+00	2.63E+02	6.10E+01	1.82E-01	2.22E-03	3.95E+02	1.59E+00
LA-TA-55-56	7.66E+01	0.00E+00	7.44E+01	3.80E+02	9.48E+01	4.20E-01	7.72E-02	6.26E+02	2.53E+00
LA-TA-55-60	4.15E-02	0.00E+00	1.88E-02	7.17E-02	2.53E-02	2.48E-04	2.12E-05	1.57E-01	6.34E-04
LA-TA-55-61	3.57E-02	0.00E+00	8.65E-02	1.38E-01	4.66E-02	2.41E-04	9.56E-05	3.07E-01	1.24E-03
LA-TA-55-62	9.26E-03	0.00E+00	8.22E-04	2.32E-02	1.10E-02	6.48E-05	9.18E-07	4.43E-02	1.79E-04
LA-TA-55-63	6.87E-03	0.00E+00	5.56E-04	7.44E-02	1.71E-02	6.37E-05	5.83E-07	9.89E-02	3.99E-04
LL-M001	9.43E+01	2.53E-01	2.42E+01	6.97E+01	3.13E+01	5.03E-01	2.13E-02	2.20E+02	8.85E-01
LL-T001	4.71E+02	0.00E+00	0.00E+00	5.32E+02	2.38E+02	3.90E+00	0.00E+00	1.24E+03	5.00E+00
LL-T002	4.65E+03	0.00E+00	1.93E+02	5.16E+03	2.11E+03	3.43E+01	1.70E-01	1.21E+04	4.88E+01
LL-T003	1.81E+02	0.00E+00	2.16E+01	1.05E+02	8.38E+01	1.36E+00	1.90E-02	3.91E+02	1.58E+00
LL-T004	1.15E+02	0.00E+00	4.43E+00	6.64E+01	5.28E+01	8.62E-01	3.90E-03	2.39E+02	9.62E-01
LL-T005	5.93E+02	1.10E+01	5.21E+01	2.47E+02	2.12E+02	3.19E+00	4.59E-02	1.10E+03	4.45E+00
LL-W018	5.05E-02	0.00E+00	0.00E+00	1.84E-02	4.21E-02	6.53E-04	0.00E+00	1.11E-01	4.48E-04
LL-W019	2.74E+01	0.00E+00	0.00E+00	1.43E+01	1.19E+01	1.91E-01	0.00E+00	5.36E+01	2.16E-01
LL-W034	1.01E+01	1.87E-01	9.11E-01	4.18E+00	3.51E+00	5.43E-02	8.03E-04	1.87E+01	7.55E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
MC-W001	1.26E-01	0.00E+00	0.00E+00	6.03E-02	0.00E+00	9.82E-05	0.00E+00	1.87E-01	7.53E-04
MU-W002	1.69E+00	0.00E+00	0.00E+00	5.24E-02	0.00E+00	0.00E+00	2.67E-12	1.74E+00	7.01E-03
NT-JAS-01	1.63E+02	0.00E+00	1.94E+01	9.44E+01	7.54E+01	1.22E+00	1.71E-02	3.52E+02	1.42E+00
NT-W001	2.45E+02	5.70E-03	3.88E+01	2.85E+03	1.89E+01	8.56E-02	4.58E-02	3.15E+03	1.27E+01
NT-W021	4.73E+00	0.00E+00	2.78E-01	3.21E+01	7.26E+00	4.38E-02	2.91E-04	4.43E+01	1.79E-01
OR-W201	5.67E+03	3.93E-01	8.33E+02	2.15E+03	2.11E+03	4.59E+01	4.43E+01	1.08E+04	4.36E+01
OR-W202	8.14E+02	8.18E+00	2.40E+03	5.52E+02	5.37E+02	1.47E+00	2.57E+00	4.31E+03	1.74E+01
OR-W203	1.79E+00	2.85E-01	3.44E-01	2.48E-02	1.75E+00	3.74E-03	3.65E-04	3.92E+00	1.58E-02
OR-W204	4.00E-01	1.18E-06	3.91E-01	4.22E-01	2.83E-01	0.00E+00	4.14E-04	1.50E+00	6.03E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.24E-01	0.00E+00	0.00E+00	0.00E+00	4.24E-01	1.71E-03
RF-MT0001	1.53E+03	0.00E+00	2.43E+00	1.95E+02	4.42E+01	3.37E-01	2.44E-03	1.78E+03	7.16E+00
RF-MT0002	1.18E+02	0.00E+00	1.86E-01	1.50E+01	3.39E+00	2.59E-02	1.87E-04	1.37E+02	5.51E-01
RF-MT0003	5.37E-01	0.00E+00	4.25E-02	3.43E+00	7.77E-01	5.90E-03	4.28E-05	4.79E+00	1.93E-02
RF-MT0007	1.35E+00	0.00E+00	0.00E+00	4.28E-01	9.67E-02	6.84E-04	0.00E+00	1.87E+00	7.56E-03
RF-MT0089	5.30E-03	0.00E+00	4.25E-04	3.43E-02	7.76E-03	5.90E-05	4.27E-07	4.78E-02	1.93E-04
RF-MT0090	1.34E+01	0.00E+00	6.02E-01	8.82E+01	1.98E+01	5.90E-02	6.05E-04	1.22E+02	4.92E-01
RF-MT0091	8.33E+02	0.00E+00	6.11E+01	5.89E+03	1.33E+03	4.87E+00	6.44E-02	8.12E+03	3.27E+01
RF-MT0092	1.19E+02	0.00E+00	7.70E+00	8.44E+02	1.94E+02	6.74E-01	7.73E-03	1.17E+03	4.70E+00
RF-MT0093	1.45E+02	0.00E+00	7.93E+00	9.11E+02	2.12E+02	5.74E-01	7.96E-03	1.28E+03	5.15E+00
RF-MT0097	7.27E+00	0.00E+00	3.50E-01	4.76E+01	9.66E+00	3.14E-02	3.52E-04	6.49E+01	2.62E-01
RF-MT0099	7.96E-03	0.00E+00	6.39E-04	5.15E-02	1.16E-02	8.88E-05	6.42E-07	7.17E-02	2.89E-04
RF-MT0290	1.98E+01	0.00E+00	1.58E+00	1.27E+02	2.88E+01	2.20E-01	1.59E-03	1.78E+02	7.16E-01
RF-MT-0292	2.49E+01	0.00E+00	2.00E+00	1.61E+02	3.64E+01	2.78E-01	2.01E-03	2.25E+02	9.06E-01
RF-MT-0299	2.93E+03	0.00E+00	5.12E+01	4.13E+03	9.34E+02	7.15E+00	5.15E-02	8.05E+03	3.25E+01
RF-MT0302	4.49E-02	0.00E+00	2.03E-03	1.78E-01	4.04E-02	2.78E-04	1.89E-05	2.66E-01	1.07E-03
RF-MT0320	5.37E+01	0.00E+00	2.10E+00	1.73E+02	3.92E+01	2.79E-01	2.13E-03	2.68E+02	1.08E+00
RF-MT0321	3.00E+01	0.00E+00	6.28E-01	5.58E+01	1.25E+01	7.83E-02	3.04E-03	9.89E+01	3.99E-01
RF-MT-0328	2.08E+00	0.00E+00	7.52E-02	6.06E+00	1.37E+00	1.04E-02	4.14E-04	9.58E+00	3.86E-02
RF-MT0330	2.16E+01	0.00E+00	8.25E-01	1.22E+02	2.99E+01	9.82E-02	8.29E-04	1.75E+02	7.05E-01

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT-0331	1.30E+02	0.00E+00	5.12E+00	5.39E+02	1.19E+02	5.69E-01	2.59E-02	7.92E+02	3.19E+00
RF-MT0332	1.86E-02	0.00E+00	1.49E-03	1.21E-01	2.71E-02	2.07E-04	1.50E-06	1.68E-01	6.76E-04
RF-MT-0335	1.49E+00	0.00E+00	6.86E-02	6.20E+00	1.41E+00	8.46E-03	6.11E-04	9.17E+00	3.70E-02
RF-MT0336	1.06E+02	0.00E+00	4.54E+00	4.40E+02	9.93E+01	4.96E-01	6.38E-03	6.49E+02	2.62E+00
RF-MT0337	5.96E+01	0.00E+00	2.50E+00	2.69E+02	5.97E+01	2.42E-01	6.36E-03	3.91E+02	1.58E+00
RF-MT0339	1.63E+02	0.00E+00	6.80E+00	5.89E+02	1.32E+02	8.77E-01	2.39E-02	8.91E+02	3.59E+00
RF-MT-0342	9.58E-01	0.00E+00	5.70E-02	5.45E+00	1.21E+00	6.42E-03	1.16E-04	7.67E+00	3.09E-02
RF-MT0371	3.24E+02	0.00E+00	1.32E+01	1.07E+03	2.40E+02	1.83E+00	1.46E-02	1.64E+03	6.62E+00
RF-MT-0372	1.41E+00	0.00E+00	9.29E-02	7.43E+00	1.68E+00	1.13E-02	3.33E-04	1.06E+01	4.28E-02
RF-MT0373	2.13E+01	0.00E+00	9.55E-01	1.39E+02	3.13E+01	9.35E-02	9.59E-04	1.93E+02	7.78E-01
RF-MT0374	6.91E-01	0.00E+00	3.41E-02	2.76E+00	6.23E-01	4.74E-03	3.76E-05	4.11E+00	1.66E-02
RF-MT0376	5.48E-01	0.00E+00	2.76E-02	2.75E+00	6.30E-01	3.49E-03	4.28E-05	3.95E+00	1.59E-02
RF-MT0377	3.25E+02	0.00E+00	1.59E+01	1.28E+03	2.89E+02	2.20E+00	2.62E-02	1.91E+03	7.72E+00
RF-MT0378	3.66E+00	0.00E+00	2.20E-01	1.77E+01	4.00E+00	3.05E-02	2.21E-04	2.56E+01	1.03E-01
RF-MT0419	5.87E+00	0.00E+00	2.05E-01	1.65E+01	3.74E+00	2.85E-02	2.06E-04	2.63E+01	1.06E-01
RF-MT0420	1.02E+00	0.00E+00	3.56E-02	2.87E+00	6.49E-01	4.96E-03	3.58E-05	4.57E+00	1.84E-02
RF-MT0423	8.67E+00	0.00E+00	2.89E-01	4.14E+01	9.08E+00	1.96E-02	2.91E-04	5.95E+01	2.40E-01
RF-MT0425	2.56E-01	0.00E+00	8.91E-03	7.18E-01	1.62E-01	1.24E-03	8.95E-06	1.14E+00	4.62E-03
RF-MT-0438	2.32E+00	0.00E+00	1.17E-01	1.27E+01	2.85E+00	1.23E-02	1.31E-04	1.80E+01	7.27E-02
RF-MT0440	8.42E-01	0.00E+00	4.20E-02	4.62E+00	1.06E+00	5.06E-03	2.07E-04	6.57E+00	2.65E-02
RF-MT0442	3.20E-01	0.00E+00	1.81E-02	1.58E+00	3.57E-01	1.88E-03	1.13E-04	2.28E+00	9.19E-03
RF-MT0443	3.94E+00	0.00E+00	2.98E-01	2.46E+01	5.56E+00	3.91E-02	4.58E-04	3.44E+01	1.39E-01
RF-MT0444	3.08E+01	0.00E+00	1.46E+00	1.19E+02	2.67E+01	2.03E-01	1.49E-03	1.77E+02	7.15E-01
RF-MT0480	8.60E+01	0.00E+00	4.11E+00	3.33E+02	7.52E+01	5.22E-01	6.59E-03	4.98E+02	2.01E+00
RF-MT0488	1.38E+02	0.00E+00	6.13E+00	4.94E+02	1.11E+02	8.51E-01	3.71E-02	7.49E+02	3.02E+00
RF-MT0490	6.24E-01	0.00E+00	3.56E-02	2.92E+00	6.60E-01	4.70E-03	4.70E-05	4.24E+00	1.71E-02
RF-MT-0491	4.90E-02	0.00E+00	1.63E-03	1.32E-01	2.98E-02	2.20E-04	3.64E-06	2.13E-01	8.58E-04
RF-MT0523A	3.88E+01	0.00E+00	1.29E+00	1.05E+02	2.36E+01	1.79E-01	1.56E-03	1.68E+02	6.78E-01
RF-MT0523B	3.88E+01	0.00E+00	1.29E+00	1.05E+02	2.36E+01	1.79E-01	1.56E-03	1.68E+02	6.78E-01

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0523C	3.88E+01	0.00E+00	1.29E+00	1.05E+02	2.36E+01	1.79E-01	1.56E-03	1.68E+02	6.78E-01
RF-MT0523D	3.88E+01	0.00E+00	1.29E+00	1.05E+02	2.36E+01	1.79E-01	1.56E-03	1.68E+02	6.78E-01
RF-MT0523E	3.88E+01	0.00E+00	1.29E+00	1.05E+02	2.36E+01	1.79E-01	1.56E-03	1.68E+02	6.78E-01
RF-MT0531	2.65E-03	0.00E+00	2.13E-04	1.71E-02	3.88E-03	2.96E-05	2.14E-07	2.39E-02	9.62E-05
RF-MT0532E	1.24E+02	0.00E+00	2.77E+00	2.28E+02	5.14E+01	3.82E-01	3.89E-03	4.06E+02	1.64E+00
RF-MT0532F	1.24E+02	0.00E+00	2.77E+00	2.28E+02	5.14E+01	3.82E-01	3.89E-03	4.06E+02	1.64E+00
RF-MT0541	4.51E+00	0.00E+00	3.99E-02	3.24E+00	7.30E-01	5.59E-03	4.01E-05	8.51E+00	3.43E-02
RF-MT0545	2.41E-02	0.00E+00	1.93E-03	1.56E-01	3.52E-02	2.69E-04	1.94E-06	2.18E-01	8.77E-04
RF-MT0800	9.16E+02	0.00E+00	9.58E-01	7.72E+01	1.74E+01	1.33E-01	1.45E-03	1.01E+03	4.08E+00
RF-MT0801	1.05E+02	0.00E+00	9.37E-01	7.58E+01	1.71E+01	1.30E-01	9.42E-04	1.99E+02	8.03E-01
RF-MT0803	2.37E+00	0.00E+00	2.10E-02	1.69E+00	3.82E-01	2.91E-03	2.11E-05	4.46E+00	1.80E-02
RF-MT0806	1.12E+00	0.00E+00	5.03E-02	7.36E+00	1.64E+00	4.92E-03	5.06E-05	1.02E+01	4.10E-02
RF-MT0807	1.41E+01	0.00E+00	3.88E-01	3.13E+01	7.07E+00	5.38E-02	3.90E-04	5.28E+01	2.13E-01
RF-MT0816	1.51E+00	0.00E+00	5.47E-02	4.41E+00	9.93E-01	7.62E-03	5.49E-05	6.97E+00	2.81E-02
RF-MT-0823	7.47E-01	0.00E+00	2.49E-02	2.01E+00	4.54E-01	3.45E-03	2.99E-05	3.24E+00	1.31E-02
RF-MT0827	3.81E+01	0.00E+00	1.38E+00	1.12E+02	2.52E+01	1.92E-01	1.39E-03	1.76E+02	7.10E-01
RF-MT0831	7.26E+01	0.00E+00	3.79E+00	3.02E+02	6.83E+01	5.07E-01	1.60E-02	4.46E+02	1.80E+00
RF-MT0832	4.34E+02	0.00E+00	1.37E+01	1.18E+03	2.65E+02	1.81E+00	4.72E-02	1.89E+03	7.61E+00
RF-MT0833	1.32E+02	0.00E+00	4.11E+00	3.40E+02	7.67E+01	5.43E-01	1.33E-02	5.52E+02	2.23E+00
RF-MT0855	2.27E-02	0.00E+00	1.83E-03	1.47E-01	3.32E-02	2.54E-04	1.83E-06	2.05E-01	8.27E-04
RF-MT0857	1.12E+00	0.00E+00	5.01E-02	7.34E+00	1.64E+00	4.91E-03	5.03E-05	1.01E+01	4.09E-02
RF-MT0H61	4.14E+01	0.00E+00	1.86E+00	2.72E+02	6.10E+01	1.82E-01	1.87E-03	3.76E+02	1.52E+00
RF-MT2116	4.66E+00	0.00E+00	1.48E-01	1.25E+01	2.83E+00	1.94E-02	5.06E-04	2.02E+01	8.14E-02
RF-MT3010	2.92E+01	0.00E+00	1.53E+00	1.24E+02	2.83E+01	2.08E-01	1.93E-03	1.84E+02	7.40E-01
RF-MT3011	2.17E+02	0.00E+00	9.55E+00	7.69E+02	1.74E+02	1.33E+00	1.74E-02	1.17E+03	4.72E+00
RF-MT420P	1.16E+03	0.00E+00	4.83E+01	6.32E+03	1.43E+03	4.33E+00	5.86E-02	8.95E+03	3.61E+01
RF-MT532A	3.05E+02	0.00E+00	6.83E+00	5.63E+02	1.27E+02	9.40E-01	9.59E-03	1.00E+03	4.04E+00
RF-MT532B	1.37E+03	0.00E+00	3.07E+01	2.53E+03	5.70E+02	4.23E+00	4.30E-02	4.50E+03	1.81E+01
RF-MT532C	2.74E+03	0.00E+00	6.16E+01	5.07E+03	1.14E+03	8.46E+00	8.65E-02	9.01E+03	3.63E+01

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT532D	1.74E+01	0.00E+00	3.88E-01	3.21E+01	7.22E+00	5.33E-02	5.45E-04	5.70E+01	2.30E-01
RF-TT0069	9.97E-02	0.00E+00	4.60E-03	3.71E-01	8.39E-02	6.42E-04	7.81E-05	5.60E-01	2.26E-03
RF-TT0200	4.73E+00	0.00E+00	1.86E-01	1.52E+01	3.46E+00	2.47E-02	1.88E-04	2.36E+01	9.52E-02
RF-TT0299	1.96E+01	0.00E+00	3.44E-01	2.78E+01	6.28E+00	4.78E-02	3.46E-04	5.40E+01	2.18E-01
RF-TT0300	1.60E+02	0.00E+00	9.81E+00	7.97E+02	1.81E+02	1.16E+00	1.82E-02	1.15E+03	4.63E+00
RF-TT0301	2.16E+01	0.00E+00	1.33E+00	1.09E+02	2.46E+01	1.58E-01	2.47E-03	1.56E+02	6.29E-01
RF-TT0302	1.07E+00	0.00E+00	4.83E-02	4.24E+00	9.60E-01	6.63E-03	4.47E-04	6.32E+00	2.55E-02
RF-TT0303	6.43E+00	0.00E+00	2.82E-01	2.28E+01	5.14E+00	3.92E-02	1.32E-03	3.47E+01	1.40E-01
RF-TT0310	2.19E+01	0.00E+00	1.33E+00	1.03E+02	2.39E+01	1.44E-01	1.52E-03	1.50E+02	6.04E-01
RF-TT0312	5.26E+02	0.00E+00	2.39E+01	2.24E+03	5.02E+02	3.02E+00	2.58E-02	3.29E+03	1.33E+01
RF-TT0317	3.31E-01	0.00E+00	2.60E-02	2.10E+00	4.74E-01	3.61E-03	2.61E-05	2.93E+00	1.18E-02
RF-TT0320	2.12E+02	0.00E+00	8.33E+00	6.85E+02	1.55E+02	1.11E+00	8.42E-03	1.06E+03	4.28E+00
RF-TT0330	7.55E+01	0.00E+00	2.89E+00	4.30E+02	1.04E+02	3.44E-01	2.90E-03	6.13E+02	2.47E+00
RF-TT-0331	3.76E+02	0.00E+00	1.49E+01	1.56E+03	3.46E+02	1.66E+00	7.52E-02	2.30E+03	9.27E+00
RF-TT-0334	1.64E+02	0.00E+00	1.21E+01	9.72E+02	2.19E+02	1.68E+00	1.21E-02	1.37E+03	5.51E+00
RF-TT0335	1.99E+02	0.00E+00	9.14E+00	8.26E+02	1.88E+02	1.13E+00	8.14E-02	1.22E+03	4.93E+00
RF-TT0336	1.76E+02	0.00E+00	7.58E+00	7.32E+02	1.65E+02	8.25E-01	1.06E-02	1.08E+03	4.36E+00
RF-TT0337	2.09E+02	0.00E+00	8.77E+00	9.45E+02	2.10E+02	8.51E-01	2.23E-02	1.37E+03	5.53E+00
RF-TT0338	8.88E+02	0.00E+00	3.18E+01	3.68E+03	8.18E+02	3.80E+00	4.02E-02	5.42E+03	2.19E+01
RF-TT0340	7.59E+00	0.00E+00	6.08E-01	4.90E+01	1.11E+01	8.46E-02	6.11E-04	6.83E+01	2.75E-01
RF-TT0342	5.08E+01	0.00E+00	3.04E+00	2.89E+02	6.40E+01	3.40E-01	6.16E-03	4.07E+02	1.64E+00
RF-TT0360	3.87E+00	0.00E+00	1.54E-01	1.29E+01	2.96E+00	2.01E-02	1.61E-04	1.99E+01	8.03E-02
RF-TT0368	7.74E+01	0.00E+00	3.10E+00	2.60E+02	5.93E+01	4.03E-01	3.24E-03	4.00E+02	1.61E+00
RF-TT0370	1.53E+02	0.00E+00	6.68E+00	5.78E+02	1.31E+02	8.56E-01	1.46E-02	8.69E+02	3.50E+00
RF-TT0371	3.31E+00	0.00E+00	1.35E-01	1.09E+01	2.45E+00	1.87E-02	1.48E-04	1.67E+01	6.75E-02
RF-TT0372	4.04E-01	0.00E+00	2.65E-02	2.12E+00	4.80E-01	3.24E-03	9.50E-05	3.03E+00	1.22E-02
RF-TT0374	1.26E+01	0.00E+00	6.22E-01	5.01E+01	1.13E+01	8.62E-02	6.85E-04	7.46E+01	3.01E-01
RF-TT0375A	1.31E-01	0.00E+00	1.02E-02	8.23E-01	1.86E-01	1.42E-03	1.03E-05	1.15E+00	4.64E-03
RF-TT0375B	1.31E-01	0.00E+00	1.02E-02	8.23E-01	1.86E-01	1.42E-03	1.03E-05	1.15E+00	4.64E-03

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0376	3.01E+01	0.00E+00	1.52E+00	1.51E+02	3.46E+01	1.92E-01	2.36E-03	2.18E+02	8.77E-01
RF-TT0377	1.69E+01	0.00E+00	8.25E-01	6.65E+01	1.51E+01	1.14E-01	1.36E-03	9.93E+01	4.00E-01
RF-TT0391	3.77E+00	0.00E+00	1.16E-01	1.68E+01	3.75E+00	2.00E-02	1.17E-04	2.45E+01	9.86E-02
RF-TT0392	1.33E+00	0.00E+00	7.29E-02	8.79E+00	1.98E+00	6.95E-03	7.34E-05	1.22E+01	4.91E-02
RF-TT0393	1.09E+02	0.00E+00	5.09E+00	4.09E+02	9.26E+01	7.05E-01	5.11E-03	6.16E+02	2.48E+00
RF-TT0398	2.38E+00	0.00E+00	1.34E-01	1.64E+01	3.68E+00	1.31E-02	1.35E-04	2.26E+01	9.12E-02
RF-TT0409	1.99E+00	0.00E+00	6.28E-02	8.48E+00	1.90E+00	5.04E-03	6.37E-05	1.24E+01	5.01E-02
RF-TT0412	1.99E+00	0.00E+00	6.28E-02	8.48E+00	1.90E+00	5.04E-03	6.37E-05	1.24E+01	5.01E-02
RF-TT0414	6.17E+01	0.00E+00	1.94E+00	2.63E+02	5.87E+01	1.56E-01	1.97E-03	3.85E+02	1.55E+00
RF-TT0430	1.80E-02	0.00E+00	1.45E-03	1.17E-01	2.64E-02	2.01E-04	1.46E-06	1.62E-01	6.55E-04
RF-TT0431	4.49E+00	0.00E+00	3.53E-01	2.87E+01	6.48E+00	4.78E-02	5.77E-04	4.00E+01	1.61E-01
RF-TT0438	2.67E+02	0.00E+00	1.35E+01	1.46E+03	3.29E+02	1.42E+00	1.50E-02	2.07E+03	8.36E+00
RF-TT0440	2.63E+01	0.00E+00	1.31E+00	1.44E+02	3.33E+01	1.58E-01	6.48E-03	2.05E+02	8.28E-01
RF-TT0441	1.29E+02	0.00E+00	6.13E+00	4.99E+02	1.13E+02	8.41E-01	1.08E-02	7.47E+02	3.01E+00
RF-TT0442	1.87E+01	0.00E+00	1.06E+00	9.23E+01	2.09E+01	1.10E-01	6.59E-03	1.33E+02	5.36E-01
RF-TT0443	4.00E-01	0.00E+00	3.04E-02	2.50E+00	5.64E-01	3.97E-03	4.66E-05	3.49E+00	1.41E-02
RF-TT0479	3.92E+00	0.00E+00	3.15E-01	2.53E+01	5.72E+00	4.37E-02	3.17E-04	3.52E+01	1.42E-01
RF-TT0480	2.67E+02	0.00E+00	1.27E+01	1.04E+03	2.33E+02	1.62E+00	2.04E-02	1.55E+03	6.24E+00
RF-TT0481	1.50E-01	0.00E+00	7.18E-03	5.81E-01	1.32E-01	9.14E-04	1.15E-05	8.71E-01	3.51E-03
RF-TT0483	4.83E-01	0.00E+00	3.88E-02	3.12E+00	7.05E-01	5.38E-03	1.72E-02	4.36E+00	1.76E-02
RF-TT0484	2.58E+00	0.00E+00	1.61E-01	1.29E+01	2.93E+00	2.24E-02	2.72E-04	1.86E+01	7.51E-02
RF-TT0485	2.12E-01	0.00E+00	9.92E-03	7.98E-01	1.81E-01	1.38E-03	2.88E-04	1.20E+00	4.85E-03
RF-TT0486	1.26E+00	0.00E+00	5.87E-02	4.74E+00	1.07E+00	8.15E-03	2.87E-04	7.13E+00	2.87E-02
RF-TT0487	6.31E+00	0.00E+00	2.00E-01	1.70E+01	3.84E+00	2.63E-02	6.85E-04	2.74E+01	1.10E-01
RF-TT0489	1.80E+00	0.00E+00	8.97E-02	7.23E+00	1.63E+00	1.25E-02	1.91E-04	1.08E+01	4.33E-02
RF-TT0490	9.94E+01	0.00E+00	5.70E+00	4.66E+02	1.05E+02	7.47E-01	7.51E-03	6.76E+02	2.73E+00
RF-TT0491	2.31E+00	0.00E+00	7.70E-02	6.24E+00	1.41E+00	1.04E-02	1.73E-04	1.00E+01	4.05E-02
RF-TT0492	7.77E-01	0.00E+00	4.34E-02	3.48E+00	7.89E-01	6.01E-03	4.36E-05	5.09E+00	2.05E-02
RF-TT0523A	5.23E+00	0.00E+00	1.74E-01	1.40E+01	3.18E+00	2.41E-02	2.10E-04	2.26E+01	9.12E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0523B	5.23E+00	0.00E+00	1.74E-01	1.40E+01	3.18E+00	2.41E-02	2.10E-04	2.26E+01	9.12E-02
RF-TT0523C	5.23E+00	0.00E+00	1.74E-01	1.40E+01	3.18E+00	2.41E-02	2.10E-04	2.26E+01	9.12E-02
RF-TT0523D	5.23E+00	0.00E+00	1.74E-01	1.40E+01	3.18E+00	2.41E-02	2.10E-04	2.26E+01	9.12E-02
RF-TT0523E	5.23E+00	0.00E+00	1.74E-01	1.40E+01	3.18E+00	2.41E-02	2.10E-04	2.26E+01	9.12E-02
RF-TT0532A	1.31E+02	0.00E+00	2.92E+00	2.42E+02	5.45E+01	4.04E-01	4.10E-03	4.30E+02	1.74E+00
RF-TT0532B	1.31E+02	0.00E+00	2.92E+00	2.42E+02	5.45E+01	4.04E-01	4.10E-03	4.30E+02	1.74E+00
RF-TT0541	2.17E-01	0.00E+00	1.74E-02	1.40E+00	3.17E-01	2.42E-03	1.75E-05	1.95E+00	7.88E-03
RF-TT0545	4.83E-02	0.00E+00	3.88E-03	3.12E-01	7.05E-02	5.38E-04	3.89E-06	4.34E-01	1.75E-03
RF-TT0601	1.68E+01	0.00E+00	6.68E-01	5.63E+01	1.29E+01	8.72E-02	6.99E-04	8.66E+01	3.49E-01
RF-TT0802	1.88E+03	0.00E+00	5.50E+01	4.44E+03	1.00E+03	7.62E+00	5.52E-02	7.37E+03	2.97E+01
RF-TT0809	1.54E+02	0.00E+00	4.51E+00	3.65E+02	8.22E+01	6.27E-01	4.53E-03	6.06E+02	2.45E+00
RF-TT0821	3.34E+02	0.00E+00	1.64E+01	1.43E+03	3.25E+02	1.86E+00	1.84E-01	2.11E+03	8.50E+00
RF-TT0822	3.69E+02	0.00E+00	1.28E+01	1.08E+03	2.42E+02	1.66E+00	1.95E-01	1.70E+03	6.85E+00
RF-TT0823	7.47E-01	0.00E+00	2.49E-02	2.01E+00	4.54E-01	3.45E-03	2.99E-05	3.24E+00	1.31E-02
RF-TT0824	7.69E+02	0.00E+00	3.50E+01	2.90E+03	6.54E+02	4.69E+00	9.77E-02	4.36E+03	1.76E+01
RF-TT0825	6.39E+02	0.00E+00	2.53E+01	2.18E+03	4.92E+02	3.11E+00	1.06E-01	3.34E+03	1.35E+01
RF-TT0832	4.73E+02	0.00E+00	1.50E+01	1.27E+03	2.88E+02	1.97E+00	5.14E-02	2.05E+03	8.27E+00
RF-TT0854	1.70E-01	0.00E+00	1.37E-02	1.10E+00	2.49E-01	1.90E-03	7.61E-04	1.53E+00	6.16E-03
RF-TT0886	2.41E-02	0.00E+00	1.93E-03	1.55E-01	3.52E-02	2.68E-04	1.94E-06	2.17E-01	8.73E-04
RF-TT2216	6.98E+00	0.00E+00	2.21E-01	1.89E+01	4.25E+00	2.91E-02	7.59E-04	3.04E+01	1.22E-01
RF-TT3010	3.73E+02	0.00E+00	1.96E+01	1.59E+03	3.61E+02	2.66E+00	2.47E-02	2.35E+03	9.46E+00
RF-TT3011	9.41E+02	0.00E+00	4.14E+01	3.33E+03	7.52E+02	5.74E+00	7.52E-02	5.06E+03	2.04E+01
RF-TT301U	7.82E+01	0.00E+00	4.37E+00	3.61E+02	8.30E+01	5.64E-01	4.55E-03	5.27E+02	2.13E+00
RF-TT310P	2.26E+01	0.00E+00	1.14E+00	1.21E+02	2.61E+01	1.18E-01	1.15E-03	1.71E+02	6.91E-01
RF-TT338S	6.60E-01	0.00E+00	5.21E-02	4.19E+00	9.48E-01	7.21E-03	5.23E-05	5.85E+00	2.36E-02
RF-TT390P	3.72E+00	0.00E+00	1.41E-01	2.04E+01	4.24E+00	1.80E-02	1.71E-04	2.85E+01	1.15E-01
RF-TT391P	2.05E+02	0.00E+00	6.34E+00	9.17E+02	2.04E+02	1.09E+00	6.36E-03	1.33E+03	5.37E+00
RF-TT392P	4.15E+02	0.00E+00	2.28E+01	2.75E+03	6.19E+02	2.17E+00	2.30E-02	3.80E+03	1.53E+01
RF-TT393R	6.14E+01	0.00E+00	3.88E+00	4.20E+02	9.52E+01	3.50E-01	4.07E-03	5.81E+02	2.34E+00

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT394P	7.62E+00	0.00E+00	2.40E-01	3.25E+01	6.80E+00	2.52E-02	2.48E-04	4.71E+01	1.90E-01
RF-TT395P	1.02E+01	0.00E+00	3.21E-01	4.34E+01	9.08E+00	3.37E-02	3.32E-04	6.30E+01	2.54E-01
RF-TT396P	2.55E+00	0.00E+00	8.01E-02	1.09E+01	2.27E+00	8.41E-03	8.29E-05	1.58E+01	6.35E-02
RF-TT398P	2.47E+02	0.00E+00	1.39E+01	1.70E+03	3.81E+02	1.35E+00	1.40E-02	2.34E+03	9.45E+00
RF-TT398R	2.03E+03	0.00E+00	2.58E+01	2.75E+03	6.16E+02	2.64E+00	2.59E-02	5.42E+03	2.19E+01
RF-TT411R	7.37E+01	0.00E+00	2.32E+00	3.14E+02	7.01E+01	1.86E-01	2.35E-03	4.60E+02	1.85E+00
RF-TT429R	1.55E+02	0.00E+00	4.98E-01	7.27E+01	1.59E+01	3.25E-02	5.00E-04	2.44E+02	9.84E-01
RF-TT433X	4.88E+01	0.00E+00	1.38E-01	2.09E+01	4.14E+00	1.29E-02	1.38E-04	7.40E+01	2.98E-01
RF-TT436R	3.57E+02	0.00E+00	1.99E+00	2.74E+02	6.11E+01	2.49E-01	2.00E-03	6.94E+02	2.80E+00
RF-TT454X	2.10E+01	0.00E+00	1.17E-01	1.61E+01	3.60E+00	1.47E-02	1.18E-04	4.08E+01	1.65E-01
RL-T101	1.06E+02	0.00E+00	7.12E+00	8.71E+02	1.93E+02	2.07E+00	6.27E-03	1.18E+03	4.75E+00
RL-T102	1.35E-03	0.00E+00	9.06E-05	1.12E-02	2.46E-03	2.63E-05	1.23E-06	1.51E-02	6.07E-05
RL-T103	9.56E+01	0.00E+00	8.62E+00	3.80E+02	8.36E+01	1.10E+00	7.60E-03	5.68E+02	2.29E+00
RL-T104	1.93E-03	0.00E+00	1.29E-04	1.58E-02	3.52E-03	3.77E-05	1.47E-07	2.14E-02	8.63E-05
RL-T105	7.42E-01	0.00E+00	4.89E-02	6.01E+00	1.33E+00	1.43E-02	8.79E-05	8.13E+00	3.28E-02
RL-T106	7.15E-01	0.00E+00	4.80E-02	5.87E+00	1.30E+00	1.39E-02	4.23E-05	7.94E+00	3.20E-02
RL-T107	1.97E+03	0.00E+00	2.82E+04	1.62E+04	3.58E+03	3.83E+01	2.57E+01	5.00E+04	2.02E+02
RL-T108	1.12E+00	0.00E+00	4.86E+00	9.24E+00	2.05E+00	2.19E-02	4.31E-03	1.73E+01	6.97E-02
RL-T109	1.55E+00	0.00E+00	1.00E-01	1.22E+01	2.71E+00	2.91E-02	2.34E-02	1.66E+01	6.71E-02
RL-T110	1.74E+02	0.00E+00	1.91E+01	1.40E+03	3.12E+02	3.34E+00	1.38E+00	1.91E+03	7.70E+00
RL-T112	6.99E+01	0.00E+00	8.07E+00	1.86E+02	4.12E+01	4.42E-01	7.43E-01	3.06E+02	1.23E+00
RL-T113	7.47E-02	0.00E+00	1.56E-02	6.13E-01	1.36E-01	1.46E-03	1.37E-05	8.39E-01	3.38E-03
RL-T114	1.14E+01	0.00E+00	7.61E-01	9.32E+01	2.07E+01	2.21E-01	6.71E-04	1.26E+02	5.08E-01
RL-T115	2.89E+02	0.00E+00	2.47E+01	1.22E+03	2.71E+02	3.26E+00	4.35E-01	1.81E+03	7.30E+00
RL-T116	1.86E+01	0.00E+00	1.25E+00	1.52E+02	3.38E+01	3.63E-01	5.73E-02	2.06E+02	8.31E-01
RL-T118	4.79E+01	0.00E+00	9.98E+00	1.51E+02	3.35E+01	3.60E-01	8.41E-01	2.44E+02	9.82E-01
RL-T120	1.16E+01	0.00E+00	1.05E+00	4.48E+01	9.84E+00	1.26E-01	9.24E-04	6.73E+01	2.71E-01
RL-T122	6.59E-01	0.00E+00	4.43E-02	5.40E+00	1.20E+00	1.29E-02	1.46E+00	8.76E+00	3.53E-02
RL-T123	1.94E+00	0.00E+00	1.30E-01	1.58E+01	3.52E+00	3.78E-02	5.98E-02	2.15E+01	8.66E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T125	3.86E+02	0.00E+00	3.21E+01	3.32E+02	1.69E+02	5.90E+00	2.83E-02	9.19E+02	3.70E+00
RL-T127	3.72E+02	0.00E+00	8.07E+00	9.91E+02	2.19E+02	2.35E+00	8.71E-02	1.59E+03	6.41E+00
RL-T128	5.50E-01	0.00E+00	1.96E-07	2.41E-05	5.32E-06	5.69E-08	1.73E-10	5.50E-01	2.22E-03
RL-T129	1.65E+00	0.00E+00	3.73E+01	1.36E+01	3.00E+00	3.22E-02	4.06E-02	5.57E+01	2.24E-01
RL-T130	3.51E-03	0.00E+00	2.36E-04	2.90E-02	6.40E-03	6.84E-05	8.32E-05	3.92E-02	1.58E-04
RL-T131	1.43E+00	0.00E+00	1.29E-01	5.52E+00	1.21E+00	1.55E-02	8.34E-03	8.29E+00	3.34E-02
RL-T132	3.40E+02	0.00E+00	2.27E+01	2.80E+03	6.19E+02	6.63E+00	2.65E-01	3.78E+03	1.52E+01
RL-T133	6.93E-03	0.00E+00	3.65E-04	4.59E-02	1.01E-02	9.40E-05	3.21E-07	6.33E-02	2.55E-04
RL-T134	1.47E-02	0.00E+00	9.81E-04	1.21E-01	2.66E-02	2.86E-04	8.64E-07	1.63E-01	6.56E-04
RL-T135	6.85E-02	0.00E+00	4.60E-03	5.63E-01	1.25E-01	1.34E-03	4.15E-03	7.66E-01	3.09E-03
RL-T137	1.11E+03	0.00E+00	1.00E+02	4.29E+03	9.44E+02	1.22E+01	9.47E-02	6.45E+03	2.60E+01
RL-T140	1.30E+03	0.00E+00	9.55E+01	4.15E+03	1.01E+03	1.03E+01	2.63E+01	6.59E+03	2.66E+01
RL-T143	8.17E+00	0.00E+00	5.47E-01	6.71E+01	1.49E+01	1.59E-01	3.91E-02	9.07E+01	3.66E-01
RL-T145	2.32E+01	0.00E+00	1.56E+00	1.91E+02	4.22E+01	4.53E-01	9.09E-02	2.58E+02	1.04E+00
RL-W407	6.68E+01	0.00E+00	3.33E+00	4.38E+02	9.70E+01	6.89E-01	2.93E-03	6.05E+02	2.44E+00
RL-W408	2.74E-04	0.00E+00	1.41E-05	1.77E-03	3.92E-04	3.55E-06	1.24E-08	2.45E-03	9.89E-06
RL-W415	6.05E-03	0.00E+00	3.10E-04	3.92E-02	8.67E-03	7.83E-05	2.73E-07	5.43E-02	2.19E-04
RL-W418	2.59E-02	0.00E+00	1.31E-03	1.68E-01	3.73E-02	2.92E-04	1.15E-06	2.33E-01	9.38E-04
RL-W437	2.19E+02	0.00E+00	1.09E+01	1.43E+03	3.18E+02	2.26E+00	9.64E-03	1.98E+03	7.99E+00
RL-W438	3.83E-04	0.00E+00	1.97E-05	2.48E-03	5.48E-04	4.96E-06	1.73E-08	3.43E-03	1.38E-05
RL-W439	1.20E+04	0.00E+00	1.08E+03	4.78E+04	1.05E+04	1.38E+02	9.54E-01	7.14E+04	2.88E+02
RL-W443	1.93E+02	0.00E+00	9.63E+00	1.26E+03	2.79E+02	1.99E+00	8.49E-03	1.75E+03	7.04E+00
RL-W444	1.43E+02	0.00E+00	7.15E+00	9.38E+02	2.08E+02	1.48E+00	6.30E-03	1.30E+03	5.22E+00
RL-W447	1.64E-02	0.00E+00	8.42E-04	1.06E-01	2.35E-02	2.13E-04	7.42E-07	1.46E-01	5.90E-04
RL-W448	1.21E-04	0.00E+00	6.22E-06	7.83E-04	1.73E-04	1.57E-06	5.48E-09	1.08E-03	4.37E-06
RL-W449	9.97E-01	0.00E+00	2.28E-04	2.24E-02	4.96E-03	2.85E-05	2.01E-07	1.02E+00	4.13E-03
RL-W450	1.83E-03	0.00E+00	9.37E-05	1.19E-02	2.62E-03	2.37E-05	8.26E-08	1.64E-02	6.61E-05
RL-W451	2.61E-04	0.00E+00	1.34E-05	1.68E-03	3.73E-04	3.38E-06	1.18E-08	2.33E-03	9.39E-06
RL-W452	1.14E-02	0.00E+00	5.76E-04	7.42E-02	1.64E-02	1.29E-04	5.07E-07	1.03E-01	4.13E-04

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W453	3.24E-03	0.00E+00	1.62E-04	2.13E-02	4.70E-03	3.35E-05	1.43E-07	2.94E-02	1.19E-04
RL-W454	4.53E-02	0.00E+00	2.27E-03	2.98E-01	6.58E-02	4.68E-04	2.00E-06	4.11E-01	1.66E-03
RL-W455	1.21E-02	0.00E+00	6.11E-04	7.87E-02	1.74E-02	1.37E-04	5.38E-07	1.09E-01	4.39E-04
RL-W456	1.59E+00	0.00E+00	7.99E-02	1.05E+01	2.31E+00	1.69E-02	7.04E-05	1.44E+01	5.82E-02
RL-W457	1.55E-01	0.00E+00	7.75E-03	1.02E+00	2.24E-01	1.63E-03	6.83E-06	1.40E+00	5.65E-03
RL-W458	4.90E-01	0.00E+00	3.96E-02	4.17E-01	2.30E-01	6.58E-03	3.49E-05	1.18E+00	4.75E-03
RL-W459	4.71E+00	0.00E+00	4.08E-01	1.04E+01	3.14E+00	6.53E-02	3.60E-04	1.86E+01	7.50E-02
RL-W460	2.87E-02	0.00E+00	1.44E-03	1.88E-01	4.17E-02	2.97E-04	1.27E-06	2.60E-01	1.05E-03
RL-W461	2.65E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.65E-02	1.07E-04
RL-W462	8.19E-03	0.00E+00	4.17E-04	5.33E-02	1.18E-02	9.71E-05	3.67E-07	7.37E-02	2.97E-04
RL-W463	4.21E-02	0.00E+00	2.11E-03	2.77E-01	6.12E-02	4.35E-04	1.86E-06	3.82E-01	1.54E-03
RL-W464	1.95E-02	0.00E+00	9.69E-04	1.27E-01	2.81E-02	2.01E-04	8.54E-07	1.76E-01	7.10E-04
RL-W465	1.30E-01	0.00E+00	6.57E-03	8.48E-01	1.88E-01	1.45E-03	5.79E-06	1.17E+00	4.73E-03
RL-W466	1.78E+00	0.00E+00	8.94E-02	1.17E+01	2.58E+00	1.93E-02	7.88E-05	1.61E+01	6.49E-02
RL-W467	9.10E-02	0.00E+00	4.60E-03	5.93E-01	1.31E-01	1.06E-03	4.05E-06	8.20E-01	3.31E-03
RL-W468	4.67E-04	0.00E+00	2.37E-05	3.04E-03	6.72E-04	5.54E-06	2.09E-08	4.20E-03	1.69E-05
RL-W469	1.89E-01	0.00E+00	9.52E-03	1.23E+00	2.74E-01	2.04E-03	8.39E-06	1.71E+00	6.89E-03
RL-W470	5.35E+00	0.00E+00	4.43E-01	4.58E+00	2.34E+00	8.20E-02	3.90E-04	1.27E+01	5.13E-02
RL-W474	2.03E-01	0.00E+00	4.89E-02	1.05E-02	8.85E-03	0.00E+00	4.31E-05	2.71E-01	1.09E-03
RL-W476	3.42E-01	0.00E+00	1.76E-02	2.29E+00	5.09E-01	3.70E-03	1.55E-05	3.16E+00	1.27E-02
RL-W480	5.58E-02	0.00E+00	2.82E-03	3.63E-01	8.06E-02	6.32E-04	2.48E-06	5.03E-01	2.03E-03
RL-W481	8.76E-02	0.00E+00	4.43E-03	5.70E-01	1.26E-01	9.92E-04	3.90E-06	7.88E-01	3.18E-03
RL-W482	1.16E+02	0.00E+00	1.47E+00	7.26E-02	1.34E-01	1.32E+00	1.30E-03	1.18E+02	4.76E-01
RL-W483	8.69E+00	0.00E+00	1.14E-01	4.70E-03	9.50E-03	9.82E-02	1.01E-04	8.82E+00	3.56E-02
RL-W484	3.68E-02	0.00E+00	9.20E-04	6.56E-02	1.55E-02	8.15E-05	8.11E-07	1.19E-01	4.79E-04
RL-W485	2.15E-03	0.00E+00	1.30E-04	7.10E-03	1.68E-03	0.00E+00	1.15E-07	1.11E-02	4.46E-05
RL-W486	9.10E-04	0.00E+00	5.50E-05	3.00E-03	7.07E-04	0.00E+00	4.84E-08	4.67E-03	1.88E-05
RL-W487	1.48E-01	0.00E+00	7.06E-03	4.29E-01	1.17E-01	7.57E-04	6.22E-06	7.02E-01	2.83E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W489	9.03E-02	0.00E+00	6.65E-03	5.56E-01	1.25E-01	1.22E-03	5.86E-06	7.77E-01	3.13E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	3.35E-02	0.00E+00	5.61E-03	5.82E-02	1.27E-02	4.44E-04	4.95E-06	1.10E-01	4.44E-04
RL-W492	1.93E-03	0.00E+00	1.38E-04	1.17E-02	2.61E-03	2.55E-05	1.22E-07	1.63E-02	6.58E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.66E+01	0.00E+00	8.01E+00	2.94E-01	2.49E-01	1.02E+00	7.06E-03	8.51E+01	3.43E-01
RL-W495	1.39E+00	0.00E+00	2.18E-02	2.82E-03	2.22E-03	1.86E-02	1.92E-05	1.41E+00	5.70E-03
RL-W496	9.00E+00	0.00E+00	2.51E-01	9.26E-03	7.37E-03	1.21E-01	2.21E-04	9.27E+00	3.74E-02
RL-W497	3.75E-01	0.00E+00	4.95E-02	5.56E-01	2.50E-01	3.16E-03	4.36E-05	1.23E+00	4.96E-03
RL-W498	1.46E+00	0.00E+00	7.35E-02	9.50E+00	2.11E+00	1.65E-02	6.48E-05	1.31E+01	5.30E-02
RL-W499	1.31E-05	0.00E+00	6.60E-07	8.51E-05	1.89E-05	1.48E-07	5.81E-10	1.18E-04	4.75E-07
RL-W500	9.30E-04	0.00E+00	8.19E-05	3.47E-03	7.65E-04	1.04E-05	7.22E-08	5.25E-03	2.12E-05
RL-W501	3.85E+01	0.00E+00	1.83E+00	1.12E+02	3.03E+01	1.96E-01	1.61E-03	1.82E+02	7.34E-01
RL-W502	6.97E-03	0.00E+00	3.53E-04	4.54E-02	1.00E-02	7.89E-05	3.11E-07	6.28E-02	2.53E-04
RL-W503	4.03E-01	0.00E+00	3.62E-02	1.60E+00	3.52E-01	4.64E-03	3.19E-05	2.39E+00	9.65E-03
RL-W504	1.48E-01	0.00E+00	7.06E-03	4.29E-01	1.17E-01	7.57E-04	6.22E-06	7.02E-01	2.83E-03
RL-W505	7.00E-03	0.00E+00	3.70E-04	4.64E-02	1.02E-02	9.50E-05	3.26E-07	6.40E-02	2.58E-04
RL-W506	2.53E-03	0.00E+00	1.46E-04	1.52E-02	3.37E-03	2.85E-05	1.28E-07	2.13E-02	8.58E-05
RL-W507	2.52E-04	0.00E+00	1.27E-05	1.64E-03	3.63E-04	2.85E-06	1.12E-08	2.27E-03	9.15E-06
RL-W508	4.63E+00	0.00E+00	4.17E-01	1.78E+01	3.92E+00	5.06E-02	3.67E-04	2.68E+01	1.08E-01
RL-W509	4.56E+01	0.00E+00	3.33E+00	1.45E+02	3.53E+01	3.62E-01	2.93E-03	2.30E+02	9.26E-01
RL-W510	3.84E+00	0.00E+00	3.41E-01	1.44E+01	3.18E+00	4.31E-02	3.01E-04	2.18E+01	8.79E-02
RL-W511	3.91E+02	0.00E+00	1.65E+01	1.93E+03	4.19E+02	2.35E+00	1.49E-02	2.76E+03	1.11E+01
RL-W512	3.42E+02	0.00E+00	1.11E+01	1.17E+03	2.87E+02	1.20E+00	9.79E-03	1.81E+03	7.28E+00
RL-W513	3.65E+04	0.00E+00	4.51E+03	1.90E+04	9.36E+03	1.91E+02	3.98E+00	6.94E+04	2.80E+02
RL-W514	1.03E-03	0.00E+00	5.18E-05	6.74E-03	1.50E-03	1.11E-05	4.56E-08	9.32E-03	3.76E-05
RL-W515	4.03E-02	0.00E+00	2.03E-03	2.63E-01	5.80E-02	4.55E-04	1.79E-06	3.63E-01	1.46E-03
RL-W516	5.59E-02	0.00E+00	2.82E-03	3.63E-01	8.06E-02	6.32E-04	2.49E-06	5.03E-01	2.03E-03
RL-W517	4.98E-10	0.00E+00	2.52E-11	3.24E-09	7.15E-10	5.90E-12	2.22E-14	4.47E-09	1.80E-11

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W518	1.41E+00	0.00E+00	1.06E-01	4.64E+00	1.11E+00	1.27E-02	9.36E-05	7.26E+00	2.93E-02
RL-W519	2.51E-01	0.00E+00	1.26E-02	1.64E+00	3.63E-01	2.68E-03	1.11E-05	2.27E+00	9.15E-03
RL-W520	2.77E-02	0.00E+00	1.42E-03	1.80E-01	3.98E-02	3.44E-04	1.25E-06	2.49E-01	1.01E-03
RL-W521	5.16E-04	0.00E+00	2.60E-05	3.36E-03	7.44E-04	5.85E-06	2.29E-08	4.64E-03	1.87E-05
RL-W522	1.08E+01	0.00E+00	9.66E-01	2.22E+01	6.30E+00	8.46E-02	8.52E-04	4.03E+01	1.62E-01
RL-W523	3.24E+00	0.00E+00	3.67E-01	1.47E+00	8.88E-01	1.68E-02	3.24E-04	5.97E+00	2.41E-02
RL-W524	1.34E+01	0.00E+00	1.41E+00	1.35E+01	5.20E+00	7.99E-02	1.24E-03	3.36E+01	1.35E-01
RL-W525	1.07E+00	0.00E+00	9.52E-02	1.60E+00	5.26E-01	6.27E-03	8.39E-05	3.29E+00	1.33E-02
RL-W526	4.04E+00	0.00E+00	3.44E-01	1.71E+01	3.80E+00	4.56E-02	3.03E-04	2.53E+01	1.02E-01
RL-W527	4.43E-01	0.00E+00	4.98E-02	1.81E+00	4.27E-01	5.33E-03	4.39E-05	2.73E+00	1.10E-02
RL-W528	1.98E+02	0.00E+00	2.12E+01	5.77E+01	5.49E+01	8.15E-01	1.86E-02	3.32E+02	1.34E+00
RL-W529	1.65E-01	0.00E+00	1.49E-02	6.37E-01	1.40E-01	1.80E-03	1.31E-05	9.57E-01	3.86E-03
RL-W530	1.94E+00	0.00E+00	1.72E-01	7.28E+00	1.60E+00	2.18E-02	1.52E-04	1.10E+01	4.43E-02
RL-W531	1.16E+02	0.00E+00	1.73E+01	3.15E+01	2.25E+01	5.80E-01	1.53E-02	1.87E+02	7.55E-01
RL-W532	3.72E-01	0.00E+00	1.88E-02	2.43E+00	5.37E-01	4.21E-03	1.66E-05	3.36E+00	1.35E-02
RL-W533	1.80E-01	0.00E+00	1.62E-02	6.95E-01	1.52E-01	1.95E-03	1.43E-05	1.04E+00	4.21E-03
RL-W534	1.04E-05	0.00E+00	5.24E-07	6.78E-05	1.51E-05	1.18E-07	4.62E-10	9.38E-05	3.78E-07
RL-W535	5.44E+01	0.00E+00	5.18E+00	8.69E+01	2.64E+01	3.58E-01	4.56E-03	1.73E+02	6.97E-01
RL-W536	1.07E+00	0.00E+00	6.97E-02	3.02E+00	6.79E-01	8.20E-03	6.47E-05	4.83E+00	1.95E-02
RL-W537	3.63E+01	0.00E+00	1.57E+00	1.85E+02	4.03E+01	2.29E-01	1.41E-03	2.63E+02	1.06E+00
RL-W538	1.32E-04	0.00E+00	6.65E-06	8.61E-04	1.91E-04	1.49E-06	5.86E-09	1.19E-03	4.80E-06
RL-W539	1.47E-02	0.00E+00	7.49E-04	9.52E-02	2.11E-02	1.82E-04	6.60E-07	1.32E-01	5.31E-04
RL-W540	2.85E+01	0.00E+00	3.30E+00	3.42E+01	1.17E+01	1.74E-01	2.91E-03	7.78E+01	3.14E-01
RL-W541	4.24E-02	0.00E+00	2.16E-03	2.76E-01	6.10E-02	5.12E-04	1.91E-06	3.81E-01	1.54E-03
RL-W542	1.97E+00	0.00E+00	1.61E-01	6.98E+00	1.60E+00	2.10E-02	1.42E-04	1.07E+01	4.32E-02
RL-W543	6.20E-03	0.00E+00	3.13E-04	4.04E-02	8.95E-03	7.05E-05	2.75E-07	5.59E-02	2.25E-04
RL-W544	1.40E-01	0.00E+00	1.28E-02	4.60E-01	1.14E-01	1.40E-03	1.12E-05	7.27E-01	2.93E-03
RL-W545	3.72E-02	0.00E+00	1.88E-03	2.42E-01	5.36E-02	4.20E-04	1.65E-06	3.35E-01	1.35E-03
RL-W546	1.63E-03	0.00E+00	8.22E-05	1.07E-02	2.35E-03	1.84E-05	7.24E-08	1.47E-02	5.93E-05

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W547	4.16E-05	0.00E+00	2.10E-06	2.71E-04	6.00E-05	4.70E-07	1.85E-09	3.75E-04	1.51E-06
RL-W548	3.60E-05	0.00E+00	1.82E-06	2.34E-04	5.18E-05	4.21E-07	1.61E-09	3.24E-04	1.31E-06
RL-W549	7.15E+00	0.00E+00	7.32E-01	1.21E+01	3.56E+00	5.33E-02	6.45E-04	2.35E+01	9.47E-02
RL-W550	3.24E+01	0.00E+00	1.39E+00	1.63E+02	3.56E+01	2.01E-01	1.24E-03	2.33E+02	9.38E-01
RL-W551	5.76E+01	0.00E+00	2.05E+00	1.84E+02	4.64E+01	2.14E-01	1.81E-03	2.90E+02	1.17E+00
RL-W552	2.23E-02	0.00E+00	1.13E-03	1.45E-01	3.21E-02	2.67E-04	1.00E-06	2.01E-01	8.10E-04
RL-W553	1.98E-03	0.00E+00	1.07E-04	1.29E-02	2.86E-03	3.37E-05	9.43E-08	1.79E-02	7.21E-05
RL-W554	3.15E-02	0.00E+00	1.59E-03	2.05E-01	4.54E-02	3.56E-04	1.40E-06	2.84E-01	1.14E-03
RL-W555	1.45E-02	0.00E+00	7.32E-04	9.45E-02	2.09E-02	1.64E-04	6.45E-07	1.31E-01	5.26E-04
RL-W563	2.08E-01	0.00E+00	1.83E-02	7.83E-01	1.72E-01	2.24E-03	1.61E-05	1.18E+00	4.77E-03
RL-W564	1.35E-01	0.00E+00	1.22E-02	5.07E-01	1.11E-01	1.72E-03	1.07E-05	7.65E-01	3.09E-03
RL-W565	1.34E-02	0.00E+00	6.83E-04	8.75E-02	1.94E-02	1.59E-04	6.02E-07	1.21E-01	4.88E-04
RL-W566	1.97E-01	0.00E+00	1.00E-02	1.28E+00	2.85E-01	2.27E-03	8.82E-06	1.78E+00	7.16E-03
RL-W567	1.37E+01	0.00E+00	2.56E-01	3.95E-02	3.17E-02	1.92E-01	2.25E-04	1.40E+01	5.64E-02
RL-W568	2.63E+02	0.00E+00	5.38E+00	1.87E+00	1.48E+00	3.97E+00	4.74E-03	2.72E+02	1.10E+00
RL-W569	2.16E-01	0.00E+00	4.05E-03	6.24E-04	5.02E-05	3.04E-03	3.57E-06	2.21E-01	8.91E-04
RL-W570	1.39E-02	0.00E+00	7.09E-04	9.28E-02	2.05E-02	1.50E-04	6.25E-07	1.28E-01	5.15E-04
RL-W571	4.44E+01	0.00E+00	2.41E+00	7.53E+00	3.74E+00	6.06E-01	2.12E-03	5.81E+01	2.34E-01
RL-W572	3.86E-02	0.00E+00	7.20E-04	4.05E-03	8.95E-05	5.43E-04	6.35E-07	4.34E-02	1.75E-04
RL-W573	4.97E+02	0.00E+00	9.23E+00	2.22E+00	1.65E+00	6.89E+00	8.13E-03	5.10E+02	2.06E+00
RL-W574	2.14E+03	0.00E+00	3.99E+01	8.48E+00	6.12E+00	3.01E+01	3.52E-02	2.19E+03	8.83E+00
RL-W575	1.39E+04	0.00E+00	2.69E+02	8.11E+01	4.89E+01	1.89E+02	2.37E-01	1.43E+04	5.77E+01
RL-W576	1.00E+03	0.00E+00	1.88E+01	4.13E+00	2.95E+00	1.42E+01	1.66E-02	1.03E+03	4.15E+00
RL-W579	8.50E-02	0.00E+00	4.95E-04	2.07E-02	4.59E-03	4.99E-05	4.36E-07	1.11E-01	4.47E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.65E-01	2.68E-02	0.00E+00	0.00E+00	1.92E-01	7.74E-04
RL-W581	9.02E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.02E-01	3.64E-03
RL-W582	5.90E-03	0.00E+00	4.20E-04	5.30E-03	2.72E-03	8.09E-06	3.70E-07	1.43E-02	5.78E-05
RL-W583	4.56E-03	0.00E+00	2.28E-04	2.99E-02	6.62E-03	4.71E-05	2.01E-07	4.13E-02	1.66E-04
RL-W584	9.07E-02	0.00E+00	1.50E-02	1.74E-01	8.48E-02	2.37E-04	1.32E-05	3.65E-01	1.47E-03

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W585	5.39E-01	0.00E+00	7.96E-02	1.02E+00	5.15E-01	7.21E-03	7.01E-05	2.15E+00	8.67E-03
RL-W586	7.19E-05	0.00E+00	3.59E-06	4.72E-04	1.04E-04	7.42E-07	3.16E-09	6.52E-04	2.63E-06
RL-W587	1.54E-03	0.00E+00	7.75E-05	1.01E-02	2.23E-03	1.67E-05	6.83E-08	1.39E-02	5.61E-05
RL-W588	6.35E-02	0.00E+00	1.26E-02	1.47E-01	7.14E-02	1.99E-04	1.11E-05	2.95E-01	1.19E-03
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	1.95E+00	0.00E+00	2.69E-01	1.14E-02	2.01E-02	2.61E-02	2.37E-04	2.25E+00	9.07E-03
RL-W591	1.11E+01	0.00E+00	3.04E-01	1.40E-02	2.60E-02	1.58E-01	2.68E-04	1.15E+01	4.62E-02
RL-W592	4.91E+01	0.00E+00	3.33E+00	6.51E-01	8.40E-01	6.37E-01	2.93E-03	5.39E+01	2.17E-01
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.35E-02	3.94E-02	0.00E+00	0.00E+00	6.29E-02	2.54E-04
RL-W594	4.42E+01	0.00E+00	5.99E-01	2.91E-02	5.33E-02	1.59E-01	5.28E-04	4.49E+01	1.81E-01
RL-W595	1.17E-01	0.00E+00	6.25E-02	1.99E-02	3.88E-02	1.58E-03	5.51E-05	2.38E-01	9.60E-04
RL-W596	3.78E-02	0.00E+00	4.86E-03	2.05E-04	3.64E-04	4.74E-04	4.28E-06	4.32E-02	1.74E-04
RL-W597	6.95E+01	0.00E+00	2.14E+00	3.97E-01	6.60E-01	8.83E-01	1.88E-03	7.27E+01	2.93E-01
RL-W598	7.35E+01	0.00E+00	1.26E+01	5.54E-01	8.23E-01	9.14E-01	1.11E-02	8.75E+01	3.53E-01
RL-W599	3.72E+00	0.00E+00	1.02E-01	4.68E-03	8.67E-03	5.27E-02	8.98E-05	3.84E+00	1.55E-02
RL-W600	2.11E-07	0.00E+00	1.06E-08	1.38E-06	3.07E-07	2.18E-09	9.31E-12	1.91E-06	7.71E-09
RL-W601	1.07E-03	0.00E+00	5.79E-05	7.01E-03	1.55E-03	1.83E-05	5.10E-08	9.69E-03	3.91E-05
RL-W602	9.34E-01	0.00E+00	4.75E-02	6.07E+00	1.35E+00	1.11E-02	4.18E-05	8.40E+00	3.39E-02
RL-W603	5.38E+00	0.00E+00	2.74E-01	3.50E+01	7.76E+00	6.37E-02	2.41E-04	4.85E+01	1.95E-01
RL-W604	1.26E-02	0.00E+00	7.18E-04	1.70E-02	8.36E-03	7.57E-05	6.32E-07	3.87E-02	1.56E-04
RL-W605	2.88E-03	0.00E+00	1.56E-04	1.88E-02	4.17E-03	4.91E-05	1.37E-07	2.60E-02	1.05E-04
RL-W606	1.16E-03	0.00E+00	6.28E-05	7.59E-03	1.68E-03	1.98E-05	5.53E-08	1.05E-02	4.23E-05
RL-W607	2.13E-03	0.00E+00	1.22E-04	2.88E-03	1.42E-03	1.28E-05	1.07E-07	6.55E-03	2.64E-05
RL-W608	2.55E-02	0.00E+00	4.72E-03	3.74E-03	4.59E-03	1.96E-04	4.16E-06	3.85E-02	1.55E-04
RL-W610	5.04E+00	0.00E+00	2.52E-01	3.31E+01	7.32E+00	5.21E-02	2.22E-04	4.57E+01	1.84E-01
RL-W612	1.19E-02	0.00E+00	6.11E-04	8.02E-02	1.78E-02	1.23E-04	5.38E-07	1.11E-01	4.46E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.37E-01	0.00E+00	0.00E+00	0.00E+00	3.37E-01	1.36E-03
RL-W622	1.99E-04	0.00E+00	9.95E-06	1.30E-03	2.88E-04	2.05E-06	8.77E-09	1.80E-03	7.26E-06
RL-W625	6.92E-03	0.00E+00	1.51E-03	6.66E-03	6.51E-03	1.11E-04	1.33E-06	2.16E-02	8.71E-05

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W626	3.72E-01	0.00E+00	3.44E-02	2.61E-01	1.55E-01	1.94E-03	3.03E-05	8.22E-01	3.32E-03
RL-W627	1.75E-03	0.00E+00	4.60E-05	1.23E-06	0.00E+00	2.31E-05	4.05E-08	1.80E-03	7.25E-06
RL-W628	5.74E-04	0.00E+00	2.89E-05	3.76E-03	8.32E-04	6.21E-06	2.55E-08	5.20E-03	2.10E-05
RL-W629	3.89E-05	0.00E+00	1.99E-06	2.53E-04	5.59E-05	4.83E-07	1.75E-09	3.50E-04	1.41E-06
RL-W630	4.28E-01	0.00E+00	3.70E-02	2.93E+00	6.74E-01	5.22E-03	3.26E-05	4.07E+00	1.64E-02
RL-W631	6.90E-03	0.00E+00	3.73E-04	4.49E-02	9.93E-03	1.18E-04	3.29E-07	6.21E-02	2.50E-04
RL-W632	3.04E+00	0.00E+00	5.03E-02	5.93E+00	1.94E+00	3.91E-02	4.44E-05	1.10E+01	4.42E-02
RL-W633	7.26E-03	0.00E+00	2.92E-04	9.32E-04	8.18E-04	4.81E-05	2.58E-07	9.31E-03	3.75E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	1.02E-02	0.00E+00	0.00E+00	0.00E+00	1.02E-02	4.09E-05
RL-W635	4.34E+01	0.00E+00	9.87E+00	4.32E+00	6.42E+00	4.86E-01	8.69E-03	6.40E+01	2.58E-01
RL-W636	4.43E-01	0.00E+00	1.86E-02	5.64E-02	4.97E-02	2.95E-03	1.64E-05	5.68E-01	2.29E-03
RL-W637	1.05E-03	0.00E+00	4.75E-04	6.35E-04	6.20E-04	1.06E-05	4.18E-07	2.78E-03	1.12E-05
RL-W638	4.63E-02	0.00E+00	4.83E-03	6.22E-03	5.82E-03	3.95E-04	4.26E-06	6.32E-02	2.55E-04
RL-W639	2.44E-03	0.00E+00	1.24E-04	1.59E-02	3.52E-03	2.76E-05	1.09E-07	2.20E-02	8.88E-05
RL-W640	8.21E-02	0.00E+00	4.11E-03	5.37E-01	1.19E-01	8.88E-04	3.62E-06	7.42E-01	2.99E-03
RL-W641	2.50E+00	0.00E+00	9.03E-01	2.58E+00	1.05E+00	1.43E-02	7.96E-04	7.04E+00	2.84E-02
RL-W642	4.89E-02	0.00E+00	9.37E-05	3.15E-02	1.59E-04	6.16E-06	8.26E-08	8.06E-02	3.25E-04
RL-W643	7.71E-01	0.00E+00	2.78E-01	7.94E-01	3.25E-01	4.39E-03	2.45E-04	2.17E+00	8.74E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.47E-02	0.00E+00	0.00E+00	0.00E+00	5.47E-02	2.20E-04
RL-W645	1.87E-02	0.00E+00	1.25E-03	1.08E-01	2.51E-02	2.40E-04	1.10E-06	1.53E-01	6.15E-04
RL-W646	1.70E-02	0.00E+00	1.12E-03	2.57E-02	1.24E-02	1.16E-04	9.84E-07	5.62E-02	2.27E-04
RL-W647	4.79E-02	0.00E+00	1.67E-01	1.10E-01	1.72E-02	3.90E-04	1.47E-04	3.42E-01	1.38E-03
RL-W648	8.48E-04	0.00E+00	2.85E-04	5.98E-05	1.17E-04	1.25E-05	2.51E-07	1.31E-03	5.29E-06
RL-W649	3.12E-03	0.00E+00	1.05E-03	2.20E-04	4.30E-04	4.59E-05	9.26E-07	4.82E-03	1.94E-05
RL-W653	1.48E-04	0.00E+00	7.52E-06	9.62E-04	2.12E-04	1.75E-06	6.63E-09	1.33E-03	5.36E-06
RL-W654	8.13E-04	0.00E+00	4.11E-05	5.30E-03	1.17E-03	9.19E-06	3.62E-08	7.32E-03	2.95E-05
RL-W655	2.00E+02	0.00E+00	9.72E+00	2.10E-01	4.93E-01	2.45E+00	8.57E-03	2.11E+02	8.49E-01
RL-W656	8.38E+02	0.00E+00	4.37E+00	4.94E-01	5.07E-01	1.17E+01	3.85E-03	8.43E+02	3.40E+00
RL-W657	4.28E+02	0.00E+00	6.45E+00	2.43E-01	4.82E-01	5.18E+00	5.69E-03	4.35E+02	1.75E+00

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W659	5.18E+01	0.00E+00	1.46E+00	4.68E-02	5.77E-02	5.85E-01	1.28E-03	5.33E+01	2.15E-01
RL-W660	2.84E+02	0.00E+00	1.75E+01	8.63E-01	1.53E+00	3.34E+00	1.54E-02	3.04E+02	1.23E+00
RL-W661	3.00E+00	0.00E+00	2.19E-02	4.16E-04	3.77E-03	4.05E-02	1.93E-05	3.03E+00	1.22E-02
RL-W662	9.45E-02	0.00E+00	1.31E-03	1.07E-04	1.90E-04	8.30E-04	1.15E-06	9.61E-02	3.88E-04
RL-W665	1.16E+03	0.00E+00	1.04E+02	1.30E+00	1.74E+00	1.65E+01	9.20E-02	1.27E+03	5.12E+00
RL-W666	2.08E+01	0.00E+00	2.56E-01	5.47E-02	5.72E-02	2.39E-01	2.25E-04	2.12E+01	8.53E-02
RL-W668	1.98E+00	0.00E+00	8.04E-03	1.44E-01	4.07E-02	5.64E-04	7.09E-06	2.17E+00	8.76E-03
RL-W669	5.78E-01	0.00E+00	2.09E-01	5.95E-01	2.43E-01	3.29E-03	1.84E-04	1.63E+00	6.55E-03
RL-W670	3.65E-02	0.00E+00	1.48E-04	2.67E-03	7.53E-04	1.04E-05	1.31E-07	4.01E-02	1.62E-04
RL-W671	5.96E+00	0.00E+00	7.61E-02	4.89E-03	5.06E-03	3.43E-02	6.71E-05	6.04E+00	2.44E-02
RL-W672	4.05E+01	0.00E+00	5.18E-01	3.34E-02	3.43E-02	2.33E-01	4.56E-04	4.11E+01	1.66E-01
RL-W673	3.90E+01	0.00E+00	4.98E-01	3.23E-02	3.31E-02	2.25E-01	4.39E-04	3.96E+01	1.60E-01
RL-W674	1.31E-01	0.00E+00	2.23E-02	1.12E+01	9.64E-02	1.57E-03	1.96E-05	1.14E+01	4.60E-02
RL-W675	4.90E-01	0.00E+00	1.23E-01	1.30E-01	1.12E-01	3.82E-03	1.08E-04	8.55E-01	3.45E-03
RL-W676	1.88E-02	0.00E+00	7.38E-04	1.46E-01	2.12E-03	1.13E-04	6.50E-07	1.68E-01	6.77E-04
RL-W677	4.35E+01	0.00E+00	1.83E+00	5.71E+00	4.94E+00	2.73E-01	1.61E-03	5.60E+01	2.26E-01
RL-W678	1.38E-01	0.00E+00	1.53E-02	5.14E-02	4.50E-02	2.14E-03	1.35E-05	2.50E-01	1.01E-03
RL-W679	8.63E-01	0.00E+00	3.41E-02	1.11E-01	9.70E-02	5.48E-03	3.01E-05	1.11E+00	4.46E-03
RL-W680	1.94E-04	0.00E+00	4.80E-05	1.73E-05	3.10E-05	2.36E-06	4.23E-08	2.91E-04	1.17E-06
RL-W681	1.19E-04	0.00E+00	1.95E-05	4.65E-04	2.30E-04	1.96E-06	1.72E-08	8.33E-04	3.36E-06
RL-W685	3.46E-01	0.00E+00	1.73E-02	2.27E+00	5.02E-01	3.57E-03	1.53E-05	3.13E+00	1.26E-02
RL-W689	8.96E-03	0.00E+00	2.08E-04	3.85E-04	0.00E+00	3.43E-06	1.83E-07	9.55E-03	3.85E-05
RL-W690	3.01E-01	0.00E+00	1.53E-02	2.02E+00	4.46E-01	3.11E-03	1.35E-05	2.78E+00	1.12E-02
RL-W691	6.98E-03	0.00E+00	3.56E-04	4.68E-02	1.03E-02	7.21E-05	3.14E-07	6.45E-02	2.60E-04
RL-W692	2.76E-01	0.00E+00	1.41E-02	1.85E+00	4.09E-01	2.85E-03	1.24E-05	2.55E+00	1.03E-02
RL-W693	3.41E-01	0.00E+00	1.74E-02	2.29E+00	5.07E-01	3.52E-03	1.53E-05	3.16E+00	1.27E-02
RL-W694	3.59E+00	0.00E+00	1.83E-01	2.42E+01	5.31E+00	3.70E-02	1.61E-04	3.33E+01	1.34E-01
RL-W695	2.97E-03	0.00E+00	0.00E+00	2.38E-03	0.00E+00	0.00E+00	0.00E+00	5.35E-03	2.16E-05
RL-W696	3.86E-03	0.00E+00	6.65E-04	2.90E-03	2.84E-03	5.08E-05	5.86E-07	1.03E-02	4.14E-05

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W697	8.94E-01	0.00E+00	1.41E+00	6.90E-03	9.41E-04	0.00E+00	1.24E-03	2.31E+00	9.32E-03
RL-W698	7.75E-02	0.00E+00	0.00E+00	3.28E-05	0.00E+00	0.00E+00	0.00E+00	7.75E-02	3.13E-04
RL-W699	1.72E-02	0.00E+00	9.37E-05	2.19E-03	2.56E-04	2.14E-04	8.26E-08	1.98E-02	7.97E-05
RL-W700	4.88E-03	0.00E+00	2.46E-04	3.18E-02	7.03E-03	5.54E-05	2.17E-07	4.39E-02	1.77E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	1.92E-01	0.00E+00	6.94E-02	1.98E-01	8.11E-02	1.10E-03	6.12E-05	5.41E-01	2.18E-03
RL-W705	1.24E-03	0.00E+00	6.39E-05	8.32E-03	1.85E-03	1.35E-05	5.64E-08	1.15E-02	4.63E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	4.44E-02	0.00E+00	2.27E-03	2.97E-01	6.57E-02	4.79E-04	2.00E-06	4.09E-01	1.65E-03
RL-W708	6.71E-03	0.00E+00	3.44E-04	4.50E-02	9.93E-03	7.26E-05	3.03E-07	6.20E-02	2.50E-04
RL-W709	2.32E+00	0.00E+00	1.19E-01	1.55E+01	3.43E+00	2.51E-02	1.05E-04	2.14E+01	8.63E-02
RL-W710	1.38E-04	0.00E+00	7.09E-06	9.28E-04	2.05E-04	1.50E-06	6.25E-09	1.28E-03	5.15E-06
RL-W711	4.32E-02	0.00E+00	2.21E-03	2.90E-01	6.40E-02	4.67E-04	1.95E-06	3.99E-01	1.61E-03
RL-W712	5.59E-02	0.00E+00	2.86E-03	3.74E-01	8.28E-02	6.06E-04	2.52E-06	5.16E-01	2.08E-03
RL-W713	4.83E-02	0.00E+00	2.47E-03	3.23E-01	7.16E-02	5.22E-04	2.18E-06	4.45E-01	1.79E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	8.34E-04	0.00E+00	4.17E-05	5.47E-03	1.21E-03	8.62E-06	3.67E-08	7.55E-03	3.04E-05
RL-W716	8.69E-03	0.00E+00	4.34E-04	5.69E-02	1.26E-02	8.98E-05	3.83E-07	7.87E-02	3.17E-04
RL-W717	2.17E-03	0.00E+00	1.09E-04	1.42E-02	3.15E-03	2.24E-05	9.56E-08	1.97E-02	7.93E-05
RL-W718	3.83E-04	0.00E+00	1.91E-05	2.51E-03	5.55E-04	3.95E-06	1.69E-08	3.47E-03	1.40E-05
RL-W719	1.72E-03	0.00E+00	8.62E-05	1.14E-02	2.51E-03	1.79E-05	7.60E-08	1.57E-02	6.32E-05
RL-W720	1.07E-02	0.00E+00	5.35E-04	7.01E-02	1.55E-02	1.10E-04	4.72E-07	9.68E-02	3.91E-04
RL-W721	7.23E-03	0.00E+00	3.62E-04	4.74E-02	1.05E-02	7.47E-05	3.19E-07	6.55E-02	2.64E-04
RL-W723	2.40E-02	0.00E+00	1.22E-03	1.61E-01	3.56E-02	2.48E-04	1.08E-06	2.22E-01	8.95E-04
RL-W724	1.59E-01	0.00E+00	8.13E-03	1.07E+00	2.37E-01	1.65E-03	7.17E-06	1.47E+00	5.93E-03
RL-W725	5.04E-02	0.00E+00	2.56E-03	3.38E-01	7.48E-02	5.20E-04	2.26E-06	4.65E-01	1.88E-03
RL-W726	3.97E-02	0.00E+00	2.02E-03	2.67E-01	5.89E-02	4.09E-04	1.78E-06	3.67E-01	1.48E-03
RL-W727	2.43E-01	0.00E+00	1.24E-02	1.63E+00	3.62E-01	2.51E-03	1.09E-05	2.25E+00	9.07E-03

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W728	2.21E-01	0.00E+00	1.13E-02	1.49E+00	3.30E-01	2.29E-03	9.97E-06	2.06E+00	8.29E-03
RL-W729	1.02E-01	0.00E+00	5.24E-03	6.87E-01	1.52E-01	1.06E-03	4.62E-06	9.47E-01	3.82E-03
RL-W730	4.00E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.00E+01	1.61E-01
RL-W731	1.29E-05	0.00E+00	0.00E+00	4.49E-04	1.83E-06	0.00E+00	0.00E+00	4.64E-04	1.87E-06
RL-W732	2.96E+01	0.00E+00	2.98E+00	1.26E+02	2.78E+01	3.78E-01	2.63E-03	1.87E+02	7.53E-01
RL-W733	3.88E-01	0.00E+00	3.88E-02	1.37E+00	3.38E-01	4.11E-03	3.42E-05	2.14E+00	8.62E-03
RL-W734	1.21E+00	0.00E+00	1.29E-01	4.74E+00	1.14E+00	1.22E-02	1.14E-04	7.22E+00	2.91E-02
RL-W735	9.92E-01	0.00E+00	9.87E-02	3.69E+00	9.10E-01	9.50E-03	8.69E-05	5.69E+00	2.30E-02
RL-W736	1.09E-03	0.00E+00	2.10E-07	2.45E-03	6.28E-04	2.91E-06	1.85E-10	4.17E-03	1.68E-05
RL-W737	8.85E-01	0.00E+00	9.00E-02	3.50E+00	8.47E-01	8.20E-03	7.93E-05	5.33E+00	2.15E-02
RL-W738	3.30E+00	0.00E+00	3.10E-01	1.12E+01	2.92E+00	2.97E-02	2.73E-04	1.77E+01	7.13E-02
RL-W739	2.82E-01	0.00E+00	2.73E-02	1.81E+00	4.10E-01	2.70E-03	2.41E-05	2.53E+00	1.02E-02
RL-W740	1.41E+01	0.00E+00	1.00E+00	4.41E+01	1.14E+01	1.36E-01	8.82E-04	7.06E+01	2.85E-01
RL-W741	2.10E+01	0.00E+00	2.36E+00	8.59E+00	6.06E+00	1.02E-01	2.08E-03	3.80E+01	1.53E-01
RL-W742	9.37E-01	0.00E+00	7.09E-02	2.79E+00	6.52E-01	8.77E-03	6.25E-05	4.45E+00	1.79E-02
RL-W743	1.69E-03	0.00E+00	1.92E-05	1.80E-03	0.00E+00	0.00E+00	1.70E-08	3.51E-03	1.42E-05
RL-W744	0.00E+00	0.00E+00	0.00E+00	8.99E-02	7.59E-02	0.00E+00	0.00E+00	1.66E-01	6.69E-04
RL-W745	2.66E-03	0.00E+00	1.35E-04	1.74E-02	3.85E-03	3.01E-05	1.19E-07	2.41E-02	9.70E-05
RL-W746	1.03E-02	0.00E+00	5.18E-04	6.69E-02	1.49E-02	1.16E-04	4.56E-07	9.25E-02	3.73E-04
RL-W747	2.78E-02	0.00E+00	1.40E-03	1.81E-01	4.01E-02	3.14E-04	1.24E-06	2.51E-01	1.01E-03
RL-W748	1.95E+02	0.00E+00	3.94E+00	3.01E-01	4.91E-01	2.37E+00	3.47E-03	2.00E+02	8.04E-01
RL-W749	2.34E-01	0.00E+00	1.20E-02	1.57E+00	3.47E-01	2.53E-03	1.06E-05	2.17E+00	8.73E-03
RL-W750	2.95E+02	0.00E+00	5.96E+00	4.93E-01	8.02E-01	3.35E+00	5.25E-03	3.03E+02	1.22E+00
RL-W751	2.67E+02	0.00E+00	5.38E+00	4.43E-01	7.27E-01	3.02E+00	4.74E-03	2.73E+02	1.10E+00
RL-W752	1.16E+02	0.00E+00	2.34E+00	1.93E-01	3.16E-01	1.31E+00	2.06E-03	1.19E+02	4.79E-01
RL-W753	1.56E+03	0.00E+00	3.15E+01	2.60E+00	4.24E+00	1.77E+01	2.78E-02	1.60E+03	6.44E+00
RP-W754	6.62E+01	0.00E+00	3.99E+00	1.85E+03	1.51E+02	1.63E-01	3.56E-01	2.07E+03	8.36E+00
RP-W755	3.51E+02	0.00E+00	2.39E+00	1.38E+03	1.14E+02	1.22E-01	1.26E+01	1.86E+03	7.51E+00
SA-T001	7.05E-01	1.17E-02	5.73E-02	3.02E+00	1.77E-02	0.00E+00	5.51E-05	3.80E+00	1.53E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
SA-W134	5.76E+00	4.55E-06	3.91E-01	1.37E+00	4.32E-01	3.10E-03	1.67E-01	8.12E+00	3.27E-02
SA-W134M	7.48E-01	5.90E-07	5.06E-02	1.79E-01	5.61E-02	4.03E-04	2.16E-02	1.06E+00	4.25E-03
T001-221F-HET	1.39E+03	0.00E+00	4.57E+04	2.87E+04	7.02E+02	1.02E+01	4.59E+01	7.65E+04	3.09E+02
T001-221H-HET	2.51E+03	0.00E+00	8.25E+04	5.18E+04	1.27E+03	1.84E+01	8.29E+01	1.38E+05	5.57E+02
T001-235F-HET	1.44E+02	0.00E+00	4.75E+03	2.98E+03	7.29E+01	1.06E+00	4.77E+00	7.94E+03	3.20E+01
T001-772F-HET	1.24E+03	0.00E+00	4.11E+04	2.57E+04	6.29E+02	9.09E+00	4.13E+01	6.87E+04	2.77E+02
T001-773A-CLAS	1.40E+01	0.00E+00	4.60E+02	2.89E+02	7.05E+00	1.02E-01	4.62E-01	7.70E+02	3.11E+00
T001-773A-HET	1.61E+02	0.00E+00	5.30E+03	3.33E+03	8.14E+01	1.18E+00	5.32E+00	8.87E+03	3.58E+01
W006-773A-VIT	2.15E-03	0.00E+00	0.00E+00	5.35E+02	0.00E+00	0.00E+00	0.00E+00	5.35E+02	2.16E+00
W026-221F-HET	4.84E+02	0.00E+00	1.59E+04	1.01E+04	2.45E+02	3.55E+00	1.60E+01	2.67E+04	1.08E+02
W026-221H-HET	3.62E+02	0.00E+00	1.19E+04	7.49E+03	1.83E+02	2.65E+00	1.20E+01	2.00E+04	8.05E+01
W026-235F-HET	5.64E+00	0.00E+00	1.86E+02	1.17E+02	2.85E+00	4.13E-02	1.87E-01	3.11E+02	1.25E+00
W026-772F-HET	1.54E+00	0.00E+00	5.06E+01	3.18E+01	7.77E-01	1.13E-02	5.09E-02	8.48E+01	3.42E-01
W026-773A-HET	2.50E+01	0.00E+00	8.25E+02	5.18E+02	1.27E+01	1.83E-01	8.29E-01	1.38E+03	5.57E+00
W027-221F-HET	1.83E+03	0.00E+00	5.38E+04	3.88E+04	9.48E+02	5.80E+00	6.52E+01	9.55E+04	3.85E+02
W027-221H-HET	7.99E+02	0.00E+00	2.35E+04	1.70E+04	4.15E+02	2.53E+00	2.85E+01	4.18E+04	1.68E+02
W027-235F-HET	2.40E+02	0.00E+00	7.06E+03	5.12E+03	1.25E+02	7.62E-01	8.57E+00	1.26E+04	5.06E+01
W027-772F-HET	4.37E+02	0.00E+00	1.29E+04	9.29E+03	2.27E+02	1.38E+00	1.56E+01	2.28E+04	9.20E+01
W027-773A-HET	6.52E+02	0.00E+00	1.92E+04	1.38E+04	3.38E+02	2.07E+00	2.32E+01	3.40E+04	1.37E+02
W027-999-HET	7.45E+02	0.00E+00	2.19E+04	1.58E+04	3.87E+02	2.36E+00	2.66E+01	3.89E+04	1.57E+02
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.97E+02	0.00E+00	0.00E+00	0.00E+00	3.97E+02	1.60E+00
WP-INW169.001	3.64E+00	0.00E+00	1.38E-01	1.53E+01	3.38E+00	2.08E-02	2.87E-04	2.25E+01	9.07E-02
WP-INW198.001	4.79E+00	0.00E+00	2.41E-01	2.75E+01	6.02E+00	3.42E-02	2.94E-04	3.85E+01	1.55E-01
WP-INW211.001	5.40E+02	0.00E+00	2.26E+01	2.55E+03	5.59E+02	3.88E+00	2.19E-02	3.67E+03	1.48E+01
WP-INW216.001-	1.96E+04	0.00E+00	1.30E+01	1.47E+03	3.25E+02	2.14E+00	2.88E-01	2.14E+04	8.64E+01
WP-INW216.001-	5.39E+03	0.00E+00	3.50E+00	3.99E+02	8.75E+01	5.80E-01	3.07E-02	5.88E+03	2.37E+01
WP-INW218.001-	3.75E+02	0.00E+00	2.29E+00	2.57E+02	5.65E+01	3.88E-01	3.88E-01	6.91E+02	2.79E+00
WP-INW218.001-	1.73E+00	0.00E+00	6.31E-02	6.99E+00	1.53E+00	1.10E-02	3.74E-02	1.04E+01	4.17E-02
WP-INW222.001	1.78E+01	0.00E+00	6.80E-01	6.83E+01	1.52E+01	9.30E-02	1.17E-03	1.02E+02	4.11E-01

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-INW243.001	4.31E+01	0.00E+00	1.47E+00	1.43E+02	3.19E+01	1.88E-01	2.16E-03	2.20E+02	8.86E-01
WP-INW247.001R	5.75E+01	0.00E+00	3.41E+00	2.75E+02	6.20E+01	3.26E-01	3.09E-03	3.98E+02	1.60E+00
WP-INW276.001	4.39E+00	0.00E+00	3.33E-01	2.72E+01	6.14E+00	2.76E-02	3.10E-04	3.80E+01	1.53E-01
WP-INW276.002	6.95E+00	0.00E+00	5.01E-01	3.99E+01	9.21E+00	4.15E-02	4.68E-04	5.66E+01	2.28E-01
WP-INW276.003	2.67E+02	0.00E+00	1.86E+01	1.48E+03	3.35E+02	1.74E+00	1.68E-02	2.10E+03	8.48E+00
WP-INW276.004	6.37E+01	0.00E+00	3.94E+00	3.14E+02	7.08E+01	3.68E-01	3.61E-03	4.52E+02	1.82E+00
WP-INW296.001-	2.33E+01	0.00E+00	9.35E-01	7.87E+01	1.77E+01	9.45E-02	8.61E-04	1.21E+02	4.87E-01
WP-INW296.001-	7.02E+01	0.00E+00	3.30E+00	2.79E+02	6.26E+01	3.41E-01	3.26E-03	4.15E+02	1.67E+00
WP-LA-TA-55-19	1.17E+00	0.00E+00	1.53E-01	2.08E+00	4.99E-01	3.38E-03	2.77E-03	3.90E+00	1.57E-02
WP-LA-TA-55-19	5.66E+01	0.00E+00	5.15E+00	2.12E+02	5.13E+01	3.36E-01	9.17E-02	3.25E+02	1.31E+00
WP-LA-TA-55-43	3.18E-01	0.00E+00	1.20E+02	3.22E-01	1.35E-01	3.01E-03	1.32E-01	1.21E+02	4.88E-01
WP-RF001.01	9.82E+01	0.00E+00	4.17E+00	4.08E+02	9.22E+01	3.39E-01	1.30E-02	6.03E+02	2.43E+00
WP-RF002.01-A	1.14E+02	0.00E+00	5.56E+00	4.60E+02	1.04E+02	7.47E-01	2.27E-02	6.84E+02	2.76E+00
WP-RF002.01-B	1.14E-01	0.00E+00	3.85E-03	4.98E-01	1.12E-01	4.69E-04	3.58E-06	7.27E-01	2.93E-03
WP-RF003.01	1.78E+03	0.00E+00	8.94E+01	8.79E+03	1.99E+03	1.23E+01	8.71E-02	1.26E+04	5.10E+01
WP-RF004.01	8.33E-01	0.00E+00	5.99E-02	5.07E+00	1.15E+00	7.05E-03	1.80E-04	7.11E+00	2.87E-02
WP-RF005.01	4.27E+03	0.00E+00	4.54E+01	4.65E+03	1.04E+03	4.91E+00	4.18E-02	1.00E+04	4.04E+01
WP-RF005.02	5.03E+03	0.00E+00	2.35E+01	2.78E+03	6.19E+02	2.52E+00	2.19E-02	8.45E+03	3.41E+01
WP-RF006.01	1.63E+03	0.00E+00	8.54E+01	7.90E+03	1.79E+03	6.37E+00	1.01E-01	1.14E+04	4.60E+01
WP-RF008.01	5.17E+02	0.00E+00	3.04E+01	2.31E+03	5.32E+02	4.20E+00	2.80E-02	3.39E+03	1.37E+01
WP-RF009.01	5.09E+04	0.00E+00	3.73E+02	5.07E+04	1.12E+04	4.83E+01	3.50E-01	1.13E+05	4.56E+02
WP-RF010.01	1.88E+01	0.00E+00	9.46E-01	7.66E+01	1.73E+01	1.49E-01	1.56E-03	1.14E+02	4.58E-01
WP-RF029.01-A	4.51E+00	0.00E+00	1.78E-01	1.34E+01	3.05E+00	3.41E-02	8.87E-04	2.12E+01	8.54E-02
WP-RF029.01-B	6.73E+00	0.00E+00	1.41E-01	1.07E+01	2.41E+00	2.70E-02	2.37E-03	1.99E+01	8.04E-02
WP-RF118.01	1.14E+04	0.00E+00	7.09E+02	5.12E+04	1.13E+04	8.88E+01	8.40E-01	7.46E+04	3.01E+02
WP-RLMPDT.001	2.43E+00	0.00E+00	2.07E-01	7.33E+00	1.89E+00	1.95E-02	1.84E-04	1.19E+01	4.78E-02
WP-RLNPDT.002	2.98E+01	0.00E+00	1.97E+00	7.20E+01	1.92E+01	2.24E-01	1.78E-03	1.23E+02	4.96E-01
WP-SR2001.001.	9.50E-01	0.00E+00	2.27E-01	6.80E+00	1.34E+00	1.22E-02	2.04E-04	9.31E+00	3.76E-02

Table PAR-53. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 125 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-SR-W027-221	7.03E+00	0.00E+00	6.65E-01	1.95E+01	5.40E+00	5.48E-02	1.87E-01	3.28E+01	1.32E-01
Total	3.76E+05	2.27E+01	4.66E+05	6.57E+05	1.05E+05	1.25E+03	5.78E+02	1.61E+06	6.47E+03

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	6.54E+01	0.00E+00	3.47E+00	2.08E+02	1.21E+02	1.12E-02	1.84E-02	3.98E+02	1.61E+00
AE-T003	8.29E+00	0.00E+00	4.62E-01	6.42E+01	2.45E+01	6.16E-03	7.97E-04	9.74E+01	3.93E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	3.67E-02	0.00E+00	1.22E+01	4.73E+01	2.82E-01	1.20E-05	1.86E-02	5.99E+01	2.42E-01
AW-T033.1325	1.34E-01	0.00E+00	4.48E+01	1.73E+02	1.03E+00	4.39E-05	6.82E-02	2.19E+02	8.83E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.68E-01	0.00E+00	0.00E+00	0.00E+00	7.68E-01	3.10E-03
BCLCH-MT01	1.36E+01	0.00E+00	3.47E+02	2.85E+01	7.38E+00	1.69E-02	5.14E-01	3.97E+02	1.60E+00
BT-T002	9.96E-03	9.17E-07	1.81E-01	7.21E-04	1.46E-03	7.43E-06	2.26E-03	1.96E-01	7.89E-04
ET-C1-B55	4.16E-02	0.00E+00	2.07E-03	6.17E-02	3.03E-02	1.31E-05	2.39E-04	1.36E-01	5.48E-04
ET-C1-D139	5.70E-03	0.00E+00	2.87E-04	8.68E-03	4.27E-03	1.75E-06	4.86E-07	1.89E-02	7.64E-05
ET-C2-SEFOR	1.41E-01	0.00E+00	0.00E+00	1.36E-01	4.51E-02	2.69E-05	0.00E+00	3.22E-01	1.30E-03
FM-MOX-MT02	1.34E-06	0.00E+00	1.15E-07	2.98E-07	1.75E-07	9.36E-10	1.80E-10	1.93E-06	7.77E-09
FM-MOX-T01	2.21E-05	0.00E+00	1.90E-06	4.91E-06	2.89E-06	1.54E-08	2.96E-09	3.18E-05	1.28E-07
IN-BN-510	5.34E+03	0.00E+00	9.82E+03	3.95E+04	3.30E+03	3.69E-03	1.65E+01	5.79E+04	2.34E+02
IN-GEM-01	6.75E+01	0.00E+00	1.95E-01	4.43E+01	9.98E+00	2.60E-03	2.89E-04	1.22E+02	4.92E-01
IN-GEM-02	1.60E+01	0.00E+00	4.64E-02	1.05E+01	2.38E+00	6.16E-04	6.87E-05	2.90E+01	1.17E-01
IN-W157.144	8.00E+01	0.00E+00	1.89E+00	3.01E+02	6.72E+01	4.62E-02	3.17E-03	4.50E+02	1.82E+00
IN-W163.1007	1.37E+01	0.00E+00	5.83E-01	9.34E+01	2.08E+01	1.42E-02	9.80E-04	1.29E+02	5.18E-01
IN-W164.153	1.31E-01	0.00E+00	5.56E-03	8.90E-01	1.99E-01	1.36E-04	9.34E-06	1.23E+00	4.94E-03
IN-W167.149	2.62E+01	0.00E+00	9.03E-01	1.44E+02	3.22E+01	2.20E-02	1.52E-03	2.03E+02	8.20E-01
IN-W174.154	0.00E+00	0.00E+00	5.11E+02	1.94E+00	3.77E+00	0.00E+00	8.59E-01	5.17E+02	2.09E+00
IN-W177.156	1.82E-02	0.00E+00	1.09E+03	1.82E+00	1.10E-02	1.89E-05	1.83E+00	1.09E+03	4.39E+00
IN-W179.158	1.22E-01	0.00E+00	1.08E+03	1.05E-01	5.40E-02	1.27E-04	1.82E+00	1.08E+03	4.37E+00
IN-W181.162	1.74E+00	0.00E+00	7.37E-02	1.17E+01	2.62E+00	1.80E-03	1.24E-04	1.62E+01	6.52E-02
IN-W188.160	1.17E+01	0.00E+00	4.95E-01	7.92E+01	1.76E+01	1.21E-02	8.32E-04	1.09E+02	4.40E-01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W216.98	1.04E+05	0.00E+00	4.04E+01	6.46E+03	1.45E+03	9.93E-01	6.78E-02	1.12E+05	4.51E+02
IN-W218.909	5.25E+02	0.00E+00	8.97E-01	1.43E+02	3.20E+01	2.20E-02	1.51E-03	7.01E+02	2.83E+00
IN-W219.110	7.12E-01	0.00E+00	3.02E-02	4.83E+00	1.08E+00	7.39E-04	5.08E-05	6.65E+00	2.68E-02
IN-W219.914	1.12E-01	0.00E+00	4.76E-03	7.62E-01	1.70E-01	1.17E-04	7.99E-06	1.05E+00	4.23E-03
IN-W220.114	3.71E+03	0.00E+00	3.18E+00	5.46E+02	1.18E+02	7.76E-02	5.34E-03	4.38E+03	1.76E+01
IN-W221.927	4.35E+00	0.00E+00	1.84E-01	2.94E+01	6.56E+00	4.52E-03	3.10E-04	4.05E+01	1.63E-01
IN-W222.116	1.48E+02	0.00E+00	6.24E+00	9.94E+02	2.22E+02	1.52E-01	1.05E-02	1.37E+03	5.53E+00
IN-W228.101	9.81E+02	0.00E+00	2.03E+00	3.25E+02	7.24E+01	4.99E-02	3.41E-03	1.38E+03	5.56E+00
IN-W240.931	1.04E+02	0.00E+00	2.59E+00	4.18E+02	9.26E+01	6.30E-02	4.36E-03	6.17E+02	2.49E+00
IN-W243.808	1.44E+02	0.00E+00	4.54E+00	7.29E+02	1.62E+02	1.12E-01	7.64E-03	1.04E+03	4.19E+00
IN-W245.301	2.13E+02	0.00E+00	8.93E+00	1.42E+03	3.18E+02	2.18E-01	1.50E-02	1.96E+03	7.91E+00
IN-W247.810	1.04E+02	0.00E+00	4.35E+00	6.95E+02	1.56E+02	1.06E-01	7.31E-03	9.58E+02	3.87E+00
IN-W249.527	0.00E+00	0.00E+00	3.04E+02	1.23E+01	0.00E+00	0.00E+00	5.11E-01	3.17E+02	1.28E+00
IN-W263.520	2.97E-02	0.00E+00	3.18E+01	8.38E+00	1.31E-02	3.08E-05	5.34E-02	4.03E+01	1.62E-01
IN-W267.1005	2.48E+01	0.00E+00	1.06E+00	1.69E+02	3.77E+01	2.58E-02	1.77E-03	2.33E+02	9.38E-01
IN-W309.609	6.66E+02	0.00E+00	1.77E+01	2.82E+03	6.30E+02	4.32E-01	2.97E-02	4.14E+03	1.67E+01
IN-W315.601	6.57E+02	0.00E+00	7.39E-02	1.18E+01	2.63E+00	1.80E-03	1.24E-04	6.71E+02	2.71E+00
IN-W319.584	3.82E+00	0.00E+00	1.62E-01	2.59E+01	5.80E+00	3.97E-03	2.72E-04	3.57E+01	1.44E-01
IN-W321.1023	3.31E+01	0.00E+00	1.40E+00	2.25E+02	5.01E+01	3.43E-02	2.36E-03	3.09E+02	1.25E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	9.07E+00	1.85E+00	0.00E+00	0.00E+00	1.09E+01	4.40E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.42E+01	4.93E+00	0.00E+00	0.00E+00	2.91E+01	1.17E-01
IN-W323.562	7.07E-02	0.00E+00	2.38E-01	2.48E-01	0.00E+00	7.34E-05	4.00E-04	5.56E-01	2.24E-03
IN-W323.951	8.34E-02	0.00E+00	2.83E-03	2.95E-01	0.00E+00	8.66E-05	4.75E-06	3.81E-01	1.54E-03
IN-W332.661	0.00E+00	0.00E+00	3.12E+00	1.28E-01	0.00E+00	0.00E+00	5.24E-03	3.25E+00	1.31E-02
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	3.02E+00	6.16E-01	0.00E+00	0.00E+00	3.64E+00	1.47E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	9.07E+00	1.85E+00	0.00E+00	0.00E+00	1.09E+01	4.40E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.94E+00	0.00E+00	0.00E+00	0.00E+00	1.94E+00	7.82E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.83E+00	0.00E+00	0.00E+00	0.00E+00	5.83E+00	2.35E-02
IN-W342.652	3.27E+00	0.00E+00	0.00E+00	4.00E-02	1.02E-17	0.00E+00	0.00E+00	3.31E+00	1.33E-02
IN-W342.953	2.18E+00	0.00E+00	0.00E+00	2.67E-02	6.83E-18	0.00E+00	0.00E+00	2.21E+00	8.90E-03
IN-W347.818	1.71E+00	0.00E+00	0.00E+00	8.21E+01	1.49E+02	0.00E+00	1.58E-08	2.33E+02	9.38E-01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W348.1012	9.04E-02	0.00E+00	2.57E+00	4.15E+02	9.26E+01	0.00E+00	4.33E-03	5.10E+02	2.06E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.49E-02	0.00E+00	0.00E+00	0.00E+00	2.49E-02	1.00E-04
IN-W357.1022	0.00E+00	0.00E+00	5.07E-03	8.14E-01	1.81E-01	0.00E+00	8.52E-06	1.00E+00	4.03E-03
IN-W358.854	0.00E+00	0.00E+00	7.64E+01	1.87E+00	3.55E+00	0.00E+00	1.21E-01	8.20E+01	3.30E-01
IN-W358.855	0.00E+00	0.00E+00	4.07E+02	9.94E+00	1.89E+01	0.00E+00	6.46E-01	4.37E+02	1.76E+00
IN-W358.948	0.00E+00	0.00E+00	8.50E+01	2.08E+00	3.93E+00	0.00E+00	1.35E-01	9.11E+01	3.68E-01
IN-W361.1021	2.40E-02	0.00E+00	4.91E-01	7.85E+01	1.75E+01	0.00E+00	8.25E-04	9.66E+01	3.89E-01
IN-W362.1020	0.00E+00	0.00E+00	6.43E+00	1.02E+03	2.30E+02	0.00E+00	1.08E-02	1.26E+03	5.08E+00
IN-W363.1019	0.00E+00	0.00E+00	3.02E-01	4.86E+01	1.09E+01	0.00E+00	5.08E-04	5.98E+01	2.41E-01
IN-W364.1011	0.00E+00	0.00E+00	4.99E-01	7.99E+01	1.78E+01	0.00E+00	8.39E-04	9.82E+01	3.96E-01
IN-W365.1010	2.24E+02	0.00E+00	3.96E-01	6.31E+01	1.41E+01	0.00E+00	6.65E-04	3.02E+02	1.22E+00
IN-W366.841	7.97E-01	0.00E+00	3.37E-01	5.38E+01	1.20E+01	0.00E+00	5.67E-04	6.70E+01	2.70E-01
IN-W372.832	3.27E+00	0.00E+00	0.00E+00	4.00E-02	1.02E-17	0.00E+00	0.00E+00	3.31E+00	1.33E-02
IN-W375.1096	0.00E+00	0.00E+00	1.24E-01	1.99E+01	4.43E+00	0.00E+00	2.09E-04	2.44E+01	9.85E-02
KN-B234TRU	1.16E+02	0.00E+00	4.76E+00	2.89E+02	9.59E+01	2.41E-02	9.00E-03	5.06E+02	2.04E+00
LA-IT-00-01	1.69E+00	5.91E-04	8.11E-01	5.82E-01	1.24E-02	4.63E-12	1.56E-03	3.09E+00	1.25E-02
LA-OS-00-01	3.75E+03	0.00E+00	3.70E+04	1.22E+03	0.00E+00	0.00E+00	5.54E+01	4.21E+04	1.70E+02
LA-PX-00-01	1.57E-02	0.00E+00	1.56E-03	9.00E-02	2.08E-02	7.67E-06	2.45E-06	1.28E-01	5.16E-04
LA-SL-00-01	0.00E+00	0.00E+00	3.29E-02	1.52E-01	0.00E+00	0.00E+00	6.27E-05	1.85E-01	7.46E-04
LA-TA-03-12	1.61E-01	0.00E+00	7.62E-01	4.33E-01	1.49E-01	4.55E-05	1.51E-03	1.51E+00	6.08E-03
LA-TA-03-13	2.08E-01	0.00E+00	2.42E+00	6.77E-01	1.57E-01	6.02E-05	4.11E-03	3.46E+00	1.40E-02
LA-TA-03-19	4.21E-01	0.00E+00	3.61E+00	1.32E+00	3.77E-01	9.32E-05	7.13E-03	5.73E+00	2.31E-02
LA-TA-03-20	2.30E-01	0.00E+00	1.71E+00	5.83E-01	2.03E-01	7.62E-05	3.22E-03	2.73E+00	1.10E-02
LA-TA-03-24	3.08E-01	0.00E+00	6.67E+00	1.08E+00	3.24E-01	7.90E-05	1.33E-02	8.40E+00	3.39E-02
LA-TA-03-26	1.58E-02	0.00E+00	2.75E-01	2.62E+00	4.24E-02	6.92E-06	1.42E-03	2.96E+00	1.19E-02
LA-TA-03-28	0.00E+00	0.00E+00	9.51E-02	2.46E-01	0.00E+00	0.00E+00	1.86E-04	3.41E-01	1.37E-03
LA-TA-03-30	7.01E-01	0.00E+00	6.78E-02	5.00E+00	1.43E+00	3.62E-04	1.32E-04	7.20E+00	2.90E-02
LA-TA-03-31	0.00E+00	0.00E+00	3.39E-03	8.75E-03	0.00E+00	0.00E+00	6.63E-06	1.22E-02	4.90E-05
LA-TA-03-40	0.00E+00	0.00E+00	5.36E-03	5.44E-02	0.00E+00	0.00E+00	1.06E-05	5.98E-02	2.41E-04
LA-TA-03-42	1.61E-05	0.00E+00	1.34E-04	3.40E-03	4.41E-05	7.58E-09	2.65E-07	3.59E-03	1.45E-05
LA-TA-21-06	1.59E-01	0.00E+00	1.48E+01	9.51E-01	2.87E-01	7.81E-05	2.89E-02	1.62E+01	6.53E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-12	5.78E-01	0.00E+00	8.91E+01	3.30E+00	9.72E-01	2.68E-04	1.74E-01	9.41E+01	3.79E-01
LA-TA-21-13	8.90E-01	0.00E+00	0.00E+00	2.92E-01	0.00E+00	0.00E+00	0.00E+00	1.18E+00	4.77E-03
LA-TA-21-14	1.46E-04	0.00E+00	1.70E+00	4.46E+00	5.14E-05	1.09E-07	2.70E-03	6.17E+00	2.49E-02
LA-TA-21-15	8.62E-02	0.00E+00	4.68E-03	1.38E+00	2.33E-01	4.41E-05	9.06E-06	1.71E+00	6.88E-03
LA-TA-21-16	9.98E-01	0.00E+00	7.21E-02	1.05E+01	2.49E+00	4.65E-04	1.42E-04	1.41E+01	5.68E-02
LA-TA-21-40	1.27E-04	0.00E+00	2.50E-01	3.31E-01	3.61E-04	1.86E-08	6.21E-04	5.82E-01	2.35E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	7.05E-01	0.00E+00	0.00E+00	0.00E+00	7.05E-01	2.84E-03
LA-TA-21-42	1.30E-02	0.00E+00	8.11E-02	1.63E-01	1.10E-02	6.07E-07	2.17E-04	2.68E-01	1.08E-03
LA-TA-21-43	4.57E+01	0.00E+00	2.69E+00	5.08E+02	1.19E+02	4.80E-03	7.12E-03	6.76E+02	2.73E+00
LA-TA-21-44	2.19E-01	0.00E+00	5.65E-01	1.14E+02	3.00E-01	6.78E-05	1.21E-03	1.15E+02	4.65E-01
LA-TA-48-01	7.10E-02	2.78E-03	2.13E-03	1.17E-01	4.85E-01	5.60E-06	5.34E-06	6.75E-01	2.72E-03
LA-TA-49-01	8.76E+00	3.45E-01	2.61E-01	1.45E+01	6.00E+01	6.92E-04	6.58E-04	8.36E+01	3.37E-01
LA-TA-50-10	2.35E-02	0.00E+00	2.48E-03	4.56E-02	0.00E+00	0.00E+00	3.85E-06	7.16E-02	2.89E-04
LA-TA-50-11	4.48E-02	0.00E+00	2.53E-03	4.63E-01	1.02E-01	5.55E-06	6.23E-06	6.12E-01	2.47E-03
LA-TA-50-15	8.83E-02	0.00E+00	3.74E-01	3.38E-01	7.48E-02	2.20E-05	6.75E-04	8.76E-01	3.53E-03
LA-TA-50-17	1.29E+01	0.00E+00	3.04E-01	1.81E+01	4.21E-04	2.01E-06	8.88E-04	3.13E+01	1.26E-01
LA-TA-50-18	7.68E-01	0.00E+00	4.02E-02	2.95E+00	5.24E-06	5.93E-08	7.93E-05	3.76E+00	1.52E-02
LA-TA-50-19	2.45E-01	0.00E+00	1.79E-02	3.93E-01	4.49E-03	7.34E-07	6.21E-05	6.60E-01	2.66E-03
LA-TA-50-20	6.72E-03	0.00E+00	0.00E+00	9.68E-03	0.00E+00	0.00E+00	0.00E+00	1.64E-02	6.62E-05
LA-TA-50-40	3.78E-03	0.00E+00	2.42E-04	1.05E-02	4.86E-03	2.35E-06	4.51E-07	1.94E-02	7.83E-05
LA-TA-50-41	4.04E-03	0.00E+00	2.44E-04	4.67E-02	1.08E-02	4.19E-06	4.09E-07	6.18E-02	2.49E-04
LA-TA-55-19	6.26E+00	0.00E+00	3.22E-01	2.62E+01	7.31E+00	2.37E-03	2.15E-03	4.01E+01	1.62E-01
LA-TA-55-20	1.01E+02	0.00E+00	3.66E+00	6.34E+02	1.51E+02	5.93E-02	1.00E-01	8.89E+02	3.59E+00
LA-TA-55-21	8.98E-01	8.23E-07	4.21E-02	4.49E+00	1.07E+00	4.89E-04	7.01E-05	6.50E+00	2.62E-02
LA-TA-55-22	2.46E+00	0.00E+00	2.38E-01	1.58E+01	3.66E+00	1.52E-03	3.96E-04	2.22E+01	8.94E-02
LA-TA-55-23	2.32E+00	0.00E+00	1.99E-01	1.08E+01	2.65E+00	1.49E-03	3.28E-04	1.60E+01	6.45E-02
LA-TA-55-24	8.74E-01	0.00E+00	3.12E-02	5.69E+00	1.31E+00	7.10E-04	4.90E-05	7.90E+00	3.19E-02
LA-TA-55-25	4.47E+00	0.00E+00	1.82E-01	2.82E+01	6.53E+00	3.64E-03	2.86E-04	3.94E+01	1.59E-01
LA-TA-55-28	1.53E+00	0.00E+00	1.01E-01	8.67E+00	2.03E+00	1.18E-03	1.60E-04	1.23E+01	4.97E-02
LA-TA-55-30	3.40E+01	7.79E-09	1.21E+00	1.42E+02	3.40E+01	8.66E-03	2.56E-03	2.11E+02	8.52E-01
LA-TA-55-32	2.76E+00	0.00E+00	6.74E+00	1.12E+01	3.43E+00	1.08E-03	1.35E-02	2.42E+01	9.75E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-33	4.13E-01	0.00E+00	1.74E-02	1.48E+00	4.68E-01	1.52E-04	3.22E-05	2.38E+00	9.59E-03
LA-TA-55-34	4.17E+01	0.00E+00	1.61E+00	2.30E+02	5.77E+01	1.83E-02	5.75E-03	3.31E+02	1.33E+00
LA-TA-55-38	1.05E+02	0.00E+00	5.30E-01	5.07E+01	1.35E+01	4.25E-03	2.67E-03	1.70E+02	6.84E-01
LA-TA-55-39	1.11E+01	0.00E+00	3.92E-01	7.57E+01	1.68E+01	7.48E-03	6.40E-04	1.04E+02	4.19E-01
LA-TA-55-41	2.64E+02	0.00E+00	8.11E-01	9.38E+01	2.22E+01	9.41E-03	1.36E-03	3.81E+02	1.54E+00
LA-TA-55-43	9.92E-02	0.00E+00	5.32E+01	1.41E-01	4.89E-02	8.28E-05	8.61E-02	5.36E+01	2.16E-01
LA-TA-55-44	8.60E-01	0.00E+00	1.25E+02	2.61E+00	7.18E-01	2.45E-04	2.34E-01	1.30E+02	5.23E-01
LA-TA-55-48	6.34E+03	0.00E+00	4.95E+02	1.68E+04	6.20E+03	2.56E+00	8.99E-01	2.98E+04	1.20E+02
LA-TA-55-49	1.36E+01	0.00E+00	6.51E+02	3.07E+01	8.54E+00	2.99E-03	1.20E+00	7.05E+02	2.84E+00
LA-TA-55-53	6.39E+01	0.00E+00	1.35E+00	2.62E+02	6.07E+01	1.64E-02	2.45E-03	3.88E+02	1.57E+00
LA-TA-55-56	7.07E+01	0.00E+00	5.01E+01	3.80E+02	9.43E+01	3.79E-02	8.59E-02	5.95E+02	2.40E+00
LA-TA-55-60	3.83E-02	0.00E+00	1.27E-02	7.16E-02	2.51E-02	2.23E-05	2.34E-05	1.48E-01	5.96E-04
LA-TA-55-61	3.30E-02	0.00E+00	5.83E-02	1.38E-01	4.64E-02	2.17E-05	1.06E-04	2.76E-01	1.11E-03
LA-TA-55-62	8.55E-03	0.00E+00	5.54E-04	2.32E-02	1.10E-02	5.83E-06	1.01E-06	4.32E-02	1.74E-04
LA-TA-55-63	6.35E-03	0.00E+00	3.74E-04	7.43E-02	1.70E-02	5.74E-06	6.48E-07	9.80E-02	3.95E-04
LL-M001	8.70E+01	3.73E-02	1.63E+01	6.96E+01	3.11E+01	4.53E-02	2.42E-02	2.04E+02	8.23E-01
LL-T001	4.34E+02	0.00E+00	0.00E+00	5.31E+02	2.37E+02	3.51E-01	0.00E+00	1.20E+03	4.85E+00
LL-T002	4.29E+03	0.00E+00	1.30E+02	5.15E+03	2.09E+03	3.09E+00	1.92E-01	1.17E+04	4.70E+01
LL-T003	1.67E+02	0.00E+00	1.45E+01	1.04E+02	8.34E+01	1.22E-01	2.15E-02	3.69E+02	1.49E+00
LL-T004	1.06E+02	0.00E+00	2.98E+00	6.63E+01	5.25E+01	7.76E-02	4.42E-03	2.28E+02	9.19E-01
LL-T005	5.47E+02	1.63E+00	3.51E+01	2.47E+02	2.11E+02	2.88E-01	5.20E-02	1.04E+03	4.19E+00
LL-W018	4.66E-02	0.00E+00	0.00E+00	1.84E-02	4.19E-02	5.88E-05	0.00E+00	1.07E-01	4.31E-04
LL-W019	2.53E+01	0.00E+00	0.00E+00	1.43E+01	1.18E+01	1.72E-02	0.00E+00	5.14E+01	2.07E-01
LL-W034	9.35E+00	2.75E-02	6.14E-01	4.18E+00	3.49E+00	4.89E-03	9.10E-04	1.76E+01	7.11E-02
MC-W001	1.17E-01	0.00E+00	0.00E+00	6.02E-02	0.00E+00	8.85E-06	0.00E+00	1.77E-01	7.13E-04
MU-W002	1.56E+00	0.00E+00	0.00E+00	5.23E-02	0.00E+00	0.00E+00	2.67E-12	1.61E+00	6.49E-03
NT-JAS-01	1.50E+02	0.00E+00	1.31E+01	9.42E+01	7.50E+01	1.10E-01	1.94E-02	3.33E+02	1.34E+00
NT-W001	2.26E+02	8.41E-04	2.61E+01	2.84E+03	1.88E+01	7.72E-03	5.03E-02	3.11E+03	1.26E+01
NT-W021	4.37E+00	0.00E+00	1.87E-01	3.20E+01	7.22E+00	3.95E-03	3.24E-04	4.38E+01	1.77E-01
OR-W201	5.24E+03	5.80E-02	5.61E+02	2.15E+03	2.09E+03	4.14E+00	4.44E+01	1.01E+04	4.07E+01
OR-W202	7.51E+02	1.21E+00	1.62E+03	5.51E+02	5.34E+02	1.33E-01	2.85E+00	3.46E+03	1.40E+01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
OR-W203	1.66E+00	4.20E-02	2.32E-01	2.48E-02	1.74E+00	3.37E-04	4.05E-04	3.66E+00	1.47E-02
OR-W204	3.69E-01	1.74E-07	2.63E-01	4.22E-01	2.82E-01	0.00E+00	4.60E-04	1.34E+00	5.39E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.24E-01	0.00E+00	0.00E+00	0.00E+00	4.24E-01	1.71E-03
RF-MT0001	1.42E+03	0.00E+00	1.63E+00	1.95E+02	4.39E+01	3.04E-02	2.72E-03	1.66E+03	6.68E+00
RF-MT0002	1.09E+02	0.00E+00	1.25E-01	1.50E+01	3.38E+00	2.33E-03	2.09E-04	1.27E+02	5.14E-01
RF-MT0003	4.95E-01	0.00E+00	2.87E-02	3.43E+00	7.73E-01	5.32E-04	4.77E-05	4.73E+00	1.91E-02
RF-MT0007	1.25E+00	0.00E+00	0.00E+00	4.27E-01	9.62E-02	6.16E-05	0.00E+00	1.77E+00	7.13E-03
RF-MT0089	4.89E-03	0.00E+00	2.87E-04	3.43E-02	7.72E-03	5.32E-06	4.77E-07	4.72E-02	1.90E-04
RF-MT0090	1.24E+01	0.00E+00	4.05E-01	8.81E+01	1.97E+01	5.32E-03	6.75E-04	1.21E+02	4.86E-01
RF-MT0091	7.69E+02	0.00E+00	4.11E+01	5.89E+03	1.32E+03	4.39E-01	7.15E-02	8.02E+03	3.23E+01
RF-MT0092	1.10E+02	0.00E+00	5.19E+00	8.43E+02	1.93E+02	6.07E-02	8.63E-03	1.15E+03	4.64E+00
RF-MT0093	1.34E+02	0.00E+00	5.34E+00	9.10E+02	2.11E+02	5.18E-02	8.89E-03	1.26E+03	5.08E+00
RF-MT0097	6.71E+00	0.00E+00	2.36E-01	4.75E+01	9.61E+00	2.83E-03	3.92E-04	6.41E+01	2.58E-01
RF-MT0099	7.35E-03	0.00E+00	4.31E-04	5.14E-02	1.15E-02	8.00E-06	7.17E-07	7.07E-02	2.85E-04
RF-MT0290	1.82E+01	0.00E+00	1.07E+00	1.27E+02	2.87E+01	1.98E-02	1.78E-03	1.75E+02	7.07E-01
RF-MT-0292	2.30E+01	0.00E+00	1.35E+00	1.61E+02	3.62E+01	2.50E-02	2.24E-03	2.22E+02	8.93E-01
RF-MT-0299	2.71E+03	0.00E+00	3.45E+01	4.13E+03	9.29E+02	6.45E-01	5.75E-02	7.80E+03	3.14E+01
RF-MT0302	4.14E-02	0.00E+00	1.37E-03	1.78E-01	4.02E-02	2.50E-05	1.91E-05	2.61E-01	1.05E-03
RF-MT0320	4.95E+01	0.00E+00	1.42E+00	1.73E+02	3.90E+01	2.52E-02	2.37E-03	2.63E+02	1.06E+00
RF-MT0321	2.77E+01	0.00E+00	4.23E-01	5.57E+01	1.24E+01	7.06E-03	3.12E-03	9.62E+01	3.88E-01
RF-MT-0328	1.92E+00	0.00E+00	5.07E-02	6.05E+00	1.36E+00	9.41E-04	4.23E-04	9.38E+00	3.78E-02
RF-MT0330	1.99E+01	0.00E+00	5.56E-01	1.22E+02	2.97E+01	8.85E-03	9.25E-04	1.73E+02	6.96E-01
RF-MT-0331	1.20E+02	0.00E+00	3.45E+00	5.38E+02	1.18E+02	5.13E-02	2.65E-02	7.79E+02	3.14E+00
RF-MT0332	1.71E-02	0.00E+00	1.01E-03	1.20E-01	2.70E-02	1.87E-05	1.67E-06	1.65E-01	6.67E-04
RF-MT-0335	1.38E+00	0.00E+00	4.62E-02	6.19E+00	1.40E+00	7.62E-04	6.19E-04	9.02E+00	3.64E-02
RF-MT0336	9.74E+01	0.00E+00	3.06E+00	4.39E+02	9.88E+01	4.47E-02	6.91E-03	6.39E+02	2.58E+00
RF-MT0337	5.50E+01	0.00E+00	1.68E+00	2.68E+02	5.94E+01	2.18E-02	6.65E-03	3.85E+02	1.55E+00
RF-MT0339	1.51E+02	0.00E+00	4.58E+00	5.89E+02	1.31E+02	7.90E-02	2.47E-02	8.75E+02	3.53E+00
RF-MT-0342	8.85E-01	0.00E+00	3.84E-02	5.44E+00	1.20E+00	5.79E-04	1.22E-04	7.56E+00	3.05E-02
RF-MT0371	2.99E+02	0.00E+00	8.89E+00	1.06E+03	2.39E+02	1.65E-01	1.61E-02	1.61E+03	6.49E+00
RF-MT-0372	1.30E+00	0.00E+00	6.26E-02	7.42E+00	1.67E+00	1.02E-03	3.44E-04	1.05E+01	4.22E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0373	1.96E+01	0.00E+00	6.43E-01	1.39E+02	3.11E+01	8.42E-03	1.07E-03	1.91E+02	7.68E-01
RF-MT0374	6.38E-01	0.00E+00	2.30E-02	2.75E+00	6.19E-01	4.27E-04	4.16E-05	4.03E+00	1.63E-02
RF-MT0376	5.06E-01	0.00E+00	1.86E-02	2.74E+00	6.27E-01	3.15E-04	4.60E-05	3.90E+00	1.57E-02
RF-MT0377	3.00E+02	0.00E+00	1.07E+01	1.28E+03	2.88E+02	1.99E-01	2.81E-02	1.88E+03	7.58E+00
RF-MT0378	3.37E+00	0.00E+00	1.48E-01	1.77E+01	3.98E+00	2.75E-03	2.46E-04	2.52E+01	1.02E-01
RF-MT0419	5.42E+00	0.00E+00	1.38E-01	1.65E+01	3.72E+00	2.57E-03	2.30E-04	2.58E+01	1.04E-01
RF-MT0420	9.42E-01	0.00E+00	2.40E-02	2.86E+00	6.46E-01	4.47E-04	3.99E-05	4.48E+00	1.80E-02
RF-MT0423	8.00E+00	0.00E+00	1.95E-01	4.14E+01	9.03E+00	1.77E-03	3.25E-04	5.86E+01	2.36E-01
RF-MT0425	2.36E-01	0.00E+00	6.00E-03	7.17E-01	1.61E-01	1.12E-04	1.00E-05	1.12E+00	4.52E-03
RF-MT-0438	2.14E+00	0.00E+00	7.88E-02	1.27E+01	2.84E+00	1.11E-03	1.44E-04	1.78E+01	7.17E-02
RF-MT0440	7.77E-01	0.00E+00	2.83E-02	4.61E+00	1.06E+00	4.55E-04	2.12E-04	6.47E+00	2.61E-02
RF-MT0442	2.95E-01	0.00E+00	1.22E-02	1.58E+00	3.55E-01	1.69E-04	1.15E-04	2.24E+00	9.05E-03
RF-MT0443	3.64E+00	0.00E+00	2.01E-01	2.46E+01	5.53E+00	3.52E-03	4.92E-04	3.39E+01	1.37E-01
RF-MT0444	2.84E+01	0.00E+00	9.84E-01	1.18E+02	2.65E+01	1.83E-02	1.66E-03	1.74E+02	7.02E-01
RF-MT0480	7.94E+01	0.00E+00	2.77E+00	3.32E+02	7.48E+01	4.71E-02	7.07E-03	4.89E+02	1.97E+00
RF-MT0488	1.27E+02	0.00E+00	4.13E+00	4.93E+02	1.11E+02	7.67E-02	3.78E-02	7.35E+02	2.96E+00
RF-MT0490	5.76E-01	0.00E+00	2.40E-02	2.91E+00	6.56E-01	4.23E-04	5.11E-05	4.17E+00	1.68E-02
RF-MT-0491	4.52E-02	0.00E+00	1.10E-03	1.32E-01	2.96E-02	1.98E-05	3.83E-06	2.08E-01	8.39E-04
RF-MT0523A	3.58E+01	0.00E+00	8.71E-01	1.04E+02	2.35E+01	1.61E-02	1.71E-03	1.65E+02	6.64E-01
RF-MT0523B	3.58E+01	0.00E+00	8.71E-01	1.04E+02	2.35E+01	1.61E-02	1.71E-03	1.65E+02	6.64E-01
RF-MT0523C	3.58E+01	0.00E+00	8.71E-01	1.04E+02	2.35E+01	1.61E-02	1.71E-03	1.65E+02	6.64E-01
RF-MT0523D	3.58E+01	0.00E+00	8.71E-01	1.04E+02	2.35E+01	1.61E-02	1.71E-03	1.65E+02	6.64E-01
RF-MT0523E	3.58E+01	0.00E+00	8.71E-01	1.04E+02	2.35E+01	1.61E-02	1.71E-03	1.65E+02	6.64E-01
RF-MT0531	2.45E-03	0.00E+00	1.44E-04	1.71E-02	3.85E-03	2.67E-06	2.39E-07	2.36E-02	9.49E-05
RF-MT0532E	1.14E+02	0.00E+00	1.87E+00	2.28E+02	5.12E+01	3.44E-02	4.21E-03	3.95E+02	1.59E+00
RF-MT0532F	1.14E+02	0.00E+00	1.87E+00	2.28E+02	5.12E+01	3.44E-02	4.21E-03	3.95E+02	1.59E+00
RF-MT0541	4.16E+00	0.00E+00	2.69E-02	3.23E+00	7.26E-01	5.03E-04	4.48E-05	8.14E+00	3.28E-02
RF-MT0545	2.23E-02	0.00E+00	1.30E-03	1.56E-01	3.50E-02	2.42E-05	2.17E-06	2.15E-01	8.66E-04
RF-MT0800	8.46E+02	0.00E+00	6.45E-01	7.70E+01	1.73E+01	1.20E-02	1.56E-03	9.41E+02	3.79E+00
RF-MT0801	9.73E+01	0.00E+00	6.32E-01	7.57E+01	1.70E+01	1.17E-02	1.05E-03	1.91E+02	7.69E-01
RF-MT0803	2.18E+00	0.00E+00	1.41E-02	1.69E+00	3.80E-01	2.63E-04	2.35E-05	4.27E+00	1.72E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0806	1.03E+00	0.00E+00	3.39E-02	7.35E+00	1.63E+00	4.44E-04	5.65E-05	1.00E+01	4.05E-02
RF-MT0807	1.30E+01	0.00E+00	2.61E-01	3.12E+01	7.03E+00	4.85E-03	4.35E-04	5.15E+01	2.08E-01
RF-MT0816	1.39E+00	0.00E+00	3.68E-02	4.40E+00	9.88E-01	6.87E-04	6.13E-05	6.82E+00	2.75E-02
RF-MT-0823	6.90E-01	0.00E+00	1.68E-02	2.01E+00	4.52E-01	3.11E-04	3.28E-05	3.17E+00	1.28E-02
RF-MT0827	3.52E+01	0.00E+00	9.32E-01	1.11E+02	2.50E+01	1.73E-02	1.55E-03	1.73E+02	6.95E-01
RF-MT0831	6.70E+01	0.00E+00	2.55E+00	3.01E+02	6.79E+01	4.56E-02	1.65E-02	4.39E+02	1.77E+00
RF-MT0832	4.01E+02	0.00E+00	9.26E+00	1.17E+03	2.63E+02	1.63E-01	4.88E-02	1.85E+03	7.44E+00
RF-MT0833	1.22E+02	0.00E+00	2.77E+00	3.39E+02	7.63E+01	4.89E-02	1.38E-02	5.40E+02	2.18E+00
RF-MT0855	2.10E-02	0.00E+00	1.23E-03	1.47E-01	3.31E-02	2.29E-05	2.05E-06	2.02E-01	8.16E-04
RF-MT0857	1.03E+00	0.00E+00	3.37E-02	7.33E+00	1.63E+00	4.43E-04	5.62E-05	1.00E+01	4.04E-02
RF-MT0H61	3.82E+01	0.00E+00	1.25E+00	2.71E+02	6.07E+01	1.64E-02	2.09E-03	3.72E+02	1.50E+00
RF-MT2116	4.30E+00	0.00E+00	9.94E-02	1.25E+01	2.82E+00	1.75E-03	5.23E-04	1.97E+01	7.96E-02
RF-MT3010	2.69E+01	0.00E+00	1.03E+00	1.24E+02	2.82E+01	1.87E-02	2.11E-03	1.80E+02	7.27E-01
RF-MT3011	2.01E+02	0.00E+00	6.43E+00	7.67E+02	1.73E+02	1.20E-01	1.85E-02	1.15E+03	4.63E+00
RF-MT420P	1.07E+03	0.00E+00	3.26E+01	6.31E+03	1.42E+03	3.91E-01	6.42E-02	8.83E+03	3.56E+01
RF-MT532A	2.81E+02	0.00E+00	4.60E+00	5.63E+02	1.26E+02	8.47E-02	1.04E-02	9.75E+02	3.93E+00
RF-MT532B	1.26E+03	0.00E+00	2.07E+01	2.53E+03	5.67E+02	3.81E-01	4.66E-02	4.38E+03	1.76E+01
RF-MT532C	2.53E+03	0.00E+00	4.15E+01	5.06E+03	1.14E+03	7.62E-01	9.37E-02	8.77E+03	3.54E+01
RF-MT532D	1.60E+01	0.00E+00	2.61E-01	3.20E+01	7.18E+00	4.80E-03	5.90E-04	5.55E+01	2.24E-01
RF-TT0069	9.21E-02	0.00E+00	3.10E-03	3.71E-01	8.35E-02	5.79E-05	7.87E-05	5.50E-01	2.22E-03
RF-TT0200	4.37E+00	0.00E+00	1.25E-01	1.52E+01	3.44E+00	2.22E-03	2.09E-04	2.32E+01	9.33E-02
RF-TT0299	1.81E+01	0.00E+00	2.32E-01	2.77E+01	6.24E+00	4.31E-03	3.86E-04	5.23E+01	2.11E-01
RF-TT0300	1.48E+02	0.00E+00	6.61E+00	7.96E+02	1.80E+02	1.05E-01	1.94E-02	1.13E+03	4.56E+00
RF-TT0301	2.00E+01	0.00E+00	8.97E-01	1.08E+02	2.45E+01	1.42E-02	2.63E-03	1.54E+02	6.20E-01
RF-TT0302	9.86E-01	0.00E+00	3.26E-02	4.24E+00	9.55E-01	5.98E-04	4.53E-04	6.21E+00	2.50E-02
RF-TT0303	5.94E+00	0.00E+00	1.90E-01	2.28E+01	5.12E+00	3.53E-03	1.35E-03	3.40E+01	1.37E-01
RF-TT0310	2.02E+01	0.00E+00	8.93E-01	1.02E+02	2.38E+01	1.29E-02	1.67E-03	1.47E+02	5.94E-01
RF-TT0312	4.85E+02	0.00E+00	1.61E+01	2.24E+03	4.99E+02	2.72E-01	2.86E-02	3.24E+03	1.31E+01
RF-TT0317	3.05E-01	0.00E+00	1.75E-02	2.10E+00	4.72E-01	3.26E-04	2.92E-05	2.89E+00	1.17E-02
RF-TT0320	1.96E+02	0.00E+00	5.61E+00	6.84E+02	1.55E+02	9.97E-02	9.40E-03	1.04E+03	4.19E+00
RF-TT0330	6.97E+01	0.00E+00	1.94E+00	4.29E+02	1.04E+02	3.10E-02	3.24E-03	6.05E+02	2.44E+00

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT-0331	3.47E+02	0.00E+00	1.00E+01	1.56E+03	3.44E+02	1.49E-01	7.69E-02	2.26E+03	9.12E+00
RF-TT-0334	1.51E+02	0.00E+00	8.13E+00	9.70E+02	2.18E+02	1.51E-01	1.35E-02	1.35E+03	5.43E+00
RF-TT0335	1.84E+02	0.00E+00	6.16E+00	8.25E+02	1.87E+02	1.02E-01	8.25E-02	1.20E+03	4.85E+00
RF-TT0336	1.63E+02	0.00E+00	5.11E+00	7.31E+02	1.64E+02	7.43E-02	1.15E-02	1.06E+03	4.29E+00
RF-TT0337	1.93E+02	0.00E+00	5.91E+00	9.43E+02	2.08E+02	7.67E-02	2.33E-02	1.35E+03	5.45E+00
RF-TT0338	8.19E+02	0.00E+00	2.14E+01	3.68E+03	8.14E+02	3.43E-01	4.40E-02	5.33E+03	2.15E+01
RF-TT0340	7.01E+00	0.00E+00	4.09E-01	4.89E+01	1.11E+01	7.62E-03	6.82E-04	6.74E+01	2.72E-01
RF-TT0342	4.69E+01	0.00E+00	2.05E+00	2.88E+02	6.37E+01	3.06E-02	6.51E-03	4.01E+02	1.62E+00
RF-TT0360	3.57E+00	0.00E+00	1.04E-01	1.29E+01	2.95E+00	1.81E-03	1.79E-04	1.95E+01	7.88E-02
RF-TT0368	7.14E+01	0.00E+00	2.09E+00	2.59E+02	5.90E+01	3.63E-02	3.60E-03	3.92E+02	1.58E+00
RF-TT0370	1.41E+02	0.00E+00	4.50E+00	5.78E+02	1.30E+02	7.72E-02	1.53E-02	8.53E+02	3.44E+00
RF-TT0371	3.05E+00	0.00E+00	9.06E-02	1.08E+01	2.44E+00	1.68E-03	1.64E-04	1.64E+01	6.62E-02
RF-TT0372	3.73E-01	0.00E+00	1.79E-02	2.12E+00	4.77E-01	2.92E-04	9.81E-05	2.99E+00	1.20E-02
RF-TT0374	1.16E+01	0.00E+00	4.19E-01	5.00E+01	1.13E+01	7.76E-03	7.58E-04	7.33E+01	2.96E-01
RF-TT0375A	1.21E-01	0.00E+00	6.90E-03	8.22E-01	1.85E-01	1.28E-04	1.15E-05	1.14E+00	4.58E-03
RF-TT0375B	1.21E-01	0.00E+00	6.90E-03	8.22E-01	1.85E-01	1.28E-04	1.15E-05	1.14E+00	4.58E-03
RF-TT0376	2.78E+01	0.00E+00	1.02E+00	1.51E+02	3.44E+01	1.73E-02	2.53E-03	2.14E+02	8.64E-01
RF-TT0377	1.56E+01	0.00E+00	5.56E-01	6.64E+01	1.50E+01	1.03E-02	1.46E-03	9.75E+01	3.93E-01
RF-TT0391	3.48E+00	0.00E+00	7.82E-02	1.68E+01	3.73E+00	1.80E-03	1.30E-04	2.41E+01	9.71E-02
RF-TT0392	1.23E+00	0.00E+00	4.91E-02	8.78E+00	1.97E+00	6.26E-04	8.19E-05	1.20E+01	4.85E-02
RF-TT0393	1.01E+02	0.00E+00	3.43E+00	4.09E+02	9.21E+01	6.35E-02	5.71E-03	6.05E+02	2.44E+00
RF-TT0398	2.20E+00	0.00E+00	9.04E-02	1.64E+01	3.66E+00	1.18E-03	1.51E-04	2.24E+01	9.01E-02
RF-TT0409	1.84E+00	0.00E+00	4.23E-02	8.47E+00	1.89E+00	4.54E-04	7.10E-05	1.22E+01	4.94E-02
RF-TT0412	1.84E+00	0.00E+00	4.23E-02	8.47E+00	1.89E+00	4.54E-04	7.10E-05	1.22E+01	4.94E-02
RF-TT0414	5.70E+01	0.00E+00	1.31E+00	2.62E+02	5.84E+01	1.41E-02	2.20E-03	3.79E+02	1.53E+00
RF-TT0430	1.67E-02	0.00E+00	9.77E-04	1.16E-01	2.62E-02	1.81E-05	1.63E-06	1.60E-01	6.46E-04
RF-TT0431	4.14E+00	0.00E+00	2.38E-01	2.86E+01	6.45E+00	4.31E-03	6.18E-04	3.95E+01	1.59E-01
RF-TT0438	2.46E+02	0.00E+00	9.06E+00	1.46E+03	3.27E+02	1.28E-01	1.66E-02	2.04E+03	8.24E+00
RF-TT0440	2.43E+01	0.00E+00	8.81E-01	1.44E+02	3.32E+01	1.43E-02	6.63E-03	2.03E+02	8.16E-01
RF-TT0441	1.20E+02	0.00E+00	4.13E+00	4.98E+02	1.13E+02	7.58E-02	1.15E-02	7.34E+02	2.96E+00
RF-TT0442	1.73E+01	0.00E+00	7.13E-01	9.22E+01	2.07E+01	9.88E-03	6.71E-03	1.31E+02	5.28E-01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0443	3.69E-01	0.00E+00	2.05E-02	2.50E+00	5.61E-01	3.58E-04	5.01E-05	3.45E+00	1.39E-02
RF-TT0479	3.62E+00	0.00E+00	2.13E-01	2.53E+01	5.69E+00	3.93E-03	3.54E-04	3.48E+01	1.40E-01
RF-TT0480	2.46E+02	0.00E+00	8.58E+00	1.03E+03	2.32E+02	1.46E-01	2.19E-02	1.52E+03	6.13E+00
RF-TT0481	1.39E-01	0.00E+00	4.83E-03	5.81E-01	1.31E-01	8.23E-05	1.24E-05	8.55E-01	3.45E-03
RF-TT0483	4.46E-01	0.00E+00	2.61E-02	3.11E+00	7.01E-01	4.85E-04	1.72E-02	4.30E+00	1.74E-02
RF-TT0484	2.39E+00	0.00E+00	1.08E-01	1.29E+01	2.92E+00	2.01E-03	2.91E-04	1.83E+01	7.39E-02
RF-TT0485	1.96E-01	0.00E+00	6.69E-03	7.97E-01	1.80E-01	1.24E-04	2.89E-04	1.18E+00	4.76E-03
RF-TT0486	1.16E+00	0.00E+00	3.96E-02	4.73E+00	1.07E+00	7.34E-04	2.94E-04	7.00E+00	2.82E-02
RF-TT0487	5.82E+00	0.00E+00	1.35E-01	1.70E+01	3.82E+00	2.37E-03	7.08E-04	2.68E+01	1.08E-01
RF-TT0489	1.66E+00	0.00E+00	6.04E-02	7.22E+00	1.62E+00	1.12E-03	2.02E-04	1.06E+01	4.26E-02
RF-TT0490	9.18E+01	0.00E+00	3.84E+00	4.65E+02	1.05E+02	6.73E-02	8.18E-03	6.66E+02	2.68E+00
RF-TT0491	2.14E+00	0.00E+00	5.19E-02	6.23E+00	1.40E+00	9.36E-04	1.82E-04	9.82E+00	3.96E-02
RF-TT0492	7.17E-01	0.00E+00	2.92E-02	3.48E+00	7.85E-01	5.41E-04	4.87E-05	5.01E+00	2.02E-02
RF-TT0523A	4.82E+00	0.00E+00	1.17E-01	1.40E+01	3.16E+00	2.17E-03	2.30E-04	2.21E+01	8.92E-02
RF-TT0523B	4.82E+00	0.00E+00	1.17E-01	1.40E+01	3.16E+00	2.17E-03	2.30E-04	2.21E+01	8.92E-02
RF-TT0523C	4.82E+00	0.00E+00	1.17E-01	1.40E+01	3.16E+00	2.17E-03	2.30E-04	2.21E+01	8.92E-02
RF-TT0523D	4.82E+00	0.00E+00	1.17E-01	1.40E+01	3.16E+00	2.17E-03	2.30E-04	2.21E+01	8.92E-02
RF-TT0523E	4.82E+00	0.00E+00	1.17E-01	1.40E+01	3.16E+00	2.17E-03	2.30E-04	2.21E+01	8.92E-02
RF-TT0532A	1.21E+02	0.00E+00	1.97E+00	2.42E+02	5.42E+01	3.64E-02	4.45E-03	4.19E+02	1.69E+00
RF-TT0532B	1.21E+02	0.00E+00	1.97E+00	2.42E+02	5.42E+01	3.64E-02	4.45E-03	4.19E+02	1.69E+00
RF-TT0541	2.00E-01	0.00E+00	1.17E-02	1.40E+00	3.15E-01	2.18E-04	1.95E-05	1.93E+00	7.78E-03
RF-TT0545	4.46E-02	0.00E+00	2.61E-03	3.11E-01	7.01E-02	4.85E-05	4.35E-06	4.29E-01	1.73E-03
RF-TT0601	1.55E+01	0.00E+00	4.50E-01	5.62E+01	1.28E+01	7.86E-03	7.77E-04	8.49E+01	3.42E-01
RF-TT0802	1.73E+03	0.00E+00	3.70E+01	4.43E+03	9.98E+02	6.87E-01	6.16E-02	7.20E+03	2.90E+01
RF-TT0809	1.42E+02	0.00E+00	3.04E+00	3.65E+02	8.18E+01	5.65E-02	5.06E-03	5.92E+02	2.39E+00
RF-TT0821	3.08E+02	0.00E+00	1.11E+01	1.43E+03	3.23E+02	1.68E-01	1.86E-01	2.07E+03	8.36E+00
RF-TT0822	3.41E+02	0.00E+00	8.60E+00	1.07E+03	2.41E+02	1.50E-01	1.97E-01	1.66E+03	6.71E+00
RF-TT0823	6.90E-01	0.00E+00	1.68E-02	2.01E+00	4.52E-01	3.11E-04	3.28E-05	3.17E+00	1.28E-02
RF-TT0824	7.10E+02	0.00E+00	2.36E+01	2.89E+03	6.51E+02	4.23E-01	1.02E-01	4.28E+03	1.73E+01
RF-TT0825	5.89E+02	0.00E+00	1.70E+01	2.18E+03	4.89E+02	2.80E-01	1.09E-01	3.27E+03	1.32E+01
RF-TT0832	4.36E+02	0.00E+00	1.01E+01	1.27E+03	2.87E+02	1.77E-01	5.31E-02	2.01E+03	8.09E+00

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0854	1.57E-01	0.00E+00	9.20E-03	1.09E+00	2.48E-01	1.71E-04	7.62E-04	1.51E+00	6.08E-03
RF-TT0886	2.23E-02	0.00E+00	1.30E-03	1.55E-01	3.50E-02	2.42E-05	2.16E-06	2.14E-01	8.62E-04
RF-TT2216	6.44E+00	0.00E+00	1.49E-01	1.89E+01	4.23E+00	2.62E-03	7.85E-04	2.97E+01	1.20E-01
RF-TT3010	3.44E+02	0.00E+00	1.32E+01	1.59E+03	3.59E+02	2.40E-01	2.70E-02	2.31E+03	9.30E+00
RF-TT3011	8.69E+02	0.00E+00	2.79E+01	3.32E+03	7.48E+02	5.18E-01	8.01E-02	4.97E+03	2.00E+01
RF-TT301U	7.22E+01	0.00E+00	2.94E+00	3.61E+02	8.26E+01	5.08E-02	5.06E-03	5.19E+02	2.09E+00
RF-TT310P	2.09E+01	0.00E+00	7.66E-01	1.21E+02	2.59E+01	1.06E-02	1.28E-03	1.69E+02	6.81E-01
RF-TT338S	6.10E-01	0.00E+00	3.51E-02	4.19E+00	9.43E-01	6.49E-04	5.84E-05	5.77E+00	2.33E-02
RF-TT390P	3.43E+00	0.00E+00	9.51E-02	2.04E+01	4.22E+00	1.62E-03	1.87E-04	2.81E+01	1.13E-01
RF-TT391P	1.89E+02	0.00E+00	4.27E+00	9.16E+02	2.03E+02	9.83E-02	7.11E-03	1.31E+03	5.29E+00
RF-TT392P	3.83E+02	0.00E+00	1.54E+01	2.74E+03	6.15E+02	1.95E-01	2.57E-02	3.76E+03	1.52E+01
RF-TT393R	5.67E+01	0.00E+00	2.61E+00	4.20E+02	9.47E+01	3.16E-02	4.52E-03	5.74E+02	2.31E+00
RF-TT394P	7.04E+00	0.00E+00	1.62E-01	3.24E+01	6.76E+00	2.27E-03	2.76E-04	4.64E+01	1.87E-01
RF-TT395P	9.42E+00	0.00E+00	2.16E-01	4.33E+01	9.03E+00	3.04E-03	3.70E-04	6.20E+01	2.50E-01
RF-TT396P	2.35E+00	0.00E+00	5.40E-02	1.08E+01	2.26E+00	7.58E-04	9.23E-05	1.55E+01	6.25E-02
RF-TT398P	2.28E+02	0.00E+00	9.36E+00	1.70E+03	3.79E+02	1.22E-01	1.56E-02	2.32E+03	9.34E+00
RF-TT398R	1.88E+03	0.00E+00	1.74E+01	2.74E+03	6.12E+02	2.38E-01	2.90E-02	5.25E+03	2.12E+01
RF-TT411R	6.80E+01	0.00E+00	1.56E+00	3.13E+02	6.98E+01	1.68E-02	2.62E-03	4.53E+02	1.82E+00
RF-TT429R	1.43E+02	0.00E+00	3.35E-01	7.26E+01	1.59E+01	2.93E-03	5.58E-04	2.32E+02	9.34E-01
RF-TT433X	4.50E+01	0.00E+00	9.28E-02	2.09E+01	4.12E+00	1.16E-03	1.55E-04	7.01E+01	2.83E-01
RF-TT436R	3.30E+02	0.00E+00	1.34E+00	2.73E+02	6.08E+01	2.24E-02	2.24E-03	6.65E+02	2.68E+00
RF-TT454X	1.94E+01	0.00E+00	7.89E-02	1.61E+01	3.58E+00	1.32E-03	1.32E-04	3.91E+01	1.58E-01
RL-T101	9.82E+01	0.00E+00	4.80E+00	8.70E+02	1.92E+02	1.87E-01	7.11E-03	1.17E+03	4.70E+00
RL-T102	1.25E-03	0.00E+00	6.10E-05	1.11E-02	2.45E-03	2.37E-06	1.24E-06	1.49E-02	6.00E-05
RL-T103	8.83E+01	0.00E+00	5.81E+00	3.80E+02	8.32E+01	9.93E-02	8.61E-03	5.57E+02	2.25E+00
RL-T104	1.79E-03	0.00E+00	8.71E-05	1.58E-02	3.50E-03	3.40E-06	1.62E-07	2.12E-02	8.54E-05
RL-T105	6.85E-01	0.00E+00	3.29E-02	6.00E+00	1.32E+00	1.28E-03	9.36E-05	8.04E+00	3.24E-02
RL-T106	6.60E-01	0.00E+00	3.24E-02	5.87E+00	1.29E+00	1.26E-03	4.79E-05	7.85E+00	3.17E-02
RL-T107	1.82E+03	0.00E+00	1.90E+04	1.62E+04	3.56E+03	3.45E+00	2.90E+01	4.06E+04	1.64E+02
RL-T108	1.04E+00	0.00E+00	3.28E+00	9.23E+00	2.04E+00	1.98E-03	4.88E-03	1.56E+01	6.28E-02
RL-T109	1.43E+00	0.00E+00	6.74E-02	1.22E+01	2.70E+00	2.62E-03	2.34E-02	1.65E+01	6.63E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T110	1.60E+02	0.00E+00	1.29E+01	1.40E+03	3.10E+02	3.01E-01	1.38E+00	1.89E+03	7.61E+00
RL-T112	6.46E+01	0.00E+00	5.44E+00	1.86E+02	4.10E+01	3.99E-02	7.44E-01	2.98E+02	1.20E+00
RL-T113	6.90E-02	0.00E+00	1.05E-02	6.12E-01	1.35E-01	1.31E-04	1.56E-05	8.27E-01	3.33E-03
RL-T114	1.05E+01	0.00E+00	5.13E-01	9.30E+01	2.05E+01	2.00E-02	7.60E-04	1.25E+02	5.02E-01
RL-T115	2.67E+02	0.00E+00	1.66E+01	1.22E+03	2.70E+02	2.94E-01	4.37E-01	1.78E+03	7.16E+00
RL-T116	1.72E+01	0.00E+00	8.42E-01	1.52E+02	3.37E+01	3.27E-02	5.74E-02	2.04E+02	8.22E-01
RL-T118	4.42E+01	0.00E+00	6.73E+00	1.51E+02	3.34E+01	3.24E-02	8.43E-01	2.36E+02	9.53E-01
RL-T120	1.07E+01	0.00E+00	7.06E-01	4.47E+01	9.78E+00	1.14E-02	1.05E-03	6.59E+01	2.66E-01
RL-T122	6.08E-01	0.00E+00	2.98E-02	5.39E+00	1.19E+00	1.16E-03	1.46E+00	8.68E+00	3.50E-02
RL-T123	1.79E+00	0.00E+00	8.73E-02	1.58E+01	3.50E+00	3.41E-03	5.98E-02	2.13E+01	8.57E-02
RL-T125	3.56E+02	0.00E+00	2.16E+01	3.31E+02	1.68E+02	5.32E-01	3.21E-02	8.77E+02	3.54E+00
RL-T127	3.43E+02	0.00E+00	5.44E+00	9.89E+02	2.18E+02	2.12E-01	8.80E-02	1.56E+03	6.27E+00
RL-T128	5.08E-01	0.00E+00	1.32E-07	2.41E-05	5.29E-06	5.13E-09	1.96E-10	5.08E-01	2.05E-03
RL-T129	1.52E+00	0.00E+00	2.51E+01	1.36E+01	2.98E+00	2.90E-03	4.49E-02	4.33E+01	1.75E-01
RL-T130	3.24E-03	0.00E+00	1.59E-04	2.89E-02	6.37E-03	6.16E-06	8.32E-05	3.88E-02	1.56E-04
RL-T131	1.32E+00	0.00E+00	8.67E-02	5.51E+00	1.20E+00	1.39E-03	8.35E-03	8.12E+00	3.28E-02
RL-T132	3.14E+02	0.00E+00	1.53E+01	2.79E+03	6.15E+02	5.98E-01	2.68E-01	3.74E+03	1.51E+01
RL-T133	6.40E-03	0.00E+00	2.46E-04	4.58E-02	1.01E-02	8.47E-06	3.64E-07	6.25E-02	2.52E-04
RL-T134	1.35E-02	0.00E+00	6.61E-04	1.20E-01	2.64E-02	2.57E-05	9.79E-07	1.61E-01	6.49E-04
RL-T135	6.33E-02	0.00E+00	3.10E-03	5.63E-01	1.24E-01	1.20E-04	4.15E-03	7.57E-01	3.05E-03
RL-T137	1.03E+03	0.00E+00	6.76E+01	4.28E+03	9.39E+02	1.10E+00	1.06E-01	6.32E+03	2.55E+01
RL-T140	1.20E+03	0.00E+00	6.43E+01	4.15E+03	1.01E+03	9.32E-01	2.63E+01	6.45E+03	2.60E+01
RL-T143	7.54E+00	0.00E+00	3.68E-01	6.70E+01	1.48E+01	1.44E-02	3.91E-02	8.97E+01	3.62E-01
RL-T145	2.15E+01	0.00E+00	1.05E+00	1.91E+02	4.20E+01	4.08E-02	9.11E-02	2.55E+02	1.03E+00
RL-W407	6.17E+01	0.00E+00	2.24E+00	4.37E+02	9.65E+01	6.21E-02	3.32E-03	5.98E+02	2.41E+00
RL-W408	2.53E-04	0.00E+00	9.47E-06	1.77E-03	3.90E-04	3.20E-07	1.40E-08	2.42E-03	9.77E-06
RL-W415	5.59E-03	0.00E+00	2.09E-04	3.92E-02	8.63E-03	7.06E-06	3.09E-07	5.36E-02	2.16E-04
RL-W418	2.39E-02	0.00E+00	8.79E-04	1.68E-01	3.71E-02	2.64E-05	1.30E-06	2.30E-01	9.27E-04
RL-W437	2.03E+02	0.00E+00	7.37E+00	1.43E+03	3.16E+02	2.04E-01	1.09E-02	1.96E+03	7.89E+00
RL-W438	3.54E-04	0.00E+00	1.32E-05	2.48E-03	5.45E-04	4.47E-07	1.96E-08	3.39E-03	1.37E-05
RL-W439	1.11E+04	0.00E+00	7.29E+02	4.77E+04	1.05E+04	1.25E+01	1.08E+00	7.00E+04	2.82E+02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W443	1.78E+02	0.00E+00	6.49E+00	1.26E+03	2.78E+02	1.79E-01	9.62E-03	1.73E+03	6.96E+00
RL-W444	1.32E+02	0.00E+00	4.81E+00	9.36E+02	2.06E+02	1.33E-01	7.13E-03	1.28E+03	5.16E+00
RL-W447	1.52E-02	0.00E+00	5.67E-04	1.05E-01	2.34E-02	1.92E-05	8.40E-07	1.45E-01	5.83E-04
RL-W448	1.12E-04	0.00E+00	4.19E-06	7.82E-04	1.72E-04	1.42E-07	6.21E-09	1.07E-03	4.32E-06
RL-W449	9.20E-01	0.00E+00	1.53E-04	2.24E-02	4.93E-03	2.57E-06	2.27E-07	9.47E-01	3.82E-03
RL-W450	1.69E-03	0.00E+00	6.32E-05	1.18E-02	2.60E-03	2.14E-06	9.36E-08	1.62E-02	6.53E-05
RL-W451	2.41E-04	0.00E+00	9.01E-06	1.68E-03	3.71E-04	3.04E-07	1.33E-08	2.30E-03	9.28E-06
RL-W452	1.05E-02	0.00E+00	3.88E-04	7.41E-02	1.63E-02	1.16E-05	5.75E-07	1.01E-01	4.08E-04
RL-W453	2.99E-03	0.00E+00	1.09E-04	2.13E-02	4.68E-03	3.02E-06	1.62E-07	2.91E-02	1.17E-04
RL-W454	4.18E-02	0.00E+00	1.53E-03	2.97E-01	6.55E-02	4.22E-05	2.26E-06	4.06E-01	1.64E-03
RL-W455	1.12E-02	0.00E+00	4.11E-04	7.86E-02	1.73E-02	1.23E-05	6.09E-07	1.08E-01	4.34E-04
RL-W456	1.47E+00	0.00E+00	5.38E-02	1.04E+01	2.30E+00	1.52E-03	7.97E-05	1.43E+01	5.75E-02
RL-W457	1.43E-01	0.00E+00	5.22E-03	1.01E+00	2.23E-01	1.47E-04	7.74E-06	1.39E+00	5.59E-03
RL-W458	4.52E-01	0.00E+00	2.67E-02	4.17E-01	2.29E-01	5.93E-04	3.96E-05	1.12E+00	4.53E-03
RL-W459	4.35E+00	0.00E+00	2.75E-01	1.03E+01	3.12E+00	5.88E-03	4.07E-04	1.81E+01	7.29E-02
RL-W460	2.65E-02	0.00E+00	9.67E-04	1.88E-01	4.15E-02	2.67E-05	1.43E-06	2.57E-01	1.04E-03
RL-W461	2.45E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.45E-02	9.87E-05
RL-W462	7.56E-03	0.00E+00	2.81E-04	5.32E-02	1.17E-02	8.75E-06	4.16E-07	7.28E-02	2.93E-04
RL-W463	3.89E-02	0.00E+00	1.42E-03	2.76E-01	6.09E-02	3.92E-05	2.10E-06	3.78E-01	1.52E-03
RL-W464	1.80E-02	0.00E+00	6.53E-04	1.27E-01	2.80E-02	1.81E-05	9.68E-07	1.74E-01	7.01E-04
RL-W465	1.20E-01	0.00E+00	4.43E-03	8.47E-01	1.87E-01	1.31E-04	6.56E-06	1.16E+00	4.67E-03
RL-W466	1.64E+00	0.00E+00	6.02E-02	1.16E+01	2.56E+00	1.74E-03	8.92E-05	1.59E+01	6.41E-02
RL-W467	8.41E-02	0.00E+00	3.10E-03	5.93E-01	1.30E-01	9.55E-05	4.59E-06	8.10E-01	3.27E-03
RL-W468	4.31E-04	0.00E+00	1.60E-05	3.03E-03	6.68E-04	4.99E-07	2.37E-08	4.15E-03	1.67E-05
RL-W469	1.75E-01	0.00E+00	6.41E-03	1.23E+00	2.73E-01	1.84E-04	9.50E-06	1.69E+00	6.80E-03
RL-W470	4.94E+00	0.00E+00	2.98E-01	4.57E+00	2.33E+00	7.39E-03	4.42E-04	1.21E+01	4.90E-02
RL-W474	1.87E-01	0.00E+00	3.29E-02	1.04E-02	8.81E-03	0.00E+00	4.88E-05	2.40E-01	9.66E-04
RL-W476	3.16E-01	0.00E+00	1.19E-02	2.29E+00	5.06E-01	3.33E-04	1.76E-05	3.12E+00	1.26E-02
RL-W480	5.15E-02	0.00E+00	1.90E-03	3.63E-01	8.01E-02	5.69E-05	2.81E-06	4.96E-01	2.00E-03
RL-W481	8.09E-02	0.00E+00	2.98E-03	5.70E-01	1.25E-01	8.94E-05	4.42E-06	7.79E-01	3.14E-03
RL-W482	1.07E+02	0.00E+00	9.92E-01	7.25E-02	1.33E-01	1.19E-01	1.47E-03	1.09E+02	4.38E-01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W483	8.02E+00	0.00E+00	7.70E-02	4.69E-03	9.45E-03	8.85E-03	1.14E-04	8.11E+00	3.27E-02
RL-W484	3.39E-02	0.00E+00	6.20E-04	6.55E-02	1.55E-02	7.34E-06	9.18E-07	1.16E-01	4.66E-04
RL-W485	1.99E-03	0.00E+00	8.77E-05	7.09E-03	1.67E-03	0.00E+00	1.30E-07	1.08E-02	4.37E-05
RL-W486	8.40E-04	0.00E+00	3.70E-05	2.99E-03	7.03E-04	0.00E+00	5.49E-08	4.57E-03	1.84E-05
RL-W487	1.37E-01	0.00E+00	4.76E-03	4.28E-01	1.16E-01	6.82E-05	7.05E-06	6.87E-01	2.77E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	8.33E-02	0.00E+00	4.48E-03	5.55E-01	1.24E-01	1.10E-04	6.64E-06	7.67E-01	3.09E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	3.09E-02	0.00E+00	3.78E-03	5.82E-02	1.26E-02	4.00E-05	5.60E-06	1.06E-01	4.25E-04
RL-W492	1.78E-03	0.00E+00	9.32E-05	1.16E-02	2.59E-03	2.30E-06	1.38E-07	1.61E-02	6.49E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.07E+01	0.00E+00	5.40E+00	2.93E-01	2.48E-01	9.22E-02	8.00E-03	7.67E+01	3.09E-01
RL-W495	1.28E+00	0.00E+00	1.47E-02	2.81E-03	2.21E-03	1.68E-03	2.18E-05	1.30E+00	5.24E-03
RL-W496	8.31E+00	0.00E+00	1.69E-01	9.25E-03	7.33E-03	1.09E-02	2.50E-04	8.50E+00	3.43E-02
RL-W497	3.46E-01	0.00E+00	3.33E-02	5.55E-01	2.49E-01	2.85E-04	4.94E-05	1.18E+00	4.77E-03
RL-W498	1.34E+00	0.00E+00	4.95E-02	9.48E+00	2.09E+00	1.48E-03	7.34E-05	1.30E+01	5.23E-02
RL-W499	1.21E-05	0.00E+00	4.44E-07	8.50E-05	1.88E-05	1.33E-08	6.59E-10	1.16E-04	4.69E-07
RL-W500	8.59E-04	0.00E+00	5.52E-05	3.47E-03	7.61E-04	9.36E-07	8.17E-08	5.14E-03	2.07E-05
RL-W501	3.56E+01	0.00E+00	1.23E+00	1.11E+02	3.01E+01	1.77E-02	1.82E-03	1.78E+02	7.19E-01
RL-W502	6.43E-03	0.00E+00	2.38E-04	4.53E-02	9.98E-03	7.10E-06	3.52E-07	6.20E-02	2.50E-04
RL-W503	3.72E-01	0.00E+00	2.44E-02	1.60E+00	3.50E-01	4.18E-04	3.61E-05	2.35E+00	9.46E-03
RL-W504	1.37E-01	0.00E+00	4.76E-03	4.28E-01	1.16E-01	6.82E-05	7.05E-06	6.87E-01	2.77E-03
RL-W505	6.46E-03	0.00E+00	2.50E-04	4.63E-02	1.02E-02	8.56E-06	3.70E-07	6.32E-02	2.55E-04
RL-W506	2.34E-03	0.00E+00	9.80E-05	1.52E-02	3.36E-03	2.56E-06	1.45E-07	2.10E-02	8.47E-05
RL-W507	2.33E-04	0.00E+00	8.58E-06	1.64E-03	3.61E-04	2.57E-07	1.27E-08	2.24E-03	9.04E-06
RL-W508	4.27E+00	0.00E+00	2.81E-01	1.78E+01	3.90E+00	4.55E-03	4.16E-04	2.63E+01	1.06E-01
RL-W509	4.21E+01	0.00E+00	2.24E+00	1.45E+02	3.51E+01	3.27E-02	3.32E-03	2.25E+02	9.06E-01
RL-W510	3.55E+00	0.00E+00	2.30E-01	1.44E+01	3.16E+00	3.89E-03	3.41E-04	2.14E+01	8.61E-02
RL-W511	3.61E+02	0.00E+00	1.11E+01	1.93E+03	4.17E+02	2.12E-01	1.68E-02	2.72E+03	1.10E+01
RL-W512	3.16E+02	0.00E+00	7.49E+00	1.16E+03	2.86E+02	1.08E-01	1.11E-02	1.77E+03	7.15E+00
RL-W513	3.37E+04	0.00E+00	3.04E+03	1.90E+04	9.31E+03	1.72E+01	4.51E+00	6.51E+04	2.62E+02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W514	9.51E-04	0.00E+00	3.49E-05	6.73E-03	1.49E-03	1.00E-06	5.17E-08	9.20E-03	3.71E-05
RL-W515	3.72E-02	0.00E+00	1.37E-03	2.62E-01	5.77E-02	4.10E-05	2.03E-06	3.59E-01	1.45E-03
RL-W516	5.16E-02	0.00E+00	1.90E-03	3.63E-01	8.01E-02	5.69E-05	2.82E-06	4.96E-01	2.00E-03
RL-W517	4.60E-10	0.00E+00	1.70E-11	3.23E-09	7.11E-10	5.32E-13	2.52E-14	4.42E-09	1.78E-11
RL-W518	1.30E+00	0.00E+00	7.15E-02	4.63E+00	1.11E+00	1.14E-03	1.06E-04	7.11E+00	2.87E-02
RL-W519	2.32E-01	0.00E+00	8.48E-03	1.64E+00	3.61E-01	2.41E-04	1.26E-05	2.24E+00	9.04E-03
RL-W520	2.56E-02	0.00E+00	9.55E-04	1.80E-01	3.96E-02	3.10E-05	1.42E-06	2.46E-01	9.92E-04
RL-W521	4.76E-04	0.00E+00	1.75E-05	3.35E-03	7.40E-04	5.27E-07	2.60E-08	4.58E-03	1.85E-05
RL-W522	9.95E+00	0.00E+00	6.51E-01	2.22E+01	6.27E+00	7.62E-03	9.65E-04	3.90E+01	1.57E-01
RL-W523	2.99E+00	0.00E+00	2.48E-01	1.47E+00	8.83E-01	1.51E-03	3.67E-04	5.59E+00	2.26E-02
RL-W524	1.24E+01	0.00E+00	9.47E-01	1.35E+01	5.18E+00	7.20E-03	1.40E-03	3.20E+01	1.29E-01
RL-W525	9.85E-01	0.00E+00	6.41E-02	1.60E+00	5.23E-01	5.65E-04	9.50E-05	3.17E+00	1.28E-02
RL-W526	3.73E+00	0.00E+00	2.32E-01	1.71E+01	3.78E+00	4.11E-03	3.44E-04	2.48E+01	1.00E-01
RL-W527	4.09E-01	0.00E+00	3.35E-02	1.81E+00	4.25E-01	4.80E-04	4.97E-05	2.68E+00	1.08E-02
RL-W528	1.83E+02	0.00E+00	1.43E+01	5.77E+01	5.46E+01	7.34E-02	2.11E-02	3.09E+02	1.25E+00
RL-W529	1.52E-01	0.00E+00	1.00E-02	6.36E-01	1.39E-01	1.62E-04	1.48E-05	9.37E-01	3.78E-03
RL-W530	1.79E+00	0.00E+00	1.16E-01	7.27E+00	1.60E+00	1.97E-03	1.72E-04	1.08E+01	4.34E-02
RL-W531	1.07E+02	0.00E+00	1.17E+01	3.14E+01	2.24E+01	5.22E-02	1.73E-02	1.73E+02	6.96E-01
RL-W532	3.44E-01	0.00E+00	1.27E-02	2.43E+00	5.34E-01	3.79E-04	1.88E-05	3.32E+00	1.34E-02
RL-W533	1.66E-01	0.00E+00	1.09E-02	6.94E-01	1.52E-01	1.76E-04	1.62E-05	1.02E+00	4.12E-03
RL-W534	9.60E-06	0.00E+00	3.53E-07	6.77E-05	1.50E-05	1.06E-08	5.23E-10	9.26E-05	3.73E-07
RL-W535	5.03E+01	0.00E+00	3.49E+00	8.68E+01	2.62E+01	3.23E-02	5.17E-03	1.67E+02	6.72E-01
RL-W536	9.84E-01	0.00E+00	4.70E-02	3.01E+00	6.75E-01	7.39E-04	7.28E-05	4.72E+00	1.90E-02
RL-W537	3.35E+01	0.00E+00	1.06E+00	1.85E+02	4.01E+01	2.07E-02	1.60E-03	2.60E+02	1.05E+00
RL-W538	1.22E-04	0.00E+00	4.48E-06	8.60E-04	1.90E-04	1.35E-07	6.64E-09	1.18E-03	4.74E-06
RL-W539	1.35E-02	0.00E+00	5.05E-04	9.50E-02	2.09E-02	1.64E-05	7.48E-07	1.30E-01	5.24E-04
RL-W540	2.63E+01	0.00E+00	2.22E+00	3.42E+01	1.16E+01	1.57E-02	3.29E-03	7.44E+01	3.00E-01
RL-W541	3.92E-02	0.00E+00	1.46E-03	2.75E-01	6.07E-02	4.61E-05	2.16E-06	3.77E-01	1.52E-03
RL-W542	1.82E+00	0.00E+00	1.08E-01	6.97E+00	1.60E+00	1.89E-03	1.60E-04	1.05E+01	4.23E-02
RL-W543	5.73E-03	0.00E+00	2.11E-04	4.04E-02	8.90E-03	6.35E-06	3.12E-07	5.52E-02	2.23E-04
RL-W544	1.29E-01	0.00E+00	8.60E-03	4.59E-01	1.14E-01	1.26E-04	1.27E-05	7.10E-01	2.86E-03

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W545	3.43E-02	0.00E+00	1.26E-03	2.42E-01	5.33E-02	3.78E-05	1.87E-06	3.30E-01	1.33E-03
RL-W546	1.50E-03	0.00E+00	5.54E-05	1.06E-02	2.34E-03	1.66E-06	8.20E-08	1.45E-02	5.86E-05
RL-W547	3.84E-05	0.00E+00	1.42E-06	2.70E-04	5.97E-05	4.23E-08	2.10E-09	3.70E-04	1.49E-06
RL-W548	3.32E-05	0.00E+00	1.23E-06	2.34E-04	5.16E-05	3.79E-08	1.82E-09	3.20E-04	1.29E-06
RL-W549	6.60E+00	0.00E+00	4.93E-01	1.20E+01	3.54E+00	4.80E-03	7.31E-04	2.27E+01	9.14E-02
RL-W550	2.99E+01	0.00E+00	9.34E-01	1.63E+02	3.54E+01	1.81E-02	1.40E-03	2.29E+02	9.25E-01
RL-W551	5.32E+01	0.00E+00	1.38E+00	1.84E+02	4.62E+01	1.92E-02	2.05E-03	2.85E+02	1.15E+00
RL-W552	2.06E-02	0.00E+00	7.64E-04	1.45E-01	3.19E-02	2.40E-05	1.13E-06	1.98E-01	8.00E-04
RL-W553	1.83E-03	0.00E+00	7.21E-05	1.29E-02	2.85E-03	3.04E-06	1.07E-07	1.77E-02	7.13E-05
RL-W554	2.90E-02	0.00E+00	1.07E-03	2.05E-01	4.52E-02	3.20E-05	1.59E-06	2.80E-01	1.13E-03
RL-W555	1.34E-02	0.00E+00	4.93E-04	9.43E-02	2.07E-02	1.48E-05	7.31E-07	1.29E-01	5.20E-04
RL-W563	1.92E-01	0.00E+00	1.23E-02	7.82E-01	1.71E-01	2.01E-04	1.83E-05	1.16E+00	4.67E-03
RL-W564	1.25E-01	0.00E+00	8.19E-03	5.06E-01	1.11E-01	1.55E-04	1.21E-05	7.50E-01	3.02E-03
RL-W565	1.24E-02	0.00E+00	4.60E-04	8.74E-02	1.93E-02	1.44E-05	6.82E-07	1.20E-01	4.82E-04
RL-W566	1.82E-01	0.00E+00	6.74E-03	1.28E+00	2.84E-01	2.04E-04	9.99E-06	1.76E+00	7.08E-03
RL-W567	1.26E+01	0.00E+00	1.72E-01	3.95E-02	3.15E-02	1.73E-02	2.55E-04	1.29E+01	5.19E-02
RL-W568	2.43E+02	0.00E+00	3.63E+00	1.87E+00	1.47E+00	3.58E-01	5.37E-03	2.50E+02	1.01E+00
RL-W569	2.00E-01	0.00E+00	2.73E-03	6.23E-04	4.99E-05	2.74E-04	4.04E-06	2.03E-01	8.19E-04
RL-W570	1.28E-02	0.00E+00	4.78E-04	9.27E-02	2.04E-02	1.35E-05	7.08E-07	1.26E-01	5.09E-04
RL-W571	4.10E+01	0.00E+00	1.62E+00	7.52E+00	3.72E+00	5.46E-02	2.40E-03	5.39E+01	2.17E-01
RL-W572	3.56E-02	0.00E+00	4.85E-04	4.05E-03	8.90E-05	4.89E-05	7.19E-07	4.02E-02	1.62E-04
RL-W573	4.58E+02	0.00E+00	6.22E+00	2.22E+00	1.64E+00	6.21E-01	9.21E-03	4.69E+02	1.89E+00
RL-W574	1.97E+03	0.00E+00	2.69E+01	8.47E+00	6.09E+00	2.71E+00	3.99E-02	2.01E+03	8.12E+00
RL-W575	1.28E+04	0.00E+00	1.81E+02	8.10E+01	4.86E+01	1.70E+01	2.68E-01	1.32E+04	5.30E+01
RL-W576	9.26E+02	0.00E+00	1.27E+01	4.13E+00	2.94E+00	1.28E+00	1.87E-02	9.45E+02	3.81E+00
RL-W579	7.84E-02	0.00E+00	3.33E-04	2.07E-02	4.57E-03	4.50E-06	4.94E-07	1.04E-01	4.19E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.65E-01	2.66E-02	0.00E+00	0.00E+00	1.92E-01	7.73E-04
RL-W581	8.32E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.32E-01	3.36E-03
RL-W582	5.44E-03	0.00E+00	2.83E-04	5.29E-03	2.71E-03	7.29E-07	4.19E-07	1.37E-02	5.53E-05
RL-W583	4.21E-03	0.00E+00	1.54E-04	2.98E-02	6.58E-03	4.24E-06	2.28E-07	4.08E-02	1.64E-04
RL-W584	8.37E-02	0.00E+00	1.01E-02	1.74E-01	8.43E-02	2.13E-05	1.49E-05	3.52E-01	1.42E-03

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W585	4.98E-01	0.00E+00	5.36E-02	1.01E+00	5.13E-01	6.49E-04	7.94E-05	2.08E+00	8.38E-03
RL-W586	6.64E-05	0.00E+00	2.42E-06	4.71E-04	1.04E-04	6.68E-08	3.58E-09	6.44E-04	2.60E-06
RL-W587	1.42E-03	0.00E+00	5.22E-05	1.00E-02	2.22E-03	1.50E-06	7.74E-08	1.37E-02	5.54E-05
RL-W588	5.86E-02	0.00E+00	8.50E-03	1.47E-01	7.10E-02	1.79E-05	1.26E-05	2.85E-01	1.15E-03
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	1.80E+00	0.00E+00	1.81E-01	1.13E-02	2.00E-02	2.35E-03	2.69E-04	2.01E+00	8.12E-03
RL-W591	1.03E+01	0.00E+00	2.05E-01	1.40E-02	2.58E-02	1.42E-02	3.03E-04	1.05E+01	4.24E-02
RL-W592	4.53E+01	0.00E+00	2.24E+00	6.50E-01	8.36E-01	5.74E-02	3.32E-03	4.90E+01	1.98E-01
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.35E-02	3.92E-02	0.00E+00	0.00E+00	6.27E-02	2.53E-04
RL-W594	4.08E+01	0.00E+00	4.04E-01	2.90E-02	5.30E-02	1.44E-02	5.98E-04	4.13E+01	1.67E-01
RL-W595	1.08E-01	0.00E+00	4.21E-02	1.99E-02	3.85E-02	1.42E-04	6.24E-05	2.08E-01	8.40E-04
RL-W596	3.49E-02	0.00E+00	3.28E-03	2.05E-04	3.62E-04	4.27E-05	4.85E-06	3.88E-02	1.56E-04
RL-W597	6.42E+01	0.00E+00	1.44E+00	3.97E-01	6.56E-01	7.95E-02	2.13E-03	6.67E+01	2.69E-01
RL-W598	6.79E+01	0.00E+00	8.50E+00	5.53E-01	8.19E-01	8.23E-02	1.26E-02	7.78E+01	3.14E-01
RL-W599	3.44E+00	0.00E+00	6.86E-02	4.67E-03	8.63E-03	4.75E-03	1.02E-04	3.52E+00	1.42E-02
RL-W600	1.95E-07	0.00E+00	7.11E-09	1.38E-06	3.05E-07	1.97E-10	1.05E-11	1.89E-06	7.62E-09
RL-W601	9.90E-04	0.00E+00	3.90E-05	7.00E-03	1.55E-03	1.65E-06	5.78E-08	9.57E-03	3.86E-05
RL-W602	8.62E-01	0.00E+00	3.20E-02	6.06E+00	1.34E+00	9.97E-04	4.74E-05	8.30E+00	3.35E-02
RL-W603	4.97E+00	0.00E+00	1.84E-01	3.50E+01	7.72E+00	5.74E-03	2.73E-04	4.79E+01	1.93E-01
RL-W604	1.16E-02	0.00E+00	4.83E-04	1.70E-02	8.32E-03	6.82E-06	7.16E-07	3.74E-02	1.51E-04
RL-W605	2.66E-03	0.00E+00	1.05E-04	1.88E-02	4.15E-03	4.43E-06	1.56E-07	2.57E-02	1.04E-04
RL-W606	1.08E-03	0.00E+00	4.23E-05	7.58E-03	1.67E-03	1.79E-06	6.27E-08	1.04E-02	4.18E-05
RL-W607	1.97E-03	0.00E+00	8.19E-05	2.87E-03	1.41E-03	1.15E-06	1.21E-07	6.33E-03	2.55E-05
RL-W608	2.35E-02	0.00E+00	3.18E-03	3.74E-03	4.57E-03	1.77E-05	4.71E-06	3.50E-02	1.41E-04
RL-W610	4.66E+00	0.00E+00	1.70E-01	3.30E+01	7.28E+00	4.70E-03	2.52E-04	4.51E+01	1.82E-01
RL-W612	1.10E-02	0.00E+00	4.11E-04	8.01E-02	1.77E-02	1.11E-05	6.09E-07	1.09E-01	4.40E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.36E-01	0.00E+00	0.00E+00	0.00E+00	3.36E-01	1.36E-03
RL-W622	1.83E-04	0.00E+00	6.71E-06	1.30E-03	2.87E-04	1.85E-07	9.94E-09	1.78E-03	7.17E-06
RL-W625	6.39E-03	0.00E+00	1.02E-03	6.65E-03	6.48E-03	1.00E-05	1.51E-06	2.05E-02	8.28E-05
RL-W626	3.43E-01	0.00E+00	2.32E-02	2.60E-01	1.55E-01	1.75E-04	3.44E-05	7.81E-01	3.15E-03
RL-W627	1.62E-03	0.00E+00	3.10E-05	1.23E-06	0.00E+00	2.08E-06	4.59E-08	1.65E-03	6.65E-06

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W628	5.30E-04	0.00E+00	1.95E-05	3.76E-03	8.28E-04	5.60E-07	2.89E-08	5.14E-03	2.07E-05
RL-W629	3.59E-05	0.00E+00	1.34E-06	2.53E-04	5.56E-05	4.35E-08	1.98E-09	3.45E-04	1.39E-06
RL-W630	3.95E-01	0.00E+00	2.50E-02	2.92E+00	6.70E-01	4.71E-04	3.70E-05	4.01E+00	1.62E-02
RL-W631	6.37E-03	0.00E+00	2.51E-04	4.48E-02	9.88E-03	1.06E-05	3.73E-07	6.13E-02	2.47E-04
RL-W632	2.81E+00	0.00E+00	3.39E-02	5.93E+00	1.93E+00	3.52E-03	5.03E-05	1.07E+01	4.31E-02
RL-W633	6.70E-03	0.00E+00	1.97E-04	9.30E-04	8.14E-04	4.33E-06	2.92E-07	8.65E-03	3.49E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	1.01E-02	0.00E+00	0.00E+00	0.00E+00	1.01E-02	4.09E-05
RL-W635	4.01E+01	0.00E+00	6.65E+00	4.31E+00	6.39E+00	4.38E-02	9.85E-03	5.74E+01	2.32E-01
RL-W636	4.09E-01	0.00E+00	1.26E-02	5.64E-02	4.94E-02	2.66E-04	1.86E-05	5.27E-01	2.13E-03
RL-W637	9.72E-04	0.00E+00	3.20E-04	6.34E-04	6.16E-04	9.55E-07	4.74E-07	2.54E-03	1.03E-05
RL-W638	4.27E-02	0.00E+00	3.26E-03	6.21E-03	5.79E-03	3.56E-05	4.82E-06	5.80E-02	2.34E-04
RL-W639	2.26E-03	0.00E+00	8.32E-05	1.59E-02	3.50E-03	2.49E-06	1.23E-07	2.18E-02	8.77E-05
RL-W640	7.58E-02	0.00E+00	2.77E-03	5.36E-01	1.18E-01	8.00E-05	4.10E-06	7.33E-01	2.95E-03
RL-W641	2.31E+00	0.00E+00	6.08E-01	2.58E+00	1.05E+00	1.28E-03	9.01E-04	6.54E+00	2.64E-02
RL-W642	4.51E-02	0.00E+00	6.32E-05	3.14E-02	1.59E-04	5.55E-07	9.36E-08	7.68E-02	3.10E-04
RL-W643	7.11E-01	0.00E+00	1.87E-01	7.93E-01	3.23E-01	3.95E-04	2.78E-04	2.02E+00	8.13E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.46E-02	0.00E+00	0.00E+00	0.00E+00	5.46E-02	2.20E-04
RL-W645	1.73E-02	0.00E+00	8.42E-04	1.07E-01	2.50E-02	2.16E-05	1.25E-06	1.50E-01	6.07E-04
RL-W646	1.57E-02	0.00E+00	7.52E-04	2.57E-02	1.23E-02	1.05E-05	1.12E-06	5.44E-02	2.20E-04
RL-W647	4.42E-02	0.00E+00	1.13E-01	1.09E-01	1.71E-02	3.51E-05	1.67E-04	2.83E-01	1.14E-03
RL-W648	7.83E-04	0.00E+00	1.92E-04	5.97E-05	1.16E-04	1.12E-06	2.85E-07	1.15E-03	4.65E-06
RL-W649	2.88E-03	0.00E+00	7.08E-04	2.20E-04	4.28E-04	4.13E-06	1.05E-06	4.24E-03	1.71E-05
RL-W653	1.36E-04	0.00E+00	5.07E-06	9.60E-04	2.11E-04	1.58E-07	7.51E-09	1.31E-03	5.29E-06
RL-W654	7.50E-04	0.00E+00	2.77E-05	5.29E-03	1.16E-03	8.28E-07	4.10E-08	7.23E-03	2.92E-05
RL-W655	1.85E+02	0.00E+00	6.55E+00	2.10E-01	4.90E-01	2.21E-01	9.70E-03	1.92E+02	7.74E-01
RL-W656	7.73E+02	0.00E+00	2.94E+00	4.93E-01	5.04E-01	1.05E+00	4.36E-03	7.77E+02	3.14E+00
RL-W657	3.95E+02	0.00E+00	4.35E+00	2.43E-01	4.79E-01	4.66E-01	6.44E-03	4.00E+02	1.61E+00
RL-W659	4.78E+01	0.00E+00	9.80E-01	4.67E-02	5.74E-02	5.27E-02	1.45E-03	4.89E+01	1.97E-01
RL-W660	2.62E+02	0.00E+00	1.18E+01	8.62E-01	1.53E+00	3.01E-01	1.75E-02	2.76E+02	1.11E+00
RL-W661	2.77E+00	0.00E+00	1.48E-02	4.16E-04	3.75E-03	3.65E-03	2.19E-05	2.79E+00	1.13E-02
RL-W662	8.72E-02	0.00E+00	8.79E-04	1.06E-04	1.89E-04	7.48E-05	1.30E-06	8.84E-02	3.57E-04

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W665	1.07E+03	0.00E+00	7.04E+01	1.30E+00	1.73E+00	1.49E+00	1.04E-01	1.15E+03	4.62E+00
RL-W666	1.92E+01	0.00E+00	1.72E-01	5.46E-02	5.69E-02	2.15E-02	2.55E-04	1.95E+01	7.85E-02
RL-W668	1.83E+00	0.00E+00	5.42E-03	1.44E-01	4.05E-02	5.08E-05	8.03E-06	2.02E+00	8.14E-03
RL-W669	5.33E-01	0.00E+00	1.41E-01	5.94E-01	2.42E-01	2.96E-04	2.08E-04	1.51E+00	6.09E-03
RL-W670	3.37E-02	0.00E+00	1.00E-04	2.66E-03	7.49E-04	9.41E-07	1.48E-07	3.72E-02	1.50E-04
RL-W671	5.50E+00	0.00E+00	5.13E-02	4.88E-03	5.03E-03	3.09E-03	7.60E-05	5.56E+00	2.24E-02
RL-W672	3.74E+01	0.00E+00	3.49E-01	3.33E-02	3.41E-02	2.10E-02	5.17E-04	3.78E+01	1.52E-01
RL-W673	3.60E+01	0.00E+00	3.35E-01	3.22E-02	3.30E-02	2.02E-02	4.97E-04	3.64E+01	1.47E-01
RL-W674	1.21E-01	0.00E+00	1.50E-02	1.11E+01	9.59E-02	1.41E-04	2.22E-05	1.14E+01	4.58E-02
RL-W675	4.52E-01	0.00E+00	8.28E-02	1.30E-01	1.12E-01	3.44E-04	1.23E-04	7.77E-01	3.13E-03
RL-W676	1.74E-02	0.00E+00	4.97E-04	1.46E-01	2.10E-03	1.02E-05	7.37E-07	1.66E-01	6.70E-04
RL-W677	4.02E+01	0.00E+00	1.23E+00	5.71E+00	4.91E+00	2.46E-02	1.83E-03	5.21E+01	2.10E-01
RL-W678	1.27E-01	0.00E+00	1.03E-02	5.13E-02	4.48E-02	1.93E-04	1.53E-05	2.34E-01	9.42E-04
RL-W679	7.97E-01	0.00E+00	2.30E-02	1.10E-01	9.65E-02	4.94E-04	3.41E-05	1.03E+00	4.14E-03
RL-W680	1.80E-04	0.00E+00	3.24E-05	1.73E-05	3.08E-05	2.12E-07	4.79E-08	2.60E-04	1.05E-06
RL-W681	1.10E-04	0.00E+00	1.31E-05	4.64E-04	2.29E-04	1.76E-07	1.94E-08	8.16E-04	3.29E-06
RL-W685	3.19E-01	0.00E+00	1.17E-02	2.27E+00	4.99E-01	3.22E-04	1.73E-05	3.10E+00	1.25E-02
RL-W689	8.27E-03	0.00E+00	1.40E-04	3.85E-04	0.00E+00	3.09E-07	2.07E-07	8.80E-03	3.55E-05
RL-W690	2.78E-01	0.00E+00	1.03E-02	2.02E+00	4.43E-01	2.80E-04	1.53E-05	2.75E+00	1.11E-02
RL-W691	6.44E-03	0.00E+00	2.40E-04	4.67E-02	1.03E-02	6.49E-06	3.55E-07	6.37E-02	2.57E-04
RL-W692	2.55E-01	0.00E+00	9.49E-03	1.85E+00	4.07E-01	2.56E-04	1.41E-05	2.52E+00	1.02E-02
RL-W693	3.15E-01	0.00E+00	1.17E-02	2.29E+00	5.04E-01	3.17E-04	1.74E-05	3.12E+00	1.26E-02
RL-W694	3.31E+00	0.00E+00	1.23E-01	2.42E+01	5.28E+00	3.34E-03	1.82E-04	3.29E+01	1.33E-01
RL-W695	2.74E-03	0.00E+00	0.00E+00	2.38E-03	0.00E+00	0.00E+00	0.00E+00	5.12E-03	2.06E-05
RL-W696	3.57E-03	0.00E+00	4.48E-04	2.89E-03	2.83E-03	4.58E-06	6.64E-07	9.74E-03	3.93E-05
RL-W697	8.25E-01	0.00E+00	9.49E-01	6.89E-03	9.36E-04	0.00E+00	1.41E-03	1.78E+00	7.19E-03
RL-W698	7.15E-02	0.00E+00	0.00E+00	3.27E-05	0.00E+00	0.00E+00	0.00E+00	7.16E-02	2.89E-04
RL-W699	1.59E-02	0.00E+00	6.32E-05	2.19E-03	2.54E-04	1.92E-05	9.36E-08	1.84E-02	7.42E-05
RL-W700	4.51E-03	0.00E+00	1.66E-04	3.17E-02	7.00E-03	4.99E-06	2.46E-07	4.34E-02	1.75E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W704	1.78E-01	0.00E+00	4.68E-02	1.98E-01	8.07E-02	9.88E-05	6.93E-05	5.03E-01	2.03E-03
RL-W705	1.15E-03	0.00E+00	4.31E-05	8.31E-03	1.84E-03	1.21E-06	6.38E-08	1.13E-02	4.57E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	4.10E-02	0.00E+00	1.53E-03	2.96E-01	6.54E-02	4.31E-05	2.27E-06	4.04E-01	1.63E-03
RL-W708	6.19E-03	0.00E+00	2.32E-04	4.49E-02	9.88E-03	6.54E-06	3.44E-07	6.12E-02	2.47E-04
RL-W709	2.14E+00	0.00E+00	7.99E-02	1.55E+01	3.41E+00	2.26E-03	1.18E-04	2.11E+01	8.53E-02
RL-W710	1.28E-04	0.00E+00	4.78E-06	9.27E-04	2.04E-04	1.35E-07	7.08E-09	1.26E-03	5.09E-06
RL-W711	3.99E-02	0.00E+00	1.49E-03	2.89E-01	6.37E-02	4.21E-05	2.21E-06	3.94E-01	1.59E-03
RL-W712	5.16E-02	0.00E+00	1.93E-03	3.74E-01	8.24E-02	5.46E-05	2.86E-06	5.10E-01	2.06E-03
RL-W713	4.46E-02	0.00E+00	1.67E-03	3.22E-01	7.12E-02	4.71E-05	2.47E-06	4.40E-01	1.77E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	7.70E-04	0.00E+00	2.81E-05	5.46E-03	1.20E-03	7.76E-07	4.16E-08	7.46E-03	3.01E-05
RL-W716	8.02E-03	0.00E+00	2.92E-04	5.69E-02	1.25E-02	8.09E-06	4.33E-07	7.77E-02	3.13E-04
RL-W717	2.00E-03	0.00E+00	7.31E-05	1.42E-02	3.13E-03	2.02E-06	1.08E-07	1.94E-02	7.83E-05
RL-W718	3.53E-04	0.00E+00	1.29E-05	2.51E-03	5.52E-04	3.56E-07	1.91E-08	3.42E-03	1.38E-05
RL-W719	1.59E-03	0.00E+00	5.81E-05	1.13E-02	2.50E-03	1.61E-06	8.61E-08	1.55E-02	6.24E-05
RL-W720	9.86E-03	0.00E+00	3.61E-04	7.00E-02	1.55E-02	9.93E-06	5.34E-07	9.57E-02	3.86E-04
RL-W721	6.68E-03	0.00E+00	2.44E-04	4.73E-02	1.05E-02	6.73E-06	3.61E-07	6.47E-02	2.61E-04
RL-W723	2.21E-02	0.00E+00	8.23E-04	1.61E-01	3.54E-02	2.23E-05	1.22E-06	2.19E-01	8.85E-04
RL-W724	1.47E-01	0.00E+00	5.48E-03	1.06E+00	2.36E-01	1.48E-04	8.12E-06	1.45E+00	5.86E-03
RL-W725	4.65E-02	0.00E+00	1.73E-03	3.37E-01	7.44E-02	4.68E-05	2.56E-06	4.60E-01	1.85E-03
RL-W726	3.66E-02	0.00E+00	1.36E-03	2.66E-01	5.86E-02	3.69E-05	2.02E-06	3.63E-01	1.46E-03
RL-W727	2.24E-01	0.00E+00	8.36E-03	1.63E+00	3.60E-01	2.26E-04	1.24E-05	2.22E+00	8.96E-03
RL-W728	2.04E-01	0.00E+00	7.62E-03	1.49E+00	3.28E-01	2.06E-04	1.13E-05	2.03E+00	8.19E-03
RL-W729	9.44E-02	0.00E+00	3.53E-03	6.86E-01	1.52E-01	9.50E-05	5.23E-06	9.36E-01	3.77E-03
RL-W730	3.70E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.70E+01	1.49E-01
RL-W731	1.19E-05	0.00E+00	0.00E+00	4.48E-04	1.82E-06	0.00E+00	0.00E+00	4.62E-04	1.86E-06
RL-W732	2.73E+01	0.00E+00	2.01E+00	1.26E+02	2.77E+01	3.41E-02	2.98E-03	1.83E+02	7.39E-01
RL-W733	3.58E-01	0.00E+00	2.61E-02	1.37E+00	3.37E-01	3.70E-04	3.87E-05	2.09E+00	8.44E-03
RL-W734	1.12E+00	0.00E+00	8.71E-02	4.73E+00	1.14E+00	1.10E-03	1.29E-04	7.08E+00	2.85E-02
RL-W735	9.16E-01	0.00E+00	6.65E-02	3.69E+00	9.05E-01	8.56E-04	9.85E-05	5.58E+00	2.25E-02

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W736	1.01E-03	0.00E+00	1.42E-07	2.45E-03	6.24E-04	2.62E-07	2.10E-10	4.08E-03	1.64E-05
RL-W737	8.17E-01	0.00E+00	6.06E-02	3.50E+00	8.42E-01	7.39E-04	8.98E-05	5.22E+00	2.11E-02
RL-W738	3.05E+00	0.00E+00	2.09E-01	1.11E+01	2.91E+00	2.68E-03	3.09E-04	1.73E+01	6.98E-02
RL-W739	2.60E-01	0.00E+00	1.84E-02	1.81E+00	4.08E-01	2.43E-04	2.73E-05	2.50E+00	1.01E-02
RL-W740	1.30E+01	0.00E+00	6.74E-01	4.40E+01	1.14E+01	1.23E-02	9.99E-04	6.91E+01	2.79E-01
RL-W741	1.94E+01	0.00E+00	1.59E+00	8.58E+00	6.03E+00	9.22E-03	2.35E-03	3.56E+01	1.44E-01
RL-W742	8.65E-01	0.00E+00	4.78E-02	2.78E+00	6.49E-01	7.90E-04	7.08E-05	4.34E+00	1.75E-02
RL-W743	1.56E-03	0.00E+00	1.30E-05	1.80E-03	0.00E+00	0.00E+00	1.92E-08	3.37E-03	1.36E-05
RL-W744	0.00E+00	0.00E+00	0.00E+00	8.98E-02	7.55E-02	0.00E+00	0.00E+00	1.65E-01	6.67E-04
RL-W745	2.46E-03	0.00E+00	9.06E-05	1.74E-02	3.83E-03	2.72E-06	1.34E-07	2.38E-02	9.59E-05
RL-W746	9.47E-03	0.00E+00	3.49E-04	6.68E-02	1.48E-02	1.04E-05	5.17E-07	9.14E-02	3.69E-04
RL-W747	2.57E-02	0.00E+00	9.45E-04	1.81E-01	3.99E-02	2.83E-05	1.40E-06	2.47E-01	9.98E-04
RL-W748	1.80E+02	0.00E+00	2.65E+00	3.00E-01	4.88E-01	2.13E-01	3.93E-03	1.83E+02	7.39E-01
RL-W749	2.16E-01	0.00E+00	8.11E-03	1.57E+00	3.45E-01	2.28E-04	1.20E-05	2.14E+00	8.63E-03
RL-W750	2.73E+02	0.00E+00	4.02E+00	4.92E-01	7.97E-01	3.02E-01	5.95E-03	2.78E+02	1.12E+00
RL-W751	2.46E+02	0.00E+00	3.63E+00	4.42E-01	7.23E-01	2.72E-01	5.37E-03	2.51E+02	1.01E+00
RL-W752	1.07E+02	0.00E+00	1.58E+00	1.93E-01	3.14E-01	1.18E-01	2.33E-03	1.09E+02	4.40E-01
RL-W753	1.44E+03	0.00E+00	2.13E+01	2.59E+00	4.22E+00	1.59E+00	3.15E-02	1.47E+03	5.92E+00
RP-W754	6.11E+01	0.00E+00	2.69E+00	1.85E+03	1.50E+02	1.47E-02	3.57E-01	2.06E+03	8.32E+00
RP-W755	3.24E+02	0.00E+00	1.61E+00	1.38E+03	1.14E+02	1.10E-02	1.26E+01	1.83E+03	7.39E+00
SA-T001	6.51E-01	1.73E-03	3.86E-02	3.01E+00	1.76E-02	0.00E+00	6.18E-05	3.72E+00	1.50E-02
SA-W134	5.31E+00	6.71E-07	2.63E-01	1.37E+00	4.30E-01	2.80E-04	1.67E-01	7.55E+00	3.04E-02
SA-W134M	6.90E-01	8.70E-08	3.41E-02	1.79E-01	5.58E-02	3.63E-05	2.16E-02	9.80E-01	3.95E-03
T001-221F-HET	1.29E+03	0.00E+00	3.08E+04	2.86E+04	6.99E+02	9.17E-01	5.13E+01	6.15E+04	2.48E+02
T001-221H-HET	2.31E+03	0.00E+00	5.56E+04	5.17E+04	1.26E+03	1.66E+00	9.25E+01	1.11E+05	4.47E+02
T001-235F-HET	1.33E+02	0.00E+00	3.20E+03	2.97E+03	7.25E+01	9.50E-02	5.32E+00	6.38E+03	2.57E+01
T001-772F-HET	1.15E+03	0.00E+00	2.77E+04	2.57E+04	6.25E+02	8.19E-01	4.61E+01	5.51E+04	2.22E+02
T001-773A-CLAS	1.29E+01	0.00E+00	3.10E+02	2.88E+02	7.01E+00	9.22E-03	5.16E-01	6.19E+02	2.49E+00
T001-773A-HET	1.48E+02	0.00E+00	3.57E+03	3.32E+03	8.10E+01	1.06E-01	5.94E+00	7.12E+03	2.87E+01
W006-773A-VIT	1.99E-03	0.00E+00	0.00E+00	5.34E+02	0.00E+00	0.00E+00	0.00E+00	5.34E+02	2.15E+00
W026-221F-HET	4.47E+02	0.00E+00	1.07E+04	1.00E+04	2.44E+02	3.19E-01	1.79E+01	2.15E+04	8.67E+01

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W026-221H-HET	3.34E+02	0.00E+00	8.03E+03	7.48E+03	1.82E+02	2.39E-01	1.34E+01	1.60E+04	6.47E+01
W026-235F-HET	5.21E+00	0.00E+00	1.25E+02	1.16E+02	2.84E+00	3.72E-03	2.08E-01	2.50E+02	1.01E+00
W026-772F-HET	1.42E+00	0.00E+00	3.41E+01	3.17E+01	7.73E-01	1.02E-03	5.68E-02	6.81E+01	2.75E-01
W026-773A-HET	2.31E+01	0.00E+00	5.56E+02	5.17E+02	1.26E+01	1.65E-02	9.25E-01	1.11E+03	4.47E+00
W027-221F-HET	1.69E+03	0.00E+00	3.63E+04	3.88E+04	9.43E+02	5.22E-01	7.15E+01	7.77E+04	3.13E+02
W027-221H-HET	7.38E+02	0.00E+00	1.58E+04	1.70E+04	4.13E+02	2.28E-01	3.13E+01	3.40E+04	1.37E+02
W027-235F-HET	2.22E+02	0.00E+00	4.76E+03	5.11E+03	1.24E+02	6.87E-02	9.40E+00	1.02E+04	4.12E+01
W027-772F-HET	4.04E+02	0.00E+00	8.65E+03	9.28E+03	2.26E+02	1.25E-01	1.71E+01	1.86E+04	7.49E+01
W027-773A-HET	6.02E+02	0.00E+00	1.29E+04	1.38E+04	3.37E+02	1.86E-01	2.55E+01	2.77E+04	1.12E+02
W027-999-HET	6.88E+02	0.00E+00	1.48E+04	1.58E+04	3.85E+02	2.13E-01	2.91E+01	3.17E+04	1.28E+02
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.97E+02	0.00E+00	0.00E+00	0.00E+00	3.97E+02	1.60E+00
WP-INW169.001	3.36E+00	0.00E+00	9.30E-02	1.53E+01	3.37E+00	1.88E-03	3.03E-04	2.21E+01	8.92E-02
WP-INW198.001	4.43E+00	0.00E+00	1.62E-01	2.74E+01	5.99E+00	3.08E-03	3.22E-04	3.80E+01	1.53E-01
WP-INW211.001	4.99E+02	0.00E+00	1.52E+01	2.55E+03	5.56E+02	3.49E-01	2.45E-02	3.61E+03	1.46E+01
WP-INW216.001-	1.81E+04	0.00E+00	8.75E+00	1.47E+03	3.23E+02	1.93E-01	2.90E-01	1.99E+04	8.03E+01
WP-INW216.001-	4.98E+03	0.00E+00	2.36E+00	3.99E+02	8.71E+01	5.22E-02	3.11E-02	5.47E+03	2.20E+01
WP-INW218.001-	3.46E+02	0.00E+00	1.54E+00	2.57E+02	5.62E+01	3.49E-02	3.88E-01	6.61E+02	2.67E+00
WP-INW218.001-	1.60E+00	0.00E+00	4.25E-02	6.98E+00	1.53E+00	9.88E-04	3.74E-02	1.02E+01	4.11E-02
WP-INW222.001	1.64E+01	0.00E+00	4.58E-01	6.82E+01	1.51E+01	8.37E-03	1.25E-03	1.00E+02	4.04E-01
WP-INW243.001	3.98E+01	0.00E+00	9.88E-01	1.43E+02	3.17E+01	1.69E-02	2.33E-03	2.16E+02	8.69E-01
WP-INW247.001R	5.31E+01	0.00E+00	2.30E+00	2.74E+02	6.16E+01	2.94E-02	3.49E-03	3.91E+02	1.58E+00
WP-INW276.001	4.05E+00	0.00E+00	2.24E-01	2.71E+01	6.11E+00	2.49E-03	3.49E-04	3.75E+01	1.51E-01
WP-INW276.002	6.42E+00	0.00E+00	3.37E-01	3.99E+01	9.16E+00	3.74E-03	5.26E-04	5.58E+01	2.25E-01
WP-INW276.003	2.46E+02	0.00E+00	1.25E+01	1.48E+03	3.34E+02	1.57E-01	1.90E-02	2.07E+03	8.36E+00
WP-INW276.004	5.88E+01	0.00E+00	2.65E+00	3.13E+02	7.04E+01	3.32E-02	4.07E-03	4.45E+02	1.79E+00
WP-INW296.001-	2.15E+01	0.00E+00	6.30E-01	7.86E+01	1.76E+01	8.52E-03	9.70E-04	1.18E+02	4.77E-01
WP-INW296.001-	6.48E+01	0.00E+00	2.22E+00	2.78E+02	6.22E+01	3.07E-02	3.65E-03	4.08E+02	1.64E+00
WP-LA-TA-55-19	1.08E+00	0.00E+00	1.03E-01	2.08E+00	4.96E-01	3.05E-04	2.79E-03	3.76E+00	1.52E-02
WP-LA-TA-55-19	5.22E+01	0.00E+00	3.47E+00	2.12E+02	5.11E+01	3.03E-02	9.23E-02	3.19E+02	1.29E+00
WP-LA-TA-55-43	2.93E-01	0.00E+00	8.09E+01	3.21E-01	1.34E-01	2.72E-04	1.46E-01	8.18E+01	3.30E-01
WP-RF001.01	9.07E+01	0.00E+00	2.81E+00	4.08E+02	9.17E+01	3.05E-02	1.35E-02	5.93E+02	2.39E+00

Table PAR-54. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 175 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF002.01-A	1.06E+02	0.00E+00	3.74E+00	4.59E+02	1.04E+02	6.73E-02	2.33E-02	6.72E+02	2.71E+00
WP-RF002.01-B	1.05E-01	0.00E+00	2.59E-03	4.97E-01	1.12E-01	4.23E-05	4.03E-06	7.16E-01	2.89E-03
WP-RF003.01	1.64E+03	0.00E+00	6.02E+01	8.78E+03	1.98E+03	1.11E+00	9.76E-02	1.25E+04	5.02E+01
WP-RF004.01	7.69E-01	0.00E+00	4.04E-02	5.06E+00	1.15E+00	6.35E-04	1.87E-04	7.01E+00	2.83E-02
WP-RF005.01	3.94E+03	0.00E+00	3.06E+01	4.64E+03	1.04E+03	4.42E-01	4.72E-02	9.65E+03	3.89E+01
WP-RF005.02	4.64E+03	0.00E+00	1.58E+01	2.77E+03	6.15E+02	2.27E-01	2.46E-02	8.04E+03	3.24E+01
WP-RF006.01	1.51E+03	0.00E+00	5.75E+01	7.89E+03	1.78E+03	5.74E-01	1.11E-01	1.12E+04	4.53E+01
WP-RF008.01	4.77E+02	0.00E+00	2.05E+01	2.31E+03	5.29E+02	3.79E-01	3.16E-02	3.33E+03	1.34E+01
WP-RF009.01	4.70E+04	0.00E+00	2.51E+02	5.06E+04	1.12E+04	4.35E+00	3.93E-01	1.09E+05	4.40E+02
WP-RF010.01	1.73E+01	0.00E+00	6.37E-01	7.64E+01	1.72E+01	1.34E-02	1.68E-03	1.12E+02	4.50E-01
WP-RF029.01-A	4.16E+00	0.00E+00	1.20E-01	1.34E+01	3.03E+00	3.07E-03	9.07E-04	2.07E+01	8.36E-02
WP-RF029.01-B	6.22E+00	0.00E+00	9.49E-02	1.06E+01	2.40E+00	2.43E-03	2.39E-03	1.94E+01	7.80E-02
WP-RF118.01	1.06E+04	0.00E+00	4.78E+02	5.11E+04	1.13E+04	8.00E+00	9.23E-01	7.34E+04	2.96E+02
WP-RLMPDT.001	2.24E+00	0.00E+00	1.39E-01	7.32E+00	1.88E+00	1.76E-03	2.09E-04	1.16E+01	4.67E-02
WP-RLNPDT.002	2.75E+01	0.00E+00	1.33E+00	7.19E+01	1.91E+01	2.01E-02	2.01E-03	1.20E+02	4.83E-01
WP-SR2001.001.	8.77E-01	0.00E+00	1.53E-01	6.79E+00	1.33E+00	1.10E-03	2.31E-04	9.15E+00	3.69E-02
WP-SR-W027-221	6.49E+00	0.00E+00	4.48E-01	1.95E+01	5.37E+00	4.94E-03	1.87E-01	3.20E+01	1.29E-01
Total	3.47E+05	3.35E+00	3.14E+05	6.56E+05	1.05E+05	1.13E+02	6.33E+02	1.42E+06	5.74E+03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	4.94E+01	0.00E+00	8.71E-01	2.07E+02	1.19E+02	2.47E-06	1.94E-02	3.76E+02	1.52E+00
AE-T003	6.26E+00	0.00E+00	1.16E-01	6.39E+01	2.40E+01	1.35E-06	9.21E-04	9.43E+01	3.80E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	2.77E-02	0.00E+00	3.07E+00	4.71E+01	2.77E-01	2.63E-09	2.19E-02	5.05E+01	2.04E-01
AW-T033.1325	1.01E-01	0.00E+00	1.13E+01	1.72E+02	1.01E+00	9.63E-09	8.03E-02	1.85E+02	7.44E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.65E-01	0.00E+00	0.00E+00	0.00E+00	7.65E-01	3.08E-03
BCLCH-MT01	1.02E+01	0.00E+00	8.71E+01	2.84E+01	7.24E+00	3.72E-06	6.07E-01	1.34E+02	5.39E-01
BT-T002	7.52E-03	1.13E-09	4.55E-02	7.17E-04	1.43E-03	1.63E-09	2.31E-03	5.75E-02	2.32E-04
ET-C1-B55	3.14E-02	0.00E+00	5.19E-04	6.14E-02	2.98E-02	2.88E-09	2.39E-04	1.23E-01	4.97E-04
ET-C1-D139	4.31E-03	0.00E+00	7.19E-05	8.63E-03	4.19E-03	3.83E-10	5.63E-07	1.72E-02	6.94E-05
ET-C2-SEFOR	1.07E-01	0.00E+00	0.00E+00	1.36E-01	4.43E-02	5.91E-09	0.00E+00	2.86E-01	1.16E-03
FM-MOX-MT02	1.01E-06	0.00E+00	2.90E-08	2.97E-07	1.72E-07	2.06E-13	2.10E-10	1.51E-06	6.08E-09
FM-MOX-T01	1.67E-05	0.00E+00	4.78E-07	4.89E-06	2.83E-06	3.39E-12	3.47E-09	2.49E-05	1.00E-07
IN-BN-510	4.03E+03	0.00E+00	2.47E+03	3.93E+04	3.24E+03	8.10E-07	1.92E+01	4.90E+04	1.98E+02
IN-GEM-01	5.10E+01	0.00E+00	4.89E-02	4.41E+01	9.80E+00	5.71E-07	3.41E-04	1.05E+02	4.23E-01
IN-GEM-02	1.21E+01	0.00E+00	1.16E-02	1.05E+01	2.33E+00	1.35E-07	8.12E-05	2.49E+01	1.01E-01
IN-W157.144	6.04E+01	0.00E+00	4.74E-01	3.00E+02	6.60E+01	1.01E-05	3.68E-03	4.27E+02	1.72E+00
IN-W163.1007	1.03E+01	0.00E+00	1.46E-01	9.30E+01	2.05E+01	3.12E-06	1.14E-03	1.24E+02	5.00E-01
IN-W164.153	9.90E-02	0.00E+00	1.39E-03	8.85E-01	1.95E-01	2.99E-08	1.08E-05	1.18E+00	4.76E-03
IN-W167.149	1.98E+01	0.00E+00	2.27E-01	1.43E+02	3.16E+01	4.83E-06	1.76E-03	1.95E+02	7.86E-01
IN-W174.154	0.00E+00	0.00E+00	1.28E+02	1.93E+00	3.70E+00	0.00E+00	9.95E-01	1.35E+02	5.44E-01
IN-W177.156	1.37E-02	0.00E+00	2.73E+02	1.81E+00	1.08E-02	4.15E-09	2.12E+00	2.76E+02	1.12E+00
IN-W179.158	9.24E-02	0.00E+00	2.72E+02	1.05E-01	5.30E-02	2.79E-08	2.11E+00	2.74E+02	1.10E+00
IN-W181.162	1.31E+00	0.00E+00	1.85E-02	1.17E+01	2.57E+00	3.96E-07	1.44E-04	1.56E+01	6.28E-02
IN-W188.160	8.82E+00	0.00E+00	1.24E-01	7.88E+01	1.73E+01	2.67E-06	9.65E-04	1.05E+02	4.24E-01
IN-W216.98	7.84E+04	0.00E+00	1.01E+01	6.43E+03	1.42E+03	2.18E-04	7.86E-02	8.63E+04	3.48E+02

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	3.96E+02	0.00E+00	2.25E-01	1.42E+02	3.14E+01	4.82E-06	1.75E-03	5.70E+02	2.30E+00
IN-W219.110	5.38E-01	0.00E+00	7.58E-03	4.81E+00	1.06E+00	1.62E-07	5.89E-05	6.41E+00	2.58E-02
IN-W219.914	8.48E-02	0.00E+00	1.19E-03	7.59E-01	1.67E-01	2.56E-08	9.27E-06	1.01E+00	4.08E-03
IN-W220.114	2.80E+03	0.00E+00	7.97E-01	5.43E+02	1.16E+02	1.70E-05	6.19E-03	3.46E+03	1.40E+01
IN-W221.927	3.28E+00	0.00E+00	4.62E-02	2.93E+01	6.43E+00	9.92E-07	3.59E-04	3.90E+01	1.57E-01
IN-W222.116	1.12E+02	0.00E+00	1.57E+00	9.89E+02	2.18E+02	3.35E-05	1.22E-02	1.32E+03	5.32E+00
IN-W228.101	7.41E+02	0.00E+00	5.09E-01	3.23E+02	7.11E+01	1.10E-05	3.95E-03	1.14E+03	4.58E+00
IN-W240.931	7.84E+01	0.00E+00	6.51E-01	4.15E+02	9.09E+01	1.38E-05	5.05E-03	5.85E+02	2.36E+00
IN-W243.808	1.09E+02	0.00E+00	1.14E+00	7.25E+02	1.59E+02	2.45E-05	8.85E-03	9.94E+02	4.01E+00
IN-W245.301	1.61E+02	0.00E+00	2.24E+00	1.41E+03	3.12E+02	4.78E-05	1.74E-02	1.89E+03	7.62E+00
IN-W247.810	7.83E+01	0.00E+00	1.09E+00	6.91E+02	1.53E+02	2.33E-05	8.47E-03	9.23E+02	3.72E+00
IN-W249.527	0.00E+00	0.00E+00	7.63E+01	1.23E+01	0.00E+00	0.00E+00	5.93E-01	8.92E+01	3.60E-01
IN-W263.520	2.24E-02	0.00E+00	7.97E+00	8.34E+00	1.29E-02	6.77E-09	6.19E-02	1.64E+01	6.62E-02
IN-W267.1005	1.88E+01	0.00E+00	2.65E-01	1.68E+02	3.70E+01	5.67E-06	2.06E-03	2.24E+02	9.04E-01
IN-W309.609	5.03E+02	0.00E+00	4.44E+00	2.81E+03	6.18E+02	9.48E-05	3.45E-02	3.94E+03	1.59E+01
IN-W315.601	4.96E+02	0.00E+00	1.85E-02	1.18E+01	2.58E+00	3.96E-07	1.44E-04	5.10E+02	2.06E+00
IN-W319.584	2.89E+00	0.00E+00	4.06E-02	2.58E+01	5.70E+00	8.71E-07	3.15E-04	3.44E+01	1.39E-01
IN-W321.1023	2.50E+01	0.00E+00	3.52E-01	2.24E+02	4.92E+01	7.54E-06	2.74E-03	2.98E+02	1.20E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	9.02E+00	1.82E+00	0.00E+00	0.00E+00	1.08E+01	4.37E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.40E+01	4.84E+00	0.00E+00	0.00E+00	2.89E+01	1.16E-01
IN-W323.562	5.34E-02	0.00E+00	5.97E-02	2.46E-01	0.00E+00	1.61E-08	4.64E-04	3.60E-01	1.45E-03
IN-W323.951	6.30E-02	0.00E+00	7.09E-04	2.94E-01	0.00E+00	1.90E-08	5.51E-06	3.57E-01	1.44E-03
IN-W332.661	0.00E+00	0.00E+00	7.83E-01	1.28E-01	0.00E+00	0.00E+00	6.08E-03	9.16E-01	3.70E-03
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	3.01E+00	6.05E-01	0.00E+00	0.00E+00	3.61E+00	1.46E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	9.02E+00	1.82E+00	0.00E+00	0.00E+00	1.08E+01	4.37E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.93E+00	0.00E+00	0.00E+00	0.00E+00	1.93E+00	7.78E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.80E+00	0.00E+00	0.00E+00	0.00E+00	5.80E+00	2.34E-02
IN-W342.652	2.47E+00	0.00E+00	0.00E+00	3.98E-02	9.99E-18	0.00E+00	0.00E+00	2.51E+00	1.01E-02
IN-W342.953	1.65E+00	0.00E+00	0.00E+00	2.66E-02	6.70E-18	0.00E+00	0.00E+00	1.67E+00	6.75E-03
IN-W347.818	1.29E+00	0.00E+00	0.00E+00	8.17E+01	1.46E+02	0.00E+00	1.58E-08	2.29E+02	9.23E-01
IN-W348.1012	6.83E-02	0.00E+00	6.46E-01	4.12E+02	9.09E+01	0.00E+00	5.02E-03	5.04E+02	2.03E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.47E-02	0.00E+00	0.00E+00	0.00E+00	2.47E-02	9.97E-05
IN-W357.1022	0.00E+00	0.00E+00	1.27E-03	8.10E-01	1.78E-01	0.00E+00	9.88E-06	9.89E-01	3.99E-03
IN-W358.854	0.00E+00	0.00E+00	1.92E+01	1.86E+00	3.49E+00	0.00E+00	1.42E-01	2.47E+01	9.95E-02
IN-W358.855	0.00E+00	0.00E+00	1.02E+02	9.89E+00	1.85E+01	0.00E+00	7.55E-01	1.31E+02	5.30E-01
IN-W358.948	0.00E+00	0.00E+00	2.13E+01	2.07E+00	3.86E+00	0.00E+00	1.58E-01	2.74E+01	1.11E-01
IN-W361.1021	1.82E-02	0.00E+00	1.23E-01	7.81E+01	1.72E+01	0.00E+00	9.57E-04	9.55E+01	3.85E-01
IN-W362.1020	0.00E+00	0.00E+00	1.61E+00	1.02E+03	2.26E+02	0.00E+00	1.25E-02	1.25E+03	5.02E+00
IN-W363.1019	0.00E+00	0.00E+00	7.58E-02	4.84E+01	1.07E+01	0.00E+00	5.89E-04	5.91E+01	2.38E-01
IN-W364.1011	0.00E+00	0.00E+00	1.25E-01	7.95E+01	1.75E+01	0.00E+00	9.73E-04	9.71E+01	3.92E-01
IN-W365.1010	1.69E+02	0.00E+00	9.93E-02	6.28E+01	1.38E+01	0.00E+00	7.71E-04	2.46E+02	9.91E-01
IN-W366.841	6.02E-01	0.00E+00	8.46E-02	5.35E+01	1.18E+01	0.00E+00	6.57E-04	6.60E+01	2.66E-01
IN-W372.832	2.47E+00	0.00E+00	0.00E+00	3.98E-02	9.99E-18	0.00E+00	0.00E+00	2.51E+00	1.01E-02
IN-W375.1096	0.00E+00	0.00E+00	3.12E-02	1.98E+01	4.35E+00	0.00E+00	2.42E-04	2.42E+01	9.74E-02
KN-B234TRU	8.76E+01	0.00E+00	1.19E+00	2.88E+02	9.41E+01	5.30E-06	1.03E-02	4.71E+02	1.90E+00
LA-IT-00-01	1.27E+00	7.29E-07	2.04E-01	5.79E-01	1.22E-02	1.02E-15	1.77E-03	2.07E+00	8.35E-03
LA-OS-00-01	2.83E+03	0.00E+00	9.30E+03	1.22E+03	0.00E+00	0.00E+00	6.53E+01	1.34E+04	5.41E+01
LA-PX-00-01	1.18E-02	0.00E+00	3.92E-04	8.95E-02	2.05E-02	1.68E-09	2.87E-06	1.22E-01	4.93E-04
LA-SL-00-01	0.00E+00	0.00E+00	8.27E-03	1.51E-01	0.00E+00	0.00E+00	7.15E-05	1.60E-01	6.44E-04
LA-TA-03-12	1.22E-01	0.00E+00	1.91E-01	4.31E-01	1.46E-01	9.98E-09	1.72E-03	8.92E-01	3.60E-03
LA-TA-03-13	1.57E-01	0.00E+00	6.07E-01	6.74E-01	1.54E-01	1.32E-08	4.76E-03	1.60E+00	6.44E-03
LA-TA-03-19	3.18E-01	0.00E+00	9.05E-01	1.32E+00	3.70E-01	2.05E-08	8.10E-03	2.92E+00	1.18E-02
LA-TA-03-20	1.73E-01	0.00E+00	4.30E-01	5.80E-01	1.99E-01	1.67E-08	3.68E-03	1.39E+00	5.58E-03
LA-TA-03-24	2.32E-01	0.00E+00	1.67E+00	1.08E+00	3.18E-01	1.74E-08	1.51E-02	3.32E+00	1.34E-02
LA-TA-03-26	1.19E-02	0.00E+00	6.90E-02	2.61E+00	4.16E-02	1.52E-09	1.49E-03	2.74E+00	1.10E-02
LA-TA-03-28	0.00E+00	0.00E+00	2.39E-02	2.44E-01	0.00E+00	0.00E+00	2.12E-04	2.68E-01	1.08E-03
LA-TA-03-30	5.30E-01	0.00E+00	1.70E-02	4.98E+00	1.40E+00	7.95E-08	1.50E-04	6.92E+00	2.79E-02
LA-TA-03-31	0.00E+00	0.00E+00	8.51E-04	8.70E-03	0.00E+00	0.00E+00	7.54E-06	9.56E-03	3.86E-05
LA-TA-03-40	0.00E+00	0.00E+00	1.35E-03	5.41E-02	0.00E+00	0.00E+00	1.20E-05	5.55E-02	2.24E-04
LA-TA-03-42	1.22E-05	0.00E+00	3.37E-05	3.38E-03	4.33E-05	1.66E-12	3.01E-07	3.47E-03	1.40E-05
LA-TA-21-06	1.20E-01	0.00E+00	3.71E+00	9.47E-01	2.81E-01	1.72E-08	3.29E-02	5.09E+00	2.05E-02
LA-TA-21-12	4.37E-01	0.00E+00	2.24E+01	3.28E+00	9.55E-01	5.89E-08	1.98E-01	2.72E+01	1.10E-01

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-13	6.72E-01	0.00E+00	0.00E+00	2.91E-01	0.00E+00	0.00E+00	0.00E+00	9.63E-01	3.88E-03
LA-TA-21-14	1.10E-04	0.00E+00	4.27E-01	4.44E+00	5.04E-05	2.39E-11	3.15E-03	4.87E+00	1.96E-02
LA-TA-21-15	6.51E-02	0.00E+00	1.17E-03	1.38E+00	2.29E-01	9.68E-09	1.03E-05	1.67E+00	6.73E-03
LA-TA-21-16	7.54E-01	0.00E+00	1.81E-02	1.05E+01	2.44E+00	1.02E-07	1.62E-04	1.37E+01	5.52E-02
LA-TA-21-40	9.57E-05	0.00E+00	6.26E-02	3.29E-01	3.54E-04	4.09E-12	6.87E-04	3.93E-01	1.59E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	7.01E-01	0.00E+00	0.00E+00	0.00E+00	7.01E-01	2.83E-03
LA-TA-21-42	9.78E-03	0.00E+00	2.04E-02	1.62E-01	1.08E-02	1.33E-10	2.38E-04	2.03E-01	8.20E-04
LA-TA-21-43	3.45E+01	0.00E+00	6.75E-01	5.05E+02	1.17E+02	1.05E-06	7.84E-03	6.58E+02	2.65E+00
LA-TA-21-44	1.66E-01	0.00E+00	1.42E-01	1.14E+02	2.95E-01	1.49E-08	1.36E-03	1.14E+02	4.61E-01
LA-TA-48-01	5.36E-02	3.43E-06	5.33E-04	1.17E-01	4.76E-01	1.23E-09	5.91E-06	6.47E-01	2.61E-03
LA-TA-49-01	6.62E+00	4.26E-04	6.56E-02	1.44E+01	5.89E+01	1.52E-07	7.28E-04	8.00E+01	3.23E-01
LA-TA-50-10	1.77E-02	0.00E+00	6.21E-04	4.54E-02	0.00E+00	0.00E+00	4.52E-06	6.38E-02	2.57E-04
LA-TA-50-11	3.38E-02	0.00E+00	6.36E-04	4.61E-01	9.99E-02	1.22E-09	6.91E-06	5.95E-01	2.40E-03
LA-TA-50-15	6.67E-02	0.00E+00	9.39E-02	3.36E-01	7.35E-02	4.82E-09	7.76E-04	5.71E-01	2.30E-03
LA-TA-50-17	9.76E+00	0.00E+00	7.63E-02	1.80E+01	4.13E-04	4.41E-10	9.70E-04	2.78E+01	1.12E-01
LA-TA-50-18	5.80E-01	0.00E+00	1.01E-02	2.94E+00	5.15E-06	1.30E-11	9.00E-05	3.53E+00	1.42E-02
LA-TA-50-19	1.85E-01	0.00E+00	4.49E-03	3.91E-01	4.41E-03	1.61E-10	6.69E-05	5.85E-01	2.36E-03
LA-TA-50-20	5.08E-03	0.00E+00	0.00E+00	9.63E-03	0.00E+00	0.00E+00	0.00E+00	1.47E-02	5.93E-05
LA-TA-50-40	2.86E-03	0.00E+00	6.07E-05	1.05E-02	4.77E-03	5.16E-10	5.16E-07	1.82E-02	7.33E-05
LA-TA-50-41	3.05E-03	0.00E+00	6.12E-05	4.65E-02	1.06E-02	9.20E-10	4.75E-07	6.02E-02	2.43E-04
LA-TA-55-19	4.73E+00	0.00E+00	8.07E-02	2.61E+01	7.17E+00	5.21E-07	2.23E-03	3.81E+01	1.54E-01
LA-TA-55-20	7.59E+01	0.00E+00	9.20E-01	6.31E+02	1.48E+02	1.30E-05	1.01E-01	8.56E+02	3.45E+00
LA-TA-55-21	6.78E-01	1.02E-09	1.06E-02	4.47E+00	1.05E+00	1.07E-07	8.14E-05	6.21E+00	2.50E-02
LA-TA-55-22	1.86E+00	0.00E+00	5.97E-02	1.57E+01	3.59E+00	3.33E-07	4.60E-04	2.12E+01	8.56E-02
LA-TA-55-23	1.75E+00	0.00E+00	4.99E-02	1.08E+01	2.60E+00	3.27E-07	3.81E-04	1.52E+01	6.12E-02
LA-TA-55-24	6.60E-01	0.00E+00	7.83E-03	5.66E+00	1.29E+00	1.56E-07	5.74E-05	7.61E+00	3.07E-02
LA-TA-55-25	3.38E+00	0.00E+00	4.56E-02	2.81E+01	6.41E+00	7.98E-07	3.35E-04	3.79E+01	1.53E-01
LA-TA-55-28	1.15E+00	0.00E+00	2.53E-02	8.63E+00	1.99E+00	2.59E-07	1.87E-04	1.18E+01	4.75E-02
LA-TA-55-30	2.57E+01	9.61E-12	3.03E-01	1.41E+02	3.33E+01	1.90E-06	2.88E-03	2.01E+02	8.09E-01
LA-TA-55-32	2.08E+00	0.00E+00	1.69E+00	1.12E+01	3.37E+00	2.37E-07	1.53E-02	1.83E+01	7.39E-02
LA-TA-55-33	3.12E-01	0.00E+00	4.37E-03	1.47E+00	4.59E-01	3.33E-08	3.68E-05	2.25E+00	9.07E-03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-34	3.15E+01	0.00E+00	4.04E-01	2.29E+02	5.67E+01	4.01E-06	6.18E-03	3.17E+02	1.28E+00
LA-TA-55-38	7.92E+01	0.00E+00	1.33E-01	5.04E+01	1.33E+01	9.33E-07	2.82E-03	1.43E+02	5.77E-01
LA-TA-55-39	8.37E+00	0.00E+00	9.83E-02	7.53E+01	1.65E+01	1.64E-06	7.45E-04	1.00E+02	4.04E-01
LA-TA-55-41	1.99E+02	0.00E+00	2.04E-01	9.34E+01	2.18E+01	2.07E-06	1.58E-03	3.15E+02	1.27E+00
LA-TA-55-43	7.49E-02	0.00E+00	1.34E+01	1.40E-01	4.80E-02	1.82E-08	1.00E-01	1.37E+01	5.53E-02
LA-TA-55-44	6.50E-01	0.00E+00	3.15E+01	2.60E+00	7.05E-01	5.37E-08	2.67E-01	3.57E+01	1.44E-01
LA-TA-55-48	4.79E+03	0.00E+00	1.24E+02	1.67E+04	6.09E+03	5.61E-04	1.03E+00	2.77E+04	1.12E+02
LA-TA-55-49	1.02E+01	0.00E+00	1.63E+02	3.06E+01	8.38E+00	6.56E-07	1.38E+00	2.14E+02	8.63E-01
LA-TA-55-53	4.82E+01	0.00E+00	3.38E-01	2.61E+02	5.95E+01	3.59E-06	2.81E-03	3.69E+02	1.49E+00
LA-TA-55-56	5.34E+01	0.00E+00	1.26E+01	3.78E+02	9.26E+01	8.32E-06	9.93E-02	5.37E+02	2.16E+00
LA-TA-55-60	2.90E-02	0.00E+00	3.18E-03	7.12E-02	2.47E-02	4.90E-09	2.68E-05	1.28E-01	5.16E-04
LA-TA-55-61	2.49E-02	0.00E+00	1.46E-02	1.38E-01	4.55E-02	4.76E-09	1.21E-04	2.23E-01	8.98E-04
LA-TA-55-62	6.46E-03	0.00E+00	1.39E-04	2.31E-02	1.08E-02	1.28E-09	1.16E-06	4.04E-02	1.63E-04
LA-TA-55-63	4.79E-03	0.00E+00	9.39E-05	7.39E-02	1.67E-02	1.26E-09	7.48E-07	9.55E-02	3.85E-04
LL-M001	6.57E+01	4.61E-05	4.10E+00	6.92E+01	3.05E+01	9.95E-06	2.86E-02	1.70E+02	6.84E-01
LL-T001	3.28E+02	0.00E+00	0.00E+00	5.28E+02	2.32E+02	7.72E-05	0.00E+00	1.09E+03	4.39E+00
LL-T002	3.24E+03	0.00E+00	3.26E+01	5.12E+03	2.06E+03	6.79E-04	2.27E-01	1.05E+04	4.22E+01
LL-T003	1.26E+02	0.00E+00	3.65E+00	1.04E+02	8.18E+01	2.69E-05	2.54E-02	3.15E+02	1.27E+00
LL-T004	8.01E+01	0.00E+00	7.49E-01	6.60E+01	5.16E+01	1.70E-05	5.22E-03	1.98E+02	8.00E-01
LL-T005	4.13E+02	2.01E-03	8.81E+00	2.45E+02	2.07E+02	6.31E-05	6.14E-02	8.74E+02	3.53E+00
LL-W018	3.52E-02	0.00E+00	0.00E+00	1.83E-02	4.11E-02	1.29E-08	0.00E+00	9.46E-02	3.82E-04
LL-W019	1.91E+01	0.00E+00	0.00E+00	1.42E+01	1.16E+01	3.78E-06	0.00E+00	4.50E+01	1.81E-01
LL-W034	7.06E+00	3.39E-05	1.54E-01	4.15E+00	3.43E+00	1.07E-06	1.07E-03	1.48E+01	5.97E-02
MC-W001	8.81E-02	0.00E+00	0.00E+00	5.99E-02	0.00E+00	1.94E-09	0.00E+00	1.48E-01	5.97E-04
MU-W002	1.18E+00	0.00E+00	0.00E+00	5.20E-02	0.00E+00	0.00E+00	2.67E-12	1.23E+00	4.95E-03
NT-JAS-01	1.14E+02	0.00E+00	3.28E+00	9.38E+01	7.37E+01	2.42E-05	2.29E-02	2.84E+02	1.15E+00
NT-W001	1.71E+02	1.04E-06	6.56E+00	2.83E+03	1.84E+01	1.69E-06	5.73E-02	3.02E+03	1.22E+01
NT-W021	3.30E+00	0.00E+00	4.70E-02	3.19E+01	7.09E+00	8.67E-07	3.74E-04	4.23E+01	1.71E-01
OR-W201	3.96E+03	7.15E-05	1.41E+02	2.14E+03	2.06E+03	9.08E-04	4.45E+01	8.33E+03	3.36E+01
OR-W202	5.68E+02	1.49E-03	4.07E+02	5.48E+02	5.25E+02	2.91E-05	3.29E+00	2.05E+03	8.27E+00
OR-W203	1.25E+00	5.19E-05	5.82E-02	2.46E-02	1.71E+00	7.40E-08	4.67E-04	3.05E+00	1.23E-02

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
OR-W204	2.79E-01	2.15E-10	6.60E-02	4.19E-01	2.77E-01	0.00E+00	5.30E-04	1.04E+00	4.20E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.21E-01	0.00E+00	0.00E+00	0.00E+00	4.21E-01	1.70E-03
RF-MT0001	1.07E+03	0.00E+00	4.10E-01	1.94E+02	4.31E+01	6.66E-06	3.16E-03	1.31E+03	5.27E+00
RF-MT0002	8.22E+01	0.00E+00	3.15E-02	1.49E+01	3.31E+00	5.11E-07	2.42E-04	1.01E+02	4.05E-01
RF-MT0003	3.74E-01	0.00E+00	7.19E-03	3.41E+00	7.59E-01	1.17E-07	5.54E-05	4.55E+00	1.84E-02
RF-MT0007	9.40E-01	0.00E+00	0.00E+00	4.25E-01	9.44E-02	1.35E-08	0.00E+00	1.46E+00	5.89E-03
RF-MT0089	3.69E-03	0.00E+00	7.19E-05	3.41E-02	7.58E-03	1.17E-09	5.54E-07	4.55E-02	1.83E-04
RF-MT0090	9.37E+00	0.00E+00	1.02E-01	8.76E+01	1.93E+01	1.17E-06	7.84E-04	1.16E+02	4.69E-01
RF-MT0091	5.81E+02	0.00E+00	1.03E+01	5.86E+03	1.30E+03	9.64E-05	8.26E-02	7.74E+03	3.12E+01
RF-MT0092	8.32E+01	0.00E+00	1.30E+00	8.39E+02	1.89E+02	1.33E-05	1.00E-02	1.11E+03	4.49E+00
RF-MT0093	1.01E+02	0.00E+00	1.34E+00	9.05E+02	2.07E+02	1.14E-05	1.03E-02	1.22E+03	4.90E+00
RF-MT0097	5.07E+00	0.00E+00	5.92E-02	4.73E+01	9.43E+00	6.21E-07	4.56E-04	6.18E+01	2.49E-01
RF-MT0099	5.55E-03	0.00E+00	1.08E-04	5.11E-02	1.13E-02	1.76E-09	8.33E-07	6.81E-02	2.75E-04
RF-MT0290	1.38E+01	0.00E+00	2.68E-01	1.27E+02	2.81E+01	4.35E-06	2.06E-03	1.69E+02	6.81E-01
RF-MT-0292	1.74E+01	0.00E+00	3.38E-01	1.60E+02	3.55E+01	5.50E-06	2.60E-03	2.14E+02	8.61E-01
RF-MT-0299	2.04E+03	0.00E+00	8.66E+00	4.11E+03	9.12E+02	1.42E-04	6.67E-02	7.07E+03	2.85E+01
RF-MT0302	3.13E-02	0.00E+00	3.43E-04	1.77E-01	3.95E-02	5.50E-09	1.95E-05	2.48E-01	1.00E-03
RF-MT0320	3.74E+01	0.00E+00	3.56E-01	1.72E+02	3.83E+01	5.53E-06	2.75E-03	2.48E+02	1.00E+00
RF-MT0321	2.09E+01	0.00E+00	1.06E-01	5.54E+01	1.22E+01	1.55E-06	3.23E-03	8.86E+01	3.57E-01
RF-MT-0328	1.45E+00	0.00E+00	1.27E-02	6.02E+00	1.34E+00	2.07E-07	4.36E-04	8.82E+00	3.56E-02
RF-MT0330	1.51E+01	0.00E+00	1.39E-01	1.22E+02	2.92E+01	1.94E-06	1.07E-03	1.66E+02	6.70E-01
RF-MT-0331	9.03E+01	0.00E+00	8.66E-01	5.35E+02	1.16E+02	1.13E-05	2.74E-02	7.42E+02	2.99E+00
RF-MT0332	1.29E-02	0.00E+00	2.52E-04	1.20E-01	2.65E-02	4.10E-09	1.94E-06	1.59E-01	6.43E-04
RF-MT-0335	1.04E+00	0.00E+00	1.16E-02	6.16E+00	1.37E+00	1.67E-07	6.31E-04	8.59E+00	3.46E-02
RF-MT0336	7.36E+01	0.00E+00	7.68E-01	4.37E+02	9.70E+01	9.81E-06	7.73E-03	6.09E+02	2.45E+00
RF-MT0337	4.16E+01	0.00E+00	4.22E-01	2.67E+02	5.83E+01	4.79E-06	7.10E-03	3.67E+02	1.48E+00
RF-MT0339	1.14E+02	0.00E+00	1.15E+00	5.86E+02	1.29E+02	1.74E-05	2.59E-02	8.29E+02	3.34E+00
RF-MT-0342	6.68E-01	0.00E+00	9.64E-03	5.41E+00	1.18E+00	1.27E-07	1.33E-04	7.27E+00	2.93E-02
RF-MT0371	2.26E+02	0.00E+00	2.23E+00	1.06E+03	2.34E+02	3.63E-05	1.85E-02	1.52E+03	6.13E+00
RF-MT-0372	9.85E-01	0.00E+00	1.57E-02	7.38E+00	1.64E+00	2.24E-07	3.60E-04	1.00E+01	4.04E-02
RF-MT0373	1.48E+01	0.00E+00	1.61E-01	1.39E+02	3.05E+01	1.85E-06	1.24E-03	1.84E+02	7.42E-01

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0374	4.82E-01	0.00E+00	5.77E-03	2.74E+00	6.08E-01	9.37E-08	4.78E-05	3.84E+00	1.55E-02
RF-MT0376	3.82E-01	0.00E+00	4.66E-03	2.73E+00	6.16E-01	6.91E-08	5.10E-05	3.73E+00	1.51E-02
RF-MT0377	2.27E+02	0.00E+00	2.69E+00	1.28E+03	2.82E+02	4.36E-05	3.09E-02	1.79E+03	7.21E+00
RF-MT0378	2.55E+00	0.00E+00	3.71E-02	1.76E+01	3.91E+00	6.03E-07	2.86E-04	2.41E+01	9.72E-02
RF-MT0419	4.09E+00	0.00E+00	3.47E-02	1.64E+01	3.65E+00	5.64E-07	2.67E-04	2.42E+01	9.76E-02
RF-MT0420	7.12E-01	0.00E+00	6.02E-03	2.85E+00	6.34E-01	9.80E-08	4.63E-05	4.20E+00	1.69E-02
RF-MT0423	6.05E+00	0.00E+00	4.89E-02	4.11E+01	8.86E+00	3.88E-07	3.77E-04	5.61E+01	2.26E-01
RF-MT0425	1.78E-01	0.00E+00	1.51E-03	7.13E-01	1.59E-01	2.45E-08	1.16E-05	1.05E+00	4.24E-03
RF-MT-0438	1.62E+00	0.00E+00	1.98E-02	1.27E+01	2.79E+00	2.43E-07	1.65E-04	1.71E+01	6.89E-02
RF-MT0440	5.87E-01	0.00E+00	7.09E-03	4.59E+00	1.04E+00	1.00E-07	2.19E-04	6.22E+00	2.51E-02
RF-MT0442	2.23E-01	0.00E+00	3.07E-03	1.57E+00	3.49E-01	3.71E-08	1.18E-04	2.15E+00	8.66E-03
RF-MT0443	2.75E+00	0.00E+00	5.04E-02	2.44E+01	5.43E+00	7.74E-07	5.46E-04	3.27E+01	1.32E-01
RF-MT0444	2.15E+01	0.00E+00	2.47E-01	1.18E+02	2.60E+01	4.01E-06	1.93E-03	1.65E+02	6.67E-01
RF-MT0480	6.00E+01	0.00E+00	6.95E-01	3.30E+02	7.35E+01	1.03E-05	7.81E-03	4.65E+02	1.87E+00
RF-MT0488	9.60E+01	0.00E+00	1.04E+00	4.91E+02	1.09E+02	1.68E-05	3.89E-02	6.96E+02	2.81E+00
RF-MT0490	4.35E-01	0.00E+00	6.02E-03	2.90E+00	6.44E-01	9.30E-08	5.75E-05	3.98E+00	1.61E-02
RF-MT-0491	3.42E-02	0.00E+00	2.75E-04	1.32E-01	2.91E-02	4.35E-09	4.12E-06	1.95E-01	7.87E-04
RF-MT0523A	2.71E+01	0.00E+00	2.19E-01	1.04E+02	2.31E+01	3.54E-06	1.94E-03	1.54E+02	6.22E-01
RF-MT0523B	2.71E+01	0.00E+00	2.19E-01	1.04E+02	2.31E+01	3.54E-06	1.94E-03	1.54E+02	6.22E-01
RF-MT0523C	2.71E+01	0.00E+00	2.19E-01	1.04E+02	2.31E+01	3.54E-06	1.94E-03	1.54E+02	6.22E-01
RF-MT0523D	2.71E+01	0.00E+00	2.19E-01	1.04E+02	2.31E+01	3.54E-06	1.94E-03	1.54E+02	6.22E-01
RF-MT0523E	2.71E+01	0.00E+00	2.19E-01	1.04E+02	2.31E+01	3.54E-06	1.94E-03	1.54E+02	6.22E-01
RF-MT0531	1.85E-03	0.00E+00	3.60E-05	1.70E-02	3.78E-03	5.86E-10	2.77E-07	2.27E-02	9.15E-05
RF-MT0532E	8.63E+01	0.00E+00	4.68E-01	2.27E+02	5.02E+01	7.55E-06	4.71E-03	3.64E+02	1.47E+00
RF-MT0532F	8.63E+01	0.00E+00	4.68E-01	2.27E+02	5.02E+01	7.55E-06	4.71E-03	3.64E+02	1.47E+00
RF-MT0541	3.14E+00	0.00E+00	6.75E-03	3.21E+00	7.13E-01	1.11E-07	5.20E-05	7.08E+00	2.85E-02
RF-MT0545	1.68E-02	0.00E+00	3.27E-04	1.55E-01	3.44E-02	5.32E-09	2.52E-06	2.07E-01	8.34E-04
RF-MT0800	6.39E+02	0.00E+00	1.62E-01	7.67E+01	1.70E+01	2.63E-06	1.73E-03	7.33E+02	2.95E+00
RF-MT0801	7.35E+01	0.00E+00	1.59E-01	7.53E+01	1.67E+01	2.57E-06	1.22E-03	1.66E+02	6.68E-01
RF-MT0803	1.65E+00	0.00E+00	3.55E-03	1.68E+00	3.73E-01	5.76E-08	2.73E-05	3.71E+00	1.49E-02
RF-MT0806	7.78E-01	0.00E+00	8.51E-03	7.31E+00	1.60E+00	9.74E-08	6.55E-05	9.70E+00	3.91E-02

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0807	9.84E+00	0.00E+00	6.56E-02	3.11E+01	6.91E+00	1.06E-06	5.05E-04	4.79E+01	1.93E-01
RF-MT0816	1.05E+00	0.00E+00	9.25E-03	4.38E+00	9.70E-01	1.51E-07	7.12E-05	6.41E+00	2.59E-02
RF-MT-0823	5.21E-01	0.00E+00	4.21E-03	2.00E+00	4.44E-01	6.82E-08	3.73E-05	2.97E+00	1.20E-02
RF-MT0827	2.66E+01	0.00E+00	2.34E-01	1.11E+02	2.46E+01	3.80E-06	1.80E-03	1.62E+02	6.54E-01
RF-MT0831	5.06E+01	0.00E+00	6.41E-01	3.00E+02	6.67E+01	1.00E-05	1.72E-02	4.18E+02	1.68E+00
RF-MT0832	3.03E+02	0.00E+00	2.32E+00	1.17E+03	2.58E+02	3.57E-05	5.13E-02	1.73E+03	6.98E+00
RF-MT0833	9.20E+01	0.00E+00	6.95E-01	3.37E+02	7.49E+01	1.07E-05	1.45E-02	5.05E+02	2.04E+00
RF-MT0855	1.59E-02	0.00E+00	3.09E-04	1.46E-01	3.25E-02	5.02E-09	2.38E-06	1.95E-01	7.86E-04
RF-MT0857	7.77E-01	0.00E+00	8.46E-03	7.29E+00	1.60E+00	9.72E-08	6.52E-05	9.68E+00	3.90E-02
RF-MT0H61	2.89E+01	0.00E+00	3.15E-01	2.70E+02	5.95E+01	3.61E-06	2.42E-03	3.59E+02	1.45E+00
RF-MT2116	3.25E+00	0.00E+00	2.50E-02	1.25E+01	2.77E+00	3.83E-07	5.50E-04	1.85E+01	7.46E-02
RF-MT3010	2.03E+01	0.00E+00	2.59E-01	1.24E+02	2.77E+01	4.11E-06	2.39E-03	1.72E+02	6.93E-01
RF-MT3011	1.52E+02	0.00E+00	1.61E+00	7.64E+02	1.70E+02	2.62E-05	2.02E-02	1.09E+03	4.38E+00
RF-MT420P	8.05E+02	0.00E+00	8.17E+00	6.28E+03	1.39E+03	8.57E-05	7.29E-02	8.49E+03	3.42E+01
RF-MT532A	2.13E+02	0.00E+00	1.16E+00	5.60E+02	1.24E+02	1.86E-05	1.16E-02	8.97E+02	3.62E+00
RF-MT532B	9.53E+02	0.00E+00	5.19E+00	2.51E+03	5.57E+02	8.37E-05	5.21E-02	4.03E+03	1.62E+01
RF-MT532C	1.91E+03	0.00E+00	1.04E+01	5.03E+03	1.11E+03	1.67E-04	1.05E-01	8.07E+03	3.25E+01
RF-MT532D	1.21E+01	0.00E+00	6.56E-02	3.19E+01	7.05E+00	1.05E-06	6.60E-04	5.11E+01	2.06E-01
RF-TT0069	6.95E-02	0.00E+00	7.78E-04	3.69E-01	8.19E-02	1.27E-08	7.94E-05	5.21E-01	2.10E-03
RF-TT0200	3.30E+00	0.00E+00	3.14E-02	1.51E+01	3.38E+00	4.88E-07	2.43E-04	2.18E+01	8.81E-02
RF-TT0299	1.37E+01	0.00E+00	5.82E-02	2.76E+01	6.13E+00	9.46E-07	4.48E-04	4.75E+01	1.91E-01
RF-TT0300	1.12E+02	0.00E+00	1.66E+00	7.92E+02	1.77E+02	2.30E-05	2.11E-02	1.08E+03	4.36E+00
RF-TT0301	1.51E+01	0.00E+00	2.25E-01	1.08E+02	2.40E+01	3.12E-06	2.87E-03	1.47E+02	5.93E-01
RF-TT0302	7.45E-01	0.00E+00	8.17E-03	4.21E+00	9.37E-01	1.31E-07	4.62E-04	5.90E+00	2.38E-02
RF-TT0303	4.49E+00	0.00E+00	4.78E-02	2.27E+01	5.02E+00	7.76E-07	1.40E-03	3.22E+01	1.30E-01
RF-TT0310	1.53E+01	0.00E+00	2.24E-01	1.02E+02	2.33E+01	2.84E-06	1.91E-03	1.41E+02	5.67E-01
RF-TT0312	3.67E+02	0.00E+00	4.05E+00	2.23E+03	4.90E+02	5.98E-05	3.29E-02	3.09E+03	1.24E+01
RF-TT0317	2.31E-01	0.00E+00	4.40E-03	2.09E+00	4.63E-01	7.15E-08	3.39E-05	2.79E+00	1.12E-02
RF-TT0320	1.48E+02	0.00E+00	1.41E+00	6.81E+02	1.52E+02	2.19E-05	1.09E-02	9.82E+02	3.96E+00
RF-TT0330	5.27E+01	0.00E+00	4.88E-01	4.27E+02	1.02E+02	6.80E-06	3.76E-03	5.82E+02	2.35E+00
RF-TT-0331	2.62E+02	0.00E+00	2.52E+00	1.55E+03	3.38E+02	3.27E-05	7.96E-02	2.16E+03	8.69E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT-0334	1.14E+02	0.00E+00	2.04E+00	9.65E+02	2.14E+02	3.32E-05	1.57E-02	1.30E+03	5.22E+00
RF-TT0335	1.39E+02	0.00E+00	1.55E+00	8.21E+02	1.83E+02	2.23E-05	8.41E-02	1.15E+03	4.62E+00
RF-TT0336	1.23E+02	0.00E+00	1.28E+00	7.27E+02	1.61E+02	1.63E-05	1.29E-02	1.01E+03	4.08E+00
RF-TT0337	1.46E+02	0.00E+00	1.48E+00	9.39E+02	2.05E+02	1.68E-05	2.49E-02	1.29E+03	5.20E+00
RF-TT0338	6.19E+02	0.00E+00	5.38E+00	3.66E+03	7.99E+02	7.52E-05	4.97E-02	5.08E+03	2.05E+01
RF-TT0340	5.29E+00	0.00E+00	1.03E-01	4.87E+01	1.09E+01	1.67E-06	7.91E-04	6.49E+01	2.62E-01
RF-TT0342	3.54E+01	0.00E+00	5.14E-01	2.87E+02	6.25E+01	6.72E-06	7.06E-03	3.85E+02	1.55E+00
RF-TT0360	2.70E+00	0.00E+00	2.61E-02	1.29E+01	2.89E+00	3.98E-07	2.07E-04	1.85E+01	7.45E-02
RF-TT0368	5.40E+01	0.00E+00	5.23E-01	2.58E+02	5.79E+01	7.96E-06	4.16E-03	3.71E+02	1.49E+00
RF-TT0370	1.07E+02	0.00E+00	1.13E+00	5.75E+02	1.28E+02	1.69E-05	1.65E-02	8.10E+02	3.27E+00
RF-TT0371	2.31E+00	0.00E+00	2.28E-02	1.08E+01	2.39E+00	3.70E-07	1.88E-04	1.55E+01	6.25E-02
RF-TT0372	2.82E-01	0.00E+00	4.48E-03	2.11E+00	4.69E-01	6.40E-08	1.03E-04	2.86E+00	1.15E-02
RF-TT0374	8.77E+00	0.00E+00	1.05E-01	4.98E+01	1.10E+01	1.70E-06	8.70E-04	6.97E+01	2.81E-01
RF-TT0375A	9.14E-02	0.00E+00	1.73E-03	8.18E-01	1.82E-01	2.81E-08	1.33E-05	1.09E+00	4.41E-03
RF-TT0375B	9.14E-02	0.00E+00	1.73E-03	8.18E-01	1.82E-01	2.81E-08	1.33E-05	1.09E+00	4.41E-03
RF-TT0376	2.10E+01	0.00E+00	2.56E-01	1.50E+02	3.38E+01	3.80E-06	2.81E-03	2.05E+02	8.28E-01
RF-TT0377	1.18E+01	0.00E+00	1.39E-01	6.61E+01	1.47E+01	2.26E-06	1.60E-03	9.27E+01	3.74E-01
RF-TT0391	2.63E+00	0.00E+00	1.96E-02	1.67E+01	3.66E+00	3.96E-07	1.51E-04	2.30E+01	9.28E-02
RF-TT0392	9.26E-01	0.00E+00	1.23E-02	8.73E+00	1.93E+00	1.37E-07	9.51E-05	1.16E+01	4.68E-02
RF-TT0393	7.61E+01	0.00E+00	8.61E-01	4.07E+02	9.04E+01	1.39E-05	6.63E-03	5.74E+02	2.31E+00
RF-TT0398	1.66E+00	0.00E+00	2.27E-02	1.63E+01	3.59E+00	2.59E-07	1.75E-04	2.16E+01	8.71E-02
RF-TT0409	1.39E+00	0.00E+00	1.06E-02	8.43E+00	1.85E+00	9.97E-08	8.24E-05	1.17E+01	4.71E-02
RF-TT0412	1.39E+00	0.00E+00	1.06E-02	8.43E+00	1.85E+00	9.97E-08	8.24E-05	1.17E+01	4.71E-02
RF-TT0414	4.30E+01	0.00E+00	3.28E-01	2.61E+02	5.73E+01	3.09E-06	2.55E-03	3.62E+02	1.46E+00
RF-TT0430	1.26E-02	0.00E+00	2.45E-04	1.16E-01	2.57E-02	3.98E-09	1.89E-06	1.54E-01	6.22E-04
RF-TT0431	3.13E+00	0.00E+00	5.97E-02	2.85E+01	6.33E+00	9.45E-07	6.82E-04	3.80E+01	1.53E-01
RF-TT0438	1.86E+02	0.00E+00	2.28E+00	1.45E+03	3.21E+02	2.80E-05	1.90E-02	1.96E+03	7.92E+00
RF-TT0440	1.83E+01	0.00E+00	2.21E-01	1.43E+02	3.26E+01	3.13E-06	6.87E-03	1.95E+02	7.84E-01
RF-TT0441	9.02E+01	0.00E+00	1.04E+00	4.96E+02	1.10E+02	1.66E-05	1.26E-02	6.97E+02	2.81E+00
RF-TT0442	1.30E+01	0.00E+00	1.79E-01	9.17E+01	2.04E+01	2.17E-06	6.90E-03	1.25E+02	5.05E-01
RF-TT0443	2.79E-01	0.00E+00	5.14E-03	2.48E+00	5.50E-01	7.85E-08	5.56E-05	3.32E+00	1.34E-02

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0479	2.73E+00	0.00E+00	5.33E-02	2.51E+01	5.59E+00	8.64E-07	4.11E-04	3.35E+01	1.35E-01
RF-TT0480	1.86E+02	0.00E+00	2.15E+00	1.03E+03	2.28E+02	3.21E-05	2.42E-02	1.44E+03	5.82E+00
RF-TT0481	1.05E-01	0.00E+00	1.21E-03	5.78E-01	1.29E-01	1.81E-08	1.36E-05	8.12E-01	3.28E-03
RF-TT0483	3.37E-01	0.00E+00	6.56E-03	3.10E+00	6.89E-01	1.06E-07	1.72E-02	4.15E+00	1.67E-02
RF-TT0484	1.80E+00	0.00E+00	2.72E-02	1.29E+01	2.86E+00	4.42E-07	3.20E-04	1.76E+01	7.08E-02
RF-TT0485	1.48E-01	0.00E+00	1.68E-03	7.93E-01	1.77E-01	2.73E-08	2.90E-04	1.12E+00	4.52E-03
RF-TT0486	8.77E-01	0.00E+00	9.93E-03	4.71E+00	1.05E+00	1.61E-07	3.04E-04	6.64E+00	2.68E-02
RF-TT0487	4.40E+00	0.00E+00	3.38E-02	1.69E+01	3.75E+00	5.20E-07	7.44E-04	2.51E+01	1.01E-01
RF-TT0489	1.25E+00	0.00E+00	1.52E-02	7.18E+00	1.59E+00	2.47E-07	2.18E-04	1.00E+01	4.05E-02
RF-TT0490	6.93E+01	0.00E+00	9.64E-01	4.63E+02	1.03E+02	1.48E-05	9.21E-03	6.36E+02	2.56E+00
RF-TT0491	1.61E+00	0.00E+00	1.30E-02	6.20E+00	1.37E+00	2.06E-07	1.96E-04	9.20E+00	3.71E-02
RF-TT0492	5.42E-01	0.00E+00	7.34E-03	3.46E+00	7.70E-01	1.19E-07	5.65E-05	4.78E+00	1.93E-02
RF-TT0523A	3.64E+00	0.00E+00	2.95E-02	1.40E+01	3.10E+00	4.77E-07	2.61E-04	2.07E+01	8.36E-02
RF-TT0523B	3.64E+00	0.00E+00	2.95E-02	1.40E+01	3.10E+00	4.77E-07	2.61E-04	2.07E+01	8.36E-02
RF-TT0523C	3.64E+00	0.00E+00	2.95E-02	1.40E+01	3.10E+00	4.77E-07	2.61E-04	2.07E+01	8.36E-02
RF-TT0523D	3.64E+00	0.00E+00	2.95E-02	1.40E+01	3.10E+00	4.77E-07	2.61E-04	2.07E+01	8.36E-02
RF-TT0523E	3.64E+00	0.00E+00	2.95E-02	1.40E+01	3.10E+00	4.77E-07	2.61E-04	2.07E+01	8.36E-02
RF-TT0532A	9.14E+01	0.00E+00	4.94E-01	2.40E+02	5.32E+01	7.99E-06	4.97E-03	3.86E+02	1.55E+00
RF-TT0532B	9.14E+01	0.00E+00	4.94E-01	2.40E+02	5.32E+01	7.99E-06	4.97E-03	3.86E+02	1.55E+00
RF-TT0541	1.51E-01	0.00E+00	2.94E-03	1.40E+00	3.09E-01	4.78E-08	2.26E-05	1.86E+00	7.49E-03
RF-TT0545	3.37E-02	0.00E+00	6.56E-04	3.10E-01	6.89E-02	1.06E-08	5.05E-06	4.13E-01	1.66E-03
RF-TT0601	1.17E+01	0.00E+00	1.13E-01	5.59E+01	1.26E+01	1.73E-06	8.98E-04	8.03E+01	3.24E-01
RF-TT0802	1.31E+03	0.00E+00	9.30E+00	4.41E+03	9.80E+02	1.51E-04	7.16E-02	6.71E+03	2.71E+01
RF-TT0809	1.08E+02	0.00E+00	7.63E-01	3.63E+02	8.03E+01	1.24E-05	5.88E-03	5.52E+02	2.22E+00
RF-TT0821	2.33E+02	0.00E+00	2.77E+00	1.42E+03	3.17E+02	3.69E-05	1.89E-01	1.98E+03	7.97E+00
RF-TT0822	2.57E+02	0.00E+00	2.16E+00	1.07E+03	2.36E+02	3.29E-05	1.99E-01	1.56E+03	6.31E+00
RF-TT0823	5.21E-01	0.00E+00	4.21E-03	2.00E+00	4.44E-01	6.82E-08	3.73E-05	2.97E+00	1.20E-02
RF-TT0824	5.36E+02	0.00E+00	5.92E+00	2.88E+03	6.39E+02	9.29E-05	1.08E-01	4.06E+03	1.64E+01
RF-TT0825	4.45E+02	0.00E+00	4.28E+00	2.17E+03	4.80E+02	6.16E-05	1.14E-01	3.10E+03	1.25E+01
RF-TT0832	3.30E+02	0.00E+00	2.53E+00	1.27E+03	2.81E+02	3.89E-05	5.58E-02	1.88E+03	7.58E+00
RF-TT0854	1.19E-01	0.00E+00	2.31E-03	1.09E+00	2.43E-01	3.75E-08	7.64E-04	1.45E+00	5.86E-03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0886	1.68E-02	0.00E+00	3.26E-04	1.54E-01	3.44E-02	5.31E-09	2.51E-06	2.06E-01	8.30E-04
RF-TT2216	4.87E+00	0.00E+00	3.74E-02	1.88E+01	4.15E+00	5.75E-07	8.24E-04	2.79E+01	1.12E-01
RF-TT3010	2.60E+02	0.00E+00	3.31E+00	1.58E+03	3.52E+02	5.26E-05	3.05E-02	2.20E+03	8.86E+00
RF-TT3011	6.56E+02	0.00E+00	7.00E+00	3.30E+03	7.35E+02	1.14E-04	8.75E-02	4.70E+03	1.90E+01
RF-TT301U	5.45E+01	0.00E+00	7.39E-01	3.59E+02	8.11E+01	1.12E-05	5.85E-03	4.95E+02	2.00E+00
RF-TT310P	1.58E+01	0.00E+00	1.92E-01	1.21E+02	2.55E+01	2.33E-06	1.48E-03	1.62E+02	6.54E-01
RF-TT338S	4.60E-01	0.00E+00	8.81E-03	4.16E+00	9.26E-01	1.43E-07	6.78E-05	5.56E+00	2.24E-02
RF-TT390P	2.59E+00	0.00E+00	2.39E-02	2.03E+01	4.14E+00	3.56E-07	2.13E-04	2.70E+01	1.09E-01
RF-TT391P	1.43E+02	0.00E+00	1.07E+00	9.11E+02	1.99E+02	2.16E-05	8.25E-03	1.25E+03	5.06E+00
RF-TT392P	2.89E+02	0.00E+00	3.86E+00	2.73E+03	6.04E+02	4.29E-05	2.98E-02	3.63E+03	1.46E+01
RF-TT393R	4.28E+01	0.00E+00	6.56E-01	4.17E+02	9.30E+01	6.93E-06	5.22E-03	5.54E+02	2.23E+00
RF-TT394P	5.31E+00	0.00E+00	4.06E-02	3.22E+01	6.64E+00	4.99E-07	3.19E-04	4.42E+01	1.78E-01
RF-TT395P	7.11E+00	0.00E+00	5.43E-02	4.31E+01	8.86E+00	6.67E-07	4.28E-04	5.92E+01	2.39E-01
RF-TT396P	1.78E+00	0.00E+00	1.36E-02	1.08E+01	2.22E+00	1.66E-07	1.07E-04	1.48E+01	5.96E-02
RF-TT398P	1.72E+02	0.00E+00	2.35E+00	1.69E+03	3.72E+02	2.68E-05	1.81E-02	2.24E+03	9.02E+00
RF-TT398R	1.42E+03	0.00E+00	4.36E+00	2.73E+03	6.01E+02	5.22E-05	3.36E-02	4.75E+03	1.92E+01
RF-TT411R	5.14E+01	0.00E+00	3.92E-01	3.12E+02	6.85E+01	3.69E-06	3.04E-03	4.32E+02	1.74E+00
RF-TT429R	1.08E+02	0.00E+00	8.41E-02	7.22E+01	1.56E+01	6.44E-07	6.48E-04	1.96E+02	7.89E-01
RF-TT433X	3.40E+01	0.00E+00	2.33E-02	2.08E+01	4.04E+00	2.55E-07	1.79E-04	5.88E+01	2.37E-01
RF-TT436R	2.49E+02	0.00E+00	3.37E-01	2.72E+02	5.96E+01	4.93E-06	2.60E-03	5.81E+02	2.34E+00
RF-TT454X	1.46E+01	0.00E+00	1.98E-02	1.60E+01	3.52E+00	2.90E-07	1.53E-04	3.42E+01	1.38E-01
RL-T101	7.42E+01	0.00E+00	1.20E+00	8.65E+02	1.88E+02	4.10E-05	8.39E-03	1.13E+03	4.55E+00
RL-T102	9.41E-04	0.00E+00	1.53E-05	1.11E-02	2.40E-03	5.21E-10	1.26E-06	1.44E-02	5.82E-05
RL-T103	6.67E+01	0.00E+00	1.46E+00	3.78E+02	8.16E+01	2.18E-05	1.02E-02	5.28E+02	2.13E+00
RL-T104	1.35E-03	0.00E+00	2.19E-05	1.57E-02	3.44E-03	7.46E-10	1.85E-07	2.05E-02	8.28E-05
RL-T105	5.17E-01	0.00E+00	8.27E-03	5.97E+00	1.30E+00	2.82E-07	1.02E-04	7.80E+00	3.14E-02
RL-T106	4.99E-01	0.00E+00	8.12E-03	5.84E+00	1.27E+00	2.76E-07	5.66E-05	7.61E+00	3.07E-02
RL-T107	1.37E+03	0.00E+00	4.77E+03	1.61E+04	3.50E+03	7.57E-04	3.41E+01	2.58E+04	1.04E+02
RL-T108	7.84E-01	0.00E+00	8.22E-01	9.18E+00	2.00E+00	4.34E-07	5.76E-03	1.28E+01	5.16E-02
RL-T109	1.08E+00	0.00E+00	1.69E-02	1.22E+01	2.65E+00	5.75E-07	2.34E-02	1.59E+01	6.43E-02
RL-T110	1.21E+02	0.00E+00	3.23E+00	1.40E+03	3.04E+02	6.61E-05	1.38E+00	1.83E+03	7.36E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T112	4.88E+01	0.00E+00	1.37E+00	1.85E+02	4.02E+01	8.75E-06	7.45E-01	2.76E+02	1.11E+00
RL-T113	5.21E-02	0.00E+00	2.64E-03	6.09E-01	1.33E-01	2.88E-08	1.84E-05	7.97E-01	3.21E-03
RL-T114	7.92E+00	0.00E+00	1.29E-01	9.26E+01	2.02E+01	4.38E-06	8.97E-04	1.21E+02	4.87E-01
RL-T115	2.02E+02	0.00E+00	4.17E+00	1.22E+03	2.65E+02	6.45E-05	4.42E-01	1.69E+03	6.81E+00
RL-T116	1.30E+01	0.00E+00	2.11E-01	1.51E+02	3.30E+01	7.19E-06	5.76E-02	1.98E+02	7.97E-01
RL-T118	3.34E+01	0.00E+00	1.69E+00	1.50E+02	3.28E+01	7.12E-06	8.44E-01	2.19E+02	8.83E-01
RL-T120	8.10E+00	0.00E+00	1.77E-01	4.45E+01	9.60E+00	2.50E-06	1.24E-03	6.24E+01	2.52E-01
RL-T122	4.59E-01	0.00E+00	7.49E-03	5.36E+00	1.17E+00	2.54E-07	1.46E+00	8.46E+00	3.41E-02
RL-T123	1.35E+00	0.00E+00	2.19E-02	1.57E+01	3.44E+00	7.48E-07	5.98E-02	2.06E+01	8.31E-02
RL-T125	2.69E+02	0.00E+00	5.43E+00	3.29E+02	1.65E+02	1.17E-04	3.79E-02	7.69E+02	3.10E+00
RL-T127	2.59E+02	0.00E+00	1.37E+00	9.84E+02	2.14E+02	4.65E-05	8.94E-02	1.46E+03	5.88E+00
RL-T128	3.84E-01	0.00E+00	3.32E-08	2.39E-05	5.20E-06	1.13E-12	2.31E-10	3.84E-01	1.55E-03
RL-T129	1.15E+00	0.00E+00	6.31E+00	1.36E+01	2.93E+00	6.36E-07	5.17E-02	2.40E+01	9.67E-02
RL-T130	2.45E-03	0.00E+00	3.99E-05	2.88E-02	6.25E-03	1.35E-09	8.32E-05	3.76E-02	1.52E-04
RL-T131	9.95E-01	0.00E+00	2.18E-02	5.48E+00	1.18E+00	3.06E-07	8.37E-03	7.69E+00	3.10E-02
RL-T132	2.37E+02	0.00E+00	3.85E+00	2.78E+03	6.04E+02	1.31E-04	2.72E-01	3.63E+03	1.46E+01
RL-T133	4.83E-03	0.00E+00	6.16E-05	4.56E-02	9.89E-03	1.86E-09	4.30E-07	6.04E-02	2.44E-04
RL-T134	1.02E-02	0.00E+00	1.66E-04	1.20E-01	2.59E-02	5.65E-09	1.16E-06	1.56E-01	6.29E-04
RL-T135	4.78E-02	0.00E+00	7.78E-04	5.60E-01	1.22E-01	2.64E-08	4.15E-03	7.35E-01	2.96E-03
RL-T137	7.77E+02	0.00E+00	1.70E+01	4.26E+03	9.22E+02	2.41E-04	1.25E-01	5.98E+03	2.41E+01
RL-T140	9.08E+02	0.00E+00	1.61E+01	4.12E+03	9.89E+02	2.05E-04	2.63E+01	6.06E+03	2.45E+01
RL-T143	5.70E+00	0.00E+00	9.25E-02	6.67E+01	1.45E+01	3.15E-06	3.92E-02	8.70E+01	3.51E-01
RL-T145	1.62E+01	0.00E+00	2.64E-01	1.90E+02	4.12E+01	8.97E-06	9.13E-02	2.48E+02	9.99E-01
RL-W407	4.66E+01	0.00E+00	5.63E-01	4.35E+02	9.47E+01	1.36E-05	3.92E-03	5.77E+02	2.33E+00
RL-W408	1.91E-04	0.00E+00	2.38E-06	1.76E-03	3.83E-04	7.02E-11	1.66E-08	2.34E-03	9.42E-06
RL-W415	4.22E-03	0.00E+00	5.23E-05	3.90E-02	8.47E-03	1.55E-09	3.65E-07	5.17E-02	2.09E-04
RL-W418	1.81E-02	0.00E+00	2.21E-04	1.67E-01	3.64E-02	5.78E-09	1.54E-06	2.22E-01	8.94E-04
RL-W437	1.53E+02	0.00E+00	1.85E+00	1.42E+03	3.10E+02	4.47E-05	1.29E-02	1.89E+03	7.62E+00
RL-W438	2.67E-04	0.00E+00	3.32E-06	2.46E-03	5.35E-04	9.81E-11	2.32E-08	3.27E-03	1.32E-05
RL-W439	8.37E+03	0.00E+00	1.83E+02	4.75E+04	1.03E+04	2.74E-03	1.28E+00	6.63E+04	2.67E+02
RL-W443	1.35E+02	0.00E+00	1.63E+00	1.26E+03	2.73E+02	3.94E-05	1.14E-02	1.67E+03	6.71E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W444	9.97E+01	0.00E+00	1.21E+00	9.32E+02	2.03E+02	2.92E-05	8.42E-03	1.24E+03	4.98E+00
RL-W447	1.14E-02	0.00E+00	1.42E-04	1.05E-01	2.30E-02	4.20E-09	9.92E-07	1.39E-01	5.62E-04
RL-W448	8.46E-05	0.00E+00	1.05E-06	7.78E-04	1.69E-04	3.11E-11	7.33E-09	1.03E-03	4.17E-06
RL-W449	6.95E-01	0.00E+00	3.85E-05	2.23E-02	4.84E-03	5.64E-10	2.68E-07	7.22E-01	2.91E-03
RL-W450	1.28E-03	0.00E+00	1.59E-05	1.18E-02	2.55E-03	4.69E-10	1.11E-07	1.56E-02	6.30E-05
RL-W451	1.82E-04	0.00E+00	2.26E-06	1.67E-03	3.64E-04	6.68E-11	1.58E-08	2.22E-03	8.95E-06
RL-W452	7.92E-03	0.00E+00	9.74E-05	7.37E-02	1.60E-02	2.54E-09	6.79E-07	9.77E-02	3.94E-04
RL-W453	2.26E-03	0.00E+00	2.74E-05	2.12E-02	4.59E-03	6.62E-10	1.91E-07	2.80E-02	1.13E-04
RL-W454	3.16E-02	0.00E+00	3.83E-04	2.96E-01	6.42E-02	9.25E-09	2.67E-06	3.92E-01	1.58E-03
RL-W455	8.43E-03	0.00E+00	1.03E-04	7.82E-02	1.70E-02	2.71E-09	7.20E-07	1.04E-01	4.18E-04
RL-W456	1.11E+00	0.00E+00	1.35E-02	1.04E+01	2.26E+00	3.34E-07	9.41E-05	1.38E+01	5.55E-02
RL-W457	1.08E-01	0.00E+00	1.31E-03	1.01E+00	2.19E-01	3.23E-08	9.14E-06	1.34E+00	5.39E-03
RL-W458	3.42E-01	0.00E+00	6.70E-03	4.14E-01	2.25E-01	1.30E-07	4.67E-05	9.87E-01	3.98E-03
RL-W459	3.28E+00	0.00E+00	6.90E-02	1.03E+01	3.06E+00	1.29E-06	4.81E-04	1.67E+01	6.74E-02
RL-W460	2.00E-02	0.00E+00	2.43E-04	1.87E-01	4.07E-02	5.87E-09	1.69E-06	2.48E-01	1.00E-03
RL-W461	1.85E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.85E-02	7.45E-05
RL-W462	5.71E-03	0.00E+00	7.04E-05	5.29E-02	1.15E-02	1.92E-09	4.91E-07	7.02E-02	2.83E-04
RL-W463	2.94E-02	0.00E+00	3.56E-04	2.75E-01	5.97E-02	8.60E-09	2.48E-06	3.64E-01	1.47E-03
RL-W464	1.36E-02	0.00E+00	1.64E-04	1.27E-01	2.75E-02	3.97E-09	1.14E-06	1.68E-01	6.77E-04
RL-W465	9.05E-02	0.00E+00	1.11E-03	8.43E-01	1.83E-01	2.87E-08	7.74E-06	1.12E+00	4.51E-03
RL-W466	1.24E+00	0.00E+00	1.51E-02	1.16E+01	2.52E+00	3.82E-07	1.05E-04	1.53E+01	6.19E-02
RL-W467	6.35E-02	0.00E+00	7.78E-04	5.90E-01	1.28E-01	2.10E-08	5.42E-06	7.82E-01	3.15E-03
RL-W468	3.25E-04	0.00E+00	4.01E-06	3.02E-03	6.56E-04	1.10E-10	2.79E-08	4.00E-03	1.61E-05
RL-W469	1.32E-01	0.00E+00	1.61E-03	1.23E+00	2.68E-01	4.03E-08	1.12E-05	1.63E+00	6.56E-03
RL-W470	3.73E+00	0.00E+00	7.49E-02	4.55E+00	2.29E+00	1.62E-06	5.22E-04	1.06E+01	4.29E-02
RL-W474	1.41E-01	0.00E+00	8.27E-03	1.04E-02	8.64E-03	0.00E+00	5.76E-05	1.69E-01	6.81E-04
RL-W476	2.39E-01	0.00E+00	2.97E-03	2.28E+00	4.97E-01	7.31E-08	2.07E-05	3.01E+00	1.22E-02
RL-W480	3.89E-02	0.00E+00	4.77E-04	3.61E-01	7.87E-02	1.25E-08	3.32E-06	4.79E-01	1.93E-03
RL-W481	6.11E-02	0.00E+00	7.49E-04	5.67E-01	1.23E-01	1.96E-08	5.22E-06	7.52E-01	3.03E-03
RL-W482	8.12E+01	0.00E+00	2.49E-01	7.21E-02	1.31E-01	2.60E-05	1.74E-03	8.16E+01	3.29E-01
RL-W483	6.06E+00	0.00E+00	1.93E-02	4.67E-03	9.28E-03	1.94E-06	1.35E-04	6.09E+00	2.46E-02

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W484	2.56E-02	0.00E+00	1.56E-04	6.52E-02	1.52E-02	1.61E-09	1.09E-06	1.06E-01	4.28E-04
RL-W485	1.50E-03	0.00E+00	2.20E-05	7.05E-03	1.64E-03	0.00E+00	1.54E-07	1.02E-02	4.12E-05
RL-W486	6.34E-04	0.00E+00	9.30E-06	2.98E-03	6.91E-04	0.00E+00	6.48E-08	4.31E-03	1.74E-05
RL-W487	1.04E-01	0.00E+00	1.19E-03	4.26E-01	1.14E-01	1.50E-08	8.32E-06	6.45E-01	2.60E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	6.29E-02	0.00E+00	1.13E-03	5.52E-01	1.22E-01	2.42E-08	7.84E-06	7.38E-01	2.98E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	2.34E-02	0.00E+00	9.49E-04	5.79E-02	1.24E-02	8.78E-09	6.62E-06	9.46E-02	3.81E-04
RL-W492	1.35E-03	0.00E+00	2.34E-05	1.16E-02	2.55E-03	5.05E-10	1.63E-07	1.55E-02	6.25E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	5.34E+01	0.00E+00	1.36E+00	2.92E-01	2.43E-01	2.02E-05	9.45E-03	5.53E+01	2.23E-01
RL-W495	9.66E-01	0.00E+00	3.68E-03	2.80E-03	2.17E-03	3.69E-07	2.57E-05	9.75E-01	3.93E-03
RL-W496	6.28E+00	0.00E+00	4.24E-02	9.20E-03	7.19E-03	2.39E-06	2.96E-04	6.34E+00	2.56E-02
RL-W497	2.62E-01	0.00E+00	8.37E-03	5.52E-01	2.44E-01	6.25E-08	5.83E-05	1.07E+00	4.30E-03
RL-W498	1.02E+00	0.00E+00	1.24E-02	9.44E+00	2.06E+00	3.25E-07	8.66E-05	1.25E+01	5.05E-02
RL-W499	9.11E-06	0.00E+00	1.12E-07	8.46E-05	1.84E-05	2.92E-12	7.78E-10	1.12E-04	4.53E-07
RL-W500	6.49E-04	0.00E+00	1.38E-05	3.45E-03	7.47E-04	2.06E-10	9.65E-08	4.86E-03	1.96E-05
RL-W501	2.69E+01	0.00E+00	3.09E-01	1.11E+02	2.96E+01	3.88E-06	2.15E-03	1.68E+02	6.76E-01
RL-W502	4.86E-03	0.00E+00	5.97E-05	4.51E-02	9.80E-03	1.56E-09	4.16E-07	5.98E-02	2.41E-04
RL-W503	2.81E-01	0.00E+00	6.12E-03	1.59E+00	3.44E-01	9.17E-08	4.26E-05	2.22E+00	8.96E-03
RL-W504	1.04E-01	0.00E+00	1.19E-03	4.26E-01	1.14E-01	1.50E-08	8.32E-06	6.45E-01	2.60E-03
RL-W505	4.88E-03	0.00E+00	6.26E-05	4.61E-02	9.99E-03	1.88E-09	4.37E-07	6.10E-02	2.46E-04
RL-W506	1.77E-03	0.00E+00	2.46E-05	1.51E-02	3.29E-03	5.63E-10	1.72E-07	2.02E-02	8.15E-05
RL-W507	1.76E-04	0.00E+00	2.15E-06	1.63E-03	3.54E-04	5.64E-11	1.50E-08	2.16E-03	8.73E-06
RL-W508	3.23E+00	0.00E+00	7.04E-02	1.77E+01	3.83E+00	1.00E-06	4.91E-04	2.48E+01	1.00E-01
RL-W509	3.18E+01	0.00E+00	5.63E-01	1.44E+02	3.45E+01	7.17E-06	3.92E-03	2.11E+02	8.52E-01
RL-W510	2.68E+00	0.00E+00	5.77E-02	1.43E+01	3.10E+00	8.53E-07	4.02E-04	2.02E+01	8.14E-02
RL-W511	2.73E+02	0.00E+00	2.78E+00	1.92E+03	4.09E+02	4.65E-05	1.98E-02	2.60E+03	1.05E+01
RL-W512	2.39E+02	0.00E+00	1.88E+00	1.16E+03	2.80E+02	2.38E-05	1.31E-02	1.68E+03	6.77E+00
RL-W513	2.55E+04	0.00E+00	7.63E+02	1.89E+04	9.14E+03	3.77E-03	5.32E+00	5.43E+04	2.19E+02
RL-W514	7.18E-04	0.00E+00	8.76E-06	6.70E-03	1.46E-03	2.20E-10	6.11E-08	8.88E-03	3.58E-05

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W515	2.81E-02	0.00E+00	3.43E-04	2.61E-01	5.67E-02	9.00E-09	2.39E-06	3.46E-01	1.40E-03
RL-W516	3.90E-02	0.00E+00	4.77E-04	3.61E-01	7.87E-02	1.25E-08	3.33E-06	4.79E-01	1.93E-03
RL-W517	3.47E-10	0.00E+00	4.27E-12	3.21E-09	6.98E-10	1.17E-16	2.97E-14	4.26E-09	1.72E-11
RL-W518	9.82E-01	0.00E+00	1.80E-02	4.61E+00	1.09E+00	2.51E-07	1.25E-04	6.69E+00	2.70E-02
RL-W519	1.75E-01	0.00E+00	2.13E-03	1.63E+00	3.54E-01	5.30E-08	1.48E-05	2.16E+00	8.72E-03
RL-W520	1.93E-02	0.00E+00	2.40E-04	1.79E-01	3.89E-02	6.80E-09	1.67E-06	2.38E-01	9.58E-04
RL-W521	3.60E-04	0.00E+00	4.40E-06	3.33E-03	7.26E-04	1.16E-10	3.07E-08	4.42E-03	1.78E-05
RL-W522	7.52E+00	0.00E+00	1.63E-01	2.21E+01	6.16E+00	1.67E-06	1.14E-03	3.59E+01	1.45E-01
RL-W523	2.26E+00	0.00E+00	6.21E-02	1.46E+00	8.67E-01	3.32E-07	4.33E-04	4.65E+00	1.88E-02
RL-W524	9.36E+00	0.00E+00	2.38E-01	1.35E+01	5.08E+00	1.58E-06	1.66E-03	2.81E+01	1.13E-01
RL-W525	7.44E-01	0.00E+00	1.61E-02	1.59E+00	5.14E-01	1.24E-07	1.12E-04	2.87E+00	1.16E-02
RL-W526	2.82E+00	0.00E+00	5.82E-02	1.70E+01	3.71E+00	9.02E-07	4.06E-04	2.36E+01	9.51E-02
RL-W527	3.09E-01	0.00E+00	8.41E-03	1.80E+00	4.17E-01	1.05E-07	5.87E-05	2.53E+00	1.02E-02
RL-W528	1.38E+02	0.00E+00	3.58E+00	5.74E+01	5.36E+01	1.61E-05	2.49E-02	2.53E+02	1.02E+00
RL-W529	1.15E-01	0.00E+00	2.51E-03	6.33E-01	1.36E-01	3.55E-08	1.75E-05	8.87E-01	3.58E-03
RL-W530	1.36E+00	0.00E+00	2.92E-02	7.23E+00	1.57E+00	4.32E-07	2.03E-04	1.02E+01	4.11E-02
RL-W531	8.09E+01	0.00E+00	2.93E+00	3.13E+01	2.20E+01	1.15E-05	2.04E-02	1.37E+02	5.53E-01
RL-W532	2.60E-01	0.00E+00	3.18E-03	2.41E+00	5.24E-01	8.33E-08	2.22E-05	3.20E+00	1.29E-02
RL-W533	1.26E-01	0.00E+00	2.74E-03	6.90E-01	1.49E-01	3.85E-08	1.91E-05	9.68E-01	3.90E-03
RL-W534	7.25E-06	0.00E+00	8.85E-08	6.74E-05	1.47E-05	2.32E-12	6.17E-10	8.94E-05	3.60E-07
RL-W535	3.80E+01	0.00E+00	8.76E-01	8.63E+01	2.57E+01	7.09E-06	6.11E-03	1.51E+02	6.09E-01
RL-W536	7.43E-01	0.00E+00	1.18E-02	3.00E+00	6.63E-01	1.62E-07	8.54E-05	4.41E+00	1.78E-02
RL-W537	2.53E+01	0.00E+00	2.66E-01	1.84E+02	3.94E+01	4.53E-06	1.88E-03	2.49E+02	1.00E+00
RL-W538	9.21E-05	0.00E+00	1.13E-06	8.56E-04	1.86E-04	2.95E-11	7.84E-09	1.14E-03	4.58E-06
RL-W539	1.02E-02	0.00E+00	1.27E-04	9.46E-02	2.06E-02	3.59E-09	8.83E-07	1.26E-01	5.06E-04
RL-W540	1.99E+01	0.00E+00	5.58E-01	3.40E+01	1.14E+01	3.45E-06	3.89E-03	6.59E+01	2.66E-01
RL-W541	2.96E-02	0.00E+00	3.65E-04	2.74E-01	5.95E-02	1.01E-08	2.55E-06	3.64E-01	1.47E-03
RL-W542	1.37E+00	0.00E+00	2.72E-02	6.93E+00	1.57E+00	4.15E-07	1.89E-04	9.90E+00	3.99E-02
RL-W543	4.33E-03	0.00E+00	5.28E-05	4.02E-02	8.74E-03	1.39E-09	3.68E-07	5.33E-02	2.15E-04
RL-W544	9.74E-02	0.00E+00	2.16E-03	4.57E-01	1.11E-01	2.77E-08	1.50E-05	6.68E-01	2.69E-03
RL-W545	2.59E-02	0.00E+00	3.17E-04	2.40E-01	5.23E-02	8.30E-09	2.21E-06	3.19E-01	1.29E-03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W546	1.13E-03	0.00E+00	1.39E-05	1.06E-02	2.30E-03	3.64E-10	9.69E-08	1.40E-02	5.66E-05
RL-W547	2.90E-05	0.00E+00	3.55E-07	2.69E-04	5.86E-05	9.30E-12	2.48E-09	3.57E-04	1.44E-06
RL-W548	2.51E-05	0.00E+00	3.08E-07	2.32E-04	5.06E-05	8.33E-12	2.15E-09	3.08E-04	1.24E-06
RL-W549	4.98E+00	0.00E+00	1.24E-01	1.20E+01	3.48E+00	1.05E-06	8.63E-04	2.06E+01	8.29E-02
RL-W550	2.26E+01	0.00E+00	2.34E-01	1.62E+02	3.48E+01	3.98E-06	1.65E-03	2.20E+02	8.86E-01
RL-W551	4.02E+01	0.00E+00	3.46E-01	1.83E+02	4.53E+01	4.22E-06	2.42E-03	2.69E+02	1.08E+00
RL-W552	1.56E-02	0.00E+00	1.92E-04	1.44E-01	3.13E-02	5.28E-09	1.34E-06	1.92E-01	7.72E-04
RL-W553	1.38E-03	0.00E+00	1.81E-05	1.29E-02	2.79E-03	6.67E-10	1.26E-07	1.71E-02	6.88E-05
RL-W554	2.19E-02	0.00E+00	2.69E-04	2.04E-01	4.44E-02	7.03E-09	1.87E-06	2.70E-01	1.09E-03
RL-W555	1.01E-02	0.00E+00	1.24E-04	9.39E-02	2.04E-02	3.24E-09	8.63E-07	1.24E-01	5.02E-04
RL-W563	1.45E-01	0.00E+00	3.10E-03	7.78E-01	1.68E-01	4.42E-08	2.16E-05	1.10E+00	4.41E-03
RL-W564	9.43E-02	0.00E+00	2.06E-03	5.03E-01	1.09E-01	3.40E-08	1.43E-05	7.08E-01	2.86E-03
RL-W565	9.37E-03	0.00E+00	1.16E-04	8.69E-02	1.89E-02	3.15E-09	8.05E-07	1.15E-01	4.65E-04
RL-W566	1.37E-01	0.00E+00	1.69E-03	1.28E+00	2.79E-01	4.48E-08	1.18E-05	1.69E+00	6.83E-03
RL-W567	9.53E+00	0.00E+00	4.33E-02	3.93E-02	3.09E-02	3.80E-06	3.02E-04	9.65E+00	3.89E-02
RL-W568	1.83E+02	0.00E+00	9.10E-01	1.86E+00	1.44E+00	7.85E-05	6.34E-03	1.88E+02	7.56E-01
RL-W569	1.51E-01	0.00E+00	6.85E-04	6.20E-04	4.90E-05	6.02E-08	4.78E-06	1.52E-01	6.14E-04
RL-W570	9.67E-03	0.00E+00	1.20E-04	9.22E-02	2.00E-02	2.96E-09	8.36E-07	1.22E-01	4.92E-04
RL-W571	3.10E+01	0.00E+00	4.07E-01	7.48E+00	3.65E+00	1.20E-05	2.84E-03	4.25E+01	1.72E-01
RL-W572	2.69E-02	0.00E+00	1.22E-04	4.03E-03	8.74E-05	1.07E-08	8.49E-07	3.11E-02	1.26E-04
RL-W573	3.46E+02	0.00E+00	1.56E+00	2.21E+00	1.61E+00	1.36E-04	1.09E-02	3.52E+02	1.42E+00
RL-W574	1.49E+03	0.00E+00	6.75E+00	8.43E+00	5.97E+00	5.95E-04	4.71E-02	1.51E+03	6.09E+00
RL-W575	9.70E+03	0.00E+00	4.55E+01	8.06E+01	4.77E+01	3.73E-03	3.17E-01	9.87E+03	3.98E+01
RL-W576	6.99E+02	0.00E+00	3.18E+00	4.11E+00	2.88E+00	2.80E-04	2.21E-02	7.09E+02	2.86E+00
RL-W579	5.92E-02	0.00E+00	8.37E-05	2.06E-02	4.49E-03	9.87E-10	5.83E-07	8.44E-02	3.40E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.64E-01	2.61E-02	0.00E+00	0.00E+00	1.90E-01	7.67E-04
RL-W581	6.29E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.29E-01	2.54E-03
RL-W582	4.11E-03	0.00E+00	7.09E-05	5.26E-03	2.66E-03	1.60E-10	4.95E-07	1.21E-02	4.88E-05
RL-W583	3.18E-03	0.00E+00	3.86E-05	2.97E-02	6.46E-03	9.32E-10	2.69E-07	3.94E-02	1.59E-04
RL-W584	6.32E-02	0.00E+00	2.53E-03	1.73E-01	8.28E-02	4.68E-09	1.76E-05	3.22E-01	1.30E-03
RL-W585	3.76E-01	0.00E+00	1.35E-02	1.01E+00	5.03E-01	1.43E-07	9.38E-05	1.90E+00	7.67E-03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W586	5.02E-05	0.00E+00	6.07E-07	4.69E-04	1.02E-04	1.47E-11	4.23E-09	6.21E-04	2.51E-06
RL-W587	1.07E-03	0.00E+00	1.31E-05	9.99E-03	2.18E-03	3.30E-10	9.14E-08	1.33E-02	5.35E-05
RL-W588	4.43E-02	0.00E+00	2.13E-03	1.46E-01	6.97E-02	3.94E-09	1.49E-05	2.63E-01	1.06E-03
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	1.36E+00	0.00E+00	4.55E-02	1.13E-02	1.96E-02	5.16E-07	3.17E-04	1.44E+00	5.79E-03
RL-W591	7.75E+00	0.00E+00	5.14E-02	1.40E-02	2.54E-02	3.12E-06	3.58E-04	7.84E+00	3.16E-02
RL-W592	3.42E+01	0.00E+00	5.63E-01	6.47E-01	8.20E-01	1.26E-05	3.92E-03	3.63E+01	1.46E-01
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.33E-02	3.85E-02	0.00E+00	0.00E+00	6.19E-02	2.49E-04
RL-W594	3.08E+01	0.00E+00	1.01E-01	2.89E-02	5.21E-02	3.15E-06	7.06E-04	3.10E+01	1.25E-01
RL-W595	8.14E-02	0.00E+00	1.06E-02	1.98E-02	3.78E-02	3.12E-08	7.37E-05	1.50E-01	6.04E-04
RL-W596	2.64E-02	0.00E+00	8.22E-04	2.04E-04	3.55E-04	9.37E-09	5.73E-06	2.78E-02	1.12E-04
RL-W597	4.85E+01	0.00E+00	3.62E-01	3.95E-01	6.44E-01	1.75E-05	2.52E-03	4.99E+01	2.01E-01
RL-W598	5.13E+01	0.00E+00	2.13E+00	5.50E-01	8.04E-01	1.81E-05	1.49E-02	5.48E+01	2.21E-01
RL-W599	2.60E+00	0.00E+00	1.72E-02	4.65E-03	8.47E-03	1.04E-06	1.20E-04	2.63E+00	1.06E-02
RL-W600	1.47E-07	0.00E+00	1.79E-09	1.38E-06	3.00E-07	4.32E-14	1.25E-11	1.82E-06	7.35E-09
RL-W601	7.48E-04	0.00E+00	9.78E-06	6.96E-03	1.52E-03	3.62E-10	6.82E-08	9.24E-03	3.73E-05
RL-W602	6.51E-01	0.00E+00	8.02E-03	6.03E+00	1.32E+00	2.19E-07	5.59E-05	8.01E+00	3.23E-02
RL-W603	3.75E+00	0.00E+00	4.63E-02	3.48E+01	7.58E+00	1.26E-06	3.23E-04	4.62E+01	1.86E-01
RL-W604	8.78E-03	0.00E+00	1.21E-04	1.69E-02	8.16E-03	1.50E-09	8.46E-07	3.40E-02	1.37E-04
RL-W605	2.01E-03	0.00E+00	2.64E-05	1.87E-02	4.07E-03	9.72E-10	1.84E-07	2.48E-02	1.00E-04
RL-W606	8.12E-04	0.00E+00	1.06E-05	7.54E-03	1.64E-03	3.93E-10	7.40E-08	1.00E-02	4.03E-05
RL-W607	1.49E-03	0.00E+00	2.06E-05	2.86E-03	1.38E-03	2.53E-10	1.43E-07	5.75E-03	2.32E-05
RL-W608	1.78E-02	0.00E+00	7.97E-04	3.72E-03	4.49E-03	3.88E-09	5.56E-06	2.68E-02	1.08E-04
RL-W610	3.52E+00	0.00E+00	4.27E-02	3.28E+01	7.15E+00	1.03E-06	2.97E-04	4.35E+01	1.76E-01
RL-W612	8.30E-03	0.00E+00	1.03E-04	7.97E-02	1.74E-02	2.44E-09	7.20E-07	1.06E-01	4.25E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.34E-01	0.00E+00	0.00E+00	0.00E+00	3.34E-01	1.35E-03
RL-W622	1.38E-04	0.00E+00	1.68E-06	1.30E-03	2.81E-04	4.06E-11	1.17E-08	1.72E-03	6.92E-06
RL-W625	4.82E-03	0.00E+00	2.56E-04	6.62E-03	6.36E-03	2.20E-09	1.78E-06	1.81E-02	7.28E-05
RL-W626	2.59E-01	0.00E+00	5.82E-03	2.59E-01	1.52E-01	3.84E-08	4.06E-05	6.76E-01	2.73E-03
RL-W627	1.22E-03	0.00E+00	7.78E-06	1.23E-06	0.00E+00	4.57E-10	5.42E-08	1.23E-03	4.96E-06
RL-W628	4.01E-04	0.00E+00	4.89E-06	3.74E-03	8.12E-04	1.23E-10	3.41E-08	4.96E-03	2.00E-05

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W629	2.71E-05	0.00E+00	3.36E-07	2.51E-04	5.46E-05	9.54E-12	2.34E-09	3.33E-04	1.34E-06
RL-W630	2.98E-01	0.00E+00	6.26E-03	2.91E+00	6.58E-01	1.03E-07	4.37E-05	3.87E+00	1.56E-02
RL-W631	4.81E-03	0.00E+00	6.31E-05	4.46E-02	9.70E-03	2.32E-09	4.40E-07	5.92E-02	2.39E-04
RL-W632	2.12E+00	0.00E+00	8.51E-03	5.90E+00	1.89E+00	7.73E-07	5.93E-05	9.92E+00	4.00E-02
RL-W633	5.06E-03	0.00E+00	4.94E-05	9.26E-04	7.99E-04	9.51E-10	3.45E-07	6.84E-03	2.76E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	1.01E-02	0.00E+00	0.00E+00	0.00E+00	1.01E-02	4.07E-05
RL-W635	3.03E+01	0.00E+00	1.67E+00	4.29E+00	6.27E+00	9.61E-06	1.16E-02	4.25E+01	1.71E-01
RL-W636	3.09E-01	0.00E+00	3.15E-03	5.61E-02	4.85E-02	5.84E-08	2.20E-05	4.17E-01	1.68E-03
RL-W637	7.34E-04	0.00E+00	8.02E-05	6.31E-04	6.05E-04	2.10E-10	5.59E-07	2.05E-03	8.27E-06
RL-W638	3.23E-02	0.00E+00	8.17E-04	6.18E-03	5.69E-03	7.81E-09	5.70E-06	4.50E-02	1.81E-04
RL-W639	1.70E-03	0.00E+00	2.09E-05	1.58E-02	3.44E-03	5.46E-10	1.46E-07	2.10E-02	8.46E-05
RL-W640	5.72E-02	0.00E+00	6.95E-04	5.33E-01	1.16E-01	1.76E-08	4.84E-06	7.07E-01	2.85E-03
RL-W641	1.75E+00	0.00E+00	1.53E-01	2.56E+00	1.03E+00	2.82E-07	1.06E-03	5.49E+00	2.21E-02
RL-W642	3.41E-02	0.00E+00	1.59E-05	3.13E-02	1.56E-04	1.22E-10	1.11E-07	6.55E-02	2.64E-04
RL-W643	5.37E-01	0.00E+00	4.70E-02	7.89E-01	3.17E-01	8.68E-08	3.28E-04	1.69E+00	6.82E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.43E-02	0.00E+00	0.00E+00	0.00E+00	5.43E-02	2.19E-04
RL-W645	1.31E-02	0.00E+00	2.11E-04	1.07E-01	2.45E-02	4.74E-09	1.47E-06	1.45E-01	5.83E-04
RL-W646	1.19E-02	0.00E+00	1.89E-04	2.55E-02	1.21E-02	2.30E-09	1.32E-06	4.97E-02	2.00E-04
RL-W647	3.34E-02	0.00E+00	2.82E-02	1.09E-01	1.68E-02	7.72E-09	1.97E-04	1.87E-01	7.56E-04
RL-W648	5.92E-04	0.00E+00	4.82E-05	5.94E-05	1.14E-04	2.47E-10	3.36E-07	8.14E-04	3.28E-06
RL-W649	2.18E-03	0.00E+00	1.78E-04	2.19E-04	4.20E-04	9.07E-10	1.24E-06	2.99E-03	1.21E-05
RL-W653	1.03E-04	0.00E+00	1.27E-06	9.55E-04	2.07E-04	3.46E-11	8.87E-09	1.27E-03	5.11E-06
RL-W654	5.67E-04	0.00E+00	6.95E-06	5.26E-03	1.14E-03	1.82E-10	4.84E-08	6.98E-03	2.81E-05
RL-W655	1.40E+02	0.00E+00	1.64E+00	2.09E-01	4.81E-01	4.85E-05	1.15E-02	1.42E+02	5.72E-01
RL-W656	5.84E+02	0.00E+00	7.39E-01	4.91E-01	4.95E-01	2.31E-04	5.15E-03	5.86E+02	2.36E+00
RL-W657	2.98E+02	0.00E+00	1.09E+00	2.41E-01	4.71E-01	1.02E-04	7.61E-03	3.00E+02	1.21E+00
RL-W659	3.61E+01	0.00E+00	2.46E-01	4.65E-02	5.64E-02	1.16E-05	1.72E-03	3.64E+01	1.47E-01
RL-W660	1.98E+02	0.00E+00	2.96E+00	8.58E-01	1.50E+00	6.60E-05	2.06E-02	2.03E+02	8.20E-01
RL-W661	2.09E+00	0.00E+00	3.70E-03	4.13E-04	3.68E-03	8.02E-07	2.58E-05	2.10E+00	8.48E-03
RL-W662	6.59E-02	0.00E+00	2.21E-04	1.06E-04	1.85E-04	1.64E-08	1.54E-06	6.64E-02	2.68E-04
RL-W665	8.10E+02	0.00E+00	1.77E+01	1.30E+00	1.70E+00	3.26E-04	1.23E-01	8.30E+02	3.35E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W666	1.45E+01	0.00E+00	4.33E-02	5.43E-02	5.59E-02	4.72E-06	3.02E-04	1.47E+01	5.91E-02
RL-W668	1.38E+00	0.00E+00	1.36E-03	1.43E-01	3.98E-02	1.12E-08	9.48E-06	1.57E+00	6.31E-03
RL-W669	4.03E-01	0.00E+00	3.53E-02	5.92E-01	2.37E-01	6.51E-08	2.46E-04	1.27E+00	5.11E-03
RL-W670	2.55E-02	0.00E+00	2.51E-05	2.65E-03	7.36E-04	2.07E-10	1.75E-07	2.89E-02	1.16E-04
RL-W671	4.15E+00	0.00E+00	1.29E-02	4.86E-03	4.94E-03	6.79E-07	8.97E-05	4.18E+00	1.68E-02
RL-W672	2.82E+01	0.00E+00	8.76E-02	3.31E-02	3.35E-02	4.61E-06	6.11E-04	2.84E+01	1.14E-01
RL-W673	2.72E+01	0.00E+00	8.41E-02	3.21E-02	3.24E-02	4.44E-06	5.87E-04	2.74E+01	1.10E-01
RL-W674	9.13E-02	0.00E+00	3.76E-03	1.11E+01	9.41E-02	3.10E-08	2.62E-05	1.13E+01	4.54E-02
RL-W675	3.41E-01	0.00E+00	2.08E-02	1.30E-01	1.10E-01	7.55E-08	1.45E-04	6.01E-01	2.43E-03
RL-W676	1.31E-02	0.00E+00	1.25E-04	1.45E-01	2.07E-03	2.24E-09	8.70E-07	1.61E-01	6.48E-04
RL-W677	3.04E+01	0.00E+00	3.09E-01	5.68E+00	4.82E+00	5.40E-06	2.16E-03	4.12E+01	1.66E-01
RL-W678	9.61E-02	0.00E+00	2.58E-03	5.10E-02	4.40E-02	4.24E-08	1.80E-05	1.94E-01	7.81E-04
RL-W679	6.02E-01	0.00E+00	5.77E-03	1.10E-01	9.47E-02	1.09E-07	4.02E-05	8.12E-01	3.28E-03
RL-W680	1.36E-04	0.00E+00	8.12E-06	1.72E-05	3.03E-05	4.66E-11	5.66E-08	1.91E-04	7.71E-07
RL-W681	8.28E-05	0.00E+00	3.29E-06	4.62E-04	2.25E-04	3.87E-11	2.30E-08	7.73E-04	3.12E-06
RL-W685	2.41E-01	0.00E+00	2.93E-03	2.26E+00	4.90E-01	7.07E-08	2.04E-05	2.99E+00	1.21E-02
RL-W689	6.25E-03	0.00E+00	3.51E-05	3.83E-04	0.00E+00	6.78E-11	2.45E-07	6.67E-03	2.69E-05
RL-W690	2.10E-01	0.00E+00	2.58E-03	2.01E+00	4.35E-01	6.15E-08	1.80E-05	2.66E+00	1.07E-02
RL-W691	4.86E-03	0.00E+00	6.02E-05	4.65E-02	1.01E-02	1.43E-09	4.20E-07	6.15E-02	2.48E-04
RL-W692	1.92E-01	0.00E+00	2.38E-03	1.84E+00	4.00E-01	5.63E-08	1.66E-05	2.43E+00	9.81E-03
RL-W693	2.38E-01	0.00E+00	2.94E-03	2.28E+00	4.95E-01	6.96E-08	2.05E-05	3.01E+00	1.21E-02
RL-W694	2.50E+00	0.00E+00	3.09E-02	2.40E+01	5.19E+00	7.32E-07	2.15E-04	3.18E+01	1.28E-01
RL-W695	2.07E-03	0.00E+00	0.00E+00	2.36E-03	0.00E+00	0.00E+00	0.00E+00	4.43E-03	1.79E-05
RL-W696	2.70E-03	0.00E+00	1.13E-04	2.88E-03	2.78E-03	1.01E-09	7.84E-07	8.46E-03	3.41E-05
RL-W697	6.23E-01	0.00E+00	2.38E-01	6.85E-03	9.19E-04	0.00E+00	1.66E-03	8.71E-01	3.51E-03
RL-W698	5.40E-02	0.00E+00	0.00E+00	3.25E-05	0.00E+00	0.00E+00	0.00E+00	5.41E-02	2.18E-04
RL-W699	1.20E-02	0.00E+00	1.59E-05	2.18E-03	2.50E-04	4.22E-09	1.11E-07	1.45E-02	5.83E-05
RL-W700	3.41E-03	0.00E+00	4.16E-05	3.16E-02	6.87E-03	1.10E-09	2.90E-07	4.19E-02	1.69E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	1.34E-01	0.00E+00	1.17E-02	1.97E-01	7.92E-02	2.17E-08	8.19E-05	4.22E-01	1.70E-03

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W705	8.67E-04	0.00E+00	1.08E-05	8.27E-03	1.81E-03	2.67E-10	7.54E-08	1.10E-02	4.42E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	3.10E-02	0.00E+00	3.85E-04	2.95E-01	6.42E-02	9.47E-09	2.68E-06	3.90E-01	1.57E-03
RL-W708	4.68E-03	0.00E+00	5.82E-05	4.47E-02	9.70E-03	1.44E-09	4.06E-07	5.91E-02	2.39E-04
RL-W709	1.62E+00	0.00E+00	2.01E-02	1.54E+01	3.35E+00	4.96E-07	1.40E-04	2.04E+01	8.23E-02
RL-W710	9.65E-05	0.00E+00	1.20E-06	9.22E-04	2.00E-04	2.96E-11	8.36E-09	1.22E-03	4.92E-06
RL-W711	3.01E-02	0.00E+00	3.74E-04	2.88E-01	6.25E-02	9.23E-09	2.61E-06	3.81E-01	1.54E-03
RL-W712	3.90E-02	0.00E+00	4.84E-04	3.72E-01	8.09E-02	1.20E-08	3.38E-06	4.92E-01	1.99E-03
RL-W713	3.37E-02	0.00E+00	4.18E-04	3.21E-01	6.99E-02	1.03E-08	2.92E-06	4.25E-01	1.71E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	5.81E-04	0.00E+00	7.04E-06	5.43E-03	1.18E-03	1.70E-10	4.91E-08	7.20E-03	2.90E-05
RL-W716	6.06E-03	0.00E+00	7.34E-05	5.66E-02	1.23E-02	1.78E-09	5.12E-07	7.50E-02	3.02E-04
RL-W717	1.51E-03	0.00E+00	1.83E-05	1.41E-02	3.07E-03	4.43E-10	1.28E-07	1.88E-02	7.56E-05
RL-W718	2.67E-04	0.00E+00	3.23E-06	2.49E-03	5.42E-04	7.81E-11	2.25E-08	3.30E-03	1.33E-05
RL-W719	1.20E-03	0.00E+00	1.46E-05	1.13E-02	2.45E-03	3.53E-10	1.02E-07	1.49E-02	6.03E-05
RL-W720	7.45E-03	0.00E+00	9.05E-05	6.96E-02	1.52E-02	2.18E-09	6.31E-07	9.23E-02	3.72E-04
RL-W721	5.04E-03	0.00E+00	6.12E-05	4.71E-02	1.03E-02	1.48E-09	4.26E-07	6.25E-02	2.52E-04
RL-W723	1.67E-02	0.00E+00	2.06E-04	1.60E-01	3.48E-02	4.90E-09	1.44E-06	2.12E-01	8.55E-04
RL-W724	1.11E-01	0.00E+00	1.38E-03	1.06E+00	2.31E-01	3.25E-08	9.58E-06	1.40E+00	5.65E-03
RL-W725	3.51E-02	0.00E+00	4.33E-04	3.35E-01	7.30E-02	1.03E-08	3.02E-06	4.44E-01	1.79E-03
RL-W726	2.77E-02	0.00E+00	3.42E-04	2.65E-01	5.75E-02	8.10E-09	2.38E-06	3.51E-01	1.41E-03
RL-W727	1.70E-01	0.00E+00	2.10E-03	1.62E+00	3.53E-01	4.97E-08	1.46E-05	2.15E+00	8.66E-03
RL-W728	1.54E-01	0.00E+00	1.91E-03	1.48E+00	3.22E-01	4.52E-08	1.33E-05	1.96E+00	7.91E-03
RL-W729	7.13E-02	0.00E+00	8.85E-04	6.82E-01	1.49E-01	2.09E-08	6.17E-06	9.04E-01	3.64E-03
RL-W730	2.79E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.79E+01	1.13E-01
RL-W731	9.00E-06	0.00E+00	0.00E+00	4.46E-04	1.79E-06	0.00E+00	0.00E+00	4.57E-04	1.84E-06
RL-W732	2.06E+01	0.00E+00	5.04E-01	1.26E+02	2.72E+01	7.48E-06	3.51E-03	1.74E+02	7.01E-01
RL-W733	2.71E-01	0.00E+00	6.56E-03	1.37E+00	3.30E-01	8.13E-08	4.57E-05	1.97E+00	7.95E-03
RL-W734	8.47E-01	0.00E+00	2.19E-02	4.71E+00	1.11E+00	2.42E-07	1.52E-04	6.69E+00	2.70E-02
RL-W735	6.92E-01	0.00E+00	1.67E-02	3.67E+00	8.88E-01	1.88E-07	1.16E-04	5.27E+00	2.12E-02
RL-W736	7.60E-04	0.00E+00	3.56E-08	2.43E-03	6.13E-04	5.75E-11	2.48E-10	3.81E-03	1.54E-05

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W737	6.17E-01	0.00E+00	1.52E-02	3.48E+00	8.27E-01	1.62E-07	1.06E-04	4.94E+00	1.99E-02
RL-W738	2.30E+00	0.00E+00	5.23E-02	1.11E+01	2.85E+00	5.88E-07	3.65E-04	1.63E+01	6.57E-02
RL-W739	1.96E-01	0.00E+00	4.62E-03	1.80E+00	4.00E-01	5.34E-08	3.22E-05	2.40E+00	9.68E-03
RL-W740	9.82E+00	0.00E+00	1.69E-01	4.38E+01	1.11E+01	2.70E-06	1.18E-03	6.50E+01	2.62E-01
RL-W741	1.47E+01	0.00E+00	3.98E-01	8.54E+00	5.92E+00	2.02E-06	2.78E-03	2.95E+01	1.19E-01
RL-W742	6.53E-01	0.00E+00	1.20E-02	2.77E+00	6.37E-01	1.74E-07	8.36E-05	4.07E+00	1.64E-02
RL-W743	1.18E-03	0.00E+00	3.25E-06	1.79E-03	0.00E+00	0.00E+00	2.27E-08	2.97E-03	1.20E-05
RL-W744	0.00E+00	0.00E+00	0.00E+00	8.93E-02	7.41E-02	0.00E+00	0.00E+00	1.63E-01	6.59E-04
RL-W745	1.86E-03	0.00E+00	2.28E-05	1.73E-02	3.76E-03	5.96E-10	1.59E-07	2.29E-02	9.25E-05
RL-W746	7.15E-03	0.00E+00	8.76E-05	6.65E-02	1.45E-02	2.29E-09	6.11E-07	8.82E-02	3.56E-04
RL-W747	1.94E-02	0.00E+00	2.37E-04	1.80E-01	3.92E-02	6.22E-09	1.65E-06	2.39E-01	9.63E-04
RL-W748	1.36E+02	0.00E+00	6.65E-01	2.99E-01	4.79E-01	4.68E-05	4.64E-03	1.37E+02	5.54E-01
RL-W749	1.63E-01	0.00E+00	2.04E-03	1.56E+00	3.39E-01	5.00E-08	1.42E-05	2.07E+00	8.33E-03
RL-W750	2.06E+02	0.00E+00	1.01E+00	4.90E-01	7.83E-01	6.62E-05	7.03E-03	2.08E+02	8.39E-01
RL-W751	1.86E+02	0.00E+00	9.10E-01	4.40E-01	7.10E-01	5.97E-05	6.34E-03	1.88E+02	7.58E-01
RL-W752	8.08E+01	0.00E+00	3.95E-01	1.92E-01	3.08E-01	2.59E-05	2.76E-03	8.17E+01	3.29E-01
RL-W753	1.09E+03	0.00E+00	5.33E+00	2.58E+00	4.14E+00	3.49E-04	3.72E-02	1.10E+03	4.43E+00
RP-W754	4.62E+01	0.00E+00	6.75E-01	1.84E+03	1.47E+02	3.22E-06	3.57E-01	2.03E+03	8.20E+00
RP-W755	2.44E+02	0.00E+00	4.05E-01	1.38E+03	1.11E+02	2.41E-06	1.26E+01	1.74E+03	7.03E+00
SA-T001	4.92E-01	2.14E-06	9.69E-03	3.00E+00	1.73E-02	0.00E+00	7.22E-05	3.52E+00	1.42E-02
SA-W134	4.01E+00	8.27E-10	6.60E-02	1.37E+00	4.22E-01	6.14E-08	1.67E-01	6.03E+00	2.43E-02
SA-W134M	5.21E-01	1.07E-10	8.56E-03	1.78E-01	5.47E-02	7.97E-09	2.16E-02	7.84E-01	3.16E-03
T001-221F-HET	9.71E+02	0.00E+00	7.73E+03	2.85E+04	6.86E+02	2.01E-04	5.95E+01	3.79E+04	1.53E+02
T001-221H-HET	1.75E+03	0.00E+00	1.39E+04	5.14E+04	1.24E+03	3.64E-04	1.07E+02	6.85E+04	2.76E+02
T001-235F-HET	1.01E+02	0.00E+00	8.02E+02	2.96E+03	7.12E+01	2.09E-05	6.18E+00	3.94E+03	1.59E+01
T001-772F-HET	8.66E+02	0.00E+00	6.95E+03	2.55E+04	6.14E+02	1.80E-04	5.35E+01	3.40E+04	1.37E+02
T001-773A-CLAS	9.73E+00	0.00E+00	7.78E+01	2.87E+02	6.89E+00	2.02E-06	5.99E-01	3.82E+02	1.54E+00
T001-773A-HET	1.12E+02	0.00E+00	8.95E+02	3.30E+03	7.95E+01	2.33E-05	6.90E+00	4.40E+03	1.77E+01
W006-773A-VIT	1.50E-03	0.00E+00	0.00E+00	5.31E+02	0.00E+00	0.00E+00	0.00E+00	5.31E+02	2.14E+00
W026-221F-HET	3.38E+02	0.00E+00	2.70E+03	9.99E+03	2.39E+02	7.01E-05	2.08E+01	1.33E+04	5.36E+01
W026-221H-HET	2.53E+02	0.00E+00	2.02E+03	7.44E+03	1.79E+02	5.25E-05	1.55E+01	9.90E+03	3.99E+01

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W026-235F-HET	3.93E+00	0.00E+00	3.14E+01	1.16E+02	2.79E+00	8.17E-07	2.42E-01	1.54E+02	6.21E-01
W026-772F-HET	1.08E+00	0.00E+00	8.56E+00	3.16E+01	7.59E-01	2.23E-07	6.59E-02	4.20E+01	1.69E-01
W026-773A-HET	1.75E+01	0.00E+00	1.39E+02	5.14E+02	1.24E+01	3.63E-06	1.07E+00	6.85E+02	2.76E+00
W027-221F-HET	1.28E+03	0.00E+00	9.10E+03	3.86E+04	9.26E+02	1.15E-04	8.12E+01	5.00E+04	2.01E+02
W027-221H-HET	5.57E+02	0.00E+00	3.97E+03	1.69E+04	4.05E+02	5.01E-05	3.55E+01	2.19E+04	8.82E+01
W027-235F-HET	1.68E+02	0.00E+00	1.19E+03	5.08E+03	1.22E+02	1.51E-05	1.07E+01	6.58E+03	2.65E+01
W027-772F-HET	3.05E+02	0.00E+00	2.17E+03	9.23E+03	2.22E+02	2.74E-05	1.94E+01	1.20E+04	4.82E+01
W027-773A-HET	4.54E+02	0.00E+00	3.24E+03	1.38E+04	3.30E+02	4.09E-05	2.89E+01	1.78E+04	7.18E+01
W027-999-HET	5.20E+02	0.00E+00	3.70E+03	1.57E+04	3.77E+02	4.67E-05	3.31E+01	2.04E+04	8.21E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.95E+02	0.00E+00	0.00E+00	0.00E+00	3.95E+02	1.59E+00
WP-INW169.001	2.54E+00	0.00E+00	2.33E-02	1.52E+01	3.30E+00	4.12E-07	3.28E-04	2.11E+01	8.51E-02
WP-INW198.001	3.34E+00	0.00E+00	4.07E-02	2.73E+01	5.88E+00	6.77E-07	3.66E-04	3.66E+01	1.47E-01
WP-INW211.001	3.77E+02	0.00E+00	3.82E+00	2.53E+03	5.46E+02	7.66E-05	2.86E-02	3.46E+03	1.39E+01
WP-INW216.001-	1.37E+04	0.00E+00	2.20E+00	1.46E+03	3.17E+02	4.24E-05	2.92E-01	1.55E+04	6.24E+01
WP-INW216.001-	3.76E+03	0.00E+00	5.92E-01	3.97E+02	8.55E+01	1.15E-05	3.17E-02	4.24E+03	1.71E+01
WP-INW218.001-	2.62E+02	0.00E+00	3.87E-01	2.55E+02	5.51E+01	7.66E-06	3.88E-01	5.73E+02	2.31E+00
WP-INW218.001-	1.21E+00	0.00E+00	1.07E-02	6.94E+00	1.50E+00	2.17E-07	3.74E-02	9.69E+00	3.91E-02
WP-INW222.001	1.24E+01	0.00E+00	1.15E-01	6.79E+01	1.48E+01	1.84E-06	1.38E-03	9.51E+01	3.84E-01
WP-INW243.001	3.00E+01	0.00E+00	2.48E-01	1.42E+02	3.11E+01	3.72E-06	2.60E-03	2.04E+02	8.22E-01
WP-INW247.001R	4.01E+01	0.00E+00	5.77E-01	2.73E+02	6.05E+01	6.45E-06	4.10E-03	3.74E+02	1.51E+00
WP-INW276.001	3.06E+00	0.00E+00	5.63E-02	2.70E+01	5.99E+00	5.46E-07	4.09E-04	3.61E+01	1.46E-01
WP-INW276.002	4.85E+00	0.00E+00	8.46E-02	3.97E+01	8.99E+00	8.20E-07	6.17E-04	5.36E+01	2.16E-01
WP-INW276.003	1.86E+02	0.00E+00	3.15E+00	1.47E+03	3.28E+02	3.45E-05	2.24E-02	1.99E+03	8.03E+00
WP-INW276.004	4.44E+01	0.00E+00	6.65E-01	3.12E+02	6.91E+01	7.28E-06	4.78E-03	4.26E+02	1.72E+00
WP-INW296.001-	1.62E+01	0.00E+00	1.58E-01	7.82E+01	1.73E+01	1.87E-06	1.14E-03	1.12E+02	4.51E-01
WP-INW296.001-	4.89E+01	0.00E+00	5.58E-01	2.77E+02	6.11E+01	6.73E-06	4.24E-03	3.88E+02	1.56E+00
WP-LA-TA-55-19	8.15E-01	0.00E+00	2.59E-02	2.07E+00	4.87E-01	6.69E-08	2.82E-03	3.40E+00	1.37E-02
WP-LA-TA-55-19	3.95E+01	0.00E+00	8.71E-01	2.11E+02	5.01E+01	6.65E-06	9.32E-02	3.01E+02	1.22E+00
WP-LA-TA-55-43	2.22E-01	0.00E+00	2.03E+01	3.20E-01	1.32E-01	5.96E-08	1.68E-01	2.11E+01	8.53E-02
WP-RF001.01	6.85E+01	0.00E+00	7.04E-01	4.06E+02	9.00E+01	6.70E-06	1.42E-02	5.65E+02	2.28E+00
WP-RF002.01-A	7.97E+01	0.00E+00	9.39E-01	4.57E+02	1.02E+02	1.48E-05	2.43E-02	6.39E+02	2.58E+00

Table PAR-55. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 350 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF002.01-B	7.91E-02	0.00E+00	6.51E-04	4.95E-01	1.10E-01	9.29E-09	4.73E-06	6.84E-01	2.76E-03
WP-RF003.01	1.24E+03	0.00E+00	1.51E+01	8.73E+03	1.94E+03	2.44E-04	1.14E-01	1.19E+04	4.81E+01
WP-RF004.01	5.81E-01	0.00E+00	1.01E-02	5.03E+00	1.12E+00	1.39E-07	1.98E-04	6.75E+00	2.72E-02
WP-RF005.01	2.98E+03	0.00E+00	7.68E+00	4.62E+03	1.02E+03	9.71E-05	5.54E-02	8.62E+03	3.48E+01
WP-RF005.02	3.50E+03	0.00E+00	3.97E+00	2.76E+03	6.04E+02	4.98E-05	2.89E-02	6.87E+03	2.77E+01
WP-RF006.01	1.14E+03	0.00E+00	1.44E+01	7.85E+03	1.75E+03	1.26E-04	1.26E-01	1.08E+04	4.34E+01
WP-RF008.01	3.61E+02	0.00E+00	5.14E+00	2.30E+03	5.20E+02	8.32E-05	3.71E-02	3.18E+03	1.28E+01
WP-RF009.01	3.55E+04	0.00E+00	6.31E+01	5.03E+04	1.10E+04	9.55E-04	4.61E-01	9.69E+04	3.91E+02
WP-RF010.01	1.31E+01	0.00E+00	1.60E-01	7.61E+01	1.69E+01	2.94E-06	1.85E-03	1.06E+02	4.28E-01
WP-RF029.01-A	3.14E+00	0.00E+00	3.01E-02	1.34E+01	2.98E+00	6.75E-07	9.39E-04	1.95E+01	7.86E-02
WP-RF029.01-B	4.69E+00	0.00E+00	2.38E-02	1.06E+01	2.35E+00	5.34E-07	2.41E-03	1.77E+01	7.12E-02
WP-RF118.01	7.98E+03	0.00E+00	1.20E+02	5.08E+04	1.10E+04	1.76E-03	1.05E+00	7.00E+04	2.82E+02
WP-RLMPDT.001	1.69E+00	0.00E+00	3.50E-02	7.28E+00	1.84E+00	3.85E-07	2.46E-04	1.09E+01	4.38E-02
WP-RLNPDT.002	2.08E+01	0.00E+00	3.33E-01	7.15E+01	1.87E+01	4.42E-06	2.36E-03	1.11E+02	4.49E-01
WP-SR2001.001.	6.62E-01	0.00E+00	3.83E-02	6.76E+00	1.31E+00	2.41E-07	2.72E-04	8.76E+00	3.53E-02
WP-SR-W027-221	4.90E+00	0.00E+00	1.13E-01	1.94E+01	5.27E+00	1.09E-06	1.87E-01	2.99E+01	1.20E-01
Total	2.62E+05	4.13E-03	7.88E+04	6.53E+05	1.03E+05	2.48E-02	7.17E+02	1.10E+06	4.43E+03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	1.74E+01	0.00E+00	5.13E-03	2.03E+02	1.11E+02	6.37E-20	1.96E-02	3.32E+02	1.34E+00
AE-T003	2.21E+00	0.00E+00	6.83E-04	6.27E+01	2.24E+01	3.49E-20	9.61E-04	8.73E+01	3.52E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	9.78E-03	0.00E+00	1.81E-02	4.62E+01	2.58E-01	6.79E-23	2.30E-02	4.65E+01	1.88E-01
AW-T033.1325	3.58E-02	0.00E+00	6.63E-02	1.69E+02	9.41E-01	2.48E-22	8.41E-02	1.70E+02	6.86E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.50E-01	0.00E+00	0.00E+00	0.00E+00	7.50E-01	3.03E-03
BCLCH-MT01	3.61E+00	0.00E+00	5.13E-01	2.79E+01	6.76E+00	9.59E-20	6.37E-01	3.94E+01	1.59E-01
BT-T002	2.65E-03	1.78E-20	2.68E-04	7.04E-04	1.33E-03	4.21E-23	2.32E-03	7.27E-03	2.93E-05
ET-C1-B55	1.11E-02	0.00E+00	3.05E-06	6.03E-02	2.78E-02	7.43E-23	2.39E-04	9.94E-02	4.01E-04
ET-C1-D139	1.52E-03	0.00E+00	4.24E-07	8.47E-03	3.91E-03	9.88E-24	5.88E-07	1.39E-02	5.61E-05
ET-C2-SEFOR	3.76E-02	0.00E+00	0.00E+00	1.33E-01	4.13E-02	1.52E-22	0.00E+00	2.12E-01	8.54E-04
FM-MOX-MT02	3.57E-07	0.00E+00	1.71E-10	2.91E-07	1.60E-07	5.30E-27	2.20E-10	8.09E-07	3.26E-09
FM-MOX-T01	5.89E-06	0.00E+00	2.82E-09	4.80E-06	2.64E-06	8.74E-26	3.64E-09	1.33E-05	5.38E-08
IN-BN-510	1.42E+03	0.00E+00	1.45E+01	3.85E+04	3.02E+03	2.09E-20	2.00E+01	4.30E+04	1.73E+02
IN-GEM-01	1.80E+01	0.00E+00	2.88E-04	4.33E+01	9.14E+00	1.47E-20	3.58E-04	7.04E+01	2.84E-01
IN-GEM-02	4.27E+00	0.00E+00	6.86E-05	1.03E+01	2.18E+00	3.49E-21	8.52E-05	1.67E+01	6.75E-02
IN-W157.144	2.13E+01	0.00E+00	2.79E-03	2.94E+02	6.16E+01	2.61E-19	3.84E-03	3.77E+02	1.52E+00
IN-W163.1007	3.65E+00	0.00E+00	8.61E-04	9.13E+01	1.91E+01	8.04E-20	1.19E-03	1.14E+02	4.60E-01
IN-W164.153	3.49E-02	0.00E+00	8.21E-06	8.69E-01	1.82E-01	7.70E-22	1.13E-05	1.09E+00	4.38E-03
IN-W167.149	6.98E+00	0.00E+00	1.33E-03	1.41E+02	2.95E+01	1.25E-19	1.84E-03	1.77E+02	7.15E-01
IN-W174.154	0.00E+00	0.00E+00	7.55E-01	1.89E+00	3.45E+00	0.00E+00	1.04E+00	7.14E+00	2.88E-02
IN-W177.156	4.85E-03	0.00E+00	1.61E+00	1.78E+00	1.00E-02	1.07E-22	2.21E+00	5.61E+00	2.26E-02
IN-W179.158	3.26E-02	0.00E+00	1.60E+00	1.03E-01	4.95E-02	7.19E-22	2.20E+00	3.98E+00	1.61E-02
IN-W181.162	4.62E-01	0.00E+00	1.09E-04	1.15E+01	2.40E+00	1.02E-20	1.50E-04	1.43E+01	5.77E-02
IN-W188.160	3.11E+00	0.00E+00	7.32E-04	7.74E+01	1.61E+01	6.87E-20	1.01E-03	9.66E+01	3.90E-01
IN-W216.98	2.77E+04	0.00E+00	5.96E-02	6.31E+03	1.33E+03	5.62E-18	8.21E-02	3.53E+04	1.42E+02

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	1.40E+02	0.00E+00	1.33E-03	1.40E+02	2.93E+01	1.24E-19	1.83E-03	3.09E+02	1.25E+00
IN-W219.110	1.90E-01	0.00E+00	4.47E-05	4.72E+00	9.86E-01	4.18E-21	6.15E-05	5.89E+00	2.38E-02
IN-W219.914	2.99E-02	0.00E+00	7.03E-06	7.45E-01	1.56E-01	6.60E-22	9.68E-06	9.30E-01	3.75E-03
IN-W220.114	9.87E+02	0.00E+00	4.70E-03	5.33E+02	1.09E+02	4.39E-19	6.46E-03	1.63E+03	6.57E+00
IN-W221.927	1.16E+00	0.00E+00	2.72E-04	2.87E+01	6.01E+00	2.56E-20	3.75E-04	3.59E+01	1.45E-01
IN-W222.116	3.94E+01	0.00E+00	9.22E-03	9.71E+02	2.04E+02	8.63E-19	1.27E-02	1.21E+03	4.89E+00
IN-W228.101	2.61E+02	0.00E+00	3.00E-03	3.17E+02	6.63E+01	2.82E-19	4.12E-03	6.45E+02	2.60E+00
IN-W240.931	2.76E+01	0.00E+00	3.83E-03	4.08E+02	8.49E+01	3.57E-19	5.28E-03	5.20E+02	2.10E+00
IN-W243.808	3.84E+01	0.00E+00	6.71E-03	7.12E+02	1.49E+02	6.31E-19	9.24E-03	8.99E+02	3.62E+00
IN-W245.301	5.67E+01	0.00E+00	1.32E-02	1.39E+03	2.91E+02	1.23E-18	1.82E-02	1.74E+03	7.00E+00
IN-W247.810	2.76E+01	0.00E+00	6.43E-03	6.79E+02	1.43E+02	6.02E-19	8.84E-03	8.49E+02	3.42E+00
IN-W249.527	0.00E+00	0.00E+00	4.49E-01	1.20E+01	0.00E+00	0.00E+00	6.19E-01	1.31E+01	5.28E-02
IN-W263.520	7.91E-03	0.00E+00	4.70E-02	8.18E+00	1.20E-02	1.74E-22	6.47E-02	8.32E+00	3.35E-02
IN-W267.1005	6.62E+00	0.00E+00	1.56E-03	1.65E+02	3.45E+01	1.46E-19	2.15E-03	2.06E+02	8.31E-01
IN-W309.609	1.77E+02	0.00E+00	2.61E-02	2.76E+03	5.77E+02	2.45E-18	3.60E-02	3.51E+03	1.42E+01
IN-W315.601	1.75E+02	0.00E+00	1.09E-04	1.16E+01	2.41E+00	1.02E-20	1.50E-04	1.89E+02	7.62E-01
IN-W319.584	1.02E+00	0.00E+00	2.39E-04	2.53E+01	5.32E+00	2.25E-20	3.29E-04	3.17E+01	1.28E-01
IN-W321.1023	8.80E+00	0.00E+00	2.07E-03	2.19E+02	4.59E+01	1.94E-19	2.86E-03	2.74E+02	1.11E+00
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	8.85E+00	1.69E+00	0.00E+00	0.00E+00	1.06E+01	4.25E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.36E+01	4.52E+00	0.00E+00	0.00E+00	2.81E+01	1.13E-01
IN-W323.562	1.88E-02	0.00E+00	3.52E-04	2.42E-01	0.00E+00	4.15E-22	4.84E-04	2.61E-01	1.05E-03
IN-W323.951	2.22E-02	0.00E+00	4.18E-06	2.88E-01	0.00E+00	4.90E-22	5.75E-06	3.11E-01	1.25E-03
IN-W332.661	0.00E+00	0.00E+00	4.61E-03	1.25E-01	0.00E+00	0.00E+00	6.35E-03	1.36E-01	5.49E-04
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	2.95E+00	5.65E-01	0.00E+00	0.00E+00	3.52E+00	1.42E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	8.85E+00	1.69E+00	0.00E+00	0.00E+00	1.06E+01	4.25E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.89E+00	0.00E+00	0.00E+00	0.00E+00	1.89E+00	7.63E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.69E+00	0.00E+00	0.00E+00	0.00E+00	5.69E+00	2.29E-02
IN-W342.652	8.70E-01	0.00E+00	0.00E+00	3.90E-02	9.32E-18	0.00E+00	0.00E+00	9.09E-01	3.66E-03
IN-W342.953	5.81E-01	0.00E+00	0.00E+00	2.61E-02	6.26E-18	0.00E+00	0.00E+00	6.07E-01	2.45E-03
IN-W347.818	4.55E-01	0.00E+00	0.00E+00	8.02E+01	1.36E+02	0.00E+00	1.58E-08	2.17E+02	8.75E-01
IN-W348.1012	2.41E-02	0.00E+00	3.80E-03	4.05E+02	8.48E+01	0.00E+00	5.24E-03	4.90E+02	1.97E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.43E-02	0.00E+00	0.00E+00	0.00E+00	2.43E-02	9.79E-05
IN-W357.1022	0.00E+00	0.00E+00	7.49E-06	7.95E-01	1.66E-01	0.00E+00	1.03E-05	9.61E-01	3.87E-03
IN-W358.854	0.00E+00	0.00E+00	1.13E-01	1.83E+00	3.25E+00	0.00E+00	1.48E-01	5.34E+00	2.15E-02
IN-W358.855	0.00E+00	0.00E+00	6.02E-01	9.71E+00	1.73E+01	0.00E+00	7.91E-01	2.84E+01	1.15E-01
IN-W358.948	0.00E+00	0.00E+00	1.26E-01	2.03E+00	3.60E+00	0.00E+00	1.65E-01	5.92E+00	2.39E-02
IN-W361.1021	6.40E-03	0.00E+00	7.26E-04	7.67E+01	1.60E+01	0.00E+00	9.99E-04	9.27E+01	3.74E-01
IN-W362.1020	0.00E+00	0.00E+00	9.51E-03	1.00E+03	2.11E+02	0.00E+00	1.31E-02	1.21E+03	4.88E+00
IN-W363.1019	0.00E+00	0.00E+00	4.47E-04	4.75E+01	9.95E+00	0.00E+00	6.15E-04	5.74E+01	2.32E-01
IN-W364.1011	0.00E+00	0.00E+00	7.38E-04	7.81E+01	1.63E+01	0.00E+00	1.02E-03	9.44E+01	3.81E-01
IN-W365.1010	5.96E+01	0.00E+00	5.85E-04	6.16E+01	1.29E+01	0.00E+00	8.05E-04	1.34E+02	5.41E-01
IN-W366.841	2.12E-01	0.00E+00	4.98E-04	5.25E+01	1.10E+01	0.00E+00	6.86E-04	6.38E+01	2.57E-01
IN-W372.832	8.70E-01	0.00E+00	0.00E+00	3.90E-02	9.32E-18	0.00E+00	0.00E+00	9.09E-01	3.66E-03
IN-W375.1096	0.00E+00	0.00E+00	1.84E-04	1.94E+01	4.06E+00	0.00E+00	2.53E-04	2.35E+01	9.47E-02
KN-B234TRU	3.09E+01	0.00E+00	7.03E-03	2.83E+02	8.78E+01	1.37E-19	1.07E-02	4.01E+02	1.62E+00
LA-IT-00-01	4.49E-01	1.14E-17	1.20E-03	5.68E-01	1.14E-02	2.62E-29	1.84E-03	1.03E+00	4.16E-03
LA-OS-00-01	1.00E+03	0.00E+00	5.47E+01	1.19E+03	0.00E+00	0.00E+00	6.85E+01	2.32E+03	9.34E+00
LA-PX-00-01	4.17E-03	0.00E+00	2.31E-06	8.79E-02	1.91E-02	4.34E-23	3.01E-06	1.11E-01	4.48E-04
LA-SL-00-01	0.00E+00	0.00E+00	4.87E-05	1.49E-01	0.00E+00	0.00E+00	7.43E-05	1.49E-01	5.99E-04
LA-TA-03-12	4.29E-02	0.00E+00	1.13E-03	4.23E-01	1.36E-01	2.57E-22	1.78E-03	6.05E-01	2.44E-03
LA-TA-03-13	5.54E-02	0.00E+00	3.57E-03	6.61E-01	1.43E-01	3.41E-22	4.97E-03	8.69E-01	3.50E-03
LA-TA-03-19	1.12E-01	0.00E+00	5.33E-03	1.29E+00	3.45E-01	5.27E-22	8.41E-03	1.76E+00	7.10E-03
LA-TA-03-20	6.11E-02	0.00E+00	2.53E-03	5.69E-01	1.86E-01	4.31E-22	3.83E-03	8.22E-01	3.31E-03
LA-TA-03-24	8.20E-02	0.00E+00	9.85E-03	1.06E+00	2.97E-01	4.47E-22	1.56E-02	1.46E+00	5.90E-03
LA-TA-03-26	4.20E-03	0.00E+00	4.06E-04	2.56E+00	3.88E-02	3.92E-23	1.51E-03	2.61E+00	1.05E-02
LA-TA-03-28	0.00E+00	0.00E+00	1.41E-04	2.40E-01	0.00E+00	0.00E+00	2.20E-04	2.40E-01	9.68E-04
LA-TA-03-30	1.87E-01	0.00E+00	1.00E-04	4.88E+00	1.31E+00	2.05E-21	1.55E-04	6.38E+00	2.57E-02
LA-TA-03-31	0.00E+00	0.00E+00	5.01E-06	8.54E-03	0.00E+00	0.00E+00	7.83E-06	8.56E-03	3.45E-05
LA-TA-03-40	0.00E+00	0.00E+00	7.92E-06	5.31E-02	0.00E+00	0.00E+00	1.25E-05	5.31E-02	2.14E-04
LA-TA-03-42	4.29E-06	0.00E+00	1.99E-07	3.32E-03	4.04E-05	4.29E-26	3.13E-07	3.37E-03	1.36E-05
LA-TA-21-06	4.23E-02	0.00E+00	2.18E-02	9.29E-01	2.63E-01	4.42E-22	3.41E-02	1.29E+00	5.20E-03
LA-TA-21-12	1.54E-01	0.00E+00	1.32E-01	3.22E+00	8.91E-01	1.52E-21	2.06E-01	4.61E+00	1.86E-02

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-13	2.37E-01	0.00E+00	0.00E+00	2.85E-01	0.00E+00	0.00E+00	0.00E+00	5.22E-01	2.11E-03
LA-TA-21-14	3.89E-05	0.00E+00	2.51E-03	4.36E+00	4.71E-05	6.15E-25	3.30E-03	4.36E+00	1.76E-02
LA-TA-21-15	2.30E-02	0.00E+00	6.91E-06	1.35E+00	2.13E-01	2.50E-22	1.07E-05	1.59E+00	6.39E-03
LA-TA-21-16	2.66E-01	0.00E+00	1.07E-04	1.03E+01	2.28E+00	2.63E-21	1.68E-04	1.28E+01	5.17E-02
LA-TA-21-40	3.38E-05	0.00E+00	3.69E-04	3.23E-01	3.31E-04	1.06E-25	7.08E-04	3.25E-01	1.31E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	6.88E-01	0.00E+00	0.00E+00	0.00E+00	6.88E-01	2.78E-03
LA-TA-21-42	3.45E-03	0.00E+00	1.20E-04	1.59E-01	1.00E-02	3.44E-24	2.45E-04	1.73E-01	6.98E-04
LA-TA-21-43	1.22E+01	0.00E+00	3.98E-03	4.96E+02	1.09E+02	2.72E-20	8.07E-03	6.18E+02	2.49E+00
LA-TA-21-44	5.84E-02	0.00E+00	8.36E-04	1.12E+02	2.75E-01	3.84E-22	1.41E-03	1.12E+02	4.52E-01
LA-TA-48-01	1.89E-02	5.39E-17	3.14E-06	1.15E-01	4.44E-01	3.17E-23	6.08E-06	5.77E-01	2.33E-03
LA-TA-49-01	2.33E+00	6.69E-15	3.86E-04	1.42E+01	5.50E+01	3.92E-21	7.50E-04	7.15E+01	2.88E-01
LA-TA-50-10	6.25E-03	0.00E+00	3.66E-06	4.46E-02	0.00E+00	0.00E+00	4.73E-06	5.08E-02	2.05E-04
LA-TA-50-11	1.19E-02	0.00E+00	3.75E-06	4.52E-01	9.32E-02	3.14E-23	7.13E-06	5.58E-01	2.25E-03
LA-TA-50-15	2.35E-02	0.00E+00	5.53E-04	3.30E-01	6.86E-02	1.24E-22	8.08E-04	4.24E-01	1.71E-03
LA-TA-50-17	3.44E+00	0.00E+00	4.49E-04	1.77E+01	3.85E-04	1.14E-23	9.95E-04	2.11E+01	8.51E-02
LA-TA-50-18	2.05E-01	0.00E+00	5.94E-05	2.88E+00	4.80E-06	3.36E-25	9.35E-05	3.09E+00	1.25E-02
LA-TA-50-19	6.53E-02	0.00E+00	2.65E-05	3.83E-01	4.11E-03	4.15E-24	6.84E-05	4.53E-01	1.83E-03
LA-TA-50-20	1.79E-03	0.00E+00	0.00E+00	9.46E-03	0.00E+00	0.00E+00	0.00E+00	1.13E-02	4.53E-05
LA-TA-50-40	1.01E-03	0.00E+00	3.57E-07	1.03E-02	4.46E-03	1.33E-23	5.37E-07	1.58E-02	6.35E-05
LA-TA-50-41	1.08E-03	0.00E+00	3.60E-07	4.56E-02	9.86E-03	2.37E-23	4.96E-07	5.66E-02	2.28E-04
LA-TA-55-19	1.67E+00	0.00E+00	4.75E-04	2.56E+01	6.70E+00	1.34E-20	2.26E-03	3.40E+01	1.37E-01
LA-TA-55-20	2.68E+01	0.00E+00	5.42E-03	6.19E+02	1.38E+02	3.36E-19	1.01E-01	7.84E+02	3.16E+00
LA-TA-55-21	2.39E-01	1.59E-20	6.22E-05	4.39E+00	9.77E-01	2.77E-21	8.50E-05	5.60E+00	2.26E-02
LA-TA-55-22	6.55E-01	0.00E+00	3.52E-04	1.54E+01	3.35E+00	8.58E-21	4.80E-04	1.94E+01	7.84E-02
LA-TA-55-23	6.18E-01	0.00E+00	2.94E-04	1.06E+01	2.43E+00	8.44E-21	3.98E-04	1.36E+01	5.50E-02
LA-TA-55-24	2.33E-01	0.00E+00	4.61E-05	5.55E+00	1.20E+00	4.02E-21	6.00E-05	6.99E+00	2.82E-02
LA-TA-55-25	1.19E+00	0.00E+00	2.69E-04	2.76E+01	5.98E+00	2.06E-20	3.50E-04	3.47E+01	1.40E-01
LA-TA-55-28	4.06E-01	0.00E+00	1.49E-04	8.47E+00	1.86E+00	6.68E-21	1.96E-04	1.07E+01	4.33E-02
LA-TA-55-30	9.05E+00	1.51E-22	1.78E-03	1.39E+02	3.11E+01	4.90E-20	2.99E-03	1.79E+02	7.22E-01
LA-TA-55-32	7.34E-01	0.00E+00	9.97E-03	1.10E+01	3.15E+00	6.10E-21	1.59E-02	1.49E+01	6.00E-02
LA-TA-55-33	1.10E-01	0.00E+00	2.57E-05	1.45E+00	4.29E-01	8.58E-22	3.83E-05	1.99E+00	8.00E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-34	1.11E+01	0.00E+00	2.38E-03	2.24E+02	5.29E+01	1.03E-19	6.32E-03	2.88E+02	1.16E+00
LA-TA-55-38	2.79E+01	0.00E+00	7.84E-04	4.95E+01	1.24E+01	2.41E-20	2.86E-03	8.98E+01	3.62E-01
LA-TA-55-39	2.95E+00	0.00E+00	5.79E-04	7.39E+01	1.54E+01	4.23E-20	7.78E-04	9.22E+01	3.72E-01
LA-TA-55-41	7.03E+01	0.00E+00	1.20E-03	9.16E+01	2.04E+01	5.33E-20	1.65E-03	1.82E+02	7.35E-01
LA-TA-55-43	2.64E-02	0.00E+00	7.87E-02	1.38E-01	4.48E-02	4.69E-22	1.05E-01	3.93E-01	1.58E-03
LA-TA-55-44	2.29E-01	0.00E+00	1.85E-01	2.55E+00	6.58E-01	1.39E-21	2.78E-01	3.90E+00	1.57E-02
LA-TA-55-48	1.69E+03	0.00E+00	7.32E-01	1.64E+04	5.68E+03	1.45E-17	1.07E+00	2.38E+04	9.59E+01
LA-TA-55-49	3.61E+00	0.00E+00	9.62E-01	3.00E+01	7.83E+00	1.69E-20	1.43E+00	4.38E+01	1.77E-01
LA-TA-55-53	1.70E+01	0.00E+00	1.99E-03	2.56E+02	5.56E+01	9.27E-20	2.93E-03	3.29E+02	1.33E+00
LA-TA-55-56	1.88E+01	0.00E+00	7.40E-02	3.71E+02	8.64E+01	2.14E-19	1.04E-01	4.76E+02	1.92E+00
LA-TA-55-60	1.02E-02	0.00E+00	1.87E-05	6.99E-02	2.30E-02	1.26E-22	2.79E-05	1.03E-01	4.16E-04
LA-TA-55-61	8.79E-03	0.00E+00	8.61E-05	1.35E-01	4.25E-02	1.23E-22	1.26E-04	1.86E-01	7.52E-04
LA-TA-55-62	2.28E-03	0.00E+00	8.18E-07	2.26E-02	1.00E-02	3.30E-23	1.21E-06	3.49E-02	1.41E-04
LA-TA-55-63	1.69E-03	0.00E+00	5.53E-07	7.25E-02	1.56E-02	3.25E-23	7.80E-07	8.98E-02	3.62E-04
LL-M001	2.32E+01	7.23E-16	2.41E-02	6.80E+01	2.85E+01	2.57E-19	3.00E-02	1.20E+02	4.83E-01
LL-T001	1.16E+02	0.00E+00	0.00E+00	5.18E+02	2.17E+02	1.99E-18	0.00E+00	8.51E+02	3.43E+00
LL-T002	1.14E+03	0.00E+00	1.92E-01	5.03E+03	1.92E+03	1.75E-17	2.38E-01	8.09E+03	3.26E+01
LL-T003	4.45E+01	0.00E+00	2.15E-02	1.02E+02	7.64E+01	6.92E-19	2.67E-02	2.23E+02	8.98E-01
LL-T004	2.83E+01	0.00E+00	4.41E-03	6.48E+01	4.81E+01	4.39E-19	5.48E-03	1.41E+02	5.69E-01
LL-T005	1.46E+02	3.15E-14	5.19E-02	2.41E+02	1.93E+02	1.63E-18	6.44E-02	5.80E+02	2.34E+00
LL-W018	1.24E-02	0.00E+00	0.00E+00	1.80E-02	3.84E-02	3.33E-22	0.00E+00	6.87E-02	2.77E-04
LL-W019	6.73E+00	0.00E+00	0.00E+00	1.40E+01	1.09E+01	9.75E-20	0.00E+00	3.16E+01	1.27E-01
LL-W034	2.49E+00	5.32E-16	9.08E-04	4.08E+00	3.20E+00	2.77E-20	1.13E-03	9.77E+00	3.94E-02
MC-W001	3.11E-02	0.00E+00	0.00E+00	5.88E-02	0.00E+00	5.01E-23	0.00E+00	8.99E-02	3.62E-04
MU-W002	4.15E-01	0.00E+00	0.00E+00	5.11E-02	0.00E+00	0.00E+00	2.66E-12	4.66E-01	1.88E-03
NT-JAS-01	4.01E+01	0.00E+00	1.93E-02	9.20E+01	6.88E+01	6.23E-19	2.40E-02	2.01E+02	8.10E-01
NT-W001	6.01E+01	1.63E-17	3.86E-02	2.78E+03	1.72E+01	4.37E-20	5.95E-02	2.85E+03	1.15E+01
NT-W021	1.16E+00	0.00E+00	2.77E-04	3.13E+01	6.62E+00	2.23E-20	3.90E-04	3.90E+01	1.57E-01
OR-W201	1.40E+03	1.12E-15	8.30E-01	2.10E+03	1.92E+03	2.34E-17	4.45E+01	5.46E+03	2.20E+01
OR-W202	2.00E+02	2.34E-14	2.39E+00	5.38E+02	4.90E+02	7.51E-19	3.42E+00	1.23E+03	4.97E+00
OR-W203	4.41E-01	8.14E-16	3.43E-04	2.42E-02	1.60E+00	1.91E-21	4.87E-04	2.06E+00	8.32E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
OR-W204	9.82E-02	3.37E-21	3.89E-04	4.12E-01	2.58E-01	0.00E+00	5.53E-04	7.69E-01	3.10E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	4.14E-01	0.00E+00	0.00E+00	0.00E+00	4.14E-01	1.67E-03
RF-MT0001	3.77E+02	0.00E+00	2.41E-03	1.90E+02	4.03E+01	1.72E-19	3.30E-03	6.07E+02	2.45E+00
RF-MT0002	2.90E+01	0.00E+00	1.85E-04	1.47E+01	3.09E+00	1.32E-20	2.53E-04	4.67E+01	1.89E-01
RF-MT0003	1.32E-01	0.00E+00	4.24E-05	3.35E+00	7.08E-01	3.01E-21	5.79E-05	4.19E+00	1.69E-02
RF-MT0007	3.32E-01	0.00E+00	0.00E+00	4.17E-01	8.81E-02	3.49E-22	0.00E+00	8.37E-01	3.38E-03
RF-MT0089	1.30E-03	0.00E+00	4.24E-07	3.35E-02	7.07E-03	3.01E-23	5.79E-07	4.19E-02	1.69E-04
RF-MT0090	3.31E+00	0.00E+00	5.99E-04	8.60E+01	1.80E+01	3.01E-20	8.19E-04	1.07E+02	4.33E-01
RF-MT0091	2.05E+02	0.00E+00	6.08E-02	5.75E+03	1.21E+03	2.49E-18	8.61E-02	7.16E+03	2.89E+01
RF-MT0092	2.93E+01	0.00E+00	7.66E-03	8.23E+02	1.77E+02	3.44E-19	1.05E-02	1.03E+03	4.15E+00
RF-MT0093	3.57E+01	0.00E+00	7.89E-03	8.88E+02	1.94E+02	2.93E-19	1.08E-02	1.12E+03	4.51E+00
RF-MT0097	1.79E+00	0.00E+00	3.49E-04	4.64E+01	8.80E+00	1.60E-20	4.76E-04	5.70E+01	2.30E-01
RF-MT0099	1.96E-03	0.00E+00	6.37E-07	5.02E-02	1.06E-02	4.53E-23	8.70E-07	6.27E-02	2.53E-04
RF-MT0290	4.86E+00	0.00E+00	1.58E-03	1.24E+02	2.63E+01	1.12E-19	2.15E-03	1.55E+02	6.27E-01
RF-MT-0292	6.12E+00	0.00E+00	1.99E-03	1.57E+02	3.32E+01	1.42E-19	2.72E-03	1.97E+02	7.93E-01
RF-MT-0299	7.21E+02	0.00E+00	5.10E-02	4.03E+03	8.52E+02	3.65E-18	6.97E-02	5.60E+03	2.26E+01
RF-MT0302	1.10E-02	0.00E+00	2.02E-06	1.74E-01	3.68E-02	1.42E-22	1.96E-05	2.22E-01	8.94E-04
RF-MT0320	1.32E+01	0.00E+00	2.10E-03	1.69E+02	3.58E+01	1.43E-19	2.87E-03	2.18E+02	8.79E-01
RF-MT0321	7.37E+00	0.00E+00	6.25E-04	5.44E+01	1.14E+01	4.00E-20	3.26E-03	7.31E+01	2.95E-01
RF-MT-0328	5.10E-01	0.00E+00	7.49E-05	5.91E+00	1.25E+00	5.33E-21	4.40E-04	7.67E+00	3.09E-02
RF-MT0330	5.31E+00	0.00E+00	8.21E-04	1.19E+02	2.73E+01	5.01E-20	1.12E-03	1.52E+02	6.13E-01
RF-MT-0331	3.18E+01	0.00E+00	5.10E-03	5.25E+02	1.09E+02	2.90E-19	2.77E-02	6.66E+02	2.68E+00
RF-MT0332	4.56E-03	0.00E+00	1.49E-06	1.18E-01	2.47E-02	1.06E-22	2.03E-06	1.47E-01	5.92E-04
RF-MT-0335	3.67E-01	0.00E+00	6.83E-05	6.05E+00	1.28E+00	4.31E-21	6.34E-04	7.70E+00	3.10E-02
RF-MT0336	2.59E+01	0.00E+00	4.52E-03	4.29E+02	9.05E+01	2.53E-19	7.99E-03	5.46E+02	2.20E+00
RF-MT0337	1.47E+01	0.00E+00	2.49E-03	2.62E+02	5.44E+01	1.24E-19	7.24E-03	3.31E+02	1.34E+00
RF-MT0339	4.01E+01	0.00E+00	6.77E-03	5.75E+02	1.20E+02	4.47E-19	2.63E-02	7.35E+02	2.96E+00
RF-MT-0342	2.36E-01	0.00E+00	5.68E-05	5.31E+00	1.10E+00	3.28E-21	1.36E-04	6.65E+00	2.68E-02
RF-MT0371	7.97E+01	0.00E+00	1.31E-02	1.04E+03	2.19E+02	9.35E-19	1.92E-02	1.34E+03	5.39E+00
RF-MT-0372	3.47E-01	0.00E+00	9.25E-05	7.24E+00	1.53E+00	5.78E-21	3.65E-04	9.12E+00	3.68E-02
RF-MT0373	5.23E+00	0.00E+00	9.51E-04	1.36E+02	2.85E+01	4.77E-20	1.30E-03	1.70E+02	6.84E-01

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0374	1.70E-01	0.00E+00	3.40E-05	2.69E+00	5.67E-01	2.42E-21	4.97E-05	3.43E+00	1.38E-02
RF-MT0376	1.35E-01	0.00E+00	2.75E-05	2.68E+00	5.75E-01	1.78E-21	5.26E-05	3.39E+00	1.37E-02
RF-MT0377	8.00E+01	0.00E+00	1.58E-02	1.25E+03	2.64E+02	1.12E-18	3.18E-02	1.60E+03	6.44E+00
RF-MT0378	8.99E-01	0.00E+00	2.19E-04	1.73E+01	3.65E+00	1.56E-20	2.99E-04	2.18E+01	8.80E-02
RF-MT0419	1.44E+00	0.00E+00	2.04E-04	1.61E+01	3.41E+00	1.45E-20	2.79E-04	2.10E+01	8.45E-02
RF-MT0420	2.51E-01	0.00E+00	3.54E-05	2.80E+00	5.92E-01	2.53E-21	4.84E-05	3.64E+00	1.47E-02
RF-MT0423	2.13E+00	0.00E+00	2.88E-04	4.04E+01	8.27E+00	1.00E-20	3.94E-04	5.08E+01	2.05E-01
RF-MT0425	6.28E-02	0.00E+00	8.87E-06	7.00E-01	1.48E-01	6.31E-22	1.21E-05	9.11E-01	3.67E-03
RF-MT-0438	5.70E-01	0.00E+00	1.16E-04	1.24E+01	2.60E+00	6.26E-21	1.72E-04	1.56E+01	6.29E-02
RF-MT0440	2.07E-01	0.00E+00	4.18E-05	4.50E+00	9.68E-01	2.58E-21	2.21E-04	5.68E+00	2.29E-02
RF-MT0442	7.87E-02	0.00E+00	1.81E-05	1.54E+00	3.25E-01	9.56E-22	1.19E-04	1.95E+00	7.85E-03
RF-MT0443	9.69E-01	0.00E+00	2.97E-04	2.40E+01	5.06E+00	2.00E-20	5.63E-04	3.00E+01	1.21E-01
RF-MT0444	7.56E+00	0.00E+00	1.46E-03	1.16E+02	2.43E+01	1.03E-19	2.01E-03	1.47E+02	5.94E-01
RF-MT0480	2.12E+01	0.00E+00	4.09E-03	3.24E+02	6.86E+01	2.66E-19	8.04E-03	4.14E+02	1.67E+00
RF-MT0488	3.39E+01	0.00E+00	6.11E-03	4.82E+02	1.01E+02	4.34E-19	3.92E-02	6.17E+02	2.49E+00
RF-MT0490	1.54E-01	0.00E+00	3.54E-05	2.84E+00	6.02E-01	2.40E-21	5.96E-05	3.60E+00	1.45E-02
RF-MT-0491	1.20E-02	0.00E+00	1.62E-06	1.29E-01	2.72E-02	1.12E-22	4.22E-06	1.68E-01	6.79E-04
RF-MT0523A	9.54E+00	0.00E+00	1.29E-03	1.02E+02	2.15E+01	9.13E-20	2.01E-03	1.33E+02	5.36E-01
RF-MT0523B	9.54E+00	0.00E+00	1.29E-03	1.02E+02	2.15E+01	9.13E-20	2.01E-03	1.33E+02	5.36E-01
RF-MT0523C	9.54E+00	0.00E+00	1.29E-03	1.02E+02	2.15E+01	9.13E-20	2.01E-03	1.33E+02	5.36E-01
RF-MT0523D	9.54E+00	0.00E+00	1.29E-03	1.02E+02	2.15E+01	9.13E-20	2.01E-03	1.33E+02	5.36E-01
RF-MT0523E	9.54E+00	0.00E+00	1.29E-03	1.02E+02	2.15E+01	9.13E-20	2.01E-03	1.33E+02	5.36E-01
RF-MT0531	6.52E-04	0.00E+00	2.12E-07	1.67E-02	3.53E-03	1.51E-23	2.90E-07	2.09E-02	8.42E-05
RF-MT0532E	3.04E+01	0.00E+00	2.76E-03	2.22E+02	4.69E+01	1.95E-19	4.87E-03	3.00E+02	1.21E+00
RF-MT0532F	3.04E+01	0.00E+00	2.76E-03	2.22E+02	4.69E+01	1.95E-19	4.87E-03	3.00E+02	1.21E+00
RF-MT0541	1.11E+00	0.00E+00	3.98E-05	3.16E+00	6.65E-01	2.85E-21	5.43E-05	4.93E+00	1.99E-02
RF-MT0545	5.93E-03	0.00E+00	1.93E-06	1.52E-01	3.21E-02	1.37E-22	2.63E-06	1.90E-01	7.68E-04
RF-MT0800	2.25E+02	0.00E+00	9.54E-04	7.52E+01	1.59E+01	6.79E-20	1.79E-03	3.16E+02	1.28E+00
RF-MT0801	2.59E+01	0.00E+00	9.34E-04	7.39E+01	1.56E+01	6.63E-20	1.28E-03	1.15E+02	4.65E-01
RF-MT0803	5.81E-01	0.00E+00	2.09E-05	1.65E+00	3.48E-01	1.49E-21	2.85E-05	2.58E+00	1.04E-02
RF-MT0806	2.74E-01	0.00E+00	5.01E-05	7.17E+00	1.50E+00	2.51E-21	6.85E-05	8.95E+00	3.61E-02

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0807	3.47E+00	0.00E+00	3.86E-04	3.05E+01	6.45E+00	2.74E-20	5.27E-04	4.04E+01	1.63E-01
RF-MT0816	3.71E-01	0.00E+00	5.45E-05	4.30E+00	9.05E-01	3.89E-21	7.44E-05	5.58E+00	2.25E-02
RF-MT-0823	1.84E-01	0.00E+00	2.48E-05	1.96E+00	4.14E-01	1.76E-21	3.88E-05	2.56E+00	1.03E-02
RF-MT0827	9.36E+00	0.00E+00	1.38E-03	1.09E+02	2.30E+01	9.80E-20	1.88E-03	1.41E+02	5.69E-01
RF-MT0831	1.79E+01	0.00E+00	3.77E-03	2.94E+02	6.22E+01	2.58E-19	1.74E-02	3.74E+02	1.51E+00
RF-MT0832	1.07E+02	0.00E+00	1.37E-02	1.15E+03	2.41E+02	9.21E-19	5.20E-02	1.49E+03	6.02E+00
RF-MT0833	3.25E+01	0.00E+00	4.09E-03	3.31E+02	6.99E+01	2.77E-19	1.47E-02	4.33E+02	1.75E+00
RF-MT0855	5.59E-03	0.00E+00	1.82E-06	1.44E-01	3.03E-02	1.29E-22	2.48E-06	1.80E-01	7.24E-04
RF-MT0857	2.74E-01	0.00E+00	4.98E-05	7.15E+00	1.50E+00	2.51E-21	6.81E-05	8.93E+00	3.60E-02
RF-MT0H61	1.02E+01	0.00E+00	1.85E-03	2.65E+02	5.56E+01	9.29E-20	2.53E-03	3.31E+02	1.33E+00
RF-MT2116	1.14E+00	0.00E+00	1.47E-04	1.22E+01	2.58E+00	9.88E-21	5.57E-04	1.60E+01	6.44E-02
RF-MT3010	7.17E+00	0.00E+00	1.53E-03	1.21E+02	2.58E+01	1.06E-19	2.48E-03	1.54E+02	6.22E-01
RF-MT3011	5.34E+01	0.00E+00	9.51E-03	7.49E+02	1.59E+02	6.76E-19	2.07E-02	9.62E+02	3.88E+00
RF-MT420P	2.84E+02	0.00E+00	4.81E-02	6.16E+03	1.30E+03	2.21E-18	7.57E-02	7.75E+03	3.12E+01
RF-MT532A	7.49E+01	0.00E+00	6.80E-03	5.49E+02	1.16E+02	4.79E-19	1.20E-02	7.40E+02	2.98E+00
RF-MT532B	3.36E+02	0.00E+00	3.05E-02	2.47E+03	5.20E+02	2.16E-18	5.39E-02	3.32E+03	1.34E+01
RF-MT532C	6.74E+02	0.00E+00	6.14E-02	4.94E+03	1.04E+03	4.31E-18	1.08E-01	6.66E+03	2.68E+01
RF-MT532D	4.26E+00	0.00E+00	3.86E-04	3.13E+01	6.58E+00	2.72E-20	6.82E-04	4.21E+01	1.70E-01
RF-TT0069	2.45E-02	0.00E+00	4.58E-06	3.62E-01	7.65E-02	3.28E-22	7.96E-05	4.63E-01	1.87E-03
RF-TT0200	1.16E+00	0.00E+00	1.85E-04	1.49E+01	3.16E+00	1.26E-20	2.54E-04	1.92E+01	7.73E-02
RF-TT0299	4.83E+00	0.00E+00	3.43E-04	2.71E+01	5.72E+00	2.44E-20	4.68E-04	3.76E+01	1.52E-01
RF-TT0300	3.93E+01	0.00E+00	9.77E-03	7.78E+02	1.65E+02	5.94E-19	2.17E-02	9.82E+02	3.96E+00
RF-TT0301	5.31E+00	0.00E+00	1.33E-03	1.06E+02	2.24E+01	8.04E-20	2.94E-03	1.34E+02	5.38E-01
RF-TT0302	2.63E-01	0.00E+00	4.81E-05	4.14E+00	8.75E-01	3.38E-21	4.64E-04	5.27E+00	2.13E-02
RF-TT0303	1.58E+00	0.00E+00	2.81E-04	2.22E+01	4.69E+00	2.00E-20	1.42E-03	2.85E+01	1.15E-01
RF-TT0310	5.39E+00	0.00E+00	1.32E-03	1.00E+02	2.18E+01	7.32E-20	1.99E-03	1.27E+02	5.13E-01
RF-TT0312	1.29E+02	0.00E+00	2.38E-02	2.18E+03	4.57E+02	1.54E-18	3.43E-02	2.77E+03	1.12E+01
RF-TT0317	8.13E-02	0.00E+00	2.59E-05	2.05E+00	4.32E-01	1.84E-21	3.54E-05	2.56E+00	1.03E-02
RF-TT0320	5.22E+01	0.00E+00	8.30E-03	6.68E+02	1.42E+02	5.65E-19	1.14E-02	8.62E+02	3.47E+00
RF-TT0330	1.86E+01	0.00E+00	2.87E-03	4.19E+02	9.50E+01	1.75E-19	3.92E-03	5.33E+02	2.15E+00
RF-TT-0331	9.24E+01	0.00E+00	1.48E-02	1.52E+03	3.16E+02	8.44E-19	8.04E-02	1.93E+03	7.79E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT-0334	4.02E+01	0.00E+00	1.20E-02	9.47E+02	2.00E+02	8.55E-19	1.64E-02	1.19E+03	4.79E+00
RF-TT0335	4.90E+01	0.00E+00	9.10E-03	8.06E+02	1.71E+02	5.75E-19	8.45E-02	1.03E+03	4.14E+00
RF-TT0336	4.33E+01	0.00E+00	7.55E-03	7.14E+02	1.51E+02	4.21E-19	1.33E-02	9.07E+02	3.66E+00
RF-TT0337	5.14E+01	0.00E+00	8.73E-03	9.21E+02	1.91E+02	4.34E-19	2.54E-02	1.16E+03	4.69E+00
RF-TT0338	2.18E+02	0.00E+00	3.17E-02	3.59E+03	7.46E+02	1.94E-18	5.15E-02	4.56E+03	1.84E+01
RF-TT0340	1.87E+00	0.00E+00	6.05E-04	4.78E+01	1.01E+01	4.31E-20	8.26E-04	5.98E+01	2.41E-01
RF-TT0342	1.25E+01	0.00E+00	3.03E-03	2.82E+02	5.84E+01	1.73E-19	7.23E-03	3.52E+02	1.42E+00
RF-TT0360	9.51E-01	0.00E+00	1.54E-04	1.26E+01	2.70E+00	1.03E-20	2.16E-04	1.63E+01	6.56E-02
RF-TT0368	1.90E+01	0.00E+00	3.08E-03	2.53E+02	5.41E+01	2.05E-19	4.33E-03	3.26E+02	1.32E+00
RF-TT0370	3.76E+01	0.00E+00	6.66E-03	5.64E+02	1.19E+02	4.37E-19	1.69E-02	7.21E+02	2.91E+00
RF-TT0371	8.13E-01	0.00E+00	1.34E-04	1.06E+01	2.23E+00	9.53E-21	1.96E-04	1.36E+01	5.49E-02
RF-TT0372	9.93E-02	0.00E+00	2.64E-05	2.07E+00	4.37E-01	1.65E-21	1.04E-04	2.60E+00	1.05E-02
RF-TT0374	3.09E+00	0.00E+00	6.19E-04	4.88E+01	1.03E+01	4.39E-20	9.06E-04	6.22E+01	2.51E-01
RF-TT0375A	3.22E-02	0.00E+00	1.02E-05	8.03E-01	1.69E-01	7.24E-22	1.39E-05	1.00E+00	4.05E-03
RF-TT0375B	3.22E-02	0.00E+00	1.02E-05	8.03E-01	1.69E-01	7.24E-22	1.39E-05	1.00E+00	4.05E-03
RF-TT0376	7.41E+00	0.00E+00	1.51E-03	1.48E+02	3.16E+01	9.80E-20	2.89E-03	1.87E+02	7.52E-01
RF-TT0377	4.16E+00	0.00E+00	8.21E-04	6.48E+01	1.37E+01	5.83E-20	1.65E-03	8.27E+01	3.34E-01
RF-TT0391	9.27E-01	0.00E+00	1.16E-04	1.64E+01	3.42E+00	1.02E-20	1.58E-04	2.08E+01	8.37E-02
RF-TT0392	3.27E-01	0.00E+00	7.26E-05	8.57E+00	1.80E+00	3.54E-21	9.93E-05	1.07E+01	4.31E-02
RF-TT0393	2.68E+01	0.00E+00	5.07E-03	3.99E+02	8.44E+01	3.60E-19	6.92E-03	5.10E+02	2.06E+00
RF-TT0398	5.86E-01	0.00E+00	1.34E-04	1.60E+01	3.35E+00	6.68E-21	1.83E-04	2.00E+01	8.05E-02
RF-TT0409	4.90E-01	0.00E+00	6.25E-05	8.27E+00	1.73E+00	2.57E-21	8.60E-05	1.05E+01	4.23E-02
RF-TT0412	4.90E-01	0.00E+00	6.25E-05	8.27E+00	1.73E+00	2.57E-21	8.60E-05	1.05E+01	4.23E-02
RF-TT0414	1.52E+01	0.00E+00	1.93E-03	2.56E+02	5.35E+01	7.96E-20	2.66E-03	3.25E+02	1.31E+00
RF-TT0430	4.44E-03	0.00E+00	1.44E-06	1.14E-01	2.40E-02	1.03E-22	1.97E-06	1.42E-01	5.73E-04
RF-TT0431	1.10E+00	0.00E+00	3.52E-04	2.80E+01	5.91E+00	2.44E-20	7.02E-04	3.50E+01	1.41E-01
RF-TT0438	6.56E+01	0.00E+00	1.34E-02	1.43E+03	2.99E+02	7.22E-19	1.98E-02	1.79E+03	7.23E+00
RF-TT0440	6.47E+00	0.00E+00	1.30E-03	1.41E+02	3.04E+01	8.07E-20	6.93E-03	1.78E+02	7.16E-01
RF-TT0441	3.18E+01	0.00E+00	6.11E-03	4.86E+02	1.03E+02	4.29E-19	1.30E-02	6.21E+02	2.51E+00
RF-TT0442	4.59E+00	0.00E+00	1.05E-03	9.00E+01	1.90E+01	5.59E-20	6.95E-03	1.14E+02	4.58E-01
RF-TT0443	9.84E-02	0.00E+00	3.03E-05	2.44E+00	5.14E-01	2.02E-21	5.73E-05	3.05E+00	1.23E-02

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0479	9.63E-01	0.00E+00	3.14E-04	2.47E+01	5.22E+00	2.23E-20	4.29E-04	3.08E+01	1.24E-01
RF-TT0480	6.56E+01	0.00E+00	1.27E-02	1.01E+03	2.12E+02	8.28E-19	2.49E-02	1.29E+03	5.19E+00
RF-TT0481	3.69E-02	0.00E+00	7.15E-06	5.67E-01	1.20E-01	4.66E-22	1.41E-05	7.24E-01	2.92E-03
RF-TT0483	1.19E-01	0.00E+00	3.86E-05	3.04E+00	6.43E-01	2.74E-21	1.72E-02	3.82E+00	1.54E-02
RF-TT0484	6.35E-01	0.00E+00	1.60E-04	1.26E+01	2.67E+00	1.14E-20	3.29E-04	1.59E+01	6.42E-02
RF-TT0485	5.22E-02	0.00E+00	9.88E-06	7.79E-01	1.65E-01	7.03E-22	2.91E-04	9.96E-01	4.02E-03
RF-TT0486	3.09E-01	0.00E+00	5.85E-05	4.62E+00	9.77E-01	4.15E-21	3.07E-04	5.91E+00	2.38E-02
RF-TT0487	1.55E+00	0.00E+00	1.99E-04	1.66E+01	3.50E+00	1.34E-20	7.54E-04	2.17E+01	8.73E-02
RF-TT0489	4.42E-01	0.00E+00	8.93E-05	7.05E+00	1.49E+00	6.37E-21	2.23E-04	8.98E+00	3.62E-02
RF-TT0490	2.44E+01	0.00E+00	5.68E-03	4.54E+02	9.59E+01	3.81E-19	9.53E-03	5.75E+02	2.32E+00
RF-TT0491	5.69E-01	0.00E+00	7.66E-05	6.09E+00	1.28E+00	5.30E-21	2.00E-04	7.94E+00	3.20E-02
RF-TT0492	1.91E-01	0.00E+00	4.32E-05	3.40E+00	7.19E-01	3.06E-21	5.90E-05	4.31E+00	1.74E-02
RF-TT0523A	1.29E+00	0.00E+00	1.73E-04	1.37E+01	2.90E+00	1.23E-20	2.71E-04	1.79E+01	7.21E-02
RF-TT0523B	1.29E+00	0.00E+00	1.73E-04	1.37E+01	2.90E+00	1.23E-20	2.71E-04	1.79E+01	7.21E-02
RF-TT0523C	1.29E+00	0.00E+00	1.73E-04	1.37E+01	2.90E+00	1.23E-20	2.71E-04	1.79E+01	7.21E-02
RF-TT0523D	1.29E+00	0.00E+00	1.73E-04	1.37E+01	2.90E+00	1.23E-20	2.71E-04	1.79E+01	7.21E-02
RF-TT0523E	1.29E+00	0.00E+00	1.73E-04	1.37E+01	2.90E+00	1.23E-20	2.71E-04	1.79E+01	7.21E-02
RF-TT0532A	3.22E+01	0.00E+00	2.91E-03	2.36E+02	4.97E+01	2.06E-19	5.14E-03	3.18E+02	1.28E+00
RF-TT0532B	3.22E+01	0.00E+00	2.91E-03	2.36E+02	4.97E+01	2.06E-19	5.14E-03	3.18E+02	1.28E+00
RF-TT0541	5.32E-02	0.00E+00	1.73E-05	1.37E+00	2.89E-01	1.23E-21	2.37E-05	1.71E+00	6.90E-03
RF-TT0545	1.19E-02	0.00E+00	3.86E-06	3.04E-01	6.43E-02	2.74E-22	5.27E-06	3.80E-01	1.53E-03
RF-TT0601	4.12E+00	0.00E+00	6.66E-04	5.49E+01	1.17E+01	4.45E-20	9.36E-04	7.07E+01	2.85E-01
RF-TT0802	4.61E+02	0.00E+00	5.47E-02	4.33E+03	9.14E+02	3.89E-18	7.47E-02	5.71E+03	2.30E+01
RF-TT0809	3.79E+01	0.00E+00	4.49E-03	3.56E+02	7.49E+01	3.20E-19	6.14E-03	4.69E+02	1.89E+00
RF-TT0821	8.20E+01	0.00E+00	1.63E-02	1.40E+03	2.96E+02	9.51E-19	1.90E-01	1.78E+03	7.16E+00
RF-TT0822	9.07E+01	0.00E+00	1.27E-02	1.05E+03	2.21E+02	8.47E-19	1.99E-01	1.36E+03	5.48E+00
RF-TT0823	1.84E-01	0.00E+00	2.48E-05	1.96E+00	4.14E-01	1.76E-21	3.88E-05	2.56E+00	1.03E-02
RF-TT0824	1.89E+02	0.00E+00	3.49E-02	2.83E+03	5.96E+02	2.39E-18	1.10E-01	3.61E+03	1.46E+01
RF-TT0825	1.57E+02	0.00E+00	2.52E-02	2.13E+03	4.48E+02	1.59E-18	1.15E-01	2.73E+03	1.10E+01
RF-TT0832	1.16E+02	0.00E+00	1.49E-02	1.24E+03	2.63E+02	1.00E-18	5.66E-02	1.62E+03	6.54E+00
RF-TT0854	4.18E-02	0.00E+00	1.36E-05	1.07E+00	2.27E-01	9.67E-22	7.64E-04	1.34E+00	5.39E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0886	5.93E-03	0.00E+00	1.92E-06	1.51E-01	3.21E-02	1.37E-22	2.62E-06	1.90E-01	7.64E-04
RF-TT2216	1.72E+00	0.00E+00	2.20E-04	1.84E+01	3.87E+00	1.48E-20	8.36E-04	2.40E+01	9.69E-02
RF-TT3010	9.16E+01	0.00E+00	1.95E-02	1.55E+03	3.29E+02	1.36E-18	3.16E-02	1.97E+03	7.96E+00
RF-TT3011	2.31E+02	0.00E+00	4.12E-02	3.24E+03	6.86E+02	2.93E-18	8.99E-02	4.16E+03	1.68E+01
RF-TT301U	1.92E+01	0.00E+00	4.35E-03	3.52E+02	7.57E+01	2.88E-19	6.10E-03	4.47E+02	1.80E+00
RF-TT310P	5.56E+00	0.00E+00	1.13E-03	1.18E+02	2.38E+01	6.02E-20	1.55E-03	1.48E+02	5.96E-01
RF-TT338S	1.62E-01	0.00E+00	5.19E-05	4.09E+00	8.64E-01	3.68E-21	7.08E-05	5.11E+00	2.06E-02
RF-TT390P	9.13E-01	0.00E+00	1.41E-04	1.99E+01	3.86E+00	9.19E-21	2.21E-04	2.47E+01	9.95E-02
RF-TT391P	5.05E+01	0.00E+00	6.31E-03	8.94E+02	1.86E+02	5.57E-19	8.62E-03	1.13E+03	4.56E+00
RF-TT392P	1.02E+02	0.00E+00	2.27E-02	2.68E+03	5.64E+02	1.11E-18	3.11E-02	3.35E+03	1.35E+01
RF-TT393R	1.51E+01	0.00E+00	3.86E-03	4.10E+02	8.68E+01	1.79E-19	5.45E-03	5.12E+02	2.06E+00
RF-TT394P	1.87E+00	0.00E+00	2.39E-04	3.17E+01	6.19E+00	1.29E-20	3.33E-04	3.97E+01	1.60E-01
RF-TT395P	2.51E+00	0.00E+00	3.20E-04	4.23E+01	8.27E+00	1.72E-20	4.46E-04	5.31E+01	2.14E-01
RF-TT396P	6.26E-01	0.00E+00	7.98E-05	1.06E+01	2.07E+00	4.29E-21	1.11E-04	1.33E+01	5.35E-02
RF-TT398P	6.06E+01	0.00E+00	1.38E-02	1.66E+03	3.47E+02	6.90E-19	1.89E-02	2.07E+03	8.34E+00
RF-TT398R	5.00E+02	0.00E+00	2.57E-02	2.68E+03	5.61E+02	1.35E-18	3.51E-02	3.74E+03	1.51E+01
RF-TT411R	1.81E+01	0.00E+00	2.31E-03	3.06E+02	6.39E+01	9.51E-20	3.18E-03	3.88E+02	1.56E+00
RF-TT429R	3.81E+01	0.00E+00	4.96E-04	7.09E+01	1.45E+01	1.66E-20	6.77E-04	1.23E+02	4.98E-01
RF-TT433X	1.20E+01	0.00E+00	1.37E-04	2.04E+01	3.77E+00	6.58E-21	1.87E-04	3.62E+01	1.46E-01
RF-TT436R	8.78E+01	0.00E+00	1.99E-03	2.67E+02	5.57E+01	1.27E-19	2.71E-03	4.10E+02	1.66E+00
RF-TT454X	5.15E+00	0.00E+00	1.17E-04	1.57E+01	3.28E+00	7.48E-21	1.59E-04	2.42E+01	9.74E-02
RL-T101	2.62E+01	0.00E+00	7.09E-03	8.49E+02	1.76E+02	1.06E-18	8.80E-03	1.05E+03	4.24E+00
RL-T102	3.32E-04	0.00E+00	9.02E-08	1.09E-02	2.24E-03	1.34E-23	1.26E-06	1.35E-02	5.42E-05
RL-T103	2.35E+01	0.00E+00	8.59E-03	3.71E+02	7.62E+01	5.62E-19	1.07E-02	4.71E+02	1.90E+00
RL-T104	4.76E-04	0.00E+00	1.29E-07	1.54E-02	3.21E-03	1.92E-23	1.93E-07	1.91E-02	7.71E-05
RL-T105	1.82E-01	0.00E+00	4.87E-05	5.86E+00	1.21E+00	7.27E-21	1.05E-04	7.26E+00	2.93E-02
RL-T106	1.76E-01	0.00E+00	4.78E-05	5.73E+00	1.18E+00	7.11E-21	5.94E-05	7.09E+00	2.86E-02
RL-T107	4.84E+02	0.00E+00	2.81E+01	1.58E+04	3.26E+03	1.95E-17	3.57E+01	1.96E+04	7.92E+01
RL-T108	2.77E-01	0.00E+00	4.84E-03	9.01E+00	1.86E+00	1.12E-20	6.04E-03	1.12E+01	4.50E-02
RL-T109	3.81E-01	0.00E+00	9.97E-05	1.19E+01	2.47E+00	1.48E-20	2.34E-02	1.48E+01	5.98E-02
RL-T110	4.27E+01	0.00E+00	1.90E-02	1.37E+03	2.84E+02	1.70E-18	1.38E+00	1.70E+03	6.84E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T112	1.72E+01	0.00E+00	8.04E-03	1.82E+02	3.76E+01	2.26E-19	7.44E-01	2.37E+02	9.56E-01
RL-T113	1.84E-02	0.00E+00	1.55E-05	5.98E-01	1.24E-01	7.43E-22	1.93E-05	7.40E-01	2.98E-03
RL-T114	2.79E+00	0.00E+00	7.58E-04	9.09E+01	1.88E+01	1.13E-19	9.41E-04	1.13E+02	4.54E-01
RL-T115	7.11E+01	0.00E+00	2.46E-02	1.19E+03	2.47E+02	1.66E-18	4.42E-01	1.51E+03	6.10E+00
RL-T116	4.58E+00	0.00E+00	1.25E-03	1.49E+02	3.08E+01	1.85E-19	5.76E-02	1.84E+02	7.42E-01
RL-T118	1.18E+01	0.00E+00	9.94E-03	1.48E+02	3.06E+01	1.84E-19	8.43E-01	1.91E+02	7.69E-01
RL-T120	2.86E+00	0.00E+00	1.04E-03	4.37E+01	8.96E+00	6.45E-20	1.30E-03	5.55E+01	2.24E-01
RL-T122	1.62E-01	0.00E+00	4.41E-05	5.26E+00	1.09E+00	6.55E-21	1.46E+00	7.97E+00	3.22E-02
RL-T123	4.77E-01	0.00E+00	1.29E-04	1.54E+01	3.21E+00	1.93E-20	5.97E-02	1.92E+01	7.73E-02
RL-T125	9.49E+01	0.00E+00	3.20E-02	3.23E+02	1.54E+02	3.01E-18	3.97E-02	5.72E+02	2.31E+00
RL-T127	9.14E+01	0.00E+00	8.04E-03	9.66E+02	2.00E+02	1.20E-18	8.98E-02	1.26E+03	5.07E+00
RL-T128	1.35E-01	0.00E+00	1.95E-10	2.35E-05	4.85E-06	2.90E-26	2.43E-10	1.35E-01	5.46E-04
RL-T129	4.06E-01	0.00E+00	3.72E-02	1.33E+01	2.73E+00	1.64E-20	5.38E-02	1.65E+01	6.67E-02
RL-T130	8.63E-04	0.00E+00	2.35E-07	2.83E-02	5.84E-03	3.49E-23	8.31E-05	3.50E-02	1.41E-04
RL-T131	3.51E-01	0.00E+00	1.28E-04	5.38E+00	1.10E+00	7.88E-21	8.37E-03	6.84E+00	2.76E-02
RL-T132	8.36E+01	0.00E+00	2.26E-02	2.73E+03	5.64E+02	3.38E-18	2.72E-01	3.38E+03	1.36E+01
RL-T133	1.70E-03	0.00E+00	3.63E-07	4.48E-02	9.23E-03	4.79E-23	4.51E-07	5.57E-02	2.25E-04
RL-T134	3.60E-03	0.00E+00	9.77E-07	1.18E-01	2.42E-02	1.46E-22	1.21E-06	1.45E-01	5.86E-04
RL-T135	1.69E-02	0.00E+00	4.58E-06	5.49E-01	1.14E-01	6.82E-22	4.14E-03	6.84E-01	2.76E-03
RL-T137	2.74E+02	0.00E+00	1.00E-01	4.18E+03	8.61E+02	6.21E-18	1.30E-01	5.32E+03	2.14E+01
RL-T140	3.20E+02	0.00E+00	9.51E-02	4.05E+03	9.23E+02	5.27E-18	2.62E+01	5.32E+03	2.14E+01
RL-T143	2.01E+00	0.00E+00	5.45E-04	6.54E+01	1.35E+01	8.12E-20	3.92E-02	8.10E+01	3.27E-01
RL-T145	5.72E+00	0.00E+00	1.55E-03	1.86E+02	3.85E+01	2.31E-19	9.13E-02	2.31E+02	9.30E-01
RL-W407	1.64E+01	0.00E+00	3.31E-03	4.27E+02	8.84E+01	3.52E-19	4.12E-03	5.32E+02	2.15E+00
RL-W408	6.73E-05	0.00E+00	1.40E-08	1.73E-03	3.58E-04	1.81E-24	1.74E-08	2.15E-03	8.68E-06
RL-W415	1.49E-03	0.00E+00	3.08E-07	3.83E-02	7.91E-03	4.00E-23	3.83E-07	4.76E-02	1.92E-04
RL-W418	6.36E-03	0.00E+00	1.30E-06	1.64E-01	3.40E-02	1.49E-22	1.61E-06	2.04E-01	8.24E-04
RL-W437	5.39E+01	0.00E+00	1.09E-02	1.40E+03	2.90E+02	1.15E-18	1.35E-02	1.74E+03	7.02E+00
RL-W438	9.43E-05	0.00E+00	1.96E-08	2.42E-03	4.99E-04	2.53E-24	2.43E-08	3.01E-03	1.21E-05
RL-W439	2.95E+03	0.00E+00	1.08E+00	4.66E+04	9.59E+03	7.06E-17	1.34E+00	5.91E+04	2.39E+02
RL-W443	4.75E+01	0.00E+00	9.59E-03	1.23E+03	2.55E+02	1.02E-18	1.19E-02	1.54E+03	6.19E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W444	3.52E+01	0.00E+00	7.12E-03	9.14E+02	1.89E+02	7.54E-19	8.84E-03	1.14E+03	4.59E+00
RL-W447	4.04E-03	0.00E+00	8.38E-07	1.03E-01	2.14E-02	1.08E-22	1.04E-06	1.28E-01	5.18E-04
RL-W448	2.98E-05	0.00E+00	6.19E-09	7.64E-04	1.58E-04	8.02E-25	7.69E-09	9.52E-04	3.84E-06
RL-W449	2.45E-01	0.00E+00	2.27E-07	2.18E-02	4.52E-03	1.45E-23	2.82E-07	2.71E-01	1.09E-03
RL-W450	4.50E-04	0.00E+00	9.34E-08	1.16E-02	2.38E-03	1.21E-23	1.16E-07	1.44E-02	5.80E-05
RL-W451	6.42E-05	0.00E+00	1.33E-08	1.64E-03	3.40E-04	1.72E-24	1.65E-08	2.04E-03	8.24E-06
RL-W452	2.79E-03	0.00E+00	5.73E-07	7.23E-02	1.50E-02	6.55E-23	7.12E-07	9.01E-02	3.63E-04
RL-W453	7.97E-04	0.00E+00	1.61E-07	2.08E-02	4.29E-03	1.71E-23	2.00E-07	2.59E-02	1.04E-04
RL-W454	1.11E-02	0.00E+00	2.26E-06	2.90E-01	6.00E-02	2.39E-22	2.80E-06	3.61E-01	1.46E-03
RL-W455	2.97E-03	0.00E+00	6.08E-07	7.68E-02	1.59E-02	6.98E-23	7.55E-07	9.56E-02	3.86E-04
RL-W456	3.92E-01	0.00E+00	7.95E-05	1.02E+01	2.11E+00	8.60E-21	9.88E-05	1.27E+01	5.12E-02
RL-W457	3.80E-02	0.00E+00	7.72E-06	9.90E-01	2.04E-01	8.34E-22	9.59E-06	1.23E+00	4.97E-03
RL-W458	1.20E-01	0.00E+00	3.95E-05	4.07E-01	2.10E-01	3.36E-21	4.90E-05	7.37E-01	2.97E-03
RL-W459	1.16E+00	0.00E+00	4.06E-04	1.01E+01	2.86E+00	3.33E-20	5.05E-04	1.41E+01	5.69E-02
RL-W460	7.07E-03	0.00E+00	1.43E-06	1.84E-01	3.80E-02	1.51E-22	1.78E-06	2.29E-01	9.22E-04
RL-W461	6.52E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.52E-03	2.63E-05
RL-W462	2.01E-03	0.00E+00	4.15E-07	5.19E-02	1.08E-02	4.95E-23	5.15E-07	6.47E-02	2.61E-04
RL-W463	1.04E-02	0.00E+00	2.10E-06	2.70E-01	5.58E-02	2.22E-22	2.61E-06	3.36E-01	1.36E-03
RL-W464	4.78E-03	0.00E+00	9.65E-07	1.24E-01	2.56E-02	1.02E-22	1.20E-06	1.55E-01	6.24E-04
RL-W465	3.19E-02	0.00E+00	6.54E-06	8.27E-01	1.71E-01	7.40E-22	8.12E-06	1.03E+00	4.15E-03
RL-W466	4.37E-01	0.00E+00	8.90E-05	1.14E+01	2.35E+00	9.85E-21	1.11E-04	1.41E+01	5.70E-02
RL-W467	2.24E-02	0.00E+00	4.58E-06	5.79E-01	1.19E-01	5.41E-22	5.69E-06	7.20E-01	2.90E-03
RL-W468	1.15E-04	0.00E+00	2.36E-08	2.96E-03	6.12E-04	2.82E-24	2.93E-08	3.69E-03	1.49E-05
RL-W469	4.65E-02	0.00E+00	9.48E-06	1.20E+00	2.50E-01	1.04E-21	1.18E-05	1.50E+00	6.05E-03
RL-W470	1.32E+00	0.00E+00	4.41E-04	4.47E+00	2.13E+00	4.18E-20	5.48E-04	7.92E+00	3.19E-02
RL-W474	4.99E-02	0.00E+00	4.87E-05	1.02E-02	8.07E-03	0.00E+00	6.05E-05	6.83E-02	2.75E-04
RL-W476	8.41E-02	0.00E+00	1.75E-05	2.23E+00	4.63E-01	1.89E-21	2.18E-05	2.78E+00	1.12E-02
RL-W480	1.37E-02	0.00E+00	2.81E-06	3.54E-01	7.34E-02	3.22E-22	3.49E-06	4.41E-01	1.78E-03
RL-W481	2.16E-02	0.00E+00	4.41E-06	5.56E-01	1.15E-01	5.06E-22	5.48E-06	6.93E-01	2.79E-03
RL-W482	2.86E+01	0.00E+00	1.47E-03	7.08E-02	1.22E-01	6.71E-19	1.82E-03	2.88E+01	1.16E-01
RL-W483	2.14E+00	0.00E+00	1.14E-04	4.58E-03	8.66E-03	5.01E-20	1.41E-04	2.15E+00	8.67E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W484	9.04E-03	0.00E+00	9.16E-07	6.40E-02	1.42E-02	4.15E-23	1.14E-06	8.72E-02	3.52E-04
RL-W485	5.29E-04	0.00E+00	1.30E-07	6.92E-03	1.53E-03	0.00E+00	1.61E-07	8.98E-03	3.62E-05
RL-W486	2.24E-04	0.00E+00	5.47E-08	2.92E-03	6.45E-04	0.00E+00	6.80E-08	3.79E-03	1.53E-05
RL-W487	3.65E-02	0.00E+00	7.03E-06	4.18E-01	1.07E-01	3.86E-22	8.73E-06	5.62E-01	2.26E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	2.22E-02	0.00E+00	6.63E-06	5.42E-01	1.14E-01	6.23E-22	8.23E-06	6.78E-01	2.73E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	8.24E-03	0.00E+00	5.59E-06	5.68E-02	1.16E-02	2.26E-22	6.94E-06	7.66E-02	3.09E-04
RL-W492	4.75E-04	0.00E+00	1.38E-07	1.14E-02	2.38E-03	1.30E-23	1.71E-07	1.42E-02	5.73E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	1.88E+01	0.00E+00	7.98E-03	2.86E-01	2.27E-01	5.22E-19	9.91E-03	1.94E+01	7.81E-02
RL-W495	3.41E-01	0.00E+00	2.17E-05	2.75E-03	2.03E-03	9.51E-21	2.70E-05	3.46E-01	1.39E-03
RL-W496	2.21E+00	0.00E+00	2.50E-04	9.03E-03	6.71E-03	6.15E-20	3.10E-04	2.23E+00	8.99E-03
RL-W497	9.22E-02	0.00E+00	4.93E-05	5.42E-01	2.28E-01	1.61E-21	6.12E-05	8.62E-01	3.47E-03
RL-W498	3.58E-01	0.00E+00	7.32E-05	9.26E+00	1.92E+00	8.39E-21	9.09E-05	1.15E+01	4.65E-02
RL-W499	3.21E-06	0.00E+00	6.57E-10	8.30E-05	1.72E-05	7.54E-26	8.16E-10	1.03E-04	4.17E-07
RL-W500	2.29E-04	0.00E+00	8.15E-08	3.39E-03	6.97E-04	5.30E-24	1.01E-07	4.31E-03	1.74E-05
RL-W501	9.47E+00	0.00E+00	1.82E-03	1.09E+02	2.76E+01	1.00E-19	2.26E-03	1.46E+02	5.88E-01
RL-W502	1.71E-03	0.00E+00	3.52E-07	4.43E-02	9.14E-03	4.02E-23	4.37E-07	5.51E-02	2.22E-04
RL-W503	9.90E-02	0.00E+00	3.60E-05	1.56E+00	3.21E-01	2.37E-21	4.47E-05	1.98E+00	8.00E-03
RL-W504	3.65E-02	0.00E+00	7.03E-06	4.18E-01	1.07E-01	3.86E-22	8.73E-06	5.62E-01	2.26E-03
RL-W505	1.72E-03	0.00E+00	3.69E-07	4.52E-02	9.32E-03	4.85E-23	4.58E-07	5.63E-02	2.27E-04
RL-W506	6.23E-04	0.00E+00	1.45E-07	1.49E-02	3.07E-03	1.45E-23	1.80E-07	1.86E-02	7.48E-05
RL-W507	6.20E-05	0.00E+00	1.27E-08	1.60E-03	3.31E-04	1.45E-24	1.58E-08	1.99E-03	8.04E-06
RL-W508	1.14E+00	0.00E+00	4.15E-04	1.74E+01	3.58E+00	2.58E-20	5.15E-04	2.21E+01	8.91E-02
RL-W509	1.12E+01	0.00E+00	3.31E-03	1.42E+02	3.22E+01	1.85E-19	4.12E-03	1.85E+02	7.46E-01
RL-W510	9.45E-01	0.00E+00	3.40E-04	1.41E+01	2.90E+00	2.20E-20	4.22E-04	1.79E+01	7.22E-02
RL-W511	9.61E+01	0.00E+00	1.64E-02	1.88E+03	3.82E+02	1.20E-18	2.07E-02	2.36E+03	9.52E+00
RL-W512	8.41E+01	0.00E+00	1.11E-02	1.14E+03	2.62E+02	6.13E-19	1.37E-02	1.48E+03	5.97E+00
RL-W513	8.98E+03	0.00E+00	4.49E+00	1.85E+04	8.53E+03	9.72E-17	5.58E+00	3.61E+04	1.45E+02
RL-W514	2.53E-04	0.00E+00	5.16E-08	6.57E-03	1.36E-03	5.67E-24	6.41E-08	8.19E-03	3.30E-05

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W515	9.90E-03	0.00E+00	2.02E-06	2.56E-01	5.29E-02	2.32E-22	2.51E-06	3.19E-01	1.29E-03
RL-W516	1.37E-02	0.00E+00	2.81E-06	3.54E-01	7.34E-02	3.22E-22	3.49E-06	4.42E-01	1.78E-03
RL-W517	1.22E-10	0.00E+00	2.51E-14	3.16E-09	6.52E-10	3.01E-30	3.12E-14	3.93E-09	1.58E-11
RL-W518	3.46E-01	0.00E+00	1.06E-04	4.52E+00	1.01E+00	6.47E-21	1.31E-04	5.88E+00	2.37E-02
RL-W519	6.17E-02	0.00E+00	1.25E-05	1.60E+00	3.31E-01	1.37E-21	1.56E-05	1.99E+00	8.04E-03
RL-W520	6.82E-03	0.00E+00	1.41E-06	1.76E-01	3.63E-02	1.75E-22	1.75E-06	2.19E-01	8.82E-04
RL-W521	1.27E-04	0.00E+00	2.59E-08	3.27E-03	6.78E-04	2.98E-24	3.22E-08	4.08E-03	1.64E-05
RL-W522	2.65E+00	0.00E+00	9.62E-04	2.17E+01	5.75E+00	4.31E-20	1.20E-03	3.01E+01	1.21E-01
RL-W523	7.96E-01	0.00E+00	3.66E-04	1.44E+00	8.09E-01	8.55E-21	4.55E-04	3.04E+00	1.23E-02
RL-W524	3.30E+00	0.00E+00	1.40E-03	1.32E+01	4.74E+00	4.07E-20	1.74E-03	2.13E+01	8.57E-02
RL-W525	2.62E-01	0.00E+00	9.48E-05	1.56E+00	4.80E-01	3.20E-21	1.18E-04	2.31E+00	9.29E-03
RL-W526	9.94E-01	0.00E+00	3.43E-04	1.67E+01	3.46E+00	2.33E-20	4.26E-04	2.12E+01	8.53E-02
RL-W527	1.09E-01	0.00E+00	4.96E-05	1.77E+00	3.89E-01	2.72E-21	6.16E-05	2.27E+00	9.13E-03
RL-W528	4.87E+01	0.00E+00	2.11E-02	5.63E+01	5.00E+01	4.15E-19	2.62E-02	1.55E+02	6.25E-01
RL-W529	4.06E-02	0.00E+00	1.48E-05	6.21E-01	1.27E-01	9.16E-22	1.84E-05	7.89E-01	3.18E-03
RL-W530	4.78E-01	0.00E+00	1.72E-04	7.10E+00	1.46E+00	1.11E-20	2.13E-04	9.04E+00	3.64E-02
RL-W531	2.85E+01	0.00E+00	1.72E-02	3.07E+01	2.05E+01	2.96E-19	2.14E-02	7.98E+01	3.22E-01
RL-W532	9.15E-02	0.00E+00	1.87E-05	2.37E+00	4.89E-01	2.15E-21	2.33E-05	2.95E+00	1.19E-02
RL-W533	4.43E-02	0.00E+00	1.62E-05	6.78E-01	1.39E-01	9.93E-22	2.01E-05	8.61E-01	3.47E-03
RL-W534	2.56E-06	0.00E+00	5.22E-10	6.61E-05	1.37E-05	5.99E-26	6.48E-10	8.24E-05	3.32E-07
RL-W535	1.34E+01	0.00E+00	5.16E-03	8.47E+01	2.40E+01	1.83E-19	6.41E-03	1.22E+02	4.93E-01
RL-W536	2.62E-01	0.00E+00	6.94E-05	2.94E+00	6.19E-01	4.18E-21	8.94E-05	3.82E+00	1.54E-02
RL-W537	8.93E+00	0.00E+00	1.57E-03	1.81E+02	3.68E+01	1.17E-19	1.97E-03	2.26E+02	9.12E-01
RL-W538	3.25E-05	0.00E+00	6.63E-09	8.40E-04	1.74E-04	7.62E-25	8.23E-09	1.05E-03	4.22E-06
RL-W539	3.61E-03	0.00E+00	7.46E-07	9.28E-02	1.92E-02	9.27E-23	9.27E-07	1.16E-01	4.66E-04
RL-W540	7.02E+00	0.00E+00	3.28E-03	3.34E+01	1.07E+01	8.90E-20	4.08E-03	5.11E+01	2.06E-01
RL-W541	1.04E-02	0.00E+00	2.15E-06	2.69E-01	5.56E-02	2.61E-22	2.67E-06	3.35E-01	1.35E-03
RL-W542	4.85E-01	0.00E+00	1.60E-04	6.81E+00	1.46E+00	1.07E-20	1.99E-04	8.75E+00	3.53E-02
RL-W543	1.53E-03	0.00E+00	3.11E-07	3.94E-02	8.16E-03	3.60E-23	3.87E-07	4.91E-02	1.98E-04
RL-W544	3.44E-02	0.00E+00	1.27E-05	4.49E-01	1.04E-01	7.14E-22	1.58E-05	5.87E-01	2.37E-03
RL-W545	9.14E-03	0.00E+00	1.87E-06	2.36E-01	4.89E-02	2.14E-22	2.32E-06	2.94E-01	1.19E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W546	4.00E-04	0.00E+00	8.18E-08	1.04E-02	2.14E-03	9.37E-24	1.02E-07	1.29E-02	5.21E-05
RL-W547	1.02E-05	0.00E+00	2.09E-09	2.64E-04	5.47E-05	2.40E-25	2.60E-09	3.29E-04	1.33E-06
RL-W548	8.84E-06	0.00E+00	1.82E-09	2.28E-04	4.72E-05	2.15E-25	2.25E-09	2.84E-04	1.15E-06
RL-W549	1.76E+00	0.00E+00	7.29E-04	1.18E+01	3.25E+00	2.72E-20	9.05E-04	1.68E+01	6.75E-02
RL-W550	7.96E+00	0.00E+00	1.38E-03	1.59E+02	3.25E+01	1.03E-19	1.73E-03	2.00E+02	8.05E-01
RL-W551	1.42E+01	0.00E+00	2.04E-03	1.80E+02	4.23E+01	1.09E-19	2.53E-03	2.36E+02	9.52E-01
RL-W552	5.49E-03	0.00E+00	1.13E-06	1.42E-01	2.92E-02	1.36E-22	1.40E-06	1.76E-01	7.11E-04
RL-W553	4.87E-04	0.00E+00	1.07E-07	1.26E-02	2.61E-03	1.72E-23	1.32E-07	1.57E-02	6.34E-05
RL-W554	7.73E-03	0.00E+00	1.58E-06	2.00E-01	4.14E-02	1.81E-22	1.97E-06	2.49E-01	1.00E-03
RL-W555	3.56E-03	0.00E+00	7.29E-07	9.21E-02	1.90E-02	8.36E-23	9.05E-07	1.15E-01	4.62E-04
RL-W563	5.11E-02	0.00E+00	1.82E-05	7.64E-01	1.57E-01	1.14E-21	2.27E-05	9.72E-01	3.92E-03
RL-W564	3.33E-02	0.00E+00	1.21E-05	4.94E-01	1.01E-01	8.76E-22	1.50E-05	6.29E-01	2.54E-03
RL-W565	3.30E-03	0.00E+00	6.80E-07	8.53E-02	1.77E-02	8.12E-23	8.45E-07	1.06E-01	4.29E-04
RL-W566	4.85E-02	0.00E+00	9.97E-06	1.25E+00	2.60E-01	1.16E-21	1.24E-05	1.56E+00	6.29E-03
RL-W567	3.36E+00	0.00E+00	2.55E-04	3.85E-02	2.89E-02	9.80E-20	3.16E-04	3.43E+00	1.38E-02
RL-W568	6.47E+01	0.00E+00	5.36E-03	1.83E+00	1.35E+00	2.02E-18	6.66E-03	6.78E+01	2.74E-01
RL-W569	5.32E-02	0.00E+00	4.03E-06	6.09E-04	4.57E-05	1.55E-21	5.01E-06	5.39E-02	2.17E-04
RL-W570	3.41E-03	0.00E+00	7.06E-07	9.05E-02	1.86E-02	7.64E-23	8.77E-07	1.13E-01	4.54E-04
RL-W571	1.09E+01	0.00E+00	2.40E-03	7.34E+00	3.41E+00	3.09E-19	2.98E-03	2.17E+01	8.74E-02
RL-W572	9.49E-03	0.00E+00	7.17E-07	3.95E-03	8.16E-05	2.77E-22	8.91E-07	1.35E-02	5.45E-05
RL-W573	1.22E+02	0.00E+00	9.19E-03	2.17E+00	1.51E+00	3.52E-18	1.14E-02	1.26E+02	5.07E-01
RL-W574	5.25E+02	0.00E+00	3.98E-02	8.27E+00	5.58E+00	1.53E-17	4.94E-02	5.39E+02	2.17E+00
RL-W575	3.42E+03	0.00E+00	2.68E-01	7.91E+01	4.46E+01	9.61E-17	3.32E-01	3.54E+03	1.43E+01
RL-W576	2.47E+02	0.00E+00	1.87E-02	4.03E+00	2.69E+00	7.22E-18	2.32E-02	2.53E+02	1.02E+00
RL-W579	2.09E-02	0.00E+00	4.93E-07	2.02E-02	4.19E-03	2.55E-23	6.12E-07	4.53E-02	1.83E-04
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.61E-01	2.44E-02	0.00E+00	0.00E+00	1.86E-01	7.48E-04
RL-W581	2.22E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.22E-01	8.94E-04
RL-W582	1.45E-03	0.00E+00	4.18E-07	5.16E-03	2.48E-03	4.13E-24	5.19E-07	9.10E-03	3.67E-05
RL-W583	1.12E-03	0.00E+00	2.27E-07	2.91E-02	6.03E-03	2.40E-23	2.82E-07	3.63E-02	1.46E-04
RL-W584	2.23E-02	0.00E+00	1.49E-05	1.70E-01	7.73E-02	1.21E-22	1.85E-05	2.70E-01	1.09E-03
RL-W585	1.33E-01	0.00E+00	7.92E-05	9.90E-01	4.70E-01	3.68E-21	9.84E-05	1.59E+00	6.42E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W586	1.77E-05	0.00E+00	3.57E-09	4.60E-04	9.50E-05	3.78E-25	4.44E-09	5.73E-04	2.31E-06
RL-W587	3.79E-04	0.00E+00	7.72E-08	9.80E-03	2.04E-03	8.50E-24	9.59E-08	1.22E-02	4.93E-05
RL-W588	1.56E-02	0.00E+00	1.26E-05	1.44E-01	6.51E-02	1.02E-22	1.56E-05	2.24E-01	9.05E-04
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	4.80E-01	0.00E+00	2.68E-04	1.11E-02	1.83E-02	1.33E-20	3.33E-04	5.09E-01	2.05E-03
RL-W591	2.73E+00	0.00E+00	3.03E-04	1.37E-02	2.37E-02	8.04E-20	3.76E-04	2.77E+00	1.12E-02
RL-W592	1.21E+01	0.00E+00	3.31E-03	6.35E-01	7.66E-01	3.25E-19	4.12E-03	1.35E+01	5.43E-02
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.29E-02	3.59E-02	0.00E+00	0.00E+00	5.89E-02	2.37E-04
RL-W594	1.09E+01	0.00E+00	5.96E-04	2.83E-02	4.86E-02	8.12E-20	7.41E-04	1.10E+01	4.42E-02
RL-W595	2.87E-02	0.00E+00	6.22E-05	1.94E-02	3.53E-02	8.04E-22	7.73E-05	8.36E-02	3.37E-04
RL-W596	9.30E-03	0.00E+00	4.84E-06	2.00E-04	3.32E-04	2.42E-22	6.01E-06	9.84E-03	3.97E-05
RL-W597	1.71E+01	0.00E+00	2.13E-03	3.87E-01	6.02E-01	4.50E-19	2.64E-03	1.81E+01	7.29E-02
RL-W598	1.81E+01	0.00E+00	1.26E-02	5.40E-01	7.50E-01	4.66E-19	1.56E-02	1.94E+01	7.82E-02
RL-W599	9.16E-01	0.00E+00	1.01E-04	4.56E-03	7.91E-03	2.69E-20	1.26E-04	9.28E-01	3.74E-03
RL-W600	5.20E-08	0.00E+00	1.05E-11	1.35E-06	2.80E-07	1.11E-27	1.31E-11	1.68E-06	6.78E-09
RL-W601	2.64E-04	0.00E+00	5.76E-08	6.83E-03	1.42E-03	9.32E-24	7.16E-08	8.51E-03	3.43E-05
RL-W602	2.30E-01	0.00E+00	4.73E-05	5.92E+00	1.23E+00	5.65E-21	5.87E-05	7.38E+00	2.98E-02
RL-W603	1.32E+00	0.00E+00	2.73E-04	3.42E+01	7.07E+00	3.25E-20	3.39E-04	4.26E+01	1.72E-01
RL-W604	3.10E-03	0.00E+00	7.15E-07	1.66E-02	7.62E-03	3.86E-23	8.87E-07	2.73E-02	1.10E-04
RL-W605	7.09E-04	0.00E+00	1.55E-07	1.84E-02	3.80E-03	2.51E-23	1.93E-07	2.29E-02	9.22E-05
RL-W606	2.86E-04	0.00E+00	6.25E-08	7.40E-03	1.53E-03	1.01E-23	7.77E-08	9.22E-03	3.72E-05
RL-W607	5.24E-04	0.00E+00	1.21E-07	2.81E-03	1.29E-03	6.52E-24	1.50E-07	4.62E-03	1.86E-05
RL-W608	6.26E-03	0.00E+00	4.70E-06	3.65E-03	4.19E-03	1.00E-22	5.83E-06	1.41E-02	5.69E-05
RL-W610	1.24E+00	0.00E+00	2.51E-04	3.22E+01	6.67E+00	2.66E-20	3.12E-04	4.01E+01	1.62E-01
RL-W612	2.93E-03	0.00E+00	6.08E-07	7.82E-02	1.62E-02	6.29E-23	7.55E-07	9.74E-02	3.93E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.28E-01	0.00E+00	0.00E+00	0.00E+00	3.28E-01	1.32E-03
RL-W622	4.88E-05	0.00E+00	9.91E-09	1.27E-03	2.63E-04	1.05E-24	1.23E-08	1.58E-03	6.38E-06
RL-W625	1.70E-03	0.00E+00	1.51E-06	6.49E-03	5.93E-03	5.67E-23	1.87E-06	1.41E-02	5.70E-05
RL-W626	9.14E-02	0.00E+00	3.43E-05	2.54E-01	1.42E-01	9.91E-22	4.26E-05	4.87E-01	1.97E-03
RL-W627	4.31E-04	0.00E+00	4.58E-08	1.20E-06	0.00E+00	1.18E-23	5.69E-08	4.32E-04	1.74E-06
RL-W628	1.41E-04	0.00E+00	2.88E-08	3.67E-03	7.58E-04	3.17E-24	3.58E-08	4.57E-03	1.84E-05

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W629	9.56E-06	0.00E+00	1.98E-09	2.47E-04	5.09E-05	2.46E-25	2.46E-09	3.07E-04	1.24E-06
RL-W630	1.05E-01	0.00E+00	3.69E-05	2.85E+00	6.14E-01	2.66E-21	4.58E-05	3.57E+00	1.44E-02
RL-W631	1.70E-03	0.00E+00	3.72E-07	4.38E-02	9.05E-03	5.99E-23	4.62E-07	5.45E-02	2.20E-04
RL-W632	7.49E-01	0.00E+00	5.01E-05	5.79E+00	1.77E+00	1.99E-20	6.23E-05	8.30E+00	3.35E-02
RL-W633	1.79E-03	0.00E+00	2.91E-07	9.09E-04	7.46E-04	2.45E-23	3.61E-07	3.44E-03	1.39E-05
RL-W634	0.00E+00	0.00E+00	0.00E+00	9.90E-03	0.00E+00	0.00E+00	0.00E+00	9.90E-03	3.99E-05
RL-W635	1.07E+01	0.00E+00	9.82E-03	4.21E+00	5.85E+00	2.48E-19	1.22E-02	2.08E+01	8.37E-02
RL-W636	1.09E-01	0.00E+00	1.86E-05	5.50E-02	4.53E-02	1.51E-21	2.30E-05	2.09E-01	8.44E-04
RL-W637	2.59E-04	0.00E+00	4.73E-07	6.19E-04	5.65E-04	5.41E-24	5.87E-07	1.44E-03	5.82E-06
RL-W638	1.14E-02	0.00E+00	4.81E-06	6.07E-03	5.31E-03	2.01E-22	5.98E-06	2.28E-02	9.18E-05
RL-W639	6.01E-04	0.00E+00	1.23E-07	1.55E-02	3.21E-03	1.41E-23	1.53E-07	1.93E-02	7.80E-05
RL-W640	2.02E-02	0.00E+00	4.09E-06	5.23E-01	1.09E-01	4.53E-22	5.08E-06	6.52E-01	2.63E-03
RL-W641	6.16E-01	0.00E+00	8.99E-04	2.51E+00	9.59E-01	7.27E-21	1.12E-03	4.09E+00	1.65E-02
RL-W642	1.20E-02	0.00E+00	9.34E-08	3.07E-02	1.45E-04	3.14E-24	1.16E-07	4.28E-02	1.73E-04
RL-W643	1.90E-01	0.00E+00	2.77E-04	7.75E-01	2.96E-01	2.24E-21	3.44E-04	1.26E+00	5.08E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.33E-02	0.00E+00	0.00E+00	0.00E+00	5.33E-02	2.15E-04
RL-W645	4.60E-03	0.00E+00	1.25E-06	1.05E-01	2.29E-02	1.22E-22	1.55E-06	1.32E-01	5.34E-04
RL-W646	4.18E-03	0.00E+00	1.11E-06	2.50E-02	1.13E-02	5.94E-23	1.38E-06	4.05E-02	1.63E-04
RL-W647	1.18E-02	0.00E+00	1.66E-04	1.07E-01	1.57E-02	1.99E-22	2.07E-04	1.35E-01	5.43E-04
RL-W648	2.09E-04	0.00E+00	2.84E-07	5.83E-05	1.07E-04	6.37E-24	3.53E-07	3.74E-04	1.51E-06
RL-W649	7.67E-04	0.00E+00	1.05E-06	2.15E-04	3.92E-04	2.34E-23	1.30E-06	1.38E-03	5.55E-06
RL-W653	3.63E-05	0.00E+00	7.49E-09	9.38E-04	1.94E-04	8.92E-25	9.30E-09	1.17E-03	4.71E-06
RL-W654	2.00E-04	0.00E+00	4.09E-08	5.16E-03	1.07E-03	4.69E-24	5.08E-08	6.43E-03	2.59E-05
RL-W655	4.92E+01	0.00E+00	9.68E-03	2.05E-01	4.49E-01	1.25E-18	1.20E-02	4.99E+01	2.01E-01
RL-W656	2.06E+02	0.00E+00	4.35E-03	4.82E-01	4.62E-01	5.97E-18	5.40E-03	2.07E+02	8.35E-01
RL-W657	1.05E+02	0.00E+00	6.43E-03	2.37E-01	4.39E-01	2.64E-18	7.98E-03	1.06E+02	4.27E-01
RL-W659	1.27E+01	0.00E+00	1.45E-03	4.56E-02	5.26E-02	2.98E-19	1.80E-03	1.28E+01	5.17E-02
RL-W660	6.98E+01	0.00E+00	1.74E-02	8.42E-01	1.40E+00	1.70E-18	2.17E-02	7.21E+01	2.91E-01
RL-W661	7.39E-01	0.00E+00	2.18E-05	4.06E-04	3.43E-03	2.07E-20	2.71E-05	7.42E-01	2.99E-03
RL-W662	2.32E-02	0.00E+00	1.30E-06	1.04E-04	1.73E-04	4.23E-22	1.61E-06	2.35E-02	9.48E-05
RL-W665	2.86E+02	0.00E+00	1.04E-01	1.27E+00	1.59E+00	8.42E-18	1.29E-01	2.89E+02	1.16E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W666	5.11E+00	0.00E+00	2.55E-04	5.33E-02	5.22E-02	1.22E-19	3.16E-04	5.22E+00	2.10E-02
RL-W668	4.87E-01	0.00E+00	8.01E-06	1.41E-01	3.71E-02	2.88E-22	9.95E-06	6.65E-01	2.68E-03
RL-W669	1.42E-01	0.00E+00	2.08E-04	5.81E-01	2.21E-01	1.68E-21	2.58E-04	9.44E-01	3.81E-03
RL-W670	8.98E-03	0.00E+00	1.48E-07	2.60E-03	6.87E-04	5.33E-24	1.84E-07	1.23E-02	4.95E-05
RL-W671	1.47E+00	0.00E+00	7.58E-05	4.77E-03	4.61E-03	1.75E-20	9.41E-05	1.47E+00	5.94E-03
RL-W672	9.95E+00	0.00E+00	5.16E-04	3.25E-02	3.13E-02	1.19E-19	6.41E-04	1.00E+01	4.04E-02
RL-W673	9.60E+00	0.00E+00	4.96E-04	3.15E-02	3.02E-02	1.15E-19	6.16E-04	9.66E+00	3.90E-02
RL-W674	3.22E-02	0.00E+00	2.22E-05	1.09E+01	8.78E-02	7.99E-22	2.75E-05	1.10E+01	4.43E-02
RL-W675	1.20E-01	0.00E+00	1.22E-04	1.27E-01	1.02E-01	1.95E-21	1.52E-04	3.50E-01	1.41E-03
RL-W676	4.62E-03	0.00E+00	7.35E-07	1.43E-01	1.93E-03	5.78E-23	9.13E-07	1.49E-01	6.02E-04
RL-W677	1.07E+01	0.00E+00	1.82E-03	5.57E+00	4.50E+00	1.39E-19	2.26E-03	2.08E+01	8.38E-02
RL-W678	3.39E-02	0.00E+00	1.52E-05	5.01E-02	4.11E-02	1.09E-21	1.89E-05	1.25E-01	5.04E-04
RL-W679	2.12E-01	0.00E+00	3.40E-05	1.08E-01	8.84E-02	2.80E-21	4.22E-05	4.09E-01	1.65E-03
RL-W680	4.78E-05	0.00E+00	4.78E-08	1.69E-05	2.82E-05	1.20E-24	5.94E-08	9.31E-05	3.75E-07
RL-W681	2.92E-05	0.00E+00	1.94E-08	4.53E-04	2.10E-04	9.99E-25	2.41E-08	6.92E-04	2.79E-06
RL-W685	8.50E-02	0.00E+00	1.72E-05	2.21E+00	4.57E-01	1.82E-21	2.14E-05	2.76E+00	1.11E-02
RL-W689	2.20E-03	0.00E+00	2.07E-07	3.76E-04	0.00E+00	1.75E-24	2.57E-07	2.58E-03	1.04E-05
RL-W690	7.40E-02	0.00E+00	1.52E-05	1.97E+00	4.06E-01	1.59E-21	1.89E-05	2.45E+00	9.88E-03
RL-W691	1.72E-03	0.00E+00	3.54E-07	4.56E-02	9.41E-03	3.68E-23	4.40E-07	5.68E-02	2.29E-04
RL-W692	6.78E-02	0.00E+00	1.40E-05	1.81E+00	3.73E-01	1.45E-21	1.74E-05	2.25E+00	9.06E-03
RL-W693	8.40E-02	0.00E+00	1.73E-05	2.23E+00	4.62E-01	1.80E-21	2.15E-05	2.78E+00	1.12E-02
RL-W694	8.82E-01	0.00E+00	1.82E-04	2.36E+01	4.84E+00	1.89E-20	2.26E-04	2.93E+01	1.18E-01
RL-W695	7.30E-04	0.00E+00	0.00E+00	2.32E-03	0.00E+00	0.00E+00	0.00E+00	3.05E-03	1.23E-05
RL-W696	9.50E-04	0.00E+00	6.63E-07	2.83E-03	2.59E-03	2.59E-23	8.23E-07	6.37E-03	2.57E-05
RL-W697	2.20E-01	0.00E+00	1.40E-03	6.73E-03	8.58E-04	0.00E+00	1.74E-03	2.31E-01	9.29E-04
RL-W698	1.91E-02	0.00E+00	0.00E+00	3.19E-05	0.00E+00	0.00E+00	0.00E+00	1.91E-02	7.70E-05
RL-W699	4.24E-03	0.00E+00	9.34E-08	2.14E-03	2.33E-04	1.09E-22	1.16E-07	6.61E-03	2.66E-05
RL-W700	1.20E-03	0.00E+00	2.45E-07	3.10E-02	6.41E-03	2.82E-23	3.04E-07	3.86E-02	1.56E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	4.73E-02	0.00E+00	6.91E-05	1.93E-01	7.40E-02	5.59E-22	8.59E-05	3.15E-01	1.27E-03

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W705	3.06E-04	0.00E+00	6.37E-08	8.12E-03	1.69E-03	6.87E-24	7.91E-08	1.01E-02	4.08E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	1.09E-02	0.00E+00	2.26E-06	2.89E-01	5.99E-02	2.44E-22	2.81E-06	3.60E-01	1.45E-03
RL-W708	1.65E-03	0.00E+00	3.43E-07	4.39E-02	9.05E-03	3.70E-23	4.26E-07	5.46E-02	2.20E-04
RL-W709	5.70E-01	0.00E+00	1.18E-04	1.51E+01	3.13E+00	1.28E-20	1.47E-04	1.88E+01	7.60E-02
RL-W710	3.40E-05	0.00E+00	7.06E-09	9.05E-04	1.86E-04	7.64E-25	8.77E-09	1.13E-03	4.54E-06
RL-W711	1.06E-02	0.00E+00	2.20E-06	2.83E-01	5.84E-02	2.38E-22	2.74E-06	3.52E-01	1.42E-03
RL-W712	1.38E-02	0.00E+00	2.85E-06	3.65E-01	7.55E-02	3.09E-22	3.54E-06	4.54E-01	1.83E-03
RL-W713	1.19E-02	0.00E+00	2.46E-06	3.15E-01	6.53E-02	2.66E-22	3.06E-06	3.92E-01	1.58E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	2.05E-04	0.00E+00	4.15E-08	5.33E-03	1.10E-03	4.39E-24	5.15E-08	6.64E-03	2.68E-05
RL-W716	2.14E-03	0.00E+00	4.32E-07	5.55E-02	1.15E-02	4.58E-23	5.37E-07	6.91E-02	2.79E-04
RL-W717	5.33E-04	0.00E+00	1.08E-07	1.39E-02	2.87E-03	1.14E-23	1.34E-07	1.73E-02	6.97E-05
RL-W718	9.41E-05	0.00E+00	1.90E-08	2.45E-03	5.06E-04	2.01E-24	2.37E-08	3.05E-03	1.23E-05
RL-W719	4.24E-04	0.00E+00	8.59E-08	1.11E-02	2.29E-03	9.11E-24	1.07E-07	1.38E-02	5.56E-05
RL-W720	2.63E-03	0.00E+00	5.33E-07	6.83E-02	1.42E-02	5.62E-23	6.62E-07	8.51E-02	3.43E-04
RL-W721	1.78E-03	0.00E+00	3.60E-07	4.62E-02	9.59E-03	3.81E-23	4.47E-07	5.76E-02	2.32E-04
RL-W723	5.89E-03	0.00E+00	1.22E-06	1.57E-01	3.25E-02	1.26E-22	1.51E-06	1.96E-01	7.89E-04
RL-W724	3.92E-02	0.00E+00	8.10E-06	1.04E+00	2.16E-01	8.39E-22	1.01E-05	1.29E+00	5.22E-03
RL-W725	1.24E-02	0.00E+00	2.55E-06	3.29E-01	6.81E-02	2.65E-22	3.17E-06	4.10E-01	1.65E-03
RL-W726	9.75E-03	0.00E+00	2.01E-06	2.60E-01	5.37E-02	2.09E-22	2.50E-06	3.24E-01	1.31E-03
RL-W727	5.98E-02	0.00E+00	1.24E-05	1.59E+00	3.30E-01	1.28E-21	1.54E-05	1.98E+00	7.99E-03
RL-W728	5.45E-02	0.00E+00	1.13E-05	1.46E+00	3.00E-01	1.17E-21	1.40E-05	1.81E+00	7.30E-03
RL-W729	2.52E-02	0.00E+00	5.22E-06	6.70E-01	1.39E-01	5.38E-22	6.48E-06	8.34E-01	3.36E-03
RL-W730	9.84E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.84E+00	3.97E-02
RL-W731	3.17E-06	0.00E+00	0.00E+00	4.38E-04	1.67E-06	0.00E+00	0.00E+00	4.43E-04	1.79E-06
RL-W732	7.27E+00	0.00E+00	2.97E-03	1.23E+02	2.54E+01	1.93E-19	3.69E-03	1.56E+02	6.29E-01
RL-W733	9.54E-02	0.00E+00	3.86E-05	1.34E+00	3.08E-01	2.10E-21	4.80E-05	1.74E+00	7.03E-03
RL-W734	2.99E-01	0.00E+00	1.29E-04	4.62E+00	1.04E+00	6.23E-21	1.60E-04	5.96E+00	2.40E-02
RL-W735	2.44E-01	0.00E+00	9.82E-05	3.60E+00	8.29E-01	4.85E-21	1.22E-04	4.68E+00	1.89E-02
RL-W736	2.68E-04	0.00E+00	2.10E-10	2.39E-03	5.72E-04	1.48E-24	2.60E-10	3.23E-03	1.30E-05

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W737	2.18E-01	0.00E+00	8.96E-05	3.42E+00	7.72E-01	4.18E-21	1.11E-04	4.41E+00	1.78E-02
RL-W738	8.12E-01	0.00E+00	3.08E-04	1.09E+01	2.66E+00	1.52E-20	3.83E-04	1.44E+01	5.79E-02
RL-W739	6.92E-02	0.00E+00	2.72E-05	1.77E+00	3.74E-01	1.38E-21	3.38E-05	2.21E+00	8.91E-03
RL-W740	3.46E+00	0.00E+00	9.97E-04	4.30E+01	1.04E+01	6.95E-20	1.24E-03	5.69E+01	2.29E-01
RL-W741	5.17E+00	0.00E+00	2.35E-03	8.38E+00	5.52E+00	5.22E-20	2.91E-03	1.91E+01	7.69E-02
RL-W742	2.30E-01	0.00E+00	7.06E-05	2.72E+00	5.94E-01	4.47E-21	8.77E-05	3.54E+00	1.43E-02
RL-W743	4.15E-04	0.00E+00	1.92E-08	1.76E-03	0.00E+00	0.00E+00	2.38E-08	2.17E-03	8.76E-06
RL-W744	0.00E+00	0.00E+00	0.00E+00	8.77E-02	6.92E-02	0.00E+00	0.00E+00	1.57E-01	6.33E-04
RL-W745	6.55E-04	0.00E+00	1.34E-07	1.70E-02	3.51E-03	1.54E-23	1.66E-07	2.12E-02	8.53E-05
RL-W746	2.52E-03	0.00E+00	5.16E-07	6.52E-02	1.35E-02	5.91E-23	6.41E-07	8.13E-02	3.28E-04
RL-W747	6.83E-03	0.00E+00	1.40E-06	1.77E-01	3.66E-02	1.60E-22	1.74E-06	2.20E-01	8.87E-04
RL-W748	4.79E+01	0.00E+00	3.92E-03	2.93E-01	4.47E-01	1.21E-18	4.87E-03	4.86E+01	1.96E-01
RL-W749	5.75E-02	0.00E+00	1.20E-05	1.53E+00	3.16E-01	1.29E-21	1.49E-05	1.91E+00	7.69E-03
RL-W750	7.26E+01	0.00E+00	5.94E-03	4.81E-01	7.31E-01	1.71E-18	7.37E-03	7.38E+01	2.98E-01
RL-W751	6.56E+01	0.00E+00	5.36E-03	4.32E-01	6.62E-01	1.54E-18	6.66E-03	6.67E+01	2.69E-01
RL-W752	2.85E+01	0.00E+00	2.33E-03	1.88E-01	2.88E-01	6.68E-19	2.89E-03	2.90E+01	1.17E-01
RL-W753	3.84E+02	0.00E+00	3.14E-02	2.53E+00	3.86E+00	9.00E-18	3.90E-02	3.90E+02	1.57E+00
RP-W754	1.63E+01	0.00E+00	3.98E-03	1.81E+03	1.37E+02	8.31E-20	3.57E-01	1.96E+03	7.90E+00
RP-W755	8.62E+01	0.00E+00	2.38E-03	1.35E+03	1.04E+02	6.21E-20	1.26E+01	1.55E+03	6.26E+00
SA-T001	1.73E-01	3.35E-17	5.70E-05	2.94E+00	1.61E-02	0.00E+00	7.55E-05	3.13E+00	1.26E-02
SA-W134	1.42E+00	1.30E-20	3.89E-04	1.34E+00	3.94E-01	1.58E-21	1.67E-01	3.32E+00	1.34E-02
SA-W134M	1.84E-01	1.68E-21	5.04E-05	1.75E-01	5.11E-02	2.06E-22	2.16E-02	4.31E-01	1.74E-03
T001-221F-HET	3.43E+02	0.00E+00	4.55E+01	2.80E+04	6.40E+02	5.19E-18	6.22E+01	2.91E+04	1.17E+02
T001-221H-HET	6.16E+02	0.00E+00	8.21E+01	5.05E+04	1.16E+03	9.37E-18	1.12E+02	5.24E+04	2.12E+02
T001-235F-HET	3.55E+01	0.00E+00	4.73E+00	2.90E+03	6.64E+01	5.38E-19	6.45E+00	3.02E+03	1.22E+01
T001-772F-HET	3.06E+02	0.00E+00	4.09E+01	2.50E+04	5.73E+02	4.63E-18	5.59E+01	2.60E+04	1.05E+02
T001-773A-CLAS	3.43E+00	0.00E+00	4.58E-01	2.82E+02	6.43E+00	5.22E-20	6.26E-01	2.92E+02	1.18E+00
T001-773A-HET	3.95E+01	0.00E+00	5.27E+00	3.24E+03	7.42E+01	6.02E-19	7.20E+00	3.37E+03	1.36E+01
W006-773A-VIT	5.29E-04	0.00E+00	0.00E+00	5.21E+02	0.00E+00	0.00E+00	0.00E+00	5.21E+02	2.10E+00
W026-221F-HET	1.19E+02	0.00E+00	1.59E+01	9.80E+03	2.23E+02	1.81E-18	2.17E+01	1.02E+04	4.11E+01
W026-221H-HET	8.91E+01	0.00E+00	1.19E+01	7.30E+03	1.67E+02	1.35E-18	1.62E+01	7.58E+03	3.06E+01

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W026-235F-HET	1.39E+00	0.00E+00	1.85E-01	1.14E+02	2.60E+00	2.11E-20	2.53E-01	1.18E+02	4.76E-01
W026-772F-HET	3.79E-01	0.00E+00	5.04E-02	3.10E+01	7.08E-01	5.75E-21	6.89E-02	3.22E+01	1.30E-01
W026-773A-HET	6.15E+00	0.00E+00	8.21E-01	5.05E+02	1.16E+01	9.35E-20	1.12E+00	5.24E+02	2.12E+00
W027-221F-HET	4.50E+02	0.00E+00	5.36E+01	3.79E+04	8.64E+02	2.96E-18	8.43E+01	3.93E+04	1.59E+02
W027-221H-HET	1.97E+02	0.00E+00	2.34E+01	1.66E+04	3.78E+02	1.29E-18	3.68E+01	1.72E+04	6.95E+01
W027-235F-HET	5.91E+01	0.00E+00	7.03E+00	4.99E+03	1.14E+02	3.89E-19	1.11E+01	5.18E+03	2.09E+01
W027-772F-HET	1.08E+02	0.00E+00	1.28E+01	9.06E+03	2.07E+02	7.06E-19	2.01E+01	9.40E+03	3.79E+01
W027-773A-HET	1.60E+02	0.00E+00	1.91E+01	1.35E+04	3.08E+02	1.06E-18	3.00E+01	1.40E+04	5.65E+01
W027-999-HET	1.83E+02	0.00E+00	2.18E+01	1.54E+04	3.52E+02	1.20E-18	3.43E+01	1.60E+04	6.46E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.87E+02	0.00E+00	0.00E+00	0.00E+00	3.87E+02	1.56E+00
WP-INW169.001	8.95E-01	0.00E+00	1.37E-04	1.50E+01	3.08E+00	1.06E-20	3.35E-04	1.89E+01	7.63E-02
WP-INW198.001	1.18E+00	0.00E+00	2.40E-04	2.68E+01	5.49E+00	1.74E-20	3.79E-04	3.35E+01	1.35E-01
WP-INW211.001	1.33E+02	0.00E+00	2.25E-02	2.49E+03	5.09E+02	1.98E-18	2.99E-02	3.13E+03	1.26E+01
WP-INW216.001-	4.82E+03	0.00E+00	1.29E-02	1.44E+03	2.96E+02	1.09E-18	2.92E-01	6.56E+03	2.64E+01
WP-INW216.001-	1.33E+03	0.00E+00	3.49E-03	3.89E+02	7.98E+01	2.96E-19	3.19E-02	1.80E+03	7.24E+00
WP-INW218.001-	9.22E+01	0.00E+00	2.28E-03	2.50E+02	5.15E+01	1.98E-19	3.88E-01	3.95E+02	1.59E+00
WP-INW218.001-	4.25E-01	0.00E+00	6.28E-05	6.81E+00	1.40E+00	5.59E-21	3.74E-02	8.68E+00	3.50E-02
WP-INW222.001	4.36E+00	0.00E+00	6.77E-04	6.66E+01	1.38E+01	4.74E-20	1.41E-03	8.48E+01	3.42E-01
WP-INW243.001	1.06E+01	0.00E+00	1.46E-03	1.40E+02	2.90E+01	9.59E-20	2.68E-03	1.79E+02	7.24E-01
WP-INW247.001R	1.41E+01	0.00E+00	3.40E-03	2.68E+02	5.65E+01	1.66E-19	4.30E-03	3.39E+02	1.37E+00
WP-INW276.001	1.08E+00	0.00E+00	3.31E-04	2.65E+01	5.59E+00	1.41E-20	4.28E-04	3.32E+01	1.34E-01
WP-INW276.002	1.71E+00	0.00E+00	4.98E-04	3.89E+01	8.39E+00	2.11E-20	6.46E-04	4.90E+01	1.98E-01
WP-INW276.003	6.56E+01	0.00E+00	1.85E-02	1.45E+03	3.06E+02	8.90E-19	2.35E-02	1.82E+03	7.33E+00
WP-INW276.004	1.57E+01	0.00E+00	3.92E-03	3.06E+02	6.45E+01	1.88E-19	5.01E-03	3.86E+02	1.56E+00
WP-INW296.001-	5.72E+00	0.00E+00	9.31E-04	7.68E+01	1.61E+01	4.82E-20	1.19E-03	9.86E+01	3.98E-01
WP-INW296.001-	1.73E+01	0.00E+00	3.28E-03	2.72E+02	5.70E+01	1.74E-19	4.43E-03	3.46E+02	1.40E+00
WP-LA-TA-55-19	2.87E-01	0.00E+00	1.53E-04	2.03E+00	4.55E-01	1.73E-21	2.82E-03	2.77E+00	1.12E-02
WP-LA-TA-55-19	1.39E+01	0.00E+00	5.13E-03	2.07E+02	4.68E+01	1.72E-19	9.33E-02	2.68E+02	1.08E+00
WP-LA-TA-55-43	7.81E-02	0.00E+00	1.20E-01	3.14E-01	1.23E-01	1.54E-21	1.75E-01	8.09E-01	3.26E-03
WP-RF001.01	2.42E+01	0.00E+00	4.15E-03	3.98E+02	8.40E+01	1.73E-19	1.45E-02	5.06E+02	2.04E+00
WP-RF002.01-A	2.81E+01	0.00E+00	5.53E-03	4.49E+02	9.50E+01	3.81E-19	2.46E-02	5.72E+02	2.31E+00

Table PAR-56. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 1,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF002.01-B	2.79E-02	0.00E+00	3.83E-06	4.85E-01	1.02E-01	2.39E-22	4.95E-06	6.15E-01	2.48E-03
WP-RF003.01	4.36E+02	0.00E+00	8.90E-02	8.57E+03	1.81E+03	6.29E-18	1.19E-01	1.08E+04	4.36E+01
WP-RF004.01	2.05E-01	0.00E+00	5.96E-05	4.94E+00	1.05E+00	3.60E-21	2.01E-04	6.20E+00	2.50E-02
WP-RF005.01	1.05E+03	0.00E+00	4.52E-02	4.53E+03	9.50E+02	2.50E-18	5.80E-02	6.53E+03	2.63E+01
WP-RF005.02	1.24E+03	0.00E+00	2.34E-02	2.71E+03	5.64E+02	1.28E-18	3.02E-02	4.51E+03	1.82E+01
WP-RF006.01	4.01E+02	0.00E+00	8.50E-02	7.71E+03	1.63E+03	3.25E-18	1.31E-01	9.74E+03	3.93E+01
WP-RF008.01	1.27E+02	0.00E+00	3.03E-02	2.25E+03	4.85E+02	2.14E-18	3.88E-02	2.86E+03	1.16E+01
WP-RF009.01	1.25E+04	0.00E+00	3.72E-01	4.94E+04	1.02E+04	2.46E-17	4.82E-01	7.21E+04	2.91E+02
WP-RF010.01	4.61E+00	0.00E+00	9.42E-04	7.47E+01	1.58E+01	7.59E-20	1.90E-03	9.50E+01	3.83E-01
WP-RF029.01-A	1.11E+00	0.00E+00	1.77E-04	1.31E+01	2.78E+00	1.74E-20	9.48E-04	1.70E+01	6.85E-02
WP-RF029.01-B	1.66E+00	0.00E+00	1.40E-04	1.04E+01	2.20E+00	1.38E-20	2.42E-03	1.42E+01	5.74E-02
WP-RF118.01	2.81E+03	0.00E+00	7.06E-01	4.99E+04	1.03E+04	4.53E-17	1.09E+00	6.30E+04	2.54E+02
WP-RLMPDT.001	5.97E-01	0.00E+00	2.06E-04	7.14E+00	1.72E+00	9.93E-21	2.58E-04	9.46E+00	3.82E-02
WP-RLNPDT.002	7.33E+00	0.00E+00	1.96E-03	7.02E+01	1.75E+01	1.14E-19	2.48E-03	9.50E+01	3.83E-01
WP-SR2001.001.	2.34E-01	0.00E+00	2.26E-04	6.63E+00	1.22E+00	6.21E-21	2.85E-04	8.08E+00	3.26E-02
WP-SR-W027-221	1.73E+00	0.00E+00	6.63E-04	1.90E+01	4.92E+00	2.80E-20	1.86E-01	2.59E+01	1.04E-01
Total	9.25E+04	6.49E-14	4.64E+02	6.41E+05	9.60E+04	6.40E-16	7.43E+02	8.31E+05	3.35E+03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	7.05E-01	0.00E+00	7.06E-10	1.92E+02	8.99E+01	9.83E-62	1.95E-02	2.82E+02	1.14E+00
AE-T003	8.94E-02	0.00E+00	9.40E-11	5.92E+01	1.81E+01	5.39E-62	9.56E-04	7.74E+01	3.12E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	3.96E-04	0.00E+00	2.49E-09	4.36E+01	2.09E-01	1.05E-64	2.28E-02	4.39E+01	1.77E-01
AW-T033.1325	1.45E-03	0.00E+00	9.12E-09	1.59E+02	7.61E-01	3.83E-64	8.37E-02	1.60E+02	6.46E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	7.08E-01	0.00E+00	0.00E+00	0.00E+00	7.08E-01	2.86E-03
BCLCH-MT01	1.46E-01	0.00E+00	7.06E-08	2.63E+01	5.47E+00	1.48E-61	6.34E-01	3.26E+01	1.31E-01
BT-T002	1.07E-04	1.01E-53	3.69E-11	6.64E-04	1.08E-03	6.50E-65	2.30E-03	4.15E-03	1.68E-05
ET-C1-B55	4.48E-04	0.00E+00	4.20E-13	5.69E-02	2.25E-02	1.15E-64	2.38E-04	8.01E-02	3.23E-04
ET-C1-D139	6.15E-05	0.00E+00	5.83E-14	8.00E-03	3.16E-03	1.53E-65	5.85E-07	1.12E-02	4.53E-05
ET-C2-SEFOR	1.52E-03	0.00E+00	0.00E+00	1.26E-01	3.34E-02	2.35E-64	0.00E+00	1.61E-01	6.47E-04
FM-MOX-MT02	1.44E-08	0.00E+00	2.35E-17	2.75E-07	1.30E-07	8.18E-69	2.19E-10	4.19E-07	1.69E-09
FM-MOX-T01	2.38E-07	0.00E+00	3.87E-16	4.53E-06	2.14E-06	1.35E-67	3.62E-09	6.91E-06	2.79E-08
IN-BN-510	5.76E+01	0.00E+00	2.00E-06	3.64E+04	2.44E+03	3.22E-62	1.99E+01	3.89E+04	1.57E+02
IN-GEM-01	7.28E-01	0.00E+00	3.96E-11	4.09E+01	7.40E+00	2.27E-62	3.56E-04	4.90E+01	1.98E-01
IN-GEM-02	1.73E-01	0.00E+00	9.44E-12	9.71E+00	1.76E+00	5.39E-63	8.47E-05	1.17E+01	4.70E-02
IN-W157.144	8.62E-01	0.00E+00	3.84E-10	2.78E+02	4.98E+01	4.03E-61	3.82E-03	3.28E+02	1.32E+00
IN-W163.1007	1.48E-01	0.00E+00	1.19E-10	8.61E+01	1.54E+01	1.24E-61	1.18E-03	1.02E+02	4.10E-01
IN-W164.153	1.41E-03	0.00E+00	1.13E-12	8.20E-01	1.47E-01	1.19E-63	1.12E-05	9.69E-01	3.91E-03
IN-W167.149	2.83E-01	0.00E+00	1.84E-10	1.33E+02	2.39E+01	1.93E-61	1.83E-03	1.57E+02	6.33E-01
IN-W174.154	0.00E+00	0.00E+00	1.04E-07	1.79E+00	2.79E+00	0.00E+00	1.03E+00	5.61E+00	2.26E-02
IN-W177.156	1.96E-04	0.00E+00	2.21E-07	1.68E+00	8.12E-03	1.65E-64	2.20E+00	3.88E+00	1.57E-02
IN-W179.158	1.32E-03	0.00E+00	2.20E-07	9.71E-02	4.00E-02	1.11E-63	2.19E+00	2.33E+00	9.38E-03
IN-W181.162	1.87E-02	0.00E+00	1.50E-11	1.08E+01	1.94E+00	1.58E-62	1.49E-04	1.28E+01	5.15E-02
IN-W188.160	1.26E-01	0.00E+00	1.01E-10	7.30E+01	1.31E+01	1.06E-61	1.00E-03	8.62E+01	3.48E-01
IN-W216.98	1.12E+03	0.00E+00	8.21E-09	5.96E+03	1.07E+03	8.68E-60	8.17E-02	8.15E+03	3.29E+01
IN-W218.909	5.65E+00	0.00E+00	1.82E-10	1.32E+02	2.37E+01	1.92E-61	1.82E-03	1.61E+02	6.51E-01
IN-W219.110	7.67E-03	0.00E+00	6.15E-12	4.45E+00	7.98E-01	6.46E-63	6.11E-05	5.26E+00	2.12E-02
IN-W219.914	1.21E-03	0.00E+00	9.67E-13	7.03E-01	1.26E-01	1.02E-63	9.62E-06	8.30E-01	3.35E-03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W220.114	4.00E+01	0.00E+00	6.46E-10	5.03E+02	8.77E+01	6.79E-61	6.43E-03	6.31E+02	2.54E+00
IN-W221.927	4.69E-02	0.00E+00	3.75E-11	2.71E+01	4.86E+00	3.95E-62	3.73E-04	3.20E+01	1.29E-01
IN-W222.116	1.59E+00	0.00E+00	1.27E-09	9.16E+02	1.65E+02	1.33E-60	1.26E-02	1.08E+03	4.37E+00
IN-W228.101	1.06E+01	0.00E+00	4.12E-10	3.00E+02	5.37E+01	4.36E-61	4.10E-03	3.64E+02	1.47E+00
IN-W240.931	1.12E+00	0.00E+00	5.27E-10	3.85E+02	6.87E+01	5.51E-61	5.25E-03	4.55E+02	1.83E+00
IN-W243.808	1.55E+00	0.00E+00	9.24E-10	6.72E+02	1.20E+02	9.75E-61	9.19E-03	7.94E+02	3.20E+00
IN-W245.301	2.29E+00	0.00E+00	1.82E-09	1.31E+03	2.36E+02	1.90E-60	1.81E-02	1.55E+03	6.24E+00
IN-W247.810	1.12E+00	0.00E+00	8.84E-10	6.41E+02	1.15E+02	9.29E-61	8.80E-03	7.57E+02	3.05E+00
IN-W249.527	0.00E+00	0.00E+00	6.19E-08	1.14E+01	0.00E+00	0.00E+00	6.15E-01	1.20E+01	4.83E-02
IN-W263.520	3.20E-04	0.00E+00	6.46E-09	7.73E+00	9.72E-03	2.69E-64	6.43E-02	7.80E+00	3.15E-02
IN-W267.1005	2.68E-01	0.00E+00	2.15E-10	1.56E+02	2.79E+01	2.26E-61	2.13E-03	1.84E+02	7.42E-01
IN-W309.609	7.18E+00	0.00E+00	3.60E-09	2.60E+03	4.67E+02	3.78E-60	3.58E-02	3.08E+03	1.24E+01
IN-W315.601	7.08E+00	0.00E+00	1.50E-11	1.09E+01	1.95E+00	1.58E-62	1.50E-04	1.99E+01	8.04E-02
IN-W319.584	4.12E-02	0.00E+00	3.29E-11	2.39E+01	4.30E+00	3.47E-62	3.27E-04	2.83E+01	1.14E-01
IN-W321.1023	3.56E-01	0.00E+00	2.86E-10	2.07E+02	3.71E+01	3.00E-61	2.84E-03	2.45E+02	9.86E-01
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	8.36E+00	1.37E+00	0.00E+00	0.00E+00	9.73E+00	3.92E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.23E+01	3.65E+00	0.00E+00	0.00E+00	2.59E+01	1.05E-01
IN-W323.562	7.61E-04	0.00E+00	4.84E-11	2.28E-01	0.00E+00	6.42E-64	4.81E-04	2.29E-01	9.25E-04
IN-W323.951	8.99E-04	0.00E+00	5.75E-13	2.72E-01	0.00E+00	7.57E-64	5.72E-06	2.73E-01	1.10E-03
IN-W332.661	0.00E+00	0.00E+00	6.34E-10	1.18E-01	0.00E+00	0.00E+00	6.31E-03	1.25E-01	5.02E-04
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	2.79E+00	4.57E-01	0.00E+00	0.00E+00	3.24E+00	1.31E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	8.36E+00	1.37E+00	0.00E+00	0.00E+00	9.73E+00	3.92E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.79E+00	0.00E+00	0.00E+00	0.00E+00	1.79E+00	7.21E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.37E+00	0.00E+00	0.00E+00	0.00E+00	5.37E+00	2.17E-02
IN-W342.652	3.52E-02	0.00E+00	0.00E+00	3.68E-02	7.54E-18	0.00E+00	0.00E+00	7.20E-02	2.90E-04
IN-W342.953	2.35E-02	0.00E+00	0.00E+00	2.47E-02	5.06E-18	0.00E+00	0.00E+00	4.82E-02	1.94E-04
IN-W347.818	1.84E-02	0.00E+00	0.00E+00	7.57E+01	1.10E+02	0.00E+00	1.57E-08	1.86E+02	7.50E-01
IN-W348.1012	9.74E-04	0.00E+00	5.23E-10	3.82E+02	6.86E+01	0.00E+00	5.21E-03	4.51E+02	1.82E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.29E-02	0.00E+00	0.00E+00	0.00E+00	2.29E-02	9.24E-05
IN-W357.1022	0.00E+00	0.00E+00	1.03E-12	7.51E-01	1.34E-01	0.00E+00	1.03E-05	8.85E-01	3.57E-03
IN-W358.854	0.00E+00	0.00E+00	1.55E-08	1.72E+00	2.63E+00	0.00E+00	1.48E-01	4.50E+00	1.82E-02

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W358.855	0.00E+00	0.00E+00	8.29E-08	9.16E+00	1.40E+01	0.00E+00	7.86E-01	2.39E+01	9.66E-02
IN-W358.948	0.00E+00	0.00E+00	1.73E-08	1.92E+00	2.92E+00	0.00E+00	1.64E-01	4.99E+00	2.01E-02
IN-W361.1021	2.59E-04	0.00E+00	9.99E-11	7.24E+01	1.30E+01	0.00E+00	9.94E-04	8.54E+01	3.44E-01
IN-W362.1020	0.00E+00	0.00E+00	1.31E-09	9.44E+02	1.70E+02	0.00E+00	1.30E-02	1.11E+03	4.49E+00
IN-W363.1019	0.00E+00	0.00E+00	6.15E-11	4.48E+01	8.05E+00	0.00E+00	6.12E-04	5.29E+01	2.13E-01
IN-W364.1011	0.00E+00	0.00E+00	1.02E-10	7.37E+01	1.32E+01	0.00E+00	1.01E-03	8.69E+01	3.50E-01
IN-W365.1010	2.41E+00	0.00E+00	8.05E-11	5.82E+01	1.04E+01	0.00E+00	8.01E-04	7.10E+01	2.87E-01
IN-W366.841	8.58E-03	0.00E+00	6.86E-11	4.96E+01	8.92E+00	0.00E+00	6.83E-04	5.85E+01	2.36E-01
IN-W372.832	3.52E-02	0.00E+00	0.00E+00	3.68E-02	7.54E-18	0.00E+00	0.00E+00	7.20E-02	2.90E-04
IN-W375.1096	0.00E+00	0.00E+00	2.53E-11	1.83E+01	3.29E+00	0.00E+00	2.52E-04	2.16E+01	8.72E-02
KN-B234TRU	1.25E+00	0.00E+00	9.67E-10	2.67E+02	7.11E+01	2.11E-61	1.06E-02	3.39E+02	1.37E+00
LA-IT-00-01	1.82E-02	6.52E-51	1.65E-10	5.36E-01	9.20E-03	4.05E-71	1.83E-03	5.65E-01	2.28E-03
LA-OS-00-01	4.05E+01	0.00E+00	7.53E-06	1.13E+03	0.00E+00	0.00E+00	6.82E+01	1.24E+03	4.98E+00
LA-PX-00-01	1.69E-04	0.00E+00	3.18E-13	8.29E-02	1.54E-02	6.70E-65	2.99E-06	9.86E-02	3.97E-04
LA-SL-00-01	0.00E+00	0.00E+00	6.70E-12	1.40E-01	0.00E+00	0.00E+00	7.39E-05	1.40E-01	5.66E-04
LA-TA-03-12	1.74E-03	0.00E+00	1.55E-10	4.00E-01	1.10E-01	3.97E-64	1.77E-03	5.13E-01	2.07E-03
LA-TA-03-13	2.24E-03	0.00E+00	4.92E-10	6.24E-01	1.16E-01	5.26E-64	4.94E-03	7.47E-01	3.01E-03
LA-TA-03-19	4.53E-03	0.00E+00	7.34E-10	1.22E+00	2.79E-01	8.14E-64	8.36E-03	1.51E+00	6.09E-03
LA-TA-03-20	2.47E-03	0.00E+00	3.48E-10	5.37E-01	1.50E-01	6.66E-64	3.81E-03	6.93E-01	2.80E-03
LA-TA-03-24	3.32E-03	0.00E+00	1.36E-09	9.99E-01	2.40E-01	6.91E-64	1.56E-02	1.26E+00	5.07E-03
LA-TA-03-26	1.70E-04	0.00E+00	5.59E-11	2.42E+00	3.14E-02	6.05E-65	1.50E-03	2.45E+00	9.89E-03
LA-TA-03-28	0.00E+00	0.00E+00	1.94E-11	2.26E-01	0.00E+00	0.00E+00	2.19E-04	2.27E-01	9.14E-04
LA-TA-03-30	7.56E-03	0.00E+00	1.38E-11	4.61E+00	1.06E+00	3.17E-63	1.55E-04	5.68E+00	2.29E-02
LA-TA-03-31	0.00E+00	0.00E+00	6.90E-13	8.06E-03	0.00E+00	0.00E+00	7.79E-06	8.07E-03	3.26E-05
LA-TA-03-40	0.00E+00	0.00E+00	1.09E-12	5.01E-02	0.00E+00	0.00E+00	1.24E-05	5.01E-02	2.02E-04
LA-TA-03-42	1.74E-07	0.00E+00	2.73E-14	3.13E-03	3.27E-05	6.62E-68	3.11E-07	3.17E-03	1.28E-05
LA-TA-21-06	1.71E-03	0.00E+00	3.01E-09	8.77E-01	2.12E-01	6.83E-64	3.39E-02	1.13E+00	4.54E-03
LA-TA-21-12	6.23E-03	0.00E+00	1.81E-08	3.04E+00	7.21E-01	2.34E-63	2.05E-01	3.97E+00	1.60E-02
LA-TA-21-13	9.59E-03	0.00E+00	0.00E+00	2.69E-01	0.00E+00	0.00E+00	0.00E+00	2.79E-01	1.13E-03
LA-TA-21-14	1.58E-06	0.00E+00	3.46E-10	4.12E+00	3.81E-05	9.50E-67	3.28E-03	4.12E+00	1.66E-02
LA-TA-21-15	9.29E-04	0.00E+00	9.52E-13	1.27E+00	1.73E-01	3.85E-64	1.07E-05	1.45E+00	5.84E-03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-16	1.08E-02	0.00E+00	1.47E-11	9.71E+00	1.84E+00	4.07E-63	1.67E-04	1.16E+01	4.66E-02
LA-TA-21-40	1.37E-06	0.00E+00	5.08E-11	3.05E-01	2.68E-04	1.63E-67	7.04E-04	3.06E-01	1.23E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	6.50E-01	0.00E+00	0.00E+00	0.00E+00	6.50E-01	2.62E-03
LA-TA-21-42	1.40E-04	0.00E+00	1.65E-11	1.50E-01	8.12E-03	5.31E-66	2.44E-04	1.59E-01	6.40E-04
LA-TA-21-43	4.93E-01	0.00E+00	5.47E-10	4.68E+02	8.85E+01	4.20E-62	8.03E-03	5.57E+02	2.25E+00
LA-TA-21-44	2.36E-03	0.00E+00	1.15E-10	1.05E+02	2.23E-01	5.92E-64	1.40E-03	1.06E+02	4.26E-01
LA-TA-48-01	7.65E-04	3.07E-50	4.32E-13	1.08E-01	3.59E-01	4.89E-65	6.05E-06	4.68E-01	1.89E-03
LA-TA-49-01	9.44E-02	3.81E-48	5.31E-11	1.34E+01	4.45E+01	6.05E-63	7.46E-04	5.80E+01	2.34E-01
LA-TA-50-10	2.53E-04	0.00E+00	5.04E-13	4.21E-02	0.00E+00	0.00E+00	4.70E-06	4.23E-02	1.71E-04
LA-TA-50-11	4.82E-04	0.00E+00	5.15E-13	4.27E-01	7.54E-02	4.85E-65	7.09E-06	5.03E-01	2.03E-03
LA-TA-50-15	9.52E-04	0.00E+00	7.61E-11	3.12E-01	5.55E-02	1.92E-64	8.03E-04	3.69E-01	1.49E-03
LA-TA-50-17	1.39E-01	0.00E+00	6.19E-11	1.67E+01	3.12E-04	1.76E-65	9.90E-04	1.68E+01	6.78E-02
LA-TA-50-18	8.28E-03	0.00E+00	8.17E-12	2.72E+00	3.89E-06	5.18E-67	9.30E-05	2.73E+00	1.10E-02
LA-TA-50-19	2.64E-03	0.00E+00	3.64E-12	3.62E-01	3.33E-03	6.42E-66	6.80E-05	3.68E-01	1.48E-03
LA-TA-50-20	7.25E-05	0.00E+00	0.00E+00	8.93E-03	0.00E+00	0.00E+00	0.00E+00	9.00E-03	3.63E-05
LA-TA-50-40	4.08E-05	0.00E+00	4.92E-14	9.71E-03	3.60E-03	2.06E-65	5.34E-07	1.34E-02	5.39E-05
LA-TA-50-41	4.35E-05	0.00E+00	4.96E-14	4.31E-02	7.98E-03	3.66E-65	4.93E-07	5.11E-02	2.06E-04
LA-TA-55-19	6.75E-02	0.00E+00	6.54E-11	2.42E+01	5.42E+00	2.07E-62	2.24E-03	2.97E+01	1.20E-01
LA-TA-55-20	1.08E+00	0.00E+00	7.45E-10	5.85E+02	1.12E+02	5.18E-61	1.01E-01	6.98E+02	2.81E+00
LA-TA-55-21	9.68E-03	9.08E-54	8.56E-12	4.14E+00	7.90E-01	4.28E-63	8.45E-05	4.94E+00	1.99E-02
LA-TA-55-22	2.65E-02	0.00E+00	4.84E-11	1.46E+01	2.71E+00	1.32E-62	4.78E-04	1.73E+01	6.98E-02
LA-TA-55-23	2.50E-02	0.00E+00	4.04E-11	9.99E+00	1.97E+00	1.30E-62	3.96E-04	1.20E+01	4.83E-02
LA-TA-55-24	9.42E-03	0.00E+00	6.34E-12	5.24E+00	9.72E-01	6.21E-63	5.97E-05	6.22E+00	2.51E-02
LA-TA-55-25	4.82E-02	0.00E+00	3.70E-11	2.60E+01	4.84E+00	3.18E-62	3.48E-04	3.09E+01	1.25E-01
LA-TA-55-28	1.64E-02	0.00E+00	2.05E-11	7.99E+00	1.50E+00	1.03E-62	1.95E-04	9.51E+00	3.83E-02
LA-TA-55-30	3.66E-01	8.60E-56	2.45E-10	1.31E+02	2.52E+01	7.57E-62	2.97E-03	1.57E+02	6.31E-01
LA-TA-55-32	2.97E-02	0.00E+00	1.37E-09	1.04E+01	2.55E+00	9.42E-63	1.58E-02	1.30E+01	5.22E-02
LA-TA-55-33	4.45E-03	0.00E+00	3.54E-12	1.37E+00	3.47E-01	1.32E-63	3.81E-05	1.72E+00	6.92E-03
LA-TA-55-34	4.50E-01	0.00E+00	3.28E-10	2.12E+02	4.28E+01	1.60E-61	6.28E-03	2.55E+02	1.03E+00
LA-TA-55-38	1.13E+00	0.00E+00	1.08E-10	4.67E+01	1.00E+01	3.71E-62	2.84E-03	5.79E+01	2.33E-01
LA-TA-55-39	1.20E-01	0.00E+00	7.97E-11	6.97E+01	1.25E+01	6.54E-62	7.74E-04	8.23E+01	3.32E-01

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-41	2.85E+00	0.00E+00	1.65E-10	8.65E+01	1.65E+01	8.23E-62	1.64E-03	1.06E+02	4.27E-01
LA-TA-55-43	1.07E-03	0.00E+00	1.08E-08	1.30E-01	3.63E-02	7.24E-64	1.04E-01	2.72E-01	1.10E-03
LA-TA-55-44	9.27E-03	0.00E+00	2.55E-08	2.41E+00	5.32E-01	2.14E-63	2.77E-01	3.23E+00	1.30E-02
LA-TA-55-48	6.83E+01	0.00E+00	1.01E-07	1.55E+04	4.60E+03	2.23E-59	1.07E+00	2.02E+04	8.13E+01
LA-TA-55-49	1.46E-01	0.00E+00	1.32E-07	2.83E+01	6.33E+00	2.61E-62	1.43E+00	3.62E+01	1.46E-01
LA-TA-55-53	6.88E-01	0.00E+00	2.74E-10	2.42E+02	4.50E+01	1.43E-61	2.91E-03	2.88E+02	1.16E+00
LA-TA-55-56	7.62E-01	0.00E+00	1.02E-08	3.50E+02	6.99E+01	3.31E-61	1.03E-01	4.21E+02	1.70E+00
LA-TA-55-60	4.13E-04	0.00E+00	2.57E-12	6.60E-02	1.86E-02	1.95E-64	2.77E-05	8.51E-02	3.43E-04
LA-TA-55-61	3.56E-04	0.00E+00	1.19E-11	1.27E-01	3.44E-02	1.90E-64	1.26E-04	1.62E-01	6.54E-04
LA-TA-55-62	9.21E-05	0.00E+00	1.13E-13	2.14E-02	8.12E-03	5.10E-65	1.20E-06	2.96E-02	1.19E-04
LA-TA-55-63	6.84E-05	0.00E+00	7.61E-14	6.85E-02	1.26E-02	5.02E-65	7.76E-07	8.11E-02	3.27E-04
LL-M001	9.38E-01	4.12E-49	3.32E-09	6.42E+01	2.31E+01	3.96E-61	2.98E-02	8.82E+01	3.56E-01
LL-T001	4.68E+00	0.00E+00	0.00E+00	4.89E+02	1.76E+02	3.07E-60	0.00E+00	6.70E+02	2.70E+00
LL-T002	4.63E+01	0.00E+00	2.64E-08	4.75E+03	1.55E+03	2.70E-59	2.37E-01	6.35E+03	2.56E+01
LL-T003	1.80E+00	0.00E+00	2.95E-09	9.62E+01	6.18E+01	1.07E-60	2.65E-02	1.60E+02	6.44E-01
LL-T004	1.14E+00	0.00E+00	6.07E-10	6.11E+01	3.89E+01	6.79E-61	5.45E-03	1.01E+02	4.08E-01
LL-T005	5.90E+00	1.80E-47	7.14E-09	2.27E+02	1.56E+02	2.51E-60	6.41E-02	3.90E+02	1.57E+00
LL-W018	5.03E-04	0.00E+00	0.00E+00	1.70E-02	3.10E-02	5.14E-64	0.00E+00	4.85E-02	1.96E-04
LL-W019	2.72E-01	0.00E+00	0.00E+00	1.32E+01	8.77E+00	1.51E-61	0.00E+00	2.22E+01	8.97E-02
LL-W034	1.01E-01	3.03E-49	1.25E-10	3.85E+00	2.59E+00	4.28E-62	1.12E-03	6.54E+00	2.64E-02
MC-W001	1.26E-03	0.00E+00	0.00E+00	5.55E-02	0.00E+00	7.73E-65	0.00E+00	5.68E-02	2.29E-04
MU-W002	1.68E-02	0.00E+00	0.00E+00	4.82E-02	0.00E+00	0.00E+00	2.65E-12	6.50E-02	2.62E-04
NT-JAS-01	1.62E+00	0.00E+00	2.66E-09	8.69E+01	5.56E+01	9.62E-61	2.39E-02	1.44E+02	5.81E-01
NT-W001	2.43E+00	9.28E-51	5.31E-09	2.62E+03	1.39E+01	6.74E-62	5.92E-02	2.64E+03	1.06E+01
NT-W021	4.71E-02	0.00E+00	3.81E-11	2.95E+01	5.35E+00	3.45E-62	3.88E-04	3.49E+01	1.41E-01
OR-W201	5.65E+01	6.40E-49	1.14E-07	1.98E+03	1.55E+03	3.62E-59	4.43E+01	3.63E+03	1.47E+01
OR-W202	8.10E+00	1.33E-47	3.30E-07	5.08E+02	3.96E+02	1.16E-60	3.41E+00	9.15E+02	3.69E+00
OR-W203	1.78E-02	4.64E-49	4.72E-11	2.28E-02	1.29E+00	2.94E-63	4.85E-04	1.33E+00	5.38E-03
OR-W204	3.98E-03	1.92E-54	5.35E-11	3.89E-01	2.09E-01	0.00E+00	5.50E-04	6.02E-01	2.43E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	3.90E-01	0.00E+00	0.00E+00	0.00E+00	3.90E-01	1.57E-03
RF-MT0001	1.53E+01	0.00E+00	3.32E-10	1.80E+02	3.26E+01	2.65E-61	3.28E-03	2.27E+02	9.17E-01

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0002	1.17E+00	0.00E+00	2.55E-11	1.38E+01	2.50E+00	2.04E-62	2.52E-04	1.75E+01	7.06E-02
RF-MT0003	5.34E-03	0.00E+00	5.83E-12	3.16E+00	5.73E-01	4.65E-63	5.76E-05	3.74E+00	1.51E-02
RF-MT0007	1.34E-02	0.00E+00	0.00E+00	3.94E-01	7.13E-02	5.39E-64	0.00E+00	4.79E-01	1.93E-03
RF-MT0089	5.27E-05	0.00E+00	5.83E-14	3.16E-02	5.72E-03	4.65E-65	5.75E-07	3.74E-02	1.51E-04
RF-MT0090	1.34E-01	0.00E+00	8.25E-11	8.12E+01	1.46E+01	4.65E-62	8.14E-04	9.59E+01	3.87E-01
RF-MT0091	8.29E+00	0.00E+00	8.37E-09	5.43E+03	9.79E+02	3.84E-60	8.56E-02	6.41E+03	2.59E+01
RF-MT0092	1.19E+00	0.00E+00	1.06E-09	7.77E+02	1.43E+02	5.31E-61	1.04E-02	9.21E+02	3.71E+00
RF-MT0093	1.45E+00	0.00E+00	1.09E-09	8.39E+02	1.57E+02	4.52E-61	1.07E-02	9.97E+02	4.02E+00
RF-MT0097	7.23E-02	0.00E+00	4.80E-11	4.38E+01	7.12E+00	2.47E-62	4.73E-04	5.10E+01	2.06E-01
RF-MT0099	7.93E-05	0.00E+00	8.76E-14	4.74E-02	8.56E-03	6.99E-65	8.65E-07	5.60E-02	2.26E-04
RF-MT0290	1.97E-01	0.00E+00	2.17E-10	1.17E+02	2.12E+01	1.73E-61	2.14E-03	1.39E+02	5.59E-01
RF-MT-0292	2.48E-01	0.00E+00	2.74E-10	1.49E+02	2.68E+01	2.19E-61	2.70E-03	1.76E+02	7.08E-01
RF-MT-0299	2.92E+01	0.00E+00	7.02E-09	3.80E+03	6.89E+02	5.63E-60	6.93E-02	4.52E+03	1.82E+01
RF-MT0302	4.47E-04	0.00E+00	2.78E-13	1.64E-01	2.98E-02	2.19E-64	1.95E-05	1.94E-01	7.84E-04
RF-MT0320	5.34E-01	0.00E+00	2.88E-10	1.59E+02	2.89E+01	2.20E-61	2.86E-03	1.89E+02	7.62E-01
RF-MT0321	2.98E-01	0.00E+00	8.60E-11	5.13E+01	9.21E+00	6.17E-62	3.24E-03	6.08E+01	2.45E-01
RF-MT-0328	2.06E-02	0.00E+00	1.03E-11	5.58E+00	1.01E+00	8.23E-63	4.38E-04	6.61E+00	2.67E-02
RF-MT0330	2.15E-01	0.00E+00	1.13E-10	1.13E+02	2.20E+01	7.73E-62	1.12E-03	1.35E+02	5.44E-01
RF-MT-0331	1.29E+00	0.00E+00	7.02E-10	4.96E+02	8.77E+01	4.48E-61	2.75E-02	5.85E+02	2.36E+00
RF-MT0332	1.85E-04	0.00E+00	2.05E-13	1.11E-01	2.00E-02	1.63E-64	2.02E-06	1.31E-01	5.29E-04
RF-MT-0335	1.48E-02	0.00E+00	9.40E-12	5.71E+00	1.04E+00	6.66E-63	6.31E-04	6.76E+00	2.73E-02
RF-MT0336	1.05E+00	0.00E+00	6.23E-10	4.05E+02	7.32E+01	3.91E-61	7.95E-03	4.79E+02	1.93E+00
RF-MT0337	5.93E-01	0.00E+00	3.42E-10	2.47E+02	4.40E+01	1.91E-61	7.20E-03	2.92E+02	1.18E+00
RF-MT0339	1.62E+00	0.00E+00	9.32E-10	5.43E+02	9.72E+01	6.91E-61	2.61E-02	6.41E+02	2.59E+00
RF-MT-0342	9.53E-03	0.00E+00	7.81E-12	5.01E+00	8.92E-01	5.06E-63	1.35E-04	5.91E+00	2.39E-02
RF-MT0371	3.23E+00	0.00E+00	1.81E-09	9.81E+02	1.77E+02	1.44E-60	1.91E-02	1.16E+03	4.68E+00
RF-MT-0372	1.41E-02	0.00E+00	1.27E-11	6.84E+00	1.24E+00	8.92E-63	3.63E-04	8.09E+00	3.26E-02
RF-MT0373	2.12E-01	0.00E+00	1.31E-10	1.28E+02	2.31E+01	7.36E-62	1.29E-03	1.52E+02	6.11E-01
RF-MT0374	6.87E-03	0.00E+00	4.68E-12	2.54E+00	4.59E-01	3.73E-63	4.95E-05	3.00E+00	1.21E-02
RF-MT0376	5.45E-03	0.00E+00	3.78E-12	2.53E+00	4.65E-01	2.75E-63	5.23E-05	3.00E+00	1.21E-02
RF-MT0377	3.24E+00	0.00E+00	2.18E-09	1.18E+03	2.13E+02	1.74E-60	3.16E-02	1.40E+03	5.64E+00

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0378	3.64E-02	0.00E+00	3.01E-11	1.63E+01	2.95E+00	2.40E-62	2.97E-04	1.93E+01	7.78E-02
RF-MT0419	5.84E-02	0.00E+00	2.81E-11	1.52E+01	2.76E+00	2.25E-62	2.77E-04	1.80E+01	7.27E-02
RF-MT0420	1.02E-02	0.00E+00	4.88E-12	2.64E+00	4.79E-01	3.90E-63	4.81E-05	3.13E+00	1.26E-02
RF-MT0423	8.63E-02	0.00E+00	3.97E-11	3.81E+01	6.69E+00	1.55E-62	3.91E-04	4.49E+01	1.81E-01
RF-MT0425	2.54E-03	0.00E+00	1.22E-12	6.61E-01	1.20E-01	9.75E-64	1.21E-05	7.83E-01	3.16E-03
RF-MT-0438	2.30E-02	0.00E+00	1.60E-11	1.17E+01	2.10E+00	9.66E-63	1.71E-04	1.39E+01	5.59E-02
RF-MT0440	8.37E-03	0.00E+00	5.75E-12	4.25E+00	7.83E-01	3.98E-63	2.20E-04	5.04E+00	2.03E-02
RF-MT0442	3.18E-03	0.00E+00	2.49E-12	1.46E+00	2.63E-01	1.48E-63	1.19E-04	1.72E+00	6.95E-03
RF-MT0443	3.92E-02	0.00E+00	4.08E-11	2.26E+01	4.10E+00	3.08E-62	5.60E-04	2.68E+01	1.08E-01
RF-MT0444	3.06E-01	0.00E+00	2.00E-10	1.09E+02	1.97E+01	1.60E-61	2.00E-03	1.29E+02	5.20E-01
RF-MT0480	8.56E-01	0.00E+00	5.63E-10	3.06E+02	5.55E+01	4.11E-61	8.00E-03	3.62E+02	1.46E+00
RF-MT0488	1.37E+00	0.00E+00	8.41E-10	4.55E+02	8.19E+01	6.70E-61	3.90E-02	5.38E+02	2.17E+00
RF-MT0490	6.21E-03	0.00E+00	4.88E-12	2.69E+00	4.87E-01	3.70E-63	5.92E-05	3.18E+00	1.28E-02
RF-MT-0491	4.87E-04	0.00E+00	2.23E-13	1.22E-01	2.20E-02	1.73E-64	4.19E-06	1.44E-01	5.82E-04
RF-MT0523A	3.86E-01	0.00E+00	1.77E-10	9.62E+01	1.74E+01	1.41E-61	2.00E-03	1.14E+02	4.60E-01
RF-MT0523B	3.86E-01	0.00E+00	1.77E-10	9.62E+01	1.74E+01	1.41E-61	2.00E-03	1.14E+02	4.60E-01
RF-MT0523C	3.86E-01	0.00E+00	1.77E-10	9.62E+01	1.74E+01	1.41E-61	2.00E-03	1.14E+02	4.60E-01
RF-MT0523D	3.86E-01	0.00E+00	1.77E-10	9.62E+01	1.74E+01	1.41E-61	2.00E-03	1.14E+02	4.60E-01
RF-MT0523E	3.86E-01	0.00E+00	1.77E-10	9.62E+01	1.74E+01	1.41E-61	2.00E-03	1.14E+02	4.60E-01
RF-MT0531	2.64E-05	0.00E+00	2.92E-14	1.58E-02	2.86E-03	2.33E-65	2.88E-07	1.87E-02	7.52E-05
RF-MT0532E	1.23E+00	0.00E+00	3.79E-10	2.10E+02	3.79E+01	3.01E-61	4.84E-03	2.49E+02	1.00E+00
RF-MT0532F	1.23E+00	0.00E+00	3.79E-10	2.10E+02	3.79E+01	3.01E-61	4.84E-03	2.49E+02	1.00E+00
RF-MT0541	4.48E-02	0.00E+00	5.47E-12	2.98E+00	5.38E-01	4.40E-63	5.40E-05	3.56E+00	1.44E-02
RF-MT0545	2.40E-04	0.00E+00	2.65E-13	1.44E-01	2.60E-02	2.12E-64	2.62E-06	1.70E-01	6.86E-04
RF-MT0800	9.12E+00	0.00E+00	1.31E-10	7.10E+01	1.28E+01	1.05E-61	1.78E-03	9.30E+01	3.75E-01
RF-MT0801	1.05E+00	0.00E+00	1.29E-10	6.97E+01	1.26E+01	1.02E-61	1.27E-03	8.34E+01	3.36E-01
RF-MT0803	2.35E-02	0.00E+00	2.87E-12	1.56E+00	2.81E-01	2.30E-63	2.84E-05	1.86E+00	7.51E-03
RF-MT0806	1.11E-02	0.00E+00	6.90E-12	6.77E+00	1.21E+00	3.88E-63	6.81E-05	7.99E+00	3.22E-02
RF-MT0807	1.40E-01	0.00E+00	5.31E-11	2.88E+01	5.21E+00	4.24E-62	5.24E-04	3.41E+01	1.38E-01
RF-MT0816	1.50E-02	0.00E+00	7.49E-12	4.06E+00	7.32E-01	6.00E-63	7.40E-05	4.81E+00	1.94E-02
RF-MT-0823	7.44E-03	0.00E+00	3.41E-12	1.85E+00	3.35E-01	2.71E-63	3.85E-05	2.19E+00	8.85E-03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0827	3.79E-01	0.00E+00	1.90E-10	1.03E+02	1.86E+01	1.51E-61	1.87E-03	1.22E+02	4.90E-01
RF-MT0831	7.23E-01	0.00E+00	5.19E-10	2.78E+02	5.03E+01	3.99E-61	1.73E-02	3.29E+02	1.33E+00
RF-MT0832	4.32E+00	0.00E+00	1.88E-09	1.08E+03	1.95E+02	1.42E-60	5.17E-02	1.28E+03	5.16E+00
RF-MT0833	1.31E+00	0.00E+00	5.63E-10	3.13E+02	5.66E+01	4.28E-61	1.47E-02	3.70E+02	1.49E+00
RF-MT0855	2.26E-04	0.00E+00	2.50E-13	1.36E-01	2.45E-02	2.00E-64	2.47E-06	1.60E-01	6.47E-04
RF-MT0857	1.11E-02	0.00E+00	6.86E-12	6.75E+00	1.21E+00	3.87E-63	6.77E-05	7.98E+00	3.22E-02
RF-MT0H61	4.12E-01	0.00E+00	2.55E-10	2.50E+02	4.50E+01	1.44E-61	2.52E-03	2.96E+02	1.19E+00
RF-MT2116	4.63E-02	0.00E+00	2.02E-11	1.16E+01	2.09E+00	1.53E-62	5.54E-04	1.37E+01	5.52E-02
RF-MT3010	2.90E-01	0.00E+00	2.10E-10	1.15E+02	2.09E+01	1.64E-61	2.46E-03	1.36E+02	5.47E-01
RF-MT3011	2.16E+00	0.00E+00	1.31E-09	7.07E+02	1.28E+02	1.05E-60	2.06E-02	8.38E+02	3.38E+00
RF-MT420P	1.15E+01	0.00E+00	6.62E-09	5.82E+03	1.05E+03	3.41E-60	7.53E-02	6.88E+03	2.78E+01
RF-MT532A	3.03E+00	0.00E+00	9.36E-10	5.19E+02	9.35E+01	7.40E-61	1.19E-02	6.15E+02	2.48E+00
RF-MT532B	1.36E+01	0.00E+00	4.20E-09	2.33E+03	4.21E+02	3.33E-60	5.36E-02	2.76E+03	1.11E+01
RF-MT532C	2.73E+01	0.00E+00	8.45E-09	4.66E+03	8.41E+02	6.66E-60	1.08E-01	5.53E+03	2.23E+01
RF-MT532D	1.73E-01	0.00E+00	5.31E-11	2.95E+01	5.32E+00	4.20E-62	6.78E-04	3.50E+01	1.41E-01
RF-TT0069	9.92E-04	0.00E+00	6.30E-13	3.42E-01	6.19E-02	5.06E-64	7.91E-05	4.05E-01	1.63E-03
RF-TT0200	4.71E-02	0.00E+00	2.55E-11	1.40E+01	2.55E+00	1.94E-62	2.52E-04	1.66E+01	6.70E-02
RF-TT0299	1.95E-01	0.00E+00	4.72E-11	2.56E+01	4.63E+00	3.77E-62	4.66E-04	3.04E+01	1.23E-01
RF-TT0300	1.59E+00	0.00E+00	1.34E-09	7.34E+02	1.33E+02	9.17E-61	2.16E-02	8.69E+02	3.50E+00
RF-TT0301	2.15E-01	0.00E+00	1.82E-10	9.99E+01	1.81E+01	1.24E-61	2.93E-03	1.18E+02	4.77E-01
RF-TT0302	1.06E-02	0.00E+00	6.62E-12	3.90E+00	7.08E-01	5.22E-63	4.61E-04	4.62E+00	1.86E-02
RF-TT0303	6.40E-02	0.00E+00	3.87E-11	2.10E+01	3.79E+00	3.09E-62	1.41E-03	2.48E+01	1.00E-01
RF-TT0310	2.18E-01	0.00E+00	1.82E-10	9.44E+01	1.76E+01	1.13E-61	1.98E-03	1.12E+02	4.53E-01
RF-TT0312	5.23E+00	0.00E+00	3.28E-09	2.06E+03	3.70E+02	2.38E-60	3.41E-02	2.44E+03	9.83E+00
RF-TT0317	3.29E-03	0.00E+00	3.56E-12	1.93E+00	3.50E-01	2.85E-63	3.52E-05	2.29E+00	9.22E-03
RF-TT0320	2.11E+00	0.00E+00	1.14E-09	6.31E+02	1.15E+02	8.72E-61	1.13E-02	7.47E+02	3.01E+00
RF-TT0330	7.52E-01	0.00E+00	3.95E-10	3.96E+02	7.69E+01	2.71E-61	3.90E-03	4.74E+02	1.91E+00
RF-TT-0331	3.74E+00	0.00E+00	2.04E-09	1.44E+03	2.55E+02	1.30E-60	7.99E-02	1.70E+03	6.85E+00
RF-TT-0334	1.63E+00	0.00E+00	1.65E-09	8.94E+02	1.62E+02	1.32E-60	1.63E-02	1.06E+03	4.27E+00
RF-TT0335	1.98E+00	0.00E+00	1.25E-09	7.61E+02	1.39E+02	8.88E-61	8.40E-02	9.01E+02	3.63E+00
RF-TT0336	1.75E+00	0.00E+00	1.04E-09	6.74E+02	1.22E+02	6.50E-61	1.33E-02	7.97E+02	3.21E+00

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0337	2.08E+00	0.00E+00	1.20E-09	8.70E+02	1.54E+02	6.70E-61	2.53E-02	1.03E+03	4.14E+00
RF-TT0338	8.83E+00	0.00E+00	4.36E-09	3.39E+03	6.03E+02	2.99E-60	5.13E-02	4.00E+03	1.61E+01
RF-TT0340	7.55E-02	0.00E+00	8.33E-11	4.51E+01	8.19E+00	6.66E-62	8.22E-04	5.34E+01	2.15E-01
RF-TT0342	5.05E-01	0.00E+00	4.16E-10	2.66E+02	4.72E+01	2.68E-61	7.19E-03	3.14E+02	1.26E+00
RF-TT0360	3.85E-02	0.00E+00	2.11E-11	1.19E+01	2.18E+00	1.58E-62	2.15E-04	1.41E+01	5.70E-02
RF-TT0368	7.70E-01	0.00E+00	4.24E-10	2.39E+02	4.37E+01	3.17E-61	4.31E-03	2.84E+02	1.14E+00
RF-TT0370	1.52E+00	0.00E+00	9.16E-10	5.32E+02	9.64E+01	6.74E-61	1.68E-02	6.30E+02	2.54E+00
RF-TT0371	3.29E-02	0.00E+00	1.84E-11	9.99E+00	1.81E+00	1.47E-62	1.95E-04	1.18E+01	4.77E-02
RF-TT0372	4.02E-03	0.00E+00	3.63E-12	1.95E+00	3.54E-01	2.55E-63	1.04E-04	2.31E+00	9.31E-03
RF-TT0374	1.25E-01	0.00E+00	8.52E-11	4.61E+01	8.34E+00	6.79E-62	9.01E-04	5.46E+01	2.20E-01
RF-TT0375A	1.30E-03	0.00E+00	1.40E-12	7.58E-01	1.37E-01	1.12E-63	1.39E-05	8.96E-01	3.61E-03
RF-TT0375B	1.30E-03	0.00E+00	1.40E-12	7.58E-01	1.37E-01	1.12E-63	1.39E-05	8.96E-01	3.61E-03
RF-TT0376	3.00E-01	0.00E+00	2.08E-10	1.39E+02	2.55E+01	1.51E-61	2.88E-03	1.65E+02	6.66E-01
RF-TT0377	1.68E-01	0.00E+00	1.13E-10	6.12E+01	1.11E+01	9.01E-62	1.64E-03	7.25E+01	2.92E-01
RF-TT0391	3.75E-02	0.00E+00	1.59E-11	1.55E+01	2.76E+00	1.58E-62	1.57E-04	1.83E+01	7.37E-02
RF-TT0392	1.32E-02	0.00E+00	9.99E-12	8.09E+00	1.46E+00	5.47E-63	9.88E-05	9.56E+00	3.86E-02
RF-TT0393	1.09E+00	0.00E+00	6.98E-10	3.77E+02	6.82E+01	5.55E-61	6.89E-03	4.46E+02	1.80E+00
RF-TT0398	2.37E-02	0.00E+00	1.84E-11	1.51E+01	2.71E+00	1.03E-62	1.82E-04	1.79E+01	7.20E-02
RF-TT0409	1.98E-02	0.00E+00	8.60E-12	7.81E+00	1.40E+00	3.97E-63	8.55E-05	9.23E+00	3.72E-02
RF-TT0412	1.98E-02	0.00E+00	8.60E-12	7.81E+00	1.40E+00	3.97E-63	8.55E-05	9.23E+00	3.72E-02
RF-TT0414	6.14E-01	0.00E+00	2.66E-10	2.42E+02	4.33E+01	1.23E-61	2.65E-03	2.86E+02	1.15E+00
RF-TT0430	1.80E-04	0.00E+00	1.99E-13	1.07E-01	1.94E-02	1.58E-64	1.96E-06	1.27E-01	5.11E-04
RF-TT0431	4.47E-02	0.00E+00	4.84E-11	2.64E+01	4.78E+00	3.76E-62	6.98E-04	3.12E+01	1.26E-01
RF-TT0438	2.66E+00	0.00E+00	1.84E-09	1.35E+03	2.42E+02	1.11E-60	1.97E-02	1.59E+03	6.42E+00
RF-TT0440	2.62E-01	0.00E+00	1.79E-10	1.33E+02	2.46E+01	1.25E-61	6.89E-03	1.58E+02	6.36E-01
RF-TT0441	1.29E+00	0.00E+00	8.41E-10	4.59E+02	8.34E+01	6.62E-61	1.29E-02	5.44E+02	2.19E+00
RF-TT0442	1.86E-01	0.00E+00	1.45E-10	8.50E+01	1.54E+01	8.64E-62	6.91E-03	1.01E+02	4.05E-01
RF-TT0443	3.98E-03	0.00E+00	4.16E-12	2.30E+00	4.16E-01	3.13E-63	5.70E-05	2.72E+00	1.10E-02
RF-TT0479	3.90E-02	0.00E+00	4.32E-11	2.33E+01	4.22E+00	3.44E-62	4.26E-04	2.75E+01	1.11E-01
RF-TT0480	2.65E+00	0.00E+00	1.74E-09	9.53E+02	1.72E+02	1.28E-60	2.48E-02	1.13E+03	4.55E+00
RF-TT0481	1.50E-03	0.00E+00	9.83E-13	5.35E-01	9.72E-02	7.20E-64	1.40E-05	6.34E-01	2.56E-03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0483	4.80E-03	0.00E+00	5.31E-12	2.87E+00	5.20E-01	4.24E-63	1.71E-02	3.41E+00	1.38E-02
RF-TT0484	2.57E-02	0.00E+00	2.20E-11	1.19E+01	2.16E+00	1.76E-62	3.27E-04	1.41E+01	5.69E-02
RF-TT0485	2.11E-03	0.00E+00	1.36E-12	7.35E-01	1.33E-01	1.09E-63	2.89E-04	8.71E-01	3.51E-03
RF-TT0486	1.25E-02	0.00E+00	8.05E-12	4.36E+00	7.90E-01	6.42E-63	3.05E-04	5.17E+00	2.08E-02
RF-TT0487	6.28E-02	0.00E+00	2.74E-11	1.57E+01	2.83E+00	2.07E-62	7.50E-04	1.86E+01	7.48E-02
RF-TT0489	1.79E-02	0.00E+00	1.23E-11	6.65E+00	1.20E+00	9.83E-63	2.21E-04	7.88E+00	3.18E-02
RF-TT0490	9.89E-01	0.00E+00	7.81E-10	4.29E+02	7.76E+01	5.88E-61	9.48E-03	5.07E+02	2.05E+00
RF-TT0491	2.30E-02	0.00E+00	1.06E-11	5.75E+00	1.04E+00	8.18E-63	1.99E-04	6.81E+00	2.74E-02
RF-TT0492	7.73E-03	0.00E+00	5.95E-12	3.21E+00	5.82E-01	4.73E-63	5.87E-05	3.80E+00	1.53E-02
RF-TT0523A	5.20E-02	0.00E+00	2.39E-11	1.29E+01	2.34E+00	1.90E-62	2.70E-04	1.53E+01	6.18E-02
RF-TT0523B	5.20E-02	0.00E+00	2.39E-11	1.29E+01	2.34E+00	1.90E-62	2.70E-04	1.53E+01	6.18E-02
RF-TT0523C	5.20E-02	0.00E+00	2.39E-11	1.29E+01	2.34E+00	1.90E-62	2.70E-04	1.53E+01	6.18E-02
RF-TT0523D	5.20E-02	0.00E+00	2.39E-11	1.29E+01	2.34E+00	1.90E-62	2.70E-04	1.53E+01	6.18E-02
RF-TT0523E	5.20E-02	0.00E+00	2.39E-11	1.29E+01	2.34E+00	1.90E-62	2.70E-04	1.53E+01	6.18E-02
RF-TT0532A	1.30E+00	0.00E+00	4.00E-10	2.23E+02	4.02E+01	3.18E-61	5.11E-03	2.64E+02	1.07E+00
RF-TT0532B	1.30E+00	0.00E+00	4.00E-10	2.23E+02	4.02E+01	3.18E-61	5.11E-03	2.64E+02	1.07E+00
RF-TT0541	2.15E-03	0.00E+00	2.38E-12	1.29E+00	2.34E-01	1.90E-63	2.35E-05	1.53E+00	6.16E-03
RF-TT0545	4.80E-04	0.00E+00	5.31E-13	2.87E-01	5.20E-02	4.24E-64	5.24E-06	3.39E-01	1.37E-03
RF-TT0601	1.67E-01	0.00E+00	9.16E-11	5.18E+01	9.50E+00	6.87E-62	9.31E-04	6.14E+01	2.48E-01
RF-TT0802	1.87E+01	0.00E+00	7.53E-09	4.09E+03	7.40E+02	6.00E-60	7.43E-02	4.85E+03	1.95E+01
RF-TT0809	1.53E+00	0.00E+00	6.19E-10	3.36E+02	6.06E+01	4.94E-61	6.11E-03	3.99E+02	1.61E+00
RF-TT0821	3.32E+00	0.00E+00	2.25E-09	1.32E+03	2.39E+02	1.47E-60	1.89E-01	1.56E+03	6.30E+00
RF-TT0822	3.67E+00	0.00E+00	1.75E-09	9.90E+02	1.78E+02	1.31E-60	1.98E-01	1.17E+03	4.73E+00
RF-TT0823	7.44E-03	0.00E+00	3.41E-12	1.85E+00	3.35E-01	2.71E-63	3.85E-05	2.19E+00	8.85E-03
RF-TT0824	7.66E+00	0.00E+00	4.80E-09	2.67E+03	4.82E+02	3.70E-60	1.09E-01	3.16E+03	1.27E+01
RF-TT0825	6.35E+00	0.00E+00	3.47E-09	2.01E+03	3.63E+02	2.45E-60	1.15E-01	2.38E+03	9.58E+00
RF-TT0832	4.70E+00	0.00E+00	2.05E-09	1.17E+03	2.12E+02	1.55E-60	5.63E-02	1.39E+03	5.61E+00
RF-TT0854	1.69E-03	0.00E+00	1.87E-12	1.01E+00	1.83E-01	1.49E-63	7.59E-04	1.19E+00	4.81E-03
RF-TT0886	2.40E-04	0.00E+00	2.64E-13	1.43E-01	2.60E-02	2.11E-64	2.61E-06	1.69E-01	6.82E-04
RF-TT2216	6.94E-02	0.00E+00	3.03E-11	1.74E+01	3.13E+00	2.29E-62	8.32E-04	2.06E+01	8.31E-02
RF-TT3010	3.71E+00	0.00E+00	2.68E-09	1.47E+03	2.66E+02	2.09E-60	3.15E-02	1.74E+03	7.00E+00

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT3011	9.37E+00	0.00E+00	5.67E-09	3.06E+03	5.55E+02	4.52E-60	8.94E-02	3.63E+03	1.46E+01
RF-TT301U	7.78E-01	0.00E+00	5.99E-10	3.33E+02	6.12E+01	4.44E-61	6.07E-03	3.95E+02	1.59E+00
RF-TT310P	2.25E-01	0.00E+00	1.56E-10	1.12E+02	1.92E+01	9.29E-62	1.54E-03	1.31E+02	5.29E-01
RF-TT338S	6.57E-03	0.00E+00	7.14E-12	3.86E+00	6.99E-01	5.68E-63	7.04E-05	4.56E+00	1.84E-02
RF-TT390P	3.70E-02	0.00E+00	1.94E-11	1.88E+01	3.13E+00	1.42E-62	2.20E-04	2.20E+01	8.85E-02
RF-TT391P	2.04E+00	0.00E+00	8.68E-10	8.44E+02	1.50E+02	8.60E-61	8.57E-03	9.96E+02	4.02E+00
RF-TT392P	4.13E+00	0.00E+00	3.13E-09	2.53E+03	4.56E+02	1.71E-60	3.09E-02	2.99E+03	1.21E+01
RF-TT393R	6.11E-01	0.00E+00	5.31E-10	3.87E+02	7.02E+01	2.76E-61	5.42E-03	4.58E+02	1.85E+00
RF-TT394P	7.58E-02	0.00E+00	3.29E-11	2.99E+01	5.01E+00	1.99E-62	3.31E-04	3.50E+01	1.41E-01
RF-TT395P	1.02E-01	0.00E+00	4.40E-11	4.00E+01	6.69E+00	2.66E-62	4.44E-04	4.68E+01	1.89E-01
RF-TT396P	2.53E-02	0.00E+00	1.10E-11	9.99E+00	1.68E+00	6.62E-63	1.11E-04	1.17E+01	4.71E-02
RF-TT398P	2.45E+00	0.00E+00	1.90E-09	1.57E+03	2.81E+02	1.07E-60	1.88E-02	1.85E+03	7.46E+00
RF-TT398R	2.02E+01	0.00E+00	3.54E-09	2.53E+03	4.54E+02	2.08E-60	3.49E-02	3.00E+03	1.21E+01
RF-TT411R	7.33E-01	0.00E+00	3.18E-10	2.89E+02	5.17E+01	1.47E-61	3.16E-03	3.41E+02	1.38E+00
RF-TT429R	1.54E+00	0.00E+00	6.82E-11	6.69E+01	1.18E+01	2.56E-62	6.73E-04	8.02E+01	3.23E-01
RF-TT433X	4.85E-01	0.00E+00	1.89E-11	1.92E+01	3.05E+00	1.02E-62	1.86E-04	2.28E+01	9.19E-02
RF-TT436R	3.55E+00	0.00E+00	2.73E-10	2.52E+02	4.50E+01	1.96E-61	2.70E-03	3.01E+02	1.21E+00
RF-TT454X	2.09E-01	0.00E+00	1.61E-11	1.49E+01	2.65E+00	1.16E-62	1.59E-04	1.77E+01	7.14E-02
RL-T101	1.06E+00	0.00E+00	9.75E-10	8.02E+02	1.42E+02	1.63E-60	8.76E-03	9.45E+02	3.81E+00
RL-T102	1.34E-05	0.00E+00	1.24E-14	1.03E-02	1.81E-03	2.07E-65	1.25E-06	1.21E-02	4.88E-05
RL-T103	9.51E-01	0.00E+00	1.18E-09	3.50E+02	6.16E+01	8.68E-61	1.06E-02	4.13E+02	1.66E+00
RL-T104	1.92E-05	0.00E+00	1.77E-14	1.46E-02	2.60E-03	2.97E-65	1.91E-07	1.72E-02	6.93E-05
RL-T105	7.38E-03	0.00E+00	6.70E-12	5.54E+00	9.79E-01	1.12E-62	1.05E-04	6.52E+00	2.63E-02
RL-T106	7.12E-03	0.00E+00	6.58E-12	5.41E+00	9.57E-01	1.10E-62	5.91E-05	6.37E+00	2.57E-02
RL-T107	1.96E+01	0.00E+00	3.87E-06	1.49E+04	2.64E+03	3.01E-59	3.55E+01	1.76E+04	7.11E+01
RL-T108	1.12E-02	0.00E+00	6.66E-10	8.50E+00	1.51E+00	1.73E-62	6.01E-03	1.00E+01	4.04E-02
RL-T109	1.54E-02	0.00E+00	1.37E-11	1.13E+01	2.00E+00	2.29E-62	2.32E-02	1.33E+01	5.37E-02
RL-T110	1.73E+00	0.00E+00	2.62E-09	1.29E+03	2.30E+02	2.63E-60	1.37E+00	1.53E+03	6.15E+00
RL-T112	6.96E-01	0.00E+00	1.11E-09	1.71E+02	3.04E+01	3.48E-61	7.40E-01	2.03E+02	8.19E-01
RL-T113	7.44E-04	0.00E+00	2.14E-12	5.65E-01	1.00E-01	1.15E-63	1.92E-05	6.65E-01	2.68E-03
RL-T114	1.13E-01	0.00E+00	1.04E-10	8.58E+01	1.52E+01	1.74E-61	9.36E-04	1.01E+02	4.08E-01

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T115	2.88E+00	0.00E+00	3.38E-09	1.13E+03	2.00E+02	2.57E-60	4.40E-01	1.33E+03	5.37E+00
RL-T116	1.86E-01	0.00E+00	1.71E-10	1.40E+02	2.49E+01	2.86E-61	5.73E-02	1.65E+02	6.67E-01
RL-T118	4.77E-01	0.00E+00	1.37E-09	1.39E+02	2.47E+01	2.83E-61	8.38E-01	1.65E+02	6.67E-01
RL-T120	1.16E-01	0.00E+00	1.44E-10	4.12E+01	7.25E+00	9.95E-62	1.29E-03	4.86E+01	1.96E-01
RL-T122	6.56E-03	0.00E+00	6.07E-12	4.97E+00	8.85E-01	1.01E-62	1.45E+00	7.31E+00	2.95E-02
RL-T123	1.93E-02	0.00E+00	1.78E-11	1.46E+01	2.60E+00	2.98E-62	5.94E-02	1.72E+01	6.95E-02
RL-T125	3.84E+00	0.00E+00	4.40E-09	3.05E+02	1.25E+02	4.65E-60	3.95E-02	4.34E+02	1.75E+00
RL-T127	3.70E+00	0.00E+00	1.11E-09	9.12E+02	1.62E+02	1.85E-60	8.93E-02	1.08E+03	4.34E+00
RL-T128	5.48E-03	0.00E+00	2.69E-17	2.22E-05	3.92E-06	4.48E-68	2.41E-10	5.50E-03	2.22E-05
RL-T129	1.64E-02	0.00E+00	5.11E-09	1.26E+01	2.21E+00	2.53E-62	5.35E-02	1.48E+01	5.98E-02
RL-T130	3.49E-05	0.00E+00	3.23E-14	2.67E-02	4.72E-03	5.39E-65	8.26E-05	3.15E-02	1.27E-04
RL-T131	1.42E-02	0.00E+00	1.76E-11	5.08E+00	8.92E-01	1.22E-62	8.32E-03	5.99E+00	2.42E-02
RL-T132	3.39E+00	0.00E+00	3.12E-09	2.58E+03	4.56E+02	5.22E-60	2.71E-01	3.04E+03	1.22E+01
RL-T133	6.89E-05	0.00E+00	5.00E-14	4.22E-02	7.47E-03	7.40E-65	4.49E-07	4.98E-02	2.01E-04
RL-T134	1.46E-04	0.00E+00	1.34E-13	1.11E-01	1.96E-02	2.25E-64	1.21E-06	1.31E-01	5.27E-04
RL-T135	6.82E-04	0.00E+00	6.30E-13	5.19E-01	9.21E-02	1.05E-63	4.12E-03	6.16E-01	2.48E-03
RL-T137	1.11E+01	0.00E+00	1.38E-08	3.95E+03	6.96E+02	9.58E-60	1.30E-01	4.66E+03	1.88E+01
RL-T140	1.30E+01	0.00E+00	1.31E-08	3.82E+03	7.47E+02	8.14E-60	2.61E+01	4.61E+03	1.86E+01
RL-T143	8.13E-02	0.00E+00	7.49E-11	6.18E+01	1.10E+01	1.25E-61	3.89E-02	7.28E+01	2.94E-01
RL-T145	2.31E-01	0.00E+00	2.14E-10	1.76E+02	3.11E+01	3.57E-61	9.08E-02	2.07E+02	8.36E-01
RL-W407	6.65E-01	0.00E+00	4.56E-10	4.03E+02	7.15E+01	5.43E-61	4.09E-03	4.75E+02	1.92E+00
RL-W408	2.73E-06	0.00E+00	1.93E-15	1.63E-03	2.89E-04	2.80E-66	1.73E-08	1.92E-03	7.76E-06
RL-W415	6.02E-05	0.00E+00	4.24E-14	3.61E-02	6.40E-03	6.17E-65	3.81E-07	4.26E-02	1.72E-04
RL-W418	2.58E-04	0.00E+00	1.79E-13	1.55E-01	2.75E-02	2.30E-64	1.61E-06	1.83E-01	7.36E-04
RL-W437	2.18E+00	0.00E+00	1.50E-09	1.32E+03	2.34E+02	1.78E-60	1.35E-02	1.56E+03	6.27E+00
RL-W438	3.82E-06	0.00E+00	2.69E-15	2.28E-03	4.04E-04	3.91E-66	2.42E-08	2.69E-03	1.08E-05
RL-W439	1.20E+02	0.00E+00	1.48E-07	4.40E+04	7.76E+03	1.09E-58	1.33E+00	5.19E+04	2.09E+02
RL-W443	1.92E+00	0.00E+00	1.32E-09	1.16E+03	2.06E+02	1.57E-60	1.19E-02	1.37E+03	5.53E+00
RL-W444	1.42E+00	0.00E+00	9.79E-10	8.63E+02	1.53E+02	1.16E-60	8.79E-03	1.02E+03	4.10E+00
RL-W447	1.63E-04	0.00E+00	1.15E-13	9.71E-02	1.73E-02	1.67E-64	1.04E-06	1.15E-01	4.62E-04
RL-W448	1.21E-06	0.00E+00	8.52E-16	7.21E-04	1.28E-04	1.24E-66	7.65E-09	8.50E-04	3.43E-06

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W449	9.91E-03	0.00E+00	3.12E-14	2.06E-02	3.65E-03	2.25E-65	2.80E-07	3.42E-02	1.38E-04
RL-W450	1.82E-05	0.00E+00	1.29E-14	1.09E-02	1.93E-03	1.87E-65	1.15E-07	1.29E-02	5.18E-05
RL-W451	2.60E-06	0.00E+00	1.83E-15	1.55E-03	2.75E-04	2.66E-66	1.64E-08	1.83E-03	7.36E-06
RL-W452	1.13E-04	0.00E+00	7.89E-14	6.83E-02	1.21E-02	1.01E-64	7.08E-07	8.05E-02	3.25E-04
RL-W453	3.22E-05	0.00E+00	2.22E-14	1.96E-02	3.47E-03	2.64E-65	1.99E-07	2.31E-02	9.32E-05
RL-W454	4.51E-04	0.00E+00	3.10E-13	2.74E-01	4.85E-02	3.69E-64	2.79E-06	3.23E-01	1.30E-03
RL-W455	1.20E-04	0.00E+00	8.37E-14	7.25E-02	1.28E-02	1.08E-64	7.51E-07	8.54E-02	3.45E-04
RL-W456	1.59E-02	0.00E+00	1.09E-11	9.62E+00	1.70E+00	1.33E-62	9.82E-05	1.13E+01	4.57E-02
RL-W457	1.54E-03	0.00E+00	1.06E-12	9.35E-01	1.65E-01	1.29E-63	9.54E-06	1.10E+00	4.44E-03
RL-W458	4.87E-03	0.00E+00	5.43E-12	3.84E-01	1.70E-01	5.18E-63	4.88E-05	5.59E-01	2.25E-03
RL-W459	4.69E-02	0.00E+00	5.59E-11	9.53E+00	2.31E+00	5.14E-62	5.02E-04	1.19E+01	4.80E-02
RL-W460	2.86E-04	0.00E+00	1.97E-13	1.73E-01	3.07E-02	2.34E-64	1.77E-06	2.04E-01	8.24E-04
RL-W461	2.64E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.64E-04	1.06E-06
RL-W462	8.15E-05	0.00E+00	5.71E-14	4.90E-02	8.70E-03	7.65E-65	5.13E-07	5.78E-02	2.33E-04
RL-W463	4.19E-04	0.00E+00	2.89E-13	2.55E-01	4.51E-02	3.43E-64	2.59E-06	3.00E-01	1.21E-03
RL-W464	1.94E-04	0.00E+00	1.33E-13	1.17E-01	2.07E-02	1.58E-64	1.19E-06	1.38E-01	5.57E-04
RL-W465	1.29E-03	0.00E+00	9.00E-13	7.81E-01	1.39E-01	1.14E-63	8.08E-06	9.21E-01	3.71E-03
RL-W466	1.77E-02	0.00E+00	1.23E-11	1.07E+01	1.90E+00	1.52E-62	1.10E-04	1.26E+01	5.10E-02
RL-W467	9.06E-04	0.00E+00	6.30E-13	5.46E-01	9.64E-02	8.35E-64	5.66E-06	6.44E-01	2.60E-03
RL-W468	4.64E-06	0.00E+00	3.25E-15	2.80E-03	4.95E-04	4.36E-66	2.92E-08	3.30E-03	1.33E-05
RL-W469	1.88E-03	0.00E+00	1.30E-12	1.14E+00	2.02E-01	1.60E-63	1.17E-05	1.34E+00	5.41E-03
RL-W470	5.33E-02	0.00E+00	6.07E-11	4.22E+00	1.73E+00	6.46E-62	5.45E-04	6.00E+00	2.42E-02
RL-W474	2.02E-03	0.00E+00	6.70E-12	9.62E-03	6.53E-03	0.00E+00	6.02E-05	1.82E-02	7.35E-05
RL-W476	3.40E-03	0.00E+00	2.41E-12	2.11E+00	3.75E-01	2.91E-63	2.16E-05	2.49E+00	1.00E-02
RL-W480	5.55E-04	0.00E+00	3.86E-13	3.35E-01	5.94E-02	4.98E-64	3.47E-06	3.94E-01	1.59E-03
RL-W481	8.72E-04	0.00E+00	6.07E-13	5.25E-01	9.28E-02	7.81E-64	5.45E-06	6.19E-01	2.50E-03
RL-W482	1.16E+00	0.00E+00	2.02E-10	6.68E-02	9.86E-02	1.04E-60	1.81E-03	1.33E+00	5.34E-03
RL-W483	8.65E-02	0.00E+00	1.57E-11	4.33E-03	7.00E-03	7.73E-62	1.41E-04	9.79E-02	3.95E-04
RL-W484	3.66E-04	0.00E+00	1.26E-13	6.04E-02	1.15E-02	6.42E-65	1.13E-06	7.22E-02	2.91E-04
RL-W485	2.14E-05	0.00E+00	1.78E-14	6.53E-03	1.24E-03	0.00E+00	1.60E-07	7.80E-03	3.14E-05
RL-W486	9.05E-06	0.00E+00	7.53E-15	2.76E-03	5.21E-04	0.00E+00	6.76E-08	3.29E-03	1.33E-05

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W487	1.48E-03	0.00E+00	9.67E-13	3.95E-01	8.63E-02	5.96E-64	8.68E-06	4.83E-01	1.95E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	8.98E-04	0.00E+00	9.12E-13	5.11E-01	9.21E-02	9.62E-64	8.19E-06	6.04E-01	2.44E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	3.33E-04	0.00E+00	7.69E-13	5.36E-02	9.35E-03	3.50E-64	6.91E-06	6.33E-02	2.55E-04
RL-W492	1.92E-05	0.00E+00	1.90E-14	1.07E-02	1.92E-03	2.01E-65	1.70E-07	1.27E-02	5.11E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	7.62E-01	0.00E+00	1.10E-09	2.70E-01	1.83E-01	8.06E-61	9.86E-03	1.23E+00	4.94E-03
RL-W495	1.38E-02	0.00E+00	2.99E-12	2.59E-03	1.64E-03	1.47E-62	2.68E-05	1.81E-02	7.28E-05
RL-W496	8.96E-02	0.00E+00	3.44E-11	8.52E-03	5.43E-03	9.50E-62	3.09E-04	1.04E-01	4.19E-04
RL-W497	3.73E-03	0.00E+00	6.78E-12	5.11E-01	1.84E-01	2.49E-63	6.09E-05	6.99E-01	2.82E-03
RL-W498	1.45E-02	0.00E+00	1.01E-11	8.74E+00	1.55E+00	1.30E-62	9.04E-05	1.03E+01	4.16E-02
RL-W499	1.30E-07	0.00E+00	9.04E-17	7.84E-05	1.39E-05	1.16E-67	8.12E-10	9.24E-05	3.73E-07
RL-W500	9.26E-06	0.00E+00	1.12E-14	3.20E-03	5.64E-04	8.18E-66	1.01E-07	3.77E-03	1.52E-05
RL-W501	3.83E-01	0.00E+00	2.50E-10	1.03E+02	2.23E+01	1.55E-61	2.25E-03	1.25E+02	5.06E-01
RL-W502	6.93E-05	0.00E+00	4.84E-14	4.18E-02	7.40E-03	6.21E-65	4.34E-07	4.93E-02	1.99E-04
RL-W503	4.01E-03	0.00E+00	4.96E-12	1.48E+00	2.60E-01	3.65E-63	4.45E-05	1.74E+00	7.01E-03
RL-W504	1.48E-03	0.00E+00	9.67E-13	3.95E-01	8.63E-02	5.96E-64	8.68E-06	4.83E-01	1.95E-03
RL-W505	6.96E-05	0.00E+00	5.08E-14	4.27E-02	7.54E-03	7.48E-65	4.56E-07	5.03E-02	2.03E-04
RL-W506	2.52E-05	0.00E+00	1.99E-14	1.40E-02	2.49E-03	2.24E-65	1.79E-07	1.65E-02	6.67E-05
RL-W507	2.51E-06	0.00E+00	1.74E-15	1.51E-03	2.68E-04	2.25E-66	1.57E-08	1.78E-03	7.19E-06
RL-W508	4.61E-02	0.00E+00	5.71E-11	1.64E+01	2.89E+00	3.98E-62	5.13E-04	1.93E+01	7.80E-02
RL-W509	4.53E-01	0.00E+00	4.56E-10	1.34E+02	2.60E+01	2.85E-61	4.09E-03	1.60E+02	6.46E-01
RL-W510	3.83E-02	0.00E+00	4.68E-11	1.33E+01	2.34E+00	3.40E-62	4.20E-04	1.57E+01	6.32E-02
RL-W511	3.89E+00	0.00E+00	2.26E-09	1.78E+03	3.09E+02	1.85E-60	2.06E-02	2.09E+03	8.43E+00
RL-W512	3.41E+00	0.00E+00	1.52E-09	1.07E+03	2.12E+02	9.46E-61	1.37E-02	1.29E+03	5.19E+00
RL-W513	3.63E+02	0.00E+00	6.19E-07	1.75E+04	6.90E+03	1.50E-58	5.55E+00	2.48E+04	9.99E+01
RL-W514	1.03E-05	0.00E+00	7.10E-15	6.20E-03	1.10E-03	8.76E-66	6.37E-08	7.32E-03	2.95E-05
RL-W515	4.01E-04	0.00E+00	2.78E-13	2.42E-01	4.28E-02	3.58E-64	2.50E-06	2.85E-01	1.15E-03
RL-W516	5.56E-04	0.00E+00	3.87E-13	3.35E-01	5.94E-02	4.98E-64	3.47E-06	3.94E-01	1.59E-03
RL-W517	4.95E-12	0.00E+00	3.46E-21	2.98E-09	5.27E-10	4.65E-72	3.10E-14	3.51E-09	1.42E-11

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W518	1.40E-02	0.00E+00	1.46E-11	4.27E+00	8.19E-01	9.99E-63	1.31E-04	5.10E+00	2.06E-02
RL-W519	2.50E-03	0.00E+00	1.73E-12	1.51E+00	2.68E-01	2.11E-63	1.55E-05	1.78E+00	7.19E-03
RL-W520	2.76E-04	0.00E+00	1.94E-13	1.66E-01	2.94E-02	2.71E-64	1.74E-06	1.96E-01	7.88E-04
RL-W521	5.14E-06	0.00E+00	3.56E-15	3.09E-03	5.48E-04	4.61E-66	3.20E-08	3.64E-03	1.47E-05
RL-W522	1.07E-01	0.00E+00	1.32E-10	2.04E+01	4.65E+00	6.66E-62	1.19E-03	2.52E+01	1.02E-01
RL-W523	3.22E-02	0.00E+00	5.04E-11	1.36E+00	6.55E-01	1.32E-62	4.52E-04	2.04E+00	8.24E-03
RL-W524	1.34E-01	0.00E+00	1.93E-10	1.25E+01	3.84E+00	6.29E-62	1.73E-03	1.64E+01	6.63E-02
RL-W525	1.06E-02	0.00E+00	1.30E-11	1.48E+00	3.88E-01	4.94E-63	1.17E-04	1.87E+00	7.56E-03
RL-W526	4.02E-02	0.00E+00	4.72E-11	1.58E+01	2.80E+00	3.59E-62	4.24E-04	1.86E+01	7.50E-02
RL-W527	4.40E-03	0.00E+00	6.82E-12	1.67E+00	3.15E-01	4.20E-63	6.12E-05	1.99E+00	8.01E-03
RL-W528	1.97E+00	0.00E+00	2.90E-09	5.32E+01	4.05E+01	6.42E-61	2.60E-02	9.56E+01	3.86E-01
RL-W529	1.64E-03	0.00E+00	2.04E-12	5.87E-01	1.03E-01	1.42E-63	1.83E-05	6.91E-01	2.79E-03
RL-W530	1.93E-02	0.00E+00	2.36E-11	6.70E+00	1.18E+00	1.72E-62	2.12E-04	7.90E+00	3.19E-02
RL-W531	1.15E+00	0.00E+00	2.37E-09	2.90E+01	1.66E+01	4.57E-61	2.13E-02	4.67E+01	1.89E-01
RL-W532	3.70E-03	0.00E+00	2.58E-12	2.24E+00	3.96E-01	3.32E-63	2.31E-05	2.64E+00	1.06E-02
RL-W533	1.79E-03	0.00E+00	2.22E-12	6.40E-01	1.12E-01	1.53E-63	2.00E-05	7.54E-01	3.04E-03
RL-W534	1.03E-07	0.00E+00	7.18E-17	6.24E-05	1.11E-05	9.25E-68	6.44E-10	7.36E-05	2.97E-07
RL-W535	5.42E-01	0.00E+00	7.10E-10	8.00E+01	1.94E+01	2.82E-61	6.37E-03	1.00E+02	4.03E-01
RL-W536	1.06E-02	0.00E+00	9.56E-12	2.78E+00	5.00E-01	6.46E-63	8.90E-05	3.29E+00	1.33E-02
RL-W537	3.61E-01	0.00E+00	2.16E-10	1.70E+02	2.97E+01	1.81E-61	1.96E-03	2.01E+02	8.09E-01
RL-W538	1.31E-06	0.00E+00	9.12E-16	7.93E-04	1.41E-04	1.18E-66	8.19E-09	9.35E-04	3.77E-06
RL-W539	1.46E-04	0.00E+00	1.03E-13	8.76E-02	1.55E-02	1.43E-64	9.22E-07	1.03E-01	4.16E-04
RL-W540	2.84E-01	0.00E+00	4.52E-10	3.15E+01	8.63E+00	1.37E-61	4.06E-03	4.04E+01	1.63E-01
RL-W541	4.22E-04	0.00E+00	2.96E-13	2.54E-01	4.50E-02	4.03E-64	2.66E-06	2.99E-01	1.21E-03
RL-W542	1.96E-02	0.00E+00	2.20E-11	6.42E+00	1.18E+00	1.65E-62	1.98E-04	7.63E+00	3.08E-02
RL-W543	6.17E-05	0.00E+00	4.28E-14	3.72E-02	6.60E-03	5.55E-65	3.84E-07	4.39E-02	1.77E-04
RL-W544	1.39E-03	0.00E+00	1.75E-12	4.23E-01	8.41E-02	1.10E-63	1.57E-05	5.09E-01	2.05E-03
RL-W545	3.70E-04	0.00E+00	2.57E-13	2.23E-01	3.95E-02	3.31E-64	2.31E-06	2.63E-01	1.06E-03
RL-W546	1.62E-05	0.00E+00	1.13E-14	9.81E-03	1.73E-03	1.45E-65	1.01E-07	1.16E-02	4.66E-05
RL-W547	4.14E-07	0.00E+00	2.88E-16	2.49E-04	4.42E-05	3.70E-67	2.58E-09	2.94E-04	1.19E-06
RL-W548	3.58E-07	0.00E+00	2.50E-16	2.15E-04	3.82E-05	3.32E-67	2.24E-09	2.54E-04	1.02E-06

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W549	7.11E-02	0.00E+00	1.00E-10	1.11E+01	2.63E+00	4.20E-62	9.01E-04	1.38E+01	5.56E-02
RL-W550	3.22E-01	0.00E+00	1.90E-10	1.50E+02	2.63E+01	1.58E-61	1.72E-03	1.77E+02	7.13E-01
RL-W551	5.73E-01	0.00E+00	2.81E-10	1.70E+02	3.42E+01	1.68E-61	2.52E-03	2.04E+02	8.24E-01
RL-W552	2.22E-04	0.00E+00	1.55E-13	1.34E-01	2.36E-02	2.10E-64	1.40E-06	1.58E-01	6.36E-04
RL-W553	1.97E-05	0.00E+00	1.47E-14	1.19E-02	2.11E-03	2.66E-65	1.32E-07	1.40E-02	5.66E-05
RL-W554	3.13E-04	0.00E+00	2.18E-13	1.89E-01	3.35E-02	2.80E-64	1.95E-06	2.23E-01	8.98E-04
RL-W555	1.44E-04	0.00E+00	1.00E-13	8.70E-02	1.54E-02	1.29E-64	9.01E-07	1.03E-01	4.13E-04
RL-W563	2.07E-03	0.00E+00	2.51E-12	7.21E-01	1.27E-01	1.76E-63	2.25E-05	8.50E-01	3.43E-03
RL-W564	1.35E-03	0.00E+00	1.67E-12	4.66E-01	8.19E-02	1.35E-63	1.50E-05	5.50E-01	2.22E-03
RL-W565	1.34E-04	0.00E+00	9.36E-14	8.06E-02	1.43E-02	1.25E-64	8.40E-07	9.50E-02	3.83E-04
RL-W566	1.96E-03	0.00E+00	1.37E-12	1.18E+00	2.10E-01	1.79E-63	1.23E-05	1.39E+00	5.62E-03
RL-W567	1.36E-01	0.00E+00	3.51E-11	3.64E-02	2.34E-02	1.51E-61	3.15E-04	1.96E-01	7.91E-04
RL-W568	2.62E+00	0.00E+00	7.37E-10	1.72E+00	1.09E+00	3.13E-60	6.62E-03	5.43E+00	2.19E-02
RL-W569	2.15E-03	0.00E+00	5.55E-13	5.75E-04	3.70E-05	2.40E-63	4.98E-06	2.77E-03	1.12E-05
RL-W570	1.38E-04	0.00E+00	9.71E-14	8.54E-02	1.51E-02	1.18E-64	8.72E-07	1.01E-01	4.06E-04
RL-W571	4.42E-01	0.00E+00	3.30E-10	6.93E+00	2.76E+00	4.77E-61	2.96E-03	1.01E+01	4.08E-02
RL-W572	3.84E-04	0.00E+00	9.87E-14	3.73E-03	6.60E-05	4.28E-64	8.86E-07	4.18E-03	1.69E-05
RL-W573	4.94E+00	0.00E+00	1.27E-09	2.04E+00	1.22E+00	5.43E-60	1.14E-02	8.21E+00	3.31E-02
RL-W574	2.12E+01	0.00E+00	5.47E-09	7.81E+00	4.51E+00	2.37E-59	4.91E-02	3.36E+01	1.36E-01
RL-W575	1.38E+02	0.00E+00	3.68E-08	7.47E+01	3.60E+01	1.49E-58	3.31E-01	2.49E+02	1.01E+00
RL-W576	9.98E+00	0.00E+00	2.57E-09	3.80E+00	2.18E+00	1.11E-59	2.31E-02	1.60E+01	6.44E-02
RL-W579	8.45E-04	0.00E+00	6.78E-14	1.91E-02	3.39E-03	3.93E-65	6.09E-07	2.33E-02	9.39E-05
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.52E-01	1.97E-02	0.00E+00	0.00E+00	1.72E-01	6.93E-04
RL-W581	8.97E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.97E-03	3.62E-05
RL-W582	5.87E-05	0.00E+00	5.75E-14	4.88E-03	2.01E-03	6.37E-66	5.16E-07	6.94E-03	2.80E-05
RL-W583	4.54E-05	0.00E+00	3.12E-14	2.75E-02	4.88E-03	3.71E-65	2.81E-07	3.24E-02	1.31E-04
RL-W584	9.02E-04	0.00E+00	2.05E-12	1.60E-01	6.25E-02	1.86E-64	1.84E-05	2.24E-01	9.02E-04
RL-W585	5.36E-03	0.00E+00	1.09E-11	9.35E-01	3.80E-01	5.68E-63	9.79E-05	1.32E+00	5.32E-03
RL-W586	7.16E-07	0.00E+00	4.92E-16	4.34E-04	7.69E-05	5.84E-67	4.41E-09	5.12E-04	2.06E-06
RL-W587	1.53E-05	0.00E+00	1.06E-14	9.26E-03	1.65E-03	1.31E-65	9.54E-08	1.09E-02	4.40E-05
RL-W588	6.32E-04	0.00E+00	1.73E-12	1.36E-01	5.26E-02	1.57E-64	1.55E-05	1.89E-01	7.62E-04

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	1.94E-02	0.00E+00	3.69E-11	1.05E-02	1.48E-02	2.06E-62	3.31E-04	4.50E-02	1.81E-04
RL-W591	1.11E-01	0.00E+00	4.16E-11	1.29E-02	1.91E-02	1.24E-61	3.74E-04	1.43E-01	5.77E-04
RL-W592	4.88E-01	0.00E+00	4.56E-10	5.99E-01	6.19E-01	5.02E-61	4.09E-03	1.71E+00	6.90E-03
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.16E-02	2.91E-02	0.00E+00	0.00E+00	5.07E-02	2.04E-04
RL-W594	4.40E-01	0.00E+00	8.21E-11	2.68E-02	3.93E-02	1.25E-61	7.37E-04	5.07E-01	2.04E-03
RL-W595	1.16E-03	0.00E+00	8.56E-12	1.83E-02	2.86E-02	1.24E-63	7.69E-05	4.81E-02	1.94E-04
RL-W596	3.76E-04	0.00E+00	6.66E-13	1.89E-04	2.68E-04	3.73E-64	5.98E-06	8.39E-04	3.38E-06
RL-W597	6.92E-01	0.00E+00	2.93E-10	3.66E-01	4.87E-01	6.95E-61	2.63E-03	1.55E+00	6.24E-03
RL-W598	7.32E-01	0.00E+00	1.73E-09	5.10E-01	6.07E-01	7.20E-61	1.55E-02	1.86E+00	7.51E-03
RL-W599	3.71E-02	0.00E+00	1.40E-11	4.31E-03	6.40E-03	4.15E-62	1.25E-04	4.79E-02	1.93E-04
RL-W600	2.10E-09	0.00E+00	1.45E-18	1.27E-06	2.26E-07	1.72E-69	1.30E-11	1.50E-06	6.06E-09
RL-W601	1.07E-05	0.00E+00	7.93E-15	6.45E-03	1.15E-03	1.44E-65	7.12E-08	7.61E-03	3.07E-05
RL-W602	9.29E-03	0.00E+00	6.50E-12	5.59E+00	9.93E-01	8.72E-63	5.84E-05	6.59E+00	2.66E-02
RL-W603	5.36E-02	0.00E+00	3.75E-11	3.23E+01	5.72E+00	5.02E-62	3.37E-04	3.80E+01	1.53E-01
RL-W604	1.25E-04	0.00E+00	9.83E-14	1.57E-02	6.16E-03	5.96E-65	8.83E-07	2.20E-02	8.86E-05
RL-W605	2.87E-05	0.00E+00	2.14E-14	1.73E-02	3.07E-03	3.87E-65	1.92E-07	2.04E-02	8.24E-05
RL-W606	1.16E-05	0.00E+00	8.60E-15	6.98E-03	1.24E-03	1.56E-65	7.72E-08	8.23E-03	3.32E-05
RL-W607	2.12E-05	0.00E+00	1.67E-14	2.65E-03	1.04E-03	1.01E-65	1.50E-07	3.71E-03	1.50E-05
RL-W608	2.53E-04	0.00E+00	6.46E-13	3.45E-03	3.39E-03	1.55E-64	5.80E-06	7.09E-03	2.86E-05
RL-W610	5.02E-02	0.00E+00	3.46E-11	3.04E+01	5.40E+00	4.10E-62	3.10E-04	3.59E+01	1.45E-01
RL-W612	1.18E-04	0.00E+00	8.37E-14	7.39E-02	1.31E-02	9.71E-65	7.51E-07	8.71E-02	3.51E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	3.10E-01	0.00E+00	0.00E+00	0.00E+00	3.10E-01	1.25E-03
RL-W622	1.98E-06	0.00E+00	1.36E-15	1.20E-03	2.12E-04	1.62E-66	1.22E-08	1.42E-03	5.71E-06
RL-W625	6.88E-05	0.00E+00	2.07E-13	6.13E-03	4.80E-03	8.76E-65	1.86E-06	1.10E-02	4.44E-05
RL-W626	3.70E-03	0.00E+00	4.72E-12	2.40E-01	1.15E-01	1.53E-63	4.24E-05	3.58E-01	1.45E-03
RL-W627	1.74E-05	0.00E+00	6.30E-15	1.14E-06	0.00E+00	1.82E-65	5.66E-08	1.86E-05	7.51E-08
RL-W628	5.72E-06	0.00E+00	3.96E-15	3.46E-03	6.13E-04	4.89E-66	3.56E-08	4.08E-03	1.65E-05
RL-W629	3.87E-07	0.00E+00	2.72E-16	2.33E-04	4.12E-05	3.80E-67	2.45E-09	2.74E-04	1.11E-06
RL-W630	4.26E-03	0.00E+00	5.08E-12	2.69E+00	4.97E-01	4.11E-63	4.56E-05	3.20E+00	1.29E-02
RL-W631	6.86E-05	0.00E+00	5.11E-14	4.13E-02	7.32E-03	9.25E-65	4.59E-07	4.87E-02	1.97E-04

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W632	3.03E-02	0.00E+00	6.90E-12	5.46E+00	1.43E+00	3.08E-62	6.19E-05	6.92E+00	2.79E-02
RL-W633	7.23E-05	0.00E+00	4.00E-14	8.58E-04	6.03E-04	3.79E-65	3.60E-07	1.53E-03	6.18E-06
RL-W634	0.00E+00	0.00E+00	0.00E+00	9.35E-03	0.00E+00	0.00E+00	0.00E+00	9.35E-03	3.77E-05
RL-W635	4.32E-01	0.00E+00	1.35E-09	3.98E+00	4.74E+00	3.82E-61	1.21E-02	9.16E+00	3.69E-02
RL-W636	4.41E-03	0.00E+00	2.55E-12	5.20E-02	3.66E-02	2.32E-63	2.29E-05	9.30E-02	3.75E-04
RL-W637	1.05E-05	0.00E+00	6.50E-14	5.85E-04	4.57E-04	8.35E-66	5.84E-07	1.05E-03	4.24E-06
RL-W638	4.61E-04	0.00E+00	6.62E-13	5.73E-03	4.29E-03	3.11E-64	5.94E-06	1.05E-02	4.23E-05
RL-W639	2.43E-05	0.00E+00	1.69E-14	1.47E-02	2.60E-03	2.18E-65	1.52E-07	1.73E-02	6.97E-05
RL-W640	8.17E-04	0.00E+00	5.63E-13	4.94E-01	8.77E-02	6.99E-64	5.05E-06	5.83E-01	2.35E-03
RL-W641	2.49E-02	0.00E+00	1.24E-10	2.37E+00	7.76E-01	1.12E-62	1.11E-03	3.18E+00	1.28E-02
RL-W642	4.87E-04	0.00E+00	1.29E-14	2.90E-02	1.18E-04	4.85E-66	1.15E-07	2.96E-02	1.19E-04
RL-W643	7.67E-03	0.00E+00	3.81E-11	7.31E-01	2.39E-01	3.45E-63	3.42E-04	9.79E-01	3.95E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	5.03E-02	0.00E+00	0.00E+00	0.00E+00	5.03E-02	2.03E-04
RL-W645	1.86E-04	0.00E+00	1.71E-13	9.90E-02	1.85E-02	1.89E-64	1.54E-06	1.18E-01	4.74E-04
RL-W646	1.69E-04	0.00E+00	1.53E-13	2.36E-02	9.14E-03	9.17E-65	1.37E-06	3.30E-02	1.33E-04
RL-W647	4.77E-04	0.00E+00	2.29E-11	1.01E-01	1.27E-02	3.07E-64	2.05E-04	1.14E-01	4.60E-04
RL-W648	8.44E-06	0.00E+00	3.91E-14	5.51E-05	8.63E-05	9.83E-66	3.51E-07	1.50E-04	6.05E-07
RL-W649	3.10E-05	0.00E+00	1.44E-13	2.03E-04	3.17E-04	3.61E-65	1.29E-06	5.52E-04	2.23E-06
RL-W653	1.47E-06	0.00E+00	1.03E-15	8.85E-04	1.57E-04	1.38E-66	9.25E-09	1.04E-03	4.21E-06
RL-W654	8.09E-06	0.00E+00	5.63E-15	4.88E-03	8.63E-04	7.24E-66	5.05E-08	5.75E-03	2.32E-05
RL-W655	1.99E+00	0.00E+00	1.33E-09	1.93E-01	3.63E-01	1.93E-60	1.20E-02	2.56E+00	1.03E-02
RL-W656	8.34E+00	0.00E+00	5.99E-10	4.55E-01	3.73E-01	9.21E-60	5.37E-03	9.17E+00	3.70E-02
RL-W657	4.26E+00	0.00E+00	8.84E-10	2.24E-01	3.55E-01	4.08E-60	7.94E-03	4.84E+00	1.95E-02
RL-W659	5.15E-01	0.00E+00	1.99E-10	4.31E-02	4.26E-02	4.61E-61	1.79E-03	6.03E-01	2.43E-03
RL-W660	2.82E+00	0.00E+00	2.40E-09	7.95E-01	1.13E+00	2.63E-60	2.15E-02	4.77E+00	1.92E-02
RL-W661	2.99E-02	0.00E+00	3.00E-12	3.83E-04	2.78E-03	3.19E-62	2.69E-05	3.31E-02	1.33E-04
RL-W662	9.40E-04	0.00E+00	1.79E-13	9.81E-05	1.40E-04	6.54E-64	1.61E-06	1.18E-03	4.76E-06
RL-W665	1.16E+01	0.00E+00	1.43E-08	1.20E+00	1.28E+00	1.30E-59	1.29E-01	1.42E+01	5.71E-02
RL-W666	2.07E-01	0.00E+00	3.51E-11	5.03E-02	4.22E-02	1.88E-61	3.15E-04	3.00E-01	1.21E-03
RL-W668	1.97E-02	0.00E+00	1.10E-12	1.33E-01	3.00E-02	4.44E-64	9.90E-06	1.83E-01	7.36E-04
RL-W669	5.75E-03	0.00E+00	2.86E-11	5.48E-01	1.79E-01	2.59E-63	2.57E-04	7.33E-01	2.96E-03

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W670	3.63E-04	0.00E+00	2.03E-14	2.46E-03	5.55E-04	8.23E-66	1.83E-07	3.38E-03	1.36E-05
RL-W671	5.93E-02	0.00E+00	1.04E-11	4.50E-03	3.73E-03	2.70E-62	9.36E-05	6.76E-02	2.73E-04
RL-W672	4.03E-01	0.00E+00	7.10E-11	3.07E-02	2.53E-02	1.83E-61	6.37E-04	4.59E-01	1.85E-03
RL-W673	3.88E-01	0.00E+00	6.82E-11	2.97E-02	2.44E-02	1.77E-61	6.12E-04	4.43E-01	1.79E-03
RL-W674	1.30E-03	0.00E+00	3.05E-12	1.03E+01	7.11E-02	1.23E-63	2.74E-05	1.03E+01	4.17E-02
RL-W675	4.87E-03	0.00E+00	1.69E-11	1.20E-01	8.27E-02	3.01E-63	1.51E-04	2.08E-01	8.38E-04
RL-W676	1.87E-04	0.00E+00	1.01E-13	1.35E-01	1.56E-03	8.92E-65	9.08E-07	1.37E-01	5.50E-04
RL-W677	4.33E-01	0.00E+00	2.51E-10	5.26E+00	3.64E+00	2.15E-61	2.25E-03	9.34E+00	3.76E-02
RL-W678	1.37E-03	0.00E+00	2.09E-12	4.73E-02	3.32E-02	1.69E-63	1.88E-05	8.19E-02	3.30E-04
RL-W679	8.59E-03	0.00E+00	4.68E-12	1.02E-01	7.15E-02	4.32E-63	4.20E-05	1.82E-01	7.33E-04
RL-W680	1.94E-06	0.00E+00	6.58E-15	1.59E-05	2.28E-05	1.86E-66	5.91E-08	4.08E-05	1.64E-07
RL-W681	1.18E-06	0.00E+00	2.67E-15	4.28E-04	1.70E-04	1.54E-66	2.40E-08	5.99E-04	2.42E-06
RL-W685	3.44E-03	0.00E+00	2.37E-12	2.09E+00	3.70E-01	2.81E-63	2.13E-05	2.46E+00	9.93E-03
RL-W689	8.91E-05	0.00E+00	2.85E-14	3.55E-04	0.00E+00	2.70E-66	2.56E-07	4.44E-04	1.79E-06
RL-W690	2.99E-03	0.00E+00	2.09E-12	1.86E+00	3.29E-01	2.45E-63	1.88E-05	2.19E+00	8.84E-03
RL-W691	6.94E-05	0.00E+00	4.88E-14	4.31E-02	7.61E-03	5.68E-65	4.38E-07	5.08E-02	2.05E-04
RL-W692	2.74E-03	0.00E+00	1.93E-12	1.70E+00	3.02E-01	2.24E-63	1.73E-05	2.01E+00	8.10E-03
RL-W693	3.40E-03	0.00E+00	2.38E-12	2.11E+00	3.73E-01	2.77E-63	2.14E-05	2.48E+00	1.00E-02
RL-W694	3.57E-02	0.00E+00	2.50E-11	2.23E+01	3.92E+00	2.92E-62	2.25E-04	2.62E+01	1.06E-01
RL-W695	2.95E-05	0.00E+00	0.00E+00	2.19E-03	0.00E+00	0.00E+00	0.00E+00	2.22E-03	8.95E-06
RL-W696	3.85E-05	0.00E+00	9.12E-14	2.67E-03	2.10E-03	4.00E-65	8.19E-07	4.80E-03	1.94E-05
RL-W697	8.89E-03	0.00E+00	1.93E-10	6.35E-03	6.94E-04	0.00E+00	1.73E-03	1.77E-02	7.13E-05
RL-W698	7.71E-04	0.00E+00	0.00E+00	3.02E-05	0.00E+00	0.00E+00	0.00E+00	8.01E-04	3.23E-06
RL-W699	1.71E-04	0.00E+00	1.29E-14	2.02E-03	1.89E-04	1.68E-64	1.15E-07	2.38E-03	9.58E-06
RL-W700	4.86E-05	0.00E+00	3.37E-14	2.92E-02	5.18E-03	4.36E-65	3.03E-07	3.45E-02	1.39E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	1.91E-03	0.00E+00	9.52E-12	1.82E-01	5.98E-02	8.64E-64	8.54E-05	2.44E-01	9.85E-04
RL-W705	1.24E-05	0.00E+00	8.76E-15	7.66E-03	1.36E-03	1.06E-65	7.87E-08	9.04E-03	3.64E-05
RL-W706		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707		4.42E-04	0.00E+00	3.12E-13	2.73E-01	4.84E-02	3.77E-64	2.80E-06	3.22E-01

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W708		6.67E-05	0.00E+00	4.72E-14	4.14E-02	7.32E-03	5.72E-65	4.24E-07	4.88E-02
RL-W709		2.31E-02	0.00E+00	1.63E-11	1.43E+01	2.53E+00	1.97E-62	1.46E-04	1.69E+01
RL-W710		1.38E-06	0.00E+00	9.71E-16	8.54E-04	1.51E-04	1.18E-66	8.72E-09	1.01E-03
RL-W711		4.30E-04	0.00E+00	3.03E-13	2.67E-01	4.72E-02	3.68E-64	2.72E-06	3.14E-01
RL-W712		5.57E-04	0.00E+00	3.93E-13	3.45E-01	6.11E-02	4.77E-64	3.52E-06	4.06E-01
RL-W713		4.81E-04	0.00E+00	3.39E-13	2.97E-01	5.28E-02	4.11E-64	3.04E-06	3.50E-01
RL-W714		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715		8.30E-06	0.00E+00	5.71E-15	5.03E-03	8.92E-04	6.79E-66	5.13E-08	5.93E-03
RL-W716		8.64E-05	0.00E+00	5.95E-14	5.24E-02	9.28E-03	7.07E-65	5.34E-07	6.18E-02
RL-W717		2.16E-05	0.00E+00	1.49E-14	1.31E-02	2.32E-03	1.76E-65	1.34E-07	1.55E-02
RL-W718		3.81E-06	0.00E+00	2.62E-15	2.31E-03	4.09E-04	3.11E-66	2.35E-08	2.72E-03
RL-W719		1.72E-05	0.00E+00	1.18E-14	1.05E-02	1.85E-03	1.41E-65	1.06E-07	1.23E-02
RL-W720		1.06E-04	0.00E+00	7.34E-14	6.45E-02	1.15E-02	8.68E-65	6.59E-07	7.61E-02
RL-W721		7.20E-05	0.00E+00	4.96E-14	4.36E-02	7.76E-03	5.88E-65	4.45E-07	5.15E-02
RL-W723		2.39E-04	0.00E+00	1.67E-13	1.49E-01	2.63E-02	1.95E-64	1.50E-06	1.75E-01
RL-W724		1.59E-03	0.00E+00	1.11E-12	9.81E-01	1.75E-01	1.30E-63	1.00E-05	1.16E+00
RL-W725		5.01E-04	0.00E+00	3.51E-13	3.11E-01	5.51E-02	4.09E-64	3.15E-06	3.66E-01
RL-W726		3.95E-04	0.00E+00	2.77E-13	2.46E-01	4.34E-02	3.22E-64	2.49E-06	2.89E-01
RL-W727		2.42E-03	0.00E+00	1.70E-12	1.50E+00	2.67E-01	1.98E-63	1.53E-05	1.77E+00
RL-W728		2.20E-03	0.00E+00	1.55E-12	1.38E+00	2.43E-01	1.80E-63	1.39E-05	1.62E+00
RL-W729		1.02E-03	0.00E+00	7.18E-13	6.32E-01	1.12E-01	8.31E-64	6.44E-06	7.46E-01
RL-W730		3.98E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.98E-01
RL-W731		1.28E-07	0.00E+00	0.00E+00	4.13E-04	1.35E-06	0.00E+00	0.00E+00	4.15E-04
RL-W732		2.94E-01	0.00E+00	4.08E-10	1.16E+02	2.05E+01	2.98E-61	3.67E-03	1.37E+02
RL-W733		3.86E-03	0.00E+00	5.31E-12	1.27E+00	2.49E-01	3.24E-63	4.77E-05	1.52E+00
RL-W734		1.21E-02	0.00E+00	1.77E-11	4.36E+00	8.41E-01	9.62E-63	1.59E-04	5.22E+00
RL-W735		9.87E-03	0.00E+00	1.35E-11	3.40E+00	6.71E-01	7.48E-63	1.21E-04	4.08E+00
RL-W736		1.08E-05	0.00E+00	2.88E-17	2.25E-03	4.63E-04	2.29E-66	2.59E-10	2.73E-03
RL-W737		8.81E-03	0.00E+00	1.23E-11	3.23E+00	6.24E-01	6.46E-63	1.11E-04	3.86E+00
RL-W738		3.29E-02	0.00E+00	4.24E-11	1.03E+01	2.15E+00	2.34E-62	3.81E-04	1.25E+01
RL-W739		2.80E-03	0.00E+00	3.74E-12	1.67E+00	3.02E-01	2.13E-63	3.36E-05	1.97E+00

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W740		1.40E-01	0.00E+00	1.37E-10	4.06E+01	8.41E+00	1.07E-61	1.23E-03	4.92E+01
RL-W741		2.09E-01	0.00E+00	3.23E-10	7.91E+00	4.47E+00	8.06E-62	2.90E-03	1.26E+01
RL-W742		9.32E-03	0.00E+00	9.71E-12	2.57E+00	4.81E-01	6.91E-63	8.72E-05	3.06E+00
RL-W743		1.68E-05	0.00E+00	2.64E-15	1.66E-03	0.00E+00	0.00E+00	2.37E-08	1.68E-03
RL-W744		0.00E+00	0.00E+00	0.00E+00	8.28E-02	5.60E-02	0.00E+00	0.00E+00	1.39E-01
RL-W745		2.65E-05	0.00E+00	1.84E-14	1.60E-02	2.84E-03	2.37E-65	1.66E-07	1.89E-02
RL-W746		1.02E-04	0.00E+00	7.10E-14	6.16E-02	1.10E-02	9.13E-65	6.37E-07	7.26E-02
RL-W747		2.76E-04	0.00E+00	1.92E-13	1.67E-01	2.96E-02	2.48E-64	1.73E-06	1.97E-01
RL-W748	1.94E+00	0.00E+00	5.39E-10	2.77E-01	3.62E-01	1.86E-60	4.84E-03	2.58E+00	1.04E-02
RL-W749	2.33E-03	0.00E+00	1.65E-12	1.45E+00	2.56E-01	1.99E-63	1.48E-05	1.71E+00	6.88E-03
RL-W750	2.94E+00	0.00E+00	8.17E-10	4.54E-01	5.91E-01	2.64E-60	7.33E-03	3.99E+00	1.61E-02
RL-W751	2.65E+00	0.00E+00	7.37E-10	4.08E-01	5.36E-01	2.38E-60	6.62E-03	3.60E+00	1.45E-02
RL-W752	1.15E+00	0.00E+00	3.20E-10	1.78E-01	2.33E-01	1.03E-60	2.88E-03	1.57E+00	6.32E-03
RL-W753	1.55E+01	0.00E+00	4.32E-09	2.39E+00	3.13E+00	1.39E-59	3.88E-02	2.11E+01	8.50E-02
RP-W754	6.59E-01	0.00E+00	5.47E-10	1.70E+03	1.11E+02	1.28E-61	3.55E-01	1.82E+03	7.32E+00
RP-W755	3.49E+00	0.00E+00	3.28E-10	1.27E+03	8.41E+01	9.58E-62	1.25E+01	1.37E+03	5.54E+00
SA-T001	7.01E-03	1.91E-50	7.85E-12	2.78E+00	1.31E-02	0.00E+00	7.51E-05	2.80E+00	1.13E-02
SA-W134	5.73E-02	7.40E-54	5.35E-11	1.27E+00	3.18E-01	2.44E-63	1.66E-01	1.81E+00	7.28E-03
SA-W134M	7.44E-03	9.60E-55	6.94E-12	1.65E-01	4.13E-02	3.18E-64	2.15E-02	2.35E-01	9.48E-04
T001-221F-HET	1.39E+01	0.00E+00	6.26E-06	2.64E+04	5.18E+02	8.02E-60	6.18E+01	2.70E+04	1.09E+02
T001-221H-HET	2.49E+01	0.00E+00	1.13E-05	4.77E+04	9.35E+02	1.45E-59	1.12E+02	4.87E+04	1.97E+02
T001-235F-HET	1.44E+00	0.00E+00	6.50E-07	2.74E+03	5.37E+01	8.31E-61	6.42E+00	2.80E+03	1.13E+01
T001-772F-HET	1.24E+01	0.00E+00	5.63E-06	2.36E+04	4.63E+02	7.16E-60	5.56E+01	2.42E+04	9.75E+01
T001-773A-CLAS	1.39E-01	0.00E+00	6.30E-08	2.66E+02	5.20E+00	8.06E-62	6.22E-01	2.72E+02	1.10E+00
T001-773A-HET	1.60E+00	0.00E+00	7.26E-07	3.06E+03	6.00E+01	9.29E-61	7.16E+00	3.13E+03	1.26E+01
W006-773A-VIT	2.14E-05	0.00E+00	0.00E+00	4.92E+02	0.00E+00	0.00E+00	0.00E+00	4.92E+02	1.98E+00
W026-221F-HET	4.82E+00	0.00E+00	2.19E-06	9.26E+03	1.81E+02	2.79E-60	2.16E+01	9.46E+03	3.82E+01
W026-221H-HET	3.60E+00	0.00E+00	1.63E-06	6.89E+03	1.35E+02	2.09E-60	1.61E+01	7.05E+03	2.84E+01
W026-235F-HET	5.61E-02	0.00E+00	2.55E-08	1.07E+02	2.10E+00	3.25E-62	2.51E-01	1.10E+02	4.42E-01
W026-772F-HET	1.54E-02	0.00E+00	6.94E-09	2.92E+01	5.73E-01	8.88E-63	6.85E-02	2.99E+01	1.21E-01
W026-773A-HET	2.49E-01	0.00E+00	1.13E-07	4.77E+02	9.35E+00	1.44E-61	1.12E+00	4.87E+02	1.97E+00

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W027-221F-HET	1.82E+01	0.00E+00	7.37E-06	3.57E+04	6.99E+02	4.57E-60	8.39E+01	3.65E+04	1.47E+02
W027-221H-HET	7.95E+00	0.00E+00	3.22E-06	1.57E+04	3.06E+02	1.99E-60	3.66E+01	1.60E+04	6.46E+01
W027-235F-HET	2.39E+00	0.00E+00	9.67E-07	4.71E+03	9.21E+01	6.00E-61	1.10E+01	4.82E+03	1.94E+01
W027-772F-HET	4.35E+00	0.00E+00	1.76E-06	8.55E+03	1.68E+02	1.09E-60	2.00E+01	8.74E+03	3.53E+01
W027-773A-HET	6.48E+00	0.00E+00	2.63E-06	1.27E+04	2.49E+02	1.63E-60	2.99E+01	1.30E+04	5.25E+01
W027-999-HET	7.42E+00	0.00E+00	3.00E-06	1.46E+04	2.85E+02	1.86E-60	3.42E+01	1.49E+04	6.01E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.66E+02	0.00E+00	0.00E+00	0.00E+00	3.66E+02	1.47E+00
WP-INW169.001	3.62E-02	0.00E+00	1.89E-11	1.41E+01	2.49E+00	1.64E-62	3.33E-04	1.66E+01	6.71E-02
WP-INW198.001	4.77E-02	0.00E+00	3.30E-11	2.53E+01	4.44E+00	2.69E-62	3.77E-04	2.98E+01	1.20E-01
WP-INW211.001	5.37E+00	0.00E+00	3.10E-09	2.35E+03	4.12E+02	3.05E-60	2.98E-02	2.76E+03	1.11E+01
WP-INW216.001-	1.95E+02	0.00E+00	1.78E-09	1.36E+03	2.39E+02	1.69E-60	2.91E-01	1.79E+03	7.22E+00
WP-INW216.001-	5.37E+01	0.00E+00	4.80E-10	3.68E+02	6.45E+01	4.57E-61	3.17E-02	4.86E+02	1.96E+00
WP-INW218.001-	3.73E+00	0.00E+00	3.14E-10	2.36E+02	4.16E+01	3.05E-61	3.86E-01	2.82E+02	1.14E+00
WP-INW218.001-	1.72E-02	0.00E+00	8.64E-12	6.43E+00	1.13E+00	8.64E-63	3.72E-02	7.62E+00	3.07E-02
WP-INW222.001	1.77E-01	0.00E+00	9.32E-11	6.29E+01	1.12E+01	7.32E-62	1.41E-03	7.42E+01	2.99E-01
WP-INW243.001	4.29E-01	0.00E+00	2.01E-10	1.32E+02	2.35E+01	1.48E-61	2.67E-03	1.56E+02	6.29E-01
WP-INW247.001R	5.72E-01	0.00E+00	4.68E-10	2.53E+02	4.57E+01	2.57E-61	4.28E-03	2.99E+02	1.21E+00
WP-INW276.001	4.36E-02	0.00E+00	4.56E-11	2.50E+01	4.52E+00	2.18E-62	4.26E-04	2.96E+01	1.19E-01
WP-INW276.002	6.92E-02	0.00E+00	6.86E-11	3.68E+01	6.79E+00	3.27E-62	6.42E-04	4.36E+01	1.76E-01
WP-INW276.003	2.65E+00	0.00E+00	2.55E-09	1.37E+03	2.47E+02	1.37E-60	2.33E-02	1.62E+03	6.51E+00
WP-INW276.004	6.33E-01	0.00E+00	5.39E-10	2.89E+02	5.22E+01	2.90E-61	4.99E-03	3.42E+02	1.38E+00
WP-INW296.001-	2.32E-01	0.00E+00	1.28E-10	7.25E+01	1.31E+01	7.44E-62	1.19E-03	8.58E+01	3.46E-01
WP-INW296.001-	6.98E-01	0.00E+00	4.52E-10	2.57E+02	4.61E+01	2.68E-61	4.41E-03	3.03E+02	1.22E+00
WP-LA-TA-55-19	1.16E-02	0.00E+00	2.10E-11	1.92E+00	3.68E-01	2.67E-63	2.81E-03	2.30E+00	9.26E-03
WP-LA-TA-55-19	5.63E-01	0.00E+00	7.06E-10	1.95E+02	3.79E+01	2.65E-61	9.28E-02	2.34E+02	9.42E-01
WP-LA-TA-55-43	3.16E-03	0.00E+00	1.65E-08	2.96E-01	9.93E-02	2.37E-63	1.74E-01	5.73E-01	2.31E-03
WP-RF001.01	9.77E-01	0.00E+00	5.71E-10	3.76E+02	6.79E+01	2.67E-61	1.44E-02	4.45E+02	1.79E+00
WP-RF002.01-A	1.14E+00	0.00E+00	7.61E-10	4.23E+02	7.69E+01	5.88E-61	2.45E-02	5.01E+02	2.02E+00
WP-RF002.01-B	1.13E-03	0.00E+00	5.27E-13	4.58E-01	8.27E-02	3.70E-64	4.92E-06	5.42E-01	2.19E-03
WP-RF003.01	1.77E+01	0.00E+00	1.23E-08	8.09E+03	1.47E+03	9.71E-60	1.18E-01	9.57E+03	3.86E+01
WP-RF004.01	8.28E-03	0.00E+00	8.21E-12	4.66E+00	8.48E-01	5.55E-63	2.00E-04	5.52E+00	2.23E-02

Table PAR-57. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 3,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF005.01	4.25E+01	0.00E+00	6.23E-09	4.28E+03	7.69E+02	3.87E-60	5.77E-02	5.09E+03	2.05E+01
WP-RF005.02	5.00E+01	0.00E+00	3.22E-09	2.56E+03	4.56E+02	1.98E-60	3.01E-02	3.06E+03	1.24E+01
WP-RF006.01	1.62E+01	0.00E+00	1.17E-08	7.28E+03	1.32E+03	5.02E-60	1.30E-01	8.61E+03	3.47E+01
WP-RF008.01	5.15E+00	0.00E+00	4.16E-09	2.13E+03	3.92E+02	3.31E-60	3.86E-02	2.52E+03	1.02E+01
WP-RF009.01	5.06E+02	0.00E+00	5.11E-08	4.66E+04	8.27E+03	3.80E-59	4.80E-01	5.54E+04	2.24E+02
WP-RF010.01	1.87E-01	0.00E+00	1.30E-10	7.05E+01	1.28E+01	1.17E-61	1.89E-03	8.34E+01	3.36E-01
WP-RF029.01-A	4.49E-02	0.00E+00	2.44E-11	1.24E+01	2.25E+00	2.69E-62	9.43E-04	1.47E+01	5.91E-02
WP-RF029.01-B	6.70E-02	0.00E+00	1.93E-11	9.81E+00	1.78E+00	2.13E-62	2.40E-03	1.17E+01	4.70E-02
WP-RF118.01	1.14E+02	0.00E+00	9.71E-08	4.71E+04	8.34E+03	6.99E-59	1.09E+00	5.56E+04	2.24E+02
WP-RLMPDT.001	2.42E-02	0.00E+00	2.84E-11	6.75E+00	1.39E+00	1.53E-62	2.57E-04	8.16E+00	3.29E-02
WP-RLNPDT.002	2.97E-01	0.00E+00	2.70E-10	6.63E+01	1.41E+01	1.76E-61	2.46E-03	8.07E+01	3.25E-01
WP-SR2001.001.	9.45E-03	0.00E+00	3.10E-11	6.26E+00	9.86E-01	9.58E-63	2.83E-04	7.26E+00	2.93E-02
WP-SR-W027-221	7.00E-02	0.00E+00	9.12E-11	1.80E+01	3.98E+00	4.32E-62	1.85E-01	2.22E+01	8.95E-02
Total	3.74E+03	3.70E-47	6.38E-05	6.05E+05	7.76E+04	9.88E-58	7.39E+02	6.87E+05	2.77E+03

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	2.85E-02	0.00E+00	9.71E-17	1.81E+02	7.27E+01	0.00E+00	1.94E-02	2.54E+02	1.02E+00
AE-T003	3.62E-03	0.00E+00	1.29E-17	5.59E+01	1.47E+01	0.00E+00	9.50E-04	7.06E+01	2.85E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	1.60E-05	0.00E+00	3.43E-16	4.12E+01	1.69E-01	0.00E+00	2.27E-02	4.14E+01	1.67E-01
AW-T033.1325	5.86E-05	0.00E+00	1.26E-15	1.51E+02	6.16E-01	0.00E+00	8.32E-02	1.51E+02	6.10E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	6.69E-01	0.00E+00	0.00E+00	0.00E+00	6.69E-01	2.70E-03
BCLCH-MT01	5.91E-03	0.00E+00	9.71E-15	2.48E+01	4.42E+00	0.00E+00	6.30E-01	2.99E+01	1.21E-01
BT-T002	4.34E-06	5.77E-87	5.07E-18	6.27E-04	8.72E-04	0.00E+00	2.29E-03	3.80E-03	1.53E-05
ET-C1-B55	1.81E-05	0.00E+00	5.78E-20	5.37E-02	1.82E-02	0.00E+00	2.36E-04	7.22E-02	2.91E-04
ET-C1-D139	2.49E-06	0.00E+00	8.02E-21	7.55E-03	2.56E-03	0.00E+00	5.81E-07	1.01E-02	4.08E-05
ET-C2-SEFOR	6.16E-05	0.00E+00	0.00E+00	1.19E-01	2.70E-02	0.00E+00	0.00E+00	1.46E-01	5.87E-04
FM-MOX-MT02	5.84E-10	0.00E+00	3.23E-24	2.60E-07	1.05E-07	0.00E+00	2.18E-10	3.65E-07	1.47E-09
FM-MOX-T01	9.64E-09	0.00E+00	5.33E-23	4.27E-06	1.73E-06	0.00E+00	3.60E-09	6.02E-06	2.43E-08
IN-BN-510	2.33E+00	0.00E+00	2.75E-13	3.43E+04	1.98E+03	0.00E+00	1.98E+01	3.63E+04	1.47E+02
IN-GEM-01	2.95E-02	0.00E+00	5.45E-18	3.86E+01	5.98E+00	0.00E+00	3.54E-04	4.46E+01	1.80E-01
IN-GEM-02	7.00E-03	0.00E+00	1.30E-18	9.17E+00	1.43E+00	0.00E+00	8.42E-05	1.06E+01	4.28E-02
IN-W157.144	3.49E-02	0.00E+00	5.28E-17	2.62E+02	4.03E+01	0.00E+00	3.80E-03	3.03E+02	1.22E+00
IN-W163.1007	5.97E-03	0.00E+00	1.63E-17	8.13E+01	1.25E+01	0.00E+00	1.17E-03	9.38E+01	3.78E-01
IN-W164.153	5.72E-05	0.00E+00	1.56E-19	7.74E-01	1.19E-01	0.00E+00	1.12E-05	8.93E-01	3.60E-03
IN-W167.149	1.14E-02	0.00E+00	2.53E-17	1.25E+02	1.93E+01	0.00E+00	1.82E-03	1.45E+02	5.84E-01
IN-W174.154	0.00E+00	0.00E+00	1.43E-14	1.69E+00	2.26E+00	0.00E+00	1.03E+00	4.97E+00	2.01E-02
IN-W177.156	7.94E-06	0.00E+00	3.04E-14	1.58E+00	6.57E-03	0.00E+00	2.18E+00	3.77E+00	1.52E-02
IN-W179.158	5.34E-05	0.00E+00	3.03E-14	9.17E-02	3.24E-02	0.00E+00	2.18E+00	2.30E+00	9.28E-03
IN-W181.162	7.57E-04	0.00E+00	2.06E-18	1.02E+01	1.57E+00	0.00E+00	1.48E-04	1.18E+01	4.75E-02
IN-W188.160	5.10E-03	0.00E+00	1.39E-17	6.90E+01	1.06E+01	0.00E+00	9.96E-04	7.95E+01	3.21E-01
IN-W216.98	4.53E+01	0.00E+00	1.13E-15	5.62E+03	8.68E+02	0.00E+00	8.12E-02	6.54E+03	2.64E+01

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W218.909	2.29E-01	0.00E+00	2.51E-17	1.25E+02	1.92E+01	0.00E+00	1.80E-03	1.44E+02	5.81E-01
IN-W219.110	3.11E-04	0.00E+00	8.46E-19	4.20E+00	6.45E-01	0.00E+00	6.08E-05	4.85E+00	1.96E-02
IN-W219.914	4.90E-05	0.00E+00	1.33E-19	6.64E-01	1.02E-01	0.00E+00	9.57E-06	7.66E-01	3.09E-03
IN-W220.114	1.62E+00	0.00E+00	8.89E-17	4.75E+02	7.10E+01	0.00E+00	6.39E-03	5.48E+02	2.21E+00
IN-W221.927	1.90E-03	0.00E+00	5.16E-18	2.56E+01	3.93E+00	0.00E+00	3.71E-04	2.95E+01	1.19E-01
IN-W222.116	6.45E-02	0.00E+00	1.75E-16	8.65E+02	1.33E+02	0.00E+00	1.26E-02	9.98E+02	4.03E+00
IN-W228.101	4.28E-01	0.00E+00	5.67E-17	2.83E+02	4.34E+01	0.00E+00	4.08E-03	3.27E+02	1.32E+00
IN-W240.931	4.53E-02	0.00E+00	7.26E-17	3.63E+02	5.55E+01	0.00E+00	5.22E-03	4.19E+02	1.69E+00
IN-W243.808	6.28E-02	0.00E+00	1.27E-16	6.34E+02	9.74E+01	0.00E+00	9.14E-03	7.32E+02	2.95E+00
IN-W245.301	9.28E-02	0.00E+00	2.50E-16	1.24E+03	1.91E+02	0.00E+00	1.80E-02	1.43E+03	5.76E+00
IN-W247.810	4.52E-02	0.00E+00	1.22E-16	6.05E+02	9.33E+01	0.00E+00	8.75E-03	6.98E+02	2.82E+00
IN-W249.527	0.00E+00	0.00E+00	8.51E-15	1.07E+01	0.00E+00	0.00E+00	6.12E-01	1.13E+01	4.57E-02
IN-W263.520	1.30E-05	0.00E+00	8.89E-16	7.29E+00	7.86E-03	0.00E+00	6.39E-02	7.36E+00	2.97E-02
IN-W267.1005	1.08E-02	0.00E+00	2.95E-17	1.47E+02	2.26E+01	0.00E+00	2.12E-03	1.70E+02	6.84E-01
IN-W309.609	2.91E-01	0.00E+00	4.95E-16	2.46E+03	3.78E+02	0.00E+00	3.56E-02	2.84E+03	1.14E+01
IN-W315.601	2.87E-01	0.00E+00	2.07E-18	1.03E+01	1.58E+00	0.00E+00	1.49E-04	1.22E+01	4.90E-02
IN-W319.584	1.67E-03	0.00E+00	4.53E-18	2.26E+01	3.48E+00	0.00E+00	3.26E-04	2.61E+01	1.05E-01
IN-W321.1023	1.44E-02	0.00E+00	3.93E-17	1.96E+02	3.00E+01	0.00E+00	2.82E-03	2.26E+02	9.10E-01
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	7.89E+00	1.11E+00	0.00E+00	0.00E+00	9.00E+00	3.63E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	2.10E+01	2.96E+00	0.00E+00	0.00E+00	2.40E+01	9.67E-02
IN-W323.562	3.08E-05	0.00E+00	6.66E-18	2.15E-01	0.00E+00	0.00E+00	4.79E-04	2.16E-01	8.71E-04
IN-W323.951	3.64E-05	0.00E+00	7.91E-20	2.57E-01	0.00E+00	0.00E+00	5.69E-06	2.57E-01	1.04E-03
IN-W332.661	0.00E+00	0.00E+00	8.73E-17	1.12E-01	0.00E+00	0.00E+00	6.28E-03	1.18E-01	4.75E-04
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	2.63E+00	3.70E-01	0.00E+00	0.00E+00	3.00E+00	1.21E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	7.89E+00	1.11E+00	0.00E+00	0.00E+00	9.00E+00	3.63E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.69E+00	0.00E+00	0.00E+00	0.00E+00	1.69E+00	6.80E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	5.07E+00	0.00E+00	0.00E+00	0.00E+00	5.07E+00	2.04E-02
IN-W342.652	1.42E-03	0.00E+00	0.00E+00	3.48E-02	6.10E-18	0.00E+00	0.00E+00	3.62E-02	1.46E-04
IN-W342.953	9.51E-04	0.00E+00	0.00E+00	2.33E-02	4.09E-18	0.00E+00	0.00E+00	2.42E-02	9.77E-05
IN-W347.818	7.45E-04	0.00E+00	0.00E+00	7.15E+01	8.92E+01	0.00E+00	1.56E-08	1.61E+02	6.48E-01
IN-W348.1012	3.94E-05	0.00E+00	7.20E-17	3.61E+02	5.55E+01	0.00E+00	5.18E-03	4.16E+02	1.68E+00

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.16E-02	0.00E+00	0.00E+00	0.00E+00	2.16E-02	8.72E-05
IN-W357.1022	0.00E+00	0.00E+00	1.42E-19	7.09E-01	1.09E-01	0.00E+00	1.02E-05	8.17E-01	3.29E-03
IN-W358.854	0.00E+00	0.00E+00	2.14E-15	1.63E+00	2.13E+00	0.00E+00	1.47E-01	3.90E+00	1.57E-02
IN-W358.855	0.00E+00	0.00E+00	1.14E-14	8.65E+00	1.13E+01	0.00E+00	7.82E-01	2.08E+01	8.37E-02
IN-W358.948	0.00E+00	0.00E+00	2.38E-15	1.81E+00	2.36E+00	0.00E+00	1.63E-01	4.33E+00	1.75E-02
IN-W361.1021	1.05E-05	0.00E+00	1.38E-17	6.83E+01	1.05E+01	0.00E+00	9.88E-04	7.88E+01	3.18E-01
IN-W362.1020	0.00E+00	0.00E+00	1.80E-16	8.91E+02	1.38E+02	0.00E+00	1.29E-02	1.03E+03	4.15E+00
IN-W363.1019	0.00E+00	0.00E+00	8.46E-18	4.23E+01	6.51E+00	0.00E+00	6.08E-04	4.88E+01	1.97E-01
IN-W364.1011	0.00E+00	0.00E+00	1.40E-17	6.96E+01	1.07E+01	0.00E+00	1.00E-03	8.02E+01	3.24E-01
IN-W365.1010	9.76E-02	0.00E+00	1.11E-17	5.49E+01	8.45E+00	0.00E+00	7.96E-04	6.35E+01	2.56E-01
IN-W366.841	3.47E-04	0.00E+00	9.44E-18	4.68E+01	7.21E+00	0.00E+00	6.79E-04	5.40E+01	2.18E-01
IN-W372.832	1.42E-03	0.00E+00	0.00E+00	3.48E-02	6.10E-18	0.00E+00	0.00E+00	3.62E-02	1.46E-04
IN-W375.1096	0.00E+00	0.00E+00	3.48E-18	1.73E+01	2.66E+00	0.00E+00	2.50E-04	2.00E+01	8.05E-02
KN-B234TRU	5.06E-02	0.00E+00	1.33E-16	2.52E+02	5.75E+01	0.00E+00	1.06E-02	3.09E+02	1.25E+00
LA-IT-00-01	7.35E-04	3.71E-84	2.27E-17	5.06E-01	7.44E-03	0.00E+00	1.82E-03	5.16E-01	2.08E-03
LA-OS-00-01	1.64E+00	0.00E+00	1.04E-12	1.06E+03	0.00E+00	0.00E+00	6.78E+01	1.13E+03	4.57E+00
LA-PX-00-01	6.83E-06	0.00E+00	4.37E-20	7.83E-02	1.25E-02	0.00E+00	2.97E-06	9.08E-02	3.66E-04
LA-SL-00-01	0.00E+00	0.00E+00	9.22E-19	1.32E-01	0.00E+00	0.00E+00	7.35E-05	1.32E-01	5.34E-04
LA-TA-03-12	7.02E-05	0.00E+00	2.13E-17	3.77E-01	8.92E-02	0.00E+00	1.76E-03	4.68E-01	1.89E-03
LA-TA-03-13	9.08E-05	0.00E+00	6.77E-17	5.89E-01	9.38E-02	0.00E+00	4.91E-03	6.88E-01	2.77E-03
LA-TA-03-19	1.84E-04	0.00E+00	1.01E-16	1.15E+00	2.26E-01	0.00E+00	8.31E-03	1.39E+00	5.58E-03
LA-TA-03-20	1.00E-04	0.00E+00	4.79E-17	5.07E-01	1.21E-01	0.00E+00	3.79E-03	6.32E-01	2.55E-03
LA-TA-03-24	1.34E-04	0.00E+00	1.87E-16	9.43E-01	1.94E-01	0.00E+00	1.55E-02	1.15E+00	4.65E-03
LA-TA-03-26	6.87E-06	0.00E+00	7.69E-18	2.28E+00	2.54E-02	0.00E+00	1.50E-03	2.31E+00	9.32E-03
LA-TA-03-28	0.00E+00	0.00E+00	2.66E-18	2.14E-01	0.00E+00	0.00E+00	2.17E-04	2.14E-01	8.63E-04
LA-TA-03-30	3.06E-04	0.00E+00	1.90E-18	4.35E+00	8.56E-01	0.00E+00	1.54E-04	5.21E+00	2.10E-02
LA-TA-03-31	0.00E+00	0.00E+00	9.49E-20	7.61E-03	0.00E+00	0.00E+00	7.75E-06	7.62E-03	3.07E-05
LA-TA-03-40	0.00E+00	0.00E+00	1.50E-19	4.73E-02	0.00E+00	0.00E+00	1.23E-05	4.73E-02	1.91E-04
LA-TA-03-42	7.03E-09	0.00E+00	3.76E-21	2.96E-03	2.65E-05	0.00E+00	3.09E-07	2.99E-03	1.20E-05
LA-TA-21-06	6.92E-05	0.00E+00	4.14E-16	8.28E-01	1.72E-01	0.00E+00	3.37E-02	1.03E+00	4.17E-03
LA-TA-21-12	2.52E-04	0.00E+00	2.49E-15	2.87E+00	5.83E-01	0.00E+00	2.03E-01	3.66E+00	1.48E-02

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-13	3.88E-04	0.00E+00	0.00E+00	2.54E-01	0.00E+00	0.00E+00	0.00E+00	2.55E-01	1.03E-03
LA-TA-21-14	6.37E-08	0.00E+00	4.76E-17	3.88E+00	3.08E-05	0.00E+00	3.26E-03	3.89E+00	1.57E-02
LA-TA-21-15	3.76E-05	0.00E+00	1.31E-19	1.20E+00	1.40E-01	0.00E+00	1.06E-05	1.34E+00	5.41E-03
LA-TA-21-16	4.35E-04	0.00E+00	2.02E-18	9.17E+00	1.49E+00	0.00E+00	1.66E-04	1.07E+01	4.30E-02
LA-TA-21-40	5.53E-08	0.00E+00	6.98E-18	2.88E-01	2.16E-04	0.00E+00	7.00E-04	2.89E-01	1.17E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	6.13E-01	0.00E+00	0.00E+00	0.00E+00	6.13E-01	2.47E-03
LA-TA-21-42	5.65E-06	0.00E+00	2.27E-18	1.42E-01	6.57E-03	0.00E+00	2.42E-04	1.49E-01	6.00E-04
LA-TA-21-43	1.99E-02	0.00E+00	7.53E-17	4.42E+02	7.16E+01	0.00E+00	7.98E-03	5.14E+02	2.07E+00
LA-TA-21-44	9.57E-05	0.00E+00	1.58E-17	9.95E+01	1.80E-01	0.00E+00	1.40E-03	9.97E+01	4.02E-01
LA-TA-48-01	3.10E-05	1.75E-83	5.95E-20	1.02E-01	2.91E-01	0.00E+00	6.02E-06	3.93E-01	1.58E-03
LA-TA-49-01	3.82E-03	2.17E-81	7.31E-18	1.26E+01	3.60E+01	0.00E+00	7.41E-04	4.86E+01	1.96E-01
LA-TA-50-10	1.02E-05	0.00E+00	6.93E-20	3.97E-02	0.00E+00	0.00E+00	4.68E-06	3.97E-02	1.60E-04
LA-TA-50-11	1.95E-05	0.00E+00	7.09E-20	4.03E-01	6.10E-02	0.00E+00	7.05E-06	4.64E-01	1.87E-03
LA-TA-50-15	3.85E-05	0.00E+00	1.05E-17	2.94E-01	4.49E-02	0.00E+00	7.99E-04	3.40E-01	1.37E-03
LA-TA-50-17	5.63E-03	0.00E+00	8.51E-18	1.57E+01	2.52E-04	0.00E+00	9.84E-04	1.58E+01	6.35E-02
LA-TA-50-18	3.35E-04	0.00E+00	1.12E-18	2.57E+00	3.14E-06	0.00E+00	9.24E-05	2.57E+00	1.04E-02
LA-TA-50-19	1.07E-04	0.00E+00	5.01E-19	3.42E-01	2.69E-03	0.00E+00	6.76E-05	3.45E-01	1.39E-03
LA-TA-50-20	2.93E-06	0.00E+00	0.00E+00	8.43E-03	0.00E+00	0.00E+00	0.00E+00	8.43E-03	3.40E-05
LA-TA-50-40	1.65E-06	0.00E+00	6.77E-21	9.17E-03	2.92E-03	0.00E+00	5.31E-07	1.21E-02	4.87E-05
LA-TA-50-41	1.76E-06	0.00E+00	6.82E-21	4.07E-02	6.45E-03	0.00E+00	4.90E-07	4.71E-02	1.90E-04
LA-TA-55-19	2.73E-03	0.00E+00	9.00E-18	2.28E+01	4.38E+00	0.00E+00	2.23E-03	2.72E+01	1.10E-01
LA-TA-55-20	4.39E-02	0.00E+00	1.03E-16	5.52E+02	9.03E+01	0.00E+00	1.00E-01	6.42E+02	2.59E+00
LA-TA-55-21	3.92E-04	5.17E-87	1.18E-18	3.91E+00	6.39E-01	0.00E+00	8.41E-05	4.55E+00	1.84E-02
LA-TA-55-22	1.07E-03	0.00E+00	6.66E-18	1.38E+01	2.19E+00	0.00E+00	4.75E-04	1.60E+01	6.43E-02
LA-TA-55-23	1.01E-03	0.00E+00	5.57E-18	9.43E+00	1.59E+00	0.00E+00	3.94E-04	1.10E+01	4.44E-02
LA-TA-55-24	3.81E-04	0.00E+00	8.73E-19	4.95E+00	7.86E-01	0.00E+00	5.94E-05	5.74E+00	2.31E-02
LA-TA-55-25	1.95E-03	0.00E+00	5.09E-18	2.46E+01	3.91E+00	0.00E+00	3.46E-04	2.85E+01	1.15E-01
LA-TA-55-28	6.65E-04	0.00E+00	2.82E-18	7.54E+00	1.21E+00	0.00E+00	1.93E-04	8.76E+00	3.53E-02
LA-TA-55-30	1.48E-02	4.90E-89	3.38E-17	1.24E+02	2.04E+01	0.00E+00	2.95E-03	1.44E+02	5.81E-01
LA-TA-55-32	1.20E-03	0.00E+00	1.89E-16	9.78E+00	2.06E+00	0.00E+00	1.57E-02	1.19E+01	4.78E-02
LA-TA-55-33	1.80E-04	0.00E+00	4.87E-19	1.29E+00	2.80E-01	0.00E+00	3.79E-05	1.57E+00	6.33E-03

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-34	1.82E-02	0.00E+00	4.51E-17	2.00E+02	3.46E+01	0.00E+00	6.25E-03	2.35E+02	9.45E-01
LA-TA-55-38	4.57E-02	0.00E+00	1.48E-17	4.41E+01	8.09E+00	0.00E+00	2.83E-03	5.23E+01	2.11E-01
LA-TA-55-39	4.84E-03	0.00E+00	1.10E-17	6.58E+01	1.01E+01	0.00E+00	7.70E-04	7.59E+01	3.06E-01
LA-TA-55-41	1.15E-01	0.00E+00	2.27E-17	8.17E+01	1.33E+01	0.00E+00	1.63E-03	9.51E+01	3.83E-01
LA-TA-55-43	4.33E-05	0.00E+00	1.49E-15	1.23E-01	2.93E-02	0.00E+00	1.04E-01	2.56E-01	1.03E-03
LA-TA-55-44	3.75E-04	0.00E+00	3.51E-15	2.28E+00	4.31E-01	0.00E+00	2.75E-01	2.98E+00	1.20E-02
LA-TA-55-48	2.76E+00	0.00E+00	1.39E-14	1.46E+04	3.72E+03	0.00E+00	1.06E+00	1.83E+04	7.40E+01
LA-TA-55-49	5.91E-03	0.00E+00	1.82E-14	2.67E+01	5.12E+00	0.00E+00	1.42E+00	3.33E+01	1.34E-01
LA-TA-55-53	2.79E-02	0.00E+00	3.77E-17	2.28E+02	3.64E+01	0.00E+00	2.89E-03	2.65E+02	1.07E+00
LA-TA-55-56	3.08E-02	0.00E+00	1.40E-15	3.31E+02	5.65E+01	0.00E+00	1.03E-01	3.87E+02	1.56E+00
LA-TA-55-60	1.67E-05	0.00E+00	3.54E-19	6.23E-02	1.51E-02	0.00E+00	2.75E-05	7.74E-02	3.12E-04
LA-TA-55-61	1.44E-05	0.00E+00	1.63E-18	1.20E-01	2.78E-02	0.00E+00	1.25E-04	1.48E-01	5.98E-04
LA-TA-55-62	3.73E-06	0.00E+00	1.55E-20	2.02E-02	6.57E-03	0.00E+00	1.20E-06	2.67E-02	1.08E-04
LA-TA-55-63	2.77E-06	0.00E+00	1.05E-20	6.46E-02	1.02E-02	0.00E+00	7.71E-07	7.48E-02	3.02E-04
LL-M001	3.80E-02	2.35E-82	4.57E-16	6.06E+01	1.86E+01	0.00E+00	2.96E-02	7.93E+01	3.20E-01
LL-T001	1.90E-01	0.00E+00	0.00E+00	4.62E+02	1.42E+02	0.00E+00	0.00E+00	6.04E+02	2.44E+00
LL-T002	1.87E+00	0.00E+00	3.63E-15	4.48E+03	1.26E+03	0.00E+00	2.36E-01	5.74E+03	2.31E+01
LL-T003	7.28E-02	0.00E+00	4.07E-16	9.08E+01	5.00E+01	0.00E+00	2.64E-02	1.41E+02	5.68E-01
LL-T004	4.63E-02	0.00E+00	8.35E-17	5.77E+01	3.15E+01	0.00E+00	5.42E-03	8.93E+01	3.60E-01
LL-T005	2.39E-01	1.02E-80	9.82E-16	2.15E+02	1.26E+02	0.00E+00	6.37E-02	3.41E+02	1.38E+00
LL-W018	2.03E-05	0.00E+00	0.00E+00	1.60E-02	2.51E-02	0.00E+00	0.00E+00	4.11E-02	1.66E-04
LL-W019	1.10E-02	0.00E+00	0.00E+00	1.25E+01	7.10E+00	0.00E+00	0.00E+00	1.96E+01	7.89E-02
LL-W034	4.08E-03	1.73E-82	1.72E-17	3.63E+00	2.09E+00	0.00E+00	1.12E-03	5.73E+00	2.31E-02
MC-W001	5.09E-05	0.00E+00	0.00E+00	5.24E-02	0.00E+00	0.00E+00	0.00E+00	5.25E-02	2.12E-04
MU-W002	6.79E-04	0.00E+00	0.00E+00	4.55E-02	0.00E+00	0.00E+00	2.63E-12	4.62E-02	1.86E-04
NT-JAS-01	6.56E-02	0.00E+00	3.66E-16	8.20E+01	4.50E+01	0.00E+00	2.38E-02	1.27E+02	5.12E-01
NT-W001	9.85E-02	5.29E-84	7.31E-16	2.47E+03	1.13E+01	0.00E+00	5.89E-02	2.49E+03	1.00E+01
NT-W021	1.91E-03	0.00E+00	5.24E-18	2.79E+01	4.33E+00	0.00E+00	3.86E-04	3.22E+01	1.30E-01
OR-W201	2.28E+00	3.65E-82	1.57E-14	1.87E+03	1.26E+03	0.00E+00	4.40E+01	3.17E+03	1.28E+01
OR-W202	3.28E-01	7.59E-81	4.53E-14	4.79E+02	3.20E+02	0.00E+00	3.39E+00	8.03E+02	3.24E+00
OR-W203	7.22E-04	2.64E-82	6.49E-18	2.15E-02	1.05E+00	0.00E+00	4.82E-04	1.07E+00	4.31E-03

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
OR-W204	1.61E-04	1.10E-87	7.37E-18	3.67E-01	1.69E-01	0.00E+00	5.47E-04	5.36E-01	2.16E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	3.69E-01	0.00E+00	0.00E+00	0.00E+00	3.69E-01	1.49E-03
RF-MT0001	6.17E-01	0.00E+00	4.57E-17	1.70E+02	2.63E+01	0.00E+00	3.26E-03	1.97E+02	7.92E-01
RF-MT0002	4.75E-02	0.00E+00	3.51E-18	1.31E+01	2.02E+00	0.00E+00	2.50E-04	1.51E+01	6.10E-02
RF-MT0003	2.16E-04	0.00E+00	8.02E-19	2.99E+00	4.63E-01	0.00E+00	5.72E-05	3.45E+00	1.39E-02
RF-MT0007	5.43E-04	0.00E+00	0.00E+00	3.72E-01	5.77E-02	0.00E+00	0.00E+00	4.30E-01	1.74E-03
RF-MT0089	2.13E-06	0.00E+00	8.02E-21	2.99E-02	4.63E-03	0.00E+00	5.72E-07	3.45E-02	1.39E-04
RF-MT0090	5.41E-03	0.00E+00	1.14E-17	7.67E+01	1.18E+01	0.00E+00	8.10E-04	8.84E+01	3.57E-01
RF-MT0091	3.35E-01	0.00E+00	1.15E-15	5.12E+03	7.92E+02	0.00E+00	8.51E-02	5.91E+03	2.38E+01
RF-MT0092	4.80E-02	0.00E+00	1.45E-16	7.34E+02	1.16E+02	0.00E+00	1.04E-02	8.49E+02	3.42E+00
RF-MT0093	5.85E-02	0.00E+00	1.50E-16	7.92E+02	1.27E+02	0.00E+00	1.07E-02	9.18E+02	3.70E+00
RF-MT0097	2.93E-03	0.00E+00	6.60E-18	4.14E+01	5.76E+00	0.00E+00	4.71E-04	4.71E+01	1.90E-01
RF-MT0099	3.21E-06	0.00E+00	1.21E-20	4.47E-02	6.92E-03	0.00E+00	8.60E-07	5.17E-02	2.08E-04
RF-MT0290	7.95E-03	0.00E+00	2.98E-17	1.11E+02	1.72E+01	0.00E+00	2.13E-03	1.28E+02	5.16E-01
RF-MT-0292	1.00E-02	0.00E+00	3.77E-17	1.40E+02	2.17E+01	0.00E+00	2.69E-03	1.62E+02	6.53E-01
RF-MT-0299	1.18E+00	0.00E+00	9.66E-16	3.59E+03	5.57E+02	0.00E+00	6.89E-02	4.15E+03	1.67E+01
RF-MT0302	1.81E-05	0.00E+00	3.83E-20	1.55E-01	2.41E-02	0.00E+00	1.93E-05	1.79E-01	7.22E-04
RF-MT0320	2.16E-02	0.00E+00	3.97E-17	1.51E+02	2.34E+01	0.00E+00	2.84E-03	1.74E+02	7.01E-01
RF-MT0321	1.21E-02	0.00E+00	1.18E-17	4.84E+01	7.45E+00	0.00E+00	3.22E-03	5.59E+01	2.25E-01
RF-MT-0328	8.35E-04	0.00E+00	1.42E-18	5.27E+00	8.15E-01	0.00E+00	4.35E-04	6.09E+00	2.45E-02
RF-MT0330	8.69E-03	0.00E+00	1.56E-17	1.06E+02	1.78E+01	0.00E+00	1.11E-03	1.24E+02	5.01E-01
RF-MT-0331	5.21E-02	0.00E+00	9.66E-17	4.68E+02	7.10E+01	0.00E+00	2.74E-02	5.39E+02	2.17E+00
RF-MT0332	7.47E-06	0.00E+00	2.82E-20	1.05E-01	1.62E-02	0.00E+00	2.01E-06	1.21E-01	4.87E-04
RF-MT-0335	6.00E-04	0.00E+00	1.29E-18	5.39E+00	8.39E-01	0.00E+00	6.27E-04	6.23E+00	2.51E-02
RF-MT0336	4.25E-02	0.00E+00	8.57E-17	3.82E+02	5.92E+01	0.00E+00	7.90E-03	4.42E+02	1.78E+00
RF-MT0337	2.40E-02	0.00E+00	4.71E-17	2.34E+02	3.56E+01	0.00E+00	7.16E-03	2.69E+02	1.09E+00
RF-MT0339	6.57E-02	0.00E+00	1.28E-16	5.12E+02	7.86E+01	0.00E+00	2.60E-02	5.91E+02	2.38E+00
RF-MT-0342	3.86E-04	0.00E+00	1.08E-18	4.73E+00	7.21E-01	0.00E+00	1.34E-04	5.45E+00	2.20E-02
RF-MT0371	1.31E-01	0.00E+00	2.49E-16	9.26E+02	1.43E+02	0.00E+00	1.90E-02	1.07E+03	4.31E+00
RF-MT-0372	5.69E-04	0.00E+00	1.75E-18	6.45E+00	1.00E+00	0.00E+00	3.61E-04	7.46E+00	3.01E-02
RF-MT0373	8.57E-03	0.00E+00	1.80E-17	1.21E+02	1.87E+01	0.00E+00	1.28E-03	1.40E+02	5.64E-01

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0374	2.78E-04	0.00E+00	6.44E-19	2.40E+00	3.71E-01	0.00E+00	4.92E-05	2.77E+00	1.12E-02
RF-MT0376	2.21E-04	0.00E+00	5.20E-19	2.39E+00	3.76E-01	0.00E+00	5.20E-05	2.76E+00	1.11E-02
RF-MT0377	1.31E-01	0.00E+00	3.00E-16	1.12E+03	1.72E+02	0.00E+00	3.15E-02	1.29E+03	5.20E+00
RF-MT0378	1.47E-03	0.00E+00	4.14E-18	1.54E+01	2.39E+00	0.00E+00	2.95E-04	1.78E+01	7.17E-02
RF-MT0419	2.36E-03	0.00E+00	3.87E-18	1.44E+01	2.23E+00	0.00E+00	2.76E-04	1.66E+01	6.69E-02
RF-MT0420	4.11E-04	0.00E+00	6.71E-19	2.49E+00	3.87E-01	0.00E+00	4.79E-05	2.88E+00	1.16E-02
RF-MT0423	3.49E-03	0.00E+00	5.46E-18	3.60E+01	5.41E+00	0.00E+00	3.89E-04	4.14E+01	1.67E-01
RF-MT0425	1.03E-04	0.00E+00	1.68E-19	6.24E-01	9.68E-02	0.00E+00	1.20E-05	7.21E-01	2.91E-03
RF-MT-0438	9.33E-04	0.00E+00	2.20E-18	1.11E+01	1.70E+00	0.00E+00	1.70E-04	1.28E+01	5.15E-02
RF-MT0440	3.39E-04	0.00E+00	7.91E-19	4.01E+00	6.34E-01	0.00E+00	2.19E-04	4.65E+00	1.87E-02
RF-MT0442	1.29E-04	0.00E+00	3.42E-19	1.38E+00	2.13E-01	0.00E+00	1.18E-04	1.59E+00	6.41E-03
RF-MT0443	1.59E-03	0.00E+00	5.62E-18	2.14E+01	3.31E+00	0.00E+00	5.57E-04	2.47E+01	9.95E-02
RF-MT0444	1.24E-02	0.00E+00	2.76E-17	1.03E+02	1.59E+01	0.00E+00	1.99E-03	1.19E+02	4.79E-01
RF-MT0480	3.46E-02	0.00E+00	7.75E-17	2.89E+02	4.49E+01	0.00E+00	7.95E-03	3.34E+02	1.35E+00
RF-MT0488	5.55E-02	0.00E+00	1.16E-16	4.29E+02	6.63E+01	0.00E+00	3.88E-02	4.95E+02	2.00E+00
RF-MT0490	2.51E-04	0.00E+00	6.71E-19	2.54E+00	3.94E-01	0.00E+00	5.89E-05	2.93E+00	1.18E-02
RF-MT-0491	1.97E-05	0.00E+00	3.07E-20	1.15E-01	1.78E-02	0.00E+00	4.17E-06	1.33E-01	5.36E-04
RF-MT0523A	1.56E-02	0.00E+00	2.44E-17	9.08E+01	1.41E+01	0.00E+00	1.99E-03	1.05E+02	4.23E-01
RF-MT0523B	1.56E-02	0.00E+00	2.44E-17	9.08E+01	1.41E+01	0.00E+00	1.99E-03	1.05E+02	4.23E-01
RF-MT0523C	1.56E-02	0.00E+00	2.44E-17	9.08E+01	1.41E+01	0.00E+00	1.99E-03	1.05E+02	4.23E-01
RF-MT0523D	1.56E-02	0.00E+00	2.44E-17	9.08E+01	1.41E+01	0.00E+00	1.99E-03	1.05E+02	4.23E-01
RF-MT0523E	1.56E-02	0.00E+00	2.44E-17	9.08E+01	1.41E+01	0.00E+00	1.99E-03	1.05E+02	4.23E-01
RF-MT0531	1.07E-06	0.00E+00	4.02E-21	1.49E-02	2.31E-03	0.00E+00	2.86E-07	1.72E-02	6.93E-05
RF-MT0532E	4.98E-02	0.00E+00	5.22E-17	1.98E+02	3.07E+01	0.00E+00	4.82E-03	2.29E+02	9.23E-01
RF-MT0532F	4.98E-02	0.00E+00	5.22E-17	1.98E+02	3.07E+01	0.00E+00	4.82E-03	2.29E+02	9.23E-01
RF-MT0541	1.82E-03	0.00E+00	7.53E-19	2.81E+00	4.35E-01	0.00E+00	5.37E-05	3.25E+00	1.31E-02
RF-MT0545	9.72E-06	0.00E+00	3.65E-20	1.36E-01	2.10E-02	0.00E+00	2.60E-06	1.57E-01	6.32E-04
RF-MT0800	3.69E-01	0.00E+00	1.81E-17	6.70E+01	1.04E+01	0.00E+00	1.77E-03	7.78E+01	3.14E-01
RF-MT0801	4.24E-02	0.00E+00	1.77E-17	6.58E+01	1.02E+01	0.00E+00	1.26E-03	7.61E+01	3.07E-01
RF-MT0803	9.52E-04	0.00E+00	3.96E-19	1.47E+00	2.28E-01	0.00E+00	2.82E-05	1.70E+00	6.85E-03
RF-MT0806	4.49E-04	0.00E+00	9.49E-19	6.39E+00	9.80E-01	0.00E+00	6.77E-05	7.37E+00	2.97E-02

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0807	5.68E-03	0.00E+00	7.31E-18	2.72E+01	4.22E+00	0.00E+00	5.22E-04	3.14E+01	1.27E-01
RF-MT0816	6.08E-04	0.00E+00	1.03E-18	3.83E+00	5.92E-01	0.00E+00	7.35E-05	4.43E+00	1.78E-02
RF-MT-0823	3.01E-04	0.00E+00	4.69E-19	1.75E+00	2.71E-01	0.00E+00	3.83E-05	2.02E+00	8.14E-03
RF-MT0827	1.53E-02	0.00E+00	2.61E-17	9.69E+01	1.50E+01	0.00E+00	1.86E-03	1.12E+02	4.51E-01
RF-MT0831	2.92E-02	0.00E+00	7.15E-17	2.62E+02	4.07E+01	0.00E+00	1.72E-02	3.03E+02	1.22E+00
RF-MT0832	1.75E-01	0.00E+00	2.59E-16	1.02E+03	1.58E+02	0.00E+00	5.14E-02	1.18E+03	4.75E+00
RF-MT0833	5.32E-02	0.00E+00	7.75E-17	2.95E+02	4.58E+01	0.00E+00	1.46E-02	3.41E+02	1.37E+00
RF-MT0855	9.15E-06	0.00E+00	3.44E-20	1.28E-01	1.98E-02	0.00E+00	2.46E-06	1.48E-01	5.96E-04
RF-MT0857	4.49E-04	0.00E+00	9.44E-19	6.38E+00	9.80E-01	0.00E+00	6.73E-05	7.36E+00	2.97E-02
RF-MT0H61	1.67E-02	0.00E+00	3.51E-17	2.36E+02	3.64E+01	0.00E+00	2.50E-03	2.73E+02	1.10E+00
RF-MT2116	1.87E-03	0.00E+00	2.78E-18	1.09E+01	1.69E+00	0.00E+00	5.51E-04	1.26E+01	5.08E-02
RF-MT3010	1.17E-02	0.00E+00	2.89E-17	1.08E+02	1.69E+01	0.00E+00	2.45E-03	1.25E+02	5.04E-01
RF-MT3011	8.75E-02	0.00E+00	1.80E-16	6.68E+02	1.04E+02	0.00E+00	2.05E-02	7.72E+02	3.11E+00
RF-MT420P	4.65E-01	0.00E+00	9.11E-16	5.49E+03	8.51E+02	0.00E+00	7.49E-02	6.34E+03	2.56E+01
RF-MT532A	1.23E-01	0.00E+00	1.29E-16	4.90E+02	7.57E+01	0.00E+00	1.19E-02	5.65E+02	2.28E+00
RF-MT532B	5.51E-01	0.00E+00	5.78E-16	2.20E+03	3.40E+02	0.00E+00	5.33E-02	2.54E+03	1.02E+01
RF-MT532C	1.10E+00	0.00E+00	1.16E-15	4.40E+03	6.80E+02	0.00E+00	1.07E-01	5.09E+03	2.05E+01
RF-MT532D	6.98E-03	0.00E+00	7.31E-18	2.79E+01	4.31E+00	0.00E+00	6.74E-04	3.22E+01	1.30E-01
RF-TT0069	4.02E-05	0.00E+00	8.68E-20	3.23E-01	5.00E-02	0.00E+00	7.87E-05	3.73E-01	1.50E-03
RF-TT0200	1.91E-03	0.00E+00	3.50E-18	1.32E+01	2.07E+00	0.00E+00	2.51E-04	1.53E+01	6.17E-02
RF-TT0299	7.90E-03	0.00E+00	6.49E-18	2.41E+01	3.74E+00	0.00E+00	4.63E-04	2.79E+01	1.12E-01
RF-TT0300	6.44E-02	0.00E+00	1.85E-16	6.93E+02	1.08E+02	0.00E+00	2.14E-02	8.01E+02	3.23E+00
RF-TT0301	8.70E-03	0.00E+00	2.51E-17	9.43E+01	1.47E+01	0.00E+00	2.91E-03	1.09E+02	4.39E-01
RF-TT0302	4.30E-04	0.00E+00	9.11E-19	3.69E+00	5.73E-01	0.00E+00	4.58E-04	4.26E+00	1.72E-02
RF-TT0303	2.59E-03	0.00E+00	5.33E-18	1.98E+01	3.07E+00	0.00E+00	1.40E-03	2.29E+01	9.23E-02
RF-TT0310	8.82E-03	0.00E+00	2.50E-17	8.91E+01	1.43E+01	0.00E+00	1.97E-03	1.03E+02	4.17E-01
RF-TT0312	2.12E-01	0.00E+00	4.51E-16	1.95E+03	2.99E+02	0.00E+00	3.39E-02	2.25E+03	9.06E+00
RF-TT0317	1.33E-04	0.00E+00	4.91E-19	1.83E+00	2.83E-01	0.00E+00	3.50E-05	2.11E+00	8.50E-03
RF-TT0320	8.55E-02	0.00E+00	1.57E-16	5.95E+02	9.27E+01	0.00E+00	1.13E-02	6.88E+02	2.77E+00
RF-TT0330	3.04E-02	0.00E+00	5.44E-17	3.74E+02	6.22E+01	0.00E+00	3.88E-03	4.36E+02	1.76E+00
RF-TT-0331	1.51E-01	0.00E+00	2.81E-16	1.36E+03	2.07E+02	0.00E+00	7.95E-02	1.57E+03	6.31E+00

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT-0334	6.58E-02	0.00E+00	2.28E-16	8.44E+02	1.31E+02	0.00E+00	1.62E-02	9.75E+02	3.93E+00
RF-TT0335	8.03E-02	0.00E+00	1.72E-16	7.18E+02	1.12E+02	0.00E+00	8.35E-02	8.30E+02	3.35E+00
RF-TT0336	7.09E-02	0.00E+00	1.43E-16	6.36E+02	9.85E+01	0.00E+00	1.32E-02	7.35E+02	2.96E+00
RF-TT0337	8.42E-02	0.00E+00	1.65E-16	8.21E+02	1.25E+02	0.00E+00	2.51E-02	9.46E+02	3.82E+00
RF-TT0338	3.57E-01	0.00E+00	6.00E-16	3.20E+03	4.88E+02	0.00E+00	5.10E-02	3.69E+03	1.49E+01
RF-TT0340	3.06E-03	0.00E+00	1.15E-17	4.26E+01	6.63E+00	0.00E+00	8.17E-04	4.92E+01	1.98E-01
RF-TT0342	2.05E-02	0.00E+00	5.73E-17	2.51E+02	3.82E+01	0.00E+00	7.15E-03	2.89E+02	1.17E+00
RF-TT0360	1.56E-03	0.00E+00	2.91E-18	1.13E+01	1.77E+00	0.00E+00	2.14E-04	1.30E+01	5.25E-02
RF-TT0368	3.12E-02	0.00E+00	5.84E-17	2.26E+02	3.54E+01	0.00E+00	4.29E-03	2.61E+02	1.05E+00
RF-TT0370	6.15E-02	0.00E+00	1.26E-16	5.03E+02	7.80E+01	0.00E+00	1.67E-02	5.81E+02	2.34E+00
RF-TT0371	1.33E-03	0.00E+00	2.54E-18	9.43E+00	1.46E+00	0.00E+00	1.94E-04	1.09E+01	4.39E-02
RF-TT0372	1.63E-04	0.00E+00	5.00E-19	1.84E+00	2.86E-01	0.00E+00	1.03E-04	2.13E+00	8.59E-03
RF-TT0374	5.07E-03	0.00E+00	1.17E-17	4.35E+01	6.75E+00	0.00E+00	8.96E-04	5.03E+01	2.03E-01
RF-TT0375A	5.28E-05	0.00E+00	1.93E-19	7.15E-01	1.11E-01	0.00E+00	1.38E-05	8.26E-01	3.33E-03
RF-TT0375B	5.28E-05	0.00E+00	1.93E-19	7.15E-01	1.11E-01	0.00E+00	1.38E-05	8.26E-01	3.33E-03
RF-TT0376	1.21E-02	0.00E+00	2.86E-17	1.32E+02	2.07E+01	0.00E+00	2.86E-03	1.52E+02	6.14E-01
RF-TT0377	6.81E-03	0.00E+00	1.56E-17	5.78E+01	8.97E+00	0.00E+00	1.63E-03	6.68E+01	2.69E-01
RF-TT0391	1.52E-03	0.00E+00	2.19E-18	1.46E+01	2.24E+00	0.00E+00	1.56E-04	1.69E+01	6.80E-02
RF-TT0392	5.35E-04	0.00E+00	1.38E-18	7.64E+00	1.18E+00	0.00E+00	9.82E-05	8.82E+00	3.56E-02
RF-TT0393	4.39E-02	0.00E+00	9.60E-17	3.56E+02	5.52E+01	0.00E+00	6.85E-03	4.11E+02	1.66E+00
RF-TT0398	9.59E-04	0.00E+00	2.53E-18	1.43E+01	2.19E+00	0.00E+00	1.81E-04	1.65E+01	6.64E-02
RF-TT0409	8.02E-04	0.00E+00	1.18E-18	7.37E+00	1.13E+00	0.00E+00	8.51E-05	8.50E+00	3.43E-02
RF-TT0412	8.02E-04	0.00E+00	1.18E-18	7.37E+00	1.13E+00	0.00E+00	8.51E-05	8.50E+00	3.43E-02
RF-TT0414	2.49E-02	0.00E+00	3.66E-17	2.28E+02	3.50E+01	0.00E+00	2.63E-03	2.63E+02	1.06E+00
RF-TT0430	7.27E-06	0.00E+00	2.73E-20	1.01E-01	1.57E-02	0.00E+00	1.95E-06	1.17E-01	4.72E-04
RF-TT0431	1.81E-03	0.00E+00	6.66E-18	2.49E+01	3.87E+00	0.00E+00	6.94E-04	2.88E+01	1.16E-01
RF-TT0438	1.08E-01	0.00E+00	2.54E-16	1.27E+03	1.96E+02	0.00E+00	1.96E-02	1.47E+03	5.92E+00
RF-TT0440	1.06E-02	0.00E+00	2.47E-17	1.25E+02	1.99E+01	0.00E+00	6.85E-03	1.45E+02	5.86E-01
RF-TT0441	5.21E-02	0.00E+00	1.16E-16	4.33E+02	6.75E+01	0.00E+00	1.28E-02	5.01E+02	2.02E+00
RF-TT0442	7.52E-03	0.00E+00	2.00E-17	8.02E+01	1.24E+01	0.00E+00	6.88E-03	9.26E+01	3.74E-01
RF-TT0443	1.61E-04	0.00E+00	5.73E-19	2.17E+00	3.36E-01	0.00E+00	5.67E-05	2.51E+00	1.01E-02

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0479	1.58E-03	0.00E+00	5.95E-18	2.20E+01	3.41E+00	0.00E+00	4.24E-04	2.54E+01	1.02E-01
RF-TT0480	1.07E-01	0.00E+00	2.40E-16	9.00E+02	1.39E+02	0.00E+00	2.47E-02	1.04E+03	4.19E+00
RF-TT0481	6.05E-05	0.00E+00	1.35E-19	5.05E-01	7.86E-02	0.00E+00	1.39E-05	5.84E-01	2.35E-03
RF-TT0483	1.94E-04	0.00E+00	7.31E-19	2.71E+00	4.21E-01	0.00E+00	1.70E-02	3.15E+00	1.27E-02
RF-TT0484	1.04E-03	0.00E+00	3.03E-18	1.13E+01	1.75E+00	0.00E+00	3.26E-04	1.30E+01	5.24E-02
RF-TT0485	8.54E-05	0.00E+00	1.87E-19	6.94E-01	1.08E-01	0.00E+00	2.87E-04	8.02E-01	3.23E-03
RF-TT0486	5.06E-04	0.00E+00	1.11E-18	4.12E+00	6.39E-01	0.00E+00	3.04E-04	4.76E+00	1.92E-02
RF-TT0487	2.54E-03	0.00E+00	3.77E-18	1.48E+01	2.29E+00	0.00E+00	7.46E-04	1.71E+01	6.89E-02
RF-TT0489	7.24E-04	0.00E+00	1.69E-18	6.28E+00	9.74E-01	0.00E+00	2.20E-04	7.26E+00	2.93E-02
RF-TT0490	4.00E-02	0.00E+00	1.08E-16	4.05E+02	6.28E+01	0.00E+00	9.43E-03	4.68E+02	1.89E+00
RF-TT0491	9.31E-04	0.00E+00	1.45E-18	5.42E+00	8.39E-01	0.00E+00	1.98E-04	6.26E+00	2.53E-02
RF-TT0492	3.13E-04	0.00E+00	8.18E-19	3.03E+00	4.70E-01	0.00E+00	5.84E-05	3.50E+00	1.41E-02
RF-TT0523A	2.10E-03	0.00E+00	3.28E-18	1.22E+01	1.89E+00	0.00E+00	2.68E-04	1.41E+01	5.68E-02
RF-TT0523B	2.10E-03	0.00E+00	3.28E-18	1.22E+01	1.89E+00	0.00E+00	2.68E-04	1.41E+01	5.68E-02
RF-TT0523C	2.10E-03	0.00E+00	3.28E-18	1.22E+01	1.89E+00	0.00E+00	2.68E-04	1.41E+01	5.68E-02
RF-TT0523D	2.10E-03	0.00E+00	3.28E-18	1.22E+01	1.89E+00	0.00E+00	2.68E-04	1.41E+01	5.68E-02
RF-TT0523E	2.10E-03	0.00E+00	3.28E-18	1.22E+01	1.89E+00	0.00E+00	2.68E-04	1.41E+01	5.68E-02
RF-TT0532A	5.28E-02	0.00E+00	5.51E-17	2.10E+02	3.25E+01	0.00E+00	5.08E-03	2.43E+02	9.79E-01
RF-TT0532B	5.28E-02	0.00E+00	5.51E-17	2.10E+02	3.25E+01	0.00E+00	5.08E-03	2.43E+02	9.79E-01
RF-TT0541	8.72E-05	0.00E+00	3.28E-19	1.22E+00	1.89E-01	0.00E+00	2.34E-05	1.41E+00	5.68E-03
RF-TT0545	1.94E-05	0.00E+00	7.31E-20	2.71E-01	4.21E-02	0.00E+00	5.21E-06	3.13E-01	1.26E-03
RF-TT0601	6.75E-03	0.00E+00	1.26E-17	4.89E+01	7.68E+00	0.00E+00	9.26E-04	5.66E+01	2.28E-01
RF-TT0802	7.55E-01	0.00E+00	1.04E-15	3.86E+03	5.98E+02	0.00E+00	7.39E-02	4.46E+03	1.80E+01
RF-TT0809	6.21E-02	0.00E+00	8.51E-17	3.18E+02	4.90E+01	0.00E+00	6.07E-03	3.67E+02	1.48E+00
RF-TT0821	1.34E-01	0.00E+00	3.09E-16	1.25E+03	1.94E+02	0.00E+00	1.88E-01	1.44E+03	5.81E+00
RF-TT0822	1.49E-01	0.00E+00	2.41E-16	9.34E+02	1.44E+02	0.00E+00	1.97E-01	1.08E+03	4.35E+00
RF-TT0823	3.01E-04	0.00E+00	4.69E-19	1.75E+00	2.71E-01	0.00E+00	3.83E-05	2.02E+00	8.14E-03
RF-TT0824	3.10E-01	0.00E+00	6.60E-16	2.52E+03	3.90E+02	0.00E+00	1.09E-01	2.91E+03	1.17E+01
RF-TT0825	2.57E-01	0.00E+00	4.77E-16	1.90E+03	2.93E+02	0.00E+00	1.14E-01	2.19E+03	8.82E+00
RF-TT0832	1.90E-01	0.00E+00	2.83E-16	1.11E+03	1.72E+02	0.00E+00	5.60E-02	1.28E+03	5.16E+00
RF-TT0854	6.85E-05	0.00E+00	2.58E-19	9.52E-01	1.48E-01	0.00E+00	7.55E-04	1.10E+00	4.44E-03

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0886	9.71E-06	0.00E+00	3.64E-20	1.35E-01	2.10E-02	0.00E+00	2.60E-06	1.56E-01	6.29E-04
RF-TT2216	2.81E-03	0.00E+00	4.17E-18	1.64E+01	2.53E+00	0.00E+00	8.27E-04	1.90E+01	7.65E-02
RF-TT3010	1.50E-01	0.00E+00	3.69E-16	1.38E+03	2.15E+02	0.00E+00	3.13E-02	1.60E+03	6.45E+00
RF-TT3011	3.79E-01	0.00E+00	7.80E-16	2.89E+03	4.49E+02	0.00E+00	8.89E-02	3.34E+03	1.35E+01
RF-TT301U	3.15E-02	0.00E+00	8.24E-17	3.14E+02	4.95E+01	0.00E+00	6.03E-03	3.64E+02	1.47E+00
RF-TT310P	9.10E-03	0.00E+00	2.14E-17	1.06E+02	1.55E+01	0.00E+00	1.53E-03	1.21E+02	4.88E-01
RF-TT338S	2.66E-04	0.00E+00	9.82E-19	3.64E+00	5.65E-01	0.00E+00	7.00E-05	4.21E+00	1.70E-02
RF-TT390P	1.50E-03	0.00E+00	2.66E-18	1.77E+01	2.53E+00	0.00E+00	2.18E-04	2.03E+01	8.17E-02
RF-TT391P	8.26E-02	0.00E+00	1.20E-16	7.97E+02	1.21E+02	0.00E+00	8.52E-03	9.18E+02	3.70E+00
RF-TT392P	1.67E-01	0.00E+00	4.31E-16	2.39E+03	3.69E+02	0.00E+00	3.08E-02	2.76E+03	1.11E+01
RF-TT393R	2.47E-02	0.00E+00	7.31E-17	3.65E+02	5.68E+01	0.00E+00	5.39E-03	4.22E+02	1.70E+00
RF-TT394P	3.07E-03	0.00E+00	4.52E-18	2.82E+01	4.05E+00	0.00E+00	3.30E-04	3.23E+01	1.30E-01
RF-TT395P	4.11E-03	0.00E+00	6.06E-18	3.77E+01	5.41E+00	0.00E+00	4.41E-04	4.31E+01	1.74E-01
RF-TT396P	1.03E-03	0.00E+00	1.51E-18	9.43E+00	1.36E+00	0.00E+00	1.10E-04	1.08E+01	4.35E-02
RF-TT398P	9.93E-02	0.00E+00	2.62E-16	1.48E+03	2.27E+02	0.00E+00	1.87E-02	1.71E+03	6.88E+00
RF-TT398R	8.18E-01	0.00E+00	4.87E-16	2.39E+03	3.67E+02	0.00E+00	3.47E-02	2.76E+03	1.11E+01
RF-TT411R	2.97E-02	0.00E+00	4.37E-17	2.73E+02	4.18E+01	0.00E+00	3.14E-03	3.14E+02	1.27E+00
RF-TT429R	6.23E-02	0.00E+00	9.38E-18	6.32E+01	9.50E+00	0.00E+00	6.69E-04	7.27E+01	2.93E-01
RF-TT433X	1.96E-02	0.00E+00	2.60E-18	1.82E+01	2.47E+00	0.00E+00	1.85E-04	2.07E+01	8.33E-02
RF-TT436R	1.44E-01	0.00E+00	3.76E-17	2.38E+02	3.64E+01	0.00E+00	2.68E-03	2.75E+02	1.11E+00
RF-TT454X	8.44E-03	0.00E+00	2.21E-18	1.40E+01	2.15E+00	0.00E+00	1.58E-04	1.62E+01	6.52E-02
RL-T101	4.28E-02	0.00E+00	1.34E-16	7.57E+02	1.15E+02	0.00E+00	8.71E-03	8.72E+02	3.52E+00
RL-T102	5.44E-07	0.00E+00	1.71E-21	9.69E-03	1.47E-03	0.00E+00	1.24E-06	1.12E-02	4.50E-05
RL-T103	3.85E-02	0.00E+00	1.63E-16	3.31E+02	4.99E+01	0.00E+00	1.06E-02	3.80E+02	1.53E+00
RL-T104	7.79E-07	0.00E+00	2.44E-21	1.38E-02	2.10E-03	0.00E+00	1.90E-07	1.59E-02	6.39E-05
RL-T105	2.99E-04	0.00E+00	9.22E-19	5.23E+00	7.92E-01	0.00E+00	1.04E-04	6.02E+00	2.43E-02
RL-T106	2.88E-04	0.00E+00	9.06E-19	5.10E+00	7.74E-01	0.00E+00	5.88E-05	5.88E+00	2.37E-02
RL-T107	7.92E-01	0.00E+00	5.32E-13	1.41E+04	2.14E+03	0.00E+00	3.53E+01	1.63E+04	6.56E+01
RL-T108	4.53E-04	0.00E+00	9.17E-17	8.03E+00	1.22E+00	0.00E+00	5.98E-03	9.25E+00	3.73E-02
RL-T109	6.24E-04	0.00E+00	1.89E-18	1.06E+01	1.62E+00	0.00E+00	2.31E-02	1.23E+01	4.95E-02
RL-T110	6.99E-02	0.00E+00	3.60E-16	1.22E+03	1.86E+02	0.00E+00	1.36E+00	1.41E+03	5.67E+00

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T112	2.82E-02	0.00E+00	1.52E-16	1.62E+02	2.46E+01	0.00E+00	7.35E-01	1.87E+02	7.55E-01
RL-T113	3.01E-05	0.00E+00	2.94E-19	5.33E-01	8.09E-02	0.00E+00	1.91E-05	6.14E-01	2.48E-03
RL-T114	4.57E-03	0.00E+00	1.44E-17	8.10E+01	1.23E+01	0.00E+00	9.31E-04	9.33E+01	3.76E-01
RL-T115	1.16E-01	0.00E+00	4.65E-16	1.06E+03	1.62E+02	0.00E+00	4.37E-01	1.23E+03	4.95E+00
RL-T116	7.51E-03	0.00E+00	2.36E-17	1.32E+02	2.02E+01	0.00E+00	5.69E-02	1.53E+02	6.15E-01
RL-T118	1.93E-02	0.00E+00	1.88E-16	1.32E+02	2.00E+01	0.00E+00	8.33E-01	1.52E+02	6.14E-01
RL-T120	4.68E-03	0.00E+00	1.98E-17	3.89E+01	5.87E+00	0.00E+00	1.28E-03	4.48E+01	1.81E-01
RL-T122	2.65E-04	0.00E+00	8.35E-19	4.69E+00	7.16E-01	0.00E+00	1.44E+00	6.84E+00	2.76E-02
RL-T123	7.81E-04	0.00E+00	2.44E-18	1.38E+01	2.10E+00	0.00E+00	5.90E-02	1.59E+01	6.42E-02
RL-T125	1.55E-01	0.00E+00	6.06E-16	2.88E+02	1.01E+02	0.00E+00	3.93E-02	3.89E+02	1.57E+00
RL-T127	1.50E-01	0.00E+00	1.52E-16	8.61E+02	1.31E+02	0.00E+00	8.87E-02	9.92E+02	4.00E+00
RL-T128	2.22E-04	0.00E+00	3.70E-24	2.09E-05	3.17E-06	0.00E+00	2.40E-10	2.46E-04	9.91E-07
RL-T129	6.64E-04	0.00E+00	7.04E-16	1.19E+01	1.79E+00	0.00E+00	5.32E-02	1.37E+01	5.52E-02
RL-T130	1.41E-06	0.00E+00	4.45E-21	2.52E-02	3.82E-03	0.00E+00	8.21E-05	2.91E-02	1.17E-04
RL-T131	5.74E-04	0.00E+00	2.43E-18	4.79E+00	7.21E-01	0.00E+00	8.27E-03	5.52E+00	2.23E-02
RL-T132	1.37E-01	0.00E+00	4.29E-16	2.43E+03	3.69E+02	0.00E+00	2.69E-01	2.80E+03	1.13E+01
RL-T133	2.79E-06	0.00E+00	6.88E-21	3.99E-02	6.04E-03	0.00E+00	4.46E-07	4.59E-02	1.85E-04
RL-T134	5.90E-06	0.00E+00	1.85E-20	1.05E-01	1.58E-02	0.00E+00	1.20E-06	1.21E-01	4.86E-04
RL-T135	2.76E-05	0.00E+00	8.68E-20	4.90E-01	7.45E-02	0.00E+00	4.10E-03	5.68E-01	2.29E-03
RL-T137	4.49E-01	0.00E+00	1.89E-15	3.73E+03	5.63E+02	0.00E+00	1.29E-01	4.29E+03	1.73E+01
RL-T140	5.24E-01	0.00E+00	1.80E-15	3.61E+03	6.04E+02	0.00E+00	2.60E+01	4.24E+03	1.71E+01
RL-T143	3.29E-03	0.00E+00	1.03E-17	5.83E+01	8.86E+00	0.00E+00	3.87E-02	6.72E+01	2.71E-01
RL-T145	9.36E-03	0.00E+00	2.94E-17	1.66E+02	2.52E+01	0.00E+00	9.02E-02	1.91E+02	7.72E-01
RL-W407	2.69E-02	0.00E+00	6.27E-17	3.81E+02	5.78E+01	0.00E+00	4.07E-03	4.39E+02	1.77E+00
RL-W408	1.10E-07	0.00E+00	2.65E-22	1.54E-03	2.34E-04	0.00E+00	1.72E-08	1.77E-03	7.15E-06
RL-W415	2.44E-06	0.00E+00	5.84E-21	3.41E-02	5.17E-03	0.00E+00	3.79E-07	3.93E-02	1.58E-04
RL-W418	1.04E-05	0.00E+00	2.46E-20	1.46E-01	2.22E-02	0.00E+00	1.60E-06	1.68E-01	6.79E-04
RL-W437	8.83E-02	0.00E+00	2.06E-16	1.25E+03	1.89E+02	0.00E+00	1.34E-02	1.44E+03	5.79E+00
RL-W438	1.54E-07	0.00E+00	3.71E-22	2.15E-03	3.27E-04	0.00E+00	2.40E-08	2.48E-03	1.00E-05
RL-W439	4.84E+00	0.00E+00	2.04E-14	4.15E+04	6.28E+03	0.00E+00	1.32E+00	4.78E+04	1.93E+02
RL-W443	7.77E-02	0.00E+00	1.82E-16	1.10E+03	1.67E+02	0.00E+00	1.18E-02	1.27E+03	5.10E+00

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W444	5.76E-02	0.00E+00	1.35E-16	8.15E+02	1.24E+02	0.00E+00	8.74E-03	9.39E+02	3.79E+00
RL-W447	6.61E-06	0.00E+00	1.59E-20	9.17E-02	1.40E-02	0.00E+00	1.03E-06	1.06E-01	4.26E-04
RL-W448	4.89E-08	0.00E+00	1.17E-22	6.81E-04	1.03E-04	0.00E+00	7.61E-09	7.84E-04	3.16E-06
RL-W449	4.01E-04	0.00E+00	4.29E-21	1.95E-02	2.96E-03	0.00E+00	2.79E-07	2.28E-02	9.20E-05
RL-W450	7.37E-07	0.00E+00	1.77E-21	1.03E-02	1.56E-03	0.00E+00	1.15E-07	1.19E-02	4.78E-05
RL-W451	1.05E-07	0.00E+00	2.52E-22	1.46E-03	2.22E-04	0.00E+00	1.64E-08	1.68E-03	6.79E-06
RL-W452	4.58E-06	0.00E+00	1.09E-20	6.45E-02	9.80E-03	0.00E+00	7.04E-07	7.43E-02	2.99E-04
RL-W453	1.31E-06	0.00E+00	3.06E-21	1.85E-02	2.80E-03	0.00E+00	1.98E-07	2.13E-02	8.60E-05
RL-W454	1.82E-05	0.00E+00	4.27E-20	2.59E-01	3.92E-02	0.00E+00	2.77E-06	2.98E-01	1.20E-03
RL-W455	4.87E-06	0.00E+00	1.15E-20	6.84E-02	1.04E-02	0.00E+00	7.47E-07	7.88E-02	3.18E-04
RL-W456	6.41E-04	0.00E+00	1.51E-18	9.08E+00	1.38E+00	0.00E+00	9.77E-05	1.05E+01	4.22E-02
RL-W457	6.23E-05	0.00E+00	1.46E-19	8.82E-01	1.34E-01	0.00E+00	9.49E-06	1.02E+00	4.10E-03
RL-W458	1.97E-04	0.00E+00	7.48E-19	3.63E-01	1.37E-01	0.00E+00	4.85E-05	5.00E-01	2.02E-03
RL-W459	1.90E-03	0.00E+00	7.69E-18	9.00E+00	1.87E+00	0.00E+00	4.99E-04	1.09E+01	4.38E-02
RL-W460	1.16E-05	0.00E+00	2.71E-20	1.64E-01	2.49E-02	0.00E+00	1.76E-06	1.88E-01	7.60E-04
RL-W461	1.07E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.07E-05	4.30E-08
RL-W462	3.30E-06	0.00E+00	7.86E-21	4.63E-02	7.04E-03	0.00E+00	5.10E-07	5.33E-02	2.15E-04
RL-W463	1.70E-05	0.00E+00	3.97E-20	2.41E-01	3.65E-02	0.00E+00	2.58E-06	2.77E-01	1.12E-03
RL-W464	7.83E-06	0.00E+00	1.83E-20	1.11E-01	1.68E-02	0.00E+00	1.19E-06	1.28E-01	5.14E-04
RL-W465	5.23E-05	0.00E+00	1.24E-19	7.37E-01	1.12E-01	0.00E+00	8.03E-06	8.49E-01	3.42E-03
RL-W466	7.15E-04	0.00E+00	1.69E-18	1.01E+01	1.54E+00	0.00E+00	1.09E-04	1.17E+01	4.70E-02
RL-W467	3.67E-05	0.00E+00	8.68E-20	5.16E-01	7.80E-02	0.00E+00	5.63E-06	5.94E-01	2.39E-03
RL-W468	1.88E-07	0.00E+00	4.47E-22	2.64E-03	4.01E-04	0.00E+00	2.90E-08	3.04E-03	1.23E-05
RL-W469	7.62E-05	0.00E+00	1.80E-19	1.07E+00	1.64E-01	0.00E+00	1.16E-05	1.24E+00	4.99E-03
RL-W470	2.16E-03	0.00E+00	8.35E-18	3.98E+00	1.40E+00	0.00E+00	5.42E-04	5.38E+00	2.17E-02
RL-W474	8.17E-05	0.00E+00	9.22E-19	9.08E-03	5.28E-03	0.00E+00	5.98E-05	1.45E-02	5.85E-05
RL-W476	1.38E-04	0.00E+00	3.32E-19	1.99E+00	3.03E-01	0.00E+00	2.15E-05	2.29E+00	9.25E-03
RL-W480	2.25E-05	0.00E+00	5.31E-20	3.16E-01	4.80E-02	0.00E+00	3.45E-06	3.64E-01	1.47E-03
RL-W481	3.53E-05	0.00E+00	8.35E-20	4.96E-01	7.51E-02	0.00E+00	5.42E-06	5.71E-01	2.30E-03
RL-W482	4.69E-02	0.00E+00	2.78E-17	6.31E-02	7.98E-02	0.00E+00	1.80E-03	1.92E-01	7.72E-04
RL-W483	3.50E-03	0.00E+00	2.16E-18	4.08E-03	5.67E-03	0.00E+00	1.40E-04	1.34E-02	5.40E-05

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W484	1.48E-05	0.00E+00	1.74E-20	5.70E-02	9.27E-03	0.00E+00	1.13E-06	6.63E-02	2.67E-04
RL-W485	8.67E-07	0.00E+00	2.46E-21	6.17E-03	1.00E-03	0.00E+00	1.59E-07	7.17E-03	2.89E-05
RL-W486	3.66E-07	0.00E+00	1.04E-21	2.60E-03	4.22E-04	0.00E+00	6.72E-08	3.03E-03	1.22E-05
RL-W487	5.98E-05	0.00E+00	1.33E-19	3.73E-01	6.98E-02	0.00E+00	8.64E-06	4.43E-01	1.79E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	3.64E-05	0.00E+00	1.26E-19	4.83E-01	7.45E-02	0.00E+00	8.14E-06	5.57E-01	2.25E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	1.35E-05	0.00E+00	1.06E-19	5.06E-02	7.57E-03	0.00E+00	6.87E-06	5.82E-02	2.35E-04
RL-W492	7.78E-07	0.00E+00	2.61E-21	1.01E-02	1.55E-03	0.00E+00	1.69E-07	1.17E-02	4.71E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	3.08E-02	0.00E+00	1.51E-16	2.55E-01	1.48E-01	0.00E+00	9.80E-03	4.44E-01	1.79E-03
RL-W495	5.58E-04	0.00E+00	4.11E-19	2.45E-03	1.33E-03	0.00E+00	2.67E-05	4.36E-03	1.76E-05
RL-W496	3.62E-03	0.00E+00	4.73E-18	8.05E-03	4.39E-03	0.00E+00	3.07E-04	1.64E-02	6.60E-05
RL-W497	1.51E-04	0.00E+00	9.33E-19	4.83E-01	1.49E-01	0.00E+00	6.05E-05	6.32E-01	2.55E-03
RL-W498	5.86E-04	0.00E+00	1.39E-18	8.25E+00	1.26E+00	0.00E+00	8.99E-05	9.51E+00	3.83E-02
RL-W499	5.26E-09	0.00E+00	1.24E-23	7.40E-05	1.13E-05	0.00E+00	8.07E-10	8.52E-05	3.44E-07
RL-W500	3.75E-07	0.00E+00	1.54E-21	3.02E-03	4.56E-04	0.00E+00	1.00E-07	3.48E-03	1.40E-05
RL-W501	1.55E-02	0.00E+00	3.44E-17	9.69E+01	1.81E+01	0.00E+00	2.23E-03	1.15E+02	4.64E-01
RL-W502	2.81E-06	0.00E+00	6.66E-21	3.95E-02	5.98E-03	0.00E+00	4.32E-07	4.54E-02	1.83E-04
RL-W503	1.62E-04	0.00E+00	6.82E-19	1.39E+00	2.10E-01	0.00E+00	4.42E-05	1.60E+00	6.46E-03
RL-W504	5.98E-05	0.00E+00	1.33E-19	3.73E-01	6.98E-02	0.00E+00	8.64E-06	4.43E-01	1.79E-03
RL-W505	2.82E-06	0.00E+00	6.98E-21	4.03E-02	6.10E-03	0.00E+00	4.53E-07	4.64E-02	1.87E-04
RL-W506	1.02E-06	0.00E+00	2.74E-21	1.32E-02	2.01E-03	0.00E+00	1.78E-07	1.53E-02	6.15E-05
RL-W507	1.01E-07	0.00E+00	2.40E-22	1.43E-03	2.16E-04	0.00E+00	1.56E-08	1.64E-03	6.63E-06
RL-W508	1.86E-03	0.00E+00	7.86E-18	1.55E+01	2.34E+00	0.00E+00	5.10E-04	1.78E+01	7.19E-02
RL-W509	1.83E-02	0.00E+00	6.27E-17	1.26E+02	2.11E+01	0.00E+00	4.07E-03	1.47E+02	5.94E-01
RL-W510	1.55E-03	0.00E+00	6.44E-18	1.25E+01	1.89E+00	0.00E+00	4.18E-04	1.44E+01	5.82E-02
RL-W511	1.57E-01	0.00E+00	3.10E-16	1.68E+03	2.50E+02	0.00E+00	2.05E-02	1.93E+03	7.78E+00
RL-W512	1.38E-01	0.00E+00	2.10E-16	1.01E+03	1.71E+02	0.00E+00	1.36E-02	1.18E+03	4.77E+00
RL-W513	1.47E+01	0.00E+00	8.51E-14	1.65E+04	5.58E+03	0.00E+00	5.52E+00	2.21E+04	8.92E+01
RL-W514	4.15E-07	0.00E+00	9.77E-22	5.86E-03	8.92E-04	0.00E+00	6.34E-08	6.75E-03	2.72E-05

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W515	1.62E-05	0.00E+00	3.83E-20	2.28E-01	3.46E-02	0.00E+00	2.48E-06	2.63E-01	1.06E-03
RL-W516	2.25E-05	0.00E+00	5.32E-20	3.16E-01	4.80E-02	0.00E+00	3.45E-06	3.64E-01	1.47E-03
RL-W517	2.00E-13	0.00E+00	4.76E-28	2.81E-09	4.26E-10	0.00E+00	3.09E-14	3.24E-09	1.31E-11
RL-W518	5.67E-04	0.00E+00	2.00E-18	4.03E+00	6.63E-01	0.00E+00	1.30E-04	4.70E+00	1.89E-02
RL-W519	1.01E-04	0.00E+00	2.37E-19	1.43E+00	2.16E-01	0.00E+00	1.54E-05	1.64E+00	6.63E-03
RL-W520	1.12E-05	0.00E+00	2.67E-20	1.57E-01	2.38E-02	0.00E+00	1.73E-06	1.80E-01	7.27E-04
RL-W521	2.08E-07	0.00E+00	4.91E-22	2.92E-03	4.43E-04	0.00E+00	3.18E-08	3.36E-03	1.35E-05
RL-W522	4.34E-03	0.00E+00	1.82E-17	1.93E+01	3.76E+00	0.00E+00	1.18E-03	2.31E+01	9.30E-02
RL-W523	1.30E-03	0.00E+00	6.93E-18	1.28E+00	5.30E-01	0.00E+00	4.50E-04	1.81E+00	7.31E-03
RL-W524	5.41E-03	0.00E+00	2.65E-17	1.18E+01	3.10E+00	0.00E+00	1.72E-03	1.49E+01	6.00E-02
RL-W525	4.30E-04	0.00E+00	1.80E-18	1.39E+00	3.14E-01	0.00E+00	1.16E-04	1.71E+00	6.88E-03
RL-W526	1.63E-03	0.00E+00	6.49E-18	1.49E+01	2.26E+00	0.00E+00	4.21E-04	1.72E+01	6.91E-02
RL-W527	1.78E-04	0.00E+00	9.38E-19	1.57E+00	2.55E-01	0.00E+00	6.09E-05	1.83E+00	7.38E-03
RL-W528	7.97E-02	0.00E+00	3.99E-16	5.02E+01	3.27E+01	0.00E+00	2.59E-02	8.30E+01	3.35E-01
RL-W529	6.64E-05	0.00E+00	2.80E-19	5.54E-01	8.33E-02	0.00E+00	1.82E-05	6.37E-01	2.57E-03
RL-W530	7.83E-04	0.00E+00	3.25E-18	6.32E+00	9.56E-01	0.00E+00	2.11E-04	7.28E+00	2.94E-02
RL-W531	4.67E-02	0.00E+00	3.26E-16	2.73E+01	1.34E+01	0.00E+00	2.12E-02	4.08E+01	1.65E-01
RL-W532	1.50E-04	0.00E+00	3.55E-19	2.11E+00	3.20E-01	0.00E+00	2.30E-05	2.43E+00	9.80E-03
RL-W533	7.25E-05	0.00E+00	3.06E-19	6.04E-01	9.09E-02	0.00E+00	1.99E-05	6.95E-01	2.80E-03
RL-W534	4.19E-09	0.00E+00	9.88E-24	5.89E-05	8.97E-06	0.00E+00	6.41E-10	6.79E-05	2.74E-07
RL-W535	2.19E-02	0.00E+00	9.77E-17	7.55E+01	1.57E+01	0.00E+00	6.34E-03	9.13E+01	3.68E-01
RL-W536	4.29E-04	0.00E+00	1.32E-18	2.62E+00	4.05E-01	0.00E+00	8.85E-05	3.03E+00	1.22E-02
RL-W537	1.46E-02	0.00E+00	2.97E-17	1.61E+02	2.41E+01	0.00E+00	1.95E-03	1.85E+02	7.46E-01
RL-W538	5.32E-08	0.00E+00	1.26E-22	7.48E-04	1.14E-04	0.00E+00	8.14E-09	8.62E-04	3.48E-06
RL-W539	5.90E-06	0.00E+00	1.41E-20	8.27E-02	1.26E-02	0.00E+00	9.17E-07	9.53E-02	3.84E-04
RL-W540	1.15E-02	0.00E+00	6.22E-17	2.98E+01	6.98E+00	0.00E+00	4.04E-03	3.68E+01	1.48E-01
RL-W541	1.71E-05	0.00E+00	4.08E-20	2.40E-01	3.64E-02	0.00E+00	2.64E-06	2.76E-01	1.11E-03
RL-W542	7.94E-04	0.00E+00	3.03E-18	6.06E+00	9.56E-01	0.00E+00	1.96E-04	7.02E+00	2.83E-02
RL-W543	2.50E-06	0.00E+00	5.89E-21	3.51E-02	5.34E-03	0.00E+00	3.82E-07	4.05E-02	1.63E-04
RL-W544	5.63E-05	0.00E+00	2.41E-19	4.00E-01	6.80E-02	0.00E+00	1.56E-05	4.68E-01	1.89E-03
RL-W545	1.50E-05	0.00E+00	3.54E-20	2.10E-01	3.20E-02	0.00E+00	2.29E-06	2.42E-01	9.77E-04

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W546	6.55E-07	0.00E+00	1.55E-21	9.26E-03	1.40E-03	0.00E+00	1.01E-07	1.07E-02	4.30E-05
RL-W547	1.68E-08	0.00E+00	3.96E-23	2.35E-04	3.58E-05	0.00E+00	2.57E-09	2.71E-04	1.09E-06
RL-W548	1.45E-08	0.00E+00	3.44E-23	2.03E-04	3.09E-05	0.00E+00	2.23E-09	2.34E-04	9.44E-07
RL-W549	2.88E-03	0.00E+00	1.38E-17	1.05E+01	2.12E+00	0.00E+00	8.95E-04	1.26E+01	5.08E-02
RL-W550	1.30E-02	0.00E+00	2.61E-17	1.42E+02	2.12E+01	0.00E+00	1.71E-03	1.63E+02	6.58E-01
RL-W551	2.32E-02	0.00E+00	3.86E-17	1.60E+02	2.77E+01	0.00E+00	2.51E-03	1.88E+02	7.57E-01
RL-W552	8.99E-06	0.00E+00	2.14E-20	1.26E-01	1.91E-02	0.00E+00	1.39E-06	1.45E-01	5.86E-04
RL-W553	7.97E-07	0.00E+00	2.02E-21	1.13E-02	1.71E-03	0.00E+00	1.31E-07	1.30E-02	5.22E-05
RL-W554	1.27E-05	0.00E+00	3.00E-20	1.78E-01	2.71E-02	0.00E+00	1.94E-06	2.05E-01	8.28E-04
RL-W555	5.83E-06	0.00E+00	1.38E-20	8.21E-02	1.24E-02	0.00E+00	8.95E-07	9.45E-02	3.81E-04
RL-W563	8.37E-05	0.00E+00	3.45E-19	6.81E-01	1.03E-01	0.00E+00	2.24E-05	7.84E-01	3.16E-03
RL-W564	5.45E-05	0.00E+00	2.29E-19	4.40E-01	6.63E-02	0.00E+00	1.49E-05	5.07E-01	2.04E-03
RL-W565	5.41E-06	0.00E+00	1.29E-20	7.60E-02	1.16E-02	0.00E+00	8.35E-07	8.76E-02	3.53E-04
RL-W566	7.94E-05	0.00E+00	1.89E-19	1.12E+00	1.70E-01	0.00E+00	1.23E-05	1.29E+00	5.19E-03
RL-W567	5.51E-03	0.00E+00	4.82E-18	3.43E-02	1.89E-02	0.00E+00	3.13E-04	5.91E-02	2.38E-04
RL-W568	1.06E-01	0.00E+00	1.02E-16	1.63E+00	8.80E-01	0.00E+00	6.58E-03	2.62E+00	1.06E-02
RL-W569	8.71E-05	0.00E+00	7.64E-20	5.42E-04	2.99E-05	0.00E+00	4.96E-06	6.64E-04	2.68E-06
RL-W570	5.58E-06	0.00E+00	1.34E-20	8.06E-02	1.22E-02	0.00E+00	8.67E-07	9.28E-02	3.74E-04
RL-W571	1.79E-02	0.00E+00	4.54E-17	6.54E+00	2.23E+00	0.00E+00	2.95E-03	8.79E+00	3.54E-02
RL-W572	1.55E-05	0.00E+00	1.36E-20	3.52E-03	5.34E-05	0.00E+00	8.81E-07	3.59E-03	1.45E-05
RL-W573	2.00E-01	0.00E+00	1.74E-16	1.93E+00	9.85E-01	0.00E+00	1.13E-02	3.13E+00	1.26E-02
RL-W574	8.60E-01	0.00E+00	7.53E-16	7.37E+00	3.65E+00	0.00E+00	4.88E-02	1.19E+01	4.81E-02
RL-W575	5.60E+00	0.00E+00	5.07E-15	7.05E+01	2.92E+01	0.00E+00	3.29E-01	1.06E+02	4.26E-01
RL-W576	4.04E-01	0.00E+00	3.54E-16	3.59E+00	1.76E+00	0.00E+00	2.30E-02	5.78E+00	2.33E-02
RL-W579	3.42E-05	0.00E+00	9.33E-21	1.80E-02	2.74E-03	0.00E+00	6.05E-07	2.08E-02	8.37E-05
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.44E-01	1.60E-02	0.00E+00	0.00E+00	1.60E-01	6.43E-04
RL-W581	3.63E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.63E-04	1.46E-06
RL-W582	2.37E-06	0.00E+00	7.91E-21	4.60E-03	1.63E-03	0.00E+00	5.13E-07	6.23E-03	2.51E-05
RL-W583	1.84E-06	0.00E+00	4.30E-21	2.60E-02	3.95E-03	0.00E+00	2.79E-07	2.99E-02	1.21E-04
RL-W584	3.65E-05	0.00E+00	2.82E-19	1.51E-01	5.06E-02	0.00E+00	1.83E-05	2.02E-01	8.15E-04
RL-W585	2.17E-04	0.00E+00	1.50E-18	8.82E-01	3.07E-01	0.00E+00	9.73E-05	1.19E+00	4.80E-03

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W586	2.90E-08	0.00E+00	6.77E-23	4.10E-04	6.22E-05	0.00E+00	4.39E-09	4.72E-04	1.90E-06
RL-W587	6.20E-07	0.00E+00	1.46E-21	8.74E-03	1.33E-03	0.00E+00	9.49E-08	1.01E-02	4.06E-05
RL-W588	2.56E-05	0.00E+00	2.38E-19	1.28E-01	4.26E-02	0.00E+00	1.54E-05	1.71E-01	6.88E-04
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	7.85E-04	0.00E+00	5.07E-18	9.86E-03	1.20E-02	0.00E+00	3.29E-04	2.29E-02	9.25E-05
RL-W591	4.47E-03	0.00E+00	5.73E-18	1.22E-02	1.55E-02	0.00E+00	3.72E-04	3.25E-02	1.31E-04
RL-W592	1.98E-02	0.00E+00	6.27E-17	5.66E-01	5.01E-01	0.00E+00	4.07E-03	1.09E+00	4.40E-03
RL-W593	0.00E+00	0.00E+00	0.00E+00	2.04E-02	2.35E-02	0.00E+00	0.00E+00	4.39E-02	1.77E-04
RL-W594	1.78E-02	0.00E+00	1.13E-17	2.53E-02	3.18E-02	0.00E+00	7.33E-04	7.56E-02	3.05E-04
RL-W595	4.70E-05	0.00E+00	1.18E-18	1.73E-02	2.31E-02	0.00E+00	7.64E-05	4.05E-02	1.63E-04
RL-W596	1.52E-05	0.00E+00	9.17E-20	1.78E-04	2.17E-04	0.00E+00	5.95E-06	4.16E-04	1.68E-06
RL-W597	2.80E-02	0.00E+00	4.03E-17	3.45E-01	3.94E-01	0.00E+00	2.62E-03	7.69E-01	3.10E-03
RL-W598	2.96E-02	0.00E+00	2.38E-16	4.81E-01	4.91E-01	0.00E+00	1.54E-02	1.02E+00	4.10E-03
RL-W599	1.50E-03	0.00E+00	1.92E-18	4.07E-03	5.17E-03	0.00E+00	1.25E-04	1.09E-02	4.38E-05
RL-W600	8.51E-11	0.00E+00	1.99E-25	1.20E-06	1.83E-07	0.00E+00	1.29E-11	1.39E-06	5.59E-09
RL-W601	4.32E-07	0.00E+00	1.09E-21	6.09E-03	9.27E-04	0.00E+00	7.08E-08	7.02E-03	2.83E-05
RL-W602	3.76E-04	0.00E+00	8.95E-19	5.28E+00	8.04E-01	0.00E+00	5.80E-05	6.08E+00	2.45E-02
RL-W603	2.17E-03	0.00E+00	5.16E-18	3.05E+01	4.63E+00	0.00E+00	3.35E-04	3.51E+01	1.42E-01
RL-W604	5.07E-06	0.00E+00	1.35E-20	1.48E-02	4.99E-03	0.00E+00	8.78E-07	1.98E-02	7.98E-05
RL-W605	1.16E-06	0.00E+00	2.94E-21	1.64E-02	2.49E-03	0.00E+00	1.91E-07	1.88E-02	7.60E-05
RL-W606	4.69E-07	0.00E+00	1.18E-21	6.59E-03	1.00E-03	0.00E+00	7.68E-08	7.60E-03	3.06E-05
RL-W607	8.59E-07	0.00E+00	2.29E-21	2.50E-03	8.45E-04	0.00E+00	1.49E-07	3.35E-03	1.35E-05
RL-W608	1.03E-05	0.00E+00	8.89E-20	3.25E-03	2.74E-03	0.00E+00	5.77E-06	6.01E-03	2.42E-05
RL-W610	2.03E-03	0.00E+00	4.76E-18	2.87E+01	4.36E+00	0.00E+00	3.09E-04	3.31E+01	1.33E-01
RL-W612	4.79E-06	0.00E+00	1.15E-20	6.97E-02	1.06E-02	0.00E+00	7.47E-07	8.04E-02	3.24E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	2.92E-01	0.00E+00	0.00E+00	0.00E+00	2.92E-01	1.18E-03
RL-W622	7.99E-08	0.00E+00	1.88E-22	1.13E-03	1.72E-04	0.00E+00	1.22E-08	1.31E-03	5.26E-06
RL-W625	2.79E-06	0.00E+00	2.85E-20	5.79E-03	3.88E-03	0.00E+00	1.85E-06	9.68E-03	3.90E-05
RL-W626	1.50E-04	0.00E+00	6.49E-19	2.27E-01	9.27E-02	0.00E+00	4.21E-05	3.20E-01	1.29E-03
RL-W627	7.05E-07	0.00E+00	8.68E-22	1.07E-06	0.00E+00	0.00E+00	5.63E-08	1.83E-06	7.40E-09
RL-W628	2.31E-07	0.00E+00	5.45E-22	3.27E-03	4.96E-04	0.00E+00	3.54E-08	3.77E-03	1.52E-05

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W629	1.57E-08	0.00E+00	3.75E-23	2.20E-04	3.33E-05	0.00E+00	2.43E-09	2.53E-04	1.02E-06
RL-W630	1.72E-04	0.00E+00	6.98E-19	2.54E+00	4.02E-01	0.00E+00	4.53E-05	2.95E+00	1.19E-02
RL-W631	2.78E-06	0.00E+00	7.04E-21	3.90E-02	5.92E-03	0.00E+00	4.57E-07	4.49E-02	1.81E-04
RL-W632	1.23E-03	0.00E+00	9.49E-19	5.16E+00	1.16E+00	0.00E+00	6.16E-05	6.31E+00	2.55E-02
RL-W633	2.92E-06	0.00E+00	5.51E-21	8.10E-04	4.88E-04	0.00E+00	3.57E-07	1.30E-03	5.25E-06
RL-W634	0.00E+00	0.00E+00	0.00E+00	8.82E-03	0.00E+00	0.00E+00	0.00E+00	8.82E-03	3.56E-05
RL-W635	1.75E-02	0.00E+00	1.86E-16	3.75E+00	3.83E+00	0.00E+00	1.21E-02	7.61E+00	3.07E-02
RL-W636	1.78E-04	0.00E+00	3.51E-19	4.91E-02	2.96E-02	0.00E+00	2.28E-05	7.89E-02	3.18E-04
RL-W637	4.24E-07	0.00E+00	8.95E-21	5.52E-04	3.70E-04	0.00E+00	5.80E-07	9.22E-04	3.72E-06
RL-W638	1.86E-05	0.00E+00	9.11E-20	5.41E-03	3.47E-03	0.00E+00	5.91E-06	8.90E-03	3.59E-05
RL-W639	9.84E-07	0.00E+00	2.33E-21	1.38E-02	2.10E-03	0.00E+00	1.51E-07	1.59E-02	6.43E-05
RL-W640	3.30E-05	0.00E+00	7.75E-20	4.66E-01	7.10E-02	0.00E+00	5.03E-06	5.37E-01	2.17E-03
RL-W641	1.01E-03	0.00E+00	1.70E-17	2.24E+00	6.28E-01	0.00E+00	1.10E-03	2.87E+00	1.16E-02
RL-W642	1.97E-05	0.00E+00	1.77E-21	2.73E-02	9.50E-05	0.00E+00	1.15E-07	2.75E-02	1.11E-04
RL-W643	3.10E-04	0.00E+00	5.24E-18	6.90E-01	1.94E-01	0.00E+00	3.40E-04	8.85E-01	3.57E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	4.75E-02	0.00E+00	0.00E+00	0.00E+00	4.75E-02	1.92E-04
RL-W645	7.54E-06	0.00E+00	2.36E-20	9.34E-02	1.50E-02	0.00E+00	1.53E-06	1.08E-01	4.37E-04
RL-W646	6.85E-06	0.00E+00	2.11E-20	2.23E-02	7.39E-03	0.00E+00	1.37E-06	2.97E-02	1.20E-04
RL-W647	1.93E-05	0.00E+00	3.15E-18	9.52E-02	1.03E-02	0.00E+00	2.04E-04	1.06E-01	4.26E-04
RL-W648	3.42E-07	0.00E+00	5.38E-21	5.20E-05	6.98E-05	0.00E+00	3.49E-07	1.23E-04	4.94E-07
RL-W649	1.26E-06	0.00E+00	1.98E-20	1.91E-04	2.56E-04	0.00E+00	1.29E-06	4.50E-04	1.82E-06
RL-W653	5.95E-08	0.00E+00	1.42E-22	8.36E-04	1.27E-04	0.00E+00	9.20E-09	9.62E-04	3.88E-06
RL-W654	3.27E-07	0.00E+00	7.75E-22	4.60E-03	6.98E-04	0.00E+00	5.03E-08	5.30E-03	2.14E-05
RL-W655	8.06E-02	0.00E+00	1.83E-16	1.83E-01	2.94E-01	0.00E+00	1.19E-02	5.69E-01	2.29E-03
RL-W656	3.37E-01	0.00E+00	8.24E-17	4.29E-01	3.02E-01	0.00E+00	5.34E-03	1.07E+00	4.33E-03
RL-W657	1.72E-01	0.00E+00	1.22E-16	2.11E-01	2.87E-01	0.00E+00	7.89E-03	6.79E-01	2.74E-03
RL-W659	2.08E-02	0.00E+00	2.74E-17	4.07E-02	3.44E-02	0.00E+00	1.78E-03	9.77E-02	3.94E-04
RL-W660	1.14E-01	0.00E+00	3.30E-16	7.50E-01	9.15E-01	0.00E+00	2.14E-02	1.80E+00	7.26E-03
RL-W661	1.21E-03	0.00E+00	4.13E-19	3.62E-04	2.25E-03	0.00E+00	2.68E-05	3.84E-03	1.55E-05
RL-W662	3.81E-05	0.00E+00	2.46E-20	9.26E-05	1.13E-04	0.00E+00	1.60E-06	2.45E-04	9.90E-07
RL-W665	4.68E-01	0.00E+00	1.97E-15	1.13E+00	1.04E+00	0.00E+00	1.28E-01	2.77E+00	1.12E-02

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W666	8.37E-03	0.00E+00	4.82E-18	4.75E-02	3.41E-02	0.00E+00	3.13E-04	9.03E-02	3.64E-04
RL-W668	7.97E-04	0.00E+00	1.52E-19	1.25E-01	2.43E-02	0.00E+00	9.84E-06	1.51E-01	6.07E-04
RL-W669	2.33E-04	0.00E+00	3.93E-18	5.17E-01	1.45E-01	0.00E+00	2.55E-04	6.63E-01	2.67E-03
RL-W670	1.47E-05	0.00E+00	2.80E-21	2.32E-03	4.49E-04	0.00E+00	1.82E-07	2.78E-03	1.12E-05
RL-W671	2.40E-03	0.00E+00	1.44E-18	4.25E-03	3.02E-03	0.00E+00	9.31E-05	9.75E-03	3.93E-05
RL-W672	1.63E-02	0.00E+00	9.77E-18	2.90E-02	2.05E-02	0.00E+00	6.34E-04	6.64E-02	2.68E-04
RL-W673	1.57E-02	0.00E+00	9.38E-18	2.80E-02	1.98E-02	0.00E+00	6.09E-04	6.41E-02	2.59E-04
RL-W674	5.27E-05	0.00E+00	4.20E-19	9.69E+00	5.75E-02	0.00E+00	2.72E-05	9.75E+00	3.93E-02
RL-W675	1.97E-04	0.00E+00	2.32E-18	1.13E-01	6.69E-02	0.00E+00	1.50E-04	1.81E-01	7.28E-04
RL-W676	7.57E-06	0.00E+00	1.39E-20	1.27E-01	1.26E-03	0.00E+00	9.03E-07	1.28E-01	5.18E-04
RL-W677	1.75E-02	0.00E+00	3.45E-17	4.97E+00	2.94E+00	0.00E+00	2.24E-03	7.93E+00	3.20E-02
RL-W678	5.55E-05	0.00E+00	2.88E-19	4.46E-02	2.69E-02	0.00E+00	1.87E-05	7.16E-02	2.89E-04
RL-W679	3.48E-04	0.00E+00	6.44E-19	9.60E-02	5.78E-02	0.00E+00	4.18E-05	1.54E-01	6.22E-04
RL-W680	7.83E-08	0.00E+00	9.06E-22	1.51E-05	1.85E-05	0.00E+00	5.88E-08	3.37E-05	1.36E-07
RL-W681	4.78E-08	0.00E+00	3.67E-22	4.04E-04	1.37E-04	0.00E+00	2.38E-08	5.41E-04	2.18E-06
RL-W685	1.39E-04	0.00E+00	3.26E-19	1.97E+00	2.99E-01	0.00E+00	2.12E-05	2.27E+00	9.16E-03
RL-W689	3.61E-06	0.00E+00	3.92E-21	3.35E-04	0.00E+00	0.00E+00	2.54E-07	3.39E-04	1.37E-06
RL-W690	1.21E-04	0.00E+00	2.88E-19	1.76E+00	2.66E-01	0.00E+00	1.87E-05	2.02E+00	8.15E-03
RL-W691	2.81E-06	0.00E+00	6.71E-21	4.07E-02	6.16E-03	0.00E+00	4.35E-07	4.68E-02	1.89E-04
RL-W692	1.11E-04	0.00E+00	2.66E-19	1.61E+00	2.44E-01	0.00E+00	1.72E-05	1.85E+00	7.47E-03
RL-W693	1.38E-04	0.00E+00	3.28E-19	1.99E+00	3.02E-01	0.00E+00	2.13E-05	2.29E+00	9.24E-03
RL-W694	1.44E-03	0.00E+00	3.44E-18	2.10E+01	3.17E+00	0.00E+00	2.23E-04	2.42E+01	9.75E-02
RL-W695	1.20E-06	0.00E+00	0.00E+00	2.07E-03	0.00E+00	0.00E+00	0.00E+00	2.07E-03	8.34E-06
RL-W696	1.56E-06	0.00E+00	1.26E-20	2.52E-03	1.70E-03	0.00E+00	8.14E-07	4.22E-03	1.70E-05
RL-W697	3.60E-04	0.00E+00	2.66E-17	6.00E-03	5.61E-04	0.00E+00	1.72E-03	8.64E-03	3.48E-05
RL-W698	3.12E-05	0.00E+00	0.00E+00	2.85E-05	0.00E+00	0.00E+00	0.00E+00	5.97E-05	2.41E-07
RL-W699	6.94E-06	0.00E+00	1.77E-21	1.90E-03	1.53E-04	0.00E+00	1.15E-07	2.06E-03	8.32E-06
RL-W700	1.97E-06	0.00E+00	4.64E-21	2.76E-02	4.19E-03	0.00E+00	3.01E-07	3.18E-02	1.28E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	7.74E-05	0.00E+00	1.31E-18	1.72E-01	4.84E-02	0.00E+00	8.49E-05	2.21E-01	8.90E-04

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W705	5.01E-07	0.00E+00	1.21E-21	7.23E-03	1.10E-03	0.00E+00	7.82E-08	8.34E-03	3.36E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	1.79E-05	0.00E+00	4.29E-20	2.58E-01	3.92E-02	0.00E+00	2.78E-06	2.97E-01	1.20E-03
RL-W708	2.70E-06	0.00E+00	6.49E-21	3.91E-02	5.92E-03	0.00E+00	4.21E-07	4.50E-02	1.82E-04
RL-W709	9.34E-04	0.00E+00	2.24E-18	1.35E+01	2.05E+00	0.00E+00	1.45E-04	1.55E+01	6.27E-02
RL-W710	5.57E-08	0.00E+00	1.34E-22	8.06E-04	1.22E-04	0.00E+00	8.67E-09	9.28E-04	3.74E-06
RL-W711	1.74E-05	0.00E+00	4.17E-20	2.52E-01	3.82E-02	0.00E+00	2.71E-06	2.90E-01	1.17E-03
RL-W712	2.25E-05	0.00E+00	5.40E-20	3.25E-01	4.94E-02	0.00E+00	3.50E-06	3.75E-01	1.51E-03
RL-W713	1.95E-05	0.00E+00	4.67E-20	2.80E-01	4.27E-02	0.00E+00	3.03E-06	3.23E-01	1.30E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	3.36E-07	0.00E+00	7.86E-22	4.75E-03	7.21E-04	0.00E+00	5.10E-08	5.47E-03	2.21E-05
RL-W716	3.50E-06	0.00E+00	8.18E-21	4.95E-02	7.51E-03	0.00E+00	5.31E-07	5.70E-02	2.30E-04
RL-W717	8.73E-07	0.00E+00	2.05E-21	1.24E-02	1.88E-03	0.00E+00	1.33E-07	1.43E-02	5.75E-05
RL-W718	1.54E-07	0.00E+00	3.61E-22	2.18E-03	3.31E-04	0.00E+00	2.34E-08	2.51E-03	1.01E-05
RL-W719	6.94E-07	0.00E+00	1.63E-21	9.86E-03	1.50E-03	0.00E+00	1.06E-07	1.14E-02	4.58E-05
RL-W720	4.30E-06	0.00E+00	1.01E-20	6.09E-02	9.27E-03	0.00E+00	6.55E-07	7.02E-02	2.83E-04
RL-W721	2.91E-06	0.00E+00	6.82E-21	4.12E-02	6.28E-03	0.00E+00	4.42E-07	4.75E-02	1.91E-04
RL-W723	9.65E-06	0.00E+00	2.30E-20	1.40E-01	2.12E-02	0.00E+00	1.49E-06	1.61E-01	6.51E-04
RL-W724	6.42E-05	0.00E+00	1.53E-19	9.26E-01	1.41E-01	0.00E+00	9.95E-06	1.07E+00	4.30E-03
RL-W725	2.03E-05	0.00E+00	4.83E-20	2.93E-01	4.46E-02	0.00E+00	3.14E-06	3.38E-01	1.36E-03
RL-W726	1.60E-05	0.00E+00	3.81E-20	2.32E-01	3.51E-02	0.00E+00	2.47E-06	2.67E-01	1.08E-03
RL-W727	9.79E-05	0.00E+00	2.34E-19	1.42E+00	2.16E-01	0.00E+00	1.52E-05	1.64E+00	6.59E-03
RL-W728	8.92E-05	0.00E+00	2.13E-19	1.30E+00	1.97E-01	0.00E+00	1.38E-05	1.49E+00	6.03E-03
RL-W729	4.12E-05	0.00E+00	9.88E-20	5.97E-01	9.09E-02	0.00E+00	6.41E-06	6.88E-01	2.77E-03
RL-W730	1.61E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.61E-02	6.50E-05
RL-W731	5.20E-09	0.00E+00	0.00E+00	3.90E-04	1.09E-06	0.00E+00	0.00E+00	3.91E-04	1.58E-06
RL-W732	1.19E-02	0.00E+00	5.62E-17	1.10E+02	1.66E+01	0.00E+00	3.65E-03	1.27E+02	5.10E-01
RL-W733	1.56E-04	0.00E+00	7.31E-19	1.19E+00	2.02E-01	0.00E+00	4.74E-05	1.40E+00	5.63E-03
RL-W734	4.89E-04	0.00E+00	2.44E-18	4.12E+00	6.80E-01	0.00E+00	1.58E-04	4.80E+00	1.94E-02
RL-W735	3.99E-04	0.00E+00	1.86E-18	3.21E+00	5.43E-01	0.00E+00	1.21E-04	3.75E+00	1.51E-02
RL-W736	4.39E-07	0.00E+00	3.97E-24	2.13E-03	3.74E-04	0.00E+00	2.57E-10	2.50E-03	1.01E-05

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W737	3.57E-04	0.00E+00	1.70E-18	3.05E+00	5.05E-01	0.00E+00	1.10E-04	3.55E+00	1.43E-02
RL-W738	1.33E-03	0.00E+00	5.84E-18	9.69E+00	1.74E+00	0.00E+00	3.79E-04	1.14E+01	4.61E-02
RL-W739	1.13E-04	0.00E+00	5.15E-19	1.57E+00	2.45E-01	0.00E+00	3.34E-05	1.82E+00	7.34E-03
RL-W740	5.67E-03	0.00E+00	1.89E-17	3.83E+01	6.80E+00	0.00E+00	1.23E-03	4.51E+01	1.82E-01
RL-W741	8.47E-03	0.00E+00	4.44E-17	7.47E+00	3.61E+00	0.00E+00	2.88E-03	1.11E+01	4.47E-02
RL-W742	3.77E-04	0.00E+00	1.34E-18	2.42E+00	3.89E-01	0.00E+00	8.67E-05	2.81E+00	1.13E-02
RL-W743	6.79E-07	0.00E+00	3.63E-22	1.57E-03	0.00E+00	0.00E+00	2.35E-08	1.57E-03	6.32E-06
RL-W744	0.00E+00	0.00E+00	0.00E+00	7.81E-02	4.53E-02	0.00E+00	0.00E+00	1.23E-01	4.98E-04
RL-W745	1.07E-06	0.00E+00	2.54E-21	1.51E-02	2.29E-03	0.00E+00	1.65E-07	1.74E-02	7.03E-05
RL-W746	4.13E-06	0.00E+00	9.77E-21	5.81E-02	8.86E-03	0.00E+00	6.34E-07	6.70E-02	2.70E-04
RL-W747	1.12E-05	0.00E+00	2.65E-20	1.57E-01	2.39E-02	0.00E+00	1.72E-06	1.81E-01	7.31E-04
RL-W748	7.84E-02	0.00E+00	7.42E-17	2.61E-01	2.93E-01	0.00E+00	4.81E-03	6.37E-01	2.57E-03
RL-W749	9.41E-05	0.00E+00	2.27E-19	1.37E+00	2.07E-01	0.00E+00	1.47E-05	1.57E+00	6.35E-03
RL-W750	1.19E-01	0.00E+00	1.12E-16	4.28E-01	4.78E-01	0.00E+00	7.29E-03	1.03E+00	4.16E-03
RL-W751	1.07E-01	0.00E+00	1.02E-16	3.85E-01	4.33E-01	0.00E+00	6.58E-03	9.32E-01	3.76E-03
RL-W752	4.67E-02	0.00E+00	4.41E-17	1.68E-01	1.88E-01	0.00E+00	2.86E-03	4.06E-01	1.64E-03
RL-W753	6.28E-01	0.00E+00	5.95E-16	2.26E+00	2.53E+00	0.00E+00	3.86E-02	5.45E+00	2.20E-02
RP-W754	2.67E-02	0.00E+00	7.53E-17	1.61E+03	8.97E+01	0.00E+00	3.53E-01	1.70E+03	6.85E+00
RP-W755	1.41E-01	0.00E+00	4.51E-17	1.20E+03	6.80E+01	0.00E+00	1.24E+01	1.28E+03	5.17E+00
SA-T001	2.84E-04	1.09E-83	1.08E-18	2.62E+00	1.06E-02	0.00E+00	7.47E-05	2.63E+00	1.06E-02
SA-W134	2.32E-03	4.22E-87	7.37E-18	1.19E+00	2.58E-01	0.00E+00	1.65E-01	1.62E+00	6.53E-03
SA-W134M	3.01E-04	5.47E-88	9.55E-19	1.56E-01	3.34E-02	0.00E+00	2.14E-02	2.11E-01	8.50E-04
T001-221F-HET	5.61E-01	0.00E+00	8.62E-13	2.49E+04	4.19E+02	0.00E+00	6.15E+01	2.54E+04	1.02E+02
T001-221H-HET	1.01E+00	0.00E+00	1.56E-12	4.50E+04	7.57E+02	0.00E+00	1.11E+02	4.59E+04	1.85E+02
T001-235F-HET	5.81E-02	0.00E+00	8.95E-14	2.59E+03	4.35E+01	0.00E+00	6.38E+00	2.64E+03	1.06E+01
T001-772F-HET	5.00E-01	0.00E+00	7.75E-13	2.23E+04	3.75E+02	0.00E+00	5.52E+01	2.28E+04	9.17E+01
T001-773A-CLAS	5.62E-03	0.00E+00	8.68E-15	2.51E+02	4.21E+00	0.00E+00	6.19E-01	2.56E+02	1.03E+00
T001-773A-HET	6.48E-02	0.00E+00	9.98E-14	2.89E+03	4.86E+01	0.00E+00	7.12E+00	2.95E+03	1.19E+01
W006-773A-VIT	8.67E-07	0.00E+00	0.00E+00	4.65E+02	0.00E+00	0.00E+00	0.00E+00	4.65E+02	1.87E+00
W026-221F-HET	1.95E-01	0.00E+00	3.01E-13	8.74E+03	1.46E+02	0.00E+00	2.14E+01	8.91E+03	3.59E+01
W026-221H-HET	1.46E-01	0.00E+00	2.25E-13	6.51E+03	1.09E+02	0.00E+00	1.60E+01	6.63E+03	2.67E+01

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W026-235F-HET	2.27E-03	0.00E+00	3.50E-15	1.01E+02	1.70E+00	0.00E+00	2.50E-01	1.03E+02	4.16E-01
W026-772F-HET	6.21E-04	0.00E+00	9.55E-16	2.76E+01	4.63E-01	0.00E+00	6.81E-02	2.81E+01	1.13E-01
W026-773A-HET	1.01E-02	0.00E+00	1.56E-14	4.50E+02	7.57E+00	0.00E+00	1.11E+00	4.59E+02	1.85E+00
W027-221F-HET	7.36E-01	0.00E+00	1.02E-12	3.37E+04	5.65E+02	0.00E+00	8.34E+01	3.44E+04	1.39E+02
W027-221H-HET	3.22E-01	0.00E+00	4.43E-13	1.48E+04	2.48E+02	0.00E+00	3.64E+01	1.51E+04	6.08E+01
W027-235F-HET	9.68E-02	0.00E+00	1.33E-13	4.45E+03	7.45E+01	0.00E+00	1.10E+01	4.53E+03	1.83E+01
W027-772F-HET	1.76E-01	0.00E+00	2.42E-13	8.07E+03	1.36E+02	0.00E+00	1.99E+01	8.23E+03	3.32E+01
W027-773A-HET	2.62E-01	0.00E+00	3.61E-13	1.20E+04	2.02E+02	0.00E+00	2.97E+01	1.23E+04	4.94E+01
W027-999-HET	3.00E-01	0.00E+00	4.13E-13	1.38E+04	2.31E+02	0.00E+00	3.40E+01	1.40E+04	5.65E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.45E+02	0.00E+00	0.00E+00	0.00E+00	3.45E+02	1.39E+00
WP-INW169.001	1.47E-03	0.00E+00	2.60E-18	1.33E+01	2.02E+00	0.00E+00	3.32E-04	1.53E+01	6.19E-02
WP-INW198.001	1.93E-03	0.00E+00	4.54E-18	2.39E+01	3.59E+00	0.00E+00	3.75E-04	2.75E+01	1.11E-01
WP-INW211.001	2.17E-01	0.00E+00	4.26E-16	2.22E+03	3.33E+02	0.00E+00	2.96E-02	2.55E+03	1.03E+01
WP-INW216.001-	7.90E+00	0.00E+00	2.45E-16	1.28E+03	1.94E+02	0.00E+00	2.89E-01	1.48E+03	5.98E+00
WP-INW216.001-	2.17E+00	0.00E+00	6.60E-17	3.47E+02	5.22E+01	0.00E+00	3.15E-02	4.01E+02	1.62E+00
WP-INW218.001-	1.51E-01	0.00E+00	4.32E-17	2.23E+02	3.37E+01	0.00E+00	3.83E-01	2.57E+02	1.04E+00
WP-INW218.001-	6.96E-04	0.00E+00	1.19E-18	6.07E+00	9.15E-01	0.00E+00	3.70E-02	7.03E+00	2.83E-02
WP-INW222.001	7.15E-03	0.00E+00	1.28E-17	5.93E+01	9.03E+00	0.00E+00	1.40E-03	6.84E+01	2.76E-01
WP-INW243.001	1.73E-02	0.00E+00	2.77E-17	1.25E+02	1.90E+01	0.00E+00	2.65E-03	1.44E+02	5.79E-01
WP-INW247.001R	2.32E-02	0.00E+00	6.44E-17	2.39E+02	3.70E+01	0.00E+00	4.25E-03	2.76E+02	1.11E+00
WP-INW276.001	1.77E-03	0.00E+00	6.27E-18	2.36E+01	3.66E+00	0.00E+00	4.24E-04	2.73E+01	1.10E-01
WP-INW276.002	2.80E-03	0.00E+00	9.44E-18	3.47E+01	5.49E+00	0.00E+00	6.38E-04	4.02E+01	1.62E-01
WP-INW276.003	1.07E-01	0.00E+00	3.51E-16	1.29E+03	2.00E+02	0.00E+00	2.32E-02	1.49E+03	6.00E+00
WP-INW276.004	2.56E-02	0.00E+00	7.42E-17	2.73E+02	4.22E+01	0.00E+00	4.96E-03	3.15E+02	1.27E+00
WP-INW296.001-	9.37E-03	0.00E+00	1.76E-17	6.84E+01	1.06E+01	0.00E+00	1.18E-03	7.90E+01	3.19E-01
WP-INW296.001-	2.83E-02	0.00E+00	6.22E-17	2.42E+02	3.73E+01	0.00E+00	4.39E-03	2.80E+02	1.13E+00
WP-LA-TA-55-19	4.71E-04	0.00E+00	2.89E-18	1.81E+00	2.97E-01	0.00E+00	2.79E-03	2.11E+00	8.50E-03
WP-LA-TA-55-19	2.28E-02	0.00E+00	9.71E-17	1.84E+02	3.06E+01	0.00E+00	9.23E-02	2.15E+02	8.67E-01
WP-LA-TA-55-43	1.28E-04	0.00E+00	2.26E-15	2.79E-01	8.04E-02	0.00E+00	1.73E-01	5.33E-01	2.15E-03
WP-RF001.01	3.96E-02	0.00E+00	7.86E-17	3.55E+02	5.50E+01	0.00E+00	1.43E-02	4.10E+02	1.65E+00
WP-RF002.01-A	4.60E-02	0.00E+00	1.05E-16	4.00E+02	6.22E+01	0.00E+00	2.43E-02	4.62E+02	1.86E+00

Table PAR-58. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 5,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF002.01-B	4.57E-05	0.00E+00	7.26E-20	4.33E-01	6.69E-02	0.00E+00	4.90E-06	5.00E-01	2.01E-03
WP-RF003.01	7.15E-01	0.00E+00	1.69E-15	7.64E+03	1.19E+03	0.00E+00	1.18E-01	8.82E+03	3.56E+01
WP-RF004.01	3.35E-04	0.00E+00	1.13E-18	4.40E+00	6.86E-01	0.00E+00	1.99E-04	5.09E+00	2.05E-02
WP-RF005.01	1.72E+00	0.00E+00	8.57E-16	4.04E+03	6.22E+02	0.00E+00	5.74E-02	4.66E+03	1.88E+01
WP-RF005.02	2.02E+00	0.00E+00	4.43E-16	2.41E+03	3.69E+02	0.00E+00	2.99E-02	2.79E+03	1.12E+01
WP-RF006.01	6.57E-01	0.00E+00	1.61E-15	6.87E+03	1.07E+03	0.00E+00	1.30E-01	7.94E+03	3.20E+01
WP-RF008.01	2.08E-01	0.00E+00	5.73E-16	2.01E+03	3.17E+02	0.00E+00	3.84E-02	2.33E+03	9.37E+00
WP-RF009.01	2.05E+01	0.00E+00	7.04E-15	4.40E+04	6.69E+03	0.00E+00	4.77E-01	5.07E+04	2.05E+02
WP-RF010.01	7.55E-03	0.00E+00	1.78E-17	6.65E+01	1.03E+01	0.00E+00	1.88E-03	7.69E+01	3.10E-01
WP-RF029.01-A	1.82E-03	0.00E+00	3.36E-18	1.17E+01	1.82E+00	0.00E+00	9.37E-04	1.35E+01	5.44E-02
WP-RF029.01-B	2.71E-03	0.00E+00	2.66E-18	9.26E+00	1.44E+00	0.00E+00	2.39E-03	1.07E+01	4.31E-02
WP-RF118.01	4.61E+00	0.00E+00	1.34E-14	4.45E+04	6.75E+03	0.00E+00	1.08E+00	5.12E+04	2.07E+02
WP-RLMPDT.001	9.78E-04	0.00E+00	3.90E-18	6.37E+00	1.13E+00	0.00E+00	2.55E-04	7.49E+00	3.02E-02
WP-RLNPDT.002	1.20E-02	0.00E+00	3.72E-17	6.25E+01	1.14E+01	0.00E+00	2.45E-03	7.40E+01	2.98E-01
WP-SR2001.001.	3.82E-04	0.00E+00	4.27E-18	5.91E+00	7.98E-01	0.00E+00	2.82E-04	6.71E+00	2.70E-02
WP-SR-W027-221	2.83E-03	0.00E+00	1.26E-17	1.70E+01	3.22E+00	0.00E+00	1.84E-01	2.04E+01	8.21E-02
Total	1.52E+02	2.11E-80	8.79E-12	5.71E+05	6.28E+04	0.00E+00	7.35E+02	6.35E+05	2.56E+03

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	5.18E-04	0.00E+00	2.57E-25	1.68E+02	5.58E+01	0.00E+00	1.93E-02	2.24E+02	9.03E-01
AE-T003	6.56E-05	0.00E+00	3.43E-26	5.20E+01	1.13E+01	0.00E+00	9.44E-04	6.33E+01	2.55E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	2.91E-07	0.00E+00	9.08E-25	3.83E+01	1.30E-01	0.00E+00	2.26E-02	3.85E+01	1.55E-01
AW-T033.1325	1.06E-06	0.00E+00	3.33E-24	1.40E+02	4.73E-01	0.00E+00	8.26E-02	1.41E+02	5.67E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	6.22E-01	0.00E+00	0.00E+00	0.00E+00	6.22E-01	2.51E-03
BCLCH-MT01	1.07E-04	0.00E+00	2.57E-23	2.31E+01	3.39E+00	0.00E+00	6.26E-01	2.71E+01	1.09E-01
BT-T002	7.88E-08	0.00E+00	1.35E-26	5.84E-04	6.69E-04	0.00E+00	2.28E-03	3.53E-03	1.42E-05
ET-C1-B55	3.29E-07	0.00E+00	1.53E-28	5.00E-02	1.40E-02	0.00E+00	2.35E-04	6.42E-02	2.59E-04
ET-C1-D139	4.52E-08	0.00E+00	2.13E-29	7.03E-03	1.96E-03	0.00E+00	5.77E-07	8.99E-03	3.63E-05
ET-C2-SEFOR	1.12E-06	0.00E+00	0.00E+00	1.10E-01	2.07E-02	0.00E+00	0.00E+00	1.31E-01	5.28E-04
FM-MOX-MT02	1.06E-11	0.00E+00	8.56E-33	2.42E-07	8.05E-08	0.00E+00	2.16E-10	3.22E-07	1.30E-09
FM-MOX-T01	1.75E-10	0.00E+00	1.41E-31	3.98E-06	1.33E-06	0.00E+00	3.57E-09	5.31E-06	2.14E-08
IN-BN-510	4.23E-02	0.00E+00	7.29E-22	3.20E+04	1.52E+03	0.00E+00	1.96E+01	3.35E+04	1.35E+02
IN-GEM-01	5.35E-04	0.00E+00	1.45E-26	3.59E+01	4.59E+00	0.00E+00	3.51E-04	4.05E+01	1.63E-01
IN-GEM-02	1.27E-04	0.00E+00	3.44E-27	8.53E+00	1.09E+00	0.00E+00	8.36E-05	9.63E+00	3.88E-02
IN-W157.144	6.33E-04	0.00E+00	1.40E-25	2.44E+02	3.09E+01	0.00E+00	3.77E-03	2.75E+02	1.11E+00
IN-W163.1007	1.08E-04	0.00E+00	4.32E-26	7.57E+01	9.58E+00	0.00E+00	1.16E-03	8.53E+01	3.44E-01
IN-W164.153	1.04E-06	0.00E+00	4.12E-28	7.20E-01	9.13E-02	0.00E+00	1.11E-05	8.12E-01	3.27E-03
IN-W167.149	2.08E-04	0.00E+00	6.70E-26	1.17E+02	1.48E+01	0.00E+00	1.80E-03	1.32E+02	5.30E-01
IN-W174.154	0.00E+00	0.00E+00	3.79E-23	1.57E+00	1.73E+00	0.00E+00	1.02E+00	4.32E+00	1.74E-02
IN-W177.156	1.44E-07	0.00E+00	8.06E-23	1.47E+00	5.04E-03	0.00E+00	2.17E+00	3.65E+00	1.47E-02
IN-W179.158	9.69E-07	0.00E+00	8.03E-23	8.53E-02	2.48E-02	0.00E+00	2.16E+00	2.27E+00	9.16E-03
IN-W181.162	1.38E-05	0.00E+00	5.47E-27	9.50E+00	1.21E+00	0.00E+00	1.47E-04	1.07E+01	4.32E-02
IN-W188.160	9.25E-05	0.00E+00	3.67E-26	6.42E+01	8.10E+00	0.00E+00	9.89E-04	7.23E+01	2.91E-01
IN-W216.98	8.22E-01	0.00E+00	2.99E-24	5.23E+03	6.66E+02	0.00E+00	8.06E-02	5.90E+03	2.38E+01
IN-W218.909	4.15E-03	0.00E+00	6.65E-26	1.16E+02	1.47E+01	0.00E+00	1.79E-03	1.31E+02	5.27E-01
IN-W219.110	5.64E-06	0.00E+00	2.24E-27	3.91E+00	4.95E-01	0.00E+00	6.04E-05	4.41E+00	1.78E-02
IN-W219.914	8.89E-07	0.00E+00	3.53E-28	6.17E-01	7.83E-02	0.00E+00	9.50E-06	6.96E-01	2.81E-03

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W220.114	2.94E-02	0.00E+00	2.36E-25	4.42E+02	5.45E+01	0.00E+00	6.35E-03	4.96E+02	2.00E+00
IN-W221.927	3.44E-05	0.00E+00	1.37E-26	2.38E+01	3.02E+00	0.00E+00	3.68E-04	2.68E+01	1.08E-01
IN-W222.116	1.17E-03	0.00E+00	4.63E-25	8.05E+02	1.02E+02	0.00E+00	1.25E-02	9.07E+02	3.66E+00
IN-W228.101	7.76E-03	0.00E+00	1.50E-25	2.63E+02	3.33E+01	0.00E+00	4.05E-03	2.97E+02	1.20E+00
IN-W240.931	8.21E-04	0.00E+00	1.92E-25	3.38E+02	4.26E+01	0.00E+00	5.18E-03	3.81E+02	1.54E+00
IN-W243.808	1.14E-03	0.00E+00	3.37E-25	5.90E+02	7.47E+01	0.00E+00	9.08E-03	6.65E+02	2.68E+00
IN-W245.301	1.69E-03	0.00E+00	6.62E-25	1.15E+03	1.46E+02	0.00E+00	1.78E-02	1.30E+03	5.23E+00
IN-W247.810	8.21E-04	0.00E+00	3.23E-25	5.63E+02	7.15E+01	0.00E+00	8.68E-03	6.34E+02	2.56E+00
IN-W249.527	0.00E+00	0.00E+00	2.26E-23	9.98E+00	0.00E+00	0.00E+00	6.08E-01	1.06E+01	4.27E-02
IN-W263.520	2.35E-07	0.00E+00	2.36E-24	6.79E+00	6.03E-03	0.00E+00	6.35E-02	6.86E+00	2.76E-02
IN-W267.1005	1.97E-04	0.00E+00	7.82E-26	1.37E+02	1.73E+01	0.00E+00	2.11E-03	1.54E+02	6.22E-01
IN-W309.609	5.27E-03	0.00E+00	1.31E-24	2.29E+03	2.90E+02	0.00E+00	3.53E-02	2.58E+03	1.04E+01
IN-W315.601	5.20E-03	0.00E+00	5.48E-27	9.58E+00	1.21E+00	0.00E+00	1.48E-04	1.08E+01	4.35E-02
IN-W319.584	3.03E-05	0.00E+00	1.20E-26	2.10E+01	2.67E+00	0.00E+00	3.23E-04	2.37E+01	9.55E-02
IN-W321.1023	2.62E-04	0.00E+00	1.04E-25	1.82E+02	2.30E+01	0.00E+00	2.80E-03	2.05E+02	8.27E-01
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	7.34E+00	8.50E-01	0.00E+00	0.00E+00	8.19E+00	3.30E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	1.96E+01	2.27E+00	0.00E+00	0.00E+00	2.18E+01	8.80E-02
IN-W323.562	5.59E-07	0.00E+00	1.76E-26	2.00E-01	0.00E+00	0.00E+00	4.75E-04	2.01E-01	8.10E-04
IN-W323.951	6.60E-07	0.00E+00	2.10E-28	2.39E-01	0.00E+00	0.00E+00	5.65E-06	2.39E-01	9.64E-04
IN-W332.661	0.00E+00	0.00E+00	2.31E-25	1.04E-01	0.00E+00	0.00E+00	6.23E-03	1.10E-01	4.44E-04
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	2.45E+00	2.84E-01	0.00E+00	0.00E+00	2.73E+00	1.10E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	7.34E+00	8.50E-01	0.00E+00	0.00E+00	8.19E+00	3.30E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.57E+00	0.00E+00	0.00E+00	0.00E+00	1.57E+00	6.33E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	4.72E+00	0.00E+00	0.00E+00	0.00E+00	4.72E+00	1.90E-02
IN-W342.652	2.59E-05	0.00E+00	0.00E+00	3.24E-02	4.68E-18	0.00E+00	0.00E+00	3.24E-02	1.31E-04
IN-W342.953	1.73E-05	0.00E+00	0.00E+00	2.17E-02	3.14E-18	0.00E+00	0.00E+00	2.17E-02	8.74E-05
IN-W347.818	1.35E-05	0.00E+00	0.00E+00	6.65E+01	6.84E+01	0.00E+00	1.55E-08	1.35E+02	5.44E-01
IN-W348.1012	7.16E-07	0.00E+00	1.91E-25	3.36E+02	4.26E+01	0.00E+00	5.14E-03	3.78E+02	1.53E+00

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	2.01E-02	0.00E+00	0.00E+00	0.00E+00	2.01E-02	8.12E-05
IN-W357.1022	0.00E+00	0.00E+00	3.76E-28	6.59E-01	8.32E-02	0.00E+00	1.01E-05	7.43E-01	2.99E-03
IN-W358.854	0.00E+00	0.00E+00	5.67E-24	1.51E+00	1.63E+00	0.00E+00	1.46E-01	3.29E+00	1.33E-02
IN-W358.855	0.00E+00	0.00E+00	3.02E-23	8.05E+00	8.68E+00	0.00E+00	7.76E-01	1.75E+01	7.06E-02
IN-W358.948	0.00E+00	0.00E+00	6.31E-24	1.68E+00	1.81E+00	0.00E+00	1.62E-01	3.65E+00	1.47E-02
IN-W361.1021	1.90E-07	0.00E+00	3.64E-26	6.36E+01	8.05E+00	0.00E+00	9.81E-04	7.17E+01	2.89E-01
IN-W362.1020	0.00E+00	0.00E+00	4.77E-25	8.29E+02	1.06E+02	0.00E+00	1.29E-02	9.35E+02	3.77E+00
IN-W363.1019	0.00E+00	0.00E+00	2.24E-26	3.94E+01	5.00E+00	0.00E+00	6.04E-04	4.44E+01	1.79E-01
IN-W364.1011	0.00E+00	0.00E+00	3.70E-26	6.47E+01	8.19E+00	0.00E+00	9.97E-04	7.29E+01	2.94E-01
IN-W365.1010	1.77E-03	0.00E+00	2.94E-26	5.11E+01	6.48E+00	0.00E+00	7.91E-04	5.76E+01	2.32E-01
IN-W366.841	6.31E-06	0.00E+00	2.50E-26	4.36E+01	5.53E+00	0.00E+00	6.74E-04	4.91E+01	1.98E-01
IN-W372.832	2.59E-05	0.00E+00	0.00E+00	3.24E-02	4.68E-18	0.00E+00	0.00E+00	3.24E-02	1.31E-04
IN-W375.1096	0.00E+00	0.00E+00	9.23E-27	1.61E+01	2.04E+00	0.00E+00	2.49E-04	1.81E+01	7.31E-02
KN-B234TRU	9.18E-04	0.00E+00	3.53E-25	2.34E+02	4.41E+01	0.00E+00	1.05E-02	2.78E+02	1.12E+00
LA-IT-00-01	1.34E-05	0.00E+00	6.02E-26	4.71E-01	5.71E-03	0.00E+00	1.81E-03	4.78E-01	1.93E-03
LA-OS-00-01	2.97E-02	0.00E+00	2.75E-21	9.90E+02	0.00E+00	0.00E+00	6.73E+01	1.06E+03	4.26E+00
LA-PX-00-01	1.24E-07	0.00E+00	1.16E-28	7.29E-02	9.58E-03	0.00E+00	2.95E-06	8.24E-02	3.32E-04
LA-SL-00-01	0.00E+00	0.00E+00	2.44E-27	1.23E-01	0.00E+00	0.00E+00	7.30E-05	1.23E-01	4.97E-04
LA-TA-03-12	1.27E-06	0.00E+00	5.65E-26	3.51E-01	6.84E-02	0.00E+00	1.75E-03	4.21E-01	1.70E-03
LA-TA-03-13	1.65E-06	0.00E+00	1.79E-25	5.48E-01	7.20E-02	0.00E+00	4.88E-03	6.25E-01	2.52E-03
LA-TA-03-19	3.33E-06	0.00E+00	2.68E-25	1.07E+00	1.73E-01	0.00E+00	8.25E-03	1.25E+00	5.05E-03
LA-TA-03-20	1.82E-06	0.00E+00	1.27E-25	4.72E-01	9.31E-02	0.00E+00	3.76E-03	5.69E-01	2.29E-03
LA-TA-03-24	2.44E-06	0.00E+00	4.95E-25	8.77E-01	1.49E-01	0.00E+00	1.54E-02	1.04E+00	4.20E-03
LA-TA-03-26	1.25E-07	0.00E+00	2.04E-26	2.13E+00	1.95E-02	0.00E+00	1.48E-03	2.15E+00	8.65E-03
LA-TA-03-28	0.00E+00	0.00E+00	7.06E-27	1.99E-01	0.00E+00	0.00E+00	2.16E-04	1.99E-01	8.03E-04
LA-TA-03-30	5.55E-06	0.00E+00	5.03E-27	4.05E+00	6.57E-01	0.00E+00	1.53E-04	4.71E+00	1.90E-02
LA-TA-03-31	0.00E+00	0.00E+00	2.52E-28	7.08E-03	0.00E+00	0.00E+00	7.69E-06	7.09E-03	2.86E-05
LA-TA-03-40	0.00E+00	0.00E+00	3.98E-28	4.40E-02	0.00E+00	0.00E+00	1.23E-05	4.40E-02	1.78E-04

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-03-42	1.28E-10	0.00E+00	9.96E-30	2.75E-03	2.03E-05	0.00E+00	3.07E-07	2.77E-03	1.12E-05
LA-TA-21-06	1.26E-06	0.00E+00	1.10E-24	7.70E-01	1.32E-01	0.00E+00	3.35E-02	9.36E-01	3.77E-03
LA-TA-21-12	4.58E-06	0.00E+00	6.61E-24	2.67E+00	4.47E-01	0.00E+00	2.02E-01	3.32E+00	1.34E-02
LA-TA-21-13	7.04E-06	0.00E+00	0.00E+00	2.37E-01	0.00E+00	0.00E+00	0.00E+00	2.37E-01	9.54E-04
LA-TA-21-14	1.16E-09	0.00E+00	1.26E-25	3.61E+00	2.36E-05	0.00E+00	3.24E-03	3.62E+00	1.46E-02
LA-TA-21-15	6.82E-07	0.00E+00	3.47E-28	1.12E+00	1.07E-01	0.00E+00	1.05E-05	1.23E+00	4.94E-03
LA-TA-21-16	7.90E-06	0.00E+00	5.35E-27	8.53E+00	1.14E+00	0.00E+00	1.65E-04	9.68E+00	3.90E-02
LA-TA-21-40	1.00E-09	0.00E+00	1.85E-26	2.68E-01	1.66E-04	0.00E+00	6.96E-04	2.69E-01	1.08E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	5.71E-01	0.00E+00	0.00E+00	0.00E+00	5.71E-01	2.30E-03
LA-TA-21-42	1.03E-07	0.00E+00	6.02E-27	1.32E-01	5.04E-03	0.00E+00	2.41E-04	1.37E-01	5.54E-04
LA-TA-21-43	3.62E-04	0.00E+00	2.00E-25	4.11E+02	5.49E+01	0.00E+00	7.92E-03	4.66E+02	1.88E+00
LA-TA-21-44	1.74E-06	0.00E+00	4.19E-26	9.26E+01	1.38E-01	0.00E+00	1.39E-03	9.27E+01	3.74E-01
LA-TA-48-01	5.62E-07	0.00E+00	1.58E-28	9.50E-02	2.23E-01	0.00E+00	5.97E-06	3.18E-01	1.28E-03
LA-TA-49-01	6.93E-05	0.00E+00	1.94E-26	1.18E+01	2.76E+01	0.00E+00	7.36E-04	3.94E+01	1.59E-01
LA-TA-50-10	1.86E-07	0.00E+00	1.84E-28	3.70E-02	0.00E+00	0.00E+00	4.64E-06	3.70E-02	1.49E-04
LA-TA-50-11	3.54E-07	0.00E+00	1.88E-28	3.75E-01	4.68E-02	0.00E+00	7.00E-06	4.22E-01	1.70E-03
LA-TA-50-15	6.99E-07	0.00E+00	2.78E-26	2.74E-01	3.44E-02	0.00E+00	7.93E-04	3.09E-01	1.25E-03
LA-TA-50-17	1.02E-04	0.00E+00	2.26E-26	1.47E+01	1.94E-04	0.00E+00	9.77E-04	1.47E+01	5.91E-02
LA-TA-50-18	6.08E-06	0.00E+00	2.98E-27	2.39E+00	2.41E-06	0.00E+00	9.18E-05	2.39E+00	9.64E-03
LA-TA-50-19	1.94E-06	0.00E+00	1.33E-27	3.18E-01	2.07E-03	0.00E+00	6.71E-05	3.20E-01	1.29E-03
LA-TA-50-20	5.32E-08	0.00E+00	0.00E+00	7.84E-03	0.00E+00	0.00E+00	0.00E+00	7.84E-03	3.16E-05
LA-TA-50-40	3.00E-08	0.00E+00	1.79E-29	8.53E-03	2.24E-03	0.00E+00	5.27E-07	1.08E-02	4.34E-05
LA-TA-50-41	3.20E-08	0.00E+00	1.81E-29	3.78E-02	4.95E-03	0.00E+00	4.87E-07	4.28E-02	1.73E-04
LA-TA-55-19	4.96E-05	0.00E+00	2.39E-26	2.13E+01	3.36E+00	0.00E+00	2.22E-03	2.46E+01	9.93E-02
LA-TA-55-20	7.96E-04	0.00E+00	2.72E-25	5.14E+02	6.93E+01	0.00E+00	9.95E-02	5.83E+02	2.35E+00
LA-TA-55-21	7.11E-06	0.00E+00	3.12E-27	3.64E+00	4.91E-01	0.00E+00	8.35E-05	4.13E+00	1.67E-02
LA-TA-55-22	1.95E-05	0.00E+00	1.76E-26	1.28E+01	1.68E+00	0.00E+00	4.71E-04	1.45E+01	5.84E-02
LA-TA-55-23	1.84E-05	0.00E+00	1.48E-26	8.77E+00	1.22E+00	0.00E+00	3.91E-04	9.99E+00	4.03E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-24	6.92E-06	0.00E+00	2.31E-27	4.60E+00	6.03E-01	0.00E+00	5.90E-05	5.21E+00	2.10E-02
LA-TA-55-25	3.54E-05	0.00E+00	1.35E-26	2.29E+01	3.00E+00	0.00E+00	3.44E-04	2.59E+01	1.04E-01
LA-TA-55-28	1.21E-05	0.00E+00	7.48E-27	7.02E+00	9.31E-01	0.00E+00	1.92E-04	7.95E+00	3.21E-02
LA-TA-55-30	2.69E-04	0.00E+00	8.95E-26	1.15E+02	1.56E+01	0.00E+00	2.93E-03	1.31E+02	5.27E-01
LA-TA-55-32	2.18E-05	0.00E+00	5.00E-25	9.10E+00	1.58E+00	0.00E+00	1.56E-02	1.07E+01	4.31E-02
LA-TA-55-33	3.27E-06	0.00E+00	1.29E-27	1.20E+00	2.15E-01	0.00E+00	3.76E-05	1.42E+00	5.70E-03
LA-TA-55-34	3.30E-04	0.00E+00	1.19E-25	1.86E+02	2.66E+01	0.00E+00	6.20E-03	2.13E+02	8.57E-01
LA-TA-55-38	8.30E-04	0.00E+00	3.93E-26	4.11E+01	6.21E+00	0.00E+00	2.81E-03	4.73E+01	1.91E-01
LA-TA-55-39	8.78E-05	0.00E+00	2.91E-26	6.13E+01	7.74E+00	0.00E+00	7.64E-04	6.90E+01	2.78E-01
LA-TA-55-41	2.09E-03	0.00E+00	6.02E-26	7.60E+01	1.02E+01	0.00E+00	1.62E-03	8.62E+01	3.48E-01
LA-TA-55-43	7.85E-07	0.00E+00	3.95E-24	1.14E-01	2.25E-02	0.00E+00	1.03E-01	2.40E-01	9.67E-04
LA-TA-55-44	6.81E-06	0.00E+00	9.30E-24	2.12E+00	3.30E-01	0.00E+00	2.73E-01	2.72E+00	1.10E-02
LA-TA-55-48	5.02E-02	0.00E+00	3.67E-23	1.36E+04	2.85E+03	0.00E+00	1.05E+00	1.65E+04	6.64E+01
LA-TA-55-49	1.07E-04	0.00E+00	4.83E-23	2.49E+01	3.93E+00	0.00E+00	1.41E+00	3.02E+01	1.22E-01
LA-TA-55-53	5.06E-04	0.00E+00	9.98E-26	2.13E+02	2.79E+01	0.00E+00	2.87E-03	2.40E+02	9.69E-01
LA-TA-55-56	5.60E-04	0.00E+00	3.72E-24	3.08E+02	4.34E+01	0.00E+00	1.02E-01	3.51E+02	1.42E+00
LA-TA-55-60	3.04E-07	0.00E+00	9.39E-28	5.80E-02	1.16E-02	0.00E+00	2.74E-05	6.96E-02	2.80E-04
LA-TA-55-61	2.61E-07	0.00E+00	4.32E-27	1.12E-01	2.13E-02	0.00E+00	1.24E-04	1.33E-01	5.38E-04
LA-TA-55-62	6.77E-08	0.00E+00	4.11E-29	1.88E-02	5.04E-03	0.00E+00	1.19E-06	2.38E-02	9.60E-05
LA-TA-55-63	5.02E-08	0.00E+00	2.78E-29	6.01E-02	7.83E-03	0.00E+00	7.66E-07	6.80E-02	2.74E-04
LL-M001	6.89E-04	0.00E+00	1.21E-24	5.64E+01	1.43E+01	0.00E+00	2.94E-02	7.07E+01	2.85E-01
LL-T001	3.44E-03	0.00E+00	0.00E+00	4.30E+02	1.09E+02	0.00E+00	0.00E+00	5.39E+02	2.17E+00
LL-T002	3.40E-02	0.00E+00	9.63E-24	4.17E+03	9.63E+02	0.00E+00	2.34E-01	5.13E+03	2.07E+01
LL-T003	1.32E-03	0.00E+00	1.08E-24	8.45E+01	3.83E+01	0.00E+00	2.62E-02	1.23E+02	4.96E-01
LL-T004	8.40E-04	0.00E+00	2.21E-25	5.37E+01	2.42E+01	0.00E+00	5.38E-03	7.79E+01	3.14E-01
LL-T005	4.33E-03	0.00E+00	2.60E-24	2.00E+02	9.70E+01	0.00E+00	6.33E-02	2.97E+02	1.20E+00
LL-W018	3.69E-07	0.00E+00	0.00E+00	1.49E-02	1.93E-02	0.00E+00	0.00E+00	3.42E-02	1.38E-04
LL-W019	2.00E-04	0.00E+00	0.00E+00	1.16E+01	5.45E+00	0.00E+00	0.00E+00	1.70E+01	6.87E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LL-W034	7.40E-05	0.00E+00	4.56E-26	3.38E+00	1.61E+00	0.00E+00	1.11E-03	4.99E+00	2.01E-02
MC-W001	9.23E-07	0.00E+00	0.00E+00	4.88E-02	0.00E+00	0.00E+00	0.00E+00	4.88E-02	1.97E-04
MU-W002	1.23E-05	0.00E+00	0.00E+00	4.23E-02	0.00E+00	0.00E+00	2.61E-12	4.24E-02	1.71E-04
NT-JAS-01	1.19E-03	0.00E+00	9.70E-25	7.63E+01	3.45E+01	0.00E+00	2.36E-02	1.11E+02	4.47E-01
NT-W001	1.79E-03	0.00E+00	1.94E-24	2.30E+03	8.64E+00	0.00E+00	5.84E-02	2.31E+03	9.32E+00
NT-W021	3.46E-05	0.00E+00	1.39E-26	2.59E+01	3.32E+00	0.00E+00	3.83E-04	2.92E+01	1.18E-01
OR-W201	4.15E-02	0.00E+00	4.17E-23	1.74E+03	9.63E+02	0.00E+00	4.37E+01	2.75E+03	1.11E+01
OR-W202	5.95E-03	0.00E+00	1.20E-22	4.46E+02	2.46E+02	0.00E+00	3.36E+00	6.95E+02	2.80E+00
OR-W203	1.31E-05	0.00E+00	1.72E-26	2.00E-02	8.02E-01	0.00E+00	4.79E-04	8.23E-01	3.32E-03
OR-W204	2.92E-06	0.00E+00	1.95E-26	3.41E-01	1.30E-01	0.00E+00	5.43E-04	4.71E-01	1.90E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	3.43E-01	0.00E+00	0.00E+00	0.00E+00	3.43E-01	1.38E-03
RF-MT0001	1.12E-02	0.00E+00	1.21E-25	1.58E+02	2.02E+01	0.00E+00	3.24E-03	1.78E+02	7.18E-01
RF-MT0002	8.62E-04	0.00E+00	9.30E-27	1.22E+01	1.55E+00	0.00E+00	2.49E-04	1.37E+01	5.53E-02
RF-MT0003	3.92E-06	0.00E+00	2.13E-27	2.78E+00	3.56E-01	0.00E+00	5.68E-05	3.13E+00	1.26E-02
RF-MT0007	9.86E-06	0.00E+00	0.00E+00	3.46E-01	4.42E-02	0.00E+00	0.00E+00	3.90E-01	1.57E-03
RF-MT0089	3.87E-08	0.00E+00	2.13E-29	2.78E-02	3.55E-03	0.00E+00	5.68E-07	3.13E-02	1.26E-04
RF-MT0090	9.82E-05	0.00E+00	3.01E-26	7.13E+01	9.04E+00	0.00E+00	8.04E-04	8.04E+01	3.24E-01
RF-MT0091	6.09E-03	0.00E+00	3.05E-24	4.77E+03	6.07E+02	0.00E+00	8.45E-02	5.37E+03	2.17E+01
RF-MT0092	8.72E-04	0.00E+00	3.85E-25	6.83E+02	8.86E+01	0.00E+00	1.03E-02	7.71E+02	3.11E+00
RF-MT0093	1.06E-03	0.00E+00	3.96E-25	7.37E+02	9.72E+01	0.00E+00	1.06E-02	8.34E+02	3.36E+00
RF-MT0097	5.31E-05	0.00E+00	1.75E-26	3.85E+01	4.42E+00	0.00E+00	4.67E-04	4.29E+01	1.73E-01
RF-MT0099	5.82E-08	0.00E+00	3.20E-29	4.16E-02	5.31E-03	0.00E+00	8.54E-07	4.69E-02	1.89E-04
RF-MT0290	1.44E-04	0.00E+00	7.91E-26	1.03E+02	1.32E+01	0.00E+00	2.11E-03	1.16E+02	4.69E-01
RF-MT-0292	1.82E-04	0.00E+00	9.99E-26	1.30E+02	1.67E+01	0.00E+00	2.67E-03	1.47E+02	5.93E-01
RF-MT-0299	2.14E-02	0.00E+00	2.56E-24	3.34E+03	4.28E+02	0.00E+00	6.84E-02	3.77E+03	1.52E+01
RF-MT0302	3.28E-07	0.00E+00	1.02E-28	1.44E-01	1.85E-02	0.00E+00	1.92E-05	1.63E-01	6.56E-04
RF-MT0320	3.92E-04	0.00E+00	1.05E-25	1.40E+02	1.80E+01	0.00E+00	2.82E-03	1.58E+02	6.37E-01
RF-MT0321	2.19E-04	0.00E+00	3.14E-26	4.51E+01	5.71E+00	0.00E+00	3.20E-03	5.08E+01	2.05E-01

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT-0328	1.52E-05	0.00E+00	3.76E-27	4.90E+00	6.25E-01	0.00E+00	4.32E-04	5.53E+00	2.23E-02
RF-MT0330	1.58E-04	0.00E+00	4.12E-26	9.90E+01	1.37E+01	0.00E+00	1.10E-03	1.13E+02	4.54E-01
RF-MT-0331	9.46E-04	0.00E+00	2.56E-25	4.36E+02	5.45E+01	0.00E+00	2.72E-02	4.90E+02	1.98E+00
RF-MT0332	1.36E-07	0.00E+00	7.46E-29	9.74E-02	1.24E-02	0.00E+00	1.99E-06	1.10E-01	4.43E-04
RF-MT-0335	1.09E-05	0.00E+00	3.43E-27	5.02E+00	6.43E-01	0.00E+00	6.23E-04	5.66E+00	2.28E-02
RF-MT0336	7.71E-04	0.00E+00	2.27E-25	3.56E+02	4.55E+01	0.00E+00	7.85E-03	4.01E+02	1.62E+00
RF-MT0337	4.36E-04	0.00E+00	1.25E-25	2.17E+02	2.73E+01	0.00E+00	7.11E-03	2.45E+02	9.87E-01
RF-MT0339	1.19E-03	0.00E+00	3.40E-25	4.77E+02	6.03E+01	0.00E+00	2.58E-02	5.37E+02	2.17E+00
RF-MT-0342	7.00E-06	0.00E+00	2.85E-27	4.40E+00	5.53E-01	0.00E+00	1.33E-04	4.96E+00	2.00E-02
RF-MT0371	2.37E-03	0.00E+00	6.59E-25	8.61E+02	1.10E+02	0.00E+00	1.89E-02	9.71E+02	3.92E+00
RF-MT-0372	1.03E-05	0.00E+00	4.64E-27	6.01E+00	7.69E-01	0.00E+00	3.59E-04	6.78E+00	2.73E-02
RF-MT0373	1.56E-04	0.00E+00	4.77E-26	1.13E+02	1.43E+01	0.00E+00	1.28E-03	1.27E+02	5.12E-01
RF-MT0374	5.05E-06	0.00E+00	1.71E-27	2.23E+00	2.85E-01	0.00E+00	4.89E-05	2.52E+00	1.01E-02
RF-MT0376	4.00E-06	0.00E+00	1.38E-27	2.22E+00	2.88E-01	0.00E+00	5.16E-05	2.51E+00	1.01E-02
RF-MT0377	2.38E-03	0.00E+00	7.94E-25	1.04E+03	1.32E+02	0.00E+00	3.12E-02	1.17E+03	4.72E+00
RF-MT0378	2.67E-05	0.00E+00	1.10E-26	1.43E+01	1.83E+00	0.00E+00	2.93E-04	1.62E+01	6.52E-02
RF-MT0419	4.29E-05	0.00E+00	1.03E-26	1.34E+01	1.71E+00	0.00E+00	2.74E-04	1.51E+01	6.08E-02
RF-MT0420	7.46E-06	0.00E+00	1.78E-27	2.32E+00	2.97E-01	0.00E+00	4.75E-05	2.62E+00	1.06E-02
RF-MT0423	6.34E-05	0.00E+00	1.45E-26	3.35E+01	4.15E+00	0.00E+00	3.87E-04	3.76E+01	1.52E-01
RF-MT0425	1.87E-06	0.00E+00	4.45E-28	5.80E-01	7.42E-02	0.00E+00	1.19E-05	6.55E-01	2.64E-03
RF-MT-0438	1.69E-05	0.00E+00	5.84E-27	1.03E+01	1.31E+00	0.00E+00	1.69E-04	1.16E+01	4.68E-02
RF-MT0440	6.15E-06	0.00E+00	2.10E-27	3.74E+00	4.86E-01	0.00E+00	2.17E-04	4.22E+00	1.70E-02
RF-MT0442	2.34E-06	0.00E+00	9.07E-28	1.28E+00	1.63E-01	0.00E+00	1.17E-04	1.44E+00	5.82E-03
RF-MT0443	2.88E-05	0.00E+00	1.49E-26	1.99E+01	2.54E+00	0.00E+00	5.53E-04	2.24E+01	9.04E-02
RF-MT0444	2.25E-04	0.00E+00	7.30E-26	9.58E+01	1.22E+01	0.00E+00	1.97E-03	1.08E+02	4.35E-01
RF-MT0480	6.29E-04	0.00E+00	2.05E-25	2.69E+02	3.44E+01	0.00E+00	7.90E-03	3.03E+02	1.22E+00
RF-MT0488	1.01E-03	0.00E+00	3.07E-25	3.99E+02	5.09E+01	0.00E+00	3.85E-02	4.50E+02	1.82E+00
RF-MT0490	4.56E-06	0.00E+00	1.78E-27	2.36E+00	3.02E-01	0.00E+00	5.85E-05	2.66E+00	1.07E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT-0491	3.58E-07	0.00E+00	8.13E-29	1.07E-01	1.36E-02	0.00E+00	4.14E-06	1.21E-01	4.87E-04
RF-MT0523A	2.84E-04	0.00E+00	6.46E-26	8.45E+01	1.08E+01	0.00E+00	1.98E-03	9.53E+01	3.84E-01
RF-MT0523B	2.84E-04	0.00E+00	6.46E-26	8.45E+01	1.08E+01	0.00E+00	1.98E-03	9.53E+01	3.84E-01
RF-MT0523C	2.84E-04	0.00E+00	6.46E-26	8.45E+01	1.08E+01	0.00E+00	1.98E-03	9.53E+01	3.84E-01
RF-MT0523D	2.84E-04	0.00E+00	6.46E-26	8.45E+01	1.08E+01	0.00E+00	1.98E-03	9.53E+01	3.84E-01
RF-MT0523E	2.84E-04	0.00E+00	6.46E-26	8.45E+01	1.08E+01	0.00E+00	1.98E-03	9.53E+01	3.84E-01
RF-MT0531	1.94E-08	0.00E+00	1.06E-29	1.39E-02	1.77E-03	0.00E+00	2.84E-07	1.56E-02	6.30E-05
RF-MT0532E	9.04E-04	0.00E+00	1.38E-25	1.84E+02	2.35E+01	0.00E+00	4.78E-03	2.08E+02	8.38E-01
RF-MT0532F	9.04E-04	0.00E+00	1.38E-25	1.84E+02	2.35E+01	0.00E+00	4.78E-03	2.08E+02	8.38E-01
RF-MT0541	3.29E-05	0.00E+00	2.00E-27	2.62E+00	3.34E-01	0.00E+00	5.33E-05	2.95E+00	1.19E-02
RF-MT0545	1.76E-07	0.00E+00	9.66E-29	1.26E-01	1.61E-02	0.00E+00	2.58E-06	1.43E-01	5.75E-04
RF-MT0800	6.70E-03	0.00E+00	4.79E-26	6.24E+01	7.96E+00	0.00E+00	1.75E-03	7.04E+01	2.84E-01
RF-MT0801	7.70E-04	0.00E+00	4.69E-26	6.13E+01	7.83E+00	0.00E+00	1.25E-03	6.91E+01	2.79E-01
RF-MT0803	1.73E-05	0.00E+00	1.05E-27	1.37E+00	1.75E-01	0.00E+00	2.80E-05	1.54E+00	6.22E-03
RF-MT0806	8.15E-06	0.00E+00	2.52E-27	5.95E+00	7.51E-01	0.00E+00	6.72E-05	6.70E+00	2.70E-02
RF-MT0807	1.03E-04	0.00E+00	1.94E-26	2.53E+01	3.24E+00	0.00E+00	5.18E-04	2.85E+01	1.15E-01
RF-MT0816	1.10E-05	0.00E+00	2.73E-27	3.57E+00	4.55E-01	0.00E+00	7.30E-05	4.02E+00	1.62E-02
RF-MT-0823	5.46E-06	0.00E+00	1.24E-27	1.63E+00	2.08E-01	0.00E+00	3.81E-05	1.83E+00	7.40E-03
RF-MT0827	2.78E-04	0.00E+00	6.91E-26	9.02E+01	1.15E+01	0.00E+00	1.85E-03	1.02E+02	4.10E-01
RF-MT0831	5.31E-04	0.00E+00	1.89E-25	2.44E+02	3.12E+01	0.00E+00	1.70E-02	2.75E+02	1.11E+00
RF-MT0832	3.17E-03	0.00E+00	6.87E-25	9.50E+02	1.21E+02	0.00E+00	5.11E-02	1.07E+03	4.32E+00
RF-MT0833	9.65E-04	0.00E+00	2.05E-25	2.75E+02	3.51E+01	0.00E+00	1.45E-02	3.10E+02	1.25E+00
RF-MT0855	1.66E-07	0.00E+00	9.13E-29	1.19E-01	1.52E-02	0.00E+00	2.44E-06	1.34E-01	5.42E-04
RF-MT0857	8.15E-06	0.00E+00	2.50E-27	5.93E+00	7.51E-01	0.00E+00	6.69E-05	6.68E+00	2.70E-02
RF-MT0H61	3.02E-04	0.00E+00	9.30E-26	2.20E+02	2.79E+01	0.00E+00	2.49E-03	2.48E+02	9.99E-01
RF-MT2116	3.40E-05	0.00E+00	7.38E-27	1.01E+01	1.30E+00	0.00E+00	5.47E-04	1.14E+01	4.61E-02
RF-MT3010	2.13E-04	0.00E+00	7.66E-26	1.01E+02	1.30E+01	0.00E+00	2.43E-03	1.14E+02	4.58E-01
RF-MT3011	1.59E-03	0.00E+00	4.77E-25	6.21E+02	7.96E+01	0.00E+00	2.04E-02	7.01E+02	2.83E+00

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT420P	8.44E-03	0.00E+00	2.42E-24	5.11E+03	6.52E+02	0.00E+00	7.44E-02	5.76E+03	2.32E+01
RF-MT532A	2.23E-03	0.00E+00	3.41E-25	4.56E+02	5.80E+01	0.00E+00	1.18E-02	5.14E+02	2.07E+00
RF-MT532B	9.99E-03	0.00E+00	1.53E-24	2.05E+03	2.61E+02	0.00E+00	5.29E-02	2.31E+03	9.30E+00
RF-MT532C	2.00E-02	0.00E+00	3.08E-24	4.10E+03	5.22E+02	0.00E+00	1.06E-01	4.62E+03	1.86E+01
RF-MT532D	1.27E-04	0.00E+00	1.94E-26	2.59E+01	3.30E+00	0.00E+00	6.70E-04	2.92E+01	1.18E-01
RF-TT0069	7.29E-07	0.00E+00	2.30E-28	3.00E-01	3.84E-02	0.00E+00	7.81E-05	3.39E-01	1.37E-03
RF-TT0200	3.46E-05	0.00E+00	9.28E-27	1.23E+01	1.58E+00	0.00E+00	2.49E-04	1.39E+01	5.61E-02
RF-TT0299	1.44E-04	0.00E+00	1.72E-26	2.25E+01	2.87E+00	0.00E+00	4.60E-04	2.53E+01	1.02E-01
RF-TT0300	1.17E-03	0.00E+00	4.90E-25	6.45E+02	8.28E+01	0.00E+00	2.13E-02	7.28E+02	2.93E+00
RF-TT0301	1.58E-04	0.00E+00	6.65E-26	8.77E+01	1.13E+01	0.00E+00	2.89E-03	9.90E+01	3.99E-01
RF-TT0302	7.81E-06	0.00E+00	2.42E-27	3.43E+00	4.39E-01	0.00E+00	4.55E-04	3.87E+00	1.56E-02
RF-TT0303	4.70E-05	0.00E+00	1.41E-26	1.84E+01	2.35E+00	0.00E+00	1.39E-03	2.08E+01	8.38E-02
RF-TT0310	1.60E-04	0.00E+00	6.62E-26	8.29E+01	1.09E+01	0.00E+00	1.95E-03	9.39E+01	3.78E-01
RF-TT0312	3.84E-03	0.00E+00	1.20E-24	1.81E+03	2.30E+02	0.00E+00	3.37E-02	2.04E+03	8.23E+00
RF-TT0317	2.42E-06	0.00E+00	1.30E-27	1.70E+00	2.17E-01	0.00E+00	3.47E-05	1.92E+00	7.72E-03
RF-TT0320	1.55E-03	0.00E+00	4.17E-25	5.54E+02	7.11E+01	0.00E+00	1.12E-02	6.25E+02	2.52E+00
RF-TT0330	5.52E-04	0.00E+00	1.44E-25	3.48E+02	4.77E+01	0.00E+00	3.85E-03	3.95E+02	1.60E+00
RF-TT-0331	2.75E-03	0.00E+00	7.45E-25	1.26E+03	1.58E+02	0.00E+00	7.89E-02	1.42E+03	5.74E+00
RF-TT-0334	1.20E-03	0.00E+00	6.03E-25	7.86E+02	1.00E+02	0.00E+00	1.61E-02	8.86E+02	3.57E+00
RF-TT0335	1.46E-03	0.00E+00	4.57E-25	6.68E+02	8.59E+01	0.00E+00	8.30E-02	7.54E+02	3.04E+00
RF-TT0336	1.29E-03	0.00E+00	3.79E-25	5.92E+02	7.56E+01	0.00E+00	1.31E-02	6.67E+02	2.69E+00
RF-TT0337	1.53E-03	0.00E+00	4.38E-25	7.64E+02	9.58E+01	0.00E+00	2.49E-02	8.60E+02	3.47E+00
RF-TT0338	6.49E-03	0.00E+00	1.59E-24	2.98E+03	3.74E+02	0.00E+00	5.06E-02	3.35E+03	1.35E+01
RF-TT0340	5.55E-05	0.00E+00	3.04E-26	3.96E+01	5.09E+00	0.00E+00	8.12E-04	4.47E+01	1.80E-01
RF-TT0342	3.71E-04	0.00E+00	1.52E-25	2.33E+02	2.93E+01	0.00E+00	7.10E-03	2.63E+02	1.06E+00
RF-TT0360	2.83E-05	0.00E+00	7.71E-27	1.05E+01	1.35E+00	0.00E+00	2.12E-04	1.18E+01	4.77E-02
RF-TT0368	5.66E-04	0.00E+00	1.55E-25	2.10E+02	2.71E+01	0.00E+00	4.26E-03	2.37E+02	9.57E-01
RF-TT0370	1.12E-03	0.00E+00	3.34E-25	4.68E+02	5.98E+01	0.00E+00	1.66E-02	5.28E+02	2.13E+00

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0371	2.42E-05	0.00E+00	6.72E-27	8.77E+00	1.12E+00	0.00E+00	1.93E-04	9.90E+00	3.99E-02
RF-TT0372	2.95E-06	0.00E+00	1.33E-27	1.72E+00	2.20E-01	0.00E+00	1.02E-04	1.93E+00	7.80E-03
RF-TT0374	9.19E-05	0.00E+00	3.11E-26	4.05E+01	5.18E+00	0.00E+00	8.90E-04	4.57E+01	1.84E-01
RF-TT0375A	9.58E-07	0.00E+00	5.12E-28	6.66E-01	8.50E-02	0.00E+00	1.37E-05	7.51E-01	3.03E-03
RF-TT0375B	9.58E-07	0.00E+00	5.12E-28	6.66E-01	8.50E-02	0.00E+00	1.37E-05	7.51E-01	3.03E-03
RF-TT0376	2.20E-04	0.00E+00	7.58E-26	1.22E+02	1.58E+01	0.00E+00	2.84E-03	1.38E+02	5.57E-01
RF-TT0377	1.24E-04	0.00E+00	4.12E-26	5.38E+01	6.88E+00	0.00E+00	1.62E-03	6.07E+01	2.45E-01
RF-TT0391	2.76E-05	0.00E+00	5.80E-27	1.36E+01	1.71E+00	0.00E+00	1.55E-04	1.53E+01	6.18E-02
RF-TT0392	9.70E-06	0.00E+00	3.64E-27	7.11E+00	9.04E-01	0.00E+00	9.75E-05	8.01E+00	3.23E-02
RF-TT0393	7.97E-04	0.00E+00	2.55E-25	3.31E+02	4.23E+01	0.00E+00	6.80E-03	3.73E+02	1.51E+00
RF-TT0398	1.74E-05	0.00E+00	6.71E-27	1.33E+01	1.68E+00	0.00E+00	1.79E-04	1.50E+01	6.03E-02
RF-TT0409	1.46E-05	0.00E+00	3.14E-27	6.86E+00	8.68E-01	0.00E+00	8.45E-05	7.73E+00	3.12E-02
RF-TT0412	1.46E-05	0.00E+00	3.14E-27	6.86E+00	8.68E-01	0.00E+00	8.45E-05	7.73E+00	3.12E-02
RF-TT0414	4.51E-04	0.00E+00	9.70E-26	2.13E+02	2.69E+01	0.00E+00	2.61E-03	2.39E+02	9.65E-01
RF-TT0430	1.32E-07	0.00E+00	7.25E-29	9.42E-02	1.21E-02	0.00E+00	1.94E-06	1.06E-01	4.28E-04
RF-TT0431	3.28E-05	0.00E+00	1.76E-26	2.32E+01	2.97E+00	0.00E+00	6.89E-04	2.62E+01	1.05E-01
RF-TT0438	1.95E-03	0.00E+00	6.72E-25	1.18E+03	1.50E+02	0.00E+00	1.95E-02	1.33E+03	5.38E+00
RF-TT0440	1.92E-04	0.00E+00	6.54E-26	1.17E+02	1.53E+01	0.00E+00	6.81E-03	1.32E+02	5.32E-01
RF-TT0441	9.46E-04	0.00E+00	3.07E-25	4.03E+02	5.18E+01	0.00E+00	1.27E-02	4.55E+02	1.84E+00
RF-TT0442	1.37E-04	0.00E+00	5.29E-26	7.46E+01	9.54E+00	0.00E+00	6.83E-03	8.42E+01	3.39E-01
RF-TT0443	2.93E-06	0.00E+00	1.52E-27	2.02E+00	2.58E-01	0.00E+00	5.63E-05	2.28E+00	9.19E-03
RF-TT0479	2.86E-05	0.00E+00	1.58E-26	2.05E+01	2.62E+00	0.00E+00	4.21E-04	2.31E+01	9.30E-02
RF-TT0480	1.95E-03	0.00E+00	6.36E-25	8.37E+02	1.07E+02	0.00E+00	2.45E-02	9.44E+02	3.81E+00
RF-TT0481	1.10E-06	0.00E+00	3.59E-28	4.70E-01	6.03E-02	0.00E+00	1.38E-05	5.30E-01	2.14E-03
RF-TT0483	3.53E-06	0.00E+00	1.94E-27	2.52E+00	3.23E-01	0.00E+00	1.69E-02	2.86E+00	1.15E-02
RF-TT0484	1.89E-05	0.00E+00	8.03E-27	1.05E+01	1.34E+00	0.00E+00	3.23E-04	1.18E+01	4.76E-02
RF-TT0485	1.55E-06	0.00E+00	4.96E-28	6.46E-01	8.28E-02	0.00E+00	2.85E-04	7.29E-01	2.94E-03
RF-TT0486	9.19E-06	0.00E+00	2.94E-27	3.83E+00	4.91E-01	0.00E+00	3.01E-04	4.32E+00	1.74E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0487	4.61E-05	0.00E+00	9.98E-27	1.38E+01	1.76E+00	0.00E+00	7.41E-04	1.55E+01	6.26E-02
RF-TT0489	1.31E-05	0.00E+00	4.48E-27	5.84E+00	7.47E-01	0.00E+00	2.19E-04	6.59E+00	2.66E-02
RF-TT0490	7.26E-04	0.00E+00	2.85E-25	3.77E+02	4.82E+01	0.00E+00	9.36E-03	4.25E+02	1.71E+00
RF-TT0491	1.69E-05	0.00E+00	3.85E-27	5.05E+00	6.43E-01	0.00E+00	1.96E-04	5.69E+00	2.30E-02
RF-TT0492	5.68E-06	0.00E+00	2.17E-27	2.82E+00	3.61E-01	0.00E+00	5.79E-05	3.18E+00	1.28E-02
RF-TT0523A	3.82E-05	0.00E+00	8.71E-27	1.14E+01	1.45E+00	0.00E+00	2.66E-04	1.28E+01	5.16E-02
RF-TT0523B	3.82E-05	0.00E+00	8.71E-27	1.14E+01	1.45E+00	0.00E+00	2.66E-04	1.28E+01	5.16E-02
RF-TT0523C	3.82E-05	0.00E+00	8.71E-27	1.14E+01	1.45E+00	0.00E+00	2.66E-04	1.28E+01	5.16E-02
RF-TT0523D	3.82E-05	0.00E+00	8.71E-27	1.14E+01	1.45E+00	0.00E+00	2.66E-04	1.28E+01	5.16E-02
RF-TT0523E	3.82E-05	0.00E+00	8.71E-27	1.14E+01	1.45E+00	0.00E+00	2.66E-04	1.28E+01	5.16E-02
RF-TT0532A	9.58E-04	0.00E+00	1.46E-25	1.96E+02	2.49E+01	0.00E+00	5.05E-03	2.21E+02	8.89E-01
RF-TT0532B	9.58E-04	0.00E+00	1.46E-25	1.96E+02	2.49E+01	0.00E+00	5.05E-03	2.21E+02	8.89E-01
RF-TT0541	1.58E-06	0.00E+00	8.69E-28	1.14E+00	1.45E-01	0.00E+00	2.32E-05	1.28E+00	5.16E-03
RF-TT0545	3.53E-07	0.00E+00	1.94E-28	2.52E-01	3.23E-02	0.00E+00	5.18E-06	2.84E-01	1.15E-03
RF-TT0601	1.22E-04	0.00E+00	3.34E-26	4.55E+01	5.89E+00	0.00E+00	9.19E-04	5.14E+01	2.07E-01
RF-TT0802	1.37E-02	0.00E+00	2.75E-24	3.59E+03	4.59E+02	0.00E+00	7.34E-02	4.05E+03	1.63E+01
RF-TT0809	1.13E-03	0.00E+00	2.26E-25	2.95E+02	3.76E+01	0.00E+00	6.03E-03	3.33E+02	1.34E+00
RF-TT0821	2.44E-03	0.00E+00	8.20E-25	1.16E+03	1.49E+02	0.00E+00	1.86E-01	1.31E+03	5.27E+00
RF-TT0822	2.70E-03	0.00E+00	6.38E-25	8.69E+02	1.11E+02	0.00E+00	1.96E-01	9.80E+02	3.95E+00
RF-TT0823	5.46E-06	0.00E+00	1.24E-27	1.63E+00	2.08E-01	0.00E+00	3.81E-05	1.83E+00	7.40E-03
RF-TT0824	5.62E-03	0.00E+00	1.75E-24	2.34E+03	2.99E+02	0.00E+00	1.08E-01	2.64E+03	1.07E+01
RF-TT0825	4.67E-03	0.00E+00	1.26E-24	1.76E+03	2.25E+02	0.00E+00	1.13E-01	1.99E+03	8.02E+00
RF-TT0832	3.45E-03	0.00E+00	7.49E-25	1.03E+03	1.32E+02	0.00E+00	5.56E-02	1.16E+03	4.69E+00
RF-TT0854	1.24E-06	0.00E+00	6.83E-28	8.86E-01	1.14E-01	0.00E+00	7.50E-04	1.00E+00	4.03E-03
RF-TT0886	1.76E-07	0.00E+00	9.65E-29	1.26E-01	1.61E-02	0.00E+00	2.58E-06	1.42E-01	5.71E-04
RF-TT2216	5.10E-05	0.00E+00	1.11E-26	1.53E+01	1.94E+00	0.00E+00	8.21E-04	1.72E+01	6.95E-02
RF-TT3010	2.72E-03	0.00E+00	9.79E-25	1.29E+03	1.65E+02	0.00E+00	3.11E-02	1.45E+03	5.86E+00
RF-TT3011	6.88E-03	0.00E+00	2.07E-24	2.69E+03	3.44E+02	0.00E+00	8.82E-02	3.03E+03	1.22E+01

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT301U	5.72E-04	0.00E+00	2.18E-25	2.92E+02	3.80E+01	0.00E+00	5.99E-03	3.30E+02	1.33E+00
RF-TT310P	1.65E-04	0.00E+00	5.68E-26	9.82E+01	1.19E+01	0.00E+00	1.52E-03	1.10E+02	4.44E-01
RF-TT338S	4.83E-06	0.00E+00	2.60E-27	3.39E+00	4.34E-01	0.00E+00	6.95E-05	3.82E+00	1.54E-02
RF-TT390P	2.72E-05	0.00E+00	7.06E-27	1.65E+01	1.94E+00	0.00E+00	2.17E-04	1.84E+01	7.44E-02
RF-TT391P	1.50E-03	0.00E+00	3.17E-25	7.41E+02	9.31E+01	0.00E+00	8.46E-03	8.35E+02	3.37E+00
RF-TT392P	3.03E-03	0.00E+00	1.14E-24	2.22E+03	2.83E+02	0.00E+00	3.05E-02	2.51E+03	1.01E+01
RF-TT393R	4.49E-04	0.00E+00	1.94E-25	3.40E+02	4.36E+01	0.00E+00	5.35E-03	3.83E+02	1.55E+00
RF-TT394P	5.57E-05	0.00E+00	1.20E-26	2.62E+01	3.11E+00	0.00E+00	3.27E-04	2.94E+01	1.18E-01
RF-TT395P	7.46E-05	0.00E+00	1.61E-26	3.51E+01	4.15E+00	0.00E+00	4.38E-04	3.93E+01	1.58E-01
RF-TT396P	1.86E-05	0.00E+00	4.01E-27	8.77E+00	1.04E+00	0.00E+00	1.09E-04	9.81E+00	3.96E-02
RF-TT398P	1.80E-03	0.00E+00	6.94E-25	1.38E+03	1.74E+02	0.00E+00	1.86E-02	1.55E+03	6.25E+00
RF-TT398R	1.49E-02	0.00E+00	1.29E-24	2.22E+03	2.82E+02	0.00E+00	3.45E-02	2.50E+03	1.01E+01
RF-TT411R	5.39E-04	0.00E+00	1.16E-25	2.54E+02	3.21E+01	0.00E+00	3.12E-03	2.86E+02	1.15E+00
RF-TT429R	1.13E-03	0.00E+00	2.49E-26	5.88E+01	7.29E+00	0.00E+00	6.64E-04	6.61E+01	2.66E-01
RF-TT433X	3.56E-04	0.00E+00	6.88E-27	1.69E+01	1.89E+00	0.00E+00	1.84E-04	1.88E+01	7.58E-02
RF-TT436R	2.61E-03	0.00E+00	9.96E-26	2.21E+02	2.79E+01	0.00E+00	2.66E-03	2.49E+02	1.01E+00
RF-TT454X	1.53E-04	0.00E+00	5.86E-27	1.30E+01	1.65E+00	0.00E+00	1.57E-04	1.47E+01	5.92E-02
RL-T101	7.77E-04	0.00E+00	3.56E-25	7.04E+02	8.82E+01	0.00E+00	8.65E-03	7.93E+02	3.20E+00
RL-T102	9.87E-09	0.00E+00	4.53E-30	9.02E-03	1.13E-03	0.00E+00	1.24E-06	1.01E-02	4.09E-05
RL-T103	6.99E-04	0.00E+00	4.31E-25	3.08E+02	3.83E+01	0.00E+00	1.05E-02	3.46E+02	1.39E+00
RL-T104	1.41E-08	0.00E+00	6.46E-30	1.28E-02	1.61E-03	0.00E+00	1.89E-07	1.44E-02	5.81E-05
RL-T105	5.42E-06	0.00E+00	2.44E-27	4.86E+00	6.07E-01	0.00E+00	1.03E-04	5.47E+00	2.21E-02
RL-T106	5.23E-06	0.00E+00	2.40E-27	4.75E+00	5.94E-01	0.00E+00	5.83E-05	5.34E+00	2.16E-02
RL-T107	1.44E-02	0.00E+00	1.41E-21	1.31E+04	1.64E+03	0.00E+00	3.51E+01	1.48E+04	5.97E+01
RL-T108	8.22E-06	0.00E+00	2.43E-25	7.47E+00	9.36E-01	0.00E+00	5.93E-03	8.41E+00	3.39E-02
RL-T109	1.13E-05	0.00E+00	5.00E-27	9.90E+00	1.24E+00	0.00E+00	2.29E-02	1.12E+01	4.50E-02
RL-T110	1.27E-03	0.00E+00	9.54E-25	1.14E+03	1.43E+02	0.00E+00	1.35E+00	1.28E+03	5.16E+00
RL-T112	5.11E-04	0.00E+00	4.04E-25	1.51E+02	1.89E+01	0.00E+00	7.30E-01	1.70E+02	6.86E-01

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T113	5.46E-07	0.00E+00	7.79E-28	4.96E-01	6.21E-02	0.00E+00	1.89E-05	5.58E-01	2.25E-03
RL-T114	8.30E-05	0.00E+00	3.80E-26	7.54E+01	9.45E+00	0.00E+00	9.24E-04	8.48E+01	3.42E-01
RL-T115	2.11E-03	0.00E+00	1.23E-24	9.90E+02	1.24E+02	0.00E+00	4.34E-01	1.12E+03	4.50E+00
RL-T116	1.36E-04	0.00E+00	6.25E-26	1.23E+02	1.55E+01	0.00E+00	5.65E-02	1.39E+02	5.59E-01
RL-T118	3.50E-04	0.00E+00	4.99E-25	1.22E+02	1.53E+01	0.00E+00	8.28E-01	1.39E+02	5.59E-01
RL-T120	8.49E-05	0.00E+00	5.24E-26	3.62E+01	4.50E+00	0.00E+00	1.27E-03	4.07E+01	1.64E-01
RL-T122	4.82E-06	0.00E+00	2.21E-27	4.36E+00	5.49E-01	0.00E+00	1.43E+00	6.34E+00	2.56E-02
RL-T123	1.42E-05	0.00E+00	6.48E-27	1.28E+01	1.61E+00	0.00E+00	5.86E-02	1.45E+01	5.83E-02
RL-T125	2.82E-03	0.00E+00	1.61E-24	2.68E+02	7.74E+01	0.00E+00	3.90E-02	3.46E+02	1.39E+00
RL-T127	2.72E-03	0.00E+00	4.04E-25	8.01E+02	1.00E+02	0.00E+00	8.81E-02	9.01E+02	3.64E+00
RL-T128	4.02E-06	0.00E+00	9.81E-33	1.95E-05	2.43E-06	0.00E+00	2.38E-10	2.59E-05	1.05E-07
RL-T129	1.21E-05	0.00E+00	1.87E-24	1.10E+01	1.37E+00	0.00E+00	5.29E-02	1.25E+01	5.02E-02
RL-T130	2.56E-08	0.00E+00	1.18E-29	2.34E-02	2.93E-03	0.00E+00	8.15E-05	2.64E-02	1.07E-04
RL-T131	1.04E-05	0.00E+00	6.44E-27	4.46E+00	5.53E-01	0.00E+00	8.21E-03	5.02E+00	2.03E-02
RL-T132	2.49E-03	0.00E+00	1.14E-24	2.26E+03	2.83E+02	0.00E+00	2.67E-01	2.55E+03	1.03E+01
RL-T133	5.06E-08	0.00E+00	1.82E-29	3.71E-02	4.64E-03	0.00E+00	4.43E-07	4.17E-02	1.68E-04
RL-T134	1.07E-07	0.00E+00	4.90E-29	9.74E-02	1.22E-02	0.00E+00	1.19E-06	1.10E-01	4.42E-04
RL-T135	5.01E-07	0.00E+00	2.30E-28	4.56E-01	5.71E-02	0.00E+00	4.07E-03	5.17E-01	2.08E-03
RL-T137	8.14E-03	0.00E+00	5.02E-24	3.47E+03	4.32E+02	0.00E+00	1.28E-01	3.90E+03	1.57E+01
RL-T140	9.52E-03	0.00E+00	4.77E-24	3.36E+03	4.64E+02	0.00E+00	2.58E+01	3.85E+03	1.55E+01
RL-T143	5.97E-05	0.00E+00	2.73E-26	5.43E+01	6.79E+00	0.00E+00	3.85E-02	6.11E+01	2.46E-01
RL-T145	1.70E-04	0.00E+00	7.79E-26	1.55E+02	1.93E+01	0.00E+00	8.96E-02	1.74E+02	7.01E-01
RL-W407	4.88E-04	0.00E+00	1.66E-25	3.54E+02	4.44E+01	0.00E+00	4.04E-03	3.99E+02	1.61E+00
RL-W408	2.00E-09	0.00E+00	7.03E-31	1.43E-03	1.80E-04	0.00E+00	1.71E-08	1.61E-03	6.50E-06
RL-W415	4.43E-08	0.00E+00	1.55E-29	3.17E-02	3.97E-03	0.00E+00	3.76E-07	3.57E-02	1.44E-04
RL-W418	1.89E-07	0.00E+00	6.52E-29	1.36E-01	1.71E-02	0.00E+00	1.59E-06	1.53E-01	6.17E-04
RL-W437	1.60E-03	0.00E+00	5.47E-25	1.16E+03	1.45E+02	0.00E+00	1.33E-02	1.31E+03	5.26E+00
RL-W438	2.80E-09	0.00E+00	9.82E-31	2.00E-03	2.51E-04	0.00E+00	2.39E-08	2.26E-03	9.09E-06

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W439	8.78E-02	0.00E+00	5.41E-23	3.86E+04	4.82E+03	0.00E+00	1.31E+00	4.35E+04	1.75E+02
RL-W443	1.41E-03	0.00E+00	4.82E-25	1.02E+03	1.28E+02	0.00E+00	1.17E-02	1.15E+03	4.64E+00
RL-W444	1.05E-03	0.00E+00	3.57E-25	7.58E+02	9.49E+01	0.00E+00	8.68E-03	8.53E+02	3.44E+00
RL-W447	1.20E-07	0.00E+00	4.21E-29	8.53E-02	1.08E-02	0.00E+00	1.02E-06	9.61E-02	3.87E-04
RL-W448	8.87E-10	0.00E+00	3.11E-31	6.34E-04	7.92E-05	0.00E+00	7.56E-09	7.13E-04	2.87E-06
RL-W449	7.28E-06	0.00E+00	1.14E-29	1.81E-02	2.27E-03	0.00E+00	2.77E-07	2.04E-02	8.22E-05
RL-W450	1.34E-08	0.00E+00	4.69E-30	9.58E-03	1.20E-03	0.00E+00	1.14E-07	1.08E-02	4.35E-05
RL-W451	1.91E-09	0.00E+00	6.68E-31	1.36E-03	1.71E-04	0.00E+00	1.62E-08	1.53E-03	6.17E-06
RL-W452	8.30E-08	0.00E+00	2.88E-29	6.00E-02	7.51E-03	0.00E+00	6.99E-07	6.75E-02	2.72E-04
RL-W453	2.37E-08	0.00E+00	8.10E-30	1.72E-02	2.15E-03	0.00E+00	1.97E-07	1.94E-02	7.81E-05
RL-W454	3.31E-07	0.00E+00	1.13E-28	2.41E-01	3.01E-02	0.00E+00	2.75E-06	2.71E-01	1.09E-03
RL-W455	8.84E-08	0.00E+00	3.05E-29	6.37E-02	7.96E-03	0.00E+00	7.42E-07	7.16E-02	2.89E-04
RL-W456	1.16E-05	0.00E+00	3.99E-27	8.45E+00	1.06E+00	0.00E+00	9.70E-05	9.51E+00	3.84E-02
RL-W457	1.13E-06	0.00E+00	3.88E-28	8.21E-01	1.03E-01	0.00E+00	9.42E-06	9.24E-01	3.72E-03
RL-W458	3.58E-06	0.00E+00	1.98E-27	3.37E-01	1.05E-01	0.00E+00	4.81E-05	4.43E-01	1.79E-03
RL-W459	3.44E-05	0.00E+00	2.04E-26	8.37E+00	1.44E+00	0.00E+00	4.96E-04	9.81E+00	3.96E-02
RL-W460	2.10E-07	0.00E+00	7.17E-29	1.52E-01	1.91E-02	0.00E+00	1.74E-06	1.71E-01	6.90E-04
RL-W461	1.94E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.94E-07	7.81E-10
RL-W462	5.99E-08	0.00E+00	2.08E-29	4.31E-02	5.40E-03	0.00E+00	5.06E-07	4.85E-02	1.95E-04
RL-W463	3.08E-07	0.00E+00	1.05E-28	2.24E-01	2.80E-02	0.00E+00	2.56E-06	2.52E-01	1.02E-03
RL-W464	1.42E-07	0.00E+00	4.84E-29	1.03E-01	1.29E-02	0.00E+00	1.18E-06	1.16E-01	4.67E-04
RL-W465	9.49E-07	0.00E+00	3.28E-28	6.86E-01	8.59E-02	0.00E+00	7.98E-06	7.72E-01	3.11E-03
RL-W466	1.30E-05	0.00E+00	4.47E-27	9.42E+00	1.18E+00	0.00E+00	1.09E-04	1.06E+01	4.27E-02
RL-W467	6.66E-07	0.00E+00	2.30E-28	4.80E-01	5.98E-02	0.00E+00	5.59E-06	5.40E-01	2.18E-03
RL-W468	3.41E-09	0.00E+00	1.18E-30	2.46E-03	3.07E-04	0.00E+00	2.88E-08	2.76E-03	1.11E-05
RL-W469	1.38E-06	0.00E+00	4.76E-28	9.98E-01	1.26E-01	0.00E+00	1.16E-05	1.12E+00	4.53E-03
RL-W470	3.91E-05	0.00E+00	2.21E-26	3.70E+00	1.07E+00	0.00E+00	5.38E-04	4.77E+00	1.93E-02
RL-W474	1.48E-06	0.00E+00	2.44E-27	8.45E-03	4.05E-03	0.00E+00	5.94E-05	1.26E-02	5.07E-05

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W476	2.50E-06	0.00E+00	8.79E-28	1.85E+00	2.33E-01	0.00E+00	2.14E-05	2.08E+00	8.40E-03
RL-W480	4.08E-07	0.00E+00	1.41E-28	2.94E-01	3.69E-02	0.00E+00	3.42E-06	3.31E-01	1.33E-03
RL-W481	6.41E-07	0.00E+00	2.21E-28	4.61E-01	5.76E-02	0.00E+00	5.38E-06	5.19E-01	2.09E-03
RL-W482	8.51E-04	0.00E+00	7.36E-26	5.87E-02	6.12E-02	0.00E+00	1.79E-03	1.23E-01	4.94E-04
RL-W483	6.35E-05	0.00E+00	5.71E-27	3.80E-03	4.35E-03	0.00E+00	1.39E-04	8.35E-03	3.37E-05
RL-W484	2.69E-07	0.00E+00	4.60E-29	5.31E-02	7.11E-03	0.00E+00	1.12E-06	6.02E-02	2.43E-04
RL-W485	1.57E-08	0.00E+00	6.51E-30	5.74E-03	7.69E-04	0.00E+00	1.58E-07	6.51E-03	2.63E-05
RL-W486	6.65E-09	0.00E+00	2.75E-30	2.42E-03	3.24E-04	0.00E+00	6.68E-08	2.75E-03	1.11E-05
RL-W487	1.09E-06	0.00E+00	3.53E-28	3.47E-01	5.36E-02	0.00E+00	8.57E-06	4.01E-01	1.62E-03
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	6.60E-07	0.00E+00	3.33E-28	4.49E-01	5.71E-02	0.00E+00	8.08E-06	5.06E-01	2.04E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	2.45E-07	0.00E+00	2.81E-28	4.71E-02	5.80E-03	0.00E+00	6.82E-06	5.29E-02	2.13E-04
RL-W492	1.41E-08	0.00E+00	6.91E-30	9.42E-03	1.19E-03	0.00E+00	1.68E-07	1.06E-02	4.28E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	5.60E-04	0.00E+00	4.01E-25	2.38E-01	1.14E-01	0.00E+00	9.73E-03	3.62E-01	1.46E-03
RL-W495	1.01E-05	0.00E+00	1.09E-27	2.28E-03	1.02E-03	0.00E+00	2.65E-05	3.33E-03	1.34E-05
RL-W496	6.58E-05	0.00E+00	1.25E-26	7.49E-03	3.37E-03	0.00E+00	3.05E-04	1.12E-02	4.53E-05
RL-W497	2.74E-06	0.00E+00	2.47E-27	4.49E-01	1.14E-01	0.00E+00	6.01E-05	5.64E-01	2.27E-03
RL-W498	1.06E-05	0.00E+00	3.67E-27	7.68E+00	9.63E-01	0.00E+00	8.93E-05	8.64E+00	3.49E-02
RL-W499	9.55E-11	0.00E+00	3.30E-32	6.88E-05	8.64E-06	0.00E+00	8.01E-10	7.75E-05	3.12E-07
RL-W500	6.80E-09	0.00E+00	4.09E-30	2.81E-03	3.50E-04	0.00E+00	9.95E-08	3.16E-03	1.27E-05
RL-W501	2.82E-04	0.00E+00	9.13E-26	9.02E+01	1.39E+01	0.00E+00	2.22E-03	1.04E+02	4.19E-01
RL-W502	5.09E-08	0.00E+00	1.76E-29	3.67E-02	4.59E-03	0.00E+00	4.29E-07	4.13E-02	1.67E-04
RL-W503	2.94E-06	0.00E+00	1.81E-27	1.30E+00	1.61E-01	0.00E+00	4.39E-05	1.46E+00	5.88E-03
RL-W504	1.09E-06	0.00E+00	3.53E-28	3.47E-01	5.36E-02	0.00E+00	8.57E-06	4.01E-01	1.62E-03
RL-W505	5.11E-08	0.00E+00	1.85E-29	3.75E-02	4.68E-03	0.00E+00	4.50E-07	4.22E-02	1.70E-04
RL-W506	1.85E-08	0.00E+00	7.27E-30	1.23E-02	1.54E-03	0.00E+00	1.77E-07	1.39E-02	5.59E-05

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W507	1.84E-09	0.00E+00	6.36E-31	1.33E-03	1.66E-04	0.00E+00	1.55E-08	1.49E-03	6.03E-06
RL-W508	3.38E-05	0.00E+00	2.08E-26	1.44E+01	1.80E+00	0.00E+00	5.06E-04	1.62E+01	6.53E-02
RL-W509	3.33E-04	0.00E+00	1.66E-25	1.18E+02	1.62E+01	0.00E+00	4.04E-03	1.34E+02	5.39E-01
RL-W510	2.81E-05	0.00E+00	1.71E-26	1.17E+01	1.45E+00	0.00E+00	4.15E-04	1.31E+01	5.29E-02
RL-W511	2.86E-03	0.00E+00	8.23E-25	1.56E+03	1.92E+02	0.00E+00	2.03E-02	1.75E+03	7.07E+00
RL-W512	2.50E-03	0.00E+00	5.55E-25	9.42E+02	1.31E+02	0.00E+00	1.35E-02	1.07E+03	4.33E+00
RL-W513	2.67E-01	0.00E+00	2.26E-22	1.54E+04	4.28E+03	0.00E+00	5.48E+00	1.97E+04	7.93E+01
RL-W514	7.53E-09	0.00E+00	2.59E-30	5.45E-03	6.84E-04	0.00E+00	6.29E-08	6.13E-03	2.47E-05
RL-W515	2.94E-07	0.00E+00	1.02E-28	2.13E-01	2.66E-02	0.00E+00	2.47E-06	2.39E-01	9.64E-04
RL-W516	4.08E-07	0.00E+00	1.41E-28	2.94E-01	3.69E-02	0.00E+00	3.43E-06	3.31E-01	1.33E-03
RL-W517	3.64E-15	0.00E+00	1.26E-36	2.62E-09	3.27E-10	0.00E+00	3.06E-14	2.94E-09	1.19E-11
RL-W518	1.03E-05	0.00E+00	5.31E-27	3.75E+00	5.09E-01	0.00E+00	1.29E-04	4.26E+00	1.72E-02
RL-W519	1.83E-06	0.00E+00	6.29E-28	1.33E+00	1.66E-01	0.00E+00	1.53E-05	1.49E+00	6.03E-03
RL-W520	2.03E-07	0.00E+00	7.09E-29	1.46E-01	1.82E-02	0.00E+00	1.72E-06	1.64E-01	6.61E-04
RL-W521	3.77E-09	0.00E+00	1.30E-30	2.71E-03	3.40E-04	0.00E+00	3.16E-08	3.05E-03	1.23E-05
RL-W522	7.88E-05	0.00E+00	4.83E-26	1.80E+01	2.88E+00	0.00E+00	1.17E-03	2.08E+01	8.40E-02
RL-W523	2.37E-05	0.00E+00	1.84E-26	1.19E+00	4.06E-01	0.00E+00	4.46E-04	1.60E+00	6.44E-03
RL-W524	9.81E-05	0.00E+00	7.03E-26	1.10E+01	2.38E+00	0.00E+00	1.71E-03	1.33E+01	5.38E-02
RL-W525	7.80E-06	0.00E+00	4.76E-27	1.30E+00	2.41E-01	0.00E+00	1.16E-04	1.54E+00	6.20E-03
RL-W526	2.95E-05	0.00E+00	1.72E-26	1.39E+01	1.74E+00	0.00E+00	4.18E-04	1.56E+01	6.28E-02
RL-W527	3.24E-06	0.00E+00	2.49E-27	1.47E+00	1.95E-01	0.00E+00	6.04E-05	1.66E+00	6.70E-03
RL-W528	1.45E-03	0.00E+00	1.06E-24	4.67E+01	2.51E+01	0.00E+00	2.57E-02	7.18E+01	2.90E-01
RL-W529	1.21E-06	0.00E+00	7.43E-28	5.15E-01	6.39E-02	0.00E+00	1.81E-05	5.79E-01	2.34E-03
RL-W530	1.42E-05	0.00E+00	8.62E-27	5.88E+00	7.33E-01	0.00E+00	2.09E-04	6.62E+00	2.67E-02
RL-W531	8.48E-04	0.00E+00	8.65E-25	2.54E+01	1.03E+01	0.00E+00	2.10E-02	3.58E+01	1.44E-01
RL-W532	2.72E-06	0.00E+00	9.40E-28	1.96E+00	2.46E-01	0.00E+00	2.28E-05	2.21E+00	8.91E-03
RL-W533	1.32E-06	0.00E+00	8.11E-28	5.62E-01	6.97E-02	0.00E+00	1.97E-05	6.32E-01	2.55E-03
RL-W534	7.60E-11	0.00E+00	2.62E-32	5.48E-05	6.88E-06	0.00E+00	6.36E-10	6.17E-05	2.49E-07

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W535	3.98E-04	0.00E+00	2.59E-25	7.03E+01	1.21E+01	0.00E+00	6.29E-03	8.23E+01	3.32E-01
RL-W536	7.79E-06	0.00E+00	3.49E-27	2.44E+00	3.11E-01	0.00E+00	8.78E-05	2.75E+00	1.11E-02
RL-W537	2.65E-04	0.00E+00	7.87E-26	1.50E+02	1.85E+01	0.00E+00	1.94E-03	1.68E+02	6.78E-01
RL-W538	9.65E-10	0.00E+00	3.33E-31	6.96E-04	8.73E-05	0.00E+00	8.08E-09	7.84E-04	3.16E-06
RL-W539	1.07E-07	0.00E+00	3.75E-29	7.70E-02	9.63E-03	0.00E+00	9.10E-07	8.66E-02	3.49E-04
RL-W540	2.09E-04	0.00E+00	1.65E-25	2.77E+01	5.36E+00	0.00E+00	4.01E-03	3.31E+01	1.33E-01
RL-W541	3.10E-07	0.00E+00	1.08E-28	2.23E-01	2.79E-02	0.00E+00	2.63E-06	2.51E-01	1.01E-03
RL-W542	1.44E-05	0.00E+00	8.03E-27	5.64E+00	7.33E-01	0.00E+00	1.95E-04	6.38E+00	2.57E-02
RL-W543	4.53E-08	0.00E+00	1.56E-29	3.27E-02	4.10E-03	0.00E+00	3.80E-07	3.68E-02	1.48E-04
RL-W544	1.02E-06	0.00E+00	6.38E-28	3.72E-01	5.22E-02	0.00E+00	1.55E-05	4.24E-01	1.71E-03
RL-W545	2.72E-07	0.00E+00	9.37E-29	1.96E-01	2.45E-02	0.00E+00	2.28E-06	2.20E-01	8.88E-04
RL-W546	1.19E-08	0.00E+00	4.11E-30	8.61E-03	1.08E-03	0.00E+00	9.98E-08	9.69E-03	3.91E-05
RL-W547	3.04E-10	0.00E+00	1.05E-31	2.19E-04	2.75E-05	0.00E+00	2.55E-09	2.46E-04	9.94E-07
RL-W548	2.63E-10	0.00E+00	9.11E-32	1.89E-04	2.37E-05	0.00E+00	2.21E-09	2.13E-04	8.58E-07
RL-W549	5.22E-05	0.00E+00	3.66E-26	9.74E+00	1.63E+00	0.00E+00	8.89E-04	1.14E+01	4.59E-02
RL-W550	2.37E-04	0.00E+00	6.93E-26	1.32E+02	1.63E+01	0.00E+00	1.70E-03	1.48E+02	5.98E-01
RL-W551	4.21E-04	0.00E+00	1.02E-25	1.49E+02	2.12E+01	0.00E+00	2.49E-03	1.70E+02	6.86E-01
RL-W552	1.63E-07	0.00E+00	5.67E-29	1.18E-01	1.47E-02	0.00E+00	1.38E-06	1.32E-01	5.33E-04
RL-W553	1.45E-08	0.00E+00	5.35E-30	1.05E-02	1.31E-03	0.00E+00	1.30E-07	1.18E-02	4.75E-05
RL-W554	2.30E-07	0.00E+00	7.94E-29	1.66E-01	2.08E-02	0.00E+00	1.93E-06	1.87E-01	7.53E-04
RL-W555	1.06E-07	0.00E+00	3.66E-29	7.64E-02	9.54E-03	0.00E+00	8.89E-07	8.59E-02	3.47E-04
RL-W563	1.52E-06	0.00E+00	9.15E-28	6.34E-01	7.87E-02	0.00E+00	2.22E-05	7.12E-01	2.87E-03
RL-W564	9.89E-07	0.00E+00	6.07E-28	4.10E-01	5.09E-02	0.00E+00	1.48E-05	4.61E-01	1.86E-03
RL-W565	9.82E-08	0.00E+00	3.41E-29	7.08E-02	8.86E-03	0.00E+00	8.29E-07	7.96E-02	3.21E-04
RL-W566	1.44E-06	0.00E+00	5.00E-28	1.04E+00	1.31E-01	0.00E+00	1.22E-05	1.17E+00	4.71E-03
RL-W567	9.99E-05	0.00E+00	1.28E-26	3.20E-02	1.45E-02	0.00E+00	3.11E-04	4.69E-02	1.89E-04
RL-W568	1.92E-03	0.00E+00	2.69E-25	1.51E+00	6.75E-01	0.00E+00	6.54E-03	2.20E+00	8.86E-03
RL-W569	1.58E-06	0.00E+00	2.03E-28	5.05E-04	2.30E-05	0.00E+00	4.92E-06	5.34E-04	2.15E-06

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W570	1.01E-07	0.00E+00	3.54E-29	7.50E-02	9.36E-03	0.00E+00	8.61E-07	8.44E-02	3.40E-04
RL-W571	3.25E-04	0.00E+00	1.20E-25	6.09E+00	1.71E+00	0.00E+00	2.92E-03	7.80E+00	3.15E-02
RL-W572	2.82E-07	0.00E+00	3.60E-29	3.28E-03	4.10E-05	0.00E+00	8.75E-07	3.32E-03	1.34E-05
RL-W573	3.63E-03	0.00E+00	4.61E-25	1.80E+00	7.56E-01	0.00E+00	1.12E-02	2.57E+00	1.04E-02
RL-W574	1.56E-02	0.00E+00	2.00E-24	6.86E+00	2.80E+00	0.00E+00	4.85E-02	9.72E+00	3.92E-02
RL-W575	1.02E-01	0.00E+00	1.34E-23	6.56E+01	2.24E+01	0.00E+00	3.27E-01	8.84E+01	3.56E-01
RL-W576	7.33E-03	0.00E+00	9.39E-25	3.34E+00	1.35E+00	0.00E+00	2.28E-02	4.72E+00	1.90E-02
RL-W579	6.21E-07	0.00E+00	2.47E-29	1.67E-02	2.10E-03	0.00E+00	6.01E-07	1.89E-02	7.60E-05
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.34E-01	1.22E-02	0.00E+00	0.00E+00	1.46E-01	5.88E-04
RL-W581	6.59E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.59E-06	2.66E-08
RL-W582	4.31E-08	0.00E+00	2.10E-29	4.28E-03	1.25E-03	0.00E+00	5.10E-07	5.53E-03	2.23E-05
RL-W583	3.33E-08	0.00E+00	1.14E-29	2.42E-02	3.03E-03	0.00E+00	2.77E-07	2.72E-02	1.10E-04
RL-W584	6.62E-07	0.00E+00	7.48E-28	1.41E-01	3.88E-02	0.00E+00	1.82E-05	1.80E-01	7.25E-04
RL-W585	3.94E-06	0.00E+00	3.98E-27	8.21E-01	2.36E-01	0.00E+00	9.66E-05	1.06E+00	4.26E-03
RL-W586	5.26E-10	0.00E+00	1.79E-31	3.82E-04	4.77E-05	0.00E+00	4.36E-09	4.29E-04	1.73E-06
RL-W587	1.13E-08	0.00E+00	3.88E-30	8.13E-03	1.02E-03	0.00E+00	9.42E-08	9.15E-03	3.69E-05
RL-W588	4.64E-07	0.00E+00	6.31E-28	1.19E-01	3.27E-02	0.00E+00	1.53E-05	1.52E-01	6.12E-04
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W590	1.43E-05	0.00E+00	1.35E-26	9.18E-03	9.18E-03	0.00E+00	3.27E-04	1.87E-02	7.54E-05
RL-W591	8.12E-05	0.00E+00	1.52E-26	1.14E-02	1.19E-02	0.00E+00	3.69E-04	2.37E-02	9.55E-05
RL-W592	3.59E-04	0.00E+00	1.66E-25	5.27E-01	3.84E-01	0.00E+00	4.04E-03	9.15E-01	3.69E-03
RL-W593	0.00E+00	0.00E+00	0.00E+00	1.90E-02	1.80E-02	0.00E+00	0.00E+00	3.70E-02	1.49E-04
RL-W594	3.23E-04	0.00E+00	2.99E-26	2.35E-02	2.44E-02	0.00E+00	7.27E-04	4.89E-02	1.97E-04
RL-W595	8.54E-07	0.00E+00	3.12E-27	1.61E-02	1.77E-02	0.00E+00	7.59E-05	3.39E-02	1.37E-04
RL-W596	2.76E-07	0.00E+00	2.43E-28	1.66E-04	1.67E-04	0.00E+00	5.90E-06	3.39E-04	1.37E-06
RL-W597	5.08E-04	0.00E+00	1.07E-25	3.21E-01	3.02E-01	0.00E+00	2.60E-03	6.26E-01	2.53E-03
RL-W598	5.37E-04	0.00E+00	6.31E-25	4.48E-01	3.77E-01	0.00E+00	1.53E-02	8.40E-01	3.39E-03
RL-W599	2.72E-05	0.00E+00	5.09E-27	3.78E-03	3.97E-03	0.00E+00	1.24E-04	7.90E-03	3.19E-05

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W600	1.55E-12	0.00E+00	5.28E-34	1.12E-06	1.40E-07	0.00E+00	1.28E-11	1.26E-06	5.08E-09
RL-W601	7.84E-09	0.00E+00	2.89E-30	5.67E-03	7.11E-04	0.00E+00	7.03E-08	6.38E-03	2.57E-05
RL-W602	6.83E-06	0.00E+00	2.37E-27	4.91E+00	6.16E-01	0.00E+00	5.76E-05	5.53E+00	2.23E-02
RL-W603	3.93E-05	0.00E+00	1.37E-26	2.83E+01	3.55E+00	0.00E+00	3.32E-04	3.19E+01	1.29E-01
RL-W604	9.20E-08	0.00E+00	3.59E-29	1.38E-02	3.83E-03	0.00E+00	8.72E-07	1.76E-02	7.09E-05
RL-W605	2.11E-08	0.00E+00	7.79E-30	1.52E-02	1.91E-03	0.00E+00	1.89E-07	1.71E-02	6.90E-05
RL-W606	8.51E-09	0.00E+00	3.14E-30	6.13E-03	7.69E-04	0.00E+00	7.63E-08	6.90E-03	2.78E-05
RL-W607	1.56E-08	0.00E+00	6.07E-30	2.33E-03	6.48E-04	0.00E+00	1.48E-07	2.97E-03	1.20E-05
RL-W608	1.86E-07	0.00E+00	2.36E-28	3.03E-03	2.10E-03	0.00E+00	5.73E-06	5.13E-03	2.07E-05
RL-W610	3.69E-05	0.00E+00	1.26E-26	2.67E+01	3.35E+00	0.00E+00	3.06E-04	3.01E+01	1.21E-01
RL-W612	8.70E-08	0.00E+00	3.05E-29	6.49E-02	8.14E-03	0.00E+00	7.42E-07	7.30E-02	2.95E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	2.72E-01	0.00E+00	0.00E+00	0.00E+00	2.72E-01	1.10E-03
RL-W622	1.45E-09	0.00E+00	4.98E-31	1.06E-03	1.32E-04	0.00E+00	1.21E-08	1.19E-03	4.78E-06
RL-W625	5.06E-08	0.00E+00	7.56E-29	5.39E-03	2.98E-03	0.00E+00	1.84E-06	8.37E-03	3.37E-05
RL-W626	2.72E-06	0.00E+00	1.72E-27	2.11E-01	7.11E-02	0.00E+00	4.18E-05	2.82E-01	1.14E-03
RL-W627	1.28E-08	0.00E+00	2.30E-30	9.98E-07	0.00E+00	0.00E+00	5.59E-08	1.07E-06	4.30E-09
RL-W628	4.20E-09	0.00E+00	1.45E-30	3.04E-03	3.81E-04	0.00E+00	3.51E-08	3.42E-03	1.38E-05
RL-W629	2.84E-10	0.00E+00	9.94E-32	2.05E-04	2.56E-05	0.00E+00	2.41E-09	2.30E-04	9.28E-07
RL-W630	3.13E-06	0.00E+00	1.85E-27	2.37E+00	3.08E-01	0.00E+00	4.50E-05	2.68E+00	1.08E-02
RL-W631	5.04E-08	0.00E+00	1.87E-29	3.63E-02	4.55E-03	0.00E+00	4.53E-07	4.09E-02	1.65E-04
RL-W632	2.23E-05	0.00E+00	2.52E-27	4.80E+00	8.86E-01	0.00E+00	6.12E-05	5.68E+00	2.29E-02
RL-W633	5.31E-08	0.00E+00	1.46E-29	7.54E-04	3.74E-04	0.00E+00	3.55E-07	1.13E-03	4.55E-06
RL-W634	0.00E+00	0.00E+00	0.00E+00	8.21E-03	0.00E+00	0.00E+00	0.00E+00	8.21E-03	3.31E-05
RL-W635	3.17E-04	0.00E+00	4.93E-25	3.49E+00	2.94E+00	0.00E+00	1.20E-02	6.44E+00	2.60E-02
RL-W636	3.24E-06	0.00E+00	9.31E-28	4.56E-02	2.27E-02	0.00E+00	2.26E-05	6.84E-02	2.76E-04
RL-W637	7.69E-09	0.00E+00	2.37E-29	5.14E-04	2.84E-04	0.00E+00	5.76E-07	7.98E-04	3.22E-06
RL-W638	3.38E-07	0.00E+00	2.42E-28	5.03E-03	2.66E-03	0.00E+00	5.87E-06	7.70E-03	3.11E-05
RL-W639	1.79E-08	0.00E+00	6.18E-30	1.29E-02	1.61E-03	0.00E+00	1.50E-07	1.45E-02	5.84E-05

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W640	6.00E-07	0.00E+00	2.05E-28	4.34E-01	5.45E-02	0.00E+00	4.99E-06	4.88E-01	1.97E-03
RL-W641	1.83E-05	0.00E+00	4.51E-26	2.09E+00	4.82E-01	0.00E+00	1.10E-03	2.57E+00	1.04E-02
RL-W642	3.57E-07	0.00E+00	4.69E-30	2.54E-02	7.29E-05	0.00E+00	1.14E-07	2.55E-02	1.03E-04
RL-W643	5.63E-06	0.00E+00	1.39E-26	6.42E-01	1.49E-01	0.00E+00	3.38E-04	7.91E-01	3.19E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	4.42E-02	0.00E+00	0.00E+00	0.00E+00	4.42E-02	1.78E-04
RL-W645	1.37E-07	0.00E+00	6.25E-29	8.69E-02	1.15E-02	0.00E+00	1.52E-06	9.84E-02	3.97E-04
RL-W646	1.24E-07	0.00E+00	5.58E-29	2.08E-02	5.67E-03	0.00E+00	1.36E-06	2.64E-02	1.07E-04
RL-W647	3.50E-07	0.00E+00	8.34E-27	8.86E-02	7.87E-03	0.00E+00	2.03E-04	9.66E-02	3.90E-04
RL-W648	6.20E-09	0.00E+00	1.43E-29	4.84E-05	5.36E-05	0.00E+00	3.47E-07	1.02E-04	4.12E-07
RL-W649	2.28E-08	0.00E+00	5.25E-29	1.78E-04	1.97E-04	0.00E+00	1.28E-06	3.76E-04	1.52E-06
RL-W653	1.08E-09	0.00E+00	3.76E-31	7.78E-04	9.72E-05	0.00E+00	9.14E-09	8.75E-04	3.53E-06
RL-W654	5.94E-09	0.00E+00	2.05E-30	4.28E-03	5.36E-04	0.00E+00	4.99E-08	4.82E-03	1.94E-05
RL-W655	1.46E-03	0.00E+00	4.86E-25	1.70E-01	2.25E-01	0.00E+00	1.18E-02	4.09E-01	1.65E-03
RL-W656	6.12E-03	0.00E+00	2.18E-25	3.99E-01	2.32E-01	0.00E+00	5.31E-03	6.42E-01	2.59E-03
RL-W657	3.13E-03	0.00E+00	3.23E-25	1.96E-01	2.21E-01	0.00E+00	7.84E-03	4.28E-01	1.73E-03
RL-W659	3.78E-04	0.00E+00	7.27E-26	3.78E-02	2.64E-02	0.00E+00	1.77E-03	6.64E-02	2.68E-04
RL-W660	2.07E-03	0.00E+00	8.75E-25	6.98E-01	7.02E-01	0.00E+00	2.13E-02	1.42E+00	5.74E-03
RL-W661	2.20E-05	0.00E+00	1.10E-27	3.37E-04	1.72E-03	0.00E+00	2.66E-05	2.11E-03	8.50E-06
RL-W662	6.91E-07	0.00E+00	6.52E-29	8.61E-05	8.68E-05	0.00E+00	1.59E-06	1.75E-04	7.07E-07
RL-W665	8.49E-03	0.00E+00	5.22E-24	1.06E+00	7.96E-01	0.00E+00	1.27E-01	1.99E+00	8.01E-03
RL-W666	1.52E-04	0.00E+00	1.28E-26	4.42E-02	2.62E-02	0.00E+00	3.11E-04	7.08E-02	2.86E-04
RL-W668	1.45E-05	0.00E+00	4.02E-28	1.17E-01	1.86E-02	0.00E+00	9.77E-06	1.35E-01	5.46E-04
RL-W669	4.22E-06	0.00E+00	1.04E-26	4.81E-01	1.11E-01	0.00E+00	2.53E-04	5.93E-01	2.39E-03
RL-W670	2.67E-07	0.00E+00	7.42E-30	2.16E-03	3.45E-04	0.00E+00	1.80E-07	2.50E-03	1.01E-05
RL-W671	4.35E-05	0.00E+00	3.80E-27	3.95E-03	2.31E-03	0.00E+00	9.24E-05	6.40E-03	2.58E-05
RL-W672	2.96E-04	0.00E+00	2.59E-26	2.70E-02	1.57E-02	0.00E+00	6.29E-04	4.36E-02	1.76E-04
RL-W673	2.85E-04	0.00E+00	2.49E-26	2.61E-02	1.52E-02	0.00E+00	6.04E-04	4.21E-02	1.70E-04
RL-W674	9.57E-07	0.00E+00	1.11E-27	9.02E+00	4.41E-02	0.00E+00	2.70E-05	9.06E+00	3.65E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W675	3.58E-06	0.00E+00	6.15E-27	1.06E-01	5.13E-02	0.00E+00	1.49E-04	1.57E-01	6.33E-04
RL-W676	1.37E-07	0.00E+00	3.69E-29	1.18E-01	9.67E-04	0.00E+00	8.96E-07	1.19E-01	4.81E-04
RL-W677	3.18E-04	0.00E+00	9.14E-26	4.62E+00	2.26E+00	0.00E+00	2.22E-03	6.88E+00	2.78E-02
RL-W678	1.01E-06	0.00E+00	7.64E-28	4.15E-02	2.06E-02	0.00E+00	1.86E-05	6.22E-02	2.51E-04
RL-W679	6.31E-06	0.00E+00	1.71E-27	8.94E-02	4.44E-02	0.00E+00	4.15E-05	1.34E-01	5.39E-04
RL-W680	1.42E-09	0.00E+00	2.40E-30	1.40E-05	1.42E-05	0.00E+00	5.83E-08	2.82E-05	1.14E-07
RL-W681	8.68E-10	0.00E+00	9.73E-31	3.76E-04	1.05E-04	0.00E+00	2.37E-08	4.81E-04	1.94E-06
RL-W685	2.53E-06	0.00E+00	8.65E-28	1.84E+00	2.30E-01	0.00E+00	2.10E-05	2.07E+00	8.33E-03
RL-W689	6.55E-08	0.00E+00	1.04E-29	3.12E-04	0.00E+00	0.00E+00	2.52E-07	3.12E-04	1.26E-06
RL-W690	2.20E-06	0.00E+00	7.64E-28	1.63E+00	2.04E-01	0.00E+00	1.86E-05	1.84E+00	7.41E-03
RL-W691	5.10E-08	0.00E+00	1.78E-29	3.78E-02	4.73E-03	0.00E+00	4.32E-07	4.26E-02	1.72E-04
RL-W692	2.02E-06	0.00E+00	7.04E-28	1.50E+00	1.87E-01	0.00E+00	1.71E-05	1.68E+00	6.79E-03
RL-W693	2.50E-06	0.00E+00	8.69E-28	1.85E+00	2.32E-01	0.00E+00	2.11E-05	2.08E+00	8.40E-03
RL-W694	2.62E-05	0.00E+00	9.13E-27	1.96E+01	2.43E+00	0.00E+00	2.22E-04	2.20E+01	8.87E-02
RL-W695	2.17E-08	0.00E+00	0.00E+00	1.92E-03	0.00E+00	0.00E+00	0.00E+00	1.92E-03	7.76E-06
RL-W696	2.83E-08	0.00E+00	3.33E-29	2.34E-03	1.30E-03	0.00E+00	8.08E-07	3.64E-03	1.47E-05
RL-W697	6.53E-06	0.00E+00	7.04E-26	5.58E-03	4.31E-04	0.00E+00	1.71E-03	7.73E-03	3.12E-05
RL-W698	5.66E-07	0.00E+00	0.00E+00	2.65E-05	0.00E+00	0.00E+00	0.00E+00	2.71E-05	1.09E-07
RL-W699	1.26E-07	0.00E+00	4.69E-30	1.77E-03	1.17E-04	0.00E+00	1.14E-07	1.89E-03	7.61E-06
RL-W700	3.57E-08	0.00E+00	1.23E-29	2.57E-02	3.22E-03	0.00E+00	2.99E-07	2.89E-02	1.17E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	1.41E-06	0.00E+00	3.47E-27	1.60E-01	3.71E-02	0.00E+00	8.43E-05	1.97E-01	7.96E-04
RL-W705	9.09E-09	0.00E+00	3.20E-30	6.73E-03	8.46E-04	0.00E+00	7.77E-08	7.58E-03	3.06E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	3.24E-07	0.00E+00	1.14E-28	2.40E-01	3.01E-02	0.00E+00	2.76E-06	2.70E-01	1.09E-03
RL-W708	4.90E-08	0.00E+00	1.72E-29	3.64E-02	4.55E-03	0.00E+00	4.18E-07	4.09E-02	1.65E-04
RL-W709	1.70E-05	0.00E+00	5.93E-27	1.26E+01	1.57E+00	0.00E+00	1.44E-04	1.41E+01	5.70E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W710	1.01E-09	0.00E+00	3.54E-31	7.50E-04	9.36E-05	0.00E+00	8.61E-09	8.44E-04	3.40E-06
RL-W711	3.16E-07	0.00E+00	1.11E-28	2.34E-01	2.93E-02	0.00E+00	2.69E-06	2.64E-01	1.06E-03
RL-W712	4.09E-07	0.00E+00	1.43E-28	3.03E-01	3.79E-02	0.00E+00	3.48E-06	3.41E-01	1.37E-03
RL-W713	3.53E-07	0.00E+00	1.24E-28	2.61E-01	3.28E-02	0.00E+00	3.01E-06	2.94E-01	1.18E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	6.09E-09	0.00E+00	2.08E-30	4.42E-03	5.53E-04	0.00E+00	5.06E-08	4.97E-03	2.01E-05
RL-W716	6.35E-08	0.00E+00	2.17E-29	4.60E-02	5.76E-03	0.00E+00	5.27E-07	5.18E-02	2.09E-04
RL-W717	1.58E-08	0.00E+00	5.42E-30	1.15E-02	1.44E-03	0.00E+00	1.32E-07	1.30E-02	5.22E-05
RL-W718	2.80E-09	0.00E+00	9.56E-31	2.03E-03	2.54E-04	0.00E+00	2.32E-08	2.28E-03	9.20E-06
RL-W719	1.26E-08	0.00E+00	4.31E-30	9.18E-03	1.15E-03	0.00E+00	1.05E-07	1.03E-02	4.16E-05
RL-W720	7.81E-08	0.00E+00	2.68E-29	5.67E-02	7.11E-03	0.00E+00	6.50E-07	6.38E-02	2.57E-04
RL-W721	5.29E-08	0.00E+00	1.81E-29	3.83E-02	4.82E-03	0.00E+00	4.39E-07	4.31E-02	1.74E-04
RL-W723	1.75E-07	0.00E+00	6.10E-29	1.30E-01	1.63E-02	0.00E+00	1.48E-06	1.47E-01	5.92E-04
RL-W724	1.17E-06	0.00E+00	4.06E-28	8.61E-01	1.08E-01	0.00E+00	9.88E-06	9.70E-01	3.91E-03
RL-W725	3.68E-07	0.00E+00	1.28E-28	2.73E-01	3.42E-02	0.00E+00	3.11E-06	3.07E-01	1.24E-03
RL-W726	2.90E-07	0.00E+00	1.01E-28	2.16E-01	2.70E-02	0.00E+00	2.46E-06	2.43E-01	9.79E-04
RL-W727	1.78E-06	0.00E+00	6.20E-28	1.32E+00	1.66E-01	0.00E+00	1.51E-05	1.49E+00	5.99E-03
RL-W728	1.62E-06	0.00E+00	5.65E-28	1.21E+00	1.51E-01	0.00E+00	1.37E-05	1.36E+00	5.48E-03
RL-W729	7.48E-07	0.00E+00	2.62E-28	5.55E-01	6.97E-02	0.00E+00	6.36E-06	6.25E-01	2.52E-03
RL-W730	2.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.93E-04	1.18E-06
RL-W731	9.43E-11	0.00E+00	0.00E+00	3.63E-04	8.37E-07	0.00E+00	0.00E+00	3.64E-04	1.47E-06
RL-W732	2.16E-04	0.00E+00	1.49E-25	1.02E+02	1.27E+01	0.00E+00	3.62E-03	1.15E+02	4.64E-01
RL-W733	2.84E-06	0.00E+00	1.94E-27	1.11E+00	1.55E-01	0.00E+00	4.71E-05	1.27E+00	5.10E-03
RL-W734	8.88E-06	0.00E+00	6.46E-27	3.83E+00	5.22E-01	0.00E+00	1.57E-04	4.35E+00	1.76E-02
RL-W735	7.25E-06	0.00E+00	4.93E-27	2.99E+00	4.16E-01	0.00E+00	1.20E-04	3.40E+00	1.37E-02
RL-W736	7.96E-09	0.00E+00	1.05E-32	1.98E-03	2.87E-04	0.00E+00	2.56E-10	2.27E-03	9.14E-06
RL-W737	6.47E-06	0.00E+00	4.50E-27	2.83E+00	3.87E-01	0.00E+00	1.09E-04	3.22E+00	1.30E-02
RL-W738	2.42E-05	0.00E+00	1.55E-26	9.02E+00	1.34E+00	0.00E+00	3.76E-04	1.04E+01	4.17E-02

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W739	2.06E-06	0.00E+00	1.37E-27	1.47E+00	1.88E-01	0.00E+00	3.32E-05	1.65E+00	6.66E-03
RL-W740	1.03E-04	0.00E+00	5.00E-26	3.57E+01	5.22E+00	0.00E+00	1.22E-03	4.09E+01	1.65E-01
RL-W741	1.54E-04	0.00E+00	1.18E-25	6.95E+00	2.77E+00	0.00E+00	2.86E-03	9.72E+00	3.92E-02
RL-W742	6.84E-06	0.00E+00	3.54E-27	2.25E+00	2.98E-01	0.00E+00	8.61E-05	2.55E+00	1.03E-02
RL-W743	1.23E-08	0.00E+00	9.62E-31	1.46E-03	0.00E+00	0.00E+00	2.34E-08	1.46E-03	5.88E-06
RL-W744	0.00E+00	0.00E+00	0.00E+00	7.27E-02	3.47E-02	0.00E+00	0.00E+00	1.07E-01	4.33E-04
RL-W745	1.95E-08	0.00E+00	6.72E-30	1.41E-02	1.76E-03	0.00E+00	1.63E-07	1.59E-02	6.39E-05
RL-W746	7.50E-08	0.00E+00	2.59E-29	5.41E-02	6.79E-03	0.00E+00	6.29E-07	6.09E-02	2.46E-04
RL-W747	2.03E-07	0.00E+00	7.01E-29	1.47E-01	1.84E-02	0.00E+00	1.70E-06	1.65E-01	6.65E-04
RL-W748	1.42E-03	0.00E+00	1.97E-25	2.43E-01	2.25E-01	0.00E+00	4.78E-03	4.74E-01	1.91E-03
RL-W749	1.71E-06	0.00E+00	6.02E-28	1.27E+00	1.59E-01	0.00E+00	1.46E-05	1.43E+00	5.77E-03
RL-W750	2.16E-03	0.00E+00	2.98E-25	3.99E-01	3.67E-01	0.00E+00	7.24E-03	7.75E-01	3.12E-03
RL-W751	1.95E-03	0.00E+00	2.69E-25	3.58E-01	3.33E-01	0.00E+00	6.54E-03	6.99E-01	2.82E-03
RL-W752	8.47E-04	0.00E+00	1.17E-25	1.56E-01	1.44E-01	0.00E+00	2.84E-03	3.04E-01	1.23E-03
RL-W753	1.14E-02	0.00E+00	1.58E-24	2.10E+00	1.94E+00	0.00E+00	3.83E-02	4.09E+00	1.65E-02
RP-W754	4.84E-04	0.00E+00	2.00E-25	1.50E+03	6.88E+01	0.00E+00	3.50E-01	1.57E+03	6.32E+00
RP-W755	2.56E-03	0.00E+00	1.20E-25	1.12E+03	5.22E+01	0.00E+00	1.23E+01	1.18E+03	4.77E+00
SA-T001	5.15E-06	0.00E+00	2.86E-27	2.44E+00	8.10E-03	0.00E+00	7.41E-05	2.45E+00	9.87E-03
SA-W134	4.21E-05	0.00E+00	1.95E-26	1.11E+00	1.98E-01	0.00E+00	1.64E-01	1.47E+00	5.94E-03
SA-W134M	5.46E-06	0.00E+00	2.53E-27	1.45E-01	2.57E-02	0.00E+00	2.12E-02	1.92E-01	7.73E-04
T001-221F-HET	1.02E-02	0.00E+00	2.29E-21	2.32E+04	3.21E+02	0.00E+00	6.11E+01	2.36E+04	9.50E+01
T001-221H-HET	1.83E-02	0.00E+00	4.12E-21	4.19E+04	5.80E+02	0.00E+00	1.10E+02	4.26E+04	1.72E+02
T001-235F-HET	1.05E-03	0.00E+00	2.37E-22	2.41E+03	3.33E+01	0.00E+00	6.34E+00	2.45E+03	9.87E+00
T001-772F-HET	9.08E-03	0.00E+00	2.05E-21	2.08E+04	2.88E+02	0.00E+00	5.49E+01	2.11E+04	8.51E+01
T001-773A-CLAS	1.02E-04	0.00E+00	2.30E-23	2.33E+02	3.23E+00	0.00E+00	6.14E-01	2.37E+02	9.57E-01
T001-773A-HET	1.18E-03	0.00E+00	2.65E-22	2.69E+03	3.73E+01	0.00E+00	7.07E+00	2.73E+03	1.10E+01
W006-773A-VIT	1.57E-08	0.00E+00	0.00E+00	4.32E+02	0.00E+00	0.00E+00	0.00E+00	4.32E+02	1.74E+00
W026-221F-HET	3.54E-03	0.00E+00	7.97E-22	8.13E+03	1.12E+02	0.00E+00	2.13E+01	8.26E+03	3.33E+01

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W026-221H-HET	2.65E-03	0.00E+00	5.96E-22	6.05E+03	8.37E+01	0.00E+00	1.59E+01	6.15E+03	2.48E+01
W026-235F-HET	4.12E-05	0.00E+00	9.28E-24	9.42E+01	1.31E+00	0.00E+00	2.48E-01	9.57E+01	3.86E-01
W026-772F-HET	1.13E-05	0.00E+00	2.53E-24	2.57E+01	3.56E-01	0.00E+00	6.76E-02	2.61E+01	1.05E-01
W026-773A-HET	1.83E-04	0.00E+00	4.12E-23	4.19E+02	5.80E+00	0.00E+00	1.10E+00	4.26E+02	1.72E+00
W027-221F-HET	1.34E-02	0.00E+00	2.69E-21	3.14E+04	4.34E+02	0.00E+00	8.28E+01	3.19E+04	1.29E+02
W027-221H-HET	5.84E-03	0.00E+00	1.17E-21	1.38E+04	1.90E+02	0.00E+00	3.62E+01	1.40E+04	5.64E+01
W027-235F-HET	1.76E-03	0.00E+00	3.53E-22	4.14E+03	5.71E+01	0.00E+00	1.09E+01	4.21E+03	1.70E+01
W027-772F-HET	3.19E-03	0.00E+00	6.42E-22	7.51E+03	1.04E+02	0.00E+00	1.98E+01	7.63E+03	3.08E+01
W027-773A-HET	4.76E-03	0.00E+00	9.57E-22	1.12E+04	1.55E+02	0.00E+00	2.95E+01	1.14E+04	4.59E+01
W027-999-HET	5.45E-03	0.00E+00	1.10E-21	1.28E+04	1.77E+02	0.00E+00	3.37E+01	1.30E+04	5.25E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	3.21E+02	0.00E+00	0.00E+00	0.00E+00	3.21E+02	1.30E+00
WP-INW169.001	2.66E-05	0.00E+00	6.90E-27	1.24E+01	1.55E+00	0.00E+00	3.29E-04	1.39E+01	5.62E-02
WP-INW198.001	3.50E-05	0.00E+00	1.20E-26	2.22E+01	2.75E+00	0.00E+00	3.72E-04	2.50E+01	1.01E-01
WP-INW211.001	3.95E-03	0.00E+00	1.13E-24	2.06E+03	2.56E+02	0.00E+00	2.94E-02	2.32E+03	9.34E+00
WP-INW216.001-	1.43E-01	0.00E+00	6.49E-25	1.19E+03	1.49E+02	0.00E+00	2.87E-01	1.34E+03	5.40E+00
WP-INW216.001-	3.94E-02	0.00E+00	1.75E-25	3.23E+02	4.01E+01	0.00E+00	3.13E-02	3.63E+02	1.46E+00
WP-INW218.001-	2.74E-03	0.00E+00	1.15E-25	2.08E+02	2.58E+01	0.00E+00	3.81E-01	2.34E+02	9.43E-01
WP-INW218.001-	1.26E-05	0.00E+00	3.15E-27	5.65E+00	7.02E-01	0.00E+00	3.67E-02	6.39E+00	2.58E-02
WP-INW222.001	1.30E-04	0.00E+00	3.40E-26	5.52E+01	6.93E+00	0.00E+00	1.39E-03	6.22E+01	2.51E-01
WP-INW243.001	3.15E-04	0.00E+00	7.33E-26	1.16E+02	1.46E+01	0.00E+00	2.63E-03	1.31E+02	5.26E-01
WP-INW247.001R	4.20E-04	0.00E+00	1.71E-25	2.22E+02	2.84E+01	0.00E+00	4.22E-03	2.51E+02	1.01E+00
WP-INW276.001	3.21E-05	0.00E+00	1.66E-26	2.20E+01	2.81E+00	0.00E+00	4.21E-04	2.48E+01	9.99E-02
WP-INW276.002	5.08E-05	0.00E+00	2.50E-26	3.23E+01	4.21E+00	0.00E+00	6.34E-04	3.65E+01	1.47E-01
WP-INW276.003	1.95E-03	0.00E+00	9.30E-25	1.20E+03	1.53E+02	0.00E+00	2.30E-02	1.35E+03	5.46E+00
WP-INW276.004	4.65E-04	0.00E+00	1.97E-25	2.54E+02	3.24E+01	0.00E+00	4.92E-03	2.86E+02	1.15E+00
WP-INW296.001-	1.70E-04	0.00E+00	4.67E-26	6.37E+01	8.10E+00	0.00E+00	1.17E-03	7.18E+01	2.89E-01
WP-INW296.001-	5.13E-04	0.00E+00	1.65E-25	2.25E+02	2.86E+01	0.00E+00	4.35E-03	2.54E+02	1.02E+00
WP-LA-TA-55-19	8.54E-06	0.00E+00	7.66E-27	1.68E+00	2.28E-01	0.00E+00	2.77E-03	1.91E+00	7.72E-03

Table PAR-59. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 7,500 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-LA-TA-55-19	4.14E-04	0.00E+00	2.57E-25	1.72E+02	2.35E+01	0.00E+00	9.16E-02	1.95E+02	7.86E-01
WP-LA-TA-55-43	2.32E-06	0.00E+00	6.00E-24	2.60E-01	6.16E-02	0.00E+00	1.72E-01	4.93E-01	1.99E-03
WP-RF001.01	7.18E-04	0.00E+00	2.08E-25	3.30E+02	4.22E+01	0.00E+00	1.42E-02	3.72E+02	1.50E+00
WP-RF002.01-A	8.36E-04	0.00E+00	2.78E-25	3.72E+02	4.77E+01	0.00E+00	2.42E-02	4.20E+02	1.69E+00
WP-RF002.01-B	8.29E-07	0.00E+00	1.92E-28	4.03E-01	5.13E-02	0.00E+00	4.86E-06	4.54E-01	1.83E-03
WP-RF003.01	1.30E-02	0.00E+00	4.47E-24	7.11E+03	9.09E+02	0.00E+00	1.17E-01	8.02E+03	3.23E+01
WP-RF004.01	6.09E-06	0.00E+00	2.99E-27	4.10E+00	5.27E-01	0.00E+00	1.97E-04	4.62E+00	1.86E-02
WP-RF005.01	3.12E-02	0.00E+00	2.27E-24	3.76E+03	4.77E+02	0.00E+00	5.69E-02	4.24E+03	1.71E+01
WP-RF005.02	3.67E-02	0.00E+00	1.17E-24	2.25E+03	2.83E+02	0.00E+00	2.97E-02	2.53E+03	1.02E+01
WP-RF006.01	1.19E-02	0.00E+00	4.27E-24	6.39E+03	8.19E+02	0.00E+00	1.29E-01	7.21E+03	2.91E+01
WP-RF008.01	3.78E-03	0.00E+00	1.52E-24	1.87E+03	2.43E+02	0.00E+00	3.81E-02	2.11E+03	8.51E+00
WP-RF009.01	3.72E-01	0.00E+00	1.87E-23	4.10E+04	5.13E+03	0.00E+00	4.74E-01	4.61E+04	1.86E+02
WP-RF010.01	1.37E-04	0.00E+00	4.73E-26	6.19E+01	7.92E+00	0.00E+00	1.87E-03	6.98E+01	2.82E-01
WP-RF029.01-A	3.30E-05	0.00E+00	8.89E-27	1.09E+01	1.40E+00	0.00E+00	9.31E-04	1.23E+01	4.95E-02
WP-RF029.01-B	4.92E-05	0.00E+00	7.04E-27	8.61E+00	1.10E+00	0.00E+00	2.37E-03	9.72E+00	3.92E-02
WP-RF118.01	8.36E-02	0.00E+00	3.54E-23	4.14E+04	5.18E+03	0.00E+00	1.07E+00	4.66E+04	1.88E+02
WP-RLMPDT.001	1.78E-05	0.00E+00	1.03E-26	5.93E+00	8.64E-01	0.00E+00	2.53E-04	6.79E+00	2.74E-02
WP-RLNPDT.002	2.18E-04	0.00E+00	9.85E-26	5.82E+01	8.77E+00	0.00E+00	2.43E-03	6.70E+01	2.70E-01
WP-SR2001.001.	6.94E-06	0.00E+00	1.13E-26	5.50E+00	6.12E-01	0.00E+00	2.80E-04	6.11E+00	2.46E-02
WP-SR-W027-221	5.14E-05	0.00E+00	3.33E-26	1.58E+01	2.47E+00	0.00E+00	1.83E-01	1.84E+01	7.43E-02
Total	2.75E+00	0.00E+00	2.33E-20	5.31E+05	4.82E+04	0.00E+00	7.30E+02	5.80E+05	2.34E+03

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
AE-T001	9.40E-06	0.00E+00	6.82E-34	1.57E+02	4.28E+01	0.00E+00	1.91E-02	1.99E+02	8.04E-01
AE-T003	1.19E-06	0.00E+00	9.08E-35	4.84E+01	8.63E+00	0.00E+00	9.37E-04	5.70E+01	2.30E-01
AW-N026.82	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AW-N027.531	5.28E-09	0.00E+00	2.41E-33	3.57E+01	9.94E-02	0.00E+00	2.24E-02	3.58E+01	1.44E-01
AW-T033.1325	1.93E-08	0.00E+00	8.82E-33	1.30E+02	3.62E-01	0.00E+00	8.20E-02	1.31E+02	5.27E-01
AW-W049	0.00E+00	0.00E+00	0.00E+00	5.79E-01	0.00E+00	0.00E+00	0.00E+00	5.79E-01	2.34E-03
BCLCH-MT01	1.95E-06	0.00E+00	6.82E-32	2.15E+01	2.60E+00	0.00E+00	6.21E-01	2.47E+01	9.97E-02
BT-T002	1.43E-09	0.00E+00	3.57E-35	5.43E-04	5.13E-04	0.00E+00	2.26E-03	3.32E-03	1.34E-05
ET-C1-B55	5.97E-09	0.00E+00	4.06E-37	4.65E-02	1.07E-02	0.00E+00	2.33E-04	5.75E-02	2.32E-04
ET-C1-D139	8.20E-10	0.00E+00	5.63E-38	6.54E-03	1.51E-03	0.00E+00	5.73E-07	8.05E-03	3.24E-05
ET-C2-SEFOR	2.03E-08	0.00E+00	0.00E+00	1.03E-01	1.59E-02	0.00E+00	0.00E+00	1.19E-01	4.78E-04
FM-MOX-MT02	1.92E-13	0.00E+00	2.27E-41	2.25E-07	6.18E-08	0.00E+00	2.15E-10	2.87E-07	1.16E-09
FM-MOX-T01	3.18E-12	0.00E+00	3.75E-40	3.70E-06	1.02E-06	0.00E+00	3.55E-09	4.72E-06	1.90E-08
IN-BN-510	7.67E-04	0.00E+00	1.93E-30	2.97E+04	1.16E+03	0.00E+00	1.95E+01	3.09E+04	1.25E+02
IN-GEM-01	9.70E-06	0.00E+00	3.83E-35	3.34E+01	3.52E+00	0.00E+00	3.49E-04	3.69E+01	1.49E-01
IN-GEM-02	2.30E-06	0.00E+00	9.12E-36	7.94E+00	8.39E-01	0.00E+00	8.30E-05	8.78E+00	3.54E-02
IN-W157.144	1.15E-05	0.00E+00	3.71E-34	2.27E+02	2.37E+01	0.00E+00	3.74E-03	2.51E+02	1.01E+00
IN-W163.1007	1.97E-06	0.00E+00	1.15E-34	7.04E+01	7.35E+00	0.00E+00	1.16E-03	7.78E+01	3.14E-01
IN-W164.153	1.88E-08	0.00E+00	1.09E-36	6.70E-01	7.01E-02	0.00E+00	1.10E-05	7.41E-01	2.99E-03
IN-W167.149	3.77E-06	0.00E+00	1.78E-34	1.09E+02	1.14E+01	0.00E+00	1.79E-03	1.20E+02	4.84E-01
IN-W174.154	0.00E+00	0.00E+00	1.00E-31	1.46E+00	1.33E+00	0.00E+00	1.01E+00	3.80E+00	1.53E-02
IN-W177.156	2.61E-09	0.00E+00	2.14E-31	1.37E+00	3.87E-03	0.00E+00	2.15E+00	3.53E+00	1.42E-02
IN-W179.158	1.76E-08	0.00E+00	2.13E-31	7.94E-02	1.91E-02	0.00E+00	2.15E+00	2.24E+00	9.05E-03
IN-W181.162	2.50E-07	0.00E+00	1.45E-35	8.84E+00	9.25E-01	0.00E+00	1.46E-04	9.76E+00	3.94E-02
IN-W188.160	1.68E-06	0.00E+00	9.74E-35	5.97E+01	6.21E+00	0.00E+00	9.82E-04	6.59E+01	2.66E-01
IN-W216.98	1.49E-02	0.00E+00	7.93E-33	4.87E+03	5.11E+02	0.00E+00	8.00E-02	5.38E+03	2.17E+01
IN-W218.909	7.54E-05	0.00E+00	1.76E-34	1.08E+02	1.13E+01	0.00E+00	1.78E-03	1.19E+02	4.81E-01
IN-W219.110	1.02E-07	0.00E+00	5.94E-36	3.64E+00	3.80E-01	0.00E+00	5.99E-05	4.02E+00	1.62E-02
IN-W219.914	1.61E-08	0.00E+00	9.35E-37	5.75E-01	6.01E-02	0.00E+00	9.43E-06	6.35E-01	2.56E-03
IN-W220.114	5.33E-04	0.00E+00	6.25E-34	4.11E+02	4.18E+01	0.00E+00	6.30E-03	4.53E+02	1.83E+00

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W221.927	6.25E-07	0.00E+00	3.62E-35	2.22E+01	2.31E+00	0.00E+00	3.65E-04	2.45E+01	9.87E-02
IN-W222.116	2.13E-05	0.00E+00	1.23E-33	7.49E+02	7.84E+01	0.00E+00	1.24E-02	8.27E+02	3.34E+00
IN-W228.101	1.41E-04	0.00E+00	3.99E-34	2.45E+02	2.55E+01	0.00E+00	4.02E-03	2.71E+02	1.09E+00
IN-W240.931	1.49E-05	0.00E+00	5.10E-34	3.15E+02	3.27E+01	0.00E+00	5.14E-03	3.47E+02	1.40E+00
IN-W243.808	2.07E-05	0.00E+00	8.93E-34	5.49E+02	5.73E+01	0.00E+00	9.01E-03	6.06E+02	2.45E+00
IN-W245.301	3.06E-05	0.00E+00	1.76E-33	1.07E+03	1.12E+02	0.00E+00	1.77E-02	1.18E+03	4.77E+00
IN-W247.810	1.49E-05	0.00E+00	8.55E-34	5.24E+02	5.49E+01	0.00E+00	8.62E-03	5.79E+02	2.33E+00
IN-W249.527	0.00E+00	0.00E+00	5.98E-32	9.29E+00	0.00E+00	0.00E+00	6.03E-01	9.89E+00	3.99E-02
IN-W263.520	4.27E-09	0.00E+00	6.25E-33	6.31E+00	4.63E-03	0.00E+00	6.30E-02	6.38E+00	2.57E-02
IN-W267.1005	3.57E-06	0.00E+00	2.07E-34	1.27E+02	1.33E+01	0.00E+00	2.09E-03	1.41E+02	5.67E-01
IN-W309.609	9.57E-05	0.00E+00	3.48E-33	2.13E+03	2.22E+02	0.00E+00	3.51E-02	2.35E+03	9.47E+00
IN-W315.601	9.44E-05	0.00E+00	1.45E-35	8.91E+00	9.29E-01	0.00E+00	1.47E-04	9.84E+00	3.97E-02
IN-W319.584	5.49E-07	0.00E+00	3.18E-35	1.96E+01	2.05E+00	0.00E+00	3.21E-04	2.16E+01	8.71E-02
IN-W321.1023	4.75E-06	0.00E+00	2.76E-34	1.69E+02	1.77E+01	0.00E+00	2.78E-03	1.87E+02	7.54E-01
IN-W322.851	0.00E+00	0.00E+00	0.00E+00	6.83E+00	6.52E-01	0.00E+00	0.00E+00	7.48E+00	3.02E-02
IN-W322.952	0.00E+00	0.00E+00	0.00E+00	1.82E+01	1.74E+00	0.00E+00	0.00E+00	1.99E+01	8.04E-02
IN-W323.562	1.02E-08	0.00E+00	4.68E-35	1.87E-01	0.00E+00	0.00E+00	4.72E-04	1.87E-01	7.54E-04
IN-W323.951	1.20E-08	0.00E+00	5.56E-37	2.23E-01	0.00E+00	0.00E+00	5.61E-06	2.23E-01	8.97E-04
IN-W332.661	0.00E+00	0.00E+00	6.13E-34	9.66E-02	0.00E+00	0.00E+00	6.19E-03	1.03E-01	4.15E-04
IN-W337.673	0.00E+00	0.00E+00	0.00E+00	2.28E+00	2.18E-01	0.00E+00	0.00E+00	2.50E+00	1.01E-02
IN-W337.957	0.00E+00	0.00E+00	0.00E+00	6.83E+00	6.52E-01	0.00E+00	0.00E+00	7.48E+00	3.02E-02
IN-W341.671	0.00E+00	0.00E+00	0.00E+00	1.46E+00	0.00E+00	0.00E+00	0.00E+00	1.46E+00	5.89E-03
IN-W341.954	0.00E+00	0.00E+00	0.00E+00	4.39E+00	0.00E+00	0.00E+00	0.00E+00	4.39E+00	1.77E-02
IN-W342.652	4.69E-07	0.00E+00	0.00E+00	3.01E-02	3.59E-18	0.00E+00	0.00E+00	3.01E-02	1.21E-04
IN-W342.953	3.13E-07	0.00E+00	0.00E+00	2.02E-02	2.41E-18	0.00E+00	0.00E+00	2.02E-02	8.13E-05
IN-W347.818	2.45E-07	0.00E+00	0.00E+00	6.19E+01	5.25E+01	0.00E+00	1.54E-08	1.14E+02	4.61E-01
IN-W348.1012	1.30E-08	0.00E+00	5.06E-34	3.12E+02	3.27E+01	0.00E+00	5.11E-03	3.45E+02	1.39E+00
IN-W353.917	0.00E+00	0.00E+00	0.00E+00	1.87E-02	0.00E+00	0.00E+00	0.00E+00	1.87E-02	7.55E-05
IN-W357.1022	0.00E+00	0.00E+00	9.97E-37	6.14E-01	6.39E-02	0.00E+00	1.01E-05	6.77E-01	2.73E-03
IN-W358.854	0.00E+00	0.00E+00	1.50E-32	1.41E+00	1.25E+00	0.00E+00	1.45E-01	2.81E+00	1.13E-02
IN-W358.855	0.00E+00	0.00E+00	8.01E-32	7.49E+00	6.66E+00	0.00E+00	7.71E-01	1.49E+01	6.02E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
IN-W358.948	0.00E+00	0.00E+00	1.67E-32	1.57E+00	1.39E+00	0.00E+00	1.61E-01	3.11E+00	1.26E-02
IN-W361.1021	3.45E-09	0.00E+00	9.66E-35	5.92E+01	6.18E+00	0.00E+00	9.74E-04	6.54E+01	2.64E-01
IN-W362.1020	0.00E+00	0.00E+00	1.27E-33	7.72E+02	8.11E+01	0.00E+00	1.28E-02	8.53E+02	3.44E+00
IN-W363.1019	0.00E+00	0.00E+00	5.94E-35	3.66E+01	3.83E+00	0.00E+00	5.99E-04	4.05E+01	1.63E-01
IN-W364.1011	0.00E+00	0.00E+00	9.81E-35	6.02E+01	6.28E+00	0.00E+00	9.90E-04	6.65E+01	2.68E-01
IN-W365.1010	3.22E-05	0.00E+00	7.78E-35	4.76E+01	4.97E+00	0.00E+00	7.85E-04	5.25E+01	2.12E-01
IN-W366.841	1.14E-07	0.00E+00	6.63E-35	4.05E+01	4.25E+00	0.00E+00	6.69E-04	4.48E+01	1.81E-01
IN-W372.832	4.69E-07	0.00E+00	0.00E+00	3.01E-02	3.59E-18	0.00E+00	0.00E+00	3.01E-02	1.21E-04
IN-W375.1096	0.00E+00	0.00E+00	2.45E-35	1.50E+01	1.56E+00	0.00E+00	2.47E-04	1.65E+01	6.67E-02
KN-B234TRU	1.67E-05	0.00E+00	9.35E-34	2.18E+02	3.38E+01	0.00E+00	1.04E-02	2.52E+02	1.02E+00
LA-IT-00-01	2.42E-07	0.00E+00	1.59E-34	4.38E-01	4.38E-03	0.00E+00	1.80E-03	4.44E-01	1.79E-03
LA-OS-00-01	5.39E-04	0.00E+00	7.28E-30	9.21E+02	0.00E+00	0.00E+00	6.68E+01	9.88E+02	3.98E+00
LA-PX-00-01	2.25E-09	0.00E+00	3.07E-37	6.78E-02	7.35E-03	0.00E+00	2.93E-06	7.51E-02	3.03E-04
LA-SL-00-01	0.00E+00	0.00E+00	6.48E-36	1.15E-01	0.00E+00	0.00E+00	7.25E-05	1.15E-01	4.62E-04
LA-TA-03-12	2.31E-08	0.00E+00	1.50E-34	3.27E-01	5.25E-02	0.00E+00	1.74E-03	3.81E-01	1.54E-03
LA-TA-03-13	2.99E-08	0.00E+00	4.75E-34	5.10E-01	5.52E-02	0.00E+00	4.85E-03	5.70E-01	2.30E-03
LA-TA-03-19	6.04E-08	0.00E+00	7.09E-34	9.96E-01	1.33E-01	0.00E+00	8.20E-03	1.14E+00	4.59E-03
LA-TA-03-20	3.30E-08	0.00E+00	3.37E-34	4.39E-01	7.15E-02	0.00E+00	3.73E-03	5.14E-01	2.07E-03
LA-TA-03-24	4.42E-08	0.00E+00	1.31E-33	8.17E-01	1.14E-01	0.00E+00	1.53E-02	9.46E-01	3.81E-03
LA-TA-03-26	2.27E-09	0.00E+00	5.40E-35	1.98E+00	1.50E-02	0.00E+00	1.47E-03	1.99E+00	8.04E-03
LA-TA-03-28	0.00E+00	0.00E+00	1.87E-35	1.85E-01	0.00E+00	0.00E+00	2.14E-04	1.85E-01	7.47E-04
LA-TA-03-30	1.01E-07	0.00E+00	1.33E-35	3.77E+00	5.04E-01	0.00E+00	1.52E-04	4.27E+00	1.72E-02
LA-TA-03-31	0.00E+00	0.00E+00	6.67E-37	6.59E-03	0.00E+00	0.00E+00	7.64E-06	6.60E-03	2.66E-05
LA-TA-03-40	0.00E+00	0.00E+00	1.05E-36	4.10E-02	0.00E+00	0.00E+00	1.22E-05	4.10E-02	1.65E-04
LA-TA-03-42	2.31E-12	0.00E+00	2.64E-38	2.56E-03	1.56E-05	0.00E+00	3.05E-07	2.58E-03	1.04E-05
LA-TA-21-06	2.28E-08	0.00E+00	2.91E-33	7.17E-01	1.01E-01	0.00E+00	3.33E-02	8.51E-01	3.43E-03
LA-TA-21-12	8.30E-08	0.00E+00	1.75E-32	2.49E+00	3.43E-01	0.00E+00	2.01E-01	3.03E+00	1.22E-02
LA-TA-21-13	1.28E-07	0.00E+00	0.00E+00	2.20E-01	0.00E+00	0.00E+00	0.00E+00	2.20E-01	8.88E-04
LA-TA-21-14	2.10E-11	0.00E+00	3.34E-34	3.36E+00	1.81E-05	0.00E+00	3.22E-03	3.37E+00	1.36E-02
LA-TA-21-15	1.24E-08	0.00E+00	9.20E-37	1.04E+00	8.22E-02	0.00E+00	1.04E-05	1.12E+00	4.53E-03
LA-TA-21-16	1.43E-07	0.00E+00	1.42E-35	7.94E+00	8.77E-01	0.00E+00	1.64E-04	8.82E+00	3.56E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-21-40	1.82E-11	0.00E+00	4.91E-35	2.49E-01	1.27E-04	0.00E+00	6.91E-04	2.50E-01	1.01E-03
LA-TA-21-41	0.00E+00	0.00E+00	0.00E+00	5.31E-01	0.00E+00	0.00E+00	0.00E+00	5.31E-01	2.14E-03
LA-TA-21-42	1.86E-09	0.00E+00	1.59E-35	1.23E-01	3.87E-03	0.00E+00	2.39E-04	1.27E-01	5.12E-04
LA-TA-21-43	6.57E-06	0.00E+00	5.29E-34	3.83E+02	4.21E+01	0.00E+00	7.87E-03	4.25E+02	1.71E+00
LA-TA-21-44	3.15E-08	0.00E+00	1.11E-34	8.61E+01	1.06E-01	0.00E+00	1.38E-03	8.63E+01	3.48E-01
LA-TA-48-01	1.02E-08	0.00E+00	4.18E-37	8.84E-02	1.71E-01	0.00E+00	5.93E-06	2.59E-01	1.05E-03
LA-TA-49-01	1.26E-06	0.00E+00	5.14E-35	1.09E+01	2.12E+01	0.00E+00	7.31E-04	3.21E+01	1.30E-01
LA-TA-50-10	3.37E-09	0.00E+00	4.87E-37	3.44E-02	0.00E+00	0.00E+00	4.61E-06	3.44E-02	1.39E-04
LA-TA-50-11	6.43E-09	0.00E+00	4.98E-37	3.49E-01	3.59E-02	0.00E+00	6.95E-06	3.85E-01	1.55E-03
LA-TA-50-15	1.27E-08	0.00E+00	7.36E-35	2.55E-01	2.64E-02	0.00E+00	7.88E-04	2.82E-01	1.14E-03
LA-TA-50-17	1.86E-06	0.00E+00	5.98E-35	1.36E+01	1.48E-04	0.00E+00	9.70E-04	1.36E+01	5.50E-02
LA-TA-50-18	1.10E-07	0.00E+00	7.90E-36	2.23E+00	1.85E-06	0.00E+00	9.11E-05	2.23E+00	8.97E-03
LA-TA-50-19	3.52E-08	0.00E+00	3.52E-36	2.96E-01	1.58E-03	0.00E+00	6.66E-05	2.98E-01	1.20E-03
LA-TA-50-20	9.66E-10	0.00E+00	0.00E+00	7.30E-03	0.00E+00	0.00E+00	0.00E+00	7.30E-03	2.94E-05
LA-TA-50-40	5.44E-10	0.00E+00	4.75E-38	7.94E-03	1.72E-03	0.00E+00	5.23E-07	9.66E-03	3.89E-05
LA-TA-50-41	5.81E-10	0.00E+00	4.79E-38	3.52E-02	3.80E-03	0.00E+00	4.83E-07	3.90E-02	1.57E-04
LA-TA-55-19	9.00E-07	0.00E+00	6.32E-35	1.98E+01	2.58E+00	0.00E+00	2.20E-03	2.24E+01	9.01E-02
LA-TA-55-20	1.45E-05	0.00E+00	7.21E-34	4.78E+02	5.32E+01	0.00E+00	9.88E-02	5.31E+02	2.14E+00
LA-TA-55-21	1.29E-07	0.00E+00	8.28E-36	3.39E+00	3.76E-01	0.00E+00	8.29E-05	3.76E+00	1.52E-02
LA-TA-55-22	3.54E-07	0.00E+00	4.68E-35	1.19E+01	1.29E+00	0.00E+00	4.68E-04	1.32E+01	5.32E-02
LA-TA-55-23	3.33E-07	0.00E+00	3.91E-35	8.17E+00	9.36E-01	0.00E+00	3.88E-04	9.10E+00	3.67E-02
LA-TA-55-24	1.26E-07	0.00E+00	6.13E-36	4.29E+00	4.63E-01	0.00E+00	5.85E-05	4.75E+00	1.91E-02
LA-TA-55-25	6.43E-07	0.00E+00	3.58E-35	2.13E+01	2.30E+00	0.00E+00	3.41E-04	2.36E+01	9.51E-02
LA-TA-55-28	2.19E-07	0.00E+00	1.98E-35	6.53E+00	7.15E-01	0.00E+00	1.91E-04	7.25E+00	2.92E-02
LA-TA-55-30	4.88E-06	0.00E+00	2.37E-34	1.07E+02	1.20E+01	0.00E+00	2.91E-03	1.19E+02	4.80E-01
LA-TA-55-32	3.96E-07	0.00E+00	1.33E-33	8.46E+00	1.21E+00	0.00E+00	1.55E-02	9.69E+00	3.91E-02
LA-TA-55-33	5.93E-08	0.00E+00	3.42E-36	1.12E+00	1.65E-01	0.00E+00	3.74E-05	1.28E+00	5.17E-03
LA-TA-55-34	6.00E-06	0.00E+00	3.17E-34	1.73E+02	2.04E+01	0.00E+00	6.16E-03	1.93E+02	7.80E-01
LA-TA-55-38	1.51E-05	0.00E+00	1.04E-34	3.82E+01	4.76E+00	0.00E+00	2.79E-03	4.30E+01	1.73E-01
LA-TA-55-39	1.59E-06	0.00E+00	7.70E-35	5.70E+01	5.94E+00	0.00E+00	7.59E-04	6.29E+01	2.54E-01
LA-TA-55-41	3.79E-05	0.00E+00	1.59E-34	7.07E+01	7.84E+00	0.00E+00	1.61E-03	7.86E+01	3.17E-01

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
LA-TA-55-43	1.43E-08	0.00E+00	1.05E-32	1.06E-01	1.73E-02	0.00E+00	1.02E-01	2.26E-01	9.11E-04
LA-TA-55-44	1.24E-07	0.00E+00	2.47E-32	1.97E+00	2.53E-01	0.00E+00	2.71E-01	2.50E+00	1.01E-02
LA-TA-55-48	9.11E-04	0.00E+00	9.74E-32	1.27E+04	2.19E+03	0.00E+00	1.05E+00	1.49E+04	5.99E+01
LA-TA-55-49	1.95E-06	0.00E+00	1.28E-31	2.32E+01	3.01E+00	0.00E+00	1.40E+00	2.76E+01	1.11E-01
LA-TA-55-53	9.18E-06	0.00E+00	2.65E-34	1.98E+02	2.14E+01	0.00E+00	2.85E-03	2.19E+02	8.84E-01
LA-TA-55-56	1.02E-05	0.00E+00	9.85E-33	2.86E+02	3.33E+01	0.00E+00	1.01E-01	3.20E+02	1.29E+00
LA-TA-55-60	5.51E-09	0.00E+00	2.49E-36	5.39E-02	8.87E-03	0.00E+00	2.72E-05	6.28E-02	2.53E-04
LA-TA-55-61	4.74E-09	0.00E+00	1.15E-35	1.04E-01	1.64E-02	0.00E+00	1.23E-04	1.21E-01	4.86E-04
LA-TA-55-62	1.23E-09	0.00E+00	1.09E-37	1.75E-02	3.87E-03	0.00E+00	1.18E-06	2.13E-02	8.60E-05
LA-TA-55-63	9.12E-10	0.00E+00	7.36E-38	5.60E-02	6.01E-03	0.00E+00	7.61E-07	6.20E-02	2.50E-04
LL-M001	1.25E-05	0.00E+00	3.21E-33	5.24E+01	1.10E+01	0.00E+00	2.92E-02	6.34E+01	2.56E-01
LL-T001	6.24E-05	0.00E+00	0.00E+00	4.00E+02	8.35E+01	0.00E+00	0.00E+00	4.84E+02	1.95E+00
LL-T002	6.17E-04	0.00E+00	2.55E-32	3.88E+03	7.39E+02	0.00E+00	2.32E-01	4.62E+03	1.86E+01
LL-T003	2.40E-05	0.00E+00	2.86E-33	7.87E+01	2.94E+01	0.00E+00	2.60E-02	1.08E+02	4.36E-01
LL-T004	1.52E-05	0.00E+00	5.86E-34	5.00E+01	1.85E+01	0.00E+00	5.34E-03	6.85E+01	2.76E-01
LL-T005	7.86E-05	0.00E+00	6.90E-33	1.86E+02	7.44E+01	0.00E+00	6.28E-02	2.60E+02	1.05E+00
LL-W018	6.70E-09	0.00E+00	0.00E+00	1.39E-02	1.48E-02	0.00E+00	0.00E+00	2.86E-02	1.15E-04
LL-W019	3.63E-06	0.00E+00	0.00E+00	1.08E+01	4.18E+00	0.00E+00	0.00E+00	1.50E+01	6.03E-02
LL-W034	1.34E-06	0.00E+00	1.21E-34	3.15E+00	1.23E+00	0.00E+00	1.10E-03	4.38E+00	1.77E-02
MC-W001	1.68E-08	0.00E+00	0.00E+00	4.54E-02	0.00E+00	0.00E+00	0.00E+00	4.54E-02	1.83E-04
MU-W002	2.24E-07	0.00E+00	0.00E+00	3.94E-02	0.00E+00	0.00E+00	2.60E-12	3.94E-02	1.59E-04
NT-JAS-01	2.16E-05	0.00E+00	2.57E-33	7.10E+01	2.65E+01	0.00E+00	2.34E-02	9.75E+01	3.93E-01
NT-W001	3.24E-05	0.00E+00	5.14E-33	2.14E+03	6.63E+00	0.00E+00	5.80E-02	2.15E+03	8.67E+00
NT-W021	6.28E-07	0.00E+00	3.68E-35	2.41E+01	2.55E+00	0.00E+00	3.80E-04	2.67E+01	1.08E-01
OR-W201	7.53E-04	0.00E+00	1.10E-31	1.62E+03	7.39E+02	0.00E+00	4.34E+01	2.40E+03	9.68E+00
OR-W202	1.08E-04	0.00E+00	3.19E-31	4.15E+02	1.89E+02	0.00E+00	3.34E+00	6.07E+02	2.45E+00
OR-W203	2.38E-07	0.00E+00	4.56E-35	1.87E-02	6.15E-01	0.00E+00	4.75E-04	6.34E-01	2.56E-03
OR-W204	5.30E-08	0.00E+00	5.17E-35	3.18E-01	9.94E-02	0.00E+00	5.39E-04	4.18E-01	1.68E-03
PA-A015	0.00E+00	0.00E+00	0.00E+00	3.19E-01	0.00E+00	0.00E+00	0.00E+00	3.19E-01	1.29E-03
RF-MT0001	2.03E-04	0.00E+00	3.21E-34	1.47E+02	1.55E+01	0.00E+00	3.22E-03	1.62E+02	6.55E-01
RF-MT0002	1.56E-05	0.00E+00	2.47E-35	1.13E+01	1.19E+00	0.00E+00	2.47E-04	1.25E+01	5.04E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0003	7.12E-08	0.00E+00	5.63E-36	2.58E+00	2.73E-01	0.00E+00	5.64E-05	2.86E+00	1.15E-02
RF-MT0007	1.79E-07	0.00E+00	0.00E+00	3.22E-01	3.39E-02	0.00E+00	0.00E+00	3.56E-01	1.44E-03
RF-MT0089	7.03E-10	0.00E+00	5.63E-38	2.58E-02	2.72E-03	0.00E+00	5.64E-07	2.86E-02	1.15E-04
RF-MT0090	1.78E-06	0.00E+00	7.97E-35	6.64E+01	6.94E+00	0.00E+00	7.98E-04	7.33E+01	2.96E-01
RF-MT0091	1.11E-04	0.00E+00	8.09E-33	4.43E+03	4.66E+02	0.00E+00	8.39E-02	4.90E+03	1.98E+01
RF-MT0092	1.58E-05	0.00E+00	1.02E-33	6.35E+02	6.80E+01	0.00E+00	1.02E-02	7.03E+02	2.84E+00
RF-MT0093	1.93E-05	0.00E+00	1.05E-33	6.85E+02	7.46E+01	0.00E+00	1.05E-02	7.60E+02	3.06E+00
RF-MT0097	9.64E-07	0.00E+00	4.64E-35	3.58E+01	3.39E+00	0.00E+00	4.64E-04	3.92E+01	1.58E-01
RF-MT0099	1.06E-09	0.00E+00	8.47E-38	3.87E-02	4.07E-03	0.00E+00	8.48E-07	4.28E-02	1.73E-04
RF-MT0290	2.62E-06	0.00E+00	2.10E-34	9.59E+01	1.01E+01	0.00E+00	2.10E-03	1.06E+02	4.27E-01
RF-MT-0292	3.30E-06	0.00E+00	2.65E-34	1.21E+02	1.28E+01	0.00E+00	2.65E-03	1.34E+02	5.41E-01
RF-MT-0299	3.89E-04	0.00E+00	6.78E-33	3.11E+03	3.28E+02	0.00E+00	6.79E-02	3.44E+03	1.39E+01
RF-MT0302	5.95E-09	0.00E+00	2.69E-37	1.34E-01	1.42E-02	0.00E+00	1.91E-05	1.48E-01	5.98E-04
RF-MT0320	7.12E-06	0.00E+00	2.79E-34	1.30E+02	1.38E+01	0.00E+00	2.80E-03	1.44E+02	5.81E-01
RF-MT0321	3.98E-06	0.00E+00	8.32E-35	4.20E+01	4.38E+00	0.00E+00	3.18E-03	4.63E+01	1.87E-01
RF-MT-0328	2.75E-07	0.00E+00	9.97E-36	4.56E+00	4.80E-01	0.00E+00	4.29E-04	5.04E+00	2.03E-02
RF-MT0330	2.86E-06	0.00E+00	1.09E-34	9.21E+01	1.05E+01	0.00E+00	1.09E-03	1.03E+02	4.14E-01
RF-MT-0331	1.72E-05	0.00E+00	6.78E-34	4.05E+02	4.18E+01	0.00E+00	2.70E-02	4.47E+02	1.80E+00
RF-MT0332	2.46E-09	0.00E+00	1.98E-37	9.06E-02	9.53E-03	0.00E+00	1.98E-06	1.00E-01	4.04E-04
RF-MT-0335	1.98E-07	0.00E+00	9.08E-36	4.67E+00	4.94E-01	0.00E+00	6.18E-04	5.16E+00	2.08E-02
RF-MT0336	1.40E-05	0.00E+00	6.02E-34	3.31E+02	3.49E+01	0.00E+00	7.79E-03	3.66E+02	1.48E+00
RF-MT0337	7.91E-06	0.00E+00	3.31E-34	2.02E+02	2.10E+01	0.00E+00	7.06E-03	2.23E+02	9.00E-01
RF-MT0339	2.16E-05	0.00E+00	9.01E-34	4.43E+02	4.63E+01	0.00E+00	2.56E-02	4.90E+02	1.98E+00
RF-MT-0342	1.27E-07	0.00E+00	7.55E-36	4.10E+00	4.25E-01	0.00E+00	1.32E-04	4.52E+00	1.82E-02
RF-MT0371	4.30E-05	0.00E+00	1.75E-33	8.02E+02	8.42E+01	0.00E+00	1.88E-02	8.86E+02	3.57E+00
RF-MT-0372	1.87E-07	0.00E+00	1.23E-35	5.59E+00	5.90E-01	0.00E+00	3.56E-04	6.18E+00	2.49E-02
RF-MT0373	2.82E-06	0.00E+00	1.27E-34	1.05E+02	1.10E+01	0.00E+00	1.27E-03	1.16E+02	4.67E-01
RF-MT0374	9.16E-08	0.00E+00	4.52E-36	2.08E+00	2.19E-01	0.00E+00	4.85E-05	2.29E+00	9.25E-03
RF-MT0376	7.26E-08	0.00E+00	3.65E-36	2.07E+00	2.21E-01	0.00E+00	5.12E-05	2.29E+00	9.23E-03
RF-MT0377	4.31E-05	0.00E+00	2.10E-33	9.66E+02	1.02E+02	0.00E+00	3.10E-02	1.07E+03	4.31E+00
RF-MT0378	4.85E-07	0.00E+00	2.91E-35	1.33E+01	1.41E+00	0.00E+00	2.91E-04	1.47E+01	5.94E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0419	7.79E-07	0.00E+00	2.72E-35	1.24E+01	1.31E+00	0.00E+00	2.72E-04	1.38E+01	5.54E-02
RF-MT0420	1.35E-07	0.00E+00	4.71E-36	2.16E+00	2.28E-01	0.00E+00	4.72E-05	2.39E+00	9.62E-03
RF-MT0423	1.15E-06	0.00E+00	3.83E-35	3.12E+01	3.19E+00	0.00E+00	3.84E-04	3.44E+01	1.39E-01
RF-MT0425	3.39E-08	0.00E+00	1.18E-36	5.40E-01	5.70E-02	0.00E+00	1.18E-05	5.97E-01	2.41E-03
RF-MT-0438	3.07E-07	0.00E+00	1.55E-35	9.59E+00	1.00E+00	0.00E+00	1.68E-04	1.06E+01	4.27E-02
RF-MT0440	1.12E-07	0.00E+00	5.56E-36	3.48E+00	3.73E-01	0.00E+00	2.16E-04	3.85E+00	1.55E-02
RF-MT0442	4.25E-08	0.00E+00	2.40E-36	1.19E+00	1.25E-01	0.00E+00	1.16E-04	1.32E+00	5.31E-03
RF-MT0443	5.23E-07	0.00E+00	3.95E-35	1.85E+01	1.95E+00	0.00E+00	5.49E-04	2.05E+01	8.25E-02
RF-MT0444	4.08E-06	0.00E+00	1.94E-34	8.91E+01	9.36E+00	0.00E+00	1.96E-03	9.85E+01	3.97E-01
RF-MT0480	1.14E-05	0.00E+00	5.44E-34	2.50E+02	2.64E+01	0.00E+00	7.84E-03	2.77E+02	1.12E+00
RF-MT0488	1.83E-05	0.00E+00	8.13E-34	3.72E+02	3.90E+01	0.00E+00	3.82E-02	4.11E+02	1.66E+00
RF-MT0490	8.28E-08	0.00E+00	4.71E-36	2.20E+00	2.32E-01	0.00E+00	5.81E-05	2.43E+00	9.78E-03
RF-MT-0491	6.50E-09	0.00E+00	2.15E-37	9.96E-02	1.05E-02	0.00E+00	4.11E-06	1.10E-01	4.44E-04
RF-MT0523A	5.15E-06	0.00E+00	1.71E-34	7.87E+01	8.29E+00	0.00E+00	1.96E-03	8.69E+01	3.51E-01
RF-MT0523B	5.15E-06	0.00E+00	1.71E-34	7.87E+01	8.29E+00	0.00E+00	1.96E-03	8.69E+01	3.51E-01
RF-MT0523C	5.15E-06	0.00E+00	1.71E-34	7.87E+01	8.29E+00	0.00E+00	1.96E-03	8.69E+01	3.51E-01
RF-MT0523D	5.15E-06	0.00E+00	1.71E-34	7.87E+01	8.29E+00	0.00E+00	1.96E-03	8.69E+01	3.51E-01
RF-MT0523E	5.15E-06	0.00E+00	1.71E-34	7.87E+01	8.29E+00	0.00E+00	1.96E-03	8.69E+01	3.51E-01
RF-MT0531	3.52E-10	0.00E+00	2.82E-38	1.29E-02	1.36E-03	0.00E+00	2.82E-07	1.42E-02	5.74E-05
RF-MT0532E	1.64E-05	0.00E+00	3.67E-34	1.72E+02	1.81E+01	0.00E+00	4.75E-03	1.90E+02	7.65E-01
RF-MT0532F	1.64E-05	0.00E+00	3.67E-34	1.72E+02	1.81E+01	0.00E+00	4.75E-03	1.90E+02	7.65E-01
RF-MT0541	5.98E-07	0.00E+00	5.29E-36	2.43E+00	2.56E-01	0.00E+00	5.30E-05	2.69E+00	1.09E-02
RF-MT0545	3.20E-09	0.00E+00	2.56E-37	1.18E-01	1.24E-02	0.00E+00	2.56E-06	1.30E-01	5.24E-04
RF-MT0800	1.22E-04	0.00E+00	1.27E-34	5.81E+01	6.11E+00	0.00E+00	1.74E-03	6.42E+01	2.59E-01
RF-MT0801	1.40E-05	0.00E+00	1.24E-34	5.70E+01	6.01E+00	0.00E+00	1.24E-03	6.30E+01	2.54E-01
RF-MT0803	3.14E-07	0.00E+00	2.78E-36	1.27E+00	1.34E-01	0.00E+00	2.78E-05	1.41E+00	5.68E-03
RF-MT0806	1.48E-07	0.00E+00	6.67E-36	5.54E+00	5.77E-01	0.00E+00	6.68E-05	6.11E+00	2.47E-02
RF-MT0807	1.87E-06	0.00E+00	5.14E-35	2.35E+01	2.48E+00	0.00E+00	5.14E-04	2.60E+01	1.05E-01
RF-MT0816	2.00E-07	0.00E+00	7.24E-36	3.32E+00	3.49E-01	0.00E+00	7.25E-05	3.67E+00	1.48E-02
RF-MT-0823	9.91E-08	0.00E+00	3.30E-36	1.51E+00	1.60E-01	0.00E+00	3.78E-05	1.67E+00	6.74E-03
RF-MT0827	5.05E-06	0.00E+00	1.83E-34	8.39E+01	8.84E+00	0.00E+00	1.83E-03	9.27E+01	3.74E-01

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-MT0831	9.63E-06	0.00E+00	5.02E-34	2.27E+02	2.40E+01	0.00E+00	1.69E-02	2.51E+02	1.01E+00
RF-MT0832	5.76E-05	0.00E+00	1.82E-33	8.84E+02	9.29E+01	0.00E+00	5.07E-02	9.77E+02	3.94E+00
RF-MT0833	1.75E-05	0.00E+00	5.44E-34	2.55E+02	2.69E+01	0.00E+00	1.44E-02	2.82E+02	1.14E+00
RF-MT0855	3.02E-09	0.00E+00	2.42E-37	1.11E-01	1.17E-02	0.00E+00	2.42E-06	1.23E-01	4.94E-04
RF-MT0857	1.48E-07	0.00E+00	6.63E-36	5.52E+00	5.77E-01	0.00E+00	6.64E-05	6.10E+00	2.46E-02
RF-MT0H61	5.49E-06	0.00E+00	2.47E-34	2.05E+02	2.14E+01	0.00E+00	2.47E-03	2.26E+02	9.11E-01
RF-MT2116	6.17E-07	0.00E+00	1.96E-35	9.44E+00	9.94E-01	0.00E+00	5.43E-04	1.04E+01	4.21E-02
RF-MT3010	3.87E-06	0.00E+00	2.03E-34	9.36E+01	9.94E+00	0.00E+00	2.42E-03	1.04E+02	4.18E-01
RF-MT3011	2.88E-05	0.00E+00	1.27E-33	5.78E+02	6.11E+01	0.00E+00	2.02E-02	6.39E+02	2.58E+00
RF-MT420P	1.53E-04	0.00E+00	6.40E-33	4.76E+03	5.01E+02	0.00E+00	7.38E-02	5.26E+03	2.12E+01
RF-MT532A	4.04E-05	0.00E+00	9.05E-34	4.24E+02	4.45E+01	0.00E+00	1.17E-02	4.69E+02	1.89E+00
RF-MT532B	1.81E-04	0.00E+00	4.06E-33	1.90E+03	2.00E+02	0.00E+00	5.25E-02	2.10E+03	8.48E+00
RF-MT532C	3.64E-04	0.00E+00	8.16E-33	3.81E+03	4.00E+02	0.00E+00	1.06E-01	4.21E+03	1.70E+01
RF-MT532D	2.30E-06	0.00E+00	5.14E-35	2.41E+01	2.53E+00	0.00E+00	6.65E-04	2.67E+01	1.08E-01
RF-TT0069	1.32E-08	0.00E+00	6.09E-37	2.79E-01	2.94E-02	0.00E+00	7.76E-05	3.09E-01	1.25E-03
RF-TT0200	6.28E-07	0.00E+00	2.46E-35	1.15E+01	1.22E+00	0.00E+00	2.47E-04	1.27E+01	5.11E-02
RF-TT0299	2.60E-06	0.00E+00	4.56E-35	2.09E+01	2.20E+00	0.00E+00	4.57E-04	2.31E+01	9.32E-02
RF-TT0300	2.12E-05	0.00E+00	1.30E-33	6.00E+02	6.35E+01	0.00E+00	2.11E-02	6.64E+02	2.68E+00
RF-TT0301	2.87E-06	0.00E+00	1.76E-34	8.17E+01	8.63E+00	0.00E+00	2.87E-03	9.03E+01	3.64E-01
RF-TT0302	1.42E-07	0.00E+00	6.40E-36	3.19E+00	3.37E-01	0.00E+00	4.52E-04	3.53E+00	1.42E-02
RF-TT0303	8.54E-07	0.00E+00	3.74E-35	1.72E+01	1.81E+00	0.00E+00	1.38E-03	1.90E+01	7.65E-02
RF-TT0310	2.91E-06	0.00E+00	1.76E-34	7.72E+01	8.39E+00	0.00E+00	1.94E-03	8.55E+01	3.45E-01
RF-TT0312	6.98E-05	0.00E+00	3.17E-33	1.69E+03	1.76E+02	0.00E+00	3.34E-02	1.86E+03	7.51E+00
RF-TT0317	4.39E-08	0.00E+00	3.45E-36	1.58E+00	1.66E-01	0.00E+00	3.45E-05	1.75E+00	7.04E-03
RF-TT0320	2.82E-05	0.00E+00	1.10E-33	5.15E+02	5.45E+01	0.00E+00	1.11E-02	5.70E+02	2.30E+00
RF-TT0330	1.00E-05	0.00E+00	3.82E-34	3.24E+02	3.66E+01	0.00E+00	3.83E-03	3.60E+02	1.45E+00
RF-TT-0331	4.98E-05	0.00E+00	1.97E-33	1.18E+03	1.22E+02	0.00E+00	7.83E-02	1.30E+03	5.23E+00
RF-TT-0334	2.17E-05	0.00E+00	1.60E-33	7.31E+02	7.70E+01	0.00E+00	1.60E-02	8.08E+02	3.26E+00
RF-TT0335	2.64E-05	0.00E+00	1.21E-33	6.22E+02	6.59E+01	0.00E+00	8.24E-02	6.88E+02	2.77E+00
RF-TT0336	2.34E-05	0.00E+00	1.00E-33	5.51E+02	5.80E+01	0.00E+00	1.30E-02	6.09E+02	2.45E+00
RF-TT0337	2.78E-05	0.00E+00	1.16E-33	7.11E+02	7.35E+01	0.00E+00	2.48E-02	7.84E+02	3.16E+00

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0338	1.18E-04	0.00E+00	4.22E-33	2.77E+03	2.87E+02	0.00E+00	5.02E-02	3.06E+03	1.23E+01
RF-TT0340	1.01E-06	0.00E+00	8.05E-35	3.69E+01	3.90E+00	0.00E+00	8.06E-04	4.08E+01	1.64E-01
RF-TT0342	6.74E-06	0.00E+00	4.03E-34	2.17E+02	2.25E+01	0.00E+00	7.05E-03	2.40E+02	9.67E-01
RF-TT0360	5.13E-07	0.00E+00	2.04E-35	9.74E+00	1.04E+00	0.00E+00	2.11E-04	1.08E+01	4.35E-02
RF-TT0368	1.03E-05	0.00E+00	4.10E-34	1.96E+02	2.08E+01	0.00E+00	4.23E-03	2.16E+02	8.72E-01
RF-TT0370	2.03E-05	0.00E+00	8.85E-34	4.35E+02	4.59E+01	0.00E+00	1.65E-02	4.81E+02	1.94E+00
RF-TT0371	4.39E-07	0.00E+00	1.78E-35	8.17E+00	8.60E-01	0.00E+00	1.91E-04	9.02E+00	3.64E-02
RF-TT0372	5.36E-08	0.00E+00	3.51E-36	1.60E+00	1.69E-01	0.00E+00	1.02E-04	1.76E+00	7.11E-03
RF-TT0374	1.67E-06	0.00E+00	8.24E-35	3.77E+01	3.97E+00	0.00E+00	8.83E-04	4.17E+01	1.68E-01
RF-TT0375A	1.74E-08	0.00E+00	1.36E-36	6.20E-01	6.52E-02	0.00E+00	1.36E-05	6.85E-01	2.76E-03
RF-TT0375B	1.74E-08	0.00E+00	1.36E-36	6.20E-01	6.52E-02	0.00E+00	1.36E-05	6.85E-01	2.76E-03
RF-TT0376	4.00E-06	0.00E+00	2.01E-34	1.14E+02	1.22E+01	0.00E+00	2.82E-03	1.26E+02	5.08E-01
RF-TT0377	2.24E-06	0.00E+00	1.09E-34	5.00E+01	5.28E+00	0.00E+00	1.61E-03	5.53E+01	2.23E-01
RF-TT0391	5.00E-07	0.00E+00	1.54E-35	1.27E+01	1.32E+00	0.00E+00	1.54E-04	1.40E+01	5.64E-02
RF-TT0392	1.76E-07	0.00E+00	9.66E-36	6.61E+00	6.94E-01	0.00E+00	9.68E-05	7.31E+00	2.95E-02
RF-TT0393	1.45E-05	0.00E+00	6.75E-34	3.08E+02	3.25E+01	0.00E+00	6.75E-03	3.40E+02	1.37E+00
RF-TT0398	3.16E-07	0.00E+00	1.78E-35	1.24E+01	1.29E+00	0.00E+00	1.78E-04	1.37E+01	5.50E-02
RF-TT0409	2.64E-07	0.00E+00	8.32E-36	6.38E+00	6.66E-01	0.00E+00	8.39E-05	7.05E+00	2.84E-02
RF-TT0412	2.64E-07	0.00E+00	8.32E-36	6.38E+00	6.66E-01	0.00E+00	8.39E-05	7.05E+00	2.84E-02
RF-TT0414	8.19E-06	0.00E+00	2.57E-34	1.98E+02	2.06E+01	0.00E+00	2.59E-03	2.18E+02	8.81E-01
RF-TT0430	2.39E-09	0.00E+00	1.92E-37	8.76E-02	9.25E-03	0.00E+00	1.92E-06	9.69E-02	3.91E-04
RF-TT0431	5.95E-07	0.00E+00	4.68E-35	2.16E+01	2.28E+00	0.00E+00	6.84E-04	2.39E+01	9.62E-02
RF-TT0438	3.54E-05	0.00E+00	1.78E-33	1.10E+03	1.15E+02	0.00E+00	1.93E-02	1.22E+03	4.91E+00
RF-TT0440	3.49E-06	0.00E+00	1.73E-34	1.09E+02	1.17E+01	0.00E+00	6.76E-03	1.20E+02	4.85E-01
RF-TT0441	1.72E-05	0.00E+00	8.13E-34	3.75E+02	3.97E+01	0.00E+00	1.26E-02	4.15E+02	1.67E+00
RF-TT0442	2.48E-06	0.00E+00	1.40E-34	6.94E+01	7.32E+00	0.00E+00	6.78E-03	7.68E+01	3.10E-01
RF-TT0443	5.31E-08	0.00E+00	4.03E-36	1.88E+00	1.98E-01	0.00E+00	5.59E-05	2.08E+00	8.38E-03
RF-TT0479	5.20E-07	0.00E+00	4.18E-35	1.90E+01	2.01E+00	0.00E+00	4.18E-04	2.10E+01	8.48E-02
RF-TT0480	3.54E-05	0.00E+00	1.69E-33	7.79E+02	8.18E+01	0.00E+00	2.43E-02	8.61E+02	3.47E+00
RF-TT0481	1.99E-08	0.00E+00	9.51E-37	4.37E-01	4.63E-02	0.00E+00	1.37E-05	4.84E-01	1.95E-03
RF-TT0483	6.40E-08	0.00E+00	5.14E-36	2.35E+00	2.48E-01	0.00E+00	1.68E-02	2.61E+00	1.05E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT0484	3.43E-07	0.00E+00	2.13E-35	9.74E+00	1.03E+00	0.00E+00	3.21E-04	1.08E+01	4.34E-02
RF-TT0485	2.81E-08	0.00E+00	1.32E-36	6.01E-01	6.35E-02	0.00E+00	2.83E-04	6.65E-01	2.68E-03
RF-TT0486	1.67E-07	0.00E+00	7.78E-36	3.57E+00	3.76E-01	0.00E+00	2.99E-04	3.94E+00	1.59E-02
RF-TT0487	8.37E-07	0.00E+00	2.65E-35	1.28E+01	1.35E+00	0.00E+00	7.36E-04	1.42E+01	5.71E-02
RF-TT0489	2.39E-07	0.00E+00	1.19E-35	5.44E+00	5.73E-01	0.00E+00	2.17E-04	6.01E+00	2.42E-02
RF-TT0490	1.32E-05	0.00E+00	7.55E-34	3.51E+02	3.69E+01	0.00E+00	9.29E-03	3.88E+02	1.56E+00
RF-TT0491	3.07E-07	0.00E+00	1.02E-35	4.70E+00	4.94E-01	0.00E+00	1.95E-04	5.19E+00	2.09E-02
RF-TT0492	1.03E-07	0.00E+00	5.75E-36	2.62E+00	2.77E-01	0.00E+00	5.75E-05	2.90E+00	1.17E-02
RF-TT0523A	6.93E-07	0.00E+00	2.31E-35	1.06E+01	1.12E+00	0.00E+00	2.65E-04	1.17E+01	4.71E-02
RF-TT0523B	6.93E-07	0.00E+00	2.31E-35	1.06E+01	1.12E+00	0.00E+00	2.65E-04	1.17E+01	4.71E-02
RF-TT0523C	6.93E-07	0.00E+00	2.31E-35	1.06E+01	1.12E+00	0.00E+00	2.65E-04	1.17E+01	4.71E-02
RF-TT0523D	6.93E-07	0.00E+00	2.31E-35	1.06E+01	1.12E+00	0.00E+00	2.65E-04	1.17E+01	4.71E-02
RF-TT0523E	6.93E-07	0.00E+00	2.31E-35	1.06E+01	1.12E+00	0.00E+00	2.65E-04	1.17E+01	4.71E-02
RF-TT0532A	1.74E-05	0.00E+00	3.87E-34	1.82E+02	1.91E+01	0.00E+00	5.01E-03	2.01E+02	8.11E-01
RF-TT0532B	1.74E-05	0.00E+00	3.87E-34	1.82E+02	1.91E+01	0.00E+00	5.01E-03	2.01E+02	8.11E-01
RF-TT0541	2.87E-08	0.00E+00	2.30E-36	1.06E+00	1.11E-01	0.00E+00	2.31E-05	1.17E+00	4.71E-03
RF-TT0545	6.40E-09	0.00E+00	5.14E-37	2.35E-01	2.48E-02	0.00E+00	5.14E-06	2.59E-01	1.05E-03
RF-TT0601	2.22E-06	0.00E+00	8.85E-35	4.23E+01	4.52E+00	0.00E+00	9.13E-04	4.68E+01	1.89E-01
RF-TT0802	2.49E-04	0.00E+00	7.28E-33	3.34E+03	3.52E+02	0.00E+00	7.29E-02	3.69E+03	1.49E+01
RF-TT0809	2.05E-05	0.00E+00	5.98E-34	2.75E+02	2.89E+01	0.00E+00	5.99E-03	3.04E+02	1.23E+00
RF-TT0821	4.42E-05	0.00E+00	2.17E-33	1.08E+03	1.14E+02	0.00E+00	1.85E-01	1.19E+03	4.81E+00
RF-TT0822	4.89E-05	0.00E+00	1.69E-33	8.09E+02	8.49E+01	0.00E+00	1.94E-01	8.94E+02	3.61E+00
RF-TT0823	9.91E-08	0.00E+00	3.30E-36	1.51E+00	1.60E-01	0.00E+00	3.78E-05	1.67E+00	6.74E-03
RF-TT0824	1.02E-04	0.00E+00	4.64E-33	2.18E+03	2.30E+02	0.00E+00	1.07E-01	2.41E+03	9.72E+00
RF-TT0825	8.47E-05	0.00E+00	3.35E-33	1.64E+03	1.73E+02	0.00E+00	1.12E-01	1.81E+03	7.31E+00
RF-TT0832	6.27E-05	0.00E+00	1.99E-33	9.59E+02	1.01E+02	0.00E+00	5.52E-02	1.06E+03	4.27E+00
RF-TT0854	2.26E-08	0.00E+00	1.81E-36	8.24E-01	8.73E-02	0.00E+00	7.45E-04	9.12E-01	3.68E-03
RF-TT0886	3.20E-09	0.00E+00	2.56E-37	1.17E-01	1.24E-02	0.00E+00	2.56E-06	1.29E-01	5.21E-04
RF-TT2216	9.26E-07	0.00E+00	2.93E-35	1.42E+01	1.49E+00	0.00E+00	8.15E-04	1.57E+01	6.34E-02
RF-TT3010	4.94E-05	0.00E+00	2.60E-33	1.20E+03	1.27E+02	0.00E+00	3.08E-02	1.33E+03	5.34E+00
RF-TT3011	1.25E-04	0.00E+00	5.48E-33	2.50E+03	2.64E+02	0.00E+00	8.76E-02	2.77E+03	1.12E+01

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RF-TT301U	1.04E-05	0.00E+00	5.79E-34	2.72E+02	2.91E+01	0.00E+00	5.95E-03	3.01E+02	1.21E+00
RF-TT310P	3.00E-06	0.00E+00	1.51E-34	9.14E+01	9.15E+00	0.00E+00	1.51E-03	1.01E+02	4.05E-01
RF-TT338S	8.76E-08	0.00E+00	6.90E-36	3.15E+00	3.33E-01	0.00E+00	6.91E-05	3.49E+00	1.41E-02
RF-TT390P	4.93E-07	0.00E+00	1.87E-35	1.54E+01	1.49E+00	0.00E+00	2.15E-04	1.68E+01	6.79E-02
RF-TT391P	2.72E-05	0.00E+00	8.39E-34	6.90E+02	7.15E+01	0.00E+00	8.40E-03	7.61E+02	3.07E+00
RF-TT392P	5.51E-05	0.00E+00	3.02E-33	2.07E+03	2.17E+02	0.00E+00	3.03E-02	2.29E+03	9.21E+00
RF-TT393R	8.15E-06	0.00E+00	5.14E-34	3.16E+02	3.34E+01	0.00E+00	5.31E-03	3.50E+02	1.41E+00
RF-TT394P	1.01E-06	0.00E+00	3.18E-35	2.44E+01	2.39E+00	0.00E+00	3.25E-04	2.68E+01	1.08E-01
RF-TT395P	1.35E-06	0.00E+00	4.25E-35	3.27E+01	3.19E+00	0.00E+00	4.35E-04	3.58E+01	1.45E-01
RF-TT396P	3.38E-07	0.00E+00	1.06E-35	8.17E+00	7.97E-01	0.00E+00	1.09E-04	8.96E+00	3.61E-02
RF-TT398P	3.27E-05	0.00E+00	1.84E-33	1.28E+03	1.34E+02	0.00E+00	1.84E-02	1.41E+03	5.70E+00
RF-TT398R	2.70E-04	0.00E+00	3.42E-33	2.07E+03	2.16E+02	0.00E+00	3.42E-02	2.28E+03	9.21E+00
RF-TT411R	9.77E-06	0.00E+00	3.07E-34	2.36E+02	2.46E+01	0.00E+00	3.10E-03	2.61E+02	1.05E+00
RF-TT429R	2.05E-05	0.00E+00	6.59E-35	5.47E+01	5.59E+00	0.00E+00	6.60E-04	6.03E+01	2.43E-01
RF-TT433X	6.47E-06	0.00E+00	1.82E-35	1.57E+01	1.45E+00	0.00E+00	1.83E-04	1.72E+01	6.93E-02
RF-TT436R	4.74E-05	0.00E+00	2.64E-34	2.06E+02	2.14E+01	0.00E+00	2.64E-03	2.27E+02	9.17E-01
RF-TT454X	2.78E-06	0.00E+00	1.55E-35	1.21E+01	1.26E+00	0.00E+00	1.55E-04	1.34E+01	5.40E-02
RL-T101	1.41E-05	0.00E+00	9.43E-34	6.55E+02	6.77E+01	0.00E+00	8.58E-03	7.23E+02	2.92E+00
RL-T102	1.79E-10	0.00E+00	1.20E-38	8.39E-03	8.63E-04	0.00E+00	1.23E-06	9.25E-03	3.73E-05
RL-T103	1.27E-05	0.00E+00	1.14E-33	2.86E+02	2.93E+01	0.00E+00	1.04E-02	3.16E+02	1.27E+00
RL-T104	2.57E-10	0.00E+00	1.71E-38	1.19E-02	1.24E-03	0.00E+00	1.88E-07	1.32E-02	5.30E-05
RL-T105	9.84E-08	0.00E+00	6.48E-36	4.52E+00	4.66E-01	0.00E+00	1.03E-04	4.99E+00	2.01E-02
RL-T106	9.49E-08	0.00E+00	6.36E-36	4.42E+00	4.56E-01	0.00E+00	5.79E-05	4.88E+00	1.97E-02
RL-T107	2.61E-04	0.00E+00	3.74E-30	1.22E+04	1.26E+03	0.00E+00	3.48E+01	1.35E+04	5.44E+01
RL-T108	1.49E-07	0.00E+00	6.44E-34	6.95E+00	7.18E-01	0.00E+00	5.89E-03	7.68E+00	3.10E-02
RL-T109	2.05E-07	0.00E+00	1.33E-35	9.21E+00	9.53E-01	0.00E+00	2.28E-02	1.02E+01	4.11E-02
RL-T110	2.30E-05	0.00E+00	2.53E-33	1.06E+03	1.09E+02	0.00E+00	1.35E+00	1.17E+03	4.71E+00
RL-T112	9.28E-06	0.00E+00	1.07E-33	1.40E+02	1.45E+01	0.00E+00	7.25E-01	1.55E+02	6.26E-01
RL-T113	9.91E-09	0.00E+00	2.07E-36	4.61E-01	4.76E-02	0.00E+00	1.88E-05	5.09E-01	2.05E-03
RL-T114	1.51E-06	0.00E+00	1.01E-34	7.01E+01	7.25E+00	0.00E+00	9.18E-04	7.74E+01	3.12E-01
RL-T115	3.84E-05	0.00E+00	3.27E-33	9.21E+02	9.53E+01	0.00E+00	4.31E-01	1.02E+03	4.10E+00

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-T116	2.47E-06	0.00E+00	1.66E-34	1.15E+02	1.19E+01	0.00E+00	5.61E-02	1.27E+02	5.10E-01
RL-T118	6.36E-06	0.00E+00	1.32E-33	1.14E+02	1.18E+01	0.00E+00	8.22E-01	1.26E+02	5.10E-01
RL-T120	1.54E-06	0.00E+00	1.39E-34	3.37E+01	3.45E+00	0.00E+00	1.26E-03	3.72E+01	1.50E-01
RL-T122	8.74E-08	0.00E+00	5.86E-36	4.06E+00	4.21E-01	0.00E+00	1.42E+00	5.90E+00	2.38E-02
RL-T123	2.57E-07	0.00E+00	1.72E-35	1.19E+01	1.24E+00	0.00E+00	5.82E-02	1.32E+01	5.32E-02
RL-T125	5.12E-05	0.00E+00	4.25E-33	2.49E+02	5.94E+01	0.00E+00	3.87E-02	3.09E+02	1.25E+00
RL-T127	4.93E-05	0.00E+00	1.07E-33	7.45E+02	7.70E+01	0.00E+00	8.75E-02	8.22E+02	3.32E+00
RL-T128	7.30E-08	0.00E+00	2.60E-41	1.81E-05	1.87E-06	0.00E+00	2.37E-10	2.01E-05	8.09E-08
RL-T129	2.19E-07	0.00E+00	4.94E-33	1.03E+01	1.05E+00	0.00E+00	5.25E-02	1.14E+01	4.58E-02
RL-T130	4.65E-10	0.00E+00	3.12E-38	2.18E-02	2.25E-03	0.00E+00	8.10E-05	2.41E-02	9.73E-05
RL-T131	1.89E-07	0.00E+00	1.71E-35	4.15E+00	4.25E-01	0.00E+00	8.16E-03	4.58E+00	1.85E-02
RL-T132	4.51E-05	0.00E+00	3.01E-33	2.11E+03	2.17E+02	0.00E+00	2.66E-01	2.32E+03	9.36E+00
RL-T133	9.19E-10	0.00E+00	4.83E-38	3.45E-02	3.56E-03	0.00E+00	4.40E-07	3.81E-02	1.54E-04
RL-T134	1.94E-09	0.00E+00	1.30E-37	9.06E-02	9.32E-03	0.00E+00	1.18E-06	1.00E-01	4.03E-04
RL-T135	9.10E-09	0.00E+00	6.09E-37	4.24E-01	4.38E-02	0.00E+00	4.04E-03	4.72E-01	1.90E-03
RL-T137	1.48E-04	0.00E+00	1.33E-32	3.23E+03	3.31E+02	0.00E+00	1.27E-01	3.56E+03	1.44E+01
RL-T140	1.73E-04	0.00E+00	1.27E-32	3.12E+03	3.56E+02	0.00E+00	2.56E+01	3.51E+03	1.41E+01
RL-T143	1.08E-06	0.00E+00	7.24E-35	5.05E+01	5.21E+00	0.00E+00	3.82E-02	5.57E+01	2.25E-01
RL-T145	3.08E-06	0.00E+00	2.07E-34	1.44E+02	1.48E+01	0.00E+00	8.90E-02	1.59E+02	6.40E-01
RL-W407	8.87E-06	0.00E+00	4.41E-34	3.30E+02	3.40E+01	0.00E+00	4.01E-03	3.64E+02	1.47E+00
RL-W408	3.63E-11	0.00E+00	1.86E-39	1.33E-03	1.38E-04	0.00E+00	1.70E-08	1.47E-03	5.93E-06
RL-W415	8.03E-10	0.00E+00	4.10E-38	2.95E-02	3.05E-03	0.00E+00	3.73E-07	3.26E-02	1.31E-04
RL-W418	3.43E-09	0.00E+00	1.73E-37	1.27E-01	1.31E-02	0.00E+00	1.57E-06	1.40E-01	5.63E-04
RL-W437	2.91E-05	0.00E+00	1.45E-33	1.08E+03	1.12E+02	0.00E+00	1.32E-02	1.19E+03	4.80E+00
RL-W438	5.09E-11	0.00E+00	2.60E-39	1.87E-03	1.92E-04	0.00E+00	2.37E-08	2.06E-03	8.30E-06
RL-W439	1.59E-03	0.00E+00	1.43E-31	3.60E+04	3.69E+03	0.00E+00	1.31E+00	3.97E+04	1.60E+02
RL-W443	2.56E-05	0.00E+00	1.28E-33	9.51E+02	9.80E+01	0.00E+00	1.16E-02	1.05E+03	4.23E+00
RL-W444	1.90E-05	0.00E+00	9.47E-34	7.06E+02	7.28E+01	0.00E+00	8.62E-03	7.78E+02	3.14E+00
RL-W447	2.18E-09	0.00E+00	1.12E-37	7.94E-02	8.25E-03	0.00E+00	1.02E-06	8.77E-02	3.53E-04
RL-W448	1.61E-11	0.00E+00	8.24E-40	5.90E-04	6.08E-05	0.00E+00	7.50E-09	6.50E-04	2.62E-06
RL-W449	1.32E-07	0.00E+00	3.02E-38	1.69E-02	1.74E-03	0.00E+00	2.75E-07	1.86E-02	7.50E-05

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W450	2.43E-10	0.00E+00	1.24E-38	8.91E-03	9.18E-04	0.00E+00	1.13E-07	9.83E-03	3.96E-05
RL-W451	3.46E-11	0.00E+00	1.77E-39	1.27E-03	1.31E-04	0.00E+00	1.61E-08	1.40E-03	5.63E-06
RL-W452	1.51E-09	0.00E+00	7.63E-38	5.58E-02	5.77E-03	0.00E+00	6.94E-07	6.16E-02	2.48E-04
RL-W453	4.30E-10	0.00E+00	2.15E-38	1.60E-02	1.65E-03	0.00E+00	1.95E-07	1.77E-02	7.13E-05
RL-W454	6.01E-09	0.00E+00	3.00E-37	2.24E-01	2.31E-02	0.00E+00	2.73E-06	2.47E-01	9.96E-04
RL-W455	1.60E-09	0.00E+00	8.09E-38	5.93E-02	6.11E-03	0.00E+00	7.36E-07	6.54E-02	2.64E-04
RL-W456	2.11E-07	0.00E+00	1.06E-35	7.87E+00	8.11E-01	0.00E+00	9.63E-05	8.68E+00	3.50E-02
RL-W457	2.05E-08	0.00E+00	1.03E-36	7.64E-01	7.87E-02	0.00E+00	9.35E-06	8.43E-01	3.40E-03
RL-W458	6.50E-08	0.00E+00	5.25E-36	3.14E-01	8.08E-02	0.00E+00	4.78E-05	3.95E-01	1.59E-03
RL-W459	6.25E-07	0.00E+00	5.40E-35	7.79E+00	1.10E+00	0.00E+00	4.92E-04	8.89E+00	3.59E-02
RL-W460	3.81E-09	0.00E+00	1.90E-37	1.42E-01	1.46E-02	0.00E+00	1.73E-06	1.56E-01	6.30E-04
RL-W461	3.52E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.52E-09	1.42E-11
RL-W462	1.09E-09	0.00E+00	5.52E-38	4.01E-02	4.14E-03	0.00E+00	5.03E-07	4.42E-02	1.78E-04
RL-W463	5.59E-09	0.00E+00	2.79E-37	2.08E-01	2.15E-02	0.00E+00	2.54E-06	2.30E-01	9.26E-04
RL-W464	2.58E-09	0.00E+00	1.28E-37	9.59E-02	9.87E-03	0.00E+00	1.17E-06	1.06E-01	4.26E-04
RL-W465	1.72E-08	0.00E+00	8.70E-37	6.38E-01	6.59E-02	0.00E+00	7.92E-06	7.04E-01	2.84E-03
RL-W466	2.36E-07	0.00E+00	1.18E-35	8.76E+00	9.04E-01	0.00E+00	1.08E-04	9.67E+00	3.90E-02
RL-W467	1.21E-08	0.00E+00	6.09E-37	4.46E-01	4.59E-02	0.00E+00	5.55E-06	4.92E-01	1.99E-03
RL-W468	6.19E-11	0.00E+00	3.14E-39	2.29E-03	2.36E-04	0.00E+00	2.86E-08	2.52E-03	1.02E-05
RL-W469	2.51E-08	0.00E+00	1.26E-36	9.29E-01	9.63E-02	0.00E+00	1.15E-05	1.03E+00	4.13E-03
RL-W470	7.10E-07	0.00E+00	5.86E-35	3.45E+00	8.22E-01	0.00E+00	5.34E-04	4.27E+00	1.72E-02
RL-W474	2.69E-08	0.00E+00	6.48E-36	7.87E-03	3.11E-03	0.00E+00	5.90E-05	1.10E-02	4.45E-05
RL-W476	4.54E-08	0.00E+00	2.33E-36	1.72E+00	1.79E-01	0.00E+00	2.12E-05	1.90E+00	7.67E-03
RL-W480	7.40E-09	0.00E+00	3.73E-37	2.73E-01	2.83E-02	0.00E+00	3.40E-06	3.02E-01	1.22E-03
RL-W481	1.16E-08	0.00E+00	5.86E-37	4.29E-01	4.42E-02	0.00E+00	5.34E-06	4.73E-01	1.91E-03
RL-W482	1.54E-05	0.00E+00	1.95E-34	5.46E-02	4.70E-02	0.00E+00	1.78E-03	1.03E-01	4.17E-04
RL-W483	1.15E-06	0.00E+00	1.51E-35	3.54E-03	3.34E-03	0.00E+00	1.38E-04	7.01E-03	2.83E-05
RL-W484	4.87E-09	0.00E+00	1.22E-37	4.94E-02	5.45E-03	0.00E+00	1.11E-06	5.48E-02	2.21E-04
RL-W485	2.86E-10	0.00E+00	1.73E-38	5.34E-03	5.90E-04	0.00E+00	1.57E-07	5.93E-03	2.39E-05
RL-W486	1.21E-10	0.00E+00	7.28E-39	2.26E-03	2.48E-04	0.00E+00	6.63E-08	2.50E-03	1.01E-05
RL-W487	1.97E-08	0.00E+00	9.35E-37	3.23E-01	4.11E-02	0.00E+00	8.51E-06	3.64E-01	1.47E-03

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W488	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W489	1.20E-08	0.00E+00	8.82E-37	4.18E-01	4.38E-02	0.00E+00	8.03E-06	4.62E-01	1.86E-03
RL-W490	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W491	4.44E-09	0.00E+00	7.44E-37	4.38E-02	4.45E-03	0.00E+00	6.77E-06	4.83E-02	1.95E-04
RL-W492	2.56E-10	0.00E+00	1.83E-38	8.76E-03	9.15E-04	0.00E+00	1.67E-07	9.68E-03	3.90E-05
RL-W493	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W494	1.02E-05	0.00E+00	1.06E-33	2.21E-01	8.73E-02	0.00E+00	9.67E-03	3.18E-01	1.28E-03
RL-W495	1.84E-07	0.00E+00	2.89E-36	2.12E-03	7.80E-04	0.00E+00	2.63E-05	2.93E-03	1.18E-05
RL-W496	1.19E-06	0.00E+00	3.32E-35	6.97E-03	2.59E-03	0.00E+00	3.03E-04	9.86E-03	3.97E-05
RL-W497	4.97E-08	0.00E+00	6.55E-36	4.18E-01	8.77E-02	0.00E+00	5.97E-05	5.06E-01	2.04E-03
RL-W498	1.93E-07	0.00E+00	9.74E-36	7.15E+00	7.39E-01	0.00E+00	8.86E-05	7.89E+00	3.18E-02
RL-W499	1.73E-12	0.00E+00	8.74E-41	6.40E-05	6.63E-06	0.00E+00	7.96E-10	7.07E-05	2.85E-07
RL-W500	1.23E-10	0.00E+00	1.09E-38	2.61E-03	2.69E-04	0.00E+00	9.88E-08	2.88E-03	1.16E-05
RL-W501	5.11E-06	0.00E+00	2.42E-34	8.39E+01	1.06E+01	0.00E+00	2.20E-03	9.45E+01	3.81E-01
RL-W502	9.24E-10	0.00E+00	4.68E-38	3.42E-02	3.52E-03	0.00E+00	4.26E-07	3.77E-02	1.52E-04
RL-W503	5.34E-08	0.00E+00	4.79E-36	1.21E+00	1.24E-01	0.00E+00	4.36E-05	1.33E+00	5.36E-03
RL-W504	1.97E-08	0.00E+00	9.35E-37	3.23E-01	4.11E-02	0.00E+00	8.51E-06	3.64E-01	1.47E-03
RL-W505	9.28E-10	0.00E+00	4.91E-38	3.49E-02	3.59E-03	0.00E+00	4.47E-07	3.85E-02	1.55E-04
RL-W506	3.36E-10	0.00E+00	1.93E-38	1.15E-02	1.18E-03	0.00E+00	1.76E-07	1.26E-02	5.10E-05
RL-W507	3.34E-11	0.00E+00	1.69E-39	1.24E-03	1.27E-04	0.00E+00	1.54E-08	1.36E-03	5.50E-06
RL-W508	6.14E-07	0.00E+00	5.52E-35	1.34E+01	1.38E+00	0.00E+00	5.03E-04	1.48E+01	5.96E-02
RL-W509	6.04E-06	0.00E+00	4.41E-34	1.09E+02	1.24E+01	0.00E+00	4.01E-03	1.22E+02	4.91E-01
RL-W510	5.10E-07	0.00E+00	4.52E-35	1.09E+01	1.12E+00	0.00E+00	4.12E-04	1.20E+01	4.83E-02
RL-W511	5.19E-05	0.00E+00	2.18E-33	1.45E+03	1.47E+02	0.00E+00	2.02E-02	1.60E+03	6.45E+00
RL-W512	4.54E-05	0.00E+00	1.47E-33	8.76E+02	1.01E+02	0.00E+00	1.34E-02	9.77E+02	3.94E+00
RL-W513	4.84E-03	0.00E+00	5.98E-31	1.43E+04	3.29E+03	0.00E+00	5.44E+00	1.76E+04	7.10E+01
RL-W514	1.37E-10	0.00E+00	6.86E-39	5.07E-03	5.25E-04	0.00E+00	6.25E-08	5.60E-03	2.26E-05
RL-W515	5.34E-09	0.00E+00	2.69E-37	1.98E-01	2.04E-02	0.00E+00	2.45E-06	2.18E-01	8.80E-04
RL-W516	7.41E-09	0.00E+00	3.74E-37	2.73E-01	2.83E-02	0.00E+00	3.40E-06	3.02E-01	1.22E-03
RL-W517	6.60E-17	0.00E+00	3.34E-45	2.43E-09	2.51E-10	0.00E+00	3.04E-14	2.69E-09	1.08E-11
RL-W518	1.87E-07	0.00E+00	1.41E-35	3.49E+00	3.90E-01	0.00E+00	1.28E-04	3.88E+00	1.57E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W519	3.33E-08	0.00E+00	1.67E-36	1.24E+00	1.27E-01	0.00E+00	1.52E-05	1.36E+00	5.50E-03
RL-W520	3.68E-09	0.00E+00	1.88E-37	1.36E-01	1.40E-02	0.00E+00	1.71E-06	1.50E-01	6.03E-04
RL-W521	6.85E-11	0.00E+00	3.45E-39	2.52E-03	2.61E-04	0.00E+00	3.14E-08	2.79E-03	1.12E-05
RL-W522	1.43E-06	0.00E+00	1.28E-34	1.67E+01	2.21E+00	0.00E+00	1.17E-03	1.89E+01	7.63E-02
RL-W523	4.30E-07	0.00E+00	4.87E-35	1.11E+00	3.12E-01	0.00E+00	4.43E-04	1.42E+00	5.73E-03
RL-W524	1.78E-06	0.00E+00	1.86E-34	1.02E+01	1.83E+00	0.00E+00	1.70E-03	1.20E+01	4.85E-02
RL-W525	1.42E-07	0.00E+00	1.26E-35	1.21E+00	1.85E-01	0.00E+00	1.15E-04	1.39E+00	5.61E-03
RL-W526	5.36E-07	0.00E+00	4.56E-35	1.29E+01	1.33E+00	0.00E+00	4.15E-04	1.42E+01	5.73E-02
RL-W527	5.87E-08	0.00E+00	6.59E-36	1.36E+00	1.50E-01	0.00E+00	6.00E-05	1.51E+00	6.10E-03
RL-W528	2.63E-05	0.00E+00	2.80E-33	4.34E+01	1.93E+01	0.00E+00	2.55E-02	6.27E+01	2.53E-01
RL-W529	2.19E-08	0.00E+00	1.97E-36	4.79E-01	4.90E-02	0.00E+00	1.79E-05	5.28E-01	2.13E-03
RL-W530	2.58E-07	0.00E+00	2.28E-35	5.48E+00	5.63E-01	0.00E+00	2.08E-04	6.04E+00	2.44E-02
RL-W531	1.54E-05	0.00E+00	2.29E-33	2.37E+01	7.91E+00	0.00E+00	2.09E-02	3.16E+01	1.27E-01
RL-W532	4.94E-08	0.00E+00	2.49E-36	1.83E+00	1.89E-01	0.00E+00	2.27E-05	2.02E+00	8.13E-03
RL-W533	2.39E-08	0.00E+00	2.15E-36	5.23E-01	5.35E-02	0.00E+00	1.96E-05	5.76E-01	2.32E-03
RL-W534	1.38E-12	0.00E+00	6.94E-41	5.10E-05	5.28E-06	0.00E+00	6.32E-10	5.63E-05	2.27E-07
RL-W535	7.22E-06	0.00E+00	6.86E-34	6.54E+01	9.25E+00	0.00E+00	6.25E-03	7.47E+01	3.01E-01
RL-W536	1.41E-07	0.00E+00	9.24E-36	2.27E+00	2.38E-01	0.00E+00	8.72E-05	2.51E+00	1.01E-02
RL-W537	4.82E-06	0.00E+00	2.09E-34	1.39E+02	1.42E+01	0.00E+00	1.93E-03	1.54E+02	6.19E-01
RL-W538	1.75E-11	0.00E+00	8.82E-40	6.48E-04	6.70E-05	0.00E+00	8.03E-09	7.15E-04	2.88E-06
RL-W539	1.95E-09	0.00E+00	9.93E-38	7.16E-02	7.39E-03	0.00E+00	9.04E-07	7.90E-02	3.19E-04
RL-W540	3.79E-06	0.00E+00	4.37E-34	2.58E+01	4.11E+00	0.00E+00	3.98E-03	2.99E+01	1.21E-01
RL-W541	5.63E-09	0.00E+00	2.86E-37	2.08E-01	2.14E-02	0.00E+00	2.61E-06	2.29E-01	9.23E-04
RL-W542	2.61E-07	0.00E+00	2.13E-35	5.25E+00	5.63E-01	0.00E+00	1.94E-04	5.81E+00	2.34E-02
RL-W543	8.23E-10	0.00E+00	4.14E-38	3.04E-02	3.14E-03	0.00E+00	3.77E-07	3.36E-02	1.35E-04
RL-W544	1.85E-08	0.00E+00	1.69E-36	3.46E-01	4.00E-02	0.00E+00	1.54E-05	3.86E-01	1.56E-03
RL-W545	4.93E-09	0.00E+00	2.48E-37	1.82E-01	1.88E-02	0.00E+00	2.26E-06	2.01E-01	8.10E-04
RL-W546	2.16E-10	0.00E+00	1.09E-38	8.02E-03	8.25E-04	0.00E+00	9.91E-08	8.84E-03	3.56E-05
RL-W547	5.52E-12	0.00E+00	2.78E-40	2.04E-04	2.11E-05	0.00E+00	2.53E-09	2.25E-04	9.06E-07
RL-W548	4.77E-12	0.00E+00	2.42E-40	1.76E-04	1.82E-05	0.00E+00	2.20E-09	1.94E-04	7.83E-07
RL-W549	9.48E-07	0.00E+00	9.70E-35	9.06E+00	1.25E+00	0.00E+00	8.83E-04	1.03E+01	4.16E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W550	4.30E-06	0.00E+00	1.84E-34	1.23E+02	1.25E+01	0.00E+00	1.69E-03	1.35E+02	5.46E-01
RL-W551	7.64E-06	0.00E+00	2.71E-34	1.39E+02	1.63E+01	0.00E+00	2.47E-03	1.55E+02	6.25E-01
RL-W552	2.96E-09	0.00E+00	1.50E-37	1.09E-01	1.13E-02	0.00E+00	1.37E-06	1.21E-01	4.86E-04
RL-W553	2.63E-10	0.00E+00	1.42E-38	9.74E-03	1.00E-03	0.00E+00	1.29E-07	1.07E-02	4.33E-05
RL-W554	4.17E-09	0.00E+00	2.10E-37	1.54E-01	1.60E-02	0.00E+00	1.92E-06	1.70E-01	6.87E-04
RL-W555	1.92E-09	0.00E+00	9.70E-38	7.11E-02	7.32E-03	0.00E+00	8.83E-07	7.84E-02	3.16E-04
RL-W563	2.76E-08	0.00E+00	2.43E-36	5.90E-01	6.04E-02	0.00E+00	2.21E-05	6.50E-01	2.62E-03
RL-W564	1.80E-08	0.00E+00	1.61E-36	3.81E-01	3.90E-02	0.00E+00	1.47E-05	4.20E-01	1.70E-03
RL-W565	1.78E-09	0.00E+00	9.05E-38	6.58E-02	6.80E-03	0.00E+00	8.24E-07	7.26E-02	2.93E-04
RL-W566	2.61E-08	0.00E+00	1.33E-36	9.66E-01	1.00E-01	0.00E+00	1.21E-05	1.07E+00	4.30E-03
RL-W567	1.81E-06	0.00E+00	3.39E-35	2.97E-02	1.11E-02	0.00E+00	3.09E-04	4.12E-02	1.66E-04
RL-W568	3.49E-05	0.00E+00	7.13E-34	1.41E+00	5.18E-01	0.00E+00	6.49E-03	1.93E+00	7.79E-03
RL-W569	2.87E-08	0.00E+00	5.37E-37	4.70E-04	1.76E-05	0.00E+00	4.89E-06	4.92E-04	1.99E-06
RL-W570	1.84E-09	0.00E+00	9.39E-38	6.98E-02	7.18E-03	0.00E+00	8.55E-07	7.70E-02	3.11E-04
RL-W571	5.90E-06	0.00E+00	3.19E-34	5.66E+00	1.31E+00	0.00E+00	2.90E-03	6.98E+00	2.81E-02
RL-W572	5.12E-09	0.00E+00	9.54E-38	3.05E-03	3.14E-05	0.00E+00	8.69E-07	3.08E-03	1.24E-05
RL-W573	6.59E-05	0.00E+00	1.22E-33	1.67E+00	5.80E-01	0.00E+00	1.11E-02	2.26E+00	9.12E-03
RL-W574	2.83E-04	0.00E+00	5.29E-33	6.38E+00	2.15E+00	0.00E+00	4.82E-02	8.58E+00	3.46E-02
RL-W575	1.85E-03	0.00E+00	3.56E-32	6.11E+01	1.72E+01	0.00E+00	3.24E-01	7.85E+01	3.17E-01
RL-W576	1.33E-04	0.00E+00	2.49E-33	3.11E+00	1.04E+00	0.00E+00	2.27E-02	4.17E+00	1.68E-02
RL-W579	1.13E-08	0.00E+00	6.55E-38	1.56E-02	1.61E-03	0.00E+00	5.97E-07	1.72E-02	6.93E-05
RL-W580	0.00E+00	0.00E+00	0.00E+00	1.24E-01	9.39E-03	0.00E+00	0.00E+00	1.34E-01	5.39E-04
RL-W581	1.20E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.20E-07	4.82E-10
RL-W582	7.82E-10	0.00E+00	5.56E-38	3.99E-03	9.56E-04	0.00E+00	5.06E-07	4.94E-03	1.99E-05
RL-W583	6.05E-10	0.00E+00	3.02E-38	2.25E-02	2.32E-03	0.00E+00	2.75E-07	2.48E-02	1.00E-04
RL-W584	1.20E-08	0.00E+00	1.98E-36	1.31E-01	2.98E-02	0.00E+00	1.80E-05	1.61E-01	6.49E-04
RL-W585	7.15E-08	0.00E+00	1.05E-35	7.64E-01	1.81E-01	0.00E+00	9.60E-05	9.45E-01	3.81E-03
RL-W586	9.54E-12	0.00E+00	4.75E-40	3.55E-04	3.66E-05	0.00E+00	4.33E-09	3.92E-04	1.58E-06
RL-W587	2.04E-10	0.00E+00	1.03E-38	7.57E-03	7.84E-04	0.00E+00	9.35E-08	8.35E-03	3.37E-05
RL-W588	8.43E-09	0.00E+00	1.67E-36	1.11E-01	2.51E-02	0.00E+00	1.52E-05	1.36E-01	5.48E-04
RL-W589	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W590	2.59E-07	0.00E+00	3.57E-35	8.54E-03	7.04E-03	0.00E+00	3.25E-04	1.59E-02	6.41E-05
RL-W591	1.47E-06	0.00E+00	4.03E-35	1.06E-02	9.11E-03	0.00E+00	3.66E-04	2.00E-02	8.08E-05
RL-W592	6.51E-06	0.00E+00	4.41E-34	4.90E-01	2.95E-01	0.00E+00	4.01E-03	7.89E-01	3.18E-03
RL-W593	0.00E+00	0.00E+00	0.00E+00	1.77E-02	1.38E-02	0.00E+00	0.00E+00	3.15E-02	1.27E-04
RL-W594	5.87E-06	0.00E+00	7.93E-35	2.19E-02	1.87E-02	0.00E+00	7.22E-04	4.13E-02	1.67E-04
RL-W595	1.55E-08	0.00E+00	8.28E-36	1.50E-02	1.36E-02	0.00E+00	7.54E-05	2.87E-02	1.16E-04
RL-W596	5.02E-09	0.00E+00	6.44E-37	1.54E-04	1.28E-04	0.00E+00	5.86E-06	2.88E-04	1.16E-06
RL-W597	9.22E-06	0.00E+00	2.83E-34	2.99E-01	2.32E-01	0.00E+00	2.58E-03	5.33E-01	2.15E-03
RL-W598	9.75E-06	0.00E+00	1.67E-33	4.17E-01	2.89E-01	0.00E+00	1.52E-02	7.21E-01	2.91E-03
RL-W599	4.94E-07	0.00E+00	1.35E-35	3.52E-03	3.05E-03	0.00E+00	1.23E-04	6.69E-03	2.70E-05
RL-W600	2.81E-14	0.00E+00	1.40E-42	1.04E-06	1.08E-07	0.00E+00	1.27E-11	1.15E-06	4.63E-09
RL-W601	1.42E-10	0.00E+00	7.67E-39	5.27E-03	5.45E-04	0.00E+00	6.98E-08	5.82E-03	2.35E-05
RL-W602	1.24E-07	0.00E+00	6.29E-36	4.57E+00	4.73E-01	0.00E+00	5.72E-05	5.04E+00	2.03E-02
RL-W603	7.14E-07	0.00E+00	3.63E-35	2.64E+01	2.72E+00	0.00E+00	3.30E-04	2.91E+01	1.17E-01
RL-W604	1.67E-09	0.00E+00	9.51E-38	1.28E-02	2.93E-03	0.00E+00	8.65E-07	1.57E-02	6.35E-05
RL-W605	3.83E-10	0.00E+00	2.07E-38	1.42E-02	1.46E-03	0.00E+00	1.88E-07	1.56E-02	6.30E-05
RL-W606	1.55E-10	0.00E+00	8.32E-39	5.71E-03	5.90E-04	0.00E+00	7.57E-08	6.30E-03	2.54E-05
RL-W607	2.83E-10	0.00E+00	1.61E-38	2.17E-03	4.97E-04	0.00E+00	1.47E-07	2.66E-03	1.07E-05
RL-W608	3.38E-09	0.00E+00	6.25E-37	2.82E-03	1.61E-03	0.00E+00	5.69E-06	4.43E-03	1.79E-05
RL-W610	6.69E-07	0.00E+00	3.34E-35	2.49E+01	2.57E+00	0.00E+00	3.04E-04	2.74E+01	1.11E-01
RL-W612	1.58E-09	0.00E+00	8.09E-38	6.04E-02	6.25E-03	0.00E+00	7.36E-07	6.66E-02	2.69E-04
RL-W615	0.00E+00	0.00E+00	0.00E+00	2.53E-01	0.00E+00	0.00E+00	0.00E+00	2.53E-01	1.02E-03
RL-W622	2.63E-11	0.00E+00	1.32E-39	9.81E-04	1.01E-04	0.00E+00	1.20E-08	1.08E-03	4.37E-06
RL-W625	9.18E-10	0.00E+00	2.01E-37	5.01E-03	2.29E-03	0.00E+00	1.83E-06	7.30E-03	2.94E-05
RL-W626	4.93E-08	0.00E+00	4.56E-36	1.96E-01	5.45E-02	0.00E+00	4.15E-05	2.51E-01	1.01E-03
RL-W627	2.32E-10	0.00E+00	6.09E-39	9.29E-07	0.00E+00	0.00E+00	5.55E-08	9.85E-07	3.97E-09
RL-W628	7.62E-11	0.00E+00	3.83E-39	2.83E-03	2.92E-04	0.00E+00	3.49E-08	3.12E-03	1.26E-05
RL-W629	5.16E-12	0.00E+00	2.63E-40	1.90E-04	1.96E-05	0.00E+00	2.40E-09	2.10E-04	8.46E-07
RL-W630	5.68E-08	0.00E+00	4.91E-36	2.20E+00	2.37E-01	0.00E+00	4.47E-05	2.44E+00	9.83E-03
RL-W631	9.15E-10	0.00E+00	4.94E-38	3.38E-02	3.49E-03	0.00E+00	4.50E-07	3.73E-02	1.50E-04
RL-W632	4.04E-07	0.00E+00	6.67E-36	4.46E+00	6.80E-01	0.00E+00	6.07E-05	5.14E+00	2.07E-02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W633	9.63E-10	0.00E+00	3.87E-38	7.01E-04	2.87E-04	0.00E+00	3.52E-07	9.89E-04	3.99E-06
RL-W634	0.00E+00	0.00E+00	0.00E+00	7.64E-03	0.00E+00	0.00E+00	0.00E+00	7.64E-03	3.08E-05
RL-W635	5.76E-06	0.00E+00	1.31E-33	3.25E+00	2.25E+00	0.00E+00	1.19E-02	5.52E+00	2.23E-02
RL-W636	5.87E-08	0.00E+00	2.47E-36	4.25E-02	1.74E-02	0.00E+00	2.25E-05	5.99E-02	2.42E-04
RL-W637	1.40E-10	0.00E+00	6.29E-38	4.78E-04	2.18E-04	0.00E+00	5.72E-07	6.96E-04	2.81E-06
RL-W638	6.14E-09	0.00E+00	6.40E-37	4.68E-03	2.04E-03	0.00E+00	5.83E-06	6.73E-03	2.71E-05
RL-W639	3.24E-10	0.00E+00	1.64E-38	1.20E-02	1.24E-03	0.00E+00	1.49E-07	1.32E-02	5.33E-05
RL-W640	1.09E-08	0.00E+00	5.44E-37	4.04E-01	4.18E-02	0.00E+00	4.96E-06	4.46E-01	1.80E-03
RL-W641	3.32E-07	0.00E+00	1.20E-34	1.94E+00	3.69E-01	0.00E+00	1.09E-03	2.31E+00	9.32E-03
RL-W642	6.49E-09	0.00E+00	1.24E-38	2.37E-02	5.59E-05	0.00E+00	1.13E-07	2.37E-02	9.57E-05
RL-W643	1.02E-07	0.00E+00	3.68E-35	5.98E-01	1.14E-01	0.00E+00	3.35E-04	7.12E-01	2.87E-03
RL-W644	0.00E+00	0.00E+00	0.00E+00	4.11E-02	0.00E+00	0.00E+00	0.00E+00	4.11E-02	1.66E-04
RL-W645	2.48E-09	0.00E+00	1.66E-37	8.09E-02	8.80E-03	0.00E+00	1.51E-06	8.97E-02	3.62E-04
RL-W646	2.26E-09	0.00E+00	1.48E-37	1.93E-02	4.35E-03	0.00E+00	1.35E-06	2.37E-02	9.55E-05
RL-W647	6.36E-09	0.00E+00	2.21E-35	8.24E-02	6.04E-03	0.00E+00	2.01E-04	8.86E-02	3.57E-04
RL-W648	1.13E-10	0.00E+00	3.78E-38	4.50E-05	4.11E-05	0.00E+00	3.44E-07	8.64E-05	3.49E-07
RL-W649	4.14E-10	0.00E+00	1.39E-37	1.66E-04	1.51E-04	0.00E+00	1.27E-06	3.18E-04	1.28E-06
RL-W653	1.96E-11	0.00E+00	9.97E-40	7.24E-04	7.46E-05	0.00E+00	9.07E-09	7.98E-04	3.22E-06
RL-W654	1.08E-10	0.00E+00	5.44E-39	3.99E-03	4.11E-04	0.00E+00	4.96E-08	4.40E-03	1.77E-05
RL-W655	2.65E-05	0.00E+00	1.29E-33	1.58E-01	1.73E-01	0.00E+00	1.17E-02	3.43E-01	1.38E-03
RL-W656	1.11E-04	0.00E+00	5.79E-34	3.72E-01	1.78E-01	0.00E+00	5.27E-03	5.55E-01	2.24E-03
RL-W657	5.68E-05	0.00E+00	8.55E-34	1.83E-01	1.69E-01	0.00E+00	7.78E-03	3.60E-01	1.45E-03
RL-W659	6.87E-06	0.00E+00	1.93E-34	3.52E-02	2.03E-02	0.00E+00	1.76E-03	5.72E-02	2.31E-04
RL-W660	3.77E-05	0.00E+00	2.32E-33	6.49E-01	5.39E-01	0.00E+00	2.11E-02	1.21E+00	4.88E-03
RL-W661	3.98E-07	0.00E+00	2.90E-36	3.13E-04	1.32E-03	0.00E+00	2.64E-05	1.66E-03	6.70E-06
RL-W662	1.25E-08	0.00E+00	1.73E-37	8.02E-05	6.66E-05	0.00E+00	1.57E-06	1.48E-04	5.98E-07
RL-W665	1.54E-04	0.00E+00	1.38E-32	9.81E-01	6.11E-01	0.00E+00	1.26E-01	1.72E+00	6.93E-03
RL-W666	2.76E-06	0.00E+00	3.39E-35	4.11E-02	2.01E-02	0.00E+00	3.09E-04	6.15E-02	2.48E-04
RL-W668	2.63E-07	0.00E+00	1.07E-36	1.09E-01	1.43E-02	0.00E+00	9.70E-06	1.23E-01	4.96E-04
RL-W669	7.66E-08	0.00E+00	2.76E-35	4.48E-01	8.53E-02	0.00E+00	2.52E-04	5.33E-01	2.15E-03
RL-W670	4.85E-09	0.00E+00	1.97E-38	2.01E-03	2.64E-04	0.00E+00	1.79E-07	2.27E-03	9.16E-06

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W671	7.90E-07	0.00E+00	1.01E-35	3.68E-03	1.77E-03	0.00E+00	9.18E-05	5.55E-03	2.24E-05
RL-W672	5.37E-06	0.00E+00	6.86E-35	2.51E-02	1.21E-02	0.00E+00	6.25E-04	3.78E-02	1.52E-04
RL-W673	5.18E-06	0.00E+00	6.59E-35	2.43E-02	1.16E-02	0.00E+00	6.00E-04	3.65E-02	1.47E-04
RL-W674	1.74E-08	0.00E+00	2.95E-36	8.39E+00	3.38E-02	0.00E+00	2.68E-05	8.42E+00	3.40E-02
RL-W675	6.49E-08	0.00E+00	1.63E-35	9.81E-02	3.94E-02	0.00E+00	1.48E-04	1.38E-01	5.55E-04
RL-W676	2.49E-09	0.00E+00	9.77E-38	1.10E-01	7.42E-04	0.00E+00	8.90E-07	1.11E-01	4.47E-04
RL-W677	5.78E-06	0.00E+00	2.42E-34	4.30E+00	1.73E+00	0.00E+00	2.21E-03	6.04E+00	2.43E-02
RL-W678	1.83E-08	0.00E+00	2.02E-36	3.87E-02	1.58E-02	0.00E+00	1.84E-05	5.45E-02	2.20E-04
RL-W679	1.15E-07	0.00E+00	4.52E-36	8.31E-02	3.40E-02	0.00E+00	4.12E-05	1.17E-01	4.73E-04
RL-W680	2.58E-11	0.00E+00	6.36E-39	1.30E-05	1.09E-05	0.00E+00	5.79E-08	2.40E-05	9.66E-08
RL-W681	1.58E-11	0.00E+00	2.58E-39	3.50E-04	8.08E-05	0.00E+00	2.35E-08	4.31E-04	1.74E-06
RL-W685	4.59E-08	0.00E+00	2.29E-36	1.71E+00	1.76E-01	0.00E+00	2.09E-05	1.88E+00	7.60E-03
RL-W689	1.19E-09	0.00E+00	2.75E-38	2.90E-04	0.00E+00	0.00E+00	2.51E-07	2.90E-04	1.17E-06
RL-W690	3.99E-08	0.00E+00	2.02E-36	1.52E+00	1.56E-01	0.00E+00	1.84E-05	1.68E+00	6.76E-03
RL-W691	9.25E-10	0.00E+00	4.71E-38	3.52E-02	3.62E-03	0.00E+00	4.29E-07	3.88E-02	1.57E-04
RL-W692	3.66E-08	0.00E+00	1.87E-36	1.39E+00	1.44E-01	0.00E+00	1.70E-05	1.54E+00	6.20E-03
RL-W693	4.53E-08	0.00E+00	2.30E-36	1.72E+00	1.78E-01	0.00E+00	2.10E-05	1.90E+00	7.66E-03
RL-W694	4.76E-07	0.00E+00	2.42E-35	1.82E+01	1.86E+00	0.00E+00	2.20E-04	2.01E+01	8.09E-02
RL-W695	3.94E-10	0.00E+00	0.00E+00	1.79E-03	0.00E+00	0.00E+00	0.00E+00	1.79E-03	7.22E-06
RL-W696	5.13E-10	0.00E+00	8.82E-38	2.18E-03	9.98E-04	0.00E+00	8.03E-07	3.18E-03	1.28E-05
RL-W697	1.19E-07	0.00E+00	1.87E-34	5.19E-03	3.30E-04	0.00E+00	1.70E-03	7.22E-03	2.91E-05
RL-W698	1.03E-08	0.00E+00	0.00E+00	2.46E-05	0.00E+00	0.00E+00	0.00E+00	2.47E-05	9.94E-08
RL-W699	2.29E-09	0.00E+00	1.24E-38	1.65E-03	8.98E-05	0.00E+00	1.13E-07	1.74E-03	7.01E-06
RL-W700	6.48E-10	0.00E+00	3.26E-38	2.39E-02	2.47E-03	0.00E+00	2.97E-07	2.64E-02	1.06E-04
RL-W702	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W703	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W704	2.55E-08	0.00E+00	9.20E-36	1.49E-01	2.85E-02	0.00E+00	8.37E-05	1.78E-01	7.16E-04
RL-W705	1.65E-10	0.00E+00	8.47E-39	6.26E-03	6.49E-04	0.00E+00	7.71E-08	6.91E-03	2.79E-05
RL-W706	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W707	5.89E-09	0.00E+00	3.01E-37	2.23E-01	2.31E-02	0.00E+00	2.74E-06	2.46E-01	9.93E-04
RL-W708	8.90E-10	0.00E+00	4.56E-38	3.39E-02	3.49E-03	0.00E+00	4.15E-07	3.73E-02	1.51E-04

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W709	3.08E-07	0.00E+00	1.57E-35	1.17E+01	1.21E+00	0.00E+00	1.43E-04	1.29E+01	5.20E-02
RL-W710	1.84E-11	0.00E+00	9.39E-40	6.98E-04	7.18E-05	0.00E+00	8.55E-09	7.70E-04	3.11E-06
RL-W711	5.73E-09	0.00E+00	2.93E-37	2.18E-01	2.25E-02	0.00E+00	2.67E-06	2.40E-01	9.70E-04
RL-W712	7.42E-09	0.00E+00	3.80E-37	2.82E-01	2.91E-02	0.00E+00	3.45E-06	3.11E-01	1.25E-03
RL-W713	6.41E-09	0.00E+00	3.28E-37	2.43E-01	2.51E-02	0.00E+00	2.98E-06	2.68E-01	1.08E-03
RL-W714	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RL-W715	1.11E-10	0.00E+00	5.52E-39	4.11E-03	4.25E-04	0.00E+00	5.03E-08	4.54E-03	1.83E-05
RL-W716	1.15E-09	0.00E+00	5.75E-38	4.29E-02	4.42E-03	0.00E+00	5.23E-07	4.73E-02	1.91E-04
RL-W717	2.88E-10	0.00E+00	1.44E-38	1.07E-02	1.11E-03	0.00E+00	1.31E-07	1.18E-02	4.77E-05
RL-W718	5.08E-11	0.00E+00	2.53E-39	1.89E-03	1.95E-04	0.00E+00	2.31E-08	2.08E-03	8.40E-06
RL-W719	2.29E-10	0.00E+00	1.14E-38	8.54E-03	8.80E-04	0.00E+00	1.04E-07	9.42E-03	3.80E-05
RL-W720	1.42E-09	0.00E+00	7.09E-38	5.27E-02	5.45E-03	0.00E+00	6.46E-07	5.82E-02	2.35E-04
RL-W721	9.60E-10	0.00E+00	4.79E-38	3.57E-02	3.69E-03	0.00E+00	4.36E-07	3.94E-02	1.59E-04
RL-W723	3.18E-09	0.00E+00	1.62E-37	1.21E-01	1.25E-02	0.00E+00	1.47E-06	1.34E-01	5.40E-04
RL-W724	2.11E-08	0.00E+00	1.08E-36	8.02E-01	8.32E-02	0.00E+00	9.81E-06	8.85E-01	3.57E-03
RL-W725	6.68E-09	0.00E+00	3.40E-37	2.54E-01	2.62E-02	0.00E+00	3.09E-06	2.80E-01	1.13E-03
RL-W726	5.26E-09	0.00E+00	2.68E-37	2.01E-01	2.07E-02	0.00E+00	2.44E-06	2.21E-01	8.93E-04
RL-W727	3.23E-08	0.00E+00	1.64E-36	1.23E+00	1.27E-01	0.00E+00	1.50E-05	1.36E+00	5.47E-03
RL-W728	2.94E-08	0.00E+00	1.50E-36	1.12E+00	1.16E-01	0.00E+00	1.36E-05	1.24E+00	5.00E-03
RL-W729	1.36E-08	0.00E+00	6.94E-37	5.17E-01	5.35E-02	0.00E+00	6.32E-06	5.70E-01	2.30E-03
RL-W730	5.31E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.31E-06	2.14E-08
RL-W731	1.71E-12	0.00E+00	0.00E+00	3.38E-04	6.42E-07	0.00E+00	0.00E+00	3.39E-04	1.37E-06
RL-W732	3.92E-06	0.00E+00	3.95E-34	9.51E+01	9.77E+00	0.00E+00	3.59E-03	1.05E+02	4.23E-01
RL-W733	5.15E-08	0.00E+00	5.14E-36	1.03E+00	1.19E-01	0.00E+00	4.68E-05	1.15E+00	4.65E-03
RL-W734	1.61E-07	0.00E+00	1.71E-35	3.57E+00	4.00E-01	0.00E+00	1.56E-04	3.97E+00	1.60E-02
RL-W735	1.32E-07	0.00E+00	1.31E-35	2.78E+00	3.19E-01	0.00E+00	1.19E-04	3.10E+00	1.25E-02
RL-W736	1.45E-10	0.00E+00	2.79E-41	1.84E-03	2.20E-04	0.00E+00	2.54E-10	2.06E-03	8.32E-06
RL-W737	1.17E-07	0.00E+00	1.19E-35	2.64E+00	2.97E-01	0.00E+00	1.09E-04	2.93E+00	1.18E-02
RL-W738	4.38E-07	0.00E+00	4.10E-35	8.39E+00	1.03E+00	0.00E+00	3.73E-04	9.42E+00	3.80E-02
RL-W739	3.73E-08	0.00E+00	3.62E-36	1.36E+00	1.44E-01	0.00E+00	3.29E-05	1.51E+00	6.08E-03
RL-W740	1.87E-06	0.00E+00	1.33E-34	3.32E+01	4.00E+00	0.00E+00	1.21E-03	3.72E+01	1.50E-01

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
RL-W741	2.79E-06	0.00E+00	3.12E-34	6.46E+00	2.13E+00	0.00E+00	2.84E-03	8.59E+00	3.47E-02
RL-W742	1.24E-07	0.00E+00	9.39E-36	2.10E+00	2.29E-01	0.00E+00	8.55E-05	2.33E+00	9.38E-03
RL-W743	2.24E-10	0.00E+00	2.55E-39	1.36E-03	0.00E+00	0.00E+00	2.32E-08	1.36E-03	5.47E-06
RL-W744	0.00E+00	0.00E+00	0.00E+00	6.76E-02	2.67E-02	0.00E+00	0.00E+00	9.43E-02	3.80E-04
RL-W745	3.54E-10	0.00E+00	1.78E-38	1.31E-02	1.35E-03	0.00E+00	1.62E-07	1.45E-02	5.83E-05
RL-W746	1.36E-09	0.00E+00	6.86E-38	5.03E-02	5.21E-03	0.00E+00	6.25E-07	5.56E-02	2.24E-04
RL-W747	3.69E-09	0.00E+00	1.86E-37	1.36E-01	1.41E-02	0.00E+00	1.69E-06	1.50E-01	6.07E-04
RL-W748	2.58E-05	0.00E+00	5.21E-34	2.26E-01	1.72E-01	0.00E+00	4.75E-03	4.03E-01	1.63E-03
RL-W749	3.10E-08	0.00E+00	1.59E-36	1.18E+00	1.22E-01	0.00E+00	1.45E-05	1.31E+00	5.26E-03
RL-W750	3.92E-05	0.00E+00	7.90E-34	3.71E-01	2.81E-01	0.00E+00	7.19E-03	6.59E-01	2.66E-03
RL-W751	3.54E-05	0.00E+00	7.13E-34	3.33E-01	2.55E-01	0.00E+00	6.49E-03	5.95E-01	2.40E-03
RL-W752	1.54E-05	0.00E+00	3.10E-34	1.45E-01	1.11E-01	0.00E+00	2.82E-03	2.59E-01	1.04E-03
RL-W753	2.07E-04	0.00E+00	4.18E-33	1.96E+00	1.49E+00	0.00E+00	3.80E-02	3.48E+00	1.40E-02
RP-W754	8.78E-06	0.00E+00	5.29E-34	1.39E+03	5.28E+01	0.00E+00	3.48E-01	1.45E+03	5.83E+00
RP-W755	4.65E-05	0.00E+00	3.17E-34	1.04E+03	4.00E+01	0.00E+00	1.23E+01	1.09E+03	4.41E+00
SA-T001	9.35E-08	0.00E+00	7.59E-36	2.27E+00	6.22E-03	0.00E+00	7.36E-05	2.28E+00	9.18E-03
SA-W134	7.63E-07	0.00E+00	5.17E-35	1.03E+00	1.52E-01	0.00E+00	1.63E-01	1.35E+00	5.44E-03
SA-W134M	9.91E-08	0.00E+00	6.71E-36	1.35E-01	1.97E-02	0.00E+00	2.11E-02	1.76E-01	7.08E-04
T001-221F-HET	1.85E-04	0.00E+00	6.06E-30	2.16E+04	2.47E+02	0.00E+00	6.06E+01	2.19E+04	8.82E+01
T001-221H-HET	3.32E-04	0.00E+00	1.09E-29	3.90E+04	4.45E+02	0.00E+00	1.09E+02	3.95E+04	1.59E+02
T001-235F-HET	1.91E-05	0.00E+00	6.29E-31	2.24E+03	2.56E+01	0.00E+00	6.29E+00	2.27E+03	9.16E+00
T001-772F-HET	1.65E-04	0.00E+00	5.44E-30	1.93E+04	2.21E+02	0.00E+00	5.45E+01	1.96E+04	7.90E+01
T001-773A-CLAS	1.85E-06	0.00E+00	6.09E-32	2.17E+02	2.48E+00	0.00E+00	6.10E-01	2.20E+02	8.88E-01
T001-773A-HET	2.13E-05	0.00E+00	7.01E-31	2.50E+03	2.86E+01	0.00E+00	7.02E+00	2.54E+03	1.02E+01
W006-773A-VIT	2.86E-10	0.00E+00	0.00E+00	4.02E+02	0.00E+00	0.00E+00	0.00E+00	4.02E+02	1.62E+00
W026-221F-HET	6.42E-05	0.00E+00	2.11E-30	7.57E+03	8.60E+01	0.00E+00	2.11E+01	7.67E+03	3.09E+01
W026-221H-HET	4.81E-05	0.00E+00	1.58E-30	5.63E+03	6.42E+01	0.00E+00	1.58E+01	5.71E+03	2.30E+01
W026-235F-HET	7.48E-07	0.00E+00	2.46E-32	8.76E+01	1.00E+00	0.00E+00	2.46E-01	8.89E+01	3.58E-01
W026-772F-HET	2.05E-07	0.00E+00	6.71E-33	2.39E+01	2.73E-01	0.00E+00	6.71E-02	2.42E+01	9.77E-02
W026-773A-HET	3.32E-06	0.00E+00	1.09E-31	3.90E+02	4.45E+00	0.00E+00	1.09E+00	3.95E+02	1.59E+00
W027-221F-HET	2.43E-04	0.00E+00	7.13E-30	2.92E+04	3.33E+02	0.00E+00	8.22E+01	2.96E+04	1.20E+02

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
W027-221H-HET	1.06E-04	0.00E+00	3.11E-30	1.28E+04	1.46E+02	0.00E+00	3.59E+01	1.30E+04	5.24E+01
W027-235F-HET	3.19E-05	0.00E+00	9.35E-31	3.85E+03	4.38E+01	0.00E+00	1.08E+01	3.91E+03	1.57E+01
W027-772F-HET	5.80E-05	0.00E+00	1.70E-30	6.99E+03	7.97E+01	0.00E+00	1.96E+01	7.09E+03	2.86E+01
W027-773A-HET	8.65E-05	0.00E+00	2.54E-30	1.04E+04	1.19E+02	0.00E+00	2.93E+01	1.06E+04	4.26E+01
W027-999-HET	9.89E-05	0.00E+00	2.90E-30	1.19E+04	1.36E+02	0.00E+00	3.35E+01	1.21E+04	4.87E+01
W053-773A-VIT	0.00E+00	0.00E+00	0.00E+00	2.99E+02	0.00E+00	0.00E+00	0.00E+00	2.99E+02	1.21E+00
WP-INW169.001	4.83E-07	0.00E+00	1.83E-35	1.15E+01	1.19E+00	0.00E+00	3.27E-04	1.27E+01	5.13E-02
WP-INW198.001	6.36E-07	0.00E+00	3.19E-35	2.07E+01	2.11E+00	0.00E+00	3.70E-04	2.28E+01	9.19E-02
WP-INW211.001	7.16E-05	0.00E+00	2.99E-33	1.92E+03	1.96E+02	0.00E+00	2.92E-02	2.11E+03	8.52E+00
WP-INW216.001-	2.60E-03	0.00E+00	1.72E-33	1.11E+03	1.14E+02	0.00E+00	2.85E-01	1.22E+03	4.93E+00
WP-INW216.001-	7.15E-04	0.00E+00	4.64E-34	3.00E+02	3.07E+01	0.00E+00	3.11E-02	3.31E+02	1.34E+00
WP-INW218.001-	4.98E-05	0.00E+00	3.04E-34	1.93E+02	1.98E+01	0.00E+00	3.78E-01	2.13E+02	8.61E-01
WP-INW218.001-	2.29E-07	0.00E+00	8.36E-36	5.26E+00	5.39E-01	0.00E+00	3.64E-02	5.83E+00	2.35E-02
WP-INW222.001	2.35E-06	0.00E+00	9.01E-35	5.14E+01	5.32E+00	0.00E+00	1.38E-03	5.67E+01	2.29E-01
WP-INW243.001	5.71E-06	0.00E+00	1.94E-34	1.08E+02	1.12E+01	0.00E+00	2.61E-03	1.19E+02	4.80E-01
WP-INW247.001R	7.63E-06	0.00E+00	4.52E-34	2.07E+02	2.18E+01	0.00E+00	4.19E-03	2.29E+02	9.21E-01
WP-INW276.001	5.82E-07	0.00E+00	4.41E-35	2.05E+01	2.15E+00	0.00E+00	4.18E-04	2.26E+01	9.11E-02
WP-INW276.002	9.22E-07	0.00E+00	6.63E-35	3.00E+01	3.23E+00	0.00E+00	6.29E-04	3.33E+01	1.34E-01
WP-INW276.003	3.54E-05	0.00E+00	2.47E-33	1.12E+03	1.18E+02	0.00E+00	2.29E-02	1.23E+03	4.98E+00
WP-INW276.004	8.44E-06	0.00E+00	5.21E-34	2.36E+02	2.49E+01	0.00E+00	4.89E-03	2.61E+02	1.05E+00
WP-INW296.001-	3.09E-06	0.00E+00	1.24E-34	5.93E+01	6.21E+00	0.00E+00	1.16E-03	6.55E+01	2.64E-01
WP-INW296.001-	9.31E-06	0.00E+00	4.37E-34	2.10E+02	2.20E+01	0.00E+00	4.32E-03	2.32E+02	9.34E-01
WP-LA-TA-55-19	1.55E-07	0.00E+00	2.03E-35	1.57E+00	1.75E-01	0.00E+00	2.75E-03	1.74E+00	7.03E-03
WP-LA-TA-55-19	7.51E-06	0.00E+00	6.82E-34	1.60E+02	1.80E+01	0.00E+00	9.10E-02	1.78E+02	7.16E-01
WP-LA-TA-55-43	4.22E-08	0.00E+00	1.59E-32	2.42E-01	4.73E-02	0.00E+00	1.71E-01	4.60E-01	1.85E-03
WP-RF001.01	1.30E-05	0.00E+00	5.52E-34	3.07E+02	3.23E+01	0.00E+00	1.41E-02	3.40E+02	1.37E+00
WP-RF002.01-A	1.52E-05	0.00E+00	7.36E-34	3.46E+02	3.66E+01	0.00E+00	2.40E-02	3.83E+02	1.54E+00
WP-RF002.01-B	1.51E-08	0.00E+00	5.10E-37	3.75E-01	3.94E-02	0.00E+00	4.83E-06	4.14E-01	1.67E-03
WP-RF003.01	2.35E-04	0.00E+00	1.18E-32	6.61E+03	6.97E+02	0.00E+00	1.16E-01	7.31E+03	2.95E+01
WP-RF004.01	1.10E-07	0.00E+00	7.93E-36	3.81E+00	4.04E-01	0.00E+00	1.96E-04	4.22E+00	1.70E-02
WP-RF005.01	5.66E-04	0.00E+00	6.02E-33	3.50E+03	3.66E+02	0.00E+00	5.65E-02	3.86E+03	1.56E+01

Table PAR-60. Isotopes Activity, Total Activity and EPA Units for CH-TRU Waste Streams at Time 10,000 years — Continued

TRU Waste Stream	AM241 (Ci)	CM244 (Ci)Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci)Non-E	U234 (Ci)	Total EPA(Ci)	EPA Unit
WP-RF005.02	6.67E-04	0.00E+00	3.11E-33	2.09E+03	2.17E+02	0.00E+00	2.95E-02	2.31E+03	9.30E+00
WP-RF006.01	2.17E-04	0.00E+00	1.13E-32	5.95E+03	6.28E+02	0.00E+00	1.28E-01	6.58E+03	2.65E+01
WP-RF008.01	6.86E-05	0.00E+00	4.03E-33	1.74E+03	1.87E+02	0.00E+00	3.79E-02	1.93E+03	7.76E+00
WP-RF009.01	6.75E-03	0.00E+00	4.94E-32	3.81E+04	3.94E+03	0.00E+00	4.70E-01	4.21E+04	1.70E+02
WP-RF010.01	2.49E-06	0.00E+00	1.25E-34	5.76E+01	6.08E+00	0.00E+00	1.85E-03	6.37E+01	2.57E-01
WP-RF029.01-A	5.98E-07	0.00E+00	2.36E-35	1.01E+01	1.07E+00	0.00E+00	9.24E-04	1.12E+01	4.51E-02
WP-RF029.01-B	8.93E-07	0.00E+00	1.87E-35	8.02E+00	8.46E-01	0.00E+00	2.36E-03	8.86E+00	3.57E-02
WP-RF118.01	1.52E-03	0.00E+00	9.39E-32	3.85E+04	3.97E+03	0.00E+00	1.06E+00	4.25E+04	1.71E+02
WP-RLMPDT.001	3.22E-07	0.00E+00	2.74E-35	5.51E+00	6.63E-01	0.00E+00	2.52E-04	6.18E+00	2.49E-02
WP-RLNPDT.002	3.95E-06	0.00E+00	2.61E-34	5.42E+01	6.73E+00	0.00E+00	2.41E-03	6.09E+01	2.46E-01
WP-SR2001.001.	1.26E-07	0.00E+00	3.00E-35	5.12E+00	4.70E-01	0.00E+00	2.78E-04	5.59E+00	2.25E-02
WP-SR-W027-221	9.33E-07	0.00E+00	8.82E-35	1.47E+01	1.90E+00	0.00E+00	1.82E-01	1.68E+01	6.76E-02
Total	4.99E-02	0.00E+00	6.17E-29	4.95E+05	3.70E+04	0.00E+00	7.25E+02	5.32E+05	2.15E+03

Table PAR-61. Isotopes Activity, Total Activity and EPA Units for RH-TRU Waste Streams

Time	RH Total										
	AM241 (Ci)	CM244 (Ci) Non-E	PU238 (Ci)	PU239 (Ci)	PU240 (Ci)	PU241 (Ci) Non-E	U234 (Ci)	CS137 (Ci)	SR90 (Ci)	EPA (Ci)	EPA Unit
0 Years	1.58E+04	7.93E+01	2.80E+03	5.38E+03	1.68E+03	2.40E+04	2.20E+01	2.39E+05	1.15E+05	3.41E+01	6.10E+04
100 Years	1.41E+04	1.73E+00	1.27E+03	5.36E+03	1.66E+03	1.95E+02	2.25E+01	2.37E+04	1.06E+04	3.41E+01	2.59E+04
125 Years	1.36E+04	6.63E-01	1.04E+03	5.36E+03	1.65E+03	5.85E+01	2.26E+01	1.33E+04	5.86E+03	3.41E+01	2.36E+04
175 Years	1.25E+04	9.79E-02	7.04E+02	5.35E+03	1.64E+03	5.27E+00	2.27E+01	4.19E+03	1.78E+03	3.41E+01	2.09E+04
350 Years	9.46E+03	1.21E-04	1.77E+02	5.32E+03	1.61E+03	1.16E-03	2.29E+01	7.34E+01	2.77E+01	3.40E+01	1.66E+04
1000 Years	3.34E+03	1.89E-15	1.04E+00	5.22E+03	1.51E+03	2.98E-17	2.29E+01	2.21E-05	5.29E-06	3.40E+01	1.01E+04
3000 Years	1.35E+02	1.08E-48	1.43E-07	4.93E+03	1.22E+03	4.61E-59	2.28E+01	1.88E-25	1.12E-26	3.37E+01	6.34E+03
5000 Years	5.46E+00	6.15E-82	1.97E-14	4.65E+03	9.86E+02	0.00E+00	2.27E+01	1.61E-45	2.38E-47	3.34E+01	5.70E+03
7500 Years	9.92E-02	0.00E+00	5.22E-23	4.33E+03	7.56E+02	0.00E+00	2.25E+01	1.32E-70	3.42E-73	3.30E+01	5.14E+03
10000 Years	1.80E-03	0.00E+00	1.38E-31	4.03E+03	5.80E+02	0.00E+00	2.24E+01	0.00E+00	0.00E+00	3.26E+01	4.67E+03

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APPENDIX PA

ATTACHMENT PORSURF

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PORSURF.1 INTRODUCTION

Creep closure of the excavation and the presence of either brine or gas in the waste disposal region both influence time-dependent changes in void volume in the waste disposal area. As a consequence, these processes influence two-phase fluid flow of brine and gases through the waste and its capacity for storing fluids. For the performance assessment (PA), a porosity surface method is used to indirectly couple mechanical closure and gas generation with two-phase fluid flow calculations implemented in the BRAGFLO code (Appendix PA, Section PA 4.2). The porosity surface approach is used because current codes are not capable of fully coupling creep closure, waste consolidation, brine availability, and gas production and migration with computational efficiency. The porosity surface method incorporates the results of closure calculations obtained from the SANTOS code, a quasistatic, large deformation finite-element structural analysis code (Stone 1997). The adequacy of the method is documented in Freeze (1996), who concludes that the approximation is valid so long as the rate of room pressurization in final calculations is bounded by the room pressurization history that was used to develop the porosity surface.

The porosity surface used in the CRA-2004 PA is the same surface that was used for the CCA PA. Consequently, the models and parameters used to calculate this surface are unchanged from the CCA PA. For information on the porosity surface used in the CCA PA, see CCA Appendix PORSURF.

A separate analysis considered the potential effects on repository performance of uncertainty in the porosity surface (Appendix PA, Attachment MASS, Section MASS.2.0). Uncertainty in the porosity surface can arise from heterogeneity in the rigidity of waste packages, and from uncertain spatial arrangement of waste in the repository. The analysis considered four porosity surfaces, including the surface from the CCA, which represented various bounding combinations of waste package rigidity and waste initial porosity. The analysis concluded that uncertainty in porosity surface did not have significant effects on repository performance, and recommended the continued use of the CCA porosity surface in PA.

PORSURF.2 CREEP CLOSURE METHOD

Creep closure is accounted for in BRAGFLO by changing the porosity of the waste disposal area according to a table of porosity values, termed the porosity surface. The porosity surface is generated using the nonlinear finite element code, SANTOS. Disposal room porosity is calculated over time, varying the rate of gas generation and the gas production potential, to construct a three-dimensional porosity surface representing changes in porosity as a function of pressure and time over the 10,000-year simulation period.

The completed porosity surface is compiled in tabular form and is used in the solution of the gas and brine mass balance equations presented in Appendix PA Section PA-4.2.1. Porosity is interpolated from the porosity surface corresponding to the calculated gas pressure at time level t_n. The porosity surface is then accessed iteratively for the remainder of the simulation at the end of each BRAGFLO time step t_{n+1}. The closure data provided by SANTOS can be viewed as a series of surfaces, with any gas generation history computed by BRAGFLO constrained to fall

on this surface. Various techniques described in Freeze et al. (1995) were used to check the validity of this approach, and it was found to be a reasonable representation of the behavior observed in the complex models.

In SANTOS, gas pressure in the disposal room is computed from the ideal gas law by the following relationship:

$$p_g = \frac{NRT}{V},$$

where N is the mass of gas in moles at a given time, R is the universal gas constant (8.23 m^3 Pa/ mole °K), T is the absolute temperature in degrees Kelvin (constant at 300° K), and V is the current free volume of the room. The mass of gas is computed as

$$N = r(t, f) \times Ndrums \times t\ ,$$

where $r(t, f)$ is the gas generation rate (moles/drum/yr) at time t for the scaling factor f and Ndrums is the number of drums of waste in the room (6804 drums per room). The base gas generation rate in SANTOS is

$$r(t,1) = \begin{cases} 2\ mol/drum/yr & 0 \le t \le 550\ yr \\ 1\ mol/drum/yr & 550\ yr \le t \le 1050\ yr \\ 0\ mol/drum/yr & 1050\ yr \le t \end{cases}.$$

The base gas generation rate $r(t,1)$ is representative of relatively high gas production rates from both microbial degradation of cellulosic, plastic and rubber materials and from anoxic corrosion of Fe-base metals (Butcher 1997b). To provide a range of SANTOS results that spans the possible range of pressure computed by BRAGFLO, the gas generation rate is varied by the scaling factor f. Thirteen values of f are used to construct the porosity surface: f = 0.0, 0.025, 0.05, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1.0, 1.2, 1.6, and 2.0. The condition of f = 0 represents the state of the repository when no gas is produced; f = 2 represents twice the base gas generation rate. The gas generation rate for each case is computed by

$$r(t, f) = f \times r(t,1).$$

The gas generation potentials and rates used in SANTOS are not the same as are used in BRAGFLO, the PA model for two-phase flow in the repository (see Appendix PA, Section PA-4.2). In SANTOS, gas generation is included to introduce a range of values for gas pressure during room closure, thereby capturing the effects of gas pressure on room closure; the use of the scaling factor f ensures that SANTOS results span a wide range of possible gas generation rates and potentials. In contrast, the BRAGFLO code computes the amount of gas generated at each time step, using a stoichiometric model that accounts for the inventory of gas-generation substrates, the saturation of the waste material, and the uncertain parameters in the gas generation model.

PORSURF.3 CONCEPTUAL MODEL FOR POROSITY SURFACE

The ability of salt to deform with time, eliminate voids, and create an impermeable salt barrier around the waste was one of the principal reasons for locating the WIPP repository in a bedded salt formation. The creep closure process is a complex and interdependent series of events starting after a region within the repository is excavated. Immediately upon excavation, the equilibrium state of the rock surrounding the repository is disturbed, and the rock begins to deform and return to equilibrium. Eventually, at equilibrium, deformation ceases, and the waste region has undergone as much compaction as is possible under the prevailing lithostatic stress field.

Creep closure of the excavation begins immediately and causes the volume of the cavity to become smaller. If the room were empty, rather than partially filled with waste, closure would proceed to the point where the void volume created by the excavation would be eliminated and the surrounding halite would return to its undisturbed, uniform stress state. In a waste-filled room, the rock will contact the waste and the rate of closure will decrease as the waste compacts and stiffens; eventually, closure will cease when the waste can take the full overburden load without further deformation. Initially, unconsolidated waste can support only small loads, but as the room continues to close after contact with the waste, the waste will consolidate and support a greater portion of the weight of the overburden. Consolidation will continue until mechanical equilibrium is reached.

The presence of gas in the room will retard the closure process due to the build-up of pressure. As the waste consolidates, pore volume is reduced and pore pressure increases (using the ideal gas law). In this process, the waste can be considered to be a skeleton structure immersed in a pore fluid (the gas). As the pore pressure increases, less of the weight of the overburden is carried by the skeleton, and more support is provided by the gas. If the gas pressure increases to lithostatic pressure, the pore pressure alone is sufficient to support the overburden.

PORSURF.4 SANTOS NUMERICAL ANALYSES

Computation of repository creep closure is a particularly challenging structural engineering problem, because the rock surrounding the repository continually deforms with time until equilibrium is reached. Not only is the deformation of the salt inelastic, but it also involves larger deformations than are customarily addressed with conventional structural deformation codes. In addition, the formation surrounding the repository is not homogeneous in composition, containing various parting planes and interbeds with different properties than the salt.

Deformation of the waste is also nonlinear, with large strains, and the response of a waste-filled room is complicated by the presence of gas. These complex characteristics of the materials comprising the repository and its surroundings require the use of highly specialized constitutive models. Appropriate models have been built into the SANTOS code over a number of years. Principal components of the SANTOS model include:

1. Disposal Room Configuration and Idealized Stratigraphy. Disposal room dimensions, computational configuration, and idealized stratigraphy are defined in Attachment 1 to

CCA Appendix PORSURF. The idealized stratigraphy is reproduced in Figure PORSURF-1 of this Attachment.

2. Discretized Finite Element Model. A two-dimensional plane strain model, as shown in Figure PORSURF-2, is used for the SANTOS analyses. The discretized model represents the room as one of an infinite number of rooms located at the repository horizon. The model contains 1,680 quadrilateral uniform-strain elements and 1,805 nodal points. Contact surfaces between the stored waste and the surfaces of the room are addressed. Justification for this model and additional detail on initial and boundary conditions is provided in Attachment 1 to CCA Appendix PORSURF.

3. Geomechanical Model. Mechanical material response models and their corresponding property values are assigned to each region of the configuration. These models include:

   A. a combined transient-secondary creep constitutive model for clean and argillaceous halite;

   B. an inelastic constitutive model for anhydrite; and

   C. a volumetric plasticity model for waste.

   Material properties are provided in CCA Appendix PORSURF.

The results of the SANTOS calculations are illustrated in Figures PORSURF-3 and PORSURF-4. Figure PORSURF-3 shows disposal room porosity as a function of time for various values of the gas generation scaling factor f. Figure PORSURF-4 shows disposal room pressure as a function of time for various values of f. When f = 0, no gas is present in the disposal room, thus, disposal room pressure is identically zero for all times, and this pressure curve is omitted from Figure PORSURF-4.

PORSURF.5 IMPLEMENTATION OF POROSITY SURFACE IN BRAGFLO

As outlined in Section PORSURF.3, the SANTOS program is used to determine time-dependent porosities and pressures in the repository under different rates of gas generation determined by the scaling factor f. Calculation with each value of f results in the porosity and pressure curves in Figures PORSURF-3 and PORSURF-4.

The porosities calculated by SANTOS are defined relative to a dynamically changing excavated volume. In contrast, BRAGFLO assumes a fixed excavated volume, with the effects of closure accounted for by a dynamically changing porosity. The pressures in Figure PORSURF-4 are pressures calculated by SANTOS, as outlined above. However, the porosities in Figure PORSURF-3 are the porosities used in BRAGFLO and are obtained from the true porosities calculated by SANTOS by correcting for the repository closure. Specifically,

$$\phi_S V_S = \phi_B V_B ,$$

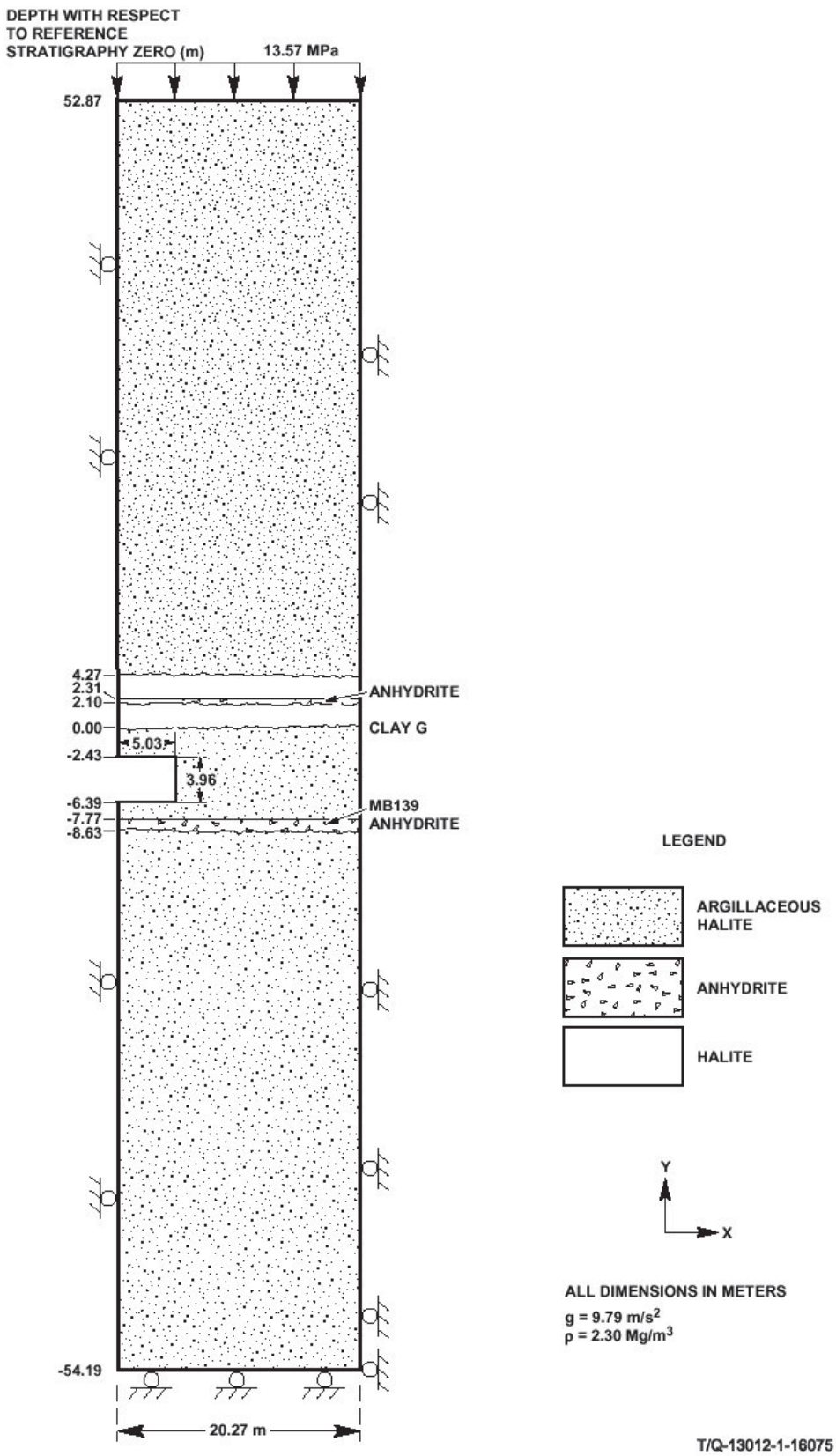

Figure PORSURF-1. Stratigraphy for the Porosity Surface Calculations.

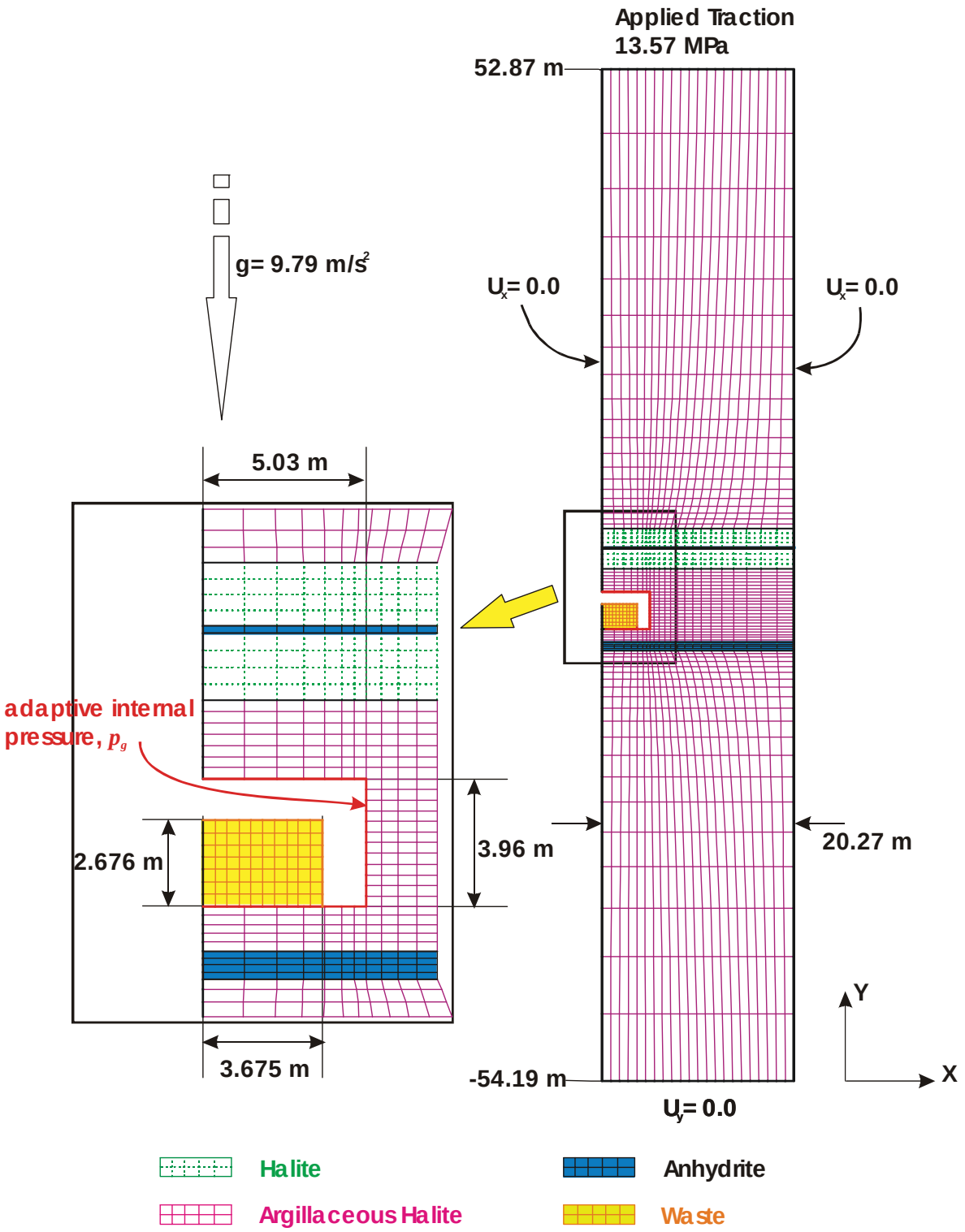

Figure PORSURF-2. Mesh Discretization and Boundary Conditions used for the Porosity Surface Calculations.

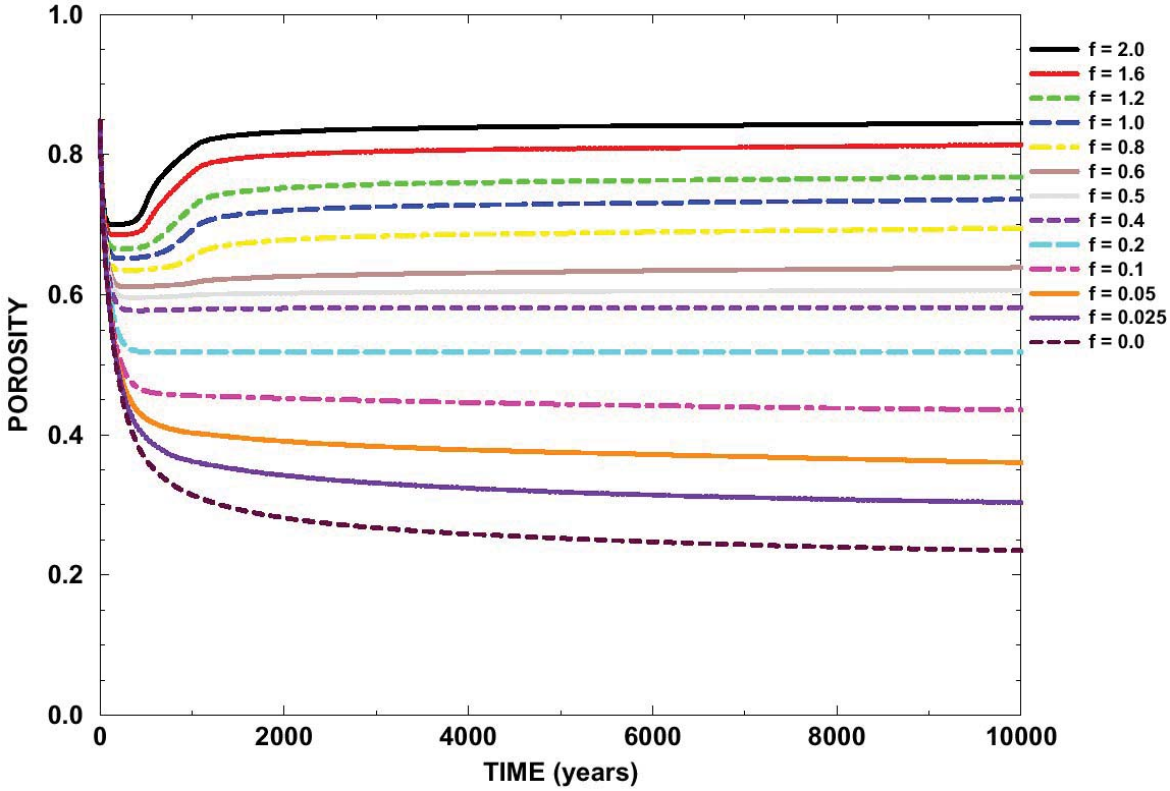

Figure PORSURF-3. Disposal Room Porosity for Various Values of the Scale Factor (f).

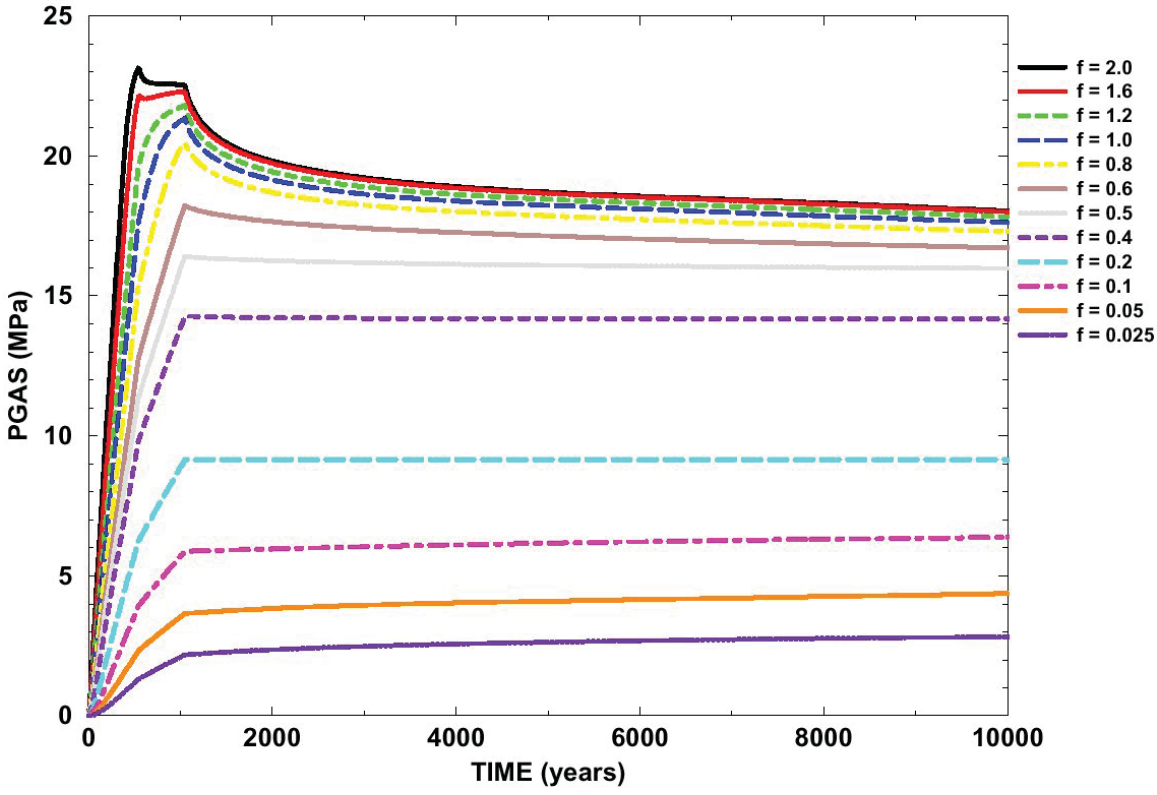

Figure PORSURF-4. Disposal Room Pressure for Various Values of the Scale Factor (f).

where ϕ_S and ϕ_B are the porosities associated with SANTOS and BRAGFLO and V_S and V_B are the total volume per excavated room as represented in SANTOS and BRAGFLO. Note that while V_S changes with time, V_B does not. This formulation conserves the total pore volume in the waste areas between SANTOS and BRAGFLO calculations.

Brine pressures $p_b(t)$ obtained in the waste disposal regions are used in conjunction with the results in Figures PORSURF-3 and PORSURF-4 to estimate porosity in the waste-filled regions for the BRAGFLO calculations. Given a value for $p_b(t)$, values f_1 and f_2 are determined such that

$$p(t, f_1) \le p_b(t) < p(t, f_2),$$

where $p(t, f_i)$ denotes the pressure (Pa) at time t obtained with gas generation rate $r_{f_i}(t)$. An f value associated with $p_b(t)$ is then given by

$$\hat{f} = f_1 + \left(\frac{p_b(t) - p(t, f_1)}{p(t, f_2) - p(t, f_1)} \right) (f_2 - f_1),$$

with $\hat{f}$ being estimated by linear interpolation on f_1 and f_2. With $\hat{f}$ determined, a corresponding porosity $\hat{\phi}$ for use with $p_b(t)$ is obtained from the porosity results in Figure PORSURF-3. Specifically,

$$\hat{\phi} = \phi(t, f_1) + \left(\frac{\hat{f} - f_1}{f_2 - f_1} \right) \left(\phi(t, f_2) - \phi(t, f_1) \right),$$

where $\phi(t, f_i)$ denotes the porosity at time t obtained with gas generation rate $r_{f_i}(t)$.

PORSURF.6 DYNAMIC CLOSURE OF THE NORTH-END AND HALLWAYS

The porosity surface method is not used to model the north end of the repository occupied by the experimental and operational regions. During development of the CCA PA, a supporting analysis compared brine and gas flow results for two models for closure of the north end of the repository: a dynamic closure model, and a baseline model, in which the porosity and permeability of these regions were held constant (Vaughn et al. 1995). The study examined the effect of these two approaches on brine releases to the accessible environment for both disturbed and undisturbed conditions, as well the effects on brine pressures and brine saturations in the modeled regions. The study concluded that the baseline case (assuming constant low porosity and high permeability) consistently led to either similar or more conservative brine pressures and brine saturations, thereby overestimating potential releases relative to the dynamic consolidation case. Consequently, PA uses the simplifying case of constant porosity and permeability in the northern end of the repository, rather than modeling dynamic closure of these areas.

PORSURF.7 ADDITIONAL INFORMATION

The following attachments were included in CCA Appendix PORSURF to document additional details of the porosity surface method:

1. Attachment 1 to Appendix PORSURF of the CCA, Proposed Model for the Final Porosity Surface Calculations. This memo documents preliminary configuration and constitutive property values for the final porosity surface calculations. Tables in the memo include elastic and creep properties for clean halite and argillaceous halite, volumetric strain data and material constants used in the volumetric-plasticity model for waste, and elastic and Drucker-Prager constants assigned to anhydrite Marker Bed 139. This attachment was supplemented and updated subsequent to the CCA by Butcher (1997a; 1997b).

2. Attachment 2 to Appendix PORSURF of the CCA, Baseline Inventory Assumptions for the Final Porosity Surface Calculations. This memo discusses the effect of changes in the Transuranic Waste Baseline Inventory Report (TWBIR) on the SANTOS analyses.

3. Attachment 3 to Appendix PORSURF of the CCA, Corrosion and Microbial Gas Generation Potentials. This memo discusses the rationale for the base gas production potentials of 1,050 moles/drum for corrosion and 550 moles/drum for microbial decay in the SANTOS analyses.

4. Attachment 4 to Appendix PORSURF of the CCA, Resolution of Remaining Issues for the Final Disposal Room Calculations. This memo provides additional detail on the disposal room elevation, determination of plastic constants for transuranic (TRU) waste, and determination of SANTOS input constants for clean halite, argillaceous halite, and anhydrite.

5. Attachment 5 to Appendix PORSURF of the CCA, Sample SANTOS Input File for Disposal Room Analysis. A representative sample input file is provided in this attachment. The only difference between this input file and the file used in the CCA calculations (see Stone 1997) is a subroutine modifying the gas generation variable.

6. Attachment 6 to Appendix PORSURF of the CCA, Final Porosity Surface Data. This attachment provides SANTOS results for selected gas generation scaling factors f = 2.0, f = 1.0, and f = 0.5. This attachment was updated and published as a formal SAND report (Stone 1997) subsequent to submittal of the CCA.

7. Attachment 7 to Appendix PORSURF of the CCA, SANTOS - A Two-Dimensional Finite Element Program for the Quasistatic, Large Deformation, Inelastic Response of Solids. This report provides documentation on the SANTOS code.

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APPENDIX PA

ATTACHMENT SCR

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ACRONYMS AND ABBREVIATIONS

AMWTP	Advanced Mixed Waste Treatment Plant
BNL	Brookhaven National Laboratory
CAG	Compliance Application Guidance
CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CDF	cumulative distribution function
CFR	Code of Federal Regulations
CH	contact-handled
CRA	Compliance Recertification Application
DBDSP	Delaware Basin Drilling Surveillance Program
DFR	driving force ratio
DOE	U.S. Department of Energy
DP	disturbed performance
DRZ	disturbed rock zone
EDTA	ethylene diamine tetra-acetate
EPA	Environmental Protection Agency
EP	event and process
ERMS	Electronic Record Management System
FEP	feature, event, and process
FGE	fissile gram equivalent
FLAC	Fast Lagranian Analysis of Continua
FMT	Fracture-Matrix Transport
FSU	Florida State University
H	human
HC	historical and current human activities
HCN	historic, current and near future human activities
LWA	Land Withdrawal Act
MB	marker bed
MgO	magnesium oxide
MPI	Mississippi Potash Inc.
N	natural
NMBMMR	New Mexico Bureau of Mines and Mineral Resources
NORM	naturally occurring radioactive material
PA	performance assessment
PAVT	performance assessment verification test
RH	remote-handled
RTC	Response to Comments Document
SKI	Statens Kärnkraftinspektion
SMC	Salado mass concrete
SNL	Sandia National Laboratories
SO-C	screened-out consequence
SO-P	screened-out probability
SO-R	screened-out regulatory
T	transmissitivity

TDS	total dissolved solids
TRU	transuranic
TSD	Technical Support Document
TWBIR	Transuranic Waste Baseline Inventory Report
UP	undisturbed performance
VOC	volatile organic compound
W	waste and repository-induced
WIPP	Waste Isolation Pilot Plant
WPO	WIPP Project Office

SCR-1.0 INTRODUCTION

The United States Department of Energy (DOE) has developed the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico for the disposal of transuranic wastes generated by defense programs. In May of 1998, the Environmental Protection Agency (EPA) certified that the WIPP would meet the disposal standards (EPA 1998a) established in Title 40 Code of Federal Regulations (CFR) Part 191, Subparts B and C (EPA 1993), thereby allowing the WIPP to begin waste disposal operations. This certification was based on performance assessment (PA) calculations that were included in the DOE's Compliance Certification Application (CCA). These calculations demonstrate that the cumulative releases of radionuclides to the accessible environment will not exceed those allowed by the EPA standard.

The WIPP Land Withdrawal Act (LWA) (U.S. Congress 1992) requires the WIPP to be recertified (demonstrate continued compliance with the disposal standards) every five years. As such, the DOE has prepared a Compliance Recertification Application (CRA-2004) which demonstrates that the WIPP continues to comply with EPA's requirements for radioactive waste disposal. The CRA-2004 includes any changes to the WIPP long-term compliance baseline since the CCA.

To assure that PA calculations account for important aspects of the disposal system, features, events, and processes (FEPs) considered to be potentially important to the disposal system are identified. These FEPs are used as a tool for determining what phenomena and components of the disposal system can and should be dealt with in PA calculations. For the WIPP CCA, a systematic process was used to compile, analyze, screen, and document FEPs for use in PA. The FEP screening process used in the CCA has also been used for the CRA-2004 and is described in detail in Section 6.2. For the CRA-2004, this process focused on evaluating any new information that may have impacts or present inconsistencies to those screening arguments and decisions presented in the CCA. Changes and updates as a result of this evaluation are described in the *FEPs Reassessment for Recertification Report* (Wagner et al. 2003).

Wagner et al. (2003) concluded that of the original 237 FEPs included in the CCA, 106 have not changed, 120 FEPs required updates to their FEP descriptions and/or screening arguments, and seven of the original baseline FEPs screening decisions required a change from their original screening decision. Four of the original baseline FEPs have been deleted or combined with other closely related FEPs. Finally, two new FEPs have been added to the baseline. These two FEPs were previously addressed in an existing FEP; they have been separated for clarity. Table SCR-1 summarizes the changes in the FEP baseline since the CCA.

Table SCR-1. FEPs Change Summary Since CCA

EPA FEP I.D.	FEP Name	Summary of Change
FEPs Combined with other FEPs		
N17	Lateral ***Dissolution***	Combined with N16, ***Shallow Dissolution.*** N17 removed from baseline.

Table SCR-1. FEPs Change Summary Since CCA - Continued

EPA FEP I.D.	FEP Name	Summary of Change
N19	***Solution Chimneys***	Combined with N20, *Breccia Pipes*. N19 removed from Baseline.
H33	***Flow Through Undetected Boreholes***	Combined with H31, *Natural Borehole Fluid Flow*. H33 removed from baseline.
W38	***Investigation Boreholes***	Addressed in H31, *Natural Borehole Fluid Flow*, and H33, *"Flow Through Undetected Boreholes."* W38 removed from baseline.
FEPs With Changed Screening Decisions		
W50	***Galvanic Coupling***	SO-P to SO-C
W68	***Organic Complexation***	SO-C to UP
W69	***Organic Ligands***	SO-C to UP
H27	***Liquid Waste Disposal***	SO-R to SO-C
H28	***Enhanced Oil and Gas Production***	SO-R to SO-C
H29	***Hydrocarbon Storage***	SO-R to SO-C
H41	***Surface Disruptions***	SO-C to UP (HCN)
New FEPs for CRA		
H58	***Solution Mining for Potash***	Separated from H13, *Potash Mining.*
H59	***Solution Mining for Other Resources***	Separated from H13, *Potash Mining.*

SCR-2.0 BASIS FOR FEATURES, EVENTS, AND PROCESSES SCREENING PROCESS

SCR-2.1 Requirement for Features, Events, and Processes

The origin of FEPs is related to the EPA's radioactive waste disposal standard's requirement to use PA methodology. The DOE was required to demonstrate that the WIPP complied with the Containment Requirements of 40 CFR § 191.13 (EPA 1993). These requirements state that the DOE must use PA to demonstrate that the probabilities of cumulative radionuclide releases from the disposal system during the 10,000 years following closure will fall below specified limits. The PA analyses supporting this determination must be quantitative and must consider uncertainties caused by all *Significant Processes and Events* that may affect the disposal system, including inadvertent human intrusion into the repository during the future. The scope of PA is further defined by EPA at 40 CFR § 194.32 (EPA 1996a), which states:

> Any compliance application(s) shall include information which:
>
> (1) Identifies all potential processes, events or sequences and combinations of processes and events that may occur during the regulatory time frame and may affect the disposal system;

(2) Identifies the processes, events or sequences and combinations of processes and events included in performance assessments; and

(3) Documents why any processes, events or sequences and combinations of processes and events identified pursuant to paragraph (e)(1) of this section were not included in performance assessment results provided in any compliance application.

Therefore, the PA methodology includes a process that compiles a comprehensive list of the FEPs that are relevant to disposal system performance. Those FEPs shown by screening analysis to have the potential to affect performance are represented in scenarios and quantitative calculations using a system of linked computer models to describe the interaction of the repository with the natural system, both with and without human intrusion. For the CCA, the DOE first compiled a comprehensive list of FEPs which was then subjected to a screening process that eventually lead to the set of FEPs used in PA to demonstrate WIPP's compliance with the long-term disposal standards.

SCR-2.2 Features, Events, and Processes List Development for the CCA

As a starting point, the DOE assembled a list of potentially relevant FEPs from the compilation developed by Stenhouse et al. (1993) for the Swedish Nuclear Power Inspectorate Statens Kärnkraftinspektion (SKI). The SKI list was based on a series of FEP lists developed for other disposal programs and is considered the best-documented and most comprehensive starting point for the WIPP. For the SKI study, an initial raw FEP list was compiled based on nine different FEP identification studies.

The compilers of the SKI list eliminated a number of FEPs as irrelevant to the particular disposal concept under consideration in Sweden. These FEPs were reinstated for the WIPP effort, and several FEPs on the SKI list were subdivided to facilitate screening for the WIPP. Finally, to ensure comprehensiveness, other FEPs specific to the WIPP were added based on review of key project documents and broad examination of the preliminary WIPP list by both project participants and stakeholders. The initial unedited list is contained in Appendix SCR, Attachment 1. The initial unedited FEP list was restructured and revised to derive the comprehensive WIPP FEP list used in the CCA. The number of FEPs was reduced to 237 in the CCA to avoid the ambiguities caused by the use of a generic list. Restructuring the list did not remove any substantive issues from the discussion. As discussed in more detail in Attachment 1, the following steps were used to reduce the initial unedited list to the appropriate WIPP FEP list used in the CCA.

- References to subsystems were eliminated because the SKI subsystem classification was not appropriate for the WIPP disposal concept. For example, in contrast to the Swedish disposal concept, canister integrity does not have a role in post-operational performance of the WIPP, and the terms near-field, far-field, and biosphere are not unequivocally defined for the WIPP site.

- Duplicate FEPs were eliminated. Duplicate FEPs arose in the SKI list because individual FEPs could act in different subsystems. FEPs had a single entry in the CCA list whether they were applicable to several parts of the disposal system or to a single part only, for

example, the FEP ***Gas Effects***. Disruption appears in the seals, backfill, waste, canister, and near-field subsystems in the initial FEP list. These FEPs are represented by the single FEP, ***Disruption Due to Gas Effects***.

- FEPs that are not relevant to the WIPP design or inventory were eliminated. Examples include FEPs related to high-level waste, copper canisters, and bentonite backfill.

- FEPs relating to engineering design changes were eliminated because they were not relevant to a compliance application based on the DOE's design for the WIPP. Examples of such FEPs are ***Design Modifications: Canister and Design Modification: Geometry***.

- FEPs relating to constructional, operational, and decommissioning errors were eliminated. The DOE has administrative and quality control procedures to ensure that the facility will be constructed, operated, and decommissioned properly.

- Detailed FEPs relating to processes in the surface environment were aggregated into a small number of generalized FEPs. For example, the SKI list includes the biosphere FEPs ***Inhalation of Salt Particles***, ***Smoking***, ***Showers and Humidifiers***, ***Inhalation and Biotic Material***, ***Household Dust and Fumes***, ***Deposition (Wet and Dry***), ***Inhalation and Soils and Sediments***, ***Inhalation and Gases and Vapors (Indoor and Outdoor***), and ***Suspension in Air***, which are represented by the FEP ***Inhalation***.

- FEPs relating to the containment of hazardous metals, volatile organic compounds (VOCs), and other chemicals that are not regulated by 40 CFR Part 191 were not included.

- A few FEPs have been renamed to be consistent with terms used to describe specific WIPP processes (for example, ***Wicking***, ***Brine Inflow***).

These steps resulted in a list of 237 WIPP-relevant FEPs retained for further consideration in the first certification PA. The 237 were screened to determine which would be included in the PA models and scenarios for the CCA.

SCR-2.3 Criteria for Screening of Features, Events, and Processes and Categorization of Retained Features, Events, and Processes

The purpose of FEP screening is to identify those FEPs that should be accounted for in PA calculations, and those FEPs that need not be considered further. The DOE's process of removing FEPs from consideration in PA calculations involved the structured application of explicit screening criteria. The criteria used to screen out FEPs are explicit regulatory exclusions (SO-R), probability (SO-P), or consequence (SO-C). All three criteria are derived from regulatory requirements. FEPs not screened as SO-R, SO-P, or SO-C were retained for inclusion in PA calculations and are classified as either undisturbed performance (UP) or disturbed performance (DP) FEPs.

SCR-2.3.1 Regulation (SO-R)

Specific FEP screening criteria are stated in 40 CFR Part 191 and Part 194. Such screening criteria relating to the applicability of particular FEPs represent screening decisions made by the EPA. That is, in the process of developing and demonstrating the feasibility of the 40 CFR Part 191 standard and the 40 CFR Part 194 criteria, the EPA considered and made conclusions on the relevance, consequence, and/or probability of occurrence of particular FEPs. In so doing, it allowed some FEPs to be eliminated from consideration.

SCR-2.3.2 Probability of Occurrence of a Feature, Event, and Process Leading to Significant Release of Radionuclides (SO-P)

Low-probability events can be excluded on the basis of the criterion provided in 40 CFR § 194.32(d), which states, "performance assessments need not consider processes and events that have less than one chance in 10,000 of occurring over 10,000 years" (EPA 1996a). In practice, for most FEPs screened out on the basis of low probability of occurrence, it has not been possible to estimate a meaningful quantitative probability. In the absence of quantitative probability estimates, a qualitative argument was used.

SCR-2.3.3 Potential Consequences Associated with the Occurrence of the Features, Events, and Processes (SO-C)

The DOE recognizes two uses for this criterion:

1. FEPs can be eliminated from PA calculations on the basis of insignificant consequence. Consequence can refer to effects on the repository or site or to radiological consequence. In particular, 40 CFR § 194.34(a) states: "The results of performance assessments shall be assembled into 'complementary, cumulative distribution functions' (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events" (EPA 1996a). The DOE has omitted events and processes from PA calculations where there is a reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed by such omissions.

2. FEPs that are potentially beneficial to subsystem performance may be eliminated from PA calculations if necessary to simplify the analysis. This argument may be used when there is uncertainty as to exactly how the FEP should be incorporated into assessment calculations or when incorporation would incur unreasonable difficulties.

In some cases, the effects of the occurrence of a particular event or process, although not necessarily insignificant, can be shown to lie within the range of uncertainty of another FEP already accounted for in the PA calculations. In such cases, the event or process may be considered to be included in PA calculations implicitly, within the range of uncertainty associated with the included FEP.

Although some FEPs could be eliminated from PA calculations on the basis of more than one criterion, the most practical screening criterion was used for classification. In particular, a regulatory screening classification was used in preference to a probability or consequence

screening classification. FEPs that have not been screened out based on any of the three criteria were included in the PA.

SCR-2.3.4 Undisturbed Performance (UP) Features, Events, and Processes

FEPs classified as UP are accounted for in calculations of undisturbed performance of the disposal system. Undisturbed performance is defined in 40 CFR § 191.12 as "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events" (EPA 1993). The UP FEPs are accounted for in the PA calculations to evaluate compliance with the Containment Requirements in 40 CFR § 191.13. Undisturbed PA calculations are also used to demonstrate compliance with the individual and groundwater protection requirements of 40 CFR § 191.15 and 40 CFR 191 Subpart C, respectively.

SCR-2.3.5 Disturbed Performance (DP) Features, Events, and Processes

The FEPs classified as DP are accounted for only in assessment calculations for disturbed performance. The DP FEPs that remain following the screening process relate to the potential disruptive effects of future drilling and mining events in the controlled area. Consideration of both DP and UP FEPs is required to evaluate compliance with 40 CFR § 191.13.

SCR-2.4 Features, Events, and Processes Categories and Timeframes

In the following sections, FEPs are discussed under the categories Natural (N) FEPs, Human-Initiated (H) Events and Processes (EPs), and Waste- and Repository-Induced (W) FEPs. The FEPs are also considered within time frames during which they may occur. Due to the regulatory requirements concerning human activities, two time periods were used when evaluating Human-Initiated EPs. These timeframes were defined as Historical, Current, and Near-Future Human Activities (HCN) and Future Human Activities (Future). These time frames are also discussed in the following section.

SCR-2.4.1 Description of Natural Features, Events, and Processes

Natural FEPs are those that relate to hydrologic, geologic, and climate conditions that have the potential to affect long-term performance of the WIPP disposal system over the regulatory timeframe. These FEPs do not include the impacts of other human related activities such as the effect of boreholes on FEPs related to natural changes in groundwater chemistry. Only natural events and processes are included within the screening process.

Consistent with 40 CFR § 194.32(d), the DOE has screened out several natural FEPs from PA calculations on the basis of a low probability of occurrence at or near the WIPP site. In particular, natural events for which there is no evidence indicating that they have occurred within the Delaware Basin have been screened on this basis. For FEPs analysis, the probabilities of occurrence of these events are assumed to be zero. Quantitative, nonzero probabilities for such events, based on numbers of occurrences, cannot be ascribed without considering regions much larger than the Delaware Basin, thus neglecting established geological understanding of the events and processes that occur within particular geographical provinces.

In considering the overall geological setting of the Delaware Basin, the DOE has eliminated many FEPs from PA calculations on the basis of low consequence. Events and processes that have had little effect on the characteristics of the region in the past are expected to be of low consequence for the regulatory time period.

SCR-2.4.2 Description of Human-Initiated Events and Processes

Human-Initiated EPs (Human EPs) are those associated with human activities in the past, present, and future. The EPA provided guidance in their regulations concerning which human activities are to be considered, the severity, and the manner in which to include them in the future predictions.

The scope of PAs is clarified with respect to human-initiated events and processes in 40 CFR § 194.32. At 40 CFR § 194.32(a), the EPA states:

> Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.

Thus, PAs must include consideration of human EPs relating to mining and drilling activities that might take place during the regulatory time frame. In particular, PAs must consider the potential effects of such activities that might take place within the controlled area at a time when institutional controls cannot be assumed to completely eliminate the possibility of human intrusion.

Further criteria concerning the scope of PAs are provided at 40 CFR § 194.32(c):

> Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

In order to implement the criteria in 40 CFR § 194.32 relating to the scope of PAs, the DOE has divided human activities into three categories: (1) human activities that are currently taking place and those that took place prior to the time of the compliance application; (2) human activities that might be initiated in the near future after submission of the compliance application; and (3) human activities that might be initiated after repository closure. The first two categories of EPs are considered under undisturbed performance, and EPs in the third category lead to disturbed performance conditions. A description of these three categories follows.

1. Historical and current human activities (HC) include resource extraction activities that have historically taken place and are currently taking place outside the controlled area. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. Current human activities taking place within the controlled area are essentially those associated with development of the WIPP repository. Historic human activities include existing boreholes.

2. Near-future human activities include resource extraction activities that may be expected to occur outside the controlled area based on existing plans and leases. Thus, the near future includes the expected lives of existing mines and oil and gas fields, and the expected lives of new mines and oil and gas fields that the DOE expects will be developed based on existing plans and leases. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. The only human activities that are expected to occur within the controlled area in the near future are those associated with development of the WIPP repository. The DOE expects that any activity initiated in the near future, based on existing plans and leases, will be initiated prior to repository closure. Activities initiated prior to repository closure are assumed to continue until their completion.

3. Future human activities include activities that might be initiated within or outside the controlled area after repository closure. This includes drilling and mining for resources within the disposal system at a time when institutional controls cannot be assumed to completely eliminate the possibility of such activities. Future human activities could influence the transport of contaminants within and outside the disposal system by directly removing waste from the disposal system or altering the geological, hydrological, or geochemical characteristics of the disposal system.

SCR-2.4.2.1 Scope of Future Human Activities in Performance Assessment

Performance assessments must consider the effects of future human activities on the performance of the disposal system. The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), which limits the scope of consideration of future human actions in PAs to mining and drilling.

SCR-2.4.2.1.1 Criteria Concerning Future Mining

The EPA provides the following additional criteria concerning the type of future mining that should be considered by the DOE in 40 CFR § 194.32(b):

> Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.

Thus, consideration of future mining may be limited to mining within the controlled area at the locations of resources that are similar in quality and type to those currently extracted from the Delaware Basin. Potash is the only resource that has been identified within the controlled area in quality similar to that currently mined from underground deposits elsewhere in the Delaware Basin. The hydrogeological impacts of future potash mining within the controlled area are accounted for in calculations of the disturbed performance of the disposal system. Consistent

with 40 CFR § 194.32(b), all economically recoverable resources in the vicinity of the disposal system (outside the controlled area) are assumed to be extracted in the near future.

SCR-2.4.2.1.2 Criteria Concerning Future Drilling

With respect to consideration of future drilling, in the preamble to 40 CFR Part 194, the EPA

> …reasoned that while the resources drilled for today may not be the same as those drilled for in the future, the present rates at which these boreholes are drilled can nonetheless provide an estimate of the future rate at which boreholes will be drilled.

Criteria concerning the consideration of future deep and shallow drilling in PAs are provided in 40 CFR § 194.33. The EPA also provides a criterion in 40 CFR § 194.33(d) concerning the use of future boreholes subsequent to drilling.

> With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

Thus, PAs need not consider the effects of techniques used for resource extraction and recovery that would occur subsequent to the drilling of a borehole in the future. Theses activities are screened SO-R.

The EPA provides an additional criterion that limits the severity of human intrusion scenarios that must be considered in PAs. In 40 CFR § 194.33(b)(1) the EPA states that:

> Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario.

SCR-2.4.2.1.3 Screening of Future Human Event and Processes

Future Human EPs accounted for in PA calculations for the WIPP are those associated with mining and deep drilling within the controlled area at a time when institutional controls cannot be assumed to eliminate completely the possibility of such activities. All other future Human EPs, if not eliminated from PA calculations based on regulation, have been eliminated based on low consequence or low probability. For example, the effects of future shallow drilling within the controlled area were eliminated from CCA PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-2.4.3 Description of Waste- and Repository-Induced Features, Events, and Processes

The waste- and repository-induced FEPs are those that relate specifically to the waste material, waste containers, shaft seals, MgO backfill, panel closures, repository structures, and investigation boreholes. All FEPs related to radionuclide chemistry and radionuclide migration are included in this category. The FEPs related to radionuclide transport resulting from future borehole intersections of the WIPP excavation are defined as waste- and repository-induced FEPs.

SCR-3.0 FEATURES, EVENTS, AND PROCESSES BASELINE FOR RECERTIFICATION

The reassessment of FEPs (Wagner et al. 2003) results in a new FEPs baseline for CRA-2004. As discussed in Section SCR.1, 106 of the original 237 WIPP FEPs have not changed. Additionally, 120 FEPs required updates to their FEP descriptions and/or screening arguments. Seven of the original baseline FEPs screening decisions have changed from their original screening decision. Four of the original baseline FEPs have been deleted or combined with other closely related FEPs. Finally, two new FEPs have been added to the baseline. These two FEPs were previously accounted for in a broader FEP. Table SCR-2 outlines the results of the assessment, and subsequent sections of this document present the actual screening decisions and supporting arguments. Those FEPs not separated by gridlines in the first column of Table SCR-2 have been addressed by group, due to close similarity with other FEPs within that group. This grouping process was formerly used in the CCA, and also by the EPA in their Technical Support Document (TSD) for §194.32 (EPA 1998c).

Table SCR-2. FEPs Reassessment Results

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N1	***Stratigraphy***	No	No change	UP
N2	***Brine Reservoirs***	No	No change	DP
N3	***Changes in Regional Stress***	No	Additional information added to FEP text, no change to italicized text.	SO-C
N4	***Regional Tectonics***	No	Additional information added to FEP text, no change to italicized text.	SO-C
N5	***Regional Uplift and Subsidence***	No	Additional information added to FEP text, no change to italicized text.	SO-C
N6	***Salt Deformation***	No	No change	SO-P
N7	***Diapirism***	No	No change	SO-P
N8	***Formation of Fractures***	No	Original FEP text revised and replaced, reference to other FEP removed from italicized text	SO-P UP (Repository)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N9	***Changes in Fracture Properties***	No	Original FEP text revised and replaced, reference to other FEP removed from italicized text	SO-C UP (Near Repository)
N10	***Formation of New Faults***	No	Additional information added to FEP text, no change to italicized text.	SO-P
N11	***Fault Movement***	No	Additional information added to FEP text, no change to italicized text.	SO-P
N12	***Seismic Activity***	No	No change	UP
N13	***Volcanic Activity***	No	Italicized text changed, FEP text unchanged	SO-P
N14	***Magmatic Activity***	No	No changes	SO-C
N15	***Metamorphic Activity***	No	No changes	SO-P
N16	***Shallow Dissolution***	No	N16 and N17 (***Lateral Dissolution***) combined, N17 deleted from baseline. FEP text modified and additional information added.	UP
N17	***Lateral Dissolution***	No	Combined with N16 (***Shallow Dissolution***) - Deleted from baseline – see N16	NA
N19	***Solution Chimneys***	No	Combined with N20 and deleted from baseline	NA
N18	***Deep Dissolution***	No	Both italicized and FEP text revised.	SO-P
N20	***Breccia Pipes***	No	N20 and N19 (***Solution Chimneys***) combined, Both italicized and FEP text revised.	SO-P
N21	***Collapse Breccias***	No	Both italicized and FEP text revised.	SO-P

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N22	***Fracture Infills***	No	No changes	SO-C - Beneficial
N23	***Saturated Groundwater Flow***	No	No change	UP
N24	***Unsaturated Groundwater Flow***	No	No change	UP SO-C in Culebra
N25	***Fracture Flow***	No	No change	UP
N27	***Effects of Preferential Pathways***	No	No change	UP UP in Salado and Culebra
N26	***Density effects on Groundwater Flow***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N28	***Thermal effects on Groundwater Flow***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N29	***Saline Intrusion [Hydrogeological Effects]***	No	Reference to other FEPs removed from the italicized text. FEP text unchanged.	SO-P
N30	***Freshwater Intrusion [Hydrogeological effects]***	No	Reference to other FEPs removed from the italicized text. FEP text unchanged.	SO-P
N31	***Hydrological Response to Earthquakes***	No	Reference to other FEPs removed from the italicized text. FEP text unchanged.	SO-C
N32	***Natural Gas Intrusion***	No	Reference to other FEPs removed from the italicized text. FEP text unchanged.	SO-P
N33	***Groundwater Geochemistry***	No	No change	UP
N34	***Saline Intrusion (Geochemical Effects)***	No	FEP N34 and N38 described together. Screening Argument revised and replaced, italicized text revised to remove reference to other FEPs	SO-C

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N38	***Effects of Dissolution***	No	FEP N34 and N38 are described together. Screening Argument revised and replaced, italicized text revised to remove reference to other FEPs	SO-C
N35	***Freshwater Intrusion (Geochemical Effects)***	No	FEP N35, N36 and N37 are described together. Screening Argument revised and replaced, italicized text revised to remove reference to other FEPs	SO-C
N36	***Changes in Groundwater Eh***	No	FEP N35, N36 and N37 are described together. Screening Argument revised and replaced, italicized text revised to remove reference to other FEPs	SO-C
N37	***Changes in Groundwater pH***	No	FEP N35, N36 and N37 are described together. Screening Argument revised and replaced, italicized text revised to remove reference to other FEPs	SO-C
N39	***Physiography***	No	No change	UP
N40	***Impact of a Large Meteorite***	No	No change	SO-P
N41	***Mechanical Weathering***	No	No change	SO-C
N42	***Chemical Weathering***	No	No change	SO-C
N43	***Aeolian Erosion***	No	No change	SO-C
N44	***Fluvial Erosion***	No	No change	SO-C
N45	***Mass Wasting [Erosion]***	No	No change	SO-C
N46	***Aeolian Deposition***	No	No change	SO-C
N47	***Fluvial Deposition***	No	No change	SO-C
N48	***Lacustrine Deposition***	No	No change	SO-C
N49	***Mass Wasting [Deposition]***	No	No change	SO-C

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N50	***Soil Development***	No	Clarification text added to the FEP text	SO-C
N51	***Stream and River Flow***	No	No change	SO-C
N52	***Surface Water Bodies***	No	No change	SO-C
N53	***Groundwater Discharge***	No	No change	UP
N54	***Groundwater Recharge***	No	No change	UP
N55	***Infiltration***	No	No change	UP
N56	***Changes in Groundwater Recharge and Discharge***	No	No change	UP
N57	***Lake Formation***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N58	***River Flooding***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N59	***Precipitation (e.g. Rainfall)***	No	No change	UP
N60	***Temperature***	No	No change	UP
N61	***Climate Change***	No	No change	UP
N62	***Glaciation***	No	No change	SO-P
N63	***Permafrost***	No	No change	SO-P
N64	***Seas and Oceans***	No	No change	SO-C
N65	***Estuaries***	No	No change	SO-C
N66	***Coastal Erosion***	No	No change	SO-C
N67	***Marine Sediment Transport and Deposition***	No	No change	SO-C
N68	***Sea Level Changes***	No	No change	SO-C
N69	***Plants***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N70	***Animals***	No	Reference to other FEPs removed from FEP and italicized text	SO-C
N71	***Microbes***	No	Additional information added to FEP text, reference to other FEPs removed from italicized text.	SO-C (UP - for colloidal effects and gas generation)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N72	***Natural Ecological Deevelopment***	No	No change	SO-C
W1	***Disposal Geometry***	No	No change	UP
W2	***Waste Inventory***	No	No change	UP
W3	***Heterogeneity of Waste Forms***	No	No change	DP
W4	***Container Form***	No	Both italicized and FEP text revised	SO-C
W5	***Container Material Inventory***	No	No change	UP
W6	***Seal Geometry***	No	No change	UP
W7	***Seal Physical Properties***	No	No change	UP
W8	***Seal Chemical Composition***	No	Both italicized and FEP text revised	SO-C Beneficial SO-C
W9	***Backfill Physical Properties***	No	Both italicized and FEP text revised	SO-C
W10	***Backfill Chemical Composition***	No	No change	UP
W11	***Post-Closure Monitoring***	No	Additional information added to FEP text.	SO-C
W12	***Radionuclide Decay and In-Growth***	No	No change	UP
W13	***Heat from Radioactive Decay***	No	No change to Italicized text, new concluding paragraph added to FEP text.	SO-C
W14	***Nuclear Criticality: Heat***	No	No change to Italicized text, additional information added to FEP text.	SO-P
W15	***Radiological Effects on Waste***	No	No change to Italicized text, FEP text revised.	SO-C
W16	***Radiological Effects on Containers***	No	No change to Italicized text, FEP text revised.	SO-C
W17	***Radiological Effects on Seals***	No	No change	SO-C
W18	***Disturbed Rock Zone (DRZ)***	No	No change	UP

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W19	***Excavation-Induced Changes in Stress***	No	No change	UP
W20	***Salt Creep***	No	No change	UP
W21	***Changes in the Stress Field***	No	No change	UP
W22	***Roof Falls***	No	No change	UP
W23	***Subsidence***	No	Minor changes to FEPs text, no changes to italicized text.	SO-C
W24	***Large Scale Rock Fracturing***	No	Minor changes to FEPs text, no changes to italicized text.	SO-P
W25	***Disruption Due to Gas Effects***	No	No change	UP
W26	***Pressurization***	No	No change	UP
W27	***Gas Explosions***	No	No change	UP
W28	***Nuclear Explosions***	No	Reference to other FEPs removed from italicized text, FEP text revised.	SO-P
W29	***Thermal Effects on Material Properties***	No	Additional information added to FEP text, grouped with similar FEPs; italicized text unchanged	SO-C
W30	***Thermally-Induced Stress Changes***	No	Additional information added to FEP text, grouped with similar FEPs; italicized text unchanged	SO-C
W31	***Differing Thermal Expansion of Repository Components***	No	Additional information added to FEP text, grouped with similar FEPs; italicized text unchanged	SO-C
W72	***Exothermic Reactions***	No	Additional information added to FEP text, grouped with similar FEPs; italicized text unchanged	SO-C

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W73	***Concrete Hydration***	No	Additional information added to FEP text, grouped with similar FEPs; italicized text unchanged	SO-C
W32	***Consolidation of Waste***	No	No change	UP
W36	***Consolidation of Seals***	No	No change	UP
W37	***Mechanical Degradation of Seals***	No	No change	UP
W39	***Underground Boreholes***	No	No change	UP
W33	***Movement of Containers***	No	Reference to other FEPs removed from italicized text, FEP text revised	SO-C
W34	***Container Integrity***	No	Reference to other FEPs removed from italicized text, FEP text revised	SO-C Beneficial
W35	***Mechanical Effects of Backfill***	No	Both italicized and FEP text revised.	SO-C
W38	***Investigation Boreholes***	Yes	Encompassed in FEPS H31 and W33, FEP H38 deleted from baseline.	NA
W40	***Brine Inflow***	No	No change	UP
W41	***Wicking***	No	No change	UP
W42	***Fluid Flow Due to Gas Production***	No	No change	UP
W43	***Convection***	No	Reference to other FEPs removed from italicized text, FEP text revised	SO-C
W44	***Degradation of Organic Material***	No	No change	UP
W45	***Effects of Temperature on Microbial Gas Generation***	No	No change	UP
W48	***Effects of Biofilms on Microbial Gas Generation***	No	No change	UP
W46	***Effects of Pressure on Microbial Gas Generation***	No	Reference to other FEPs removed from italicized text, FEP text revised	SO-C

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W47	***Effects of Radiation on Microbial Gas Generation***	No	Reference to other FEPs removed from italicized text, FEP text revised	SO-C
W49	***Gases from Metal Corrosion***	No	No change	UP
W51	***Chemical Effects of Corrosion***	No	No change	UP
W50	***Galvanic Coupling (Within the Repository)***	Yes	Decision changed from SO-P to SO-C. Both italicized and FEP text revised.	SO-C
W52	***Radiolysis of Brine***	No	Both italicized and FEP text revised.	SO-C
W53	***Radiolysis of Cellulose***	No	FEP text revised	SO-C
W54	***Helium Gas Production***	No	Both italicized and FEP text revised.	SO-C
W55	***Radioactive Gases***	No	Reference to other FEPs removed from italicized text, no change to FEP text	SO-C
W56	***Speciation***	No	No change	UP UP in disposal rooms and Culebra. SO-C elsewhere, and beneficial SO-C in cementitious seals
W57	***Kinetics of Speciation***	No	Both italicized and FEP text revised.	SO-C
W58	***Dissolution of Waste***	No	No change	UP
W59	***Precipitation of Secondary Minerals***	No	Both italicized and FEP text revised.	SO-C-Beneficial
W60	***Kinetics of Precipitation and Dissolution***	No	Both italicized and FEP text revised.	SO-C
W61	***Actinide Sorption***	No	No change	UP
W62	***Kinetics of Sorption***	No	No change	UP
W63	***Changes in Sorptive Surfaces***	No	No change	UP
W64	***Effects of Metal Corrosion***	No	No change	UP
W65	***Reduction-Oxidation Fronts***	No	Reference to other FEPs removed from FEP and italicized text	SO-P

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W66	***Reduction-Oxidation Kinetics***	No	No change	UP
W67	***Localized Reducing Zones***	No	Changes to FEPs text, no changes to italicized text.	SO-C
W68	***Organic Complexation***	Yes	Decision changed from SO-C to UP. Both italicized and FEP text revised.	UP
W69	***Organic Ligands***	Yes	Decision changed from SO-C to UP. Both italicized and FEP text revised.	UP
W71	***Kinetics of Organic Complexation***	No	Both italicized and FEP text revised.	SO-C
W70	***Humic and Flvic Acids***	No	No change	UP
W74	***Chemical Degradation of Seals***	No	No change	UP
W76	***Microbial Growth on Concrete***	No	No change	UP
W75	***Chemical Degradation of Backfill***	No	FEP text unchanged, reference to other FEPs removed from FEP and italicized text	SO-C
W77	***Solute Transport***	No	No change	UP
W78	***Colloid Transport***	No	No change	UP
W79	***Colloid Formation and Stability***	No	No change	UP
W80	***Colloid Filtration***	No	No change	UP
W81	***Colloid Sorption***	No	No change	UP
W82	***Suspensions of Particles***	No	No change	DP
W83	***Rinse***	No	No change	SO-C
W84	***Cuttings***	No	No change	DP
W85	***Cavings***	No	No change	DP
W86	***Spallings***	No	No change	DP
W87	***Microbial Transport***	No	No change	UP
W88	***Biofilms***	No	Both italicized and FEP text revised.	SO-C Beneficial

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W89	***Transport of Radioactive Gases***	No	No change to Italicized text, additional information added to FEP text.	SO-C
W90	***Advection***	No	No change	UP
W91	***Diffusion***	No	No change	UP
W92	***Matrix Diffusion***	No	No change	UP
W93	***Soret Effect***	No	No changes	SO-C
W94	***Electrochemical Effects***	No	Both italicized and FEP text revised.	SO-C
W95	***Galvanic Coupling (Outside the Repository)***	No	Reference to other FEPs removed from italicized text, no change to FEP text	SO-P
W96	***Electrophoresis***	No	Both italicized and FEP text revised.	SO-C
W97	***Chemical Gradients***	No	Reference to other FEPs removed from italicized text, additional information added to FEP text.	SO-C
W98	***Osmotic Processes***	No	Reference to other FEPs removed from italicized text, FEP text revised.	SO-C
W99	***Alpha Recoil***	No	Reference to other FEPs removed from italicized text, FEP text revised.	SO-C
W100	***Enhanced Diffusion***	No	Both italicized and FEP text revised.	SO-C
W101	***Plant Uptake***	No	No changes	SO-R
W102	***Animal Uptake***	No	No changes	SO-R
W103	***Accumulation in Soils***	No	No changes	SO-C
W104	***Ingestion***	No	No changes	SO-R
W105	***Inhalation***	No	No changes	SO-R
W106	***Irradiation***	No	No changes	SO-R
W107	***Dermal Sorption***	No	No changes	SO-R
W108	***Injection***	No	No changes	SO-R

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H1	***Oil and Gas Exploration***	No	Updated	SO-C (HCN) DP (Future)
H2	***Potash Exploration***	No	Updated	SO-C (HCN) DP (Future)
H4	***Oil and Gas Exploitation***	No	Updated	SO-C (HCN) DP (Future)
H8	***Other Resources***	No	Updated	SO-C (HCN) DP (Future)
H9	***Enhanced Oil and Gas Recovery***	No	Updated	SO-C (HCN) DP (Future)
H3	***Water Resources Exploration***	No	Both italicized and FEP text revised.	SO-C (HCN) SO-C (Future)
H5	***Groundwater Exploitation***	No	Both italicized and FEP text revised.	SO-C (HCN) SO-C (Future)
H6	***Archaeological Investigations***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H7	***Geothermal***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H10	***Liquid Waste Disposal***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H11	***Hydrocarbon Storage***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H12	***Deliberate Drilling Intrusion***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H13	***Conventional Underground Potash Mining*** ***Formerly Called "Potash Mining"***	No	Name changed from "Potash Mining" to "Conventional Underground Potash Mining." Both italicized and FEP text revised.	UP (HCN) DP (Future)
H14	***Other Resources***	No	Both italicized and FEP text revised.	SO-C (HCN) SO-R (Future)
H15	***Tunneling***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H16	***Construction of Underground Facilities (for Example Storage, Disposal, Accommodation)***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H17	***Archaeological Excavations***	No	Both italicized and FEP text revised.	SO-C (HCN) SO-R (Future)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H18	***Deliberate Mining Intrusion***	No	Both italicized and FEP text revised.	SO-R (HCN) SO-R (Future)
H19	***Explosions for Resource Recovery***	No	Both italicized and FEP text revised.	SO-C (HCN) SO-R (Future)
H20	***Underground Nuclear Device Testing***	No	No changes	SO-C (HCN) SO-R (Future)
H21	***Drilling Fluid Flow***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) DP (Future)
H22	***Drilling Fluid Loss***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) DP (Future)
H23	***Blowouts***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) DP (Future)
H24	***Drilling-Induced Geochemical Changes***	No	Reference to other FEPs removed from FEP and italicized text	UP (HCN) DP (Future)
H25	***Oil and Gas Extraction***	No	No changes	SO-C (HCN) SO-R (Future)
H26	***Groundwater Extraction***	No	No changes	SO-C (HCN) SO-R (Future)
H27	***Liquid Waste Disposal***	Yes	Additional information added to the original FEP text. Screening changed in italicized text from SO-R to SO-C (future).	SO-C (HCN) SO-C (Future)
H28	***Enhanced Oil and Gas Production***	Yes	Additional information added to the original FEP text. Screening changed in italicized text from SO-R to SO-C (future).	SO-C (HCN) SO-C (Future)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H29	***Hydrocarbon Storage***	Yes	Additional information added to the original FEP text. Screening changed in italicized text from SO-R to SO-C (future).	SO-C (HCN) SO-C (Future)
H30	***Fluid-injection Induced Geochemical Changes***	No	Reference to other FEPs removed from FEP and italicized text.	UP (HCN) SO-R (Future)
H31	***Natural Borehole Fluid Flow***	No	H31 and H33 combined. Both FEP text and italicized text revised to include H33.	SO-C (HCN) DP (Future)
H33	***Flow Through Undetected Boreholes***	Yes	Combined with H31 and deleted from FEPs baseline.	NA
H32	***Waste-Induced Borehole Flow***	No	Both FEP text and italicized text revised.	SO-R (HCN) DP (Future)
H34	***Borehole-Induced Solution and Subsidence***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	SO-C (HCN) SO-C (Future)
H35	***Borehole-Induced Mineralization***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	SO-C (HCN) SO-C (Future)
H36	***Borehole-Induced Geochemical Changes***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	UP (HCN) DP (Future)
H37	***Changes in Groundwater Flow Due to Mining***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	UP (HCN) DP (Future)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H38	***Changes in Geochemistry Due to Mining***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	SO-C (HCN) SO-R (Future)
H39	***Changes in Groundwater Flow Due to Explosions***	No	No changes	SO-C (HCN) SO-R (Future)
H40	***Land Use Changes***	No	Reference to other FEPs removed from italicized text, additional information added to FEP text.	SO-R (HCN) SO-R (Future)
H41	***Surface Disruptions***	Yes	Reference to other FEPs removed from italicized text, additional information added to FEP text.	UP (HCN) SO-R (Future)
H42	***Damming of Streams or Rivers***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) SO-R (Future)
H43	***Reservoirs***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) SO-R (Future)
H44	***Irrigation***	No	Reference to other FEPs removed from FEP and italicized text	SO-C (HCN) SO-R (Future)
H45	***Lake Usage***	No	Reference to other FEPs removed from FEP and italicized text, additional information added to FEP text.	SO-R (HCN) SO-R (Future)
H46	***Altered Soil or Surface Water Chemistry by Human Activities***	No	Reference to other FEPs removed from FEP and italicized text.	SO-C (HCN) SO-R (Future)
H47	***Greenhouse Gas Effects***	No	No changes	SO-R (HCN) SO-R (Future)
H48	***Acid Rain***	No	No changes	SO-R (HCN) SO-R (Future)

Table SCR-2. FEPs Reassessment Results — Continued

EPA FEP I.D.	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H49	***Damage to the Ozone Layer***	No	No changes	SO-R (HCN) SO-R (Future)
H50	***Coastal Water Use***	No	No changes	SO-R (HCN) SO-R (Future)
H51	***Sea water Use***	No	No changes	SO-R (HCN) SO-R (Future)
H52	***Estuarine Water Use***	No	No changes	SO-R (HCN) SO-R (Future)
H53	***Arable Farming***	No	No changes	SO-C (HCN) SO-R (Future)
H54	***Ranching***	No	No changes	SO-C (HCN) SO-R (Future)
H55	***Fish Farming***	No	No changes	SO-R (HCN) SO-R (Future)
H56	***Demographic Change and Urban Development***	No	Reference to other FEPs removed from FEP and italicized text.	SO-R (HCN) SO-R (Future)
H57	***Loss of Records***	No	Additional information added to FEP text, italicized text modified to remove reference to another FEP.	NA (HCN) DP (Future)
H58	***Solution Mining for Potash***	Yes	New FEP, ***Solution Mining*** was contained in various other FEPs – see H13	SO-R (HCN) SO-R (Future)
H59	***Solution Mining for Other Resources***	Yes	New FEP, ***Solution Mining*** was contained in various other FEPs – see H13	SO-C (HCN) SO-C (Future)

SCR-4.0 SCREENING OF NATURAL FEPS

This section presents the screening arguments and decisions for natural FEPs. Natural FEPs may be important to the performance of the disposal system. Screening of natural FEPs is done in the absence of human influences on the FEPs. Table SCR-2 provides information regarding the changes to these FEPs since the CCA. Of the 72 natural FEPs, 32 remain completely unchanged, 38 were updated to include additional information or were edited for clarity and completeness, and two were deleted from the baseline by combining with other more appropriate FEPs. No screening decisions (classifications) for natural FEPs were changed.

SCR-4.1 Geological FEPs

SCR-4.1.1 Stratigraphy

SCR-4.1.1.1 FEP Number: N1 and N2
FEP Title: ***Stratigraphy*** (N1)
Brine Reservoir (N2)

SCR-4.1.1.1.1 Screening Decision: UP

The stratigraphy of the geological formations in the region of the WIPP is accounted for in PA calculations. The presence of brine reservoirs in the Castile Formation is accounted for in PA calculations.

SCR-4.1.1.1.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-4.1.1.1.3 Screening Argument

The ***Stratigraphy*** and geology of the region around the WIPP, including the distribution and characteristics of pressurized ***Brine Reservoirs*** in the Castile Formation (hereafter referred to as the Castile), are discussed in detail in Section 2.1.3. The stratigraphy of the geological formations in the region of the WIPP is accounted for in PA calculations through the setup of the model geometries (Section 6.4.2). The presence of brine reservoirs is accounted for in the treatment of inadvertent drilling (Sections 6.4.12.6 and 6.4.8).

SCR-4.1.2 Tectonics

SCR-4.1.2.1 FEP Number: N3, N4, and N5
FEP Title: ***Regional Tectonics*** (N3)
Change in Regional Stress (N4)
Regional Uplift and Subsidence (N5)

SCR-4.1.2.1.1 Screening Decision: SO-C

The effects of regional tectonics, regional uplift and subsidence, and changes in regional stress have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.1.2.1.2 Summary of New Information

The DOE's screening designations for WIPP regional tectonics, changes in regional stress, regional uplift and subsidence appears to be technically valid. DOE described the WIPP site as located in an area with no evidence of significant tectonic activity, and with a low level of stress in the region. The WIPP is located in an area of tectonic quiescence. Seismic monitoring

conducted for the WIPP since the CCA continues to record small events at distance from the WIPP, and these events are mainly in areas associated with hydrocarbon production. Two nearby events (magnitude 3.5, 10/97, and magnitude 2.8, 12/98) are related to rockfalls in the Nash Draw mine and are not tectonic in origin (DOE 1999). These events did not cause any damage at the WIPP. There are no known nearby active faults, and one of the main tectonic features is a slight eastward dip to pre-Cenozoic formations within the basin. There is no geologic evidence of continuing tilting. These studies show short-term benchmark movements consistent with the basin tilt.

SCR-4.1.2.1.3 Screening Argument

Regional Tectonics encompasses two related issues of concern: the overall level of regional stress and whether any significant ***Changes in Regional Stress*** might occur.

The tectonic setting and structural features of the area around the WIPP are described in Section 2.1.5. In summary, there is no geological evidence for Quaternary regional tectonics in the Delaware Basin. The eastward tilting of the region has been dated as mid-Miocene to Pliocene by King (1948, pp. 120 - 121) and is associated with the uplift of the Guadalupe Mountains to the west. Fault zones along the eastern margin of the basin, where it flanks the Central Basin Platform, were active during the Late Permian. Evidence for this includes the displacement of the Rustler Formation (hereafter referred to as the Rustler) observed by Holt and Powers (1988, pp. 4 - 14) and the thinning of the Dewey Lake Redbeds (hereafter referred to as the Dewey Lake) reported by Schiel (1994). There is, however, no surface displacement along the trend of these fault zones, indicating that there has been no significant Quaternary movement. Other faults identified within the evaporite sequence of the Delaware Basin are inferred by Barrows' figures in Borns et al. (1983, pp. 58 - 60) to be the result of salt deformation rather than regional tectonic processes. According to Muehlberger et al. (1978, p. 338), the nearest faults on which Quaternary movement has been identified lie to the west of the Guadalupe Mountains and are of minor regional significance. The effects of regional tectonics and changes in regional stress have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

There are no reported stress measurements from the Delaware Basin, but a low level of regional stress has been inferred from the geological setting of the area (see Section 2.1.5). The inferred low level of regional stress and the lack of Quaternary tectonic activity indicate that regional tectonics and any changes in regional stress will be minor and therefore of low consequence to the performance of the disposal system. Even if rates of regional tectonic movement experienced over the past 10 million years continue, the extent of ***Regional Uplift and Subsidence*** over the next 10,000 years would only be about several feet (approximately 1 m). This amount of uplift or subsidence would not lead to a breach of the Salado because the salt would deform plastically to accommodate this slow rate of movement. Uniform regional uplift or a small increase in regional dip consistent with this past rate could give rise to downcutting by rivers and streams in the region. The extent of this downcutting would be little more than the extent of uplift, and reducing the overburden by 1 or 2 m would have no significant effect on groundwater flow or contaminant transport in units above or below the Salado. Thus, the effects of ***Regional Uplift and Subsidence*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.1.2.1.4 Tectonic Setting and Site Structural Features

The DOE has screened out, on the basis of either probability or consequence or both, all tectonic, magmatic, and structural related processes. The screening discussions can be found in CCA Appendix SCR. The information needed for this screening is included here and covers regional tectonic processes such as subsidence and uplift and basin tilting, magmatic processes such as igneous intrusion and events such as volcanism, and structural processes such as faulting, and loading and unloading of the rocks because of long-term sedimentation or erosion. Discussions of structural events, such as earthquakes, are considered to the extent that they may create new faults or activate old faults. The seismicity of the area is considered in Section 2.6 for the purposes of determining seismic design parameters for the facility.

SCR-4.1.2.1.5 Tectonics

The processes and features included in this section are those more traditionally considered part of tectonics-processes that develop the broad-scale features of the earth. Salt dissolution is a different process that can develop some features resembling those of tectonics.

Most broad-scale structural elements of the area around the WIPP developed during the Late Paleozoic (Appendix CCA GCR, pp. 3-58 to 3-77). There is little historical or geological evidence of significant tectonic activity in the vicinity, and the level of stress in the region is low. The entire region tilted slightly during the Tertiary, and activity related to Basin and Range tectonics formed major structures southwest of the area. Seismic activity is specifically addressed in a separate section.

Broad subsidence began in the area as early as the Ordovician, developing a sag called the Tobosa Basin. By Late Pennsylvanian to Early Permian time, the Central Basin Platform developed (Figure 2-19), separating the Tobosa Basin into two parts: the Delaware Basin to the west and the Midland Basin to the east. The Permian Basin refers to the collective set of depositional basins in the area during the Permian Period. Southwest of the Delaware Basin, the Diablo Platform began developing either in the Late Pennsylvanian or Early Permian. The Marathon Uplift and Ouachita tectonic belt limited the southern extent of the Delaware Basin.

According to Brokaw et al. (1972, p. 30), pre-Ochoan sedimentary rocks in the Delaware Basin show evidence of gentle downwarping during deposition, while Ochoan and younger rocks do not. A relatively uniform eastward tilt, generally from about 14 to 19 m/km (75 to 100 ft/mi), has been superimposed on the sedimentary sequence. P.B. King (1948, pp. 108 and 121) generally attributes the uplift of the Guadalupe and Delaware mountains along the west side of the Delaware Basin to the later Cenozoic, though he also notes that some faults along the west margin of the Guadalupe Mountains have displaced Quaternary gravels.

P.B. King (1948, p. 144) also infers the uplift from the Pliocene-age deposits of the Llano Estacado. Subsequent studies of the Ogallala of the Llano Estacado show that it varies in age from Miocene (about 12 million years before present) to Pliocene (Hawley 1993). This is the most likely range for uplift of the Guadalupe Mountains and broad tilting to the east of the Delaware Basin sequence.

Analysis of the present regional stress field indicates that the Delaware Basin lies within the Southern Great Plains stress province. This province is a transition zone between the extensional stress regime to the west and the region of compressive stress to the east. An interpretation by Zoback and Zoback (1991, p. 350) of the available data indicates that the level of stress in the Southern Great Plains stress province is low. Changes to the tectonic setting, such as the development of subduction zones and a consequent change in the driving forces, would take much longer than 10,000 years to occur.

To the west of the Southern Great Plains province is the Basin and Range province, or Cordilleran Extension province, where according to Zoback and Zoback (1991, pp. 348-351) normal faulting is the characteristic style of deformation. The eastern boundary of the Basin and Range province is marked by the Rio Grande Rift. Sanford et al. (1991, p. 230) note that, as a geological structure, the Rift extends beyond the relatively narrow geomorphological feature seen at the surface, with a magnetic anomaly at least 500 km (300 mi) wide. On this basis, the Rio Grande Rift can be regarded as a system of axial grabens along a major north-south trending structural uplift (a continuation of the Southern Rocky Mountains). The magnetic anomaly extends beneath the Southern Great Plains stress province, and regional-scale uplift of about 1,000 m (3,300 ft) over the past 10 million years also extends into eastern New Mexico.

To the east of the Southern Great Plains province is the large Mid-Plate province that encompasses central and eastern regions of the conterminous United States and the Atlantic basin west of the Mid-Atlantic Ridge. The Mid-Plate province is characterized by low levels of paleo- and historic seismicity. Where Quaternary faulting has occurred, it is generally strike-slip and appears to be associated with the reactivation of older structural elements.

Zoback et al. (1991) report no stress measurements from the Delaware Basin. The stress field in the Southern Great Plains stress province has been defined from borehole measurements in west Texas and from volcanic lineaments in northern New Mexico. These measurements were interpreted by Zoback and Zoback (1991, p. 353) to indicate that the least principal horizontal stress is oriented north-northeast and south-southwest and that most of the province is characterized by an extensional stress regime.

There is an abrupt change between the orientation of the least principal horizontal stress in the Southern Great Plains and the west-northwest orientation of the least principal horizontal stress characteristic of the Rio Grande Rift. In addition to the geological indications of a transition zone as described above, Zoback and Zoback (1980, p. 6134) point out that there is also evidence for a sharp boundary between these two provinces. This is reinforced by the change in crustal thickness from about 40 km (24 mi) beneath the Colorado Plateau to about 50 km (30 mi) or more beneath the Southern Great Plains east of the Rio Grande Rift. The base of the crust within the Rio Grande Rift is poorly defined but is shallower than that of the Colorado Plateau (Thompson and Zoback 1979, p. 152). There is also markedly lower heat flow in the Southern Great Plains (typically < 60 m Wm-2) reported by Blackwell et al. (1991, p. 428) compared with that in the Rio Grande Rift (typically > 80 m Wm-2) reported by Reiter et al. (1991, p. 463).

On the eastern boundary of the Southern Great Plains province, there is only a small rotation in the direction of the least principal horizontal stress. There is, however, a change from an extensional, normal faulting regime to a compressive, strike-slip faulting regime in the Mid-Plate

province. According to Zoback and Zoback (1980, p. 6134), the available data indicate that this change is not abrupt and that the Southern Great Plains province can be viewed as a marginal part of the Mid-Plate province.

SCR-4.1.3 Structural FEPs

SCR-4.1.3.1 Deformation

SCR-4.1.3.1.1 FEP Number: N6 and N7
FEP Title: ***Salt Deformation*** (N6)
Diapirism (N7)

SCR-4.1.3.1.1.1 *Screening Decision: SO-P*

Natural salt deformation and diapirism at the WIPP site over the next 10,000 years on a scale severe enough to significantly affect performance of the disposal system has been eliminated from PA calculations on the basis of low probability of occurrence.

SCR-4.1.3.1.1.2 *Summary of New Information*

The DOE presented extensive evidence that some of the evaporites in the northern Delaware Basin have been deformed and proposed that the likely mechanism for deformation is gravity foundering of the more dense anhydrites in less dense halite (e.g., Anderson and Powers 1978; Jones 1981; Borns et al. 1983; Borns 1987). Diapirism occurs when the deformation is penetrative, i.e., halite beds disrupt overlying anhydrites. As Anderson and Powers (1978) suggested, this may have happened northeast of the WIPP at the location of drillhole ERDA-6. This is the only location where diapirism has been suggested for the evaporites of the northern Delaware Basin. The geologic situation suggests that deformation occurred before the Miocene-Pliocene Ogallala Formation was deposited (Jones 1981). Mechanical modeling is consistent with salt deformation occurring over about 700,000 years to form the deformed features known in the northern part of the WIPP site (Borns et al. 1983). The DOE drew the conclusion that evaporites at the WIPP site deform too slowly to affect performance of the disposal system.

Because brine reservoirs appear to be associated with deformation, Powers et al. (1996) prepared detailed structure elevation maps of various units from the base of the Castile Formation upward through the evaporites in the northern Delaware Basin. Drillholes are far more numerous for this study than at the time of the study by Anderson and Powers (1978). Subdivisions of the Castile appear to be continuous in the vicinity of ERDA 6 and at ERDA 6. There is little justification for interpreting diapiric piercement at that site. The location and distribution of evaporite deformation in the area of the WIPP site is similar to that proposed by earlier studies (e.g., Anderson and Powers 1978; Borns et al. 1983; Borns and Shaffer 1985).

Surface domal features at the northwestern end of Nash Draw were of undetermined origin prior to WIPP investigations (e.g., Vine 1963), but extensive geophysical studies were conducted of these features as part of early WIPP studies (see Powers 1996). Two of the domal features were drilled, demonstrating that they had a solution-collapse origin (breccia pipes) and were not related in any way to salt diapirism (Snyder and Gard 1982).

A more recent study of structure for the Culebra Dolomite Member of the Rustler Formation (Powers 2002) shows that the larger deformation associated with deeper units is reflected by the Culebra, although the structural relief is muted. In addition, evaporite deformation in the northern part of the WIPP site, associated with the area earlier termed the "disturbed zone" (Powers et al. 1978), is hardly observable on a map of Culebra structure (Powers 2002). There is no evidence of more recent deformation at the WIPP site based on such maps.

These findings are consistent with the DOE position in the CCA that diapirism can be eliminated from PA calculations on the basis of low probability of occurrence. Although this discussion includes more recent information, the FEPs screening decision remains unchanged.

SCR-4.1.3.1.1.3 *Screening Argument*

SCR-4.1.3.1.1.3.1 *Deformation*

Deformed salt in the lower Salado and upper strata of the Castile has been encountered in a number of boreholes around the WIPP site; the extent of existing salt deformation is summarized in Section 2.1.6.1, and further detail is provided in CCA Appendix DEF.

A number of mechanisms may result in ***Salt Deformation***: in massive salt deposits, buoyancy effects or ***Diapirism*** may cause salt to rise through denser, overlying units; and in bedded salt with anhydrite or other interbeds, gravity foundering of the interbeds into the halite may take place. Results from rock mechanics modeling studies (see CCA Appendix DEF) indicate that the time scale for the deformation process is such that significant natural deformation is unlikely to occur at the WIPP site over any time frame significant to waste isolation. Thus, natural ***Salt Deformation*** and ***Diapirism*** severe enough to alter existing patterns of groundwater flow or the behavior of the disposal system over the regulatory period has been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.3.2 Fracture Development

SCR-4.1.3.2.1 FEP Number: N8
FEP Title: ***Formation of Fractures***

SCR-4.1.3.2.1.1 *Screening Decision: SO-P, UP (Repository)*

The formation of fractures has been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 years. The formation of fractures near the repository is accounted for in PA via treatment of the DRZ.

SCR-4.1.3.2.1.2 *Summary of New Information*

The screening argument for formation of fractures has been revised to reflect recent studies. The screening statement has been updated to reflect the formation of fractures near the repository (DRZ).

SCR-4.1.3.2.1.3 *Screening Argument*

The ***Formation of Fractures*** requires larger changes in stress than are required for changes to the properties of existing fractures to overcome the shear and tensile strength of the rock. It has been concluded from the regional tectonic setting of the Delaware Basin that no significant changes in regional stress are expected over the regulatory period. The EPA agrees that fracture formation in the Rustler is likely a result of halite dissolution and subsequent overlying unit fracturing loading/unloading, as well as the syn- and post-depositional processes. Intraformational post-depositional dissolution of the Rustler Formation has been ruled out as a major contributor to Rustler salt distribution and thus to new fracture formation based on work by Holt and Powers (ibid., DOE 1996a: Appendix DEF, Section DEF3.2) and Powers and Holt (1999, 2000), who believe that depositional facies and syndepositional dissolution account for most of the patterns on halite distribution in the Rustler. The argument against developing new fractures in the Rustler during the regulatory period appears reasonable. The formation of new fracture sets in the Culebra has therefore been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 years.

Repository-induced fracturing of the DRZ and Salado interbeds is accounted for in PA calculations.

A mechanism such as salt diapirism could develop fracturing in the Salado, but there is little evidence of diapirism in the Delaware Basin. Salt deformation has occurred in the vicinity of the WIPP, and fractures have developed in deeper Castile anhydrites as a consequence. Deformation rates are slow, and it is highly unlikely that this process will induce significant new fractures in the Salado during the regulatory time period. Surface domal features at the northwestern end of Nash Draw were of undetermined origin prior to WIPP investigations (e.g., Vine 1963), but extensive geophysical studies were conducted of these features as part of early WIPP studies (see Powers 1996). Two of the domal features were drilled, demonstrating that they had a solution-collapse origin (breccia pipes) and were not related in any way to salt diapirism (Snyder and Gard 1982).

The argument against developing new fractures within the Salado Formation during the regulatory period via regional stress therefore appears reasonable. Editorial changes for clarity are suggested, as well as separating the two FEPs into discrete arguments. Although the discussion of fracture development has been revised to include more recent information, the screening decision remains unchanged.

SCR-4.1.3.2.2 FEP Number: N9
FEP Title: ***Changes in Fracture Properties***

SCR-4.1.3.2.2.1 *Screening Decision: SO-C, UP (near repository)*

Naturally-induced changes in fracture properties that may affect groundwater flow or radionuclide transport in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. ***Changes in Fracture Properties*** *near the repository are accounted for in PA calculations through treatment of the DRZ.*

SCR-4.1.3.2.2.2 *Summary of New Information*

The screening argument has been updated with additional information that addresses the treatment of fractures in the near field. The screening decision has not changed.

SCR-4.1.3.2.2.3 *Screening Argument*

Groundwater flow in the region of the WIPP and transport of any released radionuclides may take place along fractures. The rate of flow and the extent of transport will be influenced by fracture characteristics. ***Changes in Fracture Properties*** could arise through natural changes in the local stress field; for example, through tectonic processes, erosion or sedimentation changing the amount of overburden, dissolution of soluble minerals along beds in the Rustler or upper Salado, or dissolution or precipitation of minerals in fractures.

Tectonic processes and features (N3 ***Changes in Regional Stress***; N4 ***Tectonics***; N5 ***Regional Uplift and Subsidence***; N6 ***Salt Deformation***; N7 ***Diapirism***) have been screened out of PA. These processes are not expected to change the character of fractures significantly during the regulatory period.

Surface erosion or deposition (e.g., FEPs N41-N49) are not expected to change significantly the overburden on the Culebra during the regulatory period. The relationship between Culebra transmissivity (T) and depth is significant (Holt, 2002; Holt and Powers, 2002), but the potential change to Culebra T based on deposition or erosion from these processes over the regulatory period is insignificant.

Shallow dissolution (FEP N16), where soluble beds from the upper Salado or Rustler are removed by groundwater, has been extensively considered. There are no direct effects on the Salado at depths of the repository. Extensive study of the upper Salado and Rustler halite units (Holt and Powers 1988; CCA Appendix FAC; Powers and Holt 1999, 2000; Powers 2002) indicates little potential for dissolution at the WIPP site during the regulatory period. Existing fracture properties are expressed through the relationship between Culebra T values and geologic factors at and near the WIPP site (Holt 2002; Holt and Powers 2002). These will be incorporated in PA (see N16, ***Shallow Dissolution***).

Mineral precipitation within fractures (N22) is expected to be beneficial to performance, and it has been screened out on the basis of low consequence. Natural dissolution of fracture fillings within the Culebra is incorporated within FEP N16 (***Shallow Dissolution***). There is no new information on the distribution of fracture fillings within the Culebra. The effects of fracture fillings are also expected to be represented in the distribution of Culebra T values around the WIPP site and are thus incorporated into PA.

Repository induced fracturing of the DRZ and Salado interbeds is accounted for in PA calculations (UP), and is discussed further in FEPs W18 and W19.

SCR-4.1.3.2.3 FEP Number(s): N10 and N11
FEP Title(s): ***Formation of New Faults*** (N10)
Fault Movement (N11)

SCR-4.1.3.2.3.1 *Screening Decision: SO-P*

The naturally induced fault movement and formation of new faults of sufficient magnitude to significantly affect the performance of the disposal system have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-4.1.3.2.3.2 *Summary of New Information*

No changes have been made to the FEP screening decision. However, the screening argument text was revised to include information on seismic monitoring since the CCA and the nearby rockfalls of non-tectonic origin in potash mines.

SCR-4.1.3.2.3.3 *Screening Argument*

Faults are present in the Delaware Basin in both the units underlying the Salado and in the Permian evaporite sequence (see Section 2.1.5.3). According to Powers et al. (1978, included in CCA Appendix GCR), there is evidence that movement along faults within the pre-Permian units affected the thickness of Early Permian strata, but these faults did not exert a structural control on the deposition of the Castile, the Salado, or the Rustler. Fault zones along the margins of the Delaware Basin were active during the Late Permian Period. Along the eastern margin, where the Delaware Basin flanks the Central Basin Platform, Holt and Powers (1988, included in CCA Appendix FAC) note that there is displacement of the Rustler, and Schiel (1994) notes that there is thinning of the Dewey Lake. There is, however, no surface displacement along the trend of these fault zones, indicating that there has been no significant Quaternary movement. Muehlberger et al. (1978, p. 338) note that the nearest faults on which Quaternary movement has been identified lie to the west of the Guadalupe Mountains.

The WIPP is located in an area of tectonic quiescence. Seismic monitoring conducted for the WIPP since the CCA continues to record small events at distance from the WIPP, and these events are mainly in areas associated with hydrocarbon production. Two nearby events (magnitude 3.5, 10/97, and magnitude 2.8, 12/98) are related to rockfalls in the Nash Draw mine and are not tectonic in origin (DOE 1999). These events did not cause any damage at the WIPP. The absence of Quaternary fault scarps and the general tectonic setting and understanding of its evolution indicate that large-scale, tectonically-induced ***Fault Movement*** within the Delaware Basin can be eliminated from PA calculations on the basis of low probability over 10,000 years. The stable tectonic setting also allows the ***Formation of New Faults*** within the basin over the next 10,000 years to be eliminated from PA calculations on the basis of low probability of occurrence.

Evaporite dissolution at or near the WIPP site has the potential for developing fractures in the overlying beds. Three zones (top of Salado, M1/H1 of the Los Medaños Member, and M2/H2 of the Los Medaños Member) with halite underlie the Culebra Dolomite Member at the site (Powers 2002). The upper Salado is present across the site, and there is no indication that dissolution of this area will occur in the regulatory period or cause faulting at the site. The Los

Medaños units show both mudflat facies and halite-bearing facies within or adjacent to the WIPP site (Powers 2002). Although the distribution of halite in the Rustler is mainly due to depositional facies and syndepositional dissolution (Holt and Powers 1988; Powers and Holt 1999, 2000), the possibility of past or future halite dissolution along the margins cannot be ruled out (Holt and Powers 1988; Beauheim and Holt 1999). If halite in the lower Rustler has been dissolved along the depositional margin, it has not occurred recently or has been of no consequence, as there is no indication on the surface or in Rustler structure of new (or old) faults in this area (e.g., Powers et al. 1978; Powers 2002).

The absence of Quaternary fault scarps and the general tectonic setting and understanding of its evolution indicate that large-scale, tectonically-induced fault movement within the Delaware Basin can be eliminated from PA calculations on the basis of low probability over 10,000 years. The stable tectonic setting also allows the ***Formation of New Faults*** within the basin over the next 10,000 years to be eliminated from PA calculations on the basis of low probability of occurrence.

SCR-4.1.3.2.4 FEP Number: N12
FEP Title: ***Seismic Activity***

SCR-4.1.3.2.4.1 *Screening Decision: UP*

The postclosure effects of seismic activity on the repository and the DRZ are accounted for in PA calculations.

SCR-4.1.3.2.4.2 *Summary of New Information*

No new information has been identified for this FEP. Any changes in the implementation of seismic activity within PA are discussed in Section 6.0.

SCR-4.1.3.2.4.3 *Screening Argument*

The following subsections present the screening argument for seismic activity (groundshaking).

SCR-4.1.3.2.4.4 *Causes of Seismic Activity*

Seismic Activity describes transient ground motion that may be generated by several energy sources. There are two possible causes of ***Seismic Activity*** that could potentially affect the WIPP site: natural- and human-induced. Natural seismic activity is caused by fault movement (earthquakes) when the buildup of strain in rock is released through sudden rupture or movement. Human-induced seismic activity may result from a variety of surface and subsurface activities, such as ***Explosions*** (H19 and H20), ***Mining*** (H13, H14, H58, and H59), ***Fluid Injection*** (H28), and ***Fluid Withdrawal*** (H25).

SCR-4.1.3.2.4.5 *Groundshaking*

Ground vibration and the consequent shaking of buildings and other structures are the most obvious effects of seismic activity. Once the repository and shafts have been sealed, however,

existing surface structures will be dismantled. Postclosure PAs are concerned with the effects of seismic activity on the closed repository.

In regions of low and moderate seismic activity, such as the Delaware Basin, rocks behave elastically in response to the passage of seismic waves, and there are no long-term changes in rock properties. The effects of earthquakes beyond the DRZ have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. An inelastic response, such as cracking, is only possible where there are free surfaces, as in the roof and walls of the repository prior to closure by creep. ***Seismic Activity*** could, therefore, have an effect on the properties of the DRZ.

An assessment of the extent of damage in underground excavations caused by groundshaking largely depends on observations from mines and tunnels. Because such excavations tend to take place in rock types more brittle than halite, these observations cannot be related directly to the behavior of the WIPP. According to Wallner (1981, 244), the DRZ in brittle rock types is likely to be more highly fractured and hence more prone to spalling and rockfalls than an equivalent zone in salt. Relationships between groundshaking and subsequent damage observed in mines will therefore be conservative with respect to the extent of damage induced at the WIPP by seismic activity.

Dowding and Rozen (1978) classified damage in underground structures following seismic activity and found that no damage (cracks, spalling, or rockfalls) occurred at accelerations below 0.2 gravities and that only minor damage occurred at accelerations up to 0.4 gravities. Lenhardt (1988, p. 392) showed that a magnitude 3 earthquake would have to be within 1 km (0.6 mi) of a mine to result in falls of loose rock. The risk of seismic activity in the region of the WIPP reaching these thresholds is discussed below.

SCR-4.1.3.2.4.6 *Seismic Risk in the Region of the WIPP*

Prior to the introduction of a seismic monitoring network in 1960, most recorded earthquakes in New Mexico were associated with the Rio Grande Rift, although small earthquakes were detected in other parts of the region. In addition to continued activity in the Rio Grande Rift, the instrumental record has shown a significant amount of seismic activity originating from the Central Basin Platform and a number of small earthquakes in the Los Medaños area. Seismic activity in the Rio Grande Rift is associated with extensional tectonics in that area. Seismic activity in the Central Basin Platform may be associated with natural earthquakes, but there are also indications that this activity occurs in association with oil-field activities such as fluid injection. Small earthquakes in the Los Medaños region have not been precisely located, but may be the result of mining activity in the region. Section 2.6.2 contains additional discussion of seismic activity and risk in the WIPP region.

The instrumental record was used as the basis of a seismic risk study primarily intended for design calculations of surface facilities rather than for postclosure PAs. The use of this study to define probable ground accelerations in the WIPP region over the next 10,000 years is based on the assumptions that hydrocarbon extraction and potash mining will continue in the region and that the regional tectonic setting precludes major changes over the next 10,000 years.

Three source regions were used in calculating seismic risk: the Rio Grande Rift, the Central Basin Platform, and part of the Delaware Basin province (including the Los Medaños). Using conservative assumptions about the maximum magnitude event in each zone, the study indicated a return period of about 10,000 years (annual probability of occurrence of 10^{-4}) for events producing ground accelerations of 0.1 gravities. Ground accelerations of 0.2 gravities would have an annual probability of occurrence of about 5×10^{16}.

The results of the seismic risk study and the observations of damage in mines due to groundshaking give an estimated annual probability of occurrence of between 10^{-6} and 10^{-8} for events that could increase the permeability of the DRZ. The DRZ is accounted for in PA calculations as a zone of permanently high permeability (see Section 6.4.5.3); this treatment is considered to account for the effects of any potential seismic activity.

SCR-4.1.4 Crustal Process

SCR-4.1.4.1 FEP Number: N13
FEP Title: ***Volcanic Activity***

SCR-4.1.4.1.1 Screening Decision: SO-P

Volcanic Activity *has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-4.1.4.1.2 Summary of New Information

No new information has been identified for this FEP. Editorial changes were made to the screening decision to remove reference to other FEPs. No changes have been made to the description or screening argument.

SCR-4.1.4.1.3 Screening Argument

The Paleozoic and younger stratigraphic sequences within the Delaware Basin are devoid of locally derived volcanic rocks. Volcanic ashes (dated at 13 million years and 0.6 million years) do occur in the Gatuña Formation (hereafter referred to as the Gatuña), but these are not locally derived. Within eastern New Mexico and northern, central, and western Texas, the closest Tertiary volcanic rocks with notable areal extent or tectonic significance to the WIPP are approximately 160 km (100 mi) to the south in the Davis Mountains volcanic area. The closest Quaternary volcanic rocks are 250 km (150 mi) to the northwest in the Sacramento Mountains. No volcanic rocks are exposed at the surface within the Delaware Basin.

Volcanic Activity is associated with particular tectonic settings: constructive and destructive plate margins, regions of intraplate rifting, and isolated hot-spots in intraplate regions. The tectonic setting of the WIPP site and the Delaware Basin is remote from plate margins, and the absence of past volcanic activity indicates the absence of a major hot spot in the region. Intraplate rifting has taken place along the Rio Grande some 200 km (120 mi) west of the WIPP site during the Tertiary and Quaternary Periods. Igneous activity along this rift valley is comprised of sheet lavas intruded on by a host of small-to-large plugs, sills, and other intrusive bodies. However, the geological setting of the WIPP site within the large and stable Delaware

Basin allows volcanic activity in the region of the WIPP repository to be eliminated from performance calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.4.2 FEP Number: N14
FEP Title: ***Magmatic Activity***

SCR-4.1.4.2.1 Screening Decision: SO-C

*The effects of **Magmatic Activity** have been eliminated from the PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.1.4.2.2 Summary of New Information

No new information has been identified for this FEP. Editorial changes were made to the screening decision to remove reference to other FEPs. No changes have been made to the description or screening argument.

SCR-4.1.4.2.3 Screening Argument

Magmatic *Activity* is defined as the subsurface intrusion of igneous rocks into country rock. Deep intrusive igneous rocks crystallize at depths of several kilometers (several miles) and have no surface or near-surface expression until considerable erosion has taken place. Alternatively, intrusive rocks may form from magma that has risen to near the surface or in the vents that give rise to volcanoes and lava flows. Magma near the surface may be intruded along subvertical and subhorizontal discontinuities (forming dikes and sills, respectively), and magma in volcanic vents may solidify as plugs. The formation of such features close to a repository or the existence of a recently intruded rock mass could impose thermal stresses inducing new fractures or altering the hydraulic characteristics of existing fractures.

The principal area of magmatic activity in New Mexico is the Rio Grande Rift, where extensive intrusions occurred during the Tertiary and Quaternary Periods. The Rio Grande Rift, however, is in a different tectonic province than the Delaware Basin, and its magmatic activity is related to the extensional stress regime and high heat flow in that region.

Within the Delaware Basin, there is a single identified outcrop of a lamprophyre dike about 70 km (40 mi) southwest of the WIPP (see Section 2.1.5.4 and CCA Appendix GCR for more detail). Closer to the WIPP site, similar rocks have been exposed within potash mines some 15 km (10 mi) to the northwest, and igneous rocks have been reported from petroleum exploration boreholes. Material from the subsurface exposures has been dated at around 35 million years. Some recrystallization of the host rocks took place alongside the intrusion, and there is evidence that minor fracture development and fluid migration also occurred along the margins of the intrusion. However, the fractures have been sealed, and there is no evidence that the dike acted as a conduit for continued fluid flow.

Aeromagnetic surveys of the Delaware Basin have shown anomalies that lie on a linear southwest-northeast trend that coincides with the surface and subsurface exposures of magmatic rocks. There is a strong indication therefore of a dike or a closely related set of dikes extending

for at least 120 km (70 mi) across the region (see Section 2.1.5.4). The aeromagnetic survey conducted to delineate the dike showed a magnetic anomaly that is several kilometers (several miles) wide at depth and narrows to a thin trace near the surface. This pattern is interpreted as the result of an extensive dike swarm at depths of less than approximately 4.0 km (2.5 mi) near the Precambrian basement, from which a limited number of dikes have extended towards the surface.

Magmatic Activity has taken place in the vicinity of the WIPP site in the past, but the igneous rocks have cooled over a long period. Any enhanced fracturing or conduits for fluid flow have been sealed by salt creep and mineralization. Continuing magmatic activity in the Rio Grande Rift is too remote from the WIPP location to be of consequence to the performance of the disposal system. Thus, the effects of magmatic activity have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.1.4.2.4 FEP Number: N15
FEP Title: **Metamorphic Activity**

SCR-4.1.4.2.4.1 *Screening Decision: SO-P*

Metamorphic Activity *has been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.*

SCR-4.1.4.2.4.2 *Summary of New Information*

No new information has been identified for this FEP. Editorial changes were made to the screening decision to remove reference to other FEPs. No changes have been made to the description or screening argument.

SCR-4.1.4.2.4.3 *Screening Argument*

Metamorphic Activity, that is, solid-state recrystallization changes to rock properties and geologic structures through the effects of heat and/or pressure, requires depths of burial much greater than the depth of the repository. Regional tectonics that would result in the burial of the repository to the depths at which the repository would be affected by ***Metamorphic Activity*** have been eliminated from PA calculations on the basis of low probability of occurrence; therefore, metamorphic activity has also been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.5 Geochemical Processes

SCR-4.1.5.1 FEP Number: N16
FEP Title: ***Shallow Dissolution (including lateral dissolution)***

SCR-4.1.5.1.1 Screening Decision: UP

Shallow Dissolution *is accounted for in PA calculations.*

SCR-4.1.5.1.2 Summary of New Information

In the vicinity of the WIPP site, the processes described in CCA Appendix SCR as ***Shallow Dissolution*** (N16) and ***Lateral Dissolution*** (N17) extensively overlap. As a result, N16 and N17 have been combined and N17 has been deleted from the FEPs baseline. FEP N16 has been modified to account for the deletion of N17. For CRA-2004, all of these interrelated processes, and their attendant features, are considered as part of shallow dissolution, which is accounted for in PA calculations.

SCR-4.1.5.1.3 Screening Argument

This section discusses a variety of styles of dissolution that have been active in the region of the WIPP or in the Delaware Basin. A distinction has been drawn between ***Shallow Dissolution***, involving circulation of groundwater and mineral dissolution, in the Rustler and at the top of the Salado in the region of the WIPP; and deep dissolution taking place in the Castile and the base of the Salado. Dissolution will initially enhance porosities, but continued dissolution may lead to compaction of the affected units with a consequent reduction in porosity. Compaction may result in fracturing of overlying brittle units and increased permeability. Extensive dissolution may create cavities (karst) and result in the total collapse of overlying units. This topic is discussed further in Section 2.1.6.2.

SCR-4.1.5.1.4 Shallow Dissolution

In the region around WIPP, ***Shallow Dissolution*** by groundwater flow has removed soluble minerals from the upper Salado as well as the Rustler to form Nash Draw; extensive solution within the closed draw has created karst features including caves and dolines in the sulfate beds of the Rustler (see Lee, 1925; Bachman, 1980, 1985, 1987a). An alluvial doline drilled at WIPP 33, about 850 m (2800 ft) west of the WIPP site boundary, is the nearest karst feature known in the vicinity of the site. Upper Salado halite dissolution in Nash Draw resulted in propagating fracturing upward through the overlying Rustler (Holt and Powers 1988). The margin of dissolution of halite from the upper Salado has commonly been placed west of the WIPP site, near, but east of, Livingston Ridge, the eastern boundary of Nash Draw. Halite occurs in the Rustler east of Livingston Ridge, with the margin generally progressively eastward in higher stratigraphic units (e.g., Snyder 1985; Powers and Holt 1995). The distribution of halite in the Rustler has commonly been attributed to ***Shallow Dissolution*** (e.g., Powers et al. 1978; Lambert, 1983; Bachman 1985; Lowenstein 1987). During early studies for the WIPP, the variability of transmissivity of the Culebra in the vicinity of the WIPP was commonly attributed to the effects of dissolution of Rustler halite and changes in fracturing as a consequence.

After a detailed sedimentologic and stratigraphic investigation of WIPP cores, shafts, and geophysical logs from the region around WIPP, the distribution of halite in the Rustler was attributed to depositional and syndepositional processes rather than post-depositional dissolution (Holt and Powers 1988; Powers and Holt 2000). Rustler exposures in shafts for the WIPP revealed extensive sedimentary structures in clastic units (Holt and Powers 1984, 1986, 1990), and the suite of features in these beds led these investigators (Holt and Powers 1988; Powers and Holt 1990, 2000) to reinterpret the clastic units. They conclude that the clastic facies represent mainly mudflat facies tracts adjacent to a salt pan. Although some halite likely was deposited in

mudflat areas proximal to the salt pan, it was largely removed by syndepositional dissolution, as indicated by soil structures, soft sediment deformation, bedding, and small-scale vertical relationships (Holt and Powers 1988; Powers and Holt 1990, 1999, 2000). The depositional margins of halite in the Rustler are the likely points for past or future dissolution (e.g., Holt and Powers 1988; Beauheim and Holt 1990). Cores from drillholes at the H-19 drillpad near the Tamarisk Member halite margin show evidence of some dissolution of halite in the Tamarisk (Mercer et al. 1998), consistent with these predictions. The distribution of Culebra T values is not considered related to dissolution of Rustler halite, and other geological factors (e.g., depth, upper Salado dissolution) correlate well with Culebra transmissivity (e.g., Powers and Holt 1995; Holt and Powers 2002).

Since the CCA was completed, the WIPP has conducted additional work on ***Shallow Dissolution***, principally of the upper Salado, and its possible relationship to the distribution of T values for the Culebra as determined through testing of WIPP hydrology wells.

AP-088 (Beauheim 2002) noted that potentiometric surface values for the Culebra in many monitoring wells were outside the uncertainty ranges used to calibrate models of steady-state heads for the unit. AP-088 directed the analysis of the relationship between geological factors and values of T at Culebra wells. The relationship between geological factors, including dissolution of the upper Salado as well as limited dissolution in the Rustler, and Culebra T is being used to evaluate differences between assuming steady-state Culebra heads and changing heads.

Task 1 for AP-088 (Powers 2002) evaluated geological factors, including shallow dissolution in the vicinity of the WIPP site that related to Culebra T. A much more extensive drillhole geological database was developed than was previously available, utilizing sources of data from WIPP, potash exploration, and oil and gas exploration and development. The principal findings related to shallow dissolution are: 1) a relatively narrow zone (~ 200-400 m wide) could be defined as the margin of dissolution of the upper Salado in much of the area around WIPP: 2) the upper Salado dissolution margin commonly underlies surface escarpments such as Livingston Ridge; and 3) there are possible extensions or reentrants of incipient upper Salado dissolution extending eastward from the general dissolution margin. The WIPP site proper is not affected by this process.

Culebra T correlates well with depth or overburden, which affects fracture apertures (Powers and Holt 1995, Holt and Powers 2002; Holt 2002). Dissolution of the upper Salado appears to increase T by one or more orders of magnitude (Holt 2002). Because there is no indication of upper Salado dissolution at the WIPP site, Holt (2002) did not include this factor for the WIPP site in estimates of base T values for the WIPP site and surroundings.

There is no new work since the CCA on the distribution of fracture fillings in the Culebra or on dissolution of the fillings. The effects of this process are represented in the distribution of Culebra T values around the WIPP site.

New work regarding shallow dissolution does not change the inclusion of the effects in the T field for the Culebra within PA calculations. The new work provides a firmer basis for understanding the effects of shallow dissolution as represented in PA.

The effects of ***Shallow Dissolution*** (including the impacts of lateral dissolution) have been included in PA calculations.

SCR-4.1.5.2 FEP Number: N17 (removed from baseline)
FEP Title: ***Lateral Dissolution***

SCR-4.1.5.2.1 Summary of New Information

FEP N17 ***Lateral Dissolution*** is so similar to FEP N16 ***Shallow Dissolution*** as features and processes that they are better treated as a single FEP N16, ***Shallow Dissolution***. Therefore, N17 has been deleted from the FEPs baseline and the text for N16 has been modified to address the combination of N16 and N17 into one FEP N16. ***Shallow Dissolution*** is accounted for in PA calculations and encompasses the nature and characteristics of lateral dissolution.

SCR-4.1.5.3 FEP Number: N18, N20 and N21
FEP Title: ***Deep Dissolution*** (N18)
Breccia Pipes (N20)
Collapse Breccias (N21)

SCR-4.1.5.3.1 Screening Decision: SO-P

Deep Dissolution *and the formation of associated features (for example,* ***Solution Chimneys****,* ***Breccia Pipes****,* ***Collapse Breccias****) at the WIPP site have been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.*

SCR-4.1.5.3.2 Summary of New Information

The DOE limited ***Deep Dissolution*** to processes involving dissolution of the Castile or basal Salado Formations and associated features such as ***Breccia Pipes*** (also known as ***Solution Chimneys***) with this process. The DOE found that deep dissolution is a process that may be operating in the Delaware Basin, but the process is limited by the hydraulic and geochemical characteristics of the expected source of water in the Delaware Mountain Group underlying the evaporite formations. Investigations of the WIPP site have not found evidence of specific features (e.g., ***Breccia Pipes, Solution Collapse***, or ***Solution Chimneys***) associated with deep dissolution. The EPA also concluded that the mechanism may be operating in the Delaware Basin, and that there is little evidence of deep dissolution at the WIPP site. The EPA concluded that the rate or magnitude of this process is not high enough that it is likely to threaten integrity of the WIPP over the next 10,000 years. These conclusions appear reasonable. The original description and screening arguments as presented in the CCA remain valid. The FEP discussion has been modified to clarify the arguments and the original screening decision as presented in the CCA has been revised to remove reference to other FEPs.

SCR-4.1.5.3.3 Screening Argument

This section discusses a variety of styles of dissolution that have been active in the region of the WIPP or in the Delaware Basin. A distinction has been drawn between ***Shallow Dissolution***, involving circulation of groundwater and mineral dissolution in the Rustler and at the top of the Salado in the region of the WIPP, and ***Deep Dissolution*** taking place in the Castile and the base

of the Salado. Dissolution will initially enhance porosities, but continued dissolution may lead to compaction of the affected units with a consequent reduction in porosity. Compaction may result in fracturing of overlying brittle units and increased permeability. Extensive dissolution may create cavities (karst) and result in the total collapse of overlying units. This topic is discussed further in Section 2.1.6.2.

SCR-4.1.5.3.4 Deep Dissolution

Deep Dissolution refers to the dissolution of salt or other evaporite minerals in a formation at depth (see Section 2.1.6.2). Deep dissolution is distinguished from shallow and lateral dissolution not only by depth, but also by the origin of the water. Dissolution by groundwater from deep water-bearing zones can lead to the formation of cavities. Collapse of overlying beds leads to the formation of ***Collapse Breccias*** if the overlying rocks are brittle or to deformation if the overlying rocks are ductile. If dissolution is extensive, ***Breccia Pipes*** or ***Solution Chimneys*** may form above the cavity. These pipes may reach the surface or pass upwards into fractures and then into microcracks that do not extend to the surface. ***Breccia Pipes*** may also form through the downward percolation of meteoric waters, as discussed earlier. ***Deep Dissolution*** is of concern because it could accelerate contaminant transport through the creation of vertical flow paths that bypass low-permeability units in the Rustler. If dissolution occurred within or beneath the waste panels themselves, there could be increased circulation of groundwater through the waste, as well as a breach of the Salado host rock.

Features identified as being the result of ***Deep Dissolution*** are present along the northern and eastern margins of the Delaware Basin. In addition to features that have a surface expression or that appear within potash mine workings, ***Deep Dissolution*** has been cited by Anderson et al. (1972, p. 81) as the cause of lateral variability within evaporite sequences in the lower Salado.

Exposures of the McNutt Potash Member of the Salado within a mine near Nash Draw have shown a breccia pipe containing cemented brecciated fragments of formations higher in the stratigraphic sequence. At the surface, this feature is marked by a dome, and similar domes have been interpreted as dissolution features. The depth of dissolution has not been confirmed, but the collapse structures led Anderson (1978, p. 52) and Snyder et al. (1982, p. 65) to postulate dissolution of the Capitan Limestone at depth; collapse of the Salado, Rustler, and younger formations; and subsequent dissolution and hydration by downward percolating waters. San Simon Sink (see Section 2.1.6.2), some 35 km (20 mi) east-southeast of the WIPP site, has also been interpreted as a ***Solution Chimneys***. Subsidence has occurred there in historical times according to Nicholson and Clebsch (1961, p. 14), suggesting that dissolution at depth is still taking place. Whether this is the result of downwards-percolating surface water or of deep groundwater has not been confirmed. The association of these dissolution features with the inner margin of the Capitan Reef suggest that they owe their origins, if not their continued development, to groundwaters derived from the Capitan Limestone.

SCR-4.1.5.3.5 Dissolution within the Castile and Lower Salado Formations

The Castile contains sequences of varved anhydrite and carbonate (that is, laminae deposited on a cyclical basis) that can be correlated between several boreholes. On the basis of these deposits, a basin-wide uniformity in the depositional environment of the Castile evaporites was assumed.

The absence of varves from all or part of a sequence and the presence of brecciated anhydrite beds have been interpreted by Anderson et al. (1972) as evidence of dissolution. Holt and Powers (CCA Appendix FAC) have questioned the assumption of a uniform depositional environment and contend that the anhydrite beds are lateral equivalents of halite sequences without significant postdepositional dissolution. Wedges of brecciated anhydrite along the margin of the Castile have been interpreted by Robinson and Powers (1987, p. 78) as gravity-driven clastic deposits, rather than the result of ***Deep Dissolution***.

Localized depressions at the top of the Castile and inclined geophysical marker units at the base of the Salado have been interpreted by Davies (1983, p. 45) as the result of ***Deep Dissolution*** and subsequent collapse or deformation of overlying rocks. The postulated cause of this dissolution was circulation of undersaturated groundwaters from the Bell Canyon Formation (hereafter referred to as the Bell Canyon). Additional boreholes (notably WIPP-13, WIPP-32, and DOE-2) and geophysical logging led Borns and Shaffer (1985) to conclude that the features interpreted by Davies as being dissolution features are the result of irregularities at the top of the Bell Canyon. These irregularities led to localized depositional thickening of the Castile and lower Salado sediments.

SCR-4.1.5.3.6 Collapse Breccias at Basin Margins

Collapse Breccias are present at several places around the margins of the Delaware Basin. Their formation is attributed to relatively fresh groundwater from the Capitan Limestone that forms the margin of the basin. ***Collapse Breccias*** corresponding to features on geophysical records that have been ascribed to ***Deep Dissolution*** have not been found in boreholes away from the margins. These features have been reinterpreted as the result of early dissolution prior to the deposition of the Salado.

SCR-4.1.5.3.7 Summary of Deep Dissolution

Deep Dissolution features have been identified within the Delaware Basin, but only in marginal areas underlain by Capitan Reef. There is a low probability that deep dissolution will occur sufficiently close to the waste panels over the regulatory period to affect groundwater flow in the immediate region of the WIPP. ***Deep Dissolution*** at the WIPP site has therefore been eliminated from *PA* calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.5.4 FEP Number: N19 (removed from baseline)
FEP Title: ***Solution Chimneys***

SCR-4.1.5.4.1 Screening Decision: NA

SCR-4.1.5.4.2 Summary of New Information

Solution Chimneys (N19) and ***Breccia Pipes*** (N20) are equivalent as used in the CCA and supporting documents for the WIPP. Neither the DOE nor the EPA discussions supporting the original certification make a clear distinction between the two. These FEPs have been combined and are addressed in FEP N20 ***Breccia Pipes***. The screening arguments have not changed as a result of consolidation.

SCR-4.1.5.5 FEP Number: N22
FEP Title: ***Fracture Infill***

SCR-4.1.5.5.1 Screening Decision: SO-C - Beneficial

*The effects of **Fracture Infills** have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-4.1.5.5.2 Summary of New Information

No new information has been identified that related to the screening of this FEP. No changes have been made.

SCR-4.1.5.5.3 Screening Argument

SCR-4.1.5.5.3.1 Mineralization

Precipitation of minerals as ***Fracture Infills*** can reduce hydraulic conductivities. The distribution of infilled fractures in the Culebra closely parallels the spatial variability of lateral transmissivity in the Culebra. The secondary gypsum veins in the Rustler have not been dated. Strontium isotope studies (Siegel et al. 1991, pp. 5-53 to 5-57) indicate that the infilling minerals are locally derived from the host rock rather than extrinsically derived, and it is inferred that they reflect an early phase of mineralization and are not associated with recent meteoric waters.

Stable isotope geochemistry in the Rustler has also provided information on mineral stabilities in these strata. Both Chapman (1986, p. 31) and Lambert and Harvey (1987, p. 207) imply that the mineralogical characteristics of units above the Salado have been stable or subject to only minor changes under the various recharge conditions that have existed during the past 0.6 million years—the period since the formation of the Mescalero caliche and the establishment of a pattern of climate change and associated changes in recharge that led to present-day hydrogeological conditions. No changes in climate are expected other than those experienced during this period, and for this reason, no changes are expected in the mineralogical characteristics other than those expressed by the existing variability of fracture infills and diagenetic textures. Formation of ***Fracture Infills*** will reduce transmissivities and will therefore be of beneficial consequence to the performance of the disposal system.

SCR-4.2 Subsurface Hydrological Features, Events, and Processes

SCR-4.2.1 Groundwater Characteristics

SCR-4.2.1.1 FEP Number: N23, N24, N25 and N27
FEP Title: ***Saturated Groundwater Flow*** *(N23)*
Unsaturated Groundwater Flow *(N24)*
Fracture Flow *(N25)*
Effects of Preferential Pathways *(N27)*

SCR-4.2.1.1.1 Screening Decision: UP

Saturated ***Groundwater Flow***, ***Unsaturated Groundwater Flow***, ***Fracture Flow***, *and the* ***Effects of Preferential Pathways*** *are accounted for in PA calculations.*

SCR-4.2.1.1.2 Summary of New Information

No new information related to the screening of these FEPs has been identified. These FEPs continue to be accounted for in PA.

SCR-4.2.1.1.3 Screening Argument

Saturated Groundwater Flow, ***Unsaturated Groundwater Flow,*** and ***Fracture Flow*** are accounted for in PA calculations. Groundwater flow is discussed in Sections 2.2.1, 6.4.5, and 6.4.6.

The hydrogeologic properties of the Culebra are also spatially variable. This variability, including the ***Effects of Preferential Pathways***, is accounted for in PA calculations in the estimates of transmissivity and aquifer thickness.

SCR-4.2.1.2 FEP Number: N26
FEP Title: ***Density Effect on Groundwater Flow***

SCR-4.2.1.2.1 Screening Decision: SO-C

Density Effects on Groundwater Flow *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.2.1.2.2 Summary of New Information

The effects of natural density variations on groundwater flow have been screened out on the basis of low consequence. Editorial changes have been made to the FEP description, argument, and screening decision.

SCR-4.2.1.2.3 Screening Argument

The most transmissive unit in the Rustler, and hence the most significant potential pathway for transport of radionuclides to the accessible environment, is the Culebra. The properties of Culebra groundwaters are not homogeneous, and spatial variations in groundwater density

(Section 2.2.1.4.1.2) could influence the rate and direction of groundwater flow. A comparison of the gravity-driven flow component and the pressure-driven component in the Culebra, however, shows that only in the region to the south of the WIPP are head gradients low enough for density gradients to be significant (Davies 1989, p. 53). Accounting for this variability would rotate groundwater flow vectors towards the east (down-dip) and hence fluid in the high transmissivity zone would move away from the zone. Excluding brine density variations within the Culebra from PA calculations is therefore a conservative assumption, and ***Density Effects on Groundwater Flow*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2 Changes in Groundwater Flow

SCR-4.2.2.1 FEP Number: N28
FEP Title: ***Thermal Effects on Groundwater Flow***

SCR-4.2.2.1.1 Screening Decision: SO-C

*Natural **Thermal Effects on Groundwater Flow** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-4.2.2.1.2 Screening Argument

The geothermal gradient in the region of the WIPP has been measured at about 30°C (54°F) per kilometer (50°C [90°F] per mile). Given the generally low permeability in the region, and the limited thickness of units in which groundwater flow occurs (for example the Culebra), natural convection will be too weak to have a significant effect on groundwater flow. No natural FEPs have been identified that could significantly alter the temperature distribution of the disposal system or give rise to ***Thermal Effects on Groundwater Flow***. Such effects have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2.2 FEP Number: N29
FEP Title: ***Saline Intrusion (hydrogeological effects)***

SCR-4.2.2.2.1 Screening Decision: SO-P

*Changes in groundwater flow arising from **Saline Intrusion** has been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 years.*

SCR-4.2.2.2.2 Summary of New Information

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-4.2.2.2.3 Screening Argument

No natural events or processes have been identified that could result in ***Saline Intrusion*** into units above the Salado or cause a significant increase in fluid density. Natural ***Saline Intrusion*** has therefore been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years. ***Saline Intrusion*** arising from human events such as drilling into a pressurized brine pocket is discussed in FEPs H21 through H24.

SCR-4.2.2.3 FEP Number: N30
FEP Title: ***Freshwater Intrusion (hydrogeological effects)***

SCR-4.2.2.3.1 Screening Decision: SO-P

*Changes in groundwater flow arising **Freshwater Intrusion** have been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 years.*

SCR-4.2.2.3.2 Summary

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-4.2.2.3.2.1 *Screening Argument*

A number of FEPs, including ***Climate Change***, can result in changes in infiltration and recharge (see discussions for FEPs N53 through N55). These changes will affect the height of the water table and hence could affect groundwater flow in the Rustler through changes in head gradients. The generally low transmissivity of the Dewey Lake and the Rustler, however, will prevent any significant changes in groundwater density from occurring within the Culebra over the timescales for which increased precipitation and recharge are anticipated. No other natural events or processes have been identified that could result in ***Freshwater Intrusion*** into units above the Salado or cause a significant decrease in fluid density. ***Freshwater Intrusion*** has therefore been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.2.2.4 FEP Number: N31
FEP Title: ***Hydrological Response to Earthquakes***

SCR-4.2.2.4.1 Screening Decision: SO-C

*A **Hydrological Response to Earthquakes** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.2.2.4.2 Summary of New Information

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-4.2.2.4.3 Screening Argument

SCR-4.2.2.4.3.1 *Hydrological Effects of Seismic Activity*

There are a variety of ***Hydrological Response to Earthquakes***. Some of these responses, such as changes in surface-water flow directions, result directly from fault movement. Others, such as changes in subsurface water chemistry and temperature, probably result from changes in flow pathways along the fault or fault zone. According to Bredehoeft et al. (1987, p. 139), further away from the region of fault movement, two types of changes to groundwater levels may take place as a result of changes in fluid pressure:

- The passage of seismic waves through a rock mass causes a volume change, inducing a transient response in the fluid pressure, which may be observed as a short-lived fluctuation of the water level in wells, or

- Changes in volume strain can cause long-term changes in water level. A buildup of strain occurs prior to rupture and is released during an earthquake. The consequent change in fluid pressure may be manifested by the drying up or reactivation of springs some distance from the region of the epicenter.

Fluid pressure changes induced by the transmission of seismic waves can produce changes of up to several meters (several yards) in groundwater levels in wells, even at distances of thousands of kilometers from the epicenter. These changes are temporary, however, and levels typically return to pre-earthquake levels in a few hours or days. Changes in fluid pressure arising from changes in volume strain persist for much longer periods, but they are only potentially consequential in tectonic regimes where there is a significant buildup of strain. The regional tectonics of the Delaware Basin indicate that such a buildup has a low probability of occurring over the next 10,000 years (see FEPs N3 and N4).

The expected level of seismic activity in the region of the WIPP will be of low consequence to the performance of the disposal system in terms of groundwater flow or contaminant transport. Changes in groundwater levels resulting from more distant earthquakes will be too short in duration to be significant. Thus, the ***Hydrological Response to Earthquakes*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2.5 FEP Number: N32
FEP Title: ***Natural Gas Intrusion***

SCR-4.2.2.5.1 Screening decision: SO-P

Changes in groundwater flow arising from natural gas intrusion have been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 years.

SCR-4.2.2.5.2 Summary of New Information

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-4.2.2.5.2.1 *Screening Argument*

Hydrocarbon resources are present in formations beneath the WIPP (Section 2.3.1.2), and natural gas is extracted from the Morrow Formation. These reserves are, however, some 4,200 m (14,000 ft) below the surface, and no natural events or processes have been identified that could result in ***Natural Gas Intrusion*** into the Salado or the units above. ***Natural Gas Intrusion*** has therefore been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.3 Subsurface Geochemical Features, Events, and Processes

SCR-4.3.1 Groundwater Geochemistry

SCR-4.3.1.1 FEP Number: N33
FEP Title: ***Groundwater Geochemistry***

SCR-4.3.1.1.1 Screening Decision: UP

Groundwater Geochemistry *in the hydrological units of the disposal system is accounted for in PA calculations.*

SCR-4.3.1.1.2 Summary of New Information

No new information related to the screening of these FEPs has been identified. These FEPs continue to be accounted for in PA.

SCR-4.3.1.1.3 Screening Argument

The most important aspect of ***Groundwater Geochemistry*** in the region of the WIPP in terms of chemical retardation and colloid stability is salinity. ***Groundwater Geochemistr***y is discussed in detail in Sections 2.2 and 2.4 and summarized here. The Delaware Mountain Group, Castile, and Salado contain basinal brines. Waters in the Castile and Salado are at or near halite saturation. Above the Salado, groundwaters are also relatively saline, and groundwater quality is poor in all of the permeable units. Waters from the Culebra vary spatially in salinity and chemistry. They range from saline sodium chloride-rich waters to brackish calcium sulfate-rich waters. In addition, a range of magnesium to calcium ratios has been observed, and some waters reflect the influence of potash mining activities, having elevated potassium to sodium ratios. Waters from the Santa Rosa are generally of better quality than any of those from the Rustler. Salado and Castile brine geochemistry is accounted for in PA calculations of the actinide source term (Section 6.4.3.4). Culebra brine geochemistry is accounted for in the retardation factors used in PA calculations of actinide transport (see Section 6.4.6.2).

SCR-4.3.1.2 FEP Number(s): N34 and N38
FEP Title(s): ***Saline Intrusion*** (geochemical effects) (N34)
Effects of Dissolution (N38)

SCR-4.3.1.2.1 Screening Decision: SO-C

*The effects of **Saline Intrusion** and dissolution on groundwater chemistry have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.3.1.2.2 Summary of New Information

The conclusion that "No natural events or processes have been identified that could result in saline intrusion into units above the Salado" (DOE 1996a, Appendix SCR) remains valid. The possibility that dissolution might result in an increase in the salinity of low-to-moderate-ionic-strength groundwaters in the Culebra also appears unlikely.

Nevertheless, ***Saline Intrusion*** and dissolution, in the unlikely event that they occur, would not affect the predicted transport of radionuclides in the Culebra because results obtained from laboratory studies (Brush 1996) with saline solutions were largely used to predict radionuclide transport for the CCA PA and the Performance Assessment Verification Test (PAVT). These results will also be used for the CRA-2004 PA.

SCR-4.3.1.2.3 Screening Argument

Saline Intrusion and ***Effects of Dissolution*** are considered together in this discussion because dissolution of minerals such as halite (NaCl), anhydrite ($CaSO_4$), or gypsum ($CaSO_4 \cdot 2H_2O$) (N38) could – in the most extreme case – increase the salinity of groundwaters in the Culebra Member of the Rustler Formation to levels characteristic of those expected after ***Saline Intrusion*** (N34).

No natural events or processes have been identified that could result in saline intrusion into units above the Salado. Injection of Castile-Formation or Salado brines into the Culebra as a result of human intrusion, an anthropogenically induced event, was included in the PA calculations for the CCA and the EPA's PAVT, and is included in the CRA-2004 PA. Laboratory studies carried out to evaluate radionuclide transport in the Culebra following human intrusion produced data that can also be used to evaluate the consequences of natural saline intrusion.

The possibility that dissolution of halite, anhydrite, or gypsum might result in an increase in the salinity of low-to-moderate-ionic-strength groundwaters in the Culebra also appears unlikely, despite the presence of halite in the Los Medaños under most of the WIPP Site (Siegel and Lambert 1991, Figure 1-13), including the expected Culebra off-site transport pathway (the direction of flow from the point(s) at which brines from the repository would enter the Culebra in the event of human intrusion to the south or south-southeast and eventually to the boundary of the WIPP site). (The Los Medaños Member of the Rustler, formerly referred to as the unnamed lower member of the Rustler, underlies the Culebra.) A dissolution-induced increase in the salinity of Culebra groundwaters is unlikely because: (1) the dissolution of halite is known to be rapid; (2) (moderate-ionic-strength) groundwaters along the off-site transport pathway (and at many other locations in the Culebra) have had sufficient time to dissolve significant quantities of

halite, if this mineral is present in the subjacent Los Medaños and if Culebra fluids have been in contact with it; and (3) the lack of high-ionic-strength groundwaters along the offsite transport pathway (and elsewhere in the Culebra) implies that halite is present in the Los Medaños but Culebra fluids have not contacted it, or that halite is not present in the Los Medaños. Because halite dissolves so rapidly if contacted by undersaturated solutions, this conclusion does not depend on the nature and timing of Culebra recharge (i.e., whether the Rustler has been a closed hydrologic system for several thousand to a few tens of thousands of years, or is subject to significant modern recharge).

Nevertheless, saline intrusion would not affect the predicted transport of thorium (Th), uranium (U), plutonium (Pu), and americium (Am) in the Culebra. This is because: (1) the laboratory studies that quantified the retardation of Th, U, Pu, and Am for the CCA PA were carried out with both moderate-ionic-strength solutions representative of Culebra groundwaters along the expected offsite transport pathway, and with high-ionic-strength solutions representative of brines from the Castile and the Salado (Brush 1996; Brush and Storz 1996); and (2) the results obtained with the saline (Castile and Salado) solutions were – for the most part – used to predict the transport of Pu(III) and Am(III); Th(IV), U(IV), Np(IV) and Pu(IV); and U(VI). The results obtained with the saline solutions were used for these actinide oxidation states because the extent to which saline and Culebra brines will mix along the offsite transport pathway in the Culebra was unclear at the time of the CCA PA; therefore, Brush (1996) and Brush and Storz (1996) recommended that PA use the results that predict less retardation. In the case of Pu(III) and Am(III); Th(IV), U(IV), Np(IV) and Pu(IV); and U(VI), the K_ds obtained with the saline solutions were somewhat lower than those obtained with the Culebra fluids. The K_ds recommended by Brush and Storz (1996) were used for the CRA-2004 PA. These K_ds are also based mainly on results obtained with saline solutions.

Finally, it is important to reiterate that the use of results from laboratory studies with saline solutions to predict radionuclide transport in the Culebra for the CCA PA, the PAVT, and the CRA PA implements the effects of saline intrusion caused by human intrusion, not natural ***Saline Intrusion***. The conclusions that natural ***Saline Intrusion*** is unlikely, that significant dissolution is unlikely, and that these events or processes would have no significant consequence – in the unlikely event that they occur – continue to be valid.

SCR-4.3.1.3 FEP Number: N35, N36 and N37
FEP Title: ***Freshwater Intrusion*** (Geochemical Effects) (N35)
Change in Groundwater Eh (N36)
Changes in Groundwater pH (N37)

SCR-4.3.1.3.1 Screening Decision: SO-C

*The effects of **Freshwater Intrusion** on groundwater chemistry have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Changes in **Groundwater** Eh and pH have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.3.1.3.2 Summary of New Information

The most likely mechanism for (natural) ***Freshwater Intrusion*** into the Culebra, ***Changes in Groundwater Eh***, ***Changes in Groundwater pH*** is (natural) recharge of the Culebra. There is still considerable uncertainty regarding the extent and timing of recharge of the Culebra. If recharge occurs mainly during periods of high precipitation (pluvials) associated with periods of continental glaciation, the consequences of such recharge are probably already reflected in the ranges of geochemical conditions currently observed in the Culebra as a whole, as well as along the likely offsite transport pathway. Therefore, the occurrence of another pluvial during the 10,000-year WIPP regulatory period would have no significant, additional consequence for the long-term performance of the repository. If, on the other hand, significant recharge occurs throughout both phases of the glacial-interglacial cycles, the conclusion that the effects of pluvial and modern recharge are inconsequential (are already reflected by existing variations in geochemical conditions) is also still valid.

The decision to screenout FEPs N35, N36, and N37 on the basis of low consequence for the long-term performance of the WIPP remains valid. However, the following discussion provides additional justification for this decision. FEPs N35, N36, and N37 are considered together in this discussion because the same process is the most likely cause, and perhaps the only plausible cause, for all three of these events or changes in these important geochemical properties of groundwaters in the Culebra Member of the Rustler Formation. To summarize, the original screening argument for these FEPs has been modified to provide a more robust basis for the low consequence decision, and ***Effects of Dissolution*** (N38) have been removed from this set of FEPs and is now addressed jointly with ***Saline Intrusion*** (N34).

SCR-4.3.1.3.3 Screening Argument

Natural changes in the groundwater chemistry of the Culebra and other units that resulted from ***Saline Intrusion*** or ***Freshwater Intrusion*** could potentially affect chemical retardation and the stability of colloids. Changes in ***Groundwater Eh*** and ***Groundwater pH*** could also affect the migration of radionuclides (see FEPs W65 to W70). No natural EPs have been identified that could result in ***Saline Intrusion*** into units above the Salado, and the magnitude of any natural temporal variation due to the effects of dissolution on groundwater chemistry, or due to changes in recharge, is likely to be no greater than the present spatial variation. These FEPs related to the effects of future natural changes in groundwater chemistry have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The most likely mechanism for (natural) ***freshwater intrusion*** into the Culebra (FEP N35), ***Changes in Groundwater*** Eh (N36), and ***Changes in Groundwater*** pH (N37) is (natural) recharge of the Culebra. (Other FEPs consider possible anthropogenically induced recharge). These three FEPs are closely related because an increase in the rate of recharge could reduce the ionic strength(s) of Culebra groundwaters, possibly enough to saturate the Culebra with (essentially) fresh water, at least temporarily. Such a change in ionic strength could, if enough atmospheric oxygen remained in solution, also increase the Eh of Culebra groundwaters enough to oxidize plutonium from the relatively immobile +III and +IV oxidation states (Pu(III) and Pu(IV)) – the oxidation states expected under current conditions (Brush 1996; Brush and Storz 1996) – to the relatively mobile +V and +VI oxidation states (Pu(V) and Pu(VI)). Similarly,

recharge of the Culebra with freshwater could also change the pH of Culebra groundwaters from the currently observed range of about 6 to 7 to mildy acidic values, thus (possibly) decreasing the retardation of dissolved Pu and Am. (These changes in ionic strength, Eh, and pH could also affect mobilities of Th, U, and neptunium (Np), but the long-term performance of the WIPP is much less sensitive to the mobilities of these radioelements than to those of Pu and Am.)

There is still considerable uncertainty regarding the extent and timing of recharge of the Culebra. Lambert (1986), Lambert and Carter (1987), Lambert and Harvey (1987), and Lambert (1991) used a variety of stable and radiogenic, isotopic-dating techniques to conclude that the Rustler (and the Dewey Lake Formation) have been closed hydrologic systems for several thousand to a few tens of thousands of years. In other words, the last significant recharge of the Rustler occurred during the late Pleistocene in response to higher levels of precipitation and infiltration associated with the most recent continental glaciation of North America, and the current flow field in the Culebra is the result of the slow discharge of groundwater from this unit. Other investigators have agreed that it is possible that Pleistocene recharge has contributed to present-day flow patterns in the Culebra, but that current patterns are also consistent with significant current recharge (Haug et al. 1987; Davies 1989). Still others (Chapman 1986, 1988) have rejected Lambert's interpretations in favor of exclusively modern recharge, at least in some areas. For example, the low-salinity of Hydrochemical Zone B south of the WIPP site could represent dilution of Culebra groundwater with significant quantities of recently introduced meteoric water (see Siegel et al. 1991, pp. 2-57 – 2-62 and Figure 2-17 for definitions and locations of the four hydrochemical facies in the Culebra in and around the WIPP site).

The current program to explain the cause(s) of the rising water levels observed in Culebra monitoring wells may elucidate the nature and timing of recharge. However, the justification of this screening decision does not depend on how this issue is resolved. If recharge occurs mainly during periods of high precipitation (pluvials) associated with periods of continental glaciation, the consequences of such recharge are probably already reflected in the ranges of geochemical conditions currently observed in the Culebra as a whole, as well as along the likely offsite transport pathway (the direction of flow from the point(s) at which brines from the repository would enter the Culebra in the event of human intrusion to the south or south-southeast and eventually to the boundary of the WIPP site). Hence, the effects of recharge, (possible) freshwater intrusion, and (possible) concomitant changes in groundwater Eh and pH can be screened out on the basis of low consequence to the performance of the far-field barrier. The reasons for the conclusion that the effects of pluvial recharge are inconsequential (are already included among existing variations in geochemical conditions) are: (1) as many as 50 continental glaciations and associated pluvials have occurred since the late Pliocene Epoch 2.5 million years ago (2.5 Ma BP); (2) the glaciations and pluvials that have occurred since about 0.5 to 1 Ma BP have been significantly more severe than those that occurred prior to 1 Ma BP (see, for example, Servant 2001); (3) the studies that quantified the retardation of Th, U, Pu, and Am for the WIPP CCA PA calculations and the EPA's PAVT were carried out under conditions that encompass those observed along the likely Culebra offsite transport pathway (Brush 1996; Brush and Storz 1996); and (4) these studies demonstrated that conditions in the Culebra are favorable for retardation of actinides despite the effects of as many as 50 periods of recharge.

It is also worth noting that the choice of the most recent glacial maximum as an upper limit for possible climatic changes during the 10,000 year WIPP regulatory period (Swift 1991 CCA

Appendix CLI) established conservative upper limits for precipitation and recharge of the Culebra at the WIPP site. The review by Swift (1991), later incorporated in CCA Appendix CLI, provides evidence that precipitation in New Mexico did not attain its maximum level (about 60-100 percent of current precipitation) until a few thousand years before the last glacial maximum. Swift pointed out that:

> Prior to the last glacial maximum 22 to 18 ka BP, evidence from mid- Wisconsin faunal assemblages in caves in southern New Mexico, including the presence of extralimital species such as the desert tortoise that are now restricted to warmer climates, suggests warm summers and mild, relatively dry winters (Harris 1987, 1988). Lacustrine evidence confirms the interpretation that conditions prior to and during the glacial advance that were generally drier than those at the glacial maximum. Permanent water did not appear in what was later to be a major lake in the Estancia Valley in central New Mexico until sometime before 24 ka BP (Bachhuber 1989). Late-Pleistocene lake levels in the San Agustin Plains in western New Mexico remained low until approximately 26.4 ka BP, and the $\delta^{18}O$ record from ostracode shells suggests that mean annual temperatures at that location did not decrease significantly until approximately 22 ka BP (Phillips et al. 1992).

Therefore, it is likely that precipitation and recharge did not attain levels characteristic of the most recent glacial maximum until about 70,000 to 75,000 years after the last glaciations had begun. High-resolution, deep-sea $\delta^{18}O$ data (and other data) reviewed by Servant (2001, Figures 1 and 2) support the conclusion that, although the volume of ice incorporated in continental ice sheets can expand rapidly at the start of a glaciation rapidly, attainment of maximum volume does not occur until a few thousand or a few tens of thousands of years prior to the termination of the approximately 100,000-year glaciations that have occurred during the last 0.5-1 Ma BP. Therefore, it is unlikely that precipitation and recharge will reach their maximum levels during the 10,000-year regulatory period.

If, on the other hand, significant recharge occurs throughout both phases of the glacial-interglacial cycles, the conclusion that the effects of pluvial and modern recharge are inconsequential (are already reflected by existing variations in geochemical conditions) is also still valid.

SCR-4.3.1.4 FEP Number: N38
FEP Title: ***Effects of Dissolution***

SCR-4.3.1.4.1 Screening Decision: SO-C

See discussion in ***Saline Intrusion*** (N34).

SCR-4.4 Geomorphological Features, Events, and Processes

SCR-4.4.1 Physiography

SCR-4.4.1.1 FEP Number: N39
FEP Title: ***Physiography***

SCR-4.4.1.1.1 Screening Decision: UP

*Relevant aspects of the **physiography**, geomorphology, and topography of the region around the WIPP are accounted for in PA calculations.*

SCR-4.4.1.1.2 Summary of New Information

No new information has been identified related to this FEP. No changes have been made.

SCR-4.4.1.1.3 Screening Argument

Physiography and geomorphology are discussed in detail in Section 2.1.4, and are accounted for in the setup of the PA calculations (Section 6.4.2).

SCR-4.4.1.2 FEP Number: N40
FEP Title: ***Impact of a Large Meteorite***

SCR-4.4.1.2.1 Screening Decision: SO-P

*Disruption arising from the **Impact of a Large Meteorite** has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-4.4.1.3 Summary of New Information

No new information has been identified related to this FEP. No changes have been made.

SCR-4.4.1.4 Screening Argument

Meteors frequently enter the earth's atmosphere, but most of these are small and burn up before reaching the ground. Of those that reach the ground, most produce only small impact craters that would have no effect on the postclosure integrity of a repository 650 m (2,150 ft) below the ground surface. While the depth of a crater may be only one-eighth of its diameter, the depth of the disrupted and brecciated material is typically one-third of the overall crater diameter (Grieve 1987, p. 248). Direct disruption of waste at the WIPP would only occur with a crater larger than 1.8 km (1.1 mi) in diameter. Even if waste were not directly disrupted, the ***impact of a large meteorite*** could create a zone of fractured rocks beneath and around the crater. The extent of such a zone would depend on the rock type. For sedimentary rocks, the zone may extend to a depth of half the crater diameter or more (Dence et al. 1977, p. 263). The impact of a meteorite causing a crater larger than 1 km (0.6 mi) in diameter could thus fracture the Salado above the repository.

Geological evidence for meteorite impacts on earth is rare because many meteorites fall into the oceans and erosion and sedimentation serve to obscure craters that form on land. Dietz (1961) estimated that meteorites that cause craters larger than 1 km (0.6 mi) in diameter strike the earth at the rate of about one every 10,000 years (equivalent to about 2×10^{-13} impacts per square kilometer per year). Using observations from the Canadian Shield, Hartmann (1965, p. 161) estimated a frequency of between 0.8×10^{-13} and 17×10^{-13} per square kilometer per year for impacts causing craters larger than 1 km (0.6 mi). Frequencies estimated for larger impacts in studies reported by Grieve (1987, p. 263) can be extrapolated to give a rate of about 1.3×10^{-12} per square kilometer per year for craters larger than 1 km (0.6 mi). It is commonly assumed that meteorite impacts are randomly distributed across the earth's surface, although Halliday (1964, pp. 267-277) calculated that the rate of impact in polar regions would be some 50 to 60 percent of that in equatorial regions. The frequencies reported by Grieve (1987) would correspond to an overall rate of about 1 per 1,000 years on the basis of a random distribution.

Assuming the higher estimated impact rate of 17×10^{-13} impacts per square kilometer per year for impacts leading to fracturing of sufficient extent to affect a deep repository and assuming a repository footprint of 1.4 km × 1.6 km (0.9 mi × 1.0 mi) for the WIPP yields a frequency of about 4×10^{-12} impacts per year for a direct hit above the repository. This impact frequency is several orders of magnitude below the screening limit of 10^{-4} per 10,000 years provided in 40 CFR § 194.32(d).

Meteorite hits directly above the repository footprint are not the only impacts of concern, however, because large craters may disrupt the waste panels even if the center of the crater is outside the repository area. It is possible to calculate the frequency of meteorite impacts that could disrupt a deep repository such as the WIPP by using the conservative model of a cylinder of rock fractured to a depth equal to one-half the crater diameter, as shown in CCA Appendix SCR, Figure SCR-1. The area within which a meteorite could impact the repository is calculated by

$$S_D = \left(L + 2 \times \frac{D}{2}\right) \times \left(W + 2 \times \frac{D}{2}\right), \tag{1}$$

Where

L = length of the repository footprint (kilometers),
W = width of the repository footprint (kilometers),
D = diameter of the impact crater (kilometers), and
S_D = area of the region where the crater would disrupt the repository (square kilometers).

There are insufficient data on meteorites that have struck the earth to derive a distribution function for the size of craters directly. Using meteorite impacts on the moon as an analogy, however, Grieve (1987, p. 257) derived the following distribution function:

$$F_D \propto D^{-18} \tag{2}$$

where

F_D = frequency of impacts resulting in craters larger than D (impacts per square kilometer per year).

If f(D) denotes the frequency of impacts giving craters of diameter D, then the frequency of impacts giving craters larger than D is

$$FD = \int_{D}^{\infty} f\ (D)\, d\, D \tag{3}$$

and

$$f\ (D) = F_1 \times 1.8 \times D^{-28}, \tag{4}$$

where

F_1 = frequency of impacts resulting in craters larger than 1 km (impacts per square kilometer per year), and

$f(D)$ = frequency of impacts resulting in craters of diameter D (impacts per square kilometer per year).

The overall frequency of meteorite impacts that could disrupt or fracture the repository is thus given by

$$N = \int_{2h}^{\infty} f\ (D) \times S_D\, dD, \tag{5}$$

Where

h = depth to repository (kilometers),

N = frequency of impacts leading to disruption of the repository (impacts per year), and

$$N = 1.8F_1 \left[1.8\ LW(2h)^{-18} + 0.8(L + W)\,(2h)^{-0.8} - 0.2(2h)^{0.2}\right] \tag{6}$$

If it is assumed that the repository is located at a depth of 650 m (2,150 ft) and has a footprint area of 1.4 km × 1.6 km (0.9 mi × 1.0 mi) and that meteorites creating craters larger than 1 km in diameter hit the earth at a frequency (F_1) of 17×10^{-13} impacts per square kilometer per year, then Equation (6) gives a frequency of approximately 1.3×10^{-11} impacts per year for impacts disrupting the repository. If impacts are randomly distributed over time, this corresponds to a probability of 1.3×10^{-7} over 10,000 years.

Similar calculations have been performed that indicate rates of impact of between 10^{-12} and 10^{-13} per year for meteorites large enough to disrupt a deep repository (see, for example, Hartmann 1979, Kärnbränslesakerhet 1978, Claiborne and Gera 1974, Cranwell et al. 1990, and Thorne

1992). Meteorite impact can thus be eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

Assuming a random or nearly random distribution of meteorite impacts, cratering at any location is inevitable given sufficient time. Although repository depth and host-rock lithology may reduce the consequences of a ***Meteorite Impact***, there are no repository locations or engineered systems that can reduce the probability of impact over 10,000 years.

SCR-4.4.1.5 FEP Number: N41 and N42
FEP Title(s): ***Mechanical Weathering*** (N41)
Chemical Weathering (N42)

SCR-4.4.1.5.1 Screening Decision: SO-C

The effects of ***Chemical and Mechanical Weathering*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.4.1.5.2 Summary of New Information

No new information has been identified related to these FEPs. No changes have been made.

SCR-4.4.1.5.3 Screening Argument

Mechanical Weathering and ***Chemical Weathering*** are assumed to be occurring at or near the surface around the WIPP site, through processes such as exfoliation and leaching. The extent of these processes is limited and they will contribute little to the overall rate of erosion in the area or to the availability of material for other erosional processes. The effects of ***Chemical and Mechanical Weathering*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.4.1.6 FEP Number: N43, N44 & N45
FEP Title: ***Aeolian Erosion*** (N43)
Fluvial Erosion (N44)
Mass Wasting (N45

SCR-4.4.1.6.1 Screening Decision: SO-C

The effects of ***Fluvial and Aeolian Erosion and Mass W asting*** *in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.4.1.6.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. No changes have been made.

SCR-4.4.1.6.3 Screening Argument

The geomorphological regime on the Mescalero Plain (Los Medaños) in the region of the WIPP is dominated by aeolian processes. Dunes are present in the area, and although some are stabilized by vegetation, ***Aeolian Erosion*** will occur as they migrate across the area. Old dunes will be replaced by new dunes, and no significant changes in the overall thickness of aeolian material are likely to occur.

Currently, precipitation in the region of the WIPP is too low (about 33 cm [13 in.] per year) to cause perennial streams, and the relief in the area is too low for extensive sheet flood erosion during storms. An increase in precipitation to around 61 cm (24 in.) per year in cooler climatic conditions could result in perennial streams, but the nature of the relief and the presence of dissolution hollows and sinks will ensure that these streams remain small. Significant ***Fluvial Erosion*** is not expected during the next 10,000 years.

Mass Wasting (the downslope movement of material caused by the direct effect of gravity) is important only in terms of sediment erosion in regions of steep slopes. In the vicinity of the WIPP, Mass ***Wasting*** will be insignificant under the climatic conditions expected over the next 10,000 years.

Erosion from wind, water, and mass wasting will continue in the WIPP region throughout the next 10,000 years at rates similar to those occurring at present. These rates are too low to affect the performance of the disposal system significantly. Thus, the effects of ***Fluvial*** and ***Aeolian Erosion*** and Mass ***Wasting*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.4.1.7 FEP Number: N50
FEP Title: **Soil Development**

SCR-4.4.1.7.1 Screening Decision: SO-C

Soil Development *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.4.1.7.2 Summary of New Information

No new information has been identified related to the screening of this FEP. Editorial changes have been made.

SCR-4.4.1.7.3 Screening Argument

The Mescalero caliche is a well-developed calcareous remnant of an extensive soil profile across the WIPP site and adjacent areas. Although this unit may be up to 3 m (10 ft) thick, it is not continuous and does not prevent infiltration to the underlying formations. At Nash Draw, this caliche, dated in Lappin et al. (1989, pp. 2-4) at 410,000 to 510,000 years old, is present in collapse blocks, indicating some growth of Nash Draw in the late Pleistocene. Localized gypsite spring deposits about 25,000 years old occur along the eastern flank of Nash Draw, but the springs are not currently active. The Berino soil, interpreted as 333,000 years old (Rosholt and

McKinney 1980, Table 5), is a thin soil horizon above the Mescalero caliche. The persistence of these soils on the Livingston Ridge and the lack of deformation indicates the relative stability of the WIPP region over the past half-million years.

Continued growth of caliche may occur in the future but will be of low consequence in terms of its effect on infiltration. Other soils in the area are not extensive enough to affect the amount of infiltration that reaches underlying aquifers. ***Soil Development*** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5 Surface Hydrological Features, Events, and Processes

SCR-4.5.1 Depositional Processes

SCR-4.5.1.1 FEP Number: N46, N47, N48 and N49
FEP Title: ***Aeolian Deposition*** (N46)
Fluvial Deposition (47)
Lacustrine Deposition (N48)
Mass Waste (Deposition) (N49)

SCR-4.5.1.1.1 Screening Decision: SO-C

*The effects of **Aeolian**, **Fluvial**, **and Lacustrine** deposition and sedimentation in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.5.1.1.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. No changes have been made.

SCR-4.5.1.1.3 Screening Argument

The geomorphological regime on the Mescalero Plain (Los Medaños) in the region of the WIPP is dominated by aeolian processes, but although some dunes are stabilized by vegetation, no significant changes in the overall thickness of aeolian material are expected to occur. Vegetational changes during periods of wetter climate may further stabilize the dune fields, but ***Aeolian Deposition*** is not expected to significantly increase the overall thickness of the superficial deposits.

The limited extent of water courses in the region of the WIPP, under both present-day conditions and under the expected climatic conditions, will restrict the amount of ***Fluvial Deposition*** and ***Lacustrine Deposition*** in the region.

Mass Wasting (Deposition) may be significant if it results in dams or modifies streams. In the region around the WIPP, the Pecos River forms a significant water course some 19 km (12 mi) away, but the broadness of its valley precludes either significant mass wasting or the formation of large impoundments.

Sedimentation from wind, water, and Mass ***Wasting*** is expected to continue in the WIPP region throughout the next 10,000 years at the low rates similar to those occurring at present. These rates are too low to significantly affect the performance of the disposal system. Thus, the effects of ***Aeolian***, ***Fluvial***, ***and Lacustrine Deposition*** and sedimentation resulting from Mass ***Wasting*** have been eliminated from PA calculations on the basis of low consequence.

SCR-4.5.2 Streams and Lakes

SCR-4.5.2.1 FEPs Number: N51
FEPs Title: ***Stream and River Flow***

SCR-4.5.2.1.1 Screening Decision: SO-C

Stream and River Flow *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.5.2.1.2 Summary of New Information

No new information has been identified related to the screening of this FEP. No changes have been made.

SCR-4.5.2.1.3 Screening Argument

No perennial streams are present at the WIPP site, and there is no evidence in the literature indicating that such features existed at this location since the Pleistocene (see, for example, Powers et al. 1978; and Bachman 1974, 1981, and 1987b). The Pecos River is approximately 19 km (12 mi) from the WIPP site and more than 90 m (300 ft) lower in elevation. ***Stream and River Flow*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5.2.2 FEP Number: N52
FEP Title: ***Surface Water Bodies***

SCR-4.5.2.2.1 Screening Decision: SO-C

The effects of ***Surface Water Bodies*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.5.2.2.2 Summary of New Information

No new information has been identified related to the screening of this FEP. No changes have been made.

SCR-4.5.2.2.3 Screening Argument

No standing ***Surface Water Bodies*** are present at the WIPP site, and there is no evidence in the literature indicating that such features existed at this location during or after the Pleistocene (see, for example, Powers et al. 1978; and Bachman 1974, 1981, and 1987b). In Nash Draw, lakes

and spoil ponds associated with potash mines are located at elevations 30 m (100 ft) below the elevation of the land surface at the location of the waste panels. There is no evidence in the literature to suggest that Nash Draw was formed by stream erosion or was at any time the location of a deep body of standing water, although shallow playa lakes have existed there at various times. Based on these factors, the formation of large lakes is unlikely and the formation of smaller lakes and ponds is of little consequence to the performance of the disposal system. The effects of ***Surface Water Bodies*** have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5.3 Groundwater Recharge and Discharge

SCR-4.5.3.1 FEP Number: N53, N54, and N55
FEP Title: ***Groundwater Discharge*** (N53)
Groundwater Recharge (N54)
Infiltration (N55)

SCR-4.5.3.1.1 Screening Decision: UP

Groundwater Recharge, Infiltration, and ***Groundwater Discharge*** *are accounted for in PA calculations.*

SCR-4.5.3.1.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-4.5.3.1.3 Screening Argument

The groundwater basin described in Section 2.2.1.4 is governed by flow from areas where the water table is high to areas where the water table is low. The height of the water table is governed by the amount of ***Groundwater Recharge*** reaching the water table, which in turn is a function of the vertical hydraulic conductivity and the partitioning of precipitation between evapotranspiration, runoff, and ***Infiltration***. Flow within the Rustler is also governed by the amount of ***Groundwater Discharge*** that takes place from the basin. In the region around the WIPP, the principal discharge areas are along Nash Draw and the Pecos River. Groundwater flow modeling accounts for infiltration, recharge, and discharge (Sections 2.2.1.4 and 6.4.10.2).

SCR-4.5.3.2 FEP Number: N56
FEP Title: ***Changes in Groundwater Recharge and Discharge***

SCR-4.5.3.2.1 Screening Decision: UP

Changes in ***Groundwater Recharge and Discharge*** *arising as a result of climate change are accounted for in PA calculations.*

SCR-4.5.3.2.2 Summary of New Information

No information has become available that would change the screening decision for this FEP. Changes in the implementation (if any) of this FEP within PA are addressed in Chapter 6.0. This FEP has been separated from N57 and N58 for editorial purposes.

SCR-4.5.3.2.3 Screening Argument

Changes in recharge may affect groundwater flow and radionuclide transport in units such as the Culebra and Magenta dolomites. Changes in the surface environment driven by natural climate change are expected to occur over the next 10,000 years (see FEPs N59 to N63). Groundwater basin modeling (Section 2.2.1.4) indicates that a change in recharge will affect the height of the water table in the area of the WIPP, and that this will in turn affect the direction and rate of groundwater flow.

The present-day water table in the vicinity of the WIPP is within the Dewey Lake at about 980 m (3,215 ft) above mean sea level (Section 2.2.1.4.2.1). An increase in recharge relative to present-day conditions would raise the water table, potentially as far as the local ground surface. Similarly, a decrease in recharge could result in a lowering of the water table. The low transmissivity of the Dewey Lake and the Rustler ensures that any such lowering of the water table will be at a slow rate, and lateral discharge from the groundwater basin is expected to persist for several thousand years after any decrease in recharge. Under the anticipated changes in climate over the next 10,000 years, the water table will not fall below the base of the Dewey Lake, and dewatering of the Culebra is not expected to occur during this period (Section 2.2.1.4).

Changes in Groundwater Recharge and Discharge are accounted for in PA calculations through definition of the boundary conditions for flow and transport in the Culebra (Section 6.4.9).

SCR-4.5.3.3 FEP Number: N57 & N58
FEP Title: ***Lake Formation*** (N57)
River Flooding (N58)

SCR-4.5.3.3.1 Screening Decision: SO-C

The effects of ***River Flooding and Lake Formation*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.5.3.3.2 Summary of New Information

The original text in CCA Appendix SCR has been modified only to remove reference to other FEPs. No substantive changes have been made to the FEP descriptions, screening arguments, or screening decision.

SCR-4.5.3.3.3 Screening Argument

Intermittent flooding of stream channels and the formation of shallow lakes will occur in the WIPP region over the next 10,000 years. These may have a short-lived and local effect on the height of the water table, but are unlikely to affect groundwater flow in the Culebra.

Future occurrences of playa lakes or other longer-term floods will be remote from the WIPP and will have little consequence on system performance in terms of groundwater flow at the site. There is no reason to believe that any impoundments or lakes could form over the WIPP site itself. Thus, ***River Flooding*** and ***Lake Formation*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.6 Climate Events and Processes

SCR-4.6.1 Climate and Climate Changes

SCR-4.6.1.1 FEP Number: N59 and N60
FEP Title: ***Precipitation*** (N59)
Temperature (N60)

SCR-4.6.1.1.1 Screening Decision: UP

Precipitation and temperature are accounted for in PA calculations.

SCR-4.6.1.1.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-4.6.1.1.3 Screening Argument

The climate and meteorology of the region around the WIPP are described in, Section 2.5.2. Precipitation in the region is low (about 33 cm (13 in.) per year) and temperatures are moderate with a mean annual temperature of about 63°F (17°C). ***Precipitation*** and ***Temperature*** are important controls on the amount of recharge that reaches the groundwater system and are accounted for in PA calculations by use of a sampled parameter for scaling flow velocity in the Culebra (Section 6.4.9 and Appendix PA, Attachment PAR).

SCR-4.6.1.2 FEP Number: N61
FEP Title: ***Climate Change***

SCR-4.6.1.2.1 Screening Decision: UP

Climate Change *is accounted for in PA calculations.*

SCR-4.6.1.2.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-4.6.1.2.3 Screening Argument

Climate Changes are instigated by changes in the earth's orbit, which affect the amount of insolation, and by feedback mechanisms within the atmosphere and hydrosphere. Models of these mechanisms, combined with interpretations of the geological record, suggest that the climate will become cooler and wetter in the WIPP region during the next 10,000 years as a result of natural causes. Other changes, such as fluctuations in radiation intensity from the sun and variability within the many feedback mechanisms, will modify this climatic response to orbital changes. The available evidence suggests that these changes will be less extreme than those arising from orbital fluctuations.

The effect of a change to cooler and wetter conditions is considered to be an increase in the amount of recharge, which in turn will affect the height of the water table (see FEPs N53 through N56). The height of the water table across the groundwater basin is an important control on the rate and direction of groundwater flow within the Culebra (see Section 2.2.1.4), and hence potentially on transport of radionuclides released to the Culebra through the shafts or intrusion boreholes. ***Climate Change*** is accounted for in PA calculations through a sampled parameter used to scale groundwater flow velocity in the Culebra (Section 6.4.9 and Appendix PA, Attachment PAR).

SCR-4.6.1.3 FEP Number: N62 and N63
FEP Title: ***Glaciation*** (N62)
Permafrost (N63)

SCR-4.6.1.3.1 Screening Decision: SO-P

Glaciation *and the effects of* ***Permafrost*** *have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-4.6.1.3.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. No changes have been made.

SCR-4.6.1.3.3 Screening Argument

No evidence exists to suggest that the northern part of the Delaware Basin has been covered by continental glaciers at any time since the beginning of the Paleozoic Era. During the maximum extent of continental glaciation in the Pleistocene Epoch, glaciers extended into northeastern Kansas at their closest approach to southeastern New Mexico. There is no evidence that alpine glaciers formed in the region of the WIPP during the Pleistocene glacial periods.

According to the theory that relates the periodicity of climate change to perturbations in the earth's orbit, a return to a full glacial cycle within the next 10,000 years is highly unlikely (Imbrie and Imbrie 1980, 951).

Thus, ***Glaciation*** has been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years. Similarly, a number of processes associated with the proximity of an ice sheet or valley glacier, such as ***Permafrost*** and accelerated slope erosion (solifluction) have been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.7 Marine Features, Events, and Process

SCR-4.7.1 Seas, Sedimentation, and Level Changes

SCR-4.7.1.1 FEP Number(s): N64 and N65
FEP Title(s): ***Seas and Oceans*** (N64)
Estuaries (N65)

SCR-4.7.1.1 Screening Decision: SO-C

*The effects of **Estuaries**, seas, and oceans have has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.7.1.1.2 Summary of New Information

No new information has been identified related to this FEP. No changes have been made.

SCR-4.7.1.1.3 Screening Argument

The WIPP site is more than 800 km (480 mi) from the Pacific Ocean and from the Gulf of Mexico. ***Estuaries*** and ***Seas and Oceans*** have therefore been eliminated from PA calculations on the basis of low consequence to the disposal system.

SCR-4.7.1.2 FEPs Number(s): N66 and N67
FEPs Title(s): ***Coastal Erosion*** (N66)
Marine Sediment Transport and Deposition (N67)

SCR-4.7.1.2.1 Screening Decision: SO-C

*The effects of **Coastal Erosion**,* and ***Marine Sediment Transport and Deposition*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.7.1.2.2 Summary of New Information

No new information has been identified related to these FEPs. No changes have been made.

SCR-4.7.1.2.3 Screening Argument

The WIPP site is more than 800 km (480 mi) from the Pacific Ocean and Gulf of Mexico. The effects of ***Coastal Erosion***, and ***Marine Sediment Transport and Deposition*** have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.7.1.3 FEP Number: N68
FEP Title: ***Sea Level Changes***

SCR-4.7.1.3.1 Screening Decision: SO-C

*The effects of both short-term and long-term **Sea Level Changes** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.7.1.3.2 Summary of New Information

No new information has been identified relating to the screening of this FEP. No changes have been made.

SCR-4.7.1.3.3 Screening Argument

The WIPP site is some 1,036 m (3,400 ft) above sea level. Global ***Sea Level Changes*** may result in sea levels as much as 140 m (460 ft) below that of the present day during glacial periods, according to Chappell and Shackleton (1986, p. 138). This can have marked effects on coastal aquifers. During the next 10,000 years, the global sea level can be expected to drop towards this glacial minimum, but this will not affect the groundwater system in the vicinity of the WIPP. Short-term changes in sea level, brought about by events such as meteorite impact, tsunamis, seiches, and hurricanes may raise water levels by several tens of meters. Such events have a maximum duration of a few days and will have no effect on the surface or groundwater systems at the WIPP site. Anthropogenic-induced global warming has been conjectured by Warrick and Oerlemans (1990, p. 278) to result in longer-term sea level rise. The magnitude of this rise, however, is not expected to be more than a few meters, and such a variation will have no effect on the groundwater system in the WIPP region. Thus, the effects of both short-term and long-term ***Sea Level Changes*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.8 Ecological Features, Events, and Process

SCR-4.8.1 Flora and Fauna

SCR-4.8.1.1 FEP Number(s): N69 and N70
FEP Title(s): ***Plants*** (N69)
Animals (N70)

SCR-4.8.1.1.1 Screening Decision: SO-C

*The effects of the natural **Plants and Animals**, (flora and fauna) in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.8.1.1.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. Only editorial changes have been made.

SCR-4.8.1.1.3 Screening Argument

The terrestrial and aquatic ecology of the region around the WIPP is described in Section 2.4.1. The ***Plants*** in the region are predominantly shrubs and grasses. The most conspicuous ***Animals*** in the area are jackrabbits and cottontail rabbits. The effects of this flora and fauna in the region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.8.1.2 FEP Number: N71
FEP Title: ***Microbes***

SCR-4.8.1.2.1 Screening Decision: SO-C
UP for colloidal effects and gas generation

*The effects of **Microbes** on the region of the WIPP has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.8.1.2.2 Summary of New Information

Microbes can be important in soil development. As dissolved actinide elements are introduced to the Culebra, it is possible that those dissolved actinides can sorb onto ***Microbes***. However, due to the size effect, ***Microbes*** will be rapidly filtered out of the advective flow domain; hence, the effect of ***Microbes*** on radionuclide transport in the Culebra will be insignificant. The original screening decision remains valid. Additional information has been included to support the screening argument.

SCR-4.8.1.2.3 Screening Argument

Microbes are presumed to be present with the thin soil horizons. Gillow et al. (2000) characterized the microbial distribution in Culebra groundwater at the WIPP site. Culebra groundwater contained $1.51 \pm 1.08 \times 10^5$ cells/ml. The dimension of the cells are 0.75 μm in length and 0.58 μm in width, right at the upper limit of colloidal particle size. Gillow et al. (2000) also found that at pH 5.0, Culebra denitrifier CDn ($0.90 \pm 0.02 \times 10^8$ cells/ml) removed 32 percent of the uranium added to sorption experiments, which is equivalent to 180 ± 10 mg U/g of dry cells. Another isolate from WIPP (Halomonas sp.) ($3.55 \pm 0.11 \times 10^8$ cells/ml) sorbed 79 percent of the added uranium. Due to their large sizes, microbial cells as colloidal particles will be rapidly filtered out in the Culebra formation. Therefore, the original FEP screening decision that ***Microbes*** in groundwater have an insignificant impact on radionuclide transport in the Culebra formation remains valid. A similar conclusion has also been arrived for Sweden repository environments (Pedersen 1999).

SCR-4.8.1.3 FEP Number: N72
FEP Title: ***Natural Ecological Development***

SCR-4.8.1.3.1 Screening Decision: SO-C

The effects of ***Natural Ecological Development*** *likely to occur in the region of the WIPP have been eliminated from* PA *calculations on the basis of low consequence to the performance of the disposal system.*

SCR-4.8.1.3.2 Summary of New Information

No new information has been identified related to the screening of this FEP. No changes have been made.

SCR-4.8.1.3.3 Screening Argument

The region around the WIPP is sparsely vegetated as a result of the climate and poor soil quality. Wetter periods are expected during the regulatory period, but botanical records indicate that, even under these conditions, dense vegetation will not be present in the region (Swift 1992; see CCA Appendix CLI, p. 17). The effects of the indigenous fauna are of low consequence to the performance of the disposal system and no natural events or processes have been identified that would lead to a change in this fauna that would be of consequence to system performance. ***Natural Ecological Development*** in the region of the WIPP has therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.0 SCREENING OF HUMAN-INITIATED EPS

The following section presents screening arguments and decisions for human-initiated EPs. Table SCR-2 provides summary information regarding changes to human-initiated EPs since the CCA. Of the 57 human-initiated EPs, 13 remain unchanged, 39 were updated with new information or were edited for clarity and completeness, 4 screening decisions were changed, 1

EP was deleted from the baseline by combining with other more appropriate EPs, and 2 EPs were added.

SCR-5.1 Human Induced Geological Events and Process

SCR-5.1.1 Drilling

SCR-5.1.1.1 FEP Number: H1, H2, H4, H8, and H9
FEP Title: ***Oil and Gas Exploration*** (H1)
Potash Exploration (H2)
Oil and Gas Exploitation (H4)
Other Resources (drilling for) (H8)
Enhanced Oil and Gas Recovery (drilling for) (H9)

SCR-5.1.1.1.1 Screening Decision: SO-C (HCN)
DP (Future)

The effects of historical, current, and near-future drilling associated with ***Oil and Gas Exploration, Potash Exploration, Oil and G as Exploitation, Drilling for Other Resources,*** *and* ***Enhanced Oil*** *and* ***Gas Recovery*** *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system (see screening discussion for H21, H22, and H23). Oil and gas exploration, potash exploration, oil and gas exploitation, drilling for other resources, and enhanced oil and gas recovery in the future is accounted for in disturbed performance scenarios through incorporation of the rate of future drilling as specified in 40 CFR § 194.33.*

SCR-5.1.1.1.2 Summary of New Information

Regulations require that drilling for resources in the future be considered in PA calculations. As such, deep drilling associated with ***Oil and Gas Exploration, Potash Exploration, Oil and Gas Exploration*** drilling for ***Other Resources***, and ***Enhanced Oil*** *and* ***Gas Recovery*** in the future is accounted for in the PA in DP scenarios via the drilling rate as calculated by the method prescribed by the EPA. For HCN time frames, deep drilling for ***Oil and Gas Exploration, Potash Exploration, Oil and Gas Exploitation,*** and drilling for ***Other Resources*** has been screened out based on consequence. Additionally, ***Drilling for the Purposes of Enhanced Oil*** *and* ***Gas Recovery*** has been screened out based on consequence because the process of drilling does not vary depending on the intended use of the borehole, be it for resource recovery, reservoir stimulation, or for other purposes such as geologic characterization and exploration. The screening decision of SO-C for HCN for these FEPs is largely based on the screening of FEPs H21 ***Drilling Fluid Flow***, H22 ***Drilling Fluid Loss***, and H23 ***Blowouts***. Because these activities are currently taking place, and will not occur within the land withdrawal boundary during the current time period nor in the near future (due to active institutional controls), the only possible impact to the repository could be from ***Drilling Fluid Flow, Fluid Loss, or Blowout*** in boreholes outside the WIPP land withdrawal boundary. The specific effects are discussed in detail within the screening discussions for FEPs H21, H22, and H23.

SCR-5.1.1.1.3 Historical, Current, and Near-Future Human EPs

Resource exploration and exploitation are the most common reasons for drilling in the Delaware Basin and are the most likely reasons for drilling in the near future. The WIPP location has been evaluated for the occurrence of natural resources in economic quantities. Powers et al. (1978) (CCA Appendix GCR, Chapter 8) investigated the potential for exploitation of potash, hydrocarbons, caliche, gypsum, salt, uranium, sulfur, and lithium. Also, in 1995, the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) performed a reevaluation of the mineral resources at and within 1.6 km (1 mi) around the WIPP site. While some resources do exist at the WIPP site, for the HCN timeframes, such drilling is assumed to only occur outside the WIPP site boundary. This assumption is based on current federal ownership and management of the WIPP during operations, and assumed effectiveness of institutional controls for the 100-year period immediately following site closure.

Drilling associated with ***Oil and Gas Exploration*** and ***Oil and Gas Exploitation*** currently takes place in the vicinity of the WIPP. For example, gas is extracted from reservoirs in the Morrow Formation, some 4,200 m (14,000 ft) below the surface, and oil is extracted from shallower units within the Delaware Mountain Group, some 2,150 to 2,450 m (7,000 to 8,000 ft) below the surface.

Potash resources in the vicinity of the WIPP are discussed in Section 2.3.1.1. Throughout the Carlsbad Potash District, commercial quantities of potash are restricted to the McNutt, which forms part of the Salado above the repository horizon. ***Potash Exploration*** and evaluation boreholes have been drilled within and outside the controlled area. Such drilling will continue outside the WIPP land withdrawal boundary, but no longer occurs within the boundary due to transfer of rights and controls to the DOE. Moreover, drilling for the evaluation of potash resources within the boundary will not occur throughout the time period of active institutional controls.

Drilling for Other Resources has taken place within the Delaware Basin. For example, sulfur extraction using the Frasch process began in 1969 and continued for three decades at the Culberson County Rustler Springs mine near Orla, Texas. In addition, brine wells have been in operation in and about the Delaware Basin for at least as long. Solution mining processes for sulfur, salt (brine), potash, or any other mineral are not addressed in this FEP; only the drilling of the borehole is addressed here. Resource extraction through solution mining and any potential effects are evaluated in H58, solution mining. Nonetheless, the drilling activity associated with the production of other resources is not notably different than drilling for petroleum exploration and exploitation.

Drilling for the purposes of reservoir stimulation and subsequent ***Enhanced Oil*** *and* ***Gas Recovery*** does take place within the Delaware Basin, although systematic, planned waterflooding has not taken place near the WIPP. Instead, injection near WIPP consists of single-point injectors, rather than broad, grid-type waterflood projects (Hall et al. 2003). In the vicinity of the WIPP, fluid injection usually takes place using boreholes initially drilled as producing wells. Therefore, regardless of the initial intent of a deep borehole, whether in search of petroleum reserves or as an injection point, the drilling event and associated processes are virtually the same. These drilling related processes are addressed more fully in H21 ***Drilling***

Fluid Flow, H22 ***Drilling Fluid Loss***, and H23 ***Blowouts***. Discussion on the effects subsequent to drilling a borehole for the purpose of enhancing oil and gas recovery is discussed in FEP H28, ***Enhanced Oil and Gas Production***.

In summary, drilling associated with ***Oil and Gas Exploration, Potash Exploration, Oil and Gas Exploitation, Enhanced Oil*** *and* ***Gas Recovery,*** and drilling associated with ***Other Resources*** has taken place and is expected to continue in the Delaware Basin. The potential effects of existing and possible near-future boreholes on fluid flow and radionuclide transport within the disposal system are discussed in FEPs H25 through H36, where low consequence screening arguments are provided.

SCR-5.1.1.1.4 Future Human EPs

Criteria in 40 CFR § 194.33 require the DOE to examine the historical rate of drilling for resources in the Delaware Basin. Thus, consistent with 40 CFR § 194.33(b)(3)(i), the DOE has used the historical record of deep drilling associated with ***Oil and Gas Exploration, Potash Exploration, Oil and Gas Exploitation, Enhanced Oil*** *and* ***Gas Recovery,*** and ***Drilling Associated With Other*** resources (sulfur exploration) in the Delaware Basin in calculations to determine the rate of future deep drilling in the Delaware Basin (see Appendix DEL, Appendix DATA; and Chapter 6.3.2).

SCR-5.1.1.2 FEP Number(s): H3 and H5
FEP Title(s): ***Water Resources Exploration*** (H3)
Groundwater Exploitation (H5)

SCR-5.1.1.2.1 Screening Decision: SO-C (HCN)
SO-C (Future)

The effects of HCN drilling associated with ***Water Resources Exploration*** *and* ***Groundwater Exploitation*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Historical shallow drilling associated with* ***Water Resources Exploration*** *and* ***Groundwater Exploitation*** *is accounted for in calculations to determine the rate of future shallow drilling.*

SCR-5.1.1.2.2 Summary of New Information

In the screening of FEPs conducted for the CCA, FEP H3 and H5 were screened out based on low consequence (SO-C) for the long-term performance of the WIPP. The CCA screening decision and argument applied to both the HCN and future time periods and remain valid for the CRA; however, additional justification for this conclusion has been provided.

SCR-5.1.1.2.3 Screening Argument

Drilling associated with ***Water Resources Exploration*** and ***Groundwater Exploitation*** has taken place and is expected to continue in the Delaware Basin. For the most part, water resources in the vicinity of the WIPP are scarce. Elsewhere in the Delaware Basin, potable water occurs in places while some communities rely solely on groundwater sources for drinking water. Even though ***Water Resources Exploration*** and ***Groundwater Exploitation*** occur in the Basin, all

such exploration/exploitation is confined to shallow drilling that extends no deeper than the Rustler Formation and thus will not impact repository performance because of the limited drilling anticipated in the future and the sizeable thickness of low permeability Salado salt between the waste panels and the shallow groundwaters. Given the limited groundwater resources and minimal consequence of shallow drilling on performance, the effects of HCN and future drilling associated with ***Water Resources Exploration*** and ***Groundwater Exploitation*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Thus, the screening argument remains the same as given previously in the CCA.

Although shallow drilling for ***Water Resources Exploration*** and ***Groundwater Exploitation*** have been eliminated from PA calculations, the Delaware Basin Drilling Surveillance Program (DBDSP) continues to collect drilling data related to water resources, as well as other shallow drilling activities. As shown in the DBDSP 2002 Annual Report (DOE 2002), the total number of shallow water wells in the Delaware Basin is currently 2,296 compared to 2,331 shallow water wells reported in the CCA, a decrease of 35 wells (attributed primarily to the reclassification of water wells to other types of shallow boreholes). Based on these data, the shallow drilling rate for ***Water Resources Exploration*** and ***Groundwater Exploitation*** is essentially the same as reported in the CCA. The distribution of groundwater wells in the Delaware Basin was included in CCA Appendix USDW, Section USDW.3.

SCR-5.1.1.2.4 Historical, Current, and Near-Future Human EPs

Water is currently extracted from formations above the Salado, as discussed in CCA Section 2.3.1.3. The distribution of groundwater wells in the Delaware Basin is included in CCA Appendix USDW, Section USDW.3. ***Water Resources Exploration*** and ***Groundwater Exploitation*** are expected to continue in the Delaware Basin.

In summary, drilling associated with ***Water Resources Exploration, Groundwater Exploitation***, ***Potash Exploration***, ***Oil and Gas Exploration***, ***Oil and Gas Exploitation***, ***Enhanced Oil and Gas Recovery***, and drilling to explore ***Other Resources*** has taken place and is expected to continue in the Delaware Basin. The potential effects of existing and possible near-future boreholes on fluid flow and radionuclide transport within the disposal system are discussed in Section SCR.5.2, where low consequence screening arguments are provided.

SCR-5.1.1.2.5 Future Human EPs

Criteria in 40 CFR § 194.33 require that, to calculate the rates of future shallow and deep drilling in the Delaware Basin, the DOE should examine the historical rate of drilling for resources in the Delaware Basin.

Shallow drilling associated with water, potash, sulfur, oil, and gas extraction has taken place in the Delaware Basin over the past 100 years. However, of these resources, only water and potash are present at shallow depths (less than 655 m (2,150 ft) below the surface) within the controlled area. Thus, consistent with 40 CFR § 194.33(b)(4), the DOE accounts for this drilling through the use of the historical record of shallow drilling associated with ***Water Resources Exploration***,

Potash Exploration, and ***Groundwater Exploitation***, in calculations to determine the rate of future shallow drilling in the Delaware Basin.

SCR-5.1.1.3 FEP Number: H6, H7, H10, H11, and H12
FEP Title: ***Archeology*** (H6)
Geothermal Energy Production (H7)
Liquid Waste Disposal (H10)
Hydrocarbon Storage (H11)
Deliberate Drilling Intrusion (H12)

SCR-5.1.1.3.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Drilling associated with ***Archeology, Geothermal Energy Production, Liquid Waste Disposal, Hydrocarbon Storage,*** *and* ***Deliberate Drilling Intrusion*** *have been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.1.3.2 Summary of New Information

Based on current Delaware Basin data (Appendix DATA, Attachment A), the regulatory exclusion based on the "future states assumption" continues to be valid; i.e., no drilling for geothermal, archeological, liquid waste disposal, or hydrocarbon storage has occurred. Only editorial changes have been made.

SCR-5.1.1.3.3 Screening Argument

SCR-5.1.1.3.3.1 *Historic, Current, and Near-Future EPs*

No drilling associated with ***Archeology*** or ***Geothermal Energy Production,*** has taken place in the Delaware Basin. Consistent with the future states assumptions in 40 CFR § 194.25(a), such drilling activities have been eliminated from PA calculations on regulatory grounds.

While numerous archeological sites exist at and near the WIPP site, drilling for archeological purposes has not occurred. Archeological investigations have only involved shallow surface disruptions, and do not require deeper investigation by any method, drilling or otherwise. Geothermal energy is not considered to be a potentially exploitable resource because economically attractive geothermal conditions do not exist in the northern Delaware Basin.

Oil and gas production byproducts are disposed of underground in the WIPP region, but such liquid waste disposal does not involve drilling of additional boreholes (see H27); therefore drilling of boreholes for the explicit purpose of disposal has not occurred.

Hydrocarbon Storage takes place in the Delaware Basin, but it involves gas injection through existing boreholes into depleted reservoirs (see, for example, Burton et al. 1993, 66-67). Therefore, drilling of boreholes for the explicit purpose of ***Hydrocarbon Storage*** has not occurred.

Consistent with 40 CFR § 194.33(b)(1), all near-future Human EPs relating to ***Deliberate Drilling Intrusion*** into the WIPP excavation have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.1.3.4 Future Human EPs

Consistent with 40 CFR § 194.33 and the future states assumptions in 40 CFR § 194.25(a), drilling for purposes other than resource recovery (such as WIPP site investigation), and drilling activities that have not taken place in the Delaware Basin over the past 100 years, need not be considered in determining future drilling rates. Thus, drilling associated with archeological investigations***, Geothermal Energy Production, Liquid Waste Disposal, Hydrocarbon Storage***, and ***Deliberate Drilling Intrusion*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2 Excavation Activities

SCR-5.1.2.1 FEP Number: H13
FEP Title: ***Conventional Underground Potash Mining***

SCR-5.1.2.1.1 Screening Decision: UP (HCN)
DP (Future)

As prescribed by 40 CFR § 194.32 (b), the effects of HCN and future ***Conventional Underground Potash Mining*** *are accounted for in PA calculations (see also FEP H37).*

SCR-5.1.2.1.2 Summary of New Information

The name of this FEP has been changed to more specifically identify the mining process. Previously, H13 was generically titled ***Potash Mining***, which broadly included all mining mechanisms and techniques such as conventional, strip or surface, and solution mining. ***Solution Mining*** for potash is addressed in FEP H58, and ***Solution Mining for brine***, ***other Minerals***, or for the ***Creation of Storage Cavities***, is addressed in FEP H59.

SCR-5.1.2.1.3 Screening Argument

Potash is the only known economically viable resource in the vicinity of the WIPP that is recovered by underground mining (see Section 2.3.1). Potash is mined by conventional techniques extensively in the region east of Carlsbad and up to 2.4 km (1.5 mi) from the boundaries of the controlled area of the WIPP. According to existing plans and leases (see Section 2.3.1.1), potash mining is expected to continue in the vicinity of the WIPP in the near future. The DOE assumes that all economically recoverable potash in the vicinity of the disposal system will be extracted in the near future, although there are no economical reserves above the WIPP waste panels (Griswold and Griswold 1999).

In summary, ***Conventional Underground Potash Mining*** is currently taking place and is expected to continue in the vicinity of the WIPP in the near future. The potential effects of HCN, and future ***Conventional Underground Potash Mining*** are accounted for in PA calculations as prescribed by 40 CFR § 194.32 (b), and as further described in the Supplementary

Information to 40 CFR 194, Subpart C, "Compliance Certification and Recertification" and in the Compliance Application Guidance (CAG), Subpart C, § 194.32, Scope of Performance Assessments.

SCR-5.1.2.2 FEP Number: H14
FEP Title: ***Other Resources (mining for)***

SCR-5.1.2.2.1 Screening Decision: SO-C (HCN)
SO-R (Future)

*HCN **Mining for Other Resources** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future **Mining for Other Resources** has been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.2.2.2 Summary of New Information

Since the CCA, no changes in the resources sought via mining have occurred. Therefore, the screening decision for mining for other resources have not changed. Minimal changes to the screening argument have been made for clarity and completeness.

SCR-5.1.2.2.3 Screening Argument

Potash is the only known economically viable resource in the vicinity of the WIPP that is recovered by underground mining. Potash is mined extensively in the region east of Carlsbad and up to 5 km (3.1 mi) from the boundaries of the controlled area. According to existing plans and leases, *potash mining* is expected to continue in the vicinity of the WIPP in the near future. The DOE assumes that all economically recoverable potash in the vicinity of the disposal system will be extracted in the near future. Excavation for resources other than potash and archaeological excavations have taken place or are currently taking place in the Delaware Basin. These activities have not altered the geology of the controlled area significantly, and have been eliminated from PA calculations for the HCN timeframe on the basis of low consequence to the performance of the disposal system.

Potash is the only resource that has been identified within the controlled area in quality similar to that currently mined elsewhere in the Delaware Basin. Future ***M ining for Other Resources*** has been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.3 FEP Number: H15 and H16
FEP Title: ***Tunneling*** (H15)
Construction of Underground Facilities (H16)

SCR-5.1.2.3.1 Screening Decision: SO-R (HCN)
SO-R (Future)

*Consistent with 40 CFR § 194.33(b)(1), near-future human-initiated events and processes relating to **Tunneling** into the WIPP excavation and **construction of underground facilities** have been eliminated from PA calculations on regulatory grounds. Furthermore, consistent with 40 CFR § 194.33(b)(1), future human-initiated EPs relating to **Tunneling** into the WIPP*

*excavation and **Construction of Underground Facilities** have been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.2.3.2 Summary

This FEP has been screened out according to the regulatory criteria in 40 CFR 194.25 (a) (characteristics of the future remain what they are at the time the compliance application). Potash mining, which includes ***Tunneling***, has taken place in the Northern Delaware Basin and potash mining is accounted for in PA calculations. The FEP description, screening argument, and screening decision remain unchanged.

SCR-5.1.2.3.3 Screening Argument

No ***Tunneling*** or ***Construction of Underground Facilities*** (for example, storage, disposal, accommodation [that is, dwellings]) has taken place in the Delaware Basin. Mining for potash occurs (a form of ***Tunneling***), but is addressed specifically in FEP H-13. Gas storage does take place in the Delaware Basin, but it involves injection through boreholes into depleted reservoirs, and not excavation (see, for example, Burton et al. 1993, pp. 66-67).

On April 26, 2001, the DOE formally requested approval the installation of the OMNISita astrophysics experiment in the core storage alcove of the WIPP underground. The purpose of the project is to develop a prototype neutrino detector to test proof of concept principles and measure background cosmic radiation levels within the WIPP underground. EPA approved the request on August 29, 2001. This project does not require additional ***Tunneling*** or excavation beyond the current repository footprint, and therefore does not impact the screening argument for this FEP.

Because ***Tunneling*** and ***Construction of Underground Facilities*** (other than WIPP) have not taken place in the Delaware Basin, and consistent with the future states assumptions in 40 CFR § 194.25(a), such excavation activities have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.4 FEP Number: H17
FEP Title: ***Archeological Excavations***

SCR-5.1.2.4.1 Screening Decision: SO-C (HCN)
SO-R (Future)

*HCN **Archaeological Excavations** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future **Archaeological Excavations** into the disposal system have been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.2.4.2 Summary of New Information

The original description for this FEP and screening argument remain valid; only editorial changes have been made.

SCR-5.1.2.4.3 Screening Argument

Archeological Excavations have occurred at or near the WIPP, but involved only minor surface disturbances. These ***Archaeological Excavations*** may continue into the foreseeable future as other archeological sites are discovered. These activities have not altered the geology of the controlled area significantly, and have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system for the HCN timeframe.

Also, consistent with 40 CFR § 194.32(a), which limits the scope of consideration of future human actions to mining and drilling, future ***Archaeological Excavations*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.5 FEP Number: H18
FEP Title: ***Deliberate Mining Intrusion***

SCR-5.1.2.5.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Consistent with 40 CFR § 194.33(b)(1), near-future human-initiated EPs relating to ***Deliberate Mining Intrusion*** *into the WIPP excavation have been eliminated from PA calculations on regulatory grounds. Furthermore, consistent with 40 CFR § 194.33(b)(1), future human-initiated EPs relating to* ***Deliberate Mining Intrusion*** *into the WIPP excavation have been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.2.5.2 Summary of New Information

No changes have been to this FEP.

SCR-5.1.2.5.3 Screening Argument

Consistent with 40 CFR § 194.33(b)(1), all future Human related EPs relating to ***Deliberate Mining Intrusion*** into the WIPP excavation have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.3 Subsurface Explosions

SCR-5.1.3.1 FEPs Number: H19
FEP Title: ***Explosions for Resource Recovery***

SCR-5.1.3.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Historical underground ***Explosions for Resource Recovery*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future underground explosions for resource recovery have been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.3.1.2 Summary of New Information

The original screening argument and decision for this FEP remain valid. Additional text has been added to describe the past use of explosives in potash mining in the Delaware Basin. This additional information is provided for completeness, and does not affect the screening argument or decision.

SCR-5.1.3.1.3 Screening Argument

This section discusses subsurface explosions associated with resource recovery that may result in pathways for fluid flow between hydraulically conductive horizons. The potential effects of explosions on the hydrological characteristics of the disposal system are discussed in H39.

SCR-5.1.3.1.4 Historical, Current, and Near-Future Human EPs

Neither small-scale nor regional-scale explosive techniques to enhance formation hydraulic conductivity form a part of current mainstream oil- and gas-production technology. Instead, controlled perforating and hydrofracturing are used to improve the performance of oil and gas boreholes in the Delaware Basin. However, small-scale explosions have been used in the past to fracture oil- and natural-gas-bearing units to enhance resource recovery. The size of explosion used to fracture an oil- or gas-bearing unit is limited by the need to contain the damage within the unit being exploited. In the area surrounding the WIPP, the stratigraphic units with oil and gas resources are too deep for explosions to affect the performance of the disposal system. Thus, the effects of ***Explosions for Resource Recovery*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Potash mining is currently taking place and is expected to continue in the vicinity of the WIPP in the near future. Potash is mined extensively in the region east of Carlsbad and up to 2.4 km (1.3 mi) from the boundaries of the controlled area. In earlier years conventional drill, blast, load, and rail-haulage methods were used. Today, continuous miners similar to those used in coal-mining have been adapted to fit the potash-salt formations. Hence, drilling and blasting technology is not used in the present day potash mines. Thus, the effects of ***Explosions for Resource Recovery*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Consistent with 40 CFR § 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, future underground ***explosions for resource recovery*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.3.2 FEPs Number: H20
FEP Title: ***Underground Nuclear Device Testing***

SCR-5.1.3.2.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Historical ***Underground Nuclear Device Testing*** *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future* ***Underground Nuclear Device Testing*** *has been eliminated from PA calculations on regulatory grounds.*

SCR-5.1.3.2.2 Summary of New Information

No new information has been identified related to this FEP. No changes have been made.

SCR-5.1.3.2.3 Screening Argument

SCR-5.1.3.2.3.1 *Historical, Current, and Near-Future Human EPs*

The Delaware Basin has been used for an isolated nuclear test. This test, Project Gnome (Rawson et al. 1965), took place in 1961 at a location approximately 13 km (8 mi) southwest of the WIPP waste disposal region. Project Gnome was decommissioned in 1979.

The primary objective of Project Gnome was to study the effects of an underground nuclear explosion in salt. The Gnome experiment involved the detonation of a 3.1 kiloton nuclear device at a depth of 360 m (1,190 ft) in the bedded salt of the Salado. The explosion created an approximately spherical cavity of about 27,000 m^3 (950,000 ft^3) and caused surface displacements in a radius of 360 m (1,180 ft). No earth tremors perceptible to humans were reported at distances over 40 km (25 mi) from the explosion. A zone of increased permeability was observed to extend at least 46 m (150 ft) laterally from and 105 m (344 ft) above the point of the explosion. The test had no significant effects on the geological characteristics of the WIPP disposal system. Thus, historical ***Underground Nuclear Device Testing*** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. There are no existing plans for ***Underground Nuclear Device Testing*** in the vicinity of the WIPP in the near future.

SCR-5.1.3.2.3.2 *Future Human EPs*

The criterion in 40 CFR § 194.32(a), relating to the scope of PAs, limits the consideration of future human actions to mining and drilling. Therefore, future ***Underground Nuclear Device Testing*** has been eliminated from PA calculations on regulatory grounds.

SCR-5.2 Subsurface Hydrological and Geochemical Events and Processes

SCR-5.2.1 Borehole Fluid Flow

SCR-5.2.1.1 FEP Number: H21
FEP Title: ***Drilling Fluid Flow***

SCR-5.2.1.1.1 Screening Decision: SO-C (HCN)
DP (Future)

Drilling Fluid Flow *associated with historical, current, near-future, and future boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The possibility of a future deep borehole penetrating a waste panel, such that drilling-induced flow results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations. The possibility of a deep borehole penetrating both the waste disposal region and a Castile brine reservoir is accounted for in PA calculations.*

SCR-5.2.1.1.2 Summary of New Information

No new information is available for this FEP. However, the screening argument has been revised for clarity and editorial purposes.

SCR-5.2.1.1.3 Screening Argument

Borehole circulation fluid could be lost to thief zones encountered during drilling, or fluid could flow from pressurized zones through the borehole to the land surface (blowout) or to a thief zone. Such drilling-related EPs could influence groundwater flow and, potentially, radionuclide transport in the affected units. Future drilling within the controlled area could result in direct releases of radionuclides to the land surface or transport of radionuclides between hydraulically conductive units.

Movement of brine from a pressurized zone, through a borehole into potential thief zones such as the Salado interbeds or the Culebra, could result in geochemical changes and altered radionuclide migration rates in these units.

SCR-5.2.1.1.3.1 *Historical, Current, and Near-Future Human EPs*

Drilling *Fluid Flow* is a short-term event that can result in the flow of pressurized fluid from one geologic stratum to another. However, long-term flow through abandoned boreholes would have a greater hydrological impact in the Culebra than a short-term event like drilling-induced flow outside the controlled area. Wallace (1996a) analyzed the potential effects of flow through abandoned boreholes in the future within the controlled area, and concluded that interconnections between the Culebra and deep units could be eliminated from PA calculations on the basis of low consequence. Thus, the HCN of ***Drilling Fluid Flow*** associated with boreholes outside the controlled area has been screened out on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H25 through H36, drilling associated with **Water Resources Exploration, Groundwater Exploitation, Potash Exploration, Oil and Gas Exploration, Oil and Gas Exploitation, Enhanced Oil and Gas Recovery,** and **Drilling to Explore Other Resources** has taken place or is currently taking place outside the controlled area in the Delaware Basin. These drilling activities are expected to continue in the vicinity of the WIPP in the near future.

SCR-5.2.1.1.3.2 *Future Human EPs*

For the future, drill holes may intersect the waste disposal region and their effects could be more profound. Thus, the possibility of a future borehole penetrating a waste panel, so that ***Drilling Fluid Flow*** and, potentially, ***Blowout***, results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations.

The units intersected by the borehole may provide sources for fluid flow (brine, oil, or gas) to the waste panel during drilling. In the vicinity of the WIPP, the Castile that underlies the Salado contains isolated volumes of brine at fluid pressures greater than hydrostatic. A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. The possibility of a deep borehole penetrating both a waste panel and a brine reservoir is accounted for in PA calculations.

A future borehole that is drilled through a disposal room wall, but does not intersect waste, could penetrate a brine reservoir underlying the waste disposal region. Such an event would depressurize the brine reservoir to some extent, and thus would affect the consequences of any subsequent intersections of the reservoir. The possibility for a borehole to depressurize a brine reservoir underlying the waste disposal region is accounted for in PA calculations.

Penetration of an underpressurized unit underlying the Salado could result in flow and radionuclide transport from the waste panel to the underlying unit during drilling, although drillers would minimize such fluid loss to a thief zone through the injection of materials to reduce permeability or through the use of casing and cementing. Also, the permeabilities of formations underlying the Salado are less than the permeability of the Culebra (Wallace 1996a). Thus, the consequences associated with radionuclide transport to an underpressurized unit below the waste panels during drilling will be less significant, in terms of disposal system performance, than the consequences associated with radionuclide transport to the land surface or to the Culebra during drilling. Through this comparison, drilling events that result in penetration of underpressurized units below the waste-disposal region have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

In evaluating the potential consequences of **Drilling Fluid Loss** to a waste panel, two types of drilling events need to be considered – those that intercept pressurized fluid in underlying formations such as the Castile (defined in CCA Section 6.3.2.2 as E1 events), and those that do not (E2 events). A possible hydrological effect would be to make a greater volume of brine available for gas generation processes and thereby increase gas volumes at particular times in the future. As discussed in CCA Section 6.4.12.6, of boreholes that intersect a waste panel in the future, 8 percent are assumed to be E1 events and 92 percent are E2 events. For either type of drilling event, on the basis of current drilling practices, the driller is assumed to pass through the

repository rapidly. Relatively small amounts of drilling fluid loss may not be noticed and may not give rise to concern. Larger fluid losses would lead to the driller injecting materials to reduce permeability, or to the borehole being cased and cemented, to limit the loss of drilling fluid.

For boreholes that intersect pressurized brine reservoirs, the volume of fluid available to flow up a borehole will be significantly greater than the volume of any drilling fluid that could be lost. This greater volume of brine is accounted for in PA calculations, and is allowed to enter the disposal room (see CCA Section 6.4.7). Thus, the effects of **Drilling Fluid Loss** will be small by comparison to the potential flow of brine from pressurized brine reservoirs. Therefore, the effects of drilling fluid loss for E1 drilling events have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

For boreholes that do not intersect pressurized brine reservoirs the treatment of the disposal room implicitly accounts for the potential for greater gas generation resulting from **Drilling Fluid Loss**. Thus, the hydrological effects of drilling fluid loss for E2 drilling events are accounted for in PA calculations within the conceptual model of the disposal room for drilling intrusions.

SCR-5.2.1.2 FEP Number: H22
FEP Title: ***Drilling Fluid Loss***

SCR-5.2.1.2.1 Screening Decision: SO-C (HCN)
DP (Future)

Drilling Fluid Loss *associated with HCN, and future boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The possibility of a future* **Drilling Fluid Loss** *into waste panels is accounted for in PA calculations.*

SCR-5.2.1.2.2 Summary of New Information

No new information is available for this FEP. However, the screening argument has been revised for clarity and editorial purposes.

SCR-5.2.1.2.3 Screening Argument

Drilling Fluid lLoss is a short-term event that can result in the flow of pressurized fluid from one geologic stratum to another. Large fluid losses would lead a driller to inject materials to reduce permeability, or it would lead to the borehole being cased and cemented to limit the loss of drilling fluid. Assuming such operations are successful, **Drilling Fluid Loss** in the near future outside the controlled area will not significantly affect the hydrology of the disposal system. Thus, **Drilling Fluid Loss** associated with historical, current, and near-future boreholes has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The consequences of **Drilling Fluid Loss** into waste panels in the future is accounted for in PA calculations for E1 and E2 events.

SCR-5.2.1.2.3.1 *Historical, Current, and Near-Future Human EPs*

Drilling Fluid Flow will not affect hydraulic conditions in the disposal system significantly unless there is substantial **Drilling Fluid Loss** to a thief zone, such as the Culebra. Typically, zones into which significant borehole circulation fluid is lost are isolated through injection of materials to reduce permeability or through casing and cementing programs. Assuming such operations are successful, **Drilling Fluid Loss** in the near future outside the controlled area will not affect the hydrology of the disposal system significantly and be of no consequence.

SCR-5.2.1.2.3.2 *Future Human EPs*

The consequences of drilling within the controlled area in the future will primarily depend on the location of the borehole. Potentially, future deep drilling could penetrate the waste disposal region. Hydraulic and geochemical conditions in the waste panel could be affected as a result of **Drilling Fluid Loss** to the panel.

Penetration of an under pressurized unit underlying the Salado could result in flow and radionuclide transport from the waste panel to the underlying unit during drilling, although drillers would minimize such fluid loss to a thief zone through the injection of materials to reduce permeability or through the use of casing and cementing. Also, the permeabilities of formations underlying the Salado are less than the permeability of the Culebra (Wallace 1996a). Thus, the consequences associated with radionuclide transport to an underpressurized unit below the waste panels during drilling will be less significant, in terms of disposal system performance, than the consequences associated with radionuclide transport to the land surface or to the Culebra during drilling. Through this comparison, drilling events that result in penetration of under pressurized units below the waste-disposal region have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

For boreholes that do not intersect pressurized brine reservoirs (but do penetrate the waste-disposal region) the treatment of the disposal room implicitly accounts for the potential for greater gas generation resulting from drilling fluid loss. Thus, the hydrological effects of **Drilling Fluid Loss** for E2 drilling events are accounted for in PA calculations within the conceptual model of the disposal room for drilling intrusions.

SCR-5.2.1.3 FEP Number: H23
FEP Title: ***Blowouts***

SCR-5.2.1.3.1 Screening Decision: SO-C (HCN)
DP (Future)

Blowouts *associated with HCN, and future boreholes that do not intersect the waste disposal region, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The possibility of a future deep borehole penetrating a waste panel, such that drilling-induced flow results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations. The possibility of a deep borehole penetrating both the waste disposal region and a Castile brine reservoir is accounted for in PA calculations.*

SCR-5.2.1.3.2 Summary of New Information

No new information is available for this FEP. However, the screening argument has been revised for clarity and editorial purposes.

SCR-5.2.1.3.3 Screening Argument

Blowouts are short-term events that can result in the flow of pressurized fluid from one geologic stratum to another. For the near future, a ***Blowout*** may occur in the vicinity of the WIPP but is not likely to affect the disposal system because of the distance from the well to the waste panels, assuming that passive and active institutional controls are in place which restrict borehole installation to outside the WIPP boundary. ***Blowouts*** associated with HCN, and future boreholes that do not intersect the waste disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. For the future, the drill holes may intersect the waste disposal region and these effects could be more profound. Thus, ***Blowouts*** are included in the assessment of future activities.

The consequences of ***Blowout*** in the future are accounted for in PA calculations.

Fluid could flow from pressurized zones through the borehole to the land surface (***Blowout***) or to a thief zone. Such drilling-related EPs could influence groundwater flow and, potentially, radionuclide transport in the affected units. Movement of brine from a pressurized zone, through a borehole, into potential thief zones such as the Salado interbeds or the Culebra, could result in geochemical changes and altered radionuclide migration rates in these units.

SCR-5.2.1.3.3.1 *Historical, Current, and Near-Future Human EPs*

Drilling associated with ***Water Resources Exploration, Groundwater Exploitation, Potash Exploration, Oil and Gas Exploration, Oil and Gas Exploitation, Enhanced Oil and Gas Recovery,*** and ***Drilling to Explore Other Resources*** has taken place or is currently taking place outside the controlled area in the Delaware Basin. These drilling activities are expected to continue in the vicinity of the WIPP in the near future.

Naturally occurring brine and gas pockets have been encountered during drilling in the Delaware Basin. Brine pockets have been intersected in the Castile (as discussed in Section 2.2.1.3) and in the Salado above the WIPP horizon (Section 2.2.1.2.2). Gas ***Blowouts*** have occurred during drilling in the Salado. Usually, such events result in brief interruptions in drilling while the intersected fluid pocket is allowed to depressurize through flow to the surface (for a period lasting from a few hours to a few days). Drilling then restarts with an increased drilling mud weight. Under these conditions, ***Blowouts*** in the near future will cause isolated hydraulic disturbances, but will not affect the hydrology of the disposal system significantly.

Potentially, the most significant disturbance to the disposal system could occur if an uncontrolled ***Blowout*** during drilling resulted in substantial flow through the borehole from a pressurized zone to a thief zone. For example, if a borehole penetrates a brine reservoir in the Castile, brine could flow through the borehole to the Culebra, and, as a result, could affect hydraulic conditions in the Culebra. The potential effects of such an event can be compared to the effects of long-term fluid flow from deep overpressurized units to the Culebra through abandoned boreholes. Wallace

(1996a) analyzed the potential effects of flow through abandoned boreholes in the future within the controlled area and concluded that interconnections between the Culebra and deep units could be eliminated from PA calculations on the basis of low consequence. Long-term flow through abandoned boreholes would have a greater hydrological impact in the Culebra than short-term drilling-induced flow outside the controlled area. Thus, the effects of fluid flow during drilling in the near future have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

In summary, ***Blowouts*** associated with historical, current, and near-future boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.3.3.2 *Future Human EPs - Boreholes that Intersect the Waste Disposal Region*

The consequences of drilling within the controlled area in the future will primarily depend on the location of the borehole. Potentially, future deep drilling could penetrate the waste disposal region. If the borehole intersects the waste in the disposal rooms, radionuclides could be transported as a result of ***Drilling Fluid Flow***: releases to the accessible environment may occur as material entrained in the circulating drilling fluid is brought to the surface. Also, during drilling, contaminated brine may flow up the borehole and reach the surface, depending on fluid pressure within the waste disposal panels; ***Blowout*** conditions could prevail if the waste panel were sufficiently pressurized at the time of intrusion.

SCR-5.2.1.3.3.3 *Hydraulic Effects of Drilling-Induced Flow*

The possibility of a future borehole penetrating a waste panel, so that ***Drilling Fluid Flow*** and, potentially, ***Blowout***, results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations.

The units intersected by the borehole may provide sources for fluid flow (brine, oil, or gas) to the waste panel during drilling. In the vicinity of the WIPP, the Castile that underlies the Salado contains isolated volumes of brine at fluid pressures greater than hydrostatic. A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. The possibility of a deep borehole penetrating both a waste panel and a brine reservoir is accounted for in PA calculations.

Future boreholes could affect the hydraulic conditions in the disposal system. Intersection of pockets of pressurized gas and brine would likely result in short-term, isolated hydraulic disturbances, and will not affect the hydrology of the disposal system significantly. Potentially, the most significant hydraulic disturbance to the disposal system could occur if an uncontrolled ***Blowout*** during drilling resulted in substantial flow through the borehole from a pressurized zone to a thief zone. For example, if a borehole penetrates a brine reservoir in the Castile, brine could flow through the borehole to the Culebra, and, as a result, could affect hydraulic conditions in the Culebra. The potential effects of such an event can be compared to the effects of long-term fluid flow from deep overpressurized units to the Culebra through abandoned boreholes. Wallace (1996a) analyzed the potential effects of such interconnections in the future within the controlled

area concluded that flow through abandoned boreholes between the Culebra and deep units could be eliminated from PA calculations on the basis of low consequence.

SCR-5.2.1.4 FEP Number: H24
FEP Title: ***Drilling Induced Geochemical Changes***

SCR-5.2.1.4.1 Screening Decision: UP (HCN)
DP (Future)

Drilling Induced Geochemical Changes *that occur within the controlled area as a result of HCN, and future drilling-induced flow are accounted for in PA calculations.*

SCR-5.2.1.4.2 Summary of New Information

No new information is available for this FEP. However, the screening argument has been revised for clarity and editorial purposes.

SCR-5.2.1.4.3 Screening Argument

Borehole circulation fluid could be lost to thief zones encountered during drilling, or fluid could flow from pressurized zones through the borehole to the land surface (***Blowout***) or to a thief zone. Such drilling-related EPs could influence groundwater flow and, potentially, radionuclide transport in the affected units. Future drilling within the controlled area could result in direct releases of radionuclides to the land surface or transport of radionuclides between hydraulically conductive units.

Movement of brine from a pressurized zone, through a borehole, into potential thief zones such as the Salado interbeds or the Culebra, could result in geochemical changes and altered radionuclide migration rates in these units.

SCR-5.2.1.4.3.1 *Historical, Current, and Near-Future Human EPs*

Drilling associated with resource exploration, exploitation, and recovery has taken place or is currently taking place outside the controlled area in the Delaware Basin. These drilling activities are expected to continue in the vicinity of the WIPP in the near future. Chemical changes induced by such drilling are discussed below.

SCR-5.2.1.4.3.2 *Geochemical effects of drilling-induced flow*

Radionuclide migration rates are governed by the coupled effects of hydrological and geochemical processes (see discussions in FEPs W77 through W100). Human EPs outside the controlled area could affect the geochemistry of units within the controlled area if they occur sufficiently close to the edge of the controlled area. Movement of brine from a pressurized reservoir in the Castile through a borehole into potential thief zones, such as the Salado interbeds or the Culebra, could cause ***Drilling-Induced Geochemical Changes*** resulting in altered radionuclide migration rates in these units through their effects on colloid transport and sorption (colloid transport may enhance radionuclide migration, while radionuclide migration may be retarded by sorption).

The treatment of colloids in PA calculations is described in Sections 6.4.3.6 and 6.4.6.2.2. The repository and its contents provide the main source of colloids in the disposal system. By comparison, Castile brines have relatively low total colloid concentrations. Therefore, changes in colloid transport in units within the controlled area as a result of HCN drilling-induced flow have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Sorption within the Culebra is accounted for in PA calculations as discussed in Section 6.4.6.2. The sorption model comprises an equilibrium, sorption isotherm approximation, employing distribution coefficients (Kds) applicable to dolomite in the Culebra (Appendix PA, Attachment MASS, Section MASS.15.2; and PAVT). The CDFs of distribution coefficients used are derived from a suite of experimental studies that include measurements of K_ds for actinides in a range of chemical systems including Culebra and Castile brines, Culebra brines, and Salado brines. Therefore, any changes in sorption geochemistry in the Culebra within the controlled area as a result of HCN drilling-induced flow are accounted for in PA calculations.

Sorption within the Dewey Lake is accounted for in PA calculations, as discussed in Section 6.4.6.6. It is assumed that the sorptive capacity of the Dewey Lake is sufficiently large to prevent any radionuclides that enter the Dewey Lake from being released over 10,000 years (Wallace et al. 1995). Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The effects of changes in sorption in the Dewey Lake and other units within the controlled area as a result of HCN drilling-induced flow have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.4.3.3 *Future Human EPs - Boreholes that Intersect the Waste Disposal Region*

The consequences of drilling within the controlled area in the future will primarily depend on the location of the borehole. Potentially, future deep drilling could penetrate the waste disposal region. If the borehole intersects the waste in the disposal rooms, radionuclides could be transported as a result of **Drilling *Fluid Flow*** and geochemical conditions in the waste panel could be affected as a result of ***Drilling-Induced Geochemical Changes.***

SCR-5.2.1.4.3.4 *Geochemical Effects of Drilling-Induced Flow*

Drilling Fluid Loss to a waste panel could modify the chemistry of disposal room brines in a manner that would affect the solubility of radionuclides and the source term available for subsequent transport from the disposal room. The majority of drilling fluids used are likely to be locally derived, and their bulk chemistry will be similar to fluids currently present in the disposal system. In addition, the presence of the MgO chemical conditioner in the disposal rooms will buffer the chemistry across a range of fluid compositions, as discussed in detail in Appendix PA, Attachment SOTERM. Furthermore, for E1 drilling events, the volume of Castile brine that flows into the disposal room will be greater than that of any drilling fluids; Castile brine chemistry is accounted for in PA calculations. Thus, the effects on radionuclide solubility of ***Drilling Fluid Loss*** to the disposal room have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Movement of brine from a pressurized reservoir in the Castile through a borehole into thief zones, such as the Salado interbeds or the Culebra, could result in geochemical changes in the receiving units, and thus alter radionuclide migration rates in these units through their effects on colloid transport and sorption.

The repository and its contents provide the main source of colloids in the disposal system. Thus, colloid transport in the Culebra within the controlled area as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region are accounted for in PA calculations, as described in Sections 6.4.3.6 and 6.4.6.2.1. The Culebra is the most transmissive unit in the disposal system and it is the most likely unit through which significant radionuclide transport could occur. Therefore, colloid transport in units other than the Culebra, as a result of ***Drilling Fluid Loss*** associated with boreholes that intersect the waste disposal region, has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21, H22, and H23, sorption within the Culebra is accounted for in PA calculations. The sorption model used incorporates the effects of changes in sorption in the Culebra as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region.

Consistent with the screening discussion in FEPs H21, H22, and H23, the effects of changes in sorption in the Dewey Lake inside the controlled area as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-5.2.1.4.3.5 *Future Human EPs - Boreholes That Do Not Intersect the Waste Disposal Region*

Future boreholes that do not intersect the waste disposal region could nevertheless encounter contaminated material by intersecting a region into which radionuclides have migrated from the disposal panels, or could affect hydrogeological conditions within the disposal system. Consistent with the containment requirements in 40 CFR § 191.13(a), PAs need not evaluate the effects of the intersection of contaminated material outside the controlled area.

Movement of brine from a pressurized reservoir in the Castile, through a borehole, into thief zones such as the Salado interbeds or the Culebra, could result in ***Drilling-Induced Geochemical Changes*** and altered radionuclide migration rates in these units.

SCR-5.2.1.4.3.6 *Geochemical Effects of Drilling-Induced Flow*

Movement of brine from a pressurized reservoir in the Castile through a borehole into thief zones, such as the Salado interbeds or the Culebra, could cause geochemical changes resulting in altered radionuclide migration rates in these units through their effects on colloid transport and sorption.

The contents of the waste disposal panels provide the main source of colloids in the disposal system. Thus, consistent with the discussion in FEPs H21, H22, and H23, colloid transport as a result of drilling-induced flow associated with future boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21, H22, and H23, sorption within the Culebra is accounted for in PA calculations. The sorption model accounts for the effects of changes in sorption in the Culebra as a result of drilling-induced flow associated with boreholes that do not intersect the waste disposal region.

Consistent with the screening discussion in FEPs H21, H22, and H23, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of drilling-induced flow associated with boreholes that do not intersect the waste disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

In summary, the effects of ***Drilling-Induced Geochemical Changes*** that occur within the controlled area as a result of historical, current, near-future, and future drilling-induced flow are accounted for in PA calculations. Those that occur outside the controlled area have been eliminated from PA calculations.

SCR-5.2.1.5 FEP Number(s): H25 and H26
FEP Title(s): ***Oil and Gas Extraction***
Groundwater Extraction

SCR-5.2.1.5.1 Screening Decision: SO-C (HCN)
SO-R (Future)

HCN ***Groundwater, Oil,*** and ***Gas Extraction*** *outside the controlled area has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.* ***Groundwater, Oil,*** and ***Gas Extraction*** *through future boreholes has been eliminated from PA calculations on regulatory grounds.*

SCR-5.2.1.5.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. Delaware Basin monitoring information (see Appendix DATA, Attachment A) does not indicate any changes in oil, gas, or water extraction that would require modification to these screening arguments or decisions. No changes have been made.

SCR-5.2.1.5.2.1 *Screening Argument*

The extraction of fluid could alter fluid-flow patterns in the target horizons, or in overlying units as a result of a failed borehole casing. Also, the removal of confined fluid from oil- or gas-bearing units can cause compaction in some geologic settings, potentially resulting in subvertical fracturing and surface subsidence.

SCR-5.2.1.5.2.2 *Historical, Current, and Near-Future Human EPs*

As discussed in FEPs H25 through H36, water, oil, and gas production are the only activities involving fluid extraction through boreholes that have taken place or are currently taking place in the vicinity of the WIPP. These activities are expected to continue in the vicinity of the WIPP in the near future.

Groundwater Extraction outside the controlled area from formations above the Salado could affect groundwater flow. The Dewey Lake contains a productive zone of saturation south of the WIPP site. Several wells operated by the J.C. Mills Ranch south of the WIPP produce water from the Dewey Lake to supply livestock (see Section 2.2.1.4.2.1). Also, water has been extracted from the Culebra at the Engle Well approximately 9.66 km (6 mi) south of the controlled area to provide water for livestock. No water wells in other areas in the vicinity of the WIPP are expected to be drilled in the near future because of the high concentrations of total dissolved solids in the groundwater.

If contaminated water intersects a well while it is producing, then contaminants could be pumped to the surface. Consistent with the containment requirements in 40 CFR § 191.13(a), PAs need not evaluate radiation doses that might result from such an event. However, compliance assessments must include any such events in dose calculations for evaluating compliance with the individual protection requirements in 40 CFR § 191.15. As discussed in Chapter 8.0, under undisturbed conditions, there are no calculated radionuclide releases to units containing producing wells.

Pumping from wells at the J.C. Mills Ranch may have resulted in reductions in hydraulic head in the Dewey Lake within southern regions of the controlled area, leading to increased hydraulic head gradients. However, these changes in the groundwater flow conditions in the Dewey Lake will have no significant effects on the performance of the disposal system, primarily because of the sorptive capacity of the Dewey Lake (see Section 6.4.6.6). Retardation of any radionuclides that enter the Dewey Lake will be such that no radionuclides will migrate through the Dewey Lake to the accessible environment within the 10,000-year regulatory period.

The effects of ***Groundwater Extraction*** from the Culebra from a well 9.66 km (6 mi) south of the controlled area have been evaluated by Wallace (1996b), using an analytical solution for Darcian fluid flow in a continuous porous medium. Wallace (1996b) showed that such a well pumping at about 0.5 g (1.9 L) per minute for 10,000 years will induce a hydraulic head gradient across the controlled area of about 4×10^{-5}. The hydraulic head gradient across the controlled area currently ranges from between 0.001 to 0.007. Therefore, pumping from the Engle Well will have only minor effects on the hydraulic head gradient within the controlled area even if pumping were to continue for 10,000 years. Thus, the effects of HCN ***Groundwater Extraction*** outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Oil and Gas Extraction outside the controlled area could affect the hydrology of the disposal system. However, the horizons that act as oil and gas reservoirs are sufficiently below the repository for changes in fluid-flow patterns to be of low consequence, unless there is fluid leakage through a failed borehole casing. Also, ***Oil and Gas Extraction*** horizons in the

Delaware Basin are well-lithified rigid strata, so oil and gas extraction is not likely to result in compaction and subsidence (Brausch et al. 1982, pp. 52, 61). Furthermore, the plasticity of the salt formations in the Delaware Basin will limit the extent of any fracturing caused by compaction of underlying units. Thus, neither the extraction of gas from reservoirs in the Morrow Formation (some 4,200 m (14,000 ft) below the surface), nor extraction of oil from the shallower units within the Delaware Mountain Group (about 1,250 to 2,450 m (about 4,000 to 8,000 ft) below the surface) will lead to compaction and subsidence. In summary, historical, current, and near-future ***Oil and Gas Extraction*** outside the controlled area has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.5.2.3 *Future Human EPs*

Consistent with 40 CFR § 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, ***Groundwater Extraction*** and ***Oil and Gas Extraction*** through future boreholes have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.6 FEP Number(s): H27, H28 and H29
FEP Title(s): ***Liquid Waste Disposal*** (H27)
Enhanced Oil and Gas Production (H28)
Hydrocarbon Storage (H29)

SCR-5.2.1.6.1 Screening Decision: SO-C (HCN)
SO-C (Future)

*The hydrological effects of HCN fluid injection (**Liquid Waste Disposal, Enhanced Oil** and **Gas Production,** and **Hydrocarbon Storage**) through boreholes outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Geochemical changes that occur inside the controlled area as a result of fluid flow associated with HCN fluid injection are accounted for in PA calculations. **Liquid Waste Disposal, Enhanced Oil and Gas Production,** and **Hydrocarbon Storage** in the future have been eliminated from PA calculations based on low consequence.*

SCR-5.2.1.6.2 Summary of New Information

Fluid injection modeling conducted since the CCA has demonstrated that injection of fluids will not have a significant effect upon the WIPP's ability to contain radioactive materials (Stoelzel and Swift 1997). The results of this modeling justify changing the screening decision for these FEPs from SO-R to SO-C for the future timeframe. Neither hydraulic fracturing nor waterflooding conducted in wells outside the controlled area have the potential to affect the disposal system in any significant way. The screening argument for this FEP has been updated to include references and conclusions from Steolzel and Swift. The hydrological effects of HCN, and future ***Hydrocarbon Storage*** (H29) have been screened out on the basis of low consequence. Only one hydrocarbon (gas) storage facility is operating in the Delaware Basin, and it is too far away to have any effect on groundwater at the WIPP under any circumstances. No changes have been made to the FEP description, although the screening decision for the future time period has

been changed from SO-R to SO-C; the screening argument has been modified slightly to include citation of a recent survey.

SCR-5.2.1.6.3 Screening Argument

The injection of fluids could alter fluid-flow patterns in the target horizons or, if there is accidental leakage through a borehole casing in any other intersected hydraulically conductive zone. Injection of fluids through a leaking borehole could also result in geochemical changes and altered radionuclide migration rates in the thief units.

SCR-5.2.1.6.3.1 *Historical, Current, and Near-Future Human EPs*

The only historical and current activities involving fluid injection through boreholes in the Delaware Basin are ***Enhanced Oil and Gas Production*** (waterflooding or carbon dioxide (CO_2) injection), ***Hydrocarbon Storage*** (gas reinjection), and ***Liquid Waste Disposal*** (by-products from oil and gas production). These fluid injection activities are expected to continue in the vicinity of the WIPP in the near future.

Hydraulic fracturing of oil- or gas-bearing units is currently used to improve the performance of hydrocarbon reservoirs in the Delaware Basin. Fracturing is induced during a short period of high-pressure fluid injection, resulting in increased hydraulic conductivity near the borehole. Normally, this controlled fracturing is confined to the pay zone and is unlikely to affect overlying strata.

Secondary production techniques, such as waterflooding, that are used to maintain reservoir pressure and displace oil are currently employed in hydrocarbon reservoirs in the Delaware Basin (Brausch et al. 1982, pp. 29-30). Tertiary recovery techniques, such as ***Carbon Dioxide*** miscible flooding, have been implemented with limited success in the Delaware Basin, but CO_2 miscible flooding is not an attractive recovery method for reservoirs near WIPP (Melzer 2003). Even if ***Carbon Dioxide*** flooding were to occur the effects (if any) would be very similar to those associated with waterflooding.

Reinjection of gas for storage currently takes place at one location in the Delaware Basin in a depleted gas field in the Morrow Formation at the Washington Ranch near Carlsbad Caverns (Burton et al. 1993, pp. 66-67; CCA Appendix DATA, Attachment A). This field is too far from the WIPP site to have any effect on WIPP groundwaters under any circumstances. Disposal of liquid by-products from oil and gas production involves injection of fluid into depleted reservoirs. Such fluid injection techniques result in repressurization of the depleted target reservoir and mitigates any effects of fluid withdrawal.

The most significant effects of fluid injection would arise from substantial and uncontrolled fluid leakage through a failed borehole casing. The highly saline environment of some units can promote rapid corrosion of well casings and may result in fluid loss from boreholes.

SCR-5.2.1.6.3.2 *Hydraulic Effects of Leakage through Injection Boreholes*

The Vacuum Field (located in the Capitan Reef, some 30 km [20 mi] northeast of the WIPP site) and the Rhodes-Yates Field (located in the back reef of the Capitan, some 70 km (45 mi)

southeast of the WIPP site) have been waterflooded for 40 years with confirmed leaking wells, which have resulted in brine entering the Salado and other formations above the Salado (see, for example, Silva 1994, pp. 67-68). Currently, saltwater disposal takes place in the vicinity of the WIPP into formations below the Castile. However, leakages from saltwater disposal wells or waterflood wells in the near future in the vicinity of the WIPP are unlikely to occur because of the following:

- There are significant differences between the geology and lithology in the vicinity of the disposal system and that of the Vacuum and Rhodes-Yates Fields. The WIPP is located in the Delaware Basin in a fore-reef environment, where a thick zone of anhydrite and halite (the Castile) exists. In the vicinity of the WIPP, oil is produced from the Brushy Canyon Formation at depths greater than 2100 m (7,000 ft). By contrast, the Castile is not present at either the Vacuum or the Rhodes-Yates Field, which lie outside the Delaware Basin. Oil production at the Vacuum Field is from the San Andres and Grayburg Formations at depths of approximately 1400 m (4,500 ft), and oil production at the Rhodes-Yates Field is from the Yates and Seven Rivers Formations at depths of approximately 900 m (3,000 ft). Waterflooding at the Rhodes-Yates Field involves injection into a zone only 60 m (200 ft) below the Salado. There are more potential thief zones below the Salado near the WIPP than at the Rhodes-Yates or Vacuum Fields; the Salado in the vicinity of the WIPP is therefore less likely to receive any fluid that leaks from an injection borehole. Additionally, the oil pools in the vicinity of the WIPP are characterized by channel sands with thin net pay zones, low permeabilities, high irreducible water saturations, and high residual oil saturations. Therefore, waterflooding of oil fields in the vicinity of the WIPP on the scale of that undertaken in the Vacuum or the Rhodes-Yates Field is unlikely.

- New Mexico state regulations require the emplacement of a salt isolation casing string for all wells drilled in the potash enclave, which includes the WIPP area, to reduce the possibility of petroleum wells leaking into the Salado. Also, injection pressures are not allowed to exceed the pressure at which the rocks fracture. The injection pressure gradient must be kept below 4.5×10^3 pascals per meter above hydrostatic if fracture pressures are unknown. Such controls on fluid injection pressures limit the potential magnitude of any leakages from injection boreholes.

- Recent improvements in well completion practices and reservoir operations management have reduced the occurrences of leakages from injection wells. For example, injection pressures during waterflooding are typically kept below about 23×10^3 pascals per meter to avoid fracture initiation. Also, wells are currently completed using cemented and perforated casing, rather than the open-hole completions used in the early Rhodes-Yates wells. A recent report (Hall et al. 2003) concludes that injection well operations near WIPP have a very low failure rate, and that failures, although rare, are remedied quickly.

Any injection well leakages that do occur in the vicinity of the WIPP in the near future are more likely to be associated with liquid waste disposal than waterflooding. Disposal typically involves fluid injection though old and potentially corroded well casings and does not include monitoring to the same extent as waterflooding. Such fluid injection could affect the performance of the

disposal system if sufficient fluid leaked into the Salado interbeds to affect the rate of brine flow into the waste disposal panels.

Stoelzel and O'Brien (1996) evaluated the potential effects on the disposal system of leakage from a hypothetical salt water disposal borehole near the WIPP. Stoelzel and O'Brien (1996) used the two-dimensional BRAGFLO model (vertical north-south cross-section) to simulate saltwater disposal to the north and to the south of the disposal system. The disposal system model included the waste disposal region, the marker beds and anhydrite intervals near the excavation horizon, and the rock strata associated with local oil and gas developments. A worst case simulation was run using high values of borehole and anhydrite permeability and a low value of halite permeability to encourage flow to the disposal panels via the anhydrite. Also, the boreholes were assumed to be plugged immediately above the Salado (consistent with the plugging configurations described in Section 6.4.7.2). Saltwater disposal into the Upper Bell Canyon was simulated, with annular leakage through the Salado. A total of approximately 7×10^5 m^3 (2.47×10^7 ft^3) of brine was injected through the boreholes during a 50-year simulated disposal period. In this time, approximately 50 m^3 (1765.5 ft^3) of brine entered the anhydrite interval at the horizon of the waste disposal region. For the next 200 years the boreholes were assumed to be abandoned (with open-hole permeabilities of 1×10^{-9} m^2 (4×10^{-8} in.)). Cement plugs (of permeability 1×10^{-17} m^2 (4×10^{-16} in.)) were assumed to be placed at the injection interval and at the top of the Salado. Subsequently, the boreholes were prescribed the permeability of silty sand (see Section 6.4.7.2), and the simulation was continued until the end of the 10,000-year regulatory period. During this period, approximately 400 m^3 (14,124 ft^3) of brine entered the waste disposal region from the anhydrite interval. This value of cumulative brine inflow is within the bounds of the values generated by PA calculations for the undisturbed performance scenario. During the disposal well simulation, leakage from the injection boreholes would have had no significant effect on the inflow rate at the waste panels.

Stoelzel and Swift (1997) expanded on Stoelzel and O'Brien's (1996) work by considering injection for a longer period of time (up to 150 years) and into deeper horizons at higher pressures. They developed two computational models (a modified cross-sectional model and an axisymmetric radial model) that are alternatives to the cross-sectional model used by Stoelzel and O'Brien (1996). Rather than repeat the conservative and bounding approach used by Stoelzel and O'Brien (1996), Stoelzel and Swift (1997) focused on reasonable and realistic conditions for most aspects of the modeling, including setting parameters that were sampled in the CCA at their median values. Model results indicate that, for the cases considered, the largest volume of brine entering MB139 (the primary pathway to the WIPP) from the borehole is approximately 1,500 m^3 (52,974 ft^3), which is a small enough volume that it would not affect Stoelzel and O'Brien's (1996) conclusion even if it somehow all reached the WIPP. Other cases showed from 0 to 600 m^3 (21,190 ft^3) of brine entering MB139 from the injection well. In all cases, high-permeability fractures created in the Castile and Salado anhydrite layers by the modeled injection pressures were restricted to less than 400 m (1,312 ft) from the wellbore, and did not extend more than 250 m in MB138 and MB139.

No flow entered MB139, nor was fracturing of the unit calculated to occur away from the borehole, in cases in which leaks in the cement sheath had permeabilities of $1 \times 10^{-12.5}$ m^2 (corresponding to the median value used to characterize fully degraded boreholes in the CCA) or lower. The cases modeled in which flow entered MB139 from the borehole and fracturing

occurred away from the borehole required injection pressures conservatively higher than any currently in use near the WIPP and either 150 years of leakage through a fully degraded cement sheath or 10 years of simultaneous tubing and casing leaks from a waterflood operation. These conditions are not likely to occur in the future. If leaks like these do occur from brine injection near the WIPP, however, results of the Stoelzel and Swift (1997) modeling study indicate that they will not affect the performance of the repository.

Thus, the hydraulic effects of leakage through HCN boreholes outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.6.3.3 *Effects of Density Changes Resulting from Leakage Through Injection Boreholes*

Leakage through a failed borehole casing during a fluid injection operation in the vicinity of the WIPP could alter fluid density in the affected unit, which could result in changes in fluid flow rates and directions within the disposal system. Disposal of oil and gas production by-products through boreholes could increase fluid densities in transmissive units affected by leakage in the casing. Operations such as waterflooding use fluids derived from the target reservoir, or fluids with a similar composition, to avoid scaling and other reactions. Therefore, the effects of leakage from waterflood boreholes would be similar to leakage from disposal wells.

Denser fluids have a tendency to sink relative to less dense fluids, and, if the hydrogeological unit concerned has a dip, there will be a tendency for the dense fluid to travel in the downdip direction. If this direction is the same as the direction of the groundwater pressure gradient, there would be an increase in flow velocity, and conversely, if the downdip direction is opposed to the direction of the groundwater pressure gradient, there would be a decrease in flow velocity. In general terms, taking account of density-related flow will cause a rotation of the flow vector towards the downdip direction that is dependent on the density contrast and the dip.

Wilmot and Galson (1996) showed that brine density changes in the Culebra resulting from leakage through an injection borehole outside the controlled area will not affect fluid flow in the Culebra significantly. Potash mining activities assumed on the basis of regulatory criteria to occur in the near future outside the controlled area will have a more significant effect on modeled Culebra hydrology. The distribution of existing leases suggests that near-future mining will take place to the north, west, and south of the controlled area (see Section 2.3.1.1). The effects of such potash mining are accounted for in calculations of undisturbed performance of the disposal system (through an increase in the transmissivity of the Culebra above the mined region, as discussed in FEPs H37, H38, and H39). Groundwater modeling that accounts for potash mining shows a change in the fluid pressure distribution, and a consequent shift of flow directions towards the west in the Culebra within the controlled area (Wallace 1996c). A localized increase in fluid density in the Culebra resulting from leakage from an injection borehole would rotate the flow vector towards the downdip direction (towards the east).

Wilmot and Galson (1996) compared the relative magnitudes of the freshwater head gradient and the gravitational gradient and showed that the density effect is of low consequence to the

performance of the disposal system. According to Darcy's Law, flow in an isotropic porous medium is governed by the gradient of fluid pressure and a gravitational term

$$\bar{v} - -\frac{k}{\mu}\left[\nabla p - \rho \bar{g}\right], \tag{7}$$

where

v	=	Darcy velocity vector	(m s^{-1})
k	=	intrinsic permeability	(m^2)
μ	=	fluid viscosity	(pa s)
∇p	=	gradient of fluid pressure	(pa m^{-1})
ρ	=	fluid density	(kg m^{-3})
g	=	gravitational acceleration vector	(m s^{-2})

The relationship between the gravity-driven flow component and the pressure-driven component can be shown by expressing the velocity vector in terms of a freshwater head gradient and a density-related elevation gradient

$$\bar{v} = -K\left[\nabla H_f + \frac{\Delta\rho}{\rho_f}\nabla E\right], \tag{8}$$

where

K	=	hydraulic conductivity	(m s^{-1})
∇H_f	=	gradient of freshwater head	
$\Delta\rho$	=	difference between actual fluid density and reference fluid density	(kg m^{-3})
ρ_f	=	density of freshwater	(kg m^{-3})
∇E	=	gradient of elevation	

Davies (1989, p. 28) defined a driving force ratio (DFR) to assess the potential significance of the density gradient

$$\mathrm{DFR} = \frac{\Delta\rho\left|\nabla E\right|}{\rho_f\left|\nabla H_f\right|} \tag{9}$$

and concluded that a DFR of 0.5 can be considered an approximate threshold at which density-related gravity effects may become significant (Davies 1989, p. 28).

The dip of the Culebra in the vicinity of the WIPP is about 0.44° or 8 m/km (26 ft/mi) to the east (Davies 1989, p. 42). According to Davies (1989, pp. 47 - 48), freshwater head gradients in the Culebra between the waste panels and the southwestern and western boundaries of the accessible environment range from 4 m/km (13 ft/mi) to 7 m/km (23 ft/mi). Only small changes in gradient arise from the calculated effects of near-future mining. Culebra brines have densities ranging

from 998 to 1,158 kg/m^3 (998 to 1,158 ppm) (Cauffman et al. 1990, Table E1.b). Assuming the density of fluid leaking from a waterflood borehole or a disposal well to be 1,215 kg/m^3 (1,215 ppm) (a conservative high value similar to the density of Castile brine [Popielak et al. 1983, Table C-2]), leads to a DFR of between 0.07 and 0.43. These values of the DFR show that density-related effects caused by leakage of brine into the Culebra during fluid injection operations are not significant.

In summary, the effects of HCN fluid injection (***Liquid Waste Disposal, Enhanced Oil and Gas Production,*** and ***Hydrocarbon Storage)*** through boreholes outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.6.3.4 *Geochemical Effects of Leakage through Injection Boreholes*

Injection of fluids through a leaking borehole could affect the geochemical conditions in thief zones, such as the Salado interbeds or the Culebra. Such ***Fluid Injection-Induced Geochemical Changes*** could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area through their effects on colloid transport and sorption.

The majority of fluids injected (for example, during brine disposal) have been extracted locally during production activities. Because they have been derived locally, their compositions are similar to fluids currently present in the disposal system, and they will have low total colloid concentrations compared to those in the waste disposal panels (see FEPs discussion for H21 through H24). The repository will remain the main source of colloids in the disposal system. Therefore, colloid transport as a result of HCN fluid injection has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21 through H24, sorption within the Culebra is accounted for in PA calculations. The sorption model used accounts for the effects of any changes in sorption in the Culebra as a result of leakage through HCN injection boreholes.

Consistent with the screening discussion in FEPs H21 through H24, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of leakage through HCN injection boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

Nonlocally derived fluids could be used during hydraulic fracturing operations. However, such fluid injection operations would be carefully controlled to minimize leakage to thief zones. Therefore, any potential geochemical effects of such leakages have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.6.3.5 *Future Human EPs*

Consistent with 40 CFR § 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole within the site boundary.

Liquid Waste dDisposal (by-products from oil and gas production), ***Enhanced Oil and Gas Production***, and ***Hydrocarbon Storage*** are techniques associated with resource recovery and are expected to continue into the future outside the site boundary. Analyses have shown that these activities have little consequence on repository performance (Stoelzel and Swift 1997). Therefore, activities such as ***Liquid Waste Disposal, Enhanced Oil and Gas Production,*** and ***Hydrocarbon Storage*** have been eliminated from PA calculations on the basis of low consequence.

SCR-5.2.1.7 FEP Number: H30
FEP Title: ***Fluid Injection-Induced Geochemical Changes***

SCR-5.2.1.7.1 Screening Decision: UP (HCN)
SO-R (Future)

Geochemical changes that occur inside the controlled area as a result of fluid flow associated with HCN fluid injection are accounted for in PA calculations. ***Liquid Waste dDisposal****,* ***Enhanced Oil and Gas Production****, and* ***Hydrocarbon Storage*** *involving future boreholes have been eliminated from PA calculations on regulatory grounds.*

SCR-5.2.1.7.2 Summary of New Information

No new information regarding this FEP has been identified. The screening argument has been enhanced; the screening decisions have not changed.

SCR-5.2.1.7.3 Screening Argument

The injection of fluids could alter fluid-flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone. Injection of fluids through a leaking borehole could also result in geochemical changes and altered radionuclide migration rates in the thief units.

SCR-5.2.1.7.3.1 *Geochemical Effects of Leakage through Injection Boreholes*

Injection of fluids through a leaking borehole could affect the geochemical conditions in thief zones, such as the Salado interbeds or the Culebra. Such ***Fluid Injection-Induced Geochemical Changes*** could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area through their effects on colloid transport and sorption.

The majority of fluids injected (for example, during brine disposal) have been extracted locally during production activities. Because they have been derived locally, their compositions are similar to fluids currently present in the disposal system, and they will have low total colloid concentrations compared to those in the waste disposal panels (see FEPs H21 through H24). The repository will remain the main source of colloids in the disposal system. Therefore, colloid transport as a result of HCN fluid injection has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21 through H24, sorption within the Culebra is accounted for in PA calculations. The sorption model used accounts for the effects of any changes in sorption in the Culebra as a result of leakage through HCN injection boreholes.

Consistent with the screening discussion in FEPs H21 through H24, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of leakage through HCN injection boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

Non-locally derived fluids could be used during hydraulic fracturing operations. However, such fluid injection operations would be carefully controlled to minimize leakage to thief zones. Therefore, any potential geochemical effects of such leakages have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.7.3.2 *Future Human EPs*

Consistent with 40 CFR § 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. ***Liquid Waste dDisposal*** (by-products from oil and gas production), ***Enhanced Oil and Gas Production***, and ***Hydrocarbon Storage*** are techniques associated with resource recovery. Therefore, the use of future boreholes for such activities and fluid injection-induced geochemical changes have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.8 FEP Number: H31 and H33
FEP Title: ***Natural Borehole Fluid Flow*** (H31)
Flow Through Undetected Boreholes (H33)

SCR-5.2.1.8.1 Screening Decision: SO-C (HCN)
SO-C (Future, holes not penetrating waste panels)
DP (Future, holes through waste panels)

The effects of natural fluid flow through existing or near-future abandoned boreholes, known or unknown, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Natural borehole flow through a future borehole that intersects a waste panel is accounted for in PA calculations. The effects of natural borehole flow through a future borehole that does not intersect the waste-disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.8.2 Summary of New Information

Natural Borehole Fluid Flow and ***Flow Through Undetected Boreholes*** have been combined because knowledge of a borehole's existence has no impact on its effects. ***Flow Through Undetected Boreholes*** has been deleted from the baseline and the description of ***Natural Borehole Fluid Flow*** was changed to include unknown boreholes. The screening argument has been modified to simplify and improve clarity.

SCR-5.2.1.8.3 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Movement of fluids through abandoned boreholes could result in borehole-induced geochemical changes in the receiving units such as the Salado interbeds or Culebra, and thus alter radionuclide migration rates in these units.

Potentially, boreholes could provide pathways for surface-derived water or groundwater to percolate through low-permeability strata and into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns. Also, fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation.

SCR-5.2.1.8.3.1 *Historical, Current, and Near-Future Human EPs*

SCR-5.2.1.8.3.2 *Abandoned water, potash, oil, and gas exploration and production boreholes exist within and outside the controlled area. Most of these boreholes have been plugged in some way, but some have simply been abandoned. Over time, even the boreholes that have been plugged may provide hydraulic connections among the units they penetrate as the plugs degrade. The DOE assumes that records of past and present drilling activities in New Mexico are largely accurate and that evidence of most boreholes would be included in these records. However, the potential effects of boreholes do not change depending on whether we know of their existence or not, hence* **Flow Through Undetected Boreholes** *and* **Flow Through Undetected Boreholes** *can be evaluated together.*

SCR-5.2.1.8.3.3 *Hydraulic Effects of Flow through Abandoned Boreholes*

Fluid flow and radionuclide transport within the Culebra could be affected if deep boreholes result in hydraulic connections between the Culebra and deep overpressurized or underpressurized units, or if boreholes provide interconnections for flow between shallow units.

SCR-5.2.1.8.3.4 *Connections Between the Culebra and Deeper Units*

Fluid flow and radionuclide transport within the Culebra could be affected if deep boreholes result in hydraulic connections between the Culebra and deep overpressurized or underpressurized units. Over the past 80 years, a large number of deep boreholes have been drilled within and around the controlled area (see Section 6.4.12.2). The effects on the performance of the disposal system of long-term hydraulic connections between the Culebra and deep units depends on the locations of the boreholes. In some cases, changes in the Culebra flow field caused by interconnections with deep units could decrease lateral radionuclide travel times to the accessible environment.

As part of an analysis to determine the impact of such interconnections, Wallace (1996a) gathered information on the pressures, permeabilities, and thicknesses of potential oil- or gas-bearing sedimentary units; such units exist to a depth of about 5,500 m (18,044 ft) in the vicinity of the WIPP. Of these units, the Atoka, some 4,000 m (13,123 ft) below the land surface, has the highest documented pressure of about 64×10^6 pascals (9,600 psi), with permeability of about 2×10^{-14} m^2 (2.1×10^{-13} ft^2) and thickness of about 210 m (689 ft). The Strawn, 3,900 m (12,795 ft) below the land surface, has the lowest pressures (35×10^6 pascals (5,000 psi), which is lower than hydrostatic) and highest permeability (10^{-13} m^2 (1.1×10^{-12} ft^2)) of the deep units, with a thickness of about 90 m (295 ft).

PA calculations indicate that the shortest radionuclide travel times to the accessible environment through the Culebra occur when flow in the Culebra in the disposal system is from north to south. Wallace (1996a) ran the steady-state SECOFL2D model with the PA data that generated the shortest radionuclide travel times (with and without mining in the controlled area) but perturbed the flow field by placing a borehole connecting the Atoka to the Culebra just north of the waste disposal panels and a borehole connecting the Culebra to the Strawn just south of the controlled area. The borehole locations were selected to coincide with the end points of the fastest flow paths modeled, which represents an unlikely worst-case condition. Although the Atoka is primarily a gas-bearing unit, Wallace (1996a) assumed that the unit is brine saturated. This assumption is conservative because it prevents two-phase flow from occurring in the Culebra, which would decrease the water permeability and thereby increase transport times. He further conservatively assumed that the pressure in the Atoka would not have been depleted by production before the well was plugged and abandoned. He also conservatively assumed that all flow from the Atoka would enter the Culebra and not intermediate or shallower units, and that flow from the Culebra could somehow enter the Strawn despite intermediate zones having higher pressures than the Culebra. The fluid flux through each borehole was determined using Darcy's Law, assuming a borehole hydraulic conductivity of 10^{-4} m/s (for a permeability of about 10^{-11} m^2 (1.1×10^{-10} ft^2)) representing silty sand, a borehole radius of 0.25 m (.82 ft), and a fluid pressure in the Culebra of 0.88×10^6 pascals (132 psi) at a depth of about 200 m (650 ft). With these parameters, the Atoka was calculated to transmit water to the Culebra at about 1.4×10^{-5} m^3/s (0.22 gpm), and the Strawn was calculated to receive water from the Culebra at about 1.5×10^{-6} m^3/s (0.024 gpm).

Travel times through the Culebra to the accessible environment were calculated using the SECOFL2D velocity fields for particles released to the Culebra above the waste panels, assuming no retardation by sorption or diffusion into the rock matrix. Mean Darcy velocities were then determined from the distance each radionuclide traveled, the time taken to reach the accessible environment, and the effective Culebra porosity. The results show that, at worst, interconnections between the Culebra and deep units under the unrealistically conservative assumptions listed above could cause less than a twofold increase in the largest mean Darcy velocity expected in the Culebra in the absence of such interconnections.

These effects can be compared to the potential effects of climate change on gradients and flow velocities through the Culebra. As discussed in Section 6.4.9 (and Corbet and Knupp 1996), the maximum effect of a future wetter climate would be to raise the water table to the ground surface. This would raise heads and gradients in all units above the Salado. For the Culebra, the

maximum change in gradient was estimated to be about a factor of 2.1. The effect of climate change is incorporated in compliance calculations through the Climate Index, which is used as a multiplier for Culebra groundwater velocities. The Climate Index has a bimodal distribution, with the range from 1.00 to 1.25 having a 75 percent probability, and the range from 1.50 to 2.25 having a 25 percent probability. Because implementation of the Climate Index leads to radionuclide releases through the Culebra that are orders of magnitude lower than the regulatory limits, the effects of flow between the Culebra and deeper units through abandoned boreholes can be screened out on the basis of low consequence.

SCR-5.2.1.8.3.5 *Connections Between the Culebra and Shallower Units*

Abandoned boreholes could also provide interconnections for long-term fluid flow between shallow units (overlying the Salado). Abandoned boreholes could provide pathways for downward flow of water from the Dewey Lake and/or Magenta to the Culebra because the Culebra hydraulic head is lower than the hydraulic heads of these units. Magenta freshwater heads are as much as 45 m (148 ft) higher than Culebra freshwater heads. Because the Culebra is generally at least one order of magnitude more transmissive than the Magenta at any location, a connection between the Magenta and Culebra would cause proportionally more drawdown in the Magenta head than rise in the Culebra head. For example, for a one order of magnitude difference in transmissivity and a 45-m (148-ft) difference in head, the Magenta head would decrease by approximately 40 m (131 ft) while the Culebra head increased by 5 m (16 ft). This head increase in the Culebra would also be a localized effect, decreasing with radial distance from the leaking borehole. The primary flow direction in the Culebra across the WIPP site is from north to south, with the Culebra head decreasing by approximately 20 m (66 ft) across this distance. A 5-m (16-ft) increase in Culebra head at the northern WIPP boundary would, therefore, increase gradients by at most 25 percent.

The Dewey Lake freshwater head at the WQSP-6 pad is 55 m (180 ft) higher than the Culebra freshwater head. Leakage from the Dewey Lake could have a greater effect on Culebra head than leakage from the Magenta if the difference in transmissivity between the Dewey Lake and Culebra observed at the WQSP-6 pad, where the Dewey Lake is two orders of magnitude more transmissive than the Culebra (Beauheim and Ruskauff 1998), persists over a wide region. However, the saturated, highly transmissive zone in the Dewey Lake has only been observed south of the WIPP disposal panels. A connection between the Dewey Lake and the Culebra south of the panels would tend to decrease the north-south gradient in the Culebra across the site, not increase it.

In any case, leakage of water from overlying units into the Culebra could not increase Culebra heads and gradients as much as might result from climate change, discussed above. Because implementation of the Climate Index leads to radionuclide releases through the Culebra that are orders of magnitude lower than the regulatory limits, the effects of flow between the Culebra and shallower units through abandoned boreholes can be screened out on the basis of low consequence.

SCR-5.2.1.8.3.6 *Changes in Fluid Density Resulting from Flow Through Abandoned Boreholes*

Leakage from historical, current, and near-future abandoned boreholes that penetrate pressurized brine pockets in the Castile could give rise to fluid density changes in affected units. Wilmot and Galson (1996) showed that brine density changes in the Culebra resulting from leakage through an abandoned borehole would not have a significant effect on the Culebra flow field. A localized increase in fluid density in the Culebra resulting from leakage from an abandoned borehole would rotate the flow vector towards the downdip direction (towards the east). A comparison of the relative magnitudes of the freshwater head gradient and the gravitational gradient, based on an analysis similar to that presented in Sections SCR.5.2.1 (FEPs H27, H28, and H29), shows that the density effect is of low consequence to the performance of the disposal system.

SCR-5.2.1.8.3.7 *Future Human EPs*

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete, the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.8.3.8 *Hydraulic Effects of Flow Through Abandoned Boreholes*

A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. Long-term ***Natural Borehole Flow*** through such a borehole is accounted for in PA calculations (see Section 6.4.8).

Deep abandoned boreholes that intersect the Salado interbeds near the waste disposal panels could provide pathways for long-term radionuclide transport from the waste panels to the land surface or to overlying units. The potential significance of such events were assessed by WIPP PA Department (1991, B-26 to B-27), which examined single-phase flow and transport between the waste panels and a borehole intersecting MB139 outside the DRZ. The analysis assumed an in situ pressure of 11 megapascals in MB139, a borehole pressure of 6.5 megapascals (975 psi) (hydrostatic) at MB139, and a constant pressure of 18 megapascals (2,700 psi) as a source term in the waste panels representing gas generation. Also, MB139 was assigned a permeability of approximately 3×10^{-20} m^2 (3.2×10^{-19} ft^2) and a porosity of 0.01 percent. The disturbed zone was assumed to exist in MB139 directly beneath the repository only and was assigned a permeability of 1.0×10^{-17} m^2 (1.1×10^{-16} ft^2) and a porosity of 0.055 percent. Results showed that the rate of flow through a borehole located just 0.25 m (0.8 ft) outside the DRZ would be more than two orders of magnitude less than the rate of flow through a borehole located within the DRZ because of the contrast in permeability. Thus, any releases of radionuclides to the accessible environment through deep boreholes that do not intersect waste panels would be insignificant compared to the releases that would result from transport through boreholes that

intersect waste panels. Thus, radionuclide transport through deep boreholes that do not intersect waste panels has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.8.3.9 *Fluid Flow and Radionuclide Transport in the Culebra*

Fluid flow and radionuclide transport within the Culebra could be affected if future boreholes result in hydraulic connections between the Culebra and either deeper or shallower units. Over the 10,000-year regulatory period, a large number of deep boreholes could be drilled within and around the controlled area (see Section 6.4.12.2). The effects on the performance of the disposal system of long-term hydraulic connections between the Culebra and deeper or shallower units would be the same as those discussed above for historic, current, and near-future conditions. Thus, the effects of flow between the Culebra and deeper or shallower units through abandoned future boreholes can be screened out on the basis of low consequence.

SCR-5.2.1.8.3.10 *Changes in Fluid Density Resulting from Flow Through Abandoned Boreholes*

A future borehole that intersects a pressurized brine reservoir in the Castile could also provide a source for brine flow to the Culebra in the event of borehole casing leakage, with a consequent localized increase in fluid density in the Culebra. The effect of such a change in fluid density would be to increase any density-driven component of groundwater flow. If the downdip direction, along which the density-driven component would be directed, is different from the direction of the groundwater pressure gradient, there would be a slight rotation of the flow vector towards the downdip direction. The groundwater modeling presented by Davies (1989, p. 50) indicates that a borehole that intersects a pressurized brine pocket and causes a localized increase in fluid density in the Culebra above the waste panels would result in a rotation of the flow vector slightly towards the east. However, the magnitude of this effect would be small in comparison to the magnitude of the pressure gradient (see screening argument for FEPS H27, H28, and H29 where this effect is screened out on the basis of low consequence.

SCR-5.2.1.9 FEP Number: H32
FEP Title: ***Waste-Induced Borehold Flow***

SCR-5.2.1.9.1 Screening Decision: SO-R (HCN)
DP (Future)

Waste-induced flow through boreholes drilled in the near future has been eliminated from PA calculations on regulatory grounds. ***Waste-Induced Borehole Flow*** *and* ***Natural Borehole Flow*** *through a future borehole that intersects a waste panel are accounted for in PA calculations.*

SCR-5.2.1.9.2 Summary of New Information

SCR-5.2.1.9.3 No new information has been identified for this FEP. This discussion for this FEP has been modified for editorial purposes.

SCR-5.2.1.9.4 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Continued resource exploration and production in the near future will result in the occurrence of many more abandoned boreholes in the vicinity of the controlled area. Institutional controls will prevent drilling (other than that associated with the WIPP development) from taking place within the controlled area in the near future. Therefore, no boreholes will intersect the waste disposal region in the near future, and ***Waste-Induced Borehole Flow*** in the near future has been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.9.4.1 *Future Human EPs*

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.9.4.2 *Hydraulic Effects of Flow Through Abandoned Boreholes*

An abandoned future borehole that intersects a waste panel could provide a connection for contaminant transport away from the repository horizon. If the borehole has degraded casing and/or plugs, and the fluid pressure within the waste panel is sufficient, radionuclides could be transported to the land surface. Additionally, if brine flows through the borehole to overlying units, such as the Culebra, it may carry dissolved and colloidal actinides that can be transported laterally to the accessible environment by natural groundwater flow in the overlying units. Long-term ***Waste-Induced Borehole Flow*** is accounted for in PA calculations (see Section 6.4.7.2).

SCR-5.2.1.10 FEP Number: H34
FEP Title: ***Borehole-Induced Solution and Subsidence***

SCR-5.2.1.10.1 Screening Decision: SO-C (HCN)
SO-C (Future)

The effects of ***Borehole-Induced Solution and Subsidence*** *associated with existing, near-future, and future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-5.2.1.10.2 Summary of New Information

The original description and screening arguments for ***Borehole-Induced Solution and Subsidence*** around existing and future boreholes remain unchanged and valid. The change in hydraulic conductivity within the Culebra from ***Borehole-Induced Solution and Subsidence*** along the flow path will have no significant affect on the long-term performance of the disposal system. The effects have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The FEP description and screening arguments have been revised to include new information related to borehole-induced subsidence by recognizing new and developing sinks in the region.

SCR-5.2.1.10.3 Screening Argument

Potentially, boreholes could provide pathways for surface-derived water or groundwater to percolate through low-permeability strata and into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns. Also, fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation.

SCR-5.2.1.10.3.1 *Historical, Current, and Near-Future Human EPs*

SCR-5.2.1.10.3.1.1 *Borehole-Induced Solution and Subsidence*

During the period covered by HCN FEPs, drilling within the land withdrawn for the WIPP will be controlled, and boreholes will be plugged according to existing regulations. Under these circumstances and during this time period, ***Borehole-Induced Solution and Subsidence*** at WIPP is eliminated from PA calculations on the basis of no consequence to the disposal system.

Outside the area withdrawn for the WIPP, drilling has been regulated, but conditions of historical and existing boreholes are highly variable. ***Borehole-Induced Solution and Subsidence*** may occur in these areas, although it is expected to be limited and should not affect the disposal system, as discussed in the following paragraphs.

Three features are required for significant ***Borehole-Induced Solution and Subsidence*** to occur: a borehole, an energy gradient to drive unsaturated (with respect to halite) water through the evaporite-bearing formations, and a conduit to allow migration of brine away from the site of dissolution. Without these features, minor amounts of halite might be dissolved in the immediate

vicinity of a borehole, but percolating water would become saturated with respect to halite and stagnant in the bottom of the drillhole, preventing further dissolution.

At, and in the vicinity of, the WIPP site, drillholes penetrating into, but not through, the evaporite-bearing formations have little potential for dissolution. Brines coming from the Salado and Castile, for example, have high total dissolved solids (TDS) and are likely to precipitate halite, not dissolve more halite during passage through the borehole. Water infiltrating from the surface or near-surface units may not be saturated with halite. For drillholes with a total depth in halite-bearing formations, there is little potential for dissolution because the halite-bearing units have very low permeability and provide little outlet for the brine created as the infiltrating water fills the drillhole. ERDA 9 is the deepest drillhole in the immediate vicinity of the waste panels at WIPP; the bottom of the drillhole is in the uppermost Castile Formation, with no known outlet for brine at the bottom.

Drillholes penetrating through the evaporite-bearing formations provide possible pathways for circulation of water. Underlying units in the vicinity of the WIPP site with sufficient potentiometric levels or pressures to reach or move upward through the halite units generally have one of two characteristics: (1) high-salinity brines, which limit or eliminate the potential for dissolution of evaporites, or (2) are gas-producers. Wallace et al. (1982) analyzed natural processes of dissolution of the evaporites by water from the underlying Bell Canyon Formation. They concluded that brine removal in the Bell Canyon is slow, limiting the movement of dissolution fronts or the creation of natural collapse features. Existing drillholes that are within the boundaries of the withdrawn land and also penetrate through the evaporites are not located in the immediate vicinity of the waste panels or WIPP workings.

There are three examples in the region that appear to demonstrate the process for ***Borehole-Induced Solution and Subsidence***, but the geohydrologic setting and drillhole completions differ from those at or near the WIPP.

An example of ***Borehole-Induced Solution and Subsidence*** occurred in 1980 about 160 km (100 mi) southeast of the WIPP site (outside the Delaware Basin) at the Wink Sink (Baumgardner et al. 1982; Johnson 1989); percolation of shallow groundwater through abandoned boreholes, dissolution of the Salado, and subsidence of overlying units led to a surface collapse feature 110 m (360 ft) in width and 34 m (110 ft) deep. At Wink Sink, the Salado is underlain by the Tansill, Yates, and Capitan Formations, which contain vugs and solution cavities through which brine could migrate. Also, the hydraulic head of the Santa Rosa (the uppermost aquifer) is greater than those of the deep aquifers (Tansill, Yates, and Capitan Formations), suggesting downward flow if a connection were established. A second sink (Wink Sink 2) formed in May 2002, near the earlier sink (Johnson et al., in press). Its origin is similar to the earlier sink. By February 2003, Wink Sink 2 had enlarged by surface collapse to a length of about 305 m (1000 ft) and a width of about 198 m (650 ft).

A similar, though smaller, surface collapse occurred in 1998 northwest of Jal, New Mexico (Powers 2000). The most likely cause of collapse appears to be dissolution of Rustler, and possibly Salado, halite as relatively low salinity water from the Capitan Reef circulated through breaks in the casing of a deep water supply well. Much of the annulus behind the casing through the evaporite section was uncemented, and work in the well at one time indicated bent and

ruptured casing. The surface collapse occurred quickly, and the sink was initially about 23 m (75 ft) across and a little more than 30 m (100 ft) deep. By 2001, the surface diameter was about 37 m (120 ft), and the sink was filled with collapse debris to about 18 m (60 ft) below the ground level (Powers, in press).

The sinkholes near Wink, Texas, and Jal, New Mexico, occurred above the Capitan Reef (which is by definition outside the Delaware Basin), and the low salinity water and relatively high potentiometric levels of the Capitan Reef appear to be integral parts of the process that formed these sinkholes. They are reviewed as examples of the process of evaporite dissolution and subsidence related to circulation in drillholes. Nevertheless, the factors of significant low salinity water and high potentiometric levels in units below the evaporites do not appear to apply at the WIPP site.

Beauheim (1986) considered the direction of natural fluid flow through boreholes in the vicinity of the WIPP. Beauheim (1986, p. 72) examined hydraulic heads measured using drill stem tests in the Bell Canyon and the Culebra at well DOE-2 and concluded that the direction of flow in a cased borehole open only to the Bell Canyon and the Culebra would be upward. Bell Canyon waters in the vicinity of the WIPP site are saline brines (e.g., Lambert 1978; Beauheim et al. 1983; Mercer et al. 1987), limiting the potential for dissolution of the overlying evaporites. However, dissolution of halite in the Castile and the Salado would increase the relative density of the fluid in an open borehole, causing a reduction in the rate of upward flow. Potentially, the direction of borehole fluid flow could reverse, but such a flow could be sustained only if sufficient driving pressure, porosity, and permeability exist for fluid to flow laterally within the Bell Canyon. A further potential sink for Salado-derived brine is the Capitan Limestone. However, the subsurface extent of the Capitan Reef is approximately 16 km (10 mi) from the WIPP at its closest point, and this unit will not provide a sink for brine derived from boreholes in the vicinity of the controlled area. A similar screening argument is made for natural deep dissolution in the vicinity of the WIPP (see N16, N17, and N18).

The effects of ***Borehole-Induced Solution and Subsidence*** through a waste panel are considered below. The principal effects of ***Borehole-Induced Solution and Subsidence*** in the remaining parts of the disposal system should be to change the hydraulic properties of the Culebra and other rocks in the system. The features are local (limited lateral dimensions) and commonly nearly circular. If subsidence occurs along the expected travel path and the transmissivity of the Culebra is increased, as in the calculations conducted by Wallace (1996c), the travel times should increase. If the transmissivity along the expected flow path decreased locally due to such a feature, the flow path should be lengthened by travel around the feature. Thus, the effects of ***Borehole-Induced Solution and Subsidence*** around existing abandoned boreholes, and boreholes drilled and abandoned in the near-future, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.10.3.2 *Future Human EPs*

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially,

contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.10.3.2.1 *Borehole-Induced Solution and Subsidence*

Future boreholes that do not intersect the WIPP excavation do not differ in long-term behavior or consequences from existing boreholes, and can be eliminated from PA on the basis of low consequence to the performance of the disposal system.

The condition of more apparent concern is a future borehole that intersects the WIPP excavation. Seals and casings are assumed to degrade, connecting the excavation to various units. For a drillhole intersecting the excavation, but not connecting to a brine reservoir or to formations below the evaporites, downward flow is limited by the open volume of the disposal room(s), which is dependent with time, gas generation, or brine inflow to the disposal system from the Salado.

Maximum dissolution, and maximum increase in borehole diameter, will occur at the top of the Salado; dissolution will decrease with depth as the percolating water becomes salt saturated. Eventually, degraded casing and concrete plug products, clays, and other materials will fill the borehole. Long-term flow through a borehole that intersects a waste panel is accounted for in disturbed performance calculations by assuming that the borehole is eventually filled by such materials, which have the properties of a silty sand (see Section 6.4.7.2). However, these calculations assume that the borehole diameter does not increase with time. Under the conditions assumed in the SCR for the CCA for an E2 drilling event at 1,000 years, about 1,000 m^3 (35,316 ft^3) would be dissolved from the lower Rustler and upper Salado Formations. If the dissolved area is approximately cylindrical or conical around the borehole, and the collapse/subsidence propagates upward as occurred in breccia pipes (e.g., Snyder and Gard 1982), the diameter of the collapsed or subsided area through the Culebra and other units would be a few tens of meters across. Changes in hydraulic parameters for this small zone should slow travel times for any hypothesized radionuclide release, as discussed for HCN occurrences. This does not change the argument for low consequence due to ***Borehole-Induced Solution and Subsidence*** for these circumstances.

If a drillhole through a waste panel and into deeper evaporites intercepts a Castile brine reservoir, the brine has little or no capability of dissolving additional halite. The Castile brine flow is considered elsewhere as part of disturbed performance. There is, however, no ***Borehole-Induced Solution and Subsidence*** under this circumstance, and therefore there is no effect on performance due to this EP.

If a borehole intercepts a waste panel and also interconnects with formations below the evaporite section, fluid flow up or down is determined by several conditions and may change over a period of time (e.g., as dissolution increases the fluid density in the borehole. Fluid flow downward is not a concern for performance, as fluid velocities in units such as the Bell Canyon are slow and should not be of concern for performance (e.g., II-G-12, 3.12.3.3.). For dissolution at the top of the evaporite section (as with boreholes considered under HCN), the process can develop a localized area around the borehole in which the hydraulic parameters for the Culebra and other

units are altered. As with boreholes considered for HCN, the local change in hydraulic parameters, if it occurs along the expected flow path, would be expected to cause little change in travel time and should increase the travel time.

In summary, the effects of ***Borehole-Induced Solution and Subsidence*** around future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.11 FEP Number: H35
FEP Title: ***Borehole Induced Mineralization***

SCR-5.2.1.11.1 Screening Decision: SO-C (HCN)
SO-C (Future)

The effects of ***Borehole -Induced Mineralization****, associated with existing, near-future, and future abandoned boreholes, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-5.2.1.11.2 Summary of New Information

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. Movement of compositionally different groundwater into the Culebra may lead to mineral precipitation, potentially changing porosity and permeability within the unit, and affecting contaminant transport. The potential effects of borehole-induced brine movement into the Culebra dolomite and mineral precipitation/ dissolution are discussed in FEPs H31 through H36. The original FEP description was slightly modified to include an evaluation of the effects of mineral precipitation on matrix diffusion.

SCR-5.2.1.11.3 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Movement of fluids through abandoned boreholes could result in ***Borehole*-Induced Geochemical Changes** in the receiving units, such as the Salado interbeds or Culebra, and thus alter radionuclide migration rates in these units.

Potentially, boreholes could provide pathways for surface-derived water or groundwater to percolate through low-permeability strata and into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns. Also, fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation.

SCR-5.2.1.11.3.1 *Borehole-Induced Mineralization*

Fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation. For example:

- Limited calcite precipitation may occur as the waters mix in the Culebra immediately surrounding the borehole, and calcite dissolution may occur as the brines migrate away from the borehole due to variations in water chemistry along the flow path.

- Gypsum may be dissolved as the waters mix in the Culebra immediately surrounding the borehole but may precipitate as the waters migrate through the Culebra.

The effects of these mass transfer processes on groundwater flow depend on the original permeability structure of the Culebra rocks and the location of the mass transfer. The volumes of minerals that may precipitate and/or dissolve in the Culebra as a result of the injection of Castile or Salado brine through a borehole will not affect the existing spatial variability in the permeability field significantly.

Predicted radionuclide transport rates in the Culebra assume that the dolomite matrix is diffusively accessed by the contaminants. The possible inhibition of matrix diffusion by secondary mineral precipitation on fracture walls, due to mixing between brines and Culebra porewater, was addressed by Wang (1998). Wang showed that the volume of secondary minerals precipitated due to this mechanism was too small to significantly affect matrix porosity and accessibility.

Consequently, the effects of ***Borehole -Induced Mineralization*** on permeability and groundwater flow within the Culebra, as a result of brines introduced via any existing abandoned boreholes, and boreholes drilled and abandoned in the near-future, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.11.4 Future Human EPs

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.11.4.1 *Borehole-Induced Mineralization*

Fluid flow between hydraulically conductive horizons through a future borehole may result in changes in permeability in the affected units through mineral precipitation. However, the effects of mineral precipitation as a result of flow through a future borehole in the controlled area will be similar to the effects of mineral precipitation as a result of flow through an existing or near-future borehole (see FEP H32 and H33). Thus, ***Borehole-Induced Mineralization*** associated

with flow through a future borehole has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.12 FEP Number: H36
FEP Title: ***Borehole-Induced Geochemical Changes***

SCR-5.2.1.12.1 Screening Decision: UP (HCN)
DP (Future)
SO-C for units other than the Culebra

Geochemical changes that occur inside the controlled area as a result of long-term flow associated with HCN, and future abandoned boreholes are accounted for in PA calculations.

SCR-5.2.1.12.2 Summary of New Information

No new information has been identified. This FEP has been modified for editorial purposes.

SCR-5.2.1.12.3 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Movement of fluids through abandoned boreholes could result in ***Borehole*-Induced Geochemical Changes** in the receiving units such as the Salado interbeds or Culebra, and thus alter radionuclide migration rates in these units.

SCR-5.2.1.12.3.1 *Geochemical Effects of Borehole Flow*

Movement of fluids through abandoned boreholes could result in ***Borehole*-Induced Geochemical Changes** in the receiving units such as the Salado interbeds or Culebra. Such geochemical changes could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area, or if they occur as a result of flow through existing boreholes within the controlled area through their effects on colloid transport and sorption.

The contents of the waste disposal panels provide the main source of colloids in the disposal system. Thus, consistent with the discussion for ***Borehole*-Induced Geochemical Changes** (H24), colloid transport as a result of flow through existing and near-future abandoned boreholes has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in H24, sorption within the Culebra is accounted for in PA calculations. The sorption model used accounts for the effects of changes in sorption in the Culebra as a result of flow through existing and near-future abandoned boreholes.

Consistent with the screening discussion in H24, the effects of changes in sorption in the Dewey Lake inside the controlled area as a result of flow through existing and near-future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-5.2.1.12.4 Future Human EPs

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.12.4.1 *Geochemical Effects of Flow Through Abandoned Boreholes*

Movement of fluids through abandoned boreholes could result in ***Borehole*-Induced Geochemical Changes** in the receiving units, such as the Salado interbeds or Culebra. Such geochemical changes could alter radionuclide migration rates within the disposal system in the affected units through their effects on colloid transport and sorption.

The waste disposal panels provide the main source of colloids in the disposal system. Colloid transport within the Culebra as a result of long-term flow associated with future abandoned boreholes that intersect the waste disposal region are accounted for in PA calculations, as described in Sections 6.4.3.6 and 6.4.6.2.1. Consistent with the discussion in H24, colloid transport as a result of flow through future abandoned boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The Culebra is the most transmissive unit in the disposal system and it is the most likely unit through which significant radionuclide transport could occur. Therefore, colloid transport in units other than the Culebra, as a result of flow through future abandoned boreholes, has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in H24, sorption within the Culebra is accounted for in PA calculations. The sorption model accounts for the effects of changes in sorption in the Culebra as a result of flow through future abandoned boreholes.

Consistent with the screening discussion in H24, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of flow through future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-5.2.2 Excavation-Induced Flow

SCR-5.2.2.1 FEP Number: H37
FEP Title: ***Changes in Groundwater Flow due to Mining***

SCR-5.2.2.1.1 Screening Decision: UP (HCN)
DP (Future)

Changes in groundwater flow due to HCN, and future potash mining are accounted for in PA calculations.

SCR-5.2.2.1.2 Summary of New Information

Changes in groundwater flow due to HCN, and future mining are included in PA calculations of groundwater flow and transport through the Culebra. The FEP description and screening argument have been modified slightly to reflect recent activities, but the screening decision is unchanged.

SCR-5.2.2.1.3 Screening Argument

Excavation activities may result in hydrological disturbances of the disposal system. Subsidence associated with excavations may affect groundwater flow patterns through increased hydraulic conductivity within and between units. Fluid flow associated with excavation activities may also result in changes in brine density and geochemistry in the disposal system.

SCR-5.2.2.1.3.1 *Historical, Current, and Near-Future Human EPs*

Currently, potash mining is the only excavation activity currently taking place in the vicinity of the WIPP that could affect hydrogeological or geochemical conditions in the disposal system. Potash is mined in the region east of Carlsbad and up to 5 km (3.1 mi) from the boundaries of the controlled area. Mining of the McNutt in the Salado is expected to continue in the vicinity of the WIPP (see Section 2.3.1.1): the DOE assumes that all economically recoverable potash in the vicinity of the WIPP (outside the controlled area) will be extracted in the near future.

SCR-5.2.2.1.3.2 *Hydrogeological Effects of Mining*

Potash mining in the Delaware Basin typically involves constructing vertical shafts to the elevation of the ore zone and then extracting the minerals in an excavation that follows the trend of the ore body. Potash has been extracted using conventional room and pillar mining, secondary mining where pillars are removed, and modified long-wall mining methods. Mining techniques used include drilling and blasting (used for mining langbeinite) and continuous mining (commonly used for mining sylvite). The DOE (Westinghouse 1994, pp. 2-17 to 2-19) reported investigations of subsidence associated with potash mining operations located near the WIPP. The reported maximum total subsidence at potash mines is about 1.5 m (5 ft), representing up to 66 percent of initial excavation height, with an observed angle of draw from the vertical at the edge of the excavation of 58 degrees. The DOE (Westinghouse 1994 pp. 2-22 to 2-23) found no evidence that subsidence over local potash mines had caused fracturing sufficient to connect the mining horizon to water-bearing units or the surface. However,

subsidence and fracturing associated with mining in the McNutt in the vicinity of the WIPP may allow increased recharge to the Rustler units and affect the lateral hydraulic conductivity of overlying units, such as the Culebra, which could influence the direction and magnitude of fluid flow within the disposal system. Such ***Changes in Groundwater Flow Due to Mining*** are accounted for in calculations of undisturbed performance of the disposal system. The effects of any increased recharge that may be occurring are in effect included by using heads measured in 2000 (which should reflect that recharge) to calibrate Culebra transmissivity fields and calculate transport through those fields (Beauheim 2002). Changes (increases) in Culebra transmissivity are incorporated directly in the modeling of flow and transport in the Culebra (see Section 6.4.6.2.3).

Potash mining, and the associated processing outside the controlled area, have changed fluid densities within the Culebra, as demonstrated by the areas of higher densities around boreholes WIPP-27 and WIPP-29 (Davies 1989, p. 43). Transient groundwater flow calculations (Davies 1989, pp. 77 - 81) show that brine density variations to the west of the WIPP site caused by historical and current potash processing operations will not persist because the rate of groundwater flow in this area is fast enough to flush the high density groundwaters to the Pecos River. These calculations also show that accounting for the existing brine density variations in the region east of the WIPP site, where hydraulic conductivities are low, would have little effect on the direction or rate of groundwater flow. Therefore, changes in fluid densities from historical and current Human EPs have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The distribution of existing leases and potash grades suggests that near-future mining will take place to the north, west, and south of the controlled area (see CCA Appendix DEL). A localized increase in fluid density in the Culebra, in the mined region or elsewhere outside the controlled area, would rotate the flow vector towards the downdip direction (towards the east). A comparison of the relative magnitudes of the pressure gradient and the density gradient (based on an analysis identical to that presented for fluid leakage to the Culebra through boreholes) shows that the density effect is of low consequence to the performance of the disposal system.

SCR-5.2.2.1.4 Future Human EPs

Consistent with 40 CFR § 194.32(b), consideration of future mining may be limited to potash mining within the disposal system. Within the controlled area, the McNutt provides the only potash of appropriate quality. The extent of possible future potash mining within the controlled area is discussed in Section 2.3.1.1. Criteria concerning the consequence modeling of future mining are provided in 40 CFR § 194.32(b): the effects of future mining may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system. Thus, consistent with 40 CFR § 194.32(b), ***Changes in Groundwater Flow Due to Mining*** within the controlled area are accounted for in calculations of the disturbed performance of the disposal system (see Section 6.4.6.2.3).

SCR-5.2.2.2 FEP Number: H38
FEP Title: ***Changes in Geochemistry Due to Mining***

SCR-5.2.2.2.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Changes in geochemistry due to HCN potash mining have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Changes in geochemistry due to future mining have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.2.2.2 Summary of New Information

The only natural resource being mined underground currently near WIPP is potash in the McNutt, and it is the only mineral considered for future mining. Potash mining is also the only excavation activity currently taking place in the vicinity of the WIPP that could affect hydrogeological or geochemical conditions in the disposal system. It appears unlikely that underground mining will impact the site geochemistry during the time of passive institutional controls, and a conclusion of no near-term consequence is screened from future events as per 40 CFR § 194.25. Changes have been made to the screening argument. However, the screening decision remains the same.

SCR-5.2.2.2.3 Screening Argument

SCR-5.2.2.2.3.1 *Historical, Current, and Near-Future Human EPs*

Potash mining is the only excavation activity currently taking place in the vicinity of the WIPP that could affect hydrogeological or geochemical conditions in the disposal system. Potash is mined in the region east of Carlsbad and up to 5 km (1.5 mi) from the boundaries of the controlled area. Mining of the McNutt in the Salado is expected to continue in the vicinity of the WIPP (see Section 2.3.1.1): the DOE assumes that all economically recoverable potash in the vicinity of the WIPP (outside the controlled area) will be extracted in the near future.

SCR-5.2.2.2.3.2 *Geochemical Effects of Mining*

Fluid flow associated with excavation activities may result in geochemical disturbances of the disposal system. Some waters from the Culebra reflect the influence of current potash mining, having elevated potassium to sodium ratios. However, potash mining has had no significant effect on the geochemical characteristics of the disposal system. Solution mining, which involves the injection of freshwater to dissolve the ore body, can be used for extracting sylvite. The impact on the WIPP of neighboring potash mines was examined in greater detail by D'Appolonia (1982). D'Appolonia noted that attempts to solution mine sylvite in the Delaware Basin failed due to low ore grade, thinness of the ore beds, and problems with heating and pumping injection water. See discussion for potash mining FEP H13. Thus, ***Changes in Groundwater Flow Due to Mining*** (HCN) have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.2.2.3.3 *Future Human EPs*

Consistent with 40 CFR § 194.32(b), consideration of future mining may be limited to potash mining within the disposal system. Within the controlled area, the McNutt provides the only potash of appropriate quality. The extent of possible future potash mining within the controlled area is discussed in Section 2.3.1.1. Criteria concerning the consequence modeling of future mining are provided in 40 CFR § 194.32(b): the effects of future mining may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system. Thus, consistent with 40 CFR § 194.32(b), changes in groundwater flow due to mining within the controlled area are accounted for in calculations of the disturbed performance of the disposal system (see Section 6.4.6.2.3). Other potential effects, such as ***Changes in Groundwater Flow Due to Mining***, have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.2.3 FEP Number H58
FEP Title: ***Solution Mining for Potash***

SCR-5.2.2.3.1 Screening Decision: SO-R (HCN)
SO-R (future)

HCN, and future ***Solution Mining*** for ***Potash*** *has been eliminated from PA calculations on regulatory grounds. HCN, and future solution mining for other resources have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-5.2.2.3.2 Summary of New Information

In the CCA, ***Solution Mining for Potash*** was not identified as a separate FEP, although all components of the solution mining process were accounted for in FEPs screening, albeit in a piecemeal fashion. For example, the drilling of the borehole necessary for solution injection or effluent recovery is addressed in FEP H8, ***Drilling For Other Resources***, mainly because the physical and mechanical effects of the drilling activity do not vary based on the type of resource being sought, nor on the final intended use of the borehole; e.g., disposal well, injection well, solution mining, or oil and gas extraction. The removal of an ore as a result of solution mining is ultimately the same as if conventional mining processes had removed the ore. Potash mining using conventional methods is addressed in FEP H13, ***Conventional Underground Potash Mining***. The ultimate effect of such ore body removal is believed to be the eventual subsidence of the overlying units and the associated impact upon hydraulic conductivity. This has been demonstrated to have a negligible effect on performance of the WIPP, and is in fact accounted for in PA by EPA's requisite treatment of potash mining above the waste area.

Although the original FEP baseline considered different types of mineral and petroleum resource exploration/exploitation, it did not initially consider the possibility of brine mining (solution mining), even though this has occurred in the Delaware Basin. EPA noted this oversight in their March 1997 letter requesting additional information regarding the CCA (EPA 1997). In response to this request, the DOE submitted two memos (Hicks 1997a, 1997b) that addressed both ***Solution Mining for Potash*** and solution mining for brine. In EPA's TSD for §194.32, "Scope of Performance Assessments," EPA noted that these memos adequately supported the screening decisions presented in the CCA.

For CRA-2004, solution mining has been explicitly represented within the FEPs baseline through the additions of FEP H58***, Solution Mining for Potash*** and FEP H59, ***Solution Mining for Other Resources***. The reassessment of these EPs confirms that no significant developments have occurred since the CCA, and the arguments used by Hicks remain valid. The creation of these FEPs will aid in clarifying and separating the activities related to solution mining from conventional mining for potash as addressed in FEP H13.

SCR-5.2.2.3.3 Screening Argument

Currently, no ***Solution Mining for Potash*** occurs in the Carlsbad Potash District (CPD). The prospect of using solution-mining techniques for extracting potash has been identified in the region, but has not been implemented. A pilot plant for secondary solution mining of sylvite in the Clayton Basin, just north of the Delaware Basin was permitted, and concept planning took place during the mid-1990s and was noted by the EPA in their Response to Comments to the CCA (EPA 1998b). Five years later, this pilot project has yet to begin. Therefore, it is premature to consider this an operational solution mining activity. More importantly, the proposed site is outside the Delaware Basin.

The potash reserves evaluated by Griswold and Griswold (1999) and NMBMMR (1995) at WIPP are of economic importance in only two ore zones; the 4th and the 10th and contain two minerals of economic importance, langbeinite and sylvite. The ore in the 10th ore zone is primarily sylvite with some langbeinite and the ore in the 4th zone is langbeinite with some sylvite. Langbeinite falls between gypsum and polyhalite in solubility and dissolves at a rate 1000 times slower than sylvite (Heyn 1997). Halite, the predominate gangue mineral present, is much more soluble than the langbeinite. Due to the insolubility of langbeinite, sylvite is the only ore that could be mined using a solution mining process. Mining for sylvite by solutioning would cause the langbeinite to be lost because conventional mining could not be done in conjunction with a solution mining process.

Communiqués with IMC Global (Heyn 1997, Prichard 2003), indicate that rock temperature is critical to the success of a solution-mining endeavor. IMC Global's solution mines in Michigan and Saskatchewan are at depths around 914 m (3,000 ft) or greater, at which rock temperatures are higher. The ore zones at WIPP are shallow, at depths of 457 to 549 m (1500 to 1800 ft), with fairly cool rock temperatures. David Prichard of IMC Global states that solution mining is energy intensive and the cool temperature of the rock would add to the energy costs. In addition, variable concentrations of confounding minerals (such as kainite and leonite) will cause problems with the brine chemistry.

Typically, solution mining is used for potash:

- when deposits are at depths in excess of 914 m (3000 ft) and rock temperatures are high or are geologically too complex to mine profitably using conventional underground mining techniques;

- to recover the potash pillars at the end of a mine's life; or

- when a mine is unintentionally flooded with waters from underlying or overlying rock strata and conventional mining is no longer feasible.

Douglas W. Heyn (chief chemist of IMC Kalium) provided written testimony to EPA related to the Agency's rulemaking activities on the CCA. Heyn concluded that "the rational choice for extracting WIPP potash ore reserves would be by conventional room and pillar mechanical means" (Heyn 1997). It is the opinion of IMC Global that no company will ever attempt solution mining of the ores in or near the WIPP (Heyn 1997, Prichard 2003).

The impact on the WIPP of neighboring potash mines was examined in detail by D'Appolonia (1982) and evaluated the possible effects of ***Solution Mining for Potash*** or other evaporite minerals. According to D'Appolonia (1982), and in agreement with Heyn (1997) of IMC Global Inc, solution mining of langbeinite is not technically feasible because the ore is less soluble than the surrounding evaporite minerals. Solution mining of sylvite was unsuccessfully attempted in the past by the Potash Company of America and Continental Potash, both ore bodies currently owned by Mississippi Chemical. Failure of solution mining was attributed to low ore grade, thinness of the ore beds, and problems with heating and pumping injection water. Unavailability of water in the area would also impede implementation of this technique. For these reasons, solution mining is not currently used in the Carlsbad Potash District.

Serious technical and economic obstacles exist that render ***Solution Mining for Potash*** very unlikely in the vicinity of the WIPP. Expectedly, no operational example of this technology exists in the CPD; that is, ***Solution Mining for Potash*** in not considered a current practice in the area. For this reason, consideration of solution mining on the disposal system in the future may be excluded on regulatory grounds. For example, the EPA stated in their Response to Comments, Section 8, Issue GG (EPA 1998b):

> …However, the Agency emphasizes that, in accordance with the WIPP compliance criteria, solution mining does not need to be included in the PA. As previously discussed, potash solution mining is not an ongoing activity in the Delaware Basin. Section 194.32(b) of the rule limits assessment of mining effects to excavation mining. Thus the solution mining scenarios proposed are excluded on regulatory grounds after repository closure. Prior to or soon after disposal, solution mining is an activity that could be considered under Section 194.32(c). However, DOE found that potash solution mining is not an ongoing activity in the Delaware Basin; and one pilot project examining solution mining in the Basin is not substantive evidence that such mining is expected to occur in the near future. (Even if mining were assumed to occur in the near future, the proposed scenarios would not be possible because, even though solution mining might occur, there would be no intruding borehole to provide a pathway into the repository: active institutional controls would preclude such drilling during the first 100 years after disposal.) Furthermore, Section 194.33(d) states that PA need not analyze the effects of techniques used for resource recovery (e.g. solution mining) after a borehole is drilled in the future.

No new data or information has become available that compromise, reduce, or invalidate the project's position on whether ***Solution Mining for Potash*** should be included in the PA calculations. Therefore, conventional mining activities will continue to be incorporated into the WIPP PA as directed by the EPA Compliance Application Guidance (CAG) (EPA 1996c). It remains to be seen if a viable potash solution mining project (or others like it) ever progress beyond the planning phase. Construction of a facility for solution mining is an expensive undertaking, and its use as a final recovery method implies that marginal (residual) ore quantities

are available. Because the Carlsbad Potash District mines are in their mature stages (declining) of production, the significant financing required for a solution mining facility may not become available. Nonetheless, at the time of this FEP reassessment, this technology is not being employed. Therefore, a screening based on the future states assumption at 40 CFR § 194.25(a) is appropriate for this mining technique. Further, the proposed site is outside the Delaware Basin making it outside the scope of consideration.

SCR-5.2.2.4 FEP Number: H59
FEP Title: ***Solution Mining for Other Resources***

SCR-5.2.2.4.1 Screening Decision: SO-C (HCN)
SO-C (future)

HCN, and future ***Solution Mining for Potash*** *has been eliminated from PA calculations on regulatory grounds. HCN, and future* ***Solution Mining for Other Resources*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-5.2.2.4.2 Summary of New Information

See summary for H58.

SCR-5.2.2.4.3 Screening Argument

Brine wells (solution mining for brine) exist within the Delaware Basin, although none within the vicinity of the WIPP. Sulfur extraction using the Frasch process began in 1969 and continued for three decades at the Culberson County Rustler Springs mine near Orla, Texas. Solution mining for the purposes of creating a storage cavity has not occurred within the New Mexico portion of the Delaware Basin.

SCR-5.2.2.4.4 Solution Mining for Brine

Oil and gas reserves in the Delaware Basin are located in structures within the Delaware Mountain Group and lower stratigraphic units. Boreholes drilled to reach these horizons pass through the Salado and Castile Formations that comprise thick halite and other evaporite units. To avoid dissolution of the halite units during drilling and prior to casing of the borehole, the fluid used for lubrication, rotating the drilling-bit cutters, and transporting cuttings (drilling mud) must be saturated with respect to halite. Most oil- and gas-field drilling operations in the Delaware Basin therefore use saturated brine (10 to 10.5 pounds per gallon) as a drilling fluid until reaching the Bell Canyon Formation, where intermediate casing is set.

One method of providing saturated brine for drilling operations is solution mining, whereby fresh water is pumped into the Salado Formation, allowed to reach saturation with respect to halite, and then recovered. This manufactured brine is then transported to the drilling site by water tanker.

Two principal techniques are used for solution mining; single-borehole operations, and doublet or two-borehole operations.

In single-borehole operations, a borehole is drilled into the upper part of the halite unit. After casing and cementing this portion of the borehole, the borehole is extended, uncased into the halite formation. An inner pipe is installed from the surface to the base of this uncased portion of the borehole. During operation, fresh water is pumped down the annulus of the borehole. This dissolves halite over the uncased portion of the borehole, and saturated brine is forced up the inner tube to the surface.

In doublet operations, a pair of boreholes are drilled, cased and cemented into the upper part of the halite unit. The base of the production well is set some feet below the base of the injection well. In the absence of natural fractures or other connections between the boreholes, hydrofracturing is used to induce fractures around the injection well. During operation, fresh water is pumped down the injection well. This initially dissolves halite from the walls of the fractures and the resulting brine is then pumped from the production well. After a period of operation a cavity develops between the boreholes as the halite between fractures is removed. Because of its lower density, fresh water injected into this cavity will rise to the top and dissolve halite from the roof of the cavity. As the brine density increases it sinks within the cavern and saturated brine is extracted from the production well.

SCR-5.2.2.4.4.1 *Current Brine Wells within the Vicinity of WIPP*

Brine wells are classified as Class II injection wells. In the Delaware Basin, the process includes injecting fresh water into a salt formation to create a saturated brine solution which is then extracted and utilized as a drilling agent. These wells are tracked by the Delaware Basin Drilling Surveillance Program on a continuing basis. Supplemental information provided to the EPA in 1997 showed 11 brine wells in the Delaware Basin. Since that time, additional information has shown that there are 15 brine wells within the Delaware basin, of which four are plugged and abandoned. This results in 11 currently active brine wells. Table SCR-3 provides information on these wells.

Table SCR-3. Delaware Basin Brine Well Status

County	Location	API No.	Well Name and No.	Operator	Status
Eddy	22S-26E-36	3001521842	City of Carlsbad #WS-1	Key Energy Services	Brine Well
Eddy	22S-27E-03	3001520331	Tracy #3	Ray Westall	Plugged Brine Well
Eddy	22S-27E-17	3001522574	Eugenie #WS-1	I & W Inc	Brine Well
Eddy	22S-27E-17	3001523031	Eugenie #WS-2	I & W Inc	Plugged Brine Well
Loving	Blk 29-03	4230110142	Lineberry Brine Station #1	Chance Properties	Brine Well
Loving	Blk 01-82	4230130680	Chapman Ford #BR1	Herricks & Son Co.	Plugged Brine Well
Loving	Blk 33-80	4230180318	Mentone Brine Station #1D	Basic Energy Services	Brine Well
Loving	Blk 29-28	4230180319	East Mentone Brine Station #1	Permian Brine Sales, Inc.	Plugged Brine Well

Table SCR-3. Delaware Basin Brine Well Status — Continued

County	Location	API No.	Well Name and No.	Operator	Status
Loving	Blk 01-83	4230180320	North Mentone #1	Chance Properties	Brine Well
Reeves	Blk 56-30	4238900408	Orla Brine Station #1D	Mesquite SWD Inc.	Brine Well
Reeves	Blk 04-08	4238920100	North Pecos Brine Station #WD-1	Chance Properties	Brine Well
Reeves	Blk 07-21	4238980476	Coyanosa Brine Station #1	Chance Properties	Brine Well
Ward	Blk 17-20	4247531742	Pyote Brine Station #WD-1	Chance Properties	Brine Well
Ward	Blk 01-13	4247534514	Quito West Unit #207	Seaboard Oil Co.	Brine Well
Ward	Blk 34-174	4247582265	Barstow Brine Station #1	Chance Properties	Brine Well

While these wells are within the Delaware Basin, none are within the vicinity of the WIPP. The nearest brine well to the WIPP is the Eugenie #WS-1, located within the city limits of Carlsbad, New Mexico. This well is approximately 48 km (30 mi) from the WIPP site.

SCR-5.2.2.4.5 Solution Mining for Other Minerals

Currently, there are no ongoing solution mining activities within the vicinity of WIPP. The Rustler Springs sulfur mine located in Culberson County, Texas, began operations in 1969 and continued until it was officially closed in 1999. This mine used the Frasch process to extract molten sulfur (Cunningham 1999).

SCR-5.2.2.4.6 Solution Mining for Gas Storage

No gas storage cavities have been solution mined within the New Mexico portion of the Delaware Basin. Five gas storage facilities exist within the general vicinity of the WIPP; however only one is within the Delaware basin. This one New Mexico Delaware Basin facility uses a depleted gas reservoir for storage and containment; it was not solution mined (Appendix DATA).

SCR-5.2.2.4.7 Solution Mining for Disposal

Solution mining can be used to create a disposal cavity in bedded salt. Such disposal cavities can be used for the disposal of naturally occurring radioactive material (NORM) or other wastes. No such cavities have been mined or operated within the vicinity of the WIPP.

SCR-5.2.2.4.8 Effects of Solution Mining

SCR-5.2.2.4.8.1 *Subsidence*

Regardless of whether the single-borehole or two-borehole technique is used for solution mining, the result is a subsurface cavity which could collapse and lead to subsidence of overlying strata. Gray (1991) quoted earlier analyses that show cavity stability is relatively high if the cavity has

at least 15 m (50 ft) of overburden per million cubic feet of cavity volume (26.9 m per 50,000 m^3). There are two studies - discussed below - of the size of solution mining cavities in the Carlsbad region. These studies concern the Carlsbad Eugenie Brine Wells and the Carlsbad Brine Well and show that neither of these cavities are currently close to this critical ratio, but that subsidence in the future, given continued brine extraction, is a possibility.

Hickerson (1991) considered the potential for subsidence resulting from operation of the Carlsbad Eugenie Brine wells, where fresh water is injected into a salt section at a depth of 178 m (583 ft) and brine is recovered through a borehole at a depth of 179 m (587 ft). The boreholes are 100 m (327 ft) apart. Hickerson noted that the fresh water, being less dense than brine, tends to move upwards, causing the dissolution cavern to grow preferentially upwards. Thus, the dissolution cavern at the Carlsbad Eugenie Brine wells is approximately triangular in cross-section, being bounded by the top of the salt section and larger near the injection well. Hickerson estimated that brine production from 1979 until 1991 had created a cavern of about 9.6×10^4 m^3 (3.4×10^6 ft^3). The size of this cavern was estimated as 107 m (350 ft) by 47 m (153 ft) at the upper surface of the cavern with a depth of 39 m (127 ft).

Gray (1991) investigated the potential for collapse and subsidence at the Carlsbad Brine Well. Based on estimated production rates between 1976 and 1991, approximately 9.6×10^4 m^3 (3.4×10^6 ft^3) of salt has been dissolved at this site. The well depth is 216 m (710 ft) and thus there are about 64 m (210 ft) of overburden per million cubic feet of capacity (112 m of overburden per 50,000 m^3 of capacity).

Gray (1991) also estimated the time required for the cavity at the Carlsbad Brine Well to reach the critical ratio. At an average cavity growth rate of 6.4×10^3 m^3 per year (2.25×10^5 ft^3 per year), a further 50 years of operation would be required before cavity stability was reduced to levels of concern. A similar calculation for the Carlsbad Eugenie Brine well, based on an overburden of 140 m (460 ft) and an estimated average cavity growth rate of 7.9×10^3 m^3 per year (2.8×10^5 ft^3 per year), shows that a further 15 years of operation is required before the cavity reaches the critical ratio.

SCR-5.2.2.4.8.2 *Hydrogeological Effects*

In regions where solution mining takes place, the hydrogeology could be affected in a number ways:

- Subsidence above a large dissolution cavity could change the vertical and lateral hydraulic conductivity of overlying units.
- Extraction of fresh water from aquifers for solution mining could cause local changes in pressure gradients.
- Loss of injected fresh water or extracted brine to overlying units could cause local changes in pressure gradients.

The potential for subsidence to take place above solution mining operations in the region of Carlsbad is discussed above. Some subsidence could occur in the future if brine operations

continue at existing wells. Resulting fracturing may change permeabilities locally in overlying formations. However, because of the restricted scale of the solution mining at a particular site, and the distances between such wells, such fracturing will have no significant effect on hydrogeology near the WIPP.

Solution mining operations in the Delaware Basin extract water from shallow aquifers so that, even if large drawdowns are permitted, the effects on the hydrogeology will be limited to a relatively small area around the operation. Since all the active operations are more than 32 km (20 mi) from the WIPP, there will be no significant effects on the hydrogeology near the WIPP.

Discharge plans for solution mining operations typically include provision for annual mechanical integrity tests at one and one-half the normal operating pressure for four hours (OCD 1994). Thus, the potential for loss of integrity and consequent leakage of freshwater or brine to overlying formations is low. If, despite these annual tests, large water losses did take place, from either injection or production wells, the result would be low brine yields and remedial actions would most likely be taken by the operators.

SCR-5.2.2.4.8.3 *Geochemical Effects*

Solution mining operations could affect the geochemistry of surface or subsurface water near the operation if there were brine leakage from storage tanks or production wells. Discharge plans for solution mining operations specify the measures to be taken to prevent leakage and to mitigate the effects of any that do take place. These measures include berms around tanks and annual mechanical integrity testing of wells (OCD 1994). The potential for changes in geochemistry is therefore low, and any brine losses that did take place would be limited by remedial actions taken by the operator. In the event of leakage from a production well, the effect on geochemistry of overlying formation waters would be localized and, given the distance of such wells from the WIPP site, such leakage would have no significant effect on geochemistry near the WIPP.

SCR-5.2.2.4.9 Conclusion of Low Consequence

Brine production through solution mining takes place in the Delaware Basin, and the DOE assumes it will continue in the near future.

Despite oil and gas exploration and production taking place in the vicinity of the WIPP site, the nearest operating solution mine is more than 32 km (20 mi) from the WIPP site. These locations are too far from the WIPP site for any changes in hydrogeology or geochemistry, from subsidence or fresh water or brine leakage, to affect the performance of the disposal system. Thus, the effects of historical, current, near-future, and future ***Solution Mining for Other Resources*** in the Delaware Basin can be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.3 Explosion-Induced Flow

SCR-5.2.3.1 FEP Number: H39
FEPs Title: ***Changes in Groundwater Flow due to Explosions***

SCR-5.2.3.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Changes in groundwater flow due to historical explosions have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Changes in groundwater flow due to future explosions have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.3.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.2.3.1.3 Screening Argument

SCR-5.2.3.1.3.1 *Historical, Current, and Near-Future Human EPs*

The small-scale explosions that have been used in the Delaware Basin to fracture oil- and natural-gas-bearing units to enhance resource recovery have been too deep to have disturbed the hydrology of the disposal system (see FEP H19).

Also, as discussed in ***Underground Nuclear Device Testing*** (H20), the Delaware Basin has been used for an isolated nuclear test (Project Gnome), approximately 13 km (8 mi) southwest of the WIPP waste disposal region. An induced zone of increased permeability was observed to extend 46 m (150 ft) laterally from the point of the explosion. The increase in permeability was primarily associated with motions and separations along bedding planes, the major pre-existing weaknesses in the rock. This region of increased permeability is too far from the WIPP site to have had a significant effect on the hydrological characteristics of the disposal system. Thus, ***Changes in Groundwater Flow Due to Explosions*** in the past have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.3.1.3.2 *Future Human EPs*

The criterion in 40 CFR § 194.32(a) relating to the scope of PAs limits the consideration of future human actions to mining and drilling. Also, consistent with 40 CFR § 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, ***Changes in Groundwater Flow Due to Explosions*** in the future have been eliminated from PA calculations on regulatory grounds.

SCR-5.3 Geomorphological Events and Processes

SCR-5.3.1 Land Use Changes

SCR-5.3.1.1 FEP Number: H40
FEP Title: ***Land Use Changes***

SCR-5.3.1.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Land Use Changes *have been eliminated from PA calculations on regulatory grounds.*

SCR-5.3.1.1.2 Summary of New Information

The Delaware Basin monitoring program monitors land use activities in the WIPP vicinity. This program has not identified new planned uses for land in the vicinity of the WIPP (DOE 2002). This FEP discussion has been updated with additional information about industrial land uses in the region.

SCR-5.3.1.1.3 Screening Argument

This section discusses surface activities that could affect the geomorphological characteristics of the disposal system and result in changes in infiltration and recharge conditions. The potential effects of water use and control on disposal system performance are discussed in FEPs H42 through H46.

SCR-5.3.1.1.4 Historical, Current, and Near-Future Human EPs

Surface activities that take place at present in the vicinity of the WIPP site include those associated with potash mining, oil and gas reservoir development, water extraction, and grazing. Additionally, a number of archeological investigations have taken place within the controlled area that were aimed at protecting and preserving cultural resources. Elsewhere in the Delaware Basin, sand, gravel, and caliche are produced through surface quarrying. The only surface activity that has the potential to affect the disposal system is potash tailings, salt tailings (both potash and WIPP) and effluent disposal. Potash tailings ponds may act as sources of focused recharge to the Dewey Lake and Rustler units.

Three potash tailings piles/ponds are in operation that might be influencing groundwater flow at the WIPP site. These are the Mississippi Potash Inc. (MPI) East tailings pile, approximately 10 km (6 mi) due north of the WIPP, the MPI West tailings pile in the northwest arm of Nash Draw, and the IMC Kalium tailings pile, approximately 10 km (6 mi) due west of the WIPP in Nash Draw. These tailings piles have been in operation for decades—disposal at the MPI East site, the youngest of the piles, began in 1965. Brine disposal at these locations affects Rustler groundwaters in Nash Draw, as shown by the hydrochemical facies D waters described by Siegel et al. (1991, p. 2-61). Brine disposal also affects heads in Nash Draw, and these head effects likely propagate to the WIPP site as well. These effects, however, predate water-level monitoring for the WIPP and have been implicitly included when defining boundary heads for Culebra flow models. The Culebra transmissivity fields developed for the CRA used water

levels measured in 2000 to define model boundary conditions. Thus, the effects of brine disposal at the tailings piles can be considered to be included in PA calculations. These effects are expected to continue in the near future.

The Delaware Basin monitoring program monitors land use activities in the WIPP vicinity. This program has not identified new planned uses for land in the vicinity of the WIPP (DOE 2002). Therefore, consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), ***Land Use Changes*** in the near future in the vicinity of the WIPP have been eliminated from PA calculations on regulatory grounds.

SCR-5.3.1.1.5 Future Human EPs

The criterion in 40 CFR § 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and PAs "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions." Therefore, no future ***Land Use Changes*** need be considered in the vicinity of the WIPP, and they have been eliminated from PA calculations on regulatory grounds.

SCR-5.3.1.2 FEP Number: H41
FEP Title: ***Surface Disruptions***

Future ***Surface Disruptions*** not affecting hydrogeologic or geologic conditions have been eliminated from PA calculations on regulatory grounds. Future tailings ponds, if situated in Nash Draw, are expected to change Culebra (and Magenta) heads, similar to existing ones. Future tailings ponds outside of Nash Draw would not be expected to alter Culebra heads because leakage from the ponds would not be able to propagate through the low-permeability lower Dewey Lake clastics and Rustler anhydrites overlying the Culebra during the 100 years or less that such a pond might be in operation. Because PA calculations already include the present-day effects of tailings ponds in Nash Draw on heads, as well as the effects of future potash mining on the permeability of the Culebra (which has much greater potential to alter flow than changes in head), future potash tailings ponds may be screened out on the basis of low consequence.

SCR-5.3.1.2.1 Screening Decision: UP (HCN)
SO-R (Future)

*The effects of HCN **Surface Disruptions** have been screened out on the basis of low consequence if they have no potential to affect the disposal system, or are implicitly included in PA calculations when they might affect the disposal system. The effects of future **Surface Disruptions** have been eliminated from PA calculations on regulatory grounds.*

SCR-5.3.1.2.2 Summary of New Information

The screening argument for ***Surface Disruptions*** has changed. Per the original screening decision, surface activities in the vicinity of the WIPP site have disrupted the surface, but most surface activities have no potential to affect the disposal system and are, therefore, screened out on the basis of low consequence. However, the effects of the activity capable of altering the

disposal system (disposal of potash effluent) are included in our modeling of current conditions (i.e., heads) at and around the site. Therefore, the screening decision has been changed from SO-C to UP for HCN. Discussion regarding these anthropogenic effects is found in Section 2.2.1.4.2.2 of the CRA. There are no planned changes to land use in the vicinity of the WIPP in the near future, and future events that might disrupt the surface at the WIPP site are screened out on the basis of regulatory criteria.

SCR-5.3.1.2.3 Screening Argument

This section discusses surface activities that could affect the geomorphological characteristics of the disposal system and result in changes in infiltration and recharge conditions. The potential effects of water use and control on disposal system performance are discussed in FEPs H42 through H46.

SCR-5.3.1.2.4 Historical, Current, and Near-Future Human EPs

Surface activities that take place at present in the vicinity of the WIPP site include those associated with potash mining, oil and gas reservoir development, water extraction, and grazing. Additionally, a number of ***Archeological Investigations*** have taken place within the controlled area that were aimed at protecting and preserving cultural resources. Elsewhere in the Delaware Basin, sand, gravel, and caliche are produced through surface quarrying. The only surface activity that has the potential to affect the disposal system is potash tailings, salt tailings (both potash and WIPP) and effluent disposal. Potash tailings ponds may act as sources of focused recharge to the Dewey Lake and Rustler units.

Three potash tailings piles/ponds are in operation that might be influencing groundwater flow at the WIPP site. These are the Mississippi Potash Inc. (MPI) East tailings pile, approximately 10 km (6 mi) due north of the WIPP, the MPI West tailings pile in the northwest arm of Nash Draw, and the IMC Kalium tailings pile, approximately 10 km (6 mi) due west of the WIPP in Nash Draw. These tailings piles have been in operation for decades—disposal at the MPI East site, the youngest of the piles, began in 1965. Brine disposal at these locations affects Rustler groundwaters in Nash Draw, as shown by the hydrochemical facies D waters described by Siegel et al. (1991, p. 2-61). Brine disposal also affects heads in Nash Draw, and these head effects likely propagate to the WIPP site as well. These effects, however, predate water-level monitoring for the WIPP and have been implicitly included when defining boundary heads for Culebra flow models. The Culebra transmissivity fields developed for the CRA used water levels measured in 2000 to define model boundary conditions. Thus, the effects of brine disposal at the tailings piles can be considered to be included in PA calculations. These effects are expected to continue in the near future.

The Delaware Basin monitoring program monitors land use activities in the WIPP vicinity. This program has not identified new planned uses for land in the vicinity of the WIPP (DOE 2002). Therefore, consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), ***Land Use Changes*** in the near future in the vicinity of the WIPP have been eliminated from PA calculations on regulatory grounds.

SCR-5.3.1.2.5 Future Human EPs

The criterion in 40 CFR § 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and PAs "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions." Therefore, no future ***Land Use Changes*** need be considered in the vicinity of the WIPP, and they have been eliminated from PA calculations on regulatory grounds.

Future ***Surface Disruptions*** not affecting hydrogeologic or geologic conditions have been eliminated from PA calculations on regulatory grounds. Future tailings ponds, if situated in Nash Draw, are expected to change Culebra (and Magenta) heads, similar to existing ones. Future tailings ponds outside of Nash Draw would not be expected to alter Culebra heads because leakage from the ponds would not be able to propagate through the low-permeability lower Dewey Lake clastics and Rustler anhydrites overlying the Culebra during the 100 years or less that such a pond might be in operation. Because PA calculations already include the present-day effects of tailings ponds in Nash Draw on heads, as well as the effects of future potash mining on the permeability of the Culebra (which has much greater potential to alter flow than changes in head), future potash tailings ponds may be screened out on the basis of low consequence.

SCR-5.4 Surface Hydrological Events and Processes

SCR-5.4.1 Water Control and Use

SCR-5.4.1.1 FEP Number(s): H42, H43, and H44
FEP Title(s): ***Damming of Streams and Rivers*** (H42)
Reservoirs (H43)
Irrigation (H44)

SCR-5.4.1.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

The effects of HCN ***Damming of Streams and Rivers, Reservoirs,*** *and* ***Irrigation*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future* ***Damming of Streams and Rivers, Reservoirs,*** *and* ***Irrigation*** *have been eliminated from PA calculations on regulatory grounds.*

SCR-5.4.1.1.2 Summary of New Information

No new information has been identified related to these FEPs. Changes have been made for editorial purposes.

SCR-5.4.1.1.3 Screening Argument

Irrigation and damming, as well as other forms of water control and use, could lead to localized changes in recharge, possibly leading to increased heads locally, thereby affecting flow directions and velocities in the Rustler and Dewey Lake.

SCR-5.4.1.1.4 Historical, Current, and Near-Future Human EPs

In the WIPP area, two topographically low features, the Pecos River and Nash Draw, are sufficiently large to warrant consideration for damming. Dams and ***Reservoirs*** already exist along the Pecos River. However, the Pecos River is far enough from the waste panels (19 km [12 mi]) that the effects of ***Damming of Streams and Rivers,*** and ***Reservoirs*** can be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Nash Draw is not currently dammed, and based on current hydrological and climatic conditions, there is no reason to believe it will be dammed in the near future.

Irrigation uses water from rivers, lakes, impoundments, and wells to supplement the rainfall in an area to grow crops. ***Irrigation*** in arid environments needs to be efficient and involves the spreading of a relatively thin layer of water for uptake by plants, so little water would be expected to infiltrate beyond the root zone. However, some water added to the surface may infiltrate and reach the water table, affecting groundwater flow patterns. ***Irrigation*** currently takes place on a small scale within the Delaware Basin but not in the vicinity of the WIPP, and the extent of ***Irrigation*** is not expected to change in the near future. Such ***Irrigation*** has no significant effect on the characteristics of the disposal system. Thus, the effects of ***Irrigation*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.4.1.1.5 Future Human EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future ***Damming of Streams and Rivers, Reservoirs,*** *and* ***Irrigation*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.4.1.2 FEP Number: H45
FEP Title: ***Lake Usage***

SCR-5.4.1.2.1 Screening Decision: SO-R (HCN)
SO-R (Future)

The effects of ***Lake Usage*** *have been eliminated from PA calculations on regulatory grounds.*

SCR-5.4.1.2.2 Summary of New Information

No new information has been identified related to this FEP. Changes have been made for editorial purposes.

SCR-5.4.1.2.3 Screening Argument

Irrigation and damming, as well as other forms of water control and use, could lead to localized changes in recharge, possibly leading to increased heads locally, thereby affecting flow directions and velocities in the Rustler and Dewey Lake. Surface activities, such as those associated with potash mining, could also affect soil and surface water chemistry. Note that the potential effects of geomorphological changes through land use are discussed in H40 and H41.

SCR-5.4.1.2.4 Historical, Current, and Near-Future Human EPs

As discussed in Section 2.2.2, there are no major natural lakes or ponds within 8 km (5 mi) of the site. To the northwest, west, and southwest, Red Lake, Lindsey Lake, and Laguna Grande de la Sal are more than 8 km (5 mi) from the site, at elevations of 914 to 1,006 m (3,000 to 3,300 ft). Laguna Gatuña, Laguna Tonto, Laguna Plata, and Laguna Toston are playas more than 16 km (10 mi) north and are at elevations of 1,050 m (3,450 ft) or higher.

Waters from these lakes are of limited use. Therefore human activities associated with lakes have been screened out of PA calculations based on regulatory grounds supported by 194.32(c) and 194.54(b).

SCR-5.4.1.2.5 Future Human EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future ***Lake Usage*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.4.1.3 FEP Number: H46
FEP Title: ***Altered Soil or Surface Water Chemistry by Human Activities***

SCR-5.4.1.3.1 Screening Decision: SO-C (HCN)
SO-R (Future)

The effects of HCN ***Altered Soil or Surface Water Chemistry by Human Activities*** *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future* ***Altered Soil or Surface Water Chemistry by Human Activities*** *have been eliminated from PA calculations on regulatory grounds.*

SCR-5.4.1.3.2 Summary of New Information

No new information has been identified related to this FEP. Changes have been made for editorial purposes.

SCR-5.4.1.3.3 Screening Argument

Irrigation and damming, as well as other forms of water control and use, could lead to localized changes in recharge, possibly leading to increased heads locally, thereby affecting flow directions and velocities in the Rustler and Dewey Lake. Surface activities, such as those associated with potash mining, could also affect soil and surface water chemistry.

SCR-5.4.1.3.4 Historical, Current, and Near-Future Human EPs

Potash mining effluent and runoff from oil fields have altered soil and surface water chemistry in the vicinity of the WIPP. However, the performance of the disposal will not be sensitive to soil and surface water chemistry. Therefore, ***Altered Soil or Surface Water Chemistry by Human Activities*** has been eliminated from PA calculations on the basis of low consequence to the

performance of the disposal system. The effects of effluent from potash processing on groundwater flow are discussed in H37.

SCR-5.4.1.3.5 Future Human EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a) that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future ***Altered Soil or Surface Water Chemistry by Human Activities*** have been eliminated from PA calculations on regulatory grounds.

SCR-5.5 Climatic Events and Processes

SCR-5.5.1 Anthropogenic Climate Change

SCR-5.5.1.1 FEP Number(s): H47, H48, and H49
FEP Title: ***Greenhouse Gas Effects*** (H47)
Acid Rain (H48)
Damage to the Ozone (N49)

SCR-5.5.1.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

*The effects of anthropogenic climate change (**Acid Rain**, **Greenhouse Gas Effects**, and **Damage to the Ozone** layer) have been eliminated from PA calculations on regulatory grounds.*

SCR-5.5.1.1.2 Summary of New Information

No new information has been identified related to this FEP. Changes have been made for editorial purposes.

SCR-5.5.1.1.3 Anthropogenic Climate Change

The effects of the current climate and natural climatic change are accounted for in PA calculations, as discussed in Section 6.4.9. However, human activities may also affect the future climate and thereby influence groundwater recharge in the WIPP region. The effects of anthropogenic climate change may be on a local to regional scale (***Acid Rain*** *(H48)*) or on a regional to global scale (***Greenhouse Gas Effects*** *(H47)* and ***Damage to the Ozone*** layer *(H49)*). Of these anthropogenic effects, only the ***Greenhouse Gas Effect*** could influence groundwater recharge in the WIPP region. However, consistent with the future states assumptions in 40 CFR § 194.25, compliance assessments and PAs need not consider indirect anthropogenic effects on disposal system performance. Therefore, the effects of anthropogenic climate change have been eliminated from PA calculations on regulatory grounds.

SCR-5.6 Marine Events and Processes

SCR-5.6.1 Marine Activities

SCR-5.6.1.1.1 FEP Number(s): H50, H51 & H52
FEP Title(s): ***Costal Water Use*** (H50)
Seawater Use (H51)
Estuarine Water (H52)

SCR-5.6.1.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

*HCN, and future **Coastal Water Use, Seawater Use,** and **Estuarine Water** use have been eliminated from PA calculations on regulatory grounds.*

SCR-5.6.1.1.2 Summary of New Information

No new information has been identified related to this FEP. Changes have been made for editorial purposes.

SCR-5.6.1.1.3 Screening Argument

This section discusses the potential for Human EPs related to marine activities to affect infiltration and recharge conditions in the vicinity of the WIPP.

SCR-5.6.1.1.4 Historical, Current, and Near-Future Human EPs

The WIPP site is more than 800 km (480 mi) from the nearest seas, and hydrological conditions in the vicinity of the WIPP have not been affected by marine activities. Furthermore, consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), consideration of HCN human activities is limited to those activities that have occurred or are expected to occur in the vicinity of the disposal system. Therefore, Human EPs related to marine activities (such as ***Coastal Water Use, Seawater Use,*** *and* ***Estuarine Water*** use) have been eliminated from PA calculations on regulatory grounds.

SCR-5.6.1.1.5 Future Human EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a) that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future marine activities (such as ***Coastal Water Use, Seawater Use,*** *and* ***Estuarine Water*** use) have been eliminated from PA calculations on regulatory grounds.

SCR-5.7 Ecological Events and Processes

SCR-5.7.1 Agricultural Activities

SCR-5.7.1.1 FEP Number(s): H53, H54, and H55
FEP Title(s): ***Arable Farming*** (H53)

Ranching (H54)
Fish Farming (H55)

SCR-5.7.1.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

*The effects of HCN **Ranching** and **Arable Farming** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The effects of changes in future **Ranching** and **Arable Farming** practices have been eliminated from PA calculations on regulatory grounds. **Fish Farming** has been eliminated from PA calculations on regulatory grounds.*

SCR-5.7.1.1.2 Summary of New Information

No new information has been identified related to these FEPs.

SCR-5.7.1.1.3 Screening Argument

Agricultural activities could affect infiltration and recharge conditions in the vicinity of the WIPP. Also, application of acids, oxidants, and nitrates during agricultural practice could alter groundwater geochemistry.

SCR-5.7.1.1.4 Historical, Current, and Near-Future Human EPs

Grazing leases exist for all land sections immediately surrounding the WIPP and grazing occurs within the controlled area (see Section 2.3.2.2). Although grazing and related crop production have had some control on the vegetation at the WIPP site, these activities are unlikely to have affected subsurface hydrological or geochemical conditions. The climate, soil quality, and lack of suitable water sources all mitigate against agricultural development of the region in the near future. Therefore, the effects of HCN ***Ranching*** *and* ***Arable Farming*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), agricultural activities, such as ***Fish Farming***, that have not taken place and are not expected to take place in the near future in the vicinity of the WIPP have been eliminated from PA calculations on regulatory grounds.

SCR-5.7.1.1.5 Future Human EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a) that limit the scope of consideration of future human activities in PAs to mining and drilling. Also, the criterion in 40 CFR § 194.25(a) concerned with predictions of the future states of society requires that compliance assessments and PAs “shall assume that characteristics of the future remain what they are at the time the compliance application is prepared.” Therefore, the effects of changes in future agricultural practices (such as ***Ranching***, ***Arable Farming***, and ***Fish Farming***) have been eliminated from PA calculations on regulatory grounds.

SCR-5.7.2 Social and Technological Development

SCR-5.7.2.1 FEP Number: H56
FEP Title: ***Demographic Change and Urban Development***

SCR-5.7.2.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Demographic Change and Urban Development *in the near future and in the future have been eliminated from PA calculations on regulatory grounds.*

SCR-5.7.2.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.7.2.1.3 Screening Argument

Social and technological changes in the future could result in the development of new communities and new activities in the vicinity of the WIPP that could have an impact on the performance of the disposal system.

Demography in the WIPP vicinity is discussed in Section 2.3.2.1. The community nearest to the WIPP site is the town of Loving, 29 km (18 mi) west-southwest of the site center. There are no existing plans for urban developments in the vicinity of the WIPP in the near future. Furthermore, the criterion in 40 CFR § 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and PAs "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared." Therefore, ***Demographic Change and Urban Development*** in the vicinity of the WIPP and technological developments have been eliminated from PA calculations on regulatory grounds.

SCR-5.7.2.2 FEP Number: H57
FEP Title: ***Loss of Records***

SCR-5.7.2.2.1 Screening Decision: NA (HCN)
DP (Future)

Loss of Records *in the future is accounted for in PA calculations.*

SCR-5.7.2.2.2 Summary of New Information

No new information has been identified for this FEP. Changes have been made for editorial purposes.

SCR-5.7.2.2.3 Screening Argument

Human activities will be prevented from occurring within the controlled area in the near future. However, PAs must consider the potential effects of human activities that might take place within the controlled area at a time when institutional controls cannot be assumed to eliminate

completely the possibility of human intrusion. Consistent with 40 CFR § 194.41(b), the DOE assumes no credit for active institutional controls for more than 100 years after disposal. Also, consistent with 40 CFR § 194.43(c), the DOE originally assumed in the CCA that passive institutional controls do not eliminate the likelihood of future human intrusion entirely. The provisions at 40 CFR 194.43(c) allow credit for passive institutional controls by reducing the likelihood of human intrusions for several hundred years. In DOE (1996a), the DOE took credit for these controls that include records retention by reducing the probability of intrusion for the first 600 years after active controls cease. EPA disallowed this credit during the original certification (EPA 1998a). DOE no longer takes credit for passive institutional controls in PA, effectively assuming that all public records and archives relating to the repository are lost 100 years after closure. Therefore, DOE continues to include the ***Loss of Records*** FEP within PA and does not include credit for passive institutional controls.

SCR-6.0 WASTE AND REPOSITORY-INDUCED FEPS

This section presents screening arguments and decisions for waste- and repository-induced FEPs. Of the original 108 waste- and repository-induced FEPs, 61 remain unchanged, 43 were updated with new information or were edited for clarity and completeness, three screening decisions were changed, and one FEP was deleted from the baseline by combining with other, more appropriate FEPs.

SCR-6.1 Waste and Repository Characteristics

SCR-6.1.1 Repository Characteristics

SCR-6.1.1.1 FEP Number: W1
FEP Title: ***Disposal Geometry***

SCR-6.1.1.1.1 Screening Decision: UP

*The WIPP repository **Disposal Geometry** is accounted for in PA calculations.*

SCR-6.1.1.1.2 Summary of New Information

Representation of the repository within the PA has changed since the CCA; however, the screening argument and decision remain unchanged. **Disposal *Geometry*** is accounted for in PA calculations.

SCR-6.1.1.2 Screening Argument

Disposal *Geometry* is described in Chapter 3, Section 3.2 and is accounted for in the setup of PA calculations (Section 6.4.2).

SCR-6.1.2 Waste Characteristics

SCR-6.1.2.1 FEP Number: W2 and W3
FEP Title: ***Waste Inventory***
Heterogeneity of Waste Forms

SCR-6.1.2.1.1 Screening Decision: UP

*The **Waste Inventory** and **Heterogeneity of Waste Forms** are accounted for in PA calculations.*

SCR-6.1.2.1.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.1.2.1.3 Screening Argument

Waste characteristics, comprising the ***Waste Inventory*** and the ***Heterogeneity of Waste Forms***, are described in Chapter 4.0. The waste inventory is accounted for in PA calculations in deriving the dissolved actinide source term and gas generation rates (Sections 6.4.3.5 and 6.4.3.3). The distribution of contact-handled (CH) and remote-handled (RH) transuranic (TRU) waste within the repository leads to room scale heterogeneity of the waste forms, which is accounted for in PA calculations when considering the potential activity of waste material encountered during inadvertent borehole intrusion (Section 6.4.7).

SCR-6.1.3 Container Characteristics

SCR-6.1.3.1 FEP Number: W4
FEP Title: ***Container Form***

SCR-6.1.3.1.1 Screening Decision: SO-C - Beneficial

*The **Container Form** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.1.3.1.2 Summary of New Information

The inventories of container materials (i.e., steel and plastic liners) are included in WIPP long-term PAs as input parameters of the gas generation model (Wang and Brush 1996). The ***Container Form*** has been eliminated from PA calculations on the basis of its beneficial effect on retarding radionuclide release. The PAs assume instantaneous container failure and waste dissolution according to the source-term model. The screening argument has been modified to incorporate additional information, although the screening decision has not changed.

SCR-6.1.3.1.3 Screening Argument

As in the CCA, the CRA calculations show that a significant fraction of steel and other Fe-base materials will remain undegraded over 10,000 years (see Helton et al. 1998). For all undisturbed cases, at least 30 percent of the steels will remain uncorroded at the end of 10,000 years. In addition, it is assumed in both CCA and CRA-2004 calculations that there is no microbial degradation of plastic container materials in 75 percent of PA realizations (Wang and Brush 1996). All these undegraded container materials will (1) prevent the contact between brine and radionuclides; (2) decrease the rate and extent of radionuclide transport due to high tortuosity along the flow pathways and, as a result, increase opportunities for metallic Fe and corrosion products to beneficially reduce radionuclides to lower oxidation states. Therefore, the container form can be eliminated on the basis of its beneficial effect on retarding radionuclide transport. Both CCA and CRA assume instantaneous container failure and waste dissolution according to the source-term model. In CCA Appendix WCL, a minimum quantity of metallic Fe was specified to ensure sufficient reactants to reduce radionuclides to lower and less soluble oxidation states. This requirement is met as long as there are no substantial changes in container materials. The 2003 update to the TWBIR Revision 3 (Appendix DATA, Attachment F) indicates that the density of steel in container materials currently reported by the sites has an average value of 170 kg/m^3. This is an increase over what was reported for the CCA (139 to 230 kg/m^3)(8.6 to 14.3 lb/ft^3). Therefore, the current inventory estimates indicate that there is a sufficient quantity of metallic iron to ensure reduction of radionuclides to lower and less soluble oxidation states. The 2003 update to the TWBIR Revision 3 (Appendix DATA, Attachment F) indicates that the density of plastic liners currently reported by the sites has an average value of 16 kg/m3. This is a decrease from 26 to 21 kg/m^3 (1.6 to 1.3 lb/ft^3) reported in the CCA.

SCR-6.1.3.2 FEP Number: W5
FEP Title: ***Container Material Inventory***

SCR-6.1.3.2.1 Screening Decision: UP

*The **Container Material Inventory** is accounted for in PA calculations.*

SCR-6.1.3.2.2 Summary of New Information

No new information has been identified that relates to the screening of this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA; however, the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.1.3.2.3 Screening Argument

The ***Container Material Inventory*** is described in Chapter 4.0, and is accounted for in PA calculations through the estimation of gas generation rates (Section 6.4.3.3).

SCR-6.1.4 Seal Characteristics

SCR-6.1.4.1 FEP Number: W6 and W7
FEP Title: ***Seal Geometry*** (W6)
Seal Physical Properties (W7)

SCR-6.1.4.1.1 Screening Decision: UP

*The **Seal Geometry** and **Seal Physical Properties** are accounted for in PA calculations.*

SCR-6.1.4.1.2 Summary of New Information

No new information has been identified that relates to the screening of these FEPs. Since these FEP are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation are described in Section 6.4.4.

SCR-6.1.4.1.3 Screening Argument

Seal (shaft seals, panel closures, and drift closures) characteristics, including ***Seal Geometry*** and ***Seal Physical Properties***, are described in Section 3.3.2 and are accounted for in PA calculations through the representation of the seal system in BRAGFLO and the permeabilities assigned to the seal materials (Section 6.4.4).

SCR-6.1.4.2 FEPs Number: W8
FEP Title: ***Seal Chemical Composition***

SCR-6.1.4.2.1 Screening Decision: SO-C Beneficial

*The **Seal Chemical Composition** has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-6.1.4.2.2 Summary of New Information

In the CCA, ***Seal Chemical Composition*** was screened out on the basis of predicted beneficial consequences, which are not credited in PA calculations. Recent publications provide support for the screening argument that chemical interactions between the cement seals and the brine will be of beneficial consequence to the performance of the disposal system, through sorption and sequestration of radionuclides. Ignoring adsorption simplifies the PA calculations, and is expected to produce somewhat more conservative results. However, because little or no upward flow is predicted to occur through the seals, the overall effect on PA results may not be significant.

The original FEP description has been modified slightly to include supporting evidence for the argument that chemical interactions between the cement seals and the brine will be of beneficial consequence to the performance of the disposal system.

SCR-6.1.4.2.3 Screening Argument

Seal (shaft seals, panel closures, and drift closures) characteristics, including ***Seal Geometry*** and ***Seal Physical Properties***, are described in CCA Chapter 3.0 and are accounted for in PA calculations through the representation of the seal system in BRAGFLO and the permeabilities assigned to the seal materials. The effect of shaft ***Seal Chemical Composition*** on actinide speciation and mobility has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.1.4.2.4 Repository Seals

Certain repository materials have the potential to interact with groundwater and significantly alter the chemical speciation of any radionuclides present. In particular, extensive use of cementitious materials in the seals may have the capacity to buffer groundwaters to extremely high pH (for example, Bennett et al. 1992, pp. 315 - 325). At high pH values, the speciation and adsorption behavior of many radionuclides is such that their dissolved concentrations are reduced in comparison with near-neutral waters. This effect reduces the migration of radionuclides in dissolved form.

Several recent publications describe strong actinide (or actinide analog) sorption by cement (Altenheinhaese et al. 1994; Wierczinski et al. 1998; Pointeau et al. 2001), or sequestration by incorporation into cement alteration phases (Gougar et al. 1996, Dickson and Glasser 2000). These provide support for the screening argument that chemical interactions between the cement seals and the brine will be of beneficial consequence to the performance of the disposal system.

The effects of cementitious seals on groundwater chemistry have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.1.5 Backfill Characteristics

SCR-6.1.5.1 FEP Number: W9
FEP Title: ***Backfill Physical Properties***

SCR-6.1.5.1.1 Screening Decision: SO-C

Backfill Physical Properties *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.1.5.1.2 Summary of New Information

No new information related to this FEP has been identified. Changes have been made for editorial purposes.

SCR-6.1.5.1.3 Screening Argument

A chemical backfill is being added to the disposal room to buffer the chemical environment. The backfill characteristics were previously described in CCA Appendix BACK with additional information contained in Appendix BARRIERS. The mechanical and thermal effects of backfill

are discussed in W35 and W72 respectively, where they have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Backfill will result in an initial permeability for the disposal room lower than that of an empty cavity, so neglecting the hydrological effects of backfill is a conservative assumption with regard to brine inflow and radionuclide migration. Thus, ***Backfill Physical Properties*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.1.5.2 FEP Number: W10
FEP Title: ***Backfill Chemical Composition***

SCR-6.1.5.2.1 Screening Decision: UP

*The **Backfill Chemical Composition** is accounted for in PA calculations.*

SCR-6.1.5.2.2 Summary of New Information

No new information related to this FEP has been identified. Changes have been made for editorial purposes.

SCR-6.1.5.2.3 Screening Argument

A chemical backfill is added to the disposal room to buffer the chemical environment. The backfill characteristics are described in Section 6.4.3.4. The mechanical and thermal effects of backfill are discussed in FEP W35 and FEP W72, respectively, where they have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. ***Backfill Chemical Composition*** is accounted for in PA calculations in deriving the dissolved and colloidal actinide source terms (Section 6.4.3).

SCR-6.1.6 Post-Closure Monitoring Characteristics

SCR-6.1.6.1 FEPs Number: W11
FEP Title: ***Post-Closure Monitoring***

SCR-6.1.6.1.1 Screening Decision: SO-C

*The potential effects of **Post-Closure Monitoring** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.1.6.1.2 Summary of New Information

The FEP screening argument has been modified to include reference to 40 CFR 194.42(d). Compliance with this requirement ensures that ***Post-Closure Monitoring*** is not detrimental to the performance of the repository. No changes have been proposed to the ***Post-Closure Monitoring*** program as presented in the CCA. The pre-closure monitoring program has not identified a condition relating to the act of monitoring that would be detrimental to the performance of the repository after closure (Annual Site Environmental Reports and Annual Compliance Monitoring Parameter Assessments). No changes have been made to the FEP description, screening argument, or screening decision.

SCR-6.1.6.1.3 Screening Argument

Post-Closure Monitoring is required by 40 CFR § 191.14(b) as an assurance requirement to "detect substantial and detrimental deviations from expected performance." The DOE has designed the monitoring program (see CCA Appendix MON) so that the monitoring methods employed are not detrimental to the performance of the disposal system (40 CFR 194.42(d)). Non-intrusive monitoring techniques are used so that ***Post-Closure Monitoring*** would not impact containment or require remedial activities. In summary, the effects of monitoring have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.2 Radiological Features, Events, and Processes

SCR-6.2.1 Radioactive Decay and Heat

SCR-6.2.1.1 FEP Number: W12
FEP Title: ***Radionuclide Decay and Ingrowth***

SCR-6.2.1.1.1 Screening Decision: UP

Radionuclide Decay and Ingrowth *are accounted for in PA calculations.*

SCR-6.2.1.1.2 Summary of New Information

No new information related to this FEP has been identified. No changes have been made.

SCR-6.2.1.1.3 Screening Argument

Radionuclide Decay and Ingrowth are accounted for in PA calculations (see Section 6.4.12.4).

SCR-6.2.1.2 FEP Number: W13
FEP Title: ***Heat From Radioactive Decay***

SCR-6.2.1.2.1 Screening Decision: SO-C

The effects of temperature increases as a result of radioactive decay have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.2.1.2.2 Summary of New Information

WIPP transportation restrictions do not allow the thermal load of the WIPP to exceed 10 kW/acre (NRC 2002). Transportation requirements restrict the thermal load from RH-TRU waste containers to no more than 300 watts per container (NRC 2002). However, the limit on the surface dose equivalent rate of the RH-TRU containers (1,000 rem/hr) is more restrictive and equates to a thermal load of only about 60 watts per container. Based on the thermal loads permitted, the maximum temperature rise in the repository from radioactive decay heat should be less than 2°C (3.6°F). The 2003 update to the TWBIR Revision 3 (Appendix DATA, Attachment F) indicates that the radionuclide inventory is lower than previously estimated for the CCA.

Thus, all CRA radioactive decay heating screening arguments are bounded by the previous CCA screening arguments.

SCR-6.2.1.3 Screening Argument

Radioactive decay of the waste emplaced in the repository will generate heat. The importance of ***Heat from Radioactive Decay*** depends on the effects that the induced temperature changes would have on mechanics (W29 - W31), fluid flow (W40 and W41), and geochemical processes (W44 through W75). For example, extreme temperature increases could result in thermally induced fracturing, regional uplift, or thermally driven flow of gas and brine in the vicinity of the repository.

The design basis for the WIPP requires that the thermal loading does not exceed 10 kW per acre. Transportation restrictions also require that the thermal power generated by waste in an RH-TRU container shall not exceed 300 watts (NRC 2002).

The DOE has conducted numerous studies related to ***Heat from Radioactive Decay***. The following presents a brief summary of these past analyses. First, a numerical study to calculate induced temperature distributions and regional uplift is reported in DOE (1980 pp. 9-149 to 9-150). This study involved estimation of the thermal power of CH-TRU waste containers. The DOE (1980 pp. 9-149) analysis assumed the following:

- All CH-TRU waste drums and boxes contain the maximum permissible quantity of plutonium. The fissionable radionuclide content for CH-TRU waste containers was assumed to be no greater than 200 grams per 0.21 m^3 (7 ounces per 7.4 ft^3) drum and 350 grams per 1.8 m^3 (12.3 ounces per 63.6 ft^3) standard waste box (plutonium-239 fissile gram equivalents).

- The plutonium in CH-TRU waste containers is weapons grade material producing heat at 0.0024 watts per gram. Thus, the thermal power of a drum is approximately 0.5 watts and that of a box is approximately 0.8 watts.

- Approximately 3.7×10^5 m^3 (1.3×10^7 ft^3) of CH-TRU waste are distributed within a repository enclosing an area of 7.3×10^5 m^2 (7.9×10^6 ft^2). This is a conservative assumption in terms of quantity and density of waste within the repository, because the maximum capacity of the WIPP is 1.756×10^5 m^3 (6.2×10^6 ft^3) for all waste (as specified by the Land Withdrawal Act [LWA]) to be placed in an enclosed area of approximately 5.1×10^5 m^2 (16 mi^2).

- Half of the CH-TRU waste volume is placed in drums and half in boxes so that the repository will contain approximately 900,000 drums and 900,000 boxes. Thus, a calculated thermal power of 0.7 watts per square meter (2.8 kW/acre) of heat is generated by the CH-TRU waste.

- Insufficient RH-TRU waste would be emplaced in the repository to influence the total thermal load.

Under these assumptions, Thorne and Rudeen (1981) estimated the long-term temperature response of the disposal system to waste emplacement. Calculations assumed a uniform initial power density of 2.8 kW/acre (0.7 W/m^2) which decreases over time. Thorne and Rudeen (1981) attributed this thermal load to RH-TRU waste, but the DOE (1980), more appropriately, attributed this thermal load to CH-TRU waste based on the assumptions listed above. Thorne and Rudeen (1981) estimated the maximum rise in temperature at the center of a repository to be 1.6°C (2.9°F) at 80 years after waste emplacement.

More recently, Sanchez and Trellue (1996) estimated the maximum thermal power of an RH-TRU waste container. The Sanchez and Trellue (1996) analysis involved inverse shielding calculations to evaluate the thermal power of an RH-TRU container corresponding to the maximum permissible surface dose of 1000 rem per hour. The following calculational steps were taken in the Sanchez and Trellue (1996) analysis:

- Calculate the absorbed dose rate for gamma radiation corresponding to the maximum surface dose equivalent rate of 1000 rem per hour. Beta and alpha radiation are not included in this calculation because such particles will not penetrate the waste matrix or the container in significant quantities. Neutrons are not included in the analysis because the maximum dose rate from neutrons is 270 millirem per hour, and the corresponding neutron heating rate will be insignificant.

- Calculate the exposure rate for gamma radiation corresponding to the absorbed dose rate for gamma radiation.

- Calculate the gamma flux density at the surface of a RH-TRU container corresponding to the exposure rate for gamma radiation. Assuming the gamma energy is 1.0 megaelectron volts, the maximum allowable gamma flux density at the surface of a RH-TRU container is about 5.8×10^8 gamma rays per square centimeter per second.

- Determine the distributed gamma source strength, or gamma activity, in an RH-TRU container from the surface gamma flux density. The source is assumed to be shielded such that the gamma flux is attenuated by the container and by absorbing material in the container. The level of shielding depends on the matrix density. Scattering of the gamma flux, with loss of energy, is also accounted for in this calculation through inclusion of a gamma buildup factor. The distributed gamma source strength is determined assuming a uniform source in a right cylindrical container. The maximum total gamma source (gamma curies) is then calculated for a RH-TRU container containing 0.89 m^3 (31.4 ft^3) of waste. For the waste of greatest expected density (about 6,000 kg/m^3 (360 lb/ft^3), the gamma source is about 2×10^4 Ci/m^3 (566 Ci/ft^3).

- Calculate the total curie load of a RH-TRU container (including alpha and beta radiation) from the gamma load. The ratio of the total curie load to the gamma curie load was estimated through examination of the radionuclide inventory presented in CCA Appendix BIR. The gamma curie load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of total curie load to gamma curie load of RH-TRU waste was calculated to be 1.01.

- Calculate the thermal load of a RH-TRU container from the total curie load. The ratio of thermal load to curie load was estimated through examination of the radionuclide inventory presented in CCA Appendix BIR. The thermal load and the total curie load for each radionuclide listed in the WIPP inventory were summed. Based on these summed loads the ratio of thermal load to curie load of RH-TRU waste was calculated to be about 0.0037 watts per curie. For a gamma source of 2×10^4 Ci/m^3 (566 Ci/ft^3), the maximum permissible thermal load of a RH-TRU container is about 70 W/m^3 (2 W/ft^3). Thus, the maximum thermal load of a RH-TRU container is about 60 W, and the transportation limit of 300 W will not be achieved.

Note that Sanchez and Trellue (1996) calculated the average thermal load for a RH-TRU container to be less than 1 W. Also, the total RH-TRU heat load is less than 10 percent of the total heat load in the WIPP. Thus, the total thermal load of the RH-TRU waste will not significantly affect the average rise in temperature in the repository resulting from decay of CH-TRU waste.

Temperature increases will be greater at locations where the thermal power of an RH-TRU container is 60 W, if any such containers are emplaced. Sanchez and Trellue (1996) estimated the temperature increase at the surface of a 60 W RH-TRU waste container. Their analysis involved solution of a steady-state thermal conduction problem with a constant heat source term of 70 W/m^3 (2 W/ft^3). These conditions represent conservative assumptions because the thermal load will decrease with time as the radioactive waste decays. The temperature increase at the surface of the container was calculated to be about 3°C (5.4°F).

In summary, analysis has shown that the average temperature increase in the WIPP repository, due to radioactive decay of the emplaced CH- and RH-TRU waste, will be less than 2°C (3.6°F). Temperature increases of about 3°C (5.4°F) may occur in the vicinity of RH-TRU containers with the highest allowable thermal load of about 60 watts (based on the maximum allowable surface dose equivalent for RH-TRU containers). Potential heat generation from nuclear criticality is discussed in W14 and exothermic reactions and the effects of repository temperature changes on mechanics are discussed in the set of FEPs grouped as W29, W30, W31, W72, and W73. These FEPs have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The previous FEPs screening arguments for the CCA used a bounding radioactivity heat load of 0.5 watts/drum for the CH-TRU waste containers. With a total CH-TRU volume of 168,500 m^3 (~5,950,000 ft^3) this corresponds to approximately 810,000 55-gallon drum equivalents with a corresponding heat load of > 400 kW used for the CCA FEPs screening arguments. From Sanchez and Trellue (1996), it can be seen that a realistic assessment of the heat load, based on radionuclide inventory data in the Transuranic Waste Baseline Inventory Report (TWBIR) is less than 100 kW. Thus, the CCA FEPs incorporate a factor of safety of at least four.

Since the 2003 update to the TWBIR Revision 3 (Appendix DATA, Attachment F) indicates that the radionuclide inventory is lower than that previously estimated for the CCA), all CRA-2004 radioactive decay heating screening arguments are bounded by the previous CCA screening arguments. Verification of the fact that heat loads for the CRA-2004 are less than those for the

CCA is provided in Djordjevic (2003). Djordjevic (2003) is a recalculation of the work of Sanchez and Trellue (1996) using radionuclide data from Appendix DATA, Attachment F.

SCR-6.2.1.4 FEPs Number: W14
FEPs Title: ***Nuclear Criticality: Heat***

SCR-6.2.1.4.1 Screening Decision: SO-P

Nuclear Criticality *has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-6.2.1.4.2 Summary of New Information

Heat generated via **Nuclear Criticality** was screened out based on the low probability that a criticality event would occur. The updated information for the WIPP disposal inventory of fissile material (Appendix DATA, Attachment F; Leigh 2003a) indicates that the expected WIPP-scale quantity is 43 percent lower than previously estimated in CCA TWBIR Rev 3. Thus, all CRA-2004 criticality screening arguments are conservatively bounded by the previous CCA screening arguments (Rechard et al. 1996, 2000, and 2001).

SCR-6.2.1.4.3 Screening Argument

Nuclear **Criticality** refers to a sustained fission reaction that may occur if fissile radionuclides reach both a sufficiently high concentration and total mass (where the latter parameter includes the influence of enrichment of the fissile radionuclides). In the subsurface, the primary effect of a nuclear reaction is the production of heat.

Nuclear criticality (near and far field) was eliminated from PA calculations for the WIPP for waste contaminated with TRU radionuclides. The probability for criticality within the repository is low (there are no mechanisms for concentrating fissile radionuclides dispersed amongst the waste). Possible mechanisms for concentration in the waste disposal region include high solubility, compaction, sorption, and precipitation. First, the maximum solubility of ^{239}Pu in the WIPP repository, the most abundant fissile radionuclide, is orders of magnitude lower than necessary to create a critical solution. The same is true for ^{235}U, the other primary fissile radionuclide. Second, the waste is assumed to be compacted by repository processes to one fourth its original volume. This compaction is still an order of magnitude too disperse (many orders of magnitude too disperse if neutron absorbers that prevent criticality (for example, ^{238}U) are included). Third, any potential sorbents in the waste would be fairly uniformly distributed throughout the waste disposal region; consequently, concentration of fissile radionuclides in localized areas through sorption is improbable. Fourth, precipitation requires significant localized changes in brine chemistry; small local variations are insufficient to separate substantial amounts of ^{239}Pu from other actinides in the waste disposal region (for example, 11 times more ^{238}U is present than ^{239}Pu).

Criticality away from the repository (following an inadvertent human intrusion) has a low probability because (1) the amount of fissile material transported from the repository is small; (2) host rock media have small porosities (insufficient for generation of sizable precipitation zone); and (3) no credible mechanism exists for the concentrating fissile material during transport (the

natural tendency is for transported to be dispersed). As discussed in Section 6.4.6.2 and CCA Appendix PA, Attachment MASS Section MASS.15, the dolomite porosity consists of intergranular porosity, vugs, microscopic fractures, and macroscopic fractures. As discussed in Section 6.4.5.2, porosity in the marker beds consists of partially healed fractures that may dilate as pressure increases. Advective flow in both units occurs mostly through macroscopic fractures. Consequently, any potential deposition through precipitation or sorption is constrained by the depth to which precipitation and sorption occur away from fractures. This geometry is not favorable for fission reactions and eliminates the possibility of criticality. Thus, **Nuclear Criticality** has been eliminated from PA calculations on the basis of low probability of occurrence.

Screening arguments made in Rechard et al. (1996) are represented in greater detail in Rechard et al. (2000, 2001). A major finding among the analysis results in the screening arguments is the determination that fissile material would need to be reconcentrated by three orders of magnitude in order to be considered in a criticality scenario. These previous arguments were based on radionuclide information from Revision 3 of the TWBIR (DOE 1996b). Of the 135 radionuclides presented in that TWBIR database, only 17 are possible contributors to fissile material. Table SCR-4 identifies these nuclides along with their conversion factors for specific activity and ^{239}Pu fissile gram equivalents (^{239}Pu fissile gram equivalent (FGE) per ANSI/ANS-18.5).

Radioactivity inventories for the fissile radionuclides used in the CCA and CRA-2004 are presented in Table SCR-5. Also shown in Table SCR-5 are the corresponding FGE inventories. Key amongst the information presented in this table is updated information for the WIPP disposal inventory of fissile material (Appendix DATA, Attachment F; Leigh 2003a) indicates that the expected WIPP-scale quantity is 43 percent lower than previously estimated in TWBIR Rev. 3. Thus, all CRA-2004 criticality screening arguments are conservatively bounded by the previous CCA screening arguments (Rechard et al. 1996, 2000, and 2001).

SCR-6.2.2 Radiological Effects on Material Properties

SCR-6.2.2.1 FEP Number: W15, W16, and W17
FEP Title: ***Radiological Effects on Waste*** (W15)
Radiological Effects on Containers (W16)
Radiological Effects on Seals (W17)

SCR-6.2.2.1.1 Screening Decision: SO-C

Radiological Effects on the Properties of the Waste, Container, and Seals *have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.2.2.1.2 Summary of New Information

The FEPs screening argument has been updated by referencing new radiological waste data. The screening decision for these FEPs has not been affected or changed by these new data.

Table SCR-4. Properties of Fissile Radionuclides in the Actinide Series

Nuclide ID	Atomic Number	Atomic Number	Half-Life(1) (sec)	Mass Excess Value(2) (MeV)	Atomic Weight(3) (gm/mole)	Specific Activity(4) (Ci/gm)	Fissile Gram Equivalent Factor(5) (^{239}Pu)
^{233}U	92	233	5.0020E+12	36.914	233.040	9.6763E-03	1.00E+00
^{235}U	92	235	2.2210E+16	40.916	235.044	2.1611E-06	1.00E+00
^{237}Np	93	237	6.7530E+13	44.868	237.048	7.0476E-04	1.50E-02
^{238}Pu	94	238	2.7690E+09	46.160	238.050	1.7115E+01	1.13E-01
^{239}Pu	94	239	7.5940E+11	48.585	239.052	6.2146E-02	1.00E+00
^{240}Pu	94	240	2.0630E+11	50.122	240.054	2.2781E-01	2.25E-02
^{241}Pu	94	241	4.5440E+08	52.952	241.057	1.0300E+02	2.25E+00
^{242}Pu	94	242	1.2210E+13	54.714	242.059	3.8171E-03	7.50E-03
^{241}Am	95	241	1.3640E+10	52.931	241.057	3.4312E+00	1.87E-02
^{242m}Am	95	242	4.7970E+09	55.513	242.060	9.7159E+00	3.46E+01
^{243}Am	95	243	2.3290E+11	57.171	243.061	1.9929E-01	1.29E-02
^{243}Cm	96	243	8.9940E+08	57.177	243.061	5.1607E+01	5.00E+00
^{244}Cm	96	244	5.7150E+08	58.449	244.063	8.0883E+01	9.00E-02
^{245}Cm	96	245	2.6820E+11	60.998	245.065	1.7165E-01	1.50E+01
^{247}Cm	96	247	4.9230E+14	65.528	247.070	9.2752E-05	5.00E-01
^{249}Cf	98	249	1.1060E+10	69.718	249.075	4.0953E+00	4.50E+01
^{251}Cf	98	251	2.8340E+10	74.128	251.080	1.5855E+00	9.00E+01

1 Half-life data originally taken from ORIGEN2 decay library (Croff 1980). Data values presented in Ref. Sanchez 1996 (WIPP WPO# 037404).
2 Mass excess values originally taken from Nuclear Wallet Cards (Tuli 1985). Data values presented in Ref. Sanchez 1996 (WIPP WPO# 037404).
3 Atomic weight calculated from: ATWT (AMU) = AN (atomic mass number) – ME (mass difference in MeV, ME of C^{12} = 0) / 931.4943 (MeV per AMU, Parrington et al. 1996, pg. 58).
4 Specific Activity calculated from: A'= (Na ln(2))/(ATWT half-life), Ref. Turner 1992, pg. 64 and A (Ci/gm) = A'(Bq/gm) / 3.7E+10 (Bq/Ci), Turner 1992, pg. 43, where Na = Avogadro's number = 6.02213676E+23 (atom/mole, Parrington, pg.59).
5 FGE (^{239}Pu based) data values from NuPac 1989 (TRUPACT-II SAR/Table 10.1/pg. 1.3.7-51 (data originally from Ref. ANSI/ANS-8.15 1981).

Table SCR-5. Fissile Equivalents of Radionuclides in the Actinide Series

Nuclide ID	Radioactivity Inventory(1) (Ci)				Nuclide Fissile Mass(2) (FGE-^{239}Pu)			
	TWBIR 3 (1995)	TWBIR 3 (2033)	2003 UpDate (2002)	2003 UpDate (2033)	TWBIR 3 (1995)	TWBIR 3 (2033)	2003 UpDate (2002)	2003 UpDate (2033)
^{233}U	1.95E+03	1.95E+03	1.27E+03	1.27E+03	2.02E+05	2.02E+05	1.31E+05	1.32E+05
^{235}U	1.74E+01	1.75E+01	2.26E+00	2.28E+00	8.05E+06	8.10E+06	1.05E+06	1.06E+06
^{237}Np	5.90E+01	6.49E+01	5.46E+00	1.01E+01	1.26E+03	1.38E+03	1.16E+02	2.14E+02
^{238}Pu	2.61E+06	1.94E+06	1.61E+06	1.25E+06	1.72E+04	1.28E+04	1.07E+04	8.27E+03
^{239}Pu	7.96E+05	7.95E+05	6.66E+05	6.64E+05	1.28E+07	1.28E+07	1.07E+07	1.07E+07
^{240}Pu	2.15E+05	2.14E+05	1.09E+05	1.09E+05	2.12E+04	2.11E+04	1.07E+04	1.07E+04
^{241}Pu	2.45E+06	3.94E+05	2.51E+06	5.38E+05	5.35E+04	8.61E+03	5.49E+04	1.18E+04

Table SCR-5. Fissile Equivalents of Radionuclides in the Actinide Series — Continued

Nuclide ID	Radioactivity Inventory[1] (Ci)				Nuclide Fissile Mass[2] (FGE-^{239}Pu)			
	TWBIR 3 (1995)	TWBIR 3 (2033)	2003 UpDate (2002)	2003 UpDate (2033)	TWBIR 3 (1995)	TWBIR 3 (2033)	2003 UpDate (2002)	2003 UpDate (2033)
^{242}Pu	1.17E+03	1.17E+03	2.71E+01	2.71E+01	2.30E+03	2.30E+03	5.33E+01	5.32E+01
^{241}Am	4.48E+05	4.88E+05	4.15E+05	4.58E+05	2.44E+03	2.66E+03	2.26E+03	2.50E+03
^{242m}Am	1.75E+00	1.47E+00	2.44E-01	2.11E-01	6.23E+00	5.23E+00	8.67E-01	7.50E-01
^{243}Am	3.26E+01	3.25E+01	2.18E+01	2.17E+01	2.11E+00	2.10E+00	1.41E+00	1.41E+00
^{243}Cm	5.23E+01	2.07E+01	8.87E-01	4.07E-01	5.07E+00	2.01E+00	8.59E-02	3.94E-02
^{244}Cm	3.18E+04	7.44E+03	1.18E+04	2.51E+03	3.54E+01	8.28E+00	1.32E+01	2.79E+00
^{245}Cm	1.15E-02	1.15E-02	1.90E-02	1.92E-02	1.00E+00	1.00E+00	1.66E+00	1.68E+00
^{247}Cm	3.21E-09	9.51E-09	9.44E+00	9.45E+00	1.73E-05	5.13E-05	5.09E+04	5.09E+04
^{249}Cf	6.87E-02	6.38E-02	7.72E-02	7.24E-02	7.55E-01	7.01E-01	8.48E-01	7.96E-01
^{251}Cf	3.78E-03	3.67E-03	5.23E-04	5.10E-04	2.15E-01	2.08E-01	2.97E-02	2.90E-02
				Σ	2.11E+07	2.12E+07	1.20E+07	1.20E+07

[1] TWBIR Rev. 3 data values originally from DOE 1996b. Data values presented in Sanchez 1997, pp. 27-30. TWBIR 2003 Update 2002 (beginning of calendar year) data from Appendix DATA, Attachment F. TWBIR 2002 Update 2033 (end of calendar year) data from Leigh 2003a.

[2] ^{239}Pu Fissile Gram Equivalents calculated from: FGE(^{239}Pu) = Inventory (Ci) * FGE Factor (from Table 1) / A'(Ci/gm, from Table 1).

SCR-6.2.2.1.3 Screening Argument

Ionizing radiation can change the physical properties of many materials. Strong radiation fields could lead to damage of waste matrices, brittleness of the metal containers, and disruption of any crystalline structure in the seals. The low level of activity of the waste in the WIPP is unlikely to generate a strong radiation field. According to the new *inventory* data, the total radionuclide inventory decreased from 7.44×10^6 (DOE 1996b) to 6.66×10^6 curies (Appendix DATA, Attachment F), about a 10 percent decrease. Such a small decrease will not change the original screening argument. In addition, PA calculations assume instantaneous container failure and waste dissolution according to the source-term model (see Sections 6.4.3.4, 6.4.3.5, and 6.4.3.6. Therefore, ***Radiological Effects on the Properties of the Waste, Container, and Seals*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3 Geological and Mechanical Features, Events, and Processes

SCR-6.3.1 Excavation-Induced Changes

SCR-6.3.1.1 FEP Number: W18 and W19
FEP Title: ***Disturbed Rock Zone*** (W18)
Excavation-Induced Change in Stress (W19)

SCR-6.3.1.1.1 Screening Decision: UP

Excavation-induced host rock fracturing through formation of a disturbed rock zone (*DRZ*) *and changes in stress are accounted for in PA calculations.*

SCR-6.3.1.1.2 Summary of New Information

No new information has been identified relating to these two FEPs. No changes have been made since the CRA.

SCR-6.3.1.1.3 Screening Argument

Construction of the repository has caused local ***excavation-induced changes in stress*** in the surrounding rock as discussed in Section 3.3.1.5. This has led to failure of intact rock around the opening, creating a DRZ of fractures. On completion of the WIPP excavation, the extent of the induced stress field perturbation will be sufficient to have caused dilation and fracturing in the anhydrite layers a and b, MB139, and, possibly, MB138. The creation of the DRZ around the excavation and the disturbance of the anhydrite layers and marker beds will alter the permeability and effective porosity of the rock around the repository, providing enhanced pathways for flow of gas and brine between the waste-filled rooms and the nearby interbeds. This excavation-induced, host-rock fracturing is accounted for in PA calculations (Section 6.4.5.3).

The DRZ around repository shafts could provide pathways for flow from the repository to hydraulically conductive units above the repository horizon. The effectiveness of long-term shaft seals is dependent upon the seals providing sufficient backstress for salt creep to heal the DRZ around them, so that connected flow paths out of the repository horizon will cease to exist. These factors are considered in the current seal design.

SCR-6.3.1.2 FEP Number: W20 and W21
FEP Title: ***Salt Creep*** (W20)
Change in the Stress Field (W21)

SCR-6.3.1.2.1 Screening Decision: UP

Salt Creep *in the Salado and resultant* ***Changes in the Stress Field*** *are accounted for in PA calculations.*

SCR-6.3.1.2.2 Summary of New Information

No new information has been identified relating to these two FEPs. No changes have been made since CRA-2004.

SCR-6.3.1.2.3 Screening Argument

Salt Creep will lead to ***Changes in the Stress Field***, compaction of the waste and containers, and consolidation of the long-term components of the sealing system. It will also tend to close fractures in the DRZ, leading to reductions in porosity and permeability, increases in pore fluid

pressure, and reductions in fluid flow rates in the repository. ***Salt Creep*** in the Salado is accounted for in PA calculations (Section 6.4.3.1). The long-term repository seal system relies on the consolidation of the crushed-salt seal material and healing of the DRZ around the seals to achieve a low permeability under stresses induced by salt creep. Seal performance is discussed further in FEPs W36 and W37.

SCR-6.3.1.3 FEP Number: W22
FEP Title: ***Roof Falls***

SCR-6.3.1.3.1 Screening Decision: UP

The potential effects of roof falls on flow paths are accounted for in PA calculations.

SCR-6.3.1.3.2 Summary of New Information

No new information has been identified relating to this FEP. No changes have been made since the CRA.

SCR-6.3.1.3.3 Screening Argument

Instability of the DRZ could to lead to localized ***Roof Falls*** in the first few hundred years. If instability of the DRZ causes roof falls, development of the DRZ may be sufficient to disrupt the anhydrite layers above the repository, which may create a zone of rock containing anhydrite extending from the interbeds toward a waste-filled room. Fracture development is most likely to be induced as the rock stress and strain distributions evolve because of creep. In the long term, the effects of roof falls in the repository are likely to be minor because **Salt *Creep*** will reduce the void space and the potential for ***Roof Falls*** as well as leading to healing of any roof material that has fallen into the rooms. However, because of uncertainty in the process by which the disposal room DRZ heals, the flow model used in the PA assumes that a higher permeability zone remains for the long term. Thus, the potential effects of ***Roof Falls*** on flow paths are accounted for in PA calculations through appropriate ranges of the parameters describing the DRZ.

SCR-6.3.1.4 FEP Number(s): W23 and W24
FEP Title(s): ***Subsidence*** (W23)
Large Scale Rock Fracturing (W24)

SCR-6.3.1.4.1 Screening Decision(s): SO-C (W23)
SO-P (W24)

*Fracturing within units overlying the Salado and surface displacement caused by **Subsidence** associated with repository closure have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The potential for excavation or repository-induced **Subsidence** to create **Large-Scale Rock Fracturing** and fluid flow paths between the repository and units overlying the Salado has been eliminated from PA calculations on the basis of the low probability of occurrence over 10,000 years.*

SCR-6.3.1.4.2 Summary of New Information

The DOE acknowledges that proximal ***Roof Falls*** (see W22, Appendix SCR, Section SCR.2.3.3) will occur and minor subsidence of stratigraphic units overlying the Salado at WIPP could occur. Subsidence of geologic formations overlying the WIPP due to ***Salt Creep*** is shown to be only modestly perturbed and the consequence is captured by the uncertainty employed in the PA. ***Roof Falls*** and large-scale ***Subsidence*** have therefore been screened out of the PA calculations based upon low consequence. The potential effects of ***Roof Falls*** on flow paths are accounted for in PA calculations through appropriate ranges of the parameters describing the DRZ. Continuous survey data, reported annually, reaffirm that ***Subsidence*** is minimal and near the accuracy of the survey itself (COMPs, annual reports). Changes for clarity and editorial purposes have been made to the screening argument.

SCR-6.3.1.4.3 Screening Argument

Instability of the DRZ could to lead to localized ***Roof Falls*** in the first few hundred years. If instability of the DRZ causes ***Roof Falls***, development of the DRZ may be sufficient to disrupt the anhydrite layers above the repository, which may create a zone of rock containing anhydrite extending from the interbeds toward a waste-filled room. Fracture development is most likely to be induced as the rock stress and strain distributions evolve because of creep and the local lithologies. In the long term, the effects of ***Roof Falls*** in the repository are likely to be minor because ***Salt Creep*** will reduce the void space and the potential for roof falls as well as leading to healing of any roof material that has fallen into the rooms. Because of uncertainty in the process by which the disposal room DRZ heals, the flow model used in the PA assumed that a higher permeability zone remained for the long term. The PAVT modified the DRZ permeability to a sampled range. Thus, the potential effects of ***Roof Falls*** on flow paths are accounted for in PA calculations through appropriate ranges of the parameters describing the DRZ.

The amount of ***Subsidence*** that can occur as a result of ***Salt Creep*** closure or roof collapse in the WIPP excavation depends primarily on the volume of excavated rock, the initial and compressed porosities of the various emplaced materials (waste, backfill, panel and drift closures, and seals), the amount of inward creep of the repository walls, and the gas and fluid pressures within the repository. The DOE (Westinghouse 1994) has analyzed potential excavation-induced subsidence with the primary objective of determining the geomechanical advantage of backfilling the WIPP excavation. The DOE (Westinghouse 1994, pp. 3-4 to 3-23) used mass conservation calculations, the influence function method, the National Coal Board empirical method, and the two-dimensional, finite-difference code, Fast Lagrangian Analysis of Continua (FLAC) to estimate ***Subsidence*** for conditions ranging from no backfill to emplacement of a highly compacted crushed salt backfill. The DOE (Westinghouse 1994, pp. 2-17 to 2-23) also investigated ***Subsidence*** at potash mines located near the WIPP site to gain insight into the expected ***Subsidence*** conditions at the WIPP and to calibrate the subsidence calculation methods.

Subsidence over potash mines will be much greater than subsidence over the WIPP because of the significant differences in stratigraphic position, depth, extraction ratio, and layout. The WIPP site is located stratigraphically lower than the lowest potash mine, which is near the base of the McNutt Potash Member (hereafter called the McNutt). At the WIPP site, the base of the

McNutt is about 150 m (490 ft) above the repository horizon. Also, the WIPP rock extraction ratio in the waste disposal region will be about 22 percent, as compared to 65 percent for the lowest extraction ratios within potash mines investigated by the DOE (Westinghouse 1994, p. 2-17).

The DOE (Westinghouse 1994, p. 2-22) reported the maximum total ***Subsidence*** at potash mines to be about 1.5 m (5 ft). This level of ***Subsidence*** has been observed to have caused surface fractures. However, the DOE (Westinghouse 1994, p. 2-23) found no evidence that ***Subsidence*** over potash mines had caused fracturing sufficient to connect the mining horizon to water-bearing units or the landsurface. The level of disturbance caused by ***Subsidence*** above the WIPP repository will be less than that associated with potash mining and thus, by analogy, will not create fluid flow paths between the repository and the overlying units.

The various ***Subsidence*** calculation methods used by the DOE (Westinghouse 1994, pp. 3-4 to 3-23) provided similar and consistent results, which support the premise that ***Subsidence*** over the WIPP will be less than ***Subsidence*** over potash mines. Estimates of maximum ***Subsidence*** at the land surface for the cases of no backfill and highly compacted backfill are 0.62 m (2 ft) and 0.52 m (1.7 ft), respectively. The mass conservation method gave the upper bound estimate of ***Subsidence*** in each case. The surface topography in the WIPP area varies by more than 3 m (10 ft), so the expected amount of repository-induced ***Subsidence*** will not create a basin, and will not affect surface hydrology significantly. The DOE (Westinghouse 1994, Table 3-13) also estimated ***Subsidence*** at the depth of the Culebra using the FLAC model, for the case of an empty repository (containing no waste or backfill). The FLAC analysis assumed the Salado to be halite and the Culebra to have anhydrite material parameters.

Maximum ***Subsidence*** at the Culebra was estimated to be 0.56 m (1.8 ft). The vertical strain was concentrated in the Salado above the repository. Vertical strain was less than 0.01 percent in units overlying the Salado and was close to zero in the Culebra (Westinghouse 1994, Figure 3-40). The maximum horizontal displacement in the Culebra was estimated to be 0.02 m (0.08 ft), with a maximum tensile horizontal strain of 0.007 percent. The DOE (Westinghouse 1994, 4-1 to 4-2) concluded that the induced strains in the Culebra will be uniformly distributed because no large-scale faults or discontinuities are present in the vicinity of the WIPP. Furthermore, strains of this magnitude would not be expected to cause extensive fracturing.

At the WIPP site, the Culebra hydraulic conductivity varies spatially over approximately four orders of magnitude, from 1×10^{-8} m (3.2×10^{-8} ft) per second (0.4 m (1.3 ft) per year) to 1×10^{-5} m (3.2×10^{-5} ft) per second (Appendix PA, Attachment TFIELD). Where transmissive horizontal fractures exist, hydraulic conductivity in the Culebra is dominated by flow through the fractures. An induced tensile vertical strain may result in an increase in fracture aperture and corresponding increases in hydraulic conductivity. The magnitude of increase in hydraulic conductivity can be estimated by approximating the hydrological behavior of the Culebra with a simple conceptual model of fluid flow through a series of parallel fractures with uniform properties. A conservative estimate of the change in hydraulic conductivity can be made by assuming that all the vertical strain is translated to fracture opening (and none to rock expansion). This method for evaluating changes in hydraulic conductivity is similar to that used by the EPA in estimating the effects of subsidence caused by potash mining (Peake 1996; EPA 1996b).

The equivalent porous medium hydraulic conductivity, *K* (meters per second), of a system of parallel fractures can be calculated assuming the cubic law for fluid flow (Witherspoon et al. 1980):

$$K = \frac{w^3 \rho g N}{12 \mu 2}, \tag{10}$$

where *w* is the fracture aperture, ρ is the fluid density (taken to be 1,000 kg/m^3), *g* is the acceleration due to gravity (9.79 m (32 ft) per second squared), μ is the fluid viscosity (taken as 0.001 pascal seconds), *D* is the effective Culebra thickness (7.7 m (26.3 ft)), and *N* is the number of fractures. For 10 fractures with a fracture aperture, *w*, of 6×10^{-5} m (2×10^{-4} ft), the Culebra hydraulic conductivity, *K*, is approximately 7 m per year (2×10^{-7} m (6.5×10^{-7} ft) per second). The values of the parameters used in this calculation are within the range of those expected for the Culebra at the WIPP site (Appendix PA, Attachment TFIELD).

The amount of opening of each fracture as a result of subsidence-induced tensile vertical strain, ε, (assuming rigid rock) is $D\varepsilon/N$ meters. Thus, for a vertical strain of 0.0001, the fracture aperture, *w*, becomes approximately 1.4×10^{-4} m. The Culebra hydraulic conductivity, *K*, then increases to approximately 85 m (279 ft) per year (2.7×10^{-6} m (8.9×10^{-6} ft) per second). Thus, on the basis of a conservative estimate of vertical strain, the hydraulic conductivity of the Culebra may increase by an order of magnitude. In the PA calculations, multiple realizations of the Culebra transmissivity field are generated as a means of accounting for spatial variability and uncertainty (Appendix TFIELD). A change in hydraulic conductivity of one order of magnitude through vertical strain is within the range of uncertainty incorporated in the Culebra transmissivity field through these multiple realizations. Thus, changes in the horizontal component of Culebra hydraulic conductivity resulting from repository-induced subsidence have been eliminated from PA calculations on the basis of low consequence.

A similar calculation can be performed to estimate the change in vertical hydraulic conductivity in the Culebra as a result of a horizontal strain of 0.00007 m/m (Westinghouse 1994, p. 3-20). Assuming this strain to be distributed over about 1,000 fractures (neglecting rock expansion), with zero initial aperture, in a lateral extent of the Culebra of about 800 m (2,625 ft) (Westinghouse 1994, Figure 3-39), then the subsidence-induced fracture aperture is approximately 6×10^{-5} m (1.9×10^{-4} ft). Using the values for ρ, *g*, and μ, above, the vertical hydraulic conductivity of the Culebra can then be calculated, through an equation similar to above, to be 7 m (23 ft) per year (2×10^{-7} m (6.5×10^{-7} ft) per second). Thus, vertical hydraulic conductivity in the Culebra may be created as a result of repository-induced ***Subsidence***, although this is expected to be insignificant.

In summary, as a result of observations of ***Subsidence*** associated with potash mines in the vicinity of the WIPP, the potential for ***Subsidence*** to create fluid flow paths between the repository and units overlying the Salado has been eliminated from PA calculations on the basis of low probability. The effects of repository-induced ***Subsidence*** on hydraulic conductivity in the Culebra have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3.2 Effects of Fluid Pressure Changes

SCR-6.3.2.1 FEP Number: W25 and W26
FEP Title: ***Disruption Due to Gas Effects*** (W25)
Pressurization (W26)

SCR-6.3.2.1.1 Screening Decision: UP

*The mechanical effects of gas generation through **Pressurization** and **Disruption Due to Gas** flow are accounted for in PA calculations.*

SCR-6.3.2.1.2 Summary of New Information

No new information has been identified relating to these FEPs. No changes have been made.

SCR-6.3.2.1.3 Screening Argument

The mechanical effects of gas generation, including the slowing of creep closure of the repository due to gas ***Pressurization***, and the fracturing of interbeds in the Salado through ***Disruption Due to Gas Effects*** are accounted for in PA calculations (Sections 6.4.5.2 and 6.4.3.1).

SCR-6.3.3 Effects of Explosions

SCR-6.3.3.1 FEP Number: W27
FEP Title: ***Gas Explosions***

SCR-6.3.3.1.1 Screening Decision: UP

*The potential effects of **Gas Explosions** are accounted for in PA calculations.*

SCR-6.3.3.1.2 Summary of New Information

No new information has been identified related to this FEP. Only editorial changes have been made to this FEP.

Explosive gas mixtures could collect in the head space above the waste in a closed panel. The most explosive gas mixture potentially generated will be a mixture of hydrogen, methane, and oxygen which will convert to CO_2 and water on ignition. This means that there is little likelihood of a ***Gas Explosion***in the long term, because the rooms and panels are expected to become anoxic and oxygen depleted. Compaction through salt creep will also greatly reduce any void space in which the gas can accumulate. Analysis (see Appendix BARRIERS**,** Attachment PCS) indicates that the most explosive mixture of hydrogen, methane, and oxygen will be present in the void space approximately 20 years after panel-closure emplacement. This possibility of an explosion prior to the occurrence of anoxic conditions is considered in the design of the operational panel closure. The effect of such an explosion on the DRZ is expected to be no more severe than a ***Roof Fall*** which is accounted for in the PA calculations (FEP W22).

SCR-6.3.3.2 FEP Number: W28
FEP Title: ***Nuclear Explosions***

SCR-6.3.3.2.1 Screening Decision: SO-P

Nuclear Explosions *have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-6.3.3.2.2 Summary of New Information

Editorial changes have been made for clarity as well as separating the two FEPs within the original SCR text into discrete arguments. Additional information is referenced to support the conclusions.

SCR-6.3.3.2.3 Screening Argument

Nuclear explosions have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years. For a ***Nuclear Explosions*** to occur, a critical mass of Pu would have to undergo rapid compression to a high density. Even if a critical mass of Pu could form in the system, there is no mechanism for rapid compression. Radioactivity inventories for the fissile radionuclides used in DOE (1996a) and CRA-2004 are presented in Table SCR-6. The updated information for the WIPP disposal inventory of fissile material (Appendix DATA, Attachment F; Leigh 2003a) indicates that the expected WIPP-scale quantity is 43 percent lower than previously estimated in TWBIR Rev. 3 (DOE 1996b). Thus, all CRA-2004 criticality screening arguments are conservatively bounded by the previous CCA screening arguments (Rechard et al. 1996, 2000, and 2001).

SCR-6.3.4 Thermal Effects

SCR-6.3.4.1 FEP Number: W29, W30, W31, W72, and W73
FEP Title: ***Thermal Effects on Material Properties*** (W29)
Thermally-Induced Stress Changes (W30)
Differing Thermal Expansion of Repository Components (W31)
Exothermic Reactions (W72)
Concrete Hydration (W73)

SCR-6.3.4.1.1 Screening Decision: SO-C

The effects of ***Thermally Induced Stress, Differing Thermal Expansion of Components,*** *and* ***Thermal Effects on Material Properties*** *in the repository have been eliminated from PA calculations on the basis of low consequence to performance of the disposal system.*

The thermal effects of exothermic reactions, including ***Concrete Hydration****, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.3.4.1.2 Summary of New Information

All potential sources of heat and elevated temperature have been evaluated and found not to produce high enough temperature changes to affect the repository's performance. Sources of heat within the repository include radioactive decay and exothermic chemical reactions such as backfill hydration and metal corrosion. The rates of these exothermic reactions are limited by the availability of brine in the repository. ***Concrete Hydration*** in the seals is a significant source of heat, but it is relatively short-lived. Energy released by the hydration of the seal concrete could raise the temperature of the concrete to approximately 53°C (127°F), and that of the surrounding salt to approximately 38°C (100°F), one week after seal emplacement. Elevated temperatures will persist for a short period of time, perhaps a few years or a few decades. The thermal stresses from these temperatures and the temperatures in the concrete itself have been calculated to be below the design compressive strength for the concrete. Thus, thermal stresses should not degrade the long-term performance of the seals. In general, the various sources of heat do not appear to be great enough to jeopardize the performance of the disposal system.

The original FEP descriptions have been changed slightly to include the effects of water release during carbonation of the backfill, and the effects of formation of metastable hydrated carbonate minerals.

SCR-6.3.4.1.3 Screening Argument

Thermally Induced Stress could result in pathways for groundwater flow in the DRZ, in the anhydrite layers and marker beds, and through seals, or it could enhance existing pathways. Conversely, elevated temperatures will accelerate the rate of ***Salt Creep*** and mitigate fracture development. Thermal expansion could also result in uplift of the rock and ground surface overlying the repository, and thermal buoyancy forces could lift the waste upward in the salt rock.

The distributions of thermal stress and strain changes depend on the induced temperature field and the ***Differing Thermal Expansion of Components*** of the repository, which depends on the components' elastic properties. Potentially***, Thermal Effects on Material Properties*** (such as permeability and porosity) could affect the behavior of the repository.

Radioactive decay (W13), ***Nuclear Criticality*** (W14), and ***Exothermic Reactions*** (W72 and W73) are three possible sources of heat in the WIPP repository. According to the new inventory data, the total radionuclide inventory decreases increases from 7.44 × 106 (DOE 1996b) to 6.66 × 106 curies (Appendix DATA, Attachment F), about a 10 percent decrease. Such a small change will not result in a significant deviation from the possible temperature rise predicted in the CCA. Exothermic reactions in the WIPP repository include MgO hydration, MgO carbonation, Al corrosion, and ***Cement Hydration*** (Bennett et al. 1996). Wang (1996) has shown that the temperature rise by an individual reaction is proportional to $\sqrt{VM}$, where V is the maximum rate of brine inflow into a waste panel for a reaction limited by brine inflow (or a specified maximum reaction rate for a reaction limited by its own kinetics) and M is the quantity of the reactant. MgO hydration, cement hydration, and Al corrosion are assumed to be limited by brine inflow, because they all consume water and have high reaction rates. For these reactions, the calculated temperature rises need to be updated for the changes in both brine inflow rate and

waste inventory. According to the CRA-2004 PA calculations, the average brine inflow rate upon a human intrusion is 156 m^3/year (204 yd^3/year), with a maximum value of 332 m^3/year (434 yd^3/year). In the CCA, the maximum brine inflow rate was assumed to be 200 m^3/year (261 yd^3/year). With the new rate of 332 m^3/year (434 yd^3/year), it is estimated that the temperature rise by each exothermic reaction is increased by 29 percent if the quantity of reactant remains the same. Changes in the amounts of reactants are tabulated in Table SCR-6.

Table SCR-6. Changes in Inventory Quantities from the CCA to the CRA

Inventory	CCA	CRA	Change
MgO (tons)	85,600[1]	72,760 (because of the elimination of mini-sacks)[a]	–15%
Cellulosics (tons)	5,940[2]	8,120[3]	37%
Plastics (tons)	3,740[2]	8,120[3]	117%
Rubber (tons)	1,100[2]	1,960[3]	78%
Aluminum alloys (tons)	1,980[2]	1,960[3]	–1%
Cement (tons)	8,540[2]	9,971[5]	17%

[1] U.S. DOE (2001)
[2] U.S. DOE (1996b). Only CH wastes are considered. Total volume of CH wastes is 1.1×10^5 m^3. This is not scaled to WIPP disposal volume.
[3] Appendix DATA, Attachment F. Only CH wastes are considered. Total volume of CH waste is 1.4 x 10^5 m^3. This is not scaled to WIPP disposal volume.
[4] This estimate is derived from data in Leigh (2003b) includes both reacted and unreacted cement. (1.2e7 kg x 1.4e5/168485 /1000 kg/ton = 9971 tons cement)

Similarly, MgO carbonation, which consumes ***Carbon Dioxide***, is limited by ***Carbon Dioxide*** generation from microbial degradation. Given a biodegradation rate constant, the total CO_2 generated per year is proportional to the total quantity of biodegradable materials in the repository. The inventory of biodegradable materials has been changed from 13,398 (5,940 + 1.7 × 3,740 + 1,100)1 tons to 23,884 (8,120 + 1.7 × 8,120 + 1,960)1 tons of equivalent cellulosics (Wang and Brush 1996a and 1996b). This increase in biodegradeable materials corresponds to a proportional increase in CO_2 generation. For MgO carbonation and microbial degradation, the calculated temperature rises have been updated for the changes in both microbial gas generation and waste inventory and are presented in Table SCR-7.

Temperature rises (^oC) by exothermic reactions are revised as follows:

Table SCR-7. CCA and CRA Exothermic Temperature Rises

Reactant	CCA[1]	CRA1
MgO hydration	< 4.5	< 4.7
Backfill Carbonation	< 0.6	< 0.7
Microbial degradation	< 0.8	< 1.4
Aluminum corrosion	< 6.0	< 6.8
Cement hydration	< 2.0	< 2.5

[1] All values are shown in degrees Celsius

[1] The 1.7 molar conversion rate for plastic is based on analyses presented in Wang and Brush (1996a and ***1996***b).

For the CCA conditions following a drilling event, aluminum corrosion could, at most, result in a short-lived (two years) temperature increase of about 6°C (10.8°F) above ambient room temperature (about 27°C (80°F)) (Bennett et al. 1996). A temperature rise of 6°C (10.8°F) represented the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously. Revised maximum temperature rises by exothermic reactions for CRA-2004 are still less than 10°C (18°F) (as shown in Table SCR-7). Such small temperature changes cannot affect material properties. Thus, ***Thermal Effects on Material Properties*** in the repository have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3.5 Mechanical Effects on Material Properties

SCR-6.3.5.1 FEP Number: W32, W36, W37 and W39
FEP Title: ***Consolidation of Waste*** (W32)
Consolidation of Seals (W36)
Mechanical Degradation of Seals (W37)
Underground Boreholes (W39)

SCR-6.3.5.1.1 Screening Decision: UP

Consolidation of Waste *is accounted for in PA calculations.* ***Consolidation of Seals*** *and* ***Mechanical Degradation of Seals*** *are accounted for in PA calculations. Flow through isolated, unsealed* ***Underground Boreholes*** *is accounted for in PA calculations.*

SCR-6.3.5.1.2 Summary of New Information

No new information has been identified for these FEPs; however, because they are accounted for (UP) in PA, the implementation may differ from that used the CCA**)**. No information has been identified that would change the screening decision of UP. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.3.6.1.3 Screening Argument

Consolidation of Waste is accounted for in PA calculations in the modeling of creep closure of the disposal room (Section 6.4.3.1).

Mechanical Degradation of Seals and ***Consolidation of Seals*** are accounted for in PA calculations through the permeability range assumed for the seal system (Section 6.4.4).

The site investigation program has also involved the drilling of boreholes from within the excavated part of the repository. Following their use for monitoring or other purposes, these ***Underground Boreholes*** will be sealed where practical, and ***Salt Creep*** will also serve to consolidate the seals and to close the boreholes. Any boreholes that remain unsealed will connect the repository to anhydrite interbeds within the Salado, and thus provide potential pathways for radionuclide transport. PA calculations account for fluid flow to and from the interbeds by assuming that the DRZ has a permanently enhanced permeability that allows flow of repository brines into specific anhydrite layers and interbeds. This treatment is also considered to account for the effects of any unsealed boreholes.

SCR-6.3.5.2 FEP Number: W33
FEP Title: ***Movement of Containers***

SCR-6.3.5.2.1 Screening Decision: SO-C

Movement of Containers *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.3.5.2.2 Summary of New Information

Movement of Containers has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The FEP description has been updated to reflect new waste inventory data (waste density).

SCR-6.3.5.2.3 Screening Argument

Movement of Waste Containers placed in salt may occur as a result two buoyancy mechanisms (Dawson and Tillerson 1978): (1) the density contrast between the waste container and the surrounding salt, and (2) the temperature contrast between a salt volume that includes a heat source and the surrounding unheated salt. When the density of the waste container is greater than the density of the surrounding salt, the container sinks relative to the salt; whereas when the salt density is greater than the container density, the container rises relative to the salt. Similarly, when a discrete volume of salt within a large salt mass is heated, the heat raises the temperature of the discrete volume above that of the surrounding salt thereby inducing density contrasts and buoyant forces that initiate upward flow of the heated salt volume. In a repository setting, the source of the heat may be radioactive decay of the waste itself or exothermic reactions of the backfill materials and waste constituents, e.g., MgO hydration, MgO carbonation, aluminum corrosion, cement hydration, and calcium oxide hydration.

For the CCA, the density of the compacted waste and the grain density of the halite in the Salado were assumed to be 2,000 kg/m^3 and 2,163 kg/m^3, respectively. Because this density contrast is small, the movement of containers relative to the salt was considered minimal, particularly when drag forces on the waste containers were also considered. In addition, vertical movement initiated in response to thermally-induced density changes for high-level waste containers of a similar density to those at the WIPP were calculated to be approximately 0.35 m (1 ft) (Dawson and Tillerson 1978, p. 22). This calculated movement was considered conservative given that containers at the WIPP will generate much less heat and will, therefore, move less. As a result, container movement was eliminated from PA calculations on the basis of low consequences to the performance of the disposal system.

The calculations performed for DOE (1996a) were based on estimates of the waste inventory. However, with the initiation of waste disposal, actual waste inventory is tracked and future waste stream inventories have been refined. Based on an evaluation of these data, two factors may affect the conclusions reached in DOE (1996a) concerning container movement.

The first factor is changes in density of the waste form. For the most part, waste density will remain as assumed in the CCA. According to new *inventory* data (Appendix DATA, Attachment F), the revised waste density has changed by at most 10 percent (lower). Some future waste

streams may however be more highly compacted, perhaps having a density roughly three times greater than that assumed in the CCA. In calculations of container movement, Dawson and Tillerson (1978, p. 22) varied container density by nearly a factor of three (from 2,000 kg/m^3 (125 lb/ft^3) to 5,800 kg/m^3 (362 lb/ft^3)) and found that an individual dense container could move vertically as much as about 28 m (92 ft). Given the geologic environment of the WIPP, a container would likely encounter a dense stiff unit (such as an anhydrite stringer) that would arrest further movement far short of this upper bound; however, because of the massive thickness of the Salado salt, even a movement of 28 m (92 ft) would have little impact on performance.

The second inventory factor that could affect container movement is the composition of the waste (and backfills) relative to its heat production. Radioactive decay, ***Nuclear Criticality***, and exothermic reactions are three possible sources of heat in the WIPP repository. According to the new inventory data, the total radionuclide inventory decreases from 7.44×10^6 (CCA) to 6.66×10^6 curies (Appendix DATA, Attachment F), about a 10 percent decrease. Such a small change will not result in a significant deviation from the possible temperature rise predicted in the CCA. As shown in Section SCR.6.3.4 (FEPs W72 and W73), temperature rises from exothermic reactions are quite small (see Table SCR-7). Note that the revised maximum temperature rises by exothermic reactions are still less than 10°C (18°F).

Based on the small differences between the temperature and density assumed in the CCA compared to those determined using *new inventory* data (Appendix DATA, Attachment F), the conclusion about the importance of container movement reported in the CCA will not be affected, even when more highly compacted future waste streams are considered. Also, the effects of the revised maximum temperature rise and higher density future waste streams on container movement are competing factors (high density waste will sink, whereas the higher temperature waste-salt volume will rise) that may result in even less movement. Therefore, ***Movement of Waste Containers*** has been eliminated from PA calculations on the basis of low consequence.

SCR-6.3.5.3 FEP Number: W34
FEP Title: ***Container Integrity***

SCR-6.3.6.3.1 Screening Decision: SO-C Beneficial

Container Integrity *has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-6.3.5.3.2 Summary of New Information

No new information has been identified relating to this FEP. Editorial changes have been made to the FEP screening argument.

SCR-6.3.5.3.3 Screening Argument

Container Integrity is required only for waste transportation. As in the CCA, the CRA-2004 calculations show that a significant fraction of steel and other Fe-base materials will remain undegraded over 10,000 years (see Helton et al. 1998). For all undisturbed cases, at least 30 percent of the steels will remain uncorroded at the end of 10,000 years. In addition, it is assumed

in both CCA and CRA-2004 calculations that there is no microbial degradation of plastic container materials in 75 percent of PA realizations (Wang and Brush 1996). All these undegraded container materials will (1) prevent the contact between brine and radionuclides; and (2) decrease the rate and extent of radionuclide transport due to high tortuosity along the flow pathways and, as a result, increase opportunities for metallic iron and corrosion products to beneficially reduce radionuclides to lower oxidation states. Therefore, the ***Container Integrity*** can be eliminated on the basis of its beneficial effect on retarding radionuclide transport. Both ***CCA*** and CRA-2004 assume instantaneous container failure and waste dissolution according to the source-term model.

SCR-6.3.5.4 FEP Number: W35
FEP Title: ***Mechanical Effects of Backfill***

SCR-6.3.5.4.1 Screening Decision: SO-C

*The **Mechanical Effects of Backfill** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.3.5.4.2 Summary of New Information

In 2001, MgO mini-sacks were eliminated from the repository, which decreases the backfill to waste volume ratio (EPA 2001). Although the backfill will provide additional resistance to creep closure, most of the resistance will be provided by the waste. Therefore, inclusion of backfill would not significantly reduce the total ***Subsidence*** in the waste rooms, and screening based on low consequence is appropriate. The screening argument has been updated to reflect the elimination of minisacks.

SCR-6.3.5.4.3 Screening Argument

The chemical conditioners or backfill added to the disposal room will act to resist creep closure. However, calculations have shown that because of the high porosity and low stiffness of the waste and the high waste to potential backfill volume, inclusion of backfill does not significantly decrease the total subsidence in the waste emplacement area or disposal room (Westinghouse 1994). Since 2001, DOE has eliminated MgO mini sacks from the repository reducing the total inventory from 85,600 short tons to 74,000 short tons, which further reduces the potential backfill volume (EPA 2001). Therefore, the ***Mechanical Effects of Backfill*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3.5.5 FEP Number: W38
FEP Title: ***Investigation Boreholes***

SCR-6.3.5.5.1 Screening Decision: NA

SCR-6.3.5.5.2 Summary of New Information

The effects of ***Investigation Boreholes*** (whether sealed or not) that penetrate the disposal horizon but do not intersect the waste panels are encompassed by the arguments made in ***Natural***

Borehole Fluid Flow (H31) and ***Flow Through Undetected Boreholes*** (H33). FEP W38 has been deleted from the FEPs baseline because it is redundant. The effects of drillholes drilled from the underground are accounted for in PA by assumptions about the permeability of the DRZ. ***Natural Borehole Fluid Flow*** (H31) and ***Flow Through Undetected Boreholes*** (H33) encompass the effects of W38. Therefore, W38, ***Investigation Boreholes,*** has been deleted from the FEPs Baseline.

SCR-6.4 Subsurface Hydrological and Fluid Dynamic Features, Events, and Processes

SCR-6.4.1 Repository-Induced Flow

SCR-6.4.1.1 FEP Number: W40 and W41
FEP Title: ***Brine Inflow*** (W40)
Wicking (W41)

SCR-6.4.1.1.1 Screening Decision: UP

Two-phase brine and gas flow and capillary rise (wicking) in the repository and the Salado are accounted for in PA calculations.

SCR-6.4.1.1.2 Summary of New Information

No new information has been identified related to these FEPs. No changes have been made to the screening decisions or screening arguments.

SCR-6.4.1.1.3 Screening Argument

Brine Inflow to the repository may occur through the DRZ, impure halite, anhydrite layers, or clay layers. Pressurization of the repository through gas generation could limit the amount of brine that flows into the rooms and drifts. Two-phase flow of brine and gas in the repository and the Salado is accounted for in PA calculations (Section 6.4.3.2).

Capillary rise (or ***Wicking***) is a potential mechanism for liquid migration through unsaturated zones in the repository. Capillary rise in the waste material could affect gas generation rates, which are dependent on water availability. Potential releases due to drilling intrusion are also influenced by brine saturations and therefore by ***Wicking***. Capillary rise is therefore accounted for in PA calculations (Section 6.4.3.2).

SCR-6.4.2 Effects of Gas Generation

SCR-6.4.2.1 FEP Number: W42
FEP Title: ***Fluid Flow Due to Gas Production***

SCR-6.4.2.1.1 Screening Decision: UP

Fluid flow in the repository and Salado due to gas production is accounted for in PA calculations.

SCR-6.4.2.1.2 Summary of New Information

No new information has been identified related to this FEP. Only editorial changes have been made.

SCR-6.4.2.1.3 Screening Argument

Pressurization of the repository through gas generation could limit the amount of brine that flows into the rooms and drifts. Gas may flow from the repository through the DRZ, impure halite, anhydrite layers, or clay layers. The amount of water available for reactions and microbial activity will impact the amounts and types of gases produced (W44 through W55). Gas generation rates, and therefore repository pressure, may change as the water content of the repository changes. Pressure changes and ***Fluid Flow Due to Gas Production*** in the repository and the Salado are accounted for in PA calculations through modeling the two-phase flow (Section 6.4.3.2).

SCR-6.4.3 Thermal Effects

SCR-6.4.3.1 FEP Number: W43
FEP Title: ***Convection***

SCR-6.4.3.1.1 Screening Decision: SO-C

Convection *has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.4.3.1.2 Summary of New Information

No new information has been identified relative to the screening of this FEP. The FEP description has been updated and modified for editorial purposes.

SCR-6.4.3.1.3 Screening Argument

Temperature differentials in the repository could initiate ***Convection.*** The resulting thermally-induced brine flow or thermally-induced two-phase flow could influence contaminant transport. Potentially, thermal gradients in the disposal rooms could drive the movement of water vapor. For example, temperature increases around waste located at the edges of the rooms could cause evaporation of water entering from the DRZ. This water vapor could condense on cooler waste containers in the rooms and could contribute to brine formation, corrosion, and gas generation.

Nuclear Criticality (W13), ***Radioactive Decay*** (W14), and ***Exothermic Reactions*** (W72) are three possible sources of heat in the WIPP repository.

The characteristic velocity, Vi, for convective flow of fluid component I in an unsaturated porous medium is given by (from Hicks 1996);

$$V_i \approx -\frac{k_i}{\mu_i}(\alpha_i \rho_{i0} g \Delta T), \qquad (11)$$

where α_i (per degree) is the coefficient of expansion of the ith component, k_i is the intrinsic permeability (square meters), μ_i is the fluid viscosity (pascal second), ρ_{i0} (kilograms per cubic meter) is the fluid density at a reference point, g is the acceleration of gravity, and ΔT is the change in temperature. This velocity may be evaluated for the brine and gas phases expected in the waste disposal region.

For a temperature increase of 10°C (18°F), the characteristic velocity for convective flow of brine in the DRZ around the concrete shaft seals is approximately 7×10^{-4} m (2.3×10^{-3} ft) per year (2×10^{-11} m (6.6×10^{-11} ft) per second), and the characteristic velocity for convective flow of gas in the DRZ is approximately 1×10^{-3} m (3.2×10^{-3} ft) per year (3×10^{-11} m (9.8×10^{-11} ft) per second) (Hicks 1996). For a temperature increase of 25°C (45°F), the characteristic velocity for convective flow of brine in the concrete seals is approximately 2×10^{-7} m (6.5×10^{-7} ft) per year (6×10^{-15} m (1.9×10^{-14} ft) per second), and the characteristic velocity for convective flow of gas in the concrete seals is approximately 3×10^{-7} m (9.8×10^{-7} ft) per year (8×10^{-15} m (2.6×10^{-4} ft) per second) (Hicks 1996). These values of Darcy velocity are much smaller than the expected values associated with ***Brine Inflow*** to the disposal rooms of fluid flow resulting from gas generation. In addition, the buoyancy forces generated by smaller temperature contrasts in the DRZ, resulting from backfill and ***Concrete Hydration*** and ***Radioactive Decay***, will be short-lived and insignificant compared to the other driving forces for fluid flow. The short-term concrete seals will be designed to function as barriers to fluid flow for at least 100 years after emplacement, and seal permeability will be minimized (Wakeley et al. 1995). Thus, temperature increases associated with ***Concrete Hydration*** will not result in significant buoyancy driven fluid flow through the concrete seal system. In summary, temperature changes in the disposal system will not cause significant thermal ***cConvection***. Furthermore, the induced temperature gradients will be insufficient to generate water vapor and drive significant moisture migration.

Temperature effects on fluid viscosity would be most significant in the DRZ surrounding the hydrating concrete seals (where temperatures of approximately 38°C (100°F) are expected). The viscosity of pure water decreases by about 19 percent over a temperature range of between 27°C (80°F) and 38°C (100°F) (Batchelor 1973, p. 596). Although at a temperature of 27°C (80°F), the viscosity of Salado brine is about twice that of pure water (Rechard et al. 1990, a-19), the magnitude of the variation in brine viscosity between 27°C (80°F) and 38°C (100°F) will be similar to the magnitude of the variation in viscosity of pure water. The viscosity of air over this temperature range varies by less than seven percent (Batchelor 1973, p. 594) and the viscosity of gas in the waste disposal region over this temperature range is also likely to vary by less than seven percent. The Darcy fluid flow velocity for a porous medium is inversely proportional to the fluid viscosity. Thus, increases in brine and gas flow rates may occur as a result of viscosity variations in the vicinity of the concrete seals. However, these viscosity variations will persist only for a short period in which temperatures are elevated, and, thus, the expected variations in brine and gas viscosity in the waste disposal region will not affect the long-term performance of the disposal system significantly.

For the CCA conditions following a drilling event, aluminum corrosion could, at most, result in a short-lived (two years) temperature increase of about 6°C (10.8°F). A temperature rise of 6°C (10.8°F) represented the maximum that could occur as a result of any combination of

Exothermic Reactions occurring simultaneously. Revised maximum temperature rises by ***Exothermic Reactions*** for CRA-2004 are still less than 10 ^{o}C (18°F) (as shown in Table SCR-7). Such small temperature changes cannot affect material properties.

In summary, temperature changes in the disposal system will not cause significant thermally-induced two-phase flow. Thermal ***cConvection*** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5 Geochemical and Chemical Features, Events, and Processes

SCR-6.5.1 Gas Generation

SCR-6.5.1.1 FEP Number: W44, W45, and W48
FEP Titles: ***Degradation of Organic Material*** (W44)
Effects of Temperature on Microbial Gas Generation (W45)
Effects of Biofilms on Microbial Gas Generation (W48)

SCR-6.5.1.1.1 Screening Decision: UP

Microbial gas generation from degradation of organic material is accounted for in PA calculations, and the ***Effects of Temperature and Biofilm Formation on Microbial Gas Generation*** *are incorporated in the gas generation rates used.*

SCR-6.5.1.1.2 Summary of New Information

No new information has been identified related to the screening of these FEPs. Editorial changes have been made to the screening argument. The screening decision remains unchanged.

SCR-6.5.1.1.3 Screening Argument

Microbial breakdown of cellulosic material, and possibly plastics and other synthetic materials, will produce mainly CO_2, but also nitrogen oxide, nitrogen, hydrogen sulfide, hydrogen, and methane. The rate of microbial gas production will depend upon the nature of the microbial populations established, the prevailing conditions, and the substrates present. Microbial gas generation from ***Degradation of Organic Material*** is accounted for in PA calculations.

The following subsections discuss the effects of temperature, pressure, radiation, and biofilms on gas production rates via their control of microbial gas generation processes.

SCR-6.5.1.1.3.1 *Effects of Temperature on Microbial Gas Generation*

Calculations and experimental studies of induced temperature distributions within the repository have been undertaken and are described in FEPs W29, W30, and W31. Numerical analysis suggests that the average temperature increase in the WIPP repository caused by radioactive decay of the emplaced CH- and RH-TRU waste is likely to be less than 3°C (5.4°F) (FEP W13).

Temperature increases resulting from ***Exothermic Reactions*** are discussed in FEPs W72 and W73. Potentially the most significant ***Exothermic Reactions*** are ***Concrete Hydration***, backfill

hydration, and aluminum corrosion. Hydration of the seal concrete could raise the temperature of the concrete to approximately 53°C (127°F) and that of the surrounding salt to approximately 38°C (100°F) one week after seal emplacement (W73).

As discussed in FEPs W72 and W73, the maximum temperature rise in the disposal panels as a consequence of backfill hydration will be less than 5.3°C (9.5°F), resulting from ***Brine Inflow*** following a drilling intrusion into a waste disposal panel. Note that active institutional controls will prevent drilling within the controlled area for 100 years after disposal. By this time, any heat generation by radioactive decay and concrete seal hydration will have decreased substantially, and the temperatures in the disposal panels will have reduced to close to initial values.

Under similar conditions following a drilling event, aluminum corrosion could, at most, result in a short-lived (two years) temperature rise of about 7.9°C (14.2°F) (see W72). These calculated maximum heat generation rates resulting from aluminum corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability; each calculation assumes that all available brine is consumed by the reaction of concern. Thus, the temperature rise of 10°C (18°F) represents the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously.

Relatively few data exist on the ***Effects of Temperature on Microbial Gas Generation*** under expected WIPP conditions. Molecke (1979, p. 4) summarized microbial gas generation rates observed during a range of experiments. Increases in temperature from ambient up to 40°C (104°F) or 50°C (122°F) were reported to increase gas production, mainly via the degradation of cellulosic waste under either aerobic or anaerobic conditions (Molecke 1979, p. 7). Above 70°C (158°F), however, gas generation rates were generally observed to decrease. The experiments were conducted over a range of temperatures and chemical conditions and for different substrates, representing likely states within the repository. Gas generation rates were presented as ranges with upper and lower bounds as estimates of uncertainty (Molecke 1979, p. 7). Later experiments reported by Francis and Gillow (1994) support the gas generation rate data reported by Molecke (1979). These experiments investigated microbial gas generation under a wide range of possible conditions in the repository. These conditions included the presence of microbial inoculum, humid or inundated conditions, cellulosic substrates, additional nutrients, electron acceptors, bentonite, and initially oxic or anoxic conditions. These experiments were carried out at a reference temperature of 30°C (86°F), based on the average temperature expected in the repository. Gas generation rates used in the PA calculations have been derived from available experimental data and are described in Section 6.4.3.3. The effects of temperature on microbial gas generation are implicitly incorporated in the gas generation rates used.

SCR-6.5.1.1.3.2 *Effects of Biofilms on Microbial Gas Generation*

The location of microbial activity within the repository is likely to be controlled by the availability of substrates and nutrients. Biofilms may develop on surfaces where nutrients are concentrated. They consist of one or more layers of cells with extracellular polymeric material and serve to maintain an optimum environment for growth. Within such a biofilm ecosystem,

nutrient retention and recycling maximize microbe numbers on the surface (see, for example, Stroes-Gascoyne and West 1994, pp. 9 – 10).

Biofilms can form on almost any moist surface, but their development is likely to be restricted in porous materials. Even so, their development is possible at locations throughout the disposal system. The ***Effects of Biofilms on Microbial Gas Generation*** may affect disposal system performance through control of microbial population size and their effects on radionuclide transport.

Molecke (1979, p. 4) summarized microbial gas generation rates observed during a range of experimental studies. The experiments were conducted over a range of temperatures and chemical conditions and for different substrates representing likely states within the repository. However, the effect of biofilm formation in these experiments was uncertain. Molecke (1979, p. 7), presented gas generation rates as ranges, with upper and lower bounds as estimates of uncertainty. Later experiments reported by Francis and Gillow (1994) support the gas generation rate data reported by Molecke (1979). Their experiments investigated microbial gas generation under a wide range of possible conditions in the repository. These conditions included the presence of microbial inoculum, humid or inundated conditions, cellulosic substrates, additional nutrients, electron acceptors, bentonite, and initially oxic or anoxic conditions. Under the more favorable conditions for microbial growth established during the experiments, the development of populations of halophilic microbes and associated biofilms was evidenced by observation of an extracellular, carotenoid pigment, bacterioruberin, in the culture bottles (Francis and Gillow 1994, p. 59). Gas generation rates used in the PA calculations have been derived from available experimental data and are described in Section 6.4.3.3. The ***Effects of Biofilms on Microbial Gas Generation*** rates are implicitly incorporated in the gas generation rates.

Biofilms may also influence contaminant transport rates through their capacity to retain and thus retard both the microbes themselves and radionuclides. This effect is not accounted for in PA calculations, but is considered potentially beneficial to calculated disposal system performance. Microbial transport is discussed in FEP W87.

SCR-6.5.1.2 FEP Number: W46
FEP Title: ***Effects of Pressure on Microbial Gas Generation***

SCR-6.5.1.2.1 Screening Decision: SO-C

*The **Effects of Pressure on Microbial Gas Generation** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.2.2 Summary of New Information

The FEP screening argument has been updated, however the screening decision has not changed.

SCR-6.5.1.2.3 Screening Argument

Directly relevant to WIPP conditions, the gas generation experiments with actual waste components at Argonne National Laboratory provide no indication of any enhancement of pressured nitrogen atmosphere (2150 psia) on microbial gas generation (Felicione et al. 2001). In

addition, microbial breakdown of cellulosic material, and possibly plastics and other synthetic materials in the repository, will produce mainly CO_2 and methane with minor amounts of nitrogen oxide, nitrogen, and hydrogen sulfide. The accumulation of these gaseous species will contribute the total pressure in the repository. Increases in the partial pressures of these reaction products could potentially limit gas generation reactions. However, such an effect is not taken into account in WIPP PA calculations. The rate of microbial gas production will depend upon the nature of the microbial populations established, the prevailing conditions, and the substrates present. Microbial gas generation from ***Degradation of Organic Material*** (W44) is accounted for in PA calculations.

Chemical reactions may occur depending on, among other things, the concentrations of available reactants, the presence of catalysts and the accumulation of reaction products, the biological activity, and the prevailing conditions (for example, temperature and pressure). Reactions that involve the production or consumption of gases are often particularly influenced by pressure because of the high molar volume of gases. The effect of high total pressures on chemical reactions is generally to reduce or limit further gas generation.

Few data exist from which the ***Effects of Pressure on Microbial Gas Generation*** reactions that may occur in the WIPP can be assessed and quantified. Studies of microbial activity in deep-sea environments suggest (for example, Kato et al. 1994, p. 94) that microbial gas generation reactions are less likely to be limited by increasing pressures in the disposal rooms than are inorganic gas generation reactions (for example, corrosion). Consequently, the ***Effects of Pressure on Microbial Gas Generation*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.3 FEP Number: W47
FEP Title: ***Effects of Radiation on Microbial Gas Generation***

SCR-6.5.1.3.1 Screening Decision: SO-C

*The **Effects of Radiation on Microbial Gas Generation** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.3.2 Summary of New Information

The FEP screening argument has been updated to reflect the new radionuclide inventory, although the screening decision has not changed.

SCR-6.5.1.3.3 Screening Argument

Radiation may slow down microbial gas generation rates, but such an effect is not taken into account in WIPP PA calculations. According to the new *inventory* data, the total radionuclide inventory decreases from 7.44×10^6 (DOE 1996b) to 6.66×10^6 curies (Appendix DATA, Attachment F), about a 10 percent decrease Such a small change will not affect the original screening argument.

Experiments investigating microbial gas generation rates suggest that the effects of alpha radiation from TRU waste is not likely to have significant effects on microbial activity (Barnhart

et al. 1980; Francis 1985). Consequently, the ***Effects of Radiation on Microbial Gas Generation*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.4 FEP Number: W49 and W51
FEP Title: ***Gasses from Metal Corrosion***
Chemical Effects of Corrosion

SCR-6.5.1.4.1 Screening Decision: UP

Gas generation from metal corrosion is accounted for in PA calculations, and the effects of chemical changes from metal corrosion are incorporated in the gas generation rates used.

SCR-6.5.1.4.2 Summary of New Information

No new information has been identified related to these FEPs. They have been modified only from an editorial perspective, and have not changed since the CCA.

SCR-6.5.1.4.3 Screening Argument

Oxic corrosion of waste drums and metallic waste will occur at early times following closure of the repository and will deplete its oxygen content. Anoxic corrosion will follow the oxic phase and will produce hydrogen, while consuming water. ***Gases from Metal Corrosion*** are accounted for in PA calculations.

The predominant ***Chemical Effect of Corrosion*** reactions on the environment of disposal rooms will be to lower the oxidation state of the brines and maintain reducing conditions.

Molecke (1979, p. 4) summarized gas generation rates that were observed during a range of experiments. The experiments were conducted over a range of temperatures and chemical conditions representing likely states within the repository. Later experiments reported by Telander and Westerman (1993) support the gas generation rate data reported by Molecke (1979). Their experiments investigated gas generation from corrosion under a wide range of possible conditions in the repository. The studies included corrosion of low-carbon steel waste packaging materials in synthetic brines, representative of intergranular Salado brines at the repository horizon, under anoxic (reducing) conditions.

Gas generation rates used in the PA calculations have been derived from available experimental data and are described in Section 6.4.3.3. The effects of chemical changes from metal corrosion are, therefore, accounted for in PA calculations.

SCR-6.5.1.5 FEP Number: W50
FEP Title: ***Galvanic Coupling*** (within the repository)

SCR-6.5.1.5.1 Screening Decision: SO-C

*The effects of **Galvanic Coupling** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.5.2 Summary of New Information

The original screening argument confused ***Galvanic Coupling*** internal and external to the repository (see W95). As such, the original screening decision for ***Galvanic Coupling*** was screened out on probability however, it is more appropriate to screen this FEP on consequence. The screening decision has therefore been changes to SO-C and a clear distinction between which FEP considers internal and external coupling was included in the FEP discussions.

Consideration ***Galvanic Coupling*** (W50), is restricted to consideration of effects between or among materials within the repository. ***Galvanic Coupling*** with materials outside the repository is considered in ***Galvanic Coupling*** (W95).

Galvanic Coupling (within the repository) is unlikely to occur on a large scale. On a very small scale, ***Galvanic Coupling*** could occur whenever two dissimilar metals are in contact and a conducting medium is present. However, the resulting corrosion would cause the same effects as the other corrosion processes already included in the assessments. Thus, ***Galvanic Coupling***, as a distinct corrosion mechanism, would have negligible effects on repository performance.

Galvanic Coupling has been screened out on the basis of low consequence. No new information has become available that affects the screening argument; the FEP screening argument and screening decision remain unchanged.

SCR-6.5.1.5.3 Screening Argument

Galvanic Coupling (i.e. establishing an electrical current through chemical processes) could lead to the propagation of electric potential gradients between metals in the waste form, canisters, and other metals external to the waste form, potentially influencing corrosion processes, gas generation rates and chemical migration.

Metallic ore bodies external to the repository are nonexistent (CCA Appendix GCR) and therefore galvanic coupling between the waste and metals external to the repository would not occur. However, a variety of metals will be present within the repository as waste metals and containers, creating a potential for formation of galvanic cells over short distances. As an example, the presence of copper could influence rates of hydrogen gas production resulting from the corrosion of iron. The interactions between metals depend upon their physical disposition and the prevailing solution conditions, including pH and salinity. Good physical and electrical contact between the metals is critical to the establishment of galvanic cells.

Consequently, given the preponderance of iron over other metals within the repository and the likely passivation of many nonferrous materials, the influence of these electrochemical interactions on corrosion, and therefore gas generation, is expected to be minimal. Therefore, the effects of ***Galvanic Coupling*** have been eliminated from PA calculations on the basis of low consequence.

SCR-6.5.1.6 FEP Number: W52
FEP Title: ***Radiolysis of Brine***

SCR-6.5.1.6.1 Screening Decision: SO-C

*Gas generation from **Radiolysis of Brine** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.6.2 Summary of New Information

No new information is available relative to this FEP and screening decision. The screening argument has been modified for editorial purposes.

SCR-6.5.1.6.3 Screening Argument

Radiolysis of Brine in the WIPP disposal rooms, and of water in the waste, will lead to the production of gases and may significantly affect the oxygen content of the rooms. This in turn will affect the prevailing chemical conditions and potentially the concentrations of radionuclides that may be mobilized in the brines.

The overall reaction for the radiolysis of water in the waste and brine is

$$H_2O = H_2 + \tfrac{1}{2} O_2 \qquad (12)$$

However, the production of intermediate oxygen-bearing species that may subsequently undergo reduction will lead to reduced oxygen gas yields. The remainder of this section is concerned with the physical effects of gas generation by radiolysis of brine.

Reed et al. (1993) studied radiolytic gas generation during experiments lasting between 155 and 182 days. These experiments involved both synthetic brines similar to those sampled from the Salado at the WIPP repository horizon, and brines occurring in reservoirs in the Castile, as well as real brines sampled from the Salado in the repository workings. The brines were spiked with ^{239}Pu(VI) at concentrations between 6.9×10^{-9} and 3.4×10^{-4} molal. During these relatively short-term experiments, hydrogen gas was observed as the product of radiolysis. Oxygen gas was not observed; this was attributed to the formation of intermediate oxygen-bearing species. However, given sufficient exposure to alpha-emission, oxygen production may reach 50 percent that of hydrogen.

An estimate of the potential rate of gas generation due to the radiolysis of brine, R_{RAD}, can be made by making the following assumptions:

- Gas production occurs following the reaction above, so that 1.5 moles of gas are generated for each mole of water consumed.
- Gas production occurs as a result of the alpha decay of ^{239}Pu.
- ^{239}Puconcentrations in the disposal room brines are controlled by solubility equilibria.

- All of the dissolved plutonium is ^{239}Pu.

R_{RAD} is then given by

$$R_{RAD} = \frac{Y_g C_{Pu} SA_{Pu} \overline{E}_\alpha V_B}{N_D N_A} \tag{13}$$

$$R_{RAD} = \frac{\left(\frac{1.5 \text{ molecule gas}}{\text{molecule } H_2O}\right)\left(3.15\times10^{7}\ \frac{\text{sec}}{\text{yr}}\right)\left(3\times10^{-4}\ \frac{\text{mol}}{\text{L}}\right)\left(5.42\times10^{11}\ \frac{\text{Bq}}{\text{mol}}\right)\left(5.15\times10^{6}\ \frac{\text{eV}}{\text{dis}}\right)\left(\frac{0.015\ H_2O}{100\ \text{eV}}\right)\left(4.36\times10^{8}\text{L}\right)}{\left(8\times10^{5}\ \text{drums}\right)\left(6.022\times10^{23}\ \frac{\text{molecules}}{\text{mole}}\right)} \tag{14}$$

R = rate of gas production (moles per drum per year)
Y_g = radiolytic gas yield, in number of moles of gas produced per number of water molecules consumed
C_{Pu} = maximum dissolved concentration of plutonium (molar)
SA_{Pu} = specific activity of ^{239}Pu (5.42×10^{11} becquerels per mole)
$\overline{E}_\alpha$ = average energy of α-particles emitted during ^{239}Pu decay (5.15×10^{6} eV)
G = number of water molecules split per 100 eV of energy transferred from alpha-particles
V_B = volume of brine in the repository (liters)
N_D = number of CH drums in the repository (~8×10^{5})
N_A = Avogadro constant (6.022×10^{23} molecules per mole)

The value of G used in this calculation has been set at 0.015, the upper limit of the range of values observed (0.011 to 0.015) during experimental studies of the effects of radiation on WIPP brines (Reed et al. 1993). A maximum estimate of the volume of brine that could potentially be present in the disposal region has been made from its excavated volume of 436,000 m^3 (520,266 yd^3). This estimate, in particular, is considered to be highly conservative because it makes no allowance for creep closure of the excavation, or for the volume of waste and backfill that will be emplaced, and takes no account of factors that may limit brine inflow. These parameter values lead to an estimate of the potential rate of gas production due to the ***Radiolysis of Brine*** of 0.6 moles per drum per year.

Assuming ideal gas behavior and repository conditions of 30°C (86°F) and 14.8 MPa (lithostatic pressure), this is equivalent to approximately 6.8×10^{4} liters (1.8×10^{4} gallons) per year.

Potential gas production rates from other processes that will occur in the repository are significantly greater than this. For example, under water-saturated conditions, microbial degradation of cellulosic waste has the potential to yield between 1.3×10^{6} and 3.8×10^{7} liters (3.4×10^{5} and 1.0×10^{7} gallons) per year; anoxic corrosion of steels has the potential to yield up to 6.3×10^{5} liters (1.6×10^{5} gallons) per year.

In addition to the assessment of the potential rate of gas generation by ***Radiolysis of Brine*** given above, a study of the likely consequences on disposal system performance has been undertaken by Vaughn et al. (1995). A model was implemented in BRAGFLO to estimate radiolytic gas generation in the disposal region according to the equation above.

A set of BRAGFLO simulations was performed to assess the magnitude of the influence of the ***Radiolysis of Brine*** on contaminant migration to the accessible environment. The calculations considered radiolysis of water by 15 isotopes of Th, Pu, U, and Am. Conditional complementary cumulative distribution functions (CCDFs) of normalized contaminated brine releases to the Culebra via a human intrusion borehole and the shaft system, as well as releases to the subsurface boundary of the accessible environment via the Salado interbeds, were constructed and compared to the corresponding baseline CCDFs calculated excluding radiolysis. The comparisons indicated that ***Radiolysis of Brine*** does not significantly affect releases to the Culebra or the subsurface boundary of the accessible environment under disturbed or undisturbed conditions (Vaughn et al. 1995). Although the analysis of Vaughn et al. (1995) used data that are different than those used in the PA calculations, estimates of total gas volumes in the repository are similar to those considered in the analysis performed by Vaughn et al. (1995).

Therefore, gas generation by ***Radiolysis of Brine*** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.7 FEP Number: W53
FEP Title: ***Radiolysis of Cellulose***

SCR-6.5.1.7.1 Screening Decision: SO-C

*Gas generation from **Radiolysis of Cellulose** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.7.2 Summary of New Information

This FEP has been updated with new inventory data related to cellulose content. In addition, the screening argument has been modified by the inclusion of gas generation information from the WIPP transportation program.

SCR-6.5.1.7.3 Screening Argument

Molecke (1979) compared experimental data on gas production rates caused by ***Radiolysis of Cellulose*** and other waste materials with gas generation rates by other processes including bacterial (microbial) waste degradation. The comparative gas generation rates reported by Molecke (1979, p. 4) are given in terms of most probable ranges, using units of moles per year per drum, for drums of 0.21 m^3 (0.27 yd^3) in volume. A most probable range of 0.005 to 0.011 moles per year per drum is reported for gas generation due to radiolysis of cellulosic material (Molecke 1979, p. 4). As a comparison, a most probable range of 0.0 to 5.5 moles per year per drum is reported for gas generation by bacterial degradation of waste.

The data reported by Molecke (1979) are consistent with more recent gas generation investigations made under the WIPP program, and indicate that radiolysis of cellulosic materials

will generate significantly less gas than other gas generation processes. Gas generation from radiolysis of cellulosics therefore can be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Radiolytic gas generation is controlled by the radioactivity of wastes and the waste properties. According to the new *inventory* data, the total radionuclide inventory decreases from 7.44×10^6 (DOE 1996b) to 6.66×10^6 curies (Appendix DATA, Attachment F), about a 10 percent decrease. Interestingly, the radionuclide inventory in the CH-TRU waste, which accounts for the most volume of WIPP wastes, decreases from 6.42×10^6 (DOE 1996b) to 5.33×10^6 curies (Appendix DATA, Attachment F). Such a small change will not affect radiolytic gas generation. However, the new inventory data indicates a 7 percent increase in the density of cellulose in waste materials (Appendix DATA, Attachment F). Because the additional cellulose component is mainly derived from the Advanced Mixed Waste Treatment Plant (AMWTP) wastes, which have relatively low radioactivity, the increase in total cellulose quantity will not significantly affect the prediction of total radiolytic gas generation.

Radiolytic gas generation is also limited by transportation requirements, which state that the hydrogen generated in the innermost layer of confinement must be no more than five percent over 60 days (DOE 2000). Thus, the maximum rate allowed for transportation is 0.201 m^3 per drum × five percent × 1000 L/m^3 per 60 days × 365 days per year = 61 L per drum per year, smaller than the maximum microbial gas generation rate. Note that this estimate is very conservative and the actual rates are even smaller. It is a general consensus within the international research community that the effect of radiolytic gas generation on the long-term performance of a low/intermediate level waste repository is negligible (Rodwell et al. 1999).

SCR-6.5.1.8 FEP Number: W54
FEP Title: ***Helium Gas Production***

SCR-6.5.1.8.1 Screening Decision: SO-C

Gas generation from helium production has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.8.2 Summary of New Information

The updated information for the WIPP disposal inventory indicates that the expected WIPP-scale radionuclide activity (2.48 million curies of TRU isotopes) is less than previously estimated in TWBIR Rev 3 (DOE 1996b). Thus, the ***Helium Gas Production*** argument for CRA-2004 is conservatively bounded by the previous CCA screening argument. The FEP screening argument and screening decision remain unchanged except for editorial changes.

SCR-6.5.1.8.3 Screening Argument

Helium Gas Production will occur by the reduction of α-particles (helium nuclei) emitted from the waste. The maximum amount of helium that could be produced can be calculated from the number α-particles generated during radioactive decay. The α-particles are converted to helium gas by the following reaction:

$$^{4}He^{2+} + 2e^{-} \rightarrow He(g) \tag{15}$$

For the screening argument used in the CCA, the inventory (I) that may be emplaced in the repository is approximately 4.07 million curies or 1.5×10^{17} becquerels (see CCA Appendix BIR). Assuming that the inventory continues to yield α-particles at this rate throughout the 10,000-year regulatory period the maximum rate of helium gas produced (R_{He}) may be calculated from

$$R_{He} = \frac{1\left(\frac{1\ \text{He atom}}{\alpha - \text{decay}}\right)}{N_A} \tag{16}$$

R_{He} is the rate of ***Helium Gas Production*** in the repository (mole per second)

I is the waste inventory, 1.5×10^{17} becquerels, assuming that 1 becquerel is equal to 1 α-decay per second, and N_A is Avogadro constant (6.022×10^{23} atoms per mole). These assumptions regarding the inventory lead to maximum estimates for helium production because some of the radionuclides will decay by beta and gamma emission.

R_{He} is approximately 5.5×10^{-7} moles per second based on an alpha-emitting inventory of 4.07 million curies. Assuming ideal gas behavior and repository conditions of 30°C (86°F) and 14.8 MPa or 146 atm (lithostatic pressure), yields approximately 1.3 liters (0.34 gallons) per year.

Gas production rates by microbial degradation of organic materials and anoxic corrosion of steel are likely to be significantly greater than 1.3 liters per year. For example, anoxic corrosion of steels is estimated to yield 0 to 6.3×10^{5} liters of hydrogen per year (Section 6.4, Appendix PA, Attachment MASS). Even if gas production by ***Microbes*** and corrosion was minimal and helium production dominated gas generation, the effects would be of low consequence because of the low total volume.

The effects of ***Helium Gas Production*** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.9 FEP Number: W55
FEP Title: ***Radioactive Gases***

SCR-6.5.1.9.1 Screening Decision: SO-C

*The formation and transport of **Radioactive Gases** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.1.9.2 Summary of New Information

No new information has become available that affects the screening argument; the FEP screening decision remains unchanged. Additional information has been added to the screening discussions.

SCR-6.5.1.9.3 Screening Argument

Based on the composition of the anticipated waste inventory as described in Appendix DATA, Attachment F, the ***Radioactive Gases*** that will be generated in the repository are radon and carbon-14 labeled CO_2 and methane (CH_4).

Appendix DATA, Attachment F indicates that a small amount of carbon-14, 0.73 grams, or 3.26 curies, will be disposed in the WIPP. This amount is insignificant in comparison with the 40 CFR § 191.13 cumulative release limit for carbon-14.

Notwithstanding this comparison, consideration of transport of ***Radioactive Gases*** could potentially be necessary in respect of the 40 CFR § 191.15 individual protection requirements. carbon-14 may partition into CO_2 and methane formed during microbial degradation of cellulosic and other organic wastes (for example, rubbers and plastics). However, total fugacities of CO_2 in the repository are expected to be very low because of the action of the MgO backfill which will lead to incorporation of CO_2 in solid magnesite. Similarly, interaction of CO_2 with cementitious wastes will limit CO_2 fugacities by the formation of solid calcium carbonate. Thus, because of the formation of solid carbonate phases in the repository, significant transport of carbon-14 as carbon dioxide-14 has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Potentially significant volumes of methane may be produced during the microbial degradation of cellulosic waste. However, volumes of methane-14 will be small given the low total inventory of carbon-14, and the tendency of carbon-14 to be incorporated into solid carbonate phases in the repository. Therefore, although transport of carbon-14 could occur as methane-14, this effect has been eliminated from the current PA calculations on the basis of low consequence to the performance of the disposal system.

Radon gas will contain proportions of the alpha emitters ^{219}Rn, ^{220}Rn, and ^{222}Rn. All of these have short half-lives, but ^{222}Rn is potentially the most important because it is produced from the abundant waste isotope, ^{238}Pu, and because it has the longest half-life of the radon isotopes ($\approx$ 4 days). ^{222}radon will exhibit secular equilibrium with its parent ^{226}Rn, which has a half-life of 1600 years. Consequently, ^{222}Rn will be produced throughout the 10,000-year regulatory time period. Conservative analysis of the potential ^{222}Rn inventory suggests activities of less than 716 curies at 10,000 years (Bennett 1996).

Direct comparison of the estimated level of ^{222}Rn activity with the release limits specified in 40 CFR § 191.13 cannot be made because the release limits do not cover radionuclides with half-lives less than 20 years. For this reason, production of radon gas can be eliminated from the PA calculations on regulatory grounds. Notwithstanding this regulatory argument, the small potential radon inventory means that the formation and transport of radon gas can also be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.2 Speciation

SCR-6.5.2.1 FEP Number: W56
FEP Title: ***Speciation***

SCR-6.5.2.1.1 Screening Decision: UP – Disposal Room
UP – Culebra
SO-C – Beneficial – Shaft Seals

*Chemical **Speciation** is accounted for in PA calculations in the estimates of radionuclide solubility in the disposal rooms, and the degree of chemical retardation estimated during contaminant transport. The effects of cementitious seals on chemical **Speciation** have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-6.5.2.1.2 Summary of New Information

No new information has been identified related to the screening of this FEP. It has been modified for editorial purposes.

SCR-6.5.2.1.3 Screening Argument

Chemical ***Speciation*** refers to the form in which elements occur under a particular set of chemical or environmental conditions. Conditions affecting chemical ***Speciation*** include the temperature, pressure, and salinity (ionic strength) of the water in question. The importance of chemical speciation lies in its control of the geochemical reactions likely to occur and the consequences for actinide mobility.

SCR-6.5.2.1.3.1 *Disposal Room*

The concentrations of radionuclides that dissolve in any brines present in the disposal rooms after repository closure will depend on the stability of the chemical species that form under the prevailing conditions (for example, temperature, pressure, and ionic strength). The method used to derive radionuclide solubilities in the disposal rooms (see Section 6.4.3.5) considers the expected conditions. The MgO backfill will buffer pH values in the disposal room to between 9 and 10. Thus, chemical ***Speciation*** is accounted for in PA calculations in the estimates of radionuclide solubility in the disposal rooms.

SCR-6.5.2.1.3.2 *Repository Seals*

Certain repository materials have the potential to interact with groundwater and significantly alter the chemical ***Speciation*** of any radionuclides present. In particular, extensive use of cementitious materials in the seals may have the capacity to buffer groundwaters to extremely high pH (for example, Bennett et al. 1992, pp. 315 – 325). At high pH values, the ***Speciation*** and adsorption behavior of many radionuclides is such that their dissolved concentrations are reduced in comparison with near-neutral waters. This effect reduces the migration of radionuclides in dissolved form. The effects of cementitious seals on groundwater chemistry

have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.2.1.3.3 *Culebra*

Chemical ***Speciation*** will affect actinide retardation in the Culebra. The dependence of actinide retardation on ***Speciation*** in the Culebra is accounted for in PA calculations by sampling over ranges of distribution coefficients (K_ds). The ranges of K_ds are based on the range of groundwater compositions and ***Speciation*** in the Culebra, including consideration of nonradionuclide solutes. The methodology used to simulate sorption in the Culebra is described in Section 6.4.6.2.1.

SCR-6.5.2.2 FEP Number: W57
FEP Title: ***Kinetics of Speciation***

SCR-6.5.2.2.1 Screening Decision: SO-C

The effects of reaction kinetics in chemical speciation reactions have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.2.2.2 Summary of New Information

No new information that would change the screening argument has arisen since the submission of the CCA. The original screening discussions have been edited for clarity of expression.

SCR-6.5.2.2.3 Screening Argument

Chemical ***Speciation*** of actinides describes the composition and relative distribution of dissolved species, such as the hydrated metal ion, or complexes, whether with organic or inorganic ligands. Conditions affecting chemical ***Speciation*** include temperature, ionic strength, ligand concentration and pH of the solution. Some ligands, such as hydroxide, may act to decrease actinide solubility, while others, such as citrate, frequently have the opposite influence, often increasing actinide solubility.

SCR-6.5.2.2.4 Disposal Room Equilibrium Conditions

The concentrations of radionuclides that can be dissolved in brines within the disposal rooms will depend on the thermodynamic stabilities and solubilities of the respective metal complexes. The Fracture-Matrix Transport (FMT) calculations and database input used to determine the brine solubilities of radionuclides takes into account the expected conditions, including temperature, ionic strength, pH, and ligand concentration. The chemical ***Speciation*** at equilibrium is accounted for in PA calculations in the estimates of radionuclide solubility in the disposal rooms.

SCR-6.5.2.2.5 Kinetics of Complex Formation

The waste that is emplaced within the WIPP contains radionuclides, including actinides or actinide bearing materials in solid phases, e.g. metal oxides, salts, coprecipitated solids, and

contaminated objects. In the event of contact with brine, the solution phase concentration of dissolved radionuclides is controlled both by the solution composition, and by the kinetics of dissolution of the solid phases, effectively approaching equilibrium from undersaturation. Solution complexation reactions of most metal ions with common inorganic ligands, such as carbonate and hydroxide, and with organic ligands such as acetate, citrate, oxalate, and ethylene diamine tetra-acetate (EDTA) are kinetically very fast, reaching equilibrium in fractions of a second, an inconsequentially short time increment on the scale of the 10,000-year regulatory period. Reactions of these types are generally so fast that special techniques must be adopted to measure the reaction rates; as a practical matter, the reaction rate is limited by the mixing rate when metal solutions are combined with ligand solutions. As a result, the rate of approach to an equilibrium distribution of solution species takes place much more rapidly than dissolution, making the dissolution reaction the rate limiting step. The effects of reaction kinetics in aqueous systems are discussed by Lasaga et al. (1994) who suggest that in contrast to many heterogeneous reactions, homogeneous aqueous geochemical ***Speciation*** reactions involving relatively small inorganic species occur rapidly and are accurately described by thermodynamic equilibrium models that neglect explicit consideration of reaction kinetics.

For that reason, the rate at which solution species approach equilibrium distribution is of no consequence to repository performance. ***Kinetics of Chemical Speciation*** may be eliminated from PA calculations on the basis of no consequence.

SCR-6.5.3 Precipitation and Dissolution

SCR-6.5.3.1 FEP Number: W58, W59, and W60
FEP Title: ***Dissolution of Waste*** (W58)
Precipitation of Secondary Minerals (W59)
Kinetics of Precipitation and Dissolution (W60)

SCR-6.5.3.1.1 Screening Decision: UP – W58
SO-C Beneficial – W59
SO-C – W60

Waste dissolution and the release of radionuclides in the disposal rooms are accounted for in PA calculations. The formation of radionuclide bearing precipitates from groundwaters and brines and the associated retardation of contaminants have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The effect of reaction kinetics in controlling the rate of waste dissolution within the disposal rooms has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.3.1.2 Summary of New Information

Precipitation of Secondary Minerals in the disposal room and in geologic units will lead to reductions in nuclide concentrations via the sequestration of radionuclides by coprecipitation and by encapsulation of radionuclide precipitates, and will retard radionuclide transport through sorption. Within the disposal room, metal oxides/oxy-hydroxides will form by corrosion of waste packages and waste components; brucite will form by hydration of MgO backfill;

carbonate minerals will form by carbonation of MgO backfill and cement phases; secondary cement alteration phases will form through brine-cement waste form interactions; and chloride and sulfate minerals will be precipitated due to water uptake during hydration and corrosion reactions. In geologic units above the repository, iron oxides/oxy-hydroxides, carbonates, sulfates may form as groundwaters mix. Mineral precipitation in geologic units above the repository is assumed to be uniform, and in addition to sorbing or sequestering radionuclides, will be beneficial by reducing permeability and slowing the groundwater flow.

During the original WIPP Certification, the EPA questioned the screening argument for ***Kinetics of Precipitation and Dissolution***. The EPA stated in EPA TSD Scope of Performance Assessment regarding ***Kinetics of Precipitation and Dissolution:***

> The screening argument in SCR.2.5.3 appears reasonable to EPA. Initially, EPA thought the argument appeared questionable because the CCA assumed that precipitation reactions are always rapid and complete. As a result, the EPA questioned the gas pressures in the repository, the chemical conditions, and the actinide solubilities. The DOE has since submitted experimental results indicating that the predicted reactions occur and time frames are somewhat rapid. The EPA reconsidered this assessment and concluded that the precipitation assumptions are necessary (and conservative), and are supported by experimental data.

Other than that stated above, no new information that would change the screening argument has arisen since the submission of the CCA. The original text has been edited for clarity of expression.

SCR-6.5.3.1.3 Screening Argument

Dissolution of Waste and ***Precipitation of Secondary Minerals*** control the concentrations of radionuclides in brines and can influence rates of contaminant transport. Waste dissolution is accounted for in PA calculations. The formation of radionuclide-bearing precipitates from groundwaters and brines and the associated retardation of contaminants have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

At low temperatures, precipitation and dissolution reactions are caused by changes in fluid chemistry that result in chemical undersaturation or oversaturation (Bruno and Sandino 1987). Precipitation can be divided into two stages: nucleation and crystal growth. Following nucleation, growth rates depend on the rates of surface processes and the transport of materials to the growth site. Mineral dissolution often depends on whether a surface reaction or transport of material away from the reaction site act as the rate controlling process. The former case may cause selective dissolution along crystallographically controlled features, whereas the latter may induce rapid bulk dissolution (Berner 1981). Thus, a range of kinetic behaviors will be exhibited by different mineral precipitation and dissolution reactions in geochemical systems.

SCR-6.5.3.1.3.1 *Disposal Room*

The waste that is emplaced within the WIPP contains radionuclides, including actinides or actinide-bearing materials in solid phases, e.g. metal oxides, salts, coprecipitated solids, and contaminated objects. In the event of contact with brine, the solution phase concentration of dissolved radionuclides is controlled both by the solution composition, and by the kinetics of

dissolution of the solid phases, effectively approaching equilibrium from undersaturation. Solution complexation reactions of most metal ions with common inorganic ligands, such as carbonated and hydroxide, and with organic ligands such as acetate, citrate, oxalate, and EDTA are kinetically very fast, reaching equilibrium in less than one second, which is infinitesimally small on the time scale of the 10,000 year regulatory period. The rate at which thermodynamic equilibrium is approached between solution composition and the solubility controlling solid phases will be limited by rate of dissolution of the solid materials in the waste. As a result, until equilibrium is reached, the solution concentration of the actinides will be lower than the concentration that is predicted based upon equilibrium of the solution phase components with the solubility limiting solid phases. The WIPP actinide source term model, which describes interactions of the waste and brine, is described in detail in Section 6.4.3.5. The assumption of instantaneous equilibrium in waste dissolution reactions is a conservative approach, yielding maximum concentration estimates for radionuclides in the disposal rooms because a time weighted average resulting from a kinetically accurate estimate of solution compositions would have lower concentrations at early times. Waste dissolution at the thermodynamic equilibrium solubility limit is accounted for in PA calculations. However, the ***Kinetics of Dissolution*** within the disposal rooms has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.3.1.3.2 *Geological Units*

During groundwater flow, radionuclide precipitation processes that occur will lead to reduced contaminant transport. No credit is given in PA calculations to the potentially beneficial occurrence of ***Precipitation of Secondary Minerals***. The formation of radionuclide-bearing precipitates from groundwaters and brines and the associated retardation of contaminants have been eliminated from PA calculations on the basis of beneficial consequence to disposal system performance. As a result ***Kinetics of Precipitation*** also has been eliminated from PA calculations because no credit is taken for precipitation reactions.

SCR-6.5.4 Sorption

SCR-6.5.4.1 FEP Number: W61, W62, and W63
FEP Title: ***Actinide Sorption*** (W61)
Kinetics of Sorption (W62)
Changes in Sorptive Surfaces (W63)

SCR-6.5.4.1.1 Screening Decision: UP – (W61, W62) In the Culebra & Dewey Lake
SO-C – Beneficial – (W61, W61) In the Disposal Room, Shaft Seals, Panel Closures, Other Geologic Units
UP – (W63)

Sorption within the disposal rooms, which would serve to reduce radionuclide concentrations, has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The effects of sorption processes in shaft seals and panel closures have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. Sorption within the Culebra and the Dewey Lake is accounted for in PA calculations. Sorption processes within other geological units of the

disposal system have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. Mobile adsorbents (for example, microbes and humic acids), and the sorption of radionuclides at their surfaces, are accounted for in PA calculations in the estimates of the concentrations of actinides that may be carried. The potential effects of reaction kinetics in adsorption processes and of ***Changes in Sorptive Surfaces*** *are accounted for in PA calculations.*

SCR-6.5.4.1.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.5.4.1.3 Screening Argument

Sorption may be defined as the accumulation of matter at the interface between a solid and an aqueous solution. Within PA calculations, including those made for the WIPP, the use of isotherm representations of ***Actinide Sorption*** prevails because of their computational simplicity in comparison with other models (Serne 1992, pp. 238 – 239).

The mechanisms that control the ***Kinetics of Sorption*** processes are, in general, poorly understood. Often, sorption of inorganic ions on mineral surfaces is a two-step process consisting of a short period (typically minutes) of diffusion-controlled, rapid uptake, followed by slower processes (typically weeks to months) including surface rearrangement, aggregation and precipitation, and solid solution formation (Davis and Kent 1990, 202). Available data concerning rates of sorption reactions involving the important radionuclides indicate that, in general, a range of kinetic behavior is to be expected.

The relevance to the WIPP of sorption reaction kinetics lies in their effects on chemical transport. Sorption of waste contaminants to static surfaces of the disposal system such as seals and host rocks acts to retard chemical transport. Sorption of waste contaminants to potentially mobile surfaces, such as colloids, however, may act to enhance chemical transport, particularly if the kinetics of contaminant desorption are slow or the process is irreversible (nonequilibrium).

The following subsections discuss sorption in the disposal rooms, shaft seals, panel closures, the Culebra, and other geological units of the WIPP disposal system. Sorption on colloids, ***Microbes***, and particulate material is also discussed.

SCR-6.5.4.1.3.1 *Disposal Room*

The concentrations of radionuclides that dissolve in waters entering the disposal room will be controlled by a combination of sorption and dissolution reactions. However, because sorption processes are surface phenomena, the amount of material that is likely to be involved in sorption mass transfer processes will be small relative to that involved in the bulk dissolution of waste. WIPP PA calculations therefore assume that dissolution reactions control radionuclide concentrations. Sorption on waste, containers, and backfill within the disposal rooms, which would serve to reduce radionuclide concentrations, has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.4.1.4 Shaft Seals and Panel Closures

Chapter 3.0 and CCA Appendix SEAL describe the seals that are to be placed at various locations in the access shafts and waste panel access tunnels. The materials to be used include crushed salt, bentonite clay, and cementitious grouts. Of these, the latter two in particular possess significant sorption capacities. No credit is given for the influence of sorption processes that may occur in seal materials and their likely beneficial effects on radionuclide migration rates. The effects of sorption processes in shaft seals and panel closures have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.4.1.4.1 *Culebra*

Sorption within the Culebra is accounted for in PA calculations as discussed in Section 6.4.6.2. The model used comprises an equilibrium, sorption isotherm approximation, employing constructed cumulative distribution functions (CDFs) of distribution coefficients (K_ds) applicable to dolomite in the Culebra. The potential effects of reaction kinetics in adsorption processes are encompassed in the ranges of K_ds used. The geochemical speciation of the Culebra groundwaters and the effects of ***Changes in Sorptive Surfaces*** are implicitly accounted for in PA calculations for the WIPP in the ranges of K_ds used.

SCR-6.5.4.1.4.2 *Other Geological Units*

During groundwater flow, any radionuclide sorption processes that occur between dissolved or colloidal actinides and rock surfaces will lead to reduced rates of contaminant transport. The sorptive capacity of the Dewey Lake is sufficiently large to prevent any radionuclides that enter it from being released to the accessible environment over 10,000 years (Wallace et al. 1995). Thus, sorption within the Dewey Lake is accounted for in PA calculations as discussed in Section 6.4.6.6. No credit is given to the potentially beneficial occurrence of sorption in other geological units outside the Culebra. Sorption processes within other geological units of the disposal system have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.4.1.4.3 *Sorption on Colloids, Microbes, and Particulate Material*

The interactions of sorption processes with colloidal, microbial, or particulate transport are complex. Neglecting sorption of contaminants on immobile surfaces in the repository shafts and Salado (for example, the clays of the Salado interbeds) is a conservative approach because it leads to overestimated transport rates. However, neglecting sorption on potentially mobile adsorbents (for example, microbes and humic acids) cannot be shown to be conservative with respect to potential releases, because mobile adsorbents may act to transport radionuclides sorbed to them. Consequently, the concentrations of actinides that may be carried by mobile adsorbents are accounted for in PA calculations (see Section 6.4.3.6).

SCR-6.5.5 Reduction-Oxidation Chemistry

SCR-6.5.5.1 FEP Number: W64 and W66
FEP Title: ***Effects of Metal Corrosion Reduction-Oxidation Kinetics***

SCR-6.5.5.1.1 Screening Decision: UP

The effects of reduction-oxidation reactions related to metal corrosion on reduction-oxidation conditions are accounted for in PA calculations. Reduction-oxidation reaction kinetics are accounted for in PA calculations.

SCR-6.5.5.1.2 Summary of New Information

No new information has been identified for these FEPs. The screening arguments have not changed. Editorial changes have been made to the discussion.

SCR-6.5.5.1.3 Screening Argument

SCR-6.5.5.1.3.1 *Reduction-Oxidation Kinetics*

In general, investigation of the reduction-oxidation couples present in aqueous geochemical systems suggests that most reduction-oxidation reactions are not in thermodynamic equilibrium (Wolery 1992, 27). The lack of data characterizing the rates of reactions among trace element reduction-oxidation couples leads to uncertainty in elemental speciation. This uncertainty in ***Reduction-Oxidation Kinetics*** is accounted for in PA calculations in the dissolved actinide source term model (see Section 6.4.3.5), which estimates the probabilities that particular actinides occur in certain oxidation states.

SCR-6.5.5.1.3.2 *Corrosion*

Other than gas generation, which is discussed in FEPs W44 through W55, the main ***Effect of Metal Corrosion*** will be to influence the chemical conditions that prevail within the repository. Ferrous metals will be the most abundant metals in the WIPP, and these will corrode on contact with any brines entering the repository. Initially, corrosion will occur under oxic conditions owing to the atmospheric oxygen present in the repository at the time of closure. However, consumption of the available oxygen by corrosion reactions will rapidly lead to anoxic (reducing) conditions. These changes and controls on conditions within the repository will affect the chemical ***Speciation*** of the brines and may affect the oxidation states of the actinides present. Changes to the oxidation states of the actinides will lead to changes in the concentrations that may be mobilized during brine flow. The oxidation states of the actinides are accounted for in PA calculations by the use of parameters that describe probabilities that the actinides exist in particular oxidation states and, as a result, the likely actinide concentrations. Therefore, the ***Effect of Metal Corrosion*** are accounted for in PA calculations.

SCR-6.5.5.2 FEP Number: W65
FEP Title: ***Reduction-Oxidation Fronts***

SCR-6.5.5.2.1 Screening Dec*ision: SO-P*

The migration of ***Reduction-Oxidation Fronts*** *through the repository has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-6.5.5.2.2 Summary of New Information

Large-scale reduction-oxidation fronts have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years. There is no new information that would change the screening decision. Editorial changes have been made to the FEP text to remove reference to other FEP descriptions, screening arguments and screening decisions.

SCR-6.5.5.2.3 Screening Argument

The development of ***Reduction-Oxidation Fronts*** in the disposal system may affect the chemistry and migration of radionuclides. ***Reduction-Oxidation Fronts*** separate regions that may be characterized, in broad terms, as having different oxidation potentials. On either side of a ***Reduction-Oxidation Fronts***, the behavior of reduction-oxidation-sensitive elements may be controlled by different geochemical reactions. Elements that exhibit the greatest range of oxidation states (for example, uranium, neptunium, and plutonium) will be the most affected by ***Reduction-Oxidation Fronts*** development and migration. The migration of ***Reduction-Oxidation Fronts*** may occur as a result of diffusion processes, or in response to groundwater flow, but will be restricted by the occurrence of heterogeneous buffering reactions (for example, mineral dissolution and precipitation reactions). Indeed, these buffering reactions cause the typically sharp, distinct nature of reduction-oxidation fronts.

Of greater significance is the possibility that the flow of fluids having different oxidation potentials from those established within the repository might lead to the development and migration of a large-scale ***Reduction-Oxidation Fronts***. ***Reduction-Oxidation Fronts*** have been observed in natural systems to be the loci for both the mobilization and concentration of radionuclides, such as uranium. For example, during investigations at two uranium deposits at Poços de Caldas, Brazil, uranium was observed by Waber (1991) to be concentrated along ***Reduction-Oxidation Fronts*** at the onset of reducing conditions by its precipitation as uranium oxide. In contrast, studies of the Alligator Rivers uranium deposit in Australia by Snelling (1992) indicated that the movement of the relatively oxidized weathered zone downwards through the primary ore body as the deposit was eroded and gradually exhumed led to the formation of secondary uranyl-silicate minerals and the mobilization of uranium in its more soluble uranium (VI) form in near-surface waters. The geochemical evidence from these sites suggests that the ***Reduction-Oxidation Fronts*** had migrated only slowly, at most on the order of a few tens of meters per million years. These rates of migration were controlled by a range of factors, including the rates of erosion, infiltration of oxidizing waters, geochemical reactions, and diffusion processes.

The migration of large-scale ***Reduction-Oxidation Fronts*** through the repository as a result of regional fluid flow is considered unlikely over the regulatory period on the basis of comparison

with the slow rates of ***Reduction-Oxidation Fronts*** migration suggested by natural system studies. This comparison is considered conservative because the relatively impermeable nature of the Salado suggests that ***Reduction-Oxidation Fronts*** migration rates at the WIPP are likely to be slower than those observed in the more permeable lithologies of the natural systems studied. Large-scale ***Reduction-Oxidation Fronts*** have therefore been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-6.5.5.3 FEP Number: W67
FEP Title: ***Localized Reducing Zones***

SCR-6.5.5.3.1 Screening Decision: SO-C

*The formation of **Localized Reducing Zones** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.5.5.3.2 Summary of New Information

The FEP screening argument has been modified from that presented the CCA to include a more complete description of the description has been updated.

SCR-6.5.5.3.3 Screening Argument

The dominant reduction reactions in the repository include steel corrosion and microbial degradation. The following bounding calculation shows that molecular diffusion alone will be sufficient to mix brine chemistry over a distance of meters and therefore the formation of ***Localized Reducing Zones*** in the repository is of low consequence.

The diffusion of a chemical species in a porous medium can be described by Fick's equation (e.g., Richardson and McSween 1989, p.132):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial X}\left(D_{eff}\ \frac{\partial C}{\partial X}\right) \tag{17}$$

where C is the concentration of the diffusing chemical species; t is the time; X is the distance; and D_{eff} is the effective diffusivity of the chemical species in a given porous medium. D_{eff} is related to the porosity (ϕ) of the medium by (e.g., Oelkers, 1996):

$$D_{eff} = \phi^2 D \tag{18}$$

where D is the diffusivity of the species in pure solution. The D values for most aqueous species at room temperatures fall into a narrow range, and 10^{-5} cm^2 (1.5×10^{-6} in^2) per second is a good approximation (e.g., Richardson and McSween 1989, p.138). From the WIPP PA calculations (Bean et al. 1996, p.7-29; WIPP PA Department, 1993, Equation B-8), the porosity in the WIPP waste panels after room closure is calculated to be 0.4 to 0.7. From Equation (19), the effective diffusivity D_{eff} in the waste is estimated to be $2 \sim 5 \times 10^{-6}$ cm^2 (7×10^{-7} in^2) per second (= $6 \sim 16 \times 10^{-3}$ m^2/year).

Given a time scale of T, the typical diffusion penetration distance (L) can be determined by scaling:

$$L = \sqrt{D_{eff}\,T}\ . \tag{19}$$

Using Equation (20), the diffusion penetration distance in the WIPP can be calculated as a function of diffusion time, as shown in Figure SCR-1.

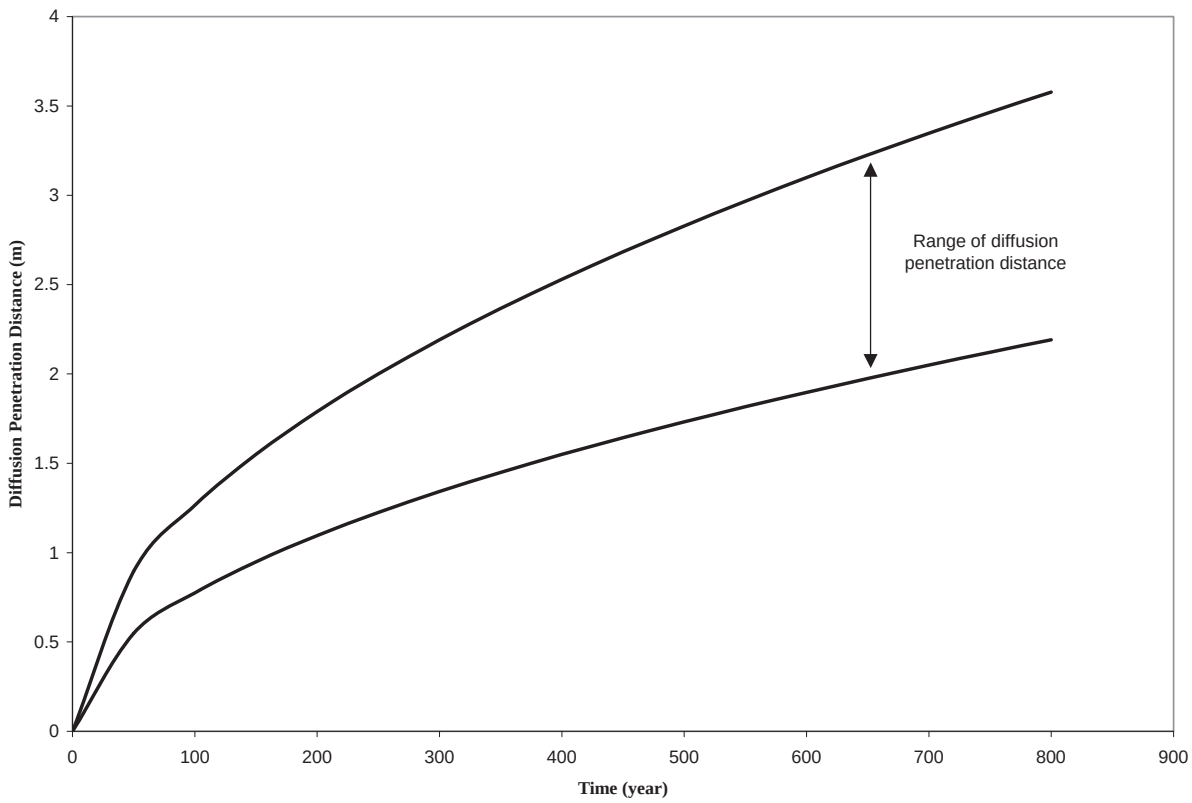

Figure SCR-1. Diffusion Penetration Distance in the WIPP as a Function of Diffusion Time

Direct brine release requires the repository gas pressure to be at least 8 MPA (Stoelzel et al. 1996). The CRA calculations show that it will take at least 100 years for the repository pressure to reach this critical value by gas generation processes. Over this time scale, according to Equation (20) and Figure SCR-1, molecular diffusion alone can mix brine composition effectively at least over a distance of ~ 1 m (3.3 ft).

The above calculation assumes diffusion only through liquid water. This assumption is applicable to steel corrosion, the humid rate of which is zero. Note that microbial reactions can also consume or release gaseous species. The diffusion of a gaseous species is much faster than an aqueous one. Thus, molecular diffusion can homogenize microbial reactions even at a much large scale.

The height of waste stacks in the repository after room closure (h) can be calculated by:

$$h = \frac{h_0 (1 - \phi_0)}{1 - \phi} \tag{20}$$

where h_0 and ϕ_0 are the initial height of waste stacks and the initial porosity of wastes, which are assumed to be 4 m and 0.88, respectively, in the WIPP PA. For ϕ = 0.4 - 0.7, h is estimated to be 0.8 to 1.4 m. This means that molecular diffusion alone can homogenize redox reaction in the vertical dimension of the repository. Therefore, the formation of localized reducing zone is unlikely. The general repository environment will become reducing shortly after room closure, due to metal corrosion and microbial reactions. Therefore, ***Localized Reducing Zones*** can be eliminated from PA calculations on the basis of low consequence to the disposal system.

SCR-6.5.6 Organic Complexation

SCR-6.5.6.1 FEP Number: W68, W69, and W71
FEP Title: ***Organic Complexation*** (W68)
Organic Ligands (W69)
Kinetics of Organic Complexation (W71)

SCR-6.5.6.1.1 Screening Decision: UP W68 and W69
SO-C W71

*The effects of anthropogenic **Organic Complexation** reactions, including the effects of **Organic Ligands**, humic, and fulvic acids, have been incorporated in the PA calculations. The kinetics of organic ligand complexation is screened out because the rate at which **Organic Ligands** are complexed to actinide is so fast that it has no consequence to repository performance.*

SCR-6.5.6.1.2 Summary of New Information

The ***Organic Complexation*** was screened out for the CCA PA, on the basis that transition metals (in particular **iron**, **nickel**, **chromium**, **vanadium**, and **manganese**, present in waste drum steel) would compete effectively with the actinides for the binding sites on the organic ligands, thus preventing significant complexation of actinides organics. Although the CRA-2004 calculations include the effects of ***Organic Ligands*** (acetate, citrate, EDTA, and oxalate) on actinide solubility calculations, based on a revised thermodynamic database, the rate at which ***Organic Ligands*** are complexed to actinides is of no consequence to repository performance. Kinetics of ***Organic Ligands*** complexation may be eliminated from PA calculations on the basis of no consequence.

SCR-6.5.6.1.3 Screening Argument

From a PA standpoint, the most important actinides are Th, U, Np, Pu, and Am. Dissolved thorium, uranium, neptunium, plutonium, and americium will speciate essentially entirely as Th(IV), U(IV) or U(VI), Np(IV) or Np(V), Pu(III) or Pu(IV), and Am(III) under the strongly reducing conditions expected due to the presence of Fe(II) and microbes. (Section SOTERM-33 – SOTERM-36).

Some ***Organic Ligands*** can increase the actinide solubilities. An estimate of the complexing agents in the transuranic solidified waste forms scheduled for disposal in WIPP is presented in Appendix DATA, Attachment F Table DATA-F-3.2-24. Acetate, citrate, oxalate, and EDTA were determined to be the only water-soluble and actinide complexing organic ligands present in significant quantities in the TWBIR. These ligands and their complexation with actinides (Th(IV), U(VI), Np(V), and Am(III)) in a variety of ionic strength media were studied at Florida State University (FSU) (Choppin et al. 2001). The FSU studies showed that acetate, citrate, oxalate, and EDTA are capable of significantly enhancing dissolved actinide concentrations. Lactate behavior was also studied at FSU because it appeared in the preliminary inventory of nonradioactive constituents of the TRU waste to be emplaced in the WIPP (Brush 1990); lactate did not appear in the TWBIR, nor does it appear in the 2003 update to the TWBIR (Appendix DATA, Attachment F).

The solubility of the actinides is calculated using FMT, a computer code for calculating actinide concentration limits based on thermodynamic parameters. The parameters for FMT are derived both from experimental investigations specifically designed to provide parameter values for this model and from the published literature.

- Although the FSU experimental work on ***Organic Ligands*** complexation showed that acetate, citrate, oxalate, and EDTA are capable of significantly enhancing dissolved actinide concentrations, SNL did not include the results in the FMT calculations for the CCA PA because (1) the thermodynamic database for ***Organic Complexation*** of actinides was not considered adequate at the time, and (2) side-calculations using thermodynamic data for low-ionic-strength NaCl solutions showed that transition metals (in particular iron, nickel, chromium, vanadium, and manganese present in waste drum steel) would compete effectively with the actinides for the binding sites on the ***Organic Ligands***, thus preventing significant complexation of actinides organics (Appendix PA, Attachment SOTERM , Sections SOTERM-36 - SOTERM-41).

The CRA-2004 calculations include the effects of organic ligands (acetate, citrate, EDTA, and oxalate) on actinide solubilities in the FMT calculations (Brush and Xiong 2003). The FMT database includes all of the results of experimental studies (Choppin et al. 2001) required to predict the complexation of dissolved An(III), An(IV), and An(V) species by acetate, citrate, EDTA, and oxalate (Giambalvo 2002a, ***2002***b).

Solution complexation reactions of most metal ions with common inorganic ligands, such as carbonate and hydroxide, and with organic ligands, such as acetate, citrate, oxalate, and EDTA, are kinetically very fast, reaching equilibrium in fractions of a second, an inconsequentially short time increment on the scale of the 10,000-year regulatory period. Reactions of these types are generally so fast that special techniques must be adopted to measure the reaction rates; as a practical matter, the reaction rate is limited by the mixing rate when metal solutions are combined with ligand solutions.

For that reason, the rate at which ***Organic Ligands*** are complexed to actinide is of no consequence to repository performance. ***Kinetics of Organic Complexation*** may be eliminated from PA calculations on the basis of no consequence.

SCR-6.5.6.2 FEP Number: W70
FEP Title: ***Humic and Fulvic Acids***

SCR-6.5.6.2.1 Screening Decision: UP

The presence of ***Humic and Fulvic Acids*** *is incorporated in PA calculations.*

SCR-6.5.6.2.2 Summary of New Information

No new information has been identified for this FEP. Editorial changes have been made to the discussion.

SCR-6.5.6.2.3 Screening Argument

The occurrence of ***Humic and Fulvic Acids*** is incorporated in PA calculations in the models for radionuclide transport by humic colloids (see Section 6.4.6.2.2).

SCR-6.5.7 Chemical Effects on Material Properties

SCR-6.5.7.1 FEP Number: W74 and W76
FEP Title: ***Chemical Degradation of Seals*** (W74)
Microbial Growth on Concrete (W76)

SCR-6.5.7.1.1 Screening Decision: UP

The effects of ***Chemical Degradation of Seals*** *and of* ***Microbial Growth on Concrete*** *are accounted for in PA calculations.*

SCR-6.5.7.1.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in DOE (1996a); however the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.5.7.1.3 Screening Argument

The concrete used in the seal systems will degrade due to chemical reaction with the infiltrating groundwater. Degradation could lead to an increase in permeability of the seal system. The main uncertainties with regard to cement degradation rates at the WIPP are the effects of groundwater chemistry, the exact nature of the cementitious phases present, and the rates of brine infiltration. The PA calculations take a conservative approach to these uncertainties by assuming a large increase in permeability of the concrete seals only a few hundred years after closure. These permeability values are based on seal design considerations and consider the potential effects of degradation processes. Therefore, the effects of ***Chemical Degradation of Seals*** are accounted for in PA calculations through the CDFs used for seal material permeabilities.

Concrete can be inhabited by alkalophilic bacteria, which could produce acids, thereby accelerating the seal degradation process. Nitrification processes, which will produce nitric acid, tend to be aerobic, and will be further limited at the WIPP by the low availability of ammonium in the brines (Pedersen and Karlsson 1995, 75). Because of the limitations on growth because of the chemical conditions, it is likely that the effects of ***Microbial Growth on Concrete*** will be small. The effects of such microbial activity on seal properties are, therefore, implicitly accounted for in PA calculations through the CDFs used for seal material permeabilities.

SCR-6.5.7.2 FEP Number: W75
FEP Title: ***Chemical Degradation of Backfill***

SCR-6.5.7.2.1 Screening Decision: SO-C

The effects on material properties of the ***Chemical Degradation of Backfill*** *have been eliminated from PA calculations on the basis of low consequence.*

SCR-6.5.7.2.2 Summary of New Information

As MgO degrades chemically, its physical properties change. Previously, DOE provided a paper by Bynum et al. (1997), which summarizes the experimental results pertaining to chemical degradation of backfill acquired by 1997. The most current MgO data, obtained after the CCA, are summarized in the 2001 MRS Proceedings paper by Snider (2001). The current data show that new MgO will essentially behave as it was designed. Changes have been made to the FEP discussion to reference new experimental results and for editorial purposes.

SCR-6.5.7.2.3 Screening Argument

Degradation of the chemical conditioners or backfill added to the disposal room is a prerequisite of their function in buffering the chemical environment of the disposal room. However, the chemical reactions (Snider 2001) and dissolution involved will change the physical properties of the material. Because the mechanical and hydraulic characteristics of the backfill have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system, the effects of the ***Chemical Degradation of Backfill*** on material properties have been eliminated from PA calculations on the same basis.

SCR-6.6 Contaminant Transport Mode Features, Events, and Processes

SCR-6.6.1 Solute and Colloid Transport

SCR-6.6.1.1 FEP Number: W77
FEP Title: ***Solute Transport***

SCR-6.6.1.1.1 Screening Decision: UP

Transport of dissolved radionuclides is accounted for in PA calculations.

SCR-6.6.1.1.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Sections 6.4.5.4 and 6.4.6.2.1.

SCR-6.6.1.1.3 Screening Argument

Solute Transport may occur by advection, dispersion, and diffusion down chemical potential gradients, and is accounted for in PA calculations (Sections 6.4.5.4 and 6.4.6.2.1).

SCR-6.6.1.2 FEP Number: W78, W79, W80, and W81
FEP Title: ***Colloidal Transport*** (W78)
Colloidal Formation and Stability (W79)
Colloidal Filtration (W80)
Colloidal Sorption (W81)

SCR-6.6.1.2.1 Screening Decision: UP

Formation of colloids, transport of colloidal radionuclides, and colloid retardation through filtration and sorption are accounted for in PA calculations.

SCR-6.6.1.2.2 Summary of New Information

No new information has been identified for these FEPs. Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the CCA, however the screening decision has not changed. Changes in implementation (if any) are described in Sections 6.4.3.6 and 6.4.6.2.2.

SCR-6.6.1.2.3 Screening Argument

Colloids typically have sizes of between 1 nm and 1 μm and may form stable dispersions in groundwaters. ***Colloid Formation and Stability*** depends on their composition and the prevailing chemical conditions (for example, salinity). Depending on their size, ***Colloid Transport*** may occur at different rates than those of fully dissolved species. They may be physically excluded from fine porous media, and their migration may be accelerated through fractured media in channels where velocities are greatest. However, they can also interact with the host rocks during transport and become retarded. These interactions may be of a chemical or physical nature and include electrostatic effects, leading to ***Colloid Sorption,*** and sieving leading to ***Colloid Filtration*** and pore blocking. ***Colloid Formation and Stability*** is accounted for in PA calculations through estimates of colloid numbers in the disposal room based on the prevailing chemical conditions (Section 6.4.3.6). Colloid sorption, filtration, and transport in the Culebra are accounted for in PA calculations (Section 6.4.6.2.2).

SCR-6.6.2 Particle Transport

SCR-6.6.2.1 FEP Number: W82, W83,W84, W85, and W86
FEP Title: ***Suspension of Particles*** (W82)
Rinse (W83)
Cuttings (W84)
Cavings (W85)
Spallings (W86)

SCR-6.6.2.1.1 Screening Decision: DP W82, W84, W85, W86
SO-C W83

The formation of particulates through **Rinse** *and subsequent transport of radionuclides in groundwater and brine has been eliminated from PA calculations for undisturbed conditions on the basis of low consequence to the performance of the disposal system. The transport of radionuclides as particulates (**Cuttings, Cavings**, and **Spallings**) during penetration of the repository by a borehole, is accounted for in PA calculations.*

SCR-6.6.2.1.2 Summary of New Information

Suspensions of Particles larger than colloids are generally unstable and do not persist for very long. The **Rinse** process likely cannot occur under undisturbed conditions because brine flow would not be rapid enough to create a suspension of particles and transport them to the accessible environment. The only reasonable conditions under which suspensions could be formed would be during a drilling event with particles of waste suspended in the drilling fluid are carried to the surface. This effect is covered in PA. Editorial changes have been made to the discussion.

SCR-6.6.2.1.3 Screening Argument

Suspensions of Particles that have sizes larger than colloids are unstable because the particles undergo gravitational settling. It is unlikely that brine flow will be rapid enough within the WIPP disposal rooms to generate particulate suspensions through **Rinse** and transport under undisturbed conditions. Mobilization of suspensions would effect a local and minor redistribution of radionuclides within the room and would not result in increased radionuclide transport from the repository. The formation of particulates through **Rinse** and transport of radionuclides in groundwater and brine has been eliminated from PA calculations for undisturbed conditions on the basis of low consequence to the performance of the disposal system.

Inadvertent human intrusion into the repository by a borehole could result in transport of waste material to the ground surface through drilling-induced flow and blowouts (FEPs H21 and H23). This waste could include material intersected by the drill bit (***Cuttings***), material eroded from the borehole wall by circulating drilling fluid (***Cavings***), and material that enters the borehole as the repository depressurizes (***Spallings***). Transport of radionuclides by these materials and in brine is accounted for in PA calculations and is discussed in Section 6.4.7.1.

SCR-6.6.3 Microbial Transport

SCR-6.6.3.1 FEP Number: W87
FEP Title: ***Microbial Transport***

SCR-6.6.3.1.1 Screening Decision: UP

Transport of radionuclides bound to microbes is accounted for in PA calculations.

SCR-6.6.3.1.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.6.3.1.3 Screening Argument

Microbes will be introduced into the disposal rooms during the operational phase of the repository and will also occur naturally in geological units throughout the disposal system. Because of their colloidal size, microbes, and any radionuclides bound to them, may be transported at different rates than radionuclides in solution. ***Microbial Transport*** of radionuclides is accounted for in PA calculations (Section 6.4.6.2.2).

SCR-6.6.3.2 FEP Number: W88
FEP Title: ***Biofilms***

SCR-6.6.3.2.1 Screening Decision: SO-C Beneficial

*The effects of **Biofilms** on microbial transport have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-6.6.3.2.2 Summary of New Information

The effects of ***Biofilms*** on ***Microbial Transport*** have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The discussion of this FEP has been updated with recent experimental work.

SCR-6.6.3.2.3 Screening Argument

Microbes will be introduced into the disposal rooms during the operational phase of the repository and will also occur naturally in geological units throughout the disposal system.

Biofilms may influence microbial and radionuclide transport rates through their capacity to retain, and therefore retard, both the microbes themselves and radionuclides. The formation of ***Biofilms*** in deep subsurface environments such as in the WIPP is controversial. Since the microbial degradation experiments at Brookhaven National Laboratory (BNL) bracket expected repository conditions, the potential effect of ***Biofilms*** formation on microbial degradation and transport, if any, has been captured in the PA parameters derived from those experiments

(Francis and Gillow 1994; Francis et. al 1997; Francis and Gillow 2000; Gillow and Francis 2001a; Gillow and Francis 2001b; Gillow and Francis 2002a; Gillow and Francis 2002b). As a matter of fact, no apparent formation of stable biofilms was observed in the BNL experiments. The formation of ***Biofilms*** tends to reduce cell suspension and mobility. This effect has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.6.4 Gas Transport

SCR-6.6.4.1 FEP Number: W89
FEP Title: ***Transport of Radioactive Gases***

SCR-6.6.4.1.1 Screening Decision: SO-C

*The **Transport of Radioactive Gases** has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.6.4.1.2 Summary of New Information

This FEP discussion has been updated to include recent inventory information. The screening decision has not changed.

SCR-6.6.4.1.3 Screening Argument

The production and potential ***Transport of Radioactive Gases*** are eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Transportable radioactive gases are comprised mainly of isotopes of radon and carbon-14. Radon gases are eliminated from PA because their inventory is small (<20 Ci; Appendix DATA, Attachment F) and their half-lives are short (<4 days), resulting in insignificant potential for release from the repository. The updated information for the WIPP disposal inventory of carbon-14 (Appendix DATA, Attachment F) indicates that the expected WIPP-scale quantity (3.3 Ci) is 70 percent lower than previously estimated (~13 Ci) in the TWBIR Rev 3 (DOE 1996b). Thus, all CRA-2004 screening arguments for carbon-14 are conservatively bounded by the previous CCA screening arguments.

SCR-6.7 Contaminant Transport Processes

SCR-6.7.1 Advection

SCR-6.7.1.1 FEP Number: W90
FEP Title: ***Advection***

SCR-6.7.1.1.1 Screening Decision: UP

***Advection** of contaminants is accounted for in PA calculations.*

SCR-6.7.1.1.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used in the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.7.1.1.3 Screening Argument

Advection (that is, the transport of dissolved and solid material by flowing fluid) is accounted for in PA calculations (Sections 6.4.5.4 and 6.4.6.2).

SCR-6.7.2 Diffusion

SCR-6.7.2.1 FEP Number: W91 and W92
FEP Title: ***Diffusion*** (W91)
Matrix Diffusion (W92)

SCR-6.7.2.1.1 Screening Decision: UP

Diffusion *of contaminants and retardation by* ***Matrix Diffusion*** *are accounted for in PA calculations.*

SCR-6.7.2.1.2 Summary of New Information

No new information has been identified for this FEP. Since this FEP is accounted for (UP) in PA, the implementation may differ from that used the CCA, although the screening decision has not changed. Changes in implementation (if any) are described in Chapter 6.0.

SCR-6.7.2.1.3 Screening Argument

Diffusion (that is, the movement of molecules or particles both parallel to and transverse to the direction of advection in response to Brownian forces) and, more specifically ***matrix diffusion***, whereby movement is transverse to the direction of advection within a fracture and into the surrounding rock matrix, are accounted for in PA calculations (Section 6.4.6.2).

SCR-6.7.3 Thermochemical Transport Phenomena

SCR-6.7.3.1 FEP Number: W93
FEP Title: ***Soret Effect***

SCR-6.7.3.1.1 Screening Decision: SO-C

The effects of thermochemical transport phenomena (the ***Soret Effect****) have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.7.3.1.2 Summary of New Information

There is no new information available that affects the screening decision; only minor editorial changes have been made to the FEP discussion.

SCR-6.7.3.1.3 Screening Argument

According to Fick's law, the diffusion flux of a solute is proportional to the solute concentration gradient. In the presence of a temperature gradient there will also be a solute flux proportional to the temperature gradient (the ***Soret Effect***). Thus, the total solute flux, J, in a liquid phase may be expressed as

$$J = - DVC - NDVT, \tag{21}$$

where C is the solute concentration, T is the temperature of the liquid, D is the solute diffusion coefficient, and

$$N = S_T C(1-C), \tag{22}$$

in which S_T is the Soret coefficient. The mass conservation equation for solute diffusion in a liquid is then

$$\frac{\partial C}{\partial t} = \nabla \bullet \left(D\nabla C + ND\nabla T\right). \tag{23}$$

When temperature gradients exist in solutions with both light and heavy solute molecules, the heavier molecules tend to concentrate in the colder regions of the solution. Typically, large temperature gradients are required for Soret diffusion to be significant compared to Fickian diffusion.

Radioactive Decay, ***Nuclear Criticality***, and ***Exothermic Reactions*** are three possible sources of heat in the WIPP repository. The DOE (1980) estimated that radioactive decay of CH-TRU waste will result in a maximum temperature rise at the center of the repository of 1.6°C (2.9°F) at 80 years after waste emplacement. Sanchez and Trellue (1996) have shown that the total thermal load of RH-TRU waste will not significantly affect the average temperature increase in the repository. Temperature increases of about 3°C (5.4°F) may occur at the locations of RH-TRU containers with maximum thermal power (60 W). Such temperature increases are likely to be short-lived on the time scale of the 10,000 year regulatory period because of the rapid decay of heat-producing nuclides in RH-TRU waste, such as ^{137}Cs, ^{90}Sr, ^{241}Pu, and ^{147}Pm, whose half-lives are approximately 30, 29, 14, and 3 years, respectively. Soret diffusion generated by such temperature gradients will be negligible compared to other radionuclide transport mechanisms.

Temperature increases resulting from exothermic reactions are discussed in W72. Potentially the most significant exothermic reactions are **Concrete Hydration**, backfill hydration, and **Aluminum Corrosion**. Hydration of the seal concrete could raise the temperature of the concrete to approximately 50°C (122°F) and that of the surrounding salt to approximately 38°C (100°F) one week after seal emplacement.

However, the concrete seals will act as barriers to fluid flow for at least 100 years after emplacement, and seal permeability will be minimized (Wakeley et al. 1995). As a result, short-term temperature increases associated with concrete hydration will not result in significant Soret diffusion through the seal system.

The maximum temperature rise in the disposal panels will be less than 5°C (9°F) as a consequence of backfill hydration. Note that active institutional controls will prevent drilling within the controlled area for 100 years after disposal. Heat generation by radioactive decay and concrete seal hydration will have decreased substantially after 100 years, and the temperatures in the disposal panels will have decreased nearly to the temperature of the undisturbed host rock.

If the repository were to be inundated following a drilling intrusion, aluminum corrosion could, at most, result in a short-lived (two years) temperature increase of about 6°C (10.8°F). These calculated maximum heat generation rates resulting from aluminum corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability; each calculation assumes that all available brine is consumed by the reaction of concern. Thus, the temperature rise of 6°C (10.8°F) represents the maximum that could occur as a result of a combination of exothermic reactions occurring simultaneously. Temperature increases of this magnitude will not result in significant Soret diffusion within the disposal system.

The limited magnitude and spatial scale of temperature gradients in the disposal system indicate that Soret diffusion will be insignificant, allowing the effects of thermochemical transport (***Soret Effect***) to be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.4 Electrochemical Transport Phenomena

SCR-6.7.4.1 FEP Number: W94
FEP Title: ***Electrochemical Effects***

SCR-6.7.4.1.1 Screening Decision: SO-C

The effects of electrochemical transport phenomena caused by electrochemical reactions have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.4.1.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.4.1.3 Screening Argument

The variety of waste metals and metal packaging in the repository may allow galvanic cells spanning short distances to be established. The interactions among the metals depend upon their physical characteristics and the chemical conditions in the repository. For example, good physical and electrical contact, which is critical to the establishment of galvanic cells, may be impeded by electrically nonconductive waste materials. Additionally, in order to establish a galvanic cell, it is necessary that the metals have different values for standard reduction potentials. For example, a galvanic cell is not expected to be formed by contact of two segments of metals with identical compositions. As a result, galvanic cells can only be established by contact of dissimilar metals, as might happen due to contact between a waste drum and the contents, or between contents within a waste package. The localized nature of electrochemical

transport is restricted to the size scale over which galvanic cells can develop, i.e., on the order of size of waste packages. Since the possible range of transport is restricted by the physical extent of galvanic activity, ***Electrochemical Effects*** cannot act as long-range transport mechanisms for radionuclides and therefore are of no consequence to the performance of the repository.

SCR-6.7.4.2 FEP Number: W95
FEP Title: ***Galvanic Coupling***

SCR-6.7.4.2.1 Screening Decision: SO-P

*The effects of **Galvanic Coupling** between the waste and metals external to the repository on transport have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.*

SCR-6.7.4.2.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.4.2.3 Screening Argument

With regard to the WIPP, ***Galvanic Coupling*** refers to the establishment of galvanic cells between metals in the waste form, canisters, and other metals external to the waste form.

Long range electric potential gradients may exist in the subsurface as a result of groundwater flow and electrochemical reactions. The development of electric potential gradients may be associated with the weathering of sulfide ore bodies, variations in rock properties at geological contacts, bioelectric activity associated with organic matter, natural corrosion reactions, and temperature gradients in groundwater. With the exception of mineralization potentials associated with metal sulfide ores, the magnitude of electric potentials is usually less than about 100 millivolts and the potentials tend to average to zero over distances of several thousand feet (Telford et al. 1976). Metals external to the waste form can include natural metallic ore bodies in the host rock. However, metallic ore bodies and metallic sulfide ores do not exist in the region of the repository (CCA Appendix GCR). As a result, galvanic coupling between the waste and metallic materials outside the repository cannot occur. Therefore, ***Galvanic Coupling*** is eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-6.7.4.3 FEP Number: W96
FEP Title: ***Electrophoresis***

SCR-6.7.4.3.1 Screening Decision: SO-C

*The effects of electrochemical transport phenomena caused by **Electrophoresis** have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.*

SCR-6.7.4.3.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.4.3.3 Screening Argument

Long range (in terms of distance) electric potential gradients may exist in the subsurface as a result of groundwater flow and electrochemical reactions. The development of potentials may be associated with the weathering of sulfide ore bodies, variations in rock properties at geological contacts, bioelectric activity associated with organic matter, natural corrosion reactions, and temperature gradients in groundwater. With the exception of mineralization potentials associated with metal sulfide ores, the magnitude of such potentials is usually less than about 100 millivolts and the potentials tend to average to zero over distances of several thousand feet (Telford et al. 1976, p. 458). Short range potential gradients due to corrosion of metals within the waste may be set up over distances that are restricted to the size scale of the waste packages.

A variety of metals will be present within the repository as waste metals and metal packaging, which may allow electrochemical cells to be established over short distances. The types of interactions that will occur depend on the metals involved, their physical characteristics, and the prevailing solution conditions. Electrochemical cells that may be established will be small relative to the size of the repository, limiting the extent to which migration of contaminants by ***Electrophoresis*** can occur. The electric field gradients will be of small magnitude and confined to regions of electrochemical activity in the area immediately surrounding the waste material. As a result, ***Electrophoretic Effects*** on migration behavior due to both long and short range potential gradients have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.5 Physiochemical Transport Phenomena

SCR-6.7.5.1 FEP Number: W97
FEP Title: ***Chemical Gradients***

SCR-6.7.5.1.1 Screening Decision: SO-C

*The effects of enhanced diffusion across **Chemical Gradients** have been eliminated from PAs on the basis of low consequence to the performance of the disposal system.*

SCR-6.7.5.1.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.5.1.3 Screening Argument

Chemical Gradients within the disposal system, whether induced naturally or resulting from repository material and waste emplacement, may influence the transport of contaminants. Gradients will exist at interfaces between different repository materials and between repository

and geological materials. Distinct chemical regimes will be established within concrete seals and adjoining host rocks. Similarly, ***Chemical Gradients*** will exist between the waste and the surrounding rocks of the Salado. Other ***Chemical Gradients*** may exist due to the juxtaposition of relatively dilute groundwaters and brines or between groundwaters with different compositions. Natural gradients currently exist between different groundwaters in the Culebra.

Enhanced diffusion is a possible consequence of ***Chemical Gradients*** that occur at material boundaries. However, the distances over which enhanced diffusion could occur will be small in comparison to the size of the disposal system. Processes that may be induced by ***Chemical Gradients*** at material boundaries include the formation or destabilization of colloids. For example, cementitious materials that will be emplaced in the WIPP as part of the waste and the seals contain colloidal-sized materials, such as calcium-silicate-hydrate gels, and alkaline pore fluids. ***Chemical Gradients*** will exist between the pore fluids in the cementitious materials and the less alkaline surroundings. Chemical interactions at these interfaces may lead to the generation of colloids of the inorganic, mineral fragment type. Colloidal compositions may include calcium and magnesium oxides, calcium hydroxide, calcium-aluminum silicates, calcium-silicate-hydrate gels, and silica. Experimental investigations of the stability of inorganic, mineral fragment colloidal dispersions have been carried out as part of the WIPP colloid-facilitated actinide transport program (Papenguth and Behl 1996). Results of the investigations indicate that the salinities of the WIPP brines are sufficient to cause destabilization of mineral fragment colloidal dispersions. Therefore, concentrations of colloidal suspensions originating from concrete within the repository are expected to be extremely low, and are considered in PA calculations.

SCR-6.7.5.2 FEP Number: W98
FEP Title: ***Osmotic Processes***

SCR-6.7.5.2.1 Screening Decision: SO-C

*The effects of **Osmotic Processes** have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.*

SCR-6.7.5.2.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.5.2.3 Screening Argument

Osmotic Processes, i.e., diffusion of water through a semi permeable or differentially permeable membrane in response to a concentration gradient, may occur at interfaces between waters of different salinities. ***Osmotic Processes*** can occur if waters of different salinities and/or compositions exist on either side of a particular lithology such as clay, or a lithological boundary that behaves as a semipermeable membrane. At the WIPP, clay layers within the Salado may act as semi permeable membranes across which ***Osmotic Processes*** may occur.

In the absence of a semipermeable membrane, water will move from the more dilute water into the more saline water. However, the migration of dissolved contaminants across an interface

may be restricted depending upon the nature of the membrane. A hydrological gradient across a semi permeable membrane may either enhance or oppose water movement by osmosis depending on the direction and magnitude of the gradient. Dissolved contaminants that cannot pass through a semi-permeable membrane may be moved towards the membrane and concentrated along the interface when advection dominates over osmosis and reverse osmosis occurs. Thus, both osmosis and reverse osmosis can restrict the migration of dissolved contaminants and possibly lead to concentration along interfaces between different water bodies. The effects of ***Osmotic Processes*** have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.7.5.3 FEP Number: W99
FEP Title: ***Alpha Recoil***

SCR-6.7.5.3.1 Screening Decision: SO-C

*The effects of **Alpha-Recoil Processes** on radionuclide transport have been eliminated from PA calculations on the basis of low consequence to performance of the disposal system.*

SCR-6.7.5.3.2 Summary of New Information

No new information relating to this FEP has been identified. The FEPs discussion has been modified for editorial purposes.

SCR-6.7.5.3.3 Screening Argument

Alpha particles are emitted with sufficiently high energies that daughter nuclides recoil appreciably to conserve system momentum. For example, ^{238}U decays to ^{234}Th with emission of a 4.1 MeV alpha particle. The law of conservation of momentum requires that the daughter nuclide, ^{234}Th, recoils in the opposite direction with an energy of approximately 0.07 MeV. The energy is great enough to break chemical bonds or cause ^{234}Th to move a short distance through a crystal lattice. If the ^{234}Th is close enough to the surface of the crystal, it will be ejected into the surroundings. ^{234}Th decays to ^{234}Pa which decays to ^{234}U with respective half-lives of 24.1 days and 1.17 minutes. The recoil and decay processes can lead to the apparent preferential dissolution or leaching of ^{234}U relative to ^{238}U from crystal structures and amorphous or adsorbed phases. Preferential leaching may be enhanced due to radiation damage to the host phase resulting from earlier radioactive decay events. Consequently, ^{234}U sometimes exhibits enhanced transport behavior relative to ^{238}U.

The influence of ***Alpha-Recoil*** processes on radionuclide transport through natural geologic media is dependent on many site-specific factors, such as mineralogy, geometry, and microstructure of the rocks, as well as geometrical constraints on the type of groundwater flow, e.g., porous or fracture flow. Studies of natural radionuclide-bearing groundwater systems often fail to discern a measurable effect of alpha-recoil processes on radionuclide transport above the background uncertainty introduced by the spatial heterogeneity of the geological system. Consequently, the effects of the ***Alpha-Recoil*** processes that occur on radionuclide transport are thought to be minor. These effects have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.5.4 FEP Number: W100
FEP Title: ***Enhanced Diffusion***

SCR-6.7.5.4.1 Screening Decision: SO-C

Enhanced Diffusion *is a possible consequence of* ***Chemical Gradients*** *that occur at material boundaries. However, the distances over which* ***Enhanced Diffusion*** *could occur will be small in comparison to the size of the disposal system. Therefore, the effects of* ***Enhanced Diffusion*** *across* ***Chemical Gradients*** *at material boundaries have been eliminated from PAs on the basis of low consequence to the performance of the disposal system.*

SCR-6.7.5.4.2 Summary of New Information

Enhanced *Diffusion* only occurs where there are higher than average chemical gradients. The spatial extent of chemical gradients should be quite limited and as enhanced diffusion occurs, it will tend to reduce the chemical gradient. Thus, the driving force for the enhanced diffusion will be reduced and eventually eliminated as the system approaches steady state or equilibrium conditions. Due to the limited spatial extent of enhanced diffusion, its effect on radionuclide transport should be small.

The effects of ***Enhanced Diffusion*** across ***Chemical Gradients*** at material boundaries have been eliminated from PAs on the basis of low consequence to the performance of the disposal system. Changes have been made to the FEP discussion for clarity and editorial purposes.

SCR-6.7.5.4.3 Screening Argument

Processes that may be induced by ***Chemical Gradients*** at material boundaries include the formation or destabilization of colloids. For example, cementitious materials, emplaced in the WIPP as part of the waste and the seals, contain colloidal-sized phases such as calcium-silicate-hydrate gels, and alkaline pore fluids. ***Chemical Gradients*** will exist between the pore fluids in the cementitious materials and the less alkaline surroundings. Chemical interactions at these interfaces may lead to the generation of colloids of the inorganic, mineral fragment type. Colloidal compositions may include calcium and MgOr, calcium hydroxide, calcium-aluminum silicates, calcium-silicate-hydrate gels, and silica. Concentrations of colloidal suspensions originating from concrete within the repository are considered in PA calculations even though expected to be extremely low.

Distinct interfaces between waters of different salinities and different densities may limit mixing of the water bodies and affect flow and contaminant transport. Such effects have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.8 Ecological Features, Events, and Processes

SCR-6.8.1 Plant, Animal, and Soil Uptake

SCR-6.8.1.1 FEP Number: W101, W102, and W103
FEP Title: ***Plant Uptake*** (W101)

Animal Uptake (W102)
Accumulation in Soils (W103)

SCR-6.8.1.1.1 Screening Decision: SO-R
SO-C for 40 CFR 191.15

Plant Uptake, Animal Uptake*, and* ***Accumulation in Soils*** *have been eliminated from compliance assessment calculations for 40 CFR § 191.15 on the basis of low consequence.* ***Plant Uptake*** *and* ***Animal Uptake*** *in the accessible environment have been eliminated from PA calculations for 40 CFR § 191.13 on regulatory grounds.* ***Accumulation in Soils*** *within the controlled area has been eliminated from PA calculations for 40 CFR § 191.13 on the basis of beneficial consequences.*

SCR-6.8.1.1.2 Summary of New Information

DOE has stated that FEPs related to ***Plant Uptake, Animal Uptake***, and ***Accumulation in Soils*** have been eliminated from the compliance assessment calculations on the basis of low consequence. DOE indicated that the screening of these FEPs is justified based upon the results of PA calculations, which show that releases to the accessible environment under undisturbed conditions are restricted to lateral migration through anhydrite beds within the Salado Formation. PAs for evaluating compliance with the EPA's cumulative release requirements in 40 CFR § 191.13 need not consider radionuclide migration in the accessible environment. Therefore, FEPs that relate to ***Plant Uptake*** and ***Animal Uptake*** in the accessible environment have been eliminated from PA calculations on regulatory grounds.

SCR-6.8.1.1.3 Screening Argument

The results of the calculations presented in Section 6.5 show that releases to the accessible environment under undisturbed conditions are restricted to lateral releases through the DRZ at repository depth. Thus, for evaluating compliance with the EPA's individual protection requirements in 40 CFR § 191.15, FEPs that relate to ***Plant Uptake***, ***Animal Uptake***, and ***Accumulation in Soils*** have been eliminated from compliance assessment calculations on the basis of low consequence.

Performance assessments for evaluating compliance with the EPA's cumulative release requirements in 40 CFR § 191.13 need not consider radionuclide migration in the accessible environment. Therefore, FEPs that relate to ***plant uptake*** and ***animal uptake*** in the accessible environment have been eliminated from PA calculations on regulatory grounds. ***Accumulation in Soils*** that may occur within the controlled area would reduce releases to the accessible environment and can, therefore, be eliminated from PA calculations on the basis of beneficial consequence.

SCR-6.8.2 Human Uptake

SCR-6.8.2.1 FEP Number(s): W104, W105, W106, W107, and W108
FEP Title(s): ***Ingestion*** (W104)
Inhalation (W105)
Irradiation (W106)

Dermal Sorption (W107)
Injection (W108)

SCR-6.8.2.1.1 Screening Decision: SO-R
SO-C for 40 CFR § 191.15

Ingestion, Inhalation, Irradiation, Dermal Sorption*, and* ***Injection*** *have been eliminated from compliance assessment calculations for 40 CFR § 191.15 and Subpart C of 40 CFR Part 191 on the basis of low consequence. FEPs that relate to human uptake in the accessible environment have been eliminated from PA calculations for 40 CFR § 191.13 on regulatory grounds.*

SCR-6.8.2.1.2 Summary of New Information

The DOE stated in the CCA that the results of the PA calculations indicate that releases to the accessible environment under undisturbed conditions are restricted to lateral migration through anhydrite beds within the Salado Formation. The DOE further stated that based upon the bounding approach taken for evaluating compliance with EPA's individual protection requirements in 40 CFR § 191.15 and the groundwater protection requirements in Subpart C of 40 CFR § 191, these abovementioned exposure pathways were found to be of low consequence. However, the analysis did not include analysis of doses from other potential exposure pathways such as stock consumption or irrigation. These weaknesses were remedied by DOE's submittal of a more detailed dose analysis, which included all of the appropriate additional pathways (DOE 1997c).

In both the PAVT and the CCA calculations (DOE 1997a, 1997b, 1997c) a very conservative bounding-analysis approach was used to estimate potential doses. Using this approach, the calculated maximum potential dose (millirems) to any internal organ due to beta particle and photon radioactivity from man-made radionuclides in drinking water was 2.9×10^{-4} in the PAVT and 4.2×10^{-3} for the CCA. Further, the annual effective dose equivalent to the total body due to beta particle and photon radioactivity is 1.5×10^{-5} in the CCA and 2.3×10^{-4} for the CCA. All of these values are well below the acceptable standard of 4 millirems per year as specified in 40 CFR § 141.16(a). Finally, the calculated maximum potential doses (millirems) to an individual due to meat consumption, vegetable consumption, and inhalation of resuspended irrigated soil are 2.7×10^{-7}, 0.031, and 2.1×10^{-5}, respectively, in the PAVT and 3.3×10^{-8}, 0.46, 3.1×10^{-4}, respectively, in the CCA. All of these values are well below the individual protection standard, an annual committed effective dose of 15 millirems as specified in 40 CFR § 191.15(a). Therefore, the original screening decisions remain valid, and no changes have been made to the FEP screening arguments or decisions.

SCR-6.8.2.1.3 Screening Argument

As described in Section 8.1.1, releases to the accessible environment under undisturbed conditions are restricted to lateral migration through anhydrite interbeds within the Salado. Because of the bounding approach taken for evaluating compliance with the EPA's individual protection requirements in 40 CFR § 191.15 and the groundwater protection requirements in Subpart C of 40 CFR Part 191 (see Sections 8.1.2.2 and 8.2.3), FEPs that relate to human uptake

by ***Ingestion, Inhalation, Irradiation, Dermal Sorption,*** and ***Injection*** have been eliminated from compliance assessment calculations on the basis of low consequence.

Performance assessments for evaluating compliance with the EPA's cumulative release requirements in 40 CFR § 191.13 need not consider radionuclide migration in the accessible environment. Therefore, FEPs that relate to human uptake in the accessible environment have been eliminated from PA calculations on regulatory grounds.

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Appendix PA

Attachment SOTERM

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ACRONYMS AND ABBREVIATIONS

An	actinide(s)
atm	atmosphere (a unit of pressure)
aq	aqueous
ASTP	Actinide Source Term Program
BNL	Brookhaven National Laboratory
brucite	$Mg(OH)_2$
calcite	$CaCO_3$
CFR	Code of Federal Regulations
CPR	cellulosics, plastics, and rubber
DOE	(U.S.) Department of Energy
DRZ	disturbed rock zone
EDTA	ethylenediaminetetra acetate
EPA	(U.S.) Environmental Protection Agency
eq	equivalent(s)
ERDA	(U.S.) Energy Research and Development Administration
FA-Suw	fulvic acid isolated from the Suwannee River acquired from the International Humic Substances Society, Golden, Colorado
FMT	Fracture-Matrix Transport
f_{CO_2}	the fugacity of a gaseous species, f_i (similar to the partial pressures of that species, p_i)
g	gaseous or gram(s)
gal	gallon(s)
GWB	Generic Weep Brine
HAal-Ald	aliphatic humic acid purchased from Aldrich Chemical Co., purified by Florida State University
HAal-LBr	aliphatic humic acid isolated from sediments collected from Lake Bradford, Florida, prepared by Florida State University
HAar-Gor	aromatic humic acid isolated from groundwaters near Gorleben, Germany, obtained from Professor J.-I. Kim, Institut für Radiochemie, München
HAar-Suw	aromatic humic acid isolated from the Suwannee River acquired from the International Humic Substances Society, Golden, Colorado
HMW/FW	Harvie-Møller-Weare/Felmy and Weare
hydromagnesite	$Mg_4(CO_3)_3(OH)_2{\cdot}3H_2O$ or $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$
L	Liter(s)
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
m	molal
M	molar
meq	milliequivalent(s)
mL	milliliter(s)
mol	mole(s)
PA	performance assessment
periclase	MgO
pH	the negative logarithm of the activity of hydrogen ion (H^+)

redox	oxidation-reduction
s	second
SIT	Specific-Ion Interaction Theory
SPC	Salado Primary Constituent
STTP	(WIPP) Actinide Source Term Waste Test Program
SWCF	Sandia National Laboratories WIPP Central File
TRU	transuranic
TWBIR	Transuranic Waste Baseline Inventory Report
UV	ultraviolet
WIPP	Waste Isolation Pilot Plant

SOTERM-1.0 INTRODUCTION

The actinide source term used in the performance assessment (PA) calculations for the Waste Isolation Pilot Plant (WIPP) represents the aqueous concentrations of thorium (Th), uranium (U), plutonium (Pu), and americium (Am) in the repository. The source term is the sum of the dissolved species (solubilities) and the mobile suspended (colloidal) species of these radioelements. The actinide source term establishes the mobile concentrations of Th, U, Pu, and Am that may be released from the repository in brine. Brine releases to the accessible environment may occur through the sealed shafts, up possible intrusion boreholes, and/or out laterally through Salado Formation interbeds. (For a discussion of release scenarios and pathways, see Chapter 6.0, Section 6.3). Quantification of the impact of these releases contributes directly to assessing compliance with Title 40 Code of Federal Regulations (CFR) Part 191. Direct releases of particulate actinides to the surface associated with solid waste resulting from drilling (cuttings, cavings, and spallings) are not included in the actinide source term.

The actinide source term is limited to those radionuclides that could significantly impact the long-term performance of the WIPP. These radionuclides are all isotopes of Th, U, Pu, and Am. From the standpoint of their potential effects on the long-term performance of the repository, the order of importance of these actinides is Pu ≈ Am >> U > Th (Helton et al. 1998). Other actinides, especially neptunium (Np), have been included in the laboratory and modeling studies used to develop the actinide source term because it was not known at the outset which actinides could significantly affect the long-term performance of the repository. Other radioelements, such as strontium (Sr), cesium (Cs), and radium (Ra), are not included in the actinide source term because of their relatively short half-lives or limited waste inventory.

Attachment SOTERM (SOurce TERM) focuses on the development of actinide-source-term parameter values and the implementation of these parameters in PA calculations. In Section 2.0, an overview of near-field chemical processes and conditions is presented. Sections 3.0 and 4.0 focus on the development of the dissolved-actinide solubility parameters and oxidation-state distribution, respectively. Section 5.0 focuses on the impact of organic ligands on dissolved actinide concentrations. The colloidal actinide source term is described in Section 6.0. In Section 7.0 the PA implementation of the dissolved and colloidal components of the source term is described.

This attachment is a supplement to information presented in Chapter 6, Sections 6.4.3.3, 6.4.3.4, 6.4.3.5, and 6.4.3.6 of this application.

SOTERM-2.0 OVERVIEW OF NEAR-FIELD PROCESSES AND CONDITIONS

This section presents an overview of near-field processes and conditions that will affect actinide solubilities in the WIPP. Ambient geochemical conditions are described first. The effects of human intrusion and waste are then described. Emphasis is placed on how various components and processes within the repository will affect the dissolution and colloidal suspension of actinides. Excess magnesium oxide (MgO) will be added to the repository for assurance

purposes, so the effect of MgO is included in this discussion. Simplifications and assumptions used to model the components and processes are discussed in each section.

SOTERM-2.1 Ambient Geochemical Conditions

The Salado is predominantly nearly pure halite (NaCl), with interbeds ("marker beds") consisting mainly of anhydrite ($CaSO_4$). The nearly pure halite contains accessory evaporite minerals such as anhydrite ($CaSo_4$), gypsum ($CaSO_4 \bullet 2H_2O$), polyhalite ($K_2MgCa_2(SO_4)_4 \bullet 2H_2O$), magnesite ($MgCO_3$), and clays. Small quantities of intergranular (grain-boundary) brines and intragranular brines (fluid inclusions) are associated with the salt at the repository horizon. These brines are highly concentrated solutions (up to 8 M) of predominantly sodium (Na^+), Mg^{2+}, potassium (K^+), chloride (Cl^-), and sulfate (SO_4^{2-}) with smaller amounts of Ca^{2+}, CO_3^{2-}, and B. These brines have been in contact with the Salado evaporite minerals for about 250 million years and are saturated with respect to these minerals.

Underlying the Salado is the Castile Formation, composed of alternating units of interlaminated carbonate and anhydrite, and nearly pure halite. The Castile in the vicinity of the WIPP site is known to contain localized brine reservoirs under sufficient pressure to force brine to the land surface if penetrated by a borehole. Castile brines are predominantly saturated NaCl solutions containing Ca^{2+} and SO_4^{2-}, and small concentrations of other elements, and are about eight times more concentrated than seawater. Overlying the Salado in the vicinity of the WIPP site is the Culebra Member of the Rustler Formation, a fractured dolomite ($CaMg(CO_3)_2$) layer. It is significant because it is expected to be the most transmissive geologic pathway to the accessible environment. Culebra brines are generally more dilute than the Salado and Castile brines, and are predominantly NaCl with K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, and CO_3^{2-}. (See Chapter 2.0, Section 2.4.2.1 of this application for information on the distribution of Culebra brine salinity.)

SOTERM-2.2 Repository Chemical Conditions

Three aspects of the repository chemical environment can have a major impact on the dissolution and colloidal suspension of actinides. These are:

- brine composition;
- microbial consumption of cellulosic, plastic, and rubber (CPR) materials and concomitant production of carbon dioxide (CO_2); and
- anoxic corrosion of steels and other iron-base (Fe-base) alloys in the waste containers and the waste and concomitant production of hydrogen (H_2).

For each of these, the effect, the range of possible behavior, and the simplifications used in modeling are discussed below.

SOTERM-2.2.1 Brine

The compositions of brines required for mobilization of actinides will affect the quantities of actinidies that may be dissolved or suspended. For example, high-ionic-strength brines have

been shown to increase the solubilities of actinides and to increase the coagulation and settling rate of mineral-fragment colloids.

In human-intrusion scenarios, Salado and/or Castile brine will enter the repository, depending on whether the intrusion penetrates a brine reservoir in the Castile. However, in addition to Salado and Castile brines, brines from the Rustler and Dewey Lake Formation could flow down the borehole to the repository, mix with the waste, and then be forced back up a borehole. Rustler and Dewey-Lake brines are considerably less concentrated than Salado and Castile brines. If the Rustler and Dewey-Lake brines flow into the repository, they would dissolve Salado halite until they attain compositions between those of Salado and Castile brines (see Section 7.1.2). Under any intrusion scenario, therefore, the brine dissolving actinides would have the composition of Salado, Castile, or a mixture of Salado and Castile brines.

The Salado and Castile brine compositions bracket the range of possibilities within the repository, so experimental and modeling studies of repository and actinide chemistry have been performed using the end-member brines only. Inclusion of brine mixing in PA has been considered and rejected because it would not be sufficiently accurate to reduce the uncertainty associated with brine mixing and related brine chemistry compared to bracketing this uncertainty with end-member brines. Brine mixing is addressed in Section 7.1.2.

The two synthetic solutions that best represent the end-member brines that could be present in the repository are: (1) Generic Weep Brine (GWB), which simulates intergranular (grain-boundary) brines from the Salado at or near the stratigraphic horizon of the repository (Snider 2003a); and (2) Energy Research and Development Administration-6 (ERDA-6), typical of fluids in Castile brine reservoirs (Popielak et al. 1983). Through the time of the CCA, Brine A (Molecke 1983) and Salado Primary Constituents (SPC) Brine, a version of Brine A from which trace elements had been removed, were used to simulate Salado brines for laboratory and modeling studies. Since the CCA, however, GWB has been shown to be more representative of intergranular Salado brines than either Brine A or SPC Brine (Brush and Xiong 2003a; Snider 2003a). In particular, the Mg^{2+} concentration of GWB (1.0 M) simulates the average concentration of this element in Salado brines more closely than Brine A (1.44 M). Table SOTERM-1 provides the compositions of GWB and ERDA-6.

In addition to using the end-member brines, other simplifying assumptions have been made, including the following:

- Any brine present in the repository is well-mixed with waste.
- Equilibria with halite and anhydrite, the most abundant Salado minerals at or near the stratigraphic horizon of the repository, are established. Oxidation-reduction (redox) equilibria with waste materials have not been assumed.
- For modeling purposes, brine compositions attained after equilibration of GWB or ERDA-6 with the MgO engineered barrier are assumed for the entire 10,000-year regulatory period.

Table SOTERM-1. Compositions of GWB and ERDA-6 Prior to Equilibration with MgO

Element or Property	GWB[2]	ERDA-6[3]
$B(OH)_3$	155 mM	63 mM
Na^+	3.48 M	4.87 M
Mg^{2+}	1.00 M	19 mM
K^+	458 mM	97 mM
Ca^{2+}	14 mM	12 mM
SO_4^{2-}	175 mM	170 mM
Cl^-	5.51 M	4.8 M
Br^-	26 mM	11 mM
Total inorganic C (as HCO_3^-)	Not reported	16 mM
pH	Not reported	6.17
Specific gravity	1.2	1.216
TDS	Not reported	330,000 mg/l

[1] From Molecke (1983).
[2] From Snider (2003a).
[3] From Popielak et al. (1983).
[4] Reported by Molecke (1983) as BO_3^{3-}.

SOTERM-2.2.2 Microbial Consumption of Cellulosic, Plastic, and Rubber Materials

A large quantity of CPR materials will be emplaced in the WIPP, and could be consumed by microorganisms. There are large uncertainties as to whether significant microbial consumption of CPR materials will occur during the 10,000-year WIPP regulatory period. Therefore, it is assumed that significant microbial consumption of CPR materials is possible, but by no means certain. To incorporate these uncertainties in PA, Wang and Brush (1996a, 1996b) developed a conceptual model for microbial activity in the repository. According to this model, there is a probability of 0.50 for significant microbial activity. In the event of significant microbial activity, microbes would consume 100 percent of the cellulosic materials in the repository. Furthermore, there is a conditional probability of 0.50 that microbes would consume all of the plastic and rubber materials after consumption of all of the cellulosic materials. Thus, there is microbial consumption of all of the cellulosic materials, but no plastic or rubber materials, in about 25 percent of the PA realizations (vectors); microbial consumption of all of the CPR materials in 25 percent of the vectors; and no microbial activity in the remaining 50 percent of the vectors.

Microbial consumption of CPR materials could affect the actinide source term in four ways:

- production of significant quantities of CO_2, which could acidify any brine present and increase the solubilities of actinide elements;
- reduction of oxidized actinide species, which in most cases are more soluble;
- consumption of solubilizing organic ligands; and

- production of humic and microbial colloids, thereby increasing the amount of actinide sorbed on colloidal surfaces.

The effect of CO_2 production is discussed in this section. The remaining three effects are considered in the analyses that have studied the oxidation-state distributions (Section 4.0), the effects of organic ligands (Section 5.0), and the effects of colloids (Section 6.0). The simplifications used in PA calculations for all four of these effects are discussed at the end of this section.

Microbial activity, if it occurs to a significant extent in the WIPP, would consume CPR materials by the following sequential reactions (Brush 1990; Francis and Gillow 1994; Brush 1995; Wang and Brush1996a; Francis and Gillow 1997):

$$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow 7.4H_2O + 6CO_2 + 2.4N_2; \quad (1)$$

$$C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S; \quad (2)$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2. \quad (3)$$

An analysis by Snider (2003b) based on the estimated quantities of CPR materials, nitrate (NO_3^-), and SO_4^{2-} (see Appendix Data, Attachment F) implies that, in the event all of the CPR materials are consumed, denitrification (Reaction (1)) would account for 4.72 mol percent, sulfate reduction (Reaction (2)) would account for 0.82 mol percent, and methanogenesis (Reaction (3)) would account for 94.46 percent of the consumption of CPR materials. (Appendix BARRIERS, Section BARRIERS-2.5, describes these calculations in detail.) Therefore, methanogenesis would be the primary microbial respiratory pathway in the repository.

Microbial consumption of CPR materials could produce significant quantities of CO_2, which could in turn acidify any brine present in the repository and increase the solubilities of the actinides relative to those predicted for neutral and mildly basic conditions. Therefore, the DOE is emplacing MgO in the repository to decrease actinide solubilities by consuming essentially all of the CO_2 that could be produced by microbial consumption of CPR materials,

and by buffering (controlling) the f_{CO_2} and pH within ranges that are favorable from the standpoint of actinide speciation and solubility (see Appendix BARRIERS, Section BARRIERS-2.0).

Laboratory and modeling studies described in Appendix BARRIERS, Section BARRIERS-2.3 have shown that, in the event of significant microbial activity in the WIPP, the carbonation reaction

$$5Mg(OH)_2 + 4CO_2(\text{aq or g}) \square Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O \quad (4)$$

will buffer f_{CO_2} at a value of $10^{-5.50}$ atm in both GWB and ERDA-6. In this reaction, $Mg(OH)_2$ is the mineral brucite (the main hydration product of the mineral periclase (MgO) expected in the WIPP); $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ is the form of the mineral hydromagnesite expected in the

repository; and "aq" and "g" are the abbreviations for "aqueous" and "gaseous," respectively. Furthermore, the brucite-dissolution reaction

$$Mg(OH)_2 \quad Mg^{2+} + 2OH^- \tag{5}$$

will buffer pH in the WIPP at a value of 8.69 in GWB and 9.02 in ERDA-6. These values of f_{CO_2} and pH were used for the actinide speciation and solubility calculations for the CRA-2004 PA vectors with significant microbial activity (see Section 3.5 below).

In the absence of significant microbial activity in the WIPP, the carbonation reaction

$$Mg(OH)_2 + Ca^{2+} + CO_2(aq \text{ or } g) \square CaCO_3 + Mg^{2+} + H_2O(aq \text{ or } g) \tag{6}$$

will buffer f_{CO_2} at a value of $10^{-5.48}$ atm in GWB and $10^{-6.15}$ atm in ERDA-6, and the brucite-dissolution reaction (Reaction (5)) will buffer pH at a value of 8.69 in GWB and 8.99 in ERDA-6 (see Appendix BARRIERS, Section BARRIERS 2.3). In this reaction, $CaCO_3$ is the mineral calcite. These values of f_{CO_2} and pH were used for the actinide speciation and solubility calculations for the CRA-2004 PA vectors without microbial activity (see Section 3.0 below).

Four effects of microbial consumption of CPR materials are recognized in modeling system performance. A simplification has been made that the effects will be time independent after 100 years. The effects are

- CO_2 production. With the addition of excess MgO, the effects of CO_2 production are minimized, and it is assumed that the system may be modeled using the brucite-hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) buffer.

- Redox effects. After 100 years, the repository will have a reducing environment. Even though significant microbial action is only 50 percent likely, the corrosion of steel will also produce a reducing environment (Section 2.2.3).

- Possible consumption of organic ligands. While some microbes are known to consume some organic ligands, there is uncertainty as to the presence or viability of these particular microbes within the repository environment. Therefore, no credit has been taken for the microbial consumption of organic ligands. Other mechanisms for reducing the effect of organic ligands are discussed in Section 5.0.

- Production of humic and microbial colloids.

SOTERM-2.2.3 Anoxic Corrosion of Steels and Other Iron-Base Alloys

The corrosion of steels, other Fe-base alloys, and other metals in the repository will have several effects on the actinide source term. Corrosion is expected to:

- reduce the oxidation states of some actinides, especially Pu, from relatively mobile oxidation states, such as Pu(V) and Pu(VI), to relatively immobile oxidation states, such as Pu(III) and Pu(IV) (Section 4.0);

- produce colloidal corrosion products on which actinides may sorb (see Section 6.0).

It is expected that oxic corrosion of steels and aerobic microbial consumption of CPR materials will quickly consume the limited amount of oxygen (O_2) trapped within the repository at the time of closure. After O_2 is consumed, anoxic corrosion of metals will occur (Brush 1990; Brush 1995; Wang and Brush 1996a. In all of the vectors for the CRA-2004 PA, the EPA's 1997 Performance Assessment Verification Test (PAVT), and the CCA PA, there were significant amounts of uncorroded steels and other Fe-base alloys in the repository throughout the 10,000-year regulatory period. WIPP-specific experiments (Telander and Westerman, 1993; 1997) showed that steels and other Fe-base alloys will corrode by the following reactions:

$$Fe + (x + 2)H_2O \Leftrightarrow Fe(OH)_2 \cdot xH_2O + H_2; \quad (7)$$

$$3Fe + 4H_2O \Leftrightarrow Fe_3O_4 + 4H_2; \quad (8)$$

$$Fe + H_2O + CO_2 \Leftrightarrow FeCO_3 + H_2; \text{ and} \quad (9)$$

$$Fe + H_2S \Leftrightarrow FeS + H_2. \quad (10)$$

Metal hydroxides such as Fe(II) hydroxide ($Fe(OH)_2 \cdot xH_2O$) are more soluble in the WIPP high-ionic-strength brines than in dilute solutions, and significant amounts of Fe(II) may dissolve. Refait and Genin (1994) estimated Fe(II) solubilities between 10^{-4} and 10^{-6} M for pH between 8.5 and 10.5 under redox conditions expected for the repository. Sagoe-Crentsil and Glasser (1993) observed even higher solubilities at pH 13 with electrolytic dissolution of Fe.

Corrosion of metals will produce reducing conditions in the repository, but redox conditions have not been predicted quantitatively. The repository is not described using Eh, because in low-temperature geochemical systems, equilibria among the many redox couples are generally not attained, and Eh is generally poorly defined. For this reason, the oxidation states of the actinides have been determined experimentally, as described in Section 4.0.

SOTERM-2.2.4 Other Effects

High pressure in the repository after closure will have an insignificant effect on actinide solubilities and the association of actinides with colloids and, therefore, its effect is not included in PA. Temperature within the repository is not expected to change by more than a few degrees from ambient (28 ºC) (Munson et al. 1987; Sanchez and Trellue 1996; Wang and Brush 1996a). Because the effect on solubilities of a few degrees Celsius is insignificant compared to uncertainty of the measurements and modeling of solubilities, temperature effects were also discounted (Section 3.3).

Radiolysis of brine may affect redox conditions in the repository. When energy from radioactive decay is absorbed by H_2O, the H_2O molecule is broken into energetic fragments that reassemble

into oxidized and reduced species. Depending on the chemical reactivity of these species, the system may be effectively more oxidizing or more reducing as a result of the radiolysis. For example, radiolysis often occurs by the following reaction:

$$2H_2O + \text{radiation} = H_2(g) + H_2O_2 \quad (11)$$

Hydrogen peroxide (H_2O_2) is more reactive than hydrogen (H_2) (g) at low temperature, and peroxide redox reactions will affect the system more than the slow H_2 reactions. If the system is initially very oxidized, H_2O_2 will cause a reduction in the effective redox state, but if the system is initially very reduced, the peroxide will cause oxidation. In the WIPP, it is expected that the repository will be quite reducing due to the large amount of metallic Fe and dissolved Fe(II) species. Any oxidized species such as H_2O_2 generated from radiolysis are expected to quickly react with the metallic Fe and Fe(II), thus negating any oxidizing effect of radiolysis. Therefore, radiolysis is not expected to affect the redox state of the repository significantly.

Other components of the waste may influence the concentration of dissolved actinides within the repository. These include, for example, organic ligands (Section 5.0); other salts such as calcium chloride ($CaCl_2$), which may raise the ionic strength of the brine; vermiculite, which may sorb actinides; and phosphate (PO_4^{3-}), which may precipitate insoluble actinide phosphates. The effects of most of these components are assumed beneficial and would be difficult to quantify, so they were not included in PA.

SOTERM-2.2.5 Summary

Chemical conditions in the repository will be affected by whether brine is present (humid or inundated conditions) and the type of brine (Salado or Castile); microbial consumption of CPR materials, which will produce mainly methane (CH_4) and CO_2, and colloidal particles; MgO , which will control f_{CO_2} and pH; and corrosion of steels, other Fe-base alloys, and other metals in the repository, which will create reducing conditions.

SOTERM-3.0 PREDICTION OF DISSOLVED ACTINIDE SOLUBILITIES

This section describes the basic approach used to predictactinide solubilities for the CRA-2004 PA. Surveys of different possible conceptual and mathematical descriptions of the system are presented, followed by a more detailed discussion of the method selected.

The material in this section is intended to provide an overview of the modeling methods. More detailed descriptions can be found in the references.

SOTERM-3.1 Previous Approaches to Estimating Actinide Solubilities in the WIPP

Brine flow through the repository was not considered early in the WIPP Project because brine was not expected to enter the repository (see CCA Appendix MASS, Section MASS.2). When it was realized that brines from a variety of sources might enter the repository, scenarios involving brine flow were developed. These scenarios necessitated the investigation of potential

mobilization mechanisms, including dissolution of actinides in high-ionic-strength aqueous solutions applicable to WIPP brines.

The solubilities of actinides in WIPP brines were initially estimated by an expert panel that reviewed the existing literature on actinide solubilities (Trauth et al. 1992). The range of solubilities obtained was about 14 orders of magnitude because the chemical conditions surveyed included extremes of acidity and other conditions. With the addition of MgO and the demonstration of reducing conditions, it was realized that these extreme conditions would not occur in the WIPP. The expert panel also estimated the effect of high CO_3^{2-} concentrations, which are known to increase actinide solubilities significantly, despite the paucity of data for CO_3^{2-}-bearing solutions. Median solubilities developed by the panel were Th: 10^{-10} M; U: 10^{-3} M; Np: 10^{-7} M; Pu: 10^{-9} M; and Am and Cm: 10^{-9} M (Trauth et al. 1992, p. 4-5; Hobart et al. 1996). Published studies of actinides under environmental conditions have focused on actinides in surface waters and groundwaters that are considerably more dilute than WIPP brines, which contributed to the wide range of solubility estimates because more pertinent data were unavailable.

Experimental investigations for other radioactive waste projects (for example, Nitsche 1987) have measured the solubilities of actinides directly. Although this is possible for well-characterized and homogeneous waste and groundwaters, the waste intended for the WIPP is heterogeneous, and a relatively wide range of chemical conditions would be possible in the repository without MgO. Measuring solubilities directly in experiments using transuranic (TRU) waste and ensuring that the measurements reflect steady-state WIPP conditions would entail an extremely large number of measurements and considerable uncertainty. This approach was determined to be neither practical nor feasible. The DOE therefore decided to estimate actinide solubilities by using a thermodynamic model based on experimental parameterization.

SOTERM-3.2 Selection of the Pitzer Activity-Coefficient Model

The thermodynamic activity of a dissolved species is the product of its actual concentration and an activity coefficient. In dilute aqueous solutions, the activity coefficient is close to unity, but in high-ionic-strength solutions such as WIPP brines, the activity coefficient may deviate significantly from unity.

The calculation of activity coefficients is the central feature of thermodynamic models in concentrated electrolyte systems. Activity coefficients represent the deviation from the nearly ideal behavior observed or assumed in dilute solutions. Aqueous-electrolyte activity-coefficient models generally include the Debye-Hückel limiting law (see, for example, Pitzer 1991, 59 et seq.) to describe behavior in the dilute region (<0.1 m), and often include one or more adjustable parameters to reproduce measured behavior in more concentrated solutions.

Numerous activity-coefficient models for concentrated electrolytes have been proposed, including the Pitzer model (Pitzer 1991, Chapter 3), Harned's Rule (Wood 1975), and the Specific-Ion Interaction Theory (SIT) (Grenthe and Wanner 1992), given in order of approximately decreasing mathematical complexity. The Pitzer activity-coefficient model contains parameters that explicitly represent the contributions to the excess free energy from every two-moiety and three-moiety interaction, where a moiety is a cationic, anionic, or neutral

aqueous species. The Harned's-Rule model asserts that the "logarithm of the activity coefficient of one electrolyte in a mixture of constant total molality is directly proportional to the molality of the other component" (Robinson and Stokes 1959, 438), and thus by extension to multicomponent systems containing parameters for two-moiety interactions. The SIT model contains parameters for two-moiety cation-anion interactions.

A primary consideration for selecting an activity-coefficient model to predict actinide solubilities in the WIPP was the demonstrated applicability of existing models and databases to the brines and evaporite minerals at WIPP. The Pitzer model, especially as parameterized by Harvie et al. (1980a), Harvie et al. (1984), and Felmy and Weare (1986), includes an established database describing solubilities in the hydrogen-ion- (H^+)-B-Na^+-Mg^{2+}-K^+-Ca^{2+}-OH^--bicarbonate-(HCO_3^-) CO_3^{2-}-SO_4^{2-}-Cl^--H_2O-CO_2 system. This system includes the significant nonradioactive constituents of WIPP brines. The Harned's-Rule model has been parameterized for the Na^+-Mg^{2+}-K^+-Ca^{2+}-Cl^- and Na^+-Mg^{2+}-$SO_4^{2-}$$Cl^-$ systems (Wood 1975), but does not include CO_3^{2-}, one of the most important actinide complexants in aqueous systems. The SIT model (Grenthe and Wanner 1992) is most commonly used for extrapolating apparent stability constants to zero ionic strength. No demonstrations that the SIT model has been applied to multicomponent, concentrated electrolytes such as brine-evaporite-mineral systems have been identified in the literature.

The chemical behavior of the concentrated brines that occur in evaporites like those at WIPP has been extensively studied and documented. The applications of the Harvie et al. (1980a), Harvie et al. (1984), and Felmy and Weare (1986) parameterization of the Pitzer model include: prediction of the mineral-precipitation sequence accompanying seawater evaporation (Eugster et al. 1980; Harvie et al. 1980b); the formation of borate minerals in Searles Lake, CA (Felmy and Weare 1986); and an analysis of Permian seawater composition based in part on fluid-inclusion data from the Salado (Horita et al. 1991). Additional applications are given in Pitzer (1991, Chapters 6 and 7).

WIPP brines range from about 0.8 m to 8 m in ionic strength. The Pitzer model is developed for and has been shown to work for electrolytes as concentrated as those at WIPP, and has been applied successfully to brines with concentrations greater than 10 m (Felmy and Weare 1986). Rather than develop a new description of the chemical behavior of the nonradioactive constituents of WIPP brines, it was decided to use the Harvie et al. (1984)/Felmy and Weare (1986) (HMW/FW) parameterization of the Pitzer model as the reference activity-coefficient model and thermodynamic database for the WIPP actinide source term. Additional research for the WIPP focused on extending the database to include the actinides that could affect the long-term performance of the WIPP and the organic ligands that could affect the solubilities of these actinides (see Section 5.0).

SOTERM-3.3 The Fracture-Matrix Transport Computer Code

The solubility and speciation code Fracture-Matrix Transport (FMT) (Babb and Nowak 1997 and addenda) uses the Pitzer activity-coefficient model to calculate the solubilities of the actinide elements in equilibrium with the appropriate solubility-controlling solids in WIPP brines by minimizing the Gibbs free energy of the system. Where appropriate parameters already existed in the HMW/FW database, they have been used in FMT calculations for the WIPP. Additional

parameters, most notably those for dissolved actinide species, have been obtained from the literature or determined from experimental data (see Section 3.4) using the NONLIN code (Novak 1995; WIPP Performance Assessment Department 1996). NONLIN calculates the Pitzer parameters using a nonlinear least-squares fitting program.

The FMT calculations were done for three actinides: Am(III), Th(IV), and Np(V) that are oxidation-state analogs for actinides in the +III, +IV, and +V oxidation states, respectively. Because actinides in the same oxidation state exhibit similar chemical behavior, these FMT model calculations apply to all actinides in the same oxidation state; for example, the Am(III) speciation and solubility model applies to Pu(III); the Th(IV) model applies to U(IV), Np(IV), and Pu(IV); and the Np(V) model applies to Pu(V). However, Pu will not persist to a significant extent in the +V oxidation state (or the +VI oxidation state) in the WIPP (see Section 4.6.)

The dissolved concentrations of the actinides Th, U, Np, Pu, and Am will be limited by solubility-controlling solid for each of these actinides in WIPP brines. The important ions in WIPP brines are H^+, Na^+, Mg^{2+}, K^+, Ca^{2+}, OH^-, CO_3^{2-}, SO_4^{2-}, and Cl^-. Other ions, for example, fluoride (F^-), aluminum (Al^{3+}), PO_4^{3-}, Fe^{2+}, and Fe^{3+}, may affect actinide solubilities significantly. Pitzer parameters for these other ions are not included in the dissolved species and source term model, but enhance understanding of the chemical environment. For example, phosphates are known to precipitate actinides (Cotton and Wilkinson 1988), but this effect has conservatively been ignored due to the uncertainty of the phosphate inventory in the WIPP and the lack of a complete set of Pitzer parameters for its inclusion. The existence of Fe(II) from the anoxic corrosion of steels and other Fe-base alloys is accounted for in the oxidation state distribution (see Section 4.0), but is expected to have an insignificant effect on the solubilities of individual actinide oxidation state and distribution.

The expected temperature of the WIPP disposal rooms during the 10,000-year regulatory period is not expected to change by more than a few degrees from ambient (28 ºC) (Munson et al. 1987; Sanchez and Trellue 1996; Wang and Brush 1996). The small differences in thermodynamic properties caused by these changes are well within acceptable uncertainty for the WIPP system. For these reasons, the small differences in properties over this temperature range are not significant for the WIPP, and all information was developed for 25°C. Literature information taken at approximately 20°C was deemed acceptable for model parameterization as well.

The development of the +III, +IV, and +V actinide solubility models consisted largely of the development of a database that includes the standard chemical potentials of the aqueous and solid actinide-bearing species, and the ion-interaction parameters required to describe the interactions between these species and other constituents of WIPP brines. The following sections describe briefly how this database was built and how the needed parameters were obtained. The development of the oxidation-state distributions reflected in these sections is discussed in Section 4.0.

Section 3.4 provides a guide to the information that is needed to predict actinide solubilities. The FMT database currently used to predict the solubilities of the +III, +IV, and +V actinides is documented in Giambalvo (2002a, 2002b, 2002c, 2002d, 2002e, 2003).

SOTERM-3.4 Overview of the Experimental Data

Studies of the solubilities and speciation of actinides, especially Pu, are often conducted by employing the oxidation-state analogy, which states that lanthanides and actinides in the same oxidation state have similar chemical behavior. There are several important advantageous aspects of the use of oxidation-state analogs, such as Th(IV) for Pu(IV). Redox-inert analogs can considerably simplify experimental design and consequently improve reliability of experimental data, in contrast to Pu, which can be a very labile experimental component. Additionally, the lanthanide and actinide analogs possess physical and chemical characteristics that allow them to be used as probes in examination of the chemical behavior of Pu. For example, the luminescence lifetime of europium(III) (Eu(III)) can be directly correlated to the number of H_2O molecules in the inner coordination sphere, which allows interpretation of the nature of complexation of the trivalent lanthanides and actinides with ligands.

The 4f orbitals of the lanthanides and 5f orbitals of the actinides constitute the valence shells of the cations. The f orbitals are more diffuse than the p and d orbitals, and, upon ionization of the atom, become lower in energy than the 5d, 6s, and 6p orbitals in the case of the lanthanides, and comparable or slightly lower than the 6d, 7s, and 7p orbitals in the case of the actinides. The contraction of the radial component of the wave function of the f orbitals upon ionization of the element usually causes these orbitals to be unavailable for overlap with orbitals on other atoms, one of the conditions necessary for the formation of molecular orbitals. As a result, the lanthanide and actinide ions exhibit very little tendency to form covalent bonds.

Formation of complexes of most ligands with f elements is due to the electrostatic attraction between the metal cation and the electron-donating functionality of the ligand molecule. The effect of polarizability and Lewis acidity or basicity on formation of Lewis-acid or Lewis-base pairs has been described by Pearson (1963). Lanthanide and actinide cations, which have high charge density and low polarizability, are classified as hard cations. Similarly, ligands featuring O-donor atoms, such as citrate and oxalate, exhibit low polarizability and strong Lewis basicity, and are referred to as hard bases. Hard-acid metals interact with hard bases through electrostatic attraction. The stability of f-element complexes with many ligands is a function of the charge density on the donor atom. For example, progressively weaker Brönsted-Lowry acids (in order of increasing pKa: trichloroacetic < dichloroacetic < monochloroacetic < acetic acids) have progressively stronger conjugate bases due to increased electron density located on the carboxylic O's. As a result, the electrostatic attraction between the O and protons increases, resulting in weaker acidic behavior and corresponding increases in pKa values. Likewise, the force of electrostatic attraction between the carboxylate group and a metal ion increases with increasing basicity of the ligand.

The magnitude of electrostatic attraction between the f-element cations and ligands is dependent upon the local effective dielectric constant of the solution, the charge on the metal ion, and the distance of separation between the metal atom and the ligating atoms on the complexing agent. The magnitude of the local dielectric constant of the solution depends upon the ordering effect created by the electric-field gradient established by the cation. The charge densities of lanthanides and actinides with the same charge are similar enough that the responses of solvent molecules are similar, yielding local dielectric constants that are nearly constant for lanthanide

and actinide cations with the same charge. The local dielectric constant is primarily dependent upon the charge of the ion; the variation due to the effect of different-magnitude electric-field gradients that result from the differences in ionic radii are small enough to be overlooked to a first approximation in the oxidation-state-analogy approach.

The factors that exert a much more pronounced influence are the ionic radii, charge on the metal ion, and, to a lesser extent, degree of solvation of the metal ion. The Gibbs free energy of complex formation is inversely proportional to the distance between the metal and ligand, and directly proportional to the product of the numerical value of the electrostatic charges on the cation and anion. There are variations in the ionic radii of lanthanide and actinide ions that have the same charge, with decreasing ionic radii corresponding to increasing atomic number within the 4f and 5f series. However, the ionic radii of some of the metal ions are very similar. For example, neodymium ion (Nd^{3+}) and Am^{3+} have nearly identical ionic radii. As a result, the behavior of Nd(III) and Am(III) are very similar, with small differences attributable to the fact that the 5f orbitals of Am are closer in energy to the 6d, 7s, and 7p orbitals than the 4f orbitals of Nd are to the 5d, 6s, and 6p orbitals. Discussions of applications to the +III, +IV, +V, and +VI actinide oxidation states follow.

SOTERM-3.4.1 The +III Lanthanides and Actinides

The actinides most likely to occur in the +III oxidation state in the WIPP are Pu, Am, and Cu. Nd(III), Eu(III), Pu(III), Am(III), and Cu(III) have been widely used in studies of trivalent f-element chemical behavior in brines. The respective ionic radii for coordination number (CN) = 8 are 111, 17, 100, 109, and 97 pm (Shannon 1976). Due to the similarity of ionic radii, the magnitude of the electrostatic attraction between the metal ions and corresponding ligands is similar, yielding comparable thermodynamic stabilities. Each of the analog elements offers noteworthy advantages in probing various aspects of trivalent f-element solution behavior. For example, Nd(III) features hypersensitive absorption bands that respond to changes in the complexation environment, allowing examination of the nature of the metal-ligand interaction. The luminescence lifetime of Eu(III) can be used to measure the number of residual waters of hydration associated with the metal ion after formation of a complex. ^{241}Am, which has a 433-year half-life, undergoes α decay that is accompanied by 59.5-keV γ ray with a 35.9-percent yield. As a result, ^{241}Am may be used at tracer concentrations by well-developed radiochemical techniques, such as solvent extraction and ion exchange, as a means to study the thermodynamic behavior of trivalent actinides. Study of the solution behavior of Am(III) is uncomplicated by redox ability, unlike the situation for Pu(III), which requires Eh and pH controls of the solution to maintain a single oxidation state. Like Nd and Eu, Cu luminescence studies are useful to examine the coordination environment of the metal ion. Pu(III) does not have useful luminescence properties, making it impossible to study its complexation behavior by methods that are effective with the analogs.

The thermodynamic database for the +III actinides currently used in FMT was described by Giambalvo (2002a). Due to the redox ability of Pu, much of the experimental work carried out to develop an understanding of the chemical behavior of the +III actinides, particularly Pu, has been performed with Nd, Am, and Cm due to the stability of the trivalent oxidation states of these three elements. Speciation and solubility data for the +III actinides were parameterized for

use in the Pitzer activity-coefficient model by Felmy et al. (1989) for the Na^+- Pu^{3+}-Cl^--H_2O system; by Felmy et al. (1990) for the Na^+-Am^{3+}-OH^--HCO_3^--H_2O system; by Rai et al. (1995) for the Na^+-Am^{3+}-PO_4^{3-}-SO_4^{2-}-H_2O system; and by Rao et al. (1996) for the Na^+-Nd^{3+}-CO_3^{2-}-HCO_3^--H_2O system. The inorganic aqueous and solubility-limiting species featured in the model for Am(III) are:

$$Am^{3+} + CO_3^{2-} \square AmCO_3^+; \quad (12)$$

$$Am^{3+} + 2CO_3^{2-} \square Am(CO_3)_2^-; \quad (13)$$

$$Am^{3+} + 3CO_3^{2-} \square Am(CO_3)_3^{3-}; \quad (14)$$

$$Am^{3+} + 4CO_3^{2-} \square Am(CO_3)_4^{5-}; \quad (15)$$

$$Am^{3+} + OH^- \square AmOH^{2+}; \quad (16)$$

$$Am^{3+} + 2OH^- \square Am(OH)_2^+; \quad (17)$$

$$Am^{3+} + 3OH^- \square Am(OH)_3(aq); \quad (18)$$

$$Am^{3+} + Cl^- \square AmCl^{2+}; \quad (19)$$

$$Am^{3+} + 2Cl^- \square AmCl_2^+; \quad (20)$$

$$Am^{3+} + SO_4^{2-} \square Am(SO_4)^-; \quad (21)$$

$$Am^{3+} + 2SO_4^{2-} \square Am(SO_4)_2^+; \quad (22)$$

$$Am^{3+} + OH^- + CO_3^{2-} \square AmOHCO_3(s); \quad (23)$$

$$Na^+ + Am^{3+} + 2CO_3^{2-} + 6H_2O \square NaAm(CO_3)_2 \bullet 6H_2O(s); \text{ and} \quad (24)$$

$$Am^{3+} + PO_4^{3-} \square AmPO_4(cryst). \quad (25)$$

In these equations, “aq,” “cryst,” and “s” are the abbreviations for “aqueous,” crystalline,” and “solid,” respectively. The actinide(III) database was extended to mixed Na^+-CO_3^{2-}-Cl^-- media, and was shown to reproduce the independently measured solubility of $NaAm(CO_3)_2(s)$ in 5.6 M NaCl (Runde and Kim 1994) and Nd(III) solubility in WIPP brines.

SOTERM-3.4.2 The +IV Actinides

The tetravalent actinides important to WIPP performance are Th(IV), U(IV), and Pu(IV). Np is not included in the WIPP actinide source term, but has been included in the WIPP Actinide Source Term Program (ASTP). The +IV oxidation state is the only stable one in aqueous solution for Th, whereas U(IV) and Np(IV) are both readily oxidized. As a result, Th is often used to represent the behavior of the +IV actinides. Th(IV) does not have spectroscopic characteristics that are valuable in its study, but does have both long-lived (^{232}Th, $t_{1/2}$ = 1.41×10^{10} year) and shorter-lived (^{228}Th and ^{230}Th $t_{1/2}$ = 1.913 and 7540 year, respectively)

isotopes that are useful in thermodynamic studies. The 105-pm ionic radius of the Th(IV) cation (C. N. = 8) is greater than the 96 pm Pu(IV) cation (Shannon 1976), resulting in complexation properties that vary in a systematic and predictable manner. The larger ionic radius of Th(IV) causes it to have complexes with stability constants lower than the corresponding complexes with Pu(IV). For example, the Pu(IV) complexes with OH^-, resulting from hydrolysis, have higher stability constants than Th(IV)-OH^- complexes. The actinide(IV) hydrolysis products are sufficiently stable that organic ligands present within the WIPP, (see Section 5.0) will be unable to effectively compete with OH^-. The net effect is that actinide(IV) complexation is dominated by OH^-, which forms very insoluble tetrahydroxide ($An(OH)_4$) precipitates. Pu has a pronounced tendency to form insoluble hydrolysis products that are less soluble than the corresponding Th(IV) oxides and hydroxides. The greater solubility of Th(IV) makes it a very good analog for Pu(IV) in the context of modeling the behavior of tetravalent actinides in the WIPP because the solubility of Th(IV) establishes an upper limit for the solubility of Pu(IV). Due to the experimental difficulty working with Pu(IV), it is more straightforward and defensible to establish upper limits rather than attempting to measure the solubility of Pu(IV) directly.

The thermodynamic database for the +IV actinides currently used in FMT was described by Giambalvo (2002c). Speciation and solubility data for Th(IV) were parameterized for the Pitzer activity-coefficient model for the Na^+-K^+-Mg^{2+}-Cl^-- SO_4^{2-}-CO_3^{2-}-HCO_3^- -OH^--H_2O system. The inorganic aqueous and solubility-limiting species featured in the model are:

$$ThO_2(am) + 2H_2O \square Th(OH)_4(aq); \quad (26)$$

$$Th^{4+} + 4OH^- \square Th(OH)_4(aq); \quad (27)$$

$$Th^{4+} + 3OH^- + CO_3^{2-} \square Th(OH)_3CO_3^-; \quad (28)$$

$$Th^{4+} + 5CO_3^{2-} \square Th(CO_3)_5^{6-}; \quad (29)$$

$$Th^{4+} + 2SO_4^{2-} \square Th(SO_4)_2(aq); \quad (30)$$

$$Th^{4+} + 3SO_4^{2-} \square Th(SO_4)_3^{2-}; \quad (31)$$

$$Th^{4+} + 2SO_4^{2-} + 9H_2O \square Th(SO_4)_2 \bullet 9H_2O(s); \quad (32)$$

$$Th^{4+} + 2SO_4^{2-} + 8H_2O \square Th(SO_4)_2 \bullet 8H_2O(s); \quad (33)$$

$$Th^{4+} + 2Na^+ + 3SO_4^{2-} + 6H_2O \square Th(SO_4)_2 \bullet Na_2SO_4 \bullet 6H_2O(s); \quad (34)$$

$$Th^{4+} + 2K^+ + 3SO_4^{2-} + 4H_2O \square Th(SO_4)_2 \bullet K_2SO_4 \bullet 4H_2O(s); \quad (35)$$

$$Th^{4+} + 4K^+ + 4SO_4^{2-} + 6H_2O \square Th(SO_4)_2 \bullet 2K_2SO_4 \bullet 2H_2O\ (s); \text{ and} \quad (36)$$

$$Th^{4+} + 7K^+ + 5.5SO_4^{2-} \square Th(SO_4)_2 \bullet 3.5K_2SO_4(s). \quad (37)$$

SOTERM-3.4.3 The +V Actinides

Both Np and Pu have accessible +V oxidation states; however, Pu(V) is not expected to persist in significant quantities in the WIPP. The model for Np(V) was developed for the German repository program (Fanghänel et al. 1995). The speciation and solubility of Np(V) were parameterized for the Na^+-Cl^--CO_3^{2-}-ClO_4^--H_2O system.

The thermodynamic database for the +V actinides currently used in FMT is described by Giambalvo (2002d). Np(V) speciation and solubility were parameterized in the Pitzer activity-coefficient model for the Na^+-K^+-Mg^{2+}-Cl^-- SO_4^{2-}-CO_3^{2-}-HCO_3^- -OH^--H_2O system. The inorganic aqueous and solubility limiting species used are:

$$NpO_2^+ + OH^- \square NpO_2OH(aq); \quad (38)$$

$$NpO_2^+ + OH^- \square NpO_2OH(s, am); \quad (39)$$

$$NpO_2^+ + OH^- \square NpO_2OH(s, aged); \quad (40)$$

$$NpO_2^+ + 2OH^- \square NpO_2(OH)_2^-; \quad (41)$$

$$NpO_2^+ + CO_3^{2-} \square NpO_2CO_3^-; \quad (42)$$

$$NpO_2^+ + 2CO_3^{2-} \square NpO_2(CO_3)_2^{3-}; \quad (43)$$

$$NpO_2^+ + 3CO_3^{2-} \square NpO_2(CO_3)_3^{5-}; \quad (44)$$

$$Na^+ + NpO_2^+ + CO_3^{2-} + 3.5H_2O \square NaNpO_2CO_3 \bullet 3.5H_2O(s); \quad (45)$$

$$3Na^+ + NpO_2^+ + 2CO_3^{2-} \square Na_3NpO_2(CO_3)_2(s); \quad (46)$$

$$K^+ + NpO_2^+ + CO_3^{2-} \square KNpO_2CO_3(s); \text{ and} \quad (47)$$

$$3K^+ + NpO_2^+ + 2CO_3^{2-} + 0.5H_2O \square K_3NpO_2(CO_3)_2 \bullet 0.5H_2O(s). \quad (48)$$

SOTERM-3.4.4 The +VI Actinides

The actinide(VI) speciation and solubility model for brines under basic conditions has not been developed sufficiently for use in FMT. The hydrolysis behavior of U(VI) is quite complicated and no satisfactory predictive models applicable to WIPP conditions are available. As documented in Hobart and Moore (1996), the solubility of U(VI) at pH 10, in the absence of CO_3^{2-}, was estimated to be 8.8×10^{-5} m.

SOTERM-3.5 Calculations of Actinide Solubilities Using the Fracture-Matrix Transport Computer Code

Details of the solubility calculations for the +III, +IV, and +V actinides and the estimation of the solubility of +VI actinides for the CRA-2004 PA are given in Brush and Xiong (2003a, 2003b, 2003c) and Downes (2003a, 2003b).

The FMT calculations of actinide solubilities for the CRA-2004 PA featured the establishment of equilibrium of Salado brine (GWB) or Castile brine (ERDA-6) with halite, and anhydrite, minerals present in large quantities in the Salado at the repository horizon. The effects of MgO included equilibration of Salado brine or Castile brine with brucite and hydromagnestie ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) in the PA vectors with microbial activity, and with brucite and calcite in the vectors without microbial activity (see Reactions (4), (5), and (6) above; and Appendix BARRIERS, Section BARRIERS-2.3). For the CCA, it was assumed that Salado brine (Brine A) or Castile brine (ERDA-6) would be in equilibrium with brucite and magnesite ($MgCO_3$) in all of the PA vectors (both with and without microbial activity) (ERDA-6). For the 1997 PAVT, equilibria among Salado brine (Brine A) or Castile brine (CCA Appendix SOTERM; CCA Appendix BACK) and brucite and hydromagnesite ($Mg_5(CO_3)4(O4)_2 \bullet 4H_2O$) was assumed (EPA 1998a, 1998b).

The FMT calculations for the CRA-2004 PA also included the effects of acetate, citrate, EDTA, and oxalate on the speciation and solubilities of the +III, +IV, and +V actinides (see Section 5.0 below).

Table SOTERM-2 provides the solubilities calculated for the +III, +IV, and +V actinides and estimated for the +VI oxidation state for the CRA-2004 PA, and compares them to the solubilities calculated or estimated for the CCA PA and the 1997 PAVT.

SOTERM-3.6 Use of Fracture-Matrix Transport Results in Performance Assessment

Table SOTERM-2. Actinide Solubilities (M) Calculated (+III, +IV, and +V) or Estimated (+VI) for the CRA-2004 PA, the 1997 PAVT, and the CCA PA

Actinide Oxidation State and Brine	CRA Solubilities, Microbial Vectors[1]	CRA Solubilities, Nonmicrobial Vectors[1]	PAVT Solubilities[2]	CCA Solubilities[3]
+III, Salado brine	3.07×10^{-7}	3.07×10^{-7}	1.2×10^{-7}	5.82×10^{-7}
+III, Castile brine	1.69×10^{-7}	1.77×10^{-7}	1.3×10^{-8}	1.3×10^{-8}
+IV, Salado brine	1.19×10^{-8}	1.24×10^{-8}	1.3×10^{-8}	4.4×10^{-6}
+IV, Castile brine	2.47×10^{-8}	5.84×10^{-9}	4.1×10^{-8}	6.0×10^{-9}
+V, Salado brine	1.02×10^{-6}	9.72×10^{-7}	2.4×10^{-7}	2.3×10^{-6}
+V, Castile brine	5.08×10^{-6}	2.13×10^{-5}	4.8×10^{-7}	2.2×10^{-6}
+VI, Salado brine[4]	8.7×10^{-6}	8.7×10^{-6}	8.7×10^{-6}	8.7×10^{-6}
+VI, Castile brine[4]	8.8×10^{-6}	8.8×10^{-6}	8.8×10^{-6}	8.8×10^{-6}

1 Brush and Xiong (2003a, 2003b) and Downes (2003a, 2003b).
2 Trovato (1997, Attachment 2), EPA (1998a, Table 5), EPA (1998b, Subsection 4.10.4, Tables 4.10-1, 4.10-3 and 4.10-4; and Subsection 12.4, Table 12.4-1), and EPA (1998c, Subsections 5.26–5.32 and Section 6.0, Table 6.4).
3 CCA Appendix SOTERM, Table SOTERM-2; based on Novak et al. (1996, Table 1, columns entitled "@Mg"), except that Novak et al. (1996) used molal instead of molar units.
4 Hobart and Moore (1996).

Uncertainties in the solubility data and the NONLIN least squares refinement result in uncertainties in the model predictions. This is evident when the data of Runde and Kim (1994) are compared with FMT model results. A measure of these uncertainties was obtained by Bynum (1996) by examining the differences between the modeled solubilities for each oxidation-state analog and comparing these to the experimental data used to generate the respective Pitzer parameters. The results of Bynum's analysis are given in Figure SOTERM-1. These results were combined as shown in Figure SOTERM-2 for entry into the parameter database as a cumulative distribution. This distribution was sampled in PA, as discussed in Section 7.1.3. Note that the median of this distribution is -0.09 and not zero, indicating that slightly more experimental values were below the model predictions than above.

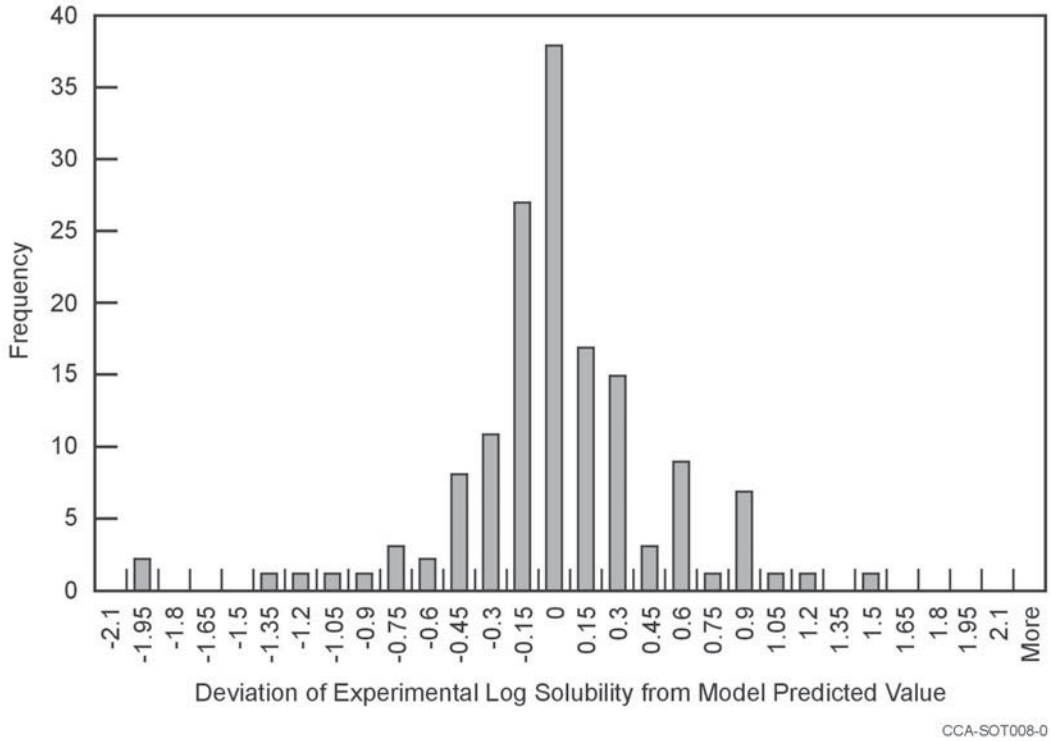

Figure SOTERM-1. Deviation of the log of 150 Experimental Solubilities from the Values Predicted by the Model.

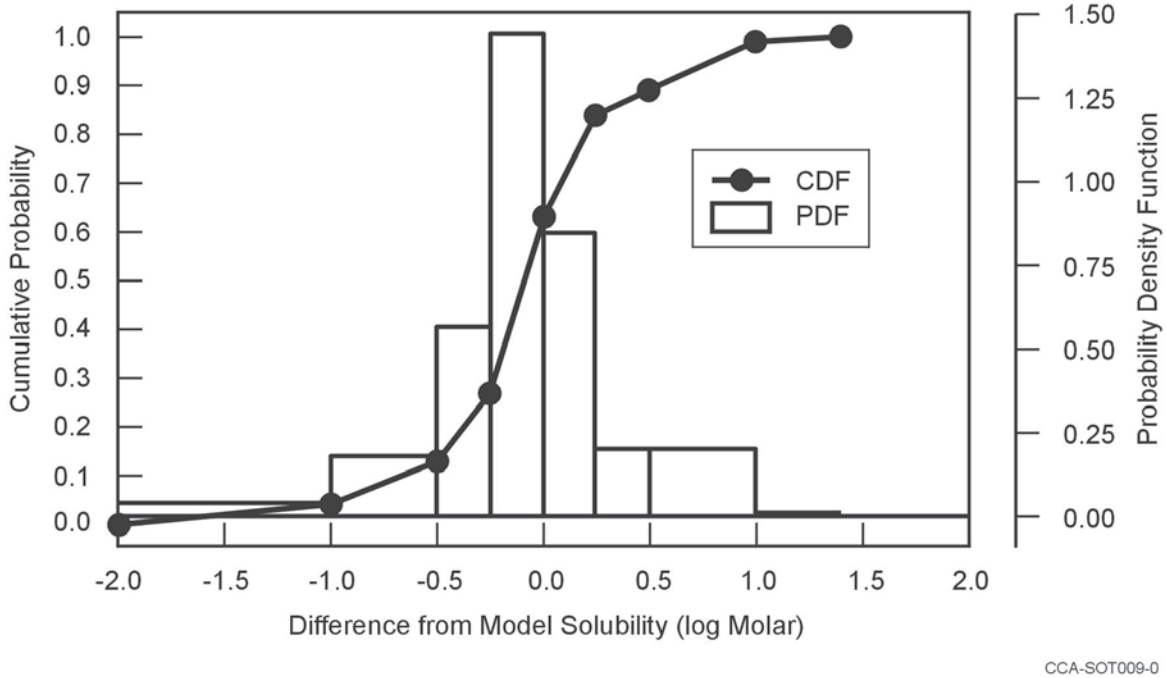

Figure SOTERM-2. Distribution of Actinide-Solubility Uncertainty Utilized in the CRA-2004 Performance Assessment.

SOTERM-4.0 OXIDATION-STATE DISTRIBUTION OF DISSOLVED ACTINIDES

This section describes the literature investigation and experimental program that identified the actinide oxidation states most likely to be stable under expected WIPP conditions.

SOTERM-4.1 Thorium

Th is a very electropositive metal, and Th(IV) is the only stable oxidation state in aqueous solutions and in the natural environment (Hobart 1990; Katz et al. 1986). Conditions in the WIPP cannot produce any other oxidation state of Th.

SOTERM-4.2 Uranium

U can exist in aqueous solution in the +III, +IV, +V, and +VI oxidation states (Hobart 1990; Keller 1971; Clark et al. 1995). The predominant oxidation states for U in the natural environment are +IV and +VI. U(III) may be prepared in aqueous solution but is easily oxidized to U(IV) (Katz et al. 1986, 1139 and following).

The standard reduction potential of U favors reduction of U(V) to U(IV) in aqueous solution, and the pentavalent oxidation state is the least stable oxidation state in solution. U(V) disproportionates in acidic aqueous solution by the reaction:

$$2UO_2^{+} + 4H^{+} \rightarrow UO_2^{2+} + U^{4+} + 2H_2. \quad (49)$$

However, the U(VI) species UO_2^{2+} is the most stable in low concentrations in the pH 2 to 4 range (Katz et al. 1986).

It is the disproportionation reaction of U(V) that limits it to trace level concentrations. U(VI) is a stable oxidation state, even under mildly reducing conditions, but may be reduced to U(IV) by a variety of reducing agents. In the chemically reducing environment expected in the WIPP, U(VI) will be reduced to U(IV). However, Reed et al. (1996) found that at pH 10 under anoxic conditions, U(VI) is stable as a CO_3^{2-} complex in simulated WIPP brines. U(IV) is the predominant oxidation state in half of the PA vectors, and U(VI) in the other half, due to uncertainty predicting the more stable oxidation state of U under WIPP conditions.

SOTERM-4.3 Neptunium

In the natural environment, Np may exist in the +IV, +V, and +VI oxidation states (Hobart 1990; Keller 1971; Clark et al. 1995). In the WIPP, Np(IV) is expected to be present (Rai and Strickert 1980; Rai et al. 1982; Kim et al. 1985; Pryke and Rees 1986). Np(V) appears to be the dominant oxidation state in natural groundwater (Hobart 1990). Nitsche and Edelstein (1985) observed that Np(V) is the most stable oxidation state in Yucca Mountain well water. Studies of the solubility of NpO_2OH in 1 M and 5 M NaCl at pH 6.5 suggest that Np(V) may be reduced to Np(IV) under these conditions (Kim et al. 1985; Neck et al. 1992). Np(VI) may be introduced into the WIPP or be produced by radiolysis, but it will not be stable in WIPP brines that contain or are in contact with reducing agents, such as metallic Fe or Fe(II) oxides and hydroxides. The reduction potential for the Np(VI)-Np(V) couple is +1.24 V in neutral solutions (Martinot and Fuger 1985, 651 et seq.) and +0.6 V in basic solutions (Katz et al. 1986, 470), suggesting that the potential for reduction of Np(VI) to Np(V) at a pH of about 9 will be about 1 V. Reed et al. (1996) found spectroscopic evidence for reduction of Np(VI) to Np(V) in ERDA-6 brine at pH 10, and observed total reduction of Np(VI) to Np(V) in G-Seep brine at pH 7. In the presence of organic ligands (see Section 5.0), Reed et al. (1996) observed rapid and complete reduction of Np(VI) to Np(V). Neck et al. (1995) showed Np(V)-CO_3^{2-} complexes to be stable in 5 M NaCl.

In order to capture the uncertainty in the redox speciation of Np, Np(IV) would be the dominant oxidation state in half of the PA vectors and Np(V) in the other half. However, Np is not transported in PA.

SOTERM-4.4 Plutonium

Pu can exist in the +III, +IV, +V, +VI, and +VII oxidation states (Katz et al. 1986, 781). Pu(III) is the favored oxidation state in acidic solutions, but oxidation of Pu(III) to Pu(IV) becomes progressively easier with increasing pH. This occurs because Pu(IV) features a very strong tendency to undergo hydrolysis, which has the effect of reducing the solution concentration of the free Pu(IV) ion Pu^{4+}. As the pH of a Pu solution is raised from acidic to neutral, Pu(IV) begins to precipitate, resulting in a shift of equilibrium concentrations of Pu(III) to Pu(IV). Consequently, Pu(III) is not a thermodynamically stable oxidation state in the basic environment that will be established by MgO in the WIPP (see Reaction (5) above). Although Pu(III) is unstable under expected WIPP conditions, Felmy et al. (1989) observed Pu(III) in PBB1 and PBB3 brines at neutral and slightly basic conditions.

Pu(V) and Pu(VI) can be produced from Pu(IV) under oxidizing conditions. It is not possible to produce Pu(V) by direct oxidation of Pu(IV) because the oxidation potential that must be applied exceeds the potential required for the oxidation of Pu(V) to Pu(VI). Therefore, in a solution with oxidizing conditions, any Pu(V) that arises from the oxidation of Pu(IV) will be immediately oxidized to Pu(VI). Pu(V) can be produced in solution only by first producing Pu(VI), followed by a carefully controlled reduction of Pu(VI) to Pu(V). Pu(V) may persist in neutral to basic solutions even when it is not the thermodynamically stable oxidation state, due to the reduction reaction's inverse fourth power dependence on the concentration of H^+, which can make the reduction of Pu(V) to Pu(IV) kinetically slow. Neither Pu(V) nor Pu(VI) will persist in significant quantities in the repository, since oxidizing conditions are required to produce them. Pu(VI) was shown to form complexes with Cl^- under oxic conditions in high-ionic-strength NaCl solutions (Clark and Tait 1996). Clark and Tait (1996) and Reed et al. (1996) showed the reduction of Pu(VI) to Pu(IV) by Fe and other reductants under expected WIPP repository conditions. Metallic Fe and Fe^{2+} reduce Pu(VI) in WIPP brines to either Pu(IV) or Pu(III). Clark and Tait (1996) and Felmy et al. (1996) experimentally observed the reduction of Pu(VI)-CO_3^{2-} complexes to Pu(IV) by either metallic Fe or Fe^{2+}. Reduction of Pu(VI) was also observed in the absence of CO_3^{2-}, but the oxidation state of the resulting species was not determined because the concentration was below the analytical detection limit, ca. 10^{-9} M. Neretnieks (1982) showed that dissolved actinides are reduced to a less soluble oxidation state and precipitated from moving groundwater upon coming in contact with Fe(II).

Pu(VII) can be produced in concentrated OH^- solutions that are also highly oxidizing. Pu(VII) will not be formed in the WIPP.

The DOE determined (Weiner 1996) that Pu(IV) will be the dominant oxidation state under WIPP conditions, but the possibility of the existence of Pu(III) cannot be excluded. As a result, Pu is modeled as Pu(III) in half of the PA vectors, and as Pu(IV) in half of the vectors.

SOTERM-4.5 Americium

Am(III) is the most stable aqueous oxidation state of Am (Katz et al. 1986, 912), and will be the only oxidation state of Am in the WIPP. Am(III) is not easily oxidized in aqueous solution (Hobart et al. 1982); however, Am(V) and Am(VI) are accessible at high pH under highly oxidizing conditions. Am(V) and Am(VI) are not stable in natural waters and are readily reduced. Am(V) and Am(VI) can oxidize H_2O, and as a result, they are thermodynamically unstable in aqueous solutions. Am(V) may be formed by oxidation of Am(III) by radiolysis products in NaCl solutions (Runde and Kim 1994), which may occur in microenvironments within WIPP disposal rooms, but Am(V) would not be stable in the homogeneous mixture of waste and brine. Solubility studies carried out by Pryke and Rees (1986) and Felmy et al. (1990) indicated that Am(V) is unstable in brine above pH 9 and reduces to Am(III). These studies also showed significant instability of Am(V) at pH 7. Due to the thermodynamic instability of Am(V) and Am(VI) in aqueous solution, and the lack of a credible mechanism for maintaining the highly oxidizing conditions necessary for persistence of these two oxidation states, Am(III) is the only oxidation state that is used in modeling the speciation and solubility of this element in the repository.

SOTERM-4.6 Curium

Cm is distinguished by the relatively great stability of the +III oxidation state with respect to oxidation or reduction (Katz et al. 1986, 970). The oxidation of Cm(III) is achieved only with the strongest oxidizing agents; one report claims evidence for an oxidation state higher than +IV (Korpusov et al. 1975). The Cm(III)-to-Cm(IV) transition has not been successfully induced by ozone or electrochemically, and the Cm(IV) phosphotungstate produced by oxidizing with peroxysulfate is considerably less stable than the Am(IV) analog (Katz et al. 1986, 971). Cm(III) is the only oxidation state expected to be stable in the WIPP. However, Cm is not transported in PA.

SOTERM-4.7 Summary of Oxidation-State Distributions

Table SOTERM-3 presents the oxidation-state distributions used in the CRA-2004 PA, the CCA PA, and the 1997 PAVT. Np would speciate entirely as Np(IV) in half of the PA vectors and as Np(V) in the other half, but Np is not transported in PA. Cm would speciate identically to Am, but Cm is not transported in PA.

Table SOTERM-3. Actinide Oxidation States Used for the CRA-2004 PA, the 1997 PAVT, and the CCA PA

Actinide Element	Oxidation States			
Th		+IV		
U		+IV		+VI
Pu	+III	+IV		
Am	+III			

SOTERM-4.8 Implications of the Source-Term Waste Test Program for Oxidation-State Distributions of Dissolved Actinides

The Actinide Source Term Waste Test Program (STTP) was an experimental program carried out at Los Alamos National Laboratory (LANL). The objective of the STTP was to examine the behavior of actinides in TRU wastes that will be present in the WIPP. The STTP was conducted by placing samples of various types of wastes from LANL in liter-scale (3-L) and drum-scale (65-gal) titanium (Ti) containers (Scherer and Villarreal 2000, 2001; Scherer et al. 2001a, 2001b, 2001c; Villarreal et al 2000; Villarreal et al. 2001a, 2001b, 2001c, 2001d; Villarreal et al. undated). This discussion focuses on the results from the liter-scale tests.

The samples were composed of process wastes solidified with Portland cement or Envirostone, and pyrochemical salts that resulted from Pu-refining processes. Metallic Fe and Nd, Th, U, Np, and Am were also added. Each waste sample was inundated with about 2 L of either Brine A or ERDA-6.

Pu(V) was identified in two of the liter-scale containers, and Pu(VI) was identified in three of these containers. The DOE's position is that the presence of Fe and other metals within the

WIPP will create and sustain a chemically reducing environment in the event of brine intrusion into the waste-disposal areas. The DOE further concludes that Pu will be maintained in the +III or +IV oxidation state due to the reducing conditions. The observance of Pu(V) and Pu(VI) in the STTP tests was noted by the EPA and the New Mexico Environmental Evaluation Group, which led to reexamination of the DOE position that Pu(V) and Pu(VI) are not expected to persist. The LANL reports on the STTP project consist primarily of process descriptions and extensive compilations of experimental data. The reports do not include extensive discussion of the meaning of the data, or explanations based on thermodynamic or kinetic principles.

Oxidized Pu was never observed in 34 of 39 liter-scale containers or in any of the 15 drum-scale containers, strongly supporting the DOE position that Pu will exist in the +III or the +IV oxidation state under the range of conditions that will exist within the repository. The data tables in the STTP final report are useful for plotting results on a container-by-container basis, to illustrate that in every case in which oxidized Pu was observed, the contents of the containers had not reached either a steady-state behavior or thermodynamic equilibrium. In many cases, first-order kinetic behavior was exhibited for both the solubilization and precipitation of solution components, including Pu. Solubilization of Pu due to oxidation as a consequence of build-up of radiolysis products is not supported by the data. A steady increase in radiolysis products, such as hypochlorite (OCl^-), would result in a steady-state condition of increased Pu(VI) concentrations. The presence of Pu(V) in two containers suggests that a reducing mechanism was available, which led to the reduction of Pu(VI) to Pu(V), followed by a kinetically slow reduction of Pu(V) to Pu(IV). LS-28 and LS-29 were the only two containers that exhibited Pu(VI) in large concentrations that did not decrease over time. However, LS-28 and LS-29 were pressurized with 60 bars of CO_2, and had pcH values about 5 (pH ≈ 4), conditions significantly different from those that will exist in the WIPP.

The STTP containers that were more nearly representative of WIPP conditions support the DOE position that oxidized Pu will not persist in the WIPP. The behavior of Nd, Th, U, Np, and Am in the STTP experiments also supports the DOE position that the solubilities of the actinides will be low in the event of brine influx into the repository.

SOTERM-5.0 THE ROLE OF ORGANIC LIGANDS

Organic ligands are present in the waste to be disposed of in the WIPP. Because organic ligands form dissolved complexes with the actinides, they could increase actinide solubilities. Therefore, the effects of these ligands have been included in the FMT calculations of actinide solubilities for the CRA-2004 PA. Organic ligands also form complexes with dissolved, cationic species of several metals that will be present in the repository, and thus metals compete with the actinides for the binding sites on these ligands. Therefore, the competitive effects of dissolved Mg^{2+} and Ca^{2+} have also been included in the solubility calculations for the CRA-2004 PA.

A number of organic ligands are capable of forming strong complexes with actinide ions, thereby increasing actinide solubilities . In general, the reactions that take place for one-to-one complexes are

$$An^{n+} + L^{m-} \rightleftharpoons AnL^{(n+m)}, \qquad (50)$$

where An is a general symbol for an actinide, with charge n, and L is a general symbol for an organic ligand with charge m. The apparent stability constant for this reaction is

$$\beta = [AnL^{(n+m)}]/[An^{n+}][L^{m-}] . \quad (51)$$

The square brackets indicate concentrations. The constant β is referred to as astoichiometric stability constant. If activities are used instead of concentrations, β is referred to as the thermodynamic stability constant.

Four organic ligands are included in FMT calculations of actinide solubilities: acetate ($CH_3CO_2^-$), citrate ($((CH_2CO_2)_2C(OH)(CO_2))^{3-}$, ethylenediaminetetraacetate (EDTA, $(CH_2CO_2)_2N(CH_2)_2N(CH_2CO_2)_2^{4-}$), and oxalate ($C_2O_4^{2-}$). These ligands are included in the solubility calculations because: (1) approximately 60 organic compounds were identified among the nonradioactive constituents of the TRU waste to be emplaced in the WIPP (Brush 1990; Drez 1991; DOE 1996a, Appendix B); (2) 10 of these 60 organic compounds could, if present in the WIPP, increase actinide solubilities because they are soluble in aqueous solutions such as WIPP brines, and because they form complexes with dissolved actinides (Choppin 1988); and (3) of these 10 H_2O-soluble organic ligands that form complexes with actinides (acetate, citrate, EDTA, and oxalate) were identified in the WIPP inventory (DOE 1996a).

Brush and Xiong (2003d) calculated the current concentrations of acetate, citrate, EDTA, and oxalate in WIPP brines that could be present in the repository after filling and sealing. Brush and Xiong (2003d) obtained the total masses of acetic acid, Na-acetate, citric acid, Na-citrate, Na-EDTA, oxalic acid, and Na-oxalate in the WIPP inventory (see Appendix Data, Attachment F). Brush and Xiong (2003d) then converted the total masses of each of these organic ligands to total moles, assumed that all these ligands will dissolve in any brine present in the repository after filling and sealing, and divided the total moles of each ligand by 29,841 m^3, "the smallest quantity of brine required to be in the repository [for] transport away from the repository" (Larson 1996). These calculations were carried out identically to those by Brush and Xiong (2003b) for the FMT calculations of actinide solubilities for the CRA-2004 PA, except that Brush and Xiong (2003b) used the masses of ligands reported by Crawford (2003, Table 2, column labeled "Scaled mass (kg)"), not the masses in Appendix Data, Attachment F.

Actinide solubilities were not recalculated using the corrected concentrations of organic ligands from Brush and Xiong (2003d) because the corrections decreased the ligand concentrations slightly. Because the concentrations of these ligands decreased, the actinide solubilities calculated using the uncorrected ligand concentrations of Brush and Xiong (2003b) are slightly higher than they would be if recalculated using the corrected ligand concentrations of Brush and Xiong (2003d).

Table SOTERM-4 provides: (1) the current, corrected concentrations of organic ligands calculated by Brush and Xiong (2003d) based on the masses in Appendix Data, Attachment F; (2) the ligand concentrations calculated by Brush and Xiong (2003b) based on the masses provided by Crawford (2003) (these concentrations were used for the actinide-solubility calculations for the CRA-2004 PA); and (3) the ligand concentrations calculated for the CCA

(CCA Appendix SOTERM, Table SOTERM-4) based on the masses of organic ligands provided by DOE (1996a). Mistakes were apparently made in the calculation of the ligand concentrations for the CCA, the most significant of which was the likely transposition of citrate and oxalate in CCA Appendix SOTERM, Table SOTERM-4.

Table SOTERM-4. Concentrations of Organic Ligands in WIPP Brines That Could Be Present in the Repository after Closure

Organic Ligand	Concentrations Based on Corrected CRA Inventory[1]	Concentrations Used in FMT for the CRA-2004 PA[2]	CCA[3]
Acetate	3.56×10^{-3} M	5.05×10^{-3} M	1.1×10^{-3} m
Citrate	2.71×10^{-4} M	3.83×10^{-4} M	7.4×10^{-3} m
EDTA	2.73×10^{-6} M	3.87×10^{-6} M	4.2×10^{-6} m
Oxalate	1.53×10^{-2} M	2.16×10^{-2} M	4.7×10^{-4} m

[1] Concentrations calculated by Brush and Xiong (2003d) based on the masses of organic ligands in Appendix Data, Attachment F.
[2] Concentrations calculated by Brush and Xiong (2003b) based on the masses of organic ligands provided by Crawford (2003).
[3] Concentrations calculated for the CCA (CCA Appendix SOTERM, Table SOTERM-4) based on the masses of organic ligands provided by DOE (1996a).

Stability constants for complexes between acetate, citrate, EDTA, lactate, and oxalate and the +III, +IV, +V, and +VI actinides (or oxidation-state analogs of these actinides) were determined to incorporate these complexes in the actinide-speciation-and-solubility models described above (see Section 3.4). Stability constants for complexes between these ligands and Mg^{2+} were also determined to include competition between Mg^{2+} and the actinides for the binding sites on these ligands. Choppin et al. (2001) provided the results of all of these experiments. Giambalvo (2002b, 2002e) incorporated these results in the FMT database used for the calculation of actinide solubilities for the CRA-2004 PA. Giambalvo (2003) described this database in detail.

Brush and Xiong (2003a) used FMT, the thermodynamic database described by Giambalvo (2003), and the concentrations of acetate, citrate, EDTA, and oxalate calculated by Brush and Xiong (2003b) to calculate the solubilities of the +III, +IV, and +V actinides for the CRA-2004 PA. (No lactate has ever been identified in the TRU waste to be emplaced in the WIPP.) In the FMT calculations with ligands, all four ligands (acetate, citrate, EDTA, and oxalate) were present simultaneously in Salado or Castile brine at the concentrations calculated by Brush and Xiong (2003b). In these calculations, the stability constants for the complexes formed by these ligands and Ca^{2+} were assigned the same values as the stability complexes formed by these ligands and Mg^{2+} (Giambalvo 2003). However, these calculations did not include competition from dissolved metals such as vanadium (V), chromium (Cr), nickel (Ni), copper (Cu), and lead (Pb), all of which could be present at significant concentrations due to dissolution of steels and other metallic constituents of TRU waste (CCA Appendix SOTERM, SOTERM.5). The results of the FMT calculations for the CRA-2004 PA demonstrate that acetate, citrate, EDTA, and oxalate will not form complexes with the +III and +IV actinides to a significant extent under expected WIPP conditions, and thus will not affect the +III and +IV actinide solubilities significantly (Brush and Xiong 2003d; Downes 2003a, 2003b).

SOTERM-6.0 MOBILE COLLOIDAL ACTINIDE SOURCE TERM

Colloidal particles will be generated in the repository as a result of microbial consumption of cellulosics, and corrosion of steel waste containers and waste constituents, by the hydrodynamic entrainment of colloidal-sized mineral fragments and several other mechanisms. Those colloidal particles may sorb dissolved actinides or the dissolved actinides themselves may form colloidal particles. In an intrusion scenario, actinide-bearing colloidal particles, together with dissolved actinides, may be transported to the Culebra by Castile or Salado brines present in the repository. Additional colloidal particles may be present in natural Culebra groundwater and could form additional actinide-bearing colloidal particles. After introduction to the Culebra, the dissolved actinides and actinide-bearing colloidal particles are transported by Culebra groundwaters. Colloidal actinides may also be transported through the fractured anhydrite interbeds of the Salado.

The actinide source term at the WIPP is defined as the sum of contributions from dissolved actinide species and mobile colloidal actinide species. Colloidal actinides that are not suspended in the aqueous phase (that is, not mobile) are not included in the colloidal actinide source term. Sorption of colloidal actinides onto fixed substrates will also reduce the mobile colloidal actinide source term, but no credit is currently being taken for reduction by that means.

In this section, the quantification of the mobile actinide-bearing colloid component of the actinide source term is described. The quantification of colloid-facilitated transport of actinides in the overlying Culebra, in the event of an intrusion into the repository, is described in Chapter 6.0 (Section 6.4.6.2.2) and Appendix PA, Attachment MASS, Section MASS-15.3.

SOTERM-6.1 Introduction

Colloidal particles are generally defined as particles with at least one dimension between 1 nm and 1 μm, suspended in a liquid, and maintained in suspension for very long periods of time by Brownian (random thermal) motion (Hiemenz 1986; Buddemeier and Hunt 1988; Stumm 1992, 1993). Those size boundaries are approximately defined on the basis of physical phenomena. Particles larger than about 1 μm are too large for Brownian motion to overcome gravitational forces, and the particles will rather quickly settle by gravity. An exception is the case of microbes, which are considered to be colloidal, but may exceed 1 μm. The specific gravities of microbes are typically quite close to that of the dispersant, and so they may not settle by gravitational forces. Generally, particles smaller than approximately 1 nm behave in transport like dissolved ionic species.

SOTERM-6.1.1 Formation and Behavior of Colloidal Particles

Inorganic colloidal particles have been reported to form by a variety of processes. Colloidal particles may form by condensation or homogenous nucleation from dissolved species when a mineral phase is supersaturated or as hydrolyzed precipitates of mixed metal ions (Kim 1992). Colloidal particles may also form by release of particles from bulk material due to disruption of fragile aggregates by changes in ionic strength or hydrodynamic forces, dissolution of a more soluble surrounding matrix (Buddemeier and Hunt 1988; Kim 1994), mechanical grinding of

mineral surfaces, or mechanical disruption of secondary minerals present at mineral surfaces (McCarthy and Zachara 1989).

Organic colloidal particles may form from microbial consumption of CPR materials, condensation reactions of organic molecules to form humic substances, or microbial activity. A variety of naturally occurring organic materials, such as viruses, microbes, and pollen, are colloidal-sized particles (McCarthy and Zachara 1989; Stumm 1992, 243).

Colloidal particles may interact with actinides to form radiocolloids in two ways (see, for example, Lieser et al. 1986a, 1986b, 1990; Kim et al. 1984a, 1984b; Buddemeier and Hunt 1988; Kim 1992, 1994). First, radiocolloids may form as a result of chemical reactions involving dissolved polyvalent actinide ions. Hydrolysis and condensation reactions have been shown to form actinide macromolecules in which the actinide ions are bridged with hydroxyl ions to form polymers. Those radiocolloids are termed "actinide intrinsic colloids," "true colloids," "real colloids," "Eigenkolloide," or "type I colloids."

A second means to form radiocolloids is by sorption of actinides by ordinarily nonradioactive colloidal particles. In the actinide environmental geochemistry literature, the nonradioactive colloidal particle has been called a "groundwater colloid." Once actinide sorption has occurred, the resulting radiocolloids may be called "pseudo colloids," "carrier colloids," "Fremdkolloide," or "type II colloids." The colloidal substrate for sorption may be a mineral fragment, a microbial cell, or a humic substance. Bates et al. (1992) recently described radiocolloids, which they called "primary colloids," forming in situ at the surfaces of vitrified radioactive waste as it reacts chemically with H_2O. Considering that coprecipitation is a continuum with adsorption (see, for example, Comans and Middleburg 1987; Stumm 1992, 253 et seq.), the "primary colloid" can be included in the carrier-colloid category, and more specifically, a mineral-fragment-type colloidal particle. A similar sort of colloid would form by isomorphous lattice substitution of actinide ions during mineral precipitation (that is, coprecipitation) or precipitation of actinide minerals.

In the traditional colloid-chemistry literature, two types of colloidal particles are defined on the basis of how they interact with the dispersant (see, for example, Alexander and Johnson 1949, 114; Vold and Vold 1983; Hirtzel and Rajagopalan 1985; Hiemenz 1986; Ross and Morrison 1988; Hunter 1991-1992). Hydrophobic colloids are stabilized by electrostatic forces, whereas hydrophilic colloids are stabilized by solvation forces. In light of increased knowledge of aqueous surface chemistry gained over the past two decades, the terms hydrophilic and hydrophobic must be used cautiously, because even hydrophobic surfaces have hydrophilic surface functional groups. It is important, however, to make the distinction between how those two types of colloidal particles behave, because they exhibit different kinetic stability behaviors in electrolytes.

Kinetic stability differs from thermodynamic stability. Thermodynamic stability refers to the chemical equilibrium between the colloidal particles and the dispersant, whereas kinetic stability refers to the rate at which colloidal particles in a colloidal dispersion are removed from suspension due to agglomeration followed by gravitational settling. Thermodynamic stability may be most important for actinide intrinsic colloids, because that type of colloid forms directly from solution by chemical reactions. Kinetic stability is inversely related to the rate of particle aggregation, which is dependent on the frequency and efficiency (the fraction resulting in

permanent joining) of collisions between colloidal particles. The behavior of colloidal particle types as a function of ionic strength is probably the single most important phenomenon affecting the importance of colloid-facilitated actinide transport at the WIPP.

Hydrophobic colloidal particles are kinetically stabilized and destabilized by electrostatic forces. In an aqueous dispersant, hydrophobic colloidal particles are attracted to one another by van der Waals forces. That electrostatic attraction is countered by repulsive forces generated by a cloud of counterions surrounding each particle (Lyklema 1978; Hiemenz 1986). In a kinetically stable colloidal dispersion, colloidal particles are usually repelled from one another before they get close enough to become agglomerated. However, as the ionic strength of the dispersion is increased, the thickness of the cloud of counterions is compressed, allowing closer particle-particle interaction. The net effect is that as colloidal particles come into proximity with one another in the dispersion, a greater chance for sticking exists, and so the rate of agglomeration increases. That phenomenon is very effective at removing colloidal particles from suspension even at fairly low ionic strengths over periods of hours to days. Mineral fragments, which are a hydrophobic colloid type, are affected by ionic strength in this way.

Hydrophilic colloidal particles are stabilized by solvation forces, which are largely independent of the ionic strength of the dispersant (Alexander and Johnson 1949). This type of colloidal particle is essentially a dissolved macromolecule. Humic materials are an example of the traditional hydrophilic colloid type. Two major categories of hydrophilic colloidal particles are recognized. Micelles are aggregates of dissolved monomers, that are in thermodynamic equilibrium with those monomers. Polyelectrolytes are charged polymers that are not in thermodynamic equilibrium with a monomeric species (examples of polyelectrolytes include gum arabic, gelatin, pectin, and proteins). An important distinction, therefore, is that micelles require a minimum threshold concentration of monomers (the critical micellization concentration, or c.m.c.) to form. In contrast, the formation of polyelectrolytes is not dependent on monomer concentration. Polyelectrolytes may act as an association colloid by adsorbing on hydrophobic colloidal particles. The resulting dispersions may be extremely kinetically stable (Hiemenz 1986, 659).

The kinetic stability of hydrophobic colloidal particles may be modified by coatings of steric stabilizing compounds, which themselves are essentially hydrophilic materials (also referred to as protective or association colloids) which modify the surface behavior to inhibit close interaction of particles. Such colloidal systems are rendered kinetically stable. Particles stabilized by organic compounds in seawater are an example of a sterically stabilized colloidal system. Microbes can be considered as stabilized in a similar manner, except that the stability is imparted by molecules (for example, polysaccharides), attached to the surface of the microbe, which have hydrophilic parts extending into the dispersant.

Colloidal particles may have rigid or flexible structures, which may affect the way in which they interact with the host rock during transport. “Hard-sphere” colloidal particles, such as mineral fragments, have discrete well-defined boundaries at the particle-H_2O interface, and are rigid. “Soft-sphere” colloidal particles, such as humic substances, have less distinct boundaries at the particle-H_2O interface, are flexible and may undergo conformational changes in response to environmental variations. “Soft-sphere” colloids are essentially dissolved macromolecules and

are closest in form and behavior to particles referred to as hydrophilic colloids in the traditional colloid-chemistry literature (Lyklema 1978; Hiemenz 1986).

SOTERM-6.1.2 Definition of Colloidal Particle Types

On the basis of the phenomena described in the previous section, several classification schemes have been proposed by various workers, and a large number of descriptive terms have evolved and been propagated in the literature. For actinide environmental geochemistry, most of the classification schemes are based on how the colloidal particle interacts with radionuclides. Colloidal particles are classified into the following four types for evaluation of the impact of colloidal particles at the WIPP site:

1. Mineral fragments are hydrophobic, hard-sphere particles that are kinetically stabilized or destabilized by electrostatic forces, and may consist of crystalline or amorphous solids. Mineral fragments may be made kinetically stable by coatings with steric stabilizers that prevent close contact. Mineral fragments may act as substrates for sorption of actinides or they may consist of precipitated or coprecipitated actinide solids.

2. Actinide intrinsic colloids are macromolecules of actinides that, at least in some cases, may mature into a mineral-fragment-type of colloidal particle. When immature, they are hydrophilic; when mature, they become hydrophobic.

3. Humic substances are hydrophilic, soft-sphere particles that are stabilized by solvation forces. They are often powerful substrates for uptake of metal cations and are relatively small (less than 100,000 atomic mass units).

4. Microbes are relatively large colloidal particles that are stabilized by hydrophilic coatings on their surfaces, which behave as steric stabilizing compounds. They may act as substrates for extracellular actinide sorption or they may actively bioaccumulate actinides intracellularly.

SOTERM-6.2 Performance-Assessment Implementation

Results of the colloidal actinide investigation were used in the CRA-2004 PA, the CCA PA, and the 1997 PAVT in three types of parameter values: (1) constant concentration values; (2) concentration values proportional to the dissolved actinide concentration; and (3) maximum concentration values. The parameter types are summarized below and are described in parameter record packages (Papenguth 1996a, 1996b, 1996c, 1996d).

For actinide intrinsic colloids and mineral-fragment colloids, actinide concentrations associated with them were described as constant values. Table SOTERM-5 summarizes the material and parameter names and descriptions.

Experiments conducted to quantify actinide concentrations associated with humic substances and microbes provided the basis for a more sophisticated representation, in which colloidal actinide concentrations were related to the dissolved actinide concentration by proportionality constants. For microbes, the proportionality relationship was made by element. For humic actinides,

however, the relationship was made by oxidation state rather than by element. For microbes and humic substances, the experiments also provided a basis to define upper limits for the actinide concentration that could be associated with each of those colloid types. For both humic and microbial actinides, the upper-limit parameter was defined by element rather than oxidation state, and is in units of molarity. The use of the two upper-limit parameters is slightly different, and is described in the sections below discussing humic substances and microbes.

SOTERM-6.3 Development of Parameter Values

In this section, the experimental basis for the parameter values is described. For each of the four types of colloids, the characteristics of the colloidal particle type are described, the experimental program is outlined, methods of interpretation are described, and results are summarized.

Table SOTERM-5. Material and Property Names for Colloidal Parameters

Material	Property	Brief Description of Parameter
Th, U, Np, Pu, Am	CONCMIN	Concentration of actinide associated with mobile mineral fragment colloids
Th, U, Np, Pu, Am	CONCINT	Concentration of actinide associated with mobile actinide intrinsic colloids
Th, U, Np, Pu, Am	PROPMIC	Proportionality constant for concentration of actinides associated with mobile microbes.
PHUMOX3 [1] PHUMOX4 PHUMOX5 PHUMOX6	PHUMCIM	Proportionality constant for concentration of actinides associated with mobile humic colloids, in Castile brine, actinide solubilities are inorganic only (complexes with man-made organic ligands are not important), solubilities were calculated assuming equilibrium with Mg-bearing minerals (brucite and magnesite);
PHUMOX3 [1] PHUMOX4 PHUMOX5 PHUMOX6	PHUMSIM	Proportionality constant for concentration of actinides associated with mobile humic colloids, in Salado brine, actinide solubilities are inorganic only (complexes with man-made organic ligands are not important), solubilities were calculated assuming equilibrium with Mg-bearing minerals (brucite and magnesite).
Th, U, Np, Pu , Am	CAPMIC	Maximum (cap) concentration of actinide associated with mobile microbes;
Th, U, Np, Pu, Am	CAPHUM	Maximum (cap) concentration of actinide associated with mobile humic colloids.

[1] Proportionality constant for concentration of actinides associated with mobile humic substances, for PHUMOX3, for actinide elements with oxidation state ***+III*** (that is, Pu(III) and Am(III)); PHUMOX4, oxidation state ***+IV*** (Th(IV), U(IV), Np(IV), and Pu(IV)); PHUMOX5, oxidation state ***+V*** (Np(V)); and PHUMOX6, oxidation state ***+VI*** (U(VI)).

SOTERM-6.3.1 Mineral-Fragment Colloids

Mineral-fragment-type colloidal particles may be present in naturally occurring groundwaters, and they may be released from the host rock due to disruption of fragile aggregates by changes in ionic strength or hydrodynamic forces, dissolution of a more soluble surrounding matrix, mechanical grinding of mineral surfaces, or mechanical disruption of secondary minerals present at mineral surfaces. Under certain conditions, such as extreme changes in ionic strength of the groundwater or by physical disruption due to natural or human-induced events, mineral-

fragment-type colloidal particles could also be produced within the Culebra. In an intrusion scenario at the WIPP, mixing of repository brines with Culebra brines may result in mineral precipitation that may include coprecipitation of actinide-bearing mineral-fragment-type colloidal particles. Within the repository, mineral-fragment-type colloidal particles may form from corrosion of Fe-bearing waste and the steel packaging materials. In addition, Portland-cement-based matrixes will be attacked and will produce mineral-fragment-type colloidal particles. Bentonite, which may be a constituent of drilling mud is itself a potential source of mineral-fragment-type colloidal material that should be considered for actinide transport.

In terms of colloidal actinide transport, mineral-fragment-type colloids act as carriers, in that actinide ions sorb onto the surfaces of the colloids. Because each mineral substrate has a different affinity for actinides, quantification of actinide concentrations associated with the wide range of mineralogies likely to be present at the WIPP is insurmountable. Instead, a bounding approach was used based on residual concentrations of colloidal particles in WIPP-relevant brines coupled with estimates of reasonable maximum concentrations of actinides that could be sorbed onto the colloid surfaces. That approach requires three pieces of information: (1) the number of mineral-fragment-type colloidal particles in the aqueous phase; (2) the geometric surface area of individual colloidal particles; and (3) the site-binding capacity of the mineral surface. In the remainder of this section, descriptions of the determination of items (1) through (3), the interpretation of that information, and the development of parameter values are provided.

SOTERM-6.3.1.1 Description of Experiments

Hydrophobic colloidal particles, such as mineral fragments, are kinetically stabilized and destabilized by electrostatic forces (refer to detailed discussion in Papenguth and Behl 1996, Sections 2.5.1 and 2.6). In an aqueous dispersant, hydrophobic colloidal particles are attracted to one another by van der Waals forces. That electrostatic attraction is countered by repulsive forces generated by a cloud of counterions surrounding each particle. In a kinetically stable colloidal dispersion, colloidal particles are usually repelled from one another before they get close enough to become agglomerated. However, as the ionic strength of the dispersion is increased, the thickness of the cloud of counterions is compressed, allowing closer particle-particle interaction. The net effect is that as colloidal particles come into proximity with one another in the dispersion, a greater chance for sticking exists, and so the rate of agglomeration increases. That phenomenon is very effective at removing colloidal particles from suspension even at fairly low ionic strengths over periods of hours to days.

The kinetic stability of the mineral-fragment-type colloids in WIPP-relevant brines was evaluated in coagulation-series experiments. Colloidal dispersions of mineral fragments were prepared by mechanical disaggregation of representative mineral, rock samples, and other materials or by chemical precipitation from laboratory reagents. Brine simulants were prepared that covered the ranges of ionic strengths observed in WIPP brines. The brines were sequentially diluted with deionized H_2O by factors of 10 and adjusted to acidic, neutral, and basic pH conditions to evaluate the effects of ionic strength and pH on kinetic stability. At the ionic strength referred to as the critical coagulation concentration (c.c.c.), colloidal particles will rapidly coagulate, forming agglomerates large enough to settle by gravitational forces. The

number population of colloidal particles remaining in suspension in the various dispersions was measured over time to assess their stability as a function of solution ionic strength and time.

Colloidal dispersions were prepared for the following minerals or materials: bentonite, kaolinite, montmorillonite, vermiculite, illite, anhydrite, calcium carbonate, magnesite, hematite (mechanically disaggregated), hematite (chemical precipitate), limonite, goethite, magnetite, quartz, siderite, brucite, strontianite, diatomaceous earth, pyrite, and cellulosic materials (Masslinn paper towels and Scott paper towels). The brine solutions used included a Salado-like brine simulant (SPC brine) and a Culebra brine simulant (H-17). For c.c.c. experiments, sequential dilutions of those brines were made that spanned approximately five orders-of-magnitude. Brine simulants consisting of 0.5 M NaCl or $CaCl_2$ were also used. For the residual concentration measurements which were used as the basis for the CRA-2004 PA, the CCA PA, and the 1997 PAVT, the one order-of-magnitude dilution (that is, 10 percent of original strength) of the Salado-like brine and the Culebra brine simulants were used. That reduction in ionic strength provides a degree of conservatism in the results.

The c.c.c. experiments for the various concentrations of WIPP brine simulants were conducted under acidic (observed pH generally ranging from 3 to 4), neutral (pH 6 to 8), and basic (pH 9 to 12) conditions. Following the introduction of an aliquot of dispersed colloidal particles to a series of test tubes containing the sequentially diluted brine, colloidal particle concentrations remaining near the top of the fluid columns (residual concentration) were measured as a function of time. The degree of coagulation and settling was quantified using an inductively coupled argon-plasma atomic emission spectrophotometer, nephelometry, and direct particle counting.

Most of the experiments conducted relating to the kinetic stability of mineral-fragment colloidal particles were qualitative to semiquantitative, and were focused on evaluating whether a c.c.c. existed. For the final experiments, however, a state-of-the-art particle spectrometer was used with significantly greater sensitivity. That device was designed for semiconductor fabrication plants, which require extremely pure processing H_2O, and use a similar instrument to ascertain purity. The final experiments were conducted over an extended period of time using the more sensitive analytical technique to determine the number and size of colloids in the brine suspensions. Those experiments were conducted in a similar fashion to previous experiments for bentonite (supplied by the Aldrich Chemical Co.), goethite, and hematite (mechanically disaggregated), but in a relatively dilute (and therefore conservative) brine simulant consisting of 0.1 M NaCl. Residual particle concentrations made with the particle spectrometer compared favorably with measurements made with spectroscopic techniques made at similar experiment times. Generally after the first day of the c.c.c. experiments, the majority (greater than 99 percent) of the colloidal particles had already settled out of suspension. With the more sensitive particle spectrometer, however, residual concentrations of colloidal particles were observed to continue to decrease. For experiments analyzed by spectroscopic or light-scattering techniques, final residual colloid number populations remaining suspended in the test vessels were determined by multiplying the initial colloid number populations determined at the start of the experiments by the fraction of suspended colloids remaining at the final reading. Using the particle spectrometer, final number populations were measured directly.

SOTERM-6.3.1.2 Interpretation and Discussion

Parameter values (CONCMIN) describing the amount of actinide element bound by mineral-fragment-type colloidal particles were determined from the information described above, combined with estimates of adsorption-site densities.

Actinides sorbed to the surfaces of colloidal particles can be estimated using ranges of values for adsorption-site densities taken from published surface complexation modeling research. The actinide concentration contained by a single mineral-fragment-type colloidal particle is calculated by considering the geometrical surface area of a spherical particle:

$$[An]_p = \frac{\pi D^2 N_s}{N_A} , \qquad (52)$$

where:

$[An]_p$ = concentration of an adsorbed actinide element (mol/particle)
D = spherical colloidal particle diameter (nm)
N_S = adsorption site density (sites/nm^2)
N_A = Avogadro's number.

An adsorption-site density of 1 site/nm^2 was used for N_S in the above equation, a value which is realistic, but probably conservative. With that site density, 1-nm- and 1-μ-diameter particles could have a maximum of about 10^{-24} and 10^{-18} mol actinide per particle, respectively. To obtain an estimate of the maximum actinide concentrations that could be associated with the colloids, the estimates of residual colloid number populations were multiplied by the estimated maximum actinide-transport capacity described by Equation (52). The use of a uniform adsorption-site density is a conservative approach, because the actual sorption on mineral surfaces should be described by some kind of isotherm that will result in less than 100 percent coverage. Further, if multivalent adsorbates are present (for example, U(VI)), multiple adsorption sites may be required for one adsorbate ion, reducing the net adsorption capacity of the surface.

Final residual colloid populations quantified by spectrophotometry or nephelometry showed that mineral-fragment-type colloidal particles are kinetically destabilized by brines similar in composition to those present at the WIPP site. Colloid number population values were, with a few exceptions, reduced to less than 5 percent of the initial values within one day. Conservative estimates of maximum actinide concentrations associated with those residual colloid populations are on the order of 10^{-7} to 10^{-9} moles actinide per liter of dispersion.

The final experiments, which utilized the particle spectrometer to measure the quantity of colloids remaining in suspension offered the most sensitive estimates. Moreover, those experiments were conducted for substantially longer periods of time than the semiquantitative c.c.c. experiments. Those experimental results are shown in Table SOTERM-6.

Table SOTERM-6. Experimental Results for Mineral-Fragment Colloids

Mineral	Time of Final Reading (days)	Estimated Actinide Concentration (moles/liter dispersion)

Hematite	12.8	1.6×10^{-8}
Goethite	12.9	9.5×10^{-10}
Bentonite	12.8	1.6×10^{-10}
Geometric mean		1.3×10^{-9}

The DOE believes that the experimental results using the particle spectrometer with the three distinct colloids (hematite, goethite, and bentonite), are representative of other mineral-fragment-type colloidal particles in terms of their behavior in brine solutions. The geometric mean was assumed to be a more representative average of the final colloid concentrations than the arithmetic mean because of the very small final colloid concentrations (which, for this particular case, is also conservative).

Mineral-fragment-type colloidal particles are unique among the four colloidal particle types addressed for the WIPP, because their concentrations are not generally linked to solubility, as are actinide intrinsic colloids and humic substances, or to a maximum supportable population in the case of microbes. Consequently, in an intrusion scenario at the WIPP, as dissolved actinide elements are introduced to the Culebra, it is possible that those dissolved actinides could sorb onto a separate population of indigenous mineral fragments, producing a supplemental source term. To account for that possibility, the geometric mean value listed above was multiplied by a factor of two, producing a final "most-likely value" of 2.6×10^{-9} moles actinide per liter of dispersion.

To capture uncertainty, mainly stemming from knowledge of the adsorption-site density value, a triangular distribution with "minimum values" and "maximum values" spanning one order of magnitude about the geometric mean was provided for the CRA-2004 PA, CCA PA, and 1997 PAVT calculations. Additional conservatism is incorporated into the mineral-fragment-parameter values in that the total concentration of actinides carried by mineral fragment colloidal particles have essentially been multiplied by a factor of five, because a separate population of colloidal particles has been assumed for each actinide element. No consideration of competition for sorption sites is incorporated into the calculations. The value used for adsorption-site density is conservative, but reasonable. For the PA calculations, however, the triangular distribution was not sampled. Instead, the maximum parameter values were used as constant values, which essentially results in a site density of 10 sites/nm^2. Parameter values for CONCMIN are summarized in Table SOTERM-11. Section 7.0 of this attachment discusses details on PA implementation.

SOTERM-6.3.2 Actinide Intrinsic Colloids

Actinide intrinsic colloids (also known as true colloids, real colloids, type I colloids, and Eigenkolloide) form by condensation reactions of hydrolyzed actinide ions and consist solely of actinide cations linked by anions. There are several stages in the development of actinide intrinsic colloids at which they have significantly different behaviors. When immature, actinide intrinsic colloids display physicochemical properties that are similar to ionized humic substances. With age, they become more similar to mineral fragment-type colloidal particles.

The experimental approach used was strongly influenced by reviews of published literature on actinide intrinsic colloids. Pertinent literature is discussed below (see also Papenguth and Behl 1996).

SOTERM-6.3.2.1 Intrinsic Colloids of Plutonium

The most well-known and well-studied actinide intrinsic colloid is the Pu(IV) intrinsic colloid, which has been used as a basis of comparison for investigating intrinsic colloids of other actinides. Most of the knowledge about the Pu(IV) intrinsic colloid comes from research at high Pu concentrations in highly acidic solutions, which was conducted to help improve the efficiency of processing techniques. The Pu(IV) intrinsic colloid is notorious in its propensity to polymerize to form a gel-like material, which can even plug process lines.

A conclusive demonstration of the mechanisms of formation of the Pu(IV) intrinsic colloid has not yet been made, but there is a preponderance of evidence that suggests that polymerization is strongly linked to hydrolysis, and that the initial polymerization, or condensation, produces a macromolecule that becomes progressively more crystalline with time. The final mature colloid has a composition between $Pu(OH)_4(am)$ and $PuO_2(c)$, although the latter compound may be only partly crystalline and both may include interstitial H_2O molecules.

The most convincing and consistent explanation for the chemistry of the Pu(IV) intrinsic colloid is presented by Johnson and Toth (1978). Those authors developed a conceptual model to explain the solution chemistry of a variety of metal cations and a variety of oxidation states. The conceptual model involves processes referred to as “olation” and “oxolation” in which metal cations become bridged with hydroxyl groups, which in turn undergo irreversible elimination of H_2O and concurrent formation of O bridges. Johnson and Toth demonstrate that the model is consistent with the observed behavior of the Pu(IV) intrinsic colloid.

Hydrolysis reactions for metal cations such as Pu may be written as follows:

first: $$Pu^{4+} + H_2O \rightleftharpoons PuOH^{3+} + H^+ \quad (53)$$

second: $$PuOH^{3+} + H_2O \rightleftharpoons Pu(OH)_2^{2+} + H^+ \quad (54)$$

third: $$Pu(OH)_2^{2+} + H_2O \rightleftharpoons Pu(OH)_3^{+} + H^+ \quad (55)$$

fourth: $$Pu(OH)_3^{+} + H_2O \rightleftharpoons Pu(OH)_4\,(aq) + H^+ \quad (56)$$

Johnson and Toth (1978) point out, however, that in interpreting the formation of the Pu(IV) intrinsic colloid, it makes better sense to include the implied waters of hydration that surround metal cations in solution. Hydrolysis Equations (53) through (56) can be rewritten as follows, where n equals 4:

first: $$[Pu(H_2O)_m]^{n+} \rightleftharpoons [Pu(OH)(H_2O)_{m-1}]^{n-1} + H^+ \quad (57)$$

second: $$[Pu(H_2O)_{m-1}]^{n-1} \rightleftharpoons [Pu(OH)(H_2O)_{m-2}]^{n-2} + H^+ \quad (58)$$

third: $$[Pu(H_2O)_{m-2}]^{n-2} \rightleftharpoons [Pu(OH)(H_2O)_{m-3}]^{n-3} + H^+ \quad (59)$$

fourth: $$[Pu(H_2O)_{m-3}]^{n-3} \rightleftharpoons [Pu(OH)(H_2O)_{m-4}]^{n-4} + H^+ \quad (60)$$

From the literature, it is clear that polymerization occurs nearly immediately after the first hydrolysis (Equation (57)) occurs. Johnson and Toth (1978) suggest the following reaction involving polymerization of two hydrolyzed species by loss of H_2O (oxolation):

$$2\{[(H_2O)_{d-2}Pu(OH)(H_2O)]^{+(y-1)}\} \rightleftharpoons [(H_2O)_{d-2}Pu(OH)(OH)Pu(H_2O)_{d-2}]^{+2(y-1)} + 2H_2O \quad (61)$$

Aging or maturation of polymer then occurs by loss of H_2O (olation) as follows:

$$[Pu(OH)(OH)Pu(OH)(OH)Pu(OH)(OH)...] \rightleftharpoons [Pu(O)Pu(O)Pu(O)...]_n + 3nH_2 \quad (62)$$

Maiti et al. (1989) and Laul et al. (1985) describe similar reactions, but it appears that they believe that the third hydrolysis reaction occurs, because they use the $Pu(OH)_3^+$ion in their proposed polymerization reaction. Use of that ion does not appear to be consistent with observations by many workers that polymerization occurs immediately after the first hydrolysis reaction.

As the actinide polyelectrolytes mature through the olation process to become closer in composition to an actinide-oxide mineral, they will be kinetically destabilized by the high ionic strengths of the WIPP brines and will not be mobile. Further, the solubilities of the mature solid phase cannot be exceeded. In fairly long-term experiments, Nitsche et al. (1992, 1994) showed that the concentration of Pu(IV) intrinsic colloid stabilized at about 10^{-8} M. It is not known whether the form was Pu(IV) polyelectrolyte or Pu(IV) mineral-fragment-type colloid.

SOTERM-6.3.2.2 Intrinsic Colloids of other Actinides

Reference is made to a variety of intrinsic colloids of other actinides, but no systematic investigations of their formation and behaviors appear to have been made. Pu is apparently unique in its propensity to form an intrinsic colloid. No mention is made in the literature of maturation of polyelectrolytes of other actinides to form mineralfragment-type colloidal particles as Pu does.

In general, the tendency of actinides to hydrolyze and to polymerize to form intrinsic colloids follows the order:

$$An^{4+} >> An(VI)O_2^{2+} > An^{3+} > An(V)O_2^+ \quad (63)$$

(Cleveland 1979a, 1979b; Choppin 1983; Kim 1992; Lieser et al. 1991, 119). The order of oxidation states in the equation above results from the ionic-charge-to-ionic-radius ratios. The tendency for hydrolysis of $An(VI)O_2^{2+}$ is greater than for An^{3+} because the effective charge on the central cation on the linear $[O\text{-}An\text{-}O]^{2+}$ ion is 3.3 ± 0.1, slightly greater than 3. This trend generally holds true for the actinide elements, because of the very small changes in ionic radii among the actinide (this is the oxidation-state analogy; refer to Novak et al. 1996). There are

differences in the behaviors of the actinides from element to element that stem from very subtle changes in the charge-to-radius ratio and the nature of the configuration of the f molecular orbital.

Considering Pu as an example, hydrolysis becomes significant for Pu^{4+}, $Pu(VI)O_2^{2+}$, Pu^{3+}, and $Pu(V)O_2^{+}$ at pH values of <1, 4-5, 6-8, and 9-10, respectively (Choppin 1983). On the basis of the hydrolysis trend, it is not likely that An(III) and An(V) species will form actinide intrinsic colloids. There are suggestions in the literature, however, that Am^{3+} may form an intrinsic colloid, which is surprising because it does not undergo hydrolysis until relatively high pH. Th does not follow the trend described by Equation (63) because its large size makes it resistant to hydrolysis (Cotton and Wilkinson 1988). Nevertheless, thermodynamic data suggest that in almost all environments (near neutral or higher pH) Th exists as $Th(OH)_4(aq)$. Moreover, Th has been reported to form a polymer (Kraus 1956; Johnson and Toth 1978), although as discussed below, this species should be referred to as an oligomer.

Examples can be found in the literature of polymeric species of many of the actinides of importance to the WIPP (see, for example, Baes and Mesmer 1976; Kim 1992). It is important, however, to note the sizes of polymers described in the literature. It is well known that as polyvalent metals, the actinides can form polynuclear species, but they are largely lower polymers (that is, oligomers) such as dimers, trimers, tetramers, and hexamers (see, for example, Choppin 1983, 46). However, in terms of physical-transport behavior, lower polymers will behave no differently than dissolved monomeric species. In contrast, the higher polymers, such as the Pu(IV)-polymer, may reach colloidal sizes (1 nm to 1 μm) and will have different hydrodynamic properties than the subcolloidal-sized dissolved species. Johnson and Toth (1978) reported a molecular weight of 4000 for a Th polymer. Assuming that it consisted of $Th(OH)_4$, that polymer would consist of about 13 Th ions (that is, the degree of polymerization number, N). That observation is consistent with Kraus (1956), in which he quotes an N value of about 9 for Th polyelectrolyte.

Empirical evidence published in the literature does not always support the suggestion that Am, as a trivalent cation, will form an intrinsic colloidal particle. Avogadro and de Marsily (1984) suggested that, like Pu, Am is a likely candidate to form an insoluble hydroxide. Buckau et al. (1986) reported the formation of Am(III) intrinsic colloids at near neutral pH conditions, with a particle size greater than 1 nm. In their study of the hydrolysis of Am(III) over a pH range from 3 to 13.5, however, Kim et al. (1984a) found only monomers of Am. Regardless of whether Am(III) intrinsic colloids will form under highly idealized laboratory environments, it would be highly unlikely that they would form in a geologic system, because of the tremendously strong sorption properties of the Am(III) ion.

SOTERM-6.3.2.3 <u>Experimental</u>

The objective of experiments, conducted at Lawrence Livermore National Laboratory (LLNL), was to test phenomena described in the published literature, under WIPP-relevant conditions:

- critical coagulation concentration for mature Pu(IV) mineral-fragment-type colloid (refer to description of experiment AIC-1 in Papenguth and Behl (1996));

- formation of Pu(IV) colloid, from oversaturation and undersaturation in the absence of CO_2 (AIC-8 and AIC-9, respectively);
- inhibition of Pu(IV) polymerization due to organic complexants (AIC-2);
- depolymerization of Pu colloid due to organic complexants (AIC-2b);
- polyelectrolyte chain termination by nonactinide metal cations (AIC-4); and
- sorption effects of WIPP repository substrates on Pu(IV) colloid (AIC-5).

The last four experiments listed above provide evidence that, under some conditions at the WIPP, the Pu(IV) colloid is less likely to form or is sorbed. To parameterize the CRA-2004 PA, CCA PA, and 1997 PAVT, however, the first two experiments listed above were used. Both sets of experiments (AIC-1, AIC-8/9) can essentially be viewed as solubility experiments. The critical coagulation-experiments are solubility experiments conducted from undersaturation conditions, in which the in-growth of free Pu(IV) is observed (and are therefore equivalent to AIC-9). In both sets of experiments (AIC-1, AIC-8/9), the Pu solution concentration is measured as a function of time for as long as five weeks, as steady-state concentration is being reached. The two sets of experiments were anticipated to provide information to resolve the question of kinetic versus thermodynamic stability control on the formation and development of the Pu(IV) colloid. That question was not resolved, but the data still provide the necessary information for parameterizing the PA calculations. The values for the parameters submitted for calculations were derived from the experiments listed in Table SOTERM-7.

Table SOTERM-7. Pu Intrinsic-Colloid Experiments

Number	Experiment	Starting Material	pcH approx.	NaCl (m)	Duration
AIC-1	c.c.c. (equivalent to undersaturation experiment AIC-9)	Pu(IV) colloid: aged 1 month: about 2×10^{-4} M	4 7 10	0.001 0.01 0.1 0.8 3.0 5.0	3 to 5 weeks
AIC-8	Oversaturation	Pu(IV) aquo ion: about 1×10^{-4} M	3 7 10	0.05 0.5 1.0 5.0	4 weeks

The data from those experiments are plotted in Figure SOTERM-3 along with regression lines for data collected by Rai et al. (1980) for $Pu(OH)_4$(am) and PuO_2 and Rai and Swanson (1981) for Pu(IV) polymer under acidic conditions. With MgO, the pH of the

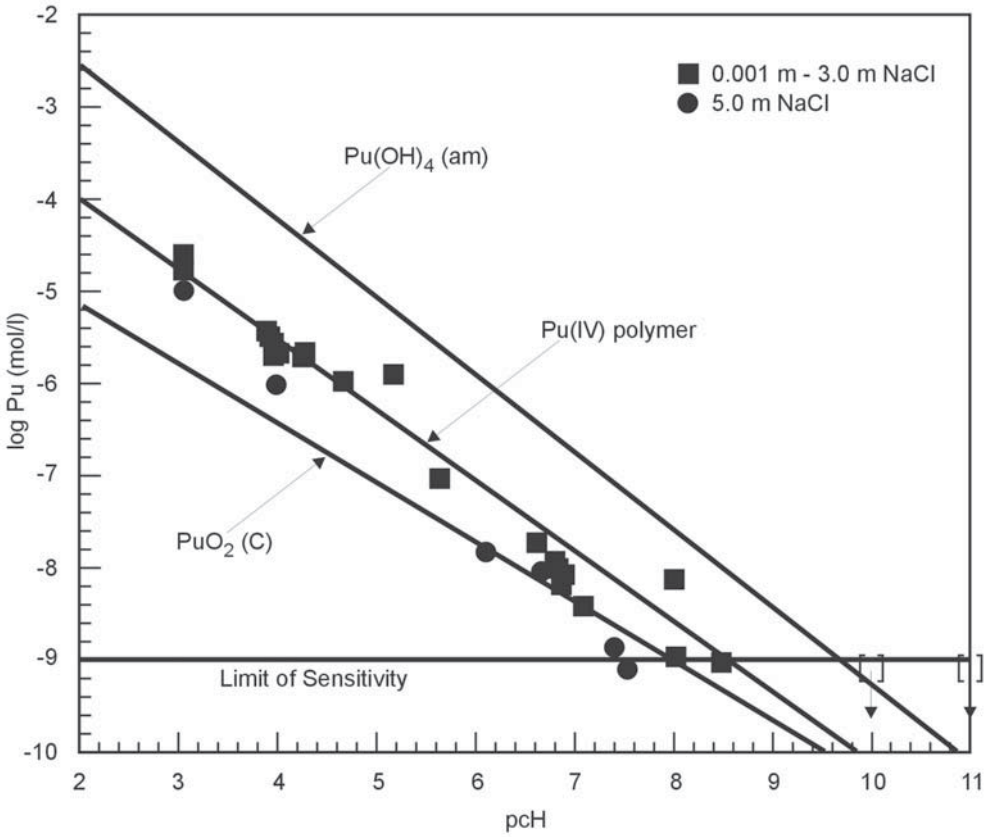

NOTE 1: Open brackets with arrows pointing down indicate Pu concentration is below the minimum analytical detection limit. Solubility lines for $Pu(OH)_{4amorphous}$ and $PuO_{2crystalline}$ are extrapolated from Rai et al. (1980). The solubility line for Pu(IV)-polymer is extrapolated from Rai and Swanson (1981). Plotted values were collected at LLNL as part of the WIPP colloid research program.

NOTE 2: Note that under basic pH conditions fixed by MgO, the solubility of the Pu(IV)-polymer is below the minimum analytical detection limit of 10^{-9} M.

CCA-SOT010-0

Figure SOTERM-3. Solubility of Pu(IV) Polymer in NaCl Media as a Function of pcH.

repository brine is expected to be between 8.69 and 9.02 (see Section 2.0), equivalent to a pcH of 9.40 to 9.72. As shown in Figure SOTERM-3, the regression line calculated from the LLNL data suggests that at a pcH of 9.40 to 9.72, the solubility of Pu(IV)-polymer is less than the minimum analytical detection limit of 1×10^{-9} M. Therefore, the detection limit was selected for use in PA. The LLNL results are consistent with the extrapolated relationships based on published results of Rai et al. (1980) and Rai and Swanson (1981).

SOTERM-6.3.2.4 Interpretation and Discussion

Parameter values (CONCINT) describing the amount of actinide element bound by actinide intrinsic colloidal particles was determined from the information described above. For the Pu(IV) polymer, the minimum analytical detection limit was selected. In the absence of conclusive evidence that intrinsic colloids of other actinides form, or form polymers rather than oligomers, the concentration of Th, U, Np, and Am intrinsic colloids was set to zero.

Geochemical conditions in the Culebra are not conducive to the formation of a new supplementary population of actinide intrinsic colloids. In particular, the concentration of actinide ions is reduced. Therefore, the source term for actinide intrinsic colloids reflects what would form in the WIPP repository, under most favorable conditions for the formation of the Pu(IV) polymer.

Parameter values for CONCINT are summarized in Appendix PA, Attachment SOTERM, Table SOTERM-11.

SOTERM-6.3.3 Humic Substances

Humic substances are defined as high-molecular-weight organic compounds generally present as anions in natural waters. Humic substances may consist of humic acids, which may be aliphatic or aromatic, or fulvic acids. The difference between humic acids and fulvic acids is largely an operational distinction; humic acids can be precipitated at pH values below about 2, whereas fulvic acids are soluble over the entire pH range. Fulvic acids generally have lower molecular weights than humic acids. The dominant functional group that may react with dissolved actinides are carboxyl groups, but phenolic hydroxyl and alcoholic hydroxyl groups also contribute to complexation. At the WIPP, humic substances may be introduced to the repository as a constituent of soil-bearing waste or may be a constituent of the organic-carbon (C) component of Castile, Salado, or Culebra groundwaters. Probably more importantly, humic substances may form from condensation reactions between microbial metabolites (for example, carboxylic acids), byproducts of the consumption of cellulosic materials, and the extracellular polymers associated with microbes. Because of the general lack of knowledge in the scientific community regarding the formation of humic substances, as well as very slow kinetics of formation, a direct attempt has not been made to quantify the amounts of humic substances that would form in situ. Instead, the contribution of humic-bound actinides was bounded through quantification of humic-actinide complexation behavior coupled with quantification of solubilities of humic substances in WIPP-relevant brines. Regardless of the source of humic substances, the total concentration of humic substance available to mobilize actinides is limited by the solubility of humic substances in WIPP brines. The chemical nature of humic substances generated in situ cannot be predicted either, but can be bounded by the three types of humic substances.

To determine the concentration of actinides associated with humic substances, four pieces of information are required: (1) the concentration of reactive humic substance in the aqueous phase (humic solubility); (2) the binding capacity of the humic substance; (3) actinide uptake (that is, actinide complexation constants); and (4) actinide solubilities. The quantification of actinide solubilities is described in Novak and Moore (1996) and results are summarized in Siegel (1996). In the remainder of this document, the focus is on the determination of items 1 through 3, the interpretation of that information, and the development of parameter values suitable for the CRA-2004 PA, CCA PA, and 1997 PAVT calculations.

SOTERM-6.3.3.1 Experimental

In general, humic substances encompass a broad variety of high-molecular-weight organic compounds. The range of their chemical behaviors, however, is covered by consideration of

three types: aliphatic humic acid (generally terrestrial); aromatic humic acid (generally marine); and fulvic acid. The following humic substances were used:

- FA-Suw: fulvic acid isolated from the Suwannee River acquired from the International Humic Substances Society, Golden, Colorado;
- HAal-LBr: aliphatic humic acid isolated from sediments collected from Lake Bradford, Florida, prepared by Florida State University;
- HAal-Ald: aliphatic humic acid purchased from Aldrich Chemical Co., purified by Florida State University;
- HAar-Gor: aromatic humic acid isolated from groundwaters near Gorleben, Germany, obtained from Professor J.-I. Kim, Institute for Radiochemistry, Munich; and
- HAar-Suw: aromatic humic acid isolated from the Suwannee River acquired from the International Humic Substances Society, Golden, Colorado.

Solubilities were measured in experiments conducted over periods of several weeks. The solubilities of humic substances remaining in the fluid column were determined using a scanning fluorometer, C coulometer, and UV/Visible light spectrophotometer, in WIPP-relevant brine simulants with FA-Suw, HAal-LBr, HAal-Ald, and HAar-Suw. In addition to spectroscopic data, visible inspection proved valuable. In oversaturation experiments, humic substances were dissolved in deionized H_2O under basic conditions to enhance dissolution and then added as a spike to a brine . In undersaturation experiments, humic substances were added directly to brines and allowed to dissolve until equilibrium was reached. In either case, equilibrium was reached between dissolved (that is, ionic) and precipitated humic substances. The precipitated humic substances coagulated and settled. The kinetics of precipitation were sufficiently slow that several weeks were required for equilibrium to be reached. Brines consisted of a NaCl matrix with various concentrations of Mg^{2+} and Ca^{2+}. The concentration of Na^{+} in the brine had little effect on solubility except at very high concentrations, but the concentration of the divalent cations had a significant impact on humic-substance solubilities. Consequently, experiments were conducted with a NaCl background electrolyte concentration with concentrations of Mg^{2+} and Ca^{2+} ranging from 10 mM each (representative of natural WIPP brines) to 500 mM each (representative of MgO). At Sandia National Laboratories (SNL), solubilities between approximately 1.5 mg/L and 2.0 mg/L were observed in systems containing 10 mM or greater Mg^{2+} and Ca^{2+}. For the calculations described below, the higher solubility value of 2.0 mg/L was used.

Site-binding-capacity values were determined by titration at Florida State University for two humic substances (HAal-LBr and HAal-Ald). Those values were supplemented with values for a variety of humic substances compiled from published literature. In general, site-binding capacities for humic substances are between 3 and 6 meq OH^{-}/g, but in isolated cases are as low as about 1.5 and as high as about 9.5 meq OH^{-}/g. For the calculations described below, values of 4.65, 5.38, and 5.56 meq OH^{-}/g were used for aliphatic humic acid, aromatic humic acid, and fulvic acid, respectively. The aliphatic humic acid value was determined from HAal-LBr at Florida State University. The aromatic humic acid value was from Gorleben (Gohy-573). The

fulvic acid value represents the mean of 11 published values for fulvic acids collected in Europe (Ephraim et al. 1995).

Actinide complexation factors for U(VI) and Am(III) binding on three humic substances (FA-Suw, HAal-LBr, and HAar-Gor) were measured at Florida State University. Complexation measurements were made at measured pH_{obs} values of approximately 4.8 and 6, conditions at which the humic substances are highly deprotonated, and U and Am have not undergone extensive hydrolysis. Those conditions were chosen to maximize complexation between the humic substances and those actinide elements. Measurements were made in NaCl media with ionic strengths of approximately 3 and 6 m. These experiments were completed prior to the DOE establishing the position that MgO would be emplaced to sequester CO_2 and fix pH at about 9. The experiments conducted at Florida State University represent conservative conditions designed to provide high-end estimates of actinide uptake by humic substances. Actinide complexation by humic substances generally decreases at basic pH values because of the reduction in actinide-complex charges due to hydrolysis. In addition, the high concentrations of Mg^{2+} in solution due to the presence of MgO will compete with actinides for binding sites on humic substances and reduce the actinide uptake. Florida State University reported the first and second stability constants defined as follows (square brackets represent concentration):

$$An + HS \rightleftharpoons AnHS;\ \beta_{1;An} = [AnHS]/[An][HS] \tag{64}$$

$$An + 2(HS) \rightleftharpoons An(HS)_2;\beta_{2;An} = [An(HS)_2]/[An][HS]^2 \tag{65}$$

where:

HS = humic substance (eq OH-/L, that is, site-binding capacity incorporated)
An = actinide element
$\beta_{1;An}$ = first stability constant, for 1:1 An:humic binding
$\beta_{2;An}$ = second stability constant, for 1:2 An:humic binding

For the calculations described below, complexation constants were selected from the most relevant experimental conditions, which were pH_{obs} 6 and 6 m NaCl. The following stability constants reported by Florida State University were used (reported as log values), as shown in Table SOTERM-8.

Table SOTERM-8. Humic Substances Experimental Results

Humic Substance	Am^{3+} : β_1	Am^{3+} : β_2	$U(VI)O_2^{2+}$: β_1	$U(VI)O_2^{2+}$: β_2
HAal-LBr	6.09 +/- 0.05	10.46 +/- 0.12	5.91 +/- 0.16	10.43 +/- 0.19
HAal-Gor	6.02 +/- 0.04	10.40 +/- 0.10	5.35+/- 0.15	8.98 +/- 0.26
FA-Suw	4.6 +/-0.3	8.95 +/- 0.45	Not measured	Not measured

The Florida State University results show that there is little difference in $U(VI)O_2^{2+}$ and Am(III) uptake by aliphatic and aromatic humic acids, but that uptake by fulvic acid is significantly less. The Florida State University results also show that an increase of NaCl ionic strength from 3 to 6 has little effect on actinide uptake. Those observations aid in justifying the use of published stability constants for other actinide elements experimentally determined at lower ionic strengths and for other humic substances. On the basis of the similarities in stability constants for $U(VI)O_2^{2+}$ and Am(III) for the humic acids, SNL has used the Am(III) stability constant for FA-Suw for $U(VI)O_2^{2+}$ on FA-Suw.

Stability constants for Th(IV) with several humic and fulvic acids were reported by Nash and Choppin (1980). In NaCl media at pH values between 3.95 and 5.03, those authors reported log stability constants between 9.7 and 13.2. Under the mildly basic conditions expected in the WIPP repository, it is likely that complexation of Th(IV) will be markedly less, because the dominant Th(IV)-bearing aqueous species will be $Th(OH)_4(aq)$ (Novak and Moore 1996). No reports of direct investigations of Th-complex binding on humic substances were found. For the calculations described herein, the published results from Baskaran et al. (1992) describing the distribution of Th(IV) in seawater were used. From that work, a ratio of dissolved versus colloidal Th(IV) of 6.349 was calculated, assuming that the solubility of colloidal organic material in seawater is equivalent to our measured value of humic substances in WIPP-relevant brines (that is, 2.0 mg/L). The nature of the humic substances is likely to be dominated by aromatic humic acid, but may also contain fulvic acid.

For the calculations described herein, a log stability constant for $Np(V)O_2^{+}$ of 3.67 measured at pH 9 for a Gorleben humic acid (Gohy-573; Kim and Sekine 1991) was used. Results presented in Rao and Choppin (1995) for Lake Bradford humic acid and a Gorleben humic acid (Gohy-573) show little effect of pH on Np(V) stability constants, presumably because of the absence of Np(V) hydrolosis over the pH range studied. The Gorleben humic acid is aromatic in nature.

No published stability constants were found for Pu. For the calculations described herein, an oxidation-state analogy was used for the Pu oxidation species, an approach that is conservative. Allard et al. (1980) have shown that at pH 9, Pu(IV) undergoes hydrolysis to a greater extent than Th(IV), which should result in reduced complexation of Pu(IV).

An oxidation-state analogy was used to develop parameter values for elements expected to have multiple oxidation states in the WIPP repository. Redox speciation of the actinide elements was evaluated as part of the dissolved ASTP. Weiner (1996) concluded that in the WIPP, the following species will be present: Th(IV); U(IV) and U(VI); Np(IV) and Np(V); Pu(III) and Pu(IV); and Am(III). The relative concentrations of the oxidation states of a particular element

are designated by their respective solubility values. The substitutions made following the oxidation-state analogy are summarized in Table SOTERM-9.

Table SOTERM-9. Oxidation State Analogy Substitutions

Required Binding Constant	Substitute	Source of Data
Th(IV)	None required	Baskaran et al. (1992)
U(IV)	Th(IV)	Baskaran et al. (1992)
U(VI)	None required	WIPP-specific data, Florida State University
Np(IV)	Th(IV)	Baskaran et al. (1992)
Np(V)	None required	Kim and Sekine (1991)
Pu(III)	Am(III)	WIPP-specific data, Florida State University
Pu(IV)	Th(IV)	Baskaran et al. (1992)
Am(III)	None required	WIPP-specific data, Florida State University

To compensate for the effects of competition for actinide complexation by the high concentrations of Mg^{2+} and Ca^{2+} in repository brines in the presence of MgO, stability constants for Mg^{2+} and Ca^{2+} were used in simultaneously solved equations (described below). Stability constants for Mg^{2+} and Ca^{2+} at basic pH values are not available, but several published reports provide values in the acidic range. Choppin and Shanbhag (1981) reported log stability constants of 2.25 to 3.32 for Ca^{+} in 0.1 M sodium perchlorate ($NaClO_4$) at pH 3.9 and 5.0 for an aliphatic humic acid (Aldrich humic acid). Schnitzer and Skinner (1967) reported log binding constants ranging from 2.2 to 3.72 for Ca^{2+} in low-ionic strength solutions over a pH range of 3.5 to 5.0 for fulvic acid. For Mg^{2+}, Schnitzer and Skinner (1967) reported log stability constants ranging from 1.23 to approximately 2.0 under the same experimental conditions. For the calculations, a log stability constant of 2.0 for the sum of Mg^{2+} and Ca^{2+} concentrations was used, which is a conservative value.

Binding of Mg^{2+} and Ca^{2+} to humic substances is described in the same way as Equation (64) above:

$$(Mg + Ca) + HS \rightleftharpoons (Mg,Ca)HS;\ \beta_{1;Mg,Ca} = [(Mg,Ca)HS]/[Mg + Ca][HS] \qquad (66)$$

where:

$\beta_{1;Mg,Ca}$ = first stability constant, for 1:1 (Mg + Ca):humic binding (note that no second stability constants exist for divalent-cation binding).

SOTERM-6.3.3.2 <u>Interpretation and Discussion</u>

Proportionality constants (PHUMCIM and PHUMSIM) describing the amount of actinide element bound to humic substances were determined from the data listed above, coupled with dissolved actinide concentrations. In addition, maximum theoretical concentrations of actinides that could be associated with humic substances (CAPHUM) were calculated from the data above.

The concentration of an actinide element of a given oxidation state was calculated by simultaneous solution of Equations (64) and (66), combined with a mass-balance expression:

$$[HS_{tot}] = [AnHS] + [(Mg,Ca)HS] + [HS] \quad (67)$$

where:

$[HS_{tot}]$ = total concentration of humic substance
$[HS]$ = concentration of uncomplexed humic substance
$[AnHS]$ = concentration of humic complexed with an actinide element
$[(CaMg)HS]$ = concentration of humic complexed with divalent cations.

Equation (67) describes the effect of two humic substances binding with one actinide ion was disregarded for these calculations, because its contribution to the total humic-bound actinide concentrations was negligible.

Rearranging Equations (64) and (66) provides:

$$[AnHS] = \beta_{1;An}\,[An]\,[HS]\,, \quad (68)$$

$$[(Mg,Ca)HS] = \beta_{1;Mg,Ca}\,[Mg + Ca]\,[HS]\,. \quad (69)$$

Substituting Equations (68) and (69) into Equation (67) results in:

$$[HS_{tot}] = \beta_{1;An}\,[An]\,[HS] + \beta_{1;\,Mg,Ca}\,[Mg + Ca]\,[HS] + [HS]\,. \quad (70)$$

Rearranging Equation (70) provides:

$$[HS] = \frac{[HS_{tot}]}{\beta_{1;An}[An] + \beta_{1;CaMg}[Ca + Mg] + 1}\,. \quad (71)$$

Equations (68), (69), (70), and (71) were used to calculate humic-bound actinide concentrations ([AnHS]). The resulting AnHS concentration values were then summed for actinide elements with multiple oxidation states, and then divided by the dissolved concentration of the respective actinide element. The final forms of the parameter values PHUMCIM and PHUMSIM are proportionality constants in units of moles humic-bound colloidal actinide per mole of dissolved actinide. The proportionality values may be multiplied by the dissolved actinide concentration expressed in molarity or molality, depending on the desired final unit.

Depending on the intrusion scenario, the WIPP repository may be dominated by Castile brine or by intergranular Salado brine, resulting in different actinide solubilities, but also different solubilities of Mg^{2+} and Ca^{2+}. Under conditions characteristic of equilibrium with MgO, solubility parameters calculated for a system buffered by brucite and magnesite were used (Siegel 1996).

Equations (68), (69), and (71) were used to determine humic-bound actinide concentrations ([AnHS]) for one or more humic substance types for Th(IV), U(VI), Np(V), and Am(III). The oxidation-state analogy is most heavily utilized for Pu, because stability constants for Pu(III) or

Pu(IV) are not available. Concentrations of Mg^{2+} and Ca^{2+} in Salado and Castile brines in equilibrium with MgO were obtained from Novak and Moore (1996). In the PA calculations, the humic-bound actinide concentration in the +III oxidation state in Castile brine was sampled. All other humic-bound actinide concentrations were held constant.

The PHUMCIM and PHUMSIM parameters, used in conjunction with materials (idmtrls) PHUMOX3, PHUMOX4, PHUMOX5, or PHUMOX6, provide the means to calculate actinide-humic concentrations by actinide oxidation state and for intrusion scenarios involving different brines. For example, in an E1 scenario under strongly reducing conditions in the WIPP repository, PHUMCIM would be used with the following materials (idmtrls) to determine actinide-humic concentrations: Th = PHUMOX4; U = PHUMOX4; Np = PHUMOX4; Pu = PHUMOX3; and Am = PHUMOX3. For an E2 scenario under relatively less reducing conditions in the WIPP repository, PHUMSIM would be used with the following idmtrls to determine actinide-humic concentrations: Th = PHUMOX4; U = PHUMOX6; Np = PHUMOX5; Pu = PHUMOX4; and Am = PHUMOX3.

Uncertainties due to analytical precision are small compared to uncertainties in knowledge of the dominant humic substance type, site-binding densities, and actinide solubilities. The proportionality-factor approach coupled with the actinide-solubility-model uncertainty results in an adequate representation of the uncertainty in the concentration of actinides bound by mobile humic substances.

The CAPHUM parameter simply represents the theoretical maximum concentration of actinides that can be bound by a humic substance. Based on a solubility-limit concentration of humic substances of 2.0 mg/L, and the highest site-binding capacity (for fulvic acids) of 5.56 meq OH^-/g, the theoretical maximum is 1.1×10^{-5} eq/L. Assuming the conservative case in which actinide species are monovalent, the maximum theoretical concentration of actinides that can be bound by humic substances is 1.1×10^{-5} M. That number is conservative, because it assumes a pool of humic substances is available for each actinide element, when in reality, actinide elements will compete for the same pool of humic substances. CAPHUM is used in an expression such as the following:

$$[\text{AnHS}] = \text{MIN}(\text{AnHS value calculated with proportionality constant}, 1.1 \times 10^{-5}) \tag{72}$$

in which the calculated concentration of a particular actinide is compared to the upper-limit value. Parameter values for PHUMCIM, PHUMSIM, and CAPHUM are summarized in Table SOTERM-11.

SOTERM-6.3.4 Microbes

Potentially important colloidal-sized microorganisms include bacteria, fungi, yeast, and protozoa. For the WIPP site, the focus is on the halophilic and halotolerant microbes identified at the site (Brush 1990; Francis and Gillow 1994). Microbes are important to consider in PAbecause they may significantly affect the characteristics of the waste stored at the WIPP, and also participate in transport of actinides. Microbes are known to actively bioaccumulate actinides intracellularly as well as act as substrates for passive extracellular sorption.

At the WIPP site, concentrations of naturally occurring microbes are on the order of 10^4 to 10^7 cells per mL (Francis and Gillow 1994, Table 1). In the presence of nutrients provided by WIPP waste constituents, including nitrates, sulfates, and cellulosics such as protective clothing and wood, the population of microbes is likely to increase. Lysis, a natural phenomenon whereby cells die and release their constituents to the solution, also provides a source of nutrients to microbes.

When introduced to nutrients, microbes typically follow a predictable growth curve (defined by the population number of microbes plotted as a function of time), consisting of an initial period of inactivity (very early log phase) ranging up to several days, followed by a sharp increase in growth (early log phase). That level of growth is sustained for one or more days (log phase) during which time microbial metabolites, including carboxylic acids, enzymes, and exocellular polymers, are generated. The growth rate eventually begins to decline (late log phase) due to the effects of those metabolites, limitations in nutrients or substrates, or population dynamics, and reaches a steady-state population (stationary phase). Viable microbes may aggregate to form clusters.

SOTERM-6.3.4.1 Description of Experiments

Several types of experiments were conducted to evaluate the impact of microbes in support of the WIPP colloid research program (refer to descriptions in Papenguth and Behl 1996): (1) evaluation of indigenous concentrations of microbes; (2) quantification of mobile concentrations under nutrient- and substrate-rich conditions; (3) quantification and characterization of actinide bioaccumulation by microbes; and (4) evaluation of toxicity effects of actinide elements on microbe growth.

Experiments were conducted at Brookhaven National Laboratory (BNL) and as a collaborative effort between BNL and LANL. Evaluation of indigenous concentrations was a collaborative effort between BNL and LANL. Quantification of mobile concentrations was conducted at BNL. The bioaccumulation and toxicity work was conducted at BNL or LANL depending on the actinide element. Th and U were investigated at BNL. The other actinide elements of interest, Np, Pu, and Am, were investigated at LANL under the guidance of BNL personnel.

Experiments to determine the mobile concentrations of microbes remaining suspended in the fluid column were conducted similarly to experiments previously conducted in support of the WIPP Gas Generation Program (Brush 1990; Francis and Gillow 1994). Bacterial cultures were introduced to a solution containing nutrient and substrate, and sealed. The bacterial population was monitored over periods of several weeks or more using measurements of optical density or by direct counting of aliquots of fixed cells. An important change in protocol from previous experiments, however, is that instead of filtering the entire contents of the vessels, only the mobile cells remaining suspended in the fluid column were counted. Results of the experiments showed that the mobile concentration of microbes was a couple of orders-of-magnitude less than the total concentration of microbes. The existence of indigenous microbes in Salado groundwaters has been demonstrated in previous work (Francis and Gillow 1994). As part of the WIPP Colloid Research Program, samples of Culebra groundwater were carefully collected from the H-19 hydropad, processed, and characterized for indigenous microbes. Concentrations of

naturally occurring microbes were on the order of 10^5 cells per mL, determined using direct counting methods.

The evaluation of indigenous concentrations of microbes and quantification of mobile concentrations provided important supporting evidence for quantifying the microbial actinide source term and for evaluating microbe-facilitated transport of actinides in the Culebra. However, the basis for developing the actual parameter values used in the CRA-2004 PA, the CCA PA, and the 1997 PAVT calculations was established with bioaccumulation and toxicity experiments, referred to herein as filtration experiments. Those experiments were conducted by combining microbe cultures with various concentrations and complexes of ^{232}Th, ^{238}U, ^{237}Np, ^{239}Pu, or ^{243}Am. The actinide reagents used were Th(IV)-NO_3^-, Th(IV)-EDTA, U(VI)-NO_3^-, U(VI)-citrate, Np(V)-EDTA, Pu(V)-HClO4, Pu(V)-EDTA, and Am(III)-EDTA. For those experiments, a pure bacterial culture (WIPP-1A) and a mixed bacterial culture (BAB) were used. Most of the experiments were conducted with the WIPP-1A culture, because of the fast growth of that pure culture. The WIPP-1A mixed culture typically reaches steady-state concentration within several days, whereas the BAB mixed culture requires several weeks. Because of the rapid response of the WIPP-1A culture, most of the experiments were conducted with that culture to expedite the research program. A complementary set of experiments were repeated with the BAB mixed culture to evaluate the representativeness of the pure culture. Experiments were conducted over periods of 11 to 15 days for the WIPP-1A microbe culture, and up to 21 days for the BAB culture. Each experiment consisted of a subset of two or three replicate test vessels that were sampled during the overall test interval to provide time-sequence data. In addition, replicate test vessels that were not innoculated with microbes were included in each experiment to provide a control. Sequential filtration with 0.03-µm, 0.4-µm, and 10-µm filters was conducted on each vessel. The following size fractions were obtained as shown in Table SOTERM-10.

Table SOTERM-10. Microbe Experimental Results

Fluid Column Sample	Particle Size	Actinide Association with
Not filtered	all	All forms listed below
0.22-µm syringe filter, filtrate	< 0.22 µm	Dissolved; lysed microbes
10-µm filter, filter retentate	> 10 µm	Clumped microbes
10-µm filter, filtrate	< 10 µm	Dissolved; dispersed microbes; lysed microbes
0.4-µm filter, filter retentate	= 0.4 to 10 µm	Dispersed microbes
0.4-µm filter, filtrate	< 0.4 µm	Dissolved; lysed microbes
0.03-µm filter, filter retentate	= 0.03 to 0.4 µm	Lysed microbes
0.03-µm filter, filtrate	< 0.03 µm	Dissolved; lysed microbes

In addition to the potential actinide associations listed above, there was some evidence of the formation of inorganic precipitates in some of the experiments. The nutrient used in many experiments was phosphate PO_4^{3-}(1g/L), which is known to coprecipitate actinide cations. The inoculated control samples provided the means to evaluate the extent of that experimental artifact. The control samples also provided the means to assess the extent of sorption of actinides onto test vessels, sampling, and filtration equipment. All sequential filters were composed of the same material, which simplifies assessment of sorption on the filtration equipment.

The toxicity experiments were conducted as a component of the filtration experiments described above, by varying the actinide concentration, and comparing growth curves measured by optical density and/or by direct cell counting. To increase the total concentration of actinides in solution, EDTA was added in some experiments in a one-to-one molar ratio with the actinide element. That approach was taken for all of the experiments with Th, Np, and Am, and for some of the experiments with Pu.

SOTERM-6.3.4.2 Interpretation and Discussion

Proportionality constants (PROPMIC) describing the amount of actinide element bound to mobile microbes were determined from the data listed above. In addition, maximum concentrations of actinides that could be associated with microbes (CAPMIC) were determined from the experimental data. Those two parameters are suitable for use in the CRA-2004 PA, CCA PA, and 1997 PAVT calculations, when coupled with dissolved actinide solubilities (refer to Section 7.2 for details).

The 0.4-µm-filter retentate and 0.03-µm filtrate (acquired from the inoculated vessels, not the uninoculated control vessels) were selected to represent the microbial actinide and dissolved actinide concentrations, respectively. The ratio between the microbial actinide and dissolved actinide, both expressed in molarity, represents the proportionality constant value used for the PROPMIC parameter. The 0.4-µm-filter retentate was selected to represent the microbial fraction because nearly all of the bacterial biomass was associated with that filter. A small

concentration of actinides was associated with suspected biomass trapped on the 10-µm filter, as clumped microbes, and on the 0.03-µm filter, as lysed microbes. The contribution of actinide-associated biomass consisting of clumped and lysed microbes was typically at least one order-of-magnitude less than the actinide concentration associated with the dispersed microbes collected on the 0.4-µm filter. The concentration of dissolved actinides measured from the 0.03-µm-filter filtrate was used in the ratio because it provides the best indication of final dissolved actinide concentration. Representative values for PROPMIC were developed on an element-by-element basis. Results of experiments using the BAB culture were disregarded, because of their lower uptake of actinides (especially Pu), and because of the limited number of experiments conducted with that culture. For the WIPP-1A culture, the first sampling period (2 to 4 days, but generally 3 days) was disregarded in determining proportionality constants because steady state population had not yet been reached. The remaining values were averaged arithmetically.

The filtration experiments discussed above also provided the basis for determining CAPMIC values. Final cell population numbers in the test vessels were estimated using measurements of optical density at a wavelength of 600 nm or by direct counting with epifluorescent microscopy. The magnitude of the toxicity effects was estimated by comparing final cell numbers obtained from a series of test vessels with varying actinide concentration. The direct-counting technique provided the most dependable measure of cell number and was used where available. The CAPMIC value is defined as the actinide concentration in molarity at which no growth was observed. For cases where growth clearly diminished as actinide concentration increased, but the actinide concentration was not great enough to stop growth, CAPMIC values were determined by linear extrapolation of population numbers, and then adding an order-of-magnitude to account for uncertainty. On the basis of WIPP experimental results (Papenguth 1996b), it appears that the toxicity effects are due to chemical toxicity rather than radiotoxicity. Because of the high radiation levels of Am and safety considerations in the laboratory facility used, the molar concentration could not be increased to the point at which toxicity effects could be observed. Consequently no CAPMIC value is currently available for Am. CAPMIC values are used similarly to the CAPHUM values (see Equation (72)), except that the upper limit for microbe concentration is due to toxicity rather than geometric limitations imposed by the colloid itself. Consequently, for microbes, the total concentration of mobile actinides in a PA realization is used in the comparison, rather than the amount of actinides associated with the microbes.

The experiments conducted do not provide sufficient information to formulate a distribution of values for PROPMIC and CAPMIC. Therefore, single values for PROPMIC and CAPMIC were used in the CRA-2004 PA, the CCA PA, and the 1997 PAVT. Uncertainties due to analytical precision are small compared to uncertainties in knowledge of the microbe culture that might predominate in the WIPP repository or in the Culebra in an intrusion scenario. The proportionality-factor approach coupled with the actinide-solubility-model uncertainty results in an adequate description of the uncertainty in the concentration of actinides bound by mobile microbes.

Parameter values for PROPMIC and CAPMIC are summarized in Table SOTERM-11.

SOTERM-6.3.5 Summary of Parameter Values

Parameter values for CONCMIN, CONCINT, PROPMIC, CAPMIC, PHUMSIM, PHUMCIM, and CAPHUM are summarized in Table SOTERM-11.

SOTERM-6.4 Summary

Results of the colloidal actinide investigation were used in the 1996 PA, the CRA-2004 PA, and the 1997 PAVT in three types of parameter values: (1) constant-concentration values for actinides associated with mineral fragment and actinide intrinsic colloids; (2) concentration values proportional to the dissolved actinide concentration for actinides associated with microbes and humic substances; and (3) maximum concentration values providing an upper limit for actinide concentrations associated with microbes and humic substances. The parameter values are summarized in Table SOTERM-11. Given the actinide solubilities calculated for Salado and Castile brines in equilibrium with MgO, the largest contributors to the mobile colloidal actinide source term are actinides associated with humic substances and microbes. The contribution from mineral fragment and actinide intrinsic colloids is comparatively small. More details can be found in the SNL WIPP Records Center (formerly referred to as the SNL WIPP Central File, SWCF) parameter record packages describing the determination of the mobile colloidal actinide source term (Papenguth 1996a, 1996b, 1996c, 1996d).

Table SOTERM-11. Colloid Concentration Factors

	CONCMIN Concentration on Mineral Fragments [1]	CONCINT Concentration as Intrinsic Colloid [1]	PROPMIC Proportion Sorbed on Microbes [2,3]	CAPMIC Maximum Sorbed on Microbes[4]	Proportion Sorbed on Humics [2]		CAPHUM Maximum Sorbed on Humics [1]
					PHUMSIM Salado	PHUMCIM Castile	
Th(IV)	2.6×10^{-8}	0.0	3.1	0.0019	6.3	6.3	1.1×10^{-5}
U(IV)	2.6×10^{-8}	0.0	0.0021	0.0021	6.3	6.3	1.1×10^{-5}
U(VI)	2.6×10^{-8}	0.0	0.0021	0.0023	0.12	0.51	1.1×10^{-5}
Np(IV)	2.6×10^{-8}	0.0	12.0	0.0027	6.3	6.3	1.1×10^{-5}
Np(V)	2.6×10^{-8}	0.0	12.0	0.0027	9.1×10^{-4}	7.4×10^{-3}	1.1×10^{-5}
Pu(III)	2.6×10^{-8}	0.0	0.3	6.8×10^{-5}	0.19	1.37[e]	1.1×10^{-5}
Pu(IV)	2.6×10^{-8}	1.0×10^{-9}	0.3	6.8×10^{-5}	6.3	6.3	1.1×10^{-5}
Am(III)	2.6×10^{-8}	0.0	3.6	NA	0.19	1.37[d]	1.1×10^{-5}

[1] In units of moles colloidal actinide per liter

[2] In units of moles colloidal actinide per mole dissolved actinide

[3] For the CRA-2004 PA, there were no microbial colloids in nonmicrobial vectors

[4] In units of moles total mobile actinide per liter

[5] A cumulative distribution from 0.065 to 1.60 with a mean value of 1.1 was used

NOTE: The colloidal source term is added to the dissolved source term to arrive at a total source term. Mineral fragments were provided with distributions, but the maximum was used as described in SOTERM-7.1.3. Humic proportionality constants for III, IV, and V were provided with distributions, but only the Castile Am(III) and Pu(III) were sampled.

SOTERM-7.0 USE OF THE ACTINIDE SOURCE TERM IN PERFORMANCE ASSESSMENT

As described in the preceding sections, the s ASTP provided the parameters that were needed to construct maximum dissolved and suspended colloidal actinide concentrations for use in modeling the mobilization and transport of actinides in the disposal system, as modeled by NUTS and PANEL. Prior to these transport calculations, however, some simplifications and manipulations (using PANEL) were required as discussed in the following sections.

SOTERM-7.1 Simplifications

The DOE has concentrated on those processes most likely to have a significant impact on system performance. Therefore, several simplifications were used in the modeling of radionuclide mobilization in the CRA-2004 PA, the CCA PA, and the 1997 PAVT calculations. These include

- using constant solubility and colloid parameters throughout the repository and regulatory period for a given realization,
- limiting the number of isotopes modeled to the ones most important to compliance,
- using the chemistries of Castile and Salado brines — the end member brines — to bracket the behavior of mixtures of these brines within the repository,
- sampling only the uncertain parameters having the most significant effect on repository performance,
- combining dissolved and colloidal species for transport within the disposal system, as modeled by NUTS and PANEL.

SOTERM-7.1.1 Elements and Isotopes Modeled

Selection of isotopes for modeling transport in the disposal system with NUTS and PANEL is described in Appendix TRU WASTE, Section TRU WASTE-2.0. PANEL runs included nearly all isotopes of the six actinides studied in the ASTP: Th, U, Np, Pu, Am, and Cm. NUTS runs included five isotopes: Th, ^{234}U, ^{238}Pu, ^{239}Pu, and ^{241}Am.

SOTERM-7.1.2 Use of Brine End Members

Brine from three sources may enter the repository, depending on the nature of future human intrusion. The general scenarios described in Chapter 6.0 (Section 6.3), and considered in the source-term calculations may be categorized into three groups: (1) undisturbed performance (UP), (2) intrusion through the repository and into the Castile intersecting a pressurized brine reservoir (E1 and E1E2); and (3) intrusion through the repository but not into a pressurized brine reservoir (E2).

Under all scenarios, brine may flow from the surrounding Salado through the disturbed rock zone (DRZ) and into the repository in response to the difference between the hydraulic head in the repository and the surrounding formation. For scenarios in which a borehole is drilled into the repository, brine may flow down the borehole from the Rustler and/or the Dewey Lake. For scenarios in which a pressurized Castile brine reservoir is intercepted, brine from the Castile may flow up the borehole into the repository. As mentioned in Section 2.2.1, the brines in these three formations have different compositions and the solubilities of actinides are somewhat different in each of these end-member compositions. The composition of the more dilute groundwaters from the Rustler and Dewey Lake, however, are expected to change rapidly upon entering the repository due to fast dissolution of host Salado minerals, about 90-95 percent halite and about 1-2 percent each of polyhalite, gypsum, anhydrite, and magnesite (Brush 1990) from the walls and floor of the repository. Calculations titrating Salado rock into dilute brines with the geochemical software package EQ3/6 (Wolery 1992; Wolery and Daveler 1992) show that gypsum, anhydrite and magnesite saturate before halite. When halite saturates, the brine composition is very similar to that of Castile brine. One hundred times as much polyhalite must be added to the system before the resulting brine has a composition similar to Salado brines. These calculations indicate that if dilute brines dissolve away only the surfaces of the repository, they will obtain Castile-like compositions, but if they circulate through the Salado after saturating with halite, they may obtain compositions similar to Salado brine. Similarly, if Castile brine circulates through enough host rock, it may also approach Salado brine composition. In either case, the actual brine within the repository may be described as a mixture of the two concentrated-brine end members — Salado and Castile. This mixture, however, is very hard to quantify, because it is both temporally and spatially variable. Only in the undisturbed scenario is the mixture well defined as 100 percent Salado brine over the 10,000-year regulatory period.

For a panel intersected by a borehole, the BRAGFLO calculations show that in the 10 percent of the repository represented by the BRAGFLO panel computational cells, the ratio of brine inflow that enters by the borehole versus inflow from the repository walls varies through time and depends on the sampled parameter values and scenario being considered. This ratio was the only measure of brine mixing available to the source-term runs in the CRA-2004 PA, CCA PA, and 1997 PAVT calculations. This ratio was quite crude because it (1) did not account for compositional changes that occur when H_2O was consumed by corrosion reactions, (2) did not resolve the details of flow, diffusion and brine interaction with internal pillars and the DRZ, and (3) was an average over one tenth of the repository. It is expected that the fraction of Salado brine will be quite high in areas of the repository distant from the borehole and the fraction will be much lower near the borehole. Because radionuclide travel up the borehole is required for significant release, it is the solubility of radionuclides near the borehole that is most important. Given these uncertainties, the DOE decided to calculate radionuclide solubilities using the Castile end-member composition for scenarios in which a borehole penetrates a brine reservoir and Salado end-member composition for scenarios where it does not.

SOTERM-7.1.3 Sampling of Uncertain Parameters

Distributions of parameter values for up to 30 source-term parameters are available, but many of these are expected to have very limited impact on disposal-system performance. The most

important parameters are expected to be the oxidation-state parameter and the solubilities of Pu(III), Pu(IV), and Am(III) in the two brine end members.

A single distribution (Figures SOTERM-1 and SOTERM-2) was provided for modeling the solubilities of all oxidation states of all actinides in both brines. However, the amount of correlation between the solubilities of the actinides was uncertain. Some factors that cause uncertainty in the solubilities affect all oxidation states of all actinides similarly and some factors will affect only some actinides or some oxidation states. For example, uncertainties in the SO_4^{2-} concentrations will have more effect in the uncertainty of the solubility of the actinides in the +IV oxidation state, while uncertainties in the ionic strength have a more generalized effect of increasing the uncertainty in the stability of any highly charged species. In nature, solubilities show correlation due to redox effects as well as compositional effects. It is therefore expected that solubilities within the WIPP should show some correlation, but not 100 percent correlation.

The use of the end-member brines in the calculations results in a correlation of solubilities due to ionic strength and major-ion effects, and the use of the oxidation-state parameter results in a correlation due to redox effects. The DOE assumes these effects (that is, ionic strength, major ions, and redox state) encompass the major correlations and therefore imposes no further correlations. A better estimate of this correlation would be necessary for more detailed chemical modeling, but for use in PA, this is unnecessary.

The parameters to be sampled were selected based on expectations of their significance of effect on disposal-system performance.

- A 100 percent correlation was made between Am and Cm solubilities. Only the parameters for Am were sampled, and these were copied for Cm.

- Np solubilities were not sampled because Np does not have a very large EPA unit during the 10,000-year regulatory period (see Appendix TRU WASTE, Section TRU WASTE-2.0 for a discussion of EPA units and the relative importance of Np).

- The parameter for actinide concentration on mineral fragments was not sampled because the concentrations of actinides that may be mobilized on mineral fragments were in most cases much lower that the possible concentrations of dissolved actinides.

- Of the humic-acid proportionality constants, only the one for the +III oxidation state in Castile brine was sampled because it was high and it applied to significant elements (Pu and Am).

Parameters not sampled were fixed at a maximum reasonable value during the calculations.

Fourteen parameters were sampled in the CRA-2004 PA for the source term (see Appendix PAR):

Material Name	Parameter Name
SOLAM3	SOLSIM, SOLCIM

SOLPU3	SOLSIM, SOLCIM
SOLPU4	SOLSIM, SOLCIM
SOLU4	SOLSIM, SOLCIM
SOLU6	SOLSIM, SOLCIM
SOLTH4	SOLSIM, SOLCIM
GLOBAL	OXSTAT
PHUMOX3	PHUMCIM

where

SOLAM3 = distribution parameter for SOLubility of AM(III),
SOLSIM = solubility variability in Salado brine,
SOLCIM = solubility variability in Castile brine,
OXSTAT = OXidation-STATe parameter,
PHUMOX3 = the Proportionality constant for HUMic colloids and actinides in the +3 OXidation state,
PHUMCIM = the Proportionality constant for HUMic colloids in Castile brine.

In the CCA PA and the 1997 PAVT, 12 parameters were sampled (all of the 14 parameters listed above except SOLU4, SOLCIM; and SOLTH4, SOLCIM).

SOTERM-7.1.4 Combining the Transport of Dissolved and Colloidal Species in the Salado

Dissolved and colloidal species may transport differently because of different diffusion rates, sorption onto stationary materials, and size exclusion effects (filtration and hydrodynamic chromatography). With maximum molecular diffusion coefficients of about 4×10^{-10} m^2 per s, actinides are estimated to diffuse about 10 m in 10,000 years, a negligible distance. Sorption and filtration have beneficial but unquantifiable effects on performance. Hydrodynamic chromatography may increase colloid transport over dissolved transport by at most a factor of two for theoretically perfect colloidal transport conditions. In real situations, the increase is much less. Given the small or beneficial nature of these effects, they were not included in the CRA-2004 PA, the CCA PA and the 1997 PAVT calculations of radionuclide transport in the repository.

Because there was no modeled mechanism to differentiate dissolved from colloidal species, the DOE combined them for transport within the Salado. In the modeling of transport within the Culebra, however, these simplifications were inappropriate. While transport within the repository is through at most hundreds of meters of poorly defined waste that is undergoing decomposition, transport through the Culebra is over kilometers in a relatively homogeneous (as compared to waste) fractured dolomite. Dissolved and colloidal species could be transported differently through the Culebra. Therefore, the mobilized actinides delivered to the Culebra by Salado transport codes are separated into five components (dissolved, humic, microbial, mineral-fragment, and intrinsic colloids).

SOTERM-7.2 Construction of Source Term

The parameters required for constructing the source term were (1) solubilities for four oxidation states in each brine end member, (2) an uncertainty distribution to be applied to the solubilities, (3) a scheme for assigning sampled oxidation states, (4) colloidal concentrations or proportionality constants for the five actinides or the four oxidation states for each of four types of colloids, and (5) caps on the actinide concentrations that may be applied to two types of colloids. Use of these parameters in the CRA-2004 PA, the CCA PA, and the 1997 PAVT calculations required combining them into a single maximum concentration for each modeled actinide. The term "total mobilized concentration" is used for the combined concentrations due to dissolved and colloidal species. The combined concentrations are not necessarily the actual concentrations, because the concentration may be lower due to inventory limits. Both NUTS and PANEL assume that the concentrations of actinides specified by the total mobilized concentration are attained instantaneously as long as sufficient inventory is available. When the inventory is insufficient, the actual mobilized concentration will be lower and is said to be inventory limited. The calculation of the total mobilized concentration is performed by PANEL, for each of 100 sampled vectors in a replicate,.

All of the source-term parameters and their distributions were entered into the PA parameter database. For each sampled parameter, the LHS code uses the distribution from the PA parameter database to create 100 sampled values. These values are combined with the parameters with constant values and stored in computational databases for each of the 100 vectors, which constitute one replicate. For each realization, PANEL uses both the constant and sampled values for all of the source-term parameters, and constructs the source term for NUTS and PANEL, as shown below. This process is repeated for scenarios using the Salado end-member total mobilized concentration and for scenarios using the Castile end-member total mobilized concentration. (Parameters that are sampled and values derived from them are indicated by italics. Parameters used by PANEL are in bold.)

$$\textit{Dissolved} = \mathbf{Model\ Solubility} * 10^{\textbf{\textit{Sampled from Solubility Distribution}}} \tag{73}$$

$$\textit{Humic} = \textit{Dissolved} * \textbf{\textit{Proportionality Constant}} \tag{74}$$

if *Dissolved* * ***Prop. Const***. < **Humic Cap**, otherwise

$$\text{Humic} = \mathbf{Humic\ Cap} \tag{75}$$

$$\textit{Microbe}\ (\text{microbial vectors only}) = \textit{Dissolved} * \mathbf{Proportionality\ Constant} \tag{76}$$

if the *Total Mobile* < **Microbe Cap**, otherwise

$$\text{Microbe} = \mathbf{Microbe\ Cap} \tag{77}$$

$$\text{Mineral} = \mathbf{Database\ Concentration} \tag{78}$$

$$\text{Intrinsic} = \mathbf{Database\ Concentration} \tag{79}$$

$$\textit{Total Mobile} = \textit{Dissolved} + \textit{Humic} + \textit{Microbe} + \text{Mineral} + \text{Intrinsic} \tag{80}$$

For actinides with more than one oxidation state, the oxidation state is specified by the oxidation-state parameter:

Lower Oxidation State if OXSTAT ≤ 0.5
Higher Oxidation State if OXSTAT > 0.5,

where OXSTAT is the oxidation-state parameter that is sampled uniformly from 0 to 1.

For example, for one realization, in Salado brine, the sampled value for OXSTAT was 0.9 so Pu would be present in the +IV state. The sample of the solubility distribution was 0.8 for the modeled solubility for the +IV state, which has a model solubility of 1.19×10^{-8} M. The humic proportionality constant for the +IV oxidation state in Salado brine is 6.3, the microbe proportionality constant for Pu is 0.3, the humic cap is 1.1×10^{-5} M, the microbe cap for Pu is 2.1×10^{-3} M, the concentration of the actinide on mineral fragments is 2.6×10^{-8} M, and the Pu intrinsic-colloid concentration is 1×10^{-9} M.

For this realization, the maximum mobilized concentration of Pu used by PA would be:

Maximum concentration of dissolved Pu:

$$C_{Pu} = (1.19 \times 10^{-8}) \times (10^{0.8}) = 2.8 \times 10^{-5} \text{ M} \tag{81}$$

(This example has been rounded to two significant figures, although PA would not round at this intermediate point.) C_{Pu} is the maximum concentration of all combined isotopes of Pu.

The maximum humic complexed Pu would be:

$$(2.8 \times 10^{-5} \text{ M})(6.3 \text{ mol adsorbed per mol}) = 1.8 \times 10^{-4} \text{ M} \tag{82}$$

This value, however, exceeds the cap for humic-mobilized Pu, 1.1×10^{-5} M. Therefore, in this case, the cap would be used for the maximum humic mobilized actinide concentration.

The maximum microbial mobilized Pu would be:

$$(2.8 \times 10^{-5} \text{ M})(0.3 \text{ mol bioaccumulated per mol}) = 8.3 \times 10^{-6} \text{ M} \tag{83}$$

which is less than the cap.

The total maximum Pu concentration or total mobilized concentration for this realization would then be the sum of the dissolved and colloidal actinides:

Dissolved + Humic + Microbe + Mineral + Intrinsic

$$2.8 \times 10^{-5} + 1.1 \times 10^{-5} + 8.3 \times 10^{-6} + 2.6 \times 10^{-8} + 1.0 \times 10^{-9} = 4.7 \times 10^{-5} \text{ M} \tag{84}$$

PANEL also calculates the fraction of each actinide mobilized by five different mechanisms, as follows:

$$\text{Fraction dissolved} = \text{Dissolved/Total Mobilized Conc.} \quad (85)$$

$$\text{Fraction on humics} = \text{Humic/Total Mobile} \quad (86)$$

$$\text{Fraction in/on microbes} = \text{Microbe/Total Mobile} \quad (87)$$

$$\text{Fraction on mineral fragments} = \text{Mineral/Total Mobile} \quad (88)$$

$$\text{Fraction as intrinsic colloid} = \text{Intrinsic/Total Mobile} \quad (89)$$

The total mobilized concentration and mobile fractions are then copied from Am to Cm. In addition, PA also combines isotopes (Appendix TRU WASTE, Section TRU WASTE-2.0) for the NUTS and SECOTP2D transport codes. For example, the U solubility is decreased to account for the shared solubility with the low-activity ^{238}U, which is not modeled, enabling NUTS to properly model the effect of the U isotopes on compliance using the single "lumped" isotope ^{234}U.

The output of the PANEL calculations is computational databases that contain the source term and effective inventories. NUTS and PANEL both assume instantaneous dissolution and colloidal mobilization up to the solubility limit when sufficient inventory is present, as discussed in Chapter 6.0 (Section 6.4.13.5). Table SOTERM-12 shows the dissolved and colloidal components of the source term and the total mobile actinide concentrations obtained when median parameter values are used.

Table SOTERM-12. Concentrations (M) of Dissolved, Colloidal, and Total Mobile Actinides Obtained Using Median Parameter Values

Actinide Oxidation State, and Brine	CRA, Microbial Vectors[1]	CRA, Nonmicrobial Vectors	PAVT	CCA
Pu(III), dissolved, Salado brine	2.50×10^{-7}	2.50×10^{-7}	9.75×10^{-8}	4.73×10^{-7}
Pu(III), colloidal, Salado brine	1.49×10^{-7}	7.44×10^{-8}	7.48×10^{-8}	2.59×10^{-7}
Pu(III), total mobile, Salado brine	3.99×10^{-7}	3.24×10^{-7}	1.72×10^{-7}	7.32×10^{-7}
Pu(III), dissolved, Castile brine	1.37×10^{-7}	1.44×10^{-7}	1.06×10^{-8}	1.06×10^{-8}
Pu(III), colloidal, Castile brine	2.56×10^{-7}	2.24×10^{-7}	4.46×10^{-8}	4.46×10^{-8}
Pu(III), total mobile, Castile brine	3.94×10^{-7}	3.68×10^{-7}	5.52×10^{-8}	5.52×10^{-8}
Am(III), dissolved, Salado brine	2.50×10^{-7}	2.50×10^{-7}	9.75×10^{-8}	4.73×10^{-7}
Am(III), colloidal, Salado brine	9.72×10^{-7}	7.34×10^{-8}	3.96×10^{-7}	1.82×10^{-6}
Am(III), total mobile, Salado brine	1.22×10^{-6}	3.23×10^{-7}	4.93×10^{-7}	2.29×10^{-6}
Am(III), dissolved, Castile brine	1.37×10^{-7}	1.44×10^{-7}	1.06×10^{-8}	1.06×10^{-8}
Am(III), colloidal, Castile brine	6.99×10^{-7}	2.13×10^{-7}	7.78×10^{-8}	7.78×10^{-8}
Am(III), total mobile, Castile brine	8.36×10^{-7}	3.57×10^{-7}	8.83×10^{-8}	8.83×10^{-8}
Th(IV), dissolved, Salado brine	9.67×10^{-9}	1.01×10^{-8}	1.06×10^{-8}	3.58×10^{-6}
Th(IV), colloidal, Salado brine	1.17×10^{-7}	8.95×10^{-8}	1.25×10^{-7}	2.21×10^{-5}
Th(IV), total mobile, Salado brine	1.27×10^{-7}	9.96×10^{-8}	1.36×10^{-7}	2.57×10^{-5}
Th(IV), dissolved, Castile brine	2.01×10^{-8}	4.75×10^{-9}	3.33×10^{-8}	4.88×10^{-9}
Th(IV), colloidal, Castile brine	2.15×10^{-7}	5.59×10^{-8}	3.39×10^{-7}	7.18×10^{-8}
Th(IV), total mobile, Castile brine	2.35×10^{-7}	6.07×10^{-8}	3.73×10^{-7}	7.67×10^{-8}
U(IV), dissolved, Salado brine	9.67×10^{-9}	1.01×10^{-8}	1.06×10^{-8}	3.58×10^{-6}

Table SOTERM-12. Concentrations (M) of Dissolved, Colloidal, and Total Mobile Actinides Obtained Using Median Parameter Values — Continued

Actinide Oxidation State, and Brine	CRA, Microbial Vectors[1]	CRA, Nonmicrobial Vectors	PAVT	CCA
U(IV), colloidal, Salado brine	8.70×10^{-8}	8.95×10^{-8}	9.26×10^{-8}	1.10×10^{-5}
U(IV), total mobile, Salado brine	9.66×10^{-8}	9.96×10^{-8}	1.03×10^{-7}	1.46×10^{-5}
U(IV), dissolved, Castile brine	2.01×10^{-8}	4.75×10^{-9}	3.33×10^{-8}	4.88×10^{-9}
U(IV), colloidal, Castile brine	1.53×10^{-7}	5.59×10^{-8}	2.36×10^{-7}	5.67×10^{-8}
U(IV), total mobile, Castile brine	1.73×10^{-7}	6.07×10^{-8}	2.69×10^{-7}	6.16×10^{-8}
Pu(IV), dissolved, Salado brine	9.67×10^{-9}	1.01×10^{-8}	1.06×10^{-8}	3.58×10^{-6}
Pu(IV), colloidal, Salado brine	9.08×10^{-8}	9.05×10^{-8}	9.67×10^{-8}	1.21×10^{-5}
Pu(IV), total mobile, Salado brine	1.01×10^{-7}	1.01×10^{-7}	1.07×10^{-7}	1.57×10^{-5}
Pu(IV), dissolved, Castile brine	2.01×10^{-8}	4.75×10^{-9}	3.33×10^{-8}	4.88×10^{-9}
Pu(IV), colloidal, Castile brine	1.60×10^{-7}	5.69×10^{-8}	2.47×10^{-7}	5.92×10^{-8}
Pu(IV), total mobile, Castile brine	1.80×10^{-7}	6.17×10^{-8}	2.80×10^{-7}	6.41×10^{-8}
U(VI), dissolved, Salado brine	7.07×10^{-6}	7.07×10^{-6}	7.07×10^{-6}	7.07×10^{-6}
U(VI), colloidal, Salado brine	8.89×10^{-7}	8.75×10^{-7}	8.89×10^{-7}	8.89×10^{-7}
U(VI), total mobile, Salado brine	7.96×10^{-6}	7.95×10^{-6}	7.96×10^{-6}	7.96×10^{-6}
U(VI), dissolved, Castile brine	7.15×10^{-6}	7.15×10^{-6}	7.15×10^{-6}	7.15×10^{-6}
U(VI), colloidal, Castile brine	3.69×10^{-6}	3.67×10^{-6}	3.69×10^{-6}	3.69×10^{-6}
U(VI), total mobile, Castile brine	1.08×10^{-5}	1.08×10^{-5}	1.08×10^{-5}	1.08×10^{-5}

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Appendix PA

Attachment TFIELD

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TFIELD-1.0 OVERVIEW OF T-FIELD DEVELOPMENT, CALIBRATION, AND MODIFICATION PROCESS

Modeling the transport of radionuclides through the Culebra Dolomite Member of the Rustler Formation is one component of the Performance Assessment (PA) performed for the Waste Isolation Pilot Plant (WIPP) Compliance Recertification Application (CRA). This transport modeling requires a model of groundwater flow through the Culebra. This Attachment describes the process used to develop and calibrate the transmissivity (T) fields for the Culebra, and then modify them for the possible effects of potash mining for use in flow modeling for the CRA-2004.

The work described in this attachment was performed under two Sandia National Laboratories Analysis Plans (APs): AP-088 (Beauheim 2002a) and AP-100 (Leigh et al. 2003). AP-088 (Analysis Plan for the Evaluation of the Effects of Head Changes on Calibration of Culebra Transmissivity Fields) dealt with the development, calibration, and modification for potash mining of the T fields. AP-100 (Analysis Plan for Calculations of Culebra Flow and Transport: Compliance Recertification Application) included the development of T-field acceptance criteria, as well as radionuclide-transport calculations not described herein.

The starting point in the T-field development process was to assemble information on geologic factors that might affect Culebra T (Section 2.0 of this attachment). These factors include dissolution of the upper Salado Formation, the thickness of overburden above the Culebra, and the spatial distribution of halite in the Rustler Formation above and below the Culebra. Geologic information is available from hundreds of oil and gas wells and potash exploration holes in the vicinity of the WIPP site, while T values are available from only 46 well locations. Details of the geologic data compilation are given in Powers (2002a, 2002b, 2003), and summarized below in Section 2.0 of this attachment.

A two-part “geologically based” approach was then used to generate Culebra base T fields. In the first part (Section 3.0 of this attachment), a conceptual model for geologic controls on Culebra T was formalized, and the hypothesized geologic controls were regressed against Culebra T data to determine linear regression coefficients. The regression includes one continuously varying function, Culebra overburden thickness, and three indicator functions that assume values of 0 or 1 depending on the occurrence of open, interconnected fractures, Salado dissolution, and the presence or absence of halite in units bounding the Culebra.

In the second part (Section 4.0 of this attachment), a method was developed for applying the linear regression model to predict Culebra T across the WIPP area. The regression model was combined with the maps of geologic factors to create 500 stochastically varying Culebra base T fields. Details about the development of the regression model and the creation of the base T fields are given in Holt and Yarbrough (2002, 2003a, 2003b).

By the nature of regression models, the base T fields do not honor the measured T values at the measurement locations. Therefore, before these base T fields could be used in a flow model, they had to be conditioned to the measured T values. This conditioning is described in McKenna and Hart (2003a, 2003b) and summarized in Section 5.0 of this attachment. Section 6.0 of this attachment presents details on the modeling approach used to calibrate the T fields to both

steady-state heads and transient drawdown measurements. Heads measured in late 2000 were used to represent steady-state conditions in the Culebra, and drawdown responses in 40 wells to pumping in 7 wells were used to provide transient calibration data. Details on the heads and drawdown data used are described in Beauheim (2002b; 2003a). Assumptions made in modeling, the definition of an initial head distribution, assignment of boundary conditions, discretization of the spatial and temporal domain, weighting of the observations, and the use of PEST in combination with MODFLOW-2000 to calibrate the T fields using a pilot-point method are described in McKenna and Hart (2003a, 2003b) and summarized in Section 6.0 of this attachment.

Section 7.0 of this attachment addresses the development and application of acceptance criteria for the T fields. Acceptance was based on a combination of objective fit to the calibration data and providing travel time results consistent with the cumulative distribution function (CDF) of travel times from the 23 best-calibrated T fields (Beauheim 2003b). Of the 146 T fields that went through the calibration process, 121 T fields were judged adequate for further use, with the 100 best T fields selected for use in the CRA-2004 transport calculations.

Section 8.0 of this attachment provides summary statistics and other information for the 121 T fields that were judged to be acceptably calibrated. Particle tracks from a point above the center of the WIPP disposal panels to the land withdrawal boundary are shown, along with information on the model fits to steady-state heads, identification of the most sensitive pilot point locations, and characteristics of an ensemble average T field. This information is summarized from McKenna and Hart (2003b).

Section 9.0 of this attachment discusses the modification of the T fields to account for the effects of potash mining both within and outside the WIPP land withdrawal boundary. Mining-affected areas were delineated, random transmissivity multipliers were applied to Ts in those areas, and particle tracks and travel times were determined (Lowry 2003). The flow fields produced by these mining-affected T fields are input to SECOTP2D for the CRA-2004 radionuclide-transport calculations.

Section 10.0 of this attachment provides a brief summary of this attachment.

TFIELD-2.0 DEVELOPMENT OF MAPS OF GEOLOGIC FACTORS

Beauheim and Holt (1990), among others, suggested three geologic factors that might be related to the transmissivity of the Culebra in the vicinity of the WIPP site:

1. thickness (or erosion) of overburden above the Culebra,
2. dissolution of the upper Salado , and
3. spatial distribution of halite in the Rustler Formation below and above the Culebra.

Culebra transmissivity is inversely related to thickness of overburden because stress relief associated with erosion of overburden leads to fracturing and opening of preexisting fractures. Culebra transmissivity is high where dissolution of the upper Salado has occurred and the

Culebra has subsided and fractured. Culebra transmissivity is observed to be low where halite is present in overlying and/or underlying mudstones. Presumably, high Culebra T leads to dissolution of nearby halite (if any). Hence, the presence of halite in mudstones above and/or below the Culebra can be taken as an indicator for low Culebra transmissivity.

Maps were developed for each of these factors using drillhole data of different types. The general area for the geologic study comprised 12 townships, located in townships T21S to T24S, ranges R30-32E (the WIPP site lies in T22S, R31E). The original sources of geologic data for this analysis are mainly Powers and Holt (1995) and Holt and Powers (1988) and new information derived by log interpretation by Powers (2002a, 2003b, 2003). All of the data are either included or summarized in the references cited above, and can be independently checked; basic data reports are available for WIPP drillholes, geophysical logs for oil and gas wells are available commercially or at offices of the Oil Conservation Division (New Mexico) in Artesia and Hobbs, and potash drillhole information is in files that can be accessed for stratigraphic information at the Bureau of Land Management (BLM), Carlsbad, NM. No proprietary data are included.

Factor A is represented by a structure contour map of the elevation of the top of the Culebra (Figure TFIELD-1) that can be digitized and then subtracted from a digital elevation model (DEM) of the land surface to obtain the thickness of overburden. Factor B is represented on a map as an approximate margin of the area beginning to be affected by dissolution of the upper Salado (Figure TFIELD-2). Factor C is delineated on a map by lines that represent as nearly as possible the boundaries of the occurrence of halite in the Los Medaños, Tamarisk, and Forty-niner Members of the Rustler Formation in the study domain (Figure TFIELD-3).

With respect to Factor B, the upper Salado has been dissolved, and presumably is still dissolving, along the eastern margin of Nash Draw. On the basis of limited core information, Holt and Powers (1988) suggested that formations overlying the dissolving upper Salado in Nash Draw are affected in proportion to the amount of Salado dissolution. The most direct way to estimate the spatial distribution of dissolution is to have cores of the upper Salado and basal Rustler and knowledge of the thickness to marker beds (MBs) in the upper Salado. The upper Salado has not been cored frequently, but geophysical logs from oil and gas wells, and descriptive logs of cores or cuttings from potash drillholes, provide a considerable amount of evidence of the thickness of the lower Rustler and upper Salado, even though cores and cuttings are no longer available from potash industry drillholes.

Potash industry geological logs examined at the BLM in Carlsbad, NM are quite variable in the quality of description and the stratigraphic interval described. Drillhole logs from the 1930s and 1950s typically are the most descriptive; recent drillhole logs are commonly useless for this project because no strata are described above portions of the McNutt potash zone of the Salado, near the middle of the formation.

The top of the Culebra and the base of the Vaca Triste Sandstone Member in the upper Salado are the most consistent stratigraphic markers spanning the upper Salado that are recognizable across various types of records. As a guide to the limits or bounds of upper Salado dissolution, a map of the thickness from top of Culebra to base of Vaca Triste was prepared (Powers 2003). In conjunction with previous work by Powers and Holt (1995) and the evidence of the structure of

the top of Culebra (see Figure TFIELD-1), an approximate boundary of dissolution was drawn as shown in Figure TFIELD-2.

With respect to Factor C, the boundaries of where halite is found in the three non-carbonate members of the Rustler have been drawn several times on the basis of different borehole data sets and different data types (e.g., core data and geophysical logs). For the most part, the different versions of the boundaries do not vary significantly. In the map shown in Figure TFIELD-3, the margins are based principally on the work of Powers and Holt (1995), which is a continuation of work reported by Holt and Powers (1988). As discussed in Powers and Holt (1995), the boundaries drawn here vary slightly from those drawn by Snyder (1985) based on core data for two reasons: (1) the Los Medaños Member (Powers and Holt 1999; formerly called the unnamed lower member) is here divided into two separate halite-bearing units (Powers and Holt 2000), and (2) geophysical log signatures are now used to identify halite in areas where cores are not available. Figure TFIELD-3 includes a stratigraphic sketch showing the relationship of halite-bearing strata to other strata in the Rustler. Following the convention established by Holt and Powers (1988), the mudstone/halite (M/H) strata are numbered consecutively starting at the base of the Rustler.

The margins for halite have now been drawn in the area north of the WIPP site around the northeastern arm of Nash Draw based on the descriptions of halite encounters in the Rustler Formation in potash drillholes. In addition, a few areas have been modified (from Powers and Holt 1995) to the south and west of the WIPP based on the records from potash drillholes as well as the records of drilling H-12 and H-17 for the WIPP.

In 12 potash drillholes, halite was reported above the upper contacts of the Culebra or Magenta Dolomite Members. The boundaries for M3/H3 and M4/H4 margins (i.e., the spatial limits of where halite is found in the mudstone intervals) have been drawn north of the WIPP based on these data. The depth below the Culebra at which halite was reported has also been used to draw the boundaries of the lower (M1/H1) or the upper (M2/H2) halite-bearing units of the Los Medaños in this area. Anhydrite A1 divides the M1/H1 (below) and M2/H2 (above) intervals. M2 (no halite) is about 3 m (10 ft) thick. If halite is reported within about 3 m (10 ft) of the base of Culebra or is clearly above A1, H2 is considered to be present. The M1/H1 interval is about 33-37 m (110-120 ft) thick at the WIPP site. In potash drillholes north of the WIPP site, where halite was reported less than 33 m (110 ft) below the Culebra, H1 is present. Within the zone for H1, other drillholes frequently reveal halite less than 33 m (110 ft) below the Culebra.

It should be noted that the report of “top of salt” or first salt in records for potash drillholes does not consistently mean the same thing and is frequently not the uppermost halite. It may instead mean the first halite that is encountered after coring begins or the first unit that is dominantly halite. Detailed inspection of logs sometimes shows halite described from cuttings, with a summary report of “top of salt” much deeper. In some cases, it appears “top of salt” is an estimate of where the Salado-Rustler contact should be.

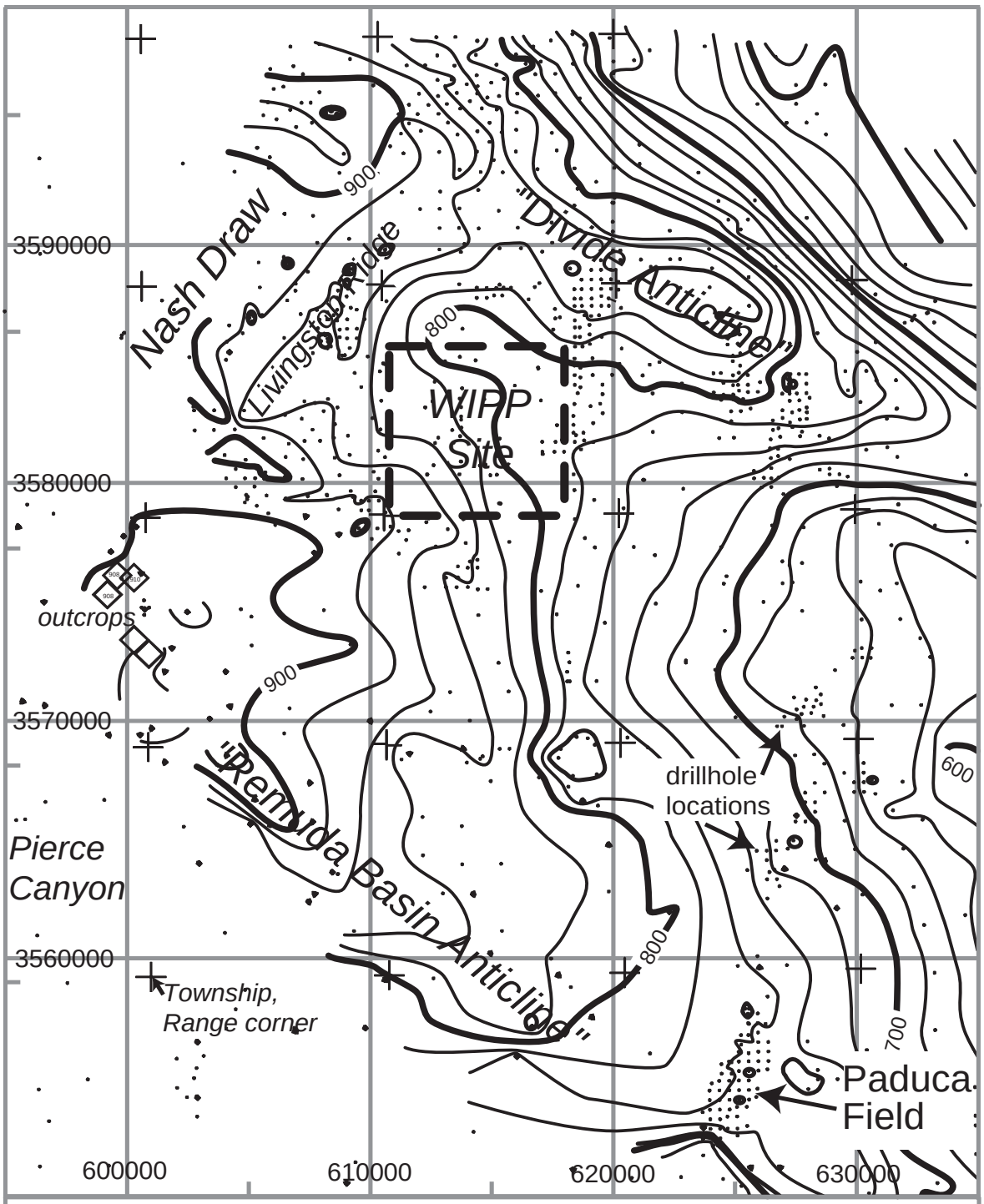

Explanation

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.
The contours for the elevation of the top of the Culebra are in meters (m) above mean sea level (amsl) (after Powers et al. 2003). Contour interval is 20 m.

Figure TFIELD-1. Structure Contour Map for the Top of the Culebra

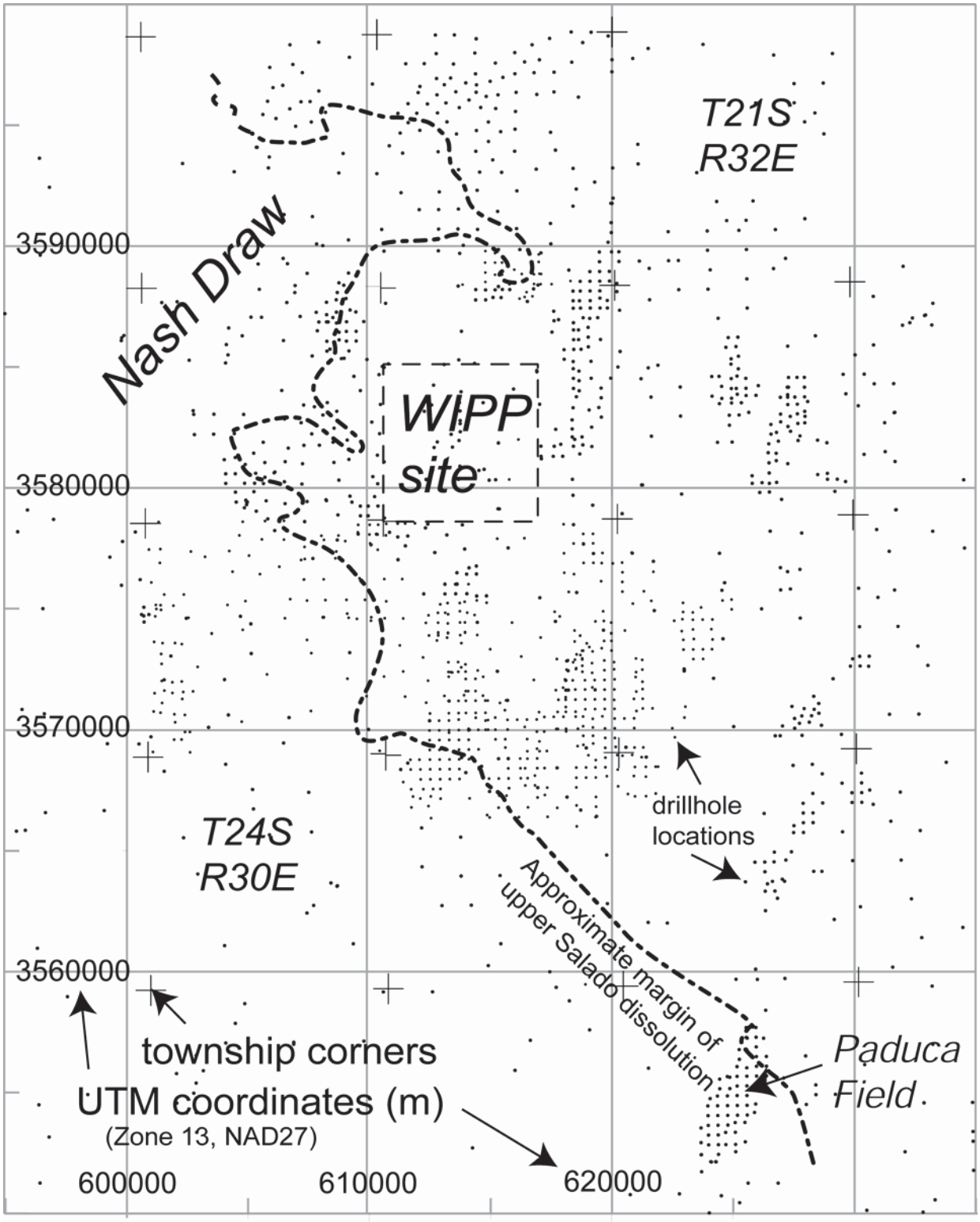

Figure TFIELD-2. Salado Dissolution Margin

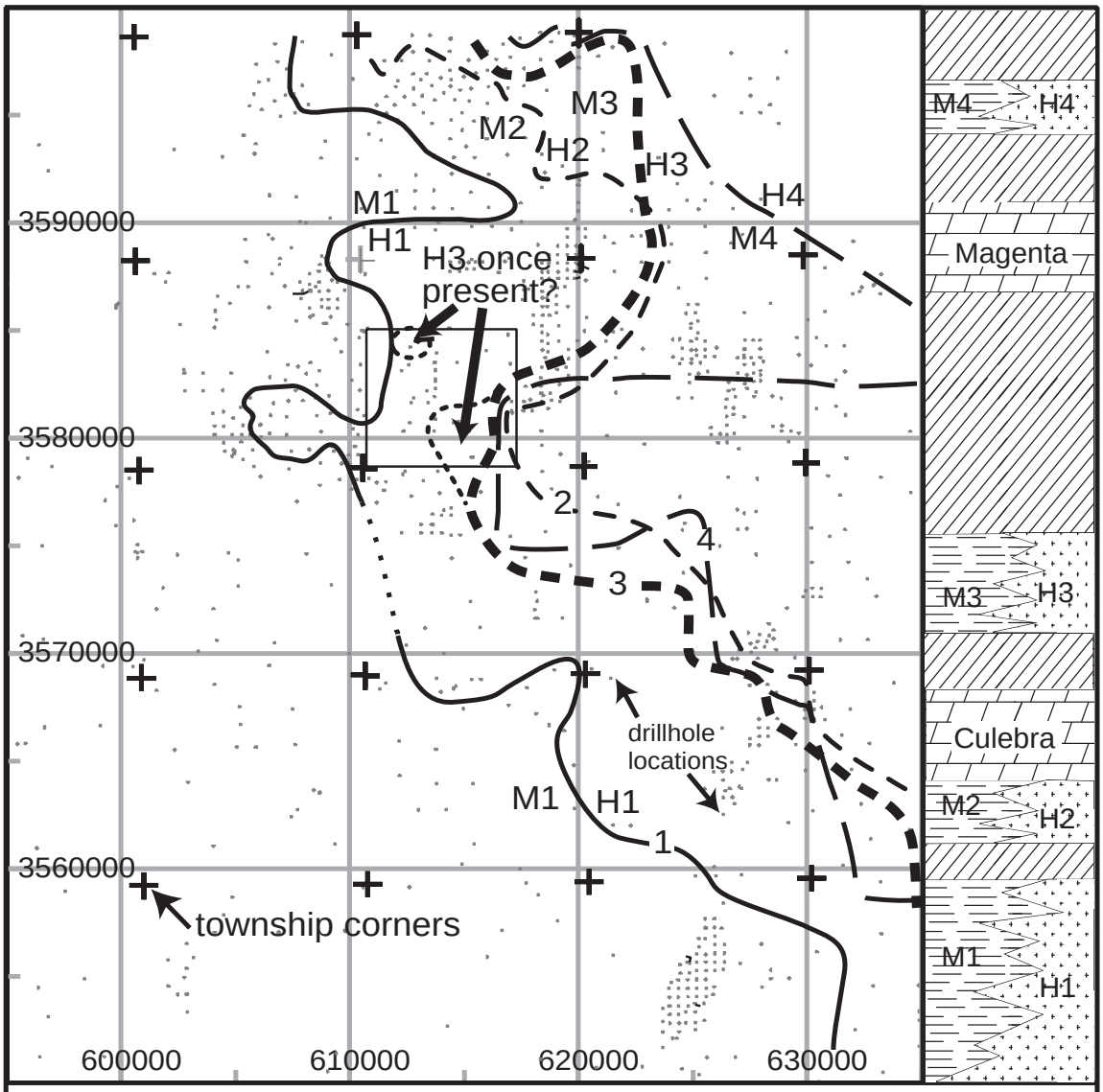

Explanation

M#, H# indicate mudstone and halitic facies on each side of estimated halite margin (numbered line on map) for stratigraphic intervals as indicated in the column to the right (key on Figure TFIELD-4).

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.

Two zones within the WIPP site boundary ("H3 once present?") indicate where halite may have been present west of the current boundary of H3 (marked by ▬ ▬ ▬ ▬ ▪).

Figure TFIELD-3. Rustler Halite Margins. See Figure TFIELD-4 for key to stratigraphic column.

Halite margins in the Rustler Formation are interpreted as mainly due to depositional limits of saltpan environments and syndepositional removal of some halite exposed in saline mud flat deposits (Holt and Powers 1988). The halite margins are expected to be the locus of halite dissolution, if any, since the Rustler was deposited. Facies including halite beds or halite cements are expected to be less permeable than the equivalent mudstone facies. As a consequence, the margin is more likely to be attacked by advection and diffusion at the margin, from the mudstone facies side of the margin. In addition, removing halite along the margin as the saltpan margin fluctuates is likely to introduce some vertical and horizontal discontinuities that persist after lithification and are not created where the saltpan persisted. Water in adjacent units or in the mudstone unit likely has more pathways along these margins, increasing the likelihood that the margins will be the locus of dissolution. Recent findings of a narrow margin along which halite is dissolved from the upper Salado (Powers et al. 2003) are consistent with the expectation that halite margins in the Rustler would be the locus of dissolution.

Two areas have been identified where halite appears to have been dissolved from the M3/H3 interval after deposition of the Rustler. These areas are shown with the annotation “H3 once present?” on Figure TFIELD-3. In the vicinity of drillhole H-19b0 and south (the southern area shown), cores of several WIPP drillholes show brecciation of the upper Tamarisk Member anhydrite in response to dissolution. Another area of dissolution, previously discussed in Holt and Powers (1988), Powers and Holt (1995), and Beauheim and Holt (1990), is around WIPP-13 (the northern area shown), and may represent an outlier of salt left behind during syndepositional removal of halite from the M3 areas west of the WIPP site (Powers and Holt 2000). These areas have not been extended interpretively on Figure TFIELD-3 as was done in Beauheim and Holt (1990), but are limited to the vicinities of the locations at which evidence of dissolution has been directly observed.

Because of the position of M2/H2 directly beneath the Culebra, dissolution of H2 might be expected to have a strong influence on Culebra T. However, the H2 depositional margin is largely east of the WIPP site, barely crossing the southern portion of the eastern WIPP site boundary (Figure TFIELD-3). H2 dissolution does not appear to be a factor affecting Culebra T in any hydrology test well for WIPP, but there are no direct observations along the H2 margin.

TFIELD-3.0 DEVELOPMENT OF MODEL RELATING CULEBRA T TO GEOLOGIC FACTORS

Holt and Powers (1988), Powers and Holt (1990), Beauheim and Holt (1990), and Holt (1997) have described the geology and geologic history of the Culebra. The following model is developed from their work and is consistent with their interpretations. It is important to note that this work follows Holt (1997) and assumes that variability in Culebra T is due strictly to post-depositional processes. Throughout the following discussion, the informal stratigraphic subdivisions of Holt and Powers (1988) are used to identify geologic units within the Rustler Formation (Figure TFIELD-4).

The spatial distribution of Culebra T on a regional scale is a function of a series of deterministic geologic controls, including Culebra overburden thickness, dissolution of the upper Salado Formation, and the occurrence of halite in units above or below the Culebra. Each of these

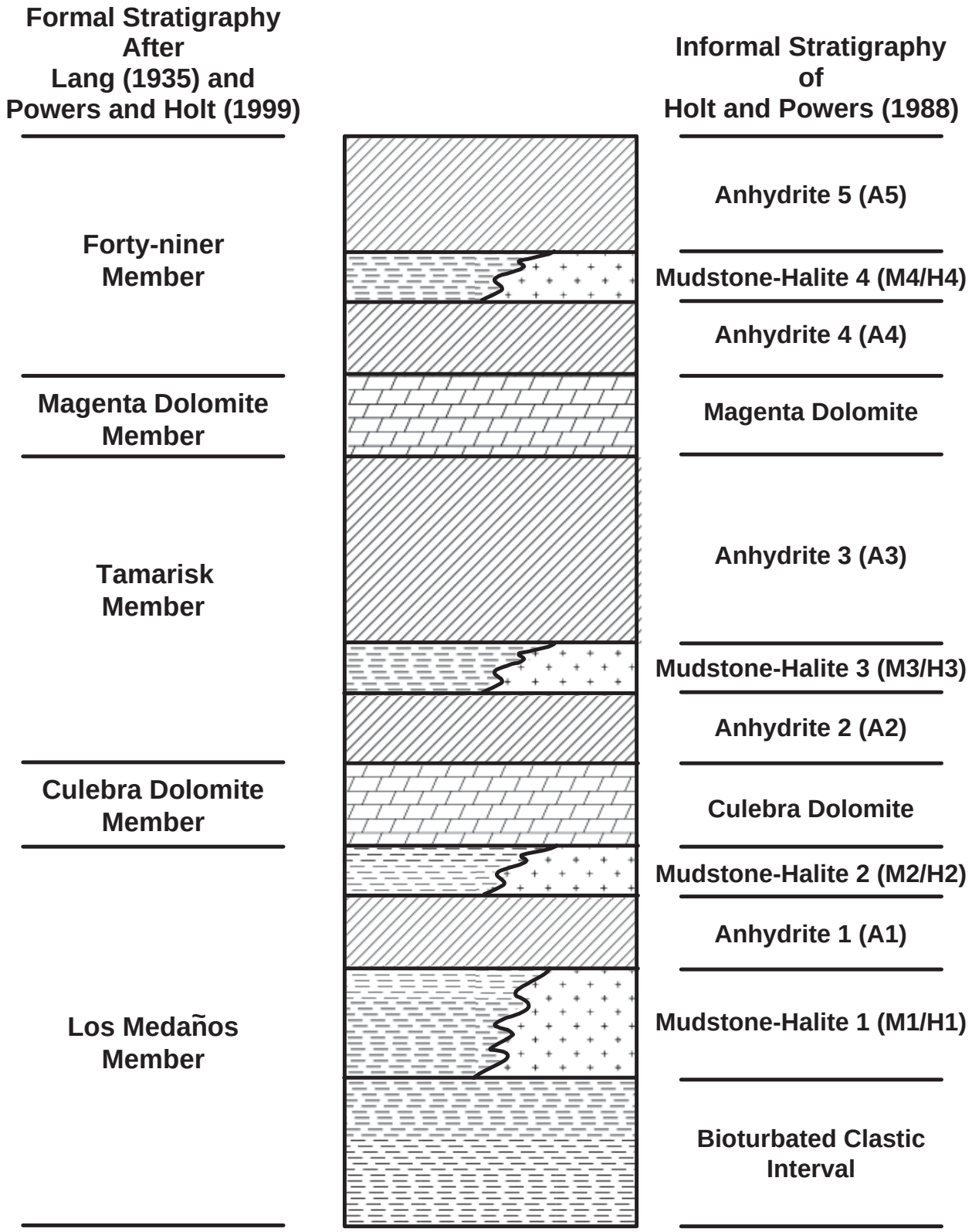

Figure TFIELD-4. Stratigraphic Subdivisions of the Rustler Formation

geologic controls can be determined at any location using geological map data. In the region between the margin of upper Salado dissolution and the margin of halite occurrence above the Culebra, which includes the WIPP site, however, high-T regions occur that cannot be predicted using geologic data. These high-T zones are treated stochastically, using what is termed a fracture-interconnectivity indicator.

In the following paragraphs, the fracture-interconnectivity indicator is defined, and then the specifics of each hypothesized control on Culebra T are outlined. Finally, a linear model relating these controls to Culebra T is presented that provides an excellent fit to the available data, is testable, and is consistent with our understanding of Culebra geology.

TFIELD-3.1 Fracture Interconnection

Culebra T data show a bimodal distribution (Figure TFIELD-5). Interpretations of hydraulic tests (e.g., Beauheim and Ruskauff 1998) and observations of the presence or absence of open fractures in core show the bimodal T distribution to be the result of hydraulically significant fractures. Some degree of fracturing is evident in all Culebra cores, but the fractures tend to be filled with gypsum at locations where the T inferred from hydraulic tests is less than approximately 4×10^{-6} m^2/s ($\log_{10} = -5.4$). Where $\log_{10}$ T (m^2/s) is greater than –5.4, hydraulic tests show double-porosity responses and open fractures are observed in core. Therefore, a fracture-interconnectivity indicator is defined based on a cutoff of $\log_{10}$ T (m^2/s) = -5.4:

$$I_f = \begin{cases} 1 & \log_{10} T(m^2/s) > -5.4 \\ 0 & \log_{10} T(m^2/s) \le -5.4 \end{cases} \tag{1}$$

Open, interconnected fractures and high Ts occur in regions affected by Salado dissolution (e.g., Nash Draw) and in areas west of the M3/H3 margin where gypsum fracture fillings are absent.

TFIELD-3.2 Overburden Thickness

An inverse relationship exists between Culebra overburden thickness and T. At the WIPP wells for which T data are available, the Culebra overburden thickness ranges from 3.7 m (at WIPP-29) to 414.5 m (at H-10) (Mercer 1983), increasing from west to east. Overburden thickness is a metric for two different controls on Culebra T. First, fracture apertures are limited by overburden thickness (e.g., Currie and Nwachukwu 1974), which should lead to lower T where Culebra depths are great (Beauheim and Holt 1990; Holt 1997). Second, erosion of overburden leads to changes in stress fractures, and the amount of Culebra fracturing increases as the overburden thickness decreases (Holt 1997). Holt (1997) estimates that at least 350 m of overburden has been eroded at the center of the WIPP site (where the Culebra is at a depth of approximately 214 m) since the end of the Triassic, with more erosion occurring west of the site center where overburden (chiefly the Dewey Lake) is thinner and less erosion occurring to the east where Triassic deposits are thicker.

TFIELD-3.3 Salado Dissolution

In regions north, south, and west of the WIPP site, Cenozoic dissolution has affected the upper Salado Formation (Figure TFIELD-2). Where this dissolution has occurred, the rocks overlying the Salado, including the Culebra, are strained (leading to larger apertures in existing fractures),

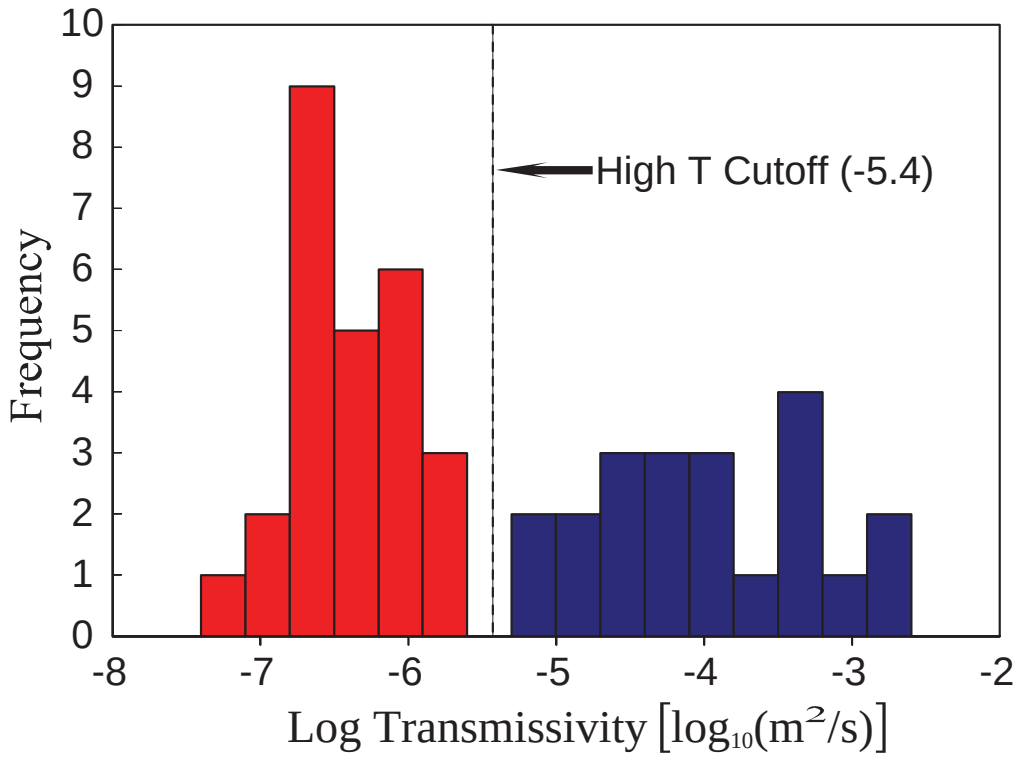

Figure TFIELD-5. Histogram of Log_{10} Culebra T. Data from DOE (1996), Beauheim and Ruskauff (1998), and Beauheim (2002c)

fractured, collapsed, and brecciated (e.g., Beauheim and Holt 1990; Holt 1997). All WIPP wells within the upper-Salado-dissolution zone fall within the high-T population, and all regions affected by Salado dissolution are expected to have well-interconnected fractures and high T.

TFIELD-3.4 Halite Overlying the Culebra

All wells (e.g., H-12 and H-17) located where halite occurs in the M3/H3 interval of the Tamarisk (Figure TFIELD-3) show low T. T data are limited in this region, but it is unlikely that halite would survive in M3/H3, only several meters from the Culebra, in regions of high T where Culebra flow rates are relatively high. High-T zones, therefore, are assumed to not occur in regions where halite is present in the M3/H3 interval.

TFIELD-3.5 Halite Bounding the Culebra

In regions where halite is present in the M2/H2 interval directly below the Culebra, no reliable quantitative estimates of Culebra T are available. Beauheim (1987) estimates T at P-18, the only tested well at which halite is present in the M2/H2 interval, to be less (probably much less) than 4×10^{-9} m^2/s ($\log_{10} = -8.4$). In much of the area where halite is present in the M2/H2 interval (including the P-18 location), halite is also present in the M3/H3 interval. Based upon geologic observations of halite-bound units elsewhere within the WIPP area, Holt (1997) suggests that porosity within the Culebra may contain abundant halite cements in these areas. Beauheim and Holt (1990) and Holt (1997) indicate that Culebra porosity shows increasing amounts of pore-filling cement east of the WIPP site. Consequently, Culebra T is assumed to be much lower in

the region where halite occurs both above (M3/H3 interval) and below (M2/H2 interval) the Culebra. Much lower T is also assumed in the area northeast of the WIPP site where halite is present in the M2/H2 interval but absent in the M3/H3 interval (see Figure TFIELD-3).

TFIELD-3.6 High-T Zones

In addition to the high T that occurs everywhere dissolution of the upper Salado has occurred, high-T zones also occur in the Culebra in the region bounded by the limit of upper Salado dissolution to the west and by the margin of where halite is present in the M2/H2 and M3/H3 intervals to the east (see Figures TFIELD-2 and TFIELD-3). Fracture openness and interconnectivity in these high-T zones are controlled by a complicated history of fracturing with several episodes of cement precipitation and dissolution (Beauheim and Holt 1990; Holt 1997). No geologic metric has yet been defined that allows prediction of where fractures are filled or open, hence our knowledge of this indicator east of the Salado dissolution margin is limited to the test well locations shown in Figure TFIELD-6. Consequently, the spatial location of high-T zones between the Salado dissolution margin and the M2/H2 and M3/H3 margins is treated stochastically.

TFIELD-3.7 Linear Transmissivity Model

Using the hypothesized geologic controls on Culebra T, the following linear model for $Y(\mathbf{x}) = \log_{10} T(\mathbf{x})$ was constructed:

$$Y(\mathbf{x}) = \beta_1 + \beta_2\, d(\mathbf{x}) + \beta_3\, I_f(\mathbf{x}) + \beta_4\, I_D(\mathbf{x}) \qquad (2)$$

where β_i (i = 1, 2, 3, 4) are regression coefficients, $\mathbf{x}$ is a two-dimensional location vector consisting of UTM X and UTM Y coordinates, $d(\mathbf{x})$ is the overburden thickness, $I_f(\mathbf{x})$ is the fracture-interconnectivity indicator given in Equation (1) that assumes the value of 1 if fracturing and high T have been observed at point $\mathbf{x}$ and 0 otherwise, and $I_D(\mathbf{x})$ is a dissolution indicator function that assumes the value of 1 if Salado dissolution has occurred at point $\mathbf{x}$ and 0 otherwise. In this model, regression coefficient β_1 is the intercept value for the linear model. Coefficient β_2 is the slope of $Y(\mathbf{x})/d(\mathbf{x})$. Coefficients β_3 and β_4 represent adjustments to the intercept for the occurrence of interconnected fractures and Salado dissolution, respectively. Although other types of linear models could be developed, this model is consistent with the conceptual model relating T to geologic controls and can be tested using published WIPP geologic and T data. Note that the regression model does not explicitly contain terms relating Culebra T to zones where the Culebra is bounded by halite in both the M2/H2 and M3/H3 intervals because of lack of data from these areas. Therefore, it cannot be used to predict T east of the M2/H2 margin.

TFIELD-3.8 Linear-Regression Analysis

A linear-regression model was written using the Windows-based program Mathcad 7 Professional© specifically for this application. Although other variables are input, this model requires only $\log_{10}$ T data from tested wells, the depth of the Culebra at those wells, and an estimate of whether dissolution of the upper Salado has or has not occurred at each location. The fracture interconnectivity indicator is defined from the $\log_{10}$ T data, and a Salado dissolution indicator is defined using the Salado dissolution data. These data are then used in a standard linear regression algorithm to determine the regression coefficients for Equation (2).

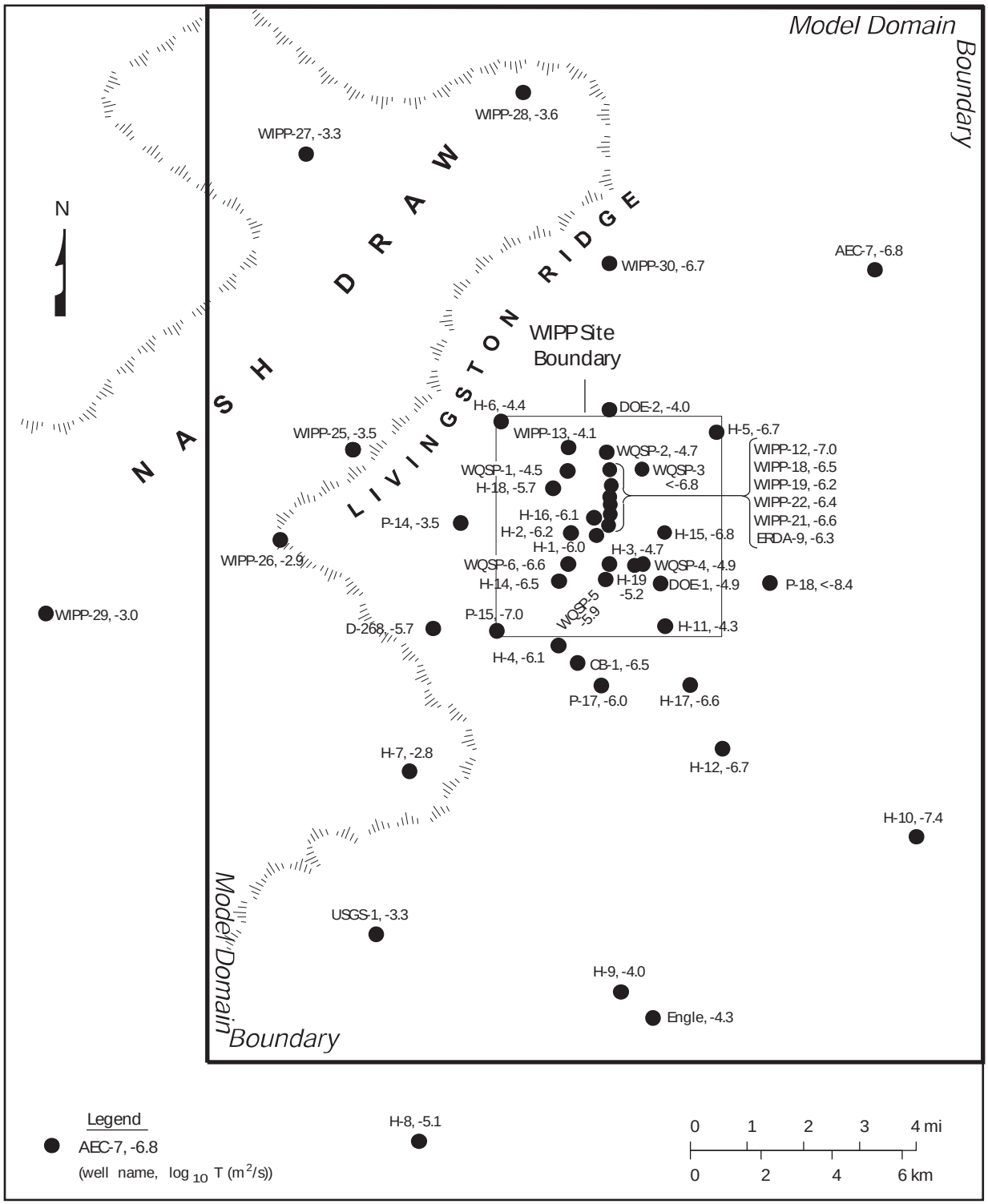

Figure TFIELD-6. Well Locations and Log_{10} Culebra Transmissivities

The regression coefficients for Equation (2) derived from this analysis are presented in Table TFIELD-1. The regression has a multiple correlation coefficient (R^2) of 0.941 and a Regression ANOVA F statistic of 222. The number of degrees of freedom about the regression (n) equals the number of observations (46) minus the number of parameters (4). The number of degrees of freedom due to the regression (m) equals the number of parameters (4) minus 1. With n = 42 and m = 3, the regression is significant above the 0.999 level. Residuals show no anomalous behavior. Accordingly, the regression model provides an accurate and reasonable description of the data. The fit of the regression to the $\log_{10}$ T data is shown in Figure TFIELD-7.

Table TFIELD-1. Regression Coefficients for Equations (2) and (3)

β_1	β_2	β_3	β_4
–5.441	-4.636×10^{-3}	1.926	0.678

The regression model does not predict T in the regions where the Culebra is underlain by halite in the M2/H2 interval because no quantitative data were available from these regions to be used in deriving the regression. In these regions, the following modified version of the regression model of Equation (2) is applied:

$$Y(\mathbf{x}) = \beta_1 + \beta_2\, d(\mathbf{x}) + \beta_3\, I_f(\mathbf{x}) + \beta_4\, I_D(\mathbf{x}) + \beta_5\, I_H(\mathbf{x}) \qquad (3)$$

where $I_H(\mathbf{x})$ is a halite indicator function. This indicator is assigned a value of 1 in locations where halite occurs in the M2/H2 interval and 0 otherwise. The coefficient β_5 is set equal to –1 so that Equation (3) reduces the predicted T values by one order of magnitude where halite occurs in the M2/H2 interval, to accord qualitatively with the expected transmissivity reduction discussed in Section 3.5 of this attachment. With knowledge (or stochastic estimations) of the values of the geologic controls (e.g., Culebra depth, fracture-interconnectivity indicator, dissolution indicator, and halite indicator), Culebra T values can be predicted at unobserved locations in the WIPP Culebra model domain using Equation (3).

TFIELD-4.0 CALCULATION OF BASE T FIELDS

In this section, a method is developed for applying the linear regression model from Section 3.0 of this attachment to predict Culebra T across a model domain encompassing the WIPP area. Culebra overburden thickness, Salado dissolution, and the presence or absence of halite in units bounding the Culebra can be deterministically evaluated across the WIPP region using maps constructed from subsurface data (Section 2.0 of this attachment). The presence of open, interconnected fractures, however, cannot be deterministically assessed across the WIPP area using maps. A geostatistical approach, conditional indicator simulation, is used to generate 500 equiprobable realizations of zones with hydraulically significant fractures in the WIPP region. These simulations are parameterized using the frequency of occurrence of WIPP wells with hydraulically significant fractures and a fit to a variogram constructed using data from those same wells. The regression model is then applied to the entire WIPP area by:

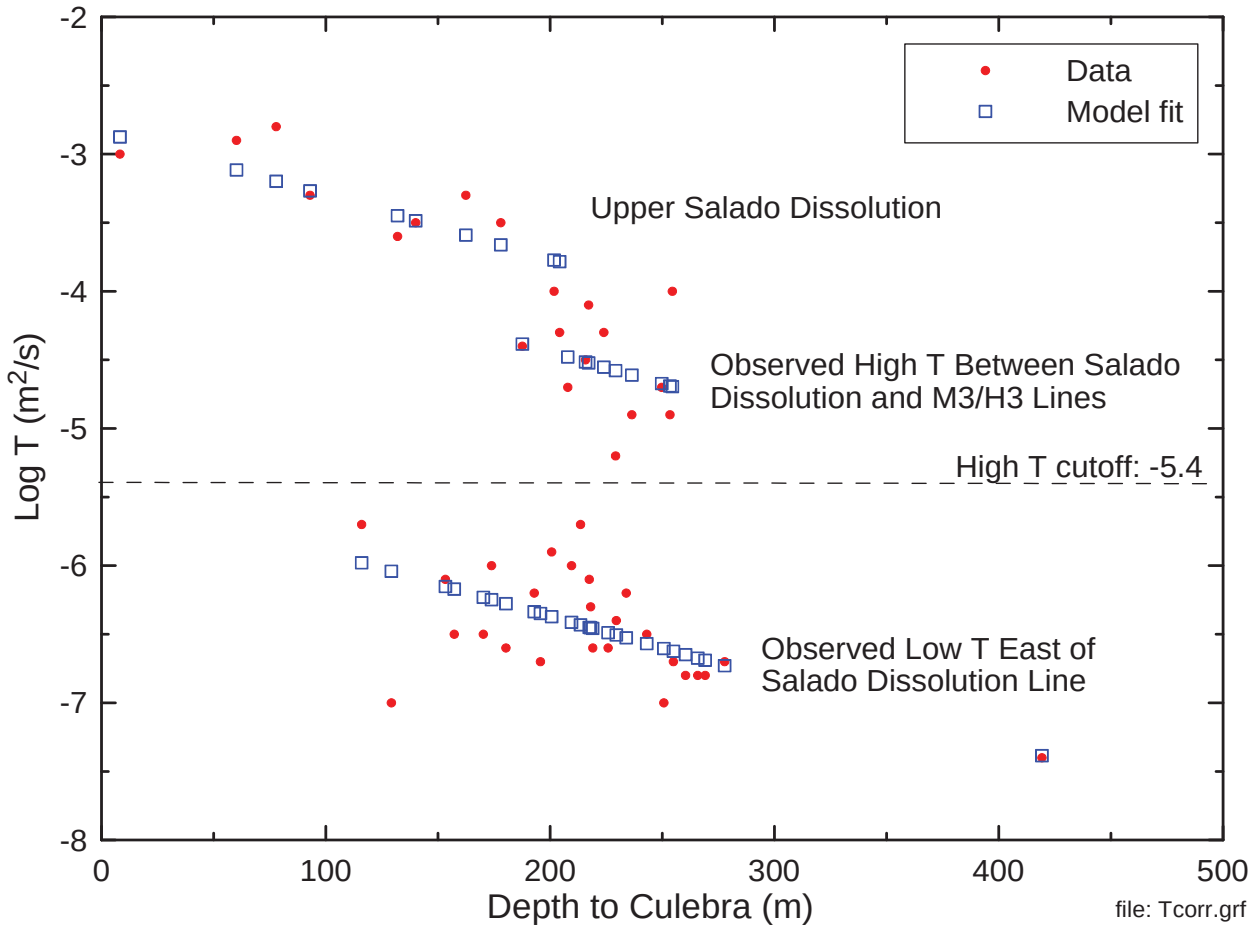

Figure TFIELD-7. Regression Fit to Observed Culebra Log_{10} T Data

1. Overlaying the geologic map data for Culebra overburden thickness, Salado dissolution, and the presence or absence of halite in units bounding the Culebra with each of the 500 equiprobable realizations of zones containing open, interconnected fractures.

2. Sampling each grid point within the model domain to determine the overburden thickness and the indicator values for Salado dissolution, overlying or underlying halite, and fracture interconnectivity.

3. Using the sampled data at each grid point with the regression model coefficients to estimate Culebra T.

When applied to the 500 equiprobable realizations of zones containing open, interconnected fractures, this procedure generates 500 stochastically varying Culebra base T fields. Details about the creation of the base T fields are given in Holt and Yarbrough (2002, 2003a, 2003b).

TFIELD-4.1 Definition of Model Domain

Two principal factors were considered in selecting the boundaries for the Culebra model domain. First, model boundaries should coincide with natural groundwater divides where feasible, or be far enough from the southern portion of the WIPP site, where transport will be modeled, to have

minimal influence in that area. Second, the model domain should encompass known features with the potential to affect Culebra water levels at the WIPP site (e.g., potash tailings ponds). The modeling domain selected is 22.4 km (13.9 mi) east-west by 30.7 km (19.1 mi) north-south, aligned with the compass directions (Figure TFIELD-6). This is the same as the domain used by LaVenue et al. (1990) except that the current domain extends 1 km (0.62 mi) farther to the west than the 1990 domain. The modeling domain is discretized into 68,768 uniform 100-m (328-ft) by 100-m (328-ft) cells. The northern model boundary is slightly north of the northern end of Nash Draw, 12 km (7.5 mi) north of the northern WIPP site boundary and about 1 km (0.62 mi) north of Mississippi Potash Incorporated's east tailings pile. The eastern boundary lies in a low-T region that contributes little flow to the modeling domain. The southern boundary lies 12.2 km (7.6 mi) south of the southern WIPP site boundary, 1.7 km (1.5 mi) south of our southernmost well (H-9) and far enough from the WIPP site to have little effect on transport rates on the site. The western model boundary passes through the IMC tailings pond (Laguna Uno of Hunter [1985]) due west of the WIPP site in Nash Draw. Boundary conditions assigned for the model are discussed in Section 6.2 of this attachment. The coordinates of each corner of the domain are given in Table TFIELD-2**,** in NAD 27 UTM coordinates.

Table TFIELD-2. Coordinates of the Numerical Model Domain Corners

Domain Corner	UTM X Coordinate (m)	UTM Y Coordinate (m)
Northeast	624,050	3,597,150
Northwest	601,650	3,597,150
Southeast	624,050	3,566,450
Southwest	601,650	3,566,450

TFIELD-4.2 Reduction of Geologic Map Data

To create useable data sets for conditional simulation of high-T zones and prediction of Culebra T, the geological maps described above in Section 2.0 of this attachment were imported into a GIS environment and digitized. A uniform 100-m (328-ft) grid was then created over the Culebra model domain. Using the Culebra structure contour map data (Figure TFIELD-1) and surface elevation data obtained from the United States Geological Survey (USGS) National Elevation Dataset (NED) (http://edcnts12.cr.usgs.gov/ned), an isopach map of the Culebra overburden on the 100-m (328-ft) model grid was created.

Using maps showing occurrence of halite in the units above and below the Culebra and well locations, soft data files were created for conditional indicator simulations. T within 120 m (374 ft) of each well is assumed to be from the same population (e.g., high or low T reflecting open, interconnected fractures or filled (poorly interconnected) fractures, respectively), and regions where the Culebra is overlain by halite in M3/H3 or underlain by halite in M2/H2 are assumed to be low-T regions.

Using maps of Salado dissolution and the occurrence of halite in the units above and below the Culebra, 100-m (328-ft) indicator grids were created over the model domain. These indicator grids were created for regions affected by Salado dissolution, regions where the Culebra is

underlain by halite in the M2/H2 interval, and a middle zone in which the Culebra is neither overlain nor underlain by halite where high-T zones occur stochastically (Figure TFIELD-8).

TFIELD-4.3 Indicator Variography

Excluding data where Salado dissolution occurs, Culebra T data are indicator transformed (1 for $\log_{10}$ T (m^2/s) > –5.4, 0 otherwise). A high-T indicator variogram is then constructed for the indicator data in the region not affected by Salado dissolution using the GSLIB program gamv (Deutsch and Journel 1998). The lag spacing for this variogram is selected to maximize variogram resolution. The resulting indicator variogram is then fit with an isotropic spherical variogram model:

$$\gamma(h) = \begin{cases} s[1.5(h/\lambda) - 0.5(h/\lambda)^3] & \text{if } h \le \lambda \\ s & \text{if } h \ge \lambda \end{cases} \tag{4}$$

where $\gamma(h)$ is the variogram as a function of lag spacing h, s is the sill value of the indicator variogram, and λ is the correlation length. This variogram model minimizes the mean squared error between the experimental and modeled variogram. The sill value was determined using:

$$s = P[\log_{10} T\ (\mathrm{m}^2/\mathrm{s}) > -5.4] - \{P[\log_{10} T\ (\mathrm{m}^2/\mathrm{s}) > -5.4]\}^2 \tag{5}$$

For the Culebra data set, excluding wells where dissolution has occurred, s = 0.201. The correlation length λ was estimated to be 1,790 m (5,873 ft). No nugget effect was included in the variogram model (Figure TFIELD-9). Variogram model parameters were then used in conditional indicator simulations of Culebra high-T zones.

TFIELD-4.4 Conditional Indicator Simulation

"Soft" indicator data were created for the indicator simulations. To ensure that no high-T regions develop in areas where halite occurs in M2/H2 or M3/H3, soft data points, indicating low T, were placed on a 200-m (656-ft) grid east of the M2/H2 and M3/H3 salt margins. This 200-m (656-ft) grid used the original 100-m (328-ft) grid excluding every other node to assure the 200-m (656-ft) soft data grid spatially overlay the 100-m (328-ft) grid. Soft data were also specified for every 100-m (328-ft) node along the combined lines of the M2/H2 and M3/H3 salt margins.

Additional soft data were created near well locations establishing a 120-m (394-ft) buffer around each well (Figure TFIELD-10). All 100-m (328-ft) grid nodes lying within the 120-m (394-ft) buffer were selected and assigned the transmissivity attribute of the well. Because all the nodes within 120 m (394 ft) of the well and the node corresponding to the block containing the well were selected as soft data, there was duplication in the input files. Only one data point can occupy a 100-m (328-ft) grid space during a realization. Therefore, the node closest to the well was eliminated from the soft data file.

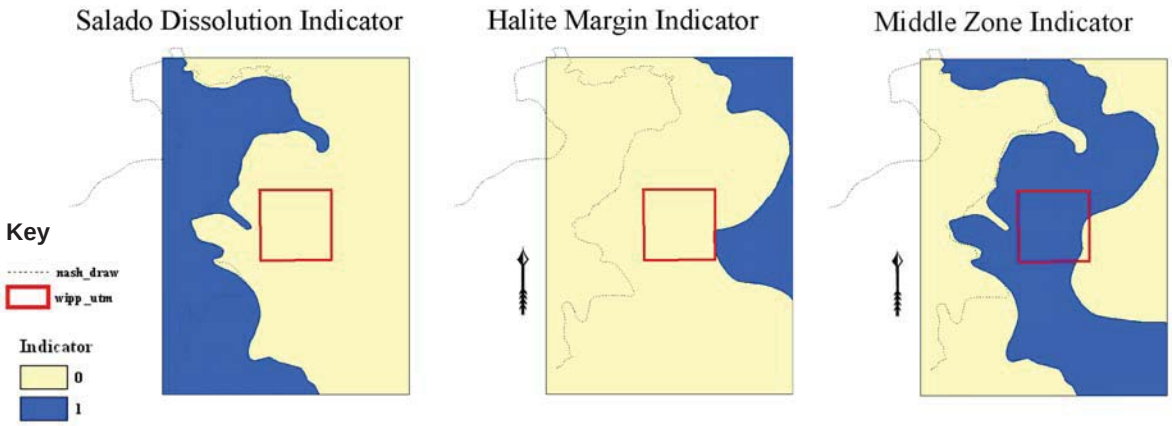

Figure TFIELD-8. Zones for Indicator Grids

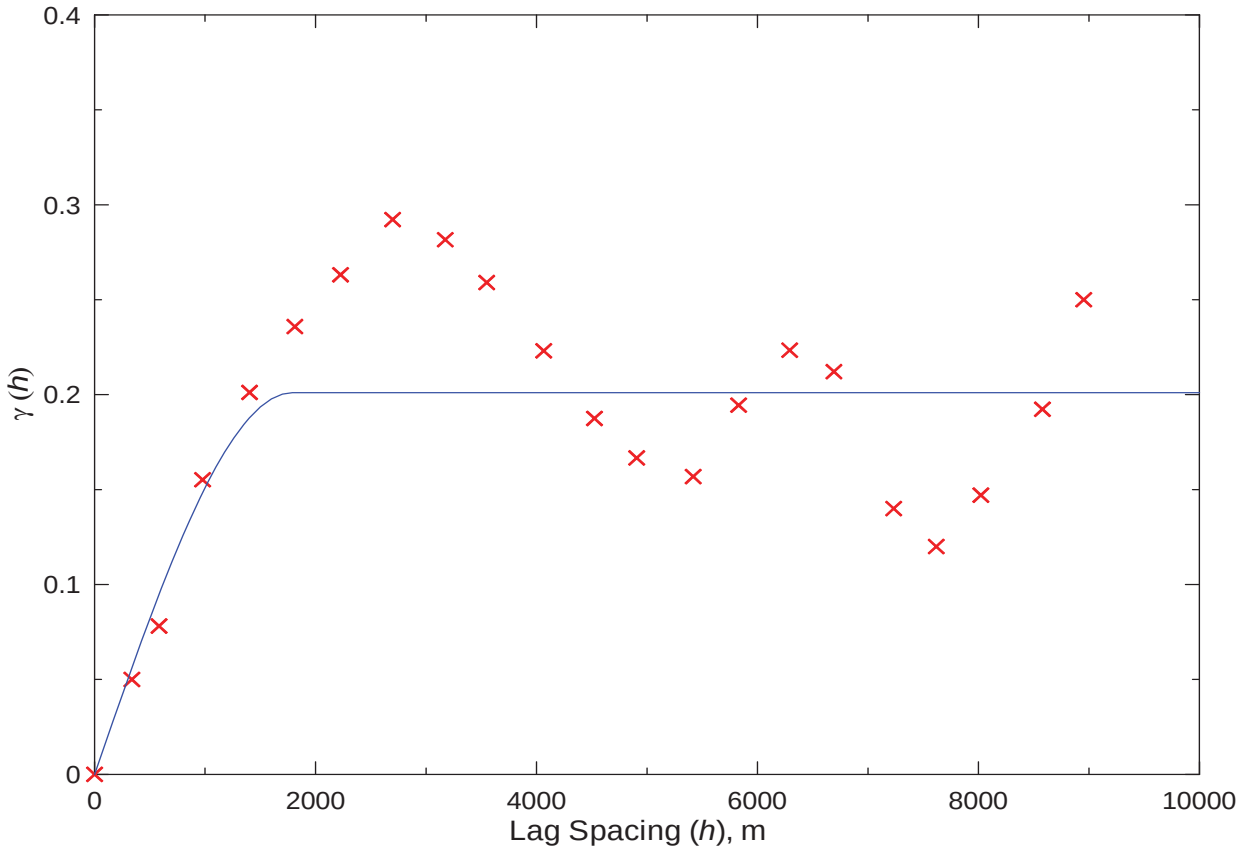

Figure TFIELD-9. High-T Indicator Model and Experimental Variograms

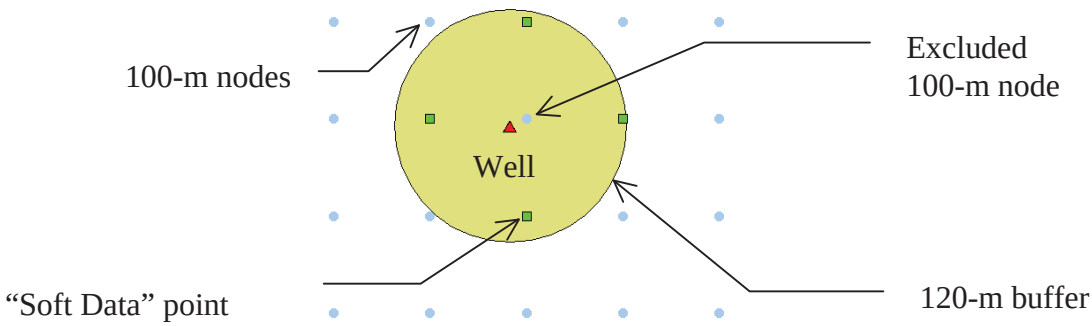

Figure TFIELD-10. Soft Data Around Wells

Five hundred conditional indicator simulations were generated on the 100-m (328-ft) model grid using the GSLIB program sisim (Deutsch and Journel 1998) with Culebra high-T indicator data, soft data for regions around wells and regions where halite underlies and overlies the Culebra, and the variogram parameters. The resulting indicator simulations were used in the construction of base T fields.

TFIELD-4.5 Construction of Base Transmissivity Fields

The linear predictor (Equation (3)) was used to generate 500 equally probable realizations of the T distribution in the Culebra model domain. This calculation required the regression coefficients discussed in Section 3.8 of this attachment, Culebra depth data (Section 3.9 of this attachment), a Salado dissolution indicator function, an indicator for where halite occurs in M2/H2, and the 500 realizations of high-T indicators discussed in Section 4.4 of this attachment.

The 500 base T fields were created in five sets. Each set consists of ten groups of ten realizations given d##r## designations. The "d" counter ranges from 01 to 50, while the "r" counter ranges from 01 to 10. An example base T field is shown in Figure TFIELD-11. Stochastically located patches of relatively high T (yellowish-green) can be clearly seen in the middle zone of the model domain. (Note: On black and white copy, these patches appear as the lightest shade of gray.)

TFIELD-5.0 CONSTRUCTION OF SEED REALIZATIONS

The base T fields described in Section 4.5 of this attachment rely on a regression model to estimate T at every location. By the nature of regression models, the estimated T values will not honor the measured T values at the measurement locations. Therefore, before using these base T fields in a flow model, they must be conditioned to the measured T values. This conditioning is performed with a Gaussian geostatistical simulation algorithm to generate a series of 500 spatially correlated residual fields where each field has a mean value of zero. These fields are conditional such that the residual value at each measurement location, when added to the value provided by the regression model (which is the same for all 500 fields), provides the known T value at that location. The result of adding the simulated residual field to the base T field is the "seed" realization.

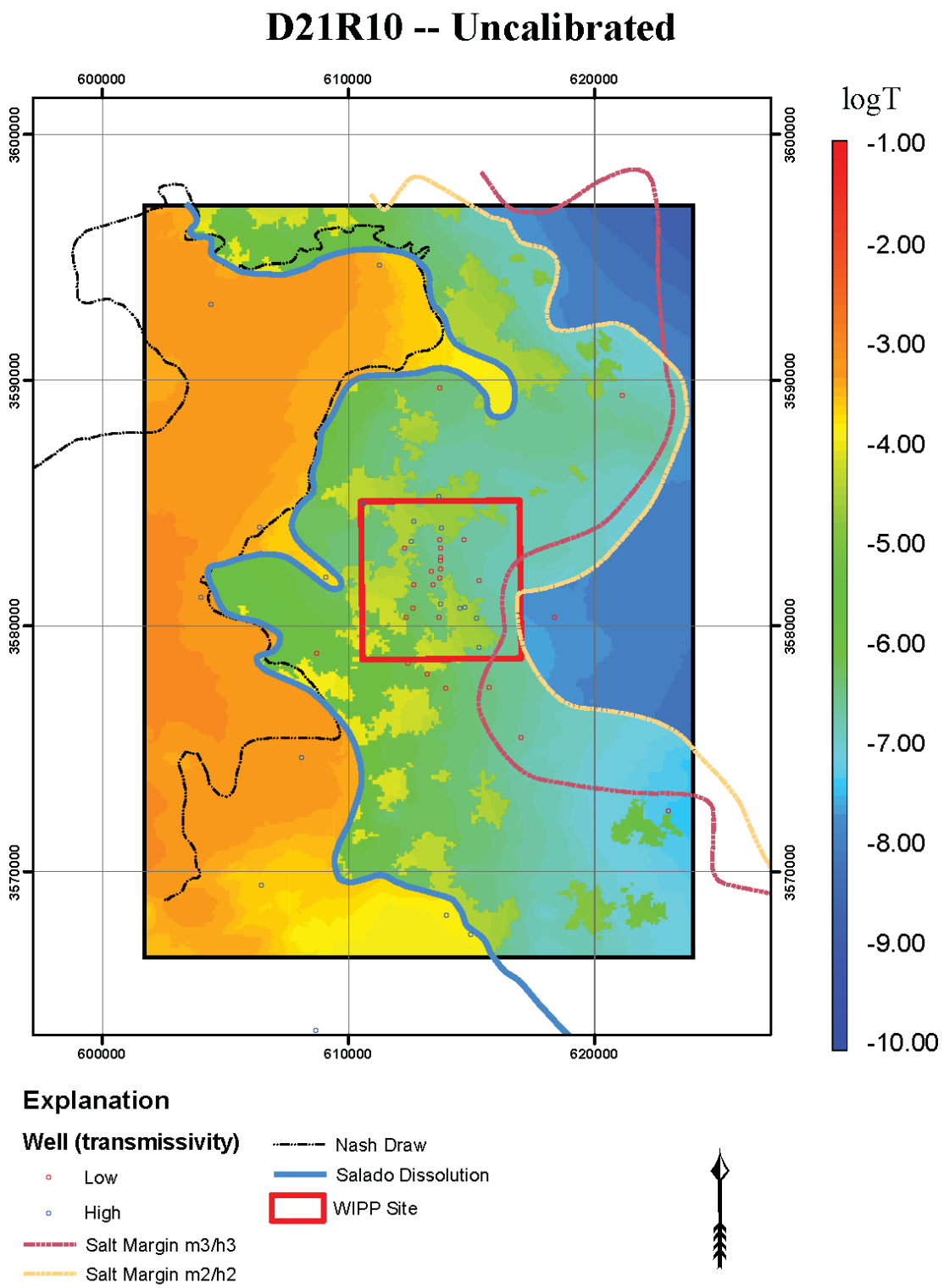

Figure TFIELD-11. Example Base T Field

This process is shown conceptually along a west-to-east cross section of the Culebra in Figure TFIELD-12. The upper image shows the value of the residuals at five T measurement locations across the cross section. These residuals are calculated as the observed (measured) T value minus the base field T value at the same locations. Positive residuals are where the measured T value is greater than that of the base T field. To create a T field from these residuals, there needs to be a way to tie the base field to the measured T values. This tie is accomplished by creating a spatial simulation of the residual values, a "residual field." The middle image of Figure TFIELD-12 is an example residual field as a (red) dashed line along the cross section. This residual field is constructed through geostatistical simulation using a variogram model fit to the residual data. The residual field honors the measured residuals at their measurement locations and returns to a mean value of zero at distances far away from the measurement locations. Finally, this residual field is added to the base T field to create the seed T field. The base T field is represented by the solid (blue) line in the bottom image of Figure TFIELD-12 and the seed T field is shown by the dotted line. The seed T field corresponds to the base T field except at those locations where it must deviate to match the measured T data. The large discontinuity shown in the base T field at the bottom of Figure TFIELD-12 is due to the stochastic simulation of high-T zones within the Culebra.

A total of 46 measured T values and corresponding residual data, both in units of $\log_{10}$ (m^2/s), are available (Table TFIELD-3). For each pair of $\log_{10}$ T and residual data, the well name and the easting (X) and northing (Y) UTM coordinates are also given (for multiwell hydropads, a single well's coordinates were used).

The process of creating the residual fields is to use the residual data to generate variograms in the VarioWin© software package and to then create conditional stochastic Gaussian geostatistical simulations of the residual field within the GSLIB program sgsim (Deutsch and Journel 1998).

To use the data in a Gaussian simulation algorithm, it is first necessary to transform the distribution of the raw residual data to a standard normal distribution. This is accomplished through a process called the "normal-score transform" where each transformed residual value is the "normal-score" of each original datum. The normal-score transform is a relatively simple two-step process. First the cumulative frequency of each original residual value, *cdf(i)*, is determined as:

$$cdf(i) = \frac{R(i) - 0.5}{N} \tag{6}$$

where *R(i)* is the rank (smallest to largest) of the ith residual value and *N* is the total number of data (46 in this case). Then for each cumulative frequency value, the corresponding normal-score value is calculated from the inverse of the standard normal distribution. By definition, the standard normal distribution has a mean of 0.0 and a standard deviation of 1.0. Further details of the normal-score transform process can be found in Deutsch and Journel (1998).

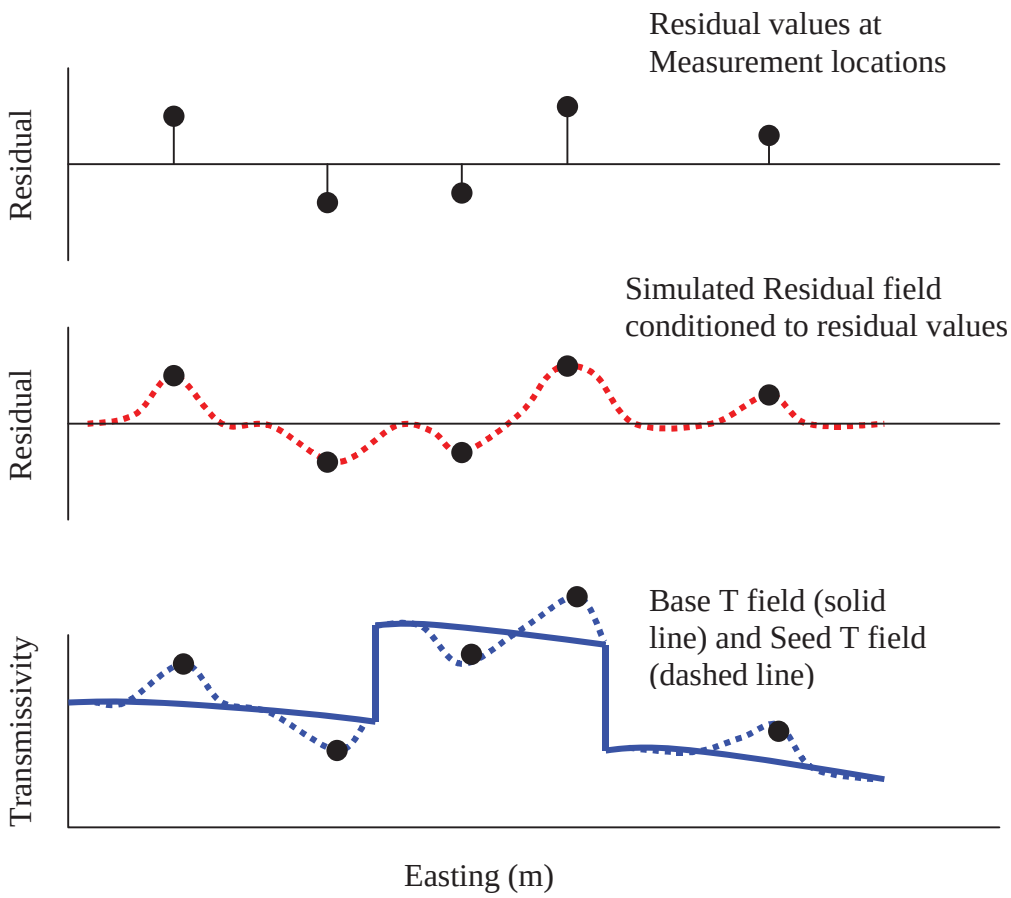

Figure TFIELD-12. Conceptual Cross Section Showing the Updating of the Residual Field and the Base T Field into the Seed T Field

Table TFIELD-3. Log_{10} Transmissivity Data Used in Inverse Calibrations

Well ID	Easting (UTM, m)	Northing (UTM, m)	log_{10} T (m^2/s)	log_{10} T residual (m^2/s)
AEC-7	621126	3589381	–6.8	–0.11078
CB-1	613191	3578049	–6.5	–0.32943
D-268	608702	3578877	–5.7	0.27914
DOE-1	615203	3580333	–4.9	–0.21004
DOE-2	613683	3585294	–4.0	0.69492
Engle	614953	3567454	–4.3	–0.51632
ERDA-9	613696	3581958	–6.3	0.15250
H-1	613423	3581684	–6.0	0.41295
H-2c	612666	3581668	–6.2	0.13594
H-3b1	613729	3580895	–4.7	–0.22131
H-4c	612406	3578499	–6.1	0.05221
H-5c	616903	3584802	–6.7	0.02946

Table TFIELD-3. Log_{10} Transmissivity Data Used in Inverse Calibrations — Continued

Well ID	Easting (UTM, m)	Northing (UTM, m)	log_{10} T (m^2/s)	log_{10} T residual (m^2/s)
H-6c	610610	3584983	–4.4	–0.01524
H-7c	608095	3574640	–2.8	0.39794
H-9c	613974	3568234	–4.0	–0.22763
H-10b	622975	3572473	–7.4	–0.01484
H-11b4	615301	3579131	–4.3	0.25314
H-12	617023	3575452	–6.7	–0.07647
H-14	612341	3580354	–6.5	–0.26934
H-15	615315	3581859	–6.8	–0.12631
H-16	613369	3582212	–6.1	0.34962
H-17	615718	3577513	–6.6	–0.14310
H-18	612264	3583166	–5.7	0.73159
H-19b0	614514	3580716	–5.2	–0.62242
P-14	609084	3581976	–3.5	0.16212
P-15	610624	3578747	–7.0	–0.95938
P-17	613926	3577466	–6.0	0.24762
USGS-1	606462	3569459	–3.3	0.28998
WIPP-12	613710	3583524	–7.0	–0.39627
WIPP-13	612644	3584247	–4.1	0.42180
WIPP-18	613735	3583179	–6.5	0.06840
WIPP-19	613739	3582782	–6.2	0.32598
WIPP-21	613743	3582319	–6.6	–0.11148
WIPP-22	613739	3582653	–6.4	0.10549
WIPP-25	606385	3584028	–3.5	–0.01378
WIPP-26	604014	3581162	–2.9	0.21598
WIPP-27	604426	3593079	–3.3	–0.03209
WIPP-28	611266	3594680	–3.6	–0.15124
WIPP-29	596981	3578694	–3.0	–0.12497
WIPP-30	613721	3589701	–6.7	–0.35131
WQSP-1	612561	3583427	–4.5	0.01540
WQSP-2	613776	3583973	–4.7	–0.02729
WQSP-3	614686	3583518	–6.8	–0.15139
WQSP-4	614728	3580766	–4.9	–0.28895
WQSP-5	613668	3580353	–5.9	0.47178
WQSP-6	612605	3580736	–6.6	–0.32261

The two-step normal-score transformation process is conducted in Microsoft Excel© (see details in McKenna and Hart 2003b). The resulting normal-score values are the distance from the mean as measured in standard deviations. The parameters describing the residual and normal-score transformed distributions are presented in Table TFIELD-4.

Table TFIELD-4. Statistical Parameters Describing the Distributions of the Raw and Normal-score Transformed Residual Data

Parameter	Raw Residual	Normal-Score Transformed Residual Data
Mean	0.000	0.000
Median	–0.015	0.000
Standard Deviation	0.330	0.997
Minimum	–0.959	–2.295
Maximum	0.732	2.295

The omnidirectional variogram is calculated with a 250-m (820-ft) lag spacing. The experimental variogram is shown in Figure TFIELD-13. The model fit to this experimental variogram is Gaussian with a nugget of 0.2, a sill of 0.8, and a range of 1,050 m (3,445 ft). The sum of the nugget and sill values is constrained to equal the theoretical variance of 1.0 by the sgsim software that is used to create the spatially correlated residual fields.

The variogram parameters for the normal-score transformed residuals are used directly in the sgsim program to create 500 conditional realizations of the residual field. Each of these 500 residual fields is used as an initial residual field and each one is assigned to an individual base T field. An example of a realization of the residual field and its combination with a base T field is shown in Figure TFIELD-14. From Figure TFIELD-14, the effect of the residual field on the base T field can be seen. The residual field perturbs the Ts to match the measured Ts at the well locations. The discrete features that are part of the original base T field (e.g., high-T zones in the middle of the domain) are retained when the residual field is added to the base field, although T values within those features may be altered to a degree.

A number of distributed locations within the modeling domain are selected and designated as "pilot points." PEST adjusts the T value at each of these pilot points to achieve a better match between the groundwater flow model results and the observed steady-state and transient head data. The adjustments in T at each pilot point cannot be made independently of surrounding T values and, therefore, these surrounding T values must be updated in a manner consistent with the change made at the pilot point. This updating is done by applying a change at each of the surrounding points that is a weighted fraction of the change made at the pilot point. The weights are calculated from the residual variogram.

These updates are necessary to create a final T field that honors all observed T measurements and matches the observed heads when used as input to a groundwater flow model. Therefore, it is also necessary to calculate and model a variogram on the raw, not normal-score transformed,

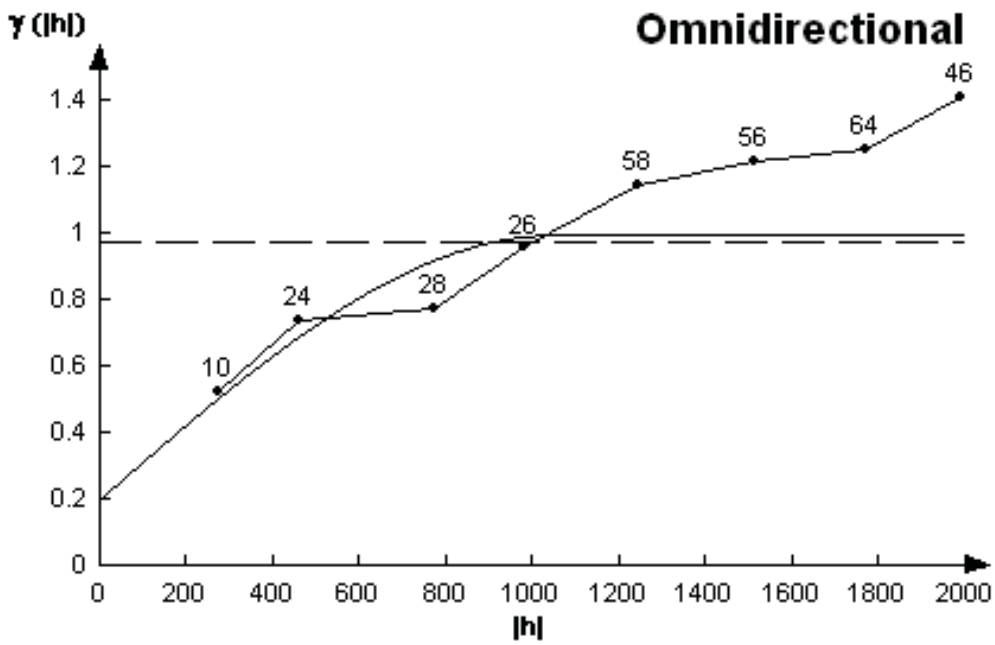

Figure TFIELD-13. Omnidirectional Variogram Model Fit to the Experimental Variogram of the Transmissivity Residuals

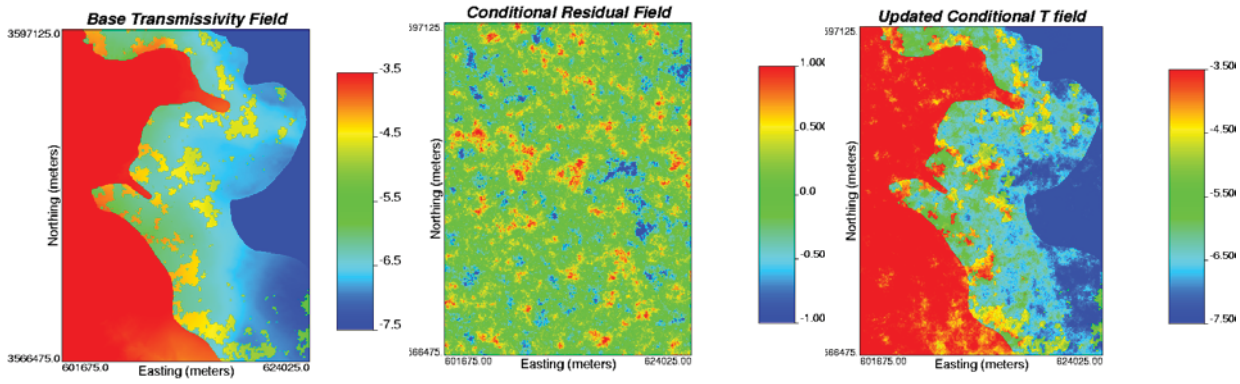

Figure TFIELD-14. An Example of the Creation of a Seed T Field. The base T field (left image) is combined with the initial residual field created through geostatistical simulation (center image) to produce the seed T field (right image). That field is then used as the initial field for the first iteration of the inverse calibration procedure. All three color scales denote the $\log_{10}$ T (m^2/s) value.

residuals for use in this kriging process. This variogram was also calculated with a 250-m (820-ft) lag and is omnidirectional. A doubly nested spherical variogram model was fit to the experimental variogram. The variogram parameters are a nugget of 0.008, a first sill and range of 0.033 and 500 m (1,640 ft), respectively, and a second sill and range of 0.067 and 1,500 m (4,921 ft), respectively (Figure TFIELD-15).

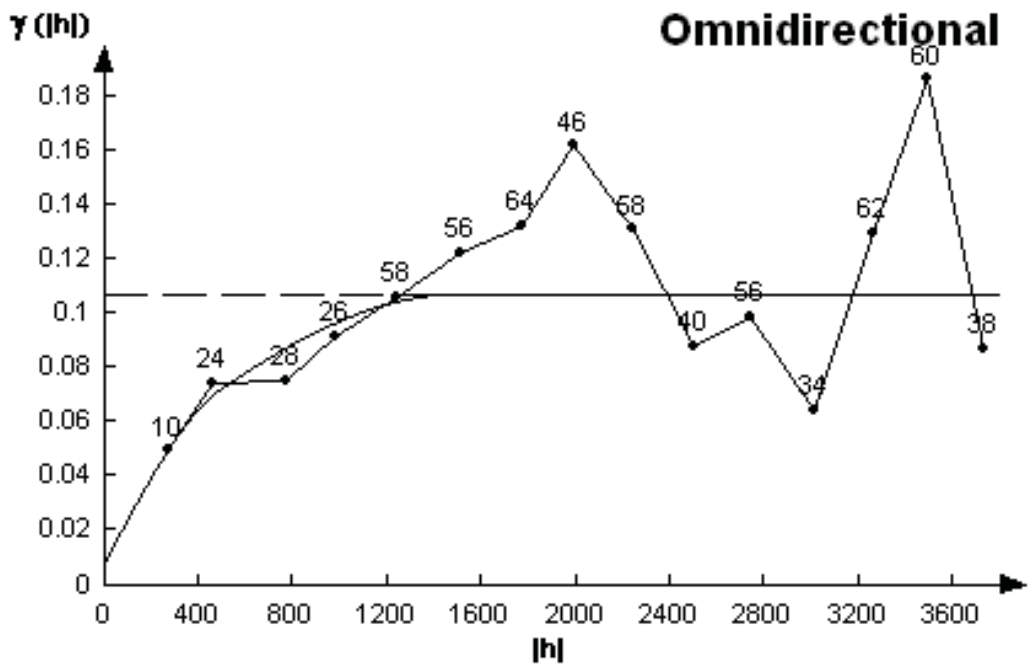

Figure TFIELD-15. Experimental and Model Variograms for the Raw-Space (Not Normal-Score Transformed) Transmissivity Residual Data

TFIELD-6.0 T-FIELD CALIBRATION TO STEADY-STATE AND TRANSIENT HEADS

This section presents details on the modeling approach used to calibrate the T fields to both the 2000 steady-state heads and 1,332 transient drawdown measurements. This section is divided into the following subsections:

1. Assumptions made in the modeling and the implications of these assumptions are provided.

2. The initial heads used for each calibration are estimated at each location in the domain using the heads measured in 2000 using kriging and accounting for the regional trend in the head values.

3. The initial heads are used to assign fixed-head boundaries to three sides of the model. The fourth side, the western edge, is set as a no-flow boundary for the model.

4. The transient head observations for each hydraulic test and each observation well are selected from the database. These heads are shown as a function of time for each hydraulic test.

5. The spatial and temporal discretization of the model domain are presented.

6. The transient head observations are given relative weights based on the inverse of the maximum observed drawdown in each hydraulic test. The relative weights assigned to the steady-state observations are also discussed.

7. The locations of the adjustable pilot points are determined using a combination of approaches.

All of these steps can be considered as preprocessing aspects of the stochastic inverse calibration procedure. The actual calibrations are done using an iterative coupling of the MODFLOW-2000 and PEST codes. The details of this process are covered in McKenna and Hart (2003a, 2003b), and are briefly summarized in this section.

TFIELD-6.1 Modeling Assumptions

The major assumptions that apply to this set of model calculations are:

1. The boundary conditions along the model domain boundary are known and do not change over the time frame of the model. This assumption applies to both the no-flow boundary along the western edge of the domain as well as to the fixed-head boundaries that were created to be consistent with the 2000 head measurements in the model domain. Implicit in this assumption is that the fixed-head boundary conditions do not have a significant impact on the transient tests that were simulated in the interior of the model at times other than the 2000 period.

2. The fracture permeability of the Culebra can be adequately modeled as a continuum at the 100-m (328-ft) × 100-m (328-ft) grid block scale and the measured T values used to condition the model are representative of the T in the 100-m (328-ft) × 100-m (328-ft) grid block in which the well test was performed. Implicit in this assumption is the prior assumption that the hydraulic test interpretations were done correctly and used the correct conceptual model.

3. Variable fluid densities in the Culebra can be adequately represented by casting the numerical solution in terms of freshwater head. Davies (1989) investigated the effects of variable fluid density on the directions of flow calculated in the Culebra using a freshwater-head approach. As the Culebra flow system was conceptualized and modeled by Davies, most of the water flowing in the Culebra in the vicinity of the WIPP site ultimately discharged to the Pecos River southwest of WIPP. When variable fluid density was taken into account, the only locations within the model domain where the flow direction changed by more than 10 degrees were regions 1.1 to 14.3 km (0.7 to 8.9 mi) south of the WIPP site, where the flow direction shifted as much as 70 degrees to the east toward a more downdip direction (but still primarily to the south) (Davies, 1989, Figures 35 and 36). As currently conceptualized, flow in the Culebra in the vicinity of WIPP does not discharge to the Pecos to the southwest, but instead goes to the southsoutheast toward the Paduca oilfield where extensive dissolution of the Salado and collapse of the Culebra has occurred (see Figure TFIELD-1). Hence, taking variable fluid density into account would have little effect on the flow direction.

TFIELD-6.2 Initial Heads

A set of initial head values was estimated across the flow model domain based on water-level measurements made in late 2000 (Beauheim 2002b). The water-level measurements were converted to freshwater heads using fluid-density data collected from pressure-density surveys performed in the wells and/or from water-quality sampling. The head values estimated at the cells in the interior of the domain were used as initial values of the heads and were subsequently updated by the groundwater flow model until the final solution was achieved. The head values estimated for the fixed-head cells along the north, east, and south boundaries of the model domain remained constant for the groundwater flow calculation. The estimation of the initial and boundary heads was done by kriging. Observed heads both within and outside of the flow model domain (Figure TFIELD-16) were used in the kriging process.

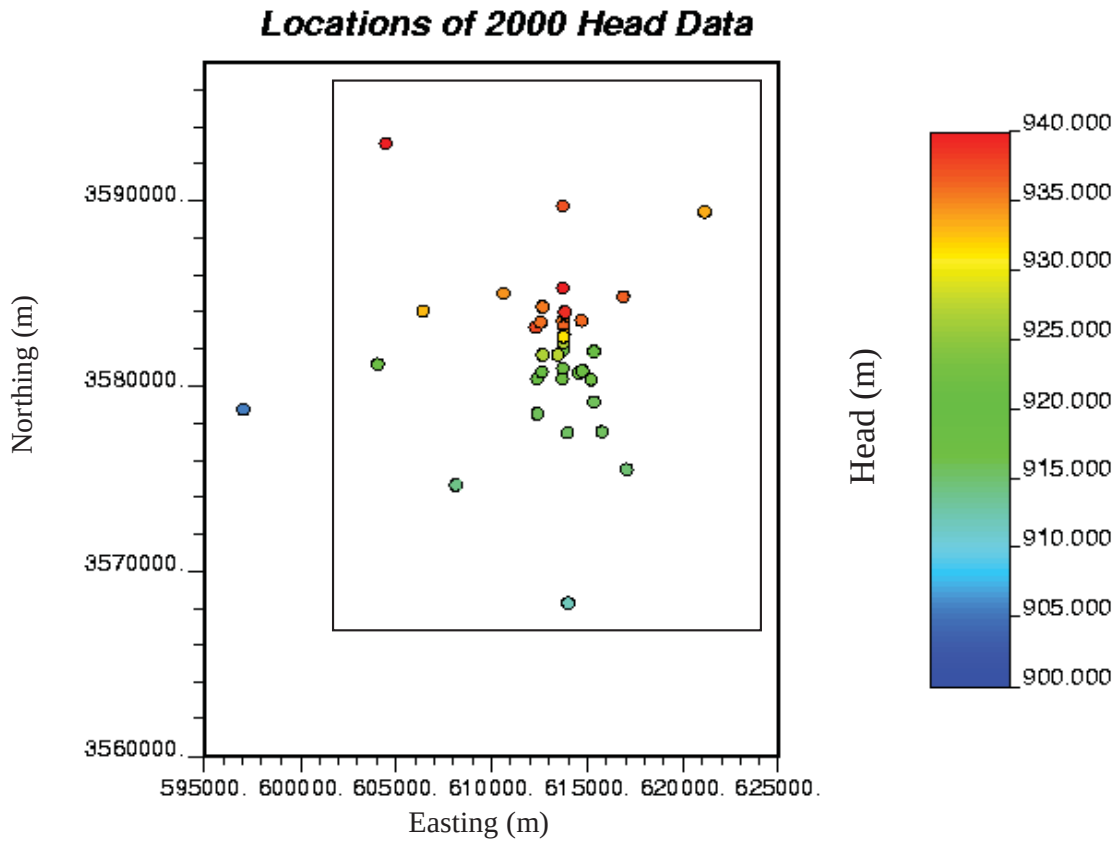

Figure TFIELD-16. Locations and Values of the 2000 Head Measurements Considered in the Steady-State Calibrations. The approximate extent of the numerical model domain is shown by the black rectangle in the image.

Kriging is a geostatistical estimation technique that uses a variogram model to estimate values of a sampled property at unsampled locations. Kriging is designed for the estimation of stationary fields (see Goovaerts 1997); however, the available head data show a significant trend (non-stationary behavior) from high head in the northern part of the domain to low head in the southern part of the domain. This behavior is typical of groundwater head values measured across a large area with a head gradient. To use kriging with this type of non-stationary data, a

Gaussian polynomial function is fit to the data, and the differences between the polynomial and the measured data (the "residuals") are calculated and a variogram of the residuals is constructed. This variogram and a kriging algorithm are then used to estimate the value of the residual at all locations within a domain. The final step in the process is to add the trend from the previously defined polynomial to the estimated residuals to get the final head estimates. This head estimation process is similar to that used in the Culebra calculations done for the CCA (Lavenue 1996).

The available head data from late 2000, comprising 37 measurements, are listed in Table TFIELD-5. In general, these head measurements show a trend from high head in the north to low head in the south. The trend was modeled with a bivariate Gaussian function. The use of this Gaussian function with five estimated parameters allows considerable flexibility in the shape of the trend that can be fit through the observed data. The value of the Gaussian function, *Z*, is:

$$Z = a \exp\left[-\frac{1}{2}\left(\left(\frac{X - X_0}{b} \right)^2 + \left(\frac{Y - Y_0}{c} \right)^2 \right) \right] \tag{7}$$

where X_0 and Y_0 are the coordinates of the center of the function and *b* and *c* are the standard deviations of the function in the *X* (east-west) and *Y* (north-south) directions, respectively. The parameter *a* controls the height of the function. The Gaussian function was fit to the data using the regression wizard tool in the SigmaPlot 2001 graphing software. The parameters estimated for the Gaussian function are presented in Table TFIELD-6. The fit of the Gaussian trend surface to the 2000 heads is shown in Figure TFIELD-17. The locations and values of the residuals (observed value – trend surface estimate) are shown in Figure TFIELD-18.

The next step in estimating the initial head values is to calculate an experimental variogram for each set of residuals and then fit a variogram model to each experimental variogram. Due to the rather limited number of data points, anisotropy in the spatial correlation of the residuals was not examined and an omnidirectional variogram was calculated. These calculations were done using the VarioWin© (version 2.21) software (Pannatier 1996). The Gaussian variogram model is:

$$\gamma(h) = C\left[1 - \exp^{\left(-\frac{3h^2}{a^2} \right)} \right] \text{ for } h > 0 \tag{8}$$

where *C* is the sill of the variogram , *h* is the distance between any two samples, or the lag spacing, and *a* is the practical range of the variogram, or the distance at which the model reaches 95 percent of the value of *C*. In addition to the sill and range, the variogram model may also have a non-zero intercept with the gamma (*Y*) axis of the variogram plot known as the nugget. Due to numerical instabilities in the kriging process associated with the Gaussian model without a nugget value, a small nugget was used in fitting each of the variogram models. The model variogram was fit to the experimental data (Figure TFIELD-19) and the parameters of this model are given in Table TFIELD-7.

Table TFIELD-5. Well Names and Locations of the 37 Head Measurements Obtained in Late 2000 Used to Define Boundary and Initial Heads

Well	UTM X (Easting) (m)	UTM Y (Northing) (m)	2000 Freshwater Head (m amsl)
AEC-7	621126	3589381	933.19
DOE-1	615203	3580333	916.55
DOE-2	613683	3585294	940.03
ERDA-9	613696	3581958	921.59
H-1	613423	3581684	927.19
H-2b2	612661	3581649	926.62
H-3b2	613701	3580906	917.16
H-4b	612380	3578483	915.55
H-5b	616872	3584801	936.26
H-6b	610594	3585008	934.20
H-7b1	608124	3574648	913.86
H-9b	613989	3568261	911.57
H-11b4	615301	3579131	915.47
H-12	617023	3575452	914.66
H-14	612341	3580354	920.24
H-15	615315	3581859	919.87
H-17	615718	3577513	915.37
H-18	612264	3583166	937.22
H-19b0	614514	3580716	917.13
P-17	613926	3577466	915.20
WIPP-12	613710	3583524	935.30
WIPP-13	612644	3584247	935.17
WIPP-18	613735	3583179	936.08
WIPP-19	613739	3582782	932.66
WIPP-21	613743	3582319	927.00
WIPP-22	613739	3582653	930.96
WIPP-25	606385	3584028	932.70
WIPP-26	604014	3581162	921.06
WIPP-27	604426	3593079	941.01
WIPP-29	596981	3578701	905.36
WIPP-30	613721	3589701	936.88
WQSP-1	612561	3583427	935.64
WQSP-2	613776	3583973	938.82
WQSP-3	614686	3583518	935.89
WQSP-4	614728	3580766	917.49
WQSP-5	613668	3580353	917.22
WQSP-6	612605	3580736	920.02

Table TFIELD-6. Parameters for the Gaussian Trend Surface Model Fit to the 2000 Heads

Trend Surface Parameters	Value
X_0	611011.89
Y_0	3780891.50
a	1134.61
b	73559.35
c	313474.40

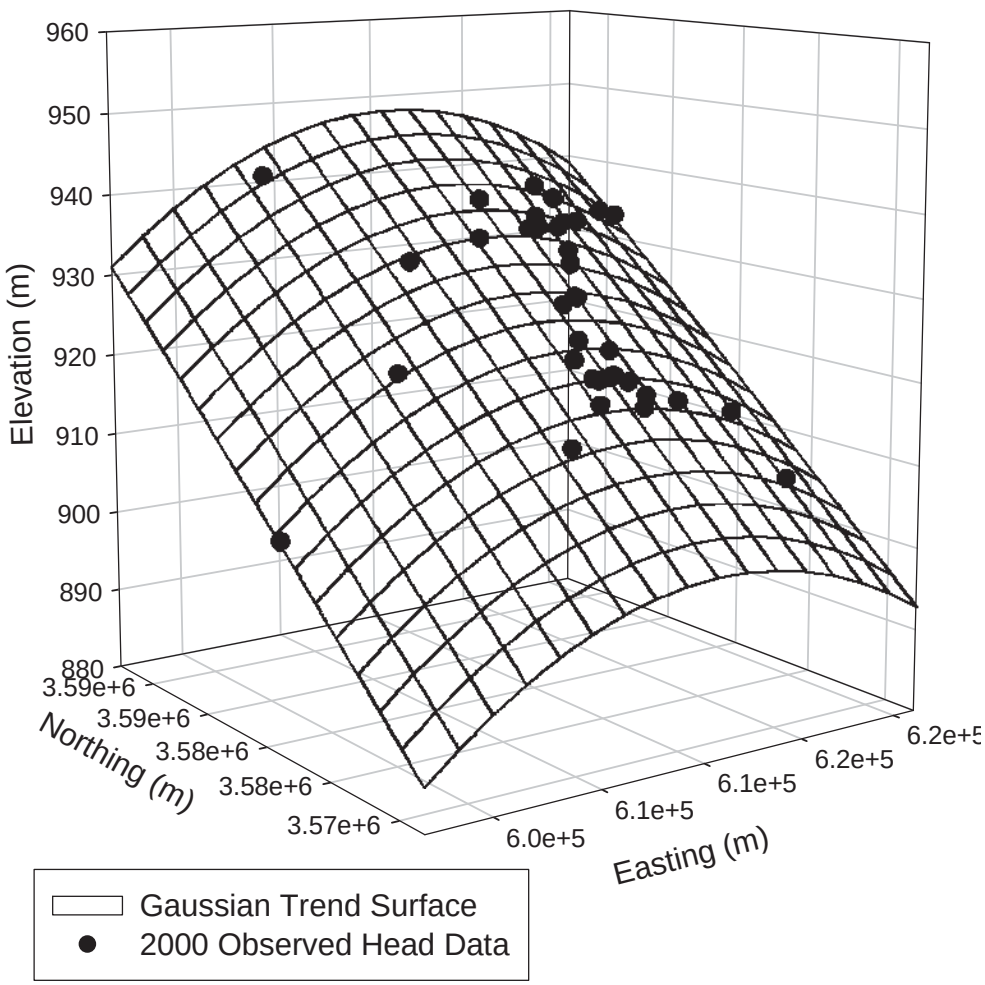

Figure TFIELD-17. Gaussian Trend Surface Fit to the 2000 Observed Heads

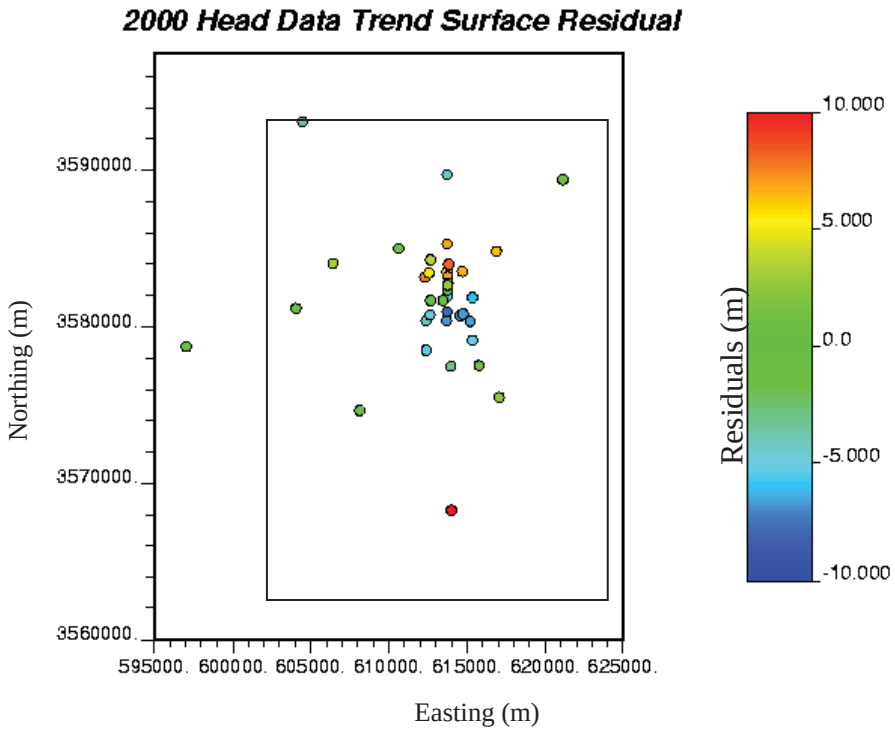

Figure TFIELD-18. Locations and Values of the Residuals Between the Gaussian Trend Surface Model and the Observed Head Data. The approximate boundary of the flow model is shown as a black rectangle in the image.

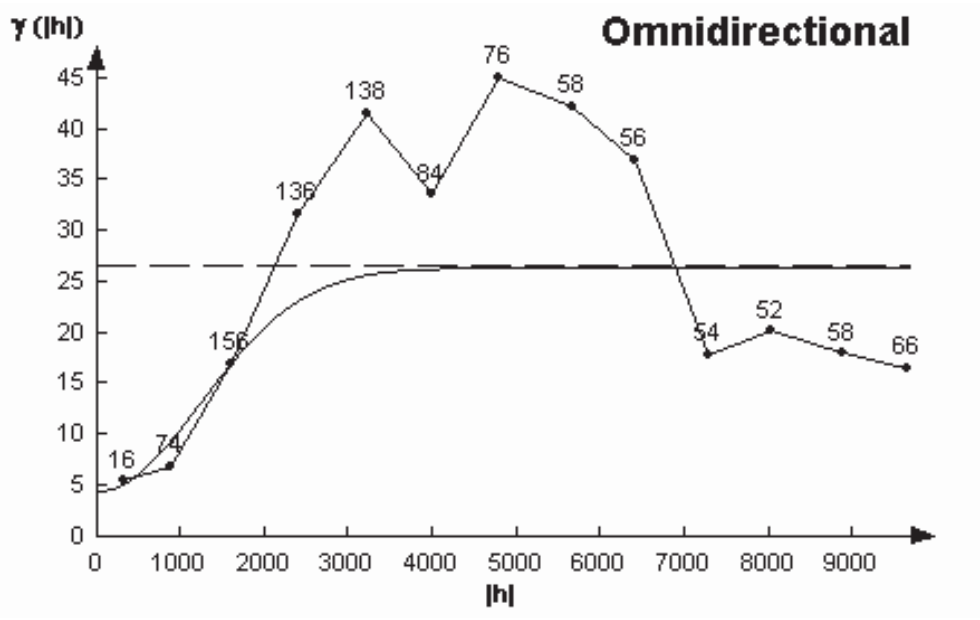

Figure TFIELD-19. Omnidirectional Experimental (Straight-Line Segments) and Model Variograms of the Head Residuals (Curves) for the 2000 Heads. The numbers indicate the number of pairs of values that were used to calculate each point and the horizontal dashed line denotes the variance of the residual data set.

Table TFIELD-7. Model Variogram Parameters for the Head Residuals

Parameter	Value
Sill	22
Range (meters)	3000
Nugget	4.5
Number of Data	37

The experimental variogram calculated on the 2000 data in Figure TFIELD-19 shows a number of points between lags 2,000 and 7,000 m (1.25 and 4.25 mi) that are above the variance of the data set (the horizontal dashed line). This behavior indicates that the Gaussian trend surface model used to calculate the residuals from the measured data did not remove the entire trend inherent in the observed data. A higher order trend surface model could be applied to these data to remove more of the trend, but the Gaussian trend surface model provides a reasonable estimate of the trend in the data.

The GSLIB kriging program kt3d (Deutsch and Journel 1998) was used to estimate the residual values at all points on the grid within the model domain. The Gaussian trend surface was then added to the estimated residual values to produce the final estimates of the initial head field.

TFIELD-6.3 Boundary Conditions

Two types of boundary conditions were specified in MODFLOW-2000: constant-head and no-flow. Constant-head conditions were assigned along the eastern boundary of the model domain, and along the central and eastern portions of the northern and southern boundaries. Values of these heads were obtained from the kriged initial head field. The western model boundary passes through the IMC tailings pond (Laguna Uno) due west of the WIPP site in Nash Draw. A no-flow boundary (a flow line) is specified in the model from this tailings pond up the axis of Nash Draw to the northeast, reflecting the concept that groundwater flows down the axis of Nash Draw, forming a groundwater divide. Similarly, another no-flow boundary is specified from the tailings pond down the axis of the southeastern arm of Nash Draw to the southern model boundary, coinciding with a flow line in the regional modeling of Corbet and Knupp (1996). Thus, the northwestern and southwestern corners of the modeling domain are specified as inactive cells in MODFLOW-2000. The initial (starting) head field is shown in Figure TFIELD-20 and the head values along each boundary of the model domain are shown in Figures TFIELD-21 and TFIELD-22.

TFIELD-6.4 Observed Steady-State and Transient Head Data Used in Model Calibration

In addition to being used to generate an initial head distribution, the water-level measurements made in 35 wells within the model domain during late 2000 were also used in steady-state model calibration. (Note that Table TFIELD-5 includes data from two wells – WIPP-27 and WIPP-29 – that were used to define model boundary conditions but are outside the area of calibration).

The transient observation data used for the transient calibrations were taken from a number of different sources listed in Beauheim (2003a). Responses to seven different hydraulic tests were employed in the transient portion of the calibration (Table TFIELD-8). Hydraulic responses for each of the seven tests were monitored in three to ten different observation wells depending on the hydraulic test.

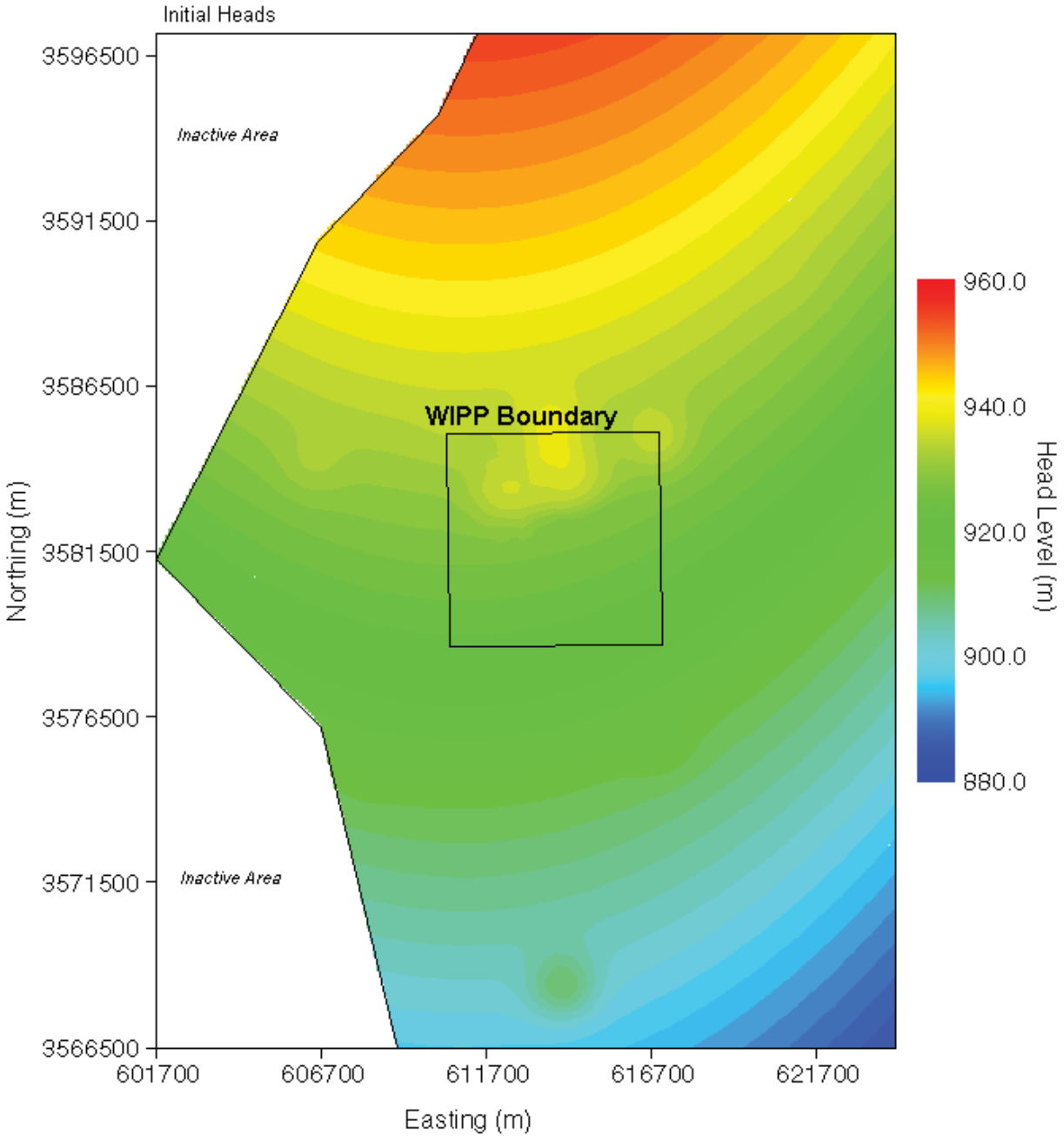

Figure TFIELD-20. Map of Initial Heads Created Through Kriging and Used to Assign Fixed-Head Boundary Conditions

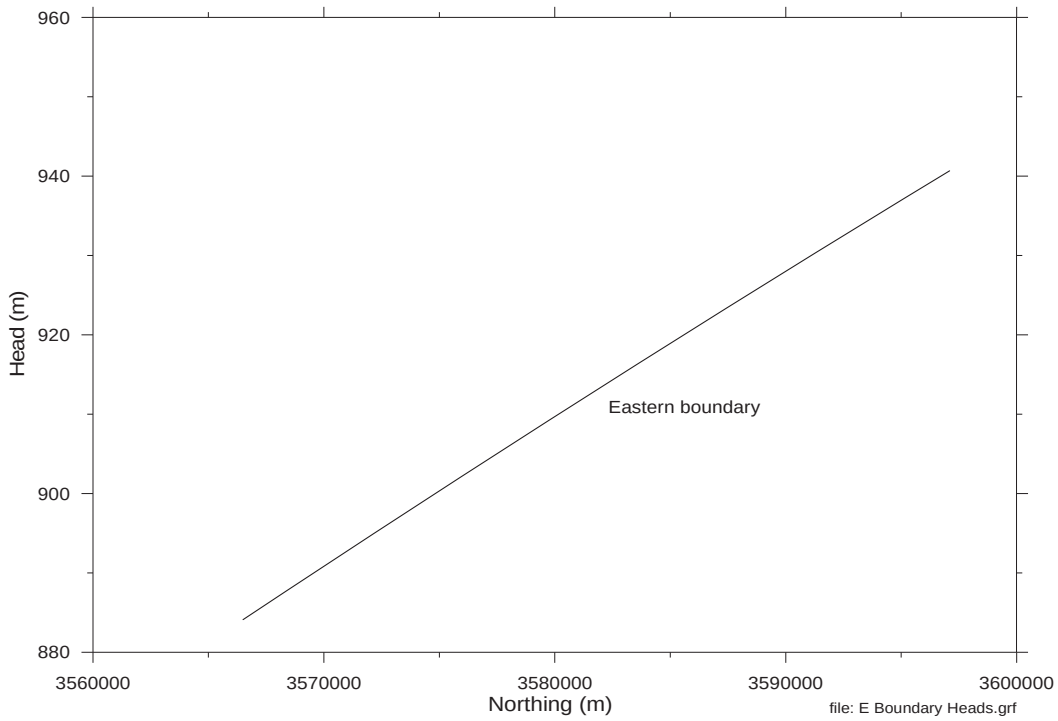

Figure TFIELD-21. Values of Fixed Heads Along the Eastern Boundary of the Model Domain

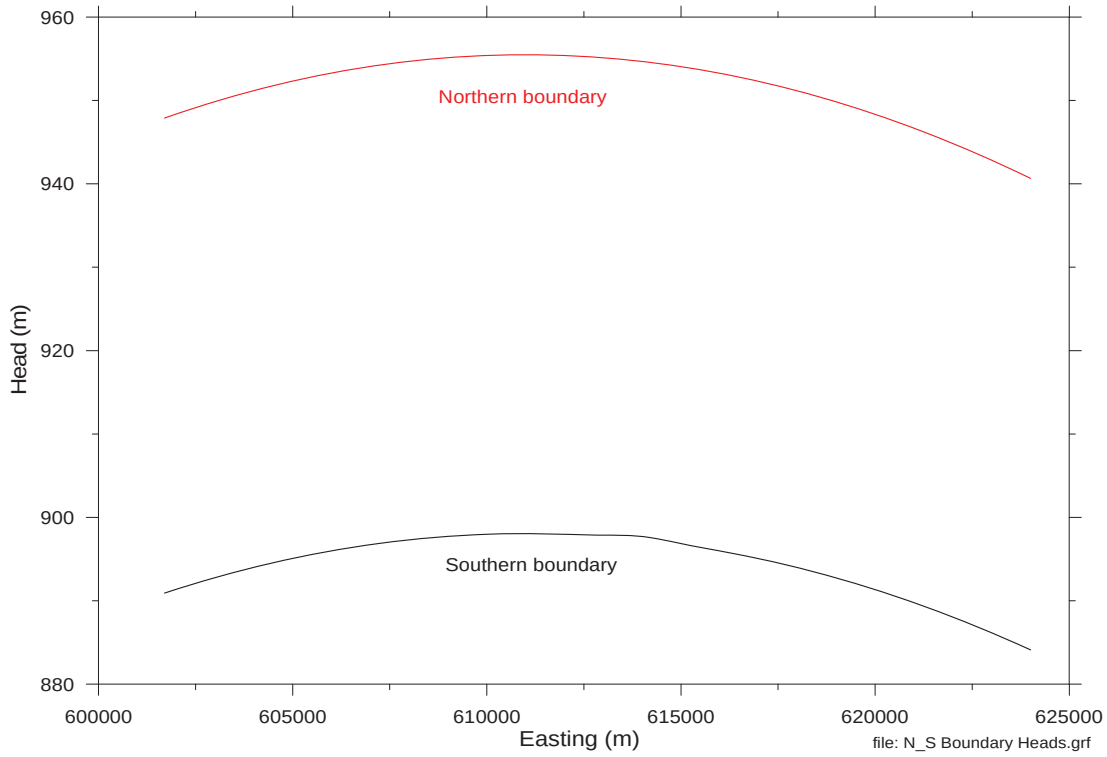

Figure TFIELD-22. Values of Fixed Heads Along the Northern and Southern Boundaries of the Model Domain. Note that not all locations along the boundaries are active cells.

Table TFIELD-8. Transient Hydraulic Test and Observation Wells for the Drawdown Data

Stress Point	Observation Well	Observation Start	Observation End	Observation Type
H-3b2	DOE-1	10/15/1985	3/18/1986	Drawdown
	H-1	10/15/1985	4/14/1986	Drawdown
	H-2b2	10/15/1985	4/2/1986	Drawdown
	H-11b1	10/15/1985	4/21/1986	Drawdown
WIPP-13	DOE-2	1/12/1987	5/15/1987	Drawdown
	H-2b2	1/12/1987	5/15/1987	Drawdown
	H-6b	1/12/1987	5/15/1987	Drawdown
	P-14	1/12/1987	5/15/1987	Drawdown
	WIPP-12	1/12/1987	5/15/1987	Drawdown
	WIPP-18	1/12/1987	5/15/1987	Drawdown
	WIPP-19	1/12/1987	5/15/1987	Drawdown
	WIPP-25	1/12/1987	4/2/1987	Drawdown
	WIPP-30	1/12/1987	5/15/1987	Drawdown
P-14	D-268	2/14/1989	3/7/1989	Drawdown
	H-6b	2/14/1989	3/10/1989	Drawdown
	H-18	2/14/1989	3/10/1989	Drawdown
	WIPP-25	2/14/1989	3/7/1989	Drawdown
	WIPP-26	2/14/1989	3/7/1989	Drawdown
H-11b1	H-4b	2/7/1996	12/11/1996	Drawdown
	H-12	2/6/1996	12/10/1996	Drawdown
	H-17	2/6/1996	12/10/1996	Drawdown
	P-17	2/7/1996	12/10/1996	Drawdown
H-19b0	DOE-1	12/15/1995	12/10/1996	Drawdown
	ERDA-9	12/15/1995	12/10/1996	Drawdown
	H-1	12/15/1995	12/10/1996	Drawdown
	H-14	2/7/1995	12/10/1996	Drawdown
	H-15	12/12/1995	12/10/1996	Drawdown
	H-2b2	2/7/1996	12/10/1996	Drawdown
	H-3b2	12/15/1995	12/10/1996	Drawdown
	WIPP-21	1/18/1996	12/9/1996	Drawdown
	WQSP-4	1/1/1996	12/10/1996	Drawdown
	WQSP-5	1/18/1995	12/10/1996	Drawdown
WQSP-1	H-18	1/25/1996	2/20/1996	Drawdown
	WIPP-13	1/25/1996	2/20/1996	Drawdown
	WQSP-3	1/15/1996	2/20/1996	Zero Response
WQSP-2	DOE-2	2/20/1996	3/28/1996	Drawdown
	H-18	2/20/1996	3/28/1996	Drawdown
	WIPP-13	2/20/1996	3/28/1996	Drawdown
	WQSP-1	2/20/1996	3/24/1996	Drawdown
	WQSP-3	2/20/1996	3/24/1996	Zero Response

A major change in the calibration data set from the CCA calculations is the exclusion of the hydraulic responses to the excavation of the exploratory (now salt) and ventilation (now waste) shafts in the current calibration. The responses to the shaft excavations were excluded because:

1. Only two wells (H-1 and H-3) responded directly to the shaft excavations and the areas between the shafts and these wells are stressed by other hydraulic tests that are included in the calibration data set (H-3b2, WIPP-13, and H-19b0).

2. It was difficult to model both the flux and pressure changes accurately during the excavation of the shafts with MODFLOW-2000. This difficulty is due to both the finite-difference discretization of MODFLOW-2000 that requires each shaft to be modeled as a complete model cell and some limitations of the data set.

3. The long-term effects of the shafts on site-wide water levels were important for the CCA modeling because that modeling sought to replicate heads over time. In the current CRA-2004 calibration effort, shaft effects are not important because drawdowns resulting from specific hydraulic tests are used as the calibration targets and shaft effects can be considered as second-order compared to the effects of the hydraulic tests that are simulated.

A small amount of processing of the observed data was necessary prior to using it in the calibration process. This processing included selecting the data values that would be used in the calibration procedure from the often voluminous measurements of head. These data were chosen to provide an adequate description of the transient observations at each observation well across the response time without making the modeling too computationally burdensome in terms of the temporal discretization necessary to model responses to these observations. Scientific judgment was used in selecting these data points. This selection process resulted in a total of 1,332 observations for use in the transient calibration.

Additionally, the modeling of the pressure data is done here in terms of drawdown. Therefore, the value of drawdown at the start of any transient test must be zero. A separate perl script was written to normalize each set of observed heads to a zero value reference at the start of the test with the exception of the H-3 test that is only preceded by the steady-state simulation. The calculations are such that the resulting drawdown values are positive.

In addition to normalizing the measured head data, some of the tests produced negative drawdown values when normalized. These negative results are due to some of the observations having heads greater than the reference value. This occurs due to some hydraulic tests that were conducted at earlier times in the Culebra but were not included in the numerical model. If the drawdowns from one of these previous tests are still recovering to zero at the start of a simulation, they can cause negative drawdowns in the simulation as the recovery continues. Most of these effects were addressed through trend removal in initial data processing (Beauheim 2003a) but some residual effects remain.

The resultant transient calibration points are shown in Figures TFIELD-23 through TFIELD-36. These sets of figures show the location of each hydraulic test and the locations of the observation wells for that test within the model domain and the time series of drawdown values for each

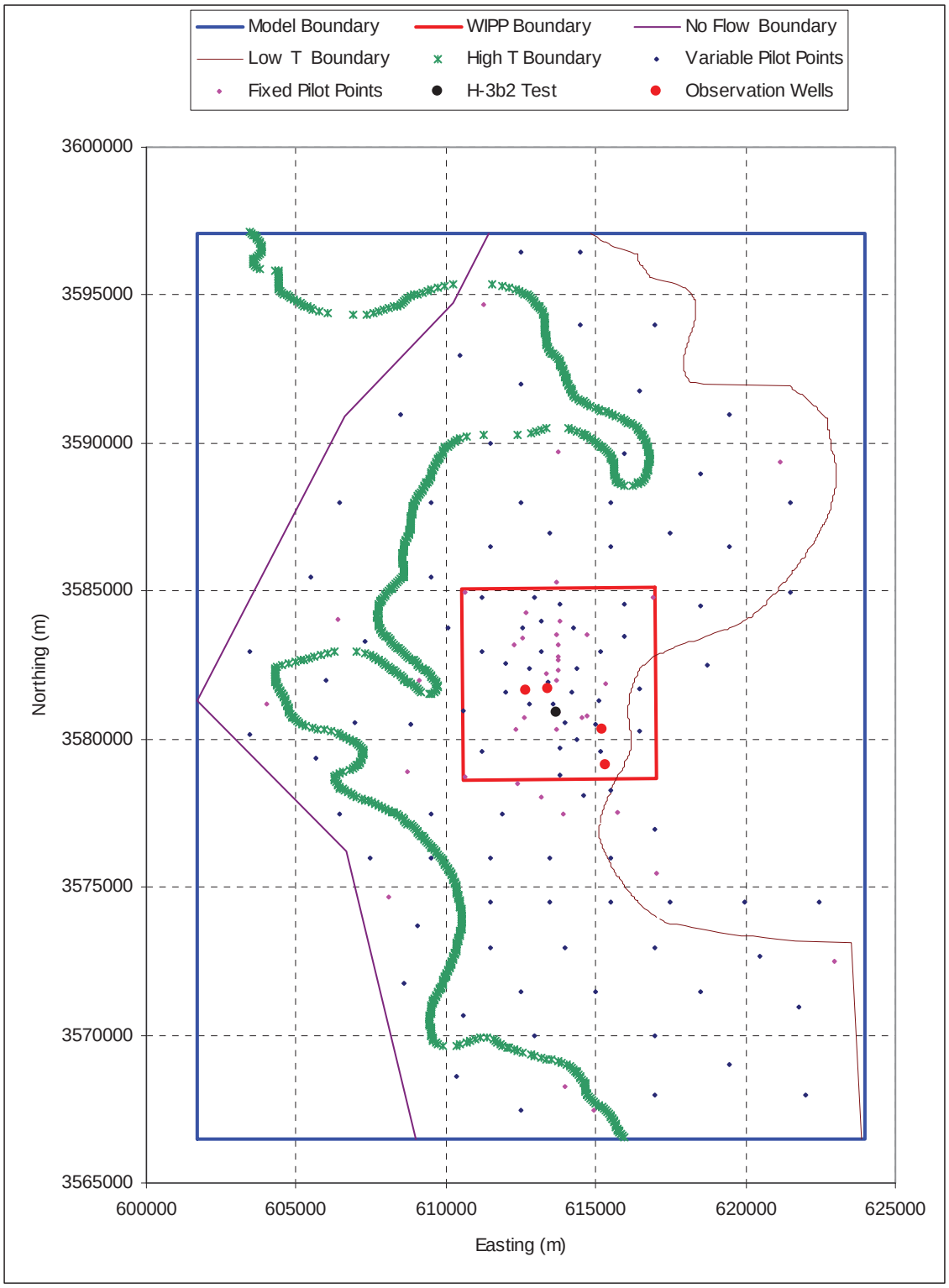

Figure TFIELD-23. Locations of the H-3b2 Hydraulic Test Well and Observation Wells

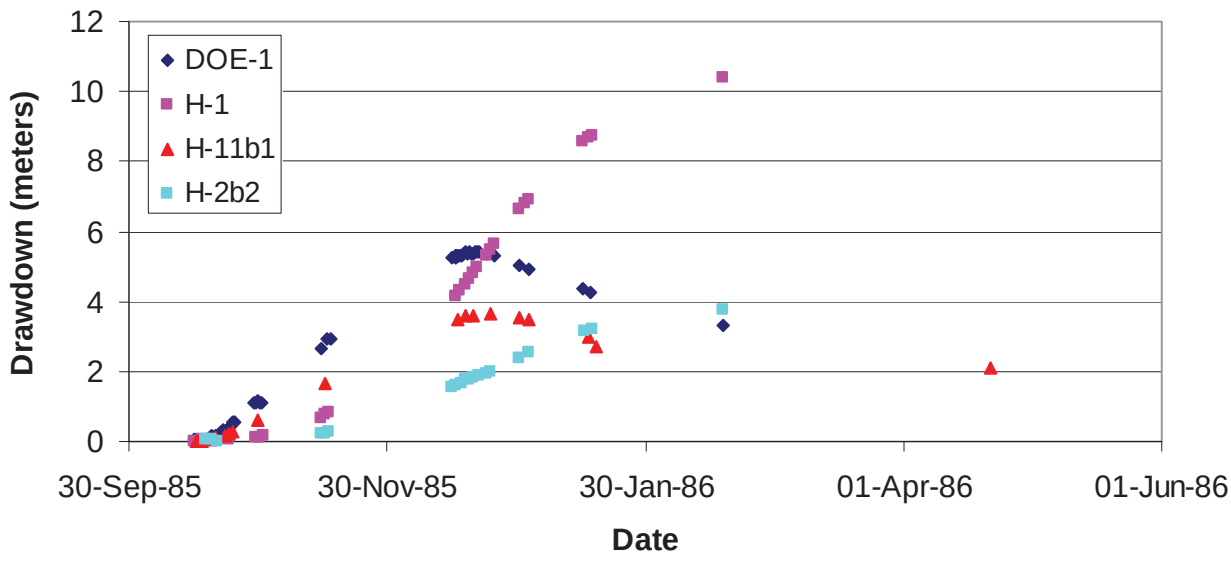

Figure TFIELD-24. Observed Drawdowns for the H-3b2 Hydraulic Test

observation well. The values of drawdown are in meters where a positive drawdown indicates a decrease in the pressure within the well relative to the pressure before the start of the pumping (negative drawdown values indicate rises in the water level). For the WQSP-1 and WQSP-2 tests, well WQSP-3 showed no response. These results are used in the calibration process by setting the observed drawdown values to zero for WQSP-3. The maps in Figures TFIELD-23 through TFIELD-35 also show the locations of the pilot points used in the calibration (these are discussed later).

TFIELD-6.5 Spatial Discretization

The flow model was discretized into 68,768 regular, orthogonal cells each of which is 100 m (328 ft) × 100 m (328 ft). A constant Culebra thickness of 7.75 m (25.4 ft) was used (CCA Appendix TFIELD.4.1.1, Culebra:Thick). The 100-m (328-ft) grid discretization was selected to make the finite-difference grid cell sizes considerably finer, on average, than those used in the CCA calculations, but still computationally tractable. In the CCA calculations, a telescoping finite-difference grid was used with the smallest cell being 100 m (328 ft) × 100 m (328 ft) near the center of the domain. The largest cells in the CCA flow model grid were 800 m (2,625 ft) × 800 m (2,625 ft) near the edges of the domain (Lavenue, 1996).

The cells in the model domain were assigned elevations based on the digitized version of Figure TFIELD-1. Of the 68,768 cells (224 east-west by 307 north-south), 14,999 (21.8 percent) lie to the west of the no-flow boundary, so the total number of active cells in the model is 53,769. This number is nearly a factor of five larger than the 10,800 (108 × 100) cells used in the CCA calculations.

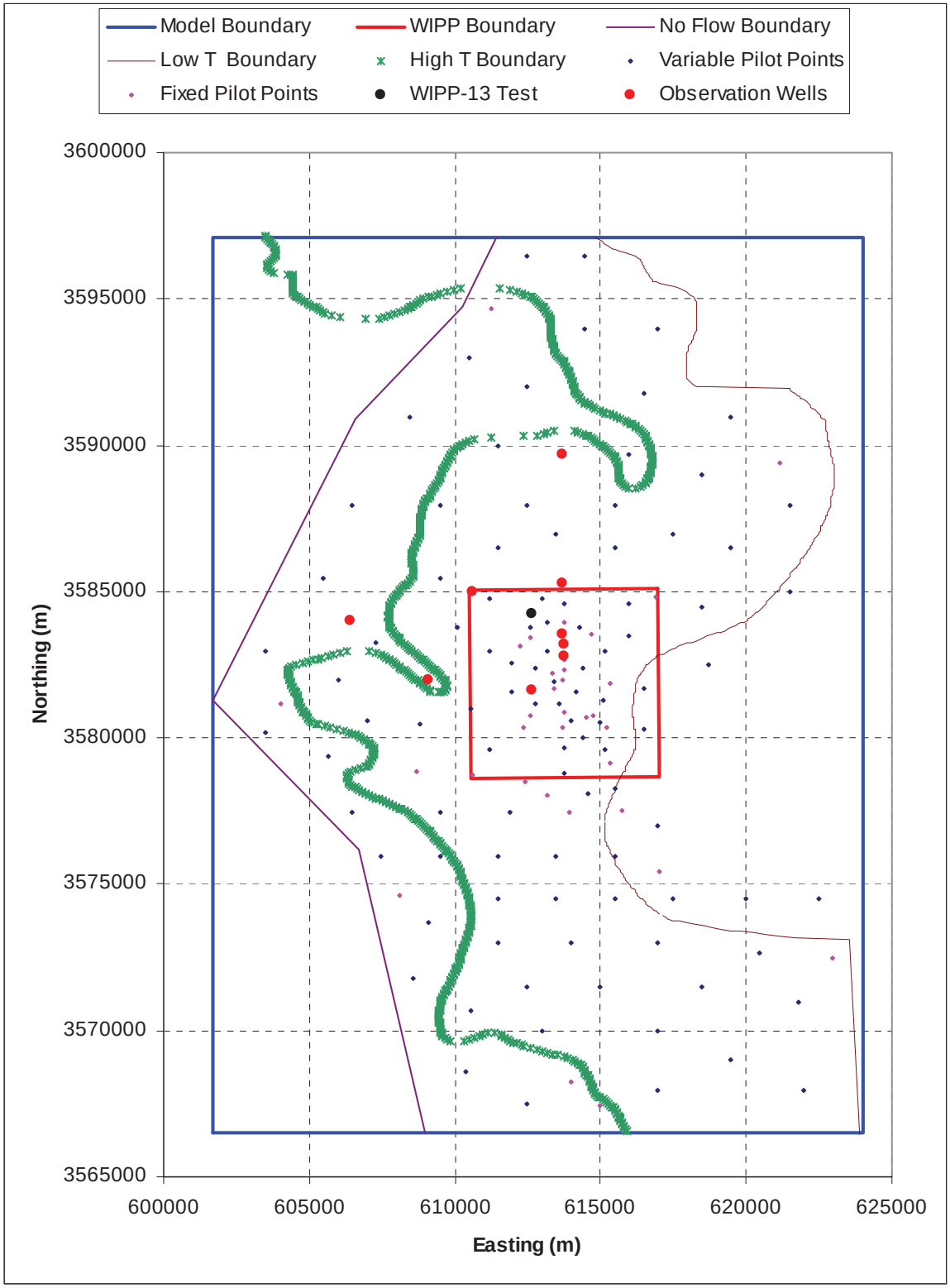

Figure TFIELD-25. Locations of the WIPP-13 Hydraulic Test Well and Observation Wells

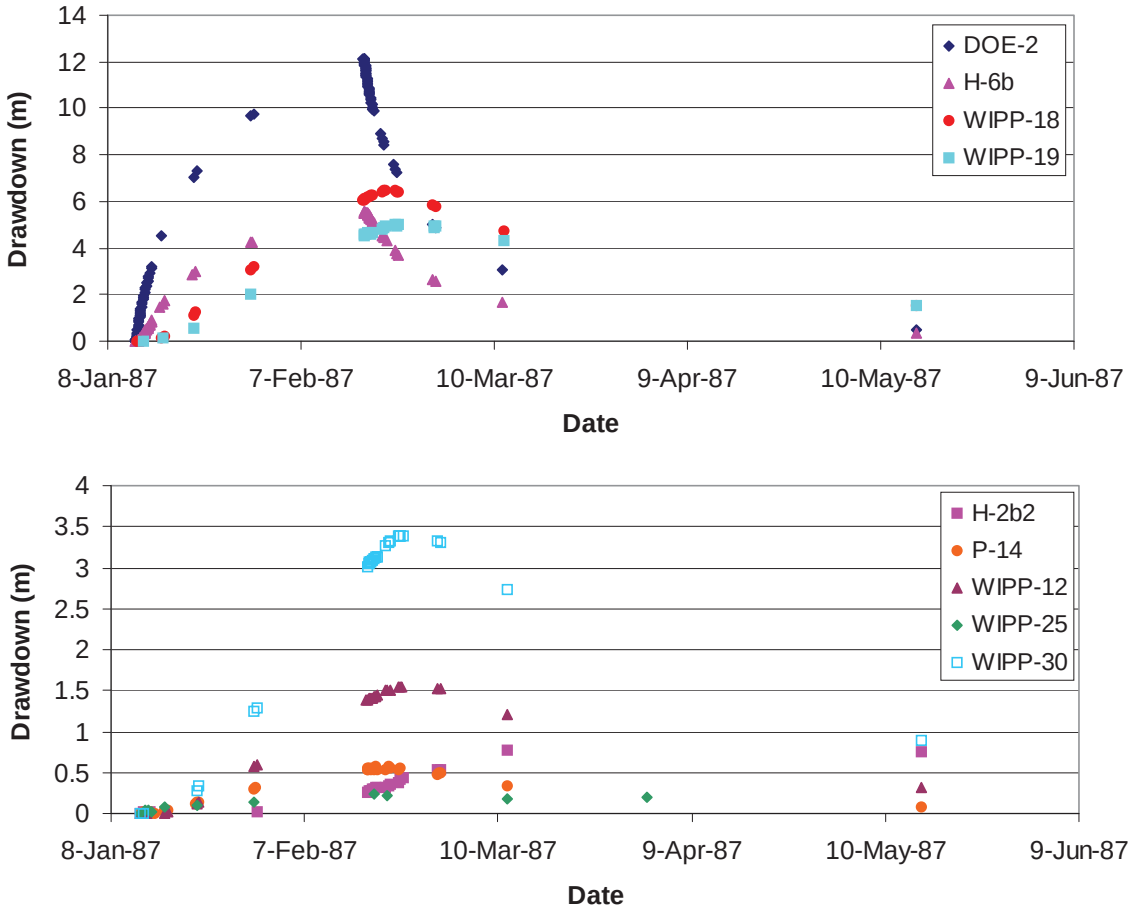

Figure TFIELD-26. Observed Drawdowns for the WIPP-13 Hydraulic Test. Note the change in the scale of the Y-axis from the upper to the lower image.

TFIELD-6.6 Temporal Discretization

The time period of nearly 11 years and 2 months covered by the transient modeling began October 15, 1985 and ended December 11, 1996. Additionally, a single steady-state calculation was run prior to the transient modeling. The length of this steady-state time period and the date at which it occurs were arbitrarily set to one day (86,400 s) occurring from October 14, 1985, to October 15, 1985. These steady-state heads were measured in the year 2000 and were only set to these October dates to provide a steady-state solution prior to the start of any transient hydraulic events. The responses to the transient events were defined by the amount of drawdown relative to the initial steady-state solution. The discretization of this time interval was dictated by the pumping history of the different wells used in the hydraulic testing and consideration of the additional computational burden required for increasingly fine time discretization.

The groundwater flow model, MODFLOW-2000, allows for the discretization of time into both "stress periods" and "time steps." A stress period is a length of time over which the boundary conditions and internal stresses on the system are constant. Even though these stresses are constant, this does not mean that the flow system is necessarily at steady state during the stress

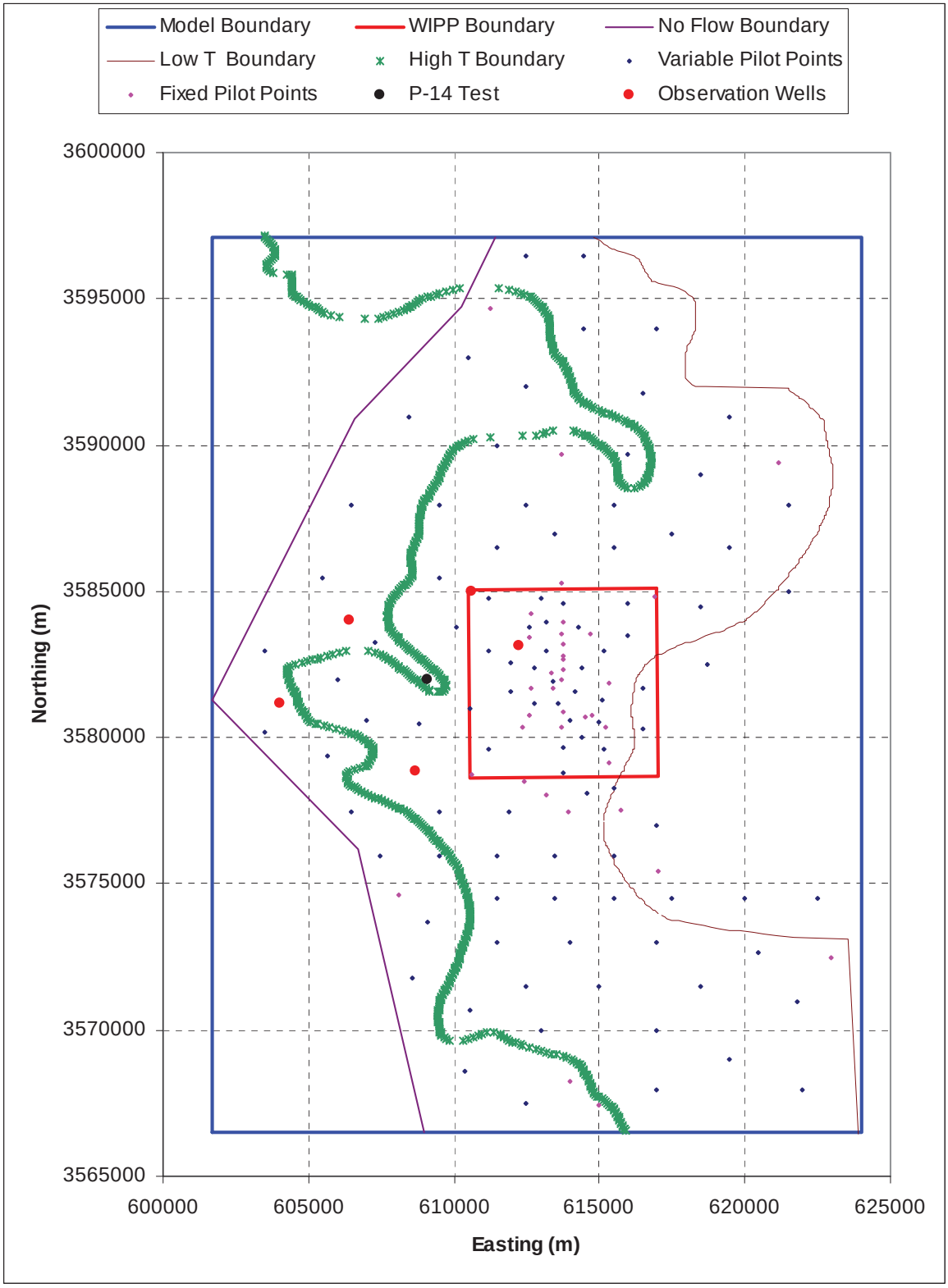

Figure TFIELD-27. Locations of the P-14 Hydraulic Test Well and Observation Wells

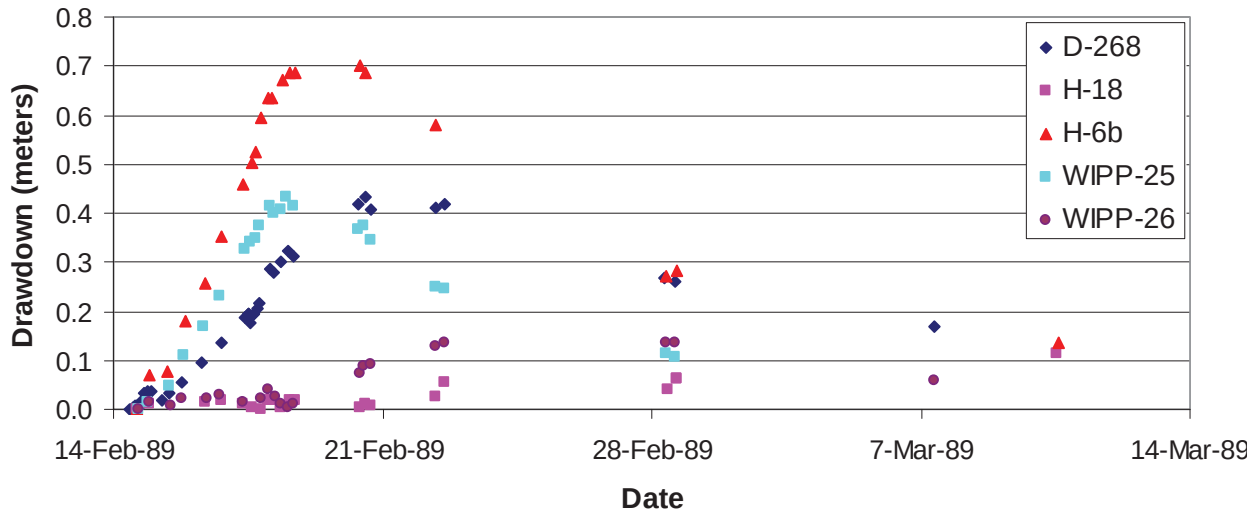

Figure TFIELD-28. Observed Drawdowns for the P-14 Hydraulic Test

period. A time step is a subdivision of a stress period. System information such as the head or drawdown values is only calculated at the specified time steps. Each stress period must contain at least one time step. MODFLOW-2000 allows for the specification of the stress period length, the number of time steps in the stress period, and a time step multiplier. The time step multiplier increases the time between successive time steps geometrically. This geometric progression provides a nearly ideal time discretization for the start of a pumping or recovery period. To save on computational costs associated with calculating head/drawdown at each time step and with writing out the heads/drawdowns, the number of time steps in the model was kept to the minimum number possible that still adequately simulated the hydraulic tests. The time discretization in MODFLOW-2000 resulted in modeled heads calculated at times that sometimes differed from the observation times. For this situation, the PEST utility, mod2obs, was used to interpolate the head, or drawdown, values in time from the simulation times to the observation times.

A summary of the time discretization is given in Table TFIELD-9. There are five separate MODFLOW-2000 simulations for each complete forward simulation of the transient events. Each separate call to MODFLOW-2000 has its own set of input and output files. In Table TFIELD-9, each call to MODFLOW-2000 is separated by a horizontal black line. The first call is the steady-state simulation. The second, third, and fourth calls to MODFLOW-2000 (H-3, WIPP-13, and P-14) are all similar in that a single well was pumped. For the H-3 and WIPP-13 calls, there were a total of three stress periods. In the first stress period, the well was pumping at a constant rate; in the second stress period, the pumped well was inactive and heads were recovering after the cessation of pumping; and the final stress period was simply a long time of no pumping activity used to advance the simulation time to be consistent with the calendar time. The first two stress periods were discretized using eight time steps and the final stress period with no pumping activity was discretized using the minimum possible number of time steps—one.

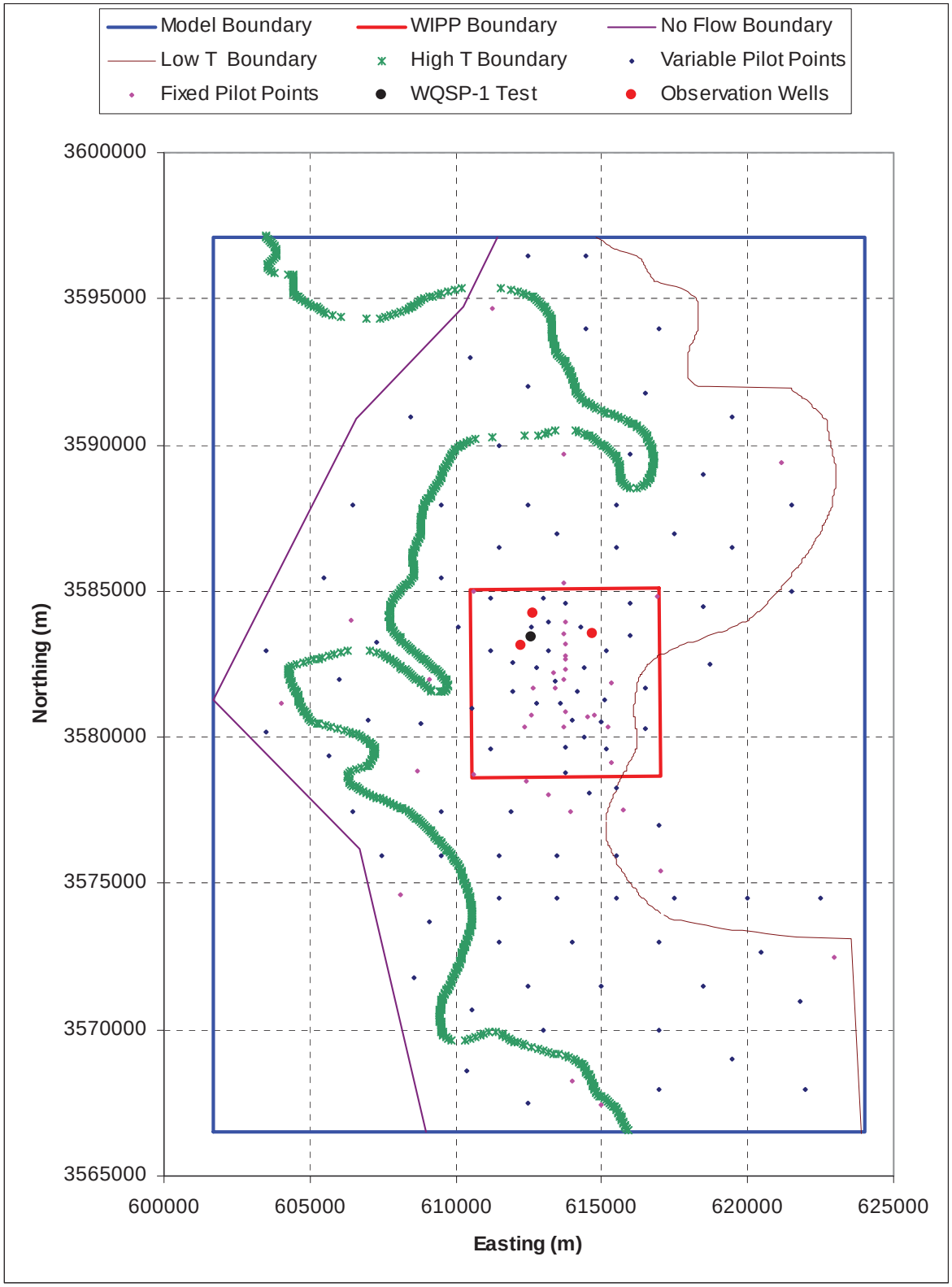

Figure TFIELD-29. Locations of the WQSP-1 Hydraulic Test Well and Observation Wells

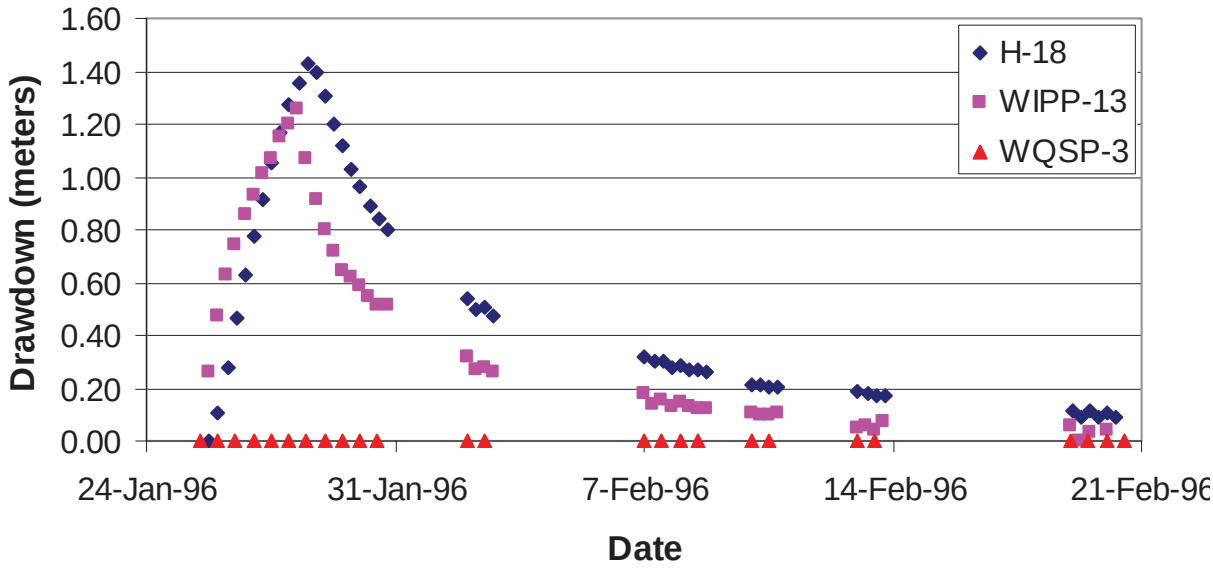

Figure TFIELD-30. Observed Drawdowns for the WQSP-1 Hydraulic Test

The final MODFLOW-2000 call, the H-19 call, was considerably more complicated than the earlier calls to MODFLOW-2000 and simulated the hydraulic conditions during the H-11, H-19, WQSP-1, and WQSP-2 hydraulic tests. This final call contained 17 stress periods with as many as three different wells pumping during any single stress period. The pumping rates of the different wells in this call to MODFLOW-2000 and the stress periods are shown as a function of time in Figure TFIELD-37. The first six stress periods in this call simulated pumping in the H-19 and H-11 wells without any observations (Table TFIELD-9). These pumping periods were added to the model solely to account for the effects of these tests in observations of later hydraulic tests and, therefore, these tests could be modeled with a single time step. The pumping rates shown in Figure TFIELD-37 are given as negative values to indicate the removal of water from the Culebra following the convention used in MODFLOW-2000.

The MODFLOW-2000 simulations could be done using a single call to MODFLOW-2000, but five separate calls were used here. Each of the five calls created separate binary output files of drawdown and head that were much smaller and easier to manage than a single output file would have been. Additionally, the simulated drawdowns at the start of each transient test must be zero (no drawdown prior to pumping). Because MODFLOW-2000 uses the resulting drawdowns and heads from the previous stress period as input to the next stress period, a single simulation would not necessarily start each transient test with zero drawdowns. Calling MODFLOW-2000 five times allowed the initial drawdowns to be reset to zero each time using shell scripts. The heads simulated at the end of the final time step in each MODFLOW-2000 call were used as the initial heads for the next call. The results of all five calls were combined to produce the 1332 model predictions prior to comparing them to the 1332 selected observation data, thus ensuring that all steady-state and transient data were used simultaneously in the inverse calibration procedure.

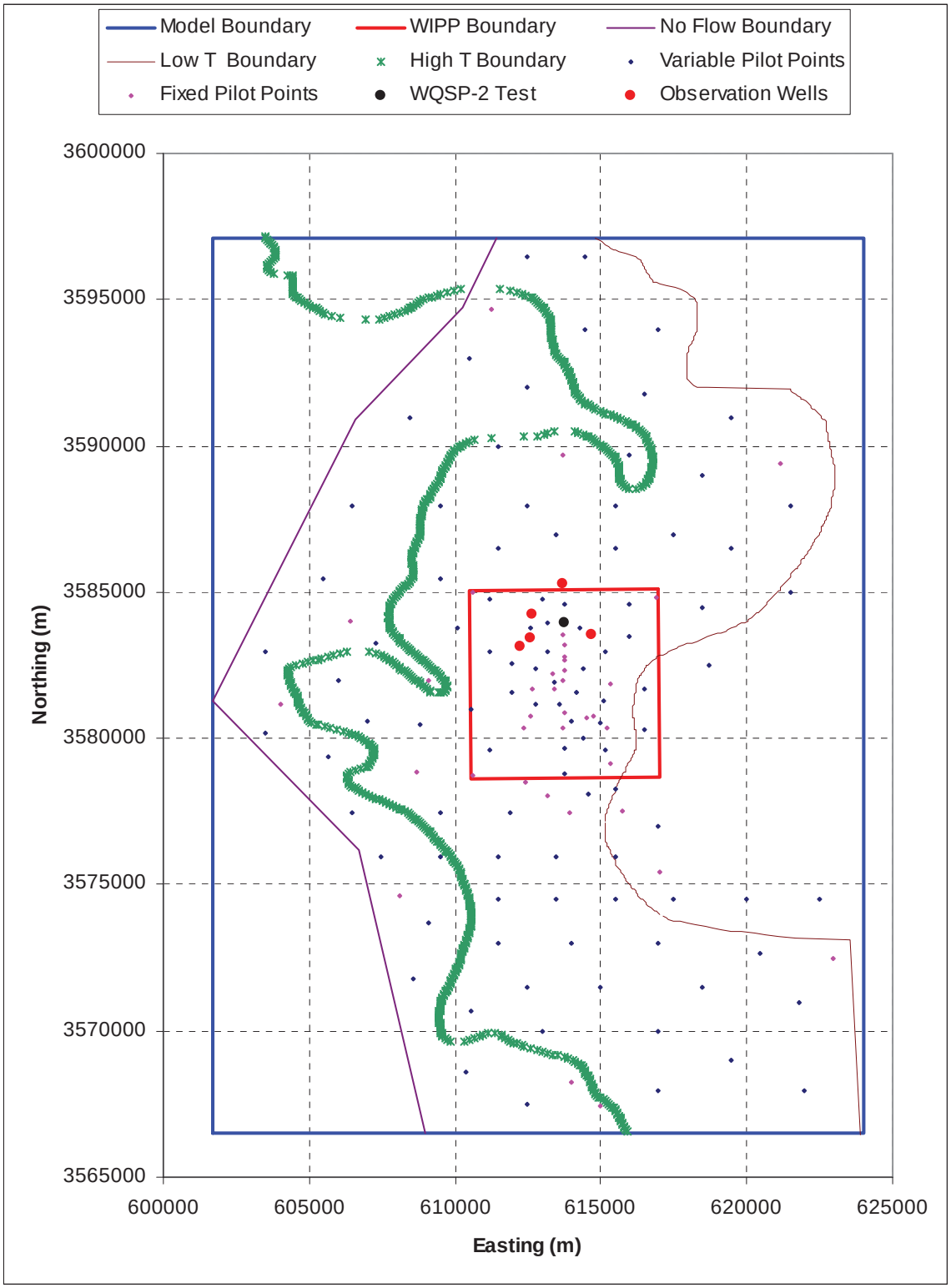

Figure TFIELD-31. Locations of the WQSP-2 Hydraulic Test Well and Observation Wells

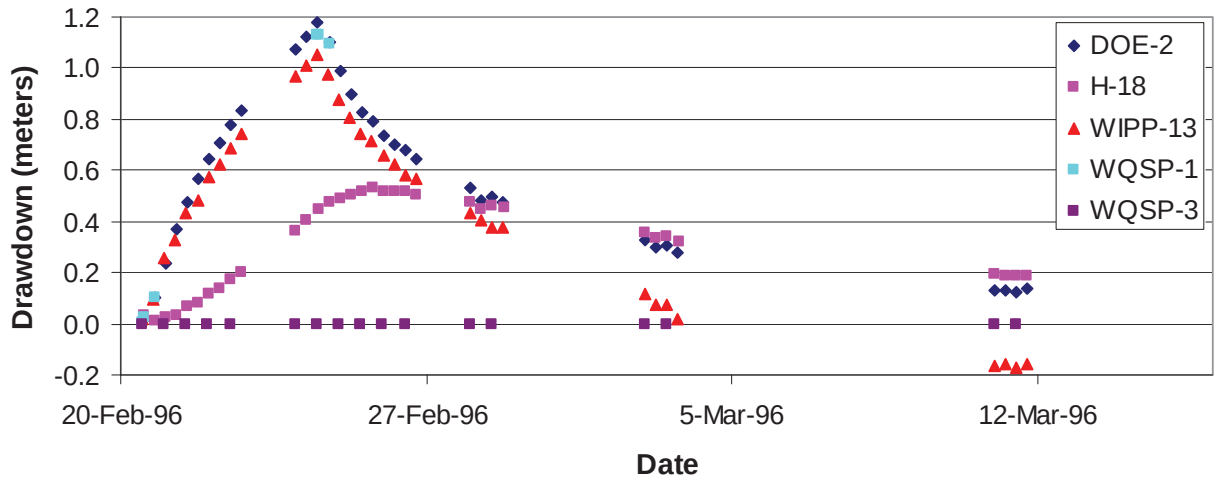

Figure TFIELD-32. Observed Drawdowns from the WQSP-2 Hydraulic Test

TFIELD-6.7 Weighting of Observation Data

The observed data for each response to each transient hydraulic test are weighted to take into account the differences in the responses across the different tests. The weights are calculated as the inverse of the maximum observed drawdown for each hydraulic test. This weighting scheme applies relatively less weight to tests with large drawdowns and relatively more weight to tests with smaller responses. This weighting scheme was used so that the overall calibration was not dominated by trying to reduce the very large residuals that may occur at a few of the observation locations with very large drawdowns. Under this weighting scheme, two tests that are both fit by the model to within 50 percent of the observed drawdown values would be given equal consideration in the calculation of the overall objective function even though one test may have an observed maximum drawdown of 10 m (33 ft) and the other a maximum observed drawdown of 0.10 m (0.33 ft).

The weights assigned in this manner ranged from 0.052 to 20.19. The observed absence of a hydraulic response at WQSP-3 to pumping at WQSP-1 and WQSP-2 was also included in the calibration process by inserting measurements of zero drawdown that were given an arbitrarily high weight of 20. Through trial and error using the root mean squared error criterion of how well the modeled steady-state heads fit the observed steady-state heads, a weight of 2.273 was assigned to the 35 steady-state observations. This weight is near that of the average of all the weights assigned to the transient events and was found to be adequate to provide acceptable steady-state matches. It is noted that the steady-state data provide measurements of head while all of the transient events provide measurements of drawdown. However, the weights were applied to the residuals between the observed and modeled aquifer responses and because both heads and drawdowns are measured in meters, there was no need to adjust the weights to account for different measurement units.

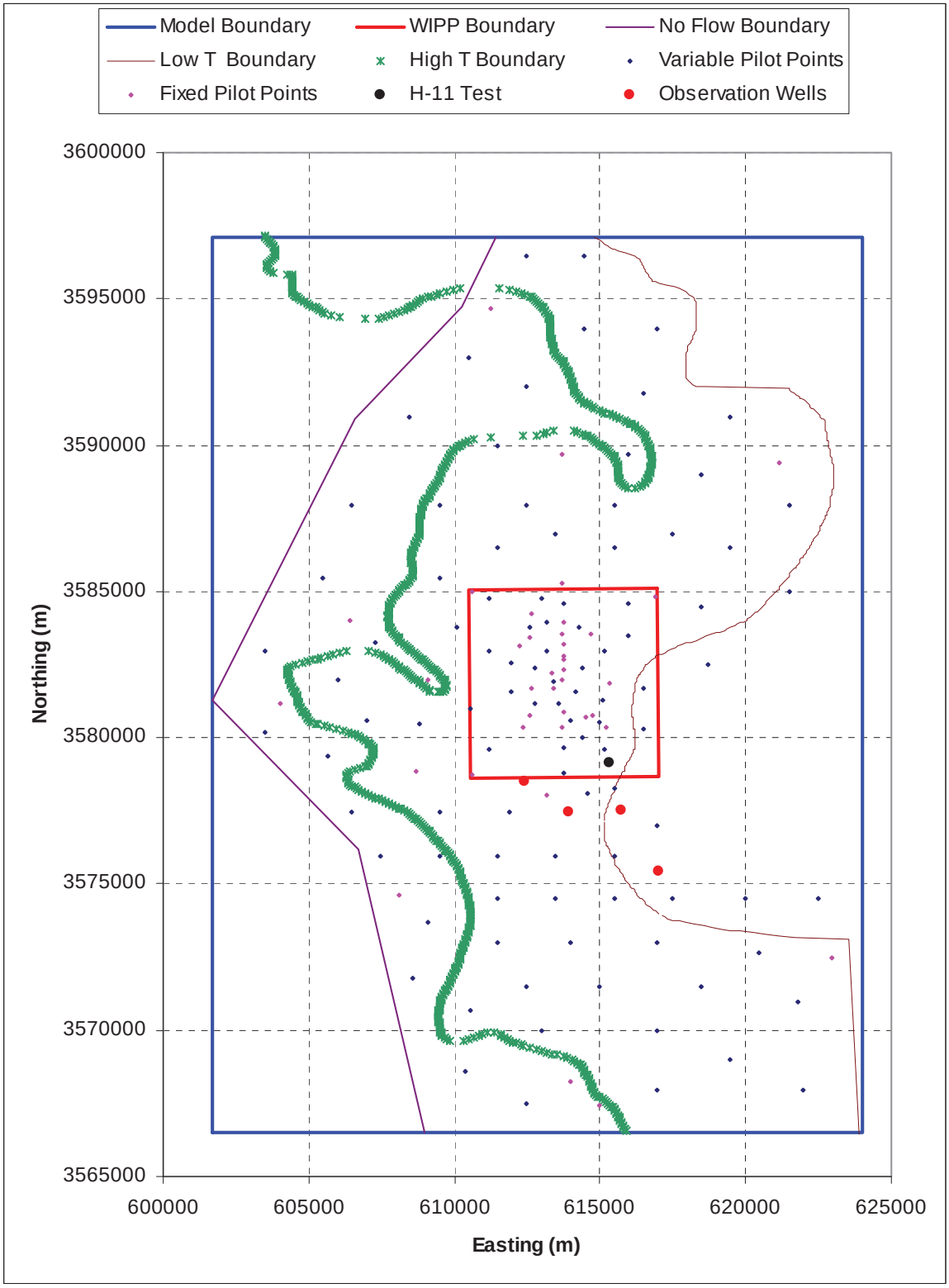

Figure TFIELD-33. Locations of the H-11 Hydraulic Test Well and Observation Wells

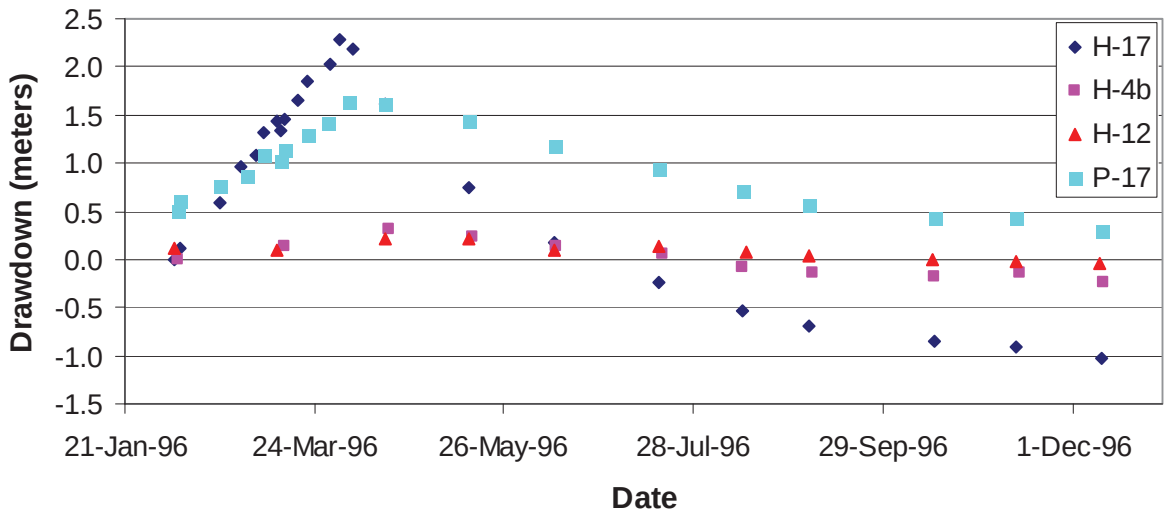

Figure TFIELD-34. Observed Drawdowns for the H-11 Hydraulic Test

The number of measurements used for calibration that were made at individual wells during individual tests ranged from 6 to 104, and the number of measurements used for calibration that were made at all wells during a single test ranged from 64 to 410. This means that different well responses and different tests carried different cumulative weights. The spatially broadest sampling of transient data possible was used in an effort to get transient coverage of as much of the modeling domain as possible. In those areas where no transient data are available, the calibration is dominated by fitting the model to the steady-state measurements. The greatest coverage of transient data is within the boundaries of the WIPP site, which is also the area of most significance for radionuclide transport.

The maximum observed drawdown, the weight assigned to all the observed test values for each test, and the total number of observations for each observation well are given in Table TFIELD-10.

TFIELD-6.8 Assignment of Pilot Point Geometry

A major development in the field of stochastic inverse modeling that has occurred since the T fields were constructed for the CCA in 1996 is that inverse techniques are now capable of simultaneously determining optimal T values at a large number of pilot points. In the T fields constructed for the CCA, pilot points were added one at a time and each point was calibrated prior to the addition of the next pilot point. Furthermore, the total number of pilot points was limited to less than or equal to the total number of T observations to avoid numerical instabilities in the solution of the inverse problem. With the techniques now available and implemented in PEST, it is possible to use many more pilot points than there are T observations and to calibrate these pilot points simultaneously.

The pilot-point locations were chosen using a combination of a regular grid approach and deviations from that grid to accommodate specific pumping- and observation-well locations

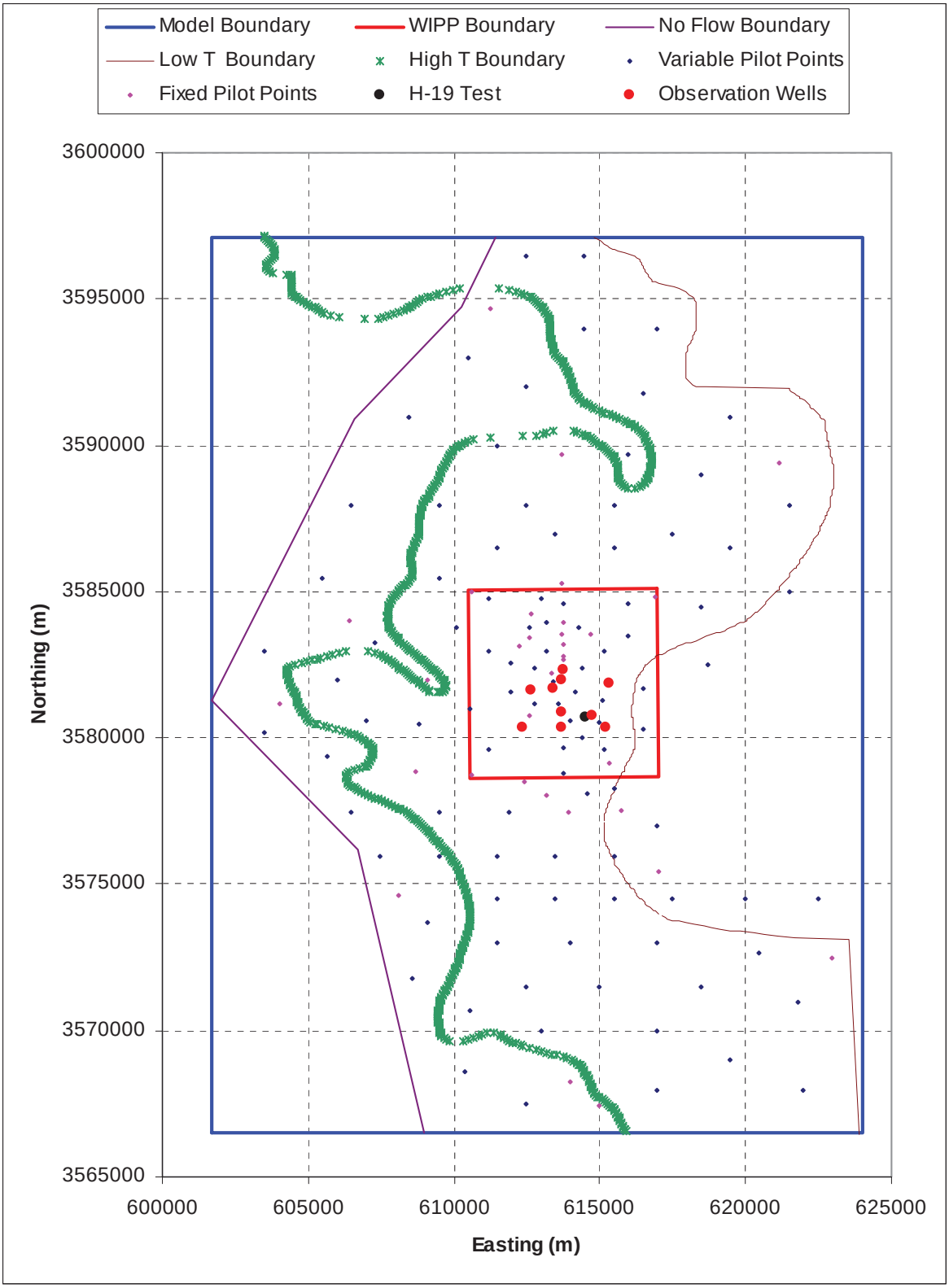

Figure TFIELD-35. Locations of the H-19 Hydraulic Test Well and Observation Wells

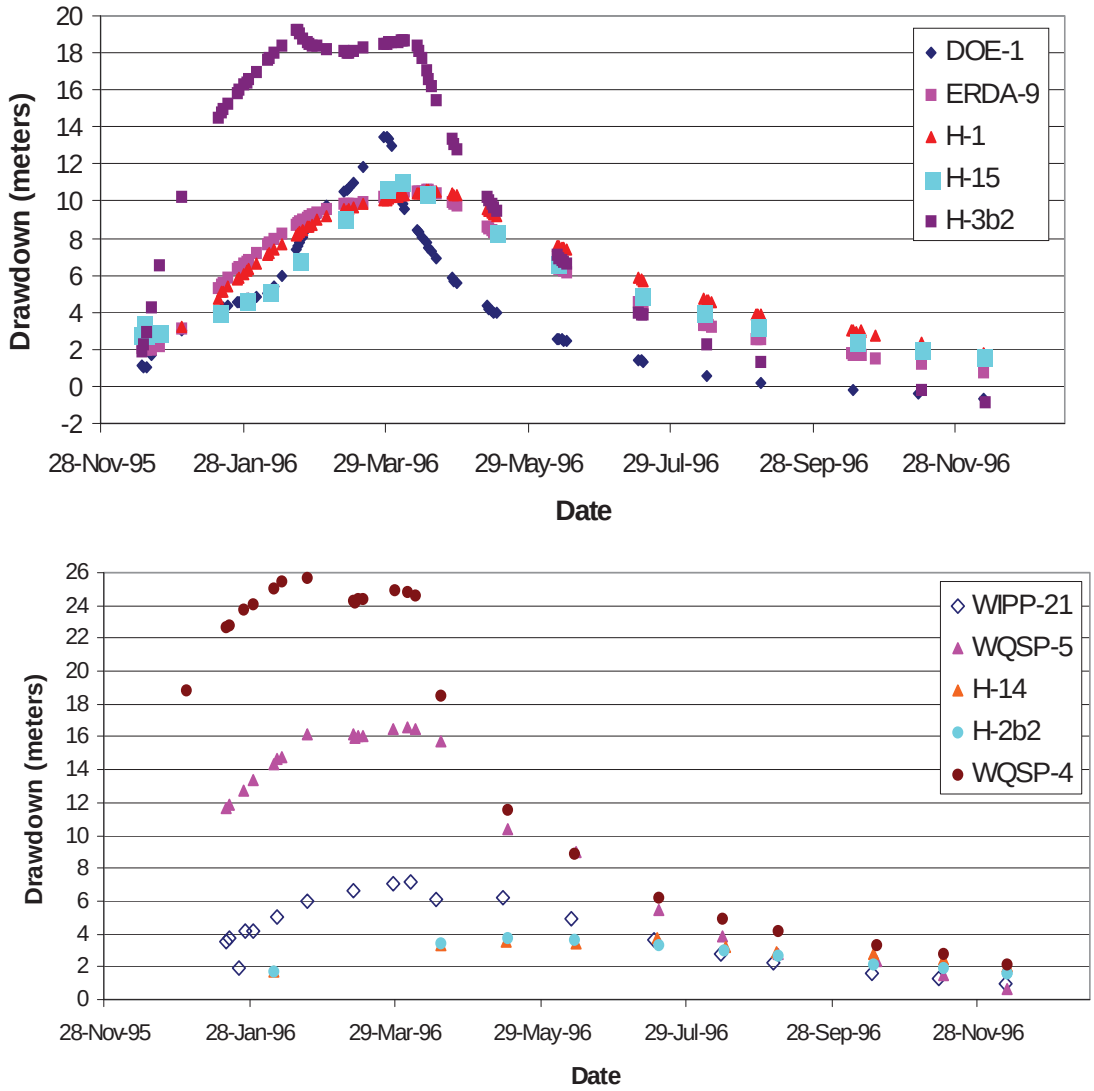

Figure TFIELD-36. Observed Drawdowns From the H-19 Hydraulic Test

(Figure TFIELD-38). The goal in these deviations from the regular grid was to put at least one pilot point between each pumping well and each of its observation wells. Details of the pilot-point locations relative to the pumping and observation wells in the WIPP site area are shown in Figure TFIELD-39. This combined approach of a regular grid with specific deviations from that grid follows the guidelines for pilot-point placement put forth by John Doherty (the author of PEST) as Appendix 1 in the work of McKenna and Hart (2003a). Pilot points located at the T measurement locations were held as fixed values during the optimization (fixed pilot points shown as magenta squares in Figure TFIELD-38). The variable pilot points (dark blue diamonds in Figure TFIELD-38) are those where the T value was adjusted during the calibration procedure. A total of 43 fixed and 100 variable pilot points was used in the T-field calibration process. The zone option in PEST was employed to limit the influence of pilot points in any one zone (e.g., high T or low T) to adjusting only locations that are in the same zone.

Table TFIELD-9. Discretization of Time into 29 Stress Periods and 127 Time Steps with Pumping Well Names and Pumping Rates

Event Name	Global Stress Period No.	Internal Stress Period No.	Stress Period Length (s)	No. of Time Steps	Start Date	Stop Date	Pumping Well(s)	Pumping Rate(s) (m^3/s)
Steady	1	1	86400	1	10/14/859:00	10/15/859:00	0	0
H-3	2	1	5356800	8	10/15/859:00	12/16/859:00	H-3	3.03E-04
	3	2	10892700	8	12/16/859:00	4/21/8610:45	None	0.00E+00
	4	3	22976100	1	4/21/8610:45	1/12/879:00	None	0.00E+00
WIPP-13	5	1	3110400	8	1/12/879:00	2/17/879:00	WIPP-13	1.89E-03
	6	2	7539900	8	2/17/879:00	5/15/8715:25	None	0.00E+00
	7	3	55359360	1	5/15/8715:25	2/14/899:01	None	0.00E+00
P-14	8	1	44928	3	2/14/899:01	2/14/8921:29	P-14	3.92E-03
	9	2	174612	8	2/14/8921:29	2/16/8922:00	P-14	3.64E-03
	10	3	50400	3	2/16/8922:00	2/17/8912:00	P-14	3.37E-03
	11	4	1820396	8	2/17/8912:00	3/10/8913:39	None	0.00E+00
	12	5	193212124	1	3/10/8913:39	4/24/95 19:42	None	0.00E+00
H-19	13	1	148860	1	4/24/9519:42	4/26/95 13:03	H-19b0	2.26E-04
	14	2	4399020	1	4/26/9513:03	6/16/9511:00	None	0.00E+00
	15	3	3614400	1	6/16/9511:00	7/28/95 7:00	H-19b0	2.36E-04
	16	4	1168200	1	7/28/95 7:00	8/10/95 19:30	None	0.00E+00
	17	5	1292700	1	8/10/9519:30	8/25/9518:35	H11	2.44E-04
	18	6	9651300	1	8/25/9518:35	12/15/9511:30	None	0.00E+00
	19	7	2878200	8	12/15/9511:30	1/17/9619:00	H-19b0	2.71 E-04
	20	8	670680	3	1/17/9619:00	1/25/9613:18	H-19b0	2.52E-04
	21	9	238980	3	1/25/9613:18	1/28/96 7:41	H-19b0, WQSP-1	2.52E-04, 4.30E-04
	22	10	872340	3	1/28/96 7:41	2/7/9610:00	H-19b0	2.52E-04
	23	11	1047000	8	2/7/9610:00	2/19/9612:50	H-19b0, H-11	2.52E-04, 2.23E-04
	24	12	81600	3	2/19/9612:50	2/20/9611:30	H-19b0, H-11	1.55E-04, 2.23E-04
	25	13	345600	3	2/20/96 11:30	2/24/9611:30	H-19b0, H-11,WQSP-2	1.55E-04, 2.23E-04, 4.5E-04
	26	14	1395000	8	2/24/96 11:30	3/11/9615:00	H-19b0, H-11	1.55E-04, 2.23E-04
	27	15	1445100	8	3/11/9615:00	3/28/96 8:25	H-19b0, H-11	1.55E-04, 3.76E-04
	28	16	1220700	8	3/28/96 8:25	4/11/9611:30	H-19b0	1.55E-04
	29	17	21074400	8	4/11/9611:30	12/11/969:30	None	0.00E+00

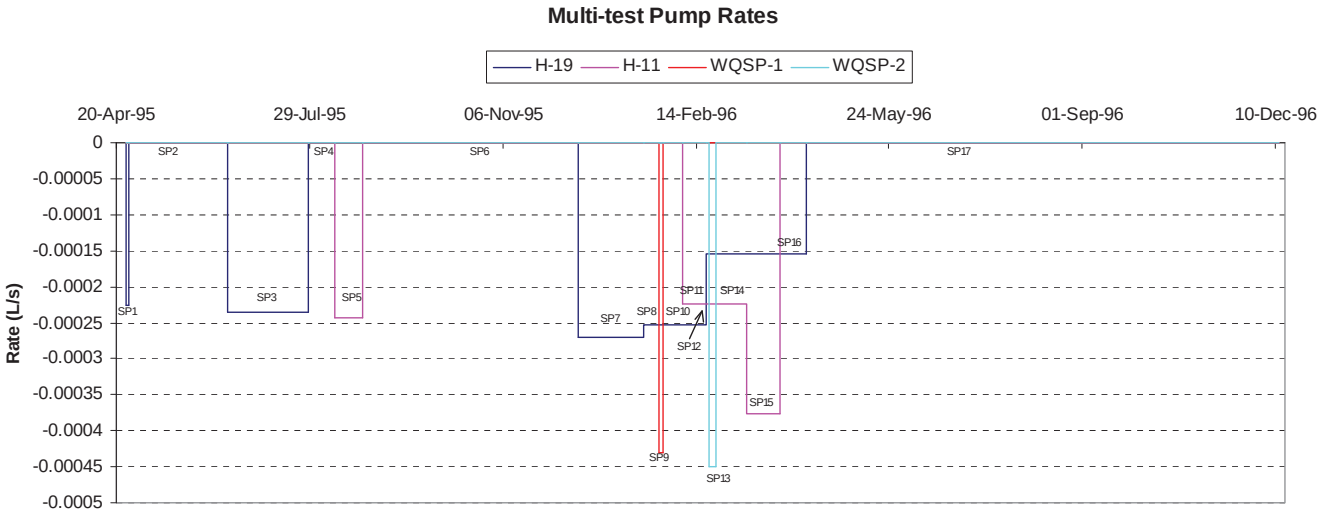

Figure TFIELD-37. Temporal Discretization and Pumping Rates for the Fifth Call to MODFLOW-2000. A total of 17 stress periods (SP*s*) are used to discretize this model call.

Table TFIELD-10. Observation Weights for Each of the Observation Wells

Test Well Observation Well	Maximum Drawdown (m)	Weight	Number of Observations
Steady	NA	2.273	35
H3-DOE1	5.426	0.184	57
H3-H1	10.396	0.096	26
H3-H11b1	3.622	0.276	19
H3-H2b2	3.781	0.265	20
W13-DOE2	12.138	0.082	104
W13-H2b2	0.781	1.281	23
W13-H6	5.545	0.180	93
W13-P14	0.570	1.755	38
W13-W12	1.553	0.644	27
W13-W18	6.481	0.154	26
W13-W19	5.048	0.198	22
W13-W25	0.246	4.062	11
W13-W30	3.391	0.295	24
P14-D268	0.432	2.317	38
P14-H18	0.113	8.850	21
P14-H6b	0.701	1.427	21
P14-W25	0.432	2.315	22
P14-W26	0.137	7.310	20
WQSP1-H18	1.431	0.699	47
WQSP1-W13	1.260	0.794	47
WQSP1-WQSP3	0.000	20.000	25
WQSP2-DOE2	1.178	0.849	34
WQSP2-H18	0.529	1.892	35
WQSP2-W13	1.053	0.949	34
WQSP2-WQSP1	1.132	0.884	6
WQSP2-WQSP3	0.000	20.000	18
H11-H17	1.030	0.971	23
H11-H4b	0.232	4.317	11
H11-H12	0.033	20.190	11
H11-P17	1.628	3.304	19
H19-DOE1	13.463	0.074	70
H19-ERDA9	10.571	0.095	80
H19-H1	10.618	0.094	80
H19-H15	11.110	0.090	22
H19-H3b2	19.283	0.052	69
H19-W21	7.153	0.140	19
H19-WQSP5	16.623	0.060	24
H19-H14	3.759	0.602	11
H19-H2b2	3.794	0.608	11
H19-WQSP4	25.721	0.462	24

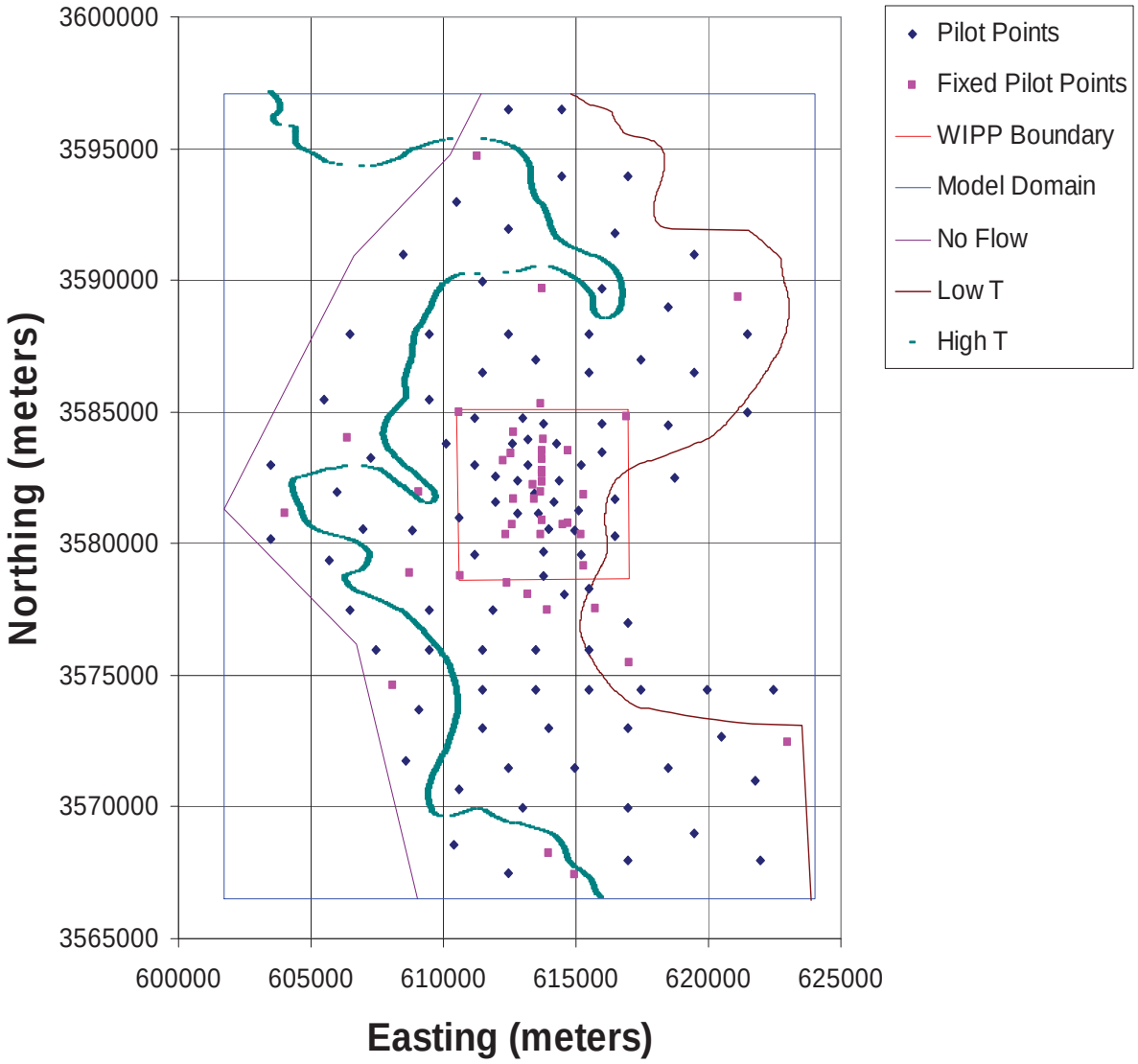

Figure TFIELD-38. Locations of the Adjustable and Fixed Pilot Points Within the Model Domain

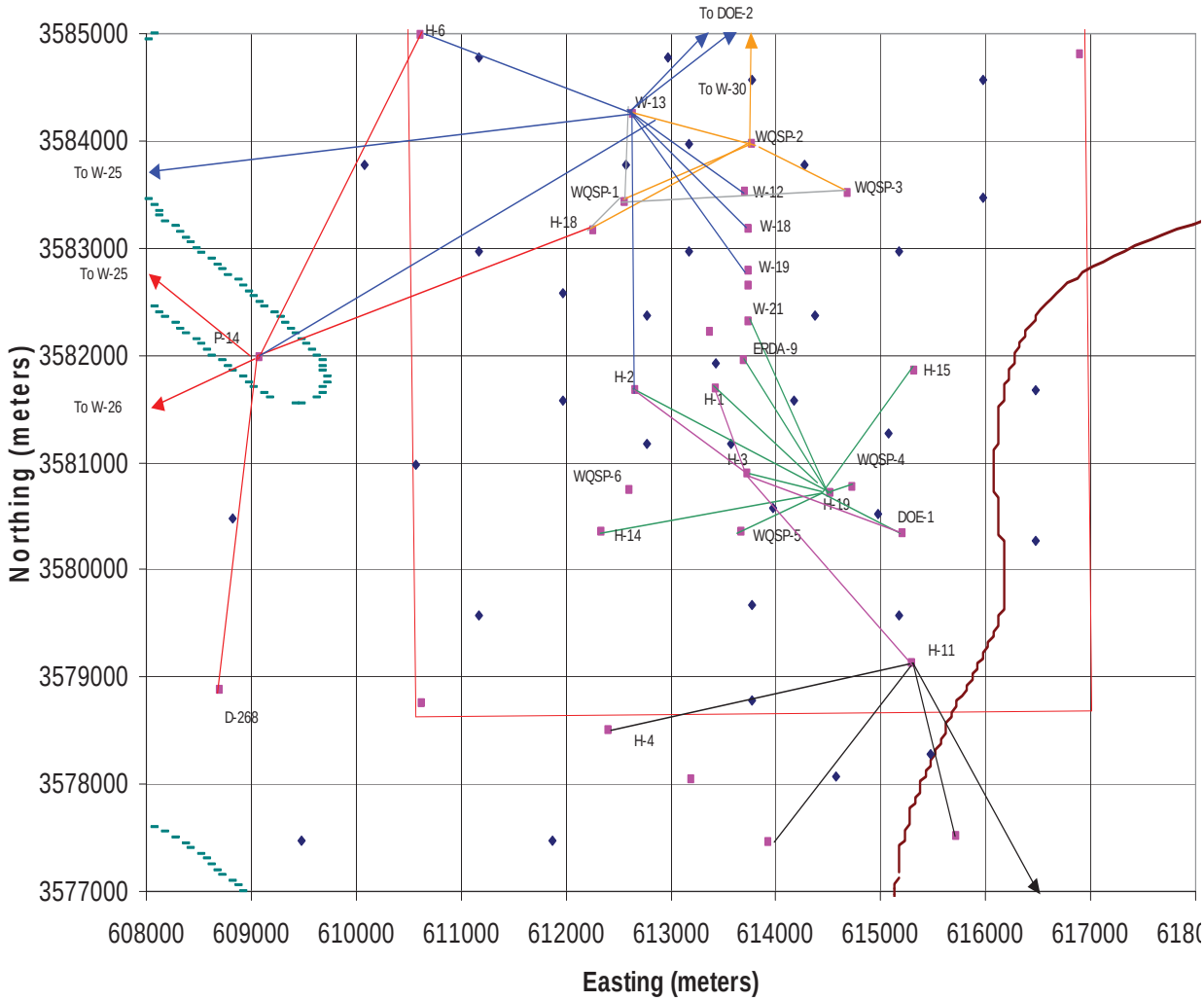

Figure TFIELD-39. Close-Up View of the Pilot-Point Locations in the Area of the WIPP Site. The colored (solid) lines connect the pumping and observation wells. The legend for this figure is the same as that for Figure TFIELD-38.

The variogram model for the residuals between the T measurements and the base field has a range of 1,050 m (3,445 ft). Because the pilot-point approach to calibration uses this range as a radius of influence, locations of the adjustable pilot points were as much as possible set to be at least 1,050 m (3,445 ft) away from other pilot points (adjustable or fixed). For maximum impact, all pilot points should be at least 2,100 m (6,890 ft) away from any other pilot point but, given the existing well geometry, this distance was not always achievable.

TFIELD-6.9 Stochastic Inverse Calibration

The seed realizations are input to the inverse model using the pilot-point method. The seed realizations are calibrated to the steady-state and transient head measurements. The residuals and the T-field calculations are done in $\log_{10}$ space so that a unit change in the residual equates to a one order of magnitude change in the value of T. The initial values of the pilot points are equal

to the value of the initial residual field at each pilot-point location. The pilot points are constrained to have a maximum perturbation of ± 3.0 from the initial value except for those pilot points within the high-T zone in Nash Draw (Figure TFIELD-11) and the low-T zone on the eastern side of the model domain that are limited to perturbations of ± 1.0. These limits are employed to maintain the influence of the geologic conceptual model on the calibrated T fields.

Figure TFIELD-11 is updated as Figure TFIELD-40 to show, conceptually, how the addition of two pilot points along the cross section can modify the residual field and then update the T field. The pilot points are shown as the open circles in Figure TFIELD-40 and are used to modify the residual field before it is added to the base T field. Compare the shape of the dashed red and blue lines in Figure TFIELD-40 to the same lines in Figure TFIELD-11. The values of the residuals at the observation points are held fixed so any adjacent pilot points cannot modify them.

At the heart of the calibration process is the iterative adjustment of the residual field at the pilot points by PEST and the subsequent updates of the residual field at the locations surrounding the pilot points based on the shape of the variogram modeled on the raw residuals. The updated residual field is then combined with the base T field (see Figure TFIELD-18) and then used in MODFLOW-2000 to calculate the current set of modeled heads. These modeled heads are then input to PEST for the next iteration.

The objective function minimized by PEST (phi) is a combination of the weighted sum of the squared residuals between the measured and observed steady-state head data, the weighted sum of the squared residuals between the measured and observed transient drawdown data, and the weighted sum of the squared differences in the estimated T value between pairs of pilot points.

Phi is defined as:

$$\phi = \sum_{i=1}^{n_{obs}^{SS}} (W^{SS}(H_i^{obs-SS} - H_i^{calc-SS}))^2 + \sum_{i=1}^{n_{wells}^{Tr}} \sum_{j=1}^{n_{obs}^{Tr}} (W_i^{Tr}(D_j^{obs-Tr} - D_j^{calc-Tr}))^2 + \sum_{i=1}^{n_{PP}} \sum_{j=j}^{n_{PP}} W_{ij}^{R}(PP_i - PP_j) \quad (9)$$

where n_{obs} is the number of head observations, n_{wells} is the number of wells, n_{PP} is the number of pilot points, W is the weight assigned to a group of measurements, H^{obs} and H^{calc} are the values of the observed and calculated heads, respectively, D^{obs} and D^{calc} are the values of the observed and calculated drawdowns, respectively, PP refers to the $\log_{10}$ T value at a pilot point, and superscripts SS, Tr, and R refer to steady-state measurements, transient measurements, and pilot-point regularization, respectively. For this work, the weights on the head and drawdown observations are as given in Table TFIELD-10. The third weighted sum of squares in the objective function is the regularization portion of the objective function. This weighted sum of squares involves the difference in T values between each pair of pilot points (PP_i - PP_j) and is designed to keep the T field as homogeneous as possible and to provide numerical stability when estimating more parameters than there are data. The pilot-point regularization weights, W_{ij}^{R}, are defined by the kriging factors and are a function of the distance between any two pilot points.

The stochastic inverse calibration process uses multiple pre- and post-processor codes in addition to PEST and MODFLOW-2000. The overall numerical approach to the T-field calibration is shown in Figures TFIELD-41 and TFIELD-42 and the details on this approach are documented

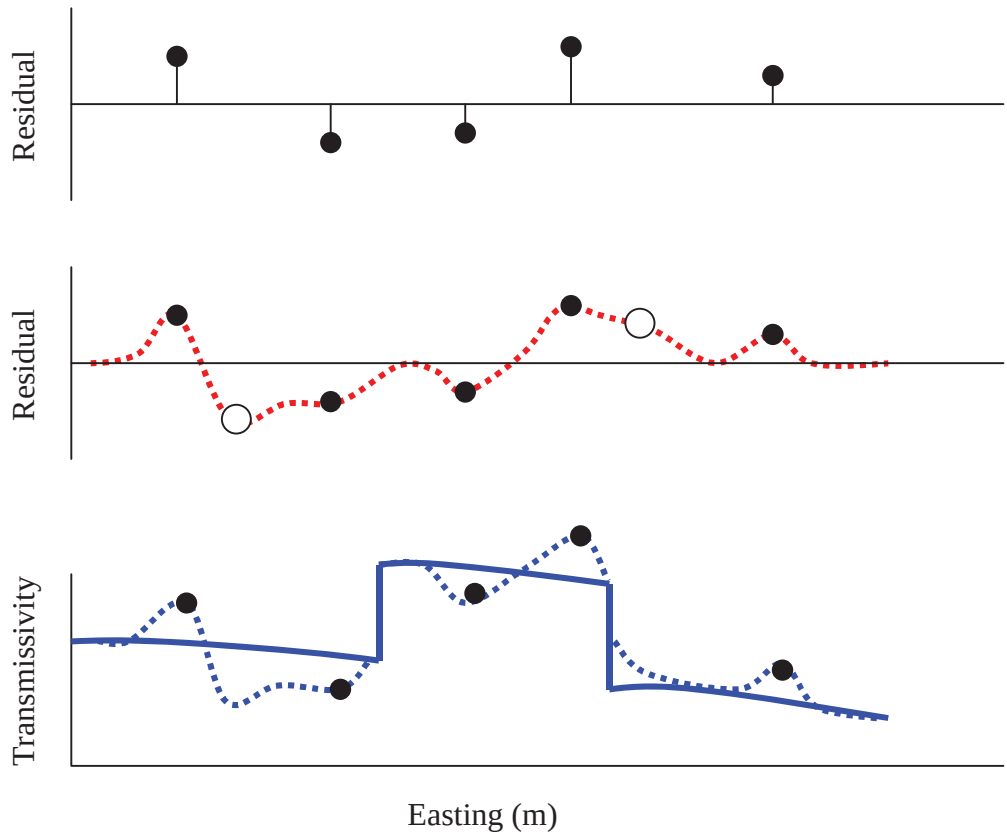

Figure TFIELD-40. Conceptual Cross-Section Showing the Addition of Pilot Points to the Optimization Process

in McKenna and Hart (2003a, 2003b). The top of Figure TFIELD-41 shows the pre-processing steps. The large oval in the middle of the figure contains the link between MODFLOW-2000 and PEST. The "model process" portion of the figure is expanded and the details are shown in Figure TFIELD-42. The output files and the connection to the particle-tracking code are shown in the bottom of Figure TFIELD-41.

The calibration process is run iteratively until at least one of three conditions are met: (1) the number of iterations reaches the maximum allowable number of 15; (2) the objective function reaches a predefined minimum value of 1,000 m^2; or (3) the value of the objective function changes by less than one percent across three consecutive iterations.

At the end of the calibration process, a residual field is created that when added to the base T field reproduces the measured T values at the 43 measurement locations and provides a minimum sum of squared errors (SSE) between the observed and model-predicted heads/drawdowns. An example of the final step in the creation of a calibrated T field is shown in Figure TFIELD-43. The computational cost of calibrating to the multiple transient events is significant. For comparison, a single forward run of MODFLOW-2000 in steady-state takes on the order of 10-15 seconds on a 1.9-GHz Athlon processor, whereas the run time for the combined steady-state and transient events is approximately three minutes (a factor of 12-18 times longer).

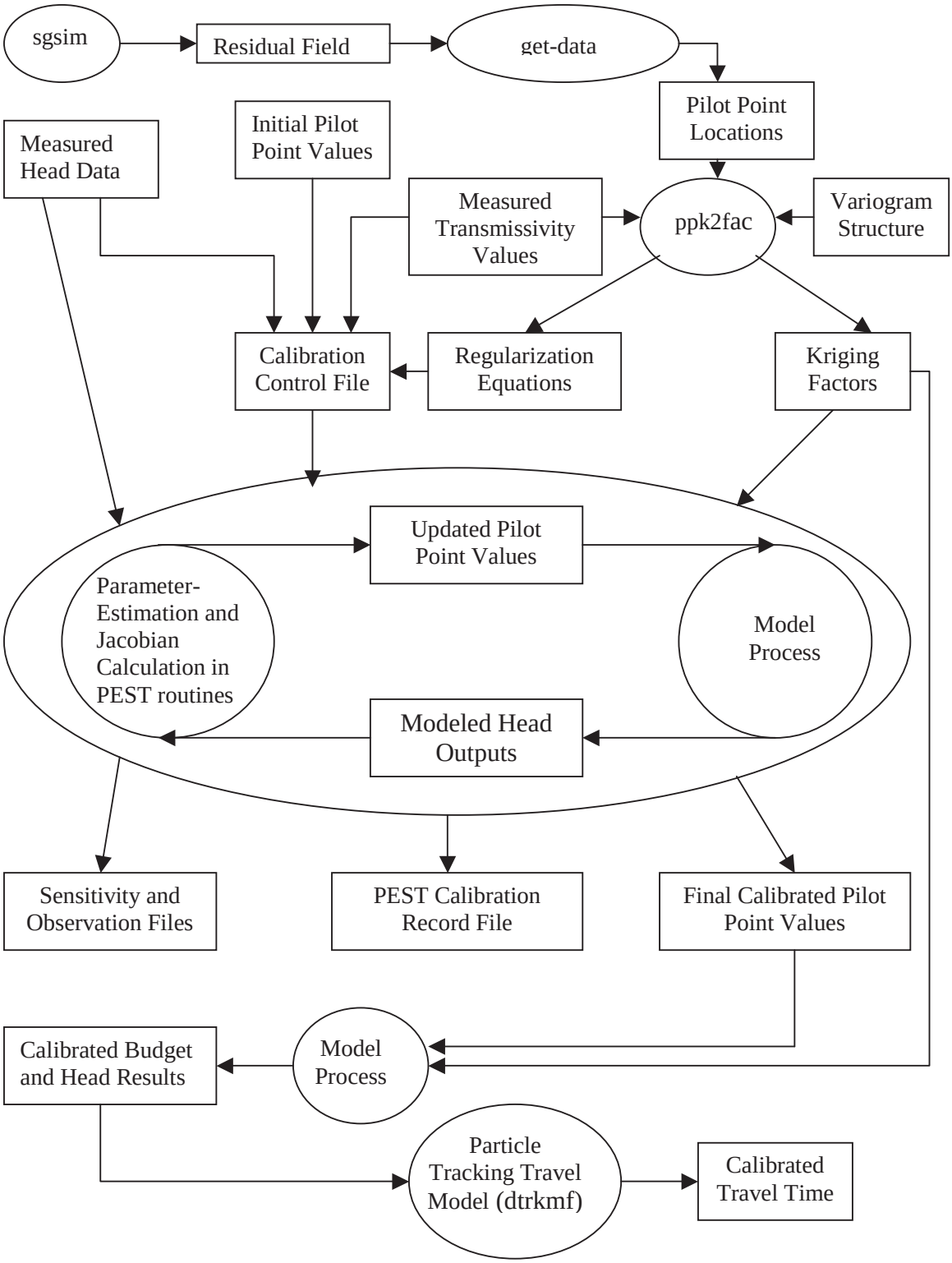

Figure TFIELD-41. Flow Chart of the Stochastic Inverse Calibration Process Used to Create the Final Calibrated Transmissivity Fields

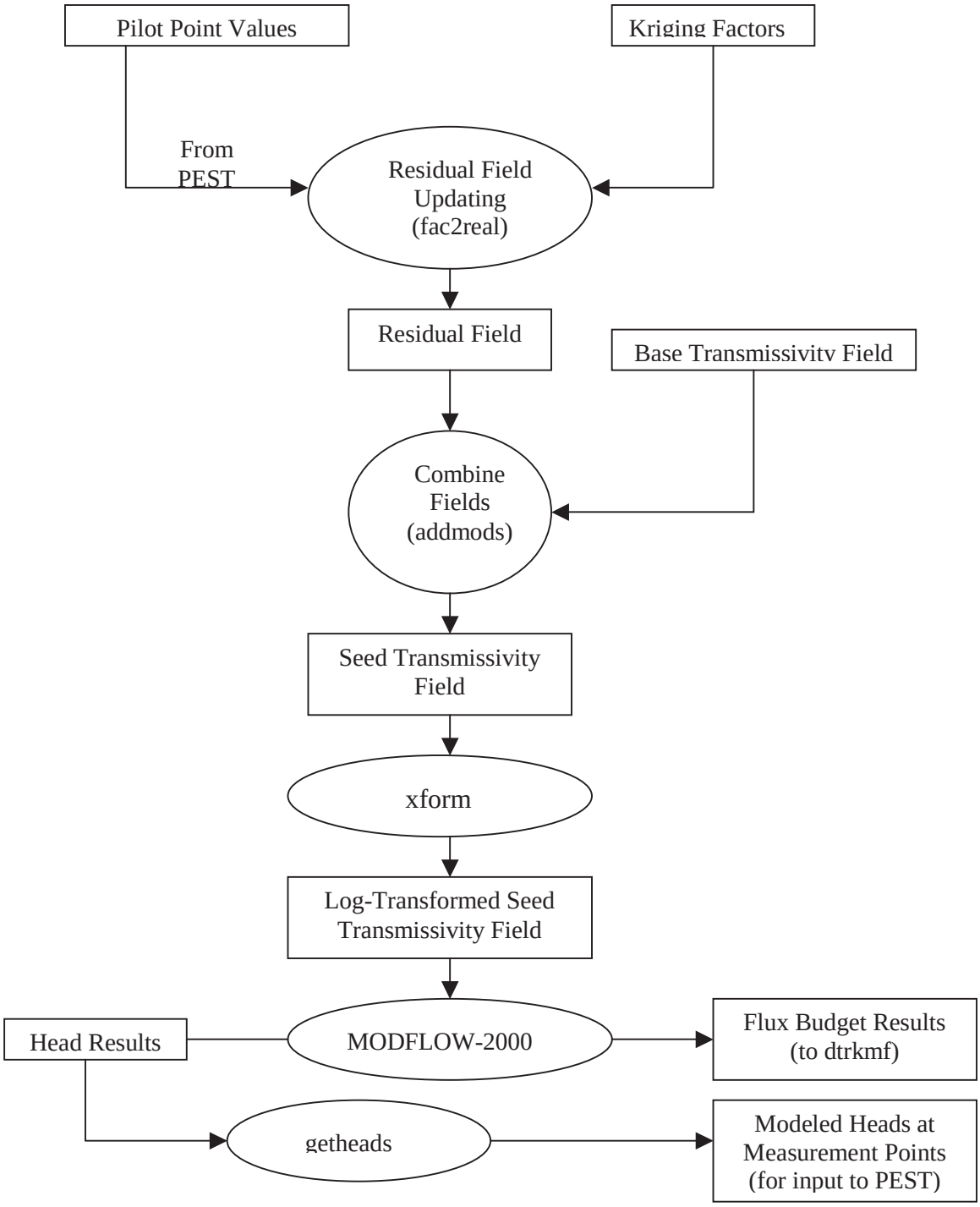

Figure TFIELD-42. Flow Chart of the Core of the Inversion Process Highlighting the Connection Between PEST and MODFLOW-2000

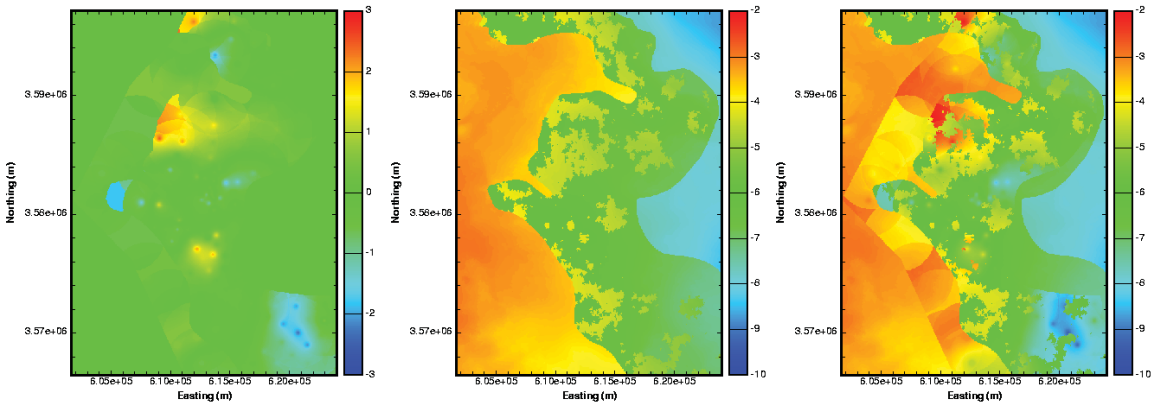

Figure TFIELD-43. Example Final Steps in the Creation of a Calibrated T Field. The calibrated residual field (left image) is added to the base T field (middle image) to get the final calibrated T field (right image). All color scales are in units of $\log_{10}$ T (m^2/s).

Due to these longer run times, two separate parallel PC clusters were employed. Each of these clusters consists of 16 computational nodes running 1.9-GHz Athlon processors with 1 gigabyte of RAM. One cluster is located in Albuquerque, NM and the other is in the Sandia office in Carlsbad, NM. Both clusters use the Linux operating system. The total number of forward runs necessary to complete the calibration process can be estimated as:

Total Runs ≅ (# of parameters) × (#of PEST iterations) × (average runs per iteration) × (# of base T fields).

The maximum number of iterations used in these runs was set to 15, although not all fields went to the maximum number of iterations. Additionally, on average for the first four iterations, PEST used forward derivatives to calculate the entries of the Jacobian matrix and each entry only required a single forward model evaluation. For the remaining 11 iterations, PEST used central derivatives to calculate the Jacobian entries and each calculation required two forward evaluations of the model (22 total). The average number of model evaluations is 1.733 = [(4 + 22)/15]. Therefore an estimate of the maximum possible total number of forward runs is equal to: 100 pilot points × 15 iterations/field × 1.73 runs/iteration × 150 T fields = 390,000 runs. The total time necessary to complete these calculations in serial mode on a single processor would be 813 days, or 2.22 years. PEST allows for parallel calculation of the Jacobian matrix, and this option was used to decrease the total run time significantly relative to the time needed for serial computation.

The model run times, as well as the time necessary to read and write input/output files across the cluster network, were examined to determine the optimal number of client, or slave, nodes for each server, or master, node. The optimal number of clients per server was determined to be eight. More clients per server degraded overall performance due to increased communication between machines and fewer clients per server resulted in underutilization of the system. By combining the client and server activities on a single machine using a virtual server setup, four different base T fields could be calibrated simultaneously on the 32 machines.

TFIELD-7.0 T-FIELD ACCEPTANCE CRITERIA

The calibration procedure described in Section 6.0 of this attachment was applied to 150 of the base T fields (the remaining 350 base fields were held in reserve, to be used only if necessary). Not all base T fields yielded a resulting calibrated T field. Four base T fields (d01r03, d01r09, d02r09, and d08r10) encountered numerical difficulties during the first iteration and did not calibrate at all. For each of the remaining 146 T fields, the calibration procedure stopped for one of three reasons:

1. PEST completed the maximum allowed number of iterations (15);
2. PEST was unable to improve the objective function (sum of squared errors of weighted residuals) for three successive iterations; or
3. the optimization became numerically unstable.

Some of the T fields probably could have been calibrated better with more effort and adjustment of some of the PEST input parameters; however, these parameters were set to work across the largest number of fields possible and no calibration process will necessarily be able to make progress on every base field given the same set of parameters.

Because the T-field calibration procedure did not stop when some objective goodness-of-fit target was achieved, criteria had to be established to define what constitutes an acceptable calibration for use in the WIPP CRA calculations. Because the T fields were to be used for calculation of radionuclide transport, the travel times calculated in the T fields for a conservative particle released above the center of the WIPP waste panels (UTM X = 613,597.5 m and Y = 3,581,385.2 m [Ramsey et al. 1996, p. 9]) to reach the WIPP land-withdrawal boundary (LWB) were used in developing acceptance criteria. That is, the sensitivity of the calculated travel-time distribution to potential acceptance criteria was used to identify those criteria that are important. Once the distribution of travel times showed no (remaining) sensitivity to continued refinement of the criteria applied (e.g., a reduction in some metric below a threshold value), all T fields meeting those criteria were considered to be acceptably calibrated.

The travel times discussed herein were obtained using the streamline particle-tracking algorithm implemented in DTRKMF v. 1.0 (Rudeen 2003) assuming a single-porosity medium with a porosity of 0.16. DTRKMF calculates particle tracks in two or three dimensions for steady-state and time-dependent, variably saturated flow fields. The particles are tracked cell-by-cell using a semi-analytical solution. DTRKMF assumes that the velocities vary linearly between the cell faces as a function of the space coordinate and, for time-dependent cases, that the velocities at the faces vary linearly between time planes. It directly reads the cell-by-cell flow budget file from MODFLOW-2000 and uses those values to calculate the velocity field. For each calibrated T field, a final forward run of MODFLOW-2000 was done and the cell-by-cell fluxes from this run were used as input to DTRKMF to calculate the travel time. For each calibrated T field, only a single particle was tracked, providing a single travel time. The MODFLOW-2000 modeling was performed using a 7.75-m (25.4-ft) thickness for the Culebra, whereas transport calculations assume that all flow is concentrated in the lower 4.0 m (13 ft) of Culebra (Meigs and McCord, 1996). Therefore, the travel times obtained from DTRKMF were scaled by multiplying by the

factor 0.516 (4/7.75). These scaled travel times were then consistent with the travel times calculated and reported by Wallace (1996) for the T fields used in the WIPP CCA (DOE 1996). These travel times do not, however, represent the actual predicted travel times of solutes, conservative or non-conservative, through the Culebra. Culebra transport modeling treats the Culebra as a double-porosity medium with transport through advective porosity (e.g., fractures) retarded by diffusion into diffusive porosity (e.g., matrix porosity) and by sorption. The travel times presented herein are intended only to allow comparison among T fields.

TFIELD-7.1 Candidate Acceptance Criteria

Four factors were evaluated for their potential to provide T-field acceptance criteria: the root mean squared error (RMSE) of the modeled fit to the measured steady-state heads, the agreement between the measured and modeled steady-state gradient/heads, the sum of squared weighted residuals (phi) for the transient data, and the agreement between the measured and modeled transient heads. These factors are not totally independent of one another, but are related in ways discussed below.

TFIELD-7.1.1 RMSE Values

The RMSE is a measure of how close MODFLOW-2000/PEST came to matching the measured steady-state heads for each T field. The RMSE is defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n_{obs}} (H_i^{obs} - H_i^{calc})^2}{n_{obs}}} \tag{10}$$

where n_{obs} is the number of head observations and H^{obs} and H^{calc} are the values of the observed and calculated heads, respectively. Previous Culebra T-field calibration exercises (e.g., LaVenue and RamaRao 1992) achieved RMSEs less than 3 m (9.5 ft) in most cases when calibration was being performed only to steady-state heads. This level of calibration was also achieved by McKenna and Hart (2003a) for four different sets of steady-state head measurements. RMSEs have not previously been reported for steady-state heads in Culebra T fields calibrated to transient heads.

TFIELD-7.1.2 Fit to Steady-State Heads

One measure of how well a T field has matched the steady-state heads can be obtained by simply plotting the measured heads versus the modeled heads. If the measured and modeled heads match exactly, the best-fit straight line through the data will have a slope of one. Exact agreement between measured and modeled heads is not to be expected, so an acceptance criterion on the slope of the best-fit line must be established.

The steady-state heads are important because the transport calculations performed in SECOTP2D rely on the steady-state velocity field provided by MODFLOW-2000. If MODFLOW-2000 has not accurately captured the steady-state heads, steady-state gradients and the associated steady-state velocities will be in error. With measured head plotted as the independent variable (x) and calculated head plotted as the dependent variable (y), a slope of the

best-fit line less than unity implies that the calculated gradient is less than the measured gradient. Low gradients should lead to excessively long travel times. Therefore, it was important to determine if a threshold value of the steady-state-fit slope exists above which the distribution of travel times is insensitive.

TFIELD-7.1.3 Phi Values

As shown in Equation (9), phi values have three components:

- A weighted sum of squared residuals for the steady-state heads,
- A weighted sum of squared residuals for the transient drawdowns, and
- A weighted sum of squared differences between T values for each pair of pilot points.

The steady-state component of phi is a weighted, squared, and summed expression of the RMSE given in Equation (10), above, and is not, therefore, meaningful to consider when RMSE is already being considered. The pilot-point-regularization component of phi relates to the smoothness of the T field, not to the goodness of fit of the measured and modeled responses. Hence, only the transient component of phi is considered in the discussion that follows.

For reasons discussed in Section 6.7 of this attachment, transient phi values do not provide a completely unbiased measure of how well a calibrated T field represents the actual T field. “Measurements” of zero drawdown were given arbitrarily high weights in the calibration process, the number of measurements used from individual wells during individual tests and the number of measurements used from all wells during a single test varied, and some parts of the modeling domain are covered by multiple wells’ responses, while other parts of the domain have no transient response data. Therefore, no simple numerical value can be established that represents an average residual of some meaningful value for each transient measurement, such as the RMSE used to evaluate T-field calibration to steady-state heads alone. Nevertheless, the transient phi values do provide an indication of how well a T field met the calibration targets as defined and could be used qualitatively to define acceptable T fields.

TFIELD-7.1.4 Fit to Transient Heads

Evaluating the model match to transient heads is not as straightforward as for the steady-state heads because the transient match involves both the magnitude and the timing of head changes. The magnitude and timing of a transient response are governed by both the transmissivity and storativity (S) of a system, but S was not included as a calibration parameter during the calibration process. A single S value of 1×10^{-5} ($\log_{10} = -5$) was used during T-field calibration. As reported by Beauheim (2003a), the apparent storativities obtained from independent analyses of the test responses used for the calibration range from 5.1×10^{-6} ($\log_{10} = -5.29$) to 7.3×10^{-5} ($\log_{10} = -4.14$). Because the calibration method only allowed PEST to adjust T to try to match the measured heads, it might actually shift T away from the correct value in trying to compensate for an inappropriate value of S. Thus, some allowance needed to be made for how close PEST could actually come to matching the measured responses.

To establish the bounds of what might be considered acceptable matches to the transient heads, a series of well-test simulations using the code nSIGHTS (Roberts 2002) was performed. For base-case parameter values, a T of 1×10^{-5} m^2/s and an S of 1×10^{-5} were used. Pumping in a well was simulated for 5, 25, and/or 50 days, and the responses that would be observed in observations wells 1, 2, and/or 3 km away were calculated. T and/or S were also varied by approximately a half order of magnitude upward and downward (3×10^{-5} and 3×10^{-6}). The results of these simulations are shown in Appendix A of Beauheim (2003b).

Based on the simulations, a set of guidelines was developed to determine if a modeled response matched a measured response within a half order of magnitude uncertainty in T and/or S. The guidelines were structured around the position of the modeled maximum drawdown relative to the measured maximum drawdown on a linear-linear plot of elapsed time on the x-axis and drawdown (increasing upward) on the y-axis. The guidelines are as follows:

- If the modeled peak occurs early and high (relative to the measured peak), S is too low and the maximum modeled drawdown can be up to three times greater than the maximum measured drawdown.

- If the modeled peak occurs early and low, T is too high and the maximum modeled drawdown can be up to two times lower than the maximum measured drawdown.

- If the modeled peak occurs late and high, T is too low and the maximum modeled drawdown can be up to two times higher than the maximum measured drawdown.

- If the modeled peak occurs late and low, S is too high and the maximum modeled drawdown can be up to three times lower than the maximum measured drawdown.

- If the modeled peak occurs at the same time as the measured peak but is high, the diffusivity (T/S) is correct, but both values are too low and the maximum modeled drawdown can be up to three times greater than the maximum measured drawdown.

- If the modeled peak occurs at the same time as the measured peak but is low, the diffusivity (T/S) is correct, but both values are too high and the maximum modeled drawdown can be up to three times lower than the maximum measured drawdown.

No quantitative criteria were established for how much earlier or later modeled peaks could occur relative to measured peaks because of the wide range observed in the simple scoping calculations (calculated peaks occurring a factor of 5 sooner to a factor of 10 later than the observed peaks) and because of the variability in pumping durations and distances to observation wells associated with the measured responses.

Using these guidelines, plots of each of the 40 transient well responses of each calibrated T field were evaluated visually to determine if the T field represented that response within a half order of magnitude uncertainty in T and/or S. A threshold number of well responses that failed this test was then considered as a possible acceptance criterion for the T fields.

TFIELD-7.2 Application of Criteria to T Fields

The four criteria described above were applied to the calibrated Culebra T fields to determine if they allowed meaningful discrimination among the fields. Given that travel time is the performance measure of most concern, the four criteria were evaluated in terms of their effects on the calculated distribution of travel times from the T fields.

TFIELD-7.2.1 RMSE Values

Steady-state RMSE values for the 146 completed T fields are plotted in Figure TFIELD-44. The data for H-9b, the southernmost well, were excluded from the RMSE calculation because the southern model boundary condition consistently caused the modeled H-9b head to be significantly lower than the measured head, disproportionately affecting the calculation of the RMSE. The exclusion of the H-9b data should provide a better measure of the accuracy of the model in the rest of the model domain.

All nine RMSE values greater than 20 m (66 ft) correspond to T fields that were not considered to have been successfully calibrated by McKenna and Hart (2003b). Figure TFIELD-45 shows the RMSE values plotted against travel time, and shows that the high RMSE values tend to be associated with long travel times. For RMSE values less than approximately 6 m (20 ft), travel times tend to cluster below approximately 50,000 years. Applying an RMSE cutoff value of 6 m (20 ft) would leave 117 T fields, with all but one having travel times less than 102,000 years (Figure TFIELD-46; the outlier with a travel time of ~241,000 years, d01r06, is not shown).

TFIELD-7.2.2 Fit to Steady-State Heads

Figure TFIELD-47 provides an example plot of measured steady-state heads versus modeled steady-state heads for one T field, with a unit-slope line shown as a reference. For each plot of steady-state heads, the slope of the best-fit line through all of the data except for the data for H-9b was calculated using the Excel SLOPE function. The data for H-9b, the southernmost well, were excluded from this calculation because the southern model boundary condition consistently caused the modeled H-9b head to be significantly lower than the measured head. Inasmuch as the gradient in the extreme southern portion of the modeling domain is unimportant with respect to transport across the southern half of the WIPP site, the exclusion of the H-9b data should improve the accuracy of the slope calculation in the area of interest.

The slopes of the best-fit lines through the measured vs. modeled steady-state heads are shown plotted against travel time in Figure TFIELD-48. Steady-state-fit slopes less than 0.5 appear to lead to significantly longer travel times, consistent with the low hydraulic gradients the low slopes imply. Of the 116 T fields with steady-state-fit slopes greater than 0.5, all but nine have travel times less than 50,000 years. Figure TFIELD-49 shows the slopes and travel times for these 116 fields (the outlier with a travel time of ~241,000 years, d01r06, is not shown), and indicates that travel time is not sensitive to steady-state-fit slopes above 0.5.

TFIELD-7.2.3 Phi Values

Transient phi values for all the completed T fields are plotted against travel time in Figure TFIELD-50. As phi values decrease, particularly as they get below approximately 5,000 m^2

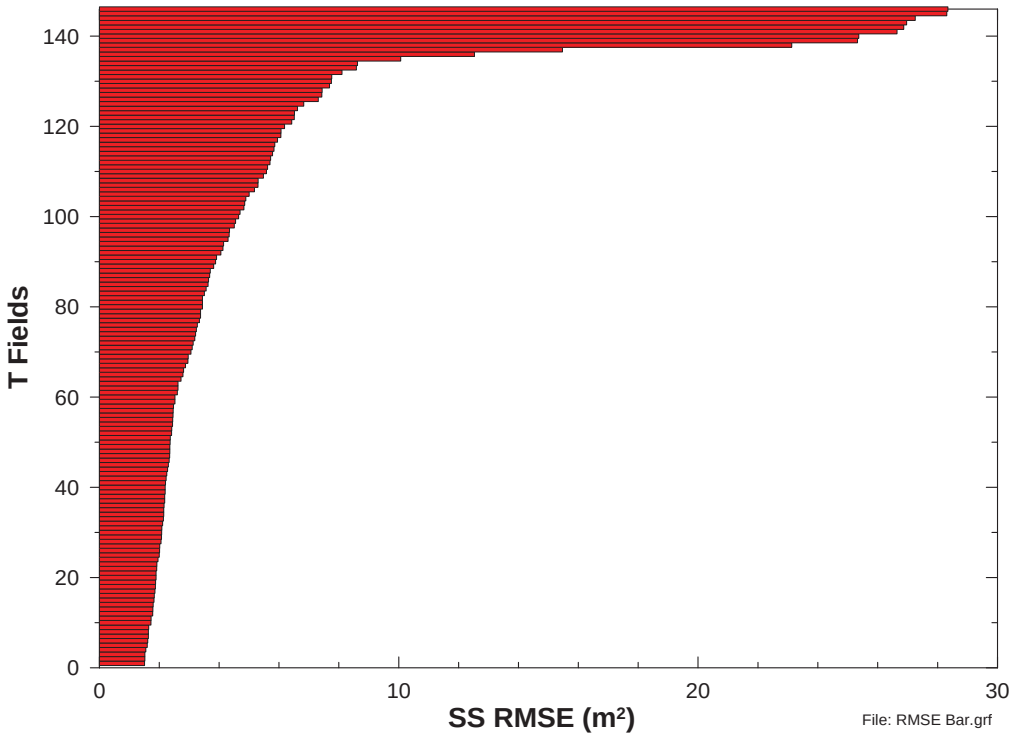

Figure TFIELD-44. Steady-State RMSE Values for 146 T Fields

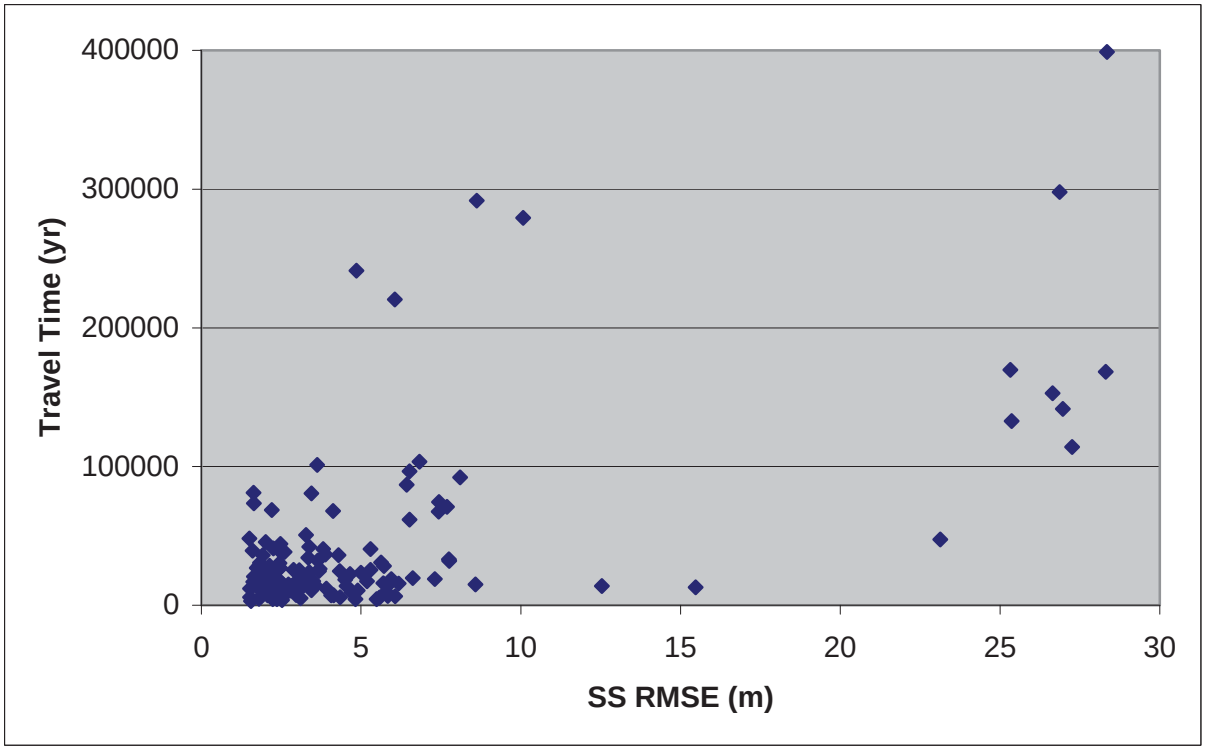

Figure TFIELD-45. Steady-State RMSE Values and Associated Travel Times

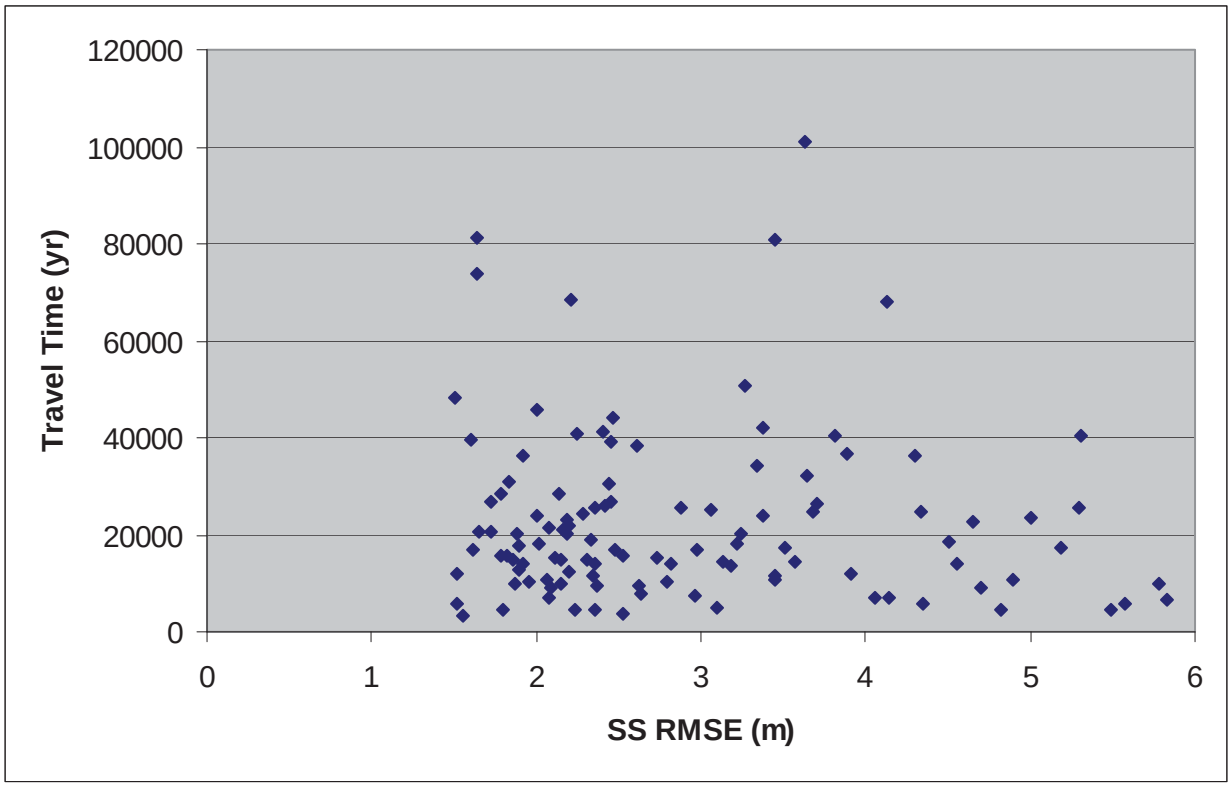

Figure TFIELD-46. Travel Times for Fields with Steady-State RMSE <6 m *(20 ft)*

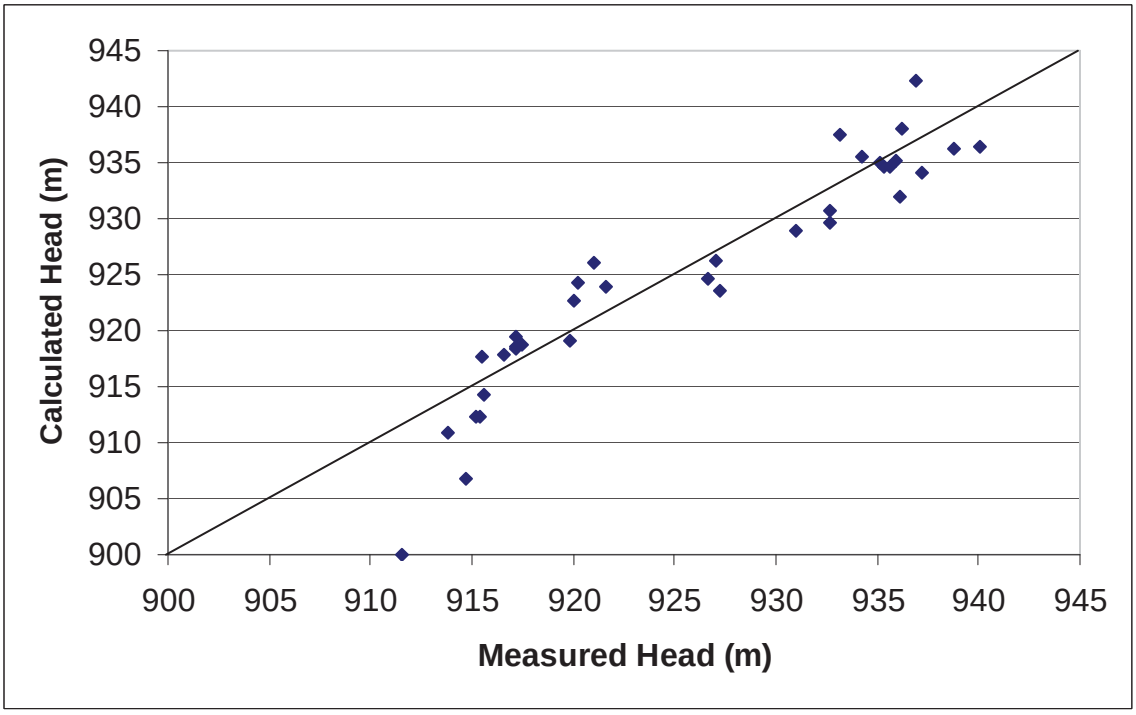

Figure TFIELD-47. Measured Versus Modeled Steady-State Heads for T Field d21r10

(53,800 ft^2), travel times tend to cluster below approximately 50,000 years, but little correlation is seen between transient phi and travel time. Figure TFIELD-51 shows transient phi versus travel time for the 123 fields with transient phi values less than 8,000 m^2 (86,000 ft^2), excluding the five outliers that have travel times greater than 168,000 years. This plot suggests that despite the clustering of travel times below 50,000 years, the overall range of travel times does not decrease significantly as phi decreases. Thus, transient phi does not appear to provide an effective tool for distinguishing among T fields.

TFIELD-7.2.4 Fit to Transient Heads

In applying the tests described in Section 7.1.4 of this attachment to the well responses simulated for each T field, it was found that insufficient data (only six measurements) had been included for the WQSP-1 response to pumping at WQSP-2 to allow any determination of model adequacy. Thus, this response was eliminated from consideration for all T fields. Figures TFIELD-52 and TFIELD-53 provide examples from T field d21r10 of well responses that were judged to PASS and FAIL, respectively, the criteria outlined in Section 7.1.4 of this attachment. The number of responses that failed for each T field is given in Table TFIELD-11. For the WQSP-3 responses to pumping at WQSP-1 and WQSP-2 (for which no clear drawdown was observed and "measured" values of zero were entered), the modeled response was accepted if it showed no more than 0.25 m (0.82 ft) of drawdown.

The number of well responses that fail the tests described in Section 7.1.3 of this attachment should be related to the transient phi for each T field because both are measures of the match between the measured and modeled transient heads. Figure TFIELD-54 shows a plot of transient phi versus the number of failed well responses for all 146 T fields. A definite correlation is evident up to a phi of approximately 8,000 m^2 (86,000 ft^2). Beyond that value, the number of failed well responses simply remains high ($\geq$14).

The number of failed well responses is plotted against travel time in Figure TFIELD-55 for each of the T fields. The scatter in travel time appears to increase with 14 or more failures, but the majority of T fields still have travel times in the same range as the fields with less than 14 failures. Thus, the number of failed well responses alone does not appear to discriminate well among T fields.

TFIELD-7.3 **Final Acceptance Criteria**

Of the criteria discussed above, the two related to the steady-state heads (RMSE and steady-state-fit slope) appear to be more effective at identifying poorly calibrated T fields than the two related to transient heads (transient phi and number of failed well responses). The range and scatter of travel times appears to increase at RMSE values beyond 6 m (20 ft). Applying an RMSE cutoff of 6 m (20 ft) leaves 117 T fields, all with travel times less than 102,000 years except one (d01r06). This cutoff also excludes all T fields with steady-state-fit slopes less than 0.45. Steady-state-fit slopes less than approximately 0.5 appear to lead to significantly longer travel times, consistent with the low hydraulic gradients the low slopes imply. If a simple cutoff of a minimum steady-state-fit slope of 0.5 is applied, 116 T fields are left, again with travel times less than 102,000 years (except d01r06), and also with RMSE values less than 8.6 m (28.2 ft). Five T fields that meet the RMSE less than 6 m (20 ft) criterion fail the steady-state-fit slope

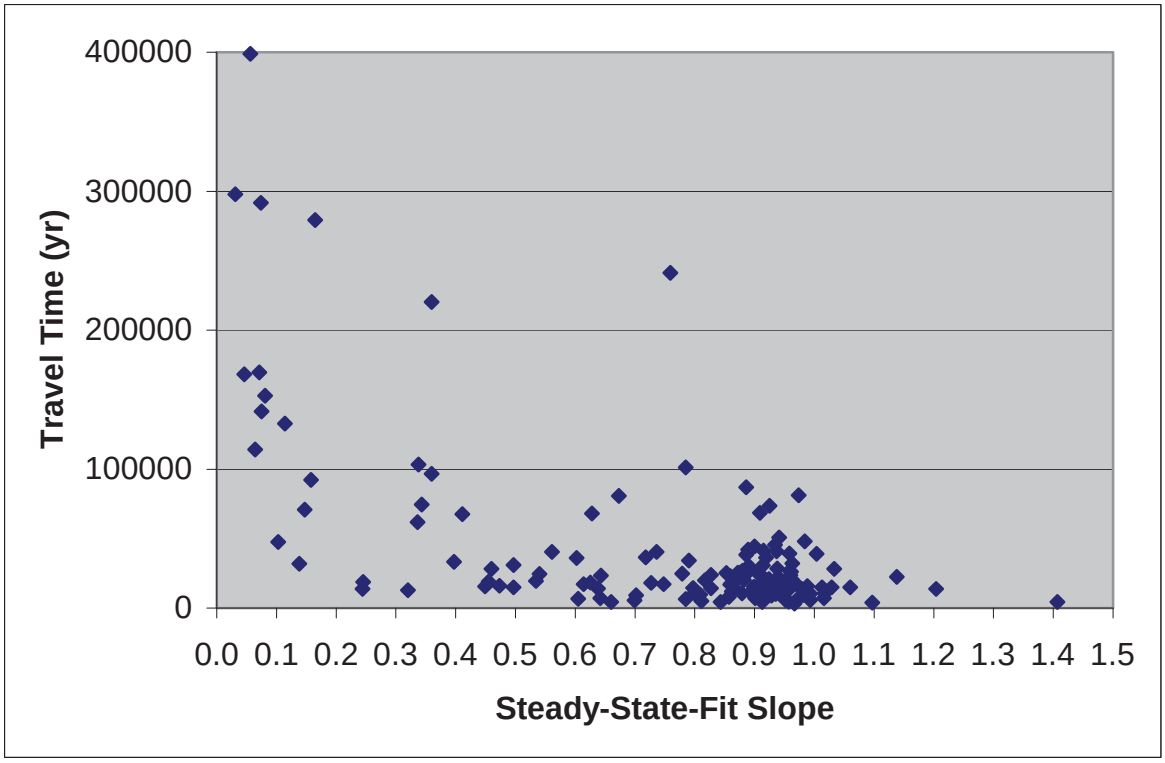

Figure TFIELD-48. Steady-State-Fit Slope Versus Travel Time for All Fields

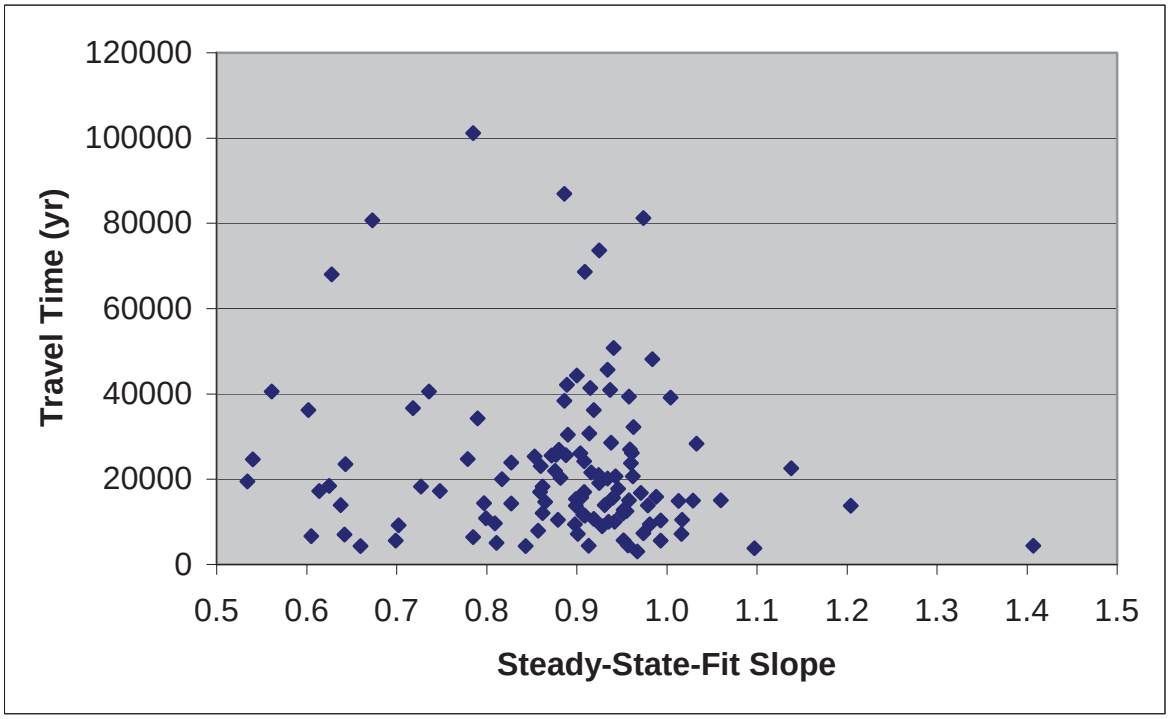

Figure TFIELD-49. Steady-State-Fit Slope Versus Travel Time for Slopes >0.5

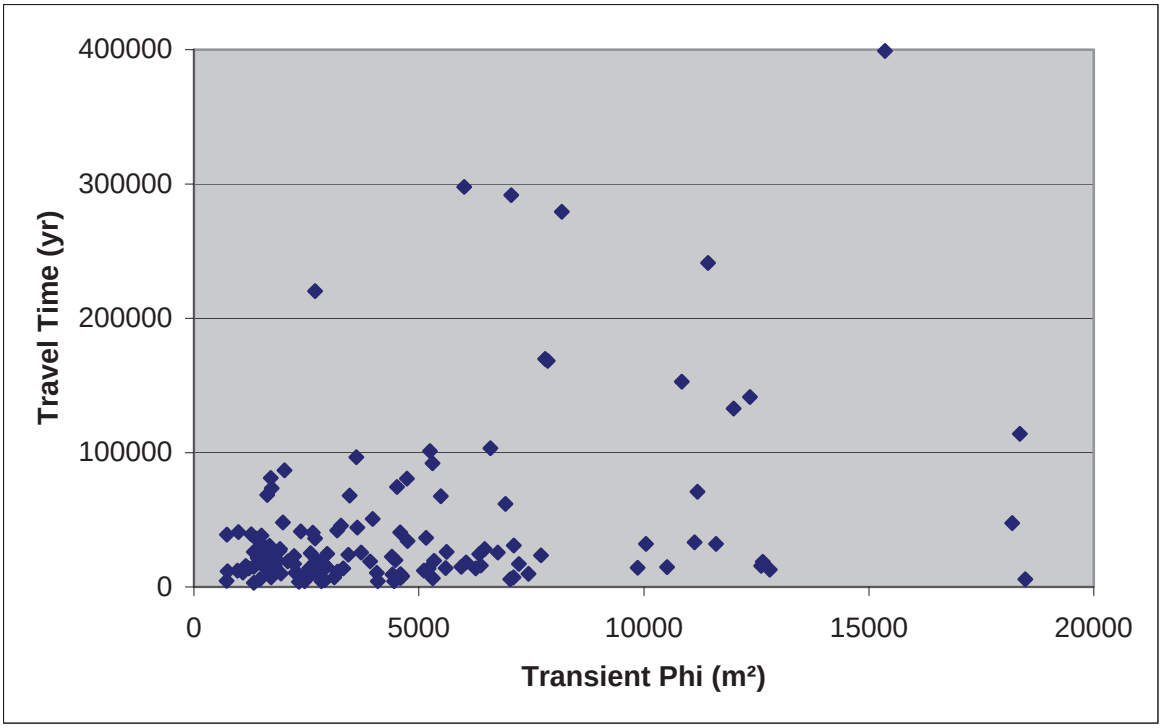

Figure TFIELD-50. Transient Phi Versus Travel Time for All Fields

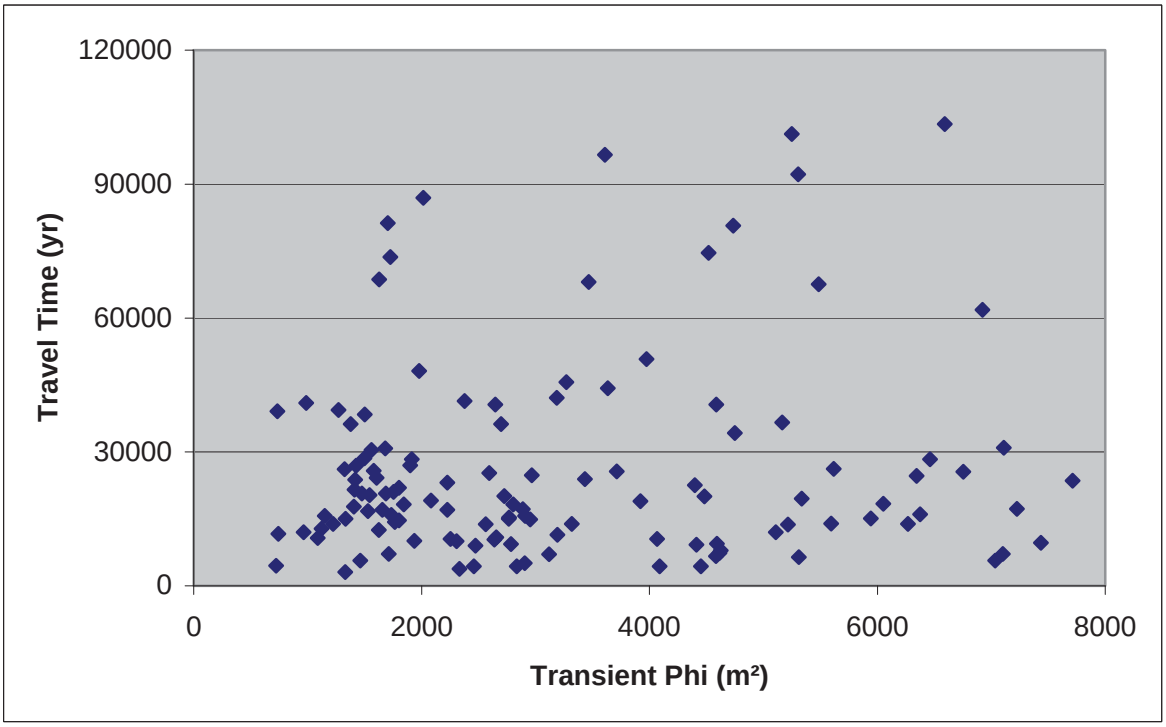

Figure TFIELD-51. Transient Phi Versus Travel Time for Phi <8,000 m^2

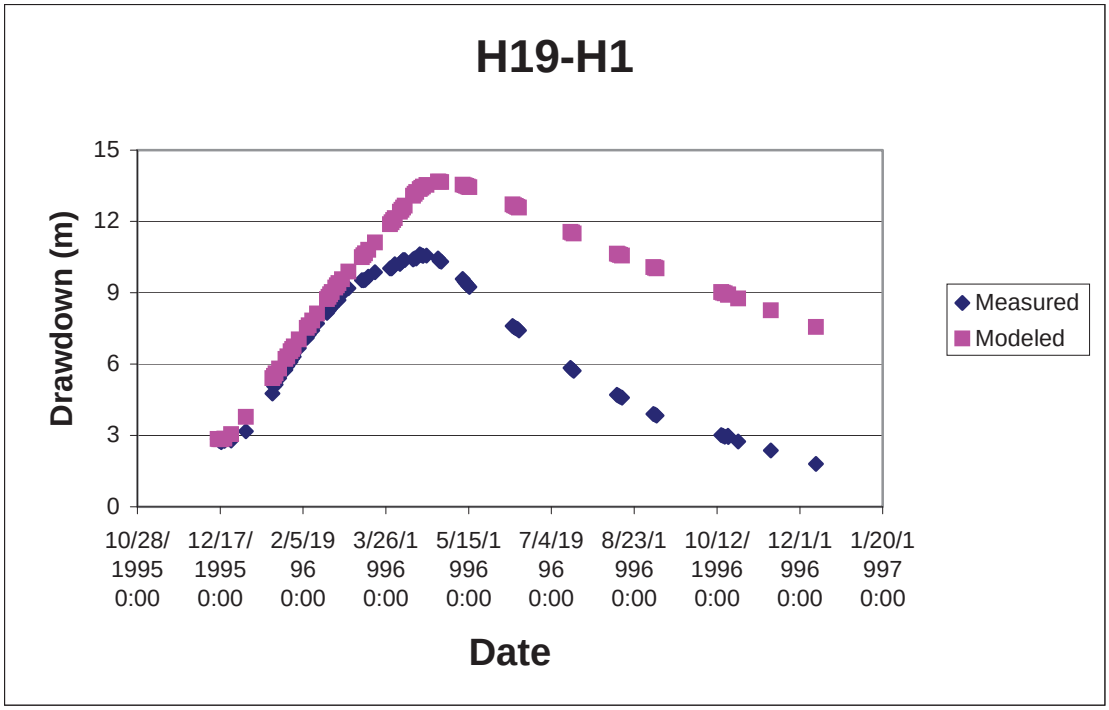

Figure TFIELD-52. Example of Passing Well Response from T Field d21r10

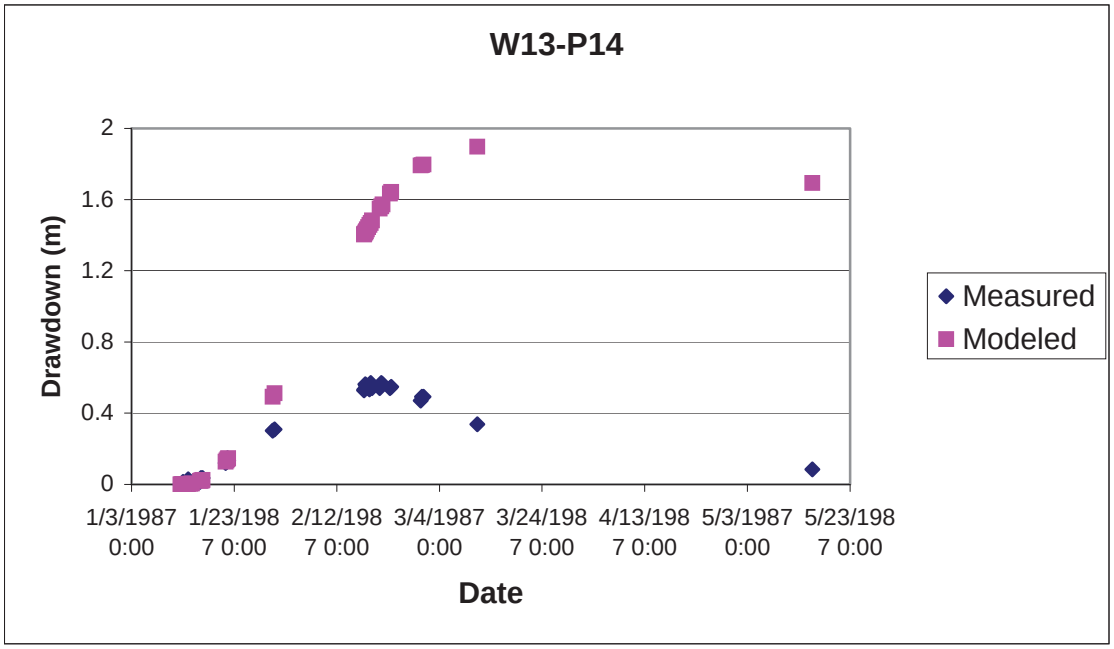

Figure TFIELD-53. Example of Failing Well Response from T Field d21r10

Table TFIELD-11. Summary Information on T Fields

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
[redacted]	7.427	10498	5486	0.411	13	67578
d01r02	3.915	3621	5110	0.862	20	12045
d01r04	2.812	2140	2563	1.204	11	13821
[redacted]	7.313	10245	12643	0.245	16	18886
d01r06	4.856	5006	11426	0.759	15	241211
d01r07	3.377	2851	3187	0.889	9	42123
d01r08	5.484	6122	4091	1.407	14	4399
d01r10	1.646	1094	1476	0.943	9	20685
[redacted]	26.966	128711	12359	0.075	19	141516
d02r02	3.507	2772	2889	0.748	11	17217
[redacted]	10.070	18606	8173	0.165	15	279242
[redacted]	8.104	12482	5305	0.158	12	92235
d02r05	5.184	5577	7224	0.614	17	17255
[redacted]	25.325	113652	7810	0.071	16	169677
d02r07	3.648	3223	10047	0.963	15	32231
d02r08	5.001	5125	7713	0.643	17	23571
d02r10	6.066	6849	5312	0.785	13	6433
d03r01	4.506	4022	6053	0.625	17	18435
[redacted]	28.346	142152	15357	0.056	16	398937
d03r03	4.146	3899	7102	1.016	17	7171
[redacted]	25.367	114006	11991	0.114	14	132833
d03r05	5.836	6873	4585	0.605	13	6638
d03r06	1.729	1208	1899	0.959	13	27006
d03r07	4.655	4740	4399	1.138	13	22599
d03r08	4.550	4250	5593	0.638	17	13942
d03r09	2.352	1574	1580	0.877	7	25757
d03r10	8.584	13811	2766	1.060	13	15054
d04r01	3.447	2370	4736	0.673	17	80690
d04r02	3.818	3175	2647	0.736	12	40593
d04r03	2.352	1659	3317	0.979	12	13888
d04r04	4.298	3692	2697	0.602	13	36245
d04r05	1.507	1059	1980	0.984	9	48168
d04r06	3.705	3146	5618	0.961	16	26199
d04r07	2.183	1397	2226	0.860	10	23105
d04r08	2.444	1759	1560	0.890	11	30470
[redacted]	27.256	131491	18356	0.064	16	114087
d04r10	3.060	2401	2593	0.853	9	25316
d05r01	6.427	8119	2015	0.886	13	86924
d05r02	5.298	5831	6755	0.872	16	25610
d05r03	3.444	2580	2655	0.799	11	10880
d05r04	5.862	6984	10518	0.497	17	14856
d05r05	4.346	4226	18478	0.952	16	5668
[redacted]	6.518	8198	3609	0.360	13	96589
d05r07	3.188	2682	5216	0.899	9	13766
[redacted]	7.686	11242	11194	0.147	16	70896
[redacted]	26.644	125685	10840	0.081	17	152818
d05r10	5.623	6497	7110	0.497	16	30955
[redacted]	6.828	9057	6592	0.338	17	103442
d06r02	1.957	1266	2639	0.993	9	10353
d06r03	1.637	1051	1703	0.974	10	81258
d06r04	3.214	2246	2805	0.727	13	18294

Table TFIELD-11. Summary Information on T Fields — Continued

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
d06r05	3.886	3516	5164	0.718	18	36644
d06r06	2.149	1254	2954	1.013	10	14935
d06r07	1.518	784	965	0.951	7	12035
[redacted]	7.440	10397	4518	0.343	18	74565
[redacted]	28.309	141764	7864	0.046	18	168281
d06r10	2.196	1455	1801	0.876	11	21990
d07r01	3.101	2326	2905	0.811	14	5082
d07r02	2.010	1327	3271	0.934	15	45647
[redacted]	15.470	42986	12795	0.320	19	12919
d07r04	5.579	6230	7033	0.699	18	5638
d07r05	2.727	1705	5942	0.958	10	15097
d07r06	4.334	3927	6345	0.540	12	24641
d07r07	2.477	1737	2225	0.908	9	17038
d07r08	2.232	1097	2836	0.843	9	4355
d07r09	2.207	1239	1628	0.909	8	68629
d07r10	1.782	839	1150	0.940	9	15680
d08r01	2.361	1736	2458	0.913	11	4388
d08r02	2.418	1168	1326	0.904	6	26115
d08r03	2.137	1489	1499	0.938	9	28570
d08r04	3.683	2674	2966	0.779	9	24773
d08r05	2.115	1384	2769	0.899	13	15358
d08r06	1.916	1388	1225	0.931	11	13917
d08r07	1.857	815	1333	1.029	10	15027
[redacted]	12.534	28547	6267	0.244	12	13885
d08r09	5.785	6674	7437	0.809	17	9691
[redacted]	8.621	13909	7050	0.074	11	291623
d09r02	3.243	2418	4482	0.817	12	20048
d09r03	2.252	1337	989	0.937	8	40948
d09r04	1.892	710	1123	0.952	8	12857
d09r05	2.061	954	1088	0.919	8	10726
d09r06	2.794	2313	2253	0.879	16	10509
d09r07	2.629	1676	4591	0.981	10	9472
d09r08	1.895	1030	1406	0.946	9	17741
d09r09	4.826	4945	4453	0.660	14	4359
d09r10	3.273	2790	3976	0.941	19	50791
[redacted]	26.867	127794	6006	0.031	14	297840
d10r02	1.554	589	1330	0.967	8	3111
d10r03	2.201	1474	1626	0.955	9	12533
d10r04	2.527	1788	2334	1.097	9	3799
d10r05	5.722	6646	6463	0.460	18	28390
d10r06	4.702	4644	4412	0.702	13	9210
d10r07	1.870	810	1937	0.935	10	10068
d10r08	2.334	1613	2083	0.925	8	19093
d10r09	4.128	3643	3466	0.628	11	68052
d10r10	1.789	982	1915	1.033	13	28367
d11r01	2.970	2297	1655	0.859	9	17015
d11r02	2.308	1799	1801	0.865	12	14677
d11r03	5.700	6093	6376	0.473	9	16014
[redacted]	6.514	8401	6922	0.336	23	61862
d11r05	5.952	7166	3921	0.455	17	18998
d11r06	2.607	1949	1503	0.886	9	38399

Table TFIELD-11. Summary Information on T Fields — Continued

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
d11r07	1.639	602	1727	0.925	9	73634
d11r08	1.801	1206	723	0.957	6	4520
d11r09	2.073	858	1712	0.901	7	7199
d11r10	3.135	2363	1767	0.827	5	14358
d12r01	3.378	2921	3432	0.827	14	23936
d12r02	2.459	1795	1426	0.880	10	26919
d12r03	1.618	558	1530	0.971	11	16780
[redacted]	6.182	7395	12605	0.449	20	15619
d12r05	1.522	918	1463	0.993	6	5655
d12r06	1.602	539	1271	0.958	13	39399
d12r07	2.016	945	1844	0.862	9	18283
d12r08	2.630	1879	4627	0.857	16	7981
d12r09	2.369	1671	2784	0.898	11	9414
[redacted]	7.762	11431	11606	0.138	18	32059
d13r01	2.163	1061	1753	0.924	11	21032
d13r02	2.881	2054	3715	0.888	14	25639
d13r03	3.444	2580	3192	0.909	11	11493
d13r04	5.302	5856	4588	0.561	13	40601
d13r05	3.343	2671	4750	0.790	12	34247
d13r06	2.410	1441	2377	0.915	10	41400
d13r07	2.280	1395	1606	0.908	10	24211
d13r08	1.879	779	1544	0.882	9	20313
d13r09	1.919	776	1379	0.919	14	36260
[redacted]	6.063	6685	2693	0.360	14	220354
d21r01	2.151	1555	2307	0.942	13	10042
d21r02	2.087	1431	2473	0.928	9	9023
d21r03	2.346	1299	744	0.907	6	11671
d21r04	2.523	1978	2908	0.905	13	15717
d21r05	2.001	932	1417	0.960	10	23750
d21r06	1.721	655	1688	0.962	8	20715
d21r07	2.182	1179	2725	0.934	9	20141
d21r08	6.620	8618	5337	0.534	14	19534
[redacted]	7.750	11501	11124	0.397	19	33308
d21r10	2.959	2226	4615	0.974	13	7384
[redacted]	23.126	94895	18190	0.103	15	47563
d22r02	3.629	3197	5250	0.785	10	101205
d22r03	4.061	3464	3119	0.642	11	7067
d22r04	4.894	5073	4068	1.017	12	10537
d22r05	3.566	3160	9863	0.797	18	14385
d22r06	2.469	1145	3635	0.900	9	44309
d22r07	2.080	999	1413	0.916	9	21589
d22r08	1.837	809	1681	0.914	10	30771
d22r09	1.822	724	1734	0.988	19	15870
d22r10	2.452	1684	735	1.004	5	39116

[redacted] signifies T fields not meeting final acceptance criteria.
Bold italics type signifies 100 final T fields as discussed in Section 7.3 of this attachment.

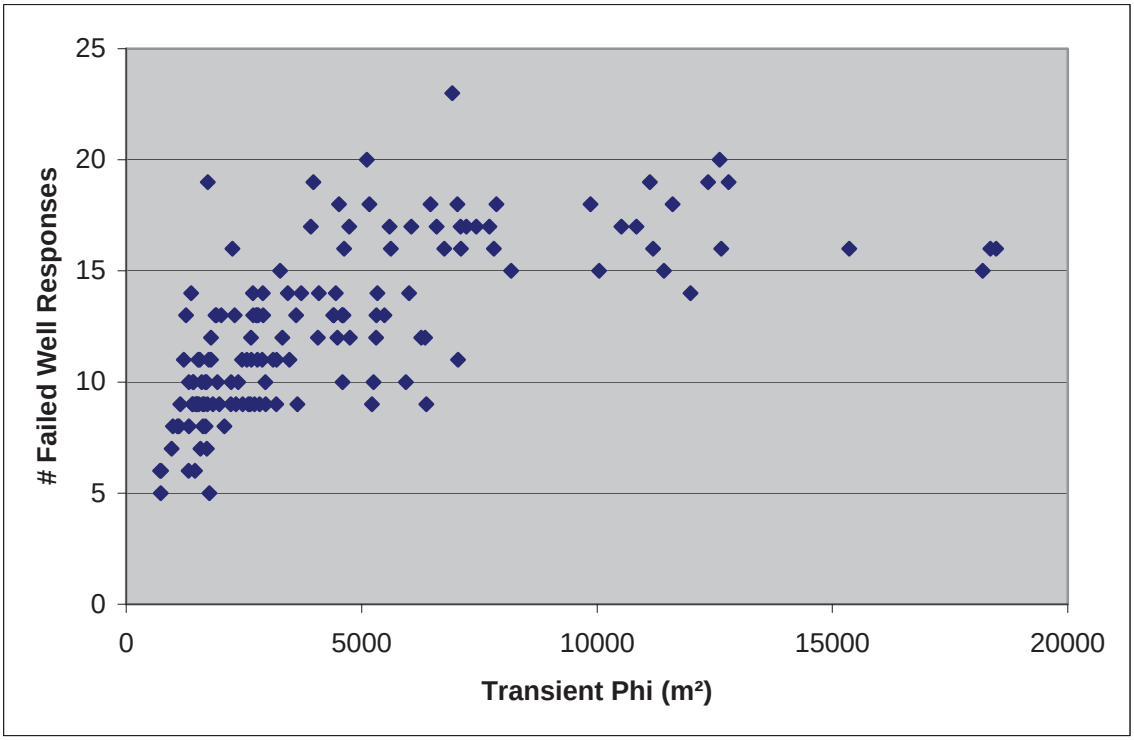

Figure TFIELD-54. Transient Phi Versus Number of Failed Well Responses

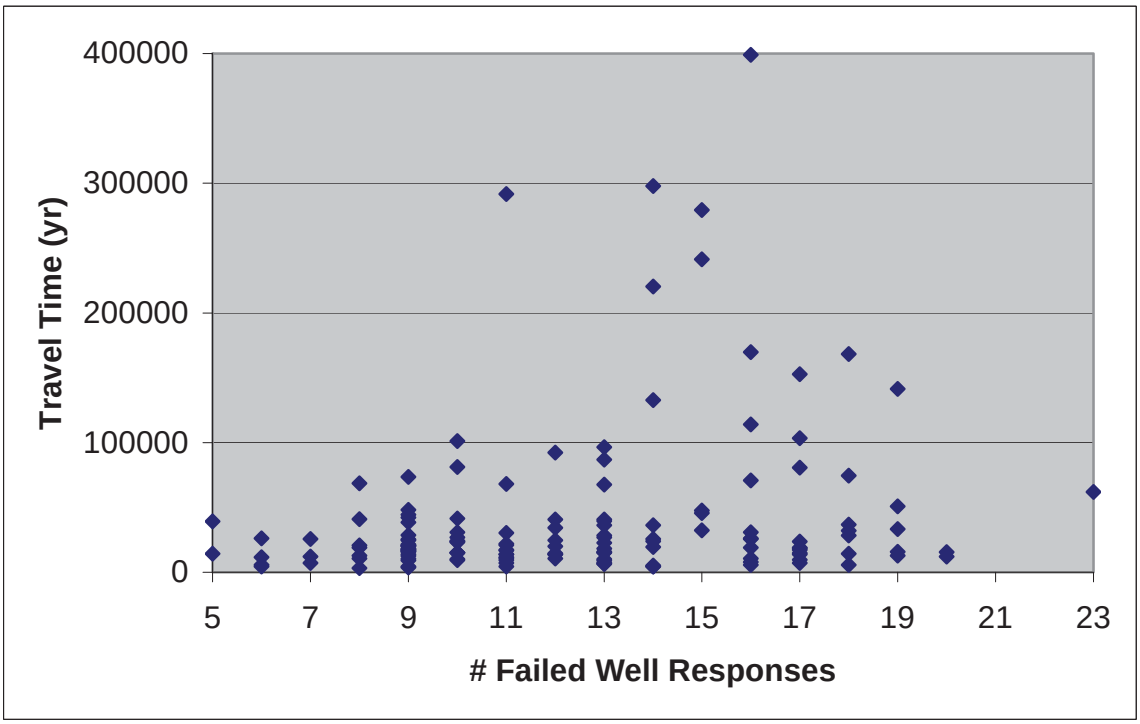

Figure TFIELD-55. Number of Failed Well Responses Versus Travel Time

greater than 0.5 criterion, while four T fields meeting the slope criterion fail the RMSE criterion. Thus, 112 T fields meet both criteria while 121 T fields meet at least one of the criteria.

Figure TFIELD-56 shows a CDF for the 121 T fields meeting the RMSE and/or steady-state-fit slope criteria discussed above. Also shown are curves representing the 100 T fields with RMSE values <5 m (16 ft) and transient phi values <8,000 m^2 (86,111 ft^2), and the 100 T fields with the largest steady-state-fit slopes (>0.72). All three CDFs are very similar, the most significant difference being that imposing a cutoff value on transient phi eliminates the T field with the longest travel time (d01r06). To illustrate the effects of imposing more stringent constraints on T-field acceptance, a fourth CDF is shown in Figure TFIELD-56 that represents the 23 T fields

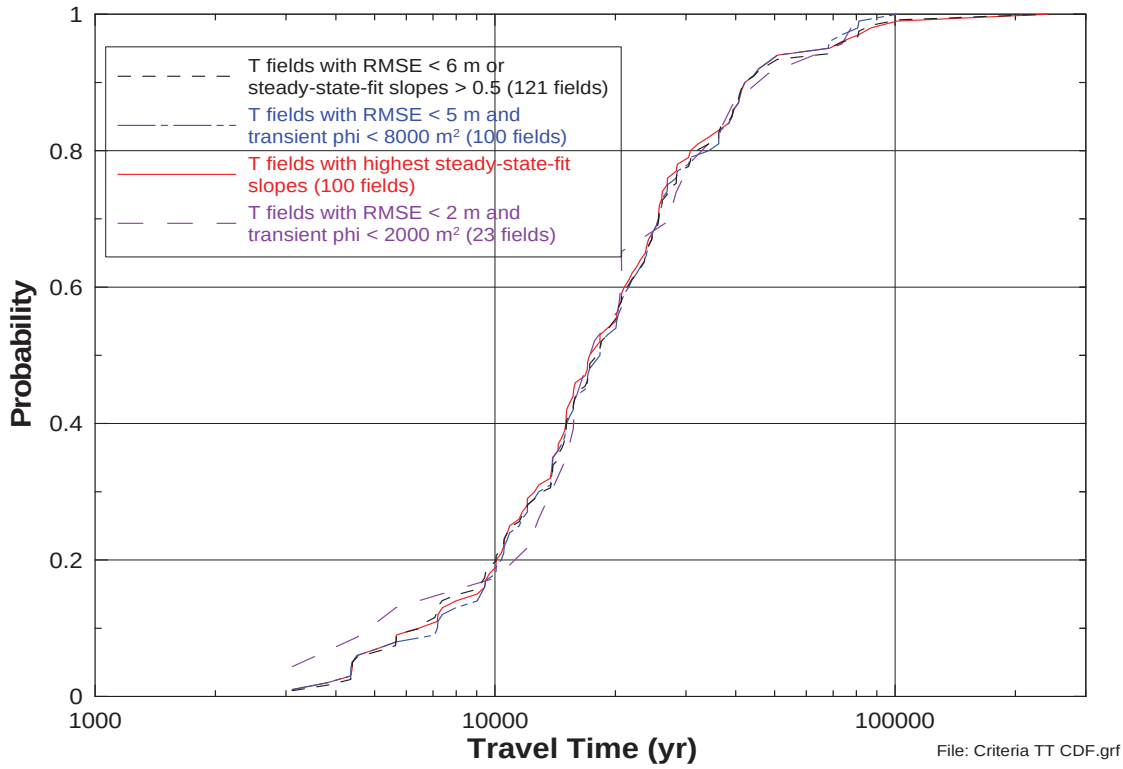

Figure TFIELD-56. Travel-Time CDFs for Different Sets of T Fields

that have RMSE values less than 2 m (7 ft) and transient phi values less than 2,000 m^2 (21,527 ft^2). These 23 T fields all have steady-state-fit slopes greater than 0.88. This CDF generally shows travel times similar to those of the other CDFs, except at the tails of the distribution which are poorly defined because of the relatively small sample size. Thus, because all the CDFs shown are similar, all 121 T fields meeting the steady-state-fit slope or RMSE criteria were considered to be acceptably calibrated. The T fields that have been rejected are shown in reverse type in Table TFIELD-11.

Because only 100 T fields were needed, the criteria were refined to eliminate more T fields. Given that lower travel times provide a conservative (in terms of leading to increased solute transport) way to discriminate among sets of T fields, the 100 T fields with RMSE values <5 m (16 ft) and transient phi values <8,000 m^2 were selected for use in CRA-2004 calculations of

radionuclide transport through the Culebra because that set excluded the calibrated T field with the longest travel time. These T fields are highlighted in ***bold italicized*** type in Table TFIELD-11.

For comparison purposes, the CDF of travel times for these 100 T fields is plotted in Figure TFIELD-57 with the CDF of travel times for the 100 transient-calibrated T fields used in the CCA (Wallace 1996). Generally speaking, travel times are two to three times as long in the CRA-2004 fields as in the CCA fields. Considering the degree of uncertainty involved in characterizing a geologic medium on the scale of the T fields, a factor of two or three difference in travel-time CDFs represents excellent agreement.

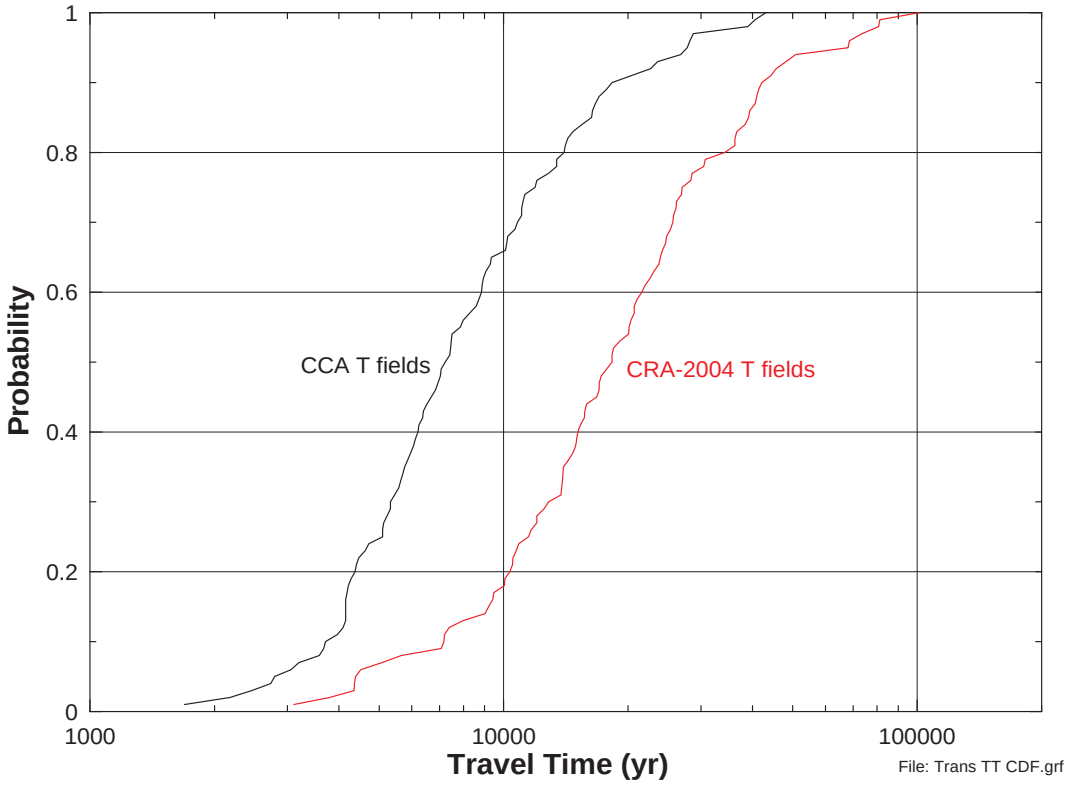

Figure TFIELD-57. Travel-Time CDFs for CCA and CRA-2004 T Fields

TFIELD-8.0 INVERSE MODELING RESULTS

Some fit statistics (phi, RMSE, etc.) for the 121 T fields that were judged to be acceptably calibrated were presented in Section 7.0 of this attachment. Visualizations of the T fields are included in Annex A. Additional properties or characteristics of the T fields are given below.

TFIELD-8.1 Particle Tracking

Particle tracking was performed in the 121 calibrated T fields from a point above the center of the WIPP disposal panels to both the LWB and the boundary of the model domain, as discussed in Section 7.0 of this attachment. The locations of all the particle tracks are show in Figures TFIELD-58 and TFIELD-59. In both figures, the particle tracks are shown using only every 20th

point along the track because of a limitation in the graphing software. This filtering leads to the particle tracks appearing less smooth than they actually are. Figure TFIELD-58 shows a close-up view of the particle tracks within the WIPP LWB. All of the particles exit the southern edge of the LWB and the majority of the particles exit the LWB to the southeast of the release point, although not as far to the east as the particle tracks for the CCA T fields showed (Ramsey et al. 1996, p. 49). Figure TFIELD-59 shows the particle tracks within the entire model domain. The majority of the particles exit the domain nearly due south of the release point. The particles that migrate to the west tend to travel along the boundary of the high-T zone. This result is due to the large amount of groundwater flux within the high-T zone creating a streamline at the high-T zone boundary.

TFIELD-8.2 Fit to Steady-State Heads

Some information about how well the calibrated T fields matched the observed steady-state heads is given in Sections 7.2.1 and 7.2.2 of this attachment. Additional information is shown in

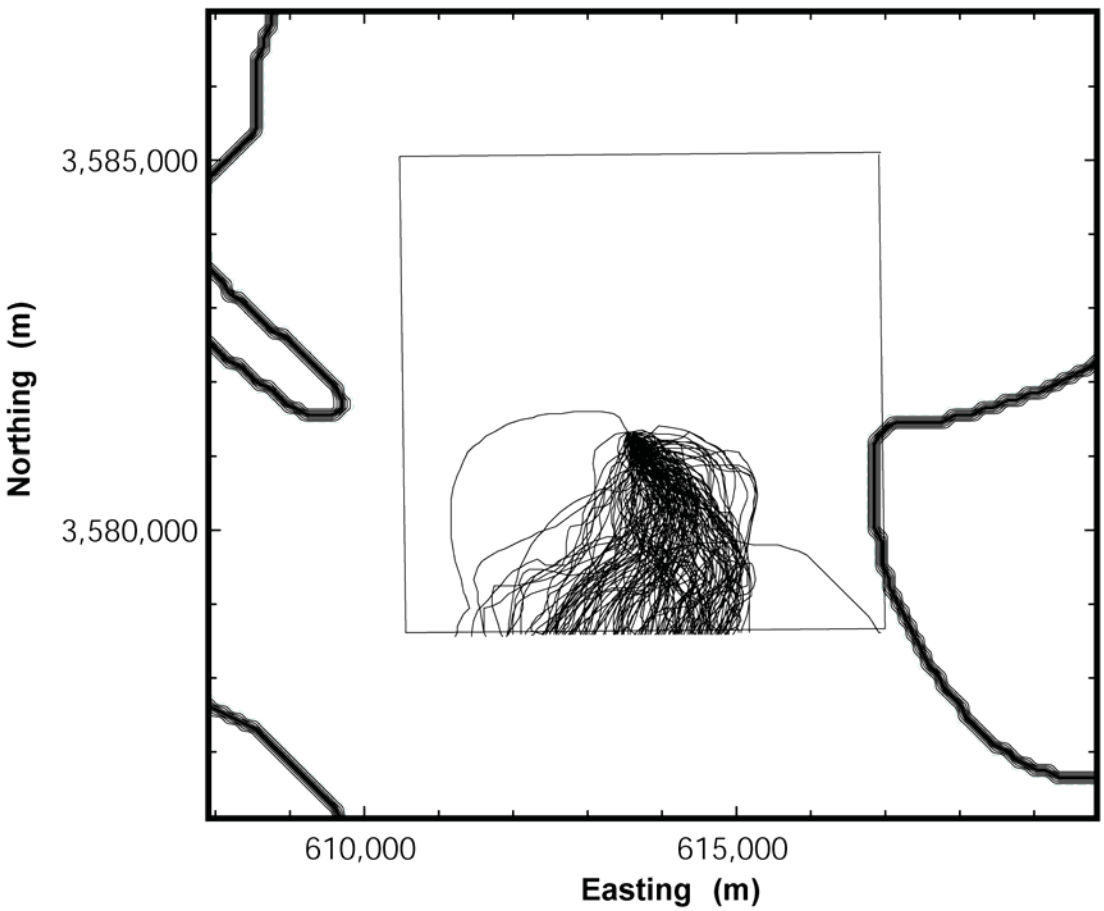

Figure TFIELD-58. All Particle Tracks Within the WIPP LWB. The bold lines show the boundaries of the high-T (left side) and low-T (right side) zones.

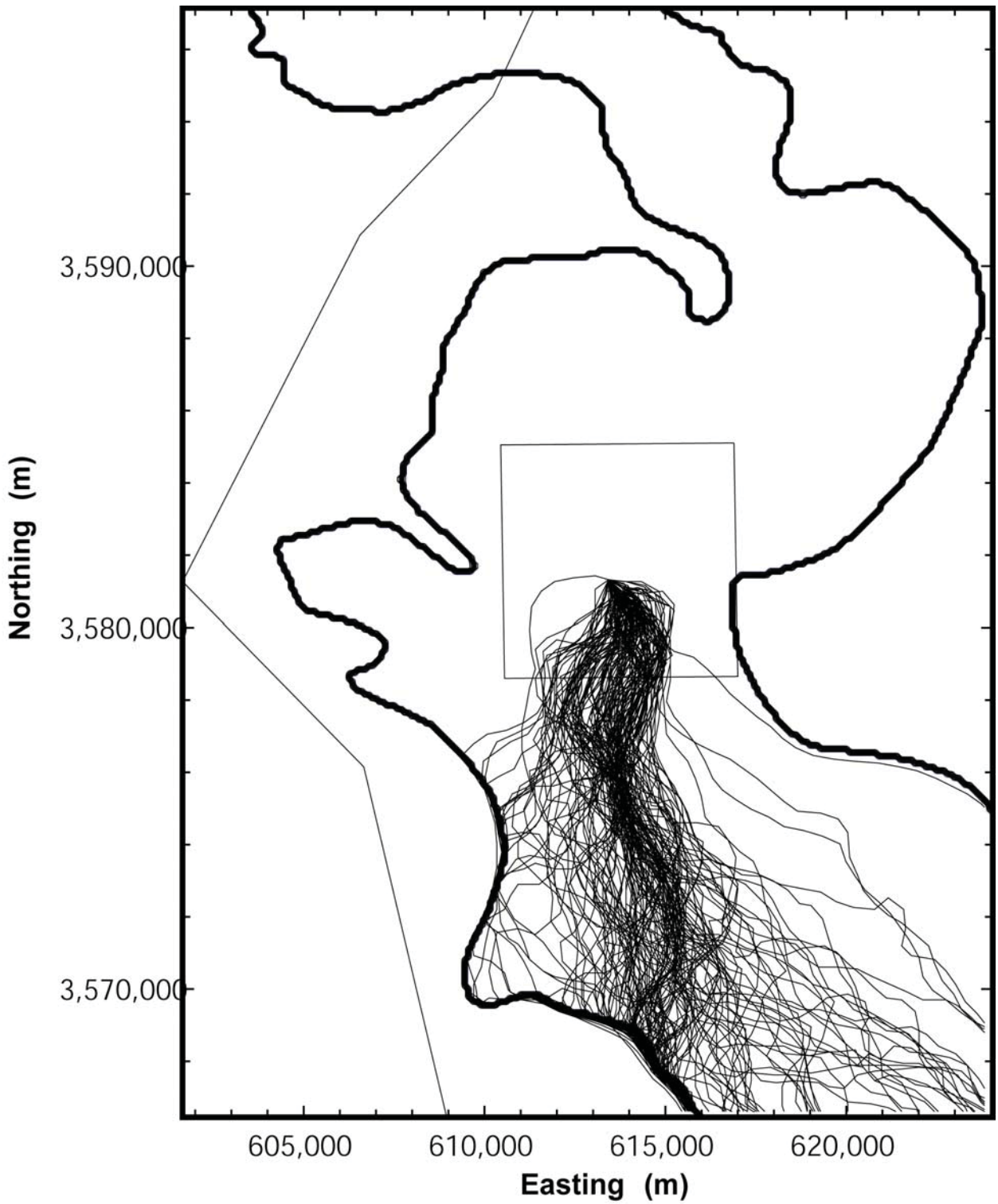

Figure TFIELD-59. All Particle Tracks Within the Model Domain. The bold lines show the boundaries of the high-T (left) and low-T (right) zone boundaries. The no-flow and WIPP site boundaries are also shown.

Figures TFIELD-60 and TFIELD-61. Figure TFIELD-60 shows a scatterplot of the modeled steady-state heads in the 121 calibrated T fields versus the measured heads. Also shown is a unit-slope line representing perfect agreement between the measured and modeled heads, and parallel lines showing a 5-m (16-ft) range on either side. Most modeled head values fall within the ±5 m (16 ft) lines, except for the modeled heads for H-9b, the well with the lowest measured head. As discussed in Section 7.2.1 of this attachment, H-9b is the southernmost well in the model domain and the southern model boundary condition consistently caused the modeled H-9b head to be significantly lower than the measured head.

Figure TFIELD-61 shows a histogram of the differences between the modeled and measured heads. The majority of modeled head values more than 8 m (26 ft) lower than the measured values are associated with H-9b. Excluding the H-9b values, the histogram shows a normal distribution of errors with 48 percent of the modeled heads within 2 m (7 ft) of the measured heads, and 79 percent of the modeled heads within 4 m (13 ft) of the measured heads. The fit between measured and modeled steady-state heads could probably have been improved by allowing PEST to perform more calibration iterations but, as shown in Section 7.3 of this attachment, the travel-time distribution for the T fields would be unlikely to be affected.

TFIELD-8.3 Pilot-Point Sensitivity

Transmissivities at each of the pilot points within the model domain were altered during the calibration process. The maximum allowable change was ± three orders of magnitude in the middle region of the model domain and ± one order of magnitude in the low-T (eastern) and high-T (western) regions of the model domain. Figures TFIELD-62 and TFIELD-63 show the percentage of calibrated T fields in which each pilot point hit the maximum and minimum possible value, respectively. The size of the bubble is proportional to the number of times the value hits one constraint or the other. Figure TFIELD-62 shows that the pilot points south of the western portion of the southern LWB were most likely to reach their maximum allowable values, indicating that the base T fields may have underestimated Ts in this area. Figure TFIELD-63 shows that the pilot point placed in the inferred dissolution reentrant between P-14 and WIPP-25 west of the LWB (see Figure TFIELD-38) was most likely to reach its minimum allowable value, indicating that this reentrant may not be as hydraulically significant as originally assumed.

TFIELD-8.4 Ensemble Average T Field

The 121 T fields that were acceptably calibrated can be combined into an ensemble average T field showing the average properties of the T fields (Figure TFIELD-64). The averaging is performed on a cell-by-cell basis, taking the arithmetic mean of the 121 T values assigned to each cell. Figure TFIELD-65 shows a close-up view of the ensemble average of the 100 T fields used for subsequent calculations in the area surrounding the WIPP site, using a different color scale with T values “binned” by order of magnitude for clarity. This figure does not show a continuous north-south high-T zone exiting the southeastern portion of the WIPP site, as was present in the ensemble average T field provided in CCA Appendix TFIELD (Figure 30). It also shows higher Ts in the southwestern portion of the WIPP site than were present in the CCA ensemble average field. These differences explain why the travel paths in the CRA-2004 T fields (Figure TFIELD-58) take a more westerly course, on average, than those in the CCA T

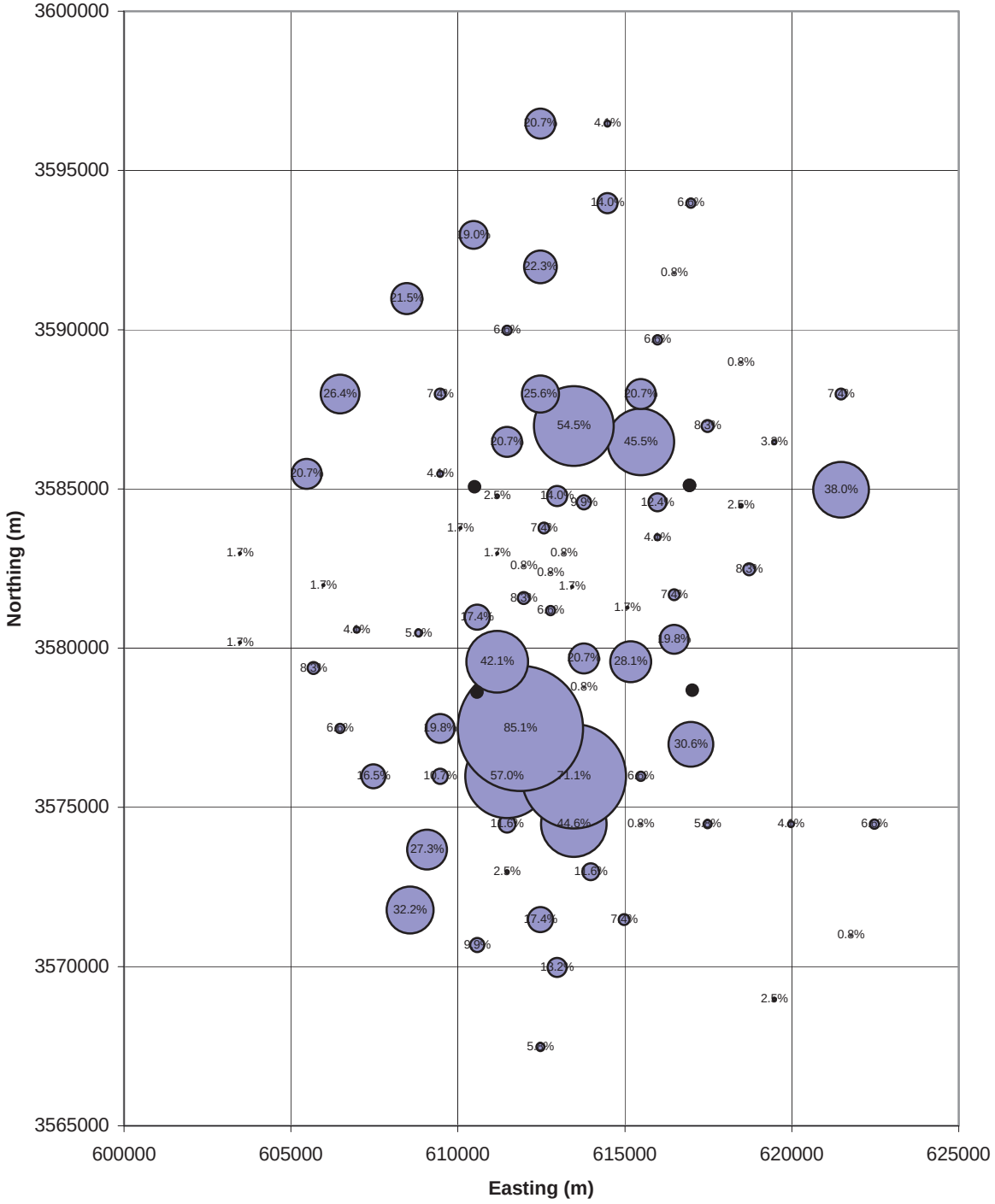

Figure TFIELD-60. Percentage of T Fields in which Pilot Points Hit Maximum Allowable Values. Corners of WIPP LWB are shown by unlabeled black dots.

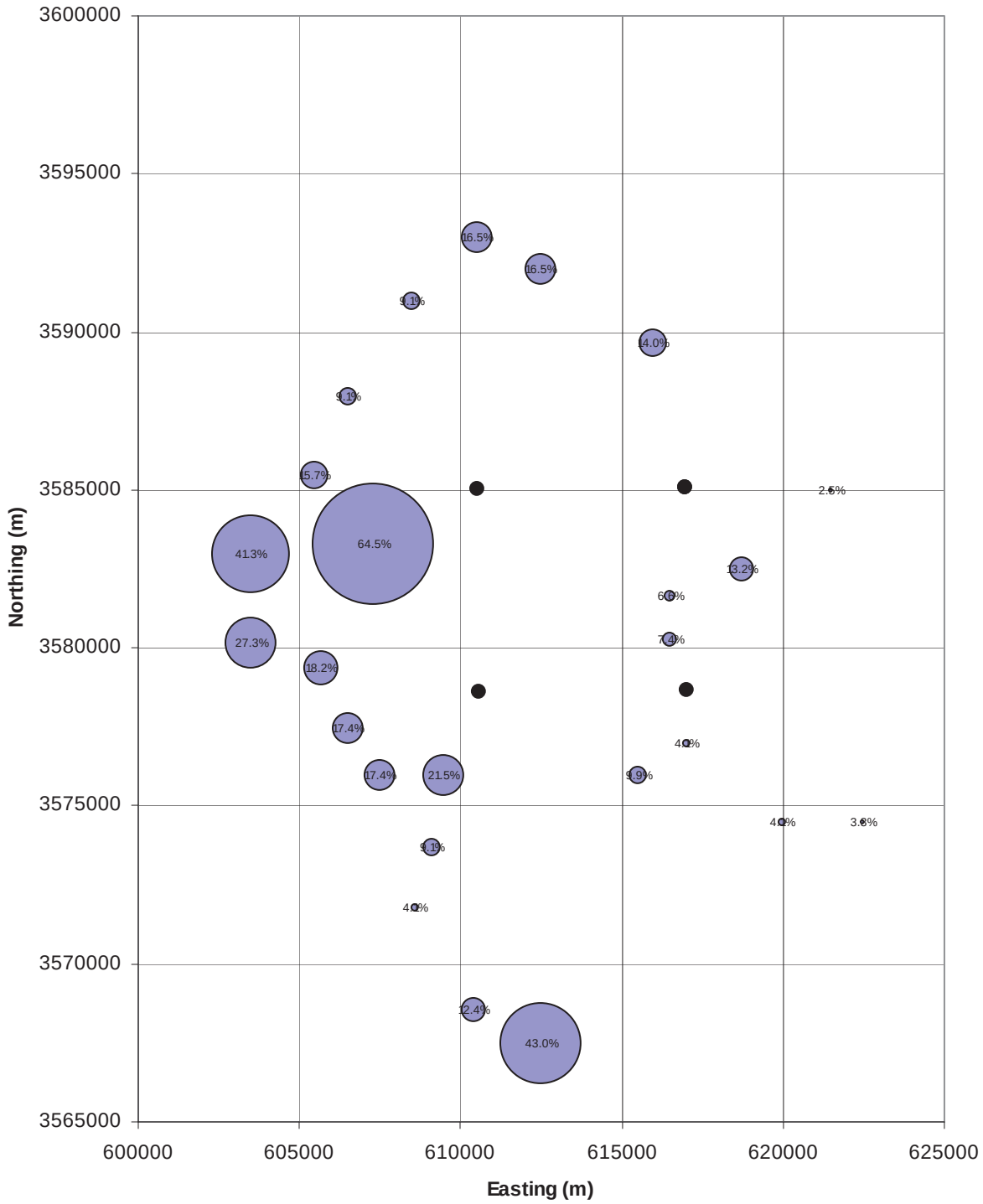

Figure TFIELD-61. Percentage of T Fields in which Pilot Points Hit Minimum Allowable Values. Corners of WIPP LWB are shown by unlabeled black dots.

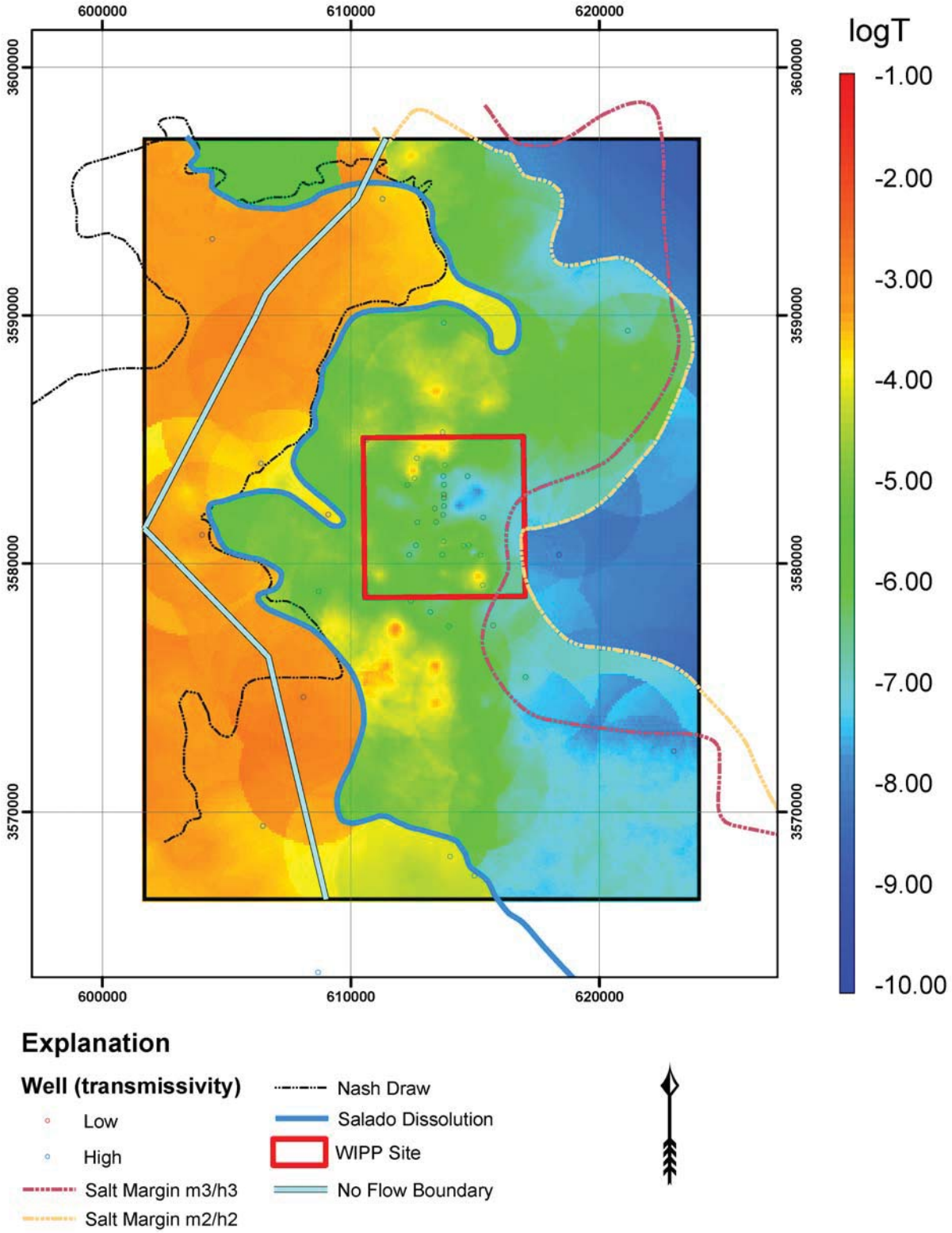

Figure TFIELD-62. Ensemble Average of 121 Calibrated T Fields

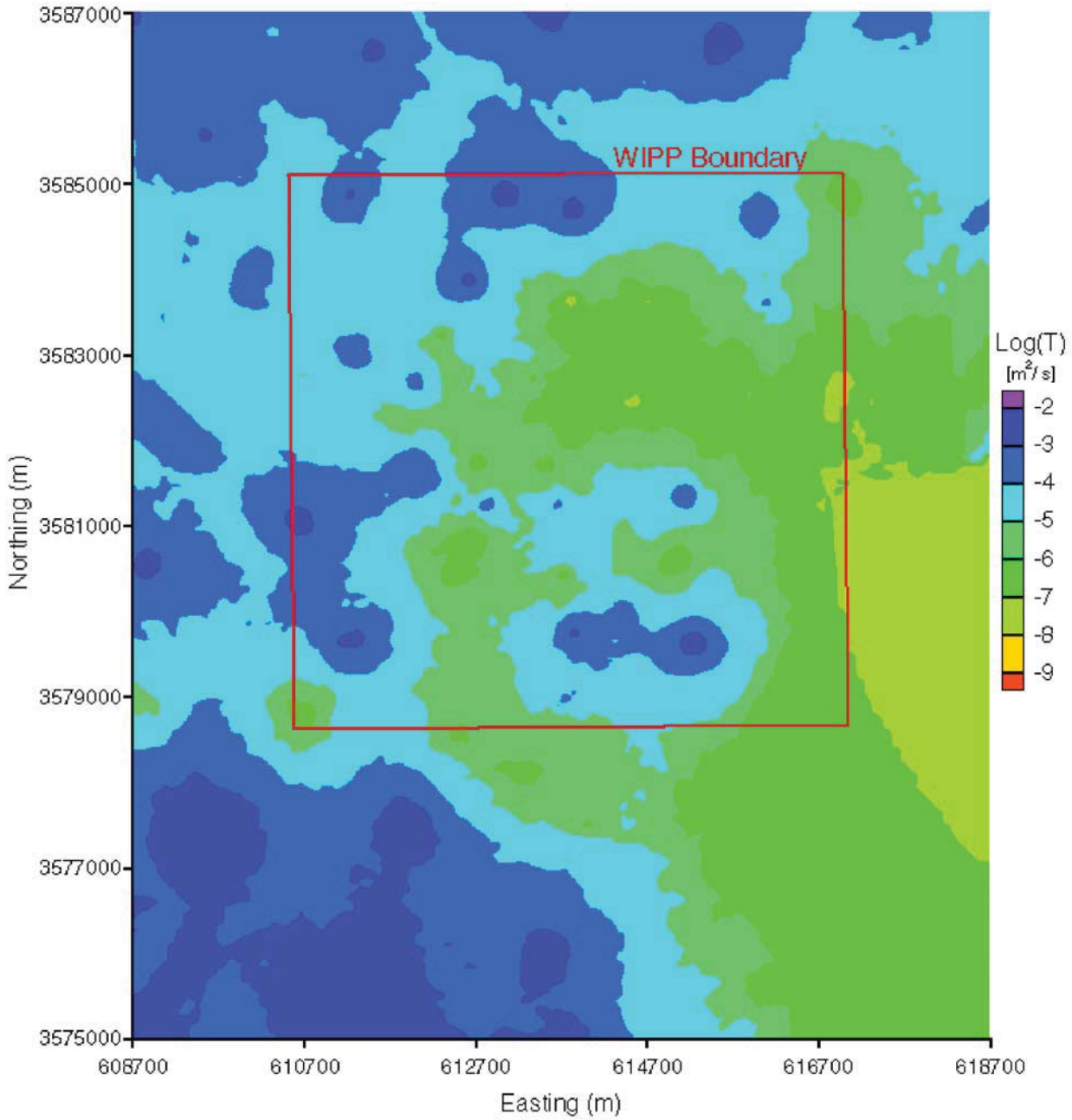

Figure TFIELD-63. Close-Up View of the Ensemble Average T Field Near the WIPP Site. Note the different $\log_{10}$ color scale from Figure TFIELD-62.

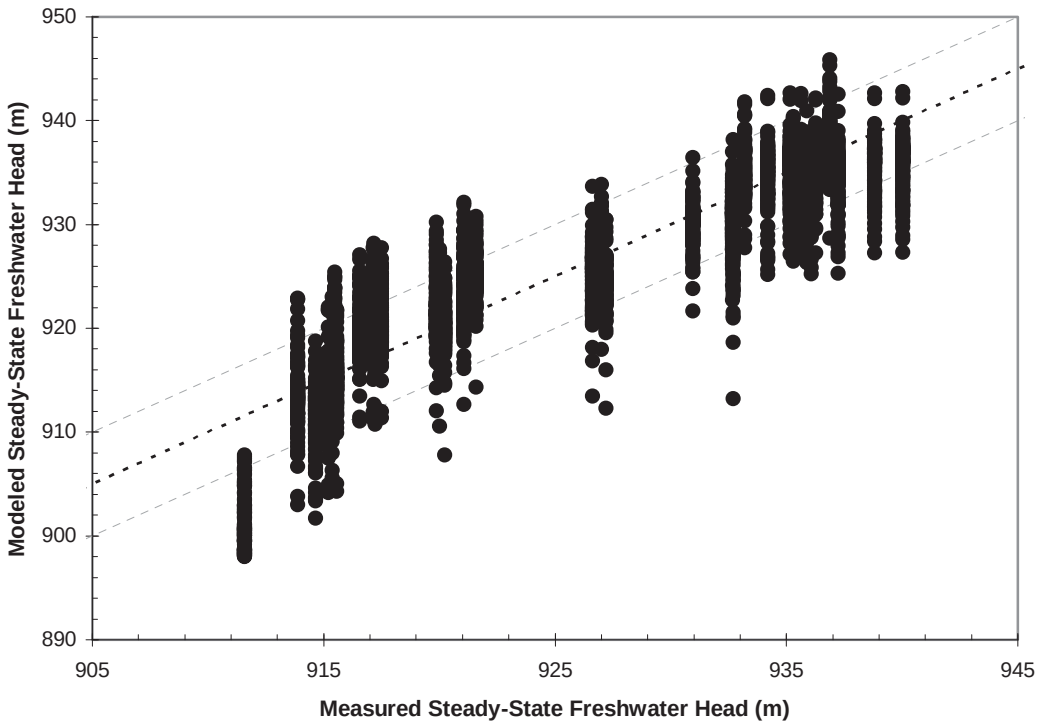

Figure TFIELD-64. Scatterplot of Measured Versus Modeled Steady-State Heads

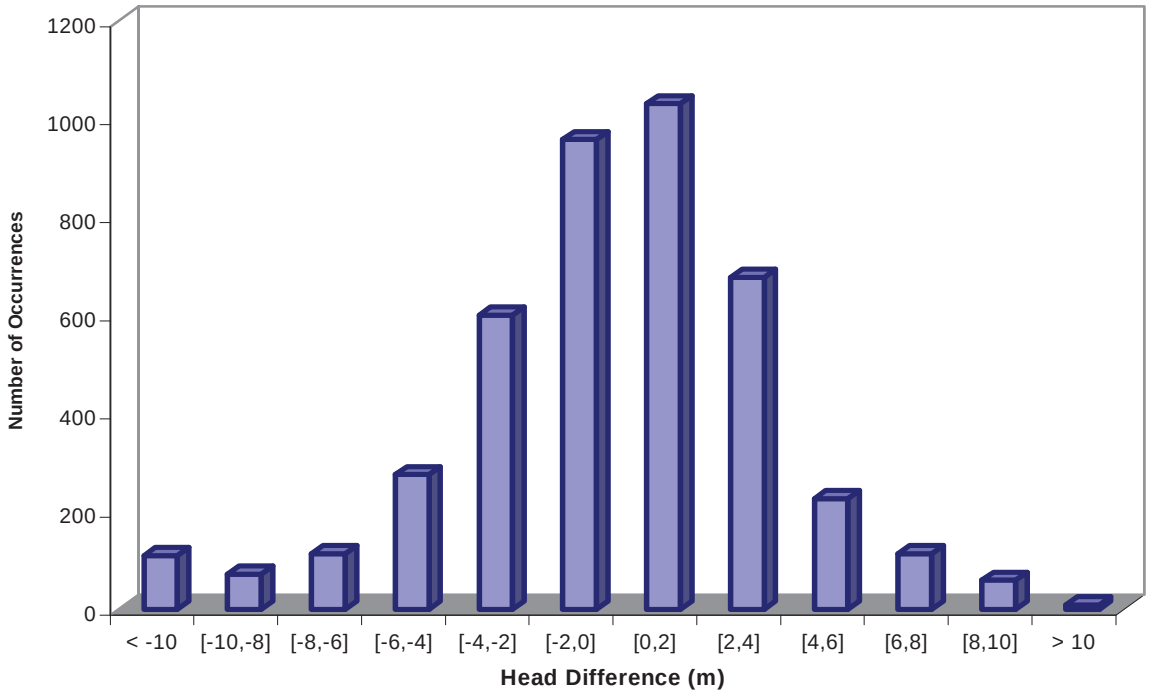

Figure TFIELD-65. Histogram of Differences Between Measured and Modeled Steady-State Heads

fields, and why the CRA-2004 travel times are longer than the CCA travel times (Figure TFIELD-57).

TFIELD-9.0 MODIFICATION OF T FIELDS FOR MINING SCENARIOS

The WIPP site lies within the Carlsbad mining district of southeastern New Mexico. Potash mining in the WIPP area involves resource extraction below the Culebra in the underlying McNutt potash zone of the Salado. In the future, potash mining is expected to occur in all areas where economically extractable ore is present, both outside and inside the WIPP LWB. It is hypothesized that mining of potash leads to subsidence and fracturing of the Culebra, resulting in increased Culebra T. This increase in T may change the regional groundwater flow pattern in the Culebra and affect the transport of any radionuclides entering the Culebra from the WIPP repository.

The EPA (1996, p. 5242) guidance for how the potential effects of future mining should be considered in WIPP PA follows:

> 40 CFR §194.32, Scope of performance assessments.
>
> (a) Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.
>
> (b) Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which suchmining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.
>
> (c) Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can reasonably be expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

The EPA (1996, p. 5229) further states:

> In order to consider the effects of mining in performance assessments, DOE may use the location-specific values of hydraulic conductivity, established for the different spatial locations within the Culebra dolomite, and treat them as sampled parameters with each having a range of values varying between unchanged and increased 1,000-fold relative to the value that would exist in the absence of mining.

Accordingly, for PA purposes, the DOE assumes that all economically extractable potash is mined outside of the WIPP LWB during the 100 years after closure of the WIPP repository during which active institutional control of the site is maintained. Following that 100-year period, the DOE assumes there is a one in 100 probability that the potash within the LWB will be mined during any given century. Therefore, all PA calculations of transport of radionuclides released to the Culebra through inadvertent human intrusion of the repository assume that all potash outside the LWB has already been mined (the “partial-mining” scenario) by the time the

intrusion occurs. The "full-mining" scenario is invoked when the sampled time of human intrusion is coincident with or later than the sampled time of mining within the LWB. Under both scenarios, the hydraulic conductivity (or T) of the Culebra is assumed to be increased by a random factor between one and 1,000 in the areas affected by mining. The process by which the calibrated Culebra T fields were modified to account for the effects of mining, and the characteristics of the resulting modified T fields, are discussed below.

TFIELD-9.1 Determination of Potential Mining Areas

Figure TFIELD-66 shows current potash mines and economically recoverable resources (reserves) in the known potash lease area around the WIPP site, which are the areas where subsidence might occur in the future. The map is based on the BLM (1993) map "Preliminary Map Showing Distribution of Potash Resources, Carlsbad Mining District, Eddy and Lea Counties, New Mexico." Whereas the BLM map shows all reserves, Figure TFIELD-66 shows only reserves that are within existing leases and that are outside the one-quarter to one-half mile (402 to 805 m) exclusion zones around oil and gas wells. Potash reserves outside the current leases will most likely never be mined because active oil and gas exploration is now underway in those areas.

This map is periodically updated as part of the Delaware Basin Drilling Surveillance Program. It also shows the locations of petroleum industry boreholes in the vicinity. The current version of the map differs from the one used for the CCA calculations in that several areas north of the LWB have been ruled out as potential mining areas in the updated version due to recent oil and gas drilling in those areas. Figure TFIELD-67 shows the estimated extent of economically extractable potash within the WIPP LWB.

Because the potash mining horizon is located in the Salado Formation, below the Culebra, the areas in the Culebra that might be disturbed by the mining activities are larger than shown on Figures TFIELD-66 and TFIELD-67 due to angle-of-draw effects associated with subsidence. The rationale for determining the extent of these effects is described in Wallace (1996) with the final conclusion stating that an additional 253-m (830-ft)-wide "collar" was to be added to the mining-impacted areas to approximate a 45-degree angle of draw. For the current T fields, a buffer of three cell widths (300 m [984 ft]) was manually digitized and added to the mining zones. This new delineation was then compared to the CCA model mining zones to make sure there were no significant differences outside of those that can be explained by different gridding of the two model domains and the addition of new data (Figure TFIELD-68). The most notable difference between the two versions is that the area of potential future mining along the northeastern boundary of the LWB is no longer directly connected to the northern boundary of the model domain, which would be expected to decrease flow to the WIPP site.

TFIELD-9.2 Scaling of Transmissivity

For each of the final 100 T fields selected as described in Section 7.4 of this attachment, a random transmissivity multiplier between 1 and 1,000 was assigned using Latin hypercube sampling (LHS) (***Long 2004***). That multiplier was then applied to the modeled T values in the mining-affected areas shown in Figure TFIELD-68 outside of the WIPP LWB to create a partial-mining T field, and to the modeled T values in mining-affected areas both inside and outside the LWB to create a full-mining T field. LHS was performed three times to provide three replicates of 100 full-mining and 100 partial-mining T fields. The purpose of using three replicates is to

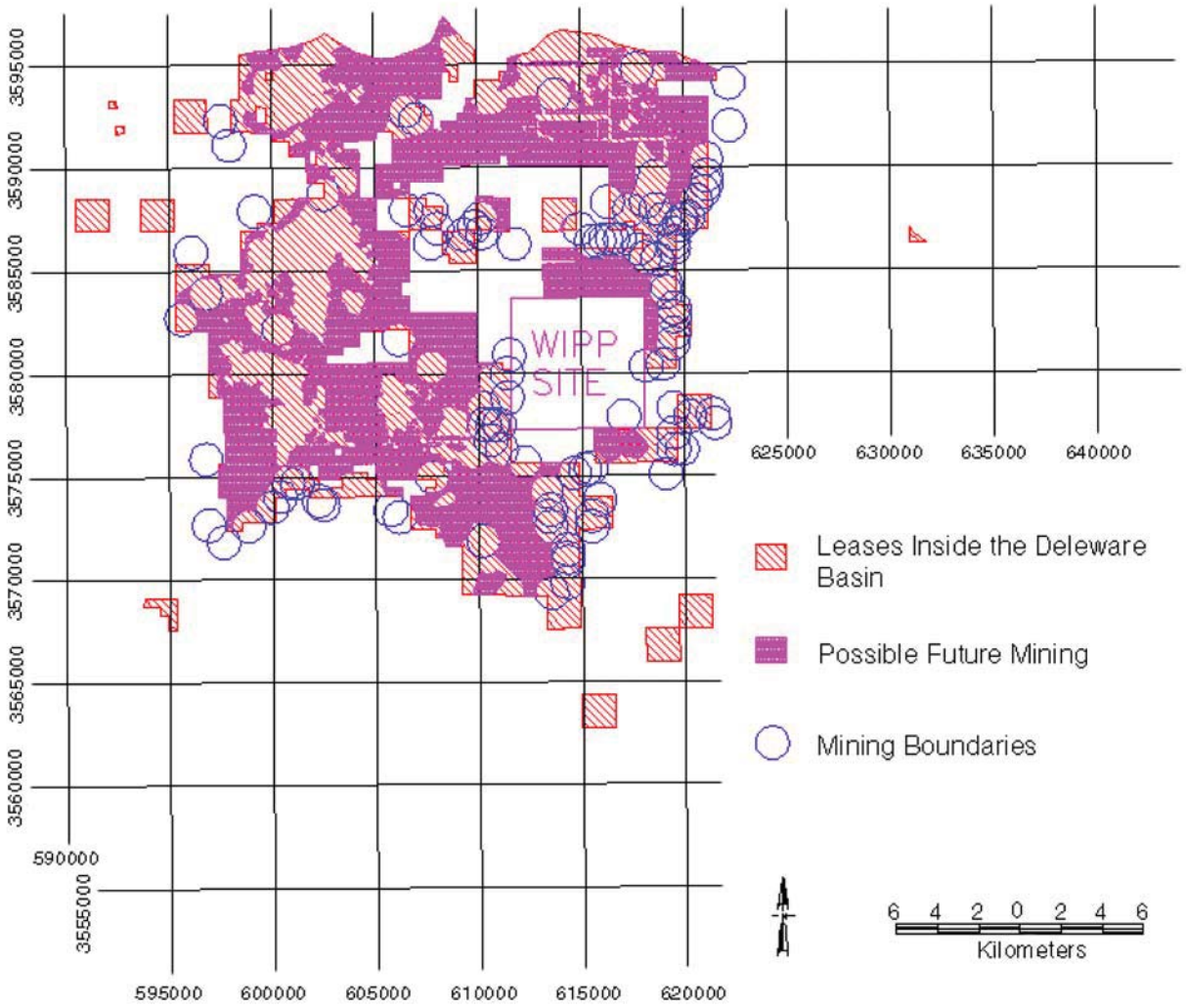

Figure TFIELD-66. Leased Potash Resources Near the WIPP Site

demonstrate that the LHS has adequately captured the uncertainty in the T fields. The transmissivity multipliers applied to each field for the three replicates are shown in Table TFIELD-12.

TFIELD-9.3 Forward Runs

A forward steady-state flow model was run for each of the 100 new T fields under each mining scenario (full and partial) for the three replicates of transmissivity multipliers, resulting in 600 simulations. Particle tracking was performed using DTRKMF on the modified flow fields to determine the flow path and groundwater travel time from a point above the center of the WIPP disposal panels to the LWB. A CDF was produced for each mining scenario (as well as an undisturbed scenario) that describes the probability of a conservative tracer reaching the LWB at a given time.

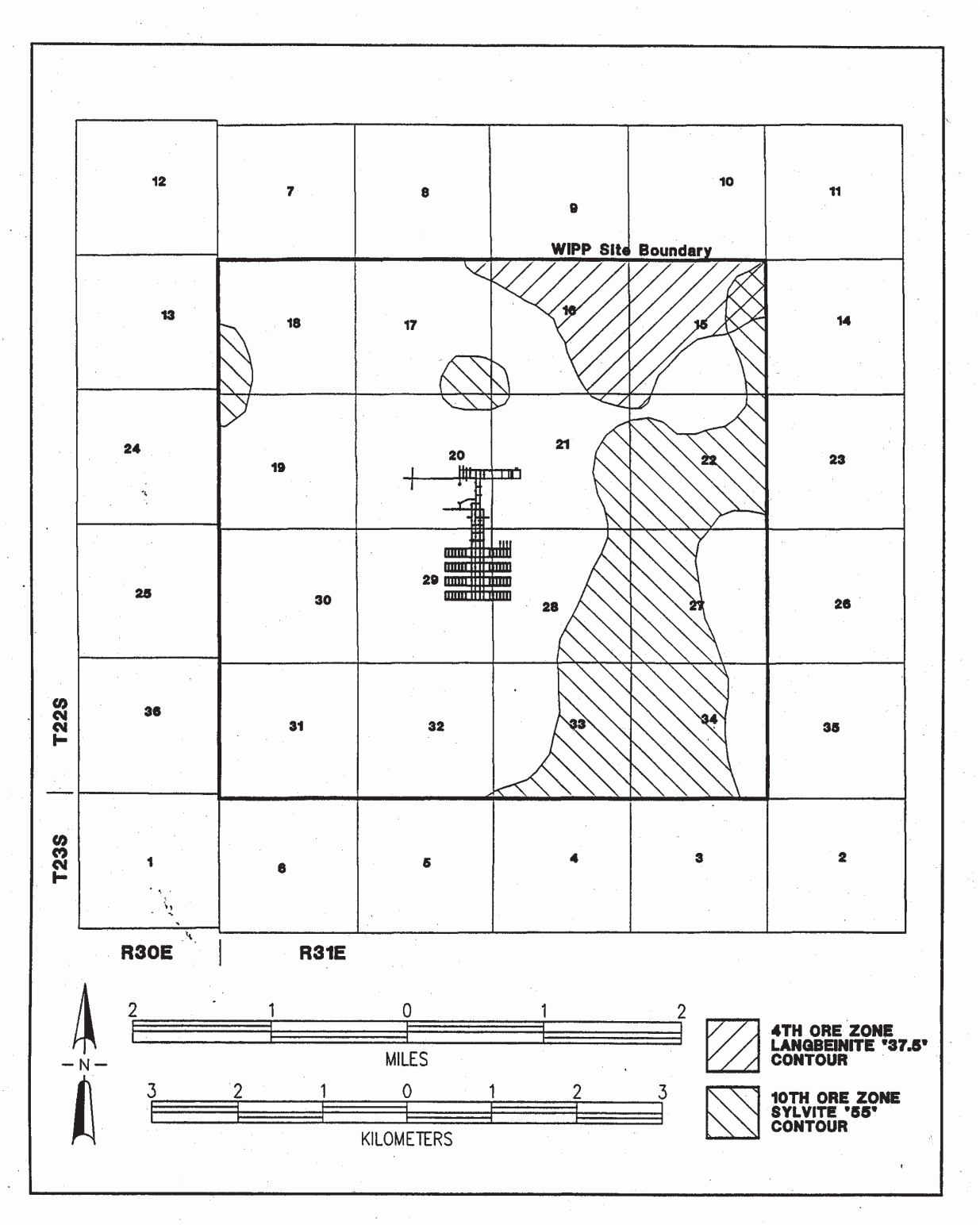

Figure TFIELD-67. Potential Potash Distribution Within the WIPP LWB. The repository excavations are shown in the center.

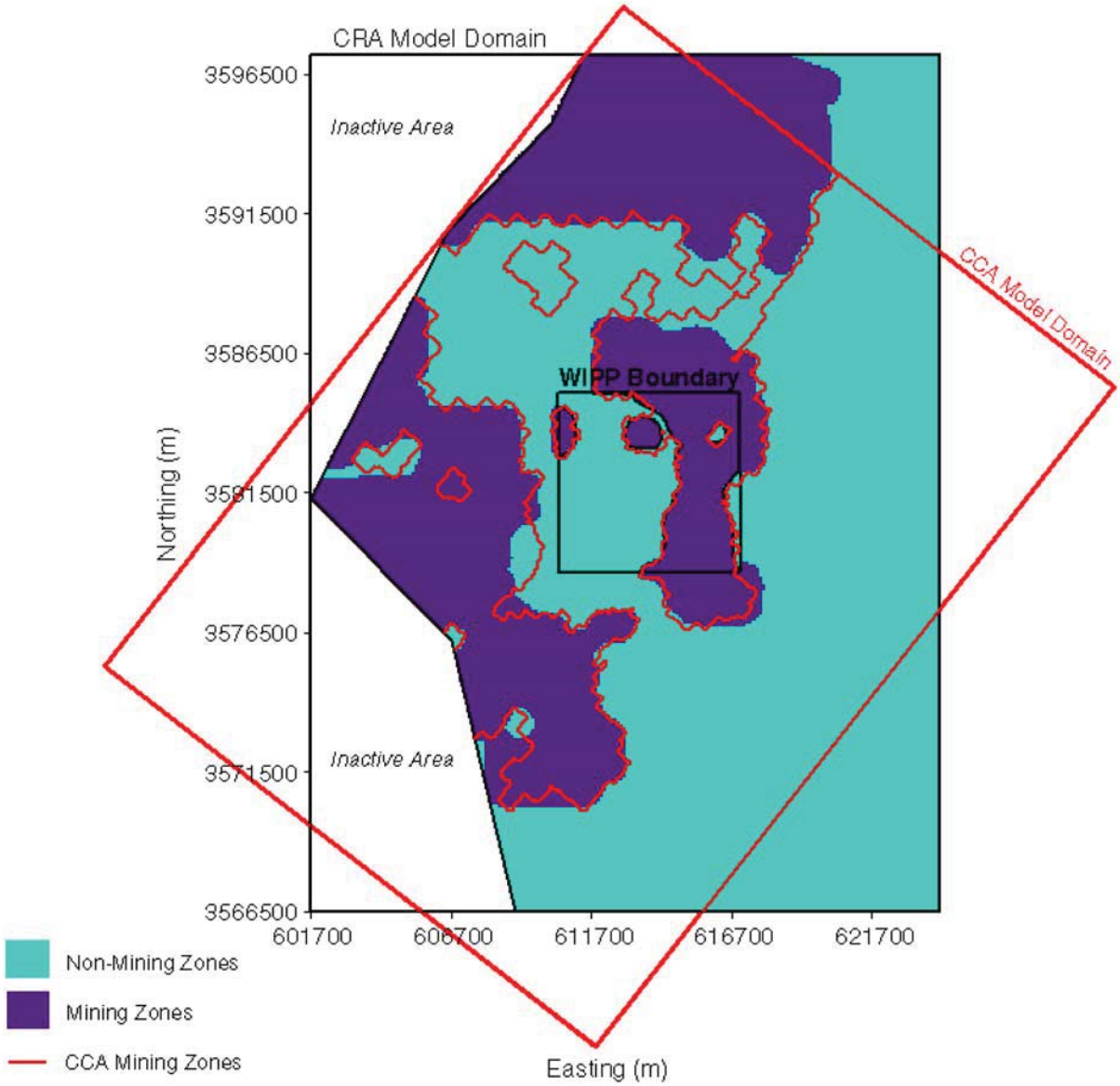

Figure TFIELD-68. Comparison of CRA-2004 and CCA Areas Affected by Mining

As was done for the CCA, it was assumed that mining impacts would not significantly change the boundary conditions used in T-field calibration. Potash mining has already occurred along the northern boundary of the model domain, and the western model boundary is in Nash Draw where subsidence and fracturing of the Culebra are already incorporated in the model.

TFIELD-9.4 Results

TFIELD-9.4.1 Travel Times

Figure TFIELD-69 shows CDFs of travel time for the unmodified T fields and for the Replicate 1 full- and partial-mining T fields. The partial-mining travel times are consistently longer than the no-mining travel times. The distribution of travel times for the full-mining case

Table TFIELD-12. T-Field Transmissivity Multipliers for Mining Scenarios

T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier	T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier
d01r02	905.50	32.85	13.54	d09r08	66.07	339.80	327.30
d01r04	508.40	345.10	202.20	d09r09	375.70	806.30	374.20
d01r07	340.30	996.50	936.30	d09r10	521.10	906.90	24.83
d01r10	615.20	828.20	391.80	d10r02	181.60	274.60	651.90
d02r02	575.30	579.30	306.80	d10r03	298.50	796.60	816.70
d03r01	104.00	760.50	955.80	d10r04	705.30	364.70	518.20
d03r03	94.06	514.90	77.79	d10r06	84.20	819.40	690.80
d03r06	913.30	187.60	238.40	d10r07	627.30	728.60	551.20
d03r07	630.50	567.10	725.20	d10r08	403.20	414.80	670.30
d03r08	208.90	475.90	85.67	d10r09	464.20	649.90	885.40
d03r09	769.30	750.00	647.80	d10r10	821.40	607.80	925.70
d04r01	130.20	630.30	478.70	d11r01	307.60	895.10	492.90
d04r02	351.90	453.30	996.70	d11r02	236.50	918.30	364.50
d04r03	46.87	310.90	123.90	d11r06	249.90	159.70	5.43
d04r04	194.60	487.90	217.30	d11r07	543.50	86.78	966.70
d04r05	806.90	923.80	138.30	d11r08	18.75	16.92	973.80
d04r06	264.40	584.00	835.30	d11r09	215.40	618.30	576.30
d04r07	931.50	733.90	802.00	d11r10	73.60	168.90	403.20
d04r08	897.90	51.08	96.80	d12r01	317.40	683.30	756.20
d04r10	32.56	256.50	34.02	d12r02	958.60	204.90	598.10
d05r03	394.10	108.30	159.00	d12r03	686.00	322.00	333.80
d05r07	998.20	535.90	145.50	d12r05	860.70	637.50	589.70
d06r02	790.00	679.40	826.70	d12r06	363.80	359.00	56.05
d06r03	384.10	171.20	261.20	d12r07	660.40	434.90	463.10
d06r04	258.50	860.00	293.90	d12r08	940.20	708.20	312.10
d06r05	432.50	754.10	257.60	d12r09	132.50	464.10	794.60
d06r06	10.02	653.20	172.50	d13r01	983.00	971.30	901.70
d06r07	514.10	221.50	915.60	d13r02	672.80	144.50	224.80
d06r10	282.90	70.11	861.40	d13r03	643.20	849.00	415.20
d07r01	927.30	694.20	625.20	d13r05	425.80	118.60	688.00
d07r02	691.30	864.90	737.80	d13r06	961.10	785.90	385.40
d07r05	738.40	775.30	241.60	d13r07	346.10	282.90	711.40
d07r06	450.20	591.70	548.70	d13r08	838.60	78.26	64.98
d07r07	609.60	447.20	841.00	d13r09	491.00	8.68	458.00
d07r08	557.70	942.30	349.00	d21r01	755.40	307.30	632.40
d07r09	538.60	98.94	285.00	d21r02	172.60	396.20	614.80
d07r10	713.60	379.60	187.30	d21r03	591.50	422.30	45.61

Table TFIELD-12. T-Field Transmissivity Multipliers for Mining Scenarios (Continued)

T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier	T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier
d08r01	849.30	408.40	194.00	d21r04	322.70	715.50	276.80
d08r02	569.70	989.10	893.90	d21r05	855.70	870.90	105.80
d08r03	419.50	43.16	356.30	d21r06	272.00	501.20	984.40
d08r04	160.00	834.00	857.00	d21r07	652.50	296.70	940.20
d08r05	971.90	881.10	671.60	d21r10	790.50	212.70	562.50
d08r06	118.80	558.90	743.20	d22r02	163.20	527.50	870.60
d08r07	741.30	130.20	706.70	d22r03	812.70	264.30	534.50
d09r02	729.70	497.00	429.30	d22r04	144.70	140.70	526.30
d09r03	483.00	197.30	168.20	d22r06	26.04	962.70	111.70
d09r04	580.60	661.30	766.40	d22r07	870.30	548.10	609.10
d09r05	228.50	240.90	481.90	d22r08	773.60	235.30	771.70
d09r06	474.10	383.50	449.10	d22r09	53.04	937.70	784.10
d09r07	887.20	952.10	503.30	d22r10	460.40	24.35	434.60

is much wider than for the other two cases; some of the full-mining travel times are shorter than the no-mining times, but most are considerably longer. The median travel times across all three replicates for the full- and partial-mining scenarios are approximately 3.6 and 2.6 times greater, respectively, than for the non-mining scenario. Figures TFIELD-70 and TFIELD-71 compare the CDFs of travel time for all three replicates of the partial- and full-mining cases, respectively, to the Replicate 1 results from the CCA T fields (Wallace 1996). These plots show, first, that all three CRA-2004 replicates provided very similar results and, second, that the new travel times are consistently longer than the CCA travel times. The primary reason for this difference is probably the absence in the CRA-2004 T fields of the direct, high-T connection between the WIPP site and the northern model boundary that was present in the CCA T fields and that provided a source of water to the Culebra within the LWB. As discussed in Section 9.1 of this attachment, this difference occurs because recent oil and gas exploratory drilling has precluded potash mining a few kilometers northeast of the LWB (see Figure TFIELD-66).

Given the increase in transmissivity due to mining, the increase in travel time may seem counter-intuitive. However, upon examination of the head contours and flow patterns of the mining cases, the high-T areas corresponding to the mining zones create preferential pathways through the system. Figure TFIELD-72 shows the normalized velocity in each cell for the T field/replicate averaged case for the full-mining scenario. The normalized velocity is the velocity magnitude in each cell divided by the maximum velocity magnitude across the domain. Since the velocity magnitudes are highly skewed, the color bands for Figure TFIELD-72 are nonuniformly scaled at the high end (i.e., a wider range of velocity magnitudes is used to designate the orange and red bands). This allows for a better qualitative comparison of the spatial distribution of high and low velocities. “T field/replicate averaged” means the T value for

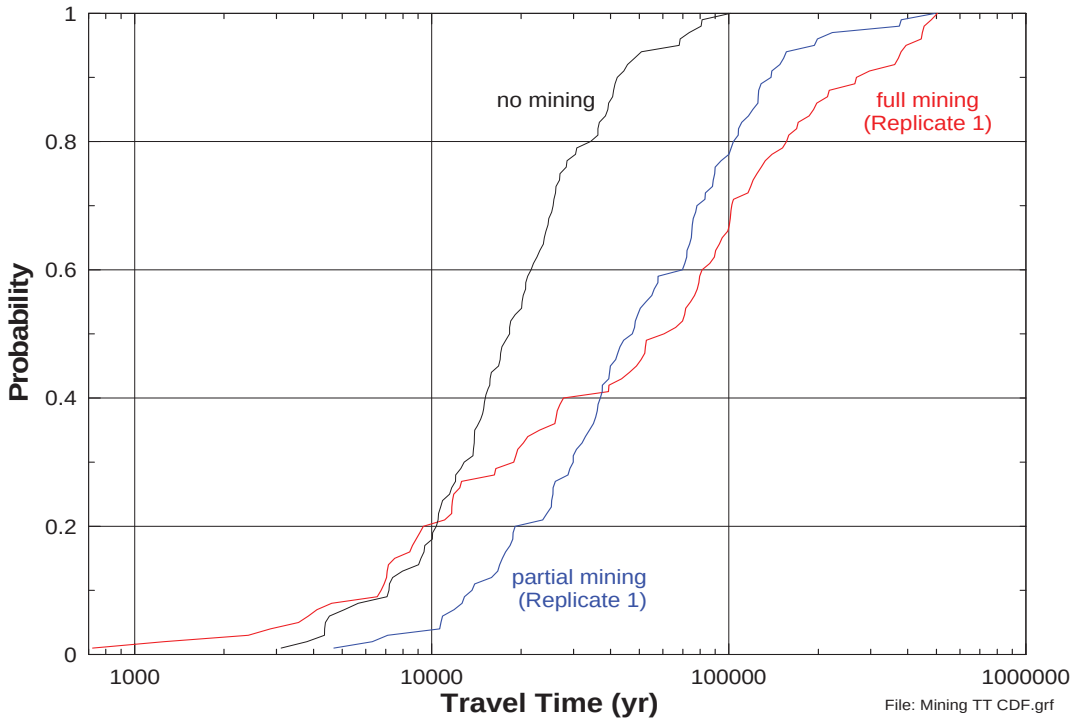

Figure TFIELD-69. CDFs of Travel Times for the Full-, Partial-, and No-Mining Scenarios

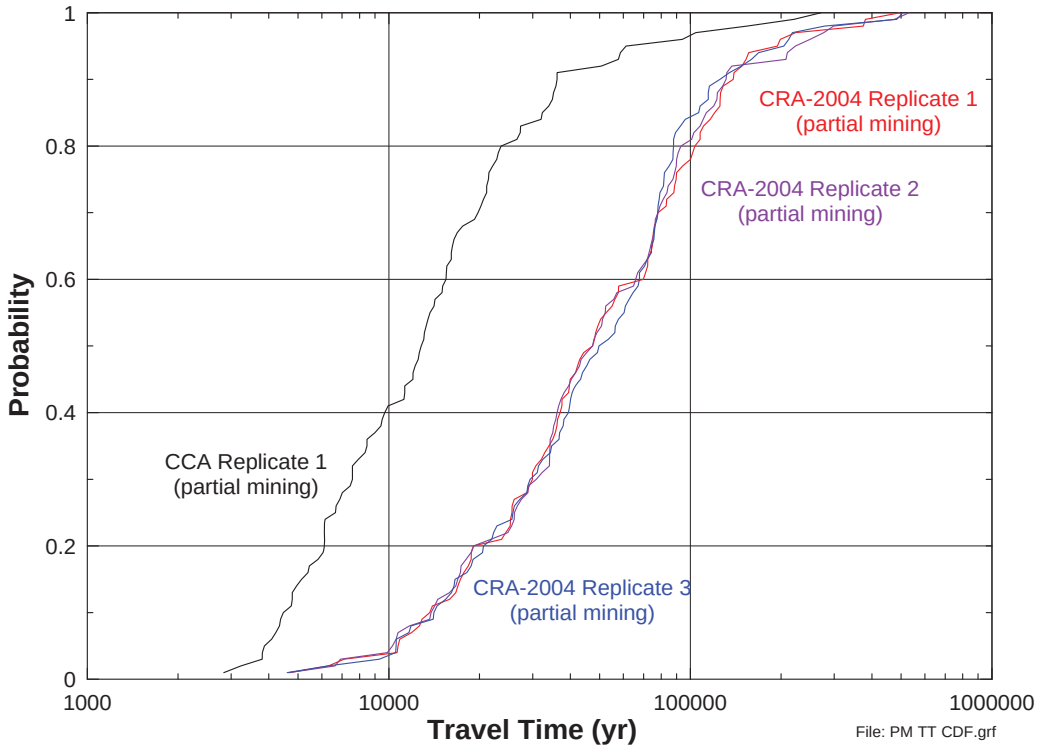

Figure TFIELD-70. CDFs of Partial-Mining Travel Times for Three CRA-2004 Replicates and One CCA Replicate

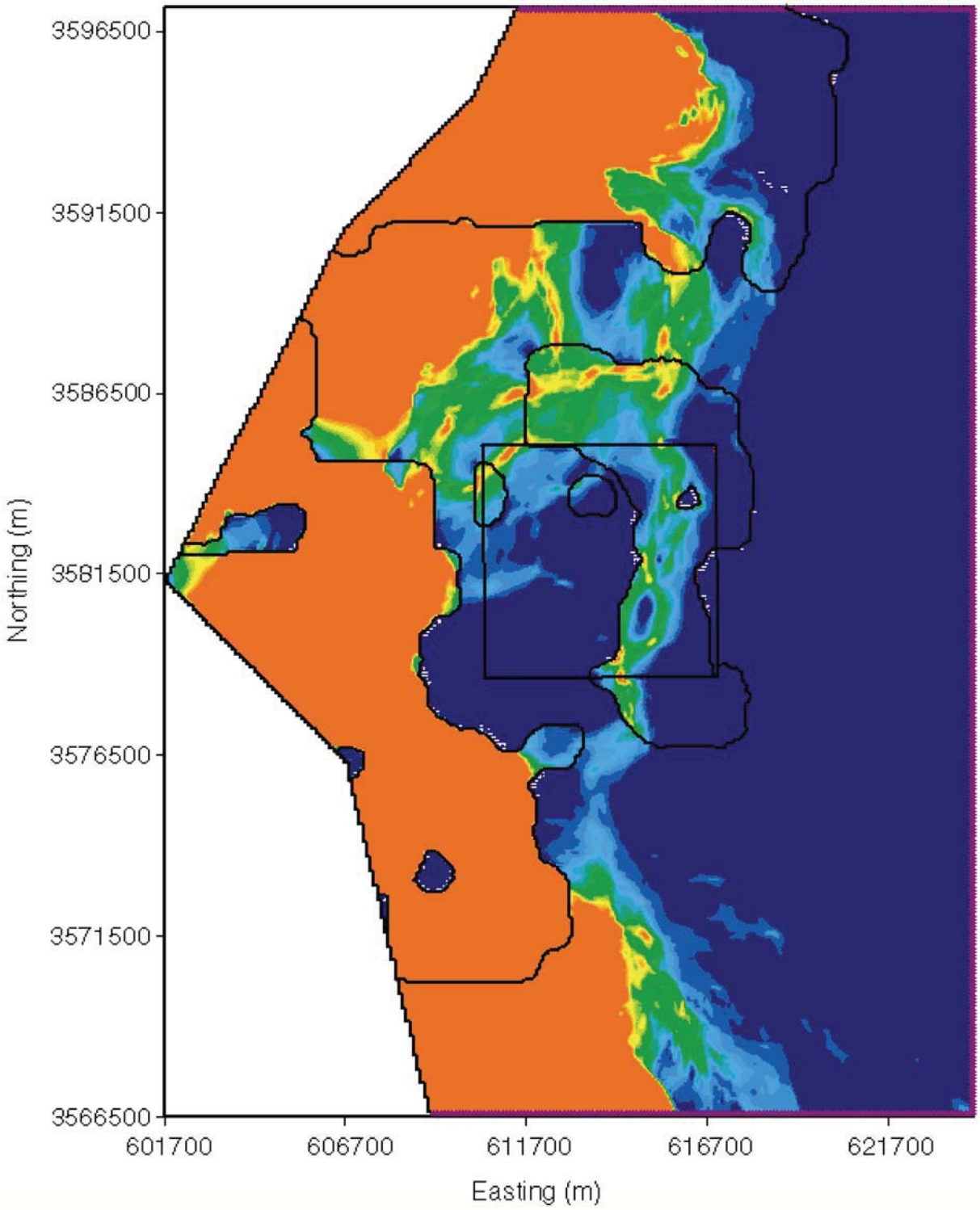

Figure TFIELD-71. Normalized Pore Velocities for the Full-Mining Case. Red indicates zones of high velocity. The black outline shows the full-mining zones and the red box is the WIPP LWB. The T field used to produce the velocity profile is averaged across all T field/replicate combinations for the full-mining scenario (300 T fields in total).

each cell is the average of the Ts across all T field/replicate combinations for the full-mining scenario (300 T fields in total). Not surprisingly, it is clear that the areas of high velocities correspond with the mining zones. The higher velocities and corresponding higher flow rates through the mining zone areas translate to slower velocities in the nonmining zone areas. In most cases, the particles for the mining scenarios stay in the lower velocity zones along the entire pathway to the LWB, which accounts for the higher average travel times. A comparison of the average, maximum, and minimum values for the full-, partial-, and no-mining scenario travel times is presented in Table TFIELD-13.

TFIELD-9.4.2 Travel Directions

The effects of mining also have an impact on the direction of transport, significantly changing where the particles cross the LWB. This is especially true of the full-mining scenario where mining within the LWB creates high head along the eastern boundary of the WIPP resulting in a general flow direction to the westsouthwest. This is in contrast to the partial-mining scenario where the tracking direction is mainly towards the south, similar to the nonmining scenario. The particle-track directions for the partial- and full-mining scenarios are illustrated in Figures TFIELD-73 to TFIELD-78.

There is a strong similarity within each replicate for each scenario. Individual tracks can be recognized from one replicate to the next, with some slight variations. This indicates that track directions are determined more by the spatial variation of the calibrated T field than by the random mining factors. As long as there is some (see below) increase in the mining zone Ts over that of the nonmining areas, the tracks for each T field will be similar from one replicate to the next.

The partial-mining particle tracks in Figures TFIELD-73 through TFIELD-75 follow paths very similar to the partial-mining particle tracks through the CCA T fields (Ramsey et al. 1996, Figure 7.12). The full-mining particle tracks in Figures TFIELD-76 through TFIELD-78 show a more westward component and are generally longer than the full-mining particle tracks through the CCA T fields (Ramsey et al. 1996, Figure 7.13).

The insensitivity of the track directions to the random mining factor also carries over to insensitivity of the travel time. Correlation analysis shows correlations between travel time and the random mining factor for the full and partial-mining scenarios as 0.091 and 0.151, respectively. Thus, like the track directions, travel times are not sensitive to the random mining factor but rather to the spatial structure of the calibrated T field.

This insensitivity to the random mining factor can be explained by recalling that the factor is applied only to zones deemed as probable mining areas. This means that velocity and flow increases are limited to the mining zones, with little change in the nonmining areas (assuming gradients are somewhat constant). Conditions within the nonmining zones are affected most for cases where the mining zone Ts are close to the non-mining zone Ts. However, the mining factor ranges uniformly from 1 to 1,000, meaning 99 percent of the T field/replicate combinations will have multipliers greater than one order of magnitude (for the 300 combinations, only two have multipliers that are less than 10). This translates into small changes within the non-mining zones for relatively large changes in the mining zones. To illustrate this,

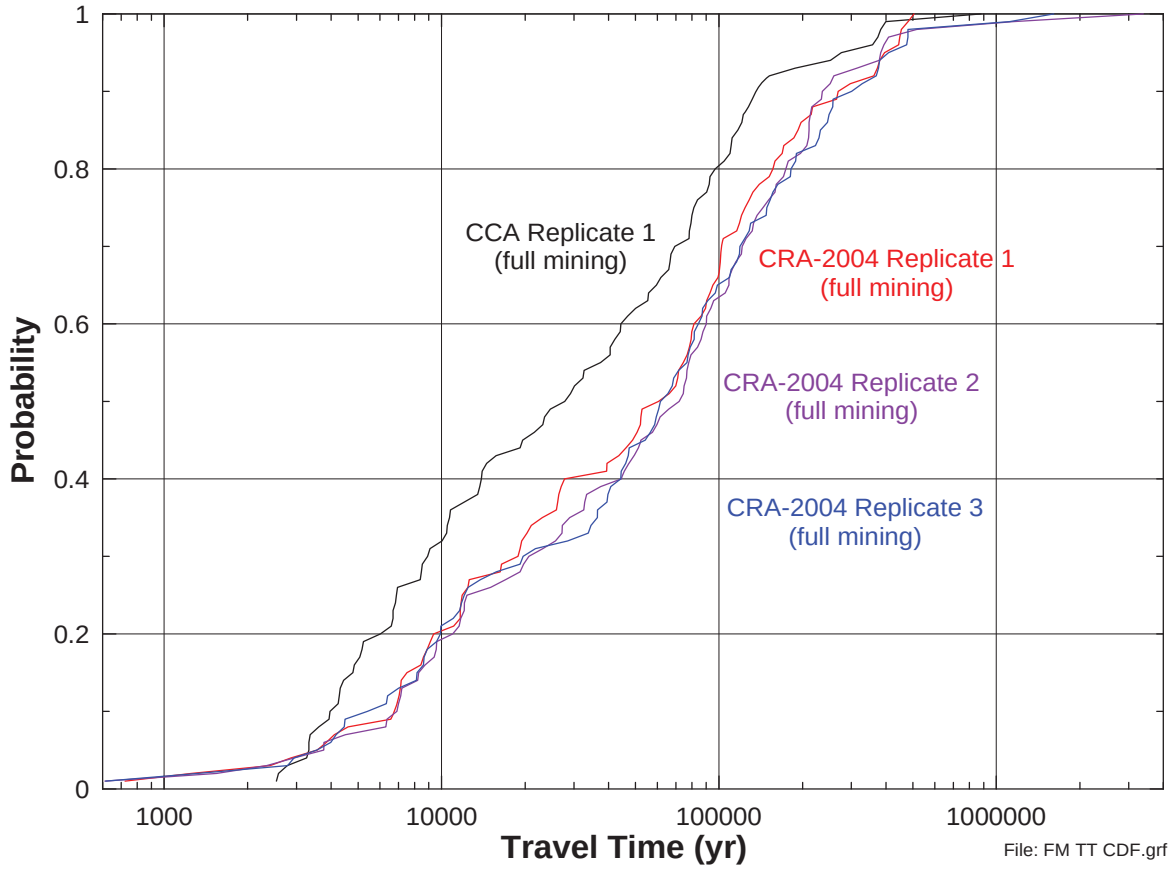

Figure TFIELD-72. CDFs of Full-Mining Travel Times for Three CRA-2004 Replicates and One CCA Replicate

Table TFIELD-13. Travel Time Statistics for the Full- and Partial-Mining Scenarios as Compared to the No-Mining Scenario

Replicate	Statistic	Full-Mining Travel Time (yr)	Partial-Mining Travel Time (yr)	No-Mining Travel Time (yr)
R1	Median	63,370	47,745	
	Maximum	504,174	494,981	
	Minimum	723	4,684	
R2	Median	73,169	47,651	
	Maximum	3,387,185	531,136	
	Minimum	611	4,654	
R3	Median	63,430	51,622	
	Maximum	1,610,979	506,438	
	Minimum	615	4,603	
Global	Median	66,048	48,290	18,289
	Maximum	3,387,185	531,136	101,205
	Minimum	611	4,603	3,111

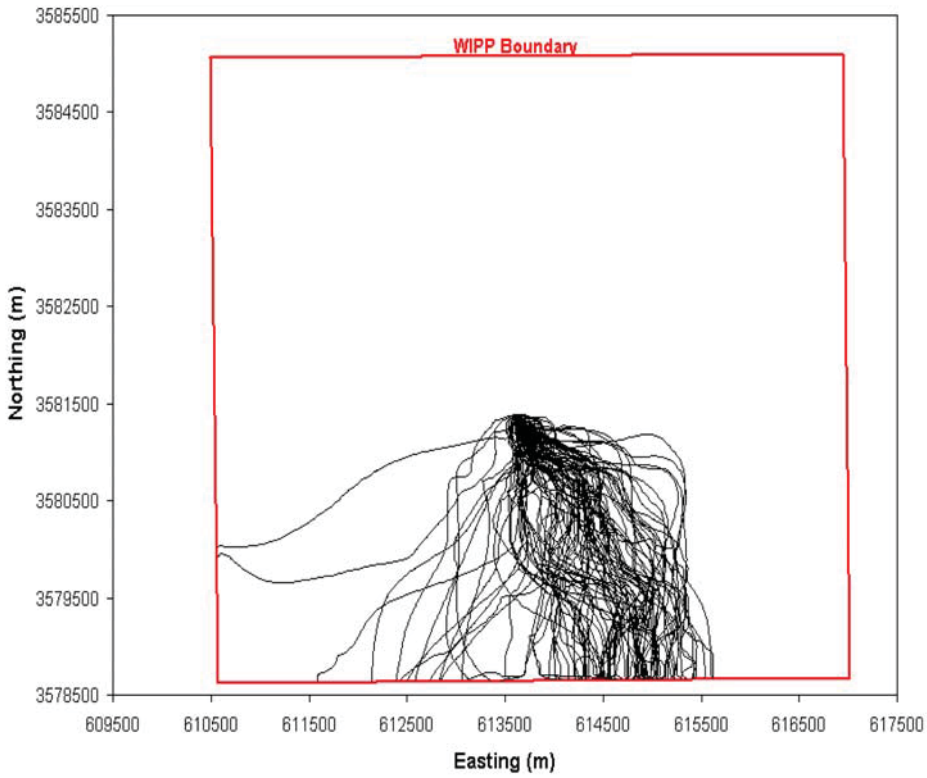

Figure TFIELD-73. Particle Tracks for Replicate 1 for the Partial-Mining Scenario

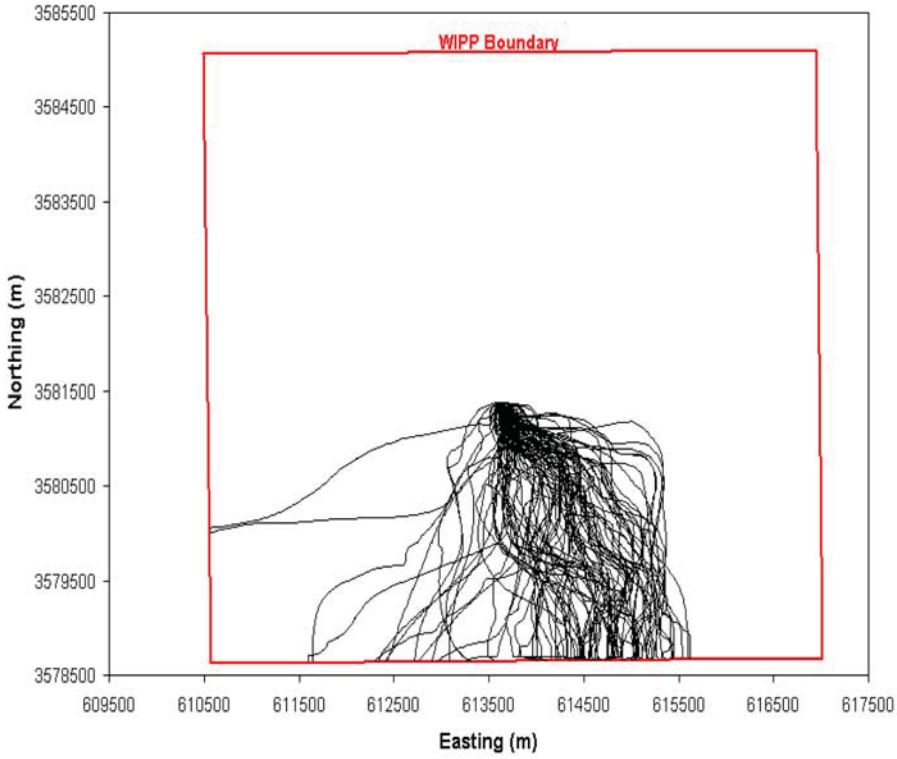

Figure TFIELD-74. Particle Tracks for Replicate 2 for the Partial-Mining Scenario

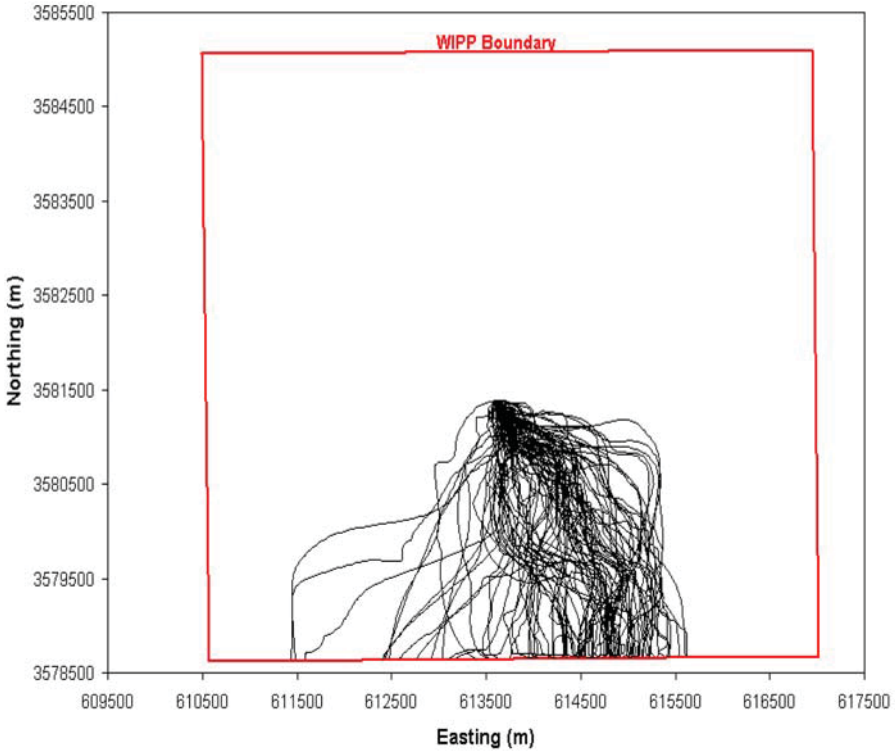

Figure TFIELD-75. Particle Tracks for Replicate 3 for the Partial-Mining Scenario

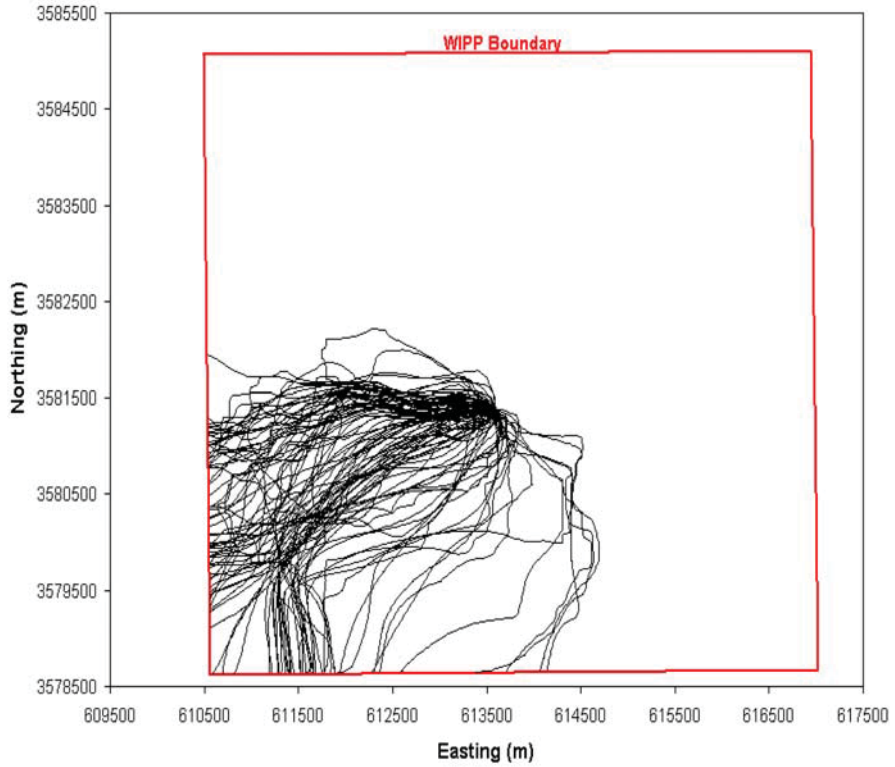

Figure TFIELD-76. Particle Tracks for Replicate 1 for the Full-Mining Scenario

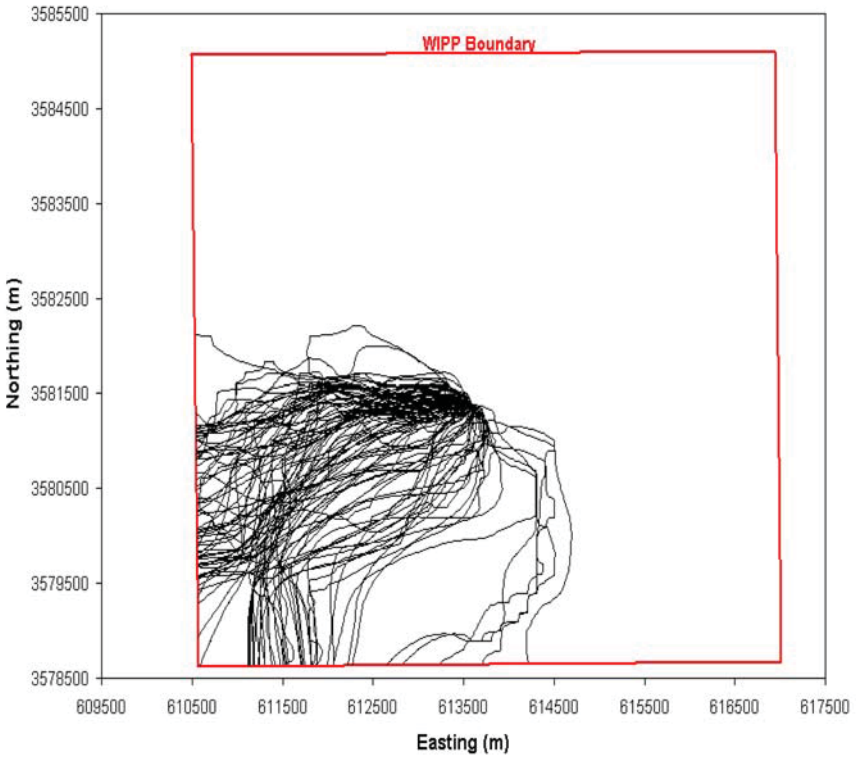

Figure TFIELD-77. Particle Tracks for Replicate 2 for the Full-Mining Scenario

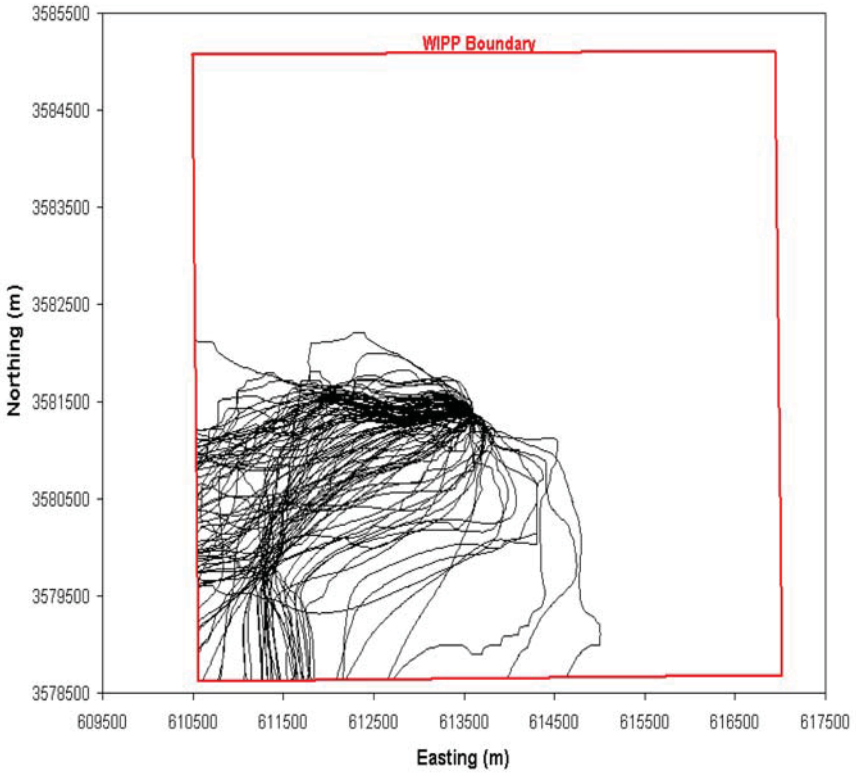

Figure TFIELD-78. Particle Tracks for Replicate 3 for the Full-Mining Scenario

Figure TFIELD-79 shows the $\log_{10}$ travel times versus the random mining factor for the full- and partial-mining scenarios across all replicates. The high scatter in both the plots is due to the independence of travel time with regards to the mining factor. This conclusion supports the mining scenario conceptual model and the use of a random mining factor to model changes in T due to mining activities. It also indicates that the controlling parameters are the spatial distribution of the non-mining scenario T field and the delineation of the mining and nonmining zones.

TFIELD-9.4.3 Extreme Values

Examination of the extreme travel time values and the causes behind those values is useful in quantifying the range of outcomes given the amount of uncertainty incorporated into the models. For the partial-mining scenario, T field d04r01 from Replicate 2 had the longest travel time of 531,136 years. In contrast, T field d08r01 from Replicate 3 had the shortest travel time of 4, 603 years. The median travel time is best represented by T field d01r04 from Replicate 1 with a travel time of 48, 472 years. Figures TFIELD-80 to TFIELD-82 show the head contours for each of these cases along with the corresponding particle tracks. The particle-tracking directions are all fairly similar.

The full-mining cases (Figures TFIELD-83 to TFIELD-85) have similar characteristics to those of the partial-mining cases except that the band of high gradient to the northwest is less pronounced and persistent. For the full-mining scenario, T field d04r01 from Replicate 2 had the longest travel time of 3, 387,185 years. T field d01r07 from Replicate 2 had the shortest travel time of 611 years. The median travel time is best represented by T field d10r09 in Replicate 1 (66, 215 years).

Overall, for both the partial- and full-mining scenarios, those T fields that contain higher and more heterogeneous Ts in the nonmining areas produce the fastest travel times. However, the partial-mining scenario shows a smaller range of values due to the lack of the large mining zone in the WIPP area. This smaller range is clearly visible in Figure TFIELD-79. What distinguishes the plots is the head distribution across the regions. For the slow case (Figure TFIELD-80), the head contours to the west of the repository are spread far apart, indicating a low gradient and thus lower groundwater velocities. The fastest case (Figure TFIELD-81) shows a high-gradient band that originates along the no-flow boundary to the northwest and runs down the western side of the WIPP site. This high gradient corresponds to higher groundwater velocities. The median case (Figure TFIELD-82) also shows this high-gradient band, but it is not as extreme as in the fast case. In all cases, the mining-zone areas look very similar, with widely spaced head contours and higher velocities relative to the nonmining zones.

TFIELD-10.0 SUMMARY

Observed Culebra T has been related to three deterministic factors: the thickness of overburden above the Culebra, the presence or absence of dissolution of the upper Salado, and the presence or absence of halite in units above and below the Culebra. Culebra T is also related to the occurrence of open, interconnected fractures, which cannot be mapped as easily as the other three factors and must be treated stochastically. A linear-regression model for Culebra T has been developed based on these factors that provides an excellent match to the observed data, and

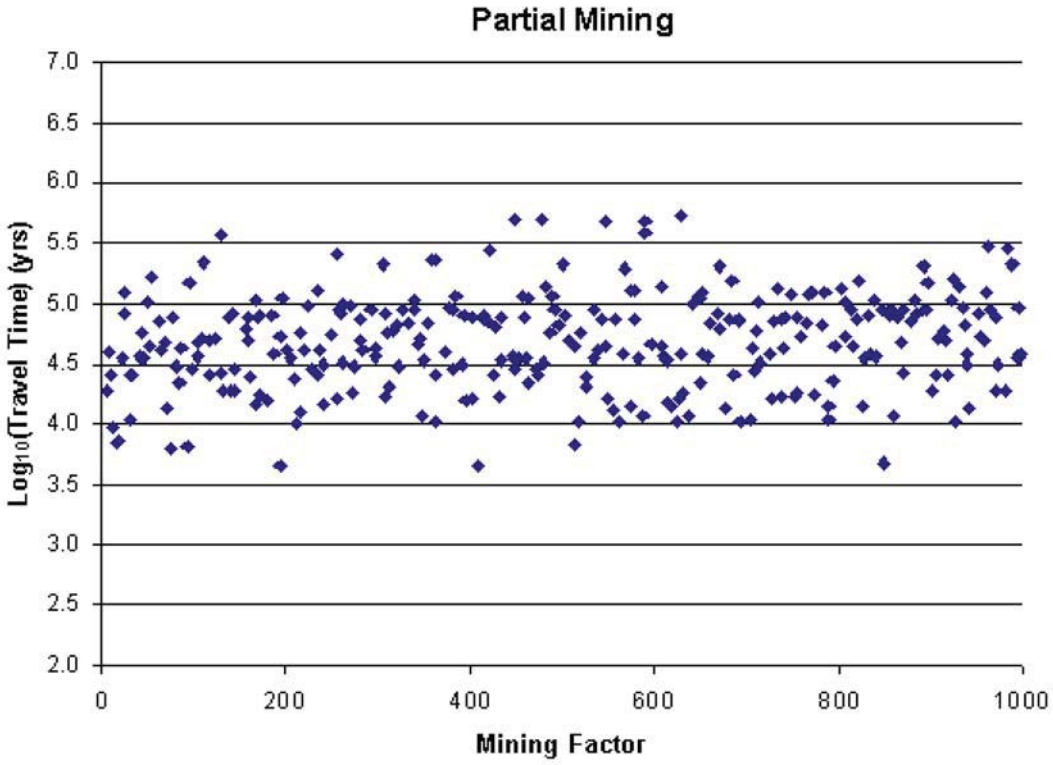

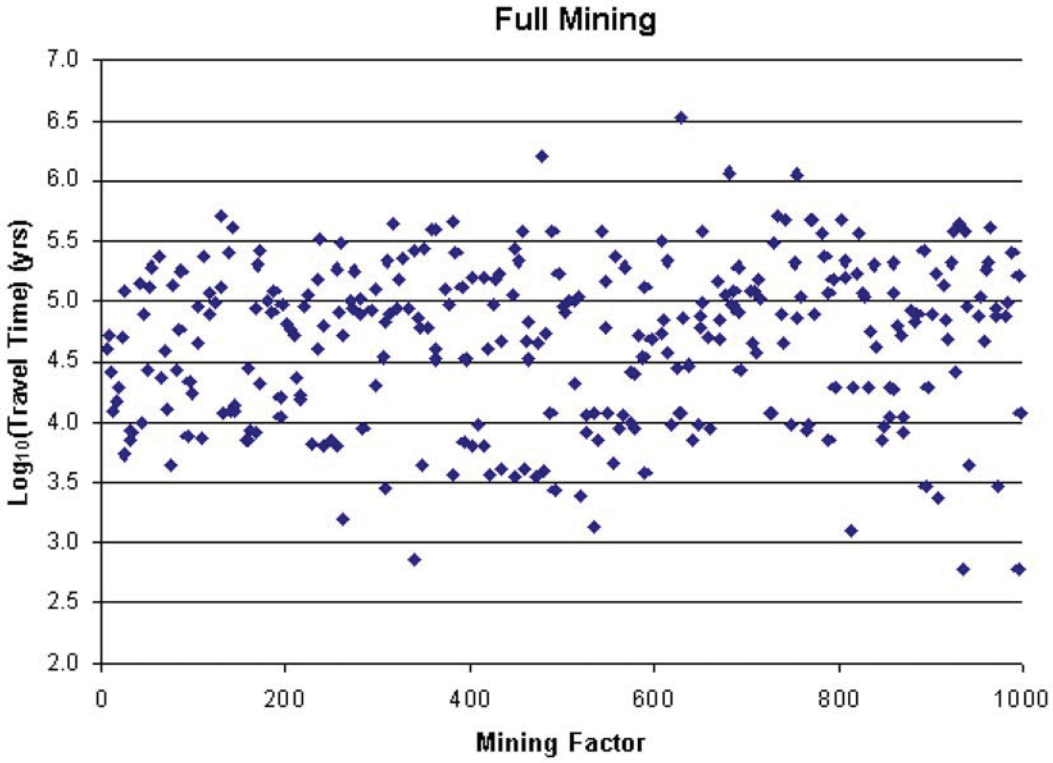

Figure TFIELD-79. Correlation Between the Random Mining Factor and Log_{10} of Travel Time

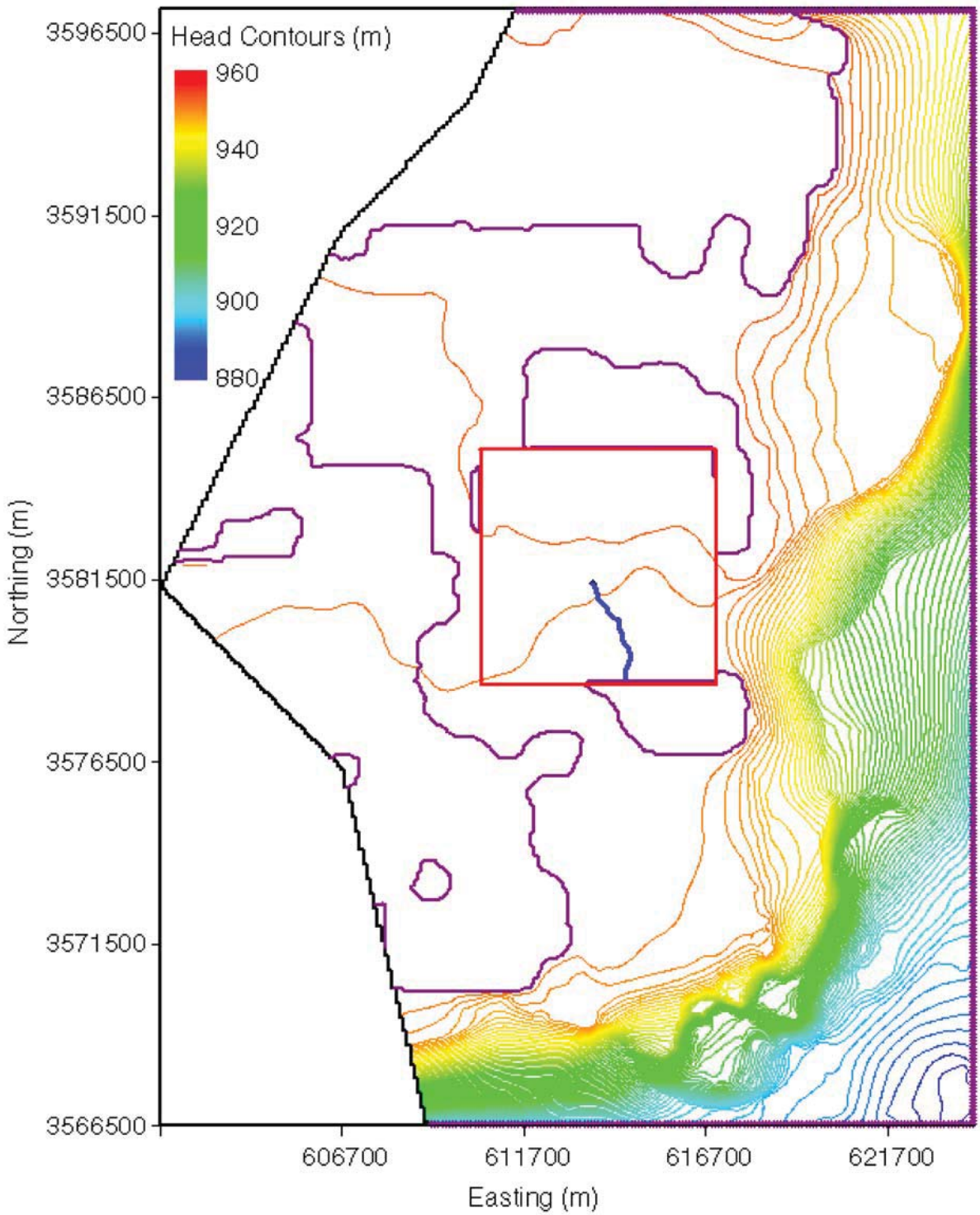

Figure TFIELD-80. Head Contours and Particle Track for the Maximum-Travel-Time T Field (d04r01-R2) for the Partial-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

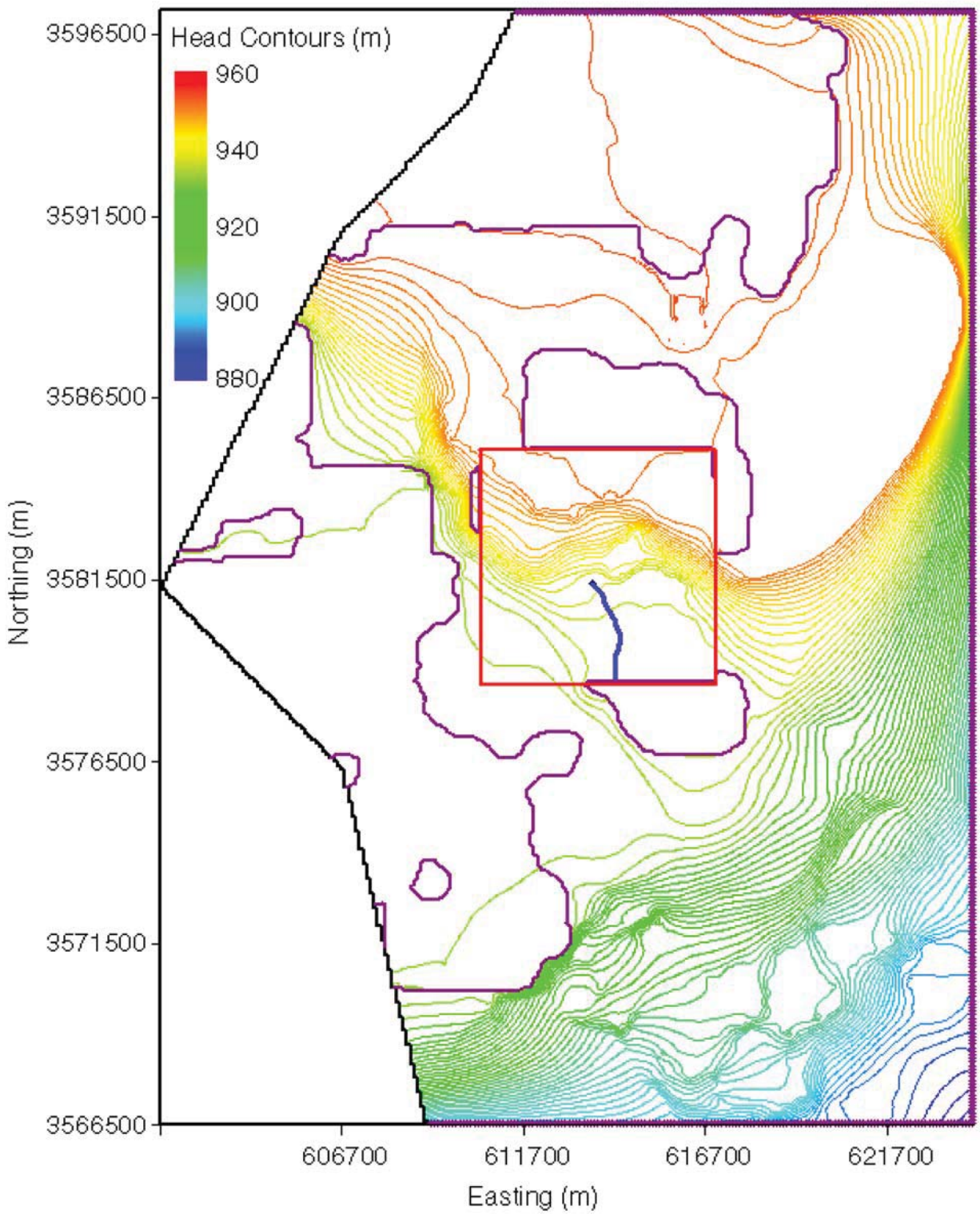

Figure TFIELD-81. Head Contours and Particle Track for the Minimum-Travel-Time T Field (d08r01-R3) for the Partial-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

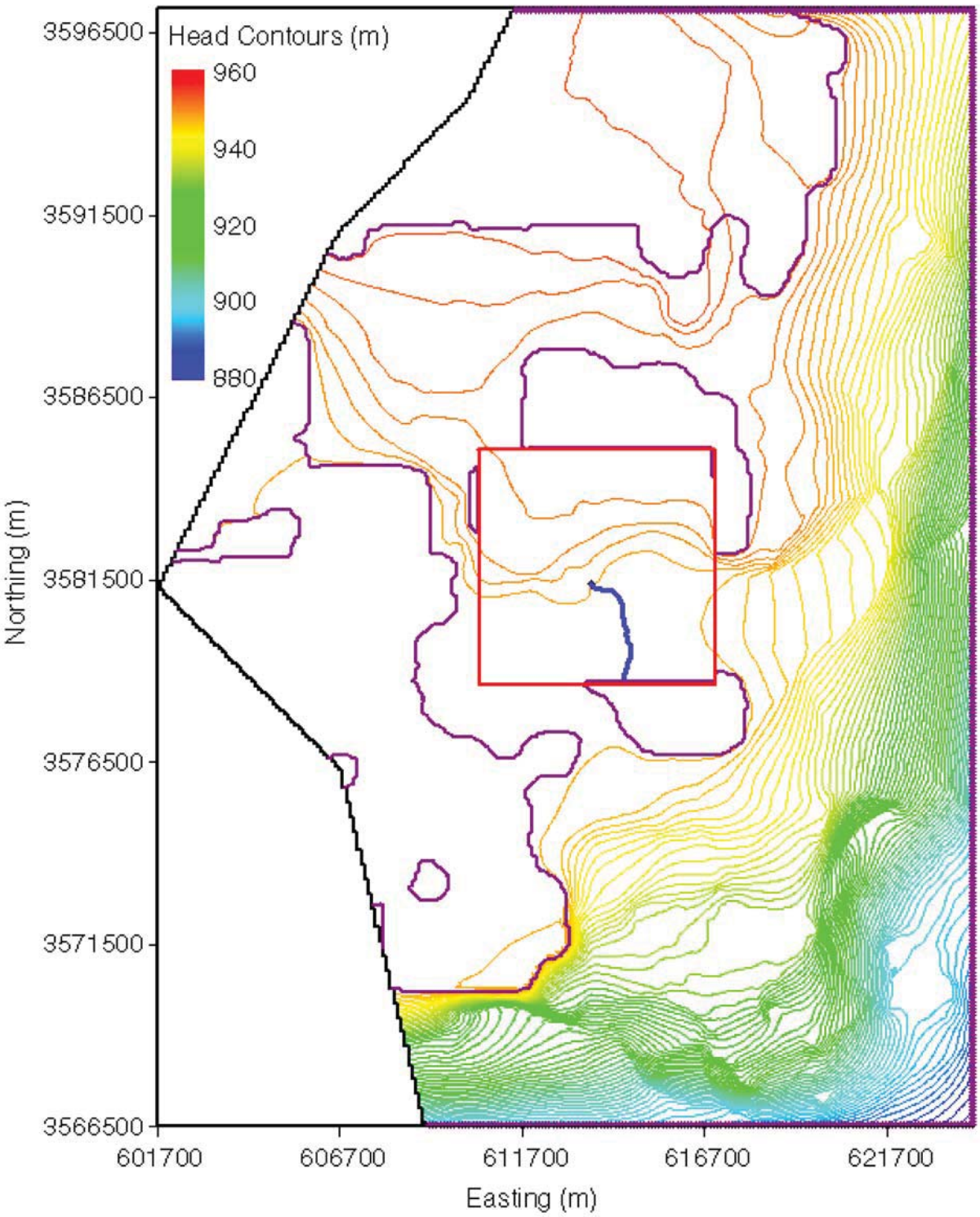

Figure TFIELD-82. Head Contours and Particle Track for the Median-Travel-Time T Field (d01r04-R1) for the Partial-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

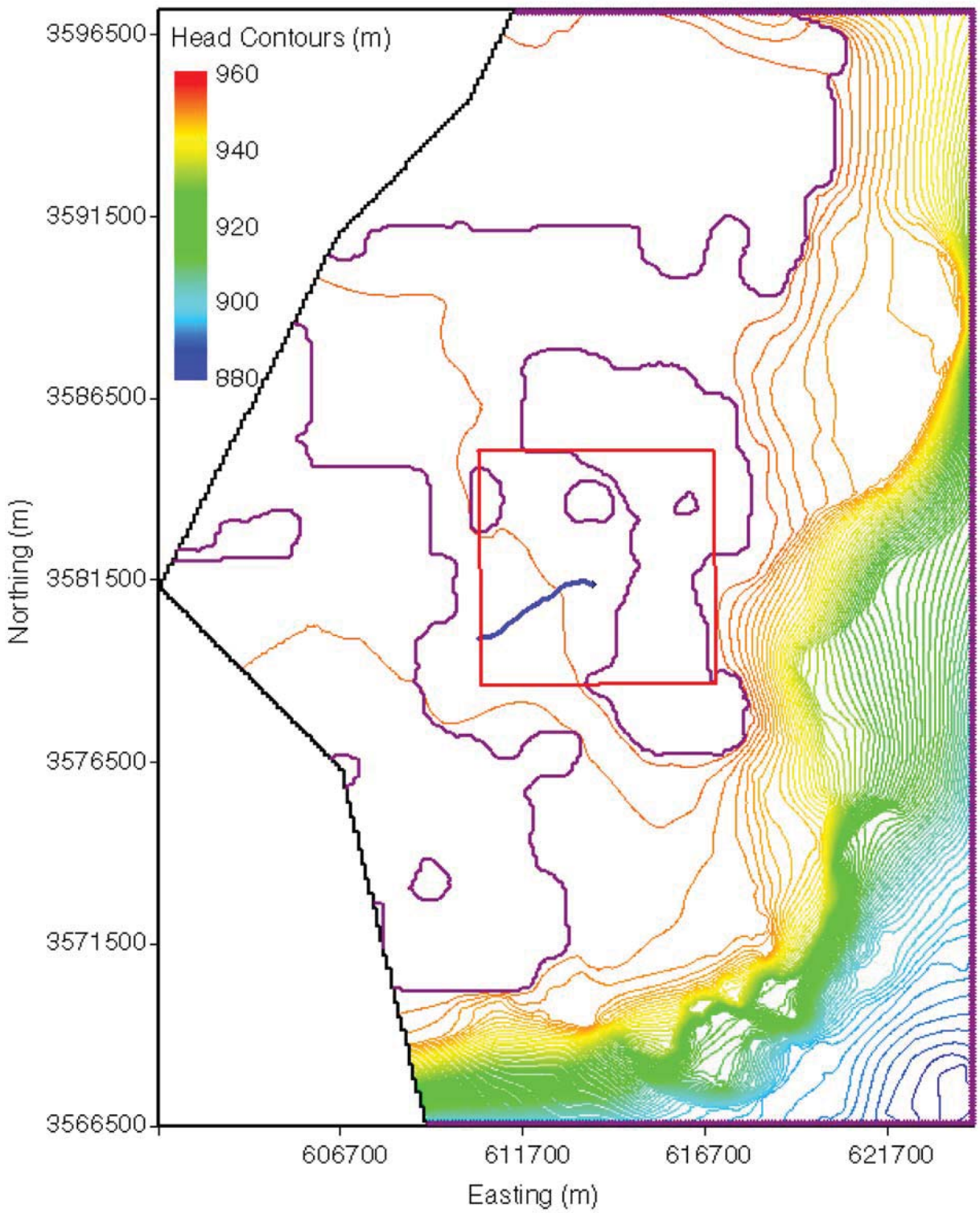

Figure TFIELD-83. Head Contours and Particle Track for the Maximum-Travel-Time T Field (d04r01-R2) for the Full-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

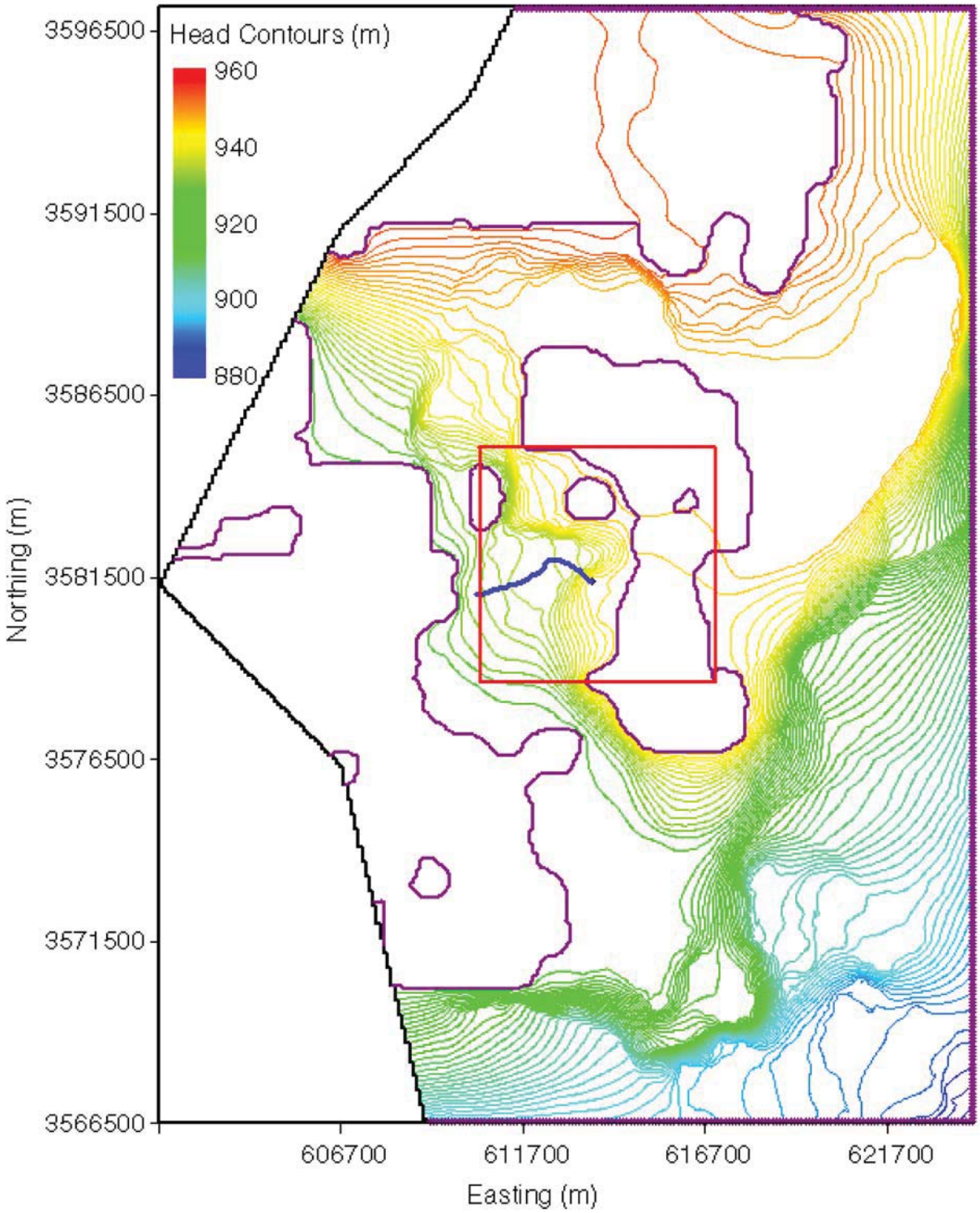

Figure TFIELD-84. Head Contours and Particle Track for the Minimum-Travel-Time T Field (d01r07-R2) for the Full-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

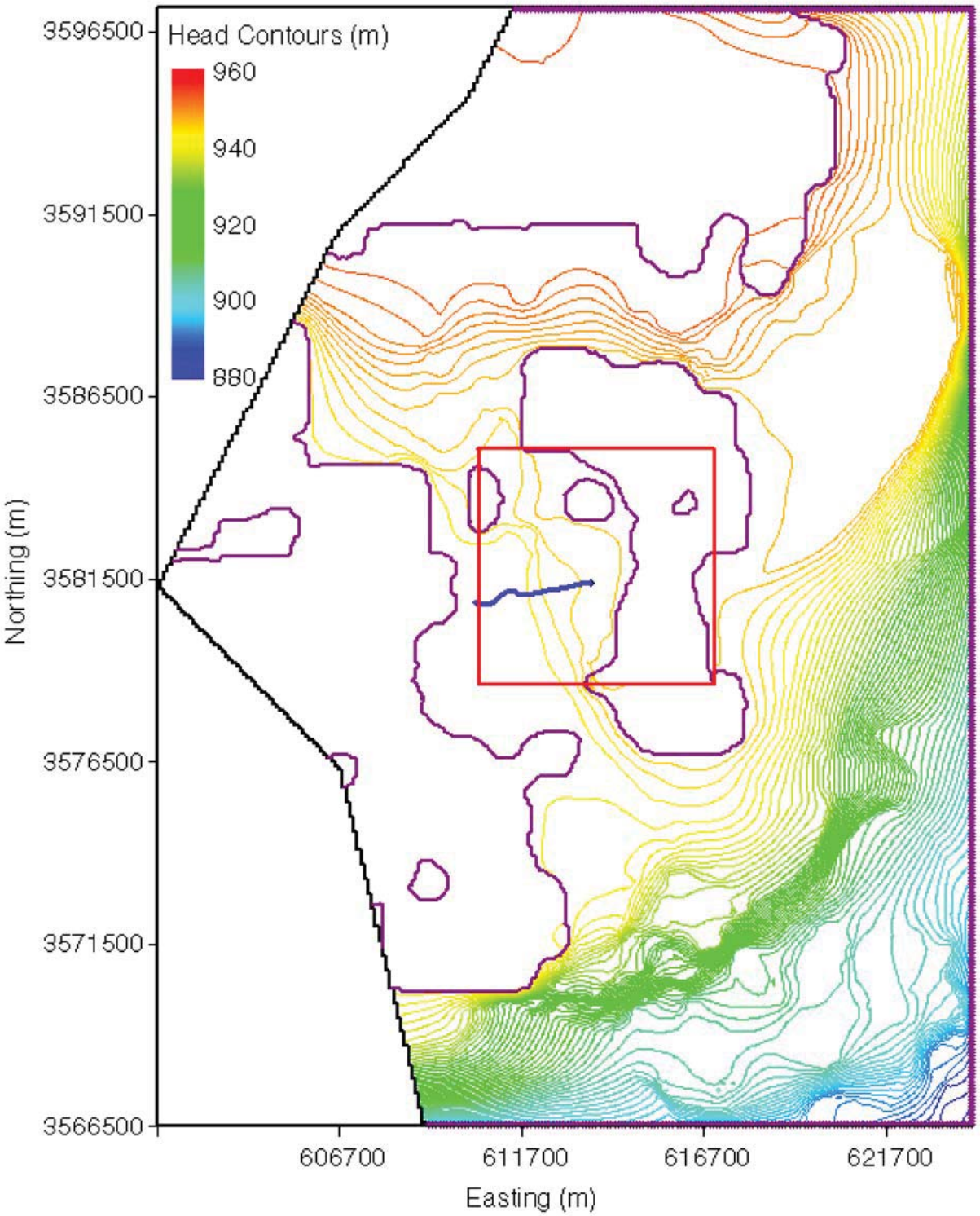

Figure TFIELD-85. Head Contours and Particle Track for the Median-Travel-Time T Field (d10r09-R1) for the Full-Mining Case. The WIPP LWB is the red box in the center of the figure and the particle track is the blue track originating from the approximate center of the WIPP.

can be tested through the collection of additional data. This model was used to create 500 stochastic realizations of the distribution of Culebra T ("base" T fields) in the vicinity of the WIPP site.

A MODFLOW-2000 modeling domain was defined extending 30.7 km (19.1 mi) north-south and 22.4 km (13.9 mi) east-west, roughly centered on the WIPP site. This domain was discretized into 68,768 uniform 100-m (328-ft) by 100-m (328-ft) cells. Water-level measurements made in 37 wells in late 2000 were used to define "steady-state" head conditions and constant-head boundary conditions on the northern, eastern, and southern extremes of the model domain. No-flow boundaries down the arms of Nash Draw, representing flow lines, were used on the western side of the model domain, reducing the number of active cells to 53,769.

MODFLOW-2000 and PEST were used to calibrate 146 of the base T fields to steady-state heads and transient drawdown responses to seven large-scale pumping tests. This calibration was done by using 100 pilot points to adjust the T values within the model domain to improve the fit to the observed heads. The pilot points were used to adjust a residual T field that was combined with a previously created base T field to yield the final calibrated T field. Of the 146 T fields, 121 were judged to be adequately calibrated for use in WIPP compliance calculations by virtue of being from a single population with respect to the CDF of travel times from a point above the center of the WIPP disposal panels to the LWB. From these 121 T fields, the 100 having the best objective fit measures were selected for further use.

The EPA requires that the potential effects of future potash mining be taken into account when evaluating the performance of the WIPP disposal system. Accordingly, transmissivities in the areas within the model domain where current or future mining might affect the Culebra were scaled by a random multiplier between 1 and 1,000 obtained from LHS. A single multiplier was used for each T field, applied first to the areas outside the WIPP LWB that might be mined to create a partial-mining T field, and then to the areas both inside and outside the LWB that might be mined to create a full-mining T field. The LHS was performed three times to create three replicates of T fields, leading to a total of 600 T fields. The MODFLOW-2000 water "budget" files from forward runs of these 600 T fields provided the input to radionuclide-transport calculations using SECOTP2D.

In all cases (no mining, partial mining, and full mining), the particle tracks on the T fields show travel times that are longer than those calculated for the T fields used in the CCA. In the case of the T fields unaltered for the effects of mining, the longer travel times are caused by a shift of relatively high Ts from the southeastern to the southwestern portion of the WIPP site relative to the CCA T fields. In the case of the T fields altered for full and partial mining, the longer travel times are the combined result of the westward shift of high Ts discussed above and a change in the definition of the areas to be mined that resulted in less water entering the Culebra on the WIPP site.

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II-G-21: Conceptual Models Second Supplementary Peer Review Report. January 1997

A Peer Review
Conducted By

Charles Wilson, Darrell Porter, John Gibbons,
Eric Oswald, Glen Sjoblom, Florie Caporuscio

for

U.S. Department of Energy
Carlsbad Area Office
Office of Regulatory Compliance

January 1997

EXECUTIVE SUMMARY

This report is a further supplement to a July 1996 report that presented the results of an independent technical peer review of the adequacy of 24 conceptual models representing features, events and processes involved in assessing the long-term performance of the Waste Isolation Pilot Plant. In its December 1996 supplementary report, the Panel stated that it continued to find two of the models not adequate to represent the future states of the repository. For the two models found not adequate, Spallings and Chemical Conditions, the Panel identified its remaining issues.

In this second supplementary report the Panel considers the U.S. Department of Energy's (DOE's) January 1997 responses to these remaining issues. The Panel's evaluation of these responses is presented in Section 3 of this report. Following review of the DOE responses, the Panel continues to find that the Spallings model and the Chemical Conditions model are not adequate to represent future states of the repository.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Conceptual Models Peer Review Panel issued its report in July 1996. The peer review was conducted in accordance with the regulatory requirements of 40 Code of Federal Regulations (CFR) 191 and the implementation of those requirements by 40 CFR 194. The U.S. Department of Energy (DOE) included the Conceptual Models Peer Review Report as part of its Compliance Certification Application (CCA) for WIPP that was submitted to the U.S. Environmental Protection Agency (EPA) in late October 1996.

In the Conceptual Models Peer Review Report of July 1996, 24 conceptual models were

evaluated using the evaluation criteria specified by the EPA, including those of NUREG 1297. The Panel's report identified 13 conceptual models as adequate for implementation in WIPP Performance Assessment and 11 as not adequate for implementation, based on information available to the Panel. The Panel's findings on each of the models judged inadequate were provided in the report. After that report was issued, DOE developed additional information, made changes to some of the conceptual models, and prepared responses to the findings in the Conceptual Models Peer Review Report of July 1996.

The DOE reconvened the Panel in October 1996 to review the changes to the conceptual models, the DOE responses to the findings in the July 1996 Panel report, and information available in the CCA. In December 1996 the Panel issued a report supplementing the July 1996 report, that assessed the changes to the models and the DOE responses. The Panel found that two of the models, Spallings and Chemical Conditions, continued to be not adequate for implementation, and identified its remaining issues.

DOE again reconvened the Panel in January 1997 to review additional information developed in response to the remaining issues of the Panel on these two models. Therefore, this report is a further supplement to the Panel's July 1996 and December 1996 reports.

Section 2 of this report describes the process for this second supplementary review. Section 3 describes the additional information provided by DOE and the Panel assessment of that information.

2.0 SUPPLEMENTARY REVIEW PROCESS

The supplementary review was conducted in accordance with the DOE Quality Assurance requirements at Sandia National Laboratories (SNL) in January 1997. The Panel was provided responses to issues in its December 1996 report during briefings and in written material. This second supplementary review used the same review criteria to judge the acceptability of conceptual models as in the July 1996 report.

3.0 MODEL EVALUATIONS

3.1. Spallings

3.1.1. Model Description

No changes to this model were presented.

3.1.2. Review of Criteria

The review of criteria for the Spallings model remains unchanged.

3.1.3. Review of Responses to Panel Findings of December 1996

3.1.3.1. Summary of Findings

The Panel's December 1996 findings with regard to the Spallings model are summarized in Section 5.0 of that report and reproduced below. A complete statement of these findings is presented in Section 3.14 of the Panel's December 1996 supplementary report.

- An adequate basis for the parameters used in the mathematical expression of the model has not been developed. In particular, ignoring capillary forces and correlating tensile strength with surface erosion have not been adequately supported by either first principles or experiment.

- The principal assumptions on which the mathematical model is based appear to be incomplete. Waste removal by entrainment in gas flow is expected to occur in a highly dynamic sequence principally involving a spalling process driven by gas flow out of the porous waste normal to the eroded surface. Subsequent erosion by gas flow parallel to the eroded surface is not expected to be the primary effect controlling the volume of spall, particularly in early times. In addition, the DOE has not adequately shown that the steady-state assumptions of the model conservatively approximate releases associated with the dynamic process of spall, and the possibility of transonic velocities has apparently not been considered.

- The experiments conducted in support of this model appear to have been designed to reproduce the assumptions on which the model is based, rather than to simulate the dynamic repository system. Although the experiments may support adoption of specific model parameters, they do not demonstrate that the model adequately represents future states of the repository.

3.1.3.2. Summary of DOE Responses to Findings

The DOE responded to the Panel's continued concerns through the SNL Spallings Release Position Paper (Hansen et al., 1997), oral presentations, subsequent discussions, and presentations of additional information. The position paper and initial oral presentations addressed the Panel's concerns by grouping them into the categories of waste characterization, analog comparisons, and conceptual model issues.

The waste characterization information included discussions of the physical condition of the waste that would be capable of release by a spallings process, the waste strength, and expectations of the significance of these results relative to spallings releases. Key points made were that any waste capable of spallings release would be at least partially degraded and have some moisture content, because without the presence of brine the elevated gas pressure that drives the spallings process could not exist. The model assumption that the degraded waste would have the average characteristics of a fine sand were considered by DOE to be highly conservative because not all of the waste would be expected to have degraded to that end state during the 10,000-year regulatory period. The 1 psi cementation strength assumed in the model

was also considered conservative, and experimental results were presented showing that dried samples of sand that had been saturated with WIPP brine had indirectly determined tensile strengths that averaged 49 psi. Higher average tensile strengths ranging up to 114 psi were found when NaCl and MgO were added to the brine. The DOE concluded that waste strength dominates spallings releases, that the assumed waste strength of 1 psi was conservatively low, and that degraded waste will be heterogeneous and cemented, significantly impeding erosion.

Analog comparisons were presented for spallings-type releases induced by pressure surging to stimulate methane production from coal beds, industrial techniques to remove cuttings by air injection during borehole drilling, the downhole pressure gradient requirements for removal of hydrofracture proppants, wellbore stability and sand production as a function of fluid velocities, and the limitations of the borehole as a transport pathway. In addition, the mathematical model used by DOE to calculate spallings releases was compared to models for sediment erosion by moving fluids and to rock mechanics models for time-dependent tensile failure by fluid pressure gradients at the borehole boundary. The DOE believes that the available quantitative data (most notably from the coal bed methane analogs) suggest that the predicted WIPP spallings release volumes were probably larger than would actually occur. The DOE also believes that support was provided for the assumption that the void created by spalling will not continue to grow indefinitely, but will achieve an equilibrium state. Where quantitative data were not available, such as in the air drilling and hydraulic fracture proppant analogs, the comparisons were interpreted to indicate that the phenomenology included in the Spallings model is appropriate and probably conservative. Based on the comparisons with other models, the DOE concluded that the Spallings model has an appropriate functional form and is probably conservative.

The conceptual model and its mathematical expression were reviewed and confirmed by DOE to have an appropriate functional form for properly characterizing the end state of the spallings process in a slightly cohesive material. Experimental and analog evidence were used to support the assumption that the process reaches an equilibrium state, that the equilibrium state establishes the maximum volume of waste released, and that the equilibrium state determined by the erosional forces assumed in the model conservatively predicts the volume of waste released. In summary, the DOE response reiterated that cohesive forces dominate the calculated release, that many key assumptions in the mathematical formulation and parameterization are conservative, and that the releases predicted by the Spallings model are conservative.

In addition to the foregoing, model calculations of pressure transients in the repository were included in an oral presentation but not in the position paper. These analyses showed that depressurization of an isolated waste room is essentially complete within about 1,000 seconds (17 minutes) following borehole penetration of the room. The pressure profiles were interpreted by DOE to illustrate a gradual drawdown of pressure in the room, mitigating a possible spall event.

At the Panel's request, the DOE provided additional information in two areas: (1) a refined estimate of the capacity of the borehole to accommodate spallings releases under WIPP-specific

conditions; and (2) an estimation of the pressure gradients required to cause tensile failure in the waste under WIPP-specific conditions. DOE's responses to these questions are summarized in the following paragraphs. The Panel also requested supplemental information in two additional areas that the DOE was unable to provide within the available schedule. These were (1) information that would further support the assumption that the equilibrium state determined by the model conservatively predicts the total volume of waste released in the spallings process; and (2) correlations between the cohesion of the degraded waste and the maximum cohesion found to exist in natural analogs where spallings releases are observed.

A more detailed analysis of the borehole capacity indicated that the borehole size was adequate to transmit spallings releases to the ground surface at the generation rates predicted by the model in the repository. The borehole was therefore determined to not be a limiting element in spallings releases.

A DOE team made preliminary scoping calculations using an elastic, Mohr-Coulomb model of waste that would be released by tensile failure using the pressure transient data described above and ranges of values for the key waste strength properties. Several cases were run in which assumed waste compressive strength and internal friction were varied. The details of these analyses are presented by Hansen and Knowles (1997). The results indicated that the volume released from a 1-m thick waste horizon (representing the fully compacted state of the waste) ranged from 0.37 to 0.59 m^3, and approached approximately 0.6 m^3 as the waste tensile strength approached zero. The limiting value of the release volume was determined by the fixed volume defined by the zone of tension around the borehole. In responding to additional questions posed by the Panel, the DOE emphasized that although the tensile failure results tended to support the model's conservatism by predicting a lower release volume, the tensile failure model results were considered to be scoping calculations providing order-of-magnitude approximations. The DOE also indicated that there were other factors likely to result in second order effects that were not incorporated into that model. Of particular significance was the consensus of the presenters that the continuing flow of gas through the waste following tensile failure could mobilize additional waste beyond the above quantities, through seepage and erosion processes.

3.1.3.3. Panel Review of Responses

The information presented by DOE in the aforementioned Position Paper and initial oral presentations was not considered by the Panel to adequately support the appropriateness of the Spallings model for use in performance assessment. While it is agreed that degradation of a significant part of the waste must occur to generate enough gas to cause a spallings release, implying that some moisture must be present, the cementation strength information presented to the Panel was determined from oven-dried samples with considerably lower moisture contents than would be expected under repository conditions. The ability of precipitates to cohesively bind a granular material may be significantly lower under partially saturated conditions than when the material is nearly dry. However, strength information for materials with higher degrees of

saturation was not available. Although waste strength may be significant in estimating spallings releases, the assumed strength of 1 psi was not adequately shown by these experiments to be conservatively low under repository conditions. The Panel also agrees that the degraded waste will be heterogeneous and is likely to be at least partially cemented; however, the degree to which this would impede spallings releases was not demonstrated.

The analog comparisons presented appeared to have varying degrees of correlation with WIPP repository conditions, making it difficult for the Panel to directly use the comparisons in making definitive conclusions regarding the degree of conservatism in the model. The coal bed methane analogs were particularly useful in identifying limiting values of cohesion above which spallings-type releases are unlikely to occur and in identifying limiting sizes of artificially induced spallings cavities. However, without waste strength data to use as a basis, conclusions regarding spallings releases under WIPP repository conditions could not be made. Although the Panel agrees that the erosion phenomenon addressed in the Spallings model may occur under repository conditions, it was not adequately demonstrated to be of primary importance in spallings releases. The Panel has come to believe that the erosion process described in the Spallings model may actually be of secondary importance when compared with the waste volumes potentially released by tensile failure and seepage forces under high pressure gradients. Because of the foregoing concerns, the Panel could not conclude, based on the analog information presented, that the Spallings model was conservative. Conversely, the analog information was considered by the Panel to present information suggesting that the Spallings model is not appropriate.

The formulation of the Spallings model as a self-limiting process is based on an analytical statement of the relationships among void volume, gas velocity, and material strength. This formulation appears to be strongly contraindicated by analytical considerations of open completion of coal gas extraction wells. Such wells demonstrate that enlargement of a cavity ceases after a finite number of well pressure surges independent of the number, pressures, or duration of additional surges. The stabilization of cavity size despite the repetition, maintenance of, or increase in gas seepage pressures over time implies that cavity volume stability is related to stress conditions, and in particular to stress geometry and magnitude resulting from arching around the void. The Spallings model does not address the stress state around the wellbore and would not predict the stabilization of cavity volume under progressively increasing surge pressures. There is no mechanism or process in the Spallings model that would predict the cessation of cavity growth if gas seepage pressures were increased. For this reason it appears that the representativeness of the predicted releases due to spalling using the end-state modeling approach of the Spallings model cannot be evaluated because critical processes and local stress conditions are not specifically considered.

The Panel's belief that erosion is of secondary importance in spallings releases, and the lack of a critical comparison between the relative roles of erosional versus tensile and seepage failure mechanisms in such releases, makes it difficult for the Panel to support the credibility of the Spallings model as currently configured. Because the credibility of the basic model assumptions

are being seriously questioned, demonstrations that key aspects of the model and its parameterization are conservative cannot be interpreted to conclude that the present model conservatively predicts the future states of the repository. Although erosion phenomena may be a later mechanism acting for dislodging waste in a spallings release, the early-time tensile failure of waste under high, transient pressure gradients may be capable of removing waste particles that would not have been predicted to be removed under the steady-state assumptions of the Spallings model, leading to underestimating the release volume. Because of these concerns, the Panel does not believe that it has been adequately demonstrated that the equilibrium state determined by the erosional forces assumed in the model conservatively predicts the volume of waste released.

Model calculations of pressure transients were new and helpful to the Panel in determining the time duration over which a spallings release may occur. However, the Panel could not concur with DOE's conclusion that the pressure gradients were sufficiently low to mitigate a spall event because of the results of the tensile failure analysis.

The new tensile failure results presented by the DOE provided insights into a failure mechanism considered by the Panel to be significant to the spallings process. The preliminary nature of the calculations, the possibility that an additional volume of waste would be released by seepage forces from subsequent gas flow in the porous waste, and the lack of information on associated effects (such as waste heterogeneity, stability of the waste cavity, the presence of moisture in the waste, and coupling between the cavity size and the stress and pore pressure fields) did not provide an adequate basis for the Panel to conclude that the spallings release volumes presented in the CCA were conservative. The tensile failure calculations did emphasize, however, the complexity of the spallings process, and are useful because they represent a phenomenologically appealing, more classical approach to such calculations. The tensile failure mechanism is more consistent with the mechanisms observed in the coal bed methane analogs.

In summary, the additional analog, waste strength, model descriptions, and calculational information provided to the Panel were either not adequately correlated with WIPP repository conditions or were not sufficiently complete or supported to provide the Panel with an adequate basis for determining that either the Spallings model or the results obtained from that model were conservative.

3.2. Chemical Conditions

3.2.1. Model Description

No changes to this model were presented.

3.2.2. Review of Criteria

The review of criteria for Chemical Conditions remains unchanged.

3.2.3. Review of Responses to Panel Findings of December 1996

3.2.3.1. Summary of Findings

In summary, the Panel's December 1996 findings were that the ability of the MgO backfill to react completely and rapidly with CO_2 to buffer the chemical system and limit actinide solubilities had not been adequately substantiated by experimental physical results that correctly simulate conditions in the repository. Although the pH buffering assumptions are of considerable importance to many other conceptual models, the conclusion that the MgO will in fact perform as assumed had not been adequately supported.

3.2.3.2. Summary of DOE Responses to Findings

The DOE provided a summary of a calculation of cumulative complimentary distribution functions (CCDFs) intended to show the importance of MgO on repository system performance. The CCDFs without MgO present showed increased releases as compared to those with MgO present. Releases with MgO present predominantly result from cuttings/cavings and spallings, but without MgO present the contribution from direct brine release significantly increases. DOE indicated that the mean CCDF without MgO present still remains lower than the EPA limit. DOE also provided additional results of experiments with MgO from the ongoing test program.

3.2.3.3. Panel Review of Responses

The Panel examined the various assumptions and parameters that were used in computing the CCDFs without MgO present and believes that the differences in CCDFs with and without MgO represent the degree of importance of the chemical getter to repository performance. The Panel believes that adding the MgO getter will positively benefit and not detract from the performance of the repository. However, the Panel identified a few additional factors that would need to be included for such a CCDF calculation to be definitive, including the effect on corrosion rates, gas generation rates, and pressures over time. However, inasmuch as calculations without MgO show that direct brine release would become an important contributor to overall releases, the Chemical Conditions model has been shown to be a significant contributor to the future states of the repository.

Furthermore, the additional results from the ongoing test program, while interesting, are not sufficient to resolve the Panel's concerns with the issue of MgO effectiveness. The results presented to the Panel concerned the effect of CO_2 diffusion into the MgO pellets. Test runs of 4 days followed by dye infusion indicate that in 24 hours the dye will travel through the reaction rims to the center of the pellet. However, the test runs were short, the reaction rims were thin and may not have been fully formed, and there were no transient information or bounding calculations to support a conclusion regarding the role of the reaction rims in impeding CO_2 diffusion. Information was not available on the diffusion rate of CO_2 into the MgO pellets, especially as a function of reaction rim thickening. The Panel believes that the aforementioned

test program has not sufficiently progressed to provide a definitive verification that the MgO will perform as planned under repository conditions. Therefore, as a result of the Panel's review of the added information, the conclusion remains that the Chemical Conditions model is not sufficiently developed to adequately support performance assessment.

3.3. Summary

In summary, the Panel concludes that the Spallings model and the Chemical Conditions model remain inadequate to represent the future states of the repository.

4.0 REFERENCES

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Hansen, F.D., and M.K. Knowles, 1997. Response to inquiries by CMPRP for spallings. Memorandum to M.S.Y. Chu, Sandia National Laboratories, Albuquerque, NM. 23 January 1997.

ACRONYMS

CCA	Compliance Certification Application
CCDF	cumulative complimentary distribution function
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
SNL	Sandia National Laboratories
WIPP	Waste Isolation Pilot Plant

APPENDIX A - SIGNATURE PAGE

I acknowledge by my signature below that I concur with the findings and conclusions documented in this Conceptual Models Peer Review Second Supplementary Report.

Florie Caporuscio
John Gibbons
Eric Oswald
Darrell Porter
Glen Sjoblom

Charles Wilson

From: Kurt W. Larson
To: malord, pvaughn, msychu
Date: 1/24/96 8:24AM
Subject: Fracture model ideas

A couple of ideas as the frac. model parameters are determined. I will be away next week, so Palmer you will have to see that the memo for Project office to consider gets written.

From brine-outflow meeting 1/23/96:

Wolfgang Wawersik thinks each interbed has a zone about 10cm thick which dilates. Each zone dilates identically. This means a different set of fracture parameters would be applied to each interbed. He and Norm Warpinski think the LEFM model is appropriate analogue. LEFM predicts about 1 cm dilation max with tremendous permeability change for pressures somewhat above lithostatic.

For MB 138 and 139, 1 cm dilation - 1% porosity change over entire thickness
For anh.A+B, 1 cm dilation - 3-5% porosity change over entire thickness (someone who knows modeled thickness can figure out more accurately)

dilation/fracturing begins is a continuous process, so initiation pressure should be low.

Additionally, Norm thinks pressures above 17-18 MPa are not realistic, and indicate too constrictive fracture model conditions. Thus, fracture model must be able to open up better than recent implementations (FEPs) which allowed pressures up to 23 MPa.

This leads me to the following recommendation:

Initiation pressure
about 0.2 MPa above initial pressure of cell
I
Final Pressure, Final Porosity, Final Permeability
I suggest using these as fitting parameters so that the following condition is attained

At about 2.5 MPa above initial pressure in cell, fracture porosity and permeability begin steep rise (commensurate with onset of real fracturing) - below this pressure shallower rises indicate interconnection/dilation of existing fractures

a. At about 3 MPa above initial pressure in cell, fracture porosity reaches 1% for MB 139, MB 138; 3-5% for Anha+b.

b. At about 3 MPa above initial pressure in cell, fracture permabiltiy reaches 87 OM greater than initial.

a+b above make a fracture that is relatively long due to high permeability and narrow due to moderate increase in porosity. condition of a+b is ideal max pressure for model, and commensurate with LEFM model.

Above about 3 MPa increase, fracture porosity and permeabity continue steep rise so that increased pressures have a mechanism for blowing off steam rapidly.

If the model is set so that there is no increased porosity or permeability above about + 3 MPa, then I think some vectors will result in pressures significantly in excess of 20 MPa.

I look forward to hearing what the final values chosen are

Kurt

Date: 1/29/96

To: Margaret Chu, Dept. 6801, MS-1325

From: Michael Lord, Dept. 6749, MS-1328

Subject: **Parameters describing the variable porosity and permeability within anhydrite material.**

I have considered ways of honoring the porosity/permeability response to pressure within the anhydrite marker beds as suggested in the enclosed memo from Kurt Larson of 1/24/96 and discussions with Palmer Vaughn. The following values typical of the performance assessment data were assigned:

pressure at fracture initiation	= 12.7 MPa
pressure at full fracture condition	= 16.5 MPa
porosity at reference condition	= 0.011 (1.1%)
permeability of intact anhydrite	= 2.5E-19 m^2
permeability at full fracture condition	= 1.0E-09 m^2

The porosity at full fracture condition was then adjusted in order to produce a change in porosity of about 1% at 2.5 MPa above fracture initiation pressure or a pressure of 15.2 MPa. This was obtained with a maximum porosity of 0.05(5%). In the attached Fig. 1 the resulting porosity response is shown. The corresponding permeability response is shown in Fig. 2. At 2.5 MPa above fracture initiation pressure, the permeability is between 3 and 4 orders of magnitude larger than the intact value. This would represent the desired response in marker beds 138 and 139. A similar analysis was done for marker bed a+b where the full fracture porosity was taken to be 0.25 (25%). For this value of maximum porosity the porosity at 2.5 MPa above fracture initiation pressure is approximately 3% above the porosity at fracture initiation pressure. This is shown in Fig 3 and the result is in line with the proposed response. Fig. 4 shows the permeability at 2.5 MPa above fracture initiation pressure as approximately 4 orders of magnitude above the intact permeability.

Based on this study I would recommend assigning the fracture parameters as follows. The fracture initiation pressure should be set as done in the FEPs calculations where it is assigned a value of 0.2 MPa above the grid block initial pressure. Therefore, there could be some small variance in the fracture initiation pressure if the reference initial pressure in the Salado is sampled. Also, there will be some small variance due to the dip in the Salado formation. However, the fracture initiation pressures should be near the 12.7 MPa value. The pressure at the full fracture condition should be an increment of 3.8 MPa above the fracture initiation pressure. This would result in a full fracture pressure of approximately 16.5 MPa. The full fracture permeability can be any large sampled or assigned value such as the 1.0E-09 m^2 used in this study. The full fracture porosity for the marker beds 138 and 139 will have value 0.05 and the full fracture

porosity for the marker bed a+b will have value 0.25. With these values the pressure dependent porosity and permeability should closely approximate the LEFM predicted values.

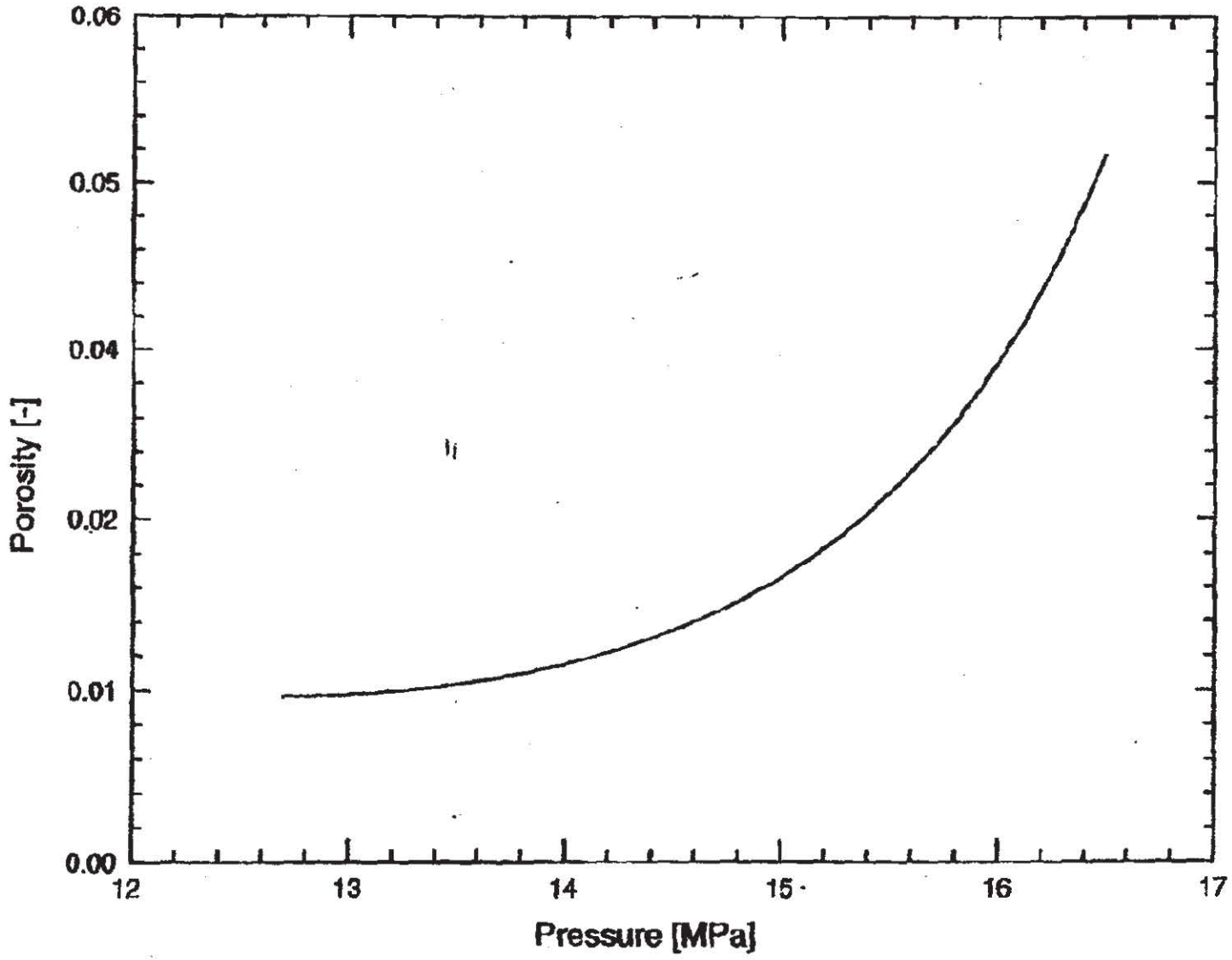

Figure 1: Porosity in Marker Bed 138 & 139 with Fracturing

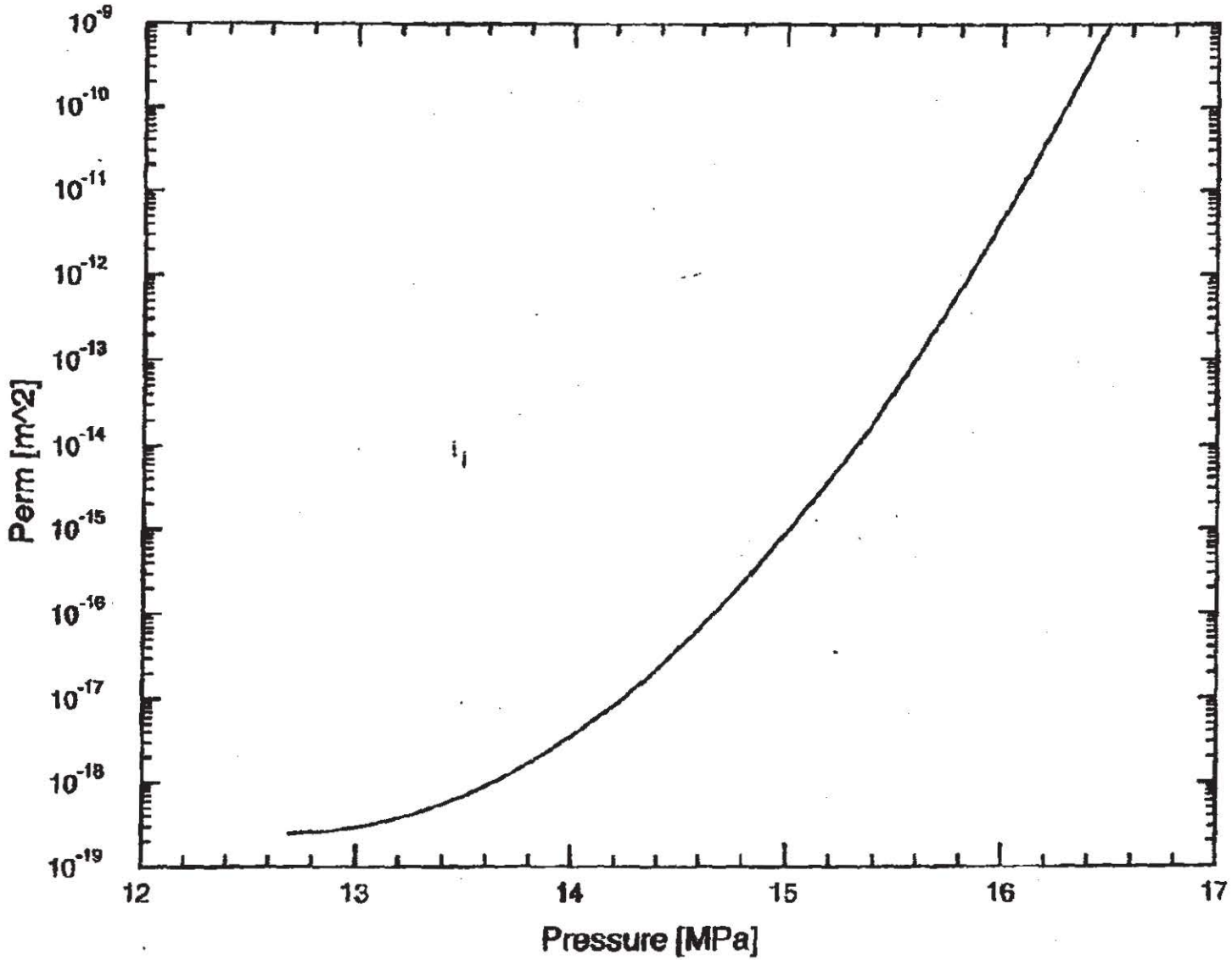

Figure 2: Permeability in Marker Bed 138 & 139 with Fracturing

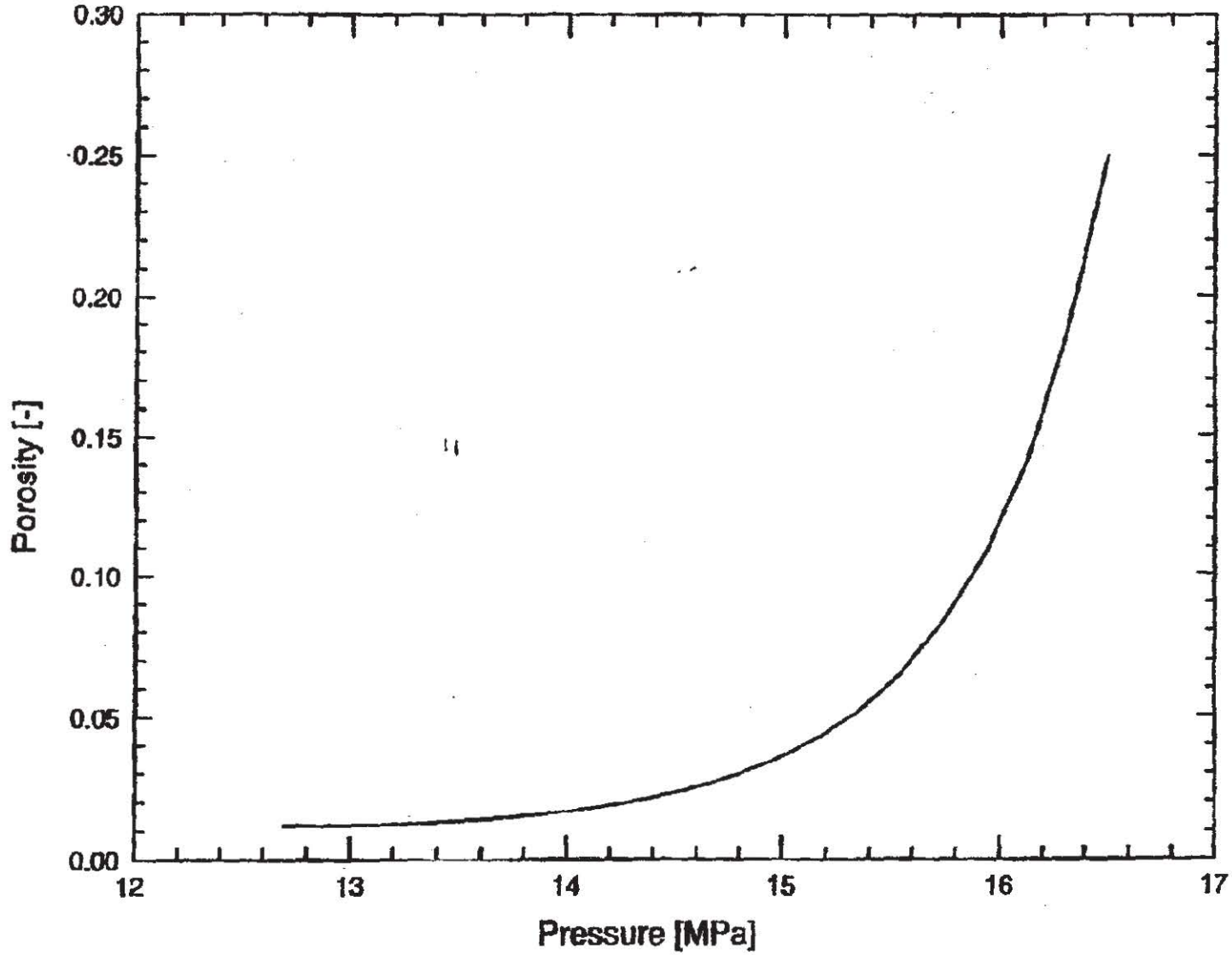

Figure 3: Porosity in Marker Bed A+B with Fracturing

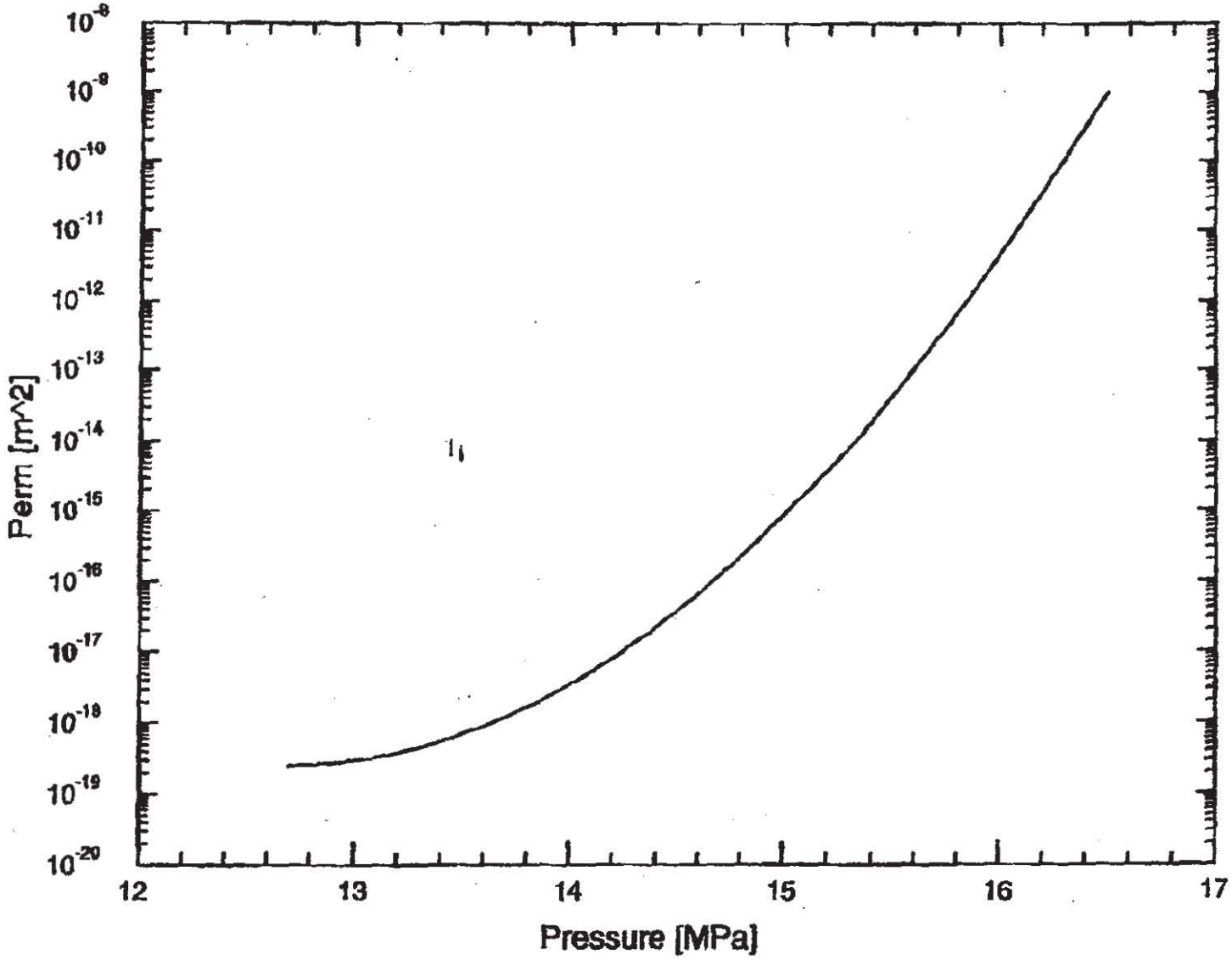

Figure 4: Permeability in Marker Bed A+B with Fracturing

Sandia National Laboratories

Albuquerque, New Mexico 87185-1341

date: August 20, 1996

to: Distribution

pp T.W. Hicks Yifeng Wang T.W. Hicks

from: David Bennett, Yifeng Wang, and Tim Hicks

subject: An Evaluation of Heat Generation Processes for the WIPP

1.0 Introduction

Nuclear criticality, exothermic reactions, and radioactive decay are possible sources of heat in the WIPP repository. Nuclear criticality has been eliminated from performance assessment calculations on the basis of low probability (see SNL Summary Memo of Record RNT-1). This memo discusses possible heat generating processes at the WIPP and the potential magnitude of the temperature increases they might induce. Heat from exothermic reactions is discussed in Section 2 and heat from radioactive decay is discussed in Section 3.

Conclusions are provided in Section 4. In summary, soon after disposal concrete hydration in the panel closures and shaft seals will give rise to temperature increases lasting a few decades. Heat from radioactive decay will generate a maximum temperature increase of less than 2°C above the ambient temperature (about 27°C) within 100 years after disposal. A number of potential exothermic reactions other than concrete hydration have been identified. These reactions are brine limited and will cause only minor perturbations to the temperature distribution within the disposal system. The maximum calculated rate of brine inflow to a waste disposal panel, and thus, the maximum exothermic reaction rates, occur for the S2 scenario involving an E1 drilling event at 350 years after disposal. By the time such a drilling event takes place heat generation from concrete seal hydration and radioactive decay will have decreased substantially, and the temperatures in the disposal rooms will have reduced to close to initial values. Note that active institutional controls are expected to prevent drilling within the controlled area for 100 years after disposal. Thus, exothermic reactions following a drilling intrusion into a waste disposal panel will be the only potentially significant heat generating processes at the time of a drilling intrusion.

The maximum temperature that could be achieved in the panel following a drilling intrusion at 350 years occurs as a result of aluminum corrosion; this reaction could result in a maximum temperature increase of about 6°C two years after the drilling event. This predicted value of temperature increase is based on several conservative assumptions. For example, it is assumed that no aluminum corrosion has occurred prior to the drilling event and that all the brine introduced to the waste panel is available for aluminum corrosion. In reality some aluminum corrosion is likely to have occurred prior to the drilling event, reducing the volume of aluminum available for the reaction, and other reactions with lower reaction enthalpies (such as backfill hydration) or lower reaction rates (such as microbial degradation) will compete with aluminum corrosion to consume brine resulting in a smaller temperature increase. Based on similar conservative assumptions, backfill hydration could result in a maximum temperature increase of less than 5°C. These maximum heat generation rates resulting from aluminum corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability. Thus, the temperature rise of 6°C represents the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously.

2.0 Heat From Exothermic Reactions

Exothermic reactions in the repository will liberate heat resulting in elevated temperatures. The magnitude and duration of this temperature increase will depend on the amount and rate of energy release, the geometry of the heat source, the thermal conductivities of the surrounding rocks, and any influence of groundwater or brine flow on heat transport.

In the WIPP a range of different types of reactions will occur, including corrosion, microbial degradation, waste dissolution, and concrete and backfill hydration, and these will liberate different amounts of heat at different times. The amount of heat liberated by the different reactions will depend on the extent of reaction that occurs (for example, how much gas generation or concrete hydration takes place), and the enthalpy of the reactions. The former will depend on the inventory of materials emplaced in the WIPP, and the subsequent chemical evolution of the repository system. The latter can be assessed by considering typical enthalpies for the reaction types of interest.

Enthalpies of reaction, $\Delta_r H°$, for example reactions representing processes that may take place in the repository are given in Table 1 (from SNL Summary Memo of Record GG-7, SP-7). The reactions shown are based on the chemical conditions expected in the WIPP. Note that negative values for $\Delta_r H°$ indicate that the reactions liberate heat as they progress from left to right.

Table 1. Enthalpies of reaction, $\Delta_r H°$, for the WIPP

Reaction	Example Stoichiometry and Standard Enthalpies of Formation, $\Delta_f H°$ (kJ/mol)	Reaction Enthalpy $\Delta_r H°$ (kJ/mol)	Data Source
Backfill hydration	$MgO_{(s)} + H_2O_{(l)} = Mg(OH)_{2(s)}$ $\Delta_f H°$ -601.7 -285.8 -925.5	-38	Krauskopf, 1982, 561
Backfill carbonation	$Mg(OH)_2 + CO_2(g) = MgCO_3 + H_2O$ $\Delta_f H°$ -925.4 -393.1 -1110.3 -285.8	-77	Drever, 1982, 351-256
Microbial degradation	$C_6H_{10}O_5 + H_2O = 3CH_4 + 3CO_2$ $\Delta_f H°$ -805.5 -285.8 3 x (-74.4) 3x (-393.5)	-312	Lide, 1994, 5-16 to 5-37
Aluminum Corrosion	$Al + 3H_2O = Al(OH)_3 + 1.5H_2$ $\Delta_f H°$ 0 3x(-285.8) 1291.9 0	-434	Drever, 1982, 351-256
Anoxic corrosion of steel	$Fe_{(s)} + 2H_2O_{(l)} = Fe(OH)_{2(s)} + H_{2(g)}$ $\Delta_f H°$ 0 2 x (-285.8) -569.0 0	+2.7	Wagman et al., 1982, Table 41
Waste dissolution	$UO_{2(s,cr)} + 2H_2O_{(l)} = U(OH)_{4(aq)}$ $\Delta_f H°$ -1085.0 2 x (-285.8) -1655.8	+0.9	Grenthe et al., 1992, Table III-1
Concrete hydration	$CaO_{(s)} + H_2O_{(l)} = Ca(OH)_{2(s)}$ $\Delta_f H°$ -635.1 -285.8 -986.1	-65.2	Wagman et al., 1982, 2-26

Even though there is uncertainty surrounding the extent of reactions that will occur, the reaction enthalpies indicate that the thermal effects of anoxic corrosion of steel and the waste dissolution reaction will be endothermic and will be of low consequence to the performance of the disposal system. However, the other reactions shown in Table 1 have the potential to evolve significant amounts of heat. The potential effects of these processes on the temperature within the disposal system are discussed below.

2.1 Backfill Hydration

Potential temperature increases in the repository as a result of exothermic backfill hydration reactions have been evaluated by Wang (1996, attachment to this memo). In his analysis, Wang (1996) made the following assumptions:

- The reaction will proceed rapidly so that the rate of heat generation will be

controlled by brine availability.

- All brine entering a waste disposal panel will contact and react with the backfill in the panel uniformly.

- All of the emplaced backfill will undergo hydration.

The maximum calculated rate of brine inflow into a panel (about 200 m^3/year) occurs for the S2 scenario involving an E1 drilling event at 350 years after disposal. The molar density of water is 5.56×10^4 moles/m^3, and thus, the reaction rate of backfill hydration in the panel will be 1.1×10^7 moles/year. Based on the reaction enthalpy shown in Table 1, backfill hydration will generate a thermal load of about 13 kW. There will be about 2×10^8 moles MgO emplaced per panel and thus the reaction could continue for about 20 years if sufficient brine was available.

Wang (1996) estimated the maximum temperature that could be generated by backfill hydration within a panel. Assuming heat loss will occur by conduction through the salt forming the roof and floor of the panel and that heat losses through the side walls are negligible, Wang (1996) calculated that the maximum temperature rise in a panel, as a consequence of backfill hydration following a borehole intrusion and subsequent brine inflow, would be about 4.5°C.

2.2 Backfill Carbonation

Wang (1996) also estimated the potential temperature rise that could occur as a result of backfill carbonation. Wang (1996) assumed that the reaction will be limited by microbial CO_2 production; the maximum rate of CO_2 production is 2.9×10^5 moles/year. Based on the reaction enthalpy shown in Table 1, backfill carbonation will generate a thermal load of about 0.7 kW. About 3.6×10^7 moles CO_2 could be produced in a single panel (see Wang, 1996) and thus the reaction could continue for about 125 years. Wang (1996) estimated the maximum temperature that could be generated by backfill carbonation within a panel to be about 0.6°C.

2.3 Microbial Degradation

Wang (1996) estimated the maximum reaction rate for microbial degradation in a panel to be about 1×10^5 moles/year and the inventory to be about 1.2×10^7 moles $C_6H_{10}O_5$ per panel. Thus, the reaction could continue for about 120 years. Based on the reaction enthalpy shown in Table 1, microbial degradation will generate a thermal load of about 1 kW. Wang (1996) estimated the maximum temperature that could be generated by microbial degradation within a panel to be about 0.8°C.

2.4 Aluminum Corrosion

Wang (1996) determined that the rate of corrosion of aluminum will be controlled by brine availability. From Table 1, the reaction rate of aluminum corrosion in the panel will be about 0.4×10^7 moles/year, assuming a brine inflow rate of 200 m^3/year (1.1×10^7 moles/year). About 8×10^6 moles of aluminum will be emplaced in each panel and thus aluminum corrosion could continue for 2 years. Based on the reaction enthalpy shown in Table 1, aluminum corrosion will generate a thermal load of about 51 kW. Wang (1996) estimated the maximum temperature that could be generated by aluminum corrosion within a panel to be about 6°C.

2.5 Concrete Hydration

Concrete hydration reactions will occur in the seals and panel closures and in the waste.

2.5.1 Seals and panel closures

Concrete hydration reactions are known to proceed for extended periods (perhaps thousands of years). However, the rates of these reactions decrease with time and, within the WIPP, the greatest evolution of heat will occur during the short periods following emplacement of panel closures during the operational phase and following shaft seal emplacement and repository closure. A quantitative analysis of the thermal effects of emplacing large concrete seals in salt at the WIPP was made by Loken (1994), Loken and Chen (1995). Their analysis showed that the energy released by the hydration of the seal concrete could raise the temperature of the concrete to approximately 53° C and that of the surrounding salt to approximately 38° C one week after seal emplacement.

2.5.2 Waste

WIPP waste contains cement which is used to solidify liquids, particulates and sludges. Storz (1996) estimated that all the waste to be emplaced at the WIPP will contain a total of about 8.5×10^6 kg of cement. This is equivalent to about 1.5×10^7 moles of calcium oxide (CaO) per waste disposal panel, representing the cement as CaO. Although a substantial amount of hydration may occur prior to waste disposal, this process will continue at a slower rate after disposal. Disregarding the hydration that will occur prior to disposal and assuming a brine inflow rate of 200 m^3/year, the reaction rate of concrete hydration in the panel will be about 1.1×10^7 moles/year, and the reaction could continue for about 1.4 years. Based on the reaction enthalpy shown in Table 1, concrete hydration will generate a thermal load of about 23 kW. Thus, using analyses similar to that used by Wang (1996) the maximum temperature that could be generated by concrete hydration of the waste within a panel is about 2°C.

3.0 Heat From Radioactive Decay

Radioactive decay of the contact handled CH and remote handled RH TRU waste emplaced in the repository will generate heat. The importance of heat from radioactive decay depends on the effects that the induced temperature changes would have on mechanics, fluid flow, and geochemical processes. For example, temperature increases could result in thermally induced fracturing, regional uplift, or thermally driven flow of gas and brine in the vicinity of the repository.

According to the Waste Acceptance Criteria (WAC), the design basis for the WIPP requires that the thermal loading does not exceed 10 kilowatts per acre. The WAC also require that the thermal power generated by waste in an RH TRU container shall not exceed 300 watts, but the WAC do not limit the thermal power of CH TRU waste containers.

A numerical study to calculate induced temperature distributions and regional uplift is reported in DOE (1980, pp.9-149–9-150). This study involved estimation of the thermal power of CH TRU waste containers. The DOE (1980) analysis assumed:

- All CH TRU waste drums and boxes contain the maximum permissible quantity of plutonium. According to the WAC, the fissionable radionuclide content for CH TRU waste containers shall be no greater than 200 grams per 0.21 cubic meter drum and 350 grams per 1.8 cubic meter standard waste box (in Pu-239 fissile gram equivalents).

- The plutonium in CH TRU waste containers is weapons grade material producing heat at 0.0024 watts per gram. Thus, the thermal power of a drum is approximately 0.5 watts and that of a box is approximately 0.8 watts.

- Approximately 3.7×10^5 cubic meters of CH TRU waste are distributed within a repository enclosing an area of 7.3×10^5 square meters. This is a conservative assumption in terms of quantity and density of waste within the repository, because the maximum capacity of the WIPP is 1.756×10^5 cubic meters for all waste (as specified by the Land Withdrawal Act [LWA]) to be placed in an enclosed area of approximately 5.1×10^5 square meters.

- Half of the CH TRU waste volume is placed in drums and half in boxes so that the repository will contain approximately 9×10^5 drums and 10^5 boxes. Thus, a calculated thermal power of 2.8 kilowatts per acre (0.7 watts per square meter) of heat is generated by the CH TRU waste.

- Insufficient RH TRU waste is emplaced in the repository to influence the total thermal load.

Thorne and Rudeen (1980) estimated the long-term temperature response of the disposal system to waste emplacement. Calculations assumed a uniform initial power density of 2.8 kilowatts per acre (0.7 watts per square meter) which decreases over time. Thorne and Rudeen (1980) attributed this thermal load to RH TRU waste, but DOE (1980), more appropriately, attributed this thermal load to CH TRU waste based on the assumptions listed above. Thorne and Rudeen (1980) estimated the maximum rise in temperature at the center of a repository to be 1.6°C at 80 years after waste emplacement.

Sanchez and Trellue (1996) estimated the maximum thermal power of an RH TRU waste container. The Sanchez and Trellue (1996) analysis involved inverse shielding calculations to evaluate the thermal power of an RH TRU container corresponding to the maximum permissible surface dose; according to the WAC the maximum allowable surface dose equivalent for RH TRU containers is 1000 rem/hr. The following calculational steps were taken in the Sanchez and Trellue (1996) analysis:

- Calculate the absorbed dose rate for gamma-ray radiation corresponding to the maximum surface dose equivalent rate of 1000 rem/hr. Beta and alpha radiation are not included in this calculation because such particles will not penetrate the waste matrix or the container in significant quantities. Neutrons are not included in the analysis because, according to the WAC, the maximum dose rate from neutrons is 270 mrem/hr, and the corresponding neutron heating rate will be insignificant.

- Calculate the exposure rate for gamma radiation corresponding to the absorbed dose rate for gamma radiation.

- Calculate the gamma flux density at the surface of a RH TRU container corresponding to the exposure rate for gamma radiation. Assuming the gamma energy is 1.0 MeV the maximum allowable gamma flux density at the surface of a RH TRU container is about 5.8×10^8 gamma rays per square centimeter per second.

- Determine the distributed gamma source strength, or gamma activity, in an RH container from the surface gamma flux density. The source is assumed to be shielded such that the gamma flux is attenuated by the container and by absorbing material in the container. The level of shielding depends on the matrix density. Scattering of the gamma flux, with loss of energy, is also accounted for in this calculation through inclusion of a gamma buildup factor.

The distributed gamma source strength is determined assuming a uniform source in a right cylindrical container. The maximum total gamma source (gamma curies) is then calculated for a RH TRU container containing 0.89 cubic meters of waste. For the waste of greatest expected density (about 6,000 kilograms per cubic meter) the gamma source is about $2x10^4$ curies per cubic meter.

- Calculate the total curie load of a RH TRU container (including alpha and beta radiation) from the gamma load. The ratio of the total curie load to the gamma curie load was estimated through examination of the radionuclide inventory presented in the WIPP Baseline Inventory Report (BIR) (DOE, 1995). The gamma curie load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of total curie load to gamma curie load of RH TRU waste was calculated to be 1.01.

- Calculate the thermal load of a RH TRU container from the total curie load. The ratio of thermal load to curie load was estimated through examination of the radionuclide inventory presented in the WIPP BIR (DOE, 1995). The thermal load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of thermal load to curie load of RH TRU waste was calculated to be about 0.0037 watts/curie. For a gamma source of $2x10^4$ curies per cubic meter the maximum permissible thermal load of a RH TRU container is about 70 watts per cubic meter. Thus, the maximum thermal load of a RH TRU container is about 60 watts, and the WAC upper limit of 300 watts will not be achieved.

Note that Sanchez and Trellue (1996) calculated the average thermal load for a RH TRU container to be less than 1 watt. Also, the total RH TRU heat load is less than 10% of the total heat load in the WIPP. Thus, the total thermal load of the RH TRU waste will not significantly affect the average rise in temperature in the repository resulting from decay of CH TRU waste.

Temperature increases will be greater at locations where the thermal power of a RH TRU container is 60 watts, if any such containers are emplaced. Sanchez and Trellue (1996) estimated the temperature increase at the surface of a 60 watt RH TRU waste container. Their analysis involved solution of a steady-state thermal conduction problem with a constant heat source term of 70 watts per cubic meter. These conditions represent conservative assumptions because the thermal load will decrease with time as the radioactive waste decays. The temperature increase at the surface of the container was calculated to be about 3°C.

In summary, analysis has shown that the average temperature increase in the WIPP repository due to radioactive decay of the emplaced CH and RH TRU waste will be about 1.6°C, with a maximum rise occurring at the center of the repository at about 80 years after waste emplacement. Temperature increases of about 3°C may occur in the vicinity of RH TRU containers with the highest allowable thermal load of about 60 watts (based on the maximum allowable surface dose equivalent for RH TRU containers).

4.0 Conclusions

Heat from exothermic reactions and radioactive decay will result in minor temperature increases in the repository. The potential temperature increases caused by these processes are summarized in Table 2.

Table 2. Maximum temperature increases at the WIPP.

Heat Source	Maximum temperature increase	Time of maximum temperature increase
Backfill hydration	4.5°C	20 years after a drilling intrusion
Backfill carbonation	0.6°C	125 years after a drilling intrusion
Microbial degradation	0.8°C	120 years after a drilling intrusion
Aluminum corrosion	6.0°C	2 years after a drilling intrusion
Concrete hydration (seals)	25°C in the shaft seal 10°C in the surrounding salt	1 week after emplacement
Concrete hydration (waste)	2.0°C	1.4 years after a drilling intrusion
Radioactive decay of CH TRU waste	1.6°C	80 years after disposal
Radioactive decay of RH TRU waste	3°C near a few containers	Within 100 years after disposal

During the operational phase and soon after disposal concrete hydration in the panel closures and shaft seals will give rise to temperature increases lasting a few decades. Heat from radioactive decay will generate a maximum temperature increase of less than 2°C within 100 years after disposal. A number of potential exothermic reactions have been identified. These reactions are brine limited and will cause only minor perturbations to the temperature distribution within the disposal system. The maximum calculated rate of brine inflow to a waste disposal panel occurs for the S2 scenario involving an E1 drilling event at 350 years after disposal. The maximum temperature that could be achieved in the panel

occurs as a result of aluminum corrosion; this reaction could result in a maximum temperature increase of about 6°C two years after the drilling event. Similarly, rapid backfill hydration could result in a maximum temperature increase of less than 5°C. These predicted values of temperature increase are based on a number of conservative assumptions. For example, the calculated temperature resulting from aluminum corrosion is based on the assumption that no corrosion has occurred prior to the drilling event and that all the brine introduced to the waste panel is available for aluminum corrosion. In reality some aluminum corrosion is likely to have occurred prior to the drilling event, reducing the volume of aluminum available for the reaction, and other reactions with lower reaction enthalpies or lower reaction rates will consume brine resulting in a smaller temperature increase.

Temperature increases of the magnitude and duration shown in Table 2 will have no significant effects on the performance of the disposal system. The effects of such temperature increases on the performance of the disposal system have been discussed in the SNL Summary Memos of Record RNT-24 (thermochemical effects), S-10 and GG-4 (thermal convection), S-11, SP-6, RM-1 (thermally-induced stress).

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Attachment: memorandum of August 19, 1996, by Yifeng Wang, to Distribution. "Evaluation of the Thermal Effect of Exothermal Chemical Reactions for WIPP Performance Assessment: A revised version," Sandia National Laboratories.

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Sandia National Laboratories

Albuquerque, New Mexico 87185-1341

date: August 19, 1996

to: Distribution

from: Yifeng Wang (Org. 6832)

subject: Evaluation of the Thermal Effect of Exothermal Chemical Reactions for WIPP Performance Assessment: A revised version

Temperature increases caused by exothermal chemical reactions in the repository have been evaluated in the memo by Wang (1996). This memo is the revised version of the previous memo. Two revisions have been made: (1) anoxic steel corrosion reaction is no longer an exothermal reaction; (2) waste panel number is adjusted from eight to ten. All revisions made here do not change the conclusion that the thermal effect of exothermal chemical reactions in the repository is negligible.

Assumptions:

The following exothermal chemical reactions are considered:

$$MgO + H_2O \rightarrow Mg(OH)_2 \quad (1)$$

$$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 \quad (2)$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2 \quad (3)$$

$$Al + 3H_2O \rightarrow Al(OH)_3 + 1.5\ H_2\ . \quad (4)$$

Anoxic steel corrosion is a major chemical reaction expected to occur in the repository:

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2. \quad (5)$$

However, this reaction is considered here, because it is not an exothermal reaction. The enthalpy change of Reaction (5) is estimated to be 0.64 Kcal/mole Fe.

Considering that the vertical dimension of the repository (~ 1 m, B. M. Butcher, personal comm.) will be much less than the horizontal extension after room closure, we assume that the heat released from the reactions will be dissipated away mainly from the ceiling and ground of the repository and the heat loss from the side walls is negligible. We also assume that all reactions will take place uniformly in a reaction region of interest. We here restrict the reaction region in a single waste panel, for the following reason: Some of the above reactions may be limited by brine inflow. BRAGFLO simulations have shown that, in the human intrusion cases, the rate of brine inflow into a borehole-penetrated waste panel will be significantly higher than that into the rest of the repository. Choosing a panel rather than the whole repository as a reaction region will make heat generation rate per unit of volume higher and the heat dissipating surface area smaller in our calculations, and

therefore it is conservative. However, this choice will not affect the calculations for the reactions that are not limited by brine inflow, as you will see below.

Theory:

Based on these assumptions, the thermal effect of an exothermal chemical reaction can be modeled by a simplified system shown in Figure 1. The temperature distribution (T) can be described by the following equations:

$$C_p \rho \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial X^2} \tag{6}$$

$$T(X,0) = T_0 \tag{7}$$

$$R\Delta H = 2Sk \left. \frac{\partial T}{\partial X} \right|_{X=0} \tag{8}$$

$$T(\infty, t) = T_0 \tag{9}$$

where C_p is the heat capacity of surrounding rocks (J/mole/K); ρ is the molar density of surrounding rocks (moles/m^3); t is time (year); X is the spatial coordinate (m); k is the thermal conductivity of surrounding rocks (J/year/m/K); T_0 is the background temperature (K); R is the reaction rate (moles/year); ΔH is the enthalpy change of the reaction (J/mole); S is the horizontal area of a waste panel (m^2).

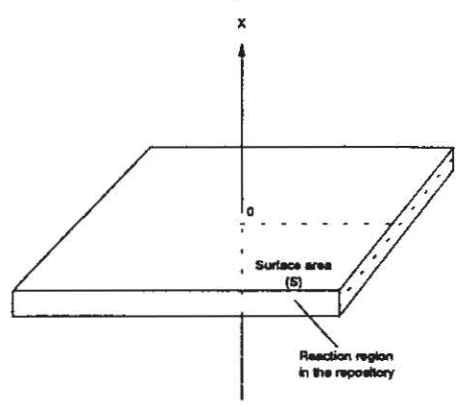

Figure 1. A modeling system for heat production and conduction.

The above equations can be solved for T with a Laplace-transformation method:

$$T - T_0 = -\frac{R\Delta H}{2S\sqrt{C_p\rho k}}\left[2\sqrt{\frac{t}{\pi}}e^{-\frac{C_p\rho X^2}{4Kt}} - \sqrt{\frac{C_p\rho}{k}}X\,erfc\left(\frac{X}{2}\sqrt{\frac{Cp\rho}{kt}}\right)\right]. \tag{10}$$

The temperature increase in the repository (ΔT) is obtained by setting X = 0 in equation (6):

$$\Delta T = T(0,t) - T_0 = -\frac{R\Delta H}{S}\sqrt{\frac{t}{\pi C_p\rho k}}. \tag{11}$$

Equation (7) shows that the repository temperature will increase with t until $t = \frac{M}{R}$, when all the reactant is consumed. Here M is the inventory of the reactant in a waste panel (moles). Therefore, the maximum temperature increase (ΔT_{max}) in the repository due to the exothermal reaction can be calculated by

$$\Delta T_{max} = T(0,t) - T_0 = -\frac{\Delta H}{S}\sqrt{\frac{RM}{\pi C_p\rho k}}. \tag{12}$$

Equation (12) shows that, for the reactions not limited by brine inflow, reducing the reaction region size does not affect ΔT_{max}, because the parameters S, R, and M will be reduced by the same factor, which is canceled out in the equation. This is not true for the brine-limited reactions, the rates of which are no longer dependent on reactant inventory.

Assuming the physical properties of the surrounding rocks can be represented by halite, we then have:

C_p = 50 J/mole/K (Lide, 1994, p. 12-158)

$\rho = 3.7\text{x}10^4$ moles/m^3 (Lide, 1994, p. 4-149)

k = 6 W/m/K = $1.9\text{x}10^8$ J/year/m/K (Lide, 1994, p. 12-165)

S = $1.2\text{x}10^4$ m^2 (Sandia WIPP Project, 1992, p. 3-4).

With these parameter values, we obtain from equation (12):

$$\Delta T_{max} = 2.5x10^{-12} \Delta H \sqrt{RM} \,. \qquad (13)$$

Results:

(1) Reaction: $MgO + H_2O \rightarrow Mg(OH)_2$

We assume that this reaction is instantaneous and thus is limited by brine inflow. Based on BRAGFLO simulations for E1 scenario (Figure 2), the conservative (maximum) estimate of the rate of brine inflow into a borehole penetrated waste panel is about 200 m^3/year, equivalent to the reaction rate of $1.1x10^7$ moles/year. With $\Delta H = -3.9x10^4$ J/mole (Drever, 1982, p. 351-356) and $M = 2x10^8$ moles, we estimate $\Delta T_{max}, \approx 4.5$ K.

(2) Reaction: $Mg(OH)_2 + CO_2(g) = MgCO_3 + H_2O$

We assume that this reaction is limited by microbial CO_2 production. It is estimated that the maximum rate of CO_2 production (R) is $2.9x10^5$ moles/year and the total CO_2 that can be produced (M) is $3.6x10^7$ moles in a single waste panel (Wang & Brush, 1996; DOE/CAO, 1996). With $\Delta H = -0.8x10^5$ J/mole (Drever, 1982, p. 351-256), ΔT_{max}, is estimated to be 0.6 K.

(3) Microbial degradation: $C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2$

The maximum reaction rate and the inventory of $C_6H_{10}O_5$ in a single waste panel are estimated to be $1x10^5$ moles/year and $1.2x10^7$ moles (Wang & Brush, 1996; DOE/CAO, 1996). With $\Delta H = -3.1x10^5$ J/mole (Lide, 1994, p. 5-16 to 5-37), ΔT_{max}, is estimated to be 0.8 K. Because of lack of thermodynamic data for cellulose materials, we here assume that the enthalpy of $C_6H_{10}O_5$ is approximately equal to that of $C_6H_{10}O_4$.

(4) Aluminum corrosion: $Al + 3H_2O \rightarrow Al(OH)_3 + 1.5\ H_2$

The inventory of Al in a single panel is about $8x10^6$ moles (DOE/CAO, 1996). Aluminum are present as foil in the waste and its thickness is estimated to be $2.54x10^{-4}$ cm. The total surface area of Al foil is thus estimated to be ~ $2.6x10^8$ m^2. With this high surface area and the measured corrosion rate (2.9 mole H_2/m^2/year, Telander & Westerman, 1996), Al corrosion reaction is expected to be limited by brine inflow, and the maximum corrosion rate is ~ $0.4x10^7$ moles/year. With $\Delta H = -4.4x10^5$ J/mole (Drever, 1982, p. 351-356), ΔT_{max}, is estimated to be 6 K.

Figure 2. SNL WIPP PA96: BRAGFLO SIMULATIONS (CCA R1 S2)

Cumulative Brine Inflow into Waste Panel

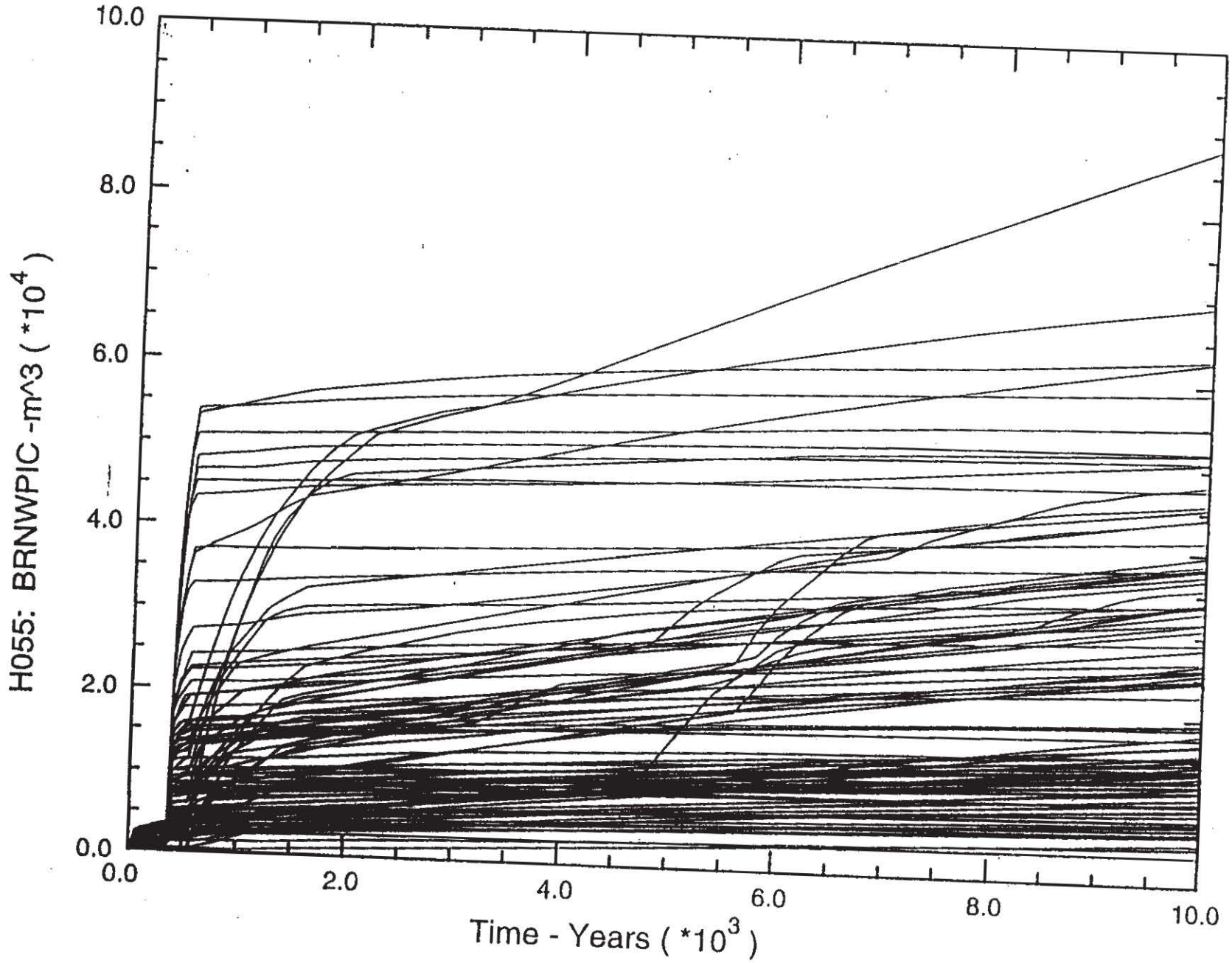

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The two brine-inflow-limited reactions - MgO hydration and Al corrosion - could possibly bring repository temperature up to 6 K. However, this temperature increase will not affect the overall repository performance, for two reasons: (1) The maximum temperature, if it is achieved, will be sustained only over a very short time period. For example, to achieve this temperature, Al has to be corroded completely within 2.5 years. After that, the accumulated heat will be dissipated away quickly. Thus, the maximum temperature, if it is attained, will last perhaps less than a year. (2) More importantly, because the two reactions are brine-limited, they will consume all free brine in the repository until all the reactants are completely consumed. Therefore, the maximum temperature will occur much earlier than enough free brine accumulates in the repository for the release of dissolved actinides. Based on the above calculations, the thermal effect of the other reactions, which are not limited by brine inflow and can last over a significant portion of 10000 year time period, are definitely negligible.

In conclusion, ignoring the thermal effect of chemical reactions (1 - 5) can not affect the overall repository performance assessment.

References:

DOE/CAO (1996) Transuranic Waste Baseline Inventory Report (Rev. 3).

Drever, J. I. (1982) The Geochemistry of Natural Water. Prentice-Hall.

Lide, D. R. (1994) Handbook of Chemistry and Physics. CRC Press.

Sandia WIPP Project (1992) Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992. Volume 3: Model Parameters. SAND92-0700/3.

Telander, M. R. & Westerman R. E. (1996) Hydrogen Generation by Metal Corrosion in Simulated Waste Isolation Pilot Plant Environments: Final Report. (Draft)

Wang, Y. & Brush, L. H. (1996) Estimate of gas-generation parameters for the long-term performance assessment. memo to M. S. Tierney, 1/26/1996, WBS 1.1.09.1.1(RC).

Wang, Y. (1996) Evaluation of the Thermal Effect of Exothermal Chemical Reactions for WIPP Performance Assessment. memo to V. R. Bynum & L. H. Brush, 7/19/1996, WBS 1.1.09.1.1(RC).

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SALADO FLOW PEER REVIEW PLAN

1. INTRODUCTION

This Peer Review Plan describes the process and documentation requirements for a peer review of the proposed changes to the Salado flow conceptual models used in the Waste Isolation Pilot Plant (WIPP) performance assessment (PA).

1.1 BACKGROUND

Peer review of conceptual models developed by the Department of Energy (DOE) for the WIPP is required by 40 CFR § 194.27 (EPA, 1996), promulgated by the Environmental Protection Agency (EPA). In accordance with this criterion, the Carlsbad Field Office (CBFO) of the DOE will conduct a peer review of specific conceptual models that are being revised due to changes invoked by the regulator or due to knowledge gained since the original conceptual models were developed. More specifically, a peer review is needed to determine whether revisions to selected Salado flow conceptual models that were developed for the Compliance Certification Application (CCA) (DOE, 1996) reasonably represent future states of the disposal system.

Sandia National Laboratories (SNL) is responsible for the development, maintenance, and conduct of WIPP performance assessments. In the PA for the CCA, SNL determined which processes were significant and developed conceptual models that represent possible future states of the disposal system and subsystems. These conceptual models were approved by the EPA during the original WIPP certification (EPA, 1998). Any proposed changes to the previously approved conceptual models must also be peer reviewed to ensure that future states of the disposal system continue to be adequately represented.

There are 24 conceptual models used in the PA. The proposed changes associated with Salado flow processes are expected to affect the following models:

- Disposal System Geometry
- Repository Fluid Flow
- Disturbed Rock Zone (DRZ)

The requirement for conducting a peer review of conceptual models is specified in 40 CFR § 194.27 (a) (1). The requirements for the peer review process and its documentation are specified in 40 CFR § 194.27(b) and (c). In summary, the peer review process shall be a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. The peer reviewers shall be independent of the work being reviewed;

independence from the work being reviewed means that the peer: a) was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to assure the work is impartially reviewed. Therefore, peer review of the subject matter provides additional assurance to the regulator and the public that the subject matter is reasonable, accurate and valid for its intended use.

1.2 PURPOSE

The purpose of this Plan is to present the plan to perform a peer review of selected Salado flow conceptual models. The process outlined in this plan must result in an independent critical review of the subject matter relevant to the revised conceptual models.

1.3 SCOPE

The Salado Flow Peer Review shall determine if proposed changes to the EPA-approved conceptual models result in revised conceptual models, which reasonably represent possible future states of the disposal system. The peer review shall be performed to meet all the requirements of NUREG-1297 (NRC, 1988), as required by 40 CFR § 194.27(b). The scope of the peer review is limited to assessing the validity of the models that result from these changes.

A peer review is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology and acceptance criteria employed, and of the conclusions drawn in the subject work. This Plan defines the management approach, resources, schedule, and technical requirements for using peer reviews to confirm the adequacy of the revised conceptual models.

2. PEER REVIEW PLANNING AND IMPLEMENTATION

2.1 APPROACH

This Plan documents the approach to conducting the peer review process. The Salado Flow Peer Review will be conducted using a rigorous proceduralized approach in accordance with NUREG-1297 (NRC, 1988). The DOE-CBFO has prepared a procedure, MP 10.5 (DOE, 2001a), for conducting peer reviews in accordance with NUREG-1297. The DOE-CBFO procedure ensures that the peer review will be a documented, critical review performed by qualified peers who are independent of the work being reviewed. Specifically the Salado Flow Peer Review Panel will:

- Follow MP 10.5 requirements. In the event of a conflict between MP 10.5 and NUREG-1297, NUREG-1297 will take precedence over MP 10.5.

- Administer and document the peer review process. Activities include documenting the selection of panel members, assignment of a panel leader, panel member independence documentation and recording and archiving meeting minutes.
- Negotiate schedule for the peer review with the DOE-CBFO Assistant Manager (or designee).
- Conduct and document peer review caucuses.
- Communicate interim peer review findings in hardcopy to the DOE-CBFO Assistant Manager (or designee).
- Produce a formal written report of the peer review findings and conclusions.
- Follow QA requirements for document preparation, control and records archiving.

2.1.1 DESCRIPTION OF CONCEPTUAL MODELS TO BE REVIEWED

Changes have been proposed to three of the conceptual models that represent Salado flow. The conceptual models affected are: Disposal System Geometry, Repository Fluid Flow, and the Disturbed Rock Zone (DRZ). The specific changes to these conceptual models are: 1) change of the shaft model in the BRAGFLO grid, 2) a change to the panel closure dimensions to conform to the Option D panel closure design mandated by the EPA, and 3) changes to the repository layout in the BRAGFLO grid. The changes to the conceptual models are the result of the EPA-mandated choice of the Option D panel closure design and a desire to improve the efficiency of the Salado flow computational model (BRAGFLO). Detailed descriptions of these changes will be provided to the peer review panel through written documentation and oral presentations.

The conceptual models under review were approved by the EPA in their certification of compliance (EPA, 1998). As such, the peer review panel is tasked with reviewing the results of the proposed changes to the conceptual models. The peer review panel shall limit the scope of the review as follows:

Changes within the Scope of the Peer Review

- Reviewing the changes to the conceptual models which include:
  - Removal of the shaft as an explicit region in the BRAGFLO grid
  - Modification of the panel closure representation in the BRAGFLO grid to represent the Option D design mandated by the regulators.
  - Changes to repository layout for the number of panel closures in the BRAGFLO grid and for the flaring of the BRAGFLO grid

These changes are expected to change the conceptual models for Disposal System Geometry, Repository Fluid Flow, and the Disturbed Rock Zone.

Items Outside the Scope of the Peer Review

- Validity of the original conceptual models and conceptual model peer reviews
- Reviewing the codes that implement the conceptual models

2.1.2 COMPOSITION OF PEER REVIEW PANEL

The peer review panel will be composed of a minimum of three individuals who possess the subject matter technical expertise to a degree at least equivalent to that needed for the original work. The panel should include personnel who have demonstrated expertise in geologic disposal systems, rock mechanics, and the numerical modeling of fluid flow.

Each panel member will become familiar with the WIPP containment system and the basis of the conceptual models that describe the containment system by reviewing documents on a required reading list and through a formal orientation process. In addition they will be presented a basic description of how the conceptual models for PA are represented in numerical models, algorithms, and codes. The panel members will become familiar with the parameter inputs to the PA codes and the results of prior PAs, sensitivity analyses, and critical comments from previous reviews. Finally, each panel member will become familiar with the peer review process through formal training in the appropriate peer review procedure(s).

2.1.3 LOGISTICS AND MANAGEMENT

Required reading material necessary to support the Salado Flow Peer Review will be provided to the Peer Review Panel. The first technical meeting will be conducted in early May. It may be necessary to conduct the peer review in a phased manner due to the varied subject matter related to the Salado flow conceptual models. The DOE-CBFO Assistant Manager (or designee) will determine the review sequence based upon the availability of the models, technical staff, panel members, and other logistic factors. Flexibility will be required by all supporting organizations to accommodate potential schedule changes.

2.2 PEER REVIEW PROCESS

The DOE-CBFO Assistant Manager (or designee) is responsible for the peer review. Time Solutions Corp. has been selected as the peer review contractor. Mr. John Thies will serve as the contractor Peer Review Manager pending the approval by the DOE-CBFO Assistant Manager (or designee). This Peer Review Plan is submitted to the DOE-CBFO Assistant Manager (or designee) for approval. This Plan meets the

requirements of MP 10.5. It is understood that MP 10.5 shall supersede any discrepancies between this Plan and MP 10.5.

Mr. Thies will not assign a Peer Review Coordinator (per MP 10.5), but will perform the coordination duties with the help of an administrative assistant since the scope of the Salado Flow Peer Review is not expected to be labor intensive.

Mr. Thies will use a selection committee to select candidates for the peer review panel. Upon verification that the peer review panel members meet the criteria outlined in MP 10.5 Attachment 1, an orientation and training meeting will be scheduled for the peer review panel members. The peer review panel members are expected to complete their review of required reading materials prior to the orientation meeting.

The peer review panel shall perform their review using the evaluation criteria discussed in Section 2.3. Since this peer review is for changes to conceptual models that were peer reviewed previously, many of the adequacy criteria are not applicable because they were determined in the first peer review. It should also be noted that the validity of the results of the previous peer reviews should not be reviewed as part of this peer review. However, the peer review panel is free to comment, as they feel necessary to complete their review.

Throughout the review, the panel is encouraged to engage in clear and frank discussions with the individuals responsible for the work under review. However, the peer review panel must observe all rules for interaction with DOE-CBFO, SNL and stakeholders outlined in MP 10.5. The results of the Panel's review shall be formally documented in a report.

In addition, MP 10.5 states that the DOE-CBFO QA Manager is authorized to conduct independent assessments of the peer review process to ensure that all aspects of the peer review conform to the guidance of NUREG-1297, MP 10.5, and the latest version of the DOE-CBFO Quality Assurance Program Description (DOE, 1999). The DOE-CBFO QA Manager shall inform the Contractor Peer Review Manager (Mr. Thies) of any EPA requests for audits or assessments. The Contractor Peer Review Manager must comply with and resolve all issues arising from such audits or assessments.

2.3 ADEQUACY CRITERIA

Conceptual models that have been selected and developed by the DOE must meet commonly accepted technical and scientific standards based on an in-depth evaluation. The peer review panel shall use the evaluation criteria in NUREG-1297 as the basis for their review. The evaluation criteria in NUREG-1297 are as follows:

- Validity of assumptions;
- Alternate interpretations;
- Uncertainty of results and consequences if wrong;
- Appropriateness and limitations of methodology and procedures;

- Adequacy of application;
- Accuracy of calculations;
  Validity of conclusions; and
  Adequacy of requirements and criteria.

Additional criteria may be defined by the Panel. For example, the first review panel for conceptual models added a criterion for Information Used to Develop the Conceptual Model. Adequacy of the revised conceptual models will be determined based on whether or not they reasonably represent possible future states of the disposal system.

2.4 SCHEDULE

Attachment A presents a preliminary schedule of peer review activities for the process described in Section 2.1.3. This schedule will serve as the baseline schedule from which requested schedule deviations will be evaluated by Mr. Thies if appropriate. Revisions to the baseline schedule will not require revision to this Plan, but must be approved by the DOE-CBFO Assistant Manager (or designee).

2.5 DELIVERABLES

The Contractor Peer Review Manager shall provide weekly status reports addressing peer review progress against the schedule to the DOE-CBFO Assistant Manager (or designee). The DOE-CBFO Assistant Manager (or designee) shall negotiate all deliverables with the Contractor Peer Review Manager such that timely information is delivered to the panel. A final peer review report is scheduled to be delivered to the DOE-CBFO Peer Review Manager by March 9, 2003.

2.5.1 Peer Review Report

The peer review report shall, as a minimum:

- Be signed by each peer review panel member
- Describe the work or issues that were reviewed
- Describe the conclusions reached by the peer review panel (e.g., the peer review panel observation comments and overall conclusions).
- Provide additional statements by the peer review panel members reflecting dissenting views or additional comments as appropriate
- List the peer review panel members and provide acceptability information (i.e technical qualifications and independence) for each member.

3. QUALITY ASSURANCE

The peer review process will be conducted and documented in a controlled manner and in compliance with the DOE-CBFO Quality Assurance Program Description, CAO-94-1012 and other applicable QA procedures. The DOE-CBFO QA Manager may appoint a QA observer to attend the peer review orientation, the peer review training, and peer review meetings. The DOE-CBFO QA Manager may schedule an assessment or audit of the contractor's peer review process and records prior to completion of the review. Upon communication with EPA, the DOE-CBFO QA Manager may schedule any audits or assessments the EPA wishes to perform.

4. RECORDS MANAGEMENT

Records generated as a result of peer review activities defined in this peer review plan and designated as QA records shall be maintained in accordance with DOE-CBFO Management Procedures MP 4.5, Generating, Receiving, Storing, and Controlling Active DOE-CBFO Project Records (DOE, 2001b), and MP 4.9, Quality Assurance Records (DOE, 2001c). Records include items generated by the DOE-CBFO, the peer review Contractor, and SNL and include:

- Salado Flow Peer Review Plan (this document)
- Peer Review Procedure(s)
- Contract documents
- Peer Review Panel Member Verification of Education/Employment Forms
- Determination of Peer Review Panel Member Independence Forms
- Peer Review Panel Selection Justification/Decision Forms
- Peer Review Panel Member Orientation and Training Forms
- Meeting minutes and presentation materials
- Written Materials presented to the Peer Review Panel by DOE-CBFO or investigators
- Written information presented to the Peer Review Panel Members by Observers
- Peer Review Report(s)

QA records shall be maintained by the Contractor Peer Review Manager until completion of the contract with the peer review organization. Duplicate records shall be generated and maintained at separate facilities. Upon completion of the peer review process, the original copy of the QA records (where possible) shall be formally

transferred and delivered to the DOE-CBFO Assistant Manager (or designee) for retention.

5. DOCUMENT CONTROL

All plans, procedures, and other documents that require document control will be processed in accordance with applicable DOE-CBFO controlled document procedures.

6.0 REFERENCES

DOE (U.S. Department of Energy), 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO 1996-2184, October 1996.

DOE (U.S. Department of Energy) 1999. Quality Assurance Program Description (QAPD), DOE-CBFO-94-1012, Revision 4, November 2002.

DOE (U.S. Department of Energy), 2001a. Peer Review, DOE-CBFO Management Procedure MP 10.5, Revision 5, February 1, 2003.

DOE (U.S. Department of Energy), 2001b. Quality Assurance Records, DOE-CBFO Management Procedure MP 4.5. February 16, 2001.

DOE (U.S. Department of Energy), 2001c. Quality Assurance Records, DOE-CBFO Management Procedure MP 4.9, Revision 1, March 4, 2001.

DOE (U.S. Department of Energy), 2001d. Document Preparation and Control, DOE-CBFO Management Procedure MP 4.4, Revision 4, January 5, 2001.

DOE (U.S. Department of Energy), 2001e. Document Review, DOE-CBFO Management Procedure MP 4.2, Interim Change Notice (ICN) #1, June 11, 2002.

EPA (U.S. Environmental Protection Agency). 1996. 40 CFR Part 194: Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations Final Rule. Federal Register, Vol. 61, No. 28, pp.5224-5245, February 9, 1996.

EPA (U.S. Environmental Protection Agency). 1998. 40 CFR Part 194: Criteria for the Certification and Re-certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations: Certification Decision; Final Rule. Federal Register, Vol. 63, No. 95, pp. 27353-27406, May 18, 1998.

NRC (U.S. Nuclear Regulatory Commission), 1988. Peer Review for High-level Nuclear Waste Repositories, General Technical Position, NUREG-1297, February 1988.

Prepared by: John A. Thice

Print name and sign

Approved by: Daryl Mercer

Print name and sign

ATTACHMENT A

SALADO FLOW CONCEPTUAL MODEL PEER REVIEW SCHEDULE

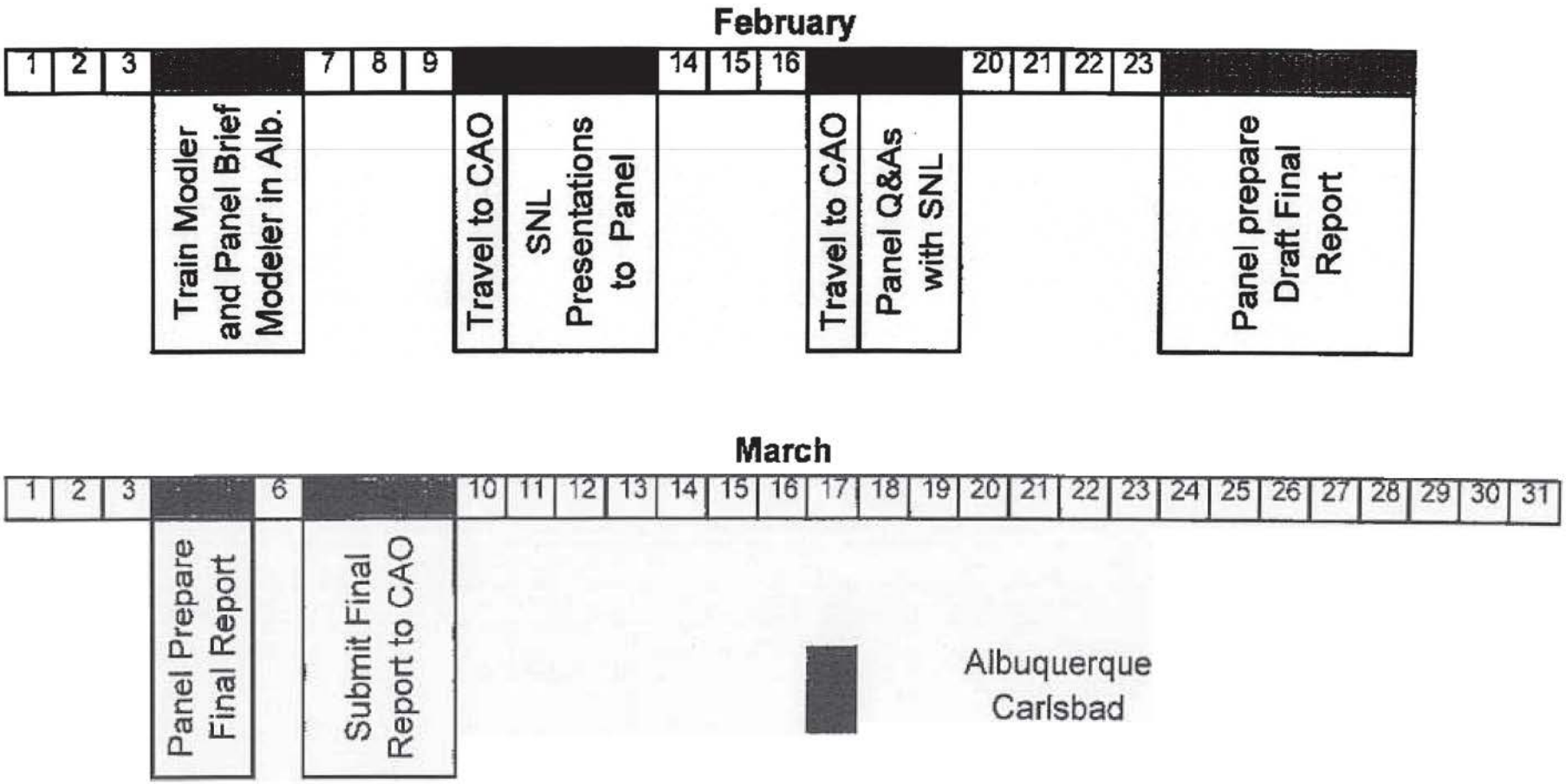

3.2.4 The Post-Penetration Wellbore Flow

In the current SNL model, it is assumed that the gas and spalled waste particles are mixed with drilling mud in the bit cavity forming a slurry; and the slurry is carried up through the wellbore to the surface by the circulating drilling mud. The motion of slurry, which contains mud, gas, salt, and waste particles, in the wellbore is governed by a compressible mixed Navier-Stokes equation. The equations are:

Mass balance equation,

$$\frac{\partial}{\partial t}(\rho V) + \frac{\partial}{\partial z}(\rho V u) = S_{mass},$$

Momentum balance equation,

$$\frac{\partial}{\partial t}(\rho V u) + \frac{\partial}{\partial z}(\rho V u^2) = -V(\frac{\partial p}{\partial z} - \rho g + F) + S_{mom},$$

The equation of state of constituents is:

For the mud, $\rho_m = \rho_{0(m)}[1 + c_m(p - p_0)]$,

For the gas, $\rho_g = \rho_{0(g)} \frac{p}{p_o}$,

and, For the salt and waste particles, $V_{s,w} = \frac{m_{s,w}}{\rho_{0(s,w)}}$.

In the above equations, u is the velocity of flow, ρ is the density of slurry, and V is the volume of slurry, i.e.,

$$V = V_{salt} + V_{waste} + V_{mud} + V_{gas}.$$

The effects of pipe friction, type of flow (laminar or turbulent), and slurry viscosity on the flow property are also taken into consideration in the calculation.

The ideal gas law is used in the formulation, the cavity is assumed to grow with drilling, and there is no momentum transfer between the gas and the mud during mixing. These assumptions are certainly reasonable.

The mass-transport formulation above addresses both the down-going and up-going mud columns in a continuous fashion. Implementation can be likened to a conveyor belt where the

first half of the belt is the down-going column and the second half is the up-going. At post-penetration, gas will be released from the repository and enter the mud-column. If spalling occurs, waste material will also enter the stream. It is important to note here that both the down-going and up-going mud columns are subject to the same boundary conditions within the cavity after post-penetration. This is the correct way to do it.

The model is sufficiently robust to adequately address the ballistic model of waste release as an extreme case. Should the repository gas pressure be sufficiently high, it is conceivable that the down-going flow could be choked off at the bit. Under this condition, there would be no mud supply to mix with the gas and waste entering the stream from the cavity. The up-going mud column would be supported only by a gas-waste column. This condition is sometimes referred to as a blow-out condition in oil field drilling.

The panel's opinion is that the above formulation is indeed proper for describing the release of spalled particles from the repository by the circulating mud during drilling. It is sufficiently robust to address all realistic scenarios.

Signature Page

for

Spallings Conceptual Model Peer Review Report

Revised

Section 3.2.4, The Post-Penetration Wellbore Flow

February 20, 2004

I acknowledge by my signature below that I concur with the attached revised Spallings Conceptual Model Peer Review Report Section 3.2.4, Post-Penetration Wellbore Flow.

Ching Yew 02/21/04

Ching Yew, Ph.D., Chairman Date

Jonathan Hanson, Ph.D. Date

Lawrence Teufel, Ph.D. Date

Signature Page
for
Spallings Conceptual Model Peer Review Report
Revised
Section 3.2.4, The Post-Penetration Wellbore Flow

February 20, 2004

I acknowledge by my signature below that I concur with the attached revised Spallings Conceptual Model Peer Review Report Section 3.2.4, Post-Penetration Wellbore Flow.

Ching Yew, Ph.D., Chairman — Date

Jonathan Hanson, Ph.D. — Date

Lawrence W. Teufel

Lawrence Teufel, Ph.D. — 02/23/04 Date

Signature Page
for
Spallings Conceptual Model Peer Review Report
Revised
Section 3.2.4, The Post-Penetration Wellbore Flow

February 20, 2004

I acknowledge by my signature below that I concur with the attached revised Spallings Conceptual Model Peer Review Report Section 3.2.4, Post-Penetration Wellbore Flow.

Ching Yew, Ph.D., Chairman — Date

Jonathan Hanson, Ph.D. — 2/23/04 Date

Lawrence Teufel, Ph.D. — Date

Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application for the Waste Isolation Pilot Plant

Appendix PEER-2004

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix PEER-2004

FOREWORD

Appendix PEER-2004 contains primarily the documents related to peer reviews performed after the submission of the Compliance Certification Application (CCA). The documents included in CCA Appendix PEER are not repeated in this Appendix, with one exception. All documents related to the Conceptual Models Peer Review (CMPR), contained in Appendix PEER are copied in Appendix PEER-2004. This is because the peer review panel, whose work was reported in CCA Appendix PEER, conducted three supplementary peer reviews after the submission of the CCA. Also, two peer reviews performed in 2003, while conducted by new peer review panels, are related to the CMPR panel's work performed in 1996-97.

In addition to the peer reviews conducted in accordance with NUREG-1297 in specific compliance with 40 CFR section 194.27 (a), CCA Appendix PEER included reviews performed by a number of review and oversight groups. This appendix includes additional reviews performed by the National Academy of Sciences (NAS), International Atomic Energy Authority (IAEA) and Nuclear Energy Authority (NEA) of the Organization for Economic Cooperation and Development (OECD), Institute for Regulatory Science (RSI), and Environmental Evaluation Group (EEG).

Chapter 9 of the Compliance Recertification Application (CRA) contains discussion of the peer review process and results, including detailed summaries of the peer reviews conducted since the submittal of the CCA in 1996.

Appendix PEER-2004 is divided into 38 attachments. These attachments break the appendix into major topical areas. Within each attachment there may be several documents of interest, as outlined in the Table of Contents.

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PEER-2004 1.0 Conceptual Models Peer Review (1996-97)

PEER-2004 1.1 Plan and Reports
PEER-2004 1.1.1 Conceptual Models Peer Review Plan (3/28/96)
PEER-2004 1.1.2 Conceptual Models Peer Review Report (July 1996)
PEER-2004 1.1.3 Conceptual Models Supplementary Peer Review Report (December 1996)
PEER-2004 1.1.4 Conceptual Models Second Supplementary Peer Review Report (January 1997)
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PEER-2004 4.1.1 The Waste Isolation Pilot Plant: A Potential Solution for the Disposal of Transuranic Waste (October 1996)
PEER-2004 4.1.2 Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant, Final Report (April 2001)
PEER-2004 4.1.3 Characterization of Remote-Handled Transuranic Waste for the Waste Isolation Pilot Plant, Final Report (July 2002)

PEER-2004 4.2 International Atomic Energy Authority (IAEA)/ Nuclear Energy Authority (NEA/OECD)
PEER-2004 4.2.1 International Peer Review of the 1996 Performance Assessment of the US Waste Isolation Pilot Plant (WIPP) (April 1997)

PEER-2004 4.3 Institute for Regulatory Sciences (RSI)
PEER-2004 4.3.1 Requirements for Disposal of Remote-Handled Transuranic Wastes at the Waste Isolation Pilot Plant (2001)
PEER-2004 4.3.2 Desirability of Performing Certain Transuranic Waste Characterization Tests (August 2003)

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PEER-2004 4.4.5	EEG-69: Sensitivity Analysis of Performance Parameters Used in Modeling the Waste Isolation Pilot Plant (May 1998)
PEER-2004 4.4.6	EEG-75: Evaluation of Risks and Waste Characterization Requirements for the Transuranic Waste Emplaced in WIPP During 1999 (May 2000)
PEER-2004 4.4.7	EEG-77: Plutonium Chemistry Under Conditions Relevant for WIPP Performance Assessment. Review of Experimental Results and Recommendations for Future Work. (September 2000)
PEER-2004 4.4.8	EEG-82: Evaluation of Proposed Panel Closure Modifications at WIPP (December 2001)
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PEER-2004 4.4.10	EEG-85: Analysis of Emplaced Waste Data and Implications of Non-Random Emplacement for Performance Assessment for the WIPP (May 2003)
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PEER 1 - Conceptual Models Peer Review

Title: CONCEPTUAL MODELS PEER REVIEW PLAN

(Assistant Manager, Office of Regulatory Compliance, Carlsbad Area Office) Date: 3/28/96

1. INTRODUCTION

This Conceptual Model Peer Review (CMPR) Plan describes the peer review and documentation the WIPP Project will use to ensure that the conceptual models used in performance assessment (PA) reasonably represent possible future states of the disposal system.

1.1 BACKGROUND

In accordance with the regulatory requirements, as specified in 40 CFR Part 191, and the criteria for the implementation of those requirements, as specified in 40 CFR Part 194, the Department of Energy (DOE) will conduct a peer review (PR) of the conceptual models used in the compliance certification application for the WIPP Project. Specifically, a PR will be conducted to determine whether the conceptual models developed and selected by DOE reasonably represent future states of the disposal system. Sandia National Laboratories (SNL) is responsible for the WIPP PA. SNL has determined which processes are significant and have developed conceptual models which represent possible future states of the disposal system and subsystems. To facilitate review of the conceptual models, they have been divided into the following three associated subsystems:

- Natural barriers (Salado and non-Salado flow and transport);
- Engineered barriers (rock mechanics and shaft/borehole seals); and
- Waste form and the disposal room.

SNL has developed a description of the conceptual models, the associated parameters, and parameter values, and is developing and implementing a process for the selection and assembly of data and other information which will be utilized to support PR of the conceptual models.

1.2 PURPOSE

The purpose of the WIPP PR process for conceptual models is to ensure that the conceptual models used in PA reasonably represent possible future states of the disposal system.

The requirement for conducting peer reviews is specified in sections 27 (a)(1) and 22 (b) of 40 CFR Part 194. Specifically, a PR is a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. The PR shall be independent of the work being reviewed; independence from the work being reviewed means that the peer: a) was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to assure the work is impartially reviewed.

1.3 SCOPE

This CMPR Plan describes the peer review process that the DOE Carlsbad Area Office (CAO) will use for review of conceptual models. A PR is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of the conclusions drawn in the original work. This Plan defines the management approach, resources, schedule, and technical requirements for using peer reviews to confirm the adequacy of the conceptual models.

2. PEER REVIEW PLANNING AND IMPLEMENTATION

2.1 APPROACH

The DOE-CAO has prepared this Conceptual Model Peer Review (CMPR) Plan to document the approach to conducting the PR process. The CMPR will be conducted using a rigorous proceduralized approach in accordance with NUREG-1297. The DOE-CAO has prepared a procedure for conducting peer reviews in accordance with sections 27 (a)(1) and 22 (b) of 40 CFR Part 194. The DOE-CAO procedure ensures that each PR will be a documented, critical review performed by qualified peers who are independent of the work being reviewed. SNL has prepared a procedure to provide the information necessary to support peer review of the conceptual models.

2.1.1 DESCRIPTION OF CONCEPTUAL MODELS TO BE REVIEWED

Section 23(a)(3)(v) of 40 CFR Part 194 requires that any compliance certification application shall include documentation that the conceptual models have undergone PR according to 40 CFR Part 194 section 27. SNL will provide a description of the conceptual models and other supporting information to the PR Manager for peer review. The following listed conceptual models have been identified to be reviewed:

CONTAINMENT SUB-SYSTEM	CONCEPTUAL MODELS
Natural Barriers (Flow & Transport)	Disposal System Geometry Culebra Repository Fluid Flow Salado Impure Halite Salado Interbeds Disturbed Rock Zone Actinide Transport (Salado) Units Above the Salado Dissolved Actinides (Culebra) Colloidal Actinides (Culebra) Exploration Boreholes Cutting/Cavings Spallings Blowout Castile & Brine Reservoir Multiple Intrusions Climate Change
Engineered Systems (Shaft Seals & Rock Mechanics)	Disposal Room Geometry Creep Closure Repository Fluid Flow Shafts & Shaft Seals Disturbed Rock Zone
Waste Form & Disposal Room (Disposal Room Closure & Chemistry)	Gas Generation Chemical Conditions Dissolved Actinide Source Term Colloidal Actinides Source Term

2.1.2 COMPOSITION OF PEER REVIEW PANEL

The CMPR Panel will be composed of a minimum of three individuals who possess the subject matter technical expertise to a degree at least equivalent to that needed for the original work. It is currently planned to have panel members who are experts in Natural Barrier System (flow and transport), Engineered Barriers (shaft seals and rock mechanics) and Waste Form and Disposal Room Chemistry.

Through a formal orientation process, each panel member will be made familiar with the WIPP containment system and the basis of the conceptual models which describe the containment system. In addition they will be provided a basic description of how

the conceptual models are represented in numerical models, algorithms, and codes. The peer reviewers will be made familiar with the parameter inputs to the PA codes and the results of prior PAs, sensitivity analyses, and critical comments from previous reviews. Each peer reviewer will be selected, oriented, and trained in accordance with approved procedures.

2.1.3 LOGISTICS AND MANAGEMENT

Not all information necessary to support peer review of conceptual models is currently available. Therefore, it is necessary to conduct the CMPR in a phased manner. The phasing dependens on information availability. The PR Manager, working closely with SNL, has developed a preliminary schedule that provides the necessary information on an "as available" basis. Flexibility is required by all supporting organizations (i.e., DOE-CAO, SNL, and the PR manager, staff and panel members) to accommodate schedule changes due to uncertainty in the timing of information availability.

2.2 SUGGESTED METHODS

The method to be used by the CMPR Panel for the adequacy and reasonableness of the conceptual models will be developed based on SNL requirements for the process of conducting PR. The methods the PR Panel uses to evaluate the subject matter shall include, as applicable, the adequacy criteria identified in section 2.3 below.

2.3 ADEQUACY CRITERIA

Conceptual models which have been selected and developed by the DOE must meet commonly accepted technical and scientific standards based on in-depth evaluation. The peer review panel will evaluate and report on, as applicable:

- Adequacy of requirements and criteria;
- Validity of assumptions;
- Alternate interpretations as appropriate;
- Uncertainty of results and consequences if wrong;
- Appropriateness and limitations of methodology and procedures;
- Adequacy of application;
- Accuracy of calculations; and
- Validity of conclusions.

Adequacy of the conceptual models will be determined based on whether or not they reasonably represent possible future states of the disposal system.

2.4 SCHEDULE

Based on the concept described in section 2.1.3, Attachment A presents a schedule of CMPR activities and milestones. This schedule will serve as the baseline schedule from which requested schedule deviations will be evaluated and approved if appropriate. Revisions to the baseline schedule will not require revision to this Plan, but will be attached to the plan by reference.

2.5 DELIVERABLES

Monthly status reports addressing CMPR progress against schedule and expenditures against budget will be submitted by the CTAC Project Manager and will be incorporated in the CTAC monthly report to the DOE-CAO. Significant variances in progress or spend rates will be explained and will include the cause of the variance, impact to the overall CMPR schedule and recommended corrective actions. A draft and final report of this PR will be submitted to DOE-CAO.

2.6 RESOURCE REQUIREMENTS

To meet the CMPR schedule as outlined in section 2.4 an estimate of the resources which may be required and the allowed manpower support levels are specified in Attachment C.

3. QUALITY ASSURANCE

The CMPR process will be conducted in a controlled manner and in compliance with the CAO Quality Assurance Program Description, CAO-94-1012, and other applicable QA procedures.

4. RECORDS MANAGEMENT

Records generated as a result of PR activities defined in this peer review plan and designated as QA records will be identified in the PR Procedure. Conceptual Models PR records will be assembled and maintained in accordance with the PR Management Procedure and the PR Desk Instruction(s). Ultimately, PR records will be dispositioned in accordance with DOE-CAO records management requirements. SNL records will be managed in accordance with SNL Records Management Procedure, SNL QAP 17-1.

5. DOCUMENT CONTROL

All plans, procedures, and other Documents which require document control will be handled in accordance with applicable DOE-CAO controlled document procedures.

ATTACHMENT A

CONCEPTUAL MODEL PEER REVIEW (CMPR) SCHEDULE

ACTIVITY	DRAFT	FINAL
CMPR Plan	3/8	3/29
PR Panel Assigned	NA	3/29
Information Package to PR Manager	3/15	4/2
Initiate CMPR	NA	4/2
Complete CMPR	NA	6/28
Submit CMPR Report	6/21	7/1

ATTACHMENT B

ESTIMATED PEER REVIEW RESOURCE REQUIREMENTS

Support	Hours
Subject matter experts	1800
Technical Coordinator	300
Clerical Support	300

CONCEPTUAL MODELS

PEER REVIEW REPORT

Final

Waste Isolation Pilot Plant

Conceptual Models Peer Review Report

A Peer Review Conducted By

Charles Wilson
Darrell Porter
John Gibbons
Eric Oswald
Glen Sjoblom
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for

U.S. Department of Energy
Carlsbad Area Office
Office of Regulatory Compliance

July 1996

FOREWORD

The U.S. Environmental Protection Agency promulgated "Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations Final Rule" in Code of Federal Regulations, Title 40, Part 194 (40 CFR Part 194) on February 9, 1996. The 40 CFR Part 194 regulation prescribes three specific peer reviews and also provides the opportunity for the Department of Energy to use peer reviews, conducted in accordance with NUREG 1297, as a means of qualifying data and information for use in the demonstration of compliance.

This report contains the results of a peer review of specific conceptual models to be used in the demonstration of WIPP compliance with 40 CFR Part 194. To ensure the independence of this review, the Department of Energy has directed the assignment of an independent contractor to administratively manage the peer review panel activities. Peer reviewers were selected based on their demonstrated independence from the work being reviewed and their technical expertise in the subject matter to be reviewed. The peer review panel members collectively possess an appropriate spectrum of knowledge and experience in the subject matter reviewed.

This peer review was conducted in full compliance with the quality assurance requirements as defined in 40 CFR Part 194.

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ACRONYMS

WIPP	Waste Isolation Pilot Plant
DOE	U.S. Department of Energy
SNL	Sandia National Laboratories
WID	Waste Isolation Division (Westinghouse)
EPA	U.S. Environmental Protection Agency
EEG	Environmental Evaluation Group
CCA	Compliance Certification Application
CFR	Code of Federal Regulations
TRU	transuranic (waste)
LWA	Land Withdrawal Act
CAO	Carlsbad Area Office
CTAC	Carlsbad Technical Assistance Contractor
ET	evapotranspiration
FEP	features, events, and processes
DRZ	disturbed rock zone
MB	marker bed
MDCF	multimechanism deformation coupled fracture
RM	reduced modules
FMT	fracture-matrix-transport
SIT	specific ion interaction

EXECUTIVE SUMMARY

This report presents the results of an independent technical peer review of the adequacy of 24 conceptual models representing features, processes, and events involved in assessing the long-term performance of the Waste Isolation Pilot Plant (WIPP). These models were identified by the U.S. Department of Energy (DOE) through its scientific advisor, Sandia National Laboratories (SNL). WIPP has been developed at a site near Carlsbad, New Mexico, by the DOE to become the nation's repository for geologic isolation of transuranic radioactive waste resulting from nuclear weapons programs. Westinghouse Electric Corporation, Waste Isolation Division (WID) is the operations contractor for the WIPP. SNL and WID have provided most of the information used in this review. This independent peer review is required by 40 Code of Federal Regulations (CFR) 194.27 as part of the compliance application prepared by the DOE. The U.S. Environmental Protection Agency (EPA) will use the peer review documentation to help ensure that an adequate scientific foundation exists for a national decision on whether to dispose of this waste at WIPP.

The independent review was conducted by a six-member interdisciplinary Review Panel (Panel) having the requisite broad experience and expertise to address the range of issues associated with the ability of WIPP to successfully isolate waste for the 10,000-year regulatory time frame. The peer review was conducted at SNL in Albuquerque, New Mexico, from April through June 1996. The Panel was given access to conceptual model descriptions, scientific reports, briefings, and SNL scientists, and to the SNL Nuclear Waste Management Program Library. During meetings of the Panel, representatives of the EPA, DOE, and New Mexico Environmental Evaluation Group (EEG) observed the Panel's deliberations. The Panel also had access to reports of prior peer reviews and had the full cooperation of the DOE, SNL, and WID throughout the review.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical processes, or intrusion scenarios, are to be represented in performance assessment. To be used in performance assessment, the conceptual model must be successfully translated into analytical statements and mathematical analogs. The Panel reviewed in detail the 24 conceptual models against criteria of the EPA, including the scientific information used to develop the model, the assumptions, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The Panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall performance assessment model. The review process and review criteria are discussed in Section 2.

The Panel has applied the stringent assessment criteria provided in NUREG 1297 and has concluded that thirteen of the models are adequate for implementation. The remaining eleven models were not found to be adequate for use in performance assessment of the WIPP. Models were judged to be inadequate if they failed to convince the Panel of their adequacy in terms of nine criteria. These criteria addressed: adequacy of information; validity of assumptions; alternatives evaluated; uncertainties; adequacy of the model and its application, accuracy, results, and conclusions; and whether the model was ready for implementation in the performance assessment process. Following is a list of the 24 models and a statement of the Panel's conclusion.

Disposal System Geometry	Adequate
Culebra Hydrogeology	Not Adequate (no consequence)*
Repository Fluid Flow	Not Adequate
Salado	Adequate
Impure Halite	Adequate
Salado Interbeds	Not Adequate
Disturbed Rock Zone	Adequate
Actinide Transport in the Salado	Adequate
Units Above the Salado	Not Adequate (no consequence)*
Transport of Dissolved Actinides in the Culebra	Adequate
Transport of Colloidal Actinides in the Culebra	Not Adequate
Exploration Boreholes	Not Adequate
Cuttings/Cavings	Adequate
Spallings	Not Adequate
Direct Brine Release	Not Adequate
Castile and Brine Reservoir	Not Adequate
Multiple Intrusions	Adequate
Climate Change	Adequate
Creep Closure	Adequate
Shafts and Shaft Seals	Adequate
Gas Generation	Not Adequate
Chemical Conditions	Not Adequate
Dissolved Actinide Source Term	Adequate
Colloidal Actinide Source Term	Adequate

*Although the conceptual model was found to be inadequate, no consequence to performance assessment is anticipated.

Several of the issues raised by the Panel could have significant effects on performance assessment. The details of evaluations and issues raised for each model are contained in Section 3 of this report. The relationships among the models are described in Section 4, and a summary of the evaluations is contained in Section 5.

The Panel believes that careful resolution of the issues discussed in Section 3, and any resulting changes to the models, will help to improve the overall quality of the performance assessment and provide a firmer basis for a national decision on whether to emplace waste at WIPP.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Conceptual Models Peer Review is one of several peer reviews being conducted by the U.S. Department of Energy (DOE). The Conceptual Models Peer Review focused on the conceptual models developed and selected by DOE through its scientific advisor, Sandia National Laboratories (SNL), to determine if they adequately and reasonably represent future states of the WIPP disposal system for use in performance assessment. This review was conducted in support of and meets the regulatory requirements of 40 Code of Federal Regulations (CFR) 191 and the implementation of those requirements by 40 CFR 194. In these regulations, this peer review of conceptual models is specifically identified by the U.S. Environmental Protection Agency (EPA) as an activity required to supplement the DOE's Compliance Certification Application (CCA) for the WIPP.

According to 40 CFR 194.27, the peer review is to be conducted in accordance with the Nuclear Regulatory Commission's document NUREG 1297, stipulating requirements for conducting peer reviews. The adequacy criteria set forth in NUREG 1297 were used by the Review Panel (Panel) as a baseline for reviewing DOE's conceptual models. To implement 40 CFR 194, DOE-Carlsbad Area Office (CAO) developed Team Procedure TP-10.5, which stipulates that a peer review is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn in the original work.

This report documents the results of the Conceptual Models Peer Review, as determined in accordance with the aforementioned requirements. Section 2 of this report presents background information relating to the WIPP facility and review methodology. This includes a description of the repository, its geologic and hydrogeologic settings, the scenarios used, review methodology, and evaluation criteria. Section 3 presents the evaluation of each of the 24 models as assessed against a predetermined list of nine evaluation criteria. Section 4 discusses the integration of the 24 models into an overall conceptual model for the waste disposal system. Section 5 provides a summary of the evaluations. These sections are followed by appendices which include administrative information and professional biographies for each of the Panel members.

2.0 BACKGROUND

The DOE was authorized in 1979 (by Public Law 96-164) and funded by the Congress to develop a facility for demonstrating the safe disposal of transuranic (TRU) radioactive wastes generated in national defense activities. The Land Withdrawal Act (LWA) of 1992 (Public Law 102-579) provided additional authorization to continue the project under a stipulated statutory process. This facility, the WIPP, is located in southeastern New Mexico. The WIPP is operationally ready to receive waste and is being proposed by DOE for EPA approval as an operating radioactive waste disposal facility through the CCA process. The purpose of the (Compliance Certification Application (CCA) is to demonstrate through performance assessments the ability of the WIPP to successfully isolate radioactive waste from the accessible environment for the 10,000-year regulatory time frame. If regulatory compliance is demonstrated and a decision to start disposal of waste at the WIPP is made, following the provisions of the LWA, the WIPP will be used for the permanent disposal of TRU wastes, including TRU wastes containing hazardous constituents (TRU mixed waste).

2.1. WIPP Overview

The WIPP facility has been constructed in southeastern New Mexico (Figure 2-1), 26 miles east of Carlsbad, on Federal land. Prior to October 1992, this land was administered by the U.S. Department of the Interior, Bureau of Land Management. In October 1992, Congress transferred jurisdiction of the land through the LWA to the Secretary of Energy. The site encompasses 10,240 acres in a sparsely populated area, with fewer than 30 people living within 10 miles of the WIPP. The immediate surrounding land is used for livestock grazing, potash mining, and oil and gas production.

Surface structures, the planned and partially developed underground repository, and four connecting shafts make up the WIPP facility. The purpose of the surface structures is to provide security and safeguards and to accommodate routine operations, administrative activities, and further scientific studies.

The underground excavation is 655 meters (2150 feet) below the surface in the bedded salt of the Salado Formation. It includes a 12-acre area used for conducting scientific investigations and experiments in which no waste will be placed, an operations area with equipment and maintenance facilities, an area in which the waste will be emplaced for permanent disposal if the disposal site approval decision is made, and four major interconnecting tunnels used for ventilation and traffic. The subsurface waste-disposal area is to cover 100 acres and will contain eight separately excavated panels, each containing

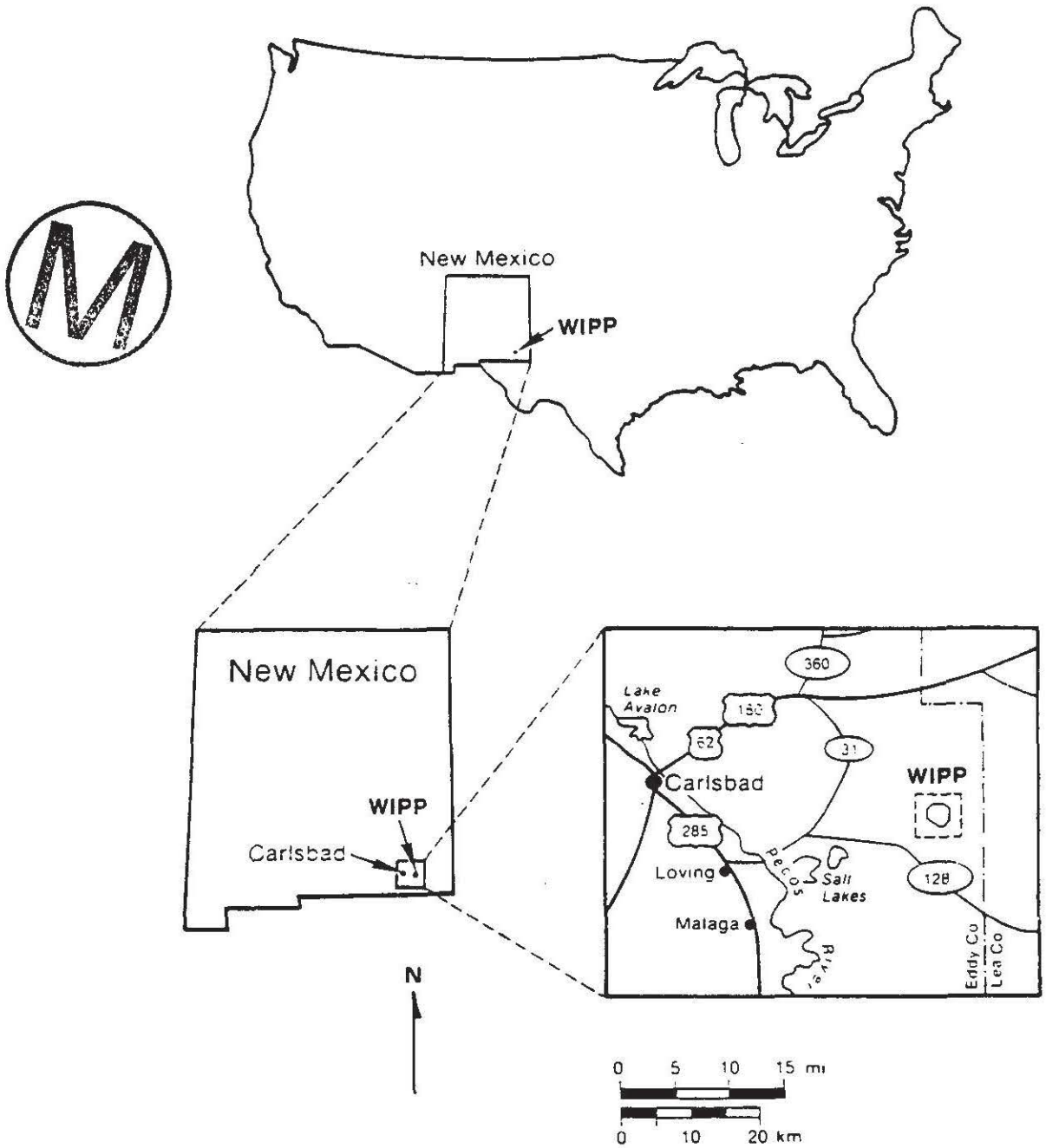

Figure 2-1. WIPP Facility Location

seven disposal rooms, and two additional panels in the area currently containing the drifts accessing the waste disposal area.

2.2. Peer Review Management

The Conceptual Models Peer Review was an independent review supported by the Office of Regulatory Compliance, DOE-CAO and delegated to its technical assistance contractor, known as the Carlsbad Technical Assistance Contractor (CTAC). CTAC commissioned Informatics Corporation, an independent firm, with the task of managing the peer reviews. The Conceptual Models Peer Review is the first of six peer reviews conducted between April 1 and August 15, 1996. The other peer reviews include: Engineered Systems Data Qualification Peer Review; Natural Barriers Data Qualification Peer Review; Waste Form and Disposal Room Data Qualification Peer Review; Passive Institutional Controls Peer Review; and Waste Characterization and Sensitivity Analyses Peer Review. Similar reviews are being conducted on engineered barrier evaluations by the WIPP operations contractor.

Each peer review was administered separately, with its own administrative coordinator and administrative assistant. Early in the review, a technical panel leader was selected from among the peer review members to serve as the focal point for the technical aspects of the review, analysis, and development of a report. The six panels shared access to an administrative document-gathering, recordkeeping, and document processing center comprised of several support staff.

The selection of panel members, training of coordinators and reviewers, and operation of the review process were governed by DOE-CAO's Team Procedure TP-10.5, the Conceptual Model Peer Review Plan, and Informatics' Desk Instruction IDI-1.0. Detailed information regarding the review process is further delineated in these documents and in the records of the Panel's review, both found in the SNL Records Center.

The Panel was requested to review the adequacy of the following 24 conceptual models that are being used by the DOE in assessing the future states of the geologic repository system.

1. Disposal System Geometry
2. Culebra Hydrogeology
3. Repository Fluid Flow
4. Salado
5. Impure Halite

6. Salado Interbeds
7. Disturbed Rock Zone
8. Actinide Transport in the Salado
9. Units Above the Salado
10. Transport of Dissolved Actinides in the Culebra
11. Transport Colloidal Actinides in the Culebra
12. Exploration Boreholes
13. Cuttings/Cavings
14. Spallings
15. Direct Brine Release
16. Castile and Brine Reservoir
17. Multiple Intrusions
18. Climate Change
19. Creep Closure
20. Shafts and Shaft Seals
21. Gas Generation
22. Chemical Conditions
23. Dissolved Actinide Source Term
24. The WIPP Colloidal Actinide Source Term

2.3. System Overview

The WIPP disposal system includes the underground repository and shaft system, the geologic host rocks, and the local and regional hydrologic system. Figure 2-2 shows the WIPP controlled area, the accessible environment, and the disposal unit boundary.

2.3.1. Repository

The WIPP surface facilities, shafts, and underground workings are shown in Figure 2-3. The WIPP repository includes four shafts (exhaust shaft, waste shaft, salt handling shaft, and air intake shaft), an experimental area, an operations area, and a waste disposal area.

Present plans call for mining eight panels of seven rooms each and two equivalent panels in the central drifts. As each panel is filled with waste, the next panel will be mined. Before the repository is closed

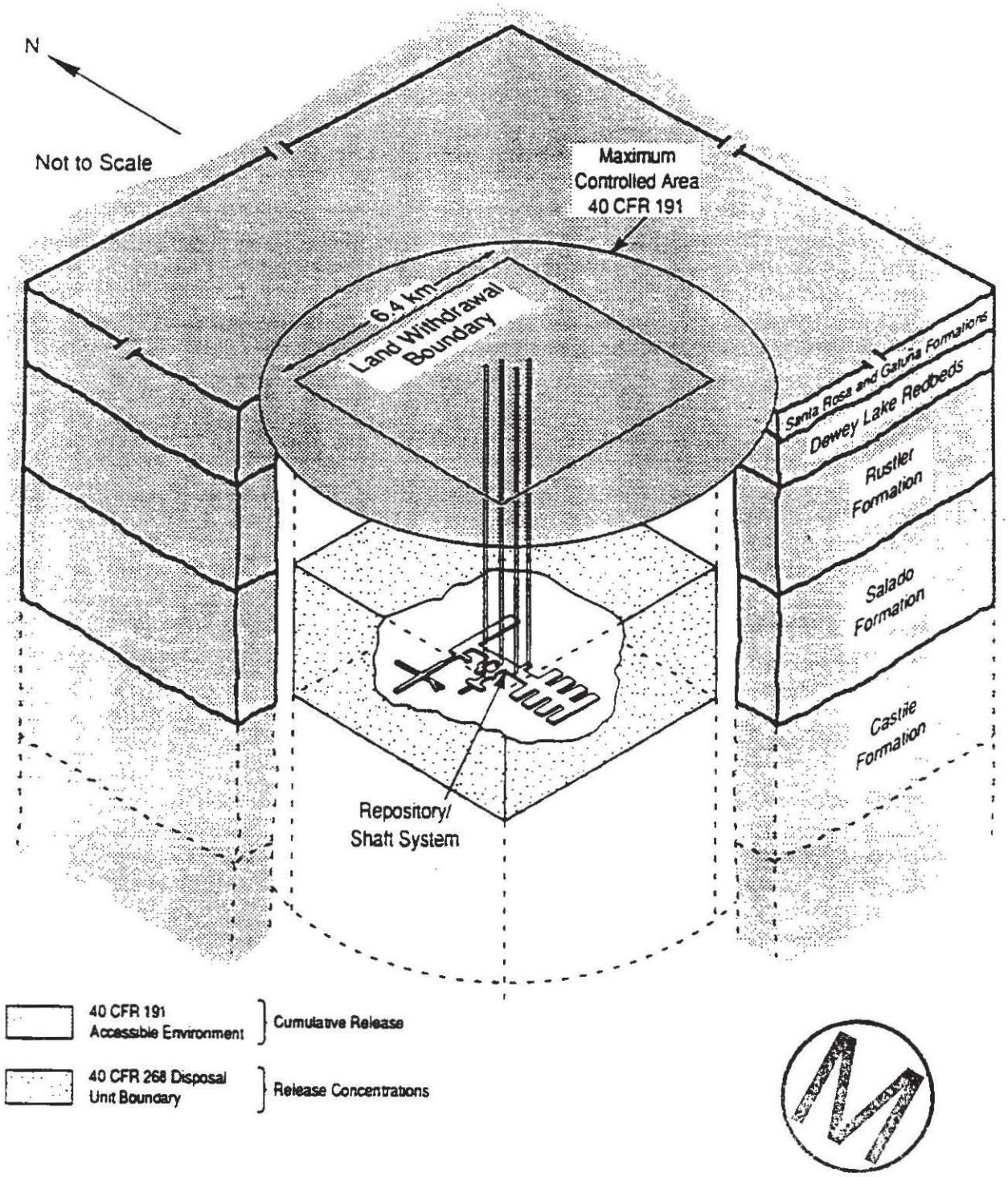

Figure 2-2. WIPP Controlled Area

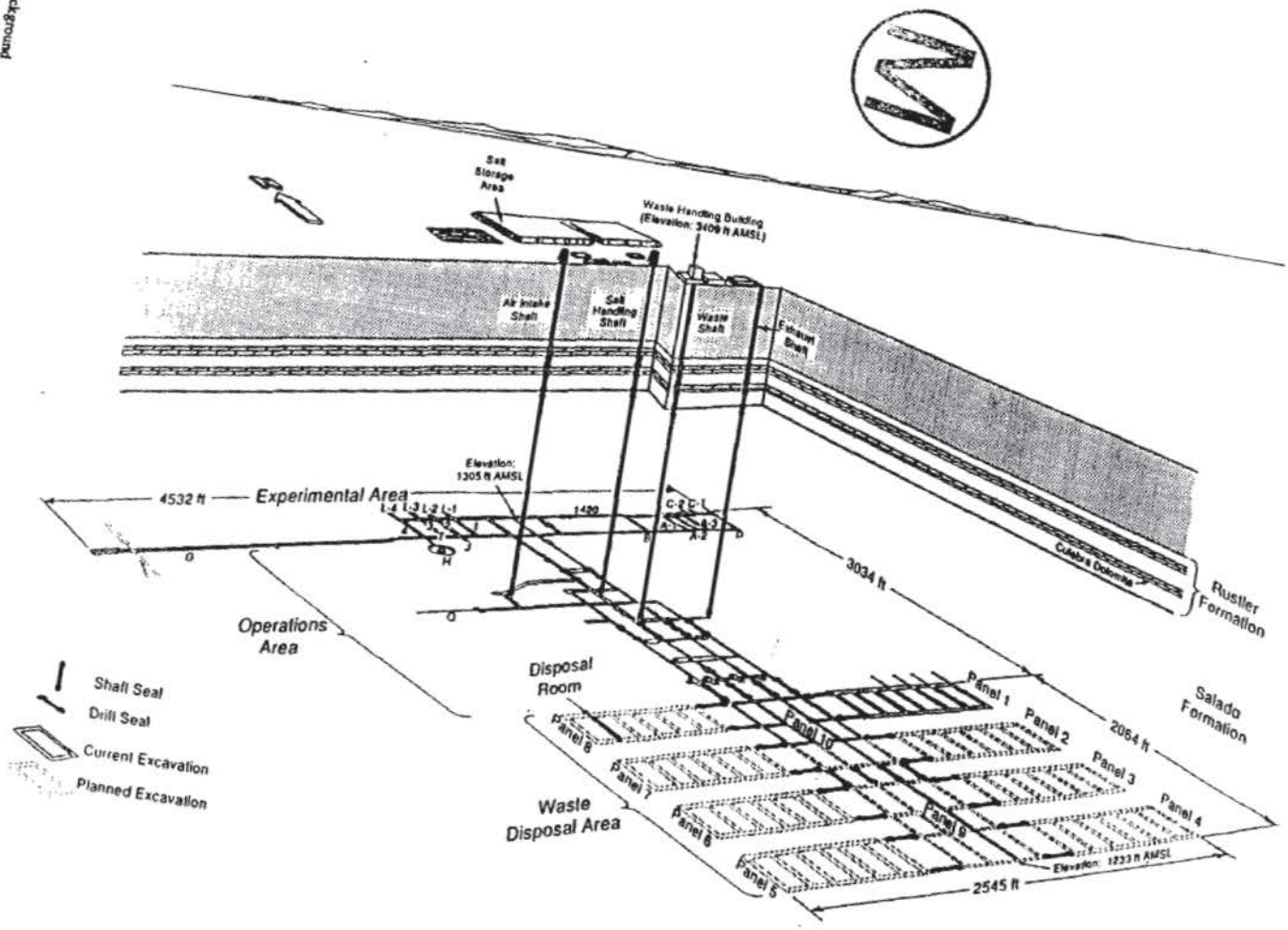

Figure 2-3. WIPP Facilities

permanently, each panel will be sealed, waste will be placed in the drifts between the panels, creating two additional panel volumes, and access ways will be sealed off from the shafts. The shafts will then be sealed to isolate the repository from the ground surface. Final closure of the facility will be facilitated by the creep closure of the salt.

2.3.2. Geologic Setting

The geologic history of southeastern New Mexico and the data collected regarding the subsurface stratigraphy at the WIPP site are important and are discussed extensively in Section 2 of the CCA (DOE 1996) and documents referenced in the CCA. The general stratigraphy at the WIPP site is presented in Figure 2-4. The relevant geologic background setting for the peer review, however, includes specific formations and their lithologies. The Bell Canyon, Castile, Salado, Rustler, Dewey Lakes, Gatuna, and Santa Rosa Formations are the lithologic units within which the conceptual models represent processes and predictions of future states of the proposed disposal system.

The sandstones, siltstones, limestones and shales of the Bell Canyon Formation define the first extensive, continuous, transmissive unit below the WIPP repository and provide a source of groundwater that could migrate vertically into the repository. The halite and anhydrite beds of the Castile Formation separate the Bell Canyon from the Salado and contain pressurized brine reservoirs. Brine reservoirs are a repository performance concern expressed in human intrusion scenarios. The halite-dominated Salado Formation contains the proposed repository and provides the primary natural barrier for containing radionuclides. The laterally extensive Culebra Dolomite Member of the Rustler Formation is the closest stratigraphic unit above the Salado with the potential to transport a radionuclide release to the accessible environment. Studies conclude that transmissivities in the Culebra vary by six orders of magnitude across the WIPP site area. Fracturing and vuggy zones account for much of the variability in the physical/hydraulic properties of the Culebra.

While other stratigraphic members of the Rustler Formation, beds of anhydrite and polyhalite, clays, and other inclusions may be important as each of the conceptual models is reviewed, the four formations and units described above define the most important components of the geologic setting for the WIPP conceptual models review.

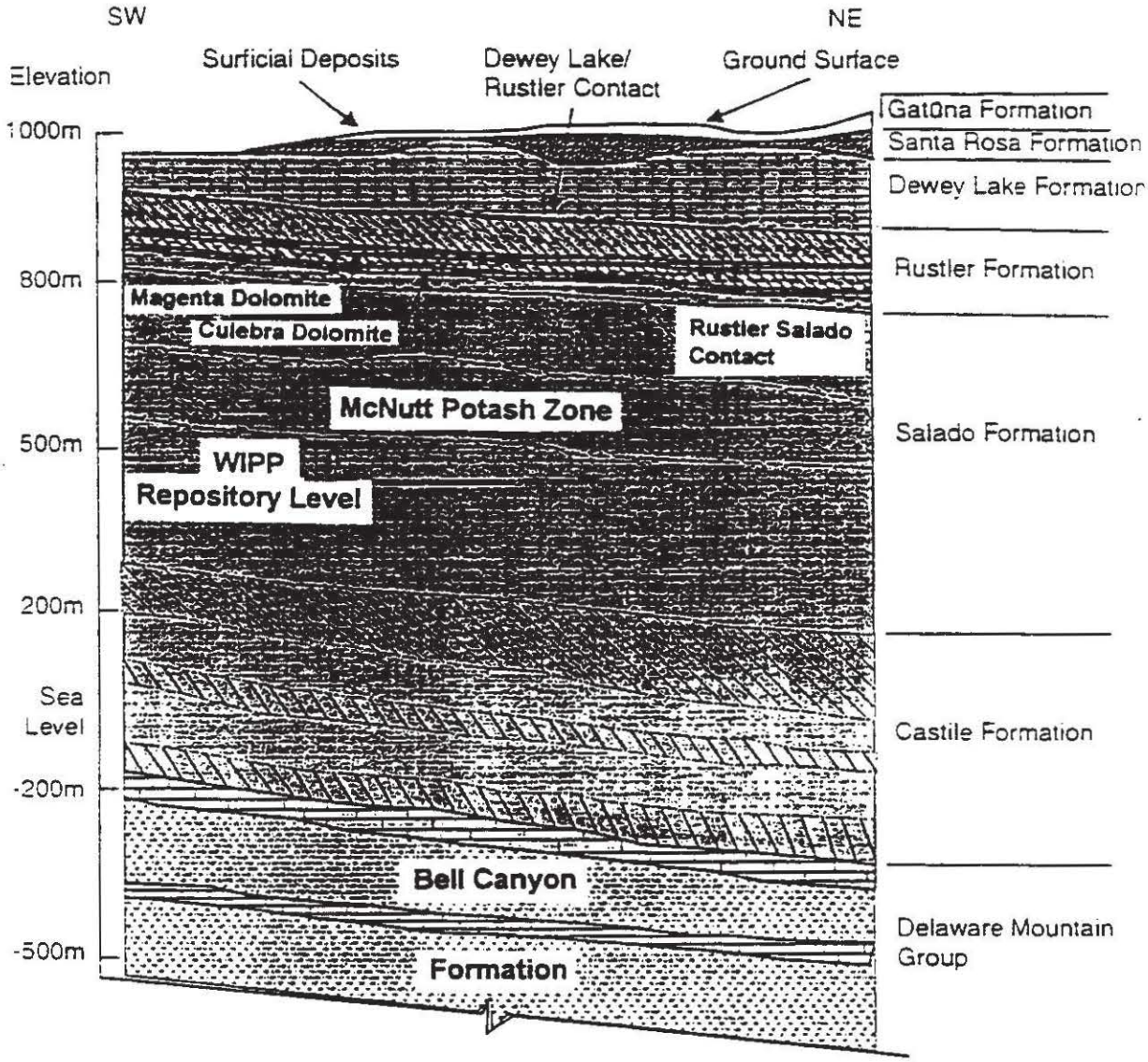

Figure 2-4. General Stratigraphy at the WIPP Site

2.3.3. Hydrologic Setting

2.3.3.1. Surface Water

The WIPP site is located within the Pecos River Basin. At its nearest point, the Pecos River flows approximately 12 miles southwest of the WIPP site boundary. There are no perennial streams at the WIPP site and in this semi-arid region, approximately 75% of annual precipitation results from intense, short-duration events between April and September. More than 90% of the mean annual precipitation is lost through evapotranspiration (ET) and on a mean annual basis, ET potential exceeds expected rainfall. EPA concluded in 1989 (EPA 1990a) that there were "no surface water features near the WIPP that could potentially affect repository performance in such a way as to influence the no-migration demonstration."

2.3.3.2. Groundwater

Extensive coring, logging and testing of boreholes in the vicinity of the WIPP site has provided data for the characterization of the hydrostratigraphy and hydrogeology important to the WIPP site region. While the deep Capitan Limestone, the Rustler-Salado contact zone near Nash Draw, and the shallower Dewey Lakes and Santa Rosa Formations are important in characterizing the WIPP region, the Bell Canyon, Castile, Salado, and Rustler Formations are the units critical to the evaluation of WIPP groundwater issues.

As presented in the geologic setting, the Bell Canyon Formation is the first continuous, transmissive, water-bearing unit beneath the WIPP. This formation provides a source of groundwater below the WIPP repository that could migrate into the repository if a pathway were available. The Bell Canyon Formation exhibits hydraulic conductivities in the range of 10^{-7} to 10^{-12} meters per second and pressures were measured in the range of 12.6 to 13.3 megapascals.

The Castile Formation is of interest to site characterization as a hydrologic barrier between the Salado and Bell Canyon Formations and because it contains isolated pressurized brine reservoirs. The Castile is predominantly low-permeability halite and anhydrite with greater permeabilities in zones of fracture and structural deformation. In the areas of higher permeability, brine pressures exist that are sufficiently above nominal hydrostatic pressure for brine to flow upward through a borehole to the surface.

The halite and anhydrite rocks of the Salado Formation are relatively impermeable and tests have shown that flows range from extremely low to no flow when appreciable pressures are applied. The Salado contains the proposed repository and provides the primary natural barrier for containing radionuclides.

The Magenta and Culebra Dolomite Members of the Rustler Formation are laterally extensive, transmissive, and display hydraulic characteristics sufficient for the lateral transport of radionuclides. Hydraulic conductivities in both members range over five to six orders of magnitude in the WIPP area, but the Magenta is generally less transmissive than the Culebra. The Culebra is the first, most extensive, and most transmissive unit above the Salado at the WIPP site. As such, the Culebra provides the most direct pathway from the WIPP repository to the accessible environment and is the most important component of the hydrogeologic setting for the conceptual models peer review.

2.4. Peer Review Panel Methodology

The review of the conceptual models commenced after a training/orientation period and was conducted in accordance with management plans, the conceptual model peer review plan, desk instructions, and other relevant protocols. Panel member qualifications are detailed in Appendix A of this report.

The work of the Panel began following training/orientation on April 5, 1996 and was scheduled to terminate on June 28, 1996 with the submittal of this final report. The Conceptual Model Peer Review Panel employed six basic approaches in their overall method of conducting and accumulating information for the reviews: 1) extensive review of available, referenced, and "roadmapped" literature relevant to the Panel; 2) attendance at briefings on conceptual models and relevant aspects of the performance assessment process; 3) conduct conceptual model or issue-focused presentations/question-and-answer sessions with DOE scientists and engineers; 4) intensive review of literature/documents discovered through continued research and focused question-and-answer sessions; 5) conduct formal and informal discussions among Panel members; and 6) participate in a tour of WIPP facilities and the local area outside the WIPP site, and in presentations/discussions associated with the tour.

The Panel was provided a list of 24 conceptual models to be independently reviewed with respect to whether or not they represent a reasonable view of future states of the proposed disposal system for the WIPP. For the review, conceptual models are defined as a set of qualitative assumptions used to describe a system or subsystem for a specific purpose. Although such a definition could limit the scope of a review, the Panel evaluated the models in accordance with NUREG 1297 criteria, from conception to their integration with mathematical representations, and paid careful attention to alternative models and approaches. In addition, the Panel recognized that individual models may warrant varying levels of reviews of their mathematical representations, computerized representations, and results.

Individual Panel members were assigned lead responsibility for specific conceptual model reviews and preparation of subsequent sections for the report. The Panel members collectively assumed writing responsibilities for introductory and conclusionary sections in the report.

Early in the review process five Panel members visited the WIPP site to tour surface and subsurface facilities and to view nearby geological features. The purpose of the visit was to view first hand the site-specific features that have potential impact on the long-term behavior of the WIPP. When touring the underground facilities, the Panel members observed the Q Room experiment site, the horizons of the Salado halite visible within the repository, fractures within the repository disturbed rock zone, and collapse features in a room where a roof had fallen. Panel members also visited the WIPP core library and observed selected core samples representative of the geological formations that could not be seen underground. Geological features viewed by the Panel near the WIPP included outcrops of the Culebra and Magenta Dolomites, Dewey Lakes Redbeds, and the Gatuna Formation. Two Panel members visited the Western AG potash mine northwest of the WIPP, where ore zones and anhydrite marker beds not visible at WIPP were seen.

Due to the large volume of project literature required for review, the Panel adopted a process in which each member would work independently in getting pertinent information on a given topic. Group briefings were reserved for the broader topics. All information was freely disseminated for consensus-building among Panel members in the completed analysis. On learning that complete information was not available to complete the Panel's scope of work on time, the Panel requested DOE to provide specific information on an accelerated interim basis. This proved to be highly beneficial to the timeliness of model reviews. It was recognized that much of this input had not been reviewed in accordance with SNL procedures and that some of the information reflected the current status of an ongoing decision process. The Panel members are aware that errors can be made in understanding and accuracy when using information of this type, and used the full access provided by DOE to those personnel necessary to provide guidance and clarification to the answers sought.

In organizing its work, the Panel established limitations on its review and the content of this report. Panel members did not review or offer comments on regulations. The Panel confined its review to the suite of conceptual models identified by DOE (Section 2.2). Finally, to maintain independence, the Panel will not offer recommendations for specific methods and approaches to address its concerns. A cutoff date of June 7, 1996 was established for receiving new information for inclusion in the review. It was

decided that if the Panel could not reach a conclusion due to a lack of information on a particular model, it would be so stated in the Panel's report.

Two additional activities were identified by DOE for the Panel. First, an overview of the Panel's finding would be presented to DOE, SNL, and observers, and the Panel would respond to questions raised to clarify the concerns identified in this report. The presentation is scheduled for July 1 and 2, 1996. Second, the Panel was requested to reconvene in August to review DOE's written responses to the Panel's findings, and prepare an addendum to this report, if necessary, indicating the adequacy with which the Panel's findings and concerns were resolved by SNL.

2.5. Criteria for Conceptual Model Review

The nine criteria used to review each of the 24 conceptual models are listed below along with a brief description of the way in which each was used by the Panel. Examples are provided where appropriate, to provide clarification. The nine criteria are based on the EPA regulation 40 CFR 194.27, NUREG 1297 Section IV.5, the EPA Compliance Application Guidance, and Panel discussions.

Information Used to Develop the Conceptual Model. This is an evaluation of data and information used to develop conceptual models and submodels. It includes attributes of the disposal system learned by DOE during site characterization activities, such as refinements to the room creep closure model or an improved understanding of disturbed rock zone characteristics.

Validity of Model Assumptions. The validity of key assumptions in the model and its application are assessed in terms of how they could affect the usefulness of the conceptual model. The review addresses the comprehensive inclusion of important features, events, processes, and other key assumptions. Examples are the assumption of Darcy flow in the various media, use of the ideal gas law at high pressures, or the method chosen to represent time-dependence of strain.

Evaluation of Alternatives. This section briefly identifies and assesses plausible alternative conceptual models or submodels seriously considered by DOE but not used, and the rationale why such alternative models were not used. Again, important features, events, and processes must be considered. The Panel does not expect the descriptions of alternative models to be as extensive as for the models chosen, but they should adequately document why the alternative models were not used. For example, the choice among matrix, dual porosity, or flow channeling in stratigraphic units, or the use of transmissivity fields versus uniform transmissivity, should be explained.

Uncertainties. This includes an evaluation of the key uncertainties in the selected conceptual models and a discussion of the consequences if aspects of the conceptual model chosen were inappropriate or incompletely constrained for the site or process. For example, if elements of the particular models used to estimate the effect of pH on actinide solubility or the permeability of the disturbed rock zone around the shaft were flawed or incorrect, how significantly would this affect performance? This is not expected to be an exhaustive evaluation, but it should raise the reasonable question, "What if the model were wrong?"

Adequacy of the Conceptual Model. Based primarily on the previous four criteria, this is a simple statement of whether the individual conceptual models and submodels represent a reasonable approximation of the actual disposal system elements.

Adequacy of Application. This is an assessment of whether it appears that the individual conceptual model is being adequately applied into an acceptable overall performance modeling system. This particular assessment does not cover the relationships among conceptual models, but whether the significant components of the individual conceptual models are appropriately implemented in support of performance assessment. For example, are the various geometrical systems and representations of the conceptual models adequately applied within the performance modeling system, or do there appear to be discontinuities between the conceptual model and its application? Also, are there apparently important alterations of key assumptions between the conceptual model and its implementation in performance modeling?

Accuracy of Results. This is a statement of whether the results of performance modeling using the conceptual model within the performance system are sufficiently accurate to adequately simulate the physical and chemical processes represented. This could either be a subjective judgment (if analytical results were not available with any necessary caveats) or a more robust and useful judgment (if results of analyses were available). Review of key results could also improve the basis for the Panel's statements about adequacy of application, overall validity of outcome of analyses, and adequacy for implementation.

Typical results that could be useful in providing a basis for these improved judgments include reports of sensitivity studies among key intermediate parameters, such as: 1) mean and extreme values of expected brine inflows, 2) gas pressurizations, 3) likelihoods of marker bed fracture, 4) directions of brine flow in the undisturbed condition, 5) the effect of mining in the vicinity of waste panels, 6) relative amounts of waste released from intrusion scenario components (direct brine releases, cuttings, cavings and spallings), and 7) initial typical complementary cumulative distribution functions. Similar results from

past performance assessments have provided a basis for improved judgments of models and modeling systems, and numerous improvements have been made in models since the 1992 performance assessment. A review of results is also desirable to facilitate making useful conclusions.

Validity of Conclusions. This is a judgment of the validity of any key conclusions that have been drawn based on results of the implementation of conceptual models in the modeling framework. The key question is whether or not conclusions from model implementations appropriately relate to the expected goal of assessing the long-term performance of the disposal system. Again, a judgment in the absence of some key output information would need to be accompanied by appropriate explanations.

Adequacy for Implementation. This is an overall, bottom-line assessment of whether the conceptual models, as intended for use in the compliance application, represent a reasonable approximation of the actual disposal system based on the eight previous criteria.

3.0 MODEL EVALUATIONS

This section presents the results of the Panel's evaluations of the 24 individual conceptual models that the DOE requested the Panel to review. Each of these models is first described and then evaluated for adequacy in accordance with the nine criteria summarized in Section 2.5. Following each evaluation, space has been provided for dissenting views; however, no dissenting views were forwarded by any Panel member. An evaluation of the integration of these conceptual models into the WIPP performance assessment is provided in Section 4.

3.1. Disposal System Geometry

3.1.1. Model Description

The Disposal System Geometry conceptual model expresses the dimensionality of the engineered system and surrounding geologic/hydrogeologic formations. The parameters of dimensionality are length, width, and height, which are expressed in individual grid blocks and remain constant for all scenarios and realizations. The processes that rely on the geometric assumptions and parameters of dimensionality are represented across the overall performance assessment system through a finite difference mathematical model called BRAGFLO. The principal processes that depend on the conceptual model for disposal system geometry are fluid flow and actinide transport. The flow fields generated by BRAGFLO are based on the geometric representation of the repository and adjacent formations and the finite difference method, and are communicated to the NUTS code that determines the transport of actinides to the accessible environment.

3.1.2. Review of Criteria

3.1.2.1. Information Used To Develop the Conceptual Model

Numerous references accompany the various background, descriptive, and features, events, and processes (FEP) screening write-ups for the repository and disposal system geometries. Except for regulatory and guidance documents, all references are to internal (SNL) reports that characterize various aspects of and inputs to the modeling of the disposal system geometry. The reports present data and information used to develop the conceptual model and background references for specific applications, but no extensive reference list on "conceptual modeling" of disposal system geometry has been compiled by DOE.

Information concerning the effects of detailed stratigraphy and stratigraphic dip on brine and gas flow, and uncertainty and parameter sensitivity analyses for gas and brine migration, is presented in WIPP

(1992a and 1992b) and Christian-Frear and Webb (1996). Other reports (WIPP 1993, Rechard et al. 1990, and Marietta et al. 1989) explain the WIPP performance assessment aspects of characterizing the disposal system geometry, and FEP screening documents present modeling alternatives. Various sections of the Compliance Certification Application (DOE 1996) summarize disposal system, repository, and intrusion event geometries. The Disposal System Geometry conceptual model is the result of integrating other models that describe the physical and chemical conditions and processes expected in the repository into a characterization of the material properties of the repository and surrounding strata. As such, the conceptual model and its application are described in terms of a process that has evolved to its current structure, and has generally been developed after the mathematical models have been defined.

3.1.2.2. Validity of Model Assumptions

The Disposal Systems Geometry conceptual model must have assumptions that are internally consistent and consistent with the assumptions of other models that represent repository processes. Since the geometry by which processes are simulated is so closely tied to the processes themselves, it is difficult to review the conceptual model for disposal system geometry totally separate from other models.

As stated in Part 2.5, the validity of key conceptual modeling assumptions will be assessed in terms of how the assumptions could affect the usefulness of the conceptual model. While the assumptions that describe the repository-process conceptual models that are closely tied to the geometry (Creep Closure, Repository Fluid Flow, Gas Generation, Chemical Conditions, Dissolved and Colloidal Actinide Source Terms) are not reviewed in this section, they are reviewed individually in Section 3, and collectively in Section 4.

Assumptions key to the disposal system geometry conceptual model for undisturbed and disturbed conditions (disposal system, disposal room, adjacent disturbed rock zone (DRZ), and geologic systems) include: 1) the three-dimensional systems can be represented by two-dimensional simplifications; 2) the associations between and relationships across regions with varying material properties can be represented by the discretized grid blocks and by the finite difference method used in the computational model; 3) the four shafts can be represented by one shaft; 4) the entire repository can be represented by the simplified floor plan used in the computation model; 5) the intrusion borehole represents the concerns of the intrusion scenarios; and 6) effects of flow in the DRZ and intact rocks outside of the repository are represented by the divergent grid to the north and south away from the repository.

The representation of relevant systems by two-dimensional simplifications not only affects the usefulness of the conceptual model, it is intended to make the model useful. As stated in Section 3.1.2.1, the geometry followed the definition of the mathematical models. Early three-dimensional mathematical models were unwieldy and computationally inefficient with respect to time, cost, and overall management. The two-dimensional representation is efficient in terms of time, cost, and managing a large number of vectors. The BRAGFLO code, as simplified (BRAGFLO is a three-dimensional code), compared favorably with a three-dimensional alternative (TOUGH 28W) used for verification with respect to the relevant outputs. Two-dimensional simplifications appear to adequately represent the structural system through which fluid flow can be simulated to the shafts or intrusion boreholes. The two-dimensional representation may not be adequate, however, for simulating fluid movement across the repository and waste panel area to the anhydrite interbeds because such flow may be unrealistically impeded by the small depths and potentially low permeabilities assigned to the cells representing the shafts and boreholes in the model. This issue is further discussed in the Repository Fluid Flow conceptual model in Section 3.3.

The conceptual approach of characterizing varying material properties by discretized grid blocks, and using finite differences and partial differential equations to compute a flow field for a series of grid points, is useful and a standard method for hydraulic routing. It is beyond the scope of the conceptual model review to conduct a detailed analysis of the BRAGFLO code, and the finite difference method will be assumed to be of standard computational design. The usefulness of this method is well established in hydrogeology, considered valid for routing liquids, and is a valuable tool for sensitivity analysis.

It appears that the one-degree dip in the Salado, the important cross sectional areas (vertical and horizontal), and distances between key system features and pathways have been retained within modeling simplifications. As these characteristics are retained, the overall geometry conceptual model remains valid. Beyond the conceptual method, the panel makes no comment on the validity of the grid block densities or volumetric variation and whether or not they adequately represent material property maps and changes in properties and their distribution.

The representation of the four shafts by a single shaft of cross sectional area and volume equal to the sum of the four shafts, is a conservative representation and simplifies the mathematical representation of brine and gas flow to and in the shaft. The single shaft is located, geometrically, in the position of the waste handling shaft, which is the closest of all four shafts to the waste disposal regions. The Panel foresees no

reasonable situation where such an assumption could compromise model usefulness and render the assumption invalid, but the presence of four sealed shafts presents four times the risk of failure of one shaft, and this may not have been taken into account. The four-shaft simplification assumption stimulates questions of reality, accuracy, and scientific credibility. While apparent conservatism, at least in the context of the scope of this review, answers most operational and performance questions, it would have been more credible, from a modeling perspective, to model the actual system.

The simplified repository floor plan represents a conservative view, and clearly provides fewer obstacles to flow in the repository than would actually be encountered by fluids. The simplifications and assigned high permeabilities answer operational and performance questions, since the conservatism and validity of the assumption was not refutable within the scope of this review. While the Panel is not satisfied that the simplifications for the sake of conservatism replace credible models of the actual systems, the assumptions remain valid.

The intrusion scenarios require assumptions about the intrusion borehole in terms of location, size, and how the brine and gas are conveyed to the borehole. The intrusion borehole is assumed to penetrate the repository and brine reservoir as appropriate to the scenario. During the intrusion scenario the represented waste panel is discretized to simulate radial flow of waste fluids to the borehole.

3.1.2.3. Evaluation of Alternatives

During the conceptual models review, information that indicated or described alternative conceptual models that were considered but not used was limited to FEP S-1 documents and unpublished informative write-ups provided by DOE (Larson 1996). Many grid configurations were experimented with in previous performance assessments, and sensitivity and uncertainty analyses (WIPP 1992a, 1992b) were conducted relative to the geometry model. Analyses that examined how detailed stratigraphy and stratigraphic dip affected brine and gas migration were reported in Christian-Frear and Webb (1996) and Webb and Larson (1996). Through all of the analyses and experiments the basic concept of the grid as the geometric framework has not changed. The specific geometric framework suitable for modeling disposal system processes and interactions was developed after the mathematical/computational system was defined. Three-dimensional and two-dimensional models were evaluated, with the three-dimensional model described as computationally inefficient for the large number of vectors required for the WIPP performance assessment, and was considered costly in terms of time and resources.

With the selection of the two-dimensional approach and the simplified BRAGFLO code, FEP S-1 screening verified (justified) the two-dimensional WIPP grid with a three-dimensional model (TOUGH 28 W). Based on the favorable comparison of outputs from the models, the DOE selected the two-dimensional model for use in the WIPP performance assessment.

Intrusion scenarios are limited to those that penetrate the repository waste panels or repository and brine reservoir. No alternative borehole intrusion scenarios are considered that miss the repository but penetrate the adjacent DRZ or strata and impact the physical properties of the DRZ or strata.

3.1.2.4. Uncertainties

The key uncertainties associated with the disposal system geometry conceptual model are associated with the simplifications made for the sake of conservatism (as opposed to, for example, operational efficiency, cost, and resource constraints) and with the question of whether the computational mesh is representative of the geometry of the system. While the two-dimensional simplifications embody assumptions key to the conceptual model, verification screening illustrates that these simplifications result in outputs of sufficient quality for use in the WIPP performance assessment (FEP S-1 1992 and 1993).

As stated in Section 3.1.2.2, the Panel concludes that there is little uncertainty or confusion with the fundamental geometric framework of discretized grid blocks or the use of the finite difference method to compute flow fields over a series of grid points. The uncertainty that exists relates to the definition of the processes by the mathematical representations and the representativeness of the computational mesh.

3.1.2.5. Adequacy of the Conceptual Model

The conceptual/geometric framework and computational method selected to characterize the material properties of the disposal system and relevant physical and chemical processes is adequate. As stated in previous sections, the implementation of the conceptual model has not been evaluated within the scope of this review and cannot be commented on.

The two-dimensional simplifications, considered part of the conceptualization of the disposal system geometry, have been subjected to verification and are considered adequate for use in characterizing releases for the WIPP performance assessment.

3.1.2.6. Adequacy of Application

The Disposal System Geometry conceptual model provides an adequate framework, method, and set of assumptions, and appears to be applied as an acceptable performance element. There are no apparent compatibility problems between the geometry and process-related conceptual models in terms of assumptions or application method that would create misrepresentations. The overall adequacy of the application should be measured by how well material properties are represented and physical and chemical processes are simulated. These measures, in turn, depend on the relevant conceptual models and data relevant to those processes being modeled. Therefore, a more definitive assessment of the adequacy of application of the Disposal System Geometry conceptual model could be determined from analyses, outputs, and results generated by the relevant process-related conceptual models, which were not available to the Panel at the time of review.

3.1.2.7. Accuracy of Results

For evaluating the accuracy of the results of the Disposal System Geometry conceptual modeling activity, model formulation results, as well as model evaluation/application results, must be reviewed. Model formulation results are the description or descriptive write-up that presents the conceptual model. Model evaluation/application results are those that indicate the performance of the conceptual model through sensitivity analyses, verification studies, or results of performance modeling of all or intermediate parameters.

The conceptual model, as defined by the geometric framework, the proposed use of a finite difference method, two-dimensional computational simplifications, and disposal system simplifications, is accurately presented as formulated. The Panel was required to consult numerous documents to acquire a comprehensive view of the conceptual model and the formulation process, but the description of the conceptual model is complete and accurate.

As presented in Section 3.1.2.6, the Disposal System Geometry model evaluation results, or results of model applications, should be measured for accuracy within the models that have conceptualized the physical and chemical processes. While the simplifications of this conceptual model have been verified as to comparability of outputs with other models (FEP S-1 1992 and 1993), the Disposal System Geometry model itself only produces results, as it represents material properties and processes conceptualized in other models. Therefore, the Panel cannot attest to the overall accuracy of the model.

3.1.2.8. Validity of Conclusions

The Panel is not aware of any results of the implementation of the Disposal System Geometry conceptual model (see Section 3.1.2.7) and therefore, there are no conclusions to validate.

3.1.2.9. Adequacy for Implementation

The conceptual model for the Disposal System Geometry provides a suitable framework for modeling the important processes and their interactions in the disposal system. The mathematical representation of the conceptual model within the BRAGFLO code has not been reviewed and, as a result, the panel offers no conclusions on the representativeness of applications using the code. The concept that the spatial effects of processes and interactions can be represented in two dimensions is defensible. The simplification in the system representation and computational method to simulate the two dimensions are defensible and adequate for implementation. The basic grid framework for representing the material properties of the disposal system, adjacent DRZ, geologic formations, and intrusion scenarios is adequate, and the proposed use of a finite difference method to connect the nodes and generate flow fields is also defensible and adequate for implementation.

3.1.2.10. Dissenting Views

There were no dissenting views for this model.

3.2. Culebra Hydrogeology

3.2.1. Model Description

The Culebra is identified as a principal potential pathway for radionuclide release to the environment. The conceptual model should support the results of hydrologic testing and provide bases for population of the model in regions lacking data. The conceptual model should correlate the regional and site scale hydrogeology with the model boundaries and help shape hydrologic gradients and local field boundaries.

The Culebra hydrogeologic characterization framework has evolved from two fundamentally different regional flow models, several formulations explaining local flow conditions represented by hydrologic testing, and several hypotheses explaining the distribution of permeability regions in the Culebra. The regional flow models include the "confinement" model and the "groundwater basin" model. The confinement model depicts the Rustler Formation (of which the Culebra is a member) as a series of perfectly isolated layers which are hydrogeologically independent. The groundwater basin model depicts

the Culebra as a layer within a series of interacting hydrologic units of varying properties which include all the hydrologic units between the ground surface and the Salado Formation. In the groundwater basin model, hydrologic gradients are thought to be vertical in the low permeability layers (Tamarisk, Forty-Niner, Unnamed Lower Member) and horizontal in the Culebra and Magenta Dolomites.

Observations in the field and shaft openings indicate that the Culebra is a dolomite averaging approximately 7 meters in thickness. Generally fine-grained, red brown in color, occasionally vuggy and fractured, the crudely layered dolomite appears to be typical of evaporite dolomites. The fractures tend to be disorderly in orientation and in some places polygonal, and the vugs are occasionally open. The MgO content of the dolomite varies greatly vertically and areally within the Culebra member. These lithologic characteristics and the sedimentological setting imply that the Culebra is a reflux dolomite, deposited originally as a calcite sediment and subsequently altered by infiltration of MgO-rich evaporite brine. The variability of MgO content, texture, and fracture distribution are most probably due to variability in volume changes due to timing, rate, and degree of dolomitization of the original calcite sediment.

Hydrologic testing of the Culebra has indicated that the hydrologic properties of the unit (principally permeability and porosity) vary strongly both vertically and areally. At some localities, the test flow rates and interactions between wells have led to hypotheses that relatively low permeabilities resulting from flow through the rock matrix dominates the hydrogeology of the Culebra over regions many tens of meters in extent. Similar tests in other localities have implied high permeabilities over distances of several kilometers, which are hypothesized to be the result of the dominance of fracture permeability along interconnected fracture zones. Other localities show intermediate flow characteristics, which may be the result of combined effects of flow-through fractures and matrix. Multiple models that hypothesize the combined and singular effects of hydrologic sample intervals across regions of vertically varying modes and rates of flow have been proposed to explain some of the variability of test results. These models have been tested by varying sample intervals and pumping rates several times in the same stratigraphic interval. It appears that sample interval does not entirely explain the composite flows observed and that dual porosity flow models are appropriate. There are regional variations in hydrologic properties in the Culebra that are too large in magnitude to be explained by variation in sample interval or proportionality of flow mechanism, and that appear to be areally distributed within and around the repository area. These areal variations in the hydrogeologic nature of the Culebra have not been clearly associated with a conceptual model of the geology of the dolomite or of the Rustler Formation as a whole. The Culebra is the most extensively tested hydrogeologic unit in the WIPP region.

Jones (1974, 1975, 1978) and Snyder and Gard (1982) postulated that the hydrology of the Culebra was primarily related to the dissolution of halite within the Rustler Formation. Jones postulated the existence of dissolution "fronts," partly the consequence of Pleistocene climatological history, which are presently active at reduced rates based on halite distribution within the Rustler and at the Rustler-Salado contact. Subsidence of the Rustler related to dissolution was the postulated mechanism for locally increased aperture of preexisting fractures. Although dissolution is certainly a strong influence on the geology of the Rustler Formation in Nash Draw and isopac maps of the Rustler Formation members show erratic thickness changes in the soluble members (Brinster 1991), workers in the region remain divided about the role of dissolution in the hydrogeology of the Rustler Formation and of the included Culebra Member. Holt and Powers (1988) argue that variations in stratigraphic thickness within the Rustler are the result of depositional processes and that changes in overburden pressure due to erosion explain the variability of hydrologic properties. Bachman (1987) and Lambert (1987) argue that solution has been inactive since mid to late Pleistocene time. Chapman (1986) contends that Culebra waters contain significant amounts of meteoric water, while Lambert argues against the presence of any meteoric water. Corbet and Wallace (1993) argues that the filling of fractures and the removal of fracture fillings by dissolution explains gross regional variations in transmissivity.

Hydrologic testing has not resolved the questions raised by arguments about the origin of variability of hydraulic properties by simple correlation with geologic features. Some fundamental geologic variables, such as fracture distribution, aperture, and orientation, as well as patterns of variation in matrix permeability and porosity, have not been sufficiently characterized to make such correlations possible. Such characterization would require a large investment in angle hole nests and extensive three-dimensional modeling. The uncertainties in the hydrogeologic character of the Culebra has led to the abandonment of attempts to formulate a detailed hydrogeologic conceptual model and there have been several attempts to generate an acceptably predictive numerical hydrologic model exclusively from testing data. These attempts are summarized in Figure 3-1 and in Table 3.1. Recent multiwell tracer tests are presently being evaluated to more fully support transport modeling.

Chapman (1986), LaVenue (1990), Siegel (1991), and Beauheim (1989) have not been able to relate detailed hydrogeologic features, hydrogeochemical facies, radiogenic ages, flow constraints, or hydrologic testing results to a consistent, detailed hydrogeological conceptual model. Neither have they been able to uniquely explain water level changes observed in monitoring of the WIPP region over the last several decades. Groundwater flow directions in the Culebra member over the Los Medanos region,

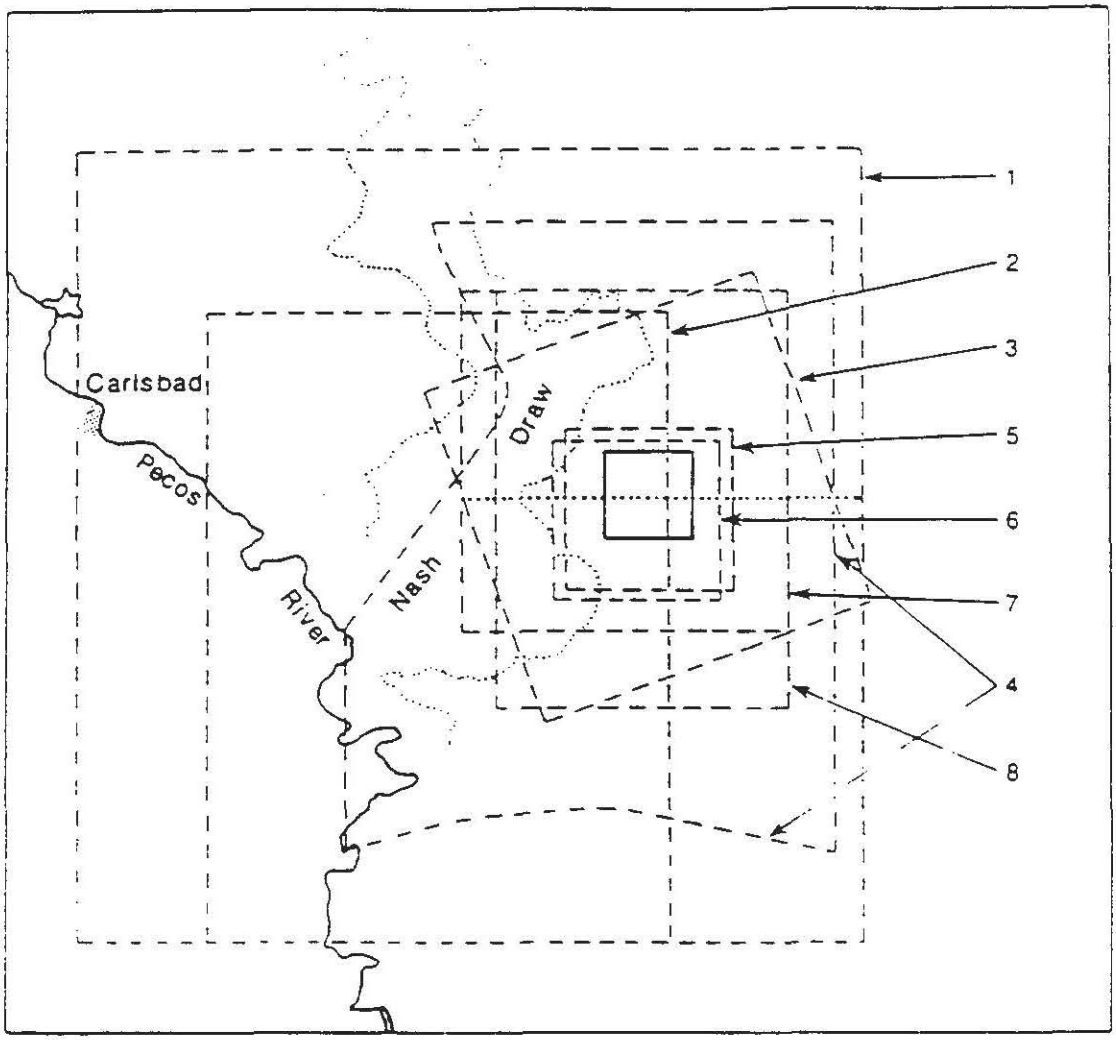

0 5 10 15 Kilometers

1 5 10 Miles

1 U.S. Department of Energy (1980a,1980b); Cole and Bond (1980)
2 D'Appolonia Consulting Engineers (1981)
3 Barr et al. (1983)
4 Davies (1989)
5 Niou and Pietz (1987)
6 Haug et al. (1987)
7 LaVenue et al. (1988)
8 Present Study

INTERA Technologies

Figure 3.1. Approximate Boundaries of Groundwater Flow Models in the WIPP (after Lappin and Hunter 1989)

Table 3.1. Summary of Modeling Investigations of the Rustler Formation or Culebra Dolomite Member in the WIPP Site Region

Investigation	Hydrogeologic Unit Modeled	Head Calibration
DOE 1980	Rustler	Steady State
D'Appolonia 1981	Rustler	Steady State
Cole and Bond 1980	Rustler	Steady State
Barr et al. 1983	Culebra	Steady State
Davies 1989	Culebra	Steady State
Niou and Pietz 1987	Culebra	Transient
Haug et al. 1988	Culebra	Steady State
LaVenue et al. 1988	Culebra	Steady State
Present Study	Culebra	Combined Steady State/Transient

as well as in other members of the Rustler Formation, are reasonably well defined. The work synthesized by LaVenue (1990) and Brinster (1991) and the intervening single and multiwell and tracer testing in the Culebra, are an attempt to characterize the hydrology of the Culebra in a well-constrained area around the WIPP on the basis of a relatively large body of hydrologic test data by numerical modeling alone. If this effort is ultimately successful, perhaps a comparison of model results with the existing hydrogeologic characterization of the Culebra will allow the formulation of a hydrogeologic conceptual model that explains transmissivity variation at the site scale. None exists at this time. The large number of hydrologic tests within the repository area and in the Los Medanos region around the repository, the variety of types of testing, and the long period of monitoring suggest that a numerical flow model may be sufficient to answer most of the performance-related questions about the Culebra at the repository.

3.2.2. Review of Criteria

3.2.2.1. Information Used to Develop the Conceptual Model

Information used to develop the conceptual model included field geologic observations, logging of cores from borings, observations from shaft mapping, petrographic and mineralogic study, subsurface mapping, groundwater geochemistry and geochronology, and hydrologic testing and monitoring including multiwell pumping and tracer tests. Several hypotheses correlating detailed variations in the hydrologic properties and results of monitoring of the Culebra with groundwater geochemistry and geohydrological aspects of the formation were proposed and tested against existing information or information acquired

specifically to test the hypotheses. All hypotheses failed to correlate the detailed hydrogeology of the Culebra with its tested hydrologic character. The information used to develop the conceptual model was insufficient to permit the formulation of the model at a sufficient scale.

The Culebra is a red-brown, fine grained dolomite, continuous over the WIPP area, which displays vugs and fractures that may be the primary sources of permeability and porosity. The lithologic aspect of the Culebra and the variability of its magnesium content suggest that it is a reflux dolomite formed by the gravity-driven infiltration of a calcite sediment by magnesium rich fluids, shortly after deposition in an evaporite sedimentological setting. The Culebra is bounded by two very low permeability anhydrite units. The hydrologic gradient in the Culebra is horizontal and generally southward over the repository area and the gradients in the adjacent beds are vertical. Some water-pressure measurements imply that the Culebra is underpressured. The transmissivity and gradient of the Culebra are capable of discharging more water than the formation is receiving in recharge, at least locally. There is more hydrologic test data for the Culebra than for any other hydrogeologic unit in the repository region. The model boundaries are defined by regional hydrogeologic features mapped and modeled by Corbett (1993). The information is inadequate to develop a conceptual model that explains hydraulic process and property variation at the site scale.

3.2.2.2. Validity of Model Assumptions

Since all detailed conceptual hydrogeologic hypotheses correlating the Culebra hydrogeology and geochemistry to the described hydrologic properties and the results of hydrogeologic testing and monitoring failed, no conceptual model was formed that could be linked to the computational flow model. No model assumptions, which have their origin in the conceptual model and impact performance assessment, exist for testing.

3.2.2.3. Evaluation of Alternatives

Alternative hydrogeologic models, which relied on apportioning fracture and matrix porosity and permeability within the Culebra as a result of: 1) solution of halite within the Rustler Formation; 2) solution of halite at the Rustler Salado interface; 3) variability of superincumbent load due to topography; and 4) dissolution due to gravity driven flow of brines of different density, were considered and discarded.

3.2.2.4. Uncertainties

Model uncertainties as a result of the conceptual model do not exist in this instance because of the absence of an accepted conceptual model at the appropriate level of detail. An alternative approach has been adopted which depends on the modeling of the hydrology of the Culebra entirely on the basis of the results of hydrologic testing. A detailed assessment of this numerical modeling effort is beyond the scope of this review.

Two sources of uncertainty are related to the absence of a conceptual model in this case. A conceptual model helps to explain the sources of variability observed in a data base derived from hydrologic testing and provides rational bases for populating the data-less areas in the model grid. Values are smoothed and gradients between varying clusters of data are shaped on the basis of hydrogeologic character. Absence of this influence on grid population reduces confidence in numerical model representativeness.

The second uncertainty is the absence of hydrogeologic bases for ruling out significant patterns of variance in the flow patterns and hydrologic properties in the Culebra hidden within data-less areas or areas of apparently incoherent variation in the testing area. The Culebra test results have exhibited relatively large, spatially dependent variations in hydraulic conductivity. The relatively dense testing data base and the ongoing multiwell and tracer testing are attempts to resolve this issue. Zones of relatively rapid fracture flow, without significant retardation of radionuclides by physical or geochemical processes, could cause accelerated transport in the Culebra. The existing transmissivity field models seem to cover the regions of greatest concern to site performance with what appears to be an adequate testing data distribution to rule out local variations in flow significant to performance of the site. The density of field testing data seems to be adequate.

The impact of ground subsidence due to repository closure on the hydrogeology of the Culebra is a source of uncertainty. Subsidence of nearby potash mines and an analysis by Westinghouse suggest a lowering of the ground surface of about .5 m and a small horizontal extensional strain in the Culebra (.007%). It has been asserted that the transmissivities represented by the two-dimensional flow model proposed for performance assessment are conservative enough to contain any enhancement of flow caused by subsidence of this scale. No conceptual arguments specific to Culebra hydrogeology or numerical analysis supporting the probable magnitude of enhancement of transmissivity or the sensitivity of the proposed model to that change have been presented.

3.2.2.5. Adequacy of the Conceptual Model

The conceptual model is not adequate to define variations in the transmissivity of the Culebra at the site scale. Its function has been replaced by an extensive hydrologic testing and modeling effort.

3.2.2.6. Adequacy of Application

See Section 3.2.2.5.

3.2.2.7. Accuracy of Results

No conceptual model is employed in performance assessment-related modeling. Assessment of the accuracy of the numerical flow modeling used in performance assessment is beyond the scope of this review.

3.2.2.8. Validity of Conclusions

The validity of the conclusions of numerical flow modeling is not impacted by the conceptual model in this case. Data distribution and density and geostatistical methods used to populate the model appear to be valid. The results make sense in a qualitative way.

3.2.2.9. Adequacy for Implementation

The conceptual model was not adequate for implementation. A numerical model based on an extensive hydrologic testing data base was substituted. The numerical model appears to meet the needs of the performance assessment, although the computational validity and accuracy of that model were not reviewed.

3.2.2.10. Dissenting Views

There were no dissenting views for this model.

3.3. Repository Fluid Flow

3.3.1. Model Description

The Repository Fluid Flow conceptual model addresses (1) fluid distribution in the waste, (2) long-term fluid flow to and from the Salado Formation and shafts, and (3) long-term fluid flow between the repository and intrusion boreholes. Related conceptual models include Disposal System Geometry, Disturbed Rock Zone, Creep Closure, Shafts and Shaft Seals, Gas Generation, Impure Halite, Salado, and Salado Interbeds, Castile and Brine Reservoirs, Exploration Boreholes, and Multiple Intrusions.

The Repository Fluid Flow conceptual model is a complex description of simultaneous, interacting hydrologic, chemical, geomechanical, engineering design, and human intrusion scenarios whose effects can be described separately, but require numerical modeling to identify the combined, integrated outcome. The conditions controlling repository fluid flow include brine inflow rates, halite creep rates, and gas generation from waste corrosion and degradation, which are themselves the objects of related but separately described conceptual models. The Repository Fluid Flow model accepts inputs from these related models and provides descriptions of pressures, flow rates, and flow directions for brine and gas within the excavated areas of the repository. A detailed description of the coupled processes in the conceptual model is presented in Freeze et al. (1995).

The layout of the waste repository is described in Section 2.3.1. The key elements of this layout pertaining to the Repository Fluid Flow conceptual model are the waste disposal area (the waste panels and access drifts), the panel seals, the operational area, the experimental area, the shafts, the WIPP site characterization boreholes in the vicinity of the repository, and any future exploration boreholes that are randomly determined to penetrate the repository. The waste panels in the disposal area will be sequentially filled to capacity with waste and isolated from the rest of the repository by 40-m long closure seals consisting of concrete plugs and crushed salt. The operations area is north of the disposal area and consists of four shafts and a network of interconnecting access drifts. Two additional sets of 40-m seals will be placed in the operations area between the waste and the shafts. The experimental area is north of the operations area and consists of a series of experimental rooms and access drifts.

In the current plan, waste will be placed in steel drums and waste boxes stacked to achieve efficient use of space. Magnesium oxide will be placed around the containers to absorb carbon dioxide gas generated during microbial decay of cellulosics in the waste. No structural backfill is planned for the repository. Analyses have indicated that decay and degradation of the waste are expected to generate little heat and the maximum repository-wide temperature excursion is expected to be about 5°C. The changes in density and viscosity for brine and gas at this temperature rise are small, and are not considered to be significant in performance assessment. Plans for shaft and borehole sealing are discussed in Sections 3.12 and 3.20. On repository closure, the Salado halite is expected to creep into the excavated rooms and crush the waste; however, some porosity will remain, resulting from the strength of the waste materials and from pressurized brine and gas in the waste. A discussion of the Creep Closure model is presented in Section 3.19.

In undisturbed scenarios, brine is expected to flow into the excavated entries of the repository at a slow rate both during and after closure. Brine will flow directly from the Salado halite, from higher conductivity anhydrite interbeds intersected by the excavations, from formations above the Salado by seepage through a DRZ around the shaft, and from brine squeezed from storage in clays in the impure halite. Flow into the repository through the halite is expected to be enhanced by a disturbed rock zone of higher permeability in the walls, floor, and back of the underground entries (see Section 3.7), from a series of 50-foot long site characterization boreholes drilled vertically upward and downward from the repository, and from rock bolt holes penetrating the back and walls of most entries. During the operational period, this inflow is expected to be removed by evaporation into the repository ventilation air. Under undisturbed conditions following closure, inflow is expected to continue at a low rate from the first three of these sources but not from the clay, which is expected to have been fully consolidated. The brine is expected to pool in low spots on the repository floor and to be wicked into the waste and magnesium oxide by capillary forces. Under disturbed conditions, additional inflows of brine may rapidly occur following closure if a borehole penetrating the repository also encounters pressurized brine in the underlying Castile Formation.

Both gas and brine will behave as fluids, filling pore volume in the repository. Gas and brine will be generated at the same time that the repository void spaces are being closed by halite creep, eventually reaching a state of equilibrium where the pressure of the gas and brine is balanced by the pressure of the halite on the remaining void spaces. Brine inflow into the remaining voids is expected to stop when the pressure of brine in the repository is the same as the pressure of brine in the halite. If gas production continues, the pressure of the gas will continue to rise, driving the brine back into the halite.

If the gas pressure exceeds the threshold pressure for its entry into the surrounding geologic media, the gas will enter the geologic media, increasing the available void volume. As the gas pressure approaches the lithostatic pressure, gas is expected to enter the anhydrite interbeds in the vicinity of the repository, increase the porosity in those interbeds by enlarging existing fractures along planes of weakness, and migrate laterally in the interbed away from the repository, until the increased pore volume sufficiently reduces gas pressure that the phenomenon stops (see Section 3.6). The lateral extent of such fracturing will depend on the rate of gas generation and the pressure and volume of gas present in the repository. Microfracturing of the intact halite from gas pressure buildup is expected to occur around the repository, but at a rate that is sufficiently slow that stress redistribution from halite creep will keep these fractures

from developing into a size that would be of concern to performance assessment. More extensive fracturing is expected in anhydrite, which is more brittle and does not have the creep characteristics of halite.

The volume of gas produced will be limited primarily by the volume of source material (primarily steel and cellulosics) in the repository, and the rate of gas production will be limited primarily by the volume of brine present and in contact with the waste. Gas pressure can be relieved if the repository is penetrated by an exploration borehole, in which case releases of gas, contaminated brine, and repository waste materials could occur at the ground surface (see Sections 3.12 and 3.17). The void volume in the repository can also increase when the gas pressure exceeds the lithostatic pressure by reversing the creep process.

The conceptual model for repository fluid flow is implemented for performance assessment using two separate models developed from the BRAGFLO code. The first model, which for purposes of this review will be called BRAGFLO, is used for analyzing long-term flow through the repository under both disturbed and undisturbed conditions. The second model is used for calculating short-term, direct brine releases when the repository is penetrated by one or more boreholes, and will be called BRAGFLO-DBR. This second model is discussed under the Direct Brine Release conceptual model in Section 3.15.

The repository is represented in BRAGFLO in two-dimensional vertical section as a series of volumes, each with homogeneous, isotropic material properties and behaviors, and each representing a major repository feature. The slight 1° southerly dip of the bedding is incorporated into the model. The effective depth of each modeled feature (the third dimension normal to the plane of the model) is addressed through adjusting the cross section areas of the cells representing the feature. The model material numbers and the dimensions of each feature are summarized in Table 3.2. Ranges of depths are given for features with variable depths that are represented by multiple columns of model cells. The heights of the intrusion borehole and shaft are not given because they extend to the ground surface, have varying material properties and behaviors, and heights that are greater than the height of the repository excavations.

The effective depths of the model cells were varied to simulate the increasing hydraulic gradients that would occur into the repository, intrusion borehole, and shaft under radial flow conditions. The model depths used for the borehole and shaft approximate the effective diameters of these features. The model depth for the borehole is held constant whether or not an intrusion borehole is assumed to have been

Table 3.2. Model Material Numbers and Feature Dimensions

Feature	Material Number	Length (m)	Height (m)	Depth (m)
Single waste panel	23	112	4	4.8 to 126.2
Intrusion borehole	1	0.27	- -	0.27
Single panel closure	25	40	4	10
Rest of repository	24	695	4	141.6
Multiple panel closure	25	80	4	18.9
Operations area	26	333	4	18.9
Shaft	2 to 11	10	- -	9.5
Experimental area	27	560	4	20.5 to 53.1

drilled. BRAGFLO is configured assuming a single shaft with a vertical permeability of the four shafts (and their disturbed rock zones) combined, and assuming a single exploratory borehole that penetrates the center of one of the downdip waste panels. The borehole cells are assigned the properties of the undisturbed media until a borehole is randomly assumed to have been drilled. The borehole can be either an E1 type (penetrates a waste panel in the repository and encounters pressurized brine in the underlying Castile Formation) or an E2 type (penetrates a waste panel but does not encounter pressurized brine). Penetration of a waste panel by more than one borehole is also addressed by this version of BRAGFLO and is discussed in Section 3.17. The presence of existing site characterization borehole ERDA-9, very near the repository, is not addressed by BRAGFLO.

The waste is simulated in BRAGFLO in two areas: Material 23, which represents a single waste panel, and Material 24, which represents the rest of the repository. The waste itself is assumed to be distributed uniformly throughout the two areas. Between the waste materials, BRAGFLO simulates a 40-m long panel closure seal (Material 25) representing the seals in the two panel access drifts. In addition, an 80-m long panel closure seal (also Material 25) separates the rest of the repository from the operations area and represents the two groups of 40-m long seals that will be placed in the operations area. The remaining cells (Materials 26 and 27) represent the operations and experimental areas, respectively, and are located on either side of the shaft. Each of these material areas is three cells high in vertical dimension, allowing vertical variations in brine and gas saturations and the resulting varying rates of corrosion and waste decomposition to be simulated.

Gas production rates are estimated as a function of brine availability. Wicking of brine into the waste will increase gas production rates and is modeled by arbitrarily adding a randomly selected value,

varying from zero to 1.0, to the brine saturation value in disposal area model cells containing brine (not to exceed a total brine saturation of 1.0). This value is called the wicking saturation. The additional brine is only used for chemical reaction purposes. The approach increases the volume of brine available for chemical reactions and increases the rate of corrosion and gas production. To simplify analysis of the mechanical effects of gas production and pressure buildup, all gases produced are assumed to have the properties of hydrogen and behave as ideal gases. Although this assumption would lead to underestimating the viscosity and overestimating the compressibility of the hydrogen-carbon dioxide mixture actually expected to be present, the error would be of no significance in view of the considerably larger uncertainties in other parameters in the model and the expected efficiency of the magnesium oxide in removing carbon dioxide from the system.

Repository closure through halite creep is modeled using the porosity surface approach discussed in Section 3.19. The waste disposal rooms are assumed to maintain a relatively high constant permeability, but a varying porosity during the creep closure process. The panel closure seals and the operations and experimental areas of the repository are assumed to have a constant permeability and porosity. BRAGFLO models the repository assuming two-phase Darcy porous medium flow throughout the closure process.

Material 22, representing disturbed halite, lies above and below the repository excavations and interconnects the repository with Marker Beds 138 and 139, and with Anhydrite Layers A and B. No disturbed halite is modeled in the walls of the excavations. The lateral outer boundaries of the model are over 2,000 m from the repository. All outer boundaries below the Rustler are assigned no-flow conditions.

3.3.2. Review of Criteria

3.3.2.1. Information Used to Develop the Conceptual Model

The conceptual model has relied greatly on the general Darcy model for flow in porous media, as amended for gas by considering the Klinkenberg effect, and for two-phase flow using a modified Brooks-Corey model that includes threshold pressures for gas entry into a brine-saturated medium. Brine salinity, density, compressibility, and viscosity are addressed in the model. Gas properties are given by the Redlich-Kwong-Soave equation of state, assuming behavior to be that of pure hydrogen. The principal basis for the conceptual model is not specific to WIPP, but was developed from the general state of knowledge of two-phase, isothermal flow of liquids and gases in porous media. This general

behavioral information was supplemented by site-specific studies that included measurements of the coupled hydromechanical properties of brine, intact salt, crushed salt, gas, and sealing materials. Although site-specific parameters for two-phase flow in the waste are lacking in the data base, representative values for these parameters would be difficult to obtain because of the expected heterogeneity of the waste. Surrogate parameters from other media are instead used for two-phase flow, and the uncertainties are compensated for by random sampling over ranges of values. Detailed modeling sensitivity studies of repository fluid flow and other coupled phenomena are summarized in Freeze et al. (1995) and Christian-Frear and Webb (1996). The information and concepts used were appropriate for developing the conceptual model.

3.3.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.3.1 and are critically reviewed here. Most assumptions are reasonable and appropriate and include the assumption of isothermal conditions for fluid flow calculations, the assumption of Darcy flow, the incorporation of two-phase flow, the treatment of wicking, and the phase stratification from gravity effects. The assumed lack of a DRZ in the walls of the modeled repository rooms is not expected to significantly affect the Repository Fluid Flow model, but would change the frequency of borehole penetration by increasing the target area. This issue is further addressed in Section 3.15. Certain aspects of the principal model assumptions were reviewed more closely and are addressed in the following paragraphs.

The two-dimensional representation of the repository in BRAGFLO is necessary to feasibly perform the many repeated model runs needed for probabilistic analysis. The effect of more explicitly representing the detailed stratigraphy was evaluated in Christian-Frear and Webb (1996), and the sensitivity of a more rigorous evaluation of coupled repository processes was reviewed in Freeze et al. (1995). The results of these studies identified key parameters and processes and support the two-dimensional approach used in BRAGFLO.

BRAGFLO uses the Brooks-Corey relative permeability model for two-phase flow within all media except the anhydrite interbeds. Although site-specific parameters are not available to support this model, the use of surrogate media and the practice of incorporating uncertainty through random sampling from a range of values is considered appropriate. The sensitivity of pressure buildup to the alternative van Genuchten-Parker two-phase model was documented in Christian-Frear and Webb (1996) and found to be relatively low. Although the Brooks-Corey model calculates slightly higher repository fluid pressures

than the van Genuchten-Parker model because of the reduced fluid mobility, the impact of this assumption was found to be small in the repository, where the porosities are high and the threshold pressures are low.

The depth of the model cells increases in a stepwise manner away from the repository to simulate radial flow into the repository, shaft, and borehole. While this is appropriate for flow to or from the shaft or borehole, it creates narrow constrictions in the two-dimensional flow field when considering flow across the shaft or borehole within the repository. The significant decrease in model depth in the vicinity of the borehole and shaft creates artificial constrictions for horizontal flow across the model. Model results were reviewed and have shown that the pressure drop across these constrictions is negligible under an undisturbed flow condition and that fluid movement is not unduly restricted. The lack of a significant pressure drop is expected to be related to the very low rates of flow and the relative mobility of the gas phase. However, this model configuration may restrict the rate of equilibration of brine saturation within the repository following an E1 borehole intrusion and the movement of brine from the "rest of the repository" to the anhydrite beds to the south.

Site characterization boreholes drilled by WIPP in the vicinity of the site are not addressed in BRAGFLO. ERDA-9, for example, penetrates the repository horizon within several meters of a drift wall in the operations area, but does not penetrate the repository excavation. The disposition of these boreholes is not addressed by DOE in the documents provided to the Panel. Unless properly sealed with a low permeability material such as a continuous concrete plug, such boreholes represent potential release pathways.

The permeabilities used in BRAGFLO for the waste materials and the panel closure seals are constants, but in reality are expected to change over time due to repository room closure. These parameters are important to repository fluid flow. The values chosen for permeability are in the high end of the range, and while they are conservative for late times, they underestimate permeabilities for early times. Both the closure seals and the waste may be highly permeable at early times, when the ability of the closure seals to effectively isolate waste panels may be in question. While the operations and experimental areas also are assigned constant permeabilities, the assigned value of 1×10^{-11} m^2 is considered conservatively high and therefore adequate for performance assessment purposes.

The permeability used in BRAGFLO for the DRZ is constant, but in reality is expected to change over time due to repository creep closure and to ultimately approach that of undisturbed halite as the fractures

in that zone heal. The actual permeability will be determined not only by the stress-induced fracturing, but also by the roof falls expected after closure and by the numerous test, characterization, and rock bolt boreholes that penetrate the zone from inside the repository and may not be sealed before closure. The permeability of 1×10^{-15} m^2 assigned to the DRZ has apparently been selected to not impede fluid flow from the repository to the anhydrite interbeds, but has not been based on an analysis to determine what the actual permeability would be. The value chosen for permeability is expected to be in the high end of the range, and while it would be conservative for late times, it may underestimate the permeability at early times.

The evaluation of the panel closure seals in restricting the effects of borehole intrusions to the penetrated waste panels suggests that the design, placement, and performance of these seals is important. The assigned constant permeability of 1×10^{-15} m^2 is equal to that of the disturbed rock zone, yet the crushed salt and concrete to be used in the seal will have considerably different and time-variant properties, depending on the seal design, methods of emplacement, and creep closure rates and pressures. The permeability of the concrete will increase over time due to degradation, while that of the crushed salt will decrease due to consolidation. The panel closures do not appear to have been formally designed and an engineering evaluation of their performance over time does not appear to have been performed.

3.3.2.3. Evaluation of Alternatives

The overall conceptual model for repository fluid flow has evolved over time and has been the subject of detailed review in which alternatives were evaluated and led to refinements in the numerical representation of the model in BRAGFLO (see, for example, Christian-Frear and Webb [1996] and Freeze et al. [1995]). The alternatives evaluated included three-dimensional versus two-dimensional representation, including and excluding gravity effects, and varying configurations of the two-dimensional representation. Based on these studies, the overall conceptual model, as configured for use in performance assessment, has been shown to be adequate; however, the validity of certain assumptions regarding components of this model has been questioned, as described in Section 3.3.2.2. These assumptions include alternative depths for model cells in BRAGFLO, committing to sealing the ERDA-9 borehole prior to repository closure, providing variable permeabilities for the waste, panel closure materials, and the DRZ, and providing an engineering design and performance evaluation of the panel closures.

3.3.2.4. Uncertainties

The principal uncertainties in the model results are expected to stem from uncertainties in the modeling theory and in the parametric data base. Emphasis in this review has been on identifying uncertainties that would lead to underestimating radionuclide releases. While the theoretical basis for the model may contain inaccuracies, it closely represents the state-of-the-art and with the exceptions noted above, does not appear to bias the results toward underestimating releases. The principal uncertainties in the parametric data base are associated with the hydrologic properties of the repository materials and are addressed in the aforementioned reports Freeze et al. (1995) and Christian-Frear and Webb (1996). Material properties with high degrees of uncertainty are generally treated as distributed variables. The properties of the panel seals, however, are not distributed variables and in the absence of a more thorough analysis of the seal design and its long-term performance, the ability of these seals to successfully isolate waste panels must be considered uncertain. Another uncertainty stems from the lack of a DRZ in the repository walls and the potential for waste releases through exploratory boreholes that penetrate the walls rather than the waste itself. The consequence of uncertainties in the models or data base is ultimately to overestimate or underestimate radionuclide releases; however, many of these parameter values reflect best estimates of future conditions and are considered adequate for performance assessment.

3.3.2.5. Adequacy of the Conceptual Model

The conceptual model for repository fluid flow is fundamentally sound and represents an appropriate effort to simulate the complex, strongly coupled fluid flow processes occurring within the repository during periods of simultaneous gas generation and creep closure. The appropriateness of the model was supported by the results of more detailed modeling reported in Freeze et al. (1995) and Christian-Frear and Webb (1996). The issues raised regarding the validity of the model assumptions (Section 3.3.2.2) are associated with specific, but potentially significant, details of the model. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.3.2.6. Adequacy of Application

With the exception of the issues raised in Section 3.3.2.2 regarding model assumptions, the application of the conceptual model in the numerical model is adequate. Principal concerns are related to the model cell depths, the treatment of material properties that vary over time, the disposition of the ERDA-9 borehole, and a more thorough evaluation of the long-term performance of panel closures as repository seals.

3.3.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. Although many simplifying assumptions are made, they are generally demonstrably conservative and are appropriate in view of the need to make the probabilistic modeling effort tractable, and in view of the relatively high degrees of uncertainty in both input parameters and the occurrence of future events. Selected modeling results were reviewed (specifically, repository pressure differences across borehole and shaft cells and at model boundaries) and were found to be reasonable. Although the accuracy of the BRAGFLO results is expected to be adequate and appropriate for performance assessment modeling, provided that the issues raised in Section 3.3.2.3 are appropriately addressed, a final determination of model accuracy cannot be made in the absence of modeling results.

3.3.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain pending resolution of the issues raised in Section 3.3.2.3. In summary, the following concerns remain.

- The sensitivity of modeling results to the depths of the cells in BRAGFLO representing the borehole and shaft does not appear to have been evaluated for a variety of flow conditions to determine if the model configuration unrealistically restricts brine movement within the waste panel area or to the anhydrite beds at the southern end of the repository. If modeling results are found to be sensitive to this model configuration, alternative configurations might be considered.

- A commitment to effectively seal the ERDA-9 borehole with a continuous concrete plug does not appear to have been made by DOE. Such a commitment is expected to be provided in Chapter 3 of the CCA; however, this chapter was not available to the Panel for review.

- The sensitivity of model results to the constant permeabilities assigned to the waste materials and panel seals does not appear to have been evaluated. Higher permeabilities at early times could lead to underestimating radionuclide releases.

- The basis for the permeability value assigned to the repository DRZ has not been adequately supported, and the sensitivity of model results to the selection of a constant value for this parameter does not appear to have been evaluated for the current performance assessment model. The presence of open, unsealed boreholes within this DRZ and the likelihood of massive fracturing during roof failure suggest that the permeability of this zone may approach that of the waste.

- The waste panel closures do not appear to have been formally designed and their long-term performance does not appear to have been evaluated in the same rigorous manner as shaft and borehole seals.

3.3.2.9. Adequacy for Implementation

The Repository Fluid Flow conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.3.2.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.3.2.10. Dissenting Views

There were no dissenting views for this model.

3.4. Salado

3.4.1. Model Description

The Salado Formation is the principle barrier between the waste and the environment and is the primary source of brine flowing into the repository. The conceptual model supports estimates of hydrologic processes and properties, as well as mechanical behavior of the halite-rich rocks of the Salado Formation. A simplified stratigraphy for hydrologic modeling is proposed and supported. The modeling of the anhydrite interbeds is discussed elsewhere.

The Salado Formation was deposited by cyclical evaporation of marine water in an imperfectly closed sub-basin of the Permian Basin. The sub-basin, called the Delaware Basin, contains the Los Medanos region in which the WIPP site is located. The cyclical nature of deposition is represented by variations in the details of the mineralogy and geochemistry of the halite, by the presence of interbeds composed mostly of anhydrite, and by the presence of clay seams. Individual depositional cycles are a few meters thick. Relatively pure and impure (argillaceous) halite layers are present. Anhydrite interbeds, generally less than a meter or two thick, represent relatively fresh water inflow at the beginning of evaporative cycles. All of these variations represent fluctuations in water chemistry and the influx of windblown and water-borne fine clastic sediments.

The layering and composition of the Salado impact the mechanical processes of room closure and the hydrologic processes (both gas and brine) that accompany room closure. A detailed stratigraphy, which defines the distribution of mechanical properties and processes, has been developed for use with the MD model (Munson et al. 1989). Christian-Frear and Webb (1996) asserts that a simplified model containing only impure halite and interbeds is sufficient for hydrologic considerations.

The presence of a significant fraction of clay (≈5%), primarily as interstitial inclusions, significantly impacts the mechanical behavior of halite rocks. The clay promotes fracture and reduces intergranular cohesion and friction, increasing the rate of creep. Impure halite is also more permeable than its purer analogue. This may be due to the interference of clay particles in intergranular spaces with the processes of pore closure related to creep under natural loads.

The pre-excavation hydrologic environment in the halite rocks of the Salado is one which may be characterized as having very low permeability and porosity due to void-filling by diagenetic processes and creep resulting from the superincumbent load. Although both display very low porosity and permeability, the pure halite rocks display lower (almost impossible to measure) permeability than the impure halite. No significant natural flow occurs in the pre-excavation Salado environment. The anhydrite interbeds are more permeable than the halite rocks and have natural fractures. This is presumed to result from the physical properties of anhydrite, which is stronger and more brittle than halite and resists creep at the repository lithostatic pressure. Beauheim (1987) documented that permeability is greater near the excavations (beyond the secondary DRZ) at distances of several meters and that pore pressures decrease near the excavations, implying that flow resulting from stress imbalance around the excavations is occurring. Brine seeps on excavation walls, collection of brine in boreholes in the repository floor, and the measured contribution of inflowing brine to humidity in the repository, are clear indications that brine inflow is occurring.

Three flow mechanisms have been proposed based on the varied, mostly qualitative data about flow into the repository (Howarth et al. 1995). These are: 1) far-field flow in response to potentiometric gradients resulting from excavation through naturally interconnected pore spaces; 2) redistribution of pore fluids (pores not necessarily originally interconnected) due to fracture and creep around the excavations; and 3) flow due to consolidation of water-bearing clay layers. None of these mechanisms can be eliminated on the basis of the existing evidence, so an inflow model combining the estimated volumes of brine from each mechanism is proposed. No consideration of the role of brine included in halite crystals is mentioned, although fracturing and some intracrystalline creep mechanisms may liberate brine from this source.

Estimates of quantities of brine inflow from each proposed flow mechanism over the repository history (to final closure) were made on the basis of best-estimate values. Although the volume of brine inflow from the far-field mechanism is theoretically unlimited, low permeability and the relatively short time

available limit the probable actual volumes of brine that could reach the repository. The far-field mechanism may deliver between 25 to 110 m^3 of brine to a single disposal room over the life of the repository. Brine from the redistribution mechanism may range from 28 to 150 m^3. The clay compaction mechanism is assumed to have mostly ceased by the end of the disposal phase of work. These estimates depend on the repository gas pressures countervening the fluid potential gradient at a reasonably early time in the repository history. In any case, these mechanisms can supply enough brine to fully corrode the waste, between 100 and 150 m^3 per disposal room (Howarth et al. 1995). Flow out of the repository, due to elevated gas pressure by matrix flow or in fractures, is likely to be multiphase and will be less efficient than brine inflow. Specific data on Salado capillary pressures are not available.

Brine inflow and outflow have been simulated using the BRAGFLO model, and some specific enhancements to tie in specific conceptual model components have been proposed. These are: (1) Stratigraphy, (2) Salt Creep, (3) Fluid Flow, (4) Transport, (5) Thermally Driven Fluid Flow (insignificant), (6) Model Initial Conditions, (7) Disturbed Rock Zone, and (8) Interbed Fracturing. The model results were compared with the small scale brine inflow and Room Q experiments. McTigue (1993) evaluated the experimental results, using an exact analytical solution based on simple Darcy flow, for three flow histories for two flow mechanisms. This analysis provided an acceptable comparison between model and experimental results.

The INTERVAL program (Howarth et al. 1995) provided partial review of the model/experimental comparison and concluded that the Darcy-based version of BRAGFLO could replicate the Room Q results consistently with refinements of the inflow models to better simulate the pore pressure field around the excavations.

Electrogeophysical experiments were performed to evaluate the extent of the interconnected pore-space field around the repository and were found to support the far-field flow model (Borns et al. 1990). That is, the extent of saturated and interconnected pore spaces was seen to be infinite in the horizontal direction in the Salado.

3.4.2. Review of Criteria

The Salado is the primary barrier to radionuclide transport out of the repository. Its mechanical properties dictate the most important aspects of room closure and its hydrologic properties control brine inflow and gas and brine outflow. The objective of the Salado model is to provide a set of process and

property descriptions unified to define the original state of Salado equilibrium with its natural environment and its responses to excavation of the WIPP facility. The mechanical aspects of the Salado model support the Creep Closure model. The hydrologic aspects of the Salado model define the framework for consideration of brine inflow and brine and gas outflow from the repository. Detailed consideration of the anhydrite interbed and impure halite behavior are presented in other conceptual model reviews. The Salado conceptual model is central to the performance assessment because of the general absence of important quantitative measurements of principal parameters describing flow in the very low permeability halite rocks.

3.4.2.1. Information Used to Develop the Conceptual Model

Surface-based hydrologic testing of the Salado was abandoned because of the extremely long times required for testing in the extremely low permeability environment. *In situ* testing in the facility excavations included testing in short boreholes in Room Q, laboratory testing on samples from the excavation, electrogeophysical surveys, and collection of water from wall seeps and openings such as unlined boreholes. Packer tests were performed to specifically examine questions about interbed permeability and critical pressures to activate interbed fractures. Mechanical property measurements include closure rate measurements and laboratory tests. Mechanical models are discussed in the Creep Closure and DRZ model reviews.

Inflow and outflow models are based on best estimates, since only indirect measurements of flow and pore pressures in the low permeability Salado in disturbed areas near the repository are available, and no actual data are available for the hydrologic properties of the undisturbed or far-field natural state of the halite rocks. Only one, yet to be qualified, hydrofract experiment far enough from the repository to imply undisturbed stress conditions, has been done. Models of flow are essentially limiting calculations based on estimated and projected process parameters. Hydrofracture of the repository is not considered in the model since such an event is considered a "conservative" result lowering gas pressure. It is also possible that interbed critical pressures are low enough that halite hydrofract pressures may never be reached. Interbed critical pressures are estimated at a maximum of 5 MPa and Salado critical pressures appear to be between 15 and 20 MPa.

3.4.2.2. Validity of Model Assumptions

The hydrologic model of the Salado assumes that the three proposed flow mechanisms (Section 3.4.1), exclusive of flow in the interbeds, are the only credible flow mechanisms and that the estimated volumes

of brine inflow are credible. The estimated volumes of brine inflow are sufficient to corrode all of the corrodable materials in the projected waste. The key assumptions appear to be valid with respect to inflow processes. The inflow volumes depend on the interaction of inflow with repository gas pressures and on the estimates of the far-field flow response to repository excavation. The assumption of Darcy flow seems valid in the far field, but is difficult to demonstrate in the region near the repository. Inflow volume estimates are difficult to validate. Outflow hydrodynamics depend on two-phase flow models, which depend on capillary pressures in the Salado. No capillary pressure measurements are available. Larger outflow into the Salado beyond the DRZ by matrix flow is a conservative influence since the process would amount to interstitial storage of contaminants. Although likely to some extent, no credit is taken in final performance assessment calculations for this phenomenon. The assumption of cessation of flow from clay compaction before the end of the repository phase is acceptable because of the small brine volumes predicted.

3.4.2.3. Evaluation of Alternatives

No alternative models were evaluated by DOE (see Section 3.4.2.2).

3.4.2.4. Uncertainties

Although somewhat uncertain, the brine inflow model predicts sufficient volumes of brine to corrode all of the corrodable waste. There are, therefore, no consequences of reasonable additional uncertainty in terms of corrosion and gas generation. Brine volumes very much greater than those predicted would have to occur before brine mechanically interferes with room closure, and is unlikely. Brine availability for biogenic waste degradation is assumed. The Room Q and other observations appear to support the general validity of brine inflow estimates and the unlikelihood of very large uncertainties. Only very large underestimations of brine inflow would have significant impact, unless the sudden dissolution of dissolved gases during human intrusion might cause direct discharge of brine in the repository to the surface. The timing of the occurrence of gas pressures sufficient to retard brine inflow is the principle control of brine volume. This timing is addressed in the Gas Generation conceptual model and the porosity surface calculations.

3.4.2.5. Adequacy of the Conceptual Model

Given that the conceptual model predicts that there will be enough brine to corrode the waste and that other assumptions appear conservative, making other impacts unlikely, the model is adequate for its intended use.

3.4.2.6. Adequacy of Application

Assuming that the interaction of the inflow model with the gas generation model and the porosity surface calculation are adequate, the application of this model is adequate.

3.4.2.7. Accuracy of Results

It is unlikely that the results of the application of this model are highly accurate, but in view of the conservative assumptions and the large margin between the assumed impact on waste degradation and other significant impacts, the results appear to be accurate enough for the intended purposes of performance assessment.

3.4.2.8. Validity of Conclusions

The conclusions appear to be valid. Estimates of inflow volumes from the mechanisms proposed in the model appear to be reasonable.

3.4.2.9. Adequacy for Implementation

The model is adequate for implementation.

3.4.2.10. Dissenting Views

There were no dissenting views for this model.

3.5. Impure Halite

3.5.1. Model Description

The Impure Halite conceptual model explains the role of impurities in influencing the mechanical and hydraulic properties of the halite-rich rocks in the Salado. The model supports the treatment of the distribution and stratigraphy of impurities in the Creep Closure and Salado conceptual models.

There are two general classes of halite rocks in the Salado Formation. These are called pure and impure halite, based on the occurrence of significant proportions of mineral phases other than halite in the impure type. Impurities include evaporite minerals such as polyhalite and anhydrite, as well as iron oxide coatings and clay. The most abundant (as much as 5%) and important impurity is clay, with the exception of the anhydrite interbeds, which are discussed elsewhere. Clay occurs as clay seams, which

are treated as mechanical discontinuities in the Creep Closure model and as sources of inflowing brine in the Salado hydrologic model. It is as dispersed, interstitial clay that impurities have the most impact on the behavior of halite-rich rock.

Pure halite is more impermeable (Howarth et al. 1995), more ductile, and stronger (lower creep rate by a factor of four) than impure halite (Munson et al. 1989). Mechanically, the elastic interstitial clay platelets probably act as flaws, concentrating stress and modifying plastic micro-mechanical strain mechanisms. Pure halite is thought to be almost perfectly impermeable because creep under natural lithostatic stress has caused adjacent crystals to conform to each other's shape along their interfaces so completely that there is almost no space for interstitial brine. Such close-fit crystal mosaics, even in the presence of thin brine films on their interfaces, have minimal interconnection between pore spaces and any movement through the interstices would be inhibited by adsorptive and film-strength forces.

Clay particles between halite crystals interfere with the closeness of fit of adjacent crystal faces, concentrate stress, and may promote solubility of pore walls. Clays are phylosillicates, which in many cases are capable of chemically driven adsorption and desorption of water, promoting flow and water storage in pore spaces. The mechanical influence of clay promotes microfracture, which may enhance flow in response to stress imbalance around the repository.

Christian-Frear and Webb (1996) has asserted that a hydrologic model of the Salado that ignores the stratigraphic variation within the halite rich rocks of the Salado leads to an acceptable and conservative flow model result if all the halite-rich rocks are modeled as impure halite. This model conservatively overestimates flow in the halite rocks to an acceptable degree and eliminates the need to consider variation in the degrees of impurity and stratigraphic complexities among pure and impure halite rocks. Conservatively chosen values for impure halite permeability make this an adequate approach to modeling of halite-rich parts of the Salado.

The geometry of flow in the impure halite is convergent/divergent as discussed under the Repository Fluid Flow conceptual model review. The probability of hydrofracture of impure halite is probably larger than for pure halite because of the loss of cohesive strength due to clay in the interstitial spaces. Hydrofracture is not considered because it would lower gas pressures (a conservative influence), and because critical pressures for fracture of impure halite are much higher than for interbed flow. Interbed threshold pressures vary from one to five MPa, while halite critical pressures approach 20 MPa. Also, outflow estimates are based on two-phase flow and are not based on measured capillary pressures.

3.5.2. Review of Criteria

The impure halite conceptual model provides a basis for the evaluation of brine inflow and outflow from the repository within the simplified stratigraphic framework based on work by Christian-Frear and Webb (1996). Although differences in the behavior of pure and impure halite, variable degrees of impurity, and complexities of stratigraphic distribution of zones of impurity exist, the modeling of all halite rocks in the Salado as impure halite is an acceptable model simplification (Christian-Frear and Webb 1996).

3.5.2.1. Information Used to Develop the Model

Measurements of impure halite hydrologic properties (see natural barriers panel review) and assumed flow geometry and mechanisms (see the Salado model review) provide the additional bases for brine inflow estimates. Christian-Frear and Webb (1996) evaluated the acceptability of the simplified stratigraphy using impure halite only for halite-rich rocks for the Salado model. The Impure Halite model lacks precise flow rates and capillary pressures from hydrologic measurements and the flow mechanism process models are based on assumptions which have only theoretical bases, but provide results that acceptably match experimental and observational data.

3.5.2.2. Validity of Model Assumptions

The model assumptions are the process models for flow mechanisms, the Darcy nature of far-field flow, and the conservatism of the simplification of stratigraphy proposed by Christian-Frear and Webb (1996). These assumptions are reasonable and are supported by arguments presented by Howarth et al. (1995), by the comparison of model elements and inflow observations by McTigue (1993), and by review of similar results by INTERVAL (Howarth et al. 1995).

3.5.2.3. Evaluation of Alternatives

Early WIPP models considered all halite-rich rocks to be unsaturated and impermeable. Observation of inflow after excavation forced the development of flow models for halite-rich rocks. All observational and most experimental data are from impure halite. No alternative flow mechanism models have been considered (Howarth et al. 1995).

3.5.2.4. Uncertainties

The impure halite model is almost entirely theoretical and no evaluation of uncertainties is considered. Results match *in situ* brine flow observations fairly well. The result of uncertainty in the case of the simplifying assumptions with regard to stratigraphy are conservative.

3.5.2.5. Adequacy of the Conceptual Model

The model appears to be adequate for the same reasons that the overall Salado model is adequate. Brine inflow sufficient to corrode the waste and to drive biogenic degradation is assumed. For error to be significant, brine inflow would have to be very large, which is unlikely.

3.5.2.6. Adequacy of Application

The impure halite submodel is applied adequately, with the assumption that its application in the Salado model and related other models is conservative.

3.5.2.7. Accuracy of Results

The results of the model are probably not highly accurate, but appear to be adequate in their application.

3.5.2.8. Validity of Conclusions

The conclusions drawn on the basis of the impure halite model are valid for performance assessment purposes.

3.5.2.9. Adequacy For Implementation

The model is adequate for implementation for performance assessment purposes.

3.5.2.10. Dissenting Views

There were no dissenting views for this model.

3.6. Salado Interbeds

3.6.1. Model Description

The three Salado interbeds are modeled in BRAGFLO and are represented by region 20 (Marker Bed [MB] 138), region 21 (anhydrite layers a and b), and region 28 (MB 139). All three interbeds have the same model parameters (see Tables 6-12 and 6-13 in Section 6.4) and initially, the parameters are spatially constant. The only initial model difference concerns bed location and thickness.

Three primary interbeds are identified in the region of the Salado Formation nearest the waste panel: MB 138, anhydrite layers a and b, and MB 139. All three interbeds are primarily composed of anhydrite, with clay seams bounding the lower contacts of MB 138 and MB 139. As discussed below, the interbeds

have differing physical and chemical properties from the halite of the Salado Formation. Anhydrite is much less soluble than halite. The interbeds appear to be one or more orders of magnitude more permeable than the surrounding halite, primarily because of subhorizontal bedding-plane fractures (both healed and open) present in the anhydrites. Under differential stress, the interbeds may fracture while, under the same stress, halite would flow by plastic deformation. Fracturing of the relatively brittle interbeds would enhance the local permeability, allowing this otherwise low-permeability rock to carry groundwater. Furthermore, since the interbeds have a large contact area with the adjacent halites, even very small fluxes from the halite into the interbeds or to the halites from the interbeds can accumulate into a significant brine inventory. In this sense, the interbeds may cause the halite to act as a source or sink for brine in the repository. The three interbeds are explicitly represented in the conceptual model because of their physical properties and their existence in the disturbed rock zone around the repository, within which fluids are able to flow with relative ease compared to surrounding rock types.

Two major conceptual features of the interbed model are represented by, 1) transmission of brines from the impure halite to the repository via the interbeds and, 2) incorporation of fracturing and dilation of the anhydrite to allow porosity and permeability variations.

Feature one allows brine flow laterally along the higher permeability interbeds toward or away from the repository, and vertically between the interbeds and low-permeability halite. Horizontal fractures, dilation, and propping are due to gas pressures exceeding the threshold pressure. Induced vertical fractures in the interbeds are caused by interconnection of branching horizontal fractures over time, or high exceedence of the threshold gas pressure (i.e., greater than lithostatic). Pre-existing vertical fractures were caused by tectonic forces or the alteration from gypsum to anhydrite and subsequent volume reduction.

Feature two, alteration of porosity and permeability, is caused by the creation of new fractures or dilation of pre-existing, partially healed fractures due to high gas pressures. *In situ* hydrofracture tests have created sustained fracture apertures to 0.2 mm. Such pressure-dependent variables have created marked permeability changes. In the BRAGFLO model, a porous medium model simulating interbed fracturing and dilation causes porosity and permeability of a computational cell to increase as the pore pressure exceeds the threshold value. In addition, interbed transmissivity increases with increased anhydrite fracturing or dilation. Fluid is able to easily flow radially outward if adequate threshold pressure is available (1 to 5 MPa) to dilate the anhydrite. The model assigns a fracture initiation pressure at which

local fracturing occurs and changes in permeability and porosity subsequently occur. Above the threshold pressure, the local compressibility of the interbed increases linearly with pressure. This greatly increases the porosity with respect to increasing pore pressure. Additionally, permeability increases as a power function of the ratio of altered porosity to initial porosity.

3.6.2. Review of Criteria

3.6.2.1. Information Used to Develop the Conceptual Model

Three primary sources of information were used to generate the conceptual model for the Salado interbeds. These included FEP documentation, position papers, and *in situ* hydraulic tests. Four FEPs were associated with the Salado Interbed conceptual model: DR-9 (anhydrite threshold displacement pressure); S-1 (verification of 2D radial flaring); S-4 (mechanical effects of gas generation); and S-5 (brine storage in anhydrite and halite). A second source of information was the Salado position paper. The third major source of information for developing the conceptual model was obtained from *in situ* field tests of the anhydrite interbeds. Location of these tests was in the vicinity of Rooms Q and L. These information sources are believed to be adequate for model development.

3.6.2.2. Validity of Model Assumptions

The main assumptions of this conceptual model are considered valid. The chemical assumption, that anhydrite is less soluble than halite in the WIPP environment, is proven by both experimental and crystal chemical factors. The Darcy flow model is also deemed reasonable. The type of fracture propagation and dilation used in the conceptual model has been substantiated by *in situ* tests. Assumptions of increased porosity and permeability due to fracturing (caused by gas generation exceeding threshold pressures) is reasonable. Therefore, the assumptions of this conceptual model that have the largest potential impact are believed to be appropriate.

Three other assumptions of the interbed model have not been well documented. The first of these is the description of the mechanism of vertical crack propagation. This potential effect of gas overpressurization needs to either be fully described or discounted from occurring in the interbeds. Second, there does not seem to be any incorporation of the fact that there are continuous clay seams at the base of MB 138 and MB 139. The physical properties of clay seams (water content, low cohesive structure, aniostropic characteristics) may have a substantial effect on the model of the interbeds. Third, the fluid storage capacity of the interbeds is not well documented.

3.6.2.3. Evaluation of Alternatives

Earlier models of the Salado Formation in the 1980 final environmental impact statement did not differentiate the anhydrite interbeds as a separate model. When the 1989 draft environmental impact statement was produced, anhydrite interbeds were included as a model. This was based on *in situ* tests that determined the interbeds had higher permeability than the remaining Salado Formation. The 1992 performance assessment concluded that the interbeds would then be the dominant fluid pathway. It was not until this factor was recognized and gas pressures were calculated to possibly reach 20 to 25 MPa (in the 1992 performance assessment) that an attempt was made to model fracturing in the anhydrite interbeds.

At the level of a conceptual model, the primary factors of the Salado Interbeds have been addressed properly. This has been accomplished by either using well-established models (Darcy flow) or *in situ* experiments, or by adopting reasonable, conservative assumptions.

The following items do not appear to have been addressed by DOE: (1) Is storage capacity of the anhydrite layers so small that brines would be forced to travel to the Land Withdrawal Act boundary? (2) What would the consequence be if the gas threshold pressure of the clay seams was very low (for example, 0.01 MPa)?

3.6.2.4. Uncertainties

The levels of uncertainty associated with the Salado Interbeds performance at the conceptual model stage appear to be quite small. The following uncertainties may affect the model but the consequences are unknown at present. The determination of consequences would hinge on a sensitivity analysis, which is presently unavailable.

The model assumes that fracture propagation would continue uniformly in a horizontal direction. In Domski et al. (1996), test results for interbeds indicate anisotropy. Assuming that the interbeds act in an isotropic manner would be conservative, especially since *in situ* values were determined for the weakest direction (laterally).

Another assumption is that enhanced porosity and permeability in the interbeds would mitigate each other in terms of gas migration responses. This does not seem plausible since permeability increases as a power function to an increase in porosity. It would seem that permeability factors would dominate and therefore allow longer gas migration distances.

The perturbation to the model that is completely unaccounted for (threshold pressure of bounding clay seams) is included as a secondary factor in Section 3.6.2.3 above.

3.6.2.5. Adequacy of the Conceptual Model

The Salado Interbed conceptual model describes fluid flow through three discrete anhydrite layers in the vicinity of the repository. CCA Section 6.4.5.2 reports flow model objectives in dealing with the anhydrite interbeds: (1) fluid flow through the interbeds, (2) fracture formation and/or dilation of the interbeds, (3) variations in porosity of the interbeds, and (4) variations in permeability of the interbeds within the constraints of the conceptual models. These requirements are thought to be adequate. The uncertainties associated with the model can not be constrained since a sensitivity analysis is not presently available.

3.6.2.6. Adequacy of Application

A much greater uncertainty is perceived when it comes to converting the field results into the mathematical model. In all but the simplest of field observations, one must make assumptions in applying a mathematical model. However, the ability to monitor the assumptions made in developing a numerical code to simulate the physical properties acting within the anhydrite interbeds is extremely difficult. SNL states at one point that parameters in the model are treated as fitting parameters and have little relation to physical behavior, except that they affect the porosity change. At no time was the logic clearly presented whereby one could track the implementation of this conceptual model into the numerical code developed for this portion of BRAGFLO. Therefore, one must state that the discussion of how the anhydrite interbed conceptual model is applied into an overall performance modeling element was not adequate.

3.6.2.7. Accuracy of Results

The results obtained for this conceptual model fall into two categories. The first set of results are those determined from physical tests. Hydraulic tests performed *in situ* near Rooms Q and L, and laboratory tests on core samples have provided results that are deemed adequate. These tests are based on standard procedures and have been qualified as to their accuracy. There is no further question as to the validity of these physical parameter results.

The second category is based on whether the results of performance modeling using the conceptual model within the performance system are sufficiently accurate to adequately represent the physical and

chemical processes modeled. It is not possible to make a judgment on this category of results since no values have been presented to indicate the outcome of this model. The 1992 performance assessment did not incorporate a fracture propagation submodel in the Salado Interbeds model, so results and sensitivity analyses from that performance assessment are not applicable to this review. Results for this section are not meant to be the final performance assessment results, but rather are the results of BRAGFLO during various permutations.

For example, hydrofracture experiments in the anhydrite beds have created sustained fracture apertures to 0.2 mm. If BRAGFLO produced fracture aperture dimensions of 5.0 mm during gas pressurization runs, one would conclude that the results are not accurate. This sort of comparison has not been possible because model runs have not been presented.

The implementation of the fracture modeling was not explained in sufficient detail in any document. The method of how the code represents the physical property is unknown and its accuracy cannot be judged. Results of the calculation could vary significantly, depending on whether the fractures propagate gradually or in a stepwise fashion.

3.6.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Salado Interbed model in the modeling framework are valid. Since the accuracy of results is inconclusive (see Section 3.6.2.7), it is difficult to assess the validity of the conclusions. The results of parameters listed in Table 6-12 of the CCA may be considered valid for the purpose of implementation in the overall performance assessment. The results listed in Table 6-13 of the CCA may not be valid at this point. Questions of validity are addressed below.

Fracture initiation pressure for MB 139 at 0.2 MPa above hydrostatic pressure is concluded to be valid. The percent increment to allow full fracture porosity for MB 138 and 139 (3.9%) is also considered valid. The same parameter for anhydrite beds a and b is 23.9%, and no discussion is presented for the large difference in the value. The increase needed to allow full fracture porosity in these two interbeds would not be expected to differ from MB 138 and 139. Such a difference should have been thoroughly explained. The conclusion of maximum permeability (10^{-9} square meters) is extremely suspect since the storativity of the beds was not calculated. These two factors are closely linked and it is hard to envision that the permeability can increase ten orders of magnitude without a dramatically substantial change in

storativity of the interbeds. Finally, the parameter "increment above fracture initiation pressure to obtain maximum fracture pressure," does not account for the effect of bounding clay seams associated with the interbeds. To assume that an increase of approximately 1.5 MPa above lithostatic pressure is needed for maximum fracturing is probably not valid when clay seams are in close proximity

3.6.2.9. Adequacy of Implementation

The conceptual model for the Salado Interbeds is well thought out and substantiated by *in situ* experiments. However, certain items were not clearly explained or documented in Chapter 6 of the CCA. It would be helpful if the following questions were clarified:

- What is the mechanism for vertical crack propagation?
- What is fluid storage capacity of the interbeds after dilation?
- Enhanced porosity and permeability are presumed to mitigate each other in terms of gas migration responses. How can this happen when permeability is a power function (not linear) of porosity?
- What assumptions and limitations are made to represent the conceptual model by the mathematical code?
- Why is the full fracture porosity increment of 23.9% for anhydrite beds a and b so different from the 3.9% for MB 138 and 139?
- What are the calculations that show that permeability increases by 10 orders of magnitude?

It is believed that this model would be adequate for implementation in the compliance application after the question raised below is fully addressed.

- How do the physical properties of clay seams at the contact of the interbeds affect the fracture propagation and permeability of the model?

3.6.2.10. Dissenting Views

There were no dissenting views for this model.

3.7. Disturbed Rock Zone

3.7.1. Model Description

The Disturbed Rock Zone model consists of a description of a fracture zone surrounding excavations that is created by induced stresses. At the WIPP, the primary DRZ exists in all rocks; the secondary DRZ is

applicable only in viscoelastic rocks such as halite. The DRZ varies in depth away from the excavation and has been reported to be up to 50 m deep for large excavations. It exists in the repository roof, floor, and walls, and around shaft and borehole walls. Because of the distinctly different stress fields in each of these locations, the DRZ can have different properties at each location. For example, it is considered to disappear under appropriate conditions and with time in the borehole seals program, and is variously applied as it relates to the repository rooms and panels. Related models include Creep Closure, Shafts and Shaft Seals, Disposal Room Geometry, Repository Fluid Flow, Salado, and Salado Interbeds.

Induced changes to the stress field occur immediately on the passage of mining equipment during excavation. In halite, as the salt adjusts to these changes through the creep process, further micro- and macro-fracturing progressively occur in the intact rock, adding to a fracture region known as the DRZ. This DRZ was first technically addressed and demonstrated by Borns et al. (1987, 1988, 1989, 1990). Van Sambeek et al. (1993) have referred to the mining-induced fractures as the initial DRZ and the progressive fracturing as the secondary DRZ. In this analysis, the Panel will not distinguish between these except for their applications. The characteristics of the DRZ include increased rock volume and permeability and decreased brine saturation due to drainage and drying, load bearing capacity, and lithostatic pressure. Clearly these properties could lead to the DRZ providing flow paths for fluids and gases from the repository to those zones that might carry them to the accessible environment. Studies by Munson et al. (1994) have characterized the DRZ and found it to be irregular in thickness and fracturing and able to heal with time under an applied confinement. Two versions of a creep model, applicable to room closure and DRZ development, have been formulated during this period. These are a model that includes both transient primary creep and steady state creep (MD model), which has been used in the porosity surface lookup table calculation of repository void space, and the MD model, with added tertiary creep fracture (MDCF), used to confirm DRZ thickness, fracture porosity, and healing characteristics. The MD model is central to the porosity surface calculation (SANTOS), which relates creep, waste compaction, and gas pressure to overall room closure rate. The DRZ is not considered in room closure calculations since all DRZ fracture porosity is assumed to be recovered by healing at final closure. For the waste room, the DRZ model is incorporated by assuming a high permeability and low porosity, with the result that the DRZ is unable to act as a constraint to brine or gas flow from the repository rooms and is unable to store brine. A primary reason for this approach is the uncertain behavior of the rock zone, which is dependent on many uncontrollable factors.

3.7.2. Review of Criteria

3.7.2.1. Information Used to Develop the Conceptual Model

The treatment of the DRZ in both the shafts and the repository rooms is the result of development of an equivalent permeability and porosity for addition to the main room and shaft seal model elements rather than by a specific DRZ input. Analyses were conducted evaluating the reasonableness of this approach, but parameters representing the DRZ over the history of WIPP were not developed. Therefore, the information supporting evaluation criteria for review of this conceptual model is essentially the completeness of the considerations and the reasonableness of the DRZ concepts.

The DRZ has several significant impacts on the performance assessment calculations. These include a) room performance, b) gas pressure calculations, especially near term, and c) permeability of the shaft regions. The DRZ in the salt around the rooms appears to be the toughest to model because of the sizes and shapes of the openings. The shaft DRZs appear to be less difficult to model because of their simpler shape. First, the shafts are smaller than the rooms, second they are stable cylindrical forms, and third, studies show that, given a stiff support against creep, the DRZ fractures will heal in a relatively short time. For example, from analysis of WIPP data, Chan et al. (1995) projects full healing within 25 years after the shaft seals have been placed. Within the healed zone, the induced high permeability drops to a level below that of the placed seals, reducing the concern of a large flow path surrounding the sealed shaft. Contrary to this favorable healing in the shafts, DRZ healing in the waste room will not be as responsive in time or extent. Because of the relatively large room, the necessary rigid backing to support the healing process is delayed, and the DRZ functions as a more open fractured rock mass. Furthermore, only the DRZ in the roof and floor of the repository are modeled; the walls of the room are not included in the Repository Fluid Flow model. Neither the roof nor the floor will receive the support needed to close the open cracks and open boreholes that are assumed to be a part of the roof DRZ. Early healing of the floor would be optimal in order to restrain fluid flow downward, and the roof will continue to develop an open fracture DRZ upward, due to roof spalling, as the room seeks its most stable shape within the stress field. The most notable impact of the open fractures to performance assessment in the near term will be in deterring brine flow to the repository because of brine storage in the fracture zone. This could have significant uncertainty effects on the gas pressure calculations.

It should be noted that no information was found concerning studies of how soon after excavation the DRZ is fully formed. It is reasonable to consider that its formation begins concomitant with excavation

and progresses until the salt creep and the stress field have stabilized. The MDCF model appears to be an excellent tool for conceptualizing the phenomenology of salt creep and its mechanisms resulting in fracture closure and healing. Excellent progress in understanding salt's viscoelastic behavior and adding this capability to the creep flow behavior has made the modeling capability a highly supportive tool critical to understanding the DRZ. Testing of these concepts has produced favorable responses that have specifically aided the shaft seals program in mitigating concerns over seals integrity. Significant among these tests are the Room Q experiments, where identification of the reduced brine flow and increased permeability in the DRZ were measured. Data from the air-intake shaft tests showed the change of permeability as a function of distance from the shaft wall and the changes in permeability with time. Knowles et al. (1996) conducted rigid inclusion tests that confirm the ability to heal the DRZ, restoring it to ambient conditions. The many parameters associated with the DRZ have been well defined to support the BRAGFLO models. The permeability and porosities appear to be the most critical parameters for use in performance assessment. Information examined for the DRZ characterization, including its extent, ability to be restored by salt creep and restraint, and ability to be represented by modeling, was found to be acceptable.

3.7.2.2. Validity of Model Assumptions

The following assumptions are basic to the DRZ model:

- A DRZ surrounds the surfaces of any mined opening.
- A permeability value is selected that assures the DRZ is not the limiting zone for fluid transport between the waste rooms and the marker beds.
- A fixed high-level permeability value should be assigned to the DRZ everywhere.
- Roof bolts or other roof support system penetrations of the halite and boreholes through the halite into the marker beds are included as part of the DRZ, and these penetrating boreholes may not close completely.
- Various other processes may contribute to fracturing in the future.
- The DRZ surrounding the shafts will progressively heal toward near complete restoration following placement of the seals.
- The porosity and permeability are increased by the DRZ, except where a rigid backing is present to support the DRZ against creep; however, a low porosity is assumed in the room DRZ to reduce the storage capacity of that zone for performance assessment.

The basic assumption that a DRZ exists at the surface of any mined opening in the Salado is fundamental to the definition of a DRZ. That the leading boundary of the DRZ will heal, provided support exists to resist the creep, has been substantiated through the WIPP research program. Basically, the outer reaches of the DRZ (microfractures) will heal in the near term, and the DRZ primary fractures will close and heal once seal material is placed in the openings to support the process. This might reliably be achieved via the vertical cylindrical openings, but the healing problem is more complex around the waste room. There it is recognized that a variety of effects may work against the reconsolidation of the DRZ. These effects range from uneven placement and non-characterized waste support against room closure to other processes, such as roof falls, that might contribute to further development of the DRZ. These assumptions concerning the DRZ existence and its behavior appear to be adequate.

Given the shaft seals design, it is assumed that the shaft DRZ heals to the point that its permeability is below the level of seal permeability, thereby reducing its importance. Therefore, flow through the sealed shafts is attributed to the permeability of the shaft seal materials, with an adjustment to account for any DRZ component to the permeability (see Section 3.20). At the waste room, the situation is far more complex and the technology less well defined. Therefore, at the room boundary, it appears that the above assumptions support the assignment of a high permeability that essentially removes the DRZ from a limiting position of flow to and from the room, and a low porosity that will not perturb storage of the brine.

3.7.2.3. Evaluation of Alternatives

Fracture zones in the walls of excavations have always been of concern to the mining and construction industries. In most cases, however, fracturing occurs in brittle materials with elastic behavior, which is largely not the case in the viscoelastic host rock of the WIPP repository. Restoration of the DRZ to the original halite properties, as described in this report, would be applicable within most salt formations. However, at locations other than in the Salado Formation at the WIPP site (such as in the Culebra, Magenta and other members of the Rustler Formation), the DRZ will not obey the concepts forwarded. Because the DRZ in MB 138 and 139, and perhaps the anhydrite interbeds a and b, are different from the DRZ discussed here, they pose a concern for the open fractured DRZ concept and its ability to heal. This concern is discussed and analyzed within the seals design (WIPP 1996). It appears from the information available that numerous alternatives have been processed in the analysis and testing programs leading to present concepts and understandings of the DRZ. The assumptions adopted for the DRZ model are alternatives that appear to appropriately represent the existence and effects of the DRZ.

3.7.2.4. Uncertainties

A DRZ thickness of 0.8 shaft radius appears to be conservative. Munson et al. (1994) state that from the air intake shaft data (Dale and Hurtado 1996), the extent of the DRZ at 6 years is certainly less than 1.0 shaft radius, and probably only 0.7 radius. Using these same data, Chan et al. (1994) show a reasonable correlation between the test data and calculations from the multimechanism deformation coupled fracture (MDCF) model. No data were found to evaluate the effects of time on the relationship between excavation and closure. Relative to the room DRZ, the behavior of the roof DRZ might be the source of additional uncertainties in other models. Except for the shaft seals, no data were found to characterize applications of the DRZ in unique locations, such as the unsupported roof and the floor buckling from unrestrained creep.

3.7.2.5. Adequacy of the Conceptual Model

Recognition of the deleterious conditions produced by the DRZ appears to be positively addressed in studies showing the effects on brine flow in the repository and on the ability to heal under conditions of support in the shaft that makes the shaft seals issue more tangible to resolve. Because the uncertainties of possible unknown future effects of the room DRZ might go beyond the recognized problems caused by the DRZ, the room DRZ is dealt with from a conservative viewpoint. It appears that the model adequately addresses the genesis and existence of the damage zone. The MDCF model provides a realistic tool by which to examine the effects and project possible DRZ performance. Research, including that in the Room Q, the air intake shaft tests, and the rigid inclusion in salt tests (Knowles et al. 1996), has been supportive in calibrating and confirming model results (see Section 3.19). Because the roof DRZ is uniquely different from the other DRZs, the model does not adequately represent flow to the overhead marker beds. This issue is discussed in Section 3.3, Repository Fluid Flow, and in the following section. Except for this caveat, this model has the appropriate elements to support its use in the WIPP performance assessment.

3.7.2.6. Adequacy of Application

Recognition of the DRZ phenomenon around the shafts and measurements of its effects are important contributions to waste containment; in some cases these effects are among the few WIPP conditions that can be dealt with in engineering terms. It was important to find that the DRZ nearly completely heals once there is adequate backing within the shaft or borehole against which the creeping salt will reestablish its original state of stress. Because of the healed state and because tests show conservatively

that the DRZ areas of influence are within 1.0 shaft radius, it is possible to demonstrate that the DRZ permeability will become lower than that of the seals. This appropriately allows the performance assessment calculations to treat the DRZ permeability as an integral part of the seal. It is important to recognize that this healing factor is a function of the shaft seals' mechanical properties and time of placement. It is also important to recognize that because of the overwhelming uncertainties of DRZ performance in the waste rooms, it be dealt with conservatively by assumption, as stated in the model description. The waste room DRZ uncertainties basically apply to specific locations such as the roof, floor, or walls, and its extent in each.

Because of the variability of the geometry and the timing of the healing of the DRZ in the different environments in which it occurs, the DOE has substituted conservative permeabilities to represent the effect of the DRZ on repository rooms and shaft seal flows. These permeabilities are carried through the processes of repository closure and the evolution of shaft seal design, taking into consideration the marked differences in characteristics of these zones. While the shaft DRZ has been carefully studied, the repository room roof and floor DRZs have not had equal attention because of their complexity. To compensate for this, the DOE chose to use a constant, conservative value for the permeability of the repository DRZ that would not be the limiting condition for flow to and from the interbeds. This approach has not been adequately supported, particularly for the roof DRZ, where the fractures may be open, large, and progress to roof collapse. Furthermore, this zone is host to drill holes that may not be plugged and can penetrate beyond the overlying marker beds. This issue has been identified as a concern for the Repository Fluid Flow model in Section 3.3. The DRZ in the room walls is not modeled, and is thought to be of little structural impact because by conservation of pore space, the initial fracture volume of this DRZ is recovered during room closure and healing.

This evaluation recognizes that the disrupted zones near the shafts have been characterized. Also, this evaluation has shown that DOE used this information in several ways, leading the Panel to conclude that the DRZ needs to be separately considered for each of its applicable areas. These areas include the roof, floor, and walls of the waste room, and the walls of the long annular openings such as shafts and boreholes. Except for modeling the roof DRZs, the Panel believes that the work to date adequately addresses the DRZ characterization for application to the performance assessment process.

3.7.2.7. Accuracy of Results

While the Room Q tests produce data that contribute to the understanding of the waste room DRZ, it appears that the value of these results is to provide background concepts and guidance for addressing the DRZ issues. After looking at the numerous unknowns or uncontrolled processes in the waste room, it seems prudent to defer analysis of the DRZ issue in the waste room until further understanding of the waste characterization becomes available, in order to more fully consider the effective resistance the waste provides to room closure by creep.

For the shafts and boreholes, the air intake shaft permeability data (Dale and Hurtado 1996), which show the extent of damage resulting from the shaft excavation to be approximately one shaft radius, has provided good basic information on this issue. Other analyses of related data and observations from the air intake shaft tests (Munson et al. 1995; Chan et al. 1995) show that the extent of the DRZ is related to shaft size, and make phenomenon amenable to incorporation in a mechanistic model. The collaboration of Munson et al. (1989) and Chan et al. (1995) has proposed one such model through coupling the DRZ fracture to the creep model (the MDCF Model). Other calculations include the determination of fracture healing time and projections of the effects of shaft seal mechanical properties on fracture healing. It should be recognized that the MDCF modeling results largely represent an early stage in this technological development and are subject to projected corrections as more time-dependent follow-up data become available. Because of the predicted low impact of the DRZ on sealed shaft permeability a few years after seal placement, it appears totally appropriate to adjust the permeability of the shaft seal components for the small contribution that the DRZ will make to the performance assessment calculations.

The same closing comments for Section 3.7.2.6 apply to this section; therefore, the results obtained are sufficiently accurate for application of the DRZ in the performance assessment process.

3.7.2.8. Validity of Conclusions

All observed considerations of analysis, study, and proposed engineered applications regarding the DRZ and its impacts on effective shaft sealing appear to be valid. The understanding developed of DRZ phenomena and data reveal that it is critical to engineering waste containment overall because of its potential for negative impact on shaft seal permeability and integrity, and fluid flow in the rooms and room seals. It appears that all considerations of this impact and the conclusions discussed here are sound and valid.

Relative to DRZs in the waste room roof and floor, the fractured zones have a high probability to exist and not much can be done to mitigate their effects, such as providing the stiff support needed to foster healing of the DRZ as shown by the Knowles (1996b) report test results. Credits taken for room closure due to creep will be beneficial, but this may not be significant help in later years, when the potential higher gas pressures may reverse the creep. At high gas pressure this problem is exacerbated by an expanding room scenario which could extend the DRZ even further. It appears the concepts of characterization of the DRZ, particularly in the floor, have not been well researched; perhaps an elicitation panel would be constructive on this. The roof DRZ should have less significance than the floor DRZ because brine is more likely to flow through the floor than the roof; however, the roof DRZ does facilitate the access of gas to the release pathways. The Panel concludes that while the conservativeness of the assigned DRZ permeability might overcome the lack of detailed information for the roof DRZ, further analysis of the roof behavior would enhance defendability of the otherwise valid model.

3.7.2.9. Adequacy for Implementation

Given the lack of tangible controls over remedying the room DRZ, but the encouraging test results for mitigating the shaft DRZs, it appears that appropriate considerations are being made for the DRZ conditions in all applications. It is clear that continued studies of the room DRZ would provide a better background to more explicitly model the waste room and to ascertain the variation of DRZ characterization for each of its location sites, such as in the roof, floor, or walls of a room. The Panel concludes that the present DRZ model is adequate to be implemented in performance calculations. However, since the roof is different, some other approach may be appropriate for this area.

3.7.2.10. Dissenting Views.

There were no dissenting views for this model.

3.8. Actinide Transport in the Salado

3.8.1. Model Description

The only transport mechanism that will be used in this conceptual model is advection. The Actinide Transport in the Salado conceptual model previously addressed three mechanisms: 1) advection (transport with bulk flow of liquid); 2 dispersion (liquid velocity differences while moving through pores

or surface irregularities); and 3 diffusion (molecular motion in presence of concentration gradients). These mechanisms are all standard contaminant transport phenomena. DOE assumed that these three transport mechanisms of actinides in brine represented the most important processes of actinide movement in the Salado Formation. All three mechanisms look at the transport of dissolved or colloidal actinides through the anhydrite interbeds (MB 138, MB 139, and anhydrite interbeds a and b).

The advection transport mechanism is implemented by the NUTS computer code in conjunction with the Salado fluid flow portion of BRAGFLO. The NUTS code is described in Section 6.4.11 of the CCA and Appendix NUTS (which were not available for Panel review). The actual inventories of actinides come from the Dissolved and Colloidal Actinide Source Term conceptual models. The actinide source terms incorporate the assumed oxidation states and solubility factors for various actinides and a proportion of all colloids permissible.

Three physical influences that may affect actinide transport in the interbeds have been left out of the conceptual model by DOE to promote a conservative philosophy. These influences are sorption of dissolved actinides on clays, retardation of colloidal actinides by surface features, and mineral precipitation containing trace actinides from brine. Sorption of actinides onto clay surfaces is a known reaction, and DOE is highly confident that it will occur; however, the model conservatively neglects the effect. With regard to retardation of colloidal actinides by surface features, it is assumed that offsetting interactions will occur. The philosophy is that colloids can be retarded by surficial features, but will travel faster than the average velocity of the bulk liquid. Precipitation of minerals as brines move into the interbeds due to chemical gradients is a possibility. Given the concept that the amount of precipitation will be minor, and that actinides will only occur in trace amounts in the crystal structures, DOE has decided to neglect this effect in the performance assessment.

Three other mechanical processes may have a lesser impact on actinide transport in the Salado. These are fracture flow, channeling, and viscous fingering. Fracture flow is accounted for in the Salado Interbed model and takes into account increased porosity and permeability through fracture propagation and dilation. DOE expects that other fracture processes and effects not taken into account in the fracture model will be negligible. One process not incorporated, channeling, has offsetting effects. Channeling is the fluid movement through large apertures of a fracture network (i.e., locally high permeability). DOE believes this mechanism will be negated for two reasons. First, if gas is present in the undisturbed state, it will preferentially occupy areas of high permeability over brine. This will preclude these regions of

fast transport from brines. Second, the incoming brine will be miscible with the interbed brine. Such miscibility will allow diffusion and mixing phenomena to broaden finger fronts (i.e., reduce concentration gradients) until they are indistinguishable from the advancing brine front.

Gases may also penetrate interbed brines as a fingered front. However, such a mechanism will not affect actinide transport because the actinides of interest are only incorporated in the liquid phase. DOE also assumes that a liquid will not displace gases in the high-permeability regions (channels) due to capillary effects.

3.8.2. Review of Criteria

3.8.2.1. Information Used to Develop the Conceptual Model

The Actinide Transport in the Salado Formation model is based primarily on the computer code NUTS, with input from BRAGFLO. Since NUTS relies on BRAGFLO input parameters, all BRAGFLO FEPs became information used in the model development. In a sort of circular logic, NUTS was used to evaluate BRAGFLO FEPs by converting flow measurements to normalized release values. The original NUTS program was extremely intricate and robust, with its basis in classical fluid transport. However, FEP studies and system prioritization events have simplified the code. NUTS now only uses advection as a transport mechanism, tracks only the wastes encountered along the flow paths, and treats downstream fluid and the fraction that came into contact with waste. The transport mechanisms of diffusion and dispersion have been excluded from the code, based on policy decisions associated with the system prioritization analysis. The exclusion of these two transport mechanisms is believed to make this conceptual model more conservative. As stated in the model description (Section 3.8.1) the exclusion of six other processes (clay sorption, surface feature retardation, mineral precipitation, fracture flow, channeling, and viscous fingering) is deemed to allow the conceptual model to be more conservative.

A second source of information critical to the NUTS code is the field of radiochemistry. Concepts dealing with radioactive decay, half-lives, and solubilities allow major assumptions to be implemented in the NUTS program.

The third major source of information folded into the actinide transport of the Salado Formation is physical properties of the anhydrite interbeds. These interbeds are the major pathways for fluid transport in the Salado. Data concerning the physical properties of anhydrite were obtained by *in situ* hydrologic tests. The fracturing properties of the beds were deduced from both field and laboratory experiments. It is deemed that the information used is adequate to develop the model.

3.8.2.2. Validity of Model Assumptions

The following assumptions are critical to the conceptual model being evaluated here. Diffusion, hydrodynamic dispersion, and channeling in discrete fractures, are not included in the model. DOE has taken the stance that by not including these factors, the actinides are not further dispersed and therefore the model is made more conservative. These assumptions are considered valid.

The assumption of lumping radionuclides by similar half lives and solubilities is based on the basic tenets of radiochemistry. If any computer run later indicates a potential to exceed EPA's criteria, such lumping factors can be recalculated using specific data for each radioisotope. Evaluations have not been performed to see if the lumping assumption could, in effect, mask runs from approaching the EPA limits. With this caveat in mind, the assumptions made about lumping can be considered valid.

Actinide source terms (dissolved and colloidal) in the repository are used as the input for NUTS. The assumption that these source terms are the limiting cases may not be valid, however that determination is not within the scope of this model (see Sections 3.23 and 3.24).

Once the total concentrations are calculated for the dissolved and colloidal sources for each run, the final value is then transported as one package at the average flow value. The assumption made is that colloids can be transported at this slower rate and still be adequate since sorption and filtration of colloids are not accounted for. This assumption has not been proven to the Panel's satisfaction.

The final major assumptions of this model are that the grid blocks and time steps from BRAGFLO are proper to use in NUTS. Although this final set of assumptions may be reasonable, numerical results must be examined to determine if this concept (and inherent coarseness) is valid. At present, such results are not available.

3.8.2.3. Evaluation of Alternatives

Earlier versions of the NUTS code were much more comprehensive than the present version. Previous compilations had the capacity to treat virtually all special effects of radionuclide migration. However, system prioritization exercises and FEPs studies indicated that a much more simplified version of NUTS was desirable, in that results were still representative and computer run time was compressed. Hence, the present version of NUTS is streamlined. Factors that have been removed (or zeroed) include diffusion,

dispersion, channeling, chemical sorption for dissolved actinides, physical retardation for colloidal actinides, fracture flow, and viscous fingering. The present version of NUTS is reasonable for its intended use.

3.8.2.4. Uncertainties

There are a multitude of uncertainties associated with this conceptual model and the NUTS code. First, there are all the uncertainties associated with the BRAGFLO conceptual model and its parameterizations (see Section 3.3). Values plugged into NUTS from BRAGFLO contain the inherent uncertainties from BRAGFLO since the input parameters are not screened for rationale values. These uncertainties will then be propagated through the NUTS code to the next step (SECOTP2D). The second group of uncertainties centers around the coarseness of the grid blocks and time steps used in NUTS. Although these parameters may be reasonable for BRAGFLO, it has not been justified that the same applies for the NUTS code.

Since Section 6.4.11 of the CCA and the Appendix NUTS are not presently available for review, many questions are unresolved and remain as potential uncertainties. These issues involve long-term transport of radionuclides in the repository rooms, repository panel seals, DRZ, and undisturbed and fractured interbeds, and input to sealed boreholes and shafts to the Culebra Formation. Advection should allow actinides to be transported directly to the Culebra Formation; however, it is not possible at the present time to evaluate how DOE handles these unknown factors.

There are also uncertainties associated with all the assumptions listed in Section 3.8.2.2. In the cases of all valid assumptions, the associated uncertainties are negligible. Since the soluble actinide source term input parameters are directly fed to NUTS, if the values are incorrect, the consequences could be significant in that the code would transmit such errors directly to the Culebra Member.

3.8.2.5. Adequacy of the Conceptual Model

The Actinide Transport in the Salado conceptual model describes the movement of the actinide source terms by advection, using hydrologic phenomena from the BRAGFLO computer code. The concepts of advection and Darcy flow are well characterized in the geosciences and are the mainstays of this conceptual model. However, the specifics of long-term transport through the components of the repository are poorly defined. Documentation that is not present includes Table 6-15, Section 6.4.11, and Appendix NUTS of the CCA. The section describing this conceptual model (Section 6.4.5.4) does not

document in any way how the "lumped" actinide source terms are transported from the rooms through the panel seals and the DRZ, how transport is performed through undisturbed and/or fractured anhydrite interbeds, and up sealed boreholes and shafts to the Culebra. Since this conceptual model is not yet fully described, the Panel can not determine if the model is adequate.

3.8.2.6. Adequacy of Implementation

The description of how this conceptual model is integrated from one computer code to the next (BRAGFLO to NUTS) is supposedly seamless. It is stated in the ten questions document that "NUTS interface with BRAGFLO is essentially perfect in completeness and validity in that NUTS takes virtually all its flow and flow-related attribute and property data from BRAGFLO and treats them as incontestable. Thus the .. interface is perfectly smooth." Hence, in the sense of transferring flow data into the NUTS code, one would conclude that the implementation is adequate.

Two other aspects of implementation are considered. One aspect involves how dissolved actinide solubility is handled in the "lumping" sense. The second aspect of implementation deals with how colloidal actinides are dealt with in the NUTS code. It seems DOE has provided a very rational way to "lump" all the various solubilities of dissolved actinides and to describe how the four main types of colloids will be "lumped" for transport. Both of these source terms have complex properties that could have been negated by the "lumping" factor. As an example, each actinide in its various oxidation states would have specific solubilities. Therefore the dissolved actinide source term is calculated for Salado and Castile brine compositions in both the low and high oxidation states. These four main permutations would then cover the possibilities for total inventories for dissolved actinides. Colloidal actinide sources are handled in a slightly different manner. Mineral fragment and intrinsic colloid values are held constant through all the runs. Humic and microbe actinide inventories are based on mass balance calculations using inventories from waste materials. These two philosophies of solubility "lumping" have been clearly explained for dissolved and colloidal actinide transport in the NUTS computer code by the Principal Investigator and, by this means, the implementation was determined to be adequate.

3.8.2.7. Accuracy of Results

Conclusions for this section are based on preliminary results provided by the Principal Investigator. The results proved to be accurate. However, without the final parameter listings of Table 6.15 of the CCA, one cannot make a final judgment of actinide transport in the Salado Formation. It would be useful to have the following information for comparison: first, actinide values after transport through the Salado

Formation to a borehole or shaft; second, what are the final values that NUTS would produce at the interface with the Culebra; third, an example of a NUTS transport run ("lumped") that approaches the EPA standard, and then a recalculated run using the individual radionuclides. This information would be very useful in determining whether the finalized results of this conceptual model are accurate. Finally, a complete model run has not been performed that transports dissolved actinides at the median velocity and colloidal actinides at maximum velocity. These results could be critical in deciding the accuracy of the model.

3.8.2.8. Validity of Conclusions

This section presents a judgment on whether the key conclusions that have been drawn based on the results of actinide transport in the Salado Formation in the modeling framework are valid. Although the concept of lumping is shown to be rational, the explanation of transporting colloids at a median velocity may be deficient. The parameter values (Table 6-15) were not available for the Panel to review and may bear on the judgment of validity for this model. Until these two final issues are resolved, it is premature to evaluate the validity of the model conclusions.

3.8.2.9. Adequacy for Implementation

This section is an overall assessment of whether this conceptual model represents a reasonable approximation of the actual phenomena and is adequate for implementation in the compliance application. Due to the lack of information provided (Table 6-15, Section 6.4.11, and the Appendix NUTS of the CCA), and the insufficient documentation of how colloid transport at a median velocity is rationalized, it is premature to say that the full conceptual model is completely adequate for implementation. However, if one assumes that BRAGFLO is a competent model for fluid flow in the repository setting, the next step of inputting hydrologic data into NUTS for actinide transport should be straightforward. Because of this, the model is wholly adequate and reasonable for implementation.

3.8.2.10. Dissenting Views

There were no dissenting views for this method.

3.9. Units Above the Salado

3.9.1. Model Description

The conceptual model of the Units Above the Salado has much in common with the conceptual model of the Culebra. The Culebra Dolomite is a member of the Rustler Formation, which is a prominent part of the supra-Salado stratigraphy. The Culebra is modeled separately (Section 3.2) because of its importance as a potential contaminant flowpath. The model of the Units Above the Salado results from a complex of several approaches to the hydrology and hydrogeology of the region and the WIPP site area. The conceptual model would ideally serve as an integrating set of hydrogeologic processes, properties, and principals that could be used to support assumptions about the potential performance of the site, to interpret regions of low data; and to place in context the results of hydrologic testing. The Units Above the Salado conceptual model provides a geometric characterization of the hydrologic system and a general description of the geometry and processes of flow. As with the Culebra, however, no correlation is provided of variation of hydrologic properties at the site scale with hydrogeologic character. The most important assumption in the model is that the Culebra Member of the Rustler Formation is the only potential pathway for radionuclide release to the environment.

The performance assessment of the Culebra is based on a considerable hydrologic testing data base, which addresses many of the potentially significant questions and issues concerning flow along the Culebra flowpath at and around the site. The significance of the hydrology and hydrogeology of the other members of the Rustler Formation and overlying formations lies partly in their interaction with Culebra hydrology and their influence on the interpretation of flow through that unit. The Culebra is treated as a confined aquifer with a much higher transmissivity than the overlying and underlying stratigraphic units and a horizontal flow gradient generally to the south. Flow in both the enclosing units (Unnamed Lower Member and Tamarisk) is believed to be predominantly vertical and into the Culebra. Water pressure in the Culebra is characterized as low because its transmissivity and gradient are capable of discharging more water than is presently being recharged.

The interpretation of the hydrologic processes for performance assessment purposes in the units above the Salado is based mostly on the results of hydrologic testing. A regional hybrid hydrogeologic/hydrologic process model (Corbet and Wallace 1993) sets model boundaries and

speculates about regional processes contributing to the transmissivity contrasts, but offers no site-scale correlation with the testing data. This model does not address mesoscale hydrogeologic variables such as fracture orientation and distribution and the distribution of matrix permeability.

The performance assessment activity associated with the units above the Salado is the two-dimensional Culebra flow model, based solely on the hydrologic testing results. The variability of transmissivity represented in that model within and around the site area is attributed to the relative proportions of flow through fractures and variably permeable matrix, and to fracture distribution and hydraulic activity. The model does not address those variations of hydrogeologic process and properties relative to petrologic, sedimentologic, or structural features, which are the primary sources of variability. The conceptual model is disconnected from the numerical hydrologic model at the scale at which hydrogeologic information could most usefully condition the numerical model.

The assumption that the Culebra is the only potential pathway for release to the environment is related to the movement of radionuclides up a borehole or up the sealed shaft region. The assumption that radionuclides reaching the Magenta Dolomite member of the Rustler Formation or the Dewey Lakes Redbeds, which overlie the Rustler Formation, are not transported to the accessible environment is based partly on the results of very limited hydrologic testing and assumed retardation in the Dewey Lakes.

Hydrogeologically, the Culebra and Magenta Dolomites bear many similarities. Both are dolomites deposited in the same sedimentary environment. They are comparable in thickness and differ in stratigraphic position by a few tens of meters. Their post-depositional histories are identical from location to location. Their porosities are nearly identical and their ranges of permeabilities overlap. The definition of the hydrologic character of the Magenta is based on modeling of approximately 15 data points constrained to a very small geographic area.

The principle hydrogeologic difference between the Culebra and Magenta is purported to be the absence of hydrologically active fractures in the Magenta. This assertion is based on two slug tests and very limited field observation in shaft excavations. The transmissivity of the Magenta is very low in all of the limited number of tests and its low transmissivity is supported by drawdown during the sinking of the air shaft. The characterization of Magenta hydrology as unfractured is based on a very limited observational and testing data base, and the conclusions that there are no regions of high transmissivity due to fractures and that all flow in the Magenta is matrix flow are weak.

The position of the groundwater table at the level of the Dewey Lakes Redbeds is very unclear. Hydrologic testing has not been done to differentiate between purported perched water zones, to characterize saturated zones with continuity to underlying units, and to identify the general hydrologic character of the Dewey Lakes Redbeds. It is presumed that most of the materials above the Dewey Lakes are unsaturated (Gatuna and Pleistocene alluvium) and that recharge through those materials is minimal.

3.9.2. Review of Criteria

The units above the Salado contain the Culebra Dolomite, which is identified as the principal potential pathway for release of radionuclides to the environment. The conceptual model for these units provides the framework for consideration of the hydrology of the Culebra and contains other hydrostratigraphic units (Magenta and Dewey Lakes) whose potential as pathways must also be evaluated.

3.9.2.1. Information Used to Develop the Conceptual Model

The conceptual model is based on stratigraphic information from site borings and shaft excavations and on the position and nature of regional hydrogeologic features. Corbet (1993) has synthesized those features well and uses them as the basis for suggesting model boundaries and to support general flow gradient direction predictions. The model used for performance assessment purposes is a two-dimensional computational flow model based entirely on hydrologic testing in the Culebra. The conceptual model generally supports the descriptions of the hydrologic roles of the units above the Salado, with reservations about the characterization of flow in the Magenta Dolomite and the universal presence of retardation in the Dewey Lakes Redbeds. Hydrologic test data are sparse or nonexistent in all units above the Salado, except the Culebra.

3.9.2.2. Validity of Model Assumptions

The assumption that the Culebra Dolomite is the only hydrostratigraphic unit within the stratigraphic sequence above the Salado, which has the potential to act as a flowpath to the accessible environment, is the principal assumption affecting this conceptual model. That assumption implies that the Magenta Dolomite and the Dewey Lakes Redbeds are not potential pathways and that flow and transport assessments of those units are unnecessary. Estimates of contaminated brine flow up an intruding borehole in the long term imply very small (0.5 m^3) volumes of brine reaching the interval above the Culebra (personal communication, P. Vaughn). This is the consequence of underpressure hydrologic conditions purported to exist in the Culebra throughout the repository area, which lead to injection of

most of the brine rising up the borehole into the Culebra. The magnitude and distribution of underpressure in the Culebra are based on averages of several measurements and an assumed process model, which explains the underpressure condition. The assumption that the Dewey Lakes and Magenta are not flowpaths is not well supported. The assumption of availability of only small amounts of brine to those units appears to be well supported.

3.9.2.3. Evaluation of Alternatives

The conceptual model has evolved over the entire period of site characterization and performance assessment. Some alternative submodels were considered and rejected (e.g., local halite dissolution and anhydrite hydration, gravitational loading). All of these submodels failed to conclusively account for the variations in transmissivity at a useful scale. The final performance assessment model is almost entirely based on numerical assessment of hydrologic test data, which are very sparse except in the Culebra Dolomite, the most thoroughly tested stratigraphic unit at the site.

3.9.2.4. Uncertainties

The principal uncertainty in the conceptual model of the units above the Salado (excluding the details of Culebra flow, treated elsewhere) is the assumption that the Magenta and Dewey Lakes units do not constitute potential release pathways. The effect of underpressure in the Culebra appears to limit flow up an intruding borehole to the upper units in such a way that there is little consequence associated with the Dewey Lakes and Magenta flowpaths.

3.9.2.5. Adequacy of the Conceptual Model

The conceptual model adequately defines the regional and general stratigraphic geometry of the units above the Salado. It does not provide supporting explanations for the variability of hydrologic parameters and processes at the site scale. If the need to assess transport in the Magenta and Dewey Lakes were shown to exist, the small hydrologic testing data base and the existing conceptual model would not be adequate to such an assessment.

3.9.2.6. Adequacy of Application

There is no application of the conceptual model to the computational flow modeling at the site scale except for the definition of stratigraphic geometry. A thorough demonstration of the potential of the Magenta and Dewey Lakes as flowpaths is absent, and the conceptual model is inadequate to support

such a demonstration. The conceptual model adequately provides geometric and process elements to support the Culebra model.

3.9.2.7. Accuracy of Results

The accuracy of results depends on the adequacy of the testing data base and the computational flow models and are beyond the scope of this review.

3.9.2.8. Validity of Conclusions

See Sections 3.9.2.6 and 3.9.2.7. Conclusions are based on the Culebra numerical flow model and are beyond the scope of this review.

3.9.2.9. Adequacy for Implementation

The conceptual model is not significantly implemented in the computational flow model used for performance assessment (the Culebra two-dimensional flow model). The conceptual model provides adequate peripheral support to the implementation of the Culebra flow model by defining geometry and a general description of flow conditions in adjoining beds. The conceptual model is not adequate to support an assessment of the Magenta and Dewey Lakes hydrostratigraphic units as flowpaths. Assumptions supported by analysis imply that the consequences of transport in the Magenta and Dewey Lakes are low because of insignificant input of contaminants as a result of human intrusion.

3.9.2.10. Dissenting Views

There were no dissenting views for this model.

3.10. Transport of Dissolved Actinides in the Culebra

3.10.1. Model Description

The transport of actinides in the Culebra Dolomite Member of the five-member Rustler Formation was determined by DOE to be a significant pathway for potential releases to the accessible environment. This model describes the transport of soluble actinides once the material has moved into the Culebra, which could occur either under undisturbed conditions by movement up the shafts, or under disturbed conditions through intrusion boreholes, which provide a path by which gas or brine can be released up to and above the Culebra. These processes are described in other models. The quantities of actinides transported into the Culebra, as well as their chemical form, are described in the source term models.

The characteristics of the Culebra that relate to flow and transport are described in Section 3.9, and the model for spatial distribution of flow rates in the region and site area is described in Section 3.2. Therefore, this model is related to output from Shaft Seals, Chemical Conditions, and Dissolved Actinide Source Term, as well as Culebra Geometry and Flow, Gas Generation, Fluid Flow in the Salado, Disturbed Rock Zone, and the models related to intrusion, Exploration Borehole, Castile Formation and Brine Reservoir, and Multiple Intrusions.

The model, Transport of Dissolved Actinides in the Culebra, is also related to a parallel model, Transport of Colloidal Actinides in the Culebra, which depends on many of the same processes. Fundamentally, the model describes the horizontal transport of dissolved actinides by water flowing through the porosity of the dolomite, and retardation that may occur along the way. The flows are confined to the lower 4 meters of relatively permeable dolomite of the 7-meter thick Culebra. The model describes advective transport, as well as holdup due to matrix diffusion and chemical retardation. The model assumes that the overall rock porosity is composed of interconnected porosity, which forms the principle paths for advective water flow, and relatively unconnected diffusive porosity, into which species may diffuse under concentration gradients. This model is therefore referred to as a double porosity model.

The advective porosity is envisioned as a web of interconnected horizontal and vertical fractures in the dolomite, with some contribution from flow through interconnected vugs, and comprising less than 1% of the overall rock volume. The diffusive porosity is described as being accessible from advective porosity through small intercrystalline pores of the Culebra rock matrix, and comprising about 15% of the overall rock volume. Physical holdup and chemical retardation are therefore described as predominantly related to the diffusive porosity, with the surface area for chemical adsorption located within the diffusive porosity. This surface area has been measured at about 1 m^2/gm of dolomite.

Diffusion into the rock is described as related to the chemical diffusive properties of dissolved species, the tortuosity of the diffusion paths within the rock, and the surface area for diffusion between advective and diffusive porosity per unit volume of diffusive rock. Chemical retardation is described as chemical adsorption onto the dolomite grains exposed in the diffusive porosity. Although clay is believed to be present in the Culebra dolomite, particularly between horizontal bedding planes, adsorption onto this clay is not specifically assumed because its distribution and quantitative effect have not been demonstrated. Chemical adsorption is further described as a linear isotherm model, with single constants, K_ds, to

describe the equilibrium relationship of the ratio of adsorbed concentrations and dissolved actinide species.

Fifteen years of development of information and models to describe actinide transport in the Culebra has considered two controversial issues. The first is whether a single matrix porosity or a double porosity model is appropriate to describe flow and retardation. The second is whether and how chemical retardation, particularly on corrensite clay, is to be modeled. The project has used a single porosity model and adsorption on clay in the past, but currently uses a dual porosity model with adsorption onto dolomite but not onto clays. This is discussed in more detail later.

3.10.2. Review of Criteria

3.10.2.1. Information Used to Develop the Conceptual Model

The site-related information used to develop the Culebra actinide transport model has included direct observation of the formation in outcrop, borehole cores and wells, and laboratory testing. These site observations have included chemistry measurements, studies of mineralogy, and field hydraulic and tracer testing. The laboratory testing has developed the quantities of actinides in solution in brine, their oxidation states and solubilities in brine, and measured adsorption properties.

Laboratory studies conducted to understand the adsorption process included column tests and the use of intact Culebra cores. Studies of adsorption on dolomite and corrensite clay were conducted, but information on the amount and distribution of clay in advective porosity pathways was judged insufficient to justify assuming adsorption onto clay. Laboratory studies have used four synthetic brine compositions representing the range of actual brines in the Salado, Castile, and Culebra. Information was developed on effects of carbon dioxide on adsorption at partial pressures expected in the Culebra. Adsorption information for plutonium, americium, uranium, thorium, and neptunium at expected oxidation states was developed using laboratory measurements and the oxidation state analogy.

Recently, the H-11 and H-19 tracer testing was completed and the results analyzed and summarized, although no reports of this key work were available to the Panel for review. This additional tracer testing was conducted because the results of earlier tracer testing with soluble dyes did not provide adequate information to convincingly show that the dual porosity model was appropriate for actinide transport purposes. The evaluation of the current work and reevaluation of earlier work has improved the information base. However, much of the work in support of this model is recent and has not yet been

published. Improved correlation with modeling analyses has been achieved for increased ranges of flow rates and other improvements in test conditions. The information base appears generally adequate, although the parameters that relate to this model will need to be carefully chosen. These parameters are the advective and diffusive porosity, the range of block sizes, the soluble species diffusion coefficients, tortuosity, and retardation coefficients.

3.10.2.2. Validity of Model Assumptions

Some of the principal assumptions are that the transport can be described in the dual porosity model, that the oxidation states of actinides in brine transferred into the Culebra do not change during subsequent flow and transport in the Culebra, that dissolved actinides will diffuse into the matrix and be physically retarded, and that dissolved actinides can adsorb on diffusive porosity surfaces.

The basis for the assumption that the transport model should assume both advective transport in principal flow paths and diffusive transport into the rock, is that results of tracer tests along principal flow paths at the WIPP site are only explained using the dual porosity model. This is believed valid in the areas of the site where transmissivity is greater than 1×10^{-6} m^2/sec. In areas of low transmissivity, which have little advective porosity and flow, a matrix diffusion model best explains results, but is not used for the performance assessment because these low transmissivity areas do not contribute significantly to the flows away from the repository. In high transmissivity areas, a single porosity assumption is not consistent with the tracer test results. Therefore, for purposes of transport, the dual porosity assumption appears appropriate.

For purposes of determining appropriate values of adsorption coefficients and solubilities, the project assumes that the oxidation states of actinides generated in the repository do not change when the deep brines are injected into the Culebra brine. Adsorption behavior would be different if oxidation states were different, while concentrations would not be different since precipitation is assumed not to occur in Culebra brine. The assumption of constant oxidation states is based on the repository brines being strongly reducing, the Culebra brine being reducing (though perhaps less so), and the rate of any changes in oxidation state that might occur at low ambient temperatures being slow. This assumption is supported by retardation research program studies involving four different brines, including Castile and Salado brine and two brines representing the Culebra, four different chemical constituents affecting conditions, including sulfides, cellulosics, iron and nitrates, and two different chemical equilibrium data bases. It was stated that 30 of the 32 possible combinations of information indicated reducing conditions,

with only some combinations of nitrates producing slightly oxidizing conditions. Measurements of the redox states of groundwater sampled from over 20 wells around the WIPP site indicated reducing conditions everywhere on and around the site, except for areas a few miles south where recharge was thought to affect redox conditions. Thus, this assumption appears fairly well supported.

The model assumes that the properties of actinides of the same oxidation state generally are similar. This issue is discussed in Section 3.23 and will not be covered here. The most recently conducted tests of adsorption parameters included column tests with crushed dolomite at Lawrence Livermore National Laboratory, and flow-through tests using dolomite cores from the WIPP air intake shaft.

The assumption that batch tests using small particles and flow-through retardation experiments can give valid results for the adsorption parameter needs consideration. In the column tests, not yet published, K_ds were measured using dolomite, with no detectable (<1%) clay, that was crushed and sieved to give particles of about 100 mm diameter. The issue was raised that this might make the internal surface area and the clay that might be present more accessible in the experiment than it is in the intact Culebra. It was noted that measured grains in dolomite are on the order of 2 mm and pore openings are approximately 0.6 mm, and therefore a dolomite particle of 100 mm would have roughly the same surface-to-volume relationships as the rock. Also, the contact times were long enough in the experiment for diffusion transport to reach equilibrium. The issue of diffusion rates into the matrix is determined by other parameters, including porosity and tortuosity, which have been measured in other testing programs.

The flow-through tests used intact horizontal Culebra cores with pressure-induced flow of non-absorbing tracers, as well as five actinides, Pu, Am, Th, Np, and U, in solution. In this case, K_ds were inferred from the overall retardation of the core. The results of these tests are being evaluated and K_ds were determined using the values for the likely oxidation state and the brine type with the lowest values. Without commenting on the specific numerical values, which have not been finalized, this appears to be a reasonable approach. Interpretation of the results of such experiments needs to be made carefully, so that values of K_ds, tortuosity, and porosity can be reliably applied into numerical models. It would also be useful to compare the values thus obtained with other data from past determinations.

One uncertainty in the column tests is that associated with the amount of clay in the tested dolomite. X-ray diffraction studies did not detect clay, with an apparent minimum detectable value of about 1%. There is also clay in the Culebra dolomite, reportedly in the range of 1 to 5%. The intent was to use clay-

free dolomite in the column tests, but it appears this experiment may inherently include the adsorption effects from whatever amount (<1%) of clay was in the dolomite matrix. While it was not shown that this was representative of truly pure dolomite, this appears to be conservative, because the clay was likely at the low end of the range. This is a tentative conclusion however, because the results of this work were not available in published form for review.

3.10.2.3. Evaluation of Alternatives

The principal alternatives considered relate to whether transport is best described by a single porosity fracture only, a single porosity matrix only, or a dual porosity model. Neither of the single porosity models explain the data from tracer tests everywhere on the site, whereas the dual porosity model best explains the data, particularly in the regions on the site where transmissivities are high.

3.10.2.4. Uncertainties

Uncertainties related to oxidation state in the repository source term translate directly into transport-related uncertainties (see Sections 3.23 and 3.24). These uncertainties could have a large effect on the result of performance assessment. However, as discussed in Section 3.10.2.3, there appears to be a reasonable basis to conclude that the oxidation states would not change significantly on entry into the Culebra from the repository. Uncertainties on the extent of adsorption could have a significant effect as well. However, at the conceptual level, the model attempts to proceed in a reasonably conservative manner in light of these uncertainties. This does not mean that particular values of K_ds to be chosen from the conceptual model are all conservative, since numerical values for these parameters have not been evaluated.

3.10.2.5. Adequacy of the Conceptual Model

It is concluded that a dual porosity model is adequate for dissolved actinide transport analyses if ranges of model parameters are chosen properly in light of uncertainties. In that the model is supported largely by evaluation of recently completed but undocumented field and laboratory experiments, this conclusion is necessarily tentative.

3.10.2.6. Adequacy of Application

This model utilizes direct input from only a few other conceptual models: the Actinide Source Term models, and the Culebra Hydrogeology model, as well as output from the flow models under undisturbed

and disturbed conditions. At the conceptual level, these model outputs appear compatible as input to the Culebra Transport model. This does not mean there could not be problems in application through the equations and mathematical formulations in the NUTS code. A more informed judgment could be made from a review of sensitivity among key parameters, such as the relationship of the sensitivity of repository releases on source term concentrations of dissolved actinides, on K_ds, on volumes of brine injected, on effects of climate change, and mine subsidence effects on Culebra transmissivities.

3.10.2.7. Accuracy of Results

A judgment on whether the conceptual model affords sufficiently accurate results for performance assessment depends on the overall importance of various model assumptions. It is judged that the dual porosity model itself is a sufficiently accurate conceptual representation for performance assessment, based primarily on verbal briefings of the results of the latest tracer testing in the Culebra and on visual observations. However, since the results of the latest tracer tests have not been documented, this judgment is tentative. Furthermore, the method of developing parameters of importance to numerical results also have not been supported by written reports of the related recent work. Therefore, these parameters have not been reviewed, although some important uncertainties were identified above. Accuracy of results imply review of results, and none using the current model and parameters were available for review. It would be useful to review results of sensitivity analyses to understand which are the key variables, and then focus on the accuracy of those key variables. Until such information is reviewed, a firm conclusion on their accuracy cannot be properly drawn.

3.10.2.8. Validity of Conclusions

The conclusion that the actinide transport in the Culebra can be adequately modeled in a dual porosity model, with advective transport in the main flow porosity, diffusion into and physical and chemical retardation in the rock matrix porosity, is valid. Other conclusions have not been presented since the model, using the chosen parameters, has not yet been used in the performance assessment.

3.10.2.9. Adequacy for Implementation

The conceptual model appears compatible with other models it intersects with directly. The implementation of the conceptual model is through mathematical formula and computer codes which have not been evaluated. It is concluded that the conceptual model is adequate for implementation. However, the selection of model parameters needs to be critically reviewed when the reports of the laboratory and field tracer tests are available.

3.10.2.10. Dissenting Views

There were no dissenting views for this model.

3.11. Transport of Colloidal Actinides in the Culebra

3.11.1. Model Description

This model is closely related to Transport of Dissolved Actinides in the Culebra (Section 3.10), and shares many aspects and assumptions of that model. This model differs from the Dissolved Actinides model in its application of colloidal properties as opposed to dissolved properties to the transport process. The issue of whether, for transport purposes, a dual porosity approach is appropriate, is not repeated since that issue was covered in Section 3.10. However, differences in how the colloids are transported in this model are covered.

Model adjustments for colloidal transport include the different properties and processes that occur for colloids. For example, colloidal particles travel slightly faster in advective transport than dissolved species due to velocity gradients in flow apertures. Colloids can be trapped along the way, and they can diffuse into the diffusive porosity in the dolomite if they are smaller than the pore throat diameter of the dolomite. Four types of colloids are considered: mineral fragments, microbes, humic and fulvic acids, and actinide intrinsic colloids. These four types are different in size and properties; for example, some are hydrophilic, some are kinetically stable, and others are less so. Colloidal particles that are small enough to enter the dolomite matrix may chemically adsorb on surfaces once inside the diffusive porosity.

The model assumes that the colloidal particles containing actinides originate in the repository and are transferred into the Culebra in the same way as dissolved actinides, as represented in the NUTS code. In this model, it is assumed that soluble actinides do not attach to colloids that may already exist in the Culebra brine when brine containing dissolved actinides is injected into the Culebra and mixes with Culebra brine.

Colloidal transport has not been considered in the earlier assessments of repository performance; therefore the only other model implicitly considered was the null hypothesis. However, experience in other environmental situations at other DOE sites has lead to consideration of colloidal transport to explain greater transport of actinides than had been expected in these other situations, based on models that considered only soluble transport.

3.11.2. *Review of Criteria*

3.11.2.1. Information Used To Develop the Conceptual Model

Information used to develop the colloidal actinide transport model included the amounts and types of colloids thought possible in the source term model, the chemical properties and physical sizes of the particles, and how these would be transported in advective flow. In addition, information was developed on diffusion coefficients, measured pore throat diameter distribution in WIPP dolomite samples, and results of experiments to quantify whether and the extent to which colloids can adsorb onto dolomite matrix surfaces. A growing body of scientific literature and various computerized numerical models have been consulted to develop the conceptual model, and to help guide implementation.

The available information and experience with colloidal actinides is not as robust as for transport of dissolved actinides and, therefore, is likely to be less able to support a completely robust model. This model was conceived to fill a weakness in models considering soluble transport only. The available information appears adequate to formulate a useful conceptual model, but this does not mean that adequate information is yet available to fully implement a conceptional colloid transport model.

3.11.2.2. Validity of Model Assumptions

Some of the key assumptions are that 1) actinide oxidation states do not change when deep brines containing these colloids are mixed in Culebra brines; 2) soluble actinides in brine from the repository do not interact with and become attached to colloidal particles that exist in the Culebra; 3) colloids can be filtered in the advective porosity but not chemically adsorbed there; and 4) colloids which are smaller than a 0.63μm can diffuse into pore throat openings in dolomite and be chemically adsorbed onto surfaces there.

The assumption of oxidation state stability is discussed in Section 3.10.2.2, and no basis has been provided to assume colloid actinides would behave differently from soluble actinides.

The assumption that dissolved actinides do not attach to preexisting Culebra colloids is difficult to justify in principle. This assumption has been made to avoid the complication of the computer code having to simultaneously solve the dissolved species problem and the colloid transport problem. If there were significant transfer of soluble actinides to large colloidal particles in the Culebra flow, the transport of this actinide material could be significantly faster than the current model, due to reduced physical and chemical retardation. If the transfer of soluble actinides to small colloids occurred, it would not increase

the transport as much, since advective transport would be slower and, more importantly, small colloids could diffuse into diffusive porosity in the dolomite matrix and be significantly retarded and perhaps chemically adsorbed. The arguments made to simplify the test plan and model do not consider this effect. Models to predict transport by adsorption onto colloidal particles along the transport path have been developed precisely because models of soluble only transport were inadequate. It is therefore judged that this assumption is unjustified based on the literature and information developed specifically for the WIPP project.

The assumption that colloidal particles can be filtered by entrapment in narrow passages in advective porosity appears viable at the conceptual level, but no information has been presented to demonstrate this occurs significantly in the Culebra, and no information has been presented to confidently quantify the effect. The assumption is implemented as a simple "decay" term for those colloids that are too large to enter diffusive porosity. On the other hand, particles in flowing systems do indeed tend to collect in areas of low flow velocity, so such a filtering process is likely to be useful if parameters are selected carefully to avoid trivializing the overall colloidal transport.

The assumption that colloidal particles smaller than the mean pore throat diameter of 0.63μm can diffuse into the dolomite matrix and be adsorbed onto the interior surface area in the dolomite matrix needs some discussion. Of the four types of colloids being considered, the humic/fulvic acid colloids and the plutonium intrinsic polymer are believed to be smaller than 0.63 μm. Measurements of many different properties of WIPP dolomite were made to develop their ranges and statistically average values, including porosity matrix interior surface area, permeability, grain density, tortuosity and pore throat sizes. Pore size distribution measurements were made on 24 samples using the mercury injection porosimetry technique. These data were interpreted to provide a mean pore throat diameter of 0.63μm. Analysis of the data showed that the accessible internal surface area was a function of pore throat size. For a typical sample with a porosity of 14.8% overall, the data indicated that no internal surface area was accessed for pore throat diameter greater than about 1μm; that about 35% of internal area was accessible at a pore throat diameter of about 0.37μm; and 50% of the internal surface area was accessible at a pore throat diameter of about 0.2μm. Total internal surface area is about 1 m^2/gm of dolomite. Humic acid colloids and the plutonium polymer are thought to be small enough to enter the dolomite. Humic acid colloids are reported to be about 0.1μm or less and single unagglomerated plutonium polymer colloids are on the order of 0.003μm. Intrinsic colloid agglomerates could be as large as 0.04μm. Microbial

colloids are 1 or 2 μm and mineral fragments are on the order of 1μm as well. Based on this information, it appears feasible that the humic/fulvic acid colloids and plutonium intrinsic polymer colloids could diffuse into the matrix, unless surface charge forces prevented this from occurring.

The assumption that colloidal particles could be adsorbed onto the surfaces in matrix porosity is a more complex process to understand because colloidal interactions are less well understood. For example, if the colloids have the same surface charge as the rock, adsorption would be prevented, and if the charges were opposite, adsorption would be relatively strong. To explore this assumption, the project attempted to measure K_ds for actinide colloidal particles of the various types in the same laboratory column tests, and core flow through tests as for soluble actinide measurements. The results showed apparent adsorption in both situations. However, for some of the flow-through experiments, soluble actinides and colloids were mixed and the resulting K_ds were found to be the same as for soluble actinides. Therefore, this experiment did not demonstrate colloidal adsorption so much as perhaps soluble adsorption or filtration, since the experiment did not obviously assure that the actinides were on colloidal particles before being contacted through the dolomite. For microbe colloid experiments, no nitrates were added to keep the microbes growing, so as to prevent changing the oxidation state of the actinides. This may have prevented bioassimilation of actinides in microbe colloids, and again lead to the measurement of K_ds with the same values as for soluble species. Resolution of these and perhaps other uncertainties would add confidence to the assumption that actinide colloids adsorb onto surfaces and the extent to which they adsorb. In the absence of a satisfying resolution, colloidal adsorption onto dolomite matrix porosity may not be a justifiable assumption in the model.

3.11.2.3. Evaluation of Alternatives

Since consideration of transport of colloidal actinide transport has only recently been included in performance assessment, no alternatives were considered.

3.11.2.4. Uncertainties

Uncertainties in the model are associated with the key assumptions discussed in Section 3.11.2.2. The Panel concludes that very large uncertainties exist with the lack of interaction of soluble actinides and Culebra colloids in the model, and with the diffusion into dolomite porosity followed by chemical adsorption. Because of the lack of availability of published reports on the recent testing, a more definite conclusion cannot be drawn.

3.11.2.5. Adequacy of the Conceptual Model

The uncertainties in the validity in some of the key assumptions cast some doubt on the adequacy of this model. Even though the overall performance assessment model is greatly improved by the addition of colloidal actinide consideration, it appears that model predictions will result in negligible transport based on the model and parameters presented to date. If this were the outcome of the fully developed and qualified model, one could have more confidence. However, since significant uncertainties exist in major features of this model, its results could not be trusted, based on the available information. It may be that the issues raised here are readily resolved, but application of colloid science in environmental transport is a new and difficult application, and a cautious approach is believed most appropriate.

3.11.2.6. Adequacy of Application

Soluble actinide interaction with colloidal particles in the Culebra has been assumed not to occur without justification. This represents an issue of integration of this model with the Dissolved Actinide Transport in the Culebra model. Other than this, other system-wide integration issues have not been identified.

3.11.2.7. Accuracy of Results

No actual results have been provided. However, on the basis of the information reviewed, it appears this model, as currently envisioned, would not provide sufficiently accurate results.

3.11.2.8. Validity of Conclusions

Since there is doubt about other criteria, this criterion is also in doubt.

3.11.2.9. Adequacy for Implementation

It does not appear that the information available demonstrates that this model provides a sufficient basis to give confidence in the adequacy of treating colloid transport in performance assessment. It should be noted that, because of the recent undertaking of this work, none of the laboratory test reports or flow-through test reports, on which significant aspects of this model are based, are completed. Further review of the information, when published, could provide a basis to resolve some of the issues raised, after adjustment of some of the assumptions and judicious choice of parameters for a numerical solution. This could lead to an adequate model for implementation.

3.11.2.10. Dissenting Views

There were no dissenting views for this model.

3.12. Exploration Boreholes

3.12.1. Model Description

The Exploration Borehole conceptual model addresses drilling locations, methods, and frequencies within the WIPP controlled area, borehole sealing, and long-term fluid flow through the sealed borehole. Short-term flow through the unsealed borehole is addressed in the Direct Brine Release conceptual model. Associated conceptual models that describe movement of contaminated materials to, within, and from the borehole include Repository Fluid Flow, Castile and Brine Reservoir, Cutting/Cavings, Spallings, Culebra Hydrogeology, and Dissolved and Colloidal Actinide Source Terms. Actinide transport accompanying long-term brine migration is addressed by the Actinide Transport in the Salado conceptual model. The Exploration Borehole conceptual model is limited to a single borehole penetrating the repository. The Multiple Intrusion conceptual model describes conditions when more than one borehole is assumed to penetrate a waste panel. The details of this model were still under development at the time of the peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 22 May 1996 Draft CCA, Section 6.4.7, The Intrusion Borehole (DOE 1996, pp. 6-64 to 6-75), from verbal descriptions, and from the cited references.

An exploration borehole may be drilled on the WIPP site for natural resources investigation and may by chance penetrate a waste panel in the repository. Such boreholes are assumed to be drilled by individuals who have no knowledge of the buried waste, after active institutional control of the site has ceased. The conceptual model for exploration boreholes is based in large part on proscriptive requirements of EPA 40 CFR 194. The EPA requirements are paraphrased as follows:

- The regulatory time frame is the time period beginning at disposal and ending 10,000 years after disposal [40 CFR 194.2].
- Both deep drilling (to or below a depth of 2,150 feet) and shallow drilling (less than a depth of 2,150 feet) that may potentially affect the disposal system during the regulatory time frame are assessed [40 CFR 194.33(a)]. The approximate depth of the repository is 2,150 feet.
- Exploratory drilling is assumed to be inadvertent and intermittent [40 CFR 194.33(b)(1)].

- Exploratory drilling for those resources provided by the waste in the disposal system or the engineered barriers designed to isolate such waste need not be considered [40 CFR 194.33(b)(1)].

- Drilling events in the Delaware Basin are assumed to occur at random intervals in time and space during the regulatory time frame [40 CFR 194.33(b)(2)].

- The frequency of deep drilling within the WIPP controlled area is assumed to be the sum of the rates of deep drilling for each resource in the Delaware Basin over the past 100 years [40 CFR 194.33(b)(3)].

- The total rate of shallow drilling at WIPP is assumed to be the sum of the rates of shallow drilling for each resource in the Delaware Basin over the past 100 years; however, in considering the historical rate of all shallow drilling, the DOE may, if justified, consider only the historical rate of shallow drilling for resources of similar type and quality to those in the controlled area [40 CFR 194.33(b)(4)].

- Future drilling practices and technology are assumed to remain consistent with practices in the Delaware Basin at the time the CCA is prepared, including the types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of boreholes that are sealed [40 CFR 194.33(c)(1)].

- Natural processes are assumed to degrade or otherwise affect the capability of boreholes to transmit fluids over the regulatory time frame [40 CFR 194.33(c)(2)].

- The effects of techniques used for resource recovery following drilling need not be considered [40 CFR 194.33(d)].

In developing a conceptual model that incorporates these assumptions, DOE has considered the following:

- Shallow boreholes will not intercept or affect the integrity of the repository and therefore need not be considered.

- Present drilling practices include the relative economic value of the target resource; on this basis, the objectives of exploration drilling at the WIPP site are assumed to be oil and gas because these are the only commercially viable resources for which exploration drilling would occur to or below the depth of the repository horizon.

- Although commercially viable reserves of potash are known to be within the WIPP controlled area, inadvertent penetration of the repository during exploratory drilling for this resource was not considered because such reserves lie above the repository depth.

- The frequency of deep borehole drilling is estimated based only on historical frequencies of drilling for resources of similar type and quality to those found at the WIPP site.

Exploratory drilling for hydrocarbon resources within the Delaware Basin is assumed by DOE to occur at a rate of 47 holes per square kilometer over the 10,000-year regulatory time frame. Although the timing of intrusions into the waste panels is randomly sampled, based on the 0.125 square kilometer area of the waste panels, the expected average rate of penetration is about 6 boreholes per 10,000 years. Boreholes penetrating the waste panel area but passing through a pillar or wall rather than through the waste are assumed to have no effect on waste releases, but may penetrate and partially deplete brine reservoirs in the Castile. The concept of partial reservoir depletion is discussed further in Section 3.16. Penetration of the operations or experimental areas of the repository by a borehole is assumed to have no significant consequence. All exploratory boreholes are assumed to be drilled in search of hydrocarbon resources and all are therefore assumed to penetrate entirely through the Salado and Castile Formations. Approximately 10% of these are tentatively assumed to encounter pressurized brine in the Castile (E1 scenarios), and the other 90% are assumed to not encounter pressurized brine (E2 scenarios) (see 23 May 1996 Draft CCA, Section 6.4.13.6 (DOE 1996, p. 6-119)).

Drilling is assumed to be conducted by standard rotary methods. At the time of repository penetration, the borehole is assumed to have been cased to the bottom of the Rustler Formation, following current standard practices. After drilling has progressed through the salt section, an intermediate casing is installed to the bottom of the Castile. Below that depth a third, final production casing is installed, which typically extends to the ground surface during production, but is only cemented near the production zones. On abandonment, the production casing is commonly cut above the cemented zone and reclaimed (Thompson et al. 1996, p. 6). Fluid and solids that flow through the open borehole immediately on repository penetration are described in the aforementioned Direct Brine Release, Cuttings/Cavings, and Spallings conceptual models. Long-term fluid flow through the sealed borehole is described in the following paragraphs.

On abandonment, three different scenarios have been adopted by DOE to describe the range of current borehole plugging practices. These are (1) a single, continuous cement plug extending from the top of the Salado to the bottom of the Castile; (2) two 40-m cement plugs, one at the bottom of the Castile (top of the Bell Canyon) and one at the bottom of the Rustler; and (3) three 40-m cement plugs, consisting of the two plugs described above plus an additional plug near the Salado/Castile contact below the repository. In addition, all boreholes have approximately 15-m long concrete surface plugs (Thompson et al. 1996, p. 3).

Degradation of the plugs generally follows the scenarios and rationale presented by Thompson et al. (1996). The continuous plug is not considered to degrade over time because of its structural integrity and the very low brine flow through it. The surface plug is also not considered to degrade over time because of the lack of physical or chemical stresses in the near-surface environment. In the two- and three-plug scenarios the steel casing in the Salado and Castile is expected to be locally pitted and leak within a few decades after abandonment. In these scenarios, within 200 years after abandonment the 40-m concrete plug and remaining casing above the repository and the open casing below the repository are assumed to fail completely from both mechanical and chemical stresses. Simultaneously, with the exception of the concrete plugs below the repository, the entire borehole is assumed to be filled with degraded concrete, corrosion products, and sloughed native materials that are assigned the hydraulic properties of silty sand in accordance with regulatory guidance. Because of increased stresses and halite creep rates below the repository, the borehole filling below the repository is subsequently assumed to be compacted, with a concurrent decrease in permeability. The cement plugs below the repository, however, are assumed to maintain their integrity for the duration of the 10,000-year regulatory time frame because degradation rates will be significantly reduced due to a less aggressive chemical environment (see 23 May 1996 Draft CCA, Section 6.4.7.2.2 (DOE 1996, p. 6-74). Long-term brine flow is expected to occur to or from the repository through the degrading upper borehole plugs as a function of brine availability and repository pressure.

The same version of the BRAGFLO code used to model repository fluid flow is used to implement the Exploration Borehole conceptual model. This model, which portrays a two-dimensional vertical section, is discussed in Section 3.3 of this report and in Section 6.4.2 of the 1 April 1996 Draft CCA (DOE 1996, p. 6-2). The exploration borehole is assumed to penetrate the center of one of the waste disposal panels in the repository. Boreholes penetrating into a waste panel were found in modeling results to not significantly affect brine saturations in neighboring panels, even over the regulatory time frame, because of low hydraulic gradients across the panel closure seals. The borehole is modeled by modifying the material properties of the cells representing the borehole as a function of the type of intrusion (E1 or E2) and the time after intrusion. Short-term brine flow in the open borehole is separately modeled (see Section 3.15).

For long-term flow, the borehole is assumed to be plugged immediately after repository penetration by randomly selecting one of the three plugging scenarios in accordance with its probability of occurrence. The basis for the random selection is discussed in CCA Section 6.4.12, which was not available to the

Panel for review. In an E2 scenario, where the borehole through the Castile is assumed to not encounter pressurized brine, the lower part of the borehole below the repository is given the properties of the surrounding media. In an E1 scenario, where pressurized brine is encountered below the repository, the lower borehole cells are specifically addressed in the model as described in the following paragraph.

The borehole plugs are degraded according to the following assumptions. The continuous plug, the surface plug, and the 40-m plugs below the repository will maintain their initial permeability of 5×10^{-17} m^2 throughout the 10,000-year regulatory time frame. The 40-m plug above the repository maintains its initial permeability of 5×10^{-17} m^2 for 200 years. The borehole between the plugs is assumed to remain open during this period and is assigned a permeability of 1×10^{-9} m^2. The casing is not specifically addressed in the long-term flow model and is assumed to not be present. After 200 years, the upper 40-m plug is assumed to fail and the entire borehole between plugs is assumed to have filled with a material with the properties of silty sand, whose permeability is sampled within the range of 1×10^{-11} m^2 to 1×10^{-14} m^2. Beginning 1,200 years after waste panel penetration, the permeability range of the filling material in the lower borehole below the repository is reduced by one order of magnitude to 1×10^{-12} m^2 to 1×10^{-15} m^2. The porosity of all borehole materials is held at a constant, conservatively high value of 0.32. Pore compressibility is assumed to be zero, giving the medium the approximate compressibility of brine. Two-phase brine and gas flow is modeled using a zero threshold pressure and zero residual brine and gas saturations.

The BRAGFLO model does not explicitly address the continuous plug configuration because the plug permeability is so low that flow is negligible. Under this configuration the borehole cells are given the material properties of the surrounding native materials. BRAGFLO also does not explicitly model the plugs beneath the repository. The plug at the base of the Castile is not modeled because it is considered as part of the impermeable lower boundary. The plug in the upper Castile/lower Salado, which is part of the three plug scenario, is not modeled because it results in conditions essentially equivalent to an E2 scenario in which pressurized brine is assumed to not be encountered in the Castile. If pressurized brine is not encountered in the Castile, the middle plug has negligible function regarding fluid flow in the repository. If pressurized brine is encountered, DOE assumes that the middle plug remains intact and provides an effective seal to brine flow from the Castile reservoir to the repository for the duration of the regulatory time frame. Thus, under either circumstance, the long-term repository fluid flow for the three-plug configuration would be essentially the same as the E2 scenario. Only the two-plug configuration is assumed by DOE to allow long-term releases from a Castile brine reservoir.

BRAGFLO input to performance assessment is accomplished through the use of reference conditions, eliminating the need to run BRAGFLO for each separate set of randomly occurring future intrusion events. Different sets of reference conditions are prepared from BRAGFLO results for each interface with other performance assessment models. For analysis of single exploration borehole penetrations, BRAGFLO is used to calculate cumulative releases over the 10,000-year regulatory time frame for four scenarios: an E1 intrusion at 350 years, an E1 intrusion at 1,000 years, an E2 intrusion at 350 years, and an E2 intrusion at 1,000 years. These calculations are accomplished by running the undisturbed case until the year of the intrusion, and subsequently modifying the properties of the borehole cells in the model over time, according to the degradation rate assumptions described above. The cumulative releases calculated in these runs are used as the reference conditions for analysis of long-term releases.

The reference conditions for long-term releases through exploration boreholes, thus, essentially consist of flow rates over time to the Culebra resulting from borehole intrusions at two specific times (350 and 1,000 years) for each type of intrusion (E1 or E2), and for each set of BRAGFLO parameter input values (that is, for each CCDF). These flow rates are used as input to the NUTS code to calculate cumulative releases to the Culebra. Flow rates (or cumulative releases) resulting from intrusions occurring at other times are determined from the releases computed for these two times by either correlation or interpolation. For intrusions occurring prior to 350 years, the release is assumed to be the same as at 350 years. For intrusions occurring between 350 and 1,000 years, the release is interpolated between the values for 350 and 1,000 years, and for intrusions occurring after 1,000 years, the release is assumed to be the same as at 1,000 years. For long-term release calculations, repository conditions are assumed to not change as a result of short-term releases, thus, repository fluid pressures and volumes are not reduced by the short-term losses.

3.12.2. Review of Criteria

3.12.2.1. Information Used to Develop the Conceptual Model

The principal elements of the conceptual model were developed by DOE in compliance with EPA requirements as summarized in Section 3.12.1 (40 CFR 194.33, Consideration of Drilling Events in Performance Assessments). Pursuant to this regulatory guidance, current borehole drilling, casing, and plugging practices were reviewed by DOE for hydrocarbon exploration boreholes in the Delaware Basin and this information was used as the basis for determining drilling frequencies and methods during the

regulatory time frame. Although documentation of these studies was not reviewed by the Panel, the approach taken appears to have provided a reasonable and appropriate response to the regulatory requirements.

3.12.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.12.1, and are critically reviewed here. Most assumptions are reasonable and appropriate and include the limitation of intrusion to hydrocarbon exploration drilling, use of the BRAGFLO code to simulate release, degradation of the continuous and upper cement plugs, degradation of the casing, permeability reduction in the borehole below the repository due to creep closure, and the assumptions used in modeling the continuous plug configuration. DOE's analysis of current drilling practices in the Delaware Basin, and the drilling frequency and plugging practice information developed from that analysis, are not considered to be conceptual models and were not reviewed by the Panel. An adequate technical basis for estimating the probability of encountering a pressurized brine reservoir in the Castile was not provided to the Panel and is addressed as an issue in Section 3.16 of this report. The method selected by DOE for randomly sampling borehole plugging configurations was also not available for review by the Panel and is not addressed here.

Several simplifying assumptions have been made by DOE that appear to be conservative and therefore acceptable for use in performance assessment. These include neglecting the effects of drilling mud loss into the repository at the time of penetration by an exploration borehole. The drilling mud would likely be a dense, low permeability, water-based brine weighted with bentonite or other additives that may partially fill available repository pore volume, reduce repository permeability, inhibit chemical degradation of the waste by limiting brine availability, and provide additional sorptive capacity for radionuclides. Although the mud could result in other, unforseen chemical reactions with the waste, the overall effect of drilling mud loss into the repository is expected to be beneficial.

The annular space between the borehole plugs is assumed in modeling to be open hole, but according to Thompson et al. (1996, p. C-3), standard practice in the Delaware Basin is to fill this space with a dense plugging mud that provides a platform for setting internal concrete plugs and remains as part of the plugging system. This mud is expected to have a low permeability and may be sufficiently dense to reduce long-term fluid movement through the sealed boreholes between the repository and a partially depressurized Castile brine reservoir. Ignoring this plug in the model may be overly conservative.

The range of permeabilities representative of a silty sand was checked against ranges given in three standard texts, and the results are tabulated below. As can be seen in Table 3.12.1, the values used in performance assessment are neither the highest nor the lowest and are appropriate.

Table 3.12.1. Range of Permeabilities

Source	Medium	High End Value (m^2)	Low End Value (m^2)
Freeze and Cherry 1979, p. 29	Silty Sand	1×10^{-10}	1×10^{-14}
USBR 1987, p. 98	Silty Sand	1×10^{-12}	1×10^{-17}
de Marsily 1986, p. 78	Fine Sand, Silt, Loess	1×10^{-12}	1×10^{-16}
WIPP Performance Assessment 1996	Silty Sand	1×10^{-11}	1×10^{-14}

The frequency of waste panel penetration by exploration boreholes is expected, on the average, to be about 6 penetrations per 10,000 years. This value is based on a waste panel target area of 0.125 square kilometers, which is the approximate area of the disposal rooms themselves and does not include the disturbed rock zone in the walls of the waste panel excavations. This disturbed zone will be fractured by spalling and halite creep and may have sufficient permeability to permit long-term hydraulic communication with the repository. Ignoring this zone in performance assessment reduces the effective area of the waste panels and decreases the frequency of penetration. This issue is discussed further in Section 3.15.

The exploration borehole is assumed by DOE to penetrate the repository within a waste panel. Although such a penetration would be expected to result in the greatest release potential, penetrations could also occur within the operations and experimental areas of the repository, where the greater area of excavations would lead to an increased frequency of penetration. Under long-term flow conditions, pressure is expected to equilibrate quickly throughout a sealed repository by relatively rapid gas movement, and advective brine movement may be small because of the low hydraulic gradients. Penetration of the operations and experimental areas could lower gas pressures throughout the repository, which is expected to be a beneficial result. Diffusive movement of dissolved radionuclides, however, could occur through the panel seals, allowing radionuclides to migrate into the other parts of the repository and be available for release through an exploration borehole. Also, an exploration borehole penetrating the operational area and pressurized brine in the Castile could release Castile brine into the operational, experimental, and waste panel areas and pressurize the entire repository.

Borehole plugs below the Salado are assumed by DOE to not degrade within the 10,000-year regulatory time frame. This lack of degradation is related to suppression of anoxic corrosion reactions, primarily by high hydrostatic pressures in the borehole, and preservation of the concrete plug by the longer term confinement offered by the casing (Thompson et al. 1996, Chapter 3). This approach is based on thermodynamic data and assumes that carbon dioxide and hydrogen disulfide will passivate and reduce the corrosion rate of steel surfaces, and that the buildup of hydrogen fugacity from the corrosion reaction will cause the conversion of iron to $Fe(OH)_2$, to cease at a pressure of about 45 atmospheres (4.5 MPa). Such a pressure is believed to prevent hydrogen bubble nucleation and loss of hydrogen from the chemical system and could be provided by brine inside the casing (Thompson et al. 1996, p. B-21). In the analysis of steel corrosion in the gas generation conceptual model, the DOE indicated that the hydrogen fugacity that would stop corrosion to $Fe(OH)_2$ was 70 atmospheres (7.0 MPa) based on another set of thermodynamic data, but that the corrosion reaction could not be counted on to stop at that pressure because the reaction could convert to Fe_3O_4 and continue until a pressure of perhaps 500 atmospheres (50 MPa) was reached. At these higher pressures, hydrogen bubble formation and loss from the system could occur down to the depths of the plugs below the repository, potentially resulting in their failure during the 10,000-year regulatory time frame. The potential for such failure is also indicated by Thompson et al. (1996, p. 17), where the two lower plugs are given median lives of about 5,000 years and a range of 500 to 50,000 years. The validity of DOE's assumed plug life in excess of 10,000 years is questioned in light of these alternative observations.

If the borehole plugs beneath the repository fail during the 10,000-year regulatory time frame, the role of Bell Canyon groundwater may become important. As previously noted, all exploratory boreholes are assumed to be drilled in search of hydrocarbon resources and all are therefore assumed to penetrate entirely through the Salado and Castile Formations into the Bell Canyon Formation. Although only about 10% of the holes drilled through the waste panels are assumed by DOE to encounter pressurized brine, 100% of the holes will penetrate the Bell Canyon and the plugs below the repository may be significant in isolating the repository from the Bell Canyon. Water pressure in the Bell Canyon is reported in Lappin and Hunter (1989, p. 3-151) to be insufficient to cause water to flow from the Bell Canyon to the Culebra in an uncased or leaky casing borehole if the increase in water density from salt dissolution in the Castile or Salado were considered. However, the potential for water movement to or from the repository horizon was not discussed. If borehole plugs below the Salado cannot be assumed to

have functional lives exceeding 10,000 years with a high degree of certainty, the validity of the assumption that Bell Canyon groundwater can be ignored in the performance assessment analysis may be erroneous.

The assumption in BRAGFLO that the lower plugs need not be explicitly modeled in performance assessment may be valid only if the assumption that they will remain viable during the 10,000-year regulatory time frame is valid. Failure of the lower plugs would provide a low-permeability pathway among the repository, the Bell Canyon, and any pressurized brine that may be encountered in the Castile. If a lifetime in excess of 10,000 years cannot be adequately supported, flow through the lower plugs may have to be explicitly modeled in BRAGFLO.

The three-plug configuration is assumed by DOE to cause an E1 scenario to be equivalent to an E2 scenario by eliminating effects on the repository of encountering pressurized brine in the Castile. The rationale for this assumption, as summarized in Section 3.12.1, does not appear to consider the potential for Castile brine to enter the repository during drilling before the hole is cased through the Salado and Castile. Such an event could increase the brine saturation in the penetrated waste panel, and affect subsequent waste corrosion and gas generation rates. Such a scenario would occur before the plugs were emplaced and thus would be independent of plug degradation rates.

The use of reference conditions, rather than direct model results, as the final input for performance assessment calculations is acknowledged to be a necessary simplification given the thousands of model runs that are necessary to produce stable CCDFs; however, the sensitivity of the current performance assessment inputs to the assumptions inherent in this approach have not been presented to the Panel. The validity of this approach is of concern, particularly when only two release values (those at 350 and 1,000 years) are used to determine releases over a 10,000-year period. Sensitivity studies performed during earlier performance assessments showed this approach to be valid (see, for example, Helton et al. 1992); however, similar studies have not been performed to help assure the validity of this approach for the current performance assessment model.

3.12.2.3. Evaluation of Alternatives

The overall Exploration Borehole conceptual model has evolved over time along with the Repository Fluid Flow model, and has been the subject of extensive sensitivity studies in previous draft performance assessments as noted above. Based on these studies, the overall conceptual model has been shown to be

adequate; however, the validity of certain assumptions regarding components of this model has been questioned as described in Section 3.12.3.2. These include: alternative borehole penetration locations in the repository; allowing for a more rapid degradation of borehole plugs below the repository horizon (including the effects of Bell Canyon groundwater and explicitly including borehole plugs below the repository horizon if adequate longevity of the lower borehole plugs cannot be reasonably assured); reevaluating effects on the repository from an E1 borehole and a three-plug configuration; and assessing the adequacy of the selected reference conditions.

3.12.2.4. Uncertainties

The principal uncertainties in model results are expected to stem from uncertainties in the parametric data base, in the performance of the borehole plugs, and in the accuracy of the reference condition approach to final performance assessment modeling. The principal uncertainties in the parametric data base are associated with the hydrologic properties of the repository materials and are addressed in Section 3.3, Repository Fluid Flow. The hydrologic properties of the seal materials are generally better known and have less uncertainty. Those parameters with the greatest uncertainty, such as the permeability of the silty-sand-like material derived from corrosion products that fill the borehole, are generally sampled from a range of values and their uncertainty is thereby reflected in the overall modeling results. The consequence of uncertainties in these parameters is ultimately to overestimate or underestimate radionuclide releases; however, many of these parameter values reflect best estimates of future conditions and are appropriate for use in performance assessment despite their high degree of uncertainty.

Uncertainty in the performance of the borehole plugs below the repository horizon is discussed in the preceding sections. Plug failure within the regulatory time frame could result in the need to explicitly model the plugs in BRAGFLO, and to consider the effects of a low-permeability pathway to the Bell Canyon Formation on flow into and releases from the repository.

The accuracy of the reference condition approach to final performance assessment modeling has not been demonstrated to the Panel. If sensitivity studies indicate that the present method is inadequate, a denser lookup table may be needed, consequently requiring more computer time to prepare the performance assessment.

3.12.2.5. Adequacy of the Conceptual Model

The conceptual model for exploration boreholes is fundamentally sound, and the issues raised in the validity of model assumptions (Section 3.12.2.2) are associated with specific, but potentially significant, details of the model. The adequacy of the current model is not known because of the unresolved issues identified in Section 3.12.3.3. Further information is required to determine, for example, whether modeling results are sensitive to exploration boreholes that penetrate the operations and experimental areas of the repository, or to the presence of a low permeability pathway to the Bell Canyon Formation. Such changes would affect both the conceptual and numerical models. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.12.2.6. Adequacy of Application

With the exception of the issues raised in Section 3.12.2.2 regarding model assumptions, the application of the conceptual model in the numerical models is adequate. Principal concerns are related to limiting borehole penetrations to the waste panel rooms, assuming no degradation of the lower borehole seals and, therefore, not explicitly modeling them or the Bell Canyon groundwater, and demonstrating the adequacy of the limited reference conditions used to provide input to the performance assessment.

3.12.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. The modeling results were not available for review and could not be checked; however, those areas where the modeling approach is questioned and could lead to inaccurate results have been identified as issues in this report.

3.12.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain pending resolution of the issues raised in Section 3.12.2.3. In summary, the following concerns remain.

- *The potential for releases or changes in repository conditions from borehole penetrations in* the operations and experimental areas of the repository does not appear to have been evaluated. Radionuclides that may have migrated into those areas through the panel closures, by diffusion or other transport mechanisms, could be released to the ground surface, gas pressures could be relieved, and brine could migrate into those areas and then into the waste panels from a borehole penetrating a Castile reservoir or through degraded plugs from the Bell Canyon.

- The assumption that shorter (40-m) borehole plugs beneath the repository horizon will not significantly degrade during the 10,000-year regulatory time frame has not been adequately supported. For the two- and three-plug configurations, degradation of these plugs could result in creation of a low-permeability pathway for fluid migration between the Bell Canyon and the repository. For the three-plug configuration, degradation could result in increased fluid migration from a Castile brine reservoir to the repository.

- The possibility that an effect on the repository could result from Castile brine encountered in an E1 borehole that is assigned a three-plug configuration does not appear to have been considered in the conceptual model. Castile brine could enter the repository during drilling before the borehole is cased and result in increased rates of corrosion, waste degradation, and gas production.

- The sensitivity of the performance assessment to the simplified approach taken to determine reference conditions for BRAGFLO output does not appear to have been evaluated for the current model configuration. If reference conditions are not provided at sufficiently frequent time intervals, the modeling results may be erroneous.

3.12.2.9. Adequacy for Implementation

The Exploration Boreholes conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.12.2.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.12.2.10. Dissenting Views

There were no dissenting views for this model.

3.13. Cuttings/Cavings

3.13.1. Model Description

The Cuttings/Cavings conceptual model describes releases during drilling of exploration boreholes. It is one of several models that address the calculation of direct waste release to the ground surface if an exploration borehole inadvertently penetrates a waste panel, creating a possible pathway for transport of waste to the surface. Other associated models include those describing Exploration Boreholes, Repository Fluid Flow, Multiple Intrusions, and Spalling.

Of the possible pathways for release during the regulatory time frame, one of the most important is that caused by the inadvertent penetration of a waste storage room by an exploratory borehole. Normal oil and gas drilling practices can provide a means for waste to be released to the ground surface in the circulating drilling fluid (mud). From this intrusion, three mechanisms used by WIPP for waste

movement are cuttings, cavings and spallings. Cuttings are waste particles released into the mud from the cutting action of the drill bit itself and from mechanical friction. Cavings are waste particles released by erosion of the borehole walls due to circulating drilling fluids. Spallings are those particulate materials removed and transported by the movement of gases.

The cuttings mechanism is the easiest to address because the volume of waste cuttings is a simple product of the borehole cross sectional area times the room height, and is equal to the waste volume produced by the drill bit moving through the waste. Cavings is somewhat more complicated as it must incorporate the erosional effects of the shearing action of the drilling mud as it moves up the borehole annulus. This shearing may be caused by either turbulent or laminar flow. Repository pressure can have effects on cavings, which is covered by the spalling process. Spallings will be discussed further as a separate model in Section 3.14.

Details of the Cuttings/Cavings model were in a state of flux at the time of this peer review and information describing the model was obtained from various sources, but mainly from the CUTTINGS_S User's Manual, several draft reports, and from numerous contacts, presentations, and discussions.

Releases of cuttings and cavings are calculated using analytical equations governing erosion by flow up through the hole bored in the waste room, based on laminar and turbulent flow (Bergland 1992) as implemented by the CUTTING_S code. This code calculates the final caved diameter of the borehole that passes through the waste by using appropriate input based on assumed physical properties of the waste and drilling parameters. Although DOE is continuing to question whether the flow of the drill mud is laminar or turbulent, and what the parameters should be, the basic model has been generally accepted. However, the amount of material predicted to be released by cavings can be small per penetration and, therefore, its contribution to surface release has not been considered critical relative to other contributions.

The WIPP repository will consist of a number of waste disposal rooms excavated in bedded halite (salt) approximately 650 m below the ground surface. Transuranic waste packed in 55-gallon drums or standard waste boxes will be placed in each room. The waste is expected to be slowly compacted vertically by salt creep, from an original waste room height of 4 m to a compacted height of 0.5 to 2 m in approximately 100 years. In unmodified form, the waste consists of a mixture of, for example, contaminated cloth, wood, rubber, plastics, metals, glass. After placement in the repository, the waste

may become exposed to brine, which is expected to corrode the metals and generate hydrogen gas. Additional gas may be generated by the biodegradation of the organic materials. The gas volumes generated by corrosion and biodegradation are expected to increase continuously for hundreds of years and the pore pressure may become very high, possibly exceeding the lithostatic overburden stress. At some time within the 10,000-year regulatory period, it is probable that one or more exploration boreholes will be drilled into and through the vertically compacted waste and some of the waste will be carried to the surface. The volume of waste removed to the ground surface will depend on the physical properties of the compacted, decomposed wastes, the drilling procedures used, and the pressures encountered. The radioactivity of this waste is determined probabilistically, based on the distribution of waste radioactivity expected in the WIPP repository.

3.13.2. Review of Criteria

3.13.2.1. Information Used to Develop the Conceptual Model

Because the Cuttings/Cavings model is highly dependent on the borehole drilling process, it is important to understand the procedures used in drilling a gas or oil well. The current performance assessment model relies on the regulatory imposed assumption that future drilling techniques will be similar to those used today. When drilling commences, a conductor pipe is set in cement to prevent surface materials from sloughing into the wellbore during later drilling. Drilling is continued to the top of the salt section, using a large-diameter drill bit, where another steel casing is set. This "surface" casing is grouted into the hole and a blowout prevention tree is attached to the casing at the surface level. Drilling in the salt section uses drilling mud mixed in saturated brine to prevent dissolution of the salt.

Drilling mud is pumped from the reserve pit down through the drillpipe and drill bit, and up the annulus formed by the drill string and drilled hole. While drilling in the salt section, no formal attempt is made to monitor the character of the cuttings or the fluid volume of the reserve pit. (In the WIPP intrusion case, this can be an important input.) The drill string generally consists of a drill bit attached to long drill collars (heavy pipe) with a smaller outside diameter than the bit but a larger diameter than the following multiple sections of 4-1/2" diameter drillpipe. Once the drill has passed the salt section (1,375 m), the hole is again cased with cemented pipe. At this point, if the repository had been penetrated, no further contact would occur between the drilling mud and exposed WIPP waste.

Cuttings are a component of the direct brine release model, and cuttings releases are assumed to be the only drilling release to occur for repository pressures less than the hydrostatic pressure of the drilling mud (approximately 8 MPa). Because the volume of cuttings removed and transported to the surface is equal to the product of the drill bit cross sectional area, drill depth and waste porosity, it is only necessary to know these three parameters. The cuttings volume calculated becomes the lower bound to the total quantity of waste removed by drilling. The computation of cuttings release in the CUTTINGS_S code is performed within a module specific to cavings.

For the cavings part of the Cuttings/Cavings model, the erosion process is assumed to be driven solely by the shearing action of the drilling fluid (mud) on the waste as it moves up the borehole annulus between the drill pipe and the waste. For the purpose of the cavings calculations, it is further assumed that the repository is not excessively pressurized by either brine or gas (i.e., the repository pressure is less than the hydrostatic pressure of a brine column to the surface). In the annulus formed by the collars or drill pipe and the borehole wall, the flow of the drilling fluid has both a vertical and rotational component. This helical flow pattern generates shear stresses by the relative motion of adjacent fluid regions and by the action of the fluid on the borehole wall. It is assumed that if the fluid shear stress at the wall exceeds the effective shear resistance to erosion of the wall material (compacted repository wastes), erosion of the wall material will occur, increasing the diameter of the bored hole. The eroded material then will be carried onto the surface, entrained in the flowing drilling fluid. The code probabilistically determines the amount of material removed by the several release mechanisms, and decays the radionuclides release to simulate the source term at the time of intrusion.

3.13.2.2. Validity of Model Assumptions

Many of the principal assumptions used in developing the model are identified in Section 3.13.1. Overall, the assumptions are found to be reasonable and appropriate. Identification of and expansion on the key assumptions are discussed below.

The concept of release due to borehole drilling relies heavily on the assumption that future drilling techniques will be similar to those in use today. The basics of the drilling process are as outlined in Section 3.13.2.1, which comes from a large, well-tested body of experience that can be expected to be reliable.

It is implicitly assumed that the drillhole will encounter waste only as it penetrates the room. This is a simplifying assumption that is realistic but does not have to be absolute. For example, there can be a DRZ over the repository that could contain contaminated brines.

For this model it is assumed that the waste volume is probabilistically determined for each penetration. The Curie calculations are a direct computation from the amount of waste removed.

The cuttings portion of the waste material removed is assumed to be strictly the result of the neat volume of material cut away by action of the drill bit. The cavings portion accounts for the other mechanisms that complement the drilling action, such as frictional drill fluid erosion. These definitions of waste source from this model are inclusive and adequate.

It is assumed by the cavings portion of this model that the fluid shear stress at the waste surface must exceed the effective shear resistance of the waste wall for any release. This is valid since erosion occurs, increasing the diameter of the borehole with the eroded material being carried away by the circulating drilling fluid.

The equations governing waste erosion are based on laminar and turbulent flow, both of which are assumed to occur, depending on the velocity.

Among the basic assumptions made for the fluid flow calculations is that, in the absence of experimental data, the effective shear resistance to erosion of the repository waste is similar to ocean bay mud or montmorillonite clay. In the absence of accurate waste characterization or knowledge of the form this waste is in as the time of intrusion, this assumption appears appropriate because of the low shear strengths of these substances.

3.13.2.3. Evaluation of Alternatives

Only one issue is identified for which an alternative might be considered. It is a possibility that the environment for cuttings and cavings will be saturated with brine. If this becomes the case, this brine might be removed by the drilling action without the benefits of erosion or cuttings. This scenario does not appear to have been incorporated in the Cuttings/Cavings model and its significance is not known.

There are no meaningful alternatives for the cuttings and cavings model, except perhaps to consider using a finite fixed assumed input value, which would be more arbitrary.

3.13.2.4. Uncertainties

Several factors contribute to model uncertainty, principally the undefined nature and complexity of the waste, both in its initial and altered states. Information as basic as granular state, chemical form, decomposed form, density, and waste strength, is unconstrained. To conservatively treat these unknowns, property values of surrogate materials are selected to represent the worse case. As such, the accuracy of the model should be realistic, but on the conservative side. Uncertainty also may arise from inappropriate applications of turbidity resulting from assumptions in turbulent flow, which is a function of the Reynolds Number data on the transition from laminar to turbulence of the fluids. Within the full scope of exposure, however, any reasonable variation from probable waste volume removed would be confined to a restricted, relatively small volume and would not appear to lead to any significant consequences per penetration.

3.13.2.5. Adequacy of the Conceptual Model

This model is fundamentally appropriate. It is based on straightforward analysis, concepts, and technology that is well developed and believed to be adequate for depicting that part of the consequences of a waste room penetration by a borehole drill that is covered by this model.

3.13.2.6. Adequacy of Application

The CUTTINGS_S model contains well thought out and evaluated mathematics, based on researched and established fluid flow technology and science. The FORTRAN computer codes used to simulate the laminar helical flow in an annulus are documented and verified against published results. For turbulent flow, the results are highly dependent on the parameter values. The values given in the CUTTINGS_S User's Manual have resulted from significant research and are believed to provide adequate solutions. The turbulent flow is found to be dependent on absolute surface roughness and the value chosen for the calculation exceeds that of very rough concrete or riveted steel piping. As a result of these considerations, the Panel believes this model is adequate for application.

3.13.2.7. Accuracy of Results

The parameters for calculations were checked as presented in the CUTTINGS_S User's Manual and found to be appropriate. The drilling parameter values were obtained from surveying industry practices and as reported, the values are appropriate for a range of customary industrial size dimensions.

3.13.2.8. Validity of Conclusions

Physically, the conceptual process of this model is simple and valid. Some subjectiveness of validity exists in the questions of turbulent or laminar flow and the state of the waste for determining its resistance to removal by the caving process. The conservative values used in the calculations appear to alleviate these concerns, however. Therefore, the validity of this conceptual model appears to be acceptable within the uncertainties discussed in Section 3.13.2.4.

3.13.2.9. Adequacy for Implementation

This model is sufficiently developed and uncomplicated that no serious concerns were raised. The model appears to be capable of accurately representing the waste that might be removed during a drilling intrusion and is fully adequate for implementation in support of the WIPP performance assessment.

3.13.2.10. Dissenting Views

There were no dissenting views for this model.

3.14. Spallings

3.14.1. Model Description

The Spallings conceptual model is one of several that address the calculation of direct waste release to the ground surface if an exploration borehole penetrates a waste panel. Other associated models include Cuttings and Cavings, Exploration Boreholes, Repository Fluid Flow, and Multiple Intrusions.

Spallings are the particulate materials introduced into drilling mud by the movement of gas from the waste into the borehole annulus. At one time, spallings were conceived to involve three mechanisms: blowout, stuck pipe, and gas-induced spall. Because the latter two were perceived to produce insignificant releases, DOE determined that this model would concentrate on blowout. The repository pressure domain, where spallings are applicable, is above the borehole fluid hydrostatic pressure because it can occur only when the repository gas pressure is capable of countering and reversing the mud-laden drilling fluid during the drilling process. When the drillhole annulus around the drill pipe is cleared of drilling fluid, it becomes a conduit for free release of repository gases.

The principal parameters in the Spallings model are the gas pressure, the volume of gas in the repository when it is penetrated, and properties of the waste such as particle diameters and resistance to erosion.

Because the release associated with spallings is sensitive to gas pressure in the repository, it is strongly coupled to the BRAGFLO-calculated conditions in the repository at the time of penetration. In particular, the spall release may be sensitive to whether the repository has been penetrated previously by another borehole.

3.14.2. Review of Criteria

3.14.2.1. Information Used to Develop the Conceptual Model

This model was based on information on drilling practices, dimensions, and characteristics of drilling equipment parameters, and standard models for gas flow, as well as results of a simple laboratory test to examine some aspects of the conceptual model. Details of the Spallings model were in a state of flux at the time of this peer review. Information describing the model was obtained from various sources, mainly from the CUTTINGS_S Users Manual, several draft reports, presentations, and numerous personal contacts and discussions.

Because this source of release is somewhat dependent on the borehole drilling process, it will be instructive to understand the procedures utilized in drilling an oil or gas well, which the EPA has directed to be the standard for WIPP characterization studies. As described in Section 3.13.2.1, drilling produces a borehole into the repository room by a bit-cutting process that produces rock fragments. The fragments are removed by circulating a mud-laden fluid down through the drill pipe and returning it up the annular space between the pipe and the hole wall. The hydrostatic pressure of this mud column must be kept in balance with the pressure at the drill bit location. When an imbalance from overpressure in the repository occurs unchecked, the mud flow on the return side will be accelerated and ejected from the hole, creating a gas vent to the repository. Until this sudden uncontrolled venting is brought under control, violent escape of gas from the repository is expected to carry with it some of the stored waste, discharging it at the well head on the ground surface. Once gases begin to vent up the drill hole, repository room pressure gradients generated by the penetration of the repository cause a flow of gas toward the borehole that fractures the waste material, permitting the escaping gas to flow within fractures rather than through a porous waste matrix. Consequently, the intrinsic permeability of the matrix does not restrict the gas flow. Gas flow velocity up the borehole is governed by the isothermal flow of gas in a long annular tube of a given cross sectional area, tube roughness, and gas pressure at the borehole entrance. The gas pressure at the borehole entrance to the repository can be assumed to be the initial gas pressure in the repository. The mass-flow rate of gas in the fractured waste at any radial cross section is

equal to the mass-flow rate up the borehole. Radial flow of gas within the fractures in the waste matrix erodes and widens the fractures. Erosion of the waste is assumed to occur if the fracture gas velocity exceeds a threshold velocity related to the terminal velocity of a waste particle at the fracture surface and to the cohesive strength afforded by moisture in the matrix.

A key part of the Spallings model is to determine how much of the waste will be lofted into the gas stream. With the uncertainty of the waste characterization (e.g., its state and chemical form), the premise that the spalling process is self-limiting is based on the assumption that particle movement will cease when the gas velocity, measured radially from the borehole axis, equals the critical entrainment velocity. All material close to the borehole is assumed to be eroded away and removed. A laboratory experiment was modeled to demonstrate a critical lofting velocity for sample materials as a function of particle size distribution. Different terminal velocities were associated with different particle diameters. Confirmative testing of the model was conducted with the standard that if the measured amount of lofted material was less than the predicted amount of erosion, the model was considered confirmed. Confirmation was not obtained because the tests showed the expected uniform gas flow through the waste was not occurring. Instead of a cavity forming around the borehole, flow channels formed that increased in width and length as erosion proceeded in the material. These results forced the latest iteration in the blowout model. The new model (WIPP PA User's Manual for CUTTINGS_S, Appendix A, Section 2.3.1.3), called the channel flow model, is the one used for CCA calculations, although it is the understanding of the Panel that the mechanisms of this model are yet to be confirmed.

A channel-flow mechanism in the model requires either precise definition of the number, geometric configuration, and location of all the channels before they form (which is not technically feasible), or scaling the model results in some manner to reflect the channeling process. The scaling method was adopted, adjusting the predicted releases to agree with experimental release observations in the laboratory test. This laboratory test was a simple, small-scale experiment that yielded useful insights, but it could hardly be an adequate representation of actual degraded waste materials. Although the uniform-flow model was independent of experiments, in the sense that release predictions did not require direct data from the tests, a coupling between experimental results and the model was necessary for scaling. This was accomplished by introducing certain experimentally determined scaling constants into the model (Lenke et al. 1996). Notwithstanding the use of these scaling factors, the model is based on well-defined first order physical principles and is applied to different gases and solid materials by prescribing well-defined material properties, such as particle size and density, viscosity, and cementation tensile

strength. The scaling factors are the only parameters of the model not directly related to geometry or material properties, but they are necessary to represent the way channels for gas flow are likely to develop.

3.14.2.2. Validity of Model Assumptions

It is assumed that the repository pressure domain is above the hydrostatic head of the drill fluid column. This is reasonable because technically, a blowout should not occur at a lower pressure.

A simplifying assumption is that the driller does not have signs of the impending penetration and is unprepared to react. Therefore, the blowout is likely to occur and may be difficult to contain. Because of this, it is assumed that the release will be process-limited rather than operator-dependent.

An implied assumption is that the surface of the cavity will be cylindrical in nature.

The model's limiting characteristic is achieved by the derived equation's function of gas velocity and waste strength. As the velocity declines, the limiting parameter becomes the property of waste strength. The use of this property is valid, but its value is subjective because of the unknowns and uncertainties of the waste itself. In fact, this property is a function of the source of waste strength, such as cohesion, adhesion, or cementation. Cementation from a salt crystallization process in the stored waste is currently being considered as a mechanism that provides a strength value for waste that might be easily validated.

At this writing, it is assumed that the latest CUTTINGS_S model assures that the model relies on channel flow instead of a uniform low porosity flow toward the borehole. It is of concern to the Panel that the mechanisms of this assumption are yet to be confirmed.

3.14.2.3. Evaluation of Alternatives

The Spallings conceptual model has changed several times during its development. Early model development focused on transient, unrestrained outgasing leading to the spall (dynamic fracture) of porous cohesive granular media (Berglund 1992, Section 3.3). An experimental program related to model development focused on almost instantaneous depressurization and was limited to a one-dimensional linear sample configuration. The pore pressures required to cause spall or dynamic fracture could be closely approximated using the tensile strength of the porous soil medium (Berglund and Lenke 1995), but the model was complex and could not be directly related to an intrusion event. In addition, although the experimental observations showed fracturing under instantaneous release of gas pressure,

sample-preparation factors were largely responsible for the locations of the fractures. The fracture patterns also depended on the one-dimensional nature of the experiments, and the model did not adequately explain how the fractured material was removed.

After extensive discussion, the dynamic fracture model was replaced with a more general three-part model based on the premise that the waste could be removed by any one of three mechanisms: blowout, stuck pipe, and gas-flow assisted erosion (as the result of gas-induced spall) (Butcher et al. 1994). Which mechanism will dominate depends on the permeability and pressure drop at the borehole. Well blowout, an uncontrolled gas release from the borehole, was considered the dominant mechanism. The remaining two mechanisms, stuck pipe (waste loosened and moved while attempting to dislodge a stuck drill pipe), and gas-flow assisted erosion, were not thought to be important because they would only occur at waste permeabilities of less than 1×10^{-16} m^2. The gas-flow assisted erosion is now the basis for the channel flow modeling in the Spallings model.

3.14.2.4. Uncertainties

Development of this model is not sufficiently complete to determine uncertainties specific to the channel flow movement of waste to the existing borehole. The lack of adequate waste characterization may also provide a set of uncertainties. Other uncertainties concern the state the waste is in at the time of intrusion, which may not be feasible to ascertain.

3.14.2.5. Adequacy of the Conceptual Model

The Spallings model gives a good conceptual view of how solid waste can be removed by gases that are being rapidly vented. The latest model is most realistic mechanistically because it is predicated on the concepts of moving particles via gas movement. The original model, which relied on instantaneous decrease in gas pressure, was judged by DOE to be unrealistic because of waste permeability and gas flow considerations. The latest model appears to be the most applicable of those that have been considered to date. Notwithstanding the need for establishing two scaling parameters and a waste strength factor, this model is conceptually appropriate, but the Panel could not find sufficient information to determine its adequacy.

3.14.2.6. Adequacy of Application

Integration of the Spallings model into the CUTTINGS_S code is a relatively simple exercise, although the equations governing the waste availability for removal do not appear to be fully developed at this

time. While the concept of scaling parameters, which are intended to address waste strength by providing factors of resistance to erosion or lofting, is appropriate, the proposed parameter value has yet to be validated. Therefore, until these details are resolved, it will not be possible to assess the adequacy of application for this model.

3.14.2.7. Accuracy of Results

On testing the latest modeling efforts for confirmation of principle, additional information was gained that should be pursued before further confirmation is sought. It seems plausible that the performance assessment exercise might use an assumed entrained waste content for a given time period and sample several scenarios for concentration and time domain. Another simplistic approach might be to assume a certain waste volume around the borehole that would be removed. Given the importance to overall performance assessment of results from this model, any laboratory tests could be supplemented by a scaled-up testing demonstration that will more convincingly verify the model. At this time there is not enough information to determine the accuracy of results from the Spallings model.

3.14.2.8. Validity of Conclusions

In the opinion of the Panel, the model development is now on an appropriate path to produce a valid outcome. However, the available information was not sufficient to present a compelling argument that adequate work has been done to confirm that the conclusions would be valid. Additional testing is required to firm up the conceptualization of the channel flow scenario.

3.14.2.9. Adequacy for Implementation

Because of perceived inability to defend a time limit for release, it became necessary to implement a model that provides a self-limiting process for waste removal. It is not reasonable to expect that the entire room would be excavated by the blowout process. If this were possible, a model would not be necessary. *Because of its unconfirmed state of development, this model is not adequate for* implementation at this time.

3.14.2.10. Dissenting Views

There were no dissenting views for this model.

3.15. Direct Brine Release

3.15.1. Model Description

The Direct Brine Release conceptual model describes short-term releases of brine from exploratory boreholes that penetrate waste panels in the repository. The model addresses releases from both single and multiple intrusions. Long-term flow from single intrusions and the assumptions regarding the physical aspects of the boreholes are addressed in the Exploration Borehole conceptual model, and long-term flow from multiple intrusions is addressed in the Multiple Intrusions conceptual model. Other related models include Repository Fluid Flow, Castile and Brine Reservoirs, and Actinide Transport in the Salado. The related Cuttings/Cavings and Spallings models address releases of solid waste materials following borehole intrusions, but do not address brine releases. The details of the Direct Brine Release model were still under development at the time of this peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 22 May 1996 Draft CCA, Sections 6.4.7.1, Releases During Drilling (DOE 1996, pp. 6-65 to 6-70), from verbal descriptions, and from the cited references.

Releases that may occur during and immediately following drilling are modeled in accordance with regulatory guidance, assuming that present standard rotary drilling practices will be used. This assumption was used by DOE to establish borehole geometry during drilling, as well as the drilling, casing, and sealing practices (Thompson et al. 1996). To help prevent blowout, the density of the drilling mud is controlled by drillers based on the fluid pressures expected at the drilling depths. Gas, as well as brine, may enter the borehole from the waste panel if the driller is unable to control the pressure in the borehole. If fluid pressures in the waste panel are sufficiently high, brine or a brine-gas mixture may flow to the ground surface. The boreholes are assumed to be cased from the ground surface to the lower Rustler before entering the Salado; thus, brine flowing up the borehole during drilling would reach the surface, but not enter the Culebra or the other permeable horizons above the Salado. The frequency with which exploration boreholes will penetrate the waste panel area is estimated based on a long-term average of 47 boreholes per square kilometer per 10,000 years, and the size of the waste panel area. This is further discussed in Section 3.12.

Before brine can flow from a waste panel to the ground surface, mobile brine must be present in the waste panel and the pressure of the brine must be greater than the pressure of the drilling mud at the repository depth. Brine is expected to enter the waste panel as seepage from the surrounding halites, anhydrite beds, and through the shaft seals, and will also enter if pressurized brine is encountered in the Castile. Mobile brine will be present in the waste panel if it has not been previously consumed by the corrosion reaction and if there is enough remaining to exceed the residual brine saturation of the waste. The residual brine saturation is the percent saturation below which the brine occurs discontinuously in the porous waste and will no longer move. The residual brine saturation in the waste panel is uncertain and is randomly sampled in performance assessment from the range of zero to 0.552 (DOE 1996, Table 6-6). The drilling mud is assumed to exert a pressure of about 8 MPa at the repository horizon; thus, for brine to be released to the ground surface its pressure in the repository must exceed this value.

In accordance with regulatory guidance, DOE does not assume that a direct brine release would be noticed by the driller, or that the driller is aware of the presence of the repository. The driller is assumed to be exploring for hydrocarbon resources, and after taking normal steps to deal with any brine releases or drilling fluid losses at the repository horizon, would continue drilling to customary depths below the Bell Canyon. Based on a review of current practices in the Delaware Basin, DOE has assumed that direct brine releases to the surface will be stopped by the driller 44 hours after penetrating the repository. Borehole plugs are assumed to be installed in three alternative configurations, and to degrade as discussed in Section 3.12. Because of the assumed degradation rates of the various plugs, only the two-plug and three-plug configurations are of consequence to direct brine releases.

Encountering pressurized brine in the Castile in a borehole is not considered by DOE to result in a direct release of repository waste. The Castile brine will be uncontaminated and, to result in a direct release, would have to be of sufficient pressure to eject the drilling mud from the borehole. Because the repository is likely to have been depressurized a short time before when it was penetrated by the same borehole, the repository pressure is expected to be lower than the Castile brine pressure and initial hydraulic gradients would be from the borehole into the repository. The longer term migration of Castile brines into the repository are addressed in the long-term BRAGFLO calculations and would affect both the long-term releases and the initial conditions (such as waste panel brine saturations and gas pressures) for the next short-term release. Direct release of waste solids by borehole wall erosion from Castile brine moving up the borehole is assumed by DOE to be negligible.

Short-term releases of dissolved or suspended radionuclides contained in brine are modeled using a two-dimensional, two-phase, transient horizontal plane model of the waste panel area, developed using the BRAGFLO code specifically for estimating short-term, direct brine flow. This model has not been specifically named, and for purposes of this report will be called the BRAGFLO-DBR model. Radionuclide transport is calculated using the PANEL code. This code conservatively assumes complete mixing in the waste panels and is further discussed in Section 3.8. BRAGFLO-DBR explicitly models all disposal rooms, pillars, panel closures, and the associated disturbed rock zone within the waste disposal area of the repository.

A one-degree dip in the repository corresponding to the average one-degree dip to the south in Salado bedding is included in the model. Including this dip has been found to be important in modeling results because of the effects of gravity. Gas movement in the anhydrite beds tends to be to the north toward areas of lower pressure, while brine tends to accumulate in the southern or lower end of the waste disposal area. Material properties in BRAGFLO-DBR are generally consistent with those in the standard version of the BRAGFLO model (called BRAGFLO in this report) used to model repository fluid flow (Section 3.3), with the exception that the intact Salado halite is assumed to be impermeable and forms an outer no-flow boundary for the model.

BRAGFLO-DBR takes its initial and boundary conditions from BRAGFLO, CUTTINGS_S, the WIPP data base, and an analytical correlation to simulate flow up the open borehole. Fluid pressures, saturations, permeabilities, porosities, two-phase flow properties, and other repository properties are determined at the time of penetration by the standard version of the BRAGFLO code. The borehole flow model has been developed from a multi-phase vertical pipe flow analysis used in the petroleum industry. Total flux and transport are determined based on a flow duration of 44 hours.

For calculating short-term releases, borehole penetrations are assumed in BRAGFLO-DBR to occur in two reference locations, at an updip location in the center of the waste panel area, and at a downdip location in the southwestern waste panel. Multiple borehole penetrations of the same waste panel are always assumed to occur at the southwestern end of the repository because the reference conditions for multiple intrusions are developed from the standard BRAGFLO model, which conservatively places the single waste panel and intrusion borehole at the downdip end of the waste panel area. Actual intrusion locations are selected randomly, but the boreholes are then assigned standardized reference locations depending on whether they penetrate the waste or a salt column, whether they are updip or downdip,

whether they are E1 or E2, and whether they are the first intrusion or a subsequent intrusion of the same waste panel. Modeling results have indicated that the effects of borehole intrusions on the repository are not significant beyond the waste panel that was penetrated; thus, second and subsequent intrusions into the same waste panel are treated separately in the model.

For the first borehole penetration in a particular waste panel, the initial and boundary conditions are determined by interpolation from reference conditions determined from undisturbed BRAGFLO results at approximately six reference times ranging from 100 to 10,000 years. BRAGFLO-DBR is run for each of these sets of reference conditions to establish a data base for interpolating short-term releases from first penetrations occurring during the regulatory time frame. Conditions for first penetrations are assumed to be the same for E1 or E2 boreholes, because at the time of penetration neither would have been drilled past the repository. Initial conditions for downdip borehole locations are taken from conditions in the single waste panel in BRAGFLO, which is at the downdip end of that model. Initial conditions for updip borehole locations are taken from the "rest of the repository" in BRAGFLO, which is at the updip end of that model.

Conditions for second penetrations are determined based on the date, type, and location of the first penetration, as well as the date, type, and location of the second penetration. Different sets of reference conditions are established for second penetrations depending on whether the first penetration was an E1 or E2, whether the second penetration occurs in the same panel or a different panel, and the lag time between the first and second penetrations. Subsequent penetrations are addressed following similar logic. Reference conditions for second and subsequent penetrations are determined from BRAGFLO calculations for E1 and E2 intrusions occurring at 350 and 1,000 years, as described in Section 3.12.

Changes in repository pressure, fluid saturation, and other repository conditions resulting from the short-term releases are not considered in the long-term flow calculations. Such effects are considered negligible by DOE over the long term because of their transient and local nature.

3.15.2. Review of Criteria

3.15.2.1. *Information Used to Develop the Conceptual Model*

The Direct Brine Release conceptual model was developed based on a combination of conceptual models for repository design and two-phase fluid flow, the physical and hydrologic properties of Castile brine reservoirs, current drilling and borehole sealing practices in the Delaware Basin, fluid flow in open

boreholes, and borehole plug degradation rates. Current practice has provided elements of this model, in accordance with regulatory requirements. This information base is considered reasonable and appropriate.

3.15.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.15.1, and are critically reviewed here. Most assumptions are reasonable and appropriate and include the general approach taken to modeling fluid flow within the boreholes and repository, treatment of borehole sealing practices, and use of reference conditions to address alternative intrusion scenarios. The frequency of drilling and the time required for a driller to control a direct brine release are based on DOE analysis of current practice and are not reviewed here. Reference conditions for direct brine releases are determined at a greater frequency than for the exploration boreholes or multiple intrusions models, and are expected to be adequate for performance assessment. The assumptions related to repository fluid flow, the physical aspects of the boreholes and borehole seals, and the characteristics of Castile brine reservoirs are discussed in Sections 3.3, 3.12, and 3.16, respectively. Changes in these assumptions would affect the approach taken to model direct brine releases. Several assumptions in the Direct Brine Release model that are potentially important to radionuclide containment and are not adequately supported are discussed in the following paragraphs.

No radionuclide release is assumed to occur from direct discharge of Castile reservoir brine in a borehole penetrating a waste panel. The rationale for this assumption does not appear to be supported by an analysis of the potential for brine mixing and borehole wall erosion. This could be more significant for penetrations occurring before complete water panel closure, when waste has not yet been fully compacted. Because the Castile brine would pass directly through a waste panel, the potential consequences of an error in this assumption could be significant.

The potential for entraining waste room brine in rapid gas flow from the waste panel is not considered in the conceptual models for either spallings or direct brine release. The Spallings model considers only the entrainment of solid particles in single-phase gas flow, and the Direct Brine Release model considers only dissolved and colloidal radionuclide transport in brine released to the surface. Brine entrainment in the gas can occur by transport of droplets or, more importantly, by air-lifting brine and waste particulates in a closed-wall pipe (the coffee percolator effect). The air-lift is in fact a method of well completion

where the violent surges from air pumped down a well are used to scour the borehole production zone and remove fine-grained sediments to enhance well production. Depending on the flow velocity in this two-phase brine/gas system, the erosional forces could be greater than for either gas or brine flow alone.

Boreholes penetrating areas of disturbed rock in the walls of the repository excavations do not appear to have been considered in performance assessment modeling. The walls will have a tendency to bow inward under the lithostatic stress, resulting in both micro- and macro-fracturing in the halite. Hydrologic tests in repository walls have shown pore pressure depressurization and reduced permeabilities within 10 m of the workings, most likely in response to halite deformation. Within this zone, pore pressures appear to have dropped to near zero at some locations, and permeabilities nearly three orders of magnitude higher than the high end of the undisturbed halite range have been measured (Lappin and Beauheim 1996). Hydrofracture measurements in horizontal boreholes within the repository have indicated that stress effects from repository excavations may extend on the order of 50 m from the end of a drift (Wawerski and Stone 1986). Boreholes very near the excavation wall could, therefore, encounter open fractures and permeabilities equivalent to those of the waste, while boreholes 10 m or more from the excavation may encounter essentially undisturbed halite. The higher permeabilities encountered in boreholes penetrating the disturbed rock zone in the excavation walls could lead to increased short- and long-term releases.

3.15.2.3. Evaluation of Alternatives

The overall conceptual model for direct brine releases is based on standard hydrogeologic and petroleum industry practices and is appropriate for use in performance assessment. Alternatives to this model may be considered, however, in the details of its application. Three fundamental issues have been identified: waste transport during the direct release of Castile brine, the entrainment of brine and waste solids in two-phase gas/brine flow from the repository, and boreholes penetrating disturbed rock in the excavation walls.

3.15.2.4. Uncertainties

Uncertainty in model results stems from uncertainties in the validity of the underlying fluid flow theory and analysis methods, from uncertainties in the input data, and from the validity of assumptions regarding the conceptual models. The underlying theory is widely used in the petroleum industry for evaluating oil reservoirs and provides a reasonable and appropriate approach to studying direct brine releases. Although the uncertainty in the input data are occasionally high, the parameter values have

generally been appropriately selected for performance assessment. The three additional processes discussed in Section 3.15.2.2 are similar in that they each address processes that were not considered by DOE. The consequence of neglecting these processes is to potentially underestimate radionuclide releases.

3.15.2.5. Adequacy of Conceptual Model

The conceptual model for direct brine releases is fundamentally sound, with the possible exception of the three processes identified in Section 3.15.2.2. These processes were not included in the conceptual model for performance assessment, and if valid, could be important to cumulative radionuclide release. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.15.2.6. Adequacy of Application

With the exception of the issues raised in Section 3.15.2.2 regarding model assumptions, the internal consistency of the conceptual model and its application in BRAGFLO-DBR is logical and is adequate for performance assessment. The simplifications required to model a complex set of conditions in an efficient manner appear to be appropriate.

3.15.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. Although the modeling results were not available for review and could not be checked, the density of reference conditions is expected to provide performance assessment inputs of suitable accuracy.

3.15.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain, pending resolution of the issues raised in Section 3.3.2.3. In summary, the following concerns remain.

- The basis for the assumption that radionuclides do not accompany the direct discharge of Castile brine has not been adequately supported. This assumption could lead to underestimating radionuclide releases if releases do, in fact, occur through this mechanism.

- Radionuclide transport through entrainment of brine and waste solids in rapid gas releases during inadvertent borehole intrusions does not appear to have been evaluated. This transport mechanism may be an important component of the conceptual model.

- Releases resulting from flow into an exploration borehole intersecting a disturbed rock zone in the wall of a waste panel do not appear to have been evaluated. Large, open fractures in the walls could significantly increase the local halite permeability, allowing gas and brine to migrate through the borehole to the ground surface.

3.15.2.9. Adequacy for Implementation

The Direct Brine Release conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.15.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.15.2.10. Dissenting Views

There were no dissenting views for this model.

3.16. Castile Formation and Brine Reservoir

3.16.1. Model Description

The Castile Formation and Brine Reservoir conceptual model addresses the hydrologic characteristics of the Castile Formation and the occurrence, size, hydrologic, and chemical characteristics of brine reservoirs that may underlie the repository within the Castile Formation. Associated models include Exploration Boreholes, Multiple Intrusions, and Repository Fluid Flow. The details of this model were still under development at the time of the peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 23 May 1996 Draft CCA, Section 6.4.8, Castile Formation and Brine Reservoir (DOE 1996, pp. 6-75 to 6-79), from verbal descriptions, and from the cited references.

The Castile Formation consists of a 360-m thick series of halite and anhydrite beds underlying the Salado Formation. Although few tests have been performed, by analogy to the Salado, the Castile is conceptualized as a very low permeability formation whose primary importance to WIPP performance assessment stems from the hydrologic isolation it provides the repository and from the pressurized brine reservoirs that have been encountered during deep drilling.

Deep exploratory boreholes that penetrate both the repository and the underlying Castile Formation may encounter a pressurized, higher-permeability, brine-filled region called a brine reservoir. If encountered, the fluid pressure in such a reservoir would be sufficient to cause brine to flow at potentially high rates

and high pressures through the repository and from the wellbore at the ground surface. The consequences of such flow are addressed in the Exploration Borehole and Multiple Intrusion conceptual models.

The brine reservoir is conceptualized by DOE as a heterogeneous, discontinuously fractured zone of limited extent within the Castile anhydrites. Transmissive pathways for brine and gas movement are provided by interconnected, primarily vertical fractures whose origin may be related to structural deformation. Fluid in the reservoirs is pressurized by the weight of the overlying geologic media and averages about 67% of the lithostatic pressure within the Delaware Basin (Freeze and Larson 1996).

Brine reservoirs are occasionally encountered during deep drilling in the Delaware Basin and, when allowed to flow, may discharge at rates estimated at 1,000 to 2,000 barrels (150 to 300 m^3) per day and last up to 4 to 5 days (Silva 1994). The observation that flows stop by themselves supports the concept that the size of individual brine reservoirs is limited. Brine reservoirs were penetrated by two boreholes (ERDA-6 and WIPP-12) drilled for WIPP site characterization purposes. The pore volumes of these reservoirs were estimated to be about 96,000 m^3 and 2,700,000 m^3, respectively, although the uncertainty in these estimates is large (Popielak et al. 1983). A geophysical survey, using time domain electromagnetic methods, completed over the WIPP-12 brine reservoir and the waste disposal panels, detected a conductor interpreted to be the WIPP-12 brine reservoir, and also indicated that similar brine occurrences may be present within the Castile under a portion of the waste disposal panels (Earth Technology Corporation 1988).

The chemistries of the brines from the ERDA-6 and WIPP-12 reservoirs were studied by Popielak et al. (1983) and found to be distinctly different from each other and from local groundwaters, supporting the concept that the reservoirs are isolated from each other and from local groundwaters. The major and minor element concentration ratios were interpreted by Popielak et al. to indicate that the brines originated from ancient seawater. Based on the geochemical and hydrological information, DOE believes the brine in the Castile reservoirs has not mixed to any significant extent with other waters and has not circulated within the Castile. Further, the brines are nearly saturated with halite and have little potential to dissolve additional halite.

The WIPP performance assessment requires information on the hydrologic characteristics and likelihood of encounter for a brine reservoir beneath the waste disposal area. Many of the characteristics of the reservoir penetrated by WIPP-12 have been used as a basis for modeling the hypothetical reservoir

underlying the waste. The WIPP-12 reservoir is the best characterized, it is relatively large and permeable, and it is the closest identified reservoir to the site. Relatively little gas has been found in the Castile reservoirs and the analyses of WIPP-12 have only considered single-phase brine flow.

The parameters needed to determine the hydrologic characteristics of the hypothetical reservoir beneath WIPP are described in several supporting documents. Reservoir pressure is described in Freeze and Larson (1996) as a distributed parameter with an expected value (12.7 MPa) equal to the estimated pressure of the WIPP-12 reservoir, and a range (11.1 to 17.0 MPa) based on pressures in other reservoirs encountered in the Delaware Basin. Reservoir porosity is described in Freeze (1996a) as a distributed parameter with a mean value (0.009) determined from laboratory measurements of intact anhydrite core from ERDA-6 and WIPP-12. Although the porosity values have not been finalized, they are currently proposed to be treated as a distributed parameter with a range of 0.001 to 0.02. Average fracture porosity in the WIPP-12 reservoir is estimated by Popielak et al. (1983, pp. G-44 to G-48) to range from 0.004 to 0.011, and is similar in magnitude to the intact rock porosity. A fracture porosity of 0.008 was used by DOE in estimating reservoir pore volume.

Bulk rock compressibility is described in Freeze (1996c) as a distributed parameter with a mean of 1×10^{-10} Pa^{-1} and a range of 5×10^{-12} Pa^{-1} to 1×10^{-8} Pa^{-1}. These values were determined as a best estimate considering compressibilities for intact anhydrite computed from elastic theory, compressibilities determined from the results of borehole hydrologic tests in disturbed Salado halites, and literature values for the compressibility range typically associated with fractured rock.

Reservoir permeability is described in Freeze (1996b) as a distributed parameter with an expected value of 1.6×10^{-12} m^2 and a range of 2.0×10^{-15} m^2 to 1.6×10^{-10} m^2. The expected value was derived from a GTFM analysis of Flow Test 3 in WIPP-12 (Reeves et al. 1991, Appendix A). This was a long-term test and the results best represent the average permeability across the volume of the reservoir. Permeability and rock compressibility are strongly coupled in hydrologic test analysis. In a low-porosity medium, their product should be maintained approximately constant for accurately simulating flow from a specific source; however, their ratio should be maintained approximately constant for accurately simulating pressure fluctuations. The most accurate characterization of these parameters is considered to be that which best matches both pressure and flow fluctuations. Because the expected value of rock compressibility used in the GTFM analysis of 1×10^{-9} Pa^{-1} was decreased in the performance assessment to 1×10^{-10} Pa^{-1}, the expected value of permeability used in performance assessment was increased from

1.6×10^{-13} m^2, determined in the GTFM analysis, to 1.6×10^{-12} m^2 to maintain good estimates of fluid flow. The low end of the range of permeabilities was based on the lowest value obtained in flow tests in ERDA-6, and the high end was based on the near-field high permeability zone encountered in WIPP-12.

The pore volume of the WIPP-12 reservoir was estimated using rock compressibility and porosity data and pressure changes measured in response to reservoir flow. The uncertainty in the volume estimate is largely derived from the uncertainty in rock compressibility. Estimates of the WIPP-12 reservoir pore volume are presented by Larson and Freeze (1996) as ranging from 32,000 m^3 to 64,000,000 m^3. This estimate is based on the nearly four order of magnitude range in compressibility used in performance assessment, and an estimated anhydrite reservoir fracture porosity of 0.008. A WIPP-12 reservoir pore volume of 3,200,000 m^3 was estimated for the expected compressibility of 1×10^{-10} Pa^{-1}.

The pore volume of a potential brine reservoir beneath the WIPP disposal panels was estimated by Larson and Freeze (1996) to range from 32,000 m^3 to 160,000 m^3. The lower end of this range was based on the minimum pore volume estimated for the WIPP-12 reservoir. The upper end of this range was based on the size of a reservoir that would extend beyond the perimeter of the WIPP disposal area. Assuming that the anhydrite layer containing the WIPP-12 reservoir is from 7 m to 24 m thick (Reeves et al. 1991, p. 2-10) and is analogous to the hypothetical reservoir beneath the site, the radius of a circular reservoir with a pore volume of 160,000 m^3 would range from about 510 m to 950 m. Larger reservoirs would likely extend beyond the limits of the waste panels, which have a perimeter of about 600 m by 800 m. Based on regulatory guidance, DOE assumes that the waste panels are partially protected from drilling by active and passive institutional controls for 700 years after repository closure. The larger reservoirs would underlie areas that are not protected by such controls and are assumed to be partially depleted by exploratory drilling penetrations before drilling over the waste would occur. In view of this depletion, the larger reservoirs are not considered in performance assessment because a smaller, undepleted reservoir is considered by DOE to be more significant to performance assessment than a larger, partially depleted reservoir.

Exploration boreholes are assumed to occur both in the waste itself and in the surrounding waste panel walls and room pillars. The probability that a borehole will encounter pressurized Castile brine beneath the WIPP disposal area is tentatively assumed in the WIPP performance assessment to be 10%. This probability is primarily based on a geostatistical analysis of the spatial distribution of known Castile brine reservoirs in the Delaware Basin and on the assumption that because of the primarily vertical

orientation of known fractures in the Castile anhydrites, the potential exists that a vertical borehole could penetrate the area of a reservoir without intersecting conductive fractures and, therefore, without encountering significant brine flow. A discussion of the development of this probability is presented in the 23 May 1996 Draft CCA, Section 6.4.12.6, Probability of Intersecting a Brine Reservoir (DOE 1996, pp. 6-109 to 6-110).

Boreholes randomly selected to penetrate the waste panel area and encounter pressurized brine in the Castile are assumed to contribute to the depressurization of that reservoir. Depressurization is currently assumed by DOE to occur to the extent that the reservoir no longer affects the repository after two penetrations for the smallest reservoir size (32,000 m^3), ranging up to ten penetrations for the largest reservoir size (160,000 m^3). Boreholes penetrating the walls and pillars of the waste panel area are assumed to result in no waste release, but will contribute to reservoir depressurization if they are randomly determined to encounter pressurized brine.

Numerical simulations of short-term and long-term flow from a Castile brine reservoir into the repository, to units overlying the Salado, and to the ground surface are handled by the BRAGFLO-DBR and BRAGFLO codes for single or multiple intrusion scenarios. These codes have the capability to model two-phase brine and gas flow, and it is anticipated that this capability will be applied to Castile brine reservoirs. Short-term flow is addressed in the Direct Brine Release conceptual model, and long-term flow is addressed in the Exploration Borehole and Multiple Intrusions models.

3.16.2. Review of Criteria

3.16.2.1. Information Used to Develop the Conceptual Model

The Castile Formation and Brine Reservoir conceptual model draws heavily on the properties of the WIPP-12 brine reservoir in developing characteristics for the hypothetical reservoir that could be encountered beneath the WIPP waste panels. Information is also taken from other brine reservoirs within the Delaware Basin, with emphasis on the ERDA-6 reservoir. Details on the sources and use of this information are presented in Section 3.16.1. Use of Delaware Basin reservoir information and emphasis on the WIPP-12 and ERDA-6 reservoirs are appropriate because of the increased relevance of local information and the relative wealth and accuracy of data from the two specific sources.

3.16.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.16.1 and critically reviewed here. Most assumptions are reasonable and appropriate and include the conceptual hydrologic role of the Castile Formation (exclusive of the brine reservoirs), consideration of the WIPP-12 reservoir as analogous to the hypothetical reservoir beneath the WIPP disposal area, the concept of a brine reservoir as a heterogeneous, discontinuously fractured zone of limited extent within Castile anhydrites, two-phase treatment of reservoir flow, and the selected values for reservoir pressure and porosity.

Bulk rock compressibility data were developed from a variety of sources including elastic modulus values, disturbed Salado surrogates, and literature values. Although the high end of the range (1×10^{-8} Pa^{-1}) is considered appropriate, the low end of the range (5×10^{-12} Pa^{-1}) and the mean value (1×10^{-10} Pa^{-1}) may be unrealistically low. The mean and maximum permeability values used in the performance assessment were adjusted upward by an order of magnitude from the original GTFM analysis of WIPP-12 to compensate for an order of magnitude downward adjustment in the original value of rock compressibility. The result of these adjustments is to decrease the storage capacity, increase the permeability, and increase the maximum size of the potential reservoir underlying the site. The estimated minimum size of the WIPP-12 reservoir directly supports the performance assessment and remains unaffected by the decrease in the mean compressibility. Although the assumption of a lower mean compressibility for the brine reservoir is not fully supported, the effects of this assumption appear to be conservative and therefore acceptable.

The assumption that reservoirs with pore volumes greater than 160,000 m^3 can be ignored is not adequately supported. Although sufficiently large reservoirs would extend beyond the area assumed to be protected by institutional controls for 700 years after closure, and could be intersected and partially depressurized by exploratory boreholes before boreholes are drilled over the waste panels, no supporting studies of the effects of this scenario have been presented to the Panel.

The assumption that reservoirs will be depleted by two to ten penetrations by exploration boreholes is also not adequately supported. Although the concept of depletion is rational, no supporting studies of the effects of this scenario have been presented to the Panel.

The assumed 10% probability of encountering pressurized Castile brine in an exploratory borehole is based on a geostatistical analysis of reported brine encounters, consideration of the relationship of brine

reservoirs to geological features or processes, and on the assumption that not all boreholes penetrating through the area of a reservoir will necessarily encounter brine. The adequacy of the assumption that significant brine releases are routinely documented was checked with Paul Knautz, a geologist with the New Mexico Oil Conservation Division in Hobbs (telephone 505-393-6161). Mr. Knautz indicated his confidence that the reporting requirements for significant releases were met by the operators. He stated that when encountered with a brine reservoir, the operator must report brine volume and pressure by telephone, and must truck the brine to a proper disposal facility.

Although no documentation of the geostatistical analysis was available for Panel review, preliminary results were verbally presented by DOE. The value of the results of this analysis was seriously weakened by a lack of data in the vicinity of the WIPP. The validity of the spatial correlations relied on the assumption that the geologic conditions supporting reservoir development at the WIPP site were similar to those in areas where hydrocarbon exploration boreholes were numerous and where a number of brine reservoirs were encountered. Unfortunately, there is little direct evidence to support or refute this assumption, but regional trends support the hypothesis that the probability of encountering brine decreases to the west. The kriging results on which the estimate of probability of encounter would be based were sensitive to historic brine encounters. The single encounter near WIPP (at WIPP-12) changed the probability over the waste panels from near zero to about 8%. A second encounter could have an equally dramatic effect. Due to the lack of data and the consequent sensitivity of the estimated probability, little credibility can be assigned to either value.

The assumption that not all boreholes penetrating through the area of a reservoir will necessarily encounter brine is reasonable, given that fractures in the anhydrite reservoir rock appear to be predominantly sub-vertical. However, this assumption must be quantified to be of more than conceptual value to performance assessment, and no basis for such quantification, nor of the way in which this concept has been used in developing the final probability value, has been presented to the Panel.

The approach for estimating the probability of a brine encounter apparently does not quantitatively consider the TDEM geophysical results reported in Earth Technology Corporation 1988, which suggest the presence of brine pockets beneath the waste panels and provide an alternative, site-specific approach for estimating the probability of encounter. In considering the reported uncertainty of ±75 m in estimated depth from the geophysical results (Earth Technology Corporation 1988), Borns (1996) estimated the proportion of waste panel area underlain by a potential brine reservoir to range from 10% to 55%, with

an expected value of 25%. A similar study performed on an alternative contouring of the original TDEM data for the 1992 WIPP preliminary performance assessment (WIPP Performance Assessment Department 1992b) identified a maximum proportion of 40%. Although these values may be reduced by evidence that a borehole penetrating the area of a reservoir may not actually encounter pressurized brine, or discarded based on evidence that the geophysical results are quantitatively unreliable, such evidence has not been presented to the Panel.

3.16.2.3. Evaluation of Alternatives

Although the fundamental hydrological behavior of the Castile Formation and its brine reservoirs is conceptually sound, concerns have been identified in Section 3.16.2.2 regarding the manner in which the encounter of pressurized brine is handled in performance assessment. Three fundamental issues are identified for which alternatives may be considered. These are alternative limits on the maximum reservoir volume, alternative concepts for reservoir depletion, and alternative probabilities of encountering pressurized brine.

3.16.2.4. Uncertainties

Uncertainty in model results stems from uncertainties in the validity of the underlying theory and from uncertainties in the input data. Although the underlying theory is widely used in the petroleum industry for evaluating oil and gas reservoirs and provides the best currently available approach, the results must be considered approximate, as illustrated by the high degree of uncertainty in the results presented, for example, by Popielak et al. (1983) and Spiegler (1982). Uncertainties associated with specific input parameters and assumptions are more tractable to address, and the key uncertainties are associated with the three principle issues identified in Section 3.16.2.3. Uncertainty in the two-phase flow parameters used in the analysis cannot be addressed because the values of these parameters had not been selected at the time of this review (see CCA Table 6-yz, draft of 5/23/96).

The uncertainty associated with rock compressibility is approximately one order of magnitude. Although this parameter is coupled with permeability, as previously discussed, the uncertainty in permeability is approximately two orders of magnitude. Uncertainties in compressibility propagate through the calculations and affect the estimates of both the permeability of the hypothetical reservoir at the site and the volume of the WIPP-12 reservoir. Because the uncertainty in permeability is even greater than the uncertainty in compressibility, the consequences of the uncertainty in compressibility may not be significant to the overall performance assessment. Uncertainty in permeability may have a greater

consequence in overestimating or underestimating flow rates from the reservoir if flow rates are controlled by the reservoir rather than by the borehole dimensions or plugging materials. High degrees of uncertainty in the related parameters of compressibility, permeability, and reservoir volume are not readily avoidable and stem from the wide range of values these parameters can have and from limitations in the state-of-the-art in measuring them.

The consequences of assuming a relatively small maximum size for a hypothetical brine reservoir beneath the site are not known because modeling results are not available, but could result in underestimating the volume of brine that could potentially be released. Alternatively, the modeling results may show that the volume of brine released during the 44-hour flow period assumed by DOE is relatively insensitive to reservoir volume if the reservoir volume is significantly greater than the volume of brine released from the reservoir. In this event, larger reservoir sizes may have little effect on performance assessment.

An unrealistically low probability of encountering pressurized brine could lead to underestimating radionuclide releases resulting from flow from Castile brine reservoirs. The consequences of underestimating this probability would be identified in modeling results, which were not available for review by the Panel.

The consequences of overestimating reservoir depletions by boreholes that do not penetrate a waste panel would be to underestimate reservoir and repository releases by boreholes that do penetrate a waste panel. The issue of reservoir depletions is tied to reservoir volumes, compressibility values, reservoir sizes, and the probability of encounter. Changes in any of these parameters would require modifications throughout the conceptual model.

3.16.2.5. Adequacy of the Conceptual Model

The hydrologic aspects of the conceptual model for the Castile Formation and Brine Reservoirs are fundamentally sound, and the issues raised in the validity of model assumptions (Section 3.16.2.2) are associated with the details of its application. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.16.2.6. Adequacy of Application

The internal consistency of the conceptual model is adequate, based on the interdependence of expected or mean values of the parameters as described in Section 3.16.2.1. Although consideration could be given to correlating values during statistical sampling, such as permeability with compressibility, the uncertainties in these values is such that it would be difficult to judge whether any combination were totally unreasonable. The correlation of porosity and reservoir volume in BRAGFLO is considered to be an artifact of the fixed model cell volume and not a true parametric correlation based on conceptual model principles. The integration of the conceptual model with the BRAGFLO and BRAGFLO-DBR codes is addressed under the Exploration Borehole (Section 3.12), Multiple Intrusion (Section 3.17), and Direct Brine Release (Section 3.15) conceptual models.

3.16.2.7. Accuracy of Results

The data base calculations were spot-checked and found to be accurate. The parameter values were also checked against values estimated by other investigators (Popielak et al. 1983; Spiegler 1982; Reeves et al. 1991) and found to be acceptable, given the ranges of uncertainties in the input parameters. The accuracy of integration with the BRAGFLO and BRAGFLO-DBR codes is discussed in Sections 3.12, 3.17, and 3.15.

3.16.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain, pending resolution of the issues raised in Section 3.16.2.3. In summary, the following key assumptions have not been adequately supported in information provided to the Panel, nor do sensitivity studies appear to have been made.

- The basis for excluding larger, potentially depressurized brine reservoirs from performance assessment has not been adequately supported. Larger reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.
- The basis for the concept of reservoir depletion through previous borehole penetrations has not been adequately supported. Non-depleted reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.
- The expected probability of encountering pressurized brine beneath the waste panels has not been adequately supported, nor has the basis for apparently ignoring the quantitative value of site-specific geophysical data been presented. Unrealistically low probabilities of encountering brine may result in underestimating radionuclide releases.

3.16.2.9. Adequacy for Implementation

The Castile Formation and Brine Reservoir conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.16.2.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.16.2.10. Dissenting Views

There were no dissenting views for this model.

3.17. Multiple Intrusions

3.17.1. Model Description

The Multiple Intrusion conceptual model is an extension of the Exploration Borehole model that describes fluid flow between the repository and multiple exploratory boreholes penetrating a single waste panel. The borehole drilling methods and frequencies, borehole plugging, and plug degradation discussed in the Exploration Borehole model in Section 3.12 are the same for multiple intrusion boreholes. Short-term flow through unsealed boreholes is addressed in the Direct Brine Release conceptual model in Section 3.15. Other related conceptual models include Repository Fluid Flow, Castile Formation and Brine Reservoirs, Cuttings/Cavings, Spallings, and Actinide Transport in the Salado. The details of this model were still under development at the time of the peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 23 May 1996 Draft CCA, Sections 6.4.13.6 and 6.4.13.7 (DOE 1996, pp. 6-119 to 6-121), from verbal descriptions, and from the cited references.

The proscriptive requirements of 40 CFR 194 for exploration boreholes also apply to multiple intrusion boreholes. The focal point of the Multiple Intrusion model is the E1-E2 scenario (worst case), wherein more than one exploration borehole penetrates a waste panel and at least one of those boreholes also encounters pressurized brine in the underlying Castile Formation. However, the Multiple Intrusion model also addresses multiple intrusions by other combinations of boreholes.

Multiple intrusions are modeled by the same two-dimensional version of the BRAGFLO code used to model repository fluid flow and single borehole intrusions. Use of this model is supported by preliminary analysis of modeling results, indicating that liquid flow through the panel closure seal

between the isolated, single waste panel in the model and the "rest of the repository" is slow enough that each waste panel is effectively independent from the rest of the repository. Thus, for a multiple intrusion to occur, two or more boreholes must penetrate the same waste panel. Gas flow does occur between panels, and for this reason short-term releases are calculated separately. However, for long-term brine flow from a single waste panel, the BRAGFLO model is considered adequate. Because the panels behave independently, different configurations of boreholes may occur in different panels. The model computes releases from these configurations separately and adds them to estimate a total cumulative release.

To accommodate the limitation in the BRAGFLO model of being configured to represent only one borehole column, the boreholes are assumed to be drilled in a series of specific sequences, with shifts in material properties in the upper and lower parts of the single modeled borehole at specific times. Background information on the development and use of reference conditions and on borehole plug degradation assumptions is presented in Section 3.12. Because 90% of all deep boreholes are assumed by DOE to be of the E2 type (DOE 1996, p. 6-119), it is most probable that the first borehole to penetrate a waste panel will be of this type. The approach taken by DOE in analyzing multiple intrusions has therefore been built around this E2-E1 scenario, which occurs under the following assumptions.

The first borehole is assumed to be an E2 type that penetrates the waste panel 800 years after closure. At 1,000 years after closure the upper seal in this borehole fails and the borehole is filled with a material that has the properties of silty sand. At 2,000 years an E1 borehole penetrates a waste panel and encounters pressurized brine in the Castile. This borehole is assumed to be sealed with the two-plug configuration, the only configuration considered in performance assessment that allows flow to occur between a Castile brine reservoir and the waste panel (Section 3.12). At 2,000 years the properties of the modeled borehole column below the repository are changed to represent an open borehole, while the properties of the borehole column above the repository are unchanged and continue to represent the long-term properties of the earlier E2 borehole for the duration of the modeling. At 2,200 years the upper plug in the E1 borehole fails and the properties of the borehole below the repository are changed to those of silty sand. At 3,200 years the permeability of the borehole below the repository is reduced by one order of magnitude to represent the effects of pore volume reduction due to creep closure. No further changes in material properties occur for the duration of the modeling.

The aforementioned series of assumptions is valid given DOE's plug degradation assumptions, with the exception that after 2,200 years the upper plugs in both the E2 and E1 boreholes have failed and two pathways, rather than one, are available for brine migration to the Culebra. The assumption that only one of these two pathways conducts flow in this scenario is considered by DOE to be consistent with the assumption of complete mixing of brines within the waste panel, which requires that flow from the brine reservoir in the E1 borehole pass through the waste panel and exit through the E2 borehole, rather than through the upper part of the E1 borehole. However, multiple borehole pathways to the Culebra are included in scenarios involving multiple E1 boreholes because flow through the repository and consequent mixing can then occur among multiple boreholes.

The foregoing scenario of an E2, followed by an E1, establishes the basis for determining a standard reference cumulative radionuclide release to the Culebra, assuming an E2 borehole drilled at 800 years is followed by an E1 borehole drilled at 2,000 years. In this drilling sequence the rate of release jumps dramatically at 2,000 years because of pressurized brine flowing from the Castile reservoir. In an actual scenario the randomly selected drilling dates for these two boreholes are likely to be different. In that event, the cumulative release is calculated using the release rate from a single E2 borehole (Section 3.12) up to the date of the E1 penetration, and then applying the reference release rate starting at the time of E1 penetration in the standard E2-E1 scenario to approximate the jump in release rate that would occur at the actual date that the E1 borehole is drilled. In this approach, the brine fluxes after penetration by an E1 borehole are those occurring at the 2,000 year date of penetration assumed in the standard E2-E1 scenario, rather than the fluxes that would have been modeled at the actual date of penetration; however, the radionuclide releases associated with those fluxes are corrected for radionuclide decay and progeny production.

If the first two boreholes are randomly selected to penetrate the waste panel in a different sequence, the following rules for determining reference conditions for long-term flow are applied.

Radionuclide transport is modeled by the NUTS code for single borehole intrusions and by the PANEL code for multiple intrusions (Section 3.8). While the NUTS code is directly coupled to BRAGFLO and uses BRAGFLO's computed velocity field vectors, PANEL is a separate model that conservatively assumes complete mixing in the waste panel. PANEL is used when two or more boreholes penetrate a panel and at least one of those boreholes is an E1 type. In applying the PANEL code, the multiple

intrusions are implicitly assumed to occur in different parts of the waste panel so that cross borehole flow and mixing will occur. The PANEL code is used for transport calculations in the standard E2-E1 scenario, and use of that scenario for multiple borehole intrusions is conservative.

Table 3.17.1. Rules for Determining Reference Conditions for Long-Term Flow

Sequence of First Two Boreholes	Basis for Brine Flux	Basis for Radionuclide Transport
E2 followed by E1	Single E2 flux followed by E2-E1 flux at time of E1 penetration	Single E2 transport followed by E2-E1 transport at time of E1 penetration
E1 followed by E2	Single E1 flux followed by E2-E1 flux at time of E2 penetration	Single E1 transport followed by E2-E1 transport at time of E2 penetration
E1 followed by E1	Single E1 flux plus E2-E1 flux at time of second E1 penetration	Single E1 transport plus E2-E1 transport at time of second E1 penetration
E2 followed by E2	Single E2 flux	Single E2 transport

The first two borehole sequences in the foregoing tabulation (E2 followed by E1 and E1 followed by E2) both assume sequential calculation of flux and transport by jumping from single borehole behavior to E2-E1 behavior at the time of the second penetration. The sequence of two E1s, however, is treated by adding the E2-E1 flux and transport to the single E1 flux and transport, beginning at the time of the second E1 penetration, because flow from two brine reservoir penetrations can circulate and mix within the repository and leave through two boreholes to the Culebra. As previously mentioned, in cases where there is only a single E1 penetration, the brine is considered by DOE to be more likely to circulate within the repository, adequately mix, and then leave only through the E2 borehole to the Culebra. In cases of two E2 penetrations, long-term brine release volume is assumed to be the same as for a single E2 penetration because flow will be controlled by the rate at which brine can be supplied by the Salado halites, rather than the rate at which brine can flow in the borehole. In cases where at least one of the boreholes previously penetrating the panel is an E1 and an additional E1 is added, additional E2-E1 flux and transport values are added to the cumulative release. In cases where none of the boreholes previously penetrating the panel is an E1 and an additional E1 is added, the flux and transport sequentially shift to the E2-E1 values. However, if only E2 boreholes are present, additional E2 boreholes do not increase the flux and transport rates. In all cases, adjustments are made for radioactive decay and progeny generation to account for the times of waste panel penetration in the cumulative releases.

3.17.2. Review of Criteria

3.17.2.1. Information Used to Develop the Conceptual Model

The information used to develop the Multiple Intrusion model is essentially the same as that used to develop the Exploration Borehole and Repository Fluid Flow models. The Multiple Intrusion conceptual model becomes active at the time that two or more boreholes are randomly selected to penetrate a single waste panel. Alternative reference conditions, repository mixing, and transport models are employed for the Multiple Intrusion model, as described in Section 3.17.1. The information used to develop the conceptual model is reasonable and appropriate.

3.17.2.2. Validity of Model Assumptions

The principal assumptions used to develop the Multiple Intrusion model are identified in Section 3.17.1 and are critically reviewed here. Assumptions related to borehole drilling methods and frequencies, borehole plugging, and plug degradation are the same as those reviewed for the Exploration Borehole model in Section 3.12. The principal assumptions specific to the Multiple Intrusion model are reasonable and appropriate for performance assessment applications and include use of the two-dimensional BRAGFLO model for this application, the somewhat gymnastic but conservative assumptions made to accommodate the single borehole column in the model, and the mixing assumptions in the model.

The assumption that only a single borehole conducts brine to the Culebra in an E2-E1 scenario is troublesome; however, the potentially nonconservative nature of this assumption is compensated by the highly conservative assumption of complete mixing of Castile brine with waste panel brine. In reality, the Castile brine would flow through the waste panel to the exit borehole by preferentially following high conductivity flowpaths with relatively little volume compared with the waste panel pore volume, and consequently with relatively little mixing. Even less mixing would occur in brine flowing from the E1 in the bottom of the waste panel and out the same E1 through the top of the waste panel.

The use of reference conditions, rather than direct model results, as the final input has been handled in a relatively conservative manner. The appropriateness of assuming that the flux associated with the E1 penetration at 2,000 years in the standard E2-E1 reference case is representative of the flux into an E1 penetration at other times has not yet been directly supported by sensitivity studies using current performance assessment calculations, but by analogy to the results of such studies performed for the

1991 draft performance assessment, such an assumption is expected to be appropriately conservative (Helton et al. 1992, Chapter 4).

3.17.2.3. Evaluation of Alternatives

The approach taken to address multiple intrusions in performance assessment is reasonable and appropriate considering the complexity of addressing the many possible scenarios in an efficient manner. Further investigation into the approaches taken have indicated that they are adequate and that no alternative approaches are required. However, the validity of the current approach is based on acceptance of DOE's assumptions regarding borehole plug degradation rates. These assumptions were questioned in Section 3.12, and if those assumptions are changed, many of the basic assumptions used in the Multiple Intrusions model should also be changed. For example, if plug degradation allows fluid to flow into the waste panel from the Bell Canyon Formation through an E2 borehole, the significance of the E2 borehole in performance assessment will become more like that of an E1.

3.17.2.4. Uncertainties

The principal uncertainties in model results stem from the same types of issues that were raised for the Exploration Borehole model and are addressed in Section 3.12.2.4. No additional significant uncertainties have been identified that are specific to the Multiple Intrusions model.

3.17.2.5. Adequacy of the Conceptual Model

The conceptual model for multiple intrusions is fundamentally sound and appropriately conservative, given the simplifications that are required to model a complex set of conditions in an efficient manner.

3.17.2.6. Adequacy of Application

The application of the conceptual model to the numerical model is adequate, again given the simplifications that are required to model a complex set of conditions in an efficient manner.

3.17.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. The modeling results were not available for review and could not be checked.

3.17.2.8. Validity of Conclusions

The validity of the conceptual model is expected to be adequate for performance assessment; however, modeling results have not been observed by the Panel and have not been checked through sensitivity studies similar to those used in previous performance assessments. Many of the modeling assumptions were based on borehole plug degradation assumptions whose validity was questioned in Section 3.12. If those assumptions are changed, many of the basic assumptions used in the Multiple Intrusion model would be questioned.

3.17.2.9. Adequacy for Implementation

The Multiple Intrusion conceptual model is adequate for implementation in performance assessment. However, the results of the model have not been checked by the Panel because sensitivity studies similar to those used in previous performance assessments have not yet been performed.

3.17.2.10. Dissenting Views

There were no dissenting views for this model.

3.18. Climate Change

3.18.1. Model Description

The long periods of time over which the isolation of radioactive waste must be considered stimulates concern over climatic cycles and occurrences that may impact the long-term performance of the disposal system. The Climate Change conceptual model provides quantitative consideration about the degree to which future climates may contribute to the uncertainty of estimates of potential radionuclide releases from the WIPP repository. The model does not attempt to predict or simulate a future climate, but intends to implement climate change effects into the performance assessment through a parameter named the Climate Index.

The formulation of the conceptual model for climate change (Climate Index) began with the screening out of the direct effects of climate change that do not involve groundwater. Factors such as wind patterns and thermal effects do not impact the WIPP due to its depth below the ground surface. Additional aspects of climate change were eliminated through the FEP screening process and the conceptualization

of climate change impacts focused on reasonably foreseeable events and the effects of these events on groundwater flow.

A three-dimensional regional groundwater basin model (Corbet and Wallace 1993) was employed to assist in characterizing the natural hydrogeologic processes as they could occur over geologically significant periods of time in the Delaware Basin. The model was bounded on the bottom by "impermeable" rock, on the top by the ground surface, and on the sides by groundwater divides. The upper boundary of the flow domain is the water table and differences in the elevation of the water table across the basin are assumed to be the driving force for groundwater flow. Other notable but standard assumptions are stratigraphic homogeneity and ignoring the unsaturated zone with respect to timing of infiltration (dry to wet periods). The results suggest that flow in the Culebra Dolomite Member of the Rustler Formation is strongly influenced by the water table elevation and the infiltration (recharge) rates associated with that elevation. Infiltration was varied as a step-function of average amounts of moisture reaching the water table. The model results indicated that changes in infiltration rates of tenths of a millimeter per year had significant impacts on flows in the Culebra. The basin modeling and later analyses (Corbet 1996b) approximated recharge rates that maintained the water table at or near the ground surface (maximum recharge situation) and the relationships between the various recharge rates and lateral-flow ratios. The assigned distributions of lateral-flow ratios became the Climate Index. The Climate Index is therefore a factor by which the lateral flow rate in the Culebra is uniformly increased to account for increases in recharge rates.

Two future climate or recharge patterns were evaluated: the step recharge function, with a 0.25 probability of representing the future, and the Holocene recharge function, with a 0.75 probability of occurring. The step recharge function (similar concept to Corbet and Wallace 1993), which represents a steady increase in heads and recharge rates into the future with the lateral-flow ratio reaching its maximum in 10,000 years, is assigned Climate Index values of 1.5 to 2.25. The Holocene pattern of future recharge results in periodic increases and decreases in heads and recharge rates that are assigned Climate Index values of 1.0 to 1.25. These two Climate Index ranges are sampled during each realization of disposal system performance, with each realization representing a different approximation of future climate.

3.18.2. Review of Criteria

3.18.2.1. Information Used to Develop the Conceptual Model

An extensive reference list supports the process of formulating the conceptual model for climate change. Wood (1994) and Campbell (1995) include isotopic quantification of recharge flux, and Corbet and Wallace (1993), Knupp (1995), and Wallace (1994) address groundwater modeling and hydraulic test interpretation. Swift (1992) and Powers (1990) discuss and include additional references on sedimentology, regional geology and geologic history, long-term climate variability, and climatic records. In addition to references used in conceptualizing climatic change at the WIPP, EPA criteria and guidance (EPA 1996), FEP screening references, performance assessment documentation, and evaluation of groundwater flow models developed in support of climate change conceptual model formulation document in detail the data and information used. Documents and reports produced internally to summarize studies and present results of studies relevant to the WIPP performance assessment (e.g., SAND Reports, professional society papers, DOE-WIPP, FEP, memos) were extremely valuable as they summarized data used and explained concepts applied. The information used to develop the conceptual model for climate change is extensive, referenced, available for review, and adequate.

3.18.2.2. Validity of Model Assumptions

The conceptual model for evaluating the effects of future climate change on the long-term performance of the WIPP began with a detailed examination of a great deal of literature, evolved through an understanding of past changes and situations/conditions of future change, and is now implemented through a dimensionless index that is used to change groundwater flow velocity in the Culebra Dolomite. The relationships between climatic extremes and such parameters as temperature, wind, precipitation, evapotranspiration, and vegetation cover have been researched, and the impacts of such factors on recharge have been evaluated. Since recharge impacts groundwater flow and flow characteristics are required by EPA for a compliance application, the Climate Change conceptual model formulation focused on evaluating the effects of climate change on flow characteristics of the Culebra Dolomite and Dewey Lakes Redbeds. After screening was completed (Corbet 1995a), effects evaluations were limited to the Culebra Dolomite. An extensive list of assumptions would be required to cover all of the modeling and evaluations conducted to represent real events and related climatic factors. The conceptual model for climate change assumes to represent ranges of conditions that are not related to specific events or the interactions between climatic factors, but represent reasonable extremes of potential future climates.

In addition to assuming that the climate will change over the next 10,000 years, the conceptual model of climate change assumes that periods of maximum precipitation are also periods of maximum recharge and that during such maximum situations, recharge is sufficient to maintain the water table at the land surface. A supporting (or bounding) assumption is that recharge in the late Pleistocene was sufficient to maintain the water table at the land surface. The conceptual model assumes that the range of recharge rates (0.1 to 5.0 mm/yr) represents the appropriate range of hydrologic conditions and the Climate Index factor distributions represent these conditions appropriately. A key assumption that is not clearly within the conceptual model or its implementation concerns representing three-dimensional flow in the Rustler Formation with a two-dimensional model of the Culebra Dolomite.

To invalidate the assumption that climate change will occur would require an assumption that the climate will remain constant for 10,000 years. This invalidating assumption would be inconsistent with the scientific view of climate. The assumptions of maximum precipitation/maximum recharge and that recharge could be sufficient to maintain the water table at the land surface are defensible, but not unconditionally validated as representative of a future extreme climate. These assumptions are supported by interpretations of sedimentary records (Swift 1992), isotopic analyses (Campbell 1995 and Wood 1994), paleo-environmental records, and other evaluations that estimate the characteristics of groundwater during varying climates. The assumed range of recharge rates is supported by isotopic recharge dating and rate estimation. The support documentation for the two-dimensional assumption is FEP NS-9 (Corbet 1995b).

The Panel members conclude that the main objectives of the conceptual model for climate change at this time are to incorporate uncertainty about the effects of future climates into the performance assessment and meet EPA expectations with regard to the effects of climate change on hydrological conditions and future state assumptions. Since the range of recharge rates represents the reasonable extremes of potential future climates and the climate index carries the representation into the implementation, the assumptions are valid in terms of the usefulness of the conceptual model, as is the Climate Index.

3.18.2.3. Evaluation of Alternatives

The conceptual model for representing the effects of climate change on the WIPP is a result of an evolution of thought requiring the characterization of climatic factors and simulating their effects. While interest in the possible effects of climate change has, historically, been in terms of recharge and groundwater, early interest considered increased rates of salt dissolution, fracture filling in the Culebra

and changes in groundwater flow direction. Early assessments of system performance did not consider that climate change could alter the transport of radionuclides in groundwater. Later performance assessments considered transport effects but as a function of head change. Sensitivity analyses conducted for the 1991 and 1992 preliminary performance assessments determined that cumulative radionuclide releases were not sensitive to head variation as applied, and the boundary-head approach was abandoned.

Alternative approaches to the characterization of climatic effects on groundwater and modeling groundwater flow have been considered and ruled out for conceptual and technical reasons. Alternatives to representing the factors of climate change have also been considered, ruled out during analyses, and screened out through the FEP screening process. In many cases, alternative approaches that attempted to closely relate climatic factors to hydrogeologic effects introduced additional uncertainty, and could have made the overall conceptual approach less defensible. The 1996 EPA guidance presented recommendations for the consideration of future climates in a compliance application. The guidance focuses considerations on natural processes, potential impacts to recharge, and groundwater flow, and indicates that effects on hydrogeologic conditions are expected to be analyzed and demonstrated in compliance and performance assessments. The selection of the Climate Index to implement the effects of climate change through direct scaling of groundwater velocity in the Culebra allows for the uncertainty of effects of future climates to be incorporated into the performance assessment. Multiple realizations provide for a representative range of future climate effects to be included in disposal system performance.

3.18.2.4. Uncertainties

Many obvious uncertainties accompany the interpretation of the magnitude and temporal aspects of historical climatic factors and the representation of such factors at the WIPP site 10,000 years into the future. The uncertainties are less overwhelming when climates are limited to those reasonably foreseeable, and the absolute timing of alternative climates is of less importance than the range of magnitude of the relevant climatic or climate-induced factors.

A primary objective of the Climate Change conceptual model is to incorporate uncertainty about future climates and their potential impacts on radionuclide releases from the disposal system. The conceptual model for climate change is implemented through a single parameter index that scales groundwater flow

in the Culebra Dolomite. Key uncertainties concern whether or not climate will change, if index values represent the appropriate range of changes, and whether or not implementation realizations sample the index in a manner representative of the range of climate change.

The uncertainties related to whether or not climate will change and the representativeness of index values are a result of predictions, analyses that are imprecise, and conclusions about the future based only on the past. While these uncertainties remain, the conservative assumption for performance assessment is that the climate will change, including periods of both drier and wetter conditions. The only relevant uncertainty with respect to the index is whether or not reasonably foreseeable climates are represented by the range of index values. It is the intent of the index to be bounded by the wet extreme of the Pleistocene glaciation and by another climate where there is little or no climatic effect on groundwater flow. Panel members conclude that significant scientific effort has been expended to characterize the periods bounding the index value and relate relevant climatic factors to the index, and that the index is appropriately conceptualized. Uncertainty with respect to implementation of the climate change model cannot be completely addressed by panel members since a detailed analysis of the implementation models and computational scheme is not within the scope of this review. However, even though climate change preliminary calculations resulted in relatively small increases in flow rates, decreased travel times had a large impact on normalized radionuclide releases under certain conditions (calculations performed for the 1992 performance assessment) (Corbet 1995a). Based on the potentially large consequence demonstrated, climate change has been tentatively retained for inclusion in performance assessment calculations.

3.18.2.5. Adequacy of the Conceptual Model

The climate change conceptual model represents a reasonable and defensible range of potential future climate extremes for incorporation into the performance assessment. The conceptual model includes a range of conditions, bounded by reasonably foreseeable future climates and their effects, that are adequate to represent impacts to groundwater flows in the Culebra Dolomite Member of the Rustler Formation. In addition to providing adequate representation of conditions for implementation, the background research and analysis supporting the formulation of the conceptual model for climate change provides adequate information for satisfying EPA guidance.

3.18.2.6. Adequacy of Application

The conceptual model for climate change is implemented through the Climate Index. This index is a dimensionless factor through which direct scaling of specific discharge for the Culebra Dolomite is accomplished in the SECOFL2D code (Section 4.1). The range of sampled index values available for realization of disposal system performance has been verified through modeling to represent the range of recharge impacts that reasonably foreseeable future climates would create. As such, the conceptual model is implemented through an acceptable and adequate performance modeling element.

The conceptual model for climate change is compatible with the closely related model of the steady-state groundwater velocity field for the Culebra, which it directly scales through the index. The relationship is simple and should be adequate for its intended use, assuming that the implementing computational scheme operates as designed.

3.18.2.7. Accuracy of Results

Model formulation results, as well as model application/implementation results, must be reviewed in assessing the overall accuracy of results for the conceptual model for climate change. The accuracy of model formulation results is judged on how well descriptions and descriptive write-ups present the conceptual model. In the case of the climate change model, background research and analysis, history of model development, screening and verification, descriptions of model parameters, assumptions, and an implementation scheme were available. Panel members were required to consult numerous sources for a comprehensive description of the conceptual model but, overall, the model formulation results were judged accurate.

As discussed in Section 3.18.2.6, the application or implementation of the conceptual model for climate change is conducted with the Climate Index. This dimensionless factor is sampled over its distribution and represented by direct scaling of the steady-state groundwater velocity field in SECOFL2D for the Culebra Dolomite. For performance assessment realizations of disposal system performance, each realization represents the effect of a different climate. The model is judged as capable of producing accurate results through implementation if realizations of disposal system performance adequately represent the range of future climates available within the distribution of the index.

While the scope of this conceptual model review did not include verification of realization computations, a single CCDF calculated to address FEP NS-8b had interesting results. The FEP NS-8b, summary

memo of record (SMOR) of 21 September 1995, stated that on the basis of relatively small increases in flow rates expected from including climate change in the performance assessment modeling system, and the associated low consequence of omitting the factor, climate change could be screened out. The SMOR also presented that a single CCDF calculated to address the FEP illustrated that screening out climate change would not be of low consequence. The CCDF illustrated that velocity fields that decreased travel times (increased flow rates) by a factor of 2 resulted in three orders of magnitude increases in releases for release probabilities less than 0.1. The reason for the large impact was not clear, but this quantitative evaluation of the climate change subsystem resulted in the retention of climate change for inclusion in future performance assessment calculations. While the quantitative subsystem evaluation did not prove the accuracy of implementation of the conceptual model, it is indicative and supportive of performance assessment sensitivity.

3.18.2.8. Validity of Conclusions

The results of the implementation of the conceptual model for climate change are the representation of the effects of a reasonably foreseeable range of future climates within realizations of disposal system performance. While Panel members found no documentation of the results of the application of the Climate Index in disposal system-scale performance assessment calculations or conclusions drawn, the FEP screening process (Corbet 1995a) SMOR addressed a quantitative analysis. The SMOR, discussed in Section 3.18.2.7, presents that the results of the quantitative evaluation stimulated the conclusion to retain climate change for inclusion in future performance assessment calculations.

The evaluation presented in the SMOR could not support conclusions to the degree possible from results of disposal system-scale performance assessment calculations and sensitivity analyses. In the absence of results from repository/disposal system-scale realizations and sensitivity analyses, no definitive, valid conclusions can be made. However, the evaluation at the subsystem level did support conceptual model sensitivity and uncertainty assessment and a valid conclusion was drawn on the basis of results of the evaluation.

3.18.2.9. Adequacy for Implementation

The conceptual model for climate change, as discussed in Sections 3.18.2.1 through 3.18.2.8 and defined for implementation by the Climate Index, is adequate for implementation. The Climate Index is capable of representing uncertainty about future climates and their potential impacts on disposal system

performance. While the conceptual model has been judged adequate for implementation, the mathematical representations in the computer code have not been reviewed and no conclusions can be made as to the overall adequacy of the applications/implementations.

3.18.2.10. Dissenting Views

There are no dissenting views for this model.

3.19. Creep Closure

3.19.1. Model Description

The Creep Closure model is part of a complex of submodels that are combined to effect the porosity surface lookup table. This table combines gas pressure, room closure, and waste compaction to pre-calculate repository void space for inclusion in several other performance assessment models. The Creep Closure model is reviewed here and other aspects of the porosity surface are discussed in support of that review. The Creep Closure model has a complex history of development, which extends into the period of review. The generic creep model impacts both the room closure and the development of the DRZ surrounding the repository openings. The DRZ models are discussed elsewhere.

Closure of the repository occurs naturally in the Salado halite as a response to the imbalance of forces created by excavation of the repository rooms and passages. Weak and plastic rock salt begins immediately to flow into the excavated spaces by processes dominated by creep. The rate of closure is the combined result of creep rates inherent to salt, repository temperatures and pressures, and resistance provided by repository contents. The creep rate proceeds to the limits determined by resistance from gas, brine, waste, backfill, or other contents in the repository until the void space is closed to the final porosity dictated by waste and seal material properties, contained fluid pressure, and lithostatic pressure. Roof fall in the disposal rooms, which may have significant impact on flow at least in the short term, is not included in the model.

Both brine and gas content of the repository vary with time. Brine inflow/outflow is partly controlled by gas pressures. The relationship between gas outflow rates and gas generation rates influences pressures within the repository. Gas pressure results from the alteration of waste by biogenic and corrosion-based processes. The rate of the corrosion process is dependent on brine availability. Repository gas and brine pressures are limited by the minimum pressures at which gas or brine would be forced out of the

repository via identified flowpaths through fractured interbeds within the Salado. The threshold pressures for initiation of outflow through these fractured anhydrite interbeds are therefore a key consideration in limiting resistance to closure due to gas and brine pressures. The fractures in the interbeds are essentially horizontal, so the pressures necessary to open the fractures or to initiate new fractures must be greater than the lithostatic load. Further, some resistance to gas release may result from travel through the fractured, rock-bolted halite between the repository and the interbeds. Resistance to gas outflow due to stress cage effects at the repository boundary and gas pressures necessary to maintain very extensive fractures may result in repository pressures larger than interbed threshold pressures. Gas pressures, which are some amount greater than the lithostatic pressure, are therefore possible at some times during the repository gas generation history. Internal gas pressures greater than the stress imbalance that drives creep inflow are conceivable. Internal pressures may contravene stresses in the salt and repository closure may cease, or repository inflation may occur in some scenarios. The stoichiometric treatment of time histories of gas generation and the volumetric model based on creep closure rates and waste compaction are combined in the SANTOS computer code to provide repository void volume estimates through time as part of lookup tables called the "porosity surface."

In the present WIPP performance assessment calculations (using BRAGFLO), the details of the mechanics of disposal room closure and/or eventual expansion are not explicitly calculated. Instead, the room-rock system behavior is obtained from the porosity surface. In this table, the three dimensions are time, total room porosity, and mass of gas in the room. The porosity surface is itself calculated prior to the BRAGFLO runs using the SANTOS code. This procedure is followed to avoid the massive computational effort that would be required to fully calculate (in an iterative sense) the mechanics of room closure for each performance assessment realization. At first, this may seem to be an invalid decoupling of the external environment and the disposal room. However, if the room porosity can be shown to be described with sufficient accuracy as a variable dependent only on time and gas mass (which is itself dependent only on time in the current model), then this approach is quite justified in view of its simplicity and efficiency. Note that brine content of the room is not mentioned at this point, nor are there any brine parameters on the porosity surface parameter list. This is a consequence of the calculation method and interaction with BRAGFLO, and is discussed below.

The porosity surface calculations using SANTOS are described by Stone (1996). The main features of these plane-strain calculations are a simplified stratigraphic model with boundaries at 50 m from the disposal room, the inclusion of the main clean halite and argillaceous halite layers, and the inclusion of

the two anhydrite layers of influence (MB 139 below and anhydrite a above), but no clay seams. The waste drums are lumped into a single rectangular mass, bounded by slip surfaces, that correctly reproduces the initial porosity and density. The simplified geometry used (as compared to the reference stratigraphy) is justified in Stone (1996), with supporting calculations given by Osnes and Lebreche (1995). In justifying the simplification, it is shown that including two types of salt and the anhydrite beds are necessary to provide the model sensitivity needed to support observations, but that the clay seams and additional complexities do not contribute. Thus, only halite and anhydrite properties are included as material properties in the parameters listed for the porosity surface. No roof failure of the room is considered in the porosity surface calculations. The porosity surface and its parameters have also been discussed in Butcher (1996), and Butcher et al. (1995).

The first full explanation of the porosity surface and its justification of use appears in Butcher and Mendenhall (1993). Since the pressure in the room depends on the amount of gas and the room pore volume, and this pressure creates the "back stress" resisting closure, the porosity surface can uniquely represent the room behavior if the relationship between gas volume and time is known. Since that relationship is specified (by corrosion rates and/or intrusion scenarios) the porosity surface can be used as prescribed.

A complication occurs, however, when brine is allowed to flow into or out of the room. Then, the porosity evaluated from the porosity surface must be treated as the gas-filled porosity and added to the brine-filled porosity to become the total porosity required in the performance assessment calculations using BRAGFLO. Furthermore, BRAGFLO, which is a fluid flow code, must be used to provide the brine content of the room for this iterative calculation. This coupling is only valid if the fluid flow is slow, which is a good assumption in the case of WIPP. Also, it must be assumed that the brine pressure is the same as the gas pressure within the room, which is true for high waste permeability.

The resistance to closure resulting from the compaction and consolidation of backfill and waste is based on empirical relationships derived from experimental studies. Some experimental laboratory and *in situ* experiments on crushed salt compaction for shaft sealing studies may provide definitive property assessments for backfill, although the final makeup or certainty of use of backfill materials is not known at this time. Limited experiments involving the compaction of waste-filled drums and simulated waste provide the basis for empirical estimates of waste behavior. The variable nature of waste form and

inventory lends a large uncertainty to the definition of waste physical behavior. The models of waste properties and mechanical behavior are reviewed elsewhere in this document.

The volumetric plasticity model has evolved significantly since it was proposed in its initial form by Kreig (1984). This formulation consisted of a synthesis of published empirical creep constitutive models, the geometry of material distribution, a calculated initial stress condition, and a set of creep constitutive properties derived from laboratory creep tests at SNL. Morgan et al. (1985) applied this initial formulation of the model to closure records from the south drift and found that it significantly under-predicted closure rates. Sjaardema and Kreig (1987) proposed that the characterization of Young's Modulus was the source of error in the initial model. They suggested an empirically derived reduction (division) of Young's Modulus by 12.5, which improved the performance of predictive calculations based on the model to satisfactory levels for use in crushed salt compaction tests for seals and subsequent closure observations. This model has been called the Reduced Modulus (RM) model in subsequent work.

Munson et al. (1989, 1991) undertook to resolve the empirically altered model with a "first principles" model derived from a set of more process-based rock mechanics theories. He demonstrated that a reliance on Von Mise's flow rule was less appropriate than that of Tresca, revised salt property estimates based on elimination of excavation strain from laboratory results, reevaluated creep parameters for argillaceous salt, added a term for primary creep, and improved the micro-mechanical creep models. These modifications enabled the steady-state creep response model (the MD model) to match observed closure rates at WIPP within 10%.

As it is presently formulated, the MD model does not include a treatment of the tertiary creep domain. Tertiary creep may be characterized as an acceleration in creep strain rate, accompanied by extensive microfracture, leading to macrofracture and failure. Chan (1996) has developed an amended version of the model (MDCF model), which includes tertiary creep for prediction of the formation of a DRZ around repository openings. The room closure model does not include tertiary creep on the grounds that all of the acceleration of strain (above the steady state rate) is due to microfracture and is recovered during the final stages of room closure due to DRZ healing. This concept is part of a larger concept called the conservation of void space. Because of void space conservation, no increase of gas pressure in the repository is attributed to this increase of strain rate.

The conservation of void space is only partly proven (experimentally or observationally) and is largely based on theoretical assumptions. In the case of tertiary creep of salt, the primary assumption is that all of the acceleration in strain rate during tertiary creep results from the onset of microfracture generation caused by the accumulation of intracrystalline lattice damage. The accumulation of lattice damage within individual crystals often results in work hardening and the elevated local stress levels may result in the initiation of strain by a "new" mechanism or mechanisms. However, no clear evidence exists that fracture is not accompanied by an undefined intracrystalline micromechanism, which may account for part of the change in the tertiary creep rate. The concept of continuation of unchanged steady state creep by micromechanisms that are unaffected by the damage accumulation to which the onset of fracture is attributed, seems incompatible. A more complex micromechanical model, which might include some acceleration due to non-fracture (plastic) processes, is not ruled out by any of the evidence. None of the closure observations at the WIPP occur over periods of time long enough to encompass the complete creep cycle observed in other salt mines.

Munson et al. (1995) estimates that only about 3% of the total creep strain is attributable to tertiary creep. The MD model matches short-term steady-state creep rates to within approximately 10%. If all or some part of the tertiary creep is not attributable to recoverable microfracture, the MD model may only be able to predict long-term closure rates to about 13% at best. Associated gas pressure changes through the porosity surface calculation are impacted by the inherent uncertainty in closure rates represented by the creep closure model predictions.

3.19.2. Review of Criteria

The room closure model includes the creep closure model (MD), the porosity surface lookup table, and interaction with BRAGFLO to iteratively specify brine inflow volumes. The porosity surface is constructed within the SANTOS model and consists primarily of creep closure, waste compaction, and gas pressure to estimate repository void space versus time. This review concentrates on the adequacy of the creep model (MD) with reference to the other associated models (e.g., BRAGFLO, SANTOS, porosity surface, gas generation) only as necessary to evaluate uncertainties.

3.19.2.1. Information Used to Develop the Conceptual Model

The initial version of the creep closure model was developed from published creep constitutive relationships and rock salt properties from intact rock salt deformation experiments at the SNL Rock

Mechanics Laboratory. The model was revised on the basis of short-term measurement of closure rates when the WIPP experimental rooms were opened. Both empirical revisions of elastic constants, based on closure rates, and revisions to the constitutive model, based on refinement of the understanding of deformation processes and flow rules, contributed to the development of later versions of the model.

Resistance to room closure (backstress) is the result of brine and gas pressure in the repository and of the strength of waste and backfill. Gas pressures used in the model are the result of the interplay between the time history of gas generation, the time history of void volume due to salt creep, and the threshold pressures governing gas outflow along the fractured anhydrite interbeds. Brine inflow is partially controlled by gas pressures. Repository pressure is modeled by an interplay between BRAGFLO and SANTOS, and interactions between gas pressure and creep are presented in the lookup table called porosity surface. Gas generation and brine inflow information are the product of other models. Threshold pressures for gas outflow in the interbeds are taken from packer tests of those horizons (Salado model). Strength of salt backfill is available from extensive experimental work done for the shafts and seals model. Waste strength may be the most uncertain type of information used in modeling room closure. Some experimental waste compaction has been done, but variation in waste form and inventory may make the characterization of waste physical properties highly variable. The creep closure model depends on the waste to resist closure and suppress rockfall and also contributes to the generation of an estimate of final waste porosity for waste dissolution estimates.

3.19.2.2. Validity of Model Assumptions

With the exceptions of the creep model, most of the assumptions in the global room closure conceptual model, as represented by the porosity surface calculation, are discussed in the consideration of other models (e.g., Gas Generation, Repository Fluid Flow). Many of the assumptions in the creep model were modified and tested during the development of the second iteration of the constitutive (MD) model. This redevelopment of the model was driven by the failure of the preliminary model to acceptably predict the short-term rates of closure of WIPP rooms. The redeveloped model contains a new flow rule and refinements of other model elements. The new model predicts short-term, steady-state salt creep rates (room closure rates in the WIPP excavations) acceptably (within 10%) implying that the principal assumptions are correct. No such correlations have been made for the transient (tertiary) creep behavior of the repository because of the limited observation times of room closure behavior. Tertiary creep is neglected in the MD creep closure model because of the assumption that all strain rate acceleration

(above the steady state rate) is due to microfracture and that the porosity caused by microfracture is recoverable during DRZ healing. This assumption is referred to as "the conservation of void space" and is largely unproven.

Because of the complexity of the natural environment and number of parameters evaluated, several assumptions are required to make the process of modeling and mechanical parameter evaluation possible. The most important of these appear to be:

- Thermal effects can be ignored since little waste heat generation is expected. This assumption is reasonable.

- Halite and anhydrite layers can be treated as continuous. This assumption is probably necessary in view of current computer modeling methods. It is also reasonable, in view of program requirements and data accuracy. However, discontinuous surfaces certainly exist within the assumed continuous layers. A good example is given by the few "anomalous" creep results reported by Senseny (1986), which were not included in the final creep parameter determination. Some of these occurred in samples that contained distinct linear clay seams. The effect of ignoring such data and other similar effects by assumption is not severe with regard to the final results, but should not be forgotten.

- Size scale effects can be ignored. Most geologic media exhibit a size scale effect. More often than not, this takes the form (in mechanical properties) of module reduction with size. In the case of WIPP, one might also expect an increase of creep rate with size. A hint of size effect is noted by Munson et al. (1989) but no model changes are proposed. Such effects are frequently attributed to discontinuities, which have differing properties as functions of scale. The assumption of no size scale effects therefore ties in with the continuum assumption discussed previously. Despite these cautions, ignoring scale effects seems reasonable within the realm of available data and accuracy of prediction required for these massive formations.

- The "unknown" long-term creep mechanism can be described by a standard equation and its parameters determined by relatively short-term tests. Virtually all of the halite creep during the lifetime of the repository will occur in response to a mechanism labeled as unknown. Therefore, the equation used for this mechanism, although a standard and acceptable activation equation, must also be labeled as unknown. This may have consequences with respect to long-term predictions. From the viewpoint of repository performance, the consequences are probably not severe since the parameters of the unknown mechanism have been empirically determined with some confidence.

- The presence of water can be ignored as an explicit mechanical properties material parameter. In most geologic media, saturation state strongly affects material properties. Here, with small amounts of water, one can argue that the explicit effects can be ignored. It does not appear that the WIPP project has investigated this, but the results are probably not severe. One area of caution is the possible conversion of anhydrite to gypsum on water absorption. This event,

if it occurs, will make the affected anhydrite zone softer and more plastic than now calculated. However, since the anhydrite beds tend to be zones of weakness to begin with, a severe adverse effect on subsequent modeling is not anticipated.

3.19.2.3. Evaluation of Alternatives

Alternative forms of the creep model were evaluated and compared to repository behavior during the redevelopment of the preliminary (Sjaardema and Kreig 1987) model. The empirical model, which was a version of the preliminary model with elastic modulus modified (RM model) on the basis of observed repository behavior, was used as a stop-gap model to allow the seals and backfill evaluation experiments to move forward. A more process-based model was ultimately developed which utilized a different flow rule and other refinements. This model (MD model) permitted a better understanding of the interaction of individual flow processes and could be more confidently extrapolated to differing initial and environmental conditions than the empirical version. The two models, one empirical (RM) and the other a process-based model (the MD model), agree well and are mutually supportive.

3.19.2.4. Uncertainties

The Creep Closure model contains two of the most important and sensitive variables involved in the potential release of radionuclides. Gas pressure resulting from the compression of gases in the repository from reduction of void volume and gas generation are the principal driving forces capable of pushing brine and dissolved and particulate waste out of the repository toward the accessible environment. Waste consolidation controls the pore space in the waste, which regulates the available surface area across which brine can dissolve radionuclides. Gas pressure is regulated by a complex set of model interactions. Permeability regulates gas outflow via fractured interbeds, and gas generation rates and rate of closure are the primary controls of gas pressure maxima. Gas pressures that exceed lithostatic pressures, sufficient to slow, stop, or reverse repository closure, are credible.

Timing of release relative to a complex interplay of variables controlling gas pressure, void volume, brine volume, residence time, and the reactivity of waste and brine as controlled by brine availability, waste permeability, and porosity are important in determining released brine radionuclide concentration and volume. The assessment of the interplay of timing of multiple processes is controlled by the stochastic manipulation of the processes by SANTOS and is preserved in the porosity surface lookup table. If the latin hypercube sampling strategy adequately addresses the timing issues, as claimed by DOE, consequences of uncertainty in the conceptual models are minimized if the assumed limits of variability in processes are conservative. Only in the case of waste compaction and its influence on the

degree of radionuclide entrainment and solution in brine is the conservatism of assumptions not verifiable. This is because the physical and, to a lesser degree, the chemical character of the waste is essentially unknowable within wide bounds. The consequence of this uncertainty is significant only if release impact is dominated by concentration of released radionuclides rather than by volume of released brine. Those aspects of the consequences of release are considered in other conceptual model reviews. Uncertainty associated with the room closure model (minimum of about 13%) must be evaluated through its sensitivity in the porosity surface calculation, and primarily impacts gas pressures.

3.19.2.5. Adequacy of the Conceptual Model

The adequacy of the Creep Closure conceptual model is demonstrated by its predictiveness of room closure in existing WIPP excavations. The uncertainties inherent in the model must be assessed through the sensitivity of the porosity surface calculation. The model appears to be adequately predictive.

3.19.2.6. Adequacy of Application

Integration of the Creep Closure model with the other component models and submodels to represent repository room closure is contained in the SANTOS code generation of the porosity surface lookup table for a large number of stochastically defined combinations of conditions, and appears to be adequate for performance assessment use.

3.19.2.7. Accuracy of Results

Accuracy of results for the salt creep conceptual model has been demonstrated to be adequate within the sensitivity of the overall room closure model by its ability to predict short-term closure rates in empty WIPP rooms and drifts (10%). The accuracy of the combined model of room closure with, for example, waste, backfill, and gas pressures, cannot be demonstrated at this time. Butcher (1996) claims that the sensitivities to undemonstrated variables in the combined model are low.

3.19.2.8. Validity of Results

The validity of the global room closure model cannot be assessed at this time in the absence of long-term room closure observations of filled and closed rooms, or of analogues or observations of releases from similar structural systems, particularly in the undisturbed scenario. This is ameliorated by the approach adopted in the generation of the porosity surface lookup table, which addresses the complexities of room closure processes and timing among the principal dynamic processes. The Room Closure model appears to be valid as part of the porosity surface calculation for performance assessment purposes.

3.19.2.9. Adequacy For Implementation

Implementation appears to be adequate. The porosity surface calculation appears to address the complex issues of timing among processes and provides a means of choosing representative parameters for individual processes with respect to uncertainty about process results and timing during dynamic process evolution. The creep closure model (MD) appears to be acceptably adequate to the approximation of timing among room closure, gas generation, waste compaction, and brine inflow for performance assessment purposes.

3.19.2.10. Dissenting Views

There were no dissenting views for this model.

3.20. Shafts and Shaft Seals

3.20.1. Model Description

Four existing shafts connecting the repository to the surface, which will be used in the operational phase, are represented in performance assessment by a single shaft with a cross section and volume equal to the total cross section and volume of the four real shafts. This composite shaft is modeled as separated from the waste regions in the model by the distance from the waste to the present waste handling shaft. On closure of the repository, the shafts will be sealed as described below and as represented in performance assessment by nine materials occupying 11 model regions in the shaft, as shown in Figure 3.2. The materials are earthen fill from the surface to the Rustler Formation; a clay region in the Rustler; asphalt at the top of the Salado; three concrete sections within the Salado; an upper clay region within the Salado; a thick section of compacted crushed salt; a lower clay section separated into upper and lower segments; and a concrete monolith at the repository horizon.

Conceptually, the shafts are assumed to be surrounded within the Salado by a DRZ with properties that vary with depth, time, and type of adjacent seal material. The performance assessment calculation grid represents only the cross sectional area of the shafts, and the permeability values for the various seal components at different times have been adjusted to account for the presence of the DRZ. Therefore, the DRZ is not represented explicitly in the BRAGFLO calculation. Thus, the flux that would occur through a shaft and its surrounding DRZ can be modeled equivalently using the shaft cross-sectional area with a higher permeability.

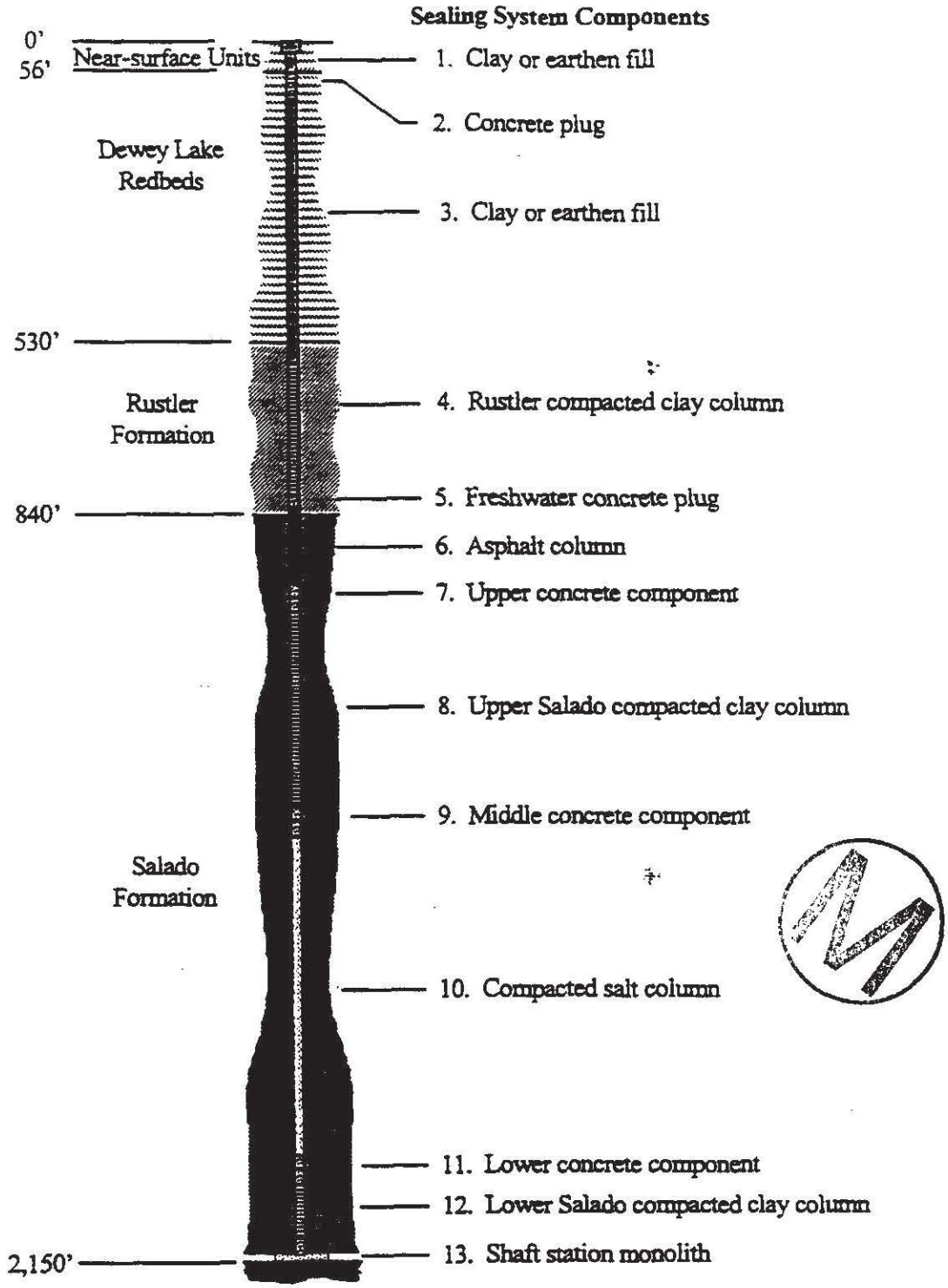

Figure 3.2. Arrangement of the Air Intake Shaft Sealing System

As described by Knowles (1996b), the shaft DRZ permeability is incorporated into the shaft permeabilities by a sampling and calculation process. DOE studies showed that the permeability can vary over an order of magnitude across the DRZ. Test data showed it is greatest near the excavation surface and decreases outward into the rock. To determine the effective permeability of the shaft DRZ, an equation was derived using the assumption that the permeability change is log linear. This equation has as variables a sampled inner DRZ permeability, intact salt permeability, shaft radius, and outer extent DRZ radius. A permeability value is computed for each shaft DRZ. A composite shaft DRZ permeability is then calculated by summing the individual products of the permeabilities and respective areas and dividing by the summed areas. Finally, the adjustment to the shaft zone permeability to account for the DRZ is computed similar to the previous step. The final shaft zone permeability is the sum of the composite permeability times the area of the combined shaft DRZs and the permeability times areas of the summed shaft area divided by the modeled shaft area. The modeled shaft area is assumed to be 95 m^2, which is the computed sum of the areas defined by the shafts' radii. The shaft seal permeability (including the DRZ) is sampled and is temporal in the BRAGFLO calculations.

3.20.2. Review of Criteria

3.20.2.1. Information Used to Develop the Conceptual Model

The conceptual model for the shafts and shaft seals used in the performance assessment has been chosen to provide a reasonable and realistic basis for simulating long-term fluid flow in either direction through the shaft seal system between the repository and brine bearing units and the surface, and to allow evaluation of the effect that uncertainty about the long-term properties of the shaft seal system may have on cumulative radionuclide releases from the disposal system.

Parameters used to characterize the shaft seal system are described in Section 6.4.4 of the CCA and in Appendix PAR. The principal parameters of interest are the permeabilities and porosities of each seal component. For salt, concrete, and clay components, permeabilities are assumed to change with time. Permeabilities are constant for asphalt and earthen fill components. These parameters include the time-dependent properties of the DRZ around the shafts to determine the hydraulic properties of the shaft seal system through time. Other parameters specified for the BRAGFLO model include pore-volume compressibility, two-phase flow parameters, and initial conditions.

The FEPs associated with model development include:

SP-1, Mechanical Effect of Gas Generation.

SP-2, WIPP Shaft Seal Degradation.

SP-4, Other Physical Degradation Mechanisms (Cracking Concrete, Erosion of Seals).

SP-5, Chemical Degradation of Seals (Alkali-Aggregate, Cement Sulfate, Cement Pore Water).

SP-6, Differing Thermal Expansion.

SP-7, Concrete Hydration.

SP-8, Effects of Microbial Growth on Concrete.

SP-9, Effect on Groundwater Chemistry.

SP-10, WIPP Investigation Boreholes.

SP-11, Evaluation of Full Shaft Conceptual Model Seal System.

This information base appears to be adequate for the intended use.

3.20.2.2. Validity of Assumptions

The basic assumptions pertinent to this model concern the applicability of the findings from the test program. Key among these are healing of the DRZ, recompaction of salt (which has application in the shaft sections filled by this material), adequately qualified parametric values for each seal component, a short-term seal to assume appropriate permeability until the salt column is reconsolidated, and implementability of the seal components.

The healing mechanism is discussed in more detail in Section 3.7 of this report. Tests are quite positive in supporting this conclusion, with the most significant of these being the results of testing the zone around a rigid inclusion in salt (Knowles et al. 1996). Recompaction of salt has been demonstrated and concerns are detailed below. Parametric values of components have been scrutinized by a qualification process for adequacy. Implementability of the seal components, as most recently described in the Draft WIPP Shaft Seal System Compliance Submittal Design Report, Appendix B, appears to be readily achievable. All of these assumptions are sufficiently supported to be acceptably valid.

3.20.2.3. Alternatives

The shaft seal system design has evolved over time (Borns and Stormont 1988; Nowak et al. 1992). The Initial Reference Seal System Design proposed a two-phase sealing strategy: short-term concrete and clay

seals and a long-term crushed salt seal. The use of native rock (i.e., crushed salt) as a permanent sealing material is considered the most effective means to eliminate the shafts as a preferred pathway for migration of hazardous constituents. Due to the time necessary for the crushed salt to reconsolidate to sufficiently low permeabilities, short-term seals were incorporated as a means to prevent fluid migration during the interim. Estimates of this interim period ranged from 100 to 200 years.

Results of the scoping calculations (CSDR 1996, Appendix D) showed that low-permeability materials were required for the shaft seals. However, the simplicity of the conceptual model limited the applicability of results to the current detailed seal system design. A comparison of the scoping calculations to the seal system design proposed for the last CCA was found in a memorandum to performance assessment (Knowles 1995a).

The current conceptual model of the WIPP shaft seals is documented in a memorandum to performance assessment (Knowles 1995b). The conceptual model is directly related to the detailed seal design both visually and technically, with all materials and components of the engineered seals being included. Parameters for the materials were developed from field and laboratory testing, literature searches, and numerical modeling. Documentation of the parameter development process is to be published.

3.20.2.4. Uncertainties

The conceptual model of the seals is based on results of detailed numerical models of the shaft seal system design that were developed to evaluate the performance of the shaft system under a range of conditions. Both fluid flow and structural response of the system were evaluated. Principal uncertainties evaluated and incorporated in the model include: 1) reconsolidation of the crushed salt component; 2) construction, permeability, and gas threshold pressure of the clay components; and 3) damage, permeability, healing, and character of the Salado and Rustler disturbed rock zones.

The consequences of uncertainty in seal component performance were a primary motivation in the development of the proposed seal system design. Although there is uncertainty in many of the materials and models, the shaft will be completely filled with high-density, low-permeability materials. The use of multiple materials and components for each sealing function resulted in a robust system. The shaft seal system being evaluated makes no distinction between "short-term" and "long-term" seal components. Instead, time dependency is incorporated directly into the model through temporal variation in seal

properties. On general overview, the uncertainties that emerged in the shaft seals program appear to have been dealt with adequately.

3.20.2.5. Adequacy of the Conceptual Model

Details concerning a description of the sealing materials and why they are expected to function as expected are to be presented in the WIPP Shaft Seal System Compliance Submittal Design Report, currently in draft. The materials include compacted earthen fill, concrete, compacted clay, asphalt, and compacted salt. These different materials are used to reduce uncertainties in performance. All materials are expected to maintain their integrity for very long periods, although for design purposes longevity only is assumed for those materials with strong scientific justification. Concrete plugs with impermeable water stops located in the Salado provide early low permeability, and the rigid support to promote healing of the DRZ. In approximately 100 years (design provides for 100 to 200 years), the compacted salt column will be sufficiently compressed to have a low permeability, thus replacing reliance on the concrete plug. The asphalt is functional as a nonpermeable plug to prevent water flow, and as a water stop within the seals in the Salado Formation. These water stops, backfilled in a one-radius kerf cut surrounding the shaft in the salt, are expected to be highly effective in deterring water flow in the DRZ surrounding the shaft. The Compliance Submittal Design report will describe the processes showing feasibility of achieving adequate placement of these seals (initial drafts appear convincing). Except for confirmation of the compactability performance of salt, this model appears to be fully adequate for implementation.

3.20.2.6. Adequacy of Application

The properties of the designed seals are realistic, achievable, and allow for controllable application. The only relatable issues for application concern the performance of recompacted salt (as discussed in Section 3.20.2.8), and performance of the DRZ. The latter issue regards the accuracy of the assumption that the DRZ will heal and accordingly can be disregarded as an explicit component of performance assessment calculations. This assumption stems from tests showing that with time, the permeability of a DRZ decreases as confirmed by tests when a stiff support is placed in an opening. The property of salt creep forces the fractures to close and original conditions to be re-established (Knowles et al. 1996). As a result of these findings, it can be assumed that following the placement of seals, the DRZ will quickly heal to create a permeability that is lower than the shaft seals provide (Chiesler 1996). Hence, it is argued that by adjusting the permeability of the seal components upward in the model, it will compensate

for the additional low flow in the DRZ, and the DRZ can be removed as an explicit input to the performance assessment calculations. Because of the relatively large extent of the DRZ and its capability of being a potential pathway for releases, this concern bears its rightful recognition in the accuracy of results.

3.20.2.7. Accuracy of Results

The results from development of the shaft sealing system pose questions of achievability, which obviously are subject to incorporating ensured quality in the design and implementation processes. On one hand, a concern may exist that the quality of materials placement might cause performance problems, and on the other hand the system is sufficiently tangible that problems can be resolved provided there is an assurance program that identifies problems in time to be addressed. Only two concerns appear to impact the concepts as discussed relative to accuracy. The first is discussed in Section 3.20.2.8, concerning establishment of a consistent and appropriate permeability value for compacted salt. The second consideration is the reliability of the expected DRZ healing process, which is an assumption of significant proportion, as discussed in Section 3.20.2.6. The results of studies, calculations, test programs, and engineering principles all appear to produce results favorable to achieving the construction of competent seals in the WIPP shafts.

3.20.2.8. Validity of Outcome

A principal conclusion from the studies and design of the WIPP shaft sealing system is that an effective and implementable design has been documented. Existing technology and use of common materials make this engineered barrier system tangible and realistic. This Panel's evaluation confirms that these attributes are fulfilled and the concepts forwarded are believed to be valid.

Two caveats were identified; however, neither threaten the validity of this model but they warrant further investigation to assure the integrity of the system. First, while the tests showing compactability of the halite adequately demonstrate the principle, to date it has not been possible to qualify an established permeability value in this medium. The principle reason lies with problems in interpretation of the test data, believed due to experimental conditions. Furthermore, having recognized that the halite is capable of being recompacted, it appears that the method of compaction by repetitive dropping of a heavy weight could cause an inhomogeneous, nonuniform packed bed. No evidence could be found that addresses this question as a requirement, as a phenomenological process, or experimentally.

The second caveat concerns the shaft monolith placed in the drift at the base of the sealing column. No evidence could be found that any analysis was made concerning whether this monolith could cause a stress condition at the shaft perimeter interface, which might create a shear zone there. The basis for this concern lies with the reality that the dimension of the monolith is sufficiently large that it creates a base platform supporting what appears to be a rigid column in a viscoelastic medium. Its effect will be that the base will be fixed at the floor datum, which might be upward moving, while the salt above in the far field is flowing downward. It appears that an analyses is warranted to assure that this is not a problem.

3.20.2.9. Adequacy for Implementation

Comments concerning two issues from the preceding section are also applicable to the model's adequacy for implementation: 1) further analysis of the salt compaction data base, firmed up with additional data, is important to support parameter permeability values, and 2) an analysis has not been found to assure the shaft monolith does not create a shear zone at the shaft perimeter interface. Aside from these, the foregoing discussions outline an insightful piece of scientific and engineering work. The shafts and seals program is well thought through and the areas of perceived concern have been addressed to various degrees of detail, each believed sufficiently adequate to support qualifying this model as adequate to proceed in supporting performance assessment.

3.20.2.10. Dissenting Views

There were no dissenting views for this model.

3.21. Gas Generation

3.21.1. Model Description

Gas generation within the disposal rooms after closure was identified as an important process to be considered in analyzing both the undisturbed and disturbed performance at WIPP. The principal features of the model are the production of hydrogen from the corrosion of iron in the waste and containers and production of carbon dioxide, methane, nitrogen and hydrogen sulfide from possible microbial degradation of cellulose, rubber, and plastics in the waste. These reactions are assumed to occur under anoxic conditions after the repository is closed and brine enters the disposal rooms and contacts the waste materials. The model also covers the removal of carbon dioxide from the gas phase by absorption and reaction with a chemical getter, magnesium oxide.

Ten to fifteen years ago it was thought that little water would be available in the dry salt to support either significant corrosion or microbial degradation of cellulose in the waste and that any gas that might be produced would be absorbed into the surrounding salt rock. However, observation of water in the underground workings, seeping from clay seams and in drilled holes, and the results of analyses and hydrologic experiments showed that interstitial water can flow into the repository. This lead to the serious consideration of corrosion and microbial action, through assessments that included laboratory analyses, some of which are ongoing. Three conceptual models have been used to describe gas generation: the so-called rates-and-potentials model, the average-stoichiometry model, and the reaction path model. These are further discussed in Section 3.21.2.3.

The amount of gas production in the repository is of considerable interest to assessment of repository disturbed and undisturbed performance. Gas pressure can counteract the brine inflow from salt, relating it to the Fluid Flow in the Salado model. Gas pressure can also drive brine out of the repository, relating it to the Actinide Transport in the Salado model. It can potentially counteract the closure of the salt around the waste, relating it to the Creep Closure model. It includes reactions that relate to the repository Chemical Conditions model and it can, thereby, also affect the Dissolved and Colloidal Actinide Source Term models. It also can affect the integrity of the Shaft Seals model. Under the various intrusion scenarios, gas is a driving force for potential releases, so it inputs to the Direct Brine Release model, as well as to the Cuttings/Cavings and Spallings models, and provides input material to the Culebra Flow and Actinide Transport models.

3.21.2. Review of Criteria

3.21.2.1. Information Used to Develop the Conceptual Model

The information used to develop the model included the quantities and compositions of the transuranic waste, particularly the quantities of radionuclides and corrodable steel and aluminum, and the quantities of water, cellulose material, and plastics, as well as any chemicals and sludges that could provide nutrients for microbial degradation of these materials. Other important information sources were the observation of brine inseepage into the underground salt cavities, and determination of the chemical compositions of brine in the Salado, in the Castile below, and in the Culebra above the repository. Direct observations were made of halophilic microbes in salt lakes in Nash Draw near the site and in repository inseepage water. Information was also obtained on corrosion-induced hydrogen generation experiments at other sites, measurements of radiolytic gas generation from plastics and water, and controlled

measurements of oxic and anoxic corrosion and microbial degradation rates of cellulose using representative brine and cultured microorganisms from the repository brine. These measurements were done for Sandia at Lawrence Livermore National Laboratory and Brookhaven National Laboratory. There is some ongoing experimental work in this latter area at the Idaho National Engineering Laboratory using actual transuranic waste materials. There is little information on the microbial degradation of plastics.

The information on brine compositions, microbe presence and populations, and the controlled experiments of corrosion and microbial processes are very useful. Due to the length of time of the experiments, no evidence for likelihood of self-limiting conditions on corrosion or microbial action were observed, although it is logical that there will be some self-limiting features that would prevent complete reaction of metal, cellulose, and plastics. A determination of whether microbial action on cellulose would have a net production or consumption of water could not be made from the information available. Experiments of potential radiolysis of water do not appear to allow direct differentiation of gas generation from dissolved versus wet particulate alpha-emitting radionuclides. The ongoing longer term experimental work being conducted at the Idaho National Engineering Laboratory could provide improved resolution of some of this information. However, overall there appear to be adequate data to develop a meaningful conceptual model of gas generation.

3.21.2.2. Validity of Model Assumptions

Regarding hydrogen generation by metal corrosion, a key assumption is that hydrogen is generated by corrosion of steel in waste drums. This is certainly valid. The model also assumes that carbon dioxide and hydrogen sulfide generated by microbial degradation will not passivate steel, which appears very valid based on the corrosion experiments and the addition of magnesium oxide as a carbon dioxide getter. Rates of steel corrosion are assumed to be higher for waste inundated or wetted in brine at the bottom of the room, and rates are somewhat lower for metals above the brine level resulting from wicking. These assumptions appear reasonable based on the direct experimental evidence. In fact, assumed rates based on the reasonably short-term iron corrosion experiments could be somewhat conservative with regard to the timing of gas generation, but probably valid for the overall amount of gas from corrosion of this source of metal.

The model ignores corrosion of aluminum, steel in rockbolts and steel netting, and other equipment to be left in the underground workings. This seems to represent an implicit assumption that corrosion of these

materials will not contribute to gas generation and is based on the relatively small amounts of these materials. Aluminum is apparently on the order of 10% by mass of the steel, based on the summary data in the 1995 Baseline Inventory Report. Aluminum is quite corrodable in brine, and rockbolts can directly contact water seeping from the anhydrite interbed above the disposal rooms. The molar quantity of hydrogen produced per mole of aluminum corrosion would be 1.5, due to the stoichiometry involved. Therefore, it seems only logical to include these materials in the corrosion model to avoid a bias.

The model also assumes that the chemical reaction representing the stoichiometry of anoxic corrosion of iron is

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H2$$

thereby yielding one mole of hydrogen per mole of iron reacted, and consumption of two moles of water. The model assumes that the corrosion of iron is not represented by the reaction

$$Fe + 4/3H_2O \rightarrow 1/3Fe3O4 + 4/3H2$$

as this reaction is not expected at low temperatures, and the amount of hydrogen generated in experiments was consistent with the first equation. Except for the initial period after repository closure, when oxygen is available, this appears valid and reasonable, especially since the chemistry conditions model predicts reducing conditions in the repository.

Regarding microbially induced gas generation, the model assumes that the probability of degradation of cellulose and plastics/rubber will be 50% and that in the event that biodegradation occurs there is a 50% probability that plastics and rubber will also be degraded. This assumption is shown schematically in the diagram below.

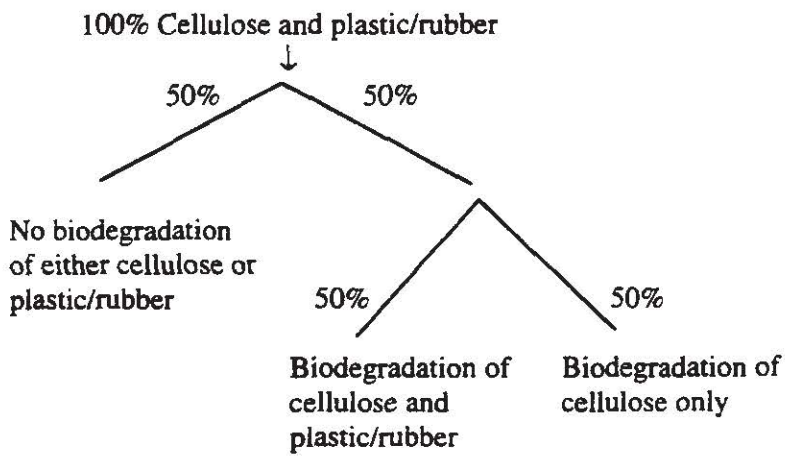

This assumption is based on major uncertainties that are described in Section 3.21.2.4 below, and represents a judgment. For performance assessment purposes, this assumption will result in less gas generation than if one were to assume total consumption of all the organic material. There is apparently no scientific evidence that plastics/rubbers degradation will occur at all with certainty, based on contemporary experience. The possibility that products from microbial degradation of cellulose, and perhaps radiolysis by alpha irradiation, could combine to break down the relatively stable plastics polymers to more consumable fragments suggests the probability should be non-zero. It is difficult to argue for a value higher or more precise than 50%, unless there were more robust long-term data, or experience with plastics degradation in, for example, landfills. Therefore, for performance assessment purposes, the assumption regarding plastics/rubber appears to be adequate.

With regard to the degradation of cellulose, the long list of uncertainties identified in Section 3.21.2.4 below suggests that less than full probability of significant microbial degradation of this more readily consumable material is a reasonably valid assumption. Also, it does not appear scientifically valid to assume that either all or none of the cellulose will be degraded in light of the significant uncertainties that microbial populations would remain viable to the extent of complete cellulose degradation. DOE is not seeking a worst case in performance assessment. Therefore the 50% probability is a reasonable assumption for modeling purposes.

3.21.2.3. Evaluation of Alternatives

The Average Stoichiometry model currently used has been in use since 1991. Its principal features and assumptions have been described in the previous sections. Two alternatives that have been seriously considered are the Rates and Potentials model from about 1989 through 1991, and the Reaction Path model, which was developed between 1992 and 1995, but has not been used.

The Rates and Potentials model used measured rates of gas generation from microbial processes and corrosion and the total potential for gas generation from the available amounts of metal and cellulose. This model assumed no gas generation from plastics, which was controversial. The results of use of this somewhat less involved model demonstrated that gas pressures could have a significant effect on the performance of the repository. This stimulated development of more complex analyses methods involving coupling gas generation with brine flow and incorporating processes of fracturing due to gas

flow into the Salado anhydrite beds. The Rates and Potentials model gave way to the Average Stoichiometry model.

The third model that has been considered is the Reaction Path model in which the reactive gases, carbon dioxide, and hydrogen sulfide produced by microbial action, were assumed to interact with and potentially passivate the surfaces of steel, thereby reducing or potentially stopping the rate of corrosion. Although some passivation was observed in experiments, corrosion films were not judged to be sufficiently adherent. Also, analysis of rates of microbial production of carbon dioxide and hydrogen sulfide showed they would not be present in sufficient quantities to provide passivation. Therefore, the reduced corrosion rates indicated could not be demonstrated reliably and effort on this model was stopped in late 1995. Furthermore, the use of a chemical getter such as magnesium oxide would absorb the carbon dioxide, raise pH and lower actinide solubility, reduce carbon dioxide pressure buildup, and somewhat lower steel corrosion rates at the higher pH.

The alternative models that were seriously considered did not offer sufficient benefits to performance assessment. However, the thermodynamic elements of the more complex Reaction Path model could, in the future, offer improved understanding and more rigorous ability to understand the complex chemical behavior in the repository room. Nevertheless, the purpose of the Gas Generation model to provide input gas generation to other models is adequately met by the Average Stoichiometry model.

3.21.2.4. Uncertainties

There appear to be greater uncertainties in the submodel describing microbial degradation than in the submodel describing metal corrosion. Uncertainties, which have been stated relative to microbial degradation, include the following:

- Will there be adequate populations of microbes capable of surviving for long periods in the disposal environment?
- Will there be adequate nutrients and electron acceptors available from the waste over long periods of time?
- Will sufficient brine enter the room to support the microbes?
- Can chemically toxic metals or radiation destroy or retard otherwise viable microbe populations?

- Will microbial degradation of plastics and rubber occur at all?
- What are the relative amounts of the various gases produced, and will microbes be net producers or consumers of water?

Despite these significant uncertainties, the Gas Generation model will predict significant but not total degradation of cellulose and plastics/rubber. Thus, these uncertainties appear to have been resolved in a conservative manner.

Uncertainties in the submodel describing corrosion-induced hydrogen gas buildup include the amount of metals present; the use of short-term metal rates of corrosion; the potential for oxic corrosion to continue due to radiolysis of water; and the potential for increased amounts of corrosion products from aluminum corrosion or increased rates from iron/aluminum galvanic couples and from corrosion of steel in the repository rock bolts and netting. It is judged that the only one of these that is potentially significant is the amount of added corrosion-induced gases from aluminum in waste and from rock bolts and netting. Another issue is whether some Fe+3 would be produced during the initial period after closure, and later due to continued generation of oxygen from radiolysis, thereby effecting actinide oxidation states.

The radiolysis of water in the waste and in brine, as well as radiolysis of plastics and rubbers, have separately been judged to have an insignificant effect on gas generation compared to the other gas generation mechanisms, and are not included in the gas generation model. For alpha particle irradiation of plastics and rubber, the measured G values (molecules of gas per 100 electron volts) were quite variable over time, leading researchers to conclude that depletion of available hydrogen atoms in plastic/rubber polymers around radioactive particles would stop the generation of such gases. However, over the long term, this conclusion is questionable since the radioactivity and waste can move around and be deformed by salt creep and gas and brine movement. Furthermore, the reported experiments involving radiolysis of brine have used soluble alpha emitters. In this situation the approximately 5 Mev per disintegration would all be dissipated in water. Depending on the solubilities, much of the actinides could remain undissolved. The review of this issue did not cover radiolysis by wetted particulate radioactive materials. This omission could be rather significant. If a significant portion of actinides are not dissolved but remain in small particulate materials that become wetted, a significant portion of the alpha energy could still be deposited in water and generate hydrogen and reactive oxygen species.

A project decision was recently made to add magnesium oxide to buffer the brine pH (in the range of approximately 10) to limit actinide solubility. The model assumes that all carbon dioxide is quickly

dissolved in brine and precipitated as magnesium carbonate, thereby also reducing gas pressure and buffering the pH at 10, rather than about 4 to 5. While this appears clearly desirable, there are significant uncertainties as to whether these benefits will be completely realized. No results have been presented of any consideration of phenomena that could limit the effectiveness of the magnesium oxide. Likewise, there have been no laboratory or pilot scale tests to demonstrate effectiveness. Some potential adverse scenarios that might be considered are as follows:

1. Brine, which slowly enters the room, bypasses the getter and penetrates the drums from below. The current design has no getter beneath the drums.

2. Carbon dioxide, which initially reacts directly in the gas phase with the magnesium oxide getter, creates an insoluble crust around the outer surfaces of the getter, thereby limiting further access of brine and carbon dioxide to the getter. Such a crust might also occur at the water level in the bags of getter stacked around the periphery of the waste rooms.

Thus, the assumption of complete and rapid removal of carbon dioxide appears quite uncertain and, for modeling purposes, seems unjustified in light of such uncertainties. The benefits being counted on in the Chemical Conditions model are extremely significant, which carries with it a very significant obligation to demonstrate the validity of this assumption.

Another uncertainty is whether the heats of the corrosion reactions, and the microbial degradation of the cellulose, will result in elevated temperatures. Analyses of thermal effects of radiogenic heat in contact-handled transuranic waste have shown this source of thermal energy is small. Likewise, analyses of radiogenic heat in remote-handled transuranic waste can result in 38-65°C in the area of canisters but only about 4°C in the repository overall. However, no thermodynamic analysis has been provided to support the single-statement conclusion in the FEP screening document that corrosion and biodegradation do not affect repository temperature due to low enthalpies of the reactions. Heat generated in contact-handled transuranic waste could not dissipate as readily as in remote-handled waste, because of the large mass and dimensions of these relatively low-conductivity wastes. Significant temperature increases could accelerate corrosion rates in the presence of brine and potentially affect other processes, such as creep closure and brine flows. This uncertainty could be resolved readily through a numerical evaluation.

3.21.2.5. Adequacy of the Conceptual Model

The Gas Generation model would represent a reasonable approximation of the most significant processes represented at the conceptual level, were it not for the four potentially significant uncertainties described above. Some modest effort to resolve these uncertainties is needed, as discussed in Section 3.21.2.8.

3.21.2.6. Adequacy of Application

The gas generation model results are applied to the overall performance modeling system known as BRAGFLO, as well as to the Chemical Conditions model. Gas pressures are calculated from molecules of gas produced and assume a reasonable equation of state. As indicated earlier, the assumption that all carbon dioxide is rapidly removed from the gas phase appears somewhat unreasonable in the absence of better chemical and engineering justification for this important assumption. Therefore, this currently represents a discontinuity in the modeling system. The processes not included in the model, including gas generation from aluminum and rock bolts and from radiolysis, represent potential changes in the model but do not affect the modeling application per se. However, if greater thermal effects due to heat generation from corrosion and biodegradation were found through analysis, this could in turn affect other system parameters and processes outside the Gas Generation model.

3.21.2.7. Accuracy of Results

In the absence of key results of the model, it is difficult to draw definite conclusions about what the accuracy of the results will be when implementing a conceptual model. If one were to properly represent the conceptual model in equations, and then properly implement the equations in a numerical system using appropriate data on parameters, the accuracy of results would presumably be that associated with the uncertainties and biases in the conceptual model above, as well as any introduced during implementation, to get numerical results.

The uncertainties and potential biases that have been identified for this model are judged to have a potentially significant effect on its accuracy in predicting gas pressures and other parameters, such as pH and actinide solubilities. However, this judgment could be tempered somewhat if key results of analyses and sensitivity studies were to indicate that the identified uncertainties and biases taken collectively were to show that the effects on waste systems releases under disturbed and undisturbed conditions were small. If this were not the case, changes to the model to account for such effects would be needed. Therefore, it is suggested that results of implementing the Gas Generation model would be useful,

including sensitivities among Gas Generation model variables and brine inflow calculations, and resulting pressure buildup over time. Also, the sensitivity of gas generation to the amounts released from human intrusion scenarios would provide useful information. Such information is believed necessary to make a more useful and informed judgment on accuracy.

3.21.2.8. Validity of Conclusions

There are two issues of concern here, first, whether the predicted outcomes in terms of inputs to other models are valid, and second, whether the outcome of larger issues on disposal system releases are valid in light of remaining issues with the Gas Generation model. A definite conclusion on either point would be somewhat speculative, at least without resolution of several of the issues raised and possibly of the results of sensitivity studies identified. One would also not want to speculate on the validity of conclusions without seeing what the conclusions might be. The following issues have not been adequately resolved:

- Analysis of hydrogen generation by corrosion of metals other than the steel in the waste is inadequate. Ignoring gases generated by corrosion of other metals could result in underestimating the gas pressure in the repository.
- Temperature increases in the repository due to corrosion and microbial degradation are not sufficiently analyzed or characterized. Higher ambient repository temperatures could increase the rates of chemical reactions, fluid flow, and halite creep.
- Due to uncertainties about the effectiveness of the magnesium oxide getter to completely remove CO_2, significant uncertainties exist regarding pH, CO_2 pressure, and actinide solubilities. The chemical conditions in the repository would significantly change if the MgO did not function as planned, and could result in underestimating radionuclide releases.
- Hydrogen and oxygen gas generation from radiolysis of dissolved and wetted particulate actinides have not been adequately evaluated. Radiolysis of cellulose and plastics without assuming local hydrogen depletion has also not been adequately evaluated. Ignoring the gases generated by these effects could result in underestimating the gas pressure in the repository.

3.21.2.9. Adequacy for Implementation

At the conceptual level, without consideration of the integration, accuracy, and conclusions criteria, the conceptual model would be adequate if the significant issues raised above are resolved. However, a bottom line assessment on whether the Gas Generation model, as used in the compliance application, represents a complete reasonable approximation of the actual disposal system, is premature unless the significant issues raised above are resolved and some key results and conclusions are available.

3.21.2.10. Dissenting Views

There were no dissenting views for this model.

3.22. Chemical Conditions

3.22.1. Model Description

This conceptual model has been developed to standardize the chemical conditions of the repository. As such, the data generated by this model are used as input parameters to other conceptual models.

The chemical conditions of the repository are a major influence on actinide solubility. It has been estimated that under specific chemical conditions (low pH), the actinide solubility may increase over expected values by up to five orders of magnitude. This model has used engineering systems to limit such variability. DOE has assumed that equilibrium has been established between the brine in the repository (Castile or Salado), waste forms, and primary minerals. In addition to this basic chemical assumption, a series of other assumptions were made to help facilitate computer code calculations. The assumptions are discussed in further detail below. The defense of model assumptions is presented in Appendix SOTERM, which was not available for the peer review.

Major variables in this conceptual model include brine compositions (fixed chemistry Salado and Castile brines), ligand concentrations, pH, fCO_2, oxidation conditions, mineral stabilities, cement inventories, actinide inventories, and MgO backfill. Of these variables, some can be held constant because of the MgO backfill. The reaction of MgO and CO_2 acts to buffer the pH of the repository and allows other variables to be fixed. The two major variables that will now be constrained are fCO_2 (low fugacity) and pH (between 9 and 10, depending on brine composition).

Certain assumptions are critical to this model. Brine and waste are modeled as a uniform mix of dissolved and solid phases. Thermodynamic equilibrium is assumed for dissolved actinides but not for redox reactions amongst the actinides. Further, chemical homogeneity and solubility equilibrium are assumed. This allows for the assumption of instantaneous reactions. Chemical microenvironments are not believed to persist for this reason. DOE assumes there will not be conditions whereby supersaturation can exist for long periods of time. Temperatures will increase a total of approximately 5.4°C (radioactive decay and exothermic reactions), and it is assumed that there will be negligible effects due to this increase.

DOE believes that calculating mixing of brine from different sources is not amenable to performance assessment. Therefore brine compositions are fixed by performance scenarios. Undisturbed performance and E2 scenarios dictate the use of Salado brine. This is because the Castile Formation is not penetrated. Scenarios E1 and E1-E2 use Castile brine as the solvent for chemical conditions.

Oxidation states of the repository are believed to be reduced. This judgment is based on the thought that available oxygen will be consumed early by oxic corrosion or aerobic microbes. Furthermore, large quantities of iron from 55-gallon drums are consumed by anoxic corrosion, producing hydrogen gas and ferrous iron. Although reducing conditions are expected, redox reactions between dissolved actinides in possible oxidation states are not addressed. DOE assumes this will produce conservative results and increase the total dissolved actinide source term.

Experimental data have shown that acidic conditions greatly enhance the solubility of actinides. Although cement materials in the waste will hydrate to $Ca(OH)_2$, CO_2 produced by microbial degradation of cellulosics will overwhelm this component and force the brine to low pH values. To reduce the potential for highly accelerated actinide dissolution, DOE decided to add MgO to the repository as backfill. The simplified reactions of concern are:

$$MgO + H_2O = Mg(OH)_2$$

$$Mg(OH)_2 + CO_2 = MgCO_3 + H_2O$$

In large enough quantities, the backfill will act as a getter of CO_2 and thereby buffer the liquid, produce low CO_2 fugacities, and provide alkaline conditions in the repository.

Because the addition of MgO will buffer the CO_2 fugacity, many processes that create time-dependent changes in the repository have been negated. The other assumptions imparted on the chemical conditions model, such as fixed ligand inventory, mineral equilibrium (halite, anhydrite, brucite), fixed brine compositions, and fixed actinide inventories have produced a fairly simple system. There is no need for a large computer code to replicate the conditions of the repository. Rather, fixed or calculated (EQ3/6) parameters (pH, fCO_2, phase equilibria, buffering equilibria) from this model are used as input to other, more complex conceptual models.

3.22.2. *Review of Criteria*

3.22.2.1. Information Used to Develop the Conceptual Model

Information used to define the Chemical Conditions conceptual model fall into four main categories: thermodynamic considerations, experimental results, numerical simulations, and results of literature reviews. The first major consideration of this model, equilibrium conditions, is a cornerstone of physical chemistry. The model uses equilibrium conditions between brine and minerals as a given; however, it dismisses the concept of redox equilibrium conditions between dissolved actinide species. The second category, experiments used in the WIPP project (especially gas generation and actinide source terms), have identified significant factors affecting the room chemistry. A clear example is that of WIPP-specific microbes generating large amounts of CO_2 gas. The third major information source is supplied by numerical modeling. Two of these examples are listed. Mineral precipitation sequences were developed from EQ3/6 computational runs. Cement inventories were produced by simple algebraic formulas. The fourth information source came from peer reviewed journal articles. An example would be that of mineral equilibria, such as Felmy and Weare (1986).

The nine FEPs were also used in the development of this conceptual model are:

1. DRG-13, Effects of chemical changes due to gas generation and corrosion.
2. Heat from exothermic reactions and concrete hydration.
3. SP-7, Heat from concrete hydration.
4. Effect of thermal gradient.
5. DR-15, Electrochemical effects.
6. DR-16, Other second-order FEPs similar to electrochemical effects.
7. RNT-25, Electrochemical effects in the repository.
8. SP-5, Chemical degradation of seals.
9. SP-8, Effects of microbial growth on concrete.

It has been decided that this gathering of information is adequate.

3.22.2.2. *Validity of Model Assumptions*

The major assumptions of the Chemical Conditions conceptual model have been listed in the model description above. To summarize, the assumptions are as follows:

1. Brine and waste are modeled as a uniform mix of dissolved and solid phases.

2. Thermodynamic equilibrium is assumed for dissolved actinides but not for redox reactions among the actinides.

3. Chemical homogeneity and solubility equilibrium are assumed. This allows for the assumption of instantaneous reactions.

4. DOE assumes there will not be conditions whereby supersaturation can exist for long periods of time.

5. It is assumed that there will be negligible effects due to the temperature increase (by radioactive decay and exothermic reactions) of approximately 5.4°C.

6. Brine compositions are fixed by performance scenarios.

7. Oxidation states of the repository are assumed to be reduced.

8. All CO_2 will be fixed by available $Mg(OH)_2$, thereby buffering the pH of the repository.

9. Actinide and ligand inventories are fixed.

Assumption (1) is reasonable when one considers the time frame involved for mixing and the difficulty of trying to numerically represent heterogeneous waste forms. Thermodynamics relies on the principal of equilibrium and, therefore, assumption (2) provides a mixed interpretation. Assuming equilibrium for dissolved actinides is valid; however, DOE claims conservatism by not assuming redox equilibrium. This cannot be considered valid without further explanation and demonstration of the conservatism. Equilibrium of solubilites and chemical homogeneity are a simplifying assumption (3) that should be wholly valid over the time frame involved. The corollary of this assumption, that reactions are instantaneous, is wrong. The effect of kinetics was never taken into account in the model.

Assumption (4) is valid as a simplifying assumption. The trade-off between long-term saturation versus supersaturation and precipitation is valid for modeling. Although assumption (5) may be valid, verification calculations that prove negligible differences have not been provided. Assumption (6) is valid for the scenarios described. In effect, these two brines provide end-member compositions for a

complete solution series. Assumption (7) is valid after approximately 100 years beyond closure. In the short term, oxidizing conditions would prevail. The limits allowed for total waste to be entombed at WIPP provide for assumption (9) to be valid.

Assumption (8) is probably the only assumption in this conceptual model that is physically unfounded and very problematic. From a thermodynamic viewpoint, the reactions are proper and the buffering capability is valid. However, there is no physical evidence that the MgO pellets will be allowed to completely react with the CO_2 generated by microbes. Reaction rims forming on the extremity of the MgO packages may not allow the majority of the backfill to be available for interaction. Such a chemical system would then not be buffered and the brine would become acidic. Studies have not been performed to demonstrate that the present engineering design will in fact work and allow all the MgO to react with CO_2 until the gas is exhausted. This is also discussed in Section 3.21, the Gas Generation conceptual model.

3.22.2.3. Evaluation of Alternatives

The majority of the chemical alternatives are described in Section 3.23.2.3 (Dissolved Actinide Source Term). By fixing many of the chemical parameters at reasonable values for repository conditions, the need for alternative models was not required. The primary alternative that is discussed in this section is whether a chemically reactive backfill is required.

In the early 1990s, no backfill was anticipated for emplacement in the repository rooms. When the test plan for soluble actinides was initiated, a large range of CO_2 pressures and pH values was anticipated. High CO_2 generation would produce sufficient carbonic acid to lower the brine pH to approximately 4 or 5. The basic conditions of the natural Salado Formation brine (9.4) would only allow restricted dissolution of the actinides. Under acidic conditions (pH 4) in experiments, actinide solubility was found to increase by approximately 5 orders of magnitude over that of the natural Salado brine. Such a solubility increase could conceivably present problems to the overall project.

It was then decided to buffer the chemistry of the repository and brines by addition of a reactive backfill. The addition of copious amounts of MgO as backfill is designed to react with the microbially generated CO_2 and buffer the overall chemical conditions of the repository. This would, in effect, fix both the pH and fCO_2 of the brine.

3.22.2.4. Uncertainties

Uncertainties associated with this conceptual model fall into three categories. General uncertainties associated with dissolved or colloidal actinides are discussed in Sections 3.23.2.4 and 3.24.2.4, respectively. This section is restricted itself to uncertainties associated with assumptions presented in Section 3.22.2.2 and the uncertainty of whether phase stability has been adequately characterized. In Section 3.22.2.2.. four of the assumptions presented (1, 4, 6, and 9) were deemed to be valid.

The five remaining assumptions presented by DOE were not clearly shown to be valid. The point to keep in mind is what magnitude of uncertainty is associated with each assumption. Although DOE has not validated the assumption of redox disequilibrium (assumption 2), the partitioning of oxidation states into lower and higher oxidation states for model runs has effectively addressed this uncertainty. Assumption 3, that chemical reactions are instantaneous, is not valid. The impact this assumption creates on the conceptual model may be significant. Reactions that are relatively fast present no problem at all. Reactions that take a couple thousand years probably introduce very little uncertainty to the model. It is those chemical reactions that never go to full completion that may invalidate the model. This uncertainty with regard to assumption # 8 is dealt with in detail below.

Assumption #5, that a 5°C increase over STP conditions is negligible, is probably correct. Any uncertainty with this assumption could be clarified with a few verification calculations. The other assumption that contains only a small uncertainty (#7) deals with anoxic conditions in the repository. Even if oxic conditions prevail for the first 1% of the regulatory time frame, only a very small amount of iron would be tied up as oxidized iron oxides (hematite, goethite, leucophane). Although these mineral phases do not react back to reduced phases due to kinetic effects, this is not expected to have any significant effects.

The assumption that $Mg(OH)_2$ will absorb all available CO_2 generated in the repository (assumption #8) contains a very large uncertainty. As mentioned above, there is no uncertainty that the chemical reaction pathway is indeed correct. The uncertainty is whether the engineering design will be effective. If a large portion of the MgO never reacts with CO_2, then the carbonic acid will remain unbuffered and the dissolved actinide source term may increase (depending on model scenario) by up to 5 orders of magnitude. This could be considered a significant uncertainty.

The final uncertainty to be commented on is that of mineral phase stability in the repository. Although the EQ3/6 computer code has been used to qualify which phases will precipitate from solution, no formal phase-stability study has been conducted. There may be phases present that have been overlooked and the consequences of that oversight would impart an unneeded uncertainty. Schreinemakers diagrams have not been calculated to determine the phase-stability fields present in the repository.

3.22.2.5. Adequacy of the Conceptual Model

The present section addresses whether the conceptual model is adequate based on the four criteria above. Since this model strictly consists of a number of chemical condition parameters, it should be easy to evaluate whether the model is valid. It is concluded that the majority of parameters for this model are both reasonable and adequate. For the present model, the uncertainties of the previous section must be dealt with to prove that the model is adequate. Even when one considers the potential uncertainties listed in Section 3.22.2.4, only two could severely impact the adequacy of the Chemical Conditions conceptual model. These are the rigorous treatment of phase stability (Schreinemakers analysis) and the ability for the backfill to sequester the CO_2. For phase-stability analysis, only the omission of a major phase from the stability fields could jeopardize the validity of the conceptual model.

Conversely, the backfill parameter is so key to the model that without test validation that the $Mg(OH)_2$ will work as a getter, the model will not be adequate. The reason is that too many other parameters of this model hinge on the pH and fCO_2 values being fixed.

3.22.2.6. Adequacy of Application

This conceptual model does not flow as total input to a single computer code, rather it functions to set the parameters and boundaries for other conceptual models. As such, the conceptual model does not integrate to larger computer models (e.g., BRAGFLO) in the typical way. Any chemical values or constraints that the model generates should be readily integrated into other conceptual models. If the model provides a specific chemical parameter, that quantity could plug directly into performance assessment codes.

3.22.2.7. Accuracy of Results

This section discusses whether the results of performance modeling using the conceptual model within the performance system are sufficiently accurate to adequately represent the chemical processes occurring. In essence, this question is not applicable to the model in review. There should be no

opportunity to corrupt or distort parameter values from the chemical conditions conceptual model to the performance assessment model. However, this idea has not yet been confirmed by test runs of the performance assessment.

The other manner by which the performance assessment could derive inaccurate results from this conceptual model is to portray thermodynamic assumptions incorrectly. There is no way to judge whether this has happened without viewing the results of the performance assessment runs.

One would assume that the WIPP project can transfer chemical parameter values correctly from the conceptual model to the performance assessment, and that thermodynamic assumptions can be accurately implemented in the same fashion.

3.22.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Chemical Conditions conceptual model in the modeling framework are valid. The conclusions presented here rely heavily on the assumption that $Mg(OH)_2$ buffers the chemistry of the repository and that all stable equilibrium phases have been identified and appropriately considered. If the MgO backfill works as proposed, and all stable phases have been appropriately considered, then it is reasonable to state that the conclusions of this model, as they apply to the full system, are valid.

3.22.2.9. Adequacy for Implementation

The Chemical Conditions conceptual model utilizes a strategy common to the physical sciences, fixing well defined parameters to allow the study of unknowns. For the most part, the model has done a very adequate job of simulating certain physical characteristics of the repository and then determining a reasonable median value. This value has become the fixed parameter (e.g., Salado brine composition) that is then passed on to other models.

To better document that a slight temperature increase in the repository beyond standard temperature and pressure (STP) conditions does not affect the repository chemical conditions, it would be reasonable to validate the assumption with a series of appropriate thermodynamic calculations.

The assumption that chemical reactions are instantaneous led to the belief that all CO_2 released to the brine would be consumed in the repository by MgO. However, this critical chemical process (MgO backfill as buffer) has not been field tested sufficiently to be confident it will work. If the technique does

not perform correctly, then the total model would fail. At a less critical level of model completeness, there is no documentation that a phase-stability review (Schreinemakers analysis) has been performed for the chemical system in question. For these two reasons, and especially that MgO has not been tested as a buffer under WIPP-like conditions, the conceptual model is not yet adequate for implementation.

3.22.2.10. Dissenting Views

There were no dissenting views for this model.

3.23. Dissolved Actinide Source Term

3.23.1. Model Description

This model is based on thermodynamic laws to predict chemical phenomena affecting dissolved actinide concentrations in the presence of actinide-bearing solids. The actinides deemed important to the performance assessment of WIPP are thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), and curium (Cm). The dissolved actinide source term determines the concentration of each actinide in solution by combining the oxidation state distribution of each actinide with the modeled solubility of that oxidation state at repository conditions and the appropriate scenario brine composition (Salado or Castile).

Several oxidation states can be screened out or substantially constrained. Oxidation states initially screened out are Np (+6), Pu (+5), Pu (+6), and Am (+5). The screening rationale are described in Appendix SOTERM (not provided to the Panel for review). Actinides limited to a single oxidation state are Th (+4), Am (+3), and Cm (+3). The model then assumes that the remaining three actinides will exist in only one oxidation state, but is unsure which of two possible states it will be. Therefore, the modeling assumes half the realizations will be in the reduced state (U +4, Np +4, and Pu +3) and half in the more oxidized state (U +6, Np +5, and Pu +4).

The factors controlling dissolved actinide concentrations are equilibrium with anhydrite, halite, MgO, actinide-bearing solid phases, appropriate brine, and water-soluble ligands.

The ligand concentrations used in the calculations are based on the Baseline Inventory Report and are reported to be acetate, citrate, oxalate and EDTA. The concentrations used represent dissolution of the entire ligand inventory. DOE believes this is a conservative approximation for the following two

reasons: (1) it does not reduce the ligand inventory by destruction mechanisms, and (2) although all ligands will dissolve in the first brine volume, the ligand concentration will stay constant for the full simulation.

Folded within the dissolved actinide conceptual model are several conceptual submodels. The solubility submodel is the Fracture-Matrix-Transport (FMT) model, which is based on the Pitzer activity coefficient model of the thermodynamics of highly concentrated electrolytes. This model uses an adaptation of the Harvie-Moller-Weare/Felmy-Weare (HMW/FW) data base. FTM parameters are fitted using the code NONLIN, which calculates the Pitzer parameters. No redox equations are used in FMT; instead, an oxidation state analogy and oxidation distribution state submodel are used.

Soluble actinide concentrations are based on solubility limits (maximum concentrations), or when a cell is partially depleted, by inventory limits. The actinide inventory is depleted on a cell-by-cell basis for the undisturbed, E1, and E2 scenarios. Processes affecting dissolved actinide concentrations in a computational cell are: dissolution of actinide solids, advection of dissolved actinides by brine flow from neighboring cells, diffusion or dispersion from neighboring cells, and interaction with colloidal particles. The E1-E2 scenario assumes homogeneous mixing within the panel for dissolved actinides moving up the borehole.

As mentioned above, the dissolved actinide source term model incorporates a very critical assumption, that of oxidation state analogy. It assumes that all actinides in the same oxidation state (ex. +III) will form the same aqueous species and isostructural solid phases. There is said to be a large data set confirming this for the 3+ oxidation state, but fewer data exist for the 5+ and 6+ oxidation states. It is also noted that such an analogy may not hold to be strictly true for the 4+ oxidation state. The rationale for using the oxidation state analogy is to allow a great reduction in the number of experiments that must be conducted.

A second assumption is that actinide precipitates formed in laboratory experiments will allow the crystallinity to mature with time. Since solids are typically less soluble than amorphous precipitates, laboratory solubility studies can then provide an upper concentration limit. The exception may be that radiolysis could cause certain solids to become more soluble.

A third assumption in the dissolved species model is that no adsorption will occur with immobile substrates in the disposal rooms. DOE however may take credit for adsorption of dissolved actinides to mineral phases in the Culebra Formation, via the Transport of Dissolved Actinides in the Culebra model.

A fourth assumption considers that dissolved actinide concentrations are also coupled to brine compositions in the disposal rooms. DOE expects this capability to greatly enhance their ability to look at site-specific solubilities based on disposal room brines and the effect of engineering modifications on dissolved actinide concentrations.

A fifth assumption centers on the presence of anoxic conditions in the repository setting. Actinide oxidation state distributions are presently unknown, since redox couples are not in equilibrium in low temperature systems. Although it is believed reasonable to expect the actinides to exist in their most reduced state because of anoxic conditions, alpha radiolysis oxidizes Am (III) to Am (V), and Pu (VI) is stabilized in the presence of carbonate. Another potential problem with the assumption is that the repository is actually under oxic conditions for the first few tens of years, due to relict atmosphere and nitrate reactions, and oxidized actinides may encounter kinetic effect problems in attaining their final reduced oxidation state.

3.23.2. Review of Criteria

3.23.2.1. Information Used to Develop the Conceptual Model

The main sources of information used are classical thermodynamics, information gleaned from appropriate journal articles, and experimental programs. The discipline of thermodynamics as a portion of the chemical sciences is well founded. A major assumption of this science is one of equilibrium conditions. The conceptual model has made liberal use of research published in the journals. Items transferred to the dissolved actinide conceptual model from journal articles range from algorithms (Harvie et al. 1987) to phase equilibria fields (Felmy and Weare 1986) to individual thermodynamic parameters (Pitzer 1991). Experimental work on actinide solubility was performed at a number of laboratories, including Sandia, Los Alamos, Argonne National Laboratories, Lawrence Berkeley Laboratory, Pacific Northwest Laboratory, and Florida State University.

Nine FEPs are used in the development of this conceptual model. These FEPs are: effects of chemical changes due to gas generation and corrosion (DR-13), electrochemical effects (DR-15), second order FEPs similar to electrochemical effects (DR-16), effect of thermal gradient (GG-4), heat from exothermic

reactions (GG-7), chemical degradation of seals (SP-5), heat from concrete hydration (SP-7), effects of microbial growth on concrete (SP-8), and electrochemical effects in the repository (RNT-25). Information gleaned from the FEPs was instrumental in both model conceptualization and test plan development.

3.23.2.2. Validity of Model Assumptions

The dissolved actinide source term model is extremely detailed, complex, and contains many implicit and explicit assumptions. One of the most significant of these assumptions is that equilibrium is maintained. Such an assumption is a basic part of thermodynamics and is considered valid only if firmly held to. However, this model picks and chooses when the concept of equilibrium is used. An example is that dissolved actinides are assumed to be in equilibrium with solids; however, redox reactions among actinides and supersaturation are not assumed to be in equilibrium. Such a philosophy may be correct for this model (it builds in conservatism) but each variance must be defended and justified adequately.

The ten other major assumptions are: (1) lack of adsorption onto immobile substrates; (2) anoxic conditions will dominate; (3) dissolved actinide concentrations are based on repository room brine compositions; (4) metastable phases in laboratory experiments become more stable with time; (5) all actinides in the same oxidation state will form the same aqueous species and isostructural solid phases; (6) the oxidation state analogy holds true; (7) experimental runs reached equilibrium; (8) fluids obtained in 1-liter experiments are representative of the tests; (9) all stable phases have been identified; and (10) the hydrogen fugacity system is completely buffered by $Mg(OH)_2$ - $MgCO_3$.

Assumption 1 is probably not valid, but by assuming so in the Salado, DOE has built a conservative estimate. Anoxic conditions in the repository (assumption 2) are valid in the long term, however short term oxidation phases were not considered. This is because activation energies needed to reduce certain oxidized phases may not occur in the repository, and the effect would be to isolate certain phases in an oxidized state. Assumptions 3 and 7 are considered valid. Assumption 4 (metastable phases become stable with time) is not a valid assumption. Time is not the only constraint on the stability of a phase, and there is no documentation that other criteria have been considered. Assumptions 5 and 9 are intimately tied together. The information provided does not confirm that an exhaustive phase equilibria stability study has been performed for this chemical system. In essence, DOE has not proved that the actinides will form the same aqueous species or solid phases, or that all phases have been identified. Regarding assumption 6, the oxidation state analogy is not truly valid. However, the assumption is oft

times conservative. This is the case for the +4 oxidation state that assumes Th solubility values. In the +3 oxidation state, however, values were obtained from another oxidation state (+5) and were not proven to be correct. The test runs for +6 phase (U) could not generate Pitzer parameters or characterize the associated solid phase. In an overall sense, it is probably inaccurate to assume the oxidation state analogy holds true. Assumption 8 (whether final liquids of 1 liter experiments are representative) is not valid due to microdomains and the absence of equilibrium conditions. However, it is not clear that these results were used in the final lookup tables. Finally, assumption 10 is only valid if the CO_2 gas is able to react completely with the $Mg(OH)_2$ backfill. As yet, no discussion exists that sufficiently assures that the reaction will go to completion. There is an equal chance that reaction rims will occur early in the process, isolate a large proportion of the backfill, and not allow the system to be buffered (see also Section 3.21.2.4).

3.23.2.3. Evaluation of Alternatives

The Dissolved Actinide Source Term conceptual model describes the quantity of actinides that would be mobilized as dissolved species in WIPP brine, and would migrate with the brines away from the repository. At one time or another over 18 years, six alternative models were proposed: (1) Expert Panel, (2) Inventory Limits, (3) Inventory Limits with Realistically Conservative Maximum Concentrations, (4) Fresh Water Estimates, (5) Chemical Model for Mobile Actinide Concentrations, and (6) Inventory Limits with Sorption. Of the six models, numbers 1, 4 and 6 were not defensible. As of December 1994, the Expert Panel model was questioned as to its credibility and technical suitability, the Fresh Water Estimate model was essentially undeveloped, and sorptive values for the Inventory with Sorption model were unavailable. Of the remaining three models presented, the Inventory Limits model was complete and defensible but highly conservative. The model that until recently was used as the baseline was the Inventory Limits with Realistically Conservative Maximum Concentrations model. Essentially, this was a combination of the Inventory Limits and Expert Panel models and was intended to be more judiciously conservative than the Inventory Limits model. The Chemical equilibrium model is based on thermodynamics and is robust but was only recently fully developed. The final model for the performance assessment (Chemical Equilibrium Model) will contain submodels that investigate the source terms for both dissolved and colloidal actinide species.

The other realm where a series of alternatives were considered was that of thermodynamic models for activity coefficients. Four modeling approaches were considered by DOE: the Pitzer model, Harned's

Rule (ion pairing), a hybrid of ion pairing and Pitzer formalism, and specific ion interaction (SIT) ion-pairing approach. Harned's Rule was only used for dilute solutions and not for brine more concentrated than 2 molal. Therefore the model was rejected. The SIT model assumes only species with opposite charges interact, and is limited to concentrations up to 3.5 molal. This model was also rejected because of its limitations. The Pitzer-SIT hybrid model did not compare the calculated lanthinide solubilities with data, so the hybrid model was dismissed. The Pitzer formalism has been applied frequently to concentrated electrolyte solutions and is backed by considerable peer reviewed journal articles. This model was therefore judged the most applicable format for characterizing the actinide solubilities in WIPP brines.

3.23.2.4. Uncertainties

There are five groups of relative uncertainty associated with the dissolved actinide source term conceptual model. The first uncertainty involves the experimental results produced by the Actinide Source Term (AST) program, while the other four uncertainties relate to how the experimental results are applied to the conceptual model.

The results of the experimental program exhibit a relatively small uncertainty (Novak 1995; Novak and Roberts 1994). When the solubility data and Pitzer coefficients from the experiments are implemented in FMT, the model results predict an uncertainty of an order of magnitude or less for the chemical conditions tested. The results of FMT modeling also compare favorably with the data of Kim et al. (1985).

The four uncertainties arising from FMT applications to the conceptual model are as follows: (1) is dissolution/precipitation steady state obtained, (2) can FMT data be extrapolated outside the realm of test parameters, (3) is the oxidation state analogy valid, and (4) are WIPP chemical conditions adequately defined? These uncertainties are much more difficult to quantify, therefore, a short discussion of each is given below.

Because of constraints imposed on the time involved in the performance assessment, the uncertainties of dissolution/precipitation steady state are fairly simple. The model assumes a long period of time in which brine will be in contact with waste and this would allow both dissolution and precipitation to equilibrate. Other assumptions that lower the uncertainty of this issue are reduced conditions, lack of

supersaturation, ample solid materials for nucleation and sorption, and brine homogeneity due to long-term mixing. All these assumptions reduce the uncertainties of achieving steady state conditions to a low level.

The second uncertainty, that of extrapolation beyond the realm of test results, has been significantly reduced by the use of MgO backfill. Originally, the experimental tests were carried out over a range of fCO_2 values, but did not entirely cover the conditions expected in WIPP. The use of MgO backfill to provide an $Mg(OH)_2$-$MgCO_3$ buffer has negated this uncertainty. The only potential problem would be if the buffer in effect did not work (see Section 3.23.2.3).

The uncertainties associated with the oxidation state analogy are more ambiguous. Actinides in the +3 state do show the same limited set of solubilities. The +5 (Np) and +6 (U) oxidation state analogies are based on experiments using those specific actinides. The remaining uncertainties all center on the +4 oxidation state analogy. Thorium was used as the test analog and it was determined that Pu and U were slightly less soluble under similar chemical conditions. The analogy of Np to Th in the +4 state was not discussed. The use of Th solubility values is still probably conservative and may raise the total +4 concentration by an order of magnitude.

The last major uncertainty concerns the chemical conditions in the repository of the Salado. The most important parameters are pH, fCO_2, brine major ion concentrations, waste material reducing capability, and organic ligand concentrations. The first two parameters (pH and fCO_2) are well controlled by the addition of MgO backfill. Such a buffering effect allows this uncertainty to be negated. Major ion concentration ranges are well constrained for Salado and Castile brines. They are not so well defined for intrusion of Culebra brine into the repository. DOE believes that the Culebra composition, after mixing with halite or anhydrite, is bounded by the Salado or Castile brines. For two of the four oxidation states, Culebra brines would be within an order of magnitude of other end-member solubilities. The uncertainties for the +4 and +6 oxidation state solubilities is larger than an order of magnitude but undefined. Reduction capabilities of waste are taken care of in a conservative sense by assigning a 50% probability to both the lower and higher oxidation states. The uncertainty concerning organic ligands is resolved by assigning an inventory value that is twice that calculated in the BIR, then incorporating the increased solubility effect of organic ligands on actinides.

In conclusion, the only outstanding large uncertainty (other than assumption validity) is that of the Culebra +4 and +6 oxidation state solubilites.

3.23.2.5. Adequacy of the Conceptual Model

The present section addresses whether the conceptual model is adequate based on the four criteria above. The outstanding issues that must be dealt with are the six unvalidated assumptions stated in Section 3.23.2.2 and the one uncertainty still unresolved in Section 3.23.2.4. When one considers the magnitude and complexity of this conceptual model, and the fact that so many issues are well addressed, these items are not overwhelming. A further nagging problem is that two major appendices of the CCA, NUTS and SOTERM, are not available. If the discussions entailed in the appendices are reasonable and logical, the assumptions are found to be valid, and the uncertainty is resolved properly, then the conceptual model would be wholly adequate.

3.23.2.6. Adequacy of Application

The issue here is whether the individual conceptual model is applied in an acceptable overall performance modeling element. As mentioned above, this is a very complex model with many variables. There is a well-documented data base for thermodynamic modeling of high concentration brines. Such data have served well as a foundation for the model. As an input to the mathematical code NUTS, this conceptual model would present its results in a lookup table. The table takes into account brine compositions, ligand availability, and oxidation state potentials, all of which allow a very robust model to be adequately applied to the performance assessment modeling elements. The true unknowns are to be found in the assumptions that the chemistry rapidly approaches equilibrium and that the waste has uniform characteristics and inventory. These fundamental assumptions are a basis of the conceptual model and are most probably adequate and reasonable.

3.23.2.7. Accuracy of Results

Preliminary results of the lookup tables have been provided to the Panel by a Principal Investigator for the conceptual model. If one assumes that the oxidation state analogy holds true, that the brine stays buffered at a pH of 9 to 10, and that the other assumptions mentioned are valid, then the results of the conceptual model are sufficiently accurate. The only qualification to this opinion is that the results may be too conservative. The solubilities calculated (and determined from experiments) are quite well

defined. To allow an order of magnitude variation on either side of the solubility parameter mean value is probably extreme and not truly representative of the chemical system involved.

The one remaining piece of information needed to thoroughly qualify the accuracy of the results would be a series of sensitivity analyses. These results are not currently available.

3.23.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Dissolved Actinide Source Term conceptual model in the modeling framework are valid. This decision is made more difficult by the fact that the appropriate tables and appendices of the CCA have not been supplied as of this date. If the information not yet available is reasonable and adequate in content, then it is reasonable to state that the conclusions of this model, as they apply to the full system, are valid.

3.23.2.9. Adequacy for Implementation

This model has turned out to be a very strong representation of how actinides would dissolve in the two major brines (Salado and Castile) of the repository and is adequate to support performance assessment. However, this model is closely linked to the Chemical Conditions model discussed in Section 3.22, and to the successful use of MgO to buffer pH conditions in the repository.

For the sake of completeness and accuracy, the remaining concerns listed in Sections 3.23.2.2 and 3.23.2.4 have not been thoroughly documented. These concerns are summarized below:

- What impact does the initial (approximately 100-year) oxygen-rich domain of the repository have on corrosion?
- What were the metastable phases in the laboratory experiments, and what stable phases did they transform to?
- Can a phase equilibria stability determination be performed for this chemical system (same as described in Section 3.22)?
- Is the oxidation state analogy valid for the +4 and +6 oxidation states?
- Did the AST 1-liter liquids reach equilibrium with the solids? If not, were the solubility results still used?
- Does the Culebra brine chemistry affect actinide solubility?

3.23.2.10. Dissenting Views

There were no dissenting views for this model.

3.24. Colloidal Actinide Source Term

3.24.1. Model Description

The Colloidal Actinide Source Term conceptual model describes the concentration of actinides sorbed to or contained in mobile colloidal particles in the disposal rooms and also describes the stable colloids that must be quantified for transport in the Culebra. The actinides addressed with this model are thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), and curium (Cm). Presently, transport of colloids in the Culebra have not been rigorously modeled because of the complexities of coupling hydrogeology, geochemistry, and colloid chemistry. Because of the chemical complexities of the integrated system and high ionic strength brines present, an attempt has been made to characterize the major colloid types believed to be present in the repository.

The four types described are "hard sphere" carrier colloids (mineral fragments), microbes, soft sphere carrier colloids or hydrophilic colloids (humic and fulvic acids) , and intrinsic colloids (true colloids). These particles develop from a variety of processes in the repository, including waste degradation, microbial activity, rock decomposition, and chemical condensation. Intrinsic colloids form by condensation of dissolved actinides in the disposal rooms. Mineral fragments and humic substances provide surfaces that dissolved actinides may sorb to. Microbes actively bioaccumulate actinides intracellularly and also act as substrates for surficially extracellular sorption (Francis 1985).

Four major decisions have been made that greatly simplify this conceptual model. First, DOE has elected to disregard the effects of competition associated with the equilibrium between dissolved actinides and actinides associated with colloidal particles. Therefore, the two source terms are not inexorably linked, resulting in an overestimation of the total concentration of mobile actinides that may leave the repository. Second, in the event that the sum of the concentrations of the dissolved actinide and colloidal actinide source terms for a particular element exceed the inventory limited concentration of that element, then a partitioning scheme is utilized. Instead of basing the partitioning on an equilibrium approach, DOE has decided to use an approach based on conservatism. The concentration of a particular actinide in the inventory is first made available to the most efficient transport mode. If the inventory is not used up, then the next most efficient transport mechanism is filled. This rationale is continued until the inventory

is exhausted by assignment to the five groups of transport vehicles (four colloidal and dissolved actinide source terms). Third, thermodynamic equilibrium is achieved by actinide intrinsic and humic colloids. And fourth, DOE has assumed that microbes and mineral fragments are present in constant quantities in the aqueous phase. This allows a steady state quantity on which the actinides can sorb.

Because of the effect of high ionic strength brines on mineral fragment colloids, which collapses the electric double layer surrounding the colloid, Van der Waals forces can cause agglomeration and settling of such colloids. Laboratory experiments using WIPP brines indicate that this settling effect largely negates mineral fragments as an effective transport mechanism. Thus, DOE has conservatively assigned a mineral fragment concentration for each actinide to be 10^{-9} m/L, one order of magnitude higher than the detection limit of the experiments.

Microbes have a large study base at WIPP, primarily to provide data for the gas generation program. This information has also been helpful in the Colloidal Actinide Source Term model. The source term concentrations associated with microbes are based on actinide uptake experimentally determined from experiments with relevant bacteria cultures. Source term values range from 10^{-5} to 10^{-11} m/L.

Humic and fulvic acids are of particular concern because of their well known capability to complex metal cations, including actinides. These soft sphere carrier colloids are not affected by high ionic strength brines, so they may be important in the transport of actinides at WIPP. To determine humic substance concentrations, actinide complexation constants from WIPP experiments or from literature are coupled with site binding densities and solubilities of humic substances in WIPP brines. Source term values range from 10^{-5} to 10^{-9} m/L.

Intrinsic colloids are well represented by the Pu(IV) polymer. The mechanism of formation of this polymer has not yet been identified; however, it is known to be stable in high concentrations in highly acidic environments. There is some evidence that the polymerization is strongly linked to hydrolysis, and that it produces an amorphous macromolecule that becomes crystalline with time. This polymer is typically on the order of nanometer size range. Hence, it is assumed to act like a hard sphere carrier colloid. Experiments were conducted by over- and undersaturation at a range of pH values to determine concentrations of Pu intrinsic colloids. The source term value of this polymer is 10^{-9} m/L. Other actinide intrinsic colloids (especially Am) were found to have negligible importance.

The computer code that will describe the transport of the Actinide Source Term model is called NUTS. NUTS is dependent on BRAGFLO (chemical conditions in waste rooms) to provide brine volumes and a lookup table to provide actinide concentrations. The actinides that will be tracked in Salado and Culebra Brines by this table are thorium (Th), uranium (U), plutonium (Pu), neptunium (Np), and americium (Am). Other chemical factors originally believed to impact colloidal source terms were pH, pCO_2, major brine constituents, ionic strength, oxidation speciation and organic ligand concentrations. Fixing the brine compositions and the addition of MgO backfill has significantly reduced the number of variables in the lookup table.

3.24.2. Review of Criteria

3.24.2.1. Information Used to Develop the Conceptual Model

The main sources of information used are journal articles, experimental programs, and classical thermodynamics. The conceptual model has made liberal use of research published in the journals. Items transferred to the Colloidal Actinide Source Term conceptual model from the journal articles are voluminous and are the basis of the experimental test program. Experimental work on actinide solubility was performed at a number of laboratories, including Sandia, Los Alamos, Lawrence Livermore, and Brookhaven National Laboratories, and Florida State University. The discipline of thermodynamics as a portion the chemical sciences is well founded. A major assumption of this science is one of equilibrium conditions.

No FEPs were included in the development of this conceptual model. In fact, colloids were not considered as a conceptual model until after the 1992 performance assessment was completed. The study of Ibaraki and Sudicky (1995) is very similar to the conceptual model developed here.

3.24.2.2. Validity of Model Assumptions

The majority of the assumptions used in the colloidal actinide source term are valid, in that they are either accurate scientific extrapolations or based on conservative measures. Four major assumptions made by DOE and discussed in the model description above are most probably valid in the context of this model. To assume that Dissolved and Colloidal Actinides Source Term models do not compete for actinides is certainly conservative and will overestimate the total actinide source term. The partitioning scheme used when the inventory is exceeded is reasonable and again conservative. The assumption that

thermodynamic equilibrium is attained for intrinsic colloids and humic colloids is valid. The assumption that there is a steady state source of mineral fragments and microbes allows for conservatism, in that it provides an abundance of sorbing material.

Two other assumptions in the conceptual model concern the use of bounding calculations. Concentrations of actinides in both intrinsic colloids (Pu+4) and mineral fragments were below the detection limits of the experiments. Therefore, the actual detection limit was used as the bounding value for the intrinsic colloid, and an order of magnitude higher bounding value than the detection limit for mineral fragments. These are probably adequate, possibly overly conservative estimates for concentrations in both cases and can be considered adequate.

3.24.2.3. Evaluation of Alternatives

The Colloidal Actinide Source Term conceptual model describes the quantity of actinides that would be mobilized as colloid species in WIPP brine, and would migrate with the brines away from the repository. At one time or another over the last four years, six alternative models were proposed for the Actinide Source term. The model names are as follows: (1) Expert Panel, (2) Inventory Limits, (3) Inventory Limits with realistically conservative Maximum Concentrations, (4) Fresh Water Estimates, (5) Chemical Model for Mobile Actinide Concentrations, and (6) Inventory Limits with Sorption. Of the six models, numbers 1, 4, and 6 were not defensible. As of December 1994, the Expert Panel model was questioned as to its credibility and technical suitability, and the Fresh Water Estimate model was essentially undeveloped. Sorptive values for the Inventory with Sorption model were unavailable. Of the remaining three models presented, the Inventory model was complete and defensible but highly conservative. The model that, until recently, was used as the baseline was the Inventory Limits with Realistically Conservative Maximum Concentrations model. Essentially, this was a combination of the Inventory Limits and Expert Panel models and was intended to be more judiciously conservative than the Inventory Limits model. The Chemical equilibrium model is based on thermodynamics and is robust but was only recently fully developed. The final model for the performance assessment (Chemical Equilibrium model) will contain submodels that investigate the source terms for both dissolved and colloidal actinide species.

The actinide inventory is originally determined by projections in the Baseline Inventory Report (BIR). A series of chemical reactions that will have a major impact on the colloidal actinide source terms are as follows:

1. Actinide dissolution reactions.
2. Reactions between brines and organic waste.
3. Reactions between brines and backfill materials.
4. Reactions between actinides and dissolved ligands (organic and inorganic).
5. Reactions that produce carrier colloids.
6. Reactions among actinides to produce actinide-intrinsic colloids.
7. Reactions between actinides and carrier colloids to produce radioactive mobile substrates.
8. Actinide sorption onto immobile substrates.

Of the eight reactions listed above, the first seven have been used in developing the current model. DOE has discarded reaction number 8. This decision is thought to be conservative and allows the possibility of more actinides being transported by colloids.

3.24.2.4. Uncertainties

The only uncertainty listed by DOE for this model involves the inventory limited concentration of the actinides. If the sum of the dissolved and colloidal actinides exceeds the inventory total, the actinide concentrations will then be proportioned between the two actinide groups (dissolved and colloidal). This philosophy appears reasonable.

Three lesser uncertainties that would add clarity to the model have not been resolved. First, it has been theorized that the Pu intrinsic colloid would act as a mineral fragment with time. Studies have not proved this theory. The mechanistic operation of this intrinsic colloid has not been determined. A second uncertainty concerns site densities available on microbes for actinides. This parameter has not been determined. Third, it is assumed that humic colloids behave like dissolved actinides. This assumption has not been adequately supported.

3.24.2.5. Adequacy of the Conceptual Model

The present section addresses whether the conceptual model is adequate based on the four criteria above. The conservative bounding values for intrinsic and mineral fragment concentrations should (in a perfect world) be discarded and real measurements taken to obtain scientifically valid results. However, when one considers the magnitude and complexity of this conceptual model, and the fact that so many issues are well addressed, these items appear almost insignificant.

The outstanding issues that must be dealt with are the three unresolved uncertainties in Section 3.24.2.4. A further nagging problem exists in that two major appendices of the CCA are not available (MASS and PAR). If the discussions entailed in the appendices are reasonable and logical, and the uncertainties are qualified, then the conceptual model would be wholly adequate and much more accurate from a scientific viewpoint.

3.24.2.6. Adequacy of Application

This section assesses whether the colloidal actinide source term conceptual model is applied into an acceptable overall performance modeling element. As discussed previously, this complex model has many variables concerning the four colloid types that are merged in. There is a well-documented data base for colloids both from the laboratory experiments specific to WIPP and journal articles. Such a series of articles has served well as a foundation for the model. As an input to the mathematical code NUTS, this conceptual model would present its results in a lookup table. The table takes into account brine compositions, proportionality constants, and oxidation state potentials, all of which allow a very robust model to be applied to the performance assessment modeling elements. The true unknowns are to be found in the assumptions that the chemistry rapidly approaches equilibrium, that the microbe culture is well known, and that the waste has uniform characteristics and inventory. These fundamental assumptions are a basis of the conceptual model and are most probably adequate and reasonable.

3.24.2.7. Accuracy of Results

Draft portions of the lookup tables were provided to the Panel by a Principal Investigator for the conceptual model. If one assumes that the dissolved actinide concentration values are accurate, that the brine stays buffered at a pH of 9-10 due to the addition of MgO, and that the other assumptions mentioned are valid, then the results of the colloidal actinide conceptual model are felt to be reasonably accurate.

The only qualification to this opinion is that the results may be too conservative. To assume concentrations no greater than detection limits of analytical equipment is deemed reasonable by regulatory agencies. However, this method may easily produce inflated values (as applied to intrinsic colloids and mineral fragments). To allow an order of magnitude increase greater than the experimental detection limit for mineral fragments is probably extreme and not truly representative of the chemical system involved.

The one remaining piece of information needed to thoroughly qualify the accuracy of the results would be a series of sensitivity analyses. These results are not currently available.

3.24.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Colloidal Actinide Source Term conceptual model in the modeling framework are valid. Since this model is inexorably linked to the solubility concentrations of the dissolved actinide source term, one may conclude that this model is valid contingent on the validity of the other model (which was determined to be valid, with minor caveats). The overall decision of outcome validity is made slightly more difficult by the fact that the final complete table (6-10) and appendices (PAR and MASS) of the CCA have not been supplied as of this date. If those pieces of information not yet available are reasonable and adequate in their content, then it is sufficient to determine that the conclusions of this model as they apply to the full system, are valid.

3.24.2.9. Adequacy for Implementation

The Colloidal Actinide Source Term model is a reasonable, if somewhat overly conservative representation of how actinides would sorb onto colloids in the two major brines (Salado and Castile) available for the repository. This conceptual model is adequate to support performance assessment. However, this model is closely linked to the Chemical Conditions model (see discussion in Section 3.22 on MgO backfill).

For the sake of completeness and accuracy, the uncertainties listed in Section 3.24.2.4 that would benefit from more supporting evidence are:

- Pu intrinsic colloids are presumed to act like mineral fragments with time, but this assumption is not adequately supported.
- Colloid site densities on microbes have not been thoroughly characterized.
- Humic acid colloids are presumed to behave like dissolved actinides, but this assumption is not adequately documented.

3.24.2.10. Dissenting Views

There were no dissenting views for this model.

4.0 INTEGRATION OF CONCEPTUAL MODELS IN PERFORMANCE ASSESSMENT

For the 24 conceptual models evaluated in Section 3.0 to be collectively useful, they must be integrated into a performance assessment model that adequately represents repository performance. The following paragraphs present a structure (reminiscent of the CCA, performance assessment code sequence) within which conceptual model integration can be illustrated and discussed. The discussion addresses criteria used for the individual conceptual model evaluations in Section 3.0. Since conceptual models are not directly used in the performance assessment, the integration of these models is, in itself, a concept equal in significance to the 24 conceptual component models.

Conceptual models provide the definition of the scope and limits of the issue addressed, define processes, enumerate variables, and provide a framework for consideration of sensitivities within an integrated system definition. The conceptual model specifies the analytical formulations to be used in numerical modeling and their relationships. Process linkages and parameter sensitivities provide a basis for data base planning and data sufficiency assessment. The conceptual model supports judgments used in generalizing data distributions for populating numerical models and supports qualitative judgments like those in the FEP process. A well established and clearly validated conceptual model for each issue is a strong element in the global integration of the overall performance assessment of a site and facility. A robust set of conceptual models for an integrated set of valid issues is the best possible control of site characterization work scope and costs.

The degree of development of conceptual models and their integration within the investigation of issues varied strongly among the models reviewed. In some cases the conceptual model and estimates based on theoretical constructs suggested by the model provided most of the information on which the review was based (for example, the Salado flow model). In some cases no conceptual model relating processes and properties to test results at a useful scale could be propounded. Robust numerical models, based on well developed testing data bases and geostatistical treatments, were successfully substituted for conceptually constrained investigations in some cases (for example, Culebra flow model). The degree to which an unquestionably valid, accurate, and precise modeling result is necessary depends on the consequence of uncertainty in any model system. Some elements of the performance model system could be adequately dealt with by assigning an unquestionably conservative result or by sampling between wide limits, based on credible analytical assessment (for example, the model). Generally, the assessment of consequences and the choice of assigned alternatives depend on strong conceptual model formulations. Where conceptual models failed or were not acceptably replaced, the formulation of a clearly defined and

systematic assessment of the relationship between the issue, processes, and data seemed to be missing. The result was sometimes the overanalysis of inadequate or low quality data or the omission of the consideration of key processes, events, or features.

4.1. Model Integration

Figure 4-1 is an illustration of where the various conceptual models represent their system or subsystem within the CCA performance assessment code sequence. BRAGFLO DBR, as illustrated, is a special, short-term application of BRAGFLO related to a drilling intrusion and includes all conceptual model system representations listed under BRAGFLO plus the Direct Brine Release model. The direct brine release element illustrates that the calculated brine volume removed from the repository by a drilling intrusion is input directly to the CCDFGF. The diamond-shaped element illustrated in the figure that receives input from NUTS and directs that input to SECO TP or CCDFGF is a decision point. If a release into the Salado has occurred, the input is directly to the CCDFGF. If the release involves transport to the Culebra, the input is directed to SECO TP. It is possible for a release scenario where NUTS output is directed to both the CCDFGF and SECO TP.

Figure 4-1 illustrates the primary associations among the conceptual models and the key WIPP performance assessment codes. One conceptual model, Chemical Conditions, is shown twice because it provides primary support to both the BRAGFLO and NUTS codes. As shown in the figure, the conceptual models do not all represent their system or subsystem in the same place in the code sequence. The figure illustrates that the conceptual models, as interpreted through the various codes, are ultimately integrated at the CCDFGF where results are prepared. The figure ignores many preparatory and post-process codes and relationships between codes that are not linear and in one direction. For example, while SANTOS is illustrated as related to BRAGFLO and receiving system representation from the conceptual model for Creep Closure, creep closure results from an iterative relationship between gas pressure, compaction, and brine characterizations from BRAGFLO and the porosity surface in SANTOS.

The integration of the conceptual models, therefore, identifies the overall performance assessment model as a complex structure that represents the 24 conceptual models through preparatory, process, flow and transport, presentation, and enabling codes.

4.2. Review of Criteria

Applying evaluation criteria to the integration of conceptual models as a concept in itself, focuses the discussion on summations of the 24 individual conceptual model evaluations. For example,

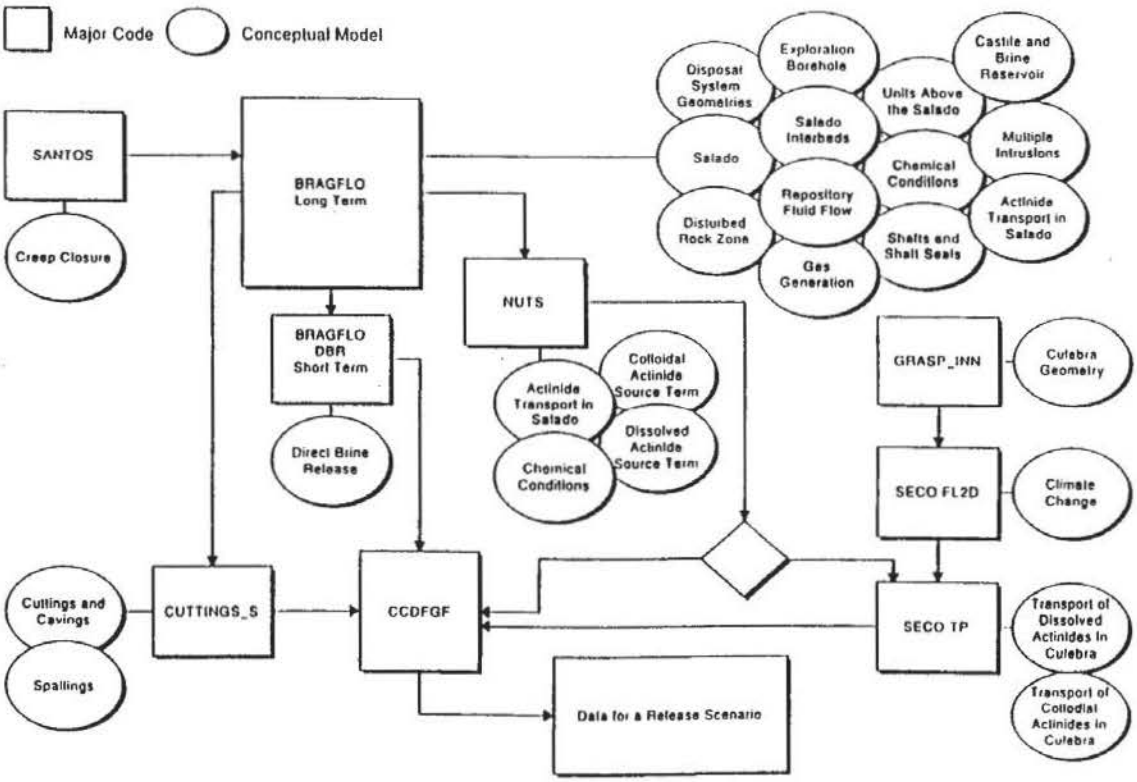

Figure 4.1. Illustration of Conceptual Model Integration

evaluations of information used in the integration, assumptions, uncertainties, adequacies, accuracy, and validity are all based on the individual conceptual models or the implementing mathematical representations or codes. The criteria have already been discussed in Section 3 for the conceptual models and without results of realizations, sensitivity analyses, and uncertainty analyses for the overall system or subsystem, conclusions cannot be made with respect to the implementing mathematics or codes.

Because the overall performance assessment modeling results were not available for Panel review, the overall adequacy for implementation of the integrated conceptual models (PA model) can only be judged at this time through the adequacy of the individual conceptual models. Some of the conceptual models are adequate but there is insufficient information (e.g., results, analysis) for the implementing structure (mathematical representations, codes, code sequence) to be judged adequate or inadequate.

5.0 SUMMARY OF EVALUATIONS

This section presents a summary of the evaluations of the WIPP Conceptual Models Peer Review Panel performed between April 2, 1996 and June 28, 1996. Over 20 years of scientific effort have been expended on the WIPP characterization project and it is beyond the scope of this report to summarize all of the positive factors and scientific evidence compiled. This section is not intended to be a reiteration of comments and discussions on the 24 individual conceptual models, but instead to provide an overview of conclusions from the evaluations. For those models found to be inadequate, the key concerns of the Panel are summarized. With the acceptable resolution of those concerns, the Panel may find most of the models to be adequate. The Culebra Hydrogeology and Units Above the Salado models are exceptions, as discussed below. The Panel's evaluations were made as a best effort over a short period of time when some models were in final development and supporting information was in flux, and therefore it is possible that some key information was available but overlooked.

Of the 24 models reviewed, 13 were found to be adequate for implementation in performance assessment for the WIPP. For most of the adequate models, minor Panel concerns remain and are identified in Section 3. These concerns primarily address issues of documentation gaps and issues with features, events, or processes that were not considered sufficiently important to find the model inadequate. The thirteen models found to be adequate are listed below.

1. Disposal System Geometry
2. Salado
3. Impure Halite
4. Disturbed Rock Zone
5. Actinide Transport in the Salado
6. Transport of Dissolved Actinides in the Culebra
7. Cuttings/Cavings
8. Multiple Intrusions
9. Climate Change
10. Creep Closure
11. Shafts and Shaft Seals
12. Dissolved Actinide Source Term
13. Colloidal Actinide Source Term

The 11 models found to be inadequate are presented in the following paragraphs with a brief discussion of the key concerns identified by the Panel. Comprehensive discussions of each of these models are presented in Section 3.

Culebra Hydrogeology

- No conceptual model was developed that explains the variability of hydrologic properties and processes in the Culebra at a scale that is useful in correlating those properties in the numerical hydrologic flow model.

- An extensive hydrologic testing data base and an apparently adequate numerical flow model were developed as a substitute for performance assessment purposes.

Although the Culebra Hydrogeology conceptual model was found to be inadequate to support numerical modeling, this inadequacy was inconsequential for performance assessment because an extensive hydrologic data base was developed and serves as an adequate substitute to support numerical modeling.

Repository Fluid Flow.

- The conceptual model and its two-dimensional numerical implementation may unrealistically restrict brine movement within the repository to the anhydrite interbeds because of the shallow depths of the borehole and shaft model cells. These restrictions could result in underestimating brine migration in the interbeds toward the accessible environment.

- The conceptual model and its two-dimensional numerical implementation do not include the presence of the unplugged ERDA-9 borehole within the wall of the operations area. This borehole could provide a pathway for gas and possibly brine to the ground surface, and no description of the plugging plan for this hole was seen in the documentation provided to the Panel.

- The sensitivity of model results to the selection of constant permeability values for the waste, panel seals, and repository DRZ has not been evaluated for the current performance assessment. Early time permeabilities may be significantly greater than the model parameter for each of these media, and could lead to underestimating radionuclide releases.

- The long-term performance of the panel closure seals has not been subjected to a detailed engineering evaluation of the type performed for the shaft seals. The role of the panel seals in restricting brine flow among the waste panels and into other parts of the repository is an important element of the conceptual model and its implementation in performance assessment.

Salado Interbeds.

- The conceptual model does not consider how the physical properties of the bounding clay seams affect model fracture propagation and permeability. Ignoring the characteristics of the

clay seams may significantly overestimate the threshold pressure at which repository gases may be released.

Units Above the Salado.

- The conceptual models and the testing data base are inadequate to exclude the Dewey Lakes Redbeds and the Magenta Dolomites as potential transport pathways for radionuclides in the event of an intrusion.

- The analysis of brine flow in the intrusion scenarios limits the quantity of radionuclides reaching the region above the Culebra to such small amounts that transport in the Dewey Lakes and Magenta have negligible consequences.

The Units Above the Salado conceptual model was found to be inadequate to support the assumption that the Culebra is the only horizon above the Salado capable of significant radionuclide transport. This inadequacy was inconsequential for performance assessment because of modeling results indicating that long-term fluid flow in exploration boreholes above the Culebra was negligible because of relatively high permeability and low pressure in the Culebra.

Transport of Colloidal Actinides in the Culebra.

- The conceptual model does not adequately support the assumption that dissolved actinides will not interact with Culebra colloids. Ignoring this phenomenon could overestimate the travel time calculated for radionuclides to reach the accessible environment.

- The experimental K_ds determined for this model are not fully defensible. Such values may overestimate the retardation of actinides in the Culebra.

- Recent experimental work to support assumptions and data for this model has not yet been published and was not available for Panel review.

Exploration Boreholes.

- The potential for releases or changes in repository conditions from borehole penetrations in the operations and experimental areas of the repository does not appear to have been evaluated. Radionuclides that may have migrated into those areas through the panel closures by diffusion or other transport mechanisms could be released to the ground surface, and gas pressures could be relieved by such boreholes. Also, brine could migrate into those areas from a borehole and then into the waste panels.

- The assumption that shorter (40 m) borehole plugs beneath the repository horizon will not significantly degrade during the 10,000-year regulatory time frame has not been adequately supported. For the two- and three-plug configurations, degradation of these plugs could result in creation of a low permeability pathway for fluid migration between the Bell Canyon and the repository. For the three-plug configuration, degradation could result in increased fluid migration from a Castile brine reservoir to the repository.

- The possibility that an effect on the repository could result from Castile brine encountered in an E1 borehole that is assigned a three-plug configuration does not appear to have been considered in the conceptual model. Castile brine could enter the repository during drilling before the borehole is cased and result in increased rates of corrosion, waste degradation, and gas production.

- The sensitivity of the performance assessment to the simplified approach taken to determine reference conditions for BRAGFLO output does not appear to have been evaluated for the current model configuration. If reference conditions are not provided at sufficiently frequent time intervals, the modeling results may be erroneous.

Spallings.

- The conceptual model for channel flow of gases toward an exploratory borehole appears to be valid but has not been adequately evaluated. Spallings is a potentially important mechanism for direct waste release to the ground surface.

- The conceptual model for waste erosion by flowing gases has not been adequately defined. The model describing the source(s) of waste erosion resistance and the parameter(s) characterizing that resistance have not been adequately evaluated. Errors in this conceptual model could lead to overestimating or underestimating the volume of waste released in the spallings process.

- The waste has not been adequately characterized and the understanding of its physical properties in its decayed state has not been adequately developed to support the Spallings model. An adequate understanding of waste erosion processes requires an adequate understanding of the properties of the waste.

Direct Brine Release.

- The basis for the assumption that radionuclides do not accompany the direct discharge of Castile brine has not been adequately supported. This assumption could lead to underestimating radionuclide releases.

- Radionuclide transport through entrainment of brine and waste solids in rapid, two-phase liquid/gas releases during inadvertent borehole intrusions does not appear to have been evaluated. This transport mechanism may be an important component of the conceptual model.

- Releases resulting from flow into an exploration borehole intersecting a disturbed rock zone in the wall of a waste panel do not appear to have been evaluated. Large, open fractures in the walls could significantly increase the local halite permeability, allowing gas and brine to migrate through the borehole to the ground surface.

Castile and Brine Reservoir.

- The basis for excluding larger, potentially depressurized brine reservoirs from performance assessment has not been adequately supported. Larger reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

- The basis for the concept of reservoir depletion through previous borehole penetrations has not been adequately supported. Non-depleted reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

- The expected probability of encountering pressurized brine beneath the waste panels has not been adequately supported, nor has the basis for apparently ignoring the quantitative value of site-specific geophysical data been presented. Unrealistically low probabilities of encountering brine may result in underestimating radionuclide releases.

Gas Generation.

- The conceptual model does not consider aluminum in the waste, steel in the rock bolts and netting, radiolysis of water by undissolved alpha emitters, and radiolysis of plastics and cellulose as sources of additional hydrogen, oxygen, and other gases. Ignoring gases generated by these effects could result in underestimating the gas pressure in the repository.

- An adequate basis has not been presented for the assumption of complete and rapid carbon dioxide removal by magnesium oxide in the waste panels. The chemical conditions in the repository would significantly change if the magnesium oxide did not function as planned, and could result in higher radionuclide releases than the model would estimate.

- An adequate basis has not been presented for ignoring the effects of heat generation from corrosion and microbial action. Higher ambient repository temperatures could increase the rates of chemical reactions, fluid flow, and halite creep.

Chemical Conditions.

- The combined temperature increase (due to radioactive decay and exothermic reactions) and its effect on repository conditions has not been adequately addressed. Significantly higher repository temperatures could accelerate chemical reactions, fluid flow, and halite creep rates.

- Phase equilibria have not been critically assessed within the chemical parameters of the conceptual model. A major element stable phase that was overlooked could significantly alter the chemical conditions of the repository and vary the actinide source terms.

- The MgO backfill has not been demonstrated to be able to react completely with CO_2 generated by microbial action. If the MgO backfill did not react as planned, the pH-buffering capability of the repository would be significantly compromised, and could result in underestimating the actinide source terms.

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WIPP Shaft Seal System Design Review, 1996. *Draft WIPP Shaft Seal System Compliance Submittal Design Report, Appendix C, Fluid Flow Analysis*, Albuquerque, NM: Sandia National Laboratories.

APPENDIX A - PANEL MEMBER INFORMATION

John Gibbons, Panel Member, is an independent geosciences consultant residing in Albuquerque, New Mexico. Dr. Gibbons has a Ph.D. in Geology from Syracuse University and Bachelors and Masters Degrees in Geology from the University of Arkansas. Dr. Gibbons has over 25 years of experience consulting to the nuclear industry and regulators. He has been involved since 1965 in several research and field studies of the behavior and geology of bedded salt deposits. He presently is a principal consultant to the Illinois Department of Nuclear Safety in its effort to license a low level nuclear waste disposal facility. His duties include the review of and contribution to work by world class contractors, national laboratories, and state scientific surveys in all aspects of site selection, characterization, and performance assessment. Dr. Gibbons has been a principal investigator for hydrogeology in many low level nuclear waste and uranium mine and mill tailings projects in the southwestern United States since 1976.

Darrell D. Porter, Panel Member, is a Senior Scientist and Manager with Science Applications International Corporation (SAIC). He has a Ph.D. in Mineral Engineering with a specialty in rock mechanics from the University of Minnesota. His M.S. degree from the Colorado School of Mines focused on experimental work in dynamic aspects of rock mechanics. He has 34 years of experience. Much of Dr. Porter's work has been in the field of blasting with high explosives and analyzing effects from a rock mechanics perspective. He has held technical management positions with the Rio Blanco Oil Shale Company where significant testing results paved the way for an effective process development resulting in four patents for Dr. Porter. During the past 13 years, Dr. Porter has supported the U.S. Geological Survey in their site characterization program for the Yucca Mountain Project. The work there included technical reviews, preparation of technical procedures, geological mapping programs, oversight of numerous contributing scientists involved in geologic sampling, mapping, modeling, technical data management, and preparation and implementation of quality assurance programs. He has collaborated with scientists from many of the National Laboratories and Universities on rock fracture and fragmentation issues.

Florie Caporuscio, Panel Member, is a Senior Scientist for Informatics Corporation. He received his Ph.D. in Geology from the University of Colorado, a Masters degree in Geology from Arizona State University, and a Bachelors degree in Geology from the University of Massachusetts. Dr. Caporuscio has 10 years of experience as a geochemist working on issues relating to high level and transuranic waste disposal.

Eric B. Oswald, Panel Member, is a Senior Scientist/Hydrologist-Water Resources Planning Specialist with the Morrison-Maierle Environmental Corporation in Tucson, Arizona. Dr. Oswald has a Ph.D. in Hydrology and Water Resources Administration and a Bachelors degree in Agricultural Economics, both from the University of Arizona. Dr. Oswald has over 25 years of experience relating to mine permitting, hazardous material contamination, flood control and flood plain design, resource damage and conservation, power generation, salinity, solid waste management, and water management. Dr. Oswald has managed many environmental programs for federal and state agencies, and municipalities.

Charles R. Wilson, Panel Technical Coordinator, has 26 years of experience managing a broad range of projects involving hydrogeology and geotechnical engineering, water resources planning, and environmental contamination. Dr. Wilson is a private consultant residing in New Mexico. He has a Ph.D. in Civil Engineering-Groundwater and a Masters degree in Geotechnical Engineering from the University of California at Berkeley. He received his Bachelors degree in Engineering from the University of California at Los Angeles. Dr. Wilson's work has included designing and conducting large scale hydrologic tests in very low permeability, fractured rock; design and regulatory permitting of large mixed radioactive/hazardous waste landfills; development of a national water resources planning agency for the Republic of the Philippines; and design of a site-wide groundwater monitoring system for the U.S. Department of Energy's Idaho National Engineering Laboratory.

Glen Sjoblom, Panel Member, is an independent consultant in the areas of nuclear waste management and safety management, residing in Great Falls, Virginia. He has a Master of Science in Chemical Engineering from University of California, Berkeley, a Bachelors of Science in Chemical Engineering from University of Minnesota, a Certificate in Nuclear Engineering from Bettis Atomic Power School, Pittsburgh, and a Certificate from the Course for Senior Managers in Government, JFK School, Harvard University. His graduate thesis dealt with two phase flow for heat and mass transfer; his undergraduate research dealt with solid liquid state chemical reaction kinetics. He was an officer in the United States Navy. He has held senior technical management positions in four different Federal Agencies over a thirty-year period, in Washington, D.C. He was responsible for the environmental controls aspects of the Naval Nuclear Propulsion Program, while on active Naval Service, including radiation protection, waste management, and environmental monitoring. He was Director of the Office of Radiation Programs at the Environmental Protection Agency, and directed development and promulgation of environmental standards for high level and transuranic waste, uranium mill tailings, Presidential Guidance to Federal Agencies on Occupational Radiation, and improved emergency response capability. He directed improvements in safety regulation and enforcement over nuclear fuel cycle facilities, industrial and

medical uses of radioactive materials, promoted improved cleanup of deactive nuclear facilities, and improved interagency coordination on chemical safety, while a Deputy Division Director at the Nuclear Regulatory Commission. He directed formation of an Environmental Management Advisory Board, and focused on improved public involvement and the use of risk assessment science in environmental restoration and waste management programs, while a Special Assistant Secretary for Environmental Management, Department of Energy. Throughout his career he has utilized risk assessment modeling and methods to promote sound decisions in the public interest.

DETERMINATIONS OF PEER REVIEW MEMBER INDEPENDENCE

C.R. Wilson

Determination of Peer Review Member Independence Form

___ Currently employed by DOE or DOE Contractor? Yes/No

X Employed by DOE or DOE Contractor previously? (Yes)/No

If yes, give dates, location, company, position type work performed.

1978 - 1983 U. of California Lawrence Berkeley Laboratory - Performed field hydrology study of Hanford Site

1983 - 1985 Hydrotechnique Inc, Berkeley CA - Performed consulting services to Hanford Site

1986 - 1996 Golder Associates Inc - Albuquerque NM - Performed consulting services to Hanford, INEL, Los Alamos Sites

___ Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Charles R Wilson

Date: 3/29/96

Peer Review Manager Approval: John A. Thies 4/8/96 Date

Darrell Porter

Determination of Peer Review Member Independence Form

Yes — Currently employed by DOE or DOE Contractor? Yes/No
yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

SRIC, my employer, has been active as a DOE Contractor for many years. To date I have had no work or other relationship to work on the DOE WIPP Programs.

NO — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Darrell Porter

Date: March 29, 1996

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

E.B. Oswald

Determination of Peer Review Member Independence Form

No — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

April through August, 1995. Albuquerque, N.M. S.M. Stoller Corporation. Served as Independent Review Team member assisting WIPP WTAC in the review of data record packages.

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

N/A

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: E.B. Oswald

Date: 3/30/96

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

Florie Caporuscio

Determination of Peer Review Member Independence Form

Yes — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

4/96 Informatics, Albuquerque NM, staff consultant Peer Review of WIPP

8/95 – 3/96 Advanced Sciences Inc, Los Alamos Office, Project Manager and Senior technical Lead, Environmental Restoration Project

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical. I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Florie A. Caporuscio

Date: 4/1/96

Peer Review Manager Approval: John A. Thies — 4-1-96 Date

Glen Sjoblom

Determination of Peer Review Member Independence Form

1. Currently employed by DOE or DOE Contractor? Yes/No
2. Employed by DOE or DOE Contractor previously? Yes/No

See below

If yes, give dates, location, company, position type work performed.

1. I have a contract with Oak Ridge Institute for Science and Education to provide an assessment of effectiveness of DOE office of Nuclear Energy Program of Assistance of nuclear reactor safety to Former Soviet Countries; this has no bearing on the proposed peer review at WIPP.
2. I was a special assistant to the Asst. Secy for Environmental Management but was not involved with activities at WIPP.

NO. Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Glen L. Sjoblom

Date: 3/29/96

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

John Gibbons

Determination of Peer Review Member Independence Form

NO — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

Battelle Alb., IRT reviewer of WIPP Data Packages 1994-1995
AFA, Alb. Site Characterization Technology Research 1992-1993
SNL Civil Systems Inc., High Level WIPP Experiment Planning
1977-1978

NO — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: [signature]

Date: NOV 29/96

Peer Review Manager Approval: [signature] John A. Thies — 4/8/96 Date

CERTIFICATIONS REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

C.R. Wilson

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer _____

Name of Offeror:_____ Signature Charles R. Wilson

Date Signed: 3/29/96 Typed name CHARLES R. WILSON

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Darrell Porter

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer 3/29/96

Name of Offeror: DARRELL PORTER Signature Darrell Porter

Date Signed: April 2, 1996 Typed name_____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

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(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

E.B. Oswald

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer 4/1/96

Name of Offeror:_____ Signature [signature]

Date Signed: _____ Typed name Eric B.Oswald

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

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(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

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(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Florie Caporuscio

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer 3/25/96

Name of Offeror: Florie A Caporuscio Signature Florie A Caporuscio

Date Signed: 4/1/96 Typed name_____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

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(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Glen Sjoblom

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No _____ Date of Offer 3/25/96

Name of Offeror: Glen L. Sjoblom Signature Glen L Sjoblom

Date Signed: 3/29/96 Typed name _____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If 'yes' provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

John Gibbons

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer _____

Name of Offeror: John Gibbons Signature _____

Date Signed: Mar 29/96 Typed Name_____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (✓) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (✓) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (✓) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (✓) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (✓) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

APPENDIX B - SIGNATURE PAGE

I acknowledge by my signature below that I concur with the findings and conclusions documented in this Conceptual Models Peer Review Report.

Florie Caporuscio

John Gibbons

Eric Oswald

Darrell Porter

Glen Sjoblom

Charles Wilson

II-G-12: Conceptual Models Supplementary Peer Review Report. December 1996

A Peer Review
Conducted By

Charles Wilson, Darrell Porter, John Gibbons,
Eric Oswald, Glen Sjoblom, Florie Caporuscio

for

U.S. Department of Energy
Carlsbad Area Office
Office of Regulatory Compliance

December 1996

EXECUTIVE SUMMARY

This report is a supplement to a July 1996 report that presented the results of an independent technical peer review of the adequacy of 24 conceptual models representing features, events, and processes involved in assessing the long-term performance of the Waste Isolation Pilot Plant (WIPP). WIPP has been developed at a site near Carlsbad, New Mexico, to become the nation's geologic repository for disposal of transuranic waste resulting from nuclear weapons programs. This independent peer review is required by 40 Code of Federal Regulations 194.27 as part of the Compliance Certification Application prepared by the U.S. Department of Energy (DOE). The U.S. Environmental Protection Agency (EPA) will use the peer review to help ensure that an adequate scientific foundation exists for a national decision on whether to dispose of this waste at WIPP.

The peer review was initially conducted from April through June 1996 at the DOE Sandia National Laboratories by a six-member interdisciplinary Review Panel having the requisite broad experience to address the range of issues associated with waste isolation over the 10,000-year regulatory time frame. The Panel selection process and the biographies of the Panel members are included in the July 1996 report.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical processes, or intrusion scenarios, are represented in the performance assessment. The Panel originally reviewed in detail the 24 conceptual models against the criteria of the EPA and NUREG 1297, including the scientific information used to develop the model, the assumptions, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The Panel then determined whether the conceptual model is adequate for

implementation in the overall performance assessment model.

In its July 1996 report, the Panel concluded that of the 24 conceptual models, 13 were adequate for implementation, and 11 were not adequate for implementation based on the Panel review of the available information and the stated EPA criteria.

In this supplementary report, the Panel provides the results of a review of the DOE responses to the Panel findings in the July 1996 report, additional information available since the earlier report (including the Compliance Certification Application) and changes that were made to eleven of the models. Following is a list of the 24 conceptual models and a statement of the Panel's current conclusions.

Disposal System Geometry	Adequate
Culebra Hydrogeology	Adequate*(1)
Repository Fluid Flow	Adequate*(2)
Salado	Adequate
Impure Halite	Adequate
Salado Interbeds	Adequate
Disturbed Rock Zone	Adequate
Actinide Transport in the Salado	Adequate
Units Above the Salado	Adequate*(3)
Transport of Dissolved Actinides in the Culebra	Adequate
Transport of Colloidal Actinides in the Culebra	Adequate
Exploration Boreholes	Adequate*(4)
Cuttings/Cavings	Adequate
Spallings	Not Adequate
Direct Brine Release	Adequate*(5)
Castile and Brine Reservoir	Adequate*(6)
Multiple Intrusions	Adequate
Climate Change	Adequate

Creep Closure	Adequate
Shafts and Shaft Seals	Adequate
Gas Generation	Adequate
Chemical Conditions	Not Adequate
Dissolved Actinide Source Term	Adequate
Colloidal Actinide Source Term	Adequate

The Panel continues to find two of the models to not be adequate, and six additional models to be adequate on the basis that there appears to be little consequence on performance assessment. For the two models found not adequate, Spallings and Chemical Conditions, the remaining issues could have a significant effect on predictions of the future state of the repository. The details of evaluations and responses to previous issues are contained in Section 3 of this supplementary report. Section 4 assesses the integration of the 24 models, and a summary of the remaining issues is contained in Section 5.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Conceptual Models Peer Review Panel issued its report in July 1996. The peer review was conducted in accordance with the regulatory requirements of 40 Code of Federal Regulations (CFR) 191 and the implementation of those requirements by 40 CFR 194. The Department of Energy (DOE) included the Conceptual Models Peer Review Report as part of its Compliance Certification Application (CCA) for WIPP that was submitted to the Environmental Protection Agency (EPA) in late October 1996.

In the Conceptual Models Peer Review Report of July 1996, 24 conceptual models were evaluated using the evaluation criteria specified by the EPA, including those of NUREG 1297. The Panel report identified thirteen conceptual models as adequate for implementation in WIPP Performance Assessment (PA) and eleven as not adequate for implementation, based on information available to the Panel. The Panel findings on each of the models judged inadequate were provided in the report. Since the Panel report was issued, DOE has developed additional information and made changes to some of the conceptual models. The DOE has also prepared responses to the findings in the Conceptual Models Peer Review Report of July 1996.

The DOE reconvened the Panel in October 1996 to review the changes to the conceptual models, the DOE responses to the findings in the July 1996 Panel report, and information available in the CCA. This report therefore supplements the July 1996 report. It is noted that preliminary DOE responses to the Panel findings were informally provided to some of the Panel members, and DOE may have reached some preliminary conclusions based on this informal

process. However, the Panel considers any such DOE conclusions as not dispositive of the Panel findings. This report contains the only definitive Panel review of the DOE responses.

Section 2 of this report describes the process for this supplementary review. For each of the 24 conceptual models, Section 3 describes any identified changes to the models and additional significant results that are important to model evaluation, as well as the DOE responses to the findings and the Panel review of those responses. Section 3 also includes any remaining findings identified, as well as the Panel conclusions on the impact of these findings on the performance assessment. Section 4 of the original report contained a discussion of the integration of the 24 models into an overall conceptual model for the waste disposal system, and Section 4 of this supplementary report provides additional discussion of model integration in the performance assessment based on the additional information now available. Section 5 provides a summary of the supplementary review including any issues remaining to be addressed. Section 5 is followed by administrative information and references. Professional biographies of each of the Panel members are included in the July 1996 report.

2.0 SUPPLEMENTARY REVIEW PROCESS

The supplementary review was conducted in accordance with DOE Quality Assurance requirements at Sandia National Laboratories (SNL) during the period October 1996 to December 1996. The Panel was provided access to written responses to earlier Panel findings, briefings and written material on changes to some of the models, results of sensitivity studies to determine the most important processes and parameters, and the final CCA, including appendices and referenced reports, as well as other information in draft form for work in progress. All this added information supplemented the information available to the Panel at the time of preparation of its July 1996 report.

This supplementary review utilized the same review criteria to judge the acceptability of conceptual models as in the July 1996 report. In the July 1996 report and in this supplementary report, a finding of adequacy was reached if any of the following were valid: (1) the model was judged technically adequate to describe the future states of the disposal system over the 10,000-year regulatory period using the EPA technical criteria; (2) adequately conservative assumptions were made for key input parameters for which a firm technical basis could not be established; or (3) the conceptual model was determined to be inconsequential to the results of performance assessment.

3.0 MODEL EVALUATIONS

3.1. Disposal System Geometry

The manner in which the dimensionality of engineered systems and surrounding geologic/hydrogeologic formations is presented in relevant chapters of the October 1996 CCA

remains substantively unchanged from previous information. Minor changes observed in the October 1996 CCA include discussions of additional intrusion scenarios and editorial inclusions that do not change the conceptual model or its adequacy. The issue raised in Section 3.1.2.2 of the July 1996 Conceptual Models Peer Review Report remains deferred to the Repository Fluid Flow conceptual model discussions in Section 3.3 of this supplementary report.

3.2. Culebra Hydrogeology

3.2.1. Model Description

No changes have been identified to the Culebra Hydrogeology model as compared to the Panel's understanding of it from the original review. An error was identified in the application of the Culebra numerical flow model which consisted of a failure to change a boundary condition from no-flow to flow at the northeast corner of the modeled area during PA calculations. This region is an area of low transmissivity, making the change a very small one. Subsequent PA calculations showed no discernible impact from this small change.

3.2.2. Review of Criteria

The review of criteria of the Culebra Hydrogeology model remains unchanged.

3.2.3. Review of Responses to Panel Findings of July 1996

3.2.3.1. Summary of Findings

The Conceptual Models Peer Review Panel found that the Culebra Hydrogeology conceptual model, though it provided support for regional hydrogeologic interpretations and model boundary conditions, did not explain the variation of hydrologic properties in the Culebra at a scale useful for flow modeling at the site scale. Although the conceptual model could not be implemented to support flow modeling at the site scale, an areally extensive hydrologic testing program at numerous sites over a significant time period had been carried out. This testing program provided the database for apparently adequate numerical flow models of the site and the site region. On the basis of the existence of these flow models, the failure of the conceptual model to provide a basis for the detailed interpretation of the hydrogeology of the Culebra was found to be without consequence to facility performance assessment.

3.2.3.2. Summary of DOE Responses to Findings

The DOE responded to the findings of the Peer Review Panel by providing extensive additional information supporting the validity of the site and site region numerical hydrologic flow models. The additional information was mostly contained in Appendix TFIELD and in results of the performance assessment calculations, which permitted the comparison of head fields based on data supplemented by the generation of pilot points and the GRASP INV code with the original measured data. These documentary sources were supplemented by presentations by and

conversations with SNL project personnel and contractors.

3.2.3.3. Panel Review of Responses

Appendix TFIELD contains an extensive explanation of the integration of regional hydrogeological concepts and the results of hydrologic testing to define general model boundary conditions, regional fields of hydrologic property variation, and preliminary fields of similar transmissivity. The measured data in transmissivity fields were augmented by the development of pilot points and Kriging, and flow model (1996 Culebra model) grids were populated following calibration (PAREST).

Measured and generated transmissivity values within each T field were sampled for PA calculations and maps, and the Panel reviewed 100 PA realizations of the head field maps for the unmined case. These were compared to the original testing measurements and to the United States Geological Survey (USGS) head field maps (Mercer 1983). The PA maps were well behaved, that is, there were no significant differences among the 100 maps reviewed, and they compared well to the original data and to the USGS maps based only on that data. This was despite the fact that the proportion of pilot points to actual data points was fairly high and that the number of adjustment steps to each point was limited. The vertical leakage to the Culebra from the overlying stratigraphic units was ignored because of the under-pressured state of the Culebra. Climatic change might make vertical leakage a significant factor in Culebra hydrology.

Detailed discussions were presented by SNL about the methods of determining the K_ds used in the range of values sampled for performance assessment and the Culebra retardation flow scenarios. The K_d values appear to be reasonable and the definitions of flow mechanisms are reasonable and typical of reflux dolomites. The proportion of flow ascribed to fractures (advection) and that to intercrystalline and intracrystalline matrix porosity (diffusion) appears to be uncertain and incompletely supported. This is in part a result of the lack of a complete hydrogeologic model and in part a function of the narrow range of inter-well distances in the multiwell tests. The scale of fracture length and the anisotropy of the fracture field are important factors in mid-distance transport, but are not likely to affect transport between the panel areas and the site margins.

In summary, it can be said that the Culebra numerical hydrologic flow model produces results that match the results of hydrologic testing well. The methodology used for generalizing the database over the T fields, the conceptual hydrologic support for the model, and the number and distribution of hydrologic tests in space and in time lend mutual support to the reasonableness of the model results. The results of the numerical flow model in performance assessment are reasonable and adequate with respect to their role in assessment of transport of radionuclides through the Culebra.

3.3. Repository Fluid Flow

3.3.1. Model Description

No changes have been identified in the Repository Fluid Flow model, and the description of the model remains unchanged.

3.3.2. Review of Criteria

The review of criteria for the Repository Fluid Flow model remains unchanged.

3.3.3. Review of Responses to Panel Findings of July 1996

3.3.3.1. Summary of Findings

The following key concerns were identified in the July 1996 Panel report for the Repository Fluid Flow model.

- The conceptual model and its two-dimensional numerical implementation may unrealistically restrict brine movement within the repository to the anhydrite interbeds because of the shallow depths of the borehole and shaft model cells. These restrictions could result in underestimating brine migration in the interbeds toward the accessible environment.

- The conceptual model and its two-dimensional numerical implementation do not include the presence of the unplugged ERDA-9 borehole within the wall of the operations area. This borehole could provide a pathway for gas and possibly brine to the ground surface, and no description of the plugging plan for this hole was seen in the documentation provided to the Panel.

- The sensitivity of model results to the selection of constant permeability values for the waste, panel seals, and repository disturbed rock zone (DRZ) has not been evaluated for the current performance assessment. Early time permeabilities may be significantly greater than the model parameter for each of these media, and could lead to underestimating radionuclide releases.

- The long-term performance of the panel closure seals has not been subjected to a detailed engineering evaluation of the type performed for the shaft seals. The role of the panel seals in restricting brine flow among the waste panels and into other parts of the repository is an important element of the conceptual model and its implementation in performance assessment.

3.3.3.2. Summary of DOE Responses to Findings

The initial DOE response to the first concern (potential restrictions to brine flow resulting from shallow cell depths in the two-dimensional BRAGFLO model) cites a similarity in fluid movement between the waste panels and the anhydrite interbeds and between other key macroscopic properties as predicted by the two-dimensional model and its three-dimensional

counterparts (see FEP Screening Analysis S-1: Verification of 2D-Radial Flaring Using 3D Geometry, SWCF-A: 1.2.07.3: PA:QA:TSK:S1, February 19, 1996). In subsequent discussions, additional information was obtained from DOE on cumulative brine flow into the repository under undisturbed conditions.

In responding to the second concern, the DOE indicated that deep, unplugged boreholes within the Land Withdrawal Area, including WIPP 13, WIPP 12, ERDA 9, and DOE 1, will be plugged with a solid concrete plug through the salt section and any water-bearing horizon.

Separate responses were provided by the DOE for each aspect of the third concern (selection of constant permeabilities in the repository). For the waste, the effect of time-varying permeability was studied and found to have an insignificant effect on key waste room conditions (see FEP Screening Analysis DR-7: Permeability Varying with Porosity in Closure Regions, SWCF-A:1.1.6.3:PA:QA:TSK:DR-7, September 28, 1995). A similar study was performed for the DRZ and a similar conclusion was reached (see FEP Screening Analysis S-6: Dynamic Alteration of the DRZ/Transition Zone (TZ), SWCF-A: 1.1.6.3:PA:QA:TSK:S-6, December 21, 1995). For the panel seals, DOE considered that repository performance will not be sensitive to the expected permeability of 1×10^{-15} m^2 or lower because flow would be diverted through the surrounding higher permeability DRZ. In addition, the concrete panel seals were not expected to significantly degrade because of low brine flux through them. This information was supplemented by subsequent information on DRZ healing and panel seal degradation provided by SNL and Carlsbad Technical Assistance Contractor (CTAC) personnel.

The fourth concern, that of the apparent lack of an engineering design for the panel seals, was addressed by presenting seal design and performance information to the Panel. Chemical degradation of the concrete was found to be minimal; however, failure by surface spalling could occur within the regulatory time frame.

3.3.3.3. Panel Review of Responses

In evaluating the response to the first concern (potential restrictions to brine flow resulting from shallow cell depths in the two-dimensional BRAGFLO model), the Panel did not consider the comparison of two- and three-dimensional model results to be adequate because the analyses included an E2 intrusion at 1,000 years which would have caused radial flow, and because the comparison was based on combined inflows in the two-dimensional model into both the single panel and the “rest of the repository.” This comparison, therefore, included flow into the southern half of the single panel that did not cross the narrow constriction created by the borehole cells. Thus, it did not adequately test the ability of brine to cross that constriction and enter the “rest of the repository,” which constitutes approximately 90% of the waste area volume. A more robust test would have been a comparison under undisturbed conditions of flow to and from the “rest of the repository,” which would have evaluated non-radial flow crossing both the constriction at the shaft and that at the borehole. In addition, the constrictions could potentially introduce a significant systematic bias into the modeling results.

In subsequent discussion of the first concern with SNL personnel, it was recognized that the majority of the rapid, early-time brine flow into the undisturbed repository (up to about 20,000 m^3) occurs because of drainage from the DRZ (Figure 3-1), which is considerably larger than the volume (up to about 6,000 m^3) that results from inflow from all anhydrite interbeds (Figure 3-2). Considering only the shaft constriction, the maximum difference in both repository inflow and outflow between the two-dimensional and three-dimensional model results was identified in the aforementioned FEP S-1 study to be about 1 x 10^6 kg of brine, or about 800 m^3 at a brine density of 1,230 kg/ m^3. If both the shaft and borehole constrictions were considered, the difference is unlikely to exceed 2,000 m^3. This volume is small compared with the approximately 20,000 m^3 that can enter by drainage from the DRZ, and its importance would diminish further in any realization involving an intrusion because the two-dimensional model is designed to simulate the radial flow induced by those intrusions. The influence of the constrictions is significantly greater for brine outflow, where FEP S-1 results indicate that the actual outflow may be on the order of twice that predicted by the two-dimensional model. This is considered conservative, however, because the total outflow volume is relatively small (generally less than 2,000 m^3)

Figure 3-1. Cumulative total brine inflow into the undisturbed repository. Not available.(7)

Figure 3-2. Cumulative brine inflow into the undisturbed repository from all anhydrite interbeds. Not available.(8)

and the presence of extra brine in the repository is expected to increase calculated releases. In view of the relatively small fluid volume involved, this first issue is considered to be adequately resolved on the basis of a lack of consequence. However, if subsequent model modifications result in significantly smaller fluid volumes in the repository, the significance of this issue should be reevaluated.

The response to the second concern (plugging of deep, unplugged boreholes) was considered by the Panel to be entirely adequate.

The response to the third concern (selection of constant permeabilities in the repository) was separately addressed by the Panel for each of the three aspects. For the waste, the key Panel concern was underestimating the permeability in early times, and thereby potentially underestimating radionuclide releases at those times. The performance assessment results have shown that the waste is compressed relatively quickly, within the first few hundred years after closure, during a period when very few intrusions occur because exploratory drilling is minimized by active and passive institutional controls. The consequence of underestimating waste permeability during this period is therefore expected to be small. In later years, when exploratory drilling is more frequent, the waste is expected to have been compressed to the extent that the assigned constant permeability will be appropriate. This conclusion is supported by the aforementioned FEP DR-7 screening analysis.

For the DRZ, the situation is more complex. The assignment of constant permeability to the DRZ is one of the more dramatic departures from actual behavior in the performance assessment

assumptions. While simplification may be justified because of the complexity of DRZ behavior, it is important to evaluate whether the assumed constant permeability is appropriate both in early times, when the actual permeability may be several orders of magnitude greater than the assumed permeability because of fracturing associated with expansion of the DRZ into the repository, and in later times, when the actual permeability may be several orders of magnitude less than the assumed value due to healing of the DRZ under lithostatic stress. In early times, the Panel's conclusions regarding the DRZ are similar to that for the waste. Even though the actual permeability may be higher than the modeled value, closure is expected to be fairly rapid and the DRZ permeability is expected to be reduced to the modeled value by the time significant exploratory drilling occurs. In later times, however, the actual permeability may be overestimated by the model and is not adequately addressed by the aforementioned FEP S-6 screening analysis, which focuses on whether the assumed DRZ permeability is high enough to allow relatively unimpeded flow between the repository and the interbeds. The impact of DRZ healing is separately addressed by the Panel for the DRZs adjacent to the roof, floor, walls, and panel seals.

Long-term maintenance of the relatively high-permeability repository DRZ assumed in the BRAGFLO model is important to performance assessment because it has been found to allow relatively unimpeded gas flow within the repository and between the repository and the interbeds. Such gas flow allows pressures within the entire repository to drop following a drilling intrusion in any part. If each waste panel were more effectively isolated, each drilling intrusion into a new panel would encounter higher, essentially undisturbed gas pressures and significantly greater releases would follow. Because of the importance of repository-wide pressure relief to long-term performance, it is necessary to evaluate the impact of the modeling assumption of constant permeability against the likelihood of DRZ healing to permeabilities several orders of magnitude lower than the assumed value.

The roof DRZ is most important to gas flow because brine that could impede such flow will tend to collect on the repository floor. Although the stress-induced fractures in that part of the roof DRZ consisting of halite are expected to heal to permeabilities approaching those of undisturbed halite, the boreholes drilled vertically through the halite for rock bolts and site characterization are not expected to close during the regulatory time frame because of their favorable orientation and circular shape. Boreholes for roof support are expected to be needed in each panel throughout the waste disposal area, and given the high conductance of an open hole, even a few such holes are expected to provide sufficient communication to the overlying anhydrite interbeds to compensate for the general loss of permeability in the halite. Because of their greater strength and reduced plasticity, deformation in the anhydrite interbeds in the roof DRZ is not expected to heal to the same extent as the halite, but rather, the interbeds are expected to retain permeabilities that are several orders of magnitude higher than their initial values. The permeability value of 1×10^{-15} m^2 assumed in performance assessment is an acceptable approximation of this disturbed anhydrite permeability. It may therefore be concluded that despite the general healing of the halite in the roof DRZ, higher conductivity

flowpaths through boreholes and disturbed anhydrites will remain between the individual waste panels and single intrusion boreholes, supporting the adoption of a constant permeability of 1×10^{-15} m^2 for the roof DRZ.

The wall DRZ is not specifically addressed in BRAGFLO and plays no role in the current performance assessment. This assumption is appropriate because in the waste panels the wall DRZ is expected to heal rapidly as soon as a back stress is applied by the laterally expanding waste. This healing is expected to occur within a few hundred years of closure, during the period of active and passive institutional control.

Healing of the floor DRZ is expected to be incomplete because the high degree of brine saturation in that area will act to maintain a higher porosity as stresses resulting from creep closure are applied. The higher porosity is expected to result in a higher permeability, and the capture of that permeability in the model is important in providing a pathway for brine to enter and exit the repository through the underlying anhydrite interbed.

The panel seals will consist of approximately 8-m long concrete plugs within the approximately 40-m long access drifts to each panel. The plug will provide a relatively strong, unyielding surface against which the surrounding DRZ is expected to rapidly heal. The concrete itself is expected to have an initial permeability of about 5×10^{-17} m^2, while the rest of the drift will remain unbackfilled and will eventually be closed by creeping halite. Although the plug and surrounding DRZ are expected to quickly form a lower permeability impediment to fluid movement than is accounted for in the constant permeability of 1×10^{-15} m^2 assigned to both system components in performance assessment, the aforementioned higher permeability pathway afforded by boreholes and disturbed anhydrites in the roof DRZ are expected to continue to allow movement of gas within the repository.

Performance assessment modeling results have shown that at the assumed permeability of 1×10^{-15} m^2 , brine flow between panels is restricted, limiting direct brine releases to the brine within a single panel. Maintenance of the panel seal at or below this assumed permeability is therefore also important to repository performance. If the ends of the concrete plug remain unsupported, it could degrade within about 4,000 to 5,000 years due to progressive spalling of the ends from a combination of applied stresses and formation of expansive minerals within the concrete. The spall would form a fine-grained residue with an initial permeability of less than 1×10^{-14} m^2 , which is similar to that of a sand-clay mixture. Compaction of this material by an applied lithostatic stress, and the closure of the open drift on either side of the plug by halite creep, provide adequate assurance that the permeability of the materials in the access drifts will remain equal to or less than the assumed value of 1×10^{-15} m^2 during the regulatory time frame. In addition, any lateral confinement of the open ends of the plug by the creeping halite is expected to prolong the life of the plug.

The response to the fourth concern (lack of engineering analysis of the panel seals) was considered by the Panel to be adequate. Although the concrete plug used in the seal may degrade within the regulatory time frame, this degradation is not expected to impair repository

performance as discussed above.

In summary, the Panel has found each of the four key concerns identified for the Repository Fluid Flow model in July 1996 to have been resolved.

3.4. Salado

There were no changes to this model and it continues to be acceptable for implementation.

3.5. Impure Halite

There were no changes to this model and it continues to be acceptable for implementation.

3.6. Salado Interbeds

3.6.1. Model Description

No changes have been identified in the Salado Interbeds model, and the description of the model remains unchanged.

3.6.2. Review of Criteria

The review of criteria for the Salado Interbeds model remains unchanged.

3.6.3 Review of Responses to Panel Findings of July 1996

3.6.3.1. Summary of Findings

This model was originally found to be well thought out and substantiated by *in situ* experiments. However, one issue in particular caused the model to be considered not adequate. The issue was:

- How do the physical properties of clay seams at the contact of the interbeds affect the fracture propagation and permeability of the model?

In addition, six other questions were posed by the Panel to enhance the clarity of the model. These are listed below:

- What is the mechanism for vertical crack propagation?
- What is the fluid storage capacity of the interbeds after dilation?
- Enhanced porosity and permeability are presumed to mitigate each other in terms of gas migration responses. How can this happen when permeability is a power function of porosity?
- What assumptions and limitations are made to represent the conceptual model by the

mathematical code?

- Why is the full fracture porosity increment of 23.9% for anhydrite beds a and b so different from the 3.9% for marker bed (MB) 138 and 139?
- What are the calculations that show the permeability increases by 10 orders of magnitude?

3.6.3.2. Summary of DOE Responses to Findings

The question that caused the model to be judged inadequate (clay seams) was specifically addressed by the DOE. The clay seams were noted to be preexisting planes of weakness. Because the *in situ* threshold pressure and permeability tests incorporated the clay seams in the test zones (which was validated by continuous core recovery), the interpreted results were considered to be representative of the combined anhydrite and clay units.

The other six questions posed to clarify the conceptual model were also answered in writing by the DOE. In summary, the abbreviated responses are listed in the same order as the questions above:

1) Fractures will propagate vertically if the least compressive stress is horizontal.

2) Simple calculations indicate storage enhancement by the following: 350% for MB 138 and 139, and 2170% for MB a and b.

3) Both permeability and porosity increase with pressure. Increased porosity provides more gas storage space and shorter migration distances. Increased permeability allows increased fluid mobility. DOE did not mean to imply that the two effects are equivalent and completely counteract each other.

4) DOE responded to this question with a description entailing two pages of the assumptions and limitations needed for the conceptual model to be represented by a mathematical code.

5) Fracture dilation is assumed to be confined to a 10 cm thickness, regardless of the thickness of the MB. Therefore, the percentage differences are based on the proportionality of the thickness differences of the interbeds (i.e., MB 138 and 139 are 5 times thicker).

6) The full fracture permeability is used as a fitting parameter so that the appropriate response is obtained. DOE believes that a ten order of magnitude permeability increase is unlikely to ever be achieved in the model.

3.6.3.3. Panel Review of Responses

The Panel has reviewed the responses by DOE on the above listed questions and finds that the model is now fully adequate for implementation.

3.7. Disturbed Rock Zone

3.7.1. Model Description

The Panel concluded that this conceptual model was adequate in its July 1996 report; however, the Panel expressed some concern for modeling the DRZ in the same manner for each of its location sites, particularly the roof and floor. The floor provides a principal repository access for brine and the roof provides a principal pathway for gas.

The DOE identified the following change. In the final CCA, the DRZ porosity was modeled as 0.29% greater than the sampled porosity of Salado impure halite, based on Room Q experimental results. At the time of the previous panel review, the DRZ porosity was not specifically linked to the halite porosity. DOE indicated that the increased porosity would increase the volume available for fluid storage in the DRZ and further delay the flow of brine into the repository. To compensate for this, the DOE assumed that the DRZ was initially saturated with brine, and concluded that the net effect of these assumptions was small.

3.7.2. Review of Criteria

The Panel agrees this change is not significant, and that this model remains adequate for implementation.

3.8. Actinide Transport in the Salado

3.8.1. Model Description

New information has been developed on this model since the Panel's July 1996 report. NUTS model runs are now performed initially in a fast tracer mode to identify BRAGFLO realizations and associated contaminated brine that never reach the top of the salt or the accessible environment in the Salado. If a tracer run indicates the possibility of a consequential release, a complete calculation of the full transport of each radionuclide is performed.

The tracer runs are performed in the following manner. The simulation considers an infinitely soluble, nondecaying, nondispersive, and nonsorbing species as a tracer element. The tracer is given a unit concentration (1 kg/m^3) in the waste disposal area. If the tracer does not reach the top of the Salado or the land withdrawal boundary in the Salado in a cumulative mass greater than or equal to 10^{-7} kg (1×10^{-6} EPA units) within 10,000 years, it is assumed that there is no consequential release to the boundary. If a mass greater than 10^{-7} kg is achieved in the tracer run, then a complete transport analysis is performed.

3.8.2. Review of Criteria

The use of NUTS as a tracer to identify which runs are capable of transporting consequential releases to the boundary is satisfactory and an efficient use of computing time. It does not

detract from the model, and therefore this conceptual model is still found to be adequate.

3.8.3. Review of Responses to Panel Findings of July 1996

3.8.3.1. Summary of Findings

In the original Conceptual Models Peer Review Report of July 1996 this model was found to be adequate. However, questions were raised in the original review of the model concerning information that was not available. These questions are listed below:

1) Validity of model assumptions - Colloids are transported at the same rate as dissolved actinides. This assumption was made because sorption and filtration of colloids are not accounted for. The assumption was not validated.

2) Validity of model assumptions - Grid blocks and time steps of BRAGFLO are proper for use in NUTS. The assumption was not validated.

3) Uncertainties - Appendix NUTS, Section 6.4.11 of CCA, and Table 6-15 were not available for review.

4) Uncertainties - Transport of radionuclides in the waste panel, panel seals, DRZ, and undisturbed and fractured interbeds was not described.

5) Uncertainties - Radionuclide input to sealed boreholes and shafts to the Culebra were not discussed.

3.8.3.2. Summary of DOE Responses to Findings

Model runs were discussed in Panel briefings by DOE and indicate that the philosophy of transporting colloidal actinides with dissolved actinides is a reasonable assumption. This assumption was also borne out in the cumulative complimentary distribution function (CCDF) runs. One preliminary NUTS model run indicated that an E2 release to the Culebra would in fact transport 18 EPA units to this boundary interface with the Culebra. Appendix SA also indicated that the CCDF runs most likely to impact the assessment are the human intrusion events involving cuttings or spallings.

BRAGFLO grid blocks and time steps have been found to be reasonable and not excessively coarse.

Appendix NUTS and Sections 6.4.10-12 are now available and have adequate explanations of the numerical codes. Table 6-15 was not used in final CCA.

Questions involving long-term transport in the repository rooms, repository panel seals, DRZ, and undisturbed and fractured interbeds have been resolved to the satisfaction of the Panel.

Sealed boreholes and shafts to the Culebra will be treated as filled with sandy material when the plug degrades.

3.8.3.3. Panel Review of Responses

The Actinide Transport in the Salado conceptual model has not changed in an adverse manner and is considered adequate.

3.9. Units Above the Salado

3.9.1. Model Description

No changes have been identified to the model of the Units Above the Salado.

3.9.2. Review of Criteria

The review of the criteria of the model of the Units Above the Salado remains unchanged.

3.9.3. Review of Responses to Panel Findings of July 1996

3.9.3.1. Summary of Findings

The Conceptual Model Peer Review Panel found that the conceptual model of the Units Above the Salado was not adequate to explain the distribution of hydrologic properties in the Magenta Dolomite or the Dewey Lake Redbeds on the site or over the site region for the purpose of the assessment of transport of radionuclides to the accessible environment. Further, the hydrologic testing database in those units is not adequate to support a numerical hydrologic flow model of the kind developed for the Culebra. The Magenta Dolomite and the Dewey Lake Redbeds are the only stratigraphic units above the Salado having significant transmissivity with respect to potential releases of radionuclides.

The Magenta Dolomite appears to be less transmissive than the Culebra, on the basis of very limited hydrologic testing. The Dewey Lake Redbeds appears to have gypsum-filled fractures throughout its lower part (raising the elevation to which brine would have to rise to enter the formation) and contains ferrous minerals that might retard radionuclide transport. Despite these possible mitigating factors, the units above the Salado cannot be adequately modeled over the controlled area to permit reliable performance assessment. However, a finding of no consequence of the inadequacy of the model of the Units Above the Salado to the performance of the facility was made based on the failure of significant quantities of brine to rise above the Culebra in the long-term performance assessment of any intrusion scenario. Volumes and rates of brine flow up and down the borehole, Culebra hydrologic pressure, and the transmissivity of the Culebra at the borehole were the principal variables considered in the calculation.

3.9.3.2. Summary of DOE Responses to Findings

The DOE made presentations to support the mitigating aspects of Magenta and Dewey Lake Redbeds hydrogeology. In addition, further PA calculations were presented using minimum values of Culebra permeabilities at the point of penetration of the intrusion borehole (BRAGFLO

code) to supplement the original calculation based on mean Culebra transmissivity.

3.9.3.3. Panel Review of Responses

The presentation by SNL on the hydrogeology of the Magenta and Dewey Lake Redbeds does provide additional reasons why these units may not be foci of concern about radionuclide releases, but does not constitute an adequate conceptual model to support PA transport modeling. The additional calculation of brine flow in the intrusion borehole through the Culebra provided additional assurance that no significant volume of brine reaches the stratigraphic units above the Culebra. The Panel's original finding that the absence of an adequate hydrogeologic conceptual model for the units above the Salado (excepting the Culebra) is of no consequence to the PA calculations is further supported by this response.

3.10. Transport of Dissolved Actinides in the Culebra

3.10.1. Model Description

This model uses a dual porosity calculation to estimate transport of dissolved actinides. DOE indicated that in implementing this conceptual model, a preliminary calculation was performed for a unit source of each of the soluble actinides, using the sampled range of K_ds based on experimental data. The results indicated an attenuation in the Culebra of more than sixteen orders of magnitude. Because of this result, DOE decided not to run the additional calculations needed to construct CCDFs for this transport pathway. DOE also stated there would be less than $1x10^{-6}$ EPA units of any of the actinides transported to the regulatory boundary through the Culebra. Additional interpretive results of hydropad tracer testing and laboratory measurements of K_ds have also become available since the Panel's July 1996 report. DOE has concluded that the Culebra could best be thought of as having several levels of advective and diffusive porosity, as shown in Figure 3-3. DOE believes that most of the flow and transport is through

Figure 3-3. Multiple scales of porosity in the Culebra.

approximately 16% of the dolomite, represented by lenses of interparticle porosity connected by vugs and fractures. The areas for adsorption are contained in these regions, as well as the intercrystalline porosity accessible only by diffusion of soluble species. This interpretation resulted from analysis of the hydropad testing that was completed after the performance assessment and the Panel's July 1996 report were completed. This added understanding was helpful in interpreting the wide range of K_ds measured.

3.10.2. Review of Criteria

The Panel in its July 1996 report concluded this conceptual model was acceptable for implementation, in that the dual porosity mathematical model provided a sufficiently accurate representation for performance assessment. However, the Panel expressed the view that the K_ds to be used needed to be properly chosen in light of uncertainties.

In its supplemental review, the Panel noted that K_ds from flow-through testing in crushed column and intact cores were significantly lower than K_ds from longer term contact testing with crushed dolomite. DOE provided information showing that the flow-through testing does not provide sufficient contact time to actually reach equilibrium values of K_d, and that therefore, the sampled ranges of K_ds provide conservative values for transport calculations.

The performance assessment used the range of K_ds from both batch tests and flow-through tests, whereas the batch test results should provide the better values. The higher K_ds were from the batch tests. However, as before, this Panel makes no conclusion on the acceptability of individual K_d values, per se, since there are other issues associated with those values that are not related to the conceptual model and that this Panel has not evaluated.

The Panel continues to find this model, as revised, adequate for implementation.

3.11. Transport of Colloidal Actinides in the Culebra

3.11.1. Model Description

DOE has identified conceptual changes in how colloids are transported, as a result of further analysis of experimental results since the Panel's July 1996 report was issued. DOE has also determined that explicit calculations of colloid transport are not needed based on this added analysis. DOE has examined the range of possible colloids by examining four specific representative types.

The model had included advective transport of colloids in advective porosity, and for small colloidal particles, diffusion followed by adsorption onto surfaces in diffusive porosity, as well as filtration of colloidal particles in pore throats. As a result of the reexamination, DOE has assigned a value of zero to K_ds for mineral fragments, microbial, and intrinsic colloids, has assigned filtration coefficients only for microbial colloids and mineral fragment colloids, and for humic colloids has assigned K_d values equal to those for soluble actinides since they are destabilized at Culebra pH conditions. The filtration coefficients are a result of the crushed column tests, and filtration was determined to be so effective at removing microbial and mineral fragment colloidal actinides that they are effectively removed in a short distance in the Culebra. The additional information not available to the Panel for its July 1996 report includes written descriptions of the various crushed dolomite column tests and core flow tests, and an improved presentation of the multiple scales of advective and diffusive porosity that are important in Culebra transport.

3.11.2. Review of Criteria

During the initial Panel review, there were some significant uncertainties that precluded a finding of adequacy for this model, particularly for the Validity of Model Assumptions. The more recent information provides the improved understanding needed for drawing conclusions.

3.11.3. Review of Responses to Panel Findings of July 1996

The Panel issues, a summary of the DOE responses, and the Panel review of the responses are provided below.

3.11.3.1. Summary of Findings

- The conceptual model does not adequately support the assumption that dissolved actinides will not interact with Culebra colloids. Ignoring this phenomenon could overestimate the travel time calculated for radionuclides to reach the accessible environment.
- The experimental K_ds determined for this model are not fully defensible. Such values may overestimate the retardation of actinides in the Culebra.
- Recent experimental work to support assumptions and data for this model has not yet been published and was not available for Panel review.

3.11.3.2. Summary of DOE Response to Findings

Regarding the assumption that dissolved actinides would not interact with Culebra colloids, DOE indicates that stable indigenous colloids in the Culebra are not expected, and that any that could be injected into the Culebra would be so rapidly filtered, based on experimental filtration coefficients, that it is conservative to assume they remain for transport only as soluble species.

Regarding the Panel-expressed issue with use of K_ds, DOE noted that values of zero were assigned to K_ds for mineral fragments, microbial colloids, and intrinsic actinides, and that for humic substances, values equal to dissolved K_ds were assigned because they would be destabilized in Culebra pH conditions and be transported as soluble species.

Regarding the lack of published reports on experimental work, published information in the CCA and its appendices responds to this issue.

3.11.3.3. Panel Review of Responses

The Panel has reviewed the changes to this model and the DOE responses to issues on this model, and concludes that these changes and responses adequately address the Panel issues of its July 1996 report. The Panel concludes that the model is adequate for implementation in performance assessment.

3.12. Exploration Boreholes

3.12.1. Model Description

No changes have been identified in the Exploration Boreholes model, and the description of the model remains unchanged.

3.12.2. Review of Criteria

The review of criteria for the Exploration Boreholes model remains unchanged.

3.12.3. Review of Responses to Panel Findings of July 1996

3.12.3.1. Summary of Findings

The following key concerns were identified in the July 1996 Panel report that were related to the Exploration Boreholes model.

- The potential for releases or changes in repository conditions from borehole penetrations in the operations and experimental areas of the repository does not appear to have been evaluated. Radionuclides that may have migrated into those areas through the panel closures by diffusion or other transport mechanisms could be released to the ground surface, and gas pressures could be relieved by such boreholes. Also, brine could migrate into those areas from a borehole and then into the waste panels.

- The assumption that shorter (40m) borehole plugs beneath the repository horizon will not significantly degrade during the 10,000-year regulatory time frame has not been adequately supported. For the two- and three-plug configurations, degradation of these plugs could result in creation of a low permeability pathway for fluid migration between the Bell Canyon and the repository. For the three-plug configuration, degradation could result in increased fluid migration from a Castile brine reservoir to the repository.

- The possibility that an effect on the repository could result from Castile brine encountered in an E1 borehole that is assigned a three-plug configuration does not appear to have been considered in the conceptual model. Castile brine could enter the repository during drilling before the borehole is cased and result in increased rates of corrosion, waste degradation, and gas production.

- The sensitivity of the performance assessment to the simplified approach taken to determine reference conditions for BRAGFLO output does not appear to have been evaluated for the current model configuration. If reference conditions are not provided at sufficiently frequent time intervals, the modeling results may be erroneous.

3.12.3.2. Summary of DOE Responses to Findings

The DOE response to the first concern cites the lack of significant consequence of borehole penetrations in the operations and experimental areas. Intrusion boreholes in those areas would have no associated cuttings, cavings, or spallings releases, and the direct brine release was stated to be negligible because of the relatively low volume of contaminated brine that would migrate through the panel seals into those areas from the waste disposal area, the dilution of radionuclide concentrations in the contaminated brine from mixing with uncontaminated brine in those areas, and the lower importance of direct brine releases to overall performance. In addition, ignoring

the repository-wide gas pressure relief that would follow such intrusions would be conservative because high gas pressures are drivers for spallings and direct brine releases. In considering brine flow in the opposite direction (from the operations and experimental areas into the waste disposal area) DOE stated that the incremental volume of brine entering the waste area would not substantially add to the brine volumes already there, and that more than enough brine was already potentially available in the waste area from other sources to react with all the waste present.

In responding to the second concern, the DOE indicated that degradation of borehole plugs beneath the repository horizon is not expected during the regulatory time frame because the service life range of 500 to 50,000 years and best estimate of about 5,000 years cited by Thompson et al. (1996) is based on overly conservative assumptions that ignore a correlation between concrete porosity and permeability, assume an unrealistically low value for the minimum concrete porosity, and assume a relatively low number of pore flow volumes required for concrete degradation. In addition, a lack of reported failures of plugs at comparable depths was cited.

The response to the third concern (the effect of Castile brine entering the repository during drilling) was provided in the form of an estimate of the volume of such brine that would enter the repository during a three-day period when the borehole is uncased during drilling. Using conservative values for borehole and repository pressures, and the standard assumptions for waste permeability and waste panel geometry used in performance assessment, the inflow volume was estimated to be less than 100 m^3. Relative to the volumes of brine inflow potentially available from other sources, this volume was not considered significant.

The fourth concern (the sensitivity of performance assessment to the use of reference conditions in determining performance assessment results) was addressed by reviewing with the Panel the shapes of the undisturbed repository pressure curves upon which the two release values for intrusions at 350 and 1,000 years were superposed. Although the response included summaries of reference conditions for other models, including Cuttings and Cavings, Spallings, and Direct Brine Release, these are based on more than two values and were correctly identified as being of lesser concern to the Panel.

3.12.3.3. Panel Review of Responses

In evaluating the response to the first concern, the Panel concurs with the DOE that, based on the performance assessment modeling results, the consequences of borehole penetrations in the operations and experimental areas are not expected to be significant. It is agreed that no cuttings, cavings, or spallings releases would occur from such penetrations. DOE's response indicated that with very few exceptions, the maximum brine flow through a panel seal was found in modeling results to be about 12,000 m^3 following an E1 intrusion, and the expected flow would be about 3,000 m^3. Under undisturbed conditions, the cumulative brine inflow into the operations and experimental areas from all sources ranges from near zero to about 10,000 m^3 (see Figures 3-4 and 3-5). This flow would, on the average, be expected to result in approximately a twofold dilution of brine flowing in from the waste area following an E1

intrusion. Under disturbed conditions with intrusion boreholes penetrating the operations and experimental areas, the inflow of uncontaminated brine and the dilution of contaminated brine would be even greater.

In the event that the operations and experimental areas are penetrated by intrusion boreholes, approximately 12,000 m^3 of brine could conceivably flow from these areas into the waste area. Performance assessment results indicate that total cumulative brine flow into the waste area is typically

Figure 3-4. Cumulative brine inflow into operations area under undisturbed conditions. Not available.(9)

Figure 3-5. Cumulative brine inflow into experimental area under undisturbed conditions. Not available.(10)

about 40,000 m^3 following an E1 intrusion at 1,000 years and about 30,000 m^3 following an E2 intrusion at 1,000 years (see Figures 3-6 and 3-7). Given that about six borehole intrusions are expected to occur during the regulatory time frame, the total volume of brine potentially available to flow into the waste area could exceed 100,000 m^3. Although the actual volume of brine inflow will depend on the interrelationships among time of intrusion, repository creep closure, gas generation, repository pressure, and other factors, the modeling results indicate that sufficient brine is potentially available from other sources that an incremental supply of as much as 12,000 m^3 would have no consequential effect on performance assessment results. However, if subsequent model modifications result in significantly smaller fluid volumes in the repository, the significance of this issue should be reevaluated.

The Panel found that DOE's response to the second concern does not support an expected lower plug service life in excess of 10,000 years because it has not been adequately demonstrated that the lower bound of the expected plug life will exceed 10,000 years. While the 500-year lower bound of the range reported by Thompson et al. (1996) may be unrealistically low, it is difficult to disregard because both the permeability (5×10^{-17} m^2) and the porosity (2%) used to compute this lower bound were reported to have been determined from field tests of an actual Bell Canyon borehole plug. The consequence of plug failure would be to open a low-permeability pathway for brine movement between the repository and the underlying Bell Canyon Formation that is not considered in performance assessment. Brine could flow along this pathway in either direction depending on pressure conditions in the repository. The volume of upward flowing Bell Canyon brine moving into the repository is not expected to be significant compared with the aforementioned volumes potentially available from other sources. Similarly, the volume of Castile Brine that would move upward into the repository following failure of the middle plug in a three-plug scenario would also have insignificant consequences.

Brine flowing downward from the repository to the Bell Canyon would only be significant if it could reach the accessible environment within the regulatory time frame of 10,000 years. A rough estimate of travel time in the Bell Canyon was prepared by the Panel based on hydrologic information provided by the U.S. Geological Survey (Mercer 1983). Primary flowpaths in the

Bell Canyon are identified by the USGS as relatively isolated, permeable channel sandstones separated by siltstones and shales with negligible permeability. Assuming the maximum reported channel hydraulic conductivity of 5 x 10^{-2} ft/day, a hydraulic gradient of 0.0038 underlying the WIPP site (from Mercer 1983, Figure 9), and an effective porosity of 10%, the travel time to the edge of the Land Withdrawal Area 2 miles away is estimated to be 15,200 years. This estimate does not consider the additional effects of chemical retardation, the travel time in the borehole, and the likelihood that a borehole would intersect the negligible permeability siltstones and shales rather than a more permeable sandstone channel. Based on this information, the Panel's second concern is considered to be resolved, based on lack of consequence.

Figure 3-6. Cumulative brine flow into repository following an E1 intrusion at 1000 years. Not available.(11)

Figure 3-7. Cumulative brine flow into repository following an E2 intrusion at 1000 years. Not available.(12)

The response to the third concern (flow of Castile brine into the repository during drilling) was considered by the Panel to be adequate.

The fourth concern (sensitivity of performance assessment to the use of reference conditions) was addressed by DOE with reference to the plot of volume-averaged pressure simulations for an undisturbed waste panel shown in Figure 3-8. As previously stated, the Panel's primary concern was with the use of only two reference conditions (350 and 1,000 years) for evaluating E1 and E2 intrusions. These reference conditions were used by applying conditions at 350 years to intrusions occurring at or before 350 years, applying conditions at 1,000 years to intrusions occurring at or following 1,000 years, and linearly interpolating conditions for intrusions occurring between 350 and 1,000 years.

Both repository pressure and brine saturation results were reviewed by the Panel in addressing this concern.

As shown in Figure 3-8, undisturbed, volume-averaged pressures are steeply climbing in virtually all realizations prior to 350 years, and applying the value at 350 years is conservative. Between 350 and 1,000 years the increase is essentially linear, and the use of linear interpolation is appropriate. After 1,000 years approximately half the curves are reasonably flat; however, the other half of the curves show continuing pressure rises for the duration of the regulatory time frame. Because of this continuing pressure rise, the assumption of constant pressure after 1,000 years is nonconservative for many realizations and may not be appropriate. Undisturbed, volume-averaged brine saturations in the waste panel and rest of the repository are shown in Figure 3-9. Again, the Panel's greatest concern is with the adequacy of assuming constant conditions after 1,000 years. The performance assessment results, however, indicate that the consequences of this concern are expected to be low. The short-term cavings, spallings, and direct brine releases, which are of primary importance to waste isolation, are computed based on a larger number of reference conditions which the Panel expects to be adequate. The two cited reference conditions associated with this concern are used only to determine long-term releases

and to provide a basis for calculating releases for second and subsequent intrusions for the short-term releases.

Figure 3-8. Volume-averaged pressure in undisturbed waste panel. Not available.(13)

Long-term releases occur via the Culebra or the anhydrite interbeds, and releases by these pathways were found in performance assessment modeling to be zero or insignificant. Second and subsequent releases were also found to not be significant because of repository pressure relief following the first penetration. Although the Panel continues to question the accuracy of results based on only two reference conditions, the concern has been adequately addressed on the basis of a lack of consequence.

In summary, the Panel has found each of the four key concerns identified for the Exploration Boreholes model in July 1996 to have been resolved.

3.13. Cuttings/Cavings

3.13.1. Model Description

DOE described a change to this model regarding the method of calculating the actinide concentration of waste that is released during drilling of exploration boreholes. Other aspects of the Cuttings/Cavings model were not changed.

Figure 3-9. Volume-averaged brine saturation in rest of repository and waste panel under undisturbed conditions. Not available.(14)

In the model as previously presented, the concentration of actinides was identified as the mean of all the concentrations of actinides in contact handled transuranic waste. DOE has revised the model to randomly sample concentrations from 569 waste streams for each of three drums assumed to be penetrated by an intrusion borehole. The average concentration from three sampled drums was used to represent the range of concentration of waste removed in Cuttings/Cavings, because the waste will be emplaced three drums high in the WIPP. DOE stated that this provides increased information on the uncertainty in waste activity levels. DOE also used nine reference times, instead of 15 reference times, to provide a basis for interpolating concentration decay curves to the random times used in CCDF construction. DOE indicates that this change does not significantly affect the model accuracy.

3.13.2. Review of Criteria

The Panel considered this model to be adequate in its July 1996 report. During review of the changes, the Panel obtained an evaluation of the significance of drilling through three drums from the same waste stream at the high end of the range of concentrations of contact handled waste, on the basis that this would be a possible, though not likely, event. DOE provided waste concentration distributions, probabilities, and corresponding releases that would result, and showed that this would not have a significant effect on the location of the highest CCDF curves.

In summary, the Panel believes this model to remain adequate, as changed.

3.14. Spallings

3.14.1. Model Description

No changes to the Spallings model have been identified as compared to the Panel's understanding of it from the original review.

3.14.2. Review of Criteria

The review of criteria for the Spallings model remains unchanged.

3.14.3. Review of Responses to Panel Findings of July 1996

3.14.3.1. Summary of Findings

Based on the three following issues, the Panel determined that this model was not adequate for implementation in performance assessment:

- The conceptual model for channel flow of gases toward an exploratory borehole appears to be valid, but has not been adequately evaluated. Spallings is a potentially important mechanism for direct waste release to the ground surface.
- The conceptual model for waste erosion by flowing gases has not been adequately defined. The model describing the source(s) of waste erosion resistance and the parameter(s) characterizing that resistance have not been adequately evaluated. Errors in this conceptual model could lead to overestimating or underestimating the volume of waste released in the spallings process.
- The waste has not been adequately characterized and the understanding of its physical properties in its decayed state has not been adequately developed to support the Spallings model. An adequate understanding of waste erosion processes requires an adequate understanding of the properties of the waste.

3.14.3.2. Summary of DOE Responses to Findings

In responding to the first concern, the DOE notes that their concept of channeling as the source of spallings release is primarily based on results of laboratory experiments conducted on graded, low-moisture silica sands. The tests showed that upon achieving a steady state gas flow rate with no additional material being removed, an irregular void space results. Plaster castings of this void show that some voids are radial channels and others are a series of thin layered lenses or shells. Data from these tests were used to calibrate the model by defining values for "effectiveness factors."

The experiments show channels that extend from the borehole outward as a result of eroding effects of flowing gas within weakened planes which result from local variations in initial porosity

and permeability, or by tensile (or shear) failure resulting from pressure gradients. DOE also describes studies of *in situ* coal fracturing for methane production (Mavor and Logan 1994) by means of rapid drops in gas pressure in the borehole.

The DOE response to the second issue relates the effects of gas movement over a surface to the erosional effects from flow of liquids or gases through a pipe. This erosion is seen to be caused by a combination of shear and tensile stresses which can be related to the force required to dislodge particles from the surface into the fluid stream. This force is seen to be related to the tensile strength and density of the waste. A mathematical model was developed from first principles that relates the particle dislodging forces to the drag forces present from the flowing gas, which are a function of individual particle dimensions and fluid viscosity, density, and velocity. This equation, when "calibrated" by means of experimentally determined effectiveness factors, is believed to be an analogue to the erosional forces described above.

The model is predicated on the assumption that the bonding strength of the particle to the waste surface is related to the macroscopic tensile strength of the degraded waste. One pound per square inch was chosen as an appropriate value for the bonding strength of waste in the calculations. Data were supplied that show this value to be within the range of literature values for strengths of soils, lab mixtures of salt and clay, and various materials mixed with MgO (Bergland et al. 1996).

The third DOE response specifies that the spallings phenomenon occurs only when there is brine inflow and waste decomposition. DOE states that because both of these are unknowable, it is assumed that the decomposed state will be a graded granular material consistent with the granular nature of decomposed geologic materials and corresponding to the end state of the decomposition process.

3.14.3.3. Panel Review of Responses

In reviewing the response to the first issue, the Panel has several basic points of discussion relevant to the DOE's evaluation of the model for adequacy:

- The forces responsible for detaching the waste pieces from their mass do not include the gases exiting the mass into the open gas-filled cavity. The Panel believes this type of gas flow will be largely responsible for the force required to counteract whatever bonding force exists. Such a force might be analogous to the forces (i.e., pressure gradient) on particles or groups of particles at the upper surface of a packed bed nearing the point of fluidization.

- The data on tensile strengths were from static tests and were not shown to be applicable in this dynamic situation. It is noted that in the Cuttings/Cavings model, static shear strengths were modified to be applicable to the dynamic situation.

- There is no evidence found in the record that time effect considerations were evaluated in

either the development of the equations or in the conduct of the experimental tests.

- The bounding equation as presented is not solidly verified, not only because of the lack of consideration for the former comments, but also because the testing results do not support the assumptions used in equation development. For example, the dropped g term dealt with cohesive forces such as water, while the only positive test results achieved were those with moisture-laden sand.

- The effect of cementation was added when formulating the final equations describing the Spallings model and the experimental work did not evaluate these effects.

- Evaluations of the models did not include analogues from other industrial or scientific disciplines to determine a basis for reasonableness. The DOE was apparently not as successful in conducting such an evaluation as it was for the Cuttings/Cavings model. The coal mining methane gas stimulation example is good; however, several others are expected to be applicable, such as chemical engineering processes (for example, fluidized beds) and the work over the years on particulate transport in volcanology. There may be existing correlations to these processes that are directly applicable.

- The experiments were basically quasi steady state, rather than demonstrating the dynamic situation. Uniform particle distribution was used, rather than a more realistic range of particle sizes. No control was maintained over the moisture content of the sand. All these issues would seem to impact the relationship between the experimental system and the repository.

- The experimental results should be subject to scaling, which was not found by the Panel to be addressed. Also, the data did not include measurements of pressure drops at various locations throughout the system (for example, at the cavity-waste interface). Both of these issues might be reanalyzed without further experimental work.

Review of the response to the second issue also raised several points for discussion relative to the design of the model.

- While the concept of cementation was included in the model, the process by which this cementation would occur was not addressed in the experimental program.

- Flow velocities that approach transonic or beyond have not been considered and, if velocities are transonic at times during the spallings process, might require a factor addressing increased effects on the pressure across the cavity-waste interface boundary.

- The process as modeled does not have a provision for processes occurring at times of high pressure gradients. It would appear realistic that some volume of the waste dislodged from the matrix would be a spall produced by a process largely unrelated to the gas velocity parallel to a surface.

Relative to the third issue, the DOE responses are acceptable as explanations of the state of the conditions bounding the effects of the Spallings model. It is important to note, however, that the assumption that the waste will be in a fully decomposed state consistent with the granular nature of decomposed materials could be unnecessarily conservative.

Following the Panel description to DOE of the above concerns, DOE provided a further verbal response addressing the conservativeness believed to exist in the Spallings model. DOE listed as conservative model elements use of a small particle diameter, constant pressure during spalling, ignoring capillary forces, tortuosity of the channels and possible plugging, channels too small or narrow to transport all the particles that may be dislodged, and the use of a low end value of the waste strength range found in the literature.

The Panel believes that because of the many unresolved issues of a fundamental nature, it cannot acknowledge that this model provides a conservative method of calculating Spalling releases.

Integration of the Spallings model in performance assessment revealed that this model is one of the major sources of radionuclide release to the surface. While changes might come about in further work relative to this model, it is realistic to expect that the Spallings model will continue to be important to the total release. Therefore, the Panel believes that this model is not adequate for predicting the future states of the repository.

3.15. Direct Brine Release

3.15.1. Model Description

Since the Panel's July 1996 report, the uncontrolled borehole flow period assumed in performance assessment was changed from 44 hours to a minimum of 72 hours (3 days) and a maximum of 11 days, depending on the rate of gas flow as determined in the model from repository pressure and gas volume. The borehole is assumed to remain uncontrolled for as long as the gas flow rate exceeds a threshold value, up to a maximum of 11 days.

3.15.2. Review of Criteria

The change in the conceptual model was based on current drilling practices in the Delaware Basin and is consistent with regulatory guidance. Although the modeling assumptions are conceptually valid, the validity of their implementation depends on current drilling practices, which are beyond the scope of the Panel to review.

3.15.3. Review of Responses to Panel Findings of July 1996

3.15.3.1. Summary of Findings

The following key concerns related to the Direct Brine Release model were identified in the July 1996 Panel report.

- The basis for the assumption that radionuclides do not accompany the direct discharge of

Castile brine has not been adequately supported. This assumption could lead to underestimating radionuclide releases.

- Radionuclide transport through entrainment of brine and waste solids in rapid, two-phase liquid/gas releases during inadvertent borehole intrusions does not appear to have been evaluated. This transport mechanism may be an important component of the conceptual model.

- Releases resulting from flow into an exploration borehole intersecting a disturbed rock zone in the wall of a waste panel do not appear to have been evaluated. Large, open fractures in the walls could significantly increase the local halite permeability, allowing gas and brine to migrate through the borehole to the ground surface.

3.15.3.2. Summary of DOE Responses to Findings

The DOE response to the first concern addressed the small likelihood that Castile brine flowing up an open borehole would circulate significantly within the repository, displacing contaminated repository brine, which would flow up the borehole. This was considered unlikely because of the unlikely set of pressure conditions that would first allow Castile brine to flow into the repository and then, a few hours or days later, would reverse and allow repository brine to flow into the borehole. Also, unless the pressure gradients were large, the volume of such flow would be small (as described in Section 3.12).

The initial response to the second concern (entrainment of solids in two-phase gas/brine flow) was addressed by modifying the fluid density in the spallings model to estimate the entrainment of solids in a fluid with the density of a gas-brine mixture. A second analysis was later provided at the Panel's request that modified both the fluid density and viscosity. This second analysis indicated that the overall effect of this change was to reduce the volume of solids from that released by the gas flow alone.

In responding to the third concern (releases from a borehole intersecting the DRZ within the wall of a waste panel), the DOE indicated that the wall DRZ is expected to heal soon after a backstress is provided by the compacted waste. This is expected to occur much more rapidly than the healing of the roof and floor of the waste panels and will be essentially complete during the period of active and passive institutional controls. Because drilling rates are very low during this period, few boreholes (if any) are expected to intersect the wall before the DRZ is healed, and the consequences of ignoring the wall DRZ are therefore not significant.

3.15.3.3. Panel Review of Responses

The DOE response to the first concern (entrainment of waste in Castile brine discharges during drilling) was considered to be adequate with regard to the circulation of Castile brine within the repository. However, the possibility of a cavings-type release through erosion of waste in the borehole wall by upward-flowing Castile brine was not addressed. In response to an information request submitted by the Panel, a conservative estimate of incremental cuttings and cavings

releases was prepared by DOE. This estimate indicated an increase in releases for an E1 event ranging from 22% to 87%, depending on the assumed waste shear resistance. The average increase was reported to be 38%. If it is conservatively assumed that the repository is typically intersected by 6 boreholes during the regulatory time frame and that from 8% to 30% of these intersect a Castile brine reservoir, the net effect of borehole wall erosion by Castile brine would be to increase the cuttings and cavings releases by from 3 to 13%. While such an increase may be considered significant, in view of the overall uncertainties in the performance assessment model, such an increase is not expected to have a strong impact on the final CCDFs and the Panel considers this concern to have been adequately addressed.

The quantitative response to the second concern (entrainment of solids in a two-phase gas/brine mixture) was appreciated by the Panel, and the conceptual approach (that of employing the Spallings model to address the issue) was considered appropriate for scoping purposes, although adjustments were not made to the model for two-phase rather than single-phase flow and for liquid rather than gas flow. However, the appropriateness of the Spallings model itself is of concern to the Panel, as discussed in Section 3.14. Until the Spallings model is found to be adequate, the results obtained from the model in addressing this concern cannot be considered valid. The Panel has chosen to find the DOE response to this concern adequate on the basis that application of the Spallings model to this concern is conceptually appropriate in a scoping sense, rather than to determine that both the Direct Brine Release and Spallings models are inadequate on the same basis. However, the Panel believes that this concern should be reevaluated when an adequate Spallings model is developed.

The response to the third concern (releases from a borehole intersecting the DRZ within the wall of a waste panel) was considered by the Panel to be adequate.

In summary, the Panel has found each of the three key concerns identified for the Direct Brine Release model in July 1996 to have been resolved.

3.16. Castile and Brine Reservoir

3.16.1. Model Description

The 10% probability of encountering a brine reservoir provisionally assumed in the early performance assessment documents was changed in the final performance assessment to 8%.

3.16.2. Review of Criteria

The change in the conceptual model was based on results obtained from a geostatistical analysis of brine encounters in boreholes drilled near the WIPP site. The basis used by DOE for estimating this probability was identified as a key concern of the Panel in its July 1996 report and is discussed below.

3.16.3. Review of Responses to Panel Findings of July 1996

3.16.3.1. Summary of Findings

The following key concerns related to the Castile and Brine Reservoir model were identified in the July 1996 Panel report.

- The basis for excluding larger, potentially depressurized brine reservoirs from performance assessment has not been adequately supported. Larger reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.
- The basis for the concept of reservoir depletion through previous borehole penetrations has not been adequately supported. Non-depleted reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.
- The expected probability of encountering pressurized brine beneath the waste panels has not been adequately supported, nor has the basis for apparently ignoring the quantitative value of site-specific geophysical data been presented. Unrealistically low probabilities of encountering brine may result in underestimating radionuclide releases.

3.16.3.2. Summary of DOE Responses to Findings

The DOE response to the first concern (the exclusion of larger reservoirs from performance assessment) indicated that brine flow up the borehole was correlated to the product of reservoir volume and pore compressibility, rather than to the reservoir volume alone. DOE also acknowledged that its range of bulk rock compressibility values may be too large, and if the smaller range of 2×10^{-11} to 1×10^{-10} Pa^{-1} recommended by Popielak et al. (1983) were used, the maximum pore volume x compressibility, product used in performance assessment (6×10^{-2} m^3/Pa) would be equivalent to a reservoir pore volume of 5.5×10^6 m^3, assuming a porosity of 0.0087. This value is considerably larger than those identified in performance assessment, and is of the same order of magnitude as the pore volumes estimated for the reservoir encountered by WIPP-12.

The response to the second concern (basis for reservoir depletion assumptions from prior drilling) was addressed for reservoirs larger than the waste panel area. Because of their size, the areas of the larger reservoirs are predicted to be penetrated more than 1,000 times over a 10,000-year period under the assumptions presented in regulatory guidance. The initial DOE response to this concern was based on the assumption that all deep boreholes would penetrate and partially deplete such reservoirs. A revised response was provided to the Panel during oral briefings in which the assumption that only 8% of the drilled boreholes will actually encounter brine was included. With this revision, depletion of the larger reservoirs was less rapid and led DOE to conclude that the analysis did not strongly support the depletion concept. The DOE response did not address the assumptions presented in the CCA for depletion of reservoirs smaller than the waste panel area, and in subsequent oral presentations it was learned that those assumptions were made without quantitative basis.

In responding to the third concern (the probability of encountering pressurized brine beneath the

repository), the DOE provided a summary of the geostatistical methods applied, as well as information indicating that the consequence of the assigned probability on performance assessment results was small. The small consequence was demonstrated by comparing the long-term effects of Castile brine flows on the key performance assessment parameters of net brine inflow, brine saturation, porosity, and gas generation in a penetrated waste panel, and total spallings releases.

3.16.3.3. Panel Review of Responses

The DOE response to the first concern (the exclusion of larger reservoirs from performance assessment) was considered by the Panel to be adequate. The compressibility range of Popielak et al. (1983) lies within the range used in performance assessment, and reservoir volume is estimated based on such compressibility data. Reservoir compressibility is acknowledged to be highly uncertain, and although the range proposed by Popielak et al. (1983) may be somewhat restrictive on the high end, minor increases in that range would not substantially alter the conclusion that if the smaller range of compressibilities were considered, the DOE *de facto* included consideration of reservoir volumes extending into the millions of cubic meters. Correlary to this issue is the likelihood that the incremental volume of brine flowing to the repository from a larger Castile reservoir would be small in comparison to the volumes potentially determined to be available in the current performance assessment (see Section 3.12) and would have no consequential effect on releases.

The response to the Panel's second concern (basis for reservoir depletion assumptions from prior drilling) was separately reviewed for reservoirs both larger and smaller than the WIPP waste area. Because their analysis did not support the assumption of depletion for the larger reservoirs, the Panel assumes that this aspect of the conceptual model will be withdrawn by DOE. The issue of depletion of these reservoirs is moot, however, because of the Panel's aforementioned conclusion that *defacto* consideration of larger reservoirs was included in the performance assessment model.

The smaller reservoirs explicitly assumed to exist beneath the waste area are assumed by DOE to range in volume from 32,000 m^3 to 160,000 m^3. Such reservoirs are assumed to be depleted to the point of no consequence by from 2 to 6 prior penetrations, which may occur from boreholes penetrating either the waste panels or the unexcavated halite within the waste area. Depletion of a 32,000 m^3 reservoir was included in the aforementioned DOE analysis. The results indicate that less than one borehole is expected to encounter brine in a reservoir of this size during the regulatory time frame because of the small surface area. Assuming the reservoir is 67 m thick, the average maximum total brine flow would be only about 400 m^3 to the surface during drilling and 1,200 m^3 to the Culebra during the following 10,000 years. Results for a 160,000 m^3 reservoir of the same thickness indicated a total brine flow of about 2,100 m^3 to the surface and 6,000 m^3 to the Culebra during the following 10,000 years. Because of the larger surface area of this reservoir, an average of 14.1 brine encounters were expected in that period. After about 6 brine encounters, the brine flow from this larger reservoir to the Culebra totaled 5,200 m^3, or

about 87% of the total.

Based on these results, the Panel concurs that the DOE response to the second concern is adequate. The larger reservoirs are considered to have been included in the performance assessment by virtue of the selection of a narrower range of compressibilities, and the depletion assumptions for the smaller reservoirs are appropriate.

A related concern is the method used to determine the probabilities that the reservoir assumed to underlie the repository would be a certain size. The selected probabilities range from 1/32 for the largest reservoir (160,000 m^3) to 10/32 for intermediate size reservoirs (64,000 and 96,000 m^3). The basis for these assignments was an event tree approach in which the repository, including the operations and experimental areas, was divided into five sections, each with a 50% probability of having an underlying reservoir. This gave 32 possible combinations. Probabilities were then assigned based on reservoir area, with the lowest probability being assigned the largest reservoir (which would have to simultaneously underlie all five sections). The Panel considers this approach to be geologically unrealistic. However, because the brine volume that would be released from even the largest of these reservoirs is low compared with the total volume of brine available to the repository (see Section 3.12), the consequence of the assigned probabilities is considered to be low. However, if subsequent model modifications result in significantly smaller fluid volumes in the repository, the significance of this issue should be reevaluated.

The Panel considers the DOE response to the third concern (the probability of encountering pressurized brine beneath the repository) to have an inadequate technical basis, but finds the concern resolved due to a lack of consequence. The following technical concerns remain: (1) there is a lack of data on brine encounters and non-encounters in the vicinity of the WIPP Site to support the geostatistical analysis, and the adopted probability of 8% appears to be quite sensitive to this lack; (2) the Panel is not confident that non-reported brine can be assumed to be a “no hit”; (3) the concept that a borehole can miss an underlying brine reservoir because of vertical fracturing is conceptually reasonable but lacks quantitative support, yet it apparently provides the primary basis for discounting the quantitative value of the TDEM data; (4) the correlation between reservoir occurrence and geologic structure is conceptually reasonable but ignores other potential correlations; and (5) not enough geological information exists at the site to support such correlations.

A lack of consequence was demonstrated by DOE for the third concern by comparing the long-term effects on the repository and on spallings releases of E1 and E2 intrusions. These comparisons are intended to show that the differences between a reservoir hit and no-hit are not highly significant. Noting that the total number of boreholes penetrating the site is unchanged by this issue, by inference the differences created by increasing the number of hits and decreasing the number of no-hits should also not be significant. The differences between E1 and E2 intrusions are illustrated in Figures 3-10 through 3-18. The net brine inflow into the waste panel for E1 and E2 penetrations at 350 years is shown in Figures 3-10and 3-11. While the early-time results differ, the longer-term results are similar, although the net inflow is on the average about

1,000 m^3 higher for an E1 than an E2. The volume-averaged brine saturation in the waste panel for E1 and E2 penetrations at 350 years is shown Figures 3-12 and 3-13. Here the results are similar for both the short- and long-term, although the number of lower saturation, outlying curves is smaller for the E1 than the E2 intrusions. Cumulative brine flow up the borehole at the bottom of the waste panel for an E1 penetration at 350 years is shown in Figure 3-14. Because the E2 borehole does not encounter a brine pocket, the corresponding E2 flow would be zero and the figure shows the incremental brine available to the repository from an E1 intrusion. Although the maximum volume in excess of 50,000 m^3 is significant, the volume is more typically less than 10,000 m^3 and is not significant in comparison with the overall volume of brine potentially available to the repository (see Section 3.12). The volume-averaged porosity in the waste panel for E1 and E2 intrusions at 350 years is shown in Figures 3-15 and 3-16. The difference between the curves is negligible. The total gas generated in the entire repository is shown for E1 and E2 intrusions at 350 years in Figures 3-17 and 3-18. Again, the difference is negligible. Spallings releases were also reviewed by the Panel for second E1 and E2 intrusions (note that spallings releases for first intrusions would be identical for E1s and E2s).

Figure 3-10. Net brine inflow into waste panel for E1 penetration at 350 years. Not available.(15)

Figure 3-11. Net brine inflow into waste panel for E2 penetration at 350 years. Not available.(16)

Figure 3-12. Volume-averaged brine saturation in waste panel for E1 penetration at 350 years. Not available.(17)

Figure 3-13. Volume-averaged brine saturation in waste panel for E2 penetration at 350 years. Not available.(18)

Figure 3-14. Cumulative brine flow up borehole at bottom of waste panel for E1 penetration at 350 years. Not available.(19)

Figure 3-15. Volume-averaged porosity in waste panel for E1 intrusion at 350 years. Not available.(20)

Figure 3-16. Volume-averaged porosity in waste panel for E2 intrusion at 350 years. Not available.(21)

Figure 3-17. Total gas generated for E1 intrusion at 350 years. Not available.(22)

Figure 3-18. Total gas generated for E2 intrusion at 350 years. Not available.(23)

Because of the moderating effect of gas pressure reduction following the first intrusions, the differences between spallings releases for the second intrusions are not significant. In summary, the Panel agrees that the differences between E1 and E2 intrusions for key repository conditions and performance criteria are small and finds the DOE response to be acceptable on the basis of a lack of significant consequence. However, if subsequent model modifications result in significantly smaller fluid volumes in the repository, the significance of this issue should be reevaluated.

In summary, the Panel finds that each of the three key concerns identified for the Castile and Brine Reservoir model in July 1996 has been resolved.

3.17. Multiple Intrusions

No key concerns were identified for the Multiple Intrusions model in the Panel's July 1996 report.

3.17.1. Model Description

The number of reference conditions for determining releases to the Culebra was reduced from 14 to seven since the July 1996 Panel report was issued.

3.17.2. Review of Criteria

The Panel does not expect the reduction in the number of reference conditions to significantly affect modeling results, and finds the change acceptable.

3.18. Climate Change

3.18.1. Model Description

The description of the Climate Change conceptual model and use of the climate index remains substantively unchanged from the July 1996 review. The model continues to be adequate.

3.18.2. Review of Criteria

The review of criteria for the Climate Change model remains unchanged; however, two issues previously identified for this model were reviewed based on new information received.

3.18.2.1. Summary of Issues

The following two issues related to climate change were reviewed.

1) The absence of a consideration of vertical leakage in the Culebra, which might be considerably enhanced by future, more humid climatic conditions, may overlook significant effects on Culebra flow.

2) The potential change in flow directions in the Culebra associated with future wet climates may impact releases through the Culebra.

3.18.2.2. Summary of New Information

Several conversations with SNL personnel confirmed that the vertical leakage issue has not been specifically addressed. New discussions in the CCA documents address changes in flow direction noted in three-dimensional simulations associated with future wet climates. These changes were excluded from PA modeling for computational efficiency and because the changes in direction were toward regions of lower conductivities.

3.18.2.3. Panel Review of New Information

The FEP NS-9, SMOR of September 21, 1995, included in the recent materials provided to the Panel as CCA Appendix MASS, Attachment 15-7, states that vertical leakage into the Culebra is ignored in flow and transport calculations. The SMOR also states that the basis for the assumption that the two-dimensional model and its boundary conditions adequately represent flow-conditions in the Culebra has not been "systematically investigated or documented." The principles of regional groundwater flow in layered sediments suggest that vertical leakage may make a significant contribution to total inflow to the Culebra within the site area boundaries. While there is limited information describing the leakage, ignoring substantial leakage could introduce error into calibrated T fields, and the resulting two-dimensional flow fields may be erroneous.

While the FEP was reviewed by the Panel earlier, prior to preparing the Conceptual Model Peer Review Report of July 1996, the fact that the Culebra conceptual model was found to be inadequate (but inconsequential since the hydrologic data base supported numerical modeling) precluded further serious inquiry. The Panel's stated lack of suitability of the two-dimensional model for determining boundary conditions and estimating changes in the boundary conditions over time, and the absence of calculations supporting the assumed conditions, re-emphasize this source of uncertainty in the Culebra flow and transport calculations.

Additional calculations with GRASP-INV that would evaluate the sensitivity of T fields, release paths, and travel times to vertical leakage are planned, but are not complete at this time. Preliminary, one-dimensional calculations (not QA[d]) indicate that T field impacts would be less than 10%, although no inverse solution of the T fields has been completed. There are neither preliminary calculations nor reasoned arguments of sufficient strength to judge the impact of the issue with respect to flow fields. In summary, the Panel concludes that there are no appropriate supporting calculations or sufficient reasoned arguments to exclude vertical recharge from flow and transport modeling in the Culebra.

New discussions in CCA documents and additional documents made available to the Panel since the July 1996 Conceptual Model Peer Review Report emphasize potential changes in flow directions in the Culebra associated with future wet climates. The CCA (October 1996, Chapter 6, Section 6.4.9) states that changes in flow direction were noted in three-dimensional simulations associated with future wet climates. It also states that such changes were excluded from modeling for computational efficiency. The only support of the exclusion is the conclusion that the flow direction change is in the direction of lower conductivities and considering only the most conductive portion of the Culebra is conservative. The CCA Appendix MASS 14.2 and 17.1 also discuss changes in flow direction in the Culebra associated with future wet climates and state that the changes are not considered in modeling.

While the new discussions and additional documents mentioned above emphasize the potential for flow direction change, there are no new, reasoned arguments or PA calculations to support the conclusions that the impacts of flow direction change are insignificant. SAND96-2133 is a recent (since the July 1996 Panel report) publication that summarizes the role of the regional

groundwater flow model in characterizing Culebra groundwater flow under various climatic conditions. It describes how the three-dimensional (3-D) regional model simulates changes in flow direction (flow paths) resulting from increased recharge during a future wet climate. The two-dimensional (2-D) model implements the increase through a spatially invariant surface function that does not require the precise definition of recharge points and locational inflows to the system. The resolution of the 3-D model includes only nine nodes within the site/regulatory boundary and therefore, the 2-D model, using numerous nodes, is employed to display the flow paths. The 2-D model is forced to display the flow paths simulated by the 3-D model by using boundary conditions and T fields from that model. As presented in Appendix MASS Attachment 15-7, the 2-D model is, at this point, well suited for the analysis of flow and transport, given the boundary conditions specified to produce the appropriate flow paths. The 2-D model is not suited to determining boundary conditions for climatic events and recharge conditions because those conditions might change over time.

The decision not to include flow direction change as a component of the Climate Change conceptual model is based on the reasoned argument that as the flow direction changes from a southeasterly to a southwesterly or westerly direction, the flow encounters lower permeability zones. With this illustration, it is considered conservative to allow the increased flow velocities associated with future wet climate scenarios to occur in the more permeable zones (more transmissive parts of the T fields). In addition, since performance assessment calculations include no realization where there is a release at the regulatory boundary under the conservative conditions, there is no consequence to excluding flow direction change from the simulations.

In the absence of specific PA calculations addressing the two remaining issues pertinent to this model, the reasoned arguments that the effect of both issues is small and that the PA calculations would not be sensitive to potential flow changes of the magnitude caused by these climatic responses at the regulatory boundary are accepted.

3.19. Creep Closure

There were no changes to this model and it continues to be acceptable for implementation.

3.20. Shafts and Shaft Seals

There were no changes identified for this model and it remains adequate for implementation.

3.21. Gas Generation

3.21.1. Model Description

There were no identified changes for this model. Additional information available since the Panel's July 1996 report is provided by performance assessment results and includes families of CCDFs, sensitivity studies among key parameters, and results related to gas generation. In particular, the results indicate that over 10,000 years, on the average less than 50% of the iron in

the repository is corroded. This means that hydrogen generation is not limited by the amount of iron present but by other parameters, such as the amount of brine available. Also, the gas generated is sufficient to reach 12 MPa in many realizations, which is the value that would open and sequester additional gas in marker beds. Additional results depict the pressure after an initial borehole intrusion, indicating that even with introduction of Castile brine into the repository, subsequent pressures are substantially vented up the initial borehole. This information is useful in putting the output of the Gas Generation model in perspective with the results of the other linked models.

3.21.2. Review of Criteria

During the initial review, significant uncertainties precluded definite conclusions on some of the evaluation criteria, particularly Adequacy of Application, Accuracy of Results, and Validity of Conclusions. Four significant issues were raised, and the Panel concluded that without resolution of these issues, a conclusion on model adequacy and validity of conclusions would be speculative. The Panel therefore stated that the Gas Generation model was not adequate for implementation. The additional information now available, coupled with the responses to the Panel's specific findings, assisted the Panel in drawing conclusions on these criteria.

3.21.3. Review of Responses to Panel Findings of July 1996

The Panel issues, a summary of the DOE response, and the Panel assessment of the responses are provided below.

3.21.3.1. Panel Findings

- Analysis of hydrogen generation by corrosion of metals other than the steel in the waste is inadequate. Ignoring gases generated by corrosion of other metals could result in underestimating the gas pressure in the repository.
- Temperature increases in the repository due to corrosion and microbial degradation are not sufficiently analyzed or characterized. Higher ambient repository temperatures could increase the rates of chemical reactions, fluid flow, and halite creep.
- Due to uncertainties about the effectiveness of the magnesium oxide getter to completely remove CO_2, significant uncertainties exist regarding pH, CO_2 pressure, and actinide solubilities. The chemical conditions in the repository would significantly change if the MgO did not function as planned, and could result in underestimating radionuclide releases.
- Hydrogen and oxygen gas generation from radiolysis of dissolved and wetted particulate actinides have not been adequately evaluated. Radiolysis of cellulose and plastics without assuming local hydrogen depletion has also not been adequately evaluated. Ignoring the gases generated by these effects could result in underestimating the gas pressure in the

repository.

3.21.3.2. Summary of DOE Responses to Findings

In Section 9 of the CCA and Appendices PEER and MASS, DOE responded to the Panel findings. Relative to the first finding, DOE provided additional information that the aluminum in the waste and steel in the rock bolts would add about 10 to 15% to corrodable metals which could potentially generate hydrogen. However, DOE showed results of the CCA calculations indicating that in all realizations over 10,000 years, the total available corrodable metals in the repository are not consumed due to an insufficient volume of brine inflow into the waste panels. Therefore, the amount of corrosion-produced hydrogen is not affected by not specifically accounting for corrosion of aluminum and rockbolts. Only in the event of borehole intrusions through a panel would gas generation become inventory limited, and only in that panel. However, due to the long-term gas flow out of the borehole, the added gas generation would be vented and not adversely affect repository performance.

Relative to the issue on potential for temperature increases due to exothermic reactions, DOE provided a conservative bounding analysis of corrosion heat generation and microbial heat generation in which water reaction was assumed to all be by corrosion of aluminum, which provides the most exothermic reaction. For this reaction, DOE stated that the maximum short-term temperature rise was estimated to be 5 to 7°K, and this is too small to have any significant effect on repository corrosion processes.

In response to the issue of uncertainties in the effectiveness of the MgO to effectively remove CO_2, DOE stated that the method of MgO emplacement within the waste room would ensure there are no brine flow paths that can bypass the backfill. DOE stated that twice as much MgO would be emplaced to react with the CO_2 produced if all the cellulosics, rubber, and plastics were consumed by microbial degradation. DOE stated that the rate of dissolution of MgO in brine is much faster than required to react with the maximum expected CO_2 generation rate.

In response to the issue regarding added gas generation due to radiolysis of water by undissolved but wetted actinide-containing particles, and due to radiolysis of cellulose and plastics, DOE did a bounding analysis based on the stoichiometry of the various possible reactions. DOE stated that if all the brine consumed by corrosion was instead consumed by radiolysis, twice as much gas would be available from this source. DOE also stated that if radiolysis of cellulose and plastics occurred instead of microbial degradation, twice as much gas would also be available from this source. Any CO_2 produced is assumed to be consumed by MgO. DOE states that the combined effect would result, at most, in a two- to threefold increase in total gas generation. DOE then stated that because at gas pressures above 12.7 MPa, gas would be vented into the interbeds, the maximum repository pressure would not exceed the values previously calculated for performance assessment (16.5 MPa). DOE states that radiolysis could result in pressures sufficient to cause spallings releases (above 8 MPa) in a greater number of realizations. However, DOE asserts this would not cause an increase in direct release because

the data from performance assessment indicate no correlation between spallings releases and repository pressure, no correlation between moles of gas generated and repository pressure, and no correlation between direct brine release volume and repository pressure.

3.21.3.3. Panel Review of Responses

The Panel agrees with the DOE responses to the two Panel issues regarding added metal for corrosion, and the effect of exothermic reactions. The Panel did not accept that no correlation exists between repository pressure and the other parameters but accepts that these relationships do not adversely affect performance assessment. The Panel does not believe that the issue of total and rapid consumption of CO_2 by the MgO getter has been fully resolved, but it has been sufficiently resolved for purposes of the Gas Generation model because all that is needed is to substantially remove CO_2 as a pressure source and not remove all of the CO_2. The Panel believes that DOE has not ruled out the possibility that initial brine contact with the surface of MgO granules could somewhat reduce accessibility to the remaining MgO due to formation of phases having lower density and lower permeability to brine and CO_2, but the Panel believes sufficient access will be present to effectively remove most of the CO_2 produced. The Panel believes that since this is important to overall performance of the repository, not just for CO_2 pressure control, the DOE-planned pilot and engineering scale testing of the MgO backfill can provide the necessary assurance that the system will function as intended.

Regarding the DOE response to the issue of added gas generation if radiolysis were to occur, the Panel believes the DOE response is adequate because radiolysis is not likely to fully replace the other gas-producing mechanisms. The Panel also notes that the DOE has not fully accounted for sequestration of water by MgO, which could reduce the availability of brine needed for corrosion of iron, microbial action, or radiolysis.

In summary, the Panel believes the Gas Generation model is adequate based on the responses provided.

3.22. Chemical Conditions

3.22.1. Model Description

This conceptual model was listed as inadequate in the July 1996 Peer Review Report. Three major issues were identified; the most critical of these was the reliability of MgO as a backfill component. The DOE responses to the issues are discussed in Section 3.22.3. Subsequent to the July 1996 findings, two new pieces of information have been identified that are pertinent to the Chemical Conditions conceptual model: 1) a laboratory scoping study has been performed to identify if MgO mixed with CO_2 in a high ionic strength brine would produce carbonate, and 2) a series of CCDFs were prepared in June 1996 to illustrate repository performance with and without MgO backfill.

3.22.2. Review of Criteria

The first new piece of information provided to the Panel (the results of a scoping MgO experimental study) is reviewed under the criterion of "Validity of Model Assumptions." This experiment was performed to ascertain whether magnesium carbonates could be generated under the most optimum conditions. This same study was described as a precursor to future experiments laid out in a recently approved Test Plan (TP 97-01) intended to provide data needed to characterize the performance issues related to MgO. The scoping study looked for maximum results in a very limited time frame. In essence, MgO pellets were placed in applicable brine solutions (Salado or Castile) in a beaker, and then CO_2 gas was bubbled through the mixture to determine the effect of backfill on pH reduction and what magnesium carbonate phases would be produced.

This preliminary experiment showed some promising results. Two metastable magnesium carbonate phases (dipingite and nesquehonite) were produced under slightly varying initial chemical environments. Furthermore, the studies indicated that over a 13-day period the chemical systems increased in pH by approximately 2 orders of magnitude. Unfortunately, the scoping experiment did not reflect the conditions present in the repository with regard to either chemical parameters (especially fCO_2 and interaction with iron oxides), time (diffusion rates), or physical constraints (orientation of backfill containers, pathways for gaseous reaction). Therefore this scoping experiment does not provide a sufficient basis to conclude that the MgO backfill will perform as indicated by thermodynamic equations, or as assumed in performance assessment.

The second new piece of information was a series of CCDFs produced with and without the addition of MgO backfill. This issue was reviewed under the criterion "Accuracy of Results." Of particular interest are two CCDFs that predict "blowout" releases with and without MgO backfill. The Panel was not provided with the assumptions used in preparing these CCDFs and is not aware how other factors (chemical conditions, gas generation, actinide source terms, transport in Salado or Culebra) were varied in preparing these calculations. Because of this lack of information, the CCDFs did not provide an adequate basis for the Panel to conclude that the addition of MgO backfill was of no consequence to repository performance.

3.22.3. Review of Responses to Panel Findings of July 1996

3.22.3.1. Summary of Findings

Three issues were involved in the determination that this conceptual model was not adequate for implementation. Two of the issues were of relatively minor importance to the acceptability of the model, and are summarized as follows.

- The combined temperature increase (due to radioactive decay and exothermic reactions) and its effect on repository conditions has not been adequately addressed. Significantly higher repository temperatures could accelerate chemical reactions, fluid flow, and halite

creep rates.

- Phase equilibria have not been critically assessed within the chemical parameters of the conceptual model. A major element stable phase that was overlooked could significantly alter the chemical conditions of the repository and vary the actinide source terms.

- The third issue was the concern raised over the use of MgO backfill. As discussed in the original peer review report, the thermodynamic equilibrium equations calculated for MgO reacting with CO_2 to produce magnesium carbonates (magnesite) and thereby buffer the chemical conditions, are reasonable and proper. However, the MgO backfill has not been demonstrated to be able to react completely with CO_2 generated by microbial action. If the MgO backfill did not react as planned, the pH-buffering capability of the repository would be significantly compromised, and could result in underestimating the actinide source term.

3.22.3.2. Summary of DOE Responses to Findings

The responses to this conceptual model that DOE presented to the panel were combined with responses to issues raised in the Gas Generation model. This was unfortunate, in that there are subtle differences in the questions raised. The first two concerns of this model were sufficiently similar to those of the Gas Generation model that the responses were not critically affected. However, the third issue, that of the effectiveness of the backfill, was not fully addressed. The actual DOE responses are summarized below.

DOE responded to the first concern with a series of calculations that centered on exothermic reactions and radioactive decay. The presentation was both thoughtful and appropriate. The final resolution was that there may be a 7° C increase in temperature if all the metal in the repository was aluminum, but that the increase would not affect the outcome of the conceptual model.

The second concern was that of phase stability and equilibria conditions in the repository. This information was thought necessary due to the large amount of MgO that would be emplaced in the waste cells. The phase diagram that was presented was limited to the system MgO-CO_2 (with excess H_2O) and only portrayed stable phases (Figure 3-19).

Figure 3-19. Phase diagram for the MgO - CO_2 system. Not available.(24)

The DOE response to the Panel's concern about MgO was based on two factors: thermodynamic equilibrium and calculations of Mg dissolution rates of the pellets. The theory that MgO would react with water to form $Mg(OH)_2$ and then react with CO_2 gas to create $MgCO_3$ was reviewed, along with the thermodynamic basis for the model. The DOE modeling calculations indicated that the MgO pellets would react completely with CO_2. Equations were developed to calculate the particle radius needed to accommodate the maximum CO_2 generation rate.

3.22.3.3. Panel Review of Responses

The first issue (temperature increases) was reasonably discussed by DOE and an appropriate resolution was obtained.

The second issue (phase equilibria) was not addressed in a vigorous manner. The DOE response on this issue was not exhaustive nor completely representative of the system. A more thorough representation would have been the system MgO-FeO-CaO-NaO-CO_2-Cl_2-SO_4 (with excess H_2O). The phase diagrams did not chart the existence of metastable phases in the system, which would have provided a clear visual representation of solid phases most likely to be formed (such as dipingite and nesquehonite) in low temperature systems. A more exhaustive series of phase diagrams would be extremely informative because metastable phases can exist for extremely long periods of time (millions of years) due to kinetics problems and lack of sufficient energy for transition to stable phases. To summarize, the phase stability discussion presented by DOE was only minimally adequate for the chemical system involved, and would lead to many instances where metastable phases (not discussed) would dominate the reactions. Therefore, the second issue (phase equilibria) was addressed in its most restrictive sense and, although not completely satisfying, the response provided sufficient information to resolve this concern.

The third, and by far most critical concern of the Panel centered around the fact that MgO had not been tested to ascertain its ability to effectively react with CO_2 in the repository system. The ability for the backfill to react properly and completely has ramifications to a multitude of other parameters. The buffering capacity of the backfill would theoretically fix many of the other chemical components such as the actinide source terms and gas generation rates. Such a critical interplay of the effect of MgO backfill on other conceptual models is further discussed in Section 4.

A possible shortcoming was identified in the equation developed to calculate MgO particle radius for dissolution. The value used for the density term was that of periclase (3.53 g/cm^3) when in fact it, would have been much more reasonable to use the density of brucite (2.39 g/cm^3). This difference would have increased the assumed particle radius to 0.55 cm, 1.5 times the radius used in the DOE calculation.

Much more important is the fact that DOE has not investigated diffusion rates into the MgO pellets instead of dissolution rates. This was clearly indicated by the fact that reaction rims were created on the exterior of the pellets used in the scoping experiment described in Section 3.22.2. Although dissolution may be the manner in which reactions could start, as soon as magnesium carbonates are formed on the exterior of the pellets, the dominant process to react the remaining $Mg(OH)_2$ would be diffusion of CO_2 into the interior of the pellets. This diffusion phenomenon has not been quantified by experiments.

The final factor that was not sufficiently investigated was whether the reaction to carbonate could seal off large percentages of the backfill, due to the engineering geometry involved, and render

the unreacted MgO inert. No experiments to date have tried to duplicate the placement of the backfill in the repository and understand the effects of the expected volume increase due to the transition from oxide to carbonate. Such a volume increase may effectively block pathways for the CO_2 to reach the backfill. Once again, this emphasizes the need to understand and quantify the diffusion rates of CO_2 gas through the carbonate and into the pristine backfill material.

Many of the above stated issues are identified as factors to be quantified in the DOE Test Plan discussed in Section 3.22.2. The Panel has performed a cursory review of this Test Plan and believes that sufficient data can be extracted from the experimental results to determine if MgO will completely react with the CO_2 and therefore buffer the chemical conditions of the repository.

The critical issue, whether the backfill will react sufficiently with CO_2 to buffer the chemical system, has not yet been substantiated by experimental physical results that correctly simulate the repository. Because the backfill issue has so many ramifications to other conceptual models, it is critical to demonstrate that this material will in fact work properly. Therefore, the Chemical Conditions conceptual model is still not considered by the Panel to be adequate for its intended use in the performance assessment.

3.23. Dissolved Actinide Source Term

3.23.1. Model Description

In the time period between the Conceptual Models Peer Review Panel's July 1996 report and this supplementary review, the CCA and its Appendix SOTERM were produced. An addition to the original conceptual model is now described in Section SOTERM.5, Role of Organic Ligands. In essence, the model now takes credit for an abundance of dissolved transition metals (Fe, Ni, Cr, Mn) from waste drums and from backfill (Mg) in the repository brine. These cations would compete for binding sites on organic ligands and significantly reduce the ability of the ligands to complex with actinides. The conclusion of this section in Appendix SOTERM is that the organic ligands would not be available to complex with actinides and thus will not be a component of the dissolved actinide source term model.

3.23.2. Review of Criteria

Although it might be questioned how completely cations such as Ni prevent complexation of actinides by organic ligands such as EDTA, the Panel believes that this change to the conceptual model has only a slight bearing on the overall prediction of source term concentrations and is not unduly impacted by the backfill component because most of the cations involved with the ligands are transition metals. Therefore, this is viewed as a minor change that only impacts the model in a conservative manner. The Panel has concluded that this is not a significant change to the conceptual model and therefore the model remains adequate.

3.24. Colloidal Actinide Source Term

3.24.1. Model Description

A change to the conceptual model was indicated in Appendix SOTERM in Section SOTERM 6.3.3.1 where it is stated " …the high concentrations of Mg^{2+} in solution due to the presence of MgO backfill will compete with actinides for binding sites on humic substances and reduce the actinide uptake." This statement seems to imply that the source term value used is conservative and in essence overestimates the true humic component source term.

3.24.2. Review of Criteria

This model was originally determined to be adequate for implementation. Although there is now a statement that magnesium in solution will compete for humic acid binding sites, DOE did not take credit for this effect and therefore the model is still deemed adequate.

4.0 INTERRELATIONSHIPS AMONG CONCEPTUAL MODELS AND THEIR SENSITIVITY IN THE PERFORMANCE ASSESSMENT

4.1. Introduction

Most of the models reviewed by the Panel can be organized into a few interrelated groupings based on critical performance issues. Some of those groupings contain some of the same models as others, and some overlapping of issues is necessary. Gas pressures are the source of the driving energy for movement of radionuclides out of the repository, in most cases. The porosity surface look-up table integrates numerous and diverse parameters which interrelate repository volume and the gas pressure history in the repository. The porosity surface calculation, illustrated in Table 4.1, was reviewed and approved by the Engineering Systems Peer Panel Review. This table provides an organizing structure for the consideration of its component parameters.

Table 4.1. Porosity Surface Calculation — Gas Generation and Repository Gas Pressure History

Gas Generation Model	→	**Porosity Surface Calculation** →		**Performance Assessment Gas Pressure History**
Parameters		**Parameters and Models**		**Calculations**
Waste Composition Brine Inflow Volumes Brine Composition Corrosion/Degradation Reactions MgO Effects		Room Closure Model Room Initial Dimensions Waste Initial Dimensions SANTOS Computational Configuration Halite Elastic Properties Halite Creep Properties Argillaceous Halite Creep Properties Anhydrite Properties Waste Composition Waste Solid Densities Waste Volume Fractions Waste Mechanical Properties Waste Pressure - Volume Relation Gas Generation - Constant Saturation Variant		BRAGFLO Code
Most of the parameters listed were reviewed by other panels.				

Gas pressure is also a critical element in the inflow of brine into the repository. High gas pressures retard the flow of brine from the surrounding Salado Formation through the disturbed rock zone, the Salado interbeds, and the matrix permeability of the impure halite. Brine is necessary to the reaction of the waste to generate gas. The coupling of gas pressure and brine inflow to the performance of the repository is illustrated in Table 4.2. The result of performance assessment calculations (100 realizations, using sampled values) is that the fraction of waste steel reacted may range from 0% to 100%. Waste steel is an important element in the gas generation model. It is a sensitive indicator of the overall waste reaction and the physical state of the waste. The great variance in this sensitive performance result is caused by the complex variability of the long chain of component models and the uncertainty in predicting the gas pressure history of the repository.

Table 4.2. Model Chain — Brine Inflow

Brine Availability	Processes	PA Results

The models show that there is enough brine available from the Salado Formation by flow through interbeds due to the permeability of the impure halite and by drainage of the DRZ to react all waste.	Gas pressure (limited by initiation pressure of interbeds) resists brine inflow → ← Inflow through DRZ, interbeds, from halite, and due to intrusion (long-term)	Wide variation in degree of brine consumption by chemical reactions in waste (Figures 4-1 and 4-2)
Models	**Models, Parameters, and Calculations**	**Calculations**
Salado Impure Halite Disturbed Rock Zone Salado Interbeds Repository Fluid Flow	Porosity Surface Calculations Salado Interbeds Gas Generation *Chemical Conditions Creep Closure DRZ Repository Fluid Flow Multiple Intrusions Exploration Boreholes SECO Code BRAGFLO Code	BRAGFLO code
*Model found inadequate for implementation and to have consequence in PA calculations.		

It is the opinion of the Panel that the structure of the conceptual model integration used in performance assessment is reasonable. The source of uncertainty lies primarily in the individual models and is partly mitigated by the use of sampling techniques and by the interrelationships of model sensitivities within the performance assessment calculations in the cases of the conceptual models which are adequate for implementation.

There are four principal conceptual pathways for release of radionuclides to the accessible environment. Release through the Salado interbeds beneath the repository due to the transport of repository brine to the edge of the land withdrawal boundary is considered unlikely due to the very large storage volume available in the interbeds. All other credible release scenarios are the result of human intrusion by drilling through the repository. Release to the surface as a consequence of drilling (Table 4.3), release through the Culebra Dolomite due to long-term flow up an intrusion borehole (Table 4.4), and release through units above the Culebra (Magenta Dolomite and Dewey Lake Redbeds, Table 4.5) are the remaining credible pathways.

Table 4.3. Model Chain — Surface Releases During Drilling

PA Calculations:	Processes	Potential Impact
Source and Volume of Waste		

1. Solid Waste Carried to Surface 2. Dissolved Radionuclides Carried To Surface	Transport of solid, dissolved, and colloidal waste and waste products up borehole annulus during intrusion.	PA calculations predict that releases of waste are probable

Models and Calculations

Cuttings and Cavings
*Spallings
Porosity Surface Calculation
Gas Generation
Direct Brine Release
Multiple Intrusions
Repository Fluid Flow
Exploration Borehole
Castile and Brine Reservoir
*Chemical Conditions
Dissolved Actinide Source Term
Colloidal Actinide Source Term
Creep Closure

* Model found inadequate for implementation and to have consequences for PA calculations.

Table 4.4. Model Chain — Release Through Culebra

PA Calculations: Volume of Brine at Culebra in Borehole →	**PA Calculations: Brine Intrusion Into Culebra** →	**PA Calculations: Radionuclide Content of Brine** →	**PA Calculations: Transport in Culebra**
Models and Parameters	**Models and Parameters**	**Models and Parameters**	**Models and Parameters**
BRAGFLO Code Repository Fluid Flow Exploration Borehole Castile Brine Reservoirs Porosity Surface Calculations Gas Generation Exploration Boreholes Multiple Intrusions Creep Closure *Chemical Conditions	Culebra Hydrologic Model BRAGFLO-SECO Interface PA Calculations of Uphole and Downhole Flow Rates Climate Change	Dissolved Actinide Source Term PA Calculations of Uphole and Downhole Flow Rates	SECO Code Sorption Flow Scenario 1. Advection 2. Diffusion Culebra Hydrologic Model K_ds

*Model found inadequate for implementation and to have consequences for PA calculations

Table 4.5. Model Chain — Releases to Units Above Culebra

Issue	Additional Considerations
Performance assessment calculations show insignificant brine available above Culebra.	Intrusion into Magenta and Dewey Lake Redbeds may be inhibited by low permeability (Magenta) and filling of fractures (Dewey Lake Redbeds). Transport in the Dewey Lake Redbeds maybe inhibited by large hypothetical retardation on ferrous minerals.
Models and Parameters	
BRAGFLO Code Porosity Surface Calculation Repository Fluid Flow Exploration Boreholes Multiple Intrusions Gas Generation *Chemical Conditions PA Calculations (BRAGFLO) Brine Down Hole Brine Up Hole Injection of Brine into Culebra Room Closure Culebra Hydrologic Model	
* Model found inadequate for implementation and to have consequences for PA calculations.	

Sensitivities, variability, and adequacy of individual conceptual models are discussed in Section 3. The sensitivity of the performance of the repository to gas pressure history, brine availability, and the models impacting the three intrusion-related release scenarios are discussed here.

4.2. Gas Pressure History — Porosity Surface Calculations and the Gas Generation Model

The porosity surface calculation is made with the SANTOS code prior to the performance assessment computations done with the BRAGFLO code. The porosity surface calculation describes the changes in repository volume with time for 13 instances of gas generation rate versus room closure resulting from halite creep. Room initial dimensions, waste dimensions, halite elastic and creep properties, waste densities, mechanical properties, and pressure/volume relations and gas generation rates form the Gas Generation model assuming complete and

constant saturation are included as parameters. Brine inflow is not included in the porosity surface but is an important part of the Gas Generation model.

The porosity surface permits the calculation of repository volumes for gas pressures at thirteen times (SANTOS code). The integration of repository volume with gas generation history is accomplished in the performance assessment calculation (BRAGFLO code) by matching gas generation with the appropriate time steps generated in the porosity surface calculation.

The Gas Generation model combines the generation of gas through corrosion of metals and microbial degradation of organic constituents. Both processes are directly dependent on the volumes and compositions of brine entering the repository. During the first round of reviews, the Gas Generation model was found to be inadequate for implementation; however, subsequent review of additional information has shown that the conceptual model is adequate. The addition of MgO backfill is expected to reduce gas generation. The interaction between gas generation and brine inflow is difficult to define with respect to gas pressure. This is because of the absence of clearly defined capillary pressures for Salado halite and the multivariate nature of the repository volume/gas pressure interrelationships within the porosity surface calculation. This wide range of uncertainty is reflected in the wide range of degrees of probable waste degradation recognized in the performance assessment calculations (Figures 4-1 and 4-2).

In the undisturbed scenario, the variation of gas pressure due to brine inflow history has no effect on any probable release. In the release scenarios related to human intrusion, the gas pressure history is related to the potential impact of releases in both the short and long terms.

4.3. Release Through the Culebra

The transport of contaminated brine up an intrusion borehole in the long term is the primary source of radionuclides to be transported in the Culebra. Brine transport up the borehole (and down from units above the Culebra) is calculated in the performance assessment process using the BRAGFLO code. Transport evaluation is supported by SECO code calculations of transport within the Culebra, which neglect the brine volume injected into the Culebra. SNL asserts that this computational method has no effect on transport over the distance from the waste panels to the site boundary.

Vertical leakage from units overlying the Culebra may, especially if enhanced by water wells, raise the pressure in the Culebra. The Culebra is at present underpressured with respect to all other stratigraphic units above the Salado. This underpressure enhances the injection of brine into the Culebra and also helps to explain the insignificance of brine from the borehole in the overall flow in the Culebra. No significant volume of brine rises above the Culebra in the intrusion scenarios based on contemporary conditions. Extensive water well development and climate change are future events that may impact this aspect of Culebra hydrology.

Figure 4-1. Fraction of steel remaining in waste panel for undisturbed conditions. Not available.(25)

Figure 4-2. Fraction of steel remaining in waste panel for an E1 intrusion at 1000 years into the waste

panel. Not available.(26)

There are four general sets of model interactions that impact transport of radionuclides in the Culebra. These are: 1) models contributing to brine volumes, gas pressures, and long-term flow up the borehole to the Culebra, 2) injection of brine from the borehole into the Culebra (entirely performance assessment calculations), 3) the Culebra hydrologic flow model and influences on that model such as climate change, and 4) flow scenarios and K_d values for retardation in the Culebra. There are significant uncertainties in each of these areas such as the influence of MgO backfill on gas generation, climate change, brine flows resulting from penetration of brine reservoirs below the repository, local impacts of brine injection from the borehole, and the proportioning of flow processes on retardation. In general, however, these uncertainties are either small in comparison to the transport distance from the waste panel to the site boundary or, as in the case of the MgO backfill, may have only beneficial impacts. SNL asserts that retardation in the Culebra is sufficient to prevent release even in the case of maximum brine flow and injection into the Culebra. Changes in flow direction resulting from climate change, related increases in recharge, changes in vertical leakage due to water well development to the Culebra, and the impact of brine injection on flow in the Culebra have not been specifically evaluated. Qualitative arguments that these sources of uncertainty are insignificant to a release through the Culebra from the waste panel area to the site boundary have been presented by SNL.

4.4. Release To Units Above The Culebra

The only two stratigraphic units above the Culebra that are permeable enough to cause concern about releases are the Magenta Dolomite and the Dewey Lake Redbeds. The primary reason for a finding of no consequence of release from these units is the performance assessment finding that no significant volume of brine rises past the Culebra in the intrusion borehole. The calculations used median and minimum Culebra permeabilities from the Culebra hydrologic model (T fields). The principal sources of uncertainty in the performance assessment calculation are those associated with models impacting brine volumes and gas pressures in the repository, which are listed in Table 4.2. Low permeabilities measured in the site region in the Magenta and gypsum-filled fractures in the lower Dewey Lake Redbeds are possible additional sources of protection against releases through these units.

4.5. Surface Releases

Four areas of model interactions are sources of uncertainty in the surface releases of radionuclides: 1) gas pressure and brine volumes in the repository, discussed elsewhere; 2) effectiveness of entrainment and transport of solid waste in brine or gas flowing up the borehole annulus; 3) solubility of radionuclides and the formation of actinide-bearing colloids in the brine in the repository; and 4) the effectiveness of the cutting/cavings and spallings processes to provide solid waste particles of an appropriate size for uphole transport.

The effectiveness of transport of both the solid and dissolved fractions of the radionuclides

depends primarily on the velocity of gas or brine flow up the borehole annulus after the drilling mud has been blown out of the hole by repository gas. This set of scenarios has been treated in the performance assessment calculation and the Direct Brine Release model and gets its uncertainty mostly from the uncertainties in gas and brine pressure and volume.

The solubility of radionuclides and the formation of colloids have been adequately treated in the source term models, although the impacts on these models of MgO backfill have not been fully assessed in the Chemical Conditions model. The volumes of particulate waste generated by drilling are adequately addressed by the Cuttings/Cavings model. The volume of solid waste particles generated by spalling is not adequately resolved by the model at this time.

Spalling is sensitive to gas pressure, the moisture content of the waste, and the physical state of the degraded waste. The physical state of the waste, particularly grain size, cementation, and cohesion, are difficult to characterize. SNL has attempted to limit these parameters and to calculate waste release due to spalling through a model which relies on the erosion of channel-shaped voids in the waste by gas overflow. The Panel has found the model inadequate for implementation. The spalling process is also sensitive to the uncertainties contained in the gas pressure history of the repository. SNL is planning further laboratory experiments to support the modeling effort and has stated that the cementing of waste by the reaction with the MgO backfill may have beneficial effects on waste spalling.

Spalling is an important component of the release to the surface. The Panel believes that the development and testing of the Spallings model is currently inadequate to support its use in performance assessment.

4.6. Sensitivity of Performance Assessment to Conceptual Model Acceptability

Three classes of model acceptability result from the peer review process:

1) Model Acceptable. Some issues may be noted, but they are not important to the final application of the model.

2) Model Unacceptable and Has Performance Assessment Consequences. Two models were found unacceptable. The Spallings model appears to be incomplete and is not confirmed by experimental evidence or numerical analysis. Several issues and sub-issues remain to be addressed with respect to this model. This model has significant impact on release of radionuclides to the surface, the most significant release issue at WIPP.

   The Chemical Conditions model is unacceptable because it does not address the impact of MgO backfill on chemical conditions in the repository. Chemical conditions are a critical factor in the results of the application of several other models. These include: Gas Generation, Repository Fluid Flow, Actinide Source Terms, Direct Brine Release, and others. Chemical conditions indirectly impact the transport models and the other models

related to surface release.

3) Model Unacceptable With No Performance Assessment Consequence. The Culebra Hydrogeology model was found unacceptable, but regional elements of the model, combined with an empirical site and site region hydrologic flow model based on testing data, have adequately replaced the missing elements of the conceptual model. The numerical hydrologic flow model and selected PA results were reviewed during this phase of review and found to be adequate.

   The Castile and Brine Reservoir model was unacceptable because the characterization of probability of reservoir interception was not adequately supported. However, the sensitivity of the performance assessment calculations to that probability were so small that the use of either the maximum or minimum conceptually defensible numbers for the probability of an intercept did not affect the computed brine volumes entering the repository. Such findings of no consequence are based on the insensitivity of the performance assessment model to the results of the conceptual model implementation within conceptually defensible limits.

   Some models, as in the case of the Exploration Borehole model, were shown to be of no consequence on the basis of conceptual elimination of the impact of specific issues. In this case, the lower borehole plug could not be shown to persist over the life of the repository. The potential consequence in this case is flow down the borehole to the Bell Canyon Formation and through this formation to the boundary of the accessible environment. A side calculation was made which shows that transport in the Bell Canyon is low enough that no radionuclides would be expected to be transported to the accessible environment if the lower borehole plug fails.

   Additionally, models were found to be acceptable based on no consequence due to low drilling rates in early repository time (for example, the assumption of constant permeability for repository waste), and models were found to be acceptable based on no consequence due to the relatively low additional brine volumes they would provide to the repository (for example, the assumption that borehole penetrations in the operations and experimental areas can be ignored).

In general, when a model is found to be inadequate it affects a chain of models bearing on a release scenario. Tables 4.2 through 4.5(27) are intended to show the associations that lead to these shared impacts for the release scenarios or parts of release scenarios that the Panel believes are the most important. No attempt has been made to propagate the resulting uncertainties through the performance assessment calculations. Such an evaluation is beyond the scope of the Panel's responsibilities. However, two generalities can be drawn with respect to overall model integration. First, the structure of model interactions used in the PA calculations seems reasonable. Second, the variability of sampled parameters in the PA plots appears to capture the distribution of those parameters, as suggested by an inspection of model uncertainties and the complexity of sequences of uncertain models. An example is the wide

distribution of waste consumption completeness represented in Figures 4-1 and 4-2. This result is related to uncertainties in the supporting models, which themselves have wide distributions of uncertain parameters. The wide variability of waste consumption results (0% to 100% consumed) appears to adequately reflect the accumulation of conceptually implied uncertainties in the supporting database.

4.7. Summary

In general, the structure of model interactions seems reasonable. The mitigating effect of sampling of uncertain variables and the sensitivity structure of the PA model may have made the compound uncertainties of complex chains of models manageable in the final performance assessment result. It is important that the effects of all future model changes be evaluated in the context of the integration of all models. This is especially important in the cases of models that were found to be inadequate but of no consequence to performance assessment. Shifts in the results of adequate models may change the sensitivity of performance assessment to models presently thought to be inconsequential.

5.0 SUMMARY OF REMAINING ISSUES

This section presents a summary of the supplementary evaluations of the WIPP Conceptual Models Peer Review Panel performed between October and December 1996. As stated in the Panel's July 1996 report, over 20 years of scientific effort have been expended on the WIPP characterization project and it is beyond the scope of the Panel to summarize all of the positive work that has been performed. This section is not intended to be a reiteration of comments and discussions on the 24 individual conceptual models, but instead to provide an overview of conclusions from the supplemental evaluations. For those models found to remain inadequate, the key concerns of the Panel are summarized. Of the remaining models, those that were found to have important technical concerns, but were nevertheless found to be adequate on the basis of a lack of consequence in modeling results, are also identified and discussed. The Panel believes that the opportunity to reconvene and review the final conceptual models, as developed by the DOE and implemented in the October 1996 Compliance Certification Application for the WIPP, has been beneficial. The DOE responses to the Panel's initial concerns, the changes that were made to the models since the Panel's July 1996 report was prepared, and the results obtained from implementing the models in performance assessment have enabled the Panel to resolve its concerns regarding all but two of the 11 models that were previously identified as inadequate. In addition, the new information obtained during this supplemental evaluation did not change the Panel's previous conclusions for the 13 models that were found to be adequate.

New information relative to the conceptual models was reviewed by the Panel and the adequacy of each model was again evaluated using the same criteria as applied in the initial review. Of the 24 models, 22 were found to be adequate for implementation in performance assessment for the WIPP. For most of the adequate models, minor Panel concerns still remain and are identified in

Section 3 of this report and of the July 1996 Panel report. These concerns primarily address issues of documentation gaps and issues with features, events, or processes that were not considered sufficiently important to find the model inadequate. The 22 models found to be adequate are listed below, and those that have important residual technical concerns but were found adequate based on a lack of consequence are identified.

1. Disposal System Geometry
2. Culebra Hydrogeology*
3. Repository Fluid Flow*
4. Salado
5. Impure Halite
6. Salado Interbeds
7. Disturbed Rock Zone
8. Actinide Transport in the Salado
9. Units above the Salado*
10. Transport of Dissolved Actinides in the Culebra
11. Transport of Colloidal Actinides in the Culebra
12. Exploration Boreholes*
13. Cuttings/Cavings
14. Direct Brine Release*
15. Castile and Brine Reservoir*
16. Multiple Intrusions
17. Climate Change
18. Creep Closure
19. Shafts and Shaft Seals
20. Gas Generation
21. Dissolved Actinide Source Term
22. Colloidal Actinide Source Term

Models identified with an asterisk (*) in the foregoing list had important technical concerns but were found to be adequate on the basis of lack of significant consequence to performance

assessment. A brief statement of the basis for approving each of these models is provided below.

Culebra Hydrogeology. No conceptual model was developed that explains the variability of hydrologic properties and processes in the Culebra at a scale that is useful in correlating those properties in the numerical hydrologic flow model. This model was found adequate because an extensive hydrologic testing data base and an adequate numerical flow model were developed as a substitute to the conceptual model for performance assessment purposes.

Repository Fluid Flow. The two-dimensional numerical implementation of the conceptual model may unrealistically restrict brine movement between the waste panels and the anhydrite interbeds in undisturbed scenarios because of the shallow depths of the borehole and shaft model cells. This model was found adequate because the error in computed flow volumes appears to be small in relation to the total volume of brine available to the undisturbed repository from early-time drainage of the DRZ.

Units above the Salado. The conceptual model and the testing data base are inadequate to exclude the Dewey Lake Redbeds and the Magenta Dolomites as potential transport pathways for radionuclides in the event of an intrusion. This model was found adequate because performance assessment results indicate that the quantity of radionuclides reaching the region above the Culebra is negligible even under low transmissivity assumptions for the Culebra, and the hydrologic characteristics of the Dewey Lake Redbeds and Magenta units are therefore of no consequence to performance assessment.

Exploration Boreholes. The assumption that shorter (40 m) borehole plugs beneath the repository horizon will have a useful life of at least 10,000 years has not been adequately supported. This model was found adequate based on an estimated groundwater travel time in the Bell Canyon to the accessible environment in excess of 10,000 years, and leakage of small amounts of repository brine into that formation would therefore be of no consequence to performance assessment.

Direct Brine Release. The direct discharge of waste materials to the ground surface through enhanced cavings-type borehole wall erosion accompanying discharge of Castile reservoir brine during drilling has not been included in performance assessment. This model was found adequate based on DOE calculations showing that the incremental waste volume released over the regulatory period is small compared with the volumes currently estimated in performance assessment modeling.

Radionuclide transport through entrainment of waste solids in rapid, two-phase liquid/gas releases during drilling was evaluated by DOE using the Spallings model. DOE concluded it was of lower consequence than entrainment of solids in gas releases. Although the approach taken and results obtained support a conclusion of no consequence, the technical adequacy of the Spallings model itself has been questioned by the Panel and this transport concern should be reevaluated at the time the Spallings model is determined to be appropriate for performance

assessment.

Castile and Brine Reservoir. The expected probability of 8% of encountering pressurized brine beneath the waste panels has not been adequately supported. DOE suggested that analyzing the differences between E1 and E2 borehole intrusions provides a basis for estimating the consequences of assuming larger probabilities. This model was found adequate based on a review of such differences, which showed that effects on key repository conditions and surface releases were small and of low consequence to performance assessment modeling.

The Panel wishes to emphasize that models were necessarily found adequate because of lack of consequence on an essentially independent basis. Determining the cumulative effect of a series of low consequence events on overall performance assessment results requires additional performance assessment modeling because of the complex interrelationships among the models and stochastic processes. Although many of the technical concerns for models found adequate on the basis of a lack of significant consequence could each result in increasing releases by a small amount, the Panel believes that unless changes are made in the modeling assumptions that significantly affect key model elements, such as repository pressure or brine saturation histories, the applied institutional controls, or the role of the Culebra as a transport pathway, the cumulative effect of these concerns with models found adequate would not significantly affect the overall performance assessment results.

The two models found to be inadequate are presented in the following paragraphs with brief discussions of the key concerns identified by the Panel. Although the consequences of the Panel's technical concerns for these two models are not known, they are believed by the Panel to be consequential because they significantly impact the release processes found in modeling results to be most significant to overall system performance. Comprehensive discussions of the specific issues on these models that were not adequately addressed are presented in Section 3.

Spallings. The number of remaining concerns for the Spallings model is extensive. Although these concerns have been generalized below for purposes of this summary, they should not be considered the Panel's formal statements of the Spallings issues. Such statements are presented in Section 3.

- An adequate basis for the parameters used in the mathematical expression of the model has not been developed. In particular, ignoring capillary forces and correlating tensile strength with surface erosion have not been adequately supported by either first principles or experiment.

- The principal assumptions upon which the mathematical model is based appear to be incomplete. Waste removal by entrainment in gas flow is expected to occur in a highly dynamic sequence principally involving a spalling process driven by gas flow out of the porous waste normal to the eroded surface. Subsequent erosion by gas flow parallel to the eroded surface in pathways that are not expected to be the primary effect controlling the volume of spall, particularly in early times. In addition, the DOE has not adequately

shown that the steady-state assumptions of the model conservatively approximate releases associated with the dynamic process of spall, and the possibility of transonic velocities has apparently not been considered.

- The experiments conducted in support of this model appear to have been designed to reproduce the assumptions upon which the model is based, rather than to simulate the dynamic repository system. Although the experiments may support adoption of specific model parameters, they do not demonstrate that the model adequately represents future states of the repository.

Chemical Conditions. The ability of the MgO backfill to perform as assumed in performance assessment remains a Panel concern, as described below.

- The ability of the MgO backfill to react completely and rapidly with CO_2 to buffer the chemical system and limit actinide solubilities has not been adequately substantiated by experimental physical results that correctly simulate conditions in the repository. Although the pH buffering assumptions are of considerable importance to many other conceptual models, the conclusion that the MgO will in fact perform as assumed has not been adequately supported.

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ACRONYMS

CCA	Compliance Certification Application
CCDF	cumulative complimentary distribution function
CFR	Code of Federal Regulations
CTAC	Carlsbad Technical Assistance Contractor
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
EPA	U.S. Environmental Protection Agency
ERDA	Energy Research and Development Administration
FEP	features, events, and processes
MB	marker bed
PA	performance assessment
SNL	Sandia National Laboratories
TP	test plan
TZ	Transition Zone
USGS	United States Geological Survey
WIPP	Waste Isolation Pilot Plant

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A Peer Review
Conducted By

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Carlsbad Area Office
Office of Regulatory Compliance

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EXECUTIVE SUMMARY

This report is a third supplement to a July 1996 report that presented the results of an independent technical peer review of the adequacy of 24 conceptual models representing features, events and processes involved in assessing the long-term performance of the Waste Isolation Pilot Plant (WIPP). The peer review was initially conducted from April through June 1996 at the U.S. Department of Energy's (DOE's) Sandia National Laboratories by a six-member interdisciplinary Review Panel having the requisite broad experience to address the range of issues associated with waste isolation over the 10,000-year regulatory time frame. The Panel selection process and the biographies of the Panel members are included in the July 1996 report.

In its January 1997 second supplementary report, the Panel stated that it continued to find two of the models not adequate to represent the future states of the repository. For the two models found not adequate, Spallings and Chemical Conditions, the Panel identified its remaining issues. In this third supplementary report the Panel considers the DOE's April 1997 responses to these remaining issues. The Panel's evaluation of these responses is presented in Section 3 of this report. For the Spallings Model, the Panel concluded that the predicted volumes of spalled materials presented in the WIPP Compliance Certification Application (CCA) are reasonable based on additional consideration of processes that could lead to spalled releases. The Panel also concluded that the MgO backfill component of the Chemical Conditions Model will function as assumed in the CCA and that this model is adequate to represent the future states of the repository.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Conceptual Models Peer Review Panel (Panel) issued its report in July 1996. The peer review was conducted in accordance with the regulatory requirements of 40 Code of Federal Regulations (CFR) 191 and the implementation of those requirements by 40 CFR 194. The U.S. Department of Energy (DOE) included the Conceptual Models Peer Review Report as part of its Compliance Certification Application (CCA) for WIPP that was submitted to the U.S. Environmental Protection Agency (EPA) in late October 1996.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical systems, or intrusion scenarios, are represented in the performance assessment. In the Conceptual Models Peer Review Report of July 1996, 24 conceptual models were evaluated using the evaluation criteria specified by the EPA, including those of NUREG 1297. The Panel's report identified 13 conceptual models as adequate for implementation in WIPP Performance Assessment and 11 as not adequate for implementation, based on information available to the Panel. The Panel's findings on each of the models judged inadequate were provided in the report. After that report was issued, DOE developed additional information, made changes to some of the conceptual models, and prepared responses to the findings in the Conceptual Models Peer Review Report of July 1996.

The DOE reconvened the Panel in October 1996 to review the changes to the conceptual models, the DOE responses to the findings in the July 1996 Panel report, and information available in the CCA. In December 1996 the Panel issued a report supplementing the July 1996 report, that assessed the changes to the models and the DOE responses. The Panel found that two of the models, Spallings and Chemical Conditions, continued to be not adequate for implementation, and identified the remaining issues with these models. DOE again reconvened the Panel in January 1997 to review additional information developed in response to the remaining issues of the Panel on these two models. The Panel issued a second supplementary report which continued to conclude that these two models were not adequate for implementation and reiterated the remaining issues.

The Panel subsequently communicated by teleconference from February through April to review action plans and monitor progress toward resolving the issues. In meetings held during the week of April 20, 1997, the Panel reviewed information detailing additional DOE work relative to Spallings and Chemical Conditions. This report documents the Panel's April 1997 findings and is a third supplement to the Panel's July 1996 report.

For the Spallings Model, DOE has not requested the Panel to reconsider its conclusion that the original model was not shown to be adequate to represent the future states of the repository, and has not asked the Panel to review a new model against the criteria of 40 CFR 194. For the present review, the Panel was instead requested to determine if the predicted volumes of spalled materials presented in the WIPP CCA are reasonable, based on additional consideration of

processes that could lead to spalled releases. Additionally, for the Chemical Conditions Model, DOE has requested the Panel to determine whether the MgO backfill will function according to the conceptual model, as used in the CCA, with respect to reaction with generated CO_2 gas.

Section 2 of this report describes the process for this third supplementary review. Section 3 describes the additional information provided by DOE and the Panel's assessment of that information. Section 4 contains a summary of the Panel's assessments and conclusions.

2.0 SUPPLEMENTARY REVIEW PROCESS

This supplementary review was conducted at Sandia National Laboratories (SNL) in accordance with the DOE Quality Assurance requirements as modified in January 1997. The Panel was provided information relative to issues in its earlier reports during briefings and in written materials. The same review criteria were used to judge the acceptability of conceptual models as in the July 1996 report.

3.0 MODEL EVALUATIONS

Section 3.1 discusses the additional considerations of the Panel relative to the Spallings calculations and Section 3.2 discusses additional considerations relative to the use of MgO as part of the Chemical Conditions Model.

3.1. Spallings

3.1.1. Model Description

No changes were presented for the Spallings Model used in performance assessment.

3.1.2.Review of Criteria

The review of criteria for the Spallings Model remains unchanged.

3.1.3.Review of Responses to Panel Findings of January 1997

3.1.3.1. Summary of Findings

In its January 1997 report, the Panel found that additional information available on analogs, waste strength, other new model descriptions and calculations of tensile failure were either not adequately correlated with WIPP repository conditions or were not sufficiently complete or supported to provide the Panel with an adequate basis for determining that either the Spallings Model or the results obtained from that model were conservative.

3.1.3.2. Summary of DOE Responses to Findings

Surrogate Waste Materials

In response to the Panel's concern about the properties of the waste that would influence the spalling process, the DOE developed analogs for waste based on ranges of waste contents, corrosion and biodegradation that would perhaps be present following extended exposure to WIPP conditions. The surrogate samples contained varying amounts of corroded and uncorroded iron metal, including addition of goetite, crushed glass and soil, salt and concrete, and MgO in some cases. Physically degraded paper, plastic and peat were added to represent chemically degraded organics in the waste. These surrogate waste materials were mixed with brine, and consolidated to either 5 or 15 MPa to simulate repository conditions. Some of the samples were subsequently dried. Standard testing procedures were used, including Brazilian and hollow cylinder tensile tests, unconfined and triaxial compression tests, and permeability tests. Various parameters, including permeability, porosity, cohesion, tensile strength, compressive strength, Young's modulus, and Poisson's ratio were determined from the results of those tests. These parameters were then used in the various analytical calculations. DOE asserted that these parameters adequately represent the degraded waste expected in WIPP.

Analogs

The Panel was presented with documentation of analogs to the spalling process at WIPP, mostly rooted in petroleum production technology. Exceptions to the oil and gas analogs, such as seepage and earthquake-induced liquefaction and kimberlite pipe genesis, were quickly dismissed because of only tenuous similarity of phenomena. Drillhole blowouts, wellbore stability, sand production, hydrofrac proppant flowback, and cold production of low gravity viscous crude oil all were discussed in more detail and, although they were of qualitative value in understanding the spalling phenomenon, they were not found to be directly applicable as credible quantitative analogs. However, the dynamic cavitation of wellbores, specifically those through coal beds, was found to have notable attributes analogous to the spalling process at WIPP.

Dynamic cavitation has many similarities to the spalling process at WIPP, such as a pressure pulse phenomenon, gas-driven particulate removal, and a highly similar physical configuration. The ability to apply established computational codes, and the available database of results from this remarkably close analog help to corroborate testing and/or computational results. The DOE's draft Spallings Release Position Paper (SNL/CTAC, 1997) presents many of the pertinent similarities with instructive comments in Table 5-3, "Properties of a Characteristic Coalbed Methane Reservoir Used in Single Cycle Surge Modeling."

Computational Methods

In response to Panel findings that the existing model used to estimate spalling inadequately represented critical components of the spalling process, DOE initiated a new, mechanistically based computational approach. This approach is composed of three new computational methods which were used to develop additional information on the spalling process. These are called the cavity growth, the quasi-static, and the numerical computation methods. This approach represents the first time that borehole hydrodynamics and cavity growth have been

linked.

The cavity growth method is presented as the primary method for estimating spall volumes. The method simulates the entire response period of the system to an intrusion event, not just the end point. Assuming initial gas pressures and waste strength, the method accounts for the progressive mechanical response of the waste to a transient solution of gas flow in the waste and includes the hydrodynamics of mud and waste ejection through the borehole. The cavity growth method predicts small spall volumes for assumed initial gas pressures below lithostatic (14.8 MPa) and a maximum spall volume of 0.25 m^3.

The quasi-static method is presented as the simplest of the three methods and, as such, is primarily used to examine sensitivities and verify complex calculations rather than estimate spall volumes. The method is applied to estimate gas volumes, gas pressure distributions and flow rates for comparison to those predicted by the cavity growth and numerical methods. Graphic comparisons of gas flows and pressures predicted by the cavity growth and quasi-static methods illustrate close agreement. The gas pressure distributions and flow-rates predicted by these two methods are higher than those predicted by the numerical solution for the important early time steps.

The numerical method is presented as a tool for evaluating complexities not clearly represented by the other methods. The numerical method couples fluid pressure to the stress response in the waste following a drilling intrusion. Numerical calculations implemented through various computer codes were used to investigate solids mass transport, sensitivity of waste panel geometry and effects of waste heterogeneity, in addition to predictions of gas pressures and flow rates.

Numerical calculations were applied to predict gas pressures and flow rates for comparison to semi-analytic results. The numerical calculations consistently predict lower pressure gradients and lower gas flow rates than the other methods. The gradients and rates predicted by the numerical method are significantly lower than those of the other methods at early time steps. Investigations of layered and random configurations of heterogeneous waste using numerical calculations resulted in a reduction in key parameters that determine spall volume. Solids mass transport was investigated and determined to be limited prior to mud ejection. Tensile strength was determined to govern the system response, thereby minimizing the overall effects of waste panel geometry and flow properties.

3.1.3.3. Panel Review of Responses

Liquefaction, Plastic Deformation, and Cavity Stability

In the seminal paper by Vaziri and Byrne (1990), the detailed discussion providing the groundwork for the consideration of the mechanical stability of deep wells cites liquefaction as the strain mechanism responsible for cavity formation. Subsequent work has developed a more complete picture of stress-strain relationships around an unstable wellbore. Stabilization of a cavity in a wellbore that is in transient instability depends, in part, on the formation of a “stress

arch" around the cavity whose extent and geometry depend on the shear strength of the geologic materials. Shear strain controls the formation of the stabilizing zone, which is in a compressive state around the cavity and is characterized by plastic deformation.

In rocks having sufficient tensile strength and cohesion, the primary strain mode leading to cavity formation may be tensile failure due to differences in pore pressures around the cavity. Models used to predict cavity formation by air pressure pulsing in coal gas recovery wells have been developed and tested against bench models and field observations. In this useful analog of cavity formation caused by the release of gas due to an intrusion by drilling into the WIPP repository, a tensile failure of the cleated coal creates the cavity, and a broad plastic zone (tens of meters wide) forms around the cavity. Even after many repeated pressure pulses the cavity in the coal eventually stabilizes and cannot be made larger. This ultimate stabilization is due to the formation of the broad zone of plastic yield and the resultant concentric compressive stress zone (arch) around the cavity following repeated perturbations.

The WIPP surrogate waste exhibits cohesion and tensile strength as well as a significant tendency to ductile (plastic) deformation under experimental conditions. This has led the DOE to characterize the cavitation process as the result of a tensile failure zone surrounding the cavity at some short distance at any moment during the single short and rapid period of failure. The details of disaggregation and fragmentation of the spalled material moved into the cavity by tensile failure around the periphery of the cavity are not considered. Liquefaction may play a role in spall fragmentation, but all stress states leading to failure at the periphery of the cavity and beyond are characterized by non-zero states of effective stress. No liquefaction is predicted at or beyond the cavity margin.

The representation of cavity formation presented by the DOE is reasonable within the range of tensile strengths and cohesions proposed on the basis of surrogate waste experiments, the proposed stress environment, and the proposed strain processes. Although strain leading to cavity formation takes place over a very short period of time, the absolute magnitudes of continuous strain are relatively small. The rapid strain rates at the time of failure tend to enhance brittle behavior, but the small strain magnitudes and the large ductilities exhibited by the surrogate waste imply that the formation of a plastic zone and a stabilizing compressive shear arch is reasonable.

Distribution of stress and subfailure strain domains in the waste may be spatially complex and subtle. The principle driving mechanism for stress in the waste is pore pressure contrast distributed around the point of repository penetration as relatively symmetrical hemispherical gradients. Formation of the plastic zone and other complexities are secondary features which are kinematic responses to cavity development and relaxation of the waste due to degassing. Small magnitude tensile stress regions outside the compressive plastic zone and stress regions of incomplete symmetry are predicted by some published models and by closed-form numerical calculations presented by the DOE. These stress regions are limited by the small predicted dimensions of the cavity formed in the waste relative to the entire volume of waste in the room

and by the inefficient transfer of small elastic strains by very porous and relatively weak media during second order kinematic adjustments. No loss of strength outside of the tensile zone in the immediate vicinity of the intruded borehole is reasonably expected.

Strength and other properties of the waste are thought to be modified by several aspects of the repository environment. Some of these aspects of waste character are speculative and are not demonstrable so that no representation of their effects is included in the spall volume calculations. Waste heterogeneity and layering, the cementing effect of MgO, and other proposed strengthening effects of degradation are examples of possible but undemonstrated factors in waste physical behavior. Halite cementation of completely dry waste is apparently demonstrated by the increased strength of surrogate waste specimens prepared with added salt, wetted with brine, compacted, dried and tested. Some specimens were tested wet and some were tested after drying. Dried specimens of similar composition were about twice as strong under tensile testing as similar saturated specimens, using two types of tensile tests. Degradation of waste reduces mean grain size and implies the presence of brine to facilitate the degradation processes. Degraded and dry waste may be considerably stronger than undegraded or wet waste.

The DOE suggests that in cases in which high gas pressures occur in the waste, brine consumption during degradation depletes moisture in the waste so that the waste encountered in the top of the repository is likely to be dry. This justifies the assumption in the DOE model that the tests exhibiting the weakest (lowest tensile strengths) surrogate material strengths are highly improbable representations of waste strength at high repository gas pressures. The combined low probabilities of high gas pressure and the presence of saturated, degraded waste during a first intrusion late in the repository history seem to support this premise.

Method Validation

The Panel raised the issue of experimental validation of the new calculational methods, particularly those used to calculate flow and pressure drop through the porous media under highly transient conditions, because these calculations are very critical to the determination of waste stress conditions. The Panel was provided with verification and validation information that generally supports the use of the series of calculational methods, although the Panel did not review all of the available material in detail. DOE stated that the flow equations use Darcy's law, which is applicable except for extremely transient conditions and higher Reynold's numbers in the waste, when gas phase inertial effects could become important. The Panel noted that these calculational methods are used in many applications in situations involving flows in geologic settings and believes they are useful and appropriate for the calculations presented to the Panel, although the literature available apparently did not contain experimental validation under highly transient conditions. The Panel did note that if the calculational flow methods were later proffered for use as part of a new Spallings Conceptual Model, it would be prudent to ensure that the flow calculational methods were fully verified and validated against experimental data for the specific range of conditions of use.

Review of Analogs

The Panel agrees with the conclusion of the DOE analog presentations that the gas pressure gradient and waste cohesion, not the magnitude of the reservoir pressure, controls failure and that the WIPP gas pressure gradients are likely to be less steep than those gradients found effective in coalbed methane production practice. This less steep WIPP gradient is further supported because the WIPP borehole size is approximately a quarter of the cross section area of that used in coalbed treatments, and there will always be a further net borehole area reduction in the WIPP case due to the presence of the downhole drill string.

In the coalbed analog, the volume of solids released increases when the well is pulsed. While pulsing is not a requirement for the cavitation, this fact is important in that the mechanism is a repetitive event and WIPP is only a single cycle, or pulse. Cohesion is also observed to be a factor in the spalling process. Based on the work of Palmer and Vaziri (1994), the DOE's Spallings Release Position Paper (SNL/CTAC, 1997) suggests that because the WIPP waste cohesion is expected to be more than 25% higher than that of the coal tested, cavitation is unlikely. The Palmer and Vaziri modeling, which simulates failure initiation and progressive cavity evacuation by explicitly coupling flow, deformation, and failure, clearly represents events that can be expected of the WIPP waste panel at a time of intrusion.

The Panel concludes that coal methane gas stimulation by cavitation is a highly plausible analog for depicting the spalling process. Its advantages over other analogs considered by DOE are its physical similarities, as well as its relationships to situations and configurations that can be further studied, tested, and defended by well established computer codes, theory, and available corroborative data. However, this analog does not necessarily cover all aspects of the spalling and release process, such as gas erosional effects, liquefactions, and borehole transport mechanisms. The cavity growth calculations presented to the Panel by DOE are based on the same physical and theoretical principles as the Palmer and Vaziri coal gas cavity completion model.

Adequacy of Surrogate Waste Strength

The Panel considered the adequacy of the values of waste tensile strength used in the tensile failure calculations. The Panel concluded that there is some uncertainty in the degree to which the values measured on waste surrogates truly represent the actual waste following extended exposure in WIPP, but that generally, the selected values are reasonable for the intended purposes. The Panel considered the magnitude of spall volume that could result if the actual waste tensile strength were as low as one half of the lower value chosen by DOE for dry waste. In this case, the calculated spall volume at 14.8 MPa initial pressure was roughly estimated by the Panel to increase from 0.25 m^3 to 0.9 m^3. DOE strongly believed that it was not correct to assume such low waste strength values because it introduced unreasonable conservatism into the calculations, and indicated that additional failure criteria would need to be considered if waste strength were significantly lower than the selected values. The Panel agreed with this belief. The Panel notes that the higher spall volume, though perhaps overly conservative, is still lower than

most of the values used in the CCA, which ranged from 0.5 m^3 to 4.0 m^3.

Occurrence of Maximum Pressure Gradient

The DOE calculations presented indicated that the maximum pressure gradients, and therefore tensile stresses within the waste adjacent to an intrusion borehole, occurred within two seconds of the drill penetration into the top of a waste panel, prior to expelling the drilling mud. The Panel questioned whether the gradients and stresses in the few seconds after the drilling mud expulsion might actually be higher. The DOE presented information which showed that this second transient was not expected to be quite as rapid as the first transient, would be at much lower pressure, and would therefore not cause additional spalling volume. The Panel accepted this explanation.

Pressure Bleedoff through the Disturbed Rock Zone

The Panel questioned whether the high gas pressures would bleed off through the disturbed rock zone and Marker Bed 138 before the drill penetrated the top of a waste panel. DOE indicated that, based on the permeability and storativity of these regions, there would not be sufficient time during drilling for such bleedoff to significantly affect waste panel pressures at the time of penetration or to stop drilling operations as a result of interruption of drilling mud flow. The Panel accepted this explanation.

Entrainment of Contaminated Brine Flow During Spallings Events and Release of Radionuclides From Beyond the Tensile Failure Zone

In its earlier reports, the Panel raised the issue of entrainment of contaminated brine in rapid gas flow during a spalling event (p. 98 of the July 1996 report and p. 32 of the December 1996 report). The Panel concluded in the December report that use of the inadequate Spallings Model could not be the basis for an adequate resolution of this issue. The Panel has revisited this issue, which questions whether, in addition to spall of solid waste material due to tensile failure and cavity formation, there would be additional releases of waste particulates and dissolved actinides in liquid brine entrained in rapid gas flow through the waste. This has not been included in spallings calculations. DOE reviewed the calculations methodology in the Direct Brine Release Model and reminded the Panel that full two-phase flow of gas and brine are included for all intrusions, thereby resolving this issue. The Panel also raised the issue of whether solid waste in localized areas of low waste strength would be preferentially released, even from beyond the zone of tensile failure. DOE indicated that these materials would have to penetrate through the other materials and this was highly unlikely. DOE also provided information showing that if channels were to form, this would greatly decrease the pressure gradients and retard the growth of the tensile failure zone. The Panel accepted this as reasonable resolution of these issues.

Effect of Repository Gas Composition

The Panel raised the issue of the effect that the actual repository gas composition would have on the spallings process, since the calculations of spallings volume were performed using gas

viscosity and density for hydrogen. Actual gas composition would be approximately one half methane, which is eight times as dense and 10 percent more viscous than hydrogen. DOE presented calculations addressing the effect of methane, which compared pressures and flows of methane and hydrogen separately. DOE indicated that the most significant effect would be to slightly slow the velocity of flow due to the higher viscosity and density. DOE concluded this would have about a 10 to 20 percent effect on the bottom hole pressure and no significant effect on the waste cavity growth.

The Panel has considered the implications of the use of viscosity and density of a mixture of hydrogen and methane, coupled with the issue of the appropriateness of Darcy flow for the highly transient conditions. It was noted that waste exit velocities are clearly well below the transonic range where further considerations would become highly important. DOE indicated that under somewhat less but still highly transient conditions, where inertial effects may be more important, a rigorous treatment would involve a more complete solution to the Navier-Stokes equation. However, as a first estimate, DOE felt that the increased pressure gradients would probably be commensurate with the steeper stress gradients calculated by the quasi-static method, as opposed to the cavity growth method, as shown in the Spallings Release Position Paper (SNL/CTAC, 1997, pp. 3-32, 33). For this reason, spallings volumes might be more in line with the values of the quasi-static method in Table 3-3 on p. 3-29 of the Spallings Release Position Paper, which represents an approximately threefold increase to a maximum of about 0.7 m^3. These higher values would still be lower than most of the values in the CCA, which ranged from 0.5 m^3 to 4 m^3. Again, the Panel believes that if a new conceptual model were proffered, the combined effects would need to be addressed more rigorously.

Waste Permeability Effects

It was noted by the Panel that the waste permeability values used in the modeling were the same as those used in performance assessment (1.7×10^{-13} m^2), rather than the lower value of about 4×10^{-15} m^2 experimentally determined for the surrogate waste. While the importance of maintaining consistency with performance assessment is understandable, in view of the analog information relating lower permeabilities with higher pressure gradients and therefore larger cavity volumes, the Panel requested the DOE to further discuss the consequences of assuming a higher waste permeability in the analyses than may actually exist in the degraded state. In responding, the DOE referred to sensitivity studies on waste permeability that had been performed with the quasi-static method in which the waste permeability was reduced to 1×10^{-15} m^2. The results indicated that although the pressure gradients did increase at these lower permeabilities, the volumetric flow rate of gas issuing from the waste was insufficient to eject the mud from the borehole, and therefore no spall event could occur. The Panel noted that this conclusion was similar to that reached from modeling studies presented by DOE in January 1997, where it was determined that partial depressurization of the waste panels would not be expected during borehole penetration of the overlying disturbed rock zone because its assigned permeability of 1×10^{-15} m^2 was too low to allow sufficient gas flow to occur. On this basis, the Panel concurred that the higher permeability values used in performance assessment were reasonable for this

application.

Concluding Statements

Upon reviewing the DOE's written materials, oral presentations, and responses to specific issues raised by the Panel, the Panel concluded that no significant issues remained regarding the reasonableness of the spallings volumes used by DOE in its CCA for the WIPP. Although the additional waste strength, analog information, and calculational results that were presented to the Panel could be further refined, the Panel determined that this information was sufficiently accurate and complete to support a conclusion that the spallings volumes used in the CCA are reasonable, and in fact appear to overestimate the actual waste volumes that would be expected to be released by the spallings process.

3.2. Chemical Conditions

3.2.1. Model Description

No changes to this model were presented.

3.2.2. Review of Criteria

The review of criteria for the Chemical Conditions Model remains unchanged.

3.2.3. Review of Responses to Panel Findings of January 1997

3.2.3.1. Summary of Findings

With regard to the Chemical Conditions Model, the Panel concluded that the ongoing test program had not sufficiently progressed to provide a definitive verification that the MgO will perform as planned under repository conditions. The Panel was particularly concerned about whether the results of early tests indicated that reaction rims would inhibit the ability of the MgO to react completely and rapidly with CO_2 to buffer the chemical system and limit actinide solubility.

3.2.3.2. Summary of DOE Responses to Findings

The DOE provided a draft report(1) to the Panel, "Chemical Conditions Model: Results of the MgO Backfill Efficacy Investigation," dated April 23, 1997, along with oral briefings on this report. This report summarizes the currently available data and analyses developed from SNL Test Plan TP-97-01.

Based on current information, DOE indicates that of the various phases formed from the contact of brine with MgO pellets, the initial phase, brucite, will crystallize to nesquehonite and hydromagnesite during short to intermediate times and, over long periods, will dehydrate to magnesite. DOE states that the brine pH and CO_2 fugacity are controlled at levels throughout the process which effectively lead to low actinide solubilities.

Earlier short-term experiments at high CO_2 contact rates indicated the formation of reaction rims. Current results for longer periods with high CO_2 contact rates indicate the growth of brucite films, followed by increasing density of nesquehonite needles projecting from the pellets. Shortly thereafter, hydromagnesite forms among the nesquehonite needles, as well as farther from the pellets. DOE concludes that while there is considerable retardation of CO_2 access to the pellets, accessibility for transfer is maintained. DOE further indicates that the predominant chemical diffusing species are $MgOH^+$ diffusing from the pellets and HCO_3^- diffusing toward the pellets. This gives rise to the precipitation of hydrous magnesium carbonates outside the pellets. DOE further indicates that, in contrast to the experiments, where relatively high CO_2 fluxes occur, the brine at WIPP will become saturated with magnesium compounds before significant introduction of CO_2 species occurs. The reactions will occur at nucleation sites still farther from the pellets, further improving the contact between the reacting species and reducing the formation of reaction rims. This supports the conceptual model assumption that the CO_2 will rapidly and completely react with the MgO. The DOE also reiterated that four times the amount of MgO needed to react with the total quantity of CO_2 generated will be emplaced in the repository.

DOE reviewed the effect of MgO control of pH and CO_2fugacity in actinide solubility, with hydromagnesite being the predominant intermediate carbonate phase. DOE concluded that most solubilities would be lower with hydromagnesite than if the transition to magnesite occurred, as had been assumed earlier. DOE also concluded that the results of the test program and analyses demonstrate that MgO will function in the WIPP according to the Chemical Conditions Model in the CCA.

3.2.3.3. Panel Review of Responses

Reaction Rim Isolation Potential

The fundamental issue that concerned the Panel was whether there would be an inability of the CO_2 to react with the interior of MgO pellets, especially as a function of carbonate reaction rim thickening. The present DOE report has efficiently dealt with this issue. A combination of experimental results, petrographic analyses (both optical and scanning electron microscopy [SEM]), modeling predictions, analog comparisons, and phase equilibria information have satisfied the Panel that reaction rims will not hinder the ability of CO_2 to react with various forms of hydrated MgO pellets. The most compelling evidence that was presented hinged on two factors: 1) the experimental results indicating that hydrous magnesium carbonate phases could nucleate away from the pellet surface and in the saturated brine, and 2) SEM photographs showing partially dissolved cores remaining within reaction rims.

Results of experimental runs were conveyed in carbon uptake curves that plot mole percent conversions versus time. An unusual S-shape to the curves (schematically shown in Figure 4-1 of the draft Chemical Conditions Report [SNL, 1997]) indicated that a substantial amount of magnesium was going into solution in the brine. During the experiments, which were accelerated

due to high CO_2 concentrations, the magnesium saturated brines would combine with CO_2 to form hydrous magnesium carbonates at the most convenient nucleation sites. These sites included pellet surfaces, interstices between pellets, and free grains in the brine (the so-called milky appearance). In Figure 5-1 of the Chemical Conditions Report, precipitation fronts were indicated for carbonate minerals in both the experimental situation and for WIPP conditions. These two diagrams indicated that for WIPP conditions in particular, magnesium would dissolve from the pellets and go into solution. Therefore, the CO_2 would not be required to react with the pellet outer surface to form hydrous magnesium carbonates. This was compelling evidence that any coating that forms on the pellets is a secondary influence of carbonate nucleation.

It was also shown by the carbon uptake curves that the materials deposited on the pellets (nesquehonite and hydromagnesite) form a porous mantling (previously thought to be reaction rims) that allows magnesium to continue dissolving out of the pellets and go into solution in the brine at a somewhat reduced rate. This factor was strongly substantiated by SEM photomicrographs (Figure 4-5 of the Chemical Conditions Report) which show various states of pellet dissolution within concentric shells of mixed nesquehonite and hydromagnesite.

Metastable Hydrous Phases

In both the written presentation (Chemical Conditions Report [SNL, 1997]) and the oral presentation (on April 25, 1997), mention was made that the predominant hydrous magnesium carbonate phases formed in the experiments were nesquehonite and hydromagnesite. That is not surprising since Christ and Hostetler (1970) state " no carbonate mineral has proven more difficult to investigate experimentally than magnesite." These hydrous phases were produced easily in the experiments because of the elevated CO_2 concentrations used. The five order of magnitude higher CO_2 concentration in the experiments relative to predicted WIPP values was used to facilitate carbonate growth in a restricted time frame. Both phases were reported to be metastable, and would dehydrate (mature) with time to magnesite. The predicted time frame for dehydration reactions ranges from approximately 100 to 1000 years, depending on exact chemical conditions in the repository. This hypothesis was well supported by the following information: 1)natural analogs, 2) phase equilibria, and 3) Arrhenius plots.

The most pertinent natural analog study is that of Usdowski (1994), which observed that hydromagnesite would undergo a phase transformation to magnesite in a natural setting in Australia. The chemical conditions of that setting (ionic concentrations relative to ionic proportion and magnesium to calcium ratios) would encompass those of the Salado and Castile brines within the WIPP, as seen in Figure 5-2 of the Chemical Conditions Report. Phase equilibria determinations by Langmuir (1965) and especially Lippman (1973), as represented by Figure 4-3, have indicated that the metastable phases nesquehonite and hydromagnesite would transform to magnesite with sufficient time. The reaction pathway is easily seen in Figure 5-5, which predicts that the two hydrous phases of interest would dehydrate (mature) with time to produce magnesite. The way in which the accelerated experiments provided by DOE could be scaled to the conditions found at WIPP are by Arrhenius plots. This is a well documented and

commonly used technique in experimental petrology to scale experimental results to field conditions that are not conducive to laboratory parameters and time frames. The Arrhenius plot presented to the Panel (Figure 5-4) indicates that magnesite would form in place of the hydrous magnesium carbonate in several hundred years. This supporting information is taken by the Panel as satisfactory evidence that the laboratory phases produced by DOE will in fact transform to magnesite well within the time constraints needed for the Chemical Conditions Model.

Water Sequestration

In the process of forming magnesian minerals in the repository, free water will be sequestered by the first step in the reaction series, the formation of brucite. Some of that water is later returned to the repository by the progressively less hydrous minerals generated in the transformations from brucite through hydromagnesite to magnesite. Since there will be excess MgO in the repository above that necessary to convert all the generated CO_2, most of this sequestered water will remain in brucite, permanently unavailable to react with the waste. The water that is returned will not change the volume of water assumed in performance assessment to be available to react with the waste. However, the reaction with that part of the water will be delayed while it is held by the metastable hydrous magnesium carbonate mineral phases. The process of carbonate hydroxide generation and the eventual dehydration of the anhydrous mineral phases which returns some free water to the system is expected to end after about 2000 years. This is during the period of most rapid brine inflow into the repository, and the return of that water to the waste is not expected to significantly change waste degradation rates at that time or later. The net overall effect of MgO hydration to brucite is to make the repository nominally drier.

Competition of Anions and Cations

The Panel asked whether other anions or cations that would be present in the waste or repository environment would inhibit the desired reaction between magnesium cation species and carbonate anion species. DOE indicated that anion species such as nitrate, sulphates, and chlorides do not significantly precipitate magnesium due to their solubility, and therefore would not prevent magnesium from being available to react with carbonate anions. Similarly, DOE indicated that other cations, such as calcium and iron would, if anything, also precipitate additional carbonate anions, and the resulting compounds are chemically compatible with magnesium carbonate species. Thus, other anions and cations would not interfere with the reactions between magnesium and carbonate species.

Conclusion

Based on the information presented to the Panel in the written material and in oral discussion, the Panel concludes that the results available provide an adequate basis to determine that the MgO backfill will function according to the Chemical Conditions Conceptual Model, as used in the CCA, with respect to reaction with generated CO_2 gas.

4.0 SUMMARY

This third supplementary report documents the Panel's evaluation of additional information regarding the two conceptual models that were not previously determined to be adequate, the Spallings Model and the Chemical Conditions Model.

The additional information on the spallings process included strength data for surrogate waste materials, analog information, and results from computational methods developed since the Panel's January 1997 report. The new information was not presented to the Panel as a new conceptual model, but rather to support DOE's belief that the spallings volumes used in the CCA were reasonable. In reviewing this additional information, the Panel was requested by DOE to determine if the predicted volumes of spalled materials presented in the WIPP CCA are reasonable, based on additional consideration of processes that could lead to spalled releases.

The written materials and oral presentations on the spallings process prepared by the DOE, and the DOE's responses to specific issues raised by the Panel, were based on a detailed evaluation of the conditions, events, and processes at the WIPP that could lead to a spallings release, and on mathematical representations describing the sequence of physical events that could occur. Although further refinement in understanding and predictive capability for spallings events would be desirable as part of a new conceptual model, the Panel has determined that the additional information presented by the DOE is sufficiently complete at this time to support a conclusion that the spallings volumes used in the CCA are reasonable, and may actually overestimate the actual waste volumes that would be expected to be released by the spallings process at the WIPP.

The significance of possible entrainment of brine by expanding gases upon intrusion of a waste panel by a borehole was raised as an issue by the Panel in its July and December 1996 reports. DOE's initial response to this issue was not accepted by the Panel because it was based on computations using the inadequate Spallings Model. In further discussion of this issue during the April 1997 meetings, it was determined that the BRAGFLO-DBR model used to calculate direct brine releases computes two-phase flow effects in both the repository and the intrusion borehole, and accounts for the driving effects of gas expansion. This issue is therefore considered by the Panel to be satisfactorily resolved.

The additional information for the Chemical Conditions Model included further data from the MgO test program regarding hydration of MgO and transition toward magnesite, reaction rates with carbonate species, control of pH, and effect on actinide solubility. The Panel's only remaining concern for this model related to the lack of a demonstrated ability of the MgO backfill to function according to the assumptions in the conceptual model as used in the CCA with respect to reaction with the generated CO_2gas. The results of the information and analysis are sufficiently complete at this time for the Panel to conclude that the MgO backfill will function as assumed in the CCA and that this model is adequate to represent the future states of the

repository.

With the exception of the Spallings Model presented in the CCA, which the Panel continues to find inadequate, all remaining conceptual models have been determined to be adequate and all significant issues regarding their adequacy have been resolved.

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ACRONYMS

CCA	Compliance Certification Application
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
SEM	Scanning Electron Microscopy
SNL	Sandia National Laboratories
WIPP	Waste Isolation Pilot Plant

DETERMINATIONS OF PEER REVIEW MEMBER INDEPENDENCE

C.R. Wilson

Determination of Peer Review Member Independence Form

___ Currently employed by DOE or DOE Contractor? Yes/No

X Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

1978 - 1983 U. of California Lawrence Berkeley Laboratory - Performed field hydrology study of Hanford Site

1983 - 1985 Hydrotechnique Inc, Berkeley CA - Performed consulting Services to Hanford Site

1986 - 1996 Golder Associates Inc - Albuquerque NM - Performed consulting Services to Hanford, INEL, Los Alamos Sites

___ Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Charles R Wilson

Date: 3/29/96

Peer Review Manager Approval: John A. Thies 4/8/96 Date

Darrell Porter

Determination of Peer Review Member Independence Form

Yes — Currently employed by DOE or DOE Contractor? Yes/No
yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

SRIC, my employer, has been active as a DOE Contractor for many years. To date I have had no work or other relationship to work on the DOE WIPP Program.

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Darrell Porter

Date: March 29, 1996

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

E.B. Oswald

Determination of Peer Review Member Independence Form

No — Currently employed by DOE or DOE Contractor? Yes/No
Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

April through August, 1995. Albuquerque, NM, S.M. Stallar Corporation Served as Independent Review Team member assisting WIPP WTAC in the review of data record packages.

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: E.B. Oswald

Date: 3/30/96

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

Florie Caporuscio

Determination of Peer Review Member Independence Form

Yes — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

4/96 Informatics, Albuquerque NM, staff consultant Peer Review of WIPP

8/93 – 3/96 Advanced Sciences Inc, Los Alamos Office, Project Manager and Senior technical Lead, Environmental Restoration Project

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer. or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Florie A Caporuscio

Date: 4/1/96

Peer Review Manager Approval: John A. Thies — 4-1-96 Date

Glen Sjoblom

Determination of Peer Review Member Independence Form

1. Currently employed by DOE or DOE Contractor? Yes No
2. Employed by DOE or DOE Contractor previously? Yes No

See below

If yes, give dates, location, company, position type work performed.

1. I have a contract with Oak Ridge Institute for Science and Education, to provide an assessment of effectiveness of DOE office of Nuclear Energy Program of Assistance of nuclear reactor safety to Former Soviet Countries; this has no bearing on the proposed peer review at WIPP.
2. I was a special assistant to the Asst. Secy for Environmental Management but was not involved with activities at WIPP.

NO

Do you or have you had any direct involvement or financial interest in the work under review? Yes No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Glen L. Sjoblom

Date: 3/29/96

Peer Review Manager Approval: John A. Thies 4/8/96 Date

John Gibbons

Determination of Peer Review Member Independence Form

NO — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

Battelle Alb., IPT reviewer of WIPP DATA packages 1994-1995
ARA, Alb. Site Characterization Technology Research 1992-1993
SNL Civil Systems Inc., High Level WIPP Experiment Planning 1977-1978

NO — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: [signature]

Date: NOV 29/96

Peer Review Manager Approval: [signature] John A. Thies — 4/8/96 Date

CERTIFICATIONS REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

C.R. Wilson

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer _____

Name of Offeror:_____ Signature Charles R Wilson

Date Signed: 3/29/96 Typed name CHARLES R. WILSON

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Darrell Porter

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer 3/29/96

Name of Offeror: DARRELL PORTER Signature Darrell D Porter

Date Signed: April 2, 1996 Typed name_____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

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E.B. Oswald

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer 4/1/96

Name of Offeror:_____ Signature _____

Date Signed: _____ Typed name: Eric B.Oswald

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

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Florie Caporuscio

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer 3/25/96

Name of Offeror: Florie A Caporuscio Signature Florie A Caporuscio

Date Signed: 4/1/96 Typed name_____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

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(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Glen Sjoblom

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No _____ Date of Offer 3/25/96

Name of Offeror: Glen L. Sjoblom Signature Glen L Sjoblom

Date Signed: 3/29/96 Typed name _____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

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(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

John Gibbons

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No._____ Date of Offer_____

Name of Offeror: John Gibbons Signature John J. Gibbons II

Date Signed: Mar 29/96 Typed Name_____

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (✓) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (✓) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (✓) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (✓) No

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(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

APPENDIX B - SIGNATURE PAGE

I acknowledge by my signature below that I concur with the findings and conclusions documented in this Conceptual Models Peer Review Report.

Florie Caporuscio

John Gibbons

Eric Oswald

Darrell Porter

Glen Sjoblom

Charles Wilson

MEMORANDUM

To: M.G. Marietta

From: T.W. Thompson, F.D. Hansen

Date: July 24, 1996

Subject: Long-term Performance of Panel Closures

---

1. INTRODUCTION

After waste has been emplaced in a panel, closures will be built to restrict flow from the panel during the remainder of the operational phase. These closures will include a length of concrete placed in the panel entries. Although it is not the intent of these closures to restrict flow over the regulatory period of 10,000 years, values for their long-term performance characteristics are required to successfully determine their contribution to overall system performance.

Flow of fluids into or out of the panels will be controlled by the conductance of the panel closure, and of the surrounding disturbed rock zone (DRZ). Performance Assessment (PA) calculations use a constant value for DRZ permeability of 10^{-15} m^2, a value which is substantiated in the records package for the waste rooms (reference). Consideration of the current panel closure designs indicates that they will maintain their structural integrity for the regulatory period. If this is the case, then the concrete element of the closure system will continue to provide resistance to inward deformation of the surrounding salt, and will prohibit the growth of the DRZ from its initial state. Since the DRZ will not increase during the regulatory period, and may decrease, the assumption of a constant DRZ permeability is reasonable.

The panel closures have been designed to limit the flow of brine and gas between panels during the operational phase, and current designs call for these operational closures to include concrete elements (Figure 1). Although these closures are designed for an operational use, it is expected that they will continue to provide fluid flow restriction during the post-closure phase. The remainder of this memorandum establishes the permeability expectations of the closures, with emphasis on the potential for concrete degradation and increase in permeability. For the purposes of these analyses the concrete elements are taken to have a length of nominally 26 ft (7.9 m) (USDOE, 1996a,b), and to be made of a material chosen so as to be compatible with the environment, such as Salado Mass Concrete (SMC: Sandia, 1996) or a similar mix. Degradation of the concrete may occur by interaction with brine flowing through the plug, or with brines flowing along the plug/salt interface or in the DRZ.

2. CONCRETE PROPERTIES

The initial permeability expected for the concrete panel closures are documented in the materials specification appendix of the Compliance Submittal Design Report (CSDR) (Sandia, 1996) developed for the shaft seal system. In addition to conventional engineering properties, the SMC has well documented permeability characteristics, permeabilities having been determined from field tests (Knowles and Howard, 1996) and laboratory studies (Pfeifle et al., 1996). Figure 2, taken from the CSDR, summarizes the available data, and indicates a permeability for as-placed SMC of between 2×10^{-21} and 1.8×10^{-17} m^2. For calculations performed in this memorandum a value of 10^{-17} m^2 is used, this being at the high end of the values used by PA for the shaft concrete components, and consistent with other data. For example, data on generic portland cement pastes shows that the permeability of oil field concrete plugs is on the order of 1×10^{-19} m^2, while data from the Bell Canyon Test indicate permeabilities for borehole concrete plugs of 5×10^{-17} m^2 (Petersen and Christensen, 1980; Christensen and Hunter, 1980).

For the purposes of calculating degradation of the concrete member an assumption of porosity is necessary. The expected value is 5 %, which is higher than the 2% estimated by Petersen and Christensen (1980) for the Bell Canyon Test plugs, but is generally consistent with practical experience of field emplaced concrete structures, and is the value for cast in-place SMC given in the CSDR (Sandia, 1996). An upper limit for porosity is taken as 10%, which is an engineering estimate for concrete.

As noted in the introduction, the concrete closure member is expected to be structurally stable for the regulatory period, and to provide support for the surrounding rock and the DRZ. In this context it can be noted that the unconfined compressive strength of SMC is greater than 4500 psi (30 MPa), and that under the confined state of stress within the closure system the ultimate strength will be greater than this (Pfeifle et al, 1996). This strength is sufficient to preclude structural failure of the concrete member in the panel entries.

3. DEGRADATION OF CONCRETE

The solid matrix that makes up concrete is composed almost entirely of amorphous to cryptocrystalline solid phases. These phases are thermodynamically unstable, and with time and exposure to water they alter into more stable and more crystalline assemblages. Thermodynamic calculations conducted by Alcorn et al (1992) have predicted the alteration phases of portland cement due to exposure to a variety of waters and brines as including tobermorite, quartz, gypsum, calcite, clays and zeolite, produced at the expense of soluble and unstable materials such as portlandite. The theoretical alteration assemblage occupies more volume than the original solids. These calculated results have been verified by subsequent experiments in which waters and cement were reacted (Onofrei et al., 1992).

At free surfaces concrete materials are not physically supported and can spall. Long term leaching experiments report that surface diffusion controlled alteration is dependent on the C_3A content of the cement and the Mg and SO_4 content of leachant (Walton et al., 1990). Creation of an alteration rind weakens the concrete and makes it subject to spalling (Wakeley et al., 1994). The mechanism for spalling is that the alteration phases occupy more volume than the original

solids, volumetric expansion increases internal pore pressures until concrete tensile strengths are exceeded and spalling occurs. Short-term, empirical studies of ordinary concrete in brine report alteration rates in the range of 0.7 to 1 mm/year (Atkinson and Hearne, 1990) - These rates are likely to be overestimates because diffusion distance varies as the square root of time. Further details are given in Appendix C of Thompson et al., 1996.

4. DEGRADATION OF CONCRETE PANEL CLOSURES

The concrete elements of the panel closures may degrade in one of two ways, either by flow of brines through the mass of the concrete element, or by flow of brines along the interface.

4.1 Flow Through the Concrete Element

An estimate of the degradation of a concrete closure element may be made based on data on the progression of concrete chemical alteration reported by Berner (1990) for both fresh water and brine leachants (Figure 3). The progression is charted in terms of the volume of water flow, and indicates that more than 100 pore volumes of leachants must pass through concrete before there is chemical evidence that the matrix is being attacked. Based on these results, it has been assumed (conservatively) that the concrete closure elements will degrade significantly after 100 pore volumes of water have passed through them. A more detailed discussion of these results is given in Thompson et. al. (1996).

This volume can be converted to performance life by using Darcy's Law and considering the flow of fluids though the plug and the surrounding DRZ. If there is a pressure difference between the panel and the rest of the repository, flow will occur through the panel closure and the surrounding DRZ, with the two elements acting as flow resistors in parallel (Figure 4). If the pressure in the panel is P_1 (Pa) and in the rest of repository is P_2 (Pa), then under brine saturated conditions, the steady state flow rate out of the panels will be Q, where:

$$Q = A*(k'/\mu)*(P_1 - P_2)/L \quad m^3/sec, \qquad (1)$$

where: A is the total flow area of the panel closure plus DRZ (m^2)
L is the flow length (m)
μ is the fluid viscosity (Pa.s)
k' is the composite permeability of the panel closure plus DRZ (m^2).

The composite permeability, k', is given by:

$$k' = (k_d A_d + k_c A_c)/(A_d + A_c), \qquad (2)$$

where: k_d, k_c are the permeabilities of the DRZ and plug closure respectively (m^2)
A_d, A_c are the flow cross-sectional areas of the DRZ and plug closure respectively (m^2).

The flow through the panel closure, q_c, will be:

$$q_c/Q = k_c A_c/(k_d A_d + k_c A_c). \quad (3)$$

The pore volume of the panel closure (V_p) is:

$$V_p = A_c L \phi \text{ m}^3,$$

where ϕ is the porosity. The number of pore volumes (N_p) flowing through the closure in unit time will be:

$$N_p = q_c/V_p \text{ pore volumes/sec},$$

and the time for 100 pore volumes to flow through the closure will be:

$$t_{100} = 100/(N_p * 3.154\text{x}10^7) \text{ years}$$

The current design (USDOE, 1996a,b) calls for a length of 7.9 m (26 ft) for the concrete closure, and a cross-sectional area of 39.6 m^2 (10 m wide by 3.96 m high). As noted in Section 2 an undegraded concrete permeability of 10^{-17} m^2, and a porosity ranging from 5% to 10% may be assumed. The DRZ around the closure is assumed to have a permeability of 10^{-15} m^2. Based on the BRAGFLO grid (reference) the DRZ may be assumed to have a height of 11.95 m above the closure and 2.23 m below. It is assumed that the DRZ in the pillars at either side of the closure heals due to creep closure onto the rigid concrete. The DRZ flow area may therefore be taken as 141.8 m^2 (11.95 + 2.23 m high by 10 m wide).

Given these values, the effective permeability of the closure and the DRZ, from equation (2), is $7.84\text{x}10^{-16}$ m^2, with an effective flow area of 181.4 m^2. When brine flows between the panel and the rest of the repository, from equation (3), only 0.28 % will flow through the closure, the remainder (99.72 %) will be through the DRZ.

An analysis of calculations made with BRAGFLO (reference) using a range of parameters, and assuming permeabilities for the closures and DRZ of 10^{-15} m2, indicates that the maximum cumulative flow between the panel and the rest of the repository for any likely E1 or E2 scenario will be of the order of 10^4 m^3 (Figure 5). With these flows, and the slit in flows indicated above, only 28 m^3 of brine will flow through the concrete closure in 10,000 years. For a porosity range of 5 % to 10 % the maximum cumulative flow through the concrete closure in 10,000 years will therefore be between 0.6 and 1.2 pore volumes. The same point is made in Figure 6, which shows the cumulative flow with closure permeabilities of 10^{-15} to 10^{-17} m^2. Degradation will be minimal with these flow volumes.

4.2 Flow Along the Interface

Flow along the interface may be more rapid due to the higher permeabilities in the DRZ. A maximum effect of this flow might be estimated to be equivalent to the free surface spall rate of 0.5 to 1 mm/yr. Such a degradation rate is unrealistically high, since the degradation will be controlled by the rate of fluid flow, and total loss of material will not occur in a physically constrained region. However this rate of spall is much less than the expected closure rates (measured at the order of 0.1 to 0.2 ft/yr. or 30 to 60 mm/yr in Panel 1: USDOE, 1996b) so even such a rapid spall rate would be more than compensated for by creep of the salt on the closure. It is therefore concluded that the effect of flow along the interface will be minimal. At most it will lead to an insignificant increase in the DRZ flow area.

5. CONCLUSIONS

It is concluded that the potential flow through the concrete closure is nearly two orders of magnitude too small to cause any significant degradation. Degradation caused by flow in the DRZ adjacent to the concrete will be taken up by creep closure. It is therefore concluded that the panel closures will retain their initial permeability in the post-closure phase. If this permeability is 10^{-17} m^2, then the effective permeability of the DRZ and the closure together will be about $8x10^{-16}$ m^2. An assumption of a permeability of 10^{-15} m^2 for the closure and the DRZ is reasonable.

It is also concluded that since no significant degradation is expected for the concrete members, these will maintain their structural integrity and will provide a rigid support to prevent growth of the DRZ during the regulatory period.

6. REFERENCES

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BRAGFLO grid (ref)

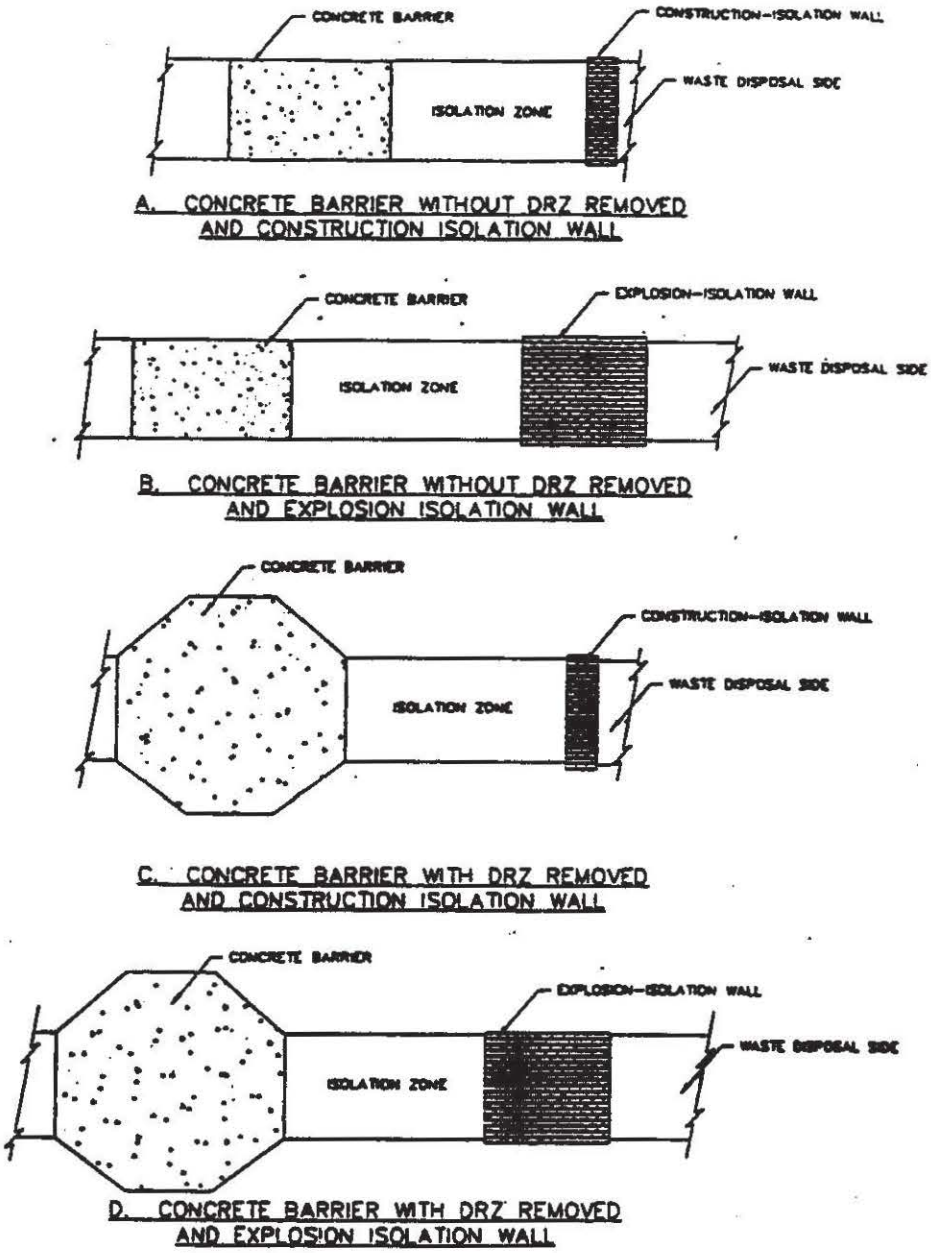

Figure 1: Panel Closure Designs (after USDOE, 1996a)

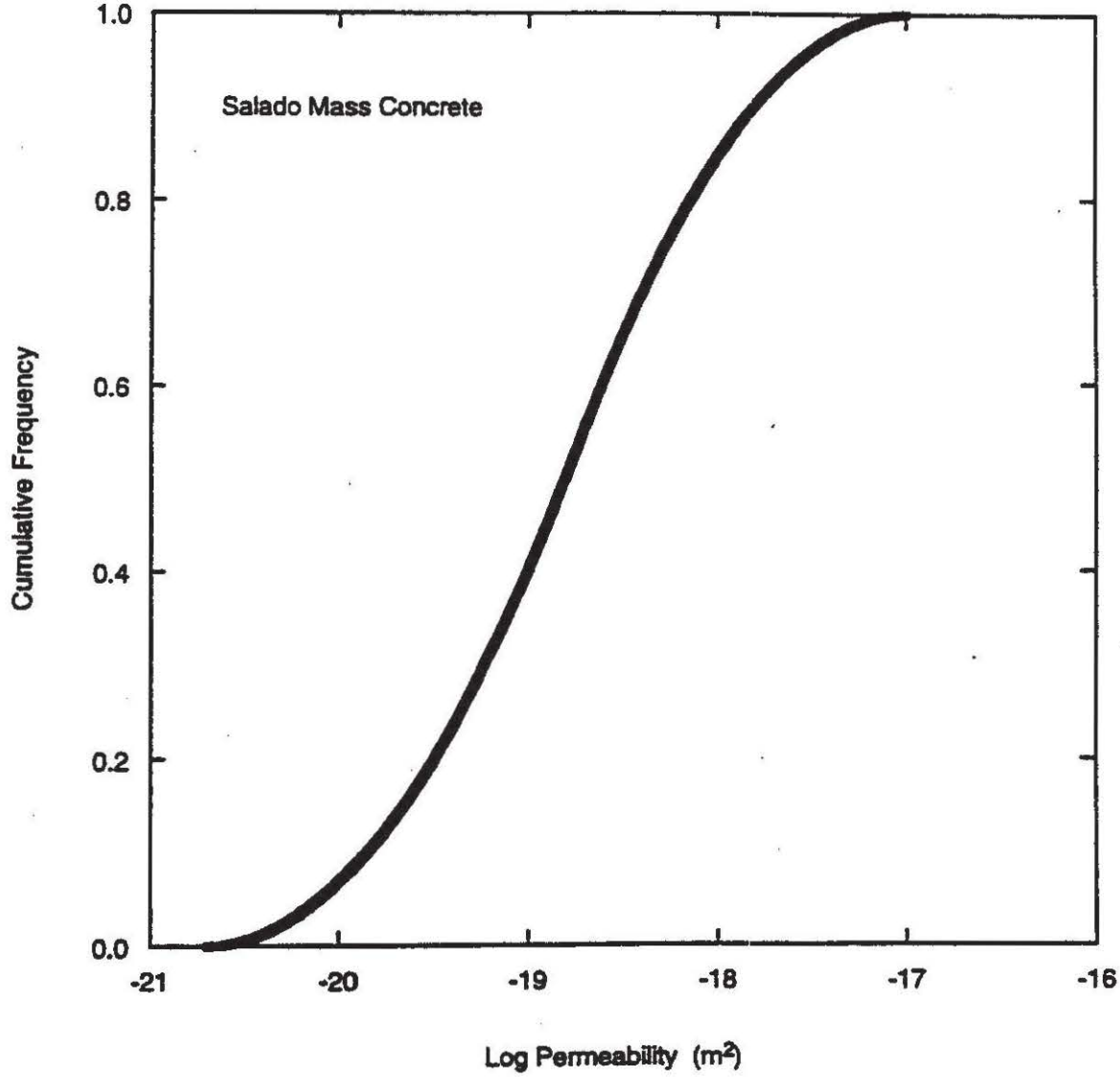

Figure 2: Cumulative Distribution Function for Permeability of SMC (after Sandia, 1996)

Figure c-3 Degradation of "HTS" in standard marl grundwater "MAR". After 6650 cycles calcite is the only solid phase present (T = 25 °C).

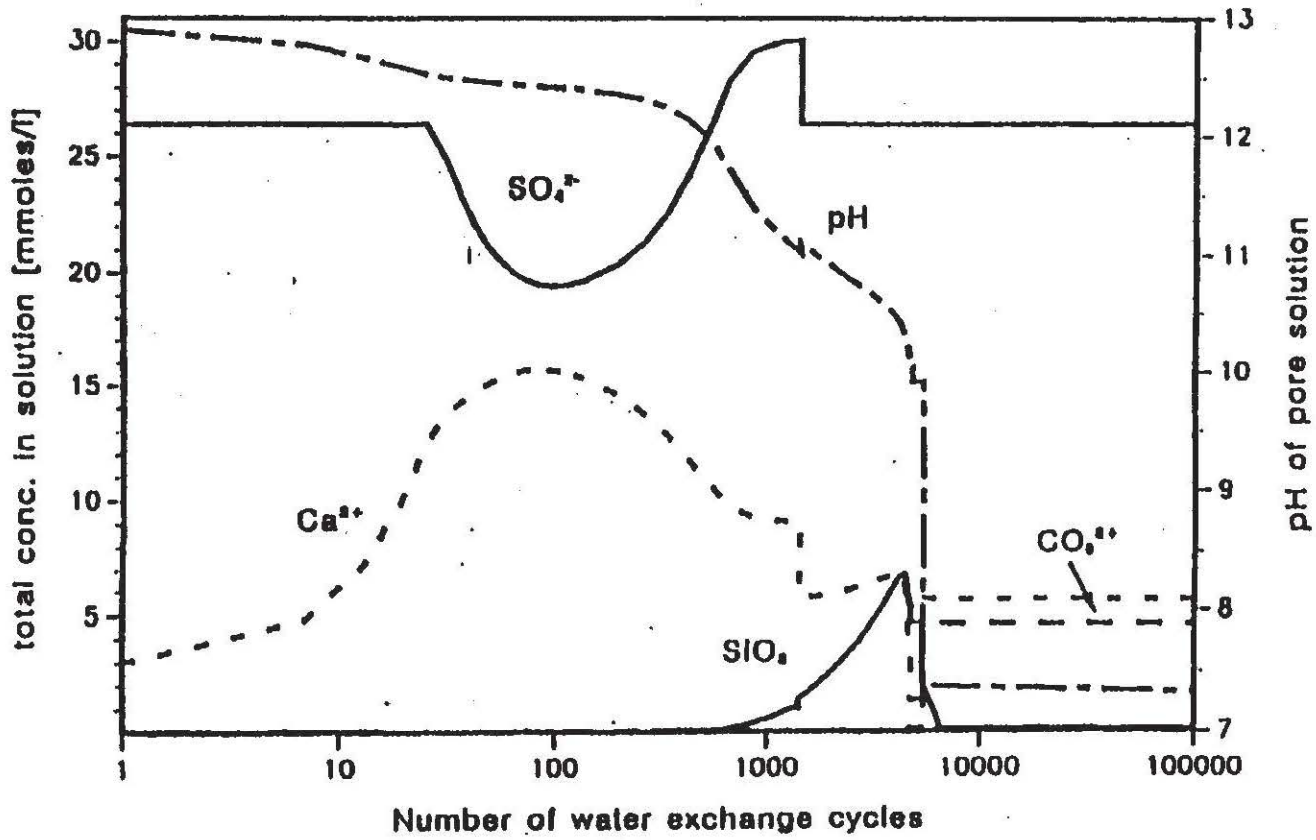

Figure 3: Degradation of Concrete in Brine (after Berner, 1990)

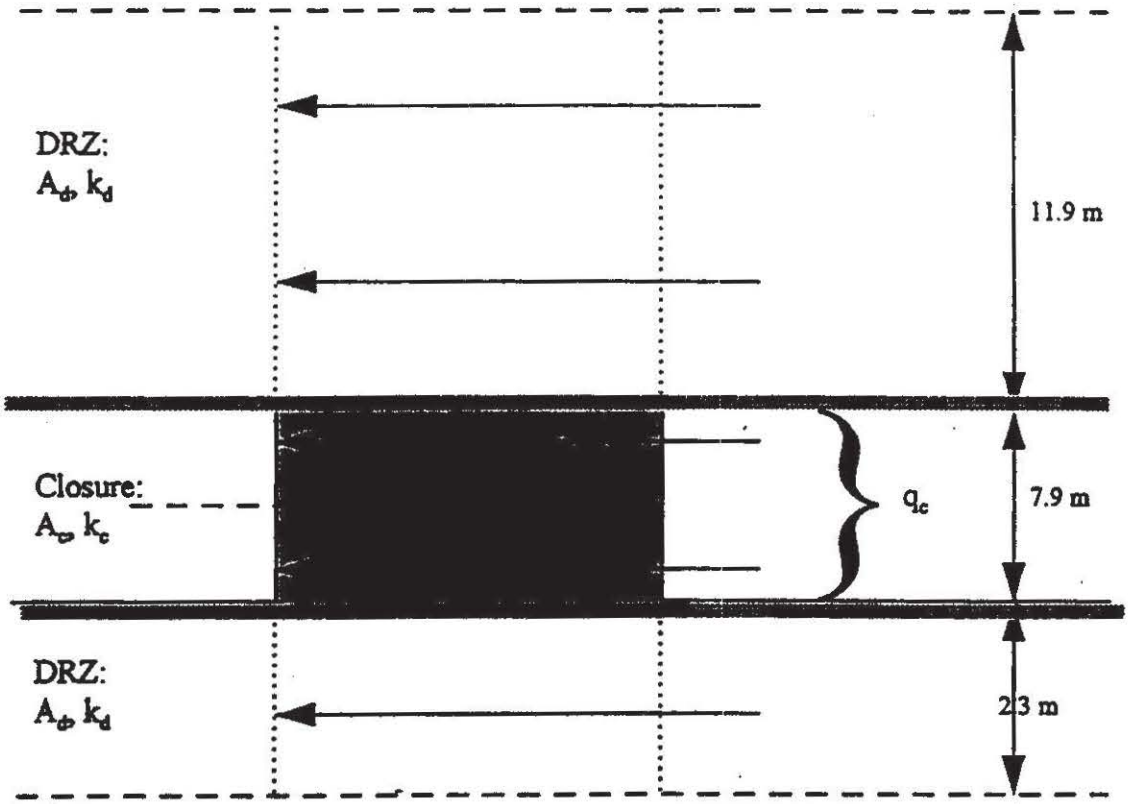

Figure 4: Parallel Flow through the Panel Closure and DRZ

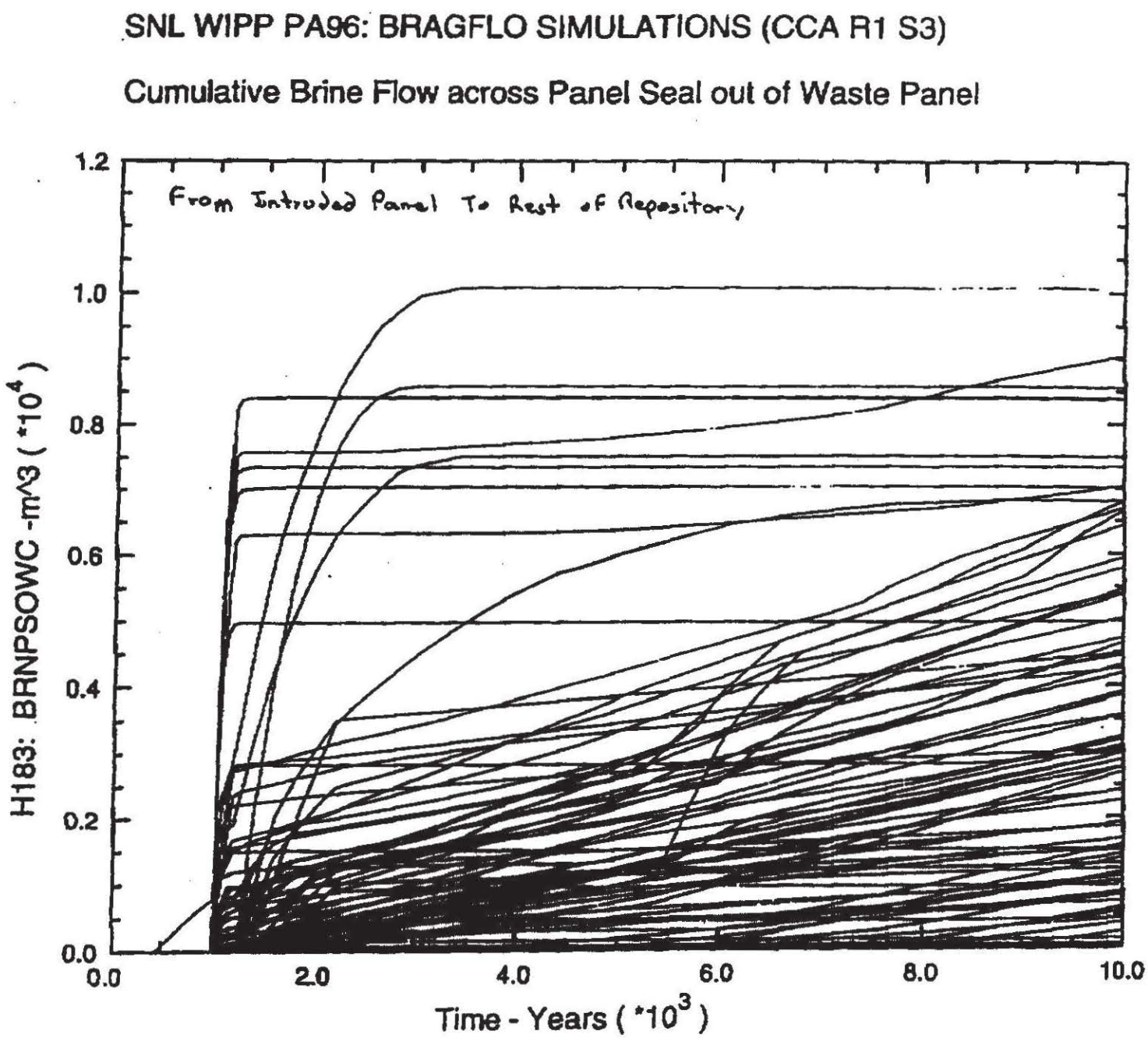

Figure 5: Cumulative flows between a panel and the rest of the repository for an E1 Intrusion at 1000 Years

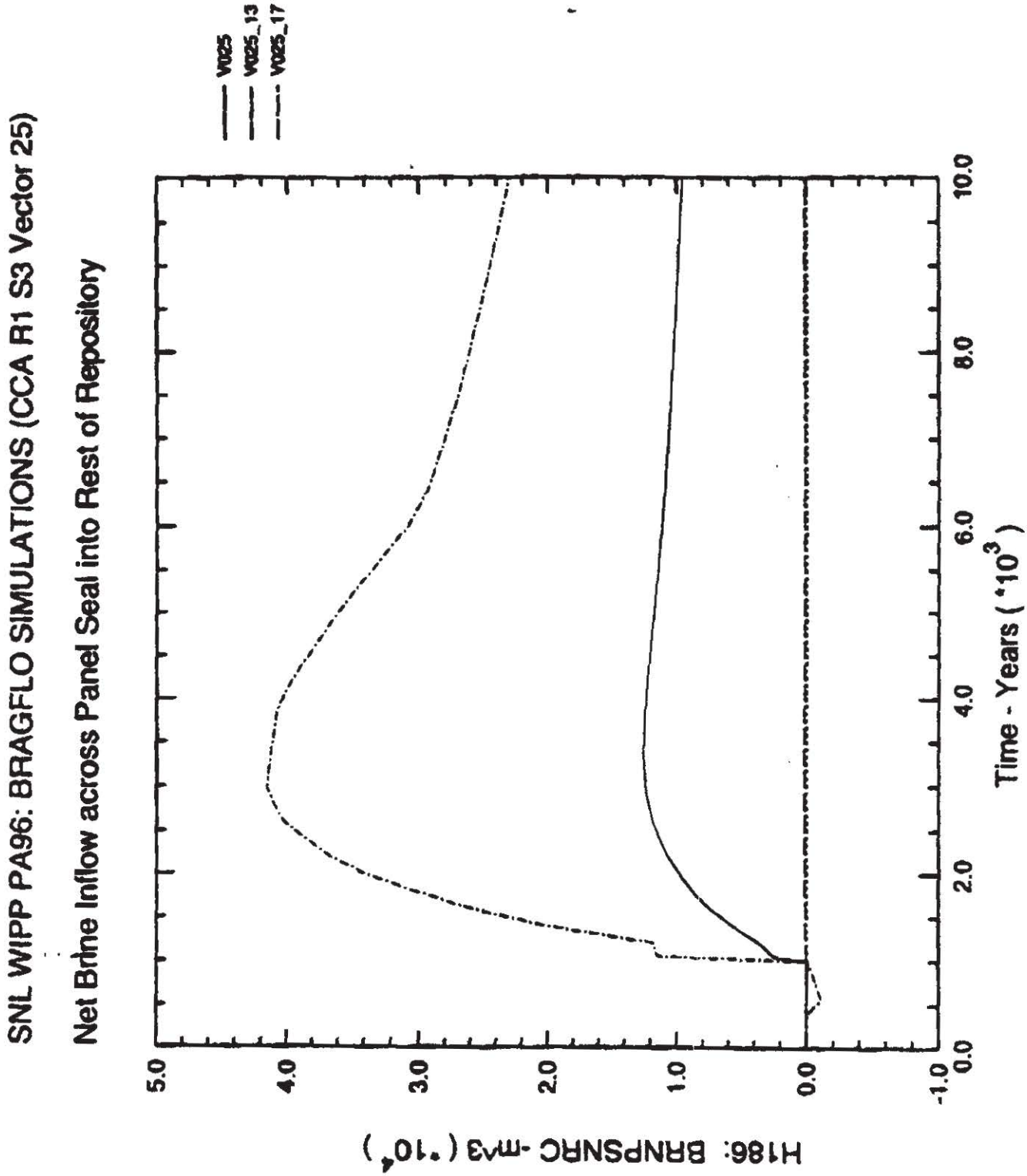

Figure 6: Cumulative flows through the Panel Closures for Permeabilities of 10^{-15} to 10^{-17} m^2. Results shown are for the Maximum Flow Case of Figure 5.

WIPP Colloidal Actinide Retardation Research Program

DOE Consultation with the State of New Mexico

21 May 1996

Carlsbad, NM

Hans W. Papenguth

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Outline of Presentation

Mobile Colloidal Actinide Source Term

- Overview
- Results

Retardation of Colloidal Actinides in the Culebra

- Conceptual models
- Program strategy
- Experiments
- Results by colloidal particle type
- Summary

Several Potential Sources of Colloidal Actinides Exist in the WIPP System

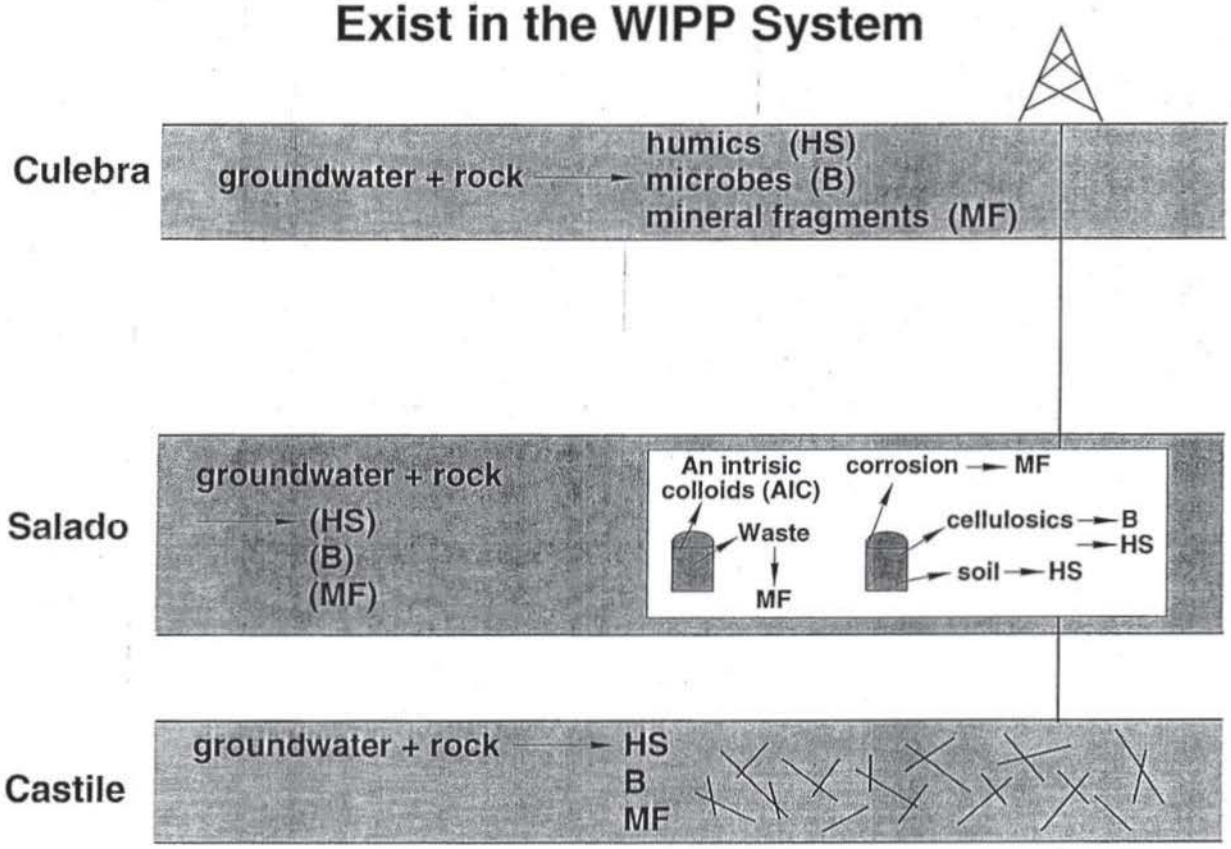

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Colloidal Particle Types Affected Differently by Chemical Conditions

Colloid Type	Stability Behavior in WIPP Brines	Uptake Mechanism for Th, U, Np, Pu, Am
mineral fragments	electrostatically destabilized	sorption
microbes	not affected	passive or active bioaccumulation
actinide intrinsic	solubility reduced; electrostatically destabilized	intrinsic
humic substances	solubility reduced	complexation

Mobile Colloidal Actinide Source Term

Concentrations dependent on repository brine scenario

- Salado brine, lower redox [Th(IV), U(IV), Np(IV), Pu(III), Am(III)]
- Salado brine, higher redox [Th(IV), U(VI), Np(V), Pu(IV), Am(III)]

- Castile brine, lower redox [Th(IV), U(IV), Np(IV), Pu(III), Am(III)]
- Castile brine, higher redox [Th(IV), U(VI), Np(V), Pu(IV), Am(III)]

Summary of ranges

(moles colloidal actinide per Liter of dispersion)

actinide	mineral	intrinsic	microbe*	humic*
Th	10^{-9}	0	10^{-8} to 10^{-5}	10^{-8} to 10^{-5}
U	10^{-9}	0	10^{-11} to 10^{-8}	10^{-8} to 10^{-5}
Np	10^{-9}	0	10^{-7} to 10^{-4}	10^{-9} to 10^{-5}
Pu	10^{-9}	10^{-9}	10^{-9} to 10^{-6}	10^{-8} to 10^{-5}
Am	10^{-9}	0	10^{-7} to 10^{-6}	10^{-7}

* based on mean actinide solubilities reported by Novak and Moore (1996)

Culebra Conceptual Hydrogeological Model

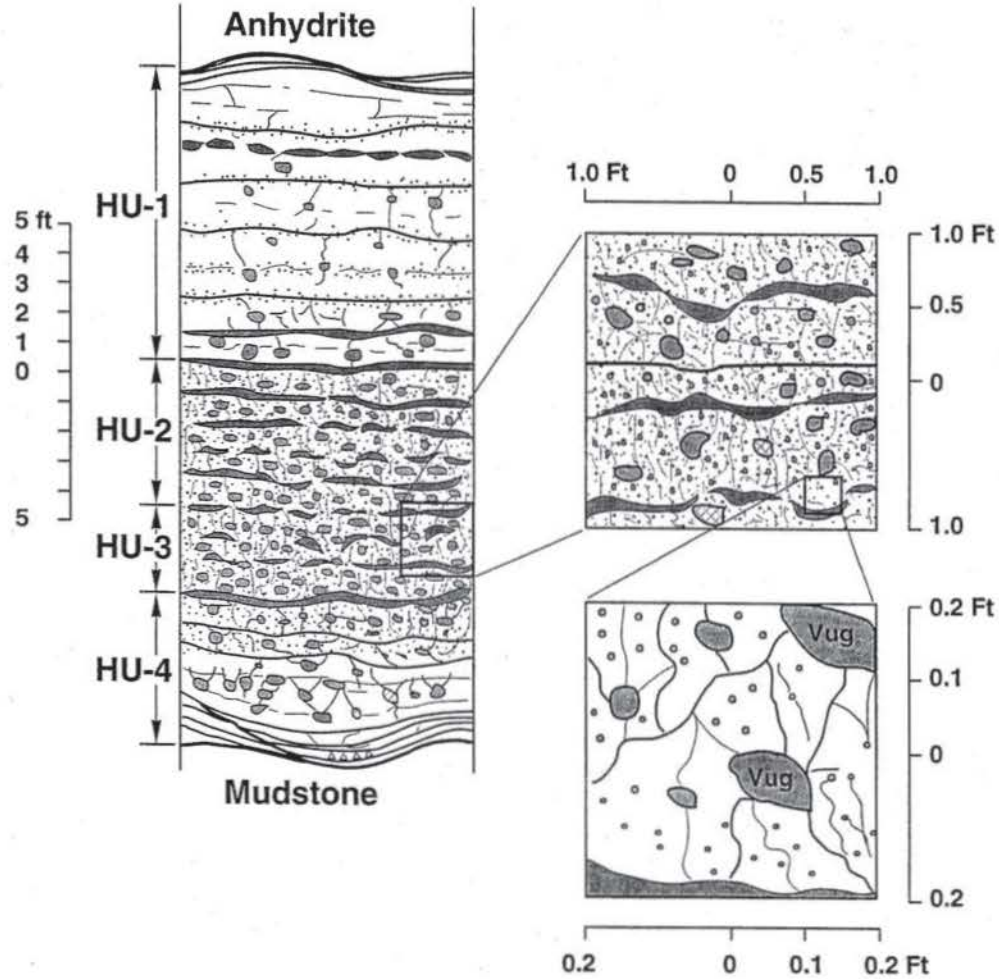

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Transport Behavior Depends on Colloid Type and Culebra Characteristics

Possible interactions between colloidal-actinides and rock:

Colloid Type	Colloid Size Range; Shape	Diffusion ?	Sorption ?	Filtration ?
mineral fragments	1 to 1000 nm; various shapes	smaller colloids only	yes	yes
microbes	250 to 2000 nm; rod shaped	no	yes	yes
actinide intrinsic	1 to 10 nm; dissolved, compact	yes	yes	no
humic substances	1 to 10 nm; dissolved, compact	yes	yes	no

*mean pore throat size in Culebra matrix is 630 nm (Kelley and Saulnier, 1990)

Experimental Approach Tailored to each Colloid Type

Batch sorption experiments (LANL) — K_d
- humic substances (Th, U, Np, Pu, Am)
- actinide intrinsic colloids [Pu(IV)-polymer]

Crushed-rock column flow experiments (SNL, BNL) — R, γ
- humic substances
- preserved microbes
- live microbes
- mineral fragments

Intact-core column flow experiments (SNL, BNL) — R
- humic substances (mixed with U, Pu, Am)
- live microbes (mixed with U, Am)

Diffusion parameter estimation (SNL) — D_{col}, M
- all colloid types

PA Parameter Values for Colloidal Actinide Retardation

Colloid	Actinide	K_d (mL/g)	γ (cm^{-1})
mineral fragments	Th, U, Np, Pu, Am	0.0[a]	0.3
microbes	Th, U, Np, Pu, Am	0.0[a]	0.5
intrinsic	Pu	0.0[b]	
	Th, U, Np, Am	0.0[c]	
humic substances	Am(III)	20 to 500[d]	
	Th(IV), U(IV), Np(IV)	900 to 20,000[d]	
	Np(V)	1 to 200[d]	
	U(VI)	0.03 to 30[d]	

Notes:
[a] chemical retardation observed, but is not included in PA calculations
[b] sorption expected but not quantifiable because of analytical detection limitations
[c] source term is zero for these intrinsic colloids
[d] from Dissolved Actinide Retardation Research Program

Crushed-Rock Column Experiments (SNL)

Packing

- Culebra (AIS; Culebra Bluffs)
- dolomite cleavage rhombohedra (Butte, Montana)
- hand crushed, washed, sieved 125-250 μm; 250-500 μm; 500-1000 μm
- hand crushed, sieved, washed, sieved, dried at low T

Colloidal particles

- humic substances
- preserved and live microbes
- quartz, goethite, hematite
- latex microspheres (non-functional; carboxylated; sulfonated)

Eluent

- H-17 brine simulant; Air intake shaft simulants; 0.001 M NaCl
- CO_2 partial pressure = $10^{-3.5}$ atm
- flow rate 0.1 to 0.5 mL/min

Test configuration

- columns 1 cm diameter; 5 to 100 cm length
- spike injections
- step injections

Crushed-Rock Column Experiments (SNL), cont.

Analytical methods

- in-line laser particle spectrometry
- scanning fluorometry, fixed wavelength fluorometry
- ICP-AES
- epifluorescence microscopy (BNL)

Porosity characterization

- equivalence of advective and measured porosity confirmed with "non-sorbing" tracers (fluoroscein, rhodamine WT, rhodamine B, sulforhodamine B, lithium, bromide)
- gravimetric determinations similar to fluoroscein
- porosity typically 45%

Evaluation of potential artifacts

- varied column lengths
- varied flow rates
- varied injection type
- reversed flow
- varied packing diameter; colloid diameter

Interpretation of Crushed-Rock Column Experiments

Transport and retardation phenomena

- advection (average linear flow velocity; v)
- dispersion and diffusion (D)
- adsorption (R or K_d)
- filtration (γ) includes interception and sieving, sedimentation, irreversible sorption

Advection-dispersion equation with adsorption:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - \frac{v}{R}\frac{\partial C}{\partial x} \qquad (1)$$

Filtration equation:

$$\frac{\partial C}{\partial x} = -\gamma C \qquad (2)$$

Interpretation of Crushed-Rock Column Flow Experiments, cont.

Advection-dispersion equation with adsorption and filtration:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - \frac{v}{R}\left(\frac{\partial C}{\partial x} + \gamma C\right) \qquad (3)$$

Solution of (3) described in Harvey and Garabedian (1991):

[peak concentration obtained from (1)] * exp(-γx) (4)

Conceptualization of the Effect of Filtration on Column Breakthrough

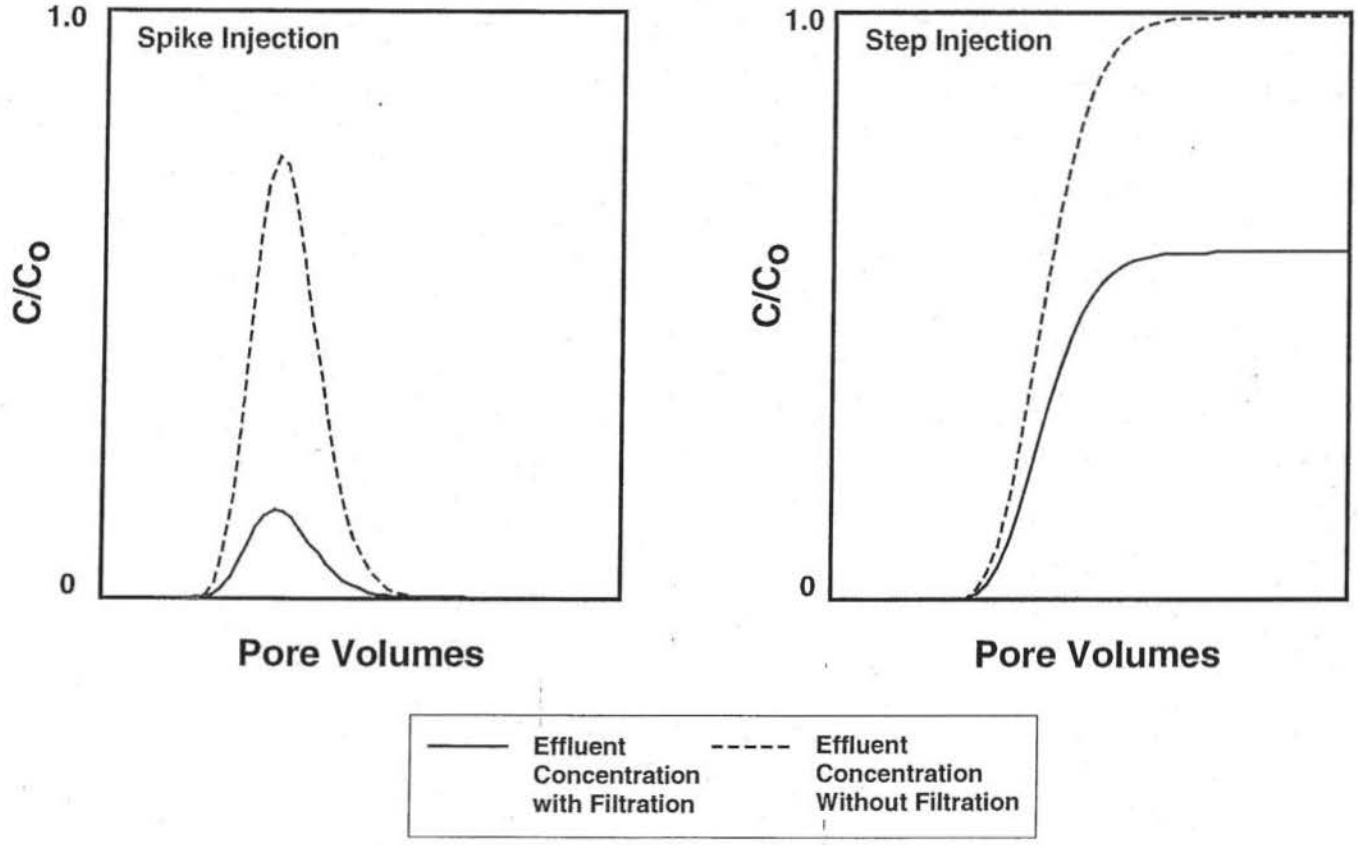

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Interpretation of Crushed-Rock Column Flow Experiments, cont.

Steps in interpretation of elution curves

- R estimated from peak position
- breakthrough curves are often noisy; not suitable for automated curve-fitting procedures
- conservative value of D is established (literature; test with conservative tracer; sensitivity analyses)
- theoretical peak height without filtration calculated with R and D using CXTFIT (Parker and Genuchten, 1984)
- γ calculated (L is column length):

observed peak concentration = theoretical peak concentration * exp($-\gamma L$)

$$\gamma = -\ln\left(\frac{\text{observed peak concentration}}{\text{theoretical peak concentration}}\right) * \frac{1}{L}$$

Batch Sorption Experiments (LANL)

Test design

- rock crushed and wet sieved; 75 to 500 μm fraction used
- rock washed with dilute HCl; rock pretreated in brine
- 1 g rock and 20 mL brine during pretreatment, sorption and desorption experiments
- brines analyzed with ICP-MS or LSC
- K_d determined from difference between initial and final actinide concentration in brine
- controls used to assess whether experimental artifacts occurred, e.g., loss to vessel or coprecipitation

Humic substance mixture consisted of equal parts of:

- purified Lake Bradford, Florida, aliphatic humic acid (FSU)
- Suwannee River aromatic humic acid (International Humic Substances Association; IHSA)
- Suwannee River fulvic acid (IHSA)
- two total concentrations used: 0.01 and 1.0 mg/L

Intact-Core Column Flow Experiments with Colloids (SNL)

Core used

- four Culebra cores extracted from the air intake shaft (AIS) from two stratigraphic horizons (HU-2 and HU-3)
- cores well preserved, intact, horizontally oriented in direction of the current flow path
- colloid test cores approximately 5.7 inches diameter x 4 inches long
- live microbe test with core VPX-27-7A (HU-3)
- humic test with core VPX-25-8A (HU-2)

Test design

- test design consisted of sequential comparison tests
  - without and with live microbes, introduced in eluent
  - without and with humic substances, introduced in eluent
- Am(III), $Pu(V)O_2^+$, $U(VI)O_2^{2+}$, tested in AIS brine
- Am and Pu injected as spikes directly on rock to minimize sorption on apparatus
- U injected as step to provide time for colloid-uranium interaction
- flow rate close to upper flow rate in Culebra (0.1 mL/min)

Microbial Actinide Transport Attenuated by Filtration

Crushed-rock column transport tests

- WIPP-relevant live and preserved microbes supplied by BNL
- experiments with live microbes conducted with and without nutrient
- packing particle size varied
- H-17 brine with or without nutrients
- step injection tests conducted with 10^6 to 10^7 cells/mL; spike injection tests conducted with 10^7 to 10^8 cells/mL

Results

- experiments with 125-250 μm packing resulted in very high filtration
- γ quantified in experiments with 250-500 μm particle size
- step injections resulted in column plugging, pressure build-up
- spike injection of low concentration allowed measurement of γ
- smaller microbes (0.2 to 0.28 μm) less attenuated than larger microbes (0.6 to 1 μm)
- elution curve from smaller microbes used to determine conservative γ
- γ values of about 0.5 cm^{-1} measured for smaller microbes
- R values of about 4 measured

Microbial Actinide Transport Attenuated by Filtration, cont.

Filtration effects confirmed with intact-core column flow tests

- elution of U matched profile of test without microbes
- Am did not elute during the test, consistent with test without microbes
- direct counts (BNL) of microbes showed background concentrations only

Microbe results supported by crushed-rock column flow tests with mineral fragments and latex microspheres

PA Implementation

- represent attenuation with γ
- set R equal to 1 due to complexities of combining R with γ values in SECOTP-2D simulation

Microbe Transport Through a Crushed-Rock Column

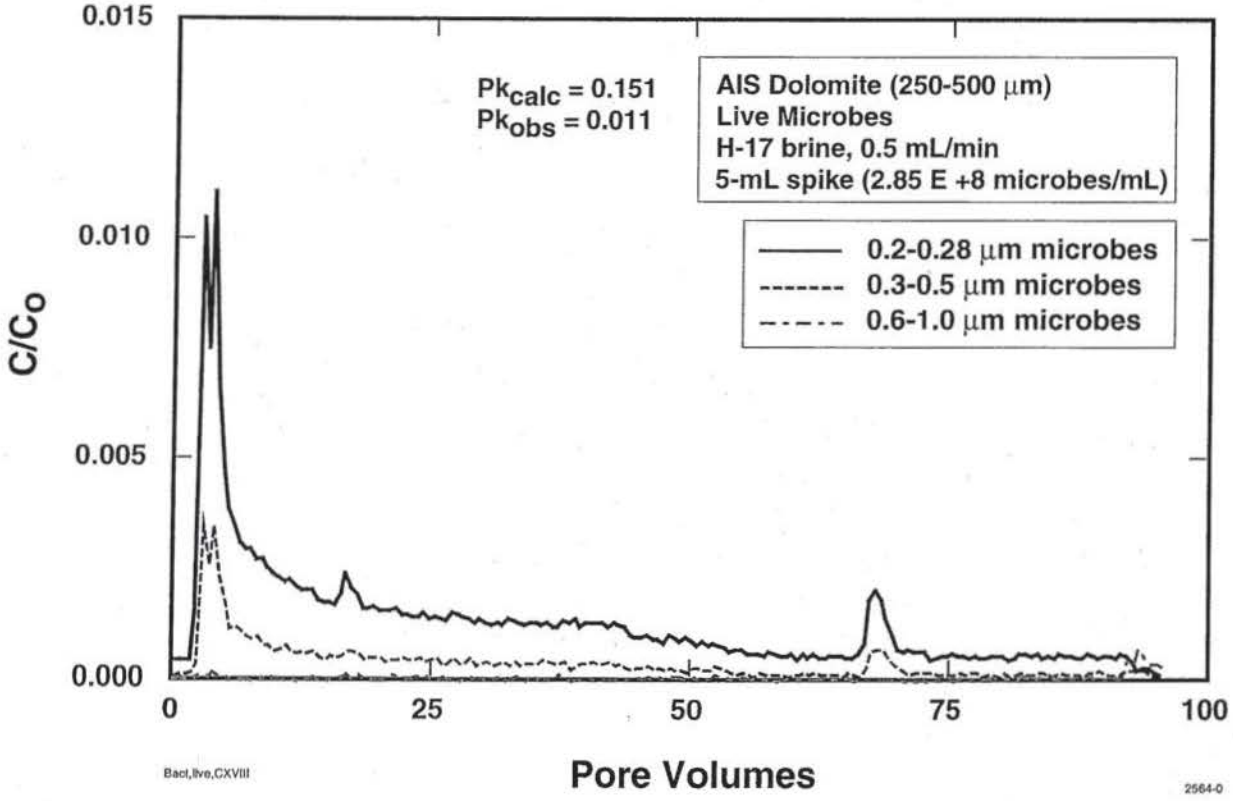

Microbe Transport Through a Crushed-Rock Column

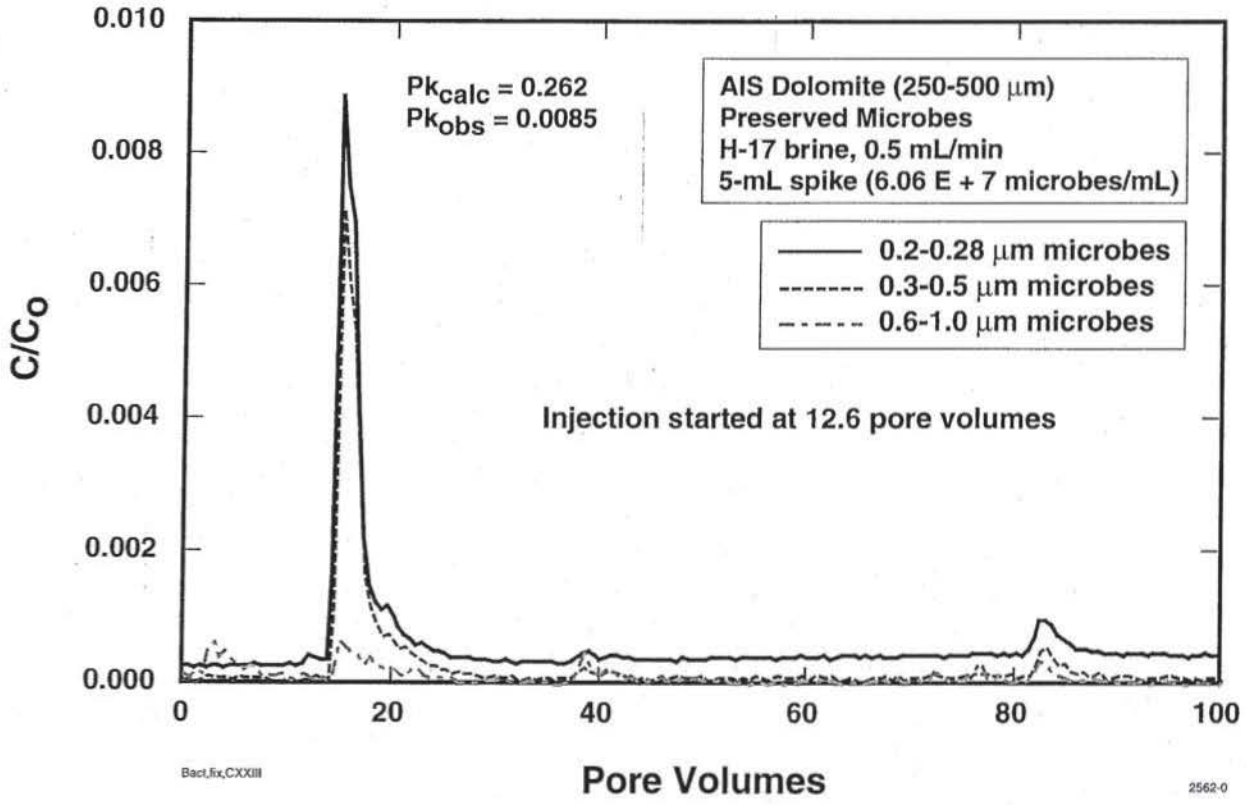

Microbe Transport Through a Crushed-Rock Column

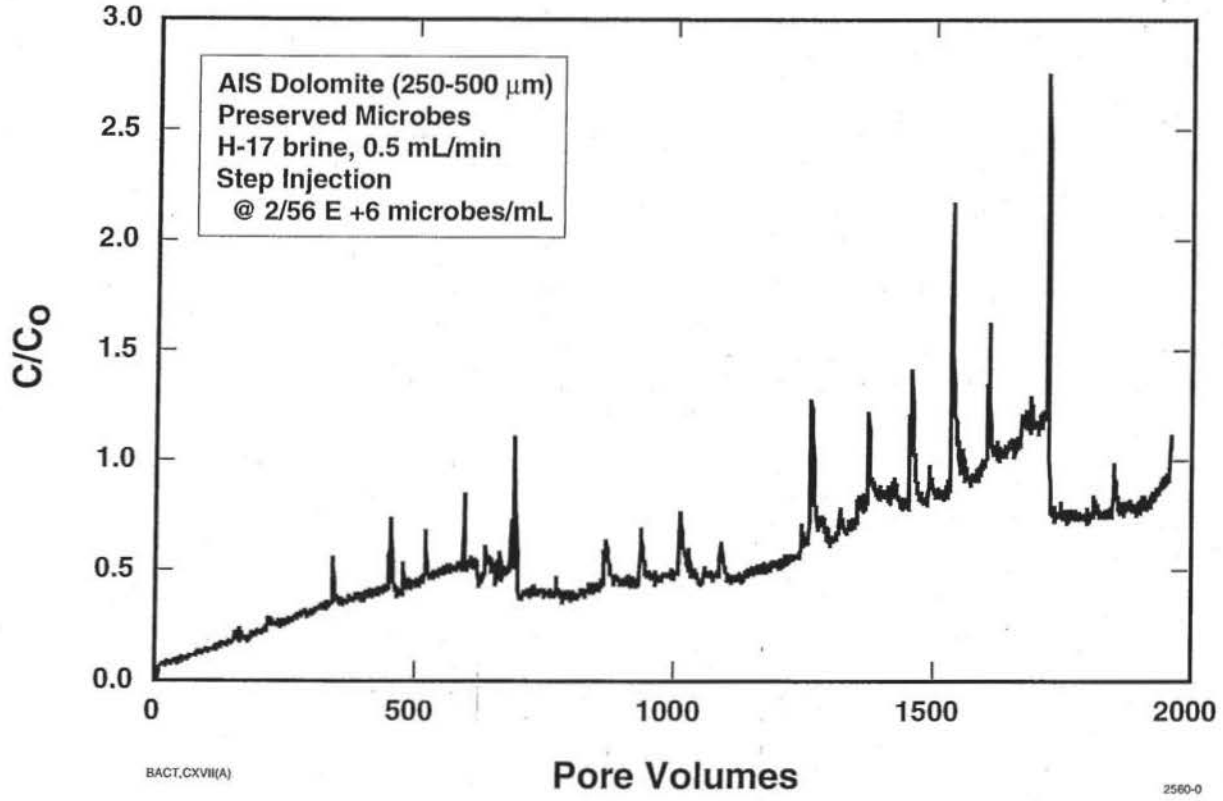

Microbial-Actinide Transport through an Intact Core

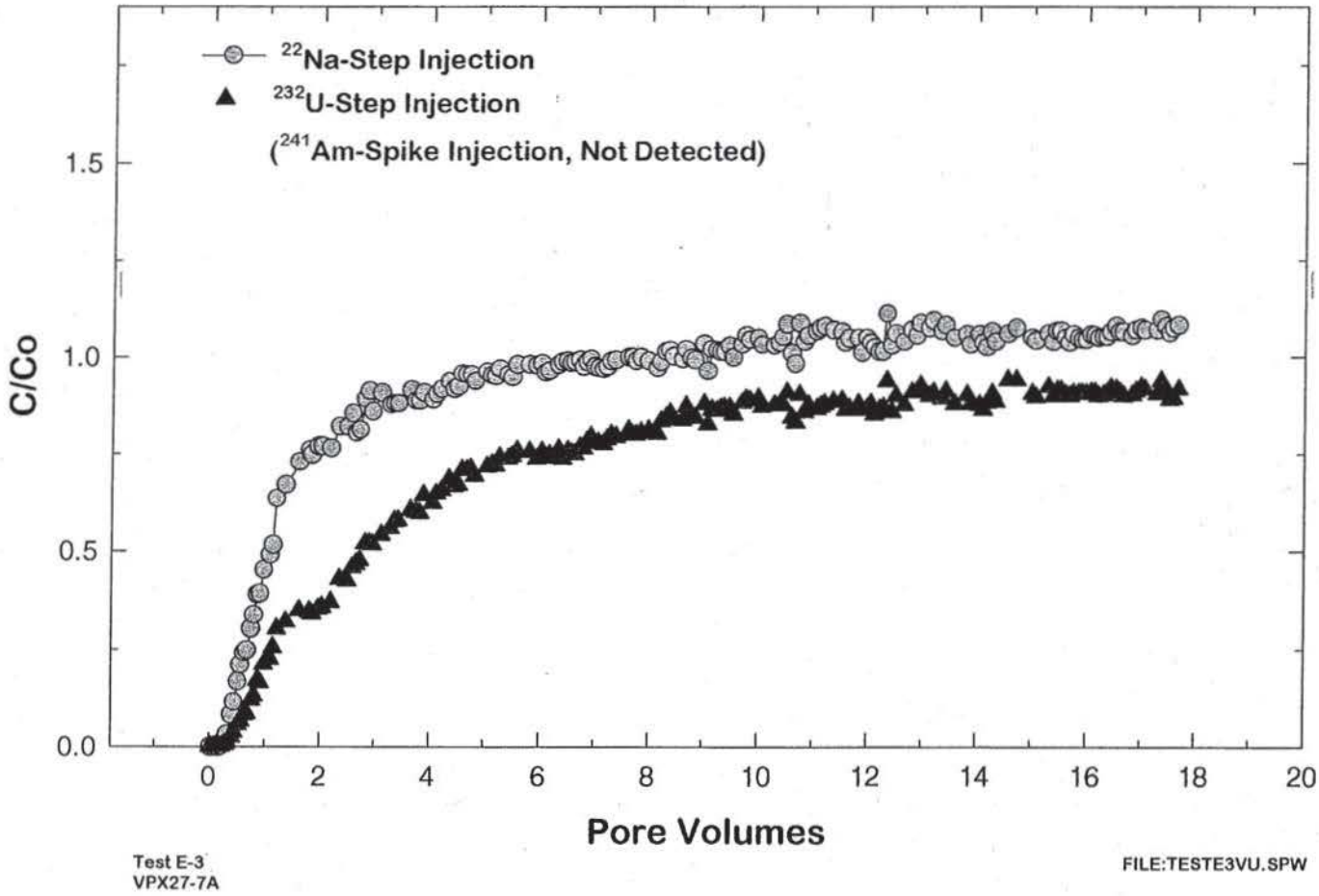

Latex Microsphere Transport Through a Crushed-Rock Column

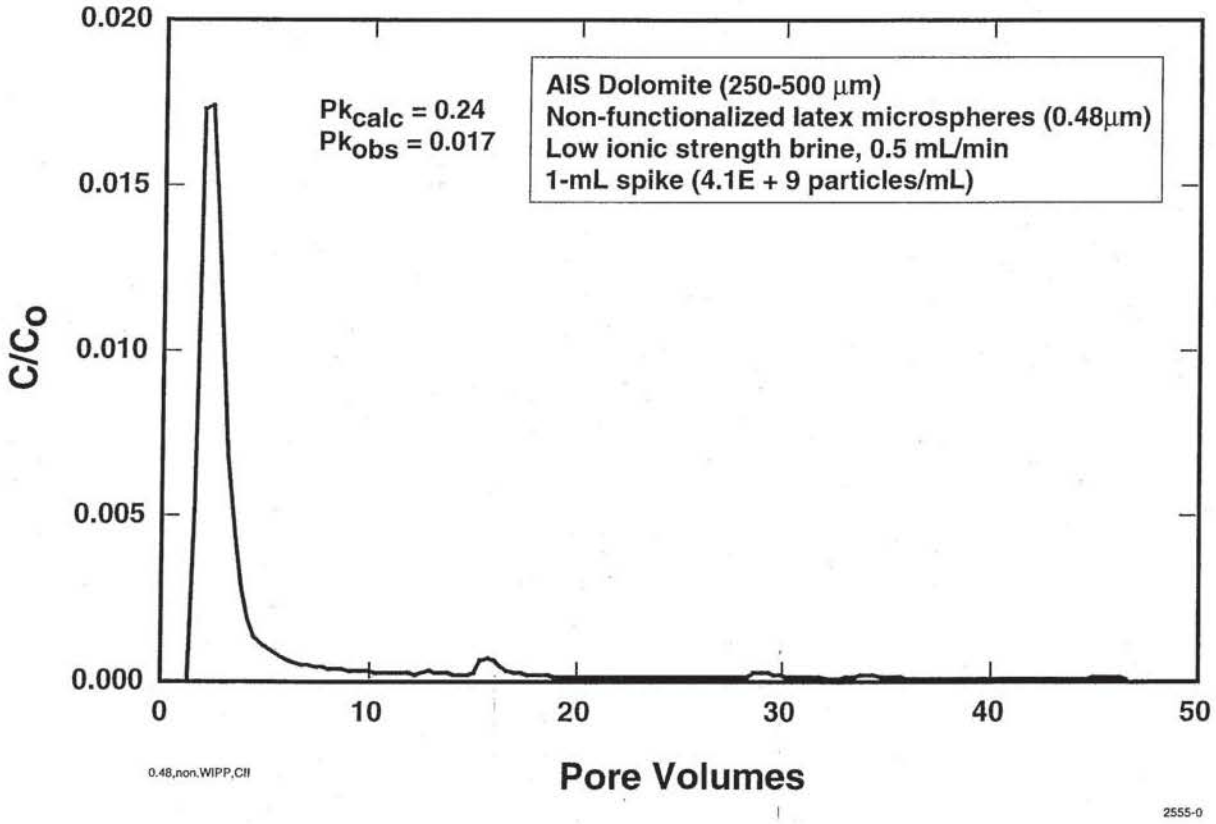

Mineral Fragment Transport Attenuated by Filtration

Crushed-rock column transport tests

- dispersions of mineral fragments prepared by chemical precipitation or mechanical milling
- colloids in spike allowed to coagulate and settle to reach a steady-state population before injection; spike filtered with 1.2 μm filter
- low ionic strength eluent used to isolate filtration effects from kinetic destabilization
- results consistent with microbe tests and latex microsphere tests

Results

- measured R values of 4 to 6 in H-17 brine
- measured γ value of 0.3 to 0.4 cm^{-1}

PA Implementation

- represent attenuation with γ
- set R equal to 1 due to complexities of combining R with γ values in SECOTP-2D simulation
- measured R values may not represent possible range for other colloids

Mineral Fragment Transport Through a Crushed-Rock Column

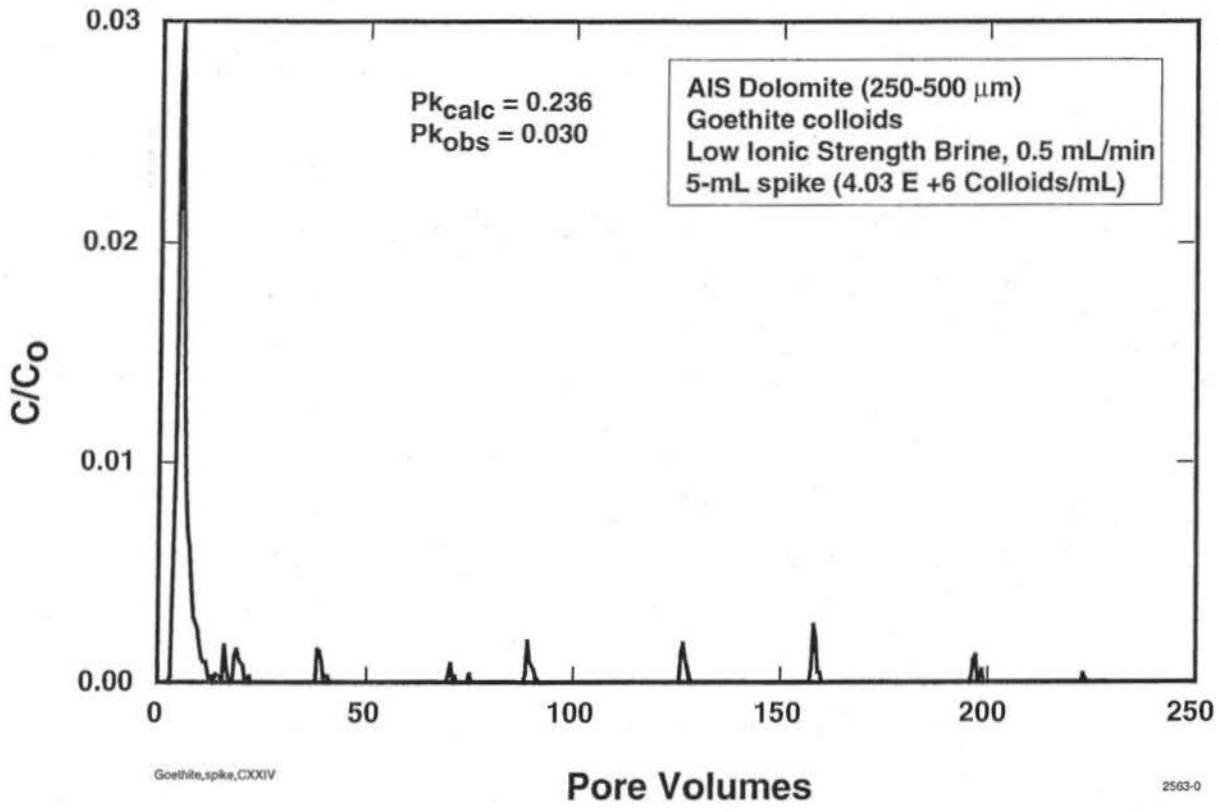

Attenuation of Humic-Actinides Similar to that of Dissolved Actinides

Crushed-rock column flow tests demonstrate no enhanced transport of humic substances (SNL)

- aliphatic humic acid (purified Aldrich; Aldrich Chemical Co.; FSU)
- aliphatic humic acid (Lake Bradford, Florida; FSU)
- aromatic humic acid (Suwannee River; IHSA)
- fulvic acid (Suwannee River; IHSA)

Batch sorption experiments with and without humic substances nearly identical (LANL)

- 1:1:1 mixture of aliphatic + aromatic humic acid + fulvic acid

Intact-core column flow tests demonstrate no difference in elution of U, Pu, Am with and without humics (SNL)

- 1:1:1 mixture of aliphatic + aromatic humic acid + fulvic acid

Retardation can by simulated using values from Dissolved Actinide Retardation Research Program

Humic Acid Transport Through a Crushed-Rock Column

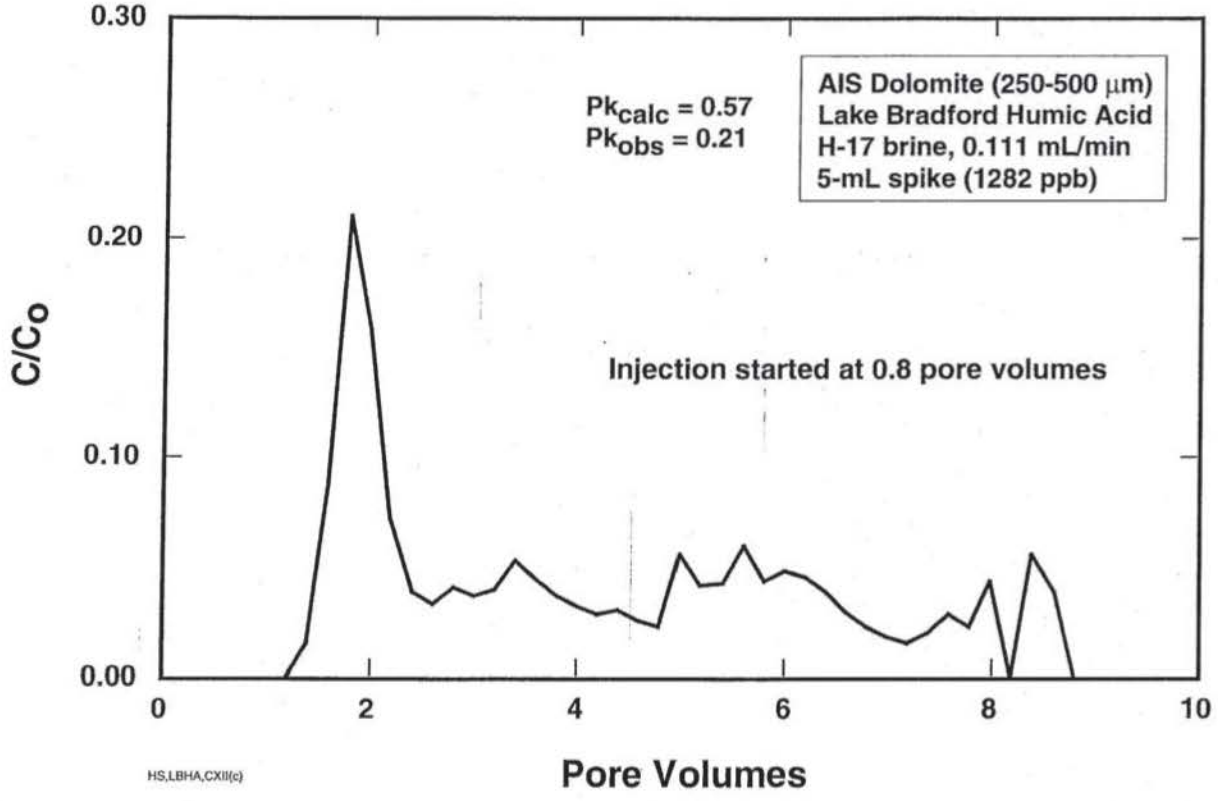

HS,LBHA,CXII(c)

2556-0

Fulvic Acid Transport Through a Crushed-Rock Column

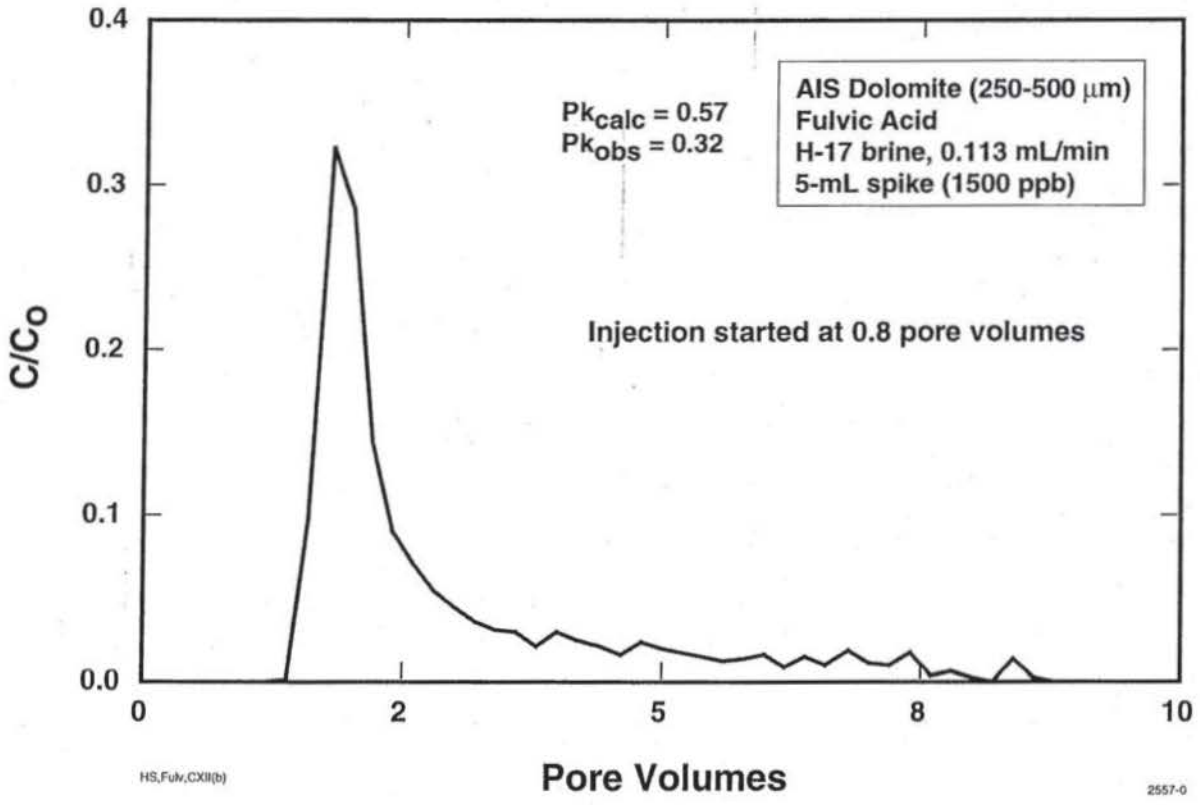

Fluoroscein (Conservative Tracer) Transport Through a Crushed-Rock Column

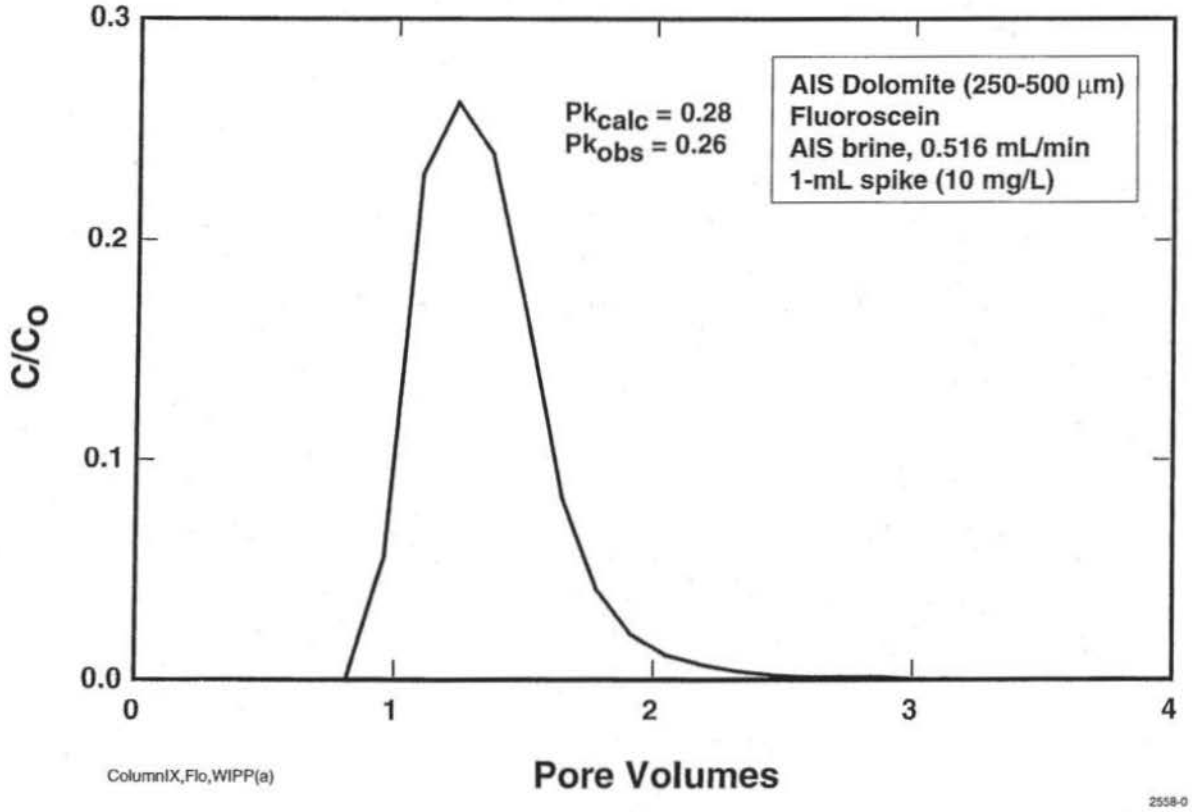

Humic-Actinide Transport through an Intact Core

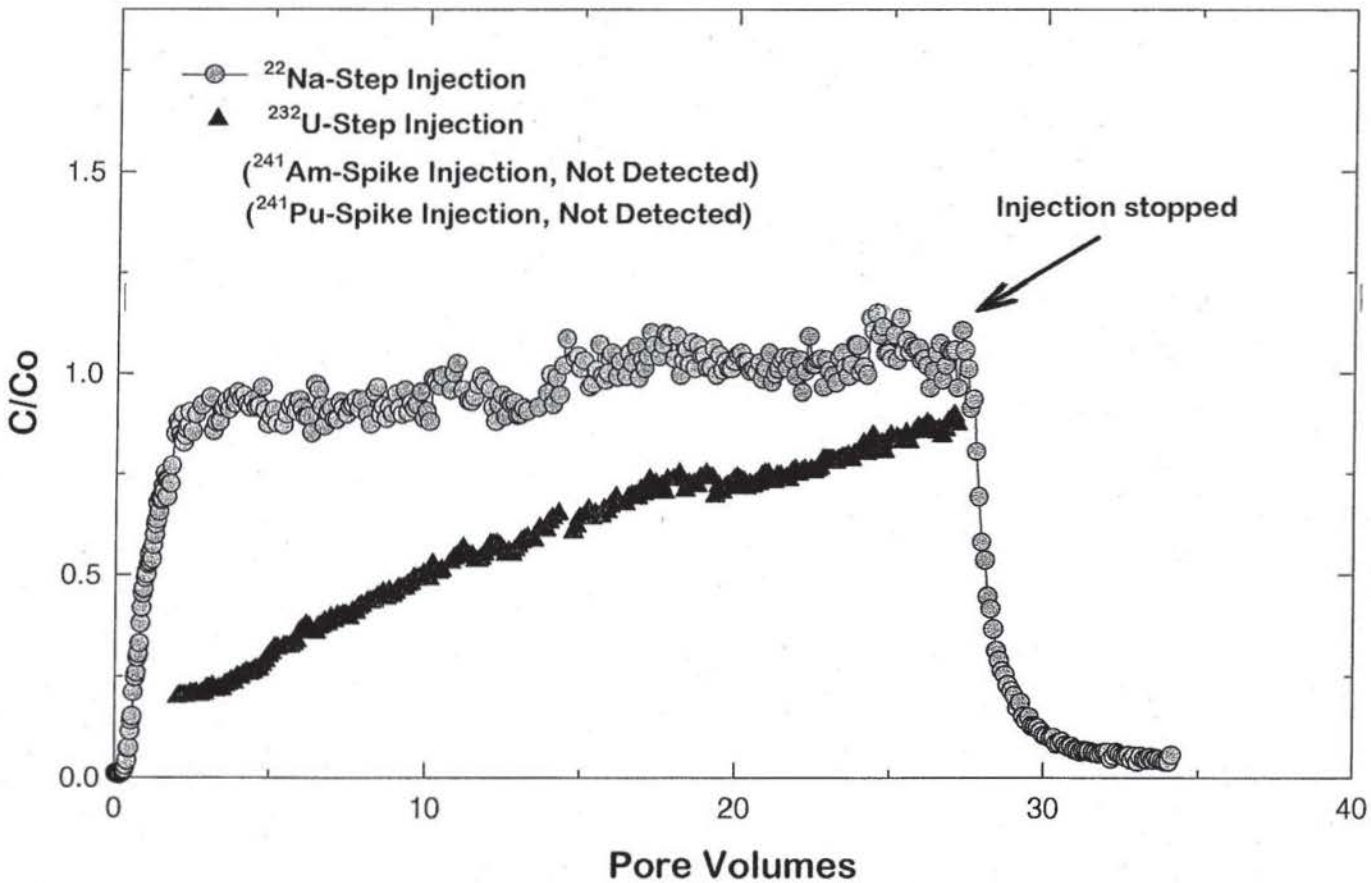

Test D-7
VPX25-8A

FILE:TESTD7VU.SPW

Humic-Actinide Batch-Sorption Results

(K_d values in mL/g)

actinide	[humic] (mg/L)	Culebra H-17; $pCO_2=10^{-3.5}$ atm		Culebra H-17; $pCO_2=10^{-1.5}$ atm		Castile ERDA-6; $pCO_2=10^{-3.5}$ atm		Castile ERDA-6; $pCO_2=10^{-1.5}$ atm	
Th(IV)	none	20	c	10	c	100	c	20	c
	0.01	10	c	10	c	100	c	20	c
	1	20	c	10	c	80	c	20	c
U(VI)	none	-2	b	-1	b	0.04	a	-0.01	a
	0.01	-1	b	-0.8	b	-0.3	a	-0.4	a
	1	-1	b	-0.7	b	0.4	a	-0.03	a
Np(V)	none	5	b	1	b	90	a	100	a
	0.01	5	b	1	b	80	a	100	a
	1	5	b	1	b	70	a	100	a
Pu(V)	none	20	b	9	b	200	a	200	a
	0.01	20	b	7	b	200	a	200	a
	1	20	b	10	b	200	a	200	a
Am(III)	none	500	c	400	c	700	c	3000	c
	0.01	600	c	400	c	1000	c	2000	c
	1	600	c	400	c	2000	c	2000	c

Notes:
reported values are averages of two replicates
LSC analytical error: "a" indicates $\leq 3\sigma$; "b" indicates 3 to 4σ; "c" indicates $> 4\sigma$

Colloid Diffusion Coefficients Required to Simulate Diffusion and Dispersion

Free-solution tracer diffusion coefficients for colloidal particles are required for SECOTP-2D

Estimates made with Einstein's equation for spherical particles (Hiemenz, 1986, p. 83):

$$D_{col} = \frac{k\,T}{3\pi\,\mu\,d_p}$$

where:
- D_{col} = free-solution tracer diffusion coefficient for colloidal particles ($cm^2\ sec^{-1}$)
- k = Boltzman constant
- T = temperature in Kelvin
- μ = brine viscosity
- d_p = colloidal particle diameter

Estimates for D_{col} as much as 1000-times less than Values for Dissolved Actinides

Colloid Type	Colloid Diameter (nm)	D_{col} (cm^2 sec^{-1})
mineral fragments	1000	2.1e-9
microbes	1000	2.1e-9
humics	100	2.1e-8
Pu(IV)-polymer	100	2.1e-8

Notes:

- laboratory measurements of Brine A (Salado-like brine simulant) used as conservative viscosity value ($2.13e10^{-2}$ g $cm^{-1}sec^{-1}$; Gelbard 1993)
- k = 1.38e-16 g cm^2 sec^{-2} $°K^{-1}$
- T = 300 °K
- D_{sol} values reported for dissolved actinides range from 1.53e-6 to 4.26e-6 cm sec^{-1} (Brush, 1996)

Results consistent with published estimations for colloids

- see, e.g., Hiemenz (1986)

Colloid Mass Concentrations Required to Simulate Diffusion

Humic substances

- measured concentration (solubility) = 2×10^{-3} g/L

Actinide intrinsic colloids [Pu(IV)-polymer]

- measured solubility limited to minimum analytical detection limit of LSC
- measured concentration (detection limit) = 1×10^{-9} moles/L = 2.4×10^{-7} g/L

Microbes

- estimate biomass using laboratory measurements and geometry
  - rod shaped with mean dimensions of 0.9 μm diameter x 1.7 μm length
  - density equal to Brine A (1.2 g/cm^3)
  - measured steady-state population of 5×10^6 cells/mL
- estimated concentration = 5×10^{-3} g/L

Mineral fragments

- estimate concentration using laboratory measurements and geometry
  - residual concentration and mean size measured in stability experiments
  - spherical shapes, specific gravity of 3, monodisperse population
- estimated concentration = 1×10^{-3} g/L

PA Parameter Values for Colloidal Actinide Retardation

Colloid	Actinide	K_d (mL/g)	γ (cm^{-1})
mineral fragments	Th, U, Np, Pu, Am	0.0[a]	0.3
microbes	Th, U, Np, Pu, Am	0.0[a]	0.5
intrinsic	Pu	0.0[b]	
	Th, U, Np, Am	0.0[c]	
humic substances	Am(III)	20 to 500[d]	
	Th(IV), U(IV), Np(IV)	900 to 20,000[d]	
	Np(V)	1 to 200[d]	
	U(VI)	0.03 to 30[d]	

Notes:
[a] chemical retardation observed, but is not included in PA calculations
[b] sorption expected but not quantifiable because of analytical detection limitations
[c] source term is zero for these intrinsic colloids
[d] from Dissolved Actinide Retardation Research Program

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Comparison of Effects of Brine Pocket Size

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BACKGROUND

The existence and size of a Castile Brine Pocket below the WIPP repository is uncertain. Brine pockets have been found in the northern Delaware Basin but there is little information on their size. The producibility of brine from these pockets is believed to be related to the interconnectedness of a fracture system. Analysis of WIPP-12 data have led to estimates for the areal extent of several hundred meters (drainage radius as small as 230 m -- dimension smaller than the WIPP waste-area footprint) to several kilometers (drainage radius as large as 19,000 m -- dimension larger than the land withdrawal boundary). DOE does not consider the 19 km radius brine pocket a realistic size, never the less it is included for comparison to other sizes. Because of the interconnectedness of the fracture system, the thickness of the brine pocket has been estimated to be from 7 m to 24 m with a maximum possible of 133.6 m (recent estimate based upon the total thickness of the Castile formation and NOT considered in the 1996 CCA calculations).

Each time a well penetrates the brine pocket, the pressure in the surrounding drainage area depletes. This pressure depletion will extend to those portions of the brine pocket which are interconnected. Passive Institutional Controls shield a region of the Castile from exploratory drilling directly under the waste panels. The 1996 CCA calculations assume that the Castile Brine Pocket under the waste panels is weakly interconnected hydraulically (with vertical and areal extents similar to the lower estimates from WIPP-12, i.e. total brine volume between 32,000 and 160,000 m^3 [Larson & Freeze, 1996]), and is not much affected by penetrations occuring outside the waste-area footprint. Therefore, the pressure underneath the waste panels in the brine pocket is assumed to not deplete until penetrated by a borehole drilled within the panel area. If the brine pocket has an extensive fracture system (and hence is strongly interconnected), the area beneath the waste panels can be depleted by penetrations outside the waste-area footprint.

This study looks at the consequences of assuming that the brine pocket is hydraulically interconnected such that borehole penetration depletion impacts are felt throughout a larger drainage area. The total brine volume which migrates from the Castile Brine Pocket to the Culebra aquifer with depletion impacts (large drainage area) is compared against the brine volume migration without depletion (small drainage area).

THEORETICAL CONSIDERATIONS

For the 1996 CCA calculations, an abnormally pressured Castile Brine Pocket is assumed (i.e. the brine pocket pressure exceeds the anticipated hydrostatic pressure). The brine pocket is assumed to be bounded (i.e. of limited thickness and areal extent) rather than infinite acting (such as the Culebra aquifer). Consistent with DOE regulatory criteria regarding the rate of future drilling activity, it is assumed that 47 boreholes will be drilled per square kilometer over the next 10,000 years (or 0.47/100 yrs/km^2). Each penetration of the abnormally pressured brine pocket will result in flows according to the following time horizons:

1) Time of intrusion to 72 hours - brine flows from the brine pocket, past the Culebra all the way to the surface during active drilling through an open borehole (assuming steady-state flow conditions). A computation to determine the length of time during which steady-state is valid (i.e. infinite acting period when the pressure sink caused by flow into the borehole has reached the extent of the drainage area) as computed by the following [Lee, 1982]:

$$t < \frac{\phi \mu c_t A t_{DA}}{k} \qquad \text{[Equation 1]}$$

where:

- t = Time (for a bounded cylindrical system is infinite acting) (sec)
- ϕ = Porosity (fraction)
- μ = Viscosity (Pa-sec)
- c_t = Total compressibility (Pa^{-1})
- A = Drainage area (defined as the land withdrawal boundary area/avg. no. of boreholes/200 years where 19.5 boreholes is taken as the average in 200 years) (m^2)
- t_{DA} = Dimensionless time (which for a bounded cylindrical system = 0.10, [Lee, 1982])
- k = Brine pocket permeability (m^2)

The solution to Equation 1 is approximately 7 hours. Although the steady-state flow assumption is valid only within 7 hours after penetration, a flow period of 72 hours was used. This is consistent with the 1996 CCA blowout time period to obtain direct brine releases from the WIPP repository. For the purposes of this investigation, pressure depletion during the 72 hour open flow period was not taken into account.

During the 72 hour flow period, flowrate is computed from the following (see nomenclature section for definition of variables):

$$Q_{bp} = \left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{bp} - P_{atm} - \rho g L_{surface} \right) \qquad \text{[Equation 2]}$$

2) 72 hours to 200 years - no brine flows from the brine pocket since the 1996 CCA calculations assume a 200 year time period immediately following intrusion during which the borehole is plugged at the Rustler and Castile formations.

3) From 200 years to 1200 years - cement plugs are no longer active. Flow occurs between the Castile Brine Pocket and the Culebra aquifer via "silty sand" abandoned boreholes with median permeabilities of 3.16E-13 m^2.

4) 1200 years to 10000 years - median abandoned borehole permeabilities are reduced one order of magnitude (3.16E-14 m^2) due to salt creep.

Abandoned Borehole Connection Between Castile Brine Pocket and Culebra Aquifer

Consider the flow rate necessary to achieve flow from the Castile Brine Pocket to the Culebra Aquifer through an abandoned borehole as depicted in Figure 1:

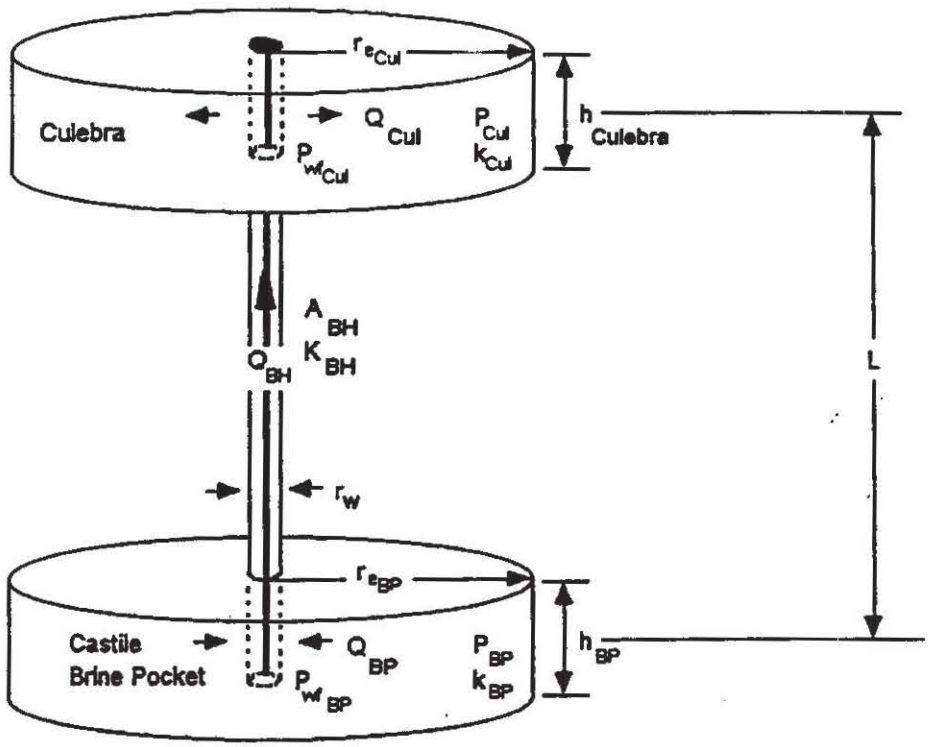

Figure 1: Representation of assumed flow path for Castile Brine Pocket to Culebra Aquifer

NOMENCLATURE

Define the following variables by:

Q = Flowrate (m^3/sec)
k = Permeability (m^2)
h = Thickness (m)
μ = Brine viscosity (Pa-sec)
ρ = Brine density (kg/m^3)
g = Acceleration due to gravity (m/sec^2)
L = Borehole length (m)
r = Radius (m)
A = Cross sectional area (m^2)
P = Pressure (Pa)
$\overline{P}$ = Average pressure between r_e and r_w (Pa)
c = Compressibility (Pa^{-1})
ϕ = Porosity (fraction)
V = Bulk volume (m^3)
ΔN = Brine volume producted between time 1 and 2 (m^3)

Define the following subscripts by:

cul = Culebra
bh = Borehole
bp = Brine pocket
e = External drainage per borehole (brine pocket area divided by number of boreholes)
w = Wellbore
wf = Abandoned wellbore flowing
atm = Atmospheric
b = Rock bulk
f = Pore volume
br = Brine
t = Total
R = Castile Brine Pocket or Culebra Aquifer
1,2 = Time 1, time 2

Refer to Figure 1, assuming steady-state flow is positive between the Castile Brine Pocket and the Culebra Aquifer, the following Darcy Law equations are used to obtain the flowrates out of the brine pocket (Q_{bp}), through the borehole (Q_{bh}) and into the aquifer (Q_{cul}), based upon the pressures, rock and fluid properties and brine pocket/abandoned borehole/aquifer geometries:

$$Q_{cul} = \left\{ \frac{k_{cul} h_{cul}}{\mu \left[\ln\left(\frac{r_{e_{cul}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{wf_{cul}} - P_{cul} \right) \qquad \text{[Equation 3]}$$

$$Q_{bh} = \left[\frac{k_{bh} A_{bh} \left(P_{wf_{bh}} - P_{wf_{cul}} - \rho g L \right)}{\mu L} \right] \qquad \text{[Equation 4]}$$

$$Q_{bp} = \left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{bp} - P_{wf_{bp}} \right) \qquad \text{[Equation 5]}$$

The flowrates through each of these systems are assumed to be equal (i.e. no fluid leaves the system), therefore:

$$Q_{bp} = Q_{bh} = Q_{cul} \qquad \text{[Equation 6]}$$

This results in four equations (Equations 3-6) and two unknowns (P_{wfbp} and P_{wfbp}) which can be algebraically solved for Q_{bp} as follows:

$$Q_{bp} = \frac{\left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{bp} - \rho g L - P_{cul} \right)}{\left[1 + \left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \right] \left\{ \frac{\mu \left[\ln\left(\frac{r_{e_{cul}}}{r_w} \right) - 0.5 \right]}{k_{cul} h_{cul}} + \frac{\mu L}{k_{bh} A_{bh}} \right\}} \qquad \text{[Equation 7]}$$

Equation 7 is the steady-state solution for flow through the brine pocket/abandoned borehole/aquifer system. To account for bounded brine pocket/aquifer sizes, pressure drawdown can be estimated by redefining the brine pocket and aquifer pressures over a series of discrete time intervals by the following:

The pore volume compressibility (c_f) as a function of rock bulk compressibility (c_b) may be defined by:

$$c_f = \frac{c_b}{\phi} \qquad \text{[Equation 8]}$$

The total compressibility (c_t) is the sum of the brine compressibility (c_{br}) and pore volume compressibility (c_f) as follows:

$$c_t = c_{br} + c_f \qquad \text{[Equation 9]}$$

The bulk volume of the bounded brine pocket is a function of the volume of brine removed, average pressure drop, compressibility and porosity as follows:

$$V_R = A_R h = \frac{\Delta N_{1,2}}{\left(\overline{P_1} - \overline{P_2}\right) c_t \phi} \qquad \text{[Equation 10]}$$

Equation 10 can be used to solve for the average pressure at the end of a given time interval by:

$$\overline{P_2} = \overline{P_1} - \frac{\Delta N_{1,2}}{V_R c_t \phi} \qquad \text{[Equation 11]}$$

METHODOLOGY AND RESULTS

Since the size of the brine pocket is unknown, comparisons were made for various areal size and thickness as shown in the following table (consistent with interpreted results from WIPP-12 data [Larson & Freeze, 1996]):

Table 1 - Constant Brine Volumes by Varying Thickness and Areal Extent

Thickness (m)	Areal Extent 1 (m^2)	Areal Extent 2 (m^2)	Areal Extent 3 (m^2)
133.6	6.0E+07	3.0E+06	3.0E+04
66.8	12.0E+07	6.0E+06	6.0E+04
24.0	33.4E+07	16.7E+06	16.7E+04

For the Culebra aquifer, the areal extent was assumed to be 100 times the LWB for all cases (4144 km^2). All other properties were median values obtained from the 1996

CCA database. The combination of three thicknesses and three areas for the Castile Brine Pocket resulted in 9 cases for comparison. Initial brine pocket pressure was assumed to be 12.7 E+07 Pa for all cases.

Table 2 shows an example spreadsheet calculation assuming an area of 6.0 E+07 m^2 and 133.6 m brine pocket thickness.

Table 2 - Example Spreadsheet Calculation

BP area	6.00E+07	m^2
Cut area	4.14E+09	m^2
Pcut (init)	850000	Pa
U	1.80E-09	Pa-s
hCut	7.7	m
L	641.5	m
total L	706.3	m
hBP	133.6	m
Pbp (init)	1.27E+07	Pa
kBH	3.16E-13	m^2
kCUL	2.16E-14	m^2
rw	0.1586	m
Area BH	0.0790922	m^2
kBP	1.58E-12	m^2
rho	220	kg/m^3
g	9.8	
rho*g*l shaft	8.5E+6	Pa
rho*g*l open	11.2E+6	Pa
s/year	3.16E+07	
porosity BP	0.008	
porosity Cut	0.151	
Cr BP	1.00E-10	1/Pa
Cr Cut	1.00E-10	1/Pa
Ct BP	1.36E-09	1/Pa
Ct Cut	6.623E-10	1/Pa
Cbrine	1.00E-09	1/Pa
Cwt BP	1.36E-09	1/Pa
Cwt Cut	1.66E-09	1/Pa
Brine Pocket bulk vol =	8.0E+8	m^3
Cutaway bulk vol =	31.9E+9	m^3
Open BH Dt	2.59E+05	seconds
No. open BH/Dt	2.98E+01	
rc BP	222.96809	
Patm	101300	Pa
drip rate=	0.47	bh/km^2/100years

Time years	Num BH in BP	Number of sand BH	Number of creep BH	BP press Pa	Cut Press Pa	BP radius per ab BH m	Cut radius per well m	Cangl	Cap open BH per well m^3/s	delta flow open m^3
200.0	56.40	0.0	0.0	12.7E+6	850.0E+3	4.37025E+13	4.37E+13	3.58E-09	0.080465874	149.6E+3
400.0	112.80	28.2	0.0	12.5E+6	850.0E+3	822.965098	4.37E+13	1.48E-09	0.017985898	131.2E+3
600.0	169.20	84.6	0.0	12.4E+6	851.3E+3	475.133342	4.37E+13	1.56E-09	0.016578236	113.9E+3
800.0	225.60	141.0	0.0	12.2E+6	852.0E+3	388.036704	4.37E+13	1.61E-09	0.013169822	96.3E+3
1,000.0	282.00	197.4	0.0	12.0E+6	850.9E+3	311.047799	4.37E+13	1.65E-09	0.010789646	78.7E+3
1,200.0	338.40	253.8	0.0	11.9E+6	848.5E+3	274.318988	4.37E+13	1.69E-09	0.008417967	61.5E+3
1,400.0	394.80	310.2	0.0	11.7E+6	877.9E+3	248.130295	4.37E+13	1.71E-09	0.006146544	44.9E+3
1,600.0	451.20	366.6	84.6	11.6E+6	880.3E+3	228.246674	475.1338	1.73E-09	0.003978128	29.1E+3
1,800.0	507.60	366.6	84.6	11.4E+6	900.2E+3	228.246674	475.1338	1.73E-09	0.001891269	13.8E+3
2,000.0	564.00	366.6	141.0	11.3E+6	911.2E+3	228.246674	366.0367	1.73E-09	0.000179623	1.3E+3
2,200.0	620.40	366.6	197.4	11.2E+6	921.7E+3	228.246674	311.0478	1.73E-09	0	000.0E+0
2,400.0	676.80	366.6	253.8	11.1E+6	931.7E+3	228.246674	274.3184	1.73E-09	0	000.0E+0
2,600.0	733.20	366.6	310.2	11.0E+6	941.2E+3	228.246674	248.1303	1.73E-09	0	000.0E+0
2,800.0	789.60	366.6	366.6	10.9E+6	950.3E+3	228.246674	228.2467	1.73E-09	0	000.0E+0
3,000.0	846.00	366.6	423.0	10.8E+6	959.0E+3	228.246674	212.4991	1.73E-09	0	000.0E+0
3,200.0	902.40	366.6	479.4	10.6E+6	967.3E+3	228.246674	199.8969	1.73E-09	0	000.0E+0
3,400.0	958.80	366.6	535.8	10.7E+6	975.2E+3	228.246674	189.7968	1.73E-09	0	000.0E+0
3,600.0	1,015.20	366.6	592.2	10.6E+6	982.6E+3	228.246674	179.5836	1.73E-09	0	000.0E+0
3,800.0	1,071.60	366.6	648.6	10.5E+6	989.7E+3	228.246674	171.589	1.73E-09	0	000.0E+0
4,000.0	1,128.00	366.6	705.0	10.5E+6	996.4E+3	228.246674	164.561	1.73E-09	0	000.0E+0
4,200.0	1,184.40	366.6	761.4	10.5E+6	1.0E+6	228.246674	158.3778	1.73E-09	0	000.0E+0
4,400.0	1,240.80	366.6	817.8	10.4E+6	1.0E+6	228.246674	152.8189	1.73E-09	0	000.0E+0
4,600.0	1,297.20	366.6	874.2	10.3E+6	1.0E+6	228.246674	147.8071	1.73E-09	0	000.0E+0
4,800.0	1,353.60	366.6	930.6	10.3E+6	1.0E+6	228.246674	143.2581	1.73E-09	0	000.0E+0
5,000.0	1,410.00	366.6	987.0	10.3E+6	1.0E+6	228.246674	139.1049	1.73E-09	0	000.0E+0
5,200.0	1,466.40	366.6	1,043.4	10.2E+6	1.0E+6	228.246674	136.299	1.73E-09	0	000.0E+0
5,400.0	1,522.80	366.6	1,099.8	10.2E+6	1.0E+6	228.246674	131.7783	1.73E-09	0	000.0E+0
5,600.0	1,579.20	366.6	1,156.2	10.1E+6	1.0E+6	228.246674	128.524	1.73E-09	0	000.0E+0
5,800.0	1,635.60	366.6	1,212.6	10.1E+6	1.0E+6	228.246674	125.4986	1.73E-09	0	000.0E+0
6,000.0	1,692.00	366.6	1,269.0	10.1E+6	1.0E+6	228.246674	122.6789	1.73E-09	0	000.0E+0
6,200.0	1,748.40	366.6	1,325.4	10.0E+6	1.0E+6	228.246674	120.0403	1.73E-09	0	000.0E+0
6,400.0	1,804.80	366.6	1,381.8	10.0E+6	1.1E+6	228.246674	117.588	1.73E-09	0	000.0E+0
6,600.0	1,861.20	366.6	1,438.2	10.0E+6	1.1E+6	228.246674	115.2368	1.73E-09	0	000.0E+0
6,800.0	1,917.60	366.6	1,494.6	9.9E+6	1.1E+6	228.246674	113.0416	1.73E-09	0	000.0E+0
7,000.0	1,974.00	366.6	1,551.0	9.9E+6	1.1E+6	228.246674	110.9672	1.73E-09	0	000.0E+0
7,200.0	2,030.40	366.6	1,607.4	9.9E+6	1.1E+6	228.246674	109.0031	1.73E-09	0	000.0E+0
7,400.0	2,086.80	366.6	1,663.8	9.9E+6	1.1E+6	228.246674	107.1368	1.73E-09	0	000.0E+0
7,600.0	2,143.20	366.6	1,720.2	9.9E+6	1.1E+6	228.246674	105.3686	1.73E-09	0	000.0E+0
7,800.0	2,199.60	366.6	1,776.6	9.8E+6	1.1E+6	228.246674	103.6828	1.73E-09	0	000.0E+0
8,000.0	2,256.00	366.6	1,833.0	9.8E+6	1.1E+6	228.246674	102.075	1.73E-09	0	000.0E+0
8,200.0	2,312.40	366.6	1,889.4	9.8E+6	1.1E+6	228.246674	100.54	1.73E-09	0	000.0E+0
8,400.0	2,368.80	366.6	1,945.8	9.8E+6	1.1E+6	228.246674	99.07215	1.73E-09	0	000.0E+0
8,600.0	2,425.20	366.6	2,002.2	9.8E+6	1.1E+6	228.246674	97.6966	1.73E-09	0	000.0E+0
8,800.0	2,481.60	366.6	2,058.6	9.8E+6	1.1E+6	228.246674	96.31961	1.73E-09	0	000.0E+0
9,000.0	2,538.00	366.6	2,115.0	9.7E+6	1.1E+6	228.246674	95.02967	1.73E-09	0	000.0E+0
9,200.0	2,594.40	366.6	2,171.4	9.7E+6	1.1E+6	228.246674	93.79444	1.73E-09	0	000.0E+0
9,400.0	2,650.80	366.6	2,227.8	9.7E+6	1.1E+6	228.246674	92.59996	1.73E-09	0	000.0E+0
9,600.0	2,707.20	366.6	2,284.2	9.7E+6	1.1E+6	228.246674	91.43948	1.73E-09	0	000.0E+0
9,800.0	2,763.60	366.6	2,340.6	9.7E+6	1.1E+6	228.246674	90.33108	1.73E-09	0	000.0E+0
10,000.0	2,820.00	366.6	2,397.0	9.7E+6	1.1E+6	228.246674	89.25201	1.73E-09	0	000.0E+0

Figure 2 is a semilog plot comparing the number of borehole penetrations for different brine pocket areal sizes based upon the DOE criterion of 0.47/100 year/km^2 drilling rate. The same number of penetrations apply to each respective areal size regardless of thickness.

Figure 2

Comparison of Drilling Penetrations to Castile Brine Pocket for Different Areas

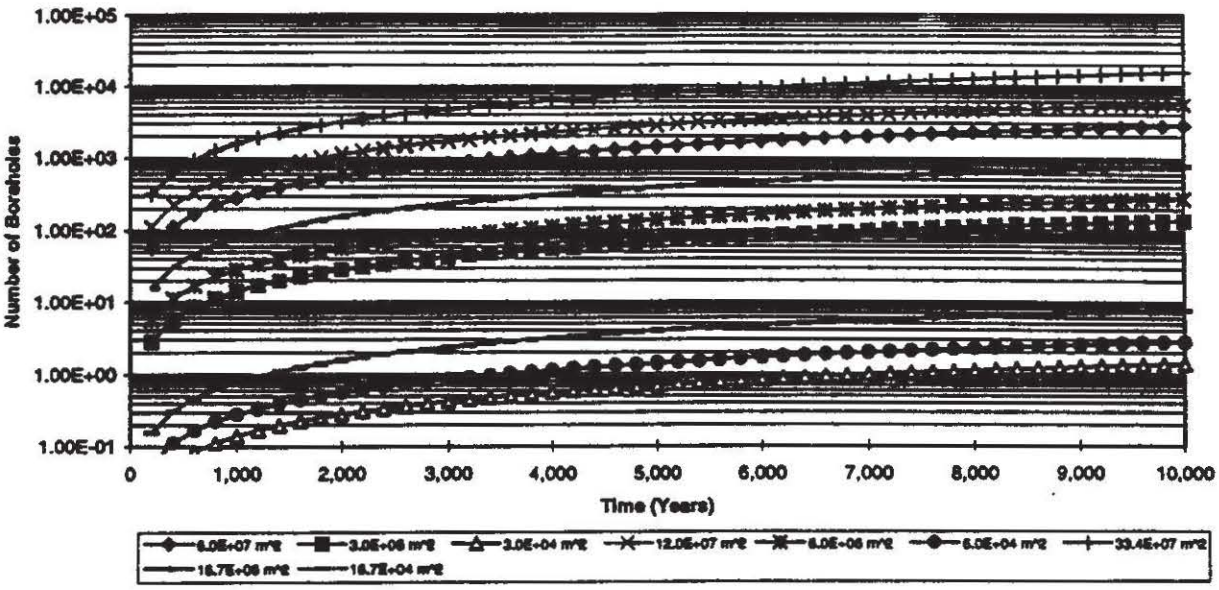

Figure 3 is a semilog plot comparing the amount of Castile brine volume which can be released. This was determined by subtracting the cumulative brine released at a given time from the total cumulative brine released at 10,000 years. The 24 m thickness cases again demonstrate faster depletion than the corresponding 133.6 m thickness cases of equivalent area. For a given thickness, the differences in remaining available flow is caused by differences in the number of depletion boreholes which is a function of the area.

Figure 3

Comparison of Remaining Castile Brine Available for Flow
(Initial Pbp = 12.7 MPa, 72 hour open flow period)

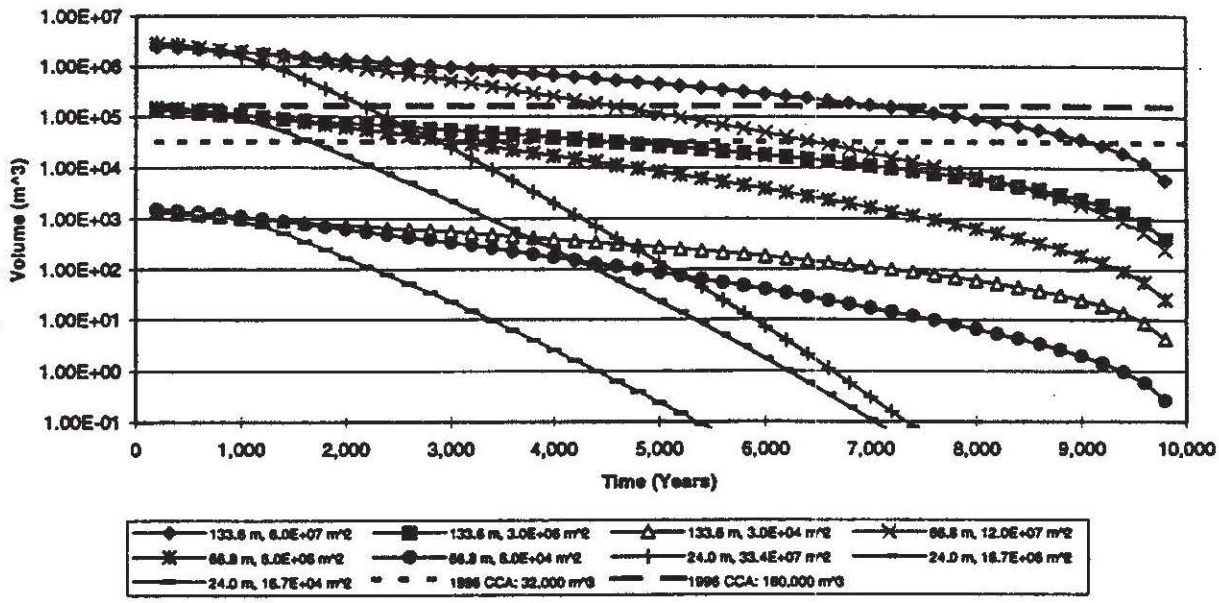

CONCLUSIONS

The 1996 CCA calculations varied the brine pocket volume from 32,000 m^3 to 160,000 m^3. From Figure 3, the only cases which show more brine available for flow for an extended period of time (~2000 to ~7000 years) are the maximum area cases. DOE does not consider the 19 km radius brine pocket to be a realistic estimate of the areal extent, rather an artifact of the unreasonably low rock compressibility ($5X10^{-12}$ pa^{-1}) used for that estimate. In addition, the DOE does not include the depressurization or volume reduction to the brine pocket that would result in numerous borehole penetrations that would statistically "miss" a WIPP panel but penetrate the brine pocket, prior to the first "E1" borehole through a panel. In the CCA calculations for E1 scenarios, the DOE assumes brine pockets of 32,000 m^3 to 160,000 m^3 pore volume at virgin (undepleted) pressures in determining potential releases to the accessible environment, which bounds the range of consequences associated with penetrating a larger but partially depleted brine pocket.

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Date: July 19,1996

To: Margaret Chu, MS-1335 (6801)

From: J. W. Berglund 6849, NMERI; J. Myers, IT Corp; L.R. Lenke, NMERI

Subject: Estimate of the Tensile Strength of Degraded Waste for use in Solids Blowout

A value of 1 psi (6895 Pa) was chosen to represent the tensile strength of decomposed waste for the purpose of computing blowout spall releases resulting from a drillbit intrusion into a pressurized waste panel. Such spall releases occur only if the gas pressure exceeds the hydrostatic drilling mud pressure of approximately 8 MPa. A chemical reaction between the waste and brine from the surroundings is necessary to generate the gas to raise the waste pore pressure to these levels. Without brine inflow, little gas will be generated and waste decomposition will be negligible. Thus the phenomenon of blowout spall requires both brine inflow and waste decomposition.

The future state of decomposed waste is both time dependent and unknowable. Therefore a decomposed state consisting of graded granular materials is assumed. This is consistent with the granular nature of decomposed geologic materials and corresponds to an end state of the decomposition process. Such materials lack significant composite strength from the interleaving of components and is the state found to be most troublesome in oil production where sand is produced from poorly consolidated sand layers. The value of 1 psi chosen for cementation strength for the decomposed waste can be reasonably expected to be conservative, i.e. lower than those data values found for many weak materials that are naturally occurring or that have been manufactured. Data to support this value can be found in the literature for the strengths of soils, laboratory produced mixtures of salt and clay, and mixtures of various materials with MgO; the latter added as a backfill material to the waste. A discussion of these data sources follows.

Soil Data

Tensile strengths for several compacted, cohesive soils e.g. Vicksburg buckshot clay (CH), Vicksburg lean clay (CL), and a sandy clay mixture from De Gray dam (SC) were measured using hollow cylinder tests and indirect tensile tests in Al-Hussaini (1981). The samples were prepared to optimum water content compacted and tested. Results for the hollow cylinder tests are shown in Table 1. All exceed 1 psi by factors of approximately 3 to 8 times. Similar results were obtained from the indirect tensile tests.

Table 1 Hollow Cylinder Tests

Material type	Tensile Strength (psi)
CL-1	2.95
CL-2	3.90
CL-3	3.93
CH-1	7.93
CH-2	7.41
CH-3	7.99
SC-1	5.90
SC-2	5.38
SC-3	4.49
CH-4	6.46
CH-5	6.12
CH-6	6.52

Direct tensile tests on simulated waste materials were also conducted by Berglund and Lenke, 1995, p13-14. Various mixtures of partially saturated silica sand and kaolin clay were used to represent the waste. The clay represented a natural material that was chosen to be a close surrogate to partially decomposed cellulosics and plastics. The sand represented the particulate structure expected of magnetite or other products of the iron corrosion reaction. The mixture was 85% sand and 15% clay, a ratio similar to the ratio of decomposition products anticipated for some waste conditions. The tensile strength measured in these experiments was 2.9 ± 1.4 psi. A second indirect method of measuring tensile strength in the Berglund, Lenke study implied an even higher tensile strength value of 4.3 ± 1 psi.

The tensile strength of the above materials (Al-Hussaini 1981, Berglund and Lenke 1995) occurred in the absence of any additional cementation process which would tend to increase these measured tensile strengths.

Salt Mixture Data

Some brine is expected to exist within the waste panels after closure of the facility. The most likely source is brine of Permian age that was trapped in the Salado formation at the time of evaporite deposition. Limited brine occurrences in the WIPP underground have been extensively sampled and analyzed, and the composition of Salado brine is well understood. These brines contain approximately 374 grams of dissolved constituents per liter and are in chemical equilibrium with halite (NaCl) anhydrite ($CaSO_4$), and magnesite ($MgCO_3$).

The removal of even a small amount of water from this brine by evaporation or chemical reaction will result in the precipitation of salts which will act as a cementation agent. One such chemical reaction that is anticipated to occur is the anoxic corrosion of iron and ferrous alloys, which constitute a significant percentage of the waste inventory in the form of steel drums and boxes, contaminated tools and sheet metal, etc.

The reaction of brine with metal will consume H_2O and generate hydrogen and some corrosion product. A typical anoxic reaction might be

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2$$

Consumption of H_2O by corrosion reactions will cause the mass of dissolved solids in the brine to precipitate as a series of evaporite minerals in close proximity to the surface of the

corroding metals forming encrustations which tend to cement the waste. Simulation of the removal of H_2O from one kg of Salado brine using the EQ6 code (Wolery T.J., and S.A. Daveler, 1992) yielded 534 grams of precipitates (anhydrite, bischofite, carnallite, halite, kieserite, and magnesite). The mass is greater than the mass of dissolved solids because of the hydrous nature of some of the precipitates.

Evidence for this process in the WIPP underground could be seen at the close of heated brine inflow experiments performed by SNL a number of years ago. In these experiments, a metal canister containing an electrical heater was placed in a vertical hole excavated in the floor of a room in the northern experimental area. The top of the hole was sealed, and anhydrous nitrogen was circulated within the annulus between the canister and the hole. Small amounts of brine flowed toward the hole in response to the pressure and temperature gradients surrounding the heated hole, and evaporated as it approached the canister. The nitrogen acted as a carrier gas for water vapor and was allowed to exit the hole where it flowed into an apparatus where the water vapor was extracted and quantified.

It was found at the close of the experiment that the canister has become firmly cemented in the hole by the precipitation of salts from the evaporating brine within the annulus. A work-over rig had to be employed to extract the canister from the hole. The removal of water from brine by any process, be it evaporation or corrosion reactions, will produce the same cementation effect by the precipitation of minerals at the site of water removal. This cementation will act to increase the strength of the waste.

A number of strength tests were done for consolidated crushed WIPP salt and mixtures of WIPP salt and bentonite (70 and 30% respectively) (Finley, 1996). Finley's memorandum presents estimates of tensile strengths of clay/salt mixtures based on experimental observations of unconfined compressive strengths and the extended Griffith criterion for tensile failure (Jaeger and Cook, 1976). These estimates are for 30/70 percent bentonite/salt mixtures at fractional densities of 0.83 to 0.88. Finley estimates tensile strengths between 10 and 100 psi.

The WIPP waste stream upon creep closure and subsequent brine saturation will consist of approximately 1350 kg of waste solids (assumed average solid density of the waste was taken as 2700 kg/m^3) and 188 kg of precipitated salt (based on dissolved salt solids of 374 gram/liter cited above) per cubic meter of repository. These numbers are based on a typical closure porosity of 0.5 (final room height of 1.2 m). The gravimetric ratio of salt precipitate to solid waste for these conditions is 0.14. This is a factor of 5 less than the ratio cited by Finley. Using this factor, it is not unreasonable to expect tensile strengths between 2 and 20 psi.

Effects of MgO on Strength

An additional process affecting the strength of the waste/backfill composite material is the chemical interactions that will occur between Salado brine and the MgO backfill. These interactions were simulated using the EQ3/6 code (Wolery, 1992; and Wolery T.J., and Daveler, 1992) with the Pitzer activity coefficient option and Harvie-Moller-Weare database. Five moles of MgO were reacted with one kilogram of Salado brine in a series of small steps. The dissolution of the five moles (202 grams) of MgO into the brine resulted in the precipitation of a total of 507 grams of minerals and the incorporation of 20 percent of the original kg of brine as water of hydration within the precipitates. These precipitates include Mg-oxychloride (63% by mass) and brucite (31% by mass), with minor amounts of anhydrite, halite, and magnesite. Similar results were found by Wang, 1996.

The two dominant precipitates (Mg-oxychloride and brucite) are the key phases in Sorel cement. In fact, Sorel cement is commercially prepared by mixing a magnesium-chloride brine (quite similar to Salado brine) with MgO. Sorel cement is known to have uniaxial compressive strengths in the range of 7,000 to 10,000 psi (Sax and Lewis, 1987). This range is equivalent to tensile strengths of from 490 to 700 psi (Dunham C.W., 1966). Thus the use of an MgO backfill will result in the cementation and strengthening of the waste/backfill composite material as long as sufficient brine is available for the chemical reactions to occur.

Conclusions

While tests to actually measure the binding forces between particles of simulated waste have not been performed, there are data available from several independent sources that suggest that the selection of 1 psi is well below the actual value of tensile strength that can be reasonably expected for decomposed waste. The tensile data presented for several soils without chemically generated salt precipitates exceed 1 psi by factors generally greater than 3. Estimated tensile strengths of consolidated halite-bentonite mixtures exceed 1 psi by factors of ten or more. The role of precipitated salts from anoxic reactions of brine with waste metals is expected to be similar though perhaps not as intense. MgO is added to the waste as a backfill material in large volumes. The reaction products of MgO plus brine are the principal components of Sorel cement which attains high compressive strengths and predicted tensile strengths of 490 to 700 psi.

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cc:

MS 1330 SWCF-A:1.1.01.2.7:DRM:QA:Waste Strength, TD

WASTE ISOLATION PILOT PLANT

SALADO FLOW CONCEPTUAL MODELS PEER REVIEW REPORT

A Peer Review

Conducted By

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for the

U.S. Department of Energy

Carlsbad Area Office

Office of Regulatory Compliance

May 2002

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Executive Summary

The WIPP site has been developed near Carlsbad, New Mexico, by the Department of Energy (DOE) as the Nation's first underground repository licensed to safely and permanently dispose of transuranic radioactive waste resulting from the research and production of nuclear weapons programs. The first shipment of transuranic waste arrived at WIPP on April 6, 1999.

Peer review of conceptual models developed by the Department of Energy (DOE) for the WIPP is required by 40 CFR § 194.27, which was promulgated by the Environmental Protection Agency (EPA) in 1996. In accordance with this requirement, the Carlsbad Field Office (CBFO) of the DOE has conducted a peer review of three conceptual models that are being revised due to changes invoked by the regulator or due to knowledge gained since the original conceptual models were developed. This peer review addressed revisions to selected Salado flow conceptual models that were developed for the Compliance Certification Application (CCA).

This report presents the results of an independent technical peer review of the adequacy of three of the twenty-four conceptual models representing features, processes, and events involved in assessing the long-term performance of the Waste Isolation Pilot Plant (WIPP). These models were identified by the U.S. Department of Energy (DOE) through its scientific advisor, Sandia National Laboratories (SNL).

This independent peer review was conducted by a three-member interdisciplinary team having the requisite broad experience and expertise to address the range of issues associated with the ability of WIPP to successfully isolate waste for the 10,000-year regulatory time frame. The peer review was conducted primarily in Carlsbad, New Mexico, at the SNL Carlsbad offices. The Peer Review Panel was given access to conceptual model descriptions, scientific reports, briefings, SNL staff, and to the SNL Nuclear Waste Management Program Library. The Panel also had access to reports of prior peer reviews and was given the full cooperation of the DOE and SNL throughout

the review. Representatives of the EPA, DOE, and the New Mexico Environmental Evaluation Group (EEG) observed the SNL technical presentations and the Panel's questions and deliberations.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical processes, or intrusion scenarios are to be represented in performance assessment. To be used in performance assessment, a conceptual model must be successfully translated into analytical statements and mathematical analogs. The Panel reviewed the three conceptual models of interest in detail, including the assumptions and scientific information used to develop the model, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The Panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall performance assessment (PA). The review process and review criteria are discussed in Section 2.

The Panel has applied the stringent assessment criteria provided in NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories,* and has concluded:

> 1) The changes to the three conceptual models appear generally sound in their structure, reasonableness, and relationship to the original models.
>
> 2) The proposed implementation of the three changed models appears reasonable; however impacts of the changes cannot be assessed at this time. Although the data presented depicts selected gas pressure and brine saturation cases, a total system PA is needed to show a complete comparison of the prior CCA results to the new results.
>
> 3) Implementation of the three changed models and their interactions with other models cannot be assessed at this time because determination of "adequacy in application" and "accuracy of calculations" requires a total system PA.

Two review criteria (adequacy of application and accuracy of calculations) require information available only after PA calculations have been performed. Recognizing that a total system PA will not be available for several months, conditional acceptance of the adequacy of the changed models is intended to permit completion of the total system PA.

The changed models should be re-reviewed in the context of the total system PA. The total system PA review may include review of the reasonableness of changes in performance estimates resulting from changes in parameter ranges or in changes to or resulting from single values. The total system PA review should evaluate changes in the conceptual structure of the models and changes in component process models and compare the performance results of the changed models with the results of the earlier models to confirm that the changes in performance estimates are reasonable in sense and magnitude. Changes in computations or in fundamental model aspects, such as gridding, should also be considered. Whatever the methodology chosen, each changed model must be shown to satisfy all of the review criteria after the next iteration of PA calculations. The final review should consider the impacts of the changed models on the implementation of related conceptual models and peripheral issues such as the Option "D" panel closures. The status of the changed models will remain "conditionally adequate" until the final review is completed. The status of any changed model may become "inadequate" if warranted by review in the context of a total system PA.

1.0 Introduction

Peer review of conceptual models developed by the Department of Energy (DOE) for the WIPP is required by 40 CFR § 194.27, which was promulgated by the Environmental Protection Agency (EPA) in 1996. In accordance with this criterion, the Carlsbad Field Office (CBFO) of the DOE has conducted a peer review of three conceptual models that are being revised due to changes invoked by the regulator or due to knowledge gained since the original conceptual models were developed. This peer review has addressed whether revisions to selected Salado flow conceptual models that were developed for the Compliance Certification Application (CCA) continue to reasonably represent the WIPP disposal system.

Sandia National Laboratories (SNL) is responsible for the development, maintenance, and conduct of WIPP performance assessment (PA). As part of the PA methodology included in the CCA, the DOE identified processes important to the WIPP waste isolation system and developed conceptual models that describe the features, events, and processes relevant to the disposal system and subsystems. These conceptual models were peer reviewed and the results were approved by the EPA during the original WIPP certification (EPA, 1998). Any proposed significant changes to the previously approved conceptual models are being peer reviewed to ensure that the disposal system, subsystems, and future state assumptions continue to be adequately represented.

Twenty-four conceptual models are used in the WIPP PA. The proposed changes associated with Salado flow processes are expected to affect the following models:

- Disposal System Geometry,
- Repository Fluid Flow, and
- Disturbed Rock Zone (DRZ).

The peer review process is a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. The peer reviewers are independent of the work being reviewed, i.e., the peer reviewers: a) have not been involved as participants, supervisors, technical reviewers, or advisors

involved with the work being reviewed, and b) to the extent practical, have sufficient freedom from funding considerations to ensure the work is impartially reviewed. Therefore, the peer-reviewed subject matter provides additional assurance to the regulator and the public that the subject matter is reasonable, accurate, and valid for its intended use.

This peer review meets the regulatory requirements of 40 CFR Part 191 and the implementation of those requirements by 40 CFR Part 194. This peer review was conducted in accordance with the Nuclear Regulatory Commission's NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories*. The adequacy criteria set forth in NUREG-1297 were those used by the peer review panel for reviewing the three conceptual models. The Peer Review Panel followed the DOE-CBFO Management Procedure MP-10.5, *Peer Review,* to perform the peer review.

This report documents the results of the subject peer review. Section 2 of this report details background information relating to the WIPP facility and the review methodology. This includes a description of the repository, its geologic and hydrogeologic settings, the review methodology, and the evaluation criteria. Section 3 presents an evaluation of each of the three models. Each model was assessed against the predetermined evaluation criteria. Section 4 discusses the integration of the peer reviewed models with the remainder of the models into an overall conceptual model of the waste disposal system to be used for the WIPP total system PA. Section 5 provides a summary of the evaluations. These sections are followed by appendices that include administrative information and professional biographies for each of the peer review panel members.

2.0 Background

The DOE was authorized in 1979 (Public Law 96-164) and funded by the Congress to develop a facility for demonstrating the safe disposal of transuranic (TRU) radioactive wastes resulting from national defense activities. The Land Withdrawal Act of 1992 (Public Law 102-579) provided additional authorization to continue the project under a stipulated statutory process. With more than 20 years of scientific investigation, public input, and regulatory oversight, the WIPP facility became the first underground repository licensed to safely and permanently dispose of transuranic radioactive waste from the research and production of nuclear weapons. The first shipment of transuranic waste arrived at WIPP on April 6, 1999.

2.1 WIPP Overview

The WIPP facility has been constructed in southeastern New Mexico 26 miles east of Carlsbad, on land owned by the Federal Government. Prior to October 1992, this land was administered by the U.S. Department of the Interior, Bureau of Land Management. In October 1992, Congress transferred jurisdiction of the land through the Land Withdrawal Act to the Secretary of Energy. The site encompasses 10,240 acres in a sparsely populated area, with fewer than 30 people living within 10 miles of the WIPP site. The immediate surrounding land is used for livestock grazing, potash mining, and oil and gas production.

Surface structures and the underground repository make up the WIPP facility. The purpose of the surface structures is to provide security and safeguards and to accommodate routine operations, administrative activities, and support further scientific studies.

The underground excavation is 655 meters (2150 feet) below the surface in the bedded salt of the Salado Formation. It includes a 12-acre area used for conducting scientific investigations and experiments in which no waste will be placed, an operations area with equipment and maintenance facilities, an area in which the waste is emplaced for

permanent disposal, and four major interconnecting tunnels that are used for ventilation and traffic. The subsurface waste-disposal area is planned to cover approximately 100 acres and will contain eight separately excavated panels, each containing seven disposal rooms, and two equivalent panels.

2.2 Peer Review Management

This Salado Flow Conceptual Models Peer Review is an independent review sponsored by the DOE CBFO and delegated to its technical assistance contractor, known as the Carlsbad Technical Assistance Contractor (CTAC). The CTAC appointed Mr. John Thies as the peer review manager.

Early in the peer review process Mr. Thies appointed a technical panel chairperson, John Gibbons, Ph.D., from among the peer review panel members to serve as the technical leader for the peer review and to lead technical development of the peer review report.

The selection and training of the peer review panel members and operation of the review process were governed by DOE CBFO's Management Procedure MP-10.5, *Peer Review,* and the *Conceptual Model Peer Review Plan*. Detailed information regarding the review process is further delineated in this document and in the peer review records.

Twenty-four conceptual models are used in the WIPP PA. This peer review addressed only the proposed changes associated with Salado flow processes expected to affect the following three models:

- Disposal System Geometry,
- Repository Fluid Flow, and
- Disturbed Rock Zone (DRZ).

2.3 System Overview

The WIPP disposal system includes the underground repository and shaft system, the geologic host rock, and the local and regional hydrologic system. Figure 2-1 shows the WIPP controlled area, the accessible environment, and the disposal unit boundary.

Figure 2-1 - WIPP Controlled Area

2.3.1 Repository Setting

The WIPP surface facilities, shafts, and underground workings are shown in Figure 2-2. The WIPP repository includes four shafts (exhaust shaft, waste shaft, salt handling shaft, and air intake shaft), an experimental area, an operations area, and a waste disposal area.

Figure 2-2 - WIPP Facilities

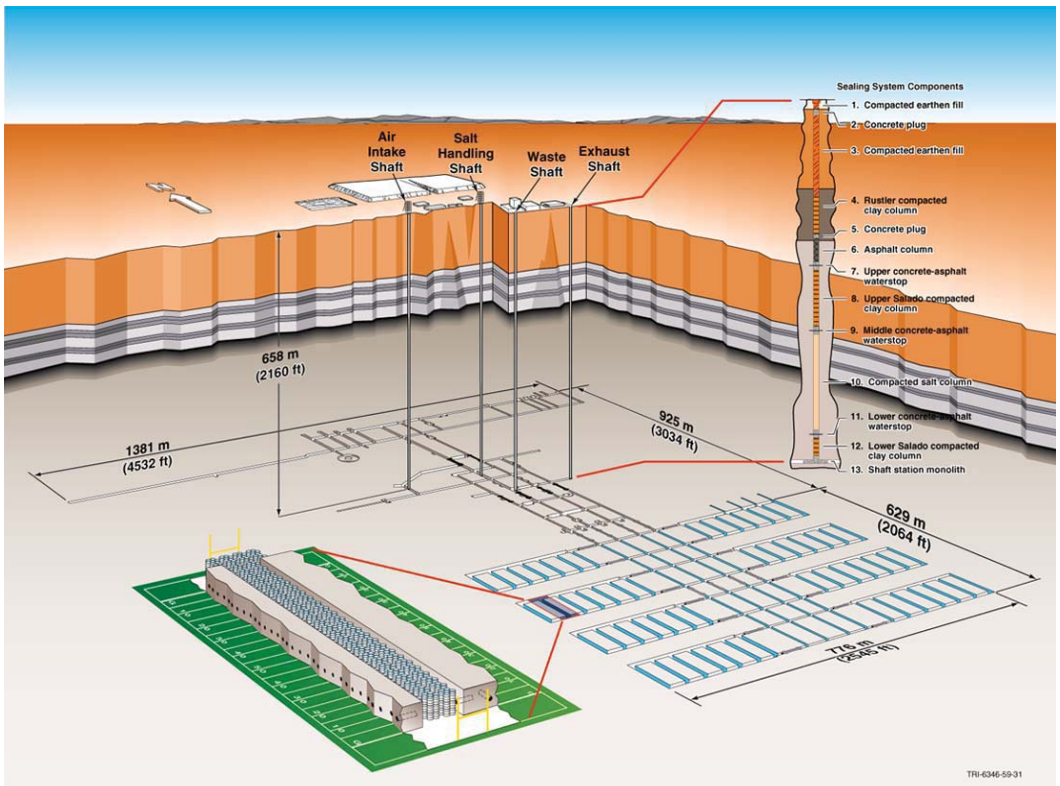

Present plans call for mining eight panels of seven rooms each and two equivalent panels in the central drifts. As each panel is filled with waste, the next panel will be mined. Before the repository is closed permanently, each panel will be closed. Waste will be placed in the drifts between the panels creating two additional panel volumes and access ways will be sealed off from the shafts. The shafts will then be sealed to isolate the repository from the ground surface. Final closure of the facility will be facilitated by creep closure of the salt.

When considering future intrusion scenarios, the DOE used the following EPA assumptions regarding future penetration of the repository:

- The regulatory time frame begins at the beginning of disposal and ends 10,000 years after disposal;
- Exploratory drilling may potentially affect the repository;
- Exploratory drilling is inadvertent and intermittent;
- Drilling events occur at random intervals; and
- Future drilling rates will be the same as the rates of deep drilling in the area over the past 100 years.

2.3.2 Geologic Setting

The geologic history of southeastern New Mexico and the data collected regarding the subsurface stratigraphy at the WIPP site are important and are discussed extensively in Section 2 of the CCA and documents referenced in the CCA. The general stratigraphy at the WIPP site is presented in Figure 2-3.

The sandstones, siltstones, limestones, and shales of the Bell Canyon Formation define the first extensive, continuous, transmissive unit below the WIPP repository and provide a source of groundwater that could migrate vertically into the repository. The halite and anhydrite beds of the Castile Formation separate the Bell Canyon from the Salado and contain pressurized brine reservoirs. The brine reservoirs are a repository performance concern expressed through human intrusion scenarios. The halite-dominated Salado Formation contains the proposed repository and provides the primary natural barrier for containing radionuclides. The laterally extensive Culebra Dolomite Member of the Rustler Formation is the closest stratigraphic unit above the Salado with the potential to transport a radionuclide release to the accessible environment. Studies conclude that transmissivities in the Culebra vary by six orders of magnitude across the WIPP site area. Fracturing and vuggy zones account for much of the variability in the physical hydraulic properties of the Culebra.

Figure 2-3 - *General Stratigraphy at the WIPP Site*

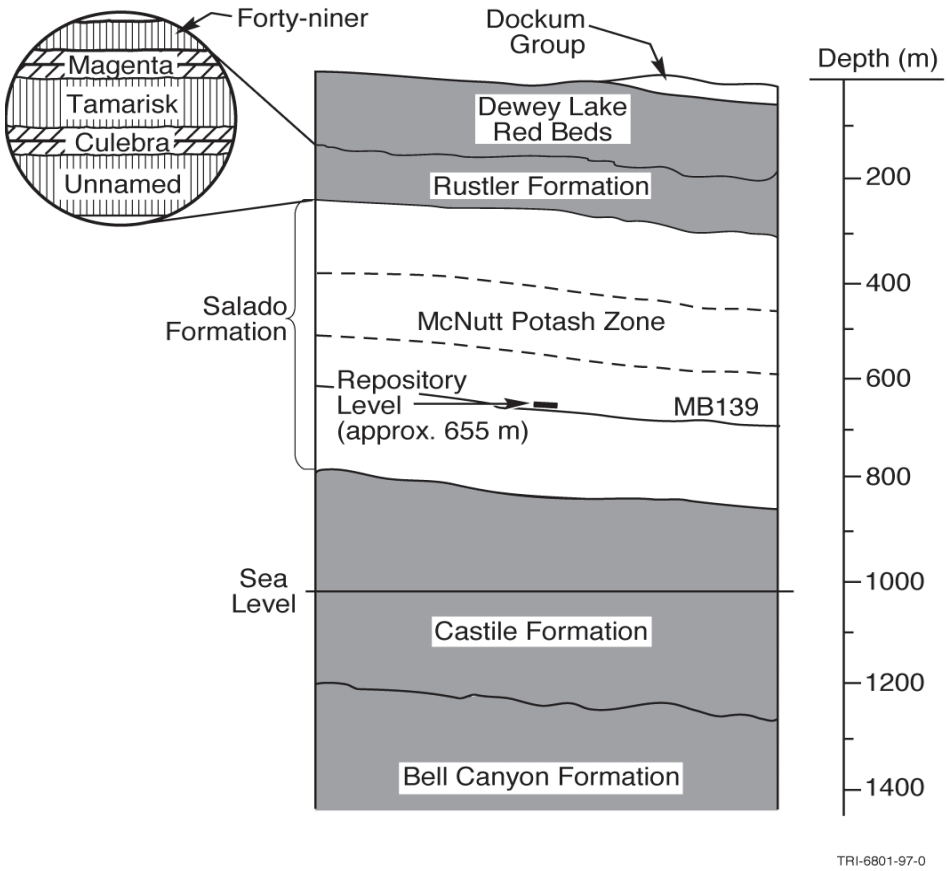

While other stratigraphic members of the Rustler Formation, beds of anhydrite and polyhalite, clays, and other inclusions may be important as each of the conceptual models is reviewed, the Four formations and units described above define the most important components of the geologic setting for the WIPP conceptual models review.

2.3.3 Hydrologic Setting

2.3.3.1 Surface Water

The WIPP site is located within the Pecos River Basin. At its nearest point, the Pecos River flows approximately 12 miles southwest of the WIPP site boundary. There are no perennial streams at the WIPP site and in this semi-arid region, approximately 75 percent of annual precipitation results from intense, short-duration events between April and

September. More than 90 percent of the mean annual precipitation is lost through evapotranspiration and on a mean annual basis, evapotranspiration potential exceeds expected rainfall. The EPA concluded in 1989 that there were "no surface water features near the WIPP that could potentially affect repository performance in such a way as to influence the no-migration demonstration."

2.3.3.2 Groundwater

Extensive coring, logging and testing of boreholes in the vicinity of the WIPP site has provided data for the characterization of the hydrostratigraphy important to the WIPP site region. While the deep Capitan Limestone, the Rustler-Salado contact zone near Nash Draw, and the shallower Dewey Lakes and Santa Rosa Formations are important in characterizing the WIPP region; the Bell Canyon, Castile, Salado, and Rustler Formations are the units critical to the evaluation of WIPP groundwater issues.

As presented in the geologic setting, the Bell Canyon Formation is the first continuous, transmissive water-bearing unit beneath the WIPP. This formation provides a source of non-potable ground water below the WIPP repository that could migrate into the repository if a pathway were available. The Bell Canyon Formation exhibits hydraulic conductivities in the range of 10^{-7} to 10^{-12} meters per second and pressures were measured in the range of 12.6 to 13.3 megapascals.

The Castile Formation is of interest to site characterization as a hydrologic barrier between the Salado and Bell Canyon Formations because it contains isolated pressurized brine reservoirs. The Castile is predominantly low-permeability halite and anhydrite with greater permeabilities in zones of fracture and structural deformation. In the areas of higher permeability brine pressures may exist that are sufficiently above nominal hydrostatic pressure for brine to flow upward through a borehole potentially reaching the surface.

The halite and anhydrite rocks of the Salado Formation are relatively impermeable and tests have shown that flows are extremely low to no flow when appreciable pressure

gradients are applied. The Salado contains the repository and provides the primary natural barrier for containing radionuclides.

The Magenta and Culebra Dolomite Members of the Rustler Formation are laterally extensive, transmissive, and display hydraulic characteristics sufficient for the lateral transport of radionuclides. Hydraulic conductivities in both members range over five to six orders of magnitude in the WIPP area but the Magenta is generally less transmissive than the Culebra. The Culebra is the most extensive and most transmissive unit above the Salado at the WIPP site. As such, the Culebra provides the most direct groundwater pathway from the WIPP repository to the accessible environment and is the most important component of the hydrogeologic setting for the conceptual models peer review.

2.3.4 Implementation of the "Option D" Panel Closure

The option "D" panel closure is a semispherical concrete closure to be emplaced in drifts and panel exits at several positions throughout the repository. The closure will be emplaced in an enlargement of the drift that will remove some material above the drift and all of the halite and the Interbed #139 below the drift floor. It is presumed that the closure will extend into the ribs of the drift a distance sufficient to remove the DRZ in that direction. Back-stress resulting from creep flow in the Salado halite into the repository will immediately begin to heal damage around the closure that may result from construction excavation. It is not expected that the closure will entirely block gas flow in Interbed #139, since flow around the limited footprint of the closure in the anhydrite is not prevented at high gas pressures. Upward gas flow from Interbed #139 into the drift beyond the closure is a possible scenario for the bypassing of the closure by gas from disposal panels. Rapid gas pressure fluctuations, as in the case of an intrusion into a single panel at a time of high overall repository gas pressures, would be significantly damped in adjacent unintruded repository spaces, but not entirely eliminated by the closure. The integrated impacts of the changed DRZ conceptual model and the role of the closure in modeling gas pressure in the waste panels before and during equilibration after intrusion are important interactions with the Repository Fluid Flow conceptual model.

Reduction in the volume of gas available during blowout (single panel isolated by closures) resulting from intrusion may impact the spalling model. Closures between panels imply that a first intrusion may not lower pressure throughout the repository, which may result in several intrusions in several panels having increased spall events. A drop in gas pressure after intrusion into a panel may accelerate brine flow toward the intruded panel. If the panel closure is left unsupported in an open drift, shear and extension stresses related to the creep closure of the spaces on either side of the panel closure may be significant to the mechanical stability of the panel closure. The mechanical stability of the option "D" panel closure in the stress environment represented by creep closure of the drift has not been modeled and should be reviewed following the next WIPP total system PA.

2.4 Peer Review Panel Methodology

The review of the conceptual models commenced after panel member orientation and training in accordance with MP 10.5, the Peer Review Plan, and other relevant information presented in the orientation and training package.

The peer review panel employed the following approaches in their overall method of conducting and accumulating information for the reviews:

- Extensive review of referenced literature relevant to the review;
- Attendance at briefings on conceptual models and relevant aspects of the PA process;
- Issue focused presentations with question-and-answer sessions with SNL scientists and engineers;
- Review of literature and documents referenced during the question-and-answer sessions; and
- Formal and informal discussions among the Panel members.

The Panel was provided several presentations addressing the three conceptual models being reviewed with respect to whether or not they represent a reasonable view of future

states of the proposed disposal system for the WIPP repository. For this review, conceptual models are defined as a set of qualitative assumptions used to describe a system or subsystem for a specific purpose. The Panel evaluated the models in accordance with the NUREG-1297 criteria. In addition, the Panel recognized that individual models may warrant varying levels of reviews of their mathematical representations, computerized representations, and results. Due to the volume and diversity of information to be reviewed, individual Panel members were assigned lead responsibility for specific conceptual model reviews. Dr. Gibbons assigned Dr. Oswald responsibility for review of the Disposal Room Geometry conceptual model; Dr. Caporuscio was assigned responsibility for review of the Repository Fluid Flow conceptual model, and Dr. Gibbons took responsibility for review of the Disturbed Rock Zone conceptual model. The information gathered by individual members during their reviews was freely disseminated among all of the Panel members.

In organizing its work, the Panel established limitations on its review and the content of this report. The Panel members did not review or offer comments on regulations. The Panel confined its review to the three conceptual models identified in the Peer Review Plan. To maintain independence, the Panel did not offer recommendations for specific methods and/or approaches to be employed in future work.

2.5 Criteria for Conceptual Model Review

The nine criteria used by the peer review members are based on the criteria in EPA regulation 40 CFR § 194.27, NUREG-1297, the EPA Compliance Application Guidance, and Peer Panel discussions.

Information Used to Review Changes in Conceptual Model. This is an evaluation of data and information used to review the changes in the conceptual models and sub-models. It includes attributes of the disposal system learned by SNL during site characterization activities, exercising the models, and a review of the science and concepts that the models are based upon. It also includes information gained during the operation of the repository.

Validity of Assumptions. The validity of key assumptions in the model and its application are assessed in terms of how they could affect the usefulness of the conceptual model. The review addresses the comprehensive inclusion of important features, events, processes, and other key assumptions. Examples are the assumption of Darcy flow in the various media, use of the ideal gas law at high pressures, and the mathematical method chosen to develop the model grid.

Alternative Interpretations. This section briefly identifies and assesses plausible alternative conceptual models or sub-models considered by SNL but not used, and the rationale why such alternative models were not used.

Uncertainty of Results and Consequences if Wrong. This includes an evaluation of the key uncertainties in the selected conceptual models and the discussion of the consequences if aspects of the conceptual model chosen were inappropriate or incompletely constrained for the site or process. This is not an exhaustive evaluation, but it does raise the question, "What if the model is wrong?"

Appropriateness and Limitations of Method and Procedures. Based primarily on the previous four criteria, this is a simple statement of whether the individual conceptual models and sub-models represent a reasonable approximation of the actual disposal system elements.

Adequacy of Application. This is an assessment of whether it appears that the individual conceptual model is being adequately applied into an acceptable overall performance assessment system. This particular assessment does not cover the relationships among conceptual models, but rather whether the significant components of the individual conceptual models are appropriately implemented in support of performance assessment. For example, are the various geometrical systems and representations of the conceptual models adequately applied within the performance modeling system, or do there appear to be discontinuities between the conceptual model and its application? Also, are there

alterations of important key assumptions between the conceptual model and its implementation in performance modeling?

Accuracy of Calculations. This is a statement of whether the results of performance modeling using the conceptual model within the performance system are reliable and accurate to adequately simulate the physical and chemical processes represented.

Validity of Conclusions. This is a judgment of the validity of any key conclusions that have been drawn based on results of the implementation of the conceptual models in the modeling framework. The key question is whether or not conclusions from model implementations appropriately relate to the expected goal of assessing the long-term performance of the disposal system. This judgment requires an evaluation of output information from the total system PA.

Adequacy for Implementation. This is an overall assessment of whether the conceptual models as implemented in the PA represent a reasonable approximation of the actual disposal system.

2.6 CONDITIONAL ADEQUACY

Two review criteria (adequacy of application and accuracy of calculations) require information available only after a total system PA has been performed. Recognizing that a total system PA will not be available for several months, conditional acceptance of the adequacy of the changed models is intended to permit completion of the total system PA.

The changed models should be re-reviewed in the context of a total system PA. The total system PA review may include review of accompanying sensitivity analyses appropriate to evaluate the reasonableness of changes in performance estimates resulting from changes in parameter ranges or in changes to or resulting from single values. The total system PA review should evaluate changes in the conceptual structure of the models and changes in component process models and compare the performance results of the changed models with the results of the earlier models to confirm that the changes in

performance estimates are reasonable in sense and magnitude. Changes in computations or in fundamental model aspects such as gridding should also be considered. Whatever the methodology chosen, each changed model must be shown to satisfy all of the review criteria after the next iteration of total system PA calculations. The final review should consider the impacts of the changed models on the implementation of related conceptual models and peripheral issues such as the Option "D" panel closures. The status of the changed models will remain "conditionally adequate" until the final review is completed. If warranted by final review in the context of a total system PA, the status of any changed conceptual model may become "inadequate".

3.0 Model Evaluations

This section presents the results of the Panel's evaluations of the three individual conceptual models that the DOE requested the Panel to review. Each of these models is first described and then evaluated for adequacy in accordance with the criteria summarized in Section 2.5. Following each evaluation, space has been provided for dissenting views. There were no dissenting views by any Panel member resulting from this peer review. An evaluation of the integration of these conceptual models into the WIPP performance assessment is provided in Section 4.

3.1 Disposal System Geometry

3.1.1 Model Description

3.1.1.1 Background

Consistent with the purposes for which the conceptual models were originally developed for the WIPP PA, the Disposal System Geometry conceptual model was developed to express the dimensionality of the engineered system and the surrounding geologic/hydrogeologic formations. The features that rely on the geometric assumptions and parameters of dimensionality for representation are expressed across the overall performance assessment system through a finite difference model called BRAGFLO. The flow fields generated by BRAGFLO, based on the geometric representations and the finite difference calculations, are communicated with the NUTS code that determines the transport of actinides through the anhydrite interbeds and boreholes. The geometry assumed for any model contains important information about the way in which physical processes are thought to act on the system. For WIPP, the model geometry assumed for the disposal system can only be understood in the context of the important processes considered to take place in a particular region during a specific time interval and for a defined purpose.

3.1.1.2 Description

This peer review focused on the changes in a specific group of conceptual models associated with the Technical Baseline Migration (TBM). Changes were evaluated to determine whether or not the models continue to reasonably represent the relevant features, processes, and future states of the disposal system. Changes to the disposal system geometry conceptual model evaluated were: 1) The removal of the shaft seal system from the models, 2) Implementation of Option "D" panel closure design, 3) Dividing the remainder of the repository into two blocks separated by a panel closure, 4) Applying a new method by which flaring is calculated, and 5) Refinement of the grid geometry.

The final certification decision (40 CFR Part 194) requires the implementation of Option "D" panel closure system. The system, characterized by a concrete monolith and an explosion wall, led to the proposed change in grid geometry since the existing grid block discretization was perceived to be too coarse for the representation of the specifics of Option "D" and the interrelated impacts on the DRZ. In general, where flow has been shown to be important, changes to the grid are proposed to add detail. The proposed grid refinement provides for greater segmentation and allows the detail of Option "D" components to be captured. The changes in the grid increased both vertical and horizontal refinement. The number of grid cells representing the repository increased from 51 in the CCA to 69 in the TBM. The total number of grid cells increased from 33 to 68 in the x-dimension and 31 to 33 in the y-dimension. The x-dimension changes in the grid required the recalculation of radial flaring. It is understood by previous peer review panels, and this panel as well, that while flow may not be truly radial, the two-dimensional flared grid is reasonable for estimating releases. The CCA grid had several scales of flaring with each calculation including a series of complicated cell wrapping procedures that are difficult to reproduce and use for characterizing changes. The TBM changes include a new flaring algorithm that uses simplified repository geometry, results in flaring representations that closely approximate those in the CCA grid, and allows for changes to be "more easily" made in the x-dimension.

Changes in the BRAGFLO model considered in this peer review, with respect to the Disposal System Geometry conceptual model, include grid spacing changes, removal of the shaft seal system material properties and replacing them with those representing the surrounding geologic units, and changes in the way flaring is calculated. Implementation of Option "D" panel closure was the stimulus for changing the grid with removal of the shaft seal system being a separate decision represented in the BRAGFLO grid.

3.1.2 Review of Criteria

3.1.2.1 Information Used to Review Changes in Conceptual Model

The 1996 peer review of the Disposal System Geometry conceptual model included review of the screening logic, numerous SNL reports, and many technical presentations and discussion sessions. As stated in the report, (July 1996) the information and background references reviewed at that time were for specific inputs and applications, i.e., a comprehensive list of references addressing the "conceptual modeling" of the Disposal System Geometry was not compiled. Information concerning the effects of detailed stratigraphy and stratigraphic dip on brine and gas flow, and uncertainty and parameter sensitivity analyses for gas and brine migration, is presented in Webb and Larson (1996), WIPP (1992a & 1992b), and Christian-Frear (1996). Other reports (WIPP 1993, Rechard 1990, and Marietta 1989) explain the WIPP performance assessment aspects of characterizing the disposal system geometry, and features, events, and processes (FEPs) screening documents present modeling alternatives. Various sections of the Compliance Certification Application (DOE 1996) summarize disposal system, repository, and intrusion event geometries. The Disposal System Geometry conceptual model, as reviewed in 1996 and as addressed in this peer review, is the result of integrating other models that describe the physical and chemical conditions and processes that are expected in the repository to produce a characterization of the repository and the surrounding strata. The references include the various background, technical descriptions and presentation materials used in conducting the evaluation of the TBM changes in the Disposal System Geometry conceptual model. Previous conceptual model peer review reports, regulatory guidance, and other appropriate documents were provided to the peer review panel early in the process, as required background reading. The key information

sources, with respect to the TBM changes were the technical presentations, supplementary technical and background materials provided by SNL and discussions with SNL scientists.

3.1.2.2 Validity of Assumptions

Along with the assumptions made for the TBM changes, it is important to briefly review the general assumptions made in the original peer review of the Disposal System Geometry conceptual model in 1996. The Disposal System Geometry conceptual model and its assumptions are so closely tied to the processes described by other models that not only is it important that the model have assumptions that are internally consistent, but the assumptions must be consistent with those of the models representing repository processes. The geometry by which processes are simulated is so closely tied to the processes themselves that it is difficult to conduct a review separate from the other models. Fluid flow and actinide transport are principal processes that rely on the geometric assumptions and these processes in turn have interrelationships with other process models. In 1996 the panel recognized the simplifications and assignment of high permeabilities for the sake of conservatism. Although, this panel's view is that it is always more credible to model the actual system, the assumptions supporting the simplifications remain valid.

Assumptions key to the original Disposal System Geometry conceptual model include: 1) the three-dimensional systems can be represented by two-dimensional simplifications, 2) the associations between and relationships across regions with varying material properties can be represented by the discretized grid blocks and by the finite difference method used in the computational model; 3) the four shafts can be represented by one shaft; 4) the entire repository can be represented by the simplified floor plan used in the computation model; 5) the intrusion borehole(s) represent the range of concerns associated with the intrusion scenarios; and 6) effects of flow in the DRZ and intact rocks outside of the repository are represented by the divergent grid to the north and south, away from the repository.

Assumptions key to the proposed TBM changes in the Disposal System Geometry conceptual model include: 1) A more refined grid spacing, generally, provide for more accurate representation of features, events, and processes and do not adversely impact the representation of sources, sinks, and pathways for radionuclide releases; 2) Flow in the shaft is negligible; 3) Removal of the shaft seal system properties and replacement with those of the surrounding geologic units will represent relevant features, processes, and future states of the disposal system; 4) The new flaring algorithm adequately represents horizontal divergent and convergent flows to the north and south of the repository; and 5) The TBM BRAGFLO grid adequately represents the Option "D" panel closure design, the DRZ, anhydrite fracture, repository fluid flow, and other components of the WIPP setting.

During the Salado Flow Peer Review, SNL presented assumptions and justifications for the material property representations proposed for use in the TBM. The panel concludes that the assumptions and justifications are defensible and appear to adequately represent the features and process of concern in TBM changes. The panel also concludes that as a result of previous PA calculations, illustrating that only negligible flows are released up the shaft, removal of the shaft seal properties and replacement of the shaft seal properties with those representing the surrounding geologic units is justified.

The changes in the Disposal System Geometry conceptual model are proposed to be implemented through the same discretized grid block and finite difference computational approach as the CCA, and if key pathways and simplifications are retained, the overall conceptual model remains valid.

3.1.2.3 Alternative Interpretations

During the Salado Flow Peer Review, information presented and considered did not include alternatives or options for changes in the Disposal System Geometry conceptual model. The final certification decision required the implementation of the Option "D" panel closure system and no other panel closure alternative changes are appropriate.

Other changes are proposed to accomplish specific objectives and no alternative approaches have been proposed for those specific changes.

3.1.2.4 Uncertainty of Results and Consequences if Wrong

The key uncertainties associated with the TBM proposed changes to the Disposal System Geometry conceptual model are related to the material property descriptions and the grid simplifications made, for the sake of conservatism, and the representativeness of the computational mesh. Even with the TBM changes the proposed BRAGFLO grid is not sufficiently detailed to describe all flow features and processes and the overall system relies on other conceptual models to reasonably describe such features and processes.

The panel concludes that there is little uncertainty associated with the basic geometric framework and finite difference method used to characterize the changes associated with the proposed TBM. The uncertainty that does exist is related to the grid block densities of the material property representations and the representativeness of the grid block densities/computational mesh. The material property changes appear justified and defensible.

The consequences of the proposed TBM changes in the Disposal System Geometry conceptual model, if they are wrong, can only be addressed in a qualitative way at this time. If the material property representations are wrong and /or the computational mesh is not representative, the consequences depend on the relative magnitude of error(s) and the resulting changes in the total system PA.

3.1.2.5 Appropriateness and Limitations of Method and Procedures

The proposed TBM changes in the Disposal System Geometry conceptual model would be made without changing the fundamental geometric framework of discretized grid blocks and the finite difference method implemented through BRAGFLO. The methodology is considered by the panel to be appropriate for the TBM application. The panel concludes that the conceptual model continues to be an appropriate methodology to

integrate and express the inputs from other conceptual models. The limitations of the methodology and procedures are directly related to validity of assumptions and uncertainties.

3.1.2.6 Adequacy of Application

The methodology employed in the Disposal System Geometry conceptual model is appropriate and adequate for application as a performance element. The proposed TBM changes in the conceptual model would be made through an adequate fundamental framework and implementation method and code. There are no apparent compatibility problems between the geometry and process-related models. Single vector BRAGFLO analyses that focused on saturation and pressure provided comparisons for the Performance Assessment Verification Test (PAVT), Technical Baseline Intermediate (TBI), and TBM. The TBI was intended to isolate Option “D” effects in the BRAGFLO grid. The single vector, time dependent comparisons produced results that were either expected or could be explained. Scatter-plots also provided comparisons where the differences could be explained.

The adequacy of the changes in material properties and their representations in the grid can only be measured by how well overall processes are approximated. These approximations and representations and changes from the previous conceptual model can only be determined through a full system PA.

3.1.2.7 Accuracy of Calculations

It was not within the scope of the Salado Flow Peer Review to evaluate BRAGFLO implementation code changes, related to TBM conceptual model changes, or the resulting representations. Descriptive write-ups and review of uncertainty/sensitivity analyses that compare the relationship between sampled inputs and dependent variables in the PAVT, TBI, and TBM provide no indications that the accuracy of the "baseline" model has been changed. However, the review was limited and the panel cannot conclude as to the overall accuracy of calculations until a total system PA is available for review.

The Disposal System Geometry conceptual model produces results using the material properties, processes, and codes from other models. As such, the results of the Disposal System Geometry conceptual model should be evaluated for accuracy in the context of a total system PA.

3.1.2.8 Validity of Conclusions

Excluding the presentation of intermediate analyses such as illustrations of time dependent vector analyses and horsetail plots, and comparisons using scatter plots that focused on pressure and saturation, the panel is not aware of any results or conclusions as to the impacts of the proposed TBM changes. However, without total system PA results, where the CCDFs and the distribution of results can be compared between the CCA baseline and the TBM changes, there can be no in-depth assessment of the impacts of the proposed changes. No conclusions can be drawn at this time.

3.1.2.9 Adequacy for Implementation

3.1.2.9.1 General

The Disposal System Geometry conceptual model continues to provide an adequate framework for modeling the important processes and their interactions in the disposal system. The concept that the spatial effects of processes and interactions can be represented in two-dimensions is defensible. The simplification in the system representation and computational method to simulate the two dimensions are defensible and adequate for implementation. The basic grid framework for representing the material properties of the disposal system, adjacent DRZ, geologic formations, and intrusion scenarios is adequate. The proposed use of a finite difference method to connect the nodes and generate flow fields is also defensible and adequate for implementation.

3.1.2.9.2 Conditional Adequacy of the Changed Disposal System Geometry Conceptual Model and Requirements for Final Review

Changes to the Disposal System Geometry conceptual model have been evaluated and the only uncertainties are related to the validity of the material property representations and the representativeness of the grid densities and computational mesh. The changed Disposal System Geometry conceptual model is found to be conditionally adequate. The model must satisfy the review criteria adequacy of application and accuracy of calculations for the conditional status to be removed. It also must be demonstrated that the changed model continues to represent relevant features, processes and future states of the disposal system and as such, the changes from the "baseline" conceptual model must be analyzed and understood in light of a total system PA.

3.1.2.10 Dissenting Views

There were no dissenting views for this model.

3.2 Repository Fluid Flow

3.2.1 Model Description

The Repository Fluid Flow conceptual model is a highly complex description of interacting hydrologic, chemical, engineering design, geomechanical, and human intrusion conceptual models whose simultaneous effects can be separately described, but require performance assessment numerical modeling to understand the combined, integrated results. The physical conditions controlling fluid flow in the repository include brine inflow rates, halite creep rates, and gas generation pressures from waste container corrosion and waste degradation. All of these physical conditions are contained in separately described conceptual models (Salado Interbeds, Creep Closure, and Gas Generation conceptual models respectively). The Repository Fluid Flow conceptual model accepts input from these related models and provides descriptions of pressures, flow rates, and flow directions for gas and brine within the disposal cells and other sections of the repository. A formal description of the coupled processes in the original conceptual model was presented in Freeze et al. (1995).

Changes to the original conceptual model are as follows: 1)Brine inflow rates and gas pressures have possibly been altered by the introduction of the Option "D" panel closure model mandated by the regulator, 2) The salt creep rate may be affected due to changes in gas pressure, 3) Gas generation is calculated using a different cellulosic molecular weight that provides approximately 10% greater gas production during microbial degradation, and 4) Flows will be redirected since the Disposal System Geometry conceptual model no longer explicitly represents a shaft in the grid.

3.2.2 Review of Criteria

3.2.2.1 Information Used to Review Changes in Conceptual Model

The Repository Fluid Flow conceptual model relies heavily on Darcy flow in porous media, as revised for gas by taking into account the Klinkenberg effect, and for two-phase flow using a modified Brooks-Corey model that includes threshold pressures for gas entry into a brine saturated environment. Gas properties are given by the Redlich-Kwong-Soave equations of state, assuming that the gas behaves as pure hydrogen. The conceptual model addresses: (1) fluid distribution in the waste, (2) long-term fluid (gas and liquid) flow to and from the Salado Formation, and (3) long-term fluid flow between the repository and the intrusion boreholes. Interactions with other conceptual models include the Disposal Room Geometry, Disturbed Rock Zone, Creep Closure, Gas Generation, Impure Halite, Salado, the Salado Interbeds, Castile and Brine Reservoirs, Exploration Boreholes, and Multiple Intrusions. In the original CCA the Repository Fluid Flow conceptual model was also related to the Shafts and Shaft Seals conceptual model. The Shafts and Shaft Seals model was removed from the present performance assessment because it was determined to have no impact. Therefore, fluid flow will now be modeled as transport exclusively up boreholes (Multiple Intrusions and Exploration).

The conceptual model for repository fluid flow is implemented for performance assessment using the BRAGFLO code. The repository is represented in BRAGFLO in two-dimensional vertical section as a series of volumes, each with homogeneous isotropic material properties and behaviors. Each volume represents a major repository feature.

The slight one degree (1°) dip of the bedding to the south is represented by the code. The effective depth of each feature (the dimension normal to the plane of the model) is accomplished by adjusting the cross sectional areas of the cells representing the feature. The effective depths of the model cells were varied to simulate the increasing hydraulic gradients that would occur in the repository and boreholes under radial flow conditions.

The original conceptual model was validated in the CCA and accepted by the Conceptual Models Peer Review in 1996. Since that time, a PAVT sensitivity study was performed. That PA included 60 parameter changes mandated by the EPA. Sensitivity analysis in the PAVT indicates that changes in the complete PA calculation set were not substantial.

Since the PAVT, there have been minor changes to the fluid pathways in and around the repository. Those changes are the result of modifications to other conceptual models and new EPA mandated parameter values. Those modifications are summarized as follows:

> The Shafts and Shaft Seals conceptual model has been removed from the overall model. With the removal of the Shafts and Shaft Seals conceptual model from the upcoming total system PA, it is estimated that with the enactment of either the Exploration Borehole or the Multiple Intrusions conceptual model, all releases will be channeled up the boreholes. The removal of this conceptual model should provide no significant change to the upcoming PA.
>
> There have been changes to the Disturbed Rock Zone conceptual model. Fluids will no longer transport from one panel to another via Marker Bed #138. Instead, fluids will now migrate along Marker Bed #139 below the floor of the panels. The fluids will not be able to circumvent the Option "D" panel closure by taking the path of least resistance in marker Bed #139. Because of permeability fluctuations now allowed by the DRZ, both gas and liquid phases may be impeded during certain BRAGFLO simulations.

The Option "D" panel closure has been incorporated into the final closure plan and has multiple potential effects on fluid flow. Although the upper DRZ still exists it is not allowed to fracture for the TBM analysis. The lower DRZ is allowed to fracture for the TBM making Marker Bed #139 the preferred pathway. Fluids will more slowly equilibrate throughout the repository after closure, which may result in changes in the output from the next total system PA. Gas pressure in the experimental area will most likely be lower than in the PAVT, since there is no gas generation in that region and no communication with the waste panels. Brine saturation in the waste panel may be lower than in PAVT, since there is less brine communication between panels due to the characteristics of the Option "D" panel closure. Brine saturation in the remainder of the repository will be the same as PAVT calculations because process models for BRAGFLO have not changed.

The parameter value changes include the cellulosic molecular structure change and the EPA mandated parameter value changes. The cellulosic chemical formula ($C_6H_{10}O_5$) provides approximately 10% greater gas production during microbial degradation. The new parameter value changes introduced by the EPA did not seem to introduce significant changes from the CCA to the PAVT CCDFs. Although the TBM CCDF has not been run yet, it is reasonable to believe that no significant changes will occur.

3.2.2.2 Validity of Assumptions

On a larger scale, the original assumptions for the Repository Fluid Flow conceptual model were validated in the original performance assessment (CCA, 1996). The validity of the assumptions hinge in part on the other conceptual models (Disturbed Rock Zone and Disposal System Geometry) currently under review. In so far as the assumptions in the other models are shown to be valid, those same assumptions will propagate through to the Repository Fluid Flow conceptual model. The BRAGFLO computer model was not

significantly changed in its assumption base (creep closure, gas generation, pressure induced fracturing, use of characteristic curves such as Brooks-Corey and van Genuchten), rather cell parameters have been improved and cell dimensions have been better adapted to critical features.

The assumptions addressed are: 1) removal of the Shafts and Shaft Seals, 2) change in representation of cellulosic molecular structure, 3) changes in the DRZ conceptual model, 4) implementation of EPA mandated changes to parameters, 5) implementation of the Option "D" panel closure, and 6) the associated ramifications to other conceptual models and the performance assessment.

The assumption that the removal of the Shafts and Shaft Seals system would affect the overall performance of the PA in a very minor way is reasonable. Maximum brine flow up the Shaft at the top of the DRZ was calculated to be approximately 30 m^3. During borehole intrusions in the upcoming PA this fluid would be directed up the borehole and would still be insignificant.

The larger molecular weight for cellulose is not an assumption, but rather a refinement of a parameter. The recalculation of the molecular weight and the slight increase in gas generation potential (10%) will produce a slightly more conservative value for overall gas generation amounts in certain PA scenarios.

The two major assumptions for the Disturbed Rock Zone conceptual model (permeability and flow geometry) are reasonable.

The 60 parameter changes listed in Table 3-1 (Summary of CCA and PAVT Parameters) and Table 3-1. (Summary of TBM Values and Distributions) appear reasonable and correct. The most notable changes concern actinide solubilities in the fluid. In all cases the solubility values are lower than in the original CCA values. Such values would produce lower value curves in the upcoming CCDFs, if all other variables remain unchanged. Most other changes involve taking a single parameter value and replacing it with a range of values that bracket the original. This is a reasonable and valid

assumption, in that it still focuses most new values near the original value, but allows the CCDF calculations a slightly wider variance.

Table 3-1. Summary of CCA and PAVT Parameters

Parameter	CCA Range and Distribution	PAVT Range and Distribution
Log of Borehole Sand Permeability	-14 to -11 log m^2 Uniform	-16.3 to -11 log m^2 Uniform
Log of Borehole Concrete Permeability	-16.3 log m^2 Constant	-19 to -17 log m^2 Uniform
Log of Disturbed Rock Zone Permeability	-15 log m^2 Constant	-19.4 to -12.5 log m^2 Uniform
Log of Waste Permeability	-12.769 log m^2 Constant	-12.6198 log m^2 Constant
PIC Reduction Factor for 100 – 700 years	0.01 Constant	1.0 Constant
Waste Shear Strength	0.05 to 10 Pa Uniform	0.05 to 77 Pa Loguniform
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Castile Brine	6.52×10^{-8} mol/l constant	1.38×10^{-8} mol/l constant
Coefficient, A, in Equation[(a)] for Solubility for Np+4, Pu(IV), Th(IV) and U(IV) in Castile Brine	6.0×10^{-9} mol/l constant	4.1×10^{-8} mol/l constant
Coefficient, A, in Equation[(a)] for Solubility for Np(V) in Castile Brine	2.2×10^{-6} mol/l constant	4.8×10^{-7} mol/l constant
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Salado Brine	5.82×10^{-7} mol/l constant	1.2×10^{-7} mol/l constant
Coefficient, A, in Equation[(a)] for Solubility for Np(IV), Pu(IV), Th(IV) and U(IV) in Salado Brine	4.4×10^{-6} mol/l constant	1.3×10^{-8} mol/l constant
Coefficient, A, in Equation[(a)] for Solubility for Np(V) in Salado Brine	2.3×10^{-6} mol/l constant	2.4×10^{-7} mol/l constant
Inundated Steel Corrosion Rate	0 to 1.59×10^{-14} m/s Uniform	0 to 3.17×10^{-14} m/s Uniform
K_d in Culebra Dolomite for Am(III) and Pu(III)	0.02 to 0.5 m^3/kg Uniform	0.009 to 0.4 m^3/kg Loguniform
K_d in Culebra Dolomite for Np(IV), Pu(IV), Th(IV), and U(IV)	0.9 to 20 m^3/kg Uniform	0.7 to 10 m^3/kg Loguniform
K_d in Culebra Dolomite for Np(V)	0.001 to 0.2 m^3/kg Uniform	0.001 to 0.2 m^3/kg Loguniform

K_d in Culebra Dolomite for U(VI)	0.00003 to 0.03 m^3/kg Uniform	0.00003 to 0.02 m^3/kg Loguniform
Probability of Hitting a Brine Pocket	0.08 Constant	0.01 to 0.60 Uniform
Drill String Angular Velocity	7.7 radians/s Constant	4.2 to 23.0 radians/s cumulative distribution with mean of 7.77 radians/s
Castile Brine Pocket Rock Compressibility	Min: $5x10^{-12}$ Pa^{-1} Max: $1x10^{-8}$ Pa^{-1} Mode $1x10^{-10}$ Pa^{-1} Triangular	Min: $2x10^{-11}$ Pa^{-1} Max: $1x10^{-10}$ Pa^{-1}; Mode $4x10^{-11}$ Pa^{-1} Triangular
Castile Brine Pocket Porosity	Not used in CCA	Min: 0.1848; Max: 0.9240; Mode 0.3696
Brine Pocket Pore Volume	(3.2, 6.4, 9.6, 12.8, 16) x 10^4 m^3 Discrete	Calculated from Brine Pocket Porosity
Inventory Waste Unit Factor	4.07 Constant	3.44 Constant

[(a)]The equation for solubility is $A \cdot 10^b$ where b is a sampled value. Only the coefficient, A, was changed in the PAVT.

Table 3-2. Summary of TBM Values and Distributions

Parameter	Range	Distribution
Log of Borehole Sand Permeability	-16.3 to -11 log m^2	Uniform
Log of Borehole Concrete Permeability	-19 to -17 log m^2	Uniform
Log of Disturbed Rock Zone Permeability	-19.4 to -12.5 log m^2	Uniform
Log of Waste Permeability	-12.6198 log m^2	Constant
PIC Reduction Factor for 100 – 700 years	1.0	Constant
Waste Shear Strength	0.05 to 77 Pa	Loguniform
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Castile Brine	1.38 x 10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np(IV), Pu(IV), Th(IV) and U(IV) in Castile Brine	4.1 x 10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np(V) in Castile	4.8 x 10^{-7} mol/l	Constant

Brine		
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Salado Brine	1.2×10^{-7} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np(IV), Pu(IV), Th(IV) and U(IV) in Salado Brine	1.3×10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np(V) in Salado Brine	2.4×10^{-7} mol/l	Constant
Inundated Steel Corrosion Rate	0 to 3.17×10^{-14} m/s	Uniform
K_d in Culebra Dolomite for Am(III) and Pu(III)	0.009 to 0.4 m^3/kg	Loguniform
K_d in Culebra Dolomite for Np(IV), Pu(IV), Th(IV), and U(IV)	0.7 to 10 m^3/kg	Loguniform
K_d in Culebra Dolomite for Np(V)	0.001 to 0.2 m^3/kg	Loguniform
K_d in Culebra Dolomite for U(VI)	0.00003 to 0.02 m^3/kg	Loguniform
Probability of Hitting a Brine Pocket	0.01 to 0.60	Uniform
Drill String Angular Velocity	4.2 to 23.0 radians/sec	Cumulative distribution based on range with mean value of 7.77 radians/s
Castile Brine Pocket Rock Compressibility	Min: 2×10^{-11} Pa^{-1} Max: 1×10^{-10} Pa^{-1} Mode 4×10^{-11} Pa^{-1}	Triangular
Castile Brine Pocket Porosity	Min: 0.1848; Max: 0.9240; Mode 0.3696	Triangular
Brine Pocket Pore Volume	Calculated from Brine Pocket Porosity	Not applicable
Inventory Waste Unit Factor	3.59	Constant

[(a)]The equation for solubility is $A \cdot 10^b$ where b is a sampled value. Only the coefficient, A, was changed in the PAVT.

More information is needed to clearly understand how implementation of the Option "D" panel closure will affect fluid flows. At this point, only vectors for three scenarios have been generated and analyzed from PAVT to TBM models, and these were concerned only with brine saturation and gas generation values. First, gas pressure in the experimental area will commonly be lower than in the PAVT, since there is no gas generation in that region and very limited communication with the waste panels. Conversely, TBM

calculations of gas pressures in the waste panels are slightly elevated relative to PAVT values. These two observations were calculated at the 1000-year time frame. At the 10,000 year time frame most TBM gas pressure values converge on the PAVT generated values. Second, brine saturation in waste panels may be lower than in PAVT representations, since there is less brine communication between panels due to the characteristics of the Option "D" panel closure. This calculation proves true for both the 1000 and 10,000 representations. However, Brine saturation in the remainder of the repository (ROR) will be the same as PAVT calculations because ROR grid parameters for BRAGFLO were not changed. Of interest is the fact that the experimental regions of the repository show higher brine saturation in TBM analysis due to the fact that the panel closures don't allow the brine to migrate down dip. Finally, TBM calculations indicate that brine flow up a borehole from a waste panel is slightly elevated relative to PAVT data. In addition, the panel closure now dampens equilibration of gas pressures during multiple borehole intrusion scenarios. During the first intrusion, the panel gas volume will escape up the borehole. However, subsequent waste panels will retain high gas pressure. Secondary or tertiary borehole intrusions may still encounter waste panels with high gas pressures indicating a possibility that spalling events may cumulatively bring more waste to the surface.

The last assumption, that the Repository Fluid Flow conceptual model will have negligible impact on the other conceptual models and the total system PA is unknown. How increased or decreased values of gas pressure and/or brine saturation will impact fluid flow has not been evaluated. Furthermore, the impact that the changes in fluid flow will have on the Spallings and Multiple Intrusions conceptual models, and on the total system PA is unknown.

3.2.2.3 Alternative Interpretations

The changes incorporated into the Repository Fluid Flow conceptual model are based on two earlier cases of the model. The earlier models represent alternative interpretations. The Repository Fluid Flow conceptual model in the CCA was fully peer reviewed and accepted. The second representation of the model was in the PAVT sensitivity study.

The changes incorporated into this rendition of the model are logical improvements based on removal of the Shafts and Shaft Seals and the incorporation of the Option "D" panel closure.

3.2.2.4 Uncertainty of Results and Consequences if Wrong

The uncertainty of results with the changed Repository Fluid Flow conceptual model hinge on the implementation of the Option "D" panel closure. The purpose of the panel closures is to impede flow around the closure between adjoining waste panels. The new Disturbed Rock Zone conceptual model implies that flow will occur in the underlying Interbed #139 at high gas pressure, and in turn, this should allow gas and liquid in the waste panels to equilibrate over time. However, vector analyses of gas pressure and brine saturation in the TBM model show that flow occurs for a limited number of vectors when pressures become high enough to cause significant fracturing. When these factors (pressure and saturation) are allowed to interact with the other conceptual models and are evaluated as part of the total system PA, other outcomes may result. Direct release conceptual models (involving cuttings, cavings, spallings, and direct brine release) provide the most significant release pathways. Since there is evidence that the waste panels do not equilibrate with the ROR nor with the experimental region, the Repository Fluid Flow conceptual model should be evaluated in the context of a total system PA.

If the direct release conceptual models intercept a waste panel with very a high gas pressure (near or above lithostatic pressures), then an increase in direct releases to the surface could occur. Similarly, if a panel with high brine saturation were encountered, it could allow for slightly higher solute transport to the surface. Conversely, if panels with low gas pressure or low brine saturation were intercepted, then the direct release could be much lower. Since specific waste panels and explicit scenarios for direct release have not been specified for the upcoming total system PA, the Peer Review Panel cannot determine the consequences from the Repository Fluid Flow conceptual model.

3.2.2.5 Appropriateness and Limitations of Method and Procedures

The methods and procedures used in the newest rendition of the model are based on refinements of the previous models and should provide representative results in the upcoming total system PA. If representative panels are chosen for the "borehole" models, this new model are expected to provide similar results to the PAVT application.

3.2.2.6 Adequacy of Application

The adequacy of application can not be judged without the total system PA and the associated CCDFs. Once the total system PA is performed, the adequacy of the newest rendition of this model can be compared to previous forms of the model and how it impacts the new CCDFs.

3.2.2.7 Accuracy of Calculations

No new calculations were reviewed by the Panel since the previous two iterations (CCA and PAVT). The accuracy of the calculations already embedded (BRAGFLO) in the Repository Fluid Flow conceptual model should be determined when the next iteration of the total system PA is complete.

3.2.2.8 Validity of Conclusions

The validity of the conclusions cannot be assessed without the total system PA and the associated CCDFs. It is still not known how the implementation of the Option "D" panel closure will affect fluid flow throughout the repository.

3.2.2.9 Adequacy for Implementation

3.2.2.9.1 General

Adequacy for implementation cannot be judged without the total system PA and the CCDFs.

3.2.2.9.2 Conditional Adequacy of the Changed Fluid Flow Model and Requirements for Final Review

The changed Repository Fluid Flow conceptual model is found to be conditionally adequate with the following conditions. The model must satisfy review criteria for adequacy of application, accuracy of calculations, and validity of conclusions for the conditional status to be removed. The information to be judged once the total system PA is available is whether the Repository Fluid Flow conceptual model still correctly couples with the other conceptual models to produce representative results.

3.2.2.10 Dissenting Views

There were no dissenting views for this model.

3.3 Disturbed Rock Zone

3.3.1 Model Description

The DRZ conceptual model, as originally conceptualized in the CCA, was composed of a layer of halite above and below the drift. This layer provided a flowpath between the drift and marker-b
eds. The halite that composed this layer was assigned an arbitrary permeability of $10^{-15}m^2$, considered a conservative value that would permit gas to escape the repository via the fractured interbed and allow gravity-driven drainage of brine from the interbed into the repository ("DRZ rain"). The model was not strongly representative of repository processes; rather it was viewed as a conservative basis for modeling waste degradation and gas generation processes in the repository.

During the PAVT sensitivity study the EPA mandated a range of permeability for the DRZ halite layer which reasonably represents the properties of extensively creep-damaged halite and anhydrite at the high permeability end, and of minimally damaged halite at the low permeability end. This range is unequally distributed around the original single value used for the halite permeability. This range is retained in the changed

conceptual `model under review, and was not previously peer reviewed. The principal change to the hydrologic processes contained in the model presently under review is the flow path through the repository floor, an average of one meter of halite, into Interbed #139 which is composed of about one meter of fractured anhydrite. This flow path represents a considerably more transmissive pathway for the exit of gas and brine from the pressurized repository, into the potential storage medium represented by the fractured anhydrite. The gravity inflow of brine through the halite layer above the repository back is still a factor in modeling brine inflow into the repository, but gas outflow will follow the path of least resistance out through the floor into Interbed #139. The change to the PAVT model under review here is described in some places in the review documents as the addition of a fracture model. The change is actually only a change in flowpath out of the repository and no new fracture model is proposed.

3.3.2 Review of Criteria

3.3.2.1 Information Used to Review Changes in Conceptual Models

The CCA version of the DRZ conceptual model consisted of a 12 meter thick zone above the emplacement panels and drifts that were assigned an assumed permeability of $10^{-15}m^2$ for the entire zone. This conceptual model had no basis in actual repository or site performance, but was rather a conservative representation of the damaged rock zone, conceived to permit brine and gas flow between the repository and the overlying Interbed #138. The PAVT sensitivity study that followed the CCA used a range of permeability values for the zone between the repository and Interbed #138 that were identified by the EPA. The EPA determined the lower bound of the range of permeability from measured gas permeability in anhydrite cores from Interbed #139 (Howarth, 1996, Beauheim, 1996, Howarth and Christian-Frear, 1997). The EPA concluded that a value of $10^{-19.4}m^2$ is an appropriate lower bound for the range of likely values. Based on sensitivity tests, the EPA selected a value of $10^{-12.5}m^2$ as the upper bound of the range of DRZ permeability. Documents held by the WIPP Project office pertaining to DRZ permeability support this range of the PAVT values (Beauheim, 1996). The more permeable limit represents halite and anhydrite heavily damaged by creep strain. The less permeable end of the range assigned to the assumed disturbed zone above the repository is a value conceived to

represent the permeability of halite that has been healed by stresses associated with repository creep closure and is supported by measured permeability values. This value ($10^{-19.5}m^2$) is comparable to the permeability of halite that has been disturbed only by far field stresses caused by creep toward the repository opening beyond the disturbed rock zone (Beauheim, in press). This range of values is an acceptable bound of the permeability of the disturbed rock zone that includes both the Salado halite and the anhydrite of the interbeds.

The change proposed to the DRZ conceptual model for the next total system PA modifies the geometry of flow associated with the DRZ but retains the range of permeability assumed for the DRZ under the PAVT sensitivity study. The changed conceptual model routes flow through the floor of the repository to Interbed #139 whose upper surface is only one meter below the floor over most of the disposal area. This flow routing represents the path of least resistance for the flow of gas out of the repository and provides a reasonable estimation of gas pressures in the repository. The 12 meter thick overhead DRZ has the same range of assumed permeability as that assumed for the floor, but its greater thickness implies that it would be less transmissive than the floor of the drifts and panels. Furthermore, arching stresses over the repository openings are likely to close fractures, reducing permeability while tensile stresses in the repository floor related to floor heave will tend to preserve transmissivity.

The changes to the DRZ conceptual model include the assumptions supporting the range of permeability values and the change in the geometry of flow from the 12 meter overhead DRZ to the 1 to 2 meter long flowpath, through the repository floor and into the fractured anhydrite of Interbed #139.

3.3.2.2 Validity of Assumptions

Assumptions used in developing the proposed changes to the DRZ conceptual model are of two kinds. The values for the permeability of the DRZ have evolved over two iterations of performance assessment. In the first performance assessment (CCA, 1996) the permeability of the thick, overhead DRZ contained in that conceptual model was a

"conservative" value assumed to permit communication between repository openings and the upper Interbed #138. The chosen value was assumed to permit free drainage of brine from the interbed into the repository and to permit gas to escape from the repository to the interbed. The permeability chosen was an intermediate single value between perceived extremes implied by the material properties of the interbed and pure halite. For the PAVT sensitivity study a range of permeability was necessary to permit sampling and development of distributions to better represent flow through this complex zone. The end members of the distribution represent the measured permeability of the fractured anhydrite interbeds and the estimated permeability of "tight" halite. Pure halite, disturbed only by very small and slow strain resulting from creep into the repository beyond the DRZ, is probably a reasonable representation of well-healed halite after the disappearance of the DRZ due to back-stress around seals or after the closure of repository open spaces. As such, these end members are reasonable limits to the permeability of the DRZ. The permeability range used in the PAVT calculations ($10^{-12.4}$m to $10^{-19.5}$m) represent reasonable parameters between the end member conditions.

Changes in the geometry of flow in the DRZ represents the second kind of assumption. The basis of this assumption is that gas flow out of the repository panels will follow the path of least resistance or the path of greatest transmissivity. The short distance (approximately one meter) between the repository floor and Interbed #139 represents a much lower resistance to flow than upward flow through 12 meters of halite that is horizontally compressed by arching stresses over the repository openings. Floor heave implies an extensional stress environment in the floor. This extensional stress and gas pressures may also help to keep the fractures in both the halite in the repository floor and in the anhydrite interbed open. The large storage space represented by the well connected fracture porosity of the interbed may provide for retention of gas and brine expelled from the repository via this flowpath.

The assumptions contained in the changes to the DRZ conceptual model are reasonable to represent repository materials, flow geometry, and system properties. The permeability range used to generate the sampled distributions that will be used in performance

assessment is based on permeability of materials similar to those in the disturbed rock zone in comparable geomechanical environments. The geometry of flow follows principles of hydraulics that are appropriate to the repository structure, stress environment, and material properties.

3.3.2.3 Alternate Interpretations

The proposed changes to the DRZ conceptual model follow two earlier iterations of the model. These earlier iterations include a full performance assessment (CCA) and a sensitivity study (PAVT) that represent alternative models that have received more detailed consideration than is usual in alternative concept evaluation. The CCA iteration was fully peer reviewed. The changes proposed to the model represent reasonable development of the earlier alternatives. The changes to the model are supported in part by recent calculations, geophysical and hydrologic measurements in the repository floor (Bryan, et al, 2001, Beauheim, 2002, Holcomb, 2001). Future alternative models of the disturbed rock zone at the WIPP, based on measured hydrologic and rock mechanical models, may be developed but are not feasible at this time.

3.3.2.4 Uncertainty of Results and Consequences if Wrong

The uncertainty of results in the changed conceptual model lie mostly in the range of porosity used to represent the flow properties of the rock along the flowpath proposed. The geometry of the flowpath is not a great source of uncertainty, in that it is the most reasonable path of least resistance for gas flow and its dimensions and material properties are well known. The range of porosity proposed as bounds of the properties of the rock through which flow will take place are reasonable. The range is supported by measured values and it will be sampled and represented by a CCDF, which is a reasonable analytical approach. Exceeding of the upper limit of the permeability range due to creep damage would allow gas to migrate from the repository more easily and reduce gas pressure. Ultimately, gas pressures depend on permeability in the anhydrite interbed where storage of gas will take place at distances from the repository far enough to be less damaged by creep. The impact of the uncertainty in the conceptual model is that the gas

pressure in the repository might be lower than predicted by modeling, a conservative influence on performance.

3.3.2.5 Appropriateness and Limitations of Methodology and Procedures

The methods and procedures used in the changed model are refinements of the previous models and will generate representative results in PA. Constituative models based on measurement of the influence of creep damage on hydrologic properties may be feasible in the future, but such models are not expected to indicate that the changed model has failed to conservatively bound repository performance. The methods and procedures are appropriate to the present state of information and the needs of PA.

3.3.2.6 Adequacy of Application

Adequacy of application of the changed model cannot be assessed at this time. At the time of the next total system PA, the impact of the changed conceptual model should be considered in comparison with the earlier iterations of the model and in terms of the impact on the overall results of PA.

3.3.2.7 Accuracy of Calculations

No new calculations are contained in the changes to the DRZ conceptual model. Confirmation of the accuracy of calculations that are part of the implementation of the conceptual model in PA should be made following the next total system PA.

3.3.2.8 Validity of Conclusions

Validity of conclusions drawn from the application of the changed DRZ conceptual model in performance assessment is the same as for those drawn from the previous iterations of the model so long as the adequacy of application and the accuracy of calculations are concluded to be appropriate. The general structure of the conceptual model was peer reviewed during the CCA and the changes to the details of flowpath and the definition of porosity appear to be valid. Unless the PA calculation indicates that the

changed model causes unreasonable changes to the predicted performance of the repository, particularly with reference to repository gas pressure, the conclusions drawn using the changed conceptual model should remain valid.

3.3.2.9 Adequacy for Implementation

3.3.2.9.1 General

Adequacy for implementation cannot be judged without the total system PA and the CCDFs.

3.3.2.9.2 Conditional Adequacy of The Changed DRZ Model and Requirements for Final Review

The changes to the DRZ conceptual model consist of the addition of a range of permeability values for the materials along the flowpath through the disturbed rock zone, and a change in the geometry of the flowpath from flow through Interbed #138 above the repository to flow through Interbed #139 below the repository. This latter change was called an "addition of a fracture model" in some of the review documents. This change is a change in flowpath length and routes flow through a different stress environment, but does not constitute a new constituative fracture model. The changed model is reasonable and its conceptual structure implies a useful definition of rock permeability and a realistic flow path in the conceptual modeling of performance of the repository. The changes are reasonable in magnitude and sense. However, because no PA has been performed since the model changes were proposed, adequacy of application and accuracy of calculations cannot be fully assessed.

The changed DRZ conceptual model is found to be conditionally adequate. The model must be shown to satisfy review criteria for adequacy of application and accuracy of calculations for the conditional status to be removed. In addition, the impact of the changed model must be shown to be reasonable on the modeling of repository fluid flow and on the modeling of the performance of the Option "D" panel closure design if that

closure system is chosen. Specifically, the impact of the changed DRZ conceptual model in modeling of pressure equilibration among repository openings in the case of intrusion must be shown to be reasonable and its impact on direct brine release and spallings release scenarios examined.

3.3.2.10 Impact of the Disturbed Rock Zone Model on Closure Performance

The relevance of the Disturbed Rock Zone conceptual model to the modeling of closure performance is limited to the application of disturbed rock zone flow parameters to, through, and from the interbed below the repository floor. It is also related to modeling the equilibration of gas pressure between repository spaces after intrusion. The changed model would be useful in defining flow between Interbed #139 and repository open spaces on either side of the closure. This gas pressure equilibrium conceptual model bears on the spalling and direct brine release scenarios as well as the Repository Fluid Flow conceptual model. These interactions should be evaluated following the next total system PA.

3.3.2.11 Dissenting Views

There were no dissenting views for this model.

4.0 Integration of Conceptual Models in Performance Assessment

4.1 Model Integration

Figure 4-1 is a simplified illustration in which selected conceptual models represent a system or subsystem within the CCA, PA code sequence. BRAGFLO DBR, as illustrated, is a special, short-term application of BRAGFLO related to a drilling intrusion and includes all conceptual model system representations listed under BRAGFLO plus the Direct Brine Release model. The direct brine release element illustrates that the calculated brine volume removed from the repository by a drilling intrusion is input directly to the CCDFGF.

Figure 4-1. Illustration of Conceptual Model Integration

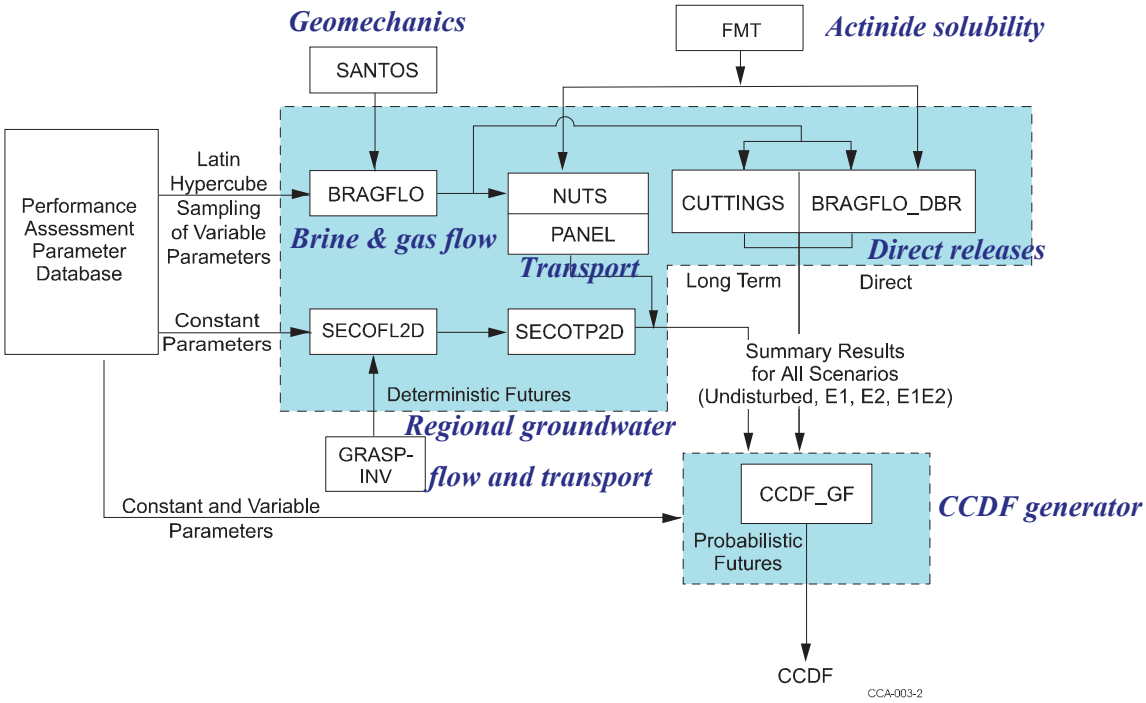

As shown in figure 4-1, the conceptual models do not all represent a system or sub-systems in the same place in the code sequence. Figure 4-1 illustrates that the conceptual models, as interpreted through the various codes, are ultimately integrated at the CCDFGF where results are prepared. The figure ignores many preparatory and post-process codes and relationships between codes that are not linear and in a single direction. For example, while SANTOS is related to BRAGFLO and receives system representation from the Creep Closure conceptual model, creep closure results from an iterative relationship between gas pressure, compaction, and brine characterizations from BRAGFLO and the porosity surface in SANTOS. The integration of the conceptual models, therefore, identifies the overall WIPP PA model as a complex structure that represents 24 conceptual models through preparatory, process, flow, and transport presentation and enabling codes.

4.2 Review of Criteria

Applying evaluation criteria to the integration of conceptual models as a step in the assessment of model adequacy results in most of the discussion being summations of the individual conceptual model evaluations. For example, evaluations of information used in the integration, assumptions, uncertainties, adequacies, accuracy, and validity are all based on the individual conceptual models or the implementing mathematical representations or codes. The criteria have been discussed in Section 3.0 for the three conceptual models reviewed. Without results of realizations, sensitivity analyses, and/or uncertainty analyses for the overall system and sub-systems, conclusions cannot be made with respect to the implementing mathematics or codes.

Because the overall total system PA was not available for Panel review, the overall adequacy for implementation of the integrated conceptual models can only be judged at this time through the adequacy of the three individual conceptual models as discussed in Section 3. There is insufficient information, i.e., total system PA and CCDFs are required, for the implementing structure (model integration, mathematical representations, codes, code sequence) to be judged adequate or inadequate.

5.0 Summary of Evaluations

This section presents a summary of the evaluations of the WIPP Conceptual Models Peer Review Panel performed between April 29, 2002 and May 31, 2002. Over twenty years of scientific effort have been expended on WIPP site characterization and there have been approximately three years of successful operational experience. It is beyond the scope of this report to summarize all of the positive factors and scientific evidence compiled concerning the WIPP site. This section is not intended to be a reiteration of comments and discussions on the individual conceptual models but to provide an overview of conclusions from the evaluations. The Panel's evaluations were made as a best effort without the benefit of the models being exercised as part of a total system PA.

The list of the twenty-four WIPP conceptual models is provided in the Table 4-1 with the three models reviewed during this peer review bolded so as to put them in the context of the total system modeling effort.

Disposal System Geometry

The TBM changes in the Disposal System Geometry conceptual model retain the adequate structure of the original conceptual model and the grid changes appear reasonable and sound. The proposed implementation of the changes appears reasonable, but the impacts of the changes and overall representativeness of the changes in the model cannot be assessed at this time. A total system PA is needed to compare the previous CCA results to the results associated with the TBM changes.

Repository Fluid Flow

The conceptual model itself has been determined to be both reasonable and adequate for its intended purpose. The identified changes (shaft removal, EPA mandated parameters, cellulosic molecular structure) appear reasonable and are expected to have minimal impact on the Repository Fluid Flow conceptual model. However, to understand the interaction of this conceptual model with the Option “D” Panel closure (and subsequent

gas pressure realizations in waste panels); and the influence the model may have when coupled with the other conceptual models requires review of total system PA results.

Disturbed Rock Zone

Two changes to the DRZ conceptual model have the potential to impact PA. These are the adoption of a range of limiting porosity values for the halite and anhydrite layers in which the disturbed rock zone is developed; and the definition of the flow path through the floor of the repository openings into Interbed #139. These appear to be reasonable changes to the model, which make it more representative of the repository processes and are based on measurements of material properties and on measured damaged rock zone processes. The impacts of these changes and the accuracy of model calculations used in their implementation cannot be evaluated until the total system PA can be reviewed.

Table 4-1. WIPP Conceptual Models

Disposal System Geometry	**Addressed During This Peer Review**
Culebra Hydrogeology	Not Addressed During This Peer Review
Repository Fluid Flow	**Addressed During This Peer Review**
Salado	Not Addressed During This Peer Review
Impure Halite	Not Addressed During This Peer Review
Salado Interbeds	Not Addressed During This Peer Review
Disturbed Rock Zone	**Addressed During This Peer Review**
Actinide Transport in the Salado	Not Addressed During This Peer Review
Units Above the Salado	Not Addressed During This Peer Review
Transport of Dissolved Actinides in the Culebra	Not Addressed During This Peer Review
Transport of Colloidal Actinides in the Culebra	Not Addressed During This Peer Review
Exploration Boreholes	Not Addressed During This Peer Review
Cuttings/Cavings	Not Addressed During This Peer Review
Spallings	Not Addressed During This Peer Review
Direct Brine Release	Not Addressed During This Peer Review
Castile and Brine Reservoir	Not Addressed During This Peer Review
Multiple Intrusions	Not Addressed During This Peer Review
Climate Change	Not Addressed During This Peer Review
Creep Closure	Not Addressed During This Peer Review
Shafts and Shaft Seals	Not Addressed During This Peer Review
Gas Generation	Not Addressed During This Peer Review
Chemical Conditions	Not Addressed During This Peer Review
Dissolved Actinide Source Term	Not Addressed During This Peer Review
Colloidal Actinide Source Term	Not Addressed During This Peer Review

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Appendix A - Panel Member Technical Qualifications

Florie Caporuscio

Los Alamos National Laboratory

- Environmental Restoration - developed criteria for and wrote portions of two-site characterization Work Plans (Los Alamos Pueblo Canyon, Canyon Core Document).
- Project Manager to characterize Omega West Reactor leak.
- Developed radiometric survey technique to investigate radionuclide transport (Pu, Cs, Sr) by geomorphic processes in Los Alamos Canyons.
- Investigated Sr transport in aqueous media in Los Alamos Canyon.
- Peer reviews of Performance Assessment of Material Disposal Area (MDA) G at TA-54, Los Alamos National Laboratory.
- Co-author of MDA Performance Assessment Core Document for Environmental Restoration Projects at LANL.

WIPP

- Final Peer Review for License Application Conceptual Models
- Peer Review Member – Natural Barriers

Environmental Protection Agency

- Principal Investigator evaluating effects of U, Th, Ra contamination and transport through geologic media at CERCLA and FUSRAP sites.
- Section Chief of US EPA WIPP Technical Review Program. Supervised review of Test and Retrieval Plan.
- EPA Principal Investigator for Gas Generation and Source Team models at WIPP (ORIA).

Pertinent Research/Other

- Oxidation of Fe oxides - characterization of oxidation state of 24,000 feet of ash flow core on Yucca Mountain.
- Determination of Fe oxidation state for paleomagnetic studies at Yucca Mountain.

- Empirical determination of Hematite-Ilmenite solvus with field samples.
- Crystal chemical studies of radioactive elements in crystal structures of mineral phases.
- Technical reviewer for *American Mineralogist* (1988-1989)

John Gibbons

Over thirty years of experience in the geology and mine mechanics of salt deposits, including New York, New Mexico, Texas, and Kansas bedded salts and domed salts in Louisiana and Texas.

Yucca Mountain Project

Preparation of site suitability documents for presidential consideration, data qualification and integration for the federal high-level nuclear waste disposal site at Nevada

WIPP

Review of conceptual models and engineered barriers models for PA in support of license application. Review of data packages for PA in support of license application.

Illinois Department of Nuclear Safety

As a principal consultant:

- Detailed review of conceptual models (hydrogeologic and site character) and integration with the MODFLOW numerical flow model. Included radionuclide transport models and the site performance assessment model for Martinsville Illinois site.
- Developed site search models for hydrogeology and seismic ground motion for a second site.
- Developed conceptual model for vertical hydrologic flow through overconsolidated, fractured glacial till.
- Developed integration plan for site characterization through performance assessment of new site including applications of STRATAMODEL three-dimensional site model and model-based tests of site hydrologic characterization adequacy.

Applied Research Associates

Principal investigator for a DOE research committee funded study to develop a model-driven site characterization technology, which integrated geophysical (down-hole and surface), cone penetrometer and borehole data acquisition systems.

Senior hydrogeologist in support to Sandia National Laboratory in development of hydrostratigraphy conceptual model of Yucca Mountain High Level Nuclear Waste Repository Site.

Dames and Moore

As a principal investigator, did proposal preparation and was project liaison to the Federal High Level Nuclear Waste Program. Site characterization planning and model integration were principal areas of technical responsibility.

E. B. Oswald

Design of Conceptual Models/Structures

- University of Arizona, Department of Hydrology and Water Resources, Dissertation, 1976. Designed a conceptual model with which to assess the socioeconomic impacts of coal-fueled power generating facilities on Native Americans in the Four Corners region of the Southwest. The conceptual model related critical social, economic and cultural parameters of Native American systems to natural resource use, economic and environmental effects and power plant location and operation phenomenon. The conceptual model was implemented through a mathematical simulation technique.
- Designed conceptual models (assumptions, structures and relationships) for evaluating the impacts of FWPCA, Section 208, non-point pollution control practices on land and surface water quality. As part of a policy analysis project under USDA, Economic Research Service, the models were published in internal, peer-reviewed working papers (1977-1984).
- Assisted in the design of the conceptual models and implementation of the mathematical realizations of a linked system of linear programs and a finite difference representation of the Navajo sandstone aquifer. The linked LPs were designed to evaluate the regional impact of power generation grid distribution and the ground water model was built to estimate the impacts of commercial water withdrawals on local wells. The modeling was done under a contract with the Ford Foundation through the University of Arizona, Department of Hydrology and Water Resources (1976-1977).
- Montana DNRC, 1995. Developed the conceptual model for evaluating the effects of high TDS water from coal mine pit discharges to the Tongue River and reservoir system.
- Montana DNRC and U.S. Bureau of Reclamation, 1994. Designed the conceptual model(s) for evaluating the impacts of increased reservoir depth and area on alluvial ground water quality and storage and shoreline erosion.

- Designed the conceptual model for evaluating water use and disposal systems at remote Missile Launch Control Facilities, Malmstrom AFB, and Montana. The model considered the timing of water use, percolation and infiltration capacities, evapotranspiration and climatic influences and resulting short and long term potential for water balance. This 1995 project was in response to recent EPA guidelines governing remote water systems.
- Montana DEQ. Currently involved in conceptualizing a model or framework for evaluating the utility and stability of post-mining reclamation. The model will involve the characterization of future land use scenarios and the assessment of economic, aesthetic, recreational, surface environmental and alluvial ground water impacts of the scenarios.

Model Operation, Application

- Operated a regional linear program-based model designed to optimize the interplay of agricultural/silvicultural production systems with imposed pollution control practices. Published as part of the USDA, Columbia River Basin Project Report, 1980-1983, Portland, Oregon.
- University of Arizona, Department of Hydrology and Water Resources, 1975. Operated a stochastic, dynamic programming model with an application to a multi-year (50 years) multi-stage water supply reservoir operation system.
- Montana, DNRC, U.S. Bureau of Reclamation, 1994. Application of MODFLOW software to an evaluation of alluvial water withdrawals and the impacts of alternative rates on surface stream flow. At issue was the volume of ground water available for consumptive use without diminishing local stream flows.
- Oregon Department of Environmental Quality, published as USDA Working Paper, ERS Working Paper Series. Design and application of a riparian habitat model to estimate the effects of various agricultural, silvicultural and mining practices on riparian zones and the aquatic and terrestrial habitats included.
- Montana DEQ, U.S. Army Corps of Engineers, 1996. Responsible for review of geochemical, limnological and mixing zone models used to predict water quality in a pit lake, the Blackfoot River and the alluvial ground water resulting from

proposed gold mine operations. The results and interpretations of the model reviews will be presented in an EIS.

- USDA, EPA, Corvallis, Oregon, 1983. Conducted review of alternative models for evaluating chemical and erosional impacts to the ground water and surface streams associated with FWPCA, Section 208 and RCWP practices. The CREAMS model developed by USDA, ARS was adopted for use.
- Reviewed and evaluated various modeling approaches to be applied to the Agricultural/Rural environment system characterized by a project area in Austria. The review and model review was conducted at the IIASA, Laxenburg, Austria during a joint effort by Russian, Austrian and U.S. scientists.
- RCRA, RFI, Malmstrom AFB, Montana. HDR Engineering, 1993. Review and evaluation of proposed deep and shallow aquifer models proposed to characterize potential containment migration.
- Final Peer Review for License Application; Conceptual Models, WIPP, 1996-1997.

Data and Models

- As project operations manager, principal hydrologist and corporate QA manager, I routinely review the raw data and data presented in environmental sampling reports. Included in the reviews are 'cursory' data validation (traceability, achieving QA goals, etc.) as well as how the data can be interpreted, statistically or otherwise.
- Compliance Certification Model Data Review and Certification WIPP, 1995-1996.
- The data reviews and QA reviews routinely lead to conceptual models of contaminant migration route; rate and the conceptual models are used to propose more extensive and/or confirmatory sampling and data collection.
- As applied science manager working on the Rocky Mountain Arsenal and CERCLA projects manager for EPA's TESIV, project data review (QA and statistical) and interpretation of data for intended uses were routine activities. Krieging and other techniques were applied to interpret data spatially, illustrate

data gaps and needs and make decisions on the appropriateness of RFI and RIFS data for proceeding with remedial action.

Appendix B

Determinations of Peer Review Member Independence

Appendix C

Certifications Regarding Organizational Conflicts of Interest

I have reviewed each of the selected peer review panel member's (Florie Caporuscio, John Gibbons, and Eric Oswald) backgrounds and employment histories. I have also interviewed each of them to determine if they have an organizational conflict of interest or a bias for or against the WIPP facility as a nuclear waste repository. Though these background investigations and interviews I have determined that none of the selected peer review panel members has an organizational conflict of interest related to the Salado Flow Conceptual Models Peer Review.

_____

John A. Thies,
Peer Review Manager

WASTE ISOLATION PILOT PLANT

SALADO FLOW CONCEPTUAL MODELS FINAL PEER REVIEW REPORT

A Peer Review

Conducted By

Florie Caporuscio, Ph.D.

John Gibbons, Ph.D.

Chunhong Li, Ph.D.

Eric Oswald, Ph.D.

for the

U.S. Department of Energy

Carlsbad Area Office

Office of Regulatory Compliance

March 2003

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Executive Summary

The Waste Isolation Pilot Plant (WIPP) site has been developed near Carlsbad, New Mexico, by the Department of Energy (DOE) as the United States' first underground repository licensed to safely and permanently dispose of transuranic radioactive waste resulting from the research and production of nuclear weapons programs. The first shipment of transuranic waste arrived at WIPP on April 6, 1999.

Peer review of conceptual models developed by the DOE for the WIPP is required by 40 CFR Part 194.27, which was promulgated by the Environmental Protection Agency (EPA) in 1996. In accordance with this requirement, the Carlsbad Field Office (CBFO) of the DOE has conducted a peer review of three conceptual models that are being revised due to changes invoked by the regulator or due to knowledge gained since the original conceptual models were developed. This peer review addressed revisions to selected salado flow conceptual models that were developed for the Compliance Certification Application (CCA).

This report presents the final results of an independent technical peer review of the adequacy of three of the twenty-four conceptual models representing features, processes, and events involved in assessing the long-term performance of the WIPP. These models were identified by the DOE through its scientific advisor, Sandia National Laboratories (SNL).

This independent peer review was conducted by a four-member interdisciplinary team having the requisite broad experience and expertise to address the range of issues associated with the ability of WIPP to successfully isolate waste for the 10,000-year regulatory time frame. The peer review was conducted primarily in Carlsbad, New Mexico, at the SNL Carlsbad offices. The peer review panel was given access to conceptual model descriptions, scientific reports, briefings, SNL staff, and to the SNL Nuclear Waste Management Program Library. The Panel also had access to reports of prior peer reviews and was given the full cooperation of the DOE and SNL throughout

the review. Representatives of the EPA, DOE, and the New Mexico Environmental Evaluation Group (EEG) observed the SNL technical presentations and the Panel's questions and deliberations.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical processes, or intrusion scenarios are to be represented in performance assessment (PA). To be used in PA, a conceptual model must be successfully translated into analytical statements and mathematical analogs. The Panel reviewed the three conceptual models of interest in detail, including the assumptions and scientific information used to develop the model, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The Panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall WIPP PA. The review process and review criteria are discussed in Section 2.

The changed models were reviewed in the context of the WIPP PA. The review did include an assessment of the reasonableness of changes in performance estimates resulting from changes in parameter ranges and in changes to, or resulting from, single values. The review evaluated changes in the conceptual structure of the models and changes in component process models and compared the performance results of the changed models with the results of the earlier models to confirm that the changes in performance estimates are reasonable in sense and magnitude. Changes in computations or in fundamental model aspects, such as gridding were also considered. The review considered the impacts of the changed models on the other WIPP conceptual models and related issues such as the Option "D" panel closures.

The Panel has applied the stringent assessment criteria provided in NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories*, and has concluded:

- The changes to the three conceptual models appear generally sound in their structure, reasonableness, and relationship to the original models.

- The proposed implementation of the three changed models appears reasonable. Impacts of the changes have been reviewed and the data from selected gas pressure and brine saturation scenarios in performance assessment indicates an acceptable comparison of new results to the prior CCA results.

- Implementation of the three changed models and their interactions with the other models appears reasonable.

1.0 Introduction

Peer review of conceptual models developed by the Department of Energy (DOE) for the Waste Isolation Pilot Plant (WIPP) is required by 40 CFR Part 194.27, which was promulgated by the Environmental Protection Agency (EPA) in 1996. In accordance with this criterion, the Carlsbad Field Office (CBFO) of the DOE has conducted a peer review of three conceptual models that are being revised due to changes invoked by the regulator or due to knowledge gained since the original conceptual models were developed. This peer review has addressed whether revisions to selected salado flow conceptual models that were developed for the Compliance Certification Application (CCA) continue to reasonably represent the WIPP waste disposal system.

Sandia National Laboratories (SNL) is responsible for the development, maintenance, and conduct of WIPP performance assessment (PA). As part of the PA methodology included in the CCA, the DOE identified processes important to the WIPP waste isolation system and developed conceptual models that describe the features, events, and processes relevant to the disposal system and subsystems. These conceptual models were peer reviewed and the results were approved by the EPA during the original WIPP certification (EPA, 1998). Any proposed significant changes to the previously approved conceptual models are being peer reviewed to ensure that the disposal system, subsystems, and future state assumptions continue to be adequately represented.

Twenty-four conceptual models are used in the WIPP PA. The proposed changes associated with Salado flow processes are expected to affect the following models:

- Disposal System Geometry,
- Repository Fluid Flow, and
- Disturbed Rock Zone (DRZ).

The peer review process is a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. The peer reviewers are independent of the work being reviewed, i.e., the peer reviewers: a) have not been involved as participants, supervisors, technical reviewers, or advisors

involved with the work being reviewed, and b) to the extent practical, have sufficient freedom from funding considerations to ensure the work is impartially reviewed. Therefore, the peer-reviewed subject matter provides additional assurance to the regulator and the public that the subject matter is reasonable, accurate, and valid for its intended use.

This peer review meets the regulatory requirements of 40 CFR Part 191 and the implementation of those requirements by 40 CFR Part 194. This peer review was conducted in accordance with the Nuclear Regulatory Commission's NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories*. The adequacy criteria set forth in NUREG-1297 were those used by the peer review panel for reviewing the three conceptual models. The Peer Review Panel followed the DOE CBFO Management Procedure MP-10.5, *Peer Review*, to perform the peer review.

This report documents the results of the subject peer review. Section 2 of this report details background information relating to the WIPP facility and the review methodology which includes a description of the repository, its geologic and hydrogeologic settings, the review methodology, and the evaluation criteria. Section 3 presents an evaluation of each of the three models. Each model was assessed against the predetermined evaluation criteria. Section 4 discusses the integration of the peer reviewed models with the other models used in the overall WIPP waste disposal system PA. Section 5 provides a summary of the evaluations. These sections are followed by appendices that include administrative information and professional biographies for each of the peer review panel members.

2.0 Background

The DOE was authorized in 1979 (Public Law 96-164) and funded by the Congress to develop a facility for demonstrating the safe disposal of transuranic (TRU) radioactive wastes resulting from national defense activities. The Land Withdrawal Act of 1992 (Public Law 102-579) provided additional authorization to continue the project under a stipulated statutory process. With more than 20 years of scientific investigation, public input, and regulatory oversight, the WIPP facility became the first underground repository licensed to safely and permanently dispose of transuranic radioactive waste from the research and production of nuclear weapons. The first shipment of transuranic waste arrived at WIPP on April 6, 1999.

2.1 WIPP Overview

The WIPP facility has been constructed in southeastern New Mexico 26 miles east of Carlsbad, on land owned by the Federal Government. Prior to October 1992, this land was administered by the U.S. Department of the Interior, Bureau of Land Management. In October 1992, Congress transferred jurisdiction of the land through the Land Withdrawal Act to the Secretary of Energy. The site encompasses 10,240 acres in a sparsely populated area, with fewer than 30 people living within 10 miles of the WIPP site. The immediate surrounding land is used for livestock grazing, potash mining, and oil and gas production.

Surface structures and the underground repository make up the WIPP facility. The purpose of the surface structures is to provide security and safeguards and to accommodate routine operations, administrative activities, and support further scientific studies.

The underground excavation is 655 meters (2150 feet) below the surface in the bedded salt of the Salado Formation. The underground excavation includes a 12-acre area used for conducting scientific investigations and experiments in which no waste will be placed, an operations area with equipment and maintenance facilities; an area in which

the waste is emplaced for permanent disposal; and four major interconnecting tunnels that are used for ventilation and traffic. The subsurface waste-disposal area is planned to cover approximately 100 acres and will contain eight separately excavated panels, each containing seven disposal rooms, and two equivalent panels.

2.2 Peer Review Management

This Salado Flow Conceptual Models Peer Review is an independent review sponsored by the DOE CBFO and delegated to its technical assistance contractor, known as the Carlsbad Technical Assistance Contractor (CTAC). The CTAC appointed Mr. John Thies as the peer review manager.

Early in the peer review process Mr. Thies appointed a technical panel chairperson, John Gibbons, Ph.D., from among the peer review panel members to serve as the technical leader for the peer review and to lead technical development of the peer review report.

The selection and training of the peer review panel members and operation of the review process were governed by DOE CBFO's Management Procedure MP-10.5, *Peer Review*, and the salado flow conceptual models peer review plan. Detailed information regarding the review process is further delineated in this document and in the peer review records.

Twenty-four conceptual models are used in the WIPP PA. This peer review addressed only the proposed changes associated with salado flow processes expected to affect the following three models:

- Disposal System Geometry,
- Repository Fluid Flow, and
- Disturbed Rock Zone (DRZ).

2.3 System Overview

The WIPP disposal system includes the underground repository and shaft system, the geologic host rock, and the local and regional hydrologic system. Figure 2-1 shows the WIPP controlled area, the accessible environment, and the disposal unit boundary.

Figure 2-1 - WIPP Controlled Area

2.3.1 Repository Setting

The WIPP surface facilities, shafts, and underground workings are shown in Figure 2-2. The WIPP repository includes four shafts (exhaust shaft, waste shaft, salt handling shaft, and air intake shaft), an experimental area, an operations area, and a waste disposal area.

Figure 2-2 - WIPP Facilities

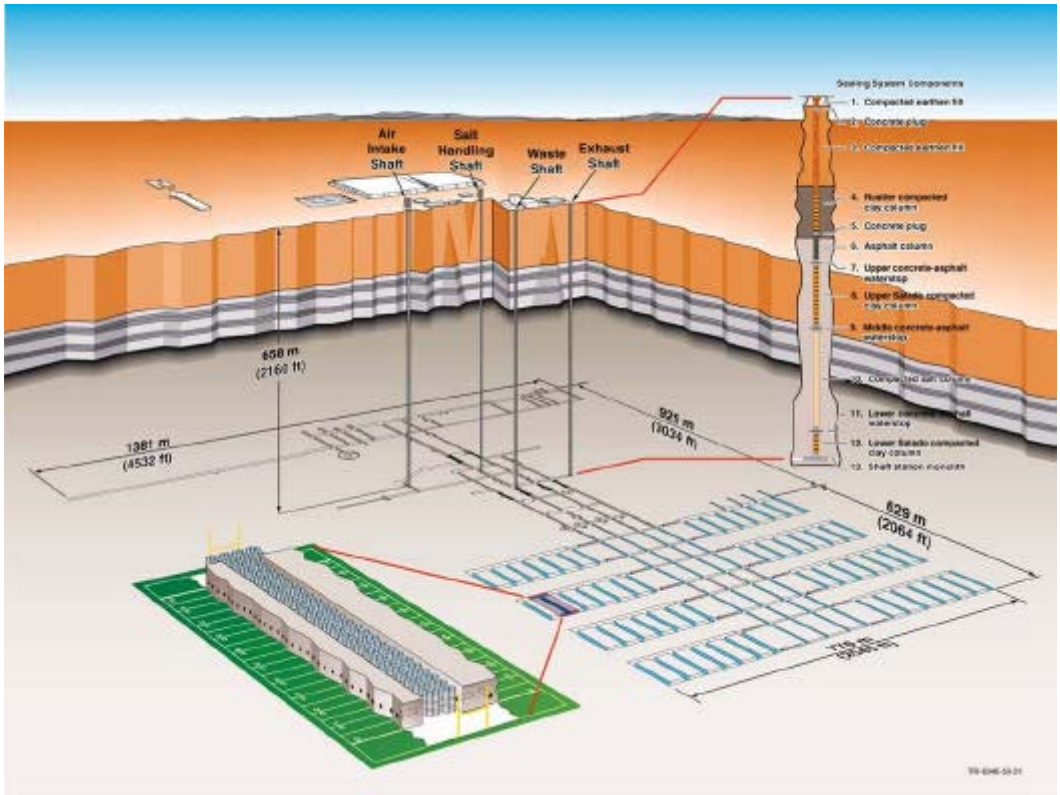

Present plans call for mining eight panels of seven rooms each and two equivalent panels in the central drifts. As each panel is filled with waste, the next panel will be mined. Before the repository is closed permanently, each panel will be closed. Waste will be placed in the drifts between the panels creating two additional panel volumes and access ways will be sealed off from the shafts. The shafts will then be sealed to isolate the repository from the ground surface. Final closure of the facility will be facilitated by creep closure of the salt.

When considering future intrusion scenarios, the DOE used the following EPA assumptions regarding future penetration of the repository:

- The regulatory time frame begins at the beginning of disposal and ends 10,000 years after disposal;
- Exploratory drilling may potentially affect the repository;
- Exploratory drilling is inadvertent and intermittent;
- Drilling events occur at random intervals; and
- Future drilling rates will be the same as the rates of deep drilling in the area over the past 100 years.

2.3.2 Geologic Setting

The geologic history of southeastern New Mexico and the data collected regarding the subsurface stratigraphy at the WIPP site are important and are discussed extensively in Section 2 of the CCA and documents referenced in the CCA. The general stratigraphy at the WIPP site is presented in Figure 2-3.

The sandstones, siltstones, limestones, and shales of the Bell Canyon Formation define the first extensive, continuous, transmissive unit below the WIPP repository and provide a source of groundwater that could migrate vertically into the repository. The halite and anhydrite beds of the Castile Formation separate the Bell Canyon from the Salado and contain pressurized brine reservoirs. The brine reservoirs are a repository performance concern expressed through human intrusion scenarios. The halite-dominated Salado Formation contains the proposed repository and provides the primary natural barrier for containing radionuclides. The laterally extensive Culebra Dolomite Member of the Rustler Formation is the closest stratigraphic unit above the Salado with the potential to transport a radionuclide release to the accessible environment. Studies conclude that transmissivities in the Culebra vary by six orders of magnitude across the WIPP site area. Fracturing and vuggy zones account for much of the variability in the physical hydraulic properties of the Culebra.

Figure 2-3 - *General Stratigraphy at the WIPP Site*

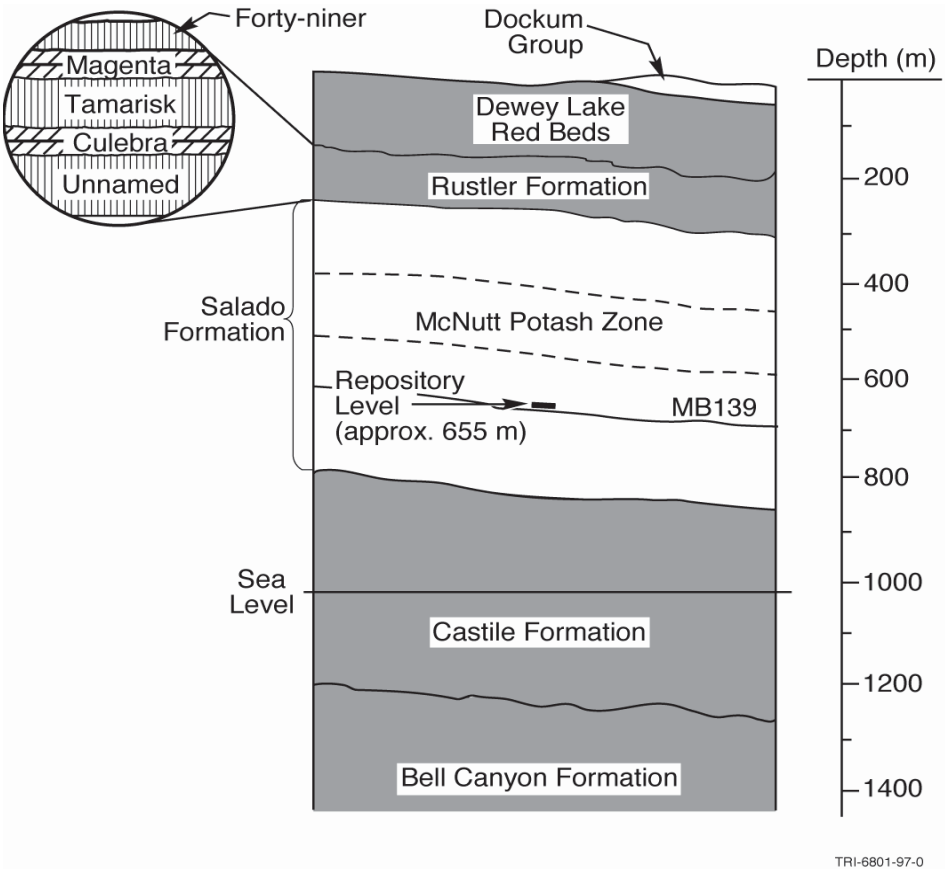

While other stratigraphic members of the Rustler Formation, beds of anhydrite and polyhalite, clays, and other inclusions may be important as each of the conceptual models is reviewed, the four formations and units described above define the most important components of the geologic setting for the WIPP conceptual models review.

2.3.3 Hydrologic Setting

2.3.3.1 Surface Water

The WIPP site is located within the Pecos River Basin. At its nearest point, the Pecos River flows approximately 12 miles southwest of the WIPP site boundary. There are no perennial streams at the WIPP site and in this semi-arid region, approximately 75 percent of annual precipitation results from intense, short-duration events between April and

September. More than 90 percent of the mean annual precipitation is lost through evapotranspiration and on a mean annual basis, evapotranspiration potential exceeds expected rainfall. The EPA concluded in 1989 that there were "no surface water features near the WIPP that could potentially affect repository performance in such a way as to influence the no-migration demonstration."

2.3.3.2 Groundwater

Extensive coring, logging and testing of boreholes in the vicinity of the WIPP site has provided data for the characterization of the hydrostratigraphy important to the WIPP site region. While the deep Capitan Limestone, the Rustler-Salado contact zone near Nash Draw, and the shallower Dewey Lakes and Santa Rosa Formations are important in characterizing the WIPP region; the Bell Canyon, Castile, Salado, and Rustler Formations are the units critical to the evaluation of WIPP groundwater issues.

As presented in the geologic setting, the Bell Canyon Formation is the first continuous, transmissive water-bearing unit beneath the WIPP. This formation provides a source of non-potable ground water below the WIPP repository that could migrate into the repository if a pathway were available. The Bell Canyon Formation exhibits hydraulic conductivities in the range of 10^{-7} to 10^{-12} meters per second and pressures were measured in the range of 12.6 to 13.3 megapascals.

The Castile Formation is of interest to site characterization as a hydrologic barrier between the Salado and Bell Canyon Formations because it contains isolated pressurized brine reservoirs. The Castile is predominantly low-permeability halite and anhydrite with greater permeabilities in zones of fracture and structural deformation. In the areas of higher permeability brine pressures may exist that are sufficiently above nominal hydrostatic pressure for brine to flow upward through a borehole potentially reaching the surface.

The halite and anhydrite rocks of the Salado Formation are relatively impermeable and tests have shown that flows are extremely low to no flow when appreciable pressure

gradients are applied. The Salado contains the repository and provides the primary natural barrier for containing radionuclides.

The Magenta and Culebra Dolomite Members of the Rustler Formation are laterally extensive, transmissive, and display hydraulic characteristics sufficient for the lateral transport of radionuclides. Hydraulic conductivities in both members range over five to six orders of magnitude in the WIPP area but the Magenta is generally less transmissive than the Culebra. The Culebra is the most extensive and most transmissive unit above the Salado at the WIPP site. As such, the Culebra provides the most direct groundwater pathway from the WIPP repository to the accessible environment and is the most important component of the hydrogeologic setting for the conceptual models peer review.

2.3.4 Implementation of the "Option D" Panel Closure

The option "D" panel closure is a semispherical concrete closure to be emplaced in drifts and panel exits at several positions throughout the repository. The closure will be emplaced in an enlargement of the drift that will remove some material above the drift and all of the halite and the Interbed #139 below the drift floor. It is presumed that the closure will extend into the ribs of the drift a distance sufficient to remove most of the DRZ in that direction. Back-stress resulting from creep flow in the Salado halite into the repository will immediately begin to heal damage around the closure that may result from construction excavation. It is not expected that the closure will entirely block gas flow in Interbed #139 or the overlaying interbeds, since flow around the closure is not prevented at high gas pressures. Upward gas flow from Interbed #139 into the drift beyond the closure is a possible scenario for bypassing the closure. Rapid gas pressure fluctuations, as in the case of an intrusion into a single panel at a time of high overall repository gas pressures, would be significantly damped in adjacent unintruded repository spaces, but not entirely eliminated by the closure over long time periods. The integrated impacts of the changed DRZ conceptual model and the role of the closure in modeling gas pressure in the waste panels before and during equilibration after intrusion are important interactions with the Repository Fluid Flow conceptual model.

Reduction in the volume of gas available during blowout (a single panel isolated by closures) resulting from intrusion may impact the spalling model. Closures between panels imply that a first intrusion may not lower pressure throughout the repository, which may result in several intrusions in several panels having increased potential for spall events. A drop in gas pressure after intrusion into a panel may accelerate brine flow toward the intruded panel. If a panel closure is left unsupported in an open drift, shear and extension stresses related to the creep closure of the spaces on either side of the panel closure may impact the mechanical stability of the panel closure.

2.4 Peer Review Panel Methodology

Review of the conceptual models commenced after panel member orientation and training in accordance with MP 10.5, the Peer Review Plan, and other relevant information presented in the orientation and training package.

The peer review panel employed the following approaches in their overall method of conducting and accumulating information for the reviews:

- Extensive review of referenced literature relevant to the review;
- Attendance at briefings on conceptual models and relevant aspects of the PA process;
- Issue focused presentations with question-and-answer sessions with SNL scientists and engineers;
- Review of literature and documents referenced during the question-and-answer sessions; and
- Formal and informal discussions among the Panel members.

The Panel was provided several presentations addressing the three conceptual models being reviewed with respect to whether or not they represent a reasonable view of future states of the proposed disposal system for the WIPP repository. For this review, conceptual models are defined as a set of qualitative assumptions used to describe a system or subsystem for a specific purpose. The Panel evaluated the models in

accordance with the NUREG-1297 criteria. In addition, the Panel recognized that individual models may warrant varying levels of reviews of their mathematical representations, computerized representations, and results. Due to the volume and diversity of information to be reviewed, individual Panel members were assigned lead responsibility for specific conceptual model reviews. Dr. Gibbons made the following assignments. Dr. Oswald was assigned responsibility for review of the Disposal Room Geometry conceptual model; Dr. Caporuscio was assigned responsibility for review of the Repository Fluid Flow conceptual model; Dr. Chunhong Li was assigned responsibility for review of overall mathematical representations and modeling; and Dr. Gibbons took responsibility for review of the Disturbed Rock Zone conceptual model. The information gathered by individual members during their reviews was freely disseminated among all of the Panel members.

In organizing its work, the Panel established limitations on its review and the content of this report. The Panel members did not review or offer comments on regulations. The Panel confined its review to the three conceptual models identified in the Peer Review Plan. To maintain independence, the Panel did not offer recommendations for specific methods and/or approaches to be employed in future work.

2.5 Criteria for Conceptual Model Review

The nine criteria used by the peer review members are based on the criteria in EPA regulation 40 CFR Part 194.27, NUREG-1297, the EPA Compliance Application Guidance, and Peer Panel discussions.

Information Used to Review Changes in Conceptual Model. This is an evaluation of data and information used to review the changes in the conceptual models and sub-models. It includes attributes of the disposal system learned by SNL during site characterization activities, exercising the models, and a review of the science and concepts that the models are based upon. It also includes information gained during the operation of the repository.

Validity of Assumptions. The validity of key assumptions in the model and its application are assessed in terms of how they could affect the usefulness of the conceptual model. The review addresses the comprehensive inclusion of important features, events, processes, and other key assumptions. Examples are the assumption of Darcy flow in the various media, use of the ideal gas law at high pressures, and the mathematical method chosen to develop the model grid.

Alternative Interpretations. This section briefly identifies and assesses plausible alternative conceptual models or sub-models considered by SNL but not used, and the rationale why such alternative models were not used. The panel assessed alternative interpretations in some instances by evaluating elements of the CCA and the PAVT as alternatives.

Uncertainty of Results and Consequences if Wrong. This includes an evaluation of the key uncertainties in the selected conceptual models and the discussion of the consequences if aspects of the conceptual model chosen were inappropriate or incompletely constrained for the site or process. This is not an exhaustive evaluation, but it does raise the question, "What if the model is wrong?"

Appropriateness and Limitations of Method and Procedures. Based primarily on the previous four criteria, this is a simple statement of whether the individual conceptual models, process models, and sub-models represent a reasonable approximation of the actual disposal system elements.

Adequacy of Application. This is an assessment of whether it appears that the individual conceptual model is being adequately applied into an acceptable overall performance assessment system. This particular assessment does not cover the relationships among conceptual models, but rather whether the significant components of the individual conceptual models are appropriately implemented in support of performance assessment. For example, are the various geometrical systems and representations of the conceptual models adequately applied within the performance modeling system, or do there appear

to be discontinuities between the conceptual model and its application? Also, are there alterations of important key assumptions between the conceptual model and its implementation in performance modeling?

Accuracy of Calculations. This is a statement of whether the results of performance modeling using the conceptual model within the performance system are reliable and accurate to adequately simulate the physical and chemical processes represented. Internal consistency among the several iterations of the PA was carefully considered.

Validity of Conclusions. This is a judgment of the validity of any key conclusions that have been drawn based on results of the implementation of the conceptual models in the modeling framework. The key question is whether or not conclusions from model implementations appropriately relate to the expected goal of assessing the long-term performance of the disposal system. This judgment requires an evaluation of output information from the total system PA.

Adequacy for Implementation. This is an overall assessment of whether the conceptual models as implemented in the PA represent a reasonable approximation of the actual disposal system.

2.6 Adequacy

The three conceptual models reviewed were deemed adequate because the changes to the models are sound in their structure, reasonableness, and relationship to the original models. The proposed implementation of the models appears reasonable based on review of selected gas pressure and brine saturation scenarios in performance assessment. Review of the CCDFs for direct brine release and spallings releases which are sensitive to repository pressure and brine volume indicates an acceptable comparison of new results to the prior CCA results. Based on their review, the Panel has judged that the three conceptual models represent a reasonable approximation of the actual WIPP disposal system performance.

3.0 Model Evaluations

This section presents the results of the Panel's review of the three individual conceptual models. Each of these models is first described and then evaluated for adequacy in accordance with the criteria summarized in Section 2.5. Following each evaluation, space has been provided for dissenting views. There were no dissenting views by any Panel member resulting from this peer review. An evaluation of the integration of these conceptual models into the WIPP PA is provided in Section 4.

3.1 Disposal System Geometry

3.1.1 Model Description

3.1.1.1 Background

Consistent with the purposes for which the conceptual models were originally developed for the WIPP PA, the Disposal System Geometry conceptual model was developed to represent the dimensionality of the engineered system and the surrounding geologic and hydrogeologic formations. The features that rely on the geometric assumptions and parameters of dimensionality for representation are expressed across the overall performance assessment system through a finite difference model called BRAGFLO. The flow fields generated by BRAGFLO, based on the geometric representations and the finite difference calculations, are communicated with the NUTS code that determines the transport of actinides through the anhydrite interbeds and boreholes. The geometry assumed for any model contains important information about the way in which physical processes are thought to act on the system. For WIPP, the model geometry assumed for the disposal system can only be understood in the context of the important processes considered to take place in a particular region during a specific time interval and for a defined purpose.

3.1.1.2 Description

This peer review focused on the changes in a specific group of conceptual models associated with the Technical Baseline Migration (TBM). Changes were evaluated to determine whether or not the models continue to reasonably represent the relevant features, processes, and future states of the disposal system. Changes to the disposal system geometry conceptual model evaluated were: 1) The removal of the baseline shaft seal system model and replacement with a simplified model, 2) Implementation of Option "D" panel closure design, 3) Dividing the remainder of the repository into two blocks separated by a panel closure, 4) Applying a new method by which flaring is calculated, 5) Refinement of the grid geometry, and 6) Changing part of the repository horizon vertically approximately 2.4 meters to Clay Seam "G".

The final certification decision (40 CFR Part 194) requires the implementation of Option "D" panel closure system. The system, characterized by a concrete monolith and an explosion wall, led to the proposed change in grid geometry since the existing grid block discretization was perceived to be too coarse for the representation of the specifics of Option "D" and the interrelated impacts on the DRZ. In general, where flow has been shown to be important, changes to the grid are proposed to add detail. The proposed grid refinement provides for greater segmentation and allows the detail of Option "D" components to be captured. The changes in the grid increased both vertical and horizontal refinement with the number of grid cells representing the repository increasing from 51 in the CCA to 69 in the TBM. The total number of grid cells increased from 33 to 68 in the x-dimension and 31 to 33 in the y-dimension. The x-dimension changes in the grid required the recalculation of radial flaring. It is understood by previous peer review panels, and this panel as well, that while flow may not be truly radial, the two-dimensional flared grid is reasonable for estimating releases. The CCA grid had several scales of flaring with each calculation including a series of complicated cell wrapping procedures that are difficult to reproduce and use for characterizing changes. The TBM changes include a new flaring algorithm that uses simplified repository geometry, results in flaring representations that closely approximate those in the CCA grid, and allows for changes to be "more easily" made in the x-dimension.

Changes in the BRAGFLO model considered in this peer review, with respect to the Disposal System Geometry conceptual model, include grid spacing changes, removal of the baseline shaft seal system model and replacement with a simplified model. The peer review panel understands that implementation of the Option "D" panel closure was the stimulus for changing the grid and modification of the shaft seal system was a separate decision represented in the BRAGFLO grid.

3.1.2 Review of Criteria

3.1.2.1 Information Used to Review Changes in Conceptual Model

The 1996 peer review of the Disposal System Geometry conceptual model included review of the screening logic, numerous SNL reports, and many technical presentations and discussion sessions. As stated in the report, (July 1996) the information and background references reviewed at that time were for specific inputs and applications, i.e., a comprehensive list of references addressing the "conceptual modeling" of the Disposal System Geometry was not compiled. Information concerning the effects of detailed stratigraphy and stratigraphic dip on brine and gas flow, and uncertainty and parameter sensitivity analyses for gas and brine migration, is presented in Webb and Larson (1996), WIPP (1992a & 1992b), and Christian-Frear (1996). Other reports (WIPP 1993, Rechard 1990, and Marietta 1989) explain the WIPP PA aspects of characterizing the disposal system geometry, and features, events, and processes (FEPs) screening documents present modeling alternatives. Various sections of the CCA (DOE 1996) summarize disposal system, repository, and intrusion event geometries. The Disposal System Geometry conceptual model, as reviewed in 1996 and as addressed in this peer review, is the result of integrating other models that describe the physical and chemical conditions and processes that are expected in the repository to produce a characterization of the repository and the surrounding strata. The references include the various background, technical descriptions, and presentation materials used in conducting the evaluation of the TBM changes in the Disposal System Geometry conceptual model. Previous conceptual model peer review reports, regulatory guidance, and other appropriate documents were provided to the peer review panel early in the process, as

required background reading. The key information sources addressing the TBM changes were the technical presentations, technical documents, and background materials provided by SNL supplemented by discussions with SNL scientists.

3.1.2.2 Validity of Assumptions

Along with the assumptions made for the TBM changes, it is important to briefly review the general assumptions made in the original peer review of the Disposal System Geometry conceptual model in 1996. The Disposal System Geometry conceptual model and its assumptions are so closely tied to the processes described by other models that not only is it important that the model have assumptions that are internally consistent, but the assumptions must be consistent with those of the models representing repository processes. Disposal system geometry processes are so closely tied to the processes that govern overall repository performance that it is difficult to conduct a review separate from the other models. Fluid flow and actinide transport are principal processes that rely on the geometric assumptions and these processes in turn have interrelationships with other process models. In 1996 the panel recognized the simplifications and assignment of high permeabilities for the sake of conservatism. Although, this panel's view is that it is always more credible to model the actual system, the assumptions supporting the simplifications remain valid.

Assumptions key to the original Disposal System Geometry conceptual model include: 1) the three-dimensional systems can be represented by two-dimensional simplifications, 2) the associations between and relationships across regions with varying material properties can be represented by the discretized grid blocks and by the finite difference method used in the computational model; 3) the four shafts can be represented by one shaft; 4) the entire repository can be represented by the simplified floor plan used in the computation model; 5) the intrusion borehole(s) represent the range of concerns associated with the intrusion scenarios; and 6) effects of flow in the DRZ and intact rocks outside of the repository are represented by the divergent grid to the north and south, away from the repository.

Assumptions key to the proposed TBM changes in the Disposal System Geometry conceptual model include: 1) The more refined grid spacing provides a more accurate representation of features, events, and processes but does not adversely impact the representation of sources, sinks, and pathways for radionuclide releases; 2) Flow in the shaft is negligible; 3) Removal of the baseline shaft seal system model and replacement with a simplified, two layer system conservatively represents the behavior of seal components in the repository system model and accurately represents shaft seal behavior as modeled in the baseline PA; 4) The new flaring algorithm adequately represents horizontal divergent and convergent flows to the north and south of the repository; 5) The TBM BRAGFLO grid adequately represents the Option "D" panel closure design, the DRZ, anhydrite fracture, repository fluid flow, and other components of the WIPP setting; 6) Moving the repository horizon vertically, approximately 2.4 meters, to Clay Seam "G" enhances operational safety and will not significantly impact the long-term performance of the facility in terms of lateral brine flow, creep closure, release pathways and available pore volume.

During the Salado Flow Peer Review, SNL presented assumptions and justifications for the material property representations proposed for use in the TBM. The panel concludes that the assumptions and justifications are defensible and appear to adequately represent the features and process of concern in the TBM changes. The panel also concludes that as a result of previous PA calculations, illustrating that only negligible flows are released up the shaft, removal of the "baseline shaft seal property details" and replacing them with a simplified, equivalent permeability system with fewer time intervals conservatively represents the behavior of seal components and is valid.

Changes in the Disposal System Geometry conceptual model are proposed to be implemented through the same discretized grid block and finite difference computational approach as was done for the CCA. The Panel judges that if key pathways and simplifications are retained, the overall conceptual model remains valid.

3.1.2.3 Alternative Interpretations

During the Salado Flow Peer Review, information presented and considered by the Panel did not include alternatives or options for changes in the Disposal System Geometry conceptual model. The final certification decision required the implementation of the Option "D" panel closure system and no other panel closure alternatives were considered by the peer review panel.

3.1.2.4 Uncertainty of Results and Consequences if Wrong

The key uncertainties associated with the TBM proposed changes to the Disposal System Geometry conceptual model are related to the material property descriptions and the grid simplifications made for the sake of conservatism, and the representativeness of the computational mesh. Even with the TBM changes the proposed BRAGFLO grid is not sufficiently detailed to describe all flow features and processes and the overall system relies on other conceptual models to reasonably describe such features and processes.

The panel concludes that there is little uncertainty associated with the basic geometric framework and finite difference method used to characterize the changes associated with the proposed TBM. The uncertainty that does exist is related to the grid block densities of the material property representations and the representativeness of the grid block densities and computational mesh. The material property changes appear justified and defensible.

The consequences of the proposed TBM changes in the Disposal System Geometry conceptual model, if they are wrong, can only be addressed in a qualitative way at this time. If the material property representations are wrong and or the computational mesh is not representative, the consequences depend on the relative magnitude of error(s) and the resulting changes in the total system PA.

3.1.2.5 Appropriateness and Limitations of Method and Procedures

The proposed TBM changes in the Disposal System Geometry conceptual model have been made without changing the fundamental geometric framework of discretized grid blocks and the finite difference method implemented through BRAGFLO. The methodology is considered by the panel to be appropriate for the TBM application. The panel concludes that the conceptual model continues to be an appropriate methodology to integrate and express the inputs from other conceptual models.

3.1.2.6 Adequacy of Application

The methodology employed in the Disposal System Geometry conceptual model is appropriate and adequate for application as a performance element. There are no apparent compatibility problems between the geometry and process-related models. Single vector BRAGFLO analyses that focused on saturation and pressure provided comparisons for the Performance Assessment Verification Test (PAVT), Technical Baseline Intermediate (TBI), and TBM. The TBI was intended to isolate Option "D" effects in the BRAGFLO grid. The single vector, time dependent comparisons produced results that were either expected or could be explained. Scatter-plots also provided comparisons that were understandable and where differences could be explained.

The adequacy of the changes in material properties and their representations in the grid can only be measured by how well overall processes are approximated. These approximations and representations, and changes from the baseline model have been evaluated through a PA for the TBM. The results of the PA indicate that total releases are nearly identical to the PAVT and direct releases are nearly identical or less that the PAVT. Based on these results, application of the changes, as modeled in the baseline, is deemed adequate.

3.1.2.7 Accuracy of Calculations

It was not within the scope of the Salado Flow Peer Review to evaluate BRAGFLO code changes. Descriptive write-ups and review of uncertainty and sensitivity analyses that compare the relationship between sampled inputs and dependent variables in the PAVT, TBI, and TBM provide no indications that the accuracy of the "baseline" model has been changed. The PA results for the TBM indicate that total releases are nearly identical to the PAVT and direct releases are nearly identical or less than the PAVT. Since the Disposal System Geometry conceptual model produces results using the material properties, processes, and codes from other models, and the TBM PA illustrates that repository performance continues to be represented as it was in the baseline, the relative accuracy of the Disposal System Geometry conceptual model has been demonstrated.

3.1.2.8 Validity of Conclusions

There are no specific conclusions drawn, with respect to the Disposal System Geometry conceptual model, other than its ability to characterize appropriate properties, processes and features. The conclusion derived from the PA is that the conceptual model continues to reasonably represent repository performance.

3.1.2.9 Adequacy for Implementation

The Disposal System Geometry conceptual model continues to provide an adequate framework for modeling the important processes and their interactions in the disposal system. The concept that the spatial effects of processes and interactions can be represented in two-dimensions is defensible. The simplification in the system representation and computational method to simulate the two dimensions are defensible and adequate for implementation. The basic grid framework for representing the material properties of the disposal system, adjacent DRZ, geologic formations, and intrusion scenarios is adequate. The proposed use of a finite difference method to connect the nodes and generate flow fields is also defensible and adequate for implementation.

The results of the PA for the TBM illustrate that the effects of changes to the baseline conceptual models, described in 3.1.1.2 and associated applications are minimal. The Disposal System Geometry conceptual model continues to be adequate for implementation.

3.1.2.10 Dissenting Views

There were no dissenting views for this model.

3.2 REPOSITORY FLUID FLOW

3.2.1 Model Description

The Repository Fluid Flow conceptual model is a highly complex description of interacting hydrologic, chemical, engineering design, geomechanical and human intrusion conceptual models whose simultaneous effects can be separately described, but require a PA to demonstrate the combined, integrated results. The physical conditions controlling fluid flow in the repository include brine and gas inflow and outflow rates, halite creep rates, and gas generation pressures from waste container corrosion and waste degradation. These physical conditions are contained in separately described conceptual models (Salado Interbeds, Creep Closure, and Gas Generation conceptual models respectively). The Repository Fluid Flow model accepts input from these related models and provides descriptions of pressures, flow rates, and flow directions for gas and brine within the disposal cells and other sections of the repository. A formal description of the coupled processes in the original conceptual model was presented in Freeze, et al. (1995).

Changes to the original conceptual model are as follows; 1) Brine inflow and outflow rates and gas pressures have potentially been altered by the introduction of the Option "D" panel closure mandated by the EPA, 2) The Disturbed Rock Zone (DRZ) properties have been altered by the allowance of fracturing both in the anhydrite beds and the salado halite and the "Flow Around" features near plugs at high pressure, 3) The salt creep rate may be affected due to changes in gas pressure, 4) Gas generation is calculated using a

different cellulosic molecular weight that provides approximately 10% greater gas production during microbial degradation, and 5) Flows will be simplified since the Disposal System Geometry conceptual model now has a simplified Shaft component.

3.2.2 Review of Criteria

3.2.2.1 Information Used to Develop Conceptual Model

The Repository Fluid Flow conceptual model relies heavily on Darcy flow in porous media, as revised for gas by taking into account the Klinkenberg effect, and for two-phase flow using a modified Brooks-Corey model that includes threshold pressures for gas entry into a brine saturated environment (Wilson, et al., 1996). Gas properties are given by the Redlich-Kwong-Soave equations of state, assuming that the gas behaves as pure hydrogen. The conceptual model addresses (1) fluid distribution in the waste, (2) long-term fluid (gas and liquid) flow to and from the Salado Formation, and (3) long-term fluid flow between the repository and the intrusion boreholes. Interactions with other conceptual models include the Disposal Room Geometry, Disturbed Rock Zone, Creep Closure, Gas Generation, Impure Halite, Salado, the Salado Interbeds, Castile and Brine Reservoirs, Exploration Boreholes, and Multiple Intrusions. In the original CCA, this model also was related to the Shafts and Shaft Seals model. However, the detailed Shafts and Shaft Seals model was replaced by a simplified Shaft Seals model incorporated into the Disposal Room Geometry conceptual model and flow out of the repository via the shafts is considered insignificant. Fluids will now be transported primarily up boreholes during disruptive events (S3 and S5).

The conceptual model for repository fluid flow is implemented for PA using the BRAGFLO code. The repository is represented in BRAGFLO in two dimensional vertical sections as a series of volumes, each with homogeneous isotropic material properties and behaviors, with each representing a major repository feature. The slight one degree ($1^?$) dip of the bedding to the south is represented by the model. The effective depth of each feature (the dimension normal to the plane of the model) is represented by

adjusting the cross sectional areas of the cells representing the feature. The effective depths of the model cells were varied to simulate the increasing hydraulic gradients that would occur in the repository and boreholes under radial flow conditions.

The original conceptual model was validated in the CCA and accepted by the Conceptual Models Peer Review in 1996. Since that time, a PAVT sensitivity study was performed. That PA included 60 parameter changes mandated by the EPA. Sensitivity analysis in the PAVT indicates that impact on the complete PA calculations were not substantial.

Since the PAVT, there have been minor changes to the fluid pathways in and around the repository. The model packages presented to the peer review panel were the Technical Baseline Migration (TBM) and the CRA (equivalent to AP-106). These changes are the result of modifications to other conceptual models and corrections of parameter values. The Shaft and Shaft Seal model has been removed from the overall performance assessment model in the TBM and replaced with a simplified Shaft Model incorporated into the Disposal Room Geometry. Modification of the Shaft and Shaft Seal model results in fluids being primarily channeled up the boreholes in the event of human intrusion by drilling in to the repository. Addition of a simplified Shaft Model into the Disposal Room Geometry conceptual model should result in no significant change in the PA.

There have been changes to the DRZ conceptual model in the TBM. Fluids would no longer transport from one panel to another via Marker Bed #138. Instead, fluids will now migrate along Marker Bed #139 below the floor of the panels. The fluids will not be able to circumvent the Option "D" panel closure by taking the path of least resistance in marker Bed #139. Because of permeability fluctuations related to gas pressure variation during the repository history, both gas and liquid phases may be impeded in their flow through the DRZ during certain BRAGFLO simulations. In the latest rendition of this conceptual model (CRA), fracturing of the Salado anhydrite beds is a primary storage and transport medium for outflow from the repository. This allows gases to now flow through Marker Bed #138, and liquids to flow preferentially through Marker Bed #139.

Furthermore, at high pressures, a “flow around” parameter has been implemented which would allow fluids to circumvent the Option “D” plug in the “z” dimension. This modification in the CRA now allows gas and liquid phases to be less impeded during some high pressure BRAGFLO simulations.

The Option “D” panel closure has been incorporated into the final closure plan and has multiple potential effects on fluid flow. Although the upper DRZ still exists it is not allowed to fracture for the TBM analysis except at very high pressures (~12 MPA). The lower DRZ is allowed to fracture for the TBM assisted by tensile stresses associated by floor heave making Marker Bed #139 the preferred pathway. Fluids will more slowly equilibrate throughout the repository after closure, which may result in changes in PA. Gas pressure in the experimental area will most likely be lower than in the PAVT, since there is no gas generation in that region and constrained communication with the waste panels. Brine saturation in the southernmost waste panels may be lower than in PAVT, since there is less brine communication between panels due to the characteristics of the Option “D” panel closure which will prevent down-dip flow of brine between repository openings. Brine saturation in the remainder of the repository will be the same as PAVT calculations because the process models for BRAGFLO have not changed. With the addition of the upper DRZ fracturing in the CRA, most of the Option “D” restrictions are less effective at high pressures. Once lithostatic pressure is realized, the anhydrite fractures can open and fluids migrate through both the upper and lower marker beds (#138 and #139, respectively). This will allow for lower maximum gas pressures and relatively increased brine flow in the waste panel. Pressure and saturation will also be affected by higher transmissivities.

The parameter value changes include the cellulosic molecular structure change and the EPA mandated parameter value changes (Table 3-1). The cellulosic chemical formula ($C_6H_{10}O_5$) provides approximately 10% greater gas production during microbial degradation. The new parameter value changes introduced by the EPA did not introduce significant changes from the CCA to the PAVT CCDFs.

3.2.2.2 Validity of Assumptions

On a larger scale, the original assumptions for the Repository Fluid Flow conceptual model were validated in the original performance assessment (CCA, 1996). The validity of the assumptions in the Repository Fluid Flow model depend in part on the other conceptual models (Disturbed Rock Zone and Disposal System Geometry) in so far as the assumptions in the other models are shown to be valid, those same assumptions will propagate through to the Repository Fluid Flow conceptual model. The BRAGFLO model was not significantly changed in its assumption base (creep closure, gas generation, pressure induced fracturing, use of characteristic curves such as Brooks-Corey and van Genuchten), rather, cell parameters have been improved and cell dimensions have been better adapted to critical features.

The assumptions addressed in the TBM are: 1) modification of the representation of the Shafts and Shaft Seals, 2) change in representation of cellulosic molecular structure, 3) changes in the DRZ conceptual model, 4) implementation of EPA mandated changes to parameters, and 5) implementation of the Option "D" panel closure.

The assumption that the modification of the Shafts and Shaft Seals system would affect the overall performance of the PA in a very minor way is reasonable. Maximum brine flow up the Shaft at the top of the DRZ was calculated to be approximately a total of 30 m^3. During borehole intrusions in the upcoming PA this fluid would be directed up the borehole and would still be insignificant. However, the EPA requested that a shaft be reintroduced. Therefore a simplified Shaft model was included in the Disposal System Geometry model. In lieu of the original 22 materials and six time intervals in the CCA, the simplified Shaft model has fewer materials, time intervals, and permeability values. With this simplified shaft most of the brine flow would still be directed up the intrusion boreholes

The larger molecular weight for cellulose is not an assumption, but rather a refinement of a parameter. The recalculation of the molecular weight and the slight increase in gas

generation potential (10%) will produce a slightly more conservative value for overall gas generation amounts in certain PA scenarios.

The two major assumptions for the Disturbed Rock Zone conceptual model (permeability and flow geometry) are reasonable in the TBM model. For the CRA the simplified shaft model is included, fracturing in the upper and lower DRZ is implemented, a high pressure "flow around" concept is extended to permit flow in all anhydrite and Salado beds, and a double concrete panel closure is included at the north end of the repository. These assumptions are reasonable for the CRA and present an acceptable approach to model how fluids would interact with the Option "D" panels.

The 60 parameter changes listed in Table 3-1 (Summary of CCA and PAVT Parameters) and Table 3-2. (Summary of TBM and CRA Values and Distributions) appear appropriate and reasonable. The most notable changes concern actinide solubilities in the fluid. In all cases the solubility values are lower than in the original CCA values. Such values would produce curves with lower values in the CCDF calculations, if all other factors remain unchanged. Most other changes involve taking a single parameter value and replacing it with a range of values that bracket the original. This is an appropriate and reasonable assumption, in that it focuses most new values near the original value, but allows the CCDF calculations a slightly wider variance.

Table 3-1. Summary of CCA and PAVT Parameters

Parameter	CCA Range and Distribution	PAVT Range and Distribution
Log of Borehole Sand Permeability	-14 to -11 log m^2 Uniform	-16.3 to -11 log m^2 Uniform
Log of Borehole Concrete Permeability	-16.3 log m^2 Constant	-19 to -17 log m^2 Uniform
Log of Disturbed Rock Zone Permeability	-15 log m^2 Constant	-19.4 to -12.5 log m^2 Uniform
Log of Waste Permeability	-12.769 log m^2 Constant	-12.6198 log m^2 Constant

PIC Reduction Factor for 100 – 700 years	0.01 Constant	1.0 Constant
Waste Shear Strength	0.05 to 10 Pa Uniform	0.05 to 77 Pa Log uniform
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Castile Brine	6.52×10^{-8} mol/l Constant	1.38×10^{-8} mol/l Constant
Coefficient, A, in Equation[(a)] for Solubility for Np+4, Pu(IV), Th (IV) and U (IV) in Castile Brine	6.0×10^{-9} mol/l Constant	4.1×10^{-8} mol/l Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (V) in Castile Brine	2.2×10^{-6} mol/l Constant	4.8×10^{-7} mol/l Constant
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu (III) in Salado Brine	5.82×10^{-7} mol/l Constant	1.2×10^{-7} mol/l Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (IV), Pu (IV), Th (IV) and U (IV) in Salado Brine	4.4×10^{-6} mol/l Constant	1.3×10^{-8} mol/l Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (V) in Salado Brine	2.3×10^{-6} mol/l Constant	2.4×10^{-7} mol/l Constant
Inundated Steel Corrosion Rate	0 to 1.59×10^{-14} m/s Uniform	0 to 3.17×10^{-14} m/s Uniform
K_d in Culebra Dolomite for Am(III) and Pu(III)	0.02 to 0.5 m^3/kg Uniform	0.009 to 0.4 m^3/kg Log uniform
K_d in Culebra Dolomite for Np (IV), Pu (IV), Th (IV), and U (IV)	0.9 to 20 m^3/kg Uniform	0.7 to 10 m^3/kg Log uniform
K_d in Culebra Dolomite for Np (V)	0.001 to 0.2 m^3/kg Uniform	0.001 to 0.2 m^3/kg Log uniform
K_d in Culebra Dolomite for U (VI)	0.00003 to 0.03 m^3/kg Uniform	0.00003 to 0.02 m^3/kg Log uniform
Probability of Hitting a Brine Pocket	0.08 Constant	0.01to 0.60 Uniform
Drill String Angular Velocity	7.7 radians/s Constant	4.2 to 23.0 radians/s cumulative distribution with mean of 7.77 radians/s
Castile Brine Pocket Rock Compressibility	Min: 5×10^{-12} Pa^{-1} Max: 1×10^{-8} Pa^{-1} Mode 1×10^{-10} Pa^{-1} Triangular	Min: 2×10^{-11} Pa^{-1} Max: 1×10^{-10} Pa^{-1}; Mode 4×10^{-11} Pa^{-1} Triangular
Castile Brine Pocket Porosity	Not used in CCA	Min: 0.1848; Max: 0.9240; Mode 0.3696

Brine Pocket Pore Volume	(3.2, 6.4, 9.6, 12.8, 16) x 10^4 m^3 Discrete	Calculated from Brine Pocket Porosity
Inventory Waste Unit Factor	4.07 Constant	3.44 Constant

[(a)]The equation for solubility is $A \cdot 10^b$ where b is a sampled value. Only the coefficient, A, was changed in the PAVT.

Table 3-2. Summary of TBM and CRA Values and Distributions

Parameter	Range	Distribution
Log of Borehole Sand Permeability	-16.3 to -11 log m^2	Uniform
Log of Borehole Concrete Permeability	-19 to -17 log m^2	Uniform
Log of Disturbed Rock Zone Permeability	-19.4 to -12.5 log m^2	Uniform
Log of Waste Permeability	-12.6198 log m^2	Constant
PIC Reduction Factor for 100 – 700 years	1.0	Constant
Waste Shear Strength	0.05 to 77 Pa	Log uniform
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Castile Brine	1.38 x 10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (IV), Pu (IV), Th (IV) and U (IV) in Castile Brine	4.1 x 10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (V) in Castile Brine	4.8 x 10^{-7} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Am(III) and Pu(III) in Salado Brine	1.2 x 10^{-7} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (IV), Pu (IV), Th (IV) and U (IV) in Salado Brine	1.3 x 10^{-8} mol/l	Constant
Coefficient, A, in Equation[(a)] for Solubility for Np (V) in Salado Brine	2.4 x 10^{-7} mol/l	Constant
Inundated Steel Corrosion Rate	0 to 3.17x10^{-14} m/s	Uniform
K_d in Culebra Dolomite for Am (III) and Pu (III)	0.009 to 0.4 m^3/kg	Log uniform
K_d in Culebra Dolomite for Np (IV), Pu (IV), Th (IV), and U (IV)	0.7 to 10 m^3/kg	Loguniform

K_d in Culebra Dolomite for Np (V)	0.001 to 0.2 m^3/kg	Log uniform
K_d in Culebra Dolomite for U (VI)	0.00003 to 0.02 m^3/kg	Log uniform
Probability of Hitting a Brine Pocket	0.01 to 0.60	Uniform
Drill String Angular Velocity	4.2 to 23.0 radians/sec	Cumulative distribution based on range with mean value of 7.77 radians/s
Castile Brine Pocket Rock Compressibility	Min: $2x10^{-11}$ Pa^{-1} Max: $1x10^{-10}$ Pa^{-1} Mode $4x10^{-11}$ Pa^{-1}	Triangular
Castile Brine Pocket Porosity	Min: 0.1848; Max: 0.9240; Mode 0.3696	Triangular
Brine Pocket Pore Volume	Calculated from Brine Pocket Porosity	Not applicable
Inventory Waste Unit Factor	3.59	Constant

[(a)]The equation for solubility is $A \cdot 10^b$ where b is a sampled value. Only the coefficient, A, was changed in the PAVT.

Scatterplots using the CRA values compare well with those using the TBM assumptions for gas generation. At 1,000 years, waste panel pressures are only slightly elevated versus the TBM. For longer periods of time (10,000 years), the CRA pressures in the waste panel coincide with TBM values. This is most probably caused by gas migration once the upper DRZ opens at high pressure. CRA scatter-plots indicate that the rest of the repository brine saturation is equivalent to TBM values (and therefore are the same as PAVT values). A few of the waste panel saturation values are lower than corresponding TBM values and may be related to slight changes in DRZ parameters related to anhydrite fracture and the double panel seal. The review panel concludes that the proposed impacts of the Option "D" closure and DRZ changes are reasonable assumptions.

The Repository Fluid Flow conceptual model is expected to have negligible impact on the other conceptual models and the total system PA. Presentations by SNL indicate that borehole intrusion scenarios will not change from those in the CCA. Increased and decreased values for gas pressure and/or brine saturation impacts on fluid flow have been evaluated and the impact that the changes in fluid flow will have on the spallings and multiple intrusions scenarios and on the PA are acceptable.

3.2.2.3 Alternative Interpretations

The changes incorporated into the Repository Fluid Flow conceptual model are based on three earlier cases of the model. The earlier models represent alternative interpretations. The Repository Fluid Flow conceptual model in the CCA was fully peer reviewed and accepted. The second representation of the model was in the PAVT sensitivity study. The changes incorporated into the third rendition of the model were logical improvements based on modification of the shafts and shaft seals model and the incorporation of the Option "D" panel closure. Adjustments to include a simplified shaft model for the CRA were requested by the EPA. Upper DRZ fracturing and flow around features now mitigate early concerns with the Option "D" closure panels.

3.2.2.4 Uncertainty of Results and Consequences if Wrong

The uncertainty of results related to the changed Repository Fluid Flow model are primarily related the implementation of the Option "D" panel closure. The purpose of the panel closures is to impede flow around the closure between adjoining waste panels. The new Disturbed Rock Zone conceptual model implies that flow will occur in both Interbed #138 and #139 at high gas pressure, and in turn, this should allow gas and liquid in the waste panels to equilibrate over time. However, vector analyses of gas pressure and brine saturation in the TBM and CRA model show that flow occurs for a limited number of vectors when pressures become high enough to cause significant fracturing. When these factors (pressure and saturation) are allowed to interact with the other conceptual models and are evaluated as part of the full system PA, other outcomes may result. Direct release conceptual models (involving cuttings, cavings, spallings, and direct brine release) provide the most significant release pathways. Since there is evidence that the waste panels do not equilibrate quickly with the rest of the repository or with the experimental region, the Repository Fluid Flow conceptual model may impact direct releases when evaluated in the context of a full system PA. If a postulated intrusion intercepts a waste panel with a high gas pressure (at or above lithostatic pressures), and with high brine saturation, it could allow for slightly higher brine transport to the surface. Conversely, if panels with low gas pressure or low brine saturation were intercepted, then the direct

release could be much lower. Since the last review of this conceptual model specific waste panels and explicit scenarios for direct brine release have been evaluated and TBM CCDF curves presented. The curves suggest that those scenarios do not adversely impact the performance of the repository.

3.2.2.5 Appropriateness and Limitations of Method and Procedures

The methods and procedures used in the Repository Fluid Flow model are based on refinements of previous models and should provide representative results.

3.2.2.6 Adequacy of Application

The adequacy of application of the model to changes in flow in the repository requires that all new definitions, processes, and applications be clearly identified. Parameters have been identified and qualified by the EPA (Table 3-1) for the PAVT. Intrusion scenarios have been defined by SNL and do not differ from the CCA. BRAGFLO calculations are identical to those used in previous applications (CCA and PAVT) of the PA and comparison of the newly generated CCDFs to the PAVT reveal relatively insignificant changes in total releases. The application of the model using redefined flow paths ("flow around" and anhydrite fracturing) and parameters does not require basic changes in the conceptual model itself. The performance of the repository in the TBM and CRA, as viewed by the presented CCDFs, confirms the adequacy of the application of the Repository Fluid Flow conceptual model.

3.2.2.7 Accuracy of Calculations

Scatterplots and CCDFs presented by SNL illustrate the changes made to calculations since the PAVT in this conceptual model and how they impact the performance assessment. No changes have been made to BRAGFLO or the application of BRAGFLO to the process models. Scatterplots presented by SNL allowed observation of how the most important sub-models (gas pressure, brine saturation and volume) respond in the repository performance assessment and variations were logically explained by SNL

personnel. For the CRA, CCDFs were presented for the most pressure sensitive scenario (Spallings) and the most brine sensitive case (DBR). The results of both scenarios were plausible, and did not vary widely from PAVT curves. Importantly, these newly generated curves did not substantially approach the EPA compliance limit. It is concluded that the accuracy of calculations for Repository Fluid Flow conceptual model has been demonstrated.

3.2.2.8 Validity of Conclusions

The conceptual model as reviewed at the time of the CCA was deemed to provide valid conclusions. Present changes to the details of the fluid flow pathway (Anhydrite fracturing, flow around, and repository geometry parameters) are reasonable and appear to be valid. The changes implemented are in the applications of the model and how it relates to other conceptual models in the PA. BRAGFLO has not changed and the conceptual model itself is deemed adequate; the calculations are judged to be accurate; and it is concluded that the changes to the Repository Fluid flow model and how they represent flow in the repository are valid.

3.2.2.9 Adequacy for Implementation

Even though the CCDFs presented were only a partial assessment and not a total system PA, the probability of outliers that would result in non conformance is minimal. The production of Single CCDF curves that represent the most sensitive scenarios (Spallings and direct brine release) in the CRA, along with the full TBM CCDFs, were enough information to judge that the minor modifications made to the Repository Fluid Flow model are reasonable and justifiable. This model is deemed adequate for implementation.

3.2.2.10 Dissenting Views

There were no dissenting views for this model.

3.3 Disturbed Rock Zone

3.3.1 Model Description

The DRZ conceptual model, as originally conceptualized in the CCA, was composed of a layer of halite above and below the drift. This layer provided a flowpath between the drift and the marker beds. The halite that composed this layer was assigned an arbitrary permeability of 10^{-15} m^2, considered a conservative value that would permit gas to escape the repository via the fractured marker bed and allow gravity-driven drainage of brine from the marker bed into the repository ("DRZ rain"). The model was not strongly representative of repository processes; rather it was viewed as a conservative basis for modeling waste degradation and gas generation processes in the repository.

During the PAVT sensitivity study the EPA mandated a range of permeability for the DRZ halite layer which reasonably represents the properties of extensively creep-damaged halite and anhydrite at the high permeability end, and of minimally damaged halite at the low permeability end. This range is unequally distributed around the original single value used for the halite permeability. This range is retained in the changed conceptual model and was not previously peer reviewed. A principal change to the hydrologic processes contained in the model presently under review is the flow path through the repository floor, an average of one or two meters of halite, into Marker Bed #139 which is composed of about one meter of fractured anhydrite. This flow path represents a considerably more transmissive pathway for the exit of gas and brine from the pressurized repository, into the potential storage medium represented by the fractured anhydrite. The gravity inflow of brine through the halite layer above the repository back is still a factor in modeling brine inflow into the repository.

Gas will sometimes, depending on the level of free brine in the repository, flow out through pathways in the repository floor to Marker Bed #139, and , especially at times of high pressure will also flow out through the pathways around the tops of panel seals. This flow will in most cases go to marker beds above and below the repository connected to

the repository by fractures opened by floor heave and by stresses associated with room closure about the rigid panel seals into the void spaces on either side of the seals.

A further change in the potential flow paths out of the repository is represented by a design change applied to several waste panels at the southern end of the repository. The purpose of the design change is to enhance repository construction safety by raising the elevation of the drift to place the back of the excavation at a clay seam (G), mitigating what might have become a parting that could increase the risk of roof fall in those waste panels. This will raise the floor of the repository slightly higher (3.8 meters) above Marker Bed #139.Since the stresses and fracture caused by floor heave in repository drifts extend to considerable depth below the drift floor, and since the role of floor fracture is primarily to connect the repository to Marker Bed #139, this design change is not expected to have any significant impact on the repository floor flowpath.

3.3.2 Review of Criteria

3.3.2.1 Information Used to Review Changes in Conceptual Models

The CCA version of the DRZ conceptual model consisted of a 12 meter thick zone above the emplacement panels and drifts that were assigned an assumed permeability of 10^{-15} m^2 for the entire zone. This conceptual model had no basis in actual repository or site performance, but was rather a conservative representation of the damaged rock zone, conceived to permit brine and gas flow between the repository and the overlying Marker Bed #138. The PAVT sensitivity study that followed the CCA used a range of permeability values for the zone between the repository and Marker Bed #138 that were identified by the EPA. The EPA determined the lower bound of the range of permeability from measured gas permeability in anhydrite cores from Marker Bed #139 (Howarth, 1996, Beauheim, 1996, Howarth and Christian-Frear, 1997). The EPA concluded that a value of $10^{-19.4}$ m^2 is an appropriate lower bound for the range of likely values. Based on sensitivity tests, the EPA selected a value of $10^{-12.5}$ m^2 as the upper bound of the range of DRZ permeability. Documents held by the WIPP Project office pertaining to DRZ permeability support this range of the PAVT values (Beauheim, 1996). The more permeable limit represents halite and anhydrite heavily damaged by creep

strain. The less permeable end of the range assigned to the assumed disturbed zone above the repository is a value conceived to represent the permeability of halite that has been healed by stresses associated with repository creep closure and is supported by measured permeability values. This value ($10^{-19.4}$ m^2) is comparable to the permeability of halite that has been disturbed only by far field stresses caused by creep toward the repository opening beyond the disturbed rock zone (Beauheim, in press). This range of values is an acceptable bound of the permeability of the disturbed rock zone that includes both the Salado halite and the anhydrite of the marker beds.

The changes proposed to the DRZ conceptual model for the next total system PA modifies the geometry of flow associated with the DRZ but retains the range of permeability assumed for the DRZ under the PAVT sensitivity study. The changed conceptual model routes flow through the floor of the repository to Marker Bed #139 whose upper surface is about 4 meters below the drift floor in the raised repository region (south part) and 1 to 2 meters in the north part of the repository. This flow routing represents the path of least resistance for the flow of gas and brine out of the repository and provides a reasonable basis for estimation of gas pressures in the repository.

The potential for flow around the top and bottom of panel seals is a topic whose consideration is made necessary by the addition of the much more restrictive option "D" panel seals. In the case of the bottom footprint of the seal, the concrete monolith is seated at the bottom of Marker Bed #139. The top of the seal is seated against a freshly excavated inset into the halite of the repository roof. At repository pressures that exceed the hydraulic activation pressures of closed fractures in the areas around the seats of the seals, flow is likely around the seals (Figure 68 SNL presentation, Feb. 19, 2003) The cited figure shows flow around the bottom of a panel seal, however, flow around the top of such a seal would differ only in that the top of the seal would be seated in halite and that gas flow only would be predominant around the top of the seal at some times in the repository history. Brine flow would almost always be the dominant flow mode in the lower seat area. This set of flow paths has some potential to impact the pressure histories of the individual spaces in the repository and the model is applied to these consequences

of changes of repository design in a manner similar to that applied to the new scenario of flow through the repository floor.

The changes to the DRZ conceptual model include the assumptions supporting the range of permeability values and the change in the geometry of flow from the 12 meter overhead DRZ (CCA) to the 1 to 3.8 meter long flowpath, through the repository floor and into the fractured anhydrite of Marker Bed #139, and flow at high pressures around the tops and bottoms of panel seals into marker beds above and below the repository (AP 106).

3.3.2.2 Validity of Assumptions

Assumptions used in developing the proposed changes to the DRZ conceptual model are of two kinds. The values for the permeability of the DRZ have evolved over two iterations of PA. In the first PA (CCA, 1996) the permeability of the thick, overhead DRZ contained in that conceptual model was a "conservative" value assumed to permit communication between repository openings and the upper Marker Bed #138. The chosen value was assumed to permit free drainage of brine from the marker bed into the repository and to permit gas to escape from the repository to the marker bed. The permeability chosen was an intermediate single value between perceived extremes implied by the material properties of the marker bed and pure halite. For the PAVT sensitivity study a range of permeability was necessary to permit sampling and development of distributions to better represent flow through this complex zone. The end members of the distribution represent the measured permeability of the fractured anhydrite marker beds and the estimated permeability of "tight" halite. Pure halite, disturbed only by very small and slow strain resulting from creep into the repository beyond the DRZ, is probably a reasonable representation of well-healed halite after the disappearance of the DRZ due to back-stress around seals or after the closure of repository open spaces. As such, these end members are reasonable limits to the permeability of the DRZ. The permeability range used in the PAVT calculations ($10^{-12.5}$ m^2 to $10^{-19.4}$ m^2) represents reasonable parameters between the end member conditions.

Changes in the geometry of flow in the DRZ represent the second kind of assumption. The basis of this assumption is that gas flow out of the repository panels will follow the path of least resistance or the path of greatest transmissivity. The short distance (4 meters in the raised repository region (south part) and 1 to 2 meters in the north part of the repository) between the repository floor and Marker Bed #139 represents a much lower resistance to flow than upward flow through 10 meters (south part) to 12 meters (north part of the repository) of halite that is horizontally compressed by arching stresses over the repository openings. Floor heave implies an extensional stress environment in the floor. This extensional stress and gas pressures may also help to keep the fractures in both the halite in the repository floor and in the anhydrite marker bed open. The large storage space represented by the well connected fracture porosity of the marker bed may provide for retention of gas and brine expelled from the repository via this flowpath.

A further assumption is that at relatively high repository pressures (high enough to activate hydraulic flow through fractures around panel seals) that repository gasses (mostly) will flow out through marker beds above the repository. Flow through these pathways will help to regulate repository pressure at certain times during repository history, but the impact on the cycle of waste decomposition, gas generation, gas pressure, and brine inflow is not expected to be important. Flow around panel seals (both top and bottom) was included in modeling of repository pressure and saturation as shown by SNL in scatterplots for the TBM and AP 106.

The assumptions contained in the changes to the DRZ conceptual model are reasonable to represent repository materials, flow geometry, and system properties. The permeability range used to generate the sampled distributions that will be used in PA is based on permeability of materials similar to those in the disturbed rock zone in comparable geomechanical environments. The geometry of flow follows principles of hydraulics that are appropriate to the repository structure, stress environment, and material properties.

3.3.2.3 Alternate Interpretations

The proposed changes to the DRZ conceptual model follow two earlier iterations of the model. These earlier iterations include a full PA (CCA) and a sensitivity study (PAVT) that represent alternative models that have received more detailed consideration than is usual in alternative concept evaluation. The CCA iteration was fully peer reviewed. The changes proposed to the model represent reasonable development of the earlier alternatives. The changes to the model are supported in part by recent calculations, geophysical and hydrologic measurements in the repository floor (Bryan, et al, 2001, Beauheim, 2002, Holcomb, 2001).

3.3.2.4 Uncertainty of Results and Consequences if Wrong

The uncertainties of results in the changed conceptual model lie mostly in the ranges of permeability used to represent the flow properties of the rock along the flow paths proposed. The geometry of the flow paths is not a great source of uncertainty, in that they are the most reasonable paths of least resistance for gas flow and their dimensions and material properties are easily characterized. The range of permeability proposed as bounds of the properties of the rock through which flow will take place is reasonable. The range is supported by measured values and it will be sampled and represented by a CCDF, which is a reasonable analytical approach. Exceeding the upper limit of the permeability range would allow gas to migrate from the repository more easily and reduce gas pressure. Ultimately, gas pressures depend on permeability in the anhydrite marker bed where storage of gas will take place at distances from the repository far enough to be less damaged by creep. The impact of the uncertainty in the conceptual model is that the gas pressure in the repository might be slightly lower than predicted by modeling at some times in repository history.

3.3.2.5 Appropriateness and Limitations of Methodology and Procedures

The methods and procedures used in the changed model are refinements of the previous models and will generate representative results in PA. Constituative models based on

measurement of the influence of creep damage on hydrologic properties may be feasible in the future, but such models are not expected to indicate that the changed model has failed to conservatively bound repository performance. The methods and procedures are appropriate to the present state of information and the needs of PA.

Changes in the repository design that impact gas and brine flow through the DRZ are clearly defined and present no new problems in characterizing flow processes and flow paths that are different from those that exist in previous PAs. The assessment of any impact on the performance of the repository can be readily accomplished by applying the existing numerical and conceptual models to changes in flow geometry and changes in the geometry and stress/strain states of the DRZ resulting from design changes. The methodologies and procedures of assessment of the repository are therefore fully appropriate

3.3.2.6 Adequacy of Application

Consideration of the adequacy of application of the model to changes in flow in the DRZ due to changes in the repository design, reinterpretation of flow paths or changed definition of properties, requires that the changed processes that impact flow be clearly identified. In the present case, the necessary scenarios have been identified and the new permeability parameters proposed by the EPA for the DRZ are justified in the PAVT. The necessary BRAGFLOW calculations are identical to those used in other iterations of the PA model except that changed (decreased grid cell size) increases resolution of modeling along new flow paths, and two earlier iterations of that model exist for comparison (CCA and PAVT). Application of the model to redefined sets of parameters or to redefined flow paths resulting from changes in the repository design, as in the case of flow over the panel seals, does not require fundamental changes in the conceptual model. The redefinition of a new principal flowpath out of the repository (through Marker Bed #139, through the heaved floor) requires only the application of the flow model to preexisting process models. Application of BRAGFLOW to cases containing new hydrologic definition of flow in the DRZ is straightforward and requires only the recalculation of the pertinent impacts on principal factors such as repository pressure and

brine volume. Those calculations are represented by scatterplots and CCDF plots in the SNL presentations and demonstrate that performance is not significantly impacted. Those representations of the performance of the changed repository are sufficient to demonstrate the adequacy of the application of the model to the changed configuration of flow in the DRZ.

3.3.2.7 Accuracy of Calculations

New calculations since PAVT that impact repository performance assessment are represented in scatterplots and CCDF plots presented by SNL. No changes in BRAGFLOW except the reduction of grid cell size which increases resolution or in the methodology of application of BRAGFLOW to the process models resulting from the changes in DRZ Conceptual Models under review have been made. The plots presented by SNL address the most important sub-models in repository PA (pressure, saturation, and brine volume) and address the variance associated with chosen individual vectors. A CCDF representing the most pressure sensitive release case (spallings) and the most brine volume sensitive case (direct brine release) were presented and the results were seen to be reasonable, lacked large unexplained variance, and did not approach noncompliant releases. It is therefore concluded that the accuracy of calculations which include the calculation of changes in flow due to changes in the DRZ hydrogeological process models is demonstrated.

3.3.2.8 Validity of Conclusions

Validity of conclusions drawn from the application of the changed DRZ conceptual model in PA is the same as for those drawn from the previous iterations of the model so long as the adequacy of application and the accuracy of calculations are concluded to be appropriate. The general structure of the conceptual model was peer reviewed during the CCA and the changes to the details of the flow paths and the definition of permeability appear to be valid. Changes consist entirely of applications of the flow model to process models that either already exist in the PA model (flow through marker beds, inflow through the DRZ,) or are readily defined (flow through fractures connecting the repository

to marker beds) or to application of the flow model to changed results of process models operating on redefined parameters (DRZ permeability). Since BRAGFLOW and the general conceptual model are adequate and the calculations appear to be accurate, the conclusion that the changes more accurately represent flow in the DRZ appears to be valid.

3.3.2.9 Adequacy for Implementation

The changed DRZ model modulates the relationship between repository pressure, waste degradation and brine inflow in a more realistic and conservative way than preexisting models, while integrating the influences of two design changes. Flow of brine and gas into and out of the repository through all of the marker beds within reasonable proximity, both above and below the repository, linked to the repository through its pressure history is more realistic than the previous single flowpath model. Assessment of the impact of the "Option D" panel seals is closely tied to the repository history and flowpath assessment. The impact of the second design change, the small elevation of the southern waste panels for reasons of construction safety, is concluded to be insignificant on conceptual grounds.

The partial PA assessment provided adequately supports the reconfiguration of the model and shows that the impact of the changes on the model is minimal. It is concluded that the changes to the DRZ flow model have not invalidated its adequacy for implementation

3.3.2.10 Impact of the Disturbed Rock Zone Model on Closure Performance

Impact of the changes in the DRZ conceptual model are shown to be small by the limited performance assessment calculations presented by SNL during this review. Although limited, these calculations addressed the most important impacts (gas pressure, brine volume, and saturation) resulting from changes at the process model level, and the release mechanisms (DBR, Spallings) most dependent on pressure and brine volume. These results and the acceptance that the aspects of the model changes leading up to the calculations are adequate indicate that the impacts of the changes to the DRZ model do not negate the compliance of the repository. It must be noted that the Spallings model

used in the calculation of the Spallings release is not the latest iteration of that model, which has yet to be reviewed.

3.3.2.11 Dissenting Views

There were no dissenting views for this model.

4.0 Integration of Conceptual Models in Performance Assessment

4.1 Model Integration

Figure 4-1 is a simplified illustration in which selected conceptual models represent a system or subsystem within the CCA, PA code sequence. BRAGFLO DBR, as illustrated, is a special, short-term application of BRAGFLO related to a drilling intrusion and includes the conceptual model system representations listed under BRAGFLO plus the Direct Brine Release model. The direct brine release element illustrates that the calculated brine volume removed from the repository by a drilling intrusion is input directly to the CCDFGF.

Figure 4-1. Illustration of Conceptual Model Integration

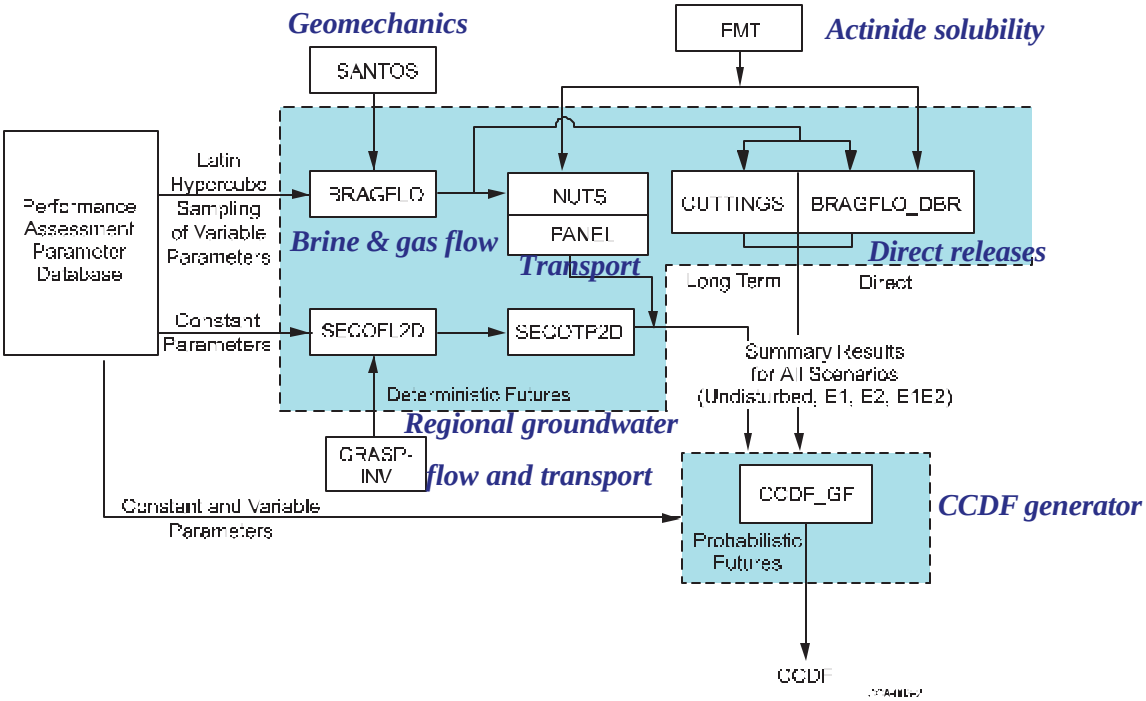

As shown in figure 4-1, the conceptual models do not all represent a system or sub-systems in the same place in the code sequence. Figure 4-1 illustrates that the conceptual models, as interpreted through the various codes, are ultimately integrated at the CCDFGF where results are prepared. The figure ignores many preparatory and post-process codes and relationships between codes that are not linear and in a single direction. For example, while SANTOS is related to BRAGFLO and receives system representation from the Creep Closure conceptual model, creep closure results from an iterative relationship between gas pressure, compaction, and brine characterizations from BRAGFLO and the porosity surface in SANTOS. The integration of the conceptual models, therefore, identifies the overall WIPP PA model as a complex structure that represents 24 conceptual models through preparatory, process, flow and transport, presentation, and enabling codes.

4.2 Review of Criteria

Applying evaluation criteria to the integration of conceptual models, as a step in the assessment of model adequacy, results in most of the discussion being summations of the individual conceptual model evaluations. For example, evaluations of information used in the integration, assumptions, uncertainties, adequacies, accuracy, and validity are all based on the individual conceptual models or the implementing mathematical representations or codes. The criteria have been discussed in Section 3.0 for the three conceptual models reviewed.

Because a total and complete system PA was not available for Peer Review Panel to review, the overall adequacy for implementation of the integrated conceptual models can only be judged at this time through the adequacy of the three individual conceptual models as discussed in Section 3. Based on the review of the individual models, implementation of the integrated conceptual models is expected to be adequate.

5.0 Summary of Evaluations

This section presents a summary of the evaluations of the WIPP Conceptual Models Peer Review Panel performed between April 2002 and March 2003. Over twenty years of scientific effort have been expended on WIPP site characterization and there have been approximately three years of successful operational experience. It is beyond the scope of this report to summarize all of the positive factors and scientific evidence compiled concerning the WIPP site. This section is not intended to be a reiteration of comments and discussions on the individual conceptual models but to provide an overview of conclusions from the evaluations.

The list of the twenty-four WIPP conceptual models is provided in the Table 4-1 with the three models reviewed during this peer review bolded so as to put them in the context of the total WIPP waste disposal system modeling effort.

Disposal System Geometry

The changes in the Disposal System Geometry conceptual model retain the necessary features of the original conceptual model and the grid changes appear reasonable and sound. The Disposal System Geometry conceptual model continues to be adequate. The results of a PA for the TBM illustrated that the effects of changes in the conceptual model are minimal. The Disposal System Geometry conceptual model continues to represent repository performance with no significant change from its representation in the baseline.

Repository Fluid Flow

The Repository Fluid Flow conceptual model has been determined to be both reasonable and adequate for its intended purpose. The identified changes (shaft simplification, EPA mandated parameters, cellulosic molecular structure, and fluid flow paths) appear reasonable and are expected to have minimal impact. The interaction of this conceptual model with the Option "D" Panel closure (with revised anhydrite fracturing and "flow around" features at high pressure), and subsequent gas pressure realizations in waste

panels have been illustrated by a series of TBM CCDF's that show very little resultant change. The influence of the model when coupled with the other conceptual models appears appropriate and adequate.

Disturbed Rock Zone

Four changes to the DRZ conceptual model have the potential to impact PA. These are the adoption of a range of limiting porosity values to replace the original (CCA) single value for the halite and anhydrite layers in which the disturbed rock zone is developed; the definition of a flow path through the floor of the repository openings into Interbed #139; flow paths around the tops and bottoms of panel seals at high pressure; and a change of elevation of the waste panels in the southern end of the repository. Based upon data and analyses presented by SNL, these changes appear to be reasonable. The change of waste panel elevation aides repository operations and is not considered a significant change in concept. The impact of these changes on PA calculations and CCDF plots appears negligible. The impact on releases sensitive to repository pressures, saturation and brine volume, show that changes in the DRZ model do not significantly impact the predicted compliance of the repository.

Table 5-1

WIPP Conceptual Models

Disposal System Geometry	**Addressed During This Peer Review**
Culebra Hydrogeology	Not Addressed During This Peer Review
Repository Fluid Flow	**Addressed During This Peer Review**
Salado	Not Addressed During This Peer Review
Impure Halite	Not Addressed During This Peer Review
Salado Interbeds	Not Addressed During This Peer Review
Disturbed Rock Zone	**Addressed During This Peer Review**
Actinide Transport in the Salado	Not Addressed During This Peer Review
Units Above the Salado	Not Addressed During This Peer Review
Transport of Dissolved Actinides in the Culebra	Not Addressed During This Peer Review
Transport of Colloidal Actinides in the Culebra	Not Addressed During This Peer Review
Exploration Boreholes	Not Addressed During This Peer Review
Cuttings/Cavings	Not Addressed During This Peer Review
Spallings	Not Addressed During This Peer Review
Direct Brine Release	Not Addressed During This Peer Review
Castile and Brine Reservoir	Not Addressed During This Peer Review
Multiple Intrusions	Not Addressed During This Peer Review
Climate Change	Not Addressed During This Peer Review
Creep Closure	Not Addressed During This Peer Review
Shafts and Shaft Seals	Not Addressed During This Peer Review
Gas Generation	Not Addressed During This Peer Review
Chemical Conditions	Not Addressed During This Peer Review
Dissolved Actinide Source Term	Not Addressed During This Peer Review
Colloidal Actinide Source Term	Not Addressed During This Peer Review

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Hansen, C.W., Leigh, C.L. 2002. *A Reconciliation of the CCA and PAVT Parameter Baselines, Revision 1*. Albuquerque, NM: Sandia National Laboratories.

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Appendix A - Panel Member Technical Qualifications

Florie Caporuscio

Los Alamos National Laboratory

- Environmental Restoration - developed criteria for and wrote portions of two-site characterization Work Plans (Los Alamos Pueblo Canyon, Canyon Core Document).
- Project Manager to characterize Omega West Reactor leak.
- Developed radiometric survey technique to investigate radionuclide transport (Pu, Cs, Sr) by geomorphic processes in Los Alamos Canyons.
- Investigated Sr transport in aqueous media in Los Alamos Canyon.
- Peer reviews of Performance Assessment of Material Disposal Area (MDA) G at TA-54, Los Alamos National Laboratory.
- Co-author of MDA Performance Assessment Core Document for Environmental Restoration Projects at LANL.

WIPP

- Final Peer Review for License Application Conceptual Models
- Peer Review Member for salado Fluid Flow
- Peer Review Member – Natural Barriers

Environmental Protection Agency

- Principal Investigator evaluating effects of U, Th, Ra contamination and transport through geologic media at CERCLA and FUSRAP sites.
- Section Chief of US EPA WIPP Technical Review Program. Supervised review of Test and Retrieval Plan.
- EPA Principal Investigator for Gas Generation and Source Team models at WIPP (ORIA).

Pertinent Research/Other

- Oxidation of Fe oxides - characterization of oxidation state of 24,000 feet of ash flow core on Yucca Mountain.

- Determination of Fe oxidation state for paleomagnetic studies at Yucca Mountain.
- Empirical determination of Hematite-Ilmenite solvus with field samples.
- Crystal chemical studies of radioactive elements in crystal structures of mineral phases.
- Technical reviewer for *American Mineralogist* (1988-1989, 2002-2003)

John Gibbons

Over thirty years of experience in the geology and mine mechanics of salt deposits, including New York, New Mexico, Texas, and Kansas bedded salts and domed salts in Louisiana and Texas.

Yucca Mountain Project

Preparation of site suitability documents for presidential consideration, data qualification and integration for the federal high-level nuclear waste disposal site at Nevada

WIPP

Review of conceptual models and engineered barriers models for PA in support of license application. Review of data packages for PA in support of license application.

Illinois Department of Nuclear Safety

As a principal consultant:

- Detailed review of conceptual models (hydrogeologic and site character) and integration with the MODFLOW numerical flow model. Included radionuclide transport models and the site performance assessment model for Martinsville Illinois site.
- Developed site search models for hydrogeology and seismic ground motion for a second site.
- Developed conceptual model for vertical hydrologic flow through overconsolidated, fractured glacial till.
- Developed integration plan for site characterization through performance assessment of new site including applications of STRATAMODEL three-dimensional site model and model-based tests of site hydrologic characterization adequacy.

Applied Research Associates

Principal investigator for a DOE research committee funded study to develop a model-driven site characterization technology, which integrated geophysical (down-hole and surface), cone penetrometer and borehole data acquisition systems.

Senior hydrogeologist in support to Sandia National Laboratory in development of hydrostratigraphy conceptual model of Yucca Mountain High Level Nuclear Waste Repository Site.

Dames and Moore

As a principal investigator, did proposal preparation and was project liaison to the Federal High Level Nuclear Waste Program. Site characterization planning and model integration were principal areas of technical responsibility.

Chunhong Li

Numerical Modeling

- Conduct numerical modeling to study groundwater flow and mass transport at the Yucca Mountain site to assist system performance analysis at the proposed high level nuclear waste repository site.
- Carried out numerical simulations to study the influence of matrix diffusion on radionuclide transport in the fractured media at Yucca Mountain site.
- Carried out numerical simulations to investigate the sensitivity of radionuclide transport to variations in transport parameters under different flow conditions in UZ/SZ at Yucca Mountain.
- Worked on scaling related problems in groundwater modeling. Carried out numerical simulations using different scaling schemes for rock permeabilities to reconstruct water imbibition process observed in laboratory experiments in Topopah Spring tuffs at Yucca Mountain site.
- Expanded the Finite Element Heat and Mass transfer code (FEHM) to handle multiple species particle tracking process with spatially distributed transient source terms.
- Developed multiple species radionuclide decay-ingrowth module for FEHM.
- Developed algorithms for use with FEHM particle tracking module to better manage memory for simulating multiple species decay-ingrowth in the unsaturated zone.
- Modified the Finite Element Heat and Mass transfer code (FEHM) for GoldSim-FEHM coupling and supported Total System Performance Assessment (TSPA) work for GoldSim-FEHM simulation runs.
- Developed code SZ_CONVOLUTE V2.2 for calculating saturated zone responsive curves based on unsaturated zone mass flux and generic breakthrough curves for risk assessment at the Yucca Mountain Project.
- Developed a numerical code using the spectral representation theorem and FFT to generate 1-D and 2-D stochastic field with different spatial correlations.
- Developed Lattice Gas Automata (LGA) code to simulate solute transport behavior in fractured porous media.

- Applied harmonic analysis to study the dynamic response of well-aquifer system to earth tides and its application in estimating aquifer parameters, Jilin, China.
- Developed Java, JSP, and Oracle application programs for the Department of Veterans Affairs Data Center at Austin, TX.

Field Investigation

- Involved in designing and setting up a 3-D (multi-level) groundwater flow and transport research site at Sevilleta, New Mexico.
- Conducted field hydrogeological investigations, field pumping tests and tracer tests, and data analysis for a water supply site at Jinan, Shandong, China.

Laboratory Experiment

- Designed and carried out laboratory experiments to investigate solute mixing behavior at fracture junctions. The experimental results were then used to verify the numerical simulation results and good agreement was observed.

E. B. Oswald

Design of Conceptual Models/Structures

- University of Arizona, Department of Hydrology and Water Resources, Dissertation, 1976. Designed a conceptual model with which to assess the socioeconomic impacts of coal-fueled power generating facilities on Native Americans in the Four Corners region of the Southwest. The conceptual model related critical social, economic and cultural parameters of Native American systems to natural resource use, economic and environmental effects and power plant location and operation phenomenon. The conceptual model was implemented through a mathematical simulation technique.
- Designed conceptual models (assumptions, structures and relationships) for evaluating the impacts of FWPCA, Section 208, non-point pollution control practices on land and surface water quality. As part of a policy analysis project under USDA, Economic Research Service, the models were published in internal, peer-reviewed working papers (1977-1984).
- Assisted in the design of the conceptual models and implementation of the mathematical realizations of a linked system of linear programs and a finite difference representation of the Navajo sandstone aquifer. The linked LPs were designed to evaluate the regional impact of power generation grid distribution and the ground water model was built to estimate the impacts of commercial water withdrawals on local wells. The modeling was done under a contract with the Ford Foundation through the University of Arizona, Department of Hydrology and Water Resources (1976-1977).
- Montana DNRC, 1995. Developed the conceptual model for evaluating the effects of high TDS water from coal mine pit discharges to the Tongue River and reservoir system.
- Montana DNRC and U.S. Bureau of Reclamation, 1994. Designed the conceptual model(s) for evaluating the impacts of increased reservoir depth and area on alluvial ground water quality and storage and shoreline erosion.

- Designed the conceptual model for evaluating water use and disposal systems at remote Missile Launch Control Facilities, Malmstrom AFB, and Montana. The model considered the timing of water use, percolation and infiltration capacities, evapotranspiration and climatic influences and resulting short and long term potential for water balance. This 1995 project was in response to recent EPA guidelines governing remote water systems.
- Montana DEQ. Currently involved in conceptualizing a model or framework for evaluating the utility and stability of post-mining reclamation. The model will involve the characterization of future land use scenarios and the assessment of economic, aesthetic, recreational, surface environmental and alluvial ground water impacts of the scenarios.

Model Operation, Application

- Operated a regional linear program-based model designed to optimize the interplay of agricultural/silvicultural production systems with imposed pollution control practices. Published as part of the USDA, Columbia River Basin Project Report, 1980-1983, Portland, Oregon.
- University of Arizona, Department of Hydrology and Water Resources, 1975. Operated a stochastic, dynamic programming model with an application to a multi-year (50 years) multi-stage water supply reservoir operation system.
- Montana, DNRC, U.S. Bureau of Reclamation, 1994. Application of MODFLOW software to an evaluation of alluvial water withdrawals and the impacts of alternative rates on surface stream flow. At issue was the volume of ground water available for consumptive use without diminishing local stream flows.
- Oregon Department of Environmental Quality, published as USDA Working Paper, ERS Working Paper Series. Design and application of a riparian habitat model to estimate the effects of various agricultural, silvicultural and mining practices on riparian zones and the aquatic and terrestrial habitats included.
- Montana DEQ, U.S. Army Corps of Engineers, 1996. Responsible for review of geochemical, limnological and mixing zone models used to predict water quality in a pit lake, the Blackfoot River and the alluvial ground water resulting from

proposed gold mine operations. The results and interpretations of the model reviews will be presented in an EIS.

- USDA, EPA, Corvallis, Oregon, 1983. Conducted review of alternative models for evaluating chemical and erosional impacts to the ground water and surface streams associated with FWPCA, Section 208 and RCWP practices. The CREAMS model developed by USDA, ARS was adopted for use.
- Reviewed and evaluated various modeling approaches to be applied to the Agricultural/Rural environment system characterized by a project area in Austria. The review and model review was conducted at the IIASA, Laxenburg, Austria during a joint effort by Russian, Austrian and U.S. scientists.
- RCRA, RFI, Malmstrom AFB, Montana. HDR Engineering, 1993. Review and evaluation of proposed deep and shallow aquifer models proposed to characterize potential containment migration.
- Final Peer Review for License Application; Conceptual Models, WIPP, 1996-1997.
- WIPP Salado Conceptual Model Peer Review, May 2002

Data and Models

- As project operations manager, principal hydrologist and corporate QA manager, I routinely review the raw data and data presented in environmental sampling reports. Included in the reviews are 'cursory' data validation (traceability, achieving QA goals, etc.) as well as how the data can be interpreted, statistically or otherwise.
- Compliance Certification Model Data Review and Certification WIPP, 1995-1996.
- The data reviews and QA reviews routinely lead to conceptual models of contaminant migration route; rate and the conceptual models are used to propose more extensive and/or confirmatory sampling and data collection.
- As applied science manager working on the Rocky Mountain Arsenal and CERCLA projects manager for EPA's TESIV, project data review (QA and statistical) and interpretation of data for intended uses were routine activities. Krieging and other techniques were applied to interpret data spatially, illustrate

data gaps and needs and make decisions on the appropriateness of RFI and RIFS data for proceeding with remedial action.

Appendix B

Determinations of Peer Review Member Independence

ATTACHMENT III
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Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE ____ or a DOE Contractor X — Yes / No

Were you employed by DOE or a DOE Contractor previously? — Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

1993 – 1996 ASI – ER project at LANL
1996 – 1997 Informatics – WIPP peer Review
1997 – present Eberline Services – Gamma Spectroscopy at LANL, two months writing procedures for TWCP prior to first WIPP shipment.

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Florie A Caporuscio

Print Name: Florie A Caporuscio

Date: 1/24/03

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE or a DOE Contractor — Yes / (No)

Were you employed by DOE or a DOE Contractor previously? — (Yes) / No
(If yes, give dates, location, organization, position, and type of work performed).

YUCCA MOUNTAIN PROJECT
APR 1999 THROUGHOUT 3/2002
DATA REVIEW, SITE SUITABILITY DOCUMENT PREPARATION
PEER REVIEW WIPP 1996-1997-1998

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / (No)
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / (No)
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / (No)
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: John F. Gibbons II

Print Name: JOHN F. GIBBONS

Date: 1/25/03

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE No or a DOE Contractor No — Yes / No

Were you employed by DOE or a DOE Contractor previously? — Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: [signature]

Print Name: CHUNHONG LI

Date: 2/5/2003

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE ____ or a DOE Contractor ___ Yes / No

Were you employed by DOE or a DOE Contractor previously? Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

A previous employer may have been a DOE contractor, at one time, or may be a DOE contractor now, but I was not involved in any aspect of DOE work.

Do you have or have you had any direct involvement or financial interest in the work under review? Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Eric B Oswald

Print Name: Eric B Oswald

Date: 23 January 2003

Appendix C

Certifications Regarding Organizational Conflicts of Interest

I have reviewed each of the selected peer review panel member's (Florie Caporuscio, John Gibbons, Chunhong Li, and Eric Oswald) backgrounds and employment histories. I have also interviewed each of them to determine if they have an organizational conflict of interest or a bias for or against the WIPP facility as a nuclear waste repository. Though these background investigations and interviews I have determined that none of the selected peer review panel members has an organizational conflict of interest related to the Salado Flow Conceptual Models Peer Review.

John A. Thies,
Peer Review Manager

Appendix D – Signature Page

I acknowledge by my signature below that I concur with the findings and conclusions documented in the Salado Flow Conceptual Models Peer Review Report.

Florie Caporuscio — Date: 3/04/03

John Gibbons — Date: March 4/3/03

Chunhong Li — Date: 3/4/03

Eric Oswald — Date: 3/3/03

I have reviewed each of the selected peer review panel member's (Florie Caporuscio, John Gibbons, Eric Oswald, and Chunhong Li) backgrounds and employment histories. I have also interviewed each of them to determine if they have any organizational conflict of interest or a bias for, or against, the WIPP facility as a nuclear waste repository. Through these background investigations and interviews I have determined that none of the selected peer review panel members has a bias or an organizational conflict of interest related to the Salado Flow Conceptual Models Peer Review.

02/07/03

John A. Thies,
Peer Review Manager

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Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE No or a DOE Contractor No — Yes / No

Were you employed by DOE or a DOE Contractor previously? — Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: [signature]

Print Name CHUNHONG LI

Date 3/5/2005

ATTACHMENT III
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Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE or a DOE Contractor X — Yes / No

Were you employed by DOE or a DOE Contractor previously? — Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

1993 - 1996 ASI - ER project at LANL
1996 - 1997 Informatics - WIPP peer Review
1997 - present Eberline Services - Gamma Spectroscopy at LANL, two months writing procedures for TWCP prior to first WIPP shipment.

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Florie A Caporuscio

Print Name Florie A Caporuscio

Date: 1/24/03

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE ____ or a DOE Contractor ___ Yes / No

Were you employed by DOE or a DOE Contractor previously? Yes / No
(If yes, give dates, location, organization, position, and type of work performed).

A previous employer may have been a DOE contractor, at one time, or may be a DOE contractor now, but I was not involved in any aspect of DOE work

Do you have or have you had any direct involvement or financial interest in the work under review? Yes / No
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? Yes / No
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? Yes / No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: [signature]

Print Name: Eric B Oswald

Date: 23 January 2003

ATTACHMENT III
Page 1 of 1

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE or a DOE Contractor — Yes / (No)

Were you employed by DOE or a DOE Contractor previously? — (Yes) / No
(If yes, give dates, location, organization, position, and type of work performed).

YUCCA MOUNTAIN PROJECT
APR 1999 THROUGH OCT 31 2002
DATA REVIEW, SITE SUITABILITY DOCUMENT PREPARATION
PEER REVIEW WIPP 1996-1997-1998

Do you have or have you had any direct involvement or financial interest in the work under review? — Yes / (No)
(If yes, describe the involvement)

If there any reason why you cannot perform an impartial peer review? — Yes / (No)
(If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of a bias in the results of your peer review? — Yes / (No)
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: John F. Gibbons II

Print Name: JOHN F. GIBBONS

Date: 1/25/03

WASTE ISOLATION PILOT PLANT

SPALLINGS

PEER REVIEW PLAN

June 20, 2003

Prepared by John A. Thies
Time Solutions Corp

INTRODUCTION

This peer review plan describes the process and documentation requirements for a peer review of the proposed spallings conceptual model to be used in the Waste Isolation Pilot Plant (WIPP) performance assessment (PA). This plan defines the management approach, resources, schedule, and technical requirements for using peer reviews to confirm the adequacy of the new conceptual model for spallings.

1.1 BACKGROUND

Peer review of conceptual models developed by the U.S. Department of Energy (DOE) for the WIPP is required by 40 CFR § 194.27 (EPA, 1996), promulgated by the U.S. Environmental Protection Agency (EPA). In accordance with this criterion, the Carlsbad Field Office (CBFO) of the DOE will have a peer review conducted of specific conceptual models that are being revised due to knowledge gained since the original conceptual models were developed. When approved, the revised conceptual models will be used in the Compliance Recertification Application (CRA) for the WIPP Project.

Sandia National Laboratories (SNL) is responsible for the development, maintenance, and conduct of WIPP PA's. As part of the PA methodology included in the Compliance Certification Application (CCA)(DOE, 1996), the DOE identified and developed conceptual models that describe the features, events, and processes relevant to the WIPP disposal system and its subsystems. These conceptual models were peer reviewed by the Conceptual Model Peer Review Panel (CMPRP) and the Panel's results were approved by the EPA during the original WIPP certification (EPA, 1998a).

The spallings conceptual model is one of 24 conceptual models used in the WIPP PA. The spallings model describes a potential release of degraded solid waste materials when repository gas pressure exceeds the hydrostatic pressure in the drilling fluid at the bottom of an intrusion borehole. The CMPRP found that the spallings conceptual model implemented in the CCA was inadequate to describe the detailed spallings process. However, the CMPRP also concluded that "the spallings volumes used in the CCA are reasonable, and may actually overestimate the actual waste volumes that could potentially be expected to be released by the spallings process at the WIPP" (Wilson et al., 1997, Section 4). The EPA agreed with the CMPRP that the spallings conceptual model was inadequate but the results were acceptable for use in PA (EPA, 1998b, Section 7).

After the CCA and Performance Assessment Verification Test (PAVT) were completed, work continued on the development of a new spallings model that would be more technically defensible than the original model. The major elements of the new spallings

model include consideration of multiphase flow processes in the intrusion borehole, consideration of fluidization and transport of waste particulates from the intact waste mass to the borehole, and a numerical solution for the coupled mechanical/hydrological response of the waste as a porous medium. New software, called DRSPALL, has been prepared to calculate the volume released during a potential spallings event.

1.2 REQUIREMENTS

The requirement for conducting a peer review of conceptual models is specified in 40 CFR § 194.27 (a)(1). The requirements for the peer review process and its documentation are specified in 40 CFR § 194.27(b) and (c). In summary, the peer review process shall be a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. A peer review is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology and acceptance criteria employed, and the conclusions drawn from the original work.

The peer reviewers shall be independent of the work being reviewed; in other words, the peer reviewer a) was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to ensure the work is impartially reviewed. Therefore, the peer-review provides additional assurance to the regulator and the public that the subject matter is reasonable, accurate and valid for its intended use.

1.3 PURPOSE

The purpose of this plan is to describe the scope, approach, and process the peer review panel will use in conducting a peer review of the WIPP spallings conceptual model.

1.4 SCOPE

The Spallings Peer Review panel will determine if the new conceptual model for spallings reasonably represents the failure of solid wastes and their subsequent transport to the surface from a borehole intrusion into a high pressure repository. The scope of this peer review is limited to assessing the new conceptual model for spallings and its implementation in WIPP PA.

PEER REVIEW PLANNING AND IMPLEMENTATION

2.1 APPROACH

This plan documents the approach to conducting the peer review process. The Spallings Peer Review will be conducted using a rigorous proceduralized approach that meets all the requirements of NUREG-1297 (NRC, 1988), in accordance with 40 CFR § 194.27(b). The DOE-CBFO has prepared a management procedure, MP 10.5, Revision 5, February 1, 2003 (DOE, 2002a), for conducting peer reviews in accordance with NUREG-1297. The DOE-CBFO procedure ensures that the peer review will be a documented, critical review performed by qualified peers who are independent of the work being reviewed. Specifically, the Spallings Peer Review Manager will:

- Follow MP 10.5, Revision 5, February 1, 2003 requirements. In the event of a conflict between MP 10.5, Revision 5, February 1, 2003 and NUREG-1297, NUREG-1297 will take precedence over MP 10.5, Revision 5, February 1, 2003.
- Administer and document the peer review process. Activities include documenting the selection of panel members, assignment of a panel leader, panel member independence documentation, and recording and archiving meeting minutes.
- Negotiate a schedule for the peer review with the DOE CBFO Assistant Manager, or designee.
- Conduct and document peer review panel caucuses.
- Communicate interim peer review findings in hardcopy to the DOE CBFO Assistant Manager, or designee.
- Produce a formal written report of the peer review findings and conclusions.
- Implement applicable quality assurance (QA) requirements for document preparation, control and records archiving.

2.1.1 DESCRIPTION OF CONCEPTUAL MODEL TO BE REVIEWED

A new conceptual model for spallings is being proposed. The new conceptual model for spallings includes: (1) the development of numerical techniques to solve the coupled mechanical-hydrologic equations for gas flow and fracture of the waste in the repository, and (2) the use of a conceptual model for multiphase flow in the intrusion borehole.

Detailed descriptions of the model components will be provided to the peer review panel through written documentation and oral presentations.

Peer review of the new conceptual model for spallings will include:

- The conceptual model for the spallings process in the repository and in the intrusion borehole.
- The mathematical representation of the new spallings conceptual model.
- The numerical solution of the mathematical representation through the DRSPALL computer program. The words “computer program” and “code” are used interchangeably in this plan.
- Incorporation of the numerical results from the DRSPALL code into the direct release calculations for PA.

When approved, the new conceptual model for spallings will be used to calculate potential spallings volumes for the Compliance Recertification Application, replacing the original spallings model. *Review of the new conceptual model for spallings will not include consideration of the validity of the original conceptual model peer review.*

2.1.2 COMPOSITION OF PEER REVIEW PANEL

The peer review panel will be composed of a minimum of three individuals who possess the subject matter technical expertise to a degree at least equivalent to that needed for the original work.

Each panel member will become familiar with the WIPP containment system by reviewing documents on a required reading list and through a formal orientation process conducted by the peer review manager. In addition, they will be presented with a basic description of how the conceptual models for PA are represented in numerical models, algorithms, and codes. The panel members will be presented the parameter inputs to the spallings code, results of prior PAs, sensitivity analyses, and critical comments from previous reviews. Finally, each panel member will become familiar with the peer review process through formal training in the appropriate peer review procedure(s).

2.1.3 LOGISTICS AND MANAGEMENT

Required reading material necessary to support the Spallings Peer Review will be provided by the DOE CBFO Assistant Manager, or designee, for distribution to the panel in time to support the first technical meeting which is scheduled for mid July.

2.2 PEER REVIEW PROCESS

The cognizant DOE CBFO Assistant Manager, or designee, is responsible for the peer review. A peer review contractor and Peer Review Manager will be selected by the CBFO Technical Assistance Contractor (CTAC). The responsible DOE CBFO AM, or

designee, shall concur with the peer review manager nominated by the service provider. The Peer Review Manager has prepared this Peer Review Plan and the DOE CBFO Assistant Manager, or designee, has reviewed and approved it. This Plan meets the requirements of MP 10.5, Revision 5, February 1, 2003. MP 10.5 shall supersede any discrepancies between this Plan and MP 10.5.

The Peer Review Manager will use a selection committee to select candidates for the peer review panel. Upon verification that the peer review panel members meet the criteria outlined in MP 10.5, Revision 5, February 1, 2003, Attachment 1, an orientation and training meeting will be scheduled. The peer review panel members shall complete their review of required reading materials prior to the orientation meeting.

Throughout the review, the panel is encouraged to engage in frank discussions with the individuals responsible for the work under review. However, the peer review panel must observe all rules for interaction with DOE CBFO, SNL, and stakeholders, as outlined in MP 10.5, Revision 5, February 1, 2003.

The results of the panel's review shall be formally documented in a report. This report will be prepared independently of the DOE CBFO to ensure the independence of the Panel's conclusions.

MP 10.5, Revision 5, February 1, 2003 states that the DOE CBFO QA Manager is authorized to conduct independent assessments of the peer review process to ensure that all aspects of the peer review conform to the guidance of NUREG-1297, MP 10.5, Revision 5, February 1, 2003, and the latest version of the CBFO Quality Assurance Program Description (DOE, 2002b). The DOE CBFO QA Manager shall inform the Peer Review Manager of any requests for audits or assessments. The Peer Review Manager shall comply with and resolve all issues arising from such audits or assessments.

2.3 ADEQUACY CRITERIA

Conceptual models that have been selected and developed by the DOE must meet commonly accepted technical and scientific standards based on an in-depth evaluation. The peer review panel shall use the evaluation criteria in NUREG-1297 as the basis for their review. The evaluation criteria in NUREG-1297 are as follows:

- Validity of assumptions,
- Alternate interpretations,
- Uncertainty of results and consequences if wrong,
- Appropriateness and limitations of methodology and procedures,
- Adequacy of application,
- Accuracy of calculations,

- Validity of conclusions, and
- Adequacy of requirements and criteria.

Adequacy of the revised conceptual model for spallings will be determined based on whether or not it reasonably represents possible future states of the disposal system.

2.4 SCHEDULE

Attachment A presents the schedule of peer review activities for the process described in Section 2.1.3. This schedule will serve as the baseline schedule from which requested schedule deviations will be evaluated by the Peer Review Manager and the CBFO. Revisions to the baseline schedule will not require revision to this plan, but must be approved by the DOE CBFO Assistant Manager, or designee.

2.5 DELIVERABLES

The Peer Review Manager will provide weekly status reports addressing peer review progress against the schedule to the DOE CBFO Assistant Manager, or designee. The DOE CBFO Assistant Manager, or designee, will work with the Peer Review Manager to ensure that timely information is delivered to the peer review panel. A final report with the panel's findings will be delivered to the cognizant DOE CBFO Assistant Manager, or designee.

2.5.1 Peer Review Report

The peer review report shall, at a minimum:

- Be signed by each peer review panel member
- Describe the work or issues that were reviewed
- Describe the conclusions reached by the peer review panel (e.g., peer review panel observation comments and overall conclusions).
- Provide additional statements by the peer review panel members reflecting dissenting views or additional comments, as appropriate
- List the peer review panel members and provide acceptability information (i.e., technical qualifications and independence) for each member.

QUALITY ASSURANCE

The peer review process shall be conducted and documented in a controlled manner and in compliance with the CBFO Quality Assurance Program Description, DOE/CBFO-94-1012, Revision 5 and other applicable QA procedures. The DOE CBFO QA Manager may appoint a QA observer to attend the orientation, training, and meetings of the peer review panel. The DOE CBFO QA Manager may schedule an assessment or audit of the peer review process and records prior to, or upon completion of the peer review. Communication between the EPA and the DOE CBFO QA Manager may also result in audits or assessments or the peer review process.

RECORDS MANAGEMENT

Records generated as a result of peer review activities defined in this peer review plan and designated as QA records shall be maintained by the Peer Review Manager in accordance with DOE CBFO MP 4.5, Generating, Receiving, Storing, and Controlling Active CBFO Project Records (DOE, 2001a), and MP 4.9, Quality Assurance Records (DOE, 2001b). Records include:

- Spallings Peer Review Plan
- Peer Review Procedure(s)
- Contract documents
- Peer Review Panel Member Verification of Education/Employment Forms
- Determination of Peer Review Panel Member Independence Forms
- Peer Review Panel Selection Justification/Decision Forms
- Peer Review Panel Member Orientation and Training Forms
- Meeting minutes and presentation materials
- Peer review Manager qualification documentation
- Peer Review Panel Member selection documentation
- Peer Review Panel Member contract documents
- Any Observer inquiry forms completed
- Written materials presented to the Peer Review Panel by CBFO or investigators
- Written information presented to the peer review panel members by observers
- Peer Review Report(s)

QA records shall be maintained by the Peer Review Manager until completion of the peer review. Upon completion of the peer review process, the original copy of the QA records (when possible) shall be formally transferred and delivered to the DOE CBFO Assistant Manager, or designee.

DOCUMENT CONTROL

The peer review plans, procedures, and other documents that require document control will be processed in accordance with applicable DOE-CBFO controlled document procedures.

REFERENCES

DOE (U.S. Department of Energy), 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO 1996-2184, October 1996.

DOE (U.S. Department of Energy), 2001a. Quality Assurance Records, CBFO Management Procedure MP 4.5, Revision 2, February 16, 2001.

DOE (U.S. Department of Energy), 2001b. Quality Assurance Records, CBFO Management Procedure MP 4.9, Revision 1, March 4, 2001.

DOE (U.S. Department of Energy), 2002a. Peer Review, CBFO Management Procedure MP 10.5, Revision 5, February 1, 2003.

DOE (U.S. Department of Energy) 2002b. Quality Assurance Program Document (QAPD), DOE/CBFO-94-1012, Revision 5, May 2003

EPA (U.S. Environmental Protection Agency). 1996. 40 CFR Part 194: Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations Final Rule. Federal Register, Vol. 61, No. 28, pp.5224-5245, February 9, 1996.

EPA (U.S. Environmental Protection Agency). 1998a. 40 CFR Part 194: Criteria for the Certification and Re-certification of the Waste Isolation Pilot Plant’s Compliance with the 40 CFR Part 191 Disposal Regulations: Certification Decision; Final Rule. Federal Register, Vol. 63, No. 95, pp. 27353-27406, May 18, 1998.

EPA (U.S. Environmental Protection Agency). 1998b. Technical Support Document for §194.23 - Models and Computer Codes. Docket A-93-02, Item V-B-6. May 1998

NRC (U.S. Nuclear Regulatory Commission). 1988. Peer Review for High-level Nuclear Waste Repositories, General Technical Position, NUREG-1297, February 1988.

Wilson, C., Porter, D., Gibbons, J., Oswald, E., Sjoblom, G., and F. Caporuscio. 1997. Conceptual Models Third Supplementary Peer Review Report, April 1997. Prepared for the U.S. Department of Energy, Carlsbad Area Office, Office of Regulatory Compliance, April 1997.

Attachment A

Schedule for Spallings Peer Review

Task Name	Completion Date
1. Identify Peer Review Contractor and Manager	
2. Receive Contract Authorization	
3. Identify Panel Selection Committee	
4. Reserve Meetings Rooms	
5. Identify Panel Members	
6. Justify Selection/Non-Selection	
7. Verify Panel Member Education	
8. Approve Panel Member Travel	
9. Prepare Final Peer Review Plan	
10. Prepare Orientation Notebook	
11. Select Peer Review Panel Chair Person	
12. DOE Delivers Spallings Documentation	
13. Orient Peer Panel	
14. Prepare 1st Meeting Agenda	
15. 1st Peer Panel Meeting	
16. 2nd Peer Panel Meeting	
17. Prepare Final Report	

Prepared by: _____

Approved by: _____

Appendix B

Determinations of Peer Review Member Independence

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE_ or a DOE contractor___? Yes/No

Were you employed by DOE or a DOE Contractor previously? Yes/No

(If yes, give dates, location, organization, position, and type of work performed).

Do you have or have you had any direct involvement or financial interest in the work under review? Yes/No
(If yes, describe the involvement)

Is there any reason why you cannot perform an impartial peer review? Yes/No
If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of bias in the results of your peer review? Yes/No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Ching H. Yew

Print Name: Ching H. Yew

Date: July 7, 2003

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE_ or a DOE contractor___? Yes/No

Were you employed by DOE or a DOE Contractor previously? Yes/No

(If yes, give dates, location, organization, position, and type of work performed).

1978-1982, Livermore, CA
LAWRENCE Livermore National Laboratory
EARTH SCIENCES DIVISION

Do you have or have you had any direct involvement or financial interest in the work under review? Yes/No
(If yes, describe the involvement)

Is there any reason why you cannot perform an impartial peer review? Yes/No
If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of bias in the results of your peer review? Yes/No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Jonathan Hanson

Print Name: JONATHAN HANSON

Date: 7/7/03

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE____ or a DOE contractor___? Yes/No

Were you employed by DOE or a DOE Contractor previously? Yes/No

(If yes, give dates, location, organization, position, and type of work performed).
Sandia National Labs from 1979-1999, Member of Technical Staff
Geomechanics primarily for oil + gas studies

Do you have or have you had any direct involvement or financial interest in the work under review? Yes/No
(If yes, describe the involvement)

Is there any reason why you cannot perform an impartial peer review? Yes/No
If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of bias in the results of your peer review? Yes/No
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Lawrence W. Teufel

Print Name: Lawrence W. Teufel

Date: 7/7/02

Statement of Unbiased Peer Review of the Spallings Model by Lawrence W. Teufel

Before accepting my current position in 1994 as the Langdon Taylor Professor of Petroleum Engineering at the New Mexico Institute of Mining and Technology I was a member of the technical staff at Sandia National Laboratories from 1979 to 1999. From 1994 to 1999 I had a joint appointment at Sandia Labs and New Mexico Tech. During my 20 year career at Sandia Labs I was involved with several cooperative DOE/Industry oil and gas projects and worked almost exclusively on petroleum-related rock mechanics studies on hydraulic fracturing, fluid-flow in natural fracture systems, *in situ* stress measurements, and reservoir compaction and subsidence. In my very early career at Sandia Labs I was involved in only one small WIPP related project, which was a rock mechanics study of the mechanical properties of anhydrite in the Salado Formation at WIPP. Colleagues at Sandia were involved with various geotechnical studies at WIPP. Over the years I have had many technical discussions with them on these projects. Since leaving Sandia Labs in 1999 I have had limited technical contact with Sandia staff members and these have been related only to tight gas projects with industry. When I was a member of the U.S. National Committee for Rock Mechanics I was asked and provided unbiased peer review of WIPP and Yucca Mountain geotechnical studies. At that time I was employed by Sandia Labs. I have no vested interest in any of the technical studies at WIPP conducted by Sandia Labs (other than my small anhydrite rock mechanics study, which went through peer review) or by any other group. I can and will provide an unbiased peer review of the Spallings Model.

Lawrence W. Teufel

Lawrence W. Teufel

Appendix C

Certifications Regarding Organizational Conflicts of Interest

I have reviewed each of the selected peer review panel member's (Jonathan M. Hanson, Lawrence W. Teufel, and Ching Hsie Yew) backgrounds and employment histories. I have also interviewed each of them to determine if they have any organizational conflict of interest or a bias for, or against, the WIPP facility as a nuclear waste repository. Through these background investigations and interviews I have determined that none of the selected peer review panel members has a bias or an organizational conflict of interest related to the Spallings Conceptual Model Peer Review. Please note that in the case of Lawrence Teufel having worked for Sandia National Laboratories, I requested a written statement by him attesting to his independence. That signed statement is attached.

John A. Thies,
Peer Review Manager

THE WASTE ISOLATION PILOT PLANT

A Potential Solution for the Disposal of Transuranic Waste

Committee on the Waste Isolation Pilot Plant

Board on Radioactive Waste Management

Commission on Geosciences, Environment, and Resources

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1996

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

Support for this study on the Waste Isolation Pilot Plant was provided by the U.S. Department of Energy, under Grant No. DE-FC01-94EW54069. All opinions, findings, conclusions, and recommendations expressed herein are those of the authors and do not necessarily reflect the views of the Department of Energy.

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Cover: Federal regulations require calculations to show that the Waste Isolation Pilot Plant (WIPP), if certified as a transuranic radioactive waste repository, is expected to isolate waste from the environment for the next ten millennia. Current plans call for the erection on site of permanent markers containing signs and symbols, intended as decipherable messages to warn future generations of the dangers to nature and to human health of digging into a filled and sealed repository below the surface.

Coincidentally, ten millennia is also the approximate age of the earliest known pottery from Asia. One millennium ago, a now-extinct Indian tribe, the Mimbres, lived in Arizona and New Mexico. The cover shows a Mimbres pottery design, perhaps representing the delicate balance of nature, using a man and two animals in a mobile arrangement. The Mimbres design is used by permission from *Art of a Vanished Race: The Mimbres Classic Black-On-White*, by Victor M. Giammattei and Nanci Greer Reichert, Published by Dillon Tyler, Publishers, P.O. Box 645, Calistoga, CA 94515.

The background photograph, provided by the Department of Energy Carlsbad Area Office, shows a close-up of a sample of Permian age salt crystals taken from the WIPP excavations. The permanence of the geologic salt formation (over 200 million years old) is an attractive feature of the WIPP site and illustrates the exceptional time scales of concern in nuclear repository design, time scales that extend well beyond the typical duration of most engineering projects, languages, and civilizations.

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ACKNOWLEDGMENTS

The committee has spent countless hours over the more than ten years since its last full report on WIPP, in discussions with staff from DOE and its contractors, EPA, officials of the State of New Mexico, the Environmental Evaluation Group, community leaders from Carlsbad, and concerned citizens. In open meetings held several times a year for more than a decade, the committee has heard a wide diversity of views on WIPP.

Genuine concerns have been expressed without rancor or polemics, but with conviction and unfailing courtesy. This is a tribute to the community involved in and concerned about WIPP. For the committee, and particularly the chair, it has been a privilege to have participated in these discussions. We sincerely appreciate all of the information and insights gained and hope that our report will be of value in arriving at an appropriate decision on the proposal to establish a TRU waste site at WIPP.

The committee thanks the many anonymous reviewers who painstakingly read and criticized our report, which has benefitted considerably from their efforts.

Finally, we wish to express our appreciation to staff colleagues of the National Research Council's Board on Radioactive Waste Management, both past and present, who have done much to assist the committee in its task. Particular thanks are due to Tom Kiess, Angela Taylor, and Erika Williams, without whose efforts the report would not have been completed.

Charles Fairhurst, *Chair*
October 1996

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Executive Summary

The Waste Isolation Pilot Plant (WIPP) is a network of underground excavations at a depth of approximately 658 m (2,160 ft), in bedded salt formations near Carlsbad, New Mexico, in the southeastern corner of the state (Figure ES.1). WIPP is intended to serve as a permanent repository for transuranic (TRU) waste, which consists of a wide variety of materials (such as protective clothing, laboratory equipment, and machine parts) that have become contaminated with radioactive transuranic elements[1] during use in defense-related activities. These materials, from U.S. Department of Energy (DOE) facilities, currently are stored at several DOE locations around the country and are classified as either CH (contact handled) or RH (remote handled) waste.

DOE has been investigating the suitability of WIPP as a TRU waste repository since the 1970s and plans to submit an application to the U.S. Environmental Protection Agency (EPA) in the fall of 1996 for a certificate of compliance to open and operate the facility. To obtain the certificate of compliance, DOE must demonstrate that the WIPP facility will comply with relevant U.S. federal regulations—chiefly, the EPA's 40 CFR 191 and 40 CFR 194.

The National Research Council (NRC) Committee on the Waste Isolation Pilot Plant was formed in 1978 at the request of DOE to provide scientific and technical evaluations of DOE investigations at WIPP. The committee's statement of task charges it to report on the current state and progress of the scientific and technical issues that form the core of a submission by DOE to EPA for certification of the WIPP facility.

Because DOE's compliance certification application to the EPA consists largely of conclusions drawn from DOE investigations, it is timely to comment on results of committee evaluations and their implications with regard to the overall suitability of WIPP as a repository for TRU waste (Box ES.1). This report presents these findings.

BOX ES.1

Uncertainty in Repository Performance

Assessing the performance of a radioactive waste repository over the long time periods of interest necessarily includes significant uncertainties. This is recognized by EPA in the standards for the disposal of TRU and high-level waste and spent nuclear fuel. Regarding the required degree of proof, EPA notes:

> *Performance assessments need not provide complete assurance that the requirements of Part 191.13(a) [i.e., the containment requirements] will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with Part 191.13(a) will be achieved.* (40 CFR Part 194.13(b))

This review of WIPP should be read with this limitation in mind; the findings and judgments reached in this report could not be achieved with absolute certainty, but instead reflect a reasonable expectation for WIPP performance based on the available evidence.

Several general committee findings regarding TRU waste disposal at WIPP are worth noting. These findings are based on the characteristics of the waste and the salt medium and from scientific and technical studies at WIPP and at potential salt repositories in other countries.

- Although TRU waste contains long-lived radionuclides that require geologic isolation, the overall

[1]Transuranic elements are those elements with atomic number greater than that of uranium. Most are radioactive because of their emission of alpha particles. TRU waste contains those with half-lives greater than 20 years in concentrations exceeding 100 nanocuries per gram.

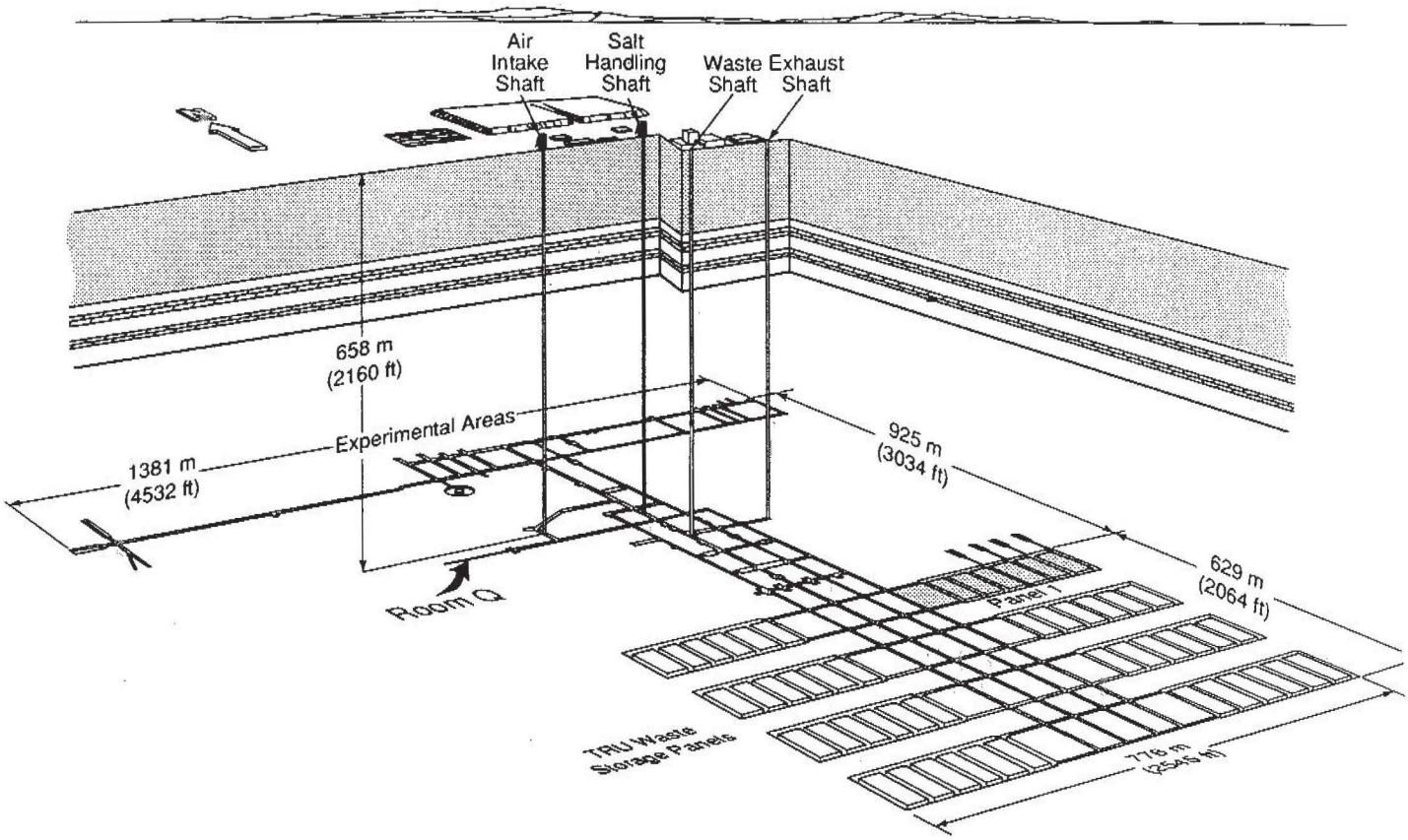

FIGURE ES.1 Three-dimensional view of the Waste Isolation Pilot Plant. The WIPP facility includes surface support buildings, a waste-handling building, four shafts, and the mined underground operations area. The repository is located approximately 658 m (2,160 ft) below the surface, within the Salado Formation, a Permian sequence of bedded salt with minor amounts of anhydrite and clay. The excavations are accessible from the surface by four vertical shafts. Only one of the planned eight panels, labeled Panel 1 in the diagram, has been excavated to date. Each panel consists of seven rectangular rooms, 10 m wide and 91 m long, separated by 30.5-m-wide pillars. Room Q, also labeled, is the site of a series of experiments on brine inflow into a 2.9-m-diameter, 109-m-long bored cylindrical tunnel. (Note: 1 meter [m] is approximately 3.28 feet [ft].) Source: Jensen et al. (1993), modified from their Figure 3-1.

level of radioactivity is much lower than that of high-level radioactive waste.[2]

• The early recognition of salt as an attractive medium for geological isolation (e.g., NRC, 1957) of radioactive waste has been confirmed by subsequent studies.

• Provided it is sealed effectively and remains undisturbed by human activity, the committee finds that the WIPP repository has the ability to isolate TRU waste for more than 10,000 years. The geologic stability and isolation capability of the Salado Formation, which consists of bedded salt, are the primary factors leading to this finding.

• The only known possibilities of serious release of radionuclides appear to be from poor seals or some form of future human activity that results in intrusion into the repository. The committee anticipates that the consequences of such human intrusion can be reduced based on available engineering design options and on improved understanding to be obtained from ongoing scientific studies.

• EPA's regulations (i.e., 40 CFR 191, as specified for WIPP in 40 CFR 194) relating to human intrusion do not take into account that if radionuclide releases to the environment via ground-water pathways at WIPP occur, they will be predominantly in non-potable water. This greatly reduces the risk of human exposure compared to a similar release in potable water.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The combination of general considerations, such as those outlined above, and detailed studies described later in this report, lead to the following conclusions and recommendations.

Based on available scientific evidence, the only probable threat to satisfactory isolation performance of the repository is the possibility of disturbance by human activity, deliberate or unintentional, that could compromise the integrity of the repository. Engineering methods are available, if needed, to reduce the consequences of human intrusion to acceptable levels.

[2]The level of radioactivity per unit volume of WIPP TRU waste is of the order of 0.1 percent of the corresponding level for U.S. spent fuel [see Chapter 1 Table 1.1].

Conclusion: Human exposure to radionuclide releases from transuranic waste disposed in WIPP is likely to be low compared to U.S. and international standards.

Consideration of the consequences of future activities that could violate the natural, or undisturbed, integrity of the repository is valuable for assessing the relative vulnerability of the repository to such activities and in identifying ways to reduce this vulnerability, but assessing human technologies thousands of years hence is highly conjectural and lacks a sound scientific foundation.[3]

Recommendation: Speculative scenarios of human intrusion should not be used as the sole or primary basis on which to judge the acceptability of WIPP (and, by extension, any geological repository).

Findings, Conclusions, and Recommendations on DOE Studies

DOE has concentrated on studies and calculations intended to determine compliance with federal regulations for WIPP in the event of human intrusion. Although the committee has not so restricted its studies, the following comments relate specifically to the DOE compliance activities. Most of the issues discussed below are significant only in the event of human intrusion.

1. *The role of Performance Assessment:* Performance assessment (PA) examines the combined effect of each component of the total system to assess the overall ability of the repository to isolate radionuclides from the biosphere. As used by DOE, PA responds to the question, "Is WIPP in compliance with federal regulations?"

Although PA has made important contributions to the WIPP project, in retrospect, it is clear that the potential of PA is higher, and important opportunities

[3]Federal regulations (40 CFR 191, 40 CFR 194) require stylized calculations on releases due to human intrusion. The level of proof required is a "reasonable expectation." See Box ES.1. The weight to be given to human intrusion possibilities is also discussed in *Technical Basis for Yucca Mountain Standards* (NRC, 1995; see especially, pp. 11, 107-111,115).

to put PA to good use have been missed. PA is valuable at all stages of the repository evaluation process. It can identify the most critical components of the system, assess the significance of engineered supplements to the natural geological barriers, and serve as an aid to planning and management decisions on the most effective allocation of staff and project resources.

2. *Conservatism of performance assessment models:* The PA models currently used by DOE are too conservative in some respects. Such conservatism masks the potential for identifying and assessing the benefits of relatively simple engineering design procedures in reducing the consequences of human intrusion.

The assumption that the Disturbed Rock Zone (DRZ) bordering the room excavations remains a relatively high-permeability region throughout the first 10,000 years of the repository appears overly conservative. This is in marked contrast to the assumption (see Chapter 4) that the DRZ around the shaft will heal, achieving a permeability of between 10^{-16} m^2 and 10^{-18} m^2 within 50 to 100 years and approaching the essentially impermeable condition of intact salt within a small fraction of 10,000 years. Such a conservative assumption with respect to the DRZ in the PA models may prevent a realistic evaluation of the major benefits of compartmentation of the waste by room and panel seals in reducing the consequences of repository disturbance by intrusion.

3. *Complexity of performance assessment models:* DOE's PA modeling of radionuclide releases from WIPP involves complex combinations of many variables such that, to the non-specialist, it is not clear how the predicted releases depend on the component features, events, and processes in the geological isolation system.

The committee recommends that DOE develop, in parallel with the complex PA models, simpler versions that provide a more transparent, traceable path from the model inputs to the predicted releases. The insights gained from the simpler model as to which components of the isolation system are most critical to improved repository performance would serve a very useful role in decision making and in resource allocation for WIPP. It is essential, of course, that the simpler PA models still identify correctly the key features, events, and processes upon which repository performance depends.

To illustrate this recommendation: because plutonium (Pu) is the dominant radioactive element of concern in the WIPP inventory, a simpler model could focus on Pu in the source term to the exclusion of other radioactive elements. However, understanding and predicting the behavior of Pu in the WIPP system is challenging, and experimental work with other actinides is necessary to develop the parameters for Pu required for the PA models, for both the full model and any simpler version. While studies of other actinides are necessary to support the chemical model developed for Pu, a simpler PA of the kind proposed here would consider only Pu isotopes as a source term, and only the dominant pathway(s) for environmental releases, with no more complexity than needed for an adequate representation.

4. *Waste characterization:* The waste characterization program being considered by DOE does not appear to be based on the needs for information important to an assessment of the long-term performance of the facility. Ideally, the PA should be used to determine what characterization is required.

5. *Nonradioactive constituents of TRU waste:* Nonradioactive hazardous constituents of TRU waste are considered to pose negligible long-term hazards compared to the radioactive constituents of WIPP waste (see Box 2.1 and discussion on 40 CFR 268 in Chapter 2).

6. *Behavior of salt at the WIPP site:* Time-dependent deformation of the salt and associated stratigraphic layers at WIPP is now understood well enough to allow reliable long-term calculations of salt deformation behavior as it relates to repository performance.

7. *Salado brine:* Small quantities of brine seep from the disturbed rock zone in the immediate vicinity of any excavation in the Salado Formation. The amount of brine accumulation is not sufficient to be a credible cause for significant escape of radionuclides from the sealed repository.

8. *Non-Salado brine:* Apart from possible effects of deep–well fluid injection in adjacent areas, brine flooding is only likely if, after loss of administrative controls, an intrusion borehole connects the repository with a deeper source of pressurized brine, such as has

been encountered by some deep boreholes in the vicinity of the repository.

9. *Gas generation in the repository*: Gas generation will be minimal in a dry or nearly dry repository such as WIPP because both chemical and biological gas-generating processes (e.g., metal corrosion and bacterial action on organic matter) require a liquid phase for mass transport of the reactants and products that are involved in gas formation.

10. *Treatment of waste:* Sophisticated treatment (e.g., incineration) of the TRU waste to be placed in a well-engineered WIPP repository is unwarranted to further improve repository performance, because gas generation is not a serious concern (see Chapter 3).

11. *Backfilling and compartmentation:* Simple repository engineering measures, such as backfilling of the rooms and tunnels in which the waste is emplaced, can be valuable and cost-effective methods of reducing the consequences of human intrusion and any associated brine flooding. Room and panel seals via backfill are relatively well-defined engineering procedures for improving the isolation process. In this regard, compartmentation is recommended by the committee to provide effective seals to eliminate hydrological communication between the waste-filled rooms.

12. *Non-Salado hydrology*: A more comprehensive understanding of the non-Salado hydrology is needed before a reasonable judgment can be made as to the role of the Rustler and adjacent formations in delaying radionuclide releases *in the event of human intrusion*. To date, studies have been overly focused on a two-dimensional analysis of the Culebra Dolomite. They have not sufficiently considered other possible hydrogeologic release pathways for radionuclides or interconnections between the Culebra and other formations. Potential releases to the Dewey Lake Red Beds, which are less conductive than the Culebra, but contain some potable water, are recommended for further study.

13. *Potash mining:* The consequences to the non-Salado hydrology of subsidence damage due to possible future mining of potash resources above the repository have not yet been evaluated by DOE. If the potential consequences are found to be seriously adverse, it is technically feasible to extract these resources pre-emptively, in a way that avoids subsidence and associated effects and that reduces the potential for human intrusion by drilling.

14. *Deep well fluid injection:* The requirement to consider the effects on the repository of fluid injection activities was a relatively new addition to the final version of EPA criteria for certification (40 CFR part 194.32(c)). Neither the probability nor the effects on the repository from nearby injection of water or brine have been evaluated in detail by the committee, nor has DOE published an analysis of this issue. A comprehensive analysis of the risks and consequences of this scenario should be completed and documented.

15. *Waste solubility and transport:* The PA completed by DOE in 1992, and all subsequent analyses, consistently have identified a set of issues that will have the greatest impact on the compliance of WIPP *in the event of human intrusion* and associated brine flooding of the repository. Prominent among these issues are

- actinide solubilities in brine,
- formation and transport of colloids containing radionuclides, and
- retardation of radionuclides during transport through the Culebra.

The EPA also has identified these issues as critical to its evaluation of the compliance certification application.

At the time of the writing of this report, the data and models to be used to represent these three issues in the next version of the PA (to support the compliance certification application) were not available for review.

16. *Continuation of experiments and analyses:* Continuation of analyses and experiments recently initiated in the WIPP program to address concerns raised in issues 12, 14, and 15 is recommended by the committee, even though the results may not be available in time to be used in the compliance submission. Results of such testing could reduce uncertainties in the long-term performance of WIPP, eliminate concern over other issues, and be useful in judging the cost effectiveness of various waste isolation procedures at WIPP and other repositories.

SUMMARY

- Provided the WIPP repository is sealed effectively and undisturbed by human activity, the committee knows of no credible or probable scenario for release of radionuclides.
- For the WIPP repository disturbed by future human activity, the committee has noted three ways in which confidence in the performance of the repository could be increased:

1. Re-evaluation of the probability and/or consequences assigned to highly speculative scenarios of future human activities may reduce the estimated risk of radionuclide release.
2. Experimental and field programs in progress or planned may show that key parameters (e.g., actinide transport) are well within the range required to reduce the impacts of human activities on radionuclide releases substantially.
3. The implementation of available engineering options (e.g., compartmentation, treated backfill), which have not been considered in published DOE analyses, could reduce the consequences of human intrusion. The cost effectiveness of these options will depend on the outcome of (1) and (2) above.

The committee believes that some combination of the above three considerations will very probably be sufficient to allow DOE to demonstrate that a WIPP repository will keep radionuclide release within acceptable levels for the disturbed case.

Chapter 1

Introduction

The Waste Isolation Pilot Plant (WIPP) is an underground facility in bedded salt approximately 658 m (2,160 ft.) below the surface in a semi-arid region near Carlsbad, New Mexico, in the southeastern corner of the state (see Figure 1.1). A U.S. Department of Energy (DOE) facility, WIPP has been studied intensively to determine its suitability as a permanent repository for disposal of the category of intermediate-level radioactive waste known as defense-related transuranic (TRU) waste.

WIPP is a pioneering effort in the assessment of geological site suitability and design procedures for a waste repository. It is the first geological repository in the nation for which an application to begin permanent geological isolation is being submitted for a regulatory decision. If approved, WIPP will be the first "deep" designed repository in the world. (The low and intermediate-level radioactive waste repository at Olkiluoto, Finland, is located at a shallower depth of 125 m; the German repository near Morsleben is an abandoned salt mine, not designed initially as a repository.)

This report discusses the key technical issues that influence the suitability of WIPP for isolation of TRU waste. This chapter describes the radioactive wastes under consideration for storage at WIPP, the design concept of long-term storage in geological formations, and a brief description of the history of work at the WIPP site. Following chapters address specific technical issues that arise in considering the various pathways or scenarios by which radionuclides could move from the repository and be released to the accessible environment.

TRANSURANIC WASTE: WHAT IT IS, WHERE IT COMES FROM, WHERE IT MUST GO

Transuranic waste results chiefly from the production of nuclear weapons from plutonium and enriched uranium. The term transuranic indicates that the waste contains radionuclides with atomic numbers greater than 92, that is, greater than that of uranium (see Box 1.1). Existing amounts of the principal isotopes of these and other elements and estimates of their projected total quantity in DOE facilities are listed in Table 1.1.

TRU waste consists of a wide variety of contaminated materials from laboratory and production operations, including discarded protective clothing, laboratory test equipment and reagents, machine components, and solidified sludge. This waste has accumulated over the past 50 years as a result of weapons development and production at U.S. defense facilities. Future TRU waste generation is expected to come from cleanup of the contaminated sites and decommissioned facilities of the U.S. weapons complex. Packed in 55-gallon steel drums and wooden boxes, TRU waste currently is being stored at various sites across the nation.

Although not as hazardous as high-level waste (see Table 1.1), TRU waste contains long-lived radionuclides that, if released to the biosphere, pose a risk to humans and the environment for many thousands of years into the future. Of all the actinide isotopes, plutonium-239 (Pu-239) is the one of greatest concerns substantially beyond about 500 years because of its high concentration in the materials to be stored at WIPP (Table 1.1) and its long half-life. Because of its long-lived toxicity, TRU waste, like high-level waste, must be isolated from the biosphere for times greater than 10,000 years. Disposal in deep, stable geological formations, so that very little of its radioactive content will reach the accessible environment by any natural means, has been proposed. The WIPP facility has been designed for the disposal of defense-related TRU waste to meet these conditions.

BOX 1.1 What Is Transuranic Waste?

The Department of Energy, which is responsible for the management and disposal of defense-related TRU waste, uses the following definition: TRU waste is waste that is not high-level waste and that is "contaminated with alpha[1]-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram" (DOE Order 5820.2A). The Land Withdrawal Act of 1992 and the EPA 40 CFR part 191 contain the legal, regulatory definitions that agree with this language. Further details on exclusions and inclusions to WIPP-bound waste are contained in these references.

The most important transuranic elements for judging the suitability of WIPP as a TRU waste repository are plutonium (Pu), the major component; americium (Am), a moderate component; and neptunium (Np), a minor component because of its relatively lower inventory. Common usage of the term TRU waste often includes all elements in the actinide group with atomic number 90 (thorium) or higher. Thorium (Th) and uranium (U) isotopes are minor components of the WIPP inventory (Table 1.1), smaller components than americium. Other radioactive elements are present in the waste but in amounts so small that they have a less significant influence on the determination of the performance of the proposed repository.

Some of the isotopes of the actinide elements are long-lived alpha emitters with half-lives ranging up to billions of years. For many isotopes, however, the concentrations are low. Plutonium-239 (Pu-239), with a half-life of about 24,000 years, is the isotope of greatest abundance beyond about 500 years.

The radioactive constituents of TRU waste pose a radiological health hazard and are regulated by EPA in 40 CFR 191 and 40 CFR 194. Some TRU waste is mixed with chemically hazardous materials (e.g., certain toxic metals and organic compounds); the health consequences of exposure are derived from the chemical effect of these materials on the human body. EPA standards in 40 CFR 268 (also known as the Resource Conservation and Recovery Act of 1976, or RCRA) regulate the chemically hazardous constituents. An amendment (P.L. 104-201) to the WIPP Land Withdrawal Act (P.L. 102-579) exempts WIPP from federal RCRA requirements.

[1]Radionuclides that emit positively charged (alpha) particles in the process of decaying to more stable nuclides. Alpha radiation is the least penetrating of the three common forms (beta and gamma radiation are the other two) and cannot penetrate human skin. However, alpha emitters can be harmful if ingested or inhaled, or if they enter the body through other means, for example, through contact with a cut in the skin.

GEOLOGIC DISPOSAL OF RADIOACTIVE WASTE IN SALT

The objective of the U.S. nuclear waste disposal program is to place the waste in a location where harmful quantities cannot return to the biosphere by any foreseeable processes. The decision to develop a waste disposal facility in salt arose from an assessment by a committee of the National Research Council (NRC) appointed to study the problem of how to dispose of accumulating inventories of high-level radioactive waste. In its report, *The Disposal of Radioactive Waste in Land,* published in 1957, the committee recommended further work to assess the suitability of burying high-level radioactive wastes in stable geological formations at depths on the order of 500-1,000 m below the surface (NRC, 1957). Every other country that must deal with radioactive waste isolation, including Belgium, Canada, China, Finland, France, Germany, Japan, Russia, Sweden, Switzerland, Taiwan, and the United Kingdom, plans to use geological disposal to isolate radioactive waste.

The 1957 committee was particularly attracted to the notion of burying the waste in rock salt, either in salt domes or in thick salt beds It cited the following advantages:

- Salt can be mined easily.
- It is known to flow slowly under the pressure of overlying beds, and so will consolidate around the waste and isolate it in place.
- It is essentially impermeable.

TABLE 1.1 December 1995 Estimates of Inventory of Actinide Waste[a]

	CH-TRU	RH-TRU
Total anticipated activity (Ci), all isotopes	7,880,000	1,020,000
Design capacity of WIPP (m^3)	168,500	7,080
Total anticipated volume of WIPP (m^3)	110,000	27,000
Average activity WIPP TRU waste (Ci/m^3) [b]	46.8	143
Average activity of anticipated volume (Ci/m^3) [c]	71.6	37.8

Isotope	Half-life[e] (years)	Total CH-TRU (Ci)	Total RH-TRU (Ci)
Th-232[d]	1.41×10^{10}	9.11×10^{-1}	9.24×10^{-2}
U-233[d]	1.59×10^{5}	2×10^{3}	3.18×10^{1}
U-234[d]	2.45×10^{5}	5.53×10^{2}	3.93×10^{1}
U-235[d]	7.0×10^{8}	1.28×10^{1}	5.2×10^{0}
U-238[d]	4.47×10^{9}	3.96×10^{1}	1.44×10^{0}
Np-237	2.14×10^{6}	5.49×10^{1}	4.85×10^{-2}
Pu-238	8.77×10^{1}	3.8×10^{6}	1.45×10^{3}
Pu-239	2.4×10^{4}	7.82×10^{5}	1.03×10^{4}
Pu-240	6.5×10^{3}	2.08×10^{5}	5.07×10^{3}
Pu-241[d]	1.44×10^{1}	2.61×10^{6}	1.42×10^{5}
Pu-242	3.7×10^{5}	1.17×10^{3}	1.5×10^{-1}
Am-241	4.33×10^{2}	4.39×10^{5}	5.96×10^{3}

NOTE: CH-TRU = contact-handled transuranic waste; RH-TRU = remote-handled transuranic waste. The design capacity of RH-TRU is legally specified as 250,000 cubic feet (7,080 cubic meters). As the table shows, the anticipated volume specified in (DOE, 1995c) exceeds this quantity. This discrepancy could be resolved by a future change in the numerical estimates of anticipated volumes, or by a future renegotiation to augment the legally specified limit, or by waste processing to reduce the volume of the RH-TRU transported to WIPP to be less than the volume generated. Both DOE documents and EPA standards measure radioactivity in curies, where one curie, 3.7×10^{10} disintegrations per second, is the historical unit representing approximately the radioactivity of one gram of radium 226. The Systeme Internationale (SI) unit for radioactivity is the Becquerel, 1 disintegration per second. U. S. regulations express dose equivalent in roentgen-equivalent-man (rem) units, another historical unit differing from the SI unit, the Sievert (Sv), where one Sv is 100 rem. Because the U. S. work on WIPP uses these older units, they are used in this report.

[a] Not shown are minor concentrations of many other isotopes.

[b] The Ci/m^3 values shown here derive from the total activity (Ci) and the design capacity of the WIPP repository (m^3). By comparison, the average activity of U.S. spent fuel high level waste is 140×10^3 Ci/m^3 (10-year-old waste) and 140×10^2 Ci/m^3 (100-year-old waste). See Roddy et al. (1986).

[c] The Ci/m^3 values shown here indicate the ratio of total activity in curies (Ci) to the total anticipated volume (m^3) of waste to be shipped to WIPP.

[d] Because the half-life of Pu-241 is less than 20 years, it falls outside the EPA 40 CFR 191 definition of TRU waste, although it is a transuranic isotope. The thorium and uranium isoptopes are likewise actinides shown here that are excluded from classification as TRU waste, since they are not transuranic isotopes.

[e] The level of radioactivity decreases exponentially with time, with the half-life denoting the time at which the initial amount of any radionuclide is halved. After ten half lives, approximately 0.1 percent of the initial radioactivity remains. For long times, the WIPP inventory is dominated by Pu-239, ten half lives of which is a quarter of a million years. This time, at which approximately 0.1 percent of the initial amount of Pu-239 remains, is only roughly 0.1 percent of the present age of the geologic formation in which WIPP is excavated.

Source: (DOE, 1995c, Tables ES-3, ES-4, and 3-4).

• Salt that has existed underground for millions of years will almost certainly remain stable for thousands of years into the future.

These advantages, and others also, were noted in a subsequent study (NRC, 1970).

HISTORY OF WIPP

Selection of the present WIPP site came after rejection of a previous candidate site, an abandoned salt mine near Lyons, Kansas. Investigated from the mid-1960s to the early 1970s, the Kansas site was abandoned because of the large number of boreholes penetrating the formation and salt dissolution issues (Powers et al., 1978). Renewed efforts at a nationwide site selection and characterization process resulted in a focus of attention on the New Mexico region of the Delaware Basin (see Appendix A).

Exploratory drilling began in 1974 for a possible deep geologic TRU-waste disposal site in salt beds in New Mexico. The first location selected for study was rejected as the permanent site principally because of irregular subsurface geology (Powers et al., 1978). Recommendation of the present site was made in 1975. In 1976, the name "Waste Isolation Pilot Plant" was given to the project, and ERDA-9, the first exploratory hole located at the present site, was drilled (Powers et al. 1978; NRC, 1984). In 1979, the WIPP site, about 40 km, (25 miles), east of Carlsbad, NM in the southeastern corner of the state (Figure 1.1), was authorized, after preliminary testing, as a "research and development facility for demonstrating safe disposal of radioactive waste from defense activities and programs" (U.S. Congress, 1980). Construction of WIPP, together with studies of its suitability as a TRU repository, proceeded through the 1980s.

THE WIPP UNDERGROUND FACILITY TODAY

The WIPP facility is located approximately 658 m below the surface in the layered salt of the Permian Salado Formation (see Figure ES.1). Four vertical shafts from the surface provide access to the repository horizon and underground excavations. Drifts (underground roadways) link the shafts to the waste disposal area, which is planned to consist of eight panels (the rectangular sections off the main haulage ways in Figure ES.1), each subdivided into seven rectangular rooms excavated between access drifts (corridors that provide passage to the individual disposal rooms, bounded by 30.5-m-wide pillars on each side). To date, only one of these panels has been excavated. Disposal room dimensions are 4 m high by 10 m wide by 91 m long. The drifts are essentially the same height but narrower than the rooms and are of varying lengths. Rooms have been excavated to follow the nonhalite marker beds that occur throughout the Salado, which dip at about 1° (from horizontal) to the south. Thus, the system of excavations is essentially horizontal.

THE DISPOSAL PLAN

The disposal plan involves stacking TRU waste-filled drums in each room until the room is filled. Some material may be packed into the spaces around the drums to fill the void spaces, a process termed "backfilling." Waste-filled rooms could be backfilled with crushed salt (excavated from the repository); crushed salt mixed with bentonite (a water-absorbing clay mineral); other materials combined with the salt (e.g., additives to reduce the solubility of plutonium in brine); or grout (Butcher, 1990; DOE, 1991). The specific plans for backfill have not been revealed in repository designs published prior to 1996.

A separate series of drifts and rooms for underground experiments has been excavated at the north end of the facility, several hundred meters from the disposal area (Figure ES.1). Various underground tests have been performed since the 1980s (see, for example, Butcher and Mendenhall, 1993), but these are now considered complete. The experimental area will not be used for waste disposal.

REGULATION AND LICENSING OF WIPP

In 1992, the WIPP Land Withdrawal Act (LWA; P.L. 102-579) transferred control of land at the WIPP site from the Secretary of the Interior to the Secretary of Energy and granted authority to the Secretary of Energy to close the area and its immediate surroundings to public use. A major provision of the LWA requires

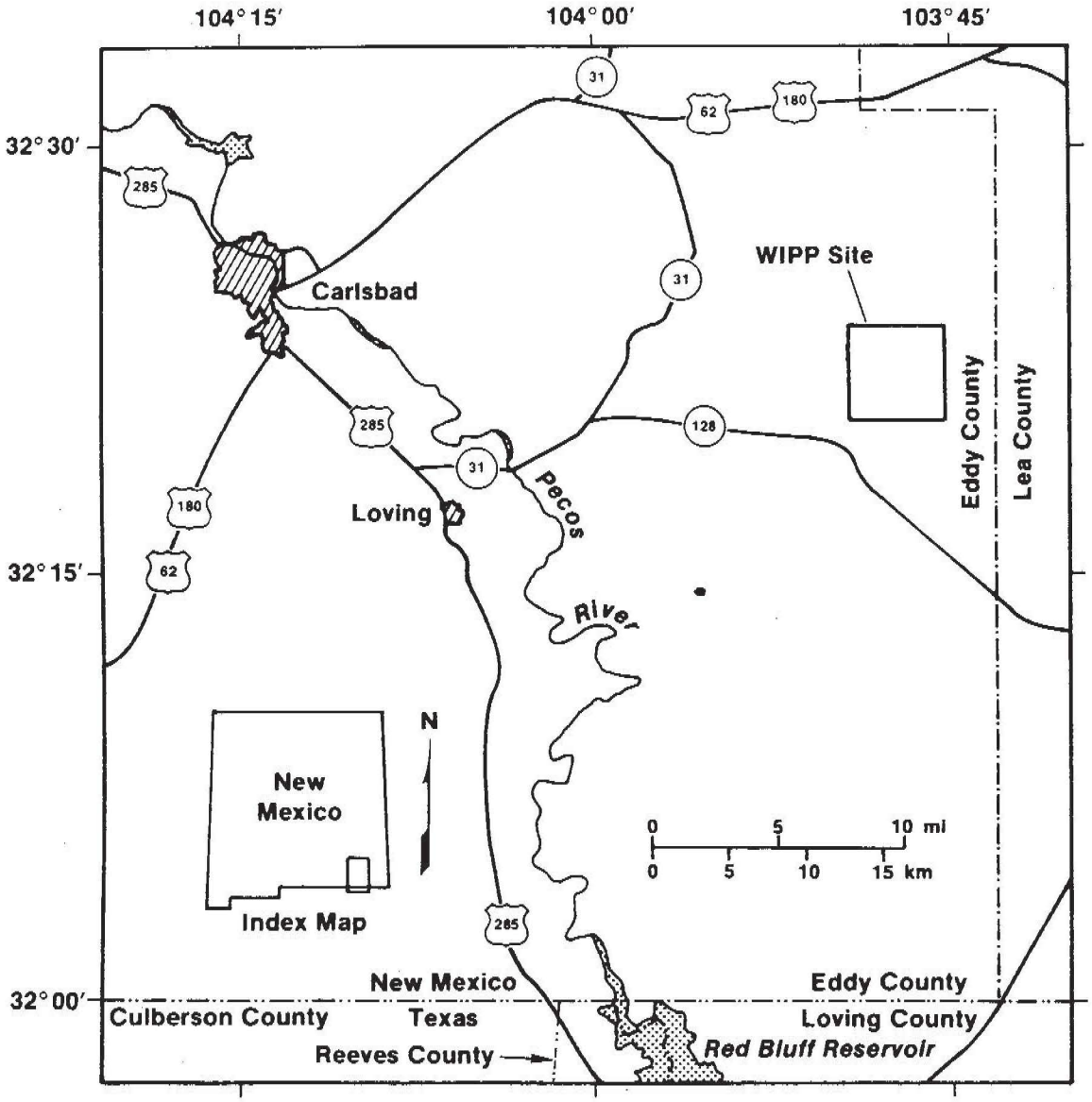

FIGURE 1.1 Location of the Waste Isolation Pilot Plant site. Inset map shows approximate location of map area in the state of New Mexico. Source: Modified slightly from Sewards et al. (1991, Figure III-1).

BOX 1.2 Compliance and Safety

The U.S. Environmental Protection Agency is responsible for ensuring that any U.S. geological repository for radioactive waste does not result in significantly adverse effects on human health and the natural environment. Federal standards have been promulgated to this end, and any proposed repository must be shown to be in compliance with these standards before it can be opened and operated to accept waste. When applied to a particular repository such as WIPP, features not anticipated in formulating the *compliance* standards could affect the overall *safety* of the repository. It is conceivable that a repository could comply with the standard, yet be significantly more or less safe than the measure of safety implicitly understood when the standard was formulated. This distinction could be important, because the federal standard (40 CFR 191) has never been applied to a real repository licensing situation.

The difference between compliance and safety can be illustrated by a simple example from the WIPP repository. EPA has defined the "accessible environment" as the region outside a 5-km-radius vertical cylinder around the center of the WIPP site, extending downward without limit from the surface (see Figure 1.2). DOE has chosen to define the boundary used in the compliance calculations as a smaller region, a 4 mile (N-S) by 4 mile (E-W) square region (6.4 km by 6.4 km square region) placed centrally within the 5-km-radius circle and also extending downwards without limit from the surface. Any migration of radionuclides across this boundary in excess of limits specified in the standard (40 CFR 191) constitutes a violation—that is, a failure to comply. This is independent of the depth at which the migration occurs and without consideration of the pathway by which the radionuclides would reach the surface.

Most of any "escaping" radionuclides would reach the accessible environment by transport in water. At WIPP, the most probable "escape route" to the surface is in the brine of the Culebra Dolomite, but this brine is for the most part undrinkable, even to cattle. This greatly reduces the safety risk compared to transport of the same quantity of radionuclides in fresh water. However, the containment requirement of the EPA standard does not address the potability of water containing the released radionuclides. Releases to salty, unpotable water near the surface thus may pose a *compliance* problem while presenting little *safety* hazard.

The committee found no probable situation for which the WIPP repository could be found to be in compliance with 40 CFR 191 and yet not be safe.

DOE to show that the repository will comply with federal regulations. The LWA designated the Environmental Protection Agency (EPA) as the regulator to determine whether or not compliance with appropriate regulations has been achieved (see Box 1.2). Chief among EPA regulations is the 40 CFR 191 standard, which describes general radiation protection requirements. Two other important regulations are EPA's 40 CFR 194, which describes the specific requirements at the WIPP site for compliance with 40 CFR 191; and EPA's 40 CFR 268 Resource Conservation and Recovery Act (RCRA) requirements on the chemically hazardous constituents of WIPP-bound waste.

Over the past two decades, DOE has conducted an extensive program of investigations to assess the suitability of WIPP as a TRU waste repository—that is, as a site that will adequately isolate the waste from the environment. Sandia National Laboratories has served as chief technical adviser, with help from many sources, including the nearby Los Alamos National Laboratory, several other national laboratories, the U.S. Geological Survey, universities, and private engineering and consulting firms.

FRAMEWORK FOR THE REPORT

Presently, DOE is preparing an application to the EPA for a certification of compliance of the WIPP facility to demonstrate that the proposed repository meets regulatory requirements. Because the compliance certification application consists largely of conclusions drawn from DOE's scientific and technical investigations, it is timely to comment on results of the committee's investigations to date and their implications with regard to the overall performance of WIPP as a repository for TRU waste. Like the previous studies of the WIPP Committee (NRC, 1984), this

report is a review of ongoing activities and should be viewed as a progress report rather than a final evaluation (see also Box 1.3).

Analyses of the performance and regulatory compliance of WIPP are addressed via performance assessment (PA), a process for identifying, for hypothetical future conditions, the potential pathways by which radionuclides could most probably be released to the environment. Chapter 2 reviews the allowable releases of radionuclides in EPA standards, describes the PA methodology used to demonstrate compliance with these release limits, and discusses PA results related to WIPP.

A detailed examination by DOE has been carried out over the past decade to study possible ways in which releases could occur, ranging from inadequate sealing of the repository to meteorite impact, climatic change, glacial erosion of the overlying formations to expose the waste, and many others. These possibilities were reduced by DOE to the 75 most credible features, events, and processes (FEPs), which were then examined in greater detail.

This examination indicated that eight combinations of events, or scenarios, warranted careful scrutiny (see Figure 2.2). From this group, the so-called "E1E2" scenario emerged as potentially the most serious way in which the isolation integrity of the repository could be violated. This scenario, which is discussed in more detail in Chapter 2 (see Figure 2.5), involves the drilling, some time within the next 10,000 years, of two oil or gas wells (either for exploration or for production), both of which intersect the repository. One of the wells also connects into a large reservoir of pressurized brine in the Castile Formation below the repository. It is further assumed that both wells would be "capped" (that is, sealed) near the surface and that the well casings would have corroded so that brine from the Castile could flow under high pressure through the repository, up the second hole, and into the Rustler Formation (principally the Culebra Dolomite), which lies above the Salado Formation. From there, the radionuclide-contaminated brine could flow more or less horizontally in the regional ground-water system, eventually reaching the accessible environment via a well drilled into the Rustler Formation to provide drinking water for cattle.

Detailed investigation of the factors that could influence the radionuclides released by the E1E2 and other scenarios has led to the identification of several issues that could be important in demonstrating the suitability of WIPP as a TRU waste repository. Chapters have been arranged to cover each of these issues. The performance assessment methodology used to calculate compliance integrates information from geological, hydrological, chemical, and repository design influences on radionuclide releases to the environment. The geological and hydrological influences of the salt beds that serve as host rock for the repository are discussed in Chapter 3. The significance of repository design options and waste treatment are discussed in Chapter 4. The chemistry of the radionuclides in brine and mechanisms of radionuclide

BOX 1.3 NRC Committee on WIPP

In March 1978, DOE asked the NRC to review the scientific and technical criteria and guidelines for designing, constructing, and operating the Waste Isolation Pilot Plant to isolate radioactive wastes from the biosphere. The panel (now committee) on the WIPP was established within what is now the NRC's Board on Radioactive Waste Management.

Since 1978, the committee has provided guidance to DOE on the scientific and technical adequacy of DOE programs designed to assess both the capability of the facility to isolate TRU waste and the overall performance of the facility. Two current members (Fred Ernsberger and former Chair Konrad Krauskopf) served on the original 1978 panel; three others (John Blomeke, Rodney Ewing, and Charles Fairhurst) began service in 1984.

The last comprehensive report issued by the committee was in 1984 (NRC, 1984). Eight letter reports on specific issues at WIPP (NRC, 1979a,b, 1987, 1988a, b, 1989, 1991, 1992) also have been produced by the committee.

The committee's current official statement of task is as follows:

> The Waste Isolation Pilot Plant Committee would prepare a report on the current status and progress of the scientific and technical issues that form the core of a submission by DOE to EPA for certification of the WIPP facility as a safe long-term repository for radioactive transuranic waste that complies with relevant regulations.

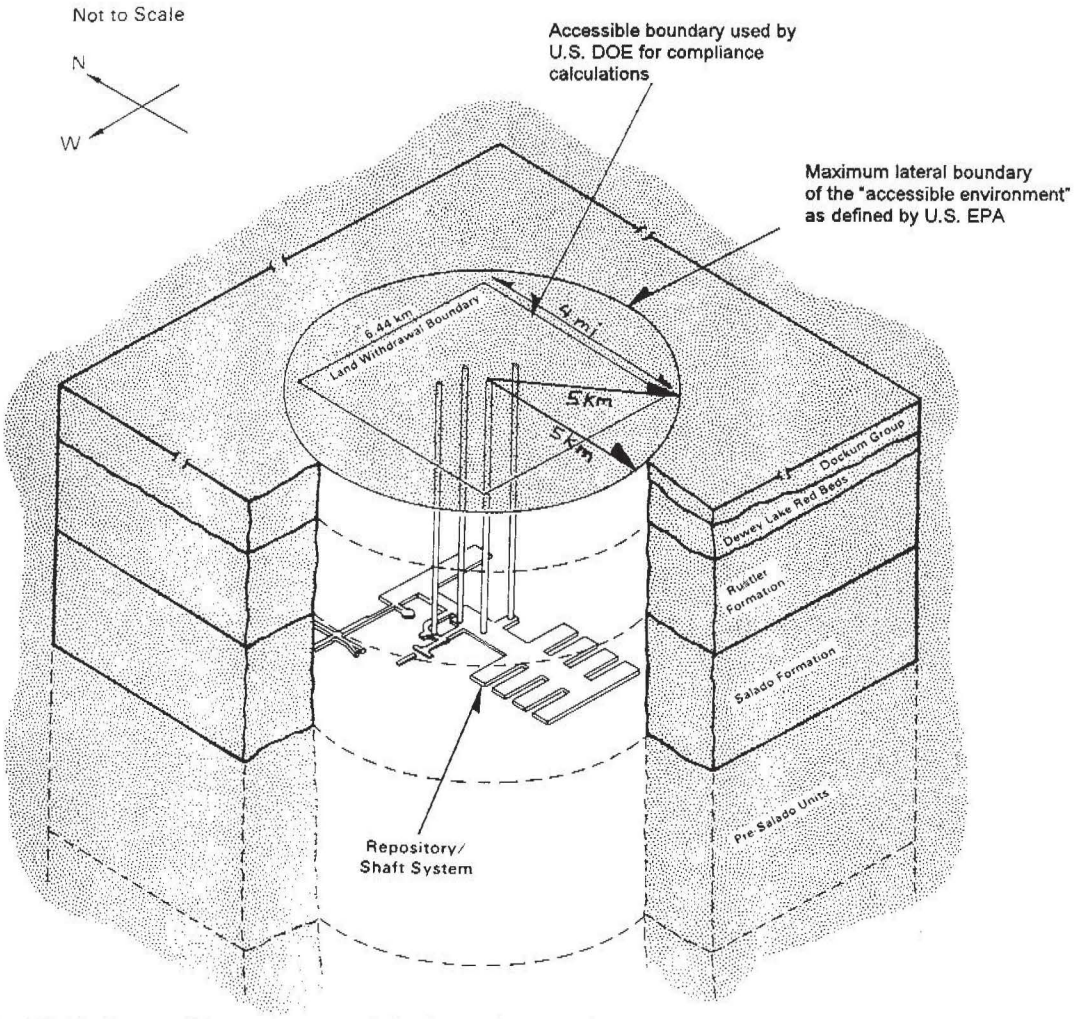

FIGURE 1.2 The EPA's "accessible environment" is shown here as the region outside a vertical cylinder of 5-km radius, centered on the WIPP repository. DOE calculations are aimed at demonstrating compliance within a smaller region, a volume bounded by vertical sides that extend downwards without limit from a 4 mile by 4 mile (6.4 km by 6.4 km) square cross section. Source: Adapted from Marietta et al. (1989, p. II-3).

transport in the subsurface environment are discussed in Chapter 5. Chapter 6 discusses the state of knowledge of the hydrological characteristics of the geological strata above the salt at WIPP, that is, the strata that would serve as a final barrier to releases of radionuclides to the accessible environment. Finally, Chapter 7 provides a summary of the conclusions reached in the committee's investigations. The first seven appendixes to the report provide supplementary information on specific aspects of the chapter discussions. An overview of the WIPP program, intended to assist readers in following the main themes and findings of the report, is presented in Appendix G.

The focus of the committee's review has been on the long-term, post-closure performance of WIPP. The issues associated with the operational phase, both surface and sub-surface, as well as the activities that must occur at other DOE sites, are not included in this evaluation. It is the committee's belief that the scientific basis for these other activities, both by DOE and by the various regulatory agencies involved, has been considered adequately in previous reports, except for a few issues that cut across both the operational phase and the post-closure phase. An example of this type of activity is waste characterization, which is discussed in Chapter 2.

Chapter 2

Regulatory Compliance and Repository Performance

To dispose of transuranic (TRU) wastes in the Waste Isolation Pilot Plant (WIPP), the Department of Energy (DOE) must demonstrate that the repository complies with applicable regulatory standards. These standards address

- transport of TRU wastes to WIPP,
- protection of workers from hazardous materials and mining hazards during operations, and
- the long-term performance of WIPP after wastes have been emplaced and the facility has been closed.

This report focuses on the third issue.

Two general standards of the Environmental Protection Agency (EPA), the first of which is defined in two parts, concern long-term repository performance:

1. a. EPA's *Standard for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Wastes,* 40 CFR Part 191 (or "Part 191"): 40 CFR 191 specifies requirements of geologic disposal systems in the United States.

   b. EPA's *Criteria for the Certification and Determination of the Waste Isolation Pilot Plant's Compliance with Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*, 40 CFR Part 194 (or "Part 194"): 40 CFR 194 addresses the specific application of 40 CFR 191 to WIPP.

2. The Resource Conservation and Recovery Act (RCRA) of 1976, 40 CFR Part 268: This law establishes a procedure to track and control hazardous wastes from the time of generation to the time of disposal.

This chapter is devoted mainly to a discussion of what is and what is not known by the committee about the long-term performance of WIPP in terms of the EPA standards. Compliance issues relating to RCRA are addressed in less detail. Issues associated with operations of the repository and transportation of waste to the repository are not considered. The most likely pathways, or "scenarios," through which radioactive materials could be released to the accessible environment are described, together with the performance assessment (PA) approach used to evaluate those scenarios against the EPA standards and some of the results to date. The chapter concludes with comments on the quality of the performance assessment work for WIPP, a brief discussion of other long-term radiological compliance issues, and some overall conclusions.

EPA STANDARDS FOR RADIOACTIVE WASTE

The EPA standard for long-term isolation of the types of radioactive wastes intended for emplacement in WIPP consists of both (1) the quantitative containment requirements and individual and ground-water protection requirements, and (2) the more qualitative assurance requirements, which are intended to provide confidence that the desired level of protection is achieved. The assurance requirements for waste characterization and monitoring are discussed later in this chapter.

A key aspect of the quantitative standards of 40 CFR Part 191 is the distinction between disturbed and undisturbed performance of the repository.

Undisturbed and Disturbed Repository Performance

Undisturbed performance refers to the case in which any releases of radionuclides to the accessible environment occur as the result of reasonably foreseeable natural processes. Releases due to human intrusion or from unlikely natural events—defined in

Part 191 as events having less than a 1 in 10,000 chance of occurring in 10,000 years—are excluded from the undisturbed case.

Undisturbed performance of the repository is governed by the individual and ground-water protection requirements of 40 CFR Part 191. The individual protection requirements limit the committed effective dose to any individual resulting from releases from the undisturbed repository to 0.15 milliSievert (15 mrem) per year. The ground-water protection requirements set concentration limits for potable sources of ground water that might come in contact with the wastes.

Disturbed performance includes consideration of inadvertent human intrusion into the repository. The EPA standard, Part 191, and supporting guidance require that releases of radionuclides resulting from drilling into the WIPP repository be considered, along with other specified disruptive events, named below, that could affect the performance of the repository. **The containment requirements, reproduced below, apply to the disturbed performance of the repository.**

Part 194 directs DOE to assume that the frequency of boreholes drilled into the WIPP site be based on the rate of drilling observed in the Delaware Basin during the 100 years prior to the time of the compliance application, by taking into account both deep drilling (i.e., boreholes that would reach the depth of the WIPP repository) and shallow drilling (i.e., boreholes that would not reach the depth of the repository). EPA specifies that the assumptions about future drilling practices with regard to borehole diameter and plugging practices should be consistent with practices in the Delaware Basin at the time of the compliance application.

Part 194 also requires that DOE consider the effect that mining of any potash of economic grade (in today's market) would have on the hydraulic conductivity of formations above the repository, and the effect that fluid injection for enhanced oil recovery in nearby oil and gas wells would have on the repository.

Containment Requirements

40 CFR 191.13 requires that

> *disposal systems for . . . transuranic radioactive wastes shall be designed to provide a reasonable expectation, based on performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:*
>
> *1. Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A)*[1]*; and*
> *2. Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).* (40 CFR 191, 1995, p. 11)

The key words in this regulation are "reasonable expectation," in recognition of the uncertainties inherent in making assessments over a 10,000-year time frame.

In paraphrasing 40 CFR 191.12, a performance assessment is defined as an analysis that identifies all significant processes and events that could affect the repository and evaluates the likelihood of each process or event and the effects of each on the release of radionuclides to the environment. To the extent practicable, these estimates are combined into an overall probability distribution displaying the likelihood that the amount of radioactive material released to the environment will exceed the values specified in Table 1, Appendix A to 40 CFR 191 (40 CFR 191, 1995, p. 11).

40 CFR 191 and 40 CFR 194 Radiation Dosage and Containment Requirements

In comparison to the radioactive waste standards adopted by most countries, Part 191 is unique in that, in addition to regulation based on radiation dose, repository compliance also is based on calculations of release fractions of selected radionuclides (Table 2.1). The containment requirement addresses the ability of a

[1]Table 1 of Appendix A of 40 CFR 191 is shown in this report as Table 2.1.

TABLE 2.1 Part 191 Containment Requirements for Selected Isotopes. Source: 40 CFR 191, Appendix A (1995)

Radionuclide	Release Limit (Ci/MTHM)
Thorium-230 or 232	10
Uranium-233, 234, 235, 236, or 238	100
Neptunium-237	100
Plutonium-238, 239, 240, or 242	100
Americium-241 or 243	100

The release limits specified here scale with the quantity of waste in a repository; for this reason, they are specified in terms of curies (Ci) that may be released per 10,000 years per 1,000 metric tons of heavy metal (MTHM). For a repository such as WIPP, which is intended to contain transuranic wastes, EPA has established in 40 CFR 191 that 1,000 MTHM is equivalent to 1,000,000 curies of TRU wastes with greater than 20-year half-lives. Therefore, the limits specified are applicable per million curies of TRU waste.

repository to isolate waste from the environment, without distinguishing releases that would lead to significant doses from those that would not. One advantage of this requirement is that, unlike a dose limit, it does not require assumptions about where people will live, how and where they will grow food, and what water sources will be used. A disadvantage is that the Part 191 containment requirements do not differentiate between transport of radionuclides off-site in a pristine aquifer that is a likely exposure pathway and—in the case of WIPP—transport via the Culebra Dolomite, in which the high content of dissolved solids makes the water unfit for human consumption.

Quantitative Assessment of Human Intrusion

Dealing quantitatively with human intrusion is a difficult issue. Any assessment of releases or risks from human intrusion into a repository is inherently arbitrary because the nature and rate of future intrusion over a 10,000-year time frame cannot be known. One advantage of basing the future human intrusion rate on the historical rate, as EPA does, is that the effect of known resources on past exploration and production activities is considered. However, whether or not this knowledge will predict accurately what may happen in the future—especially when institutional controls preventing intrusion have been lost—is uncertain. The difficulty does not concern specific details of EPA's guidance regarding how to treat intrusion in performance assessment, but rather that such guidance is arbitrary and of unknown validity with respect to how future events actually will occur. The same issue is of concern in Europe and other countries dealing with the regulation of geological repositories. In general, radionuclide releases resulting from human intrusion tend to be treated qualitatively in these countries, for example, as a consideration in site selection.

The way in which human intrusion is handled in regulations 40 CFR 191 and 194 implies that WIPP, or any potential repository, could "pass or fail" on the basis of a human intrusion scenario that is, by necessity, arbitrary, especially in its assumptions concerning future technology. **Indeed, human intrusion rates or scenarios could be devised that would cause *any* geological repository to comply or fail to comply with EPA standards.** This issue of human intrusion has been considered at length in the NRC report *Technical Bases for Yucca Mountain Standards* (NRC, 1995).

40 CFR 268 Hazardous Waste Requirements

Until recently, federal law dictated that WIPP must comply with both the radioactive waste standard (40 CFR 191) and the RCRA standard (40 CFR 268), the latter of which establishes requirements for the disposal of chemically hazardous wastes (see Box 2.1). The 40 CFR 268 standard prohibits the land-based disposal of untreated hazardous wastes under most circumstances. This "land ban" has a "no-migration" provision by which a variance can be granted to permit the disposal

Box 2.1 Chemically Hazardous Waste Issues

Based on information presented by EPA and DOE contractor staff, it appears to the committee that RCRA performance will not be a limiting factor in the long-term performance of WIPP. Nonetheless, the following simple comparison can be made of the quantities and toxicities of the radioactive and chemical constituents of WIPP waste.

Source-term data reported in DOE's 1995 Draft Compliance Certification Application (DCCA) indicate that, in an average cubic meter (m^3) of contact-handled waste, the inventory of radioactive actinides with half-lives greater than 20 years, multiplied by EPA's risk factors for ingestion of these radionuclides, is equal to 8,500.* Thus, the risk from one cubic meter of contact-handled WIPP waste, if ingested, is quite high. By contrast, the inventory of volatile organic chemicals (VOCs) in 1 m^3 of WIPP waste, multiplied by the unit risk factors for inhalation of the VOCs, is reported in the WIPP Draft No-Migration Variance Petition to equal 46.

The EPA unit risk factors are based on daily inhalation of 20 m^3 of air for 70 years. Conversion of the risk factors associated with the inhalation of VOCs in 1 m^3 of waste gives a risk of 9×10^{-5}—that is, 9 chances in 100,000. This suggests that the relative toxicity (i.e., the ratio of the quantity of hazardous material, weighted by its toxicity) of ingested radionuclides to inhaled VOCs is of the order of 10^8. If the risk factors for *inhalation* (rather than for *ingestion*) of radionuclides are used, the toxicity of radionuclides relative to that of VOCs is of the order of 10^{10}.

This simple comparison of the quantity and toxicity of the waste components supports EPA's statement that the hazardous nature of WIPP waste is due to radioactive materials and that provisions for the long-term protection of public health and the environment from radionuclides in WIPP will also offer adequate protection against public health risks from chemical hazards.

* Normally, the product obtained by multiplying a quantity of hazardous material by its unit risk factor is the risk associated with the ingestion or inhalation of that material. However, a risk greater than 1 has no meaning. In such cases, the resultant product should simply be considered a toxicity-weighted inventory of hazardous material.

of untreated waste if the applicant can demonstrate that the waste will not move after disposal. In 1989, DOE submitted a No-Migration Variance Petition for the planned underground test program at WIPP and received approval for a 10-year period. In 1995, a Draft No-Migration Variance Petition was submitted by DOE for full-scale operations at WIPP.

During the 104th Congress, bills (U.S. Congress, House of Representatives, 1995, 1996; U.S. Congress, Senate, 1996) were introduced to amend the WIPP Land Withdrawal Act. Among other features, these bills would exempt WIPP from compliance with long-term RCRA requirements. In hearings on a House bill, EPA indicated that it was not opposed to such a change. An attachment to a letter from Mary Nichols, EPA Assistant Administrator for Air and Radiation, and Elliot Laws, EPA Assistant Administrator for Solid Waste and Emergency Response, to Senators Craig and Kempthorne, stated that

> *. . . the Agency, therefore, believes that in the narrow context of the WIPP, which is subject to comprehensive regulation under the AEA [Atomic Energy Act], the WIPP LWA [Land Withdrawal Act], and RCRA, that a demonstration of no migration of hazardous constituents will not be necessary to adequately protect human health and the environment.* (Nichols and Laws, 1995)

In this letter, EPA indicated that, under current law, it was obligated to continue to enforce RCRA provisions at WIPP. The letter illustrates the degree to which DOE and EPA have worked in a cooperative, constructive manner to address significant issues regarding compliance with RCRA regulations. On September 23, 1996, the President signed into law (P.L. 104-201) an amendment to the WIPP LWA that exempts WIPP from the federal RCRA requirements.

PERFORMANCE ASSESSMENT

Performance assessment (PA) encompasses the overall process of assessing whether or not a waste disposal system meets a set of performance criteria. For the WIPP PA, the system is a deep geologic repository disposal system in bedded salt for DOE TRU waste, and the performance criteria are various

long-term environmental metrics in U.S. government regulations (Rechard, 1995, p. Glos-14).

Methodology

Iterative PAs of WIPP are being performed for DOE by Sandia National Laboratories. The performance assessments are intended to provide interim guidance while final compliance evaluations are being prepared.

The methodology has been developed to calculate a performance measure in the form of a complementary cumulative distribution function (CCDF) that permits comparison with the EPA release limits for radioactive waste disposal. The CCDF, a generally accepted form for depicting risk by a specific performance measure, was popularized by the Reactor Safety Study (U.S. Nuclear Regulatory Commission, 1975) for point estimates and by the Zion/Indian Point risk studies performed by industry (Pickard et al., 1981) for estimates with uncertainty. For WIPP performance assessments, the performance measure takes the form of normalized releases to the accessible environment of the radionuclides listed in Table 2.1. Under a normalized release limit, the estimated release is reported as the fraction of the release limit allowed under Table 1, Appendix A of Part 191. A release estimate equal to the allowable limit would be a normalized release of 1. Figure 2.1 is a hypothetical CCDF illustrating compliance with the 40 CFR 191.13 containment requirements.

The basic framework of the WIPP performance assessment methodology is the Kaplan and Garrick (1981) "triplet" definition of risk. This definition of risk is founded on the principle that to determine risk, the following three basic questions must be answered:

1. What can go wrong?
2. How likely is it to go wrong?
3. What are the consequences?

"What can go wrong" is examined in the form of scenarios that can lead to releases of specific radionuclides to the accessible environment; "how likely," is examined by calculating the probabilities of those scenarios; and the "consequences" are examined in terms of the overall likelihood of various levels of release. The results are then cast into CCDFs of the form illustrated in Figure 2.1. The procedure for developing the CCDFs results in a structured set of scenarios leading to the specific consequences of interest; summing the probabilities of the scenarios for each release set; and plotting the complementary cumulative probabilities as a function of normalized release rates, usually on log-log coordinates (see Appendix B for more details).

A key part of the performance assessment model involves deciding on an appropriate set of scenarios, that is, identifying what can go wrong. The WIPP performance assessment team used the following five-step selection process for human-initiated scenarios (Cranwell et al., 1990):

1. compiling features, events, and processes (FEPs) that could affect the disposal system;
2. classifying events and processes to enhance consistency and completeness;
3. screening individual events and processes;
4. combining events and processes into specific scenarios; and
5. screening scenarios to identify and eliminate those that have little or no effect on the performance assessment.

Final selection of the scenarios in Figure 2.2 was based on screening events and processes according to probability, consequence, and physical reasonableness. The process resulted in the set of eight scenarios illustrated, although calculations were made on the basis of the first four scenarios only. A more detailed discussion of scenarios is presented later in this chapter.

The complexity in the performance assessment results from two main factors:

1. The numerous variables (approximately 50 in all) that represent the hydrological, chemical, mechanical, thermal, and transport processes involved in the transport and physical process models.
2. The effort required to perform sensitivity and uncertainty analyses on the models.

Documentation detailing the WIPP performance assessment effort includes a wide range of source materials documented in various reports and studies—including a 1992 Performance Assessment (the 1992 PA; Sandia National Laboratories, 1992, Vol. 3); the various iterations of the systems prioritization method (SPM; Sandia National Laboratories, 1995); and the Draft Compliance Certification Application (DCCA; DOE, 1995a).

Uncertainties in the knowledge base were propagated through the scenarios, and sensitivity studies were performed so that results of the analysis include a quantification of the uncertainties associated with the calculated release rates.

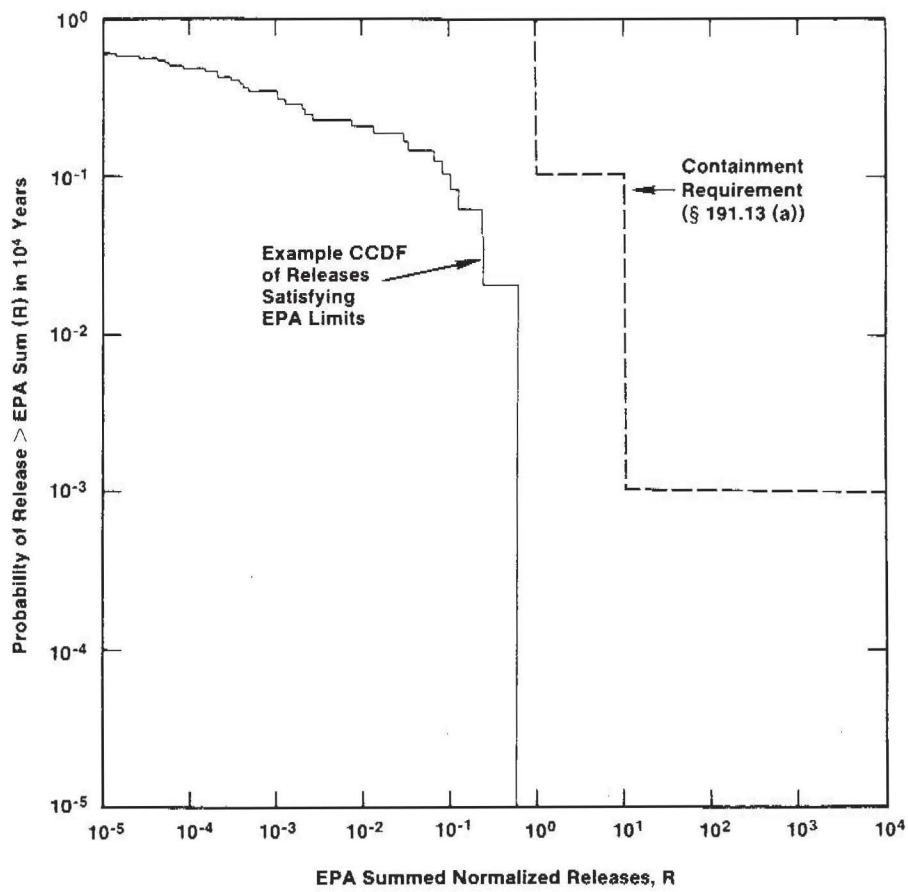

FIGURE 2.1 Hypothetical CCDF illustrating compliance with the containment requirements. Source: Sandia National Laboratories (1992, Vol. 1, Figure 3.3).

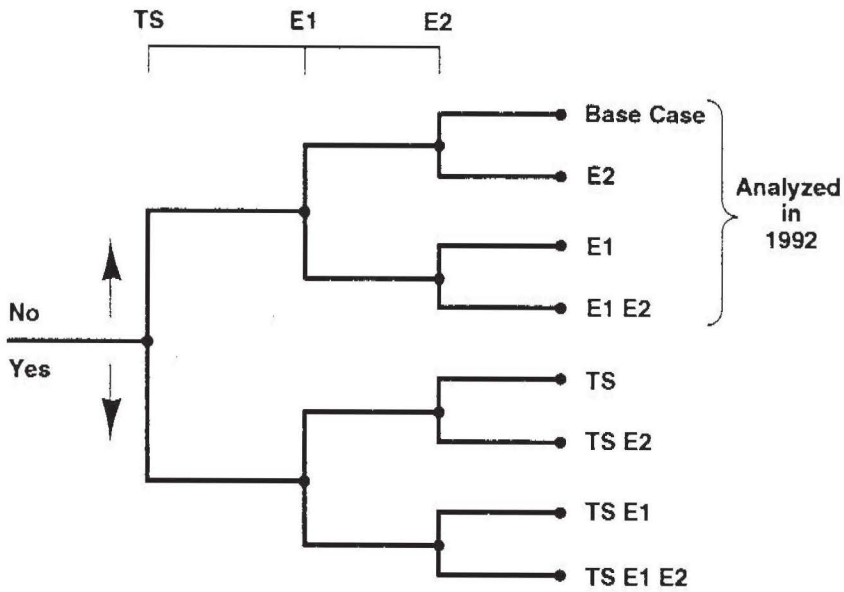

TS Is an Event in which Subsidence Results from Mining of Potash

E1 Is an Event in which One or More Boreholes Pass through Waste Panel and into a Brine Pocket

E2 Is an Event in which One or More Boreholes Pass through Waste Panel without Penetration of a Brine Pocket

FIGURE 2.2 Potential scenarios for the WIPP disposal system. Source: Sandia National Laboratories (1992, Vol. 1, Figure 4.1). NOTE: TS refers to an event in which subsidence results from potash mining; the yes/no decision answers the question of whether potash mining is considered in the scenario. The base case depicted here represents the undisturbed repository. The E1 and E2 scenarios are discussed later in this chapter (see Figures 2.4 and 2.5). For further discussion of potash mining, see Chapter 4.

Results from Containment Requirement Calculations

On March 31, 1995, DOE submitted to EPA a draft analysis of WIPP compliance with 40 CFR 191 for the undisturbed case; this multivolume submission was supplemented in July 1995 with a performance analysis for the disturbed case (i.e., human intrusion; DOE, 1995a). DOE's current schedule calls for new performance assessment calculations for the compliance certification application to be completed and documented by September 1996, for subsequent submission to EPA a month later. Earlier performance results have been published in the 1992 PA (Sandia National Laboratories, 1992) and in the SPM analyses (Sandia National Laboratories, 1995). Compared to these earlier analyses, the DCCA included updates to

the analytical codes and revisions of specific analytical assumptions, where dictated by EPA guidance (although this DOE submission predated the release of the final version of Part 194). The analytical assumptions of the DCCA appear to be largely unchanged from those of the 1992 PA and the SPM.

Although the DCCA indicates compliance with Part 191 containment requirements, the results of this analysis are too aggregated to allow any conclusions to be drawn about which scenarios and pathways contributed to the calculated releases. However, careful study of the 1992 PA does provide some insight into the relative magnitude of release scenarios.

CCDF curves summarizing radionuclide releases to the accessible environment resulting from cuttings removal and ground-water transport fall substantially below release limits promulgated by EPA. Although this is an important result, it must be noted that the rate of intrusion assumed in the 1992 analysis was less than is now required in the final Part 194, issued on February 9, 1996. The two main contributors to radionuclide releases to the accessible environment identified in the 1992 PA were (1) drill cuttings brought to the surface from exploratory drilling and (2) radionuclides transported by ground water flowing through the Culebra following human intrusion.

Some of the results from the 1992 PA with respect to the 10,000-year containment requirements of the EPA standard are as follows:

- Where the intrusion probabilities are based on expert judgment and dual-porosity transport with chemical retardation, the mean CCDF is *more than an order of magnitude below EPA limits.*[2]
- Where an intrusion rate of 30 boreholes per square kilometer per 10,000 years and dual-porosity transport without chemical retardation are assumed, the mean CCDF is *approximately one order of magnitude below EPA limits.*
- Where an intrusion rate of 30 boreholes per square kilometer per 10,000 years and single-porosity, fracture-only transport (with little retardation) are assumed, the mean CCDF is *less than an order of magnitude below EPA limits.*

These three 1992 PA results represent a sample of all the different modeling assumptions and parameter values that were examined to assess their impact on the mean CCDF. The compliance outcome is a common result, with variations on the degree of sensitivity. Of course, individual scenarios can be found to produce CCDF curves that exceed the EPA limits, but for them the important issue is their likelihood, or frequency of occurrence (see Appendix B for more details). This information is used to determine the mean CCDF curve, the one used to assess compliance.

The containment requirement for WIPP (defined by Table 1 of Part 191, shown here as Table 2.1) specifies a release limit of 100 curies of plutonium per million curies of TRU waste, equivalent to a release fraction of about 10^{-4}, at least initially. Although release limits are specified in Part 191 for various isotopes, plutonium appears to be the most significant, in terms of both the inventory and compliance. Based on inventory estimates (DOE, 1995c) adjusted for the estimated date at which the repository would be closed, the WIPP inventory of thorium, uranium, neptunium, plutonium, and americium isotopes with half-lives greater than 20 years (which determine the release limit), is around 6 million curies. The corresponding release limit for plutonium-239 (Pu-239) would be 600 curies, or about 10 kg (approximately 20 pounds).

Figure 2.3, taken from the 1991 PA (Sandia National Laboratories, 1991), describes the radionuclide inventory as a function of time. The inventory is expressed in EPA units used for a single waste panel. An EPA unit is a convenient way to express the inventory, based on release limit definitions in Appendix A of 40 CFR 191. As can be seen, after about 500 years, Pu-239 is the dominant radionuclide of concern at WIPP.

[2]The CCDF results are in the form of mean values as permitted by Appendix C to 40 CFR 191. The means were calculated from a family of curves, each representing different percentiles, and are a direct result of the uncertainty analysis. A CCDF is generated for each "realization," which consists of a particular random choice of value of each of the model parameters (a choice within the range specified for that parameter). A mean CCDF is obtained from a set of CCDF curves generated this way, by averaging the cumulative release quantity for each value of the cumulative probability (see Appendix B).

Results Regarding Individual and Ground Water Protection Requirements

As noted earlier, the EPA standard sets forth two other quantitative requirements in addition to the containment requirements: (1) individual protection requirements; and (2) ground-water protection requirements. The individual protection requirement considers the radiation dose to humans in the accessible environment for 10,000 years of undisturbed performance. Because performance assessment results indicate that for the undisturbed case, brine (the medium for radionuclide transport) in contact with waste will not migrate more than a few "tens of meters" from the waste emplacement panels in 10,000 years, the 1992 PA did not include performance estimates for individual protection requirements. Subsequent assessments (e.g., SPM, DCCA) have also concluded that, under undisturbed conditions, waste would not migrate. The PA work (DOE, 1995a, Section 8.1) uses a bounding calculation to show doses to humans resulting from brine transport to be orders of magnitude below natural background; hence, compliance with the individual protection requirement can be demonstrated easily for the undisturbed scenario at WIPP.

The PA work has noted that the ground-water protection requirement does not apply to WIPP because there is no source of potable ground water as defined in the EPA standard (Sandia National Laboratories, 1992, Vol. 1).

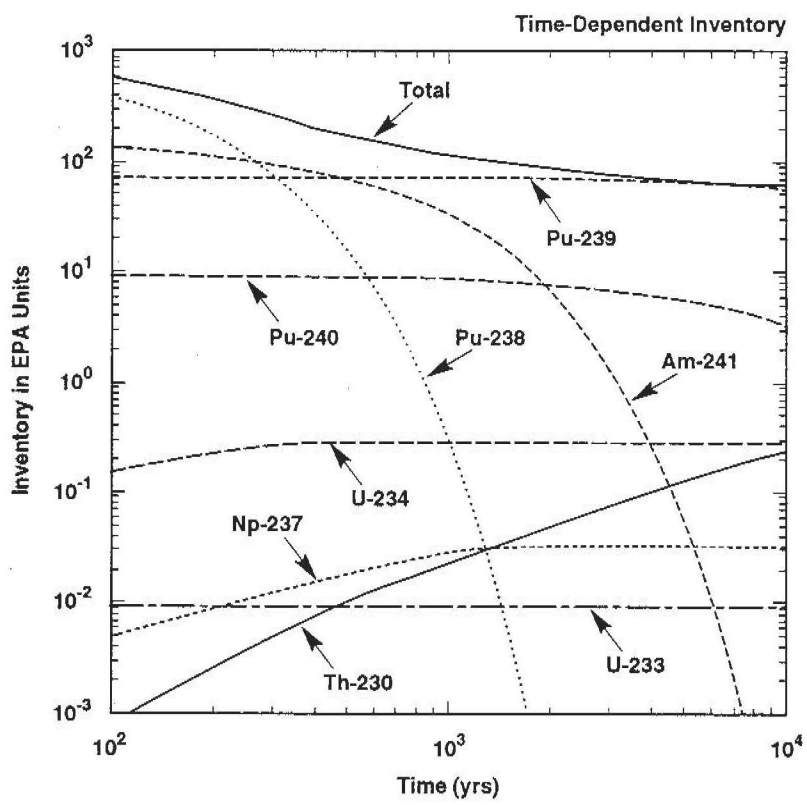

FIGURE 2.3 Time-dependent inventory expressed in EPA units for a single waste panel. Source: Sandia National Laboratories (1991, Vol. 4, Figure 2.4.2). More recent estimates (DOE, 1995c) of the WIPP inventory differ from those used in this figure.

In summary, the sole long-term radiological compliance issue is whether or not the containment requirements are met. Performance calculations indicate that if the shaft seals are effective, there will be little, if any, release or exposure from the undisturbed repository. For the disturbed case, compliance depends directly on the assumptions and analyses made for the frequency and consequences of human intrusion into the repository.

RADIONUCLIDE RELEASE SCENARIOS

Assessment of the likely performance of WIPP begins with the identification of scenarios by which wastes could be released from the repository. The scenarios that have been evaluated in greatest detail are those considered by DOE to represent the major mechanisms and routes for release of radioactive materials.

Undisturbed Case

Scenarios applicable to the undisturbed case considered in WIPP PA work include the following:

1. leakage of brines containing radioactive materials up the shaft and/or through a disturbed rock zone around the shaft up to the Culebra Dolomite and flow to the defined accessible environment via the Culebra; and
2. flow of WIPP brines directly along anhydrite marker beds in the Salado Formation-salt.

These scenarios are mentioned briefly here and represent mechanisms for potential release of radionuclides that underlie the considerations in Chapters 3 and 4.

Under the first scenario, human exposures could occur due to water extraction from the Culebra to add water to stock ponds,[3] and subsequent consumption of beef from cattle that have consumed this water. This scenario, involving flow out of the Culebra, is evaluated against both the containment requirements and the individual protection requirements.

The scenario involving flow along the anhydrite marker beds is evaluated against the containment requirements only, because the marker bed brines are not potable (Davies, 1989; Brinster, 1991; Yaron and Frenkel, 1994; Sexton, 1996), nor do they reach the surface.

Disturbed Case

Scenarios for the disturbed case involve releases resulting from boreholes drilled inadvertently into the waste. One scenario considered is the direct release of waste through drill cuttings brought to the surface. Other disturbed case scenarios include releases that occur through flow up a borehole into the Culebra dolomite, with subsequent transport in the Culebra; the effect of potash mining above the repository; and water flooding from nearby water injection for enhanced oil recovery.

Release of Waste Through Cuttings

The analysis of releases of radionuclides through cuttings brought to the surface in drilling mud includes several factors. In addition to the direct volume of waste displaced by the borehole (i.e., the area of the borehole times the repository height, with the assumption that all such wastes reach the surface), Sandia has made calculations of additional releases due to the erosion of wastes by drilling mud and the movement of wastes in the vicinity of the borehole because of internal gas pressure in the waste.

The quantity of waste intersected directly by a borehole can be determined simply from the frequency and diameter of boreholes assumed to be drilled for the period beginning 100 years after repository closure and continuing until 10,000 years after closure. The previous analyses based on the 1992 PA assumed 30 boreholes per square kilometer per 10,000 years; the current (1996) 40 CFR 194 requirement specifies that the historic record over the past 100 years should be the basis for the borehole rate, which, based on presentations to the committee by EPA and DOE staff,

[3]Without dilution, ground water from the Culebra Dolomite immediately above the WIPP repository site is not potable by livestock or humans. Potable ground water from the Culebra Dolomite in the immediate vicinity is to the southwest, which is not on a projected pathline emanating from any hypothetical release.

Box 2.2 What Fraction of Waste Is Released Through Cuttings from Boreholes?

The degree to which cuttings may contribute to total releases in comparison to the release limits of Part 191 can be illustrated by the following simple calculation. Assume N boreholes per square kilometer per 10,000 years and the surface area of the repository occupied by waste A (m^2). The expected number of boreholes intersecting the waste over a 10,000-year period (I) is then given by

$$I = N\ (\text{boreholes/km}^2) \cdot 10^{-6}\ (\text{km}^2/\text{m}^2) \cdot A\ (\text{m}^2).$$

The volume of waste W (m^3) displaced by these boreholes, by neglecting erosion and spalling and assuming a borehole area B_a (m^2), is

$$W = I \cdot B_a \cdot h,$$

where h is the repository height (m).

The fraction (F) of the repository that is released through these cuttings is simply the volume (W) of cuttings released, divided by the total repository volume (A·h):

$$F = W/A \cdot h.$$

Combining terms yields:

$$F = N \cdot B_a \cdot 10^{-6}.$$

leads to an intrusion rate closer to 45-50 boreholes per square kilometer during a 10,000-year period.

For 50 boreholes per square kilometer per 10,000 years with a 0.073-m^2 cross-sectional area (i.e., 12-inch diameter) borehole, the fraction F of waste released from cuttings (see Box 2.2) is 3.6×10^{-6} (this includes an adjustment to account for no intrusion during the first 100 years after closure). As noted above, the allowable fractional release is about 10^{-4}, initially, and increases with time. Thus, for 12-inch diameter boreholes drilled at a rate of 50 boreholes per square kilometer per 10,000 years, direct cutting releases apparently are less than 4 percent of the allowable limits. Even when allowing for increased release due to waste erosion by drilling mud and spallation, extraction of the waste as cuttings is unlikely to approach the release limits.

This calculation illustrates that the fraction of the Table 2.1 limit released as cuttings is independent of

1. the volume of waste disposed of in WIPP,
2. the geometry of the waste rooms (i.e., the ratio of height to width and length), and
3. the plutonium content of the waste.

To the extent that erosion and spallation are low in comparison to the volume of waste that would be released directly by displacement, the release fraction also does not depend on any waste treatment technology that may be employed. The cuttings release fraction *does* depend on (1) the assumed intrusion frequency, and (2) the assumed diameter of the intrusion borehole.

Therefore, the cuttings calculation is largely independent of the characteristics of the waste and the repository design. Furthermore, it is related to the location of the facility only to the extent that the location affects the assumptions made regarding the frequency and nature of intrusions over the next 10,000 years.

Release of Waste Through Boreholes: The E1 and E1E2 Scenarios

In the "E1" and "E1E2" scenarios, DOE postulates that a borehole through the repository may encounter a pressurized brine pocket in formations below the Salado Formation in which WIPP is located, resulting in the release of radioactive materials. The two specific scenarios analyzed for this type of release are illustrated in Figures 2.4 and 2.5. Figure 2.4 shows the E1 scenario, in which a single borehole penetrates the facility and continues downward into a pressurized brine pocket; Figure 2.5 shows the E1E2 scenario, in which two boreholes penetrate the repository. Because brine is assumed to migrate through the waste in the E1E2 scenario, this scenario is the more significant contributor to total calculated release.

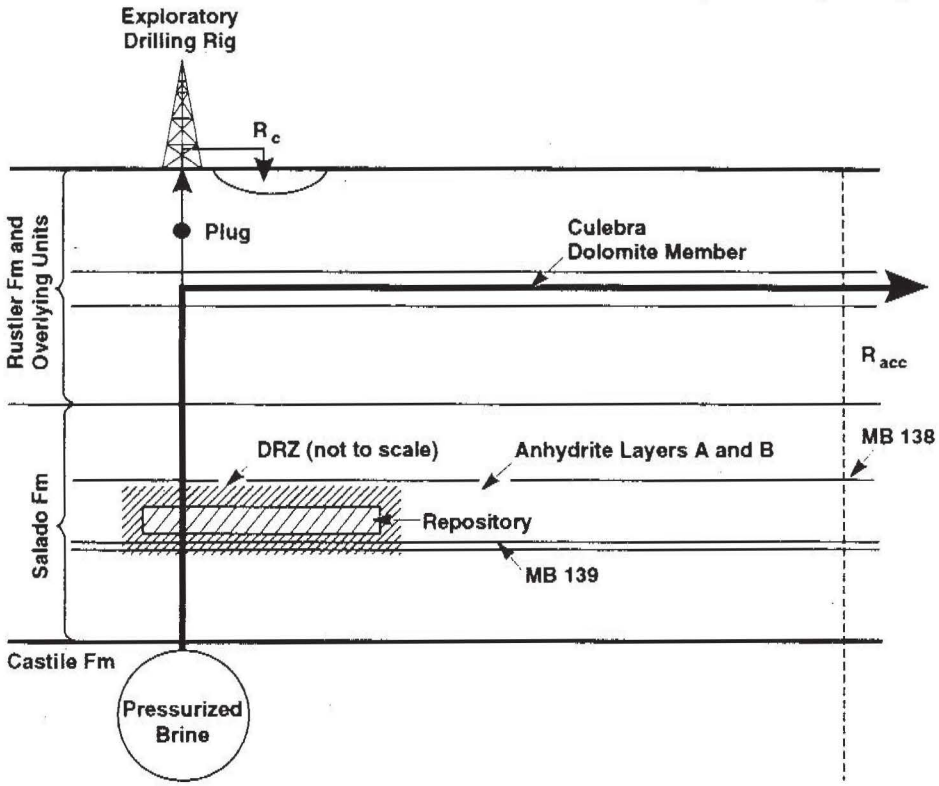

FIGURE 2.4 Conceptual model for the E1 scenario. Source: Sandia National Laboratories (1992, Vol. 1, Figure 4.2).

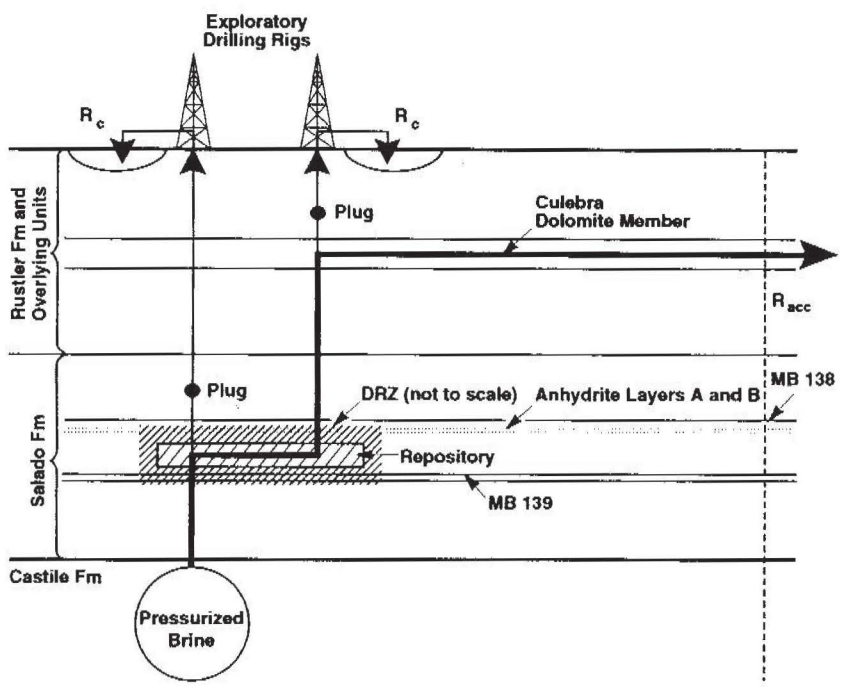

FIGURE 2.5 Conceptual model for the E1E2 scenario. Source: Sandia National Laboratories (1992 Vol. 1, Figure 4.3).

Such brine flow, presumably, would augment the salinity of existing water in the surface and shallow subsurface regions. As noted previously, ground water from the Culebra Dolomite at the WIPP site and in adjacent areas downstream of a hypothetical release already is too high in concentrations of dissolved solids to be potable to livestock or for humans. Regions of potable water from the Culebra are southwest of the site and are not in the direct path of a hypothetical release.

The rate and quantity of plutonium released to the accessible environment through the E1 and E1E2 scenarios depend on a number of factors. In PA sensitivity analyses, the three factors that were found to have a significant effect on calculated releases are

1. the solubility of plutonium in WIPP brines,
2. the potential for retardation of radionuclides in the Culebra, and
3. the potential for movement of actinides in colloids.

As a result of these PA results, expanded work to determine the effects of solubility, colloid formation and retardation on releases has been undertaken (see Chapter 5).

DISCUSSION OF PA MODELING EFFORTS

The committee believes that the PA model assessments of the E1, E1E2, and other scenarios involve technically unrealistic assumptions that have not been probed in past sensitivity analyses. For these scenarios, these technical assumptions also appear to be unreasonably conservative, specifically in the lack of credit given for compartmentation of the waste panels and rooms. These issues are discussed in more detail below.

Assumptions Regarding a Permanent Disturbed Rock Zone

Construction of the repository produces a network of stress-induced cracks that form a disturbed rock zone (DRZ) in the Salado salt bordering the excavated areas. The cracks are expected to close and heal in time due to salt creep. The permeability of the DRZ region, initially higher than that of the undisturbed halite because of these cracks, is restored to a value close to that of the intact salt over time.

The July 1995 update of the DCCA (DOE, 1995a) assumes that the salt around the repository between marker beds 138 and 139 (the anhydrite beds above and below the repository) remains an unconsolidated disturbed rock zone (DRZ) for the full 10,000-year regulatory period, with a permeability of 10^{-15} m^2. For comparison, the undisturbed halite is assumed to have a permeability that ranges between 10^{-24} m^2 (i.e., essentially impermeable) and 10^{-20} m^2. The draft compliance document does note that "although the DRZ is modeled conservatively in this assessment, it is the subject of a modeling study, and assumptions and treatment of this region may be different in the final Compliance Certification Application" (DOE, 1995a, p. 6-76).

The unconsolidated DRZ assumption appears to be inconsistent with the well-established properties of salt. A major feature of salt is that it behaves as a viscous liquid and creeps. The salt around waste rooms will reconsolidate as the pressure on the DRZ exerted by the backfilled rooms rises back to the lithostatic level. Such reconsolidation is estimated to take on the order of a few hundred years at most after repository closure.

A consequence of this conservative assumption is that boreholes that penetrate the salt between waste rooms are assumed to communicate with the waste and serve as release pathways, no matter when the boreholes are drilled. In addition, boreholes that penetrate *different panels* are analyzed as an E1E2 pathway, because under the conditions assumed throughout the entire repository, flow is calculated to occur via the DRZ. Sealing of rooms and panels so that this communication is prevented seems to the committee to be an entirely practical, cost-effective way to reduce the significance of the two-borehole (E1E2) scenario (see Chapter 4).

The more realistic treatment advocated here, of modeling time-dependent DRZ closure, adds complexity to the PA model. This complexity is warranted because it removes the non-physical conservative assumption that the DRZ does not heal. Removing an unrealistic assumption from the PA model has the added benefit of making the sensitivity analyses

derived from the PA more accurate representations of the true dependencies on parameters in the model.

Characterization of Boreholes

It is conservatively assumed in the performance assessment that boreholes retain their initial diameter and have a permeability equivalent to that of a silty sand (10^{-14} m^2) for the entire 10,000-year regulatory period, based on present information of known and defensible natural processes that would fill the hole in time. No credit is given to mechanisms that would cause the boreholes to plug or shrink or that would interrupt the hypothetical flow of radioactively contaminated brine along the greater than 650-m borehole length. However, if further study should identify a natural mechanism that would cause the flow in the boreholes to be restricted, this could result in a significant reduction in calculated releases. Flow through an E1E2 scenario can occur only if both boreholes are open. With boreholes that stay open for times that are short in comparison to the 10,000-year regulatory period (e.g., 1,000 years), some borehole pairs from drilling events at random times will not result in a release because the first borehole will have closed before the second has been drilled. Further study to develop a better understanding of potential borehole closure mechanisms is recommended by the committee to examine an important component of the model calculation of releases.

Apparent Value of Compartmentation

As noted previously, calculations of releases over 10,000 years based on a DRZ that does not reconsolidate close to the value for intact salt are unrealistic (see also Box 4.1 in Chapter 4). This overly conservative assumption prevents the creep and healing behavior of the Salado halite from being properly included in past sensitivity analyses of WIPP performance. With effects such as DRZ reconsolidation excluded from a sensitivity analysis, an opportunity is lost to evaluate the full potential for cost-effective measures to demonstrate compliance. Stated another way, realistic DRZ modeling may lead to a demonstration of compliance using a cost-effective engineering feature such as backfill, which would lessen the dependence of the compliance demonstration on the work addressing each of the three key factors enumerated above. These factors have emerged from the existing PA work and associated sensitivity analysis, and they involve technically complex experimental work. For example, addressing the first factor, that of plutonium solubility, involves completion of ongoing plutonium solubility tests that could be the time-limiting step in determining WIPP compliance, if no more straightforward and cost-effective way to demonstrate compliance were identified. If the DRZ healing behavior were included in the PA sensitivity analysis, confidence in compliance might be increased due to a lesser dependence on results from work in these three more complex areas.

Overly conservative (to the point of being physically unrealistic) analytical assumptions, such as those described above, not only lead to a pessimistic assessment of potential repository releases, but also prevent the identification of design factors that are important to performance. If one assumes, for example, that the salt reconsolidates in times much less than 10,000 years, then compartmentation of WIPP has enormous benefits regarding calculated releases through the E1E2 scenario. The probability of one borehole being drilled into any given area of the repository decreases in direct proportion to the area involved. The probability of two or more such boreholes penetrating the same waste area decreases even more rapidly as the area is reduced. When one also considers that, for flow to occur, boreholes must overlap both in location and in a time window determined by their duration, the great potential value of compartmentation is clear.

A high degree of compartmentation can be obtained at relatively low cost. The current plan calls for waste panels consisting of seven rooms plus access drifts along each end of the rooms in a "ladder" arrangement (Figure ES.1). If, after the rooms are filled with waste, the access drifts are backfilled with compacted salt, then a high degree of isolation would be obtained. Changes in the design layout to ensure improved compartmentation seem entirely feasible, especially if, as is currently estimated (DOE, 1995c), the TRU waste inventory stored in WIPP is significantly less than the original design inventory. This issue is discussed in more detail in Chapter 4.

DISCUSSION OF REPOSITORY PERFORMANCE

The main mechanism through which individuals could be exposed to radioactive materials from WIPP is the migration (through mechanisms discussed below) of material carried by water that is to be used directly or indirectly by humans. Some ground-water sources at WIPP are too saline for consumption by humans or livestock or for irrigation, so therefore, these do not appear to pose a significant risk to humans, even if WIPP radionuclides were to migrate into them. The ground-water pathway that could most directly result in human exposure at WIPP is movement of water containing radionuclides into the Dewey Lake Red Beds (see Appendix A), in which existing ground water is known to be potable, with exposure resulting from direct or indirect human use of this water.

Although many analyses of radionuclide releases from WIPP have been made by Sandia National Laboratory and other DOE contractors, the radiation doses that could result have not been assessed for some reasonably identifiable scenarios and pathways. Most analyses of WIPP performance have focused on regulatory compliance with the EPA containment requirements, that is, calculations to estimate the quantity of radioactive materials that could be released across an arbitrary compliance boundary within 10,000 years. There has been less analysis of individual doses because the individual dose requirements of the EPA standard apply only to an undisturbed repository. For example, because of the high salinity of water in the Culebra, the analyses of releases to the Culebra do not directly translate into an assessment of doses to individuals. However, these analyses do contribute to understanding of how WIPP would perform because they include extensive consideration of processes, mechanisms, and parameters associated with the site and with the transport of radioactive materials from the repository.

Undisturbed Repository Performance

The individual protection requirements (i.e., EPA's 40 CFR 191.15(a)) require that the committed effective dose for the undisturbed repository not exceed 15 mrem/yr for 10,000 years. Because limitation of individual doses under the undisturbed case is a regulatory requirement, DOE has conducted analyses (DOE, 1995a; DOE, 1990; Lappin et al., 1989) of this issue. The process addressed by these analyses is the leakage of radionuclide-containing brines through shaft seals into the Culebra. Human doses are calculated based on the assumption that water from the Culebra dolomite is used in stockponds for cattle, and human exposure occurs through beef consumption (see Box 2.3). The individual doses for the undisturbed repository are estimated to have a peak value of about 10^{-8} mrem/yr, well below the EPA standard of 15 mrem/yr (and below the natural background level of roughly 300 mrem/yr).

Three important features of early analyses are that water in the Culebra appears to be too saline for consumption by cattle, transport by colloids was not considered, and pathways to the Dewey Lake were not included. In addition, the analytical treatment of the behavior of the shaft seals and repository in this analysis appears to be conservative, that is, likely to over-estimate the releases (see Chapter 4).[4] Taking all these considerations together, the committee concludes that the net effect will probably be to lower the already very low concentrations and doses indicated by DOE's analysis of radionuclide releases through shaft seals.

The ground-water protection requirements (i.e., EPA's 40 CFR 191.24(a)) require a calculation of levels of radioactivity in ground water in the accessible environment from an undisturbed repository for 10,000 years. These requirements were not evaluated in the 1992 PA work under the assumption that no relevant potable ground-water sources exist. Recent estimates of radioactivity released from an undisturbed WIPP repository to ground water are 10^{-3} pCi/l, well below not only the EPA standards (ranging from 5 to 15 pCi/l), but also the natural background level of roughly tens of pCi/l (DOE, 1995a).

Thus, for the effectively sealed and undisturbed WIPP repository, the committee has identified no

[4]The seal permeability of $10^{-16}m^2$ results in no releases at 10,000 years (see Figure 4.1). As discussed in Chapter 4, the actual permeability is likely to be even lower than this design value, so that releases beyond 10,000 years are likely to be very small also.

Box 2.3 Human Exposure to Radionuclide Releases from WIPP

Human beings can be exposed to radiation in one of three ways: (1) direct external exposure, (2) exposure from inhaled materials, and (3) exposure from ingested materials. For most WIPP waste release scenarios, plutonium (Pu) is the main radionuclide of concern. Hence, the discussion here is specific to that element. The findings identified below for plutonium apply to other radionuclides in the projected WIPP inventory.

Direct external exposure to WIPP waste (via releases from drill cuttings brought to the surface) would not result in significant doses of radiation (DOE, 1995a), principally because plutonium's hazard is due to alpha radiation, which will not penetrate the skin.

Inhalation exposure occurs when radioactive material is inhaled and subsequently deposited in the respiratory tract or elsewhere in the body. Some low level of inhalation exposure could occur at WIPP if small radioactive particles in the drill cuttings at the surface were picked up and carried by the wind. In such a case, potential exposures to the drillers could be significant, but exposures to individuals off-site would be far less so (Rechard, 1995).

Ingestion exposure occurs when radioactive material that has been released into the accessible environment is ingested by a receptor (a human or some animal, plant, or water that may become part of the human food chain). As discussed in Chapters 5 and 6, the primary release pathway for radioactive material considered for WIPP is through the migration of plutonium in brine. Exposure by ingestion could occur at WIPP if radioactive material were transported underground in brines to a stock well, cattle drank contaminated water from the well, and humans then consumed meat from the contaminated livestock. However, the committee believes that the possibility of ingestion exposure occurring is remote, and that the potential health effects of this type of exposure are of little concern because:

1. Culebra water in the immediate vicinity of WIPP is not potable, even to cattle;
2. even if cattle were to drink the briny water, most of the plutonium would pass through unabsorbed, assuming that the gastrointestinal (GI) tracts of cattle and humans behave similarly (see point 4 below);
3. plutonium absorbed by livestock is deposited preferentially in bone, not meat; and
4. human ingestion is very inefficient in depositing plutonium in the body (a low absorption of Pu occurs in the human GI tract [EPA, 1988]—EPA guidance stipulates that only about one particle in 100,000 entering the GI tract would be absorbed, making ingested plutonium less toxic than inhaled plutonium).

The EPA standard regulates individual doses only for the case in which the repository remains undisturbed. Because the wastes do not appear to migrate under these conditions, DOE studies to date have not addressed specific health consequences of exposure to radiation from WIPP wastes in this case. Some preliminary DOE calculations of possible doses to individuals in the case of human intrusion by drilling suggest that the risk would be very low (see Rechard, 1995).

With the exception of the Dewey Lake aquifer, the major pathways by which plutonium and brine could migrate do not produce potable water. Certain concerns that have been raised by the committee about the possibility of transport of radioactive material to the Dewey Lake aquifer are discussed in Chapter 6. For a discussion of salinity limits appropriate for drinking water of livestock, see Yaron and Frenkel (1994, pp. 32-33, 42).

credible, probable mechanism for release of, or exposure to, radionuclides and concludes that DOE will be able to demonstrate compliance with the EPA standard by a wide margin.

Disturbed Repository Performance

As discussed earlier, DOE's PA showed that cuttings produced by drilling through the repository do not appear likely to cause the release limits to be exceeded. That is, although inhalation exposure from dust containing radionuclides that are brought to the surface as drill cuttings represented the dominant release scenario in the 1992 PA, the releases were within regulatory limits. If this is correct, compliance will depend on the results of other scenarios, such as the E1 and E1E2 scenarios, in which pressurized brine from below the repository horizon flows through the

repository, into the Culebra Dolomite, and then into the defined accessible environment. Releases associated with these scenarios appear to have been calculated by using highly conservative assumptions about the disturbed rock zone around the repository.

Individual exposures that might result from WIPP in the event of human intrusion have not been analyzed extensively because such exposures are not covered by the standard. The scenario thought to represent the dominant exposure pathway is an ingestion exposure assumed to result from the following sequence of events. Two vertical boreholes are inadvertently drilled through the repository in the future, one of which punctures a hypothesized pocket of pressurized brine in the Castile Formation. As a result, brine from the Castile Formation flows through the repository, dissolving and entraining radionuclides that flow up the second drill-hole into the Culebra, which is above the repository but below the surface. These radionuclides would then sorb onto the mineral surfaces of the Culebra (see Appendix A for a more complete discussion of the geologic formations at the WIPP site). Ground water from this formation would then be withdrawn and fed to cattle[5], which subsequently, would be eaten by humans.

This Culebra-to-beef scenario is not the only one that is relevant to an assessment of all possible exposure pathways to humans. That is, using PA calculations of the Culebra pathway as a basis for inferring that minimal exposure would result from a WIPP repository depends on the assumption that there are no other pathways or scenarios worth considering. This is not yet certain. For example, in addition to the postulated main pathway through the Culebra, an alternative (or secondary) pathway exists through the shallower Dewey Lake Red Beds. The committee believes that the potential for individual doses received by drinking water drawn from this formation, located closer to the surface than the Culebra, should be analyzed and documented. That is, the first element of the triplet definition of risk, "what can go wrong," should include the possibility of a borehole release from the repository to the Dewey Lake Red Beds. This is a concern because the Dewey Lake is known to contain potable ground water, and because it is the shallowest water-bearing unit in the area, it is also the easiest subsurface unit to be tapped for water supply by a future society. Thus, the potential for individual doses to be received by individuals (as a consequence of contamination from a breached repository) may be greater than those arising from an equivalent release into the Culebra. Because the Dewey Lake is less transmissive than the Culebra, the relative amount of plutonium reaching the Dewey Lake and the rate of lateral spreading may be less than for the Culebra. A quantitative analysis of this issue has not yet been presented to the committee in documented form for review.

Assessment of the isolation performance of the repository when disturbed by human intrusion is more complicated than in the undisturbed case. Because of gaps in the data available to date and the preliminary nature of the PA work reviewed by the committee to date (i.e., prior to the 1996 PA), it is not possible to make a compelling case that the radionuclide releases will comply with the EPA standard for the disturbed case. However, for the WIPP repository disturbed by future human activity, the committee has noted three ways in which on-going or additional work may lead to a demonstration of compliance. These are:

1. Re-evaluation of the probability and/or consequences assigned to highly speculative scenarios of future human activities may reduce the estimated risk of radionuclide release.
2. Experimental and field programs in progress or planned may show that key parameters (e.g., actinide solubility, sorption, radionuclide travel times, colloidal transport) are well within the range required to reduce the impacts of human activities such that releases fall within the acceptable range.
3. The implementation of available engineering options (e.g., compartmentation, treated backfill), which have not been considered in published DOE PA analyses, can substantially reduce the consequences of human intrusion.

[5]This Culebra-to-beef-to-humans pathway does not seem to account for the fact that the water withdrawn from the Culebra in areas downgradient from a hypothetical leak is too saline to be potable, even for cattle.

Based on the PA analyses published by DOE to date, which the committee believes include some very conservative assumptions (i.e., tending to over-estimate releases), the committee concludes that incorporating the above three considerations very probably will allow DOE to demonstrate that a WIPP repository can comply with the EPA standard for the disturbed case. These topics are treated in the remaining chapters of the report.

GENERAL QUALITY OF WIPP PERFORMANCE ASSESSMENT ACTIVITIES

Development of the WIPP PA has been a pioneering effort: it was the first detailed assessment of an actual radioactive waste repository to be published and has been the model for many subsequent analyses worldwide. The linkage of many computer codes and the capacity to use probability distributions for parameters and to propagate uncertainty through the analysis are major technical achievements. Nonetheless, in several important aspects, the full potential of the PA has not been realized in the WIPP project.

The committee noted several concerns above regarding the analytical treatment of some aspects of WIPP performance, for example, in the failure to consider salt reconsolidation and compartmentation of the waste rooms in the assessment. A more general problem is that the parameter values used in the PA reflect an uneven mixture of conservatism and realism. This is not unusual in risk assessment in which it is accepted practice to use a series of iterative assessments, based initially on conservative bounding values, followed by substitution of more realistic analyses that make a significant difference. A potential problem with this approach in the case of a complex analysis is that sensitivity analyses will fail to identify parameters that are most important to performance when those parameters are represented by a bounding value. A concern also is raised in Chapter 6 that some parameters assumed to be independent are, in fact, interrelated.

The PA identification of actinide solubility in brine and retardation as being among the most important parameters of WIPP performance is probably correct, but to a lesser degree than indicated by the sensitivity analysis. This is because other performance factors, such as DRZ permeability, were not sampled as analytical variables and, thus, their importance was not identified by the sensitivity analysis. As a result, an opportunity may have been missed to demonstrate compliance more quickly and economically than could be done through work on solubility and retardation.

In several iterations (the 1992 PA and SPM efforts), DOE has conducted sensitivity analyses of analytical parameters and used them to identify program research priorities. However, the PA modeling capability does not appear to have been used in a similar way to evaluate design alternatives, despite opportunities to do so. In 1991, DOE published the report of an Engineering Alternatives Task Force (EATF; DOE, 1991), a study conducted at least in part to respond to recommendations from the WIPP Committee (NRC, 1989). A similar study was published in September 1995 (DOE, 1995b) in response to EPA requirements. As described in Chapter 4, both of these reports included very positive comments about the value of sealing waste rooms; however, the current design (DOE, 1995b, p. ii) calls for panel seals but not room seals. Despite these two engineering studies, the PA model has not been used to evaluate what may well be the major potential benefit of such a design modification.

OTHER LONG-TERM RADIOLOGICAL COMPLIANCE ISSUES

Waste Characterization

Waste characterization—the process of identifying and classifying the chemical, physical, and radiological constituents of each drum of waste—is a critical aspect of every waste management project. For a project such as WIPP, many of the waste characterization needs are set by agencies such as the EPA, the New Mexico Environment Department (NMED), the U.S. Nuclear Regulatory Commission, and DOE itself. It is obviously impractical, if not impossible, simply to overlay the requirements of each of these individual agencies. Attempting to do so quickly degenerates into an exercise in a complete analysis of every possible component. Such analysis is costly and time-consuming and would result in the highest potential

health hazard to the employees involved, with no clear need for all of the information collected.

DOE has in view the implementation of "performance-based" waste acceptance criteria for WIPP and extension of that concept to define waste characterization requirements (DOE, 1995a, Section 4.3.2, pp. 4-7). The concept is straightforward and reasonable: the waste characteristics that should receive the most attention in characterization are those that are most important from the viewpoint of the performance measures on which the isolation capability of WIPP is evaluated.

With respect to long-term radiological protection, the requirements proposed by EPA in 40 CFR 194.24(b) are consistent with a performance-based approach. For each performance measure important to isolation capability (e.g., activity, permeability, and porosity), EPA proposes that DOE use performance assessment to establish a range of waste characteristics within which the facility will comply with regulatory standards. For those waste characteristics that are comparatively unimportant to isolation, the ranges will be wide. This approach should help avoid unnecessarily detailed characterization efforts.

The extent to which existing waste drums will have to be opened and characterized is not yet clear, because specific details of the characterization required have not yet been established. In particular, the method by and extent to which a knowledge of historical processes can be used to characterize existing wastes have not been established. Similarly, the requirements for using statistical methods to characterize waste based on measured values from a subset of that waste are not yet defined.

In the committee's view, it is essential that any waste characterization program be established with a clear understanding of potential uses of the characterization information. Measurements of TRU waste characteristics can be expensive and may lead to occupational exposures. The value of information gained by such analysis must exceed the cost and risk of obtaining the information, but these trade-offs can be considered only if the sensitivity of repository performance to different waste characteristics is understood. Where costly waste characterization requirements appear to offer little value in terms of ensuring health protection, DOE should seek to have the requirements reinterpreted.

Existing waste characterization regulations have been developed for surface waste management facilities rather than for a deep repository. These regulations reflect a general bias that more waste characterization is better than less and that the applicant has the burden of explaining why particular requirements should be waived in a particular case. 40 CFR 194 states that "any compliance application shall describe the chemical, radiological and physical composition of all existing waste proposed for disposal . . ." (40 CFR 194.24(a), Federal Register, p. 5240).

This is consistent with a performance-based waste characterization because a description of composition is not the same as a full characterization. The need for descriptive material is recognized. In the committee's opinion, there is no scientific basis for requiring a full characterization.

It appears that the project is concentrating too much on the problem of how to characterize waste and insufficiently on the question of whether to characterize it. The value of extensive characterization of WIPP wastes is questionable on several counts:

1. Whatever the current physical properties of wastes, they are likely to change significantly over the 10,000-year regulatory period of the facility. As the repository consolidates due to salt creep, the waste will be compressed and compacted.

2. The containment requirement of 40 CFR 191 limits the fraction of WIPP wastes that can be released over 10,000 years in terms of a percentage of the initial inventory; the absolute quantities that can be released are not defined. The total amount of radioactivity in WIPP will determine the release limits. For releases as cuttings, inventory information is largely irrelevant (see discussion of human intrusion earlier in this chapter). For releases due to solubility-limited flow, such releases may be largely independent of inventory, but release limits will depend on the total radiological inventory–that is, for the solubility-limited case, the more waste that is placed at WIPP, the easier it will be to comply with 40 CFR 191.

3. Performance assessments to date indicate that little, if any, waste migrates under undisturbed

conditions and that releases from human intrusion—assessed for various stylized scenarios, which include some apparently very conservative assumptions—appear to be small compared to the release limits. If the waste is not going to migrate to locations where humans may come into contact with it later, then the qualitative, common-sense answer to characterization is that it does not matter what the waste contains. A quantitative answer to the degree of characterization required would emerge rigorously from PA calculations, using the release limits specified by EPA standards, which apply irrespective of whether the releases pose a risk to humans.

Monitoring

DOE is required to perform a monitoring study as part of the information to be submitted in the compliance certification documentation. DOE is required to assess the feasibility of monitoring in both pre- and post-closure phases. A key element is that the monitoring techniques cannot impair or degrade the containment of waste.

In the committee's opinion, this DOE monitoring study should distinguish carefully between current technologies and expectations for future technologies. The committee believes that this study should also assess carefully those technologies that must penetrate the integrity of the closed repository to be effective. Simply stated, it may be easy to monitor parameters that will not provide any useful information about the facility and very difficult to monitor parameters that could be informative but almost assuredly require breaching the repository so that probes, cables, and other devices, can be routed to the surface. DOE and EPA must recognize that a monitoring program typical for RCRA facilities may be impossible to implement for the WIPP facility. Although the committee believes that the requirement for DOE to perform this monitoring study is appropriate, both EPA and DOE must be prepared to face a situation in which long-term, postclosure monitoring within the repository may be impractical. EPA, importantly, recognizes that such a monitoring program may be impossible to achieve without impairing the integrity of the repository. However, monitoring of the subsurface environment above the Salado (in particular, with sensors in the Culebra) could provide warning of a breach, probably without compromising the repository.

The 40 CFR 191 regulation require "long-term monitoring" of the closed facility, but without indicating what this implies. How long is long-term? What is to be monitored? The committee believes that long-term monitoring must be done from the surface. Observations that would require instrumentation inside the seals pose a risk of adding potential leakage pathways. The risk from monitoring systems that fail and become part of a leakage circuit could be higher than the risk due to leakage from a reliable unmonitored facility. Considerable advances are being made in remote investigation and monitoring by geophysical methods, but these have not yet matured sufficiently to provide monitoring of a repository. In summary, the committee believes that the EPA, in 40 CFR 194, has proposed monitoring requirements that do not appear feasible today.

The need for a monitoring study nonetheless provides an excellent example of how information from the operational phase at WIPP can be used to deal with compliance issues. It may be feasible, for example, to install probes and conduits into a room or panel that is then sealed. This would provide a direct measure of the ability to perform the monitoring anticipated in the regulations and to assess the reliability and integrity of the monitoring system. Should one of the seals fail because of the monitoring system, the consequences will be relatively slight because the failure could be recognized and repaired easily. A pilot study during the operating period should be informative regarding any early failures of the monitoring systems.

Peer Review and Quality Assurance of the WIPP Project

Two of the most common practices for enhancing the quality of technical work are a process of competent peer review and an appropriate quality assurance program. The WIPP performance assessment activity has been under substantial review, by peer review groups and others, since 1989. With WIPP, the question is not a lack of review, but rather the quality of the review and whether or not the reviews being performed are the ones needed. The reviews fall into three main categories: (1) formal technical reviews, (2)

continuing review and feedback, and (3) miscellaneous review and advisory groups.

The first group of reviews is most likely to have continuity of impact. Reviews that appear to be particularly important are those from the PA Peer Review Panel, the State of New Mexico (both the Environmental Evaluation Group [EEG] and the Attorney General's Office), stakeholder reviews, and the EPA.

Despite the many peer review efforts and the superior technical ability of those performing them, the WIPP PA effort is centered on complex models, making meaningful probes difficult by outside review groups interested in understanding the effects and parameters most important to the outcome and interested in developing a simple, effective way in which these dependencies can be properly viewed. Given the earlier comments about the apparent conservatism in the analysis and the resultant misidentification of sensitivities, it appears that the peer reviews have overlooked these important shortcomings of the WIPP PA and have not resulted in a balanced, realistic assessment of WIPP performance.

One reason for this may be that the technical experts engaged in performance assessment have valued incremental technical innovations over transparency of the process. Understanding of the key aspects of WIPP radionuclide isolation performance need not be buried in a complex computer model. The descriptions of WIPP release scenarios described above are an attempt to indicate that the identified scenarios through which wastes could be released from WIPP are easy to visualize and that the factors contributing to releases can be identified readily. As the WIPP project moves forward in the compliance process, the hope of the committee is that the value of technical transparency and accessibility will be embraced by the project.

The quality assurance (QA) philosophy and procedures covering performance assessment are still under development. This documentation (see Sandia National Laboratories, 1991; 1992) covers QA procedures for (1) parameter selection and use of expert judgment, (2) analyses and report reviews, and (3) computer software supporting PA.

The development and implementation of QA procedures have progressed most visibly in the first of these three activities. Ideally, the QA program is to be implemented fully before final PA results are considered suitable for comparison with 40 CFR 191. However, full implementation alone is not sufficient to guarantee a high-quality result, which can be achieved only through the combination of a competent project team, peer review, and regulatory compliance. The final results have yet to be seen.

CONCLUSIONS

Performance assessment has a major role to play in demonstrating compliance with EPA standards and providing assurance to the public that transuranic waste can be stored without posing a significant health risk to the public in the Waste Isolation Pilot Plant. Although performance assessment did not originate with WIPP, the project has done much to advance the development and applicability of PA to radioactive waste disposal. As with any new development, be it a machine or a thought process such as performance assessment, initial expectations typically are much higher than actually can be achieved. Part of any criticism of the WIPP PA program may reflect these initial expectations.

Federal regulations relating to waste disposal define performance assessment as an assessment of the likelihood that the amount of radioactive material released to the environment will exceed a set of specified values. The analyses required to make such an assessment are capable of much more than merely demonstrating compliance with specific radionuclide release limits; they can be used on a much broader scale to enhance decision making and the overall efficiency of the WIPP project. The committee believes that these opportunities have not been exploited fully by DOE.

The general conclusion is that the WIPP performance assessment program is providing valuable insights on the performance capability of the repository, including the integration of features, events, and processes associated with total repository performance. The program is essential to success in opening the repository and can serve as the primary knowledge base for a meaningful risk management program during the operational phase. The extent to which performance assessment can become a primary monitor of repository

performance clearly depends on the scope and resource base of the PA effort. The committee believes that scope must include performance measures that go beyond radionuclide release rates to the accessible environment. In particular, the WIPP PA, although quite responsive to the letter of the law, is too narrow in scope to serve as a robust basis for risk management—a goal beyond that explicitly required by federal regulations but clearly in the interest of public health and efficient management of public resources.

An example of an opportunity for continued use of PA in the manner recommended here is in waste characterization. PA can provide guidance to waste characterization requirements. The impacts, both in terms of economics and of human exposure to the radioactive materials, can be significant. However, both DOE and EPA seem committed to an extensive waste characterization program that is only minimally defined by the need for information as input to the PA process. EPA is apparently requiring waste characterization efforts well beyond that necessary for assessing performance of the closed repository. The DOE seems intent on fulfilling these requirements with no clear scientific basis for the need for this information.

Remaining issues of concern relate to the timeliness of PA results, the transparency of the PA model, and its limited scope in terms of aiding WIPP program decision making. The complexity of the model and its limited set of performance measures handicap its usefulness in project decision making, because the mechanisms, processes, parameters, and events that contribute to risk are difficult to understand. If a simpler model could be developed that would represent the full model reasonably and adequately, such a simpler model—with expanded performance measures—would benefit the project. Similarly, the results and insights of the performance analysis, as reported in the DCCA, are largely inscrutable. A simplified description of the scenarios and associated processes under which waste from WIPP could be released and people could be exposed to radionuclides would be a valuable complement to the WIPP performance assessment report.

Chapter 3

Salado Hydrogeology, Gas Pressure, and Room Closure

Studies of physical, chemical, and biological processes involving the rock salt environment provide important conclusions about the behavior of waste-filled excavations in the Salado Formation. This information is reviewed briefly in the following four sections. The first discusses the hydrogeological properties of WIPP salt (see also Appendix C). The second draws general conclusions about gas generation. The third section discusses the influence of room closure, with local stratigraphy (Appendix A) and the creep behavior of salt (Appendix D) used as additional inputs. The final section discusses the combined effects of brine inflow, gas generation, and room closure.

SALADO HYDROGEOLOGY

In assessing deep geological disposal as a potential means of isolating radioactive waste from the biosphere and worthy of further research, the National Research Council suggested rock salt as a particularly suitable geological material (NRC, 1957). The fact that water-soluble formations such as the Salado Formation in New Mexico have remained in place for hundreds of millions of years indicates that, except for slow dissolution at the margins, they are hydrologically inactive. Another desirable characteristic of salt is that over time, it will flow around the waste and encapsulate it completely.

The Salado is approximately 600 m thick, extending about 400 m above and 200 m below the horizon selected for the WIPP repository. The Salado contains bedded, continuous layers of relatively pure halite, impure halite with clay and polyhalite constituents, and interbeds of anhydrite, accompanied by underlying clay seams (Freeze et al., 1995a, pp. 1-8).

Some of the interbeds are clearly evident and continuous over many kilometers and have been designated as "marker" beds. They serve as a guide in keeping the excavations within given bedded layers and maintaining a fixed separation from the nearest anhydrite interbeds above and below.

Excavations at WIPP have not revealed any feature that would cause DOE to question the assumption of the very low permeability of the Salado. However, concerns have been raised (Bredehoeft, 1988) that although the Salado appears to be dry, it may still be saturated with brine, that is, the microscopic voids between the crystals that make up the salt beds could be filled with brine and the voids interconnected (see Box 3.1).

In this case, interstitial brine would tend to flow down the pressure gradient and into the excavated repository. Although the porosity of the halite is not high,[1] such a permeable-medium model considers the entire Salado Formation as a brine reservoir, able to flow into and fill the excavations. The brine would corrode the metallic waste containers, generating an underground "slurry" of contaminated brine. Through chemical and bacteriological processes, this brine might generate enough gas to raise the pressure above lithostatic (i.e., the pressure generated by the weight of overlying rock).

Several underground investigations and analyses of the interconnection model have been conducted, and a number of inconsistencies have been noted (Freeze and Christian-Frear, in preparation; Beauheim et al., 1991; McTigue, 1993). These include the following:

- Brine seepage into excavations in the Salado halite occurs in variable small quantities in unpredictable locations.
- Brine composition is quite variable, even among samples separated by distances of only tens of centimeters. Over a period of 230 million years (the

[1]The porosity of the Salado is generally about 1 percent by volume, and the interstitial moisture content is typically less than 0.5 percent by weight.

BOX 3.1 Permeability and Fluid Inclusions of the Salado Formation

The permeability of the Salado Formation salt is an important parameter in evaluating the capability of the WIPP repository to withstand hypothesized future flooding by an external source of water that would flow through any interconnected pores in the salt. Valuable insight into permeability is achieved by examining the composition of fluid inclusions. Fluid inclusions are tiny quantities of liquid or liquid plus gas enclosed in salt crystals of the Salado, which represent samples of the fluid from which the salt crystals formed or were subsequently recrystallized. Compositions of the inclusions show substantial variety, which has led some researchers (e.g., Roedder et al., 1987) to speculate that the salt may have recrystallized in the presence of different fluids that have flooded the salt beds at various times since their formation. However, more recent work (Bein et al., 1991) suggests that variations in chemistry of fluid inclusions is attributable to depositional and recrystallization processes that occurred millions of years ago and indicates that these variations do not require fluid flow through interconnected pores. The most recent work by Jones and Anderholm (1993, 1996) also suggests that the observed variations in fluid inclusion composition can be explained by natural and expected variations in the marine and marine-marginal environmental conditions during Salado deposition in the Permian. This means that the inclusion fluids probably have been isolated since the salt was formed. Thus, the Salado salt probably has remained essentially impermeable since its formation (see also Appendix C).

Salt mines elsewhere in the world have indeed flooded on occasion, but this is typically due to a combination of excessive extraction of salt during mining, presence of fractures in the salt caused by the disturbance of the mining, and close proximity to aquifers or surface water bodies. However, these conditions do not exist for the WIPP repository. The overburden pressure and deformation properties of salt (Appendix D) will close and heal any fractures that might develop in the disturbed rock zone and seal and isolate any residual gas-filled or brine-filled void spaces in the repository horizon. No permeable formations in the vicinity of the repository would serve as a suitable "source" or "sink" of ground water.

age of the Salado), these compositional differences would have been eliminated by diffusion had the pores of the formation been interconnected.

- Rock salt behaves essentially as a viscous fluid, with a zero yield (shear) stress, when the load is applied over a long time (see Appendix D). Such flow behavior would eliminate the possibility of connected pathways between the salt pores. Certainly, rock salt cannot sustain stress concentrations around microfissures over geological time. The inability of salt to sustain a shear stress over a long time is also indicated by the fact that the in-situ state of stress in the salt is isotropic (i.e., equal in all directions).
- Brine pore pressure in both halite and anhydrite marker bed units at WIPP has been found to be approximately 12 MegaPascals (MPa), which is between hydrostatic (6 MPa) and lithostatic (15 MPa). These measurements are consistent with isolated brine.
- In-situ testing (see Appendix C, and Beauheim et al., 1993b) indicates a large variability in intrinsic permeability, ranging from less than 10^{-21} m^2 for pure halite to as high as 10^{-18} m^2 (Freeze et al., 1995a) for anhydrite interbeds. When anhydrite is subjected to internal pressures (e.g., by high gas or brine pressures in the waste rooms) approaching lithostatic, its permeability may increase significantly due to the generation of incipient fractures and eventually open macroscopic fractures. Median values of 10^{-21} m^2 and 2.5×10^{-19} m^2 are used in computations by the Department of Energy (DOE, 1995a, pp. 6-73, 6-75) for halite and anhydrite permeabilities, respectively.
- Stress concentrations around underground boreholes and excavations in the Salado generate a disturbed rock zone (DRZ). The DRZ is a local region of enhanced permeability consisting of microfractures that spread at a slow and exponentially decreasing rate into the salt from any newly generated surface (created, for example, by borehole drilling).

All of these observations support an alternative to the interconnection (Darcy flow) model. In the alternative model, the undisturbed salt is essentially impermeable. Brine seepage comes from isolated domains of porosity containing brine that, in the undisturbed state, will be at lithostatic pressure. These domains become interconnected if they are penetrated by the micro and

macrofissures of the DRZ. If the DRZ should extend to the marker beds, Darcy flow from these beds into the excavations could occur.

Appendix C addresses brine flow into excavations in the Salado and considers the following two possibilities: (1) impermeable salt containing permeable marker beds, from which brine flows into the excavations; and (2) a permeable Salado Formation with Darcy flow into the excavations. In both cases, by using the permeability values considered to be most appropriate on the basis of current data, the total inflow appears to the committee to be too small to result in significant brine accumulation in the rooms. With appropriate design width and sealing of the entrance drifts to the rooms, it should be possible to minimize extension of the DRZ to the marker beds and avoid connection between the beds and the excavation (see discussion of room seals in Chapter 4).

In conclusion, brine inflow to excavations in the Salado is likely to be significantly less than was thought to be the case several years ago—and will occur primarily via anhydrite marker beds. Careful attention to room filling and backfilling could aid in further limiting brine inflow.

GAS PRESSURE

Because the current design of WIPP calls for sealing all shaft communication between the repository horizon and the surface, gas generation could conceivably create a pressurized repository. Three sources of gas generation in the sealed repository have been identified (Lappin and Hunter, 1989):

1. radiolysis;
2. anoxic corrosion, caused by any inflow of brine that might react chemically with the carbon steel waste drums, generating gas (predominantly hydrogen); and
3. bacterial reactions with some of the organic constituents (e.g., cellulose).

The worst case scenario would involve total dissolution of all steel drums in brine, with generation of the equivalent amount of hydrogen, plus bacteriological conversion of all cellulosics, plastics, and rubbers to a mixture of methane, CO, and CO_2. Based on this scenario, by considering gas compressibility but not solubility, reactivity, or the likelihood of interbed fracturing at lithostatic pressure, an early calculation (see Molecke, 1979a, b) indicated that the resulting pressure in the sealed repository could exceed lithostatic.

The generation of such quantities of gas cannot occur under undisturbed conditions because the quantity of brine required in this calculation is not available inside a sealed repository, and an external brine reservoir is sealed off from contact with the waste. However, the E1 and E1E2 scenarios do postulate an unlikely but possible mechanism for the introduction of very large quantities of pressurized brine. Accordingly, theoretical and experimental studies of gas generation have been undertaken (Freeze et al., 1995a) to provide estimates of the amount of gas generation to be expected under any credible set of conditions.

Early in the gas generation studies, DOE-sponsored researchers concluded that the amount of ionizing radiation in the expected WIPP inventory would not be enough to generate significant quantities of gas by radiolysis (see Molecke, 1979a, b). The remaining two sources of gas have been studied in more detail.

Laboratory Studies

Early laboratory experiments at Sandia National Laboratories (Molecke, 1979a, b) designed to permit estimates of chemical and biological gas generation rates were inconclusive because of the small and sometimes inconsistent effects observed. After a hiatus of several years, a larger program (Brush, 1990) was undertaken. This program, performed by recognized specialists, is now approaching completion (Brush, 1994; Beauheim et al., 1995).

The following conclusions about the major corrosion process have been reported:

> *Anoxic corrosion of steels . . . will produce significant quantities of H_2 and consume significant quantities of H_2O if*
>
> *(1) . . . sufficient brine enters the repository after filling and sealing;*

> *(2) significant microbial activity . . . does not occur (microbial activity will produce CO_2 or CO_2 and H_2S, which will passivate steels . . .)* (Brush, 1994, p. 6),

and

> *Under humid conditions (gaseous, but not aqueous, H_2O present), anoxic corrosion of steels and other Fe-base alloys will not occur . . .* (Brush, 1994, p. 7).

With respect to microbial activity, the conclusion announced in the same document is less definite: *". . . although significant microbial gas production is possible, it is by no means certain"* (Brush, 1994, p. 7).

Results of experimental studies (Brush, 1994) show that anaerobic gas generation rates in brine are likely to be quite low—approximately one micron per year rate of dissolution of the steel surface (Brush, 1994, p. E-9) and to be negligible if the waste is exposed only to gaseous phase "brine humid" conditions rather than being immersed in liquid brine.

Time Dependence of Bacterial Activity

Even if the experimental program eventually succeeds in measuring bacterial gas generation rates, a question will remain about extrapolating short-term, laboratory-derived rates to repository compliance time scales. Linear extrapolation may be appropriate for certain physical and chemical processes, but living organisms are more complex. Can bacteria continue to be active metabolically over extremely long periods in a closed system?

Because biologists ordinarily do not deal with long times and closed systems, there seems to be no literature on this subject, especially for the halophilic environment. However, literature does exist on life in extreme environments, and there are basic principles that are true for all forms of life under all conditions.

In the closed WIPP facility, organic and inorganic nutrients must be supplied from the emplaced waste and the enclosing salt. Neither of these can be regarded as a rich source of the complete range of compounds and elements required by the organisms likely to be present. Because extremely halophilic bacteria tend to have unusually complex nutritional requirements, they are not likely to thrive in an environment with a restricted range of substrates (Kushner, 1978). Nevertheless, it is probable that limited amounts of suitable nutrients are present and therefore, that the potential exists for metabolism and cell reproduction.

Unlike the culture medium in a laboratory flask, WIPP waste would not be homogeneous. Bacteria require an aqueous medium to dissolve and transport nutrients and to disperse metabolic products. Unless the repository floods, there is no continuous aqueous medium to give full access to the scattered supply of nutrients.

If a repository room does become flooded (by human intrusion, for example), biological activity will bloom for a time. The activity cannot continue indefinitely because of the bacterial generation of waste products that inhibit further metabolism and the conversion of limiting nutrients to forms that are not available to succeeding generations of bacteria.

Consider a specific example. Phosphorus typically makes up 2-3 percent of the dry weight of a microorganism. Phosphorus is indispensable to life; it is a component of the genetic material (DNA) of every living cell. Some of this phosphorus may be recycled promptly after the death and lysis of a particular cell. However, in a closed environment such as WIPP, a small remainder may be retained in a biologically inactive form for long periods. DNA samples at least 50,000 to 100,000 years old have been isolated from several sources (Williams, 1995). The phosphate deposits of Florida and Tennessee are a striking example of the way a life process can steadily lose a critical material in a "side stream."

Similar arguments can be made concerning other elements and compounds essential for the metabolic activities of bacteria in WIPP. In a closed system, it can be anticipated that at least one of these materials eventually will become limiting, thereby halting reproduction and metabolism.

"Real Waste" Tests

The DOE WIPP program plan of 1990 called for an engineering-scale program of "real" gas evolution tests to be run in parallel with laboratory studies. The plan involved emplacing a large number of drums of actual waste in one or more underground rooms, which would then be sealed and monitored. When this program encountered both practical and political objections, it was redesigned to use specially constructed metal "bins" to be filled with actual waste, placed underground, and monitored. This program also was canceled.

What remains of the real waste concept is the Source Term Test Program set up in 1994 at Los Alamos National Laboratory (LANL; see Chapter 5). As part of this program, gas evolution from selected samples of actual waste under various conditions is to be monitored at both the drum and the liter scale. As discussed in Chapter 5, no results from this program have been reported yet.

Conclusions on Gas Generation and Gas Pressure

The committee thinks that pressurization by gas generated in an undisturbed repository is not a serious concern for three reasons:

1. Laboratory experiments have recently established that hydrogen generation by anaerobic chemical corrosion of steel can occur in WIPP, but only when liquid brine and metal come into physical contact. Gas evolved from such brine-induced corrosion is limited by the contact area of brine with the steel drums. The brine-humid conditions anticipated in the repository restrict the expected gas-generating mechanisms to fewer than the set originally considered.
2. Biological gas generation will be no more than a brief transient because it will be limited by brine availability as well as by nutrient depletion.
3. Although gas sealed in waste-filled rooms can eventually approach lithostatic pressure due to creep closure of the rooms, it will represent a small total volume and a small gas pressure energy.

ROOM CLOSURE

As a result of an extensive rock mechanics research program, prediction of creep closure of repository excavations at WIPP is relatively straightforward. The time-dependent stress-strain behavior of salt is understood sufficiently well to predict closure for most design situations (Freeze et al., 1995b; Freeze and Christian-Frear, in preparation; Munson, in press). Studies to date show agreement between predicted and observed room closure rates within less than 10 percent. Further details are presented in Appendixes C and D.

Marker Bed Considerations

The main source of brine inflow to the repository rooms would be from three adjacent anhydrite layers, two above and one below the rooms. Marker bed (MB) 139, located about 1.5 m below the 4-m-high disposal room, is about 0.9 m thick. Anhydrite "a" and anhydrite "b" (each 0.1-0.2 m thick) are some 2 to 4 m above the 4-m-high disposal room, and MB 138 (approximately 0.2 m thick) is about 11 m above the ceiling (see Figures 3.1, 3.2; and Beauheim et al., 1993a).

The rooms are wide enough (10 m) that the normal rock fracturing and collapse processes around the rooms (i.e., formation of the DRZ) may cause these layers to be brought into hydrological connection with the waste rooms. Over a period of several years from the time of excavation, the DRZ will extend progressively to a distance above and below the repository comparable to the half-width of the room (i.e., about 5 m above and 5 m below the room).

The waste emplacement room dimensions (4 m high × 10 m wide × 91 m long) and the proximity of marker beds suggest that the DRZ formed around each room (including roof sag, floor uplift, and wall fractures) could, after some time, provide hydrologic contact between the waste-filled rooms and one or more marker beds.

Hydrologic contact is a matter of concern because it could create a path for fluid transfer between adjacent rooms. Even when undisturbed, the marker beds are more permeable than the neighboring halite. The

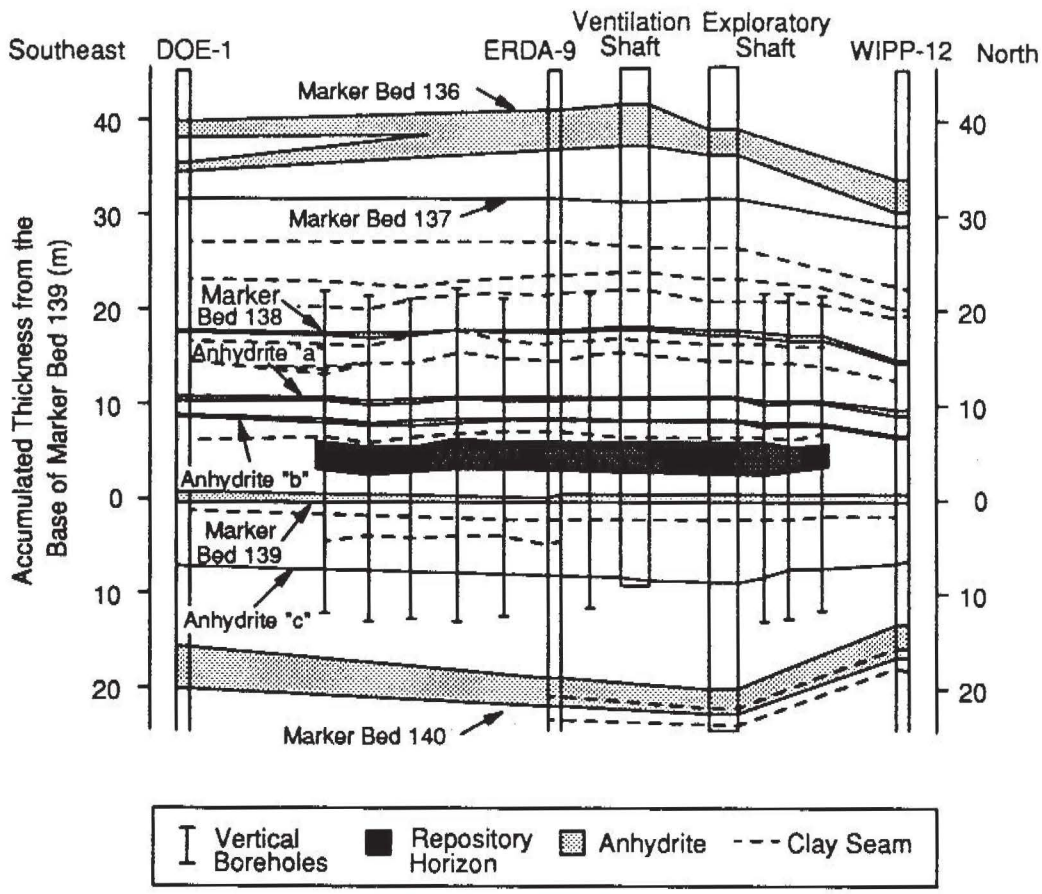

FIGURE 3.1 Stratigraphy of the Salado Formation near the repository horizon, showing adjacent anhydrite layers. Source: Freeze et al.(1995a).

"best-estimate" anhydrite permeability is of the order of 10^{-19} m^2, which is two orders of magnitude greater than the corresponding best estimate permeability for undisturbed halite (Freeze et al., 1995a, b). (See the discussion below on Backfilling and Compartmentation.)

If this interconnection should develop while the gas pressure in the WIPP excavation is below the fluid pressure in the adjacent rock, brine will flow in from the marker beds. The amount of brine available is theoretically large because the MB strata are areally extensive. However, the absolute quantity of Salado Formation brine that can enter an excavation in the repository horizon is limited by the remaining void volume of unconsolidated material during creep closure of the salt (see Appendixes C and D).

Should brine come in contact with the steel drums, gas generation would occur. However, several effects, identified and discussed below, suggest that this gas pressure buildup would be limited.

1. A pressure rise due to gas generation will reduce the rate of flow into the excavations. If the gas pressure reaches lithostatic, it would open fractures in the marker beds, greatly increasing the marker bed permeability to outward flow from the rooms. Gas would tend to flow out of the rooms.

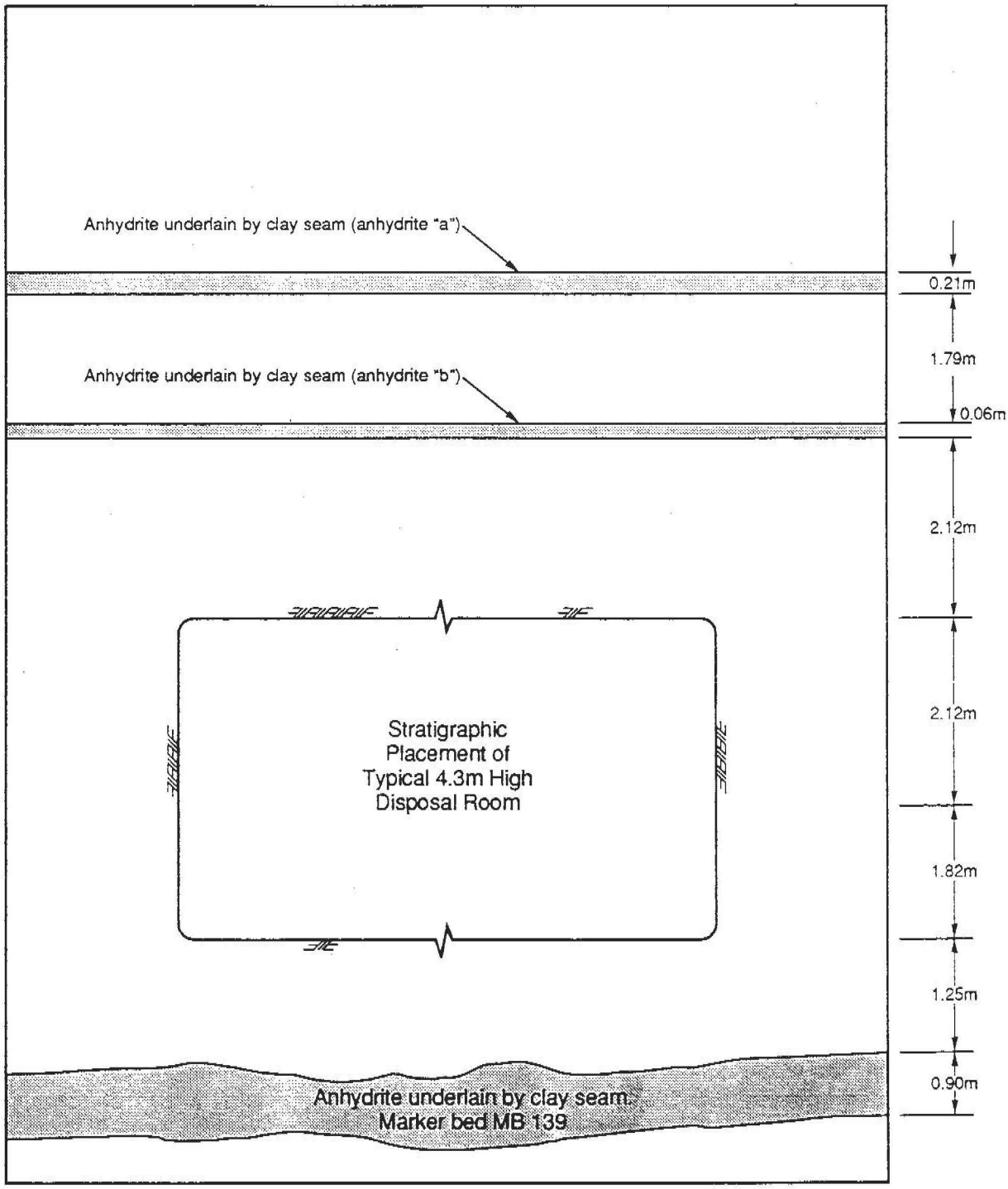

FIGURE 3.2 Close-up of stratigraphy of the Salado Formation at the repository horizon. Source: Department of Energy (1991, Figure 1-4).

Another possible effect of an intersection of the DRZ with the marker beds (particularly those above the repository) is the escape of gas by two-phase flow into the coarser fractures of the marker bed. This becomes appreciable only if the gas-brine pressure approaches lithostatic, when opening of fractures in the anhydrite layers would occur, resulting in a substantial increase in permeability of the marker beds. In this case, as shown by Webb and Larson (1996, Figure 4.9d, p. 37), the 1° inclination of the marker beds results in countercurrent flow (i.e., brine flows into the excavation as gas flows out), increasing the amount of brine inflow. Although variable, the increased inflow is of the same order of magnitude as flow into the unpressurized open excavation.

At gas pressures below lithostatic (i.e., without interbed fracturing), countercurrent flow is not significant. Furthermore, gas pressure acts to reduce brine inflow.

2. During earlier stages of room closure (i.e., 50-100 years), the floor uplift in each waste-filled room would tend to isolate the waste from liquid brine. During this period, the waste drums would be subjected to only a moderately humid environment, in which, as discussed in the previous section, gas generation by drum corrosion is considered negligibly small. However, if the brine remains in communication with the waste-filled drums, the desirability and feasibility of engineered designs to reduce or eliminate return of entrained brine to the waste rooms should be considered.

THE COMBINED EFFECTS OF BRINE INFLOW, GAS GENERATION, AND ROOM CLOSURE

The preceding discussion indicates that the predicted consequences of the combined effects of creep closure of the waste-filled disposal room, formation (and eventual healing) of the disturbed rock zone (DRZ), brine inflow, and gas generation can vary considerably depending on the particular assumptions made with respect to each of these variables (see also Freeze et al., 1995a). From the arguments outlined earlier in this chapter, the committee concludes that the amounts of brine and pressurized gas are likely to be small.

To assess the overall consequences of these issues on radionuclide isolation, it is necessary to incorporate the "room effects" into the entire network of excavations, including the shafts and seals. DOE has made the very conservative assumption that all waste-filled rooms remain permanently interconnected via a relatively high permeability DRZ (see Chapter 2) There is strong evidence, however, that placement of crushed salt seals between rooms and back filling of all other underground excavations with salt from mining operations will result in an overall low permeability within the excavation close to that of the intact salt (of the order of 10^{-20} m^2 or lower) within a few hundred years (see Callahan et al. [1996] and Appendix C). Each waste-filled room will then be an isolated compartment within the essentially impermeable Salado Formation. This compartmentation would greatly reduce the probability and consequences of an E1E2 borehole intrusion (see Chapter 2) and also the potential for brine flow up the sealed shafts.

Backfilling and Compartmentation

The development of hydrological contact between the marker beds and the waste-filled rooms could be inhibited somewhat by the use of well-placed (e.g., pneumatically injected) crushed salt backfill in the waste-filled rooms. Although this probably will not reduce the early development of the DRZ significantly because of the difficulty of packing the fill to a high enough density to obtain a rapid build-up of back pressure in the early stages of room closure, sufficient back pressure eventually will develop to reduce the aperture and hence the permeability of the marker beds.

Hydrological communication between the marker beds and the waste-filled rooms is of little significance provided hydrological communication between rooms is prevented. Careful design of entry rooms and early installation of room and panel seals to ensure that waste-filled rooms are isolated effectively from each other, or compartmented—as discussed in Chapter 4—could greatly reduce the vulnerability of a WIPP repository to human intrusion by drilling (see Chapter 2) or by water injection (see Box 3.2).

BOX 3.2 Potential Consequences of Brine Injection from Petroleum Recovery Operations on Repository Inflow

Although the permeability of halite in the Salado Formation is probably negligible, there remains some concern about flow through marker beds and other impurities in the formation. In oil-producing regions such as southeastern New Mexico, it is common to inject fluids into the deep subsurface, either to stimulate secondary recovery of oil in partly depleted oil reservoirs (e.g., by waterflooding) or to dispose of the large volumes of brine that typically are produced simultaneously with oil. Both types of operations involve high-pressure injection of fluids into a deep rock formation. If there is a failure in the well casing or in the grout or cement outside the casing, fluid can leak into overlying formations and flow laterally along one of the many anhydrite layers in the Salado.

One such recent occurrence, in the Rhodes Yates Field of Lea County in southeastern New Mexico, apparently caused significant flow through the Salado (reported as an unexpected flow of over 1,000 barrels per hour encountered by a well being drilled in 1991; see Silva, 1994, 1996). The unexpected flow through the Salado was attributed to injection into old (1940s-1950s) production wells in the Yates Formation, some 200 m below and 3 km away from the Salado horizon in the well where the flow was encountered. The flow probably was transmitted through anhydrite marker beds.

Because injection wells operate close to the WIPP site now and similar operations can reasonably be anticipated in the future, accidental leaks from such operations might represent a source of fluid that could migrate into the repository. Brine volumes under such conditions would be much greater than those that would seep into the repository from the Salado under undisturbed conditions. The committee believes that the likelihood and consequences of this type of disturbance occurring at the WIPP site should be evaluated by DOE.

There are differences between the petroleum production operations in the vicinity of WIPP and those in the Rhodes Yates Field (see Fig. A.6, Appendix A). Near WIPP, oil is produced below the 500-m-thick Castile anhydrite and salt formation, which underlies the Salado. The main gas-producing horizons are approximately 600 m deeper. Thus, injection for secondary recovery would be 700 m or more below the repository horizon. At Rhodes Yates, the Salado lies unconformably on the oil-producing Guadalupian series. The Castile Formation is absent.

Given the current improved well completion practices and the presence of the Castile into which fugitive brine may flow before reaching the Salado, the probability that fluid injected for enhanced recovery near WIPP would invade the repository horizon would seem to be lower than the Rhodes Yates incident. The potential of such a leak due to the injection of brine for disposal directly into the Castile, closer to the repository, for the period during which petroleum production at WIPP is likely to continue, is of greater concern. The committee recommends that DOE demonstrate how the performance of the repository will be assured against fluid injections.

Conclusion on the Combined Effects of Brine Inflow, Gas Generation, and Room Closure

The initial brine inflow into rooms is likely to be low enough that rates of gas generation will also be very low. Gas pressure will develop slowly (over hundreds of years) and more rapidly if the void volume of the room is reduced by backfill. Eventually, that is, in some hundreds of years, salt creep will close the rooms around the waste containers, with gas isolated in the voids between the waste in individual rooms and pressurized to the order of the lithostatic pressure. The hazard of such "pockets" of pressurized gas is considered by the committee to be negligible because of its small volume and small gas pressure energy. The committee believes that placement of effective room and panel seals will reduce greatly the potential for hydrological communication between the individual rooms.

SUMMARY AND CONCLUSIONS

After some hundreds to perhaps a thousand years, the steady-state condition of the undisturbed repository will be one in which the residual void in each room is a small fraction (10-15 percent) of the original room volume. This residual volume will be occupied by a mixture of deoxygenated gases, mostly hydrogen, probably at a pressure approximating lithostatic. These conditions would be established by Darcy flow of brine along the interbeds, controlled by room gas pressure and interbed permeability. In the absence of adventitious brine, only "brine humid" conditions are

expected. Creep closure and gas pressure buildup will serve to limit liquid brine entry.

Waste-filled rooms would probably be isolated from each other, so that the consequences of human intrusion should be considerably less severe than for the "interconnected rooms" scenario considered in the DOE PA. Chapter 4 discusses the engineering feasibility of compartmentation and other, relatively simple, engineering measures that may be taken to further improve the overall performance of WIPP as a TRU waste repository.

Chapter 4

Engineering to Improve Predicted Repository Performance

As discussed in Chapter 2, the committee judges the probability of radionuclide release from a well-sealed Waste Isolation Pilot Plant (WIPP) repository under undisturbed conditions to be very small. Concern has been raised that corrosion of the steel waste containers exposed to brine could generate gas at substantial pressure in the repository. Although the gas itself would be essentially nonradioactive, it could entrain radioactive material in the process of being released if a drill hole penetrated the repository at some time in the future.

In examining such possibilities, it is useful to consider ways in which the likelihood of potential releases could be reduced by changing the design of the repository or the form of the waste before it is placed underground. It is technically possible, for example, to incinerate the waste at the surface, thereby eliminating the possibility of gas generation underground. However, incineration also poses some risk of radionuclide exposure and would be very costly.

The Department of Energy (DOE) has conducted a number of studies (Lappin and Hunter, 1989; Marietta et al., 1989; Butcher, 1990; DOE, 1991, 1995b)[1] to examine a variety of such options to reduce risks. A short list of engineered alternatives is discussed below.

REPOSITORY DESIGN AND EXCAVATION ALTERNATIVES

Contact of drums with brine could be substantially lower than suggested in Chapter 3 because of both the probable behavior of the excavations (see Box 4.1) and the use of relatively simple engineering design changes, as noted below.

Natural and Engineered Sumps

Closure of the waste storage rooms, which are designed to be 4 m high × 10 m wide, will result from roof sag and floor uplift. Development of the disturbed rock zone (DRZ) and the associated floor uplift will create a "sink" for any brine flowing into the room, while simultaneously raising the waste drums above the brine, thus minimizing any immersion of the drums were liquid brine to be present. Also, because the rooms will follow the 1° inclination (i.e., a dip of 1.8 percent) of the marker beds (MBs), brine will tend to accumulate at the lower end of each storage room, creating the possibility of a drainage sump at this end of the rooms to remove the brine from contact with waste.

Design Considerations to Minimize DRZ Effects

If entrances to each room were to consist of *two* excavations, each 3 m wide, 3 m high, and about 25 m long, separated by a wider pillar, and if the center height of the excavations was located midway between the anhydrite layers, it should be possible to reduce the DRZ for each 3-m-wide excavation to no more than about 1.5 m above and 1.5 m below the roof and floor horizons, respectively (probably considerably less if the rooms are excavated and filled rapidly, within several weeks). In this way, it should be possible to avoid disturbing the anhydrite (brine-bearing) layers or connecting them with the DRZ, thus avoiding any inflow of brine into this section of the excavations. The 25-m section could be sealed with crushed salt or prefabricated compacted salt blocks, thereby isolating each room or panel from its neighbors; these seals (free

[1]DOE (1991) is a comprehensive study of a variety of engineered alternatives by a group of more than 50 engineers and scientists, known as the Engineered Alternatives Task Force (EATF). Results of the EATF study are referred to later in this report. DOE (1995b) is known as the Engineered Alternatives Cost /Benefit Study (EACBS).

BOX 4.1 Creep Closure and the Disturbed Rock Zone

Excavations will creep closed by movement inwards from the entire volume of salt, and eventually by a lowering (subsidence) of the surface, and/or gaps between the salt and overlying more elastic formations. A crude analogy to the viscous behavior of salt is the filling of a cavity of air made in a volume of water. The air cavity will fill by flow of water towards the cavity. The water occupying the volume of the cavity will result in a (slight) lowering of the water surface level.

Measurements at WIPP show that open rooms tend to close at a constant rate of about 1 percent per year. After about a hundred to a thousand years, then, it will be difficult to identify where the original rooms were excavated, because these rooms would be filled in by flow of the entire salt mass.

The Disturbed Rock Zone (DRZ) refers to a region, usually within one diameter or less of the walls of an excavation, in which the difference between the rock stresses prior to and after excavation is sufficient to produce microcracks in the salt. In the immediate vicinity of the walls the microcracks may coalesce to form open fractures. It has been shown, both by laboratory experiment and field observations at WIPP, that the microcracks and fractures can be healed when the deformation of the salt towards the excavation is resisted by a "back-pressure." This back-pressure can be generated by placement of seals or by back-filling the excavations with crushed salt. Calculations (Callahan et al., 1996) indicate that the permeability of a shaft seal of crushed salt that has been dynamically compacted to 90 percent of the density of intact salt (Hansen and Ahrens, 1996; Brodsky et al., 1996) will achieve a value close to that of the intact salt within 50-100 years. The DRZ will disappear over the same time period. Back-filled rooms will require longer to come to equilibrium at lithostatic pressure, but should certainly reach a condition similar to the shaft within a few hundred years.

of brine flow into the DRZ) should close as rapidly and tightly as the shaft seals.

Some redesign of the room and pillar layout may be needed if room compartmentation is introduced. The general principle of designing operations to minimize disturbance of the marker beds prior to room sealing is a useful one to follow. Such seals also should reduce potential impacts of the E1E2 human intrusion scenario substantially (see Chapter 2). Because the projected inventory of transuranic (TRU) waste destined for WIPP may be less than the design capacity of the repository (DOE, 1995c), the separation of individual rooms could be increased and the room seal designs improved.

Room Seals, Panel Seals, and Backfill

Once filled with waste and backfilled, the rooms should close within about 100 years, given the absence of brine in the DRZ (see Appendixes C and D). Although a central "core" of crushed waste materials in the rooms will probably retain significant local permeability, these materials can be isolated from each other by effective room and panel seals. There seems to be no reason why such seals cannot be designed to be as effective as shaft seals. Thus, the room and panel seal permeabilities would decrease progressively (e.g., to 10^{-16} m^2 or lower within 100 years), as assumed for the shaft seals (see discussion below), and, given the essentially viscous long-term behavior of salt, would approach the undisturbed value for salt (i.e., essentially zero) after 500 to 1,000 years. Thus, for at least 9,000 of the 10,000 years for which E1E2 intrusions must be considered, individual waste-filled rooms would be isolated from each other.

The effectiveness of room and panel seals in reducing radionuclide releases has been noted in DOE reports:

> *The concept of sealing individual rooms or portions of rooms, using thick salt 'dikes' which isolate smaller volumes of waste from each other, was considered the most feasible facility design alternative . . . .* (DOE, 1991, p. A-39)

and

> *This alternative was considered for mitigating the effects of the two-borehole* [i.e.,

> the E1E2] *scenario, and to a limited extent, the single borehole drilled into the Castile brine. The EAMP* [Engineered Alternatives Multidisciplinary Panel] *modified this alternative by suggesting that floor to ceiling salt seals could be installed at each end of the waste disposal rooms, as well as at appropriate locations within the rooms. This would decrease the effective permeability of each waste disposal panel, and prevent hydraulic communication between the two boreholes. If this alternative is implemented, it would appear to effectively eliminate the effects of the two-borehole scenario . . . .* (DOE, 1991, p. A-30)

A final report of the Engineered Alternatives Cost/ Benefit Study (EACBS) (DOE, 1995b) considers a wide variety of engineered alternatives, ranging from the use of backfill around the waste drums to reduce the void volume (and, hence, the time required to compact and seal in the waste) to the sealing of individual rooms. The prudence of considering relatively simple measures such as room seals has been recognized in concluding statements such as the following: "Communication between the rooms during an intrusion scenario is significantly reduced (gas, brine, and radionuclides)" (DOE, 1995b, p. B-7).

The committee is disappointed that, as of the time of preparation of this report, these engineered alternatives, despite their appearance in the Engineered Alternatives Task Force (EATF) and EACBS reports and their benefits being noted in Systems Prioritization Method (SPM) efforts (Sandia National Laboratories, 1995), have been neither evaluated by the WIPP program in past compliance documents nor incorporated into the 1995 performance assessment process (DOE, 1995a). The 1995 baseline model used (DOE, 1995b, Introduction) for compliance purposes is a connected repository, a suboptimal design (see Chapter 2). The benefits of using backfill are also supported by recent SPM results (Prindle et al., 1996).

Pre-Emptive Mining of Potash

The McNutt Member of the Salado Formation above the repository horizon contains potash that could be attractive for mining in the future. The field extraction methods currently used in New Mexico potash mines result in substantial ground deformation, both above and below the mined-out horizon, and surface subsidence. The ground deformation and subsidence over the mined-out area involve fracturing of the overlying strata, such as the Culebra Dolomite and the Dewey Lake Red Beds. This, in turn, may increase the hydraulic transmissivity of these layers significantly.

It is not yet clear how important this increased transmissivity might be in compromising the ability of the Culebra and associated strata to delay release of radionuclides from the repository. Studies by DOE are in progress. Should it be determined that the effects are sufficiently adverse to warrant corrective action, it is technically possible, although expensive, to extract the potash "pre-emptively" (i.e., as part of the engineering design of the repository) in such a way as to avoid subsidence and associated damage to the overlying strata.

Extraction of potash would be carried out in two stages, using a room and pillar method with cemented backfill (Brady and Brown, 1987). In the first stage, approximately half of the potash is mined across the entire minable area. The rooms are then filled with cemented backfill. In the second stage, the ore remaining between the cement-filled areas is extracted, and the voids are again filled with cemented fill. In this way, deformation of the overlying formations would be negligible. If desired, special backfill material could serve as a protective cap over the repository and as a deterrent to future drilling.

Waste Form Modification

Concern about potential gas generation in WIPP (Bredehoeft, 1988) arose from the possibility that large quantities of brine might accumulate in the repository during waste storage (see Appendix C). The 1991 EATF (DOE, 1991), a multi-disciplinary group of over fifty scientists and engineers, considered a wide range of waste form alternatives based on existing technologies or on technologies that could be developed within a few years. Such technologies include methods to shred; compact; cement or grout; incinerate; vitrify; melt metal (producing ingots or slag); add pH buffers, salt, or sorbents; decontaminate metals; and use

noncorrosive containers. Changes in facility design also were considered. These options were screened to fourteen combinations that were chosen for detailed evaluation. Although such technologies either were available or probably could improve the waste form, the 1991 EATF report found that

- costs would be higher than if wastes were untreated,
- worker risk would be higher than for untreated waste handling,
- a waste treatment system would take significant time to implement, and
- treatment options would involve more complicated regulatory requirements.

In general, waste treatment options were viewed as properly held in reserve in case a need to supplement more readily implementable alternatives, such as backfill, arose. The 1995 EACBS (DOE, 1995b) chose to evaluate eighteen alternatives and reached similar conclusions and provided a specific ranking of the various alternatives.

In the committee's view, the conclusions of the EATF and EACBS are appropriate. As discussed in Chapter 3, gas generation is not anticipated to be a significant problem at WIPP; therefore, the use of advanced treatments such as incineration is unwarranted.

Findings, Conclusions, and Recommendations on Engineered Features

The committee believes that the WIPP design should incorporate engineered alternative features, and the performance assessment (PA) should reanalyze the human intrusion scenarios, incorporating (1) the existence of effective room/panel seals, and (2) a DRZ permeability that decreases with time, consistent with the known behavior of salt. Further, it is feasible, probably with no major increase in cost, to design the repository so that waste containers avoid contact with brine, thereby essentially eliminating gas generation, and to ensure that waste panels are isolated from each other effectively by seals that are comparable in permeability (10^{-16} m^2) to shaft seals.

The committee thinks that it is prudent to consider such engineering measures as backfilling of the waste rooms to ensure early reconsolidation of the DRZ and minimization of brine inflow. More advanced options, such as incineration or vitrification of TRU waste, are unwarranted.

SEALING OF SHAFTS AND BOREHOLES

In the committee's view, the flow of radionuclide-contaminated brine through inadequately sealed vertical shaft excavations at WIPP is the most probable pathway for release of radionuclides from the repository to the accessible environment under *undisturbed* conditions. Calculations (DOE, 1995d; and Appendix C) indicate that a seal permeability of 10^{-16} m^2 or less, over a minimum seal height of 100 m, is needed over the total (100 m^2) cross-sectional area of the four shafts to limit brine flow sufficiently through the seals to provide adequate isolation of the repository for 10,000 years. Figure 4.1 shows the results of PA calculations on the cumulative flow through the seals in 10,000 years.

In the figure, the net total brine flow through a 100-m-high seal of crushed salt (in each shaft) is plotted for various assumed values of the seal permeability. Each of the different flow values shown for a given seal permeability is the result of one "run" (or CCDF "realization"—see Appendix B) of the repository seal model. This model involves a number of parameters such as salt permeability, brine inflow to the rooms, gas generation, room closure, and gas pressure. Values for each parameter were selected at random from a range of values, and the model was run, computing for the particular combination of parameters selected the mean brine pressure at the bottom of the shaft over 10,000 years. In some cases, this mean pressure over 10,000 years was less than the net flow, or "cumulative release" was negative, that is, brine flowed *into* the repository. In other cases, the reverse was true, that is, the mean pressure below the shaft seal was greater than hydrostatic and so brine flowed *out* of the repository. Thus, Figure 4.1 shows both positive (outflow) and negative (inflow) values at each permeability tested. For permeability of $10^{-16}m^2$ or lower, the flows were negligibly small in all cases tested.

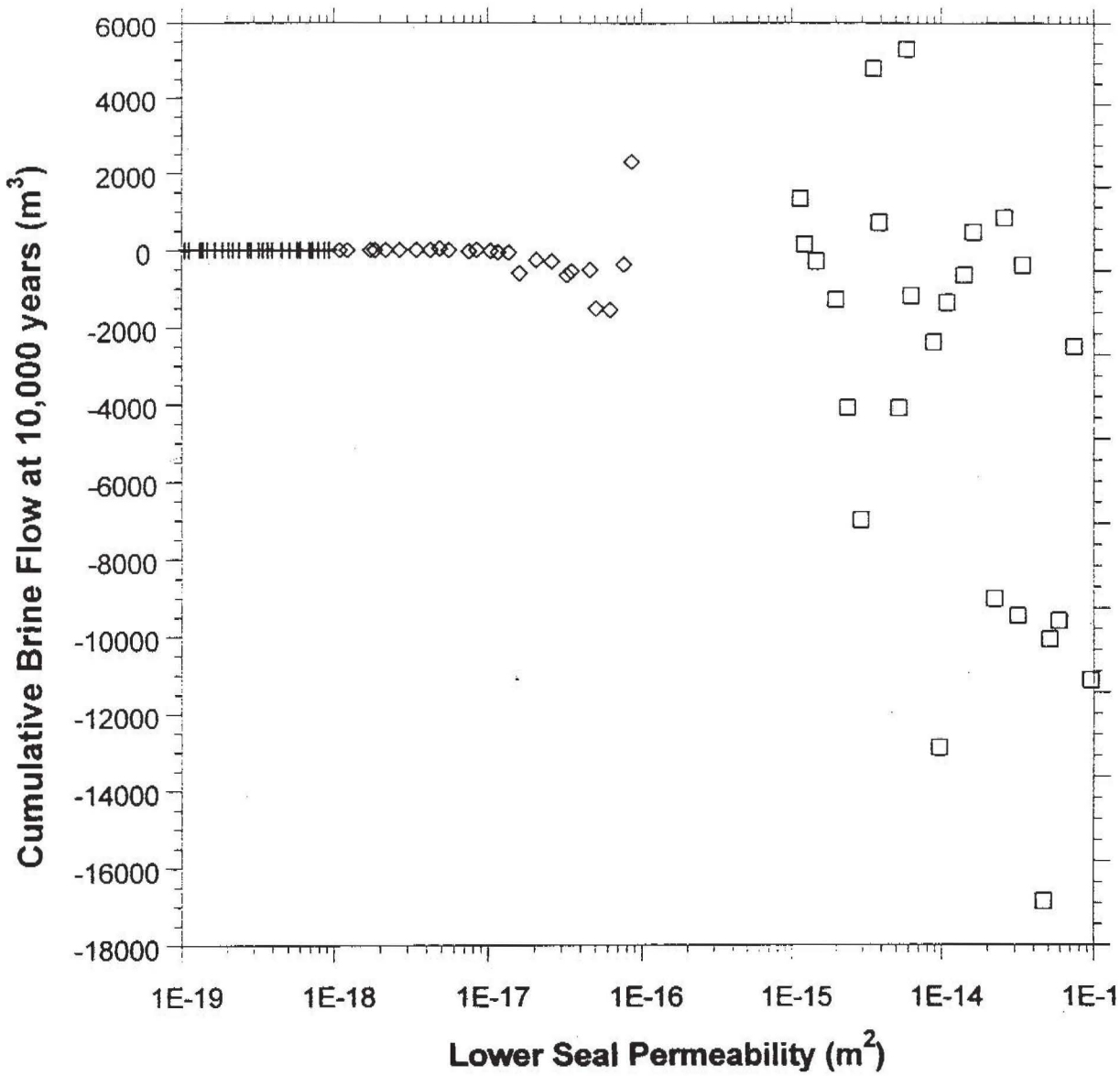

FIGURE 4.1 Predicted cumulative brine flow through (100-m-high) lower seals of the WIPP shaft. Source: Department of Energy (1995d, Figure C-1, p. C-5). This is a compilation of three sets of PA sampling calculations varying the Lower Seal Permeability. Squares indicate the cumulative flow for seal permeabilities in the range 10^{-13} to 10^{-15} m^2; diamonds, in the range 10^{-16} to 10^{-18} m^2; and plus signs, 10^{-18} to 10^{-19} m^2. In the calculation, the rate of brine flow through the seal depends on the *difference* between the pressure below and above the seal and lessens as the seal permeability decreases. The negative results in the figure indicate that the average pressure generated in the repository over the first 10,000 years is less than the pressure (hydrostatic) above the seal—so fluid flows *into* the repository. Thus, the Cumulative Brine (out) Flow is negative (i.e., it is a net inflow). When the permeability is 10^{-16} m^2 or less, there is little flow in or out. These PA calculations are based on the assumption that there are no designed seals in any of the underground excavations. Thus, shaft seals alone are sufficient to prevent radionuclide release for the undisturbed case.

It is seen that a lower seal permeability (abscissa) of 10^{-16} m^2 or less is needed to reduce the cumulative brine flow at 10,000 years (ordinate) to negligible levels for all repository parameter combinations. The accuracy of this result is shown by independent calculations performed by the committee and given in Appendix C. Similarly, a permeability of 10^{-18} m^2 or less is needed to limit gas flow through the seal (DOE, 1995d).[2]

The four shafts at WIPP are each approximately 6.1 m (20 ft) in diameter and approximately 660 m (2,160 ft) deep. The upper 256 m (840 ft) of the shafts passes through relatively permeable water-bearing sediments consisting of evaporites, carbonates, and clastic rocks. The remaining 404 m (1,325 ft) to the bottom of the shaft (and the repository horizon) consists of bedded salt in the Salado Formation. The Salado also extends approximately 200 m below the repository horizon.

Once the repository has been filled with TRU waste, the entire 660-m column of each shaft will be sealed with a variety of seal materials, as shown in Figure 4.2. In designing the seal system, it is necessary to incorporate features that effectively will prevent vertical flow of fluid both within the shaft itself and within an annular region extending about one-half to one shaft radius from the shaft wall into the rock. Within this region, referred to as the DRZ, the initially intact, essentially impermeable salt has been fractured as a consequence of rock stress changes introduced by the process of excavation and by the continuing changes that have occurred over the decade or so since the WIPP shafts were excavated (Figure 4.3). Given the additional 30-40 years needed to fill the repository, these time-dependent effects would be operative for a total of approximately 50 years before shaft sealing could start, creating an annulus of relatively high permeability around the shaft (Figure 4.3). This annular pathway for fluid flow must be eliminated to seal the shafts effectively.

[2]Although concentrations of hazardous gases are not likely to be sufficient to exceed Resource Conservation and Recovery Act regulatory limits on gas leakage to the accessible environment, the gas pressure of the repository is an important design consideration. Any pressurized gas in fractures in the DRZ around the shaft and in the interstices of the crushed salt used to seal the shaft could reduce the rate of salt recompaction significantly, both in the seal and in the DRZ. Brine within the same interstices could have a similarly retarding effect on salt consolidation.

Development and Healing of the Disturbed Rock Zone

The "damage" induced in the DRZ varies progressively from small, isolated microcracks in the regions of low stress change remote from the shaft, through a coalescence of the microcracks, to extensive through-going vertical fractures in the immediate vicinity of the shaft wall. Only in this more extensively fractured region is shaft permeability increased significantly.

Recent gas and brine flow permeability tests (Dale and Hurtado, 1996) around the Air Intake Shaft at the 660-m level and at the top of the Salado (256 m) reveal that there is no measurable change in permeability of the salt at either location, except within an annulus extending approximately 1 m from the shaft wall.[3] Thus, the region of increased permeability is likely to be a small part (10 to 20 percent [maximum] of the shaft radius) of the DRZ around each shaft.

Laboratory studies (Brodsky, 1995) clearly indicate that stress-induced fractures in salt specimens can be eliminated when the damaged region is subjected to sustained moderate confining pressure (approximately 5 MPa [MegaPascals]). The permeability of the cracked specimens is found to approach that of intact salt within a few days.

In the full-scale shaft sealing situation, the rate of reclosing or "healing" of induced (permeable) fracture zones around a shaft in the Salado will depend on the rate of buildup of the confining stress. This depends, in turn, on the compressibility of the shaft seal material and the rate of steady-state creep of salt around the shaft (Figure 4.4).

Numerical simulations by DOE contractors indicate that the width of the DRZ annulus at the time the shaft is filled (i.e., 50 years after excavation) will vary from $0.6R$ (where R [= 6.1 m] is the shaft radius) at a depth of 256 m (i.e., at the top of the Salado, where the lithostatic pressure is 6 MPa) to approximately $0.85R$ at 660-m depth (i.e., at the bottom of the shaft, where

[3]Because the rate of increase in the extent of the DRZ decreases exponentially with time, the 1 m of DRZ developed in about 10 years (the approximate age of the Air Intake Shaft) would grow to no more than about 2 m in 50 years.

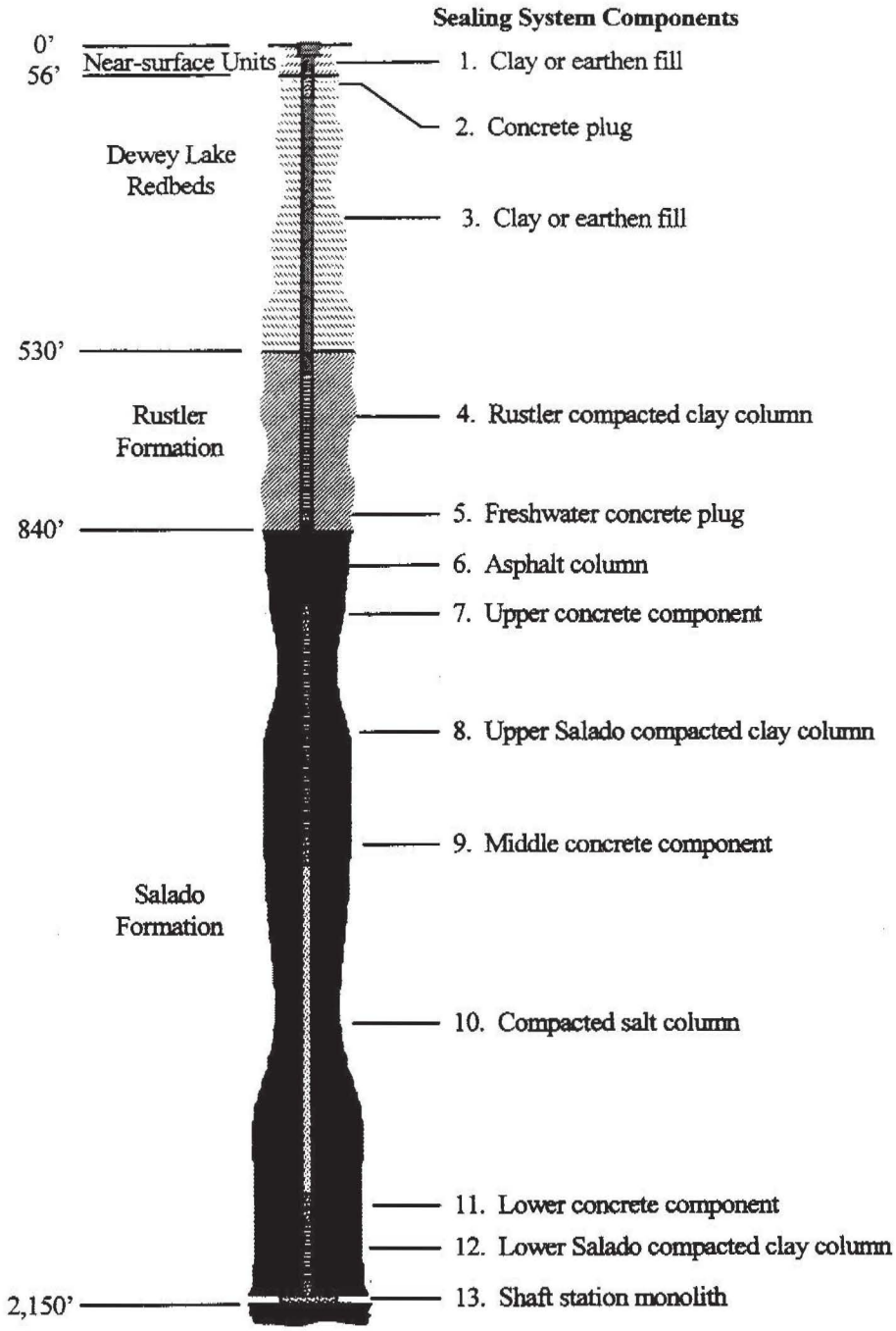

FIGURE 4.2 Arrangement of the WIPP shaft sealing system. Source: Department of Energy (1995d, Figure 2-1, p. 19).

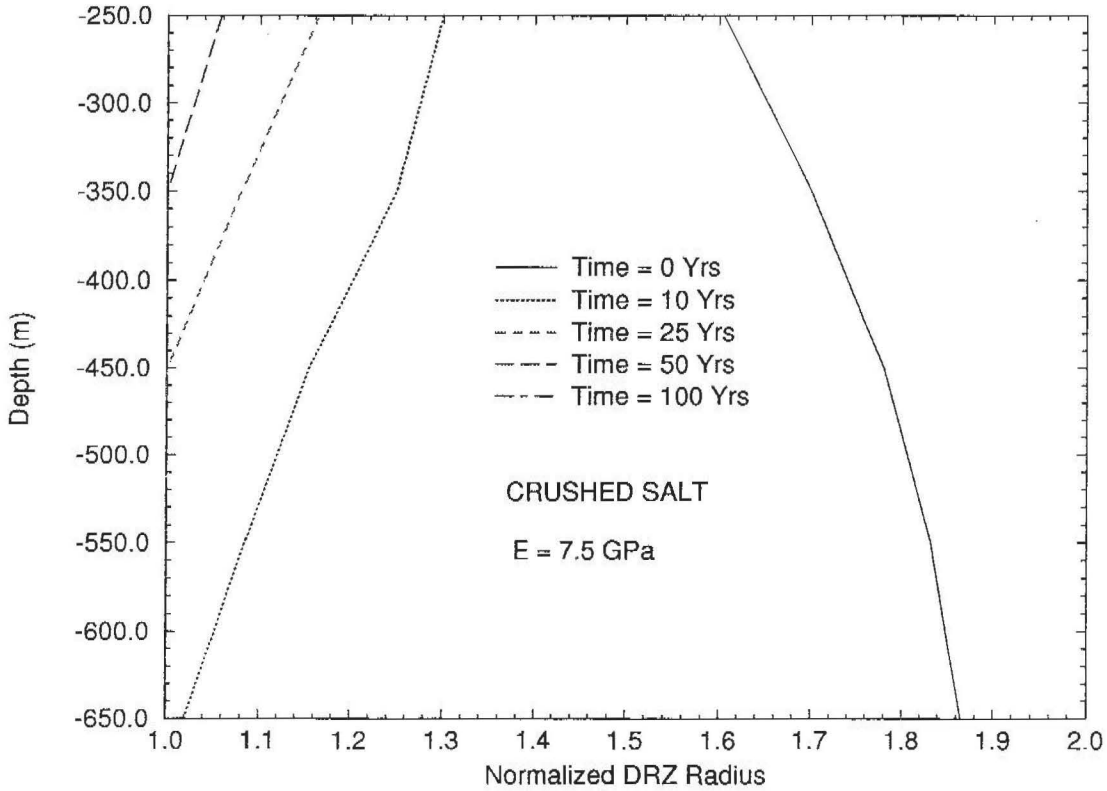

FIGURE 4.3 Calculated radial extent of DRZ annulus around a seal of crushed salt, compacted to 90 percent of the intact salt density. Source: RE/SPEC calculations done under contract to the Sandia WIPP Shaft Sealing Program, in RSI Calculation File 325/11/05.

the lithostatic pressure is 15 MPa). Computations (see Figures 4.3 and 4.4) indicate that with crushed salt that is compacted to 90 percent of the density of intact salt, the DRZ annulus will, 50 years after filling the shaft, have been reduced to $0.05R$ at the top of the Salado and totally eliminated between 350 m and the bottom of the shaft (660 m), that is, over almost 300 m. After 50 more years, the DRZ is eliminated over the entire 400-m Salado section. Because the region of increased permeability in the DRZ is confined to the portion immediately around the shaft wall, it seems probable that the entire 400-m Salado section in the shaft will achieve a permeability close to that of intact salt within 50 years of filling the shaft.

The computations above do not allow for the delaying effect of adventitious brine or high-pressure gases that could be introduced into the DRZ fractures. As mentioned earlier, the presence of these fluids would inhibit closure of both the DRZ and the compacted salt. Eventually, the connected, fluid-filled fractures in the DRZ (and regions in the crushed salt) would probably degenerate into isolated spherical inclusions containing gas or brine at lithostatic pressure within the "healed" salt, but the elimination of permeability may be delayed substantially. It is therefore desirable to ensure that the DRZ fractures and intergranular regions of compacted salt are maintained free of brine or gas during the 50-100 years required for full compaction under dry conditions.

To this end, several strategies have been proposed, including the introduction of supplementary seals above and below the region of the compacted salt seal. Use of the concrete seals, which have a significantly higher initial stiffness than the compacted salt, will result in a

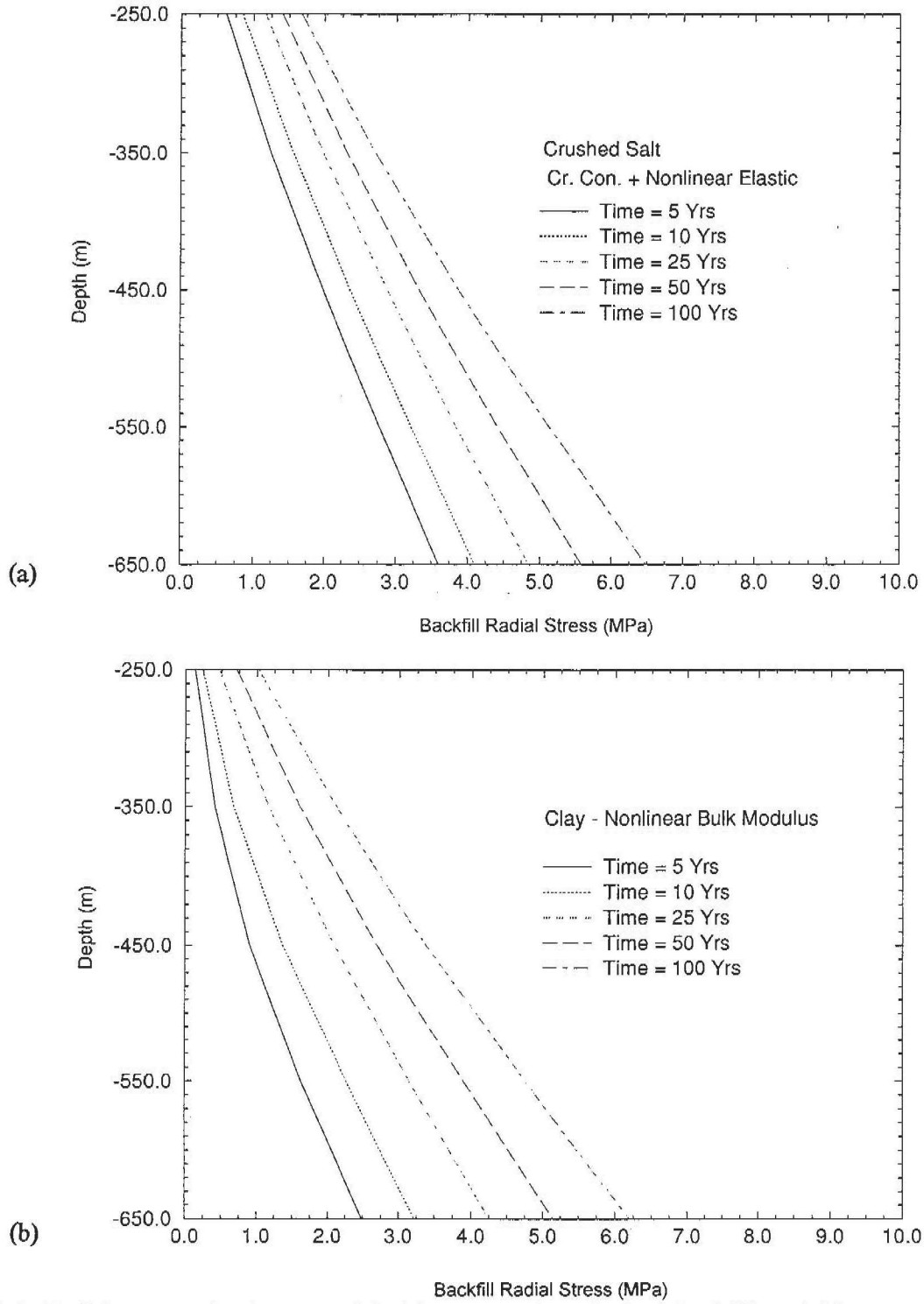

FIGURE 4.4 Radial stresses (back-pressure) in (a) compacted crushed salt backfill, and (b) compacted clay in the WIPP shafts as a function of time and depth. Source: RE/SPEC calculations done under contract to the Sandia WIPP Shaft Sealing Program, in RSI Calculation Files 325/11/03, 325/11/04, and in RE/SPEC External Memorandum RSI(RCO)-325/11/95/23 (November 1995).

more rapid buildup of back-pressure and correspondingly more rapid elimination of any permeability in the DRZ above and below the compacted salt section, thereby sealing this section early against brine inflow. Brine and gas inflow to the compacted salt column can be eliminated effectively by placing a compacted clay column above and below the compacted salt (Figure 4.2). Although probably unnecessary, it is feasible, at the time of sealing, to "ream out" this inner portion (i.e., about 10-20 percent of the shaft radius, as noted earlier) of the DRZ above and below the compacted salt sections where the concrete is to be placed. The reamed-out sections then would be filled with rapid-curing concrete as soon as possible after reaming, ensuring very early protection of the DRZ in the compacted salt section against inflow of brine.

The benefit of retarding release of radionuclides by placing compacted clay columns at various sections in the shaft (Figure 4.2) should be considered fully in the design and PA analysis of the effectiveness of shaft seals. Present PA sensitivity studies model shaft seal permeabilities but not extensive, detailed shaft designs.

No large-scale demonstrations of the effectiveness of proposed shaft-sealing designs have been carried out. However, the reality of salt creep is indisputable; salt around the shaft definitely will flow to seal in the shaft plug and reheal the disturbed rock zone. Because DOE proposes to use compacted crushed salt as the shaft seal material, this too should reconsolidate eventually to a density and impermeability comparable to that of intact salt. The practical feasibility of using temporary seals to eliminate water from the permanent seal sections during closure has to be examined and demonstrated carefully. Because these seals will be required only at the end of the operational phase of WIPP, there is adequate time to address this design problem.

In the proposed multicomponent shaft seal system (illustrated in Figure 4.2), reconsolidated salt is expected to constitute the major long-term seal component. Ahrens and Hansen (1995) demonstrated the feasibility of large-scale dynamic compaction of crushed natural salt in a shaft configuration to achieve 90 percent of its intact density, providing greater confidence in the efficiency of its reconsolidation to produce an effective long-term seal.

As noted previously, major short-term concrete seal components are expected to provide structural support as well as to retard brine or gas flow substantially during the intervening period before the salt seal components are adequately consolidated. This performance of the concrete component has been documented recently by the Department of Energy (1995d) and, in more detail, in individual reports (Stormont, 1984, 1986, 1988; Van Sambeek et al., 1993). The importance of designing concrete to be chemically compatible and durable in the salt-dominated WIPP horizon has been emphasized by several investigators (e.g., Roy et al., 1983, 1985; Wakeley et al., 1993, 1994, 1995). In-place permeabilities of experimental salt-saturated concrete plugs (1-m diameter) in WIPP showed decreased permeabilities with time (less than 4×10^{-19} m^2) after six years (Wakeley et al., 1993). Some remaining concerns exist regarding compatibility of concrete with magnesium-rich brines found at WIPP. Additional confidence in the performance of concrete is provided by field studies of sealing methods in salt or potash mines (Eyermann et al., 1995). The stoppage of major (10 m^3/min) flow of pressurized brine in the Rocanville Potash Mine, Saskatchewan, is a good example of the ability to seal excavations effectively in potash (or salt) using current technology.

The seal design incorporates additional components of shaft seals, planned to perform individual functions (DOE, 1995d). These seals include compacted clays (Meyer and Howard, 1983) for use in both non-Salado and Salado members, asphalt to act as a water-stop between concrete members, and possibly other impermeable chemical seal components to act essentially as an O-ring. Issues of concern about the potential use of asphalt as a seal component have not been resolved fully. As with many organic-based materials, there are issues of potential degradation and gas generation, including microbial attack. Addition of lime to the asphalt mix has been suggested as a possible remedial measure (DOE, 1995d). The influence of the different compressibilities of the seal material (here crushed salt and clay) on the rate of buildup of radial stresses in the seal and the shaft wall is illustrated in Figure 4.4.

The sealing of exploratory and other boreholes, as necessary, is expected to draw on extensive experience

with cementing and plugging technology in the oil and gas industry, much of which has involved bedded salt environments. Impressive early tests of the performance of the borehole plug (cementitious materials) under high well pressure conditions in the specific WIPP environment (Gulick et al., 1980) have been followed by other studies, demonstrations, and plug material development (Finley and Tillerson, 1992; Wakeley et al., 1995).

SEALING OF ROOMS AND PANELS

Sealing sections of horizontal drifts presents essentially the same problems as sealing vertical shafts, except that in this case, gravity acts to accentuate development of the DRZ in the roof and to retard it in the floor. One difference is that during placement, it is difficult to compact crushed salt in a horizontal drift to the same density as in a vertical shaft.

Salt creep should compact horizontal seals eventually to the same high level of impermeability (for both the DRZ and the excavation) as in the shafts. If it is assumed, for example, that 100 m of drift can be packed with crushed salt at 70 percent of the intact salt density (i.e., rather than the 90 percent density for the shafts), 200 or 300 years probably will be required to reach 10^{-16} m^2 seal permeability, rather than the 50-100 years needed for the shaft. Technologies of placing drift seals to isolate radioactive waste have been, or are being, examined elsewhere, for example, in Stripa (Sweden) and Pinawa (Atomic Energy of Canada, Ltd., Canada). Salt has the distinct advantage over most other rocks of exhibiting creep, allowing rehealing of the DRZ, and progressive reduction of seal permeability.

Thus, it seems technically feasible to provide, between the waste storage rooms and panels, drift seals that are sufficiently tight, perhaps 300 years after waste emplacement, to eliminate brine communication between the waste-filled rooms and panels at WIPP. Note that any such communication between rooms via anhydrite marker beds (e.g., MB 138, MB 139) would not be affected by the drift seals. These beds have a low permeability, of median value 2.5×10^{-19} m^2 (DOE, 1995a, p. 6.75) and therefore would contribute negligible brine, with regions near the excavations becoming drained during the period that the rooms are open before waste emplacement. As discussed at the beginning of this chapter, with careful room and panel seal designs, it should be possible to inhibit room-room hydrologic communication.

Whether or not drift seals contribute to the overall isolation capability of the repository depends on the credence given to the human intrusion scenarios that must be examined according to 40 CFR 194. For the undisturbed case, PA studies by DOE in which no drift seals are assumed show that the shaft seals alone are sufficient to prevent radionuclide release. Thus, for the undisturbed case, drift seals are not necessary to demonstrate compliance (see discussion of Figure 4.1).

Currently it is assumed, for example, as part of the E1E2 scenario (see Chapter 2), that brine from a pressurized reservoir will flow through the repository, carrying radionuclide-contaminated brine to the surface via a second borehole. Provision of drift seals would reduce the possibility of establishing such a flow path and hence would considerably reduce the significance of this "two-hole" type of human intrusion.

CONCLUSIONS

The ability of salt to flow under stress is a particularly valuable attribute with respect to sealing excavations in the WIPP repository. While careful attention to good practice during seal construction is very important, it appears to the committee that the design of effective shaft and panel or room seals at WIPP is entirely possible by using currently available technology. The shaft seal design system proposed for WIPP (DOE, 1995d) includes large factors of conservatism and redundancy, which ensure that the requirements of 40 CFR 191 with respect to sealing of excavations at WIPP can be met by a large margin.[4] Although room and panel seals are not essential for adequate waste isolation at WIPP given undisturbed conditions, they would reduce the significance of an E1E2 intrusion event considerably.

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[4]This is a properly conservative design of the engineered seal. There is no contradiction between the conservatism advocated here and the critical remarks against conservatism in Chapter 2. The latter were levied against unrealistic assumptions of salt performance that could lead to a mischaracterization of how WIPP could perform.

Chapter 5

Actinide Source Term

In the performance assessment (PA) of the repository described in Chapter 2, compliance with the Environmental Protection Agency (EPA) requirements is discussed relative to two scenarios, E1 and E1E2 (Figures 2.4 and 2.5), in which pressurized brine from below the Salado Formation flows into the repository and then either directly to the surface or through the Culebra Dolomite to the accessible environment. The amount of radioactive material that might move into the environment obviously will depend on the amounts of the five actinide elements (plutonium [Pu], americium [Am], neptunium [Np], uranium [U], and thorium [Th]) that the flowing brine can transport. This quantity is the actinide source term (AST), defined more specifically by scientists at Sandia National Laboratories as the cumulative amounts, concentrations in solution, and chemical nature of the radioactive materials that conceivably could be moved in solution or suspension from the Waste Isolation Pilot Plant (WIPP) repository into the environment.

Clearly, an estimate of the AST is an important part of any performance assessment. Although the AST program includes an evaluation of five actinides, the most important issue for periods greater than a thousand years is the fate of the more abundant, long-lived isotopes of plutonium (e.g., Pu-239 and Pu-240; see Table 1.1). The study of the other actinides is important because they provide a basis for the oxidation state model in which plutonium may assume a variety of oxidation states. As an example, the following elements may be used to model the behavior of plutonium: Am(III)[1] for Pu(III), Th(IV) for Pu(IV), $Np(V)O_2^+$ for Pu(V), and $U(VI)O_2^{2+}$ for Pu(VI) (Novak, 1995b).

Evaluation of the AST depends principally on the following:

- the total inventory of radioactive material (Table 1.1) and its decrease due to radioactive decay as a function of time;
- conditions within panels of the repository and along the route of transport (e.g., the volume of brine exposed to the waste and transported out of the repository); and
- the timing of potential release events.

The challenge in making a reasonable estimate of the AST is to gain an understanding of the coupling between the chemistry of the system and the boundary conditions and assumptions (e.g., redox potential, flow rate, gas generation, distribution of sorbing clays, presence of ligands) used in the performance assessment.

As noted in Chapter 2, performance assessments to date (e.g., that for 1992) confirm that if the repository, after completion, is left undisturbed by human activity, the presence of brine in contact with waste will not lead to migration and release of appreciable radioactivity beyond the WIPP boundary. The geologic barriers, combined with the planned engineered barriers discussed in Chapter 4, will be sufficient to prevent radionuclide escape. *Thus, for the undisturbed case, the magnitude of the AST is of no consequence for assessing compliance.*

If the repository is disturbed at some time in the future, however, it is possible that some radioactive material might escape. Therefore, estimates of possible amounts of released radioactivity are required for detailed assessment of the performance of the repository under various assumed conditions. In any such assessment, the magnitude of the AST is an important parameter.

In making a performance assessment of the scenarios described in Chapter 2, Department of Energy (DOE) scientists have undertaken an elaborate program of experimental work (Novak, 1995a) to ascertain the

[1]The Roman numerals specify the actinide oxidation state.

possible range of actinide concentrations in the brine as it moves from the panels in the repository to the WIPP boundary. This chapter reviews DOE's proposed experimental program (Novak, 1995b; Papenguth and Behl, 1996a, b) on the AST.

Although the committee has been given a good overview of the work on the AST that has been completed or is still in progress (see Appendix E), much of the research on the source term is not yet complete, and some important results of the program will not be available for review in the immediate future (e.g., experimental studies of Pu speciation in brine). Consequently, this chapter should be viewed as a review of work in progress and cannot serve as an evaluation of the quality or applicability of the final experimental results.

ACTINIDE SOURCE TERM MODEL

Brine that has been in contact with transuranic (TRU) waste (described in Chapter 1) likely will contain actinides as compounds or ions in solution and as colloidal particles. As the brine moves through rock units, the amount of actinide transported will change. Actinide concentrations in brine may be expected to decrease owing to precipitation of actinide-bearing phases or sorption on mineral surfaces; alternatively, actinide concentrations could increase in response to the formation of complexes in solution. To determine the amounts of actinides that might reach the compliance boundary, estimates of the following are required for each element of concern (particularly plutonium):

1. the concentration in solution, as controlled by the solubilities of the actinide-bearing phases and the kinetics of the dissolution process;
2. the amount that could form and be transported as colloidal particles; and
3. the amount that could be removed from solution by sorption on the surfaces of dolomite or other minerals (e.g., the corrensite-lined fractures of the Culebra Dolomite) as the brine moves from the repository into the surrounding rock.

DOE analyses (Sandia National Laboratories, 1992, 1995; DOE, 1995a) consistently have identified these three quantities as important to the long-term performance of WIPP. The same three quantities also have been identified as important by EPA and the Environmental Evaluation Group (EEG; Neill et al., 1996).

Estimates of these quantities can be approached theoretically with models using tabulated chemical data and basic chemical principles, and empirically through either carefully controlled laboratory experiments or measurements under actual field conditions. Each approach has advantages, and all have weaknesses. Although well-controlled experiments using ideal or model systems may provide a fundamental understanding of the chemical processes, conditions of the experiments may be simplified to the point that their direct applicability to the larger-scale, more complex conditions in a waste panel is not clear. Field-scale experiments (e.g., sorbing tracer tests) or experiments with actual waste (e.g., Source Term Test Program [STTP] experiments at the Los Alamos National Laboratory [LANL]) may be difficult to interpret, but they do provide qualitative information on potential chemical interactions and bounding estimates of actinide concentrations in brine. Confidence in the models used in performance assessment will rest inevitably on consistency in the results and the general applicability of the models to all results—experimental, theoretical, and field.

Three principal factors currently being investigated by DOE that determine actinide transport in brine—solubility, colloids, and retardation by sorption—are examined below. Only limited attention is being paid to other factors (e.g., kinetics and redox effects on the reactions) that may also finally influence the transport of actinides to the accessible environment.

Solubility

Estimating actinide solubilities from published data is particularly difficult because the electrolyte concentrations in brines are very high, whereas most existing tabulated data apply to dilute solutions. This means that the thermodynamic formalism related to solubility must incorporate the use of correction factors. Of the numerous such factors that have been proposed, the generally accepted approach has proven to be the parameters developed by Pitzer (Pitzer, 1991). These are the correction factors used by DOE scientists

(see Appendix E for a more detailed discussion of Pitzer parameters).

Difficulties in determining actinide solubilities are compounded by the many gaps in published tables of thermodynamic data. DOE scientists are responsible for filling such gaps through their experimental work. A further complication is the fact that the solubilities of a number of actinide compounds are influenced by the formation of complexes, either with inorganic ions such as Cl^- and CO_3^{2-} or with C-H-O compounds from the organic materials present in much TRU waste. Add the difficulty of knowing or determining the relative proportions of the oxidation states of an actinide element in a given solution, and the complicated nature of the task that DOE researchers have set for themselves becomes apparent.[2]

Based on a review of the AST program, the committee has identified areas of concern that are described in Appendix E. Although the experimental approach chosen to estimate actinide solubilities is acceptable, it will be defensible only when supported by extensive experimental data, which were unavailable at the time of preparation of this report. When compared to published experimental data, current modeling efforts are not capable of conservatively estimating actinide solubilities. For example, Novak and Roberts (1995) found that their model for Np(V) predicted solubilities as much as an order of magnitude less than those determined experimentally. Thus, completing the experimental program in order to generate Pitzer parameters for all oxidation states of the actinides is essential for obtaining credible estimates of dissolved actinide concentrations.

Additionally, the estimate of actinide concentrations in a brine will depend on the solubilities of actinide-bearing phases. In most of the experimental programs, too little attention is being paid to identification of the solubility-limiting phases. These phases may be unusual in composition, and thus difficult to identify, because of the complex composition of the brine and the waste inventory. Many of the thermodynamic data required by geochemical codes to model actinide concentrations in solution are either absent or contradictory. A key factor in the final result will be the "fairly subjective" choice of the solubility-limiting phase (McKinley and Savage, 1993).

Colloids

In the repository environment, many processes can lead to the formation of colloidal suspensions (Laaksoharju et al., 1995), some of which may include actinide elements. In fact, the transport of actinides by colloids greatly can exceed that anticipated from models based solely on the solubility of actinide-bearing phases (Kim, 1994). Recent results (Reed et al., 1994) have demonstrated the important potential role of colloids in retaining plutonium in suspension, with subsequent transport potentially being greater than expected (Ibaraki and Sudicky, 1995).

When a solid actinide compound is precipitated from solution, it may form suspended colloidal particles rather than a crystalline solid, or actinide ions may attach themselves to colloidal particles formed in other ways, either as inorganic particles or as complex compounds derived from organic constituents of the waste. Some of the varieties of bacteria that grow in the waste solution may themselves be particles of colloidal size and may contain sorbed actinides.

Colloid particles (usually in the size range of 10^{-9} to 10^{-5} m) generally have an electric charge, either positive or negative, that helps keep the particles apart and prevents their flocculation as a precipitate. In concentrated electrolyte solutions such as WIPP brines, the charge on particles is neutralized readily and the colloids are generally unstable. This is especially true for colloids of inorganic material (either colloids consisting entirely of actinide molecules or inorganic

[2]Because alpha radiation exists as a continuous source of electron acceptors (reductants), "autooxidation" by alpha bombardment is possible. In some environments this has affected redox-sensitive reactions, because Eh of the fluids is important in solubility determinations. However, the pH and Eh conditions at WIPP are controlled by the geologic environment and by constituents of the waste, particularly the metal of the waste containers and the abundant organic material in the waste. A slight change caused by alpha bombardment is expected to be negligible for both the disturbed and the undisturbed repository. Alpha-radiolysis causing oxidative corrosion is a minor concern in spent fuel storage (Shoesmith et al., 1996). Alpha-radiolysis is expected to be an even more minor concern at WIPP, because a comparison of the U.S. spent fuel inventory to the TRU waste inventory, in an isotope-specific curie comparison of transuranics only, shows spent fuel to be orders of magnitude more radioactive.

compounds with sorbed actinides) and less so for colloids in which the particles consist largely of organic material. The former are called "hard-sphere" or hydrophobic colloids; the latter, "soft-sphere" or hydrophilic colloids. In general, hard-sphere colloids readily flocculate in a strong electrolyte and, hence, are ineffective in mobilizing actinides in the WIPP environment. In contrast, some soft-sphere colloids (including colloidal-size bacteria) remain stable even in concentrated solutions and so can serve as effective transporters of actinides. It is emphasized that colloid stability is a complex function of many other variables, such as acidity and alkalinity, the nature of sorbed ions, and the kinds of organic matter and electrolytes present.

Bacteria may be the most effective vehicle for transport of actinides in the Culebra Dolomite. Their total numbers, sizes, and morphologies in indigenous Culebra brines will be determined, as well as the increase in their numbers if nutrients are added from organic material in the waste. Bacteria can influence the behavior of actinides in several ways:

1. Their metabolic activity will tend to keep conditions slightly acidic, thus helping to determine the oxidation state of actinide elements and so affecting their solubilities.
2. By sorbing ions from solution, bacteria obviously can aid in the transport of actinides.
3. The well-known tendency of microorganisms to adhere to surfaces (Marshal, 1976) may serve to retard actinide transport.
4. If significant quantities of gas are produced as a result of microbial metabolism, this gas also may influence the movement of actinides.

In addition to bacterial activity, any corrosion process will influence the pH and/or the gas content of the brine and thereby influence solubilities and subsequent transport of actinides.

The possibility of substantial transport of actinides in colloidal form has been recognized only fairly recently (Kim, 1994) and has spurred much effort by DOE scientists to investigate the complexities of colloid behavior in strong electrolyte solutions such as WIPP brines (Papenguth and Behl, 1996a). From the proposed experimental program, DOE scientists expect to learn whether there is a serious threat of active transport of actinides by colloidal particles and what measures might be taken to modify conditions in the WIPP repository to reduce this threat.

The DOE study began with a comprehensive review of recent literature on the formation and stability of colloids in electrolyte solutions and now includes detailed plans for experiments designed to answer the many remaining questions about this mode of actinide transport (see Appendix E). This effort is commended by the committee, with the expectation that these results will provide much of the new information needed to gain a deeper understanding of colloids as part of the actinide source term. The experimental work has started and is scheduled for completion soon (see Table E.1), but no results have been presented to the committee.

Retardation

If, as postulated, the dissolved and colloidal actinides that make up most of the source term move with the brine into the accessible environment through the Culebra Dolomite, their transport will be retarded to some extent by sorption on the surfaces of the dolomite and minor amounts of clay minerals (e.g., corrensite) contained in this member. Thus, the amount of radioactive material that might actually reach the accessible environment depends on the effectiveness of this sorption. Accordingly, the amount of sorption is a critical factor in any attempt to estimate whether or not the WIPP project complies with EPA regulations.

As with solubility, the study of retardation by sorption is made difficult by the high concentration of dissolved material in the brine. For dilute solutions, determining the amount of material sorbed is straightforward and experimentally simple. It is commonly expressed in terms of K_ds, or distribution coefficients, which are merely the ratios of amounts sorbed to amounts left in solution. Complexities arise with concentrated solutions, however, because (1) many substances are competing for places on any given sorption site, and (2) the nature of the sorbing substance is influenced by its speciation and the chemical conditions (e.g., acidity and alkalinity) of the solution (see discussion in Appendix E). Additionally, batch K_ds measured in the laboratory rarely have been

used successfully to predict sorption on a larger field scale.

Because simple K_ds are of little use as predictors, amounts of sorption are best determined by direct experiments in which samples of natural or synthetic brine are allowed to flow through samples of the intended sorbent material, and actinide concentrations are measured before and after the passage (see Appendix E). Such experiments have been planned carefully and should give a good indication of the effectiveness of sorption in controlling actinide concentrations; however, no results of the experiments completed to date have been presented to the committee. The experimental results will have to be confirmed by results from actual field experiments. Throughout the history of the WIPP project, such studies ("sorbing tracer tests") have been planned, delayed, and canceled. The status of such tests at present is unclear. It will be difficult for DOE to take credit for sorption in the Culebra (or any other rock unit) in the absence of well-planned and completed field tests.

SCHEDULE

As noted above, the ambitious schedule DOE has set for completion of experimental work for the AST (1996) is unrealistic in that final, definitive values for some of the numbers being sought cannot possibly be obtained and evaluated critically in so short a time. Enough data may be generated to provide a reasonable basis for the proposed compliance application, but important details about the source term and its appropriate use in performance assessment will almost certainly require additional work. Strictly accurate final values are not essential for showing compliance with EPA regulations, but are nevertheless numbers for which DOE will find many uses later. The committee recommends that selected research programs be extended into the operational phase of the repository.

SUMMARY AND DISCUSSION

The actinide source term can be envisioned as the entire mass of actinides destined for disposal at WIPP, partly dissolved and partly in colloidal suspension in a brine similar in composition to Salado Formation or Castile Formation brines (or a mixture of the two). That the entire mass would ever be dissolved or suspended is hardly likely, but a minor fraction could plausibly be mobilized at some time or times in the future. Determining how large this fraction might be requires knowledge of the solubility of each of the actinide elements in brine and its behavior as a colloid, plus data on the sorption of ions and colloidal particles onto mineral surfaces with which the brine may come in contact. Data of this sort, both from the literature and from experimental work, have been and are being accumulated in impressive amounts by DOE scientists and contractors.

Data on the source term, as noted previously, will have no importance if the repository remains undisturbed by human activity for 10,000 years because no appreciable radioactivity will likely escape to the surface. However, for any of the scenarios considered in Chapter 2 describing the results of possible human disturbance of the repository, knowledge about the source term is essential for estimating possible radioactive releases from various assessments of repository performance and, hence, for making a decision on the application for a certificate of compliance to open the WIPP repository.

The ongoing experiments in DOE laboratories and DOE-sponsored universities, if carried to completion, would begin to provide the necessary information. The present schedule will not allow all the work to be finished and evaluated before the Fall of 1996. Nonetheless, enough preliminary data will be obtained to make possible a reasoned judgment of whether WIPP meets the compliance criteria for the disturbed case.

Overall, the scientific program outlined by DOE for study of the source term is adequate, provided that the program is carried to completion. Because the program at this time consists largely of work planned or in progress, it has not been possible to critically review experimental results or to judge whether these results are used appropriately in the PA analysis. Much of the AST work has not been subjected to the type of peer review that is part of publication in scientific journals, and the committee recommends that such review be sought as the work progresses. Interaction between principal investigators in the AST program and modelers in performance assessment has been

disappointingly limited, and the committee recommends that this situation be corrected.

In the opinion of the committee, as soon as substantial results are available from the experiments—provided, of course, that the results show the expected low solubilities, which will permit calculation of low actinide releases based on some of the less improbable variants of the borehole scenario—then DOE will have the information on actinide solubilities needed to prepare the certification of compliance.

Experiments should continue for as long as is needed to obtain reliable values for actinide solubilities, colloidal transport, and nuclide retardation by sorption, a time during which the repository will be in full operation. The new data obtained will be important at the WIPP site as a basis for changes in operational procedures (e.g., use of backfill, improved seals, or reduced waste loading) and, more generally, for providing the fundamental understanding needed to predict actinide behavior in other situations. Actinide chemistry is important, for example, in the disposal of other kinds of radioactive waste and in the nationwide environmental remediation program that DOE has undertaken. Because the experimental work will provide basic data needed for a variety of purposes, the committee recommends that DOE continue this work beyond the scheduled completion dates in mid-1996.

There appears to be no reason that the further required work on the actinide source term cannot be accomplished simultaneously with the disposal of waste in the repository. This additional work will improve the scientific basis of the performance assessment and increase public confidence in the ability of WIPP to isolate TRU waste.

CONCLUSIONS AND RECOMMENDATIONS

The committee offers the following conclusions regarding the actinide source term:

- *For the undisturbed case, the magnitude of the actinide source term is of no consequence to the demonstration that WIPP can isolate waste from the biosphere effectively for many thousands of years.*
- *In the disturbed case, if it is necessary to rely on estimates of actinide concentrations in the brine, colloidal transport, or nuclide retardation by sorption, a well-documented, reviewed, scientific and technical basis for these estimates does not yet exist. With this in mind, the following observations and recommendations are made.*

With the exception of specific scientific issues raised in this chapter (and detailed in Appendix E), the scientific program outlined by DOE is adequate if the proposed program is carried to completion.

Plutonium is the principal radionuclide of interest in any release scenario. Although some aspects of its geochemical behavior can be estimated by studies of other actinides using the oxidation state model, ideally, data for each oxidation state should be followed by experiments with plutonium.

Because the AST program at this time consists mainly of proposed work, the committee has not had the opportunity to review experimental results or to evaluate whether these results were used appropriately in the performance assessment analysis. At present, much of the AST work in support of the WIPP project has not been subjected to the type of peer review that is part of publication in scientific journals. This review process is the essence of quality assurance, and the committee recommends that scientific results of the AST program continue to be published in peer-reviewed journals.

The existing schedule (see Table E.1) will not allow for the timely (i.e., by the Fall of 1996) completion of the proposed experimental work, proper analysis of the results, or publication in peer-reviewed scientific journals. In addition to the STTP, long-term scientifically based experiments are crucial in evaluating the long-term extrapolations that are required by PA analysis. These experiments are not part of the present experimental program; however, they should be an essential aspect of the iterative PA process, which will be required even during the operational phase of the repository. The needs of the AST program are not unique to the WIPP project. DOE inevitably will need a strong program in basic actinide chemistry as part of its nationwide environmental remediation effort. Prudent and efficient planning could consolidate the needs of the WIPP program within a broader program of basic research in actinide chemistry.

The interaction between principal investigators in the AST program and modelers in performance assessment has been disappointingly limited. Thus, it still is not clear how the AST data (experimental or theoretical) will be used in the performance assessment. The PA analysis has not yet provided the type of guidance to the experimental program that is required in order to determine when the work is, in fact, complete.

Concerning the use of performance assessment, there is still no clear distinction between the uncertainty associated with the selection of conceptual models in the AST and the uncertainty that results from the experimental data. This distinction is essential in evaluating the impact of the AST on PA analysis and conclusions.

The use of experimentally determined batch K_ds alone is not sufficient to justify the assumption of retardation of actinides during transport through the Culebra Dolomite. Field confirmation and/or a more fundamental understanding of sorption processes are needed.

Based on the current assessment of the WIPP site, the committee believes that the required work on the actinide source term (actinide concentrations in brine, colloid formation and transport, and nuclide retardation) can be performed simultaneously with the operation of the facility.

Chapter 6

Non-Salado Hydrology

The purpose of this chapter is to review and comment on the state of the U.S. Department of Energy's (DOE's) understanding of hydrology in formations at the WIPP site above the Salado. Studies of these subsurface aquifers ideally should aim to define the flow of ground water as well as possible. Virtually all feasible pathways by which radionuclides can move from the repository to the accessible environment depend on ground-water transport.

Site hydrology considerations are thus relevant to predicting the fate of any radionuclide release from a WIPP repository. Any such release will depend predominantly on three factors:

1. the volume of water (brine) that circulates through the waste-filled rooms and is released;[1]
2. the concentration of radionuclides in this brine; and
3. the rate of transport of the radionuclide-contaminated brine through the permeable sediments above the Salado Formation (e.g., Culebra Dolomite, Dewey Lake Red Beds) to the accessible environment.

WIPP repository design measures that can be taken to reduce the volume of brine release have been discussed in Chapter 4. Detailed studies to determine radionuclide solubilities, and hence concentrations, in brine have been discussed in Chapter 5. This chapter considers the third factor, considerations of ground-water flow and radionuclide transport.

If it can be demonstrated reliably that the concentration of radionuclides in the water and their rate of movement through the repository to the accessible environment together do not cause the release limits specified in 40 CFR 191 to be exceeded, then the repository can be considered to be in compliance with these regulations. Such a demonstration would, in principle, involve a combination of the three factors enumerated above, with their relative importance dictated by the natural site characteristics and any engineered enhancements to the repository design.

REGIONAL HYDROGEOLOGIC MODELING

In the interests of brevity in this overall report, the significant advances in the understanding of the hydrogeologic framework that have been made since the WIPP investigations were started (i.e., since the mid-1970s) are not discussed in detail in this chapter. Appendix A summarizes the regional hydrogeology of the WIPP site.

The latest formal analysis available to the committee and discussed here is the 1992 Performance Assessment (PA). This model assumed a two-dimensional, steady state, horizontal flow of ground water in the Culebra Dolomite, with simple parameterizations of both chemical and physical retardation mechanisms to describe solute transport.

The discussion below outlines the main shortcomings of the 1992 PA models and analysis. Some of the criticisms reflect current limitations of the state of art of ground-water and transport study in general. Some criticisms can be resolved relatively easily, but other criticisms may require considerable effort to address.

The assumptions of the 1992 PA predicted a release of a mass of contaminants under disturbed conditions that, for a compliance demonstration, required a reliance on two features: long ground-water travel times in the Rustler Formation (primarily in the Culebra Dolomite) overlying the Salado Formation, and significant retardation of radionuclides. If this remains true in the PA calculation submitted as part of DOE's compliance certification submission in October 1996, then the committee believes that DOE will have to

[1]For 40 CFR 191 compliance, the total volume over 10,000 years is to be considered.

improve the case presented in the 1992 PA substantially to establish the technical credibility of the assumptions and values used in the analysis.

Most of the critiques in the following discussion of non-Salado hydrology relate to assumptions or numerical methods in the 1992 PA that need to be documented better or evaluated further before a high degree of reliance can be placed in the overall model results. For example, the PA models allow chemical retardation or matrix diffusion to attenuate radionuclides after release to the Culebra. Although it seems likely to the committee that some chemical retardation and matrix diffusion will occur, the documented basis for the assumptions about retardation in the 1992 PA is very weak. It is possible, and in some cases probable, that the final PA models and more recent experimental results—which have not yet been reviewed by the committee, but which will be included in the final compliance submission—will resolve many of these concerns.

Considerable effort has been expended by DOE over the last four years to increase its understanding of the ground-water and transport regimes at WIPP, and informal reports of significant progress have been made. The considerations raised in the following discussions point out shortcomings in past (i.e., 1992) modeling efforts, but the committee has determined that they do not challenge its position that DOE should be able to complete the work required to show that WIPP can comply with 40 CFR 191, and that the repository can probably be shown to present a low risk of human exposure to radionuclides, even in the event of a severe (E1E2) intrusion. However, to the extent that compliance demonstrations may rely on ground-water flow and transport in the non-Salado formations, they will require examination of at least some of the hydrogeology and transport issues discussed below.

FLOW AND TRANSPORT MODELING

A general discussion of ground-water modeling efforts and common difficulties is provided in this section (see Box 6.1 for a summary of key features). Supplemental background discussions of these issues are included in Appendix F. Models that simulate ground-water flow and transport processes are an essential tool in the characterization, analysis, and performance assessment of WIPP. Model predictions also lie at the heart of the PA process for the WIPP site (see Chapter 2). Therefore, it must be demonstrated that a high level of confidence in the PA models is justified.

The accuracy and precision of predictions of transport of radionuclides through a deep regional aquifer system depend on the level of understanding of the processes governing flow and transport through that system, how well the relevant properties of the system are defined, and how accurately the boundary conditions of the system are known. If the assessment of the isolation capability of the site is expected to provide a reasonable level of confidence that the predictions bound the range of plausible values, then the predictions must be based on an appropriate and adequate level of understanding of the processes, properties, and boundaries of the aquifer system and of how these factors may change in the future. If the numerical PA models represent the wrong processes, ignore relevant processes, or incorporate erroneous or biased assumptions or coefficients, then the results may be misleading. These considerations of ground-water modeling efforts as applied to WIPP are discussed below.

Sources of Modeling Error

In applying ground-water models to field problems, there are three primary sources of error, as described by Konikow and Bredehoeft (1993):

1. *Conceptual errors:* theoretical misconceptions about the basic processes that are incorporated in the model.
2. *Numerical errors:* the difference between a true and exact solution to the governing equations and the solution developed by the equation-solving algorithm.
3. *Uncertainties and inadequacies in the input data:* errors arising from the inability to describe actual aquifer properties, stresses, and boundaries. These include measurement errors, interpolation and extrapolation errors, and inaccurate predictions of future conditions.

BOX 6.1 Flow and Transport Modeling

Modeling of transport in this regional flow system requires the following:

1. An adequate conceptual model of the flow system, including
   - water table and potentiometric elevations
   - definition of major hydrostratigraphic units
   - description of potential preferential flow paths, such as fractures
   - evaluation of temporal changes (whether or not system is at steady state)
2. For significant hydrostratigraphic units, descriptions of
   - flow and transport mechanisms
   - flow and transport properties
   - nature and rates of chemical reactions, such as sorption, to estimate chemical retardation
3. Mathematical models that
   - incorporate the relevant processes
   - are not subject to large numerical errors

In most model applications, conceptualization problems and uncertainty concerning the data are the most common sources of error. All three aspects of error are discussed below with reference to the PA models for WIPP.

Conceptual Errors

If the conceptual models upon which the PA models are based are in error, then all of the complementary cumulative distribution functions (CCDFs; see Chapter 2 and Appendix B) and risk assessments derived from the PA also may be in error. Although the tool of PA is designed to account for uncertainties in the parameters, this assessment of uncertainty is necessarily within the context of the PA model used. Factors and processes that are not incorporated into this model are conceptual errors that are not treated by the PA sensitivity analysis.

The 1992 PA for WIPP did not assess adequately the uncertainties in the underlying conceptual model, which might be a more significant effect than the uncertainties in the parameters. For example, because the 1992 PA ground-water model was two dimensional, it cannot be used directly to evaluate the importance of a three-dimensional flow. Errors in a conceptual model are often difficult to detect, and sometimes field measurements can be reproduced by several alternative conceptual models. The alternative models may make little difference over the short duration of a field test but may make a large difference over the life of the repository and predictive horizon. It is therefore critical that the PA conceptual models be rigorously and independently tested.

There also must be consistency among the various conceptual models that describe different elements of the subsurface ground-water system. For example, hydrologic concepts indicate that ground water in the Culebra Dolomite at and near the WIPP site flows generally from north to south. Chapman (1988), among others, notes that there are significant decreases in salinity and changes in water quality in the direction of flow. Siegel and Anderholm (1994, p. 2299) state that "no plausible geochemical process has been identified that would cause this transformation in a hydrologically confined unit." Thus, geochemical interpretations appear to conflict with hydrologic

understanding.[3] Such a discrepancy reflects a lack of comprehensive understanding of the subsurface system, which opens the possibility that some aspects of the overall conceptual model of the Culebra are flawed, and that predictions based on this model are likewise uncertain.

Numerical Errors

The 1992 PA model used the SECO ground-water modeling computer codes to simulate flow and transport. The SECO codes have been developed by recognized experts in numerical methods, and the transport code apparently represents a major advance in controlling and limiting numerical dispersion. However, because the SECO codes are not yet used widely, some "bugs" and other problems in the use of the codes may still remain undetected. Experience with other ground-water model codes indicates that code developers often cannot comprehensively test the code for all possible ranges and combinations of parameter values. Model applications by a variety of users and organizations to a range of problem types and hydrogeologic conditions often will result in the discovery of code deficiencies that were not detected by the model developers, regardless of how comprehensive their testing efforts.

The SECO codes have not yet been subject to extensive benchmarking or international comparisons with other widely accepted codes, such as have been performed for other codes under the recent International Hydrologic Code Intercomparison Project (HYDROCOIN) and the International Project to Study Validation of Geosphere Transport Models (INTRAVAL; Swedish Nuclear Power Inspectorate, 1987, 1990). The committee believes that it is inappropriate to rely exclusively on these relatively new codes before such benchmarking evaluations have been completed in an open, broad-based scientific forum to yield more confidence in the codes.

[3]Possible explanations are that prehistoric flow was in a different direction than current flow, or that geochemical or hydraulic interpretations are flawed, or that vertical components of past or present flows exist that have not been accounted for.

Data Uncertainty

The PA models make predictions based on ranges of values of parameters. The 1992 PA assumed that most of the parameters in the model are "independent random variables even though it is known that some were dependent on others" (Sandia National Laboratories, 1992). It is further stated (Sandia National Laboratories, 1992, p. 1-21) that "the effects of neglecting correlations on the sensitivity/uncertainty analyses are generally unknown." It may be a reasonable first approximation to assume independence of parameters in sampling (i.e., to ignore interactions between variables and their codependence on other factors). However, such an assumption must be carefully tested, and refined if necessary, before a final PA is completed. Independent sampling can yield simulations based on implausible (or contradictory) combinations of parameters. If results of these simulations yield low-risk outcomes, then including the results of such simulations in the generation of CCDFs might skew or bias statistical distributions of the results.

The committee recommends that the assumed independence, ranges, and distributions for the various parameters that are sampled in PA analysis be examined closely for reasonableness and consistency with observed data.

WIPP 1992 PA MODEL ANALYSIS

Regional Ground-Water Flow

As noted previously, the 1992 PA models assumed that ground-water flow through the Culebra Dolomite was two-dimensional, steady-state, and horizontal. Investigations of the larger three-dimensional regional system, of which the Culebra is actually a part, have begun relatively recently but have not yet been completed. These investigations include a new synthesis of all the regional hydrogeologic data and will lead to the development of a three-dimensional numerical flow model. This more comprehensive analysis of the ground-water flow system is very important and relevant to the larger issue of conceptual uncertainty. Among other benefits, this type of analysis may help to resolve existing discrepancies between the

geochemical data and the present conceptual model of the flow system. Until the results of these ongoing studies have been completed and their impact on assumptions about the Culebra has been evaluated, it is too early to determine whether or not many of the simplifying assumptions incorporated into the 1992 PA were reasonable.

Ground-water flow and solute transport are affected strongly by heterogeneity in aquifer properties. Fractures represent an extreme but prevalent type of heterogeneity, so their characterization is important for reliable model development. However, the properties, continuity, and extent of fractures in the Culebra are still highly uncertain. One cost-effective approach to characterize fractures is to complete detailed mapping of any surficial expressions of fracture traces and lineaments at both local and regional scales. This should have been completed in the early stages of site characterization, but there is no written documentation of such analyses having been done.

Fracture and lineament mapping have been applied successfully to several potential fractured-rock repository sites (e.g., for applications in Sweden, see Wikberg et al., 1991; Ahlbom et al., 1992; Swedish Nuclear Fuel and Waste Management Company, 1995). Surface and subsurface features that might represent fracture zones and lineaments were defined by using remote-sensing methods (such as aerial photography and satellite imagery), topographic data (including computer analysis of digital elevation data), and several geophysical surveying techniques (including geomagnetic, electrical, and seismic methods and some recently developed high-resolution, three-dimensional tomographic techniques).

These approaches have helped to clarify the possible existence and spacing of major through-going fracture zones. Although the lithology at WIPP is different from that at the Swedish sites, these approaches have worked in other sedimentary rock basins, and the committee believes that they should be applied in the characterization of the WIPP site. An approach to fracture definition that is potentially more definitive, but also significantly more expensive, would involve drilling of slanted or even horizontal boreholes. However, because this probably would require an extremely expensive and time consuming operation, the possible benefits should be carefully weighed against the likely costs before a decision to undertake such a study is made.

Confidence in PA Analysis of Regional Ground-Water Flow

Significant accomplishments in site characterization have advanced the level of understanding of the regional ground-water flow system at the WIPP site during the past 20 years (see Appendix A for a summary discussion). However, the degree and comprehensiveness of the understanding of some aspects of the local and regional ground-water flow systems are lower than desirable relative to the importance of the repository and to the time and money spent studying the WIPP site and constructing the repository. The following points support this contention:

- There is a disparity (as discussed above) between the regional flow system as determined by geochemical and isotopic interpretations and that indicated by hydrologic analyses. This disparity reflects an inadequate level of understanding of the whole system, and it should be resolved.
- The water table in the region, which represents the top of the saturated zone, has not been defined. This important boundary should be defined, or a reasonable explanation of either why it is not important or why it is technically or economically infeasible to determine should be documented.
- The rates, locations, and mechanisms of natural recharge to and discharge from the Culebra Dolomite are poorly defined (see Brinster, 1991).
- Apparently, there have been no detailed hydrologic studies of the unsaturated zone at the site. Such studies would help to (1) estimate if, why, and how much recharge may exist in the vicinity of the site; (2) define the water-table position; (3) predetermine an appropriate response should there be a spill or accident on the land surface at the WIPP site; and (4) predict how much and where recharge might increase under a scenario of climate change that yields increased precipitation.
- An adequate explanation is lacking for observed changes in water levels in the Culebra, where trends of rising water levels have persisted for several years.

Observed changes in water levels from assumed steady-state conditions were not incorporated into the 1992 PA analysis. However, if the causes of the observed water-level changes during the last several years are unknown, then how is it to be known that even greater changes in the flow field might not occur in the near future? Such changes might invalidate the PA assumptions and predictions.

- These water-level changes are affecting hydraulic gradients, flow directions, and flow velocities and thereby provide some evidence against the assumption that steady-state flow prevails in the aquifer, an assumption that is the basis of many WIPP hydrologic analyses. Small "violations" of this assumption probably would not affect the conclusions to a noticeable degree. However, if the trends observed over the past five or six years persist, recur, or become more widespread, flow systems might change enough to negate the PA analyses based on the assumed steady-state flow field.
- There has been too little accounting for the three-dimensional nature of ground-water flow and consequent leakage through confining layers. If vertical components of flow do materially affect the Culebra, then the ground-water models of the Culebra that were calibrated under the assumption that flow is horizontally two dimensional must include compensating errors to offset ignoring the vertical leakage. Such errors can induce a bias in long-term predictions of flow and transport.

Some necessary and feasible experiments and analyses (of the kind mentioned here), which would lead to a more comprehensive understanding of the ground-water flow system and to more reliable PA models, have either not been undertaken or are not completed yet.

Ideally, the regional system should be understood with sufficient accuracy and precision that professional hydrologists will have confidence in the analyses and predictions, will believe that additional data collection is not critical, and will be convinced that there are no major "surprises" left in the characterization of the system.

Although it is difficult to define precisely when a requisite level of confidence in the hydrogeologic analyses has been achieved, the committee does not believe it has been reached in the 1992 PA. Too many questions remain about the models, assumptions, and data used to analyze the cases in which a significant release of contaminants to the Culebra or other formations is projected to occur.

The potential weaknesses in the ground-water models will be important to a demonstration of compliance only if there are significant releases from WIPP to the stratigraphic units shallower than the Salado. The weaknesses in hydrogeologic modeling discussed in this chapter should be balanced against an examination of the assumptions from which the estimated releases are derived, and assumptions concerning pathways to cattle that drink from stockwells tapping the Culebra. For example, even if contaminants were transported through fast-pathway fractures in the Culebra and were not subject to any retardation processes, the very same conditions that would enable this to occur would assure that the water carrying the contaminants would be far too saline for cattle to consume. This would appear to eliminate the potential for future human exposure, which is an underlying basis for the overall concerns about radionuclide releases.

The non-potable saline character of the ground water in the Culebra will greatly reduce the exposure hazard even though the radionuclides released to the accessible environment may exceed the limits required for compliance in 40 CFR 191. Should the 1996 PA analysis be able to demonstrate convincingly that the releases are sufficiently low to meet compliance standards, then the exposure hazard would be correspondingly lower.

Solute Transport

Transport of radionuclides released into an active ground-water system can and may occur at a rate less than the rate of the ground-water flow, due to physical and chemical interactions with neighboring rock. This radionuclide retardation, where it can be shown to exist, can add important additional assurance with respect to the radionuclide containment capability of the repository. Hence, studies of the radionuclide retardation properties of water-conducting rock formations at WIPP (see Appendix A) are an important complement to the studies of ground-water flow.

Following this discussion of solute transport, the specific retardation mechanisms are treated in turn.

The solute-transport model of the Culebra Dolomite is based on a theoretical understanding of transport and dispersion processes in ground water. However, this underlying theory is itself somewhat weak because the scientific understanding of transport processes in heterogeneous media, particularly in fractured rock systems, is still in a stage of relatively rapid development and evolution. Much remains to be learned, and much ongoing research is devoted to developing a better understanding of the governing processes and parameters at large scales in complex field environments. Recent research indicates that many transport processes and parameters are highly scale dependent. This is one reason why there is often little basis for extrapolation of theory and lab tests to the field environment for predictive purposes.

The 1992 PA separately sampled and independently varied porosity, fracture spacing, and transmissivity. However, it is known that correlations exist among these parameters. Thus, it seems likely that the existing approach may yield unreasonable or unlikely combinations of these parameters in some of the individual simulations. The net impact on the overall PA is uncertain, but the committee believes that the parameter sampling procedure should be examined closely and refined if necessary.

The PA models represent leakage from a borehole into the Culebra as an initial concentration of solute in the transport model for a steady-state flow field. However, transient changes in the flow field, which are induced by the volume of water carrying the radionuclides into the Culebra, are not considered. While the leak is occurring, the velocity away from the well would be greater than the velocity under steady-state conditions, and some of the radionuclides would migrate faster and further than represented in the PA model. The committee recommends that the PA process carefully test and demonstrate that the steady-flow assumption and simplification, which ignore the initial fast advection, are reasonable and do not introduce significant errors.

Confidence in PA Analysis of Solute Transport

The effective porosity (ε) is a critical transport parameter for which few measurements are available. If one assumes that $\varepsilon = 0.001$, which is representative of fracture flow, then travel times to the regulatory boundary would be on the order of hundreds of years. However, if $\varepsilon = 0.16$, which is representative of the rock matrix, travel times would be on the order of many thousands to tens of thousands of years. This could mean the difference between compliance and noncompliance of the site.

The 1992 PA assumed that porosity and transmissivity vary independently. This is a potential weakness in the analysis that needs to be tested, because physically reasonable arguments lead to correlations between the two variables. In this regard, a key issue for the PA flow model is whether the relation between transmissivity and porosity is in fact independent, or if the relation is direct or inverse. Either relation could be conceptualized (or perhaps rationalized), based on present knowledge of the Culebra Dolomite. However, any consistent relation would be contrary to the WIPP Project PA procedure of sampling independently from the populations (or distributions) of transmissivity and porosity. Thus, many simulations would be based on unlikely or contradictory combinations of parameter values. This could bias the PA model-generated statistics on which the CCDFs are based.

The PA sampling approach has yielded some individual outcomes to date that have exceeded the compliance standard. These particular simulations should be examined carefully to highlight and document the combinations of parameter values and boundary conditions that led to prediction of an unacceptable release of radionuclides to the environment. This evaluation would allow analysts and reviewers to focus on an assessment of the reasonableness of those specific and critical conditions, and would serve as a quality assurance check on the statistics generated by the PA analyses.

Some of the 1992 PA simulations of solute transport have allowed physical and/or chemical retardation, as would be derived from matrix diffusion and chemical sorption, respectively. To date, however, no reliable and representative field measurements of the

parameters controlling matrix diffusion and chemical retardation have been carried out at the WIPP site.

Physical Retardation Via Matrix Diffusion

In the 1992 PA model of the Culebra Dolomite, physical retardation may occur in response to matrix diffusion in a dual-porosity system. The magnitude of the retardation is proportional to the effective surface area and volume of the blocks adjacent to the fractures through which advection is occurring. If the contaminant plume spreads through a larger volume of the aquifer, then matrix diffusion will be more effective in removing contaminants from the active flow field. If the transport model artificially spreads the contaminant plume into a larger volume of the aquifer than would actually occur, then the model will overestimate the retardation caused by matrix diffusion, even if the diffusion parameters themselves are estimated accurately.

The artificial spreading of contaminants can arise from errors in the numerical solution, from errors in the initial conditions, and from errors in the conceptual model. All are present to some degree in the WIPP PA model. The committee recommends that PA assumptions and analyses for cases including matrix diffusion be supported by additional model studies to demonstrate that the analyses do not overestimate the magnitude of matrix diffusion because of artificial spreading of the plume. This can be accomplished, for example, by applying a transient ground-water flow model that uses, for a relatively short time period, a much finer spatial grid and smaller time steps near the area close to a human intrusion (HI) borehole. These results can then be compared with those of the coarser PA model for equivalent travel distances and elapsed times.

Confidence in PA Analysis of Physical Retardation

If PA results indicate that repository compliance with EPA standards depends strongly on matrix diffusion, more reliable field evidence to support the assumed range of coefficients should be obtained. In this case, field tests should be completed at several different locations in the vicinity of the WIPP site because of the spatial variability in the properties of the system.

Chemical Retardation Via Reactions

The PA models combine all of the complex chemical reaction processes, such as sorption or exchange, that might retard the movement of a particular chemical species relative to the movement of a nonreactive solute into a single simple parameter—the retardation factor R_f. This factor, in turn, is related to a distribution coefficient K_d. Although the concept of a retardation factor is computationally efficient, it inherently assumes that reaction processes are linear, instantaneous, reversible, and homogeneous.

The concept generally works well in chemical plants where chemical engineers apply it to fluid flow and solute transport through tanks filled with relatively homogeneous, reactive, porous media. However, in a complex regional aquifer system, the reactions rarely are subject to these ideal conditions. The theoretical basis for applying a retardation factor to a field environment is therefore weak, at best, and its application to large-scale hydrogeologic settings, without restrictions or qualifications, has been criticized in the literature (e.g., Reardon, 1981; Miller and Benson, 1983; Valocchi, 1984).

From the perspective of a compliance assessment, use of the simplifying retardation factor may either underestimate or overestimate the overall amount of retardation of a solute relative to the flow of water, depending on the particular chemical species and the types and rates of reactions that affect its fate and transport. To probe this issue, the nature of the expected isotherm for each solute of concern (and within the range of expected concentrations) should be determined experimentally.

Scientists from Sandia National Laboratories recognize the numerous difficulties and weaknesses in applying a linear sorption model for predicting radionuclide transport through the Culebra Dolomite, and many of these concerns have been documented (Novak, 1992). As an example of one of several serious concerns, Novak (1992) points out that available K_d data for uranium sorption in the Culebra are very sensitive to water composition and vary by more than three orders of magnitude for selected representative compositions of Culebra brine. Novak (1992, p. 55) states that "existing radionuclide K_d data are insufficient for predicting radionuclide migration in

the Culebra with a sound scientific basis within reasonable certainty." Ongoing experiments will help to resolve this uncertainty, but results and analyses are not yet available for review.

Confidence in PA Analysis of Chemical Retardation

If performance assessment results indicate that compliance is contingent on the occurrence of chemical retardation, it will be necessary to provide more evidence that the PA approach is reasonable for these conditions. The committee believes that the use of sorbing tracer tests in the field would be highly beneficial for building confidence in the analysis and approach to chemical retardation, in addition to determining whether or not the conceptual model is applicable to the field environment. Because the specific solutes of interest here, such as plutonium and americium, cannot be used in tracer tests, reasonably appropriate surrogate tracers must be used, or field evidence of sorptive behavior must be ascertained from analysis of previous accidental releases elsewhere.

As hypothesized for flow parameters for the Culebra Dolomite, a correlation may also exist between K_d (or R_f) and either transmissivity or porosity. For example, relatively high transmissivity values might coincide with zones of low or zero clay content. Because clay probably yields a higher sorptive capacity per unit volume than dolomite, where transmissivity and flow velocity are the highest, there may be very little chemical retardation. This illustrates one type of predictive error that might be associated with applying one average effective R_f to the entire ground-water system. The greatest risk of release in that case is related to flow through transmissive fractures having a lower than average R_f.

It is unclear whether the PA approach to sampling values of R_f is appropriate if the chemical retardation in critical high-transmissivity channels is not represented accurately by the average R_f assumed for the entire aquifer system. Again, the only way to address this issue in a manner that would instill confidence in the predictive analyses is through a series of in-situ tracer tests or other field-based analyses.

DISCUSSION AND SUMMARY OF FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

This chapter and Appendix F have focused on potential sources of error in the preliminary PA modeling of the Culebra Dolomite. Therefore, the reader should not infer from the tone of this chapter that the WIPP ground-water models are necessarily inaccurate or unacceptable. Rather, the intent is to indicate where the preliminary analyses presented in the 1992 PA need to be revised, strengthened, or better documented. Because there have been four years of additional studies since the 1992 PA, it is possible that recent experimental results and the final PA models, which have not yet been reviewed by the committee, will have resolved many of these questions.

A key question is whether the uncertainties in the properties of the subsurface system above the Salado Formation need to be resolved (or minimized) further to demonstrate adequately the integrity of the WIPP site with respect to containment of radionuclides. Alternatively, is enough information about the subsurface system already available to predict that any potential release from the proposed repository will not cause radionuclides to migrate faster or further than is acceptable from a regulatory standpoint?

These issues are addressed separately for the undisturbed case and the disturbed (i.e., HI) cases described in Chapter 2.

Undisturbed Repository

The committee finds that it is reasonably certain that the WIPP repository will provide an adequate level of long-term isolation of TRU waste under a broad range of natural conditions and stresses for tens of thousands of years into the future. Provided that seals and plugs (as discussed in Chapter 4) are effective, there is no evidence to indicate that any brine that might be contained in the repository after it is closed is likely to leak through the Salado Formation and be released into the regional ground-water flow system in shallower formations. Nor would the committee expect that ground water flowing above or below the Salado might dissolve the salt or in any other way come in contact with the wastes that would be stored in the repository.

For consideration of the undisturbed case, the present state of understanding of the ground-water flow system above the Salado is adequate. The committee finds that the overall permeability and creep properties of the Salado are such that, with effective repository seals and without some form of human intrusion, the flow of radionuclide-contaminated brine from the Salado is very unlikely. Further studies of the hydrogeology of non-Salado units are therefore not necessary to support compliance for the undisturbed case.

Summary of Undisturbed Case

Provided that plugs and seals in the Salado Formation are effective (see Chapter 4), there is high confidence in the conclusion that the WIPP repository will isolate TRU waste adequately from the environment for many thousands of years if it remains undisturbed by future societies. For this undisturbed case, continued studies of non-Salado hydrogeology are not necessary.

Disturbed Repository

In the WIPP PA (see Chapter 2), the HI scenario assumes that future drilling will facilitate upward leakage of brine from the repository through a borehole, thereby permitting radionuclides to be released into an overlying geologic formation through which lateral migration offers a possible pathway for release of radionuclides to the accessible environment. If releases exceed regulatory limits, then a predicted rate of transport in the regional ground-water system above the Salado Formation becomes a critical factor in estimating cumulative releases.

The analysis of the disturbed case hinges on predicting flow and transport through rock formations above the Salado (see Appendix A). The issue of concern to the committee is whether the 1992 PA was based on an adequate conceptual understanding of the regional ground-water flow system near WIPP and whether the relevant parameters had been quantified adequately to support either "realistic" or "bounding" models in the PA.

For example, the 1992 PA assumed that the most likely pathway for a lateral release of radionuclides is through the Culebra Dolomite. However, a release to the shallower Dewey Lake Red Beds also is possible and does not appear to have been considered or evaluated adequately. Releases of saline ground water from leaking deep boreholes directly to the water table are known to have occurred historically in other areas (for example, see Van der Leeden et al., 1975). The Dewey Lake is a plausible exposure pathway because it is known to contain some potable water. Among other concerns, climate changes can increase the recharge rate and raise water levels. In the committee's opinion, releases to the Dewey Lake cannot be discounted summarily; if a borehole to the Salado or to the Castile Formation were to connect these formations to brine at a pressure near lithostatic, then the hydraulic gradient (driving Darcy flow) would be sufficient to enable leakage into both the Culebra and the Dewey Lake if a pathway to either formation were to exist.

Also, the amount and rate of brine release appear to be very sensitive to the assumed permeability of the material that is filling the leaky borehole. In light of the importance of that parameter, values for borehole permeability that are used must be realistic and technically defensible.

If the final analyses of the disturbed-case scenarios yield projected releases of contaminants to formations above the Salado that are less than the release limits of 40 CFR 191 (i.e., for which compliance results even if the releases moved across the regulatory boundary in less than 10,000 years), then no further hydrogeologic characterization work is needed. This means that compliance could be demonstrated even if one assumes that no retardation occurs and that ground-water flow and transport occur through fractures.

Summary of Disturbed Case

For the disturbed case, if the mass of contaminants and brine released is as great as assumed in the 1992 PA, then the ability of the site to isolate waste satisfactorily under such "disturbed" conditions has not yet been demonstrated adequately. However, such a demonstration appears to be a plausible outcome if the following problems, issues, or limitations of present models and data are resolved through further studies.

1. The PA approach must assess the sensitivity of the predictions to uncertainties in the underlying conceptual

models. Alternative conceptual models are feasible, and those that are plausible and that could lead to significant releases should be evaluated. Completion of ongoing three-dimensional analyses of the regional ground-water flow system is critical to this effort and should be given a high priority.

2. The non-Salado site characterization efforts and PA models have been overly focused on a two-dimensional flow analysis of the Culebra Dolomite. The minimal levels of consideration and evaluation of other potential hydrogeologic release pathways (such as the Dewey Lake Red Beds) and of the interconnection between the Culebra and adjacent formations have not been justified adequately.

3. Fractures are a dominant control on the transmissivity of the aquifer system at the WIPP site and represent the highest-velocity channels for migration of contaminants. A better definition and understanding of the nature, density, spacing, length, and interconnectedness of fractures and fracture networks are critically needed. As one step to help achieve this understanding, the committee recommends that modern topographic and geophysical methods of analysis be applied in the site characterization efforts.

4. In general, the types of chemical and geochemical reactions, rates of reactions, and their dependence on spatially heterogeneous mineralogy and changing aqueous geochemical parameters (e.g., salinity, pH, and Eh) are not well characterized for the HI scenario at the WIPP site. Representing all of these sources of variation in the PA model as a single parameter (i.e., an effective retardation factor), as was done in the 1992 PA, has a very weak scientific basis. If the PA assumes that chemical retardation occurs in the Culebra, then supporting evidence from the field environment should be available before any predictions based on that assumption are accepted.

5. Similarly, if matrix diffusion is to be relied upon in the PA models to demonstrate compliance, then additional controlled field experiments must be completed to define rates of diffusion more accurately and to assess spatial variability in the process and parameters. Furthermore, additional testing and documentation are needed to eliminate concern that the net retardation caused by matrix diffusion is being calculated inaccurately in the numerical models.

6. For the disturbed case, if it can be shown that the mass of contaminants and brine released would be significantly less than previously estimated (as might be derived, for example, due to changes in the estimated severity of human intrusion, refinements in estimates of the actinide source term, or in the effects of borehole closure), then further studies of the Culebra would not be necessary. That is, if the total amount of solute entering the non-Salado formations is determined to be sufficiently small to assure compliance, then studies of ground-water transport are not needed for this purpose.

PERSPECTIVE BASED ON INTERNATIONAL REPOSITORY SITING EFFORTS

Insight into the difficulties of hydrogeologic site characterization issues is offered based on examples from and comparisons with international siting efforts. In efforts to site geologic repositories in other countries, a good quantitative understanding of the regional ground-water flow regime and the influence of the geological environment of the repository on radionuclide transport are often the most critical factors needed to determine whether or not a potential repository site can provide adequate long-term isolation of the waste. This is usually true for both the undisturbed and the disturbed cases.

Several countries have opted to site repositories in rock masses of low permeability, such as granites, in regions of low hydraulic gradient, so that flow rates will be very small. Determination of the rock-mass permeability in these cases is often complicated by the presence, on the field scale, of fractures that are not usually present or tested in laboratory specimens. Fractures also complicate larger-scale tests conducted directly in the field, making it difficult to extrapolate to the regional scale. Fractures tend to follow a log-normal distribution in which well-developed, extensive, and often highly conductive fractures are spaced widely apart, with smaller, less extensive fractures becoming progressively more abundant. On the smaller scales, these are not always interconnected and hence may be nonconductive. Definition of rock-mass permeability of fractured systems is difficult, and factors that influence radionuclide transport processes are at least as complex.

Predicting regional ground-water flow and radionuclide transport behavior with the reliability and detail required for repository performance assessment is a complex and formidable challenge. It has been a main focus of international research related to repository siting and design for more than 25 years. Although substantial advances have been made—with project scientists and consultants making notable contributions—significant problems remain. Each potential repository site has unique features. To the extent that long ground-water travel times and significant physical and chemical retardation are necessary to ensure adequate isolation of radionuclides from the accessible environment, characterization of the site is correspondingly necessary to address these problems.

Most repository sites worldwide are located in rock that is part of an active regional ground-water regime. In these cases, except for engineered barriers in the immediate vicinity of the waste, the repository is physically close to circulating ground water. By contrast, locating WIPP centrally within the 400-m-thick, essentially impermeable, Salado bedded salt deposit, some 200 m below the permeable, saturated sedimentary Rustler Formation, which consists of fractured limestones and dolomites, is a major design advantage of this repository. The restrictions to ground-water transport provided by the Salado Formation provide a valuable "buffer zone" between the repository and the non-Salado permeable formations above it, to which the site hydrology considerations of this chapter apply.

Chapter 7

Perspectives

The NRC Committee on the WIPP has followed the WIPP project from its infancy in 1978. There have been some changes in committee membership, but there has been sufficient continuity that the committee has remained aware of the significant scientific and technological issues, as well as the associated policy and budgetary constraints on the WIPP project. This report focuses on the committee's understanding of the specific scientific and technological issues that form the core of DOE's compliance application to the U.S. Environmental Protection Agency and their influence on the perceived ability of WIPP to isolate TRU waste from the biosphere.

During its deliberations, the committee also has arrived at several general conclusions with respect to the overall integrity of WIPP, the difficult problem of human intrusion, and the role of Performance Assessment. Because of their importance to this report and the overall integrity of WIPP, the committee provides a general discussion of these issues in this chapter.

INTEGRITY OF THE WASTE ISOLATION SYSTEM

A previous National Research Council report provides a useful introduction to the topic of geologic isolation at WIPP. The report states that the objective of a geologic waste isolation system is

> *to protect humans now and in the future by isolating the waste from the environment effectively enough and for a period of time long enough that the amount of radioactive material ever reaching the biosphere will present no unacceptable hazard. To achieve this objective, a hierarchy of mechanisms exists to reduce the release of radionuclides to the biosphere and thus have the waste isolation system meet the criterion of overall performance. One or more of the following release control mechanisms must be sufficient to meet the panel's criterion:*
>
> - *delay of ingress of water*
> - *slow dissolution of radionuclides*
> - *slow release from the waste package*
> - *long groundwater travel time*
> - *delay due to sorption in the geologic medium*
> - *dispersion*
> - *dilution*
>
> *The system must guard against an unacceptable release of the radioactive material into groundwater and the transport of this contaminated water to the biosphere—a principal pathway by which some portion of the buried radioactive material may eventually reach humans.* (NRC, 1983, pp. 3-4)

Although the 1983 report gives primary emphasis to geologic isolation for high-level, spent reactor fuel or reprocessed waste (hence the high ranking given above to "slow release from the waste package"), the list of important criteria is essentially the same for a transuranic (TRU) waste repository. The total radioactivity per unit volume of TRU waste planned for WIPP is roughly on the order of one-thousandth of the activity for an equal volume of spent fuel waste, but many of the same long-lived radioactive isotopes are present, and so geologic isolation is necessary.

In the committee's opinion, location of the WIPP repository within the 600-m-thick Salado Formation, some 400 m below the overlying, permeable water-saturated sediments is an exceptionally robust way in which to delay ingress of water to the repository or, equivalently, egress of radionuclides from the repository to the accessible biosphere. Natural salt

creep will result in the encapsulation of waste within what becomes essentially intact salt a few hundred years at most after emplacement. Sealing of the shafts with crushed and compacted salt also should ensure that, by natural salt creep processes, these potential conduits to the biosphere are sealed effectively. Thus, the waste should be sealed, permanently, within the Salado Formation, which has been stable for over 200 million years.

The committee is confident in asserting that, provided the repository is sealed effectively and remains undisturbed by human activity after final closure, WIPP will isolate TRU waste for long enough (i.e., many tens of thousands of years) to ensure that the radioactivity in the waste will have decayed to very low levels.

HUMAN INTRUSION

From the point of view of waste isolation, salt does have one drawback—it is frequently found in association with mineral resources, especially oil and gas. Drilling for these resources could result in one or more holes penetrating the repository and would provide a pathway to bring the waste into direct contact with ground water and the accessible biosphere.

An intrusive drilling event could remove the isolation from ground water provided by the 200-m-thick envelope of salt. Because dispersion and dilution are not significant factors at WIPP, the two remaining mechanisms to control radionuclide releases noted in the NRC (1983) report would be (1) slow dissolution of radionuclides, and (2) delay due to sorption in the geologic medium. Although WIPP does not include a "waste package," the backfill and seals around each waste room and panel serve a similar function. In fact, the salt "package" does not have the limited lifetime of a high-level waste canister. For WIPP, assurance of protection from excessive release of radionuclides due to drilling intrusion relies on (1) engineering efforts to improve repository performance (see Chapter 4); (2) improved understanding of the actinide source term (see Chapter 5); and (3) understanding of non-Salado Hydrology (see Chapter 6)—the same three mechanisms that are identified in the NRC (1983) report.

ROLE OF PERFORMANCE ASSESSMENT

What contribution can be expected from each of these component factors, and how much is needed, to ensure effective long-term isolation of the waste?

Total System Performance Assessment, or PA, is the method that has been used at WIPP to identify and examine all credible pathways by which radionuclides could be released to the biosphere from the repository and to estimate the contribution of each component of the pathway. Although both the undisturbed and disturbed (by drilling) cases have been examined, the DOE PA team has placed appropriate emphasis on the more complex and critical disturbed case.

The latest "complete" performance assessment available to the committee was published in 1992. The 1992 PA identified the same three key factors noted above, and its results suggest that WIPP could comply with the EPA release standards if certain levels of performance were attained from each component.

As noted principally in Chapters 2, 5, and 6, the committee has identified several significant deficiencies in the 1992 PA. These include the following:

1. The assumed permeabilities governing the flow of brine through the underground excavations were much too high. As a result, predicted flow through the repository due to an E1E2 intrusion (see Chapter 2, Figure 2.5) greatly overestimated brine flow, and hence radionuclide release.

In the 1992 PA, no credit was given for the ability of the excavations, especially when back-filled with crushed salt, to close within the order of a few hundred years, or for the potential of room and/or panel engineered seals and various other available engineering techniques to reduce both the consequences and the probability of serious drilling intrusions. For example, if the values for repository permeability used in the assessment are reduced progressively towards the value of intact salt (10^{-23} m^2) over 10,000 years, rather than maintained at a constant 10^{-15} m^2, the total predicted brine flow and radionuclide release would be much lower than indicated in the 1992 PA.

2. There was insufficient experimental justification for the assumptions made with respect to actinide

solubility, colloidal transport, and ground-water flow/radionuclide transport in the Rustler Formation overlying the Salado Formation.

Experimental studies to improve the basis for estimating actinide solubility and Rustler Formation hydrology and transport have now started, but these will require several years of additional work in order to arrive at reliable results. At this stage—with the results of the 1996 PA not yet available, and important experimental studies still in progress—the committee does not know how the results will affect predicted releases and compliance. It does appear to the committee that engineered design features to reduce the adverse consequences of an intrusion are available, but not all of these features may be cost effective or needed if low actinide solubilities and/or sufficiently long travel times and radionuclide retardation can be demonstrated by the PA. Thus, to inform decisions on implementing costly engineering design features, it is important that these experimental studies be continued to completion.

3. The 1992 PA was directed at demonstrating compliance with the radionuclide release limits stipulated in 40 CFR 191. No analyses were made of the health risks associated with these releases. At WIPP, radionuclides would be transported in brine that is considered to be, to a large extent, unpotable even to cattle. Consequently, the health risk will be very much smaller than if the water were potable.

In considering the radionuclide exposure hazard of WIPP to humans (see also Box 1.2), the committee recognizes the unpotable nature of much of the water in the Rustler above the Salado. The committee believes that accounting for the unpotable nature of the water could reduce the health risk by one or more orders of magnitude compared to the same release into a freshwater aquifer that is similar in size and has similar regional flow characteristics.

Taking into account all of the above considerations, the committee is confident in its judgment that DOE should be able to demonstrate that radionuclide releases at WIPP will be within the limits allowed by EPA, for both the undisturbed and disturbed cases, even with the severe criteria defined in 40 CFR 194. The associated health risks are likely to be well below the levels allowed under international standards. The results of the 1996 PA are awaited with interest as a test of this judgment.

The heavy emphasis placed in the 1992 PA on the analysis of compliance with 40 CFR 191 for the "disturbed case"—that is, assessing the consequences of human intrusion—is appropriate in the committee's judgment because of the added complexity of the radionuclide pathways introduced by intrusion. Even so, it is important to recognize the remarkable ability of the salt at WIPP to isolate waste under undisturbed conditions.

THE NATURE AND FREQUENCY OF HUMAN INTRUSION

Although the consequences of some form of human intrusion should be assessed, it is also evident to the committee that there is no scientific justification for estimating the precise nature or frequency of such intrusions over the next 10,000 years. For compliance purposes at WIPP, EPA has decided that the frequency of drilling for oil and gas exploration and production during the past century will continue unchanged for the next 10,000 years, even though it is acknowledged that the oil and gas reserves near WIPP will be practically exhausted within the near future (i.e., in less than 50 to 100 years).

The EPA assumes that today's drilling activities are representative of the type of drilling activities that will occur in the future. Although the resources drilled for today may not resemble those drilled for in the future, the EPA

> *believes it is reasonable for the average rate to be projected over the next 10,000 years, based on the assumption that while oil and natural gas may be depleted, other resources (which are not currently economical to recover, or whose uses are not yet evident) may become more valuable. This assumption leads* [the EPA] *to the conclusions that it is reasonable to project oil and gas drilling rates (based on the historical record) over the regulatory time frame; and second, that since these rates are surrogates for other potential resources, it is inappropriate to include consequences of activities or secondary*

recovery techniques specific to oil drilling. (EPA, 1996, pp. 12-7, 12-8)

In effect, the EPA assumes that resources equivalent to more than 100 oil and gas fields, comparable to those now being exploited, will be explored for and developed at the WIPP site by borehole extraction methods, using the drilling density of the past century over the 10,000-year regulatory time frame. (Note: the mining of potash, using techniques in current use near WIPP, would not involve borehole extraction.)

The EPA prescription in 40 CFR 194 with respect to human intrusion illustrates both the difficulty and the subjective judgment involved in arriving at a regulatory standard for WIPP. Prescribing a future frequency of intrusive drilling based on past and present-day technologies is inherently speculative, highly subjective, and untestable by the scientific method (NRC, 1995). It is disconcerting to the committee that a repository such as WIPP, which appears to be an excellent choice based on geological considerations, could be judged "non-compliant" solely on the basis of a criterion which has a poor scientific basis.

The committee considers the approach proposed in the NRC (1995) report, *Technical Bases for Yucca Mountain Standards* (TYMS), to be a more appropriate way in which to assess the significance of human intrusion. The TYMS report recommends that the consequences of a single or combined drilling intrusion (such as E1E2—see Figure 2.5 of this report) be examined qualitatively, rather than quantitatively as in 40 CFR 191, in order to assess the severity of the consequences and to indicate what repository design measures may be appropriate to reduce the severity.

The incremental risk assumed by accepting human intrusion could also be compared with the long-term risks associated with leaving TRU waste on the surface.

RETROSPECTIVE

The WIPP Compliance Certification Application is the first test of a unique legal framework, which necessarily will not be based on prior experience. Inevitably, such a legal framework will contain controversial and weak elements. DOE and EPA will need to work closely, in the public interest, to ensure that such elements of the complex legal framework are resolved expeditiously, through negotiation based upon scientific understanding.

WIPP also is a pioneering effort in the assessment of geological site suitability and design procedures for a waste repository. It is the first repository in the nation for which an application to begin permanent, deep, geological disposal is being submitted for a decision.

The scientific and technical questions posed, particularly to earth scientists, required unprecedented levels of quantitative assessment of the response of a rock mass over tens of thousands to hundreds of thousands of years. A great deal of original research was necessary to demonstrate the applicability of laboratory data to field-scale conditions and to develop and assess the reliability of computer models to reproduce these complex systems. Teams of specialists were assembled, and scientific programs defined. Total System Performance Assessment was introduced and refined. Inevitably perhaps, the scientific emphases, budget allocations, and the most critical information needs identified by PA were not always in concert. These difficulties notwithstanding, a great deal has been accomplished.

In retrospect, one valuable lesson from WIPP is the importance of establishing site-specific PA early in the repository site characterization and design process, both to identify the critical research needs and to establish the overall goals of the project. Scientific programs, priorities, and budget allocations must be identified and periodically re-examined, all in the context of PA.

Significant uncertainties are implicit in extrapolating from one or two decades of data, at most, to tens or hundreds of thousands of years—but a well coordinated integrated program, using PA effectively, should be able to produce sufficiently credible answers to establish, with "reasonable expectation" and within a finite time and budget, whether or not a proposed repository site and design are appropriate for effective long-term isolation of radioactive waste.

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1. Native yucca in bloom near Carlsbad, New Mexico; the U.S. Department of Energy's Waste Isolation Pilot Plant (WIPP) is in the background.

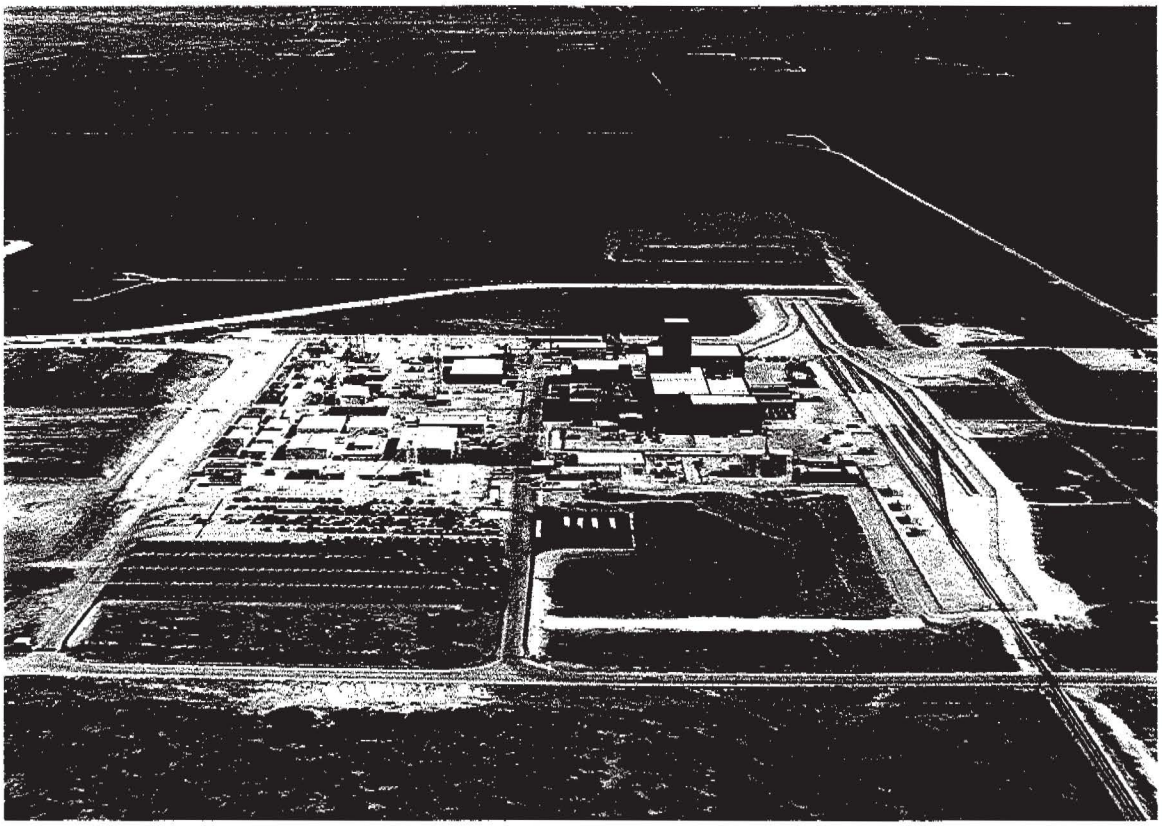

2. Aerial view of WIPP.

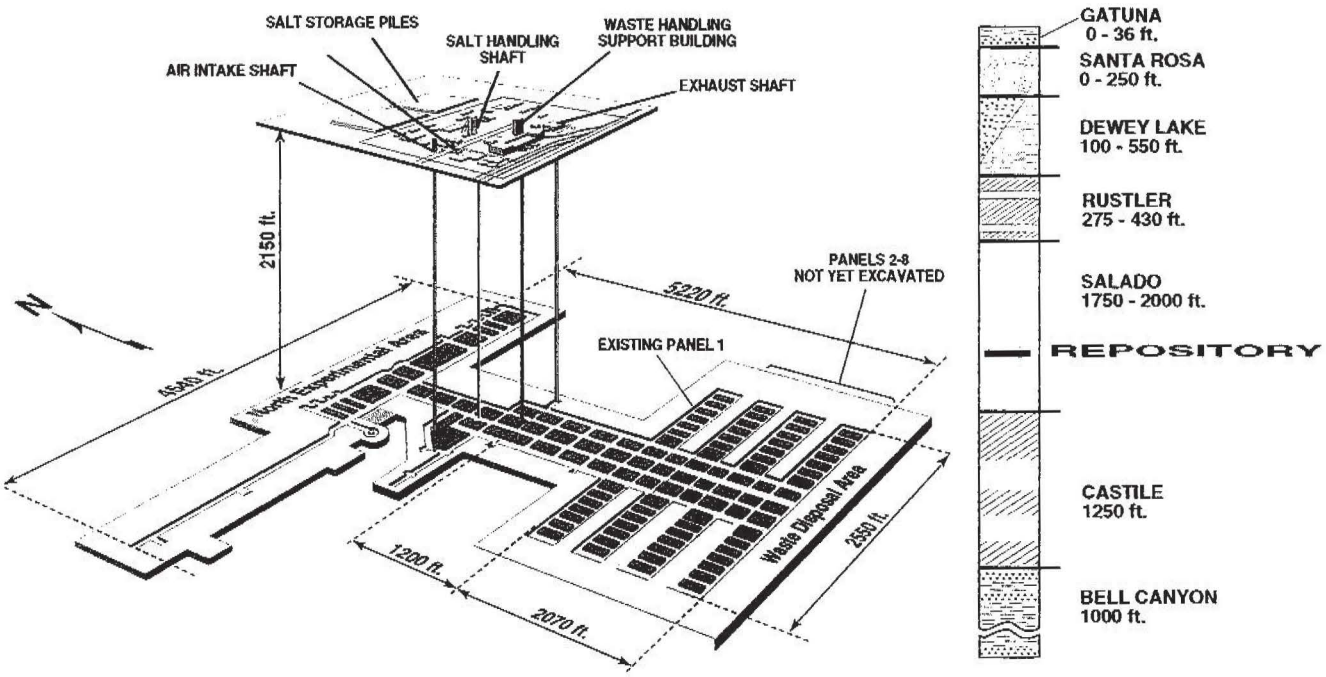

3. Three-dimensional view of the WIPP facility. Panel 1 is the only one of the eight panels shown that has been excavated in the waste disposal area to date. The typical stratigraphy is shown in cross-section on the right of the diagram. WIPP is located in the bedded salt Salado Formation, approximately 660 m below the surface. The Salado is approximately 230 million years old.

4. View of Room 1, Panel 1, underground at WIPP.

5. A tractor-trailer travels to WIPP with U.S. Nuclear Regulatory Commission-certified containers, using the Transuranic Package Transporter (TRUPACT-II) transportation system. The tractor-trailer and containers are designed specially for shipment of radioactive waste for disposal at WIPP. The location of the TRUPACT-II can be pinpointed within 150 m at any time by a satellite tracking system.

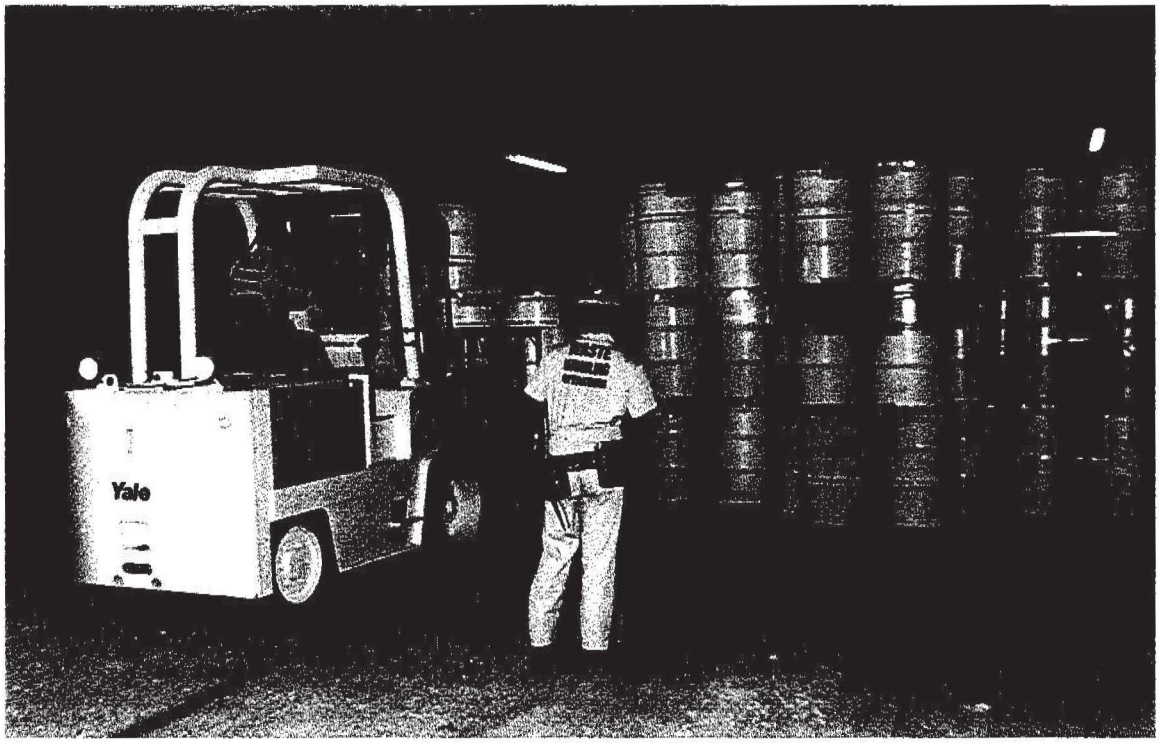

6. Stacking of simulated contact-handled transuranic waste approximately 660 m underground at WIPP.

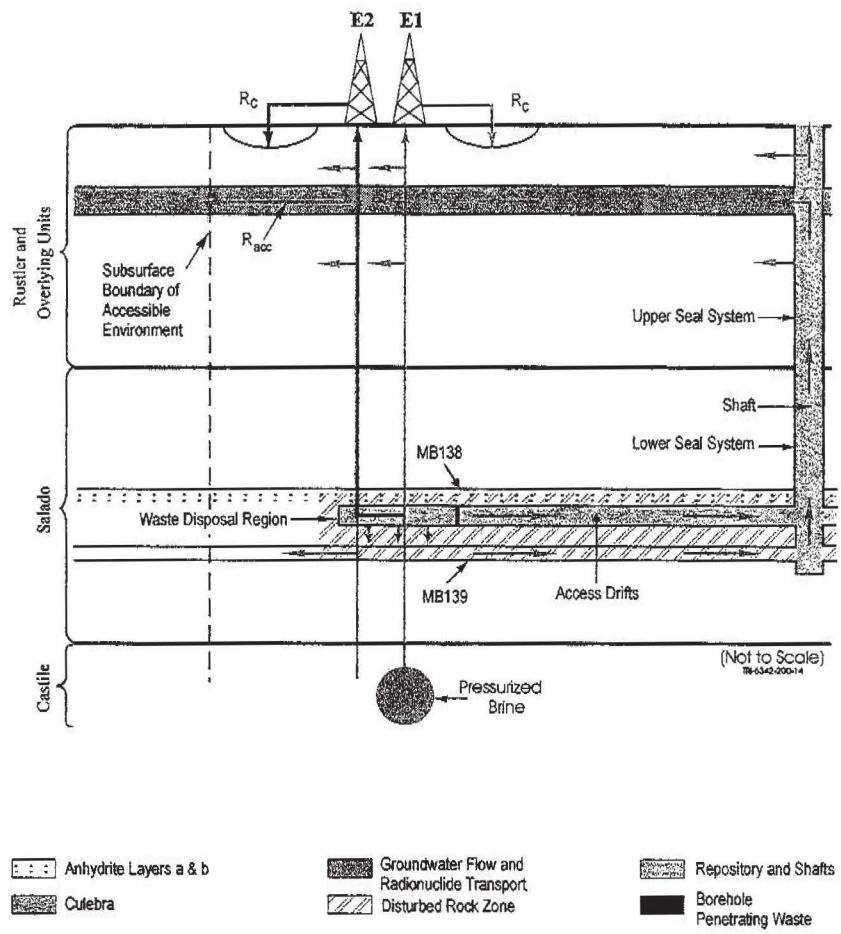

7. Conceptual release pathways for the E1E2 human intrusion event (see Chapter 2). It is assumed that at some time in the next 10,000 years, a borehole penetrates both the waste and a region of pressurized brine in the underlying Castile formation. A second borehole is also assumed to penetrate the waste but not the pressurized brine. Arrows indicate the hypothetical direction of ground water flow and radionuclide transport; R_c indicates material released at the surface directly from the drilling operation; R_{acc} indicates radionuclides released below the surface into a permeable bed of Culebra dolomite. This and other release pathways are considered in calculations made to evaluate whether or not a WIPP repository would comply with U.S. Environmental Protection Agency (EPA) standards.

Source: The figure is taken from the DRAFT-DOE/CAO-2056, p. 6-51 (July 1995 update).

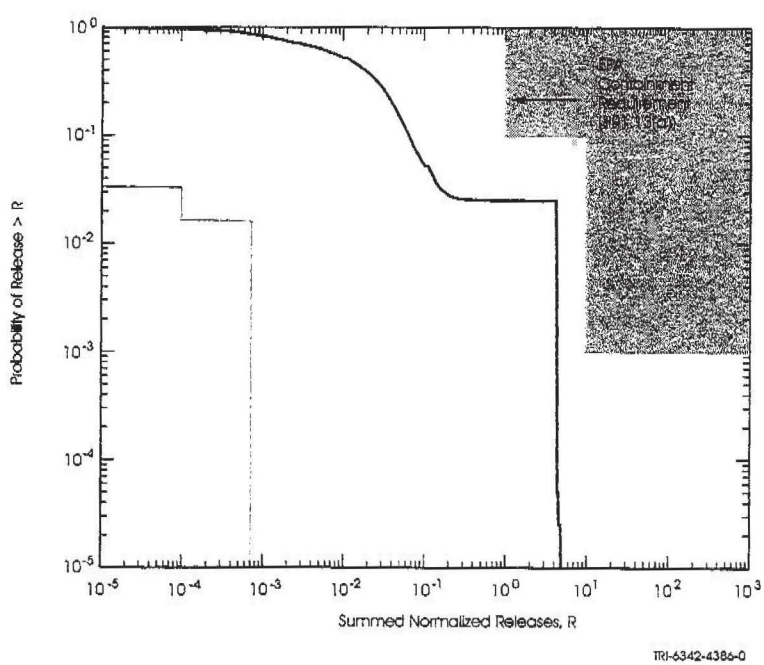

8. Mean Complementary Cumulative Distribution Functions (CCDFs) showing the probability of radionuclide releases from WIPP over 10,000 years for undisturbed conditions (red) and intrusive drilling scenarios (blue). This figure illustrates the dominant influence of intrusion scenarios on the predicted releases. These preliminary CCDFs are based on early models and data and do not address all the requirements of EPA regulations 40 CFR 191 or 40 CFR 194. The EPA release limits are shown as the left-hand-side limits of the region in green. Compliance is achieved if the mean CCDF never enters the green region.

Source: The figure is taken from DRAFT-DOE/CAO-2056, p. 6-59 (Vol. I, March 1995) and p. 6-101 (July 1995 update).

Appendixes

Appendix A

Natural Setting and Resources

As for any deep geologic facility, the natural setting of the Waste Isolation Pilot Plant (WIPP) is important in determining the facility's performance as a repository for radioactive waste. The natural setting consists of the geology, hydrology, geochemistry, climate, and natural resources of the region and local area immediately surrounding WIPP, some of which are discussed below.

GEOLOGIC FRAMEWORK

For a large part of the early geologic history of the North American continent, the land now occupied by southeastern New Mexico was part of an ancient ocean south of the continent. For hundreds of millions of years, this region experienced almost uninterrupted deposition of marine shoreline sediments, primarily beach sands, and shallow water lime and clay muds. In the Pennsylvanian Period and later, coarser continental shelf and slope deposits occasionally slid into deeper basins. The relatively warm, calm seas promoted an abundance of marine life, which, upon death, accumulated in the muds and sands, altered to simple hydrocarbons, and eventually became the oil and gas found in some of these rock layers in recent years.

In pre-Permian periods, the collision of tectonic plates of the earth's mobile crust caused mountains to form to the southeast, north, and west of the WIPP site. The southeastern corner of New Mexico and western Texas remained relatively stable through the Permian Period of earth history (286 million to 245 million years ago [Ma])[1], although some instability caused the earth's crust beneath this region to rise in some places and sink in others, in a belated response to the collision pressures. These fluctuations resulted in shallow areas on the sea floor ("shelves" or "platforms") and deeper areas ("basins") at the beginning of the Permian Period in southeastern New Mexico and western Texas (Figure A.1).

It was in the sediments accumulating in these deep basins that oil was generated, which moved into adjacent shelf environments to form the richest oil pools. One of these deep basins, the Delaware Basin, underlies WIPP and part of southeastern New Mexico. Most of these older rocks beneath WIPP are far too deep to bear on the performance of the repository. However, the presence of oil is considered a possible reason for inadvertent, or even deliberate, human intrusion into the repository in the future.

Late in the Permian, the warm and shallow seas encouraged the formation of reefs, similar to contemporary coral reefs in shallow tropical marine environments. As they grew, the reefs blocked off parts of the sea from time to time. With circulation of seawater restricted by the reef, the seawater began to evaporate, resulting in highly concentrated brines. As the brines continued to evaporate because of the warm temperature and restricted inflow of seawater, crystalline salts began to precipitate and accumulate on the bottom of the restricted basin. The salts varied in chemical composition, depending on the amount of water that had evaporated and on the concentrations of calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), and other components of the common "evaporite" deposits.

As a result of these conditions, the WIPP area is underlain by a total accumulation of hundreds to thousands of meters of reef limestone (calcium carbonate, $CaCO_3$); dolomite [calcium magnesium carbonate—$CaMg(CO_3)_2$]; gypsum [a hydrous (water-bearing) calcium sulfate, $CaSO_4 \cdot 2H_2O$); halite (rock salt, NaCl, the source of common table salt); smaller amounts of anhydrite ($CaSO_4$); and potassium salts (collectively known as "potash," a commercially useful deposit).

[1]Older geologic dating extended the Permian to 225 Ma; more recent methods date the end as 245 Ma.

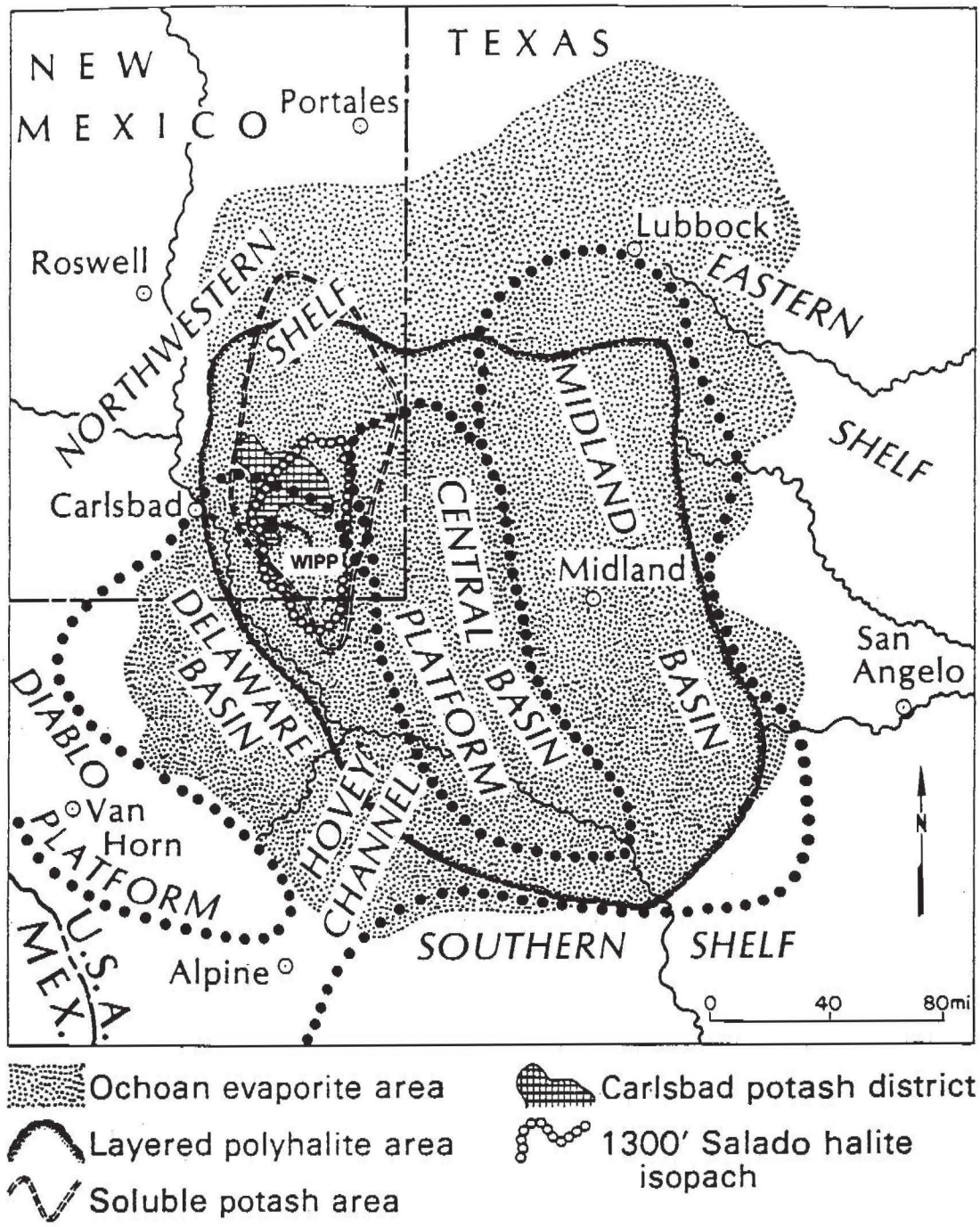

FIGURE A.1 Regional subsurface geology, showing features from before and during the Permian Period. Heavy black dots outline the Pennsylvanian to middle Permian (Guadalupian) shoreline, showing the shallow platforms and shelf areas and the adjoining deeper basins. Superimposed on that background in fine, close-spaced dotted shading is the extent of the late Permian (Ochoan) evaporating sea. A solid black line delineates the extent of layered varied salt deposits. The enclosed form of open circles shows where the Salado Formation salt beds are 396 m (1,300) ft thick. The Carlsbad Potash District is shown in cross-hatch pattern. Source: Barker and Austin (1995).

Within part of the Permian, the Ochoan, during which the sea was blocked intermittently, the following four groups of rocks present at the WIPP site were formed successively:

1. Castile Formation,
2. Salado Formation,
3. Rustler Formation, and
4. Dewey Lake Red Beds.

Castile Formation

The oldest and deepest of these rock units is the Castile Formation. Castile rocks are composed mainly of anhydrite with alternating thin limestone layers and a few thick layers of halite. Anhydrite and/or gypsum begins to precipitate from brines when 75 percent of the original amount of seawater has evaporated, continuing to be deposited until 90 percent has evaporated, at which point halite begins to precipitate (Kay and Colbert, 1965, p. 202). The alternating character of the Castile suggests that limited amounts of fresh seawater were able to enter the basin intermittently.

Salado Formation

The Salado ("salty" in Spanish) Formation, in which the WIPP facility is located at 658 m below the surface, is composed predominantly of layers (beds) of rock salt, 200-400 m thick. It contains very thin layers (typically 0.1-1 m thick) of other materials (such as clay, anhydrite, and potash minerals) intercalated throughout the formation. Because these evaporite beds have been undisturbed by tectonic forces (large-scale movements of the earth's crust) for approximately 240 million years since their original accumulation, they are essentially horizontal and therefore can be traced continuously for great distances. The thin, distinctly identifiable nonhalite interbeds, called "marker beds" (MBs), have been numbered for identification from the lowest, at the top of the formation, to the highest, near the bottom. Marker beds have been used in the construction of the WIPP facility to keep the floor at a specific stratigraphic level, about 660 m below the surface. The floor of the facility is just above anhydrite MB 139 (Figure A.2).

About midway between the bottom and top of the Salado Formation is a notably thick series of beds, known as the McNutt member of the Salado, which contains economically valuable amounts of potash. The McNutt member, stratigraphically above the salt in which WIPP is located (Figure A.2), is about 120 m thick (Griswold, 1995) but is limited in areal extent within the evaporite basin (Figure A.1). The potash minerals, however, are of sufficient quantity for mining and extraction to have been a source of major economic activity in the area for many years.

Rustler Formation

Overlying the Salado Formation is the Rustler Formation, a thinner-bedded series of strata consisting of five distinct subunits (such sequences are called "members" of a formation). At the bottom of the formation are nonevaporite beds derived from clay muds and sands alternating with layers of halite, anhydrite, limestone and dolomite, and gypsum. The total thickness of the Rustler is about 100 m. The presence of nonevaporite materials such as the clay, silt, and sand (called "clastic deposits" or "clastics") indicates that periodic fluctuations in basin water levels and intermittent inflow of river and marine waters carried clastics into the basin material that sometimes formed separate layers without evaporites, such as sandstones and shales, or settled with the evaporites. The Culebra Dolomite Member of the Rustler Formation, which lies directly above the lowest Rustler clastic strata, is only about 7-8 m thick. The chemical, mineral, and hydrogeologic characteristics of the Culebra are important to a ground-water flow model for the WIPP area.

Dewey Lake Red Beds

The youngest (uppermost) Permian strata in the WIPP vicinity are thin, reddish beds of clay, silt, and sandy sediments produced in a restricted marine environment. The red color derives from the oxidized iron dispersed throughout the clay and sand, suggesting semiarid conditions during deposition of the sediments.

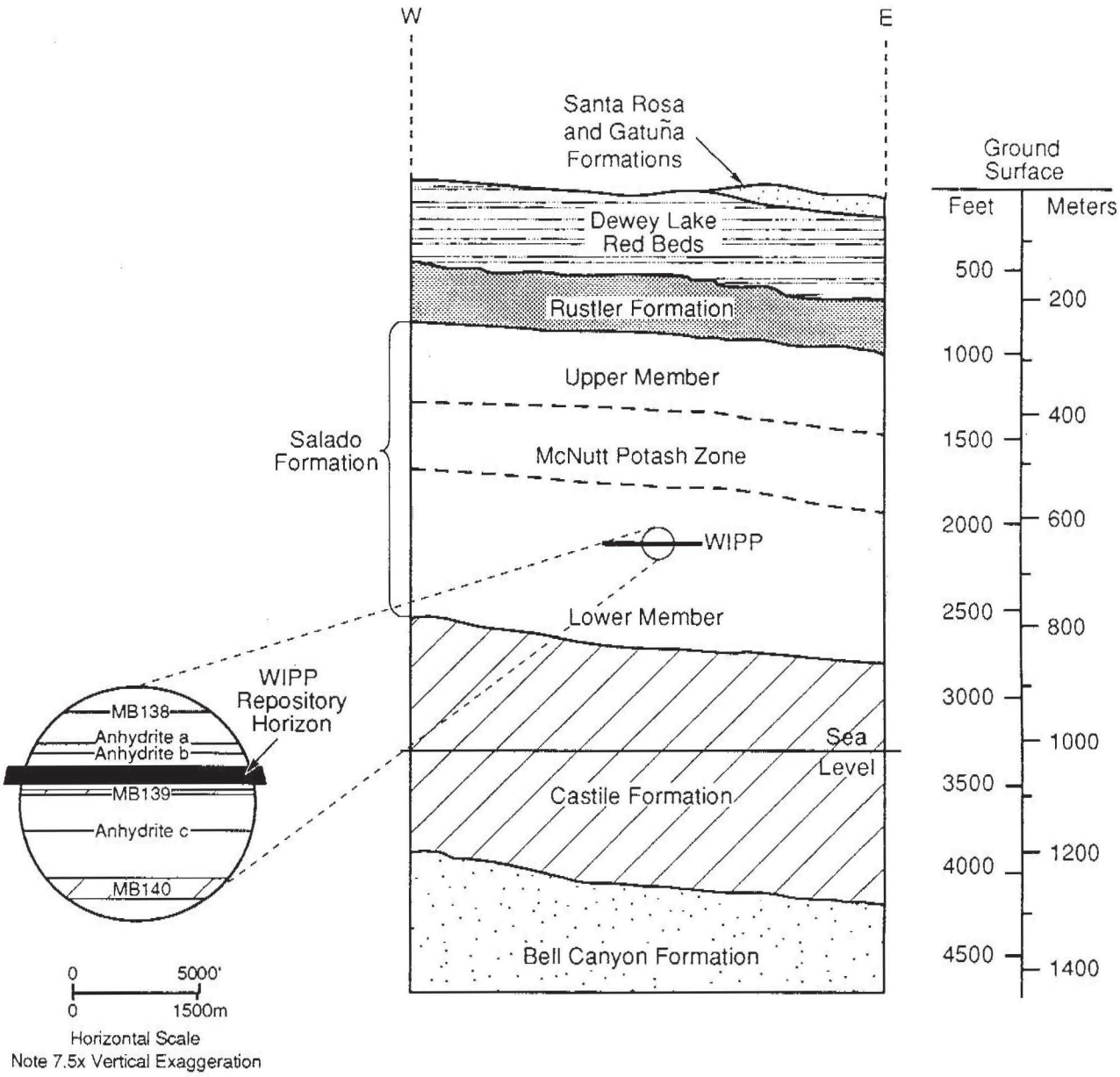

FIGURE A.2 WIPP stratigraphy and depths of four key formations (Castile Formation, Salado Formation, Rustler Formation, and Dewey Lake Red Beds), including the position of the WIPP repository within the Salado. Inset shows finer-scale stratigraphy around the repository horizon, with marker beds and other thin beds. Source: Jensen et al. (1993).

Post-Permian Rocks

An assortment of rock types and ages younger than Permian is present in different locales around the region. Some discontinuous surface deposits were carried by high-energy streams that formed from the melting glaciers to the north during the Ice Age (the Pleistocene, from about 1.6 Ma to 10,000 years ago). One of the Pleistocene stream channels is still present west of the WIPP area as a broad, shallow valley, called Nash Draw, that is wider than 6 km in places (Figure A.3). The valley formed when the high-energy streams eroded down through the rock layers and exposed parts of the Rustler Formation, which are now visible in the walls of the valley. Nash Draw plays a role in determining the regional and local hydrology in the vicinity of WIPP.

HYDROLOGIC SETTING OF WIPP

Because flowing ground water is one of the most likely means by which contaminants could reach the accessible human environment, it is important to understand the hydrogeologic character of the region.

Most of the hydrologic studies of the WIPP site and surrounding region have focused on the Rustler Formation in general, and on the Culebra Dolomite Member in particular. Because the latter is a water-bearing unit that is exposed in Nash Draw, it is a major concern in assessing the capabilities of WIPP to isolate radioactive wastes. However, the other major formations also play a role in WIPP hydrology for varying reasons.

The top of the Castile Formation lies about 200 m below the level of the Salado Formation at which the WIPP facility is located (Figure A.2). Under natural conditions, there is no flow of ground water between the Castile and Salado Formations. However, during exploratory drilling to locate a site for WIPP, project scientists found large, highly permeable zones (pockets) at depths within the Castile, filled with brine under very high pressure (from the weight of hundreds of meters of overlying rocks). This is considered significant in evaluating the WIPP facility because brine in pressurized pockets, once penetrated by drilling, flows out to the surface rapidly and could continue to flow for hours or days, depending on the depth of the pocket, the volume, and pressure of the brine.

Hydrogeology of the Salado Formation

The mechanical behavior of salt, especially massively bedded salt, provides the basis for the inference that water cannot flow continuously through salt along interconnected pathways as it does in many other types of geologic materials. As a weak solid, salt flows under low pressure after a period of time, much as glacial ice flows.

Both are solids, but under pressure such as its own weight or the weight of material above, the crystal structure of the individual minerals that make up the rock salt deforms, causing movement within the minerals (intracrystalline gliding) and movement between crystals (intercrystalline slip) over time. This type of movement, termed "creep," is a very slow process in human terms, in which the actual movement of the salt cannot be seen, although the results of creep are readily observable in room closure and the deformation of boreholes.

The continuous creep of rock salt causes opening and closing of pore spaces that trap droplets of water and prevent the continuous flow of ground water through the interconnected pore spaces in the rock from one location to another. Creep also closes fractures and "heals" them as salt crystals flow into them and interconnect with other salt crystals. For this reason, the permeability of salt (the degree of interconnected pore spaces that allows flow of ground water through the rock matrix or fractures) is generally regarded as extremely low to zero. Pressure tests done on the Salado Formation at various times, both from wells drilled at the surface and from underground tests after the facility was constructed, have indicated that the salt permeabilities are very low, close to the sensitivity limits of the instruments (Mercer, 1987; Beauheim et al., 1991, McTigue, 1993).

During the construction phase of the WIPP facility, brine was observed flowing or seeping into the space created whenever a new opening was made in the salt, whether in a narrow hole or in a large room. These observations led to consideration of the possibility that the disposal rooms could be flooded over the time required for isolation of the long-lived radionuclides

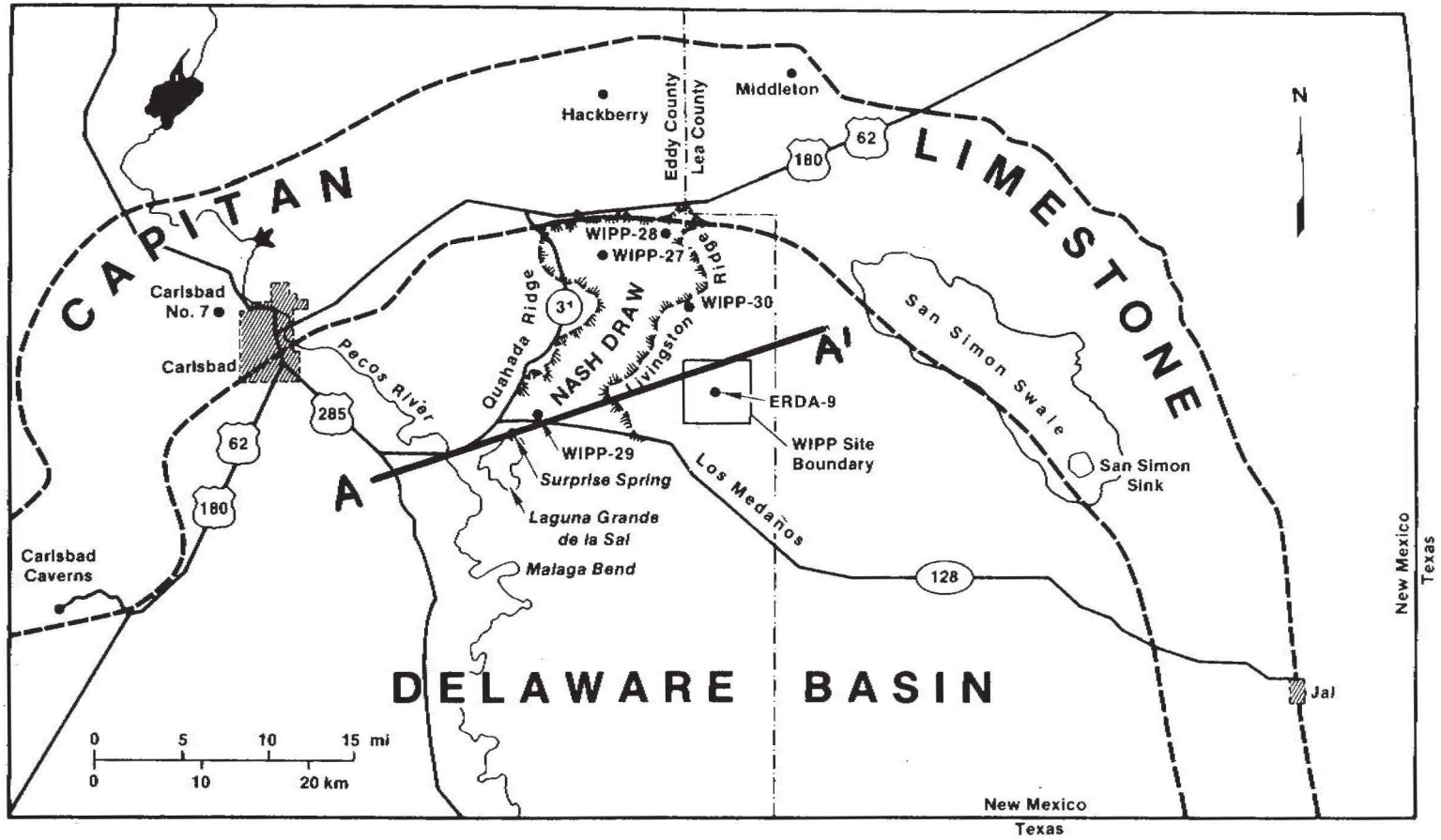

FIGURE A.3 Position of Nash Draw with respect to WIPP. Other features of interest are the location of the Pecos River and the outline of the buried Capitan reef limestone, which encloses the Delaware Basin on the north. Source: Siegal et al. (1991).

and that the consequent chemical reaction of the brine with metal containers would produce large volumes of hydrogen gas (Brush, 1994). These considerations assumed that brine was flowing in from the far field and had a continuous source. However, tests to monitor and measure the inflow of brine over a period of years have shown that the rate of inflow is greatest immediately following the disturbance of the salt to produce a new opening, then declines rapidly, and finally tapers to almost immeasurable amounts (Deal et al., 1991a, b).

These observations have led WIPP project researchers to consider that brine inflow into a newly created opening results when the salt is disturbed by drilling or mining and fracturing occurs in a zone around the new opening (disturbed rock zone, or DRZ), thus releasing brine from entrapped pore spaces (Stormont et al., 1991). Further details and discussion of this issue can be found in Chapter 3 and Appendixes C and D.

The only likely source of measurable Darcy flow in the Salado is the nonhalite interbeds, especially the anhydrite interbeds, which show varying degrees of fracturing. Fracture permeability can provide interconnected pathways for ground water.

Hydrogeology of the Culebra Dolomite

The geological units comprising the Rustler Formation are illustrated in the stratigraphic column shown in Figure A.4. Note that the lithologies represented in this figure are generalized representations for the region and do not necessarily depict the exact distribution of rock types encountered in the Rustler at the WIPP site itself. As illustrated in Figure A.4, the Rustler outcrops are in the Nash Draw area several miles west of the WIPP site, but the formation lies at a depth of about 200 m below the land surface at WIPP.

Ground-water flow in the Rustler Formation is restricted mostly to the Rustler–Salado contact zone, the Culebra Dolomite Member, and the Magenta Dolomite Member (Brinster, 1991). Of these, the Culebra is the most transmissive. Although it is relatively thin (the thickness of the Culebra is generally between 7 and 8 m), it is also extensive in area.

The Rustler Formation, especially the Culebra Dolomite Member, has been the principal focus of hydrogeologic characterization of the WIPP vicinity (Lappin, 1988). The ground-water system in the Rustler is generally characterized by relatively low permeability (or transmissivity) and relatively poor water quality (i.e., too salty to be potable). The Rustler contains a predominance of secondary permeability features, such as fractures, bedding planes, and dissolution features; these may dominate flow in parts of the system, complicate analysis, and render quantitative descriptions difficult. At the very least, these features imply that the ground-water flow system is three-dimensional in a heterogeneous framework that is a challenge to model and understand properly. Both observation and water-supply wells are relatively scarce, contributing to the difficulty and expense of characterization. Although much excellent work has been done during the past 20 years in an attempt to characterize the relatively complex hydrogeology of the area near the WIPP site, some large uncertainties remain in the understanding of the subsurface system above the Salado. The recent state of knowledge has been summarized by Brinster (1991).

A number of water-level measurements and observations of drawdown and/or recovery during hydraulic tests have been used to measure the hydraulic heads and transmissivities in the Culebra. The changes in head over distance determine the hydraulic gradient. Transmissivity, which can vary significantly in value from point to point, is a measure of the ability of the rock to let water flow through it under a given hydraulic gradient.

However, some inconsistencies remain in the interpretation of the long-term flow history of the Culebra based on hydrologic evidence, compared to that inferred on the basis of geochemical and isotopic indicators. These inconsistencies, which reflect some degree of lack of understanding of present or past flow regimes within the Culebra, mean that there is uncertainty in the conceptual model that underlies the performance assessment (PA) model.

Ground-Water Flow Directions

In general, the direction of ground-water flow in the Culebra Dolomite in the WIPP area is from north to

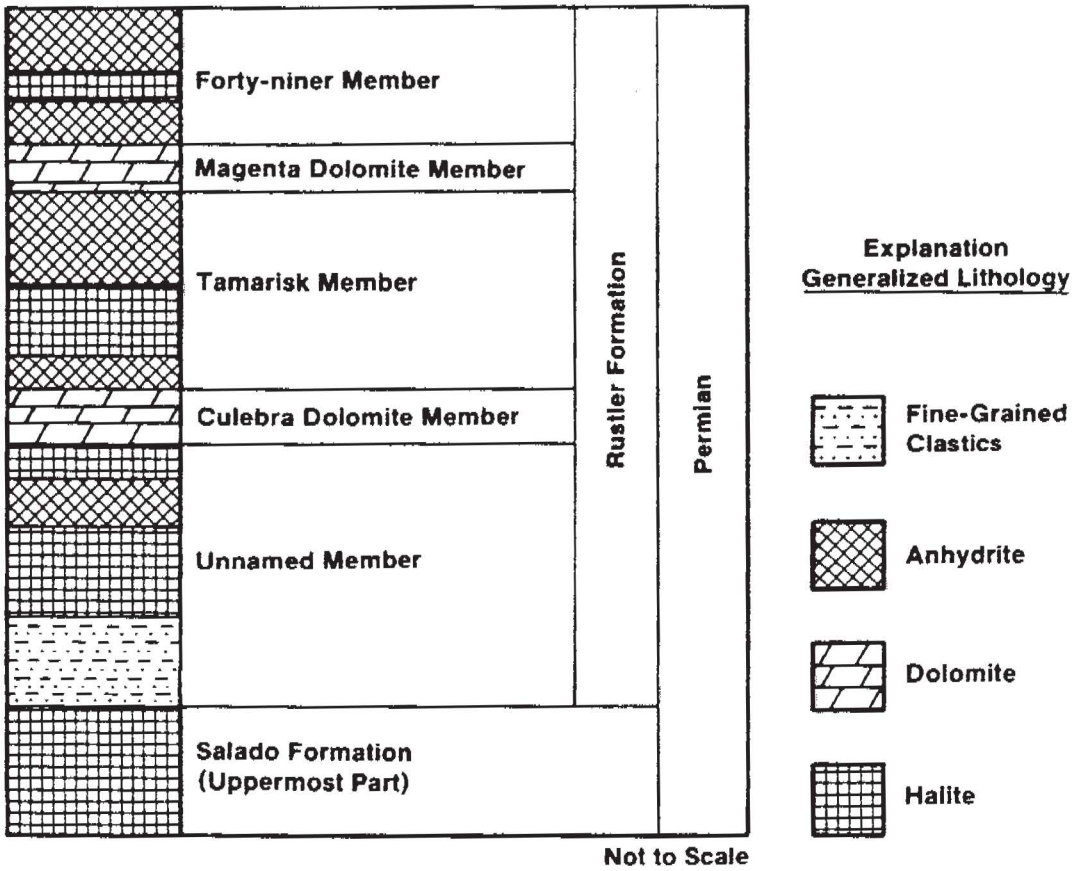

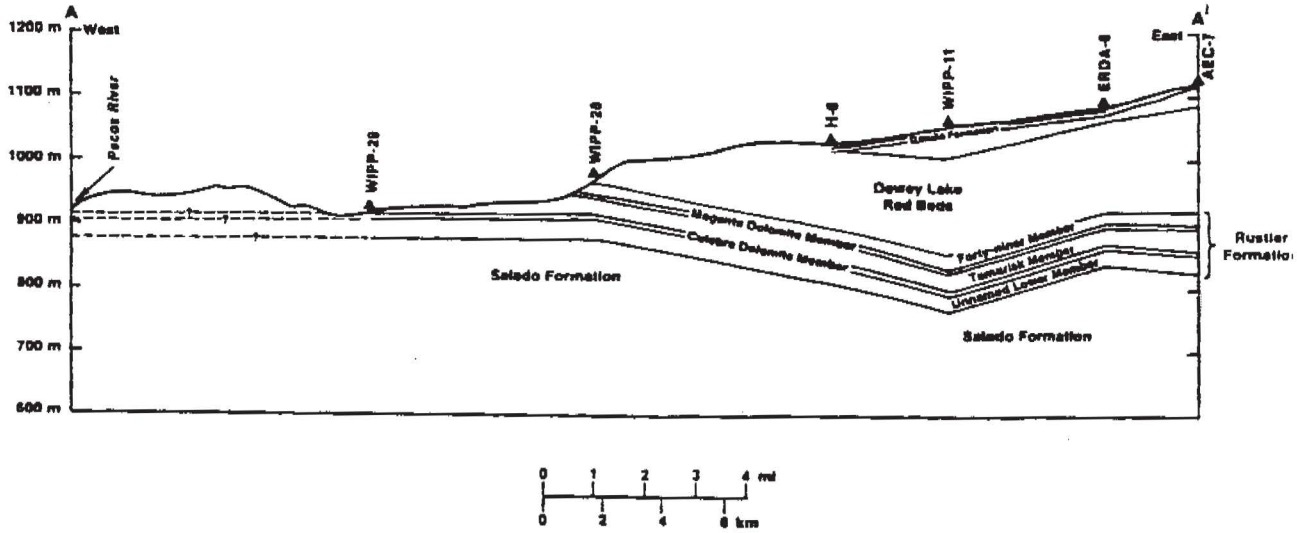

FIGURE A.4 General stratigraphic column showing the five members of the Rustler Formation (top), and cross section from A to A' of Figure A.3 showing Rustler Formation stratigraphy (bottom). Source: Brinster (1991).

south. Because the salinity of the ground water is high and variable, the fluid density also varies significantly. Davies (1989) analyzed variable density flow in the Culebra and concluded that, at least in areas south of WIPP, flow directions can be calculated accurately only if variations in fluid density also are evaluated. Potentiometric data in the Magenta Dolomite indicate that the flow direction is predominantly from east to west. Differences in flow directions within the Rustler Formation reflect the complexity of the hydrogeologic system and may be influenced by vertical components of flow.

A fair degree of uncertainty remains about the amounts and locations of recharge to and discharge from the Culebra. In general, Brinster (1991) notes that recharge occurs north of the WIPP site, although some recharge may also occur east of WIPP because of vertical leakage from the Magenta. Natural discharge is south of WIPP, with some discharge to the Pecos River likely occurring at Malaga Bend.

Transmissivity Estimates

Transmissivity estimates for the Culebra Dolomite in the WIPP area and in Nash Draw range over more than six orders of magnitude. Transmissivity is lowest east of WIPP ($\sim 10^{-10}$ m^2/s) and tends to increase to the west ($\sim 10^{-3}$ m^2/s). However, the transmissivity is highly variable and spatially correlated (e.g., LaVenue et al., 1995). In some areas, the transmissivity is controlled largely by fracture permeability, whereas in other areas it is governed by primary intergranular properties.

Travel Time

The time it takes for a parcel of water in the Culebra Dolomite to travel from the center of the WIPP site to its southern boundary is an important characteristic of the system controlling the transport of any contaminants released into the Culebra. This travel time depends on the transmissivity, hydraulic gradient, and effective porosity. Analyses assuming that the effective porosity governing transport is a value characteristic of the rock matrix (about 0.16) indicate that the mean travel time would be of the order of 14,000 years (LaVenue et al., 1990). However, if one assumes that the effective porosity is characteristic of fracture porosity (~0.0015), then the travel time is reduced to only about 200 years (Davies et al., 1991).

Hydrogeology of the Dewey Lake Red Beds

The Dewey Lake Red Beds are believed to be less permeable than the Culebra Dolomite. However, very few hydraulic tests of this unit have been completed, and few observation wells are available to characterize the flow system. Brinster (1991) reports that although a continuous saturated zone has not been found, some localized zones of relatively high permeability have been identified. Potable water has been reported in some parts of Dewey Lake, perhaps because it is sufficiently shallow to receive direct recharge from precipitation events.

NATURAL RESOURCES

The geologic evolution of this region has resulted in the presence of economically valuable natural resources. The late Permian evaporating basin accumulated a large deposit of potash. The region in earlier Permian time can be characterized as a marine shoreline and some deeper offshore basins accumulating sands and limestone, clastics, and organic debris that resulted in accumulations of economically recoverable oil and gas in rock strata below the evaporites. Thus, the two major activities to extract mineral wealth from the WIPP region are the mining of potash and the drilling and extracting of oil and gas.

Potash Mining

Potash, the commercial name for potassium-bearing minerals, is mined for its potassium, one of the three main plant nutrients in fertilizer. The potassium minerals are concentrated in a middle zone of the Salado Formation, the McNutt Member, which is about 140 m thick (Figure A.2). The Carlsbad Potash District contains the largest potash reserves in the United States (Barker and Austin, 1995; see also Figure A.1). The district is bounded on the west by the dissolution of the shallow Salado strata caused by circulating ground water in the Pecos River drainage area to the west and south of Nash Draw.

Potash mining has been going on in the WIPP vicinity for more than 60 years. Potash was discovered in southeastern New Mexico in 1925. The first mine shaft to the potash 324 m (1,062 ft) below the surface was completed in 1930, and the first commercial shipment took place in 1931. Over the next 30 years, development and production advanced steadily as a large number of companies grew and merged. By the 1940s, New Mexico was the largest domestic potash producer, supplying 85 percent of the country's consumption.

This growth came to a halt and started to decline when potash was discovered, produced, and exported to the United States from Canada in the early 1960s at a lower cost than was economically feasible for U.S. producers. By 1970, Canadian imports exceeded domestic production. The decline continued despite a favorable ruling of dumping against Canadian producers by the International Trade Commission in 1987. Shortly thereafter, the former Soviet Union countries began exporting potash to the United States, further increasing competition and depressing both price and demand. Because of the foregoing and other economic and declining resource factors, the potash industry in the WIPP region is now much depressed, and very few companies are still active (Barker and Austin, 1995).

The mining front is now close to the WIPP site boundary and has reached the edge of the study area on the southwest side of the WIPP site (Figure A.5). In the future, the southwest or north side of the WIPP boundary may be the next target area for mining (Griswold, 1995).

In assessing potential future impacts of potash mining on the WIPP facility, the adoption of solution mining of potash minerals, a technique now being used in Canada, has been mentioned as a possible development. However, of the two dominant potash minerals being mined in the Carlsbad Potash District, sylvite and langbeinite, only sylvite is sufficiently soluble to make this mining process economically and practically feasible. According to specialists familiar with potash mining in this area, the beds containing sylvite are considered too thin for solution mining to be practical, but mine owners have not discounted this process as a future development in the area (Griswold, 1995).

If the potash resources overlying the repository were mined in the future, the resulting subsidence could significantly increase the transmissivity of the Culebra Dolomite, located approximately 200 m above the potash (Figure A.2). This could result in faster release of radionuclides to the environment following a human intrusion event.

Oil and Gas Resources

After the strata below the evaporites of the Delaware Basin had been bypassed for many years as unlikely to be producers of economically recoverable oil resources in the WIPP area, oil was discovered in the late 1980s and early 1990s. Indications in earlier exploration had suggested that mostly water was present in these strata. New techniques in analyzing the geophysical logs led to identification of several commercial oil pools in the Delaware Mountain Group of rocks at and below about 2,500 to 2,700 m in depth.

Major oil drilling activity began in the Delaware Basin following the discovery. This is now one of the most active areas of oil exploration and extraction in the United States (Broadhead et al., 1995, p. XI-10; Figure A.6). In the vicinity of WIPP, four major pools have been discovered, at least one within 1 km of the site boundary.

New technologies in oil drilling have improved recovery, safety, and cost efficiency. Improvements in well productivity result from advances in directional drilling, completion technologies, and stimulation techniques (Hareland, 1995). These advances and projected future oil and gas production were used to calculate the estimated value of oil and gas underneath the WIPP land withdrawal area. The estimated total primary and secondary recovery of probable resources in oil reservoirs under WIPP is about 54 million barrels of oil and gas condensate (Broadhead et al., 1995).

The secondary oil recovery technique known as waterflooding has been used in some areas around WIPP. A concern has been raised that such a process could introduce large amounts of water into the Salado Formation that could find its way to the WIPP facility by flow through marker beds, a process that has been observed in some oil fields in the region. In 1991, a flow of up to 1,200 barrels per hour of brine inflow was encountered in a hole being drilled for petroleum

production. At the time of inflow, the hole was approximately 100 m above the base of the Salado. The inflow was attributed to a waterflooding operation in the Rhodes Yates Field in which a large number of old wells were simultaneously injected. These injections occurred in the Yates Formation some 100 m below the base of the Salado, and 2 miles (3 km) from the well where the inflow occurred. This has raised concerns that similar inflows may occur due to waterflooding operations near WIPP and could compromise the integrity of the repository. This is further discussed in Chapter 3 (Box 3.2). See Figure A.7. A full discussion of waterflooding is presented in Broadhead et al. (1995).

A key issue is whether a future society would be aware of WIPP and its hazardous contents. The presumption that the existence or significance of WIPP would be lost is subjective and unquantifiable and therefore beyond the realm of rigorous scientific prediction. A second issue is whether such a society would elect to drill through it if knowledge of WIPP's existence were retained.

If future societies retain a knowledge of the existence of WIPP, yet still want to explore for or recover petroleum resources below WIPP, then directional drilling is feasible and likely. With present technology, a drilling operation could avoid damage to the repository if it were operated from the surface beyond the WIPP site boundary, and directed to avoid the waste horizon.

Manmade site markers, to be emplaced after closure, are required under the EPA standards. The reason for this requirement is that such markers, if they persist over time and are understood, could reduce the likelihood of inadvertent intrusion. The intent of erecting markers is to lead drillers to reconsider vertical boreholes that would penetrate the repository, and to choose instead alternative methods such as directional drilling techniques.

The assumption that the WIPP area would be drilled by today's methods for the next 10,000 years is also questionable. The recent advances in directional drilling techniques show that technology evolves in time.

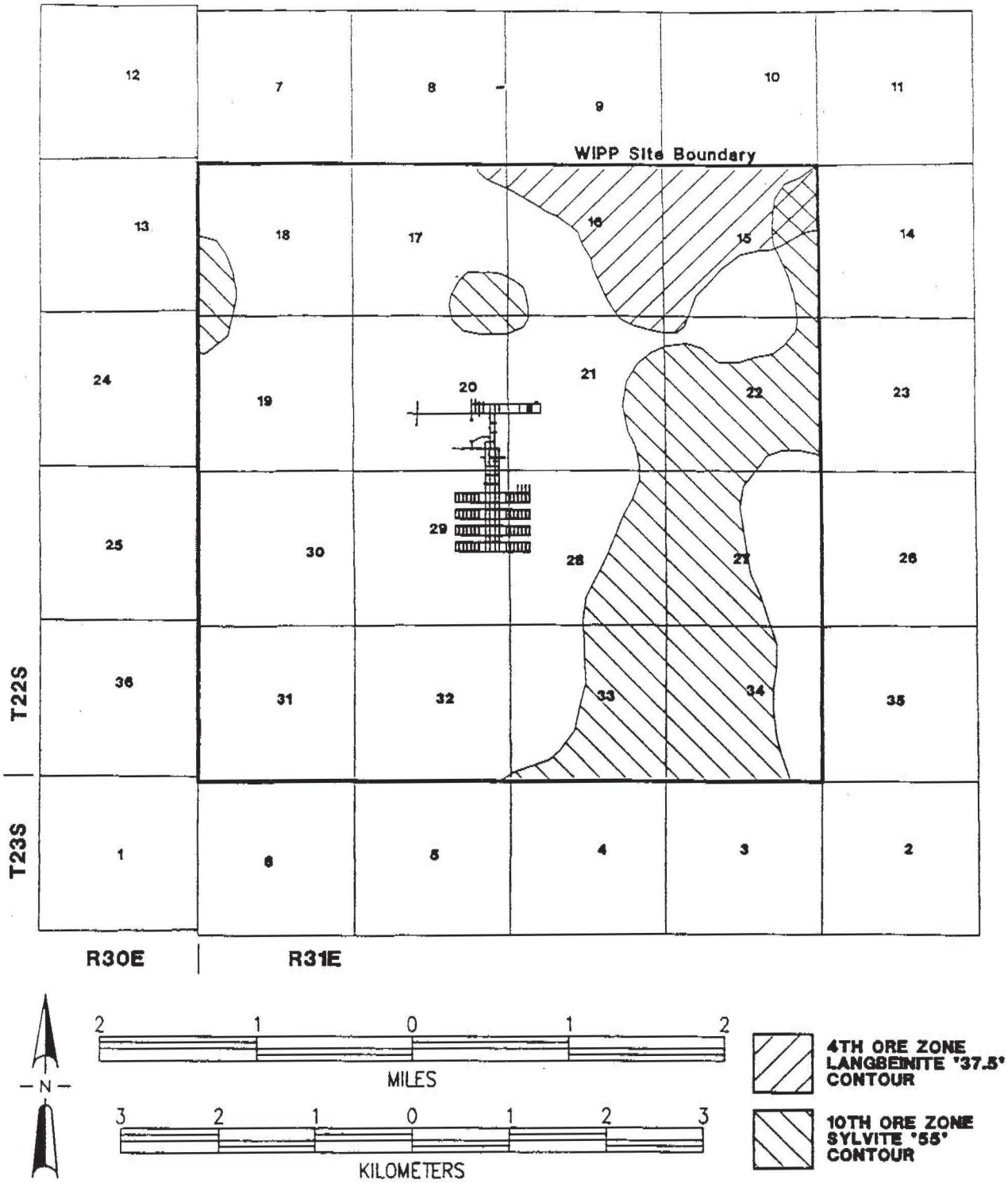

FIGURE A.5 Contours showing potash ores (both langbeinite and sylvite) near WIPP. (The contours are interpolated from figures 4 and 30 of Griswold [1995]). Also shown is the location of the WIPP facility of Figure ES.1.

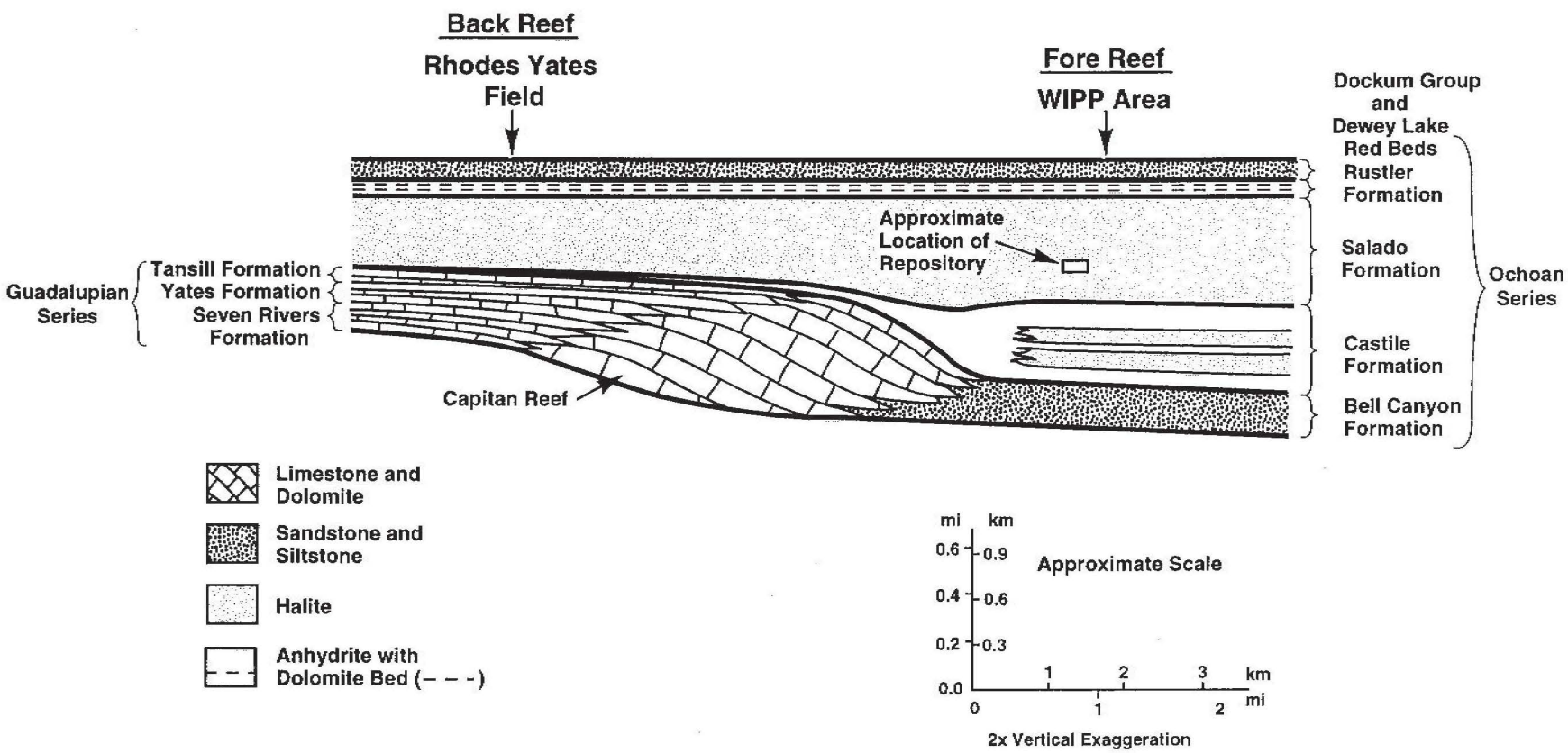

FIGURE A.6 Cross section depicting the relative locations of the Rhodes Yates Field and the WIPP repository. Source: Sandia National Laboratories, unpublished. Data from the State of New Mexico Bureau of Mines.

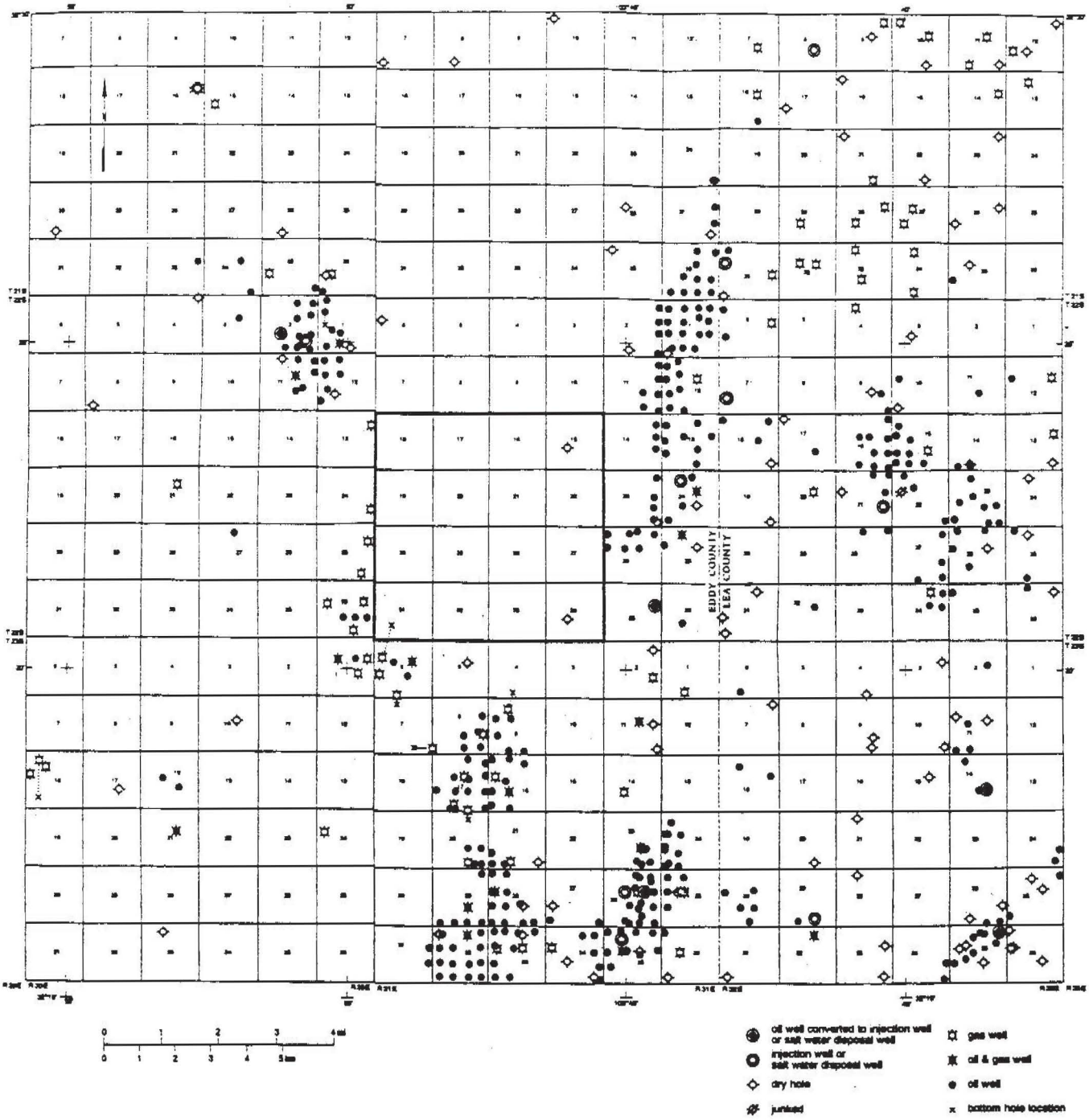

FIGURE A.7(a) Wells drilled for oil and gas in and around the WIPP site, surrounding 1-mile-wide study area, and nine-township project study area. Note that some wells are right at the WIPP boundary. No producing wells are within the WIPP exclusion zone. Source: Adapted from Griswold (1995).

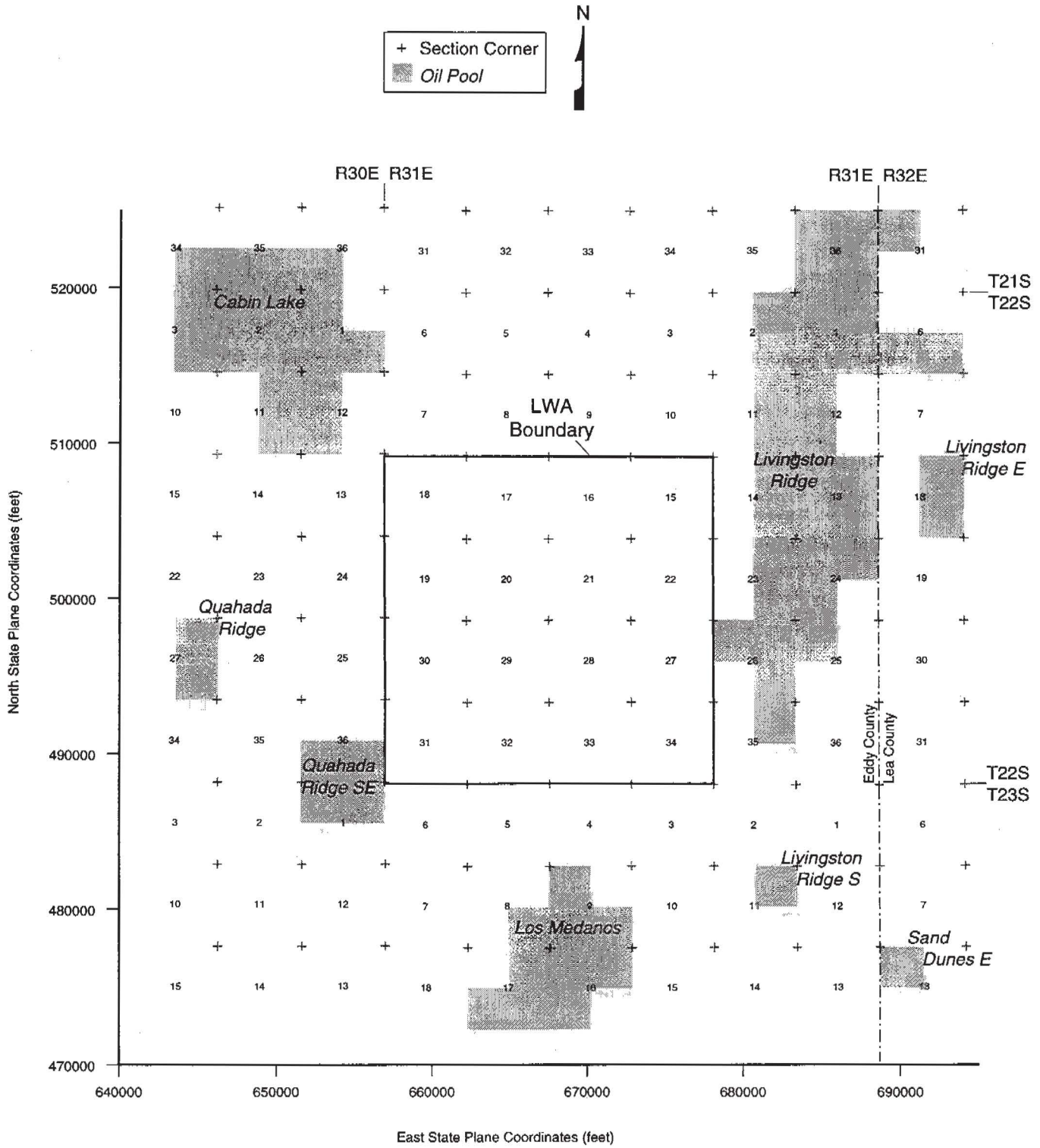

FIGURE A.7(b) Oil pools near the WIPP site, outside of the Land Withdrawal Act boundary, shown on state plane coordinates. Note that two pools abut the LWA boundary. Source: Sandia National Laboratories, unpublished. Data from the Petroleum Institute.

Appendix B

The Complementary Cumulative Distribution Function: The Risk Curve

Risk assessment, including performance assessment, has created the ubiquitous complementary cumulative distribution function (CCDF). Although some advocate a less imposing label such as "the risk curve," CCDF seems to have found its place in the risk literature as the preferred name. As shown below, the words do have mathematical meaning.

What is a CCDF? One answer is that the CCDF is an aggregated response to the triplet definition of risk noted in Chapter 2 of this report. In particular, for the Waste Isolation Pilot Plant (WIPP) performance assessment, the CCDF consists of plots on log-log graph paper of exceedance probability versus consequence. There may be several CCDFs to cover several different consequences of interest. There may also be several CCDFs for a particular consequence to indicate the range of uncertainty involved.

Most people are familiar with the concept of a bell-shaped curve as a way to convey confidence, or probability, in the value of a parameter, such as the number of curies released from an inventory of radionuclides. Such a curve tells how much of the probability is associated with intervals of curies released. This curve, called the probability density function, is the probability per unit interval of curies released. Of course such curves can be discrete, as in a histogram, or smooth, as in a continuous function (see Figure B.1[a]).

A more interesting question than the probability per release interval is referred to in risk assessment as "the exceedance question." This is the probability that the release will exceed a certain value (in the above example, exceed a certain number of curies of a particular radionuclide). This question can be answered by a summing, or integration operation, on the probability density function (Figure B.1[b]). The result of such a summation is called the cumulative distribution function. The complement—that is, one minus the parameter (here, the cumulative probability)—and the log-log scale are the additional steps taken to achieve the desired form (Figures B.1[c] and [d]). These steps result in a compact form for representing parameters that cover an extremely wide range of values.

Suppose, in the spirit of the triplet definition of risk, that a performance assessment has been conducted and a set of scenarios has been developed, each with its own probability density function of the number of curies of a particular radionuclide released. To cast the results in complementary cumulative form, the scenarios are structured in order of increasing release fractions and the probabilities are cumulated from the bottom to the top as a function of the different release fractions. Plotting the results on log-log graph paper generates a curve of the form shown in Figure B.1(d).

Figure B.1(d) does not represent reality, because it suggests that the outcome of a consequence is known with complete certainty. In practice, there are no absolutes; rather, there is significant uncertainty, starting with the uncertainties of the many individual inputs that are used to calculate a CCDF for a typical risk assessment. Thus, it is impossible to specify a single CCDF as the unambiguous outcome of a risk assessment. Instead, there are many possible CCDF curves (Figure B.2), each with its own likelihood of being correct. The spread of these CCDF curves provides a measure of the confidence with which the CCDF, for the consequence under consideration, can be estimated.

The uncertainty that gives rise to the CCDF curves in Figure B.2 is typically characterized by developing a probability distribution for each imprecisely known

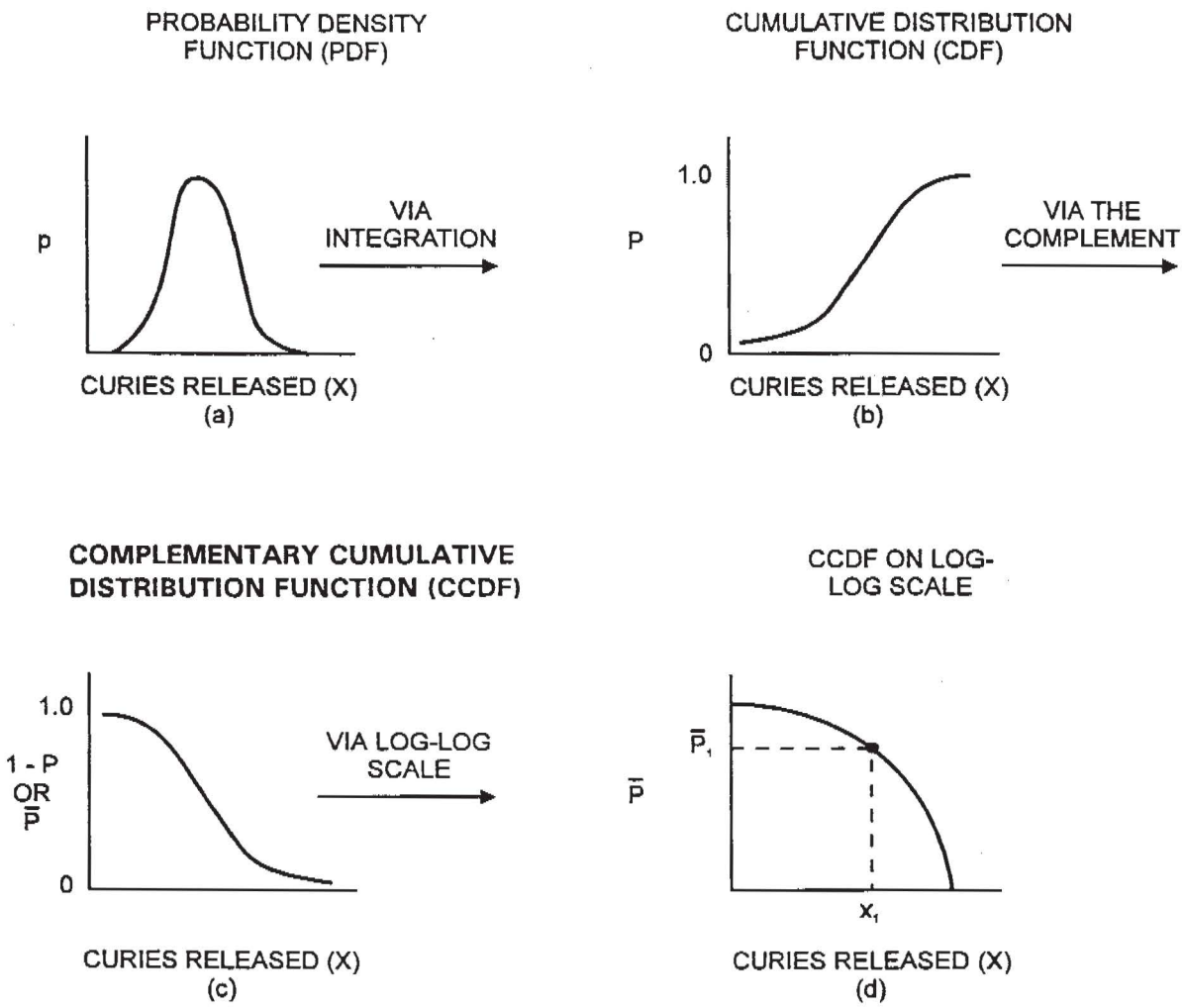

FIGURE B.1 This figure provides an exact interpretation of the parameters $\overline{P}$ and X. In particular, the CCDF representation says that the probability $\overline{P}$ of releasing x_1 curies, or more, does not exceed $\overline{P}_1$.

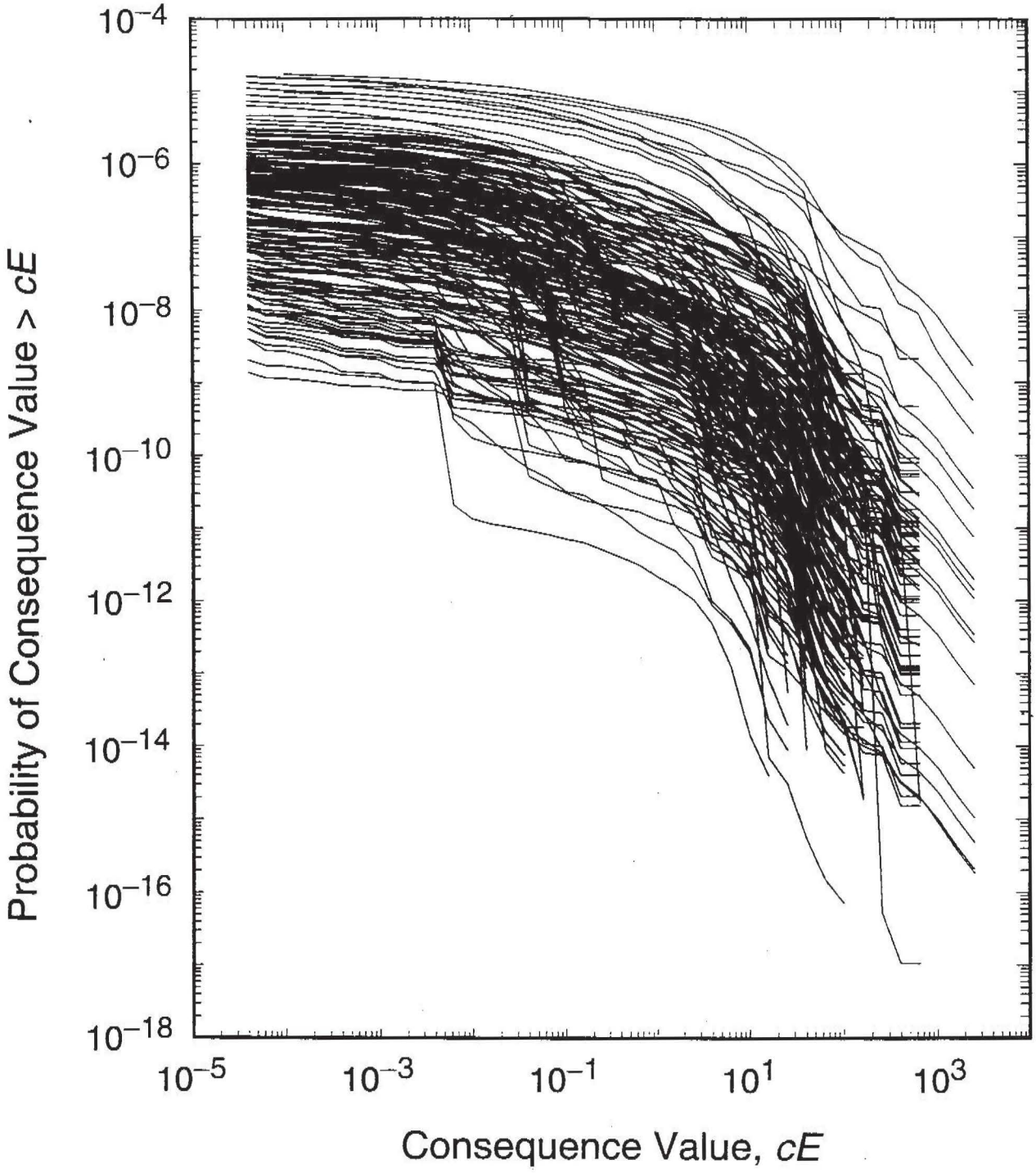

FIGURE B.2 Example distribution of CCDF curves obtained by sampling imprecisely known analysis inputs. Source: Helton et al. (1991).

input used in the analysis. These distributions mathematically describe a degree of belief, based on all the available evidence (e.g., data, background knowledge, analyses, experiments, expert judgment), of the range and weight, in terms of likelihood, of the input values used in the analysis. An example of an input might be a distribution coefficient for a radionuclide transport calculation. Such distribution coefficients cannot be assigned a fixed number because of the uncertainty of what that number should be. Thus, the input has to be in the form of a probability distribution that expresses the analyst's state of knowledge about what the number should be. It tells a much fuller story than would be provided by a single number. The CCDF curves in Figure B.2 arise from the distributions assigned to the individual inputs.

The usual computational procedure is to generate a sample (e.g., random or Latin hypercube[1]) from the uncertain inputs according to their assigned distributions and then to construct one CCDF of the form appearing in Figure B.2 for each element of this sample. With this procedure, each CCDF is constructed from a set of input values (sometimes referred to as a "realization") that is consistent with all available information. Further, the assignment of distributions to individual inputs, and the propagation of these distributions through to the distribution of CCDF curves in Figure B.2, provide a representation of the uncertainty in the final outcome of the risk assessment, where this outcome is a CCDF. Put another way, the distribution of CCDF curves in Figure B.2 provides a measure of the confidence with which the outcome of the risk assessment can be estimated. A tight grouping of CCDF curves in Figure B.2 indicates a high confidence in the estimated location of the CCDF of interest; conversely, a wide spread in the CCDF curves indicates a low confidence in the estimated location of this CCDF.

Although Figure B.2 provides a complete summary of the distribution of CCDF curves obtained by propagating the uncertainty in the individual analysis inputs, it is rather crowded and difficult to read. A less crowded summary can be obtained by plotting the mean value and selected percentiles for each consequence value on the abscissa. For example, the mean plus the 5th, 50th (i.e., median), and 95th percentile values might be used (Figure B.3). The percentile curves then provide a measure of confidence as to the location of the exceedance probabilities for individual consequence values (e.g., there is a degree of belief probability of .9 that the exceedance probability for a particular consequence value is located between the 5th and 95th percentile curves). Further, the mean CCDF, obtained by vertically averaging the individual CCDF curves in Figure B.2, provides a measure of central tendency; the 50th percentile curve provides a related, but different, measure of central tendency. However, it is the distribution of CCDF curves that provides the overall measure of confidence that can be placed in the results of the risk assessment.

The distribution of CCDF curves in Figure B.2, and hence the mean and percentile curves in Figure B.3, are typically obtained by sampling-based techniques and therefore are approximate. However, if a robust sampling procedure is used, these results should show little variation from one sample to the next (Figure B.4). In concept, the mean and percentile curves in Figure B.3 can be specified uniquely by approximately defined integrals; in practice, these integrals have to be approximated by sampling-based techniques.

[1]Latin hypercube sampling is a sampling scheme in which the probability distributions of the input variables are discretized into intervals of equal probability. The advantage of Latin hypercube sampling is claimed to be greater accuracy due to the more detailed sampling of regions of higher probability.

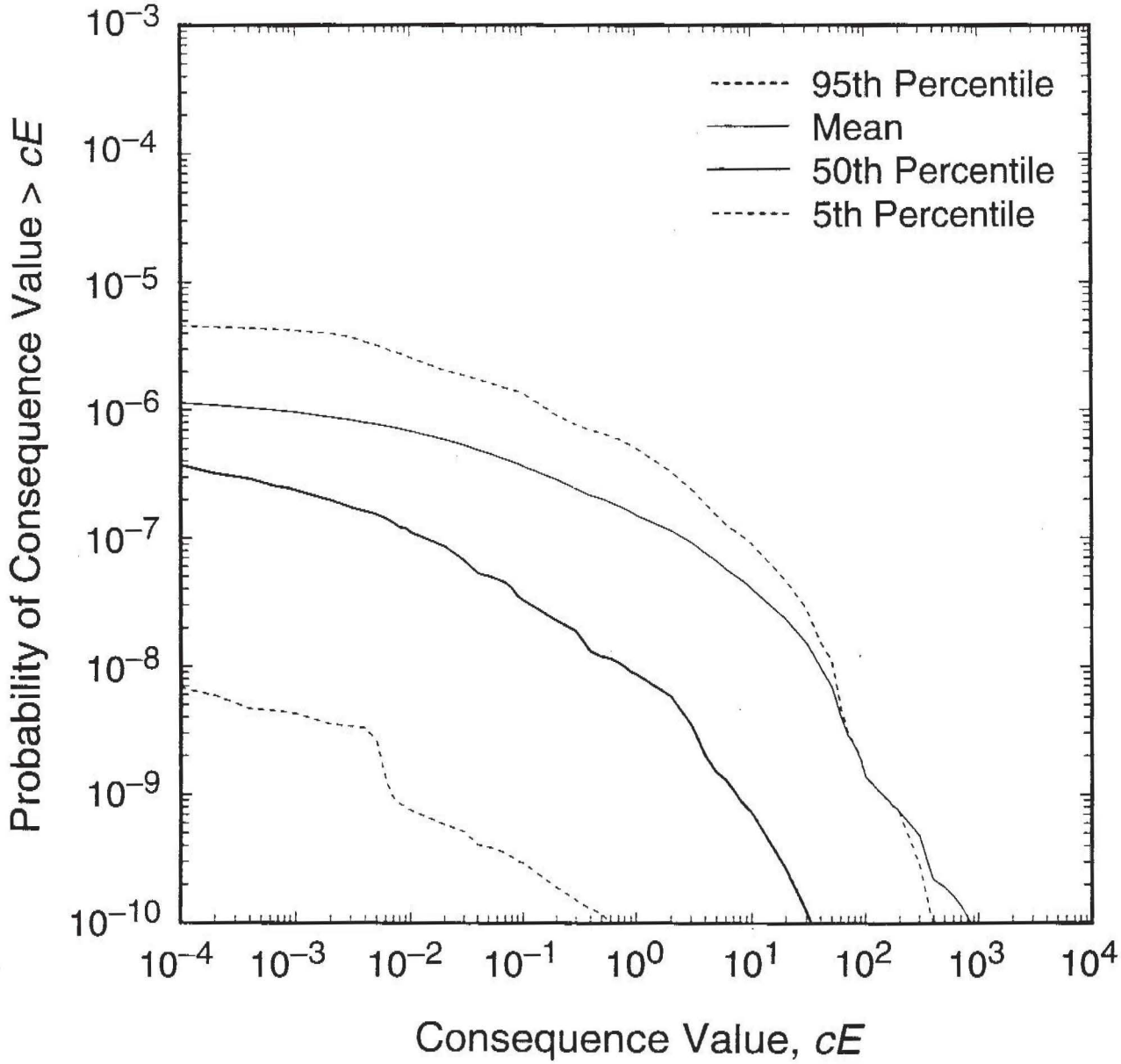

FIGURE B.3 Example summary curves derived from an estimated distribution of CCDF curves. The curves in this figure were obtained by calculating the mean and the indicated percentiles for each consequence value on the abscissa in Figure B.2. Source: Helton et al. (1991).

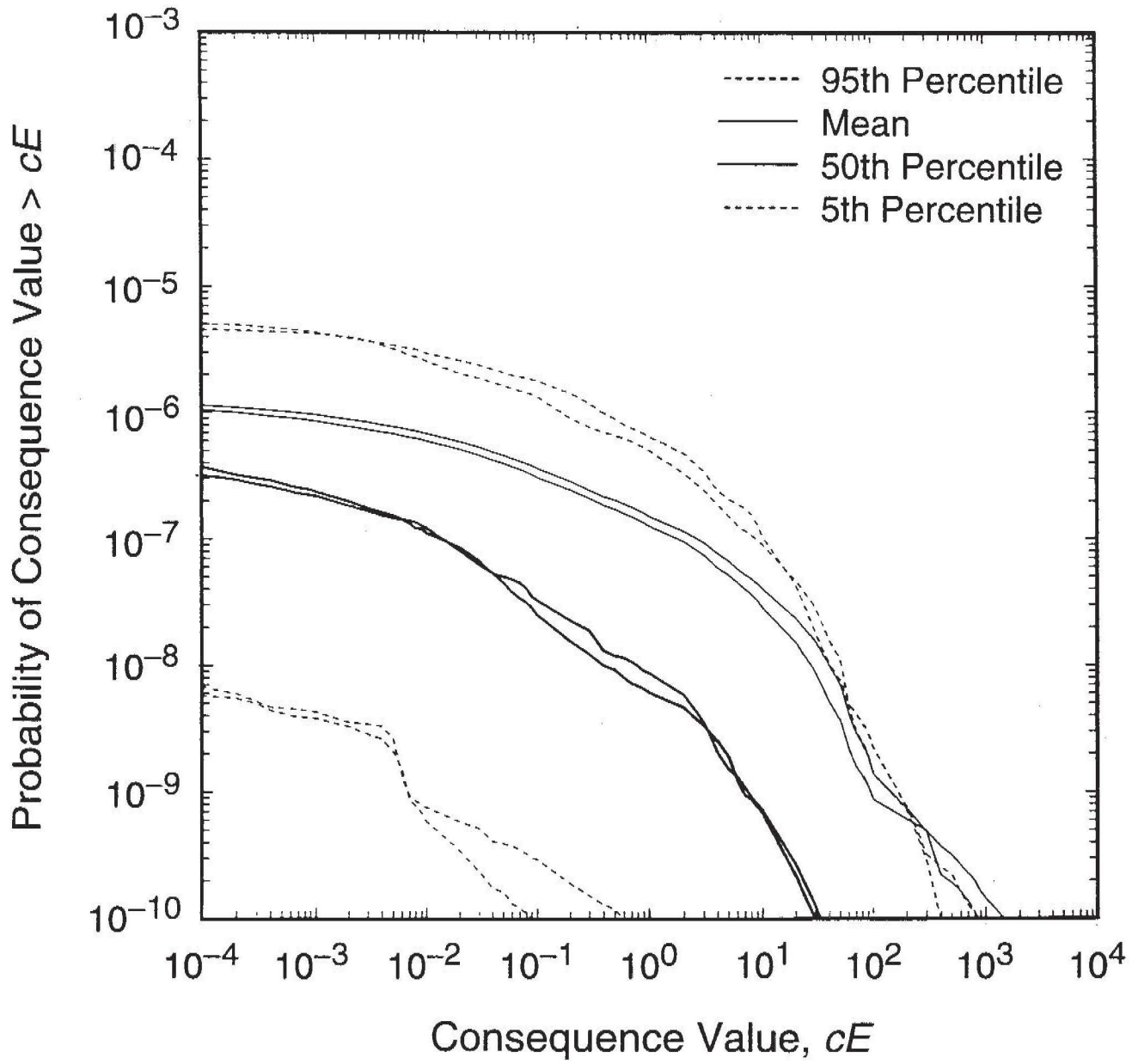

FIGURE B.4 Example of mean and percentile curves obtained with two independently generated samples for the results shown in Figure B.3. Source: Helton et al. (1991).

Appendix C

Brine Inflow to Excavations in the Salado

PERMEABILITY OF WIPP SALT ANHYDRITE AND INTERBEDS

Observation of brine seeps into excavations (both tunnels and boreholes) at the WIPP has led to the assumption that the Salado salt has a finite, but extremely low (~ 10^{-21} – 10^{-23} m^2) permeability in the classical sense of Darcy flow. There are several inconsistencies in this model. An alternative model in which undisturbed salt is assumed to contain brine only in unconnected porosity appears in better agreement with underground observations at WIPP. In this model, "damage" to the salt (i.e., development of the disturbed rock zone, DRZ) resulting from introduction of the excavation, leads to the development of a local zone of interconnected porosity characterized by a finite permeability. It is the release of the brine in the previously unconnected pores by the stress-induced damage that produces the brine seeps—at least in the initial stages (Borns, 1995).

McTigue (1995a,b) has examined this alternative model in detail. he notes:

> *Data for flow to boreholes in WIPP Room D are represented well qualitatively by the classical model. However, the capacitance indicated by fitting model calculations to the field data is orders of magnitude larger than that expected on the basis of the compressibilities of salt and brine. That is, the decay of the brine flux into the boreholes takes place over a time scale that is much too long to be explained in terms of the processes assumed in the development of the classical model. The classical model invokes an unbounded domain of interconnected porosity. This concept is contradicted by both mechanical arguments and geochemical observations. (McTigue 1995b).*

The mechanical arguments from the same reference point out that salt creeps at vanishingly small deviatoric stress (i.e., stress difference). Thus, over long time frames, interconnected porosity can not be sustained. Brine will be confined to local domains of isolated porosity containing fluid at a pressure equal to (minus) the mean [i.e., lithostatic] stress in rock.

Geochemical observations, however, indicate that

> *...brine chemistry is highly variable, even among samples separated by distances of the order of tens of centimeters. If these brines were derived from an interconnected pore network, one would expect that molecular diffusion would have eliminated any significant contrasts in brine composition over the very long existence of the formation....Over a period of 230 Ma the diffusion length, L_a, is...of the order of hundreds of meters. The observation that compositional differences persist in the brines over short length scales and very long time, then, suggests strongly that the brine in undisturbed salt is local, isolated domains. (McTigue, 1995b)*

McTigue (1991) later analyzes brine seepage rates into Room Q and again concludes that this experiment confirms the view that undisturbed salt is impermeable.

Borns (1995) notes that measured changes in the electrical resistivity in the DRZ around Room Q indicate an initial desaturation (as the DRZ develops)

followed by a resaturation over a period of approximately three years. This could suggest that Darcy flow may occur in the salt, but it could also be the result of the progressive development of the DRZ, which eventually connects the anhydrite layers hydrologically to the room excavation.

The McTigue and Borns observations can be reconciled by a model in which classical Darcy flow occurs in the anhydrite marker beds (e.g., MB 139), but the salt between these layers is impermeable.

The following calculations indicate the order of magnitude of brine inflow predicted on the basis of assuming

1. an impermeable salt containing anhydrite interbeds that exhibit Darcy flow;
2. salt with a small, but finite, permeability, allowing classical Darcy flow radially into a circular excavation. (In this case, the permeable interbeds are assumed to be an integral part of the homogeneously permeable salt.)

ONE-DIMENSIONAL FLOW IN ANHYDRITE INTERBEDS IN IMPERMEABLE SALT

The instantaneous rate of fluid inflow q, at some time t, per meter of tunnel length* from a horizontal permeable layer (Figure C-1), thickness d and of infinite extent (one-dimensional flow) can be calculated (Churchill, 1972) from the formula shown in (C-1):

$$q = kd\frac{\phi_0}{\sqrt{\pi ct}} \qquad \text{(C-1)}$$

where $k = \kappa\rho g/\mu$ is the brine conductivity, d is the thickness of the layer, ϕ_0 is the initial head, and $c = k/S_s$ is the diffusivity. (Other symbols are defined in Tables C-1 and C-2.) In the case of a constant head at a finite distance L from the tunnel along the layer, the instantaneous rate of inflow can be written (Churchill and Brown, 1987) in dimensionless form:

$$\bar{q} = 2\sum_{m=0}^{\infty}\exp\left(-m^2\pi^2\tau\right) - 1 \qquad \text{(C-2)}$$

where $\bar{q} = Lq/dk\phi_0$ and $\tau = tc/L^2$. The dimensionless rates of inflow, from an infinite layer and from a layer with a fixed head at the finite distance L, as a function of dimensionless time, are shown in Figure C-2.

The total inflow Q per meter of the tunnel—one side of the tunnel only—from an infinite layer can be obtained by integrating (C-1):

$$Q = \int_0^t q(t)\,dt = 2dk\phi_0\sqrt{\frac{t}{\pi c}} \qquad \text{(C-3)}$$

The curves shown in Figure C-3 are calculated by using the parameters for an anhydrite layer in salt, as shown in Table C-1. Total inflows (C-1) from an infinite layer for the base case mentioned above and two cases used by McTigue (1991) (parameters shown in Table C-2) are compared in Figure C-4.

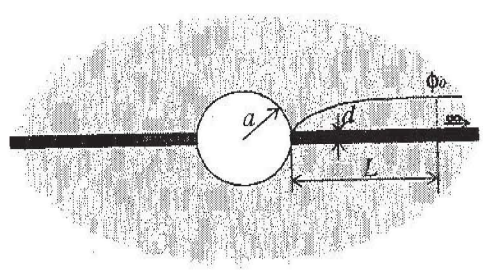

Figure C-1: Model of one-dimensional flow.

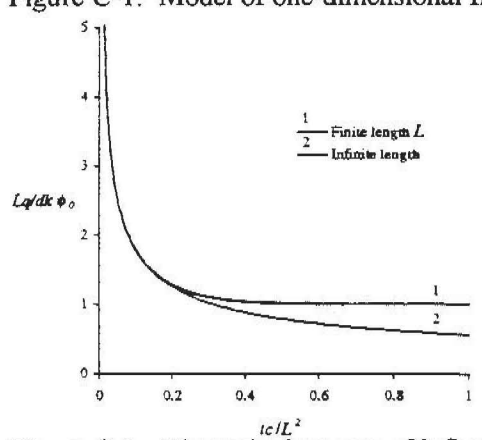

Figure C-2. Dimensionless rate of inflow from one side of a permeable layer.

* Only one side of the tunnel is considered–the total inflow into the tunnel would be double the values shown in equations (C-1), C-2), and (C-3). The remainder of the rock mass is assumed to be impermeable.

permeability	κ	10^{-18}	(m^2)
brine viscosity	μ	$1.8 \cdot 10^{-3}$	(Pa·s)
specific weight	ρ	1230	(kg/m^3)
initial head	ϕ_0	650	(m)
fixed head distance	L	1000	(m)
layer thickness	d	1	(m)
specific storage	S_s	$1.5 \cdot 10^{-7}$	(1/m)
conductivity	k	$6.69 \cdot 10^{-12}$	(m/s)
diffusivity	c	$4.45 \cdot 10^{-5}$	(m^2/s)

Table C-1. Base case values of parameters used to calculate brine inflow into a tunnel from a horizontal anhydrite layer.

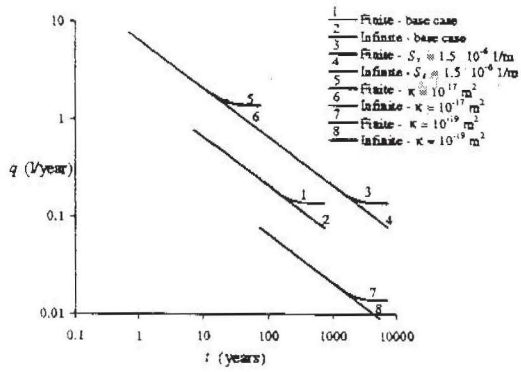

Figure C-3. Rates of inflow from the anhydrite layer (per meter of length along the tunnel). (The rates shown are for one side of the tunnel only, i.e., total inflow rates are double those shown).

	Base case	McTigue case 1	McTigue case 2	
κ	10^{-18}	10^{-21}	10^{-22}	(m^2)
μ	$1.8 \cdot 10^{-3}$	$1.60 \cdot 10^{-3}$	$1.60 \cdot 10^{-3}$	(Pa s)
ρ	1230	1230	1230	(kg/m^3)
ϕ_0	650	815	815	(m)
d	1	1	1	(m)
k	$6.69 \cdot 10^{-12}$	$7.67 \cdot 10^{-15}$	$7.67 \cdot 10^{-16}$	(m/s)
c	$4.45 \cdot 10^{-5}$	$6.20 \cdot 10^{-8}$	10^{-10}	(m^2/s)

Table C-2. Values of parameters used in "base case" and by McTigue to calculate brine inflow from an anhydrite layer into a tunnel.

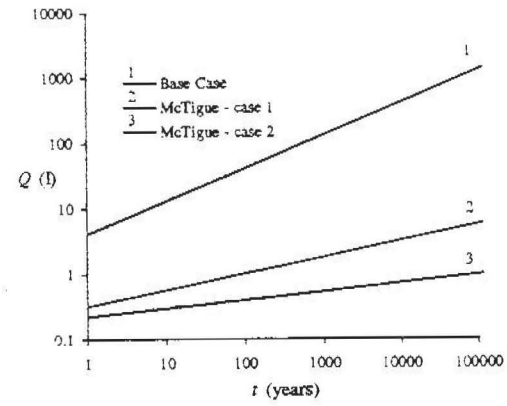

Figure C-4. Total inflow into a tunnel from an anhydrite layer (one side of tunnel only).

RADIAL FLOW INTO EXCAVATIONS IN PERMEABLE SALT

The Laplace transform of the instantaneous rate of inflow $\tilde{q}$ into a circular opening in an infinite, homogeneous, porous medium (Figure C-5) is as follows (Detournay and Cheng, 1988):

$$\tilde{q} = 2\pi a \phi_0 k \frac{K_1(a\sqrt{s/c})}{\sqrt{sc}\, K_0(a\sqrt{s/c})} \qquad \text{(C-4)}$$

where K_0 and K_1 are the modified Bessel functions of the second kind, of order zero and one respectively.

Inversion of (C-4) is performed numerically. The total inflow Q (per meter along the tunnel) for $k = 6.25 \cdot 10^{-14}$ m/s (corresponding to $\kappa = 10^{-20}$ m^2), radius of tunnel $a = 1.524$ m, and an initial hydrostatic pressure $p_0 = 6$ MPa, is shown in Figure C-7.

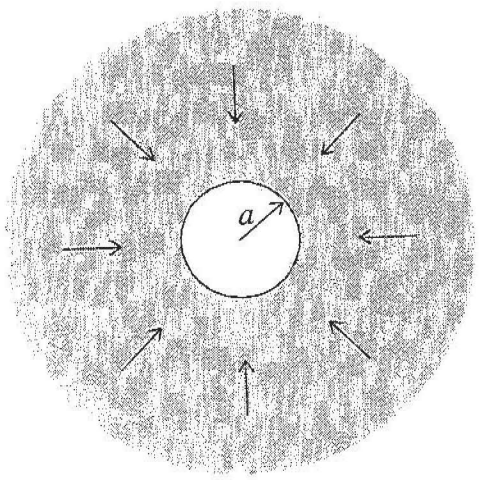

Figure C-5. Model of radial flow into circular tunnel.

BREDEHOEFT CALCULATION (BREDEHOEFT, 1988)

Around 1987, observations of brine inflow into underground excavations at the WIPP led Dr. J.D. Bredehoeft, then a member of the NRC WIPP committee, to suggest that the Salado formation at WIPP could have finite, albeit low, permeability in the classical Darcy sense and that the Salado was possibly saturated with brine. In defining the Salado, he (Bredehoeft, 1988) did not distinguish between the salt and anhydrite interbeds. He calculated, numerically, the daily brine inflow into rectangular excavations for several assumed values of hydraulic conductivity k. [For WIPP brine the intrinsic permeability κ (m^2) = $0.16 \cdot 10^{-6} k$ (m/s). Thus $k = 6.25\ 10^{-14}$ m/s corresponds to $\kappa = 10^{-20}$ m^2, etc.].

Figure C-6 compares Bredehoeft's results (curves 1-4) with those obtained analytically by using (C-4). It is seen that the two sets of results are consistent. The principal difference is due to the higher range of brine conductivities assumed by Bredehoeft. The values used in the current calculations are based on more recent values used by DOE.

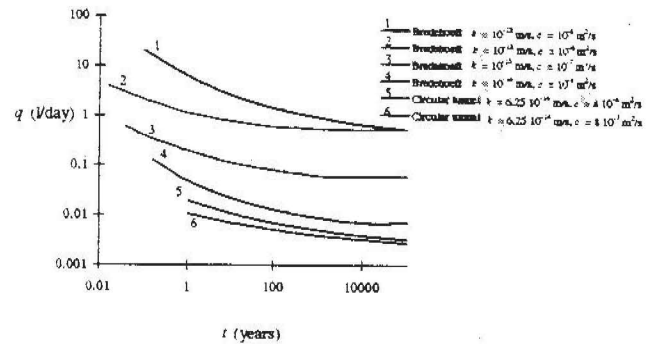

Figure C-6. Rates of inflow into tunnel, as calculated numerically by Bredehoeft (curves 1 to 4) and analytically)(curves 5 and 6).

Using a Darcy flow model to interpret recent in-situ measurements, Beauheim et al., (1993a) conclude that "*the vertically averaged hydraulic conductivities of the tested intervals (primarily anhydrite interbeds) range from about $1 \cdot 10^{-14}$ to $2 \cdot 10^{-12}$ m/s (permeabilities of $2 \cdot 10^{-21}$ to $3 \cdot 10^{-19}$ m^2). Storativities of the tested intervals range from about $1 \cdot 10^{-8}$ to $2 \cdot 10^{-6}$ and values of specific storage range from $9 \cdot 10^{-8}$ to $1 \cdot 10^{-5}$ 1/m. ...*" Anhydrite interbeds appear to be one or more orders of magnitude more permeable than the surrounding halite, primarily because of sub-horizontal bedding-plane fractures present in the anhydrites.

Freeze and Christian-Frear (in preparation) attempting to interpret the brine inflow results for Room Q, indicate that a value of "*far-field permeability of $5 \cdot 10^{-22}$ m^2 with a bulk rock compressibility of $5.4 \cdot 10^{-12}$ 1/Pa*" fits the apparent brine inflow rates from two to five years. Interpretation was complicated by the absence of very early time (0-6 months) brine inflow data—due to malfunctioning of the room seals. Thus, it seems that the hydraulic conductivity of (i) Salado halite (interpreted in terms of Darcy flow model) is of the order of 10^{-13} to 10^{-16} m/s (permeability 10^{-20} to 10^{-23} m^2) and (ii) anhydrite interbeds is 10^{-12} to 10^{-14} m/s (permeability 10^{-19} to 10^{-21} m^2). Since the anhydrite interbeds are relatively thin layers within the halite, an overall value for conductivity (permeability) of the Salado would tend to be at the lower end of the combined anhydrite—halite

range (i.e., say 10^{-14} m/s), resulting in the inflows in the range of curves 4, 5, and 6 in Figure C-6.

Figure C-7 shows the total inflow per meter length of excavation for the lower permeability results (curves 5 and 6) shown in Figure C-6. It is seen that after 100 years, a total of about 200 liters (or 0.3 m^3) of brine has flowed into the excavation. If a 10-m excavation width (or "width" of waste material) is assumed, this amount of brine would occupy a height of 2 cm over the 10-m width. If the compacted waste is assumed to occupy 70% of the original space (i.e., leaving 30% voids), then the height of brine would increase to (2/0.3) cm, or approximately 6 cm of the height of compacted waste. However, since the DRZ would exist for at least a substantial part of the 100 years, then much of this brine would gravitate into the fractured rock in the DRZ underlying the waste. Brine from MB 139, below the excavation, would also flow into the same fractured rock below the floor. It seems probable, therefore, that much of the brine will not come into contact with the waste but instead will flow down-gradient in the DRZ below the waste. This suggests that with appropriate repository design, rooms could be maintained in a "brine humid" condition rather than a "brine-flooded" condition. According to Brush, gas generation caused by corrosion of the steel waste drums in brine humid conditions is negligibly small.

Should there be a more significant rate of gas generation, pressure in the rooms would tend to rise, thereby reducing brine inflow—and the associated gas generation rate. Although it is possible, under some conditions, for gas to flow out of the room [e.g., along the (finite permeability) marker beds] at the same time as brine flows in, a recent DOE study by Webb and Larson (1996) indicates that such "counter-current" flow is unlikely for the 1° dip of the marker beds at the WIPP until the gas pressure in the excavation is close to lithostatic pressure. Any gas at lower pressure will directly reduce the hydraulic pressure differential and, hence, reduce the brine inflow into the excavation as well. This, in turn, will limit corrosion and the associated gas generation. If the gas pressure reaches (and "attempts" to exceed) lithostatic, the permeability of the anhydrite interbeds would increase substantially since fracturing of the interbeds would occur and counter-current flow (gas out, brine in) in the 1° updip section of the anhydrite interbed would result in increased brine inflow into the excavation. From curves presented by Webb and Larson (1996) in inflow appears to be or the order of twice the inflow rate observed for the unpressurized (i.e., open) excavation. With the low brine inflows calculated earlier and the associated low gas generation rates, it seems unlikely that gas pressure could approach lithostatic before the waste-filled excavations had closed to their residual (compacted) volumes.

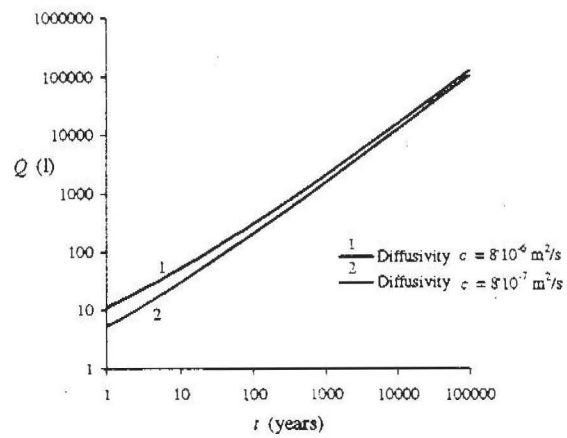

Figure C-7. Total inflow into a tunnel, if radial flow is assumed.

SHAFT SEALS – APPROXIMATE CHECK ON PA FLOW CALCULATIONS

If Darcy flow is assumed,

$$q = -kA\frac{d\phi}{dl} \qquad \text{(C-5)}$$

where q is the volumetric flow rate (m^3/s), k is the hydraulic conductivity of the (porous) seal (m/s), dl is the length (m) across which $d\phi$ (m) is measured, and A is the cross-sectional area (m^2) normal to the flow direction.

The hydraulic conductivity may be determined from the properties of the porous (seal) material and the saturating fluid. Thus,

$$k = \frac{\kappa \rho g}{\mu} \tag{C.6}$$

where κ is the intrinsic permeability of the porous (seal) material (m^2); ρ is the fluid density (kg/m^3); g is the gravitational acceleration (m/s^2); and μ is the fluid viscosity[Pa·s].†

The term "hydraulic conductance" C (m^2/s) is sometimes used, where

$$C = \frac{kA}{L} \tag{C.7}$$

and L is the length of the porous material (i.e., the shaft seal in this case).

$$q = -C \cdot \phi \tag{C.8}$$

where ϕ is the fluid pressure (head) differential (m) over the length L, and

$$v_z = \frac{q}{A} = \frac{C}{A}\phi \tag{C.9}$$

where v_Z is the Darcy velocity‡ or specific discharge (m/s) of the fluid in the porous medium (seal) with a head differential of ϕ (m).

Using PA assumed values (i.e., a shaft seal length L = 100 m; total area of the four shaft seals A = 100 m^2; seal permeability κ of $1 \cdot 10^{-16}$ m^2; brine viscosity of 0.0018 Pa·s; fluid density of 1230 kg/m^3; and gravitational acceleration of 9.792 m/s^2), yields (U.S. Department of Energy, 1995d, p. 5):

$$\begin{aligned} C &= \frac{\kappa A}{L}\frac{\rho g}{\mu} = \frac{10^{-16} \cdot 100}{100}\frac{1.23 \cdot 10^3 \cdot 9.792}{18 \cdot 10^{-4}} \\ &= 6.7 \cdot 10^{-10}\ \mathrm{m^2/s} \text{ or } 211.3\ \mathrm{m^2/10^4\ years} \\ v_z &= 2.1 \cdot \phi\ \mathrm{m/10^4\ years} \\ q &= 211.3 \cdot \phi\ \mathrm{m^3/10^4\ years} \\ & \left[10^4\ \mathrm{years} \simeq 3.15 \cdot 10^{11}\ \mathrm{s}\right] \end{aligned}$$

At the time the seal is first installed, the repository will be essentially dry and fluid flow through the seal initially will be downward—primarily from the Rustler formation overlying the Salado. Flow upward through the seal will begin only when the fluid pressure exerted at the bottom of the shaft seal exceeds the hydrostatic pressure due to the height of water in the shafts.

The predicted change in pressure with time at the shaft bottom will depend on a complex interaction of several repository variables, such as the total amount of void space in the waste-filled rooms and all of the (back-filled or open) excavated space; rate of reduction in void space due to salt creep; rate of inflow of brine into the void space; rate of gas generation and room pressurization; loss in fluid pressure due to fluid flow from the waste-filled rooms to the bottom of the seal, etc. Depending on the particular combination of assumed values of these variables used in a calculation, the brine pressure at the shaft bottom may remain very small for a long time after sealing or may increase after a period of the order of several hundreds of years, when gas generated by brine corrosion of the steel waste containers develops an increasing pressure in the repository.

The relationship between seal permeability and flow through the seal over a given time [Eq. (C.8)] is linear, so the net cumulative flow, over a period of time through a seal of a given permeability can be determined simply from the average driving fluid pressure [i.e., the pressure ϕ above hydrostatic at the bottom of the seal over the same time (This is 650 m for the water-filled shaft.)]. If the pressure ϕ is initially below hydrostatic (i.e., negative), then flow during this period will be negative, that is, downward through the seal.

† Pa·s = $(N/m^2)\cdot s = (kg_{mass}\cdot m/s^2)\cdot s/m^2 = kg_{mass}/m\cdot s$.

‡ See discussion of Darcy velocity.

It is seen from (C-8) that the net cumulative flow over 10,000 years through a shaft seal of assumed permeability 10^{-16} m^2 will be 10,000 m^3, if the average (over 10,000 years) pressure head ϕ at the shaft bottom is $\phi = 10{,}000/211 = 40$ m (above hydrostatic). For a seal of permeability of 10^{-17} m^2, the average pressure head required to produce a cumulative upward flow of 10,000 m^3 over 10,000 years will be $\phi = 470$ m above hydrostatic—(650 m) or a total average brine pressure head of 110 m. Similarly, for a seal permeability of 10^{-18} m^2, a total average pressure head of 1120 m would produce a net cumulative brine outflow of 1,000 m^3 in 10,000 years.

Figure 4.1 in Chapter 4 of this report shows the results of a number of calculations—each for a randomly chosen combination of repository parameter values (closure rate, brine inflow rate, etc.)—of the cumulative brine flow through the seals over 10,000 years, as a function of seal permeability. It is seen that, especially at the higher permeabilities, flow *into* the repository (i.e., the negative values) tends to be more likely. For a permeability of 10^{-16} m^2 or lower, the net flow is essentially zero.

Creep of the salt around the shaft will result in further consolidation of the 100-m-high seal of crushed, compacted salt, so that the permeability of the seal will tend eventually towards the permeability of intact salt. As noted above, intact pure salt likely to be impermeable. Where intact salt is assumed to have a finite permeability, this is usually taken as about 10^{-21} ~ 10^{-23} m^2. Calculations indicate (Callahan et al., 1996) that a seal of crushed salt at a depth between 550 m ~ 650 m, initially compacted to a permeability about 10^{-16} m^2 is likely to achieve a permeability of 10^{-20} m^2 or so within 100 years after placement.

Thus, it appears that seals consisting of 100-m-high layers of compacted crushed salt should provide an effective barrier to release of radionuclide contaminated brine to the accessible environment over 10,000 years or longer.

The height to which the brine would rise above the seals depends on the average porosity of the material in the shaft (see discussion of Darcy flow below). Thus, if the shaft above the seal was left completely open and the (total) cross-sectional area (of the shafts) was assumed to remain constant at 100 m^2, a cumulative brine flow of 10,000 m^3 would create a brine column 100 m high above the seal. If the average porosity of the material in the shaft was 1%, the brine would rise, hypothetically, 100 times higher. In the case of WIPP, the brine would rise to the top of the Salado and then would be able to flow laterally into the Culebra.) In both cases, the *total* volume of brine outflow would be essentially unchanged. For a given concentration of raduonuclides in this same volume of brine, the radionuclide release will also be the same, independent of the porosity of the material through which it flows.

Darcy Velocity

The Darcy velocity (or specific discharge) is the volumetric rate of flow per unit area through which flow occurs. Hence, it has the same dimensions as velocity, but it is not the speed at which the fluid moves. To derive the average fluid velocity in the pore space from the Darcy velocity, it is necessary to divide the latter by the effective porosity of the rock through which flow occurs (i.e., if the effective porosity of the rock is 10% of the total volume of the rock, the average fluid velocity in the pores is ten times the Darcy velocity). The volume of fluid flowing across the cross-section over a given time, which is the relevant quantity for determination of radionuclide flow through the seals (i.e., this is strictly not a "release", since there are additional barriers, such as upper levels of the shaft and the Culebra, between the seals and the accessible environment)—given a known radionuclide concentration in the fluid—is the same for both calculations, that is, with or without porosity.

Conclusion

These approximate calculations confirm the general impression that effective sealing of the repository is achievable using the designs proposed by DOE.

Appendix D

Creep Behavior of WIPP Salt

One of the main attributes of salt as a rock formation in which to isolate radioactive waste is the ability of the salt to creep, that is, to deform continuously over time. Excavations into which the waste-filled drums are placed will close the salt eventually, flowing around the drums and sealing them within the formation. A good understanding of the rate of closure and associated phenomena, such as the development and healing of fractures around the excavations, is essential for the design of an effective repository in salt.

The program of investigations into the mechanics of deformation of salt at the Waste Isolation Pilot Plant (WIPP) has been more extensive and comprehensive than any previous studies world-wide. Carried out over the past decade and a half, it has included theoretical studies coupled with small-scale laboratory tests and full-scale field investigations underground at WIPP.

Initial predictions of the rate of closure of underground excavations—based on deformation parameters derived from laboratory tests—were found to be some three to six times lower than the closure rates observed underground. Continued research to improve fundamental understanding has resulted in a very substantial reduction in this discrepancy. Thus, for the majority of the in situ cases studied, agreement between the closure rates predicted from small-scale laboratory test data and those actually observed is now within approximately 10 percent. Larger discrepancies can be attributed, in some cases, to exclusion of the following from the three-dimensional numerical codes used for the predictions:

- discrete slip surfaces (e.g., between the salt and anhydrite interbeds) in the vicinity of the excavations, and
- separation of interbeds and salt layers in the roof of the excavations.

These limitations are not serious for the assessment of closure performance of the excavations at WIPP since, in both cases, actual closure will somewhat exceed the predicted value. Thus, predictions will be conservative.

Although salt deformation appears to involve a complex interaction of a multiplicity of microscopic mechanisms, these combine to produce a relatively simple, essentially constant rate of room closure (Figures D.1 and D.2).

As shown in Figure D.3, the strain-time behavior of salt can be considered to consist of several regions, namely, ε_E, an elastic strain, which appears immediately upon loading (the amount of elastic strain increases with increase in the applied stress); this is followed by

1. a region of primary or transient creep strain;
2. a region of secondary or "steady-state creep" (where the strain rate $\dot{\varepsilon}_p$ is essentially constant); and
3. a region of tertiary or "accelerating creep" strain.

Accelerating strain indicates a progressive disintegration of the salt structure, leading eventually to collapse.

It is well known that the strain rates involved in salt creep increase in a highly nonlinear manner with increases in temperature and applied stress.

An extensive series of laboratory investigations has led to the definition of a new constitutive model (i.e., relationship between steady-state creep rate and applied load) for WIPP salt. This model is known as the modified Munson-Dawson or multimechanism deformation (M-D) constitutive model.

In the M-D model, the total steady-state creep rate ($\dot{\varepsilon}_s$) is considered to be the sum of three component rates, each dependent on a different fundamental mechanism to creep in the salt: Thus

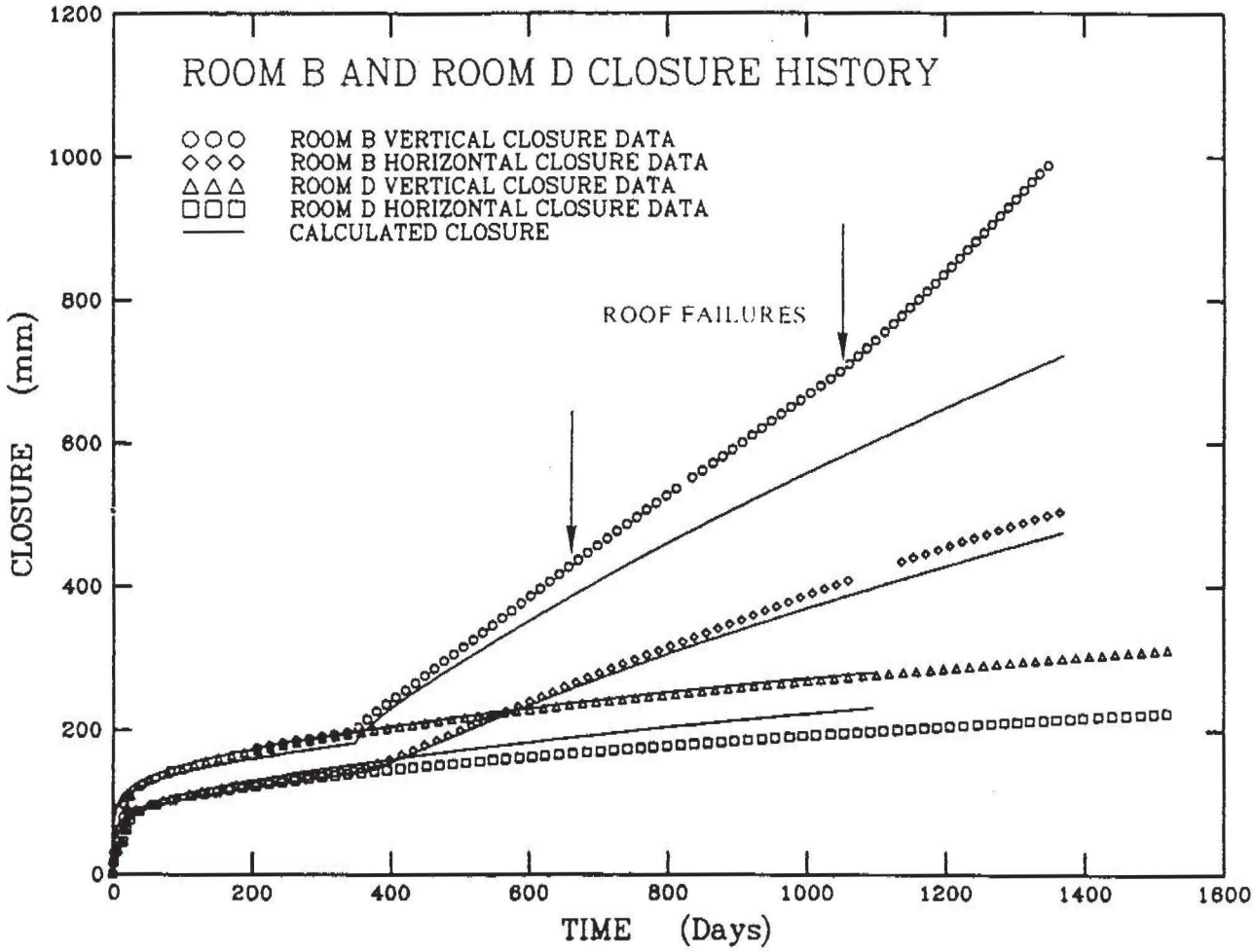

FIGURE D.1 Comparison between predicted and actual room closure rates for Rooms B and D. Note the increase in measured closure compared to calculated closure as roof failures develop. Source: Munson (1996).

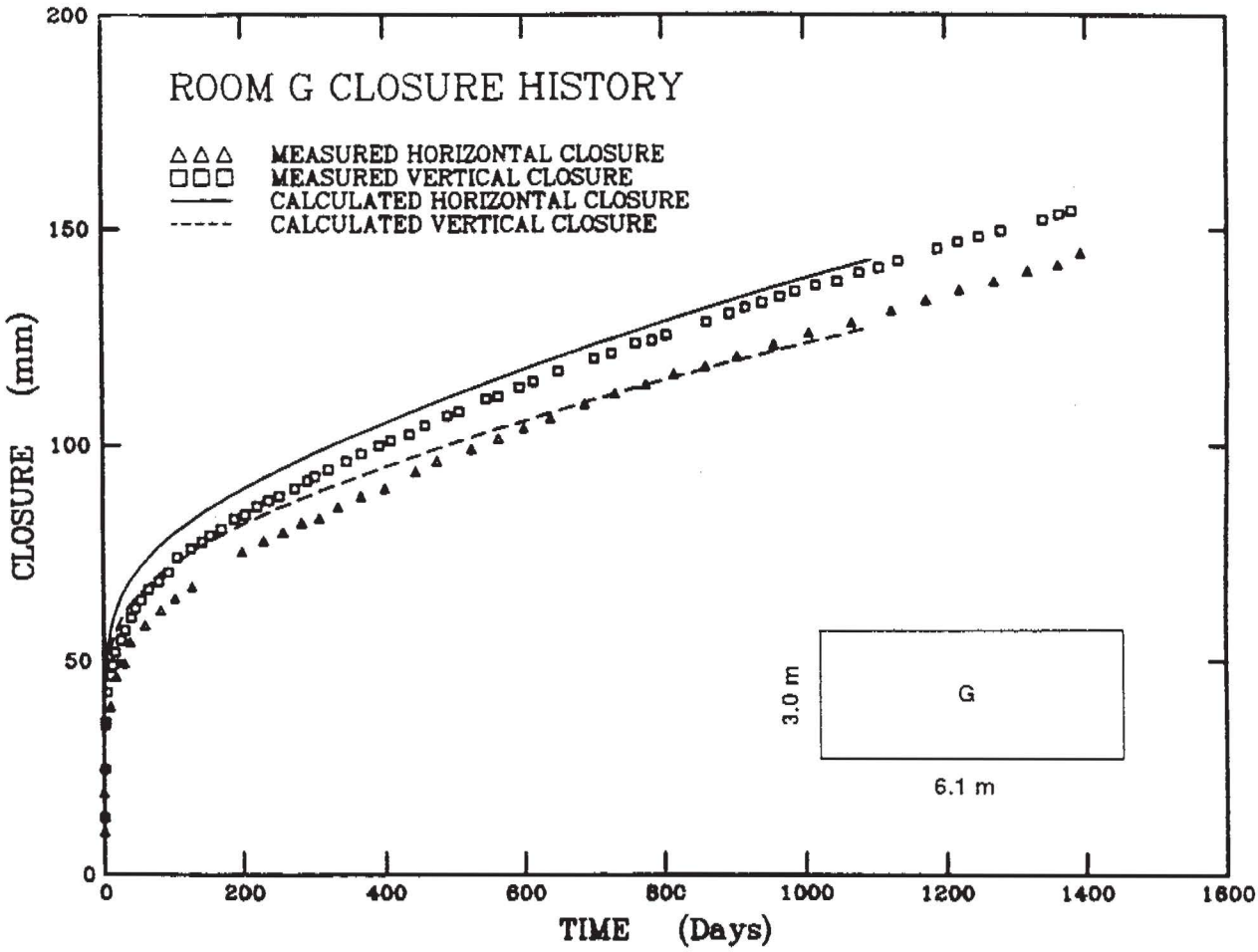

FIGURE D.2 Comparison between predicted and actual room closure rates for Room G. Source: Munson (1996).

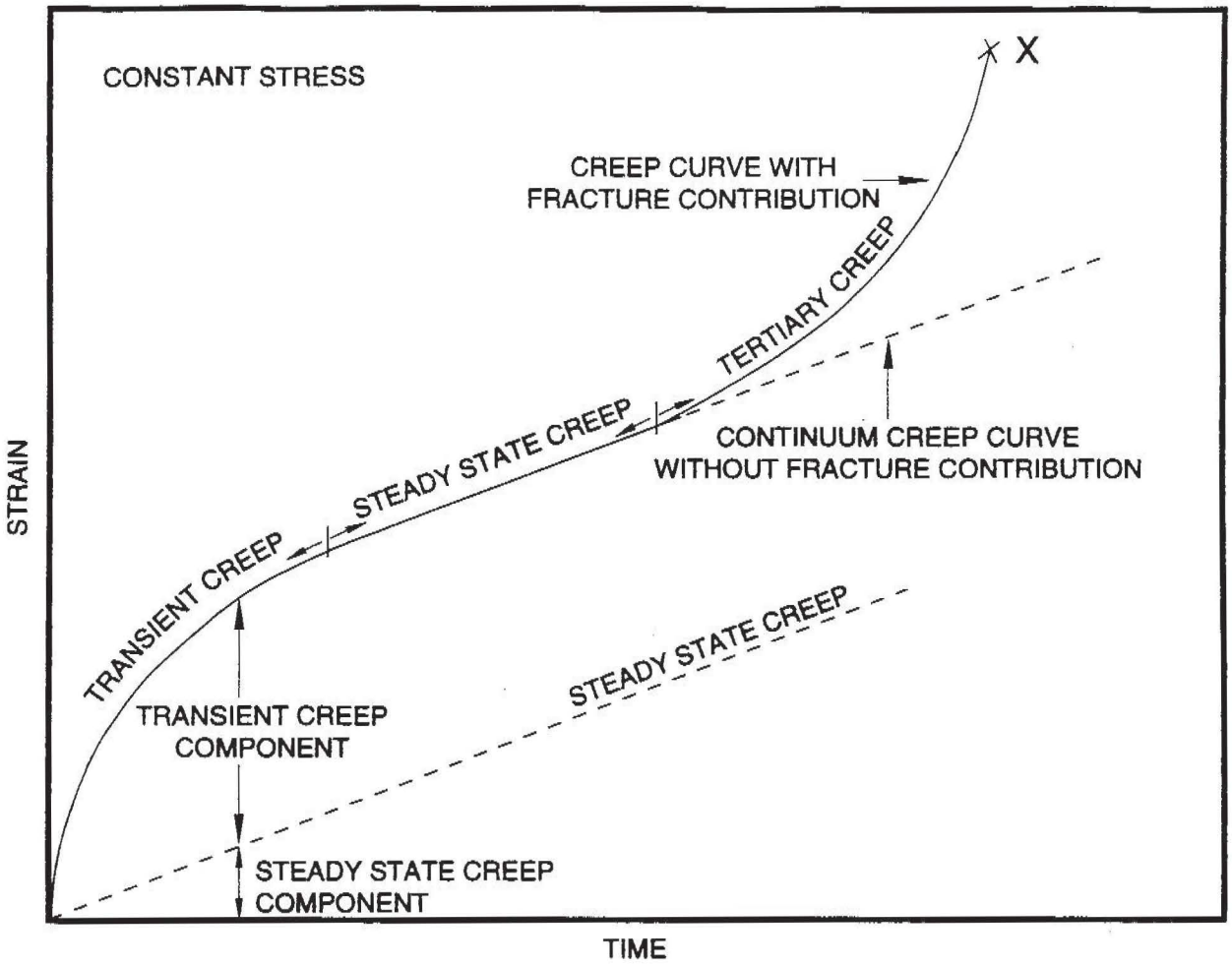

FIGURE D.3 Classical creep-deformation behavior of salt. Source: Munson et al. (1995).

$$\dot{\varepsilon}_s = \sum_{i=1}^{3} \dot{\varepsilon}_{s_i} \tag{1}$$

where the individual steady-state rates of the three relevant mechanisms are given by

$$\dot{\varepsilon}_{s_1} = A_1 e^{-Q_1/RT} \left(\frac{\sigma}{\mu}\right)^{n_1} \tag{2a}$$

$$\dot{\varepsilon}_{s_2} = A_2 e^{-Q_2/RT} \left(\frac{\sigma}{\mu}\right)^{n_2} \tag{2b}$$

$$\dot{\varepsilon}_{s_3} = H(\sigma - \sigma_0)\left[B_1 e^{-Q_1/RT} + B_2 e^{-Q_2/RT}\right] \sinh\left[\frac{q(\sigma - \sigma_0)}{\mu}\right] \tag{2c}$$

where A and B are constants; Q is the activation energy; T is the absolute temperature; R is the universal gas constant; μ is the shear modulus; σ is the generalized stress; n is the stress exponent; g is the stress constant; σ_0 is the lower stress limit of the dislocation slip mechanism; and H is the Heaviside step function with argument $\sigma - \sigma_0$ [i.e., $H(\sigma - \sigma_0) = 0$ for $\sigma < \sigma_0$; 1 for $\sigma > \sigma_0$].

A complete list of the values of the various constants in Equations (2a - c) for WIPP salt is presented in Munson (1996). For the current discussion, it is sufficient to note the following:

1. WIPP underground excavations will not be subject to any significant temperature changes (except for remote—handled transuranic waste locations, where some moderate temperature increases may occur). Thus, temperature dependence on creep closure need not be considered to a first approximation.

2. The value of σ_0 has been determined to be 20.57 MPa (megaPascals). For most of the underground locations at WIPP, since the initial stress state is isotropic (lithostatic pressure in every direction) at approximately 15 MPa, then $H(\sigma - \sigma_0) = 0$, implying that $\dot{\varepsilon}_s = 0$ for these locations.

3. Using the values $n_1 = 5.5$ and $n_2 = 5.0$ for the exponents in Equations (2a) and (2b), the steady-state strain rate $\dot{\varepsilon}_s$ reduces to the expression

$$\dot{\varepsilon}_s = k_1(\sigma)^{5.5} + k_2(\sigma)^{5.0} \tag{3}$$

where the generalized stress $\sigma = (\sigma_1 - \sigma_3)$; σ_1 and σ_3 are the maximum and minimum principal stresses, respectively; and k_1 and k_2 are constants representing combinations of terms in Equations (2a) and (2b), respectively.

For simplicity, it is assumed that both components of Equation (3) have the same exponent (i.e., assuming $n_2 \approx n_1 = 5.5$), so Equation (3) can be written as

$$\dot{\varepsilon}_s = k(\sigma_1 - \sigma_3)^{5.5} \tag{4}$$

where $k = k_1 + k_2$. It is seen that the stress dependence of the creep rate is very strong. For example, if an open borehole in salt closes at the steady-state rate $(\dot{\varepsilon}_p)_{open}$ at some depth h (meters) (i.e., where the lithostatic [driving] stress is $0.023h$ MPa), then a brine-filled borehole (with a hydrostatic pressure

in the hole of $0.01h$ MPa) will close at a rate $(\dot{\varepsilon}_p)_{\text{fluid-filled}}$, where

$$\frac{\dot{\varepsilon}_{\text{fluid-filled}}}{\dot{\varepsilon}_{\text{open}}} = \left(\frac{0.023\text{h} - 0.01\text{h}}{0.023\text{h}}\right)^{5.5} \approx \frac{1}{37}$$

Thus, if an open unlined borehole closes in approximately 100-200 years, an unlined, fluid-filled borehole at the same depth would not close for 3,700-7,400 years. This is a significant change when estimating the consequences of human intrusion events.

Research at WIPP has also confirmed the following:

1. The stress at which inelastic flow of salt occurs is governed by a Tresca or maximum shear stress yield criterion, rather than the more frequently used Von Mises, or maximum octahedral shear stress yield criterion. Given the highly non-linear dependence of the strain and strain rate on stress level, the difference between the two criteria can be very significant. A part of the initial discrepancy between prediction and observation was corrected by making the change to a Tresca criterion.

2. The value of the shear stress at which inelastic strain develops tends toward very low levels at low strain rates. At the very low strain rates associated with geological loading, the yield stress of salt is essentially zero. In other words, at these extremely low loading rates, salt behaves as a (viscous) fluid, unable to maintain a shear stress. This is seen in equation (4) above, which indicates that the salt will have a nonzero strain rate ($\dot{\varepsilon}_s$) as long as $\sigma_1 \neq \sigma_3$. Thus, over long times (especially geological time—here 200 million years) creep will continue until $\sigma_1 = \sigma_3$, (i.e. the in-situ stress state is isotropic).

Hydraulic fracturing measurements of in situ stress conditions of WIPP confirm that the stress state in the salt is isotropic. The isotropic condition and the creep flow characteristic of salt imply that salt in situ should be essentially impermeable, since the connected pathways needed to allow flow of fluid would lead to localized stress concentrations in the vicinity of the connected cracks, etc., that represent the permeability. Such concentrations (stress differences) would produce flow of the salt, leading to closing of the pathway and elimination of the permeability.

3. At the higher strain rates associated with stress redistribution around excavations, salt can behave in a much more brittle manner. Fractures can and do develop progressively in the walls, roof, and floor of the excavation as the result of stress concentrations around the excavations. These fractures produce what is known as the disturbed rock zone (DRZ) around the excavations. The DRZ is important on several counts:

- It could provide a region of connected fractures that allow a high-permeability path around the excavations and brine access to the waste-filled drums. Such fractures (and DRZs) appear around excavations in other rock types, but salt has the attractive feature that fractures in the DRZ in salt can "heal" (i.e., disappear) with the buildup of a "back-stress" (i.e., resistance to closure generated by waste and/or backfill or a shaft lining or seal). This healing can be inhibited by the presence of water in the fractures as back-stress builds up. In the shaft seal designs discussed in Chapter 4, the DOE must take special measures to ensure that the fractures remain "drained" during the period of back-stress buildup. It is worth noting, however, that the fluid pressure required to resist crack closure can develop only if the fluid is sealed in the crack, that is, if it is not part of a permeable connected system of fluid flow.
- Since the DRZ develops in the floor of the excavations as well as the roof and sides, this zone serves as a depository and conduit for any brine flowing into the waste-filled rooms. Because closure of the waste-filled rooms involves floor "heave" as well as roof "sag," the waste drums will tend to be lifted above the brine, especially during the early years after loading of the rooms with waste. This phenomenon has important implications for the question of gas generation due to corrosion of steel waste drums at WIPP.

The practical implications of these deformation properties of salt are discussed in Chapters 3 and 4.

Appendix E

Actinide Source Term

As background for preparing its review of the actinide source term (AST), the AST subcommittee (Clark, Ewing, and Krauskopf) was supplied with abundant literature, including both in-house documents and articles from refereed journals that were considered by the Department of Energy (DOE) to be relevant to the Waste Isolation Pilot Plant (WIPP) program—many of which are listed at the end of Chapter 5. In addition, the subcommittee visited Los Alamos National Laboratory (LANL) in 1994 to view the proposed experiments with real and actinide-spiked waste (these are described as the Source Term Test Program [STTP]). In 1995 and early 1996, DOE scientists and contractors met with the AST subcommittee several times (March 6, April 27-28, and June 29, 1995; and February 14, 1996) to present the rationale for the AST program and some data from experiments completed in the past, and to describe experimental work in progress or still being planned (Novak, 1995a, b).

As late as April 1996, the subcommittee was still receiving revised versions of the proposed test plans, but no results of recent experiments or of the STTP program at LANL were available for review. The subcommittee was given a conceptual outline of the use of actinide source term data in the performance assessment (PA; Ruth Weiner, Sandia National Laboratories, personal communication to S. Clark, January 18, 1996); however, in the absence of experimental data explicitly used in the performance assessment, it was not possible to review this part of the program. Substantive review of AST results must await completion of at least a major part of the proposed work. *To the extent that the actinide source term is an important parameter in the performance assessment and the determination of compliance, it will be necessary to review carefully the final data package, the selection and use of conceptual models, and the final incorporation of data and models into the performance assessment.*

The remainder of this appendix discusses specific issues related to some of the tests planned as part of the DOE experimental program for the AST. The test plans may have changed after they were presented to the subcommittee and even before the experimental program was initiated; thus, these comments are applicable only to those portions of the test plans that have not changed.

The principal laboratories, principal investigators, and status of various components of the AST program are listed in Table E.1. This provides an indication of the materials that were reviewed by the AST subcommittee.

EXPERIMENTAL WORK ON ACTINIDE SOLUBILITIES

Pitzer Parameters

The application of Pitzer parameters (Pitzer, 1973, 1977) specifically to concentrated saline solutions has been described by Harvie et al. (1984) and by Felmy and Weare (1986). The methods of calculating solubilities suggested by these authors have been applied to the WIPP brines by DOE researchers. Particular advantages of using the Pitzer approach, rather than other means of correcting tabulated thermodynamic data to conditions of concentrated electrolytes, include the following:

1. The model is designed specifically for the geochemical conditions anticipated at WIPP and is well described in the peer-reviewed literature.
2. Data are available for many of the constituents in brine, making additional experiments unnecessary.
3. The model provides for complex interactions among more than just two species, reflecting the situation anticipated in highly saline media.

TABLE E.1 Actinide Solubility Work

Program Experimental Component	Principal Investigator (SNL/Subcontractor)	Subcontractor Laboratory	Date Initiated	Experimental Termination Date
Dissolved Concentration Model - Oxidation State Analogy				
An(III) Model Inorganic Interactions	Novak/Felmy, Rai, Rao	PNL	Jul-93	Apr-96
An(IV) Model - Inorganic Interactions	Novak/Felmy, Rai, Rao	PNL	Jul-93	Apr-96
An(V) Model-Part I Inorganic Interactions	Novak/Al Rafai	LBL	Feb-95	Mar-96
An(V) Model-Part II Inorganic Interactions	Novak/Runde	GTS/ITS	Feb-95	Jul-96
An(VI) Model- Inorganic Interactions	Novak/Palmer	LLNL	Jan-95	Mar-96
Organic Interactions An(III, IV, V, VI)	Novak/Moore	FSU	Feb-95	Apr-96
Alternative An(VI) Model-SIT Formalism	Novak/Jenecky	LANL	May-95	Mar-96
SNL Data Interpretation	Novak, Moore, Weiner	SNL	Feb-95	Feb-96
Dissolved Concentration Model - Challenges to the Oxidation State Model				
Tests of Conceptual Model Against Exper. with Actual TRU	Crafts/Villareal	LANL	Liter Scale: Mar-95 Drum Scale:	3-5 yrs. from initiation or steady state
Waste - STTP			Jun-95	
Empirical Solubility for An(IV, V, VI) in WIPP Brines	Moore/Reed	LANL	Jun-95	Sep-96
Further Oxidation State Studies	Weiner/Clark Felmy, Rai	LANL,PNL	Jun-95	?
Oxidation State Studies in STTP Experiments	Weiner/Clark	LANL	June-95	?
Mineral Fragments		SNL	Oct-93	Jan-96
Actinide Intrinsic Colloids		LLNL,LANL	Jul-95	May-96
Humic Substances		SNL, LANL, Gatson	Jul-95	Jul-96
Microbes		BNL, LANL	Jul-95	Feb-96

Source: Papenguth and Behl (1996 a,b); Novak (1995b); Novak et al. (1995).

An additional general cautionary note is in order regarding the estimation of solubilities in concentrated solutions with the use of the Pitzer parameters. The thermodynamic formalism involved in such estimates is based on the assumption that equilibrium exists between material in solution and solids in contact with the solution—in other words, that all reactions leading to formation or dissolution of solids go rapidly to completion. There is no assurance that these assumptions are correct for the experiments or for in situ WIPP conditions. In fact, some of the experimental work has shown that concentrations in a solution, after a solid has precipitated, may change slowly over the course of months or a few years as the solid alters its form, for example, from an amorphous precipitate to a crystalline phase (Nitsche et al., 1994).

Because changes in the solid are generally in the direction of greater and greater stability (Ostwald's step rule), and thus lower and lower solubility, such changes commonly are thought to ensure concentrations of actinides lower than those first measured, and hence not to be important in estimating cautiously conservative values for actinide solubilities. As a general rule this is true; however, for solutions as concentrated, and with compositions as complex as WIPP brines, exceptions can readily be imagined.

Resolving issues such as this will require extending some of the solubility experiments well beyond their scheduled termination dates. These experiments can be conducted at the bench scale under carefully controlled conditions, so that the fundamental aspects of actinide solubility in brine can be determined. Such experiments may be needed for interpretation of the more complex experiments performed as part of the STTP at LANL. These longer-term experiments should not delay compliance of the repository if all else is favorable, but they represent one example of the kinds of research efforts that are recommended to continue after wastes are first brought to the repository.

Concerns

The following are specific concerns about details of the planned experimental work on actinide solubility:

- Most aspects of the experimental program and assumptions in the performance assessment are based on thermodynamic models; however, reaction kinetics may be important in determining the actinide concentrations measured in experiments or modeled in the performance assessment.
- One question is the suitability of the specific-ion interaction theory (SIT), activity coefficient formalism, which has been used in the test plan for the Alternative +6 Actinide Model (Grenthe and Wanner, 1992). This approach for estimating concentrations of actinides in the +VI oxidation state is not scientifically defensible, because SIT theory is designed specifically to extrapolate to zero ionic strength; it is not applicable at ionic strengths higher than 3.5 molal; and it is typically used for applications involving a single dominant electrolyte, rather than the complex brines anticipated at WIPP.
- Another question regards the use of experiments planned in the STTP as direct challenges to the submodel of solubilities. The STTP involves measuring actinide concentrations in solutions formed by allowing waste containers to stand for long periods in contact with brines having compositions similar to those at WIPP; in other words, determining concentrations under laboratory conditions set up to duplicate, as nearly as possible, the conditions expected in the WIPP repository. Such experiments will certainly provide useful qualitative data on actinide concentrations, and this program is applauded. However, the assumption that experimental conditions can be made similar in all respects to repository conditions over time seems tenuous at best. Experiments that challenge the thermodynamic model will require not only careful solution analyses as a function of extended periods of time (more than a year), but the identification of the actinide-bearing solids that are in equilibrium with the solution. This will be difficult, because many of the solids are poorly characterized and may have fairly complex compositions.
- Although the oxidation state model (the assumption that the chemistry of a given oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviations from the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy.

EXPERIMENTS ON COLLOIDS

Although actinide concentrations in WIPP brines are expected to be low, the possibility of transport via colloids must be considered one means by which actinides may reach the accessible environment (Kim, 1994). There are two issues: (1) whether colloids will form in a concentrated brine, and (2) whether these colloids can transport significant quantities of actinides effectively.

In designing their research effort, Papenguth and Behl (1996a, b) distinguish four kinds of colloidal particles:

1. mineral fragments, hard-sphere or hydrophobic particles that may contain actinides or have sorbed actinides on their surfaces;
2. actinide intrinsic colloids, particles consisting of actinide macromolecules that may mature on standing into mineral–fragment type colloids;
3. humic substances, hydrophilic or soft-sphere particles that readily sorb actinide ions from solution; and
4. bacteria, which may themselves be colloidal-sized particles and may contain actinides as part of their structure or sorbed on their surfaces.

All types of colloidal particles are relatively unstable in strong electrolyte solutions, and some of the experiments are designed to show what concentration of electrolyte ("critical coagulation concentration," or c.c.c.) is required to produce destabilization and precipitation.

The procedure is simple: small amounts of a simulated Salado-Castile brine are added to samples of colloid until coagulation is noted. Mineral fragments and mature actinide intrinsic colloids are expected to be the most sensitive to electrolytes (i.e., to have the lowest c.c.c.), whereas humic substances and bacteria will not precipitate as readily. For these latter two types, DOE plans more elaborate experiments to explore the effects of pH and the addition of specific ions and organic solutes.

The simple laboratory experiments on colloids will be supplemented with transport experiments designed to show the extent to which various kinds of colloids may be retarded, by precipitation or sorption, if the solution containing them travels through the dolomite of the Culebra Dolomite. Solutions carrying the colloids will be made up to simulate brine concentrations expected in the Culebra, and samples of the solutions will flow through both crushed dolomite and intact-core columnar dolomite. Transport experiments with bacteria as colloidal particles will be especially important, because microorganisms may serve either to increase radionuclide transport by sorbing abundant actinide ions or to decrease transport because the organisms carrying sorbed actinides are themselves strongly sorbed on rock surfaces (Marshal, 1976).

Again, to the extent that colloid formation and transport remain important issues in the performance assessment, the proposed experimental programs may well extend beyond their planned end dates. Long-term experiments on colloid stability and transport may be required even into the operational phase of the repository.

RETARDATION EXPERIMENTS

During transport, actinide concentrations in brine may be lowered by sorption onto rock and mineral surfaces. Such phenomena can be studied by batch experiments to determine K_d values, column experiments with actual rock units from the relevant geologic horizons, or field-scale tracer tests. The limitations of laboratory-scale tests are discussed briefly in Appendix F as part of the discussion of regional hydrology. The inherent weakness of the concept of a retardation factor determined in laboratory experiments, combined with highly uncertain and variable values for the retardation, requires careful analysis of the laboratory data and some field-scale verification. The proposed suite of DOE experiments has been planned carefully and should give a good indication of the effectiveness of sorption in controlling actinide concentrations; however, no results of the experiments completed to date were available.

Concerning the column experiments, the sorbing materials to be used are cylinders of Culebra Dolomite, 10-50 cm long, cut out of the bed with a drill bit and mounted vertically in metal containers. Various

samples of dolomite will be chosen to ensure adequate representation of different permeabilities, different grain sizes, and different proportions of clay mineral impurities. It is emphasized that the column experiments (plus, hopefully, the field experiments) should be carried on long enough and with sufficient variation in conditions to ensure an adequate replica of the natural situation. In particular, the amount of sorption provided by the corrensite coating on parts of the Culebra dolomite requires careful study, a point on which the State of New Mexico Environmental Evaluation Group (EEG) has expressed considerable skepticism regarding the DOE approach.

Appendix F

Regional Hydrogeology

APPROACHES TO STUDYING REGIONAL AQUIFER SYSTEMS

In the broadest sense, a primary objective of studying a deep regional aquifer system is to improve understanding of the relevant processes and properties. Even after a given study has defined the properties of such a system, there will always remain much uncertainty. A unique definition of the system and its properties is simply not attainable, regardless of the amount of data collected. Data collection is very expensive in deep regional aquifer systems, and the costs of data collection and analysis must be weighed carefully against the benefits of additional data. There is no clear-cut point at which it can be determined objectively or scientifically that additional investments in data collection are either necessary or superfluous. Rather, a subjective assessment must be made on the basis of some type of consensus and in light of the significance of the problem, technical considerations, and economic constraints.

Although it is obvious that the properties of a regional aquifer must be defined with some accuracy in order to permit reliable predictions of ground–water flow and transport, it may be less clear that it is also necessary to define accurately the boundary conditions, recharge, and discharge in order to fully define and calibrate a model of the aquifer system. Studies of regional aquifer systems are most comprehensive when the study area extends to the natural geologic or hydrologic boundaries of the system and includes as much of the natural recharge and discharge areas of the system as possible. In reviewing the relevance of hydraulic analyses to contaminant transport problems, Reilly et al. (1987, p. 9) state that "although the details of the flow system in the immediate vicinity of the contaminant plume are of the utmost importance, an understanding of the regional ground-water flow system is required in order to understand the local system."

Because of the uncertainty and variability (heterogeneity) inherent in deep hydrogeologic systems, data collection in general, and drilling of new test wells in particular, often encounter unanticipated difficulties and frequently lead to some "surprises" in the definition or understanding of the properties of the system. Although experienced hydrogeologists expect this, such surprises unfortunately often lead to delays and tend to confound efforts to keep data collection and analysis to a strict, planned time line or budget.

GROUND-WATER MODELS

Ground-water simulation models help analysts improve their understanding of the subsurface system at the Waste Isolation Pilot Plant (WIPP) site faster than otherwise would be possible by integrating site-specific data with a theoretical understanding of the principles of flow and transport. The models offer a quantitative and objective means of testing hypotheses, evaluating the sensitivity of parameters, and guiding the data collection and experimentation process. Furthermore, if the models are based on reasonable and appropriate concepts, if they are adequately tested and calibrated, and if analysts have high confidence in their reliability, then the models can be used to predict how a particular system will respond to a particular stress or change in boundary conditions. However, even a well-calibrated model is still an approximation of the real system and incorporates many simplifying assumptions.

Sources of Error

In most model applications, conceptualization problems and uncertainty concerning the data are the most common sources of error. All three aspects of error are discussed below with reference to the performance assessment (PA) models for WIPP.

Conceptual Errors

Conceptual errors are derived from theoretical misconceptions about the basic processes, dimensionality, and/or boundary conditions that are incorporated in the model. Conceptual errors include neglecting relevant processes and representing inappropriate ones. Examples of such errors are applying a model based on Darcy's Law to materials or flow regimes for which Darcy's law is inappropriate, or using a two-dimensional model where significant flow or transport occurs in the third dimension.

That the PA models have a number of simplifying assumptions built into them is not, in itself, a problem, but rather reflects the very nature of models. Questions about ground-water models more typically center on whether the assumptions are too simple or too complex and whether they are appropriate for the system and problem at hand. However, there will never be a sure or precise way of measuring this. The reasonableness of the assumptions is perhaps best evaluated by a consensus of experts. If the conceptual models on which the PA models are based are, in fact, judged to be either too simple or inaccurate, then all of the complementary cumulative distribution functions (CCDFs) and risk assessments derived from the PA must be questioned.

The PA models start with the assumption that the primary release of contaminants under the human intrusion (HI) scenario is from leakage into the Culebra Dolomite. This assumption is part of the conceptual model. The risks and consequences of leakage into other formations have not been assessed or documented thoroughly. Release into the Culebra also is constrained by assumptions about the permeability of the material filling the borehole through which leakage occurs. However, in previous PA analyses, the assumed borehole permeability and assumed depths of impermeable plugs appear to be somewhat arbitrary.

Many of the concepts built into PA models may be based on preliminary judgments and assessments that are not well documented. For those ideas that may be critical but are based on minimal evidence, a range of alternative conceptual models should be evaluated in sufficient detail to document their consideration and the basis for their elimination. Examples of alternative conceptual models that should be evaluated further include (but are not limited to)

- contaminant leakage from a HI breach into formations shallower than the Culebra;
- flow and transport through the Culebra as part of a three-dimensional aquifer system;
- impact of changes in the flow field due to transient effects, climate change, or other factors; and
- internal "structure" of the Culebra, including the existence of vertical fracture zones and correlations between transmissivity and other parameters.

More detailed discussions of model testing, model calibration, predictive accuracy of models, and related issues are presented by Anderson and Woessner (1992), Bredehoeft and Konikow (1993), de Marsily et al. (1993), and Konikow and Bredehoeft (1993).

Numerical Errors

The partial differential equations describing ground–water flow and transport can be solved mathematically by using numerical methods. The continuous variables of the governing equations are replaced with discrete variables that are defined at grid blocks (or cells, elements, or nodes). Thus, the continuous differential equation that defines hydraulic head or solute concentration everywhere in the system is replaced by a finite number of algebraic equations that define the hydraulic head or concentration at specific points. This system of

algebraic equations generally is solved by using matrix techniques.

However, numerical methods yield only approximate (rather than exact) solutions to the governing equation (or equations); they require discretization of space and time. The variable internal properties, boundaries, and stresses of the system are approximated within the discretized format. Because numerical methods do not yield exact solutions, *numerical errors* will exist in the solution because of truncation errors, round-off errors, and numerical dispersion. As long as the sources of numerical errors are recognized and the magnitude of the error is controlled, the solution may be sufficiently accurate for use.

The solute-transport equation is in general more difficult to solve accurately using numerical methods than is the ground–water flow equation, largely because the mathematical properties of the transport equation vary depending on which terms in the equation are dominant in a particular situation. Thus, numerical errors often are negligible in solutions to the flow equation but can be significant in numerical solutions to the solute-transport equation.

Where solute transport is dominated by advective transport, as is common in many field problems, the transport equation approximates a hyperbolic type of equation (similar to those describing the propagation of a wave or of a shock front). In contrast, where a system is dominated by dispersive fluxes, such as might occur where fluid velocities are relatively low and aquifer dispersivities are relatively high, the transport equation becomes more parabolic in nature (similar to the transient ground–water flow equation).

In solving advection-dominated transport problems, in which a relatively sharp front (or steep concentration gradient) is moving through a system, it is numerically difficult to preserve the sharpness of the front. Obviously, if the width of the front is narrower than the node spacing, it is inherently impossible to calculate the correct values of concentration in the vicinity of the sharp front without using complex nonlinear mathematical functions or complex nonstandard numerical algorithms. However, even in situations where a front is less sharp, the numerical solution technique can calculate a greater dispersive flux than would occur by physical dispersion alone or would be indicated by an exact solution of the governing equation.

That part of the calculated dispersion introduced solely by the numerical solution algorithm is called *numerical dispersion*. The consequence of numerical dispersion is that the solute is artificially diluted, peak concentrations are lower than they should be, and the solute is distributed throughout a larger than actual area and volume of the aquifer. Although this alone may or may not represent a significant problem, the errors can in fact be magnified and accumulate if the model incorporates a representation of solute retardation processes in which rates or magnitudes are functions of the solute distribution and/or concentration gradients. Because the effectiveness of matrix diffusion and chemical retardation, for example, depends in part on the surface area of aquifer solids that are in contact with ground water containing the solute (or contaminant), numerical dispersion may yield erroneously high rates of matrix diffusion and chemical retardation. Therefore, special care must be taken to assess and minimize numerical errors that artificially would add "numerical" spreading to the calculated spatial distribution of a contaminant.

Data Uncertainty

Data errors arise from uncertainties and inadequacies in the input data. A reasonable way to accommodate such uncertainty is to estimate the mean and the uncertainty in each relevant parameter on the basis of available data, and then use the simulation models to make predictions based on *ranges* of values of the parameters, rather than on single values. Outcomes from the deterministic models can then be presented and assessed in a probabilistic framework. In essence, this is the approach taken by the PA models.

The reliability of site-specific ground-water models typically requires that input data be based on field measurements of critical parameters at a scale appropriate to the size of the model. Unfortunately, very few field measurements are

available for the critical parameters describing the nature of fractures and retardation mechanisms in the Culebra.

Although the probabilistic approach is beneficial and appropriate, it must be cautioned that the results will be affected by assumptions about the statistical distributions and independence of parameters; that is, there is uncertainty in the estimates of uncertainty. The sensitivity of results to assumed frequency distributions should be evaluated.

In addition, the system behavior for some processes is governed essentially by the magnitude of nondimensional parameter groups (or ratios). The rationale for independently sampling the individual parameters comprising such a group is unclear and may result in unlikely parameter ratios.

Hydrologic Performance Assessment Models

Ground-Water Flow

In developing PA models for flow and transport through the Culebra Dolomite, estimates of recharge and transmissivity are keyed into the a priori assumptions that ground-water flow is two dimensional, steady state, and horizontal. In reality, the Culebra is one part of a three-dimensional flow system. Although flow may be predominantly horizontal, some vertical components of flow and transport undoubtedly exist, and they may significantly affect the flow, transport, travel times, and concentration distributions in the Culebra in areas downgradient from a potential release.

Fractures are the high-permeability avenues (or pathways) through which the fastest flow and transport of dissolved contaminants would occur. Fractures thus represent the most likely fatal flaw in site integrity if the HI scenario enables significant leakage of contaminants into the Culebra. In general, where vertical or near-vertical fractures exist, they

1. tend to persist across formation boundaries,
2. often yield some subtle but detectable expression or indication at the land surface, and
3. tend to "channelize" ground-water flow.

Because the presence of a few high-permeability fractures will have a large effect on solute transport, additional efforts to characterize fracture properties are warranted.

Confidence in PA Analysis of Regional Ground-Water Flow

The existence and importance of heterogeneity in the Culebra Dolomite is well recognized. Modern, sophisticated, and complex geostatistical methods have been applied to analyze the statistical properties of the variability in transmissivity and to estimate values of transmissivity in areas where no measurements are available. Accomplished with the assistance and advice of a team of world-class experts, this is a state-of-the-art approach to estimating point values and spatially correlated trends in transmissivity based on existing data, as well as to assessing the reliability of these estimates.

In 1995, a new set of wells was drilled into the Culebra for the purpose of conducting multiwell tracer tests. The site (designated as H-19) was selected in part because it is in the area where the coupling of geostatistical methods and ground-water modeling indicates a relatively high transmissivity zone. If hydraulic testing at this new site confirms prior estimates, it would provide a basis for increased confidence in previous analyses. This new drilling site also would provide a control area in which to apply and test the effectiveness of high-resolution geophysical methods and topographic analyses, in order to better define fracture zones. The result of such analyses could then be correlated with the results of planned tracer tests.

Some concern remains about scale effects on permeability and transmissivity. For example, a comparison of transmissivity values for wells H-14, H-15, and H-17 that were estimated from single-well tests (Beauheim, 1987) with values for the same wells as calculated from data collected during a larger-scale pumping test at H-11 (Beauheim, 1989) shows that the latter are 20 to 60

times greater. Garven (1995) states that fractures in carbonate aquifers tend to increase the hydraulic conductivity at the regional level. He presents a curve indicating that at a regional scale of 1 km or greater, hydraulic conductivity may be a few orders of magnitude higher than estimated from borehole measurements at scales of less than 100 m.

This is relevant to WIPP studies and of some concern to the committee because the assumed transmissivity distributions are keyed to transmissivity values measured in boreholes (see LaVenue et al., 1995, for a detailed discussion of the methodology and its application to the WIPP site). These types of borehole measurements typically sense aquifer properties only in the immediate vicinity (perhaps a few meters) of the borehole. If some of those borehole measurements underestimate the larger-scale effective transmissivity in that area, the regional transmissivity values generated may be too low for purposes of large-scale transport predictions. Although the generated transmissivity fields are calibrated by using observed head measurements from both the assumed steady-state flow field and transient hydraulic tests at a few sites, the heads are less sensitive to transmissivity variations than are seepage velocities.

Geostatistical analysis does not explain why transmissivity varies the way it does. It does not answer the question of whether higher transmissivities are related to increases in fracture density (decrease in fracture spacing), increases in fracture aperture, increases in fracture length (and connectivity), changes in fracture orientation, increases in primary porosity, changes in the amount of evaporite minerals dissolved, and/or changes in mineralogy.

Some might ask whether it is important or necessary to understand the cause of these variations in order to predict ground–water flow and transport. Finding the answers to such questions is not merely an academic exercise; the answers are relevant to the PA models and analyses because whatever is causing the changes in transmissivity will most likely also affect the effective porosity and retardation processes. Developing a better understanding of the causes and controls of transmissivity variations may require improved geological and geophysical mapping of primary and secondary geological properties and characteristics of the Culebra dolomite, particularly fractures.

Franke et al. (1987, p. 2) state that "selection of the boundary surface and boundary conditions is probably the most critical step in conceptualizing and developing a model of a ground-water system." Neither the PA ground-water model of the Culebra nor any of the preceding deterministic models of the system extended to the natural boundaries of the regional aquifer. This makes it difficult to assess the reasonableness of the boundary conditions specified at the outer edges of the PA model, which encompasses only a small part of the entire regional system. It is similarly difficult to calibrate the flux through the Culebra and to distinguish between recharge-discharge in outcrop areas and recharge-discharge from leakage through confining beds. In addition to providing another example of a less than desirable level of understanding of the system of interest, this difficulty also casts doubt on the ability to evaluate and predict the impact of climate change because it is not known how a projected change in climate might interact with the aquifer system in general or with the Culebra in particular.

Future climate change may significantly affect the regional ground–water flow system. The PA assumes that the maximum amount of increased recharge to the Culebra can be represented by increasing assumed boundary heads in the model to the elevation of the land surface. However, because it is well known that heads in confined aquifers can be significantly higher than land surface, it is not clear that this assumption really represents a bounding case. If future climate change induces greater diffuse recharge to the water table, then the saturated thickness of the Dewey Lake Red Beds may increase significantly, resulting in greater transmissivity values and higher flow velocities. Since the recharge would likely retain a relatively low content of dissolved solids, use of the Dewey Lake as a drinking water source might increase significantly in the future. In such circumstances, the Dewey Lake Red Beds could

prove to be a greater long-term environmental risk than the Culebra.

Solute Transport

Solute-transport processes include advection, in which solutes move with the average seepage velocity of the flowing ground water, and hydrodynamic dispersion, which has the net effect of causing the solute distribution to spread about the positions indicated by the mean seepage velocity. Of these two primary processes, advection is the most important to predict accurately, because it controls when the center of mass of a contaminant plume will arrive at the regulatory boundary. Any errors in the solution to the flow equation or in the estimates of effective porosity will affect advection.

The dispersion process in ground-water systems is still the subject of much active research. Although conventional theory holds that the dispersivity coefficients are generally an intrinsic property of the aquifer, in practice they are found to be dependent on and proportional to the scale of the measurement. Recent controlled field experiments and theoretical advances in the study of transport processes indicate that large-scale (macroscopic) dispersion results largely from spatial variations in velocity, caused by spatial variations in hydraulic conductivity and effective porosity (see Gelhar et al., 1992). In that sense, dispersion and advection are interrelated.

Experimental field studies of solute transport at sites that include a dense network of observation wells tend to show that contaminant plumes emanating from known point sources are narrower than expected and that actual dispersion is much less than anticipated by conventional theory (e.g., see Garabedian et al., 1991). The implication for a release of contaminants into the Culebra Dolomite under the HI scenario is that the resulting plume may be longer, narrower, and more sharply bounded than predicted with existing PA models. Overestimating dispersion would have the net effect of diluting the contaminant by spreading its mass through a larger volume of aquifer. In a homogeneous single-porosity medium for a nonreactive solute, this would have no net effect on the center of mass. However, in a heterogeneous system such as the Culebra, overestimating dispersion also forces too much solute into lower-velocity parts of the flow field. This will bias the results toward yielding lower releases during a given time period. Also, if the solute is subject to retardation, overestimating dispersion can lead to a bias of overestimating the magnitude of retardation, as discussed below.

Confidence in PA Analysis of Solute Transport

Because solute-transport processes could be critical to establishing a sufficiently low level of radionuclide releases at WIPP, achieving high confidence in the analyses is important. Although several tracer tests run in the field were valuable steps in this direction, they had to be run under forced-gradient conditions because of time and cost constraints. Running a long-term natural-gradient tracer test should be considered as well, because it would serve as an indicator of true long-term migration paths and velocities under conditions expected after a breach via the HI scenario. However, because such a test might require decades of monitoring, which could be done at very long intervals, it is not recommended that this type of test be performed prior to a compliance decision. Rather, it is suggested that its feasibility be evaluated for possible use as an operational and postclosure monitoring procedure.

Retardation Mechanisms

As solutes migrate through the aquifer, the apparent mean velocity of a particular solute may be retarded relative to the apparent velocity of the water because of several processes that may cause molecules or ions of that particular chemical species to be removed temporarily from the active flow field. Retardation processes thus provide another margin of confidence for the WIPP repository in that retardation will delay (but not prevent) the arrival of a contaminant at the regulatory boundary.

Matrix Diffusion and Physical Retardation

The PA models assume that solute transport through the Culebra Dolomite occurs through continuous sets of horizontal parallel fractures. However, some of the field tests have estimated parameter values for different types of fracture sets and distributions, such as orthogonal sets. The differences in conceptualization must not yield inconsistencies in the effective surface area of fractures per unit volume of aquifer between the field estimates and the PA models, because such inconsistencies might affect the calculated rates of matrix diffusion.

Overestimates of the amount of plume spreading can occur if the assumed dispersion coefficients are too large or if assumed patterns of heterogeneity artificially induce divergence of flow. These effects would be of minor consequence for transport of nonreactive solutes in a single-porosity system. However, if matrix diffusion is a simultaneous process, then the problem is more serious, since the net result would be too much retardation.

Inaccurate or imprecise initial conditions also can lead to significant artificial spreading of the contaminant plume. The HI scenario assumes that the contaminant is introduced into the Culebra by leakage from a borehole (or well) that has a diameter on the order of 0.3 m. In the 1992 PA model, that contaminant source is introduced as an initial condition at the finite-difference cell representing the well. Because that cell has dimensions of 125 m by 125 m, the initial width of the plume at the start of the simulation is perhaps several tens of times greater than it would actually be. The width of the plume then spreads out even more as it is advected and dispersed in a downgradient direction by the regional ground–water flow system.

If the initial width of the plume is much greater than it should be, it has the net effect of giving matrix diffusion an unrealistic "head start" and a growing "advantage" in retarding the movement of the contaminant plume by allowing the plume to be in contact with an erroneously large surface area of the matrix. In a fracture-dominated carbonate aquifer, it is possible that contaminant plumes can migrate long distances with very little lateral spreading, which would minimize any retardation induced by matrix diffusion.

Numerical dispersion also causes artificial plume spreading. The SECO transport code solves the transport equation by using a type of finite-difference scheme. When finite-difference methods are used to solve advection-dominated transport problems, some amount of numerical dispersion is likely to be induced in the solution. Because the numerical code has not been widely available for outside testing and evaluation, it is difficult to know how much numerical dispersion is present. However, any numerical dispersion will necessarily result in overestimates of matrix diffusion.

Confidence in PA Analysis of Matrix Diffusion

The PA models assume that matrix diffusion will be controlled by the intergranular properties of the matrix (including porosity and tortuosity), the free water diffusion coefficient for a particular constituent, and the concentration gradient. *Tortuosity* is a parameter reflecting the fact that the actual tortuous flowpath that a fluid particle would travel through the liquid phase of a saturated porous medium is longer than the length of the porous medium sample. However, tortuosity has been estimated only indirectly in laboratory measurements on a limited number of Culebra samples (Kelley and Saulnier, 1990), where it is shown that the diffusion porosity is usually about two to eight times lower than the porosity measured by other standard methods on the same samples. It is unclear whether these laboratory measurements can be transferred to the field environment.

Field tests by the WIPP project to date have yielded somewhat ambiguous results regarding the occurrence and rates of matrix diffusion. If matrix diffusion must be relied upon to demonstrate compliance, further field studies are necessary to support the model assumptions. Field evidence is needed over moderate distance and time scales and could likely be obtained as part of a series of multiwell tracer tests. Sandia has proposed using single-well injection-recovery tracer tests to

demonstrate the existence of matrix diffusion. However, it is doubtful that such tests could provide either unambiguous results or meaningful measurements of the relevant parameters.

It is also possible that in the field, solute transfer between the fractures and the matrix may be hindered by some type of skin effect or discontinuity at the interface between a fracture and the matrix. Sharp et al. (1995) note that fracture skins are an important and integral part of natural, fractured rock systems and that skin permeabilities and mean pore diameters may be reduced by more than an order of magnitude relative to the matrix. They state that "an extreme case is where the fracture skins have zero permeability and porosity so that no interchange of fluids, colloids and solutes between the fracture and the matrix is possible." Analytical methods are available to interpret the results of tracer tests conducted in fractured aquifers having skin effects (see Moench, 1984; Sharp et al., 1995). The presence of a skin effect would render meaningless any projections of matrix diffusion rates based solely on the physical properties of the matrix. This possibility needs to be given further consideration.

Reactions and Chemical Retardation

As noted in Chapter 6, the appropriateness of predicting the transport of reactive solutes on the basis of a retardation factor (R_f) is questionable. Furthermore, if the use of a retardation factor represents a poor conceptual model, then it is doubtful that the theoretical difficulties can be overcome by simply evaluating a range of values for R_f. For example, if the governing reaction is chemical precipitation of a solid phase, rather than sorption, the species either is less likely to redissolve into the liquid phase in which transport occurs or will do so at a much slower rate. In this case, use of a retardation factor will probably indicate faster and further transport than might occur (but it will still depend on the precipitation rate).

Alternatively, too much retardation could be calculated if the governing process is indeed a type of sorption controlled by surface chemistry. For example, sorption is sometimes characterized by a Langmuir isotherm, which is one type of nonlinear isotherm (although it should not be inferred that a Langmuir isotherm would necessarily be applicable at the WIPP site). In such cases, retardation is greatest at very low concentrations, but at high concentrations the slope of the isotherm approaches zero and the medium will not adsorb additional solute (see Figure F.1). Thus, if sorption is actually governed by a Langmuir isotherm or a similar nonlinear isotherm, applying a retardation factor may lead to a calculation of too much retardation at the high end of the concentration range—the very part of the spectrum at which the greatest toxicity is likely to exist. This illustrates a major weakness of the linear R_f model: it places no upper limit on the amount of the chemical that can be sorbed. However, if it is known that the solute concentration will always remain relatively low, then even if the governing isotherm is nonlinear over the full range of possible concentrations, the sorption behavior within the range of expected conditions will not differ materially from that predicted by a linear isotherm model. If chemical retardation is to be relied on for compliance of WIPP, it must first be demonstrated that the use of a retardation factor is an appropriate representation of reaction processes in the Culebra for the solutes of interest over the transport scales anticipated.

Although most types of reactions tend to retard the transport of a reactive solute, the presence of colloids in the fluid may increase the mobility of solutes that otherwise are retarded or relatively immobile. For example, Ibaraki and Sudicky (1995) cite a case at a liquid waste disposal site at Los Alamos, New Mexico, where both plutonium and americium migrated more than 30 m. They report that predictions based on laboratory results that ignored the role of colloids severely underestimated the migration as just a few millimeters. Colloid-facilitated transport is an issue that warrants additional consideration to justify its exclusion from the PA evaluation.

Confidence in PA Analysis of Chemical Retardation

Not only is the concept of a retardation factor a theoretically weak one for predicting radionuclide transport through the Culebra, but the underlying parameter values for the equivalent K_d are highly uncertain, spatially variable, and based on minimal laboratory experiments that have questionable relevance to the large-scale field environment. Most of the available K_d values obtained by the WIPP project were determined from batch experiments on crushed or powdered samples of rock. There is little evidence that these K_d values are transferable to the field environment, in part because the effective surface areas for water-mineral interactions in crushed samples would be very different from those in situ. For example, Lienert et al. (1994) studied uranium transport in a sand and gravel aquifer and found that the in-situ K_d is much lower than most K_d values obtained from laboratory experiments.

Significant spatial variability in values of K_d may exist and, if so, is probably related to variations in mineralogy. However, in contrast to the consideration of spatial variability in transmissivity, no data are currently available to provide a basis for estimating the magnitude of such variability. A recently published review of transport of reactive contaminants in heterogeneous media concludes that "the transport of reactive solutes appears to be influenced most greatly by subsurface heterogeneity and rate-limited mass transfer interactions" (Brusseau, 1994, p. 306). In discussing the application of theory and laboratory measurements to field-scale systems, the paper further concludes (p. 307): "Of course, true field-scale behavior can be obtained only by performing experiments in the field."

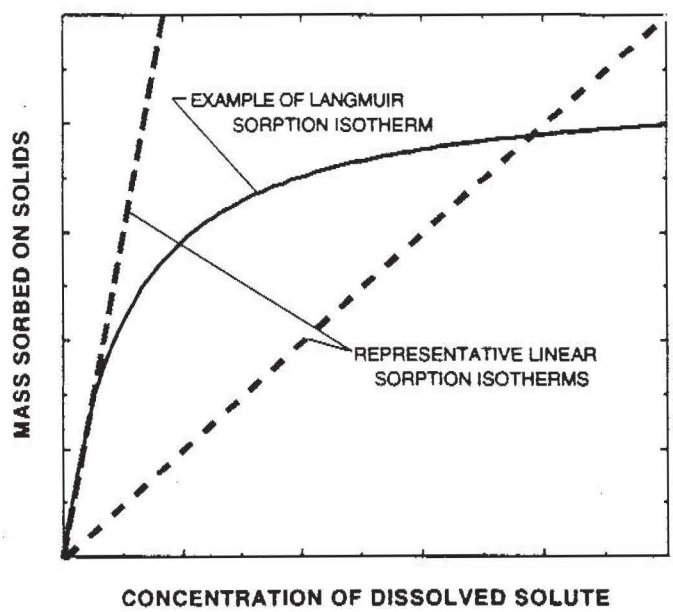

FIGURE F.1. Schematic comparison of representative linear isotherms, describing instantaneous reversible sorption-desorption reactions, with an example of a nonlinear Langmuir isotherm. The distribution coefficient K_d is equal to the slope of the linear isotherm and is directly proportional to the solute retardation factor R_f. Source: Modified from Goode and Konikow (1989).

Appendix G

An Overview of WIPP Compliance Issues

This appendix is a nontechnical synopsis of the major themes and findings of this report. The primary goal of this report is to present a scientific and technical appraisal of DOE activities in connection with the Waste Isolation Pilot Plant (WIPP) radioactive waste isolation program. This entails detailed discussions of complex issues related to engineering measures, biochemical processes, and hydrogeological aspects of the site. Radioactive waste isolation is also a topic of considerable interest and concern to the general public, and it is important that the public understand the basic concepts underlying the design and operation of the WIPP facility.

This appendix aims to describe the WIPP project clearly and concisely by using a "nonspecialist" approach—that is, one that avoids specialized technical terminology as much as possible—to discuss salient issues pertaining to the project. It traces the history of the facility and summarizes the committee's main concerns, conclusions, and recommendations regarding Department of Energy (DOE) activities at WIPP.

DEEP GEOLOGIC DISPOSAL

The objective of the nation's nuclear waste disposal program is to place solid waste in a location where it cannot return to the biosphere by any foreseeable natural process. A generic method has been selected: bury the material deep within the earth's rocky crust. Salt beds are particularly suitable because they are very stable over geological time scales and have the ability to flow and permanently seal the excavations in which the waste is placed. WIPP is located in such a formation.

The plan for waste disposal at WIPP is to excavate a series of underground rooms in the salt deep below the earth's surface. Radioactive waste will be emplaced in the rooms, and then the shafts to the surface will be filled with salt and other materials to close the facility. The weight of the overlying rocks will compress the disturbed salt and reduce its ability to transmit fluids and gases to the very low values of the undisturbed salt, thereby "sealing" the repository.

The worldwide use of salt cavities to store compressed gases attests to the remarkably low permeability of deeply buried salt (Berest and Brouard, 1996). Salt also has a well-known ability to flow under applied stresses. At the depth selected for the repository, crushed salt will reconsolidate to the same low permeability as that of the original formation, and even large cavities eventually will disappear.

Numerical modeling can predict the flow behavior of salt far into the future for any defined situation. The flow is slow enough to allow ample time for underground operations, yet fast enough to be essentially complete in a hundred years or so.

PROJECT ADMINISTRATION AND REGULATION

The WIPP project was begun in the mid-1970s. It has been the responsibility of DOE and its predecessor agencies, but many years passed before it was determined that the U.S. Environmental Protection Agency (EPA) would be responsible for certification. Disposal regulations then had to be developed in parallel with field activities. The "Final Rule" for the Criteria for Certification was published on February 9, 1996, as this report was being prepared.

CERTIFICATION CRITERIA

The long timeline associated with transuranic (TRU) waste poses problems for the regulation of WIPP, just as it does for design and construction. It seems obvious that protection of human health should be fundamental, yet it is impossible to predict what humanity will be doing in the vicinity of WIPP during the next ten

millennia. Given the nature of the EPA standard and the apparent lack of release scenarios for WIPP under undisturbed conditions, it is not necessary to calculate individual doses as part of a compliance analysis. The part of the EPA standard that is relevant to WIPP is a release limit that avoids the necessity of making arbitrary assumptions about population distributions and human activities in the far future. Unfortunately, this release limit fails to account for one of the advantages of the WIPP location—namely, that most of the ground water in the area is so salty (i.e., brine) that it is undrinkable.

The release limit is specified in a rather surprising way: not as an absolute amount, but as a fraction of the waste inventory. The amount is measured conventionally in curies (a measure of radioactivity) rather than mass. This specification can be translated approximately for nonspecialists as follows: the expected waste inventory is of the order of 6 million curies, and the permitted release fraction of plutonium-239, the dominant radioactive isotope of concern, is 0.0001 of that, or 600 curies. This is the same as a mass of Pu-239 of about 20 pounds.

Regulation in terms of release did not entirely relieve EPA from the necessity of making arbitrary decisions. How long a period is implied by the word "permanent"? EPA settled on 10,000 years, although the half-life of plutonium is 24,000 years. How long can one assume "administrative control" of the WIPP area after closure? The EPA chose 100 years. What kind and frequency of human intrusion should be considered? The EPA chose, reconsidered, then chose again. DOE is now required to assume that drilling will continue in the same manner and intensity as today for the next 10,000 years. What credit should be given to the present generation for assuming extra risks that reduce risks to future generations? The EPA is silent on this point.

The simultaneous presence of radioactive and chemically toxic wastes in WIPP presents a "mixed-waste" conundrum. Must EPA enforce Resource Conservation and Recovery Act (RCRA) provisions (relating to disposal of hazardous waste) at WIPP? A recent law (P.L. 104-201) removes this requirement at the federal level, providing DOE with an exemption from the need to demonstrate that volatile organic compounds (VOCs) would not escape from the repository. The justification for this exemption is based on the assessment that the toxicity of the radionuclides in WIPP is far more important than that of the chemicals.

CERTIFICATION OF WIPP

In October 1996, DOE intends to submit to EPA an application for a certificate of compliance. A critical item in the documentation package will be the results of the performance assessment (PA) group at Sandia National Laboratories (SNL). PA is a set of methodologies used to model the long-term behavior of radioactive waste disposal systems.

The purpose of a performance assessment is to answer three questions:

1. What can go wrong?
2. How likely is it to go wrong?
3. What are the consequences?

The first question was answered years ago by inviting interested parties to submit "scenarios" in which human or natural events lead to the release of radionuclides from the repository. After extensive review of a large number of proposed scenarios, eight were selected on the basis of their credibility and significance.

The PA group at SNL is charged with answering the other two questions, using an approach mandated by EPA. The group is developing a large computer model of WIPP. The model interconnects many large special-purpose programs, addressing, for example, site hydrology, geology, and design features. Into this model go descriptions of the eight scenarios, along with data on the many physical and chemical parameters and rate constants required for the computations.

Providing data for this model has been and continues to be a major activity of SNL and its subcontractors. Laboratory and field work play a large part; other approaches include the systematic "elicitation" of expert opinion for matters that are difficult to measure (e.g., the solubility of certain actinides in saturated brine) or impossible to measure (e.g., the best way to communicate to future generations the danger of digging within the WIPP reservation).

In one of the eight scenarios, the repository remains undisturbed by humans after it is closed. For this "undisturbed" case, neither the committee nor DOE's contractors could think of any way in which there is a credible possibility for release of radionuclides.

The other seven scenarios involve human intrusions (HI) of three kinds, alone and in combination, and with various frequencies. A variety of possible circumstances, such as the presence or absence of brine, accompanies each of these "disturbed" scenarios. The existence of many possible scenarios and many kinds of data makes the computations very complex. The computer can handle this complexity, but the computations are nearly inscrutable to all but specialists.

A problem arises for certain data used in the computations: what numerical value should be used when only a broad range of possible values is available? Choosing the "worst case" value (i.e., the least desirable value) of every range maximizes conservatism but introduces an unnatural bias. When faced with such uncertainty, statistical theory provides a means to make predictions on the basis of a defined range in values. This is accomplished by making many simulations for the same scenario, but in each simulation a different value for each uncertain parameter is selected randomly. If implemented carefully and if a large number of such model simulations are made, the average of the numerous predictions can provide a reasonable estimate of the likely outcome for comparison with the compliance criteria.

The output of such simulations is a calculation of hypothetical releases of radionuclides from the repository. Associated with each calculated release is a calculated likelihood (probability) that such a release will occur. Each of these calculations of release and probability of release is called a "realization." The realizations are thus a series of related probabilities and releases that can be plotted on orthogonal axes (e.g., horizontal and vertical, with releases on the horizontal axis and probability on the vertical axis). The releases appear as points, and the curve connecting them would look like a stepped line or a smooth curve, depending on the number of realizations. The analysis of each scenario includes many realizations.

Finally (see Figure 2.1), scenario probabilities are combined for graphical display as complementary cumulative distribution functions (CCDFs). Plotted on the same scale is a single, rather simple graph representing in probability form the EPA maximum-release specifications.

CHEMISTRY, BIOLOGY, AND GEOTECHNOLOGY

It has been the practice of the PA group to be conservative in modeling. This is sensible, except that two or three excessively cautious estimates may combine to produce an unrealistic model result, or a conservative assumption may come to be regarded as a "given." Therefore, it is important that conservative assumptions be confronted constantly with new information as it is developed. This confrontation has not always occurred in the WIPP PA.

For example, the pre-1996 PA efforts used release scenarios that assumed the following:

- all storage rooms were interconnected and able to be flooded with brine;
- brine might dissolve all the steel containers and all the TRU elements within them; and
- gas production by chemical and biological processes might raise the pressure within the sealed repository to and beyond the pressure of the overburden (lithostatic pressure).[1]

These assumptions may be erroneous. The amount of brine that can enter the repository from rock in the immediate vicinity is in fact quite small in the undisturbed case. Brine occurs in the Salado Formation as pockets in "seams" of clay and/or anhydrite (calcium sulfate), and in porous regions that occur irregularly within the otherwise nonporous salt. There appears to have been little or no interconnection within the pockets of brine in the salt for millions of years.

[1]Gas generation is of particular concern because, if excessive, it could lead to a rise in pressure capable of rupturing the repository, with generation of cracks that would provide a pathway for brine to enter and radionuclide-laden brine to migrate out.

Excavation disturbs the brine pockets in the vicinity of the cavity. During excavations, the rock immediately around the excavation becomes fractured, leading to what is called the "disturbed rock zone" (DRZ). Some of the fractures penetrate the brine pockets and cause the brine to drain toward the excavation. The rate of brine collection has been observed to peak within a few years and then drop off as the DRZ ceases to grow.

Hydrogen generation from reaction between the brine and the waste containers also has been overestimated. Laboratory work has established that brine dissolves steel only when there is actual contact between liquid and metal; where there is no contact, only a thin "tarnish" film forms.

Microbiological experiments have not yet given a definitive answer about biological gas generation, but this too requires liquid water. Moreover, there are fundamental reasons for doubting that organisms can continue to be active metabolically for long periods in an isolated environment containing only limited amounts of the many organic and inorganic factors that are required, even when the food (carbohydrate) supply for microorganisms is unlimited.

The committee uses these considerations to judge that there is only a small likelihood that significant amounts of brine will enter the repository and react with the waste to produce hydrogen gas.

On the other hand, brine flooding does occur in scenarios in which a borehole connects the repository with a pressurized brine reservoir in the Castile Formation below the Salado. The possibility of this type of event is given serious consideration, in part because such a reservoir was encountered in a test boring in the 1970s.

THE ACTINIDE SOURCE TERM

Scenarios that assume brine flooding followed by leakage of contaminated brine upward into a near-surface aquifer require data on the possible amount and concentration of radionuclides. The "actinide source term" (AST) refers to the kinds and amounts of dissolved or suspended radionuclides that could be released to the biosphere.

The total quantity of radioactive materials expected to be emplaced in WIPP has been estimated from inventory records of the sites where wastes are currently stored. However, estimates of the proportion of waste that actually would be dissolved in the case of brine flooding are very uncertain. This seems like a straightforward chemistry problem, but few laboratories are equipped to handle plutonium (a large component of the radionuclide inventory at WIPP). There is little useful information about this issue in the published literature.

An experimental study of this problem was begun at Los Alamos National Laboratory (LANL) in 1994, but no data have yet become available. The current suite of experiments is scheduled for completion in May 1996. It is possible that useful data will be available in time to be included in the PA in the October 1996 certification package. Evidence from the German waste isolation program, which is also considering a salt repository, suggests that plutonium solubility in brine is likely to be low, but it is important to ensure that the brine at WIPP, which is different chemically in some respects from the German brine, behaves in a similar fashion with respect to solubility.

HYDROLOGY ABOVE THE SALADO FORMATION

Some scenarios specify that the radionuclide-contaminated brine will be under sufficient pressure to be transported upward into strata above the repository, where it mixes with water of lower salinity, forming a "plume" of contamination.

Much of the radioactivity in the plume may be trapped in the host rock or at least slowed (retarded) by a combination of known effects including precipitation (formation of a solid chemical compound), sorption (chemical reactions with rock surfaces that inhibit transport), and matrix diffusion (egress into fractured rock pores). However, it is difficult to make reliable predictions of these effects. Laboratory experiments with powdered rock are not necessarily good analogues for the natural environment, and even percolation experiments using columns of intact rock cored from the formation are problematical.

Only extensive field experiments can hope to deal directly with the problem of radionuclide transport in the subsurface around WIPP. Unfortunately, the state

of art is such that even this approach is not necessarily definitive.

As used in this report, the term "non-Salado hydrology" refers to ground-water flow that occurs in aquifers within the rock formations that lie above the Salado Formation. The Culebra Dolomite is the major aquifer, and it is the only one considered in the 1992 PA model. The water in this aquifer, however, is too salty for consumption by either humans or livestock, making the Culebra a poor potential route for radionuclides to reach the food chain in the vicinity of WIPP.

A considerable amount of field work has been completed to better define the properties of the Culebra, and significant advances have been made. However, the data base and the level of understanding of this flow system still contain notable gaps. A major gap is the lack of attention to a possible radionuclide contamination route through the Dewey Lake Red Beds, in which the water is known to be potable for both humans and livestock. Although a unique definition of the properties of a deep regional system is neither attainable nor necessary, the committee believes uncertainty about some critical issues could and should be reduced further. Field tests in seven new wells drilled at pad H19 at WIPP are scheduled for completion in April 1996, and the results may provide useful new information on contaminant transport and matrix diffusion for the 1996 PA.

Past PA studies have indicated that releases into the Culebra might be serious enough to disqualify WIPP for certification unless it can be shown that source-term concentrations are lower than the high values now conservatively assumed, or that retardation within the Culebra is much greater than zero. In other words, the combination of high plutonium solubility and low retardation under the assumptions of the 1992 PA have the potential to generate noncompliance. A full description of which combinations of parameter values generate noncompliance is an outcome of the PA analysis, and in particular, of the sensitivity analysis derived from the model. Results from past PA studies are illustrative, but use assumptions (such as the number of future boreholes drilled per unit area per unit time) that differ from the parameter assumptions specified by the recent guidance of 40 CFR 194. The future CCDF results of the 1996 PA, especially the derived sensitivity analysis, would contain the quantitative answer to the dependencies on each parameter of the model.

REPOSITORY DESIGN USING COMPARTMENTATION

Pre-1996 PA calculations were based on a repository design in which separate waste-filled rooms would be connected by the DRZ, which would provide a passage way for gas or liquid. An alternative design would use crushed salt to seal closed each waste-filled room, so that gas or liquid entering one room is prevented from reaching another.

This alternative design provides an approach to demonstrating compliance that the committee expects would lessen the dependencies on (and concerns about) gas generation, the actinide source term, and non-Salado hydrology. Other engineering measures can also be used to improve the repository design. The reconsolidation of salt, discussed earlier, is a powerful design tool, which can be used to create a fully compartmented repository. Access tunnels can be backfilled with some of the salt removed during excavation. Compartmentation and isolation of the waste rooms can be achieved through the use of backfill materials to make effective seals (i.e., barriers to the movement of liquids and gases) to plug all connections made during excavation. Following consolidation of the plugs of backfill material into a tight seal, penetration of any one compartment will have no effect on the rest of the repository.

Such compartmentation would reduce both the probability and the extent of any potential brine flooding associated with human intrusion scenarios. If the rooms were isolated from each other, problems associated with brine entry would be in general reduced, compared with a fully connected repository. By incorporating such a design, the committee believes that the PA model would show that the current state of knowledge about source term and non-Salado hydrology is sufficient to ensure compliance. This expected outcome remains to be demonstrated. However, even should it be possible to certify compliance of WIPP with the available information base, the studies of source term and hydrology should be continued, since these problems are generic to all

concepts of geological waste disposal and could provide considerable additional confidence in the long-term performance of WIPP.

SUMMARY, CONCLUSIONS, AND PERSPECTIVE

The readiness of WIPP to open and operate as a radioactive waste repository is the issue at hand in DOE's efforts to demonstrate compliance with EPA regulations. This appendix presents some of the relevant technical issues. The scientific and engineering work of the past several years will be used for the PA computer model calculations by SNL. These calculations compare the projected, estimated performance of WIPP to EPA requirements. The results, a CCDF curve, contain the quantitative assessment of whether the facility can comply with the regulations.

For the undisturbed repository, compliance depends on the ability of the crushed salt seals in the WIPP shafts to develop a sufficiently low permeability to retard the movement of water into and radionuclides out of the repository. This occurs by natural creep processes in a relatively short time (50-100 years), with the salt seals tending to become impermeable eventually, so that releases should be well below the limits of the EPA standard (see Chapter 4).

For a repository disturbed by human intrusion, when evaluated on the basis of reasonable expectation of intrusive activities and their consequences, and using models that would implement available engineering features and do not make overly conservative assumptions, the consensus of the committee is that the WIPP repository could be shown by DOE to comply with the EPA standard.

Compliance with the EPA standard does not address human exposure for the disturbed case. In some release scenarios, such as releases of radionuclides into water at depth in the Salado, the lack of a credible exposure pathway to humans provides an extra margin of reserve in addition to the compliance requirements.

Appendix H

Biographical Sketches of Committee Members

FAIRHURST, Charles, ***Chair***—T.W. Bennett Professor of Civil Engineering at the University of Minnesota in Minneapolis. He holds a Ph.D. degree in mining engineering from Sheffield University, England. His professional interests are in rock mechanics, mining, and underground construction, and he has consulted widely in this field for private clients and government agencies—foreign and domestic. Prior to joining the University of Minnesota, he worked in underground mining with the Northwestern Division of the National Coal Board in the U.K. Dr. Fairhurst is a member of the National Academy of Engineering and the Royal Swedish Academy of Engineering Sciences, the American Institute of Mining, Metallurgical & Petroleum Engineers, the American Society of Civil Engineers, and the American Underground Construction Association and was former president of the International Society for Rock Mechanics. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1984.

ADLER, Howard I.—Vice President for Research and Development at Oxyrase, Inc. in Knoxville, Tennessee and adjunct Professor of Microbiology, University of Tennessee. He holds B. S., M. S. and Ph. D. degrees in bacteriology from Cornell University. Dr. Adler has conducted work in this and related fields as senior staff member at Oak Ridge National Laboratory and as Director of Microbiology at Oak Ridge Associate Universities. He is a member of the American Society of Microbiology, American Association for the Advancement of Science, and Sigma Xi. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1991.

BLOMEKE, John 0.—Holds B. S. and M. S. degrees in chemical engineering from the University of Texas and a Ph. D. degree in chemical engineering from Georgia Tech. He cultivated his professional interest in chemical engineering while working on the Manhattan Project at the University of Chicago and the Clinton Laboratory in Oak Ridge, Tennessee. Dr. Blomeke has been actively engaged at Oak Ridge National Laboratory in the development and evaluation of commercial nuclear fuel waste management. He has remained very active in this field through his retirement in 1988. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1980.

CLARK, Sue B.—Assistant Professor of Chemistry at Washington State University in Pullman, Washington. She holds a B.S. degree from Lander College and M. S. and Ph.D. degrees in inorganic/radiochemistry from Florida State University. Prior to joining Washington State University, she worked as an assistant research ecologist at the Savannah River Ecology Laboratory at the University of Georgia and a research assistant at Katholieke University te Leuven in Belgium. Dr. Clark has received the Westinghouse Savannah River Company's Total Quality Achievement Award and the National Academy of Science's Young Investigator Award. She is a member of Sigma Xi and the American Chemical Society. She has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1994.

ERNSBERGER, Fred M.—Adjunct Professor of Materials Science at the University of Florida, Gainesville, Florida. He holds an A.B. degree in chemistry from Ohio Northern University and a Ph.D. degree in physical chemistry from Ohio State University. Prior to joining the University of Florida he was Senior Scientist in

the Glass Research Center for PPG Industries, Inc. He has received the George W. Morey Award, the Toledo Glass & Ceramic Award, and the Bleininger Medal of the American Ceramic Society. Dr. Ernsberger is a member of the American Chemical Society and a fellow of the American Ceramic Society. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1978.

EWING, Rodney C.—Regents Professor in the Department of Earth and Planetary Sciences at the University of New Mexico where he has been a member of the faculty for 22 years. He holds a B.S. degree in geology from Texas Christian University (summa cum laude) and M.S. and Ph.D. degrees in geology from Stanford University. His professional interests are in mineralogy and materials science. He has conducted research in Sweden, Germany, Australia, and Japan as well as the United States. Dr. Ewing is a fellow of the Geological Society of America and the Mineralogical Society of America. Presently, he is the vice-president and president-elect of the International Union of Materials Research Societies. He has served on the National Research Council's the Waste Isolation Pilot Plant Committee since 1984.

GARRICK, B. John—Chairman and founder of PLG, Inc., an international engineering, applied science, and management consulting firm in Newport Beach, California. He received his B.S. degree from Brigham Young University and his M.S. and Ph.D. degrees in engineering and applied science from the University of California, Los Angeles. His professional interests involve risk assessment in fields such as nuclear energy, space and defense, chemical and petroleum, and transportation. He received the Society for Risk Analysis Distinguished Achievement Award and was appointed to the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste in 1994, of which he is now Vice Chairman. Dr. Garrick is a member of the National Academy of Engineering and is currently Vice Chairman of the National Research Council's Board on Radioactive Waste Management. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1989.

KONIKOW, Leonard F.—Research Hydrologist with the U.S. Geological Survey in Reston, Virginia. He holds a B.A. degree in geology from Hofstra University and M.S. and Ph.D. degrees from Pennsylvania State University. His research interests include the development and application of solute-transport models to ground-water contamination problems. Previously, he has served on the Editorial Board of *Ground Water* journal, as Associate Editor for *Water Resources Research,* and as Chairman of the Hydrogeology Division of the Geological Society of America. He served on the National Research Council's Committee on Ground Water Modeling Assessment and has been a member of the Committee on the Waste Isolation Pilot Plant since 1989.

KRAUSKOPF, Konrad B.—Professor of Geochemistry Emeritus at Stanford University in California. He holds an undergraduate degree from the University of Wisconsin, and Ph.D. degrees in chemistry from the University of California and in geology from Stanford University. He has received several honors, including Day Medal from the Geological Society of America and the Goldschmidt Medal from the Geochemical Society. He is a member of the National Academy of Sciences and has served as chairman of the National Research Council's Board on Radioactive Waste Management. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1978.

ROY, Della M.—Professor of Materials Science Emerita at the Materials Research Laboratory and Materials Science and Engineering at Pennsylvania State University. She holds a B.S. degree from the University of Oregon and M. S. and Ph.D. degrees from Pennsylvania State University. Her research interests include material synthesis and characterization in inorganic, ceramic, cement, and mineral systems, and nuclear and chemical waste management. She is founding editor and editor-in-chief of *Cement and Concrete Research.*

She is a fellow of the American Ceramic Society, the American Concrete Institute, the Mineralogical Society of America, and the American Association for the Advancement of Science. Dr. Roy is a member of the National Academy of Engineering. She has served on the National Research Council's Committee on the Waste Isolation Pilot Plant since 1995.

WAITE, David A.—Vice President of Health and Safety at Kaiser Hill Co., LLC in Rocky Flats, Colorado. He holds a B.A. degree in physics from Emporia State University, an M.S. degree in radiation physics from Vanderbilt University, and a Ph.D. in general engineering from Oklahoma State University. Prior to joining Kaiser Hill, he conducted work in this and related fields with other companies, including Envirosphere and the Battelle Memorial Institute. Dr. Waite is a member of Lambda Delta Lambda, Sigma Pi Sigma, and the American Board of Health Physics. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1994.

WHIPPLE, Chris G.—Vice President of ICF Kaiser Engineers in Oakland, California. He holds a B.S. degree from Purdue University and a Ph.D. degree in engineering science from the California Institute of Technology. His professional interests are in risk assessment, and he has consulted widely in this field for private clients and government agencies. Prior to joining ICF Kaiser Engineers, he conducted work in this and related fields at the Electric Power Research Institute. He served on the National Research Council's Board on Radioactive Waste Management from 1985 to 1995 and as its Chair from 1992 to March 1995. He has been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant since 1989.

ZORDAN, Thomas A.—President of Zordan Associates, Inc. and concurrently, Senior Project Manager at ICF Kaiser Engineers in Pittsburgh, Pennsylvania. He holds a B.S. degree from Northern Illinois University and a Ph.D. degree in physical chemistry from the University of Louisville. His professional and research interests include environmental management, risk assessment, waste management, software development, and thermochemistry. Prior to joining ICF Kaiser he conducted work in this and related fields with companies such as Science Applications International Corporation, Westinghouse Electric Corporation, and Gulf Research & Development Company. He has served on the National Research Council's Committee on the Waste Isolation Pilot Plant since 1992.

Appendix I

Glossary

absorbed dose—energy imparted to matter in a volume element by ionizing radiation, divided by the mass of irradiated material in that volume element. The SI derived unit of absorbed dose is the gray (Gy); 1 Gy = 100 rad = 1 J per kilogram.

accessible environment—region outside a rectangular block of rock 5 km long on each side placed symmetrically around the Waste Isolation Pilot Plant repository, with vertical sides extending upward to the land surface and indefinitely downward into the earth.

actinide—element with atomic number 90 (thorium) or greater.

actinide source term—cumulative amounts, concentrations in solution, and chemical nature of all radioactive materials to be disposed of at WIPP, which could be moved in solution or suspension (or retarded by sorption on surrounding rock units) from the WIPP repository into the environment.

advection—solute-transport process in which chemical species are carried through an aquifer by the flowing ground water in which they are dissolved.

anhydrite—anhydrous calcium sulfate.

aquifer—formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Becquerel—radiation unit equal to one disintegration per second.

Castile Formation—oldest of the Ochoan sequence of rocks, consisting of alternating layers of anhydrite and thin layers of limestone, with several thick layers of halite. At depth, highly pressurized pockets of brine have been found in this formation.

clastic—term describing rocks or sediments made up of fragments of other rocks. For example, sandstone and shale are clastic rocks.

colloid—particles of size ranging from 10^{-3} to 1 micron (10^{-9} to 10^{-6} m), finer than clay size, and held in suspension in a medium such as water. Because of their fine size, colloids have very large surface areas.

committed effective dose—a measure of human exposure to radioactivity. An ingestion of, inhalation of, or direct contact with radionuclides deposits energy from radioactive decays into bodily tissues. This absorbed dose is multiplied by a weighting factor dependent on the type of radiation to calculate an equivalent dose. The weighted sum of equivalent doses to all bodily tissues and summed over the time of exposure is the committed effective dose, measured in rem. The SI unit, the Sievert (Sv), is equivalent to 100 rem.

compartmentation—filling of tunnels and drifts around rooms and panels, so that the waste is isolated in compartments.

complex—stable association of a metal ion with one or more bulky groups (ligands), resulting in a profound change in the properties of the ion.

corrensite—clay mineral with a structure that represents interstratification of vermiculite and chlorite structures.

creep—slow movement over time of salt as shear stresses cause movement within or between individual crystals.

Culebra Dolomite—second-oldest member of the Rustler Formation ranging from approximately 7-8 m thick at the WIPP site. The Culebra consists of dolomite with some clay minerals. Because it is a water-bearing unit, the Culebra is important to the ground–water flow model for the WIPP site.

curie—measure of the quantity of radioactive material in a sample, equal to 3.7×10^{10} disintegrations per second.

Darcy's law—empirical hydraulic principle stating that the flow rate of a fluid through a porous material is proportional to the hydraulic gradient and the hydraulic conductivity of the material.

Darcy velocity—volumetric flow rate per unit surface area of sample, on the assumption that flow is laminar and that inertia can be neglected. This is more properly called the "specific discharge."

Delaware Basin—sedimentary basin in which the WIPP site is located. The Delaware Basin formed in a Permian sea and was gradually filled with thick, extensive layers of sediments and evaporite deposits.

Dewey Lake Red Beds—youngest of the Ochoan series of rocks, consisting of thin beds of clay, silt, and sandy sediments, red in color.

diffusion length—distance over which chemical species diffuse, or spread out and thoroughly mix, over a period of time, approximated as the square root of the product of diffusivity and time.

distribution coefficient—ratio of the amount of a substance sorbed to the amount in solution when chemical equilibrium exists (also see isotherm); ratio of the concentrations of a substance in two phases at equilibrium.

disturbed repository performance—radionuclide releases from the repository as a result of reasonably foreseeable natural processes as well as inadvertent human intrusion.

disturbed rock zone (DRZ)—localized region of permeability consisting of microfractures in the salt. The DRZ is generated by stress concentrations at a new surface and spreads at a slow and decreasing rate from that surface.

dolomite—a sedimentary rock consisting mostly of the mineral dolomite, calcium magnesium carbonate.

effective porosity—fraction of interconnected void space per unit volume of porous material. It is less than the total porosity because it includes only pores that comprise active flow paths through the medium and excludes voids in isolated or dead-end pores.

Eh—measure of the oxidation-reduction state of a solution.

electrical resistivity—characteristic of a solution depending on the concentration of ions in the solution and measured as the resistance of a centimeter cube of a substance to the passage of a current perpendicular to two parallel faces of the cube.

EPA unit— isotopic-specific unit of measure, used by Sandia National Laboratories, that is equal to the number of curies represented by the release limit of the EPA requirements in 40 CFR part 191.

evaporite—natural deposit of water-soluble salts formed by the evaporation of a body of water.

flocculation—aggregation or clumping together of particles suspended in solution so that they precipitate.

flow path—pathway a particle of ground water would travel, starting from a specified point.

halite—common rock salt, with chemical formula NaCl.

half-life—time required for 50 percent of any amount of a radioactive element to decay.

high-level waste—radioactive waste resulting from the reprocessing of spent fuel rods from nuclear reactors, or of other radioactive materials used for defense purposes.

human intrusion—inadvertent creation of a radiation pathway by human actions.

hydraulic conductivity—capacity for a porous medium to conduct water; defined formally as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow through a porous material. This coefficient incorporates the properties of both the porous medium and the liquid.

hydraulic diffusivity—K/S_s, where K is hydraulic conductivity and S_s is specific storage. It represents the hydraulic conductivity (K) of a saturated porous medium when the unit volume of water diffusing is that involved in changing the head of a unit amount in a unit volume of medium. The time involved for a given head change to occur at a particular point in response to a greater change in head at another point is inversely proportional to the hydraulic diffusivity.

hydraulic gradient—change in static (or hydraulic) head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

hydraulic head—height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point. The hydraulic head is the sum of the elevation head and the pressure head. Under conditions to which Darcy's law may be applied, the velocity of ground-water flow is so low that the velocity head is negligible. Stated more simply, hydraulic head is the height of free surface of water above a given subsurface point.

hydrostatic pressure—pressure exerted in all directions by a body of water at rest.

hydrostratigraphic unit—formation, part of a formation, or group of formations of considerable lateral extent that compose the geologic framework for a reasonably distinct hydrologic system.

ionic strength—half the sum of the products of molality and square of charge for each ion in a solution.

ionization—any process by which an atom, molecule, or ion gains or loses electrons.

ionizing radiation—radiation consisting of directly ionizing particles.

isotherm—line or curve describing the relation between the amount of a substance sorbed and the amount in solution when the chemical system is in equilibrium. The relation is typically very sensitive to temperature changes, so data used to construct such a curve are normally based on experiments conducted at a constant temperature—hence, the name isotherm. The slope of a linear isotherm is often called a distribution coefficient.

isotropic—equal in all directions.

kinetics—general term for rates of reaction.

langbeinite—potash mineral with chemical formula $K_2Mg_2(SO_4)_3$ of economic importance as a source of K_2SO_4.

ligand—compound or molecule in solution that can combine with the ion or molecule of an actinide to form a complex.

lithostatic pressure—pressure exerted by a column of overlying rock at a point in the earth's crust.

Magenta Dolomite Member—second-youngest member of the Rustler Formation, 7-8.5 m thick, consisting of dolomite with gypsum and bearing ground water.

marker bed—horizontally extensive nonhalite interbed in the Salado, numbered from the top of the Salado to the bottom and used to keep the repository at the same level within the Salado.

matrix diffusion—transfer of solute mass by diffusion, driven by a concentration gradient, between an actively flowing part of a ground–water system and low-permeability (often stagnant) parts of the saturated medium. An example is diffusion from a high-permeability fracture into dead-end pores of the adjacent rock matrix.

McNutt Member—a 120-m-thick series of beds midway between the top and bottom of the Salado Formation, which lies stratigraphically above the WIPP repository. The McNutt member contains economically significant potash deposits that have been mined in the area for many years.

molality—number of moles of solute per 1,000 g of solvent in a solution.

Nash Draw—broad shallow valley that developed as a stream channel at the end of the Pleistocene (1.6 million to 10,000 years ago) glaciation. Rocks of the Rustler Formation are exposed in the walls of the Nash Draw.

numerical dispersion—artificial smearing of calculated gradients in a dependent variable (such as concentration) that results from discretization in a numerical solution to the governing partial differential equations (such as the solute-transport equation).

Ochoan—Late Permian stratigraphic series consisting of, from lowermost to uppermost, the Castile, Salado, Rustler, and Dewey Lake Formations.

Ostwald's step rule—rule stating that an unstable phase passes through successive steps of increasing stability as it becomes a final stable phase.

parameter—an algebraic symbol representative of a well defined physical quantity with a numerical value. An adjustable parameter is envisioned to assume any value within its range (between the maximum and minimum numerical bounds). Any particular choice of a value renders a parameter a numerical constant.

Pennsylvanian Period—period of time from 320 million to 286 million years ago.

permeability—capacity of a material to transmit fluids. A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. Permeability depends on the size, shape, and degree of interconnectedness of pores and is generally measured in millidarcies. It is a property of the medium alone and independent of the nature of the liquid.

performance assessment—risk-based assessment of the safety performance of a nuclear waste facility.

Permian Period—period of time from 286 million to 245 million years ago[1].

pH—measure of the acidity of a solution phase; negative logarithm of the hydrogen ion concentration.

[1]Older geologic dating extended the Permian to 225 Ma; more recent methods date the end as 245 Ma.

Pitzer parameters—correction factors for calculating solubilities in strong electrolyte solutions.

potash—group of potassium salts, mined for various uses including plant fertilizers.

potentiometric elevation—elevation that represents the hydraulic head. For an aquifer, it is defined by the level to which water will rise in a tightly cased well. The water table is a particular potentiometric surface.

radiolysis—decomposition brought about by high-energy irradiation.

radionuclide—radioactive nuclide.

recharge—addition of water to the saturated zone; either natural or artificial.

redox potential—number specifying the "oxidation state" of a solution or, alternatively stated, a measure of the ability of a natural environment to control the equilibrium of oxidation-reduction reactions. Redox potential is a synonym for oxidation potential.

retardation factor—in solute-transport analysis, a parameter that describes the ratio of the net apparent velocity of the concentration of a particular chemical species to the velocity of a nonreactive species (or of water). It is proportional to the slope of a sorption isotherm; thus, if the isotherm is nonlinear, the retardation factor is not constant and depends on solute concentration.

risk—probability of a selected set of consequences from the existence of a hazard (e.g., nuclear waste in a repository) or the operation of a facility.

Rustler Formation—second youngest Ochoan formation, overlying the Salado Formation, and consisting of five sequences (members) of thin-bedded strata. The lowermost beds consist of mudstone and sandstone interbedded with evaporites. The upper part of the formation consists of alternating evaporite and dolomite beds. The Culebra Dolomite Member is the second member from the bottom of the formation. The total thickness of the Rustler Formation near the WIPP site is approximately 100 m.

safety—protection against the adverse health effects of hazards (such as radiation and chemicals), regardless of cause.

Salado Formation—second-oldest Ochoan geologic formation consisting of a 230-million year old deposit of rock salt (halite) in near-horizontal beds, in total 200-400 m thick. Very thin layers of clay, anhydrite, and potash minerals are interbedded with the halite beds. Lying at a depth of approximately 660 m (2,160 ft) at the WIPP site, the Salado hosts the WIPP repository.

saturated zone—that part of the water-bearing material in which all voids are filled with water under pressure greater than atmospheric.

sorbing tracer tests—field experiments designed to measure the amount of sorption of a substance.

sorption—chemical reaction processes that result in the accumulation of ions and molecules at a fluid-solid interface. Sorption depends on the balance between the affinity of a substance for a surface and its affinity for an aqueous solution. The term is sometimes used in a general sense to include ion exchange, surface complexation, and surface precipitation.

spalling/spallation—breaking off of very thin sheets from a rock surface.

specific discharge—rate of discharge of ground water per unit area measured at right angles to the direction of flow (see also Darcy velocity).

specific storage—volume of water released from or taken into storage per unit volume of a porous medium per unit change in head. This property is normally considered in problems of three-

dimensional transient flow in a compressible ground–water system.

specific weight—mass per unit volume of a substance.

storativity (or storage coefficient)—volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

sylvite—potash mineral with chemical formula KCl, the principal ore of potassium.

tortuosity—ratio of the length of a fluid particle's path to the length of a straight line between the beginning and ending points of the path. According to this definition, the tortuosity will always have a value greater than one. Note that tortuosity is sometimes defined on the basis of an inverse of this relation; in such cases it will always have a value less than one.

transmissivity—rate at which water of prevailing properties is transmitted through a unit width of an aquifer under a unit hydraulic gradient. For horizontal flow in a homogeneous aquifer, it is equal to the hydraulic conductivity times the saturated thickness. Transmissivity is measured in units of length squared per time (e.g., m^2/s).

transuranic waste—radioactive waste consisting of radionuclides with atomic numbers greater than 92 in excess of agreed limits. A more precise definition, in DOE Order 5820.2A, EPA regulation 40 CFR 191, and the Land Withdrawal Act, is waste that is not high level waste that is "contaminated with alpha-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram." The regulatory definition excludes actinide elements with atomic numbers between 90 and 92 (most significantly, Th and U isotopes), which is in agreement with the literal meaning of "transuranic." However, common usage of "transuranic waste" is often understood to include all actinides.

undisturbed repository performance—radionuclide releases from the repository as a result of reasonably foreseeable natural processes

unsaturated zone—subsurface zone above the water table in which some of the pore spaces are occupied by air and some by water.

waste characterization—process of identifying and classifying the chemical, physical, and radiological constituents of each drum of waste.

waterflooding—technique used in the secondary recovery of petroleum and gas whereby water is injected into a petroleum or gas reservoir so that the pressure of the water expels the petroleum or gas.

water table—surface in an unconfined ground–water system at which the pressure is atmospheric, in the field environment defined by the levels at which water stands in wells that penetrate the saturated zone just far enough to hold standing water.

Appendix J

List of Acronyms and Symbols

ε	effective porosity
AEA	Atomic Energy Act
AEC	Atomic Energy Commission
AST	actinide source term
BRAGFLO	computer code modeling regional hydrology
CAO	U.S. Department of Energy Carlsbad Area Office
c.c.c.	critical coagulation concentration
CCDF	complementary cumulative distribution function
CH	contact handled
Ci	curie
DCCA	Draft Compliance Certification Application
DEIS	Draft Environmental Impact Statement
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
E1	a scenario in which the WIPP repository is breached by one borehole extending down to a Castille brine pocket
E1E2	a scenario in which the WIPP repository is breached by two boreholes, one extending down to a Castille brine pocket and sealed above the repository horizon, and the other providing a flow path above the Salado
EACBS	Engineered Alternatives Cost/Benefit Study
EAMP	Engineered Alternatives Multidisciplinary Panel
EATF	Engineered Alternatives Task Force
EEG	State of New Mexico Environmental Evaluation Group
EPA	U.S. Environmental Protection Agency
ERDA	Energy Research and Development Administration
FEPs	features, events, and processes
GI	gastrointestinal
HI	human intrusion
HYDROCOIN	International Hydrologic Code Intercomparison Project
INTRAVAL	International Project to Study Validation of Geosphere Transport Models
K_d	distribution coefficient
LANL	Los Alamos National Laboratory
LWA	Land Withdrawal Act
Ma	millions of years ago
MB	marker bed
MPa	megapascal
MTHM	metric tons of heavy metal
NAS	National Academy of Sciences
NMED	New Mexico Environment Department
NRC	National Research Council
ONWI	Office of Nuclear Waste Isolation
PA	performance assessment
QA	quality assurance
RCRA	Resource Conservation and Recovery Act
R_f	retardation factor
RH	Remote handled
SECO	computer code used in modeling hydrology
SIT	specific-ion interaction theory
SNL	Sandia National Laboratories
SPM	systems prioritization method
STTP	Source Term Test Program
TRU	literally, transuranic (i.e., with atomic number greater than that of uranium); however, TRU waste is commonly used to refer to all actinide-bearing waste (i.e., containing thorium and uranium isotopes)
VOC	volatile organic compound
WIPP	Waste Isolation Pilot Plant

Appendix K

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Improving Operations AND Long-Term Safety OF THE Waste Isolation Pilot Plant

Final Report

Committee on the Waste Isolation Pilot Plant
Board on Radioactive Waste Management
Division on Earth and Life Studies
National Research Council

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Cover: The four drawings on the left represent the natural process of salt encapsulating transuranic waste drums in the WIPP repository. From top to bottom, the chronological sequence is 0 years, 10-15 years, 50 years, and 1,000 and more years (Hansen et al., 1997). Reproduced with permission. The image in the center shows a sample of Permian age salt crystals, about 225 million years old, taken from the WIPP excavations. The picture on the right shows typical scenery in proximity to the WIPP repository.

Back cover: Picture of three trucks transporting transuranic waste to the WIPP. *Source:* DOE.

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Finally, the committee wishes to thank Barbara Pastina, Angela Taylor, and Kevin Crowley, staff of the National Research Council's Board on Radioactive Waste Management, Thomas Kiess, former staff officer and study director, and Elizabeth Ward of Garrick Consulting for great team effort to support this project.

List of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Frank L. Parker, Vanderbilt University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Preface

This study was sponsored by the U.S. Department of Energy (DOE) Carlsbad Field Office, formerly known as Carlsbad Area Office (CAO). To accomplish this project, the National Research Council (NRC) empanelled a 15-member committee on the Waste Isolation Pilot Plant (WIPP). Committee members were chosen for their expertise in relevant technical disciplines such as nuclear engineering, health physics, chemical and environmental engineering, civil and transportation engineering, performance assessment, analytical chemistry, materials science and engineering, plutonium geochemistry, hydrogeology, rock and fracture mechanics, petroleum engineering, and mining engineering. The committee is operated under the auspices of the Board on Radioactive Waste Management of the NRC.

The first committee on the Waste Isolation Pilot Plant was formed in 1978, at the request of the DOE, to provide scientific and technical evaluations of the investigations at the WIPP. That committee functioned as a standing committee until late 1996 at which time it published its final report (NRC, 1996a), *The Waste Isolation Pilot Plant, A Potential Solution for the Disposal of Transuranic Waste.*[1] This was the last report of the committee prior to certification of the site. The committee concluded that "human exposure to radionuclide releases from transuranic waste disposed in the WIPP is likely to be low compared to U.S. and international standards." The report went on to say, "The only known possibilities of serious release of radionuclides appear to be from poor seals or some form of future human activity that results in intrusion into the repository." The report recommended that "speculative scenarios of human intrusion should not be used as the sole or primary basis on which to judge the acceptability of the WIPP (and, by extension, any geological repository)."

Following the publication of the 1996 report, this WIPP committee was created to carry out the statement of task reported in Sidebar P.1. The committee has produced two reports to cover the statement of task, an interim report published in April 2000 and this final report. The complete interim report has been reproduced as Appendix A1.

[1] Transuranic (TRU) waste is waste contaminated with alpha-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram. For more details see Sidebar 1.2 and the glossary.

Sidebar P.1 Statement of Task

The purpose of this study is to identify the limiting technical components of the WIPP program, with a twofold goal of (i) improving the understanding of long-term performance of the repository and (ii) identifying technical options for improvements to the National Transuranic (TRU) Program (i.e., the engineering system that defines TRU waste handling operations that are needed for these wastes to go from their current storage locations to the final repository destination) without compromising safety.

To accomplish this goal, the study will address two major issues:

1. The first is to identify research activities that would enhance the assessment of long-term repository performance. This study would examine the performance assessment models used to calculate hypothetical long-term releases of radioactivity, and would suggest future scientific and technical work that could reduce uncertainties.

2. The second is to identify areas for improvement in the TRU waste management system that may increase system throughput, efficiency, cost effectiveness, or safety to workers and the public. This study will examine, among other inputs, the current plans for TRU waste handling, characterization, treatment, packaging, and transportation.

In October 2000, the DOE provided a comprehensive response to the recommendations made in the interim report. The response is reported in Appendix A2. The committee is very encouraged by the quality of the responses and the actions the DOE is taking. Although the responses will not have a full impact on this final publication because of the report's tight schedule, the committee has been able to acknowledge a number of them in this report.

As is the normal practice of the National Academies, committee members do not represent the views of their institutions but form an independent body to author the report using the information gathered together with their collective knowledge and experience. The report reflects a consensus of the committee and has been reviewed in accordance with NRC procedures.

B. John Garrick, *Chair*
Committee on the Waste Isolation Pilot Plant
April 2001

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Executive Summary

The Waste Isolation Pilot Plant (WIPP) is a deep underground mined facility for the disposal of transuranic waste resulting from the nation's defense program. Transuranic waste is defined as waste contaminated with transuranic radionuclides with half-life greater than 20 years and activity greater than 100 nanocuries per gram. The waste mainly consists of contaminated protective clothing, rags, old tools and equipment, pieces of dismantled buildings, chemical residues, and scrap materials. The total activity of the waste expected to be disposed at the WIPP is estimated to be approximately 7 million curies, including 12,900 kilograms of plutonium distributed throughout the waste in very dilute form. The WIPP is located near the community of Carlsbad, in southeastern New Mexico. The geological setting is a 600-meter thick, 250 million-year-old saltbed, the Salado Formation, lying 660 meters below the surface.

The National Research Council (NRC) has been providing the U.S. Department of Energy (DOE) scientific and technical evaluations of the WIPP since 1978. This is the first full NRC report issued following the certification of the facility by the U.S. Environmental Protection Agency (EPA) on May 18, 1998. An interim report was issued by the committee in April 2000 and is reproduced in this report as Appendix A1. The main findings and recommendations from the interim report have been incorporated into the body of this report.

The committee's task is twofold: (1) to identify technical issues that can be addressed to enhance confidence in the safe and long-term performance of the repository and (2) to identify opportunities for improving the National Transuranic (TRU) Program for waste management, especially with regard to the safety of workers and the public. The complete statement of task is reported in Sidebar P.1 of the Preface.

The **overarching finding and recommendation** of this report is that the activity that would best enhance confidence in the safe and long-term performance of the repository is to monitor critical performance parameters during the long pre-closure phase of repository operations (35 to possibly 100 years). Indeed, in the first 50 to 100 years the rates of important processes such as salt creep, brine inflow (if any), and microbial activity are predicted to be the highest and will be less significant later. The committee recommends that the results of the on-site monitoring program be used to improve the performance assessment for recertification purposes. These results will determine whether the need for a new performance assessment is warranted. For the National TRU Program, the committee finds that the DOE is

implementing many of the recommendations of its interim report. It is important that the DOE continue its efforts to improve the packaging, characterization, and transportation of the transuranic waste.

The committee's **specific findings and recommendations** have been grouped into three categories: (1) site performance, (2) site characterization, and (3) the National TRU Program.

SITE PERFORMANCE

Every five years, the WIPP must obtain recertification from the EPA by showing that the repository is performing as predicted. Site performance refers to activities, phenomena, or events that occur as a result of repository construction and waste emplacement in the time frame between placement of the waste and final sealing[1] of the repository shaft. Site performance has been evaluated by the DOE in its Compliance Certification Application (CCA) (DOE, 1996). The CCA relies on a model, called a "performance assessment," that calculates the probability and consequence of several scenarios by which radionuclides could be released into the environment. The performance assessment also identifies the major uncertainties and their impact on the overall performance of the system. To reduce some of the uncertainties in the performance assessment and to add confidence in the containment performance of the repository, *the committee recommends taking advantage of the long (35 to possibly 100 years) pre-closure operating period to monitor selected performance indicators,* including those listed below:

1. Brine migration is a key issue because it provides the most realistic mechanism for mobilizing and transporting radionuclides from the waste. The mixing of brine and waste could also result in the generation of gas in the repository. **The committee recommends pre-closure monitoring to gain information on brine migration and moisture access to the repository. Observation should continue at least until the repository shafts are sealed and longer if possible. The committee recommends that the results of the on-site monitoring program be used to improve the performance assessment for recertification purposes.**

2. Gas pressure generation is an important issue in the assessment of human intrusion scenarios. In the committee's opinion, there are uncertainties in some of the assumptions about gas generation used in the performance assessment of the CCA. **The committee recommends pre-closure monitoring of gas generation rates, as well as of the volume of hydrogen, carbon dioxide, and methane produced. Such monitoring could enhance confidence in the performance of the repository, especially if no gas generation is observed. Observation should continue at least until the repository shafts are sealed and longer if possible. The results of the gas generation monitoring program should be used to improve the performance assessment for recertification purposes.**

3. Magnesium oxide (MgO) is used as backfill in WIPP to provide some control of the chemical environment of the waste and, to a lesser extent, to fill voids in the disposal locations, thus enhancing the healing process. The chemical performance of MgO depends on gas generation and brine inflow as well as other chemical processes taking place in the repository. The committee finds that there is uncertainty about the effectiveness of MgO in controlling the chemical environment of the waste. Therefore, **the**

[1] The terms "sealing" and "healing" are both used in this report in relation to the repository. Repository sealing refers to the emplacement of engineered barriers preventing access or leakage to and from the repository. Repository healing indicates a natural process by which the mined salt creeps in around the waste to fill all the void spaces in the repository. See also "salt creep" and "engineered barriers" in the Glossary.

committee recommends that the net benefit of MgO used as backfill be reevaluated. The option to discontinue emplacement of MgO should be considered.

4. Deformation of rock salt and interaction of salt with TRU waste containers are of interest as a part of the pre-closure performance confirmation. The creep of salt is expected to entomb the waste drums in 100 to 150 years; thus, the radionuclide mobility values used in the performance assessment might have been overestimated. This implies less migration of radionuclides from the repository into the environment. **The committee recommends pre-closure monitoring of the status of room deformation and of the disturbed rock zone[2] (DRZ) healing. Seal performance should also be assessed. Observation should continue at least until the repository shafts are sealed and longer if possible. The results of the monitoring of room deformation and DRZ healing should be included in the PA and used for recertification purposes.**

SITE CHARACTERIZATION

The WIPP program has engaged in a comprehensive program of site characterization that, in general, has been adequate to support certification of the facility. *The committee identified four areas in which additional site characterization or monitoring is recommended.* The four site characterization programs are described below:

1. A program for the hydrologic characterization of the Culebra, the most transmissive unit in the Rustler Formation. The Culebra could provide a pathway for the release of radionuclides into the environment in the event of human intrusion. **The committee recommends a monitoring program to characterize the geohydrology of the Culebra Dolomite. Tests and measurements that should be considered include angled boreholes, natural gradient tracer tests, and additional pump or injection tests. These new data should be used to confirm, or modify, the conceptual and numerical models now proposed as reasonable simulation of the actual system.**

2. A program for the detection of deep brine reservoirs below the waste disposal horizon. To improve site characterization and increase confidence in repository performance in view of the recertification application, **the committee recommends the use of seismic survey techniques for detecting large brine reservoirs below the repository.[3] In case a brine reservoir were found beneath the WIPP and its size were larger than what is already taken into account in the PA, then the DOE should conduct an extensive review of the impact of such reservoir on the repository performance. A basis would then exist to take appropriate action to ensure the safety of the repository.**

3. A program for monitoring oil, gas, and mineral production in the area. Oil, gas, and mineral extraction activities in the vicinity of the repository could threaten its integrity. **The committee recommends the development of a database to collect information on drilling, production enhancement,**

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[2] The disturbed rock zone is the zone around an excavation, in the host rock salt, where the stress field has been modified sufficiently to cause the formation of microfractures in the rock salt.

[3] The committee recognizes that small brine reservoirs, including brine occurring as a saturated continuum, could not be detected by seismic surveys, or other noninvasive remote sensing techniques.

mining operations, well abandonments, and unusual events (accidents and natural events) in the vicinity of the WIPP site.

4. A program for establishing the baseline for naturally occurring radioactive material (NORM) in subsurface brines and hydrocarbons in the vicinity of the site. The NRC interim report recommended that the DOE develop and implement a plan to sample oil-field brines, petroleum, and solids associated with current hydrocarbon production to identify the background concentrations of naturally occurring radioactive material in the vicinity of the WIPP site, for baselining purposes. In response to this recommendation, the DOE has started to collect data and is developing a database on NORM. **The committee recommends that the DOE continue the implementation of its plan to sample oil-field brines, petroleum, and solids associated with current and future hydrocarbon production, as necessary to assess the magnitude and variability of NORM in the vicinity of the WIPP site for baselining purposes.**

THE NATIONAL TRU PROGRAM

The National TRU Program, administered by the DOE Carlsbad Field Office, is a program to accommodate all applicable external regulations and internal requirements that are associated with the characterization, certification, packaging, and transportation of TRU waste to the WIPP facility. The committee addressed two main issues pertaining to the National TRU Program: (1) waste characterization and packaging and (2) waste transportation.

Waste Characterization and Packaging

The committee reviewed some of *the waste characterization and packaging requirements* established by the National TRU Program from a safety and cost point of view. This issue was detailed in the committee's interim report. A new issue concerning the *total inventory of organic material allowed in the repository* surfaced after the committee visited the WIPP site.

1. Waste characterization and packaging requirements. A principal finding of the interim report (Appendix A1) was that many requirements and specifications having to do with waste characterization and packaging lacked a safety or legal basis. In fact, the committee concluded that some of the requirements penalized the program by adding unnecessary costs and safety risks. Examples of self-imposed waste characterization requirements are waste repackaging to dilute the hydrogen-producing components and visual examination to verify the content of waste drums and avoid miscertifications. Therefore, the committee recommended in the interim report that the DOE should eliminate self-imposed waste characterization requirements that lack a safety or legal basis. The DOE has responded to this recommendation by initiating a review of all waste characterization and packaging requirements (Appendix A2). **The committee recommends that the DOE's efforts to review waste characterization and packaging requirements continue and that changes be implemented over the entire National TRU Program. The committee recommends that the resources required to complete these improvements be made available by the DOE.**

2. Total inventory of organic materials allowed in the repository. Buried with the waste is a considerable inventory of organic materials, such as plastic film used to stabilize the drums, plastic bags and corrugated cardboard, wooden waste boxes, plastic liners of waste drums, and pressed wood "slip sheets."

The principal concern of the committee is that the DOE does not appear to keep an accurate inventory of such organic material. **The committee recommends a risk-based analysis of the total organic material regulatory limits in WIPP. If accounting for the organic material is important to the safety of the repository, an inventory record system should be implemented as soon as possible to provide a basis for meaningful safety analysis.**

Waste Transportation

The committee has examined various aspects of the WIPP TRU waste transportation system, focusing on system safety and the cost-effectiveness of planned and ongoing activities. In its interim report (Appendix A1), the committee reviewed DOE's TRANSportation Tracking and COMmunication (TRANSCOM) system and its emergency response program. In addition to the *DOE's communication and notification program* and its *emergency response training,* two other issues have been revisited in this report: the potential use of *rail as a transportation option for certain TRU waste,* and *gas generation safety analysis for Transuranic Package Transporter, Model II (TRUPACT-II) containers.*

1. DOE's communication and notification program. The committee's interim report (Appendix A1) reviewed the transportation system for WIPP waste and particularly addressed the issue of the DOE's communication and notification system TRANSCOM and its emergency response program. The committee raised questions about the reliability and ease of use of the TRANSCOM system. Meanwhile, the DOE appears to be moving systematically toward the implementation of an efficient, comprehensive, and state-of-the-art communication and notification system, called TRANSCOM 2000. **The committee recommends that the DOE implement as soon as possible the new TRANCOM 2000 communication and notification system. Moreover, because the human factor is an important element of transportation system quality, TRANSCOM 2000 should include methods to minimize the occurrence and impact of human errors.**

2. DOE's emergency response training. Although the committee is aware of the fact that the DOE is not directly responsible for the emergency response program, DOE should nevertheless identify the resources (e.g., responders, medical facilities, recovery equipment, response teams) that might be necessary to respond to a transportation incident. **The committee recommends that the DOE facilitate the involvement of states in developing and maintaining an up-to-date, practical, and cost-effective spatial information database system to coordinate emergency responses. The DOE should also develop an ongoing assessment program for states' emergency response capabilities and allocate training resources to address deficiencies in coverage along WIPP routes.**

3. Rail as a transportation option for certain TRU waste. Among the generator sites, some have rail-loadings and tracking capabilities that could be used for railway shipping of TRU waste to WIPP. The objective of the following recommendation is to minimize the number of road shipments, and therefore the related risk, and to optimize the waste load for shipments of inner waste packages that are unsuitable for placement in TRUPACT-II overpacks. **The committee recommends that all reasonable transportation options including reduction in the number of shipments, such as rail and road transportation with better-adapted containers, should be part of the decision-making process of transporting TRU waste from generator and storage sites to the WIPP. Future transportation studies should consider railway shipments and their impact on both the safety and the cost of the program. The**

DOE should also continue to pursue the development of packaging alternatives for materials not suitable for TRUPACT-II containers.

4. Gas generation safety analysis for TRUPACT-II containers. Hydrogen gas is generated in the shipping containers by radiolytic decomposition of the organic materials in waste during transportation of TRU waste to the WIPP. The root issue is the interpretation of the U.S. Nuclear Regulatory Commission's (USNRC's) regulations on shipments involving possible flammable gases. The questions of interpretation center around the allowed volume fractions of flammable gases and the definition of the confinement barrier. Depending on interpretation, the regulations can become a severe constraint on TRU waste shipments, with no apparent benefit. In particular, the committee was unable to verify the technical basis for some of the interpretations of the regulations as they relate to the safety of the workers and the public. **The committee recommends a risk-informed analysis of WIPP specific shipment issues to identify core problems related to hydrogen generation and, perhaps, provide a basis for alternative cost-effective criteria while reducing the risk. The committee recommends the use of such risk-informed analysis in the application for revision of the USNRC certificate of compliance concerning hydrogen generation limits for transportation purposes.**

1

Introduction

The Waste Isolation Pilot Plant (WIPP) is the world's first deep underground operational geological repository for the disposal of radioactive waste. The WIPP consists of an underground mined facility located in a 250 million-year-old bedded salt formation (the Salado Formation), which lies 660 meters below the surface in a semiarid desert near the community of Carlsbad, New Mexico. The WIPP repository has been established for the disposal of transuranic (TRU) waste resulting from the nation's defense program. The advantages of the WIPP as a transuranic waste disposal are listed in Sidebar 1.1. Figures 1.1-1.3 show the location, layout, and geologic stratigraphy of the WIPP.

Transuranic waste contains alpha-emitting radionuclides that have atomic numbers greater than 92, the atomic number of uranium, the heaviest natural element. The WIPP Land Withdrawal Act (LWA) (U.S. Congress, 1992) defined TRU waste as waste contaminated with transuranic radionuclides with half-life[1] greater than 20 years and activity greater than 100 nanocuries per gram. It mainly consists of contaminated protective clothing, rags, old tools and equipment, pieces of dismantled buildings, chemical residues, and scrap material. Tables 1.1 and 1.2 provide, respectively, the inventory of major radionuclides in the WIPP and the repository inventory by waste category. More details on transuranic waste are given in Sidebar 1.2. Figure 1.4 shows pictures of typical TRU waste. Even though the backfill magnesium oxide (MgO) appears in the repository inventory, it is not considered to be waste. Water is also not part of the waste inventory. There is only a negligible amount of water in the waste, mostly water vapor and less than 1 volume percent of free liquids as allowed by the Waste Acceptance Criteria (DOE, 1999).

Packed in 55-gallon steel drums and wooden boxes, TRU waste is currently being stored at various sites across the nation. The source of the waste is the manufacture of nuclear warheads and the cleanup of the nuclear weapons sites. The risks associated with transuranic waste are related primarily to plutonium. Plutonium's long half-life (24,000 years for plutonium-239)[2] and toxicity must be considered in assess-

[1] The half-life is the time required for half of the atoms of a radioactive substance to disintegrate.

[2] Plutonium-239 indicates the isotope of mass number 239 of the element plutonium. The same notation is used for other radionuclides throughout this report.

Sidebar 1.1 Why the WIPP?

The rationale for isolating nuclear wastes through deep geologic disposal is based on a large body of U.S. and international research. The National Academy of Sciences observed in 1957 (NRC, 1957): "The best means of long-term disposal . . . is deep geological emplacement. . . ." The Academy reaffirmed and expanded on this view in NRC (1984) and in NRC (1996a). The WIPP repository is carved out of a bedded salt formation, with the following features that make it ideal for transuranic waste disposal:

Dry environment. Large salt beds are found only in geologic regions that lack significant flows of groundwater. This deep, relatively dry underground environment greatly reduces the possibility that wastes could be carried out of a repository by natural processes. The saltbed at the WIPP site has been stable for 225 million years. It can be expected, with high confidence, to remain that way for many thousands of years into the future.

Waste immobilization. Salt tends to "heal" itself after being mined because it gradually creeps under the pressure from overlying earth and fills any openings. After several hundred years, the salt at the WIPP is expected to close in on the waste and lock it deep below the surface.

Since the mid-1970s, the Department of Energy (DOE) and its scientific adviser, Sandia National Laboratories, have studied the WIPP site to make sure it is a safe place to isolate transuranic waste. The WIPP addresses the following two key national needs:

Reducing risk. As long as transuranic waste remains at storage sites, there will be some level of risk to populations near these sites. Also, workers who must maintain current sites and monitor wastes are frequently exposed to low levels of radiation.

Providing disposal. The WIPP is a first-of-its-kind deep geologic disposal facility and will provide a model for radioactive waste disposal. In addition to the existing inventory of stored transuranic waste, estimated at about 2.32 million cubic feet, the WIPP will be the disposal site for more than 3.7 million cubic feet of transuranic waste expected to be generated during the next 35 years as DOE sites are closed. Under current law, the DOE is allowed to store 6.2 million cubic feet of transuranic waste at the WIPP. SOURCE: Citizens' Guide to the Compliance Certification Application (DOE, 1996b).

SOURCE: Citizens' Guide to the Compliance Certification Application (DOE, 1996b).

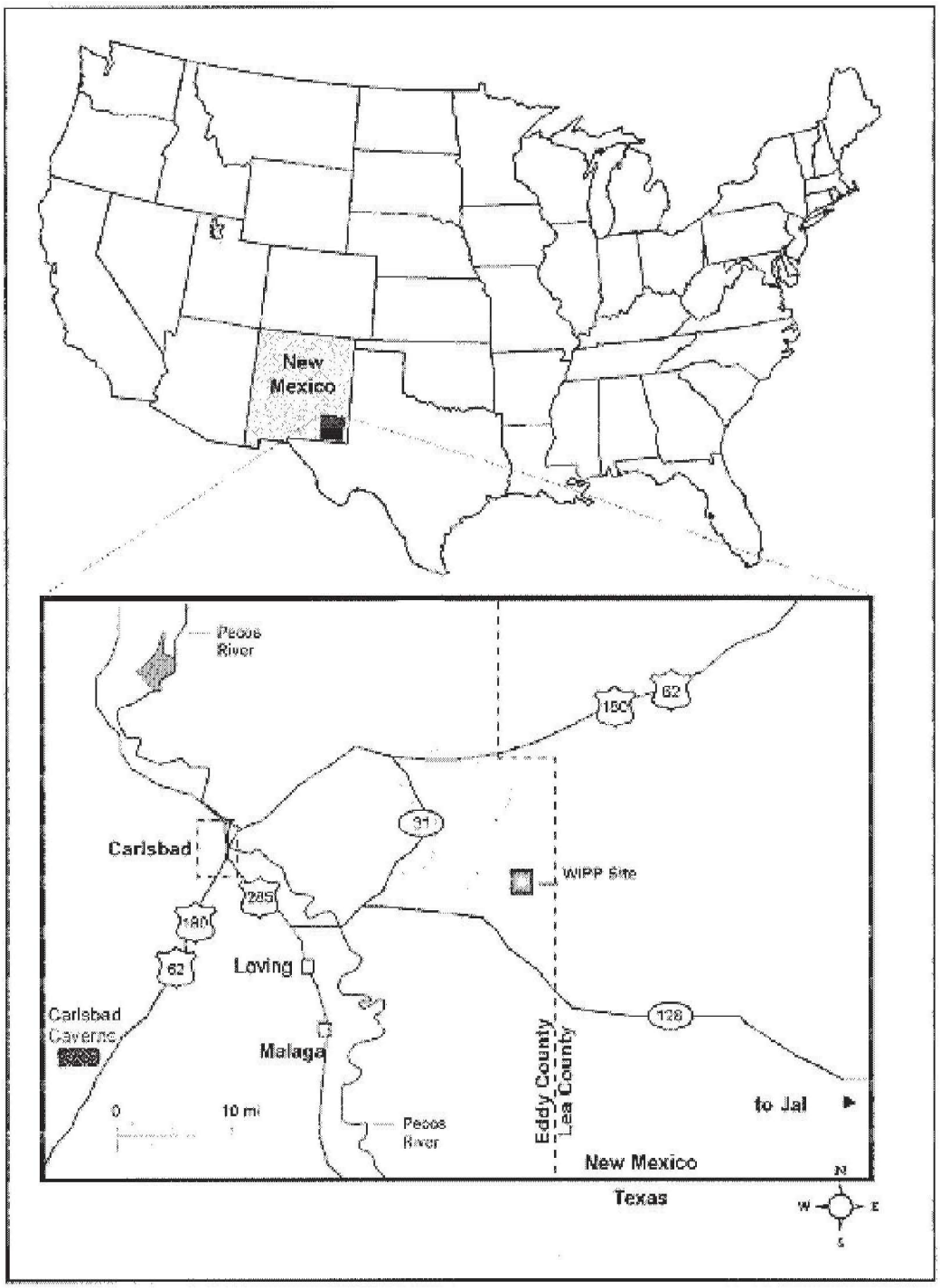

Figure 1.1 Location of the WIPP site. SOURCE: DOE, 2000g.

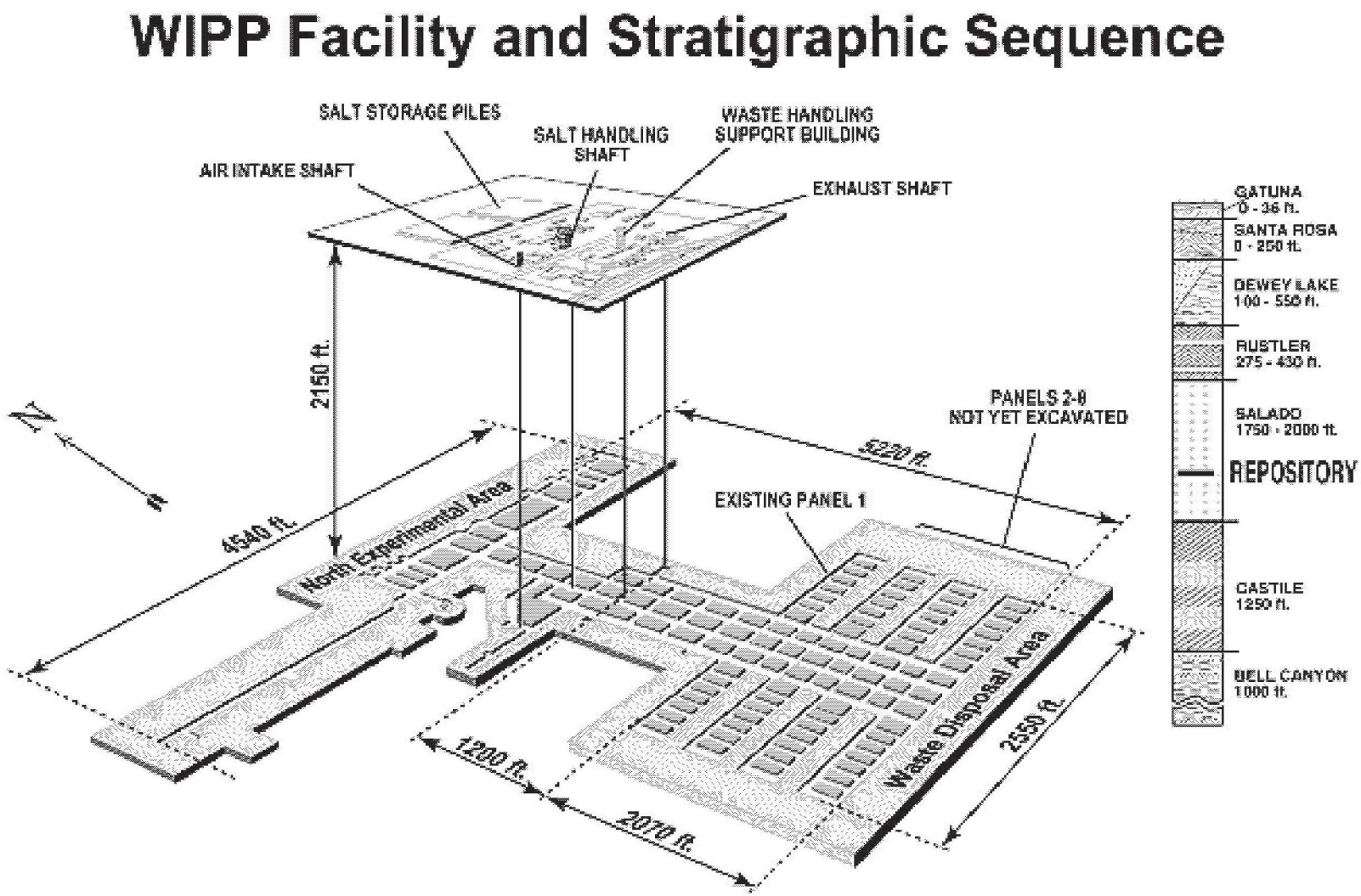

Figure 1.2 The WIPP facility and stratigraphic sequence. Panel 1 is currently in use. The mining of Panel 2 was completed on October 13, 2000. SOURCE: DOE, 2000h.

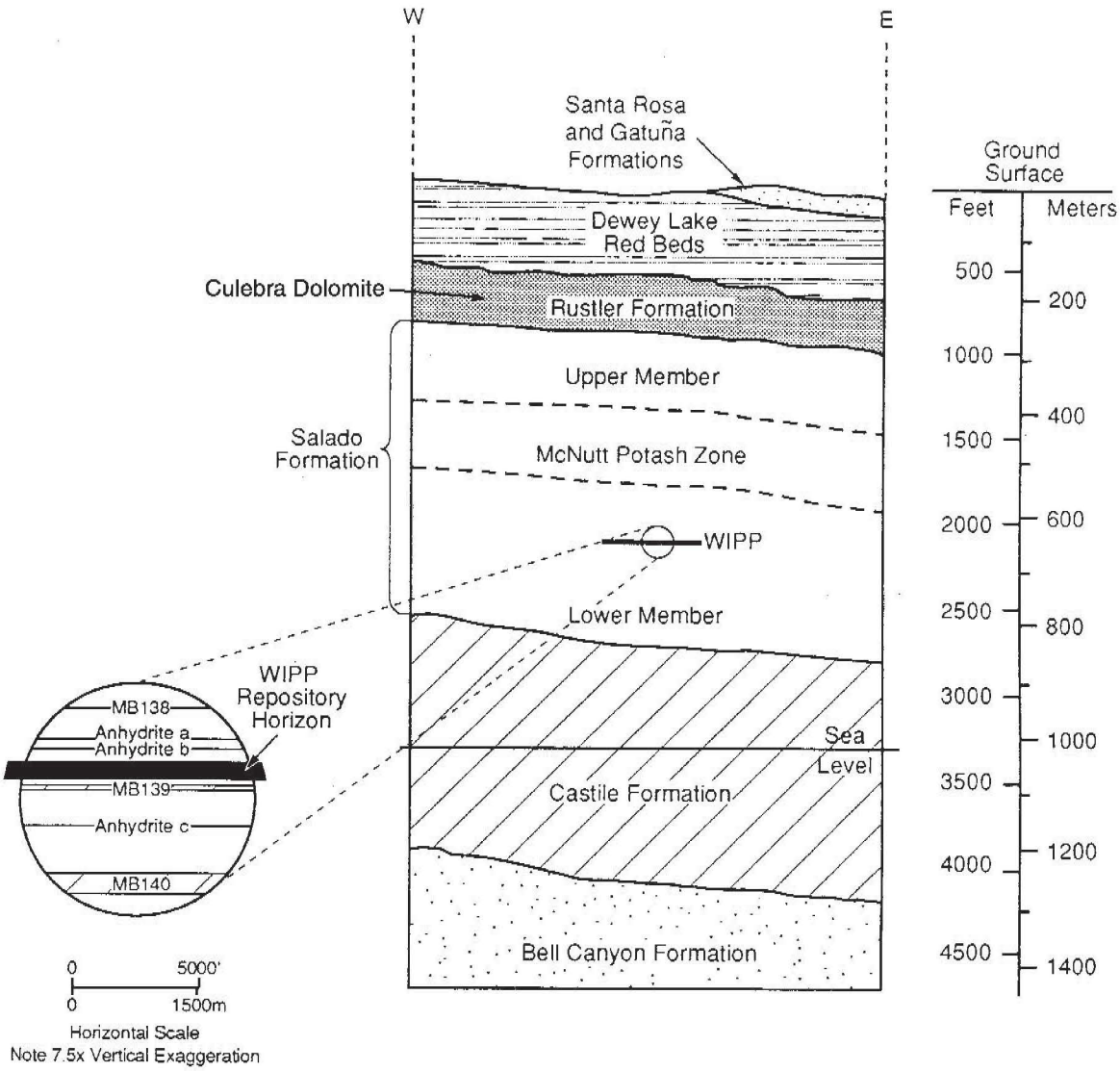

Figure 1.3 WIPP stratigraphy and depths of four key formations (Castile Formation, Salado Formation, Rustler Formation, and Dewey Lake Red Beds) including the position of the WIPP repository within the Salado. The Culebra Dolomite is one of the members of the Rustler Formation. It is approximately 7-8 meters thick at the WIPP site. Because it is a relatively transmissive unit, the Culebra is important to the groundwater flow model for the WIPP site. Inset shows finer-scale stratigraphy around the repository horizon, with marker beds and other thin beds. Adapted from Jensen et al. (1993).

Table 1.1 Inventory of the Most Abundant Radionuclides Expected in the Repository.[a]

Radionuclide	Contact Handled (CH)-Transuranic (TRU) Waste (Ci/m^3)	Remote Handled (RH)-Transuranic (TRU) Waste (Ci/m^3)
Am-241	2.62	0.842
Ba-137m	4.53×10^{-2}	28.9
Cm-244	0.187	4.45×10^{-2}
Co-60	3.83×10^{-4}	1.47
Cs-137	4.78×10^{-2}	30.5
Pu-238	15.5	0.205
Pu-239	4.66	1.45
Pu-240	1.25	0.715
Pu-241	13.7	20.0
Sr-90	4.07×10^{-2}	29.5
Y-90	4.07×10^{-2}	29.5

[a]The expected volumes of CH waste and RH waste are, respectively, 160,000 and 7,079 cubic meters.

SOURCE: DOE, 1996.

Table 1.2 Repository Inventory by Waste Category

Waste Category	Inventory (wt%)
Iron-based metal, alloys	14
Steel container material	12
Aluminum-based metal, alloys	1
Other metal, alloys	6
Other inorganic materials	3
Vitrified	5
Cellulosics	4
Rubber	1
Plastics	3
Plastic container or liner material	2
Solidified inorganic material (including cement)	4
Solidified organic material (not including cement)	0
Solidification cement	4
Soils	4
MgO backfill	37

SOURCE: Knowles et al., 2000.

ing not only the long-term risk of the WIPP, but also the potential radiation exposure of workers who handle, repackage, and transport the waste.

The WIPP has been under study since the mid-1970s, began construction in January 1981, was certified by the U.S. Environmental Protection Agency (EPA) in May 1998, and received its first transuranic waste shipment from the Los Alamos National Laboratory in March 1999. The first out-of-state shipment was received in June 1999 from the Rocky Flats Environmental Technology Site, and in September 2000, the first mixed-waste shipment was received from the Idaho National Engineering and Environmental Laboratory (INEEL). Figure 1.5 shows the main waste generators and the transportation routes to the WIPP.

Sidebar 1.2 What Is TRU Waste And How Is It Classified?

Transuranic waste is waste that contains alpha particle-emitting radionuclides with atomic numbers greater than that of uranium (92), half-lives greater than 20 years, and concentrations greater than 100 nanocuries per gram of waste. TRU waste is classified according to the radiation dose rate at package surface. As defined in the LWA, **contact-handled** (CH) TRU waste has a radiation dose rate at package surface not greater than 200 millirem per hour; this waste can safely be handled directly by personnel. **Remote-handled** (RH) TRU waste has a radiation dose rate at package surface of 200 millirem per hour or greater, but not more than 1,000 rem per hour (U.S. Congress, 1992); this waste must be handled remotely (i.e., with machinery designed to shield the handler from radiation). Alpha radiation is the primary factor in the radiation health hazard associated with TRU waste. Alpha radiation is not energetic enough to penetrate human skin but poses a health hazard if it is taken into the body (e.g., inhaled or ingested). In addition to alpha radiation, TRU waste also emits gamma and/or beta radiation, which can penetrate the human body and requires shielding during transport and handling. RH TRU waste has gamma and/or beta radiation-emitting radionuclides in greater quantities than exist in CH TRU waste (DOE, 2000a).

TRU waste is further classified as TRU waste or **mixed** TRU waste. Mixed TRU waste contains both radioactive materials regulated under the Atomic Energy Act and hazardous chemical compounds regulated under the Resource Conservation and Recovery Act.

The total activity of the waste expected to be disposed at the WIPP is estimated to be approximately 7 million curies (of which 6 million is from CH waste), including 12,900 kilograms of plutonium distributed throughout the waste in very dilute form. According to the Compliance Certification Application (CCA), the volume of CH waste expected in WIPP is 160,000 cubic meters and that of RH waste is 7,079 cubic meters (DOE, 1996).

The WIPP is designed to dispose of approximately 175,000 cubic meters of transuranic waste. Total activity of the waste is estimated to be approximately 7 million curies. The largest fraction of this activity comes from approximately 12,900 kilograms of plutonium distributed throughout the waste in very dilute form. TRU waste is classified as contact-handled (CH) and remote-handled (RH) waste, according to the radioactivity at the container surface [3] (see Sidebar 1.2). According to the National TRU Waste Management Plan, the disposal of RH waste will not begin before early 2002 (DOE, 2000a). Since most of the radioactivity is coming from the plutonium in CH waste (approximately 85 percent of the total curies inventory, see Table 1.1), the disposal of RH waste should not represent a significant added risk to the repository. A further issue concerning RH waste will be discussed in relation with the emplacement of backfill in Chapter 2.

This report presents the results of a National Research Council (NRC) study of operational, technical, and programmatic issues associated with the long-term performance of the WIPP. Previous studies

[3] This type of classification is intended for the protection of workers handling radioactive waste. Public health protection standards have also been taken into account in the design and operation of the WIPP.

Figure 1.4 Radiography of a transuranic waste drum. SOURCE: DOE, 2000i.

by the NRC's committee on the WIPP covered ongoing activities in preparation for the opening of the facility. This study is the first to address the WIPP as an operational repository.

The seeds for this report were planted during the preparation of the 1996 report by the previous WIPP committee (NRC, 1996a). That committee observed that the long operating period of the WIPP (at least 35 years and possibly much longer) provides an opportunity to conduct studies and investigations that would decrease some of the uncertainties about the long-term safety performance of the repository.

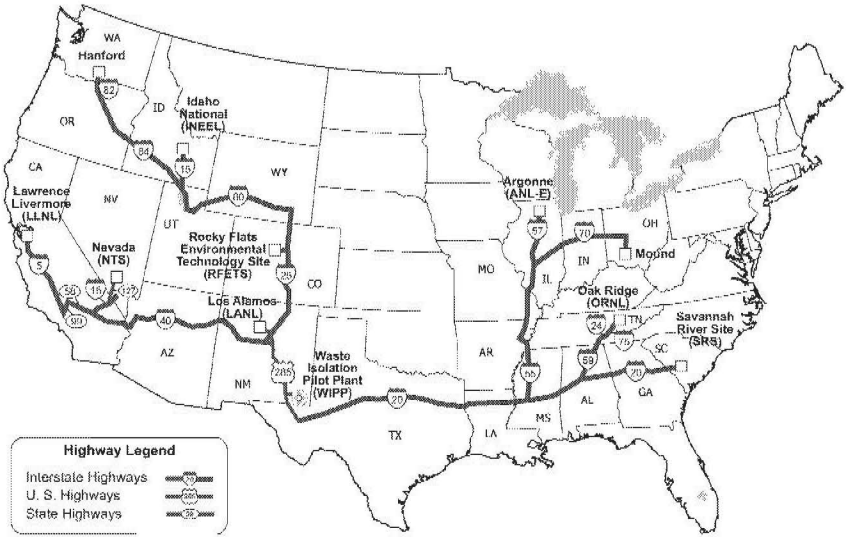

Figure 1.5 Defense transuranic waste generating and storage sites and primary transportation routes. SOURCE: DOE, 2000j.

Thus, this committee has focused on identifying studies and investigations "that would enhance the assessment of long-term repository performance," as noted in the statement of task in the Preface to this report. The second part of this committee's statement of task addresses potential improvements to the National Transuranic Waste Management Plan, also known as the National TRU Program. This program coordinates the management and disposal activities of TRU waste between the WIPP and the 23 generator sites. As written in the statement of task, the committee must "identify areas for improvement in the TRU waste management system that may increase system throughput, efficiency, cost-effectiveness, or safety to workers and the public." The result is the consideration of issues having to do with waste characterization, packaging requirements, waste transportation and handling, and emergency preparedness.

The two-part statement of task required very different skills and approaches: the first part is related to site performance, while the second is programmatic. The committee has chosen to structure this report into two primary sections that can be mapped directly to the two principal requirements of the statement of task. The part of the statement of task relevant to the long-term performance of the repository is addressed in the context of the repository performance confirmation program, in reference to enhancing confidence in the performance assessment models. The task relating to programmatic issues is addressed in the context of the National TRU Program.

SITE PERFORMANCE AND CHARACTERIZATION

To evaluate the long-term performance of the disposal system, the DOE uses a technique developed especially for predicting the behavior of geologic repositories over the thousands of years required for waste isolation. This technique is called "performance assessment." Performance assessment (PA) is a multidisciplinary, iterative, analytical process that begins by using available information that characterizes the waste and the disposal system (the design of the repository, the repository seals, and the natural barriers provided by the host rock and the surrounding formations). To obtain certification for the WIPP,

the DOE used the PA tool to estimate the releases of radionuclides within the first 10,000 years, based on the probabilities of relevant features, events, and processes occurring.

The performance of the repository has been assessed for two main scenarios: the undisturbed repository scenario and the human intrusion scenario. If the repository is left undisturbed, the only release pathway for radionuclide release into the environment is through leakage of brines containing radioactive materials into the environment. Scenarios for the disturbed case involve releases resulting from boreholes drilled inadvertently into the waste. According to the Land Withdrawal Act (U.S. Congress, 1992), the DOE must exercise active institutional controls[4] on a perimeter of land extending up to 5 kilometers from the boundaries of the WIPP site for 100 years after the closure of the repository. During this period, there will be no natural resource extraction activities in the site. Between 100 and 700 years after the closure of the repository, the site will be under passive institutional controls.[5] During this period, drilling activity is expected to resume and to reach its maximum after 700 years, when the land will be released to public use and the WIPP site will be no longer controlled. Uncontrolled extraction activities would increase the probability of drilling directly into the repository.

Sensitivity analyses are used by the DOE to determine which parameters of the disposal system exert the greatest effect on performance (DOE, 1996). Performance assessment calculations show that in the absence of human intrusion, brine inflow and gas generation are the most important parameters affecting the performance of the WIPP (Helton, 2000d). In the case of the disturbed scenario, the most important parameter is the borehole permeability (Helton, 2000e). Sidebar 1.3 describes the main results of the performance assessment and their implication for the long-term performance of the WIPP. For a complete review of the PA for the WIPP see Apostolakis et al. (2000). The containment requirements are set by the regulatory agency, the U.S. Environmental Protection Agency, and are listed in Sidebar 1.4. More information on regulatory compliance can be found in the previous NRC report on the WIPP (NRC, 1996a).

The EPA certified the WIPP on the basis of the performance assessment included in the Compliance Certification Application (CCA). While various mechanisms and scenarios, including their uncertainties, were considered in the performance assessment, the question now is how to enhance the degree of confidence expressed by the performance assessment results. The conceptual structure and the development of scenarios for the WIPP's PA are described respectively in reference Helton et al. (2000a) and Galson et al. (2000).

The uncertainties in the PA for the WIPP are analyzed in Helton et al. (2000b,c). The current committee on the WIPP believes that better knowledge of site performance and better site characterization are important in decreasing the uncertainties, and therefore possibly enhancing the confidence, in the performance assessment of the repository. The committee's approach to examining the PA was to focus on underlying assumptions and results of the performance assessment. Of particular interest to the committee was how the results could be impacted by uncertainties and relied upon EPA's certification for proof of the ability of the computer program to represent the model adequately. The issues and their uncertainties are discussed in Chapter 2 as site performance and site characterization issues.

THE NATIONAL TRANSURANIC PROGRAM

The National Transuranic Waste Management Plan, also known as the National TRU Program, is a plan that organizes the activities concerning storage, characterization, packaging, handling, transporta-

[4] Active institutional controls imply restrictions on land access or use.

[5] Passive institutional controls imply the identification of the controlled area through signs or markers; also, records are kept on the repository and land use.

Sidebar 1.3 Performance Assessment and Regulatory Acceptance

The Environmental Protection Agency's certification of the WIPP facility was based on the performance assessment submitted as a part of the U.S. Department of Energy's Compliance Certification Application. The regulatory basis for the PA for the WIPP is described in Howard et al. (2000). The PA is a computerized, mathematical model that evaluates the performance of the WIPP repository over its lifetime. The main results of this model are shown in Figure A below, and are compared there with the acceptance criterion established by the EPA shown as the line in the upper right corner. These requirements are reported in Sidebar 1.4. The horizontal axis is a measure *C*, of the total radioactivity released from the repository to the biosphere during its nominal 10,000-year lifetime. The vertical axis shows the "probability of release, " that is, at any value of *C*, the probability that the actual release from the repository will exceed that value. Such a curve is called a "complementary cumulative distribution function (CCDF)." It expresses quantitatively the state of knowledge of the analysis team about how much radioactivity will be released from the repository over its lifetime. It is important to observe that the curve is well to the left of the regulatory acceptance boundary set by the EPA, meaning that the repository is in compliance with the regulation.

A variation on this form of presentation is shown in Figure B. In this figure, a family of CCDFs is traced to show the different effects of uncertainties arising from possible human intrusions into the repository (mainly by drilling into it) and the geotechnical uncertainties (e.g., physical and chemical properties of the salt). Again, the important result is that the whole family of curves is well to the left of the EPA acceptance boundary. In addition, the curves bunched close together indicate a reasonable bound on the uncertainties and add confidence that a substantial margin of safety exists.

continued

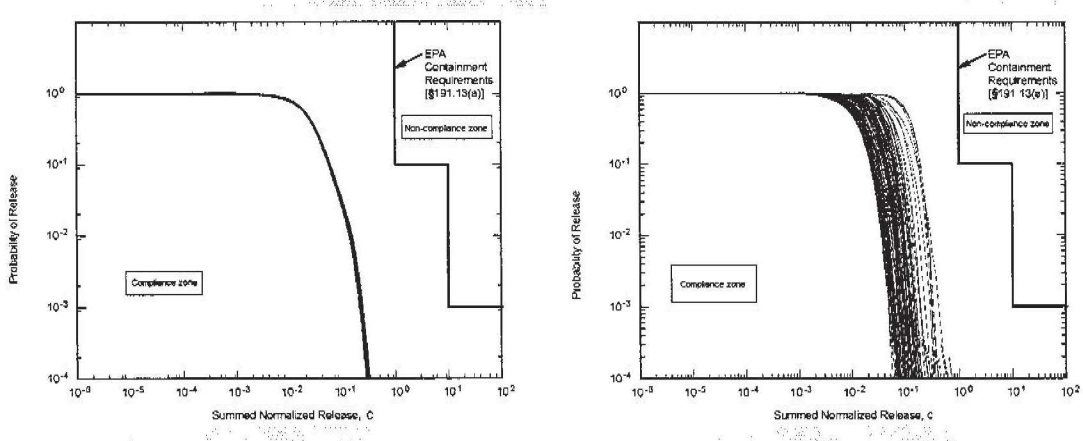

Figures A (*left*) **and B** (*right*) Complementary cumulative distribution functions resulting from the performance assessment. In A, the probability of radionuclide release from the repository is compared to the acceptance criteria. In B, a family of CCDF curves is traced to show the effect of different uncertainties. The "summed normalized release" of radionuclides C, is related to WIPP containment requirements in Sidebar 1.4. The term "normalized" release means that the release *Cj* is divided by the release limit *Lj*. The use of the term "summed" indicates the sum of all *Cj/Lj* over all the radionuclides with half-life greater than 20 years. The summed normalized release represents the total radioactivity released from the repository to the biosphere during its nominal 10,000-year lifetime. More details on CCDFs can be found in NRC (1996a). SOURCE: DOE, 2000k.

Sidebar 1.3 Continued

The committee recognizes that computing the performance of an underground repository over many millennia into the future cannot be done today with the accuracy with which, for example, the performance of an airplane wing can be simulated. Nevertheless, the results of this performance assessment are considered adequate by experts and regulators to support the decision to move waste from its surface storage to the WIPP (EPA, 1998).

Sidebar 1.4 Containment Requirements

Title 40 CFR 191.13 requires that "disposal systems for . . . transuranic radioactive wastes shall be designed to provide a reasonable expectation, based on performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:

1. Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 . . .; and
2. Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1. . .".

To explain how these requirements are applied to the WIPP, let L_j be the limit shown in the above table for radionuclide j. Suppose for the moment that WIPP had only one radionuclide, j, and let C_j be the total release of that radionuclide to the environment, measured in curies per 1000 metric tons of heavy metal (MTHM), during its 10,000 year lifetime. Then the first requirement of 40 CFR 191.13 means that the probability of C_j being greater than L_j should be less than 0.1.

That is: $p(C_j/L_j > 1)$ should be < 0.1

The second requirement then indicates that

$p(C_j/L_j > 10)$ should be < 0.001.

The actual inventory of radionuclides C, is defined as:

$$C = \sum_{j}^{N_j} \frac{C_j}{L_j}$$

with N_j being the total number of radionuclides with a half-life greater than 20 years.
The requirements then become:

$p(C>1)$ should be < 0.1
$p(C>10)$ should be < 0.001

Table 1. Release Limits per 1,000,000 Curies of TRU Waste per 10,000 Years[a]

Radionuclide	Release Limit (curies per 1000 MTHM)
Americium-241 or 243	100
Carbon-14	100
Cesium-137 or 137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, 239, 240, or 242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230 or 232	10
Tin-126	1,000
Uranium-233, 234, 235, 236, or 238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life grater than 20 years that does not emit alpha particles	1,000

[a] Containment requirements for selected isotopes as declared in Title 40 CFR 191, Appendix A (EPA, 1995). The release limits specified here scale with the quantity of waste in a repository; for this reason, they are specified in terms of curies that may be released per 10,000 years per 1,000 metric tons of heavy metal (MTHM). For a repository such as WIPP, which is intended to contain transuranic wastes, EPA has established in 40 CFR 191 that 1,000 MTHM is equivalent to 1,000,000 curies of TRU wastes with greater than 20-year half-lives. Therefore, the limits specified are applicable per million curies of TRU waste.

tion, and disposal of defense-related transuranic waste to the WIPP from the 23 generator sites. The National TRU Program is administered by the DOE's Carlsbad Field Office. The goals of the National TRU Program are the following:

- achieving regulatory compliance among all the sites,
- reducing risk while maximizing rate of TRU waste disposal,
- reducing mortgage costs by closing the generators' sites as soon as possible, and
- using the WIPP effectively by coordinating the shipments with the repository's waste-handling and disposal capabilities.

The issues considered in this report relate primarily to waste characterization and packaging and waste transportation. Because of their importance in the near term for achieving the beginning of operation at the WIPP, the committee focused on these issues in its interim report, reported in Appendix A1. In Chapter 3 of this final report, the committee re-visits the issues related to characterization, packaging, and transportation of the wastes, including communication systems and emergency preparedness. The issue of hydrogen gas generation, as it applies to both waste characterization and transportation, is also discussed in Chapter 3.

2

Repository Performance Confirmation

The performance of geological repositories is evaluated on the basis of their ability to comply with a series of regulatory performance criteria, defined in Title 40 of the Code of Federal Regulations Part 191 (40 CFR 191; EPA, 1985). In the case of the WIPP, the time of compliance with the containment requirements formulated by the U.S. Environmental Protection Agency (EPA) is 10,000 years (see Sidebar 1.4). Of course, the issue does not end at 10,000 years; for example, the risk-controlling radionuclide in the WIPP is plutonium-239, which has a half-life of 24,000 years. The intent of a geological repository is to contain the waste for the indefinite future (e.g., > 10,000 years).

The WIPP was certified by the EPA through a comprehensive process based primarily on a detailed performance assessment (DOE, 1996; see also Sidebar 1.2). Of course, acceptance of the performance assessment (PA) is conditional on several factors that are designed to offset the many uncertainties involved. One of the EPA's requirements is that the DOE must implement a monitoring program designed to provide confidence in the assessed performance of the repository. Furthermore, every five years, the DOE must apply to the EPA for recertification of the WIPP. The recertification application must show evidence that the repository is performing as assessed.

A monitoring program that emphasizes factors contributing mostly to performance uncertainties could provide important evidence of the ability of the repository to perform its intended function. Therefore, the committee has chosen as the theme of this review to be "performance confirmation through monitoring." The strategy of the committee is to focus on safety and monitoring activities that would best enhance confidence in the long-term performance and reduce uncertainties in the performance assessment of the WIPP.

The recommendation to implement an in-situ monitoring program was endorsed by a previous NRC committee on the WIPP in a letter report to the Hon. L. P. Duffy (NRC, 1992). Quoting from that report, "The panel emphasizes that it supports the notion of underground testing with TRU wastes, provided that the underground location does not prevent important tests from being carried out (e.g., the measurement of brine compositions in contact with real waste or progression of gas generation experiments without purging), and that the tests can be continued for sufficient time to provide useful information."

The long operational phase of the WIPP repository (at least 35 years and possibly as long as 100 years) provides an unusual, and perhaps unprecedented, opportunity to implement a monitoring program and reexamine the performance assessment with information based on direct observations of the total system prior to closure of the repository. Although a time frame of 35-100 years is short compared to the 10,000-year period of compliance, the committee believes that it is long enough to develop and implement a monitoring program to observe the development of repository responses. Indeed, the rates of important processes such as salt creep, brine inflow, and microbial activity are predicted to be the highest during the first 50 to 100 years (Knowles and Economy, 2000; NRC, 1996a). If these responses confirm assumptions in the performance assessment, this will reduce uncertainty in the projections of long-term performance of the repository and could improve public confidence in the repository performance.

The ongoing DOE's monitoring program required by the EPA as part of the certification, is described in the next section. The committee strongly supports such a program but believes it could be more focused and risk-informed. The difference in focus between what is planned and what the committee suggests is also discussed.

REGULATORY REQUIREMENTS FOR MONITORING

A monitoring plan for the WIPP was included in 40 CFR 194 under the requirements for the certification of the repository by the EPA. The purpose of the monitoring plan is to confirm that the repository is performing as expected according to the model in the Certificate of Compliance Application. The DOE proposed a monitoring plan, which was accepted by the EPA in 1998 in the certification decision, to address the requirements of the regulations in 40 CFR 194.

The DOE described its monitoring program in the CCA and indicated that it would span 150 years (50 years pre-closure and 100 years post-closure). The DOE program evolved from screening 91 potentially significant parameters down to 10. The 10 parameters were divided among physical measurements in the Salado Formation, hydrological properties in the non-Salado settings, and activity levels of the waste. The four parameters to be measured in the Salado Formation relate to creep closure and stresses, extent of deformation, initiation of brittle deformation, and displacement of deformation features. The program calls for pre-closure monitoring only for the Salado parameters and pre- and post-closure for the non-Salado parameters. Waste activity is to be monitored only during pre-closure. In the DOE program, pre-closure monitoring in waste storage rooms ends with the sealing of individual panels of rooms; hence, pre-closure monitoring of emplaced waste is very limited. The parameters that the DOE is currently monitoring to comply with 40 CFR 194 are shown in Table 2.1.

The committee's proposed performance confirmation monitoring plan is very similar to the DOE's monitoring program. The significant difference between the DOE monitoring program and the committee proposal is that the committee's recommended plan includes monitoring rooms and panels after sealing of the panels and extends until closure of the repository and sealing of the shafts. The committee has put greater emphasis on such issues as brine inflow, gas generation, salt rock deformation following sealing of the panels, auxiliary material inventory in the repository, and radiogenic measurements.

The committee identified important issues relative to the long-term safe performance of the WIPP repository on the basis of the DOE's performance assessment (DOE, 1996), past committee reports, and numerous briefings on the WIPP. The criteria for identifying issues were related principally to the sources of uncertainty in the performance assessment and to the safety of workers and the public. Several of the issues are interrelated but are treated separately to emphasize important points. The following paragraphs describe in detail the issues of consideration in the performance confirmation monitoring program proposed by the committee. The issues have been grouped as *site performance* issues and *site characterization* issues.

Table 2.1 Parameters Currently Monitored by the DOE to Comply with 40 CFR Part 194.42[a]

Parameter Monitored in the WIPP	Pre-closure Monitoring?	Post-closure Monitoring?
Salado physical parameters		
Creep closure and stresses	YES	NO
Extent of deformation	YES	NO
Initiation of brittle deformation	YES	NO
Displacement of deformation features	YES	NO
Non-Salado hydrological properties		
Culebra groundwater composition	YES	YES
Probability of encountering a Castile brine reservoir	YES	YES
Drilling rate	YES	YES
Culebra change in groundwater flow	YES	YES
Subsidence measurements	YES	YES
Waste related parameters		
Waste activity	YES	NO

[a] EPA (1996).

SITE PERFORMANCE ISSUES

The key site issues that should be monitored during the pre-closure period to confirm the performance of the WIPP repository are described below.

Brine Migration and Moisture Access to the Repository

The presence or absence of brine in the WIPP rooms is a key issue in the performance of the repository. Without brine there will be no radionuclide mobilization and transport or any gas generation from corrosion of the steel drums. The brine sources for the undisturbed repository are seepage from brine-filled void spaces in the undisturbed geological setting, the humidity of the repository air, and water used during mining operations. In the long term, after repository closure, additional sources of brine could include accidental fluid injections by inadvertent human intrusions (see section "Oil, Gas, and Mineral Production" and Appendix B). Brine volumes from enhanced recovery fluid injection operations have the potential to be a source of much greater brine inflow than that expected from any other water sources in the undisturbed geological setting. A concern is the possible failure of a well casing or cement outside the casing during an injection operation and fluid leaking into overlying formations and flowing laterally along one of the several anhydrite layers in the Salado Formation.

A previous NRC committee analyzed the brine accumulation issue and concluded that "the formation of an abundant mobile fluid in a repository at the WIPP site . . . is very improbable." Nevertheless, the same committee recommended a "well conceived experimental program at WIPP to reduce remaining uncertainties" (NRC, 1988). The present committee is also in favor of a monitoring program to complement DOE's current program. It would be informative to monitor the brine flow rate into the first panel, or panels, of the WIPP facility that are filled and sealed. Monitoring from inside the face of the seal should be possible for decades after the panel is sealed and would contribute to enhancing confi-

dence in the performance of the repository. Monitoring the humidity and the accumulation of standing brine would indicate the ingress of brine, although salt mines are notoriously dry and probably no standing water will develop. The monitoring of brine inflow and of the humidity in the WIPP should continue at least until the shafts are sealed and longer if feasible.

According to Knowles and Economy (2000), the brine inflow rate will be maximum within the first 50 to 100 years from the mining of the repository and will stabilize progressively after 200 years. The rate of brine inflow depends on the porosity of the medium. The mining of the salt in the repository creates alterations of the stress field of the surrounding rock and forms micro fractures in the salt around the excavation (disturbed rock zone, or DRZ). Compared to the intact salt, the DRZ will have an increased porosity because of all the micro fractures. Over time, the porosity of the DRZ decreases as salt creep continues, thereby decreasing brine inflow. Therefore, the monitoring of brine inflow is particularly important during the pre-closure phase.

At closure, the panel conduits for the instrumentation would be plugged permanently to ensure the sealing of the repository. Maintaining instrumentation at the repository horizon beyond closure of the shafts could be impractical, unless new technologies allow remote monitoring of the repository avoiding instrument conduits through the seals.

***Recommendation:* The committee recommends pre-closure monitoring of the WIPP repository to gain information on brine migration and moisture access to the repository. Observation should continue at least until the repository shafts are sealed and longer if possible. The committee recommends that the results of the on-site monitoring program be used to improve the performance assessment for recertification purposes.**

Gas Generation in the Repository

Gas generation within the WIPP is one of the issues for consideration in the overall performance of the repository. There are two possible effects of gas in the repository. The first is a physical effect due to pressure buildup from any gas. Gas may generate sufficient pressure to eject repository materials during a human intrusion event. Gas pressure could also retard creep closure and brine inflow. Gas pressure in the repository is considered one of the main uncertainties in the PA concerning radionuclide release from the WIPP (Berglund et al., 2000; Helton et al., 2000d; Stoelzel et al., 2000; Vaughn et al., 2000). A performance assessment scenario that could cause violation of the EPA repository release limits involves ejection of waste material through a borehole. In this scenario, it is calculated that the gas pressure at the repository horizon has to be greater than approximately 8 megapascals[1] to result in ejection of cuttings, cavings, and spallings that might contain radionuclides from the repository (Berglund, et al., 2000; DOE, 1996). If the gas pressure approaches the lithostatic pressure, a radionuclide release along open fractures could result.

The second effect of gas generation in the repository is chemical. The main gaseous products potentially formed in the repository are carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4), nitrogen (N_2 or

[1] The value of 8 megapascals is the pressure exerted by a column of brine-saturated drilling fluid at the depth of the repository (Stoelzel and O'Brien, 1996). This threshold in pressure was calculated in the PA on the basis of drilling technologies using mud. The public strongly criticized this assumption because it did not take into account the increasingly popular air drilling technology. However, the EPA analyzed the PA, performed supplementary calculations, and reached the conclusion that the repository would still be in compliance with release limits, even in the event of a human intrusion through air drilling (EPA, 1998).

various nitrous oxides), and hydrogen sulfide (H_2S) (Lappin and Hunter, 1989). Most of concerns come from H_2 and CO_2. Hydrogen is a flammable gas and, in the presence of certain amounts of oxygen or water vapor, could lead to an explosion. In the case of CO_2, its solubility in any brine seeping into the repository could lower the pH of the brine, which would increase actinide solubility (Novak and Moore, 1996) as shown later in this chapter.

The sources of gas generation in the repository are three: radiolysis, metal corrosion, and bacterial action. The PA shows that total gas production is negligible under humid conditions for all substrates.[2] The main uncertainty concerns CO_2 production by microbial degradation reactions; this uncertainty was acknowledged in the PA by assigning a probability of 0.5 to the occurrence of significant microbial activity (DOE, 1996; Larson, 2000). The previous NRC committee on the WIPP (NRC, 1996a) also concluded that gas generation will be minimal, even when microbial degradation of organic material is taken into account. Although this committee concurs with the previous NRC committee and with the DOE that there is "minimal" evidence of gas generation in the WIPP, uncertainties concerning gas generation are still present. The committee is concerned that experimental data were extrapolated from laboratory experiments performed under conditions that are not indicative of the actual environment in the repository.

For instance, in the case of gas generated by radiolysis of brine and organic materials, the majority of experiments were performed with high doses of radiation, which does not apply to TRU waste. Moreover, factors that significantly decrease the rate of radiolysis—matrix depletion, pressure, and inhibition by other chemical compounds—were not taken accurately into account (INEEL, 1998; Molecke, 1979b).

In the case of microbial degradation of cellulosic compounds, rates of gas generation were extrapolated from laboratory experiments performed under humid conditions (70 percent humidity), which are not representative of the intrinsic dryness of salt repositories (Francis et al., 1997). In the case of metal corrosion, gas will not result without brine inflow, an event strongly affected by uncertainties. Furthermore, the nature of the interactions between gas-phase chemicals, the influence of pressure, and of corrosion rates is still not well understood (Telander and Westerman, 1996).

The gas generation rate is expected to be maximum during the pre-closure period because it depends on the brine inflow rate for microbial degradation, corrosion, and radiolysis (NRC, 1996a). As shown in the previous section, the brine inflow rate is expected to be maximum at the beginning of the repository life. Therefore, it is important to monitor gas generation rates and volumes during the first 35 to possibly 100 years. Furthermore, continuous monitoring for gas could lead to the early detection of anomalous behavior of the repository.

Recommendation: **The committee recommends pre-closure monitoring of gas generation rates, as well as of the volume of hydrogen, carbon dioxide, and methane produced. Such monitoring could enhance confidence in the performance of the repository, especially if no gas generation is observed. Observation should continue at least until the repository shafts are sealed and longer if possible. The results of the gas generation monitoring program should be used to improve the performance assessment for recertification purposes.**

[2] A substrate is a generic material, whether it is metal, natural fiber, or plastic, that generates gas via various mechanisms described in this section.

Magnesium Oxide Backfill

In the framework of repository performance confirmation, an issue closely related to brine access and gas generation in the WIPP is the performance of magnesium oxide (MgO) used as backfill. The backfill is introduced in the rooms to fill voids in the disposal locations, thus enhancing the healing process and facilitating the encapsulation of waste in salt. The choice of MgO as backfill is based on its chemical properties in addition to its properties as backfill. If brine is present in the repository, MgO will mix with it to form a compact material that will encapsulate the waste (Berglund et al., 1996). The water uptake of MgO from the brine will result in a volume expansion and in the precipitation of salt from the brine that will heal all pathways for later brine penetration.[3] If brine is not present in the rooms, creep encapsulation of waste would not progress as readily.

The chemical role of MgO is to provide some control of the chemical environment of the waste by reacting with brine and scavenging the CO_2 potentially formed in the repository. In presence of CO_2, brine pH will be decreased by the formation of carbonic acid. In the acid pH range, soluble actinide carbonate complexes can then form, increasing actinide solubility (Novak and Moore, 1996). In presence of MgO scavenging all CO_2, the pH will remain in the alkaline range (9.2 - 9.9), where actinides are less soluble and less likely to be released into the environment. The rationale for this expected action of MgO relies on the following assumptions:

1. There would be significant inflow of brine into the repository's rooms.
2. Microbes would be present and react with organic waste material to form CO_2.
3. CO_2 would dissolve and acidify the brine by forming carbonic acid.
4. MgO would react with water in the brine to precipitate brucite [$Mg(OH)_2$].
5. Brucite would remove carbonic acid from the solution to form magnesite ($MgCO_3$) via intermediate products such as hydromagnesite [$4MgCO_3 \bullet Mg(OH)_2 \bullet 4H_2O$].
6. These reactions with MgO would maintain the pH of brine between 9.2 and 9.9.

As mentioned in the previous section, there are uncertainties concerning assumption 1 about the presence of a significant amount of brine in the rooms. Since assumption 2 relies on microbial generation of CO_2 under repository conditions, it is also affected by uncertainties (see previous section). Moreover, it is unclear whether the rates of reactions in assumptions 4 to 6 are sufficiently high to be effective. The committee has several concerns. How quickly does brucite form at 25°C (Krumhansl et al., 1999; Papenguth et al., 1999)? How quickly does brucite react with carbonate at various carbonate concentrations and brine compositions?[4] When will the water trapped in hydromagnesite be returned to the fluid phase?[5]

There are also uncertainties in other factors related to the chemical environment, including the amount and timing of brine inflow to form the MgO-based chemical buffer and the presence and effectiveness of microbes responsible for the CO_2. On the issue of brine inflow, there is evidence that the salt will creep in the rooms and fill all of the openings in 100 to 150 years (Callahan and DeVries, 1991;

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[3] If the rate of brine inflow is too high, it is uncertain whether MgO can form a compact material around the waste.

[4] The rate to reach the compliance objective (26 mole percent MgO converted) decreases with decreasing CO_2 partial pressure (Krumhansl et al., 1999).

[5] The time to transform hydromagnesite to magnesite was reported to vary between 18-200 (Zhang et al., 1999) and 2.5-1,500 years (Krumhansl et al., 1999), depending on brine composition.

Knowles et al., 2000; Stone, 1997). The absence of void spaces should provide additional protection against extensive chemical reactions between brine and the waste in a short period of time.[6]

The use of MgO in the repository as chemical backfill raises the additional issue of its placement. Because MgO must be in close contact with the drums to better scavenge all CO_2 generated from the waste and because of the way the drums are stacked in the rooms, it is not possible to add MgO mechanically after the room is filled. MgO backfill is as a dry, granular, pelletized material packaged in bags of two different sizes: a smaller bag of about 25 pounds, called the "minisack," and a large bag weighing approximately 4,000 pounds, known as the "supersack." The minisacks are placed manually around and between the drums, and the supersacks are placed with a forklift on the top of each waste stack.

Based on a study by the DOE, it appears that emplacing MgO around the waste adds about 0.726 person-rem per year to the collective dose caused by waste handling. Given that the expected collective dose to waste-handling personnel is 14.6 person-rem per year, this corresponds to about 5 percent of the total dose incurred from waste operations (DOE, 2000b). The committee does not consider this additional dose to be significant. However, once remote-handled (RH) waste and possibly high-specific-activity waste in CH waste such as plutonium-238 or americium-241 are introduced into the repository, the exposures to personnel placing the MgO bags will be considerably increased.

Considering the uncertainties about the chemical performance of the MgO backfill, the committee questions the value of its use in the repository. The same concern was expressed by some of the peer review panels of the CCA (DOE, 1996, Chapter 9.3.2). This is especially true given the small but measurable additional radiation exposure to workers involved in MgO bags emplacement. The committee is not convinced of any major chemical advantages of the MgO backfill and, if its benefits to the long-term performance of the repository cannot be verified, the option to discontinue its use should be considered.

Recommendation: **The committee recommends that the net benefit of MgO used as backfill be reevaluated. The option to discontinue emplacement of MgO should be considered.**

Salt Healing and Disturbed Rock Zone Integrity

The period between placement of waste and closure of the repository provides a window of opportunity to monitor significant deformation of the salt and self-healing of the DRZ. The DRZ is the zone around an excavation in the host rock salt where the stress field has been modified sufficiently to cause the formation of microfractures in the rock salt. Substantial deformation of the salt will occur during the operation phase, which is important in assessing the self-sealing (healing) characteristics of the repository. After an initial period of rapid deformation (a few years to decades), the rooms are expected to deform, crush, and be entirely entombed by salt within 100 to 150 years (Callahan and DeVries, 1991; Knowles et al., 2000; Stone, 1997). Since the waste drums will be immobilized in a relatively short period of time (compared to 10,000 years of compliance), the radionuclide mobility values used in the performance assessment might have been overestimated. This implies less migration of radionuclides from the repository into the environment. In addition to the general deformation and local healing of rooms and panels, an important general healing must take place in the DRZ around rooms, panels, and shafts to achieve complete closure of the disposal region.

The effect of the DRZ around WIPP rooms and panels and around the shaft seal system is important in assessing the safety performance of the repository. A complete analysis of the performance of the

[6] A short period of time compared to the 10,000 years mentioned in the containment requirements (see Sidebar 1.4).

shaft seal system is given in Hansen and Knowles (2000). As with all the factors affecting the performance of the repository and because of the complexity of salt rock behavior, there is uncertainty in the timing and degree of self-healing of the DRZ needed to achieve the expected isolation in the mined regions. In the committee's opinion, there is also uncertainty concerning the behavior of rigid panel seals in the ductile salt surrounding them. Therefore, frequent monitoring during the pre-closure period and assessing the status of room deformation and DRZ healing are the best approaches for reducing the uncertainties associated with closure of the waste disposal area.

Recommendation: **The committee recommends pre-closure monitoring of the status of room deformation and DRZ healing. Seal performance should also be assessed. Observation should continue at least until the repository shafts are sealed and longer if possible. The results of the monitoring of room deformation and DRZ healing should be included in the PA and used for recertification purposes.**

SITE CHARACTERIZATION ISSUES

The committee finds that there are a number of site characterization actions that would decrease uncertainties in the long-term performance of the repository. Among these, site characterization issues related to human activities are particularly important because they constitute the major risk of radionuclide release, according to the performance assessment (NRC, 1996a; Rechard, 2000). Site characterization issues and activities are described in the sections below.

Geohydrological Characterization of the Rustler Formation

The WIPP disposal panels and rooms are located in the Salado Formation, approximately 660 meters from the ground surface, as shown in Figure 1.3. The Rustler Formation, overlying the Salado Formation, consists of five sequences (members) of thin-bedded strata. The Culebra Dolomite member, also called simply Culebra, is the second member from the bottom of the formation and is the most transmissive unit in the Rustler. Thus, the Culebra is important to the groundwater flow model for the WIPP site. The geologic and hydrologic setting of the WIPP have been thoroughly described in Corbet and Swift (2000). A detailed description of radionuclide transport in the Culebra can be found in Ramsey et al. (2000). The Culebra provides pathways for the release of radionuclides into the environment in all main human intrusion scenarios (see Appendix B).

These pathways can conceivably be developed when new wells are drilled through the Culebra. High-pressure fluids are used in the drilling of oil, gas, and injection wells to contain the flow from the high pressure in formations contacted during the drilling process. Formations at shallower depths, which tend to be at low pressure, are protected from the high-pressure drilling fluids by borehole casings. However, if the drilling intersects a pressurized brine reservoir before the borehole casing is placed, and if the pressure in the formation is unexpectedly higher than the pressure exerted by the drilling fluid, the high-pressure formation fluids could flow into the wellbore and cause an underground blowout into the Culebra. Drillers would use a blowout preventer to contain any immediate surface release of brine from the repository horizon. However, release to the Culebra could be synonymous with release to the accessible environment if there were high flow rates and little retardation[7] of radionuclides.

[7] Parameter that describes the ratio of the net apparent velocity of the concentration of a particular chemical species to the velocity of a non-reactive species.

All human intrusion assessment models in the PA require some retardation in the Culebra to meet the EPA's repository performance requirements. Similarly, the PA models require a low flow velocity in the Culebra. Unfortunately, these models are not based on sufficient hydrological characterization of the Culebra. There is uncertainty about flow directions, flow rates, retardation characteristics, and the amounts and location of groundwater recharge and discharge to and from the Culebra. This is due partly to uncertainties about the density, size, and spatial distribution of fractures and potential karstic features. These uncertainties can be reduced through a well-designed monitoring program.

The monitoring program should include angled boreholes to verify assumptions about vertical fractures or karst conduits; monitoring wells to check on conditions of recharge and discharge, water levels, and chemical properties. The program should also include a series of tracer tests to determine spatial flow rates of groundwater and local tracer tests, including the use of new logging technologies. Tracer tests should include suites of conservative tracers injected in differing wells to test the complexities of the flow system over and beyond those withdrawn by the LWA. The tests should span the entire preclosure phase of the repository (35 to 100 years). New data should be implemented continually into scenario models, and PA calculations should be revised as appropriate.

Recommendation: **The committee recommends a monitoring program to characterize the geohydrology of the Culebra Dolomite. Tests and measurements that should be considered include angled boreholes, natural gradient tracer tests, and additional pump or injection tests. These new data should be used to confirm, or modify, the conceptual and numerical models now proposed as reasonable simulation of the actual system.**

Oil, Gas, and Mineral Production

The oil, gas, and mineral reserves in the vicinity of WIPP are considerable. As shown in the interim report (see Appendix A1, Figure 2), there have been multiple drilling operations near the WIPP site and a future increase in production activities is expected. As indicated in the previous section, brine (or any fluid) inflow to the disposal region of the WIPP repository is a serious threat to the containment of radionuclides in the repository. Therefore, it is critical that pathways are not created by human intrusion, either intentionally or unintentionally. Such pathways would allow transport of radioactive materials from the repository to the surface or would bring water or brine in contact with the substances stored in the repository.

No human intrusion should occur during the first 100 years of the repository's life because of the active institutional controls. However, drilling activity will increase progressively during the period of passive institutional controls (100 to 700 years) and will not be controlled beyond that period. Uncontrolled extraction activities would increase the probability of drilling directly into the repository. Extraction activities can be divided into *drilling activities* and *mining activities*.

Drilling Activities

Two scenarios related to drilling activities are of particular interest to the WIPP site: the Hartman scenario and the intersection of a pressurized brine reservoir.

1. The Hartman scenario. In 1993, while drilling in the Rhodes Yates oil field located approximately 45 miles from the WIPP site, Mr. Hartman experienced a well blowout followed by an uncontrollable flow of brine to the surface (Silva, 1996). This event has come to be known as the Hartman scenario

(see additional details in Appendix B, Box B.1). The reason for the blowout has not been fully determined, although there is evidence that it may have been caused by a high-pressure, water-flooding operation approximately 1 mile from the well that blew out. In oil-producing regions such as southeastern New Mexico, it is common to inject high-pressure fluids into the deep rock formations of the subsurface.

The purpose of these fluid injections is to stimulate secondary recovery of oil in partly depleted oil reservoirs (e.g., by water flooding) or to dispose of large volumes of brine produced simultaneously with oil. If there is a failure in the well casing or in the grout or cement outside the casing, fluid can leak into overlying formations and flow laterally along one of the many anhydrite layers in the Salado (NRC, 1996a). Mr. Hartman might have drilled into a hydraulic fracture possibly induced by such water-flooding operation, causing the well to blow out. Bredehoeft and Gerstle (Bredehoeft and Gerstle, 1997; Gerstle and Bredehoeft, 1997) studied the implication of the Hartman scenario for the safety of the WIPP. They argued that if there were an oilfield water-flooding operation in the vicinity of the WIPP, a large amount of brine could flow from a leaky injection well and induce a hydraulic fracture in the anhydrite (or marker bed) directly above or below the WIPP repository (see Appendix B, Box B.2). If, at some later time, another well were drilled through the repository and into this brine-filled fracture, the high-pressure brine in the fracture could flow through the borehole and flood the repository causing a release of radioactive materials. Bredehoeft's analysis was disputed by researchers at Sandia National Laboratories (SNL; Swift et al., 1997; Vaughn et al., 1998). The discussion focused on the size of this potential hydraulically induced fracture and on whether this fracture could reach the anhydride beds directly below or above the repository site.

The committee's opinion is that there are considerable uncertainties concerning both the mechanism of the Hartman scenario and its likelihood to develop at the WIPP site. For instance, if the hypothesis of a hydraulically induced fracture were valid, and the fracture would indeed extend directly below or above the repository, a surge of brine would be expected only when the drillbit penetrates the brine-filled fracture. The volume of brine inflow would not be large enough to damage the repository because hydraulic fractures have small opening widths and high internal flow resistances. Furthermore, a leaky well could not provide sufficient energy and fluid volume to cause a brine inflow into the repository for an extended period of time; also, the energy stored in the room and in the fracture would not be enough to push the waste to the surface.

In addition, the repository is partitioned into isolated rooms, which will be closed progressively by salt creep, so that radionuclides should not be mobilized by the brine inflow. Finally, based on the information gathered and on geotechnical subcommittee's discussions, it appears that the geological setting of the WIPP is different from that of the Rhodes Yates oil field. The geological configuration near the WIPP site is likely to interfere with fluid movement thereby reducing the likelihood of flow from a hydraulic fracture into the repository. Therefore, in the committee's opinion, the Hartman Scenario is not likely to cause a problem in the performance of the repository.

2. *Intersection of a pressurized brine reservoir.* Groundwater containing high levels of dissolved solids (brine) may occur beneath the WIPP site either as discrete pockets (brine pockets) or as a saturated continuum. The committee uses the term "brine reservoir" to refer to both of these occurrences. At present, there is a great deal of uncertainty as to the location and form (i.e., discrete pocket or saturated continuum) of brine reservoirs beneath the WIPP repository. The committee recognizes that direct drilling through the repository into underlying high-pressure brine reservoirs could result in a release of radionuclides.

A survey study of brine reservoirs in the Castile Formation (Popielak et al., 1983) has suggested that the brine reservoirs in the area are not large enough to affect the safety of the WIPP site and that

there is no high-pressure brine reservoir directly underlying the repository. However, this finding is challenged by Silva et al. (1999). Using data from test well WIPP-12, Silva demonstrated that the probability of a large brine reservoir, approximately 260 meters below the repository, is rather high. The issue remains unresolved at the present time. Direct drilling (see Appendix B, Boxes B.1, and B.4) into the WIPP repository would allow circulating drill fluid to bring radioactive materials to the surface through a borehole as cuttings or spallings. In the performance assessment, SNL evaluated different possibilities of drilling into a brine reservoir (see Appendix B).

In the committee's opinion, the upsurging pressure from drilling through a pressurized brine reservoir could be counteracted by the weight of drilling mud. However, the situation could be serious if the brine reservoir were large and contained a significant amount of energy. An intersection with such a reservoir, although extremely rare, could cause the well to blow out and could result in a catastrophic safety problem for the WIPP. In the committee's opinion, when the drillbit penetrates a brine reservoir below the repository, there would be an initial surge of brine flowing through the borehole into the repository, but the rate of brine inflow would decrease rapidly unless this high-pressure brine reservoir had a gas subpocket above it. Because of the low compressibility of brine, without a gas subpocket, the energy stored in the reservoir would not be sufficient to cause a large brine upsurge through the borehole into the repository.

It is therefore important to determine the existence of a brine reservoir directly below the repository. This would be done using seismic techniques, which cannot measure the pressure in the reservoir but can detect its size. The committee recognizes that small brine reservoirs, including brine occurring as a saturated continuum, could not be detected by seismic surveys, or other noninvasive remote sensing techniques. Most seismic surveys are performed from the surface. However, it is possible to perform measurements at a depth, such as in wells or from within the repository. There would be advantages to performing a seismic survey at repository depth (660 meters below the surface) because the unwanted signal from near-earth formations could be eliminated.

The committee is aware of the numerous geophysical surveys that have been performed on the WIPP area in the past (ETC, 1988; Popielak et al., 1983; Silva et al., 1999) and does not suggest repeating what has been already done. However, seismic interpretation technology has improved dramatically in the last decade. These improvements, including but not limited to the almost universal three-dimensional seismic techniques, have greatly enhanced resolution capability and are currently used in the oil industry. Detailed three-dimensional seismic studies results, however, are often highly proprietary because they are performed by the oil industry. The DOE could consider acquiring the results of these studies to obtain new information on possible brine reservoirs in the region.

In case a brine reservoir were found beneath the WIPP site and its size were larger than what is already taken into account in the PA, then the DOE should conduct an extensive review of the impact of such a reservoir on the repository performance. A basis would then exist to take appropriate action to ensure the safety of the repository. If the reservoir is pressurized, the option of drilling a well into it to release the pressure could be considered. In case of drilling, precautionary methods, such as directional drilling, should be taken to prevent brine from entering the repository.

Recommendation: **The committee recommends the utilization of seismic survey techniques to detect the presence of a large brine reservoir below the repository.[8] In case a brine reservoir were**

[8] The committee recognizes that small brine reservoirs, including brine occurring as a saturated continuum, could not be detected by seismic surveys, or other noninvasive remote sensing techniques.

found beneath the WIPP and its size were larger than what is already taken into account in the PA, then the DOE should conduct an extensive review of the impact of such a reservoir on the repository performance. A basis would then exist to take appropriate action to ensure the safety of the repository.

Mining Activities

A further human activity that could threaten the safety of the repository is potash mining in proximity of the WIPP site. Potash mining could impact the performance of the repository by modifying flow pathways in the overlying formations or by creating a path for brine intrusion, if methods such as flood or solution mining are employed. The potential impact of potash mining on WIPP performance is not considered significant, but it is important that the DOE monitor during the operational phase all mining activities in close proximity of the area addressed in the LWA to ensure that the WIPP repository performance is not affected.

After reviewing the analyses performed for the human intrusion scenarios as a part of the performance assessment and given the reasons mentioned above, the committee finds that oil, gas, and mineral activities will not unduly threaten the integrity of the repository. However, there are uncertainties associated with these extraction operations. These uncertainties could be reduced by monitoring and documenting oil, gas, and mineral activities. The DOE could establish a database on oil, gas, and mineral activities in the WIPP area containing information such as:

1. location, depth, and type of each well surrounding the WIPP site;
2. data on accidents or unusual events reported by drilling contractors or operators;
3. data on production-enhancing activities such as water or CO_2 flooding, hydraulic or cryogenic fracturing, and acidizing in surrounding wells;
4. production rates of oil, gas, and brine from nearby wells;
5. data on disposal of drill cuttings and brine from the operators;
6. data from abandoned wells, in particular those relevant to gas leakages; and
7. extent of potash mining in the vicinity of the LWA.

Recommendation: **The committee recommends the development of a database to collect information on drilling, production enhancement, mining operations, well abandonments, and unusual events (accidents and natural events) in the vicinity of the WIPP site.**

Baseline Radiogenic Analysis of Subsurface Fluids

The issue of baseline values for naturally occurring radioactive material (NORM) in the vicinity of the WIPP site is important for future monitoring of any changes in radioactivity levels in and around the site. The reason for concern is that subsurface oil and gas in the vicinity of the site already contains NORM. The potential discovery of radioactive material in oil and gas could mistakenly be assumed to come from the repository and thereby cast a doubt on the performance of the nearby WIPP.

One of the findings of the committee's interim report (Appendix A1) identified an absence of radiological baseline information for subsurface brines and hydrocarbons near the site, even though there has been extensive monitoring of radioactivity in the air, soils, fluvial sediments, surface water, shallow groundwater, and populace. Therefore, the committee recommended that the DOE develop and implement a plan to sample oil-field brines, petroleum, and solids associated with current hydrocarbon production to assess the magnitude and variability of naturally occurring radioactive material in the vicinity

of the WIPP site. The radionuclides of interest include those that contribute to the site's NORM background radioactivity and those present in the TRU waste inventory destined for WIPP. The NORM activity may include contributions from potassium-40, isotopes of uranium and thorium, and daughter products such as isotopes of radium. Radionuclides in TRU waste include isotopes of uranium and TRU elements and, in remote-handled TRU waste, fission and activation products.

Since some TRU inventory radionuclides are not found commonly in nature, sampling to determine whether such radionuclides are present in the environment may be a good way to distinguish radioactivity due to NORM from that due to TRU waste. Further details can be found in Appendix A1. In its interim report, the committee recommended a simple but reliable analysis of the samples that do not include species depending on equilibria that can be shifted by a change in the chemical or physical parameters of the sample.

In response to the interim report, the DOE stated that the New Mexico State University Carlsbad Environmental Monitoring and Research Center (CEMRC) has undertaken a project to carry out the recommended assessment, as part of CEMRC's WIPP environmental monitoring project (Appendix A2). This project will include "completion of a database of active wells and operators, development of sample collection and handling plans, and identification of commercial sample collection services." The CEMRC has also developed analytical methods for NORM in subsurface fluids to complement standard methods. The committee supports and encourages the pursuit of this initiative.

Recommendation: **The committee recommends that the DOE continue the implementation of its plan to sample oil-field brines, petroleum, and solids associated with current and future hydrocarbon production, as necessary to assess the magnitude and variability of NORM in the vicinity of the WIPP site for baselining purposes.[9]**

[9] On March 12, 2001 the DOE-Carlsbad Field Office informed the committee that the efforts to collect data on NORM have received little support from oil companies and that cooperation seems unlikely. The small number of positive responses received would still not provide enough information to constitute a representative baseline of NORM in the region.

3

National Transuranic Waste Management Program

The National Transuranic Waste Management Program, also called the National TRU Program, addresses waste acceptance criteria and requirements for packaging and shipping waste to the WIPP repository. One of the committee's tasks is to identify areas for improvement in the National TRU Program that may increase safety to workers and the public, system throughput, efficiency, or cost-effectiveness. The National TRU Program was reviewed in detail in the committee's interim report (Appendix A1). This chapter gives a status report on the issues discussed in the interim report and reviews other issues that have emerged during the committee's deliberations. The issues addressed in this chapter relate to two areas: (1) *waste characterization and packaging* and (2) *waste transportation.*

WASTE CHARACTERIZATION AND PACKAGING

The committee has identified opportunities for improvement in the TRU waste management system concerning waste characterization and packaging requirements and the total inventory of organic material in the repository.

Waste Characterization and Packaging Requirements

The issues of waste characterization and packaging requirements have been discussed in detail in the interim report (Appendix A1). The principal finding was that many requirements and specifications concerning waste characterization and packaging lacked a safety or legal basis. In addition, many of these same requirements resulted in health and safety risks and added costs. The added safety risks derive from radiation exposure of workers due to the extra handling of waste imposed by some of the requirements. For instance, visual examination of a fraction of waste stream containers to confirm radiography results and information from the history of the container (acceptable knowledge) is a procedure not required by the EPA that increases radiation exposure of workers. The committee recommended in its interim report that the DOE eliminate self-imposed waste characterization requirements that lack a safety or legal basis.

The committee is encouraged by progress made since the interim report to eliminate unnecessary

procedures. In particular, the DOE has initiated a program to review all waste characterization and packaging requirements and to reduce or eliminate those that do not contribute to improved safety or that are not required by law. The DOE may obtained a tenfold reduction of the number of containers to be opened for visual examination by requesting a modification of the WIPP's Hazardous Waste Facility Permit (Appendix A2).

Recommendation: **The committee recommends that the DOE's efforts to review waste characterization and packaging requirements continue and that changes be implemented over the entire National TRU Program. The committee recommends that the resources required to complete these improvements be made available by the DOE.**

Total Inventory of Organic Material in the Repository

A new issue concerning waste characterization has emerged since the committee visited the WIPP site in May 2000. This issue addresses the regulatory limits on the total inventory of organic material allowed in the repository. The performance assessment indicates that there could be significant carbon dioxide generation in the repository due to the decomposition of organic material. Although the committee does not consider gas generation an important safety issue (see Chapter 2), it is concerned whether the current monitoring program will provide the information required to assess compliance with total repository limits of organic material. Title 40 CFR 194.24 states that "the Department [of Energy] shall specify the limiting value ... of the total inventory of such waste proposed for disposal" (EPA, 1996). The DOE has therefore established the limit for organic material in the repository to be 20 million kilograms (DOE, 1996; Table 4-0) on the basis of the average waste composition.

However, the DOE's definition of "waste" includes only what is inside the waste container and does not include either the container itself or any of the auxiliary material buried with the waste. Examples of such auxiliary material are plastic films used to stabilize drums for shipping and handling, plastic bags and corrugated cardboard used as magnesium oxide containers, wooden waste boxes, plastic liners of waste drums, and pressed wood "slip sheets" used between layers of drums and waste boxes. Figure 3.1 shows a picture of waste and auxiliary material in one of the rooms of the repository. Thus, there is a considerable inventory of materials, mostly cellulosics, that are not considered TRU waste but are foreign to the natural setting of the Salado Formation. The principal concern of the committee is that the auxiliary material does not appear to be accurately inventoried. Therefore, it is impossible to know whether the total organic material limit is exceeded.

Recommendation: **The committee recommends a risk-based analysis of the total organic material regulatory limits in the WIPP. If accounting for the organic material is important to the safety of the repository, an inventory record system should be implemented as soon as possible to provide a basis for meaningful safety analysis.**

WASTE TRANSPORTATION

The committee has examined various aspects of the WIPP TRU waste transportation system, focusing on system safety and on cost-effectiveness of planned and ongoing activities. In its interim report (Appendix A1), the committee reviewed the DOE's TRANSportation tracking and COMmunication (TRANSCOM) system and its emergency response program. Two other issues have been revisited in this report: the potential use of rail as a shipping option for a fraction of TRU waste and the gas genera-

Figure 3.1 Standard waste boxes and packs stacked in one room of the WIPP repository. Notice the layers of plastic film around the drums. SOURCE: DOE, 2000d.

tion safety analysis for the Transuranic Package Transporter, Model II (TRUPACT-II) containers. Figure 3.2 shows the internal structure of a TRUPACT-II container. Figure 3.3 shows a truck transporting three TRUPACT-II containers.

DOE's Communication and Notification Program

In its interim report (Appendix A1), the committee recommended that the DOE improve the reliability and ease of use of the TRANSCOM system. On November 21, 2000, a truck hauling waste to WIPP strayed from its designated route as the driver missed the exit from Interstate 25 onto Route 285 toward Carlsbad. The driver proceeded 27 miles before the New Mexico State Police, equipped with a TRANSCOM system, realized the error and turned the truck around. It appears that the TRANSCOM headquarters situated in Oak Ridge, Tennessee, did not notify the driver until a state policeman noticed the error (DOE, 2001). This "strayed truck" episode is an example of the poor reliability of the system, not from a technical point of view since the TRANSCOM was apparently functioning correctly, but from the perspective of the human factor.

The DOE appears to be systematic and expeditious in its development and use of a new, efficient, comprehensive, and state-of-the-art communication and notification system, known as TRANSCOM 2000. The new system will use off-the-shelf, advanced information and communication technologies to track shipments from start to end. Full-scale implementation of TRANSCOM 2000 is scheduled for June 2001. After discussion with transportation management staff and in reaction to the DOE's response to its

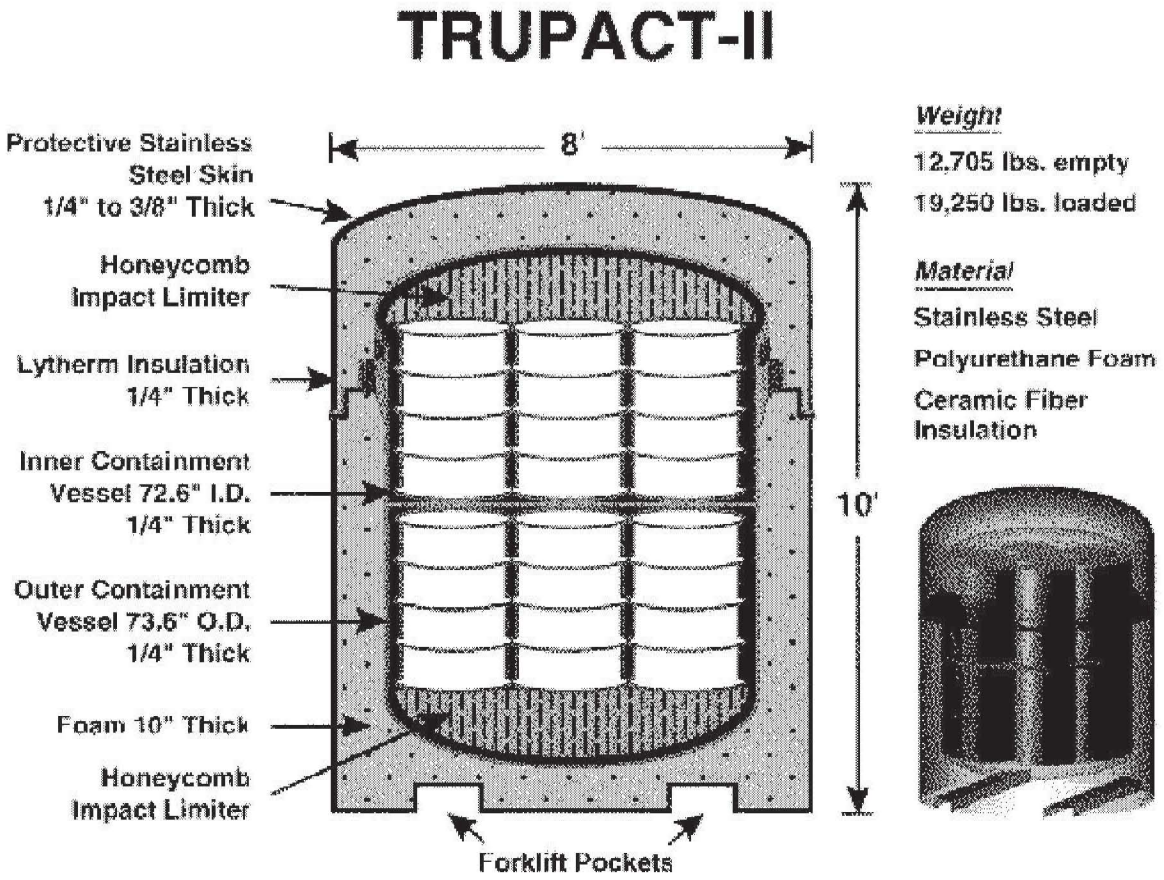

Figure 3.2 Structure of TRUPACT-II container, certified by the USNRC. SOURCE: DOE, 2000l.

Figure 3.3 Truck transporting three TRUPACT-II containers to the WIPP. SOURCE: DOE, 2000m.

interim report (Appendix A2), the committee finds that overall, the DOE has taken active steps to address concerns about the reliability and ease of use of the TRANSCOM system. Moreover, the DOE has integrated new features into TRANSCOM 2000, such as alarms, more frequent satellite and computer tracking, and stronger training for truck drivers to avoid future "strayed truck" episodes. Other suggestions to improve the safety and reliability of TRANSCOM could be the use of checklists, key schedule reporting, and "call-ins" at important route changes.

There may also be further opportunities to improve the performance of the TRANSCOM 2000 system. For instance, integrating TRANSCOM 2000 with other corridor states' information technology programs such as intelligent transportation systems (ITS). More generally, TRANSCOM 2000 must meet performance-monitoring standards similar to those of other advanced systems, such as the air traffic control system, particularly as shipments become routine and drivers and supervisors may become complacent. Investment in tracking and communication systems for the WIPP will also be useful for future radioactive waste transportation systems.

Recommendation: **The committee recommends that the DOE implement as soon as possible the new TRANSCOM 2000 communication and notification system. Moreover, because human factors are an important element of transportation system quality, TRANSCOM 2000 should include methods to minimize the occurrence and impact of human errors.**

DOE's Emergency Response Program

Concerning the emergency response program for the WIPP, the committee recommended, in its interim report (Appendix A1), that the DOE explore with corridor states and other interested parties how to develop processes and tools for maintaining up-to-date spatial information on the location, capabilities, and contact information for the following:

- responders,
- medical facilities,
- recovery equipment,
- regional response teams, and
- other resources that might be needed to support effective emergency response in the event of a transportation incident involving a WIPP shipment.

This recommendation was made in recognition of the fact that, presently, there is no quality control program in existence to evaluate periodically and systematically the extent of training, emergency capabilities, and deficiencies within the states and along WIPP transportation corridors. The committee fully understands and recognizes that the primary responsibility for management and response to hazardous material incidents in transportation rests with state and local authorities and jurisdictions. Although WIPP corridor states actively coordinate in varying degrees with the DOE to ensure the safety of WIPP shipments, the general public may often view this responsibility as ultimately resting with the DOE as the system manager. The public might well expect qualified and trained emergency response coverage along an entire route. In the committee's view, the DOE could face heavy criticism if an event demonstrates weaknesses in the emergency response program, regardless of whether the safety consequences are serious. Any system-level integration necessary to ensure adequate emergency response would have to recognize and coordinate among the jurisdictional boundaries of the various responsible state and local agencies.

To date, the committee is concerned about the progress being made in the emergency response area. For example, only 7 of the 20 states situated along the transportation corridor participated in the last DOE emergency response training class in Carlsbad, New Mexico (DOE, 2000e). The committee acknowledges the challenges faced by the respective states in providing resources to ensure adequate coverage. There continues to be a need for the DOE to facilitate the involvement of states and other interested parties to determine where emergency response capabilities are lacking along transportation routes and to support the states in correcting deficiencies. The committee is encouraged by the new DOE training program, through which DOE trainers have traveled to Indiana, Colorado, Louisiana, and Nevada to teach emergency response professionals what to do in case of an accident involving a WIPP shipment (Westinghouse News, 2001a,b,c,d). A further example for DOE to improve the corridor states' involvement in the emergency response program is to organize training courses through distant learning.

Recommendation: **The committee recommends that the DOE facilitate the involvement of states in developing and maintaining an up-to-date, practical, and cost-effective spatial information database system to coordinate emergency responses. The DOE should also develop an ongoing assessment program for states' emergency response capabilities and allocate training resources to address deficiencies in coverage along WIPP routes.**

Rail as a Transportation Option for Certain TRU Waste

In its interim report (Appendix A1), the committee recommended that DOE reduce the number of truckloads required to transport waste to WIPP, thereby reducing the associated transportation risks.[1] The committee suggested that a way to reduce the number of shipments is to reevaluate the technical and regulatory feasibility of shipping high-wattage TRU waste using a railcar shipping system. The WIPP has access already to rail via a rail spur siding, which runs into the facility.

In response to this recommendation, the DOE (2000c) recently issued a report *CH-TRU Waste Transportation System Rail Study*. This study examined the feasibility of shipping CH-TRU waste from four DOE facilities to WIPP by commercial rail and compared the relative costs of using rail rather than the present use of the highway. The study also examined the feasibility and cost-effectiveness of using several alternative packaging to TRUPACT-II. TRUPACT-II containers, because of their size, shape, or regulatory limits, are not always efficiently utilized during transportation; therefore, an increased number of shipments or repackaging of the waste is sometimes required. The DOE concluded that rail shipment of TRU waste to WIPP might be competitive if certain conditions are satisfied. Those conditions involve negotiation of a more favorable rail rate and development of an alternate type B overpack to TRUPACT-II that would accommodate more packages, thus reducing the number of shipments required.

A recent article (Neill and Neill, 2000) asserts that rail offers considerable advantages, at least with respect to shipments from the Hanford and the Idaho National Engineering and Environmental Laboratory sites. The authors make specific recommendations concerning the use of rail that might enable the DOE to ship TRU waste more efficiently while reducing transportation risk. The committee suggests

[1] On November 2, 2000, a new type of container, called HalfPACT, designed to supplement TRUPACT-II for road transportation, was certified by the U.S. Nuclear Regulatory Commission. The new container is approximately 30 inches shorter than TRUPACT-II and can be utilized more efficiently to transport TRU waste. The DOE estimated that the new HalfPACT container will eliminate about 2,000 projected shipments to the WIPP site.

Sidebar 3.1 The ATMX Railcar System as an Alternative Transportation System?

"ATMX" is an acronym to denote the railcars used by the DOE to ship nuclear weapons components and TRU waste. "AT" stands for Atchison Topeka, the rail carrier. "M" signifies munitions, and "X" on a railcar signifies private ownership (in this case, by the U.S. government), rather than ownership by the railroad company. This system was used by the DOE (and formerly the U.S. Atomic Energy Commission) from about 1968 to 1989 to safely transport more than 1,100 shipments of CH-TRU waste from the Mound Laboratory and Rocky Flats to the Idaho National Engineering Laboratory. The ATMX (600 series) is a specially designed steel railcar with a bolted-on steel cover and an interior compartmentalized by steel frames. Closed steel boxes or bins are positioned and stored in each compartment, and internal packagings are placed in the boxes or bins. Internal packagings need only meet U.S. Department of Transportation (DOT) Type A package test standards and are relieved from Type B (accident-resistant) package test parameters. Each ATMX railcar can accommodate a maximum of 20 crates or 140 55-gallon steel drums. In June 1999, the DOT issued the tenth revision of DOT-E 5948, authorizing the shipment of TRU waste by rail from Miamisburg, Ohio (the Mound Laboratory), to a yet-to-be-designated DOE facility where it will be processed for eventual shipment to the WIPP in TRUPACT-II containers. This option appears to be a very reasonable and cost-effective method of transferring the relatively small amount of TRU waste at Mound to another DOE facility for processing as an alternative to setting up a facility at Mound itself. Since the ATMX system is not certified by the USNRC, its use for rail shipments directly to the WIPP is precluded by the provisions of the Land Withdrawal Act and the Agreement with the State of New Mexico, which require that shipments to the WIPP be in USNRC-certified packages. To obtain USNRC "approval," the DOE would have to support an application to the USNRC for exemption from certain test requirements for the Type B package mentioned in Title 10 CFR Part 71. For certain materials that eventually will not be transportable in TRUPACT-II containers due to high thermal loading, this would appear to be a desirable option for future consideration and possible pursuit by the DOE.

that the DOE develop a strategy to negotiate and reduce the overall rail freight costs and to identify the infrastructure (e.g., costs, emergency preparedness, and schedules) necessary for rail shipments.

In its interim report, the committee recommended the ATMX railcar system as an alternative transportation system for certain materials (see Sidebar 3.1). Specifically, the committee recommended that a risk-informed study should be prepared by the DOE to support an application to the United States Nuclear Regulatory Commission (USNRC) authorizing the use of the ATMX railcar system for shipments of inner waste packages that are unsuitable for placement in TRUPACT-II containers.

Recommendation: **The committee recommends that all reasonable transportation options including reduction in the number of shipments, such as rail and road transportation with better-adapted containers, should be part of the decision-making process of transporting TRU waste from generator and storage sites to the WIPP. Future transportation studies should consider railway shipments and their impact on both the safety and the cost of the program. The DOE should also**

continue to pursue the development of packaging alternatives for materials not suitable for TRUPACT-II containers.

Gas Generation Safety Analysis for TRUPACT-II Containers

The issue of hazardous gas generation in TRUPACT-II shipping containers stems from a U.S. Nuclear Regulatory Commission requirement (USNRC, 1999). The requirement states that, for the shipping container, "hydrogen and other flammable gases comprise less than 5% by volume of the total gas inventory within any confinement volume." The problem is whether a flammable mixture could be generated and trigger an ignition, exothermic reaction, or explosive event with sufficient energy to breach the containment. Excessively restrictive gas generation requirements have severe consequences. The waste is repackaged to redistribute waste in containers to meet the wattage limits derived from gas generation requirements. This repackaging of waste exposes workers to radiation and increases the number of containers, thereby diluting the waste into a greater volume. Transportation-related risks (and costs) are also incurred in repackaging because the extra containers require additional shipping loads and additional truck trips, thereby increasing the likelihood of accidents.

For instance, plutonium-238 found in CH waste is considered a "high-wattage waste" because of its high specific activity (17.3 curies per gram). The USNRC significantly restricts the amount of plutonium-238 that can be transported by TRUPACT-II because of gas generation concerns. The DOE estimates that the repackaging of plutonium-238 in CH waste may involve more than a tenfold increase in the number of shipments of plutonium-238, to as many as 150,000 extra drums (Lechel and Leigh, 1998). The USNRC uses a decay heat limit in watts, originally established by the DOE, based on limiting the volume of hydrogen to less than 50 milliliters per liter of volume in the "innermost confinement barrier." According to waste acceptance criteria for the WIPP, the wattage limit for TRUPACT-II containers is 40 watts (DOE, 1999).

Thus, there is also the matter of what constitutes the innermost confinement barrier in TRUPACT-II, since the containers may consist of separate individual plastic bags of waste (see Figure 3.2). One interpretation is that the requirement applies to these "inner packages." Obviously, there are situations in which such an interpretation would make the flammable gas volume limitation a severe constraint on TRU waste shipments, given the plastic bag packaging practice and the number of different sizes that may occur in a single TRUPACT-II container. Finally, it is the understanding of the committee that the 5 percent volume limitation on hydrogen is intended to preclude the need for a specific safety analysis, which suggests that this limitation is a major source of conservatism and may not be cost-effective or risk-informed.

The committee was unable to verify the technical basis for the several sub-issues that are involved, including a realistic assessment of the conditions that could result in an explosive event in TRUPACT-II containers and a clear definition of what constitutes the innermost barrier. As already recommended in its interim report, the committee reiterates that a risk-informed analysis of WIPP-specific shipments would contribute to a better understanding of the real safety issues and, perhaps, provide a basis for alternative cost-effective criteria while reducing the risk.

In its response to the interim report (Appendix A2), the DOE agreed with the committee's recommendation that a safety analysis be performed to determine the quantity of hydrogen that, upon ignition, could damage the TRUPACT-II shipping container and possibly rupture the seals of the package. The committee is aware of and supports the DOE's initiative of obtaining more realistic G-values[2] for hydro-

[2] The G-value is the measure of radiolytic yield. It is expressed by the number of molecules, in this case of H_2, produced by 100 electronvolts of the ionizing radiation's energy absorbed by the medium, in this case the TRU waste.

gen generation and of exploring the use of hydrogen getters and inerted inner containers as a means of increasing wattage limits for transportation. Moreover, the DOE has applied for a revision of the USNRC's certificate of compliance to authorize the use of lower G-values for hydrogen generation based on matrix depletion, options for mixing of shipping categories, and use more realistic G-values for non-gas generating materials that are present. The committee supports this request.

Recommendation: **The committee recommends a risk-informed analysis of WIPP specific shipment issues to identify core problems related to hydrogen generation and, perhaps, provide a basis for alternative cost-effective criteria while reducing the risk. The committee recommends the use of such risk-informed analysis in the application for revision of the USNRC certificate of compliance concerning hydrogen generation limits for transportation purposes.**

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Summary

The committee is confident that the WIPP can meet its general performance objectives as requested by the certification process. However, uncertainties remain in the long-term performance of the repository. Some of the recommendations in this report were released in the committee's interim report (Appendix A1) to which the DOE has responded with a number of actions taken (see Appendix A2). The committee encourages implementation of the improvements suggested by the DOE to address its recommendations. In Chapters 2 and 3, the committee addresses some new issues concerning the operation and long-term safety of the WIPP and reiterates for emphasis some of the recommendations of the interim report. This chapter closes the study with an overarching finding and recommendation.

OVERARCHING FINDING

The committee finds that the monitoring of selected performance indicators during the estimated 35-year or longer pre-closure phase of the WIPP is needed to possibly enhance confidence in the long-term safety performance of the repository. Although 35 to possibly 100 years is a short time compared to the 10,000-year period of compliance, the committee believes that it is long enough to reduce the uncertainties in many critical performance parameters. The rates of important processes such as salt creep, brine inflow (if any), and gas generation are predicted to be highest during this period; therefore, monitoring during the pre-closure phase is particularly important. Moreover, the committee finds that there are a number of specific actions that can be taken in the National TRU Program to facilitate operation of the WIPP while increasing safety and reducing costs.

OVERARCHING RECOMMENDATION

The committee recommends that the DOE develop and implement a program during the pre-closure phase to monitor selected performance indicators that specifically relate to the creation of a radionuclide source term and to pathways for radionuclide transport. Monitoring should continue throughout the pre-closure phase and longer, if possible. Emphasis in the monitoring should be on waste mobilization and

transport mechanisms, including brine inflow, gas generation, geochemical reactions, room sealing, and surface and subsurface hydrology. The committee recommends that the results of the on-site monitoring program be used to improve the performance assessment for recertification purposes. These results will determine whether the need for a new performance assessment is warranted. Given the uncertainties, it is impossible to predict if the results of the monitoring program will be different than those modeled by the performance assessment. However, it is important to ensure that, if there are changes, these will be detected.[1] Moreover, actions should be taken to improve and better define the National TRU Program for issues related to waste characterization and packaging requirements, total inventory of organic materials, communication and notification system, emergency response training, and gas generation during transportation.

The committee did not have all of the information necessary to prioritize the issues mentioned in this report. However, it has provided a selected number of recommendations that are believed to improve the operation and long-term safety of the WIPP. The committee recognizes that the recommendations in this report will have some economic impact on the transuranic waste management program. The DOE needs to balance costs against the improved assurance of facility performance in the longer term.

[1] Only measurable changes are important to verify the performance of the repository; for instance, a few drops of brine do not imply that the repository is not in compliance with containment requirements.

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APPENDIXES

Appendix A1

Interim Report

IMPROVING OPERATIONS AND LONG-TERM SAFETY OF THE WASTE ISOLATION PILOT PLANT

INTERIM REPORT

Committee on the Waste Isolation Pilot Plant
Board on Radioactive Waste Management
Commission on Geosciences, Environment, and Resources

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

NOTICE: The project that is the subject of this interim report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council (NRC) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Tom Borak, Colorado State University
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Although the individuals listed above have provided constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by E-an Zen, appointed by the Commission on Geosciences, Environment, and Resources, and Frank Parker, appointed by the Report Review Committee, who were responsible for making certain that an independent examination of this report was carried out in accordance with NRC procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the NRC.

Preface

This report is the product of a National Research Council (NRC) committee study sponsored by the U. S. Department of Energy (DOE). The first NRC Committee on the Waste Isolation Pilot Plant (WIPP) began in 1978, and this committee and its successors issued eight letter reports during 1979-1992 and two full reports in 1984 and 1996. The current WIPP committee study is operating under a revised statement of task (see box) derived from a DOE request (Dials, 1997). This interim report addresses selected issues associated with the task statement, as explained below. The committee will comprehensively address the statement of task in the final report.

The specific approach taken in this interim report was to consider how to assess (1) the performance of WIPP in isolating waste from the environment and (2) the basic, minimal requirements and procedures that should be applied to waste management operations. The committee provides recommendations on several issues that it believes merit immediate consideration and action by DOE. Specifically, these issues include the determination of the natural background radioactivity in the area surrounding WIPP, and improvements in TRU waste operations.

This study is organized within the NRC's Board on Radioactive Waste Management and is being conducted by a 15-member committee. Committee members were chosen for their expertise in relevant technical disciplines such as nuclear engineering, health physics, chemical and environmental engineering, civil and transportation engineering, performance assessment, analytical chemistry, materials science and engineering, plutonium geochemistry, hydrogeology, rock and fracture mechanics, petroleum engineering, and mining engineering. As is normal practice of the National Academies, committee members do not represent the views of their institutions, but form an independent body to author this report.

To conduct the study and prepare this interim report, the committee gathered information principally through meetings and reviews of relevant literature. The committee met several times in open public sessions to hear from DOE and its contractors, as well as from other invited speakers such as regulatory agency personnel and groups with an interest in the WIPP program. Committee members prepared this report

using these inputs together with their collective knowledge and experience. The report reflects a consensus of the committee and has been reviewed in accordance with NRC procedures.

Statement of Task

The purpose of this study is to identify the limiting technical components of the WIPP program, with a two-fold goal of (i) improving the understanding of long-term performance of the repository and (ii) identifying technical options for improvements to the National TRU Program (i.e., the engineering system that defines TRU waste handling operations that are needed for these wastes to go from their current storage locations to the final repository destination) without compromising safety.

To accomplish this goal, the study will address two major issues:

(1) The first is to identify research activities that would enhance the assessment of long-term repository performance. This study would examine the performance assessment models used to calculate hypothetical long-term releases of radioactivity, and would suggest future scientific and technical work that could reduce uncertainties.

(2) The second is to identify areas for improvement in the TRU waste management system that may increase system throughput, efficiency, cost effectiveness, or safety to workers and the public. This study will examine, among other inputs, the current plans for TRU waste handling, characterization, treatment, packaging, and transportation.

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Summary

The National Research Council convened a committee of experts to advise the U.S. Department of Energy (DOE) on the operation of the Waste Isolation Pilot Plant (WIPP), a geologic repository for disposal of defense transuranic (TRU) waste near Carlsbad, New Mexico. The committee was asked to provide recommendations on the following two issues: (1) a research agenda to enhance confidence in the long-term performance of WIPP; and (2) increasing the throughput, efficiency, and cost-benefit without compromising safety of the National TRU Program for characterizing, certifying, packaging, and shipping waste to WIPP.

The committee has written this interim report to provide DOE with recommendations on several issues that the committee believes merit immediate consideration and action. In developing this report, the committee has been guided by the principle of "reasonableness" with respect to risks, costs, and the ALARA (as low as reasonably achievable) principle. In the committee's judgment, implementing the recommendations contained in this report will contribute to the continued safe operation of WIPP. The committee will provide a more comprehensive response to its task statement (see the Preface) in the final report, which is scheduled for completion in the spring of 2001.

Research to Enhance Confidence in Long-Term Repository Performance

There has been extensive monitoring of radioactivity in the air, soils, fluvial sediments, surface water, and shallow groundwater in the area surrounding WIPP. However, the committee has determined that radiological baseline information is not available for subsurface brines and hydrocarbons near the WIPP site. This baseline information is important for environmental monitoring in the operational and post-operational phases of the repository.

Recommendation: The committee recommends that DOE should develop and implement a plan to sample oil-field brines, petroleum, and solids associated with current hydrocarbon production to assess the magnitude and variability of naturally occurring radioactive material

(NORM) in the vicinity of the WIPP site. Samples should be collected and analyzed for the radionuclides that will be present in transuranic waste emplaced at WIPP and the radionuclides common in NORM. These samples should be archived to permit subsequent analysis for constituents that may be of interest in the future. The committee recommends that a sampling plan be implemented prior to the closure of any underground rooms in WIPP that contain TRU waste.

Improvements to the National TRU Program

The National TRU Program is administered by the DOE Carlsbad Area Office and is designed to meet all applicable external regulations and internal requirements associated with the characterization, certification, packaging, and transportation of waste to WIPP. A reasonable goal for the National TRU Program is to send DOE TRU waste to WIPP at a minimum risk (from all sources of risk, including radiological exposure and highway accidents) and cost. The current system for managing TRU wastes does not achieve this goal. **The committee recommends that waste management procedures be reviewed and revised, with reduction of risk and cost as the guiding principles.**

The committee offers recommendations in this interim report to improve the following three aspects of the National TRU Program: (1) waste characterization and packaging requirements, (2) gas generation, and (3) the transportation system.

Waste Characterization and Packaging Requirements

The committee found inadequate legal or safety bases for some of the National TRU Program requirements and specifications. That is, some waste characterization specifications have no basis in law, the safe conduct of operations to emplace waste in WIPP, or long-term performance requirements. The National TRU Program waste characterization procedures involve significant resources (e.g., expenditures of several billion dollars) and potential for exposure of workers to radiation and other hazards. Insofar as some of this waste characterization may be unnecessary, such characterization is inconsistent with economic efficiency or the ALARA principle that guides radiation protection practices.

Recommendation: DOE should eliminate self-imposed waste characterization requirements that lack a legal or safety basis. One way to justify a reduction in waste characterization requirements is through implementation of joint U.S. Nuclear Regulatory Commission–U.S. Environmental Protection Agency guidance (62 Federal Register 62079; see Appendix B), which appears to the committee to provide appropriate guidelines for implementation and integration of Resource Conservation and Recovery Act (RCRA) requirements for mixed TRU waste. Another way to justify a reduction is to identify the origins of all waste characterization requirements and to eliminate those requirements that lack a technical or safety basis. Such reductions may require modifications to exist-

ing permits granted by external regulating authorities such as the Environmental Protection Agency and New Mexico Environment Department.

Gas Generation

The extreme assumptions used in DOE's current gas generation model results in gross overestimates of hydrogen (H_2) concentrations in waste packages to be shipped to WIPP. As a consequence, DOE plans to repackage some of the waste to dilute the hydrogen-producing components. These repackaging operations result in additional risks of radiation exposure to workers and highway accidents, the latter due to the increased number of truckload shipments required to transport waste in diluted form.

Recommendations:

1. DOE should derive a more realistic radiolytic gas generation model, validate it through confirmatory testing, use the results to recalculate gas generation limits, and seek regulatory approval to implement them.
2. DOE should perform a safety analysis to determine the concentration and quantity of hydrogen that, upon ignition, could damage the seals of the TRUPACT-II shipping container. The goal of the safety analysis would be to demonstrate whether such an event could occur inside a waste package, and whether the energy associated with such an event could result in rupturing the containment provided by the TRUPACT-II. This analysis could provide the rationale to obtain relief from the 5 percent hydrogen flammability limit and should form the basis for a future modification to the present TRUPACT-II license.
3. DOE should consider technical approaches for reducing hazards from hydrogen generation, such as filling the headspace of the waste containers or the shipping containers with an inert gas.
4. DOE should reevaluate the technical and regulatory feasibility of shipping high-wattage TRU waste using a railcar shipping system.

The goal of these recommendations is to expedite the transport of TRU waste to WIPP by increasing the amount of waste that can be safely carried in each truckload or trainload, without compromising the level of safety and containment that is provided by the shipping container. These recommended options would reduce the number of truckloads required to transport the waste to WIPP and the associated transportation risks.

Transportation Communication and Notification

DOE bases its system of communication and notification on the TRANSportation tracking and COMmunication (TRANSCOM) system, a satellite-based system initially developed more than a decade ago and used to track all DOE shipments of radioactive materials. Users have found the current level of performance of TRANSCOM to be less than

fully reliable. Although efforts are being made by DOE to keep the system current, it has not kept pace with the rapid development of information technology. As a result, the TRANSCOM system is obsolete when compared to presently available communications systems.

Recommendations: DOE should consider cost-effective ways to improve the reliability and ease of use of the TRANSCOM system, either by improving or replacing it. If DOE decides to replace the current system, the committee strongly encourages the use or adaptation of existing commercial systems. In the near term, the DOE should develop an interim plan for maintaining an adequate communication and notification system until any such alternative system or TRANSCOM upgrade is ready for full-scale implementation. This plan should be driven by a comprehensive assessment of TRANSCOM component performance based on anticipated usage. In the long term, DOE should ensure that the system it employs is designed to meet the needs of WIPP shipment users and other major stakeholders in a timely and cost-effective fashion.

Transportation Emergency Response

The responsibility for emergency response is divided between DOE and the states along WIPP shipment corridors. In the committee's view, a system to maintain up-to-date information on response capability would contribute significantly to the effectiveness of the transportation system. The WIPP emergency response program has not assessed sufficiently whether adequate and timely emergency response coverage for a transportation incident exists along the full extent of each WIPP route. No formal system presently exists to identify areas where coverage may be inadequate.

Recommendations: The committee recommends that DOE explore with states and other interested parties how to develop processes and tools for maintaining up-to-date spatial information on the location, capabilities, and contact information of responders, medical facilities, recovery equipment, regional response teams, and other resources that might be needed to respond to a WIPP transportation incident. This assessment should explore which organization(s) should develop and maintain the capability to generate and maintain such information. DOE should also determine where emergency response capability is currently lacking, identify organization(s) responsible for addressing these deficiencies, and take action to address them.

Introduction

The Waste Isolation Pilot Plant (WIPP)[1] is a series of excavations in a Permian-age bedded salt formation approximately 660 m below the surface near Carlsbad, New Mexico (see Figure 1). Since the mid-1970s, this site has been studied for use as a geologic repository for the disposal of transuranic[2] (TRU) waste resulting from the nation's defense program. This waste contains transuranic isotopes, predominantly plutonium isotopes, which are characteristically long-lived radionuclides and therefore a long-term safety hazard. Removing these wastes from the biosphere, for example, through isolation in geologic repositories, is an appropriate strategy for protection of human health and the environment.

At WIPP, packaged waste is disposed by emplacing it in rooms excavated in the salt. Because salt under pressure flows (or "creeps") and because of the underground pressure exerted on the room ceiling, floor, and walls, over time the salt rock at these surfaces will consolidate around the waste. In time, the salt heals so as to be essentially impermeable, isolating the waste-filled rooms from the rest of the environment.

WIPP is the first deep geological repository that has been designed and engineered for radioactive waste disposal and approved by an external regulatory authority. Operations at WIPP to receive TRU waste and emplace it underground began in 1999, when TRU waste shipments were received from three U.S. Department of Energy (DOE) sites. Drums of TRU waste from the Los Alamos National Laboratory, the Idaho National Engineering and Environmental Laboratory, and the Rocky Flats Environmental Technology Site were first sent to WIPP in March, April, and June 1999, respectively.

The committee has prepared this report to provide findings and recommendations that it considers important for the safe and cost-effective operation of WIPP. The perspective of the committee has been the establishment of "reasonableness" with respect to risks, costs, and the ALARA (as low as reasonably achievable) principle (see footnote 8). The committee believes that the implementation of these recommendations will contribute to the continued safe operation of WIPP.

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[1]A complete list of acronyms used in this report appears in Appendix D.

[2]Transuranic waste contains radionuclides with atomic numbers greater than 92 and half-lives greater than 20 years in concentrations exceeding 100 nanocuries per gram.

As noted in the preface to this report, the first component of the statement of task is "to identify research activities that would enhance the assessment of long-term repository performance" (see Appendix A). The committee considers that data from radiological site characterization measurements would provide a necessary baseline to compare against future measurements, should the integrity of WIPP ever be challenged. This issue is explored in the next section.

The second component of the statement of task pertains to improvements of the DOE TRU waste management system. To address this issue, the committee sought to identify the technical, regulatory, legal, and/or safety bases of waste management activities that significantly impacted the overall system throughput, efficiency, cost, and safety. These issues are addressed in the last section of this report.

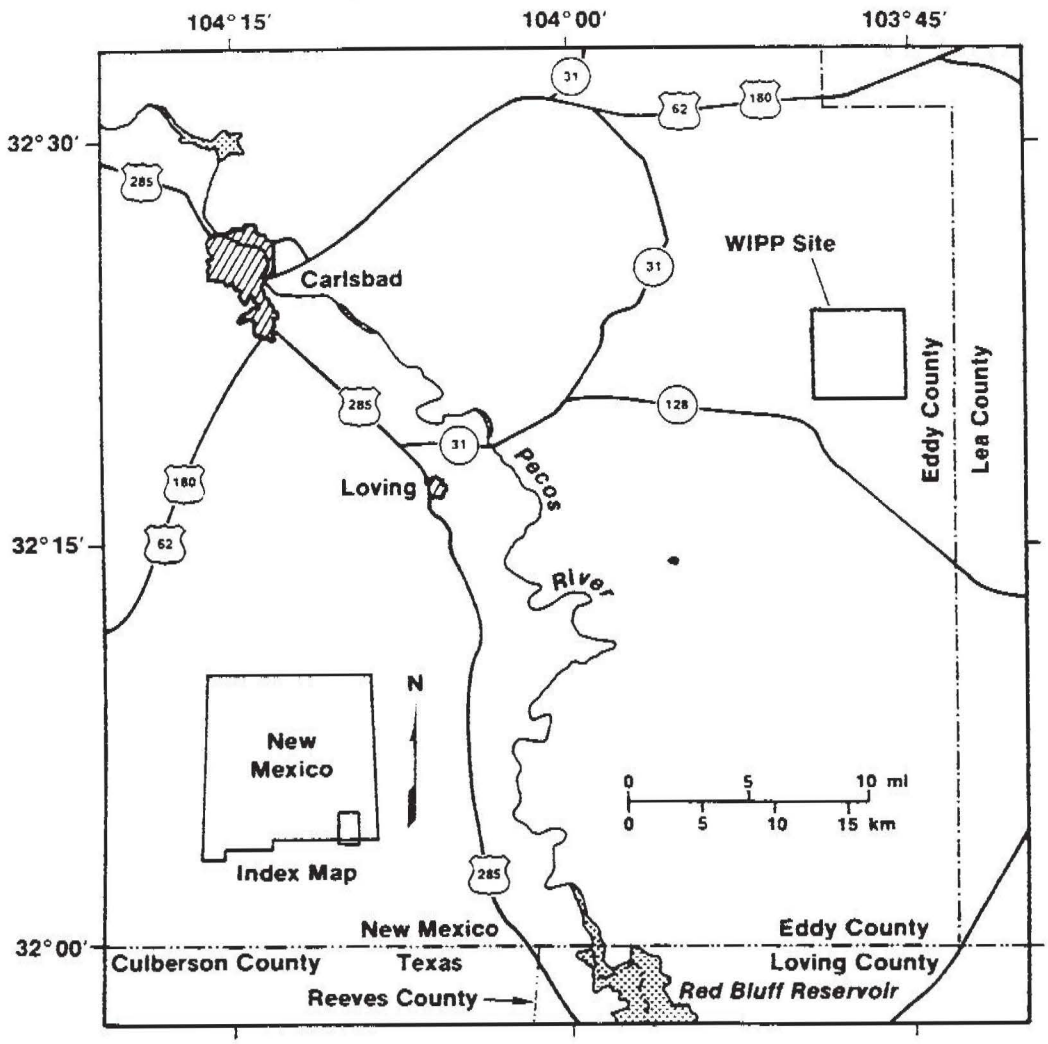

FIGURE 1 Location of the Waste Isolation Pilot Plant. Inset shows the approximate location of the map area in New Mexico. SOURCE: NRC (1996, Figure 1.1.).

Baseline Radiogenic Analysis of Subsurface Fluids

In this section the committee provides recommendations on research activities to enhance confidence in the long-term performance of WIPP. In particular, the committee considered how "baseline" studies undertaken during the early phases of repository operation could be used to support future efforts to assess repository performance.

Finding: There has been extensive monitoring of radioactivity in the air, soils, fluvial sediments, surface water, and shallow groundwater in the area surrounding WIPP.[3] However, the committee has determined that radiological baseline information is not available for subsurface brines and hydrocarbons near the WIPP site. This baseline information is important for environmental monitoring in the operational and post-operational phases of WIPP.

Recommendation: The committee recommends that DOE should develop and implement a plan to sample oil-field brines, petroleum, and solids associated with current hydrocarbon production to assess the magnitude and variability of naturally occurring radioactive material (NORM) in the vicinity of the WIPP site. Samples should be collected and analyzed for the radionuclides that will be present in transuranic waste emplaced at WIPP and the radionuclides common in NORM. These samples should be archived to permit subsequent analysis for constituents that may be of interest in the future.[4,5] The committee recommends that a

[3]See, for example, Conley (1999); DOE (1997c); Herczeg et al. (1988); and Kenney et al. (1999). Additionally, previous Environmental Evaluation Group studies on radiation monitoring of air, surface soil, and biota samples near the WIPP site include Neill et al. (1998); Kenney et al. (1990, 1995, 1998); Kenney and Ballard (1990); and Kenney (1991, 1992, 1994). Ramey (1985) summarizes U.S. Geological Survey data on simple radiological characterization (i.e., gross alpha, gross beta, dissolved radium, and dissolved uranium) of fluids in the Rustler Formation. References to other studies are contained in annual reports of the Carlsbad Environmental Monitoring Research Center (CEMRC, 1999) and on the CEMRC website, http://www.cemrc.org.

[4]A reanalysis of a sample using a different detection method could yield a different value. These detection limitations should be understood and distinguished from true natural differences in background radiation.

sampling plan be implemented prior to the closure of any underground rooms in WIPP that contain TRU waste.

Rationale: Early studies discounted the potential for hydrocarbon production in the vicinity of WIPP, but over the past 20 years this way of thinking has changed dramatically. The site is now surrounded by wells (see Figure 2) for hydrocarbon production (Broadhead et al., 1995), and drilling activities continue. Furthermore, it is relatively common for brines associated with hydrocarbons to be radiogenic (Bloch and Key, 1981; Fisher, 1995). Oil-field brines in the Delaware Basin share this property (Fisher, 1995). The information available on oil-field brines and petroleum resources generally consists of gross radiation measurements (i.e., gross activity), rather than analytical data on the radionuclide constituents. Such analytical data on the radioactivity of oil-field brines and petroleum resources at the WIPP site have not been made available to the committee and may not exist.

If, during or after WIPP operations, increased radioactivity in the vicinity of WIPP is observed, is this the result of a failure of the WIPP to contain its waste, or is it due to NORM? This question cannot be answered easily unless the oil-field brines, petroleum, and solids associated with hydrocarbon production (e.g., suspended solids, precipitated scale, sludges, and formation fragments) are analyzed for their naturally occurring radiation. Analyses for radioactivity and radionuclides will be necessary if disputes arise about potential releases of radionuclides from the repository. An example of the need to obtain adequate NORM background data already has been observed with occurrences of natural surface contamination on the exterior of truck transportation packages while en route to WIPP during the first three months of operation.

"Human intrusion scenarios" involving hydrocarbon exploration and production are now considered processes through which radionuclides might be released from WIPP (Kirkes, 1998). If brines have a measurable NORM content, then human intrusion that results in brine flow through WIPP to the surface is a means by which radioactivity could be carried to the surface that is not due to the TRU waste emplaced in WIPP. If oil-field brine NORM is present, then it is conceivable that NORM releases would be greater than releases from the TRU waste contents of WIPP, even if drilling breaches the repository.

Transport and disposal of oil-field brines that have high NORM contents are also potential mechanisms for localized increases in radiation. Any such increases in radiation in the vicinity of WIPP cannot necessarily be attributed to WIPP operations or the failure of WIPP to contain its waste.

There are data suggesting that oil-field brines near WIPP might contain NORM. Otto (1989, reproduced in Fisher, 1995; see Figure 3)

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[5]The archiving of monitoring data, as well as samples, is also a long-term challenge due to the evolution of information technology and the changes in state-of-the-art storage media that will likely take place over the three decades in which WIPP is projected to be open and operational. Any data records not in paper form would be subject to such challenges.

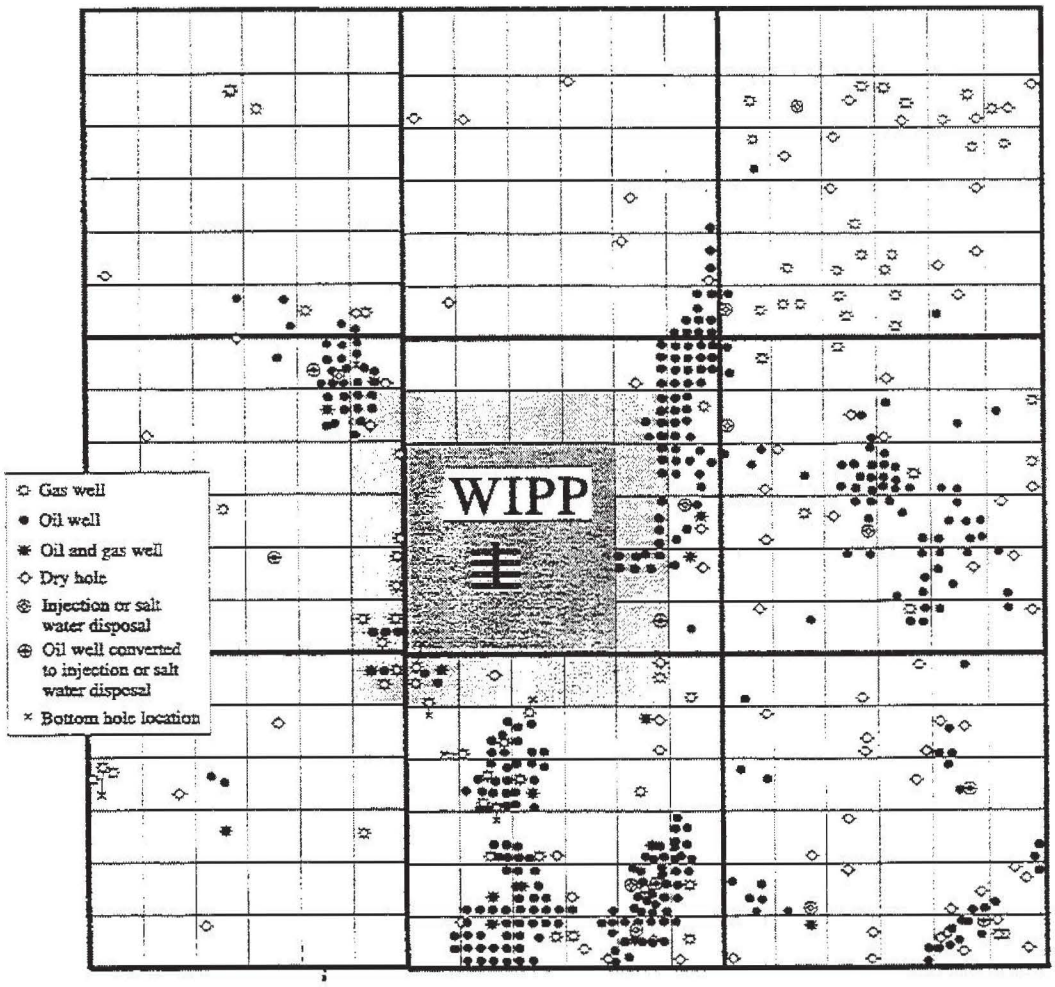

FIGURE 2 Petroleum wells in the vicinity of the WIPP site. See Figure 1 for an inset map showing the WIPP site's approximate location within New Mexico. SOURCE: Silva (1996, p. 24).

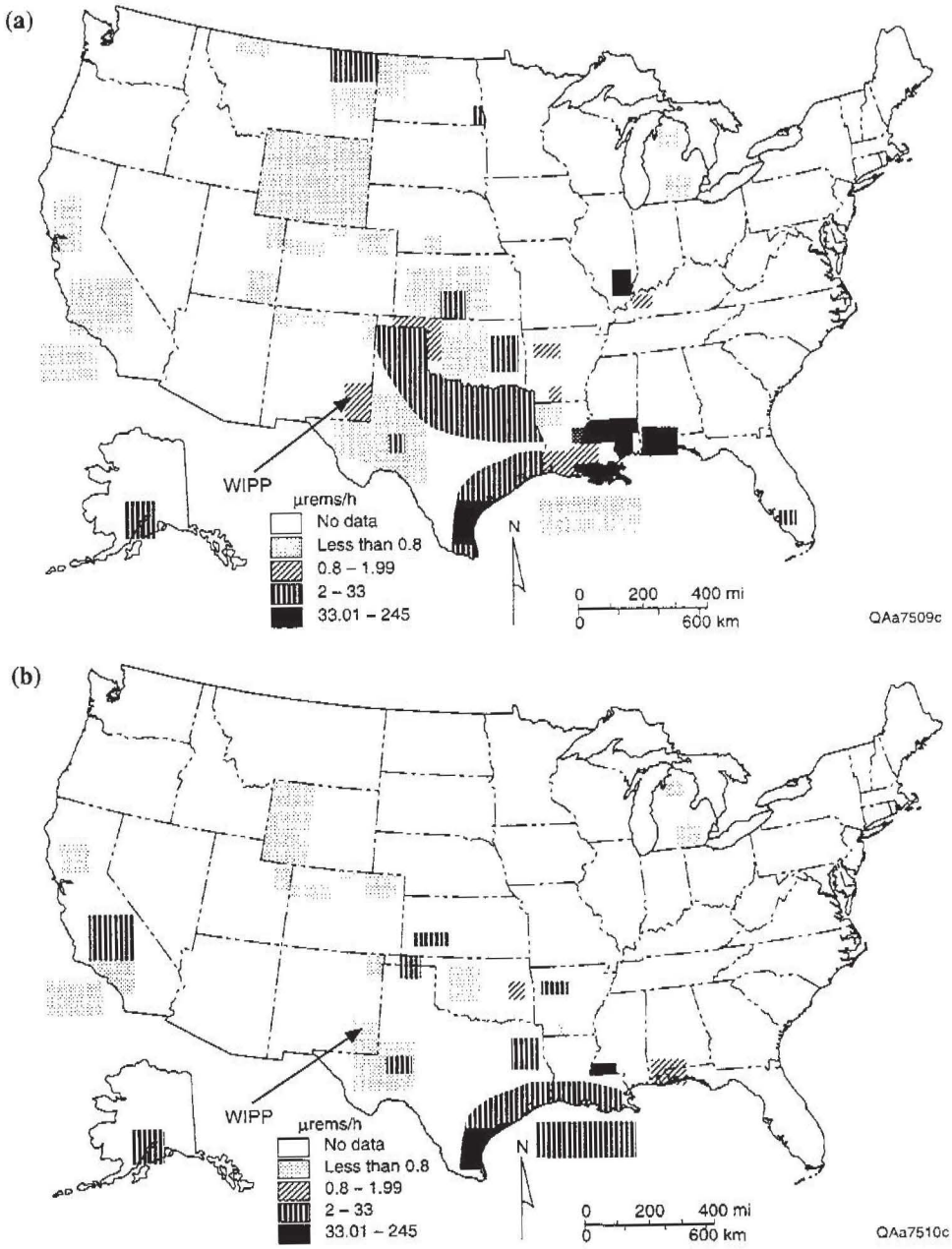

FIGURE 3 Regions of high activity from NORM in the United States from (a) oil-producing facilities and (b) gas-producing facilities. Values are aggregated median differences over background. The legend shows various shadings corresponding to various ranges of dose rates measured in microrems per hour (µrem/h). These dose rates are radioactivity measurements of NORM deposits in piping and in fluids brought to the surface. These measurements describe the concentration of radioactive species, a characteristic of the NORM deposits at any locality that is not directly dependent on the local production rate (of hydrocarbons or brine) or on the amounts of fluid that were extracted to produce the deposits. SOURCE: Fisher (1995), after Otto (1989).

shows the Delaware Basin of southeast New Mexico as a region of NORM activity in oil-and gas-producing facilities. Fisher states that "(1) not every major oil or gas field has associated high NORM levels, and (2) no major hydrocarbon-producing basin in Texas is exempt from high levels of radioactivity." The major hydrocarbon-producing basins in Texas described by Fisher include the Delaware Basin, which contain producing formations near the WIPP site, and the adjacent Central Basin Platform (Hill, 1996, p. 26).

In response to committee requests for information, DOE has answered that no data have been collected on "naturally occurring radionuclides in the underground brines and hydrocarbons near WIPP by DOE. In addition, DOE is unaware of any related information collected by the oil and gas industry" (Mewhinney, 1998b).

The need for these data is clear—no effective monitoring of the WIPP area can be successful without understanding potential sources of radiation in the environment. Air, soils, sediments, ground and surface waters, biota, and people have been analyzed to provide a database (e.g., through CEMRC activities). NORM from local hydrocarbon operations must also be analyzed. The NORM data will

- identify sources of future contamination events that might (wrongly) be attributed to a failure of WIPP;
- place any radioactivity releases from human intrusion scenarios (e.g., from petroleum exploration and production) in perspective; and
- improve the monitoring efforts.

The committee recommends near-term action to collect and analyze these data based on an appropriate sampling plan. The plan must include frequency of sampling and analyses; radionuclides to be analyzed; collection of data to assess NORM radioactivity and to estimate its variability; sampling, analysis, and archiving protocols; and producing formations to be tested. These formations should include both past (if applicable) and present producing zones, new producing zones as they become exploited in the future, and formations from which brine is (or likely will be) extracted.

Samples could come from ongoing well-based operations that generate separator streams of oil, gas, and water. These separators and separator streams are owned by the operators of the leases. The drilling of new wells would be justified if data from separator streams prove to be inadequate.

The radionuclides of interest include both those that contribute to the site's NORM background radioactivity and those in the DOE TRU inventory destined for WIPP. The NORM activity may include contributions from potassium-40, isotopes of uranium and thorium, and daughter products such as isotopes of radium. Radionuclides in TRU waste include isotopes of uranium and TRU elements and, in remote-handled[6] TRU

[6]Remote-handled waste is classified as that with a surface dose rate greater than or equal to 200 mrem per hour. Such waste contains fission products and activation products such as cobalt-60, strontium-90, yttrium-90, ruthenium-106,

waste, fission and activation products. Since some TRU inventory radionuclides are not commonly found in nature, sampling to determine whether such radionuclides are present in the environment may be a good way to distinguish radioactivity due to NORM from that due to TRU waste.

For the reasons given above, the committee supports the collection of NORM data on deep subsurface fluids, even though the isotopic signatures of NORM and TRU waste radioactivity are expected to differ and therefore to be readily distinguishable. In the committee's view, DOE would be better served to possess these NORM data prior to any reported discovery of significant radioactivity in the region; hence, in its recommendation the committee proposes that this survey to sample deep subsurface fluids be conducted in the near term. This survey need not continue once the measurement objectives, as proposed in this recommendation, have been met.

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cesium-137, barium-137, and europium-152. These and other radioisotopes emit penetrating beta and gamma radiation that requires shielding.

Transuranic Waste Management Program

Transuranic waste management operations are performed under the auspices of the DOE National TRU Program administered by the DOE Carlsbad Area Office. This program has been designed and developed, based on initial efforts in the 1980s and subsequent modifications, to accommodate all applicable external regulations and internal requirements that are associated with the characterization, certification, packaging, and transportation of TRU waste to WIPP. These procedures, described briefly in Appendix A, were applied in 1999 for the first contact-handled TRU waste shipments to WIPP from DOE sites that have generated and stored such waste. The remote-handled TRU waste management system is still under development and is not reviewed in this report.

The committee considered three topics associated with TRU waste management: (1) waste characterization and packaging requirements, (2) gas generation, and (3) transportation. These topics are discussed in the following subsections.

Waste Characterization and Packaging Requirements

Finding: The committee found inadequate legal or safety bases for some of the National TRU Program requirements and specifications. That is, some waste characterization specifications have no basis in law, the safe conduct of operations to emplace waste in WIPP, or long-term performance requirements.[7] The National TRU Program waste characterization procedures involve significant resources (e.g., expenditures of several billion dollars) and potential for exposure of workers to radiation and other hazards. Insofar as some of this waste characterization may be unnecessary, such characterization is inconsistent with economic efficiency and the ALARA principle that guides radiation protection practices.[8] The committee regards the 30+ years of waste emplacement op-

[7]A recent study (DOE, 1999c) has also shown that some waste characterization procedures are not prescribed by safety or legal requirements.

[8]ALARA requires that all operations be done with the lowest possible radiation exposure consistent with other requirements of safety and basic programmatic objectives. See, for example, 10 CFR 835, which are requirements for

erations and related worker safety issues at WIPP as posing no significant needs for waste characterization information, because no use of characterization data is made in any handling, shipping, or emplacement operations.

Recommendation: DOE should eliminate self-imposed waste characterization requirements that lack a legal or safety basis. One way to justify a reduction in waste characterization requirements is through implementation of joint U.S. Nuclear Regulatory Commission (USNRC)–U.S. Environmental Protection Agency (EPA) guidance (62 Federal Register 62079; see Appendix B), which appears to the committee to provide appropriate guidelines for implementation and integration of Resource Conservation and Recovery Act (RCRA) requirements for mixed TRU waste. Implementation of this regulatory guidance could significantly reduce the testing protocols and associated radiation exposure of personnel. Another way to justify a reduction is to identify the origins of all waste characterization requirements and to eliminate those requirements that lack a technical or safety basis. Such reductions may require modifications to existing permits granted by external regulating authorities such as the EPA and New Mexico Environment Department.

Rationale: The National TRU Program has developed waste restrictions, as described in the waste acceptance criteria (DOE, 1996a, 1999d), and requirements for waste generating sites presented in the quality assurance program plan (DOE, 1998b). These criteria and plans impose many required procedures on waste-generating sites. EPA and DOE Carlsbad Area Office audits are conducted to certify (i.e., approve for shipment) TRU waste streams. Additionally, each container of waste from a certified waste stream must be characterized, and shipping sites must prepare documentation on characterization data for each waste container. At the Los Alamos National Laboratory, the time to obtain all the requisite documentation and administrative approvals was greater than the time to process a drum of waste through the characterization and packaging protocols that had been developed. At all sites, the assembly, management, and storage of waste characterization information are resource-intensive activities, and drum handling is a major source of worker exposure. Of interest to the committee is the origin of these required procedures, because they increase the cost or risk or decrease the efficacy of operations.

The committee sought to identify the connection between the National TRU Program procedures and the various regulatory, legal, and technical requirements that the procedures should be devised to meet. The committee views these requirements in a hierarchy, at the top of which are legal and safety requirements, with regulatory specifications at the next tier, procedures proposed by DOE to meet regulatory requirements at the third tier, and the DOE protocols for these procedures at the fourth tier.

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worker protection referenced in DOE radioactive waste management practices (specifically, in DOE Order 435.1 [DOE, 1999a]).

The approach used by the committee was to focus on six primary National TRU Program procedures representative of high-level requirements that drive operational activities in waste characterization and repackaging (see Appendix A for an overview of these activities):[9]

1. determination that the TRU waste is of defense origin;
2. sampling and analysis of homogeneous waste;
3. headspace gas sampling and analysis;
4. radioassay of the plutonium content;
5. real-time radiography; and
6. visual examination.

These procedures are incorporated into the terms of the WIPP facility's RCRA "Part B" permit, which was issued in October 1999. The EPA guidelines that are specific to RCRA requirements are presented in Appendix B. However, the committee notes that the permit terms are subject to negotiation in a regulatory permitting process, based on the procedures proposed by DOE that became accepted as meeting regulatory requirements. A recent study (DOE, 1999c) has traced these and other TRU waste characterization requirements to their root origins in either (1) Carlsbad Area Office mandates, (2) regulatory certification and permit terms, (3) regulatory requirements or DOE orders, or (4) legal requirements.

A review of these six procedures revealed that one may be interpreted too strictly by DOE and three are without a technical or legal foundation:

Procedure 1: Determination that the TRU waste is of defense origin. WIPP is limited to defense-related waste as stipulated in the Land Withdrawal Act, with defense activities defined in the Nuclear Waste Policy Act of 1982. The committee notes that this definition includes the words "in whole or in part", which can be interpreted to include mixtures of defense and nondefense waste, although DOE does not appear to take advantage of this (see DOE, 1997a; Nordhaus, 1996). That is, waste such as plutonium-238 (^{238}Pu)-contaminated scrap from a facility used for both defense and nondefense missions at Los Alamos National Laboratory would appear to qualify as defense waste under the definition, without the need for waste segregation restrictions.

Procedure 2: Sampling and analysis of homogeneous waste. DOE has written, "There is no regulatory requirement to conduct homogeneous waste sampling and analysis, however, in an effort to meet the intent of 40 CFR 264.13, WIPP has imposed additional characterization requirements on the waste generators" (Nelson, 1999a, p. 2). No operational decisions are made based on these data; that is, the results of the sampling and analysis do not affect how waste is handled, so it is not clear what justifies the additional radiation exposure risk and cost of this procedure. In the committee's view, this sampling and analysis applied only to homogeneous waste is unnecessary: If acceptable knowledge documentation

[9]A more comprehensive list of TRU waste characterization procedures and their origin is found in DOE (1999c).

(see Appendix A) provides sufficient characterization information for heterogeneous waste, the committee can identify no technical reason why acceptable knowledge should not also be adequate for homogeneous waste.

Procedure 3: Headspace gas sampling and analysis. DOE informed the committee that "there is no regulatory requirement to conduct headspace gas sampling and analysis, however, in an effort to meet the intent of 40 CFR 264.13, WIPP has imposed additional characterization requirements on the waste generators" (Nelson, 1999a, p. 3). The headspace gas sampling and analysis was developed as a means of checking on conformance with USNRC and the U.S. Department of Transportation (DOT) requirements (see Appendix A for relevant sections of these regulations); however, these requirements can be met by other means (see the recommendations that follow on the issue of gas generation).

Procedure 6: Visual examination. Visual examination is done on a fraction of the waste containers to confirm the real-time radiography and acceptable knowledge waste characterization information (Nelson, 1999a, p. 5). However, there is no requirement for verification of real-time radiography results. An alternative way to confirm these results without operator exposure would be to use standardized test drums. The visual examination confirmation is a self-imposed procedure that yields no benefit but results in increased risk of exposure and cost.

A DOE study (1999c) also confirms that procedures 2, 3, and 6 identified above are based on terms negotiated in a permit and not on a required regulation or legal mandate. The committee sees no utility in the information that these procedures provide. Any speculative benefits of acquiring this information must be weighed against the risks and costs. The committee's judgment is that the collection of these data from superfluous procedures increases, rather than decreases, the risk and safety of the overall TRU waste operations.

These superfluous characterization and intrusive procedures also represent a conflict with the ALARA principle. The issue of how to handle conflict between regulatory requirements for waste characterization information and ALARA is beyond the scope of the committee's statement of task. At issue, however, is whether the present TRU waste management program results in significantly more worker radiation exposure than is justified to satisfy safety and nonnegotiable regulatory requirements.

Gas Generation

Finding: The extreme assumptions used in DOE's current gas generation model result in gross overestimates of hydrogen concentrations in waste packages to be shipped to WIPP. As a consequence, DOE's plans to repackage some of the waste to dilute the hydrogen-producing components. These repackaging operations result in additional risks of radiation exposure to workers and highway accidents due to the increased number of truckload shipments required to transport waste in diluted form.

Recommendations:

1. DOE should derive a more realistic radiolytic gas generation model, validate it through confirmatory testing, use the results to recalculate gas generation limits, and seek regulatory approval to implement these limits.
2. DOE should perform a safety analysis to determine the concentration and quantity of hydrogen that, upon ignition, could damage the seals of the TRUPACT-II shipping container. The goal of the safety analysis would be to demonstrate whether such an event could occur inside a waste package, and whether the energy associated with such an event could result in the rupture of containment provided by the TRUPACT-II. This analysis could provide the rationale to obtain relief from the 5 percent hydrogen flammability limit and should form the basis for a future modification to the present TRUPACT-II license.
3. DOE should consider technical approaches for reducing hazards from hydrogen generation, such as filling the headspace of the waste containers or the shipping containers with an inert gas to displace air and thereby reduce the flammability hazard.
4. DOE should reevaluate the technical and regulatory feasibility of shipping high-wattage TRU waste using ATMX[10] railcar shipping system.

The goal of these recommendations is to expedite the transport of TRU waste to WIPP by increasing the amount of waste that can be carried safely in each truckload or trainload, without compromising the level of safety and containment that is provided by the shipping container. These recommended options would reduce the number of truckloads required to transport the waste to WIPP and the associated transportation risks.

Rationale: The amount of TRU waste in each waste drum and truck shipment is limited because of the potential for radiolytic generation of hydrogen gas (H_2). Within TRU waste, radiolytic hydrogen gas generation is due primarily to the co-disposal of alpha emitters with organic materials. The DOE has developed a radiolysis model to calculate hydrogen generation rates and the hydrogen concentration in each headspace[11] inside a waste container. Limiting any H_2 concentration to 5 percent leads to a restriction, expressed as maximum allowable wattage, on alpha activity (i.e., the amount of alpha-emitting radionuclides) within each waste container (e.g., a 55-gallon drum). The value of 5 percent H_2 (as a mole

[10] "ATMX" is an acronym to denote the railcars used by DOE to ship nuclear weapons components and TRU waste. The "AT" stands for Atchison Topeka, the rail carrier. The "M" signifies munitions, and the "X" on a railcar signifies private ownership (in this case, by the U.S. government), rather than ownership by the railroad company. As noted elsewhere in this report, these railcars have been used to ship TRU waste for decades.

[11] In many waste containers, waste is contained in one or more plastic bags that were used for radiological protection against any inadvertent spread of radioactivity. These plastic bags provide resistance to diffusive transport of hydrogen gas, thereby providing multiple headspaces.

fraction) in air as a "flammability limit" can be used in any USNRC license application on a transportation package without the need for further safety analysis because of its conservatism. This allowable wattage is a function of the G value[12] of the solid matrix of the waste materials adjacent to each alpha emitter and the total resistance to the flow of hydrogen gas that the waste and packaging contents provide, due primarily to the layers of plastic bags in the waste.

Wattage limits based on this model determine whether or not a waste container may be transported to WIPP without repackaging. The gas generation model, and the wattage limits derived from it, specify the terms of operation that are contained in the DOE safety analysis report for the TRUPACT-II transportation package. These terms of operation are also specified in DOE's application to the USNRC for regulatory approval of the TRUPACT-II transportation package. The certificate of compliance for TRUPACT-II issued by the USNRC is subject to modifications (and in fact has been amended several times since the original certificate was issued in the late 1980s), provided that DOE can offer sufficient adequate safety assurances and comply with applicable regulations, principally the USNRC's 10 CFR 70-71 and DOT's 49 CFR 171-173.

The current model is based on worst-case scenario of H_2 generation and wattage limits. Because of this worst-case approach and the extreme assumptions used in the model, the calculations often exceed experimental observations by orders of magnitude. The explanations for these large discrepancies are only beginning to be studied (see Idaho Engineering and Environmental Laboratory, 1998; Mewhinney, 1998a). Specific examples follow.

1. A G value of 3.4 is used for the plastic bags in the safety analysis report for the TRUPACT-II (DOE, 1997b). In this analysis, no credit is taken for matrix depletion (i.e., exhaustion of the H_2 source). Therefore, DOE is seeking relief from unrealistically large G values in revisions 17-19 of the safety analysis report and certificate of compliance for the TRUPACT-II (DOE, 1999b).

2. The model assumes that all layers of plastic bags are intact and behave as a new bag (i.e., no credit is taken for changes in permeability with age).

The results of these gas generation model assumptions have severe consequences.[13] Repackaging is carried out to redistribute waste in containers (e.g., 55-gallon drums) in order to meet the wattage limits derived from the gas generation model for each container. This repackaging of waste exposes workers to radiation and increases the number of containers, thereby diluting the waste into a greater volume.

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[12]The G value is the number of electrons (or, equivalently, the number of electron-ion pairs, with H^+ the chief ion produced in materials containing hydrogen compounds) produced in a material per 100 eV of energy that is deposited within it by irradiation.

[13]In general, the use of extreme assumptions that result in overestimating consequences is not a conservative approach, because attending to these overestimated consequences results in unnecessary actions, each of which has its own risks, thus potentially increasing the risks of the overall operations.

Transportation-related risks (and costs) are also incurred in repackaging, because the extra containers require additional shipping loads with many additional truck trips. DOE estimates reveal that this repackaging of ^{238}Pu contact-handled TRU waste may increase the number of ^{238}Pu shipments by more than a factor of ten, to as many as 150,000 extra drums (Lechel and Leigh, 1998).[14] Another consequence of such volume expansions that should be considered is the impact on WIPP's volume limit.[15] Therefore, the maximum allowable wattage imposed by the gas generation model is a major technical restriction of the National TRU Program.

Recent information (DOE, 1999b; Gregory, 1999) suggests that significant progress is being made toward developing technical information to support planned future applications to the USNRC to amend the terms of the TRUPACT-II safety analysis report and certificate of compliance. Research continues to investigate the use of hydrogen getters[16] (Mroz et al., 1997, 1999), methods for puncturing bags, use of vented bags (Gregory, 1999), and relief from the restrictive G values (Idaho Engineering and Environmental Laboratory, 1998).

To provide containment of its radioactive contents, the TRUPACT-II shipping container uses outer O-rings that generate a vacuum seal. In this package design, internally generated gas, such as H_2, builds up to pressurize the internal gas volume. Other transportation package designs are possible that are less sensitive than the TRUPACT-II to the potential for H_2 gas generation. One such system for transport of TRU wastes was the ATMX railcar system, which DOE used for hundreds of shipments over several decades to safely transport TRU waste from the Mound Laboratory in Ohio and from the Rocky Flats Environmental Technology Site in Colorado to the Idaho National Engineering and Environmental Laboratory. Based on the integrity provided by the railcar, this system was exempted (DOT exemption number DOT-E 5948) from the double-containment and vacuum seal requirements for packages used to transport plutonium (classified as "Type B" fissile packages). As a result, this system did not suffer limitations of the kind that are imposed on the TRUPACT-II due to radiolytic gas generated and trapped within the shipping container.

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[14]The actual number of containers to be repackaged and procedures to be used have not yet been determined by DOE but are under active study, as is an analysis of technical options. If each truck carried the maximum number of TRUPACT-II transporters per shipment to WIPP, and each TRUPACT-II carried the maximum number of 55-gallon drums, 150,000 drums would be equivalent to 3,600 additional truck shipments.

[15]The Land Withdrawal Act (P.L. 102-579) specifies a total TRU waste volume limit of 175,600 m^3; if waste were sufficiently diluted, WIPP would be filled to this volume limit without having disposed the total TRU inventory in curies. Therefore, there is a minimum "filling ratio" of curies to volume that must be achieved, on average, for WIPP to contain the total TRU inventory in curies by the time the volume restriction is reached.

[16]A getter is a material designed to absorb gas such as hydrogen.

Transportation

The committee has examined various aspects of the WIPP transportation system, focusing on system safety and the cost-effectiveness of planned and ongoing activities. Based on this review (see DOE, 1999b; Mewhinney, 1998a,b), the committee has identified two issues—DOE's communication and notification system (TRANSCOM[17]) and DOE's emergency response program—that warrant immediate attention.

DOE's Communication and Notification Program

Finding: DOE bases its system of communication and notification on TRANSCOM, a satellite-based system developed more than a decade ago and used to track all DOE shipments of radioactive materials. Users have found the current level of performance of TRANSCOM to be less than fully reliable. Although efforts are being made to keep the system current (Nelson, 1999b), it has not kept pace with the rapid development of information technology. As a result, TRANSCOM is obsolete compared to presently available communications systems (for a summary of recent transportation communication initiatives using information technology, see Allen [1998]).

Recommendations: DOE should consider cost-effective ways to improve the reliability and ease of use of the TRANSCOM system, either by improving or replacing it. If DOE decides to replace the current system, the committee strongly encourages the use or adaptation of existing commercial systems. In the near term, DOE should develop an interim plan for maintaining an adequate communication and notification system until any such alternative system or TRANSCOM upgrade is ready for full-scale implementation. This plan should be driven by a comprehensive assessment of TRANSCOM component performance based on anticipated usage. In the long term, DOE should ensure that the system it employs is designed to meet the needs of WIPP shipment users and other major stakeholders in a timely and cost-effective fashion.

Rationale: Public confidence in a transportation communication and notification system is essential. This will become increasingly important with the growing number of shipments to WIPP. The magnitude of shipping activity and the public interest in WIPP transportation safety dictate the need for a state-of-the-art communications system.

As a means of obtaining information on the current effectiveness of TRANSCOM, the committee contacted 27 users located across the nation, requesting information on their experience with the system. Serious concerns were raised about system reliability and ease of use, giving the impression that key transportation stakeholders have little confidence in TRANSCOM. Comments of the 11 users who responded (from two tech-

[17]The DOE TRANSportation Tracking and COMmunication System, or TRANSCOM, is a satellite-based telecommunications system designed to enable users to track WIPP truck shipments in essentially real time while en route to WIPP on the approved highway routes.

nology companies and various institutions involved in emergency response monitoring in Colorado, Illinois, Pennsylvania, Idaho, Wyoming, Oregon, Arizona, North Carolina, and Utah) to a committee survey are shown below. On a scale of 1 to 5, with 1 = inadequate, 2 = poor, 3 = average, 4 = good, and 5 = excellent, the average scores for TRANSCOM system on five issues were as follows:

Category	Average Score on Scale of 1 to 5
Accuracy	3.5
Cost	3.4
Ease of use	3.2
Communication capability	3.0
Reliability	2.5

Most survey responders also wrote either explicitly or by using examples that the system was (1) unreliable (citing frequent downtime, connection or access problems, or other hardware or software problems), (2) not user friendly (citing features such as slow data rates, the time required to download information, and "old technology"), and (3) not economical because of the high costs for modem connections. Of those survey responders who had experience with at least one other transportation tracking system, each provided written comments attesting to the "unreliable" and/or "not user-friendly" features of TRANSCOM.

The committee concludes from this survey and from other materials received (e.g., presentations at committee meetings in October 1998, May 1999, and July 1999) that the TRANSCOM system has failed to give its users confidence in its reliability, ease of use, and the timeliness with which accurate information can be accessed. The committee regards these features as important for engendering public confidence and trust in WIPP's transportation program, especially for incidents in which some sort of emergency response is required.

The committee considers that given the potential interest in and visibility of WIPP shipments, the tracking system should provide reliable, real-time, and user-friendly access to information for the state users and other interested parties. In principle, this could be accomplished through upgrades to the current TRANSCOM system. However, rather than maintaining and upgrading a technically obsolete system, the committee believes that it would be more prudent for DOE to implement a less expensive, higher-quality system using a currently available commercial communications product (for a summary of transportation communication initiatives using information technology, see Allen [1998]). Careful screening of vendors is necessary to ensure that the desired system can perform to specification and be delivered on schedule and within budget.

Recent DOE efforts (Nelson, 1999b) are aimed at developing upgraded information technology capabilities ("TRANSCOM 2000") for the TRANSCOM system. Specifically, modem connections to access data of interest (e.g., the commercial bill of lading for a shipment) are to be replaced in the near future by internet postings. These plans for improved user interface and data distribution capabilities do not address other parts of the system, such as the speed with which data are acquired and proc-

essed prior to posting. These data acquisition and processing activities appear to introduce time delays that limit system performance; for example, position updates showing the locations of trucks along routes are delayed by several (up to seven) minutes (Nelson, 1999b). An as-yet-unspecified element of these planned upgrades is the extent to which future stakeholder participation will be solicited and used to provide sufficient feedback to ensure that the product ultimately developed addresses user concerns. Moreover, the timetable for off-the-shelf availability of TRANSCOM 2000 appears to the committee to be several years in the future, a problematic scenario for a WIPP shipping activity that is already underway.

One issue relevant to these planned information disclosures in TRANSCOM 2000 is the extent to which such information is needed or useful, by which parties, and to what ends. For example, the terrorist hazard and/or the potential for deliberate sabotage would presumably increase as this information is disseminated more broadly. If restricted access to certain information were important, security firewalls could be used to prevent internet information from being accessed outside of the TRANSCOM user community.

At present, the National TRU Program is one of many DOE users of the TRANSCOM system that is managed by another DOE program unit, the DOE transportation center in Albuquerque, New Mexico; other DOE transportation users include shippers of low-level waste and spent nuclear fuel. If the DOE transportation program that maintains TRANSCOM cannot provide sufficient improvements to fully implement the above recommendations, another approach would be for the National TRU Program to adapt a commercially available tracking system for use on WIPP shipments only. If the tracking system need only meet WIPP shipment requirements, the system specifications would likely be simpler, with a correspondingly greater likelihood that a commercially available product could be adapted for use. For example, WIPP shipments involve unclassified material, which may allow relief from the full suite of TRANSCOM system requirements that have been developed for all of DOE shipping needs.

DOE's Emergency Response Program

Finding: The responsibility for emergency response is divided between DOE and the states along WIPP shipment corridors. In the committee's view, a system to maintain up-to-date information on response capability would contribute significantly to the effectiveness of the transportation system. The WIPP emergency response program has not assessed sufficiently whether adequate and timely emergency response coverage for a transportation incident exists along the full extent of each WIPP route. No formal system presently exists to identify areas where coverage may be inadequate.

Recommendations: The committee recommends that DOE explore with states and other interested parties how to develop processes and tools for maintaining up-to-date spatial information on the location, capabilities, and contact information of responders, medical facilities, re-

covery equipment, regional response teams, and other resources that might be needed to respond to a WIPP transportation incident. This assessment should explore which organization(s) should develop and maintain the capability to generate and maintain such information. DOE should also determine where emergency response capability is currently lacking, identify organization(s) responsible for addressing these deficiencies, and take action to address them.

Rationale: To respond appropriately to any accident or other incident associated with a WIPP shipment, an emergency response system has been developed involving the DOE and state and local governments. Four levels of emergency response teams have been established. The first responders, typically the local police or local fire department, are to alert others. Their "911" call routes the incident to the attention of the second responders, the state emergency management agency, which then involves the state police and any state hazardous material (HAZMAT) or radiological response teams. The third responders are DOE Radiological Assistance Program teams that would be sent from major DOE sites (e.g., Idaho Engineering and Environmental Laboratory or the DOE Carlsbad Area Office) to conduct radiological emergency (medical) response. The fourth level of response is DOE remediation teams who perform measures such as righting a truck and any necessary site cleanup and restoration activities (DOE, 1998a).

Because of the required integrity of the TRUPACT-II shipping container, which is tested and certified to conform to the USNRC's 10 CFR 71 regulatory requirements, the containment offered by this container normally cannot be breached in an accident scenario. Therefore, emergency response procedures in these four levels of response normally would preclude any consideration of releases of materials from the TRUPACT-II. Under normal conditions, the emergency response procedures would still be needed for traffic management and other necessary operations in accident-related situations.

DOE's emergency response program relies heavily on WIPP corridor states to conduct emergency responder training and develop response plans in the event of a transportation incident. DOE also maintains its own specialized response capabilities that can be deployed on an as-needed basis. Although this approach offers certain advantages in terms of state and local involvement, system-level integration is a significant concern.

Maintaining an effective emergency response program necessitates that, if an incident should occur anywhere along a WIPP route, qualified responders can reach the scene in a timely fashion. Emergency preparedness is a formidable challenge given the thousands of miles of highway that comprise WIPP routes.

While WIPP corridor states are coordinating with DOE to ensure the safe transport of WIPP shipments[18] (DOE, 1995, 1999b; Klaus, 1999; Ross, 1999; Wentz, 1999), the public may view this responsibility as ulti-

[18]These activities have included training drills that have been conducted over the past several years to simulate real transportation procedures and accident scenarios.

mately resting with DOE as the system manager. The public might well expect qualified emergency response coverage along the entire length of each WIPP route, and in the committee's view, DOE could be heavily criticized if an event occurs that demonstrates weaknesses in the emergency response program, regardless of whether serious consequences are involved. Hence, although the recommendations in this section are not legal requirements, these assessments of the emergency response capabilities are, in the committee's view, important for providing a well-orchestrated transportation system.

The system-level integration necessary to ensure adequate emergency response would have to manage the jurisdictional boundaries between the various responsible government agencies. For example, under the federal Occupational Safety and Health Act (specifically, 29 CFR 1910.120), an employer is responsible for providing training; consequently, the state has the responsibility to determine the extent and adequacy of training (i.e., who is trained and in what capabilities) for first- and second-level responders. States have, to date, offered free WIPP-related training opportunities. No "quality assurance" program yet exists to evaluate periodically and systematically the extent of training and response capabilities within states. Moreover, the database lists trained personnel by state only, rather than by local region (e.g., county). As required by the Land Withdrawal Act, DOE provides the states with WIPP-specific hazard information, but DOE does not furnish protective, detection, monitoring, or communication equipment to states.

These and other demarcations of responsibilities should be managed to ensure that prompt and effective response capability for any transportation incident exists anywhere along a WIPP route. Although the training and response time associated with the first and second responders are not under DOE's direct control, a system to assess the extent and adequacy of this response coverage would be useful for DOE to properly prepare for and manage WIPP transportation incidents.

Committee Perspective on National TRU Program Requirements

A reasonable goal for the National TRU Program is to send DOE TRU waste to WIPP at a minimum risk (from all sources of risk, including radiological exposure and highway accidents) and cost. The current system for managing TRU wastes does not achieve this goal. The current transportation system cannot be used to ship a large fraction of the TRU waste volume without significant repackaging (Connolly and Kosiewicz, 1997; DOE, 1999b; Mroz et al., 1997). For the waste inventory that does qualify for shipment in this system, risk and cost considerations have not been optimized.

The terms and activities selected by DOE Carlsbad Area Office for submission to its regulatory authorities to satisfy applicable regulations and other concerns do not produce an optimum balance between risk and cost, in the spirit of ALARA. **The committee recommends that waste management procedures be reviewed and revised, with reduction of risk and cost as the guiding principles.**

As experience is gained in the WIPP shipping program, empirical data could be gathered to improve upon the initial estimates of risk and cost that are associated with each operation. The effort to reduce risks and costs necessarily would include some consideration of uncertainty, the procedures needed to adequately bound this uncertainty, and an assessment of which TRU waste program elements are the most important to control.

For example, the current National TRU Program has many procedures to control certain program elements. Over time, the most effective of such controls could be identified and retained. The reduction of risks and costs is possible in a management approach that takes into consideration public preferences for certain restrictions and implements procedures to minimize relevant uncertainties. As empirical data and experience are gathered, estimates of risks and costs of various components of the TRU waste operations can be refined. Such risk and cost estimates are useful to probe the elements of the waste management system that need to be controlled most restrictively, whether to meet legal or technical safety restrictions or to address public preferences for how radioactive waste is to be managed and transported.

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Appendix A

Background Information

The material in this appendix provides background information on the long-term performance of the Waste Isolation Pilot Plant (WIPP) as well as waste characterization and transportation activities associated with the National TRU Program.

Assessment of Long-Term Performance

The ability of WIPP to isolate radioactive waste from the accessible environment has been studied and modeled in a performance assessment calculation. The performance assessment organizes information relevant to long-term (i.e., over a 10,000-year period) repository behavior by assessing the probability and consequence of major scenarios by which radionuclides can be released to the environment surrounding the WIPP site. Important scenarios include those due to human activities, whether deliberate or unintentional, that might occur near the WIPP site and potentially compromise the integrity of the repository. For example, drilling for hydrocarbon resources in formations underlying WIPP is currently practiced in the Delaware Basin on land surrounding the WIPP site; therefore, stylized "human intrusion" scenarios in which future boreholes are drilled through WIPP have been analyzed in the performance assessment model.

Using this performance assessment, the U.S. Department of Energy (DOE) has modeled the long-term performance of the WIPP repository to meet regulatory requirements. As specified by the 1992 Land Withdrawal Act (P.L. 102-579) passed by the U.S. Congress, the U.S. Environmental Protection Agency (EPA) is the external regulatory authority for WIPP, using as a regulatory standard the rule 40 CFR 191.[1] The performance assessment model formed the basis of the 1996 DOE application to the EPA to obtain a certificate of compliance with the 40 CFR 191 standard to open and operate WIPP. The EPA granted this certificate in 1998, and EPA oversight continues in periodic (i.e., every five years)

[1]For compliance with the standard of 40 CFR 191, the EPA issued rule 40 CFR 194 in 1996 to provide a regulatory interpretation of how these requirements would apply to WIPP.

recertifications. Changing some of the repository features (e.g., the design of the engineered seals to close underground rooms once they are filled with waste or the design of the seals to close the vertical shafts to the surface) would require regulatory approval because of their importance to the model of long-term performance.

DOE Management of TRU Waste

Transuranic (TRU) wastes are stored and managed at several DOE sites nationwide. To dispose of these wastes at WIPP, they must be retrieved from storage, characterized, repackaged (if necessary), and transported to WIPP, where they are unloaded from shipping containers and sent underground for emplacement in the disposal rooms.

These activities are conducted under the auspices of the National TRU Program administered by the DOE Carlsbad Area Office. DOE sites sending waste to WIPP must meet the waste characterization and transportation specifications that are contained in the WIPP waste acceptance criteria. The specifications on characterization and transportation operations are designed to meet all applicable regulations that have been promulgated by the EPA (chiefly through the Resource Conservation and Recovery Act, or RCRA), the U.S. Nuclear Regulatory Commission (USNRC), and the U.S. Department of Transportation (DOT). The waste characterization activities and the transportation system are described in more detail below.

Waste Characterization Activities

The characterization program described here has been developed for contact-handled[2] TRU waste and applied to date on non-mixed waste.[3] The methods, equipment, procedures, determination of uncertainty, and other protocols used at DOE sites to perform these characterizations are approved by both the DOE Carlsbad Area Office and the EPA. The major procedures are as described in the following sections:

Determination of the Origin and Composition of the Waste by Acceptable Knowledge. Acceptable knowledge of the origin and composition of the waste must be available in documentation to prove that the waste is of defense origin (by the terms of the Land Withdrawal Act, only defense-related TRU waste may legally be sent to WIPP) and to provide

[2]Contact-handled waste is that for which the maximum radiation dose rate at the surface of the waste container is less than 200 mrem per hour. Essentially no shielding other than the waste container is needed. Much of the DOE TRU waste has radioactivity due primarily to alpha-emitting actinides. Because alpha particles are relatively easy to shield, such waste would have a low surface dose rate and therefore would be classified as contact-handled waste.

[3]Mixed waste is waste with radioactive constituents regulated under the Atomic Energy Act mixed with hazardous chemical materials regulated under RCRA. Non-mixed radioactive waste is waste that can be shown not to contain RCRA-regulated materials.

characterization information on the waste constituents. The DOE Carlsbad Area Office and EPA use the acceptable knowledge documentation to certify each "waste stream" (i.e., waste-generating process), and TRU waste sent to WIPP must come from a certified waste stream.

Sampling and Analysis of Homogeneous Waste for RCRA Constituents. Most of the TRU waste is heterogeneous in nature and requires no further characterization beyond acceptable knowledge to satisfy the regulatory requirements of RCRA. For homogeneous waste, a fraction of the waste containers (e.g., 55-gallon drums or standard waste boxes) are cored to extract representative samples that are analyzed for constituents (e.g., volatile and semi-volatile organic compounds, toxic metals, and other hazardous chemicals) regulated by RCRA. Both the acceptable knowledge procedure (for heterogeneous waste) and the sampling and analysis procedure (for homogeneous waste) were proposed by DOE for the terms of operation that would be specified in its RCRA Part B permit. These terms have been accepted by New Mexico, which has authority delegated by the EPA to regulate RCRA materials and mixed waste and which issued the RCRA Part B permit in October 1999.

Real-Time Radiography. A real-time radiography procedure using x-rays is performed on all waste containers to look for items such as pressurized cans or free-standing liquids that are prohibited from being transported under DOT regulations. If any of these items are present in a waste container, its contents are repackaged, at which time the prohibited materials are removed. Another purpose of the radiography examination is to confirm the acceptable knowledge characterization information.

Visual Examination. A visual examination is performed on a fraction of the waste containers, by spilling the waste contents into a glovebox, to verify the acceptable knowledge and real-time radiography information. The value of this fraction was proposed by DOE to be two percent of the initial population of containers of each waste stream, and if these evaluations resulted in few miscertifications, then the percentage of subsequent waste containers to undergo visual examination would be reduced. In October 1999, New Mexico in its RCRA Part B permit stipulated the initial fraction of containers to undergo visual examination to be 11 percent.

Radioassay and Determination of Fissile Isotope Content. The number of curies of each transuranic isotope is determined by radioassay (e.g., gamma scans) to a specified precision and accuracy. The fissile isotope content is assessed using methods such as passive-active neutron systems. This information is used to ensure criticality safety, a USNRC requirement, which imposes a restriction on the amount (several hundred grams) of each fissile species per container. This restriction is less stringent than the amount derived from the gas generation model, discussed below.

Headspace Gas Sampling. Headspace gas sampling is carried out on all waste containers for flammable gases (specifically, volatile organic compounds, hydrogen, and methane). This procedure has been proposed

as a means of checking on conformity with the DOT regulations (e.g., 40 CFR 173 and 40 CFR 177) and USNRC regulations (e.g., 10 CFR 71) that address the transport of flammable and/or gas-generating substances with radioactive materials (Mewhinney, 1998b). These regulations include the following statements:

- 49 CFR 173.21(g): "Packages which give off a flammable gas or vapor, released from a material not otherwise subject to this subchapter, likely to create a flammable mixture with air in a transport vehicle" are forbidden.
- 49 CFR 173.21(h): "Packages containing materials which will detonate in a fire" are forbidden.
- 49 CFR 173.24(b)(3): "There will be no mixture of gases or vapors in the package which could, through any credible spontaneous increase of heat or pressure, significantly reduce the effectiveness of the packaging."
- 49 CFR 177.848 specifies that flammable gases and radioactive materials "may not be loaded, transported, or stored together in the same transport vehicle or storage facility during the course of transportation unless separated in a manner that, in the event of leakage from packages under conditions normally incident to transportation, commingling of hazardous materials would not occur."
- 10 CFR 71.43(d): "A package must be made of materials and construction that assure that there will be no significant chemical, galvanic, or other reaction among the packaging components, among package contents, or between the packaging components and the package contents, including possible reaction resulting from in leakage of water, to the maximum credible extent. Account must be taken of the behavior of materials under irradiation."

DOE has proposed the headspace gas sampling procedure in its application to the USNRC for a licensing certificate on the transportation package (named the TRansUranic PACkage Transporter, or TRUPACT-II) that is loaded with waste containers for transport by truck to WIPP.

Repackaging of Waste to Meet Wattage Limits Imposed by a Radiolytic Gas Generation Model. Gas generation can occur during the transport of a waste container to WIPP. The radiolytic generation of hydrogen gas in TRU waste comes from the co-disposal of organic materials (containing hydrogen) with alpha-emitting radionuclides, which irradiate the organic matter to produce H^+ ions that combine to form H_2 molecules. The current gas generation model is based on assumptions about the configuration of organic materials and radionuclides. It relates the concentration of hydrogen gas in any headspace to the alpha activity (i.e., activity from alpha-emitting radionuclides) within each waste container. More than one gaseous headspace can exist in a waste container, primarily because TRU waste, when generated and disposed in DOE facilities, was contained within layers of confinement provided by plastic bags that may still be intact and thereby inhibit the flow of hydrogen.

By placing a 5 percent (mole fraction) limit on the maximum H_2 concentration within any headspace, this gas generation model calculates an upper limit, commonly expressed as a maximum thermal wattage, on the alpha activity allowed for the entire waste container. These wattage limits are a function of the waste materials and the number of layers of confinement provided by plastic bags. Because of its conservatism, the value of 5 percent H_2 (as a mole fraction) in air as a "flammability limit" can be used in any USNRC license application for a transportation package without the need for further safety analysis.

For example, for a 55-gallon drum containing a plastic liner and heterogeneous debris with plutonium inside three layers of sealed plastic bags, the wattage limit is approximately 0.028 W (DOE, 1996b, p. 5-6e), which corresponds to a limit of 14 g (0.89 Ci) of plutonium-239 or 0.049 g (0.84 Ci) of plutonium-238. Waste containers containing more wattage than the maximum value allowed by the model have their waste contents repackaged to distribute the TRU waste into configurations that will meet these wattage limits. This is accomplished by spilling these contents into shielded gloveboxes and dividing the waste into several new containers, each filled with a fraction of the contents of the original waste container. At Los Alamos National Laboratory in 1998-1999, gas generation restrictions resulted in the repackaging of 36 drums of plutonium-238 waste from the waste stream "TA-55-43" into approximately 120 drums that were placed inside standard waste boxes.[4]

The output of the characterization program is a set of characterization data for each waste container. If the characterization information is within acceptable limits as determined by the waste acceptance criteria and quality assurance program plan (or waste analysis plan) specifications, the waste container is certified and approved for shipment to WIPP.

Truck Transportation to WIPP

At the DOE sites containing TRU waste, the certified TRU waste containers are loaded inside TRUPACT-II shipping containers that are then sealed with a vacuum-tight seal. The TRUPACT-II is classified and regulated as a "Type B" package for fissile materials.[5] To ensure that the waste contents are safely contained during normal shipment conditions and accident scenarios, this transportation package must meet design features such as double containment (i.e., it must have an inner and outer container) and a vacuum seal. Within the inner container, two standard waste boxes, fourteen 55-gallon drums, or one standard waste box and seven 55-gallon drums can be placed. These waste containers are loaded into the TRUPACT-II using an overhead crane in a bay of a building that a truck can drive into to avoid the need to unfasten the TRUPACT-II from the trailer.

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[4]A 55-gallon drum has a volume of approximately 0.2 m^3, whereas a standard waste box is a 1.9m^3 container that can hold three 55-gallon drums.

[5]This designation is a regulatory term to designate packages used to transport plutonium isotopes, which are contained in TRU waste.

The trucks travel to WIPP on approved highway routes during approved times and maintain communication with a DOE control center. In addition to a cellular telephone and a citizens band radio, each truck contains a satellite transponder that enables it to be tracked en route using DOE's satellite-based telecommunications system, the TRANSportation Tracking and COMmunication (TRANSCOM) System. The TRUPACT-IIs are inspected at the WIPP site and their contents (waste-filled drums or boxes) are unloaded and delivered to an underground elevator for emplacement into rooms excavated in the subsurface salt bed.

Appendix B

Joint USNRC and EPA Guidance on Mixed Waste

A joint U.S. Nuclear Regulatory Commission (USNRC) and U.S. Environmental Protection Agency (EPA) document (62 FR 62079, 1997) provides regulatory guidance outlining the testing requirements for mixed radioactive and hazardous waste. In this dual agency guidance document, the EPA and USNRC position is that a combination of common sense, modified sampling procedures, and cooperation between state and federal regulatory agencies will minimize any hazards associated with sampling and testing mixed waste.

Waste generators may determine whether their waste is a Resource Conservation and Recovery Act (RCRA) hazardous waste based on knowledge of the materials or chemical processes that were used. That is, RCRA regulations do not require testing of the waste.

Therefore, where sufficient knowledge of materials or of the process exists, the generator need not test the waste to determine that it possesses a hazardous characteristic, which would necessitate that RCRA be applied (although generators and subsequent handlers would be in violation of RCRA if they managed hazardous waste erroneously classified as nonhazardous outside the RCRA hazardous waste system). For this reason, facilities wishing to minimize testing often assume that a questionable waste is hazardous and handle it accordingly.

Flexibility exists in the hazardous waste regulations for generators; operators of treatment, storage, and disposal facilities; and mixed waste permit writers to tailor mixed waste sampling and analysis programs to address radiation hazards. For example, upon the request of a generator, a person preparing a RCRA permit for such a facility has the flexibility to minimize the frequency of mixed waste testing by specifying a low testing frequency in a facility's waste analysis plan. The EPA position, as stated in 55 FR 22669 (1990), is that the frequency of testing is best determined on a case-by-case basis by the permit writer.

The joint USNRC-EPA agency guidance document (62 FR 62079, 1997) appears to the committee to provide appropriate guidelines for implementation and integration of RCRA requirements for mixed TRU waste. Implementation of this regulatory guidance could significantly reduce the testing protocols and associated radiation exposure of personnel. At present, the procedures specified in the waste acceptance criteria

and quality assurance program plan documents and in the RCRA Part B permit for the testing of mixed waste seem at odds with the ALARA (as low as reasonably achievable) principle.

Appendix C

Biographical Sketches of Committee Members

B. John Garrick, *Chair*, independent consultant, is a co-founder of PLG, Inc., an international engineering, applied science, and management consulting firm in Newport Beach, California. He received his B.S. degree from Brigham Young University and his M.S. and Ph.D. degrees in engineering and applied science from the University of California, Los Angeles. His professional interests involve risk assessment in applications in fields such as nuclear energy, space, and defense, and in the chemical, petroleum, and transportation industries. He has received numerous awards, including the Society for Risk Analysis Distinguished Achievement Award. He was appointed to the U. S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste in 1994, for which he is now Chairman. Dr. Garrick was elected to the National Academy of Engineering in 1993. He has been a member of the Committee on the Waste Isolation Pilot Plant since 1989.

Mark Abkowitz, professor of civil engineering at Vanderbilt University and director of the Center for Environmental Management Studies, has many years of experience in hazardous materials transport. He has published widely on transportation issues such as the risks of transporting high-level radioactive waste. He is a member and former chairman of the NRC Transportation Research Board standing committee on hazardous materials transport.

Alfred W. Grella, independent nuclear and hazardous materials transportation consultant, retired in 1990 from a career in U.S. government service, first at the Department of Transportation and later at the U.S. Nuclear Regulatory Commission. His distinguished career spans 40 years as a professional in health physics, health protection, transportation, inspection and enforcement, training, and related regulatory activities. Mr. Grella received a Bachelor's degree in chemistry from the University of Connecticut and completed the one-year management program at the National Defense University Industrial College of the Armed Forces. He has authored over 30 published papers. He is a member of the American Nuclear Society and a Fellow of the Health Physics Society. Mr. Grella received the M. Sacid (Sarge) Ozker Award in 1996 for distinguished serv-

ice and eminent achievement in the field of radioactive waste management.

Michael Hardy, president of Agapito Associates, Inc., has experience in numerical modeling and field experimentation in practical, engineering-oriented studies to gather characterization data and to evaluate the merits of design features of proposed high-level waste repositories. Dr. Hardy is a member of the Society of Mining, Metallurgical and Exploration Engineers, Inc., and the American Society of Civil Engineers (ASCE). He is Chairman of the Underground Technical Research Council, a joint ASCE/American Institute of Mining, Metallurgical, and Petroleum Engineers Committee.

Stanley Kaplan, principal of Kaplan & Associates, Inc., is one of the early practitioners of the discipline now known as Quantitative Risk Assessment and a major contributor to its theory, language, philosophy and methodology. Dr. Kaplan is a Fellow of the Society for Risk Analysis and the author of a number of the seminal papers in this field. He is one of the first contributors to the Russian science TRIZ, the Theory of the Solution of Inventive Problems, and currently consults and teaches in this area. He is a founder and board chairman of Bayesian Systems, Inc., a Washington-based company developing diagnostic, decision, simulation, and business management software. Dr. Kaplan is the recipient of several awards and honors, including the Society for Risk Analysis Distinguished Achievement Award in 1996. Dr. Kaplan was elected to the National Academy of Engineering in 1999.

Howard M. 'Skip' Kingston is professor of chemistry in the Department of Chemistry and Biochemistry and in the Center for Environmental Research and Education. Also at Duquesne University, he is director of the Center for Microwave and Analytical Chemistry. His research interests include the development, automation, and standard encapsulation and transfer of analytical analysis methods. For the past several years, he has been actively involved in advancing the area of microwave sample preparation through basic research and the development of procedures that have been adopted by the EPA as standard methods. From 1976 to 1991 he was a supervisory research chemist in the Inorganic Analytical Research Division of the National Institute of Standards and Technology (NIST), where he conceived and managed the Consortium on Automated Analytical Laboratory Systems dedicated to developing automated analytical capability for industry. He has received numerous awards for his pioneering work in several areas, including R&D 100 Awards in 1996 and 1998, the IR 100 Award in 1987, the 1988 "Pioneer in Laboratory Robotics" award, the 1990 NIST Applied Research Award, the Department of Commerce Bronze Medal in 1990, the Award of Merit from the Federal Laboratory Consortium in 1991, and the EPA RCRA Service to Others Award in 1998. He has co-edited and co-authored the American Chemical Society professional reference texts *Introduction to Microwave Sample Preparation: Theory and Practice* (1988) and *Microwave Enhanced Chemistry: Fundamentals, Sample Preparation, and Applications* (1997).

He holds multiple patents in the field of speciation, microwave chemistry, and chelation chromatography.

W. John Lee, Peterson Chair and professor of petroleum engineering at Texas A&M University and formerly executive vice-president of technology at S. A. Holditch & Associates, Inc., has expertise in petroleum reservoir imaging, flow tests in low-permeability formations, and enhanced recovery practices. Professor Lee was elected to the National Academy of Engineering in 1993.

Milton Levenson, independent consultant, is a chemical engineer with over 50 years of experience in nuclear energy and related fields. His technical experience includes work in nuclear safety, fuel cycle, water reactor technology, advanced reactor technology, remote control technology, and sodium reactor technology. His professional experience includes research and operations positions at Oak Ridge National Laboratory, Argonne National Laboratory, the Electric Power Research Institute, and Bechtel. Mr. Levenson is the past president of the American Nuclear Society; a fellow of the American Nuclear Society and the American Institute of Chemical Engineers; and the recipient of the American Institute of Chemical Engineers' Robert E. Wilson Award. He is the author of over 150 publications and presentations and holds three U.S. patents. He received his B.Ch.E. from the University of Minnesota. He was elected to the National Academy of Engineering in 1976.

Werner F. Lutze, professor of chemical and nuclear engineering at the University of New Mexico and director of the UNM Center for Radioactive Waste Management (CeRaM), has over 25 years of research experience in materials science and geochemical issues relevant to the management of radioactive wastes, including selective mineral ion-exchange processes, repository near-field chemistry, waste form development, and trace analyses. He has published widely on weapons plutonium immobilization, waste disposal, and the chemistry of nuclear materials. Professor Lutze is a member of several professional organizations, including the Materials Research Society, the German Nuclear Society, and Sigma Xi.

Kimberly Ogden, associate professor of chemical and environmental engineering at the University of Arizona, has conducted research with Los Alamos National Laboratory collaborators to design treatment methods for remediating hazardous waste sites containing both toxic metals and organics, including plutonium-cellulose mixtures. She is also engaged in collaborations with ECO Compliance Inc. in preparing proposals and reports for the remediation of hazardous waste sites. Professor Ogden has authored or co-authored several book chapters, papers, and presentations in environmental science and technology. She is a member of the American Institute of Chemical Engineers, the American Association for the Advancement of Science, and the American Chemical Society.

Martha Scott, associate professor of oceanography at Texas A&M University, is a researcher in marine radiochemistry and geochemistry. Her

present research involves radionuclide distribution in the Russian Arctic. Her work has dealt with the interaction between oceans and rivers, transport of materials in the marine environment, and chemistry of manganese nodules. The behavior of plutonium isotopes in rivers, estuaries, and marine sediments has been one of her longstanding research interests. She served for two years as an associate program director for chemical oceanography at the National Science Foundation (1992-1993). She received the Ph.D. degree from Rice University and was a National Science Foundation post doctoral fellow at Yale University.

John M. Sharp, Chevron Centennial Professor of Geology at The University of Texas at Austin, leads an active research program in hydrology. Professor Sharp has authored and co-authored over 200 journal articles, books, reports, and presentations. He is a fellow of the Geological Society of America and recipient of its O.E. Meinzer award (1979) and the American Institute of Hydrology's C.V. Theis Award (1996). Dr. Sharp is the current editor of *Environmental and Engineering Geoscience*. He received his B. Geological E. with Distinction from the University of Minnesota and his M.S. and Ph.D. degrees in Geology from the University of Illinois.

Paul G. Shewmon, emeritus professor of materials science and engineering at the Ohio State University, received a B.S. degree in metallurgical engineering from the University of Illinois and M.S. and Ph.D. degrees, also in metallurgical engineering, from the Carnegie Institute of Technology. He recently retired as Humbolt Senior Scientist at the Max Planck Institute Metallforschung in Stuttgart. He has received the ASM deMille Campbell Lecture and Award and the TMS Institute of Metals Lecture & Mehl Medal. He was elected to the National Academy of Engineering in 1979.

James Watson, Jr., professor of environmental sciences and engineering and the Director of the Air, Radiation, and Industrial Hygiene Program at the University of North Carolina at Chapel Hill, holds an M.S. degree in physics from North Carolina State University and a Ph.D in environmental sciences and engineering from the University of North Carolina at Chapel Hill. Professor Watson is accomplished in the fields of environmental radioactivity and radioactive waste management. He has received the Underwood and McGavran Awards for excellence in teaching and the Greenberg Alumni Endowment Award for excellence in teaching, research, and service. He is a past president of the Health Physics Society and a past chairman of the Radiological Health Section of the American Public Health Association. He has served on the Environmental Protection Agency's Radiation Advisory Committee and the executive committee of the agency's Science Advisory Board. He is a past chairman of the North Carolina Radiation Protection Commission and currently chairs the commission's Committee on Low-Level Radioactive Waste Management.

Ching H. Yew, an independent consultant and emeritus professor from The University of Texas at Austin, has specialized in the study of hydraulic fracturing and borehole stability. Dr. Yew is a fellow of the America Society of Mechanical Engineers and a member of the Society of Petroleum

Engineers. Dr. Yew has authored a text and published several articles concerning hydraulic fracturing and borehole stability. The computer code developed by him has been adopted for field use by many oil and gas industries.

Appendix D

Acronyms

ALARA	as low as reasonably achievable
ATMX	Atchison Topeka Munitions private railcar
CFR	Code of the Federal Regulations
CEMRC	Carlsbad Environmental Monitoring Research Center
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
NORM	naturally occurring radioactive material
NRC	National Research Council
RCRA	Resource Conservation and Recovery Act
TRANSCOM	TRANSportation Tracking and COMmunication system
TRU	transuranic
TRUPACT	TRansUranic PACkage Transporter
USNRC	U.S. Nuclear Regulatory Commission
WIPP	Waste Isolation Pilot Plant

Appendix A2

DOE's Response to the Interim Report

Department of Energy
Carlsbad Field Office
P. O. Box 3090
Carlsbad, New Mexico 88221
October 30, 2000

National Research Council
Committee on the Waste Isolation Pilot Plant
Board on Radioactive Waste Management
C/O Kevin D. Crowley, Director
2101 Constitution Avenue, NW
Washington, DC 20418

Dear Committee members:

Thank you for your excellent work on the Waste Isolation Pilot Plant Interim Report. We have read your report with great interest and agree with its principles. I am attaching a response to each of the recommendations which you may wish to consider in developing your Final Report.

To briefly summarize, our responses are as follows:

- Data on NORM is being collected and a database developed.
- We are actively pursuing reduction and elimination of self-imposed waste characterization requirements that lack a technical or safety basis.
- We are working closely with the Nuclear Regulatory Commission to minimize the impact of the 5% hydrogen limit, and to reduce or eliminate unnecessary repackaging of waste.
- TRANSCOM has been completely revised to include requested updates and to incorporate specific WIPP requirements.
- We are working with the states to identify and remedy gaps in emergency response coverage.

In conclusion, your recommendations have been adopted as the cornerstone of our planning to bring WIPP to its full potential as the solution to managing our nation's TRU waste.

Sincerely,

Inés Triay

Dr. Inés Triay, Manager

Attachments
Additional copies of Rail Study
sent under separate cover

cc: Lynne Wade, EM 23
Matthew Silva, EEG

CBFO:OOM:IRT:KJB 00-0467 UFC #5480

Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

I. NORM in the WIPP Vicinity

Recommendation: "DOE should develop and implement a plan to sample oil-field brines, petroleum, and solids associated with current hydrocarbon production to assess the magnitude and variability of naturally occurring radioactive material (NORM) in the vicinity of the WIPP site."

Response: DOE agrees with this recommendation. The New Mexico State University Carlsbad Environmental Monitoring & Research Center (CEMRC) has undertaken a project to carry out the recommended assessment, as part of CEMRC's ongoing WIPP Environment Monitoring project. Although analyses of certain naturally occurring radioactive materials in hydrocarbon and scale matrices are somewhat standardized, the sensitivity of the standard methods will likely not be acceptable for at least a portion of the matrices targeted, resulting in the need for method enhancement research. In addition, no published methods are available for analyses of plutonium, americium and other TRU components of concern in hydrocarbons, so this analytical task will require extensive method development and validation prior to initiation of analyses of actual samples.

NORM is an extremely sensitive topic in the oil and gas production industry in the region of the WIPP. As an example, one major exploration and production company that operates in Lea and Eddy counties recently submitted 48 pages of critique on draft Regulation Guidelines for the Management of NORM in the Oil and Gas Industry in New Mexico, which was issued by the New Mexico Environment Department in 1999. Initial contacts with those familiar with local and regional companies indicate that it is likely that many if not most operators will decline to cooperate. To create the maximum likelihood of obtaining cooperation, an option for anonymity will be offered to the operators, using a form of "double-blind" identification. This system would involve collection of samples by a commercial third-party service company that is acceptable to the operator, submittal of the samples to CEMRC without identification of the operator or well location (formation and production pool only), resulting in CEMRC reporting of results without specific operator or well identification.

Path Forward: CEMRC received approval in August 2000, from DOE to proceed with the project without direct involvement of DOE in contacting affected production operators. A plan for a study entitled "Characterization of radioactive elements in oil and gas production in the vicinity of the WIPP" was developed by CEMRC. The initial phases of the study are in progress, including completion of a database of active wells and operators, development of sample collection and handling plans, and identification of commercial sample collection services currently operating in the area. Initial contacts with operators to solicit participation in the study will occur during November through February 2000. Contingent on cooperation of enough operators to create a representative sampling design, sample collection would be conducted during March through August 2001.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

II. Waste Characterization

Recommendation: "DOE should eliminate self-imposed waste characterization requirements that lack a legal or safety basis."

Response: DOE agrees with this recommendation. DOE has developed and begun the implementation of a strategy to systematically improve the Waste Analysis Plan by reducing the frequency of waste characterization and implementing methods that make characterization simpler, less expensive and, above all, safer.

On August 8, 2000, the New Mexico Environment Department approved two packages of Class 2 modifications to the WIPP's Hazardous Waste Facility Permit. These two packages include three requests submitted on April 5, 2000 and three submitted April 20, 2000.

Approval of these modifications results in significant cost savings associated with waste characterization and will reduce radiation exposures to workers. A summary of the approved modifications follows:

- The "miscertification rate" of TRU waste was revised to apply to the waste summary category group instead of each waste stream. This results in a ten-fold reduction in number of drums that must be opened for visual examination (VE).

- The solids sampling requirements for analysis of VOCs have been revised to allow use of one subsample instead of three subsamples. This will avoid a cost of approximately ten million dollars that INEEL would have had to spend in re-analyzing the samples.

- The number of headspace gas samples required has been reduced for two types of waste streams to a statistically selected number of drums, instead of 100% sampling. The two types of waste streams now eligible for statistical headspace gas sampling are wastes that have been thermally processed and homogeneous wastes with "acceptable knowledge" that demonstrates no volatile organic compounds have been present in the waste.

Several modifications have been prepared and submitted that specifically address safety issues associated with TRU waste handling and disposal. One such modification, submitted in October 2000, will allow generators to remove from consideration for VE any containers that pose a safety concern. For example, if a generator determines that opening a container with a high fissile gram content is a safety hazard, that container can be ruled ineligible for VE and another container selected.

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Path Forward: The next modification request, which will be submitted in November 2000, will provide alternatives to VE as a quality control check on radiography. Should the modification be granted, DOE intends to implement this change across the complex.

The Permit modification requesting authorization for remote handled waste disposal at WIPP (to be submitted in December 2000) presents a performance based waste analysis plan that emphasizes the use of nonintrusive characterization techniques and eliminates the need for headspace gas sampling and analysis, solids sampling and analysis, VE, and other confirmatory measurements.

The DOE also plans to collect data from waste characterization activities that will allow the systematic reduction or elimination of headspace gas sampling, solids sampling, VE, and radiography. These changes will be promptly implemented as suitable supporting data are identified.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

III.A Derive A More Realistic Gas Generation Model

Recommendation: "DOE should derive a more realistic radiolytic gas generation model, validate it through confirmatory testing, use the results to recalculate gas generation limits, and seek regulatory approval to implement these limits."

Response: DOE agrees with this recommendation. An application for Revision 19 of the TRUPACT-II Safety Analysis Report was submitted to the Nuclear Regulatory Commission in April 2000. Among other things, the application includes the following:

- Matrix Depletion – The g-values of organic materials decline as a function of absorbed radiation dose. Testing performed at Los Alamos National Laboratory demonstrated that the g-value of polyethylene declines from an initial g-value of 3.4 to 1.1. The application requests the use of the lower g-value. When approved this new g-value will increase the allowable wattage up to a factor of 3 (depending on the packaging configuration).

- Option for the mixing of shipping categories that will allow the sites to ship payloads with different waste forms and to take credit for the use of dunnage containers (additional void volume and reduced gas concentrations).

- Use of more realistic g-values to take credit for non-gas generating materials present in the waste, based on percentages of moisture or organic material present. The previous model assumed a worst-case, 100% moisture/organic material scenario. (This change has been approved by the Nuclear Regulatory Commission.)

- Use of a new shipping category notation that accurately reflects the packaging configuration of the waste. The previous notation grouped all sites under selected worst-case packaging configurations. (This change has been approved by the Nuclear Regulatory Commission.)

Path Forward: The application for Revision 19 was submitted to the Nuclear Regulatory Commission in April 2000 and is scheduled for approval in January 2001. We believe this to be a very responsive review cycle. Taken as a whole, Revisions 17, 18, and 19 provide an increase of up to 100 times the wattage that was allowed under Revision 16.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

III.B Safety Analysis to Determine the Damaging Concentration of Hydrogen

Recommendation: "DOE should perform a safety analysis to determine the concentration and quantity of hydrogen that, upon ignition, could damage the seals of the TRUPACT-II shipping container. The goal of the safety analysis would be to demonstrate whether such an event could occur inside a waste package, and whether the energy associated with such an event could result in the rupture of containment provided by the TRUPACT-II. This analysis could provide the rationale to obtain relief from the 5 percent hydrogen flammability limit and should form the basis for a future modification to the present TRUPACT-II license."

Response: DOE agrees with the recommendation. Performing the safety analysis, which may include testing, would be the first step toward an application. Preliminary review of the recommendation has raised an issue of handling drums at the WIPP that could have a potentially flammable gas mixture. The safety analysis should be extended to waste handling operations at WIPP. If the safety analysis indicates that there is not a safety concern, then an application would be submitted to the Nuclear Regulatory Commission for their review and approval. One proposed solution is to encapsulate the waste in a manner that would contain any detonation that might occur. It is noted that there is no precedence for Nuclear Regulatory Commission approval of shipment of a flammable gas and radioactive material in the same package. Also, the U.S. Department of Transportation (DOT) prohibition against shipping containers of flammable gas and radioactive material on the same vehicle if they could co-mingle would have to be addressed.

Path Forward: The following steps will be pursued to respond to this recommendation:

- Perform a safety analysis to determine whether WIPP could unload drums of waste that contained flammable gas.
- Assess ArrowPAK™ suitability for macro-encapsulation to contain potential deflagration events.
- Determine the incremental quantity of waste that could benefit from implementation of this recommendation (assuming the current application for Revision 19 to the TRUPACT-II Safety Analysis Report is approved).
- Perform the recommended analysis and/or testing.
- Prepare an application and submit to the Nuclear Regulatory Commission for review.
- Seek DOT concurrence.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

III.C Technical Approaches to Reduce Hazards Such As Inert Gas

Recommendation: "DOE should consider technical approaches for reducing hazards from hydrogen generation, such as filling the headspace of the waste containers or the shipping containers with an inert gas to displace air and thereby reduce the flammability hazard."

Response: DOE agrees with this recommendation and is actively pursuing several alternative technologies such as hydrogen "getters." There are several technical issues associated with this recommendation that would have to be investigated:

- Would a drum containing multiple layers of confinement around the TRU waste benefit from the proposed technology; e.g., inert gas in the drum headspace?
- Does the proposed technology require opening individual payload containers or does it apply to the TRUPACT-II; i.e. inert the TRUPACT-II ICV headspace?
- Does the proposed technology prevent or mitigate detonation/deflagration inside multiple layers of confinement or inside the TRUPACT-II? (See recommendation III.B above.)

A method of measuring the flammable gas concentration in the headspace of a 55-gallon drum has been included in the application for Revision 19 of the TRUPACT-II Safety Analysis Report. This only requires a single measurement that can be made in real-time instead of a lengthy gas generation rate test that requires measuring the rate of change of hydrogen gas over several hours or days.

Path Forward: The following steps will be pursued to respond to this recommendation:

- Alternative technical recommendations such as inert gas or hydrogen getters will be considered and a report prepared.
- Perform analysis and/or testing of those alternative technologies that look promising.
- Submit an application to the NRC for any technologies that can be supported by analysis or test results.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

III.D Reevaluate the Feasibility of Rail

Recommendation: "DOE should reevaluate the technical and regulatory feasibility of shipping high-wattage TRU waste using ATMX railcar shipping system."

Response: DOE agrees with the recommendation to reconsider the use of rail. DOE is currently reviewing a recently commissioned rail study report (included as an attachment). The report concluded that shipment of TRUPACT-II by rail is not cost effective unless significantly reduced rail rates are available. The report also recommended investigation of a new shipping package (TRUPACT-III) for shipping high wattage waste and oversize boxes by rail or truck.

DOE has not made a decision regarding the use of ATMX railcar for shipments to WIPP. Using ATMX would require one of the following to occur:

1. Approval by the NRC – this would require exemption(s) from several of the requirements in 10 CFR 71.

   Or,

2. Revision of the Consultation and Cooperation Agreement between the State of New Mexico and DOE, plus revision to the WIPP Land Withdrawal Act.

Path Forward: The following steps will be pursued to respond to this recommendation:

- Determine the incremental inventory of TRU waste that could benefit from rail shipment (assuming the current application for Revision 19 to the TRUPACT-II Safety Analysis Report is approved).
- Evaluate and compare the benefits and regulatory difficulty of two options – TRUPACT-III vs. ATMX.
- Make a decision based on information obtained.
- Proceed with the chosen option.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

IV. DOE's Communication and Notification Program

Recommendation: DOE should consider cost-effective ways to improve the reliability and ease of use of the TRANSCOM system, either by improving or replacing it utilizing current technologies, and ensure the future system meets the WIPP and other stakeholders needs.

Response: DOE agrees with the recommendations and, in fact, has been working toward this effort since mid-1998. On September 12, 2000 in Albuquerque NM, the DOE National Transportation Program-Albuquerque (NTPA) presented a response to the Interim Report recommendations. Committee members represented were Dr. Mark Abkowitz and Mr. Al Gruella. The presentation included improvements to the present TRANSCOM system and a demonstration of the new web-based TRANSCOM2000 system.

- NTPA has identified the problems and has provided resolution that has increased reliability and stability of the present client server Windows-based system for over 7 months. These problems included difficulty in logging in, extended download times, loss of positional data, and date and time anomalies. Feedback from system users indicates that the system provides consistently reliable and accurate information, is more user friendly, and is meeting the needs of our customers. Customer complaints related to using the client-server version have been reduced to a very rare occurrence.

- In May 1999, NTPA hosted a TRANSCOM user application design session to team with DOE, State and Tribal TRANSCOM users, to develop system requirements for a new Internet-based communications and tracking system. In August 2000, the new application was beta-tested and discrepancies were identified and addressed.

- TRANSCOM2000 uses various commercial state-of-the-art Internet compatible software elements. These include: Object F/X GIS mapping software and engine, QTRACS satellite positional and two-way communications software, Oracle Relational DBMS 8I, Oracle Report and Oracle Forms 6I. The TRANSCOM Communications Center will have up-to-the-minute satellite weather service available.

- Security elements on the new application include native Oracle encryption, operation on the Secure Socket Layer (SSL), and multiple layers of application access security down to the database level. A firewall will also reside between the public and the application server.

- Positional update information will be received via frame-relay between the satellite service provider and the TRANSCOM2000 database. These positional updates will be requested every 2 minutes and should be available to the users on average of 2-5 minute intervals.

Path Forward: The estimated schedule for implementation of the TRANSCOM2000 is mentioned below. Firewall configuration and connectivity to the WIPP has been established. The WIPP Central Monitoring Room operators will be trained during the initial implementation process.

- The Major Application Security and Test Plans are under development. These plans must be approved prior to implementation per DOE Order. Completion date: November 2000.

- DOE/AL Operations configuration: in process. Weather and Qtracs servers being installed, firewall server built and awaiting software installation, Operations Center fully staffed. Completion Date: November/December 2000.

- Demonstration of operational readiness: December 2000.

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Response to National Research Council Recommendations
Committee on the Waste Isolation Pilot Plant – Interim Report

V. DOE's Emergency Response Program

Recommendation: The committee recommends that DOE explore with states and other interested parties how to develop processes and tools for maintaining up-to-date spatial information on the location, capabilities, and contact information of responders, medical facilities, recovery equipment, regional response teams, and other resources that might be needed to respond to a WIPP transportation incident. This assessment should explore which organization(s) should develop and maintain the capability to generate and maintain such information. DOE should also determine where emergency response capability is currently lacking, identify organization(s) responsible for addressing these deficiencies, and take action to address them.

Response: The information that needs to be gathered and analyzed must come from the state, tribal, and local governments. According to preliminary telephone calls to the Western Governors' Association and the Federal Emergency Management Agency, there is not a national or state system that currently tracks the information that the Committee recommends the DOE collect and analyze. DOE must determine what level of participation the state, tribal and local governments are willing to have in the collection of this information and the maintaining of a database or reports. Logistically, the DOE will be trying to collect information from 30 states and 12 tribal governments which translates to data on over 100,000 emergency responders, and thousands of fire and police departments, ambulance services, and hospitals.

Path Forward: DOE will send letters to the regional, state, and Indian Tribal governments with whom it has cooperative agreements, asking them to communicate the recommendation of the Committee to all of its affected members. They will be asked to analyze their current data collections systems, and to define their willingness to participate in a regular assessment as recommended by the Committee.

They will further be asked to define their funding and manpower requirements, to submit the required data, and make counter recommendations that may fulfill the intent of the recommendation. This would include their recommendations on where the information is to be maintained and who will have the responsibility to analyze and make recommendations for improvement based on that data.

Appendix B

Human Intrusion Scenarios

Oil, gas and other mineral resources are frequently found in association with salt beds, such as the Salado, where the WIPP is situated. The region around the WIPP has known a high rate of drilling activities in the past and future energy trends indicate that there will be incentives to explore the region again, once institutional controls are removed (starting 100 years after the closure of the repository). The risk of drilling directly into the repository and thus creating pathways for the release of radionuclides into the environment will then increase. Drilling through the repository could transport radioactive materials from the repository to the surface or bring water in contact with substances stored in the repository. The following two scenarios are possible sources of concern about the performance of the repository and have been taken into account in the performance assessment of the WIPP.

1. If there were an oilfield water-flooding operation in the vicinity of WIPP, a large amount of brine could flow from a leaky injection well and induce a hydraulic fracture in the anhydrite (or marker bed) directly above or below the WIPP repository (Box B.1). If, at some later time, another well were drilled through the repository and into this brine-filled fracture, the high-pressure brine in the fracture could flow through the borehole and flood the repository causing a release of radioactive materials. The scenario is known as the Hartman scenario.

2. Direct drilling into the WIPP repository could allow circulating drilling fluid to bring radioactive materials to the surface through a borehole as cuttings or spallings. The situation could be serious if the repository were flooded with high-pressure brines. The Sandia National Laboratories examined three possible flooding scenarios, designated as E1, E2, and E1E2, in their performance assessment. These scenarios are briefly explained in Boxes B.2, B.3, and B.4 and they are described in detail in the Compliance Certification Application (DOE, 1996).

The Hartman Scenario

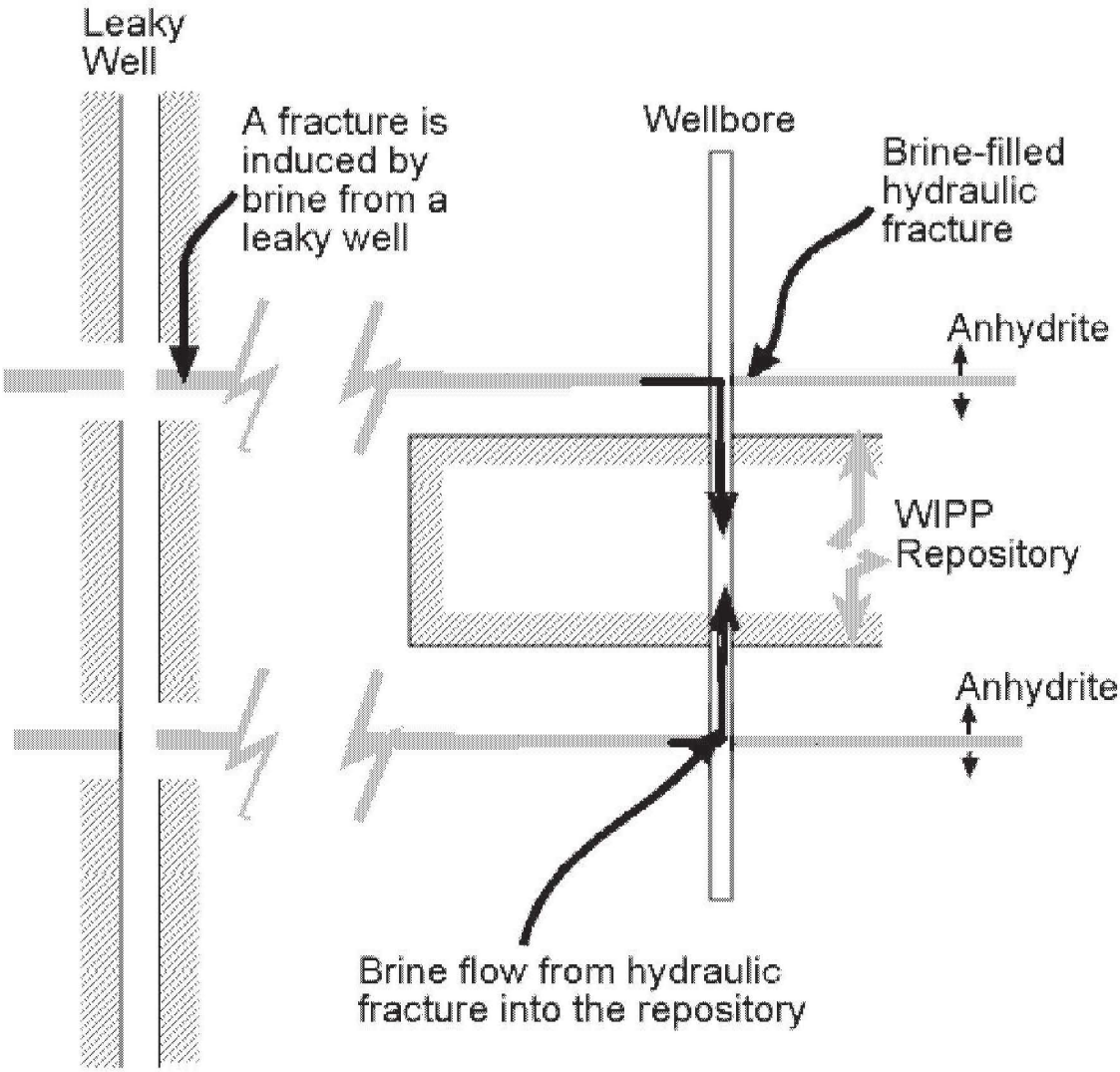

Box B.1: The Hartman Scenario is a scenario in which water from a leaky injection well induces a hydraulic fracture in the anhydrite below or above the repository. If, at some later time, another well is drilled through the repository, the water in the fracture could flow through borehole into the repository.

The E1 Scenario

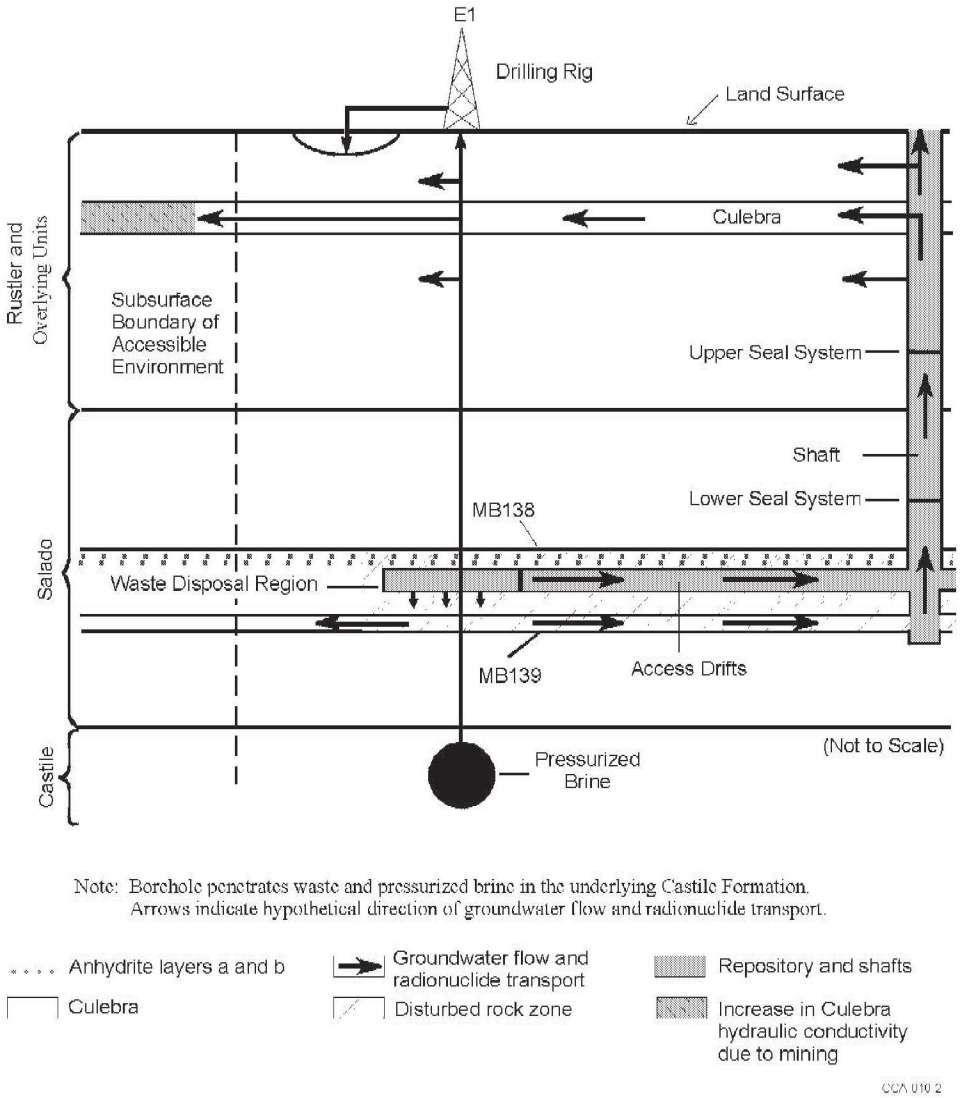

Box B.2: The E1 Scenario is any inadvertent penetration of a waste panel by a borehole that also penetrates a Castile brine reservoir. Sources of brine in the E1 scenario are the brine reservoir, the Salado, and under certain conditions, the units above the Salado.

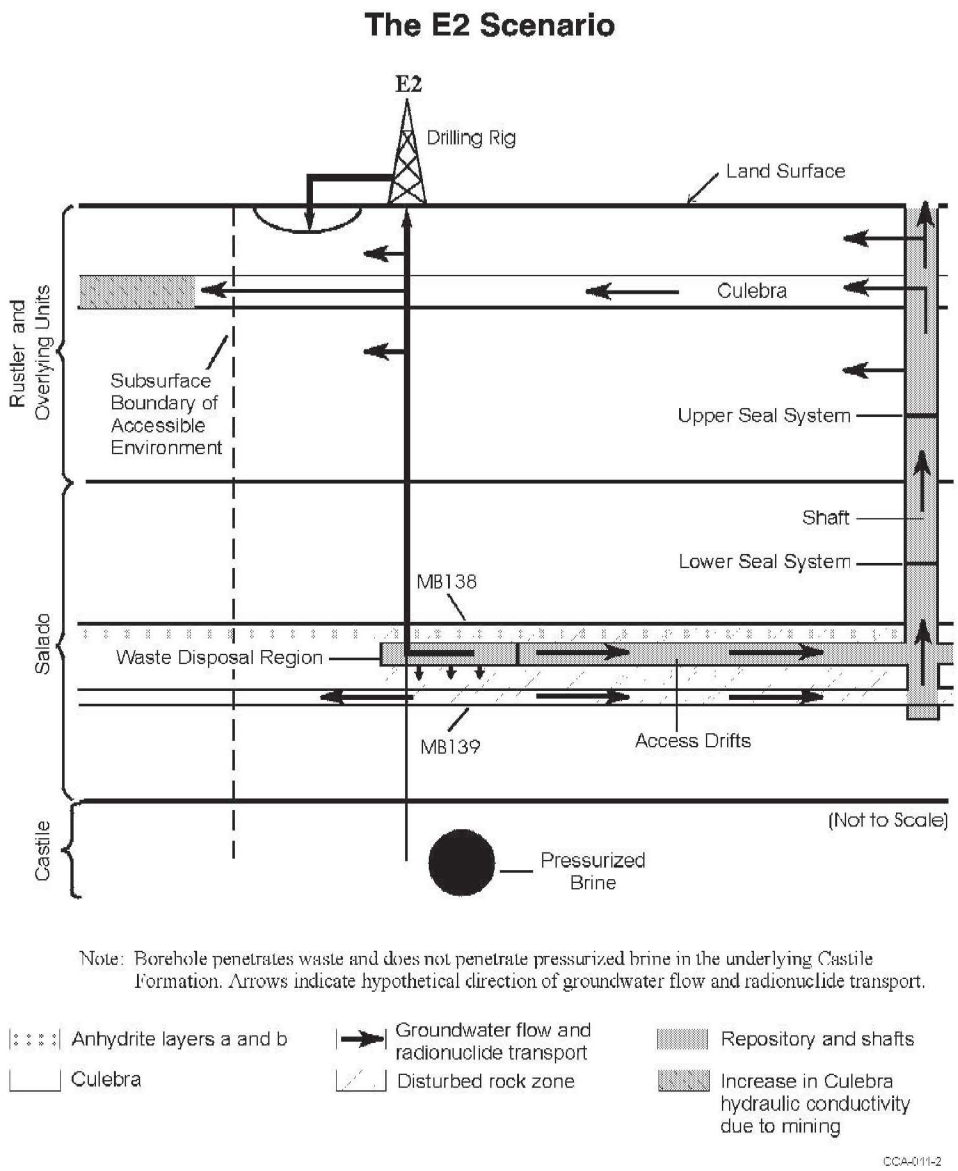

Box B.3: E2 is the simplest scenario for inadvertent human intrusion into a waste disposal panel. In this scenario, a panel is penetrated by a drill bit; cuttings, caving, spallings, and brine flow releases may occur in the borehole after it is plugged and abandoned. Cuttings will be discharged at the surface and may contain waste material if the borehole penetrates waste drums. *Cavings*, which include material eroded from the borehole wall during drilling, may also contain radionuclide waste from the repository horizon. Spallings include solid material carried into the borehole during rapid depressurization of the waste disposal region. The repository horizon could be pressurized by gas generation from degradation of the waste, organic materials and metal corrosion. Brine can be present in the Salado from natural sources or human activities associated with other drilling or production activities. Release to the biosphere is either to the surface or through the Culebra via a leaking *casing.*

The E1E2 Scenario

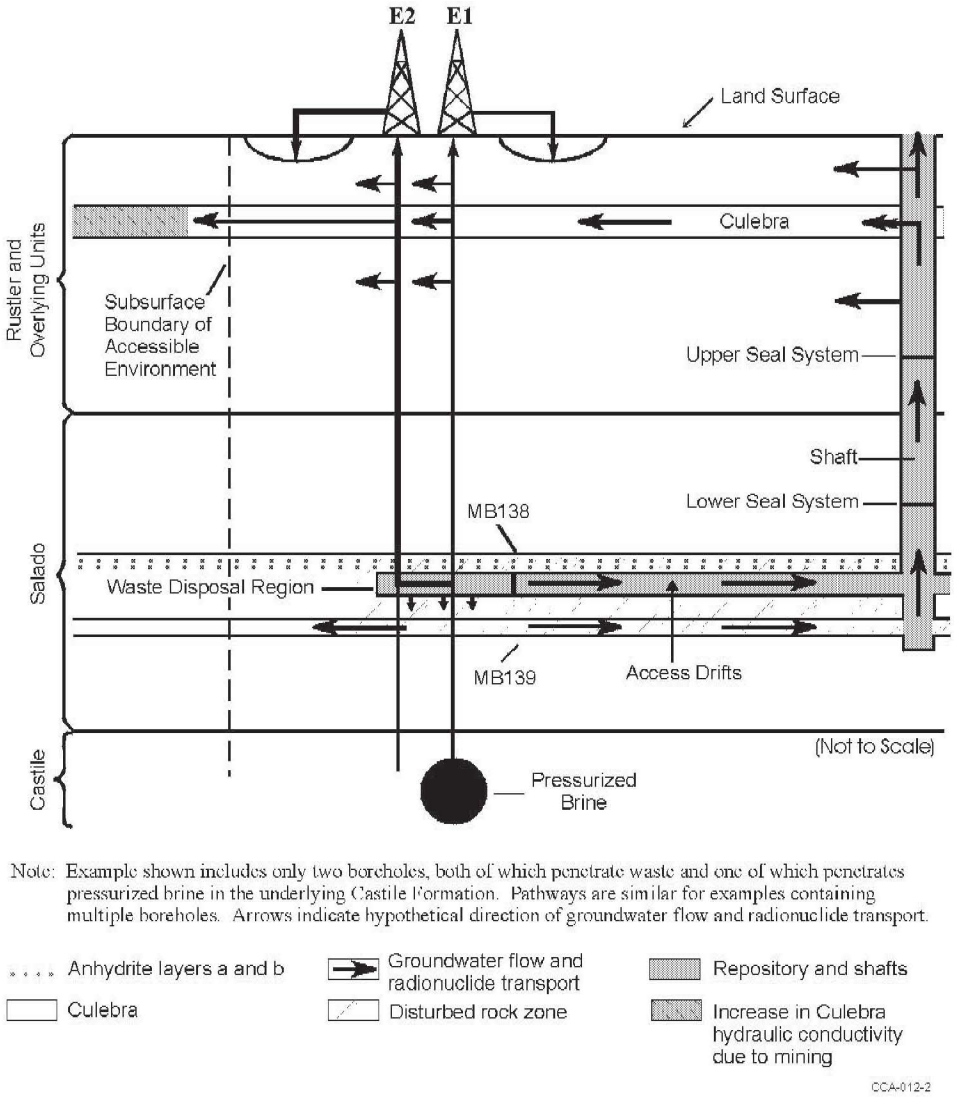

Note: Example shown includes only two boreholes, both of which penetrate waste and one of which penetrates pressurized brine in the underlying Castile Formation. Pathways are similar for examples containing multiple boreholes. Arrows indicate hypothetical direction of groundwater flow and radionuclide transport.

Box B.4: The E1E2 scenario involves multiple well penetrations of a waste panel, with one well penetrating a high-pressure brine panel below. Brine flows from a brine source through well E1 through the repository and is released through well E2. This flow path has the potential to bring large quantities of brine in direct contact with waste in the panel and to bring the contaminated brine to the overlying Salado or Culebra.

Appendix C

Biographical Sketches of Committee Members

Garrick, B. John, ***Chair,*** independent consultant, was a co-founder of PLG, Inc., an international engineering, applied science, and management consulting firm formerly in Newport Beach, California. He retired as president and chief executive officer in 1997. He received his B.S. degree in physics from Brigham Young University and his M.S. and Ph.D. degrees in engineering and applied science from the University of California, Los Angeles, and is a graduate of the Oak Ridge School of Reactor Technology. His professional interests involve risk assessment in fields such as nuclear energy, space and defense, chemical and petroleum and transportation. He is a past president of the Society for Risk Analysis. Dr. Garrick is a fellow of three professional societies and has received numerous awards, including the Society for Risk Analysis' Distinguished Achievement Award. He was appointed to the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste in 1994, of which he is now chairman. Dr. Garrick was elected to the National Academy of Engineering in 1993. He has been a member of the committee on the Waste Isolation Pilot Plant since 1989.

Mark D. Abkowitz, professor of civil engineering at Vanderbilt University and director of the Center for Environmental Management Studies, has an extensive background in environmental risk management, use of advanced information technologies in crisis management, and strategic and operational deployment of intelligent transportation systems. Dr. Abkowitz has been involved in hazardous materials transport education, research, product development, and technology transfer for manufacturers, transporters, regulators, and emergency response personnel. He has authored more than 70 journal publications and study reports, covering issues such as the risks of transporting high-level radioactive waste. Dr. Abkowitz has served on several national and international technical and advisory committees, including as chairman of the NRC Transportation Research Board standing committee on hazardous materials transport.

Alfred W. Grella, independent nuclear and hazardous materials transportation consultant, retired in 1990 from a career in U.S. government service, first at the DOT and later at the USNRC. His distinguished career spans 40 years as a professional in health physics, health protection, transportation, in-

spection and enforcement, training, and related regulatory activities. Mr. Grella received a bachelor's degree in chemistry from the University of Connecticut and completed the one-year management program at the National Defense University Industrial College of the Armed Forces. He has authored more than 30 published papers. He is a member of the American Nuclear Society and a fellow of the Health Physics Society. In 1965, the American Board of Health Physics awarded Mr. Grella certification as a health physicist. Mr. Grella received the M. Sacid (Sarge) Ozker Award in 1996 for distinguished service and eminent achievement in the field of radioactive waste management.

Michael P. Hardy, president of Agapito Associates, Inc., has experience in characterization, numerical modeling, design, and field experimentation for underground mines and high-level nuclear waste repositories at the BWIP site near Hanford, Washington, and Yucca Mountain, Nevada. Dr. Hardy is a member of the Society of Mining, Metallurgical and Exploration Engineers, Inc., and the American Society of Civil Engineers (ASCE). He is a former chairman of the Underground Technical Research Council, a joint ASCE-American Institute of Mining, Metallurgical, and Petroleum Engineers committee. Dr. Hardy received his bachelor of engineering from the University of Adelaide in Australia and his Ph.D. from the University of Minnesota in geoengineering.

Stanley Kaplan is one of the early practitioners of the discipline now known as quantitative risk assessment and a major contributor to its theory, language, philosophy, and methodology. Dr. Kaplan is a fellow of the Society for Risk Analysis and author of a number of seminal papers in this field. He is one of the first American contributors to the Russian science TRIZ, the Theory of the Solution of Inventive Problems, and currently consults and teaches in this area. He is a founder and board chairman of Bayesian Systems, Inc., a Washington-based company developing diagnostic, decision, simulation, and business management software. Dr. Kaplan is the recipient of several awards and honors, including the Society for Risk Analysis' Distinguished Achievement Award in 1996. Dr. Kaplan was elected to the National Academy of Engineering in 1999.

Howard M. Kingston, professor of chemistry and director of the Duquesne Environmental Research and Education Center at Duquesne University, has expertise in analytical chemistry techniques in environmental applications of hazardous waste characterization and remediation. His research interests include the development, automation, and standard encapsulation and transfer of analytical analysis methods. For the past several years, he has been actively involved in advancing the area of microwave sample preparation through basic research and the development of procedures that have been adopted by the EPA as standard methods. He has received numerous awards for his pioneering work and holds multiple patents in the fields of speciation, microwave chemistry, and chelation chromatography. He has co-edited and co-authored two of the American Chemical Society professional reference texts.

W. John Lee, Peterson Chair and professor of petroleum engineering at Texas A&M University, has expertise in petroleum reservoir analysis, pressure transient testing, and enhanced recovery methods. His professional experience includes research, operations, and consulting at Exxon Company U.S.A. and S.A. Holditch & Associates. He has received numerous awards from the Society of Petroleum Engineers, including the Reservoir Engineering Award, the Distinguished Service Award, the John F. Carll Award, Distinguished Membership, Distinguished Faculty Achievement Award, Distinguished Lecturer, and Honorary Membership. He is a member of the Georgia Tech Academy of Distinguished Engineering Alumni and he was elected to the National Academy of Engineering in 1993.

Milton Levenson, independent consultant, is a chemical engineer with more than 50 years of experience in nuclear energy and related fields. His technical experience includes work in nuclear safety, fuel cycle, water reactor technology, advanced reactor technology, remote control technology, and sodium reactor technology. His professional experience includes research and operations positions at the Oak Ridge National Laboratory, the Argonne National Laboratory, the Electric Power Research Institute, and Bechtel. Mr. Levenson is past president of the American Nuclear Society; a fellow of the American Nuclear Society and the American Institute of Chemical Engineers; and recipient of the American Institute of Chemical Engineers' Robert E. Wilson Award. He is the author of more than 150 publications and presentations and holds three U.S. patents. He received his B.Ch.E. from the University of Minnesota. He was elected to the National Academy of Engineering in 1976.

Werner F. Lutze, professor of chemical and nuclear engineering at the University of New Mexico (UNM) and director of the UNM Center for Radioactive Waste Management, has more than 25 years of research experience in materials science and geochemical issues relevant to the management of radioactive wastes, including selective mineral ion-exchange processes, repository near-field chemistry, waste form development, and trace analyses. He has published widely on weapons plutonium immobilization, waste disposal, and the chemistry of nuclear materials. Professor Lutze is a member of several professional organizations, including the Materials Research Society, the German Nuclear Society, and Sigma Xi.

Kimberly Ogden, associate professor of chemical and environmental engineering at the University of Arizona, has conducted research with Los Alamos National Laboratory collaborators to design treatment methods for remediating hazardous waste sites containing both toxic metals and organic materials, including plutonium-cellulose mixtures. She is also engaged in research investigating the merger of the semiconductors and biotechnology. Professor Ogden has authored or co-authored several book chapters, journal articles, and presentations. She is a member of several professional organizations including the American Institute of Chemical Engineers, the American Society of Engineering Education, and the American Chemical Society. She received her B.S.E degree in chemical engineering from the University of Pennsylvania and her M.S. and Ph.D. degrees from the University of Colorado.

Martha Scott, associate professor of oceanography at Texas A&M University, is a researcher in marine radiochemistry and geochemistry. Her present research involves radionuclide distribution in the Russian Arctic. Her work has dealt with the interaction between oceans and rivers, transport of materials in the marine environment, and chemistry of manganese nodules. The behavior of plutonium isotopes in rivers, estuaries, and marine sediments has been one of her longstanding research interests. She served for two years as an associate program director for chemical oceanography at the National Science Foundation (1992-1993). She received her Ph.D. degree from Rice University and was a National Science Foundation postdoctoral fellow at Yale University.

John M. Sharp, Jr., Chevron Centennial Professor of Geology, leads an active program in hydrogeology at The University of Texas at Austin. Professor Sharp has authored and co-authored more than 250 journal articles, books, reports, and presentations. His current research interests include characterization of groundwater flow and transport in fractured and karstic rocks; thermohaline free convection, hydrogeology of semi-arid zones, subsidence, and the effects of man on groundwater systems. He is a fellow of the Geological Society of America and recipient of its O.E. Meinzer Award (1979) and the American Institute of Hydrology's C.V. Theis Award (1996). Dr. Sharp is currently the editor of *Environmental and Engineering Geoscience* and the 2000 AT&T Industrial Ecology Fellow. He received his

bachelor of geological engineering with distinction from the University of Minnesota and his M.S. and Ph.D. degrees in geology from the University of Illinois.

Paul G. Shewmon, emeritus professor of materials science and engineering at the Ohio State University, received a B.S. degree in metallurgical engineering from the University of Illinois and M.S. and Ph.D. degrees, also in metallurgical engineering, from the Carnegie Institute of Technology. He has lead work on fast breeder reactor materials at Argonne National Laboratory and served for 16 years on the USNRC's Advisory Committee on Reactor Safeguards. He has published 130 technical papers and two textbooks generally in the area of physical metallurgy and has received numerous awards for his research. He was elected to the National Academy of Engineering in 1979.

James E. Watson, Jr., professor of environmental sciences and engineering and director of the air, radiation, and industrial hygiene program at the University of North Carolina at Chapel Hill, holds a M.S. degree in physics from North Carolina State University and a Ph.D. in environmental sciences and engineering from the University of North Carolina at Chapel Hill. Professor Watson is accomplished in the fields of environmental radioactivity and radioactive waste management. He has received several awards for excellence in teaching, research, and service. He is a past president of the Health Physics Society and a past chairman of the Radiological Health Section of the American Public Health Association. He has served on the EPA's Radiation Advisory Committee and Executive Committee of the Agency's Science Advisory Board. He is a past chairman of the North Carolina Radiation Protection Commission and currently chairs the commission's Committee on Low-Level Radioactive Waste Management.

Ching H. Yew, an independent consultant and emeritus Halliburton professor of engineering mechanics at the University of Texas at Austin, received a B.S. degree in mechanical engineering from the National Taiwan University and M.S. and Ph.D. degrees in mechanical engineering from Cornell University and the University of California, Berkeley. Dr. Yew has specialized in solid mechanics and experimental mechanics, is a fellow of the American Society of Mechanical Engineers, and is a member of the Society of Petroleum Engineers. Dr. Yew has authored a book on the mechanics of hydraulic fracturing and published many articles concerning hydraulic fracturing and borehole stability.

Appendix D

Glossary

Actinide: Element with atomic number 90 (thorium) or greater.

Anhydrite: Anhydrous calcium sulfate.

Backfill: Earth or other material used to replace material removed during construction or mining. Backfill in excavations may or may not be the material originally removed. In the WIPP, magnesium oxide is the engineered backfill that replaces the mined salt and is placed in the free spaces surrounding the waste containers. Magnesium oxide is intended to chemically stabilize the radionuclides and minimize their solubility.

Borehole: Deep, circular hole of small diameter, such as an oil well or a water well.

Borehole Plugs: Engineered plugs to block the flow of liquid in either direction and to curtail the potential for movement of contaminants to the human environment. Several unplugged boreholes, presently being used to collect information for the WIPP, exist within the WIPP Land Withdrawal Area.

Brine: Water with dissolved salts at levels higher than seawater. Generally, brines are considered to have a total dissolved solids content of more than 100,000 milligrams per liter.

Brine Reservoir: Groundwater containing high levels of dissolved solids (brine) that may occur beneath the WIPP site either as discrete pockets (brine pockets) or as a saturated continuum. The committee uses the term "brine reservoir" to refer to both of these occurrences. At present, there is a great deal of uncertainty as to the location and form (i.e., discrete pocket or saturated continuum) of brine reservoirs beneath the WIPP repository.

Brucite: Magnesium dihydroxide, $Mg(OH)_2$.

Casing: Heavy metal pipe lowered into a borehole during or after drilling and cemented into place. It prevents the sides of the hole from caving and, prevents loss of drilling mud or other fluids into the hole.

Castile Formation: Oldest of the late Permian stratigraphic sequence of rocks, consisting of alternating layers of anhydrite and thin layers of limestone, with several thick layers of halite. See Figure 1.3.

Culebra Dolomite: Second-oldest member of the Rustler Formation ranging from approximately 7-8 meters thick at the WIPP site. The Culebra consists of dolomite with some clay minerals. Because it is a relatively transmissive unit, the Culebra is important to the groundwater flow model for the WIPP site.

Curie: Measure of the quantity of radioactive material in a sample, equal to 3.7×10^{10} disintegrations per second.

Cuttings: Rock chips cut by a bit in the process of well drilling and removed from the hole in the drilling mud in rotary drilling or by the bailer in cable-tool drilling. Well cuttings collected at closely spaced intervals provide a record of the strata penetrated.

Delaware Basin: Sedimentary basin in which the WIPP site is located. The Delaware Basin formed in the Permian sea and was gradually filled with thick, extensive layers of sediments and evaporite deposits.

Disturbed Rock Zone (DRZ): Zone around an excavation, in the host rock salt, where the stress field has been modified sufficiently to cause the formation of microfractures in the rock salt. Compared to the intact rock salt, the DRZ will have increased porosity because of the microfracturing, increased permeability as a result of interconnection of the microfractures, and decreased load-bearing capacity or strength.

Dolomite: Sedimentary rock consisting mostly of the mineral dolomite, calcium magnesium carbonate.

Dose: Energy imparted to matter in a volume element by ionizing radiation, divided by the mass of irradiated material in that volume element. The International System (IS) derived unit of absorbed dose is the gray (Gy); 1 Gy = 100 rad = 1 (Joule) per kilogram.

Drillbit or drill: A tool that cuts with its end by revolving or by a succession of blows.

Engineered Barriers: Man-made waste-isolating features that complement and strengthen natural waste-isolating barriers. These barriers are shaft seals, panel closures, borehole plugs, and backfill.

G-Value: Radiolytic yield unit. It corresponds to the number of molecules produced per 100 electronvolts of energy absorbed in the medium interacting with the ionizing radiation.

Half-Life: Time required for half of the atoms of a radioactive substance present at the beginning to disintegrate.

Hydraulic Fracture: Fracture of a rock in an oil or gas reservoir by pumping in water (or other fluid) and sand under high pressure. The purpose is to produce artificial openings in the rock to increase

permeability. The pressure opens cracks and bedding planes, and sand introduced into these serves to keep them open when the pressure is reduced.

Hydrogen Getter: Material capable of capturing hydrogen gas.

Hydromagnesite: Mixed compound of magnesium carbonate and hydroxide, $4MgCO_3 \cdot Mg(OH)_2 \cdot 4H_2O$.

Injection Well: Well in an oil or gas field through which water, gas, steam, or chemicals are pumped into a reservoir or formation for pressure maintenance or secondary recovery, or for storage or disposal of the injected fluid.

Karst: Type of topography that is formed of limestone, gypsum, and other rocks by dissolution and is characterized by sinkholes, caves, and underground drainage.

Lithostatic Pressure: Pressure exerted by a column of overlying rock at a point in the earth's crust.

Magnesite: Magnesium carbonate, $MgCO_3$.

Marker Bed: Horizontally extensive formation that can be identified readily at different locations. For instance, the nonhalite interbed in the Salado, is numbered from the top of the Salado to the bottom and used to keep the repository at the same level within the Salado.

Panel Closures: Panel closures will limit the interaction of brine and gases among waste disposal panels. These closures will consist of a rigid concrete barrier and an isolation wall made of concrete construction block with an isolation zone between them.

Parameter: Algebraic symbol representative of a well-defined physical quantity with a numerical value. An adjustable parameter is envisioned to assume any value within its range (between the maximum and minimum numerical bounds). Any particular choice of a value renders a parameter a numerical constant.

Performance Assessment: Risk-based assessment of the safety performance of a nuclear waste facility.

Permeability: Capacity of a material to transmit fluids. A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. Permeability depends on the size, shape, and degree of interconnectedness of pores and is generally measured in square meters. It is a property of the medium alone and is independent of the nature of the liquid.

pH: Measure of the acidity of a solution phase; negative logarithm of the hydrogen ion concentration.

Post-closure Period: Period beginning when the shafts of the disposal system are backfilled and sealed and ending 100 years later.

Pre-closure Period: Period between the beginning of operation and the time at which the shafts of the disposal system are backfilled and sealed. The operation period has been set as 35 years.

Radiogenic: Said of a product of a radioactive process.

Radiolysis: Decomposition brought about by ionizing radiation.

Radionuclide: Radioactive atom characterized by its mass and atomic number.

Retardation: Parameter that describes the ratio of the net apparent velocity of the concentration of a particular chemical species to the velocity of a non-reactive species. It is proportional to the slope of a sorption isotherm; thus, if the isotherm is nonlinear, the retardation factor is not constant and depends on solute concentration.

Rustler Formation: Second-youngest Permian Ochoan Formation, overlying the Salado, and consisting of five sequences (members) of thin-bedded strata. The lowermost beds consist of mudstone and sandstone interbedded with evaporites. The upper part of the formation consists of alternating evaporite and dolomite beds. The Culebra Dolomite member is the second member from the bottom of the formation. The total thickness of the Rustler Formation near the WIPP site is approximately 100 meters.

Salado Formation: Second-oldest Ochoan geologic formation consisting of a 230 million-year-old deposit of rock salt (halite) in near-horizontal beds; its total thickness lies between 200 and 400 meters. Very thin layers of clay, anhydrite, and potash minerals are interbedded with the halite beds. Lying at a depth of approximately 660 meters (2,160 feet) at the WIPP site, the Salado hosts the WIPP repository.

Salt Creep: Slow movement of salt over time as shear stresses cause movement within or between individual crystals. Mined salt "heals" as the creep restores its integrity.

Shaft: Vertical or inclined excavation through which a mine is worked.

Shaft Seals: Engineered barrier designed to limit fluid flow through the repository shafts. Once the repository has been filled, the entire column of each shaft will be backfilled with materials that prevent vertical flow of fluid. Materials include concrete, clay, asphalt, compacted salt, grout, and earthen fill.

Spallings: Chipping, fracturing, or fragmentation, and the upward and outward heaving, of rock caused by the interaction of a shock (compressional) wave at a free surface. Spallings in the WIPP can be caused by oil extraction and other human intrusion activities.

Transuranic (TRU) Waste: Radioactive waste consisting of radionuclides with atomic numbers greater than 92 in excess of agreed limits. A more precise definition, in DOE Order 5820.2A, EPA regulation 40 CFR 191, and the Land Withdrawal Act, is waste that is not high-level waste but is "contaminated with alpha-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram." The regulatory definition excludes actinide elements with atomic numbers between 90 and 92 (most significantly, thorium and uranium isotopes), which is in agreement with the literal meaning of "transuranic." However, common usage of the term "transuranic waste" is often understood to include all actinides.

TRUPACT-II: Transuranic Package Transporter, Model II. Container for road transport of contact-handled transuranic waste (see Figure 3.2). The TRUPACT-II container has been certified by the U.S. Nuclear Regulatory Commission.

Waste Characterization: Process of identifying and classifying the chemical, physical, and radiological constituents of each drum of waste.

Water Flooding: Technique used in the secondary recovery of petroleum and gas whereby water is injected into a petroleum or gas reservoir so that the pressure of the water expels the petroleum or gas.

Wattage Limit: In this report, the allowed maximum amount of heat generated by radioactive decay during transportation of TRU waste. The wattage limit for TRUPACT-II containers is 40 watts (40 joules per second).

Appendix E

Acronyms and Symbols

ASCE: American Society of Civil Engineers
CCA: compliance certification application
CCDF: Complementary Cumulative Distribution Function
CEMRC: Carlsbad Environmental Monitoring and Research Center
CH: Contact Handled
CH_4: Methane
CO_2: Carbon dioxide
DOE: U.S. Department of Energy
DOT: U.S. Department of Transportation
DRZ: Disturbed rock zone
EEG: State of New Mexico Environmental Evaluation Group
EPA: U.S. Environmental Protection Agency
H_2: Hydrogen
H_2S: Hydrogen sulfide
INEEL: Idaho Engineering and Environmental Laboratory
ITS: Intelligent transportation system
LWA: Land Withdrawal Act
MgO: Magnesium oxide
MTMH: Metric tons of heavy metal
N_2: Nitrogen
NORM: Naturally occurring radioactive material
NRC: National Research Council
PA: Performance assessment
RCRA: Resource Conservation and Recovery Act
RH: Remote handled
SNL: Sandia National Laboratories
TRANSCOM: Transportation Tracking and Communication

TRIZ: Theory of the Solution of Inventive Problems
TRU: Transuranic
TRUPACT-II: Transuranic Package Transporter, Model II
UNM: University of New Mexico
USNRC: U.S. Nuclear Regulatory Commission
WIPP: Waste Isolation Pilot Plant

Appendix F

Other Relevant Documents

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CHARACTERIZATION
OF REMOTE-HANDLED TRANSURANIC WASTE FOR
THE

WASTE ISOLATION PILOT PLANT

FINAL REPORT

Committee on the Characterization of Remote-Handled Transuranic Waste for the Waste Isolation Pilot Plant

Board on Radioactive Waste Management

Division on Earth and Life Studies

National Research Council

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Cover: Remote-handled transuranic waste re-packaging operations in a ‘‘hot cell’’ at Battelle Columbus Laboratories-West Jefferson North Campus. From top to bottom: a robotic manipulator arm transfers several pool filters into a new container and closes the lid. In the background: picture of sludge at the bottom of the K-Basins at the Hanford Site. The sludge will be removed and pieces larger than 0.25 inches will be separated. The sludge, which is expected to be remote-handled transuranic waste, will be solidified while the larger pieces will be handled as debris waste. The debris could be transuranic or low-level waste.

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Preface

The U.S. Department of Energy (DOE) is seeking authorization to dispose of its remote-handled transuranic (RH-TRU) waste in the Waste Isolation Pilot Plant (WIPP), a geologic repository located in New Mexico. The DOE-Carlsbad Field Office asked the National Research Council to provide an independent review of its proposed characterization plan for RH-TRU waste.

To this end, the National Research Council appointed an ad hoc committee of seven members and one consultant with expertise in the following disciplines: knowledge of the DOE weapons complex, particularly with respect to the generation of RH-TRU waste; TRU waste characterization techniques; health physics; actinide chemistry; environmental policy; public policy; and risk assessment. The committee's statement of task is in Sidebar P.1. The biographical sketches of committee members can be found in Appendix A.

SIDEBAR P.1 Statement of Task

The objective of this study is to review and evaluate the U.S. Department of Energy's (DOE's) plan to characterize remote-handled transuranic (RH-TRU) waste to be disposed of at Waste Isolation Pilot Plant (WIPP). The committee will provide recommendations, as necessary, for improving the plan's technical soundness, protection of worker safety, and compliance with applicable regulatory requirements. This study does not address transportation issues related to RH-TRU waste.

Examples of criteria that could be used by the committee to review DOE's characterization plan for RH-TRU waste are the following: validity of assumptions used for the proposed plan; quality of information available on RH-TRU waste; uncertainties on process knowledge data and consequences if wrong; appropriateness and sensitivity of overall system safety to uncertainties in the waste specifications; limitations of the methodologies and procedures to characterize RH-TRU waste; and validity of DOE's conclusions concerning its characterization plan.

The committee met four times, from June 2001 to May 2002, to complete its review of DOE's characterization plan. The committee interacted with DOE, generator sites, WIPP's primary regulatory agencies (Environmental Protection Agency and the New Mexico Environment Department), the New Mexico Environmental Evaluation Group, and the public to gather information on the status of RH-TRU waste across DOE's complex, characterization requirements, and expectations for this new plan. The diverse mix of participants from DOE (headquarters and the sites), regulatory agencies, and national laboratories contributed to lively discussions and great insights into the committee's task.

The committee gathered information from the following sites: Battelle Columbus Laboratories, Idaho Engineering and Environmental Laboratory, Oak Ridge National Laboratory, Los Alamos National Laboratory, Argonne National Laboratory-West, and

the Hanford Site. These sites were selected because they are the main RH-TRU waste generators or, in the case of Battelle Columbus Laboratories, because this site has begun RH-TRU waste characterization operations. The committee also visited Battelle and the WIPP site. Information-gathering meeting agendas and speakers are listed in Appendix B.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the National Research Council in making the published report technically sound and to ensure that the report meets National Research Council institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Robert M. Bernero, U.S. Nuclear Regulatory Commission (retired)
David C. Camp, Lawrence Livermore National Laboratory
Rodney C. Ewing, University of Michigan
Harry D. Harmon, Harmon Consulting
Darleane C. Hoffman, Lawrence Berkeley Laboratory
Robert H. Neill, Environmental Evaluation Group (retired)
Victoria J. Tschinkel, Victoria J. Tschinkel Environmental Policy and Management
Raymond G. Wymer, Oak Ridge National Laboratory (retired)

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Chris G. Whipple, ENVIRON International, Inc. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

This study could not have been completed without the assistance of many individuals and organizations. The committee thanks many DOE staff members in the Carlsbad Field Office, in the Office of Environmental Management, and at RH-TRU waste generator sites, including contractors, for their active participation in committee meetings and for promptly responding to requests of information. The committee is especially grateful to Roger Nelson, chief scientist at the DOE-Carlsbad Field Office, who served as primary contact for this study and provided outstanding support to committee's activities; Clayton Gist, RH-TRU waste program manager, and Inés Triay, manager of the Carlsbad Field Office. The committee also expresses its deep appreciation to those who organized site tours, especially James Eide at Battelle Columbus Laboratories and Norbert Rempe at the WIPP.

The committee is equally grateful to Steve Zappe of the New Mexico Environment Department and Scott Monroe of the U.S. Environmental Protection Agency for their input on WIPP's regulatory requirements. Matthew Silva, George Anastas, and James Channell of the New Mexico Environmental Evaluation Group also provided the committee with helpful technical and historical perspectives on the characterization of RH-TRU waste.

Finally, the committee thanks the following National Research Council staff members: Kevin Crowley, who provided guidance in separating science from policy; Angela Taylor, who made certain our committee meetings were as pleasant as possible; Darla Thompson who provided strong research support; and Barbara Pastina, whose knowledge, patience, and organizational and writing skills are unparalleled. She anticipated the obstacles and smoothed the way for the committee to deal with issues in the statement of task during this fast-track project. Any success of the project is because of her dedication.

Eula Bingham, *Chair*
Committee on the Characterization of Remote-Handled Transuranic Waste for the WIPP
July 2002

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Executive Summary

The Department of Energy's (DOE's) Carlsbad Field Office asked the National Research Council to review a proposed characterization plan for remote-handled transuranic (RH-TRU)[1] waste and to provide recommendations, as necessary, for improving the plan's technical soundness, protection of worker safety and health, and compliance with regulatory requirements.

There are approximately 3,800 cubic meters of defense-related RH-TRU waste to be removed from DOE's weapons complex. DOE is seeking authorization to dispose of this RH-TRU waste in the Waste Isolation Pilot Plant (WIPP), a geologic repository in southeastern New Mexico. WIPP is regulated by the Environmental Protection Agency (EPA) and the New Mexico Environment Department (NMED).

WIPP is currently certified by the EPA and permitted by the NMED to dispose only of contact-handled (CH) and mixed[2] CH-TRU waste. To obtain authorization to ship RH-TRU waste to WIPP, DOE must submit to the regulatory agencies a characterization plan for RH-TRU waste and request a modification of the EPA Certification and RCRA Permit. The regulatory agencies may accept, reject, or propose modifications to the characterization plan and, eventually, may authorize RH-TRU waste disposal in WIPP.

S.1 Technical and Regulatory Context of RH-TRU Waste Characterization

Remote-handled TRU waste presents a long-term (i.e., 10,000 years) radiological hazard associated with TRU radionuclides (related to the presence of long-lived alpha-emitting isotopes) and a short-term (less than 300 years) radiological hazard associated with short-lived gamma-emitting radionuclides (related to the presence of fission and activation products). Gamma radiation can penetrate through the walls of waste containers and the skin; therefore, RH-TRU waste presents a potential for radiation doses to workers during waste characterization, handling, and emplacement. The associated costs due to the heavy shielding and remote-handling equipment, necessary to protect workers from radiation, are also significant. The long-term radiological hazard of RH-TRU waste is associated with the potential for TRU radionuclide release into the environment once the waste is disposed of in WIPP.

S.1.1 DOE's RH-TRU Waste Inventories

While RH-TRU waste volume represents a small fraction of the allowed TRU waste in WIPP (3,800 cubic meters out of approximately 176,000 cubic meters), it accounts for

[1]Transuranic waste is radioactive waste containing alpha-emitting radionuclides of atomic number greater than 92, half-life greater than 20 years, and activity greater than 100 nanocuries per gram of waste. Transuranic waste is classified as remote-handled or contact-handled depending on the radiation dose rate at the surface of the package. A more detailed definition is given in Sidebar 1.1.

[2]Transuranic waste can be mixed with hazardous components regulated under the Resources Conservation and Recovery Act (RCRA). This type of waste is called mixed TRU waste and is regulated by NMED as hazardous waste.

14 percent of the total curie activity in DOE's TRU inventory. However, the number of TRU (i.e., from alpha-emitting radionuclides with a half-life greater than 20 years) curies in the RH-TRU waste inventory is 2 orders of magnitude lower than that in the CH-TRU waste inventory expected in WIPP. Also, most of the total (CH plus RH) long-term (i.e., TRU) activity expected in WIPP comes from CH-TRU waste, with only a 0.5 percent contribution from RH-TRU waste (see Table 2.3 in Chapter 2).

Remote-handled TRU waste to be emplaced in WIPP is stored or is to be generated as the result of cleanup activities at 13 DOE weapons complex sites (see Chapter 2). Approximately 1,600 cubic meters of projected RH-TRU waste is waste that originates from the dismantlement of hot cells and other facilities used for defense-related purposes, waste that must be recovered and separated from other wastes (such as at the Hanford Site), or waste that must be reprocessed to eliminate hazardous components prohibited in WIPP (such as at Oak Ridge National Laboratory). Already stored at DOE sites are approximately 2,200 cubic meters of RH-TRU waste, but most of this inventory must be characterized and repackaged to meet waste transportation criteria. Only 5 percent of the waste has been characterized and packaged in a form that could be suitable for shipment to WIPP. To obtain authorization to ship RH-TRU waste to WIPP, generator sites must characterize all their RH-TRU waste inventories according to a plan approved by EPA and NMED.

S.1.2 Regulatory Context

Congress designated WIPP as the nation's defense-related transuranic waste repository in the Land Withdrawal Act of 1992. This Act allows the geologic disposal in WIPP of up to 175,564 cubic meters of TRU waste, including 7,080 cubic meters (4 percent of the total volume) of RH-TRU waste. The EPA, under this Act, regulates the radiological release limits for WIPP over a period of 10,000 years. The NMED, under RCRA, regulates the non-radiological risks related to hazardous waste disposal during the operational phase and up to 30 years following repository closure.

The EPA Certification and RCRA Permit establish characterization requirements for all TRU waste (CH and RH) to be emplaced in WIPP. Contact-handled TRU waste is characterized according to a plan that was negotiated for almost two decades among DOE and the regulators prior to the certification of the WIPP facility. This plan consists of 100 percent confirmation of acceptable knowledge (AK)[3] information through visual examination, radioassay, headspace gas sampling, or radiography. A DOE review of the CH-TRU waste characterization procedures revealed that DOE developed self-imposed waste restrictions in the waste acceptance criteria and in the implementation documents used by generator sites to characterize CH-TRU waste. A previous National Research Council committee found that these self-imposed procedures lack technical, safety, or legal basis (see Sidebar 3.1). DOE is now facing the challenge of proposing a characterization plan for RH-TRU waste that meets EPA and NMED requirements but follows a different approach than that used for CH-TRU waste.

[3]According to the EPA's definition, AK consists of historical information on a particular waste stream, which may include administrative, procurement, and quality control documentation associated with the generating process, past sampling and analytical data, information about the process used to generate the waste, material inputs to the process, and the time period during which the waste was generated (see Sidebar 2.1).

S.2 DOE's Proposed Characterization Plan for RH-TRU Waste

The following two documents include DOE's proposed characterization plan for RH-TRU waste:

- Document 1: Notification of Proposed Change to the EPA Title 40 CFR Part 194 Certification of the WIPP.
- Document 2: Request for RCRA Class 3 Permit Modification to the NMED.

On June 28, 2002 DOE submitted Documents 1 and 2 to EPA and NMED, respectively. The committee reviewed two drafts of the above documents prior to their submission. Findings and recommendations in this report apply to the characterization plan as presented in the March 2002 draft.

DOE's goal is to adopt a performance-based approach to meet EPA and NMED requirements for waste characterization. This approach relies on the impact of the RH-TRU waste inventory on the performance of WIPP. The Sandia National Laboratories undertook two performance assessment analyses showing that the characteristics of RH-TRU waste will have a negligible impact on the potential long-term release of radionuclides into the environment. This is due to the characteristics of DOE's RH-TRU waste inventories in terms of volume and radiological composition.

To address the EPA and NMED regulatory requirements, DOE proposes to use the following characterization methods: dose-to-curie conversion, visual examination, radiography, direct assay, counting containers, AK, and characterization at the time of packaging. The dose-to-curie method consists of correlating a surface dose rate measurement with documented waste isotopic distributions through the use of empirically developed conversion factors. Visual examination involves the removal of items from the container (by remote-handled methods) for inspection and identification. Visual examination does not provide information on the isotopic composition of waste. Radiography utilizes penetrating radiation (typically X-rays) to investigate the contents of containers. Direct assay consists of radiochemical analyses using the same methods approved for CH-TRU waste characterization. Counting containers is the method used to determine the amount of metal emplaced in WIPP by an automatic inventory of the number of containers during packaging. Characterization at the time of packaging consists of visual examination and the use of other characterization methods (i.e., AK, radiochemical analysis, or radiography) as waste is generated, packaged, or repackaged in a form suitable for shipment to WIPP. The AK method, which is the primary method of compliance for waste characterization, consists of collecting historical information and new information obtained through the "characterization at the time of packaging" method (see Finding 1B below). Further details are provided in Chapter 4.

Unlike the current CH-TRU waste characterization approach, which requires 100 percent confirmation of the AK information, for RH-TRU waste characterization DOE proposes performing confirmatory measurements only on 10 percent of the waste. This confirmation activity is proposed when AK is insufficient to address a characterization requirement.

S.3 Committee's Assessment of DOE's Proposed Characterization Plan

This report is not meant to be a comprehensive review of the entire RH-TRU waste program, which encompasses RH-TRU waste transportation, storage, waste

certification, operational safety issues, occupational health and safety regulations, waste generator states' regulations, waste acceptance criteria, as well as DOE orders.

The committee used the criteria listed in the statement of task to assess DOE's proposed characterization plan (see Sidebar P.1 in the Preface). Findings and recommendations address: 1) the context of RH-TRU waste characterization, 2) the characterization plan's technical soundness, 3) protection of worker safety and health, and 4) compliance with regulatory requirements. Findings are referenced (in parentheses) according to the order they are presented in Chapter 5. Each finding is followed by the corresponding recommendation (in bold characters). The rationales are provided in Chapter 5.

1) Context of RH-TRU Waste Characterization

The committee did not verify the data provided by DOE on its RH-TRU waste inventories. Acknowledging the past fluctuations of RH-TRU waste inventories, the committee assumes that DOE presented the most up-to-date information available. Even if the information presented in DOE inventories were not accurate, by law the RH-TRU waste emplaced in WIPP cannot exceed 4 percent of the total volume inventory and 5.1 million curies. According to DOE inventories, 95 percent of the RH-TRU waste to be disposed of in WIPP has yet to be generated or needs to be processed, packaged, or repackaged. This waste will be characterized (through visual examination and physical and chemical analyses) at the time of packaging (Finding 1A). **DOE should emphasize the argument that the characterization information collected for most of RH-TRU waste does not need confirmatory measurements because the repackaging or generation of waste will be carried out under a certified quality assurance program.** If the volume of RH-TRU waste represents between 2 and 4 percent of the volume of TRU waste, and the information collected for over 95 percent of RH-TRU waste does not need confirmation, then only the remaining 5 percent of the RH-TRU waste inventory (between 0.1 and 0.2 percent of the total inventory) needs confirmatory activities.

As previously mentioned, DOE uses the term "AK" to indicate both the historical information and the newly generated characterization information collected at the time of waste generation, packaging, or repackaging. However, for 95 percent of the RH-TRU waste inventory, AK refers mostly to the latter (Finding 1B). **The committee recommends that DOE use a different term than "AK" for this newly generated information.** Using AK for both historical and newly generated information is potentially confusing because AK is generally associated with historical information, which requires some type of confirmation.

2) Characterization Plan's Technical Soundness

The committee found that DOE's proposed characterization plan is not completely performance based and that several characterization activities are based on non-technical considerations (Finding 2A). The committee questions the technical basis of some of these characterization activities. The committee acknowledges that non-technical considerations may be important for maintaining effective working relationships among DOE, EPA, and NMED; however, **DOE should propose only characterization activities that have a technical, health and safety, or regulatory basis.**

The committee provides the following examples of activities lacking a technical basis in the context of RH-TRU waste characterization: determination of radiological activity, free water/liquid, ferrous metal, cellulosics, plastic, rubber, and polychlorinated biphenyls

content. According to the Sandia impact analyses, these RH-TRU waste parameters will have only a negligible impact on the performance of the repository. Also, DOE did not provide the technical basis for selecting 10 percent of the waste as a representative waste sample to perform confirmation activities.

In some instances, the plan lacked specificity because most of the operational details are site-specific and were not available at the time of writing (Finding 2B). It is the committee's understanding that, along with Documents 1 and 2, DOE will submit three site-specific documents containing a completed characterization plan for selected RH-TRU generator sites. The committee supports this initiative. **The site-specific documents should present clear and technically defensible data qualification requirements for RH-TRU waste characterization.**

Also, tolerable decision error rates are never clearly defined in Documents 1 and 2 (Finding 2C). Tolerable decision error rates are determined by weighing the consequences of mischaracterization against the costs (including worker risks) of achieving better characterization. Once established, tolerable decision error rates can be used to identify the attendant quality assurance requirements for sampling (i.e., the measurement quality objectives, which DOE calls quality assurance objectives[4]). **DOE's proposed characterization plan should address tolerable decision error rates associated with characterization information. These errors should not be overly stringent so as to negatively impact the sites' ability to implement ALARA.**[5]

For the 5 percent of the RH-TRU waste inventory that does not require packaging or repackaging, it is not clear how visual examination and radiography can confirm AK information for prohibited items (Finding 2D). For example, visual examination and radiography cannot distinguish between corrosive and non-corrosive liquids, whereas AK may provide records of the existence of such liquids in the waste. Historical AK may be a better indicator of some of the currently prohibited items than visual examination and radiography. **The characterization plan should clarify under which conditions confirmation of historical AK is warranted and what are the most effective methods proposed.** The committee could not determine the effectiveness of specific technologies, such as X-ray radiography, in providing confirmatory data for the high-dose-rate fraction of RH-TRU waste containers (Finding 2E). **DOE should provide justification for the technologies proposed for obtaining confirmatory data and provide evidence of their effectiveness across the entire spectrum of dose rates for RH-TRU waste.**

Overall, in the context of RH-TRU waste characterization and from a performance point of view, the committee found that the general approach DOE is proposing is technically sound. However, Documents 1 and 2 do not present a performance-based plan as effectively as they could.

3) Protection of Worker Safety and Health

Potential worker radiation doses and related characterization costs are distinguishing features of RH-TRU waste compared to CH-TRU waste, but estimates of worker doses and characterization costs for RH-TRU waste are limited, site-specific, and not completely reliable (Finding 3A). **DOE could strengthen the rationale of its**

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[4]DOE's "quality assurance objectives" are the accuracy, precision, completeness, comparability, and representativeness of the characterization data.

[5]The ALARA (As Low As is Reasonably Achievable) principle requires that a reasonable effort be made to keep workers radiation exposures as far below the regulatory dose limits as is practical (see Chapter 4).

characterization plan for RH-TRU waste by including a discussion of estimates of worker doses and characterization costs in the three site-specific plans accompanying the submittal documents. Discussion of worker doses and costs is relevant since radiation protection standards and criteria are predicated on the concept of assessing the decrement in risk per increment in cost. It is also important to recognize that tolerable decision error rates associated with characterization methods will have an impact on the implementation of the ALARA principle at generator sites (see Finding 2C).

Documents 1 and 2 provide flexibility to the generator sites in the implementation of the RH-TRU waste characterization plan (Finding 3B). **DOE should continue its effort in ensuring sufficient flexibility to generator sites in the implementation of the characterization plan. However, characterization activities that share common elements across sites should be standardized.** Given the differences among generator sites (for instance, in the composition of waste streams, quality of AK and inventories, and characterization and repackaging facilities), flexibility in a waste characterization plan is important to adapt the sites' implementation programs. A rigid, overly prescriptive characterization plan may lead to unnecessary radiation doses to workers and characterization costs. However, standardization of common elements of the characterization program may facilitate characterization compliance verifications and, possibly, reduce characterization costs.

4) Compliance with Regulatory Requirements

The difficulty of this latter part of the statement of task lies in performing a review of a characterization plan for RH-TRU waste against compliance with existing characterization requirements that currently exclude RH-TRU waste. The task is further complicated by the existence of the characterization approach approved by EPA and NMED that is currently used for CH-TRU waste. It is important to emphasize the difference between regulatory requirements and the approach to meet such requirements. While the regulatory requirements for CH- and RH-TRU waste characterization are the same, the approach to address these requirements can be different. The committee evaluated, from a technical point of view, the approach DOE is proposing to characterize RH-TRU waste and how it addresses regulatory requirements. The committee was not asked to comment on these requirements nor was it asked to determine if the plan complies with the regulatory requirements. The latter is obviously a policy decision belonging to the regulatory agencies.

The committee found that DOE's proposed characterization plan for RH-TRU waste deliberately tracks the characterization plan for CH-TRU waste (Finding 4A). **The committee recommends that DOE evaluate whether existing characterization practices for CH-TRU waste, when applied to the characterization of RH-TRU waste, have an impact on the protection of the environment, health and safety of public and workers, and cost-effectiveness of the characterization program.** Also, like in the CH-TRU waste characterization plan, Documents 1 and 2 include, as basis for characterization objectives, requirements other than those applicable to EPA certification and RCRA permit, for instance transportation requirements or waste acceptance criteria (Finding 4B). **The committee recommends that submittal documents focus on regulatory requirements under the relevant agency's purview and distinguish between these requirements and ancillary information describing the context of RH-TRU waste characterization.** While it is important to provide, in the submittal documents, the full context of the characterization of RH-TRU waste, including material outside the regulatory jurisdiction of EPA and NMED may unnecessarily complicate the

regulatory review process. It would be helpful for both DOE and the regulatory agencies if the submittal documents indicate which requirements are to be reviewed and which are given for information purposes. This would allow the regulator and DOE to keep track of various requirements and to streamline characterization practices as experience is gained.

S.3.1 Overall Assessment of DOE's Characterization Plan

The committee observed a net improvement between the July 2001 and March 2002 drafts of the characterization plan. Concerning the plan's technical soundness, DOE itself recognized that this plan is not completely performance based and that other considerations played a role in its development. The committee identified some characterization activities lacking technical bases in the context of RH-TRU waste and a potential technical problem with radiographic examination of waste. Also, DOE's proposed characterization plan does not adequately address the issue of tolerable decision error rates associated with all characterization information.

In some instances, the plan lacks specificity because most of the operational details are site-specific and were not available at the time of writing. The site-specific accompanying documents should provide useful clarifications. In the context of RH-TRU waste characterization and from a performance point of view, the committee found that the general approach DOE is proposing is technically sound. However, Documents 1 and 2 do not present a performance-based plan as effectively as they could.

Concerning the plan's protection of worker health and safety, the committee recommends that the approved characterization plan not include overly stringent tolerable decision error rates that could negatively impact the sites' ability to manage worker risks. It is important to recognize that the allowable uncertainties in the final characterization plan approved by EPA and NMED may have an impact on generator sites' radiation protection programs.

Concerning compliance with regulatory requirements in the EPA Certification and RCRA Permit, the committee did not observe any requirement that was not addressed in DOE's characterization plan. In fact, the proposed characterization plan for RH-TRU waste addresses some requirements that are not under the relevant agency's purview. Moreover, the characterization plan for RH-TRU waste deliberately tracks that for CH-TRU waste. The committee recommends evaluating whether existing characterization practices for CH-TRU waste, when applied to the characterization of RH-TRU waste, have an impact on the protection of the environment, health and safety of public and workers, and cost-effectiveness of the characterization program.

1

Introduction

The purpose of this report is to provide an independent technical review of the U.S. Department of Energy's (DOE's) proposed characterization plan for defense-related remote-handled (RH) transuranic (TRU) waste. Remote-handled transuranic waste is defined in Sidebar 1.1.

Transuranic waste is classified as remote-handled (RH) or contact-handled (CH) depending on the radiation dose rate measured at the surface of waste containers. While CH-TRU waste can be safely handled by direct contact, RH-TRU waste requires heavy container shielding or remote-handling equipment. Therefore, the main issues with RH-TRU waste characterization are the potential for worker exposure to radiation and the associated costs.

Because of its radiological hazard, TRU waste requires geologic isolation. Congress designated the Waste Isolation Pilot Plant (WIPP), in southeastern New Mexico, as the nation's geologic disposal facility for defense-related transuranic waste (U.S. Congress, 1992). Figures 1.1, 1.2, and Sidebar 1.2 provide a schematic representation and a brief description of the WIPP facility. DOE is seeking authorization to dispose of RH-TRU waste in WIPP as part of its commitment to safely manage and clean up contamination from over 50 years of nuclear materials research and production. About 3,800 cubic meters of defense-related RH-TRU waste (corresponding to approximately 1 million curies) is the current estimated volume of RH-TRU waste to be disposed in WIPP.

The U.S. Environmental Protection Agency (EPA) and the New Mexico Environment Department (NMED) are WIPP's regulatory agencies. In 1998, the EPA, which regulates TRU waste, granted WIPP a Certification of Compliance (referred to as the EPA Certification) with the geologic disposal standards established in Title 40 of the Code of Federal Regulations Part 191 (40 CFR 191). In 1999, the NMED, which regulates hazardous waste disposal under the Resources Conservation and Recovery Act (RCRA), granted WIPP a hazardous waste facility permit (referred to as the RCRA Permit). Regulatory requirements addressing radioactive and hazardous waste will be discussed in Chapter 3.

EPA and NMED authorize only CH- and mixed CH-TRU waste in WIPP. Remote-handled TRU waste is not allowed in this facility because, according to these agencies, DOE does not have an appropriate characterization plan for this type of waste (see Chapter 3).

The EPA Certification and RCRA Permit contain characterization requirements for TRU waste to be emplaced in WIPP. These characterization requirements were negotiated among DOE, EPA, and NMED and they are the basis of the current characterization plan for CH-TRU waste.

SIDEBAR 1.1 Definition of Transuranic Waste and Classification

Transuranic (TRU) waste is radioactive waste containing alpha-emitting radionuclides of atomic number greater than 92, half-life[a] greater than 20 years, and activity greater than 100 nanocuries per gram of waste, except for: high-level radioactive waste; waste that the Department of Energy (DOE) has determined, with the concurrence of the Environmental Protection Agency (EPA), does not need the degree of isolation required by the disposal regulations; or waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with Title 10 of the Code of Federal Regulations Part 61 (U.S. Congress, 1992).

Transuranic waste can consist of sludge or solid material, such as pieces of clothing, tools, and debris. This type of waste was produced during the processing of nuclear materials and continues to be generated in the cleanup of DOE weapons sites. The main alpha-emitting radionuclides in TRU waste (and their respective half-lives indicated in parenthesis) are plutonium-238 (87.7 years), plutonium-239 (24,100 years), plutonium-240 (6,560 years), and americium-241 (433 years). Other long half-life isotopes, such as uranium-233 (159,200 years), uranium-234 (24,600 years), uranium-235 (704 million years), and uranium-238 (4.47 billion years) may also be present in transuranic (TRU) waste.

Transuranic waste is classified as *contact-handled* (CH) or *remote-handled* (RH), according to the dose rate measured at the container surface. According to Land Withdrawal Act, "the term 'contact-handled transuranic waste' means transuranic waste with a surface dose rate not greater than 200 millirem per hour. The term 'remote-handled transuranic waste' means transuranic waste with a surface dose rate of 200 millirem per hour or greater" (U.S. Congress, 1992). The legal definitions of CH-TRU and RH-TRU waste do not clearly address container surface dose rates of exactly 200 mrem per hour. Therefore, waste packages approaching 200 mrem per hour are handled directly or remotely, depending on site-specific practices.

Transuranic waste is further classified as *mixed* or *non-mixed*. Mixed TRU waste contains both radioactive material regulated under the Atomic Energy Act and hazardous waste material regulated under the Resource Conservation and Recovery Act, or RCRA (U.S. Congress, 1976). RCRA is a federal law addressing hazardous waste designed to ensure that the generation, transportation, treatment, storage, and disposal of hazardous wastes are conducted in a manner that protects human health and the environment (EPA, 1994). The statutory definition of hazardous waste is provided in Section 1004(5) of RCRA as follows (EPA, 1994; page 1.3):

> "A solid waste, or combination of solid waste, which because of its quantity, concentration, or physical, chemical, or infectious characteristics may 1) cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or 2) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed."

Examples of hazardous waste material are ignitable, corrosive, reactive, and toxic substances. For an overview of the Atomic Energy Act and major environmental laws, including RCRA, the reader may refer to "The Nuclear Waste Primer" (The League of Women Voters, 1993).

[a]For a definition of half-life see the glossary, Appendix I.

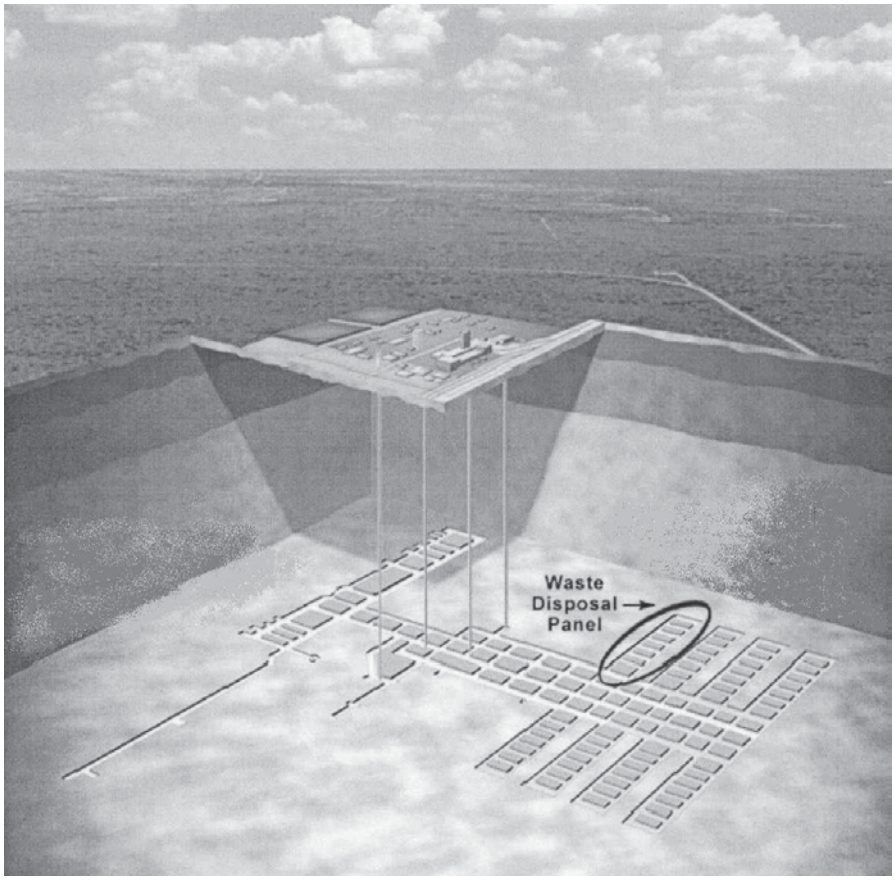

FIGURE 1.1 Schematic representation of the WIPP Facility. The facility will have eight disposal panels, each divided into seven rooms. Only two of the eight panels have been mined to date. SOURCE: DOE (DOE-CBFO, 2000).

To obtain authorization to dispose of RH-TRU waste in WIPP, DOE must request a modification of the EPA Certification and RCRA Permit and present a proposed characterization plan for this type of waste. This proposed characterization plan is the focus of this report.

DOE's proposed characterization plan for RH-TRU waste consists of the following two documents:

- Document 1: Notification of Proposed Change to the EPA Title 40 CFR Part 194 Certification of the WIPP.
- Document 2: Request for RCRA Class 3 Permit Modification[1] to the NMED.

Documents 1 and 2 will often be referred to in this report as the “submittal documents.”

[1]Class 3 permit modifications, as determined by NMED, are considered major changes to the permit. This class of permit modification requires a public notice, a 60-day comment period, and hearings, including testimony and cross-examination of witnesses, before NMED issues the final draft permit language.

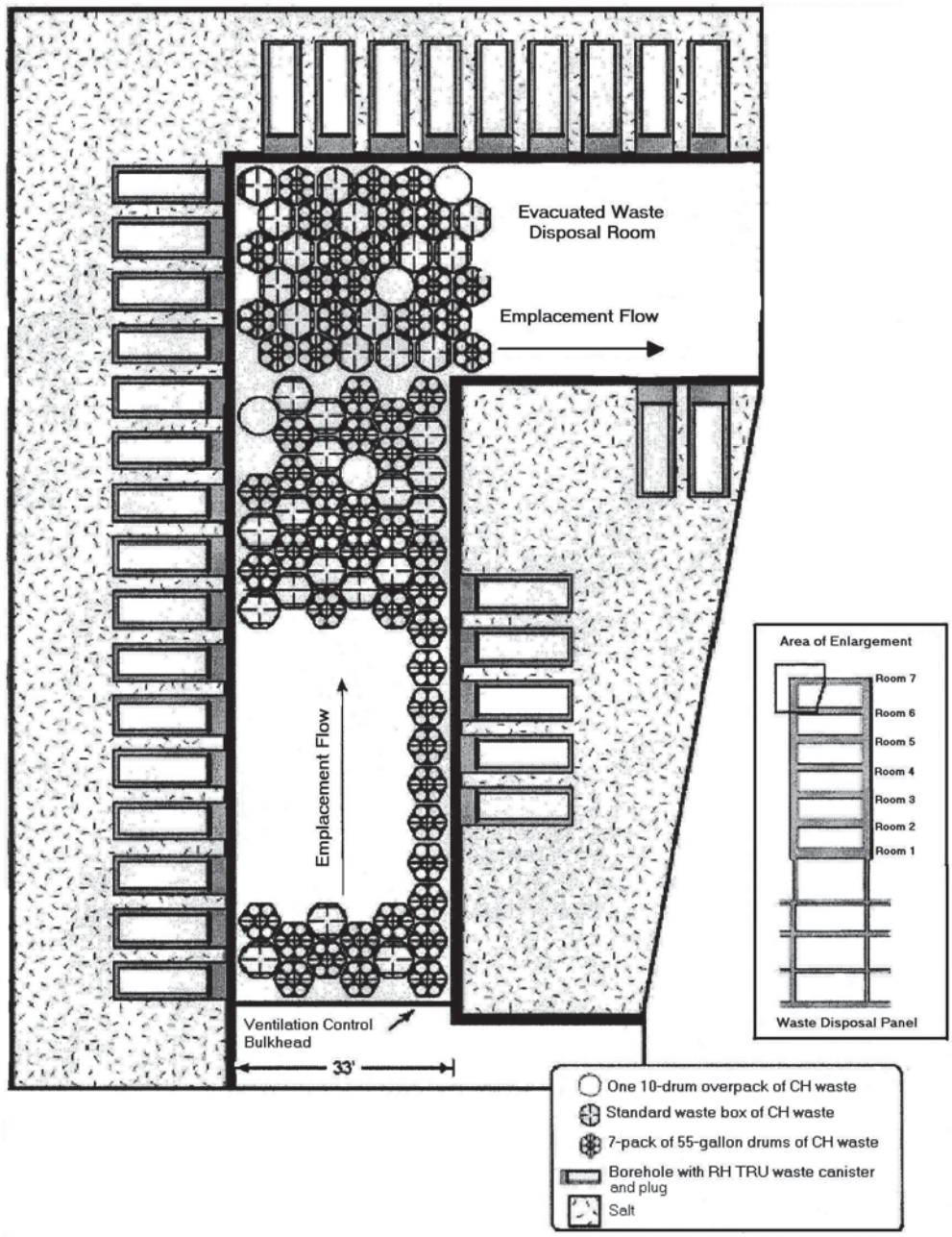

FIGURE 1.2 Plan view of a section of a typical underground disposal area showing CH-TRU and RH-TRU waste emplacement. SOURCE: National Transuranic Waste Management Program, Rev. 2, Figure 3.2.1.1-2 (DOE-CBFO, 2000; page 69).

Document 1 contains EPA regulatory requirements to ensure that the waste emplaced in WIPP falls within the envelope limits required to maintain compliance with radiological disposal standards. Document 2 contains regulatory requirements to ensure that the non-radiological hazardous characteristics of the waste emplaced in WIPP are compatible with RCRA requirements. Documents 1 and 2 also contain additional

information, such as the WIPP's waste acceptance criteria, transportation requirements, description of surface storage and handling facilities, and waste certification process.

DOE's proposed characterization plan must address the characterization requirements in the EPA Certification and RCRA Permit in the context of RH-TRU waste. As shown in Chapter 2, this context is different from that of CH-TRU waste because of the different inventories and radiological properties.

EPA and NMED may accept, reject, or propose modifications to the characterization plan and eventually they may authorize RH-TRU waste disposal in WIPP. Once the characterization methods for RH-TRU waste are finalized, it is the committee's understanding that DOE will produce one document combining all regulatory requirements to help generator sites implement their characterization programs.

SIDEBAR 1.2 The Waste Isolation Pilot Plant

The Waste Isolation Pilot Plant (WIPP), located near Carlsbad in New Mexico, is the nation's defense-related transuranic waste repository, as designated by Congress in the Land Withdrawal Act of 1992. This Act allows the disposal of 175,564 cubic meters of transuranic waste in WIPP, of which 7,080 cubic meters can be remote-handled transuranic (RH-TRU) waste with a maximum radioactivity of 5.1 million curies. Other legal criteria for WIPP related to RH-TRU waste are discussed in Chapter 3.

The WIPP disposal area is located 660 meters below ground in a salt bed, called the Salado Formation (see Figure 1.1). Large salt beds such as this are found only in regions that lack significant flows of groundwater. This deep, relatively dry, underground environment greatly reduces the possibility of waste releases from the repository by natural processes. Moreover, after approximately 200 years, the mined salt will heal and encapsulate the waste, thereby permanently locking it deep beneath the surface (Knowles and Economy, 2000).

The underground waste disposal area in WIPP consists of eight panels, each containing seven rooms. Contact-handled transuranic (CH-TRU) waste drums and boxes are being stacked in three layers in the center of each room. Remote-handled TRU waste is currently not authorized in WIPP. Should the U.S. Environmental Protection Agency (EPA) and the New Mexico Environment Department (NMED) allow disposal of RH-TRU waste in WIPP, it will be emplaced inside horizontal boreholes drilled into the walls of each room. Figure 1.2 shows the CH-TRU and RH-TRU waste emplacement configurations. According to WIPP's design, the diameter of a borehole for RH-TRU waste containers is 76.2 cm and the length is 487.68 cm (DOE-CAO, 1995). A shield plug will cap each RH-TRU waste borehole to provide workers with the necessary protection against radiation.

The WIPP has been under study since the mid-1970s and under construction since January 1981. The facility received the first CH-TRU waste shipment in March 1999 and the first mixed CH-TRU waste shipment in September 2000. To date (July 2002), more than 900 shipments of CH-TRU waste from 26 generator sites have been sent to WIPP.

After three years of operation, the first panel has been almost completely filled with CH-TRU waste. Because CH-TRU waste now blocks the access to the rooms walls, RH-TRU waste cannot be disposed in this first panel. Emplacement of CH-TRU waste in the second panel is currently scheduled to begin in December 2002.

1.1 Committee's Task and its Boundaries

At the request of DOE-Carlsbad Field Office, the National Research Council appointed the Committee on the Characterization of Remote-Handled Transuranic Waste for the Waste Isolation Pilot Plant, referred to as "the committee" in the rest of this report. The committee roster and biographical sketches can be found in Appendix A. The committee's statement of task is reproduced in Sidebar P.1 of the Preface. The committee followed the examples of criteria listed in the statement of task to assess DOE's proposed characterization plan.

The committee was asked to provide recommendations, as necessary, for improving the characterization plan's technical soundness, protection of worker safety and health, and compliance with regulatory requirements. The difficulty of this latter part of the task lies in performing a review of a characterization plan for RH-TRU waste that must show compliance with existing characterization requirements. These requirements exclude RH-TRU waste. Moreover, the approach currently used to characterize CH-TRU waste is different than the approach DOE proposed for RH-TRU waste. It is important to emphasize the distinction between regulatory requirements and the approach to meet such requirements. While the regulatory requirements for the characterization of TRU waste destined for WIPP, established in the EPA Certification and RCRA Permit, apply to both CH- and RH-TRU waste, the waste characterization plans may propose different approaches to address these requirements. The committee evaluated, from a technical point of view, the approach DOE is proposing to characterize RH-TRU waste and how DOE proposes to address regulatory requirements. The committee was not asked to comment on these requirements nor was it asked to determine if the plan complies with the regulatory requirements. The latter is obviously a policy decision belonging to the regulatory agencies.

During this study, the committee reviewed two drafts of Documents 1 and 2, dated July 2001 (DOE-CBFO, 2001a, 2001b) and March 2002 (DOE-CBFO, 2002a, 2002b). The committee provided initial findings and recommendations in an interim report (see excerpt in Appendix C).

The committee did not verify data provided by DOE on RH-TRU waste inventories. Acknowledging the past fluctuations of RH-TRU waste inventory information, the committee assumes that DOE presented the most up-to-date information available. The committee was not asked to identify other potential sources of RH-TRU waste or discuss the origin of RH-TRU waste streams at generator sites.

Also, the committee did not assess the validity of supplementary information supporting the characterization plan, such as the Sandia Inventory Impact Assessment Reports in Document 1 (DOE-CBFO, 2002a; Attachment 2) and Document 2 (DOE-CBFO, 2002b; Supplement 2). The committee did, however, assess how DOE interpreted and used the results of these reports in its characterization plan.

This document is not meant to be a comprehensive review of the entire RH-TRU waste program, which encompasses RH-TRU waste transportation, storage, waste certification, operational safety issues, occupational health and safety regulations, waste generator states' regulations, waste acceptance criteria, as well as DOE orders. The National Research Council is undertaking a more general study on the characterization of TRU waste (including relevant transportation requirements) and its impact on DOE's National Transuranic Waste Management Program.

Documents 1 and 2 were submitted to the regulatory agencies on June 28, 2002. The committee did not review the submittal version of these documents; therefore, findings and recommendations in this report apply to the characterization plan as presented in March 2002.

1.2 Organization of the Report

Following this introduction, Chapter 2 contains updated information on life cycle, status, and inventories of RH-TRU waste at selected generator sites. Chapter 3 describes the regulatory context for the disposal of RH-TRU waste. DOE's proposed characterization plan for RH-TRU waste is described in Chapter 4. Chapter 5 provides the committee's assessment of DOE's proposed characterization plan. In December 2001, the committee released an interim report with initial findings and recommendations relevant to the July 2001 draft. These findings and recommendations can be found in Appendix C. DOE's response to the committee's interim report is reproduced in Appendix D.

2

Remote-Handled Transuranic Waste

This chapter provides the context of RH-TRU waste characterization. The information presented on isotopic composition, life cycle, generator sites, and inventories for RH-TRU waste is provided on the basis of the knowledge gathered during committee meetings and has not been verified. DOE's inventories have been updated since the committee's interim report (released in December 2001).

2.1 Technical Context of Remote-Handled Transuranic Waste Characterization

The radiation-related health hazard associated with TRU waste is due primarily to alpha and gamma radiation. Alpha radiation cannot penetrate human skin but poses a potential health hazard if particles containing alpha-emitting radionuclides are inhaled or ingested. Contact-handled TRU waste typically emits relatively little gamma radiation; therefore, when properly packaged, it can be handled directly by workers.

Remote handled-TRU waste also contains activation and fission products (half-lives are indicated in parenthesis), such as cobalt-60 (5.3 years), plutonium-241 (14.4 years), strontium-90[1] (29 years), cesium-137 (30 years), and their progenies. Some of these products emit gamma radiation, which can penetrate human skin and even the walls of waste containers. Therefore, RH-TRU waste requires heavy shielding and remote-handling equipment. Gamma rays represent the main radiological health hazard to workers during normal RH-TRU waste handling operations.[2] Although alpha-radiation exposure has a greater health risk per unit of energy deposited, the likelihood that workers will be exposed to alpha radiation while handling RH-TRU waste is lower compared to the likelihood for exposure to gamma radiation, because alpha radiation is stopped by the container's walls.

In summary, RH-TRU waste presents a long-term (i.e., 10,000 years) radiological hazard associated with TRU radionuclides (related to the presence of long-lived alpha-emitting isotopes) and a short-term (less than 300 years) radiological hazard associated with short-lived gamma-emitting radionuclides (related to the presence of fission and activation products). Today, most of the radioactivity in DOE's inventory of RH-TRU waste is due to the short-lived non-TRU radionuclides listed above. Nearly all of this activity will decay in 300 years, corresponding to approximately 10 half-lives of the

[1]Strontium-90 and plutonium-241 also emit beta particles (contributing to approximately 35 percent of the curie inventory for RH-TRU waste) but their energy is not high enough to penetrate the walls of RH-TRU waste containers.

[2]Normal waste handling operation implies that the RH-TRU waste container is not breached and workers are not directly exposed to alpha-emitting particles.

gamma-emitting radionuclides. Therefore, the long-term activity of RH-TRU waste is due to the remaining long-lived alpha-emitting (i.e., TRU) radionuclides.

2.2 Life Cycle of Remote-Handled Transuranic Waste

The life cycle of RH-TRU waste, from its generation to its designated final disposal at WIPP, generally consists of the following:

1. waste generation or recovery from its current storage location;
2. processing;
3. characterization;
4. packaging or repackaging;[3]
5. storage on site or off site prior to shipment to WIPP;
6. road transportation to WIPP;
7. receipt, handling, surface interim storage; and
8. underground emplacement at WIPP.

Remote-handled waste is generated during deactivation and decommissioning activities of DOE sites or it is already stored at generator sites and must be recovered for shipment to WIPP. Recovery activities can be complex if containers are difficult to access, if their integrity has been compromised with time, or if storage records are not available. For instance, part of the RH-TRU waste stored at Oak Ridge National Laboratory consists of a sludge that must be processed before shipment to WIPP (see Appendix E).

Waste processing activities consist of converting waste to a form suitable for disposal in WIPP. For instance, wet sludge must be dried because liquids are considered prohibited items (if more than 1 percent by waste volume) in WIPP's RCRA Permit. Waste characterization is necessary prior to waste shipment to WIPP. Waste characterization may be performed at the time of packaging or repackaging of the waste. Packaging is necessary for waste that has not yet been generated. Repackaging is necessary for stored waste that is packaged in a container that does not meet transportation requirements; or for waste that needs processing to remove hazardous material (see Section 2.4). Solid RH-TRU waste will be repackaged in shielded facilities, such as hot cells.[4] During this step, waste can be inspected by visual examination. As the waste is removed from an old container and sorted into new containers, a video camera records the operations on tape while an operator describes the various items. This inspection method requires skilled operators since it is done entirely by remote methods (see Finding 2D in Chapter 5). Volume-reducing operations, such as mechanical waste compacting, are also performed during the repackaging process.

Once a waste stream[5] is characterized and packaged, it must be certified by EPA and NMED and stored on site prior to shipment to WIPP. Selected waste streams may

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[3]For most of the RH-TRU waste inventory, characterization will be performed at the time of packaging or repackaging of waste (see Chapters 4 and 5).

[4]A hot cell is a large chamber for handling highly radioactive materials. It is usually equipped with thick walls with shielding and viewing windows, remote-operated overhead cranes, closed-circuit televisions, and a variety of specialized tools and measuring devices. Throughout DOE complex other shielded facilities may be used with the same purpose as hot cells.

[5]A waste stream is defined as waste material generated from a single process or activity or as waste in multiple containers having similar physical, chemical, or radiological characteristics.

not need certification if they are shipped to other major DOE sites for interim storage. Prior to shipment to WIPP, these interim storage sites will ensure certification of all their waste, including that received from other sites.

Finally, RH-TRU waste must be loaded into transportation casks, transported by road[6] to WIPP, received, temporarily stored at the surface, and finally emplaced underground.

2.3 Generation of Remote-Handled Transuranic Waste

According to DOE's latest inventory, there are approximately 3,800 cubic meters of RH-TRU waste to be removed from DOE sites across the nation. Figure 2.1 shows the geographic locations of the major RH-TRU waste generator sites. These sites are the following:

1. Hanford Site, Washington;
2. Idaho National Engineering and Environment Laboratory;
3. Los Alamos National Laboratory, New Mexico; and
4. Oak Ridge National Laboratory, Tennessee.

There are also nine smaller RH-TRU waste generator sites, not shown in Figure 2.1. Tables 2.1 and 2.2 show DOE's RH-TRU waste inventories in terms of volume and radioactivity. Additional information about the nature and history of RH-TRU waste at selected generator sites is provided in Appendix E.

Tables 2.1 and 2.2 show the substantial variability among generator sites concerning waste volumes and radioactivity contents. These tables show that 60 percent of the stored volume of RH-TRU waste and about 89 percent of the total curie activity is located at Oak Ridge National Laboratory. About two-thirds of the Oak Ridge RH-TRU waste consists of wet sludge, stored in Melton Valley storage tanks, and the rest is debris waste. Debris waste consists of debris from hot cells and glove boxes packaged in shielded concrete casks. This wet sludge and debris waste contains significant sources of neutrons, due to the spontaneous fission of californium-252 and from (alpha, n) reactions (see Appendix E). These reactions involve the capture of highly energetic alpha particles, such as those emitted from curium-244, by nuclei of low-atomic-number elements, such as oxygen and fluorine, and the subsequent emission of neutrons. The neutron emission is primarily a handling, processing, and particularly a characterization issue in the near term for this site. The waste containers that will be used to ship RH-TRU waste from Oak Ridge to WIPP are specially designed to shield neutrons.

To meet the milestones set in the Federal Facility Compliance Act between DOE and the state of Tennessee, the Oak Ridge National Laboratory (through its contractor Foster Wheeler) is building a treatment facility to process, characterize, and package its RH-TRU waste (EPA, 1992). The current plan is to characterize RH-TRU waste following a plan similar to that for CH-TRU waste characterization. Homogeneous samples of wet sludge would be characterized by radiochemical assays performed in a laboratory on site. The sludge would then be dewatered and dried in preparation for shipment. Debris would be characterized by visual and non-destructive examination[7] inside a hot cell

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[6]The U.S. Nuclear Regulatory Commission certifies the design of transportation casks. Currently, these containers are designed for road transportation only.

[7]The definition of non-destructive examination can be found in the glossary, Appendix I.

during repackaging. Debris waste would undergo volume-reduction operations during packaging. Oak Ridge records show that there is considerable historical information available on debris waste (ORNL, 1989).

The processing of RH-TRU waste sludge had been scheduled to begin in December 2002 with shipments to WIPP beginning in January 2003. Debris RH-TRU waste would have been processed and shipped to WIPP between 2004 and 2008. Because of the recent submission of DOE's characterization plan to EPA and NMED (June 28, 2002), the characterization plan will likely not be finalized in time to meet this schedule. Oak Ridge is now organizing waste processing and on-site storage as it waits for authorization to ship RH-TRU waste to WIPP (Forrester et al., 2002).

While most of the stored RH-TRU waste volume is located at Oak Ridge National Laboratory, most of the RH-TRU waste to be emplaced in WIPP has yet to be generated. This waste will come from the Hanford Site cleanup activities. The RH-TRU waste at this site consists mostly of sludge at the bottom of the fuel pools, or equipment inside waste tanks (such as pumps, mixers, and pipelines) or is buried in caissons and drums. Because this waste has yet to be generated and packaged, the Hanford Site has less detailed knowledge of its RH-TRU waste inventory than the other major generator sites.

At the Idaho National Engineering and Environmental Laboratory, the stored RH-TRU waste consists mostly of solids generated during the destructive examination of irradiated experimental fuel pins in a hot cell. The RH-TRU waste stored at this site was generated at Argonne National Laboratory-East from defense-related experiments on nuclear fuel. The destructive examination and testing operations of spent fuel pins involved cutting, grinding, and polishing for subsequent examination.

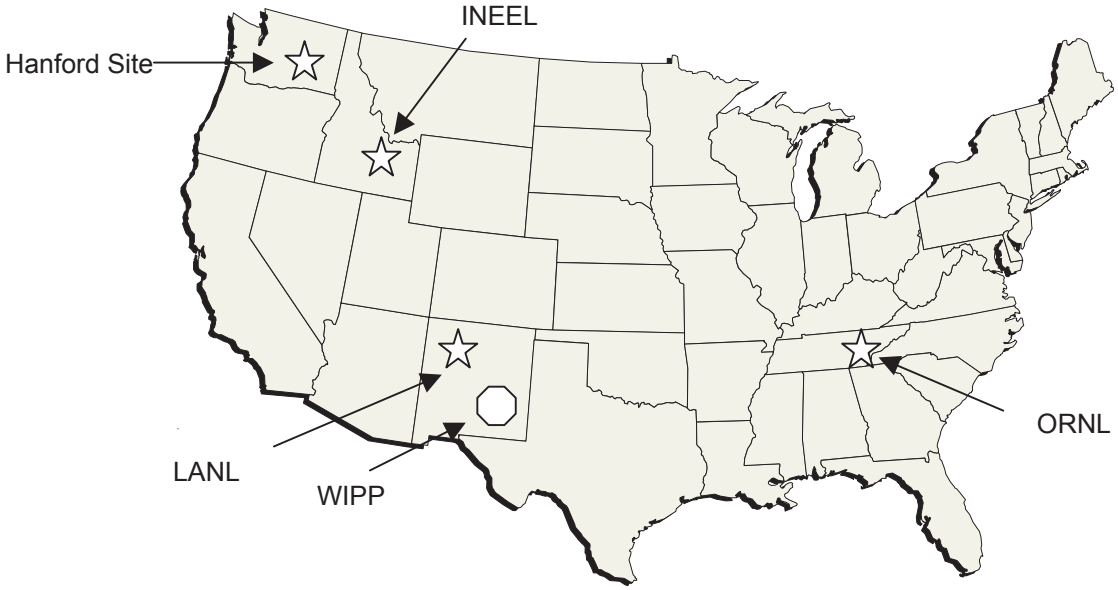

FIGURE 2.1 Geographic locations of the Waste Isolation Pilot Plant (WIPP) and the four major RH-TRU waste sites: Hanford Site, Idaho National Engineering and Environmental Laboratory (INEEL), Oak Ridge National Laboratory (ORNL), and Los Alamos National Laboratory (LANL). There are nine other smaller RH-TRU waste generator sites and several other sites throughout the nation that store CH-TRU waste. SOURCE: DOE (DOE-CBFO, 2001c).

TABLE 2.1 DOE's Inventory of Stored, Projected, Total, and Planned Volumes of RH-TRU Waste

Site Name	RH TRU Waste Volume (cubic meters)				Estimated Range of Concentration of CPR[5] (average kg per cubic meter)	Reported Estimates of Dose Rates[6] (rem per hour)
	Stored[1]	Projected[2]	Total[3]	Planned Disposal[4]		
Hanford Site	207	944	1,151	1,048	0 - 477 (24)	0.2 - 1,000
Idaho National Engineering and Environmental Laboratory[7]	84	52	136	279	0 - 439 (41)	0.2 - 100
Los Alamos National Laboratory	98	24	122	122	0 - 980 (95)	1 - 100
Oak Ridge National Laboratory	1,308	534	1,841	453	0 - 902 (74)	0.2 - 1,000
Total	1,697	1,554	3,250	1,902		
Small-Quantity Sites						
Argonne National Laboratory-East[8]	2	8	10	10	NA	0.2 - 10
Argonne National Laboratory-West	1.1	5	6.1		0 - 1,350 (110)	1 - 100
Battelle Columbus Laboratories[8]	0	20.8	20.8	20.8	0 - 1,430 (117)	0.2 - 150
Bettis Atomic Power Laboratory	2	0	2	2	0 - 1,430 (117)	1 - 100
Energy Technology Engineering Center[8]	8	0	8.7	5.5	0 - 74 (5.2)	0.2 - 1
General Electric-Vallecitos Nuclear Center	11.8	0	11.8	11.8	NA	1 - 100
Knolls Atomic Power Laboratory	3.1	6.8	9.9	10.5	NA	1 - 100
Sandia National Laboratories[8]	1.5	22	23.5		NA	NA
West Valley Demonstration Project[9]	470.5	8.4	478.9		NA	NA
Total Waste Volumes	2,197.7	1,625	3,821.7	1,962.6		

NOTE: The committee did not verify the information in this table.
[1]Stored=waste awaiting treatment or disposal capability, in such a manner as to constitute disposal of the waste.
[2]Projected=the part of the inventory that has not been generated but is currently estimated to be generated at some time in the future.
[3]Total=sum of the stored plus projected volumes.
[4]Planned Disposal=volume expected to be disposed at WIPP. The quantities reflect any volumetric change that would occur during waste processing.
[5]Dose Rate Ranges=the dose rates estimated for as-packaged containers. Dose rates are measured at the container's surface.
[6]CPR=cellulosics, plastics, and rubber. A zero in the average CPR concentration indicates a container including other materials, such as metals or sludge.
[7]It is estimated that about 896 cubic meters of waste will be shipped from Idaho Nuclear Technology and Engineering Center for disposal at WIPP. This waste is expected to be categorized as "Waste Incidental to Reprocessing" and has not yet been approved for disposal at WIPP. Therefore, it is not included in the table.
[8]Current plans are to send the RH-TRU waste at this site to an interim site. Los Alamos National Laboratory's inventory includes Sandia's RH-TRU waste disposal volume. Argonne National Laboratory-East, Battelle Columbus Laboratories, and Energy Technology and Engineering Center are also expected to go to interim sites, but the specific interim sites have not yet been determined. Therefore, the waste volume is included here for completeness.
[9]The West Valley Demonstration Project is not a DOE site, even though it stores some RH-TRU waste. This waste has not yet been determined to be a defense-related waste. It is believed to be commercially derived and therefore not disposable at WIPP in accordance with the Land Withdrawal Act. However, for completeness, this waste is included in the RH-TRU waste inventory.
SOURCE: Document 1, Supplemental Information, Attachment 3, Table 1 (DOE-CBFO, 2002a; page 5).

TABLE 2.2 DOE's Summary Activity Estimates for the RH-TRU Waste Inventory

Site Name	Estimated Stored Activity (total curies)
Hanford Site	36,000
Idaho National Engineering and Environmental Laboratory	6,360
Los Alamos National Laboratory	10,700
Oak Ridge National Laboratory	587,000
Small-Quantity Sites	
Argonne National Laboratory-East	NR
Argonne National Laboratory-West	NR
Battelle Columbus Laboratories	5,800
Bettis Atomic Power Laboratory	16,300
Energy Technology Engineering Center	8
General Electric-Vallecitos Nuclear Center	NR
Knolls Atomic Power Laboratory	118
Sandia National Laboratories	NR
West Valley Demonstration Project	NR
Total Waste Activity	662,286

NOTE: These estimates are for waste currently in storage. They do not take into account "to be generated" RH-TRU waste. The current estimate for stored and future RH-TRU waste is about 1 million curies. NR=Not Reported. NR typically denotes that the site did not report the information for a variety of reasons (e.g., the data are not readily available, the pedigree of the data may be questionable, recent characterization has not been performed, or the site did not respond). The committee did not verify the information in this table.
SOURCE: Document 1, Supplemental Information, Attachment 3, Table 2 (DOE-CBFO, 2002a; page 6).

A fine fuel particulate adhered to the tools required for these operations and contaminated them with TRU elements. These tools (e.g., grinding and cutting wheels, glassware, light bulbs, rags) have been sent to the Idaho National Engineering and Environmental Laboratory. A formal determination of the defense origin for this waste stream will be submitted for approval to DOE prior to disposal at WIPP (Bhatt, 2001). The fuel pin segments, integral fuel pins, and the fuel dust are still stored at Argonne National Laboratory-East, as high level waste or spent nuclear fuel.

Most of the RH-TRU waste stored at Los Alamos National Laboratory was characterized and packaged between 1989 and 1994. The waste was characterized using a similar approach to that approved for CH-TRU waste characterization. Visual examination, non-destructive assay methods, radiography, and radiochemical analyses were used. Characterization operations were performed in a hot cell, except for small quantities of waste analyzed in a laboratory for radiochemical composition.

Among the nine smaller generator sites, the Battelle Columbus Laboratories in Ohio is the only site that is actively characterizing RH-TRU waste. This site is the first originally scheduled to ship RH-TRU waste to WIPP (January 2003). The agreement between Battelle Columbus Laboratories and the state of Ohio requires RH-TRU waste removal from the site by 2002 to meet a 2006 decontamination and decommissioning-completion milestone (Biedscheid et al., 2002).

Battelle Columbus Laboratories began RH-TRU waste characterization activities in October 2001 following a characterization program similar to that used for CH-TRU waste. This characterization program relies on visual examination, performed during

waste repackaging, and previous knowledge of the waste, also called "acceptable knowledge" (AK). Acceptable knowledge is discussed in Sidebar 2.1. The repackaging phase, which occurs in a shielded facility, is necessary because RH-TRU waste containers at this site do not meet transportation requirements. Visual examination is used to estimate physical waste parameters, including weight percentages of metals, cellulosics, plastics, and rubber in the waste, and to determine the absence of prohibited items, including free liquids (see Chapter 3). Acceptable knowledge combined with computer modeling is used to estimate radiological waste parameters, including total activity on a waste container basis (see Appendix G). Acceptable knowledge combined with radiochemical analysis is also used on a fraction of RH-TRU waste for confirmation purposes. For a detailed description of the Battelle Columbus Laboratories' characterization program see Biedscheid et al. (2002).

This site is now seeking interim storage for its RH-TRU waste at the Hanford Site until shipments to WIPP are authorized. Work on a memorandum of agreement among DOE offices in Ohio, Carlsbad, and Richland is in progress (DOE-BCL, 2002) as part of the Hanford Site cleanup acceleration program. One element of this program is a proposal to transform the Hanford Site into a TRU waste-processing center for small generator sites, including Battelle Columbus Laboratories.

2.3.1 Remote-Handled Transuranic Waste Volume Inventory

Table 2.1 shows that the projected total volume inventory of RH-TRU waste in WIPP is 3,821 cubic meters, of which 2,197 cubic meters are currently stored at DOE sites and 1,625 cubic meters are yet to be generated (see the column "Projected"). For reference, the total volume of RH-TRU waste would correspond to approximately 20,000 RH-TRU waste containers (assuming they are all 55-gallon drums). Further volume-reducing[8] operations (mainly at Oak Ridge National Laboratory) may decrease the waste volume to be emplaced in WIPP to 1,963 cubic meters, as shown in the "Planned Disposal" column. According to these data, RH-TRU waste volume inventory represents between 1 and 2 percent of the total TRU (CH-TRU plus RH-TRU) volume allowed in the WIPP facility (175,564 cubic meters). The volume of RH-TRU waste to be emplaced in WIPP is also well below the regulatory limit of 7,080 cubic meters set by the Land Withdrawal Act.

There have been substantial variations in the estimated volumes of RH-TRU waste in DOE weapons complex, as also observed by the New Mexico Environmental Evaluation Group (EEG, 1994). These variations arise mostly from changes in the RH-TRU waste management or treatment plans. For example, DOE's earlier data for the Savannah River Site, in South Carolina, originally indicated a large RH-TRU waste inventory, reflecting disposal of materials stored in the separations canyons as TRU waste. However, the Savannah River Site now plans to send this material to the high-level waste tanks and process it (i.e., transform it into a glass waste form) with other high-level wastes for eventual disposal in a federal high-level waste repository. DOE also indicated that other potential sources of RH-TRU waste at the Idaho National Engineering and Environmental Laboratory are currently being reviewed (DOE-CBFO, 2002b; Supplement 1; page 2). Other potential changes in the RH-TRU waste inventory are noted in Table 2.1. The uncertainties in the estimated volumes can also be significant for the sites that have yet to generate their RH-TRU waste, such as Hanford.

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[8]Packaging of Idaho National Engineering and Environmental Laboratory RH-TRU waste will actually increase its total volume, as indicated in Table 2.1.

SIDEBAR 2.1 Acceptable Knowledge

The Environmental Protection Agency's (EPA's) interpretation of acceptable knowledge (AK) is associated with historical information about the waste. The following is an excerpt of the guidance manual for waste analysis at facilities that generate, treat, store, and dispose of hazardous wastes (EPA, 1994):

> "Wherever feasible, the preferred method to meet the waste analysis requirements is to conduct sampling and laboratory analysis because it is more accurate and defensible than other options. [...] However, generators and TSDFs [treatment, storage, or disposal facilities] also can meet waste analysis requirements by applying AK. Acceptable knowledge can be used to meet all or part of the waste analysis requirements.

Acceptable knowledge can be broadly defined to include:

- 'Process knowledge,' whereby detailed information on the wastes is obtained from existing published or documented waste analysis data or studies conducted on hazardous wastes generated by processes similar to that which generated the waste. […] Therefore, with many listed wastes the application of AK is appropriate because the physical/chemical makeup of the waste is generally well known and consistent from facility to facility.
- Waste analysis data obtained from facilities which send wastes off site for treatment, storage, or disposal (e.g., generators).
- The facility's records of analysis performed before the effective date of RCRA regulations. While seemingly attractive because of the potential savings associated with using existing information (such as published data), the facility must ensure that this information is current and accurate (pages I-11 to I-12). […]

Generators and treatment, storage, or disposal facilities may use AK alone or in conjunction with sampling and laboratory analysis. […] However, there are situations where it may be appropriate to apply AK, including:

- Hazardous constituents in wastes from specific processes are well documented […].
- Wastes are discarded unused commercial chemical products, reagents or chemicals of known physical, and chemical constituents. […]
- Health and safety risks to personnel would not justify sampling and analysis (e.g., radioactive mixed waste).
- Physical nature of the waste does not lend itself to taking a laboratory sample" (Pages I-13 to I-14).

For remote-handled waste characterization, the Department of Energy adopts a broader definition of AK, based on historical and new information, as explained in Chapter 4.

2.3.2 Remote-Handled Transuranic Waste Radioactivity Inventory

Table 2.2 (see above) shows that the activity of RH-TRU waste currently in storage is approximately 660,000 curies. DOE calculated the total activity of the RH-TRU (stored plus projected) waste inventory to be approximately 1 million curies (DOE-CAO, 1996a; Appendix BIR). According to this estimate, the amount of RH-TRU curies to be emplaced in WIPP is about 20 percent of the total amount of curies from RH-TRU waste allowed by the Land Withdrawal Act (5.1 million curies). For comparison, the total activity to be emplaced in WIPP from CH- and RH-TRU waste is estimated to be 7.4 million curies, of which 6.4 million come from CH-TRU waste (DOE-CAO, 1996c; Appendix BIR).

Table 2.3 shows a comparison between the principal TRU and non-TRU radionuclides in CH and RH-TRU waste to be emplaced in WIPP. In 1995, the total activity of RH-TRU waste represented approximately 14 percent of the total activity of the TRU inventory (from CH-TRU and RH-TRU waste). However, the activity due to TRU radionuclides in RH-TRU waste corresponds only to 0.5 percent of the total TRU activity expected in WIPP. Table 2.3 also shows a comparison of the isotopic characteristics of CH- and RH-TRU waste expected inventories in WIPP. The total curie inventory in RH-TRU waste represents roughly 16 percent of the total curie inventory in CH-TRU waste but the number of TRU curies in the latter is two orders of magnitude higher than in RH-TRU waste. Only TRU radionuclides (i.e., radionuclides with a half-life greater than 20 years) have an impact on the long-term[9] performance of WIPP since non-TRU radio-

TABLE 2.3 Principal TRU and Non-TRU Radionuclides in WIPP Disposal Inventory

Radionuclide (half-life)	CH-TRU Waste (total curies)	RH-TRU Waste (total curies)	Ratio RH/CH
Plutonium-238 (87.7 years)	2,610,000	1,000	0.0004
Plutonium-239 (24,100 years)	785,000	10,000	0.013
Plutonium-240 (6,560 years)	210,000	5,000	0.024
Plutonium-241 (14.4 years)	2,310,000	142,000	0.061
Americium-241 (433 years)	442,000	6,000	0.014
Cesium-137 (30.2 years)	8,000	216,000	27
Barium-137m (2.6 minutes)	8,000	204,000	25.5
Cobalt-60 (5.3 years)	0	10,000	N/A
Strontium-90 (29.1 years)	7,000	209,000	30
Yttrium-90 (64 hours)	7,000	209,000	30
Total TRU curies (> 20 years)	4,048,000	22,000	0.005
Total curies (TRU and non-TRU)	6,390,000	1,012,200	0.158

NOTE: Activities for RH- and CH-TRU waste were estimated in 1995, the year of inventory compilation. Activities decrease very rapidly for RH-TRU waste because of the short half-lives of its radionuclides. Total curies calculated assuming a volume of 7,080 cubic meters for RH-TRU waste and 168,500 cubic meters of CH-TRU waste. TRU radionuclides, by definition, have a half-life greater than 20 years.
SOURCE: Appendix BIR, Table 3-1 in TWBIR Rev 3. Supplemental Disposal Inventory Information, June (DOE, 1996c).

[9]Long-term refers to the 10,000 years of regulatory compliance with radionuclide release limits established by the EPA in Title 40 Code of Federal Regulations Part 191 (see Chapter 3).

nuclides will decay away in approximately 300 years.[10]

Therefore, RH-TRU waste has a negligible impact on the long-term performance of WIPP compared to CH-TRU waste because of the small volume to be emplaced in WIPP. However, RH-TRU waste presents a significant short-term potential for radiation exposure to workers during the waste characterization, handling, and emplacement period because of the short-lived gamma-emitting radionuclides.

2.4 Packaging Status of Remote-Handled Transuranic Waste

A different way of sorting the RH-TRU waste inventory (other than the four categories in Table 2.1) is to consider its packaging status. As previously mentioned, before TRU waste is shipped to WIPP, it must be packaged in a suitable form for transport and underground emplacement.

In the March 2002 draft of DOE's characterization plan, the RH-TRU waste inventory is divided into four categories:

- "Packaged - Waste is packaged in a final form suitable for transport to and disposal at WIPP (i.e., the waste is either canisterized [Los Alamos National Laboratory RH-TRU waste] or in a package that may be transported for canisterization at another facility without repackaging).
- To Be Generated - Future waste generation, includes projected generation due to new activities and planned environmental restoration activities (i.e., retrieval from burial grounds, such as the 618 area at Hanford).
- To Be Repackaged - Waste is currently packaged in some form, but is not suitable for transport and disposal as packaged, possibly due to package size, package condition, or knowledge of contents. It will be repackaged into containers suitable for transport and disposal at WIPP. If a decision has already been made to package the waste for disposal at WIPP [i.e., the Oak Ridge National Laboratory RH-TRU waste debris], then this waste volume has been included in the To Be Packaged estimates.
- To Be Packaged - Waste is either not yet packaged (i.e., tank sludges) or the decision has been made to package the current form differently [i.e., RH-TRU waste debris waste at Oak Ridge National Laboratory]" (DOE-CBFO, 2002b; Supplement 1; page 2).

The current RH-TRU inventory of stored and projected waste is distributed among these four categories as shown in Figure 2.2. For comparison with Table 2.1, "Projected Waste" corresponds to the "To Be Generated" column. All other packaging situations correspond to the "Stored" column. The four packaging categories add up to the total number of cubic meters in Table 2.1. In its characterization plan, DOE also indicated that the inclusion of the Idaho Nuclear Technology and Engineering Center waste will further increase the "To Be Packaged" component by increasing the amount of waste in this category by approximately 900 cubic meters.

The committee's interim report discussed the RH-TRU waste inventory using DOE's initial distinction between "Retrievably Stored Waste" and "Newly Generated Waste"

[10]Short-lived radionuclides in RH-TRU waste are included in the calculation of the regulatory release limits. The scenario that would mostly affect release limits from RH-TRU waste is a drilling intrusion in WIPP occurring less than 300 years after closure. This scenario is taken into account in the performance assessment calculation (see Chapter 3, Section 3.2.1).

(NRC, 2001b). Retrievably stored waste is any waste produced after 1970[11] but prior to implementation of an approved RH-TRU waste characterization plan (as of July 2002, no plan has been approved by EPA and NMED). Newly generated waste is waste produced after the development, approval, and implementation of a waste characterization plan and meets the requirements set forth by the regulatory agencies. In this report the committee adopts DOE's new classification system, as shown in Figure 2.2.

Earlier inventory information recorded that 80 percent of the waste was to be repackaged or generated, as cited in the committee's interim report (NRC, 2001b). Updated information in the March 2002 draft indicated that 98 percent of the waste has to be generated or packaged (see Figure 2.2). However, in several other instances, Documents 1 and 2 mention that the fraction of waste to be generated, packaged, or repackaged corresponds to 95 percent of the RH-TRU waste inventory. In this report, the committee uses a conservative estimate of 95 (rather than 98) percent of waste to be packaged. The committee also uses the word "packaged" for waste that has to be packaged for the first time or repackaged.

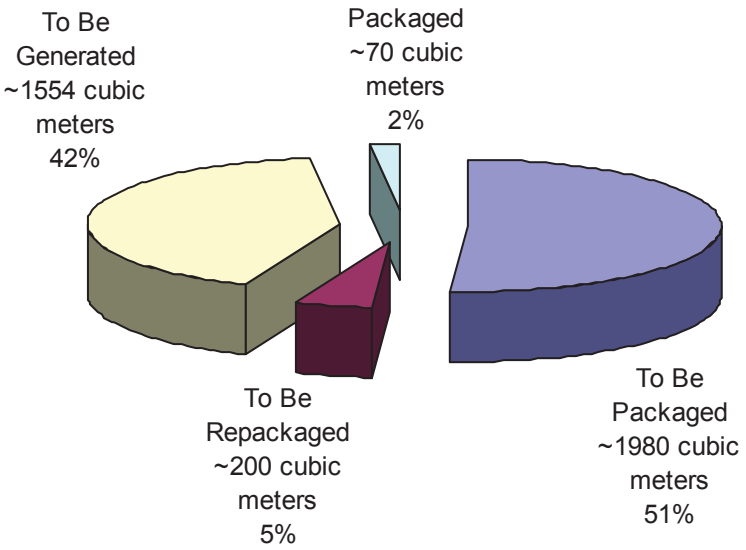

FIGURE 2.2 Packaging status of the RH-TRU inventory. SOURCE: DOE (DOE-CBFO, 2002a).

[11]In 1970, the defense operation division of the U.S. Atomic Energy Commission (predecessor to DOE) first identified TRU waste as a separate category of radioactive waste. That same year the Atomic Energy Commission determined that all TRU waste generated after 1970 must be segregated from low-level waste and placed in retrievable storage pending shipment to, and disposal in, an approved geological repository. Transuranic waste produced in support of the nuclear weapons program from the 1940s through 1970 was disposed of by shallow land burial and other techniques at a number of sites owned and operated by the federal government. This type of waste is referred to as "buried transuranic waste," and most of this waste is considered irretrievable. The characterization plan reviewed by the committee does not address buried TRU waste.

The RH-TRU packaged waste consists of waste from three sites: Hanford, Los Alamos National Laboratory, and Battelle Columbus Laboratories. Waste at Hanford and Battelle is stored in 55-gallon drums. At Los Alamos, waste is stored in 17 canisters, of which 16 were generated during program activities and 1 from hot cell cleanup after the work was completed. Though these canisters are packaged, they are not ready for shipment to WIPP because they have not been characterized in accordance with the current characterization requirements in the EPA Certification and RCRA Permit.[12] Nevertheless, thorough records of process knowledge, visual examination, and prohibited items determination (see Chapter 3, Section 3.3) were kept during the packaging of the 17 canisters stored at Los Alamos.

[12]For instance, when waste was packaged, the records do not demonstrate that the operator was qualified to interpret the videotape, and the headspace gases have not been collected.

3

Regulatory Context for the Disposal of Remote-Handled Transuranic Waste

The Land Withdrawal Act, Public Law 102-579, is the guiding legislation for WIPP (U.S. Congress, 1992). In this Act, Congress established the scope and legal criteria for the facility. The Land Withdrawal Act also assigned EPA regulatory authority over public exposure to radiation from the management and storage of TRU waste at WIPP during the operational period (nominally lasting until 2033) and over radioactivity releases into the environment up to 10,000 years after repository closure. The hazardous non-radioactive component of TRU waste is regulated by the NMED under RCRA (EPA, 1990). The NMED standards for a hazardous waste disposal facility (such as WIPP) seek to minimize releases[1] of non-radiological hazardous constituents during the operational phase and for a nominal 30-year period following repository closure.

The two main regulatory documents for WIPP are the EPA Certification and the RCRA Permit. To continue disposal operations, WIPP must show continued compliance with the EPA Certification and the RCRA Permit. One of the conditions contained in the EPA certification is that EPA and NMED must approve site-specific characterization measures and quality assurance programs before generator sites ship waste to WIPP. Therefore, the EPA Certification and RCRA Permit establish waste characterization requirements for all TRU waste (CH or RH) to be emplaced in WIPP.

The requirements for TRU waste characterization used by EPA and NMED originate from the following standards for owners and operators of hazardous waste treatment, storage, and disposal facilities (40 CFR 264.13):

> "(a)(1) Before an owner treats, stores, or disposes of any hazardous wastes, or nonhazardous wastes if applicable under §264.113(d), he must obtain a detailed chemical and physical analysis of a representative sample of the wastes. At a minimum, the analysis must contain all the information which must be known to treat, store, or dispose of the waste in accordance with this Part and Part 268 of this chapter" (40 CFR 264.13).

EPA indicates in the same document that characterization information can be obtained either by direct measurement or indirectly through AK (see Sidebar 2.1).

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[1]With an exemption from Land Disposal Restriction regulations (40 CFR 268), Congress determined that WIPP waste does not need treatment prior to disposal. As a result, the NMED imposed groundwater and air monitoring requirements to ensure that any detectable releases remain below specific limits that have been established to protect human health and the environment.

The regulatory requirements for the characterization of TRU waste in WIPP originate from the Land Withdrawal Act, the EPA Certification, and the RCRA Permit. These requirements are described below.

3.1 Land Withdrawal Act Requirements for Transuranic Waste in WIPP

The Land Withdrawal Act establishes the five main legal requirements for TRU waste in WIPP, some of which apply specifically to RH-TRU waste. These requirements are the following:

- Nature of waste to be disposed of in WIPP: the WIPP can only receive transuranic waste generated by atomic energy defense activities.
- Total volume of transuranic waste: the WIPP is allowed to contain up to 175,564 cubic meters of transuranic waste.
- Volume of RH-TRU waste: the WIPP is allowed to contain up to 7,080 cubic meters of RH-TRU waste, which represents about 4 percent of the total volume of TRU waste allowed.
- Total activity of RH-TRU waste: RH-TRU waste received at WIPP shall not exceed 23 curies per liter maximum activity level (averaged over the volume of the container). The total curies of RH-TRU waste received at WIPP shall not exceed 5.1 million curies.[2]
- Surface dose rate: no TRU waste received at WIPP may have a surface dose rate exceeding 1,000 rems per hour. No more than 5 percent by volume of RH-TRU waste received at WIPP (354 cubic meters) may have surface dose rates exceeding 100 rems per hour.

Tolerable uncertainties are not specified in the Land Withdrawal Act for the above limits. Laws seldom specify accuracy or precision of limits; it is generally the duty of the implementer to propose tolerable decision errors, such as accuracy or uncertainty, derived from a tradeoff among relevant parameters, such as risk or costs.

3.2 Characterization Requirements in the EPA Certification

In 1998, EPA promulgated the criteria for the certification and recertification of the Waste Isolation Pilot Plant's compliance with the 40 CFR 191, subparts B and C (40 CFR 194). The EPA declared WIPP to be in compliance with its disposal regulations and granted the facility a certification of compliance. The purpose of the EPA characterization requirements is to ensure that WIPP remains in compliance with the EPA disposal regulations and limits set forth in the Land Withdrawal Act. Compliance is ensured if the waste inventory in WIPP stays within the waste envelope limits specified in WIPP's performance assessment. The performance assessment is a tool used to evaluate the safety performance of any nuclear waste facility, as explained below.

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[2]Note that the total activity limits for RH-TRU waste do not distinguish between the activity due to the TRU nuclides and that due to other radionuclides.

3.2.1 WIPP's Performance Assessment

The performance assessment evaluates the ability of a repository to satisfy the release limits (listed in 40 CFR 191, Appendix A) on the release of radionuclides from a repository over a period of 10,000 years. The performance assessment organizes information relevant to long-term repository behavior by assessing the probabilities and consequences of major scenarios by which radionuclides can be released into the environment. Important scenarios include those due to human activities, whether deliberate or unintentional, that might compromise the integrity of the repository. The performance assessment process consists of:

1. compiling features, events, and processes that could affect the disposal system;
2. classifying events and processes to enhance consistency and completeness;
3. screening individual events and processes for likelihood of occurrence and consequences;
4. combining events and processes into specific scenarios;
5. screening scenarios to identify and eliminate those that have little or no effect on the performance assessment;
6. modeling the scenarios;
7. calculating the releases; and
8. comparing the calculated values with the allowable releases.

From the quantitative results of its performance assessment, DOE identified the ten radionuclides most important to the long-term performance of WIPP: americium-241, cesium-137, plutonium-238, plutonium-239, plutonium-240, plutonium-242, strontium-90, uranium-233, uranium-234, and uranium-238. Of these ten, strontium-90, uranium-233, and cesium-137 are important to RH- but not CH-TRU waste streams (due to the gamma and beta emissions).

A sensitivity analysis of the performance assessment also identified the non-radiological waste parameters most important to the performance of the repository (Helton et al., 1998). These parameters are the following:

- Amount of free water: The EPA Certification requirements include a limit on the total amount of water or brine present in the waste. This parameter is important because water is the only means to release radionuclides in the environment and because it controls several other factors, such as corrosion and gas generation.[3] The total limit for free water in WIPP is 1 percent by volume in the entire TRU waste inventory (175,564 cubic meters), which corresponds to 1,756 cubic meters. This limit derives from a transportation requirement forbidding shipment of hazardous waste containing more than 1 percent of free liquids by volume.[4] DOE used this requirement as one of the initial assumptions in the performance assessment calculation, which was part of the compliance certification application. This free water

[3]The main gases potentially generated in WIPP in the presence of brine are carbon dioxide, methane, and hydrogen. These gases are generated by microbial waste degradation inside WIPP. In addition, hydrogen can also be produced by radiolysis or by corrosion of metal containers. An increase in gas pressure inside the repository could affect room closure rates, fracture development, brine inflow, and the possibility of waste entrainment in gas during a drilling event (called spalling).

[4]The committee does not review transportation requirements in this report.

requirement is now integrated as part of the EPA Certification to ensure compliance with release limits.

- Amount of ferrous metals: The EPA Certification requirements include a minimum amount of ferrous metals (20 million kilograms) to ensure a reducing environment inside the WIPP repository. A reducing environment maintains radionuclides in a low oxidation state, which usually corresponds to a minimum solubility. Therefore, waste characterization must ensure that the amount of corrodible metals in the waste is above the minimum.
- Amount of non-ferrous metals: The EPA Certification requirements include a minimum amount (2,000 kilograms) of non-ferrous metals in WIPP. Non-ferrous metals form complexes with organic ligands present in waste (such as EDTA or citric acid[5]). This prevents actinides from binding with these organic ligands and becoming mobile. Therefore, waste characterization must ensure that the amount of non-ferrous metals in the waste is above the minimum.
- Amount of biodegradable cellulosics, plastic, and rubber: The EPA Certification requirements include a maximum amount (20 million kilograms) of cellulosics, plastic, and rubber in the waste to take into account the potential for gas generation from the decomposition of these organic materials. Therefore, waste characterization must ensure that the amount of cellulosics, plastic, and rubber in the waste is below the maximum.

Tolerable uncertainties have not been specified in the compliance certification application for the above limits. In its final certification decision, EPA writes:

> "[T]he EPA confirmed the results of the performance assessment using the same upper and lower limiting values in the performance assessment verification test ("PAVT"). Those upper and lower limiting values apply to contact-handled, remote-handled, and to-be-generated waste from numerous generator sites. Thus, in today's action, EPA certifies that the WIPP will comply with the 40 CFR Part 191 containment requirements to the extent that emplaced waste falls within the waste envelope limits that were shown by the performance assessment, and confirmed by the PAVT, to be compliant with the 40 CFR Part 191 standards" (40 CFR 194).

In summary, the waste characterization requirements appearing in the EPA Certification are aimed to determine:

1. activity and radiological inventory of the waste;
2. surface dose rate;
3. amount of metals (ferrous and non-ferrous);
4. absence of free water; and
5. amount of cellulosics, plastic, and rubber.

Chapter 4 describes the approach DOE proposes to determine these 5 characterization parameters in RH-TRU waste.

[5]EDTA (ethylenediaminetetraacetic acid) and citric acid are common cleaning agents.

3.3 Characterization Requirements in the RCRA Permit

The purpose of the NMED characterization requirements is to ensure that the non-radiological hazardous characteristics of the waste emplaced in WIPP are compatible with the RCRA requirements as codified in Part 20 of the New Mexico Administrative Code. The cornerstone of any RCRA permit is the waste analysis plan, which allows generators and disposal facilities to identify, treat, store, and properly dispose of all hazardous wastes. Waste analysis involves identifying or verifying the chemical and physical characteristics of a waste by performing a detailed chemical and physical analysis of a representative sample of the waste or, in certain cases, by applying AK (EPA, 1994*).*

The characterization plan in the RCRA Permit is aimed at minimizing the possibility of a fire, explosion, or any unplanned sudden or non-sudden release of TRU mixed waste or mixed waste constituents to air, soil, groundwater, or surface water which could threaten human health or the environment (see NMED, 1999a; Module II General Facility Conditions; page II-1).

Currently, the waste characterization requirements in the RCRA Permit are aimed at determining the following information:

1. physical form of waste (homogeneous solids, soil or gravel, debris); and
2. exclusion from waste of the following prohibited items[6]:
   - Liquid waste.
   - Non-radionuclide pyrophorics (addressed by the hazardous waste codes[7]).
   - Hazardous wastes that do not contain TRU waste.
   - Incompatible chemicals (addressed by the hazardous waste codes).
   - Polychlorinated biphenyls greater than or equal to a concentration of 50 ppm.
   - Explosives (addressed by the hazardous waste codes) and compressed gases.
   - Ignitable, corrosive, and reactive wastes (addressed by the hazardous waste codes).
   - Remote-handled transuranic mixed waste.

Prohibited items listed in the RCRA Permit are items that are incompatible (e.g., ignitable, reactive) or inappropriate for the WIPP facility. If combined, incompatible wastes are capable of spontaneous combustion, toxic gas generation, or explosions (EPA, 1994). The selection of waste parameters must include measures to ensure that the waste is appropriate for WIPP's scope and that inappropriate waste is identified and excluded prior to shipment.

The current RCRA Permit excludes RH-TRU mixed waste because:

> "The Applicant [DOE] failed to submit an approvable waste analysis plan describing the procedures for obtaining a detailed chemical and physical analysis of RH [mixed] waste destined for disposal at WIPP. Moreover, there

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[6]Additional prohibited items for WIPP are waste containers that do not have volatile organic compound concentrations reported for the headspace, waste containers that have not undergone radiographic or visual examination, and waste containers that do not have a certified waste stream profile form (see the glossary).

[7]The definition of hazardous waste codes can be found in the glossary, Appendix I.

are substantial questions regarding the applicability of CH waste characterization techniques and the Applicants' capability to characterize RH [mixed] waste" (NMED, 1999b).

To remove the RH-TRU waste prohibition from the RCRA Permit, NMED recommends that DOE build its proposed RH-TRU waste characterization plan upon the requirements in the existing permit and provide justification for any difference between the RH-TRU and the existing CH-TRU characterization plan (Zappe, 2001).

3.4 History of Characterization Requirements at WIPP

When DOE first applied for the EPA certification of WIPP, it proposed the same characterization plan for RH-TRU and CH-TRU waste (DOE-CAO, 1996a). DOE, EPA, and NMED negotiated the characterization requirements for TRU waste during nearly two decades prior to the certification of WIPP. Records of the negotiation process show that DOE proposed to the regulators some waste characterization requirements that lacked a technical, safety, or legal basis (see Sidebar 3.1). These requirements eventually became part of the EPA Certification and RCRA Permit and are now addressed in the CH-TRU waste characterization plan.

Eventually, EPA and NMED declared that DOE did not provide an adequate waste characterization method for RH-TRU waste and prohibited this waste from being shipped to WIPP. Both agencies also stated that DOE did not adequately describe its full RH-TRU waste inventory. DOE is now submitting a new characterization plan for RH-TRU waste to address EPA and NMED characterization requirements. While the regulatory requirements to be addressed are the same for CH- and RH-TRU waste, DOE proposes a different approach to characterize RH-TRU waste than that used for CH-TRU waste, as described in the following chapter.

SIDEBAR 3.1 Findings of the Previous National Research Council's Committee on the Waste Isolation Pilot Plant

A previous National Research Council committee on the Waste Isolation Pilot Plant (WIPP) found that some of the elements in the characterization plan for contact-handled transuranic (CH-TRU) waste are based on terms negotiated in the Resource Conservation and Recovery Act (RCRA) Permit rather than being performance-based characterization requirements (NRC, 2001a; Appendix A1). These requirements concern the sampling and analysis of homogeneous waste, headspace gas sampling and analysis, and visual examination procedures. For instance, the Department of Energy (DOE) proposed to conduct homogeneous waste and headspace gas sampling and analyses on the totality of CH-TRU waste containers to confirm acceptable knowledge (AK) information. Moreover, there appears to be no requirement in the law for the verification of radiography results by visual examination.

These requirements were proposed by DOE during the development of the characterization plan and "have no basis in law, the safe conduct of operations to emplace waste in WIPP, or long-term performance requirements" (NRC, 2001a; page 77). Therefore, the 1998 Committee recommended that DOE "eliminate self-imposed waste characterization requirements" from the CH-TRU waste

characterization plan (NRC, 2001a; page 78). DOE agreed with that committee on the fact that some waste characterization procedures are indeed not prescribed by safety or legal requirements and were introduced to facilitate the WIPP certification process (Kehrman, 2002; DOE-CAO, 1999a). A DOE review of the CH-TRU waste characterization procedures revealed that DOE developed self-imposed waste restrictions in the waste acceptance criteria and in the requirements for waste generating sites presented in the quality assurance program plan. The definitions of waste acceptance criteria (DOE-CAO, 1996b) and quality assurance program plan (DOE-CAO, 1998) can be found in the glossary, Appendix I.

4

Department of Energy's Proposed Characterization Plan

This chapter describes DOE's proposed characterization plan for RH-TRU waste. Because the plan must address EPA and NMED regulatory requirements, the characterization plan consists of two documents: a notification of proposed change to the EPA Certification (Document 1) and a Request for RCRA permit modification (Document 2). On June 28, 2002 DOE submitted Documents 1 and 2 to the respective agencies. This chapter addresses the March 2002 draft characterization plan and the main differences with the July 2001 draft.

It is the committee's understanding that DOE will submit to EPA and NMED, along with Documents 1 and 2, a sample of completed characterization documents for three RH-TRU generator sites (Energy Technology Engineering Center, Battelle Columbus Laboratories, and Oak Ridge National Laboratory). Once Documents 1 and 2 are submitted to the regulatory agencies, and characterization requirements for RH-TRU waste are finalized, DOE will produce one document combining all regulatory requirements to guide generator sites in the development of their characterization programs. Each site-specific RH-TRU waste characterization plan will undergo audits by DOE, EPA, and NMED before the beginning of shipments to WIPP. The new characterization requirements will be combined in a revised version of the waste acceptance criteria incorporating changes to allow RH-TRU waste in WIPP.

4.1 DOE's Considerations in Composing the Characterization Plan

According to the information gathered, several factors played a role in DOE's approach to the characterization of RH-TRU waste, such as: DOE's mission to safely dispose of radioactive waste; WIPP's regulations; federal and state laws and agreements; and DOE's internal drivers to improve the National Transuranic Waste Management Program. The list of considerations, expanded below, is not in hierarchical order and may not be complete.

One of DOE's missions is to safely dispose of radioactive waste, including RH-TRU waste, generated during defense-related activities (DOE-EM, 2002a). To this end, DOE is seeking authorization to dispose of RH-TRU waste stored at 13 sites across the country in WIPP. The proposed characterization plan must meet the requirements in the EPA Certification and RCRA Permit (the latter issued by NMED). Besides strict regulatory requirements, DOE is also taking into account non-technical considerations to maintain an effective working relationship with the regulatory agencies, in particular NMED.

DOE and its RH-TRU waste generator sites must also meet sites' cleanup milestones, set forth by DOE's compliance agreements with EPA and generator states' regulators, such as Federal Facility Compliance Agreements and Tri-Party Agreements.

DOE is also required to comply with Title 10 of the Code of Federal Regulations Part 835, which instructs DOE to apply the ALARA principle to protect workers' health and safety in every DOE facility (10 CFR 835). ALARA (as low as is reasonably achievable), as defined by the Nuclear Regulatory Commission, requires that a reasonable effort be made to keep workers radiation exposures as far below the regulatory dose limit[1] as is practical. Moreover, DOE must ensure that all waste is managed in a manner that is protective of worker and public health and safety, and the environment, as specified in DOE's Order 435.1.

Timeliness and cost of cleanup are two internal DOE drivers. A "Top-to-Bottom" review report on DOE's Office of Environmental Management, which manages the cleanup of all defense-related radioactive waste, recommended adopting an accelerated risk-based cleanup strategy across the DOE complex. The following is an excerpt from this report:

> "National security will be improved through the consolidation of all special nuclear materials in modern safeguarded facilities and through accelerated disposal of transuranic (TRU) waste currently stored at sites around the country (page IV-1) […] [A] limited amount of TRU waste is highly radioactive and must be handled remotely. Efforts to dispose of these materials in WIPP will be accelerated (page IV-2). […] [T]here are thousands of TRU waste drums stored in above-ground EM facilities that require high-priority funding for safety and security. While most of these storage facilities are inexpensive to maintain, there are dozens of them across the complex, so the cumulative annual fixed cost is significant. Certification and disposal of TRU waste are major cost drivers for the EM program. Efforts to expedite shipments to the Waste Isolation Pilot Plant (WIPP) and streamline regulatory procedures would result in obvious cost savings" (page V-13) (DOE-EM, 2002b).

In its WIPP Disposal Phase Final Environmental Impact Statement, DOE estimated the life-cycle cost of the treatment facilities for RH-TRU waste to be $2.94 billion. This corresponds to 15 percent of the total cost of the $19 billion WIPP Project (DOE-CAO, 1997; Volume 5; pages 5-10). DOE also stated in the same reference that the life-cycle cost of the treatment facilities for all the CH- and RH-TRU waste was $11.8 Billion, or 62 percent of the total cost of the WIPP Project. Although these estimates may be outdated, they still demonstrate the magnitude of the characterization costs for TRU waste, in particular for RH-TRU waste.

4.2 DOE's Goal: A Performance-Based Characterization Plan

Given the above considerations, DOE's stated goal is to adopt a "performance-based" approach to characterize RH-TRU waste. Although Documents 1 and 2 do not provide a definition of a "performance-based characterization plan," the committee found the following definition in EPA's Compliance Application Review Document No. 24:

> "DOE must provide waste inventory information for use in the performance assessment, including the radionuclide content of waste and the physical and

[1]The Nuclear Regulatory Commission's limits for radiation doses to workers are established in Title 10 CFR Part 20 (10 CFR 20.1003).

chemical components that may affect disposal system performance" (EPA, 1998; pages 21-1).

EPA defines a "waste characteristic" as "a property of the waste that has an impact on the containment of waste in the disposal system" (40 CFR 194.2). The committee interprets "performance-based characterization plan" as a plan requiring only that information needed to ensure repository integrity, protection of the environment, and health and safety of the public and workers while keeping in consideration tradeoffs between greater characterization accuracy and worker risks.

While the characterization requirements to be addressed are the same, this proposed performance-based approach is quite different from the approach used for CH-TRU waste characterization, as explained later in this chapter. The rationale for this different approach relies on the differences in volume and isotopic inventory of RH-TRU waste compared to CH-TRU waste (see Chapter 2).

To evaluate the impact of RH-TRU waste on the performance of WIPP, the Sandia National Laboratories performed two performance assessment calculations. In these calculations, the effects of the inventories of CH- and RH-TRU waste are decoupled and several bounding scenarios for RH-TRU waste parameters are used. Documents 1 and 2 include two impact assessments: one for the impact of the radiological parameters of RH-TRU waste and one for the non-radiological parameters listed in the EPA Certification.

The Sandia impact analyses showed that radioisotope, free liquids, cellulosics, plastics, rubber, and ferrous metal content in the RH-TRU waste inventory have a negligible impact on repository performance. This is due to the smaller volume and the different radiological composition of the RH-TRU waste inventory compared to the CH-TRU waste inventory projected in WIPP. These performance assessment calculations use the same mathematical models and input parameters used in the compliance certification application (see Chapter 3, Section 3.2.1).

The result of the calculations shows that the characterization of waste material parameter weights (e.g., ferrous metals, cellulosics, plastic, and rubber) and the amount of free liquid for RH-TRU waste can be assumed to be as high as the bounding values and still result in WIPP compliance. The bounding values for RH-TRU waste parameters are the same as those used for EPA Certification. The Sandia impact analyses also show that if all the total (both TRU and non-TRU) activity in RH-TRU waste were due to plutonium-239, there would be only a negligible performance impact on WIPP. Therefore, from a performance point of view, waste characterization activities to quantify the above waste parameters could be unnecessary.

Even though the impact of RH-TRU waste parameters on the performance of WIPP is negligible, DOE is proposing to collect all the waste information requested in the EPA Certification and RCRA Permit using AK as the primary method of compliance. When AK is not complete or not available, additional compliance methods can be applied to a representative portion of the waste. In contrast to the approach used for CH-TRU waste, this plan does not recommend making measurements for the sole purpose of confirming AK or other measurements unless such confirmation is needed to qualify the AK characterization information (DOE-CBFO, 2002a; page 22).

4.2.1. Acceptable Knowledge

The heart of DOE's proposed performance-based characterization plan is the use of AK to collect the necessary information about a waste stream. DOE plans to use two types of AK: one based on historical information of existing waste, which the committee

terms "historical AK" and which is the most widespread interpretation of AK (see Sidebar 2.1), and one based on new information collected during waste generation or packaging.

Historical AK may include administrative, procurement, and quality control documentation associated with the generating process, or past sampling and analytical data. Elements of process knowledge may include information about the process used to generate the waste, material inputs to the process, and the time period during which the waste was generated. Acceptable knowledge is applied on a waste stream basis and may be supplemented with sampling and measurement programs or container-by-container measurements.

DOE also considers AK newly generated characterization information, as described in Document 1:

> "[F]or the RH-TRU waste characterization program, 95 [percent] of the waste will be packaged or repackaged during its preparation for shipment to the WIPP. Information collected under these packaging and repackaging programs is also considered to be AK information. This allows the same AK procedure and guidance to be used in assembling historic AK information or compiling new AK information" (DOE-CBFO, 2002a; Attachment B; page 23).

As shown above, DOE's rationale for proposing AK as the major compliance tool is based on the analysis of the RH-TRU waste inventory. According to the information gathered, 95 percent of RH-TRU waste will either be generated or packaged. This waste will be visually examined during repackaging operations and undergo physical and chemical characterization (for instance, through radiography or radiochemistry) during waste generation and packaging.

Based upon EPA's requirements set forth in 40 CFR 194.22(b), existing information collected before an approved quality assurance program is in place must be qualified for use as AK. Title 40 CFR 194.22(b) lists four methods that may be used individually or in combination to qualify such data: 1) peer review, 2) use of corroborative evidence, 3) confirmation by measurements, or 4) qualification of previous quality assurance programs. DOE is proposing to limit confirmatory measurements only to those cases where historical records are incomplete. DOE proposes not to confirm the newly generated information for 95 percent of the waste since this information will be collected under a certified quality assurance characterization program. The specific needs for waste analysis are described in DOE's proposed characterization plan as data quality objectives and quality assurance objectives.

4.3 Data Quality Objectives and Quality Assurance Objectives

Data quality objectives are proposed by the implementer, in this case DOE, to define what information is necessary to characterize waste. They are qualitative and quantitative statements that clarify program's objectives, define appropriate types of data, and specify tolerable decision error rates that will be used as the basis for establishing the quality and quantity of data needed to support decisions.

The EPA document SW-846 "Test Methods for Evaluating Solid Waste Physical/Chemical Methods" defines data quality objectives as:

> "Data quality objectives … for the data collection activity describe the overall level of uncertainty that a decision-maker is willing to accept in results derived from environmental data" (EPA, 2002; pages 1-2).

Quality assurance objectives establish minimum requirements for the measurement and representation of data. Quality assurance objectives are designed to provide information that will satisfy the data quality objectives. They correspond to EPA's "measurement quality objectives." The elements of the quality assurance objectives are:

- Data accuracy: the degree to which data agree with an accepted reference or true value.
- Data precision: a measure of the mutual agreement between comparable data gathered or developed under similar conditions expressed in terms of a standard deviation.
- Data representativeness: the degree to which data accurately and precisely represent a characteristic of a population, a parameter, variations at a sampling point, or environmental conditions.
- Data completeness: a measure of the amount of valid data obtained compared to the amount that was expected.
- Data comparability: a measure of the confidence with which one data set can be compared to another [40 CFR 194.22(c)].

Documents 1 and 2 describe the data quality objectives and quality assurance objectives to meet the requirements in WIPP's EPA Certification and RCRA Permit, respectively.

4.4 DOE's Proposed Characterization Plan to Address EPA Requirements

The characterization requirements in the EPA Certification, addressing also the requirements in the Land Withdrawal Act, are described in Chapter 3. The data quality objectives, characterization, and implementation methods to address these requirements are provided in Document 1 and summarized in Table 4.1. The characterization methods to meet EPA requirements are the following:

- Acceptable Knowledge: the type of information used to define waste streams is described in Sidebar 2.1. For the RH-TRU waste characterization program, 95 percent of the waste will be packaged or repackaged during its preparation for shipment to the WIPP. Information collected under these packaging and repackaging programs is considered to be AK information along with historical data.
- Dose-to-Curie Conversion: the curie content of waste is based on a dose rate measurement taken with a calibrated field instrument. The dose rate measurement is associated with documented isotopic distributions in the waste through the use of empirically developed conversion factors. Dose-to-curie estimates may also be based on the measurement of an indicator activity (e.g., cesium-137) and correlation of other radionuclides by isotopic conversion factors. This method requires good knowledge of the isotopic distribution in the waste.
- Visual Examination: this method involves the removal of items from the container and their inspection and identification. The examination will be recorded on a signed data form accompanied by visual evidence such as an audio or video tape. Visual examination only provides a visual image of the content of waste containers. It does not provide any information on the isotopic composition of waste.
- Radiography: this method involves the use of penetrating radiation to investigate the contents of containers. The examination will be recorded on a signed data form

accompanied by visual evidence such as an audio or video tape or other media. Radiography only provides an image of the content of waste containers. It does not provide any information on the isotopic composition of waste.

- Characterization at the Time of Packaging: this method involves visual examination and other characterization methods applied as waste is packaged for shipment to WIPP. DOE distinguishes this method from visual examination for the following reasons:

  1. it applies to 100 percent of the waste in the waste stream;
  2. it generally focuses on the development or collection of AK information as opposed to the confirmation of such information;
  3. it applies to waste that is not in its final shipping container; and
  4. it may require the use of other characterization methods (i.e., AK, visual examination, or radiography) to determine the contents of smaller containers that cannot be readily characterized without testing.[2]

- Direct Assay: this method involves using radioassay systems that are qualified for CH-TRU waste characterization.
- Counting containers: this method involves automatically counting containers to maintain the record of the amount of metals introduced in the repository.

4.5 DOE's Proposed Characterization Plan to Address NMED Requirements

The characterization requirements in the current RCRA Permit are described in Chapter 3. The proposed data quality objectives and characterization methods to address these characterization requirements are presented in Document 2 and summarized in Table 4.2.

Characterization methods and the relative quality assurance objectives of precision, accuracy, representativeness, completeness, and comparability are discussed in Attachment R of Document 2. The same characterization methods have been discussed for Document 1 (see above). Radiography, along with other non-destructive examination and non-destructive assay methods, is also briefly described in Appendix G.

[2]The committee observes that "characterization at the time of packaging" may cause a semantic confusion with AK, which is usually associated with historical information. Characterization at the time of packaging generates new information through visual examination, radiography, or other characterization methods; it may also include historical data on a particular waste stream.

TABLE 4.1 DOE's Data Quality Objectives, Characterization and Implementation Methods to Address EPA Requirements

No.	Data Quality Objectives	Characterization Method	Implementation Methods
1	Account for TRU activity. Rationale: This requirement is related to the LWA's definition of TRU waste and to 40 CFR 191. The purpose for this data quality objective is twofold: 1) ensure that waste is TRU (TRU activity equal to or greater than 100 nanocuries per gram of waste); and 2) determine the plutonium-239 content to satisfy the release limits set forth in 40 CFR 191.	1. AK method 2. Dose to curie 3. Direct assay 4. Characterization at the time of packaging[1]	Use AK to determine the relationship of TRU activity to total activity (see no. 6 below) for each waste stream (confirmation unnecessary). AK must include TRU information (sufficient to demonstrate the waste stream concentration exceeds 100 nanocuries per gram), or the waste stream value must be established by sampling and measurement, or the TRU activity must be measured for each container.
2	Ensure that waste is of defense origin. Rationale: The LWA allows only disposal of defense-related transuranic waste in WIPP.	1. AK method	Use AK to determine whether waste was generated in a defense-related activity.
3	Ensure waste is RH (surface dose equal to or greater than 200 mrem per hour). Rationale: operational requirement to determine handling and characterization requirements.	1. Standard industry survey methods 2. Characterization at the time of packaging	Use standard industry survey methods to measure and report surface dose rate. Survey instrument calibrations must be traceable by the National Institute of Standards and Technology.
4	Account for total activity. Rationale: this requirement comes from the LWA limit of 5.1 million curie of total activity for RH-TRU waste.	1. AK method 2. Dose to curie 3. Direct assay 4. Characterization at the time of packaging	Use AK to determine total activity of the waste stream (confirmation unnecessary), or establish a waste stream value by sampling and measurement, or measure the total activity of each container.
5	Limit canister activity to less than 23 curies per liter. Rationale: this requirement comes from the LWA limit on canister activity.	1. AK method 2. Dose to curie 3. Direct assay 4. Characterization at the time of packaging	Use AK to evaluate each waste stream and show that this limit cannot feasibly be approached for that particular waste stream. For the rare exception where AK indicates that 23 curies per liter is hypothetically feasible, measurements of Total Activity should be obtained on few representative containers to establish a waste stream value, or a site may choose to measure the total activity of each container.

6	Limit surface dose rate of each container to less than 1,000 rem per hour. Rationale: This is a LWA requirement.	1. Standard industry survey methods 2. Characterization at the time of packaging	Survey instrument calibrations must be traceable by the National Institute of Standards and Technology.
7	Limit WIPP inventory to 5 percent by volume of canisters with a dose rate greater than 100 rem per hour. Rationale: This is a LWA requirement.	1. Standard industry survey methods 2. Characterization at the time of packaging	Use standard industry survey methods to measure and report Surface Dose Rate. Survey instrument calibrations should be traceable by the National Institute of Standards and Technology.
8	Account for ferrous and non-ferrous metals. Rationale: this is a requirement introduced in the EPA's Certification.	1.Count containers	WWIS [WIPP Waste Information System] electronically counts waste containers. Confirmation unnecessary.
9	Account for cellulosics, plastics, rubber. Rationale: this is a requirement introduced in the EPA Certification	1. AK method 2. Visual examination 3. Characterization at the time of packaging	Use AK to determine Summary Category Group (SCG) of each waste stream. Use generator/storage site SCG designation from site documents. WWIS electronically calculates and assigns for each emplaced container (0 for homogenous solids and soils/gravel, and 50 percent of container weight for debris). Confirmation unnecessary if AK information is complete.
10	Account for free water (up to 1 percent of free water by volume). Rationale: WIPP was certified on the basis of a performance calculation using 1 percent of water by volume in the waste. This limit originates from a transportation requirement.	1. AK method 2. NDE such as Radiography 3. Visual examination 4. Characterization at the time of packaging	If AK documents the use of liquid management procedures (e.g., removal or absorption), or a process that precludes liquids (e.g., material input records or thermal treatment), then assign 0 percent of liquid by volume for each waste stream. Otherwise assign 1 percent volume to the entire waste stream. Confirmation unnecessary. When AK is lacking, use a non- destructive examination, visual examination, or characterization at the time of packaging on a sampling basis to show that a waste stream contains less than one percent residual liquids.

NOTE: AK=acceptable knowledge; LWA=Land Withdrawal Act, NDE=non-destructive examination. Information in this table is presented in Document 1 and supplemented with additional information provided to the committee.

[1]Characterization at the time of packaging is defined in Document 1 as a characterization method. However, this encompasses several activities, such as visual examination, chemical assays, as explained in the description of characterization methods.

SOURCE: DOE (DOE-CBFO, 2002a; 2002c).

TABLE 4.2 DOE's Data Quality Objectives, Characterization and Implementation Methods to Address NMED Requirements

No.	Data Quality Objectives	Characterization Method	Implementation Method
1	Assign hazardous waste codes. Rationale: RCRA requirement as it applies to WIPP.	1. AK method 2. Tests on waste samples	Use AK to delineate waste streams, assign hazardous waste codes and summary category groups (SCG) to waste streams, and assign individual containers to waste streams. Use generator/storage site records of container assignments to the waste stream. Confirmation unnecessary. If AK is insufficient, perform tests on a representative (10 percent) sample of the waste.
2	Identify Physical Form. Rationale: RCRA requirement as it applies to WIPP.	1. AK method 2. Visual examination 3. NDE such as radiography	Summary category groups define the physical form of the waste as solidified solids (SCG=S3000), soil/gravel (SCG=S4000), or debris (SCG=S5000). Confirmation is unnecessary. If AK is insufficient, perform tests such as VE and NDE on a representative (10 percent) sample of the waste.
3	Limit residual liquids to less than 1 percent volume of RH canister (or drum for 160B). Rationale: residual liquids limit arises from transportation and operational safety considerations. Note that the rationale is different from that in Table 4.1 item 10. Residual liquids are a prohibited item in the current RCRA Permit.	1. AK method 2. Visual examination 3. NDE such as radiography	Use AK to demonstrate that the waste stream does not contain residual liquid, or that individual containers contain less than 1 percent by volume of residual liquid (confirmation unnecessary), or sample and NDE/VE to determine the waste stream does not contain residual liquid, or NDE/VE each container in a waste stream. AK must document the use of liquid management procedures (e.g., removal or absorption), or a process that precludes liquids (e.g., material input records or thermal treatment), or there must be a record for each container indicating less than 1 percent by volume of residual liquid, or NDE/VE of a few representative containers (10 percent[1]) from the waste stream can show the absence of residual liquids, or every container must undergo NDE/VE.
4	Limit residual polychlorinated biphenyls to less than 50 ppm. Rationale: polychlorinated biphenyls are a prohibited item in RCRA Permit if present in a concentration greater than or equal to 50 ppm.	1. AK method 2. Visual examination 3. NDE such as radiography	Use AK to determine the absence of possible sources of polychlorinated biphenyls such as transformer oil. If AK is insufficient, perform tests such as VE and NDE on a representative (10 percent) sample of the waste. VE and NDE are used, for instance, to look for parts of or entire transformers.
5	Exclude additional prohibited items	Use EPA hazardous waste	Additional prohibited items listed in the RCRA Permit (see

	(such as pyrophorics, incompatible chemicals, explosives, compressed gases, ignitable, corrosive, and/or reactive wastes). Rationale: these items are prohibited in the current RCRA Permit.	codes	Chapter 3) are addressed by the EPA hazardous waste codes assigned to an RH-TRU waste stream. RH-TRU waste containing any one of these items would have EPA hazardous waste codes that would disqualify it from management, storage, and disposal under the WIPP Part A requirements.
6	Identify and quantify volatile organic compounds. Rationale: any waste container that does not have volatile organic compounds concentrations reported for the headspace is currently a prohibited item in the RCRA Permit.	No volatile organic compounds measurement proposed on RH-TRU waste.	Use bounding analysis for RH-TRU waste contribution to reduce current RCRA Permit Room Limits.

NOTE: AK=acceptable knowledge; NDE/VE=non-destructive and visual examination (see Appendix G); VE=visual examination. Information in this table is presented in Document 2 and supplemented with additional information provided to the committee.

[1]See committee's Finding 2A, Example #6 in Chapter 5. Other elements of this table are also discussed in Chapter 5.

SOURCE: DOE (DOE-CBFO, 2002b; 2002c).

4.6 Major Differences Between the July 2001 and the March 2002 Drafts

As noted in Chapter 1, the committee reviewed two drafts of the proposed characterization plan. This section outlines the five major differences between the two drafts, as follows:

- *Change in the approach to the determination of prohibited items in Document 2.* The determination of the absence of all the prohibited items listed in the RCRA Permit was part of the requirements in the July 2001 draft of Document 2 (DOE-CBFO, 2001b; Item 2; pages 2-27). In the March 2002 draft, the only prohibited items explicitly listed as data quality objectives are residual liquids (if more than 1 percent by volume of waste) and polychlorinated biphenyls (if equal to or greater than 50 ppm). Remaining incompatible prohibited items (ignitable, corrosive, reactive, pyrophoric and incompatible waste, explosives, and compressed gases) will be addressed by excluding from shipment hazardous waste with codes corresponding to ignitable (D001), corrosive (D002), and reactive waste (D003). Pyrophoric materials, explosives and compressed gases fall under the definition of reactive waste (D003). Other waste prohibited in WIPP, such as explosives and compressed gases, can be excluded through hazardous waste code screening because any material whose code does not appear in the list of hazardous waste codes allowed in WIPP cannot be shipped. This drives the determination of the remaining prohibited items from a container-by-container basis to a waste stream level, where hazardous waste code assignment decisions are typically made. The hazardous waste code(s) determination will be accomplished using AK. According to DOE, the 1 percent free liquid criterion was retained as a RCRA operational compliance consideration rather than for performance reasons (see Appendix D).
- *Definition of a representative sample of containers to perform additional tests when AK is insufficient.* The March 2002 draft defines for the first time a representative sample as “at least 10 percent of the samples,” selected by the generator site (DOE-CBFO, 2002a; Attachment B; page 26). The committee discusses the issue of 10 percent representative sample size in Chapter 5, Finding 2A, Example #6.
- *Change of quality assurance objective to determine the total activity of waste by direct assay.* The July 2001 draft of Document 1 read:

> “Track the RH-TRU waste total activity inventory by the quantification of total activity for a unit (waste stream or individual container) within a factor of five of the true value with a confidence level of 95 percent” (DOE-CBFO, 2001a; Attachment A; page 10).

In the March 2002 draft of Document 1, this quality assurance objective was replaced by the quality assurance objective used for CH-TRU waste (DOE-CBFO, 1999b, Appendix A). Moreover, each site will demonstrate the ability of its direct assay measurement system to meet the criteria but will not be subject to the CH-TRU waste performance demonstration program.

- *Distinction between visual examination and characterization at the time of packaging.* Most of the RH-TRU waste will either be generated or repackaged. DOE makes a distinction between the characterization at the time of packaging and visual examination (DOE-CBFO, 2002a; Attachment B; pages 26 and 29). The rationale for the distinction is given above (see also the definition of the method “characterization at the time of packaging” in Section 4.4).

- *More detailed description of characterization requirements and RH-TRU waste inventory in both documents.* The March 2002 draft reports data quality objectives and quality assurance objectives for both EPA and RCRA Permit requirements. The documents also present additional information about generator sites and RH-TRU waste inventories.

While CH- and RH-TRU waste share the same characterization requirements described in WIPP's RCRA Permit and EPA Certification, DOE's approach to meet these requirements for RH-TRU waste is quite different from the way the are met for CH-TRU waste, as explained below.

4.7 Comparison Between the CH- and RH-TRU Waste Characterization Plans

The CH-TRU waste characterization plan approved by EPA and NMED is described in Appendix F. Briefly, the characterization plan for CH-TRU waste is based on a 100 percent confirmation of AK information collected on each waste stream. Confirmation is accomplished by radioassay, headspace gas sampling, radiography, or visual examination. For homogeneous wastes,[3] this includes taking core samples of a fraction of waste containers prior to their shipment to WIPP. For debris wastes, a 100 percent confirmation program (with headspace gas and radiography determinations for RCRA compliance, and non-destructive assay and radiography determinations for EPA's compliance) was negotiated between DOE and NMED. Rather than proposing the same approach as for CH-TRU waste, DOE proposes a "performance-based" approach to characterize RH-TRU waste because of the high radiation fields and the negligible impact of this waste on the performance of the repository.

The most significant difference between the CH- and the proposed RH-TRU waste characterization plans is that the latter does not require confirmatory testing, sampling, or analysis on 100 percent of containers and allows radiography and visual examination only on a representative selection of containers. DOE proposes to use AK whenever possible to accumulate the information on RH-TRU waste and to perform confirmation measurements only when the information collected on the waste stream is not qualified as AK. The rationale provided by DOE in Document 2 relies on the 95 percent of RH-TRU waste volume that is to be generated or repackaged. Instead of confirming AK, generator sites must provide assurances that the waste is adequately characterized at the time of packaging.

On the basis of the Sandia impact analyses, DOE determined that the proposed RH-TRU characterization plan does not require the determination of material parameter category weights and headspace gas analysis, whereas they are required in the CH-TRU waste characterization plan. Instead, DOE proposes to use bounding values for these parameters for RH-TRU waste. Concerning the WIPP's limit on volatile organic compound emissions, the characterization plan for CH-TRU waste requires tracking individual waste container headspace gas concentrations, which are determined by headspace gas sampling and analysis of CH-TRU waste containers.

There is no characterization objective for a direct measurement of the headspace gases in the proposed RH-TRU waste characterization plan because canisters will be located in the walls of the disposal rooms behind shield plugs. Calculations have shown

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[3]Homogeneous waste is one of the "Summary Category Groups" that indicate the final form of the waste. Homogeneous waste is waste consisting of one main constituent (for instance, sludge) as opposed to the other two category groups: soils and gravel, and debris waste.

that it is possible to account for volatile organic compounds emission rates from RH-TRU waste indirectly.[4] This is accomplished by conservatively incorporating the maximum potential volatile organic compounds contribution from RH-TRU waste in the maximum allowable volatile organic compounds emission limits established by the RCRA Permit (Spangler et al., 2002).

[4]To the best of committee's knowledge, experiments on volatile organic compound emissions from RH-TRU waste have not been conducted.

5

Assessment of the Proposed Characterization Plan

This chapter provides the committee's assessment of DOE's proposed plan for the characterization of RH-TRU waste. On June 28, 2002 DOE submitted the characterization plan to EPA and NMED. The committee did not review the plan as submitted; therefore, findings and recommendations in this chapter apply only to the March 2002 draft.[1]

According to the statement of task, findings and recommendations are organized as follows:

1. context of RH-TRU waste characterization;
2. characterization plan's technical soundness;
3. protection of worker safety and health; and
4. compliance with regulatory requirements.

This assessment is based on technical considerations and on the criteria listed in the statement of task (Sidebar P.1).

5.1 Context of Remote-Handled Transuranic Waste Characterization

Below are some general findings about the DOE's RH-TRU waste inventories. According to the information gathered, the RH-TRU waste volume estimated for shipment to WIPP will be about 3,800 cubic meters or 2 percent of the total TRU waste volume allowed in the repository. Even if the information presented in DOE inventories were not accurate, the RH-TRU waste emplaced in WIPP cannot exceed the limits for RH-TRU waste established in the Land Withdrawal Act: 7,080 cubic meters (about 4 percent of the total allowed TRU volume) and 5.1 million curies.

While RH-TRU waste volume represents a small fraction of the allowed TRU waste in WIPP, it accounts for 14 percent of the total curie activity in DOE's TRU inventory. However, the number of TRU curies in the RH-TRU waste inventory is 2 orders of magnitude lower than that in the CH-TRU waste inventory expected in WIPP (see Table 2.3 in Chapter 2). Also, most of the total (CH plus RH) long-term (i.e., TRU) activity expected in WIPP comes from CH-TRU waste, with only a 0.5 percent contribution from RH-TRU waste.

According to the performance assessment calculations by Sandia National Laboratories, the inventory of RH-TRU waste expected in WIPP will have a negligible

[1]The committee also reviewed a previous draft (July 2001), which was the object of its interim report (see excerpt in Appendix C).

impact on the repository's compliance with EPA radiological regulatory standards, compared to CH-TRU waste.

The committee acknowledges that there are uncertainties in DOE's volume and radioactivity inventories of RH-TRU waste. Also, the committee did not assess the validity of the Sandia impact analyses. However, the committee notes that these performance assessment calculations were performed using a peer-reviewed and EPA-approved performance assessment tool, which was the basis for WIPP certification. The committee recognizes that there may be uncertainties associated with the results of these impact analyses and that there may be scenarios that require a new set of performance assessment calculations.[2] In response to the committee's question on uncertainties, Sandia National Laboratories reported that:

> "Uncertainties in Performance Assessment are dominated by those associated with geologic processes, chemical interactions of the waste, and possible human activities in the future. For example, the intrinsic permeability of the proximal host rock can vary over seven orders of magnitude; uncertainties with respect to microbial degradation of organic materials affect several key intermediate variables, such as long-term repository pressure and saturation; assumptions regarding human activities introduce the most notable impacts on repository performance. With these uncertainties in mind, it can be stated that any additional uncertainty associated with waste components within the currently estimated RH-TRU inventory are not significant to long-term repository performance" (Knowles, 2002).

These considerations, as well as the findings and recommendations in this section, set the context for RH-TRU waste characterization. This context is different than that of CH-TRU waste characterization because of the differences in volumes and in isotopic composition, as explained in Chapter 2.

Finding 1A: According to DOE inventories, 95 percent of the RH-TRU waste to be disposed of in WIPP has yet to be generated or needs to be processed, packaged, or repackaged. This waste will be characterized (through visual examination and physical and chemical analyses) at the time of packaging. **Recommendation: DOE should emphasize the argument that the characterization information collected for most of RH-TRU waste does not need confirmatory measurements because the repackaging or generation of waste will be carried out under a certified quality assurance program.**

Rationale: According to the information provided by DOE, over 95 percent of the RH-TRU waste inventory (to be generated, to be packaged or repackaged waste in Figure 2.2) will be characterized using visual examination[3] and physical and chemical methods. This leaves a small fraction of RH-TRU waste with more limited historical, analytical, radioassay, and visual examination information or which was not

[2]An unexpected brine saturation of the repository in less than 300 years, a change in the scope of the WIPP facility, or a change in the configuration of underground disposal are examples of scenarios for which a new set of performance assessment calculations for both CH- and RH-TRU waste would be warranted.

[3]The committee notes that visual examination only provides an image of the content of waste containers. It does not provide any information on the isotopic composition of waste.

characterized under a certified quality assurance program; in this case, AK may require confirmation.

Therefore, for over 95 percent of RH-TRU waste, confirmatory measurements may not be necessary as long as this waste is generated or repackaged using a certified quality assurance program plan. If the volume of RH-TRU waste represents between 2 and 4 percent of the total inventory of TRU waste (176,000 cubic meters), and the information collected for over 95 percent of RH-TRU waste does not need confirmation, then only between 0.1 and 0.2 percent of the total TRU inventory needs confirmatory activities for AK. This is an important observation and it could have a substantial impact on characterization programs proposed for RH-TRU waste.

Finding 1B: For 95 percent of the RH-TRU waste inventory, AK refers to newly generated information acquired during waste generation and packaging. **Recommendation: DOE should utilize a different term than "AK" for this newly generated information.**

Rationale: This newly generated information does not include only historical information on the waste. It can include, for instance, analytical data, radioassay data, and visual examination records obtained during waste generation or repackaging. DOE considers this newly generated information, which may not require confirmation, as AK. The committee believes that this is a potentially confusing terminology because AK is usually associated with historical information, which requires some confirmation (see also Sidebar 2.1).

The committee acknowledges that visual examination during RH-TRU waste generation or repackaging does not provide information on the radiological content or on the presence of corrosive, reactive, or chemically hazardous waste. However, visual examination is not the only characterization method proposed for newly generated or repackaged waste (see description of the "characterization at the time of packaging" method in Chapter 4, Section 4.4).

5.2 Characterization Plan's Technical Soundness

DOE's stated objective is to propose a performance-based characterization plan for RH-TRU waste. The committee interprets "performance-based characterization plan" as a plan ensuring repository integrity, protection of the environment, and health and safety of the public and workers while keeping in consideration tradeoffs between greater characterization accuracy and worker risks (see Chapter 4). This section addresses the characterization activities that DOE proposes to implement the data quality objectives listed in Tables 4.1 and 4.2.

Finding 2A: The committee found that several characterization activities are based on non-technical considerations. Therefore, this characterization plan is not completely performance based. The committee questions the technical basis of some of the characterization activities proposed by DOE with respect to its stated goal of adopting a performance-based approach**. Recommendation: The committee acknowledges that DOE must consider many non-technical factors in composing its characterization plan. However, DOE should propose only characterization activities that have a technical, health and safety, or regulatory basis.**

Rationale: DOE itself recognizes that the characterization plan is based on various considerations other than science and technology. In its response to the findings in the committee's interim report, DOE stated:

> "Nearly all resulting characterization objectives are unrelated to repository performance or to safety/technical considerations" (see Appendix D).

and, during a recent conference on waste management, DOE explains:

> "Based on the results of repository modeling … the DOE believes there are no specific RH TRU waste parameters that need to be measured with precision in order to assure repository integrity and assure protection of human health and the environment. This does not mean that no characterization of RH TRU waste is necessary. To the contrary, in order to meet the requirements of the facility design and the facility waste acceptance criteria, specific needs for waste analysis have been identified" (Gist, et al., 2002; pages 2-3).

The facility design and the waste acceptance criteria address the requirements in the EPA Certification and RCRA Permit. Regulatory drivers are listed in Chapter 3 and other non-technical considerations at the beginning of Chapter 4. Most of the characterization activities proposed by DOE do not have a technical basis but arise from considerations aimed at maintaining an effective working relationship among DOE, EPA, and NMED. The committee acknowledges that maintaining an effective working relationship among DOE and WIPP's regulators is important; however, DOE should propose only characterization activities that correspond to technical, health and safety, or regulatory objectives.

Concerning the technical basis of some of the characterization activities in Documents 1 and 2, the Sandia impact analyses show that radioisotope, free liquids, cellulosics, plastics, rubber, and ferrous metal content in the RH-TRU waste inventory do not have an impact on repository performance (see Chapter 4).

In spite of these impact analyses, Documents 1 and 2 still propose characterization activities to determine the above parameters in RH-TRU waste. The committee provides below examples of characterization activities that do not appear to have a technical basis in the context of RH-TRU waste characterization.

Example #1: DOE justifies the characterization requirement concerning free water or liquid content for both EPA and NMED as a transportation-related requirement or as a requirement present in the WIPP Safety Analysis Report.[5] DOE provides the rationale for this characterization requirement as follows:

> "*[EPA Characterization Objectives] Account for Free Water*, is a regulatory expectation that the RH-TRU Team believes is prudent to meet even though no amount of free water in the RH-TRU waste will impact repository performance. Note that Appendix WCL.5 [of the compliance certification application] states that, 'Consequently, there is no need to monitor water in the waste for

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[4]An unexpected brine saturation of the repository in less than 300 years, a change in the scope of the WIPP facility, or a change in the configuration of underground disposal are examples of scenarios for which a new set of performance assessment calculations for both CH and RH-TRU waste would be warranted.

[5]For a definition of Safety Analysis Report see the glossary, Appendix I.

> compliance with 40 CFR § 194.24(c).' The RH-TRU Team recommends that free water in RH-TRU waste be accounted for by some means.
> *[NMED Characterization Objectives] Limit residual liquids to [less than] 1 [percent] volume of RH canister (or drum for 160B)*, is related to a regulatory requirement to provide secondary containment at the WIPP for potential spills. An analysis justifying the 1 [percent] for CH-TRU waste at the WIPP is part of the HWFP [Hazardous Waste Facility Permit] record, however a similar analysis has not been done for RH-TRU waste. The RH-TRU Team believes it is prudent to include this limit as an RH-TRU waste requirement also" (see Appendix D).

DOE acknowledges that the free water/liquid requirement is an operational concern that does not affect the long-term performance of WIPP. Given the results of the Sandia impact analyses, the committee questions the technical basis of this characterization activity.

Example #2: One of the data quality objectives listed in Document 1 is the determination of TRU activity (expressed as plutonium-239 content) of RH-TRU waste to comply with the EPA radionuclide release limits. The Sandia impact analyses showed that, even if the entire RH-TRU waste radionuclide inventory were composed of plutonium-239, WIPP would still be in compliance with 40 CFR 191 because of the small volume of RH-TRU waste to be emplaced in WIPP. Therefore, the actual measurement of TRU activity does not have a technical basis for RH-TRU waste. The determination of TRU activity could be addressed by assigning a conservative boundary value of plutonium-239 representing the total RH-TRU waste inventory.

Example #3: In the EPA compliance certification application, DOE established limits for ferrous metal content of waste to be emplaced in WIPP. The rationale is the following:

> "Ferrous and ferrous-alloy metals (and their corroded products) provide the reactants that reduce radionuclides to lower and less-soluble oxidation states. As discussed in Appendix WCA [Waste Characterization Analysis in the compliance certification application], the anticipated quantity of these metals to be emplaced in WIPP is two to three orders of magnitude in excess of the quantity required to assure reducing conditions. The waste containers supply more than enough iron to provide adequate reductant. Therefore, no upper or lower limit need be established for the quantity of ferrous and ferrous-alloy metals that may be emplaced, beyond the present projection of containers" (DOE, 1996a; Appendix WCL.2).

According to the information gathered, the minimum amount of ferrous metals will be satisfied by CH-TRU waste containers. The committee was unable to determine the reason for including the implementation of this characterization objective in the RH-TRU waste characterization plan, even though the method (counting containers) is a simple practice performed during waste packaging.

Example #4: The Sandia impact analyses showed that, even if the entire RH-TRU waste inventory were composed of cellulosics, plastics, and rubber, it would only have a negligible impact on the repository performance because of the small volume of RH-TRU waste emplaced. Yet, DOE proposes the implementation of this characterization objective in Document 1. Although this objective is not performance based in the case of RH-TRU waste, the committee acknowledges that DOE does not propose to actually measure cellulosics, plastics, and rubber in the waste but uses a conservative estimate described in Table 4.1.

Example #5: The determination of prohibited items (see Section 3.3, Chapter 3) listed in the RCRA Permit may not be appropriate for RH-TRU waste when the risks associated with hazardous chemical waste are balanced against radiological risks and costs associated with characterization. According to the information gathered, the prohibited items' determination represents one of the major difficulties in the characterization of RH-TRU waste. In DOE's characterization plan, there is no analysis of the health and safety implications of the prohibited items in RH-TRU waste. It is important to analyze these yet-undefined safety implications and balance them against potential radiological risks to workers and associated costs of identifying prohibited items in RH-TRU waste. Such an analysis would be helpful to DOE in comparing workers risks and the associated characterization costs. The results of the analysis could support and strengthen DOE's RH-TRU waste characterization activities with respect to prohibited items.

DOE's proposed characterization plan was significantly modified between July 2001 and March 2002 concerning the determination of prohibited items in RH-TRU waste. In the latter draft, DOE proposes to determine the absence of only free liquids and polychlorinated biphenyls (within their limits). The remaining prohibited items listed in the RCRA Permit (ignitable, corrosive, reactive, pyrophoric and incompatible waste, explosives, and compressed gases) are determined using the EPA hazardous waste codes. This determination is accomplished using AK on a waste stream basis.

This change drives the prohibited items determination (except for residual liquids and polychlorinated biphenyls) from a container-by-container basis to a waste stream basis where hazardous waste code assignment decisions are typically made. The committee supports this change since it streamlines characterization operations but still addresses the prohibited items objective in the RCRA Permit.

The committee could not determine the technical basis for including the determination of polychlorinated biphenyls (over 50 ppm) in the context of RH-TRU waste. DOE provided the following rationale:

> "Polychlorinated biphenyls are subject to EPA regulation under TSCA [Toxic Substances Control Act] and are regulated regardless of whether or not they are included in a RCRA permit as a prohibition" (see Appendix D).

In the case of a change in the polychlorinated biphenyl disposal regulations,[6] DOE must submit a request for a change in the RCRA Permit to remove the 50 ppm provision. This would not be necessary if this provision were not explicitly mentioned in the RCRA permit.

Example #6: The March 2002 draft indicates that, if AK data are not sufficient, then 10 percent of waste should be characterized with alternative methods (see Tables 4.1 and 4.2). The committee could not determine the technical basis for choosing 10 percent of waste as a representative sample of the waste stream. In general, the size of a representative sample is the result of an analysis involving statistical considerations as

[6]The new polychlorinated biphenyls disposal regulations (Disposal of Polychlorinated Biphenyls (PCBs), 63 Federal Register 35384, effective August 28, 1998) allows polychlorinated biphenyl-contaminated radioactive waste to be disposed of without a TSCA permit provided the waste meets the requirements for disposal in a non-hazardous waste landfill or a hazardous waste landfill. This recent regulatory change would allow disposal at WIPP of some polychlorinated biphenyls-contaminated wastes where the polychlorinated biphenyls component exceeds 50 ppm. On March 22, 2002 DOE submitted an "Initial Report" to EPA Region VI requesting authorization to dispose of polychlorinated biphenyls in WIPP.

well as waste stream profile considerations. No such analysis or any other justification was provided in the March 2002 draft. A 10 percent waste sample size may be too big or too small, depending on the waste stream, on the quality of AK available, and on the tolerable decision error rates (see Finding 2C).

Finding 2B: The requirements to qualify information collected on each waste stream, whether by AK or by any other method described in 40 CFR 194.22(b), have not been established with specificity in the submittal documents. **Recommendation: In the site-specific accompanying documents, DOE should present clear and technically defensible data qualification requirements for its RH-TRU waste characterization plan.**

Rationale: The committee recommends that DOE follow a more structured approach in the development of its characterization plan. A structured approach, such as that provided by defining data quality objectives and quality assurance objectives, would clearly define the data needed for characterization, identify the basis for the data need, and then logically determine how to meet those needs. The committee does not expect quantitative quality assurance objectives, especially for AK information. However, it is important to discuss how to determine when or whether AK could meet data quality objectives and under which conditions it would be necessary to supplement AK using other characterization methods (e.g., dose to curie conversion, visual examination, radiography, time of packaging methods, direct assay, surface dose rate). This recommendation is also consistent with the recommendation of a second peer review on DOE's characterization plan.[7]

According to the information gathered, DOE will submit to EPA and NMED along with the draft characterization plan, a sample of completed characterization documents for three RH-TRU waste generator sites (Energy Technology Engineering Center, Battelle Columbus Laboratories, and Oak Ridge National Laboratory). The committee supports this initiative. These companion documents to the characterization plan should be useful in clarifying the intended methods of implementation. The committee could not review these methods, given that these documents were not available at the time this report was written.

Finding 2C: DOE's proposed characterization plan does not adequately address the issue of tolerable decision error rates associated with all characterization information. **Recommendation: DOE's proposed characterization plan should address tolerable decision error rates associated with characterization information. These errors should not be overly stringent so as to negatively impact the sites' ability to implement ALARA.**

Rationale: Tolerable decision error rates are never clearly defined in Document 1 and Document 2. Tolerable decision error rates are determined by weighing the consequences of mischaracterization against the costs (including worker risks) of achieving better characterization. Once established, tolerable decision error rates can be

[7]The Institute for Regulatory Sciences, which reviewed the July 2001 draft of DOE's proposed characterization plan, recommended the following: "A detailed procedure for determining whether there is sufficient AK available on a waste, should be developed as part of the permit application. This procedure should be consistent across all waste generating sites. […] [A] detailed procedure should be provided to go to other characterization methods if AK is found to be insufficient" (Institute for Regulatory Sciences, 2001; page 77).

used to identify the attendant quality assurance requirements for sampling (i.e., the measurement quality objectives, which DOE calls quality assurance objectives). Tolerable decision error rates may not be specified in laws and regulations, but they are a critical judgment that an implementer should propose when interpreting legal or regulatory limits to address the uncertainties inherent in characterization data. As an illustration, Document 1 reads as follows:

> "Tolerable decision error: The limit on residual liquids has been specified with no associated error; therefore, any container that contains more than 1 percent by volume residual liquids cannot be shipped to WIPP" (DOE-CBFO, 2002a; Attachment B; page 7).

The tolerable decision error (and its rate) in the measurement of the liquid volume in a container is never clearly defined. More importantly, the above quote from Document 1 seems to suggest that there is a zero tolerable decision error (and a zero tolerable decision error rate) on the determination of residual liquids. Another example of unclear tolerable decision error rate concerns the quantification of the total activity. The March 2002 draft proposes to use the same quality assurance objective for the total activity of waste as the one used for CH-TRU waste (see Chapter 4, Section 4.6). However, the committee still cannot determine with clarity what is tolerable decision error rate associated with the measurement of the total activity.

It is premature for DOE to develop quality assurance objectives until it has proposed tolerable decision error rates that limit risks related to the waste, and that recognize potential tradeoffs in costs and worker risks. Without setting tolerable decision error rates to create a bridge between the data quality objectives and the characterization methods, it will be impossible to determine whether the waste characterization plan requires too much or too little in terms of the quality of the data needed. The quality assurance objectives should be presented in the site-specific implementation plans and could vary from site to site. The committee supports DOE's plan to submit to EPA and NMED the three site-specific (Energy Technology Engineering Center, Battelle Columbus Laboratories, and Oak Ridge National Laboratory) implementation plans.

It is important to recognize that tolerable decision error rates will have an impact on characterization operations at the generator sites. The ALARA principle must be applied at DOE facilities according to the Code of Federal Regulations (10 CFR 835.101). Therefore, the proposed characterization plan should not set forth overly stringent requirements (such as zero tolerable decision error rates) that could negatively impact the sites' ability to implement ALARA (see also Finding 3A).

Finding 2D: It is not clear how visual examination and radiography can confirm AK information for prohibited items. For example, visual examination and radiography cannot distinguish between corrosive and non-corrosive liquids, whereas AK may provide records of the existence of such liquids in the waste. Historical AK may be a better indicator of some of the currently prohibited items than visual examination and radiography. **Recommendation: The characterization plan should clarify under which conditions confirmation of historical AK is warranted and what are the most effective methods proposed.**

Rationale: This finding applies to the approximately the 5 percent of the RH-TRU waste inventory that does not require packaging or repackaging. The committee observes that the March 2002 draft better explains how AK could be, in some cases, the most suitable method to determine the absence of certain prohibited items. In this draft,

DOE proposes to use AK to identify hazardous waste codes to prevent ignitable, corrosive, and reactive waste from being disposed of in WIPP. However, DOE does not clearly explain under what circumstances AK should be confirmed and what are the results expected from supplementary characterization methods. DOE recognizes that visual examination and radiography are inadequate techniques for addressing the entire list of prohibited items.

From the operational experience acquired with CH-TRU waste, it is possible to obtain some indication of the effectiveness of AK as a characterization method. Most of the information collected for CH-TRU waste characterization consists of historical records about waste streams, which the committee termed "historical AK" (see Sidebar 2.1). Effectiveness of AK for CH-TRU waste is demonstrated by the "AK Information Accuracy Reports" from the various generator or storage sites (DOE-CBFO, 2001c). DOE presented to the committee the results of an analysis of the effectiveness of historical AK for CH-TRU waste. Contact-handled TRU waste generators use radiography or visual examination, headspace gas sampling and analysis, and/or solids sampling and analysis to confirm AK information accuracy.

Results showed a high accuracy of historical AK: above 95 percent for the determination of waste matrix codes at the major CH-TRU waste generator sites and above 93 percent for the determination of hazardous waste codes. The only exception was observed at the Idaho Environmental and Engineering Laboratory, where an accuracy of 80 percent was achieved in the hazardous waste codes determination. This lower accuracy was obtained because this site assigned hazardous waste codes on a waste stream basis, rather than on an individual container basis.

Document 2 provides further feedback on AK confirmation for CH-TRU waste by headspace gas analysis:

> "To date, the headspace gas from over 16,000 CH TRU waste containers has been sampled and analyzed and no hazardous waste numbers have been added to a waste stream. This indicates that the additional benefit from using headspace gas sampling and analysis to confirm the hazardous waste determination are limited" (DOE-CBFO, 2002b; pages 5-21).

The committee emphasizes that these effectiveness analyses provided by DOE are relevant only to AK for CH-TRU waste, which is historical AK. In the case of the 95 percent of RH-TRU waste, most of the information comprising AK will be collected during waste generation or repackaging under a certified quality assurance program and would likely have higher accuracy.

Finding 2E: DOE's characterization plan calls for application of specific technologies, such as X-ray radiography, to provide confirmatory data. The committee could not determine the effectiveness of these technologies in characterizing the high-dose-rate fraction of RH-TRU waste containers. **Recommendation: DOE should provide justification for the technologies proposed for obtaining confirmatory data and provide evidence of their effectiveness across the entire spectrum of dose rates for RH-TRU waste.**

Rationale: Given the importance placed on radiography to determine the presence of prohibited items, the characterization plan should clarify and support the information on the method's effectiveness in high radiation fields expected for a small fraction of RH-TRU waste. The lack of information on the effectiveness of characterization methods for RH-TRU waste was also NMED's main argument to prohibit this type of waste in WIPP

(see Chapter 3). Moreover, this recommendation is consistent with the Institute for Regulatory Sciences' peer review of the July 2001 draft of the characterization plan.[8]

In Documents 1 and 2, the committee did not find adequate justification for the effectiveness of technologies proposed for obtaining confirmatory data, such as radiography, particularly for RH-TRU waste with higher surface dose rates. In its response to the committee's interim report, DOE states:

> "For the minimal use of NDA [non-destructive assay] and RTR [real-time radiography] that will still be required in the overall program, the standard technologies currently being employed in the CH-TRU waste program are more than adequate. The RH Team recommended program […] calls for NDE [non-destructive examination] to be used only to detect 1 [percent] residual liquid and only for a small percentage of the total RH-TRU waste inventory (most RH-TRU waste will be repackaged or newly generated). Resolution of current RTR systems, even in high radiation fields, is adequate for this determination" (see Appendix H).

DOE never addresses the issue of the fraction of waste containers with high surface dose rates. The current DOE inventory in Table 2.1 shows that both the Hanford Site and Oak Ridge National Laboratory have or will generate RH-TRU waste with a surface dose rate as high as 1,000 rem per hour. Moreover, some Oak Ridge National Laboratory RH-TRU waste also emits neutrons, which further complicates non-destructive characterization methods. In Documents 1 and 2, radiography is cited as lead technology to confirm AK, where necessary, or to examine the contents of small containers prior to placing them into the final shipping containers. DOE's proposal to use radiography across the entire spectrum of dose rates warrants an explanation, however small the fraction of high dose-rate containers may be.

The committee was unable to find elsewhere information on whether radiography could be used for RH-TRU waste containers with the highest dose rates. DOE indicated to the committee that:

> "Though DOE collected some data and analysis indicating that there are no fundamental obstacles to radiographing RH TRU wastes, there has not been a systematic demonstration of that capability. As a consequence, there is lingering doubt regarding its feasibility in general. The simplest means to put these doubts to rest is to design and perform a systematic evaluation" (Taggart, 2001).

The committee gathered additional information on non-destructive characterization techniques and there appear to be uncertainties and technical difficulties in high radiation fields (see Appendix G). Under the committee's request for additional information, DOE provided a publication on X-ray radiography applied to RH-TRU waste characterization (Roney and White, 2001). This study, although performed on surrogate waste, showed that X-ray technology could indeed investigate the content of RH-TRU waste drums, although it was discussed for surface dose rates only up to 100 rem per hour. It is unfortunate that this study is not mentioned in DOE's characterization plan. To

[8]The Institute for Regulatory Sciences recommended: "More detail and specificity on WAC [waste acceptance criteria] using AK, VE [visual examination], and [r]adiography (including types of instrumentation to be used) should be provided in the permit application" (Institute for Regulatory Sciences, 2001; page 77).

the best of its knowledge, the committee believes that the application of radiography in the presence of very high radiation fields may be problematic.

Other non-destructive assay and examination techniques are being developed for the characterization of RH-TRU waste (see Appendix G). According to the information gathered, the only example of non-destructive assay characterization performed on actual RH-TRU waste was the characterization of 10 canisters of RH-TRU waste at Los Alamos National Laboratory. This was done using a passive/active neutron assay technique (Estep et al., 1989). Further development and application of non-destructive assay and examination techniques is pending the outcome of the final RH-TRU waste characterization plan.

5.3 Protection of Worker Safety and Health

The main issues concerning the handling of RH-TRU waste are potential radiation worker doses and assorted characterization costs.

Finding 3A: Potential worker radiation doses and related characterization costs are distinguishing features of RH-TRU waste compared to CH-TRU waste. Available estimates of worker doses and characterization costs for RH-TRU waste are limited, site-specific, and not completely reliable**. Recommendation: DOE could strengthen the rationale of its characterization plan for RH-TRU waste by incorporating a discussion of estimates of worker doses and characterization costs in the three site-specific plans accompanying the submittal documents.**

Rationale: The committee observes that the data presented on waste dose rates and characterization cost estimates in the July 2001 draft have been removed from the March 2002 draft. The committee recognizes that, since the characterization plan for RH-TRU waste is not yet finalized, information on worker doses and characterization costs for RH-TRU waste is scarce. The only data available on RH-TRU waste are from Battelle Columbus Laboratory, WIPP, and Argonne National Laboratory-East, and they may not be representative of all RH-TRU waste generator sites (see Appendix H).

The committee also recognizes that the sites are also responsible for applying the ALARA principle to minimize radiation doses to workers during characterization operations. It follows that each site will produce a different implementation plan for waste characterization and worker radiation protection programs based on ALARA will also be different.

However, a risk perspective of worker doses and costs could be illuminating in developing characterization requirements and in adding credibility to the plan. Discussion of worker doses and costs is relevant since radiation protection standards and criteria are predicated on the concept of assessing the decrement in risk per increment in cost as outlined by the International Commission on Radiological Protection (ICRP, 1977). The approach to estimate worker doses would be to structure different scenarios, rank the scenarios on the basis of the supporting evidence, and calculate the worker doses. This type of dose information would add much to the discussion of the differences between CH- and RH-TRU waste characterization plans. An equivalent approach could be adopted to better estimate characterization costs.

The committee recommends that the estimated doses and costs be an integral part of the three implementation plans from representative generator sites that will accompany Documents 1 and 2. Understanding worker doses and underlying characterization costs is important in developing effective radiation protection programs

based on the ALARA principle. The committee provides in Appendix H examples of estimates of worker doses and characterization costs. In Section 5.2, the committee also recommended that DOE's characterization plan should not set forth overly stringent tolerable decision error rates that could negatively impact the sites' ability to implement ALARA (see Finding 2C).

Finding 3B: The submittal documents provide flexibility to the generator sites in the implementation of the RH-TRU waste characterization plan. **Recommendation: DOE should continue its effort in ensuring sufficient flexibility to generator sites in the implementation of the characterization plan. However, characterization activities that share common elements across sites should be standardized.**

Rationale: One of the findings of the committee's interim report is that there is substantial variability among RH-TRU waste generator sites, including:

1. variability in the composition of the waste streams;
2. variability in the extent of AK available;
3. variability in the characterization and repackaging facilities available; and
4. variability and uncertainties in the current and projected inventories of RH-TRU waste.

The committee acknowledges that the March 2002 draft better addresses the substantial RH-TRU waste variability from site to site compared to the earlier draft. DOE's characterization plan allows flexibility to the generator sites in implementing the RH-TRU waste characterization program. In Document 1, DOE directs each TRU waste site to develop standard operating procedures to implement the waste characterization plan at that specific site (DOE-CBFO, 2002a; Section 3.2.2 of Attachment B). DOE also addresses data validation, usability, and reporting at the individual sites in Section 3.5 of Attachment B. Also, Attachment 6 of the application is designated "Site Specific Documentation," but this section has yet to be written. Document 2 requires the sites to develop their own RH-TRU mixed waste characterization programs in compliance with the requirements of the overall waste analysis plan (Document 2, Section R 4.0). These programs are to include characterization strategies, equipment, and health and safety protocols; site-specific characterization methods; quality-assurance plans; and training programs.

Flexibility in a waste characterization plan is important to allow the sites to adapt each characterization requirement to their type of waste inventory and characterization facilities. A rigid, overly prescriptive characterization plan may lead to unnecessary radiation doses to workers and characterization costs. For example, small sites that do not have adequate characterization facilities may find themselves in a difficult situation if the characterization plan mandates specific confirmatory activities, even in the presence of adequate AK. If the site must perform confirmatory measurements or visual examination in a hot cell it would have to ship its waste to a different site[9] equipped with a hot cell or use a mobile hot cell. Therefore, the added costs of such confirmatory measurements could be significant.

The committee reiterates its recommendation that common elements among the sites be standardized to facilitate characterization compliance verifications and, possibly, reduce characterization costs. In the effort of standardizing characterization activities,

[9]Shipments from site to site are allowed before the waste characterization plan is approved because DOE's waste characterization plan applies only to waste shipped to WIPP.

DOE will submit to EPA and NMED a sample of completed characterization documents for three RH-TRU generator sites (Energy Technology Engineering Center, Battelle Columbus Laboratories, and Oak Ridge National Laboratory). The committee supports this initiative.

The committee observes that, in the sites' inventories description, DOE did not differentiate mixed RH-TRU waste from non-mixed RH-TRU waste. DOE indicated that, although some waste streams could be identified as non-mixed RH-TRU waste, all waste is deliberately treated as mixed RH-TRU waste, as a policy decision. In fact, according to the RCRA Permit, all waste emplaced in WIPP (mixed or non-mixed) must be analyzed according to a characterization plan approved by NMED (DOE-CBFO, 2002c). The committee acknowledges DOE's policy decision, although it lacks a technical basis.

5.4 Compliance with Regulatory Requirements

The committee evaluated how DOE proposes to address EPA and NMED requirements from a technical point of view. The committee was not asked to determine if the plan complies with the regulatory requirements. The latter is obviously a policy decision that belongs to the regulatory agencies.

One of the challenges of this characterization plan is to meet characterization requirements specified in the EPA Certification and RCRA Permit that were negotiated with WIPP's regulatory agencies for CH-TRU waste and exclude RH-TRU waste. Moreover, the only TRU waste characterization plan approved by EPA and NMED is that currently used for CH-TRU waste. With this characterization plan DOE proposes to meet EPA and NMED requirements following a different approach than that used for CH-TRU waste.

Finding 4A: The proposed characterization plan for RH-TRU waste deliberately tracks the characterization plan for CH-TRU waste. **Recommendation: DOE should evaluate whether existing characterization practices for CH-TRU waste, when applied to the characterization of RH-TRU waste, have an impact on the protection of the environment, health and safety of public and workers, and cost-effectiveness of the characterization program.**

Rationale: DOE proposes to address regulatory requirements for RH-TRU waste characterization using a performance-based approach, a different approach than that used for CH-TRU waste. The committee observes that the characterization plan for RH-TRU waste has not yet been finalized. The implementation activities for RH-TRU waste to address characterization objectives will be finalized only after negotiations based on the submittal documents take place between DOE and WIPP's regulatory agencies. However, the existence of a characterization plan for CH-TRU waste does not imply that the same approach should be proposed for the characterization of RH-TRU waste.

It is not the committee's intention to say that there are unnecessary regulatory requirements in the current EPA Certification and RCRA Permit. However, there is reason to believe (Kehrman, 2002; NRC, 2001a; DOE, 1999a) that DOE proposed some characterization practices in the CH-TRU waste characterization plan to facilitate negotiations with the regulatory agencies and obtain authorization to operate the WIPP facility. The previous National Research Council committee on WIPP found that some of these self-imposed practices lacked a technical, safety or legal basis (see Sidebar 3.1). The current committee emphasizes that, because of the additional radiological and cost

considerations associated with RH-TRU waste, it is even more important that DOE refrains from proposing characterization requirements that do not have a technical, health and safety, or regulatory basis.

Given the different context of RH-TRU waste characterization described earlier, the committee acknowledges that DOE's efforts to introduce a performance-based approach are technically justified. However, the committee does not find the proposed plan to be completely performance based (see Finding 1A). The committee does not suggest that DOE should do only the "bare minimum" to characterize RH-TRU waste. Rather, the characterization program should ensure repository integrity, protection of the environment and of the health and safety of the public and workers, while keeping in consideration tradeoffs between greater characterization accuracy and worker risks.

Finding 4B: The submittal documents include, as basis for characterization objectives, waste acceptance criteria and other requirements than those applicable to the EPA Certification and RCRA Permit. **Recommendation: Submittal documents should focus on regulatory requirements under the relevant agency's purview and should distinguish between these requirements and ancillary information describing the context of RH-TRU waste characterization.**

Rationale: Document 1 contains the RH-TRU Waste Acceptance Requirements and Criteria. These are the "controlling (i.e., the most restrictive) requirements to be used by the sites in preparing their waste for transportation to and disposal at the WIPP" (DOE-CBFO, 2002a; Section 3.0 of Attachment A). The waste acceptance criteria are drawn from transportation and hazardous waste considerations, as well as repository-performance considerations.

For instance, the waste transportation quality assurance requirements are described in Section 4.3 of Attachment A. Since Document 1 is an application for a change in the EPA Certification, it is not clear why requirements and criteria other than those relating to repository performance are given in the document. Historically, DOE included the waste acceptance criteria in the characterization plan for CH-TRU waste (DOE-CAO, 1996a). This does not need to be the case for the RH-TRU waste characterization plan since, to the best of the committee's knowledge, EPA does not require these criteria to be part of the application. Documents 1 and 2 also contain requirements originating from the Nuclear Regulatory Commission, the Department of Transportation, and the Occupational Health and Safety Administration. While it is important to provide in the submittal documents the full context of the characterization of RH-TRU waste, including material outside the regulatory jurisdiction of EPA and NMED may unnecessarily complicate the regulatory review process.

In the future, DOE may wish to negotiate other requirements with different regulatory agencies than EPA and NMED (for instance, transportation requirements with the Nuclear Regulatory Commission and the Department of Transportation). These negotiations could become more complex if the original requirements had also become a part of a document reviewed and approved by the EPA or NMED. See also the comment on polychlorinated biphenyl limits discussed in Finding 2A, example #5.

The committee believes that it would be helpful for both DOE and the regulatory agencies if the submittal documents indicate which requirements are to be reviewed and which are given for information purposes. This would allow the regulator and the implementer (DOE) to keep track of various requirements, and to streamline characterization practices as experience is gained. This recommendation applies to the submittal documents only. The committee supports the current practice of combining all

regulatory requirements into one document to guide generator sites in the development of their characterization programs.

5.5 Overall Assessment of DOE's Characterization Plan

The committee observed a net improvement between the July 2001 and March 2002 drafts of the characterization plan. Concerning the plan's technical soundness, DOE itself recognized that this plan is not completely performance based and that several other considerations played a role in the development of this plan. The committee identified some characterization activities lacking technical bases in the context of RH-TRU waste and a potential technical problem with radiographic examination of waste. Also, DOE's proposed characterization plan does not adequately address the issue of tolerable decision error rates associated with all characterization information.

In some instances, the plan lacks specificity because most of the operational details are site-specific and were not available at the time of writing. The site-specific accompanying documents should provide useful clarifications. In the context of RH-TRU waste characterization and from a performance point of view, the committee found that the general approach DOE is proposing is technically sound. However, Documents 1 and 2 do not present a performance-based plan as effectively as they could.

Concerning the plan's protection of worker health and safety, the committee recommends that the approved characterization plan not include overly stringent tolerable decision error rates that could negatively impact the sites' ability to manage worker risks. It is important to recognize that the allowable uncertainties in the final characterization plan approved by EPA and NMED may have an impact on generator sites' radiation protection programs.

Concerning compliance with regulatory requirements in the EPA Certification and RCRA Permit, the committee did not observe any requirement that was not addressed in DOE's characterization plan. In fact, the proposed characterization plan for RH-TRU waste addresses some requirements that are not under the relevant agency's purview. Moreover, the characterization plan for RH-TRU waste deliberately tracks as close as possible that for CH-TRU waste. The committee recommends evaluating whether existing characterization practices for CH-TRU waste, when applied to the characterization of RH-TRU waste, have an impact on the protection of the environment, health and safety of public and workers, and cost-effectiveness of the characterization program.

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Appendix A

Biographical Sketches of Committee Members

Eula Bingham, *Chair*, is professor of environmental health at the University of Cincinnati. Dr. Bingham's interests include risk assessment, regulatory toxicology, environmental carcinogenesis, and occupational health surveillance. Previously, she was a volunteer investigator at the National Institute of Environmental Health Sciences and assistant secretary of labor (Occupational Safety and Health Administration). She is the recipient of the Rockefeller Public Service Award from Princeton University (1980) and the first William Lloyd Award for occupational safety. Throughout her career Dr. Bingham has served on numerous national and international advisory groups, including advisory committees of the National Research Council, Food and Drug Administration, Department of Labor, National Institute for Occupational Safety and Health, National Institutes of Health, Natural Resources Defense Council, and the International Agency for Research on Cancer. These committees addressed research needs in health risk assessment and the potential health effects of environmental exposure to chemicals. In 1989, Dr. Bingham was elected to the Institute of Medicine. She earned her M.S. and Ph.D. in physiology from the University of Cincinnati.

Sanford Cohen is founder and president of S. Cohen & Associates (SC&A, Inc.), an energy and environmental consulting firm providing expertise in radiation sciences, management, health and safety analyses, communications services, and information management. He has managed several contracts for agencies of the U.S. government, including the Environmental Protection Agency, Centers for Disease Control and Prevention, Council on Environmental Quality, Congressional Office of Technology Assessment, Department of Energy, and Nuclear Regulatory Commission. Dr. Cohen is involved in regulatory guidance pertaining to environmental management (including Resources Conservation and Recovery Act/Comprehensive Environmental Response, Compensation, and Liability Act requirements), remediation of contaminated sites, safe disposal of hazardous wastes, site characterization in support of decontamination and decommissioning projects, recycling of scrap metal from nuclear facilities, electric and magnetic fields effects, and indoor radon. Prior to founding SC&A in 1981, Dr. Cohen was vice president and manager of Teknekron, Inc. (Washington Operations), and president of Teknekron Research, Inc., a consulting group working with the above government agencies. Dr. Cohen earned his B.S. in science engineering at Northwestern University and his Ph.D. in nuclear engineering at the University of Michigan.

Milton Levenson is an independent consultant and chemical engineer with more than 50 years of experience in nuclear energy and related fields. His technical experience includes work in technologies related to nuclear safety, fuel cycle, water reactors, advanced reactors, and remote control. His professional experience includes research

and operations positions at the Oak Ridge National Laboratory, Argonne National Laboratory, Electric Power Research Institute, and Bechtel. Mr. Levenson is a fellow and past president of the American Nuclear Society, a fellow of the American Institute of Chemical Engineers, and a recipient of the American Institute of Chemical Engineers' Robert E. Wilson Award. He is the author of more than 150 publications and presentations and holds three U.S. patents. Mr. Levenson served as chairman or committee member for several National Research Council studies, including the most recent study on the Waste Isolation Pilot Plant. He was elected to the National Academy of Engineering in 1976. He received his B.Ch.E. from the University of Minnesota.

Kenneth L. Mossman is professor of health physics and director of the Office of Radiation Safety at Arizona State University in Tempe, where he has also served as assistant vice president for research. Prior to his arrival at Arizona State University, Dr. Mossman was a faculty member of the medical and dental schools at Georgetown University in Washington, D.C., and was professor and founding chairman of the Department of Radiation Science of Georgetown's Graduate School. His research interests include radiological health and safety and public policy. Dr. Mossman has authored over 130 publications, including six books and proceedings related to radiation health issues. He has presented testimony before the U.S. House of Representatives and the U.S. Senate. Dr. Mossman served as president of the Health Physics Society and received its prestigious Elda Anderson Award, the Marie Curie Gold Medal, and the Founder's Award. He also served as a Sigma Xi distinguished lecturer. He has been a fellow of the Health Physics Society and the American Association for the Advancement of Science and has served on committees for the National Research Council, National Institutes of Health, Nuclear Regulatory Commission, Nuclear Energy Agency of the Organization for Economic Cooperation and Development (Paris), and the International Atomic Energy Agency (Vienna). Dr. Mossman earned a B.S. in biology from Wayne State University, M.S. and Ph.D. degrees in radiation biology from the University of Tennessee, and an M.Ed. degree in higher education administration from the University of Maryland.

Ernest Nieschmidt is director of the Laser Laboratory and adjunct associate professor of physics at Idaho State University, College of Engineering. His research interests span the development of a neutron activation analysis facility, sonoluminescence, and the destruction of hazardous organic components of mixed waste by free-radical chemistry. He is also involved in the development of the Laser Isotope Separation Laboratory to pursue research into the separation of isotopes using selective excited states induced by laser. For most of his career, Mr. Nieschmidt worked for different contractors at the Idaho National Engineering and Environmental Laboratory on techniques to assay radioactive and transuranic waste material. These included passive and active neutron interrogation, analysis of active gamma rays and gamma rays produced by neutron inelastic scattering, neutron capture, chronoimaging, time correlations, and the application of position-sensitive detectors. He has authored 106 publications related to topics in physical sciences. Mr. Nieschmidt earned his M.S. in physics from San Diego State College.

John Plodinec is director of the Diagnostic Instrumentation and Analysis Laboratory at Mississippi State University. His laboratory specializes in developing instrumentation for unusual environments and in characterizing processes and technologies under real-world conditions. Dr. Plodinec is an internationally recognized expert in waste management and glass science. He has made important contributions in several areas

of radioactive waste management, ranging from waste characterization to glass durability modeling. Prior to joining Mississippi State University, he worked for 22 years at the Department of Energy's Savannah River Site, where he collaborated in building and operating the first remote in-cell melter and served as primary technical lead for the product qualification program. In that capacity he oversaw the remote-handled transuranic waste streams produced by the Savannah River Site. He has authored over 90 publications, primarily on waste vitrification and thermodynamics of waste management. He holds a patent on a device to sample high-level waste and a patent on a slurry-feeding device for glass melters. Dr. Plodinec earned his Ph.D. in physical chemistry from the University of Florida.

Anne E. Smith is a vice president at Charles River Associates, an economics consulting firm. Dr. Smith is an expert in risk management, cost-benefit analysis, economic modeling, and integrated assessment of complex environmental and energy issues. Issues that she has analyzed include contaminated sites, global climate change, air quality, and emissions trading. Dr. Smith has developed and reviewed decision support tools for risk-based ranking of contaminated sites and for making risk tradeoffs in selecting remediation alternatives. She has submitted formal comments on the development of the Environmental Protection Agency Hazard Ranking System for identifying Superfund sites, has served on committees of the National Research Council on assessing contaminated site risk management activities, was a project leader in a review for the U.S. Congress of Superfund and Resources Conservation and Recovery Act concerns about the U.S. nuclear weapons facilities, and her testimony has been sought by committees of the U.S. Senate on air quality issues. Dr. Smith has a Ph.D. in economics from Stanford University, with a minor in engineering-economic systems. Prior to joining Charles River Associates, Dr. Smith was a vice president of Decision Focus Inc. She also served as an economist in the Environmental Protection Agency's Office of Policy Planning and Evaluation.

Appendix B

Information-Gathering Meetings

This appendix describes the three committee's information-gathering sessions throughout the study. The committee held an additional meeting devoted to the writing of this report.

B.1 First Meeting: August 1-2, 2001 (Columbus, Ohio)

Overview of the Battelle Columbus Laboratories: History, Remote-Handled (RH) Waste Inventory, Milestones, Plans for Characterization (James Eide and Craig Jensen, Battelle Columbus Laboratories)

Overview of Characterization Techniques for RH Waste (Greg Becker, Idaho Engineering and Environmental Laboratory)

RH waste at Los Alamos National Laboratory (Larry Field, Los Alamos National Laboratory)

RH Waste at Idaho National Engineering and Environmental Laboratory (Raj Bhatt, Idaho Engineering and Environmental Laboratory)

RH waste at Argonne National Laboratory-West (William Russ, Argonne National Laboratory)

RH Waste at the Hanford Site (Ken Hladek, Waste Management Federal Services of Hanford, Inc.)

RH Waste at Oak Ridge National Laboratory (Gary Riner, Oak Ridge National Laboratory)

Department of Energy (DOE)-Carlsbad Field Office. Introductions. Sponsor's Hopes and Expectations for the Study (Ines Triay, DOE-Carlsbad Field Office)

DOE Strategy for NMED [New Mexico Environment Department] and EPA [Environmental Protection Agency] Submission (Byran Howard, DOE-Carlsbad Field Office)

RH Inventory and Baseline (Joe Harvill, DOE-Carlsbad Field Office)

Repository Performance—RH Impact (Roger Nelson, DOE-Carlsbad Field Office)

Application of Acceptable Knowledge for RH/TRU [Remote-handled transuranic] Waste (Robert Kehrman, DOE-Carlsbad Field Office)

Data Quality Objectives and the State of the Art in Non-Destructive Assay/Non-Destructive Execution Techniques (Dan Taggard, Los Alamos National Laboratory)

The RH Program Audit Process—Emphasis on AK (Marlin Horseman, Carlsbad Field Office Technical Assistance Contractor)

Summary: RH-TRU Small—Volume-Small Impact (Ines Triay, DOE-Carlsbad Field Office)

Environmental Protection Agency Overview of the Regulatory Requirements: Criteria to Evaluate DOE's Characterization Plan (Scott Monroe, U.S. Environmental Protection Agency)

Public Comment Period

Field Trip to the Battelle Columbus Laboratories Site-West Jefferson North Campus

B.2 Second Meeting: October 4, 2001 (Albuquerque, New Mexico)

Introductions and Opening Remarks (Ines Triay, DOE-Carlsbad Field Office)

Updating the RH Inventory—Recent Information on RH Across the Complex (Joe Harvill, DOE-Carlsbad Field Office)

Doses from RH Waste Disposal: From Generator Site to WIPP Emplacement (Chuan Fu Wu, DOE-Carlsbad Field Office)

Transportation Requirements for RH TRU Waste (Brad Day, DOE-Carlsbad Field Office)

Proposed Standardized RH—TRU Characterization Methods for Non-Destructive Assay (Dan Taggart, Los Alamos National Laboratory)

AK Accuracy Analysis—How Well AK Does for CH Waste Characterization (Sean White and Robert Kehrman, DOE-Carlsbad Field Office)

Results of the Battelle Columbus Laboratories Surveillance—Confirming AK with Supplemental Measurements (Wayne Ledford, DOE-Carlsbad Field Office)

Summary and Open Questions and Answers (Ines Triay, DOE-Carlsbad Field Office)

View of the New Mexico Environment Department (Steve Zappe, New Mexico Environment Department)

RCRA [Resources Conservation and Recovery Act] Requirements According to the Environmental Protection Agency (David Neleigh, U.S. Environmental Protection Agency, New Mexico Office)

Views of the Environmental Evaluation Group (Matthew Silva, Environmental Evaluation Group)

The Other Peer Review: Findings and Conclusion (M.C. Kirkland, Institute for Regulatory Sciences)

Public Comment Period

B.3 Third Meeting: February 4-5, 2002 (Carlsbad, New Mexico)

DOE's Presentations on the New Characterization Plan; DOE's expectations from the Committee; How DOE Plans to Use the Committee's Final Report (various speakers, DOE-Carlsbad Field Office)

New Mexico Environment Department's Comments on the Committee's Interim Report (Steve Zappe, New Mexico Environment Department)

Environmental Evaluation Group's Comments on the Committee's Interim Report (George Anastas, Environmental Evaluation Group)

Environmental Protection Agency's Comments on the Committee's Interim Report (Scott Monroe, U.S. Environmental Protection Agency)

Public Comment Period

Field Trip to the WIPP Site

Appendix C

Excerpt from the Committee's Interim Report: Chapter 5

This appendix consists of an excerpt from the committee's interim report (Box C1). This report focuses on the July 2001 draft of DOE's proposed characterization plan (NRC, 2001b).

BOX C1 Excerpt from the Committee's Interim Report: Chapter 5

5
Committee's Preliminary Findings and Recommendations

The following are the committee's preliminary findings and recommendations concerning DOE's proposed characterization plan for RH-TRU waste. The committee also provides observations and issues for further clarification to help DOE in future drafts of the plan's supporting documents. As noted previously, findings and recommendations specific to Document 1 and Document 2 are based on the July 2001 draft.

Finding 1: With this new characterization plan for RH-TRU waste, DOE has an opportunity to introduce a truly performance-based characterization plan containing only requirements relevant to the long-term performance of WIPP and that have a safety, technical, or legal basis. **Recommendation: DOE should not include in its characterization plan unnecessary requirements that do not affect the long-term performance of the repository and that do not have a safety, technical, or legal basis.**

Rationale: The committee observes that characterization requirements for RH-TRU waste do not yet formally exist. Characterization requirements specific to RH-TRU waste will be finalized after DOE submits its characterization plan to EPA and NMED. The only legal requirements applying specifically to RH-TRU waste are those in the Land Withdrawal Act (see Chapter 3).

When DOE first applied for the certification of WIPP in 1996, it proposed a characterization plan for both CH- and RH-TRU waste. To facilitate the certification process, DOE imposed extra characterization requirements in the CH-TRU waste characterization plan, which was accepted by EPA and NMED (National Research Council, 2001, Appendix A1). DOE failed to realize that those characterization requirements would become a burden for the generator sites.[1] Also, DOE did not foresee that characterization requirements for CH-TRU waste would become a standard against which to evaluate the RH-TRU characterization plan. In fact, according to the information gathered by the committee, EPA and NMED intend to compare RH-TRU waste characterization requirements to those in the CH-TRU waste characterization plan, as explained in Chapter 4.

The draft RH-TRU waste characterization plan may be following the same path as the CH-TRU waste characterization plan. That is, by wanting to facilitate the certification process for RH-TRU waste, DOE is failing to ask the most important question about the characterization of RH-TRU waste: what is the purpose of waste characterization for WIPP? The answer is the following: to evaluate the impact of waste components on the long-term performance of the repository. The

committee recommends that existing requirements for CH-TRU waste, when applied to the characterization of RH-TRU waste, should be evaluated on the basis of their impact on the performance of the repository. The existence of regulatory requirements in the CH-TRU waste characterization plan does not imply that the same requirements should be included in the characterization plan for RH-TRU waste.

Finding 2: The committee questions the relevance of some of the requirements in the RH-TRU waste characterization plan to DOE's stated objective. According to the performance-based evaluation of RH-TRU waste by Sandia National Laboratories, presented in the characterization plan, none of the RH-TRU waste components have an effect on the long-term performance of the repository. **Recommendation: DOE should evaluate characterization requirements in the proposed plan against safety, their impact on the performance of the repository, and regulatory compliance.**

Rationale: The committee questions the relevance of some of the requirements proposed in the characterization of RH-TRU waste. For example, the detection of prohibited items, the determination of metal content, and the attribution of waste summary category groups do not seem to be characterization requirements based on the long-term performance of the repository (see examples below). According to the performance-based evaluation of RH-TRU waste by Sandia National Laboratories (Appendix 1 of Document 1 and Attachment B of Document 2), none of the RH-TRU waste components have an effect on the long-term performance of the repository. Many of the requirements in the proposed characterization plan of RH-TRU waste derive from the CH-TRU waste characterization plan described in WIPP's RCRA permit and EPA's certification. Concerning the CH-TRU characterization plan, the 1998 Committee found that "many requirements and specifications concerning waste characterization and packaging lacked a safety or legal basis"[2] (National Research Council, 2001, page 4). The present committee also recognizes that many such requirements were self-imposed and should be removed from the characterization plan of RH-TRU waste. The committee acknowledges that DOE's approach to use mostly AK without requiring 100 percent confirmatory activities is a positive step in this direction. However, the characterization plan's supporting documents should provide an analysis of the legal and safety requirements proposed for RH-TRU waste on the basis of their impact on the performance of the repository. Of course, legal requirements, like those in the Land Withdrawal Act, cannot be changed or removed, but these legal requirements are few and not excessively restrictive. The committee provides the following examples to support this finding and recommendation:

Example 1: The list of prohibited items contained in the RCRA permit for CH-TRU waste may not be appropriate for RH-TRU waste when the risks associated with hazardous chemical waste are balanced against radiological risks and costs. In Documents 1 and 2, there is no analysis of the safety implications of the prohibited items in WIPP. It is important to analyze the yet-undefined safety implications of these prohibited items and balance these implications against potential radiological risks to workers and associated costs of identifying prohibited items in RH-TRU waste. Such an analysis would be helpful to DOE in comparing the risks workers are exposed to and the associated costs of characterizing RH-TRU waste for prohibited items. The results of the analysis will support and strengthen DOE's RH-TRU waste characterization plan or point out deficiencies in it.

Example 2: In the CCA, DOE wrote: "Ferrous and ferrous-alloy metals (and their corroded products) provide the reactants that reduce radionuclides to lower and less-soluble oxidation states. As discussed in Appendix WCA [Waste Characterization Analysis], the anticipated quantity of these metals to be emplaced in WIPP is two to three orders of magnitude in excess of the quantity required to assure reducing conditions. The waste containers supply more than enough iron to provide adequate reductant. Therefore, no upper or lower limit need be established for the quantity of ferrous and ferrous-alloy metals that may be emplaced, beyond the present projection of containers" (DOE, 1996a, Appendix WCL.2). Nonetheless, in the CCA, DOE imposed a lower limit for ferrous material in the repository at 2×10^7 kg. Nowhere else in the CCA is this limit discussed or justified. This self-imposed limit has somewhat severe consequences because it requires DOE to use steel containers throughout the disposal phase. This example of

a self-imposed requirement is acknowledged by DOE-CBFO itself. In fact, DOE informed the committee of its intention to request the elimination of this limit during the re-certification process (DOE-CBFO, 2001f).

Example 3: Waste summary category groups indicate the final form of the waste as it is emplaced in WIPP. These groups are: homogeneous waste, soils and gravel, and debris waste. The CH-TRU waste requirements for NMED direct DOE to attribute a summary category group to each waste container. However, this information does not have any impact on the long-term performance of the repository. According to the information gathered thus far, this information is not used by NMED in any type of decision-making process concerning RH-TRU waste in the repository. Therefore, the committee questions why this requirement is being included in the RH-TRU waste characterization plan. A similar recommendation was made by the Institute for Regulatory Sciences peer review on DOE's characterization plan.[3]

Finding 3: The RH-TRU waste draft characterization plan reviewed by the committee does not clearly present DOE's stated objective of characterizing waste based on its impact on performance of WIPP, while protecting worker safety, reducing costs, eliminating unnecessary self-imposed requirements, and complying with regulatory requirements. In the committee's opinion, the documents reviewed do not put forward a performance-based characterization plan. **Recommendation: In the supporting documents, DOE should clarify the objectives of the characterization plan and how to achieve them.**

Rationale: DOE presented the objectives of its characterization plan for RH-TRU waste during the two information-gathering meetings with the committee. The committee expected these objectives to be clearly presented and pursued in Documents 1 and 2, but this was not the case. Document 2 mentions that DOE's characterization plan adopts a "Performance-Based Measurement System" but the committee struggled to find a clear explanation of this concept and its implementation in the supporting documents. The committee found a clear explanation of a "performance-based characterization plan" in EPA's Compliance Application Review Document No. 24, concerning waste characterization. This document reads: "DOE must provide waste inventory information for use in the performance assessment, including the radionuclide content of waste and the physical and chemical components that may affect disposal system performance" (EPA, 1998, page 21-1). EPA also defines a "waste characteristic" as "a property of the waste that has an impact on the containment of waste in the disposal system" (40 CFR 194.2). DOE's stated objective is in agreement with EPA's statements concerning waste characterization. However, the supporting documents do not explicitly outline the state objectives and the way DOE intends to implement its "performance-based characterization plan." The committee acknowledges that, in Attachment B of Document 1 and in Appendix 1 of Document 2, DOE provides two performance assessment analyses of RH-TRU waste in WIPP. However, these analyses and the performance assessment tool are not fully used to support a performance-based characterization plan. The performance assessment tool played a central role in WIPP's certification process. If the characterization plan were properly built upon performance assessment results, it would be easier for EPA and NMED to assess the plan and it could add credibility to the proposed characterization approach.

Finding 4: From the information gathered during the two committee meetings, it appears that most of the RH-TRU waste to be disposed of at WIPP will be newly generated waste, repackaged waste, or waste that has already been characterized following the CH-TRU waste characterization plan. Therefore, most RH-TRU waste does not need confirmatory measurements because the information collected during repackaging or generation can meet characterization requirements. **Recommendation: In the documents supporting its characterization plan, DOE should discuss the relative volumes of retrievably stored waste and newly generated waste in the context of the different qualities of AK. DOE should also consider the impact of these volumes and AK differences on the characterization plan.**

Rationale: According to DOE, about 80 percent of the RH-TRU waste inventory will be waste to be generated in the future or existing waste that must be repackaged (see Chapter 2). For this

large amount of waste, the information constituting AK will be collected during the generation or the repackaging of the waste. The committee agrees with DOE that AK for newly generated waste can meet the data quality objectives developed under the new RH-TRU waste characterization plan. Therefore, for about 80 percent of RH-TRU waste, confirmatory measurements may not be necessary as long as this waste is generated or repackaged using the approved quality assurance program plan.

Documents 1 and 2 do not mention that over 80 percent of the RH-TRU waste inventory will be newly generated or newly packaged waste. The committee recognizes that DOE made the distinction between the two qualities of AK (Attachment A, Document 1) for newly generated waste and retrievably stored waste. However, the committee suggests that the waste characterization plan distinguish not only AK qualities but also the relative volumes of newly generated waste and retrievably stored waste. This information may help DOE, the regulatory agencies, and the public to frame the context of the characterization plan for RH-TRU waste. If the volume of RH-TRU waste represents between 1 and 4 percent of the volume of TRU waste, and 80 percent of RH-TRU waste will meet AK, then only between 0.2 and 0.8 percent of the waste will need confirmatory activities for AK. This is an important observation, and it could have a substantial impact on characterization requirements proposed for RH-TRU waste.

Finding 5: There is substantial variability among RH-TRU waste generator sites, including:

- variability in the composition of the waste streams,
- variability in the extent of AK available,
- variability in the characterization and repackaging facilities available, and
- variability and uncertainties in the current and projected inventories of RH-TRU waste.

DOE's current characterization plan allows some flexibility to the sites, but it does not account explicitly for the above variability. **Recommendation: The RH-TRU waste characterization plan should recognize the large variabilities from site to site and should ensure sufficient flexibility to accommodate them. However, characterization activities that share common elements across sites should be standardized.**[4]

Rationale: The committee received the information about the RH-TRU waste inventories during its two information-gathering meetings. These data are reported in Tables 1 and 2 in Chapter 2. This information is barely present, as supplemental information, in Document 2. In the supporting documents, the committee expected a discussion about RH-TRU waste inventories at the different generator sites, their characterization plans, and capabilities. Including this discussion in Documents 1 and 2 could help DOE to recognize both the large variances from site to site and common elements across sites. Flexibility is important to adapt each characterization requirement to the site's RH-TRU waste inventory and characterization facilities. A rigid, overly prescriptive characterization plan may lead to unnecessary radiation exposures to workers and characterization costs. For example, small sites that do not have adequate characterization facilities may find themselves in a difficult situation if the characterization plan mandates specific confirmatory activities, even in the presence of adequate AK. If the site must perform confirmatory measurements or visual examination in a hot cell it would have to ship its waste to a different site[5] equipped with a hot cell or use a mobile hot cell. Therefore, the added costs of such confirmatory measurements could be significant. The committee also recommends that common elements among the sites be standardized to facilitate characterization compliance verifications and, possibly, reduce characterization costs.

Finding 6: The requirements to qualify information collected on each waste stream, whether by AK or by any other method described in 40 CFR 194.22(b), have not been established with any specificity in the supporting documents. **Recommendation: DOE should revise the supporting documents by adding clear and technically defensible data qualification requirements for its RH-TRU waste characterization plan. Additionally, each data quality objective should have a safety, technical, or legal basis.**

Rationale: To optimize waste characterization activities, it is important to define how generator sites will use AK, radiography, or visual examination to characterize their RH-TRU waste streams, the data qualification requirements, and the procedures to meet those requirements. This recommendation is also consistent with the recommendation of a second peer review on DOE's characterization plan.[6] The committee provides below an example of a missing or an unclear technical basis for one of the data quality objectives in Document 1.

Example: In Document 1, DOE does not provide a technical basis for the requirement that the quantification of the total activity "must be within a factor of 5 of the true value, with a confidence value of 95 percent." DOE provided an explanation during an information-gathering meeting: "The need to accumulate information regarding the total activity of RH-TRU waste is driven by limits set forth in the Land Withdrawal Act. The Land Withdrawal Act limits are derived from original DOE estimates about the RH-TRU inventory. The Transuranic Waste Baseline Inventory Report indicates that the total RH-TRU inventory to be disposed of at WIPP corresponds to a total activity of approximately one million curies (TWBIR, 1996). This corresponds to approximately one-fifth of the Land Withdrawal Act limit (5.1 million curies), hence the factor of five. Allowing an uncertainty of a factor of five (with a confidence level of 95 percent or greater) ensures that, even if the cumulative measurement of the estimated one million curies of RH-TRU waste activity were offset by a factor of five and biased low, the Land Withdrawal Act limit would not be violated (Nelson, 2001). The committee observes that, just because DOE expects to emplace one-fifth of the curies specified in the Land Withdrawal Act, this does not justify a requirement that the measured activity for a unit be within a factor of five of the "true value."

Finding 7: Available estimates of worker exposure and characterization costs for RH-TRU waste are scarce and may not be representative of all RH-TRU waste generator sites. **Recommendation: To better develop and support its characterization plan, DOE should provide more detailed and site-specific estimates of worker exposure and characterization costs for RH-TRU waste. The characterization plan should clearly demonstrate how it minimizes radiation exposure to workers and associated costs.**

Rationale: Since the characterization plan for RH-TRU waste is not yet finalized, information on worker exposure and characterization costs for RH-TRU waste is scarce. The only data available are from BCL and LANL, and they may not be representative for all RH-TRU waste generator sites (see Chapter 2). However, exposure and cost estimates can be calculated quite well, particularly if the uncertainties become a part of the results. The committee found the risk/cost impact study in Document 2 (Supplemental Information) to be very informative. However, this study only considered three characterization scenarios to estimate exposure risks and costs: the full characterization used for CH-TRU waste (see Appendix A), AK only, and visual or radiographic examination. A detailed risk perspective of worker exposure and costs could be very illuminating in developing characterization requirements and in adding credibility to the plan. The approach to estimate exposures would be to structure different scenarios, rank the scenarios on the basis of the supporting evidence, and calculate the exposures and doses. This type of dose and exposure information would add much to the discussion of the differences between CH- and RH-TRU waste characterization plans. An equivalent approach could be adopted to better estimate characterization costs. A similar recommendation was also provided by Restrepo and Millard.[7]

Finding 8: DOE's characterization plan calls for application of specific technologies, such as X-ray radiography, to provide confirmatory data. The committee could not determine the effectiveness of these technologies in characterizing the high-dose-rate fraction of RH-TRU waste containers. **Recommendation: DOE should provide complete and defensible justification for the technologies proposed for obtaining confirmatory data and provide evidence of their effectiveness.**

Rationale: DOE specifically mentions "X-ray scanning of waste containers to identify and verify waste contents" (Document 1, Attachment A, page 15). Given the importance placed on radiography to determine the presence of prohibited items, the characterization plan should clarify

and support the information on the method's effectiveness in high radiation fields expected for RH-TRU waste. In general, DOE should provide complete and defensible justification for the technologies proposed for obtaining confirmatory data and provide evidence of their effectiveness. This issue was also raised by NMED during the committee's information-gathering meeting (Zappe, 2001). This recommendation is also consistent with a recommendation by the RSI peer review on DOE's characterization plan.[8] DOE also concurs on this matter by stating: "Though DOE collected some data and analysis indicating that there are no fundamental obstacles to radiographing RH-TRU wastes, there has not been a systematic demonstration of that capability. As a consequence, there is lingering doubt regarding its feasibility in general. The simplest means to put these doubts to rest is to design and perform a systematic evaluation" (Taggart, 2001e). The committee supports this suggestion.

Observations and Issues for Further Clarification

To improve understanding, corroborate, and add credibility to its characterization plan, DOE should clarify the following points in its supporting documents:

Observation 1: The committee observes that the information in the supporting documents for the RH-TRU waste characterization plan is sometimes convoluted, difficult to understand, difficult to find, and repetitious. Examples are provided below.

Example 1: DOE presents an analysis that shows that the gamma-emitting radionuclides in RH-TRU waste will have a minimal impact on the long-term performance of the repository. DOE also presents an analysis that shows that RH-TRU waste components (metals, free liquids, cellulosics, plastic, rubber, and hazardous material) will have a minimal impact on the repository performance. These analyses are presented in Attachment B of Document 1 and in Appendix A of Document 2, respectively. The body of the text supporting the characterization plan barely refers to these two key analyses. DOE should give these analyses a more prominent role in Documents 1 and 2 and explicitly refer to these analyses to support its characterization plan.

Example 2: Some aspects of the characterization plan are difficult to evaluate because terms such as "representative selections" and "appropriate samples" are not properly defined.

Example 3: The plan, as described in Documents 1 and 2, lacks specificity. For example, for the CPR and free water, when is AK and when is radiography employed? Are surveys conducted by the same mechanisms for lower and higher surface dose rates? What is the link between the surface dose rates and the total curies by waste stream? How is a waste stream determined to be suitable for disposal at WIPP (i.e., transuranic waste of defense origin)? How are the ten radionuclides important to the long-term performance of WIPP (see Sidebar 2) identified and quantified?

Observation 2: There are conflicting statements and discrepancies between Document 1 and Document 2. The committee acknowledges that the two documents address different agencies and requirements. However, to improve the understanding and add credibility to its characterization plan, the documents could be made consistent with each other and conflicts and discrepancies resolved whenever possible. The committee provides three examples of conflicts or discrepancies between Document 1 and Document 2.

Example 1: Document 1 states that the differences between the RH- and CH-TRU characterization plans are not significant: "Because the RH-TRU waste characterization program does not represent a significant change to the existing certification, the 40 CFR 194 process will be the compliance mechanism for obtaining EPA's approval of each individual TRU waste site for disposal of its RH-TRU waste at WIPP" (Document 1, EPA01 Notice, page 6). However, Document 2 finds the differences significant: "The proposed modification is classified as a Class 3 permit modification per 20.4.1.900 NMAC…As indicated above, the additional provisions being requested in this permit modification, deemed necessary to provide for management, storage, and disposal of RH-TRU wastes, are indeed substantial and therefore meet the criteria and intent of a Class 3 modification" (DOE, 2001b).

Example 2: In Document 2, DOE allows for estimates of CPR, metals, and volatile organic compounds in the characterization of these waste constituents. Yet, DOE requires measurements without any specification of allowable uncertainties of the quantities of free water. This appears to be in conflict with the analysis in Document 1, Appendix A, which concludes that the performance of the repository is insensitive to the water content of the waste.

Example 3: Some of the statements made in Document 2 appear to contradict the approach to waste characterization discussed in Document 1. For example, on page 2-5 of ITEM 2, Document 2, DOE states: "This demonstrates that the waste material parameter weights and amount of free liquid for RH-TRU waste are not needed to ensure the integrity of the repository; therefore, waste characterization activities to identify these parameters are not necessary." Yet in Document 1, DOE lays out a program to measure the amount of free liquid in each waste container. The supporting documents should clearly specify that free liquid limits are necessary to meet transportation requirements and are not directly relevant to repository performance.

Observation 3: It is not clear how visual examination and radiography can differentiate all prohibited from non-prohibited items. For example, visual examination and radiography cannot distinguish between corrosive and non-corrosive liquids, whereas AK may provide records of the existence of such liquids in the waste. Therefore, AK may be a better indicator of some of the currently prohibited items than visual examination and radiography.

Closing Remarks

The statement of task directs the committee to provide recommendations based on scientific and technical considerations. The committee recognizes that some of its recommendations may not be implemented because of regulatory or policy decisions, which may not be based on scientific or safety considerations. These decisions ultimately belong to the regulatory agencies. The committee acknowledges and supports DOE's endeavors to improve worker safety, reduce costs, and eliminate unnecessary self-imposed requirements. However, the documents prepared for EPA and NMED to present the characterization plan for RH-TRU waste do not address these goals as effectively as they could. The committee acknowledges that DOE has been extremely responsive in revising the characterization plan on the basis of discussions during the information-gathering meetings. Also, staff of DOE-CBFO efficiently provided additional information whenever requested. The committee looks forward to future drafts of the characterization plan for RH-TRU waste. The committee will hold two more meetings to discuss the next draft of the characterization plan (if available), further address issues identified in this interim report, and develop its final report, which will be issued in the summer 2002.

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[1]DOE, during the second committee meeting, declared that the "contact-handled TRU waste characterization program is inefficient and costly" (DOE-CBFO, 2001d).

[2]According to the 1998 Committee, the requirements that do not have a technical basis are: sampling and analysis of homogeneous waste, headspace gas sampling and analysis, and visual examination procedures to characterize CH-TRU waste (see Chapter 4).

[3]The RSI peer review recommended: "DOE should evaluate the necessity of identifying waste streams by EPA's Hazardous Waste Numbers or Characteristics. If there is no impact on WIPP performance and integrity, the DOE should work with the regulatory agencies to remove this requirement" (RSI, 2001, page 77).

[4]According to the information provided by DOE, DOE is already amending its characterization plan to standardize as much as possible common elements across the complex.

[5]Shipments from site to site are allowed before the waste characterization plan is approved because DOE's waste characterization plan applies only to waste shipped to WIPP.

[6]The RSI recommended the following: "A detailed procedure for determining whether there is sufficient AK available on a waste should be developed as part of the permit application. This procedure should be consistent across all waste generating sites…[A] detailed procedure should be provided to go to other characterization methods if AK is found to be insufficient" (RSI, 2001,

page 77).

[7]The authors of the risk/cost analysis study in Document 2 recommend that "a detailed risk/cost impact analysis should be performed for individual site generators to quantify waste characterization option costs, potential worker dose rates, worker risks, and overall impact. This would facilitate a more rigorous evaluation of risks and costs for characterization options" (Restrepo and Millard, 2001, page iii).

[8]In its peer review, the RSI recommended: "More detail and specificity on WAC [waste acceptance criteria] using AK, VE [visual examination], and radiography (including types of instrumentation to be used) should be provided in the permit application" (RSI, 2001, page 77).

NOTE: References in this appendix apply to the committee's interim report (NRC, 2001b).

Appendix D

DOE's Response to the Committee's Interim Report

In response to the committee's interim report, the Department of Energy (DOE)-Carlsbad Field Office transmitted a summary of proposed resolutions or action items for the following draft of its characterization plan.

D.1 DOE's Response

DOE's response to the committee's interim report consists of two following two elements: 1) a letter containing DOE's proposed resolution and action items as a result of the committee's findings and recommendations and 2) an attachment to the letter, named Attachment 1. The letter and its attachment are presented in Boxes D.1 and D.2, respectively.

BOX D.1 DOE's Response to the Committee's Interim Report

PROPOSED RESOLUTION/ACTION ITEMS

Concerning NAS Finding and recommendation #1: We have reevaluated the characterization information needs consistent with this recommendation. The process considered long-term repository performance information needs, safety and technical considerations, regulatory requirements, and legal requirements and led to the development of a discreet list of Characterization objectives. Attachment 1 is the result of this effort.
Attachment 1 [see below] is being used to revise the Characterization Implementation Plan in the EPA submittal, as well as the WAP in the RCRA submittal. Attachment 1 also indicates whether or not we believe the characterization objectives require confirmation, and the methods we will propose in the submittal documents to obtain the characterization information.

Concerning NAS Finding and recommendation #2: The aforementioned Attachment 1 is the result of the reevaluation process we conducted as proposed by the NAS WIPP Panel.

Example 1: The list of prohibited items in the draft WAP (July 2001) will not be included as a specific list in the next draft WAP. With the exception of residual liquids, these "items" will be excluded from the list of prohibited items, but will continue to be dealt with by determining the hazardous waste numbers and prohibiting D001, D002, and D003. This effectively drives the decision from the container level to the stream level where hazardous waste code assignment decisions are typically made. The hazardous waste code(s) determination will be accomplished using AK. The 1% free liquid criteria was retained as a RCRA operational compliance consideration rather than for safety or performance reasons. The next draft WAP will be modified consistent with this change.
See Attachment 1 for the rationale and justification for hazardous waste numbers and residual liquids.
Example 2: CBFO may, in the future, choose to remove the metals limits set in the CCA.

Until this change is made, the proposed RH-TRU characterization program must continue to require tracking of metals. Contrary to the NAS statement ("severe consequences") the CBFO believes the "limits" do not impact the program, and the proposed characterization method of counting containers is simple to implement. For other reasons steel is the preferred material for waste containers, but the "limit" does not prohibit the use of other materials. The DOE anticipates that a minor amount of CH-TRU waste and no RH-TRU waste will be shipped in non-metal containers. We therefore do not view the consequences of the limitation as severe.

Example 3: The NAS is correct in pointing out that Summary Category Groups (SCG) have no impact on long-term repository performance. SCG is in the current CH RCRA Permit in order to affect a decision on what kind of waste analysis is required by the Permit (S3000 and S4000 waste streams must be sampled and chemically analyzed). No sampling and analysis is proposed for RH-TRU waste, however the SCG requirement is retained in the program because it allows for an easy method of accounting for cellulosics, plastics, and rubber (CPR), which are related to repository performance. Since SCG determination is relatively easy and is part of the EPA program anyway, it will be included in the RCRA program as an activity complying with 40CFR264.13.

Concerning NAS Finding and recommendation #3: The re-evaluation discussed for Finding #1 considered characterization objectives from a performance driven perspective as well as from regulatory and legal aspects. *Nearly all resulting characterization objectives are unrelated to repository performance or to safety/technical considerations.*
New supporting documentation will clearly show the basis for each characterization objective.

Concerning NAS Finding and recommendation #4: Consistent with this recommendation, DOE is preparing completed characterization documents for three major RH-TRU sites. These documents will be submitted directly to the EPA for its approval through the formal rulemaking process, and they will also be submitted to the NMED as examples along with a new draft request for RCRA Permit modification.

Concerning NAS Finding and recommendation #5: Submittals to both the NMED (RCRA compliance) and the EPA (40CFR194 compliance) are being redrafted to balance flexibility with standardization as appropriate.
The characterization documents discussed for Finding #4 will provide detailed inventory information which will assist in determining what aspects of the program can be standardized and how to allow for flexibility in site programs.

Concerning NAS Finding and recommendation #6: This Finding and Recommendation is also fully addressed by the Resolution discussed for Finding #1.
DOE agrees with the Panel that the former DQO associated with Total Activity is legally based and not technically based. As a result of the re-evaluation process described in the Resolution to Finding #1, it will be removed from the draft regulatory submittal documents.

Concerning NAS Finding and recommendation #7: After re-evaluating the approach to RH-TRU waste characterization, as discussed in Finding #1, DOE continues to believe that nearly all required RH-TRU waste characterization can be accomplished using AK. Therefore worker exposure is no longer a significant issue related to RH-TRU waste, and eliminating most characterization physical activities has minimized program costs.
Characterization activities may still be required on a very small percentage of the RH-TRU waste inventory, but these activities will always be conducted in such a way as to minimize worker exposure.

Concerning NAS Finding and recommendation #8
As suggested by the Panel, DOE will complete the "systematic evaluation" recommended by Taggart to conclusively demonstrate that current RTR technology is adequate for RH-TRU waste characterization use; however, the revised characterization program no longer requires that

confirmatory data be generated. For the minimal use of NDA and RTR that will still be required in the overall program, the standard technologies currently being employed in the CH-TRU waste program are more than adequate.
The RH Team recommended program (see Attachment 1) calls for NDE to be used *only to detect 1% residual liquid and only for a small percentage of the total RH-TRU waste inventory* (most RH-TRU waste will be repackaged or newly generated). Resolution of current RTR systems, even in high radiation fields, is adequate for this determination.

Concerning NAS Observation #1: Example 1: The next draft of the regulatory submittals will clearly reference the supporting analyses, and each characterization objective will have an explicit pointer to its basis.

Example 2: The redrafted documents will be purged of imprecise language and important terms will be properly defined.

Example 3: After the re-evaluation discussed in Finding #1, CPR will not be measured, it will be conservatively assigned a weight (based on the analyses referred to in Observation #1). However, in general, other techniques are to be employed only for the few (and usually small) waste streams for which there are insufficient AK. There is no direct link between surface dose rate and total curies that is used by the proposed program, however in some individual cases for some individual waste streams, if enough is known about the waste stream (AK), surface dose rate measurements can be used to adequately estimate the activity. The Defense Waste determination for RH-TRU waste will follow the acceptable precedent that has been established in the CH-TRU waste characterization program. The modified EPA submittal will provide detail concerning the TRU versus LLW determination. The ten radionuclides *are not important to repository performance* (See RH Impact Assessment included in the EPA submittal). This requirement will therefore not be included in the revised submittal document.

Concerning NAS Observation #2: Example 1: The statement made in Document 1 (the EPA submittal) was made in the context of what is significant relative to 40CFR194 and also allows that the EPA has the final decision regarding significance. The statement made in Document 2 (the RCRA submittal) was made in the context of what is significant relative to 20.4.1.900 NMAC. In addition, the NMED has made it very clear that they consider this to be a Class 3 modification.

Example 2: The modified Documents will no longer require estimates for CPR, metals, or VOCs. Some method of assurance that there is less than 1% residual liquids in a waste container is still required to address RCRA operational requirements, however no statement of allowable uncertainties is derived since there is no technical basis for an uncertainty statement.

Example 3: The redrafted supporting documents will make it clear that the origin of the 1% liquid requirement is from transportation, has no bearing on repository performance, and is only indirectly related to RCRA regulatory requirements.

Concerning NAS Observation #3: *The NAS is correct in the observation that VE and RTR are inadequate techniques for distinguishing the list of prohibited items in the previous draft.*
RTR or VE are suitable techniques for detecting and distinguishing residual liquids, and the re-evaluation requested in Finding #1 has determined that RTR or VE will only be used for that purpose. See also the Resolution to Finding #8.

NOTE: This table has been edited for formatting purposes. The emphasis (italicized text) was added by DOE-Carlsbad Field Office.
SOURCE: DOE (DOE-CBFO, 2002).

BOX D.2 Attachment 1 Accompanying DOE's Letter to the Committee (see Box D.1)

ATTACHMENT 1
RH-TRU WASTE CHARACTERIZATION PROGRAM

Objectives, Characterization Methods, Implementation Standards
RH-TRU Team Rationale and Justification

Introduction

The RH-TRU Team has reached consensus on what the basic elements of an RH-TRU waste characterization program should consist of (i.e., characterization objectives, characterization method, and implementation). This consensus was achieved by taking a "performance based approach" and examining from the "ground up" what the minimum characterization requirements should be to satisfy 40CFR194.24 (EPA) requirements and RCRA (NMED) requirements. Previous recommendations, findings, and observations from RSI and NAS/NRC reviews were heavily considered, and as the re-evaluation process progressed, each potential requirement was examined with respect to its basis; that is safety, repository performance, legal, or regulatory.

Table 1 for EPA requirements and Table 2 for NMED requirements present the RH-TRU Team consensus recommendations of what basic characterization elements should be used to build an EPA and NMED compliant RH-TRU waste characterization program. This paper explains the RH-TRU Team rationale or justification for each entry in the attached Tables. [see Box D.1]

Table Definitions (Columns) and Entry Justification/Rationale

There is a separate Table for the EPA related RH-TRU waste characterization elements and the NMED related RH-TRU waste characterization elements, however the column definitions are identical for both.

Characterization Objectives: This column lists the necessary overall program objective that must be accomplished by collecting waste characterization information. It is the basic question being asked and stems from safety, repository performance, regulatory, or legal considerations.

EPA Characterization Objectives

1. *Account for ferrous and non-ferrous metals*, is related to repository performance in that the CCA Appendix WCL requires a minimum of metals (20 million kilograms of ferrous metals and 2,000 kilograms of non-ferrous metals) be included in the final WIPP repository inventory. Thus it is necessary to account for disposed metals, by some means, in order to ensure that the specified minimums are emplaced. Once the minimum is achieved, no further accounting is necessary.

2. *Account for Cellulosics, Plastics, Rubber (CPR)*, is related to repository performance in that the CCA Appendix WCL limits total WIPP repository disposed inventory of CPR to a maximum of 20 million kilograms. Thus it is necessary to account for disposed CPR inventory, by some means, in order to ensure that the 20 million kilograms is not exceeded.

3. *Account for Free Water*, is a regulatory expectation that the RH-TRU Team believes is prudent to meet even though no amount of free water in the RH-TRU waste will impact repository performance. Note that CCA Appendix WCL.5 states that, "Consequently, there is no need to monitor water in the waste for compliance with 40 CFR § 194.24(c)." The RH-TRU Team recommends that free water in RH-TRU waste be accounted for by some means.

4. *Account for TRU Activity*, is a regulatory expectation that the RH-TRU Team believes is prudent to meet even though, for RH-TRU waste, it is unrelated to repository performance. Note that CCA Appendix WCL.1 states that, "The total activity of the waste is not important for 40CFR194.24(c), because the containment requirements are normalized to the initial inventory." The relationship of TRU activity to total activity is also explained in WCL.1, "The total activity of the waste at emplacement and during the entire 10,000-year performance period is dominated by the activities of four emplaced radionuclides: Am241, Pu238, Pu239, and Pu240." The RH-TRU Team recommends that TRU activity in RH-TRU waste be accounted for by some means.

5. *Ensure waste is TRU (activity ≥100 nCi/gm)*, is a legal requirement from the WIPP Land Withdrawal Act (LWA). The Team is in agreement that it is prudent to include it in the EPA Table, even though some members of the Team do not believe it to be of EPA regulatory concern.

6. *Account for Total Activity*, is related to the LWA legal requirement that WIPP final RH-TRU waste inventory be limited to 5.1 million total curies. Thus it is necessary to account for disposed RH-TRU waste total activity, by some means.

7. *Limit canister activity to <23 curies per liter*, is a LWA invoked legal requirement. This limit is specifically included in 40CFR194 as an EPA regulated Characterization Objective.

8. *Limit Surface Dose Rate of each container to <1000 rem/h*, is a LWA invoked legal requirement. This limit is specifically included in 40CFR194 as an EPA regulated Characterization Objective.

9. *Limit WIPP inventory to <5% by volume for >100 rem/h on a canister basis*, is a LWA invoked legal requirement. Thus canisters with surface dose rate exceeding 100 rem/h must be identified by some means.

10. *Ensure waste is RH (surface dose ≥200 mrem/h)*, is a de facto legal requirement of the LWA. The Team is in agreement that it is prudent to include it in the EPA Table, even though some members of the Team do not believe it to be of EPA regulatory concern.

NMED Characterization Objectives

1. *Assign Hazardous Waste Numbers*, is related to the regulatory requirement to comply with the terms and conditions of the WIPP Hazardous Waste Facility Permit (HWFP). The WIPP HWFP specifically prohibits hazardous wastes with the numbers D001, D002, and D003. Some other hazardous waste numbers have not been applied for and therefore are not allowed by the HWFP.

2. *Identify Physical Form*, is a regulatory requirement that is indirectly related to 40CFR264.13.

3. *Limit residual liquids to <1% volume of RH canister (or drum for 160B)*, is related to a regulatory requirement to provide secondary containment at the WIPP for potential spills. An analysis justifying the 1% for CH-TRU waste at the WIPP is part of the HWFP record, however a similar analysis has not been done for RH-TRU waste. The RH-TRU Team believes it is prudent to include this limit as an RH-TRU waste requirement also.

   Note 1: The current HWFP for CH-TRU waste also includes residual liquid restrictions for internal containers (i.e., "Waste shall contain as little residual liquid as is reasonably achievable by pouring, pumping and/or aspirat-ing, and internal containers shall contain less than 1 inch or 2.5 centimeters of liquid in the

bottom of the container.”). The RH-TRU Team did not retain these requirements for RH-TRU waste since their main purpose was related to eliminating the need to characterize liquids in internal containers (i.e., containers are RCRA “empty”). NMED Characterization Objective Number 1, *Assign Hazardous Waste Numbers*, requires the assignment of appropriate hazardous waste codes to containers, and the driver to further characterize liquids is eliminated.

Note 2: In addition to liquids the September 2001 draft RH-TRU waste WAP included the following “prohibited items:”

- Pyrophoric materials
- Incompatible waste
- Explosives and compressed gases
- PCBs with concentrations greater-than-or-equal-to 50 ppm

The RH-TRU Team concluded that it is unnecessary to specifically identify these “items” in the WAP or as specific Characterization Objectives. Pyrophoric materials, explosives and compressed gases fall under the RCRA definition of reactives (D003) and therefore are precluded by NMED Characterization Objective number 1, *Assign Hazardous Waste Numbers*. All wastes with HWFP acceptable Hazardous Waste Numbers have been demonstrated to be compatible, and therefore NMED Characterization Objective number 1, *Assign Hazardous Waste Numbers*, assures that there are no incompatible wastes. PCBs are subject to EPA regulation under TSCA and are regulated regardless of whether or not they are included in a RCRA permit as a prohibition. Therefore the RH-TRU Team has not included any of these “prohibited items” in the proposed RH-TRU waste characterization program as specific characterization objectives.

4. *Identify and Quantify VOCs*, is related to health and safety considerations derived from other (than RCRA) EPA release and exposure limits imposed by the NMED. The existing VOC conditions in the HWFP (e.g. Room Based Limits for VOCs) are based on an extremely conservative analysis of bounding VOC releases. The RH-TRU Team recommends that a bounding analysis specific to the small volume of RH-TRU waste will obviate the need for generator/storage sites to characterize RH-TRU waste for VOCs. This RH-TRU Team recommended approach for VOCs is exactly that already proposed in the September 2001 draft Class 3 Request for RCRA Permit Modification for RH-TRU waste.

Characterization Method: This column lists the general method to be used (as recommended by the RH-TRU Team) to accomplish the *Characterization Objectives* from the first column.

EPA Characterization Methods

1. *Count containers emplaced in the WIPP*, is a simple administrative accounting using the WIPP Waste Information System (WWIS) that meets the metals Characterization Objective. This method has already been approved by the EPA in the 40CFR191/194 “Final Rule” and is currently employed in the CH-TRU waste program. This is not a generator/storage site characterization requirement; it is a WIPP administrative requirement.

2. *Characterization method—Use AK to determine Summary Category Group (SCG) of each waste stream. WIPP admin requirement—Use WWIS to assign 620 kg/m^3 up to container tare weight for debris waste.* Relative to the CCA total inventory limit of 20 million kilograms of CPR, any practical contribution to the CPR inventory from RH-TRU waste is inconsequential. The *RH-TRU Inventory Impact Assessment Report* (Sandia, June 2001) used 620 kg/m^3 of plastic for a bounding analysis that demonstrated

repository performance is not affected by RH-TRU waste CPR. Out of the three Summary Category Groups, (S3000—homogeneous solids, S4000—soils and gravel, S5000—debris) only S5000—debris contains significant quantities of CPR. Thus a very simple and conservative approach for meeting the CPR Characterization Objective is to use AK to identify S5000—debris waste streams, and use the WWIS to electronically calculate and assign a CPR weight value for every S5000—debris RH-TRU waste container that is emplaced in the repository. Because this assignment is based on a bounding analysis, and because there will always be enough AK to make the simple SCG designation, no confirmation of this designation is required.

3. *Use AK to assign either 0% or 1% by volume for each waste stream.* The *RH-TRU Inventory Impact Assessment Report* (Sandia, June 2001) assumed that the final RH-TRU waste inventory in the WIPP was 50% by volume water. This bounding analysis demonstrated repository performance is not affected by any amount of water in RH-TRU waste. Thus a very simple and conservative approach for meeting this Characterization Objective is to use AK to either assign 0% volume of liquid to a specific RH-TRU waste stream or assign 1% volume. The RH-TRU Team chose 1% rather than 50% because transportation requirements will not allow more than 1% to be transported. Because the Sandia bounding analysis effectively demonstrates that selecting either 0% or 1% makes no difference in repository performance, and because AK will, in some cases, allow a definitive 0% decision to be made for a waste stream (e.g., thermally treated waste) or a default 1% will be assigned, no confirmation of this AK determination is required.

4. *Use AK to determine the relationship of TRU Activity to Total Activity for each waste stream, or establish a waste stream value by sampling and measurement, or measure the TRU Activity of each container.* The *RH-TRU Inventory Impact Assessment Report* (Sandia, June 2001) assumed, for a bounding analysis, that the entire RH-TRU waste curie loading allowed by the LWA (5.1 million curies) was composed of Pu239 and showed that even this impossible condition would still comply with the 40CFR191 containment requirement. Thus any minimal AK information available with which to roughly estimate the ratio of TRU to Total Activity is sufficient to meet this Characterization Objective without the need for confirmation. If this minimal AK information is not available, measurements of Total Activity and TRU Activity should be obtained on a few randomly selected containers from the waste stream to establish a waste stream value. Alternatively a generator/storage site may choose to measure the TRU Activity of each container. Note that the method for meeting this Characterization Objective (EPA number 4) is closely tied to, and interrelated with, the following two methods for EPA Characterization Objectives numbers 5 and 6.

5. The same Characterization Method used for TRU Activity (Characterization Method No. 4) is also used to make the TRU determination. Usually AK can be used to make a determination of TRU (versus LLW) for an entire waste stream if there is loading information (activity or mass) regarding Pu238 or Am241 and Pu239. Since this is a "legal" limit with no safety or repository performance implications, this AK determination need not be confirmed. If the TRU determination cannot be made using AK, a waste stream TRU determination may be made by measuring a few randomly selected containers. A TRU determination may also be made by measuring the value of TRU concentration for each container.

6. *Use AK to determine Total Activity of the waste stream, or establish a waste stream value by sampling and measurement, or measure the Total Activity of each container.* Any minimal AK information available with which to roughly estimate the Total Activity is sufficient to meet this Characterization Objective without the need for confirmation. *Characterization Parameters, Data Quality Objectives, and Methods* (LANL, July 2001) pointed out that the expected (from the TWBIR) RH-TRU waste total activity inventory could be biased low by a factor of five before the LWA limit is challenged. If this minimal

AK information is not available, measurements of Total Activity should be obtained on a few randomly selected containers from the waste stream to establish a waste stream value. Alternatively a generator/storage site may choose to measure the Total Activity of each container.

7. The same Characterization Method used for Total Activity (Characterization Method No. 6) may also be used to meet Characterization Objective number 7. *Characterization Parameters, Data Quality Objectives, and Methods* (LANL, July 2001) showed that for the vast majority of RH-TRU waste streams AK will demonstrate that it is not feasible to load a canister (or any container) to 23 curies per liter. For the rare exception where AK indicates 23 curies per liter is hypothetically feasible, measurements of Total Activity should be obtained on a few randomly selected containers from the waste stream to establish a waste stream value. Alternatively a generator/storage site may choose to measure the Total Activity of each container.

8. *Use standard industry survey methods to measure and report Surface Dose Rate.* This is a standard practice measurement using standard equipment. Any container that has a measured Surface Dose Rate of 1000 rem/h or greater cannot be shipped to the WIPP. This measurement also is used for achieving Characterization Objectives 9 and 10.

9. *Use standard industry survey methods to measure and report Surface Dose Rate.* This is a standard practice measurement using standard equipment. The Surface Dose Rate measured value of each container that is shipped to the WIPP must be reported in the WWIS. The WIPP will use WWIS data to load manage and assure no more than 5% of the containers of RH-TRU waste emplaced in the repository exceed a Surface Dose Rate of 100 rem/h.

10. *Use standard industry survey methods to measure and report Surface Dose Rate.* This is a standard practice measurement using standard equipment. If the Surface Dose Rate measured value of a container is less than 200 mrem/h then that container should be managed as Contact Handled TRU (CH-TRU) waste.

NMED Characterization Methods

1. *Use AK to delineate waste streams, assign Hazardous Waste Numbers and Summary Category Group (SCG) to waste streams, and assign individual containers to waste streams.* Hazardous Waste Numbers and SCG are assigned on a waste stream basis; therefore the population of containers constituting a specific waste stream must be identified. AK must be used for the majority of this information. There are no other reasonable means (i.e., measurement) or confirmation techniques. For example, F codes depend on the generation process and therefore can only be identified by knowledge of the process used (part of AK). Because all allowable hazardous wastes (identified by Hazardous Waste Numbers) are managed identically at the WIPP, Hazardous Waste Numbers, or lack thereof, are not used for any operational management decisions. <u>Confirmation of Hazardous Waste Number assignment is therefore not required.</u>

2. The Characterization Method for establishing SCG is the same as described in the preceding NMED Characterization Method number 1.

3. *Use AK to demonstrate that the waste stream does not contain residual liquid, or that individual containers in a waste stream contain <1% residual liquid, or sample and NDE/VE to determine the waste stream does not contain residual liquid, or NDE/VE each container in a waste stream.* AK may provide definitive information (e.g., all liquids are eliminated by thermal process) to show that the waste stream contains no residual liquids. <u>If so, no confirmation is required.</u> Or AK may provide a record for each container

showing that there is <1% liquid. If so, no confirmation is required. If AK is not definitive, NDE or VE of a few representative containers may show that the waste stream does not contain residual liquids. If AK or sampling indicates that there may be some containers with >1% residual liquid, then NDE or VE of each container should be done.

4. *Use bounding analysis for RH contribution to reduce current HWFP Room Limits.* This is not a Characterization Method. This analysis has already been completed and can be found in Appendix 2 of the September 2001 draft Request for Class 3 Permit Modification (RH-TRU). This analysis bounded the possible contribution of VOCs from RH-TRU waste, and correspondingly lowered the Room Based Headspace VOC Limits set in the current HWFP. Reducing the Room Based VOC concentration limits eliminates the need to characterize RH-TRU waste for VOC concentrations.

Implementation: This column sets the standard of adequacy, sufficiency, or acceptability for the *Characterization Methods* selected in the adjacent column.

EPA Implementation

1. *WWIS electronically counts.* As pointed out in the corresponding Characteriza-tion Method column, this is a WIPP administrative action, not a characterization activity and therefore no adequacy standard is set.

2. *Use generator/storage site SCG designation from site documents.* If a site has previously determined a waste stream(s) to be one of three SCGs (S3000—homogeneous solids, S4000—soils and gravel, S5000—debris), then that determination is acceptable for program use. If the site has not determined the SCG and AK shows the process that generated the waste produces a uniform and homogeneous product, then designate the waste stream as S3000 or S4000 as appropriate, otherwise designate the waste stream as S5000. Current RH-TRU waste inventory information indicates that every retrievable RH-TRU waste stream that is a candidate for WIPP disposal already has a SCG designation. The associated WIPP administrative action is described in the Characterization Method.

3. *AK documents use of liquid management procedures, or a process that precludes liquids; otherwise assign 1%.* To assign 0%, AK is sufficient if it is documented that the waste stream generation procedures included liquid management procedures (e.g., procedures required the removal of liquids or the absorption of liquids), or it is documented that the waste stream generation process precludes liquids (e.g., material balance input records, thermal treatment, etc.). If this AK information is negative or unavailable, a default assignment of 1% is made.

4. *AK must include TRU information (sufficient to demonstrate waste stream concentration exceeds 100 nCi per gram), or the waste stream value must be established by sampling and measurement, or the TRU Activity must be measured for each container.*
    - Because the same AK information is used for both the TRU Activity Characterization Objective and the TRU versus LLW determination, the more stringent TRU/LLW Characterization Objective sets the AK adequacy standard. Generally, AK is sufficient if the predominant TRU isotopes are identified (usually Pu238 or Pu239 and Am241), and there is waste stream activity information regarding those isotopes.
    - If sufficient AK information is not available, TRU Activity for the waste stream can be established by measuring TRU Activity of representative containers. As with AK, only the predominant TRU isotope (usually Pu238 or Pu239 and Am241) need be measured. A sufficient number of containers shall make up the sample size in order to establish that the waste stream value exceeds 100 nCi per gram with 67% certainty.

- If a site elects to measure the TRU Activity of each container, measurement of the predominant TRU isotope is sufficient. If activity of the predominant isotope is marginally below 100 nCi per gram, a site may choose to include additional TRU isotopes in the measurement.

5. See Implementation item number 4 above.

6. *AK must include sufficient information with which to make an estimate of Total Activity for the waste stream, or the waste stream value must be established by sampling and measurement, or the Total Activity must be measured for each container.*
   - AK is sufficient if the predominant high activity isotopes (e.g., Cs137) have been identified for the waste stream and there is a record of a few activity determinations for those isotopes.
   - If sufficient AK information is not available, Total Activity for the waste stream can be established by measuring Total Activity of representative containers. A sample size of two to ten containers, depending on waste stream size, and measurement of only the predominant high activity isotopes, is sufficient to establish a Total Activity value for the waste stream.
   - If a site elects to measure the Total Activity of each container, measurements of the predominant high activity isotopes are sufficient.

7. The analysis from Characterization Method eliminates any need for Implementation.

8. *Industry standard survey instruments.* This is a straightforward, common practice application of standard industry techniques to measure surface dose rate and requires no further explanation.

9. *Industry standard survey instruments.* This is a straightforward, common practice application of standard industry techniques to measure surface dose rate and requires no further explanation.

10. *Industry standard survey instruments.* This is a straightforward, common practice application of standard industry techniques to measure surface dose rate and requires no further explanation.

NMED Implementation

1. *Use generator/storage site waste stream designation, records of container assignments, Hazardous Waste Numbers if mixed waste, and SCG assignment.* Every RH-TRU site planning to ship RH-TRU waste to the WIPP is currently operating under an EPA authorized State RCRA program. Waste streams have previously been designated under these programs, hazardous waste numbers have been assigned when appropriate, and the SCG for each waste stream has been determined.

2. Implementation for Physical Form is included in the above Implementation number 1.

3. *AK must document the use of liquid management procedures, or a process that precludes liquids, or there must be a record for each container indicating <1% residual liquid, or NDE/VE of a few representative containers from the waste stream can show the absence of residual liquids, or every container must undergo NDE/VE.*
   - Liquid management procedures are standard operating procedures used in the waste generation process that eliminate or mitigate the presence of free liquids (e.g., removal or absorption). Examples of processes that preclude liquids are material input records that show no liquids were introduced to the process or a thermal treatment process that removes liquids.
   - If sufficient AK information is not available, the absence of residual liquids in any

container in a waste stream can be demonstrated with a statistical degree of certainty by NDE/VE of representative containers. A sufficient number of containers shall make up the sample size in order to establish that less than 10% of the containers in a waste stream contain more than 1% by volume residual liquids (with 67% certainty).
- A site may elect to NDE/VE every container in order to demonstrate that every container has less than 1% by volume residual liquid.

4. No Implementation is required for VOCs.

DQO: The RH-TRU Team applied the DQO process to each element of the proposed RH-TRU waste characterization program in order to ascertain whether formal DQOs need be developed. The DQO process was designed by the EPA primarily as a decision making tool applied to sampling and analysis studies for contaminated site remediation; however the process remains useful in the RH-TRU waste characterization program as a screening tool to determine if DQOs should apply. The seven-step DQO process is described in "Guidance for the Data Quality Objectives Process, EPA QA/G-4." Essentially DQOs establish what information is needed, and what level of quality the data should have associated with it, in order for a meaningful, risk based or consequence based decision to be made. "Data quality objectives (DQOs) for the data collection activity describe the overall level of uncertainty that a decision-maker is willing to accept in results derived from environmental data" (EPA SW-846). Using this process, the RH-TRU Team determined that there are no DQOs needed for the Characterization Objectives established for the RH-TRU waste characterization program.

EPA and NMED DQOs

- Step 1 of the DQO process is to "State the Problem." The problem statements for each element of the proposed RH-TRU waste characterization program are the Characterization Objectives listed in the first column of the attached Tables.
- Step 2 of the DQO process is to "Identify the Decision."
  - There are no decisions to be made as a result of characterization activities for Table 1 EPA elements 1, 2, 3, 4, 6, and 9. These are all data collection activities to provide information for management, administrative, or load management decisions that may be needed in the future. Thus there are no DQOs for these elements.
  - There are no decisions to be made as a result of characterization activities for Table 2 NMED elements 1, 2 and 4. Elements 1 and 2 are both administrative labeling activities done for the purpose of regulatory compliance that have no safety, repository performance, or technical consequences. NMED element 4 is potentially a data collection activity to enable future load management decisions regarding RCRA Permit *Room Based VOC Limits.* However the approach (Characterization Method from the Tables) taken for RH-TRU waste VOCs has eliminated this element as a RCRA characterization objective. Thus there are no DQOs for NMED elements 1, 2, and 4.
- Step 6 of the DQO process is to "Specify Tolerable Limits on Decision Errors."
  - The decision(s) to be made for EPA elements 5, 7, and 8 are receive-not-receive at the WIPP, and for EPA element 10 the decision is receive as RH-TRU waste or CH-TRU waste. Legal and regulatory limits and/or definitions drive decisions for each of these four elements, and there are no technical, safety, or repository performance consequences. Therefore "Tolerable Limits on Decision Errors" cannot be established for these four elements, and thus there are no DQOs for these elements.
  - The decision to be made for NMED element 3 is receive-not-receive at the WIPP. Regulatory operational compliance drives this decision, and since there are no technical, safety, or repository performance consequences, no "Tolerable Limits on Decision Errors" can be established. Thus there is not a DQO for

NMED element 3.

QAO: The WIPP project has historically listed “accuracy,” “precision,” “representative-ness,” “comparability,” and “completeness” as the elements of QAOs. These are the same elements used in the EPA SW-846 (2.1) definition of DQOs. From an EPA perspective, QAOs are synonymous with DQOs, and thus the RH-Team established no QAOs for either EPA or NMED Characterization Objectives for the same reasons DQOs were not applicable.

NOTE: This copy has been edited for formatting purposes. The emphasis (italicized text) was added by DOE-Carlsbad Field Office. This table is part of the document DOE’s Proposed Resolution and Action Items in Response to the Committee’s Interim Report.
SOURCE: DOE (DOE-CBFO, 2002).

REFERENCE

DOE-CBFO. 2002. This material was submitted to the committee on January 18, 2002. This record is publicly available.

Appendix E

Information About Selected Transuranic Waste Generator Sites

The Department of Energy (DOE) provided this information in the March 2002 draft of both Document 1 (Notification of Proposed Change to the U.S. Environmental Protection Agency (EPA) Title 40 Code of Federal Regulations Part 194 Certification of the Waste Isolation Pilot Plant (WIPP), Attachment 3) and Document 2 (Request for RCRA Class 3 Permit modification to the NMED, Supplement 1). The committee did not verify or review this information. Table E.1 lists the Environmental Protection Agency (EPA) hazardous waste codes relevant to the sites mentioned in this appendix.

E.1 Hanford Site

The Hanford Site is one of the major contributors to the remote-handled transuranic (RH-TRU) waste inventory projected in WIPP (see Chapter 2).

E.1.1 Location and Description

The Hanford Site is located north of the Tri Cities (Richland, Kennewick, and Pasco), in Washington on a 1,450 km^2 area of semiarid land in the Columbia River Basin in the southeastern corner of the State. Normal Columbia River elevations range from 119 m, where the Columbia River enters the Hanford Site near the Priest Rapids Dam, to 104 m where it leaves the Hanford Site near the 300 area. Activities at Hanford are centralized in numerically designated areas. The reactor facilities are located along the Columbia River in what is known as the 100-Area. The reactor fuel processing and waste management facilities are in the 200-Area. The 300-Area, located adjacent to and north of Richland, contains the reactor fuel manufacturing facilities and the research and development laboratories. The 400-Area, 5 miles northwest of the 300-Area, contains the Fast Flux Test Facility, a sodium-cooled fast breeder reactor. The 600-Area covers all locations not specifically given an area designation. Adjacent to and north of Richland, the 1100-Area contains facilities associated with administration, maintenance, transportation, and materials procurement and distribution. The 3000-Area contains engineering and administrative offices. Administrative buildings, including the Federal Building, are located in the 700-Area, which is in downtown Richland. The Hanford Site is administered by the DOE Richland Operations Office.

E.1.2 Mission

The Hanford Site was acquired by the federal government in 1943 for the construction and operation of facilities to produce plutonium for the atomic weapons program during World War II. For more than 30 years, Hanford Site facilities were primarily dedicated to the production of plutonium for national defense and management of the wastes generated by chemical processing operations. In later years, programs at the Hanford Site became increasingly diverse, involving research and development for advanced reactors, renewable energy technologies, waste disposal technologies, and cleanup of contamination from past practices. The DOE has ended the production mission at the Hanford Site and is currently reorienting activities toward waste management and cleanup at the site. The mission now is one of environmental management, demonstration and application of advanced remediation technologies, and restoration of the Hanford Site.

E.1.3 Waste Information

Remote-handled TRU wastes from Hanford are the result of multiple sources. Some of these sources generated waste that now needs to be segregated between the categories of low-level waste, contact-handled transuranic (CH-TRU), and remote-handled transuranic waste. Some RH-TRU waste is currently stored in the 200-W Area in the Central Waste Complex and retrievably stored in the 200-E and 200-W areas in the Low-Level Burial Grounds. Future generation is forecast from activities related to the Hanford cleanup. The mission of the Central Waste Complex is to receive and store solid radioactive waste in a safe and environmentally compliant manner. The Central Waste Complex provides interim storage for mixed low-level waste, transuranic waste, and a small amount of low-level waste, awaiting treatment and final disposal. The design storage capacity is approximately 80,000 55-gallon drum equivalents; the operational capacity is 64,000 drum equivalents. The Central Waste Complex receives waste from both on-site and off-site waste generators.

Receipt of transuranic waste drums retrieved from the Low Level Burial Grounds began in 1999. All newly generated waste must meet acceptance criteria set by the Hanford Site Solid Waste Acceptance Program. Waste is generally packaged in 55-gallon drums unless alternate packages are dictated by size, shape, or other form of waste.

Each drum is handled individually using a hand truck, forklift, or crane. Drums are placed on wooden pallets with a maximum of four drums banded together; the pallets can then be stacked three high, or 12 drums per stack.

The storage buildings or pads have physical features that provide for segregated storage areas to maintain appropriate separation between groups of incompatible waste. Some RH-TRU waste will be segregated from the waste retrieved from the Low-Level Burial Grounds in the 200-Area. The waste to be retrieved from the Low-Level Burial Grounds is believed to primarily be low-level waste, though the waste will be segregated as it is retrieved and characterized. The RH-TRU wastes will be characterized and packaged at the M-91 facility. Another source of RH-TRU waste is the Plutonium Uranium Extraction Plant located in the 200-E Area. Products from this plant were weapons-grade plutonium, fuel-grade plutonium, depleted uranium, slightly enriched uranium, neptunium, and thorium. The plutonium conversion, process solution sampling, laboratory analyses, plant ventilation, and facility ventilation generated waste that was common to all these PUREX operations, including surgical gloves, plastic (polyvinyl

chloride and polyethylene), tape, paper, glass, glovebox gloves, and metal tools and equipment.

The overall PUREX plant process consisted of seven fundamental interfacing processing units: feed preparation; solvent extraction, separation, and purification; solvent recovery and treatment for recycling; back-cycle waste system; acid recovery; waste treatment; off-gas treatment; and conversion of plutonium nitrate to plutonium oxide. Wastes generated were old failed equipment, port covers, replaced windows, brackets and hardware, and acid-soaked rags. Process solution sampling operations extract liquid samples from process control points to be used in system analysis and control. After use, all liquids were drained to the PUREX liquid waste system. Waste generated at this facility included broken glassware and plasticware, wet rags and paper, and piping and valving equipment. Laboratory Analysis Operations were performed on liquid process samples used for system analysis and control. After use, all liquids were drained to the PUREX liquid waste system. Again, wastes generated were broken glassware and plastic-ware, and wet rags and paper.

RH-TRU waste is also being stored in two spent nuclear fuel basins known as the K-Basins in Hanford's 100-K Area. This source consists of approximately 50 cubic meters of layered particulate material, which is generally called sludge. This sludge will be collected and transported to a stable interim storage location away from the Columbia River and eventually sent to a final disposal location. Sludge is found on the K-Basins, floors, in canisters, and in the basin pits. Several different types of sludge exist depending on the basin, canister type, and pit location where the particular sludge is found. Each type of sludge is a unique nonhomogeneous mixture possibly containing corroded fuel (i.e., uranium oxides, hydrates, hydride), cladding pieces, debris such as wind-blown sand or insects, rack and canister corrosion products, ion exchange resin beads, polychlorinated biphenyls, and/or fission products. In addition to the existing sludge material, other particulate materials are expected to be generated in the processing of fuel elements for dry storage. The sludge in the basins is commingled with spent nuclear fuel and is not considered a waste; however, when the sludge is separated from the spent nuclear fuel and removed from the basins, it will be dispositioned as RH-TRU waste.

For the purposes of differentiating spent nuclear fuel and debris from sludge, any material that is less than or equal to 0.64 cm (1/4 in.) in diameter is defined as sludge. Finally, RH-TRU waste will be generated from future activities related to facility stabilization and cleanup, maintenance of process equipment, laboratory operations, and Office of River Protection tank farm cleanup operations. This waste includes miscellaneous debris, equipment, and components and instrumentation trains removed during remediation of the high level waste tanks. The current estimates are that 207 cubic meters of RH-TRU is stored and an additional 944 cubic meters of waste will be generated. No canisterization of this waste has been performed with the majority of this waste to be generated (i.e., packaged) in the future.

The major radionuclides reported are cobalt-60, cesium/barium-137, strontium/yttrium-90, uranium-233, americium-241, plutonium-238, plutonium-239, plutonium-240, and plutonium -241. Based on known information about program activities, the estimated dose rate range is expected to be between 0.2 to 1,000 rem per hour. Due to the variety of processes, the presence of hazardous constituents will need to be ascertained on a stream-by-stream evaluation of the acceptable knowledge available on the generating process. Based on information previously reported in the TRU Waste Baseline Inventory Report, the following hazardous waste codes have been reported for RH-TRU wastes: F001, F002, F003, F004, F005, D001, D002, D005, D006, D007, D008, D009.

E.2 Idaho National Engineering and Environmental Laboratory

The Idaho National Environmental and Engineering Laboratory stores RH-TRU waste generated in national defense programs and research activities from across the country. For volume and radioactive waste inventory information, see Chapter 2.

E.2.1 Location and Description

The Idaho National Environmental and Engineering Laboratory is located in two primary areas: (1) the remote areas known as “the site” along the northern edge of the Snake River Plain in southeastern Idaho and (2) multiple locations southeast of the site in the city of Idaho Falls. Lying at the foot of the Lost River, Lemhi, and Bitterroot-Centennial Mountain ranges, the site covers nearly 2,300 square km (890 mi^2) of dry, cool desert. Most of the land withdrawn from public domain for use by DOE is undeveloped. The facilities located in Idaho Falls include administrative, scientific support, and nonnuclear research laboratories. During World War II, the U.S. Navy and U.S. Army Air Corps used a portion of the present site as a gunnery range. In 1949 the site was formally established as the National Reactor Testing Station, a place where the Atomic Energy Commission could build, test, and operate various types of nuclear reactors. Fifty-two reactors have been built at the Idaho National Engineering and Environmental Laboratory; of these, seven are operating or operable. The Radioactive Waste Management Complex encompasses 144 acres in the southwestern corner of the Idaho National Engineering and Environmental Laboratory. The Radioactive Waste Management Complex was established in 1952 as a controlled area for burial of solid radioactive wastes generated by Idaho National Engineering and Environmental Laboratory operations. In 1954 the burial ground was designated as a solid TRU waste disposal site. Until 1970, all TRU was buried below grade at the Radioactive Waste Management Complex. In November 1970 the Transuranic Storage Area was established for retrievable storage of waste contaminated with greater than 10 nanocuries of TRU alpha activity per gram of waste. In November 1976 the Intermediate Level TRU Storage Facility was established for retrievable storage of RH-TRU contaminated waste (greater than 200 millirem per hour). At the Intermediate Level TRU Storage Facility the radioactive waste is stored in above-grade vaults.

E.2.2 Mission

The Idaho National Engineering and Environmental Laboratory is a multi-program laboratory and has provided innovative technologies, defense-related support, and unique scientific and engineering capabilities to the nation. At present, areas of primary emphasis include nuclear reactor technology research and development, waste management and environmental restoration, advanced energy production and utilization technology development, defense-related support, technology transfer, and nonnuclear research and development projects. Development, transfer, and deployment of technologies to avoid and/or dispose of hazardous and/or radioactive waste and for remediation/restoration of previous disposal sites to protect the public, employees, and environment are also part of the Idaho National Engineering and Environmental Laboratory’s mission.

E.2.3 Waste Information

RH-TRU waste generated in national defense programs and research activities from across the country was buried or stored at the Radioactive Waste Management Complex. The majority of the RH-TRU was generated at off-site facilities and shipped to the Idaho National Engineering and Environmental Laboratory for disposal or storage. These wastes came from Rocky Flats Environmental Technology Site, Argonne National Laboratory-East, Argonne National Laboratory-West, Battelle Columbus Laboratories, and other sites. The physical descriptions for these wastes are therefore consistent with the physical waste descriptions provided for each of these sites in different sections of this appendix, and the reader is directed there for those descriptions. In the case of Rocky Flats Environmental Technology Site, the RH-TRU was only differentiated from the CH-TRU shipped for disposal or storage at the Idaho National Engineering and Environmental Laboratory by its surface dose rate. The physical constituents of this TRU waste were typically the same and included cloth, paper, plastics, metals, rubber, sludge, or concrete. The TRU waste received at the Idaho National Engineering and Environmental Laboratory from November 1970 through July 1980 was placed on asphalt pads with an earthen cover to protect the waste from the environment until it could be permanently disposed of. Waste received after this time frame was placed in air-supported buildings for interim storage. The current estimate is that 84 cubic meters of RH-TRU is stored and that an additional 52 cubic meters of waste will be generated or recovered. No canisterization of this waste has been performed. Storage drums are typically 30 or 55 gallons. Major radionuclides reported include cobalt-60, cesium/barium-137, strontium/yttrium-90, uranium-235, americium-241, plutonium-238, plutonium-239, plutonium-240, and plutonium-241. Due to the wide variety of program activities, the estimated dose rate range is expected to vary from 0.2 to 100 rem per hour. Due to the variety of sources of RH-TRU at the Idaho National Engineering and Environmental Laboratory, the hazardous constituents could be varied, ranging from solvents and degreasers to metals, such as lead or cadmium. The presence of these hazardous wastes will need to be ascertained on a stream-by-stream evaluation of the acceptable knowledge available on the generating process at each generating sites. Based on information previously reported in the TRU Waste Baseline Inventory Report, the following hazardous waste codes have been reported for RH-TRU wastes: D008, D022, D028, D029, F001, F002, F003, and F005.

E.2.4 Supplemental Information

Additional potential sources of RH-TRU waste are being identified during review of Idaho National Engineering and Environmental Laboratory programs. One source is anticipated to be generated at the Idaho National Engineering and Environmental Laboratory from the Idaho Nuclear Technology and Engineering Center. This volume is anticipated to be about 900 cubic meters. The facility was previously known as the Idaho Chemical Processing Plant and was established in the early 1950s. Its original mission was to reprocess spent nuclear fuels by chemically separating out the reusable uranium and subsequently calcining the resultant high-level waste. The current mission is the storage of low-level, mixed low-level, and high-level waste and spent nuclear fuel and the development of treatment methods for high-level waste. Several evaluations are now in process to assess the treatment options for packaging the RH-TRU waste generated during processing of the high-level waste. This waste is expected to be classified as Waste Incidental to Reprocessing and disposed of at WIPP. Evaluations are also under way to examine treatment and packaging options for disposal. Depending on the option

selected, the final packaged volume could be significantly greater than the current estimate of 900 cubic meters.

E.3 Los Alamos National Laboratory

The Los Alamos Scientific Laboratory was established in 1943 by the U.S. Army's Manhattan Engineering District for the purpose of developing the first atomic weapons. Known as the Los Alamos Scientific Laboratory for many years, the name was changed to the Los Alamos National Laboratory in December 1980.

E.3.1 Location and Description

The Los Alamos National Laboratory is located approximately 97 km north of Albuquerque and 40 km west of Santa Fe in Los Alamos County, New Mexico. The laboratory facilities are dispersed among numerous technical areas spread over a 111-km^2 site on the Pajarito Plateau. The plateau consists of several finger-like mesas extending eastward from the Jemez Mountains to the Rio Grande Valley, with steep eroded canyons separating the mesas. The elevation of the mesas ranges from 1,890 to 2,377 m. Some Technical Areas are located in canyons.

E.3.2 Mission

Los Alamos National Laboratory was the research, development, engineering, design, and testing center for the Manhattan Project. The mission was the application of science and technology to problems of national security, including the maintenance of a strong defense, the fulfillment of arms controls commitments, and the guarantee of a secure energy supply for the future. Los Alamos National Laboratory's mission since World War II has included nuclear device design, research, development, testing, stockpile certification, and plutonium storage. Major programs currently include research in nuclear and conventional weapons development; nuclear fission and fusion; nuclear safeguards and security; verification and control technologies; fundamental research in particle physics, mathematics, chemistry, and materials; and waste management technology development and testing. Research on peaceful uses of nuclear energy has included space applications, power reactor programs, magnetic and inertial fusion, radiobiology, and medicine. Other programs include astrophysics, earth sciences, lasers, computer sciences, solar energy, geothermal energy, biomedical and environmental research, and nuclear waste management research.

E.3.3 Waste Information

RH-TRU waste is primarily generated by the Irradiated Materials Examination Group. This waste consists of solid wastes from laboratory and hot cell operations and includes small laboratory and hot cell equipment, materials such as fines resulting from grinding and cuttings, miscellaneous fuel specimens and their containers, and general debris from hot cell cleanup and decontamination. The general debris consists primarily of combustible waste, such as paper, rags, plastic, and rubber, with the plastic component consisting of tape, polyethylene and vinyl gloves, Tygon tubing, polystyrene, plastic vials, Teflon, and plexiglass. The cellulosic portion consists of rags, wood, cardboard, lab coats and coveralls, and paper. Noncombustible wastes that are present include

cans, lids, graphite molds, furnaces, pyrochemical salts and related equipment, and glassware.

Some RH-TRU waste will be received from programmatic activities at the Sandia National Laboratory. The current estimate is that 98 cubic meters of RH-TRU is in storage and that 24 cubic meters of RH-TRU waste will be generated. The Los Alamos National Laboratory is unique in that it is the only site with waste packaged into canisters for handling and disposal at WIPP. Seventeen canisters of waste are currently packaged and stored in the waste storage area at Los Alamos National Laboratory. Other RH-TRU wastes are typically stored in small (1- to 5-gallon containers) and will be canisterized prior to disposal at WIPP. Major radionuclides reported include cesium/barium-137, strontium/yttrium-90, americium-241, plutonium-238, plutonium-239, plutonium-240, and plutonium-241. The estimated dose rate ranges are expected to be 1 to 100 rem per hour. Potential hazardous wastes included various cleaners and degreasers, cadmium, and lead. Based on information previously reported in the TRU Waste Baseline Inventory Report, the following hazardous waste codes have been reported for TRU wastes at Oak Ridge National Laboratory: F001, D006, D008.

E.4 Oak Ridge National Laboratory

The Oak Ridge National Laboratory is the site that stores most of the existing RH-TRU waste in DOE's inventory (see Chapter 2).

E.4.1 Location and Description

The Oak Ridge National Laboratory is located 10 miles southwest of downtown Oak Ridge, Tennessee, and 32 km northwest of Knoxville, Tennessee. The Oak Ridge National Laboratory site occupies about 10,000 acres of the 35,252-acre-Oak Ridge Reservation. The site covers portions of both Melton and Bethel valleys. Approximately 1,100 acres in the Melton and Bethel valleys has been developed. The Oak Ridge National Laboratory is under the auspices of the DOE/Oak Ridge Operations Office, which supports production of nuclear weapon components for national defense programs, production of enriched uranium for defense requirements and for fueling nuclear power plants, processing of uranium feed materials for DOE’s plutonium production reactors, and extensive energy research and development in all DOE program areas.

E.4.2 Mission

The Oak Ridge National Laboratory was established in 1942 in support of the Manhattan Project. The primary mission of the Oak Ridge National Laboratory has been to carry out applied research and engineering development in fission, fusion, and other energy technologies and to conduct scientific research in basic physical and life sciences. Relevant missions include isotope production and processing, research and development, waste management, and decontamination and decommissioning of operating units, and advanced reactor development work. In addition, the Oak Ridge National Laboratory conducts several activities for DOE defense programs. The principal nonweapons-related activities include nuclear power development and magnetic fusion research.

E.4.3 Waste Information

Most of the RH-TRU waste at Oak Ridge National Laboratory has been generated as a result of special isotope separation activities. The Radiochemical Engineering Development Center at Oak Ridge National Laboratory has processed americium-curium targets that were irradiated in the High Flux Isotope Reactor to produce higher actinides such as californium, berkelium, einsteinium, and fermium. The ion exchange processing of these targets generated and consists of two distinct waste streams, a solid stream (debris waste) and a sludge/liquid stream. Solid RH-TRU debris waste consists primarily of miscellaneous hot cell waste (e.g., paper, glass, plastic tubing, shoe covers, wipes), high-efficiency particle activated filters from off-gas cleanup systems, and discarded equipment (e.g., chemical processing racks, vacuum pumps). This waste was contaminated with the original target material and the higher actinides, except for the einsteinium and fermium, which decayed quickly due to their very short half-lives. This solid debris is stored in concrete casks as RH-TRU waste. There is substantial historical process knowledge about the content of each cask (ORNL, 1989). For example, some casks contain a large number of 1 gallon pails of hot cell waste while others may have a single failed piece of equipment. The unshielded individual waste packages in the casks typically have radiation levels that measure 10 to 2,000 rem per hour; the majority are below 100 rem per hour.

Hazardous wastes in RH-TRU solid waste primarily consist of lead that was used as shielding and limited amounts of mercury from discarded mercury vapor lamps. The RH-TRU solid waste is typically contained in cylindrical concrete casks 1.4 m (4.5 ft.) in diameter by 2.3 m (7.5 ft.) high. Wall thickness of the casks are currently either 15.2 or 30.5 cm (6 or 12 in.) thick, depending on the radiation level of the contents.

The majority of RH-TRU sludges at the Oak Ridge National Laboratory are the result of waste accumulation from the past 50 years of liquid waste operations there. These sludges are residuals from sluicing operations conducted in the early 1980s when the majority of the inactive gunite tank contents were removed for hydrofracture disposal at Oak Ridge National Laboratory. This liquid waste is now stored in the Melton Valley Storage Tanks. RH-TRU sludges continue to accumulate due to on going research and development programs, that produce transuranic isotopes for medical, industrial, and government applications.

The surface dose rates of these sludges are generally near 10 rem per hour (unshielded). The current estimate is that 1,308 cubic meters of RH-TRU is stored and that an additional 534 cubic meters of waste will be generated. No canisterization of this waste has yet been performed, but canisterization is scheduled to begin in fiscal year 2003 and will be performed by Foster-Wheeler, the contractor performing the characterization and packaging activities. Major radionuclides reported include cobalt-60, cesium/barium-137, strontium/yttrium-90, europium-152, europium-154, uranium-233, uranium-235, uranium-238, americium-241, plutonium-238, plutonium-239, plutonium-240, plutonium-241, curium-244, and californium-252. The estimated dose rate range is expected to be 0.2 to 1,000 rem per hour. Based on information previously reported in the TRU Waste Baseline Inventory Report, the following hazardous waste codes have been reported for RH-TRU wastes at Oak Ridge National Laboratory: D006, D007, D008, D009, D011.

E.5 Energy Technology Engineering Center

The Energy Technology Engineering Center is a small generator site. This site will serve as model to other small generator sites in the implementation of the RH-TRU waste characterization plan. The site-specific RH-TRU waste characterization implementation plan from this site will be submitted to the regulatory agency along with Documents 1 and 2 (see Chapters 4 and 5).

E.5.1 Location and Description

The Energy Technology Engineering Center occupies 90 of 290 acres of land shared with the Santa Susana Field Laboratory. The Santa Susana site consists of a total of 2,700 acres located in the Simi Hills of Ventura County, California, approximately 48 km northwest of downtown Los Angeles. The facilities include former fuel fabrication facilities, a hot cell, a reactor test building, a storage vault, an on-site transport cask, and other radiologically contaminated support laboratories and areas.

E.5.2 Mission

Energy Technology provides facilities for the testing of equipment, materials, and components for nuclear and other energy programs. Components include steam generators, pumps, valves, instrumentation, and other support elements for power plant design. Various types of testing include reliability, seismic, and performance demonstrations. Current activities include non-nuclear testing and cleanup and environmental restoration from prior nuclear testing programs, such as decontamination and decommissioning of a hot cell licensed by the Nuclear Regulatory Commission that was used for DOE activities.

E.5.3 Waste Information

The RH-TRU waste at Energy Technology Engineering Center was generated during DOE fuel decladding and decontamination and decommissioning operations. The RH-TRU waste consists of two waste streams: (1) hot laboratory drain line residue and (2) a single drum of debris waste from multiple sources. The drain line residue is currently stored in 28 concrete-shielded 55-gallon drums and one 30-gallon drum. An additional amount of about 22 gallons of sludge is estimated to be in a 3,000-gallon drain tank and about 10 gallons of residue in two weir boxes. The total volume of the unpackaged waste is about 0.3 cubic meters. The total volume of the drain line residue material when all of the material is repackaged for on-site storage in concrete-shielded drums is estimated to be forty 55-gallon drums plus one 30-gallon drum, or about 8.5 cubic meters. The single 55-gallon drum from the debris waste has a total volume of 0.21 cubic meters. The total RH-TRU volume is therefore 8.7 cubic meters. There are no plans to canisterize RH-TRU waste at the Energy Technology Engineering Center. The RH-TRU waste will be sent to an intermediate site for final waste disposal characterization and final packaging. It is anticipated that the intermediate site may either be Oak Ridge or Hanford. Major radionuclides expected include cobalt-60, cesium/barium-137, strontium/yttrium-90, americium-241, plutonium-239, plutonium-240, and plutonium-241. Dose rates are relatively low in the range of 0.2 to 10 rem per hour. Based on acceptable knowledge documentation, such as process records, and supplemental analyses, the Energy Technology Engineering Center has assigned waste codes below to these waste streams. Recent tests have also shown that the drain line

residue stream has polychlorinated biphenil levels approaching 100 ppm. The Energy Technology Engineering Center plans to manage its RH-TRU waste as three separate waste streams. Based on information previously reported in the TRU Waste Baseline Inventory Report, the following hazardous waste codes have been reported for RH-TRU wastes at this site: D008 and D009.

E.6 Battelle Columbus Laboratories

This site is the only one actively characterizing its RH-TRU waste inventory. This site is seeking authorization to ship its RH-TRU waste to the Hanford Site for interim storage (see Chapter 2).

E.6.1 Location and Description

The Battelle Columbus Laboratories consists of two research complexes: one at 505 King Avenue in the city of Columbus, Ohio, and the second, the West Jefferson Site in Madison County west of Columbus. The King Avenue facility houses corporate offices and general research laboratories. The West Jefferson site consists of a number of facilities formerly dedicated to nuclear research. The King Avenue facility is located in the western central portion of the city of Columbus. The 10-acre complex accommodates 21 buildings and is bounded on the north by King Avenue, on the east by Battelle Boulevard, on the south by Fifth Avenue, and on the west by the Olentangy River. The Columbus campus of Ohio State University lies immediately north across King Avenue. The remaining contiguous area is a moderately dense residential neighborhood. The West Jefferson Site is located in West Jefferson, Ohio, approximately 24 km west of the King Avenue facility. The 1,000-acre tract accommodates 21 buildings in the Engineering Area, Experimental Ecology Area, and Nuclear Services Area. The site boundary on the north is about 1 mile south of I-70, on the east is Big Darby Creek, on the south are the Conrail tracks, and on the west is the Georgeville-Plain City Road. The land to the north, west, and south for 2 miles is cleared farmland and/or wood lots.

E.6.2 Mission

The mission of Battelle in 1943 was to perform atomic energy research and development activities for the Manhattan Engineering District. Since that time Battelle has continuously performed research and development at these facilities. Past programs have included uranium ore processing and benefaction studies, metallurgical and ceramic process development, corrosion studies, fabrication of weapons components, ballistics experiments, hot cell work, critical assembly and criticality experiments, and an experimental reactor.

E.6.3 Waste Information

The main DOE-sponsored work currently being done at Battelle Columbus Laboratories is decontamination and decommissioning of the contaminated buildings and hot cells at the West Jefferson location. This work is being performed under the direction of the Battelle Columbus Laboratories Decommissioning Project. The decontamination and decommissioning activities involve removing from the hot cells equipment used in the fuel examination process, materials such as fines resulting from grinding and cuttings, miscellaneous fuel specimens and their containers, and general

debris. The current estimate is that a total of 20.8 cubic meters of RH-TRU waste will be generated; some of this waste is currently in the process of being packaged. The proposal is to consolidate this waste at an intermediate facility for disposal characterization and any additional packaging. A memorandum of agreement is currently under development for use of the Hanford Reservation as the intermediate site. None of the RH-TRU waste is canisterized for transport in the RH-72B cask. The current plan is to use the CNS 10-160B to ship the majority of waste; therefore, the RH-TRU waste is being packaged in 55-gallon drums. Major radionuclides reported include cobalt-60, cesium/barium-137, strontium/yttrium-90, americium-241, plutonium-239, plutonium-240, and plutonium-241. Measured dose rates range from 0.2 to 150 rem per hour. Based on acceptable knowledge documentation (e.g., production and process records, analytical lab records), the following hazardous waste codes have been reported for RH-TRU wastes: D005, D007, D009, D011, F001, F002, and F005.

TABLE E.1 EPA Hazardous Waste Codes Relevant to this Appendix

Hazardous Waste Code	Criteria and Characteristics of Hazardous Waste
D001	Ignitability
D002	Corrosivity
D003	Reactivity
D004-D029	Toxicity: A solid waste whose extract under the test procedure specified under 40 Code of Federal Regulations Part 261.24 contains one or more constituents at concentrations greater than those specified in the Maximum Concentration of Contaminants for the Toxicity Characteristic Table. The toxicity characteristics of selected hazardous waste codes together with their maximum concentration of contaminants are listed below (D004-029).
D004	Arsenic > 5 mg/L
D005	Barium > 100 mg/L
D006	Cadmium > 1 mg/L
D007	Chromium > 5 mg/L
D008	Lead > 5 mg/L
D009	Mercury > 0.2 mg/L
D011	Silver, > 5 mg/L
D022	Chloroform > 6 mg/L
D028	Dichloroethane (1,2-) > 0.5 mg/L
D029	Dichloroethylene (1,1-) > 0.7 mg/L
	Hazardous Waste from Non Specific Sources
F001	The following spent halogenated solvents used in degreasing: Tetrachloroethylene, trichloroethylene, methylene chloride, 1,1,1- trichloroethane, carbon tetrachloride, and chlorinated fluorocarbons; all spent solvent mixtures/blends used in degreasing containing, before use, a total of 10% or more (by volume) of one or more of the above-halogenated solvents or those solvents listed in F002, F004, and F005 and still bottoms from the recovery of these spent solvents and spent solvent mixtures.
F002	The following spent halogenated solvents: Tetrachloroethylene, methylene chloride, trichloroethylene,1,1,1-trichloroethane, chlorobenzene, 1,1,2-trichloro-1,2,2-trifluoroethane, ortho-dichlorobenzene, trichlorofluoromethane, and 1,1,2-trichloroethane; all spent solvent mixtures/blends containing, before use, a total of 10% or more (by volume) of one or more of the

	above-halogenated solvents or those listed in F001, F004, or F005 and still bottoms from the recovery of these spent solvents and spent solvent mixtures.
F003	The following spent non halogenated solvents: xylene, acetone, ethyl acetate, ethyl benzene, ethyl ether, methyl isobutyl ketone, N-butyl alcohol, cyclohexanone, and methanol; all spent solvent mixtures/blends containing, before use, only the above spent non halogenated solvents; and all spent solvent mixtures/blends containing, before use, one or more of the above non halogenated solvents, and a total of 10% or more (by volume) of one or more of those solvents listed in F001, F002, F004, and F005; and still bottoms from the recovery of these spent solvents and spent solvent mixtures.
F004	The following spent non halogenated solvents: Cresols and cresylic acid, and nitrobenzene; all spent solvent mixtures/blends containing, before use, a total of 10% or more (by volume) of one or more of the above non halogenated solvents or those solvents listed in F001, F002, and F005; and still bottoms from the recovery of these spent solvents and spent solvent mixtures.
F005	The following spent non halogenated solvents: Toluene, methyl ethyl ketone, carbon disulfide, isobutanol, pyridine, benzene, 2-ethoxyethanol, and 2-nitropropane; all spent solvent mixtures/blends containing, before use, a total of 10% or more (by volume) of one or more of the above non halogenated solvents or those solvents listed in F001, F002, or F004; and still bottoms from the recovery of these spent solvents and spent solvent mixtures.

REFERENCE

ORNL (Oak Ridge National Laboratories). 1989. L. S. Dickerson, Remote-Handled Transuranic Solid Waste Characterization Study: Oak Ridge National Laboratory, ORNL/TM-11050. Oak Ridge National Laboratory. Oak Ridge, Tenn.

Appendix F

Overview of the Contact-Handled Transuranic Waste Characterization Plan

The characterization program described here has been developed for contact-handled transuranic (TRU) waste and applied to date to TRU mixed waste. The methods, equipment, procedures, determination of uncertainty, and other protocols used at DOE sites to perform these characterizations have been approved by the Department of Energy (DOE) Carlsbad Field Office, New Mexico Environment Department (NMED) and EPA. The major procedures are described in the following sections:

F.1 Determination of the Origin and Composition of the Waste by Acceptable Knowledge

Acceptable knowledge (AK) of the origin and composition of the waste must be documented to provide evidence that the waste has a defense origin (by the terms of the Land Withdrawal Act, only defense-related TRU waste may legally be sent to the Waste Isolation Pilot Plant (WIPP) and to provide characterization information on the waste constituents. The DOE Carlsbad Area Office and EPA use the AK documentation to certify each “waste stream” (i.e., waste-generating process), and TRU waste sent to WIPP must come from a certified waste stream.

F.2 Sampling and Analysis of Homogeneous Waste for Resource Conservation Recovery Act Constituents

Most of the TRU waste is heterogeneous in nature and requires no further characterization beyond AK to satisfy the regulatory requirements of Resource Conservation Recovery Act (RCRA). For homogeneous waste a fraction of the waste containers (e.g., 55-gallon drums or standard waste boxes) are cored to extract representative samples that are analyzed for constituents (e.g., volatile and semivolatile organic compounds, toxic metals other hazardous chemicals) regulated by RCRA. Both the AK procedure (for heterogeneous waste) and the sampling and analysis procedure (for homogeneous waste) were proposed by DOE for the terms of operation that would be specified in its RCRA permit. These terms have been accepted by New Mexico, which was delegated authority by EPA to regulate RCRA materials and mixed waste and to issue the RCRA Part B permit in October 1999.

F.3 Radiography

A radiography procedure using X rays, also called real-time radiography, is performed on all waste containers to look for items such as pressurized cans or free-standing liquids that are prohibited from being transported under U.S. Department of Transportation regulations. If any of these items are present in a waste container, the prohibited materials are removed and the contents repackaged. This radiographic examination is also used to confirm the AK characterization information.

F.4 Visual Examination

A visual examination is performed on a fraction of the waste containers by placing the waste contents into a glovebox to verify the AK and real-time radiography information. DOE proposed that 2 percent of the initial population of containers of each waste stream be visually examined, and if these evaluations resulted in few miscertifications, the percentage of subsequent waste containers to undergo visual examination would be reduced. In October 1999, New Mexico in its RCRA permit stipulated the initial fraction of containers to undergo visual examination to be 11 percent.

F.5 Radioassay and Determination of Fissile Isotope Content

The number of curies of each transuranic isotope is determined by radioassay (e.g., gamma scans) to a specified precision and accuracy. The fissile isotope content is assessed using non-destructive assay methods, such as passive-active neutron systems. This information is used to meet the Nuclear Regulatory Commission requirement restricting the amount (several hundred grams) per container of each fissile species to ensure criticality safety.

F.6 Headspace Gas Sampling

Headspace gas sampling is carried out on all waste containers for flammable gases (specifically, volatile organic compounds, hydrogen, and methane). This procedure has been proposed as a means of checking on conformity with the U.S. Department of Transportation regulations, such as Title 40 Code of Federal Regulations (CFR) Part 173 and Title 40 CFR Part 177, and U.S. Nuclear Regulatory Commission regulations, such as Title 10 CFR Part 71, that address the transport of flammable and/or gas-generating substances with radioactive materials. DOE has proposed the headspace gas sampling procedure in its application to the U.S. Nuclear Regulatory Commission for a licensing certificate on the transportation package (named the TRansUranic PACkage Transporter, or TRUPACT-II) that is loaded with waste containers for transport by truck to WIPP.

Appendix G

Non-Destructive Techniques for Remote-Handled Transuranic Waste Characterization

This appendix is based on information gathered by the committee in the time frame allowed by this study. It should not be considered a comprehensive review of all techniques being considered to characterize remote-handled transuranic (RH-TRU) waste.

Non-destructive characterization of RH-TRU waste is challenging because of the high surface dose rate of waste canisters (up to 1,000 rem per hour) resulting from the high background gamma and neutron radiation generated by fission and activation products in the waste. To reduce the risk of worker exposure during characterization of RH-TRU waste, non-destructive examination and assay techniques are needed to avoid performing destructive analysis such as visual examination and radiochemical assays. According to the information gathered from DOE's Transuranic and Mixed Waste Focus Area: "Non-destructive examination and assay techniques to characterize remote-handled wastes must still be developed and demonstrated" (DOE-ID, 2001).

Non-destructive assay (NDA) identifies radioactive components, and non-destructive examination (NDE) determines the physical makeup of the waste. These non-destructive technologies must be capable of accurately identifying the physical and radiological properties of wastes in lead-lined containers as well as correcting for precision or bias problems caused by matrix effects (such as heterogeneity problems and interferences with heavy metals in waste) and by the high radiation background. In particular, the neutron emitting RH-TRU solid debris waste at Oak Ridge National Laboratory is the most challenging to characterize.

The following is a brief overview of the major non-destructive characterization techniques currently under development by various Department of Energy (DOE) generator sites, contractors, and private companies. Further development of these techniques and demonstration on actual RH-TRU waste is pending the outcome of the characterization plan for RH-TRU waste. The major NDA/NDE techniques considered for RH-TRU waste are the following:

G.1 Radiography

This NDE technique is often referred to as X-ray radiography or real-time radiography (RTR). X-rays provide a direct measure of material density and as such can be used to establish the physical form of the waste and identify certain prohibited items. In addition, operators can be trained to look for indicators of prohibited items such as electrical components that could contain polychlorinated biphenyls. This technique consists of an X-ray source combined with a TV camera attached to an X-ray detector.

Roney and White (2001) studied the characterization of RH-TRU and lead-lined drums using X-ray imaging techniques. (Roney and White, 2001). Although no real RH-TRU waste was used in their work, they demonstrated the applicability of radiography to surface dose rates up to 100 rem per hour. TMFA states that: "current real time radiography (RTR) techniques cannot analyze the content of the lead-lined drums. Similarly, RH waste inserts and casks are too thick for conventional RTR analysis and interrogation may be further complicated by high radiation levels and contributed 'white noise' from inside the drum" (DOE-TMFA, 2002a).

To the best of the committee's knowledge, radiography has not been demonstrated on real or surrogated waste with surface dose rates close to 1,000 rem per hour.

G.2 Gamma-Ray Spectroscopy

Gamma-ray spectroscopy uses the gamma emission and transmission properties of radionuclides contained in the waste to obtain qualitative and quantitative information of radionuclide content. Gamma-ray tomography is a variation of gamma spectroscopy and is used to determine the spatial and quantitative information of radionuclide distribution in waste containers. Matrix interferences are corrected by scanning for known gamma-ray sources. For further information on related technologies, see, for example, Meeks and Chapman (1997).

G.3 Gamma-Ray Spectroscopy Combined with Acceptable Knowledge

The GSAK approach is used to determine the quantities and types of radionuclides in waste drums. This technique is based on measurement of the radionuclide distribution in the waste followed by normalizing this distribution to the activity of a gamma-emitter such as cesium-137 or cobalt-60, which can be measured outside the waste drum. Based on the measured surface dose rates for cesium-137 or cobalt-60, the amount of these two radionuclides inside the drum can be estimated. This in turn allows the activity of the other radionuclides in the waste drum to be estimated using their ratio to cesium-137 or cobalt-60. The radionuclide distribution may be determined through gamma spectroscopy methods or other nuclear counting methods for alpha- and beta-emitters. Because alpha- and beta-emitters are often difficult to measure in waste, measurements are sometimes used in conjunction with detailed computer modeling to develop a radionuclide distribution that includes these hard-to-measure radionuclides. This technique requires an accurate knowledge of the waste to be characterized before measurements are integrated with computer modeling.

The Battelle Columbus Laboratories have demonstrated this technique with actual RH-TRU waste (Biedscheid et al., 2002). The Idaho Engineering and Environmental Laboratory is also planning to use this technique for its RH-TRU waste originated in Argonne National Laboratory-East (Bhatt and Clements, 2001). For further information about this technique and its demonstrations see Hartwell et al. (1997, 2000), Jensen (2001), and Klann and Grimm (2000).

G.4 Passive and Active Neutron Measurement

Passive and active neutron measurements are widely used in waste management and safeguard operations for fissile mass measurements (usually plutonium-239,

plutonium-241, or uranium-235) and for determination of alpha contents for disposal sites. This technique is based on the spontaneous fission rate determination of fissile material present in the container in (passive neutron measurement mode) and on the induced fission rate by neutron interrogation (active neutron measurement mode). The technique is sensitive to extraneous neutrons coming from secondary alpha decays and from cosmic background. This technique was used to characterize 10 actual RH-TRU waste containers and over 200 containers of surrogate RH-TRU waste at Los Alamos National Laboratory (Estep et al., 1989; Estep, 2001, 2002). For further information on this technique and its variations see DOE (1998), Ensslin et al. (2000), Royce and Lucero (2001), and Schultz et. al. (1995).

G.5 Multi-Detector Analysis System

The multi-detector analysis system (MDAS) technique is used to obtain a direct isotopic measurement with no prior knowledge of the waste. MDAS interrogates the (unshielded) waste with neutrons, and then collects energy coincidence measurements through multiple detectors for both gamma and neutron data over a small period of time. Coincident neutrons provide information on the quantity of fissile material present, and coincident gamma rays provide information on specific isotopes from fission products. This technique is designed to reduce background measurement interferences so that a direct isotopic measurement is provided. Uncertainties associated with current passive/active neutron measurement techniques are reduced by measuring the coincidence energies fast neutrons. A demonstration of this technique on RH-TRU waste was scheduled for 2001 but did not take place due to problems with the external neutron source. For further information on this technique, see DOE-TMFA (2002b), DOE-ID (2001) and Shelton-Davis (2001).

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Appendix H

Waste Dose Rates and Characterization Cost Estimates

The committee provides the following worker dose and characterization cost estimates as examples of the type of assessments that could be presented in the three implementation plans (from Battelle Columbus Laboratories, Energy Technology Engineering Center, and Oak Ridge National Laboratory) that the U.S. Department of Energy (DOE) is planning to submit to the U.S. Environmental Protection Agency and the New Mexico Environment Department along with its characterization plan for remote-handled transuranic (RH-TRU) waste. The committee's assessment is based on the information gathered during the study. It is not to be considered complete and is not meant to replace DOE's own assessment of worker doses and costs.

The predominant exposure pathways for workers from routine waste handling activities are direct exposure to external penetrating radiation or inhalation from surface contamination, and inhalation of airborne radioactive material generated during characterization and handling activities. The radiogenic health effects associated with TRU waste are due primarily to alpha and gamma radiation. Beta particles and neurons may also pose health concerns for RH-TRU waste if the container is breached or waste is exposed during handling or characterization.

H.1 Committee's Example of Estimate for Waste Dose Rates

Because of the high surface dose rates, all of the handling operations involving RH-TRU waste are performed in hot cells, where available, and/or by remote-handling equipment. Good radiological safety practices require that all radiological activities must maintain worker dose levels ALARA (as low as reasonably achievable). In the absence of appropriate radiological safety measures, the potential for significant radiation exposure is high. The estimated volume-weighted mean RH drum surface dose rate at individual generator sites is 470 mSv per hour (47,000 mrem per hour) (Wu, 2001). Therefore, the cost associated with the handling of RH-TRU waste may be substantial.

Doses from handling RH-TRU waste are expected to be less than contact-handled transuranic (CH-TRU) waste due to requirements for remote handling. For instance, the DOE-Carlsbad Field Office estimated for the period 1999-2001 that the collective dose for handling CH-TRU waste at the Waste Isolation Pilot Plant (WIPP) is approximately 0.08 person-mSv (0.008 person-rem) per transportation cask type TRUPAC-II. According to Wu (2001), this is about two times higher than the estimated collective dose to workers handling a RH72-B type cask of RH-TRU waste.

Doses to workers depends on several factors including the number of drums characterized and handled, types of sampling and measurements conducted, number of workers involved in the characterization and drum handling, worker experience and training, and facilities, equipment and shielding. Table H.1 compares estimated

collective doses to workers at three different sites. Because these data are from different sites they may not be comparable.

TABLE H.1 Committee's Estimates of Worker Doses at Selected Sites

Site	Collective Dose	Comment
Battelle Columbus Laboratories	1.0 person-mSv (100 person-mrem) per container	This dose corresponds to an average of five workers handling the containers and includes waste characterization and handling containers for storage.[1]
Argonne National Laboratory-East	0.22-0.64 person-mSv (22-64 person-mrem) per container	Range of collective doses for four different location and storage scenarios.[2]
Waste Isolation Pilot Plant (WIPP)	0.02 person-mSv (2 person-mrem) per container	Waste is shipped to WIPP in RH72-B waste canisters (assume each canister contains 3 containers of 55 gallons). Waste handlers receive 80 % of the dose.[3]

NOTE: Collective doses may not be representative of all RH-TRU waste generator sites. This table was compiled by the committee as an example of worker dose estimates on the basis of information gathered during the study. It is not intended to be complete and may contain inaccuracies.
[1]Memorandum from Dr. Rigley at Battelle Columbus Laboratories (BCL, 2000).
[2]Radiological risk assessment at Argonne National Laboratory-East (Cheng et al., 2002).
[3]Information presented to the committee during the second meeting (Wu, 2001).

The Battelle Columbus Laboratories in Ohio developed its own RH-TRU waste characterization plan, which involves visual examination of the waste during re-packaging. The re-packaging step, which occurs in a hot cell, is necessary because the this site's RH-TRU waste containers do not meet transportation requirements. At this site, the worker dose per container (100 person-mrem per 5 persons corresponds to 20 mrem) is within the range of worker doses for CH-TRU waste characterization (Wu, 2001). It is unclear how representative Battelle Columbus Laboratories worker exposure data are for other RH-TRU waste generators. However, the Battelle data are informative because this is the only site actively characterizing RH-TRU waste.

A radiological risk assessment for RH-TRU waste has been performed for storage options at Argonne National Laboratory-East (Cheng et al. 2002). Although characterization of RH-TRU waste has not begun at this site, risk assessments have been conducted to analyze potential radiation exposures associated with various on-site storage scenarios. Detailed analyses of container handling activities at the Alpha Gamma Hot Cell Facility show that the major determinants of worker collective dose are manipulation of containers for waste loading and placing and securing container lids. These two activities account for 75 percent of the collective dose to workers (Cheng et al., 2002).

The WIPP facility has estimated worker doses for the handling and emplacement of RH-TRU waste (Wu, 2001). WIPP is currently not authorized to receive RH-TRU waste; estimates of worker doses are based on calculated average container surface dose rates, shielding characteristics of the RH72-B canister, and remote-handling of waste canisters. Worker doses are substantially lower than doses estimated at the generator sites primarily because of RH72-B canister shielding.

As shown in Table H.1, collective dose may vary widely between and within sites. For instance, container handling methods and procedures (the key determinant of worker dose) may differ. Further, the relative importance of worker exposures incurred during the characterization phase compared to that incurred in other handling operations will likely differ at the generator sites. Accordingly, it is important that ALARA programs be site-specific.

H.2 Committee's Example of Cost Estimates

Characterization costs including facilities and instrumentation for RH TRU waste sampling and measurements are significant. According to DOE and the generator sites, the characterization of an RH-TRU waste container under the CH-TRU waste characterization requirements is estimated to cost in the range of $20,000 to $300,000 per container (Restrepo and Millard, 2001). In contrast, the cost of characterizing CH-TRU waste is about $3,800 per container (DOE-EM, 2001). The large range in RH-TRU characterization cost estimates is due to the variability in the waste content and the characterization processes among the sites. In addition, these cost estimates are not site-specific and take into account only a few characterization scenarios. Associated infrastructure costs in support of full characterization of RH-TRU waste have been estimated to be $100,000 per container (Restrepo and Millard, 2001). The Committee has not verified these cost estimates.

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Appendix I

Glossary

20.4.1 (The New Mexico Administrative Code Chapter 20, Section 4, Part 1): New Mexico Environment Department. Establishes the regulations for the management of hazardous waste consistent with the New Mexico Hazardous Waste Act and Federal Resource Conservation and Recovery Act (RCRA) regulations, Titles 40 Code of Federal Regulations (CFR) Parts 260 through 270.

20.4.1.200: New Mexico Environment Department (NMED). This regulation (incorporating Title 40 CFR Parts 261.24, 261.31, and 361.33) requires the US. Department of Energy (DOE) to identify and list hazardous wastes.

20.4.1.500: New Mexico Environment Department. This regulation (incorporating Title 40 CFR 264) requires DOE to conduct a detailed analysis of the hazardous waste components of transuranic mixed waste to obtain all the information on how to treat, store or dispose of the waste. DOE must demonstrate that the design and operation of the facility will minimize the possibility of the release of TRU mixed waste, a fire, or an explosion. NMED prohibits the following at WIPP:

1. liquid waste;
2. pyrophoric materials;
3. non-mixed hazardous wastes;
4. chemically incompatible wastes;
5. explosives and compressed gases;
6. polychlorinated biphenyl concentrations; and
7. ignitable, corrosive, and reactive waste.

20.4.1.900: New Mexico Environment Department. This document contains the hazardous waste permit program requirements issued by the NMED (incorporating 40 CFR 270). These requirements must be met by the DOE to receive NMED approval of the waste analysis plan submitted as Part B of the permit application (see Hazardous Waste Permit) for mixed transuranic waste.

10 CFR 20: (Title 10 Code of Federal Regulations Part 20): United States Nuclear Regulatory Commission. Standards for Protection Against Radiation.

10 CFR 835: U.S. Department of Energy. Occupation Radiation Protection. Establishes the standards, limits, and program requirements for protecting individuals from ionizing radiation resulting from DOE activities.

40 CFR 191: U.S. Environmental Protection Agency (EPA). Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Final Rule. December 20, 1993. Federal Register (FR) 58(242): 66398-66416. This regulation prescribes EPA environmental radiation protection standards that will apply to all sites (except Yucca Mountain) for the deep geologic disposal of highly radioactive waste. Congress required EPA to evaluate whether the WIPP complies with Subparts B and C of the disposal regulations set forth in this document for the management and disposal of transuranic radioactive wastes.

40 CFR 194: U.S. Environmental Protection Agency. Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's compliance with the 40 CFR Part 191 Disposal Regulations, Final Rule. May 18, 1998. Federal Register 63(95): 27353-2740. This regulation stipulates that DOE must provide a list to the EPA that identifies and describes waste characteristics that can impact the WIPP's performance. This list may be derived from methods that include process knowledge and non-destructive assay/examination. On May 18, 1998, the EPA issued a final rule certifying that the WIPP was compliant with applicable EPA TRU waste disposal regulations set forth in 40 CFR 191 and the compliance criteria of 40 CFR 194 (63 FR 27354).

40 CFR 194.22(b): U.S. Environmental Protection Agency. This section includes the quality assurance requirements for waste characterization activities and assumptions. The quality assurance provisions allow the characterization of waste by 1) peer review; 2) corroboration with new data, 3) confirmation by measurement, or 4) qualification of previous QA programs.

40 CFR 261: U.S. Environmental Protection Agency. Identification and Listing of Hazardous Waste. This part identifies those solid wastes that are subject to regulation as hazardous wastes under Parts 262-265, 268, 270, 271, and 124 of Title 40 of the Code of Federal Regulations. Codified in New Mexico as 20 NMAC 4.1, Subpart II.

40 CFR 264: U.S. Environmental Protection Agency. This part consists of "Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities." This subpart establishes minimum national standards, that define the acceptable management of hazardous waste. Codified in New Mexico as 20 NMAC 4.1, Subpart V.

40 CFR 270: U.S. Environmental Protection Agency. This regulation establishes provisions for the Hazardous Waste Permitting Program under Subtitle C of the Resource Conservation and Recovery Act. This regulation and the associated State of New Mexico regulations require the permitting of the WIPP as a hazardous waste management unit. Codified in New Mexico as 20 NMAC 4.1, Subpart IX.

Acceptable Knowledge (AK): a term used by the EPA that encompasses process knowledge and results from previous testing, sampling, and analysis of waste. Acceptable knowledge includes information regarding the raw materials used in a process or operation, process description, products, and associated wastes. Acceptable knowledge documentation includes the site history and mission, site-

specific processes or operations administrative building controls, and all previous and current activities that generate a specific waste.

ALARA (As Low As is Reasonably Achievable): radiation protection program for minimizing personnel exposure to radiation. ALARA means making every reasonable effort to maintain exposures to radiation as far below the dose limits in the DOE guidance as is practical consistent with the purpose for which the activity is undertaken.

Audit: a planned and documented investigative evaluation of an item or process to determine the adequacy and effectiveness as well as compliance with established procedures, instructions, drawings, and other applicable documents.

Buried Transuranic Waste: radioactive waste meeting the current definition of TRU waste, which was disposed of by shallow land burial and other techniques at a number of sites owned and operated by the federal government in support of the nuclear weapons program from the 1940s through 1970. In 1970 the Atomic Energy Commission first identified TRU waste as a separated category of radioactive waste, and all TRU waste generated after 1970 has been segregated from low-level waste and placed in retrievable storage pending shipment to and disposal in an approved geologic repository. Most of this buried waste is considered irretrievable.

Compliance Certification Application (CCA): DOE submits this application (Title 40 CFR Part 191, Compliance Certification Application for the Waste Isolation Pilot) to the EPA in order to request certification from the EPA for the WIPP facility.

Certified Waste: containers of waste that meet the WIPP waste acceptance criteria.

Code of Federal Regulations (CFR): 1) a codification of the general and permanent rules published in the Federal Register by the department and agencies of the federal government. The CFR is divided into 50 titles that represent broad areas subject to federal regulation. It is issued quarterly and revised annually. 2) All federal regulations in force are published annually in codified form in the CFR.

Contact-handled (CH) waste: Transuranic waste that has a measured radiation dose rate at the container surface of 200 millirem per hour or less and can be safely handled without special equipment when in closed containers. [LWA]

Cellulosics, Plastic, Rubber (CPR): the characterization objectives for RH-TRU waste set forth by the EPA in 40 CFR 191 and 40 CFR 194 require that DOE account for the volume of CPR because of the potential gas generation from the decomposition of these organic materials.

Curies (Ci): unit of radioactivity. One curie equals 3.7×10^{10} nuclear transformations per second. This unit reflects the intensity of a radioactive source.

Data Quality Objectives (DQO): qualitative and quantitative statements that clarify program technical and quality objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.

Defense Waste: 1) radioactive waste from any activity performed in whole or in part in support of DOE atomic energy defense activities; excludes waste under purview of the Nuclear Regulatory Commission or generated by the commercial nuclear power industry. 2) Nuclear waste derived mostly from the manufacturing of nuclear weapons, weapons-related research programs, the operation of naval reactors, and the decontamination of weapons production facilities.

Environmental Evaluation Group (EEG): The New Mexico Environmental Evaluation Group conducts an independent technical evaluation of the operations of the Waste Isolation Pilot Plant (WIPP) to ensure the protection of public health and safety, and the environment of New Mexico. The EEG has been serving New Mexico in this capacity since 1978. Public Law 100-456 articulates EEG's role and responsibilities relating to WIPP.

Gray (Gy): the standard unit of absorbed ionizing-radiation dose. One gray is equivalent to one joule of energy absorbed per kilogram of matter. One gray is equal to 100 rad.

Hazardous Constituent: those chemicals identified in Appendix VIII of 20 NMAC 4.1 Subpart II (40 CFR Part 261).

Hazardous Waste: As defined in 40 CFR 261.3, waste that because of its quantity, concentration, or physical, chemical or infectious characteristics, may cause or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible illness, or pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed. Hazardous wastes are listed in 20 NMAC 4.1 Subpart II (40 CFR Part 261) and/or exhibit one of the four characteristics - ignitability, corrosivity, reactivity, and toxicity in 20 NMAC 4.1 Subpart II (40 CFR Part 261).

Hazardous Waste Codes: numbers assigned to identify the EPA category of hazardous waste. Hazardous waste codes' assignment for RH TRU waste ensures that only those wastes that are permitted at the WIPP are disposed of and to ensure waste compatibility during the operational phase at the WIPP.

Headspace Gas: the gas within the free volume at the top of a closed container (between the container lid and the waste inside the container) or containment, such as a drum or bin, containing TRU mixed or simulated waste. The gas may be generated from biological, chemical, or radiolytic processes; this includes contributions from volatile organic compounds (VOC) present in the waste.

Headspace Gas Analysis: headspace gas is sampled using a gas-tight syringe to draw a gas sample from beneath the drum or box lid. The sample is analyzed by gas chromatography and/or mass spectrometry for hydrogen, methane, and volatile organic compounds.

Land Withdrawal Act (LWA): Public law 102-579 withdraws the land at the WIPP site from "entry, appropriation, and disposal." It transfers jurisdiction of the land from the secretary of the interior to the secretary of energy and reserves the land for activities associated with the development and operation of the WIPP. It requires DOE to comply with the EPA's radioactive waste standards and final disposal regulations

and to conduct studies to analyze the impact of RH-TRU wastes on repository performance. It includes many other requirements and provisions pertaining to the protection of public health and the environment. The LWA was signed into law on October 30, 1992.

New Mexico Hazardous Waste Act (HWA): the New Mexico legislation that establishes the state hazardous waste management program.

Newly Generated TRU Waste: waste generated after the development, approval, and implementation of the TRU waste characterization program that meets the requirements outlined in the TRU waste characterization quality assurance program plan. Part of the inventory might not have been generated yet but is estimated to be generated at some time in the future by the TRU waste generator/storage sites.

Non-destructive Assay (NDA): NDA is a general term for a number of techniques, such as gamma spectroscopy and passive/active neutron measurement. These techniques provide information on the radionuclide content of waste and sometimes on its spatial distribution inside containers.

Non-destructive Examination (NDE): NDE is a general term for a number of techniques, such as radiography or computer tomography. Radiography is a non-destructive qualitative and semi-quantitative technique that involves X-ray scanning of waste containers to identify and verify waste container contents. Because of the shielding associated with RH TRU waste, computer tomography, which involves several sources to produce a three-dimensional image may be required rather than the more commonly used radiography.

Packaging: the assembly of components necessary to ensure compliance with packaging requirements, it may consist of one or more receptacles, absorbent material, spacing structures, thermal insulation, radiation shielding, and devices for cooling or absorbing mechanical shocks.

Performance Assessment: risk-based assessment of the safety performance of a nuclear waste facility. The purpose of the performance assessment for WIPP is to evaluate the ability of the repository to isolate radioactive waste from the accessible environment. The performance assessment organizes information relevant to long-term (i.e., over a 10,000-year period) repository behavior by assessing the probabilities and consequences of major scenarios by which radionuclides can be released to the environment surrounding the WIPP site. Important scenarios include those due to human activities, whether deliberate or unintentional, that might occur near the WIPP site and potentially compromise the integrity of the repository.

Pyrophoric: spontaneously ignitable materials.

Process Knowledge: the determination of waste container contents through the study of existing records on the production history of the waste.

Quality Assurance: the planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service.

Quality Assurance Program Plans (QAPP): documents that describe the overall program plans and activities to meet the project's quality assurance goals.

Rad: unit of absorbed dose. It represents 0.01 joules of energy absorbed per kilogram of matter. Rad and rem are important units regarding WIPP because requirements are expressed in rem, a derivative or rad.

Radioassay: a term used to define measurement methods for determining the radionuclide content of waste and includes both non-destructive assay (NDA) and destructive assay (e.g. radiochemistry).

Radiological Survey: Measurements of radioactive contamination levels or dose rates associated with a site together with the appropriate documentation and data evaluation. When AK indicates that some containers may approach 1000 rem/h or that some containers exceed 100 rem/h then radiological surveys of each container may be required. Industry standard survey instruments can be used in this process and are required to discriminate at 100 rem/h and 1000 rem/h.

Radiography: a non-destructive, non-intrusive radiographic examination technique that enables a qualitative (and in some cases quantitative) evaluation of the contents of a waste container. Radiography utilizes X rays to inspect the contents of the waste container in real time. It is used to examine and verify the physical form of the waste for certain waste forms, identify individual waste components, and verify the absence of certain non-compliant items.

RCRA: see Resources Conservation and Recovery Act.

RCRA Part B Permit: issued for the WIPP on October 27, 1999 by the NMED. This permit (incorporating 20.4.1.500 and 20.4.1.900) determines that DOE's disposal plan for mixed TRU waste is acceptable. Also called the Hazardous Waste Facility Permit.

Rem (Roentgen Equivalent Man): unit of absorbed radiation dose used to derive a quantity called equivalent dose. This relates the absorbed dose in human tissue to the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Equivalent dose is often expressed in terms of thousandths of a rem, or mrem. The equivalent dose (rem) is determined by multiplying the absorbed dose (rad) by a quality factor (Q) that accounts for different biological effects caused by different radiations. Dose requirements regarding WIPP are expressed in this unit.

Remote-handled (RH) Waste: transuranic wastes that have a measured radiation dose rate at the container survey of 200 millirem per hour or greater but not more than 1,000 rem per hour. This waste must be handled remotely (i.e., with machinery designed to shield the handler from radiation).

Resource Conservation and Recovery Act (RCRA): established a system for tracking and regulating hazardous wastes from the time of their generation through disposal. The law requires safe and secure procedures to be used by hazardous waste generators in treating, handling, transporting, storing, and disposing of hazardous substances. RCRA is designed to prevent new uncontrolled hazardous waste sites.

The law also regulates the disposal of solid waste that may not be considered hazardous. Note: 20 NMAC 4.1 and 40 CFR Parts 260-281 are the regulations for complying with RCRA with respect to hazardous waste and hazardous waste treatment, storage, and disposal facilities in New Mexico.

Retrievably Stored TRU Waste: waste generated after 1970. In 1970 the Atomic Energy Commission (predecessor to the DOE) first identified TRU waste as a separate category of radioactive waste. The same year, the Atomic Energy Commission determined that all TRU waste generated after 1970 must be segregated from low-level waste and placed in retrievable storage pending shipment to and disposal in an approved geologic repository. Federal facilities in Washington, Idaho, California, Colorado, New Mexico, Nevada, South Carolina, Ohio, Tennessee, and Illinois are currently storing TRU waste. See also Buried Transuranic Waste.

Roentgen: unit used to measure a quantity called exposure. The roentgen is that quantity of X or gamma radiation less than 3 MeV in energy that produces 1 electrostatic unit of charge, 2.58×10^{-4} coulombs, in 1 kilogram of dry air at 0 degree Celsius and at an atmospheric pressure of 760 mmHg. Many radiation measuring instruments measure the roentgen (ionization) directly. It is a measure of the ionizations of the molecules in a mass of air. The main advantage of this unit is that it is easy to measure directly, but it is limited because it is only for deposition in air, and only for gamma and X rays.

Safety Analysis Report (SAR): document representing a statement and commitment by the DOE that the WIPP can be operated safely and at acceptable risk. This document summarizes the safety analyses to ensure the safety of workers, the public, and the environment from the hazards posed by WIPP waste handling and emplacement operations during the disposal phase and hazards associated with the decommissioning and decontamination phase. The WIPP SAR is prepared to satisfy: (1) the commitments in the Working Agreement for Consultation and Cooperation between the State of New Mexico and the U.S. Department of Energy; and (2) to ensure compliance with DOE's 10 CFR 830 about nuclear safety management.

Sievert: unit of measurement of radiation dose equivalent. One sievert is the absorbed dose, expressed in gray, multiplied by a quality factor to account for different biological effects caused by different radiations.

Summary Category Group: categories for each waste stream to facilitate RCRA waste characterization that reflect the final waste forms acceptable for WIPP disposal. The waste summary categories are identified by the generators and are the following:

S3000: Homogeneous solids
S4000: Soils/gravel
S5000: Debris waste

Transuranic Waste: radioactive waste consisting of radionuclides with atomic numbers greater than 92 in excess of agreed limits. A more precise definition, in DOE Order 5820.2A, EPA regulation 40 CFR 191, and the Land Withdrawal Act, is waste that is not high-level waste "contaminated with alpha-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram." The regulatory definition excludes actinide elements with atomic numbers between 90 and 92 (most significantly, Th and U

isotopes), in agreement with the literal meaning of “transuranic.” However, common usage of “transuranic waste” is often understood to include all actinides.

Transuranic mixed waste: transuranic waste contaminated with hazardous constituents as identified in 20 NMAC 4.1 Subpart II (40 CFR 261), Subparts C and D.

Toxic Substances Control Act (TSCA): Act enacted by Congress in 1976 to give EPA the ability to track the 75,000 industrial chemicals currently produced or imported into the United States. EPA repeatedly screens these chemicals and can require reporting or testing of those that may pose an environmental or human-health hazard. EPA can ban the manufacture and import of those chemicals that pose an unreasonable risk.

Visual Examination (VE): process consisting of physically examining TRU waste by removing it from the container it was originally packaged in.

Volatile Organic Compounds (VOC): RCRA regulated organic compounds that readily pass into the vapor state and are present in transuranic mixed waste.

Waste Acceptance Criteria (WAC): set of conditions established for permitting transuranic wastes to be packaged, shipped, managed, and disposed of at the WIPP.

Waste Analysis Plan (WAP): document describing the procedures that will be carried out at a facility to obtain chemical and physical analysis of each waste managed so that all information will be known to treat, store or dispose of the waste in accordance with 40 CFR 264.13.

Waste Characterization: sampling, monitoring, and analysis activities to determine the nature of the waste.

Waste Matrix Code: code assigned by the TRU waste generator/storage sites to categorize mixed and some non-mixed waste streams in the DOE system into a series of five-digit alphanumeric codes (e.g., S5400; Heterogeneous Debris) that represent different physical/chemical matrices. These codes were developed by DOE in response to the Federal Facility Compliance Act of 1992.

Waste Profile Form: form that waste generator must complete to properly identify and document the characterization of any solid, liquid, hazardous, radioactive, or mixed waste. The Waste Profile Form must provide a complete and concise description of the waste, including the details of the generating process. The Waste Profile Form process provides generators with guidance to help make the determination of the waste’s physical, chemical, and radiological characteristics with sufficient accuracy to permit proper segregation, treatment, and disposal according to the final treatment/disposal facility’s waste acceptance criteria.

Waste Stream: waste material generated from a single process or activity or as multiple containers with similar physical, chemical, or radiological characteristics.

Appendix J

Acronyms

AK: acceptable knowledge
ALARA: as low as reasonably achievable
CAO: Carlsbad Area Office
CBFO: Carlsbad Field Office
CH-TRU: contact-handled transuranic
DOE: U.S. Department of Energy
EPA: U.S. Environmental Protection Agency
NMED: New Mexico Environment Department
PUREX: plutonium uranium extraction
RH-TRU: remote-handled transuranic
RCRA: Resource Conservation and Recovery Act
SCG: summary category group
WIPP: Waste Isolation Pilot Plant
WWIS: WIPP Waste Information System

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International Peer Review

of the 1996 Performance Assessment

of the US Waste Isolation Pilot Plant (WIPP)

April 1997

Report of the NEA/IAEA
International Review Group

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OECD/NEA - IAEA JOINT INTERNATIONAL REVIEW OF WASTE ISOLATION PILOT PLANT 1996 PERFORMANCE ASSESSMENT

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Ref. EN/S/5242

Issy-les-Moulineaux, 9 April 1997

Dear Mr. Dials,

Please find enclosed the final report of the international peer review of the 1996 Performance Assessment of the Waste Isolation Pilot Plant (WIPP) as documented in "Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant" (CCA). This technical review was commissioned by the Carlsbad Area Office of the United States Department of Energy (DOE) and jointly organised by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development and the International Atomic Energy Agency as part of their routine services to their member Countries.

The review report is based on the best understanding obtained after several months of deep involvement of the Joint Secretariat and the experts of the International Review Group (IRG) which were especially set up and appointed for this purpose. It represents the combined views of the members of the IRG and is directed to the DOE and thus drafted for a technical audience familiar with contents of the CCA. It contains information which was considered useful and worth bringing to the attention of DOE. This cover letter highlights the main findings of the review in order to place them in a broad perspective, but it does not substitute for a thorough reading and interpretation of the actual report.

The primary focus of the review was on the technical soundness of the analyses and of the DOE approach to post-closure performance assessment, examined from an international perspective. The review report does not formally cover compliance aspects with the national regulations.

Not all parts of the CCA documentation were reviewed at the same level of detail, and specific points were looked at in greater depth according to the technical background, experience and judgement of each member of the IRG. The IRG also took into account additional information provided by the DOE in the course of the review, as well as their knowledge of the WIPP studies gained from previous international contacts. To preserve independence, the IRG did not examine reviews of the WIPP by other groups.

The IRG concluded that the performance assessment methodology is well-founded and has confidence in the majority of judgements and assumptions made in developing the calculational models. The quality of assessment codes and data handling is also generally good. Thus, the analyses reported in the CCA are, in the main, technically sound. The nature of the critical review has tended to identify and emphasise areas where improvements could be made, however, and comments and suggestions are also proposed for consideration by the DOE in future iterations of their assessments of the WIPP, e.g. during the re-certification phase of the facility. These should be considered within the context of the overall positive view of the IRG on the technical soundness and quality of the WIPP performance assessment as documented in the CCA. In particular, two areas are considered as deserving further attention by the DOE: (a) the implications, favourable and unfavourable, of the magnesium oxide backfill, and (b) the assumption of rapidly-reached, homogeneous conditions within the disposal rooms.

From the experience of the review, the IRG believes that, in the case of undisturbed performance, the WIPP facility would meet individual radiation dose standards typical of those used in other countries, even beyond the 10,000 years regulatory period. A judgement could not be reached for the case of disturbed performance, although supplementary analyses by the DOE indicated that a risk target, as internationally accepted, would be met in respect of a direct drilling scenario of the type specified in the regulations.

You will note that the review makes an overall judgement of the 1996 Performance Assessment of the Waste Isolation Pilot Plant rather than emphasizing views on specific aspects, and the report needs to be considered in its entirety. We trust that if the report is read from that perspective, it will prove valuable to the DOE.

On behalf of the IRG and the Joint Secretariat, we would like to take this occasion to thank you and your colleagues for your openness and assistance in the course of the review.

Yours sincerely,

Claudio Pescatore

Dr. Claudio Pescatore
On behalf of the IRG Chairman
and the Joint NEA/IAEA Secretariat

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International Peer Review

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April 1997

Report of the NEA/IAEA
International Review Group

International Peer Review of the 1996 Performance Assessment of the U.S. Waste Isolation Pilot Plant (WIPP)

Report of the NEA/IAEA International Review Group

Preface

In January 1996, the United States Department of Energy (DOE) requested the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA) and the International Atomic Energy Agency (IAEA) to jointly organise an international peer review of the 1996 post-closure performance assessment of the Waste Isolation Pilot Plant (WIPP). This assessment is described in the DOE document "Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant", issued in October 1996 and referred to as the CCA.

The NEA and the IAEA accepted the invitation and, in June 1996, Terms of Reference for the review were agreed between the DOE, the NEA and the IAEA .

The review was carried out, in the period October 1996 to March 1997, by a team of experts invited by the NEA and the IAEA, referred to as the International Review Group (IRG). The review included an examination of the relevant parts of the CCA, a visit to the WIPP site, and focused discussions between the IRG and DOE staff and contractors.

This report presents the combined, personal views of the members of the IRG, and offers the DOE an independent, international perspective on the 1996 performance assessment of the WIPP. The protocol for the review does not foresee further exchange between the DOE and the IRG and therefore the report is final.

This report has not been checked by the DOE. The IRG has made its best effort to ensure that all information in this report is accurate and takes responsibility for any factual inaccuracies.

International Peer Review of the 1996 Performance Assessment of the U.S. Waste Isolation Pilot Plant (WIPP)

Report of the NEA/IAEA International Review Group

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List of abbreviations

CCA	Title 40 CFR Part 191 Compliance Certification Application for the WIPP
CCDF	complementary, cumulative distribution function
CFR	Code of Federal Regulations
CH	contact-handled (TRU waste)
DOE	United States Department of Energy
DRZ	disturbed rock zone
EPA	United States Environmental Protection Agency
FEPs	features, events and processes
IAEA	International Atomic Energy Agency
IRG	International Review Group
LWA	Land Withdrawal Act
NEA	Nuclear Energy Agency of the Organisation for Economic Co-operation and Development
RH	remote-handled (TRU waste)
TRU	transuranic (waste)
US	United States (of America)
WIPP	Waste Isolation Pilot Plant

1. Introduction

This chapter outlines the background to the review, the composition of the International Review Group, and the process of the review, including the objective and scope. The structure of the report is also outlined.

1.1 Background to the Review

In the United States, the Department of Energy (DOE) is responsible for managing transuranic (TRU[1]) wastes generated by the production of nuclear weapons and other defence-related activities. The Waste Isolation Pilot Plant (WIPP) has been sited and designed to meet the criteria established by the US Environmental Protection Agency (EPA) for the safe, long-term disposal of such wastes. The facility is located near Carlsbad in south-eastern New Mexico and consists of above-ground and below-ground parts. The underground facility (repository) is located at a depth of 650 metres below the surface in a 600-metre-thick, bedded-salt formation.

The EPA regulations require, inter alia, that the DOE demonstrates a reasonable expectation that the WIPP repository will isolate the wastes placed in it from the accessible environment for 10,000 years. The DOE has developed an approach to demonstrating the long-term performance of the WIPP repository based on probabilistic performance assessment. This is designed to estimate how the WIPP disposal system[2] will perform during the 10,000-year regulatory period, taking account of uncertainties in events and processes which could affect the repository in the future.

Beginning in 1980, the DOE has carried out a series of iterative analyses of the long-term performance of the WIPP facility[3]. The latest, the 1996 performance assessment, is described in the DOE document "Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant" [DOE 1996], hereafter referred to as the CCA. The primary purpose of the CCA is to present the information required by the EPA to assess compliance with specific regulations (see Chapter 2). The CCA consists of Volume I plus over 50 appendices.

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[1] TRU waste is defined by the EPA as waste that contains more than 100 nanocuries (3,700 becquerels) of alpha-emitting transuranic isotopes, with half-lives greater than 20 years, per gram of waste, but excluding high-level radioactive waste and certain other wastes, c.f. 40 CFR 191 §191.02(i).

[2] Disposal system means any combination of engineered and natural barriers that isolate the radioactive waste after disposal, c.f. 40 CFR 191 §191.12.

[3] These earlier performance assessment documents have not been examined as part of this review.

1.2 The International Review Group

The International Review Group (IRG) assembled by the NEA and the IAEA included seven members actively involved in national radioactive waste management programmes - from waste management organisations, national regulatory bodies, universities and scientific consultancies. The IRG was completed by two representatives each from the NEA and the IAEA who provided a joint Secretariat and contributed technically to the review.

The names and summaries of experience of members of the IRG are provided in Appendix 1. Mr. Ken Bragg agreed to act as Chairman.

None of the members of the IRG had ever worked directly on the WIPP Project (or worked as a contractor or subcontractor to the DOE). All, however, had participated in international meetings, projects and comparison exercises in which the WIPP project had been represented, and had some prior knowledge of the project and of performance assessment as practised by the DOE. In some cases, this knowledge was extensive and detailed, and gained over many years in bi-lateral or multi-lateral exchanges.

1.3 The Review Process

1.3.1 Objective

The Terms of Reference for the review were negotiated between the DOE, the NEA and the IAEA, based on a first proposal by the DOE. The significant parts of the Terms of Reference are reproduced in Appendix 2. Therein, it is stated that:

> "The objective of the international review is to examine whether the post-closure performance assessment of the WIPP in the CCA is appropriate, technically sound and in conformity with international standards and practices."

The interpretation of this objective was discussed at length within the IRG, especially the phrase "in conformity with international standards and practices".

The IRG decided to conduct its examination to answer the following broad questions stemming from above statement.

Is the WIPP 1996 post-closure performance assessment:

1. appropriate ?

The IRG agreed that this should be interpreted as meaning appropriate in the context of the objective of the CCA, which is to satisfy the EPA regulations. The IRG also agreed that it should not undertake a formal comparison with the EPA regulations since this is the responsibility of the EPA. In this respect, it is emphasised that this review was organised to provide the DOE an independent, international perspective on the 1996 post-closure performance assessment of the WIPP.

2. **technically sound ?**

The IRG agreed that this item should be the primary focus of the review. For example, have adequate data and process information been used, are the conceptual models and their underlying assumptions scientifically-based or reasonable, have adequately tested mathematical and computer tools been applied ?

3. **in conformity with international practices?**

That is, are the scope of the assessment, methods of analysis and quality of application consistent with good practice in other countries ?

4. **in conformity with international guidance and standards?**

That is, are the calculated end-points consistent with international guidance[4] and standards in the manner these are formulated in other countries ?

1.3.2 Scope

The Terms of Reference identify the CCA Volume I as the primary material to be reviewed. After individual examination of this document, and joint discussions, the IRG made the following initial observations and decisions:

- The CCA has been prepared by the DOE to comply with the EPA regulations. These provide detailed guidance on how to demonstrate compliance, and are focused on the evaluation of specific performance indicators.
- The CCA Volume I does not constitute a self-contained or sufficient description of the 1996 performance assessment. Rather, it is necessary to examine many of the CCA appendices in order to find technical information at the level required by the IRG.
- The iterative programme of performance assessment of the WIPP has been the subject of a number of previous independent reviews, notably by the US National Academy of Sciences [NAS 1996]. These other reviews, several of which are summarised in Chapter 9 of the CCA Volume I, would not be examined as part of this review.
- In coming to a view on the four broad questions identified in Section 1.3.1, the IRG considered that it would also be able to examine and comment on other issues indicated by the Terms of Reference, such as the clarity and transparency of the documentation.

1.3.3 Conduct of the review

A summary of the history and conduct of the review is given in Box 1.

The IRG did not review the whole of the CCA at the same level of detail. The focus was on the DOE approach to post-closure performance assessment, technical soundness at a

[4] A list of relevant international documents is annexed to the Terms of Reference, see Appendix 2.

conceptual level, and the performance of the disposal system. Specific points were identified and examined according to the technical background, experience and judgement of each reviewer. During the review, the DOE provided additional information orally, in some cases supported by overheads. This information has been taken into account by the IRG, but has not been formally reviewed.

In their work, the IRG identified technical issues of concern, both general and detailed, made specific comments to define the issues and, in many cases, made suggestions to the DOE on how concerns might be alleviated. It is for the DOE to decide if, or when, any of the suggestions will be implemented in their work[5].

1.4 Structure of the Report

The findings of the review are presented as follows:

- Chapter 2 introduces the EPA regulations which the CCA has been designed to satisfy, identifies and comments on the requirements which have had most influence on the assessment approach adopted in the CCA, and highlights points of interest from an international perspective. The aim of the chapter is to separate observations by the IRG on points related to the EPA regulations from the technical review of work by the DOE.

- Chapter 3 comments on the 1996 performance assessment mainly from a technical perspective. In particular, it examines the technical quality of the stages of post-closure assessment - compilation of data, identification of FEPs and scenarios, treatment of processes and sub-system modelling, system modelling and calculations. Comments are also made on the CCA documentation.

- Chapter 4 summarises the results of the review. This includes observations on the specificity of the WIPP case, the evaluation of the 1996 performance assessment of the WIPP facility against the Terms of Reference, and the overall judgement arising from the experience of the review.

The report assumes that the reader is familiar with the WIPP project and the CCA and presents a minimum of introductory material related to either.

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[5] The Terms of Reference of the review do not ask for recommendations for the future programme of the DOE, and the future programme was not discussed during the review. It is understood, however, that the DOE has already taken action on some of the points raised by the IRG during the discussion meetings, and there are opportunities for further actions to be taken during the WIPP re-certification process.

Box 1: History and Conduct of the International Review

In January 1996, the Manager of the Carlsbad Area Office of the DOE approached the NEA and the IAEA to ascertain their willingness to organise a review of the 1996 performance assessment of the WIPP. In February and March, the NEA and the IAEA agreed, in principle, to carry out such a review, and formal agreement to carry out a jointly organised review was reached in June 1996. The NEA and IAEA formed a joint Secretariat and invited individual experts to participate in the review so that, by July 1996, a team covering the range of relevant expertise was identified - the International Review Group (IRG).

A copy of Volume I of the CCA was supplied to members of the IRG in October 1996. IRG members made a preliminary examination of the document and, in November 1996, met in Vienna to discuss the objectives and approach to conducting the review. The coverage of the various sections of the CCA by the IRG was discussed, and each member was assigned a selection of those CCA appendices and supporting references that he might need to examine. These documents were supplied to individual reviewers by the DOE, mainly by the end of November 1996.

Each reviewer then examined the CCA Volume I, selected appendices and references, and formulated a series of questions arising from the examination. These preliminary questions were compiled and submitted to the DOE in early January 1997 in order to have a more focused meeting between the IRG and DOE later that month. The compiled list included over 100 questions, organised into broad subject headings such as "presentation of safety assessment results", "FEP and scenario identification methods", "radionuclide inventory", etc.. Some of these questions were very specific, referring to particular data items and identified pages of the CCA; others were more general and were requests for clarification about DOE methods as described in the CCA; a few asked for supplementary information not included in the scope of the CCA, e.g. related to radiological consequences. Written answers were not provided, but the questions were used by the DOE to plan a set of focused presentations to the IRG, see below.

The DOE provided an electronic version of the CCA, including its appendices and references, to members of the IRG in early January. The reviewers were not able to take full advantage of these CD-ROMs in their main review work due to the late availability. The CD-ROMs, and the cross-references and search tools which they include, are undoubtedly useful, however, and were used later during the editing of the review report to check specific information in the CCA.

From 26 to 31 January 1997, the IRG met in Carlsbad, New Mexico. In this time, the IRG visited the WIPP facility, received focused presentations from DOE staff and contractors based on the questions previously submitted, and held meetings in closed session to review and confirm individual and joint views on the WIPP post-closure performance assessment. The presentations by the DOE were the starting point for detailed technical discussions which served to answer most of the questions originally raised by the IRG members. The visit to the WIPP facility, and associated discussions with DOE staff, were especially valuable to the reviewers in developing their understanding of the WIPP project and disposal system. During the meetings, information was provided orally, in some cases supported by overheads. This information has been taken into account by the IRG, but has not been formally reviewed.

On the final day of the week, a preliminary oral report was given to DOE representatives by the IRG Chairman.

A first draft report of the review was compiled and circulated to the IRG members for comment in February 1997. These comments were assimilated, and a second draft was produced and discussed at a meeting of the Secretariat, Chairman and consultant in Paris on 12 March 1997. A third draft was prepared and circulated to the IRG members for final comments. After incorporation of final comments, and unanimous approval by the IRG, the final report (this document) was submitted to the DOE on 9 April 1997.

2. The EPA Regulations and their Influence on the CCA

This chapter introduces the EPA regulations which the CCA has been designed to satisfy, identifies and comments on the requirements which have had most influence on the approach to performance assessment adopted in the CCA, and highlights points of interest from an international perspective. The aim of the chapter is to separate observations of the IRG on points related to the EPA regulations, from the technical review of work by the DOE, which is reported in Chapter 3.

In this chapter, factual and neutral observations are given in plain text. Opinions of the IRG are given in italics.

2.1 The EPA Regulations

The DOE was self-regulating until the Land Withdrawal Act (LWA) for the WIPP was promulgated in 1992. Amongst other provisions, the LWA designated the EPA as the regulator for radiological safety of the WIPP facility.

The design and operation of the WIPP are governed by a comprehensive set of US federal and state regulations. The regulations relevant to the post-closure radiological performance of the WIPP, which the CCA is designed to address[6], are contained in two EPA standards:

- **40 CFR Part 191** - Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes - which sets out general requirements for geological disposal systems in the US;
- **40 CFR Part 194** - Criteria for the Certification and Re-certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations - which details the application of 40 CFR Part 191 to the WIPP.

In addition, the EPA has issued guidance on the interpretation of 40 CFR Part 194 in a Compliance Application Guidance document [EPA 1996].

40 CFR 191 was first issued in 1985, remanded in 1987 and re-issued in 1993. The regulation applies to spent nuclear fuel, high-level and transuranic (TRU) radioactive wastes, and sets out environmental standards for management and storage (Subpart A), disposal (Subpart B) and groundwater protection (Subpart C).

40 CFR 194 was issued in February 1996 and became effective two months later. The regulation sets out guidance specific to the WIPP project on the approach to performance assessment that the DOE should adopt and on the structure and content of the CCA. It provides detailed guidance on containment, assurance, and groundwater protection requirements, and includes paragraphs on, for example:

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[6] Compliances with other regulations are dealt with in separate submissions by the DOE.

§194.14 Content of compliance certification application.

§194.22 Quality assurance.

§194.23 Models and computer codes.

§194.25 Future state assumptions.

§194.26 Expert judgement.

§194.27 Peer review.

§194.32 Scope of performance assessments.

§194.33 Consideration of drilling events in performance assessments.

§194.41 Active institutional controls.

§194.43 Passive institutional controls.

§194.45 Consideration of the presence of resources.

Appendix 3 reproduces extracts from 40 CFR 191 and 40 CFR 194 which are most pertinent to this review, including definitions of selected terms. In the following section, where paragraph numbers of 40 CFR 191 and 40 CFR 194 are referred to, the relevant paragraphs, or parts of paragraphs, can be found in Appendix 3.

2.2 The Influence of the EPA Regulations

The DOE designed the CCA to satisfy the requirements of 40 CFR 191 and 40 CFR 194. It is not surprising, therefore, that the structure and contents of the CCA, and the 1996 performance assessment, are strongly influenced by these regulations.

The IRG has not undertaken an analysis of the EPA requirements, nor attempted to systematically check whether the DOE has fulfilled these requirements. In many instances, however, the IRG found that points on which it wished to comment were a result of the requirements of the EPA regulations. This section identifies the more important of these points[7]. This is not intended as criticism of the regulations, nor of the DOE which is obliged to follow them, but to highlight points which are of interest from an international perspective.

2.2.1 Undisturbed and disturbed performance

The EPA regulations set requirements in respect of "undisturbed performance"[8] and "performance taking account of all significant processes" (disturbed performance). The disturbed and undisturbed performance are both judged relative to a "containment

[7] The implications of the the EPA regulations penetrate deeply into the technical details of the 1996 performance assessment. Some of the more detailed implications are perforce mentioned in Chapter 3.

[8] Term defined in 40 CFR §191.12, see Appendix 3. Note that the undisturbed performance includes the effects of human actions, potash mining and deep drilling, that may occur in the future outside the "controlled area".

requirement", based on collective dose considerations, which places a limit on the total release of radionuclides (40 CFR §191.13). The undisturbed performance is also judged relative to an individual dose limit (40 CFR §191.15) and groundwater protection requirements.

This separate consideration of disturbed and undisturbed performance is consistent with regulations in other countries. In several countries, for example, a distinction is made between expected events and processes or a normal scenario, and unexpected events and processes or altered scenarios. In most countries, the criteria applying to the two conditions are derived from the same basis - radiological risk to an individual. The EPA containment requirement, however, is based on collective dose considerations, and cannot be directly related to individual dose and radiological risk standards.

The IRG considers that it is appropriate to assess the undisturbed and disturbed performance separately, and this is in accord with practice in other countries. It is unusual, however, that a different basis for assessment should apply to each.

2.2.2 The 10,000-year regulatory period

The containment, individual dose, and groundwater protection requirements (see above and Appendix 3) all refer to a 10,000-year regulatory period. The EPA does not require any assessment beyond 10,000 years after closure, even in terms of qualitative arguments.

The reliability of performance assessment results declines at times in the far future because of the increasing uncertainty about future conditions, especially of the surface environment and human behaviour. For this reason, in most countries, it is considered that, in respect of performance in the far future, the requirement for quantitative assessments should be less stringent, with more qualitative arguments being allowed [IAEA 1994].

The Canadian, German and French regulations, for example, specify 10,000 years as the maximum time to which quantitative assessment needs be continued, but require qualitative arguments that releases will not increase dramatically beyond this time. In Switzerland, regulatory guidance indicates that calculations should be carried out at least until the estimated maximum of impacts has been reached, even if it is acknowledged that this may be beyond the limits of validity of the models.

The IRG was surprised that it did not find descriptions or arguments in the CCA indicating the possible performance of the WIPP facility beyond the end of the 10,000-year regulatory period. Such descriptions or arguments, including an indication of the mechanisms, likelihood, timing and possible maximum of impacts at longer times, would be an important element of performance assessment in most other countries.

2.2.3 The containment requirement

The major part of the performance assessment work presented in the CCA (Chapter 6 of Volume I) is to demonstrate compliance with the containment requirement (40 CFR §191.13).

The formulation of the containment requirement has several implications not already discussed:

- it is probabilistic and leads to the adoption of a probabilistic methodology to calculate the cumulative release (see also Section 2.2.5);
- it is only concerned with the total cumulative release to 10,000 years, not the timing or rates of release within this period;
- issues of individual dose and risk, as well as the biosphere, are not considered.

Results in the CCA are almost entirely probabilistic because of the focus of the CCA on compliance. The probabilistic systems modelling approach brings important benefits in investigating uncertainties in complex coupled systems and produces integrated measures of impact. Attention must be given, however, to presenting the results of the analysis in an accessible and transparent form. In particular, deterministic analyses may be useful to illustrate the model behaviour and support the probabilistic analyses[9].

Information on the temporal evolution of conditions and releases is important to understanding the physical evolution and performance of the disposal system, and can give confidence in the overall release results which are otherwise opaque. Such information is lacking in the CCA, although supplementary information was presented to the IRG during the meeting in Carlsbad[10]. Whereas the EPA requirements do not seem to exclude the presentation of results as a function of time, the focus of the DOE on compliance may have led to them not being presented.

The EPA containment requirement is based on consideration of collective dose and, moreover, relates to the total activity contained in the repository expressed in terms of EPA units (see 40 CFR 191 Table 1, reproduced in Appendix 3). The IRG found this difficult to relate to safety standards based on individual dose and radiological risk with which they are more familiar. The IRG therefore asked the DOE to provide supplementary information on doses that might be received. These are discussed in Section 3.4.4.

The IRG accepts the probabilistic approach, but found that the focus of the CCA on probabilistic estimates of total cumulative release, and lack of presentation of deterministic calculations or results as a function of time, hampered the understanding of the performance of the disposal system. It would have been helpful to present such results even if they are not required by the EPA.

2.2.4 Treatment of human actions

The EPA regulations give guidance on the assessment of future human actions at the WIPP site. They specify that:

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[9] The relative merits of probabilistic and deterministic methodologies in assessments have been discussed internationally, for example within the NEA Integrated Performance Assessment Group [IPAG 1997].

[10] "Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 CCA for the WIPP", memo by J. Helton, 12/23/96.

- the characteristics of the future (at least in respect of human actions) are assumed to remain as they are at the present day (40 CFR §194.25);
- the assessment shall consider mining, deep drilling and shallow drilling (40 CFR §194.32a);
- in respect of mining, only the effects of changes in hydraulic conductivity of hydrogeologic units should be considered (40 CFR §194.32b);
- inadvertent intrusion by drilling for resources should be assumed to be the most severe scenario, and the method of estimating the future occurrence of drilling is specified, based on the frequency of drilling in the Delaware Basin in the last 100 years (40 CFR §194.33b);
- resource recovery activities, subsequent to drilling of a borehole, need not be considered (40 CFR §194.33d);

It is likely that mining of potash will occur within the controlled area at some time during the regulatory period. The only impact that the EPA asks the DOE to consider, however, is calculated to be beneficial for long-term performance (see Section 3.1.2).

The EPA specification of how to estimate a future drilling rate, plus the assumption of random occurrence in space and time, leaves little uncertainty in the inputs for the assessment of drilling. The actual situation is that there is a very large uncertainty concerning future human actions. Moreover, the case selected for analysis considers an activity that, based on knowledge of the resources in the Delaware Basin (see Section 3.1.2), is not sustainable for more than a few tens of years into the future.

The specification by the EPA on how to assess future human actions leads to a feeling that the performance assessment is arbitrary. The IRG accepts that, given the irreducible uncertainties associated with future human actions, it may be convenient from a regulatory standpoint to define reference events or scenarios that should be the basis of compliance calculations. The IRG, however, would have liked some discussion of the assumptions adopted and, in particular, why other human actions such as resource recovery need not be considered (see Section 3.2.3) and whether the assumptions adopted in representing mining and deep drilling can be considered to be conservative or sufficiently representative.

2.2.5 Results of performance assessment and treatment of uncertainty

The EPA requires that the results of the performance assessment are assembled into complementary, cumulative distribution functions (CCDFs), and that the uncertainty of disposal system parameters should be considered to generate a set of CCDFs (40 CFR §194.34). The regulations also set conditions on the statistical accuracy of results (see Section 3.4.3).

The CCDF is a generally accepted method of depicting uncertain outcomes commonly adopted in reactor safety studies. The DOE has developed the methodology to calculate the

radionuclides releases from the controlled area[11] in the form of CCDFs that can be compared to the EPA containment requirement.

The DOE methodology adopts the Kaplan and Garrick [1981] definition of risk[12] and approach to the treatment of uncertainty. This leads to the generation of a single CCDF where each 'scenario' forms a single-point estimate of consequence and probability on the CCDF. The uncertainty incorporated in this single CCDF, which relates to uncertainty about what might happen in the future, is termed stochastic uncertainty. There is also uncertainty about starting conditions, or values of parameters that must be incorporated in the consequence models. Kaplan and Garrick refer to this as subjective uncertainty on the basis that the parameters do have some "true" or fixed value, but this is imprecisely known. Accounting for this uncertainty in disposal system parameters leads to a family of CCDFs.

The IRG observes that the separation of uncertainty related to disposal system parameters and uncertainty related to future events is presentationally useful and operationally convenient, but is to some extent misleading[13].

The above approach deals with parameter uncertainty. The EPA does not require, and the DOE does not consider, the uncertainty related to choice of features, events and processes, or choice of alternative models[14]. These sources of uncertainty are generally considered to be important internationally [IPAG 1997].

The lack of discussion of other uncertainties, not included through parameter uncertainty, would be considered a serious omission internationally when judging the results of performance assessment, although it is not required by the EPA for compliance calculations.

2.2.6 Institutional controls

The EPA regulations require the DOE to present descriptions of the active and passive institutional controls (defined in 40 CFR §191.12) that are proposed for the site. Further, the EPA allows the DOE to take credit, in terms of a reduced likelihood of human intrusion, for up to a maximum of 100 years after disposal in respect of active controls and "several hundred years"[15] in respect of passive controls (40 CFR §194.41 and 43).

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[11] Term defined in 40 CFR §191.12, see Appendix 3.

[12] According to Kaplan and Garrick, risk is composed of three elements: what can happen, i.e. what scenarios can be identified; how likely is this, i.e. what probability should be assigned to each scenario; what is the consequence, i.e. what is the result, in terms of total release, for each scenario.

[13] It supposes, for example, there is a true long-term rate of drilling applicable to the site, and that the uncertainty in time of occurrence is only a result of statistical variation. This is untrue - the future rate is highly uncertain and may not even be a physically meaningful parameter depending on the model adopted. In addition, the sampling of so-called subjective uncertainty is related, not just to present-day characteristics, but also to what those characteristics might be over the 10,000-year regulatory period.

[14] The EPA does require descriptions of alternative conceptual models that are seriously considered but assumes that one model set, that "accurately portrays the performance of the disposal system", will be used in support of an application (see 40 CFR §194.23, not included in Appendix 3).

[15] The guidance document [EPA 1996] further clarifies this point. It specifies that the EPA will allow up to approximately 700 years of credit (after closure), provided the applicant can support this assumption.

The prevailing international view is that, in the post-closure period, active institutional controls cannot be relied upon to exist for more than a few hundred years[16], which accords with the EPA regulations. Beyond this time, it is accepted that record keeping would be a useful precaution that might reduce the likelihood of future inadvertent human intrusion into the repository but cannot be relied on for long [NEA 1995]. There is no international consensus on the value of passive controls, such as markers, further in the future. Some experts consider that markers could attract unwanted interest in the site [Sumerling et. al. 1996; IAEA 1996], while others consider that markers could be effective in stimulating a search for records and are, overall, useful [SSI 1993].

The IRG observes that the EPA regulations require the applicant to propose a system of passive institutional controls, including site markers, and allow the applicant to take some credit in performance calculations for the effect that these might have. To our knowledge, no other country formally allows credit to be taken for site markers in performance calculations. There is, however, no definitive position on this internationally.

The DOE does take this credit offered by the EPA. The IRG observes that it would be more defensible to demonstrate compliance without attempting to take credit for passive site controls, the effectiveness of which must be uncertain[17].

2.2.7 Terminology

The terminology used in the WIPP performance assessment community, and in some cases formalised by the EPA regulations, is somewhat different from that used in other countries and familiar to the IRG.

The IRG was surprised, for example, that the CCA states that expert judgement is not used, whereas it is clear that the judgements of the project staff have had a very important influence on the performance assessment. This arises because the term 'expert judgement' has a specific meaning in the EPA regulations, indicating formal elicitation of experts independent of the project.

Another example is the DOE use of the term 'scenario' to mean a single simulation of the future (see Section 2.2.5), whereas internationally it is more often used to denote a general description of a possible future [NEA 1992].

The terminology in the CCA did pose some initial problems for the IRG in conducting the review, and also reduces the readability of the documents. The IRG is supportive, however, of the principle of maintaining a well-defined and consistent use of terminology between a regulator and applicant, and recognises that the prime requirement is that the CCA is unambiguous in relation to the EPA.

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[16] The value assumed varies from country to country, usually 100 or 300 years.

[17] The Appendix EPIC, on which the DOE bases its claim to assume a reduced frequency of human intrusion up to 700 years after closure, presents a partial view of the archaeological evidence. The IRG believes that this view would not be generally upheld.

2.3 Discussion

2.3.1 Overall implications for the CCA

The EPA regulations provide detailed guidance and are prescriptive, not only in terms of the quantities that they require an applicant to calculate, but also in terms of the scope of assessment, presentation of results and even fixing of certain key assumptions. The goal of the EPA is to make judging compliance as straightforward as possible by setting out specific requirements. This can simplify the tasks of both the applicant and the regulator. It means, however, that important decisions relating to safety and what is a sufficient method and scope of assessment have already been taken.

Equivalent regulations in most other countries are written in a more general way. Principles and safety targets are set, but the responsibility of preparing a safety case in an appropriate form is left with the applicant. All relevant issues must be addressed, but the applicant has the flexibility to choose a suitable approach. In this case, some communication will usually take place between the applicant and the regulator to explore what might constitute an acceptable approach and scope of assessment.

The location of the WIPP site, in an area rich in mineral resources, requires that the focus of the performance assessment is on human intrusion. This is different from most other geologic environments considered for radioactive waste disposal, where assessments most often focus on an undisturbed case. Any quantitative assessment of future human actions is liable to be arbitrary to a large extent. Attention must therefore focus on the choice of assumptions underlying the analysis, e.g. whether they are reasonable, conservative and acceptable to stakeholders. This is not discussed in the CCA because the EPA specifies the assumptions that should be applied.

The IRG observes that the CCA is precisely designed to satisfy the EPA regulations, and these do not require the applicant to present a comprehensive argument related to safety. Thus, the analysis presented in the CCA appears somewhat arbitrary and does not represent a complete, self-standing, performance assessment as understood in other countries.

2.3.2 Implications for the review

The IRG was initially aware that the CCA is strongly influenced by the EPA regulations, but only became fully aware, during the review process, of the detail to which the regulations specify the technical approach of an applicant.

In preparing this report, the IRG has tried to distinguish between the decisions that have been determined by the EPA regulations (discussed mainly in this chapter), and the decisions made by the DOE, for which the DOE must take technical responsibility (discussed mainly in the next chapter).

3. The 1996 Performance Assessment of the WIPP

This chapter comments the 1996 performance assessment of the WIPP mainly from a technical perspective. In particular, it examines the technical quality of the various stages of post-closure assessment - compilation of data. identification of FEPs and scenarios, treatment of processes and sub-system modelling, system modelling and calculations. Comments are also made on the CCA documentation.

Although the detailed comments are aimed specifically at the CCA, the IRG has built its judgment on the technical soundness of the 1996 performance assessment, not only on its examination of the CCA, but also on the basis of prior knowledge of the WIPP project and work by the DOE and its contractors over a number of years.

In this chapter, factual and neutral observations are given in plain text. The views of the IRG and suggestions to the DOE are given in italics.

3.1 The Compilation of Data

3.1.1 Site geology and hydrogeology

The regional geology of the Delaware Basin is well known, because of the long experience arising from potash mining and hydrocarbon exploration in south-eastern New Mexico. This extensive regional knowledge has been compiled and well assimilated within the DOE programme. The stable focus of the WIPP on the currently selected site, over a period of more than 20 years, has allowed a very thorough investigation of the local and adjacent geology and hydrogeology.

The geological, hydrogeological and tectonic settings provide strong and multiple evidences of the natural long-term stability and isolation capacity of the Salado formation over time scales far in excess of the 10,000-year regulatory time frame. Due to these very favourable geological characteristics, most of the naturally occurring features, events and processes (FEPs) that could be thought of as having the potential to disrupt a geological repository can be screened out. A stronger reference in the CCA to these positive site-specific features could further support the intrinsic containment capacity of the Salado, and thus the safety case.

The existence of natural resources in the region highlights the possibility of human actions aimed at exploiting these resources. Thus, the presence of brine reservoirs in the Castile formation, which have been encountered during drilling for oil and gas mainly at the north-east margin of the Delaware Basin, is of concern. Apparently, no direct or indirect methodology exists to precisely characterise the extension and volume of these brine reservoirs. The lateral extent and volume of the brine reservoir encountered by the WIPP-12 borehole are not well known and the assessment calculations have to rely on a geostatistical approach covering the whole Delaware Basin.

The most recent investigation for the presence of Castile brine reservoirs underlying the facility was done, from the surface, about ten years ago. The possibilities for investigating brine reservoirs beneath, and local to, the WIPP site and, especially, for developing further methods to characterise their extent and volume from the underground, should be borne in mind during the construction phase of the underground facility.

The evidence for the very low permeability of massive salt beds such as the Salado is based on good physical arguments and on extensive measurements. Attention thus focuses on the anhydrite beds within the Salado. These constitute the only possible natural paths for gas, brine and contaminant transport away from the repository, and may also be a route for incoming brines that may react with waste components to produce gas. Hence, their properties are important in determining the pressure evolution of the repository.

A detailed characterisation of these beds has been performed, but it is not clear to the IRG, that the changes that will be induced in these units by repository excavation, subsequent salt creep movements, and gas pressure build-up are as well understood or characterised. The lack of complete understanding is handled by conservative choice of parameter ranges in the BRAGFLO calculations.

In the strata above the Salado most of the water is saline and is not potable, even by livestock, without substantial dilution. This is especially true for the Culebra dolomite, which is the most transmissive unit at the WIPP site, and is considered to be a potential pathway for radionuclide release from the controlled area. Potable water is reported from shallow drilling in the Dewey Lake formation (although not necessarily in the immediate vicinity of the WIPP site).

The IRG considers that, from a dose perspective, greater attention could be given to considering whether any credible scenarios exist in which contaminants might reach these potable or nearly potable resources, under present day and alternative climate conditions[18].

3.1.2 Natural resources

The existence of potash resources at the WIPP site and in the immediate area has been the subject of extensive investigation. This is an unusual situation for a radioactive waste disposal site. Not only is it expected that (unless prevented) mining will occur within a few years, but also, because of the well-understood nature of the potash deposits, it can be estimated which areas of the ore horizons will be mined over the site.

The potential impacts of mining (at the repository horizon and on potential paths for brine and contaminant movement) are not fully discussed in the CCA Volume I, because the EPA has restricted the range of effects to be considered in performance assessment, see Section 2.2.4. The only effect considered, an increase in the hydraulic permeability of the Culebra over the mined areas, turns out to be beneficial: it increases the transport times and hence reduces the calculated release of radionuclides during the 10,000-year regulatory period.

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[18] From a dose perspective, the containment requirement may be conservative where the releases occur in media which man is unlikely to exploit or come into contact with, i.e. saline water in the anhydrite beds or in the Culebra.

It would be preferable to see information on the observed effects of potash mining locally. Reasoned arguments could then be presented on the selection of the processes that are represented in the analysis.

The hydrocarbon resources of the Delaware Basin are well known. They consist of oil and associated gas reservoirs found in the Permian strata, and gas condensate in the Pennsylvanian strata. These strata exist beneath the WIPP site and immediately surrounding areas. The relevant information is presented in Appendix DEL, but is poorly discussed in the CCA Volume I, probably because the EPA specifies the assumptions to be adopted in demonstrating compliance, see Section 2.2.4.

A historical description on the rate of development of oil and gas wells, and discussion of alternative scenarios for future exploitation of oil and gas resources, based on actual practice and the extent of resources in the basin, could set the assumptions used in the analysis in perspective. Depending on the future needs of energy and the current trend towards shallow oil exploitation in the Delaware basin, there is a possibility that the drilling rate in the near future will be greater than the one in the last 100 years, although the rate would not be sustainable over the 10,000-year regulatory period.

3.1.3 The underground facility

The WIPP project has accumulated an impressive database on rock mechanics based on extensive and long-term laboratory and in-situ measurements. This is complemented by detailed and high quality modelling of rock-salt creep, for example, by the SANTOS model. The precise knowledge of the stratigraphy in the salt formation, and salt properties, has facilitated the development of quite detailed repository layouts and designs for various seal elements.

The high quality and extent of the data base, with very specific data relevant to rock mechanical processes and design, provides a high level of confidence in the analyses made on these components.

The DOE gives considerable attention to the design of the multiple-component shaft seals intended to prevent hydraulic connection and movement of brine or contaminants in the shafts after closure. In the long term, the lengths of crushed, compacted rock-salt can be expected to be restored to a low permeability, similar to the host formation, as a consequence of salt creep. The longer-term performance of elements above and below must be less certain since they represent chemical and physical anomalies within the formation. The performance of these elements, however, need only be assured over a period of a few hundreds of years during which the crushed rock salt sections achieve low permeability.

The IRG is content that shaft seals can be constructed to provide the required long-term performance.

Information on the detailed mechanical modelling of the shaft and its associated disturbed rock zone (DRZ) is summarised in Volume I of the CCA and presented in detail in Appendix SEAL. In the BRAGFLO performance calculations, however, a range of time-independent properties are assigned to the shaft and DRZ.

The IRG was not able to fully trace the parameters concerning shaft and DRZ properties given in Appendix PAR to the information in Appendix SEAL. Thus, it is unclear whether the simplified treatment of the shaft and DRZ in performance calculations results from a lack of confidence in estimating time-dependent properties of the shaft seals and DRZ, or a pragmatic finding that the performance of the disposal system is relatively insensitive to a range of shaft and DRZ properties.

Not much data is available on waste compaction, and, due to the variability of the waste, it is difficult to have confidence in the data provided.

The mechanical resistance of the waste is not considered in the modelling of the room closure, and it is not clear whether this approach is conservative, see Section 3.2.4.

A DRZ also forms around the disposal rooms as a consequence of unloading the rock in the vicinity of the excavation. Increased permeability is created by micro-fractures along grain boundaries and by bed separation along lateral seams. Following closure, salt creep will tend to restore low permeabilities within the salt beds, however, some fracturing in non-halitic rock, such as anhydrite, and bed separation on clay seams, may be irreversible.

An area where an improved confidence in the repository evolution might be useful is the understanding of the gas and brine permeability of the DRZ around the disposal rooms. At present, this zone is assumed to release brine to the disposal rooms and to connect the repository-waste void with the anhydrite marker beds above and below the repository horizon. A good understanding of variability of the zone properties and their evolution, especially "healing", might allow a less conservative treatment in assessment models.

3.1.4 The waste inventory

The WIPP facility is designed to receive radioactive and mixed waste, which results mainly from nuclear weapons production and associated activities in the US. By its origin and composition, this is not a waste type which occurs in many other countries. The waste components in the TRU waste are similar to what are internationally called low- and intermediate-level wastes with long-lived radionuclides.

The waste that is expected to be disposed of in WIPP is well documented in appendices of the CCA: the origin, form, characteristics and inventory of the different waste types are described, as well as the characterisation methodologies and controls. Two classes of waste are considered: remote-handled (RH)-TRU-waste and 599 different types of contact-handled (CH)-TRU-waste. Volumes and characteristics are forecast for each class and type.

Only a limited fraction of the wastes to be disposed of is conditioned and packaged already and the characteristics of wastes yet to arise are forecast. As waste processing may change with time, the eventual waste inventory may differ in content and characteristics from those now forecast. This source of uncertainty is not addressed in the CCA.

Repository-based emplacement limits have been imposed by the Land Withdrawal Act (LWA), which specifies a total volume capacity (of RH- and CH-TRU waste) of 6.2 million cubic feet (175,600m^3) and total activity capacity for RH-TRU waste of 5.1 million curies

(1.9×10^5 TBq). Radionuclide inventory limits have been established by the DOE on this basis.

The IRG noted that the inventory of Cs-135 considered in the CCA appears to be inconsistent with that of Cs-137 based on typical fission ratios for these two isotopes. In particular, the Cs-135 inventory appears to be underestimated by three to four orders of magnitude. The implications for the performance calculations were preliminarily checked by the DOE during the IRG visit to the WIPP and found to be insignificant within the EPA regulatory framework. The latter focuses the attention on long-lived alpha emitters, whereas a regulatory context based on dose to the individual would enhance the role of more mobile long-lived radionuclides such as Cs-135. In any event, this inconsistency reveals a weakness in the exchange of information between the waste producers and the performance assessors.

3.2 Identification of Relevant FEPs and Scenarios

3.2.1 General procedure and documentation

According to the CCA, the starting point for the identification of relevant features, events and processes (FEPs) is a compilation of several performance assessment FEP lists made in support of the Swedish SITE-94 study [Stenhouse et al. 1993]. The original purpose of this compilation was to provide a list against which to audit a list of FEPs that were specific to the case of a KBS-3 style repository in Swedish bedrock, where the list of site-specific FEPs was achieved through an independent consideration by yet another study group.

There must be some doubt as to whether a list that was originally intended for one quite specific purpose, related to high-level wastes in a hard rock site in northern Europe, is a sufficiently representative starting point for a catalogue of FEPs related to disposal of transuranic wastes in a bedded salt formation in south-eastern New Mexico.

In the CCA Volume I it is stated: "Finally, to ensure comprehensiveness, other FEPs specific to the WIPP were added based on review of key project documents and broad examination of the preliminary WIPP list by both project participants and stakeholders."

There is no clear indication in Volume I or in Appendix SCR of exactly how this review and examination was managed, or specifically what additions or modifications resulted. The IRG finds this surprising because conversations with WIPP project staff indicated a quite encyclopaedic knowledge of the site and relevant processes. The record shown in the CCA does not indicate that this resource was fully used, although in practice it may have been.

The qualitative and semi-quantitative arguments regarding FEPs that are collected in the Appendix SCR are a key component of the assessment.

This appendix is clear in recording what FEPs are and are not carried forward to further analysis, but does not give a sufficient level of evidence or support for many of the screening decisions. The methodology is satisfactory in principle, but the IRG has difficulties in

understanding the rationale for screening out of individual FEPs[19]. *The IRG suggests that the Appendix SCR should be more critically reviewed with a view to bringing forward more detailed information to support the decisions made.*

Several FEPs were rejected on the basis of regulatory considerations[20].

It would improve the confidence of the reader if the DOE presented the logical or physical arguments for not considering these processes in the assessment, in addition to noting that they are not required in a compliance demonstration. Otherwise, there is an impression that processes that might deserve consideration from a safety perspective have been eliminated.

3.2.2 Climatic and geologic FEPs

The potential for climatic and geological changes within the 10,000-year regulatory period is well documented in the CCA.

The DOE has investigated an appropriate range of future climatic and geological processes, and the possible effects within the 10,000-year regulatory period have been considered. For perspective, it would be helpful to include some qualitative discussion of the possible impact of climatic and geologic FEPs over longer time periods.

3.2.3 Future human actions

The selection of FEPs related to future human actions to be considered in the CCA are closely specified by the EPA (see Section 2.2.4).

Examination of the CCA and conversations with project staff identified a number of events and processes that are not analysed and might deserve consideration from a radiological safety perspective. These are:

- water flooding due to nearby brine injection to aid oil recovery, and possibly other secondary and tertiary recovery methods;
- solution extraction of salt, e.g. for use in drilling muds or other purposes;
- solution mining of underground cavities for storage, e.g. of oil or gas, or for disposal of other wastes;
- disturbance of flow regime due to extraction boreholes just outside the controlled area[21].

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[19] An example of the further documentation on FEPs and screening procedures in project records was provided by the DOE.

[20] The IRG presumes that the EPA decision to constrain and limit the analysis is based on an earlier evaluation of the relative importance of various processes. As far as the IRG is aware, however, this is not documented in the open literature.

[21] A borehole outside the controlled area could affect flow and transport because it would modify the boundary conditions for the flow calculations. In the Salado formation, the dilution effect for the transport of radionuclides along the marker beds, which is observed in the dose calculations, might then be reduced by a more focused flow towards the borehole. This scenario should be included in the undisturbed performance, e.g. assumed to occur with some probability.

All of these, except the last, are ruled out by the EPA regulations.

From a safety perspective, the IRG considers that the documentation and evaluation of FEPs related to future human actions is incomplete. Even if the CCA is focused on regulatory compliance, a demonstration that those processes that must be considered in regulatory compliance are indeed an appropriate and sufficiently representative set, would make the DOE performance assessment more widely acceptable[22].

3.2.4 Waste and repository-related FEPs

The wastes to be disposed of in the WIPP facility are highly heterogeneous. This will lead to a heterogeneity (of initial conditions at least) in the emplaced waste within each waste room both in terms of physical properties, chemical properties and radioactivity. Moreover, as rooms and panels will be filled sequentially over time, and there will be variations in wastes arising, there may be significant variation in physical, chemical and radionuclide inventory between disposal rooms.

The effects of heterogeneity at the room scale are of most concern: in particular, whether the homogenous physical and chemical conditions assumed for the source term and repository modelling will be achieved in reality. This is important because the expected mode of release from the repository involves discrete interceptions of quite small volumes within the total repository volume. The specific conditions at that small volume scale, and immediate vicinity, may be quite different from the averaged mixed conditions of the whole repository. The IRG suggests that (1) additional qualitative thinking is done to identify possible effects of waste heterogeneity and emplacement, and this is supported by (2) quantitative detailed modelling to investigate the possible physical and chemical evolutions within small sections of the repository (of the order of a few square metres).

Flow and transport processes in the repository area depend on the pressure build-up due to the production of gas. The pressure build-up depends on the available void or pore volume in the repository. This volume is reduced by the creep convergence of the salt.

The creep calculations in the CCA account for the pressure build-up itself but not for the mechanical resistance of the waste or for volumetric change of the backfill material (see below). Taking these processes into account could reduce the convergence rate. It is unclear whether neglecting these processes is conservative or not.

The specification of a magnesium oxide (MgO) backfill with the purpose of controlling pH, and hence actinide solubilities, around the wastes is a very late development. Indeed, the most relevant entry of the Appendix SCR - SCR.2.1.5 "Backfill characteristics" - does not say what the backfill material is, referring to it as a "chemical conditioner". The subject is discussed in more detail elsewhere, e.g. Section 6.4.3.4 of Volume I and Appendix BACK. These discussions, however, focus on the desired chemical effects assuming an intimate and instantaneous mixing effect with incoming brine.

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[22] While the EPA regulations allow the DOE not to evaluate the above scenarios, they do not forbid the DOE from presenting ancillary analyses of the scenarios.

The IRG considers that (1) confidence has not been developed that wastes within individual drums, or the brines entering these drums, will undergo the rapid chemical conditioning effect assumed (see comments on heterogeneity above), and (2) insufficient attention has been given to the volumetric expansion and other effects due to MgO reactions[23] *(see Section 3.3.2).*

3.3 Treatment of the Relevant Processes and Sub-system Models

3.3.1 Evolution of the geochemical environment

There is a large amount of mixed organic material contained within the TRU waste which is prone to bio-degradation and CO_2 production in contact with water. This makes the waste packages unstable under the disposal conditions. Therefore, the addition of a backfill material is necessary to stabilise both the pH and partial CO_2 pressure within the repository.

The DOE specifies a MgO backfill, and refers to this as an Assurance Requirement. However, the presumed effect is taken account of in the performance modelling and the IRG considers that a chemical conditioning backfill is required in order to make the performance of the system sufficiently predictable.

The waste panels in the WIPP repository will undergo a complex geochemical evolution that has to be properly addressed in the source term calculations. The processes to be considered in estimating the geochemical evolution include:

- corrosion of the steel waste containers by the contacting fluids;
- degradation of the organic content of the waste with the corresponding generation of both CH_4 and CO_2;
- hydration and subsequent carbonation of the MgO backfill material;
- dissolution of the actinide inventory.

In the CCA, instantaneous equilibrium is assumed in all the processes involved, except for the redox distribution of the actinide species. The result is that the PANEL code calculates radionuclide mobility out of the repository in a well-mixed reactor fashion.

The outcome in terms of actinide releases is non-conservative, as the assumption of full mixing has a beneficial effect on the repository pH and partial CO_2 pressure which is not fully backed up by the experimental evidence reported by the DOE.

The IRG suggests that (1) more detailed modelling is required of the assumed transition from heterogeneous to homogeneous physical and chemical conditions (see Section 3.2.3), and (2)

[23] Appendix SCR entry SCR.2.1.5 states, without further support, that backfill physical properties have been eliminated on the basis of low consequence.

the radionuclide release calculations should include the possibility of failure or insufficient reaction with the backfill and evolving CO_2.[24].

3.3.2 Processes related to the magnesium oxide backfill

The magnesium oxide (MgO) backfill will react with the incoming brines and form magnesium hydroxide ($Mg(OH)_2$). If CO_2 is present, e.g. from waste degradation, magnesite ($MgCO_3$) will be formed after passing through intermediate, thermodynamically meta-stable phases such as dypingite, nesquehonite, and possibly others. This has implications for repository void volume, temperature and water budget as discussed below.

The chemical reaction of the MgO will result in a volumetric expansion of the backfill material. The reactions from MgO into magnesium hydroxide, and then into magnesite, increase the volume by factors of 2.2 and 2.4, respectively. Higher expansion factors can be reached when the intermediate phases between magnesium hydroxide and magnesite are considered.

This volumetric expansion is important and affects, for instance, the void volume that needs to be considered in the analyses of gas pressurisation effects, and may even reduce the pore volume locally to such an extent that uniform chemical mixing of the pore fluids cannot be assumed. Overall, the volumetric expansion of the MgO may entail both positive and negative implications, and a full examination needs to be carried out.

The hydration of MgO is an exothermic process. The heat generated will be deposited locally in each waste panel and it may not be readily dispersed as assumed in the CCA. This is because the waste panel material - mixed waste, backfill, and gas-filled void spaces - will have a relatively low thermal conductivity compared with halite, for example.

The thermal problem warrants a more complete analysis taking into account uncertainties in geometry and other parameters. The implications for the evolution of the underground facility will then need to be examined.

The hydration of MgO requires water, but its carbonation releases the water taken up in the hydration step. Thus water is not consumed in the hydration-carbonation process and will be available for further reaction with the waste and the backfill, and for radionuclide release.

This additional source of water and feedbacks to thermal and volumetric expansion processes are not addressed in the CCA, and warrant fuller consideration.

Overall, the IRG concludes that not all the physical implications of the chemical reactions that the MgO backfill may undergo have been explored in the CCA. This is an important omission. At the very least, the processes have the potential to modify the temporal evolution of the physical environment in the waste panels. The IRG recommends that the DOE give

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[24] There are two issues here: insufficient chemical conditioning at the disposal room scale which would affect releases in the undisturbed case and E1E2 scenario; insufficient chemical conditioning at a smaller scale which may be relevant to the E1 and E2 scenarios.

urgent attention to a fuller examination of the physical implications of the hydration and carbonation of the MgO backfill material.

3.3.3 Calculation of actinide solubilities

The methodology used by the DOE to calculate the actinide solubilities in the repository assumes thermodynamic equilibrium for the main driving geochemical reactions, but excludes the possibility of redox equilibrium for the dissolved actinides.

This probably results in conservative estimates of actinide solubilities, although it is unsatisfactory from a chemical point of view.

The methodology for the derivation of the solubilities as reported in the CCA and Appendix SOTERM does not accord with the procedures used to derive similar parameters in performance assessments in other countries [e.g. SKB 1992; Nagra 1994]. Through discussions with the DOE and contractor staff responsible of this area, and by examining tertiary reports and scientific papers, however, the IRG confirmed that the procedures used in the calculation and derivation of the actinide solubilities were reasonable in terms of the quality of primary laboratory data used and the method of the calculations.

To accord with the methodologies used in other performance assessments, the DOE should include the key thermodynamic data used to derive the actinide solubilities, as well as the procedures used to independently check the validity of the solubility data in a comprehensive and accessible report, either as part of the Appendix SOTERM or as an additional document within the CCA document set.

3.3.4 Two-phase-flow and coupled mechanical and hydraulic modelling

Brine and gas movements in and around the repository and the Salado formation are affected by creep and the production and movement of gas. The coupled processes of brine and gas movement are accounted for by applying the BRAGFLO two-phase-flow model. The modelling also includes other basic features of the disposal system such as the generation of gas by different sources, the change of permeability of the marker beds due to the pressure in the repository, and the creep convergence as a function of the pressure.

The BRAGFLO model is state-of-the-art in two-phase, gas-brine modelling, and its application in performance assessment is in advance of practice in other countries. The model appears to represent all the important coupled hydrologic processes which could take place at repository level and within the marker beds.

The creeping of salt and the pressure build-up in the repository, i.e. the coupling between mechanical and hydraulic processes, is not represented mechanistically. The creeping of salt is modelled in the code SANTOS and the pressure built-up is handled in BRAGFLO. These codes run independently. A porosity surface, which gives the porosity as a function of time and pressure is generated by SANTOS, and the porosity values are picked up by BRAGFLO from this two-dimensional function at each time step.

It is not shown that this method is conservative under all circumstances.

To model brine intrusion into the repository from a Castile reservoir after a future drilling, the brine release to the repository model is estimated by a simple model in which the volume of the brine reservoir and its compressibility are sampled. The parameter range for the volume of the reservoir appears to be an underestimate, whereas the compressibility covers unrealistically high values.

This is a simple approach, but may be sufficient on the basis of currently available data (see, however, comments in Section 3.1.1). The combination of parameter values in the model leads to a very broad range of releases which exceeds the available amount of brine, and probably encompasses a sufficient degree of conservatism.

3.3.5 Modelling of the Culebra hydrology

The Culebra is a fractured and inhomogeneous aquifer system, varying in both horizontal and vertical directions. It is modelled as a horizontal, confined, porous-medium layer with the heterogeneity of the formation represented by statistically generated transmissivity fields. The modelling effort concerning the flow and transport in the Culebra has been considerable in the last few years, and has been the basis for an international intercomparison exercise.

The variability of the hydraulic properties of the Culebra has been treated by a state-of-the-art modelling approach. However, the IRG could not fully trace the incorporation of individual features, such as the instationarity of the flow regime and the density effects to the flow scheme. A more simplified and traceable approach might be preferable in the performance assessment calculations.

An issue of concern for the modelling of the Culebra flow (and especially for the definition of future flow direction on the basis of present head measurements) is the inconsistency between the measured geochemical and isotopic data, and the flow directions inferred from head and transmissivity measurements.

This issue is poorly reported in the CCA and deserves more attention. From the information received during the review, it seems that more recent 3D-modelling of the Culebra[25] could help to correlate flow directions and observed geochemical and isotopic data.

3.3.6 Modelling of radionuclide transport

The modelling of nuclide transport in the Salado formation is based on the time-dependent, advective flow field for the liquid phase from the two-phase-flow modelling. The transport in the Salado formation does not account for diffusion and dispersion terms.

Diffusion is likely to be significant in such a low flow environment, and dispersion may be significant in the anhydrite marker beds. Examination of time-dependent results indicate

[25] The recent study simulates the hydrogeology of the regional basin over the period from 14,000 years in the past to 10,000 years in the future. Infiltration from the overlying beds and the regional transient response to changes in the rate of recharge due to past climatic changes are represented.

that there is significant numerical dispersion, and this may be greater than the true physical effects of diffusion and dispersion. This is unsatisfactory from a modelling point of view and, taking into account the time cut-off of the assessment, the results are not necessarily conservative.

The modelling of nuclide transport in the Culebra formation is based on the steady-state flow fields from the groundwater flow modelling, and modelling of a conservative-tracer. Other processes such as sorption and radioactive decay are then factored in multiplicatively. The chemical retardation of actinide transport is conceptualised by sorption on to the dolomite component of the formation. No credit is given to the existence of clays in the formation, but there is a reliance on matrix diffusion effects as a retardation factor.

The conceptual model used to handle the chemical retardation of actinides through the Culebra appears to be conservative, and the contribution of matrix diffusion is backed up by extensive hydrogeological and tracer tests of the formation. This, however, is not well documented in the CCA. The confidence of the IRG in the experimental basis for the dual-porosity concept applied to the Culebra (and especially the importance of matrix diffusion) comes from prior knowledge of the WIPP programme.

The colloidal transport of radionuclides is considered in detail in the CCA. Different colloidal forms (i.e. humic, microbial, mineral fragment and intrinsic actinide colloids) are distinguished. In the Salado, sorption and filtration processes of dissolved and colloidal forms are neglected. In the Culebra, colloidally transported radionuclides are assumed to remain associated with their colloid carriers. The transport of microbial and mineral-fragment colloids is neglected due to filtration effects. Intrinsic actinide colloids are assumed to occur in insignificant quantities. The sorption of humic colloids is assumed to be the same as the sorption of dissolved radionuclides.

The experimental basis for the above model assumptions is sparse, at least as documented in the CCA. The treatment in the Salado is clearly conservative but the situation is less clear for the modelling of actinide transport in the Culebra.

3.4 System Modelling and Calculations

3.4.1 The system model framework

The WIPP performance assessment is based on a probabilistic analysis using an integrated system model. The major computer codes and the flow of information among them, as they are used to generate radionuclide releases are illustrated, e.g. in Figure 6.25 of Volume I of the CCA, and well documented in Appendix CODELINK.

The limited examination of CCA documents by the IRG, indicates good code configuration and management of data flows. The IRG has confidence that the procedures applied in these areas are consistent with best practice for performance assessment internationally. The IRG is also aware of the long involvement of the WIPP project in international comparison exercises which gives confidence in the performance of several of the component models.

The strategy for connecting submodels is different from that usually adopted in assessment of multi-barrier systems. Usually, an assessment model will consider a linear set of sub-models (e.g. source term, near field, geosphere, biosphere) which may be supported by more detailed models of specific processes (e.g. hydrogeology, geochemistry). In the CCA, a relatively detailed model of hydraulic performance (coupling mechanical and hydraulic pressure, repository gas generation, gas and brine movements) of the whole disposal system - BRAGFLO - is at the core of the analysis.

The codes are not run as a directly coupled system. Rather, for reasons of computing efficiency and convenience, families of simulations are performed with each code (in particular the BRAGFLO, BRAGFLO_DBR and CUTTINGS codes) and outputs held in intermediate files ready to be picked up for uncertainty analysis or input to further calculation (see Section 3.4.3).

Subjective uncertainty in the disposal system parameters (see Section 2.2.5) is represented by latin-hypercube sampling (LHS) of parameters within the BRAGFLO and NUTS models. Parameters which are expected to evolve significantly over time, such as fluid pressure, saturation and porosity, are calculated as a time-evolving function of time-independent parameters. Uncertainty in the models adopted is not addressed directly, although, in some cases, the parameter distributions represent alternative assumptions concerning the possible evolution of the repository.

The overall system-model framework is appropriate, and well suited to the physical and phenomenological characteristics of the disposal system. However, operational factors affect the way the codes are run and linked together (see Section 3.4.3).

3.4.2 Undisturbed performance calculations

Within the 10,000-year period considered, the only pathway by which releases are estimated to occur is through movement of contaminated brine through the marker beds. Movement up the sealed shafts is modelled but no releases occur within the period of regulatory interest. Contamination reaches the site boundary by migration in the marker beds in 9 of 300 calculations.

Although there is no plausible path by which contaminants in the marker beds should then reach the human environment, the EPA requires the DOE to calculate doses corresponding to this release. To effect a calculation, it is assumed that brine from the beds is diluted with fresh water by a factor of about 30 to bring the total dissolved solids of the solution down to about 10,000 mg l^{-1}. This water is then used as a source of human drinking water at a rate of 2 l d^{-1}. This scenario, which must be considered conservative, gives rise to dose estimates in the range zero (for most simulations) to 0.5 mrem y^{-1} (0.005 mSv y^{-1}) compared to a dose limit of 15 mrem y^{-1} specified by the EPA.

The analysis may be sufficient for the EPA requirement. The IRG observes, however, that only two or three of the 300 simulations would contribute to the arithmetic mean of dose, i.e. the result is unlikely to be converged, although so low as to be of no concern.

3.4.3 Disturbed performance calculations

To represent the disturbed case the detailed model - BRAGFLO - is run 300 times for each of six subjectively-selected deterministic scenarios (determined sequences of future drilling penetrating the repository). These results are used to generate a look-up table of estimated conditions of brine and gas pressure, and their evolution after repository penetration, for other times of intrusion. A larger number of calculations by BRAGFLO_DBR and CUTTINGS are required to generate look-up information on radionuclide releases considering radioactive decay. The CCDF-GF code is then used to generate random sequences of future drilling, including times of intrusion. The code automatically picks appropriate results from the previously-generated look-up tables.

This procedure, which is adopted for operational reasons, carries a possibility of introducing bias. It would be prudent to verify the procedure by running the detailed model set for a selected set of time sequences generated by CCDF_GF and to compare outputs (e.g. time history of release and total release) with the results from the interpolation procedure employed in the CCA calculations. The selected sequences should include at least some in which multiple drilling events occur at early times when radioactive decay is most rapid. Satisfactory agreement in respect of total release in a 10,000-year period will be much easier to achieve than satisfactory agreement over time. Therefore, the IRG estimates that the bias is unlikely to be significant for the cumulative estimates of release required by the EPA.

The concentration of radionuclides in solid waste and in brine, calculated by CUTTINGS and BRAGFLO_DBR respectively, is depleted only in respect of radioactive decay, i.e. the inventory of solid wastes is not depleted due to dissolution in brine and the total inventory of the repository is not depleted due to movement of contaminated brine away from the wastes, e.g. into the marker beds.

This is conservative, leading to some "double-counting" of activity in direct brine and cutting releases and, possibly, to an over-estimate of radionuclides in direct releases, especially for more mobile elements.

To investigate the range of model behaviours that can be generated by subjective uncertainty, 300 simulations are carried out for each subjectively selected deterministic scenario (see above).

There is a concern over whether this relatively small sample size is sufficient to adequately explore the range of behaviours of such a complex model. Time-dependent intermediate results[26] *indicate the presence of outlying results, which reinforce this concern. The requirements set by the EPA in respect of statistical meaningfulness of the result are trivial. To meet the EPA containment requirement is a much less demanding condition statistically*[27] *than if the end-point of concern was risk or mean dose. The IRG observes that it is likely that*

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[26] "Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 CCA for the WIPP", memo by J. Helton, 12/23/96.

[27] For example, simulations with a probability of less than 1 in 1,000 are of no concern at all. This is in contrast to assessments of risk in which simulations with a much lower probability than this can contribute significantly to total risk or mean dose.

the behaviour of the models has not been fully explored but that the number of samples may be sufficient for the purpose of demonstrating compliance with EPA regulations.

Overall, the IRG concludes that the analysis of disturbed performance in the CCA is a competent technical analysis and may be sufficient to meet the EPA requirements. The CCDFs are an appropriate method of summary presentation. The case, however, could have been considerably strengthened by presentation of additional intermediate results, especially as a function of time. These would have given better quantitative understanding of the physical processes operating, and hence confidence in the results as expressed in the form of the CCDFs.

3.4.4 Supplementary radiological calculations

The IRG requested the DOE to provide information on the levels of contamination at the surface and radiation doses which might be received as a result of drilling of a borehole into the repository. This information is not required by the EPA and is not available in CCA. The DOE was able to provide this information, informally, for an intrusion at 1,000 years after closure, by extending calculations already made within the analysis of disturbed performance.

The drilling scenario considers the transfer of radionuclides from the repository to the surface environment in the form of drilling cuttings, spallings and brine releases. Radiation doses are estimated to the drill operator from external irradiation due to the handling of drill core samples and due to exposure to radionuclides which accumulate in a mud pit. The dose to the workers during the remediation of the mud pit due to the inhalation of wind-borne material is also evaluated, as are the concentrations of radionuclides that would remain as a potential radioactive anomaly after remediation.

These supplementary calculations have not been formally reviewed by the IRG. They are, however, of value to set the impacts of the drilling scenario in perspective. In particular, they allow the IRG to draw the conclusion that, at least for this scenario, it is likely that the WIPP facility could meet an individual risk-based standard typical of those used in other countries.

3.5 Documentation

The IRG appreciates the very substantial effort that is required to document a performance assessment and its basis at the level of detail that is presented in the CCA. The IRG also appreciates that the documentation was drafted and assembled in a remarkably short period of time, consistent with schedule requirements of the DOE . Cross-referencing, at least between the Volume I and Appendices, is generally good, and is much eased by the use of the electronic version on CD-ROM.

Overall, the IRG finds the CCA difficult to follow and is disappointed with the CCA as a technical description. The main criticisms are that:

- *the documents are repetitious;*
- *many statements concerning the need, or not, to represent processes in the analyses are not sufficiently supported, e.g. by site-specific and experimental evidence, reasoned arguments and reference to natural analogues;*
- *relevant or important information is not always brought forward into Volume I of the CCA, and reviewers had to go deeply into the appendices or referenced documents.*

As a result, it was laborious for the IRG to understand, from the CCA, what was done in the performance assessment: not all the issues of concern could be traced, even using the electronic version of the documentation.

The clarity and general usefulness of the CCA documents to wider audiences have suffered as a result of the guidance from the EPA on content, and possibly also as a result of the limited time available for internal scientific review by the DOE. The IRG suggests that, provided this would not interfere with its prime requirement to achieve approval of the CCA from the EPA, the DOE should consider preparing a more generally-based performance assessment overview document at a level suited to a general technical audience.

4. Conclusions

The results of the review are summarised in the following sections which present:

- observations on the specificity of the WIPP case;
- the evaluation of the CCA against the Terms of Reference specified for the review, in particular, whether the 1996 performance assessment is:
  - appropriate in the context of the EPA requirements,
  - technically sound,
  - in conformity with international practices, and
  - in conformity with international guidance and standards;
- the overall judgement arising from the experience of the review.

4.1 Observations on the Specificity of the WIPP Case

The WIPP project, and the CCA, are different in several respects from geological disposal projects, and assessment documentation, in other countries.

- The WIPP facility is sited in an area in which mineral resources are being actively and extensively exploited.
- The regulator has provided detailed guidance on the assessment approach, documentation and, for the assessment of future human actions, model assumptions.
- The CCA is tightly focused on compliance with the EPA regulations, and does not represent a full safety case as understood in most other countries.

These observations are statements of fact, not criticisms. Such differences, however, have had a strong influence on the performance assessment carried out by the DOE, and have been taken into account by the IRG in formulating its conclusions.

4.2 Evaluation with Respect to the Terms of Reference

4.2.1 Appropriateness

The CCA was specifically designed by the DOE to meet the requirements of the EPA regulations. The IRG has not, during its review, found any indication that the information presented is not appropriate in the context of the EPA requirement. This, however, is a matter for the EPA to judge.

4.2.2 Technical soundness

The analyses contained in the CCA are based on an extensive geological data set resulting from high quality acquisition programmes and compilation of regional data. This has been supplemented by a focused geotechnical and experimental programme that has provided a world-leading understanding of processes relevant to rock-salt behaviour. The uncertainty associated with characterisation of the wastes, processes related to waste and backfill evolution in the repository, and chemical speciation of radionuclides in the repository environment, are less well understood. In particular:

(1) the CCA does not sufficiently explore the possible physical implications of the chemical reactions that the magnesium oxide backfill may undergo. These implications may be both favourable and unfavourable to the performance of the facility;

(2) the CCA does not support the assumption, applied in the performance calculations, that the physically and chemically heterogeneous array of waste, packaging, backfill, reaction products, and void space, will quickly reach well-mixed homogeneous conditions within the disposal rooms. The basis for this assumption and implications of heterogeneities need to be analysed further.

The CCA indicates good code configuration and management of data flows. The IRG has confidence that the procedures applied in these areas are consistent with best practice for computer simulation internationally. The IRG is also aware of the long involvement of WIPP project in international comparison exercises, which gives added confidence in the performance of several of the detailed models.

Thus, the IRG has overall confidence in the majority of judgements and assumptions made in developing calculational models of the disposal system, and concludes that, in the main, the analyses presented in the CCA are based on appropriate studies and are technically sound.

4.2.3 Conformity with international practices

The methods used to assess the performance of the WIPP facility are generally in conformity with practices used in other countries. These include:

- the selection of features, events and processes (FEPs);
- development of scenarios and models representing the evolution of conditions in the repository, and the release of radionuclides;
- quantitative analysis of selected scenarios by means of a linked set of models and comparison of the results to regulatory limits.

The probabilistic analysis methods used by the DOE are comparable to those employed in a number of other countries, and the DOE contractors have contributed substantially to the development of probabilistic methods in the field of repository post-closure assessment.

Specific aspects of the assessment carried out by the DOE do not accord with assessment practices in other countries, and this can be partly traced to the influence of the EPA regulations and the strong focus of the CCA on compliance. For example:

- the probabilistic approach applied by the DOE deals only with parameter-based uncertainty. Conceptual model and scenario uncertainty, are not discussed in the CCA. These are considered to be important internationally;

- results in the CCA focus on the CCDFs of cumulative radionuclide release. Information on the behaviour of intermediate parameters and results of representative deterministic calculations, especially as a function of time, are lacking. Without this, it may not be possible to develop a good understanding of the behaviour of the disposal system;

- the EPA has ruled that the DOE only needs to consider a limited set of future human actions, and has specified the assumptions to make in assessing these actions. Thus, some scenarios that might affect safety have not been evaluated. The lack of a logically-argued explanation for the choice of scenarios analysed, or evaluation of these other scenarios, leads to the impression that the assessment is arbitrary.

4.2.4 Conformity with international guidance and standards

The CCA focuses on a demonstration of compliance with the EPA containment requirement. The latter is based on collective dose considerations, refers to the total activity in the repository, and cannot be related to the standards based on individual dose and risk adopted in most other countries. Moreover, the EPA regulations do not require the applicant to present descriptions or arguments concerning the performance of the disposal system beyond the 10,000-year regulatory period. Thus, for the general case, the CCA does not present calculated end-points that can be compared with international guidance and standards as implemented in other countries.

The CCA does present dose estimates for the undisturbed performance within the 10,000-year regulatory period based on a conservative hypothetical dose pathway. In this case, the results indicate that the WIPP can easily meet typical performance criteria based on dose to the individual. It is likely that, if undisturbed, the facility could meet individual dose criteria over much longer times, due to the long-term stability of the site and the absence of viable fresh water resources locally.

The IRG asked for information, not included in the CCA, on doses that might be received in the disturbed case, as result of drilling of a borehole into the repository. The results provided by the DOE indicated that, for this scenario, the WIPP facility would meet an individual risk-based standard typical of those used in other countries. The CCA does not demonstrate, however, that no other scenarios could contribute significantly to risk.

4.3 Overall Judgement

The WIPP project and the CCA are markedly different from geological disposal projects and assessment documentation in other countries. In particular, important decisions relating to what is a sufficient method and scope of assessment have already been taken, and the CCA is not required to present a complete performance assessment as understood internationally.

The CCA documentation is not transparent and is difficult to follow even from the point of view of experienced performance assessment practitioners. Technical issues are often difficult to trace and some of the choices made and modelling assumptions are not well supported. This, combined with the specificity of the EPA regulations, made it challenging to distinguish between decisions determined by the regulator and those made by the DOE.

Focusing on the decisions for which the DOE must take technical responsibility, the IRG finds that the performance assessment methodology implemented in the CCA is generally acceptable and conforms to practices in other countries. The IRG also has overall confidence in the majority of judgements and assumptions made in developing calculational models, and believes that the quality of assessment codes and data handling is generally good. Thus, in the main, the analyses contained in the CCA are technically sound.

On specific points, the IRG considers that the DOE should give further attention to:

(1) the implications - favourable and unfavourable - that the behaviour of the magnesium oxide backfill may have on the performance of the facility;

(2) the basis for the assumption that homogeneous conditions will be rapidly reached in the disposal rooms, and the potential consequences of heterogeneities in the source term.

The IRG is of the view that, in the case of undisturbed performance, the WIPP facility would meet radiological performance standards typical of those used in other countries. This judgement is based on the analysis presented in the CCA in respect of the 10,000-year regulatory period and, in respect of times beyond 10,000 years, on the geological stability of the site and the absence of viable fresh water resources. The case of disturbed performance is less clear: supplementary analyses by the DOE indicate that a risk target would be met in respect of an exploratory borehole drilling scenario. The CCA does not (and need not) make the case that this is the most important scenario to consider and, therefore, the IRG cannot reach a definite judgement.

Finally, from the experience of the review, the IRG observes that, by commissioning this international peer review the DOE has demonstrated a commendable openness and commitment to improving confidence in the performance assessment of the WIPP facility. The DOE and their contractors were very open in their discussions with the IRG, and were able to provide useful responses, often at short notice, on most issues raised. This was very useful and helpful to the review.

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Appendix 1: The Members of the Review Group

Ken BRAGG (AECB, Canada) - Group Chairman

Ken Bragg graduated from the University of Toronto in 1965 with a Bachelor of Applied Science in Engineering Physics. He has 25 years' experience with industry and several government departments (Mines branch, Environment, and the Atomic Energy Control Board) covering a wide variety of industrial and radioactive wastes, such as uranium and other mine tailings, low-level radioactive waste, spent nuclear fuel, municipal waste and various effluent discharges from industry.

He served as a member of the Secretariat of the OECD/NEA in Paris for three years. He joined the Atomic Energy Control Board (AECB) in 1979 with responsibilities for uranium mine tailings and spent-fuel disposal. His current position is Head of the Nuclear Fuel Wastes & Special Assessments Section.

He has been a member of the Radioactive Waste Management Committee (RWMC) of the OECD/NEA since 1983, and the Chairman of the IAEA Working Group on Principles and Criteria for Radioactive Waste Disposal and of the NEA Working Group on the Regulatory Aspects of Future Human Actions at Radioactive Waste Disposal Sites.

Arnold BONNE (IAEA) - Secretariat

Arnold Bonne graduated from the University of Leuven (Belgium) in geological sciences. He completed a Ph.D. in Natural Sciences (Metallogeny) in 1973, at the same university, and for the following 5 years held a research position at the Belgian National Research Foundation. He joined the National Nuclear Research Establishment SCK/CEN at Mol in Belgium in 1978 and was involved in the Geological Disposal research programme. From 1989 to 1993 he headed the Research Unit on Disposal and Waste. He acquired a broad experience in site investigation, performance assessment and waste characterisation and became acquainted with the international approaches to them through his participation in numerous advisory groups and committees, e.g. he was member of the Steering Committee of the European Commission's PAGIS programme (Performance Assessment of Geological Isolation Systems).

In 1993, he joined the International Atomic Energy Agency (IAEA), Vienna, to lead the unit on disposal of radioactive waste and was appointed Acting Head of the Waste Management Section (now Waste Technology Section) in mid-1995. He is also programme manager of the Waste Management Technical Review Programme (WATRP) at the IAEA.

Jordi BRUNO (QuantiSci, Spain)

Jordi Bruno holds a Master's Degree (M.Sc.) in Analytical and Inorganic Chemistry from the Autonomous University of Barcelona, Spain (1978), and a Ph.D. in Inorganic Chemistry from the Royal Institute of Technology, Stockholm, Sweden (1986). From 1988 to 1990 he was Associate Professor at the same Institute, where he headed the Natural Waters Chemistry Group. He also holds a Master of Business Administration (MBA) from the School of Economics of Stockholm, Sweden (1990). Since 1990, he has been a consultant in the field of environmental issues, and is now Managing Director of QuantiSci SL in Barcelona, Spain. Since 1996, he has been Associate Professor to the Institute of Environmental Sciences of the Autonomous University of Barcelona, Spain.

His areas of professional expertise include spent-fuel dissolution, actinide thermodynamics, radionuclide geochemistry and mobilisation, geochemical modelling, and performance assessment. He performed research work for the SKB (Sweden), and ENRESA (Spain). He has been involved in several international programmes within the European Commission (e.g. MIRAGE) and the OECD/NEA (e.g. GEOVAL, Sorption Modelling Project).

Klaus KÜHN (Technical University of Clausthal, Germany)

Klaus Kühn graduated from the Clausthal School of Mines (now Technical University of Clausthal) with a Dipl. Ing. in Mining Engineering, in 1963. He then worked as an assistant at the Mineralogical-Petrographic Institute of the same University. In 1968, he obtained a Ph.D. (Dr. Ing.) from the Technical University of Clausthal for a thesis on the geochemistry of nickel and cobalt. In 1987, he was appointed Honorary Professor at the same University where he is presently teaching and carrying out research part-time.

His professional activities have concerned all aspects pertaining to the disposal of radioactive waste, notably by substantial involvement in the development of the GSF-Institut für Tieflagerung. In 1973, he was appointed Director of the Institute and Head of its Department of Repository Technology. After the Institute disbanded in 1995, he was appointed Senior Scientist to the Asse Research Mine, where the majority of the in-situ investigations for the German disposal program are performed. He has also been a member of the Reaktor-Sicherheitskommission (RSK) which advises the Ministry of the Environment, Nature Conservation and Reactor Safety (BMU) on all topics related to safety of nuclear installations including the nuclear fuel cycle.

For some ten years he was one of the German representatives to the IAEA's "Technical Review Committee on Underground Disposal of Radioactive Wastes (TRCUD)", and, in 1993, chaired the International Peer Review Team which reviewed the radioactive waste management program of Finland in the WATRP framework. He was the first Chairman of the OECD/NEA "Co-ordinating Group on Geological Disposal" in 1975, and served for about seven years.

Philippe LALIEUX (OECD/NEA) - Secretariat

Philippe Lalieux is a geologist and geophysicist with ten years' professional experience in the field of radioactive waste disposal. He graduated from the University of Brussels (Belgium) in 1983 with a B.Sc. in Geological Sciences and obtained a Master's Degree (M.Sc.) in Geophysical Sciences from the same university in 1984. From 1986 to 1994 he was a staff member of the Belgian Agency for the Radioactive Waste and Enriched Fissile Material (ONDRAF/NIRAS). His responsibilities included the management and supervision of geoscientific characterisation of potential sites for deep and near-surface repositories, and natural analogue studies. He was also in charge of the co-ordination and defence of a Safety Assessment and Feasibility Interim Report (SAFIR).

He joined the OECD/NEA Secretariat in 1995. He is in charge, within the Radiation Protection and Radioactive Waste Management Division, of the programmes on site characterisation and evaluation. In particular he is responsible for the Technical Secretariat of the Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal (SEDE). His current activities also entail involvement in the NEA performance assessment related activities, notably through the launching of the GEOTRAP project on radionuclide transport.

Gordon LINSLEY (IAEA) - Secretariat

Gordon Linsley graduated from the University of Sheffield, in the United Kingdom in 1964 with a B.Sc. in physics. He went on to complete a Ph.D. in solid state physics, awarded in 1969, from the same university. From 1967, he worked in the field of medical physics for the Western Regional Hospital Board, in Glasgow, Scotland before specialising in the area of radiation protection. He was a staff member of the United Kingdom's National Radiological Protection Board (NRPB), Harwell, Oxfordshire, from its inception in 1970 until 1984. During a period as a radiation protection advisor, he acquired a broad experience in relation to the uses of ionising radiations in industry, research and medicine. In 1976, the focus of his work changed to environmental impact assessment and subsequently, he led a section at NRPB, working on this subject.

In 1984, he joined the International Atomic Energy Agency (IAEA), Vienna, Austria, to lead a small group concerned with the environmental aspects of radioactive waste management, safety assessment and radiological criteria for application to waste management. In 1996, he was appointed Head of the newly-formed Waste Safety Section at the IAEA. This section is responsible for establishing international safety standards in the area of waste management.

Sören NORRBY (SKI, Sweden)

Sören Norrby is a chemist with more than twenty-five years' experience in the field of radioactive waste management and disposal. He obtained his M.Sc. in Chemistry at the University of Uppsala, Sweden, in 1970. He worked for five years at the University of Uppsala on research projects mainly in the field of chemical radionuclide separation techniques. He worked for eight years at the Swedish Radiation Protection Institute (SSI) and was engaged in radioactive waste management and disposal matters.

Since 1980 he has worked for the Swedish Nuclear Power Inspectorate (SKI), since 1987 as the Director of the Office of Nuclear Waste. He has been engaged in supervision, regulatory review and licensing of nuclear waste management and disposal facilities in the Swedish nuclear waste programme (e.g. an intermediate storage facility for spent-fuel and a repository for low- and intermediate-level waste). He is also engaged in the review of the Swedish R&D programme on final disposal of spent nuclear fuel. He has served on several governmental committees to review Swedish legislation on nuclear waste. He is active in many aspects of international co-operation in the field of radioactive waste management and disposal.

He is a member of the Radioactive Waste Safety Standards Advisory Committee (WASSAC) at the IAEA and of the Radioactive Waste Management Committee (RWMC) at the OECD/NEA. He is the Chairman of the ACPM for the Community Plan of Action in the Field of Radioactive Waste.

Claudio PESCATORE (OECD/NEA) - Secretariat

Claudio Pescatore obtained a Laurea, *cum laude*, in Applied Physics from the University of Bologna in 1975 and a Ph.D. in Nuclear Engineering from the University of Illinois, Urbana-Champaign (US) in 1982. He has 19 years' experience in research and development, technical assistance to government and industry, university lecturing, and management of international programmes in the field of nuclear waste covering low-level waste, high-level waste, and spent-fuel storage and disposal.

He joined the Brookhaven National Laboratory in 1982 and was involved in: the study of high-level waste and spent-fuel disposal concepts in basalt, salt, and tuff formations; reliability and modelling studies of waste package materials during storage and disposal; analyses of gaseous and aqueous pathways for radionuclide migration; peer reviews of environmental impact assessments studies and site characterisation plans. In 1989 he was nominated Group leader for Radioactive Waste Performance Assessment. Through 1995, he also was adjoint Professor of Marine Environmental Sciences at the University of New York at Stony Brook.

He joined the NEA/OECD Secretariat in 1992 in the Division of Radioactive Waste Management. He is in charge of the Agency's performance assessment programmes, and provides the technical secretariat of the Performance Assessment Advisory Group, the Probabilistic System Assessment Group, the group on validation/confidence building in safety assessments, and the Integrated Performance Assessment Group. He also contributes in the field of site characterisation, and has been at the centre of several international initiatives such as the ASARR and GEOTRAP projects, and the GEOVAL'94 symposium. He was a Secretariat member of the international peer reviews of SKI's Project 90 and of the AECL Postclosure Assessment for the EIS on the Concept for Disposal of Canada's Nuclear Fuel Waste.

Richard STORCK (GRS, Germany)

Richard Storck was educated at the Technical University of Berlin as a nuclear engineer. He graduated from the same university with a thesis on probabilistic risk assessment of technical nuclear facilities (1980). He then worked as a scientific employee of the Technical University of Berlin for four years, on the first German project on the long-term safety of deep underground disposal systems for radioactive waste in salt formations (PSE).

He continued this work as a Group and Project Manager at the GSF research centre in Braunschweig. He was involved in the European performance assessments for high-level (PAGIS) and low-level waste (PACOMA), the long-term safety assessment for the application of the abandoned iron ore mine at the Konrad site for disposal of non-heat-producing radioactive waste, performance assessments for the planned repository at the Gorleben site for all types of waste including spent-fuel (SAM).

In 1995, he joined GRS (Gesellschaft fur Anlagen und Reaktorsicherheit) following the transfer of the repository research area of the GSF research centre to the GRS. Since that time he has been Head of the Long-Term Safety Analyses Department. One of his current main tasks is the long-term safety assessment of the Morsleben repository for low-level waste in the eastern part of the country.

Trevor SUMERLING (Safety Assessment Management Ltd., United Kingdom)

Trevor Sumerling obtained a 1st class honours degree in physics from Lancaster University in 1975. He spent 8 years at the UK National Radiological Protection Board where he gained experience in the fields of in vivo monitoring, internal dosimetry and environmental transfer of radionuclides, and became responsible for the in vivo measurement facilities and various environmental field studies at the NRPB. For the past 10 years he has worked in scientific and engineering consultancies on aspects of radioactive waste disposal assessment and assessment management. In this period, he has contributed significantly to nuclear waste disposal assessment projects in the UK, Switzerland, Sweden, Canada and Japan. He is now Director of Safety Assessment Management Limited, an independent consultancy specialising in radioactive waste disposal assessment.

His more recent experience has included:

- project co-ordination for an independent performance assessment of the Sellafield site and review of the proponent's safety documentation on behalf of the UK regulator, as well as development of assessment procedures and contributions to UK regulatory guidance documentation;
- scenario methodology development and application to both the Kristallin-I (HLW) project and Wellenberg (L/ILW) site, as well as technical work and editing contributing to the Kristallin-I safety assessment report, for the Swiss National Co-operative for Radioactive Waste Disposal;
- carrying out an international comparison of disposal concepts and assessments of nuclear fuel wastes for Atomic Energy of Canada Limited as input to the federal review process in Canada;
- participation in the NEA OECD "FEP Database" and "Integrated Performance Assessment" working groups.

Mr. Sumerling was retained as a consultant to assist the Secretariat in compiling and editing the report of the current review.

Hiroyuki UMEKI (PNC, Japan)

Hiroyuki Umeki is a nuclear-chemical engineer with more than 15 years' experience in the field of radioactive waste management. He obtained his Bachelor's and Master's degrees in Nuclear Engineering from the University of Tokyo in 1977 and 1979 respectively, following which, he worked for 6 years at the University of Tokyo on research and education pertaining to the nuclear fuel cycle, in particular, radioactive waste management.

After he obtained his Ph.D. in 1987, from the University of Tokyo with a thesis on radionuclide transport modelling and uncertainty analysis for the performance assessment of the disposal system, he joined the Power Reactor and Nuclear Fuel Development Corporation (PNC) which is a leading R&D organisation for the Japanese high-level waste disposal programme. His current positions are the Deputy General Manager and Senior Engineer of the Isolation System Research Programme in the Radioactive Waste Management Project. He is responsible for all performance assessment activities in the R&D programme for high-level waste disposal. This includes the H3 project completed in 1992, and the H12 project now on-going. He has been a member of the OECD/NEA Performance Assessment Advisory Group (PAAG) since 1988.

Appendix 2: Terms of Reference for the Review

Terms of Reference for the international review of the Waste Isolation Pilot Plant 1996 performance assessment were negotiated between the DOE, the NEA and the IAEA. Relevant parts of the Terms of Reference, agreed to in June 1997, are reproduced below.

Introduction

A joint international review of the post-closure part of the Compliance Certification Application (CCA) of the US Program for safe disposal of transuranic radioactive waste (TRUW) is to be organized by the Nuclear Energy Agency of the Organisation of Economic Co-operation and Development (NEA) and the International Atomic Energy Agency (IAEA). The review will be conducted by a group of independent experts appointed by the NEA and the IAEA (hereafter referred to as the Expert Group). A joint NEA/IAEA Secretariat will be established for the purpose, and will be managed by the NEA. This Expert Group will examine whether the post-closure performance assessment of the Waste Isolation Pilot Plant (WIPP) disposal system for TRUW is appropriate, technically sound, and in conformity with international standards and practices. 'The results of this international review will be submitted to the US Department of Energy (DOE) in a joint report.

The International Review Process

The international review will be organised jointly by the NEA and the IAEA as part of their international review services programs. The review is at the request of and sponsored by the DOE.

The Expert Group will draw on the experience of the world's leading experts in radioactive waste disposal and safety assessments and their views on the approaches taken by other countries towards the safe disposal of long-lived radioactive waste. As part of the review, the Expert Group may want to meet with scientific and technical groups and government agencies involved in the WIPP.

Objective of the International Review

The objective of the international review is to examine whether the post-closure performance assessment of the WIPP in the CCA is appropriate, technically sound, and in conformity with international standards and practices.

Scope of the International Review

The review should include an assessment of the state of the WIPP *(performance assessment)* technology in comparison to other nations' programs, and should include but not be limited to scenario development, conceptual model and computational model development, data/parameter acquisition and selection, computational model construction, and the results of the probabilistic analysis including tracking of uncertainty. The clarity and transparency of the documentation of the post-closure performance assessment results should also be reviewed. Finally, the Expert Group will review, from an international perspective, the technical soundness and appropriateness of the methodologies used and the arguments presented for the post-closure performance assessment on which the CCA was developed.

In carrying out the review, the Expert Group may consider comparing the post-closure part of the CCA with approaches being taken by other countries on the management and disposal of long lived radioactive waste.

Documentation for this review will primarily consist of the applicable portions of the CCA, the FEIS, the cited references, details of formal past licensing decisions concerning WIPP, and other information as may be requested. All relevant information used by the Expert Group should be listed in the final report resulting from this international review.

The issues which fall outside the scope of the post-closure part of the CCA and which have been dealt with separately or at an earlier stage of the decision-making process, such as repository siting and design, waste form and other pre-closure issues, should not be addressed as such. However, it is recognized that such issues may

have a direct influence on post-closure performance and the Expert Group might wish to comment on how such an influence has been evaluated and taken into account from the point of view of post-closure performance assessment.

The scope of the review should exclude chemical toxicity aspects, socio-economic or political considerations, all aspects of the development of regulations, as well as any issues related to timing and institutional arrangements for the implementation of disposal.

It is anticipated that the international review will be carried out over a 6-month period. The material for the review (see Annex 1) will be made available to the joint NEA/IAEA Secretariat by October 1, 1996. The review will be completed and delivered to the CAO by March 30, 1997.

Deliverable

A report containing the Expert Group's findings will be delivered to the DOE Carlsbad Area Office (CAO). Prior to finalizing report, the Expert Group will present its findings to the CAO to ensure that all pertinent information and data were considered in the review.

Annex 1: US DOE reference documents

Primary Material to be reviewed:

- The CCA's main text, i.e. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, Volume I.

Other Information:

- FEIS Record of Decision.
- Appendices and references cited in the aforementioned documents, as required.
- Other information, as identified by the reviewers themselves.

Annex 2: International reference documents

1. IAEA, The Principles of Radioactive Waste Management, Safety Fundamentals, Safety Series No. 11 I-F (1995)
2. IAEA, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (sponsored by FAO, IAEA, ILO, OECD/NEA, PAHO, WHO), Safety Series No. 115, (1996)
3. ICRP, Radiation Protection Principles for the Disposal of Solid Radioactive Waste, ICRP Publication 46, (1986)
4. OECD/NEA, Disposal of Radioactive Waste: Review of Safety Assessment Methods, (1991)
5. IAEA, Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Wastes, Safety Series No. 99 (1989)
6. IAEA, Safety Indicators in Different Timeframes for the Safety Assessment of Underground Radioactive Waste Repositories, TECDOC-767, (1994)
7. OECD/NEA, Safety Assessments of Radioactive Waste Repositories: Future Human Actions at Disposal Sites, (1995)
8. OECD/NEA, Safety Assessments of Radioactive Waste Repositories: Systematic Approaches to Scenario Development (1992)
9. OECD/NEA, Disposal of Radioactive Waste: Can Long-term Safety be Evaluated ? An International Collective Opinion, jointly sponsored by the NEA, IAEA and CEC (1991).
10. OECD/NEA, The Management of Long-Lived Radioactive Waste: The Environmental and Ethical Basis of Geological Disposal, A collective Opinion of the NEA Radioactive Waste Management Committee (1995).

Appendix 3: Selected Paragraphs From the EPA Regulations

This appendix reproduces selected parts of paragraphs and definitions from 40 CFR 191 and 40 CFR 194 which are referred to in Chapter 2 of the main report. It is emphasised that these have been selected as background to points on which the IRG wished to comment. They are not intended to summarise the EPA regulations.

A3.1 Selected paragraphs from 40 CFR 191

§191.13 Containment requirements.

(a) Disposal systems ... shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment* for 10,000 years after disposal from all significant processes and ... shall:

(1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A)*; and

(2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A)*.

(b) Performance assessments need not provide complete assurance that the requirements of §191.13(a) will be met. ... Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance ... will be achieved.

§191.14 Assurance requirements.

To provide the confidence needed for long-term compliance with the requirements of §191.13, ... :

(a) Active institutional controls* over disposal sites should be maintained for as long a period of time as is practicable ... however, performance assessments ... shall not consider any contributions from active institutional controls for more than 100 years after disposal.

(b) Disposal systems shall be monitored after disposal ...

(c) Disposal sites shall be designated by the most permanent markers, records, and other passive institutional controls* practicable ...

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* Terms denoted by an asterisk have defined meanings, see Section A3.3.

(d) Disposal systems shall use different types of barriers to isolate the wastes ... engineered and natural barriers ...

(e) Places where there has been mining for resources, or where there is a reasonable expectation of exploration ... should be avoided in selecting disposal sites. Resources to be considered include minerals, petroleum or natural gas ... Such places shall not be ... unless the favorable characteristics of such places compensate for their greater likelihood of being disturbed in the future.

§191.15 Individual protection requirements.

(a) Disposal systems ... shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance* of the disposal system shall not cause the annual committed effective dose, ... to any member of the public ... to exceed 15 millirems (150 microsieverts).

A3.2 Selected paragraphs from 40 CFR 194

Containment Requirements

§194.25 Future State Assumptions

(a) Unless otherwise specified ... performance assessments and compliance assessments conducted pursuant the provisions of this part to demonstrate compliance with § 191.13, § 191.15 ... shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions. ...

§194.32 Scope of performance assessments.

(a) Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.

(b) Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur.

Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.

§194.33 Consideration of drilling events in performance assessments.

(a) Performance assessments shall examine deep drilling and shallow drilling that may potentially affect the disposal system during the regulatory time frame.

(b) The following assumptions and process shall be used... (1) Inadvertent and intermittent intrusion by drilling for resources (other ... the waste ... or engineered barriers ...) is the most severe human intrusion scenario. (2) ... drilling events shall be assumed to occur in the Delaware Basin at random intervals in time and space during the regulatory time frame. (3) The frequency of deep drilling shall be calculated in the following manner: (i) Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years ... (ii) The total rate of deep drilling shall be the sum of the rates of deep drilling for each resource. ...

(c) ... assumed that: (1) Future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. ... The types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of such boreholes that are sealed by humans; ...

(d) ... performance assessments need not analyse the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

§194.34 Results of performance assessments.

(a) The results of performance assessments shall be assembled into "complementary, cumulative distribution functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events.

(b) Probability distributions for uncertain disposal system parameter values used in performance assessments shall be developed ...

(c) Computational techniques, which draw random samples from across the entire range of the probability distributions... shall be used in generating CCDFs ...

(d) The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated

exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability. ...

(e) Any compliance application shall display the full range of CCDFs generated.

(f) ... demonstrates that there is at least a 95 percent level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 ...

Assurance Requirements

§194.41 Active institutional controls.

(a) ... include detailed descriptions of proposed active institutional controls ... Assumptions pertaining to active institutional controls and their effectiveness in terms of preventing or reducing radionuclide releases shall be supported by such descriptions.

(b) Performance assessments shall not consider any contributions from active institutional controls for more than 100 years after disposal.

§194.43 Passive institutional controls.

(a) ... include detailed descriptions of the measures that will be employed to preserve knowledge about the location, design, and contents of the disposal system. ... (1) Identification of the controlled area by markers ... (2) Placement of records in the archives and land record systems of local, State, and Federal governments, and international archives, ... (3) Other passive institutional controls practicable to indicate the dangers of the waste and its location.

(c) The Administrator may allow the Department to assume passive institutional control credit, in the form of reduced likelihood of human intrusion, if the Department demonstrates ... that such credit is justified ... Such credit ... cannot be used for more than several hundred years and may decrease over time. ...

§194.45 Consideration of the presence of resources.

Any compliance application shall include information that demonstrates that the favorable characteristics of the disposal system compensate for the presence of resources in the vicinity of the disposal system and the likelihood of the disposal system being disturbed as a result of the presence of those resources. If performance assessments predict that the disposal system meets the containment requirements of § 191.13 of this chapter, then the

Agency will assume that the requirements of this section and § 191.14(e) of this chapter have been fulfilled.

A3.3 Selected definitions from 40 CFR 191 and 40 CFR 194

§191.02 Definitions.

Transuranic radioactive waste, ... means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years, per gram of waste, except for: (1) High-level radioactive wastes; (2) wastes that the Department has determined, with the concurrence of the Administrator, do not need the degree of isolation required by this part; or (3) wastes that the Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR Part 61.

§191.12 Definitions.

Accessible environment means: (1) The atmosphere; (2) land surfaces; (3) surface waters; (4) oceans; and (5) all of the lithosphere that is beyond the controlled area.

Active institutional control means: (1) Controlling access to a disposal site by any means other than passive institutional controls; (2) performing maintenance operatione or remedial actions at a site, (3) controlling or cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance.

Controlled area means: (1) A surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location.

Disposal system means any combination of engineered and natural barriers that isolate spent nuclear fuel or radioactive waste after disposal.

Passive institutional control means: (1) Permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system.

Performance assessment means an analysis that: (1) Identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties,

caused by all significant processes and events. These estimates shall be incorporated into an overall probability distribution of cumulative release to the extent practicable.

Undisturbed performance means the predicted behaviour of a disposal system, including consideration of the uncertainties in predicted behaviour, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events.

A3.4 Appendix A to 40 CFR 191 - Table for Subpart B

TABLE 1--RELEASE LIMITS FOR CONTAINMENT REQUIREMENTS[Cumulative releases to the accessible environment for 10,000 years after disposal]

Radionuclide	Release limit per 1,000 MTHM or other unit of waste (see notes) (curies)
Americium-241 or -243	100
Carbon-14	100
Cesium-135 or -137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, -239, -240, or -242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230 or -232	10
Tin-126	1,000
Uranium-233, -234, -235, -236, or -238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1,000

Note 1: Units of Waste. The release limits in Table 1 apply to the amount of wastes in anyone of the following:

(e) An amount of transuranic (TRU) wastes containing one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years.

Note 2: To develop Release Limits for a particular disposal system, the quantities in Table 1 shall be adjusted for the amount of waste included in the disposal system. For example:

(b) If a particular disposal system contained three million curies of alpha-emitting transuranic wastes, the Release Limits for that system would be the quantities in Table 1 multiplied by three (three million curies divided by one million curies).

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Technical Peer Review Report

Report of the Review Panel

Requirements for Disposal of Remote-Handled Transuranic Wastes at the Waste Isolation Pilot Plant

ASME International

Institute for Regulatory Science

DISCLAIMER

This report was prepared through the collaborative efforts of the American Society of Mechanical Engineers (ASME) Center for Research and Technology Development and the Institute for Regulatory Science (referred to thereafter with the collaborators as the Society) for the Office of Science and Technology Development of the U.S. Department of Energy (referred to hereafter as the Sponsor).

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Preface

This report contains the results of a peer review performed jointly by the American Society of Mechanical Engineers (ASME) and the Institute for Regulatory Science (RSI). Based on a request from the Carlsbad Operations Office of the U.S. Department of Energy (DOE), a Review Panel was established to review the "Requirements for the Disposal of Remote-Handled Transuranic Wastes at the Waste Isolation Pilot Plant."

Preliminary negotiations between the DOE and New Mexico Environment Department indicated a desire of the New Mexico Environment Department to cosponsor the peer review. Accordingly, there were extensive negotiations between managers of the peer review program and the New Mexico Environment Department (NMED) on the role and responsibilities of cosponsors of the peer review. After considerable discussion within the NMED, based on legal reasons, a decision was made not to cosponsor the peer review. However, the NMED expressly recognized the need for peer review and the credibility of the current peer review program.

Keeping with the ASME Process, the following Review Panel (RP) was appointed by the Peer Review Committee (PRC) of ASME:

Alan S. Corson
Tom A. Hendrickson
M.C. Kirkland
Peter B. Lederman, Chair
James E. Martin
Wade O. Troxell
Richard Wilson

During the period covered by this report, the ASME PRC overseeing the peer review consisted of the following individuals:

Charles O. Velzy, Member of EP, Chair
Ernest L. Daman, Member of EP
Nathan H. Hurt, Member of EP
A. Alan Moghissi, Member of EP, Principal Investigator of the PR Program
Gary A. Benda
Erich W. Bretthauer
Irwin Feller
Robert A. Fjeld

John T. Greeves
William T. Gregory, III
Peter B. Lederman
Jeffrey A. Marqusee
Lawrence C. Mohr, Jr.
Goetz K. Oertel
Glen W. Suter, II

The supporting staff were the following individuals:

Carolyn Davis: Director of Research at the Center for Research and Technology Development of ASME in Washington DC; Administrative Manager of the ASME PRC

Betty R. Love: Executive Vice President, RSI, Columbia, MD; Administrative Manager of the Peer Review Program. During this peer review, Betty Love was also responsible for management of stakeholder participation.

Sorin R. Straja: Vice President for Science and Technology, RSI; Technical Secretary

Sharon D. Jones: Director of Training Programs, RSI; Manager of Review Panel Operations

The biographical summaries of the members of the RP, the PRC, and the technical staff are located at the end of this report.

Extensive written material was provided by the DOE to the Technical Secretary at the beginning of the process. The Technical Secretary extracted a draft summary for inclusion in this report. This summary was provided to DOE for review and was revised accordingly. Based on the information provided to the Technical Secretary, the Summary included in this report is an accurate representation of the project. The written material provided by DOE was made available to the members of the Review Panel in advance of the meeting in Carlsbad, NM. The agenda of the meeting in Carlsbad appears in the Appendix of this section.

The RP considered materials provided by the DOE and presentations during the Carlsbad meeting. The RP benefitted from a site visit to the Waste Isolation Pilot Plant on the morning of Monday, July 30, 2001 immediately prior to the

presentations and from presentations during a workshop convened in conjunction with the peer review meeting. At the end of the meeting, the Review Panel met in an executive session and completed its report. The report of the Review Panel was subsequently copy-edited. Consistent with the procedures established by ASME, this report was provided to DOE for identification of potential errors; misunderstandings; and areas of ambiguity; and was revised accordingly.

The completion of this peer review within the rather short time frame could not have been possible without the support of a number of people. The assistance and cooperation of Bryan Howard, Norbert Rempe, and Phil Gregory are appreciated. The cooperation of Dr. Peter Maggiore, Secretary of the New Mexico Environment Department, and the staff of that Department was most helpful during the peer review.

Charles O. Velzy
A. Alan Moghissi

Appendix

ASME/RSI Peer Review and Workshop
Requirements for Disposal of Remote Handled Transuranic Wastes at the Waste Isolation Pilot Plant
Carlsbad, NM - July 30 - August 3, 2001

AGENDA

Monday, July 30, 2001

Waste Isolation Pilot Plant

8:30 a.m.	Site Visit
11:30 a.m.	Lunch

Pecos River Village Conference Center
Carousel House, Carlsbad, NM

Session 1: Introduction and Regulatory Requirements
Chair: Chuck Wiggins

1:00 p.m.	Welcoming Address	Chuck Wiggins Mayor Pro Tem of Carlsbad
1:10 p.m.	Welcoming Address	Ines Triay Manager, Carlsbad Field Office
1:20 p.m.	Introduction to Panel Workshop	A. Alan Moghissi Institute for Regulatory Science/ASME
2:00 p.m.	NMED Perspective	James Bearzi New Mexico Environment Department
2:30 p.m.	EPA Perspective	Rajani Joglekar U.S. Environmental Protection Agency
3:00 p.m.	Break	

Session 2: DOE Strategy for RH-TRU Waste Disposal
Chair: Betty R. Love

3:15 p.m.	The DOE RH-TRU Waste Characterization Program	Bryan Howard Los Alamos National Laboratory
4:00 p.m.	Discussion Responding to Audience Questions (Bearzi, Joglekar, Howard)	
5:00 p.m.	Adjournment	

ASME/RSI Peer Review and Workshop
Requirements for Disposal of Remote Handled Transuranic Wastes at the Waste Isolation Pilot Plant
Carlsbad, NM - July 30 - August 3, 2001

AGENDA

Tuesday, July 31, 2001

Pecos River Village Conference Center
Carousel House, Carlsbad, NM

Session 3: **Chair:**	**Review of DOE Submission** **Bryan Howard**	
8:00 a.m.	RH Inventory and Compliance Impacts	Joe Harvill Westinghouse TRU Solutions
8:45 a.m.	Repository Performance	M. Kathryn Knowles Sandia National Laboratory
9:45 a.m.	Break	
Session 4: **Chair:**	**Review of DOE Submission (Cont'd)** **Bryan Howard**	
10:00 a.m.	Application of Acceptable Knowledge for RH-TRU Waste	Bob Kehrman Westinghouse TRU Solutions
11:00 a.m.	Characterization Objectives and NDA/NDE Measurement Systems	Dan Taggart Los Alamos National Laboratory
12:00 p.m.	Lunch	
Session 5: **Chair:**	**Placing RH-TRU Waste in Perspective** **Phil Gregory**	
1:00 p.m.	Summary: RH-TRU: Small Volume-Large Impact	Ines Triay, CBFO
2:00 p.m.	Summary: NAS/NRC: WIPP Report	Werner Lutze Center for Radioactive Waste Management
2:30 p.m.	Discussion Responding to Audience Questions (Triay, Lutze)	
3:00 p.m.	Break	

ASME/RSI Peer Review and Workshop
Requirements for Disposal of Remote Handled Transuranic Wastes at the Waste Isolation Pilot Plant
Carlsbad, NM - July 30 - August 3, 2001

AGENDA

Tuesday continued

Session 6:	**Risk Issues**	
Chair:	**Joe Harvill**	
3:15 p.m.	Risk Assessment of Intrusive RH Waste Characterization Methods	Fritz Seiler Sigma Five Associates
4:00 p.m.	Risk/Cost-Impact Analysis for Intrusive RH Waste Characterization Methods	Louis Restrepo OMICRON
4:30 p.m.	Discussion Responding to Audience Questions (Seiler, Restrepo)	
5:00 p.m.	Adjournment	

Wednesday, August 1, 2001

Pecos River Village Conference Center
Carousel House, Carlsbad, NM

Session 7:	**Regulatory Experience**	
Chair:	**M. Kathryn Knowles**	
8:00 a.m.	Application of 40 CFR 260, 262, and 264 to RH-TRU Mixed Waste Characterization	Matt Strauss Clay Associates
9:00 a.m.	Application of 40 CFR 191/194 to RH-TRU Waste Characterization	John Bartlett SC&A
9:45 a.m.	Break	
Session 8:	**Stakeholders**	
Chair:	**A. Alan Moghissi**	
10:00 a.m.	Discussion Responding to Audience Questions and Statements by Stakeholders Addressing Peer Review Criteria	
12:00 p.m.	Lunch	
1:00 p.m.	Discussion Responding to Audience Questions and Statements by Stakeholders Addressing Peer Review Criteria	
4:00 p.m.	Adjournment	

ASME/RSI Peer Review and Workshop
Requirements for Disposal of Remote Handled Transuranic Wastes at the Waste Isolation Pilot Plant
Carlsbad, NM - July 30 - August 3, 2001

AGENDA

Wednesday continued
Lyndam Hotel, Albuqerque, NM

6:00 p.m. Executive Session

Thursday, August 2, 2001

Lyndam Hotel, Albuqerque, NM

Executive Session

8:00 a.m Writing of the Report *(ASME Review Panel Members only)*

5:00 p.m. Adjournment

Friday, August 3, 2001

Lyndam Hotel, Albuqerque, NM

Executive Session

8:00 a.m Writing of the Report *(ASME Review Panel Members only)*

5:00 p.m. Adjournment

Peer Review Process

INTRODUCTION

There is consensus within the technical community on the definition, process, and key criteria for the acceptability of peer review. Peer review consists of a critical evaluation of a topic by individuals who—by virtue of their education, experience, and acquired knowledge—are qualified to be peers of an investigator engaged in a study. A peer is an individual who is able to perform the project, or the segment of the project that is being reviewed, with little or no additional training or learning.

Recognizing that peer review constitutes the core of acceptability of scientific and engineering information, virtually all professional societies of scientists and engineers have instituted formal procedures for peer review for their activities. The American Society of Mechanical Engineers (ASME), also known as ASME International, has over a century of experience in peer review. Consistent with its mission and tradition, ASME recently established a peer review program devoted to the technologies supported by the Office of Science and Technology of the U.S. Department of Energy (DOE). This program is performed in cooperation with the Institute for Regulatory Science (RSI). The reports of the peer reviews resulting from this program have been published (ASME 1997, 1998, 1999, 2000).

PEER REVIEW PROCESS

The structure of the peer review process established by the ASME/RSI team consists of a tiered system. For each specific area of technology, the entire process is overseen by a Peer Review Committee (PRC). The review of specific topics is performed by Review Panels (RPs).

Peer Review Committee

The PRC is a standing committee formed to oversee peer review for one particular program in an agency. Its members are chosen on the basis of their education, experience, and peer recognition. An attempt is made to ensure that all needed technical competencies and diversity of technical views are represented in the PRC. The members of the PRC must be approved by the Board on Research and Technology Development of the Council on Engineering of the ASME. The PRC includes an Executive Panel (EP) that is responsible for the day-to-day operation of the PRC. Except for the EP, membership in the ASME is not required for appointment to the PRC. As the overseer of the entire peer review process, the PRC enforces all relevant ASME policies, including compliance with professional and

ethical requirements. A key function of the PRC is the approval of the appointment of members of RPs for a specific project.

Review Panels

The review of a project, a document, a technology, or a program is performed by a RP consisting of a small group of highly-knowledgeable individuals. Upon the completion of their task, the RPs are disbanded. The selection of reviewers is based on the competencies required for the specific review assignment. The number of individuals in a RP depends upon the complexity of the subject to be reviewed. The selection of a reviewer is based on the totality of that individual's qualifications. However, there are several generally-recognized and fundamental criteria for assessing qualifications of a reviewer. These are as follows:

1. **Education and relevant experience:** A minimum of a B.S. degree and preferably an advanced degree in an engineering or scientific field is required for any peer reviewer. In addition, the reviewer must have significant experience in the area that is being reviewed.

2. **Peer recognition:** Election to an office of a professional society, serving on technical committees of scholarly organizations, and similar activities are considered to be a demonstration of peer recognition.

3. **Contributions to the profession:** Contributions to the profession may be demonstrated by publications in peer-reviewed journals. In addition, patents, presentations at meetings where the papers were peer-reviewed, and similar activities are also considered to be contributions to the profession.

4. **Conflict of Interest:** One of the most complex and contested issues in peer review is a set of subjects collectively called conflict of interest. The ideal reviewer is an individual who is intimately familiar with the subject and yet has no monetary interest in it. Despite this apparent difficulty, the ASME and similar organizations have successfully performed peer review without having a real or an apparent conflict of interest. The guiding principle for conflict of interest is as follows: *An individual who has a personal stake in the outcome of the review may not act as a reviewer or participate in the selection of reviewers.*

Due to the multidisciplinary nature of many projects reviewed by the ASME/RSI team, rapid identification of qualified peer reviewers and their availability to

participate in the review process are key ingredients for a successful program. The process used for the identification of reviewers is multifaceted. The Administrative Manager of the Peer Review Program receives recommendations from sources within ASME; previous members of the RP; sister societies; other organizations and individuals; the DOE; DOE contractors; and others. However, the selection of peer reviewers is entirely based on criteria identified by ASME. The details of various aspects of peer review, including conflict of interest, can be found in ASME *Manual for Peer Review* (ASME 2000) and the *Associated Procedures* (RSI 2000).

COOPERATION WITH OTHER PROFESSIONAL SOCIETIES

The ASME is a large professional engineering society having in excess of 125,000 members. Although the predominant discipline of the members is mechanical engineering, there are members who—by virtue of their education, training, or experience—are competent in other disciplines. The Council on Engineering includes divisions ranging from classical mechanical engineering (design, heat transfer, and power) to solar engineering; environmental engineering; and safety and risk analysis. Despite the diverse competency within the ASME, it is recognized that on occasion it will become necessary to peer review activities which include disciplines that are outside the areas of competency of the ASME and its members. These disciplines may include geology, hydrology, toxicology, and ecology. Consequently, ASME has reached formal and informal agreements with its sister societies to identify qualified reviewers in areas outside of those covered by the membership of ASME.

PERFORMING ORGANIZATIONS

The Center for Research and Technology Development of ASME manages a number of scientific and engineering activities, including peer review for the Office of Science and Technology (OST). Because of ASME's conscious effort to maintain a small in-house staff, it relies upon other organizations to provide detailed project management services in its research, development, and similar activities. Accordingly, ASME and RSI joined forces in a collaborative effort to perform the peer review for OST. While the ASME staff in Washington, DC provides the staff support for the PRC, the detailed management and staff support for the RPs is provided by RSI.

American Society of Mechanical Engineers

As one of the largest professional engineering societies, ASME has a long and distinguished history. Its activities are carried out primarily by members who volunteer their time in support of engineering and scientific advancement. For obvious reasons, ASME also has a paid staff to manage the day-to-day operations of such a large professional society. The ASME has a detailed structure for its operation consisting of councils, boards, divisions, and committees. The Council on Engineering has 38 divisions, including: Environmental Engineering; Solid Waste Processing; Nuclear Engineering; and Safety Engineering and Risk Analysis. The Council on Codes and Standards develops ASME codes and standards that are the backbone of many industries—including power production—worldwide. The Council on Codes and Standards is also responsible for the development of standards for activities such as certification of incinerator operators. The ASME was a founding member of the American Association of Engineering Societies and a founding member of the American National Standards Institute.

Institute for Regulatory Science

RSI is a not-for-profit organization chartered under section 501(c)3 of the Internal Revenue Service. It is dedicated to the idea that societal decisions must be based on the best available scientific and engineering information. According to the RSI mission statement, peer review is the foundation of the best available scientific and engineering information. Consequently, RSI has promoted peer review within government and industry as the single most important measure of reliability of scientific and engineering information. In its activities, RSI seeks the cooperation of scholarly organizations. Historically, a large number of RSI activities have been performed in cooperation with ASME. RSI is located in the Washington, DC, Metropolitan Area.

WIPP Facility

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is the principal facility for the disposal of our nation's transuranic (TRU) radioactive waste generated as a result of over 50 years of nuclear weapons research, development, and production. The selection of the WIPP site followed a lengthy search and extensive studies for the identification of a site for disposal of TRU wastes (NRC 1983, 1984). These efforts led to the selection of a 41 km^2 (16 mi^2) site, 26-miles (42-km) east of Carlsbad, NM. Following studies conducted of geological formations stable enough to contain wastes for thousands of years during the 1950s, the National Research Council (NRC 1957) identified deep geologic isolation in salt as a most desirable disposal mode for radioactive waste. Experiments conducted on salt mines revealed that there were no technical difficulties with waste disposal in salt (NRC 1984). The Carlsbad site was selected by the DOE because the deep salt beds located there are expected to provide the necessary stability for waste disposal. The site and the region surrounding it had been studied for many years, and mineral exploration of both potash and hydrocarbon deposits provided additional knowledge regarding the geology of the region. The U.S. Geological Survey and other agencies assisted DOE in identifying the New Mexico location for the repository. The salt deposit at this site, known as the Salado Formation, is a minimum of 2,000 ft (610 m) thick and located at a depth of 1,000-2,000 ft (305-610 m) (Fig. 1).

Salt allows significant deformation without fracturing. The Salado Formation is regionally extensive, and includes continuous beds of salt without complicated structures. The DOE identified the following four advantages of the site:

1. The salt deposit is in a stable geological area with little seismic activity, assuring the stability of a waste repository for thousands of years.
2. Salt deposits indicate the absence of flowing fresh water which could move waste to the surface. Water, if it had been or were present, would have dissolved the salt beds.
3. Salt is relatively easy to mine.
4. Rock salt exhibits a characteristic mechanical behavior, creep, that makes it an excellent host for waste isolation. In response to excavation-induced stress changes, salt slowly flows (or creeps), to close the mined openings. Creep closure starts immediately and continues until the salt has regained its original density and stress distribution. Salt formations tend to slowly and progressively fill mined areas and safely seal radioactive waste from the environment.

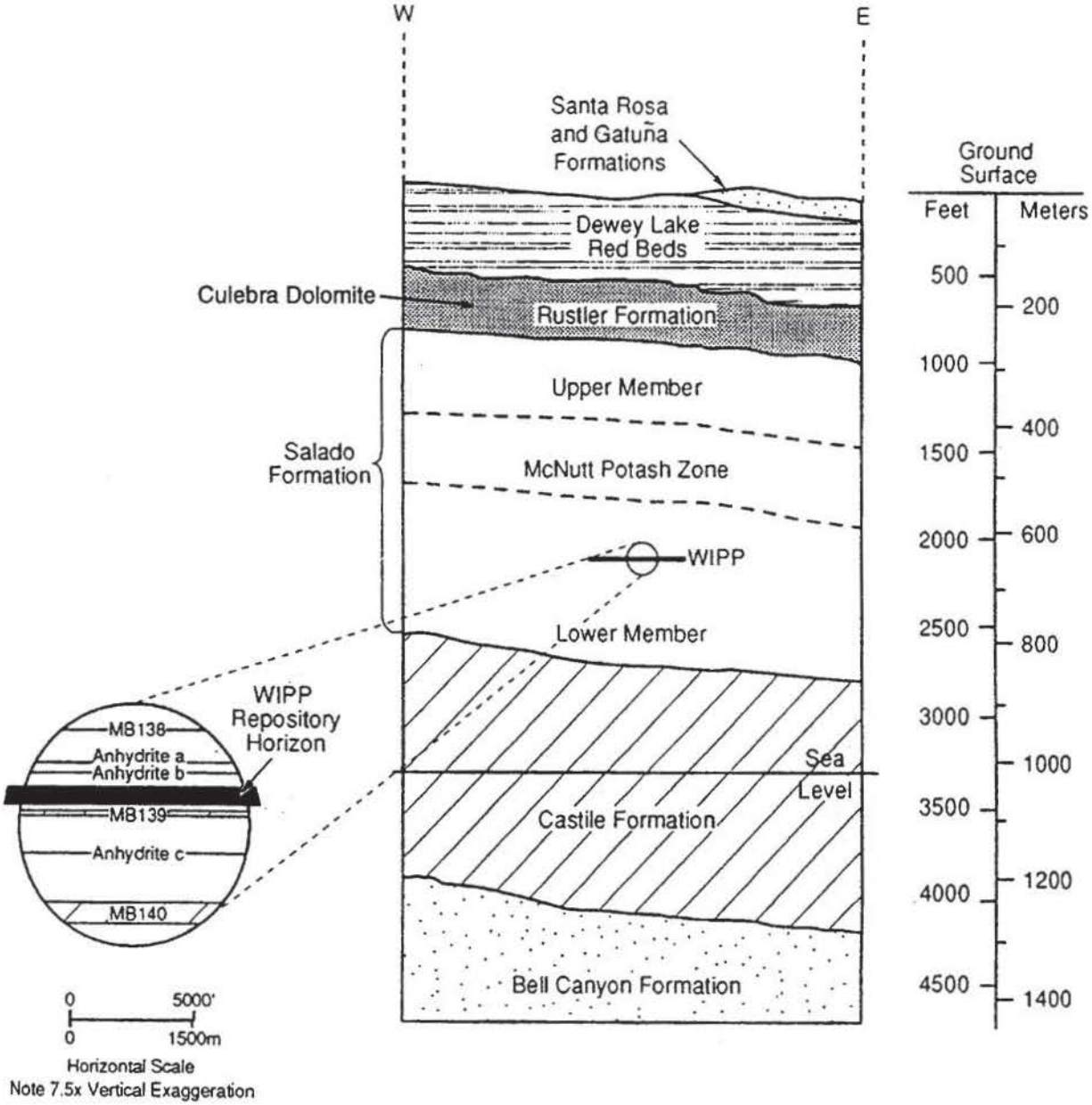

Fig. 1. WIPP Repository and local stratigraphy.

Geological data were collected from the WIPP site and surrounding area to evaluate its suitability as a radioactive waste repository. These data were collected principally by the DOE; the DOE's predecessor agencies; the U.S. Geological Survey; the New Mexico Bureau of Mines and Mineral Resources; and private organizations engaged in natural resource exploration and extraction. The DOE analyzed the data and has stated that the site is suitable for long-term isolation of radioactive waste.

The geology of the WIPP site has specific advantages identified by the DOE against potentially adverse environmental impacts. At the depth of the WIPP repository, the salt will slowly encapsulate the buried waste in the stable rock. Salt rock also shields radioactivity, providing a protection similar to that of concrete. Waste placed in the excavation at the WIPP is expected to be encapsulated and all waste-filled spaces closed over a period of 75-200 years. The waste disposal depth of 2,150 ft (650 m) is close enough to the surface to make access reasonable.

Subsequent to the investigation of the subsurface geology, the DOE selected the Salado Formation as the site of the WIPP repository for the following reasons:

1. The Salado halite units have low permeability to fluid flow, which impedes groundwater flow into and out of the repository;
2. It is regionally widespread;
3. It includes continuous halite beds without complicated structure;
4. It is deep with little potential for dissolution;
5. It is close enough to the surface that access is reasonable; and
6. It is largely free of mobile groundwater, as compared to existing mines and other potential repository sites.

Another of the favorable aspects of subsurface geology at the WIPP site is that the groundwater hydrology in the immediate proximity is characterized by geologic strata with low transmissivity and low hydrologic gradients.

SUBSURFACE GEOLOGY

The WIPP site is located in the northern portion of the Delaware Basin, a structural basin underlying present-day southeastern New Mexico and western Texas, and containing a thick sequence of sandstones, shales, carbonates, and evaporites. At the repository depth of 2,150 ft (650 m), the natural rock is of the Permian age. The

sediments accumulated during the Permian period represent the thickest portion of the sequence in the northern Delaware Basin and are divided into four series. From oldest to youngest, these series are: the Wolfcampian, Leonardian, Guadalupian, and Ochoan. As shown in Fig. 2, the Ochoan series is divided into four formations. From oldest to youngest, these formations are: Castile, Salado, Rustler, and Dewey Lake.

Salado formation

This massive bedded salt formation, predominately halite (sodium chloride), is thick and laterally extensive. The Salado formation is approximately 530 to 610 m (1,740 to 2,000 ft) thick in the WIPP site area, and the repository is located in the thickest part. The Salado formation is comprised of three members. From oldest to youngest, these are: Lower Member, McNutt Potash Member, and Upper Member. The WIPP repository is located in the Lower Member. The Salado formation contains many distinctive and laterally continuous layers composed mostly of anhydrite (a potassium-magnesium-calcium sulfate mineral). These layers have been designated by geologists as "marker beds" and numbered to designate vertical position within the Salado Formation.

Castile formation

This formation directly underlies the Salado Formation and comprises the base of the Ochoan Series (Fig. 2). It is found 244 m (800 ft) below the level of the repository. The Castile Formation near the WIPP typically contains three relatively thick anhydrite/carbonate units and two thick halite units. The thickness of the Castile varies regionally as well as locally beneath the WIPP, and there is considerable evidence from borehole data and geophysical surveys that the units of the Castile are deformed. The more brittle anhydrite units of the Castile are probably fractured, and the fracture zones are relatively permeable and act as zones for accumulation of brine originating in the Castile. The Castile is exposed at the surface over a considerable area along the western side of the Delaware Basin. In the eastern part of the basin, it is approximately 430 to 460 m (1,400 to 1,500 ft) thick. At the northern boundary of the WIPP, the Castile's thickness has been measured at 301 m (989 ft).

Bell Canyon formation

The Bell Canyon Formation underlies the Castle Formation and is the uppermost formation of the Guadalupian Series. Near the WIPP, the Bell Canyon is comprised

SYSTEM	SERIES	GROUP	FORMATION	MEMBER	DEPTH AT WIPP WASTE SHAFT meters (feet)
RECENT	RECENT		SURFICIAL DEPOSITS		
QUATER-NARY	PLEISTO-CENE		MESCALERO CALICHE		
			GATUNA		
TRIASSIC		DOCKUM	SANTA ROSA		30 (97)
PERMIAN	OCHOAN		DEWEY LAKE		164 (538)
			RUSTLER	Forty-niner	182 (596)
				Magenta Dolomite	189 (621)
				Tamarisk	215 (707)
				Culebra Dolomite	222 (729)
				lower unnamed	257 (844)
			SALADO	upper	409 (1,343)
				McNutt Potash	526 (1,727)
				lower WIPP	655 (2,150)
			CASTILE		~810 (2,650)
	GUADALUPIAN	DELAWARE MOUNTAIN	BELL CANYON		~1,200 (4,000)
			CHERRY CANYON		~1,550 (5,100)
			BRUSHY CANYON		~1,900 (6,200)

Fig. 2. Regional geologic column.

of a layered sequence of sandstones, shales, siltstones, and limestones approximately 300 m (1,000 ft) or more in thickness. It is the uppermost target of hydrocarbon exploration in the local area and is known from outcrops on the west side of the Delaware Basin and from oil and gas exploration boreholes.

Rustler formation

The Rustler Formation directly overlies the Salado Formation and contains five members (Fig. 2). From the base of the Rustler, these member are: Los Medanos Member (formerly referred to as the unnamed lower member), Culebra Member, Tamarisk Member, Magenta Member, and Forty-niner Member. The Culebra and Magenta Members are gypsum-bearing dolomites containing numerous cavities, fractures, and silty zones. The other three members contain various amounts of anhydrite, siltstone, claystone and halite. The Rustler is the youngest (uppermost) formation in the Delaware Basin that primarily contains evaporite deposits. In the WIPP region, the Rustler can be 152 m (500 ft) thick, although it ranges from 91 to 107 m (300 to 350 ft) thick within the WIPP boundary.

Dewey Lake formation

This formation overlies the Rustler Formation at the WIPP. Consisting largely of reddish-brown siltstones and claystones with lesser amounts of sandstone, the Dewey Lake Formation is about 30 to 170 m (100 to 560 ft) thick in the vicinity of the WIPP.

Santa Rosa formation

This formation of Triassic Age, also called the Dockum Group, overlies the Dewey Lake Formation. Characterized by the light reddish-brown sandstones and conglomerates, the Santa Rosa Formation is anywhere between thin to absent within the WIPP site boundaries, but is thicker to the east.

Gatuna formation

This formation overlies the Santa Rosa Formation and is somewhat similar in lithology and color, although the Gatuna is characterized by a wide range of

lithologies (coarse conglomerates to gypsum-bearing claystones). The Gatuna is Pleistocene in age, based on the 600,000-year old volcanic ash layer in the Upper Gatuna.

FACILITIES CONSTRUCTED AT THE WIPP

The major construction activities at the WIPP occurred between 1981 and 1990, and the facility accepted its first shipment of Transuranic (TRU) wastes in March 1999. Underground facilities were excavated 655 m (2,150 ft) beneath the surface of the land and include: four shafts; the waste disposal area; an experimental area (now closed); an equipment and maintenance area; and connecting tunnels. The DOE has also excavated the first and second of eight planned panels (designated as Panels 1 and 2) as shown in Fig. 3. Panel 1 has received wastes.

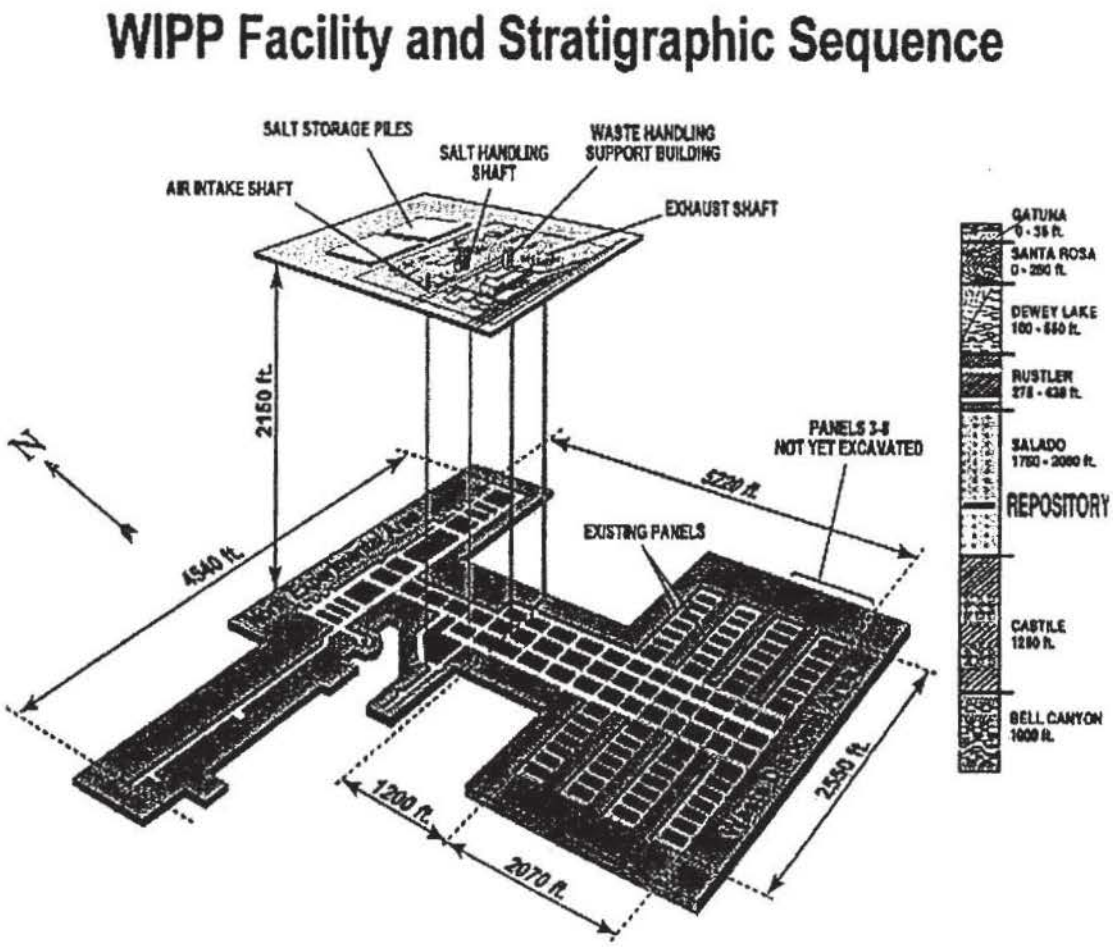

Fig. 3. WIPP facility and stratigraphic sequence.

Each panel is expected to take five years to mine, fill, and close. In addition, panel-equivalents 9 and 10 in Fig. 3 are located in the north-south mine access ways and are calculated to be required to complete the burial of the 1.75×10^5 m^3 (6.2×10^6 ft^3) of TRU waste permissible under the Land Withdrawal Act (LWA). All panels consist of seven waste disposal rooms, each about 91 m (300 ft) long, 10 m (33 ft) wide, and 4 m (13 ft) high. Pillars between rooms are 30 m (100 ft) wide.

A number of surface facilities have been constructed. The principal surface structure at the WIPP is the Waste Handling Building (WHB) where TRU wastes are unloaded from their transportation containers and transferred to the underground disposal area through the Waste Shaft. The WHB contains four functional areas: 1) the Contact Handled (CH) TRU waste handling area; 2) the Remote Handled (RH) TRU waste handling area; 3) the WHB support area; and 4) the Waste Shaft.

Other WIPP surface facilities include the hoist houses; Support Building; Guard and Security Building; Water Pump House; Transuranic Package Transporter, Model 2 (TRUPACT-II) Maintenance Facility; Training Building; office trailers; Exhaust Filter Building; warehouse and shops; Engineering Building; Core Storage Building; and the Safety and Emergency Services Building.

The underground support facilities include those needed to service and maintain equipment for excavation and disposal operations; monitor for contamination; and allow limited decontamination of personnel and equipment, if necessary. All underground facilities are inspected by the Mine Safety and Health Administration.

Waste Handling Building (WHB)–container storage unit

This building is the surface facility where TRU handling activities will take place. The WHB has a total area of approximately 84,000 ft^2 (7,804 m^2), of which 33,175 ft^2 (3,082 m^2) are designated for the waste handling and container storage of CH TRU mixed waste. The concrete floors are sealed with a coating that makes them impervious to the chemicals and facilitates decontamination if necessary.

The vehicles used to transport TRU mixed waste containers will be received through one of three air-lock entries to the CH Bay of the WHB Unit. The WHB heating, ventilation, and air conditioning system maintains the interior of the WHB at a pressure lower than the ambient atmosphere to ensure that air flows into the WHB, preventing the inadvertent release of radioactive constituents as the result of

a contamination event. The doors at each end of the air lock are interlocked to prevent both from opening simultaneously and equalizing CH Bay pressure with outside atmospheric pressure.

The waste containers are visually inspected for physical damage (e.g., severe rusting, apparent structural defects, signs of pressurization) and leakage to ensure that they are in good condition prior to storage. Waste containers are also checked for external surface contamination. If a primary waste container is not in good condition, the DOE will overpack the container.

Parking area container storage unit–parking area unit

The parking area south of the WHB is to be used for storage of waste containers within sealed shipping containers awaiting unloading. The Parking Area Unit provides storage space for 12 loaded containers, corresponding to 1,591 ft^3 (45 m^3) of CH TRU mixed waste. Secondary containment and protection of the waste containers from standing liquid are provided by the transportation containers. Wastes placed in the Parking Area Unit will remain sealed in their TRUPACT-II transportation containers at all times while in this area.

CONTAINER MANAGEMENT PRACTICES

Containers are to be managed in a specified manner that does not result in spills or leaks. Containers are required to be closed at all times, unless waste is being placed in the container or removed. Because containers at the WIPP contain radioactive waste, safety concerns require that containers be continuously vented to obviate the buildup of gases within the container. These gases could result from radiolysis, which is the breakdown of moisture by radiation. The vents are filtered to enable any potential generated gas to escape while particulate matter is retained. Derived waste containers are kept closed at all times unless waste is being added or removed.

Containers with residual liquids

Defense production facilities are prohibited from shipping liquid wastes in the containers sent to the WIPP. In no case is the total residual liquid allowed to equal or exceed 1% (by volume) of the waste container. Consequently, calculations made to determine the secondary containment as required by regulations are based on

10% of 1% of the volume of the containers, or 1% of the largest container, whichever is greater.

Description of containers

Waste containers are to be in good condition prior to shipment from the generator sites, i.e., containers will be of high integrity, intact, and free of surface contamination above established limits. This condition is to be verified upon receipt of the waste at WIPP. Containers are vented through filters, allowing any gases that are generated by radiolytic and microbial processes within a waste container to escape, thereby preventing over-pressurization or development of conditions within the container that would lead to the development of ignitable, corrosive, reactive, or other characteristic wastes.

The volatile organic compounds (VOC) in the headspace of waste containers are limited to maximum allowable VOC room-averaged headspace concentration limits specified in the permit. There are no maximum allowable headspace gas concentration limits for individual containers, as some containers can exceed these values as long as container headspace averages in a disposal room do not.

Containers for CH TRU mixed waste will be either 55-gal (208-L) drums arranged singly in 7-packs; 85-gal (321-L) drums arranged singly in 4-packs; 100-gallon drums, arranged singly or as three-packs; ten-drum overpacks (TDOP) either as overpacks or direct-loaded; or standard waste boxes (SWBs). Following is a summary description for each container type.

Standard 55-gallon drums: These drums meet the requirements for U.S. Department of Transportation (DOT) specification 7A regulations. A standard 55-gal (208-L) drum has a gross internal volume of 7.4 ft^3 (0.208 m^3). One or more filtered vents (as described in Permit Section M1-1d(1)) is to be installed in the drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential for pressurization. Standard 55-gal (208-L) drums are constructed of mild steel and may also contain rigid, molded polyethylene (or other compatible material) liners.

Standard Waste Boxes (SWBs): One or more filtered vents are to be installed in the standard waste box lid or body to prevent the escape of any radioactive

particulate matter and to eliminate any potential of pressurization. SWBs have an internal volume of 66.3 ft^3 (1.88 m^3).

One hundred-gallon drums: A 100-gal (379-L) drum has a gross internal volume of 13.4 ft^3 (0.39 m^3). One or more filtered vents are installed in the drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate potential pressurization. These drums are constructed of mild steel and may also contain rigid, molded polyethylene (or other compatible material) liners. These drums may be used as overpacks or may be direct-loaded.

Ten-Drum Overpack: The TDOP is a metal container, similar to a SWB, and is certified to be noncombustible. It is a welded-steel cylinder, approximately 74 in (1.9 m) high and 71 in. (1.8 m) in diameter with a gross internal capacity of 160 ft^3. The maximum loaded weight of a TDOP is limited to 6,700 lbs (3,040 kg). A bolted lid on one end is removable; sealing is accomplished by clamping a neoprene gasket between the lid and the body. Filter ports are located near the top of the TDOP. One or more filtered vents are installed in the ten-drum overpack lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential for pressurization. A TDOP may contain up to ten standard 55-gal (208-L) drums or one SWB. The TDOPs may be used to overpack drums or SWBs containing CH TRU mixed waste. The TDOP may also be direct-loaded with waste items that are too large to fit into the standard 55-gallon (208-L) drum; the 85-gallon drum; or the SWB.

Eighty-five gallon drums: The 85-gal (321-L) drum overpack is to be used primarily for overpacking contaminated 55-gal (208 L) drums at the WIPP facility. The 85-gal (321-L) drums may be direct-loaded with CH TRU-mixed waste and may be used to collect derived waste. One or more filtered vents are to be installed in the 85-gal (321-L) drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential of pressurization.

Container compatibility: All containers are made of steel, and some will contain rigid, molded polyethylene liners. Requirements to conduct compatibility studies include container materials to assure that containers are compatible with the waste.

WASTE PROCESSING STEPS AT THE WIPP

The handling and disposal of CH TRU wastes at the WIPP involves the following series of steps:

1. A waste shipment arrives at the WIPP by truck. Each truck is capable of carrying up to three TRU Packaging Transport Model IIs (TRUPACT-IIs).
2. After an initial security inspection, a radiological survey, and a shipping documentation review, the truck is parked near the WHB for additional inspection and radiological survey. A forklift is used to transfer each TRUPACT-II from the trailer, through an air lock, and into the WHB, where it is placed in an area called a TRUDOCK, which is used by workers to unload the waste from the TRUPACT IIs.
3. Radiological surveys are conducted to confirm that waste containers have not sustained damage during shipment or waste container removal.
4. At the TRUDOCK, an overhead crane is used to remove the waste containers from the TRUPACT-II and place them on a facility pallet.
5. A forklift moves the loaded facility pallet to the conveyance loading car at the waste handling shaft. The conveyance loading car is used to load the facility pallet onto the waste hoist.
6. The waste hoist descends 2,150 ft (705 m) to the WIPP repository.
7. An underground transporter pulls the loaded facility pallet off the hoist onto the trasporter bed and moves the waste to the appropriate disposal room where a forklift removes the waste containers from the facility pallet and places them in the disposal area. Containers may be stacked three high in the disposal area.
8. Bags of magnesium oxide are placed on top of the stack of containers to serve as backfill. The magnesium oxide will control the solubility of radionuclides and is an added measure of assurance for long-term repository performance.

Legal Requirements

INTRODUCTION

The Waste Isolation Pilot Plant project was authorized in 1979 (PL96-164) as a research and development activity to demonstrate the safe disposal of radioactive waste originating from the U.S. nuclear weapons program. This and several other laws and regulations have resulted in the construction and operation of WIPP as a unique facility for the disposal of transuranic (TRU) waste.

TRU waste is defined as a waste containing alpha-emitting isotopes of transuranic elements which emits more than 100 nCi/g of waste. The half-lives of the isotopes of these elements must be greater than 20 years (LWA 1992; EPA 1993).

Much of the TRU waste contains chemical constituents subject to the regulations of the Resource Conservation and Recovery Act (RCRA) and the New Mexico Hazardous Waste Act. TRU wastes that contain both chemical and radioactive waste are referred to as Mixed TRU. According to RCRA, WIPP is required to have a hazardous waste permit to receive waste containing hazardous waste constituents. The state of New Mexico has adopted the relevant RCRA regulations by reference and thus is authorized to issue hazardous waste permits. WIPP received a permit (NMED 1999) on October 27, 1999 for contact-handled (CH) waste, defined as having a surface radiation dose rate not greater than 200 mrem/h (2 mSv/h). TRU waste with a greater dose rate is defined as Remote Handled (RH) TRU Mixed Waste.

The enactment of the Land Withdrawal Act (LWA 1992) resulted in permanent withdrawal and transfer of the administration of federal land for the site from the U.S. Department of Interior to the DOE. This law mandated that the U.S. Environmental Protection Agency (EPA) certify the DOE's compliance with EPA's relevant, generally applicable environmental standards for radioactive materials. Subsequently, the EPA (1996a) issued the criteria to be used in certifying compliance. In response, the DOE provided the EPA with appropriate documents; models; and evaluations of the geology, hydrology, and climate as well as projected performance of the entire disposal system, including the mined repository, shaft seals, panel closures, borehole plugs, and mine backfill. Finally, the EPA (1998) certified that the WIPP met all of the criteria required for the disposal of TRU waste.

The LWA limited the amount and types of TRU wastes that can be emplaced at WIPP. The limits include the following:

1. The WIPP capacity is limited to 1.75×10^5 m^3 (6.2×10^6 ft^3) total TRU waste by volume.
2. No more than 5% (by volume) of RH-TRU waste may have a surface dose rate in excess of 100 rem/h (1 μSv/h).
3. No RH-TRU waste may have a surface dose rate in excess of 1,000 rem/h (10 Sv/h).
4. RH-TRU waste containers shall not exceed 23 Ci/L (851 GBq/L) maximum activity level averaged over the volume of the container.
5. The total radioactivity of RH-TRU waste shall not exceed 5.1 MCi (188.7 PBq).
6. Of the allowed waste disposal volume of 1.75×10^5 m^3 (6.2×10^6 ft^3), the Consultation and Cooperation Agreement with the State of New Mexico limits the volume of RH-TRU waste to 7,080 m^3 (250,000 ft^3).

The 41 km^2 (16 mi^2) area under DOE's jurisdiction at WIPP is deemed sufficient to ensure that at least 1.6 km (1 mi) of intact salt exists laterally between the waste disposal area and the accessible environment, and also to ensure that no permanent residences will be established in close proximity to the facility.

EPA'S CRITERIA FOR WIPP CERTIFICATION

Criteria for certification and recertification of WIPP were published in final form by the EPA (1996a). These criteria were detailed and contained specific requirements. In its regulations, EPA provided requirements not only for quality assurance and characterization but also specific requirements for expert judgement and peer review. The following are excerpts from EPA's regulations:

"§ 194.22 Quality assurance.

(a)(1) As soon as practicable after April 9, 1996, the Department shall adhere to a quality assurance program that implements the requirements of ASME NQA-1-1989 edition, ASME NQA-2a-1990 addenda, part 2.7, to ASME NQA-2-1989 edition, and ASME NQA-3-1989 edition (excluding Section 2.1 (b) and (c), and Section 17.1). (Incorporation by reference as specified in § 194.5.)
(2) Any compliance application shall include information which demonstrates that the quality assurance program required pursuant to paragraph (a)(1) of this section

has been established and executed for:

(i) Waste characterization activities and assumptions;

(ii) Environmental monitoring, monitoring of the performance of the disposal system, and sampling and analysis activities;

(iii) Field measurements of geologic factors, ground water, meteorologic, and topographic characteristics;

(iv) Computations, computer codes, models and methods used to demonstrate compliance with the disposal regulations in accordance with the provisions of this part;

(v) Procedures for implementation of expert judgment elicitation used to support applications for certification or re-certification of compliance;

(vi) Design of the disposal system and actions taken to ensure compliance with design specifications;

(vii) The collection of data and information used to support compliance application(s); and

(viii) Other systems, structures, components, and activities important to the containment of waste in the disposal system.

(b) Any compliance application shall include information which demonstrates that data and information collected prior to the implementation of the quality assurance program required pursuant to paragraph (a)(1) of this section have been qualified in accordance with an alternate methodology, approved by the Administrator or the Administrator's authorized representative, that employs one or more of the following methods: Peer review, conducted in a manner that is compatible with NUREG–1297, "Peer Review for High-Level Nuclear Waste Repositories," published February 1988 (incorporation by reference as specified in § 194.5); corroborating data; confirmatory testing; or a quality assurance program that is equivalent in effect to ASME NQA-1-1989 edition, ASME NQA-2a-1990 addenda, part 2.7, to ASME NQA-2-1989 edition, and ASME NQA-3-1989 edition (excluding Section 2.1 (b) and (c) and Section 17.1). (Incorporation by reference as specified in § 194.5.)

(c) Any compliance application shall provide, to the extent practicable, information which describes how all data used to support the compliance application have been assessed for their quality characteristics, including:

(1) Data accuracy, i.e., the degree to which data agree with an accepted reference or true value;

(2) Date prevision, i.e., a measure of the mutual agreement between comparable data gathered or developed under similar conditions expressed in terms of a standard deviation;

(3) Data representativeness, i.e., the degree to which data accurately and precisely represent a characteristic of a population, a parameter, variations at a sampling point, or environmental conditions;
(4) Data completeness, i.e., a measure of the amount of valid data obtained compared to the amount that was expected; and
(5) Data comparability, i.e., a measure of the confidence with which one data set can be compared to another.
(d) Any compliance application shall provide information which demonstrates how all data are qualified for use in the demonstration of compliance.
(e) The Administrator will verify appropriate execution of quality assurance programs through inspections, record reviews and record keeping requirements, which may include, but may not be limited to, surveillance, audits and management systems reviews."

"§ 194.24 Waste characterization.

(a) Any compliance application shall describe the chemical, radiological and physical composition of all existing waste proposed for disposal in the disposal system. To the extent practicable, any compliance application shall also describe the chemical, radiological and physical composition of to-be-generated waste proposed for disposal in the disposal system. These descriptions shall include a list of waste components and their approximate quantities in the waste. This list may be derived from process knowledge, current non-destructive examination/assay, or other information and methods.
(b) The Department shall submit in the compliance certification application the results of an analysis which substantiates:
(1) That all waste characteristics influencing containment of waste in the disposal system have been identified and assessed for their impact on disposal system performance. The characteristics to be analyzed shall include, but shall not be limited to: Solubility, formation of colloidal suspensions containing radionuclides; production of gas from the waste; shear strength compactability; and other waste-related inputs into the computer models that are used in the performance assessment.
(2) That all waste components influencing the waste characteristics identified in paragraph (b)(1) of this section have been identified and assessed for their impact on disposal system performance. The components to be analyzed shall include, but shall not be limited to: metals, cellulosics; chelating agents; water and other liquids; and activity in curies of each isotope of the radionuclides present.
(3) Any decision to exclude consideration of any waste characteristic or waste component because such characteristic or component is not expected to

significantly influence the containment of the waste in the disposal system.
(c) For each waste component identified and assessed pursuant to paragraph (b) of this section, the Department shall specify the limiting value (expressed as an upper or lower limit of mass, volume, curies, concentration, etc.), and the associated uncertainty (i.e., margin of error) for each limiting value, of the total inventory of such waste proposed for disposal in the disposal system. Any compliance application shall:
(1) Demonstrate that, for the total inventory of waste proposed for disposal in the disposal system, WIPP complies with the numeric requirements of § 194.34 and § 194.55 for the upper or lower limits (including the associated uncertainties), as appropriate, for each waste component identified in paragraph (b)(2) of this section, and for the plausible combinations of upper and lower limits of such waste components that would result in the greatest estimated release.
(2) Identify and describe the method(s) used to quantify the limits of waste components identified in paragraph (b)(2) of this section.
(3) Provide information which demonstrates that the use of process knowledge to quantify components in waste for disposal conforms with the quality assurance requirements found in § 194.22.
(4) Provide information which demonstrates that a system of controls has been and will continue to be implemented to confirm that the total amount of each waste component that will be emplaced in the disposal system will not exceed the upper limiting value or fall below the lower limiting value described in the introductory text of paragraph (c) of this section. The system of controls shall include, but shall not be limited to: Measurement; sampling; chain of custody records; record keeping systems; waste loading schemes used; and other documentation.
(5) Identify and describe such controls delineated in paragraph (c)(4) of this section and confirm that they are applied in accordance with the quality assurance requirements found in § 194.22.
(d) The Department shall include a waste loading scheme in any compliance application, or else performance assessments conducted pursuant to § 194.32 and compliance assessments conducted pursuant to § 194.54 shall assume random placement of waste in the disposal system.
(e) Waste may be emplaced in the disposal system only if the emplaced components of such waste will not cause:
(1) The total quantity of waste in the disposal system to exceed the upper limiting value, including the associated uncertainty, described in the introductory text to paragraph (c) of this section; or
(2) The total quantity of waste that will have been emplaced in the disposal system, prior to closure, to fall below the lower limiting value, including the associated uncertainty, described in the introductory text to paragraph (c) of this section.

(f) Waste emplacement shall conform to the assumed waste loading conditions, if any, used in performance assessments conducted pursuant to § 194.32 and compliance assessments conducted pursuant to § 194.54.
(g) The Department shall demonstrate in any compliance application that the total inventory of waste emplaced in the disposal system complies with the limitations on transuranic waste disposal described in the WIPP LWA.
(h) The Administrator will use inspections and records reviews, such as audits, to verify compliance with this section."

"§ 194.26 Expert judgment.

(a) Expert judgment, by an individual expert or panel of experts, may be used to support any compliance application, provided that expert judgment does not substitute for information that could reasonably be obtained through data collection or experimentation.
(b) Any compliance application shall:
(1) Identify any expert judgments used to support the application and shall identify experts (by name and employer) involved in any expert judgment elicitation processes used to support the application.
(2) Describe the process of eliciting expert judgment, and document the results of expert judgment elicitation processes and the reasoning behind those results. Documentation of interviews used to elicit judgments from experts, the questions or issues presented for elicitation of expert judgment, background information provided to experts, and deliberations and formal interactions among experts shall be provided. The opinions of all experts involved in each elicitation process shall be provided whether the opinions are used to support compliance applications or not.
(3) Provide documentation that the following restrictions and guidelines have been applied to any selection of individuals used to elicit expert judgments:
(i) Individuals who are members of the team of investigators requesting the judgment or the team of investigators who will use the judgment were not selected; and
(ii) Individuals who maintain, at any organizational level, a supervisory role or who are supervised by those who will utilize the judgment were not selected.
(4) Provide information which demonstrates that:
(i) The expertise of any individual involved in expert judgment elicitation comports with the level of knowledge required by the questions or issues presented to that individual; and
(ii) The expertise of any expert panel, as a whole, involved in expert judgment

elicitation comports with the level and variety of knowledge required by the questions or issues presented to that panel.
(5) Explain the relationship among the information and issues presented to experts prior to the elicitation process, the elicited judgment of any expert panel or individual, and the purpose for which the expert judgment is being used in compliance application(s).
(6) Provide documentation that the initial purpose for which expert judgment was intended, as presented to the expert panel, is consistent with the purpose for which this judgment was used in compliance application(s).
(7) Provide documentation that the following restrictions and guidelines have been applied in eliciting expert judgment:
(i) At least five individuals shall be used in any expert elicitation process, unless there is a lack of unavailability of experts and a documented rationale is provided that explains why fewer than five individuals were selected.
(ii) At least two-thirds of the experts involved in an elicitation shall consist of individuals who are not employed directly by the Department or by the Department's contractors, unless the Department can demonstrate and document that there is a lack or unavailability of qualified independent experts. If so demonstrated, at least one-third of the experts involved in an elicitation shall consist of individuals who are not employed directly by the Department or by the Department's contractors.
(c) The public shall be afforded a reasonable opportunity to present its scientific and technical views to expert panels as input to any expert elicitation process."

"§ 194.27 Peer review.

(a) Any compliance application shall include documentation of peer review that has been conducted, in a manner required by this section, for:
(1) Conceptual models selected and developed by the Department;
(2) Waste characterization analyses as required in § 194.24(b); and
(3) Engineered barrier evaluation as required in § 194.44.
(b) Peer review processes required in paragraph (a) of this section, and conducted subsequent to the promulgation of this part, shall be conducted in a manner that is compatible with NUREG-1297, "Peer Review for High-Level Nuclear Waste Repositories," published February 1988. (Incorporation by reference as specified in § 194.5.)
(c) Any compliance application shall:
(1) Include information that demonstrates that peer review processes required in paragraph (a) of this section, and conducted prior to the implementation of the

promulgation of this part, were conducted in accordance with an alternate process substantially equivalent in effect to NUREG-1297 and approved by the Administrator or the Administrator's authorized representative; and
(2) Document any peer review processes conducted in addition to those required pursuant to paragraph (a) of this section. Such documentation shall include formal requests, from the Department to outside review groups or individuals, to review or comment on any information used to support compliance applications, and the responses from such groups or individuals."

The packaging of waste at the originating sites; transport to the site; transport vehicles; and disposal of heat-generating waste are beyond the scope of this study and are not dealt with in this report.

The health and safety consequences of the postulated repository failure mechanisms appear to be so minimal that simplifications in design may be justified, and cost-effectiveness studies should be carried out to determine whether they would be acceptable. However, the probability and the consequences of potentially rapid flow of brine solutions containing radionuclides, through more permeable formations, have not been completely determined. Once these have been resolved, conventional safety considerations (e.g., number of shafts and packaging of waste for highway transport) might determine the optimum design.

Relaxation of the WIPP waste acceptance criteria (e.g., elimination of the incineration of some of the waste at the Process Experimental Pilot Plant (PREPP) facility and removal of the requirement for the use of steel-case overpack of the wooden boxes) may also have minimal consequences.

EPA'S CERTIFICATION DECISION

Subsequent to the publication of the EPA's regulations on criteria for WIPP certification, DOE undertook a major effort to comply with the EPA's requirements. The result was the decision by the EPA (1998) to certify that WIPP has met the EPA's criteria. However, this certification included certain limitations and requirements. Excerpts of the EPA's certification decision are as follows:

"The EPA finds that DOE has demonstrated that the WIPP will comply with EPA's radioactive waste disposal regulations at Subparts B and C of 40 CFR Part 191.

This decision allows the WIPP to begin accepting transuranic waste for disposal, provided that other applicable environmental regulations have been met and once a 30-day Congressionally-required waiting period has elapsed. EPA's decision is based on a thorough review of information submitted by DOE, independent technical analyses, and public comments. The EPA determined that DOE met all of the applicable requirements of the WIPP compliance criteria at 40 CFR Part 194. However, DOE must meet certain conditions in order to maintain a certification for the WIPP and before shipping waste for disposal at the WIPP."

"The EPA will continue to have a role at the WIPP after this certification becomes effective. As discussed above, DOE must submit periodic reports on any activities or conditions at the WIPP that differ significantly from the information contained in the most recent compliance application. The EPA may also, at any time, request additional information from DOE regarding the WIPP. The Agency will review such information as it is received to determine whether the certification must be modified, suspended, or revoked. Such action might be warranted if, for example, significant information contained in the most recent compliance application were no longer to remain true. The certification could be modified to alter the terms or conditions of certification—for example, to add a new condition, if necessary to address new or changed activities at the WIPP. The certification could be revoked if it becomes evident in the future that the WIPP cannot or will not comply with the disposal regulations. Either modification or revocation must be conducted by rule-making, in accordance with the WIPP compliance criteria (§§ 194.65-66). Suspension may be initiated at the Administrator's discretion, in order to promptly reverse or mitigate a potential threat to public health. For instance, a suspension would take effect if, during emplacement of waste, a release from the WIPP occurred in excess of EPA's containment limits."

"In addition to reviewing annual reports from DOE regarding activities at the WIPP, EPA periodically will evaluate the WIPP's continued compliance with the WIPP compliance criteria and disposal regulations. As directed by Congress, this "recertification" will occur every five years. For recertification, DOE must submit to EPA for review the information described in the WIPP compliance criteria (although, to the extent that information submitted in previous certification applications remains valid, it can be summarized and referenced rather than resubmitted) (§ 194.14). In accordance with the WIPP compliance criteria, documentation of continued compliance will be made available in EPA's dockets, and the public will be provided at least a 30-day period in which to submit comments. The EPA's decision on recertification will be announced in the *Federal Register* (§ 194.64)."

"Notices announcing EPA inspections or audits to evaluate implementation of quality assurance ("QA") and waste characterization requirements at generator facilities will be published in the *Federal Register*. The public will have the opportunity to submit written comments on the waste characterization and QA program plans submitted by DOE. As noted above, EPA's decisions on whether to approve waste generator QA program plans and waste characterization systems of controls—and thus, to allow shipment of specific waste streams for disposal at the WIPP—will be conveyed by a letter from EPA to DOE. A copy of the letter, as well as any EPA inspection or audit reports, will be placed in EPA's docket."

"Finally, the WIPP compliance criteria provide EPA the authority to conduct inspections of activities at the WIPP and at all off-site facilities which provide information included in certification applications. (§ 194.21) The Agency expects to conduct periodic inspections, both announced and unannounced, to verify the adequacy of information relevant to certification applications. The Agency may conduct its own laboratory tests, in parallel with those conducted by DOE. The Agency also may inspect any relevant records kept by DOE, including those records required to be generated in accordance with the compliance criteria. For example, EPA intends to conduct ongoing inspections or audits at the WIPP and at waste generator sites to ensure that approved quality assurance programs are being adequately maintained and documented. The EPA plans to place inspection reports in its docket for public examination."

BRIEF WIPP CHRONOLOGY

1957 National Research Council recommended salt as host rock, Identified areas to investigate, and Identified favorable siting criteria

1974 Atomic Energy Commission selected site near Carlsbad for exploratory work

1979 Congress authorized WIPP for research and development for safe disposal of defense-generated radioactive waste

1980 DOE issued Final Environmental Impact Statement (FEIS)

1981 DOE issued Record of Decision

1981 DOE began construction of WIPP Exploratory Shaft

1985 EPA issued 40 CFR 191--radioactive waste disposal standards applicable to WIPP

1986 EPA stated facilities must comply with Resource Conservation and Recovery Act (RCRA) for disposal of mixed (hazardous and radioactive) waste

1990 New Mexico was authorized by EPA to regulate mixed waste

1990 DOE issued first Supplemental Environmental Impact Statement (SEIS)

1991 DOE submitted Parts A and B of the RCRA Permit Application to New Mexico

1992 WIPP Land Withdrawal Act permanently segregates land for WIPP and gave EPA regulatory authority to certify WIPP compliance to 40 CFR 191.

1995 DOE submitted revised RCRA Permit Application to New Mexico Environment Department

1996 EPA issued 40 CFR 194, compliance criteria in February

1996 DOE submitted 84,000 page Compliance Certification Application to EPA

1998 DOE issued SEIS II in January

1998 EPA certified WIPP ready for disposal

1998 New Mexico Environment Department issued draft hazardous waste facility permit (HWFP) for disposal of transuranic mixed waste

1999 First shipment non-mixed waste in March

1999 New Mexico Environment Department issued Hazardous Waste Facility Permit

2000 First shipment of mixed waste in September

Current Permitted Methodologies for CH TRU Wastes

INTRODUCTION

TRU waste for disposal at the WIPP is characterized to meet RCRA driven requirements; EPA characterization requirements stemming from 40 CFR Parts 191 (EPA 1993) and 194, (EPA 1998) transportation requirements; and WIPP operations and safety requirements. Only the RCRA and 40 CFR 194 requirements are subjects of this review; hence, the transportation and WIPP characterization requirements are not discussed in this report.

RCRA CH TRU WASTE CHARACTERIZATION

Waste characterization for disposal at the WIPP is conducted on a waste stream basis (i.e., waste material generated from a single process or activity that is similar in material, physical form, isotropic make-up, and hazardous constituents) and also on a container basis. Defense production facilities assign the waste stream identifier for each container of waste that is shipped. The waste designation is selected from one of three broad categories of solid wastes: Homogenous Solids, Soil/Gravel, and Debris Wastes (NMED 1999). In addition, a number of sub-categories are assigned to the wastes. Characterization and analysis methods vary for each category and sub-category of waste.

The Waste Analysis Plan (WAP), which is part of the Permit (DOE 1997), describes waste characterization activities that a TRU waste generator/storage site must complete before shipping waste to the WIPP for disposal. These activities include test methods; details of planned waste sampling and analysis processes; a description of the waste shipment screening and verification process; and a description of the quality assurance/quality control program. Before the WIPP manages, stores, or disposes of CH TRU mixed waste from a generator/storage site, the site is required to characterize waste in accordance with WAP requirements. For each container of waste destined for disposal, defense production facilities provide the WIPP operators with a written characterization summary known as a Waste Stream Profile Form (WSPF). A four-page sample is shown in Fig. 4 (NMED 1999).

WIPP WASTE STREAM PROFILE FORM

Waste Stream Profile Number: _____

Generator Site Name: _____ Technical Contact: _____

Generator Site EPA ID: _____ Technical Contact phone number: _____

Date of audit report approval by NMED: _____

Title, version number, and date of documents used for WAP certification: _____

_____

Did your facility generate this waste? ☐ Yes ☐ No

If no, provide the name and EPA ID of the original generator: _____

_____

WIPP ID: _____ Summary Category Group: _____

Waste Matrix Code Group: _____ Waste Stream Name: _____

Description from the WTWBIR: _____

_____

Defense Waste: ☐ Yes ☐ No Check one: ☐ CH ☐ RH

Number of SWBs: _____ Number of Drums: _____ Number of Canisters: _____

Batch Data Report numbers supporting this waste stream characterization: _____

List applicable EPA Hazardous Waste Codes: _____

Applicable TRUCON Content Codes: _____

Acceptable Knowledge Information

[For the following, enter supporting the documentation used (i.e., references and dates)]

Required Program Information

- Map of site: _____
- Facility mission description: _____

Fig. 4. WIPP waste stream profile form.

- Description of operations that generate waste: _____

_____

- Waste identification/categorization schemes: _____
- Types and quantities of waste generated: _____
- Correlation of waste streams generated from the same building and process, as appropriate: _____

_____

- Waste certification procedures: _____

Required Waste Stream Information

- Area(s) and building(s) from which the waste stream was generated: _____
- Waste stream volume and time period of generation: _____
- Waste generating process description for each building: _____
- Process flow diagrams: _____

_____

- Material inputs or other information identifying chemical/radionuclide content and physical waste form: _____

_____

- Which Defense Activity generated the waste: (check one)

  ☐ Weapons activities including defense inertial confinement fusion

  ☐ Naval Reactors development

  ☐ Verification and control technology

  ☐ Defense Research and development

  ☐ Defense nuclear waste and material by products management

  ☐ Defense nuclear materials production

  ☐ Defense nuclear waste and materials security and safeguards and security investigations

Supplemental Documentation

Process design documents: _____

Fig. 4. (cont'd)

Standard operating procedures: _____

Safety Analysis Reports: _____

Waste packaging logs: _____

Test plans/research project reports: _____

Site data bases: _____

Information from site personnel: _____

Standard industry documents: _____

Previous analytical data: _____

Material safety data sheets: _____

Sampling and analysis data from comparable/surrogate waste: _____

Laboratory notebooks: _____

Sampling and Analysis Information

[For the following, when applicable, enter procedure title(s), number(s), and date(s)]

Radiography: _____

Visual examination: _____

Headspace Gas Analysis

VOCs: _____

Flammable: _____

Other gases (specify): _____

Homogeneous Solids/Soils/Gravel Sample Analysis

Total metals: _____

PCBs: _____

VOCs: _____

Nonhalogenated VOCs: _____

Semi-VOCs: _____

Other (specify): _____

Waste Stream Profile Form Certification

I hereby certify that I have reviewed the information in this Waste Stream Profile Form, and it is complete and accurate to the best of my knowledge, I understand that this information will be made available to regulatory agencies and that there are significant penalties for submitting false information, including the possibility of fines and imprisonment for knowing violations.

_____	_____	_____
Signature of Site Project Manager	Printed Name and Title	Date

NOTE: (1) Use back of sheet or continuation sheets, if required.
(2) If radiography, visual examination, headspace gas analysis, and/or homogeneous solids/soils/gravel sample analysis were used to determine EPA Hazardous Waste Codes, attach signed Characterization Information Summary documenting this determination.

Fig. 4. (cont'd)

Waste characterization based on 40 CFR 194

Waste characterization as described in 40 CFR 194 (EPA 1998) requires that a system be in place to track and control the inventory of waste components to assure that limits associated with the components are not exceeded. The waste components to be tracked and controlled, and the associated limits, are set by a Performance Assessment (PA) conducted by the DOE to show that the WIPP complies with the performance criteria of 40 CFR 191(EPA 1993). The waste components and the limits, all of which are total inventory limits at repository closure, are presented in the WIPP Compliance Certification Application (CCA).

The current CH/TRU waste characterization program characterizes each container of TRU waste for each of the limited components. However, characterizing on a waste stream basis, as is done for RCRA waste characterization, is more than adequate to assure adherence to the large limits allowed at repository closure. The Performance Agreement (PA) and the Compliance Certification Application (CCA) specify no corresponding limit associated with radionuclides; however, the current CH/TRU waste characterization program also quantifies a list of specified radionuclides on a container basis.

ORIGIN OF CH TRU WASTE AND ITS ACCEPTANCE CRITERIA AT WIPP

The TRU mixed wastes that are shipped to the WIPP originate at DOE generator/storage sites and contain both radiological and hazardous waste constituents. The DOE and EPA agreed that, of the hundreds of radionuclides present within these wastes, only ten are important for the WIPP performance assessment: ^{241}Am, ^{244}Cm, ^{137}Cs, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{90}Sr, ^{233}U, and ^{234}U. Of these ten, ^{234}Sr, ^{233}U, and ^{137}Cs are important for RH but not for CH waste streams.

Major types of operations generating waste

Examples of the major types of operations that generate this waste include the following:

Production of nuclear products: This category includes reactor operation; radionuclide separation or finishing; and weapons fabrication and manufacturing. The majority of the TRU mixed wastes were generated by weapons fabrication and radionuclide separation or finishing processes. More specifically, wastes resulting from this category consist of residues from chemical processes; air and liquid filtration; casting; machining; cleaning; product quality sampling; analytical activities; and maintenance and refurbishment of equipment and facilities.

Plutonium recovery: These wastes are residues from the recovery of plutonium-contaminated molds; metals; glass; plastics; rags; salts used in electro-refining; precipitates; firebrick; soot; and filters.

Research and development: This group includes a variety of hot-cell or glovebox activities that often simulate full-scale operations described above, producing similar TRU mixed wastes. Other types of R&D projects include metallurgical research; actinide separations; process demonstrations; and chemical and physical properties determinations.

Decontamination and decommissioning: Facilities and equipment that are no longer needed or usable are decontaminated and decommissioned, resulting in TRU mixed wastes consisting of scrap materials; cleaning agents; tools; piping; filters; plexiglass; gloveboxes; concrete rubble; asphalt; cinder blocks; and other building materials. These materials are expected to be the largest category by volume of TRU mixed waste to be generated in the future.

The TRU mixed wastes that are to be shipped to the WIPP facility for disposal have been placed into waste categories based on their physical and chemical properties (Table 1). The waste generating processes can be described in five general categories:

1. Wastes (such as combustible waste) that result from cleaning and decontamination activities in which items such as towels and rags become contaminated both with hazardous waste constituents and radioactivity. In these cases, the hazardous waste and the radioactive constituent are intimately mixed, both on the rag or towel used for cleaning and as residuals on the surface of the object being cleaned. These waste forms are not homogeneous in nature; however, they are generated in a fashion that ensures that the hazardous and radioactive contaminants coexist throughout the waste matrix.
2. Wastes generated when materials which contain metals and metal ions believed to exhibit the toxicity characteristic (EPA 1996b) become contaminated with radioactivity as the result of plutonium operations (leaded rubber, some glass, and metal waste are typical examples). These materials may also become contaminated with solvents during decontamination or plutonium recovery activities.
3. A class of plutonium processes where non-metallic objects are used and become contaminated with radioactive materials. These objects are subsequently cleaned with solvents to recover plutonium. Surfaces of the objects (such as graphite, filters, and glass) are contaminated with both radioactive and hazardous constituents.
4. Waste generating processes involving foundry operations where impurities are removed from plutonium. These impurities may result in the deposition of toxicity characteristic (EPA 1996b) metals and metal ions
5. In all of the process waste categories in the second half of Table 1, the hazardous and radioactive constituents are physically mixed together as a result of the treatment process. In these wastes, the release of any portion of the waste matrix will involve both the hazardous and the radioactive waste components, because the treatment process generates a relatively homogeneous waste form.

Table 1. Summary of waste generation processes and waste forms.

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Combustibles	F001, F002, F003, D008, D019	Cloth and paper wipes are used to clean parts and wash down gloveboxes. Wood and plastic parts are removed from gloveboxes after they are cleaned. Lead may occur as shielding tape or as minor noncombustible waste in this category.	Materials such as metals may retain traces of organics left on surfaces that were cleaned. Waste may remain on the cloth and paper that was used for cleaning or for wiping up spills.
Graphite		Graphite molds, which may contain impurities of metals, are scraped and cleaned with solvents to remove the recoverable plutonium.	Surfaces may retain residual solvents. Lead may be used as shielding or may be an impurity in the graphite.
Filters	F001, F002	Filters are used to capture radioactive particulate in air streams associated with numerous plutonium operations and to filter particulate from aqueous streams.	Filter media may retain organic solvents that were present in the air or liquid streams.
Benelex® and Plexiglas®	F001, F002, D008	Materials are used in gloveboxes as neutron absorbers. The glovebox assembly often includes leaded glass. All surfaces may be wiped down with solvents to remove residual plutonium.	Surfaces may retain residual solvents from wiping operations. Leaded glass may also be present.
Firebrick and Ceramic Crucibles	F001, F002, F005, D006, D007, D008	Firebrick is used to line plutonium processing furnaces. Ceramic crucibles are used in plutonium analytical laboratories. Both may contain metals as surface contaminants.	Metals deposited during plutonium refining or analytical operations could remain as residuals on surfaces. Surfaces may retain residual solvents.
Leaded Rubber	D008	Leaded rubber includes lead oxide impregnated materials such as gloves and aprons.	The leaded rubber could potentially exhibit the toxicity characteristic.

Table 1. (cont'd)

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Metal	F001, F002, D008	Metals range from large pieces removed from equipment and structures to nuts, bolts, wire, and small parts. Many times, metal parts will be cleaned with solvents to remove residual plutonium.	Solvents may exist on the surfaces of metal parts. The metals themselves potentially exhibit the toxicity characteristic.
Glass	F001, F002, D006, D007, D008, D009	Glass includes Raschig rings removed from processing tanks, leaded glass removed from gloveboxes, and miscellaneous laboratory glassware.	Solvents may exist as residuals on glass surfaces and in empty containers. The leaded glass may exhibit the toxicity characteristic.
Inorganic Wastewater Treatment Sludge	F001-F003, D006-D009, P015	Sludge is vacuum filtered and stabilized with cement or other appropriate sorbent prior to packaging.	Traces of solvents and heavy metals may be contained in the treated sludge which is in the form of a solid dry monolith, highly viscous gel-like material, or dry crumbly solid.
Organic Liquid and Sludge	F001, F003	Organic liquids such as oils, solvents, and lathe coolants are immobilized through the use of various solidification agents or sorbent materials.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.
Solidified Liquid	F001, F003, D006, D008	Liquids that are not compatible with the primary treatment processes and have to be batched. Typically these liquids are solidified with portland or magnesium cement.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.
Inorganic Process Solids and Soil	F001, F002, F003, D008	Solids that cannot be reprocessed or process residues from tanks, firebrick fines, ash, grit, salts, metal oxides, and filter sludge. Typically solidified with portland or gypsum-based cements.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.

Table 1. (cont'd)

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Pyrochemical Salts	D007	Molten salt is used to purify plutonium and americium. After the radioactive metals are removed, the salt is discarded.	Residual metals may exist in the salt depending on impurities in the feedstock.
Cation and Anion Exchange Resins	D008	Plutonium is sorbed on resins and is eluted and precipitated.	Feed solutions may contain traces of solvents or metals depending on the preceding process.

Categories of TRU mixed waste

TRU mixed wastes from the above operations are listed by defense production facilities as belonging in one of three broad Summary Category Groups. The characterization is based on the final physical form of the wastes as follows:

Summary category group S3000—homogeneous solids: These wastes include a minimum of 50% (by volume) solid inorganic process residues such as inorganic sludge, salt waste, and pyrochemical salt waste—but exclude soil. Other waste streams are included in this Summary Category Group based on the specific waste stream types and final waste form. This Summary Category Group is expected to contain toxic metals and spent solvents.

Summary Category Group S4000—Soils/Gravel: This Category is assigned to waste streams containing at least 50% (by volume) soil and gravel. This Summary Category Group is expected to contain toxic metals and is also further categorized by the amount of debris included in the matrix.

Summary Category Group S5000—Debris Wastes: These are heterogenous wastes that are at least 50% (by volume) materials that exceed 2.36 inch (60 mm) particle size and that are manufactured objects; plant or animal matter; or natural geologic materials. Smaller particles may be considered debris if they are manufactured objects and if they do not belong to S3000 or S4000. Examples of S5000 waste include gloves; hoses; aprons; floor tile; insulation; plastic; rubber; wood; paper; cloth; and biological materials.

The most common RCRA-regulated hazardous constituents in TRU mixed waste

1. Metals and metal ions: Some of the TRU mixed waste to be emplaced in the WIPP facility contains toxic metals contained in EPA hazardous waste codes D004 through D011 (EPA 2000a). Cadmium, chromium, lead, mercury, selenium, and silver are present in discarded tools and equipment; solidified sludge; cemented

laboratory liquids; and waste from decontamination and decommissioning activities. A large percentage of the waste consists of lead-lined gloveboxes; leaded rubber gloves and aprons; lead bricks and piping; lead tape; and other lead items. Lead, because of its radiation-shielding applications, is the most prevalent toxicity-characteristic metal present.

2. Halogenated volatile organic compounds: Some of the TRU mixed waste to be emplaced in the WIPP facility contains spent halogenated volatile organic compound (VOC) solvents listed as EPA hazardous waste numbers F001 through F005 (EPA 2000a). Tetrachloroethylene; trichloroethylene; methylene chloride; carbon tetrachloride; 1,1,1-trichloroethane; and 1,1,2-trichloro-1,2,2-trifluoroethane (EPA hazardous waste codes F001 and F002) are the most prevalent halogenated organic compounds identified in TRU mixed waste that may be managed at the WIPP facility during the Disposal Phase. These compounds are commonly used to clean metal surfaces prior to plating, polishing, or fabrication; to dissolve other compounds; or as coolants. Because they are highly volatile, only small amounts typically remain on equipment after cleaning or, in the case of treated wastewater, in the sludge after clarification and flocculation. Radiolysis may also generate halogenated volatile organic compounds.

3. Non-halogenated volatile organic compounds: Xylene, methanol, and n-butanol are the most prevalent nonhalogenated VOCs in TRU mixed waste that may be managed at the WIPP facility. Like the halogenated VOCs, they are used as degreasers and solvents and are similarly volatile. The same analytical methods that are used for halogenated VOCs are used to detect the presence of nonhalogenated VOCs.

Prohibited Items

The TRU mixed waste forms describe both radioactive and hazardous characteristics exhibited by the wastes. The Permit Treatment, Storage, and Disposal Facility Waste Acceptance Criteria (TSDF-WAC) places limits on the

waste that can be shipped to the WIPP facility based on the characteristics of the waste form. The following TRU mixed wastes are prohibited at the WIPP facility:

1. Liquid waste. Residual liquid in the container in excess of what is reasonably achievable by pouring, pumping, and/or aspirating; liquid in the internal container in excess of 1 inch (2.5 cm) of liquid in the bottom of the container; or total residual liquid in any payload container (e.g., 55 gallon drum or standard waste box) in excess of 1% (by volume) of that container.
2. Pyrophoric materials, such as elemental potassium.
3. Hazardous wastes not occurring as co-contaminants with TRU wastes.
4. Wastes incompatible with backfill; seal and panel closures materials; container and packaging materials; shipping container materials; or other wastes.
5. Wastes containing explosives or compressed gases.
6. Wastes with polychlorinated biphenyl (PCB) concentration of 50ppm (50 mg/kg) or more.
7. Wastes exhibiting the characteristic of ignitability, corrosivity, or reactivity (EPA Hazardous Waste Numbers D001, D002, or D003).
8. Any waste container that does not have VOC concentration values reported for the headspace.
9. Any waste container which has not undergone either radiographic or visual examination.
10. Any waste container from a waste stream which has not been preceded by an appropriate, certified Waste Stream Profile Form.

Before accepting a container holding TRU mixed waste, WIPP operators audit the radiography or visual examination (VE) data records of the generator/storage sites to verify that the container holds no unvented compressed gas, and that residual liquid does not exceed 1% (volume) in any payload container. Radiography tapes are to be selected randomly for at least 1% of containers received at the WIPP, at which time they are reviewed and compared to radiographic data forms. If waste does not include at least 50% of any given category by volume, characterization shall be performed using the waste characterization process required for the category constituting the greatest volume of waste for that waste stream. To ensure

the integrity of the WIPP facility, waste streams identified as containing incompatible materials or materials incompatible with waste containers are not to be shipped to the WIPP unless they are treated to remove the incompatibility.

Waste generated as a result of waste container handling and processing activities at the WIPP facility are known as "derived" wastes. Because derived wastes can contain only those RCRA-regulated materials present in the waste from which they were derived, no additional characterization of the derived waste is required for disposal purposes. In other words, generator/storage site characterization data as well as knowledge of the processes at the WIPP facility will be used to identify and characterize hazardous waste and hazardous constituents in derived waste.

TRU waste, by definition, must contain 100 nCi or more of transuranic elements per gram of waste, which means that the radioactive component of the waste will always be present within the waste in significant concentrations. The TSDF-WAC limitations and restrictions are provided to ensure that any waste form received at the WIPP facility is stable and can be managed safely. One benefit of waste form restrictions— such as no liquids—is that they limit the kinds of releases that could occur to those that would be readily detectable through visual inspection (i.e., large objects that fall out of ruptured containers) or through the use of radiation monitoring—either locally or within the adjacent area—to detect materials that have escaped from containers.

Releases and spills

Some waste forms only contain radioactive contamination on the surface, because they are not the result of a treatment process or are not porous in form. These include glass, leaded rubber, metals, graphite, ceramics, firebricks, and plastics. In theory, a hazardous waste release could occur if the interiors of these materials became exposed and were involved in a release or spill. Such an occurrence is not likely during operations, because no activities are planned or anticipated that would result in the breaking of these materials to expose fresh surfaces. The WIPP facility will handle only sealed containers of waste and derived waste. The practice of handling sealed containers minimizes the opportunity for releases or spills. For the purposes of safety analysis, it was assumed that releases and spills during operations occur by either of two mechanisms: 1) surface contamination, and 2) accidents.

Regardless of how the release occurs, the nature of the waste and the processes that generated it is such that the radioactive and hazardous components are intimately mixed. A release of one without the other is not likely, except for releases of VOCs from containers. Surface contamination is the only credible source of contamination external to the containers during normal operations. Surface contamination is assumed to be caused by waste management activities at the generator site that result in the contamination of the outside of a waste container. Contamination would most likely consist of particulate matter (dirt or dust) that would be deposited during generator-site handling/loading activities. This contamination may not be detected by visible inspections. Surface contamination is monitored upon arrival at the WIPP facility through the use of swipes and radiation monitoring equipment, as specified in the WIPP Permit (NM Hazardous Waste Regulations, Title 20; NMED 1999). Detection using radioactivity is very sensitive and allows for the detection of contamination that may not be visible on the surface of the container. This exceeds the capability required by the RCRA, which is generally limited to inspections that detect only visible evidence of spills or leaks. Releases can occur from accidents, and those that occur within the waste handling process are assumed to result in the release of radioactive contaminants and VOCs. Radioactive releases are detectable using surface-sampling (swipe) techniques. The most common RCRA-regulated hazardous constituents in TRU mixed waste to be managed at the WIPP facility consist of: metals; halogenated volatile organic compounds; and nonhalogenated volatile organic compounds.

WASTE STREAM IDENTIFICATION

Waste characterization activities at generator/storage sites include the following, although not all of these techniques will be used on each container:

1. Radiography, which is an x-ray technique, to determine physical contents of containers.
2. Visual examination (VE) of opened containers as an alternative way to determine their physical contents or to verify radiography results.
3. Headspace-gas sampling to determine VOC content of gases in the void volume of the containers.
4. Sampling and analysis of waste forms that are homogeneous and can be representatively sampled to determine concentrations of hazardous waste constituents and toxicity-characteristic contaminants of waste in containers.

5. Compilation of acceptable knowledge (AK) documentation into an auditable record, including process knowledge and prior sampling and analysis data.
6. Non-destructive assay, typically segmented gamma scans (SGS) and passive/active neutron interrogation (PAN), to quantify radionuclides for 40 CFR 194 waste characterization compliance.

Auditable records allow DOE operators to conduct a systematic assessment, analysis, and evaluation of generator/storage site compliance with the WAP and the Permit. Waste analysis parameters to be characterized include confirmation of physical form; presence of toxicity characteristic contaminants; and exclusion of prohibited items. The characterization techniques used by generator/storage sites include AK, which incorporates confirmation by headspace-gas sampling and analysis; radiography; and homogeneous waste sampling and analysis. All confirmation and characterization activities are to be performed in accordance with the WAP. The analytical requirements are specified by the analytical method being used (e.g., Fourier Transform Infrared Spectroscopy (FTIRS), Gas Chromatography/Mass Spectrometry (GC/MS)).

Waste analysis parameters characterized for the 40 CFR 194 (EPA 1998) characterization program are quantity of metals; quantities of cellulosics; plastics; and rubber; quantity of free water; and a list of ten radionuclides. The characterization techniques used by generator/storage sites for these parameters also include AK and radiography as well as non-destructive assay (NDA).

Radiography

Radiography techniques have been developed by the DOE to aid in the examination and identification of containerized waste. There are specific requirements that relate to radiography methods used at respective facilities. A radiography system typically consists of: 1) an X-ray-producing device; 2) an imaging system; 3) an enclosure for radiation protection; 4) a waste container handling system; 5) an audio/video recording system; and 6) an operator control and data acquisition station.

Although these six components are required, it is expected that there will be some variation within a given system between sites. The radiography of a waste container is recorded by an audio/videotape or equivalently non-alterable media and is maintained as a non-permanent record. The estimated waste material parameter and weights should be determined by compiling an inventory of waste items, residual materials, and packaging materials. Containers whose contents prevent full examination to the extent expected for the radiography technique and waste form, are subject to visual examination.

Visual examination

As an additional quality control (QC) check on radiography, or in lieu of radiography, the waste container contents are verified directly by visual examination. The visual examination consists of a semi-quantitative and/or qualitative evaluation of the waste container contents, and is recorded on audio/videotape. Visual examination is performed on a statistically determined portion of waste containers to verify the results of radiography. This verification includes use of the Waste Matrix Code; waste material parameter weights; and the ensurance of the absence of prohibited items.

Visual examination includes describing the contents of a waste container, and estimating or measuring the weight of the contents. The description identifies the discernible waste items, residual materials, packaging materials, and waste material parameters. Estimated weights are established through the use of historically derived waste weight tables and an estimation of the waste volumes.

Headspace-gas sampling and analysis

Headspace-gas sampling is performed on waste containers that are in compliance with the container temperature equilibrium requirements (i.e., 72 h at 18°C or higher). Waste containers designated as summary category S5000 (Debris waste) are sampled for headspace gas a minimum of 142 d after packaging. Waste containers designated as Summary Categories S3000 (Homogenous solids) and

S4000 (Soil/gravel) are sampled a minimum of 225 d after packaging. This drumage criteria ensures that the drum contents have reached 90 % of steady state concentration within each layer of confinement to allow a representative sample to be taken (NMED 1999.) Two types of headspace-gas sampling protocols may be employed: 1) the manifold headspace-gas sampling protocol, and 2) the direct canister headspace-gas sampling protocol.

Once the headspace gas sample has been collected in accordance with the HWFP requirements, the sample is taken to a laboratory for analysis. The laboratory analyzes the sample using the allowable methods in the HWFP and reports the concentration of all analytes on the target analyte list. In addition, the presence of any tentatively identified compounds (TICs) observed during the analysis is reported.

Sampling and analysis of homogenous solids and soil/gravel

The methods used to collect samples of TRU mixed waste classified as homogenous solids and soil/gravel from waste containers, are designed to ensure that the samples are representative of the waste from which they are taken. A sufficient number of samples are collected to adequately represent the waste being sampled. For those waste streams defined as Summary Category Groups S3000 or S4000, debris that may also be present within these wastes need not be sampled. Samples of retrievably stored waste containers are collected using appropriate coring equipment or other EPA-approved methods to collect a representative sample. Newly-generated wastes that are sampled from a process as they are generated may be sampled using EPA-approved methods—including scoops and ladles—that are capable of collecting a representative sample.

The QC requirements for sampling homogenous solids and soil/gravel include: collecting co-located samples from cores or other sample types to determine precision; equipment blanks to verify cleanliness of the sampling and coring tools and sampling equipment; and analysis of reagent blanks to ensure that reagents, such as deionized or high pressure liquid chromatography (HPLC) water, are of sufficient quality.

Once the homogeneous solid or soil/gravel sample has been collected in accordance with the HWFP requirements, the sample is taken to a laboratory for analysis. The

laboratory analyzes the sample using the allowable methods in the HWFP and reports the concentration of all analytes on the target analyte list. In addition, the presence of any tentatively-identified compounds (TICs) observed during the analysis is reported.

Acceptable knowledge

This characterization technique incorporates confirmation by headspace-gas sampling and analysis; radiography; and homogeneous waste sampling and analysis. Both RCRA regulations and the New Mexico Hazardous Waste Management Regulations (NMED 1997) authorize the use of AK in appropriate circumstances by waste generators—or treatment, storage, or disposal facilities—to characterize hazardous waste. Acceptable knowledge is described by the EPA (EPA 1994) as an alternative to sampling and analysis; it can be used to meet all or part of the waste characterization requirements under the RCRA. AK includes a number of techniques used to characterize TRU mixed waste, such as process knowledge; records of analysis acquired prior to RCRA; and other supplemental sampling and analysis data (EPA 1994). AK is used in TRU mixed waste characterization activities in three ways:

1. To delineate TRU mixed waste streams
2. To assess if TRU mixed heterogeneous debris wastes exhibit a toxicity characteristic (NMED 1997)
3. To assess if TRU mixed wastes are listed (NMED 1997)

TRU mixed waste streams are evaluated by applicable provisions of the AK process prior to management, storage, or disposal by the Permittees at the WIPP. TRU mixed waste management AK information defines waste categorization schemes and terminology; provides a breakdown of the types and quantities of TRU mixed wastes that are generated and stored at the site; and describes how wastes are tracked and managed at the site—including historical and current operations. Information related to TRU mixed waste certification procedures and the types of documentation (e.g., waste profile forms) used to summarize AK are also provided. The amount and type of supplemental AK information required from

generator/storage sites is site-specific and cannot be mandated, but sites collect information as appropriate to support required AK information.

The AK written record includes a summary that identifies all sources of waste characterization information used to delineate the waste stream. For each TRU mixed waste stream, the generating sites compile all process information and data supporting the AK used to characterize that waste stream. The type and quantity of supporting documentation will vary by waste stream, depending on the process generating the waste and site-specific requirements imposed by the DOE.

Non-destructive assay (NDA)

Radioassay is a term used to define measurement methods for determining the radionuclide content of waste. The isotopic composition of RH-TRU waste is usually determined from documented AK and, in some cases, from measurements taken on the product material during processing at each site. NDA techniques allow an item to be assayed without altering its physical or chemical form. NDA techniques can be classified as active or passive. Passive NDA is based on the observation of spontaneously-emitted radiations created through radioactive decay of the isotopes of interest or their radioactive daughters. Most active NDA is based on the observation of gamma or neutron radiation that is emitted from a target isotope when that isotope undergoes a transformation resulting from an interaction with stimulating radiation provided by an appropriate external source.

STATISTICAL METHODS USED IN SAMPLING AND ANALYSIS

Generator/storage sites use statistical methods to: 1) select waste containers for visual inspection; 2) select retrievably-stored waste containers for totals analysis; 3) set the upper confidence limit; and 4) apply control charting for newly-generated waste stream sampling. Statistical sampling techniques are not currently employed in waste characterization activities employed for 40 CFR 194 (EPA 1999) compliance.

Selecting waste containers for visual examination

As a QC check on the radiographic examination of waste containers, a statistically-selected portion of the certified waste containers is opened and visually examined. The data from visual examination is used to verify the matrix parameter category, waste material parameter weights, and absence of prohibited items, as determined by radiography. The data obtained from the visual examination can also be used to determine— with acceptable confidence—the percentage of miscertified waste containers from the radiographic examination. Miscertified containers are those that radiography indicates meet the WIPP Waste Acceptance Criteria and Transuranic Package Transporter-II Authorized Methods for Payload Control, but visual examination indicates do not meet these criteria. Participating sites initially use an 11% miscertification rate to calculate the number of waste containers that are visually examined until a site-specific miscertification rate has been established.

The site-specific miscertification rate is applied initially to each Summary Category Group to determine the number of containers in that Summary Category Group requiring visual examination. However, a Summary Category Group-specific miscertification rate is determined when either six months have passed since radiographic characterization commenced on a given Summary Category Group or at least 50% of a given Summary Category Group has undergone radiographic characterization, whichever occurs first. The Summary Category Group is then subject to the visual examination requirements of this reevaluated Summary Category Group-specific miscertification rate to ensure that the entire Summary Category Group is appropriately characterized. The site-specific miscertification rate is reassessed annually.

Statistical sampling and analysis of homogeneous solids and soil/gravels for totals

The statistical approach for characterizing retrievably-stored homogeneous solids and soil/gravel waste using sampling and analysis relies on using acceptable knowledge to segregate waste containers into relatively homogeneous waste

streams. Once segregated by waste stream, random selection and sampling of the waste containers followed by analysis of the waste samples are performed to ensure that the resulting mean contaminant concentration provides an unbiased representation of the true mean contaminant concentration for each waste stream.

Preliminary estimates of the mean concentration and variance of each RCRA-regulated contaminant in the waste are used to determine the number of waste containers to select for sampling and analysis. The preliminary estimates are made by obtaining a preliminary number of samples from the waste stream or from previous sampling from the waste stream. Preliminary estimates are based on samples from a minimum of five waste containers. Samples collected to establish preliminary estimates that are selected, sampled, and analyzed in accordance with applicable provisions of the WAP are used as part of the required number of samples to be collected.

The calculated total number of required waste containers can then be randomly sampled and analyzed. Waste container samples from the preliminary mean and variance estimates may be counted as part of the total number of calculated required samples if and only if:

1. There is documented evidence that the waste containers for the preliminary estimate samples were selected in the same random manner as is chosen for the required samples.
2. There is documented evidence that the method of sample collection in the preliminary estimate samples were identical to the methodology to be employed for the required samples.
3. There is documented evidence that the method of sample analysis in the preliminary estimate samples was identical to the analytical methodology employed for the required samples.
4. There is documented evidence that the validation of the sample analyses in the preliminary estimate samples was comparable to the validation employed for the required samples. In addition, the validated samples results should indicate that all sample results were valid according to the analytical methodology.

Upon collection and analysis of the preliminary samples, or at any time after the preliminary samples have been analyzed, the generator/storage site may assign

hazardous waste codes to a waste stream. For waste streams with calculated upper confidence limits below the regulatory threshold, the site must collect the required number of samples if the site intends to establish that the constituent is below the regulatory threshold.

Statistical headspace gas sampling and analysis

If a waste stream meets the conditions for representative headspace gas sampling, then headspace-gas sampling of that waste stream may be done on a randomly-selected portion of containers in the waste stream. The minimum number of containers that are sampled is determined by taking an initial VOC sample from 10 randomly-selected containers. These samples are analyzed for all the target analytes.

Waste container samples from the preliminary mean and variance estimates may be counted as part of the total number of calculated required samples if and only if:

1. There is documented evidence that the waste containers for the preliminary estimate samples were selected in the same random manner as is chosen for the required samples.
2. There is documented evidence that the method of sample collection in the preliminary estimate samples were identical to the methodology to be employed for the required samples.
3. There is documented evidence that the method of sample analysis in the preliminary estimate samples were identical to the analytical methodology employed for the required samples.
4. There is documented evidence that the validation of the sample analyses in the preliminary estimate samples were comparable to the validation employed for the required samples. In addition, the validated samples results should indicate that all sample results were valid according to the analytical methodology.

The mean and standard deviation calculated after sampling n containers is then used to calculate a UCL_{90} for each of the headspace gas VOCs.

Control charting for newly-generated waste stream sampling

Significant process changes and process fluctuations associated with newly-generated waste are determined using statistical process control (SPC) charting techniques; these techniques require historical data for determining limits for indicator species, and subsequent periodic sampling to assess process behavior relative to historical limits. SPC is performed on waste prior to solidification or packaging for ease of sampling. If the limits are exceeded for any toxicity characteristic parameter, the waste stream can be recharacterized, and the characterization can be performed according to procedures required in the WAP.

A Shewhart control chart (Gilbert 1987) is a control chart for statistical means that is used for checking whether current data are consistent with past data and whether shifts or trends in means have occurred. If a current sample mean from the process lies within the limits, the process is said to be "in control," or consistent with historical data. If the current mean exceeds the limits, the process has likely changed from historical periods. Logical sets of historical data to be used for the construction of limits in this application are the data from the initial characterization of the waste stream, if available; from characterization of a different lot of the waste stream, or from a retrievably-stored waste stream of the same type from the same process. At a minimum, the logical set includes ten representative sample values collected and analyzed from the newly-generated waste stream. The data used for construction of the limits is justified. The underlying assumptions for control charts are that the data are independent and normally-distributed with constant mean μ and constant variance σ^2. The statistical tests for normality can be conducted and data transformation to normality performed, if necessary. Transformations should take place prior to any calculations that use the data.

Each limit is constructed such that there is a 90 % confidence that the true mean does not exceed a limit. One-sided control limits are used because once a waste stream has been determined to be RCRA-hazardous and the limit exceedance of interest is on the lower side—that is when the process may become nonhazardous. Likewise, once a waste stream has been determined not to be RCRA-hazardous and the limit exceedance of interest is on the upper side—that is when the process may become RCRA-hazardous. Whether or not exceeding the limit would result in a

change in the RCRA-hazardous nature of the waste stream depends on how close the observed control limits are to RCRA limits.

Current process data are collected and averaged for comparison to the control limit for the mean. The collection period and number of samples included in the average are dependent on the waste stream characteristics. A small number of samples will reflect more of the process variability and there will be more limit exceedances. If two or three samples are collected for the mean in the required annual (or batch) sampling of a relatively homogeneous waste stream, limit exceedances may not occur. If the waste stream is less homogeneous, it will be necessary to collect more samples to meet the required confidence limit. Periodically, it will be necessary to update the control limit for a process. An update that includes all historical data is performed if there is no evidence of a trend in the process or a shift in the mean for the process. If there has been a shift in the mean, only more recent data that reflect the shift are used. Control limits shall be based on at least ten data points that are representative of the process and do not exhibit outliers or a trend with time.

Characterization Approaches Proposed for RH-TRU Wastes

INTRODUCTION

The characterization program proposed by the DOE for RH-TRU wastes is a modified version of what is already approved for CH TRU wastes. The proposed characterization program is a Performance-Based Measurement System (PBMS) approach that focuses on ensuring that sufficient data is collected to meet characterization objectives. The approach allows flexibility in applying the allowable methods to collect the necessary information. This is in contrast to the CH waste characterization approach which requires, for most characterization activities, that a specific method be used to collect data from 100% of the waste.

In order to minimize potentially-large RH-TRU waste characterization costs and also to minimize worker radiation exposure to highly-radioactive RH-TRU waste containers canisters, changes to the characterization approach are necessary. Procedures that rely on AK, which in turn relies largely on process knowledge, are proposed for quantifying and tracking the important RH-TRU waste components. Proposed tracking of the waste components is based on waste stream information. When AK does not provide the necessary waste component information, sampling programs or direct measurement characterization methods (radiography, radioassay, and/or VE) will be used as appropriate. The DOE's approach allows sites to tailor their programs to lower worker exposure, while ensuring that necessary information is collected to meet characterization objectives for safely managing and disposing of the waste.

RH-TRU wastes may contain both radioactive and non-radioactive chemical components. To comply with RCRA requirements, chemical components must be identified. Three chemical constituents have a potential impact on the long-term performance of the repository. These are: 1) the amount of free water; 2) the amount of corrodible metals; and 3) the amount of cellulosics, plastics, and rubber.

The challenges for safely characterizing RH-TRU mixed wastes are substantially greater than for CH TRU wastes. The RH-TRU mixed wastes have the same physical characteristics as the CH TRU wastes (i.e., debris, homogeneous solids, and soils/gravel). However, the distinguishing difference between the two wastes is the radioactivity of relatively short-lived beta and gamma emitters (including the fission and activation products, that can have a surface dose rate of up to 5,000 times more than the largest allowable CH rate) are characteristic of RH-TRU mixed wastes. The higher external dose rates of the RH wastes necessitate additional

precautions be taken in waste management procedures. Whereas CH wastes are stored in unshielded buildings, moved using operators and forklifts, and inspected by physically viewing its condition, RH-TRU mixed wastes are typically stored in heavily shielded vaults or hot cells and managed by indirect management of the waste containers. The proposed RH-TRU mixed waste operations incorporate specially-designed equipment and shielded containers and storage areas to unload, move and store the wastes. The process is intended to minimize operator/technician exposure to the penetrating radiation associated with RH-TRU mixed wastes. The indirect interaction includes inspecting the waste using remote cameras and using specially-designed equipment and shielded containers to move the waste.

Since the volume of RH wastes to be disposed at the WIPP is less than 5% of the total CH wastes, the decision was made to place the RH waste containers in horizontal holes pre-drilled in the walls of the underground rooms where the CH wastes containers are to be stacked. Thus the RH wastes must be placed prior to stacking the CH wastes on the repository floor.

RH CHARACTERIZATION

The proposed RH characterization program (WAP) incorporates a characterization approach that relies on both AK and testing of the waste. The waste characterization proposal is based on EPA guidance published by the EPA's Office of Solid Waste and Emergency Response for a Performance-Based Measurement System (PBMS). The implementing plan (EPA 1994) outlines guiding principles for such a system and states:

"PBMS conveys what needs to be accomplished, but not prescriptively how to do it. Under a performance-based approach, EPA would specify questions to be answered by monitoring, the decisions to be supported by the data, the level of uncertainty acceptable for making the decisions, and the documentation to be generated to support the PBMS approach in the monitoring program."

The EPA further clarified the PBMS approach by stating:

"Regulatory methods are written so that they may be used as quantitative trace analytical methods to demonstrate that a waste does not contain constituents that require it to be managed as a hazardous waste. If particular RCRA applications do

not require this rigor, looser analytical criteria may be applied, provided that they satisfy the data quality requirements for the particular application. Since data quality needs are project-specific in the RCRA Program, in order to successfully perform analyses it is necessary to address data quality issues prior to initiating any analyses. Good science indicates that, at a minimum, the following questions should be asked before beginning any analyses:

1. What is the purpose of this analysis? (Why are we doing this analysis?)
2. How (for what action) is the data generated from this analysis to be used?
3. What are the data quality needs for this project, i.e. how good does the data have to be to be useful for its intended purpose (including regulatory drivers, target analytes, matrices, concentration levels, statistical confidence levels, etc.)?

CHARACTERIZATION METHODS

The characterization methods in the proposed RH WAP are AK, radiography, and VE; site specific methods are selected to ensure quality control. The RH WAP requires that AK be used in making hazardous waste determinations. Under the proposed approach, AK may also be used to determine the physical form of the waste and the absence of prohibited items. Hazardous waste determinations made using AK may be supplemented with applicable information obtained through radiography and/or VE if the AK information alone is insufficient for applying hazardous waste numbers. Testing is required to confirm the characterization that is done using AK as the sole characterization technique; this confirmation utilizes radiography and/or VE. The assignment of hazardous waste numbers by using AK does not have to be confirmed. Due to differences in site-specific AK information and the intense radiation associated with RH-TRU wastes, the process used for confirming the AK must also be site-specific. Each site is to provide confirmation on a representative sample of the waste stream.

The characterization methods in the proposed program for compliance with 40 CFR 94 requirements are AK, radioassay, radiography, and radiological survey. In this program AK is used to identify the physical form of the waste (summary category group), to quantify the important waste components (metals, cellulosics, plastics, rubber, free water)—and where feasible—to quantify the total radioactivity of waste

streams. AK may be supplemented with applicable information obtained through radioassay or radiography if the AK information alone is insufficient to meet characterization objectives.

AK refers to applying knowledge of the wastes based on the materials or processes used to generate the wastes. AK includes documented attributes of waste streams, such as chemical, physical, and radiological properties. This may include process knowledge, which relies on the generators' knowledge of the material properties associated with the waste-generating processes; the fate of those materials during and subsequent to the processes; and associated administrative controls. Process knowledge commonly includes detailed information on the waste obtained from existing waste analysis data; review of waste-generating processes; or detailed information relative to the properties of the wastes that are known due to site-specific and/or process-specific factors (e.g., material accountability and tracking systems or waste management databases may supply information on wasted isotopic composition and/or quantity of radionuclides, among other waste attributes).

Waste characterization using AK involves the compilation and evaluation of information concerning waste-generating processes or activities at a site. AK information may include previous testing data; waste generating procedures; chemical inputs to the processes; time period that the processes took place; the facilities involved; types of waste generated; and past sampling, analytical data, and hazardous waste determinations made to satisfy host state requirements. AK information may contain reference materials; process flow diagrams; personnel interviews; analytical results; hazardous waste determinations under RCRA; and packaging logs and videotapes. AK information may also include administrative controls as a basis for the absence of prohibited items in the waste.

AK is used in program activities to characterize RH-TRU wastes to the extent practicable as determined on a site-by-site basis depending upon the types of wastes being characterized and the types of data required. Hence, AK balances requirements for providing definitive characterization data of waste streams where sampling and analysis are not feasible or necessary (e.g., waste streams for which it is difficult to obtain a representative sample because of physical form and/or heterogeneous composition—including metals, glass, combustibles).

Radiography may be used for determining physical form; the absence of prohibited items; and quantifying non-radioactive waste components. Additionally,

radiography may be used on a limited basis to supplement AK in assuring that appropriate EPA hazardous waste numbers are assigned. Radiography is a nondestructive qualitative and semi-quantitative technique that involves X-ray scanning of waste containers to identify and verify container contents. When radiography data is required, representative selections of containers will be used for these measurements. However, due to the intense radiation and lead shielding associated with RH-TRU wastes, it may not be possible to image all of the waste containers using a site's radiography equipment. Therefore, those sub-populations selected according to the operational constraints associated with the radiography operations (including image quality and operator safety) may be used. To reduce waste characterization worker exposure, the RH WAP does not propose a replicate scan, as is required for radiography of CH TRU wastes. A replicate scan requires removing the container from the radiography system and then replacing it at a later time, resulting in additional exposure. Using VE as a quality control check on radiography also is not proposed in order to reduce waste characterization worker exposure.

The VE is a characterization technique of the proposed RH WAP that may be used for determining physical form and absence of prohibited items, and may be used on a limited basis to supplement AK to ensure that appropriate EPA hazardous waste numbers are assigned. The proposed RH WAP does not make any distinction between newly-generated and retrievably-stored waste for characterization (unlike the CH WAP); therefore, the RH WAP proposes to use VE as a characterization technique for any container. The proposed RH WAP requires that either a videotape (or equivalent) be made of all VE characterizations, or that dual operator signatures be documented in lieu of a tape. Use of existing videotape records (or equivalent) is permitted as it eliminates additional exposure of the waste characterization worker, while ensuring quality control.

Similar to the requirements for radiography in the proposed RH WAP, VE is not required on every container. VE on every container would result in additional exposure to the waste characterization worker and may not be needed to meet quality control supported by VE. Due to the intense radiation associated with RH-TRU waste, it may not be possible to open all of the RH-TRU waste containers for VE due to operational constraints (e.g., hot cell limitations on maximum dose rate). Therefore, subpopulations based on the VE operational constraints may be used. If VE data are being used to meet quality control, containers examined must be representatively selected. Detailed information regarding selection of a

representative container must be included in the site-specific implementation procedures. Because VE operations can produce data that are similar in type and quality to radiography, the procedures parallel those for radiography in the proposed RH WAP.

In addition to the characterization techniques required by the RH WAP, the characterization program for RH waste includes AK and radioassay techniques for determining the radionuclide content of the waste. Radioassay is a term used to define measurement methods for determining the radionuclide content of wastes, and includes both nondestructive assays (NDA) and destructive assays (i.e., radiochemistry). The isotopic composition of RH-TRU wastes is usually determined from documented AK and, in some cases, from measurements taken on the product material during processing at each site. The isotopic composition of the waste need not be determined by direct analysis or measurement of the waste unless AK is not available.

The NDA techniques allow an item to be assayed without altering its physical or chemical form. NDA techniques can be classified as active or passive. Passive NDA is based on the observation of spontaneously-emitted radiations created through radioactive decay of the isotopes of interest or their radioactive daughters. Most active NDA is based on the observation of gamma or neutron radiation that is emitted from a target isotope when that isotope undergoes a transformation resulting from an interaction with stimulating radiation provided by an appropriate, external source.

In the destructive assay technique, a representative sample is collected from the waste and physically and/or chemically processed for subsequent analysis by standard radioactivity counting methods. Radiochemical analyses are to demonstrate that sampling methods and analytical equipment used can produce results with sufficient precision and accuracy to meet disposal requirements.

Dose rate measurements can provide estimates of the radionuclides present in the waste. Measurements are taken of the containerized waste and correlated to a known isotopic inventory to provide estimated curie contents of the container. This process requires knowledge of the isotopic ratios for the waste stream. The isotopic ratios can be determined by AK or by measurement of a sample of the waste. The sample can be a smear taken on the waste or an aliquot of the waste subjected to radiochemistry.

Radiochemistry is a destructive assay technique in which a representative sample is collected from the waste and physically and/or chemically processed for subsequent analysis by standard radioactivity counting methods. Radiochemistry is most commonly used to analyze the radionuclide content of homogeneous waste forms resulting from liquids such as process sludge or other sludge waste forms. (DOE 2001 b)

COMPARISON OF THE RH WAP AND CH WAP

The RH-TRU wastes are currently prohibited at the WIPP because it has not yet been demonstrated that RH-TRU waste could be characterized in the same manner as CH TRU waste. The DOE submits that RH-TRU waste should not be characterized using the same criteria as those used for CH TRU waste; thus, there are differences between the RH WAP and CH WAP. The major differences, which reflect the Performance-based measurement system (PBMS) approach in the RH WAP, are summarized in Tables 2 through 5. In general, the proposed RH WAP requires AK, radiography, and/or VE as characterization methods for RH-TRU waste. The CH WAP requirements for each of the proposed methods has been maintained except where the specific requirement conflicts with the PBMS approach, or could lead to unnecessary additional waste characterization worker exposure. The CH WAP requires sampling and analysis to confirm AK and the application of some characterization techniques on every container. The proposed RH WAP does not require confirmatory testing, sampling, or analysis and allows for representative selection of containers for radiography and VE; thus workers are not unnecessarily exposed to the additional penetrating radiation associated withconducting confirmatory activities.

Any RH-TRU waste container that has not been characterized by AK—supplemented as necessary by radiography and/or VE—is prohibited at the WIPP facility.

Data Quality Objectives		
RH WAP Requirement	**Difference from CH WAP**	**Justification**
Determine the physical form of the waste at the Summary Category Group level • S3000: Homogeneous Solids • S4000: Soil Gravel • S5000: Debris	Only the Summary Category Group is necessary for RH-TRU waste	Evaluation of the repository modeling indicates that the amount of waste in the individual material parameter categories does not affect repository integrity. (See Appendix 1)
Determine the absence of prohibited items • Liquids (Permit Module II, Section II.C.3.a • Pyrophoric materials (Permit Module II, Section II.C.3.b) • Incompatible waste (Module II, Section II.C.3.d) • Explosives and compressed gases (Permit Module II, Section II.C.3.e) • PCBs with concentrations greater-than-or-equal-to 50 ppm (Module II, Section II.C.3.f)	None	N/A
Determine the listed and characteristic hazardous constituents in the waste • Determine if a waste is listed as specified in 20.4.1.200 NMAC (incorporating 40 CFR §261.31 and 33); assign the appropriate US EPA hazardous waste number(s); and ensure that the US EPA hazardous waste number(s) are listed in Permit Attachment O. • Determine if a waste exhibits the toxicity characteristic as specified in 20.4.1.200 NMAC (incorporating 40 CFR §261.24); assign the appropriate US EPA hazardous waste number(s); and ensure that the US EPA hazardous waste number(s) are listed in Permit Attachment 0.	None	N/A

Table 2. (cont'd)

Data Quality Objectives		
RH WAP Requirement	**Difference from CH WAP**	**Justification**
Identification of Appendix VIII constituents	Not required for RH-TRU waste	Identifying the presence of additional Appendix VIII constituents that do not overlap with the hazardous constituents identified for a characteristic or listing does not affect the integrity of the repository and is not necessary to store or dispose of the waste at WIPP.

Table 3. Differences between Proposed RH-TRU Mixed Waste Characterization Acceptable Knowledge Method and the CH TRU Mixed Waste Characterization Acceptable Knowledge Method.

Acceptable Knowledge		
RH Requirement	**Difference from CH**	**Justification**
Administrative controls for prohibited items Sites may rely on administrative controls to ensure absence of prohibited items. Sites must implement a procedure(s) which addresses the following elements associated with administrative controls: • Organization(s) responsible for compliance with administrative controls. • A description of the administrative controls used by the site to ensure that prohibited items are documented and managed in accordance with site-specific certification plans. • The oversight actions, and frequency of actions, to verify compliance with administrative controls. • On-the-job training specific to administrative control procedures. • A statement that personnel may stop work if noncompliance with administrative controls is identified. • The nonconformance and corrective action process	None	N/A
List of information necessary The Permittees shall obtain from each Department of Energy (DOE) RH-TRU waste generator/storage site (site), AK information for meeting the required DQOs in Section R-1c.	The RH WAP requires that only information necessary to meet the applicable DQO(s) be collected and maintained, rather than requiring a prescriptive list of information for all AK.	Based on the PBMS approach, only the data related to the intended purpose need be collected.

Table 3. (cont'd)

Acceptable Knowledge		
RH Requirement	**Difference from CH**	**Justification**
AK auditing The AK process and waste stream documentation must be evaluated through assessments by quality assurance organizations. Audit checklists for AK shall be used to review applicable elements based on the DQOs that are being met using AK data.	Only the information required by the site procedure, which specifies the information necessary to meet the intended DQO(s), will be subject to audit.	Based on the PBMS approach, only the data related to the intended purpose need be collected or evaluated. Each site will establish the requirements that are necessary to meet the intended DQO(s) in their procedure.
AK required for determining listed constituents AK is required to identify toxicity characteristic and listed U.S. EPA hazardous waste numbers pursuant to 20.4.1.200 NMAC (incorporating 40 CFR §§ 261.24,261.31 and 261.33). As allowed by 20.4.1.500 NMAC (incorporating 40 CFR 264.13(a)(2)), the assignment of U.S. EPA hazardous waste numbers in compliance with the generator host-state requirements is considered AK for this RH WAP.	None	N/A
Hazardous waste numbers must be applied conservatively If different sources of information indicate different hazardous wastes are present, then sites shall include all sources of information in its records and conservatively assign all appropriate U.S. EPA hazardous waste numbers.	None	N/A
Use of hazardous waste determinations made in accordance with host-state requirements as AK As allowed by 20.4.1.500 NMAC (incorporating 40 CFR 264.13(a)(2)), the assignment of U.S. EPA hazardous waste numbers in compliance with the generator host-state requirements is considered AK for this RH WAP.	This information is used as AK for CH TRU waste, but was not specifically called out in the CH WAP.	Hazardous waste determinations must be conducted in accordance with the minimum requirements of RCRA, regardless of the state in which they are made. 40 CFR 264.13(a)2 allows for the use of data developed under 40CFR Part 261, which is the process that is used to establish the hazardous waste determination in the host state.

Table 3. (cont'd)

Acceptable Knowledge		
RH Requirement	**Difference from CH**	**Justification**
Use of AK information from similar waste streams • If sites can demonstrate correlations and similarities between the CH and RH-TRU waste operations, characterization information for the CH TRU waste stream may be used to determine the physical form, U.S. EPA hazardous waste number(s), and absence of prohibited items for the RH-TRU waste stream. • If sites can demonstrate correlations and similarities between the RH- TRU waste operations at other sites, characterization information for that RH-TRU waste may be used to determine the physical form, U.S. EPA hazardous waste number(s), and absence of prohibited items for their RH-TRU waste stream.	None	N/A
Training Site personnel responsible for compiling AK, assessing AK, and resolving discrepancies associated with AK shall be qualified and trained in the following areas at a minimum: • RH WAP and the RH TSDF-WAC • State and Federal RCRA regulations associated with solid and hazardous waste characterization • The nonconformance and corrective action process • Site-specific procedures associated with waste characterization using AK	None	N/A

Table 3. (cont'd)

Acceptable Knowledge		
RH Requirement	**Difference from CH**	**Justification**
QAO: Precision The qualitative determinations, such as compiling and assessing AK documentation, do not lend themselves to statistical evaluations of precision. Therefore, precision requirements are not established for AK. However, the acceptable knowledge information is subject to audits as specified in Permit Attachment R3.	None	N/A
QAO: Accuracy The qualitative determinations, such as compiling and assessing AK documentation, do not lend themselves to statistical evaluations of accuracy. Therefore, accuracy requirements are not established for AK. However, AK must be confirmed if it is used as the sole characterization technique to meet a DQO. In addition, the AK process is subject to audits as specified in Permit Attachment R1.	Testing data are required to confirm AK if it is used as the sole characterization technique and the audit process will be used to ensure that the information was accurately collected.	Newly collected data under the WAP should not require additional confirmation. Only information brought into the program through the AK process requires confirmation and only if it is the only information used to meet one or more of the DQOs.
QAO: Completeness The AK record shall contain sufficient information to meet the DQO(s) in Section R-2 that are being supported using AK data or supplemental information must be collected. If additional AK information is part of the identified supplemental information, the additional AK information must be collected and documented to ensure AK completeness.	Only the information that is relevant to the intended DQO(s) must be 100% complete based on the site procedure.	Based on the performance-based approach, only the data related to the intended purpose need be collected.
QAO: Comparability Comparability is ensured through sites meeting the training requirements and minimum standards outlined in this RH WAP. Sites shall ensure appropriate U.S. EPA hazardous waste numbers are assigned in accordance with Permit Attachment R3 and ensure information regarding its waste is available to other sites.	None	N/A
QAO: Representativeness Representativeness will be satisfied by ensuring that the process of obtaining, evaluating, and documenting AK information is performed in accordance with the requirements established in Permit Attachment R3.	None	N/A

Table 3. (cont'd)

Acceptable Knowledge		
RH Requirement	**Difference from CH**	**Justification**
AK Confirmation If AK is used as the sole characterization method to meet a DQO, an AK confirmation program must be developed and implemented by the generator/storage site.	AK must only be confirmed if it is not supported by new testing to meet the DQO. Confirmation must be conducted on a representative sample rather than 100%.	If new testing is conducted, the results of that testing are used in addition to the AK information to meet the DQO providing an implicit confirmation of the AK information used. If no new testing is needed to meet the DQO, the AK information requires explicit confirmation with new testing data. Representative sampling meets the regulatory requirements for sampling.

Table 4. Differences between Proposed RH-TRU Mixed Waste Characterization Radiography Method and the CH TRU Mixed Waste Characterization Radiography Method.

Radiography		
RH Requirement	**Difference from CH**	**Justification**
Material parameter category weight estimation	Not required for RH-TRU waste	Evaluation of the repository modeling indicates that the integrity of the repository is not affected by conservatively bounding the material parameters in RH waste.
Requirement to use other characterization technique if contents cannot be resolved due to interference If a site operates a radiography system that is not capable of X-ray penetration or image quality sufficient to provide information to meet the DQOs, then another suitable waste characterization technique must be used (i.e., AK or VE).	None	N/A
Complete Data Form A radiography data form is also used to document the physical form(s) of the waste and the overall summary category group, the absence of prohibited items and, to a limited extent, hazardous constituents that can be correlated to physical indicators, depending on the DQOs that are being met using radiography data.	None	N/A
Videotape Operation To perform radiography, the operator scans waste container while viewing a video image. A videotape recording (or equivalent) is made of the waste container scan.	None	N/A
Independent Observation Independent observations of the video output of the radiography process shall be performed under uniform conditions and procedures.	None	N/A

Radiography		
RH Requirement	**Difference from CH**	**Justification**
Replicate scan	Not required for RH-TRU waste	Independent observations of radiography are used to meet the accuracy QAO; therefore, any additional worker exposure associated with performing a replicate scan is not necessary.
Contents Test drum is required to contain items common to the waste streams to be generated/stored at the generator/storage site.	None	N/A
Formal and On-the-job Training Although the site-specific training programs will vary to some degree, the Permittees shall require each site's program to contain the following required elements based on the DQOs that are being met using data from radiography: Formal Training 1. Project Requirements 2. State and Federal Regulations 3. Basic Principles of Radiography 4. Radiographic Image Quality 5. Radiographic Scanning Techniques 6. Application Techniques 7. Radiography of Waste Forms 8. Standards, Codes and Procedures for Radiography 9. Site-specific instruction	Training curriculum and drum are only required to contain items that are relevant to the DQO that is being met with radiography data.	Training that is not relevant to the intended purpose of radiography is unnecessary.

Table 4. (cont'd)

Radiography		
RH Requirement	**Difference from CH**	**Justification**
On-the-Job Training 1. System Operation 2. Identification of Summary Category Groups (only required if radiography data are used to support determining the physical waste form) 3. Identification of Prohibited Items (only required if radiography data are used to support determining the absence of prohibited items) 4. Identification of Physical Indicator Parameters Used for Assigning U.S. EPA Hazardous Waste Numbers (only required if radiography data are used as a supplement to AK for ensuring appropriate U.S. EPA hazardous waste numbers are assigned)		
QAO: Precision The precision of the radiography image is verified prior to use of the system through viewing and being able to distinguish an image test pattern.	No change to image test pattern requirement. Relative percent difference (RPD) calculated for CH TRU waste material parameter weights not required.	Material parameter weights are not necessary to ensure the integrity of the repository and are not measured.
QAO: Accuracy An independent observation will be conducted by comparing the contents of a radiography data form to the videotape (or equivalent) of the associated radiography scan by a qualified independent reviewer at the frequency of one per testing batch or once per day, whichever is less frequent.	Use independent observation of radiography rather than VE to ensure accuracy.	Independent observations provide assurance that accuracy is maintained without additional worker exposure during visual examination.
QAO: Completeness A videotape (or equivalent) of the radiography examination and an associated complete data form will be obtained for all waste containers subject to radiography.	None	N/A
QAO: Comparability The comparability of radiography data from different sites shall be enhanced by using standardized radiography operator qualifications that comply with this RH WAP.	None	N/A
QAO: Representativeness Representativeness for waste selected for radiography will be ensured through random container selection.	RH WAP requires radiography of representative waste container selected randomly from the population. There is no CH QAO for representativeness due to the requirement to do 100% radiography	Additional worker exposure from performing 100% radiography is not necessary if a representative waste container is selected.

Table 5. Differences between Proposed RH-TRU Mixed Waste Characterization Visual Examination Method and the CH TRU Mixed Waste Characterization Visual Examination Method.

Visual Examination		
RH Requirement	**Difference from CH**	**Justification**
Material parameter category weight estimation	Not required for RH-TRU waste	Repository modeling demonstrates that the repository integrity is not affected by conservatively bounding the material parameters in RH-TRU waste.
Complete Data Form The results of VE documented on the data form shall clearly identify the physical form(s) and the overall summary category group, the absence of prohibited items and, to a limited extent, hazardous constituents that can be correlated to physical indicators depending on the DQOs that are being met using VE data.	None	N/A
Videotape Operation The VE shall consist of a qualitative evaluation of the waste container contents, and shall be recorded on videotape (or equivalent) or, if two trained operators perform the VE a videotape (or equivalent) is not required.	None	N/A
Independent Observation Oversight functions (i.e., data validation, Permit Attachment R2) include independent review of VE data forms by a qualified VE operator other than the individual who performed the first examination.	Independent observations are required if a single operator conducts the VE.	Independent observation of the VE is necessary to meet the accuracy QAO if two operators are not used.
Representative Sample	Perform VE on representative waste containers selected randomly from the population.	20.4.1.500 NMAC (incorporating 40 CFR 264.13(a)1) requires that a representative sample be taken; any additional worker exposure associated with additional VE is not necessary if a representative waste container is selected.

Table 5. (cont'd)

Visual Examination		
RH Requirement	**Difference from CH**	**Justification**
Training Curriculum Although site-specific training programs will vary to some degree, the Permittees shall require each site's program to contain the following required elements: Form Training 1. Project Requirements 2. State and Federal Regulations 3. Application Techniques 4. Site-Specific Instruction On-the-Job Training 5. Identification of Summary Category Groups (only required if VE data are used to support determining the physical waste form) 6. Identification of Prohibited Items (only required if VE data are used to support determining the absence of prohibited items) 7. Identification of Physical Indicator Parameters Used for Assigning U.S. EPA Hazardous Waste Numbers (only required if VE data are used as	Requires the training curriculum to cover material that is relevant to the DQO that is being met using visual examination data.	Training that is not relevant to the intended purpose of VE is unnecessary.
Training Drum Contents	Training drum is required to contain items that are relevant to the DQO that is being met with visual examination data.	Training that is not relevant to the intended purpose of VE is unnecessary.

Table 5. (cont'd)

Visual Examination		
RH Requirement	**Difference from CH**	**Justification**
Training Examinations Qualification of VE operators shall, at a minimum, encompass the following requirements: 1. Successfully pass a comprehensive exam based upon training enabling objectives. The comprehensive exam will address the VE training requirements and implementation stipulated in this RH WAP. A minimum score of 80% is required to pass the exam. 2. Demonstrate capability in the presence of the appointed site VE expert.	Successfully passing a comprehensive examination is required.	Passing an examination is required because standardized VE operator qualification is used to meet the comparability QAO.
QAO: Precision Precision - The qualitative determinations, such as identifying the summary category group, made during VE do not lend themselves to statistical evaluation of precision because of the qualitative nature of the inspection. Therefore, precision requirements are not established for VE. However, the VE information is subject to the Permittees' Audit and Surveillance Program.	VE provides qualitative data, so a precision is not established. There is no QAO for VE precision in the CH WAP.	N/A
QAO: Accuracy An independent observation will be performed by comparing the contents of a VE data form to the videotape (or equivalent) of the associated examination at the frequency of one per testing batch on once per day, whichever is less frequent. In the case of VE performed by two operators, dual signatures on the data form will verify accuracy in lieu of the independent observation.	Use independent observation or dual signatures for VE to ensure accuracy. There is no QAO for VE accuracy in the CH WAP.	Independent observations or signatures of both operators performing visual examination provide assurance that accuracy is maintained.

Table 5. (cont'd)

Visual Examination		
RH Requirement	**Difference from CH**	**Justification**
QAO: Completeness A videotape (or equivalent) of the VE and an associated complete data form will be obtained for all waste containers subjected to VE. In the case of VE performed by two operators, dual signatures on the data form will verify completeness.	Videotape of the VE of dual signatures on the data form. Data forms must be fully completed. There is no QAO for VE completeness in the CH WAP.	Fully completed data forms and videotapes or dual signatures provide assurance of completeness.
QAO: Comparability The comparability of VE data from different sites shall be enhanced by using standardized VE operator qualifications that comply with this RH WAP.	Standardized training that meets the WAP is required. There is no QAO for VE comparability in the CH WAP.	Using standardized training requirements ensure that comparability is enhanced.
QAO: Representativeness Representativeness for waste selected for VE will be ensured through random container selection.	Require representative sample taken randomly from the population. There is no QAO for VE representativeness in the CH WAP.	Using a representative sample meets the regulatory requirements.

Peer Review Criteria, Findings, and Recommendations of the Review Panel

PEER REVIEW CRITERIA AND FINDINGS

The findings of the RP with respect to the review criteria are as follows:

Criterion 1

Is the draft *RCRA Class 3 Permit Modification* (DOE 2001a) optimized in format and content to facilitate the regulatory review and approval process?

Finding of the RP

The draft *RCRA Class 3 Permit Modification* (DOE 2001a) is optimized in a format to facilitate the regulatory review and approval process. Throughout the document the text has been modified to show the new information added, and there are strike-outs to show the information deleted. The Overview section includes tables showing the regulatory references and their corresponding location in the document. In addition, Table 2 lists all of the sections of the document that have been modified. However, the draft *RCRA Class 3 Permit Modification* (DOE 2001a) is lacking some information that would facilitate the regulatory review and approval process as described in the Findings to several of the Criteria.

Criterion 2

Are the parameters—for which RH-TRU waste will be analyzed—appropriate, and the rationale for the selection of these parameters adequately justified in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a)?

Finding of the RP

The draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) lists the appropriate parameters and attempts to justify the selection of these parameters in the "ITEM 2" section of the document. This section includes the characterization approach, characterization methods, and data reporting and validation requirements. Table 2-1 attempts to justify all of the modifications of CH-TRU parameters to account for RH-TRU. Table 2-2 addresses the differences for Data Quality Objectives (DQOs). Table 2-3 addresses the differences for the Acceptable Knowledge (AK) criteria. Table 2-4 addresses the differences for Radiography, and Table 2-5 addresses the differences for Visual Examination. However, some of the information is presented only as background information and is not referenced in the permit.

Criterion 3

Is the acceptability of relying on AK as the sole analysis tool to meet characterization requirements chosen in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) consistent with relevant regulations as interpreted jointly by the U.S. Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission (USNRC) (1997)?

Finding of the RP

In many cases, reliance on AK as the analysis tool to meet the waste characterization requirements listed in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) as the sole analysis tool can be consistent with the relevant regulations as interpreted by the EPA and the USNRC. There may be cases where AK is not sufficient to meet the regulatory requirements. The WIPP has proposed additional characterization methodologies in a hierarchy of methods to allow for the characterization of all wastes accepted at the WIPP that will meet the DQOs. There will be cases where AK alone is sufficient, but this will be determined on a case-by-case basis depending on the nature of the AK available.

Criterion 4

Is AK alone sufficient to meet the DQOs?

Finding of the RP

In many cases, AK alone will be sufficient to meet the DQOs. Whether or not it is sufficient will be dependent on the nature of the waste and the source and completeness of the data that constitute the AK. For example, AK for waste generated from a chemical conversion process may consist of: 1) material balance and operating data; 2) historical records of the analyses of samples of the waste; and 3) inventory and custody records. Such AK should be sufficient to meet the DQOs. The AK for a drum of scrapped equipment and other waste (not specified) from a decommissioning activity may not provide sufficient information to meet the DQOs.

Criterion 5

Does the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) make a clear distinction between characterization activities using AK versus

supplementary; confirmatory; or verification activities involving physical and other measurements?

Finding of the RP

The draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) makes a distinction between characterization activities using AK versus supplementary, confirmatory, or verification activities involving physical and other measurements. Detailed records exist at the generating sites on many waste forms that will require disposal. Depending on process knowledge and other information sources, AK can be used successfully to fully characterize wastes to meet WIPP acceptance criteria. In some cases the existing information may be insufficient to meet the characterization requirements. When this occurs, supplementary information must be developed by other means. In the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a), several characterization methods—including AK, Radiography, and Visual Examination—are described, as well as their intended use in characterization activities. However, in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a), figures such as R-2 do not provide for the use of other characterization methods should AK be insufficient.

Criterion 6

Is the application of the Performance-Based Measurement System approach consistent with the relevant EPA guidance on performance-based measurement systems?

Finding of the RP

The application of the Performance-Based Measurement System approach meets the EPA's guidance on performance-based measurement systems. The performance-based approach is designed to produce the desired results which eliminate characterization processes that do not produce information used to meet performance requirements. The DOE chose a performance-based approach to meet EPA's guidelines for RH-TRU waste. The characterization objectives for EPA requirements cover metals; residual liquids; cellulosic; plastics and rubber; total radioactivity; and surface dose rate. Baseline calculations for CH-TRU were used for comparisons to determine the relative effects of bounding assumptions regarding characterization data. The performance factors are specified in 40 CFR 191 (EPA 1993) and 40 CFR 194 (EPA 1996a). Section 40 CFR 194.24 (c)(3) of EPA

regulations allows AK and requires the QA standards—as specified in 40 CFR 194.22—to be applied to the process. Furthermore, 40 CFR 194.24 (c)(4) requires a system of controls and packaging of waste components to confirm that the total amount of each waste component falls within the performance limits. It appears that the EPA expects the performance assessment of an RH-TRU package to include uncertainty estimates, and that the actual diverse RH waste steams radionuclide contents be below the estimates.

Criterion 7

Does the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) present an RH-TRU waste characterization program that is consistent with the recommendations of the National Research Council?

Finding of the RP

The draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) presents an RH-TRU waste characterization program that is not consistent in all cases with the recommendations of the National Research Council. The draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) still includes characterization requirements which the National Research Council criticized as being self-imposed and overly conservative. The draft request presents evolutionary steps regarding characterization as site programs evolve.

Criterion 8

Does the *Waste Analysis Plan* (WAP) included in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) meet the requirements for characterizing hazardous waste?

Finding of the RP

The WAP included in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) broadly meets the requirements for characterizing hazardous waste. The RH-TRU waste analysis plan has been prepared for the management, storage, and disposal activities at the WIPP facility, to meet the requirements of the New Mexico Administrative Code (NMED 1997) that incorporates the EPA's 40 CFR 264.13 regulations. However, the WAP, as presented, is not sufficiently detailed and clear on the information that each waste-generating site must supply to the

WIPP—particularly with respect to AK (see also Findings 1 and 2). Guidance concerning the characterization of mixed, hazardous, and radioactive waste has been incorporated into the preparation of the RH WAP. This RH WAP addresses waste stream identification requirements; waste stream parameters; waste characterization and confirmatory methods; data validation; and reporting. Characterization requirements for RH-TRU mixed waste are the same regardless of waste stream designation (i.e., debris, homogeneous solids, soil/gravel) or when the waste was generated (i.e., newly generated versus retrievably stored).

Criterion 9

Does the WAP included in the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) contain excessive requirements for characterizing hazardous waste?

Finding of the RP

Although the WAP follows guidance documents for characterizing hazardous waste, DOE has interpreted the requirements quite conservatively such that various proposed characterization methods have no legal or safety basis.

Criterion 10

Is the *Notification of Proposed Change to the EPA 40 CFR Part 194 Certification of the Waste Isolation Pilot Plant* (DOE 2001b) clear and descriptive of the nature and scope of the proposed RH-TRU waste Characterization Program?

Finding of the RP

Section 2.0 "Nature and Scope" of the *Notification of Proposed Change to the EPA 40 CFR Part 194 Certification of the Waste Isolation Pilot Plant* (DOE 2001b) describes the nature and scope of the proposed RH-TRU Waste Characterization Program. Attachment C is a matrix that lists 40 CFR Part 194 requirements and the manner that the RH-TRU program complies with the requirements. Attachment D is a checklist that demonstrates how the RH-TRU program—as compared to the CH-TRU program—complies with the EPA's Compliance Application Guidelines (CAG). All items are completed as suggested by the EPA's CAG. There are no items completed differently than suggested by the CAG, and there are no open items.

Criterion 11

Is the DOE's assessment of the consequences for compliance with EPA disposal regulations clearly and adequately presented in the *Notification of Proposed Change* (DOE 2001b) document?

Finding of the RP

Consistency with EPA disposal regulations is fully demonstrated and documented in resource documents. The performance assessment conducted by Sandia National Laboratory is complete and consistent with EPA regulations in 40 CFR 191 and 40 CFR 194. Also, this conclusion is validated by the recent National Research Council's analysis of disposing RH-TRU at WIPP. The RP fully concurs with the analysis as presented.

Criterion 12

Is the significance of the change in the *Notification of Proposed Change* (DOE 2001b) clearly and adequately addressed?

Finding of the RP

The significance of the change in the *Notification of Proposed Change* (DOE 2001b) is clearly and adequately addressed in section 2.0 "Nature and Scope" and section 3.0 "New Information." Section 2.0 reviews the historical record leading to the need to submit a change to the EPA's WIPP 40 CFR 194 certification to permit the disposal of RH-TRU in the WIPP. It also summarizes the RH-TRU Waste Characterization Program that is discussed in detail in Appendix A "RH-TRU Waste Characterization Implementation Plan." Section 3.0 explains the changes in the DOE's TRU waste characterization program to accommodate RH-TRU.

Criterion 13

Are the consequences for compliance determinations clearly stated in the *Notification of Proposed Change* (DOE 2001b) document and technically justified in the *RH TRU Inventory Impact Assessment Report* (DOE 2001b)?

Finding of the RP

The consequences for compliance determinations are clearly-stated in the *Notification of Proposed Change* (DOE 2001b) document and are technically justified in the *RH TRU Inventory Impact Assessment Report* (DOE 2001b) which is Attachment B of the *Notification of Proposed Change* (DOE 2001b) document. Attachment B demonstrates by analysis that the repository performance of the WIPP would not be compromised even for large deviations from the planned inventories of both radioactive and non-radioactive waste placed in the repository.

Criterion 14

Does the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) present a viable, effective, and efficient performance-based waste characterization program?

Finding of the RP

The *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) presented meets the performance factors of the waste characterization program. Applying knowledge of the characteristics of the waste using available information minimizes additional risk and exposure due to RH-TRU. There is an overall balance in the program activities to characterize RH-TRU waste to the extent possible. The efficiencies are gained by balancing the requirements for providing definitive characterizations data of the waste streams with those circumstances where sampling and analysis are neither feasible nor necessary, given the need for the data. The AK—when used appropriately in combination with NDA/NDE—yields a viable, effective, and efficient performance-based waste characterization program. The *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) provides the sites with considerable latitude in meeting the WIPP-Waste Acceptance Criteria (WAC) requirements; it would be better if WIPP provided definitive requirements for the different sites.

Criterion 15

Does the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) clearly identify and justify the waste components to be characterized?

Finding of the RP

Comprehensive RH-TRU inventory and waste streams were identified, along with a comparison between CH and RH-TRU disposal volume projections. The waste components have been identified and justified in a general sense, but a detailed description of waste streams from the waste-generating sites is lacking. The documents fail to adequately describe the contact and communication among WIPP and the RH-TRU generators.

Criterion 16

Is the associated DQO appropriate for each waste component and consistent with the relevant guidance of the EPA?

Findings of the RP

The documents and the Project Team presentation indicate that the DOE-Carlsbad Field Office has adopted DQOs for metals; liquids; and cellulosic, plastics, and rubber (CPR) materials. The programmatic AK steps outlined in the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) are sufficient to accomplish the DQOs adopted by the DOE-Carlsbad Field Office and can be reasonably relied upon to meet the DQOs for materials received at WIPP. The DQOs are somewhat conservative but they are consistent with the NMED and EPA requirements.

The WIPP-limiting values for radiological components in RH-TRU waste are based on surface-level exposure rates. The methodologies for determining exposure levels are well established, and these levels will be measured and documented for all shipments and disposal containers. These measured values constitute one of the criteria for meeting the DQOs for RH-TRU exposure levels, and therefore, supplement AK.

Criterion 17

Is the reliance on AK as the primary method to meet DQOs and satisfy characterization objectives fully-justified?

Finding of the RP

The acceptability of relying on AK as the primary method in order to: 1) meet the DQOs; and 2) satisfy the characterization objectives, is fully justified for those RH-TRU wastes that have well-documented information regarding their generation and control. The DQOs for the WIPP facility were established using the EPA's Guidance for the DQO's Process (EPA 2000c). Furthermore, the DQOs are identified in the proposed WAP, and they reflect parameters that must be known in order to dispose of waste at the WIPP facility. The DQOs are derived from making a determination of the following waste characteristics: physical form of the waste; absence of prohibited items; and hazardous constituents in the waste. In many cases, the existing documentation would allow these DQOs to be verified with no further characterization efforts required on the part of the waste generator. If the physical form or the absence of prohibited items can not be determined from AK, then other methods (such as radiography) can be used to supplement AK in making a determination that satisfies both the DQOs and the characterization objectives.

Criterion 18

Is the acceptability of relying on AK as the sole method to meet characterization requirements and any DQOs sufficiently explained in relation to the relevant regulations—as interpreted jointly by the EPA and USNRC?

Finding of the RP

The use of AK as a sole method is not sufficiently explained or justified. The AK can be the dominant measure for determining DQOs for RCRA-regulated materials and even for meeting the DQO for radionuclide concentration limits for RH-TRU materials. The explanation of the acceptability of sole reliance on AK represents an apparent inconsistency because as explained in Finding 16 of the RP, meeting the DQOs for RH components at WIPP relies on measured radiation levels for all containers which supplant AK. Therefore, although AK can be a dominant method and sometimes a completely adequate method, it is unlikely to be the sole method.

Criterion 19

Does the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) draw a clear distinction between characterization activities using AK versus supplementary; confirmatory; or verification activities involving physical measurement?

Finding of the RP

The distinction among the characterization activities, AK, supplementary, confirmatory, or verification is inadequate in the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b), and is made particularly confusing by the definitions. All available information about the state of the waste should be used in deciding whether or not the characterization is adequate. It is inefficient to perform additional measurements unnecessarily. The AK is information that has already been obtained (such as process knowledge) before any specific WIPP RH-TRU requirements have been established and sometimes when the waste is already in a container. Supplementary information is used to fill in gaps in the required knowledge. Confirmatory and verification data determine whether the AK is reliable, but the distinction between confirmatory and verification is less clear. There are insufficient examples showing how the required information will be obtained using each of the various methods for each of the major types of waste.

Criterion 20

Does the *Notification of Proposed Change* (DOE 2001b) adequately explain and justify how AK and the WIPP Waste Information System are used to satisfy quantification and control requirements?

Finding of the RP

The *Notification of Proposed Change* (DOE 2001b) adequately explains and justifies how AK and the WIPP Waste Information System (WWIS) are used to satisfy the quantification and control requirements. The WWIS tracking and control system is currently in use in the CH-TRU waste program, and it is operating satisfactorily. To meet additional tracking and control requirements imposed on RH-TRU waste by the Land Withdrawal Act, WWIS will be modified by the addition of data fields. Each waste cannister will be assigned an identification number that will be entered into the WWIS. Characteristics such as curie content and surface dose rates (when the dose equivalent rate exceeds 100 rem/h) will be entered into WWIS to enable tracking and control for that particular container.

Criterion 21

Does the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) adequately describe a Quality Assurance program that meets or exceeds appropriate requirements?

Finding of the RP

In general, the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) describes a Quality Assurance program that addresses the appropriate requirements but lacks sufficient detail. However, to meet the WIPP WAC, the site must develop and implement a quality assurance program that addresses all the applicable requirements specified in the waste analysis plan. Sites may use AK, Radiography, and/or Visual Examination (VE) to assist in the characterization of the waste streams. Qualitative data generated by AK, Radiography, and VE are not amenable to statistical data quality analysis. Rather, these methods provide qualitative data useful for determining the Summary Category Group: EPA Hazardous Waste numbers; and the absence of prohibited items in a waste container. Quality Assurance Objectives (QAOs) complement the DQOs by defining the precision, accuracy, completeness, comparability, and representativeness for each of the characterization methods (AK, Radiography, VE) that may be used. The validation methods are appropriately described and evaluated in Attachment R3 of the *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) .

Criterion 22

Does the Plan clearly and adequately explain how the provisions of 40 CFR 194.22 (b) will be utilized in the RH-TRU waste characterization program?

Finding of the RP

Use of the provisions of 40 CFR 194.22 in waste characterization is sufficiently-explained; however, it is important for DOE-CBFO to recognize that additional amplification (similar to that provided to the RP during the peer-review meeting) may be needed. The NMED's earlier limitation of its certification to CH-TRU was clearly based on the information provided which was deemed insufficient for inclusion of RH-TRU in the permit.

Criterion 23

Does the Plan present an RH-TRU waste characterization program that is consistent with recommendations from the National Research Council's Report, *Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant* (2000; 2001)?

Finding of the RP

The RH-TRU waste characterization program is reasonably consistent with the National Research Council's Report, *Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant* (2000; 2001), including its finding of self-imposed requirements that have no legal or safety basis.

Criterion 24

Are the *Request for RCRA Class 3 Permit Modification* (DOE 2001a) and *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) consistent with the ALARA concept?

Finding of the RP

The *Request for RCRA Class 3 Permit Modification* (DOE 2001a) and *RH TRU Waste Characterization Program Implementation Plan* (DOE 2001b) are consistent with the ALARA concept. However, the reduction of worker exposure—as interpreted by the USNRC Guidance RM-30-2—is by itself not an argument for a modification, nor is it possible to use ALARA to justify repackaging in the interest of repository performance. In the proposed modification, there is no explicit explanation of why the AK-based waste characterization approach is needed to maintain repository integrity and avoid exposures. Reference is made to 40 CFR 194 and a presumption is made that if the requirements of 40 CFR 194 are met, the integrity of the repository will be maintained and such exposures will be ALARA.

Additional Findings of the RP

Finding 25

The AK is the key methodology proposed by the WIPP for characterization of RH-TRU waste. The AK can be most useful. However, its usefulness can be improved by ensuring that the stakeholders achieve a clear understanding of the basis for, and use of AK in a suite of analytical characterization tools.

Finding 26

The communication between the regulated and regulatory communities does not appear to be optimal for the efficient processing of permit modifications. It appears

that there are not sufficient free and full exchanges to keep all parties fully informed of each other's needs and accomplishments. An example of this is the apparent lack of communication regarding the advances in nondestructive testing using radiography to identify the absence of prohibited items.

Finding 27

Although there is a clear statement of the regulatory requirements for the characterization of the waste, there is no statement of the scientific requirements for such characterization upon which the regulatory requirements are based. It would, for example, be useful to know that many safety factors are already included in these requirements before discussing whether or not the requirements can be met. A failure to discuss such matters inevitably results in requirements not justified by safety as decried by the National Research Council's review panel.

Finding 28

Communication between WIPP and the waste-generating sites is not at a level to foster efficient planning and implementation of WIPP WAC.

Finding 29

The draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) has a good basic structure but lacks—in many cases—sufficient details and specificity to facilitate regulatory review.

Finding 30

Audit plans were not provided to the RP.

Finding 31

It is unclear what fraction of the RH-TRU waste has already been containerized or packaged as compared to that which is still to be generated or is stored in bulk.

Finding 32

Significant emphasis is placed on determining EPA's Hazardous Waste Numbers for either listed or characteristic wastes, which in some cases may include organic

compounds. Based on the impact study (Appendix B of the *Notification of Proposed Change* (DOE 2001b), there appears to be no impact on repository performance that depends on this identification.

Finding 33

In keeping with the National Research Council's recommendation to "think smart" good health physics practice and the ALARA philosophy, the efforts to swipe all RH-TRU waste containers is questionable. The containers hold sealed units that have been determined by waste generators and shippers to be "free" of contamination. The commitment to take and analyze six smears—because of the difficulty and complexity of the remote swiping operation—can be a single-point failure in an otherwise straightforward system of waste receipt and emplacement. This approach appears to have evolved from conservative health physics practices used in laboratories and facilities that are relatively clean and quite variable. Records of contamination detected on CH-TRU packages already received could provide a useful baseline of the effectiveness of the waste system in controlling contamination and the degree to which such information has affected WIPP operations. For example, is minimal contamination on one smear (or the absence of a smear result) a basis for not placing an RH-TRU container in the WIPP?

RECOMMENDATIONS

Based on a careful assessment of the information presented to the RP and the findings developed in response to the review criteria, the RP provides the following recommendations:

1. A detailed procedure for determining whether there is sufficient AK available on a waste, should be developed as part of the permit application. This procedure should be consistent across all waste- generating sites.
2. In the final *Request for RCRA Class 3 Permit Modification* (DOE 2001a) a detailed procedure should be provided to go to other characterization methods if AK is found to be insufficient. For example, figures such as Figure R-2 of the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) and the accompanying text, should be reviewed.
3. The DOE should implement the National Research Council's recommendation that review of characterization and packaging requirements continue, especially implementation "... over the entire National TRU Program."

4. The DOE should provide to the EPA a complete inventory of radionuclides and waste forms so that the EPA may verify the repository performance (that WIPP complies with 40 CFR 191 and 40 CFR 194) using its own methods for certification.
5. The DOE should initiate a more appropriate interaction with the EPA and the NMED, not only to determine and meet their respective requirements but also to ensure that the relevant recommendations—such as those by the National Research Council—are evaluated and implemented.
6. Prior to submission, all permit-related documents—in addition to currently planned reviews—should be reviewed in detail for completeness, specificity, and clarity by a team experienced in the permitting process.
7. The *Request for RCRA Class 3 Permit Modification* (DOE 2001a) must be expanded to include more specifics and examples for clarity and completeness.
8. The discussion for Table 1 of the draft *Request for RCRA Class 3 Permit Modification* (DOE 2001a) should be expanded to justify why sections of the documents require "no action" or "no changes".
9. As part of the permit application, supplemental information should be supplied detailing the waste characterization plans for each waste-generating site and DOE's procedures for determining that these plans meet the WIPP WAC.
10. Detailed audit procedures for WIPP and the waste-generating sites should be provided as part of the permit application.
11. More detail and specificity on WAC using AK, VE, and Radiography (including types of instrumentation to be used) should be provided in the permit application.
12. The DOE should evaluate the necessity of identifying waste streams by the EPA's Hazardous Waste Numbers or Characteristics. If there is no impact on WIPP performance and integrity, the DOE should work with the regulatory agencies to remove this requirement.
13. Whereas it is desirable to preclude contamination and its potential spread, a complete review should be made of what is gained from the remote swiping procedure for "clean" RH-TRU containers and how the information will be used.

Stakeholder Participation

INTRODUCTION

The request for peer review included a consideration for stakeholder participation. Recognizing the significance of the subject, the ASME Peer Review Committee established an ad hoc committee to evaluate possible approaches and procedures for stakeholder participation. The ad hoc committee evaluated a process developed by Love et al. and recommended appropriate revisions. The revised version of that approach was used during this review.

In preparation for stakeholder participation, two guides were prepared: one for the sponsoring agency and the other for stakeholders. In addition, a questionnaire was prepared to evaluate the validity of the approach. After the validity of the process was confirmed in subsequent reviews, Love et al. (2001) published a manual describing the process. One of the key issues advanced by Love et al. was the classification of stakeholders as Personally Impacted, Administratively Impacted, and Generally Concerned Stakeholders. Forms RSI-F-023 and RSI-F-024 in the appendix of this chapter show the guides for the sponsoring agency and the stakeholders respectively. Form RSI-F-025 in the appendix of this chapter is the questionnaire used to seek the views of the stakeholders.

THE PROCESS

Prior to the meeting, the DOE was provided a guidance document (RSI-F-023) containing the definition of stakeholders and certain rules governing participation in a professional society meeting. In addition, the planning of the meeting considered the tradition of all professional societies, indicating that all segments of the meeting—except the executive sessions of the Review Panel—were open to the public. All participants in the peer review meeting were registered and received a name badge. Their registration packets included a summary of the project; peer review criteria; an agenda of the meeting; guidance for stakeholders (RSI-F-024); and a questionnaire (RSI-F-025).

During the introduction, the rules of the stakeholder participation were described. Members of the audience were told that they could ask questions from the speakers

and that they could also make statements during the program designated for that purpose. In every case, the individual who wanted to ask a question or make a statement had to indicate his/her name, affiliation, and the class of stakeholder—if any. Consistent with the peer review process, members of the Review Panel were not introduced to anyone. Review Panel members who wanted to ask questions were instructed to introduce themselves as "I am a panelist". The audience was also asked to fill out the questionnaire (RSI-F-025).

At the end of the meeting, the questionnaires were collected and subsequently evaluated. During the meeting, those who asked questions or made statements appeared to have no difficulties in placing themselves in the correct class.

RESULTS OF THE SURVEY

The respondents overwhelmingly agreed that the definitions of stakeholders as shown in the document provided to them were reasonable. Many respondents complained that the presentations were at a technical level that they could not follow. Even more respondents suggested that the one-to-two weeks notice of the meeting was too short. Most of the other questions were answered positively.

This and similar surveys performed since the initiation of this process suggest that:

1. The classification of stakeholders as Personally Impacted, Administratively Impacted, and Generally Concerned is reasonable.
2. Even those who were opposed to the activity being proposed found the stakeholder participation process as used in the peer review meeting to be fair.
3. Several stakeholders had difficulty assigning their questions or statements to a review criterion and needed help from organizers of the peer review meeting.

Appendix

INSTITUTE FOR REGULATORY SCIENCE STAKEHOLDER PARTICIPATION IN PEER REVIEW MEETINGS

GUIDANCE FOR ORGANIZATIONS REQUESTING STAKEHOLDER PARTICIPATION IN ASME/RSI PEER REVIEW MEETINGS

The American Society of Mechanical Engineers (ASME) and the Institute for Regulatory Science (RSI) have joined forces to provide peer review services to various government agencies. The decision to ask for the participation of stakeholders rests with the agency sponsoring the peer review. When such participation is authorized by the agency, the ASME/RSI team encourages the participation of stakeholders not only as observers, but also as active participants. The details of ASME/RSI peer review may be found at www.NARS.org.

Many federal and state agencies, as well as private industries, desire to include the views of stakeholders in their decision process. This guide is an excerpt from a report which is being prepared by Betty R. Love et al. to assist government agencies and private industry in identifying stakeholders and classifying them in accordance with their respective roles. This guide specifically applies to stakeholder participation in ASME/RSI peer review.

There are three classes of stakeholders as follows:

Personally Impacted Stakeholders: This class consists of individuals whose lives are directly impacted by the action under consideration.

Administratively Impacted Stakeholders: This class consists of elected, appointed, or employed individuals who must ensure that the action under consideration is prepared, reviewed, approved, or implemented in accordance with applicable laws, regulations, permits, licenses, or agreements.

Generally Concerned Stakeholders: This class includes individuals who, by virtue of their personal philosophies, beliefs, or ideologies, are interested in or concerned about the action under consideration.

The participation of stakeholders should be based on the priority placed by the sponsoring organization on the significance of the impact of the decisions to be made on each class of stakeholders. As a general rule, an affirmative outreach is necessary to ensure the participation of personally impacted stakeholders. Experience shows that these stakeholders are reluctant to participate in peer review unless they perceive a significant impact on their daily lives. Accordingly, an affirmative outreach approach is necessary to ensure their participation.

The participation of administratively impacted stakeholders is somewhat less complicated. The mayor of the town; state, federal, and other elected officials representing the locality in which the action under consideration will occur, are desirable stakeholders yet are unlikely to be willing to participate. In contrast, members of agencies responsible for preparation, regulation, and implementation of an action are easier to entice to participate. However, at a minimum, those immediately responsible for the action in these agencies should participate in a well-run program.

The generally concerned stakeholders are normally informed via public media. Their participation is normally determined by the sponsoring agency. As a general rule, they are accommodated after the other two classes are accommodated, and on a first-come first-served basis.

INSTITUTE FOR REGULATORY SCIENCE STAKEHOLDER PARTICIPATION IN PEER REVIEW MEETINGS

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The peer review is performed by a Review Panel consisting of individuals whose qualifications for the specific review have been approved by the ASME's Peer Review Committee. All presentations, statements, and discussions are intended to benefit the Review Panel in its deliberations, which result in the *Report of the Review Panel.* There is ample evidence suggesting that participation of stakeholders enhances the outcome of certain activities, notably peer reviews.

All peer review meetings are normally chaired by a representative of the Peer Review Program. All segments of a peer review meeting, except the executive sessions of the Review Panel, are open to the public. Stakeholders can attend these meetings, provided the following criteria are met:

1. Consistent with the tradition of professional societies, all attendees must register. All registered individuals will be provided a name tag, which must be worn while attending the meeting. All registrants will receive a registration package, which includes the list of review criteria provided to the Review Panel. There is no registration fee for these peer review meetings.
2. During the meeting, all attendees may ask questions of the speakers. These questions are limited to clarification of specific issues presented by the speaker.

A segment of the meeting has been slated for comments by stakeholders. Those making statements should be aware that their comments should be directly related to a specific review criterion. General statements that are not related to the review criteria are not considered by the Review Panel and thus, cannot be permitted.

Due to time constraints, lengthy statements should be avoided as there may not be enough time to accommodate all who wish to participate. Therefore, stakeholders designated by the sponsors of the peer review will be provided specific times with a specific duration in the program to state their case. All other stakeholders wishing to make a statement should limit their statements to only a few minutes to allow as many people as possible to make their concerns and questions known during the time allotted for stakeholders' comments.

Members of the Review Panel may ask questions from all speakers, including those asking questions. However, no question may be directed to the members of the Review Panel.

The Chair of the peer review meeting will be responsible for ensuring that the audience adheres to these requirements.

INSTITUTE FOR REGULATORY SCIENCE

ASME Peer Review

Requirements for Disposal of Remote Handled Transuranic Wastes at the Waste Isolation Pilot Plant
July 30 - August 3, 2001 - Carlsbad, NM

QUESTIONNAIRE FOR STAKEHOLDERS

THE PROCESS

1. Was the notification process adequate?
   ❑Yes ❑No Comments_____

2. Were the stakeholders provided sufficient time to identify and describe their concerns?
   ❑Yes ❑No Comments_____

PRESENTATIONS

1. Did presenters explain the sometimes highly technical issues in a language understandable to an audience of knowledgeable non specialists?
   ❑Yes ❑No Comments_____

2. Did presenters explain technical terms in understandable form?
   ❑Yes ❑No Comments_____

3. Did the presentations address the peer review criteria?
   ❑Yes ❑No Comments_____

4. Were the questions from the stakeholders responsive to peer review criteria?
   ❑Yes ❑No Comments_____

5. Were the statements by the stakeholders responsive to peer review criteria?
   ❑Yes ❑No Comments_____

6. Did questions from the Review Panel directly relate to peer review criteria?
❑Yes ❑No Comments_____

_____

_____

LOCAL ARRANGEMENTS:

1. Was registration performed in a professional manner?
❑Yes ❑No Comments_____

_____

_____

2. Was the registration form acceptable?
❑Yes ❑No Comments_____

_____

_____

3. Was the organization of the meeting room acceptable?
❑Yes ❑No Comments_____

_____

_____

4. Were audiovisual arrangements acceptable?
❑Yes ❑No Comments_____

_____

_____

DEFINITION OF STAKEHOLDERS:

Personally Impacted Stakeholders (PI): This class consists of individuals whose lives are directly impacted by the action under consideration.

Administratively Impacted Stakeholders (AI): This class consists of elected, appointed, or employed individuals who must ensure that the action under consideration is prepared, reviewed, approved, or implemented in accordance with applicable laws, regulations, permits, licenses, or agreements.

Generally Concerned Stakeholders (GC): This class includes individuals who, by virtue of their personal philosophies, beliefs, or ideologies, are interested in or concerned about the action under consideration.

1. Is the definition of various classes of stakeholders as described above reasonable?
❑Yes ❑No Comments_____

_____

_____

_____

2. Please tell us to which class of stakeholders you belong:
❑PI ❑AI ❑GC

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Biographical Summaries

Gary A. Benda* is President of U.S. Energy Corp.—an environmental management firm specializing in radioactive mixed waste management, health physics, decontamination and decommissioning, and technology development. Previously, he was Vice-President, General Manager of the Programs Division for NUKEM Nuclear Technologies, Inc. His responsibilities included developing and maintaining federal programs in North America that specialized in engineering and waste-processing services. Prior to NUKEM, he spent over 17 years with Chem-Nuclear Systems/WMX Technologies in various management roles. He also directed the site investigation, geophysical analysis, site screening, and license application, as well as managed the public hearings and licensing operations associated with local and national regulatory agencies for new low-level waste sites. He has over 20 years of experience in environmental restoration, technology development, and waste management, and has instructed over 20 national and international professional courses on radioactive waste management, mixed waste, and technology development. He is a member of the American Society of Mechanical Engineers (ASME), American Nuclear Society, and Health Physics Society. He has served as Chair of the ASME National Mixed Waste Committee, Environmental Remediation Committee, and Environmental Engineering Division. He has also chaired over 100 technical sessions at numerous national and international conferences on environmental management. He has authored and coauthored various scientific papers, reports, book chapters, and articles on the nuclear environment. Gary Benda is a Certified Health Physicist. He received a B.S. in Health Physics from Oklahoma State University, an M.S. in Applied Nuclear Science from Georgia Institute of Technology, and an M.B.A. from Seattle City University.

Erich W. Bretthauer* is currently President of the Bryce Meadows Development Corporation. He held the position of research professor at the University of Nevada-Las Vegas from January 1993 to March 1995. In that capacity, he served as Executive Director of Nevada Industry, Science Engineering & Technology, a public-private partnership which developed programs to enhance the scientific infrastructure of the state of Nevada. He was Assistant Administrator for Research and Development at the U.S. Environmental Protection Agency (EPA) from March 1990 until January 1993. In that capacity, he managed the Research and Development activities of a large and multi-disciplinary agency. Erich Bretthauer rose through the ranks of the EPA and served in a number of capacities ranging from a bench scientist to policy manager at national and international levels. He directed the EPA's emergency and long-term monitoring program after the accident at Three Mile Island, as well as its bioremediation program in Prince William

Sound after the Valdez oil spill. He also directed the EPA's ecological research program from 1983-1986 and was Director of EPA's Environmental Monitoring Systems Laboratory in Las Vegas from 1986-1990. He is a member of Sigma Xi, the American Chemical Society, the American Association for the Advancement of Science, and the American Water Works Association, and has served on the Federal Advisory Committee to the Civil Engineering Research Foundation. Erich Bretthauer is the author and coauthor of numerous papers, reports, and other publications. He received his B.S. and M.S. in chemistry from the University of Nevada, Reno.

Alan S. Corson is a consultant in hazardous waste issues. He has over 25 years of experience in a number of environmental issues, notably those related to the regulations and management of hazardous waste. Subsequent to his retirement from the U.S. Environmental Protection Agency (EPA), he served in an advisory role to Jacobs Engineering Group and to the Versar Corporation for both government and private sector clients regarding hazardous waste management programs. During his employment at the EPA, he worked at the Office of Solid Waste where he was responsible for regulatory programs and establishing national standards for generators and transporters of hazardous waste; development of sampling and analytic methods for evaluating solid/hazardous waste including the quality assurance/quality control program; and development and management of programs to establish risk assessment of hazardous waste management practices. Alan Corson was instrumental in the development of the original regulatory program defining standards for solid waste and hazardous waste, and setting national standards for recycling hazardous waste. He also initiated, developed, and managed the original program for restricting hazardous wastes from land disposal management options. The framework developed under this program is currently in-place and used for all evaluations in the land-ban program. Alan Corson served as the EPA Office of Solid Waste representative on many intra- and inter-agency workgroups including PCBs, Reportable Quantities, chlorinated solvents, and transportation of hazardous materials. He developed a guide for effective management of infectious wastes—a predecessor to the current regulatory program for medical wastes; characteristics and listings of hazardous waste; and many regulatory options papers for presentation. Alan Corson managed the preparation of numerous regulatory packages for all aspects of the program implementing the Resource Conservation and Recovery Act (RCRA). He has spoken widely and has taught numerous courses on RCRA and its various regulations. He served on numerous national and international panels including review panels of the American

Society of Mechanical Engineers. He received a B.S. in Electrical Engineering and an M.S. in Engineering Management from the Drexel Institute of Technology in Philadelphia, PA.

Ernest L. Daman* is Chairman Emeritus of Foster Wheeler Development Corporation where he previously served as Director of Research and Chairman of the Board. He also held the position of Senior Vice President at the parent company, FWC. He is a Past President of the American Society of Mechanical Engineers (ASME) and was elected to the National Academy of Engineering. Ernest Daman is a Fellow of the Institute of Energy (England) and the American Association for the Advancement of Science, and Past Chairman of the American Association of Engineering Societies. He served on several ASME committees as member or chairman. Ernest Daman is the author of numerous papers and holds 18 patents. He was responsible for the design and development of a combined steam gas turbine plant, fluidized bed combustion, fast breeder reactor components, supercritical steam generators, environmental control processes, and advanced high-efficiency power generation systems. Ernest Daman received his B.M.E. from the Polytechnic Institute of Brooklyn.

Irwin Feller* is Director of the Institute for Policy Research and Evaluation (IPRE) and Professor of Economics at The Pennsylvania State University, where he has been on the faculty since 1963. His current research interests include the economics of academic research, the University's role in technology-based economic development, and the evaluation of federal and state technology programs. He is the author of *Universities and State Governments*: A Study in Policy Analysis, and over 100 refereed journal articles, final research reports, book chapters, reviews, and numerous papers presented to academic, professional, and private organizations. He is former Chair of the Committee on Science, Engineering, and Public Policy, American Association for the Advancement of Science. Irwin Feller was the American Society of Mechanical Engineers Pennsylvania State Fellow in 1996-1997. He has been appointed to the National Academy of Science's Committee on Science, Engineering, and Public Policy, International Benchmarking of U.S. International Competitiveness-Immunology; Transportation Research Board, Research and Technology Coordinating Committee, National Research Council; and National Institute of Standards and Technology-Manufacturing Extension Partnership National Advisory Board. Irwin Feller is Chair of the National Science Foundation's Advisory Committee on Social, Behavioral, and Economic Sciences.

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Robert A. Fjeld* is Dempsey Professor of Environmental Engineering and Science at Clemson University. He coordinates the Department's nuclear environmental focus area, which is concerned with the environmental aspects of nuclear technologies including environmental health physics, radioactive waste management, and risk assessment. Previously, he served as a faculty member in the Nuclear Engineering Department at Texas A&M University. Robert Fjeld is a member of the Health Physics Society, American Nuclear Society, Society for Risk Analysis, and the American Society of Mechanical Engineers, where he serves as newsletter editor for the Mixed Waste Committee. He has served on two National Research Council Committees studying decontamination and decommissioning issues. Robert Fjeld has over 80 technical publications and presentations on topics such as radiation measurements, environmental transport of radionuclides, risk assessment, and aerosol physics. He has active research on actinide transport in soils, instrumentation for measuring radioactivity in environmental samples, and environmental risk assessment. Robert Fjeld received a B.S. from North Carolina State University, and an M.S. and Ph.D. from The Pennsylvania State University. All three degrees are in Nuclear Engineering. He is a registered Professional Engineer.

John T. Greeves* is currently Director of the Division of Waste Management at the U.S. Nuclear Regulatory Commission (USNRC). His experience in the field of nuclear materials management spans 30 years, and includes work in both the private sector and the federal government. Prior to joining the USNRC, he worked for the Bechtel Power Corporation as an engineer responsible for the design and construction of nuclear and conventional power plants. John Greeves has worked for the U.S. government since 1974—with increasing responsibilities in various divisions—including Industrial and Medical Nuclear Safety, and Fuel Cycle Safety and Safeguards. John Greeves has served on a number of national and international panels regarding waste management activities. He is the USNRC's representative to the Waste Safety Standards Advisory Committee of the International Atomic Energy Agency, and has participated extensively in the development of the International Radioactive Waste Management Convention. John Greeves is the recipient of the Presidential Meritorious Rank Award and a member of the

American Society of Civil Engineers. He received a B.S. from the University of Maryland and is a registered Professional Engineer.

William T. Gregory, III* is currently Principal of Vinculum Marketing Solutions. Prior to forming Vinculum, he was Director of Government Programs for Foster Wheeler Environmental Corporation, an engineering and construction firm providing environmental and waste management services to government and private sector clients world-wide. Previously, he held a number of operational and business development positions at equipment manufacturing and service provision firms supporting nuclear utilities, industrial and process industries, and government agencies. His work has involved the management, processing, and disposition of hazardous, radioactive, and mixed wastes. He has also worked on the decontamination and decommissioning of nuclear facilities and on providing a wide range of environmental services in response to regulatory drivers. Prior to entering the private sector, he served with the U.S. Navy on nuclear submarines and at the operational command center for submarine operations in the Atlantic Fleet. William Gregory is actively involved with a number of international, national, and local organizations including: the American Society of Mechanical Engineers (ASME); the American Nuclear Society; and he is a founding member of the Board of Directors for the annual international Waste Management Symposium. William Gregory has served as an elected officer of several ASME divisions. He received a B.S. in Geology from the University of New Mexico, and an M.B.A. from Lamar University. He also attended naval nuclear power, nuclear weapons, and engineering schools as a U.S. Naval officer.

Tom A. Hendrickson is currently an Independent Consultant in the fields of energy, engineering, and technology. His career encompassed service to both government and industry. He was a Senior Executive of Raytheon Federal Engineers & Constructors Company, developing high technology projects which included a privately-financed New Production Reactor; the Accelerator Production of Tritium; and the North Korean nuclear energy program. While working at DOE during the previous Bush Administration, he was Principal Deputy Assistant Secretary of the Office of Nuclear Energy including: Civilian Reactor Development; the Naval Nuclear Propulsion Program; Uranium Enrichment; Space and Defense Power Systems; Isotope Production; and Nuclear Safety Policy. He later became the Director of the New Production Reactors for the DOE, responsible for designing and building new trituim production capacity for nuclear weapons;

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Michael C. Kirkland is an independent consultant who led a team that performed a Congressionally-mandated External Independent Review of the $1.3 billion Spallation Neutron Source Project at Oak Ridge. He assisted in the planning and review of a management assessment at a U.S. Department of Energy (DOE) Site that involved the restart of a plutonium facility. He participated in planning, procurement, and review activities in the environmental remediation area that included decommissioning activities at a shut down nuclear test reactor; designed and installed a ground water cleanup technology. He also provided design oversight for a new facility related to the DOE weapons complex. During his tenure at Savannah River Site (SRS), Michael Kirkland was a Technical Advisor, Project Manager, and Director of the Project Engineering Division. He evaluated nuclear and mixed waste conditions and aspects of high level wastes and spent nuclear fuel; determined material inventories; performed pollution prevention and environmental health and safety evaluations for a proposed waste treatment facility; served as technical advisor to a study administered by the Savannah River Operations Office; and developed integrated schedules defined for this project. Michael Kirkland was director of the Project Engineering Division and managed the SRS design and construction program. He has been involved with waste management and

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Peter B. Lederman* is a consultant with over 48 years of experience in all facets of process engineering, environmental management, control, and policy development. This includes hazardous substance management; environmental remediation; environmental audit; pollution prevention; development of air pollution control devices; and reuse of waste products. He recently retired as Executive Director of the Center for Environmental Engineering & Science, Executive Director for Patents and Licensing, and Research Professor of Chemical Engineering and Environmental Policy at the New Jersey Institute of Technology. Peter Lederman managed major programs in industrial waste treatment research and development,and in oil and hazardous material spill control and remediation. Most recently, he was responsible for a study of the Economic Impact of Environmental Regulations. He has been responsible for technology transfer efforts including the maturing and licensing of innovative environmental technologies. He is a Fellow of the American Institute of Chemical Engineers (AIChE); a Diplomat of the American Academy of Environmental Engineers; and a member of the American Society of Mechanical Engineers. He has served on several committees of the National Research Council and is the chair of the NRC Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program. He chaired AIChE's Environmental Division and is currently chair of its Societal Impacts Operating Council. Peter Lederman received a B.S.E., M.S.E., and Ph.D. (All in Chemical Engineering) from the University of Michigan in Ann Arbor, MI and is a registered Professional Engineer.

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A. Alan Moghissi* is currently President of the Institute for Regulatory Science (RSI), a non-profit organization dedicated to the idea that societal decisions must be based on best available scientific information. The activities of the Institute include research, scientific assessment, and science education at all levels—particularly the education of minorities. Previously, Alan Moghissi was Associate Vice President for Environmental Health and Safety at Temple University in Philadelphia, PA and Assistant Vice President for Environmental Health and

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* Members of ASME Peer Review Committee

List of Acronyms

AK	Acceptable Knowledge
ALARA	As Low As Reasonably Achievable
ASME	American Society of Mechanical Engineers
CAG	Compliance Application Guidelines
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CERCLA	Comprehensive Environmental Response Compensation and Recovery Act
CFR	Code of Federal Regulations
CH	Contact-Handled
CPR	Cellulosic, Plastic, and Rubber
DOE	U. S. Department of Energy
DOT	U. S. Department of Transportation
DQA	Data Quality Objective
EIS	Environmental Impact Statement
EP	Executive Panel
EPA	U. S. Environmental Protection Agency
FEIS	Final Environmental Impact Statement
FTIRS	Fourier Transform Infrared System
GC	Gas Chromathography
HPLC	High Pressure Liquid Chromatography
HWFP	Hazardous Waste Facility Permit
LWA	Land Withdrawal Act
MS	Mass Spectrometry
NDA	Non-Destructive Assay
NDE	Nondestructive Evaluation
NEPA	National Environmental Policy Act
NMAC	New Mexico Administrative Code
NMED	New Mexico Environmental Department
NQA	Nuclear Quality Assurance
NRC	National Research Council
NUREG	Nuclear Regulatory Guidelines
OST	Office of Science and Technology
PA	Performance Assessment
PAN	Passive/Active Neutron
PBMS	Performance-Based Measurement System
PCB	Polychlorinated Biphenyl
PRC	Peer Review Committee (of ASME)
PREPP	Process Experimental Pilot Plant

QA	Quality Assurance
QAO	Quality Assurance Objective
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
RH	Remote-Handled
RP	Review Panel
RSI	Institute for Regulatory Science
SEIS	Supplemental Environmental Impact Statement
SGS	Segmented Gamma Scans
SPC	Statistical Process Control
SWB	Standard Waste Box
TDOP	Ten-Drum Overpack
TIC	Tentatively Identified Compound
TRU	Transuranic
TRUDOCK	Waste handling area of WIPP
TRUPACT-II	Transuranic Package Transporter, Model 2
TSDF	Permit Treatment, Storage and Disposal Facility
TSDF-WAC	Permit Treatment, Storage and Disposal Facility Waste Acceptance Criteria
UCL	Upper Confidence Limit
USNRC	U. S. Nuclear Regulatory Commission
VE	Visual Examination
VOC	Volatile Organic Compound
WAC	Waste Acceptance Criteria
WAP	Waste Analysis Plan
WHB	Waste Handling Building
WIPP	Waste Isolation Pilot Plant
WSPF	Waste Stream Profile Form
WWIS	WIPP Waste Information System

Report of the Review Panel

Desirability of performing certain transuranic waste characterization tests

Institute for Regulatory Science

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Preface

This report contains the results of an independent peer review performed by the Institute for Regulatory Science (RSI). Based on a request from Bob Forrest, Mayor of Carlsbad, NM, a Review Panel (RP) was established to independently review the desirability of eliminating certain tests performed for characterization of hazardous waste constituents of transuranic waste. This request was precipitated by an anticipated action of the U.S. Senate mandating the elimination of these tests.

Most of the activities performed by RSI are in cooperation with certain professional societies. Consequently, detailed policies and procedures have been developed and implemented for performing independent peer review and assessment studies. The process requires the formation of a group consisting of individuals with appropriate education, experience, and peer recognition, that oversees the process. Consistent with these requirements, a Commission on Assessments and Reviews (CAR) has been formed. One of the primary tasks of CAR is to approve the qualifications of members of the RP for a specific peer review or assessment and ensure implementation of policies related to conflict of interest.

The members of the CAR are as follows:

Melvin W. Carter, Chair
Erich W. Bretthauer
Ernest L. Daman
Nathan H. Hurt
Peter Maggiore
Lawrence C. Mohr, Jr.
John E. Moore
Goetz K. Oertel
Harold W. Olsen
Charles O. Velzy
Roger P. Whitfield
Richard Wilson

The Principal Technical Secretary of the Peer Review Program at RSI prepared a list of potential members of the RP and provided it to the CAR for review and approval. This list was modified based on the comments of the CAR. Members of the RP approved by the CAR are as follows:

Goetz K. Oertel, Chair
Bruce M. Thomson, Vice Chair
Alan S. Corson
Robert E. Luna
Fritz A. Seiler

In addition, Peter Maggiore was a consultant to the Panel. The supporting staff of the assessment study for this report are as follows:

Betty R. Love: Executive Vice President, RSI; and Administrative Manager of the Peer Review Program.

Sorin R. Straja: Vice President for Science and Technology, RSI; and Principal Technical Secretary.

Michael C. Kirkland: Vice President Southeast Office, RSI, Aiken, SC.

Wren Prather-Stroud: Manager Western Office, RSI, Carlsbad, NM.

Sharon Jones: Director of Training Programs, RSI; Manager of Review Panel Operations.

The biographical summaries of the members of the RP, the CAR, and the technical staff are located at the end of this report.

The letter from Mayor Forrest (see Appendix 1) included three specific questions (review criteria) which were provided to the RP. The Mayor also asked for the principal conclusions of the RP to be available within a rather short time period. Consistent with RSI policy, the RP was instructed to limit its findings and recommendations to technical issues and avoid social; political; and other non-technical considerations.

In preparation for the review, the RSI staff undertook a concerted effort to gather relevant information from a variety of sources as quickly as possible. Primary sources of information included two reports of the National Research Council (NRC 2001, 2002), the research arm of the National Academy of Sciences; the National Academy of Engineering; and the Institute of Medicine. Dr. Matthew Silva, Director of Environmental Evaluation Group, was asked to provide relevant publications.

Several parts of this *Report of the Review Panel* were prepared by the staff of RSI. The *Process for Independent Peer Review and Independent Technical Assessment* describes various aspects of the process used to produce this report. The two subsequent sections—*Waste Isolation Pilot Plant Facility* and *RCRA Waste Characterization*—were prepared by the staff of RSI from peer-reviewed literature. The two other sections—*Legal Requirements* and the text of *U.S. Senate Report and Bill S. 1424*—are reproduced from official documents. Biographical summaries of participants in this peer review were prepared by the staff of RSI and approved by the relevant individuals.

Based on the desire of Mayor Forrest, the RP provided its principal conclusions in a letter (Appendix 2). Subsequently, the *Report of the Review Panel* was completed by the RP and underwent the customary copy editing.

This peer review was performed as a public service with no external funding. The completion of this report could not have been possible without the support of a number of individuals. We greatly appreciate the contribution of members of the CAR and the RP during various phases of preparation of this report.

Goetz Oertel, Chair of the Review Panel
A. Alan Moghissi, President, RSI

Appendix 1

CARLSBAD

Post Office Box 1569
Carlsbad, NM 88221-1569
(505) 887-1191
1-800-658-2713

BOB FORREST
Mayor

JON R. TULLY
City Administrator

August 12, 2003

A. Alan Moghissi, Ph.D.
President, Institute for Regulatory Science
5457 Twin Knolls Road, Suite 200
Columbia, MD 21045

Dear Dr. Moghissi:

This letter is to confirm our recent discussion of an issue of prime importance to the remediation of the nation's transuranic waste sites. I hereby request that the institute for Regulatory Science perform an independent peer review based on the following criteria:

1. Is the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S.1424 supported by the recommendations of the National Research Council Report "Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant?"

2. Is the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S.1424 supported by various statements and other publications of the New Mexico Environmental Evaluation Group?

3. Based on the information presented to the Review Panel, is the permit modification listed under Section 310 of U.S. Senate Bill 1424 technically defensible?

COUNCILORS

Ward 1	Ward 2	Ward 3	Ward 4
JIMMIE S. CISNEROS	MANUEL C. ANAYA, JR.	H. CALVIN BOWDITCH	LARRY HENDERSON
PAUL C. AGUILAR	JEFF DIAMOND	JUDI WATERS	ROBERT C. MURRAY II

Since time is of the essence, I would appreciate receiving the principal conclusions of the Review Panel no later than August 22, 2003. The full report could follow at a later date.

Sincerely,

Bob Forrest,
Mayor of Carlsbad, New Mexico

Appendix 2

RSI
Institute For Regulatory Science
5457 Twin Knolls Road, Suite 200, Columbia, MD 21045 USA
Phone: 301-596-1700 Fax: 301-596-1707

August 22, 2003

The Honorable Bob Forrest
Mayor of Carlsbad, NM
P.O. Box 1569
Carlsbad, NM 88221

Dear Mayor Forrest:

Thank you for your letter dated August 12, 2003 confirming our verbal agreement on a peer review to be performed by the Institute for Regulatory Science (RSI). In accordance with your request, RSI sought the assistance of the Commission on Assessment and Reviews (CAR) whose membership consists of 12 highly qualified and distinguished individuals. The biographical summaries of the members of the CAR appear in "*Assessment of Desirability of the Formation of a Center of Excellence on Hazardous Materials Management in Carlsbad, New Mexico.*" Through the efforts of the CAR, a Review Panel (RP) was formed consisting of the following individuals:

Goetz K. Oertel, Ph.D., Chair
Bruce M. Thomson, Ph.D., Vice Chair
Alan S. Corson
Robert E. Luna, Ph.D.
Fritz A. Seiler, Ph.D.

Additionally, Peter Maggiore served as a consultant to the RP.

Enclosed are the principal conclusions of the RP. The *Report of the Review Panel* will be made available to you as soon as it is completed.

Enclosed also for your information are the biographical summaries of the members of the RP and the consultant.

Sincerely,

A. Alan Moghissi, Ph.D.
President

AAM:brl

Enclosures

DESIRABILITY OF PERFORMING CERTAIN TRANSURANIC CHARACTERIZATION TESTS

PRINCIPAL CONCLUSIONS OF THE REVIEW PANEL

The Review Panel (RP) was asked to respond to three review criteria identified by the Mayor of Carlsbad, NM. During its deliberations, the RP limited its responses to the review criteria entirely to scientific and engineering issues and specifically avoided political, societal, and other non-technical considerations.

The RP reviewed the report *Improving operations and long-term safety of the Waste Isolation Pilot Plant* of the National Research Council (NRC)—the research arm of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine. In addition, the RP reviewed a number of documents published by the Environmental Evaluation Group (EEG). The RP has concluded its deliberations, and its report is being copyedited. The RP will review the final draft shortly.

The principal conclusions of the RP are as follows:

1. Based on careful evaluation of the NRC report, the RP concludes that the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S.1424 is supported by the NRC.

2. It appears that EEG agrees that the current characterization requirements are excessive. It appears that EEG also agrees that monitoring VOCs in underground disposal rooms is sufficient.

3. Based on the information presented to the RP, the permit modification listed under Section 310 of U.S. Senate Bill 1424 is technically defensible. There is no reason to perform waste confirmation tests that: 1) provide insignificant health and safety benefits to the U.S. population;

and 2) pose serious radiological and occupational health and safety risks for the workers performing these tests.

The RP recommends that the Mayor of Carlsbad make available its report to the U.S. Senate Committee for Energy and Water.

Goetz K. Oertel, Ph.D.
Chair of the Review Panel

8-22-2003
Date

Executive Summary

This report contains the results of an independent peer review performed by the Institute for Regulatory Science (RSI) responding to a request from Bob Forrest, Mayor of Carlsbad, NM to critically review a claim included in a Senate Committee report. The Senate language indicated that the National Academy of Sciences and the Environmental Evaluation Group (EEG) had endorsed the elimination of certain tests currently performed to characterize hazardous waste constituents of transuranic (TRU) waste for disposal at the Waste Isolation Pilot Plant (WIPP). Consistent with the tradition of professional societies, RSI relied upon the Commission on Assessments and Reviews (CAR), a group of individuals with appropriate education, experience, and peer recognition, to oversee the assessment process. The CAR approved the qualifications of members of the Review Panel (RP) to evaluate the desirability of eliminating certain tests performed for characterization of hazardous waste constituents of TRU waste. Consistent with the RSI policy, the RP was instructed to limit its findings and recommendations to technical issues and avoid social, political, and other non-technical considerations.

The RP reviewed two relevant reports of the National Research Council (NRC 2001, 2002)—the research arm of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine. In addition, the RP reviewed a number of documents published by the EEG, an independent group associated with New Mexico Institute of Mining and Technology.

As the principal facility for disposal of the nation's TRU waste generated as a result of nuclear weapons research, development, and production, WIPP must comply with relevant requirements of the U.S. Environmental Protection Agency (EPA) and New Mexico Environmental Department. Whereas the EPA regulates certain aspects of the radioactivity content of TRU waste, the New Mexico Environment Department regulates the hazardous waste constituents of TRU waste. In addition, WIPP must comply with relevant transportation regulations. Compliance with these requirements is based on certain characterization tests. In general, waste characterization activities include the following, although not all of these techniques are used on each container:

1. Radiography, which is an x-ray technique to determine physical contents of containers
2. Visual examination of opened containers as an alternative way to determine their physical contents or to verify radiography results
3. Headspace-gas sampling to determine volatile organic compounds (VOCs) content of gases in the void volume of the containers
4. Sampling and analysis of waste forms that are homogeneous and can be representatively sampled to determine concentrations of hazardous waste constituents and toxicity-characteristic contaminants of waste in containers
5. Compilation of acceptable knowledge (AK) documentation into an auditable record, including process knowledge and prior sampling and analysis data
6. Non-destructive assay, typically segmented gamma scans and passive/active neutron interrogation, to quantify radionuclides.

Confirmation that the waste complies with the requirement that it is not ignitable, corrosive, or reactive is accomplished by AK or appropriate tests.

The U.S. Senate Bill S.1424 states that waste confirmation for all waste received for storage and disposal be limited to:

1. confirmation that the waste contains no ignitable, corrosive, or reactive waste through the use of either radiography or visual examination of a statistically representative subpopulation of the waste; and

2. review of the Waste Stream Profile Form to verify that the waste contains no ignitable, corrosive, or reactive waste and that assigned Environmental Protection Agency hazardous waste numbers are allowed for storage and disposal by the WIPP Hazardous Waste Facility Permit.

Furthermore, the U.S. Senate Bill S.1424 states that compliance with the disposal room performance standards of the Waste Analysis Plan shall be demonstrated exclusively by monitoring airborne volatile organic compounds in underground disposal rooms in which waste has been emplaced until panel closure.

The Review Panel (RP) was asked to respond to three review criteria identified by the Mayor of Carlsbad, NM. During its deliberations, the RP limited its responses to the review criteria entirely to scientific and engineering issues and specifically avoided political, societal, and other non-technical considerations.

After careful review of documents provided to the RP and appropriate deliberations, the RP provided three Findings and one Recommendation. The principal conclusions of the RP are as follows:

1. Based on careful evaluation of the two relevant NRC reports, the RP concludes that the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S.1424 is supported by the NRC.

2. It appears that EEG agrees that the current characterization requirements are excessive. It appears that EEG also agrees that monitoring VOCs in underground disposal rooms is sufficient.

3. Based on the information presented to the RP, the permit modification listed under Section 310 of U.S. Senate Bill 1424 is technically defensible. There is no reason to perform waste confirmation tests that: 1) provide insignificant health and safety benefits to the U.S. population; and 2) pose serious radiological and occupational health and safety risks for the workers performing these tests.

The RP recommends that the Mayor of Carlsbad make available its report to the U.S. Senate Committee for Energy and Water.

Peer Review Process

INTRODUCTION

There is a large degree of consensus within the technical community on basic criteria for acceptability of scientific information. However, the implementation of these criteria requires a reasonably detailed process for identification of the status of scientific information and for the establishment of reliability of the information regardless of its status.

The formation of the Institute for Regulatory Science (RSI) was based on the notion that societal decisions must be based on best available science (BAS). The implementation of the BAS concept required a systematic evaluation of various aspects of scientific information. Consequently, a hierarchy of scientific information and classification of scientific information was developed.

CLASSIFICATION OF SCIENTIFIC INFORMATION

The scientific information was classified into six categories as follows (Moghissi 1996):

Category Ia - Scientific Laws: This class consists of information that is clearly and unambiguously accepted by the scientific and engineering community.

Category Ib - Applied Science: This class consists of application of scientific laws to specific areas. Much of the engineering and many other areas of applied sciences such as industry and commerce fall into this class.

Category IIa - Extrapolated Science: Much of the contested areas of science falls into this class. This category is based on extrapolation of scientific laws beyond their accepted applicability.

Category IIb - Technical Judgement: In many cases, little or no scientific or engineering information is available and the decision maker must rely upon the judgement of qualified individuals.

Category IIIa - Speculation: This class is information that is based on speculation.

Category IIIb - Pseudo Science: Sometimes called "junk" science, this class is clearly based on information which contradicts basic scientific principles.

Similarly, the reliability of scientific information was categorized into four groups as follows:

Group I - Personal Opinion: This group is entirely unreliable unless it is based on the third or fourth group in this grouping system.

Group II - Gray Literature: This group consists of government reports, reports by private organizations, and all other information that has not been subjected to independent peer review. The reliability of this group is questionable.

Group III - Peer-Reviewed Information: This group is the most reliable information. It is based on an assessment of the information by those who are peers to the investigators and are independent of those who have a stake in the outcome of the review.

Group IV - Consensus-Processed Information: This group is particularly applicable to Category IIa and Category IIb of the scientific information. It is based on the notion that information falling into those classes is likely to be contested, and as additional knowledge is gained, the contested area may move to Category Ib or even Category Ia of the classification system. However, the collective wisdom of a profession can be used to reach a conclusion which has a high probability to be correct. For example, in a contested area of mechanical engineering, the collective judgement of the mechanical engineers, as represented by the American Society of Mechanical Engineers (ASME), is the most efficient method to reach a consensus on the likely answer.

PEER REVIEW VS TECHNICAL ASSESSMENT

Peer review consists of a critical evaluation of a product consisting of a document, a study, a program, a technology, a strategy, or any other topic

by a group of individuals who—by virtue of their education, experience, and acquired knowledge—are qualified to be peers to the author of the subject that is being reviewed. In effect, the peers are asked to judge an existing, and partially or entirely completed activity. In its simplest form, peer review responds positively or negatively to the question: Is the claim of the author valid?

In contrast to peer review, a technical assessment guides the requester to a pathway that leads to a decision. In most cases, technical assessments provide detailed information on how an objective can be achieved. Instead of answering a question positively or negatively, an assessment provides a technical judgement on the approach, direction, and implementation of an issue.

PRINCIPLES OF PEER REVIEW AND TECHNICAL ASSESSMENT

Independent peer review, independent technical assessment, and the consensus process are key ingredients of acceptability of scientific information. A peer is an individual who is able to perform the project—or the segment of the project that is being reviewed—with little or no additional training or learning.

Recognizing that peer review constitutes the core of acceptability of scientific and engineering information, virtually all professional societies of scientists and engineers have instituted formal procedures for peer review for their activities. The peer review program of the RSI was developed as a result of its joint efforts with the ASME. The reports of the peer reviews resulting from this program have been published by ASME/RSI (1997, 1998, 1999, 2000, 2001a, 2001b, 2001c, 2002a, 2002b, 2002c, 2002d, 2002e, 2003a, 2003b) and RSI (1998, 2002, 2003).

The most important requirements for independent peer review or independent technical assessment are as follows:

Principle 1: *The selection of members of the review or assessment panel and the outcome of the review or assessment must result from the consensus of a group rather than the decision of an individual.*

This principle implies that all decisions dealing with selection of reviewers and the review must be made collectively by a group of qualified individuals rather than a single individual. Consequently, the RSI process uses the Commission on Assessment and Reviews (CAR) for the appointment of Panels who in turn perform the assessment or the review. Although individuals are involved in the identification of peer reviewers and their nomination, ultimately CAR makes the final decision. Wherever necessary, the CAR decides to change the makeup of the panels, thus demonstrating the necessary oversight.

Principle 2: *Clear and unambiguous policies must be provided to ensure that conflict of interest is avoided.*

The issue of conflict of interest is normally addressed by having each panel member sign a conflict-of-interest form certifying that the individual has no conflict of interest. However, this approach leaves the judgement entirely to the reviewer.

An independent peer review or independent technical assessment process requires clear policies indicating what constitutes a conflict of interest. The CAR relies upon the general conflict-of-interest policies of professional societies resulting in the policy: *Those who have a stake in the outcome of the review or assessment may not act as panel members or participate in the selection of panel members.*

Principle 3: *The findings and recommendations of the review or assessment panel must address unambiguous and clear questions (sometimes called criteria or lines of inquiry) identified by the sponsoring agency.*

Various terms are used in describing review or assessment criteria. These include criteria, questions, and lines of inquiry. During the evolution of the RSI process, much skepticism resulted from the past practice in which panel members had a free reign in addressing any issue. A properly-managed independent peer review or assessment should be based on clearly-identified criteria. These criteria must be technically reasonable and must respond to the needs of the manager.

Principle 4: *The findings and recommendations responding to the assessment or review criteria must be critical, constructive, professional, and collegial rather than adversarial.*

An important and hereto under-emphasized principle is an appreciation of the reason for peer review or assessment. A peer review or an assessment is intended to assist the managers in their decision process. Therefore, the outcome should be helpful to the decision makers rather than being confrontational.

Principle 5: *The participation of appropriately-selected stakeholders significantly enhances the credibility and acceptability of the results of peer review or assessment study.*

The participation of those who are personally impacted by a decision; those who must deal with it during the course of their occupation; and all others who have an interest in the outcome of the peer review or an assessment is desirable. Experience indicates that a properly-managed program of stakeholder participation can avoid the sometimes disorderly and chaotic conditions that can result from such participation. Also, the experience gained during this program indicates that a properly-designed and properly-conducted review or assessment will enhance the acceptance of the decision.

THE PROCESS

The structure of the peer review or technical assessment process established by RSI consists of a tiered system. The process is overseen by the CAR. The review or assessment of specific topics is performed by Review Panels (RPs) or Assessment Panels (APs).

Commission on Assessments and Reviews

The CAR oversees the peer review and assessment studies. Its members are chosen on the basis of their education, experience, and peer recognition. An attempt is made to ensure that all needed technical competencies and diversity of technical views are represented in the CAR.

As the overseer of the entire process, the CAR enforces all relevant policies, including compliance with professional and ethical requirements. A key function of the CAR is the approval of the appointment of members of RPs or APs for a specific project.

Panels

The review of a project, a document, a technology, or a program is performed by a panel consisting of a small group of highly-knowledgeable individuals. Upon the completion of their task, the panel is disbanded. The selection of panel members is based on the competencies required for the specific assignment. The same process is used for the formation and operation of Assessment Panels. The number of individuals in a panel depends upon the complexity of the subject to be reviewed or assessed. The selection of a panel member is based on the totality of that individual's qualifications. However, there are several generally-recognized and fundamental criteria for assessing qualifications of a panel member as follows:

1. **Education:** A minimum of a B.S. degree and preferably an advanced degree in an engineering or scientific field is required for any candidate.

2. **Experience:** In addition to education, the individual must have significant experience in the area that is being evaluated.

3. **Peer recognition:** Election to office of a professional society; serving on technical committees of scholarly organizations; and similar activities are considered to be a demonstration of peer recognition.

4. **Contributions to the profession:** The contributions to the profession may be demonstrated by publications in peer-reviewed journals. In addition, patents, presentations at meetings where the papers were peer-reviewed, and similar activities are also considered to be contributions to the profession.

5. **Conflict of Interest:** One of the most complex and contested issues is a set of subjects collectively called conflict of interest. The ideal panel member is an individual who is intimately familiar with the subject and yet

has no monetary interest in it. The guiding principle for conflict of interest is as follows:

Those who have a stake in the outcome of the review or assessment may not act as a panel member or participate in the selection of panel members.

Institute for Regulatory Science

RSI is a not-for-profit organization chartered under section 501(c)3 of the Internal Revenue Service. It is dedicated to the idea that societal decisions must be based on the best available scientific and engineering information. According to the RSI mission statement, peer review or assessment is the foundation of the best available scientific and engineering information. Consequently, RSI has promoted peer review or assessment within government and industry as the single most important measure of reliability of scientific and engineering information. In its activities, RSI seeks the cooperation of scholarly organizations. Historically, a large number of RSI activities have been performed in cooperation with professional societies. RSI is located in the Washington, D.C. Metropolitan Area with offices in Carlsbad, NM and Aiken, SC.

Project Summary

WASTE ISOLATION PILOT PLANT FACILITY

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is the principal facility for the disposal of the nation's transuranic (TRU) radioactive waste generated as a result of over 50 years of nuclear weapons research, development, and production. The selection of the WIPP site followed a lengthy search and extensive studies for the identification of a site for disposal of TRU wastes (NRC 1983, 1984). These efforts led to the selection of a 41-km^2 (16-mi^2) site, 26 mi (42 km) east of Carlsbad, NM. Following studies conducted during the 1950s of geological formations stable enough to contain wastes for thousands of years, the National Research Council (NRC 1957) identified deep geologic isolation in salt as a most desirable disposal mode for radioactive waste. Experiments conducted on salt mines revealed that there were no technical difficulties with waste disposal in salt (NRC 1984). The Carlsbad site was selected by the U.S. Department of Energy (DOE) because the deep salt beds located there are expected to provide the necessary stability for waste disposal. The site and the region surrounding it had been studied for many years, and mineral exploration of both potash and hydrocarbon deposits provided additional knowledge regarding the geology of the region. The U.S. Geological Survey and other agencies assisted DOE in identifying the New Mexico location for the repository. The salt deposit at this site, known as the Salado Formation, is a minimum of 2,000 ft (610 m) thick and located at a depth of 1,000-2,000 ft (305-610 m).

Salt allows significant deformation without fracturing. The Salado Formation is regionally extensive, and includes continuous beds of salt without complicated structures. The DOE identified the following four advantages of the site:

1. The salt deposit is in a stable geological area with little seismic activity, assuring the stability of a waste repository for thousands of years.
2. Salt deposits indicate the absence of flowing fresh water which could move waste to the surface. Water, if it had been or were present, would have dissolved the salt beds.

3. Salt is relatively easy to mine.
4. Rock salt exhibits a characteristic mechanical behavior (creep) that makes it an excellent host for waste isolation. In response to excavation-induced stress changes, salt slowly flows (or creeps), to close the mined openings. Creep closure starts immediately and continues until the salt has regained its original density and stress distribution. Salt formations tend to slowly and progressively fill mined areas and safely seal radioactive waste from the environment.

Geological data were collected from the WIPP site and surrounding area to evaluate its suitability as a radioactive waste repository. These data were collected principally by the DOE; the DOE's predecessor agencies; the U.S. Geological Survey; the New Mexico Bureau of Mines and Mineral Resources; and private organizations engaged in natural resource exploration and extraction. The DOE analyzed the data and has stated that the site is suitable for long-term isolation of radioactive waste.

The geology of the WIPP site has specific advantages identified by the DOE against potentially adverse environmental impacts. At the depth of the WIPP repository, the salt will slowly encapsulate the buried waste in the stable rock. Salt rock also shields radioactivity, providing a protection similar to that of concrete. Waste placed in the excavation at WIPP is expected to be encapsulated and all waste-filled spaces closed over a period of 75-200 years. The waste disposal depth of 2,150 ft (650 m) is close enough to the surface to make access reasonable.

Subsequent to the investigation of the subsurface geology, the DOE selected the Salado Formation as the site of the WIPP repository for the following reasons:

1. The Salado halite units have low permeability to fluid-flow, which impedes groundwater-flow into and out of the repository.
2. It is regionally widespread.
3. It includes continuous halite beds without complicated structure.
4. It is deep with little potential for dissolution.
5. It is close enough to the surface that access is reasonable.
6. It is largely free of mobile groundwater, as compared to existing mines and other potential repository sites.

Another of the favorable aspects of subsurface geology at the WIPP site is that the groundwater hydrology in the immediate proximity is characterized by geologic strata with low transmissivity and low hydrologic gradients.

WASTE PROCESSING STEPS AT WIPP

The handling and disposal of Contact-Handled (CH) TRU wastes at WIPP involve the following series of steps:

1. A waste shipment arrives at WIPP by truck. Each truck is capable of carrying up to three TRU Packaging Transport Model IIs (TRUPACT-IIs).
2. After an initial security inspection, a radiological survey, and a shipping documentation review, the truck is parked near the Waste Handling Building (WHB) for additional inspection and radiological survey. A forklift is used to transfer each TRUPACT-II from the trailer, through an air lock, and into the WHB, where it is placed in an area called a TRUDOCK, which is used by workers to unload the waste from the TRUPACT-IIs.
3. Radiological surveys are conducted to confirm that waste containers have not sustained damage during shipment or waste container removal.
4. At the TRUDOCK, an overhead crane is used to remove the waste containers from each TRUPACT-II and place them on a facility pallet.
5. A forklift moves the loaded facility pallet to the conveyance loading car at the waste handling shaft. The conveyance loading car is used to load the facility pallet onto the waste hoist.
6. The waste hoist descends 2,150 ft (705 m) to the WIPP repository.
7. An underground transporter pulls the loaded facility pallet off the hoist onto the transporter bed and moves the waste to the appropriate disposal room where a forklift removes the waste containers from the facility pallet and places them in the disposal area. Containers may be stacked three high in the disposal area.
8. Bags of magnesium oxide are placed on top of the stack of containers to serve as backfill. The magnesium oxide will control the solubility of radionuclides and is an added measure of assurance for long-term repository performance.

CONTAINER MANAGEMENT PRACTICES

Containers are to be managed in a specified manner that does not result in spills or leaks. Containers are required to be closed at all times, unless waste is being placed in the container or removed. Because containers at WIPP contain radioactive waste, safety concerns require that containers be continuously vented to obviate the buildup of gases within the container. These gases could result from radiolysis, which is the breakdown of moisture by radiation. The vents are filtered to enable any potential generated gas to escape while particulate matter is retained. Derived waste containers are kept closed at all times unless waste is being added or removed.

Containers with residual liquids

Defense production facilities are prohibited from shipping liquid wastes in the containers sent to the WIPP. In no case is the total residual liquid allowed to equal or exceed 1% (by volume) of the waste container. Consequently, calculations made to determine the secondary containment as required by regulations are based on 10% of 1% of the volume of the containers, or 1% of the largest container, whichever is greater.

Description of containers

Waste containers are to be in good condition prior to shipment from the generator sites, i.e., containers will be of high integrity, intact, and free of surface contamination above established limits. This condition is to be verified upon receipt of the waste at WIPP. Containers are vented through filters, allowing any gases that are generated by radiolytic and microbial processes within a waste container to escape, thereby preventing overpressurization or development of conditions within the container that would lead to the development of ignitable, corrosive, reactive, or other characteristic wastes.

The volatile organic compounds (VOC) in the headspace of waste containers are limited to maximum allowable VOC room-averaged headspace concentration limits specified in the permit. There are no maximum allowable headspace gas concentration limits for individual containers, as some containers can exceed these values as long as container headspace averages in a disposal room do not.

Containers for CH TRU mixed waste will be either 55-gal (208-L) drums arranged singly in 7-packs; 85-gal (321-L) drums arranged singly in 4-packs; 100-gallon drums arranged singly or as three-packs; ten-drum overpacks (TDOP) either as overpacks or direct-loaded; or standard waste boxes (SWBs). Following is a summary description for each container type.

Standard 55-gallon drums: These drums meet the requirements for U.S. Department of Transportation specification 7A regulations. A standard 55-gal (208-L) drum has a gross internal volume of 7.4 ft^3 (0.208 m^3). One or more filtered vents (as described in Permit Section M1-1d(1)) is to be installed in the drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential for pressurization. Standard 55-gal (208-L) drums are constructed of mild steel and may also contain rigid, molded polyethylene (or other compatible material) liners.

Standard Waste Boxes (SWBs): One or more filtered vents are to be installed in the standard waste box lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential of pressurization. SWBs have an internal volume of 66.3 ft^3 (1.88 m^3).

One hundred-gallon drums: A 100-gal (379-L) drum has a gross internal volume of 13.4 ft^3 (0.39 m^3). One or more filtered vents are installed in the drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate potential pressurization. These drums are constructed of mild steel and may also contain rigid, molded polyethylene (or other compatible material) liners. These drums may be used as overpacks or may be direct-loaded.

Ten-Drum Overpack: The TDOP is a metal container, similar to a SWB, and is certified to be noncombustible. It is a welded-steel cylinder, approximately 74 in (1.9 m) high and 71 in (1.8 m) in diameter with a gross internal capacity of 160 ft^3. The maximum loaded weight of a TDOP is limited to 6,700 lbs (3,040 kg). A bolted lid on one end is removable; sealing is accomplished by clamping a neoprene gasket between the lid and the body. Filter ports are located near the top of the TDOP. One or more filtered vents are installed in the ten-drum overpack lid or body to prevent the escape of any radioactive particulate matter

and to eliminate any potential for pressurization. A TDOP may contain up to ten standard 55-gal (208-L) drums or one SWB. The TDOPs may be used to overpack drums or SWBs containing CH TRU mixed waste. The TDOP may also be direct-loaded with waste items that are too large to fit into the standard 55-gallon (208-L) drum; the 85-gallon drum; or the SWB.

Eighty-five gallon drums: The 85-gal (321-L) drum overpack is to be used primarily for overpacking contaminated 55-gal (208-L) drums at the WIPP facility. The 85-gal (321-L) drums may be direct-loaded with CH TRU-mixed waste and may be used to collect derived waste. One or more filtered vents are to be installed in the 85-gal (321-L) drum lid or body to prevent the escape of any radioactive particulate matter and to eliminate any potential of pressurization.

Container compatibility: All containers are made of steel, and some will contain rigid, molded polyethylene liners. Requirements to conduct compatibility studies include container materials to assure that containers are compatible with the waste.

RCRA WASTE CHARACTERIZATION

INTRODUCTION

There are certain waste characterization requirements for the radioactive content of transuranic (TRU) waste mandated by the U.S. Environmental Protection Agency (EPA). Compliance with characterization requirements of TRU waste for disposal at the Waste Isolation Pilot Plant (WIPP) is accomplished on a waste stream basis (i.e., waste material generated from a single process or activity that is similar in material, physical form, isotropic make-up, and hazardous constituents) and also on a container basis. Defense production facilities assign the waste stream identifier for each container of waste that is shipped. The waste designation is selected from one of three broad categories of solid wastes: Homogenous Solids, Soil/Gravel, and Debris Wastes (NMED 1999). In addition, a number of sub-categories are assigned to the wastes. Characterization and analysis methods vary for each category and subcategory of waste.

The Waste Analysis Plan (WAP), which is part of the Permit (DOE 1997b), describes waste characterization activities that a TRU waste generator/storage site must complete before shipping waste to WIPP for disposal. These activities include test methods; details of planned waste sampling and analysis processes; a description of the waste shipment screening and verification process; and a description of the quality assurance/quality control program. Before WIPP manages, stores, or disposes of Contact-Handled (CH) TRU mixed waste from a generator/storage site, the site is required to characterize waste in accordance with WAP requirements. For each container of waste destined for disposal, defense production facilities provide the WIPP operators with a written characterization summary known as a Waste Stream Profile Form (WSPF).

Waste characterization based on 40 CFR 194

Waste characterization, as mandated by the Resource Conservation and Recovery Act (RCRA); and as described in 40 CFR 194 (EPA 1998) requires that a system be in place to track and control the inventory of

waste components to assure that limits associated with the components are not exceeded. The waste components to be tracked and controlled, and the associated limits, are set by a Performance Assessment (PA) conducted by the U.S. Department of Energy (DOE) to show that the WIPP complies with the performance criteria of 40 CFR 191 (EPA 1993). The waste components and the limits, all of which are total inventory limits at repository closure, are presented in the WIPP Compliance Certification Application (CCA).

ORIGIN OF CH TRU WASTE AND ITS ACCEPTANCE CRITERIA AT WIPP

The TRU mixed wastes that are shipped to the WIPP originate at DOE generator/storage sites and contain both radiological and hazardous waste constituents. The DOE and EPA agreed that, of the hundreds of radionuclides present within these wastes, only ten are important for the WIPP performance assessment: ^{241}Am, ^{244}Cm, ^{137}Cs, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{90}Sr, ^{233}U, and ^{234}U. Of these ten, ^{234}Sr, ^{233}U, and ^{137}Cs are important for Remote-Handled (RH) but not for CH waste streams.

Major types of operations generating waste

Examples of the major types of operations that generate this waste include the following:

Production of nuclear products: This category includes reactor operation; radionuclide separation or finishing; and weapons fabrication and manufacturing. The majority of the TRU mixed wastes were generated by weapons fabrication and radionuclide separation or finishing processes. More specifically, wastes resulting from this category consist of residues from chemical processes; air and liquid filtration; casting; machining; cleaning; product quality sampling; analytical activities; and maintenance and refurbishment of equipment and facilities.

Plutonium recovery: These wastes are residues from the recovery of plutonium-contaminated molds; metals; glass; plastics; rags; salts used in electro-refining; precipitates; firebrick; soot; and filters.

Research and development: This group includes a variety of hot-cell or glovebox activities that often simulate full-scale operations described above, producing similar TRU mixed wastes. Other types of R&D projects include metallurgical research; actinide separations; process demonstrations; and chemical and physical properties determinations.

Decontamination and decommissioning: Facilities and equipment that are no longer needed or usable are decontaminated and decommissioned, resulting in TRU mixed wastes consisting of scrap materials; cleaning agents; tools; piping; filters; plexiglass; gloveboxes; concrete rubble; asphalt; cinder blocks; and other building materials. These materials are expected to be the largest category by volume of TRU mixed waste to be generated in the future.

The TRU mixed wastes that are to be shipped to the WIPP facility for disposal have been placed into waste categories based on their physical and chemical properties (Table 1). The waste generating processes can be described in five general categories:

1. Wastes (such as combustible waste) that result from cleaning and decontamination activities in which items such as towels and rags become contaminated both with hazardous waste constituents and radioactivity. In these cases, the hazardous waste and the radioactive constituent are intimately mixed, both on the rag or towel used for cleaning and as residuals on the surface of the object being cleaned. These waste forms are not homogeneous in nature; however, they are generated in a fashion that ensures that the hazardous and radioactive contaminants coexist throughout the waste matrix.

2. Wastes generated when materials which contain metals and metal ions believed to exhibit the toxicity characteristic (EPA 1996b) become contaminated with radioactivity as the result of plutonium operations (leaded rubber, some glass, and metal waste are typical examples). These materials may also become contaminated with solvents during decontamination or plutonium recovery activities.

3. A class of plutonium processes where non-metallic objects are used and become contaminated with radioactive materials. These objects

are subsequently cleaned with solvents to recover plutonium. Surfaces of the objects (such as graphite, filters, and glass) are contaminated with both radioactive and hazardous constituents.

4. Waste-generating processes involving foundry operations where impurities are removed from plutonium. These impurities may result in the deposition of toxicity characteristic (EPA 1996b) metals and metal ions.

5. In all of the process waste categories in the second half of Table 1, the hazardous and radioactive constituents are physically mixed together as a result of the treatment process. In these wastes, the release of any portion of the waste matrix will involve both the hazardous and the radioactive waste components, because the treatment process generates a relatively homogeneous waste form.

Table 1. Summary of waste generation processes and waste forms.

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Combustibles	F001, F002, F003, D008, D019	Cloth and paper wipes are used to clean parts and wash down gloveboxes. Wood and plastic parts are removed from gloveboxes after they are cleaned. Lead may occur as shielding tape or as minor noncombustible waste in this category.	Materials such as metals may retain traces of organics left on surfaces that were cleaned. Waste may remain on the cloth and paper that was used for cleaning or for wiping up spills.
Graphite		Graphite molds, which may contain impurities of metals, are scraped and cleaned with solvents to remove the recoverable plutonium.	Surfaces may retain residual solvents. Lead may be used as shielding or may be an impurity in the graphite.
Filters	F001, F002	Filters are used to capture radioactive particulate in air streams associated with numerous plutonium operations and to filter particulate from aqueous streams.	Filter media may retain organic solvents that were present in the air or liquid streams.

Table 1. (cont'd)

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Benelex® and Plexiglas®	F001, F002, D008	Materials are used in gloveboxes as neutron absorbers. The glovebox assembly often includes leaded glass. All surfaces may be wiped down with solvents to remove residual plutonium.	Surfaces may retain residual solvents from wiping operations. Leaded glass may also be present.
Firebrick and Ceramic Crucibles	F001, F002, F005, D006, D007, D008	Firebrick is used to line plutonium processing furnaces. Ceramic crucibles are used in plutonium analytical laboratories. Both may contain metals as surface contaminants.	Metals deposited during plutonium refining or analytical operations could remain as residuals on surfaces. Surfaces may retain residual solvents.
Leaded Rubber	D008	Leaded rubber includes lead oxide impregnated materials such as gloves and aprons.	The leaded rubber could potentially exhibit the toxicity characteristic.
Metal	F001, F002, D008	Metals range from large pieces removed from equipment and structures to nuts, bolts, wire, and small parts. Many times, metal parts will be cleaned with solvents to remove residual plutonium.	Solvents may exist on the surfaces of metal parts. The metals themselves potentially exhibit the toxicity characteristic.
Glass	F001, F002, D006, D007, D008, D009	Glass includes Raschig rings removed from processing tanks, leaded glass removed from gloveboxes, and miscellaneous laboratory glassware.	Solvents may exist as residuals on glass surfaces and in empty containers. The leaded glass may exhibit the toxicity characteristic.
Inorganic Wastewater Treatment Sludge	F001-F003, D006-D009, P015	Sludge is vacuum filtered and stabilized with cement or other appropriate sorbent prior to packaging.	Traces of solvents and heavy metals may be contained in the treated sludge which is in the form of a solid dry monolith, highly viscous gel-like material, or dry crumbly solid.

Table 1. (cont'd)

Waste Category	Hazardous Waste Codes	Description of Processes	Description of Waste Form
Organic Liquid and Sludge	F001, F003	Organic liquids such as oils, solvents, and lathe coolants are immobilized through the use of various solidification agents or sorbent materials.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.
Solidified Liquid	F001, F003, D006, D008	Liquids that are not compatible with the primary treatment processes and have to be batched. Typically these liquids are solidified with portland or magnesium cement.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.
Inorganic Process Solids and Soil	F001, F002, F003, D008	Solids that cannot be reprocessed or process residues from tanks, firebrick fines, ash, grit, salts, metal oxides, and filter sludge. Typically solidified with portland or gypsum-based cements.	Solvents and metals may be present within the matrix of the solids created through the immobilization process.
Pyrochemical Salts	D007	Molten salt is used to purify plutonium and americium. After the radioactive metals are removed, the salt is discarded.	Residual metals may exist in the salt depending on impurities in the feedstock.
Cation and Anion Exchange Resins	D008	Plutonium is sorbed on resins and is eluted and precipitated.	Feed solutions may contain traces of solvents or metals depending on the preceding process.

Categories of TRU mixed waste

TRU mixed wastes from the above operations are listed by defense production facilities as belonging in one of three broad Summary Category Groups. The characterization is based on the final physical form of the wastes as follows:

Summary category group S3000—homogeneous solids: These wastes include a minimum of 50% (by volume) solid inorganic process residues such as inorganic sludge, salt waste, and pyrochemical salt waste—but exclude soil. Other waste streams are included in this Summary Category Group based on the specific waste stream types and final waste form. This Summary Category Group is expected to contain toxic metals and spent solvents.

Summary Category Group S4000—Soils/Gravel: This Category is assigned to waste streams containing at least 50% (by volume) soil and gravel. This Summary Category Group is expected to contain toxic metals and is also further categorized by the amount of debris included in the matrix.

Summary Category Group S5000—Debris Wastes: These are heterogenous wastes that are at least 50% (by volume) materials that exceed 2.36 inch (60 mm) particle size and that are manufactured objects; plant or animal matter; or natural geologic materials. Smaller particles may be considered debris if they are manufactured objects and if they do not belong to S3000 or S4000. Examples of S5000 waste include gloves; hoses; aprons; floor tile; insulation; plastic; rubber; wood; paper; cloth; and biological materials.

The most common RCRA-regulated hazardous constituents in TRU mixed waste

1. **Metals and metal ions:** Some of the TRU mixed waste to be emplaced in the WIPP facility contains toxic metals contained in EPA hazardous waste codes D004 through D011 (EPA 2000). Cadmium, chromium, lead, mercury, selenium, and silver are present in discarded tools and equipment; solidified sludge; cemented laboratory liquids; and waste from decontamination and decommissioning activities. A large percentage of the waste consists of lead-lined gloveboxes; leaded rubber gloves and aprons; lead bricks and piping; lead tape; and other lead items. Lead, because of its radiation-shielding applications, is the most prevalent toxicity-characteristic metal present.

2. **Halogenated volatile organic compounds:** Some of the TRU mixed waste to be emplaced in the WIPP facility contains spent

halogenated volatile organic compound (VOC) solvents listed as EPA hazardous waste numbers F001 through F005 (EPA 2000). Tetrachloroethylene; trichloroethylene; methylene chloride; carbon tetrachloride; 1,1,1-trichloroethane; and 1,1,2-trichloro-1,2,2-trifluoroethane (EPA hazardous waste codes F001 and F002) are the most prevalent halogenated organic compounds identified in TRU mixed waste that may be managed at the WIPP facility during the Disposal Phase. These compounds are commonly used to clean metal surfaces prior to plating, polishing, or fabrication; to dissolve other compounds; or as coolants. Because they are highly volatile, only small amounts typically remain on equipment after cleaning or, in the case of treated wastewater, in the sludge after clarification and flocculation. Radiolysis may also generate halogenated volatile organic compounds.

3. **Non-halogenated volatile organic compounds:** Xylene, methanol, and n-butanol are the most prevalent nonhalogenated VOCs in TRU mixed waste that may be managed at the WIPP facility. Like the halogenated VOCs, they are used as degreasers and solvents and are similarly volatile. The same analytical methods that are used for halogenated VOCs are used to detect the presence of nonhalogenated VOCs.

Prohibited Items

The TRU mixed waste forms describe both radioactive and hazardous characteristics exhibited by the wastes. The Permit Treatment, Storage, and Disposal Facility Waste Acceptance Criteria (TSDF-WAC) places limits on the waste that can be shipped to the WIPP facility based on the characteristics of the waste form. The following TRU mixed wastes are prohibited at the WIPP facility:

1. Liquid waste which includes residual liquid in the container in excess of what is reasonably achievable by pouring, pumping, and/or aspirating; liquid in the internal container in excess of 1 inch (2.5 cm) of liquid in the bottom of the container; or total residual liquid in any payload container (e.g., 55 gallon drum or standard waste box) in excess of 1% (by volume) of that container
2. Pyrophoric materials, such as elemental potassium
3. Hazardous wastes not occurring as co-contaminants with TRU wastes

4. Wastes incompatible with backfill; seal and panel closures materials; container and packaging materials; shipping container materials; or other wastes
5. Wastes containing explosives or compressed gases
6. Wastes with polychlorinated biphenyl (PCB) concentration of 50ppm (50 mg/kg) or more
7. Wastes exhibiting the characteristic of ignitability, corrosivity, or reactivity (EPA Hazardous Waste Numbers D001, D002, or D003)
8. Any waste container that does not have VOC concentration values reported for the headspace
9. Any waste container which has not undergone either radiographic or visual examination
10. Any waste container from a waste stream which has not been preceded by an appropriate, certified Waste Stream Profile Form

Before accepting a container holding TRU mixed waste, WIPP operators audit the radiography or visual examination (VE) data records of the generator/storage sites to verify that the container holds no unvented compressed gas, and that residual liquid does not exceed 1% (volume) in any payload container. Radiography tapes are to be selected randomly for at least 1% of containers received at the WIPP, at which time they are reviewed and compared to radiographic data forms. If waste does not include at least 50% of any given category by volume, characterization shall be performed using the waste characterization process required for the category constituting the greatest volume of waste for that waste stream. To ensure the integrity of the WIPP facility, waste streams identified as containing incompatible materials or materials incompatible with waste containers are not to be shipped to the WIPP unless they are treated to remove the incompatibility.

Waste generated as a result of waste container handling and processing activities at the WIPP facility are known as “derived” wastes. Because derived wastes can contain only those RCRA-regulated materials present in the waste from which they were derived, no additional characterization of the derived waste is required for disposal purposes. In other words, generator/storage site characterization data as well as knowledge of the processes at the WIPP facility will be used to identify and characterize hazardous waste and hazardous constituents in derived waste.

TRU waste, by definition, must contain 100 nCi/g or more of transuranic elements of waste, which means that the radioactive component of the waste will always be present within the waste in significant concentrations. The TSDF-WAC limitations and restrictions are provided to ensure that any waste form received at the WIPP facility is stable and can be managed safely. One benefit of waste form restrictions—such as no liquids—is that they limit the kinds of releases that could occur to those that would be readily detectable through visual inspection (i.e., large objects that fall out of ruptured containers) or through the use of radiation monitoring—either locally or within the adjacent area—to detect materials that have escaped from containers.

Releases and spills

Some waste forms only contain radioactive contamination on the surface, because they are not the result of a treatment process or are not porous in form. These include glass, leaded rubber, metals, graphite, ceramics, firebricks, and plastics. In theory, a hazardous waste release could occur if the interiors of these materials became exposed and were involved in a release or spill. Such an occurrence is not likely during operations, because no activities are planned or anticipated that would result in the breaking of these materials to expose fresh surfaces. The WIPP facility will handle only sealed containers of waste and derived waste. The practice of handling sealed containers minimizes the opportunity for releases or spills. For the purposes of safety analysis, it was assumed that releases and spills during operations occur by either of two mechanisms: 1) surface contamination; and 2) accidents. Regardless of how the release occurs, the nature of the waste and the processes that generated it is such that the radioactive and hazardous components are intimately mixed. A release of one without the other is not likely, except for releases of VOCs from containers. Surface contamination is the only credible source of contamination external to the containers during normal operations. Surface contamination is assumed to be caused by waste management activities at the generator site that result in the contamination of the outside of a waste container. Contamination would most likely consist of particulate matter (dirt or dust) that would be deposited during generator-site handling/loading activities. This contamination may not be detected by visible inspections. Surface contamination is monitored upon

arrival at the WIPP facility through the use of swipes and radiation monitoring equipment, as specified in the WIPP Permit (NM Hazardous Waste Regulations, Title 20; NMED 1999). Detection using radioactivity is very sensitive and allows for the detection of contamination that may not be visible on the surface of the container. This exceeds the capability required by the RCRA, which is generally limited to inspections that detect only visible evidence of spills or leaks. Releases can occur from accidents, and those that occur within the waste handling process are assumed to result in the release of radioactive contaminants and VOCs. Radioactive releases are detectable using surface-sampling (swipe) techniques. The most common RCRA-regulated hazardous constituents in TRU mixed waste to be managed at the WIPP facility consist of: metals; halogenated volatile organic compounds; and non-halogenated volatile organic compounds.

WASTE STREAM IDENTIFICATION

Waste characterization activities at generator/storage sites include the following, although not all of these techniques will be used on each container:

1. Radiography, which is an x-ray technique to determine physical contents of containers
2. Visual examination (VE) of opened containers as an alternative way to determine their physical contents or to verify radiography results
3. Headspace-gas sampling to determine VOC content of gases in the void volume of the containers
4. Sampling and analysis of waste forms that are homogeneous and can be representatively sampled to determine concentrations of hazardous waste constituents and toxicity-characteristic contaminants of waste in containers
5. Compilation of acceptable knowledge (AK) documentation into an auditable record, including process knowledge and prior sampling and analysis data
6. Non-destructive assay, typically segmented gamma scans and passive/active neutron interrogation, to quantify radionuclides for 40 CFR 194 waste characterization compliance

Auditable records allow DOE operators to conduct a systematic assessment, analysis, and evaluation of generator/storage site compliance with the WAP and the Permit. Waste analysis parameters to be characterized include confirmation of physical form; presence of toxicity characteristic contaminants; and exclusion of prohibited items. The characterization techniques used by generator/storage sites include AK, which incorporates confirmation by headspace-gas sampling and analysis; radiography; and homogeneous waste sampling and analysis. All confirmation and characterization activities are to be performed in accordance with the WAP. The analytical requirements are specified by the analytical method being used such as Fourier Transform Infrared Spectroscopy, and Gas Chromatography/Mass Spectrometry.

Waste analysis parameters characterized for the 40 CFR 194 (EPA 1998) characterization program are quantity of metals; quantities of cellulosics; plastics; and rubber; quantity of free water; and a list of ten radionuclides. The characterization techniques used by generator/storage sites for these parameters also include AK and radiography as well as non-destructive assay.

Radiography

Radiography techniques have been developed by DOE to aid in the examination and identification of containerized waste. There are specific requirements that relate to radiography methods used at respective facilities. A radiography system typically consists of: 1) an X-ray-producing device; 2) an imaging system; 3) an enclosure for radiation protection; 4) a waste container handling system; 5) an audio/video recording system; and 6) an operator control and data acquisition station.

Although these six components are required, it is expected that there will be some variation within a given system between sites. The radiography of a waste container is recorded by an audio/videotape or equivalently non-alterable media and is maintained as a non-permanent record. The estimated waste material parameter and weights should be determined by compiling an inventory of waste items, residual materials, and packaging materials. Containers whose contents prevent full examination to the extent expected for the radiography technique and waste form, are subject to visual examination.

Visual examination

As an additional quality control (QC) check on radiography, or in lieu of radiography, the waste container contents are verified directly by visual examination. The visual examination consists of a semi-quantitative and/or qualitative evaluation of the waste container contents, and is recorded on audio/videotape. Visual examination is performed on a statistically determined portion of waste containers to verify the results of radiography. This verification includes use of the Waste Matrix Code; waste material parameter weights; and the assurance of the absence of prohibited items.

Visual examination includes describing the contents of a waste container, and estimating or measuring the weight of the contents. The description identifies the discernible waste items, residual materials, packaging materials, and waste material parameters. Estimated weights are established through the use of historically-derived waste weight tables and an estimation of the waste volumes.

Headspace-gas sampling and analysis

Headspace-gas sampling is performed on waste containers that are in compliance with the container temperature equilibrium requirements (i.e., 72 h at 18°C or higher). Waste containers designated as summary category S5000 (Debris waste) are sampled for headspace gas a minimum of 142 d after packaging. Waste containers designated as Summary Categories S3000 (Homogenous solids) and S4000 (Soil/gravel) are sampled a minimum of 225 d after packaging. This drum-age criteria ensures that the drum contents have reached 90% of steady state concentration within each layer of confinement to allow a representative sample to be taken (NMED 1999.) Two types of headspace-gas sampling protocols may be employed: 1) the manifold headspace-gas sampling protocol, and 2) the direct canister headspace-gas sampling protocol.

Once the headspace gas sample has been collected in accordance with the Hazardous Waste Facility Permit (HWFP) requirements, the sample is taken to a laboratory for analysis. The laboratory analyzes the sample using the allowable methods in the HWFP and reports the concentration

of all analytes on the target analyte list. In addition, the presence of any tentatively identified compounds (TICs) observed during the analysis is reported.

Sampling and analysis of homogenous solids and soil/gravel

The methods used to collect samples of TRU mixed waste classified as homogenous solids and soil/gravel from waste containers, are designed to ensure that the samples are representative of the waste from which they are taken. A sufficient number of samples are collected to adequately represent the waste being sampled. For those waste streams defined as Summary Category Groups S3000 or S4000, debris that may also be present within these wastes need not be sampled. Samples of retrievably stored waste containers are collected using appropriate coring equipment or other EPA-approved methods to collect a representative sample. Newly-generated wastes that are sampled from a process as they are generated may be sampled using EPA-approved methods—including scoops and ladles—that are capable of collecting a representative sample.

The QC requirements for sampling homogenous solids and soil/gravel include: collecting co-located samples from cores or other sample types to determine precision; equipment blanks to verify cleanliness of the sampling and coring tools and sampling equipment; and analysis of reagent blanks to ensure that reagents, such as deionized or high-pressure liquid chromatography (HPLC) water, are of sufficient quality.

Once the homogeneous solid or soil/gravel sample has been collected in accordance with the HWFP requirements, the sample is taken to a laboratory for analysis. The laboratory analyzes the sample using the allowable methods in the HWFP and reports the concentration of all analytes on the target analyte list. In addition, the presence of any TICs observed during the analysis is reported.

Acceptable knowledge

This characterization technique incorporates confirmation by headspace-gas sampling and analysis; radiography; and homogeneous waste sampling

and analysis. Both RCRA regulations and the New Mexico Hazardous Waste Management Regulations (NMED 1997) authorize the use of AK in appropriate circumstances by waste generators—or treatment, storage, or disposal facilities—to characterize hazardous waste. Acceptable knowledge is described by the EPA (EPA 1994) as an alternative to sampling and analysis; it can be used to meet all or part of the waste characterization requirements under the RCRA. AK includes a number of techniques used to characterize TRU mixed waste, such as process knowledge; records of analysis acquired prior to RCRA; and other supplemental sampling and analysis data (EPA 1994). AK is used in TRU mixed waste characterization activities in three ways:

1. To delineate TRU mixed waste streams
2. To assess if TRU mixed heterogeneous debris wastes exhibit a toxicity characteristic (NMED 1997)
3. To assess if TRU mixed wastes are listed (NMED 1997)

TRU mixed waste streams are evaluated by applicable provisions of the AK process prior to management, storage, or disposal by the Permittees at the WIPP. TRU mixed waste management AK information defines waste categorization schemes and terminology; provides a breakdown of the types and quantities of TRU mixed wastes that are generated and stored at the site; and describes how wastes are tracked and managed at the site—including historical and current operations. Information related to TRU mixed waste certification procedures and the types of documentation (e.g., waste profile forms) used to summarize AK are also provided. The amount and type of supplemental AK information required from generator/storage sites is site-specific and cannot be mandated, but sites collect information as appropriate to support required AK information.

The AK written record includes a summary that identifies all sources of waste characterization information used to delineate the waste stream. For each TRU mixed waste stream, the generating sites compile all process information and data supporting the AK used to characterize that waste stream. The type and quantity of supporting documentation will vary by waste stream, depending on the process generating the waste and site-specific requirements imposed by the DOE.

STATISTICAL METHODS USED IN SAMPLING AND ANALYSIS

Generator/storage sites use statistical methods to: 1) select waste containers for visual inspection; 2) select retrievably-stored waste containers for totals analysis; 3) set the upper confidence limit; and 4) apply control charting for newly-generated waste stream sampling. Statistical sampling techniques are not currently employed in waste characterization activities employed for 40 CFR 194 (EPA 1998) compliance.

Selecting waste containers for visual examination

As a QC check on the radiographic examination of waste containers, a statistically-selected portion of the certified waste containers is opened and visually examined. The data from visual examination is used to verify the matrix parameter category, waste material parameter weights, and absence of prohibited items, as determined by radiography. The data obtained from the visual examination can also be used to determine—with acceptable confidence—the percentage of miscertified waste containers from the radiographic examination. Miscertified containers are those that radiography indicates meet the WIPP Waste Acceptance Criteria and Transuranic Package Transporter-II Authorized Methods for Payload Control, but visual examination indicates do not meet these criteria. Participating sites initially use an 11% miscertification rate to calculate the number of waste containers that are visually examined until a site-specific miscertification rate has been established.

The site-specific miscertification rate is applied initially to each Summary Category Group to determine the number of containers in that Summary Category Group requiring visual examination. However, a Summary Category Group-specific miscertification rate is determined when either six months have passed since radiographic characterization commenced on a given Summary Category Group or at least 50% of a given Summary Category Group has undergone radiographic characterization, whichever occurs first. The Summary Category Group is then subject to the visual examination requirements of this reevaluated Summary Category Group-specific miscertification rate to ensure that the entire Summary Category Group is appropriately characterized. The site-specific miscertification rate is reassessed annually.

Statistical sampling and analysis of homogeneous solids and soil/gravels for totals

The statistical approach for characterizing retrievably-stored homogeneous solids and soil/gravel waste using sampling and analysis relies on using acceptable knowledge to segregate waste containers into relatively homogeneous waste streams. Once segregated by waste stream, random selection and sampling of the waste containers followed by analysis of the waste samples are performed to ensure that the resulting mean contaminant concentration provides an unbiased representation of the true mean contaminant concentration for each waste stream.

Preliminary estimates of the mean concentration and variance of each RCRA-regulated contaminant in the waste are used to determine the number of waste containers to select for sampling and analysis. The preliminary estimates are made by obtaining a preliminary number of samples from the waste stream or from previous sampling from the waste stream. Preliminary estimates are based on samples from a minimum of five waste containers. Samples collected to establish preliminary estimates that are selected, sampled, and analyzed in accordance with applicable provisions of the Waste Analysis Plan (WAP) are used as part of the required number of samples to be collected.

The calculated total number of required waste containers can then be randomly sampled and analyzed. Waste container samples from the preliminary mean and variance estimates may be counted as part of the total number of calculated required samples if and only if:

1. there is documented evidence that the waste containers for the preliminary estimate samples were selected in the same random manner as is chosen for the required samples.
2. there is documented evidence that the method of sample collection in the preliminary estimate samples were identical to the methodology to be employed for the required samples.
3. there is documented evidence that the method of sample analysis in the preliminary estimate samples was identical to the analytical methodology employed for the required samples.
4. there is documented evidence that the validation of the sample analyses in the preliminary estimate samples was comparable to the

validation employed for the required samples. In addition, the validated samples results should indicate that all sample results were valid according to the analytical methodology.

Upon collection and analysis of the preliminary samples, or at any time after the preliminary samples have been analyzed, the generator/storage site may assign hazardous waste codes to a waste stream. For waste streams with calculated upper confidence limits below the regulatory threshold, the site must collect the required number of samples if the site intends to establish that the constituent is below the regulatory threshold.

Statistical headspace gas sampling and analysis

If a waste stream meets the conditions for representative headspace gas sampling, then headspace-gas sampling of that waste stream may be done on a randomly-selected portion of containers in the waste stream. The minimum number of containers that are sampled is determined by taking an initial VOC sample from 10 randomly-selected containers. These samples are analyzed for all the target analytes.

The mean and standard deviation calculated after sampling *n* containers is then used to calculate a UCL_{90} for each of the headspace gas VOCs.

Control charting for newly-generated waste stream sampling

Significant process changes and process fluctuations associated with newly-generated waste are determined using statistical process control (SPC) charting techniques. These techniques require historical data for determining limits for indicator species, and subsequent periodic sampling to assess process behavior relative to historical limits. SPC is performed on waste prior to solidification or packaging for ease of sampling. If the limits are exceeded for any toxicity characteristic parameter, the waste stream can be recharacterized, and the characterization can be performed according to procedures required in the WAP.

A Shewhart control chart (Gilbert 1987) is a control chart for statistical means that is used for checking whether current data are consistent with

past data and whether shifts or trends in means have occurred. If a current sample mean from the process lies within the limits, the process is said to be "in control," or consistent with historical data. If the current mean exceeds the limits, the process has likely changed from historical periods. Logical sets of historical data to be used for the construction of limits in this application are the data from the initial characterization of the waste stream, if available; from characterization of a different lot of the waste stream; or from a retrievably-stored waste stream of the same type from the same process. At a minimum, the logical set includes ten representative sample values collected and analyzed from the newly-generated waste stream. The data used for construction of the limits is justified. The underlying assumptions for control charts are that the data are independent and normally-distributed with constant mean μ and constant variance σ^2. The statistical tests for normality can be conducted and data transformation to normality performed, if necessary. Transformations should take place prior to any calculations that use the data.

Each limit is constructed such that there is a 90% confidence that the true mean does not exceed a limit. One-sided control limits are used because once a waste stream has been determined to be RCRA-hazardous and the limit exceedance of interest is on the lower side—that is when the process may become nonhazardous. Likewise, once a waste stream has been determined not to be RCRA-hazardous and the limit exceedance of interest is on the upper side—that is when the process may become RCRA-hazardous. Whether or not exceeding the limit would result in a change in the RCRA-hazardous nature of the waste stream depends on how close the observed control limits are to RCRA limits.

Current process data are collected and averaged for comparison to the control limit for the mean. The collection period and number of samples included in the average are dependent on the waste stream characteristics. A small number of samples will reflect more of the process variability and there will be more limit exceedances. If two or three samples are collected for the mean in the required annual (or batch) sampling of a relatively homogeneous waste stream, limit exceedances may not occur. If the waste stream is less homogeneous, it will be necessary to collect more samples to meet the required confidence limit. Periodically, it will be

necessary to update the control limit for a process. An update that includes all historical data is performed if there is no evidence of a trend in the process or a shift in the mean for the process. If there has been a shift in the mean, only more recent data that reflect the shift are used. Control limits shall be based on at least ten data points that are representative of the process and do not exhibit outliers or a trend with time.

Legal Requirements

INTRODUCTION

The Waste Isolation Pilot Plant project was authorized in 1979 (PL96-164) as a research and development activity to demonstrate the safe disposal of radioactive waste originating from the U.S. nuclear weapons program. This and several other laws and regulations have resulted in the construction and operation of the Waste Isolation Pilot Plant (WIPP) as a unique facility for the disposal of transuranic (TRU) waste.

TRU waste is defined as a waste containing alpha-emitting isotopes of transuranic elements equal to or in excess of 100 nCi/g of waste. The half-lives of the isotopes of these elements must be greater than 20 years.

Much of the TRU waste contains chemical constituents subject to the regulations of the Resource Conservation and Recovery Act (RCRA) and the New Mexico Hazardous Waste Act. TRU wastes that contain both chemical and radioactive waste are referred to as TRU mixed waste. According to RCRA, WIPP is required to have a hazardous waste permit to receive waste containing hazardous waste constituents. The State of New Mexico has adopted the relevant RCRA regulations by reference and thus is authorized to issue hazardous waste permits. WIPP received a permit (NMED 1999) on October 27, 1999 for contact-handled (CH) waste, defined as having a surface radiation dose rate not greater than 200 mrem/h (2 mSv/h). TRU waste having a greater dose rate than 200 mrem/h (2 mSv/h) is defined as Remote Handled (RH) TRU Waste.

The enactment of the WIPP Land Withdrawal Act (WIPP/LWA 1992) resulted in permanent withdrawal and transfer of the administration of federal land for the site from the U.S. Department of Interior to the DOE. This law mandated that the U.S. Environmental Protection Agency (EPA) certify the DOE's compliance with EPA's relevant, generally applicable environmental standards for radioactive materials. Subsequently, the EPA (1996a) issued the criteria to be used in certifying compliance. In response, the DOE provided the EPA with appropriate documents; model; and evaluations of the geology, hydrology, and climate as well as projected performance of the entire disposal system, including the mined repository, shaft seals, panel closures, borehole plugs, and mine backfill. Finally, the

EPA (1998) certified that the WIPP met all of the criteria required for the disposal of TRU waste.

The WIPP/LWA limited the amount and types of TRU wastes that can be emplaced at WIPP. The limits include the following:

1. The volume WIPP capacity is limited to 1.75 x 10^5 m^3 (6.2 x 10^6 ft^3) total TRU waste.
2. No more than 5% (by volume) of RH-TRU waste may have a surface dose rate in excess of 100 rem/h (1Sv/h).
3. No RH-TRU waste may have a surface dose rate in excess of 1,000 rem/h (10 Sv/h).
4. RH-TRU waste containers shall not exceed 23 Ci/L (851 GBq/L) maximum activity level averaged over the volume of the container.
5. The total radioactivity of RH-TRU waste shall not exceed 5.1 MCi (188.7 Gbq).
6. Of the allowed waste disposal volume of 1.75 x 10^5 m^3 (6.2 x 10^6 ft^3), the Consultation and Cooperation Agreement with the State of New Mexico limits the volume of RH-TRU waste to 7,080 m^3 (250,000 ft^3).

The 41 km^2 (16 mi^2) area under DOE's jurisdiction at WIPP is deemed sufficient to ensure that at least 1 mi. (1.6 km) of intact salt exists laterally between the waste disposal area and the accessible environment, and also to ensure that no permanent residences will be established in close proximity to the facility.

BRIEF WIPP CHRONOLOGY

1957 National Research Council recommended salt as host rock, identified areas to investigate, and identified favorable siting criteria

1974 Atomic Energy Commission selected site near Carlsbad for exploratory work

1979 Congress authorized WIPP for research and development for safe disposal of defense-generated radioactive waste

1980 DOE issued Final Environmental Impact Statement (FEIS)

1981 DOE issued Record of Decision

1981 DOE began construction of WIPP Exploratory Shaft

1985 EPA issued 40 CFR 191—radioactive waste disposal standards applicable to WIPP

1986 EPA stated facilities must comply with Resource Conservation and Recovery Act (RCRA) for disposal of mixed (hazardous and radioactive) waste

1990 New Mexico was authorized by EPA to regulate mixed waste

1990 DOE issued first Supplemental Environmental Impact Statement (SEIS)

1991 DOE submitted Parts A and B of the RCRA Permit Application to New Mexico

1992 WIPP Land Withdrawal Act permanently segregated land for WIPP and gave EPA regulatory authority to certify WIPP compliance to 40 CFR 191.

1995 DOE submitted revised RCRA Permit Application to New Mexico Environment Department

1996 EPA issued 40 CFR 194, compliance criteria in February

1996 DOE submitted 84,000 page Compliance Certification Application to EPA

1998 DOE issued SEIS II in January

1998 EPA certified WIPP ready for disposal

1998 New Mexico Environment Department issued draft hazardous waste facility permit (HWFP) for disposal of transuranic mixed waste

1999 First shipment non-mixed waste in March

1999 New Mexico Environment Department issued Hazardous Waste Facility Permit

2000 First shipment of mixed waste in September

EPA'S CRITERIA FOR WIPP CERTIFICATION

Criteria for certification and re-certification of WIPP were published in final form by the EPA (1996a). These criteria were detailed and contained specific requirements related to the radioactivity content of TRU waste. In its regulations, EPA provided requirements not only for quality assurance and characterization but also specific requirements for expert judgement and peer review. Although EPA's certification and re-certification do not apply to radioactive waste constituents of TRU waste, the description of peer review requirements may be useful as they can be advantageously used also for hazardous waste constituents. The following are excerpts from EPA's regulations:

"§ 194.27 Peer review.

(a) Any compliance application shall include documentation of peer review that has been conducted, in a manner required by this section, for:

(1) Conceptual models selected and developed by the Department;

(2) Waste characterization analyses as required in § 194.24(b); and

(3) Engineered barrier evaluation as required in § 194.44.

(b) Peer review processes required in paragraph (a) of this section, and conducted subsequent to the promulgation of this part, shall be conducted in a manner that is compatible with NUREG-1297, "Peer Review for High-Level Nuclear Waste Repositories," published February 1988. (Incorporation by reference as specified in § 194.5.)

(c) Any compliance application shall:

(1) Include information that demonstrates that peer review processes required in paragraph (a) of this section, and conducted prior to the implementation of the promulgation of this part, were conducted in accordance with an alternate process substantially equivalent in effect to NUREG-1297 and approved by the Administrator or the Administrator's authorized representative; and

(2) Document any peer review processes conducted in addition to those required pursuant to paragraph (a) of this section. Such documentation shall include formal requests, from the Department to outside review groups or individuals, to review or comment on any information used to support compliance applications, and the responses from such groups or individuals."

The packaging of waste at the originating sites; transport to the site; transport vehicles; and disposal of heat-generating waste are beyond the scope of this study and are not dealt with in this report.

The health and safety consequences of the postulated repository failure mechanisms appear to be so minimal that simplifications in design may be justified, and cost-effectiveness studies should be carried out to determine whether they would be acceptable. However, the probability and the consequences of potentially rapid flow of brine solutions containing radionuclides, through more permeable formations, have not been completely determined. Once these have been resolved, conventional safety considerations (e.g., number of shafts and packaging of waste for highway transport) might determine the optimum design.

Relaxation of the WIPP waste acceptance criteria (e.g., elimination of the incineration of some of the waste at the Process Experimental Pilot Plant (PREPP) facility and removal of the requirement for the use of steel-case overpack of the wooden boxes) may also have minimal consequences.

PUBLIC LAW 102-579
THE WASTE ISOLATION PILOT PLANT LAND WITHDRAWAL ACT

as amended by Public Law 104-201
(H.R. 3230, 104th Congress)

SECTION I. SHORT TITLE; TABLE OF CONTENTS.

(a) SHORT TITLE.—This Act may be cited as the "Waste Isolation Pilot Plant Land Withdrawal Act".

(b) TABLE OF CONTENTS.—

Sec. 1. Short title; table of contents.
Sec. 2. Definitions.
Sec. 3. Land withdrawal and reservation for WIPP.
Sec. 4. Establishment of management responsibilities.
Sec. 6. Test phase activities.
Sec. 7. Disposal operations.
Sec. 8. Environmental Protection Agency disposal regulations.
Sec. 9. Compliance with environmental laws and regulations.
Sec. 10. Sense of Congress on commencement of emplacement of transuranic waste.
Sec. 11. Mine safety.
Sec. 12. Ban on high-level radioactive waste and spent nuclear fuel.
Sec. 13. Decommissioning of WIPP.
Sec. 14. Savings provisions.
Sec. 15. Economic assistance and miscellaneous payments.
Sec. 16. Transportation.
Sec. 17. Access to information.
Sec. 18. Judicial review of EPA actions.
Sec. 19. Technology study.
Sec. 20. Statement for purposes of Public Law 96-164.
Sec. 21. Consultation and cooperation agreement.
Sec. 22. Buy American requirements.
Sec. 23. Authorization of appropriations.

SEC. 2. DEFINITIONS.

For purposes of this Act:

(1) ADMINISTRATOR.—The term "Administrator" means the Administrator of the Environmental Protection Agency.

(2) AGREEMENT.—The term "Agreement" means the July 1, 1981, Agreement for Consultation and Cooperation, as amended by the November 30, 1984 "First Modification", the August 4, 1987 "Second Modification", and the March 18, 1988 "Third Modification" or as it may be amended after the date of enactment of this Act between the State and the United States Department of Energy as authorized by section 213(b) of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub. L. 96-164; 93 Stat. 1259, 1265).

(3) CONTACT-HANDLED TRANSURANIC WASTE.—The term "contact-handled transuranic waste" means transuranic waste with a surface dose rate not greater than 200 millirem per hour.

(4) DECOMMISSIONING PHASE.—The term "decommissioning phase" means the period of time beginning with the end of the disposal phase and ending when all shafts at the WIPP repository have been back-filled and sealed.

(5) DISPOSAL.—The term "disposal" means permanent isolation of transuranic waste from the accessible environment with no intent of recovery, whether or not such isolation permits the recovery of such waste.

(6) DISPOSAL PHASE.—The term "disposal phase" means the period of time, during which transuranic waste is disposed of at WIPP, beginning with the initial emplacement of transuranic waste underground for disposal and ending when the last container of transuranic waste, as determined by the Secretary, is emplaced underground for disposal.

(7) DISPOSAL REGULATIONS.—The term "disposal regulations" means the environmental regulations for the disposal of spent nuclear fuel, high-level radioactive waste, and transuranic waste under section 8.

(8) EEG.—The term "EEG" means the Environmental Evaluation Group for the Waste Isolation Pilot Plant referred to in section 1433 of the National Defense Authorization Act, Fiscal Year 1989 (Pub. L. 100-456; 102 Stat. 1918, 2073).

(9) ENGINEERED BARRIERS.—The term "engineered barriers" means backfill, room seals, panel seals, and any other manmade barrier components of the disposal system.

(10) HIGH-LEVEL RADIOACTIVE WASTE.—The term "high-level radioactive waste" has the meaning given such term in section 2(12) of the Nuclear Waste Policy Act of 1982 (42 U.S.C. 10101(12)).

(11) NO-MIGRATION DETERMINATION.—The term "No-Migration Determination" means the Final Conditional No-Migration Determination for the Department of Energy Waste Isolation Pilot Plant published by the Environmental Protection Agency on November 14, 1990 (55 Fed. Reg. 47700), and any amendments thereto, pursuant to the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.).

(12) REMOTE-HANDLED TRANSURANIC WASTE.—The term "remote-handled transuranic waste" means transuranic waste with a surface dose rate of 200 millirem per hour or greater.

(13) RETRIEVAL.—The term "retrieval" means the removal of transuranic waste and the container in which it has been retained and any material contaminated by such waste from the underground repository at WIPP.

(14) SECRETARY.—The term "the Secretary" means the Secretary of Energy.

(15) SPENT NUCLEAR FUEL.—The term "spent nuclear fuel" has the meaning given such term in section 2(23) of the Nuclear Waste Policy Act of 1982 (42 U.S.C. 10101(23)).

(16) STATE.—The term "the State" means the State of New Mexico.

(17) SUPPLEMENTAL STIPULATED AGREEMENT.—The term "Supplemental Stipulated Agreement" means the Supplemental Stipulated Agreement Resolving Certain State Off-Site Concerns Over WIPP, dated December 27, 1982, to the Stipulated Agreement Between DOE and the State in *State of New Mexico ex rel. Bingaman v. DOE*, Case No. CA 81-0363 JB (D. N. Mex.), dated July 1, 1981.

(18) TRANSURANIC WASTE.—The term "transuranic waste" means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for—

(A) high-level radioactive waste;

(B) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations; or

(C) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with part 61 of title 10, Code of Federal Regulations.

(19) WIPP.—The term "WIPP" means the Waste Isolation Pilot Plant project authorized under section 213 of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub. L. 96-164; 93 Stat. 1259 1265) to demonstrate the safe disposal of radioactive waste materials generated by atomic energy defense activities.

(20) WITHDRAWAL.—The term "Withdrawal" means the geographical area consisting of the lands described in section 3(c).

SEC. 3. LAND WITHDRAWAL AND RESERVATION FOR WIPP.

(a) LAND WITHDRAWAL, JURISDICTION, AND RESERVATION.—

(1) LAND WITHDRAWAL.—Subject to valid existing rights, and except as otherwise provided in this Act, the lands described in subsection (c) are withdrawn from all forms of entry, appropriation, and disposal under the public land laws, including without limitation the mineral leasing laws, the geothermal leasing laws, the material sale laws (except as provided in section 4(b)(4) of this Act), and the mining laws.

(2) JURISDICTION.—Except as otherwise provided in this Act, jurisdiction over the Withdrawal is transferred from the Secretary of the Interior to the Secretary.

(3) RESERVATION.—Such lands are reserved for the use of the Secretary for the construction, experimentation, operation, repair and maintenance, disposal, shutdown, monitoring, decommissioning, and other authorized activities associated with the purposes of WIPP as set forth in section 213 of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub. L. 96-164; 93 Stat. 1259, 1265), and this Act.

(b) REVOCATION OF PUBLIC LAND ORDERS.—Public Land Order 6403 of June 29, 1983, as modified by Public Land Order 6826 of January 28, 1991, and any memoranda of understanding accompanying such land orders, are revoked.

(c) LAND DESCRIPTION.—

(1) BOUNDARIES.—The boundaries depicted on the map issued by the Bureau of Land Management of the Department of the Interior, entitled "WIPP Withdrawal Site Map," dated October 9, 1990, and on file

with the Bureau of Land Management, New Mexico State Office, are established as the boundaries of the Withdrawal.

(2) LEGAL DESCRIPTION AND MAP.—Within 30 days after the date of the enactment of this Act, the Secretary of the Interior shall—

(A) publish in the Federal Register a notice containing a legal description of the Withdrawal; and

(B) file copies of the map described in paragraph (1) and the legal description of the Withdrawal with the Congress, the Secretary, the Governor of the State, and the Archivist of the United States.

(d) TECHNICAL CORRECTIONS.—The map and legal description referred to in subsection (c) shall have the same force and effect as if they were included in this Act. The Secretary of the Interior may correct clerical and typographical errors in the map and legal description.

(e) WATER RIGHTS.—This Act does not establish, nor may any provision be construed to establish, a reservation to the United States with respect to any water or water rights. Nothing in this Act shall affect any water rights acquired by the United States prior to the date of enactment of this Act. The United States may apply for and obtain water rights for purposes associated with this Act only in accordance with the substantive and procedural requirements of the laws of the State.

SEC. 4. ESTABLISHMENT OF MANAGEMENT RESPONSIBILITIES.

(a) GENERAL AUTHORITY.—The Secretary shall be responsible for the management of the Withdrawal, consistent with the Federal Land Policy and Management Act of 1976 (43 U.S.C. 1701 et seq.), this Act, and other applicable law, and shall consult with the Secretary of the Interior and the State in discharging such responsibility.

(b) MANAGEMENT PLAN.—

(1) DEVELOPMENT.—Within 1 year after the date of the enactment of this Act, the Secretary, in consultation with the Secretary of the Interior and the State, shall develop a management plan for the use of the Withdrawal until the end of the decommissioning phase.

(2) PRIORITY OF WIPP-RELATED USES.—Any use of the Withdrawal for activities not associated with WIPP shall be subject to such conditions and restrictions as may be necessary to permit the conduct of WIPP-related activities.

(3) NON-WIPP RELATED USES.—The management plan developed under paragraph (1) shall provide for the maintenance of wildlife habitat and shall provide that the Secretary may permit such non-WIPP related uses of the Withdrawal as the Secretary determines to be appropriate, including domestic livestock grazing and hunting and trapping in accordance with the following requirements:

(A) GRAZING.—The Secretary may permit grazing to continue where established before the date of the enactment of this Act, subject to such regulations, policies, and practices as the Secretary, in consultation with the Secretary of the Interior, determines to be necessary or appropriate. The management of grazing shall be conducted in accord with applicable grazing laws and policies, including—

(i) the Act entitled "An Act to stop injury to public grazing lands by preventing overgrazing and soil deterioration, to provide for their orderly use, improvement, and development, to stabilize the livestock industry dependent upon the public range, and for other purposes," approved June 28, 1934 (43 U.S.C. 315 et seq., commonly referred to as the "Taylor Grazing Act");

(ii) title IV of the Federal Land Policy and Management Act of 1976 (43 U.S.C. 1751 et seq.); and

(iii) the Public Rangelands Improvement Act of 1978 (43 U.S.C. 1901 et seq.).

(B) HUNTING AND TRAPPING.—The Secretary may permit hunting and trapping within the Withdrawal in accordance with applicable laws and regulations of the United States and the State, except that the Secretary, after consultation with the Secretary of the Interior and the State, may issue regulations designating zones where, and establishing periods when, no hunting or trapping is permitted for reasons of public safety, administration, or public use and enjoyment.

(4) DISPOSAL OF SALT TAILINGS.—The Secretary shall dispose of salt tailings extracted from the Withdrawal that the Secretary determines are not needed for backfill at WIPP. Disposition of such tailings shall be made under sections 2 and 3 of the Act of July 31, 1947, (30 U.S.C. 602, 603; commonly referred to as the "Materials Act of 1947").

(5) MINING.—

(A) IN GENERAL.—Except as provided in subparagraph (B), no surface or subsurface mining or oil or gas production, including slant drilling from outside the boundaries of the Withdrawal, shall be permitted

at any time (including after decommissioning) on lands on or under the Withdrawal.

(B) EXCEPTION.—Existing rights under Federal Oil and Gas Leases No. NMNM 02953 and No. NMNM 02953C shall not be affected unless the Administrator determines, after consultation with the Secretary and the Secretary of the Interior, that the acquisition of such leases by the Secretary is required to comply with the final disposal regulations.

(c) CLOSURE TO PUBLIC.—If during the land withdrawal made by section 3(a) the Secretary determines, in consultation with the Secretary of the Interior, that the health and safety of the public or the common defense and security require the closure to the public use of any road, trail, or other portion of the Withdrawal, the Secretary may take whatever action the Secretary determines to be necessary to effect and maintain the closure and shall provide notice to the public of such closure.

(d) MEMORANDUM OF UNDERSTANDING.—The Secretary and the Secretary of the Interior shall enter into a memorandum of understanding to implement the management plan developed under subsection (b). Such memorandum shall remain in effect until the end of the decommissioning phase.

(e) SUBMISSION OF PLAN.—Within 1 year after the date of the enactment of this Act, the Secretary shall submit the management plan developed under subsection (b) to the Congress and the State. Any amendments to the plan shall be submitted promptly to the Congress and the State.

SEC. 6. TEST PHASE ACTIVITIES.

(a) STUDY—The following study shall be conducted:

(1) IN GENERAL.—Within 3 years after the date of the enactment of this Act, the Secretary shall complete a study on remote-handled transuranic waste in consultation with affected States, the Administrator, and after the solicitation of views of other interested parties.

(2) REQUIREMENTS OF STUDY.—Such study shall include an analysis of the impact of remote-handled transuranic waste on the performance assessment of WIPP and a comparison of remote-handled transuranic waste with contact-handled transuranic waste on such issues

as gas generation, flammability, explosiveness, solubility, and brine and geochemical interactions.

(3) PUBLICATION.—The Secretary shall publish the findings of such study in the Federal Register.

(b) PERFORMANCE ASSESSMENT REPORT.—

(1) IN GENERAL.—The Secretary shall publish a performance assessment report as necessary to demonstrate the long-term performance of WIPP. Each such report shall be provided to the State, the Administrator, the National Academy of Sciences, and the EEG for their review and comment.

(2) RESPONSES BY SECRETARY TO COMMENTS.—If, within 120 days of the publication of a performance assessment report under paragraph (1), the State, the Administrator, the National Academy of Sciences, or the EEG provide written comments on the report, the Secretary shall submit written responses to the comments to the State, the Administrator, the National Academy of Sciences, and the EEG, and to other appropriate entities or persons after consultation with the State, within 120 days of receipt of the comments.

SEC. 7. DISPOSAL OPERATIONS.

(a) TRANSURANIC WASTE LIMITATIONS.—

(1) REM LIMITS FOR REMOTE-HANDLED TRANSURANIC WASTE.—

(A) 1,000 REMS PER HOUR.—No transuranic waste received at WIPP may have a surface dose rate in excess of 1,000 rems per hour.

(B) 100 REMS PER HOUR.—No more than 5 percent by volume of the remote-handled transuranic waste received at WIPP may have a surface dose rate in excess of 100 rems per hour.

(2) CURIE LIMITS FOR REMOTE-HANDED TRANSURANIC WASTE.—

(A) CURIES PER LITER.—Remote-handled transuranic waste received at WIPP shall not exceed 23 curies per liter maximum activity level (averaged over the volume of the canister).

(B) TOTAL CURIES.—The total curies of the remote-handled transuranic waste received at WIPP shall not exceed 5,100,000 curies.

(3) CAPACITY OF WIPP.—The total capacity of WIPP by volume is 6.2 million cubic feet of transuranic waste.

(b) REQUIREMENTS FOR COMMENCEMENT OF DISPOSAL OPERATIONS.—The Secretary may commence emplacement of transuranic waste underground for disposal at WIPP only upon completion of—

(1) the Administrator's certification under section 8(d)(1) that the WIPP facility will comply with the final disposal regulations;

(2) the acquisition by the Secretary (whether by purchase, condemnation, or otherwise) of Federal Oil and Gas Leases No. NMNM 02953 and No. NMNM 02953C, unless the Administrator determines under section 4(b)(5) that such acquisition is not required; and

(3) the 30-day period beginning on the date on which the Secretary notifies Congress that the requirements of section 9(a)(1) have been met.

SEC. 8. ENVIRONMENTAL PROTECTION AGENCY DISPOSAL REGULATIONS.

(a) REINSTATEMENT.—

(1) IN GENERAL.—Except as provided in paragraph (2), the disposal regulations issued by the Administrator on September 19, 1985, and contained in subpart B of part 191 of title 40, Code of Federal Regulations, shall be in effect.

(2) EXCEPTIONS.—Paragraph (1) shall not apply to—

(A) the 3 aspects of sections 191.15 and 191.16 of such regulations that were the subject of the remand ordered in Natural Resources Defense Council, Inc. v. United States Environmental Protection Agency, 824 F.2d 1258 (1st Cir. 1987); and

(B) the characterization, licensing, construction, operation, or closure of any site required to be characterized under section 113(a) of Public Law 97-425.

(b) ISSUANCE OF REGULATIONS.—

(1) IN GENERAL.—Subject to the limitation in paragraph (2), the Administrator shall issue, not later than 6 months after the date of the enactment of this Act, final disposal regulations. Such regulations shall be issued in a rulemaking proceeding conducted under section 553 of title 5, United States Code, except that sections 556 and 557 of such title shall not apply.

(2) LIMITATION.—The regulations required by this subsection shall not be applicable to the characterization, licensing, construction, operation,

or closure of any site required to be characterized under section 113(a) of Public Law 97-425.

(c) ISSUANCE OF CRITERIA FOR CERTIFICATION OF COMPLIANCE WITH DISPOSAL REGULATIONS.—

(1) PROPOSED CRITERIA.—Not later than 1 year after the date of the enactment of this Act, the Administrator shall, by rule pursuant to section 553 of title 5, United States Code, propose criteria for the Administrator's certification of compliance with the final disposal regulations, and sections 556 and 557 of such title shall not apply.

(2) FINAL CRITERIA.—Not later than 2 years after the date of the enactment of this Act, the Administrator shall, by rule pursuant to section 553 of title 5, United States Code, issue final criteria for the Administrator's certification of compliance with the final disposal regulations, and sections 556 and 557 of such title shall not apply.

(d) DISPOSAL REGULATIONS.—

(1) APPLICATION FOR COMPLIANCE.—Within 30 days after the date of the enactment of the Waste Isolation Pilot Plant Land Withdrawal Amendment Act, the Secretary shall provide to Congress a schedule for the incremental submission of chapters of the application to the Administrator beginning no later than 30 days after the date of the submittal of the schedule. The Administrator shall review the submitted chapters and provide requests for additional information from the Secretary as needed for completeness within 45 days of the receipt of each chapter. The Administrator shall notify Congress of such requests. The schedule shall call for the Secretary to submit all chapters to the Administrator no later than October 31, 1996. The Administrator may at any time request additional information from the Secretary as needed to certify, pursuant to paragraph (2), whether the WIPP facility will comply with the final disposal regulations.

(2) CERTIFICATION BY ADMINISTRATOR.—Within 1 year of receipt of the application under paragraph (1), the Administrator shall certify, by rule pursuant to section 553 of title 5, United States Code, whether the WIPP facility will comply with the final disposal regulations, and sections 556 and 557 of such title shall not apply.

(3) JUDICIAL REVIEW.—Judicial review of the certification of the Administrator under paragraph (2) shall not be restricted by the provisions of section 221 c. of the Atomic Energy Act of 1954 (42 U.S.C. 2271(c)).

(4) LIMITATION.—Any certification of the Administrator under paragraph (2) may only be made after the full application has been submitted to the Administrator under paragraph (1).

(e) CONFLICT RESOLUTION.—If the State disagrees with the Secretary's application under subsection (d)(1)(A), the State may invoke the conflict resolution provisions of the Agreement.

(f) PERIODIC RECERTIFICATION.—

(1) BY SECRETARY.—Not later than 5 years after the initial receipt of transuranic waste for disposal at WIPP, and every 5 years thereafter until the end of the decommissioning phase, the Secretary shall submit to the Administrator and the State documentation of continued compliance with the final disposal regulations.

(2) CONCURRENCE BY ADMINISTRATOR.—The Administrator shall, not later than 6 months after receiving a submission under paragraph (1), determine whether or not the WIPP facility continues to be in compliance with the final disposal regulations. A determination under this paragraph shall not be subject to rulemaking or judicial review.

(g) ENGINEERED AND NATURAL BARRIERS, ETC.—The Secretary shall use both engineered and natural barriers and any other measures (including waste form modifications) to the extent necessary at WIPP to comply with the final disposal regulations.

SEC. 9. COMPLIANCE WITH ENVIRONMENTAL LAWS AND REGULATIONS.

(a) IN GENERAL.—

(1) APPLICABILITY.—Beginning on the date of the enactment of this Act, the Secretary shall comply with respect to WIPP, with—

(A) the regulations issued by the Administrator establishing the generally applicable environmental standards for the management and storage of spent nuclear fuel, high-level radioactive waste, and transuranic radioactive waste and contained in subpart A of part 191 of title 40, Code of Federal Regulations;

(B) the Clean Air Act (40 U.S.C. 7401 et seq.);

(C) the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.);

(D) title XIV of the Public Health Service Act (42 U.S.C. 300f et seq.; commonly referred to as the "Safe Drinking Water Act");

(E) the Toxic Substances Control Act (15 U.S.C. 2601 et seq.);

(F) the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (42 U.S.C. 9601 et seq.);

(G) all other applicable Federal laws pertaining to public health and safety or the environment; and

(H) all regulations promulgated, and all permit requirements, under the laws described in subparagraphs (B) through (G).

With respect to transuranic mixed waste designated by the Secretary for disposal at WIPP, such waste is exempt from treatment standards promulgated pursuant to section 3004(m) of the Solid Waste Disposal Act (42 U.S.C. 6924(m)) and shall not be subject to the land disposal prohibitions in section 3004(d), (e), (f), and (g) of the Solid Waste Disposal Act.

(2) PERIODIC OVERSIGHT BY ADMINISTRATOR AND STATE.—The Secretary shall, not later than 2 years after the date of the enactment of this Act, and biennially thereafter, submit documentation of continued compliance with the laws, regulations, and permit requirements described in paragraph (1) to the Administrator, and, with the law described in paragraph (l)(C), to the State.

(3) DETERMINATION BY ADMINISTRATOR OR STATE.—The Administrator or the State, as appropriate, shall determine not later than 6 months after receiving a submission under paragraph (2) whether the Secretary is in compliance with the laws, regulations, and permit requirements described in paragraph (1) with respect to WIPP.

(c) DETERMINATION OF NONCOMPLIANCE DURING DISPOSAL PHASE AND DECOMMISSIONING PHASE.—

(1) DETERMINATION BY THE ADMINISTRATOR.—If the Administrator determines at any time during the disposal phase or decommissioning phase that the WIPP facility does not comply with any law, regulation, or permit requirement described in subsection (a)(1), the Administrator shall request a remedial plan from the Secretary describing actions the Secretary will take to comply with such law, regulation, or permit requirement.

(d) SAVINGS PROVISION.—The authorities provided to the Administrator and to the State pursuant to this section are in addition to the enforcement authorities available to the State pursuant to State law and to the Administrator, the State, and any other person, pursuant to the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.) and the Clean Air Act (40 U.S.C. 7401 et seq.).

SEC. 10. SENSE OF CONGRESS ON COMMENCEMENT OF EMPLACEMENT OF TRANSURANIC WASTE.

It is the sense of Congress that the Secretary should complete all actions required under section 7(b) to commence emplacement of transuranic waste underground for disposal at WIPP not later than November 30, 1997, provided that before that date all applicable health and safety standards have been met and all applicable laws have been complied with.

SEC. 11. MINE SAFETY.

(a) MINE SAFETY AND HEALTH ADMINISTRATION.—The Mine Safety and Health Administration of the Department of Labor shall inspect WIPP not less than 4 times each year and in the same manner as it evaluates mine sites under the Federal Mine Safety and Health Act of 1977 (30 U.S.C. 801 et seq.), and shall provide the results of its inspections to the Secretary. The Secretary shall make the results of such inspections publicly available and shall take necessary actions to ensure the prompt and effective correction of any deficiency, including suspending specific activities as necessary to address identified health and safety deficiencies.

(b) BUREAU OF MINES.—The Bureau of Mines of the Department of the Interior shall prepare an annual evaluation of the safety of WIPP.

SEC. 12. BAN ON HIGH-LEVEL RADIOACTIVE WASTE AND SPENT NUCLEAR FUEL.

The Secretary shall not transport high-level radioactive waste or spent nuclear fuel to WIPP or emplace or dispose of such waste or fuel at WIPP.

SEC. 13. DECOMMISSIONING OF WIPP.

The Secretary shall develop a plan for the management and use of the Withdrawal following the decommissioning of WIPP or the termination of the land withdrawal. The Secretary shall consult with the Secretary of

the Interior and the State in the preparation of such plan and shall submit such plan to the Congress.

SEC. 14. SAVINGS PROVISIONS.

(a) CAA AND SWDA.—Except for the exemption from the land disposal restrictions described in section 9(a)(1), no provision of this Act may be construed to supersede or modify the provisions of the Clean Air Act (42 U.S.C. 7401 et seq.) or the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.).

(b) EXISTING AUTHORITY OF EPA AND STATE.—No provision of this Act may be construed to limit, or in any manner affect, the Administrator's or the State's authority to enforce, or the Secretary's obligation to comply with—

(1) the Clean Air Act (42 U.S.C. 7401 et seq.);

(2) the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.), except that the transuranic mixed waste designated by the Secretary for disposal at WIPP is exempt from the land disposal restrictions described in section 9(a)(1); or

(3) any other applicable clean air or hazardous waste law.

SEC. 15. ECONOMIC ASSISTANCE AND MISCELLANEOUS PAYMENTS.

(a) 14-YEAR AUTHORIZATION.—There are authorized to be appropriated to the Secretary for payments to the State $20,000,000 for each of the 14 fiscal years beginning with fiscal year 1998. The authorization of appropriations for funds for payments to the State under the preceding sentence shall be separate from any authorization of appropriations of funds for WIPP.

(b) SUBSEQUENT AUTHORIZATIONS.—There are authorized to be appropriated to the Secretary, for payments to the State for any fiscal year after the last fiscal year to which subsection (a) applies, such sums as the Congress may, by law, authorize to be appropriated.

(c) INFLATION ADJUSTMENT.—

(1) IN GENERAL.—In the case of any fiscal year after the first fiscal year to which subsection (a) applies, the dollar amount specified in such subsection shall be increased or decreased, as the case may be, by an amount equal to—

(A) such dollar amount; multiplied by

(B) the inflation increase or decrease determined under paragraph (2).

(2) CALCULATION OF INFLATION INCREASE OR DECREASE.—For purposes of paragraph (1), the inflation increase or decrease for any fiscal year is the percentage (if any) by which the inflation index for the preceding fiscal year is greater than or less than, as the case may be, the inflation index for the fiscal year prior to the first fiscal year to which subsection (a) applies.

(3) INFLATION INDEX.—For purposes of paragraph (2), the inflation index for any fiscal year is the average of the Consumer Price Index (as published by the Department of Labor) for the 12 months in such fiscal year.

(d) ELIGIBLE ASSISTANCE.—A portion of the payments under this section—

(1) shall be made available to units of local government in Lea and Eddy counties in the State; and

(2) may also be provided for independent environmental assessment and economic studies associated with WIPP.

SEC. 16. TRANSPORTATION.

(a) SHIPPING CONTAINERS.—No transuranic waste may be transported by or for the Secretary to or from WIPP, except in packages—

(1) the design of which has been certified by the Nuclear Regulatory Commission; and

(2) that have been determined by the Nuclear Regulatory Commission to satisfy its quality assurance requirements. The determination under paragraph (2) shall not be subject to rulemaking or judicial review.

(b) NOTIFICATION.—In addition to activities required pursuant to the Supplemental Stipulated Agreement, prior to any transportation of transuranic waste by or for the Secretary to or from WIPP, the Secretary shall provide advance notification to States and Indian tribes through whose jurisdiction the Secretary plans to transport transuranic waste to or from WIPP.

(c) ACCIDENT PREVENTION AND EMERGENCY PREPAREDNESS.—

(1) TRAINING.—

(A) IN GENERAL.—In addition to activities required pursuant to the Supplemental Stipulated Agreement, the Secretary shall, to the extent provided in appropriation Acts, provide technical assistance and funds for the purpose of training public safety officials, and other emergency responders as described in part 1910.120 of title 29, Code of Federal Regulations, in any State or Indian tribe through whose jurisdiction the Secretary plans to transport transuranic waste to or from WIPP. Within 30 days of the date of the enactment of this Act, the Secretary shall submit a report to the Congress and to the States and Indian tribes through whose jurisdiction the Secretary plans to transport transuranic waste on the training provided through fiscal year 1992.

(B) ONGOING TRAINING.—If determined by the Secretary, in consultation with affected States and Indian tribes, to be necessary and appropriate, training described in subparagraph (A) shall continue after the date of the enactment of this Act until the transuranic waste shipments to or from WIPP have been terminated.

(C) REVIEW OF TRAINING.—The Secretary shall periodically review the training provided pursuant to subparagraph (A) in consultation with affected States and Indian tribes. The training shall also be reviewed by the Occupational Safety and Health Administration, and the National Institute for Occupational Safety and Health, for compliance with part 1910.120 of title 29, Code of Federal Regulations.

(D) COMPONENTS OF TRAINING.—The training shall cover procedures required for the safe routine transportation of transuranic waste, as well as procedures for dealing with emergency response situations, including—

(i) instruction of government officials and public safety officers in procedures for the command and control of the response to any incident involving the waste;

(ii) instruction of emergency response personnel in procedures for the initial response to an incident involving transuranic waste being transported to or from WIPP;

(iii) instruction of radiological protection and emergency medical personnel in procedures for responding to an incident involving transuranic waste being transported to or from WIPP; and

(iv) a program to provide information to the public about the transportation of transuranic waste to or from WIPP.

(2) EQUIPMENT.—The Secretary shall enter into agreements to assist States through monetary grants or contributions in-kind, to the extent provided in appropriation Acts, in acquiring equipment for response to an incident involving transuranic waste transported to or from WIPP.

(d) TRANSPORTATION SAFETY PROGRAMS.—The Secretary shall, to the extent provided in appropriation Acts, provide in-kind, financial, technical, and other appropriate assistance to any State or Indian tribe through whose jurisdiction the Secretary plans to transport transuranic waste to or from WIPP, for the purpose of WIPP-specific transportation safety programs not otherwise addressed in this section. These programs shall be developed with, and monitored by, the Secretary.

(e) SANTA FE BYPASS.—No transuranic waste may be transported from the Los Alamos National Laboratory to WIPP until—

(1) an amount of funds sufficient to construct the Santa Fe bypass has been made available to the State;

(2) the Santa Fe bypass has been completed; or

(3) the Administrator has made the certification required under section 8(d)(1)(B).

(f) STUDY OF TRANSPORTATION ALTERNATIVES.—

(1) IN GENERAL.—The Secretary shall conduct a study comparing the shipment of transuranic waste to the WIPP facility by truck and by rail, including the use of dedicated trains, and shall submit a report on the study in accordance with paragraph (2). Such report shall include—

(A) a consideration of occupational and public risks and exposures, and other environmental impacts;

(B) a consideration of emergency response capabilities; and

(C) an estimation of comparative costs.

(2) REPORT.—The report required in paragraph (1) shall be submitted to the Congress not later than 1 year after the date of the enactment of this Act.

(g) EMERGENCY RESPONSE MEDICAL TRAINING.—

(1) DETERMINATION OF SECRETARY.—If the Secretary determines that emergency response medical training for incidents involving transuranic waste being transported to or from WIPP is inadequate, the Secretary shall take immediate action to correct the inadequacies and, if necessary, suspend transportation of such transuranic waste. If the State disagrees with the Secretary's determination under

this paragraph, the State may invoke the conflict resolution provisions of the Agreement.

(2) STATE ADVISORY GROUP.—The Secretary shall encourage the Governor of the State to appoint, within 30 days after the date of the enactment of this Act, an advisory group of health professionals and other experts in the field to review emergency response medical training programs for incidents involving transuranic waste being transported to or from WIPP. If such advisory group is established—

(A) its purpose shall be to review, within 60 days after its establishment and annually thereafter, the Department of Energy's emergency response medical training programs for incidents involving transuranic waste being transported to or from WIPP, and to report its findings to the State, the Secretary of Labor, acting through the Occupational Safety and Health Administration, and the Secretary; and

(B) the Secretary shall review the findings of the advisory group in consultation with the Secretary of Labor, acting through the Occupational Safety and Health Administration.

SEC. 17. ACCESS TO INFORMATION.

(a) IN GENERAL.—The Secretary shall—

(1) provide the State, the National Academy of Sciences, and the EEG with free and timely access to data relating to health, safety, or environmental issues at WIPP;

(2) provide the State and the EEG with preliminary reports relating to health, safety, or environmental issues at WIPP; and

(3) to the extent practicable, permit the State and the EEG to attend meetings relating to health, safety, or environmental issues at WIPP with expert panels and peer review groups.

(b) EVALUATION AND PUBLICATION.—The State, the National Academy of Sciences, and the EEG may evaluate and publish analyses of the Secretary's plans for test phase activities, monitoring, transportation, operations, decontamination, retrieval, performance assessment, compliance with Environmental Protection Agency regulations, decommissioning, safety analyses, and other activities relating to WIPP.

(c) CONSULTATION AND COOPERATION.—The Secretary shall consult and cooperate with the EEG under the terms of Contract No. DE-AC04-89AL53309 in the performance of its responsibility to conduct

an independent technical review and evaluation of WIPP under section 1433 of the National Defense Authorization Act, Fiscal Year 1989 (102 Stat. 2073).

SEC. 18. JUDICIAL REVIEW OF EPA ACTIONS.

A civil action for judicial review of any final action of the Administrator under this Act may be brought only in the United States Court of Appeals for the Tenth Circuit or for the District of Columbia, and shall be brought not later than the 60th day after the date of such final action.

SEC. 19. TECHNOLOGY STUDY.

Within 3 years after the date of the enactment of this Act, the Secretary shall submit to the Congress a study reviewing the technologies that are available and that are being developed for the processing or reduction of volumes of radioactive wastes. The study shall include an identification of technologies involving the use of chemical, physical, and thermal (including plasma) processing techniques.

SEC. 20. STATEMENT FOR PURPOSES OF PUBLIC LAW 96-164.

For purposes of subsection (c) of section 213 of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub. L. 96-164; 93 Stat. 1265), this Act shall be considered to amend such section.

SEC. 21. CONSULTATION AND COOPERATION AGREEMENT.

Nothing in this Act shall affect the Agreement or the Supplemental Stipulated Agreement between the State and the United States Department of Energy except as explicitly stated herein.

SEC. 22. BUY AMERICAN REQUIREMENTS.

(a) COMPLIANCE WITH BUY AMERICAN ACT.—No funds appropriated or transferred pursuant to this Act may be expended by an

entity unless the entity agrees that in expending the assistance the entity will comply with sections 2 through 4 of the Act of March 3, 1933 (41 U.S.C. 10a-10c, popularly known as the "Buy American Act").

(b) PURCHASE OF AMERICAN-MADE EQUIPMENT AND PRODUCTS.—

(1) IN GENERAL.—In the case of any equipment or product that may be authorized to be purchased with financial assistance provided under this Act, it is the sense of the Congress that entities receiving the assistance should, in expending the assistance, purchase only American-made equipment and products.

(2) NOTICE TO RECIPIENTS OF ASSISTANCE.—In providing financial assistance under this Act, the Secretary shall provide to each recipient of the assistance a notice describing the statement made in paragraph (1) by the Congress.

SEC. 23. AUTHORIZATIONS OF APPROPRIATIONS.

(a) FOR ADMINISTRATOR.—

(1) IN GENERAL.—There are authorized to be appropriated to the Administrator for the purpose of fulfilling the responsibilities of the Administrator under this Act, $10,000,000 for fiscal year 1992, $12,000,000 for fiscal year 1993, $14,000,000 for fiscal year 1994, and such sums as may be necessary for fiscal years 1995 through 2001.

(2) REPORT.—The Administrator shall, not later than September 30, 1993, and annually thereafter, issue a report to the Congress on the status of and resources required for the fulfillment of the Administrator's responsibilities under this Act.

(b) TRANSFERS FROM SECRETARY TO ADMINISTRATOR AND SECRETARY OF LABOR.—The Secretary is authorized to transfer from amounts appropriated for environmental restoration and waste management for fiscal years 1992 and 1993, and (to the extent approved in appropriation Acts) for fiscal years 1994 through 2001, such sums as may be necessary to fulfill the responsibilities of the Administrator under this Act and the Secretary of Labor under, paragraphs (4) and (6) of section 6(b).

(c) ACQUISITION OF LEASEHOLD.—There are authorized to be appropriated to the Secretary such sums as may be necessary to acquire the Federal Oil and Gas Leases No. NMNM 02953 and No. NMNM 02953C.

Approved October 30, 1992.
Amended September 23, 1996.

U.S. NUCLEAR REGULATORY COMMISSION

U.S. ENVIRONMENTAL PROTECTION AGENCY

Joint Guidance on Testing Requirements for Mixed Radioactive and Hazardous Waste

Clarification of RCRA Hazardous Waste Testing Requirements for Low-Level Radioactive Mixed Waste—Final Guidance

Disclaimer: The policies discussed in this document are not final Agency actions, but are intended solely as guidance. They are not intended, nor can they be relied upon, to create any rights enforceable by any party in litigation with the United States. The Environmental Protection Agency and Nuclear Regulatory Commission may follow the guidance, or act at variance with the guidance, based on an analysis of specific site circumstances. The agencies also reserve the right to change the guidance at any time, without public notice.

I. Background

Mixed waste is defined as waste that contains both hazardous waste subject to the requirements of the Resource Conservation and Recovery Act (RCRA) and source, special nuclear, or byproduct material subject to the requirements of the Atomic Energy Act (AEA).[1] This guidance addresses testing activities related to mixed low-level waste (LLW), which is a subset of mixed waste.[2] The term ''mixed waste,'' for the purposes of this document, will refer to mixed LLW. Additional information on the testing of hazardous wastes, which could apply to both mixed LLW and other types of mixed waste (e.g., high-level and transuranic mixed waste), is found in Appendix A. The information below is intended for use by Nuclear Regulatory Commission (NRC) licensees that may not be familiar with the hazardous waste characterization and testing requirements that apply to mixed waste. The guidance assumes that the reader is familiar with the NRC's regulations and regulatory framework for the management of radioactive material and focuses on compliance with the Environmental Protection Agency's (EPA's) requirements for the management of hazardous waste. Although it is written for commercial mixed

waste generators, the guidance may also be useful for Federal facilities that generate mixed waste.

Users of this guidance should have a good understanding of how mixed waste is defined (see above), and what authority, or authorities, regulate mixed waste testing activities. The hazardous component of mixed waste is regulated by EPA in those States where EPA implements the entire RCRA Subtitle C hazardous waste program (i.e., unauthorized States). Currently, EPA regulates mixed waste in Alaska, Hawaii, Iowa, Puerto Rico, the Virgin Islands, and American Samoa. In most instances mixed waste is regulated by State governments. Thirty-nine States and one territory (Guam) have been delegated authority by EPA to implement the base RCRA hazardous waste program and to regulate mixed waste activities (see 51 *FR* 24504, July 3, 1986, and Appendix B). These States are referred to as ''mixed waste authorized States.'' Nine additional States are authorized for the RCRA base hazardous waste program but have not been delegated authority by EPA to regulate mixed waste.[3] In these States mixed waste is not regulated by EPA, but may be regulated by States under the authority of State law. It is important that licensees contact the State hazardous waste agencies in authorized States to determine the specific testing, analysis, and other hazardous waste requirements that may apply to mixed waste managed in their State, because their State may have more stringent requirements than the Federal requirements discussed in this guidance.

This guidance describes:

(1) The current regulatory requirements for determining if a waste is a RCRA hazardous waste;
(2) The role of waste knowledge for hazardous waste determinations;
(3) The waste analysis information necessary for proper treatment, storage, and disposal of mixed waste; and,
(4) The implications of the RCRA land disposal restrictions (LDRs) on the waste characterization and analysis requirements.

This information should be useful for:

(1) radioactive waste generators, who must determine if their waste is a RCRA hazardous waste, and therefore a mixed waste;

(2) for those generators storing mixed waste on-site in tanks, containers or containment buildings for longer than 90 days, that consequently become responsible for complying with RCRA and NRC storage requirements; and
(3) those facilities that accept mixed waste for off-site treatment, storage, or disposal.

Generators and/or treatment, storage, and disposal facilities (TSDFs) handling wastes under RCRA must characterize their waste for several purposes:

(1) To determine if their waste is a hazardous waste (40 CFR 262.11);
(2) To comply with general waste analysis requirements for new or permitted TSDFs, for TSDFs operating under interim status, and for certain generators that treat land disposal prohibited wastes in 40 CFR 264.13, 265.13 and 268.7, respectively. These analysis requirements include:
(a) chemical/physical analysis of a representative sample (and/or, in some cases, use waste knowledge (see below); and,
(b) preparation of a waste analysis plan.
(3) To meet the waste analysis requirements that apply to the specific waste management methods in 40 CFR 264.17, 264.314, 264.341, 264.1034(d), and 268.7;
(4) To ensure, prior to land disposal, that the restricted waste meets the required treatment standard (40 CFR 268.7).[4]

This guidance addresses the need for chemical analysis of mixed wastes to meet these purposes. The guidance also emphasizes ways in which unnecessary testing of mixed waste may be avoided. This is important when handling mixed waste, since each sampling, workup, or analytical event may involve an incremental exposure to radiation. This guidance encourages mixed waste handlers to use waste knowledge, such as process knowledge, where possible, in making RCRA hazardous waste determinations involving mixed waste. It also encourages the elimination of redundant testing by off-site treatment and disposal facilities, where valid generator-supplied, and certified, data are available.

Because mixed waste testing may pose the possibility of increased radiation exposures, this guidance also describes methods by which individuals

who analyze mixed waste samples may reduce their occupational radiation exposure and satisfy the intent of the RCRA testing requirements. Testing to determine whether wastes are hazardous under the RCRA toxicity characteristic may pose special concerns which are examined in Section III of this guidance.

All of the activities described in this guidance are subject to the requirements of both the AEA and RCRA. The focus of this guidance is the RCRA requirements. NRC and NRC Agreement State licensees are authorized to receive, possess, use (which includes storing, sampling, testing, and treating), and dispose of AEA-licensed materials. NRC licensees handling mixed waste should ensure that their RCRA hazardous waste testing activities are consistent with NRC, or Agreement State, regulations and license conditions. Flexibility in the RCRA requirements is emphasized so that the As Low As is Reasonably Achievable (ALARA) concept can be incorporated into the mixed waste testing activities.[5] If other AEA requirements, or RCRA requirements are difficult to meet in a specific mixed waste management situation, licensees should seek resolution by requesting license amendments, approval of modifications to their RCRA permits or interim status Part A applications, or resolution under both authorities.

Section 1006(a) of RCRA states ''Nothing in this Act shall be construed to apply to (or authorize any State, interstate, or local authority to regulate) any activity or substance which is subject to * * * the Atomic Energy Act of 1954 * * * except to the extent that such application (or regulation) is not inconsistent with the requirements of such Acts.'' If a resolution cannot be achieved through the flexibility provided by the two regulatory frameworks, then and only then, should licensees seek resolution under Section 1006(a) of RCRA. Licensees should note that, if an inconsistency exists, relief will be limited to that specific RCRA requirement, and that the determination of an inconsistency would not relieve the licensee from all other RCRA requirements. Section 1006(a) and radiological hazard considerations are addressed more fully in Sections III and IV of this guidance. NRC licensees should also include the necessary flexibility in their RCRA permit waste analysis plans to accommodate the sampling and testing required to meet AEA requirements.

II. Use of Waste Knowledge for Hazardous Waste Determinations

The use of waste knowledge by a generator and/or a TSDF to characterize mixed waste is recommended throughout this document to eliminate unnecessary or redundant waste testing. EPA interprets ‘‘waste knowledge’’ or ‘‘acceptable knowledge’’ of a waste broadly to include, where appropriate:

- ‘‘Process knowledge’’;
- Records of analyses performed by generator or TSDF prior to the effective date of RCRA regulations; or,
- A combination of the above information, supplemented with chemical analysis.

Process knowledge refers to detailed information on processes that generate wastes subject to characterization, or to detailed information (e.g., waste analysis data or studies) on wastes generated from processes similar to that which generated the original waste. Process knowledge includes, for example, waste analysis data obtained by TSDFs from the specific generators that sent the waste off-site, and waste analysis data obtained by generators or TSDFs from other generators, TSDFs or areas within a facility that test chemically identical wastes.[6]

Waste knowledge is allowed by RCRA regulations for the following hazardous waste characterization determinations:

- To determine if a waste is characteristically hazardous (40 CFR 262.11(c)(2)) or matches a RCRA listing in 40 CFR Part 261, Subpart D (40 CFR 262.11(a) and (b));
- To comply with the requirement to obtain a detailed chemical/physical analysis of a representative sample of the waste under 40 CFR 264.13(a);
- To determine whether a hazardous waste is restricted from land disposal (40 CFR 268.7(a)); and,
- To determine if a restricted waste the generator is managing can be land disposed without further treatment (see the generator certification in 40 CFR 268.7(a)(3) and information to support the waste kn/wledge determination in 40 CFR 268.7(a)(6)).

Hazardous waste, including mixed waste, may be characterized by waste knowledge alone, by sampling and laboratory analysis, or a combination of waste knowledge, and sampling and laboratory analysis. The use of waste knowledge alone is appropriate for wastes that have physical properties that are not conducive to taking a laboratory sample or performing laboratory analysis. As such, the use of waste knowledge alone may be the most appropriate method to characterize mixed waste streams where increased radiation exposures are a concern. Mixed waste generators should contact the appropriate EPA regional office to determine whether they possess adequate waste knowledge to characterize their mixed waste.

III. Determinations by Generators That a Waste Is Hazardous

A solid waste is a RCRA hazardous waste if it meets one of two conditions:

(1) the waste is specifically ''listed'' in 40 CFR Part 261, Subpart D, or; (2) the waste exhibits one of the four ''characteristics'' identified in 40 CFR Part 261, Subpart C. These characteristics are:

- Ignitability;
- Corrosivity;
- Reactivity; or,
- Toxicity.

(a) Listed Hazardous Wastes

Generators of waste containing a radioactive and solid waste component must establish whether the solid waste component is a RCRA hazardous waste. Determinations of whether a waste is a listed hazardous waste can be made by comparing information on the waste stream origin with the RCRA listings set forth in 40 CFR Part 261, Subpart D. These listings are separated into three major categories or lists, and are identified by EPA hazardous waste numbers. Most hazardous waste numbers are associated with a specific waste description, specific processes that produce wastes, or certain chemical compounds. For example, K103 waste is defined as ''process residues from aniline extraction from the production of aniline.'' A generator who produces such residues should know,

without any sampling or analysis, that these wastes are ''listed'' RCRA hazardous wastes by examining the K103 hazardous waste description in the hazardous waste lists. Other hazardous waste numbers describe wastes generated from generic processes that are common to various industries and activities. These wastes are referred to as hazardous wastes from nonspecific sources. Radioactively contaminated spent solvents are the most likely mixed wastes to be nonspecific source listed wastes. For example, a generator using one of the F002 halogenated solvents (e.g., tetrachloroethylene, trichloroethylene, and chlorobenzene, etc.) to remove paint from a radiologically contaminated surface, can determine that this waste is a listed RCRA hazardous waste by examining the F002 waste definition for the solvent type, and for a solvent mixture/blend, the percent solvent by volume.

In addition to wastes that are specifically listed as hazardous, the ''derived from'' and ''mixture'' rules state that any solid waste derived from the treatment, storage, or disposal of a listed RCRA hazardous waste, or any solid waste mixed with a listed RCRA hazardous waste, respectively, is itself a listed RCRA hazardous waste until delisted (see 40 CFR 261.3).[7] (Note that soil and debris can be managed as hazardous wastes if they contain listed hazardous wastes or they exhibit one or more hazardous waste characteristics. See hazardous debris definition in 40 CFR 268.2.)

Exceptions to the ''mixture rule'' and ''derived from'' rules exist for certain solid wastes. For example, wastewater discharges subject to Clean Water Act permits, under certain circumstances, are not RCRA hazardous (see 40 CFR 261.3(a)(2)(iv)). Also, hazardous wastes which are listed solely for a characteristic identified in Subpart C of 40 CFR Part 261 (e.g., a F003 spent solvent which is listed only because it is ignitable) are not considered hazardous wastes when they are mixed with a solid waste and the resultant mixture no longer exhibits any characteristic of a hazardous waste (see 40 CFR 261.3(a)(2)(iii)). Likewise, waste pickle liquor sludge ''derived from'' the lime stabilization of spent pickle liquor (e.g., K062) is not a RCRA listed hazardous waste, if the sludge does not exhibit a hazardous waste characteristic (see discussion below on characteristic hazardous wastes). It should be noted, however, that wastes such as F003 and K062 *must* meet LDR treatment standards. Outside of the exceptions mentioned here and in the RCRA regulations, a hazardous

waste that was generated via the ‘‘mixture rule’’ or the ‘‘derived from’’ rule must be delisted through a specific EPA petition process for the listed waste to be considered only a solid waste, and no longer managed as a listed hazardous waste under the RCRA Subtitle C system.

When applying the mixture rule to hazardous wastes, including mixed wastes, generators should be aware that EPA prohibits the dilution (i.e., mixing) of land disposal restricted waste or treatment residuals as a substitute for adequate treatment (see 40 CFR 268.3). An exception to the prohibition is the dilution of purely corrosive, and in some cases, reactive, or ignitable nontoxic wastes to eliminate the characteristic, or the aggregation of characteristic wastes in (pre)treatment systems regulated under the Clean Water Act (55 *FR* 22665).

(b) Characteristic Hazardous Wastes

Hazardous characteristics are based on the physical/chemical properties of wastes. Thus, physical/chemical testing of waste may be appropriate for determining whether a waste is a characteristic hazardous waste. *RCRA regulations, however, do not require testing. Rather, generators must determine whether the waste is a RCRA hazardous waste.* Such a determination may be made based on one’s knowledge of the materials or chemical processes that were used. EPA’s regulations are clear on this point. 40 CFR 262.11(c) states:

‘‘. . . if the waste is not listed [as hazardous waste] in Subpart D [of 40 CFR Part 261], the generator must then determine whether the waste is identified in Subpart C of 40 CFR Part 261 by either:

(1) Testing the waste according to the methods set forth in Subpart C of 40 CFR Part 261, or according to an equivalent method approved by the Administrator under 40 CFR 260.21; or
(2) Applying knowledge (emphasis added) of the hazardous characteristic of the waste in light of the materials or the processes used.’’

Therefore, where sufficient material or process knowledge exists, the generator need not test the waste to make a hazardous characteristic determination, although generators and subsequent handlers would be in

violation of RCRA, if they managed hazardous waste erroneously classified as non-hazardous, outside of the RCRA hazardous waste system. For this reason, facilities wishing to minimize testing often assume a questionable waste is hazardous and handle it accordingly.

A generator must also comply with the land disposal restriction regulations in 40 CFR 268 which require the generator to determine whether the waste is prohibited from land disposal (refer to Section V for a detailed discussion of these requirements).[8] With respect to the hazardous characteristic, and the determination as to whether a waste is restricted from land disposal under 40 CFR 268.7(a), a generator may select the option of using waste knowledge. However, if the waste is determined to be land disposal restricted in 40 CFR 268.7(a), some testing will generally be required prior to land disposal, except where technologies are specified as the treatment standard. For mixed waste, EPA recommends that the frequency of such testing be held to a minimum, in order to avoid duplicative testing and repeated exposure to radiation.

In determining whether a radioactive waste is a RCRA hazardous waste, the generator may test a surrogate material (i.e., a chemically identical material with significantly less or no radioactivity) to determine the RCRA status of the radioactive waste. This substitution of a surrogate material may either partially or completely supplant the testing of the waste. A surrogate material, however, should only be used if the surrogate material faithfully represents the hazardous constituents of the mixed waste.[9] The following example discusses the use of surrogates. A generator is required to determine if a process waste stream containing lead (D008) exceeds the regulatory level of 5.0 milligrams per liter for the toxicity characteristic (40 CFR 261.24). If this determination cannot be made based on material and process knowledge only, the generator would need to test the hazardous material. Rather than testing the radioactive waste stream, the generator may opt to test a surrogate or chemically identical non-radioactive, or lower activity, radioactive waste stream generated by similar maintenance activities in another part of the plant. This substitution of materials is acceptable as long as the surrogate material faithfully represents the characteristics of the actual waste, and testing provides sufficient information for the generator to reasonably determine if the waste is hazardous under RCRA. Non-radioactive or lower activity quality

control samples/species and spiked solutions, for instance, are acceptable to minimize exposure to radiation from duplicative mixed waste testing.

As part of the hazardous waste determination, a generator must document test results or other data and methods that it used. Specifically, 40 CFR 262.40(c) states that "a generator must keep records of any test results, waste analyses, or other determinations made in accordance with 40 CFR 262.11 for at least three years from the date that the waste was last sent to on-site or offsite treatment, storage, or disposal." Section V of this guidance contains information on record keeping requirements for land disposal restricted hazardous (and mixed) wastes.

In summary, testing listed wastes to make the hazardous waste determination is not necessary, because most RCRA hazardous waste codes or listings identify specific waste streams from specific processes or specific categories of wastes. Testing will most often occur to determine if a waste exhibits a hazardous characteristic. However, testing is not required if a generator has sufficient knowledge about the waste and its physical/chemical properties to determine that it is non-hazardous.[10] It is recognized that certain mixed waste streams, such as wastes from remediation activities or wastes produced many years ago, may have to be identified using laboratory analysis, because of a lack of waste or process information on these waste streams. Nonetheless, hazardous waste determinations based on generator knowledge can be used to reduce the sampling of mixed waste and prevent unnecessary exposure to radioactivity. The same principle holds for a generator's determination that a waste is subject to the RCRA land disposal restrictions in 40 CFR 268.7(a).

IV. Testing Protocols for Characteristics

When testing is conducted to determine whether a waste is a RCRA hazardous waste, there are acceptable test protocols or criteria for each of the four characteristics. Testing for characteristics must be done on a representative sample of the waste or using any applicable sampling methods specified in Appendix I of 40 CFR 261.[11]

Ignitability—For liquid wastes, other than aqueous solutions containing by volume less than 24 percent alcohol, the flash point is to be determined by a Pensky-Martens Closed Cup Tester, using the test method specified

in American Society of Testing and Materials (ASTM) Standard D–93–79 or D–93–80, or a Setaflash Closed Cup Tester, using the test method specified in ASTM Standard D–3278–78, or as determined by an equivalent test method approved by the Administrator under procedures set forth in 40 CFR 260.20 and 260.21 (see "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods," 3rd Ed., as amended, EPA, OSWER, SW–846, Methods 1010 and 1020[12]). (Non-liquid wastes, compressed gases, and oxidizers may exhibit the characteristic of ignitability as described in 40 CFR 261.21 (a)(2–4).)

Corrosivity—For aqueous solutions, the pH is to be determined by a pH meter using either an EPA test method (i.e., SW–846, Method 9040 or an equivalent test method approved by the Administrator under procedures set forth in 40 CFR 260.20 and 260.21.) For liquids, steel corrosion is to be determined by the test method specified in National Association of Corrosion Engineers (NACE) Standard TM–01–69 as standardized in "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods," 3rd Ed., as amended (EPA, OSWER, SW–846, Method 1110), or an equivalent test method approved by the Administrator under procedures set forth in 40 CFR 260.20 and 260.21.

Reactivity—There are no specified test protocols for reactivity. 40 CFR 261.23 defines reactive wastes to include wastes that have any of the following properties:

(1) normally unstable and readily undergoes violent change without detonating;
(2) reacts violently with water;
(3) forms potentially explosive mixtures with water;
(4) generates dangerous quantities of toxic fumes, gases, or vapors when mixed with water;
(5) in the case of cyanide- or sulfide-bearing wastes, generates dangerous quantities of toxic fumes, gases, or vapors when exposed to acidic or alkaline conditions;
(6) explodes when subjected to a strong initiating force or if heated under confinement;
(7) explodes at standard temperature and pressure; or
(8) fits within the Department of Transportation's forbidden explosives, Class A explosives, or Class B explosives classifications.[13]

EPA has elected to rely on a descriptive definition for these reactivity properties because of inherent deficiencies associated with available methodologies for measuring such a varied class of effects, with the exception of the properties discussed in No. 5, above. The method used, as guidance but not required, to quantify the reactive cyanide and sulfide bearing wastes is provided in Chapter 7 of ''Test Methods for Evaluating Solid Waste, Physical/Chemical Methods,'' 3rd Ed., as amended, EPA, OSWER, SW–846.

Toxicity Characteristic—The test method that may be used to determine whether a waste exhibits the toxicity characteristic (TC) is the Toxicity Characteristic Leaching Procedure (TCLP), as described in 40 CFR Part 261, Appendix II (SW–846, Method 1311). The TCLP was modified and revised in 55 *FR* 11798, March 29, 1990. Note that this revised TCLP is used (in most cases) for land disposal restriction compliance determinations as well. Differences between the TCLP and the previously required Extraction Procedure (EP) include improved analysis of the leaching of organic compounds, the elimination of constant pH adjustment, the addition of a milling or grinding requirement for solids (waste material solids must be milled to particles less than 9.5 mm in size), and other more detailed alterations.[14] Additionally, the TC rule added 25 organic compounds to the toxicity characteristic. The TCLP (Method 1311) recommends the use of a minimum sample size of 100 grams (solid and liquid phases as described in Section 7.2). *For mixed waste testing, sample sizes of less than 100 grams can be used, if the analyst can demonstrate that the test is still sufficiently sensitive to measure the constituents of interest at the regulatory levels specified in the TCLP and representative of the waste stream being tested*. Other variances to the published testing protocols are permissible (under 40 CFR 260.20–21), but must be approved prior to implementation by EPA. Use of a sample size of less than 100 grams is highly recommended for mixed wastes with concentrations of radionuclides that may present serious radiation exposure hazards. Additionally, Section 1.2 of the TCLP allows the option of performing a ''total constituent analysis'' on a hazardous waste or mixed waste sample, instead of the TCLP. Section 1.2 of Method 1311 states:

If a total analysis of the waste demonstrated that the individual analytes are not present in the waste, or that they are present, but at such low

concentrations that the appropriate regulatory levels could not possibly be exceeded, the TCLP need not be run.

For homogenous samples, the use of total constituent analysis in this manner eliminates the need to grind or mill solid waste samples. The grinding or milling step in the TCLP has raised ALARA concerns for individuals who test mixed waste. The use of total constituent analysis, instead of the TCLP, may also minimize the generation of secondary mixed or radioactive waste through the use of smaller sample sizes and reduction, or elimination, of high dilution volume leaching procedures.

Flexibility in Mixed Waste Testing

Flexibility exists in the hazardous waste regulations for generators, TSDFs, and mixed waste permit writers to tailor mixed waste sampling and analysis programs to address radiation hazards. For example, upon the request of a generator, a person preparing a RCRA permit for a TSDF has the flexibility to minimize the frequency of mixed waste testing by specifying a low testing frequency in a facility's waste analysis plan. EPA believes, as stated in 55 FR 22669, June 1, 1990, that ''the frequency of testing is best determined on a case-by-case basis by the permit writer.''

EPA's hazardous waste regulations also allow a mixed waste facility the latitude to change or replace EPA's test methods (i.e., *Test Methods for Evaluating Solid Waste* (SW–846)) to address radiation exposure concerns. There are only fourteen sections of the hazardous waste regulations that require the use of specific test methods or appropriate methods found in SW–846 which are outlined in Appendix A.[15] However, any person can request EPA for an equivalent testing or analytical method that would replace the required EPA method (see 40 CFR 260.21).

In a recent amendment to the testing requirements, EPA added language to SW–846 that describes fourteen citations in the RCRA program (listed in Appendix A) where the use of SW–846 methods is mandatory (Update II, 60 FR 3089, January 13, 1995). In all other cases, the RCRA program functions under what we call the Performance Based Measurement System (PBMS) approach to monitoring. Language clarifying this approach was included in the final FR Notice which promulgated Update III (62 FR 32542, June 13, 1997) and in appropriate sections

(Disclaimer, Preface and Overview, and Chapter 2) of SW–846. Under PBMS, the regulation and/or permit focus is on the question(s) to be answered by the monitoring, the degree of confidence (otherwise known as the Data Quality Objective (DQO)) or the measurement quality objectives (MQO) that must be achieved by the permittee to have demonstrated compliance, and the specific data that must be gathered and documented by the permittee to demonstrate that the objectives were actually achieved. ''Any reliable method'' may be used to demonstrate that one can see the analytes of concern in the matrix of concern at the levels of concern. Additional reference documents on the characterization and testing methods are listed in Appendix C.

NRC regulations do not describe specific testing requirements for wastes to determine if a waste is radioactive. However, both NRC and Department of Transportation regulations contain requirements applicable to characterizing the radioactive content of the waste before shipment. For example, NRC's regulations in 10 CFR 20.2006 require that the waste manifest include, as completely as practicable, the radionuclide identity and quantity, and the total radioactivity. NRC regulations also require that generators determine the disposal Class of the radioactive waste, and outline waste form requirements that must be met before the waste is suitable for land disposal. These regulations are referenced in 10 CFR 20.2006, and are outlined in detail at 10 CFR 61.55 and 61.56. Mixed waste generators are reminded that both RCRA waste testing and NRC waste form requirements must be satisfied. Generators may also be required to amend their NRC or Agreement State licenses in order to perform the tests required under RCRA. In addition, if an NRC licensee uses an outside laboratory to test his or her waste, that laboratory may be required to possess an NRC or Agreement State license. It is the responsibility of the generator to determine if the outside laboratory possesses the proper license(s) prior to transferring the waste to the laboratory for testing.

Where radioactive wastes (or wastes suspected of being radioactive) are involved in testing, it has been suggested that the testing requirements of RCRA may run counter to the aims of the AEA. The AEA requirements that have raised inconsistency concerns with respect to RCRA testing procedures include ALARA, criticality, and security. Neither EPA nor NRC is aware of any specific instances where RCRA compliance has

been inconsistent with the AEA. However, both agencies acknowledge the potential for an inconsistency to occur.[16] A licensee or applicant who suspects that an inconsistency may exist should contact both the AEA and RCRA regulatory agencies. These regulatory agencies may deliberate and consult on whether there is an unresolvable inconsistency and, if one exists, they may attempt to fashion the necessary relief from the particular RCRA provision that gives rise to the inconsistency. However, all other RCRA regulatory requirements would apply. That is, such a conclusion does not relieve hazardous waste facility owner/operators of the responsibility to ensure that the mixed waste is managed in accordance with all other applicable RCRA regulatory requirements. Owner/operators of mixed waste facilities are encouraged to address and document this potential situation and its resolution in the RCRA facility waste analysis plan which must be submitted with the Part B permit application, or addressed in a permit modification.

Both agencies also believe that the potential for inconsistencies can be reduced significantly by a better understanding of the RCRA requirements, a greater reliance on materials and process knowledge, the use of surrogate materials when possible, and the use of controlled atmosphere apparatuses for mixed waste testing. Where testing is conducted, the use of glove boxes and other controlled atmosphere apparatuses during the testing of the radioactive waste material lessens radiation exposure concerns significantly. These protective measures may also help to reconcile the required testing requirements (including milling) with concerns about maintaining exposures to radiation ALARA and complying with other AEA protective standards. If such protective measures do not exist, or do not adequately reduce individual exposure to radiation or address other factors of concern, relief may be available under Section 1006 of RCRA.

V. Determinations by Treatment, Storage, or Disposal Facility Owner/Operators and Certain Generators to Ensure Proper Waste Management

General Waste Analysis

Owner/operators of facilities that treat, store, or dispose of hazardous wastes must obtain a chemical and physical analysis of a representative

sample of the waste (see 40 CFR 264.13 for permitted facilities, or 40 CFR 265.13 for interim status facilities).[17] The purpose of this analysis is to assure that owner/operators have sufficient information on the properties of the waste to be able to treat, store, or dispose of the waste in a safe and appropriate manner.

The waste analysis may include data developed by the generator, and existing, published, or documented data on the hazardous waste or on hazardous waste generated from similar processes. In some instances, however, information supplied by the generator may not fully satisfy the waste analysis requirement. For example, in order to treat a particular waste, one may need to know not only the chemical composition of the waste, but also its compatibility with the techniques and chemical reagents used at the treatment facility. Where such information is not otherwise available, the owner/operator will be responsible for gathering relevant data on the waste in order to ensure its proper management.

The analysis must be repeated only if the previous analyses are inaccurate or needs updating. EPA regulations at 40 CFR 264.13(a)(3) do require that, at a minimum, a waste must be re-analyzed if:

(1) The owner/operator is notified, or has reason to believe, that the process or operation generating the waste has changed [in a way such that the hazardous property or characteristics of the waste would change]; and (2) For off-site facilities, when the results of the verification analysis indicate that the [composition or characteristics of the] waste does not match the accompanying manifest or shipping paper.

The requirements and frequency of waste analysis for a given facility are described in the facility's waste analysis plan. As required by 40 CFR 264.13(b), the waste analysis plan must specify the parameters for which each hazardous waste will be analyzed; the rationale for selecting these parameters (i.e., how analysis for these parameters will provide sufficient information on the waste's properties); and the test methods that will be used to test for these parameters. The waste analysis plan also must specify the sampling method that will be used to obtain a representative sample of the waste to be analyzed; the frequency with which the initial analysis of the waste will be reviewed or repeated, to ensure that

the analysis is accurate and up to date; and, for off-site facilities, the waste analyses to be supplied by the hazardous waste generators. Finally, the waste analysis plan must note any additional waste analysis requirements specific to the waste management method employed, such as the analysis of the waste feed to be burned in an incinerator.

The appropriate parameters for each waste analysis plan are determined on an individual basis as part of the permit application review process. To reduce the inherent hazards of sampling and analyzing radioactive material, and in particular, the potential risk to workers from exposure to radiation posed by duplicative testing of mixed wastes, redundant testing by the generator and off-site facilities should be avoided. In addition, waste analysis plans must include provisions to keep exposures to radiation ALARA, and incorporate relevant AEA-related requirements and regulations.

Analysis Required to Verify Off-site Shipments

The owner/operator of a facility that receives mixed waste from off-site must inspect and, *if necessary,* analyze each hazardous waste shipment received at the facility to verify that it matches the identity of the waste specified on the accompanying LDR notification or manifest (see 40 CFR 264.13 or 265.13(c)). This testing is known as verification testing. Such inspections and analysis will follow sampling and testing procedures set forth in the facility's waste analysis plan, which is kept at the facility.

It should also be emphasized that, where analysis is necessary, *RCRA regulations do not necessarily require the analysis of every movement of waste received at an off-site facility*. As explained above, the purpose of the waste analysis is to verify that the waste received at off-site facilities is correctly identified, and to provide enough information to ensure that it is properly managed by the facilities.

For example, if a facility receives a shipment of several sealed drums of mixed waste, a representative sample from only one drum may be adequate, if the owner/operator has reason to believe that the chemical composition of the waste is identical in every drum. In such a case, the drum containing the least amount of measurable radioactivity could be sampled to minimize radiation exposures (variations in radioactivity do

not necessarily suggest different chemical composition). This procedure also would apply to a shipment of several types of waste. If the owner/operator has reason to believe that the drums in the shipment contain different wastes, then selecting a representative sample might involve drawing a sample from each drum or drawing a sample from one drum in each ''set'' of drums containing identical wastes. Once this waste analysis requirement has been satisfied, routine retesting of later shipments would not be required if the owner/operator can determine that the properties of the waste he or she manages will not change.

Fingerprint Analysis Versus Full Scale Analysis

Full scale analysis (i.e., detailed physical and chemical analysis) may be used to comply with the waste analysis plan, including verification of off-site shipments. However, for mixed waste, abbreviated analysis or ''fingerprint analysis'' may be more appropriate to meet general waste analysis requirements. The test procedure should be determined on a case-by-case basis.

Fingerprint analysis (which may involve monitoring pH, percent water, and cyanide content) is particularly recommended for mixed waste streams with high radiation levels that are received by an off-site TSDF for RCRA waste manifest verification purposes. It may be appropriate to use full scale analysis, instead of, or after, fingerprint analyses, if the facility suspects that the waste was not accurately characterized by the generator, information provided by a generator is incomplete, waste is received for the first time, or the generator changes a process or processes that produced the waste.

Generators Who Treat LDR Prohibited Waste In Tanks, Containers or Containment Buildings To Meet LDR Treatment Requirements

Hazardous waste generators may treat hazardous wastes in tanks or containers without obtaining a permit if the treatment is done in accordance with the accumulation timeframes and requirements in 40 CFR 262.34. However, generators who treat hazardous waste (including mixed wastes) to meet the EPA treatment standards for land disposal prohibited wastes must also prepare a waste analysis plan similar to that prepared by TSDFs.

The plan must be based on a detailed analysis of a representative sample of the LDR prohibited waste that will be treated. In addition, the plan should include all the information that is necessary to treat the waste, including the testing frequency (See 40 CFR 268.7(a)(5)).

VI. Determinations Under the Land Disposal Restrictions

Generators, as well as treatment facilities and land disposal facilities, that handle mixed waste may have to obtain or amend their radioactive materials licenses if they test or treat mixed waste under the LDRs. The following discussion assumes that generators and treatment and disposal facilities have satisfied the requirement to obtain, or amend, their radioactive materials licenses, as appropriate.

Waste knowledge may also be used to satisfy certain waste characterization requirements imposed by the LDRs for mixed wastes. The Hazardous and Solid Waste Amendments (HSWA) to RCRA (P.L. 98–616), enacted on November 8, 1984, established the LDR program. This Congressionally mandated program set deadlines (RCRA Sections 3004(d)-(g)) for EPA to evaluate all hazardous wastes and required EPA to set levels, or methods, of treatment which would substantially diminish the toxicity of the waste, or minimize the likelihood of migration of hazardous constituents from any RCRA waste. Beyond specified dates, prohibited wastes that do not meet the treatment standards before they are disposed of, are banned from land disposal unless they are disposed of in a so-called ''no-migration'' unit (i.e., a unit where the EPA Administrator has granted a petition which successfully demonstrated to a reasonable degree of certainty that there will be no migration of hazardous constituents from the disposal unit for as long as the wastes remain hazardous) (40 CFR 268.6). Certain categories of prohibited wastes also may be granted extensions of the effective dates of the land disposal prohibitions (i.e., case-by-case and national capacity variances (40 CFR 268.5 and Subpart C, respectively). However, these wastes are still restricted and, if disposed in landfills or surface impoundments, must be disposed of in units meeting the minimum technology requirements.[18]

The requirements of the LDR program apply to generators, transporters, and owner/operators of hazardous waste treatment, storage, and

disposal facilities. Not all hazardous wastes are subject to 40 CFR Part 268. For instance, certain wastes that are identified or listed after November 8, 1984, such as newly identified mineral processing wastes for which land disposal prohibitions or treatment standards have not yet been promulgated, are not regulated under 40 CFR Part 268.[19]

Determinations by Generators

Under 40 CFR 268.7(a), generators must determine whether their waste is restricted from land disposal (or determine if they are subject to an exemption or variance from land disposal (40 CFR 268.1)) by testing their waste (or a leachate of the waste developed using the TCLP or, in certain cases, the Extraction Procedure Toxicity Test (EP), or by using waste or process knowledge). If the waste exhibits the characteristic of ignitability (and is not in the High Total Organic Constituents (TOC) Ignitable Liquids Subcategory or is not treated by the "CMBST" or "RORGS" treatment technology in 40 CFR 268.42, Table 1), corrosivity, reactivity and/or organic toxicity, the generator must also determine the underlying hazardous constituents (UHCs) in the waste. Two exceptions to this requirement are:

(1) if these wastes are treated in wastewater treatment systems subject to the Clean Water Act (CWA) or CWA equivalent; or,
(2) if they are injected into a Class I, nonhazardous Underground Injection Control well. A UHC is any constituent listed in 40 CFR 268.48, Table UTS Universal Treatment Standards, with the exceptions of nickel, zinc and vanadium, which can reasonably be expected to be present at the point of generation of the hazardous waste, at a concentration above the constituent-specific UTS treatment standard. Determining the presence of the UHCs may be made based on testing or knowledge of the waste. The UHCs must meet the UTS before the waste may be land disposed.

If a generator chooses to test the waste rather than use waste or process knowledge for hazardous waste that is not listed and exhibits a characteristic only, the generator must use the TCLP. The only exception is TC metals.

Until the "Phase IV" LDR rule is promulgated in the spring of 1998, generators who characterize their wastes as TC toxic only for metals

may use the EP instead of the TCLP result to determine if their waste is land disposal restricted, because the TC wastes do not have final EPA treatment standards whereas, at this time, the EP metals do. If the EP result is negative, the waste will still be considered hazardous, but is not prohibited from land disposal. The TCLP generally yields similar results as the EP. However, in certain matrices the TCLP yields higher lead and arsenic concentrations than the EP. The rationale for using the EP instead of the TCLP for characteristic wastes is explained in 55 FR 3865, January 31, 1991. For further guidance on using the EP for the land disposal restriction determination, refer to the Figures 1 and 2, of this guidance.

If a waste is found to be land disposal restricted, generators must determine if the waste can be land disposed without further treatment. A prohibited waste may be land disposed if it meets applicable treatment standards (whether through treatment or simply as generated), or is subject to a variance from the applicable standards. As explained above, this determination can be made either based on knowledge of the waste or by testing the waste, or waste leachate using the TCLP.

Generators who determine that their listed waste meets the applicable treatment standards must certify to this determination and notify the treatment, storage, or land disposal facility that receives the waste (40 CFR 268.7(a)(3)). Notification to the receiving facility must be made with the initial shipment of waste and must include the following information:

- EPA Hazardous Waste Number;
- Certification that the waste delivered to a disposal facility meets the treatment standard, and that the information included in the notice is true, accurate, and complete;
- Waste constituents that will be monitored for compliance if monitoring will not include all regulated constituents, for wastes F001-F005, F039, D001, D002, and D012-D043;
- Whether the waste is a non-wastewater or wastewater;
- The subcategory of the waste (e.g., ‘‘D003 reactive cyanide’’), if applicable;
- Manifest number; and,
- Waste analysis data (if available).

If a generator determines that a waste that previously exhibited a characteristic is no longer hazardous, or is subject to an exclusion from the definition of hazardous waste, a onetime notification and certification must be place in the generator's files (40 CFR 268.7(a)(7) or 268.9).

Generators who determine that their waste does not meet the applicable treatment standards must ensure that this waste meets the applicable standards prior to disposal. These generators may treat (or store) their prohibited wastes on-site for 90 days or less in qualified tanks, containers (40 CFR 262.34), or containment buildings (40 CFR 268.50), and/or send their wastes off-site for treatment.[20] When prohibited listed wastes are sent off-site, generators must notify the treatment facility of the appropriate treatment standards (40 CFR 268.7(a)(2)). This notification must be made with the initial shipment of waste and must include the following information:

- EPA Hazardous Waste Number;
- Waste constituents that the treater will monitor if monitoring will not include all regulated constituents, for wastes F001–F005, F039, D001, D002, and D012–D043;
- Whether the waste is a non-wastewater or wastewater;
- The subcategory of the waste (e.g., ''D003 reactive cyanide''), if applicable;
- Manifest number; and,
- Specified information for hazardous debris.

Generators whose wastes are subject to an exemption such as a case-by-case extension under 40 CFR 268.5, an exemption under 40 CFR 268.6 (a no-migration variance), or a nationwide capacity variance under 40 CFR 268, Subpart C must also notify the land disposal facility of the exemption. In addition, records of all notices, certifications, demonstrations, waste analysis data, process knowledge determinations, and other documentation produced pursuant to 40 CFR Part 268 must be maintained by the generator for at least three years from the date when the initial waste shipment was sent to on-site or off-site treatment, storage, or disposal (40 CFR 268.7(a)(8)).

Determinations by Treaters and Disposers

Owner/operators of treatment facilities that receive wastes that do not meet the treatment standards are responsible for treating the wastes to the applicable treatment standards or by the specified technology(ies). In addition, the owner/operators of treatment facilities must determine whether the wastes meet the applicable treatment standards or prohibition levels by testing:

(1) The treatment residues, or an extract of such residues using the TCLP, for wastes with treatment standards expressed as concentrations in the waste extract (40 CFR 268.40); and
(2) The treated residues (not an extract of the treated residues) for wastes with treatment standards expressed as concentrations in the waste extract (40 CFR 268.40).

This testing should be done at the frequency established in the facility's waste analysis plan. Owner/operators of treatment facilities, however, do not need to test the treated residues or an extract of the residues if the treatment standard is a specified-technology (i.e., a technology specified in 40 CFR 268.40 or 268.45, Table 1.—Alternative Treatment Standards for Hazardous Debris).

Owner/operators of land disposal facilities under the LDRs are responsible for ensuring that only waste meeting the treatment standards (i.e., wastes not prohibited from disposal or wastes that are subject to an exemption or variance) is land disposed. Like a treatment facility, a disposal facility must test a treatment residue or an extract of the treatment residue, except where the treatment standard is a specified technology.

Owner/operators must periodically test wastes received at the facility for disposal (i.e., independent corroborative testing) as specified in the waste analysis plan to ensure the treatment has been successful and the waste meets EPA treatment standards, except where the treatment standard is expressed as a technology.[21] The results of any waste analyses are placed in a TSDF's operating records along with a copy of all certifications and notices (40 CFR 264.73 or 40 CFR 265.73).[22]

Mixed Waste Under the LDRs

As clarified in the Land Disposal Restrictions rule published on June 1, 1990 (see EPA's "Third Third rule," 55 FR 22669, June 1, 1990), the frequency of testing, such as corroborative testing for treatment and disposal facilities, should be determined on a case-by-case basis and specified in the RCRA permit. This flexibility is necessary because of the variability of waste types that may be encountered. Mixed waste is unique for its radioactive/hazardous composition and dual management requirements. Each sampling or analytical event involving mixed waste may result in an incremental exposure to radiation, and EPA's responsibility to protect human health and the environment must show due regard for minimizing this unique risk. These are factors which should be considered in implementing the flexible approach to determining testing frequency spelled out in the Third Third Rule language. This flexible approach encourages reduction in testing where there is little or no variation in the process that generates the waste, or in the treatment process that treats the waste, and an initial analysis of the waste is available. Also, the approach may apply to mixed wastes shipped to off-site facilities, where redundant testing is minimized by placing greater reliance on the characterization developed and certified by earlier generators and treatment facilities. On the other hand, where waste composition is not well-known, testing frequency may be increased. Waste analysis plan conditions in the permits of mixed waste facilities should reflect these principles.

Revised Treatment Standards for Solvent Wastes

EPA promulgated revised treatment standards for wastewater and non-wastewater spent solvent wastes (F001–F005) in 57 FR 37194, August 18, 1992. The revision essentially converts the treatment standards for the organic spent solvent waste constituents (F001–F005) from TCLP based to total waste constituent concentration based. This conversion of the spent solvent treatment standards is particularly advantageous to mixed waste generators, since the entire waste stream or treatment residual must be analyzed (instead of a waste or treatment residual extract). This holds true for other mixed waste streams where the hazardous component is measured using a total waste analysis. As discussed in Section IV of this guidance, total constituent analysis has several advantages over the use of the TCLP for high activity waste streams.

EPA and NRC are aware of potential hazards attributable to testing hazardous waste. Moreover, EPA and NRC recognize that the radioactive component of mixed waste may pose additional hazards to laboratory personnel, inspectors, and others who may be exposed during sampling and analysis. All sampling should be conducted in accordance with procedures that minimize exposure to radiation and ensure personnel safety. Further, testing should be conducted in laboratories licensed by NRC or the appropriate NRC Agreement State authority. EPA and NRC believe that a combination of common sense, modified sampling procedures, and cooperation between State and Federal regulatory agencies will minimize any hazards associated with sampling and testing mixed waste.

Note: Section V, ''Determinations under the Land Disposal Restrictions (LDRs)'' and the following flow charts represent a brief summary of the Land Disposal Restriction Regulations. They are not meant to be a complete or detailed description of all applicable LDR regulations. For more information concerning the specific requirements, consult the **Federal Registers** cited in the document and the Code of Federal Regulations, Title 40 Parts 124, and 260 through 271.

FIGURE ONE: TESTING REQUIREMENTS
FOR CHARACTERISTIC LEAD AND ARSENIC NONWASTEWATERS ONLY[a]

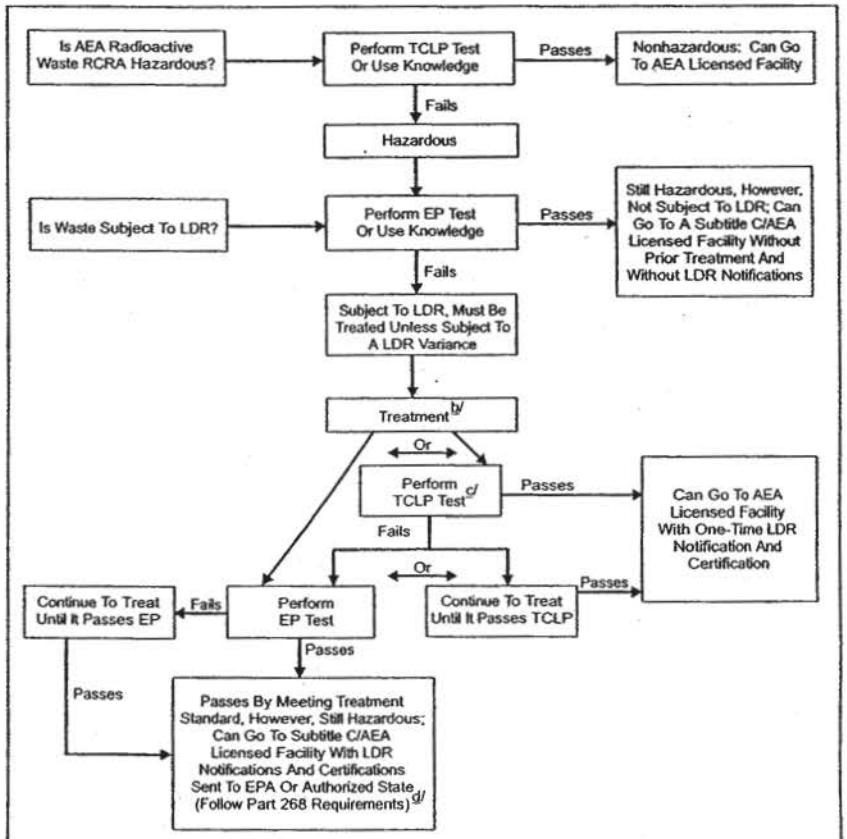

a/ Logic tree assumes the waste also contains AEA regulated radioactive waste.

b/ If the treatment standard is expressed as a specified technology, no further testing is required. However, the mixed waste must go to a Subtitle C/AEA licensed facility with LDR notifications and certifications.

c/ TCLP generally yields higher concentrations than EP for lead and arsenic in certain matrices.

d/ If the waste meets the treatment standard and passes the TCLP, it can go to an AEA licensed facility with one-time LDR notification and certification.

FIGURE TWO: TESTING REQUIREMENTS
FOR ALL OTHER CHARACTERISTIC METALS[a]

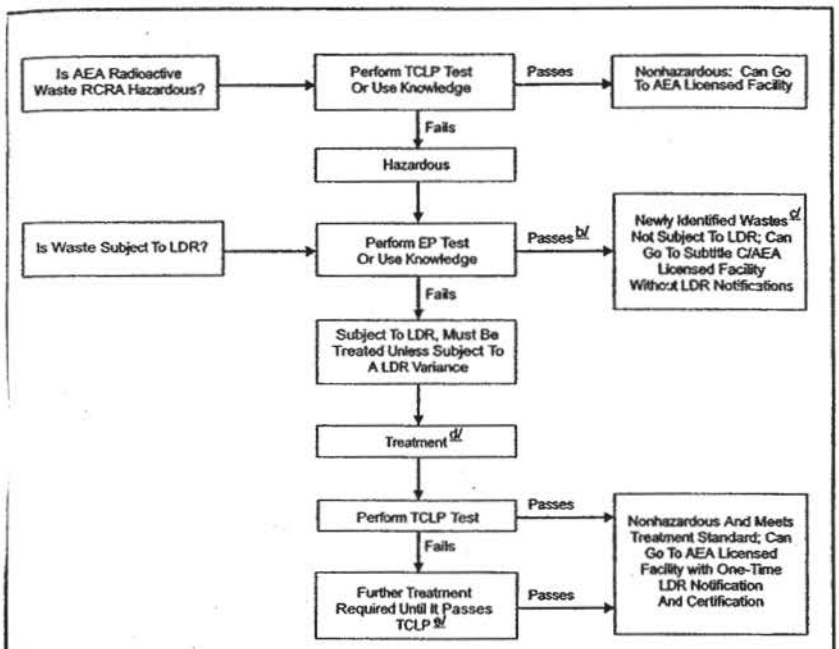

a/ Logic tree assumes the waste also contains AEA regulated radioactive waste.

b/ This should be rare, since the two tests usually yield similar results.

c/ Wastes exhibiting the toxicity characteristic but not the EP are newly identified wastes and, therefore, are not subject to the land disposal restrictions at this time.

d/ If the treatment standard is expressed as a specified technology, no further testing is required. However, the mixed waste must go to a Subtitle C/AEA licensed facility with LDR notifications and certifications.

e/ Selenium is the one exception because it has a treatment standard slightly above the characteristic level.

FIGURE THREE: TESTING REQUIREMENTS
FOR RCRA LISTED HAZARDOUS WASTES ONLY[a]

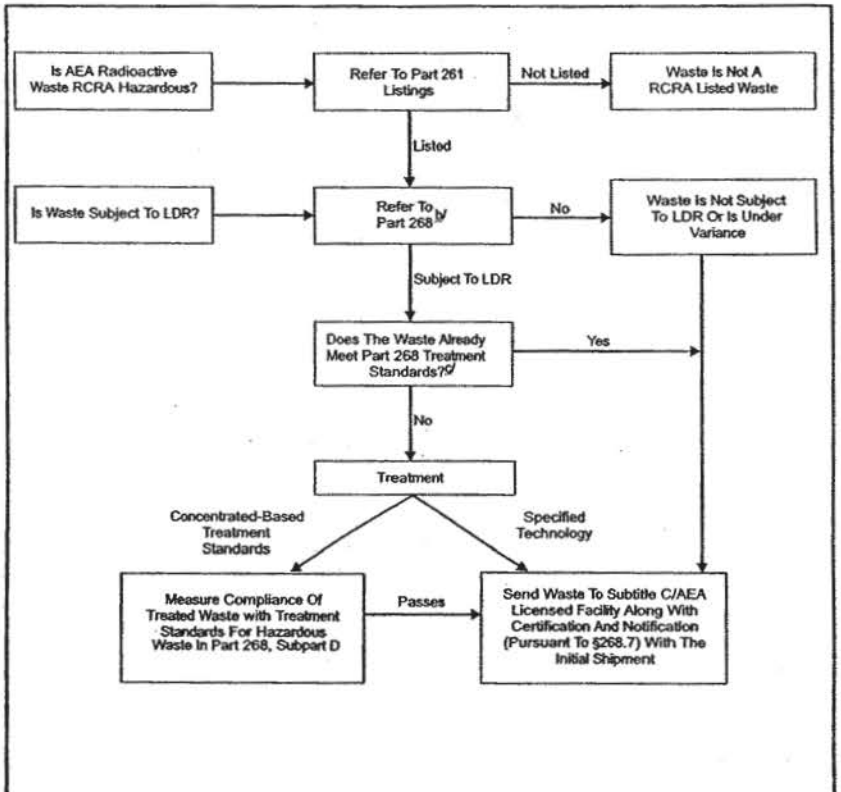

a/ Logic tree assumes the waste also contains AEA regulated radioactive waste.

b/ Refer to §268.1 to determine if LDR is applicable to waste. If so, test using TCLP or use process knowledge to determine if waste is restricted (§268.7).

c/ Test using TCLP or use process knowledge.

FIGURE FOUR: ORGANIC TOXICITY CHARACTERISTIC (TC) WASTES AND PESTICIDE WASTES[a]

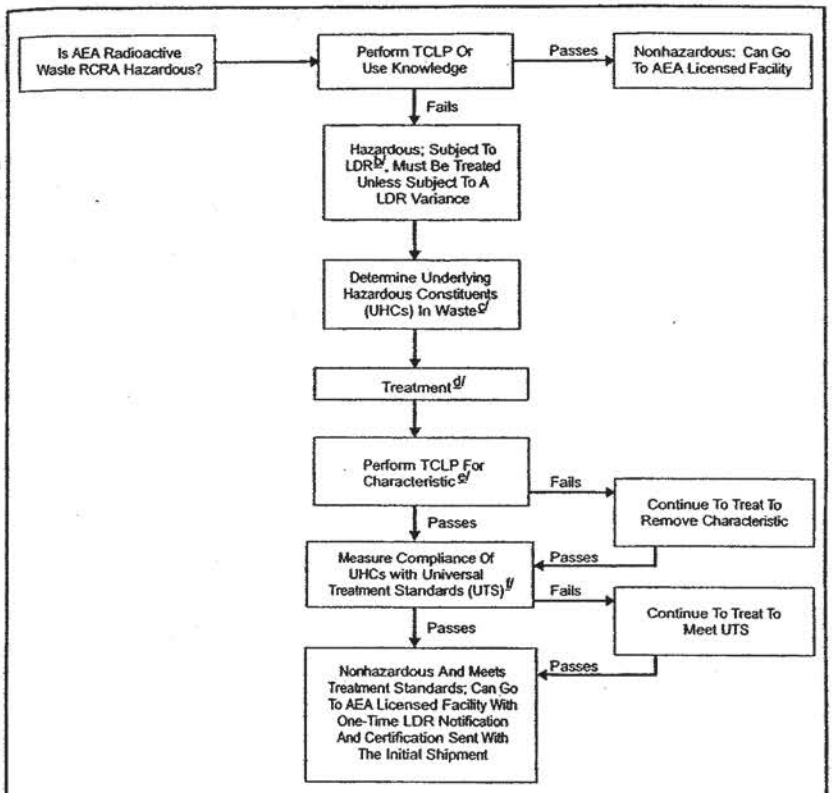

a/ Logic tree assumes the waste also contains AEA regulated radioactive waste.

b/ Restriction applies to TC organic and pesticide wastes managed in non-CWA/non-CWA equivalent/ non-Class I SDWA systems only.

c/ Testing or knowledge of waste may be used. A UHC is any constituent listed in §268.48 Table UTS, except zinc, that can reasonable be expected to be present at the point of generation of the hazardous waste, at a concentration above the constituent-specific UTS treatment standard.

d/ If the treatment standard is expressed as a specified technology, no further testing is required. However, the mixed waste must go to a Subtitle C/AEA facility with LDR notifications and certifications.

e/ Refer to the table "Treatment Standards for Hazardous Wastes" in 40 CFR Part 268, Subpart D.

f/ Compliance should be measured based on the appropriate testing protocols (see SW-846).

Appendix A—RCRA Regulations That Require Specific EPA Test Methods

The use of an SW–846 method is mandatory for the following nine Resource Conservation and Recovery Act (RCRA) applications contained in 40 CFR Parts 260 through 270:

- Section 260.22(d)(1)(I)—Submission of data in support of petitions to exclude a waste produced at a particular facility (i.e., delisting petitions);
- Section 261.22(a)(1) and (2)—Evaluations of waste against the corrosivity characteristic;
- Section 261.24(a)—Leaching procedure for evaluation of waste against the toxicity characteristic;
- Section 261.35(b)(2)(iii)(A)—Evaluation of rinsates from wood preserving cleaning processes;
- Sections 264.190(a), 264.314(c), 265.190(a), and 265.314(d)—Evaluation of waste to determine if free liquid is a component of the waste;
- Sections 264.1034(d)(1)(iii) and 265.1034(d)(1)(iii)—Evaluation of organic emissions from process vents;
- Sections 264.1063(d)(2) and 265.1063(d)(2)—Evaluation of organic emissions from equipment leaks;
- Section 266.106(a)—Evaluation of metals from boilers and furnaces;
- Sections 266.112(b)(1) and (2)(I)—Certain analyses in support of exclusion from the definition of a hazardous waste for a residue which was derived from burning hazardous waste in boilers and industrial furnaces;
- Sections 268.7(a), 268.40(a), (b), and (f), 268.41(a), 268.43(a)—Leaching procedure for evaluation of waste to determine compliance with land disposal treatment standards;
- Sections §270.19(c)(1)(iii) and (iv), and 270.62(b)(2)(I)(C) and (D)—Analysis and approximate quantification of the hazardous constituents identified in the waste prior to conducting a trial burn in support of an application for a hazardous waste incineration permit; and
- Sections 270.22(a)(2)(ii)(B) and 270.66(c)(2)(I) and (ii)—Analysis conducted in support of a destruction and removal efficiency (DRE) trial burn waiver for boilers and industrial furnaces burning low risk wastes, and analysis and approximate quantification conducted for a trial burn in support of an application for a permit to burn hazardous waste in a boiler and industrial furnace.

Appendix B.—States and Territories with Mixed Waste Authorization [As of June 30, 1997].

State/territory	FR date	Effective date	FR cite
Colorado	10/24/86	11/7/86	51 FR 37729.
Tennessee	6/12/87	8/11/87	52 FR 22443.
S. Carolina	7/15/87	9/13/87	52 FR 26476.
Washington	9/22/87	11/23/87	52 FR 35556.
Georgia	7/28/88	9/26/88	53 FR 28383.
Nebraska	10/4/88	12/3/88	53 FR 38950.
Kentucky	10/20/88	12/19/88	53 FR 41164.
Utah	2/21/89	3/7/89	54 FR 7417.
Minnesota	4/24/89	6/23/89	54 FR 16361.
Ohio	6/28/89	6/30/89	54 FR 27170.
Guam	8/11/89	10/10/89	54 FR 32973.
N. Carolina	9/22/89	11/21/89	54 FR 38993.
Michigan	11/24/89	12/26/89	54 FR 48608.
Texas	3/1/90	3/15/90	55 FR 7318.
New York	3/6/90	5/7/90	55 FR 7896.
Idaho	3/26/90	4/9/90	55 FR 11015.
Illinois	3/1/90	4/30/90	55 FR 7320.
Arkansas	3/27/90	5/29/90	55 FR 11192.
Oregon	3/30/90	5/29/90	55 FR 11909.
Kansas	4/24/90	6/25/90	55 FR 17273.
N. Dakota	6/25/90	8/24/90	55 FR 25836.
New Mexico	7/11/90	7/25/90	55 FR 28397.
Oklahoma	9/26/90	11/27/90	55 FR 39274.
Connecticut	12/17/90	12/31/90	55 FR 51707.
Florida	12/14/90	2/12/91	55 FR 51416.
Mississippi	3/29/91	5/28/91	56 FR 13079.
S. Dakota	4/17/91	6/17/91	56 FR 15503.
Indiana	7/30/91	9/30/91	56 FR 41959.
Louisiana	8/26/91	10/26/91	56 FR 41959.
Wisconsin	4/24/92	4/24/92	57 FR 15092.
Nevada	4/29/92	6/29/92	57 FR 18083.
California	7/23/92	8/1/92	57 FR 32725.
Arizona	11/23/92	1/22/93	57 FR 54932.
Missouri	1/11/93	3/12/93	58 FR 3497.
Alabama	3/17/93	5/17/93	58 FR 14319.
Vermont	6/7/93	8/6/93	58 FR 31911.
Montana	1/19/94	3/21/94	59 FR 2752.
New Hampshire	11/14/94	1/13/95	59 FR 56397.
Wyoming	10/04/95	10/18/95	60 FR 51925.
Delaware	8/8/96	10/7/96	61 FR 41345.
Total: 39 States and 1 Territory.			

Appendix C: Testing Reference Documents

The following references provide information on approved methods for testing hazardous waste samples:

American Public Health Association, *Standard Methods for the Examination of Water and Wastewater, 17th Edition.* 1989. Available from the Water Pollution Control Federation, Washington, D.C., #S0037.

U.S. Environmental Protection Agency, *Design and Development of a Hazardous Waste Reactivity Testing Protocol.* EPA Document No. 600/2–84–057, February 1984.

U.S. Environmental Protection Agency, *Methods for Chemical Analysis of Water and Waste.* EPA–6001114–79–020. Washington, D.C., 1983.

U.S. Environmental Protection Agency, *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods.* SW–846. Third Edition (1986) as amended. Available from the Government Printing Office, by subscription, 955–001–00000–1, or from the National Technical Information Service, PB88–239–223. Washington, D.C., January, 1995.

U.S. Environmental Protection Agency, *The New Toxicity Characteristic Rule: Information and Tips for Generators.* Office of Solid Waste, 530/SW–90–028, April, 1990.

U.S. Environmental Protection Agency, ORD, and U.S. Department of Energy, *Characterizing Heterogenous Wastes: Methods and Recommendations.* EPA/600/R-92/033, February 1992.

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. ‘‘Joint EPA/NRC Guidance on the Definition and Identification of Commercial Mixed Low-Level Radioactive and Hazardous Waste,’’ Directive No. 9432–00–2, October 4, 1989.

Appendix D: List of Regulations

Environmental Protection Agency General Regulations for Hazardous Waste Management, 40 CFR Part 260.

Environmental Protection Agency Regulations for Identifying Hazardous Waste, 40 CFR Part 261.

Environmental Protection Agency Regulations for Hazardous Waste Generators, 40 CFR Part 262.

Environmental Protection Agency Standards for Owners and Operators of Hazardous Waste Treatment, Storage and Disposal Facilities, 40 CFR Part 264.

Environmental Protection Agency Interim Status Standards for Owners and Operators of Hazardous Waste Facilities, 40 CFR Part 265.

Environmental Protection Agency Regulations on Land Disposal Restrictions, 40 CFR Part 268.

Nuclear Regulatory Commission Regulations—Standards for Protection Against Radiation, 10 CFR Part 20.

Nuclear Regulatory Commission Regulations—Rules of General Applicability to Domestic Licensing of Byproduct Material, 10 CFR Part 30.

Nuclear Regulatory Commission Regulations—Domestic Licensing of Source Material, 10 CFR Part 40.

Nuclear Regulatory Commission Regulations—Domestic Licensing of Production and Utilization Facilities, 10 CFR Part 50.

Nuclear Regulatory Commission Regulations—Licensing Requirements for Land Disposal of Radioactive Waste, 10 CFR Part 61.

Nuclear Regulatory Commission Regulations—Domestic Licensing of Special Nuclear Material, 10 CFR Part 70.

[FR Doc. 97–30528 Filed 11–19–97; 8:45 am]

FOOTNOTES

[1] See 42 U S.C. §6903 (41), added by the Federal Facility Compliance Act of 1992 (FFCA).

[2] See revised *Guidance on the Definition and Identification of Commercial Low-Level Radioactive and Hazardous Waste and Answers to Anticipated Questions,* October 4, 1989.

[3] The RCRA base hazardous waste program is the RCRA program initially made available for final authorization and includes Federal regulations up to July 26, 1982. However, authorized States have revised their programs to keep pace with Federal program changes that have taken place after 1982 in accordance with EPA regulation.

[4] Refer to Appendix A for specific EPA regulations pertaining to (1)–(4).

[5] ALARA, codified in 10 CFR Part 20, refers to the practice of maintaining all radiation exposures, to workers and the general public, as low as is reasonably achievable.

[6] For a more detailed discussion on process knowledge, see Section 1.5 in ''Waste Analysis at Facilities That Generate, Treat, Store, and Dispose of Hazardous Wastes'' OSWER 9938.4–03, April 1994.

[7] The ''mixture'' and ''derived-from'' rules were vacated and remanded due to EPA's failure to provide adequate notice and opportunity for comment before their 1980 promulgation, in *Shell Oil* v. *EPA,* No. 80–1532 (D.C. Cir. Dec. 6, 1991). At the Court's suggestion, EPA reinstated the ''mixture'' and ''derived-from'' rules as interim final until the rules are revised through new EPA rulemaking. The ''mixture'' and ''derived from'' rules adopted by those States with authorized RCRA programs were not affected by the court case or the subsequent reinstatement by EPA. For further information, see 57 *FR* 49278, October 30, 1992, and 60 *FR* 66344, December 21, 1995.

[8] Generators who also treat their waste are subject to the requirements for treatment facilities unless they treat waste in accumulation tanks,

containers, or containment buildings, for 90 days or less in accordance with 40 CFR 262.34(a). Treatment facilities must periodically test the treated waste residue from prohibited wastes to determine whether it meets the best demonstrated available technology (BDAT) treatment standards and may not rely on materials and process knowledge to make this determination (40 CFR 268.7(b)). This testing must be conducted according to the frequency specified in the facility's waste analysis plan (refer to Section IV of this guidance for a detailed discussion of treatment, storage, and disposal facility requirements).

[9] This definition of surrogate should not be confused with the definition of surrogate for the purposes of sampling and analysis quality control in Section 1.1.8 of "*Evaluating Solid Waste—Volume IA: Laboratory Test Methods Manual Physical/Chemical Methods.*"

[10] Note that characteristic only wastes (which are neither wastewater mixtures or RCRA listed hazardous wastes when generated) may be treated so that they no longer exhibit any of the four characteristics of a hazardous waste. However, these wastes may still be subject to the requirements of 40 CFR Part 268, even if they no longer exhibit a hazardous characteristic at the point of land disposal. After treatment this waste must not exhibit any RCRA hazardous waste characteristic *and* must meet applicable treatment standards before it can be considered a non-hazardous waste (see 57 *FR* 37263, August 18, 1992, and 58 *FR* 29869, May 24, 1993).

[11] Note that hazardous and mixed waste samples analyzed for waste characteristics or composition, and samples undergoing treatability studies may be exempt from all or part of the RCRA regulations if they are managed in accordance with 40 CFR 261.4 (d), (e) or (f).

[12] EPA incorporated by reference into the RCRA regulations (58 *FR* 46040, August 31, 1993), a third edition (and its updates) of "Test Methods for the Evaluation of Solid Waste, Physical/Chemical Methods." The updates can be found in 60 *FR* 3089, January 13, 1995 (update II), 59 *FR* 458, January 4, 1994 (update IIA), 60 *FR* 17001, April 4, 1995 (update IIB), and 62 *FR* 32452, June 13, 1996 (update III). Hazardous and mixed waste

generators and management facilities should verify that the analytical method that they use to analyze hazardous waste has not been superseded in the third edition.

[13] When evaluating test protocols for explosive mixed waste, consideration should be given to the likelihood for dispersing radioactivity during detonation. Using process knowledge or a surrogate material would, in most instances, be appropriate for these wastes.

[14] Note that when using the TCLP, if any liquid fraction of the waste positively determines that hazardous constituents in the waste are above regulatory levels, then it is not necessary to analyze the remaining fractions of the waste. Extraction using the zero headspace extraction vessel (ZHE) is not required, furthermore, if the analysis of an extract obtained using a bottle extractor demonstrates that the concentration of a volatile compound exceeds the specified regulatory levels. The use of a bottle extractor, however, may not be used to demonstrate that the concentration of a volatile compound is below regulatory levels (40 CFR Part 261 Appendix II Sections 1.3 and .4).

[15] With the exception of the fourteen areas (see Appendix D) where test methods are required by hazardous waste regulation, use of EPA's *Test Methods for the Evaluation of Solid Waste* (SW–846) is not required, and should be viewed as guidance on acceptable sampling and analysis methods.

[16] An inconsistency occurs when compliance with one statute or set of regulations would necessarily cause non-compliance with the other. It may stem from a variety of considerations, including those related to occupational exposure, criticality, and other safeguards.

[17] A representative sample is defined in 40 CFR 260.10 as "a sample of a universe or whole (e.g., waste pile, lagoon, ground water) which can be expected to exhibit the average properties of the universe or whole." For further guidance see Chapter 9 of the EPA's testing guidance entitled *Test Methods for Evaluating Solid Waste* or SW–846.

[18] A prohibited waste may not be land disposed unless it meets the treatment standards established by EPA. These standards are usually based on the performance of the BDAT. A waste that is subject to an extension, such as a national capacity variance, does not need to comply with the BDAT treatment standards, but is ''restricted'' and if it is going to be disposed in a landfill or surface impoundment, it can only be disposed of in a unit that meets the minimum technology requirements (MTRs). An exception exists for interim status surface impoundments which may continue receiving newly identified and restricted wastes for four years from the date of promulgation of the listings or characteristics before being retrofitted to meet the MTRs (RCRA Section 3005(j)(6)), so long as the only hazardous wastes in the impoundment are newly identified or listed.

[19] The treatment standards for mineral processing wastes and certain additional newly listed waste streams were proposed in 61 *FR* 2338, January 25, 1996, and a second supplemental proposed rule signed April 18, 1997.

[20] Non-wastewater residues (e.g., slag) that result from high temperature metals recovery that are excluded from the definition of hazardous waste by meeting the conditions of 40 CFR 261.3(c)(2)(ii)(C), and hazardous debris that is excluded from the definition of hazardous waste in 40 CFR 261.3(f) have reduced LDR notification requirements. Specifically, these wastes, and characteristic hazardous wastes that are rendered non-hazardous, do not require a notification and certification accompanying each shipment. Instead, they may be sent to an AEA-licensed facility with a one-time notification and certification sent to the EPA Region or authorized State.

[21] Note that verification testing is a means to verify that the wastes received match the waste description on the manifest, which is required under 40 CFR 264.13 and 40 CFR 265.13(c). The main objective of corroborative testing is to provide an independent verification that a waste meets the LDR treatment standard.

[22] Land disposal facilities must maintain a copy of all LDR notices and certifications transmitted from generators and treaters (40 CFR 268.7(c)).

ACRONYMS/ABBREVIATIONS USED IN THIS GUIDANCE

AEA	Atomic Energy Act.
ALARA	As Low As Is Reasonably Achievable.
BDAT	Best Demonstrated Available Technology.
CFR	Code of Federal Regulations.
EP	Extraction Procedure (toxicity test).
EPA	Environmental Protection Agency.
FR	Federal Register.
HSWA	Hazardous and Solid Waste Amendments.
LDR	Land Disposal Restrictions.
NRC	Nuclear Regulatory Commission.
OSWER	Office of Solid Waste and Emergency Response.
RCRA	Resource Conservation and Recovery Act.
SW–846	Test Methods for Evaluating Solid Wastes, Physical/Chemical Methods.
TC	Toxicity Characteristic.
TCLP	Toxicity Characteristic Leaching Procedure.
TSDF	Treatment, Storage or Disposal Facility.
WAP	Waste Analysis Plan.

Excerpts from U.S. Senate Report 108-105 and Bill S.1424

U.S. Senate Energy & Water Report 108-105

"Waste Analysis Requirements for the Waste Isolation Pilot Plant.—The Committee recognizes that the WIPP facility is central to the cleanup of the nuclear weapons complex and that waste should be emplaced as quickly and safely as possible—for reasons of reducing clean-up costs, public safety, and with the growing threat of radiological terrorism, for national security. Current law and regulation regarding the sampling and analysis of waste destined for WIPP produces substantial health and safety risks to workers with little if any corresponding public benefit. Both the New Mexico Environmental Evaluation Group, an independent WIPP oversight group, and the National Academy of Sciences have strongly suggested that waste destined for disposal at WIPP should not undergo hazardous waste sampling and analysis. To this end, the Committee believes that eliminating dangerous and excessive waste confirmation requirements that offer little if any benefit to the health and safety of the public will serve the national interests inherent in the safe and expeditious cleanup of the nuclear weapons complex. For these reasons, the Committee has included language in section 310 that requires that waste characterization be limited to determining that the waste is not ignitable, corrosive, or reactive. This confirmation will be performed using radiography or visual examination of a representative subpopulation of the waste. The language further directs the Secretary of Energy to seek a modification to the WIPP Hazardous Waste Facility Permit to implement the provisions of this bill by December 31, 2003. The Committee recommendation includes $1,000,000 for regulatory and technical assistance to the State of New Mexico to amend the existing WIPP Hazardous Waste Permit to comply with the provisions of the bill."

U.S. Senate Bill S.1424

Title: An original bill making appropriations for energy and water development for the fiscal year ending September 30, 2004, and for other purposes.
Sponsor: Sen Domenici, Pete V. [NM] (introduced 7/17/2003)
Cosponsors: (none)

"SEC. 310. (a) The Secretary of Energy is directed to file a permit modification to the Waste Analysis Plan (WAP) and associated provisions

contained in the Hazardous Waste Facility Permit for the Waste Isolation Pilot Plant (WIPP). For purposes of determining compliance of the modifications to the WAP with the hazardous waste analysis requirements of the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.), or other applicable laws waste confirmation for all waste received for storage and disposal shall be limited to (1) confirmation that the waste contains no ignitable, corrosive, or reactive waste through the use of either radiography or visual examination of a statistically representative subpopulation of the waste; and (2) review of the Waste Stream Profile Form to verify that the waste contains no ignitable, corrosive, or reactive waste and that assigned Environmental Protection Agency hazardous waste numbers are allowed for storage and disposal by the WIPP Hazardous Waste Facility Permit.

(b) Compliance with the disposal room performance standards of the WAP shall be demonstrated exclusively by monitoring airborne volatile organic compounds in underground disposal rooms in which waste has been emplaced until panel closure."

Peer Review Criteria, Findings, and Recommendation of the Review Panel

The findings of the Review Panel (RP) with respect to the review criteria are as follows:

Criterion 1

Is the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S. 1424 supported by the recommendations of the National Research Council (NRC) report "Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant"?

Finding 1 of the RP

The NRC committee was formed to respond to specific issues identified by the U.S. Department of Energy (DOE) and was disbanded in 2001. Consequently, the RP had no other choice but to rely exclusively upon the text of the NRC (2001) report.

The DOE has been exploring the waste characterization requirements necessary to satisfy the U.S. Environmental Protection Agency (EPA) and the requirements necessary to satisfy the New Mexico Environment Department (NMED). The EPA regulates the long-term repository containment of radionuclides. The following characterization requirements are needed to comply with EPA regulations:

1. Acceptable Knowledge (AK) and Non-Destructive Assay requirements listed in Appendix A of *Contact-Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant*; and

2. Radiography results for ferrous and non-ferrous metals; cellulose; rubber; plastics; and liquids.

The NMED focuses on the containment of materials regulated by Resource Conservation and Recovery Act (RCRA). Characterization requirements of NMED are as follows:

1. AK
2. Headspace gas
3. Solids sampling and analysis

4. Real-Time Radiography/Visual Examination (RTR/VE)
5. Compliance with Waste Acceptance Criteria as described in the Attachments B to the WIPP Hazardous Waste Facility Permit (HWFP)

Characterization requirements in compliance with transportation regulations are:

1. AK
2. RTR/VE
3. Headspace gas flammables analysis
4. Payload container surface dose measurements
5. Fissile material quantity measurements for payload containers
6. Radionuclide description for at least 95% of the activity in each shipment

In complying with transportation regulations, DOE determines when characterization activities beyond the initial AK would need to be used. For some wastes, AK contains sufficient information to comply with transportation regulations.

The U.S. Senate Bill S. 1424 states that waste confirmation for all waste received for storage and disposal shall be limited to:

1. confirmation that the waste contains no ignitable, corrosive, or reactive waste through the use of either radiography or visual examination of a statistically representative sub-population of the waste; and

2. review of the Waste Stream Profile Form to verify that the waste contains no ignitable, corrosive, or reactive waste and that assigned Environmental Protection Agency hazardous waste numbers are allowed for storage and disposal by the WIPP Hazardous Waste Facility Permit.

Reference is made to the 2001 NRC Report under the heading "Waste Characterization and Packaging Requirements",

Pages 77-78:

*"**Finding:** The committee found inadequate legal or safety bases for some of the National TRU Program requirements and specifications.*

That is, some waste characterization specifications have no basis in law, the safe conduct of operations to emplace waste in WIPP, or long-term performance requirements [...]. The National TRU Program waste characterization procedures involve significant resources (e.g., expenditures of several billion dollars) and potential for exposure of workers to radiation and other hazards. Insofar as some of this waste characterization may be unnecessary, such characterization is inconsistent with economic efficiency and the ALARA principle that guides radiation protection practices [...]. The committee regards the 30+ years of waste emplacement operations and related worker safety issues at WIPP as posing no significant needs for waste characterization information, because no use of characterization data is made in any handling, shipping, or emplacement operations."

Page 78:

*"**Recommendation:** DOE should eliminate self-imposed waste characterization requirements that lack a legal or safety basis. One way to justify a reduction in waste characterization requirements is through implementation of joint U.S. Nuclear Regulatory Commission (USNRC)-U.S. Environmental Protection Agency (EPA) guidance (62 Federal Register 62079;[...]), which appears to the committee to provide appropriate guidelines for implementation and integration of Resource Conservation and Recovery Act (RCRA) requirements for mixed TRU waste. Implementation of this regulatory guidance could significantly reduce the testing protocols and associated radiation exposure of personnel. Another way to justify a reduction is to identify the origins of all waste characterization requirements and to eliminate those requirements that lack a technical or safety basis. Such reductions may require modifications to existing permits granted by external regulating authorities such as the EPA and New Mexico Environment Department."*

Pages 78-80:

*"**Rationale:** .... The committee sought to identify the connection between the National TRU Program procedures and the various regulatory, legal, and technical requirements that the procedures*

should be devised to meet. The committee views these requirements in a hierarchy, at the top of which are legal and safety requirements, with regulatory specifications at the next tier, procedures proposed by DOE to meet regulatory requirements at the third tier, and the DOE protocols for these procedures at the fourth tier.

"The approach used by the committee was to focus on six primary National TRU Program procedures representative of high-level requirements that drive operational activities in waste characterization and repackaging [...]:

1. *determination that the TRU waste is of defense origin;*
2. *sampling and analysis of homogeneous waste;*
3. *headspace gas sampling and analysis;*
4. *radioassay of the plutonium content;*
5. *real-time radiography; and*
6. *visual examination.*

".... A review of these six procedures revealed that one may be interpreted too strictly by DOE and three are without a technical or legal foundation:

"Procedure 1: Determination that the TRU waste is of defense origin. WIPP is limited to defense-related waste as stipulated in the Land Withdrawal Act, with defense activities defined in the Nuclear Waste Policy Act of 1982. The committee notes that this definition includes the words 'in whole or in part', which can be interpreted to include mixtures of defense and nondefense waste, although DOE does not appear to take advantage of this (see DOE, 1997a; Nordhaus, 1996). That is, waste such as plutonium-238 (^{238}Pu)-contaminated scrap from a facility used for both defense and nondefense missions at Los Alamos National Laboratory would appear to qualify as defense waste under the definition, without the need for waste segregation restrictions.

"Procedure 2: Sampling and analysis of homogeneous waste. DOE has written, There is no regulatory requirement to conduct homogeneous waste sampling and analysis, however, in an effort to meet the

intent of 40 CFR 264.13, WIPP has imposed additional characterization requirements on the waste generators (Nelson, 1999[...], p. 2). No operational decisions are made based on these data; that is, the results of the sampling and analysis do not affect how waste is handled, so it is not clear what justifies the additional radiation exposure risk and cost of this procedure. In the committee's view, this sampling and analysis applied only to homogeneous waste is unnecessary: If acceptable knowledge documentation [...] provides sufficient characterization information for heterogeneous waste, the committee can identify no technical reason why acceptable knowledge should not also be adequate for homogeneous waste.

"Procedure 3: Headspace gas sampling and analysis. DOE informed the committee that there is no regulatory requirement to conduct headspace gas sampling and analysis, however, in an effort to meet the intent of 40 CFR 264.13, WIPP has imposed additional characterization requirements on the waste generators (Nelson, 1999[...], p. 3). The headspace gas sampling and analysis was developed as a means of checking on conformance with USNRC and the U.S. Department of Transportation (DOT) requirements [...]; however, these requirements can be met by other means [...].

"Procedure 6: Visual examination. Visual examination is done on a fraction of the waste containers to confirm the real-time radiography and acceptable knowledge waste characterization information (Nelson, 1999[...], p. 5). However, there is no requirement for verification of real-time radiography results. An alternative way to confirm these results without operator exposure would be to use standardized test drums. The visual examination confirmation is a self-imposed procedure that yields no benefit but results in increased risk of exposure and cost."

Furthermore the NRC (2001) suggested that a DOE study (1999) confirms that sampling and analysis of homogeneous waste (which frequently requires drilling into a radioactive waste container using a large drill to obtain a core sample), headspace gas sampling and analysis (which requires workers to establish a pathway into a radioactive waste container to attach a sample line, frequently done with a large needle), and

visual examination (which requires workers to open a radioactive waste container and physically sort through its contents), are based on terms negotiated in a permit and not on a required regulation or legal mandate.

Page 80:

"....The committee sees no utility in the information that these procedures provide. Any speculative benefits of acquiring this information must be weighed against the risks and costs. The committee's judgment is that the collection of these data from superfluous procedures increases, rather than decreases, the risk and safety of the overall TRU waste operations." [The RP notes that the second term 'safety' in the quoted phrase conveys the opposite meaning from the first term 'risk'. Upon reading the complete text of the cited report, the RP concludes that the cited phrase should be read 'to reduce risk' rather than 'reduce risk and safety.']

"These superfluous characterization and intrusive procedures also represent a conflict with the ALARA principle. The issue of how to handle conflict between regulatory requirements for waste characterization information and ALARA is beyond the scope of the committee's statement of task. At issue, however, is whether the present TRU waste management program results in significantly more worker radiation exposure than is justified to satisfy safety and nonnegotiabie regulatory requirements."

Based on the careful evaluation of the NRC (2001) report, the RP concludes that the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S. 1424 is supported by the NRC.

Criterion 2

Is the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S. 1424 supported by various statements and other publications of the New Mexico Environmental Evaluation Group?

Finding 2 of the RP

As the Senate language was based on the statements and other publications of Environmental Evaluation Group (EEG), the RP had to rely upon the existing materials prepared by the EEG.

Responding to a question of the NRC (EEG 2003, page 2, #5): "What WIPP waste characterization requirements, if any, has DOE imposed that go beyond EPA, NMED, and transportation requirements?", the EEG response was:

"*None that the EEG is aware of. The DOE established a unique system for waste characterization in order to satisfy the various requirements for opening the WIPP facility and allowing TRU wastes from across the country to be disposed of in New Mexico. These were worked out over several years through various methods with the various agencies and the DOE Generator/Storage Sites, involving give-and-take on both sides. During these negotiations, the DOE wished to deviate from the usual hazardous waste processes for a disposal facility. These deviations were apparently because of the DOE's limited knowledge about the TRU waste, the introduction of RCRA requirements to the DOE holdings, the complications caused by the presence of radionuclides, a desire to have the waste analyzed by those most familiar with them (the generator/storage sites), the uniqueness of the WIPP as a geological repository rather than a landfill, and other considerations. Thus, it is less a condition of whether or not the DOE has imposed requirements that go beyond those of the regulatory agencies than it of whether or not the DOE is going beyond the agreements established with the agencies.*"

Silva (2002b, page 1) provided EEG's views to a committee of NRC by stating:

"*These previous EEG statements reflect our basic criteria regarding waste characterization:*
1. 'We believe overall waste characterization requirements are excessive .... However, any proposed relaxation needs to be evaluated in sufficient detail to convince regulators, EEG, and stakeholders that the modification is justified' ...."

2. "In our October 4, 2001 Statement to the NAS Committee on the Characterization of Remote-Handled Transuranic Wastes for the Waste Isolation Pilot Plant we said, 'The conclusions from EEG-72 were that for routine operations the radiological risk was on the order of 10,000 times the hazardous waste risks, all from Volatile Organic Compounds (VOCs).... The fact that radiological risks are much greater than hazardous waste risks needs to be kept in mind by DOE, regulatory agencies, peer review groups, this Committee, and oversight agencies when addressing possible changes to waste characterization requirements'."

3. "The relaxation of audit requirements and QA/QC is not an appropriate way to reduce the waste characterization burden. These requirements should maintain the current level of stringency. The appropriate way to reduce the waste characterization burden is to eliminate unnecessary requirements, not to reduce the degree of compliance."

Silva (2002b, page 8) has also stated that:

"We see no technical reason why it is necessary to analyze for metals and chemicals at all. [...] Our reasons are: (1) the quantity of these materials to be emplaced in the repository was not important enough to DOE to estimate in the HWFP Application nor for the New Mexico Environment Department to request, (2) the data are not to be used for any regulatory control under the HWFP, and (3) evaluations in EEG-72 concluded that human exposures to hazardous metals and chemicals would only occur from the same type of operational and human intrusion accidents that released radioactive materials. In EEG-72, the calculated radionuclide risk would be $\geq 5x10^5$ times the hazardous metals risk.

"Despite the above statement, we do recognize an advantage of toxic metals sampling; the possible detection of prohibited items, such as PCB concentrations greater than 50 parts per million." [The RP does not understand this statement as it appears inconsistent with the above paragraph.]

"Our concerns about VOC or SVOC sampling are the same as for headspace gas sampling (that room based concentration limit and

transportation requirements be met in some manner). The Committee may wish to explore the need for VOC and SVOC sampling in order to provide additional information on homogenous wastes."

In May 2002, based on the results of an EEG Report (Channell and Neill 1999), Silva (May 2002a, page 5) stated that:

"With respect to waste characterization for non-radiological constituents such as VOCs, the EEG's analyses indicate that the non-radiological risks are substantively less than the radiological risks[...]. The analyses suggest that these constituents do not require the same level of sampling characterization. Furthermore, it has been suggested that additional waste characterization of the non-radiological constituents may increase radiological risks to workers. The EEG recommends that the DOE analyze the efficacy of AK for RH TRU in the absence of confirmatory testing. However, until the data are generated and evaluated, the DOE should not deviate from the characterization process used for CH TRU. The DOE also needs to address the documents identified by the EEG which raise questions about AK at the generator/storage sites."

Furthermore, Channell and Walker (2000 page 60) of EEG concluded that:

"Even if VOC emissions are much higher than expected, the Confirmatory VOC Monitoring Plan at WIPP would detect concentrations that are three orders of magnitude below allowable Permit limits. Any hazardous emissions from pre-Permit wastes would likely be reported and acted on long before Permit limits were reached."

It appears that EEG agrees that the current characterization requirements are excessive. It appears that EEG also agrees that monitoring VOCs in underground disposal rooms is sufficient. The RP was unable to identify more details on views of EEG regarding the elimination of the waste confirmation requirements mentioned in U.S. Senate Report 108-105 and Bill S. 1424.

Criterion 3

Based on the information presented to the Review Panel, is the permit modification listed under Section 310 of U.S. Senate Bill S. 1424 technically defensible?

Finding 3 of the RP

In assessing the need for various characterization tests, the RP first evaluated the regulatory requirements. Regulations promulgated in implementing requirements of RCRA provide guidance on compliance with RCRA. Briefly, each generator is required to perform specific tasks as follows:

1. If the process used by the waste generator does not use or produce any of the classes covered under RCRA, then the waste is not covered under RCRA. Many organizations use the process knowledge to demonstrate exception from RCRA.

2. The generator performs specific tests as provided in the regulations, and can demonstrate a lack of presence of listed waste or passage of specific characteristic wastes.

3. The generator has also the option to request a delisting of the waste even if the process knowledge or the tests indicate coverage under RCRA. The delisting process is intended to remove those waste streams that pose insignificant risks from unnecessary and costly compliance with RCRA requirements.

4. If the process knowledge or various tests demonstrate that the waste is legally covered under RCRA and the waste is not delisted, the generator must treat the waste prior to its disposal. This latter requirement is referred to as Land Disposal Restrictions (LDR) and is intended to ensure the long-term safety of Disposal facilities permitted under RCRA.

For transuranic (TRU) waste, WIPP Managers have chosen to accept the fact that TRU waste includes RCRA constituents. As stated above, the consequence of such a decision is compliance with the requirements of LDR. However, the Waste Isolation Pilot Plant/Land Withdrawal Act

exempts the WIPP from the coverage of LDR. Consequently, it appears that the WIPP managers would have to comply only with those RCRA requirements that are unrelated to LDR. These include those tests that would be required for the safety of operations. The safety-related requirements are those that are also covered by the transportation requirements—notably corrosivity, reactivity, and ignitability/flammability.

Acceptable knowledge can be one way in which compliance with the legal requirements is confirmed. EPA provides guidance in this regard. In particular, EPA (1994) provides guidance regarding waste analysis at facilities that generate, treat, store, and dispose of hazardous waste. Although EPA views representative sampling and laboratory analysis as the preferred method, acceptable knowledge is considered to be a viable alternative to meet waste analysis requirements. EPA (1994, page 1-11) indicates that:

"... generators and TSDFs also can meet waste analysis requirements by applying acceptable knowledge. Acceptable knowledge can be used to meet all or part of the waste analysis requirements."

Moreover, on pages 1-13 to 1-14 of EPA (1994) it is stated that:

"... there are situations where it may be appropriate to apply acceptable knowledge, including:
• Hazardous constituents in wastes from specific processes are well documented, such as with the F-listed and K-listed wastes.
• Wastes are discarded unused commercial chemical products, reagents or chemicals of known physical, and chemical constituents. Several of these fall into the P-listed and U-listed categories...
• Health and safety risks to personnel would not justify sampling and analysis (e.g., radioactive mixed waste).
• Physical nature of the waste does not lend itself to taking a laboratory sample."

The RP finds itself in agreement with the NRC (2001, page 77) that:

"... some waste characterization specifications have no basis in law, the safe conduct of operations to emplace waste in WIPP, or long-term performance requirements."

The NRC (2001, page 80) identifies three tests as having no legal foundation and

"... sees no utility in the information that these procedures provide. Any speculative benefits of acquiring this information must be weighed against the risks and costs. The committee's judgment is that the collection of these data from superfluous procedures increases, rather than decreases, the risk and safety of the overall TRU waste operations." [The RP notes that the second term 'safety' in the quoted phrase conveys the opposite meaning from the first term 'risk'. Upon reading the complete text of the cited report, the RP concludes that the cited phrase should be read 'to reduce risk' rather than 'reduce risk and safety.']

In addition to NRC (2001) report, the RP evaluated a more recent relevant NRC (2002) report. The latter report adopts the conclusions of the NRC (2001) report, and provides the following recommendation (NRC 2002, page 49):

"The committee acknowledges that DOE must consider many non-technical factors in composing its characterization plan. However, DOE should propose only characterization activities that have a technical, health and safety, or regulatory basis."

As no evidence was provided that the views of the EEG—as presented in its statements and reports—had been subjected to independent peer review, the RP used the EEG information cautiously.

DOE has already agreed with the NRC recommendation to eliminate self-imposed waste characterization requirements that lack a legal or safety basis (NRC 2001, page 113). DOE has developed and begun the implementation of a strategy to systematically improve the Waste Analysis Plan by reducing the frequency of waste characterization and implementing methods that make characterization simpler, less expensive—and above all—safer. On August 8, 2000, the New Mexico Environment Department approved two packages of Class 2 modifications to the WIPP's Hazardous Waste Facility Permit that include:

1. The "miscertification rate" of TRU waste was revised to apply to the waste summary category group instead of each waste stream. This could result in a ten-fold reduction in the number of drums that must be opened for VE.

2. The solids sampling requirements for analysis of VOCs have been revised to allow use of one subsample instead of three subsamples. This could avoid a cost of approximately ten million dollars that the Idaho National Engineering and Environmental Laboratory would have had to spend in re-analyzing the samples.

3. The number of headspace gas samples required has been reduced for two types of waste streams to a statistically-selected number of drums, instead of 100% sampling. The two types of waste streams now eligible for statistical headspace gas sampling are: wastes that have been thermally processed; and homogeneous wastes with "acceptable knowledge" that demonstrate no volatile organic compounds have been present in the waste.

Approval of these modifications could result in significant cost savings associated with waste characterization and will reduce radiation exposures to workers.

Additionally, several modifications have been prepared and submitted that specifically address safety issues associated with TRU waste handling and disposal. One such modification, submitted in October 2000, will allow generators to remove from consideration for VE any containers that pose a safety concern. For example, if a generator determines that opening a container with a high fissile gram content is a safety hazard, that container can be ruled ineligible for VE and another container selected.

Based on the information presented to the Review Panel, the permit modification listed under Section 310 of U.S. Senate Bill S. 1424 is technically defensible. There is no reason to perform waste confirmation tests that:

1. provide insignificant health and safety benefits to the U.S. population; and
2. pose serious radiological and occupational health and safety risks for the workers performing these tests.

RECOMMENDATION

The RP recommends that the Mayor of Carlsbad make available this report to the U.S. Senate Committee for Energy and Water.

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Biographical Summaries

Erich W. Bretthauer is currently President of the Bryce Meadows Development Corporation. He held the position of research professor at the University of Nevada-Las Vegas from January 1993 to March 1995. In that capacity, he served as Executive Director of Nevada Industry, Science Engineering & Technology, a public-private partnership which developed programs to enhance the scientific infrastructure of the state of Nevada. He was Assistant Administrator for Research and Development at the U.S. Environmental Protection Agency (EPA) from March 1990 until January 1993. In that capacity, he managed the Research and Development activities of a large and multi-disciplinary agency. Erich Bretthauer rose through the ranks of the EPA and served in a number of capacities ranging from a bench scientist to policy manager at national and international levels. He directed the EPA's emergency and long-term monitoring program after the accident at Three Mile Island, as well as its bioremediation program in Prince William Sound after the Valdez oil spill. He also directed the EPA's ecological research program from 1983-1986 and was Director of EPA's Environmental Monitoring Systems Laboratory in Las Vegas from 1986-1990. He is a member of Sigma Xi; the American Chemical Society; the American Association for the Advancement of Science; and the American Water Works Association; and has served on the Federal Advisory Committee to the Civil Engineering Research Foundation. Erich Bretthauer is the author and coauthor of numerous papers, reports, and other publications. He received his B.S. and M.S. in chemistry from the University of Nevada, Reno, NV.

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Alan S. Corson is a consultant in hazardous waste issues. He has over 25 years of experience in a number of environmental issues, notably those related to the regulations and management of hazardous waste. Subsequent to his retirement from the U.S. Environmental Protection Agency (EPA), he served in an advisory role to Jacobs Engineering Group and to the Versar Corporation for both government and private sector clients regarding hazardous waste management programs. During his employment at the EPA, he worked at the Office of Solid Waste where he was responsible for regulatory programs and establishing national standards for generators and transporters of hazardous waste; development of sampling and analytic methods for evaluating solid/hazardous waste including the quality assurance/quality control program; and development

and management of programs to establish risk assessment of hazardous waste management practices. Alan Corson was instrumental in the development of the original regulatory program defining standards for solid waste and hazardous waste, and setting national standards for recycling hazardous waste. He also initiated, developed, and managed the original program for restricting hazardous wastes from land disposal management options. The framework developed under this program is currently in-place and used for all evaluations in the land-ban program. Alan Corson served as the EPA Office of Solid Waste representative on many intra- and inter-agency workgroups including PCBs, Reportable Quantities, chlorinated solvents, and transportation of hazardous materials. He developed a guide for effective management of infectious wastes—a predecessor to the current regulatory program for medical wastes; characteristics and listings of hazardous waste; and many regulatory options papers for presentation. Alan Corson managed the preparation of numerous regulatory packages for all aspects of the program implementing the Resource Conservation and Recovery Act (RCRA). He has spoken widely and has taught numerous courses on RCRA and its various regulations. He served on numerous national and international panels including review panels of the American Society of Mechanical Engineers. He received a B.S. in Electrical Engineering and an M.S. in Engineering Management from the Drexel Institute of Technology in Philadelphia, PA.

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Nathan H. Hurt is a consultant in management and engineering with Technical and Management Consulting. He provides services to industrial firms and government agencies involved in environmental clean-up and waste management—both chemical and radioactive. He has extensive experience in the areas of executive management; plant management; engineering management; project management; marketing; and sales. He specializes in the areas of: uranium enrichment/production; engineering; development and marketing; plant management of rubber chemicals; petrochemicals; and thermoplastics. He also specializes in the engineering management of synthetic rubber and lattices; vinyl monomers and copolymers; polyesters; U.S. Department of Energy (DOE) weapons plants; quality assurance management; and operational readiness review. Nathan Hurt has been involved with the decommissioning of nuclear facilities. He was the Corporate Sponsor or Program Manager for seven decommissioning contracts at the DOE Complexes in Oak Ridge, TN; and Pinellas, FL. Previously, Nathan Hurt worked for Sharp and Associates, Inc. as the Director and Project Manager at the Oak Ridge Office. He was Vice President and Director of Oak Ridge Operations for IDM Environmental Corp., where he was responsible for the marketing and sales of decontamination, decommissioning, and waste management. He served as Project Manager for the laboratory quality assurance program at Westinghouse Hanford; DOE's Rocky Flats Plant—plant-wide identification of electrical equipment. He managed a study for a waste treatment and storage facility at the Portsmouth Area Uranium Enrichment Facility which included incineration and compaction of low-level radioactive wastes. He also worked for The Goodyear Tire and Rubber Company, including Goodyear Atomic, as Director of Research and Development, and President, where he was responsible for the operation of the Portsmouth Area Uranium Enrichment Facility. Nathan Hurt is a past President of, the American Society of Mechanical Engineers. He has been a member of: the American Association of Engineering Societies' Board of Governors; the American Institute of Chemical Engineers; and the Institute of Nuclear Materials Management. He is also a member of Tau Beta Pi Honorary Engineering Society; Pi Tau Sigma Honorary Mechanical Engineering Society; and was a

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Michael C. (M.C.) Kirkland is an independent consultant who led a team that performed a Congressionally-mandated External Independent Review of the $1.3 billion Spallation Neutron Source Project at Oak Ridge. He assisted in the planning and review of a management assessment at a U.S. Department of Energy (DOE) Site that involved the restart of a plutonium facility. He participated in planning, procurement, and review activities in the environmental remediation area that included decommissioning activities at a shut down nuclear test reactor; designed and installed a ground water cleanup technology. M.C. Kirkland managed several environmental and construction projects that employed many soil investigative techniques including significant work with cone penetrometers. Additionally, he provided consulting services to a large environmental remediation services company regarding Dense Non-Aqueous Phase Liquid locating and removal techniques. During his tenure at the SRS, M.C. Kirkland was a Technical Advisor, Project Manager, and Director of the Project Engineering Division. He evaluated nuclear and mixed waste conditions and aspects of high level wastes and spent nuclear fuel; determined material inventories; performed pollution prevention and environmental health and safety evaluations for a proposed waste treatment facility; served as technical advisor to a study administered by the Savannah River Operations Office; and developed integrated schedules defined for this project. M.C. Kirkland was director of the Project Engineering Division and managed the SRS design and construction program. He has been involved with waste management and environmental projects; cutting-edge technology programs; and worked with lasers and magnetic containment. He served as Director of the Waste and Fuel Cycle Technology Office, and planned and coordinated the programs of the DOE National High Level Waste Technology Office; the SR Fuel Cycle Technology Program; and the Commercial Interim Spent Fuel Management Program. M.C. Kirkland holds a B.S. in Mechanical Engineering from the University of South Carolina. He is registered as a Professional Engineer in South Carolina.

Betty R. Love is currently Executive Vice President of the Institute for Regulatory Science. In that capacity, she is responsible for the management of day-to-day operations of the Institute, and for administration of several projects. She is the Administrative Manager of a large-scale peer review program in collaboration with the American Society of Mechanical Engineers for a number of organizations including the U.S. Department of Energy. Her current research activities center around the development and implementation of a systematic approach to stakeholder participation, notably in scientific meetings. Previously, Betty Love was Director, Department of Training and Information within the Office of Environmental Health and Safety of Temple University in Philadelphia, PA. During that period she was instrumental in the development of a "Handbook of Environmental Health and Safety". She also developed and implemented a large-scale training program not only for the faculty and staff of the University but also for others. Betty Love is currently Managing Editor of *Technology.* She has published several papers in peer-reviewed journals; has edited a number of compendia; and is the primary author of *Manual for Public and Stakeholder Participation*. Betty Love received a B.S. degree in Business Administration from Virginia State University in Petersburg, VA, and an M.S. degree in Developmental Clinical Psychology from Antioch College in Yellow Springs, OH.

Robert E. Luna is currently a private consultant involved in the packaging and transportation of a wide variety of radioactive materials at national and international levels. His current interests range from risk assessment related to packaging and transportation of radioactive materials, to nuclear weapon accident phenomenology. Previously, he was Senior Manager for the Waste Legacy Program Development Office at Sandia National Laboratory. In that capacity, he was responsible for business development for the mining industry; Department of Defense environmental cleanup needs; U.S. Nuclear Regulatory Commission transportation technology; and application of environmental remediation technology to various U.S. Department of Energy sites. In addition, he was involved in the study of nuclear weapon safety, transportation risk assessment, and cask sabotage source terms. Prior to that position, he managed a number of programs dealing with environmental characterization and monitoring technology, and while at Sandia National

Laboratory, he was involved in the development of the Environmental Impact Statement for the Pantex Plant in Amarillo, TX. For nearly 20 years, Robert Luna was involved with increasing responsibility in various aspects of radioactive and hazardous material package design and transportation, including: package design and testing; structural and thermal analysis; material development; and information management. He led the development of RADTRAN risk assessment code; managed the development of regulatory guide NUREG 0170; and led national efforts related to the risk assessment of packaging and transportation of high level waste/spent nuclear fuel at Sandia. Robert Luna represented the U.S. Department of Energy at the International Atomic Energy Agency in the development of the document regulations for the transportation of radioactive materials and related topics. He managed and contributed to experiments which defined sabotage threat and the potential impact of the sabotage of spent nuclear fuel transportation casks, including: threat evaluation, source-term development, and damage evaluation. He was involved in the development of generation, transport, and the fate of aerosols resulting from nuclear weapons accidents, including mishaps during the stages of assembly, disassembly, deployment, and storage. Robert Luna is a Fellow of the American Society of Mechanical Engineers; a member of the American Nuclear Society; and a member of ANSI N14 Management Committee for Nuclear Material Packaging. He is on the Editorial Board of the *International Journal of Radioactive Material Transportation.* He was past Chair of the Bernalillo County Air Quality Control Board. He received the Department of Energy Award of Excellence for "Significant Contributions to the Nuclear Weapons Program in Plutonium Safety Issues". He is the author or coauthor of more than 100 publications. Robert Luna holds a B.S. degree in Mechanical Engineering from Rutgers University; an M.S. degree in Mechanical Engineering and a Ph.D. in Aerospace and Mechanical Sciences from Princeton University; and Master of Management degree from the Anderson Schools of Management, University of New Mexico. He is a registered Professional Engineer in New Mexico.

Peter Maggiore is currently Principal Scientist with Portage Environmental, in San Antonio, TX. There, he is a corporate resource regarding regulatory analysis, environmental compliance, and scientific matters. In addition, Peter Maggiore has responsibilities in the areas of quality

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the congressionally-mandated Defense Waste Management Plan, and for managing the related technology development, operations, and projects. He led the initiation of the Defense Waste Processing Facility, and saw it and the Waste Isolation Pilot Plant through technical, managerial, stakeholder, and political challenges. He was National Aeronautics and Space Administration Space Science Chief and Program Manager, and Aerospace Engineer at Langley. He was a Fellow in the White House with the President's Science Advisor and the Office of Management and Budget's Space and Energy branch. He chaired the Westinghouse West Valley Corporation Technical Advisory Group for high-level nuclear waste vitrification and management before, during, and after that project's successful vitrification campaign. He is a member of the American Physical Society, Sigma Xi, and other professional organizations. He is a Fellow of the American Association for the Advancement of Science. He is Chair or member of boards and committees of the National Research Council; George Mason University; the American Society of Mechanical Engineers; International University Exchange; and Westinghouse West Valley Corporation. He is a founding member of the Editorial Board for "Data Science", the new international on-line journal of Codata. He published numerous peer-reviewed papers and was awarded two patents. Trained as electrical engineer and physicist, he received a Vordiplom in Physics and Chemistry from the University of Kiel while on German industrial and governmental scholarships, and a Ph.D. in Physics from University of Maryland at College Park under a Fulbright scholarship.

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Administration contract through the University of Colorado entitled *Identification and Mapping of Expansive Clay Soils in the Western U.S. Using Field Spectrometry and AVIRIS Data*; and a National Science Foundation grant entitled *The Importance of Osmosis in the Volumetric Behavior of Earth Materials.* Formerly, he was a Research Civil Engineer at the U.S. Geological Survey Engineering Geology Branch and Earthquake and Landslide Hazards Branch. His projects included the investigation of physicochemical and physical phenomena that can increase the vulnerability of ground to failure with time, and that can be used to strengthen and stabilize weak or failed ground. These phenomena include chemical causes of groundwater movement, and chemical and saturation effects on the permeability, compressibility, and strength of argillaceous materials. Harold Olsen conducted reviews of geotechnical aspects of Preliminary Safety Analysis Reports concerning proposed nuclear reactor sites for the Atomic Energy Commission. He also has worked as a Geotechnical Consultant in U.S. Geological Survey Technical Assistance Programs in Peru, Indonesia, and Bangladesh. He is an expert on soil properties and behavior, and the application of geotechnical data to studies of terrestrial and marine environments. Harold Olsen has been Editor-In-Chief of the American Society of Civil Engineers' Journal *Geotechnical and Geoenvironmental Engineering,* and a member of the American Society of Civil Engineers' Geo-Institute Awards Committee. His current professional society activities include membership in the: American Society of Civil Engineers' Geo-Institute Technical Publications Committee; American Society of Civil Engineers' Committee on Engineering Geology; American Society for Testing and Materials Committee D-18 on Soil and Rock for Engineering Purposes; and Highway Research Board Committee A2L03 on the Physicochemical Properties of Soils. He has authored or coauthored over 100 papers, reports, and conference contributions. Harold W. Olsen received S.B., S.M., and Sc.D. degrees in Civil Engineering from the Massachusetts Institute of Technology in Cambridge, MA. He is a certified Professional Hydrologist (Groundwater).

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Department Distinguished Fellow Award. He has published numerous papers in trade journals. He received a BSME degree from the University of Alabama in Tuscaloosa, AL, along with the Machinery Magazine Design Award and an MBA degree from Florida State University in Tallahassee, FL.

Richard Wilson is currently emeritus Mallinckrodt Research Professor of Physics at Harvard University in Cambridge, MA. He is also an affiliate of the Center for Middle Eastern Studies; the Harvard Center for Risk Analysis; and of the Program on Science and International affairs at the Kennedy School of Government. He used the principle of detailed balance to measure the spin of the pi-zero meson and studied nucleon-nucleon scattering at the Harvard Cyclotron Laboratory. He was involved in converting the Harvard University Cyclotron from nuclear physics use to medical treatment. He was the first to analyze elastic scattering data in terms of the electric and magnetic form factors. He studied nucleon structure by electron-proton scattering and muon proton scattering. He was a participant in the Cambridge Electron Accelerator "by-pass" program, which demonstrated an unusually large cross-section for producing hadrons. Richard Wilson closely followed the Russian and Ukrainian radiation accidents at Chernobyl in the Ukraine, and the accidents at the Techa River and the Mayak production complex in the Ural Mountains. He performed research on the risk assessment of chemical carcinogens. Richard Wilson is Chairman of the visiting committee of the radiation medicine department at Massachusetts General Hospital. He is Chairman of an International Advisory Committee to the newly formed Sakharov College of Radioecology in Minsk, Belarus, and serves as a member of the Board of Directors of the Andrey Sakhorov Foundation of New York and Moscow. He was the first Chairman of the Harvard Cyclotron Operating Committee and is still a member. He is a Fellow of the American Physical Society, Chaired its committee to study the radiological consequences of severe nuclear power accidents, and received its "Forum Award". Richard Wilson chaired an advisory committee for the Minister of Economic Affairs of the Republic of China. He is a founder/member of the Society of Risk Analysis, as well as the recipient of its Distinguished Service Award. He is a member of the American Nuclear Society and the Society of Toxicology. He served as the Director of the NE Regional Center of the National Institute of Global Environmental

Change. He has held various positions as a Visiting Professor, Scholar, and Scientist and served on numerous government advisory committees in many different agencies and countries. Richard Wilson is the author or coauthor of more than 800 published papers. He is the editor of the English translation of the Russian Journal, *Radiation and Risk,* which is published by the Russian Medical Research Laboratory in Obninsk and is mainly about the effects of Chernobyl. Richard Wilson holds a B.A. degree; an M.A. degree and a Ph.D. degree; all in Physics and all from Christ Church, Oxford University, Oxford, England.

Acronyms

AEA	Atomic Energy Act
AK	Acceptable Knowledge
ALARA	As Low As Reasonably Achievable
ASME	American Society of Mechanical Engineers
BAS	Best Available Science
BDAT	Best Demonstrated Available Technology
CAR	Commission on Assessment and Reviews
CCA	Compliance Certification Application
CFR	Code of Federal Regulations
CH	Contact-Handled
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EEG	Environmental Evaluation Group
EP	Extraction Procedure
EPA	U.S. Environmental Protection Agency
FR	Federal Register
FTIRS	Fourier Transform Infrared System
GC	Gas Chromathography
HPLC	High Pressure Liquid Chromatography
HSWA	Hazardous and Solid Waste Amendments
HWFP	Hazardous Waste Facility Permit
INEEL	Idaho National Engineering and Environmental Laboratory
LDR	Land Disposal Restrictions
MS	Mass Spectrometry
NAS	U.S. National Academy of Sciences
NDA	Non-Destructive Assay
NMED	New Mexico Environmen~~tal~~ Department
NRC	National Research Council
NUREG	Nuclear Regulatory Guidelines
OSWER	Office of Solid Waste and Emergency Response
PA	Performance Assessment
PAN	Passive/Active Neutron
PCB	Polychlorinated Biphenyl
PREPP	Process Experimental Pilot Plant
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
RH	Remote-Handled

RP	Review Panel
RSI	Institute for Regulatory Science
RTR	Real-Time Radiography
SGS	Segmented Gamma Scans
SPC	Statistical Process Control
SVOC	semi-volatile organic compound
SW–846	Test Methods for Evaluating Solid Wastes, Physical/ Chemical Methods
SWB	Standard Waste Box
TC	Toxicity Characteristic
TCLP	Toxicity Characteristic Leaching Procedure
TDOP	Ten-Drum Overpack
TIC	Tentatively Identified Compound
TRU	Transuranic
TRUDOCK	Waste handling area of WIPP
TRUPACT-II	Transuranic Package Transporter, Model 2
TSDF	Permit Treatment, Storage and Disposal Facility
TSDF-WAC	Permit Treatment, Storage and Disposal Facility Waste Acceptance Criteria
UCL	Upper Confidence Limit
USNRC	U.S. Nuclear Regulatory Commission
VE	Visual Examination
VOC	Volatile Organic Compound
WAC	Waste Acceptance Criteria
WAP	Waste Analysis Plan
WHB	Waste Handling Building
WIPP	Waste Isolation Pilot Plant
WIPP/LWA	Waste Isolation Pilot Plant/Land Withdrawal Act
WSPF	Waste Stream Profile Form

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FLUID INJECTION FOR SALT WATER DISPOSAL AND ENHANCED OIL RECOVERY AS A POTENTIAL PROBLEM FOR THE WIPP: PROCEEDINGS OF A JUNE 1995 WORKSHOP AND ANALYSIS

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Environmental Evaluation Group
New Mexico

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, is being constructed as a repository for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, continues the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the generator sites' compliance with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

Robert H. Neill
Director

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EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP) is a facility of the U.S. Department of Energy (DOE), designed and constructed for the permanent disposal of transuranic (TRU) defense waste. The repository is sited in the New Mexico portion of the Delaware Basin, at a depth of 655 meters, in the salt beds of the Salado Formation. The WIPP is surrounded by reserves and production of potash, crude oil and natural gas.

In selecting a repository site, concerns about extensive oil field development eliminated the Mescalero Plains site in Chaves County (U.S. DOE 1980, 2-10) and concerns about future waterflooding in nearby oil fields helped eliminate the Alternate II site in Lea County (Griswold 1977, 13). Ultimately, the Los Medaños site in Eddy County was selected, relying in part on the conclusion that there were no oil reserves at the site (U.S. DOE 1980, 2-15).

For oil field operations, the problem of water migrating from the injection zone, through other formations such as the Salado, and onto adjacent property has long been recognized (Ramey 1976). In 1980, the DOE intended to prohibit secondary recovery by waterflooding in a one mile buffer surrounding the WIPP Site (U.S. DOE 1980, 8-4). However, the DOE relinquished the right to restrict waterflooding (McGough 1983) based on a natural resources report (Brausch et al. 1982, 30) which maintained that there was a minimal amount of crude oil likely to exist at the WIPP site, hence waterflooding adjacent to the WIPP would be unlikely.

In the early 1990s, the Delaware Basin experienced a drilling boom that included oil field discoveries surrounding and underlying the WIPP Site (Broadhead et al. 1995). Salt water disposal wells are now operating throughout the area (Silva 1994; Broadhead et al. 1995) and waterflooding is just beginning with new oil field pressure maintenance programs underway (Broadhead et al. 1995).

Beginning in 1988, sudden water level rises in the Culebra aquifer to the south of the WIPP site raised questions about the water injection activities of the oil and gas industry (Bailey 1990; LaVenue 1991). LaVenue (1991) cautioned the WIPP Performance Assessment (PA) team about the yet to be determined impact of these activities. However, the WIPP PA team did not include the impact of fluid injection in the calculations citing either "low consequence" arguments for human activities adjacent to the WIPP (SNL 1991, SNL 1992) or "consequences greater than that of exploratory drilling" in the case of human intrusion (SNL 1992). In 1993, the WIPP project was again cautioned about injected oil field water fracturing the Salado Formation and migrating into adjacent properties. An oil and gas producer in southeast New Mexico had suffered a major salt water blowout as a result of a waterflood operation two miles away (Hartman 1993).

The potential impact of brine injection on the long-term performance of the WIPP prompted the Environmental Evaluation Group (EEG) to organize a June 13, 1995, workshop on the issue. This report publishes the workshop presentations (Chapter 2) and presents the author's analysis of the workshop issues (Chapter 3) based on information from the scientific literature, public records, the draft compliance application submitted by the DOE to the U.S. Environmental Protection Agency (EPA), and the WIPP specific compliance Criteria promulgated by the EPA. The workshop included presentations describing the extent of oil and gas resources, the anomalous water level rises in the Culebra Aquifer, the documented effects of water flooding on the Salado Formation, the geology of waterflooded areas in southeast New Mexico, the current petroleum production practices, the treatment of water injection by the performance assessment effort, and the need for a water flooding scenario in the WIPP PA calculations. As was intended, a number of issues were deliberated. On many issues there was no consensus. Nonetheless, the workshop was an excellent example of cooperation and open exchange of information by various federal and state agencies, private industry, the university sector, and other interested parties.

In addition to exploring the potential impact of waterflooding and salt water disposal on the WIPP, Chapter 3 identifies a number of unresolved issues. Some unresolved topics are currently in litigation between oil and gas companies and the federal government for operations adjacent to the WIPP. The issues identified in Chapter 3 include questions about a) the productive life of an oil field in the Delaware Basin, b) the extent of oil and gas reserves in unexplored areas, c) the potential for waterflooding and other secondary recovery methods, d) the volumes of water to be injected, e) the availability of water for waterflooding, f) delays in oil and gas drilling due to the presence of potash g) the true extent of potash reserves, h) evidence of communication between formations above and below the WIPP through vertical pathways possibly created by the improper abandonment of wells, poorly cemented and cased wells, degraded well casings and cement in saline environments, and i) violation of existing regulations.

This report also raises questions about how much credit for protection from out-of-zone injection the WIPP project can justify, based on state regulations unique to the Known Potash Lease Area. The state regulations were never intended to address the needs of WIPP. Rather, the state regulations were promulgated to address the concerns of the potash and oil and gas industries (LeMay et al. 1988). In light of the information presented in this report, it would seem prudent for the WIPP project to analyze the historical effectiveness of the New Mexico regulations specifically intended to address fluid injection, Rule 701, 702, and 703.

The potash companies carefully monitor activities with a potential impact on the Salado Formation. For instance, the New Mexico Oil Conservation Division held a hearing on November 16, 1995, for a proposed oil field pressure maintenance well to be located one mile from the outer boundary of the WIPP and eight miles from IMC's existing potash mine workings. At the hearing IMC expressed concern that injected water could escape or otherwise migrate from the proposed injection interval into potash bearing formations. The DOE was notified of the hearing but did not attend (LeMay 1995b). The injection well was approved to

operate at a pressure that exceeds the lithostatic pressure at the WIPP horizon.

The oil and gas industry is also concerned about the operation of injection wells in close proximity to its hydrocarbon reserves. When Yates Petroleum proposed converting an oil production well to salt water injection, another oil company objected. Mitchell Energy was concerned about excessive injection pressures and the loss of reserves as a result of injection into potential oil producing horizons (Stephenson 1991). An agreement was reached between the two oil companies (Kellahin 1991). The salt water disposal well was approved by the New Mexico Oil Conservation Division (LeMay 1991). The DOE appeared unaware that there was a salt water injection well operating within one mile of the WIPP Site Boundary and continued to list the well as an oil producing well (Arthur 1993a; Arthur 1993b; Silva 1994, 55-56; Kehrman 1995, 254, lines 18-20).

The DOE Draft Compliance Certification Application (DCCA), submitted to EPA in July 1995, did not include fluid injection in the performance assessment calculations. Citing Cranwell et al. (1990), fluid injection within the WIPP site was screened out on the basis of "regulatory guidance" (U.S. DOE 1995, 6-38), but this criterion is not found in Cranwell et al. (1990). Furthermore, DOE's expert elicitation exercise of 1990 identified industrial fluid injection as a potential human intrusion activity for the full 10,000 year regulatory period (Hora et al. 1991, Table IV-16). Fluid injection due to activities on adjacent properties was screened out on the basis of "low consequence" although the DOE draft application had no documentation to support that position (U.S. DOE 1995, SCR-72). With respect to fluid injection adjacent to the WIPP Site, the February 1996 EPA Criteria (40 CFR 194) require performance assessment to include the effects of any near future activities on lands surrounding the WIPP. A credible compliance application should include performance assessment calculations that fully consider the distinct activities of 1) fluid injection for resource recovery and 2) waste disposal activities within the site and adjacent to the site for the regulatory period of 10,000 years.

1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is intended to serve as a repository for the disposal of transuranic (TRU) waste generated by the defense activities of the United States Government. The WIPP is situated in the lower portion of the Salado Formation in a resource rich area in southeastern New Mexico. Natural resources in the immediate vicinity of the WIPP site include economically attractive reserves of potash, crude oil, and natural gas (Foster 1974; Keesey 1976, 1977, and 1979; Griswold 1977; Powers et al. 1978; U.S. DOE 1980; Brausch et al. 1982; Neill et al. 1983; Weart 1983; Silva 1994; Griswold 1995a; Broadhead et al. 1995; U.S. DOE 1995).

1.1 Natural Resources and Water Injection at Other Candidate Sites

The problem of natural resources and the use of water injection in the vicinity of a nuclear waste repository has long been recognized. In 1972, the Lyons, Kansas site for a proposed TRU waste repository was rejected because there were too many drill holes in the area that could not be positively located, and nearby solution mining was experiencing unexplained water losses (U.S. DOE 1980, 2-7; U.S. DOE 1993, 26). Of the three areas in New Mexico chosen for further study, the Mescalero Plains area in Chaves County was disqualified because of extensive oil field development (U.S. DOE 1980, 2-10). In the Carlsbad vicinity, two of eight sites survived the screening criteria, the current Los Medaños site and the Alternate II. However, Alternate II in Lea County was rejected for a variety of reasons including the observation that it lay adjacent to the Double X and Triple X oil fields where waterflooding for secondary recovery could occur (Griswold 1977, 13).

1.2 Oil Field Waterflooding and the Salado

Typical oil field operations include two types of water injection activities - salt water disposal and waterflooding. In a successful salt water disposal operation,

the unwanted brine is injected through a disposal well into an approved zone or zones. The production of oil, particularly in the Delaware Basin, is often accompanied by the production of large volumes of reservoir brine.

Oil production by primary recovery relies on natural reservoir energy to drive oil towards the well bore. These sources of natural energy include fluid and rock expansion, solution gas drive, gravity drainage, and the influx of water from connected aquifers. As oil, gas, and reservoir brine are produced, the natural reservoir energy is expended. Waterflooding aims to enhance crude oil recovery by restoring or supplementing reservoir energy (Willhite 1986). A successful waterflood injects pressurized water through the well bore into the oil bearing zone to force additional oil to flow towards the producing well.

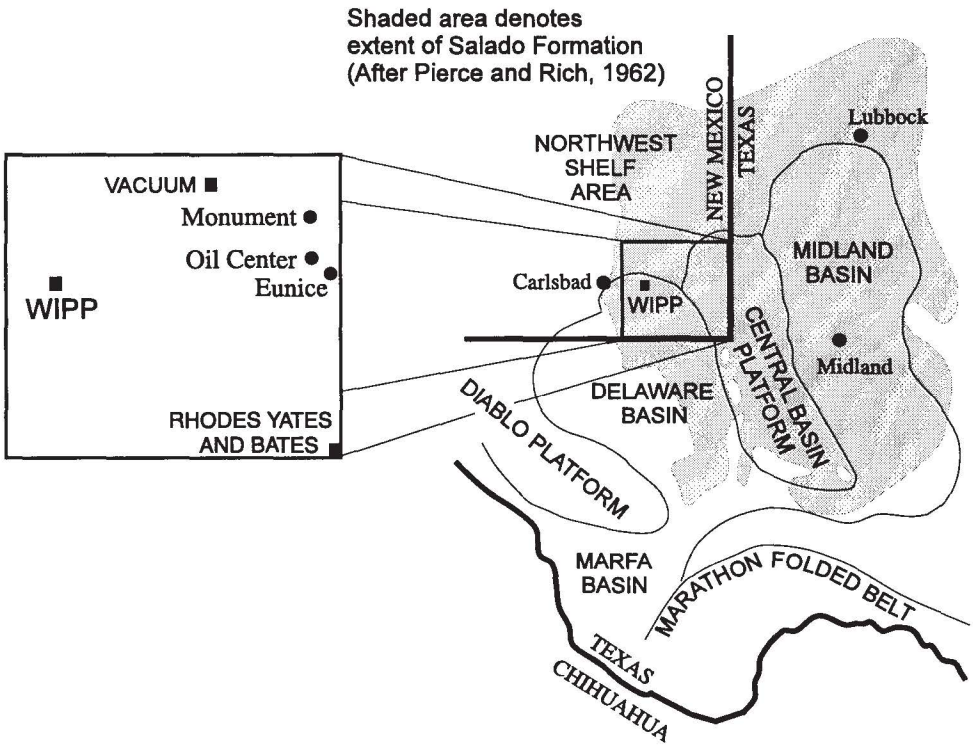

Figure 1-1. Physiographic provinces, extent of the Salado Formation, and oil field locations.

Figure 1-1 shows the locations of the physiographic zone and oil fields mentioned throughout the report. For oil fields underlying the Salado Formation, the problem of water escaping from the injection zone and migrating through the Salado Formation to adjacent properties has long been well known. For example, in a May 5, 1976, letter, Joe D. Ramey, Director of the Oil Conservation Division, advised the Secretary of the New Mexico Energy and Minerals Department (NMEMD), John F. O'Leary, of the situation:

> It has recently come to our attention that there are numerous salt water flows in and around waterfloods in Lea County... Basically the problem is that water injected at around 3600' is escaping from the injection interval, migrating upward to the base of the salt section and then moving horizontally through this section. Waterflows of 5000-6000 barrels per day and recorded surface pressures of 1600 pounds on wells outside waterflood areas are not uncommon. This had resulted in collapsed casing in several wells but the critical aspect in this is the threat of widespread contamination of fresh water.... (Ramey 1976)

In 1980, the U.S. Department of Energy (DOE) intended to prohibit secondary recovery by waterflooding (U.S. DOE 1980, 8-4) in former control zone IV - the area that now forms much of the one mile buffer outside the 4-mile by 4-mile WIPP Land Withdrawal Boundary.[1] The DOE natural resources report (Brausch et al. 1982) maintained there was a minimal amount of crude oil likely to exist at the WIPP site and did not evaluate the potential impact of waterflooding. The DOE subsequently relinquished the right to restrict waterflooding for hydrocarbon recovery in former control zone IV (McGough 1983b).

---

[1]See Silva (1994) for a discussion of how previous control zone III was squared off to form the current WIPP site boundary.

FORMATION		DEPTH TO CONTACT AT WIPP (FEET)	PRINCIPAL LITHOLOGY
Surficial Sand			Blanket sand and dune sand, some alluvium included.
		10	
Mescalaro Caliche and Gatuna Fm.			Pale reddish-brown, fine-grained friable sandstone; capped by a 5-10 ft. hard, white crystalline caliche (limestone) crust
		40	
Santa Rosa Sandstone			Pale red to gray, cross-bedded, non-marine, medium to course-grained friable sandstone; pinches out accross site.
		50	
Dewey Lake Redbeds			Uniform dark red-brown marine mudstone and sitlestone with interbedded very fine-grained sandsonte; thins westward.
		540	
Rustler			Anhydrite with siltstone interbeds. Contains two dolomite marker beds: Magenta and Culebra. Thickens eastward due to increasing content of undissolved rock salt.
		850	
Salado	Upper member		Mainly rock salt (85-90%) with minor interbedded anhydrite (43 marker beds), polyhalite and clayey to silty clastics. Potash minerals in McNutt Zone.
	McNutt member		
	Lower member	←	WIPP REPOSITORY
		2825	
Castile	Anh. III-IV		Varved anhydrite-calcite units alternating with thick halite (rock salt).
	Hal. II		
	Anh. II →		
	Hal. I		
	Anh. I		
		4075	
Delaware Mountain Group	Bell Canyon		Mostly fine-grained sandstone with shaly and limy intervals. Bell Canyon is used for salt water disposal. Cherry Canyon and Brushy Canyon contain oil producing zones.
	Cherry Canyon		
	Brushy Canyon	~8000	

Figure 1-2. Stratigraphic cross section at the WIPP Site.

In April 1988, anomalous water level rises in the Culebra Dolomite aquifer were measured in several observation wells to the south of the WIPP site (Beauheim 1990). LaVenue (1991) conducted an investigation that raised serious questions about oil field operations. Bailey (1990), a certified professional geologist and petroleum engineer with the New Mexico State Land Office, described waterflooding problems for the Vacuum Field (an oil field overlain by the Salado and Rustler Formations) in a letter to Marsh LaVenue and suggested that the anomalous water level rises in the WIPP wells may have similar origin:

> Although the Vacuum Field, located in Township 17-18 South, Ranges 34-35 East, is located some distance northeast of the monitor wells in question, I believe the hydrogeologic setting is analogous to the well field you are currently investigating. The Vacuum Field is also overlain with Dewey Lake Red Beds and the Rustler and Salado Formations. Numerous water flows in the Salado were creating oil field casing failures and drilling and cementing problems and many people were concerned that the situation could cause contamination of the Ogallala aquifer.
>
> Discussions at the Vacuum Field Salt Water Flow Committee meetings with the Oil Conservation Division in 1986-1987 indicated that the uppermost water flow occurred at the base of the Rustler and the lowest flow occurred at the top of the Tansill Formation. The most numerous flows were found near the crest of the anticline, but flows were encountered throughout the field. Spot checking of old oil well drilling records indicate water flow drilling problems and numerous casing leak repairs in the Dewey Lake Red Beds, Rustler and Salado formation for many years. These water flows are still occurring in the Vacuum Field although at a lesser rate than during the 1970's and 1980's.

These water flows are characterized as strong, intermittent and spotty. Not all wells have encountered flows, but when they did, the flows were estimated at 1,000 - 2,000 barrels [42,000 - 84,000 gallons] per day. The flows often would last 4-5 days before stopping by themselves. The Oil and Gas Conservation District was greatly concerned about the effects of these flows and the potential for dissolution, vertical fracturing and collapse of the upper beds, and the contamination of the Ogallala aquifer.

After years of study, thousands of pressure tests, installation of pressure monitoring wells, and chemical analyses, the Water Flow Committee, decided that no one knew the origin of the early flows, or specifically where the water was stored. However, individual flows were correlated throughout the field to distinct horizons within the Salado Formation where fluid flow is facilitated along bedding planes at clastic-evaporite interfaces. Chemical dissolution of bounding salts and mechanical fracturing enable large volumes of fluids to be transported over large areas.

Chemical and isotopic analyses of the waterflow brines indicated that the waters were not naturally occurring connate waters produced by the evaporation of Permian seawater. (18)Oxygen/(16)Oxygen ratios and (18)Oxygen/Magnesium ratios indicated injected produced water as a strong candidate as a source of at least some of the water flows in the Salado Formation. Because the Vacuum waterflood project injection zone is at an approximate depth of 4320'-4720', casing leaks through the salt section are the most logical pathways for introduction of fluids into the Salado Formation (Bailey 1990).

The problem of injected water migrating "out of zone" is widespread. Bailey (1990) noted that waterfloods in and around Eunice, Oil Center, and Monument (Fig. 1-1) resulted in water flow problems through the Salado Formation. Nor is this strictly a problem of the past. Water migrating out of zone continues to plague other oil fields underlying the Salado.

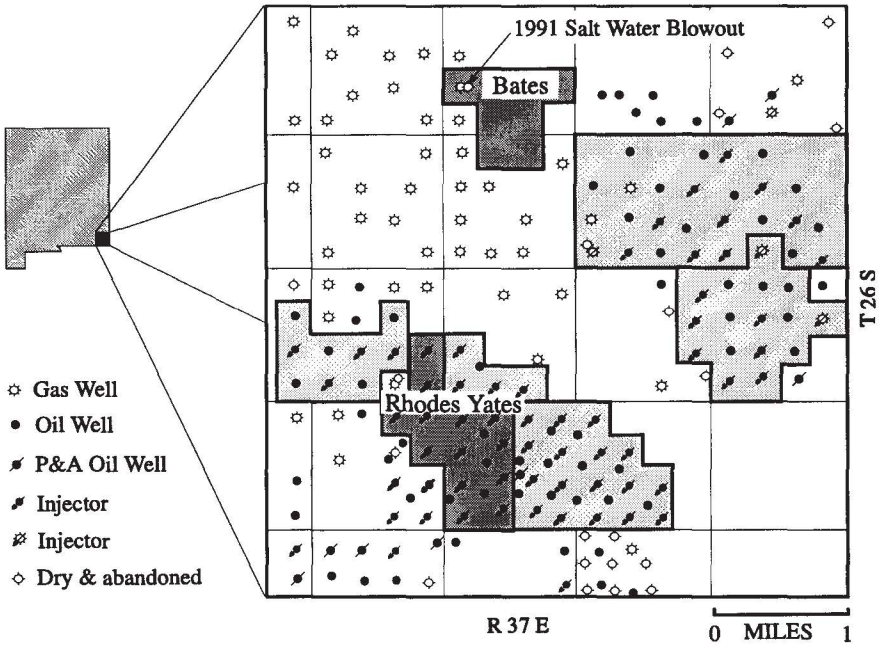

Figure 1-3. Bates Lease (Hartman), Rhodes Yates Waterflood (Texaco) and other nearby leases with injection wells.

1.2.1 Hartman vs. Texaco

On November 22, 1993, Mr. Doyle Hartman (1993) sent Sandia National Laboratories a copy of his November 17, 1993, Complaint (CIV93 1349M) filed in the Federal Court for the District of New Mexico. He stated that he furnished a copy of the complaint to familiarize Sandia "with the Lea County situation so that the proper safety measures will always be taken to preclude the occurrence of such a potentially disastrous event in the close vicinity of the WIPP site in Eddy County, New Mexico." Mr. Hartman claimed that a neighboring waterflood, Texaco's Rhodes Yates, allowed large quantities of injected water to escape out

of the approved injection zone, part and dissolve the Salado Formation, and migrate to Hartman's Bates Lease (Hartman 1993, 13).

On January 15, 1991, while drilling through the Salado Formation, Hartman experienced a salt water blowout, which flowed uncontrolled for five days. The suspected waterflood operation was approximately two miles away. On December 12, 1994, after two weeks of hearing testimony and viewing exhibits, the jury found in favor of Hartman's claim for damages. On January 20, 1995, the court ordered the defendant, Texaco, to compensate Hartman for 5.6 million dollars for damages and for value of the property injured and destroyed due to defendants' trespass (Herrera 1995).[2]

Observations of waterflows during drilling and production in waterflood areas appear to be fairly widespread in time and location. Part of the evidence gathered by Hartman's engineers included a listing of 189 waterflows reported throughout various oil and gas fields in District One[3] of southeast New Mexico for the time period from 1978 to 1993. These may not represent all the water flows encountered in this district because not every waterflow encountered during drilling is reported to the New Mexico Oil Conservation Division (NMOCD) (Lanphere and Sullivan 1994a).

1.2.2 Bass vs. United States of America

The potential impact of water flooding and fluid injection on the WIPP has been cited in the recent denial of a valid lease to directionally drill oil wells under the WIPP site from a surface location immediately adjacent to the WIPP site. In April 1993, Bass Enterprises submitted applications to directionally drill eight

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[2]The Environmental Evaluation Group understands that portions of this judgment may be in the appeal process. The Environmental Evaluation Group has no direct nor implied opinion about the case.

[3]District One of the New Mexico Oil Conservation District consists of Lea, Roosevelt, Curry, and part of Chavez County.

additional oil wells beneath the WIPP Land Withdrawal Area for the production of crude oil from the 320 acre lease (NM 02953C) in the southern half of Section 31, T22S, R31E. Drilling would have initiated on the surface outside the WIPP site Boundary, proceeded downward 6,000 feet, then deviated into the WIPP site Boundary. On August 22, 1994, the BLM denied approval to drill the eight proposed wells "due to the uncertainty of when a final determination will be made, ***and the unknown impacts from injection wells and water flooding***"[4] (Calkins 1994). On January 23, 1995, Bass Enterprises et al. (1995) filed suit against the federal government for a taking.[5]

1.3 Oil Field Salt Water Disposal

Waterflooding to promote oil recovery is not the only oil field water injection practice of concern. In a memo to LaVenue, Bailey (1990) suggested that a salt water disposal well may be the source of the water level rises south of the WIPP site:

> Because a water injection well or salt water disposal well is the most logical source of a long term or continuous increases in fluids in the monitor well (H-9), I investigated locations of such wells in the area, concentrating on any wells located north-northeast. Spot checking of production wells in the section adjacent to the monitor well had not shown a logical production well as the source of a large fluid pressure increase.... In my opinion, the most likely source of increased fluid pressure is the Devon Energy Corp. Todd 26 Federal Well #3 salt water disposal (SWD) well located northeast and upgradient of the monitor well... Since 1971,

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[4]Emphasis added.

[5]The Environmental Evaluation Group understands that this case may be in litigation. The Environmental Evaluation Group has no direct nor implied opinion with respect to this case.

> 2,962,402 barrels of produced water have been injected at a current average pressure of 795 psi. No records of any casing repairs are found in the OCD well files.

This observation invites the following questions. Is there evidence to indicate that the Todd 26 Federal #3 well is the source of the water level rises? How was this well completed? What is the status of this well? If the casing, tubing, and cement of this well are intact, are there other available pathways in the area providing communication? Most importantly, over the next 10,000 years, to what extent will there be salt water disposal in the vicinity of the repository?

The first four questions are explored in the EEG workshop presentations and analysis. As to the last question, salt water disposal in the vicinity of the WIPP is already taking place. As noted by Matthew Silva, Ron Broadhead, and Dan Stoelzel, in their respective presentations (Chapter 2), the Delaware wells surrounding the WIPP site produce a very high fraction of water (water cut), on the order of 50% to 70% by volume, as reflected in production records and tabulated by Broadhead et al. (1995, Table 8). Silva (1994, Figure 13) showed four salt water disposal wells within two miles of the WIPP site Boundary as of 1993. Broadhead et al. (1995, Table 7) tabulates ten salt water disposal wells and two pressure maintenance wells within the nine township area surrounding the WIPP as of 1994.

1.4 Oil Field Brine Disposal and the Potash Industry

The issue of salt water disposal in the Delaware Basin appears to be of concern to members of the potash mining industry, which also operate in the Salado Formation. On November 19, 1993, representatives from Bass Enterprises Production Company, an oil company, met with representatives from Western Ag-Minerals Company, a potash mining company, to discuss the Bass proposal to operate a brine injection well two miles west of the WIPP site. Western Ag was concerned about its substantial potash reserves surrounding the well location.

Rather than rely solely on state regulations to protect their portion of the Salado Formation, Western Ag outlined twelve additional operating provisions that would satisfy their concerns (Heinen 1994). The twelve provisions included notification of any request to increase injection pressure above 765 psi, immediate notification of tubing, casing, or packing failure and cessation of injection until the problem is corrected, an annual chemical analysis of injected brine, an annual test to determine migration of brine into other formations, and specifications for well abandonment.

1.5 Well Abandonment

Concerns about improper abandonment of wells appear to be justified. As discussed by Silva (1994), inadequate practices on U.S. Bureau of Land Management (BLM) properties are documented (U.S. DOI 1989, 1990; Baier 1990). A 1989 evaluation (U.S. DOI 1989) by the Inspector General for the U.S. Department of Interior identified considerable problems on the BLM properties resulting largely from "violations of existing regulations" (U.S. DOI 1989, 4). The report cited problems with wells in BLM's Carlsbad Area (U.S. DOI 1989, 6-7)

In arguing a difference between exploratory and development wells[6], the DOE has also brought the problem of improperly abandoned oil and gas wells to the attention of the EPA. As the DOE Carlsbad Area Office noted:

> Development wells are generally abandoned only after many years of production. Many development wells change ownership several times during their operational lifespan, and may not produce continuously. They may ultimately be abandoned improperly (Dials 1994, Supplemental Information to Options 2, 4 and 3, 12).

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[6]For other views on well definitions see Neill 1995; Vaughn 1995; Carroll and Bogle 1996; also Gorenflo vs Texaco, 566 F. Supp. 722 (1983); Sun vs. Jackson, 715 S.W. 2D 199 (1986) and 783 S.W. 2d 202 (1989).

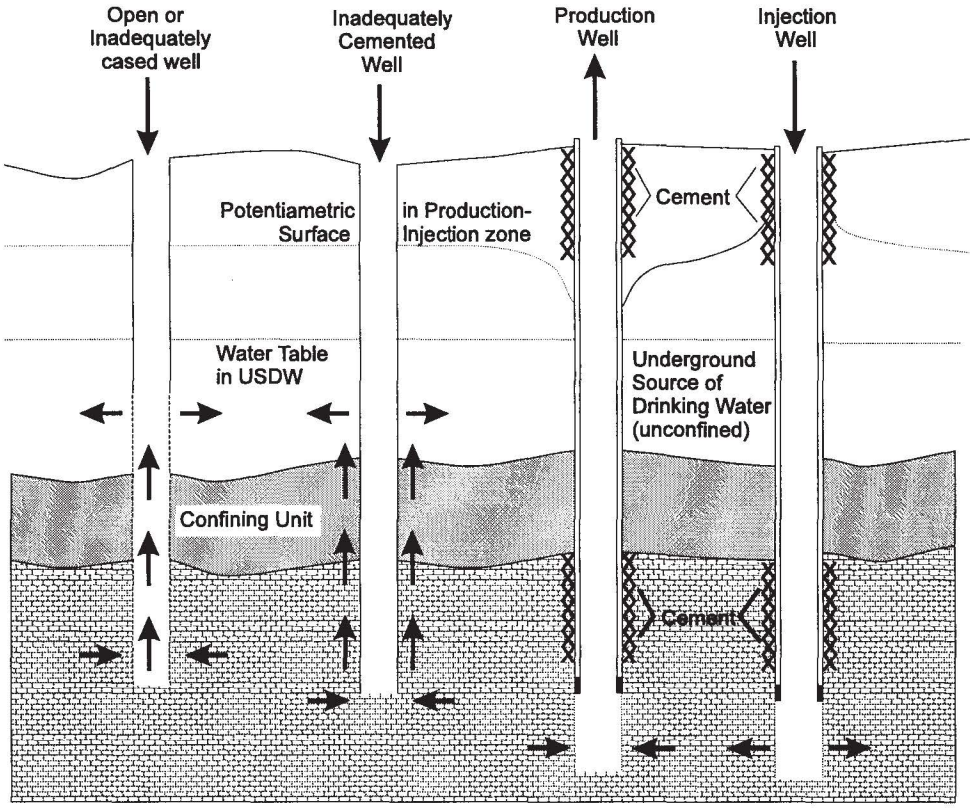

Figure 1-4. Upward flow from underlying hydrocarbon-producing zone to an underground source of drinking water through inadequately plugged wells. After Kreitler et al., 1994.

Improperly abandoned wells, in the vicinity of oil field injection wells, can serve as a pathway for contamination of underground sources of drinking water. The Texas Bureau of Economic Geology, with funding from the American Petroleum Institute, designed a method for use by regulators and operators to identify such areas (Kreitler et al. 1994).

In developing the method, Kreitler et al. (1994 pp. 64, 77) plotted the estimated density and distribution of oil field brine injection wells, as shown in Figure 1-5, and abandoned wells, as shown in Figure 1-6, throughout the greater Permian Basin, which includes the Delaware Basin.

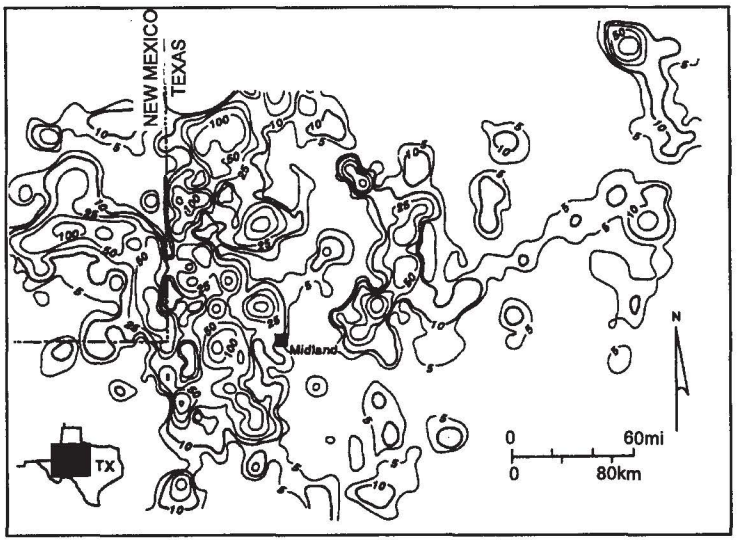

Figure 1-5. Density of Class II injection wells at 0.1°× 0.1° scale. After Kreitler et al. 1994.

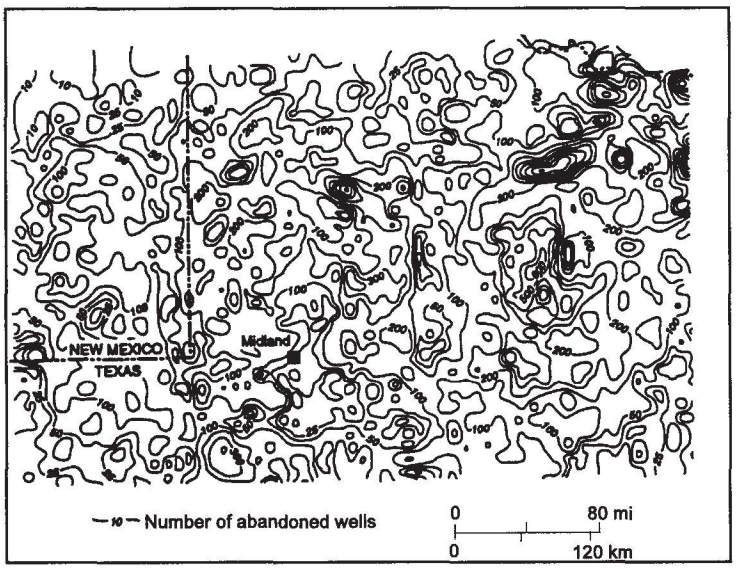

Figure 1-6. Estimated distribution of abandoned wells at 0.1°× 0.1° scale. After Kreitler et al. 1994.

They found that the most extensive area of upward hydraulic gradients occurs in the eastern Delaware Basin, Central Basin Platform, and western Midland Basin. Residual mapping indicates upward gradients with hydraulic head differentials as large as 6,000 ft (1,800 m) (Kreitler, et al. 1994, 73-74).

As part of their study, Kreitler et al. (1994) also offered insight into the problem of abandoned wells completed through salt formations. They note that in addition to less stringent construction and abandonment standards in past decades, the mechanical degradation of older wells may also reflect lengthy periods of exposure to corrosive brines. In the Permian Basin, wells that pass

through a larger number of saline units are of particular concern (Kreitler et al. 1994, 76). LaVenue also commented on 20 to 30 years of exposure to the corrosive saline environment promoting a leak in the casing and/or degrading the grout holding the casing in place (LaVenue 1991, 2). This is consistent with the DOE position that the highly saline environment of some units can promote rapid corrosion of well casings and may result in fluid loss from wellbores (U.S. DOE 1995, SCR-73). All well casings to be abandoned in the WIPP vicinity will be exposed to more than two thousand feet of salt, not only in the Salado Formation, but also in the Castile Formation, a formation unique to the Delaware Basin. It seems prudent to assume saline environments promote rapid corrosion of well casing (Kreitler et al. 1994, 76; LaVenue 1991, 2; U.S. DOE 1995, SCR-73), existing regulations are violated (U.S. DOI 1989), and wells are improperly abandoned (U.S. DOI 1989; Dials 1994). Given these observations, do the existing and yet to be drilled wells in the vicinity of the WIPP represent viable vertical pathways for the upward migration of injected fluids either into the interbeds of the Salado Formation or into overlying aquifers such as the Culebra, the Magenta, and the Dewey Lake Redbeds?

1.6 WIPP and Performance Assessment

To proceed with TRU waste disposal, the WIPP Land Withdrawal Act requires the DOE to receive certification from the EPA that the facility is in compliance with the EPA radioactive waste disposal regulations (U.S. EPA 1985; 1993, 40 CFR 191) including containment and assurance requirements. This requires analyses that the probability and amount of radionuclides released to the accessible environment over the next 10,000 years will not exceed limits specified in the EPA Standards. The performance assessment (PA) calculations published to date have identified future drilling for oil and gas reserves as an event that could disrupt the repository and release radionuclides in excess of the standards (SNL 1992, 4.1.2). The calculations have not addressed the impact on WIPP's performance of the oil and gas industry practices of salt water disposal and

waterflooding for enhanced oil recovery - two expanding activities now underway in the vicinity of the WIPP.

The 1991 DOE PA stated that such fluid injection could be eliminated from consideration in performance assessment on the basis of low consequence:

> The effects of injection wells on groundwater flow in units shallower than the Salado Formation is likely to be negligible. Units selected for injection will be thousands of feet deeper than the Rustler Formation, which is the most likely path for the groundwater transport of radionuclides to the accessible environment. The low permeability Bell Canyon, Castile, and Salado Formations are approximately 4,000 feet (1,220 meters) thick at the WIPP (Powers et al. 1978), and these low-permeability units will isolate flow in the Rustler Formation from the pressure increases in the much deeper units caused by the injection of fluids (SNL 1991, 1:4-36).

This explanation appears to be inconsistent with salt water disposal practices in the Delaware Basin, the observed water level rises in the Culebra, LaVenue's analyses (1991), and Bailey's comments (1990).[7] Records indicate that every salt water disposal well within the nine township area surrounding the WIPP injects into the Bell Canyon Formation (see Broadhead et al. 1995, Table 7). Hence, the Bell Canyon is not serving as an impermeable layer. Further, LaVenue's (1991) analyses indicated that the Bell Canyon Formation, which is below the WIPP horizon, is already in communication with the Rustler Formation, which is above the WIPP horizon. Hence, thousands of feet of vertical separation by

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[7]Despite a January 28, 1991, distribution to the WIPP PA Department, the memos of LaVenue (1991), Bailey (1990), and Ramey (1976) are not referenced in either the December 1991 PA publication or in the December 1992 PA publication.

impermeable layers of salt do not appear to be isolating the Rustler from the fluid injected into the deeper units.

The 1992 PA also did not calculate the effect of adjacent fluid injection on performance assessment, maintaining that injection wells that do not penetrate the repository can be screened out on the basis of low consequence despite the 1976 Ramey memo, 1990 Bailey memo, and the 1991 LaVenue memo, and public records on fluid injection practices in the Delaware Basin.

With respect to any human related activity within the site, including fluid injection, the 1992 PA introduced a new criteria not found in Cranwell et al. (1990) for screening events and processes (SNL 1992, 2:4-3 to 4-4). The 1992 PA stated that the EPA regulations did not require the impact of fluid injection to be evaluated. The WIPP PA Department's interpretation (SNL 1992, 2:4-3) of the non-binding guidance for the disposal of transuranic waste (SNL 1992, 2:4-4) advances the argument that disruptive human activities, such as fluid injection, need not be considered because the consequences are greater than that of exploratory drilling (SNL 1992, 2:4-4). The impact of a future disposal well was limited to drilling and the consequences were assumed to be identical to drilling an exploratory well (SNL 1992, 2:4-4).

1.7 Issue

WIPP is surrounded by new oil producing wells. Many more are planned but have been delayed due to the presence of potash (Woodard 1992; Burski 1994). Oil production is accompanied by salt water injection either for salt water disposal or waterflooding. Forcing large volumes of such brine into the designated formation requires energy in the form of fluid pressure (force per unit area). Brine migration, with energy in the form of pressure, is the same mechanism by which radionuclides can be carried out of the repository and away from the WIPP site.

The potential impact of brine injection on the long-term performance of the WIPP prompted the Environmental Evaluation Group to organize a June 13, 1995, workshop on the issue. The workshop included presentations describing the extent of oil and gas resources, the anomalous water level rises in the Culebra Aquifer, the documented effects of water flooding on the Salado Formation, the geology of waterflooded areas in southeast New Mexico, the current petroleum production practices, the treatment of water injection by the performance assessment effort, and the need for a water flooding scenario in the WIPP PA calculations. As was intended, a number of issues were deliberated. On many issues there was no consensus. The workshop did not address the impact of solution mining of potash surrounding the WIPP or the disposal of potash brine.

2. WORKSHOP PRESENTATIONS

The presentations made at the June 13, 1995, workshop are contained in this chapter. A synopsis of each presentation, distributed by the authors at the workshop, is followed by their presentations. As with any verbal dialogue, some paraphrasing of the presentations was necessary. Nonetheless, every effort was made to preserve the message of the presenters and the thrust of the questions and answers. Also, some figures, most of which were provided by the authors on diskette, required modification from their overhead format into a report format. The cooperation, patience, and understanding of the presenters and participants in addressing these difficult, but important issues, is appreciated.

2.1 R.H. Neill - Opening Statement

All of us are extremely pleased to see this large turnout for this technical workshop. I think it is a good example of the cooperation between the various federal and state authorities with representation from the Department of Energy, the Environmental Protection Agency, the Bureau of Land Management, the National Academy of Sciences, the New Mexico Environment Department, the New Mexico Oil Conservation Division, the New Mexico Bureau of Mines and Mineral Resources, Sandia National Laboratories, Oklahoma University and, of course, the Environmental Evaluation Group.

It is interesting to step back a moment to evaluate our efforts in performance assessment in predicting the behavior of the repository. The focus has been on existing fluids, whether it is the interstitial brine within the Salado or the large brine reservoirs associated with the Castile Formation or the two dolomitic aquifers above the repository horizon and in the perched water aquifer in the Dewey Lake Redbeds. We are now looking at the impact of fluid injection into nearby formations on the long-term behavior of the repository — perhaps from three different standpoints, although we will only be looking at two today. The first is to enhance the recovery of oil. The second is on salt water disposal, which

would be another reason for injecting fluids. The third might well be, in the future, to look at solution mining for potash, although we are not going to address that issue here today.

It might be helpful to mention a few things that we are not going to do today - to put everyone at ease. We are not going to address the legal issues associated with any court cases that have occurred, are pending, or will occur. Specifically, I'm referring to the Hartman vs. Texaco case. There is some very interesting, relevant, technical information associated with that case, but in no way should this workshop be construed as reopening the legal issues associated with that case. I want to make that quite clear.

We also are not going to be able today to determine the consequences of the impact of some of these actions. And although we can get some insights, perhaps, on the probability of events, one is not going to be able to determine the impact.

We look forward to each of us speaking as individuals — no one is being quoted on behalf of their agency. And also none of us have come here with a preconceived position on these issues.

I thought it might be important to those who are familiar with the performance assessment approach to acknowledge the uniqueness of the WIPP in the context that it is the only repository under consideration where there are substantial natural resources - oil, gas, and potash. And for those of you who are not in the business of performance assessment, in order to bring waste to WIPP it is necessary to be able to predict the behavior of these transuranic wastes over 10,000 years and convince EPA of the validity of those calculations and analyses. The way this is done is to come up with scenarios on how this could occur, design a model and then write the equations governing that, whether it is conservation of momentum or mass, conservation of radioactivity, the driving force, solve the equations, and then estimate the amount that arrives at the accessible environment in 10,000

years. You then look up the release limit table of the EPA standard. If the postulated releases are greater than the limits, you have problems. If they are less, you are home free.

On the current schedule, DOE expects to complete all this work by January 1997. We note that the deadline for the models is as early as September 1995, the end of this summer.

If we consider the 4-mile by 4-mile area of the WIPP site, the question comes up regarding the injection of fluids at depths greater than 4,000 feet outside the WIPP site. If by some mechanism, there is vertical movement of the brines or the fluids outside the repository, can this induce hydrofracturing in the Salado for a distance of 2 miles laterally to the repository, which may in turn flood the repository? And the question is, could this have a role in moving radionuclides laterally to the accessible environment, and exceed the EPA limits?

In terms of the location, the injection, and the timing, one can look at it in perhaps four different ways. The first is on the operational consideration of the time period from minus 20 years to t equals zero, and outside of the 4 mile x 4 mile area where this could have some potential effect on the hydrogeological real estate associated with the repository. The second is a period from T=0 to T=100 years where institutional control would prevent anyone from injecting fluids within the 4 mile x 4 mile area. The third might be a period from 100 years to several hundred years; that is not specified in the EPA criteria but it is presumed that one could take steps during that time period to prevent the injection of fluids. And the fourth is when knowledge of the repository is lost at some future date, and one could have brine injection occurring in the 4 mile x 4 mile site. We are not going to focus that much on the fourth one today, because we have some people that are able to contribute in a major way on the first three.

2.2 Evaluation of Oil and Gas Resources at the WIPP Site

Ronald F. Broadhead[1], Fang Luo[1], and Stephen W. Speer[2]

[1]New Mexico Bureau of Mines and Mineral Resources

[2]Independent Geologist, Roswell, New Mexico

2.2.1 Synopsis

Rigorous, quantitative estimates were made of oil, natural gas, and natural gas condensate resources that exist beneath the 16 mi^2 area of the WIPP land withdrawal area and an additional one-mile wide study area around the WIPP site. Calculations were made for resources that are extensions of known, currently producible oil and gas resources thought to extend underneath the WIPP land withdrawal area with reasonable certainty (probable resources). Qualitative estimates were also made of oil and gas that may be present in undiscovered pools and fields beneath the WIPP land withdrawal area (possible resources). Possible resources were not quantified.

Probable resources consist mostly of oil and associated gas in Permian strata and nonassociated gas and gas condensate in Pennsylvanian strata. Currently, most oil and associated gas production in the vicinity of the WIPP site has been obtained from sandstone reservoirs in the Delaware Mountain Group (Permian) at depths of 7,000 to 8,000 ft. Sandstones and carbonates in the Bone Spring Formation (Permian) at depths of 8,000 to 11,000 ft and carbonates in the Wolfcamp Group (Permian) at a depth of approximately 12,000 ft are secondary oil reservoirs. Carbonates in the Strawn Group (Pennsylvanian) at a depth of approximately 13,000 ft are secondary, but important, reservoirs of gas and light oil or condensate. Most nonassociated gas and condensate production in the vicinity of the WIPP site has been obtained from sandstone reservoirs in the Atoka and Morrow Groups (Pennsylvanian) at depths of 13,000 to 14,000 ft.

Probable oil and condensate resources within the boundaries of the WIPP land withdrawal area are 12.3 million bbls of oil and gas condensate recoverable by

primary production methods and an additional 6.4 million bbls of oil potentially recoverable by secondary recovery with waterfloods (Table 1). Probable resources within the one-mile wide additional study area surrounding the WIPP land withdrawal area are 22.9 million bbls oil and gas condensate recoverable by primary production methods and an additional 13.8 million bbls of oil potentially recoverable through waterflooding.

Probable gas resources within the boundaries of the WIPP land withdrawal area are 186 BCF gas (Table 1); 89% of this gas is nonassociated and will be produced from the deep Atoka and Morrow reservoirs. The remainder is associated gas, most of which will be produced from relatively shallow reservoirs in the Delaware Mountain Group. Probable gas resources underneath the one-mile wide additional study area surrounding the WIPP land withdrawal area are 168 BCF gas; 79% of this gas is nonassociated and will be produced from the deep Strawn, Atoka, and Morrow reservoirs.

In addition to probable resources, there are significant possible resources of oil, gas, and gas condensate beneath the WIPP land withdrawal area and the additional study area.

These will be oil and associated gas in untapped sandstones of the Delaware Mountain Group in largely unexplored and unevaluated sandstones and carbonates of the Bone Spring Formation, and in carbonate reservoirs in the Wolfcamp and Strawn Group. Possible resources of nonassociated gas and gas condensate will occur in sandstone reservoirs in the Atoka and Morrow Groups and in the pre-Pennsylvanian section (Siluro-Devonian and Ordovician strata). The elusive nature of possible resources makes their quantification difficult or impossible for an area of limited extent such as WIPP.

2.2.2 Presentation by Ron Broadhead

The New Mexico Bureau of Mines and Mineral Resources (NMBM&MR) contracted to evaluate the resources under the WIPP Site and an adjacent area extending one mile beyond the WIPP Land Withdrawal Area. The evaluation included oil, gas, and other mineral resources.

One purpose of the work was to estimate the total of proven and probable oil and gas resources that could be obtained by primary and secondary recovery. With respect to oil and gas, the WIPP area remains essentially undrilled. Estimating resources is a geological task.

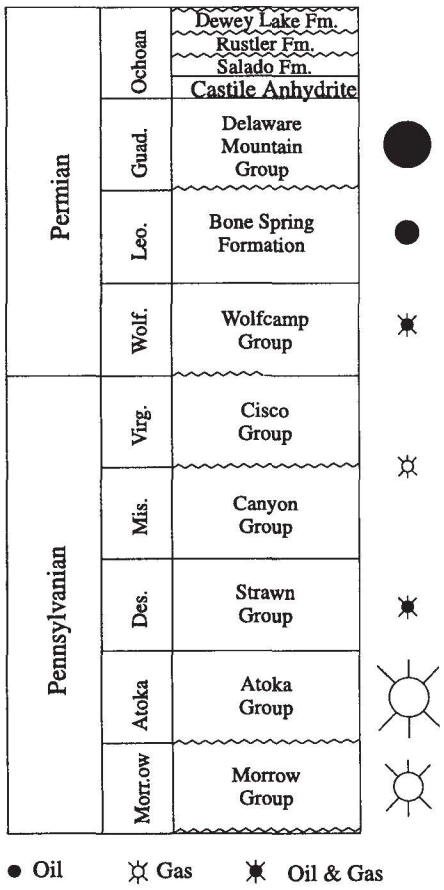

Figure 2.2-1. Productive oil and gas formations in the vicinity of the WIPP Site. Adapted from Broadhead et al. 1995.

The DOE needed a scientific, unbiased, third party estimate of the oil and gas resources. The principal data sources were well records on file at the New Mexico Bureau of Mines and Mineral Resources: Petroleum Information, Midland Oil Scouts Association, the Bureau's Niell Wills Collection, Bureau data gathered through the years, official state data from the New Mexico Oil Conservation Division, data from the U.S. Bureau of Land Management and the U.S. Geological Survey, an extensive collection of electrical logs, and the official production data reported to the State.

2.2.2.1 WIPP Area Description

Figure 2.2-1 shows the principal oil and gas producing formations within the WIPP

Site Area and surrounding areas. The principal oil production is shown by the solid circles and the principle gas production is shown by the open circles with the spikes. The major oil producing group in the area is the Delaware Mountain Group followed by the Bone Spring. There is a some production from the Wolfcamp, Cisco, and Canyon Group. Most of the gas production comes from the Atoka and Morrow Groups.

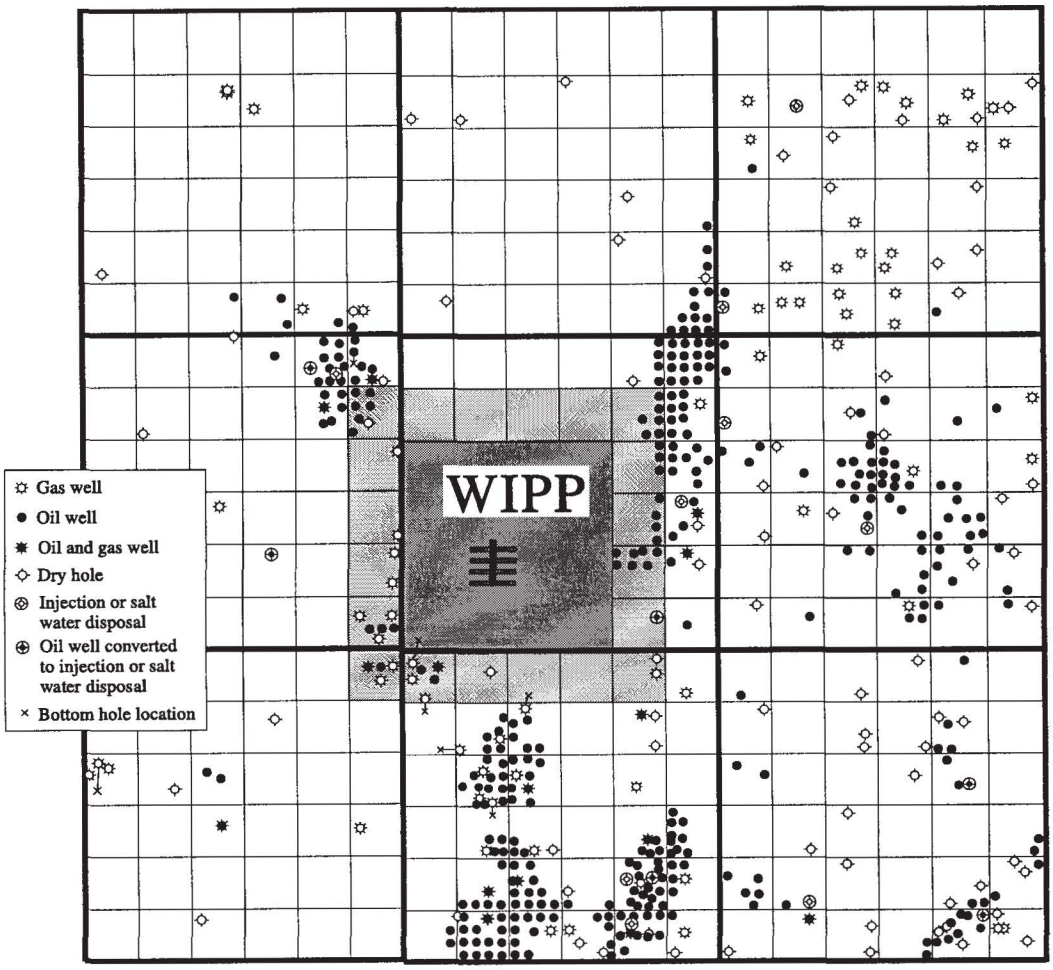

Figure 2.2-2. Oil, gas, and injection wells at WIPP Site, one-mile additional study area, and nine-township project study area.

Figure 2.2-2 shows the four mile by four mile land withdrawal area, the additional one mile wide study area, and the total nine township study area. Solid circles

represent productive oil wells at the close of 1993, or early 1994. The open circles with the eight spikes are productive gas wells. The open circles with (four) spikes are non-productive. There is only one well that produces from under the WIPP Land Withdrawal Area. That is the Bass well in the southwestern part of section 31. That deviated well was directionally drilled under the Land Withdrawal Area. Most of the oil wells produce from the Delaware Mountain Group and most of the gas wells produce from the Atoka and Morrow Groups. A couple of the wells along the western edge of the WIPP produce from the Strawn Group.

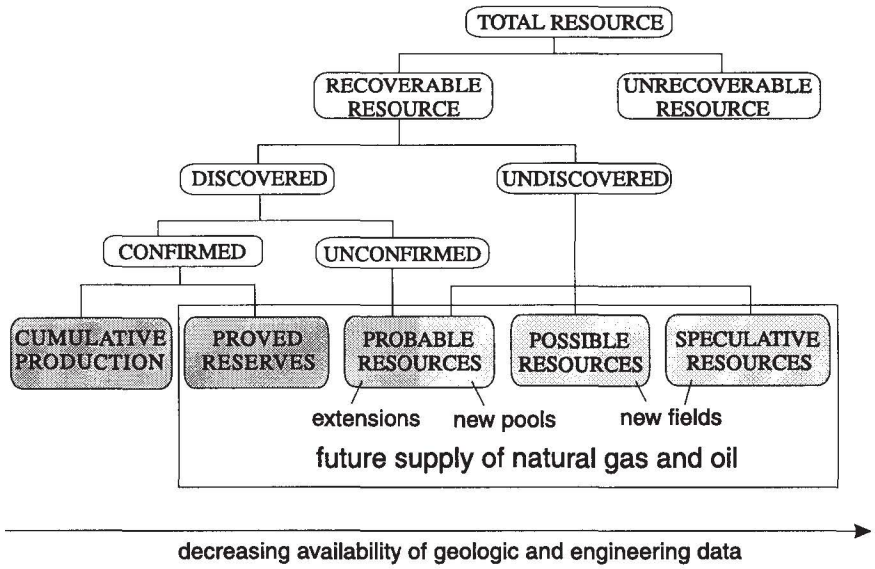

Figure 2.2-3. Oil and natural gas resource categories. From Potential Gas Committee (1993).

2.2.2.2 Method of Assessing Resource Potential

What was estimated and what was not estimated? Figure 2.2-3 illustrates the classification scheme of the Potential Gas Committee of the Potential Gas Agency. This classification can be applied to oil as well as gas. The total resource can be divided into recoverable and unrecoverable resources. The unrecoverable resource represents that which can not be taken from the rock. The recoverable resource

includes the discovered and undiscovered. The numerical estimates are based on that which is discovered. Discovered can be divided between confirmed and unconfirmed. Confirmed is divided between cumulative production and proved reserves. Cumulative production is obviously that which has been produced. Proved reserves are those reserves in known identified traps and accumulations that can be recovered by existing wells. Note there is only one well which produces from within the WIPP Land Withdrawal Area. Hence, there are very little actual proved reserves under the WIPP itself. In the additional study area there are several producing wells.

Most of the estimates included probable reserves. Probable reserves are extensions of known petroleum accumulations that have been discovered. Those are reserves on the flanks of the existing, known accumulations.

Some qualitative assessment of possible reserves was made, but a quantitative assessment of possible reserves was not made. Possible reserves are untested traps, deeper or intermediate pools that have not been drilled, and have not been proven to be productive.

2.2.2.3 History of Drilling

As to the drilling history in this area, Figure 2.2-4 shows that through the 1920s, 30s, 40s, and 50s, drilling bumped along at no wells per year or maybe one well per year. Shallow wells were drilled down to 4,000, 5,000, or 6,000 feet and the wells proved to be non-productive. From the 1960s through the 1980s, there were little spurts of drilling within the nine township area surrounding the WIPP. There were some discoveries of oil but most were discoveries of gas. Around 1990, there was a big increase in drilling - *the Delaware Play*. Delaware Pools were discovered at Livingston Ridge, East Livingston Ridge, Los Medaños, Cabin Lake and a number of other smaller Delaware fields. This occurred throughout the Delaware Basin, not only around the WIPP Site, but throughout southeast New Mexico.

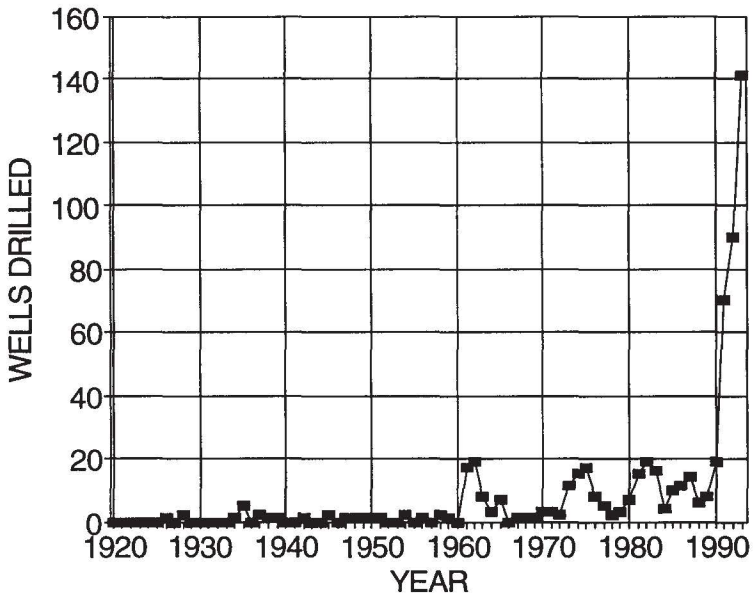

Figure 2.2-4. Annual number of oil and gas wells completed in the nine-township area centered on the WIPP Site.

People had been drilling through the Delaware Mountain Group for decades without realizing that oil could be produced economically. Log analyses and formation testing showed high amounts of water. Operators thought that these formations would produce mostly water and very little oil. With the advent of modern electric log analyses, it became apparent that oil could be economically produced. Oil discoveries were made, mostly in abandoned deep gas wells. As discoveries were made, a flurry of activity followed as the pools were developed.

The following example shows the methodology for estimating the per well resources. Production is obtained from the Brushy Canyon, the lowest formation in the Delaware Mountain Group. The sandstone is primarily interbedded with shales. The production is from stratigraphic traps. The production in the Delaware is oil and associated gas. Reservoir depths near the WIPP are 7,000 to 8,200 feet. Spacing is on forty acres, in other words, one well per forty acres. Production is from deep basin clastics and submarine fans. In order to project

production away from where it presently exists and in order to project into the undrilled areas, we need a geologic model.

The depositional models for the Delaware sands are deep marine sandstones deposited on submarine fans. Closest to the shelf area, in the northern most parts of the Delaware Basin, the sands were deposited in channels. So they are channel like environments. As you get into more distal areas, the sands become unchannelized and become more laterally continuous.

The Livingston Ridge Pool and Lost Tank Pool are administratively separated. But for geologic and engineering purposes, they form the same pool. Figure 2.2-5 shows an isopach map of the main pay at the Livingston Ridge/Lost Tank Pools. The main pay forms a nice channel going from zero feet to a maximum of eighty feet or so in the middle of the channel. The east west cross section of the main pay shows that in the center the pool is fairly thick. It pinches out on the eastern edge. A north-south cross section shows almost constant thickness throughout the pool in that direction. Hence, the variation is

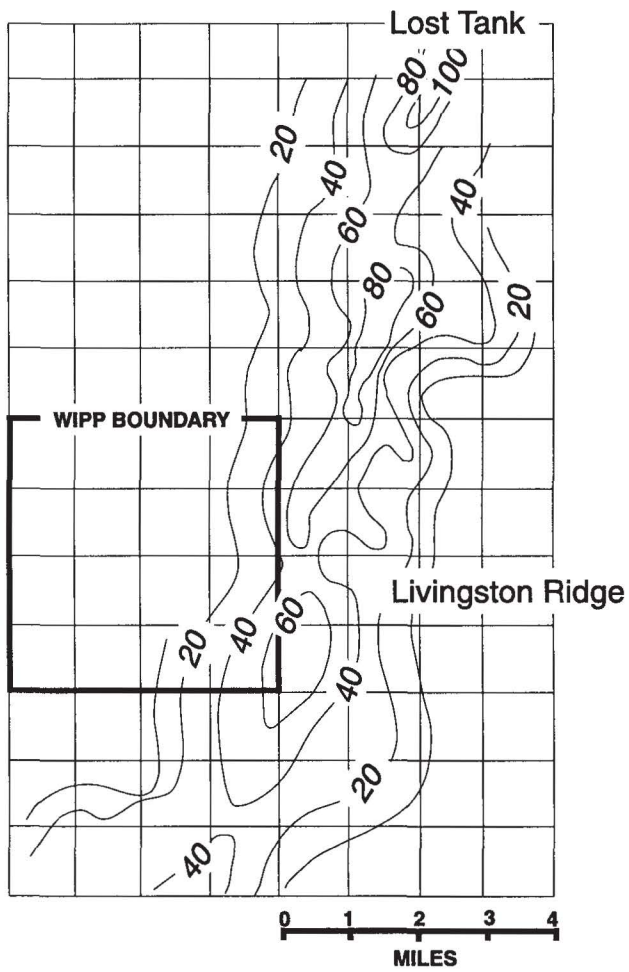

Figure 2.2-5. Isopach of gross channel thickness of Livingston Ridge main pay zone.

in the east-west direction. Economic production takes place where there is forty feet or more of main pay. From this, one can project into undrilled areas[1].

The question then is, are these pools entirely stratigraphic? Most of them seem to be primarily controlled by stratigraphy. The structure map shows that the dip is from the southeast (see Figure 25 of Broadhead et al. 1995). Projecting this channel shows that the WIPP Land Withdrawal Area is either at equal elevation or updip from the present production. Basically, the isopach map and the structural map can be superimposed to determine the areas of probable resources from the projections of known pools.

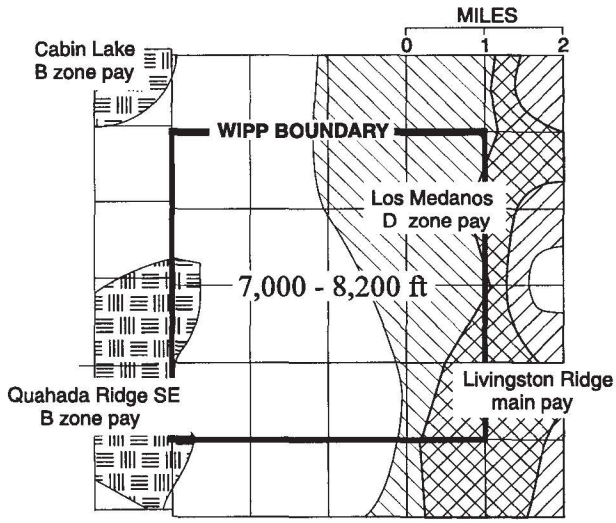

Figure 2.2-6. Areas of known and probable oil and gas resources for Delaware pools.

In Figure 2.2-6, the shaded area along the eastern edge of the WIPP Site shows the projection of the Livingston Ridge Pool. Also shown are other productive pools within the Delaware Mountain Group.

How much oil is each of these forty acre drilling or spacing units going to produce? In the case of the Lost Tank Delaware, a plot of production shows a production decline from roughly 3,500 barrels per month, down after thirty six

[1]Not shown in this report are the control wells and cross sectional diagrams as presented by Broadhead. See Figures 19, 20, and 24 of Broadhead et al., 1995 for the location of the control wells and the cross sectional diagrams.

months, to roughly 1,000 barrels per month. For an exponential curve, there is a high correlation coefficient of 0.87 for this particular well (see Figure 5 of Broadhead et al. 1995).

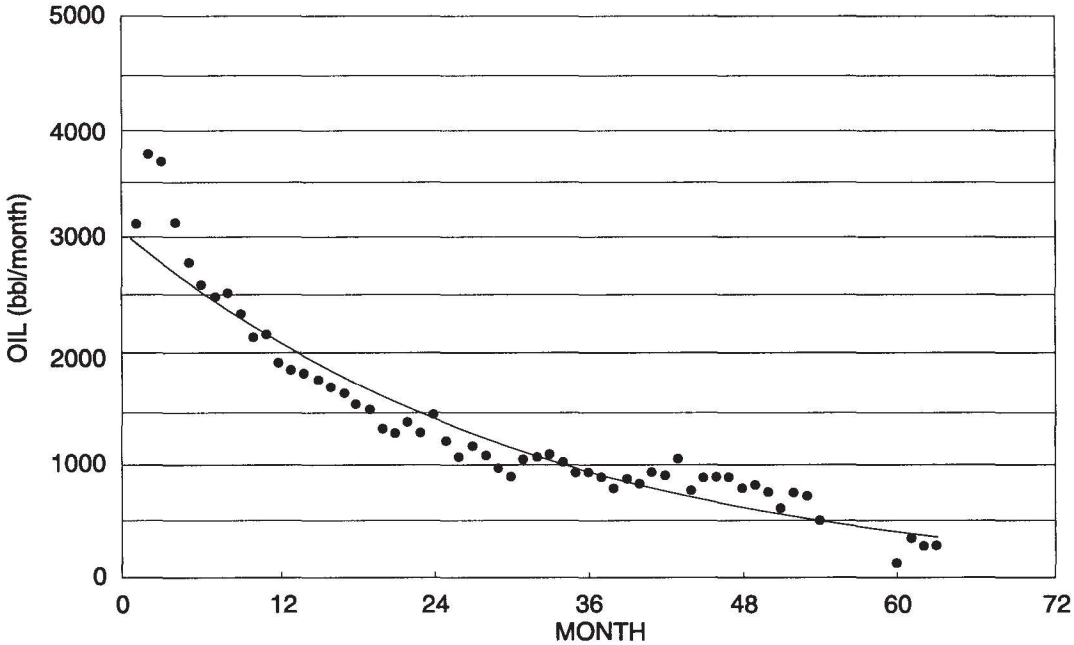

Figure 2.2-7. Average oil production decline curve for Livingston Ridge - Lost Tank Delaware pools, main pay.

As shown in Figure 2.2-7, an average production decline curve was constructed for the Livingston Ridge - Lost Tank pool. Integration of the area underneath that curve yields the resources for an average individual well. In the case of Livingston Ridge, for an assumed economic cutoff of 150 barrels per month, the average well will produce about 89,000 barrels of oil and about 116 million cubic feet of gas. The potentially productive area (calculated in spacing units) is multiplied by the resources for the average well to get an estimate of production for that pool. This was done for each of the Delaware Pools and each of the deeper pools in the area.

Figure 2.2-8 shows an isopach of one of the deep Livingston Ridge zones, the D zone, which produces to the south and the west. The isopach map shows a difference from the Livingston Ridge pay zone and an absence of discrete channels. The result is a blanket type deposit with unchannelized flows containing local thicks and thins and maximums of up to 120 to 140 feet of sand. It never pinches out to zero within the map area.

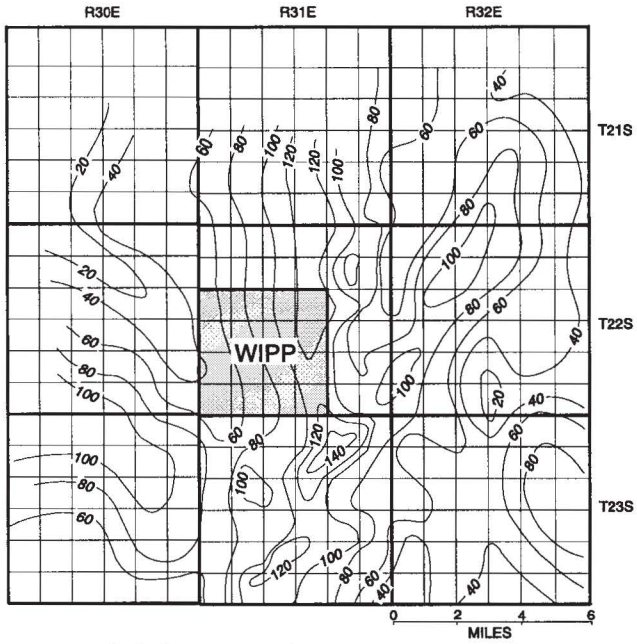

Figure 2.2-8. Isopach of Lower Brushy Canyon Formation zone D.

The deeper sandstones of the 3rd Bone Spring sand produce from stratigraphic or combination traps of deep basin turbidite reservoirs just outside the southwestern boundary of the WIPP Site. Production is oil and associated gas from about 11,000 feet. There are four forty-acre units for probable resources within the WIPP.

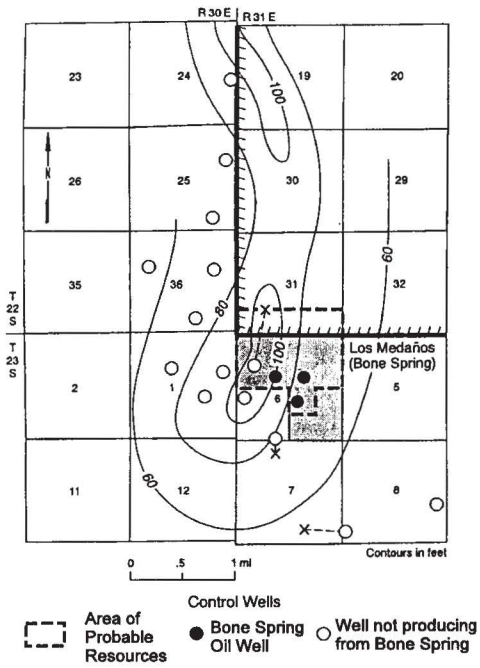

Figure 2.2-9. Isopach of Los Medanos Bone Spring Pool.

For the deeper Strawn Group, production is from limestones interbedded with shales. The reservoirs are bioherms developed on paleogeographic highs. Traps are stratigraphic. Production is gas and liquid condensate at the surface. Reservoir depths are 12,100 to 13,600 feet near the WIPP Site. Spacing is on 320 acres. There are two wells per section. Known and probable resources lie in the northwestern area of the WIPP Land Withdrawal Area.

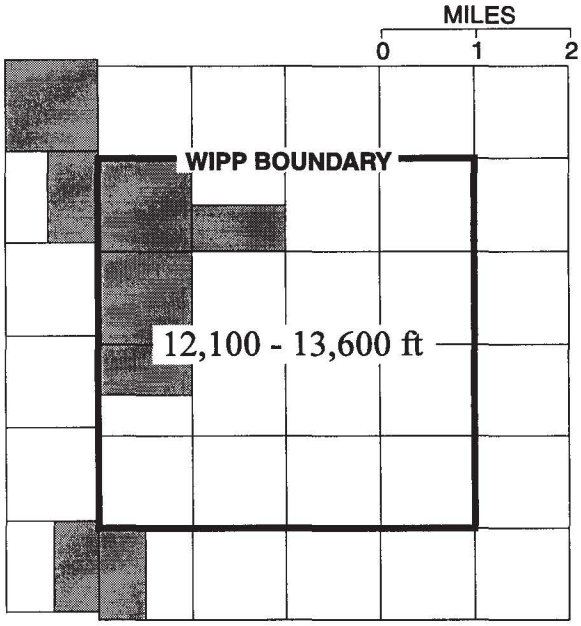

Figure 2.2-10. Areas of known and probable oil and gas resources for Strawn pools projected to extend under WIPP site.

Production of gas and condensate from the Atoka is from sandstones interbedded with shales and limestones. Production is from sandstone channels and a stratigraphic trap near the WIPP. Reservoir depths range from 12,400 to 13,800 feet near WIPP. Well spacing is 320 acres. There are two channels of probable resources that are extensions of existing known discovered traps

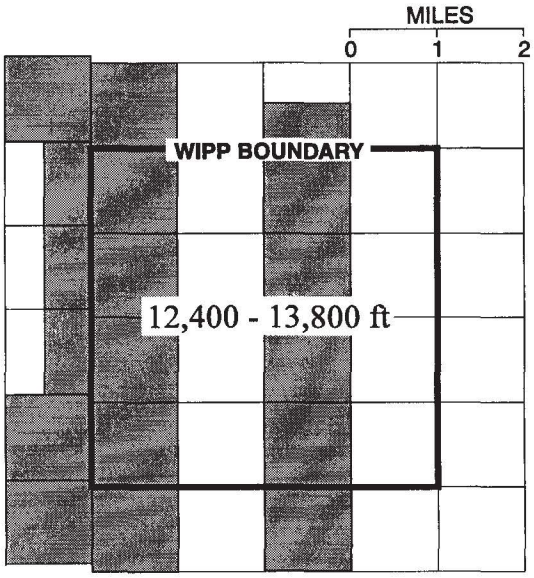

Figure 2.2-11. Areas of known and probable oil and gas resources for Atoka pools projected to extend under the WIPP site.

or pools. There are many sands in the Atoka that are untapped. At this stage of development, it is uncertain whether they are going to be productive or not. The Atoka is the main gas producing zone near WIPP.

The Morrow Group provides the deepest production in the area. Production is from the sandstones of the lower Morrow, interbedded with shales. A whole complex of different geologic models was used to predict production. It produces from stratigraphic, structural, and diagenetic traps. Production is gas and gas condensate. Reservoir depths are 14,300 to 14,800 feet near WIPP. As with the other producing gas zones such as the Atoka and the Strawn, spacing is on 320 acres. Shown are the areas of known and probable oil and gas resources. There is some established production to the south of the WIPP Site. There is no established Morrow production under the Land Withdrawal Area.

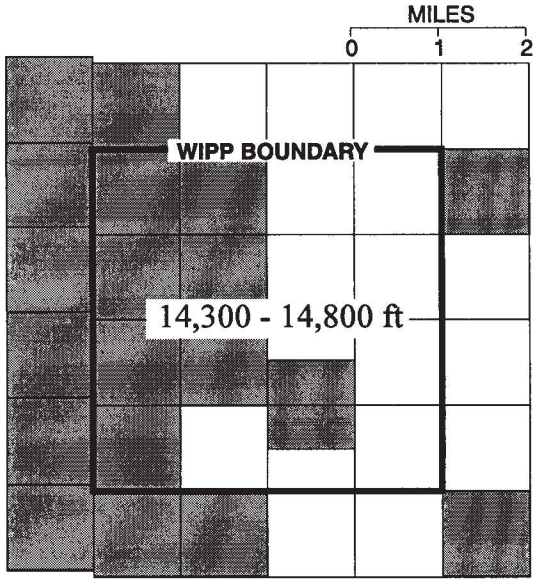

Figure 2.2-12. Areas of known and probable oil and gas resources for Morrow pools projected to extend under the WIPP site.

Table 2.2-1. Probable Resources.

	WIPP LWA	Additional Study Area
Oil and Condensate Primary Recovery (million bbls)	12.3	22.9
Oil Waterflood Recovery (million bbls)	6.4	13.8
Natural Gas (billion ft^3)	186	168

Table 2.2-1 summarizes the probable resources within the WIPP Land Withdrawal Area and the probable resources in the additional one mile wide study area. Under the WIPP Land Withdrawal Area, resources recoverable by primary production are 12.3 million barrels of oil and 186 billion cubic feet of gas. Within the additional one-mile wide study area, resources recoverable by primary production are 22.9 million barrels of oil and 168 billion cubic feet of natural gas.

2.2.2.4 Secondary Recovery Potential

If people decide to waterflood, what could they get if anything? Is it technically possible to waterflood the oil reservoirs, which would be primarily the Delaware under the WIPP Site?

First we looked at the feasibility of waterflooding. Is waterflooding the Delaware technically feasible? Yes, it does appear to be technically feasible although the pools that are under WIPP have not yet been waterflooded. Yes, water has been injected into eight Delaware Pools in southeast New Mexico for secondary recovery. Waterfloods have recently begun in the Avalon and Parkway Pools in the Delaware. One of those is in the Brushy Canyon. If we take a look at the Cabin Lake Pool which produces from the Delaware near the northwestern boundary of the WIPP, there has been some water injection for pressure maintenance purposes and it has showed some good response. There seems to be a chance for technical feasibility for waterflooding.

Feasibility also depends on economics. Obviously, revenues must exceed expenditures. Profits must meet or exceed expected profits from other possible ventures that a company could get into including waterflooding other fields and pools and drilling for primary recovery elsewhere. So even if something is technically feasible, it may not be economically feasible. Our studies show that waterflooding probably is economically feasible. But even if it is economically feasible, it may not be done because there could be a better return on an investment elsewhere.

Within the limited time available, we analyzed two mature waterfloods within the Delaware Mountain Group in southeast New Mexico. We used historical production data to estimate ultimate recovery from each of those mature waterfloods.

One of the mature floods examined was the Paduca Delaware Field. Primary production started in 1961. Projection of the exponential decline curves showed an estimated recovery of 8-1/2 million barrels of oil by primary production and 5-1/4 million barrels by secondary recovery. In the case of Paduca, there was a 61% increase in production by waterflooding the reservoir. Projecting primary and secondary recovery for the Indian Draw (Delaware) Field yields an 81% increase in production by waterflooding. Worthington made an industry estimate of a 100% increase in recovery from Brushy Canyon by waterflooding the East Shugart Delaware field, which has not been waterflooded at this time.

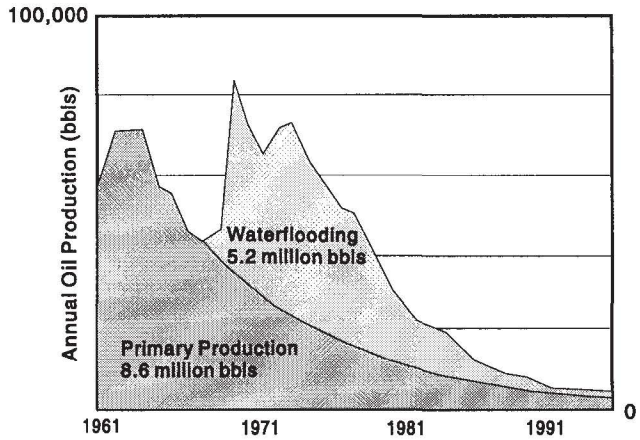

Figure 2.2-13. Production from Paduca Field.

None of the reservoirs under the WIPP Site have been waterflooded yet. Given the three estimates of 61%, 81%, and 100% additional oil recovery by waterflooding, the Bureau used a conservative estimate of 60% additional recovery by waterflooding to project recovery by waterflooding reservoirs in the vicinity of the WIPP Site. Further, there was proprietary information from the oil companies operating in the area indicating that they anticipated 70% to 80% increase in production by waterflooding the Brushy Canyon Formation. To accommodate the uncertainty, the Bureau used a very conservative estimate.

Production from the Cabin Lake Delaware Pool, just outside the northwestern corner of the WIPP Site, was used to provide technical information on the feasibility of waterflooding. Phillips Petroleum is the primary operator of this pool. Figure 2.2-14 shows the initial production at about 4,000 barrels per month for this well and a gradual production decline. The operator completed two wells nearby for pressure maintenance, which is a very early-stage form of waterflooding. The immediate response to water injection is clearly shown. The Delaware sands in the vicinity of the WIPP seem to be amenable to waterflooding. It doesn't mean someone is going to waterflood, it just means that the fields are amenable to waterflooding.

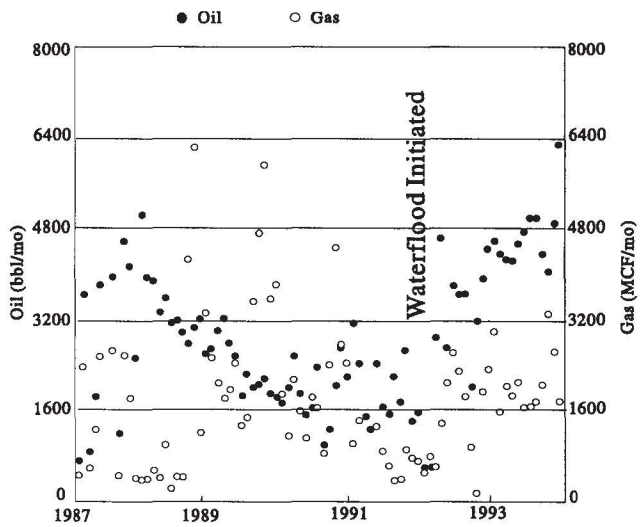

Figure 2.2-14. Monthly production of oil and gas, Phillips Petroleum Company No. 2 James A well, Cabin Lake Delaware pool.

2.2.2.5 Summary

In the Delaware Mountain Group, there is approximately 10 million barrels of oil recoverable by primary production and another 7 million barrels recoverable by secondary recovery. A very conservative estimate shows a little oil recoverable from the Bone Springs Formation and some condensates recoverable from the Strawn, Atoka, and Morrow Formations.

As to gas resources within the WIPP Land Withdrawal Area, approximately 125 billion cubic feet of gas is recoverable from the Atoka Formation, about 30 bcf non-associated gas from the Morrow Formation, and about 20 bcf associated gas

from the Delaware Mountain Group. The Strawn Formation and the Bone Spring Formation would also produce gas.

The above estimates are limited to probable resources. There are probably undiscovered resources under the WIPP Site. But the area has not been drilled. Until then, there is no way of knowing for certain the extent of such resources. For years, operators drilled through the Delaware without knowing of the presence of economically recoverable oil in those formations.

2.2.2.6 Questions:

Wendell Weart: I was wondering if you could provide an average number for the lifetime of a well in this area of the basin, and an average pool lifetime.

Ron Broadhead: Lifetime of the wells. Even though there are some differences from well to well and pool to pool, we can use the average well from the Livingston Ridge to give some idea of a well lifetime. From initial production until about 150 barrels per month, this well is going to produce about 92 months of primary recovery. It is less than ten years for an average Delaware well. Probably production in Delaware pools is going to be in the ten year range, maybe less, because these pools tend to be drilled out and developed very quickly.

Chuck Byrum: What if you add secondary recovery to that? How much would that extend the field life?

Ron Broadhead: Secondary recovery will extend the field life. Secondary recovery will have to start while the primary well is producing. If you wait until the wells are plugged out, secondary recovery is not going to be economically feasible. Secondary recovery is going to have to start when production is around fifty percent, maybe as low as thirty percent of the peak primary production. There are ten years, at the most of secondary recovery, probably less.

Peter Swift: You described the pay zones as about forty feet thick for each pool. Is that all oil saturated or is that just the sand thickness you need in order to have a productive oil zone?

Ron Broadhead: For economic production from Livingston Ridge at present, you need at least forty feet.

Peter Swift: Forty feet of oil or forty feet of sand?

Ron Broadhead: Forty feet of pay, of channel. There is actually less sand. If you get less than forty feet you are going to require a multiple completion. There are a few wells that are completed in multiple zones.

Peter Swift: Is there an oil water contact in that forty feet?

Ron Broadhead: No, there is not.

Chuck Byrum: How much water is being produced during primary recovery per well on average and how much during secondary recovery? Is there a difference?

Ron Broadhead: I don't have an exact number. I can't recall exactly what the water production is from primary. But these wells in the Delaware produce a very high water cut.

Chuck Byrum: Some of the numbers that I have seen, it is like a four to one ratio.

Ron Broadhead: Yes, the water cut is very high. These are fairly unconventional sands. They are pretty fine grained. There is a high water saturation. There is a lot of moveable oil and moveable water. It is not being driven by an oil-water contact. It is water in the actual pore space with the moveable oil.

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2.3 Observations of Water Level Rises in the Culebra Aquifer

2.3.1 Presentation by Rick Beauheim (no synopsis)

The purpose of the presentation was to summarize the observed water level rises since 1988 and offer thoughts on explaining the water level rises, starting with the wells to the south and working northward. The plots start at 1988 because it was in 1988 that water level rises were first noticed in well H-9.

Shown at right are the locations of the Culebra Dolomite Wells in the vicinity of the WIPP Site. Well H-9 is approximately six miles to the south of the WIPP Site. In 1988, a rise in the water levels was first noticed at well H-9. The water level rise propagated north to other wells.

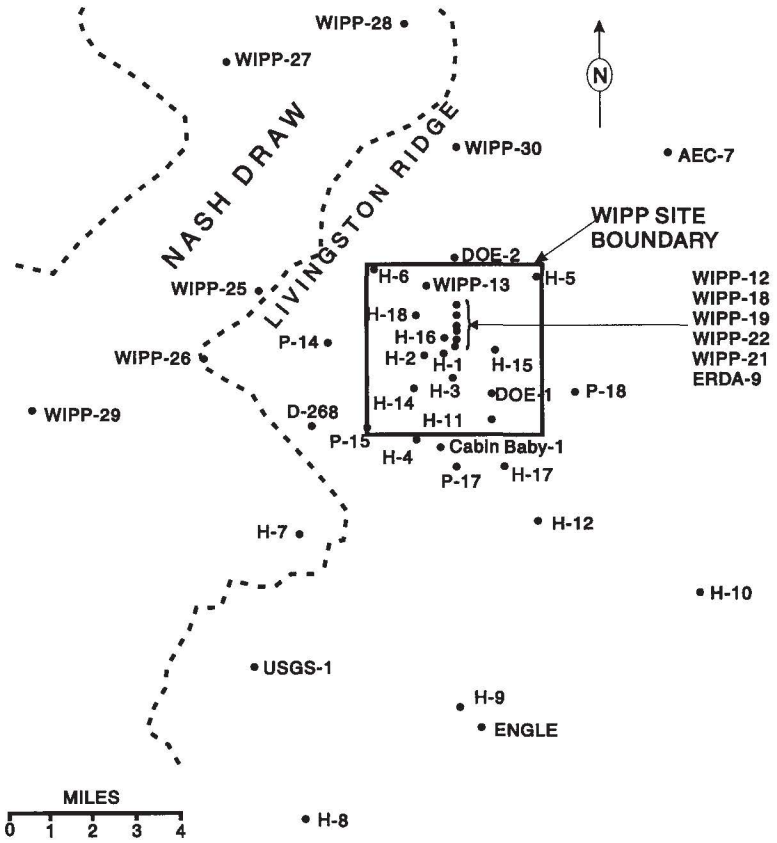

Figure 2.3-1. Locations of Culebra Dolomite Wells in the vicinity of the WIPP Site.

Since that time there have been other Culebra water rises related to other phenomena. To explain the other phenomena, the presentation was divided into three regions around the WIPP Site, starting with each well to the south, covering each well about the center, and finishing with the wells to the north.

2.3.1.1 Southern Region of the WIPP Site

For at least five years prior to 1988, the water level at H-9 was very stable at 431 to 432 feet below the surface. Between March and April of 1988, the water level took an abrupt turn and kept on climbing. In a natural system, that is a system undisturbed by man, you do not expect to see a steady water system and then in the space of one month, the whole thing turn. That is not a natural kind of phenomena. It screams that some event has occurred. Some human induced event has occurred. The rise generally continued from 1988 until about 1993. In 1993, the water level fell off rather abruptly, has been fluctuating, and is now on another rise. The events at H-9 are the result of some phenomena, most likely some well effect.

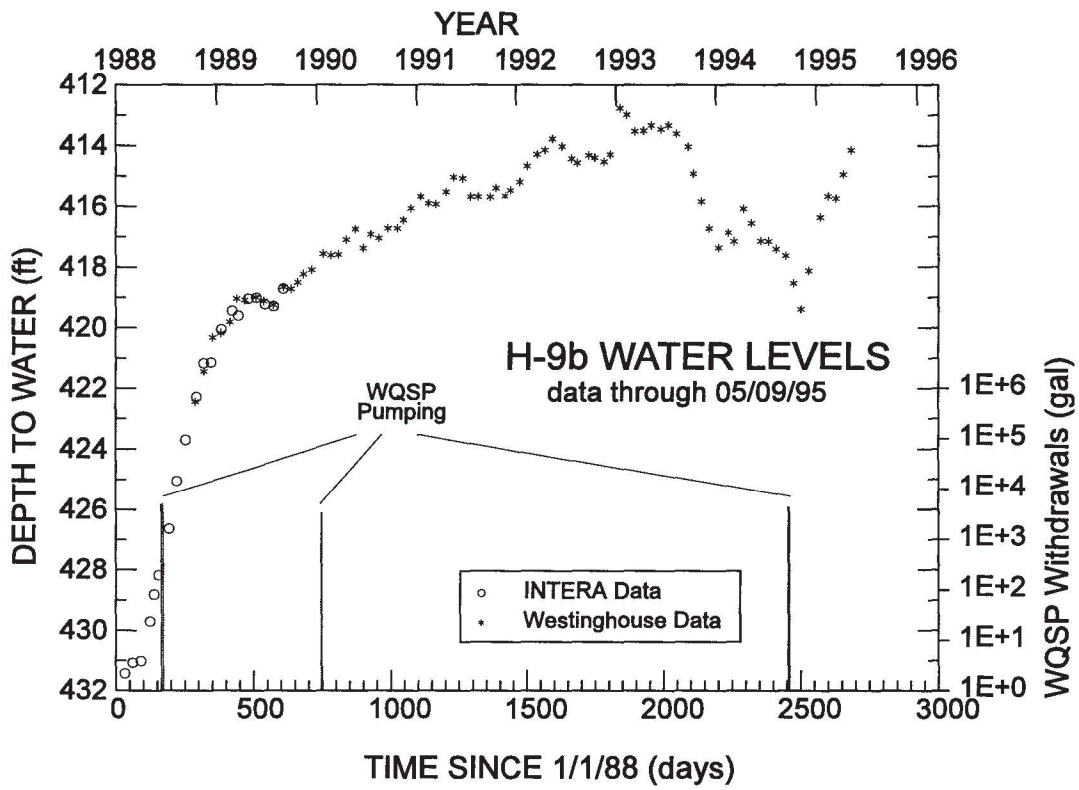

Figure 2.3-2. Well H-9b water levels.

The first well to the north of H-9 is H-12. At the time water levels at H-9 began rising, the water levels at H-12 were controlled by other events. One of those events was the H-11 multipad test. But after the conclusion of the pumping test, the water level was going to clearly recover past the point prior to the pumping test. A water quality sampling test brought the water level down, but at the end of the sampling test the water level continued climbing steadily. The total water level rise at H-12 was on the order of nine feet.

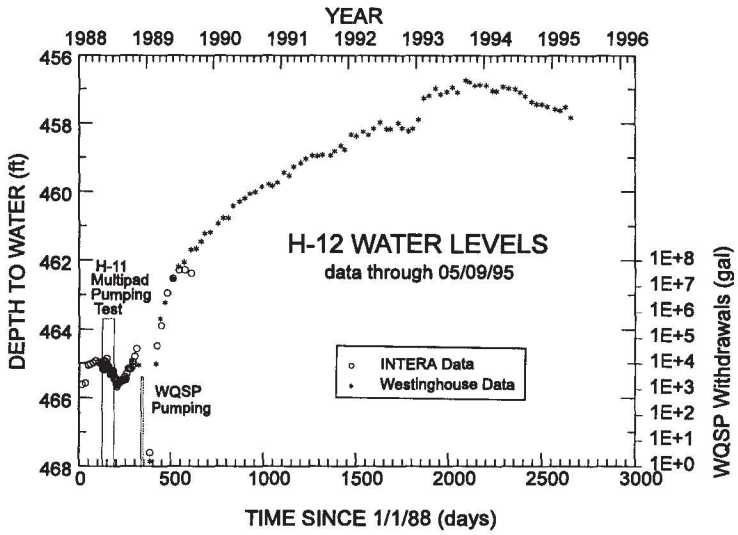

Figure 2.3-3. Well H-12 water levels.

Well H-17 lies a little further to the north of well H-12. Again, after the response to the H-11 multiwell drawdown test, the recovery continued to climb. The water level has fairly well stabilized at the upper end. From 1993, there is not the same kind of detail that is seen in some of the other wells.

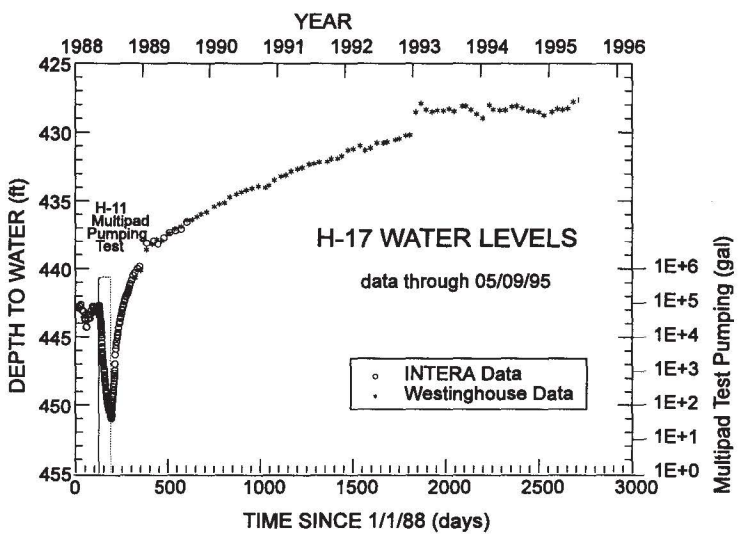

Figure 2.3-4. Well H-17 water levels.

Well P-17, which is due west of H-17, shows the same kind of behavior but it does seem to be a little more in touch with the other fluctuations that have occurred since 1993. There was, again, on the order of nine feet of water level rise.

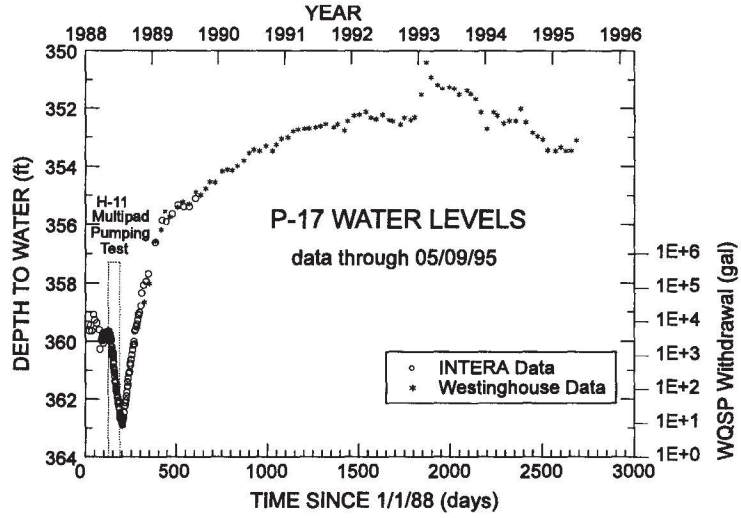

Figure 2.3-5. Well P-17 water levels.

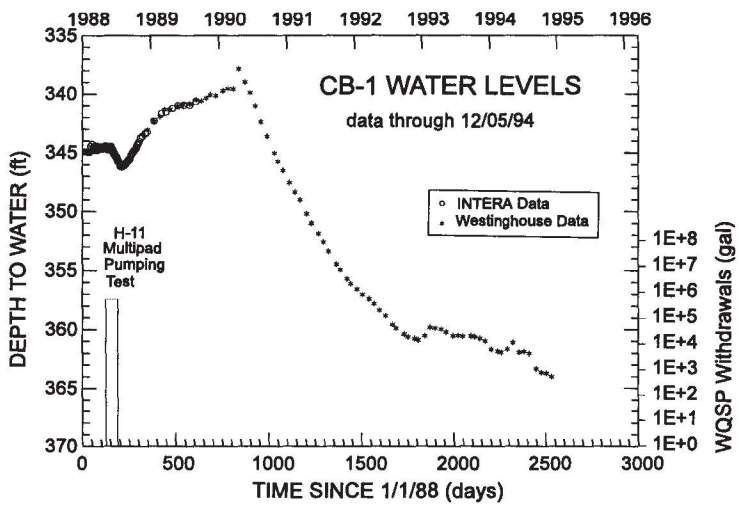

Figure 2.3-6. Well CB-1 water levels.

Cabin Baby [CB-1], which is just to the northwest of P-17, saw the H-11 multipad test response. The water level was continuing to rise and then the packers and bridge plug failed. That drawdown response (after early 1991) has nothing to do with the Culebra. At that time, the Culebra and everything else in that well were interconnected. Late last year we replaced the packers in that well and put in a new bridge at the base of the casing. Westinghouse may not be aware of that and needs to go back to measuring the water levels.

Well H-4b is the next well slightly to the northwest of Cabin Baby, and again you see the same response to the H-11 well and then this rise. Westinghouse takes water samples from time to time resulting in an occasional drawdown, but the well does recover. But they also went into H-4b and a number of other wells. Some of these older wells were caving in and were not providing full access to the Culebra Formation. Some of these wells were cleaned out. The cleaning required Culebra water, but Culebra water was not available from well H-4b. Water from well H-3 was used for all of these 1992 cleaning exercises. The water from H-3 has a different density from the density of the water in the wells that were cleaned out. As a result, upon completion of the cleaning exercise the water level had declined. The foreign water was pumped out and the water level rose sharply as a result of density change more than anything else. The water level has continued to decline. The decline in the H-4b well may reflect the decline in the Cabin Baby well because H-4b and Cabin Baby are very close to each other. The Culebra saw a pressure decline in the Cabin Baby well, which would create the drawdown in well H-4.

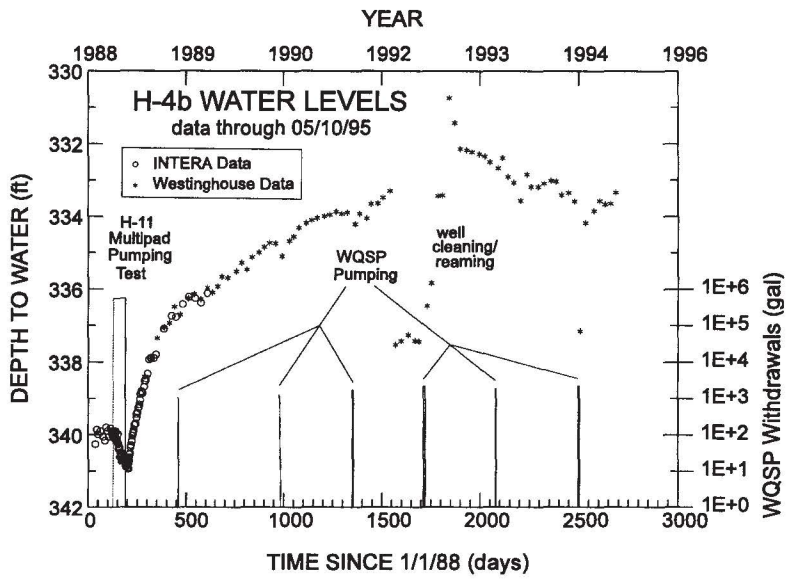

Figure 2.3-7. Well H-4b water levels.

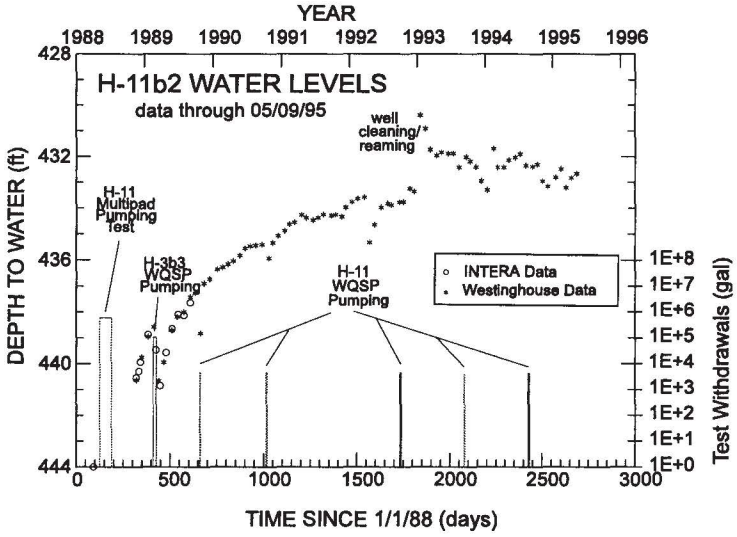

Figure 2.3-8. Well H-11b2 water levels.

After the H-11b2 multipad pumping test, there was pumping at H-3 that effected the water levels at H-11. After the recovery from the H-3 pumping test, the water level continued to rise. The plot shows the response to the cleaning exercise. The water level rose with the density change. The water level has continued to rise since then (with the rest of the response very similar to that at H-4b).

Well P-15 shows the same type of response (as H-11b2).

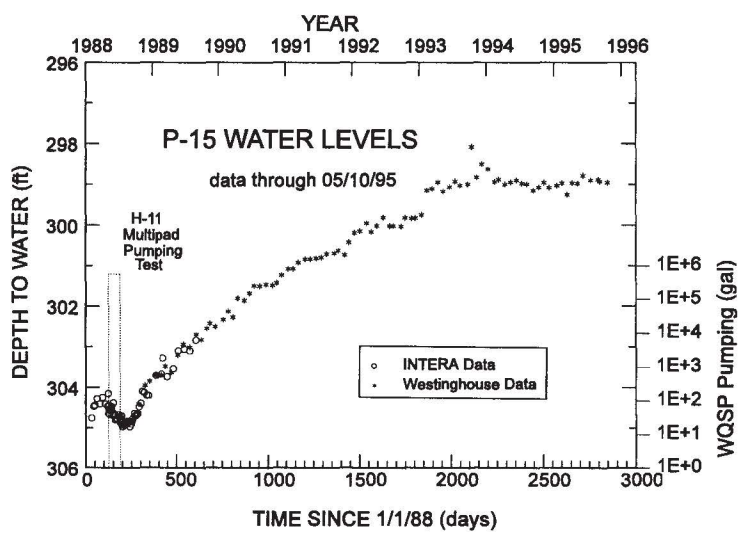

Figure 2.3-9. Well P-15 water levels.

Well H-10 lies northeast of H-9. Well H-10 has quite low transmissivity. It is a very tight well. It appears that whatever happened at H-9 or in the vicinity of H-9 took a number of years to propagate over to H-10 because of the low permeability. It wasn't until the end of 1990 and beginning of 1991 that the water level in H-10 began to take off. The water level has definitely climbed about three feet in the last three or four years.

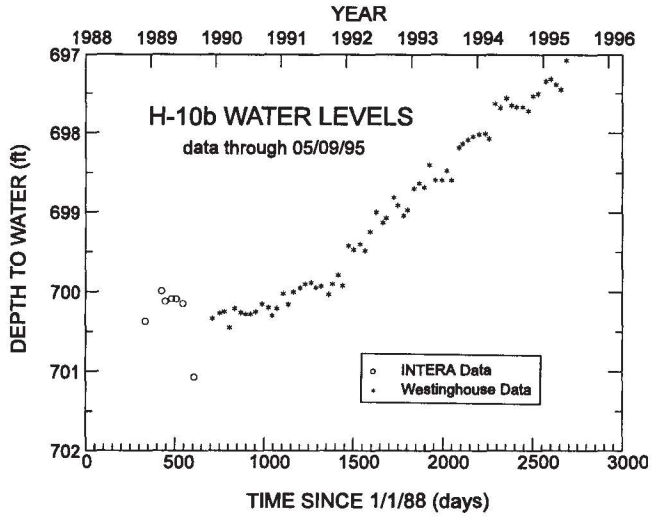

Figure 2.3-10. Well H-10 water levels.

Well H-7 lies off to the west in an extremely high permeability region. H-7 may also be under water table conditions. The scale in the water level plot is on the order of three feet. What appear to be large amplitude fluctuations are actually less than a foot in water level change. Most of these changes are probably due to barometric effects, earth tides, or something of that nature. The changes are just a fraction of a foot. But, one gets the sense that, for

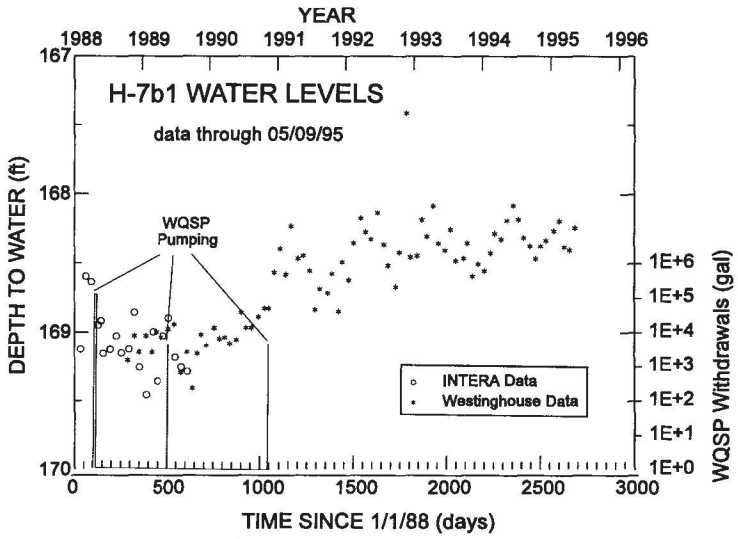

Figure 2.3-11. Well H-7 water levels.

years, the water level seems to be stable at about 169 feet. One does get a sense that the water level is climbing a bit at H-7.

So what might be going on? In 1990, Marsh LaVenue looked at all these rising water levels to the south and went out looking for injection wells in the vicinity of H-9 that might be a cause of this kind of a water level rise. He identified a number of injection wells, some of which the operators thought might be leaking. We really had no evidence that the leakage was specifically going into the Culebra. We were mainly interested in figuring out if that type of a hypothesis, that is a leaking injection well somewhere in the vicinity of H-9, could cause the types of water level rises that we have observed.

LaVenue identified one well not too far from H-9 that was injecting about 12 gallons per minute into a deeper formation. So we decided to play a "what if" game. What if some of the water being injected into this well is actually leaking into the Culebra? Using the existing regional groundwater flow model, LaVenue simulated injection at that well location. LaVenue found that if he put the full 12 gpm, into the Culebra, at that location, he could very nearly match the observed water level rises. Now that is in no way, shape, or form, proof that that [salt water disposal] well is the cause of these water level rises. It merely shows that if something is being injected into the Culebra, in that region, and at about 12 gallons per minute, you can get this kind of a response. It confirms our hypothesis that it really does take some kind of discrete event, turning on a pump, turning on injection, something changing to cause these kinds of water level responses.

From my standpoint, it's really not important what well might be responsible for this. It could be any well out there. The point is, in the future, we won't know. In a hundred years from now we won't know what wells might be leaking. We won't know what casing has failed, what cement jobs have gone bad. The point

is simply that other units can be connected to the Culebra. They can cause changes in the water levels.

So what is the overall implications with respect to compliance? Well, in this particular instance, this well is to the south of the WIPP Site. Rising water levels to the south, that propagate to the north, as they propagate, they diminish in magnitude. What this in effect does, in this instance, is decrease the gradients, the natural gradients, within the Culebra, which are from north to south. So, under ordinary conditions, you have a particular gradient which in the event of a breach of the repository, would drive radionuclides to the south under the existing gradient. Well, what this kind of event does, is it decreases that gradient. So this would actually slow things down a bit. I don't think that is significant because I don't expect this to be a particularly long lived kind of response, probably on the order of tens of years, then it will damp out, reach some new equilibrium. Climate changes in the future could cause similar types of gradient changes, so I really don't think it's important. Let's continue to look at the other water levels and I will show you some other things that are going on.

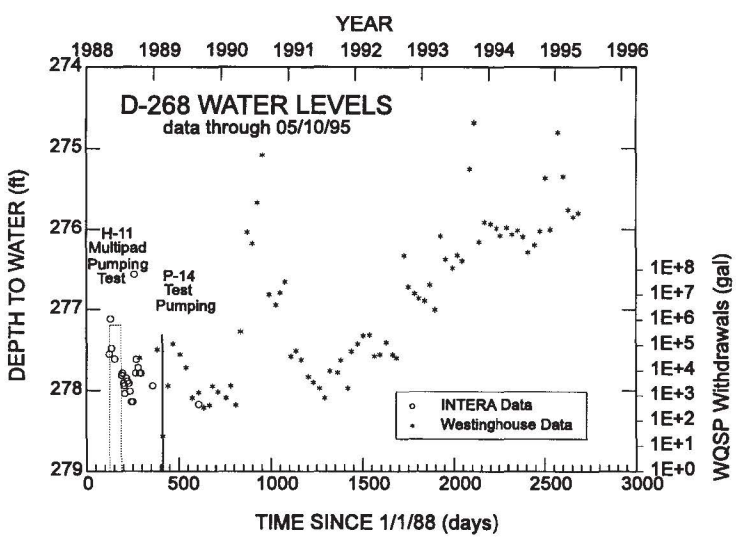

Figure 2.3-12. Well D-268 water levels.

D-268 is off the southwestern corner of the site. We have a troublesome packer in this well. It has to be continually reinflated. It likes to deflate. It sees a lot of water fluctuations as that packer loses its integrity and as

the packer is reinflated and reestablishes its integrity. There may be a slight rise in the water level at D-268.

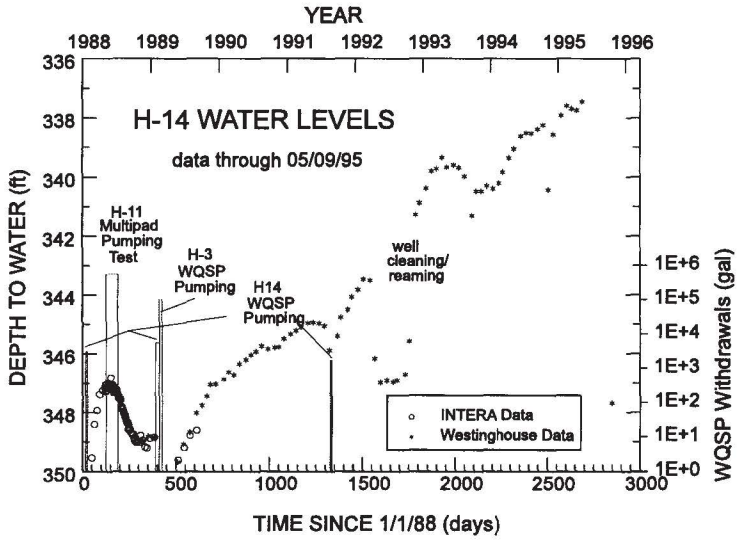

At H-14, there is the same type of response as observed at the other wells - a well cleaning exercise - pumped out - changes in fluid density.

Figure 2.3-13. Well H-14 water levels.

This is a greatly expanded scale, with sixty feet on the vertical scale to capture the response to the H-11 multipad pumping test. The water level continued to rise after the H-11 test. Then there was a packer failure in DOE-1. That packer has since been replaced and the water level is starting to recover from that event.

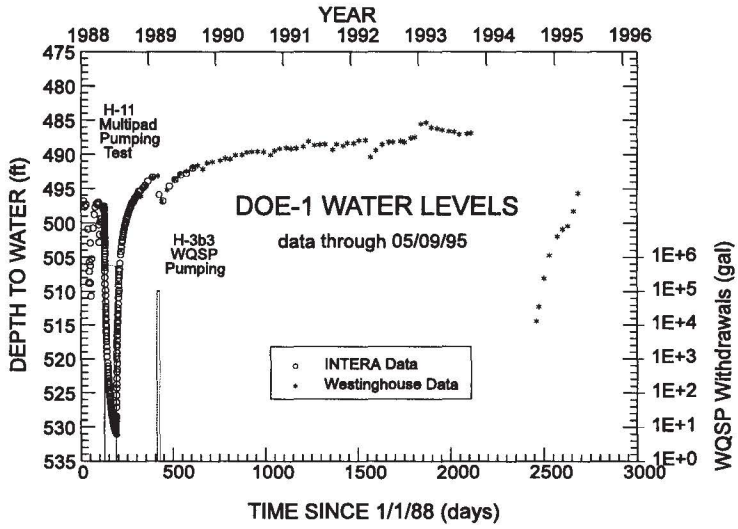

Figure 2.3-14. Well DOE-1 water levels.

Well H-15 shows a type of response similar to that of DOE-1.

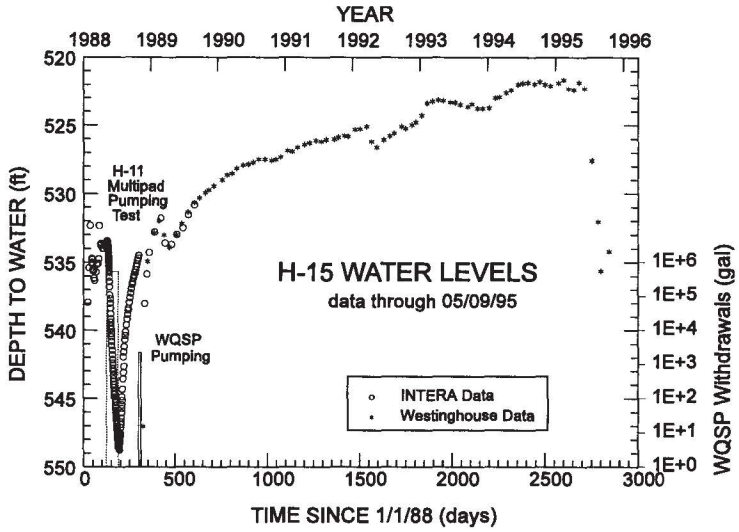

Figure 2.3-15. Well H-15 water levels.

2.3.1.2 Central Region of the WIPP Site

The shafts at WIPP caused a large cone depression in the Culebra. Starting back in 1981, when the exploratory shaft was first drilled, there has been leakage into all the shafts at the WIPP Site and that leakage has brought water levels down, in the Culebra, over the entire site. Over the years, there have been a number of episodes of shaft grouting which have been of varying effectiveness, and sometimes that effectiveness has been limited in time. So, some of the grouting jobs were repeated.

The most recent shaft at WIPP is the air intake shaft. Before the air intake shaft was drilled, we put in an observation well, H-16, fifty feet away to monitor the responses of the Culebra to the construction of the air intake shaft. The pressures that have been measured at H-16 since about August 1987 are shown. The stabilized pressure in the Culebra before the air intake shaft was drilled, was about 128 psig. When the pilot hole for the AIS was drilled, the hole was loaded with drilling mud. Once the drillers hit the Culebra, the pressure at H-16 rose in response to the pressure exerted by the drilling mud. Once the drillers holed through to the underground, the column of drilling mud shot into the underground

resulting in an atmospheric pressure condition in the Culebra. So the pressure in the Culebra at H-16 dropped significantly at H-16. The drillers then upreamed through the Culebra. The pressure again dropped significantly at H-16. The air intact shaft was then lined. The pressure started recovering. Then Fred Gelbard went into the air intake shaft and drilled four horizontal core holes into the Culebra. That caused the pressure to drop at H-16 because of the free drainage into the holes. Those [core holes] were then pressure grouted because the pressure had increased and then the pressure started climbing again. The interesting thing about the pressure grouting is that by simply pressure grouting those four holes, the pressures rise, the buildup was much more than one might have expected. By grouting those holes, the overall leakage into the shaft was greatly reduced.

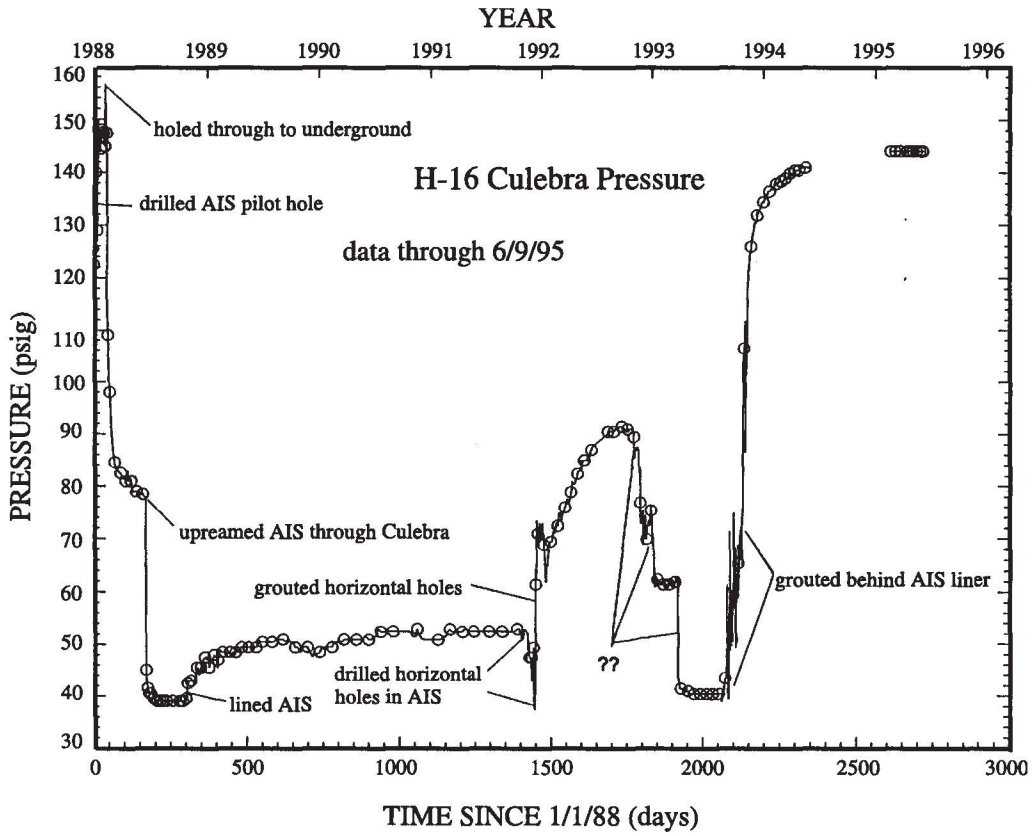

Figure 2.3-16. Well H-16 Culebra Pressures.

There were a number of episodes that I have not been able to pin down. Something happened around the air intake shaft that caused the pressure to drop in at least three distinct steps. I am not quite sure exactly what happened. The pressure stabilized around 40 psig until two summers ago when the project grouted behind the liner. This was a very serious grouting exercise and by far the most effective grouting exercise that has ever been done at WIPP. Sandia was working with the grouting contractor, providing the contractor with pressure data in almost real time. We could show them every single time they drilled a hole into the Culebra to grout. We could see the pressure response at H-16, the immediate drawdown response to drilling that hole. As soon as they did grout that hole, we saw the pressure spike associated with it. So we could track the effectiveness of their grouting program in progress. As soon as the grouting was completed, the pressure at H-16 rose and is now stabilized at 144 psig. Recall that in 1987, the level was stabilized at 128 psig. This grouting job was very effective. The pressure is now higher than it was before the air intake shaft went in. I spent this much time on this well because the other wells exhibit similar behavior. Well H-16 is only fifty feet from the air intake shaft but all of these responses propagated throughout the center of the site. Similar responses are seen for wells ERDA 9, H-1, H-2b2, H-3b2, WIPP-21, WIPP-22, WIPP-18, WIPP-19 and WIPP-12. The responses are more subdued with increased distance from the air intake shaft.

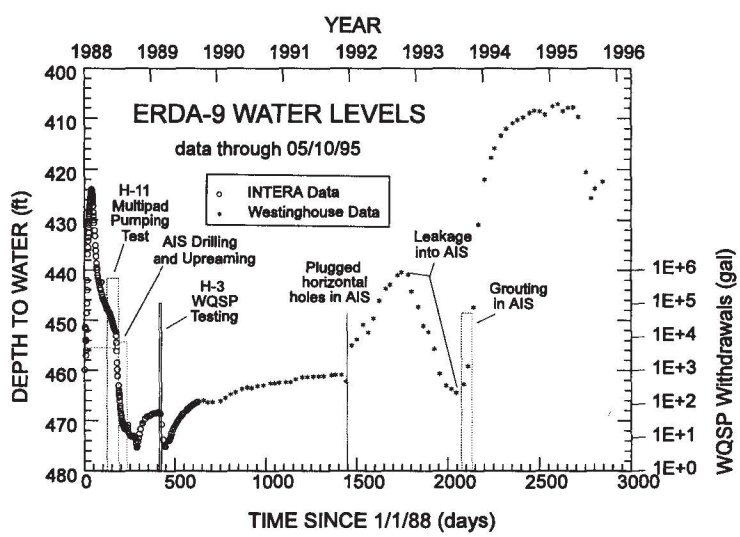

Figure 2.3-17. Well ERDA 9 water levels.

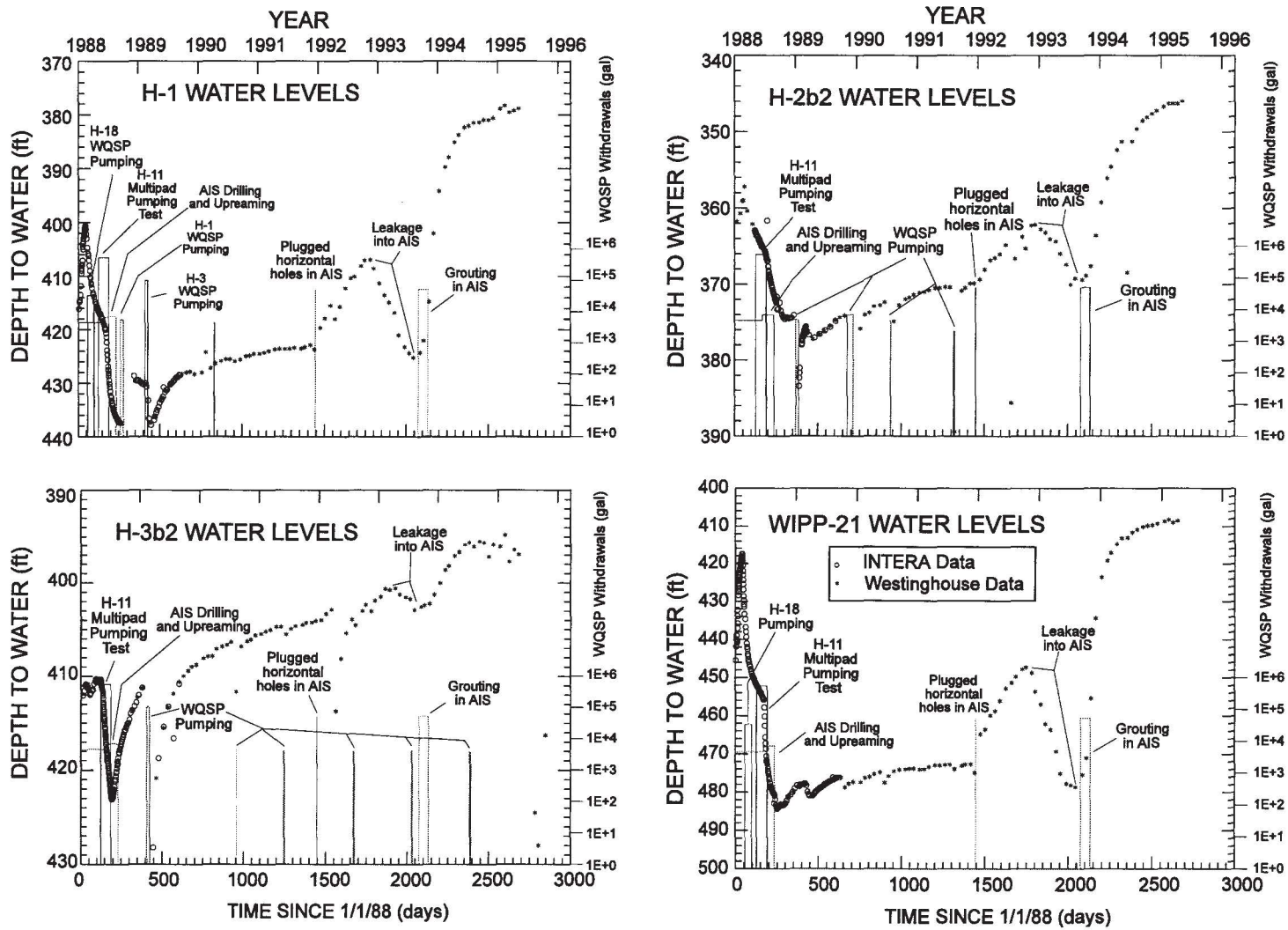

Figure 2.3-18. Wells H-1, H-2b2, H-3b2, and WIPP-21 water levels.

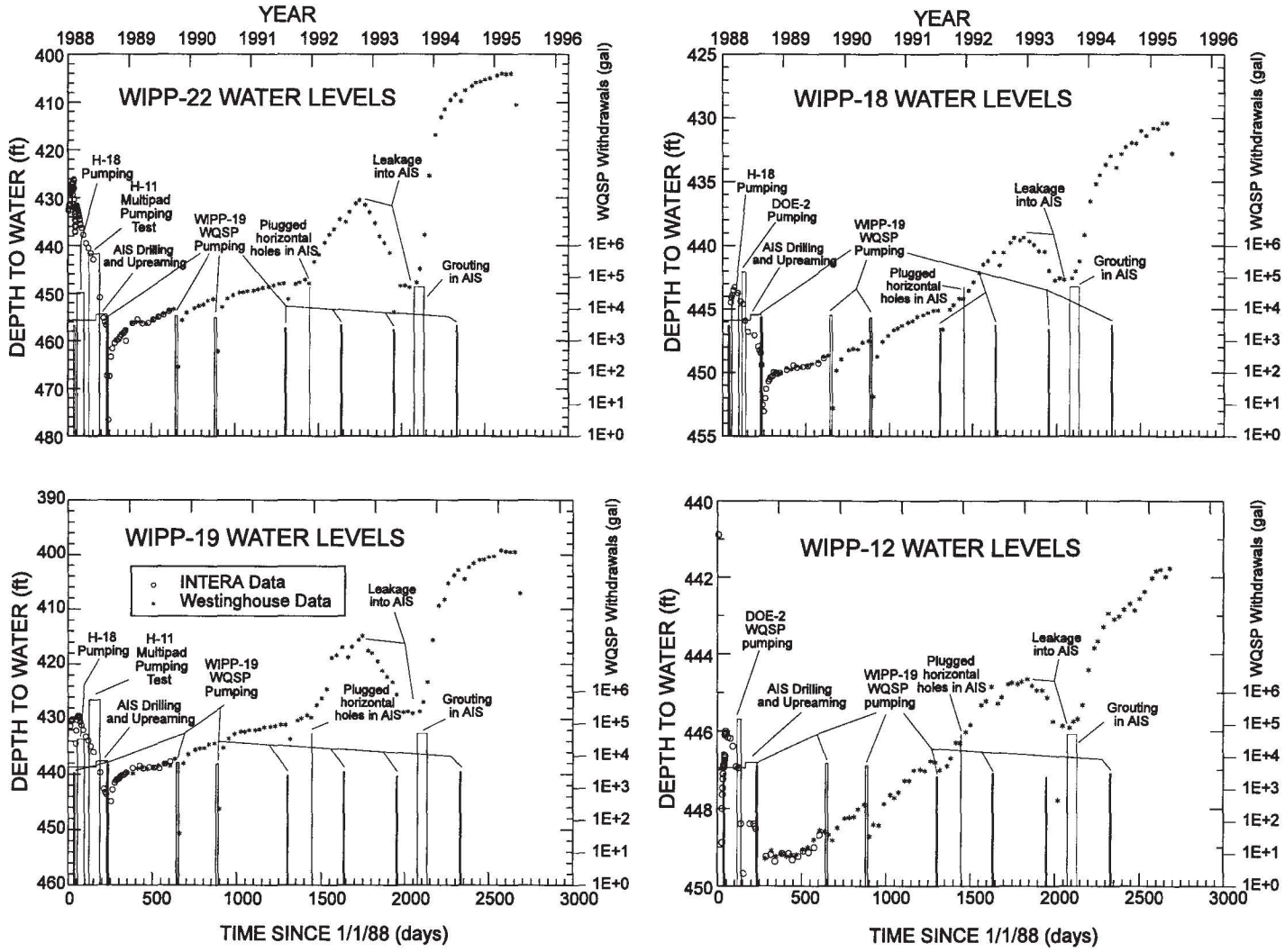

Figure 2.3-19. Wells WIPP-22, WIPP-18, WIPP-19, and WIPP-12 water levels.

Well H-18 shows a general rise in water levels.

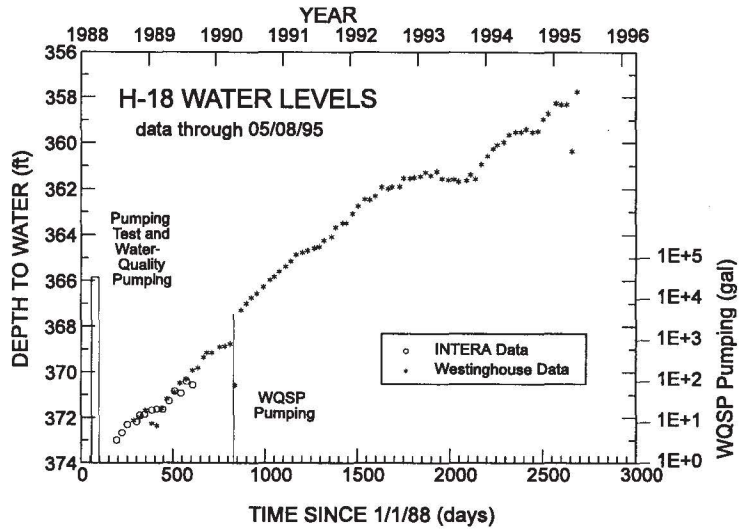

Figure 2.3-20. Well H-18 water levels.

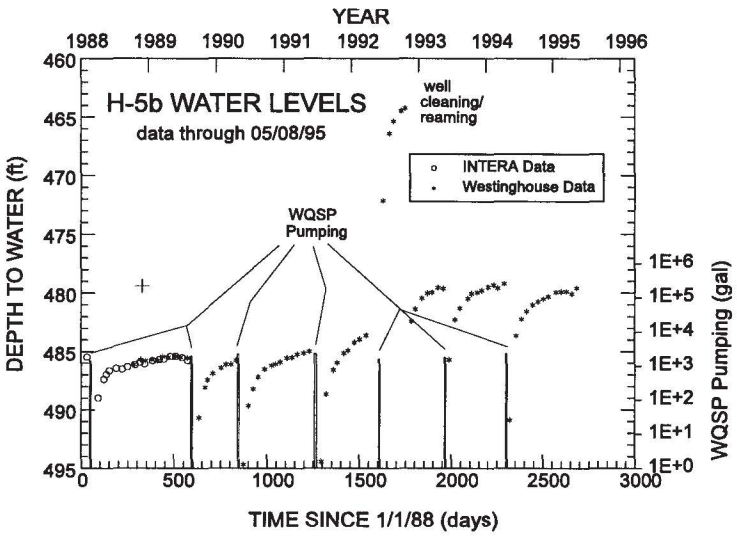

Figure 2.3-21. Well H-5b water levels.

Well H-5b is in the extreme northeast corner of the WIPP Site. It is in a very low permeability zone and it takes a lot to make anything happen at H-5. It is pretty much isolated from other events. It does show that for each water quality sampling, the well takes a time to recover and is still recovering when the next sample is taken. The water level sharply increased, for a while, in response to the well cleaning and reaming. Now the water level is in line with where it should be.

Well DOE-2 shows a water level rise up until mid-1992. Since then the water level has been falling off. This one is pretty anomalous. You don't see this kind

of fall off in any of the surrounding wells. DOE-2 is like DOE-1 and Cabin Baby and some of the other wells. It has a bridge plug in the base of the casing which isolates the Culebra from the Salado and the Castile. There is another deep bridge plug which isolates the Castile from the Bell Canyon. Looking at the water level plot, I would guess that one or both of those bridge plugs have failed and we need to reenter that well and put in a new bridge to isolate the Culebra.

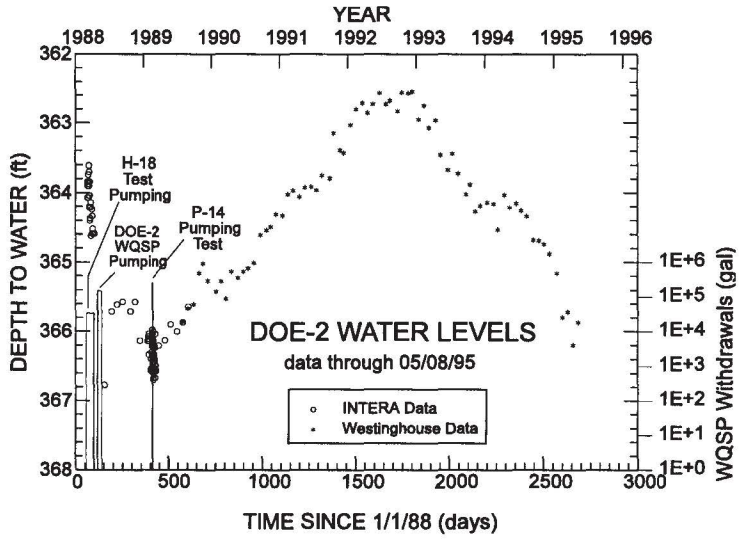

Figure 2.3-22. Well DOE-2 water levels.

WIPP-13 shows a water level rise. As you continue north towards Nash Draw, you see this kind of rise. This rise may be due to a combination of events. The wells are far enough away from the shaft so that they won't see a distinct response to a distinct episode at the air intake shaft. Instead you see a

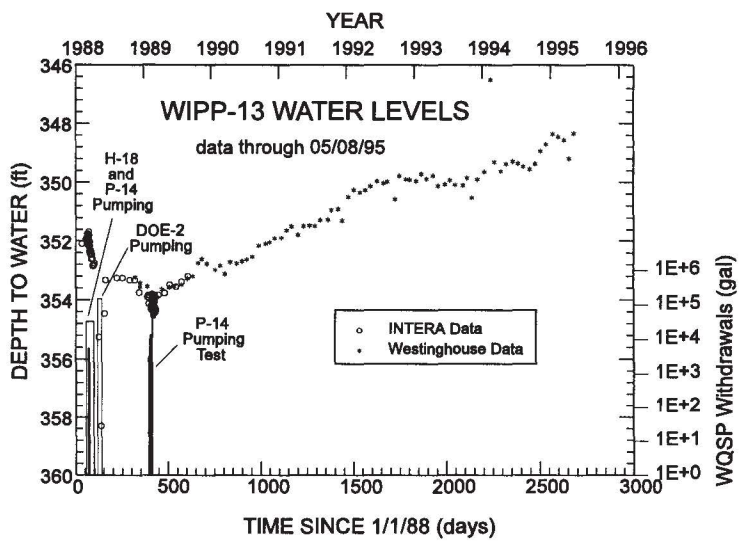

Figure 2.3-23. Well WIPP-13 water levels.

generalized response. In general, leakages into all of the shafts have decreased over the years. The rise in the wells to the north just reflects an overall recovery to the leakage into the WIPP shafts.

H-6 has risen on the order of about 4 or 5 feet since 1989. It is important to remember that H-6 has been there since the late 1970's. Even though it appears that the water level is rising, today's water level does not represent an all time high. Today's water level is approaching the water level of the late 1970's before any of the WIPP shafts were drilled. This appears to be a recovery to the drainage into the WIPP shafts.

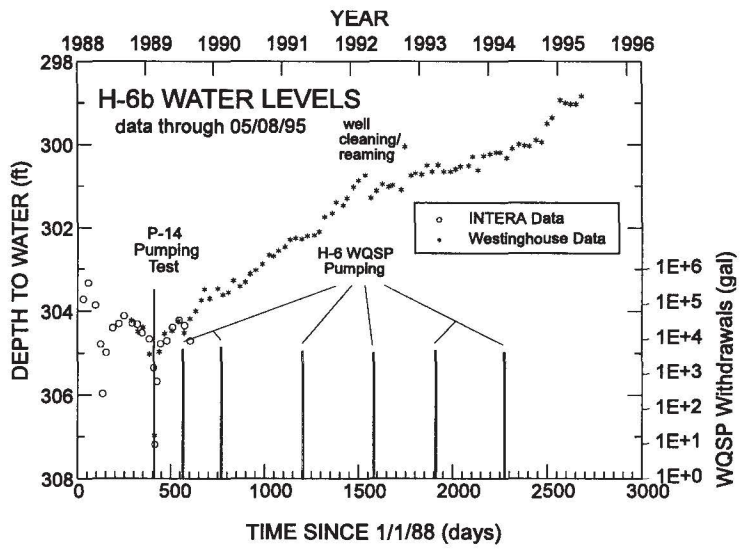

Figure 2.3-24. Well H-6b water levels.

P-14 is in a very high transmissivity region. The water level had been fairly stable. Now it looks like P-14 is going through an historic high.

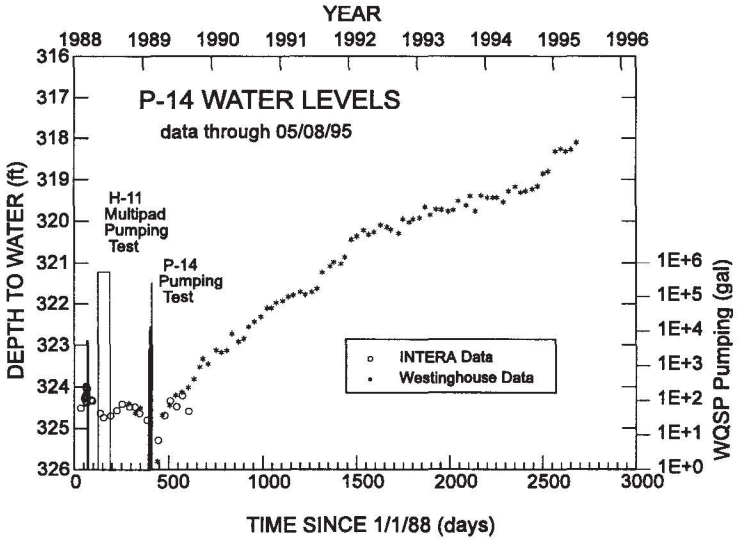

Figure 2.3-25. Well P-14 water levels.

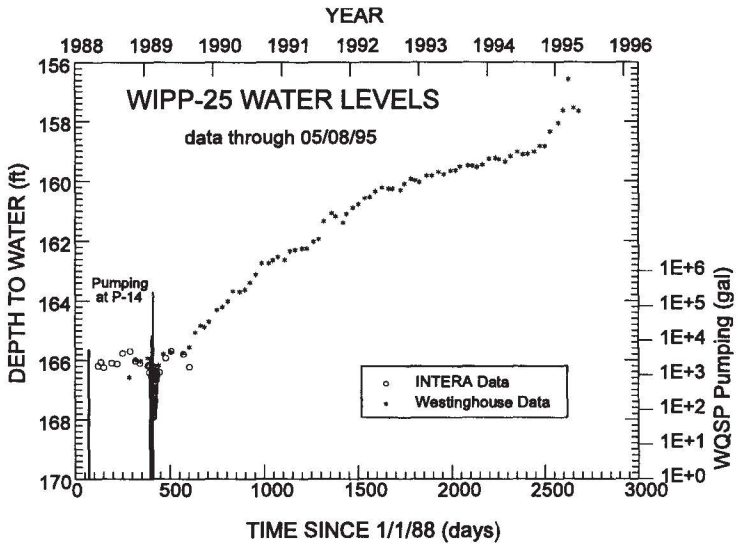

Figure 2.3-26. Well WIPP-25 water levels.

WIPP-25, in Nash Draw, shows a rise. WIPP-25 is in a high permeability region and it takes a fair amount of water to change the water level.

WIPP-26 seemed to be rising, but now it seems to have stopped.

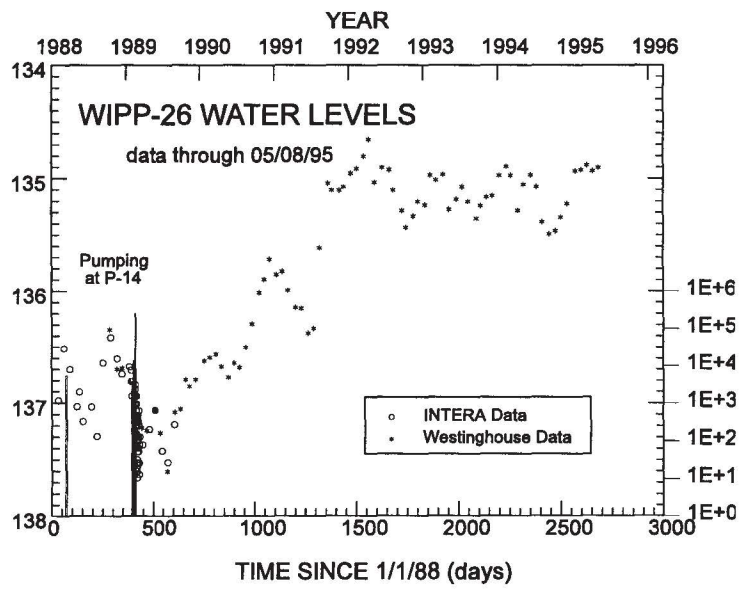

Figure 2.3-27. Well WIPP-26 water levels.

2.3.1.3 Northern Region

WIPP-27 is in the northern part of Nash Draw, very close to one of the potash mines. The potash mines discharge various amounts of effluent into Nash Draw depending on their production. When there is not much production, there is not much discharge into Nash Draw. When there is more mining and more refining, they discharge more. WIPP-27 has a lot of distinct features. The plot of water level rise does not exhibit the noise seen in the plot for WIPP-26. Instead, WIPP-27 is responding to

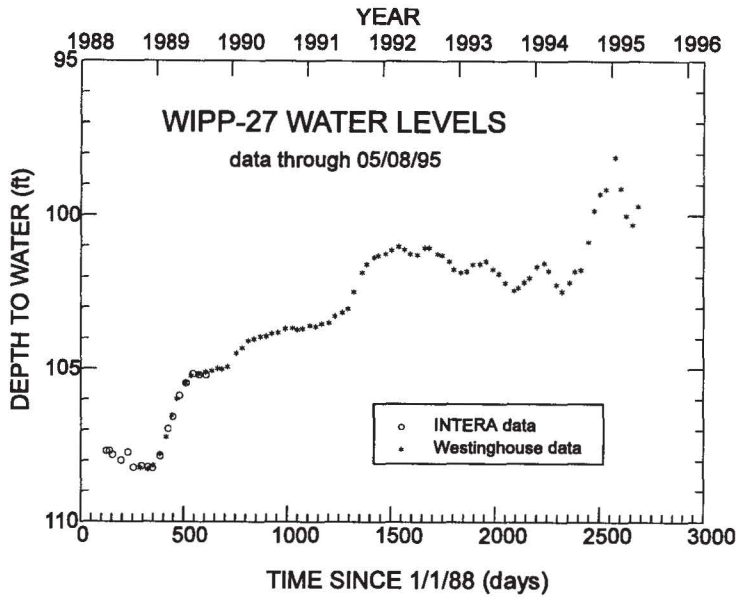

Figure 2.3-28. WIPP-27 water levels.

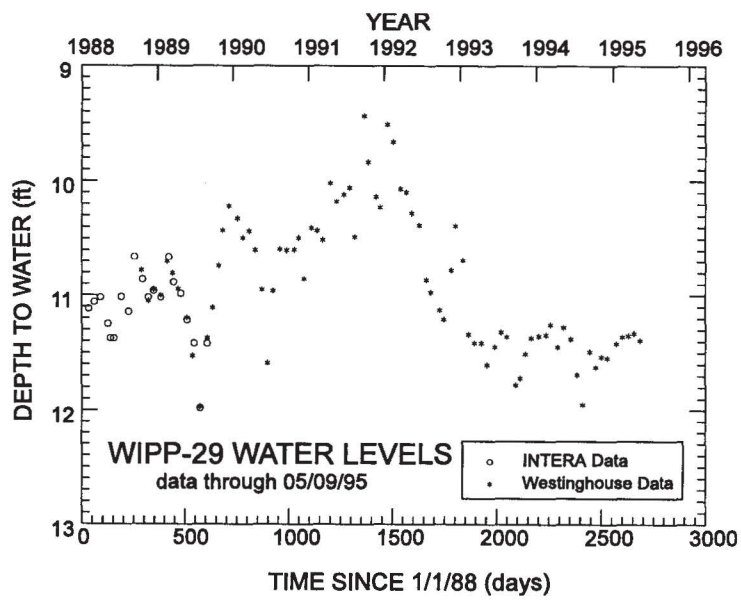

Figure 2.3-29. WIPP-29 water levels.

something fairly distinct. WIPP-27 appears to be providing a good indication of the discharge into Nash Draw. Some of these changes probably propagate through Nash Draw towards the northern part of the WIPP Site. But the changes get more diffuse as they get there.

WIPP-29 is so shallow, 11 feet to water, that it could be responding to almost anything.

WIPP-30 showed a rise, a stabilization for a few years, and now appears to be on another rise.

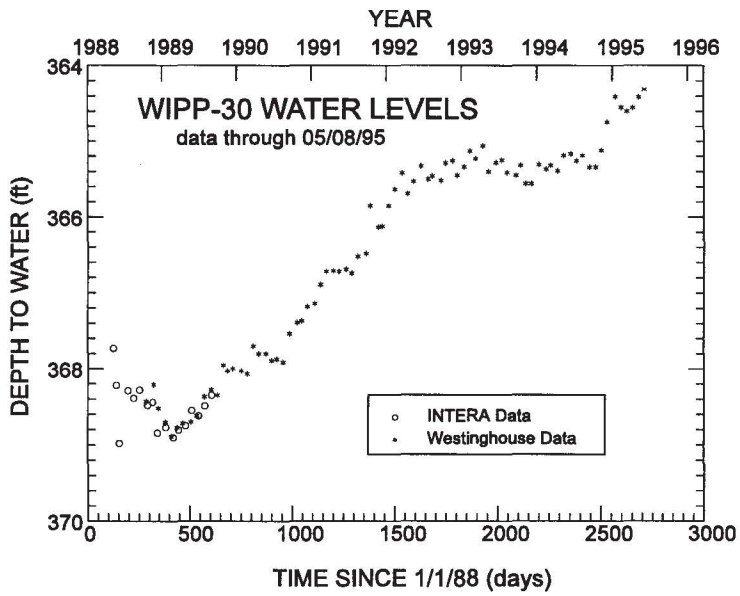

Figure 2.3-30. WIPP-30 water levels.

Well P-18 continues to rise. It is not clear where P-18 is headed. In contrast to all of the other plots, which begin in 1988, this plot begins in 1977. This is the complete water level history on P-18. Until

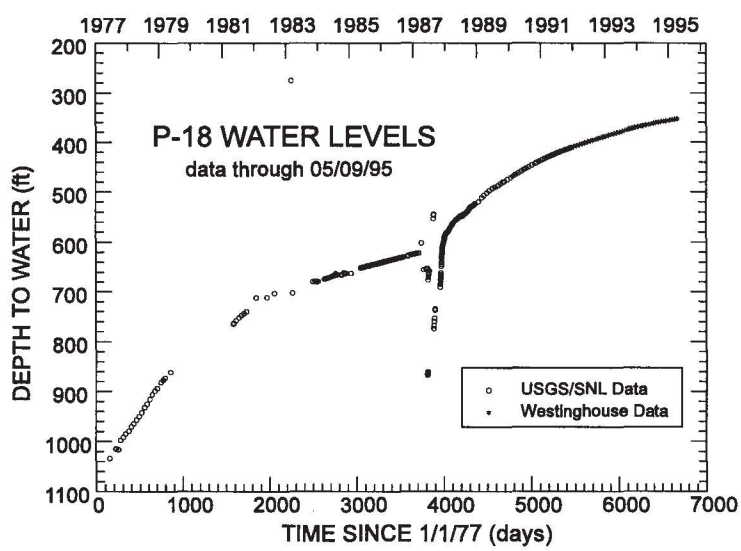

Figure 2.3-31. Well P-18 water levels.

about 1987, the water level was rising in a 4-inch well casing. It never actually stabilized. Then in 1987 we put a pip in the well. So, now the water level is rising in 2-3/8 inch tubing instead of 4 inch casing so it goes up faster because of the smaller diameter. The water level still hasn't stabilized there. A lot of people over the years, including myself, have hypothesized that we may not have the best connection to the Culebra in this well. There may be a problem with the cement bond. This is a cased, cemented, and perforated well. There may be a problem with the bridge plug at the bottom. There may be problem with the cement job. We don't have a lot of confidence that what we are seeing here is the Culebra.

2.3.1.4 Summary

To summarize, I see three different things going on with the water levels at the WIPP Site. To the south, centered around H-9, you see one very distinct water level rise that began abruptly in 1988, reached its peak at H-9 and seemed to propagate to the north, which I think is probably related to some kind of injection from some other well in that region. As you get to the center of the WIPP Site and more or less propagating out from the center of the WIPP Site you see recoveries and drawdowns related to events at the WIPP shafts. Those shafts are pretty well sealed right now, so the overall response you see today is rises in water level. As you move to the North and get into Nash Draw, I think you can probably see responses to the discharge of potash mill effluent into Nash Draw. I'm not sure about the availability of discharge records there. It might be possible to try to reconstruct a discharge history and try to relate that to the water levels we have seen. Again, I'm not sure that it's really relevant to WIPP compliance. The water levels and the flow directions are not from the WIPP Site towards Nash Draw. Any minor changes in gradient, in any event, are not going to effect the results of our performance assessment. We are not on such a hair trigger that a difference of 10% or even 100% is really going to make any difference.

2.3.1.5 Questions:

Dennis Powers: For wells H-7, WIPP-26, and WIPP-27. Are the data precise enough for annual changes?

Rick Beauheim: I have doubts about H-7. H-7 at one time pumped at 80 gpm and the responses we saw at the observation wells on the order of 100 feet away were dominated by earth tides. And the earth tidal responses were almost as great as the pumping test response. It may be of interest to no one but me, but earth tides are changes in water level affected by moon tidal affects and the changes in the configuration in the earth in response to tide. Actually, some of the first work on earth tides was done in Nash Draw, in the Culebra, back in the late 1920s, early 1930s. So H-7 is very close to the location where the very first earth tide research was done. The other ones, Dennis, -- yes I think it is possible that you could try to do that -- I'm not sure what you would turn up, but it might be worth a shot.

Tim Gum: Rick, on your model study where you indicated the 12 gallon per minute increases in fluid level, what was the total volume which had to be injected in order to get the total rise all the way?

Rick Beauheim: The way the modeling was done, the 12 gpm was turned on. I guess I'm not sure exactly when in 1988. In early 1988 this 12 gpm was turned on and was simply allowed to run for the duration of the modeling simulation. At the time that was done, the water levels were all continuing to rise. So the modeling was simply turned on and we watched the hydrograph to see if the simulator hydrograph matched what we observed.

Tim Gum: From 1988 on?

Rick Beauheim: From 1988 on to however long it ran. I honestly don't recall if we just ran a simulation through 1991 at the time or projected further. But we didn't turn it off and then on.

Tom Peake: Yes, do you think this affected your response times, due to rises from the South to the North, up to the Cabin Baby and H-4? Do you think that has any implications for suggesting that there are higher transmissivities in the South Central part of the WIPP site than are currently being modeled?

Rick Beauheim: I think you can look at the pattern of water level responses and learn something about the transmissivities. P-17 and H-17, for instance, lie on an east-west line. Yet their responses were different. I look at those two responses, H-17 and P-17, and what they say to me is there is a high transmissivity feature passing between those two wells. A few responses we observed tell me that the high transmissivity feature is more likely closer to P-17 than it is to H-17. Because the P-17 response seems clearer. It seems to catch the subtleties of the response better than the H-17 response. The propagation on toward Cabin Baby, H-4, P-15, I guess I really could not say whether it holds any surprises. I think it would provide an opportunity to take a closer look with our existing Culebra model to see if our current transmissivity distribution would match the responses that you see that much further away in detail.

Robert Neill: It is an extremely important area. In fact we have a half hour scheduled this afternoon to address this in greater detail. Rick, a quick question. Do you see any merit, at this point, in trying to obtain some water samples from these wells to examine, from a standpoint of chemistry, any change as both a function of location and a function of time?

Rick Beauheim: I really don't think so. We are looking at pressure transient propagation here which can be relatively rapid whereas actual transport of ground water is an extremely slow process. I don't think there is any chance at all of us seeing changes in water chemistry as a result of this.

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2.4. Observations of the Effects of Water Flooding on the Salado Formation

Dennis W. Powers, Consulting Geologist, Anthony, Texas

2.4.1 Synopsis

The Hartman vs. Texaco lawsuit and subsequent discussions with different people focused my attention on a physical condition common to several concerns. The basic physics or hydrology of liquid and gas movement laterally or vertically through the evaporites, especially the Salado, is common to decisions about oil and gas exploration vs. potash mining, deviated or vertical drilling through evaporites outside WIPP boundaries, and the fate of any gas generated by decomposition of waste at WIPP.

Exclusion zones for drilling and potash mining are presumed to be based on two principal concerns: safety and the desired development of resources. Exclusion zones presumably increase as real (or perceived) safety concerns increase; fewer resources are developed in consequence. Among the safety concerns is the possibility of lateral movement of hydrocarbons along evaporite beds from a leaking well into a mine. The same general setting can exist for WIPP from the nearest well to the underground workings. Gas generation at WIPP raised the possibility of movement away from the disposal mine to a boundary or well. And the Hartman Bates well raised the possibility of injected fluids reaching a well at a distance of about 2 miles from the injection field boundary and in a formation overlying the injection horizon.

Perhaps each situation has to be resolved separately (monetary settlement for Hartman, scenario analysis for WIPP, some other means for potash vs. oil and gas exploration). Nonetheless, as similar occasions arise, there will be a continuing need to understand the hydrology of liquid and gas transport parallel to bedding within the Salado or other rock units. There are probably no better investigations yet of these phenomena than for WIPP, and there will be increasing pressure to

understand and apply the results to different versions of the same fundamental problem.

2.4.2 Presentation by Dennis Powers

Today I want to cover a few different topics. The title that is listed for you is a little bit misleading. First, I want to give you a little bit of my impression of some things out of the Hartman vs. Texaco lawsuit that struck me. I also want to talk about some common problems, some underlying principles of physics that are important to several different projects and several different ways of thinking about the Salado.

Today, I am speaking on my own behalf and I am not here representing any organization at WIPP even though, I think most you are aware, I am under contract to one or more organizations to do work at WIPP. I am not a lawyer; this is not a legal analysis of the Hartman vs. Texaco case. I think that the comments that Bob Neill made at the beginning were important. This is not a rehash of that case. But there are some items of technical interest.

2.4.2.1 Background

Let's take a look at the setting for that well and the relationship to the Rhodes/Yates waterflooding unit principally operated by Texaco. In January 1991, Hartman and his company began to drill the Bates #2 well on an acquired lease that had previously been drilled by El Paso Natural Gas and had been producing for about 35 years before plugging and abandoning the Bates #1 well. The Bates lease is located in the southeast corner of New Mexico. It is located in the back reef and not in the Delaware Basin. It was drilled to try to produce Yates gas in the lease that Hartman had obtained. At about 2,240 feet the well begin to produce high volumes of high pressure brine. Drilling operations were stopped at 2,280 feet. The New Mexico Oil Conservation Division was notified. Out of concern that an underground blowout might occur, the driller was not allowed to

shut the well in for any extended period of time. Casing had been cemented back to the surface from about 456 feet in an approved drilling plan.

The flow, at times, was on the order of 1,200 barrels per hour. Nearly 300 truck loads of brine were hauled away and a pipe line was put in to take brine away to the South Leonard Waterflood Unit. It took five days to work out a final solution in consultation with the New Mexico Oil Conservation Division. That solution was to cement the annulus first, to go back in and check the cement job, and then to cement back to the surface, leaving the drill pipe in place. Thus ended Bates #2.

At that point Hartman and his company began to wonder where this had come from. The question that came up - was this a natural flow or was it not natural, that is, brought by some other means such as the water flood unit operated at Rhodes-Yates field? I am giving you some of my impressions and can't speak to the actual thought processes of anyone involved, but late last fall I was contacted. It appeared that there would be a defense during the legal proceedings that this was a natural event, that it was similar to the high pressure brines in the Castile Formation and several wells in the vicinity of WIPP. It bears certain resemblances to the data that had been obtained from underground testing at the WIPP — data that had been obtained by drilling small diameter holes and testing them with rather sophisticated means over a period of time to determine what the pressure buildup was. Hartman called me to see if I would be available to help counter these arguments. I spent some time reviewing the data and decided that the approach that they wanted to take was consistent with what I believed was going on so I joined their team, for a while, to provide consulting services. I was named as a potential rebuttal witness. I did not testify at trial. That gives you a little bit of a background. I thought that was important so you would know where I was coming from and you can judge accordingly whatever is said.

Some notes - the Bates #1 was drilled in 1953 by El Paso Natural Gas. It produced, again, for about 35 years and then was plugged and abandoned. The Bates #2 well is approximately 100 feet away from Bates #1 well on the surface. To my knowledge, there are no directional surveys. I cannot tell you how far apart they might be at the bottom of the hole which is about 2,280 feet.

At the point where the flow began, there is an anhydrite unit. It's on the order of 10-15 feet thick, based on geophysical logs from that well and nearby wells that can be correlated. We are in the Salado Formation. I have not tried to correlate the individual marker beds with those in the Delaware Basin. It's my guess we are somewhere in the range of marker beds 140 to 142, which would put it below the WIPP repository horizon, which is just above marker bed 139. There is, on the natural gamma log signatures for that drill hole and others, a slight gamma kick at the base of that anhydrite, which is consistent with what we see in shafts and drill cores and other logs of boreholes. But there is probably some clay or argillaceous zones besides anhydrite.

The distance from the Bates #2 well to the administrative boundaries of the Rhodes-Yates water flooding operations is approximately two miles. Structurally, the Bates well is generally updip.

2.4.2.2 Observations

The salt water blowout and the subsequent case raised interesting technical issues. One was the unresolved differences in the estimates of the true pressure in the Bates #2 well. The New Mexico Oil Conservation Division was concerned that if the well were shut-in, the high pressure brine would be injected into other formations (an underground blowout). Hence, the well could not be shut-in for an extended period of time to obtain a good bottom hole shut-in pressure. The consultants for Hartman believed that the best shut-in pressure came after the annulus had been cemented and there had been circulation and flow equal to the cementing job which should have relieved any pressure problem, or most of the

pressure brought on by a cementing job. That pressure was on the order of 1,000 psi at the surface. The consultants for Texaco had believed there was a more appropriate pressure that was several hundred psi lower. That would have brought the pressure gradient and the formation pressures down considerably from what the Hartman consultants had estimated. Nonetheless, the pressure measurements were less than desirable 1) because of the condition of the hole and 2) because of the inability to shut the well in and obtain a good shut-in pressure.

It was suggested that the pressure gradients can be used as indicators as to whether the water flows were induced by nature or induced by some other source. For the Rhodes-Yates water flood, the injection pressures at the surface ran 1,200 psi and above. Some injection pressures approached 2,000 psi at the surface. If those are correct, those surface injection pressures begin to produce pressure gradients greater than 1 psi per foot vertical. Typically, the measured pressure gradients from brine reservoirs in either the Castile or the very low flows in the Salado are considerably less than 1 psi per foot, ranging down to 0.8 psi per foot or less. The difference in pressures can be used to distinguish between natural or human induced occurrences.

There was testimony on both sides as to whether or not there were unaccounted injection fluids. The consultant for Hartman estimated that there might be as much as 20 million barrels of fluid that had been injected that was unaccounted for in terms of total production and storage capacity of the formation within the water flood unit. Consultants for Texaco testified that they did not believe, by their analysis, that there were any unaccounted for fluids.

There are differences between the geology at the Bates lease and the geology at the WIPP. The Bates well blowout was a large volume, high pressure flow. The bottom of the borehole was in the Salado Formation. The Castile does not exist in the area of the Bates well.

In the WIPP area there are high pressure, high volume reservoirs within the Castile. One brine reservoir was tapped at WIPP-12, approximately 1 mile north of the site center. Those kinds of brine reservoirs are in the Castile and are generally associated with a zone of relatively high deformation of the Castile, within a few miles of the margin of the Capitan Reef.

At the Bates #2 well, the Salado shows little deformation. It shows a general dip, but nothing of any magnitude comparable to the kinds of deformation observed in the Castile in the area of the Capitan Reef. The WIPP pressures from the Salado testing underground, suggests that the projected pressures will show a gradient on the surface much less than the Castile.

The Hartman-Bates well blowout raised interesting questions about expectations for institutional responses and institutional controls and how they change with time. Presumably they get better, but it is one thing that needs to be looked at.

There is a technical basis for scenario development. In the Hartman case, one has to either accept a natural cause or, if it is not natural, one must believe that fluid was transmitted along a bedding plane to the Bates lease perhaps for a distance of 2 miles. Transport along the bedding plane is the best explanation. For years the (WIPP) project has been concerned about gas, generated by waste degradation, either diffusing, fracing (fracturing), or otherwise moving along bedding planes. It is the same problem but moving in a different direction. With any kind of drilling, including water flood operation, around the boundaries at the site, the same issue comes back again. How are we going to address whether fluids can move along bedding planes or within the formation, a certain distance under different conditions? How will we address that?

BLM is having to try to address the issue, I believe, through litigation of the contrasting desires of oil and gas exploration vs. potash mining. How far away from mining is it safe to drill a hole or mine up to a hole? There are cases where mining has hit petroleum casing underground. That makes people nervous — that

there is an oil or gas well and that you get that gas leaking into a mine. Several things are going to happen. None of them are good. The most benign is that their expenses go up to try to deal with a gassy mine and they go out of business. It is not very benign. People are working with stock holders. That might be one of the more benign consequences, if such a leak did occur. But of course, every time you change that boundary, you say, well, we need to protect the potash and keep the oil and gas away. That just simply magnifies the amount of resources unavailable for both sides. Obviously, if you were going to maximize the resources, what you'd like to be able to say is "It's safe". You can co-exist. Everybody gets their way that way. So those are some issues that have some common problems.

What I see is that everybody will probably attempt to solve it uniquely because nobody likes to try to produce a general solution for all of the world. It is expensive and difficult. If you can produce a simple solution for your problem or concern or issue, whatever it might be, if you can produce that solution for yourself very simply, you'll do it. But it might be good for the different organizations to be thinking about this with a little bit longer term (framework) and to recognize that there may be consequences, even unintended consequences, from one solution to another one's problems. Even if it's a modeling approach that makes certain assumptions that the modeler says don't cause a problem, somebody else might have some difficulty with those assumptions. We need to make sure that those are specific, unique, and identified as being adequate for that problem but not necessarily general assumptions. Those are a couple of the things I wanted to talk about this morning. I believe that the pressure on the WIPP underground data and related data from the WIPP will increase. By pressure I mean there will be a lot more demands for it and a lot more desire to interpret it, to make sense out of the particular application that you have, from BLM trying to resolve oil and gas versus potash mining, to other people. They need to be

aware of that and to think about how best to integrate interactive folks. Thank you, any questions?

2.4.2.3 Questions:

Wendell Weart: Do you know, Dennis, if there is presently a standoff distance, either legal or practical that the industries have used to keep certain separation between potash excavations and petroleum holes?

Dennis Powers: The number I heard was 500 feet but I also know that some of the potash mines have generally, inadvertently drilled into a few, or mined into a few holes, too. Five hundred feet is the number I heard but I haven't seen it written down in some regulatory fashion - it may be there. And there may be somebody that knows that number better than I do.

Dan Stoelzel: You said there has been inadvertent mining into petroleum wells. To your knowledge, is there any record of gas leaking into these mines?

Dennis Powers: I haven't seen any, no. What they did, the records that I saw, indicated that the casings got marked up. Tungsten carbide bits will do that. And then there were various measures to go ahead and protect the drill casing. In one case, I'm trying to remember which mine it was, there was a caisson built and a big cement block support around it.

Dan Stoelzel: What about naturally occurring gas in the potash mines?

Dennis Powers: Well they are not classified as gassy mines with methane residence, but there are occasionally these blowouts of gas which have been trapped, most of which is nitrogen. Lokesh [Chaturvedi] has written, edited, and put together a volume that discusses gases occurring in the Salado Formation. That's one good source and there are other sources within some of the Sandia publications that describe some of the gases. But basically it is nitrogen-dominated and few other minor gases. But potash mining people desperately wish

to avoid the gassy classification because if they ever wind up in a gassy classification, at least at this point, they'll be out of business. And right now I don't see any — there is no particular reason to fear that, as far as I know.

Chuck Byrum: Dennis, do you know why they inadvertently hit some well bores while they were mining?

Dennis Powers: No. It may be known, I just don't know.

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2.5 Geologic Considerations and the Implications for Waterflooding near WIPP

Lori J. Dotson, Sandia National Laboratories

Current Petroleum Practices and their Application to WIPP area Development

Daniel M. Stoelzel, Sandia National Laboratories

2.5.1 Combined Synopsis

A Rhodes Yates/Vacuum Field scenario (where injected water migrated to the overlying salt) is highly unlikely at WIPP because of: differences in geology, changes in oil-well completion practices from the 1940's, and improved reservoir management. In addition, new state regulations are in place to reduce the possibility of a petroleum well leaking into the Salado.

The differences in geology between WIPP and the Vacuum and Rhodes Yates Fields is significant. WIPP is located in a fore reef environment where a thick zone of anhydrite and halite (the Castile Formation) exists. Oil production is from the Brushy Canyon Formation at depths greater than 7,000 feet (5,000 feet below the WIPP repository). By contrast, the Castile Formation is missing at both the Vacuum and Rhodes Yates Fields which are located in reef and fore reef environments, respectively. Oil production at the Vacuum Field is from the San Andres and Grayburg Formations at depths of approximately 4,500 feet and oil production at the Rhodes Yates Field is from the Yates and Seven Rivers Formations at depths of approximately 3,000 feet. At the Rhodes Yates Field, for example, there is only a couple hundred feet of vertical separation between the Salado Formation and the waterflood injection zone. In addition, the oil pools near WIPP are characterized by channel sands with thin net pay zones, low permeabilities, high irreducible water saturations and high residual oil saturations. Therefore, large-scale waterflooding near WIPP is unlikely. The estimated life of the pools near WIPP is less than 10 years for primary production and less than 10 years for secondary production.

The petroleum industry has made many advances since the time when the Vacuum and Rhodes Yates fields were first developed. Improvements in drilling, casing, and cementing technology have greatly reduced the occurrences of leaks in oil wells. An industry-wide effort to reduce formation damage and increase production has led to improvements in completion design and advances in stimulation. Open-hole (non-cased) production/injection wells and nitroglycerin treatments are no longer used. Acid stimulation and hydraulic fracturing techniques have improved considerably in the last ten years. Service industry support has made this technology available to both the large and small operator. The availability of inexpensive software has lead to improved reservoir management, including waterflood design.

State regulations require a salt isolation casing string for all wells drilled in the WIPP area. Injection pressures are not allowed to exceed fracture pressures for all injection/disposal wells. Operators obey these regulations because the State has power to levy fines and/or shut wells in, should they become aware of a violation.

In conclusion, geological differences, modern petroleum development practices, and regulatory oversight will greatly reduce the risk of oil wells leaking to the Salado in the WIPP area.

2.5.2 Geologic Considerations and the Implications for Waterflooding near the Waste Isolation Pilot Plant - Presentation by Lori J. Dotson

There are three main points I'd like to make here.

1) The oil pools near WIPP are relatively small scale when compared to the Vacuum Field and the Rhodes Yates Field.

2) Large scale waterfloods are unlikely. It is not a foregone conclusion that all of the fields will be waterflooded or that any of the fields will be waterflooded.

3) Most importantly, there are a lot of geologic differences between the Rhodes-Yates Field, where the Hartman-Bates well was and WIPP. For one thing there is five thousand feet of vertical separation between the producing interval, at WIPP being the Brushy Canyon Formation of the Delaware Mountain Group and the WIPP repository. It is true that there is salt water disposal in the Bell Canyon Formation, but that is still a vertical separation of about 2,500 feet. In contrast, at the Rhodes-Yates field, you are only looking at a vertical separation of a few hundred feet between where Texaco was water injecting and Hartman encountered the blowout. The Vacuum Field is being produced from the San Andres and Grayburg Formations at approximately 4,500 feet. The Rhodes-Yates is being produced from the Yates and Seven Rivers Formation which is located about 3,000 feet below the ground surface. The producing interval of the Brushy Canyon is located about 3,000 feet below the Bell Canyon. The Castile Formation is present at the WIPP Site but is absent in the backreef at the Rhodes Yates Field.

As to the second point, about generally small pools and thin pay zones, at Livingston Ridge and Lost Tank, you heard Ron Broadhead talk about forty foot of net pay. That's where it is economic to produce oil. There are a lot of wells in the Livingston Ridge area where there is only ten to twenty feet perforated

casing. So there are some pretty small pay zones. In contrast, at the Vacuum Field, one block that I looked at had three hundred feet of gross pay. So we're talking not an order of magnitude difference, but close to it. In the Los Medanos and Sand Dunes there are pay zones that range from less than twenty feet up to one hundred forty feet.

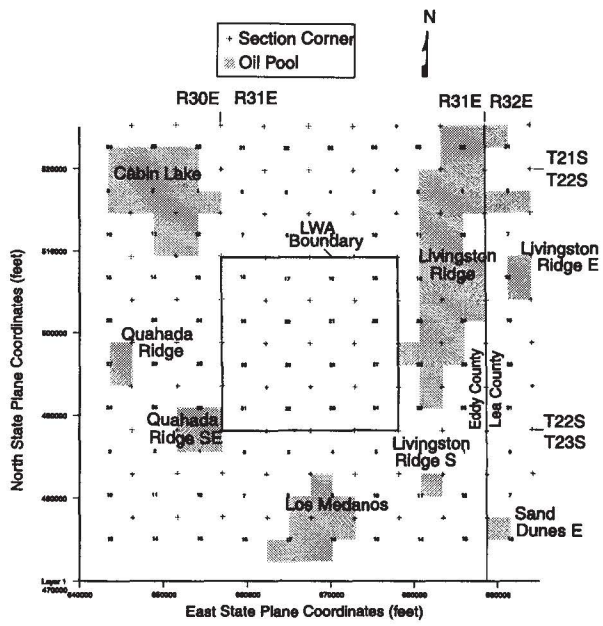

Figure 2.5.2-1. Producing oil field leases surrounding the WIPP.

Another point that Ron made that was really good, the primary production from area around WIPP from the Brushy Canyon is going to be less than ten years and for secondary production, less than ten years of secondary recovery. Production from these fields is going to play out in less than twenty years. Water injection, if water flooding took place, would be less than ten years. Just to give you a reference, the Vacuum Field for instance, over 300 million barrels of oil and 200 BCF of gas have been produced. I will have to get the exact figures from Ron, but we will have to leave that for the discussion. But we are looking at order of magnitudes difference between what is going on at the WIPP area and what we have at some of the larger fields.

This last point, the reservoir characteristics, the 7 to 24 millidarcies is actually a number for the Bell Canyon. The information for Brushy Canyon is actually pretty scarce and the characteristics of the Brushy are such that the permeability

would actually be less. The Brushy Canyon is siltstone and sandstones, but also there is authigenic clays which tend to clog the pores and reduce the permeability somewhat. What this means is that water flooding could occur, but they may have to space the injection wells closer. But then you get into an economic question. There is a technical question and an economics question. It just may not be economical to drill additional wells. The reservoir is also characterized by highly irreducible water saturation and high residual oil saturation. That emphasizes my previous statement. Yes, you can waterflood these fields, you can waterflood those that have better characteristics, but it is an economics issue. If you have to drill additional wells, it may be too costly to get that oil out.

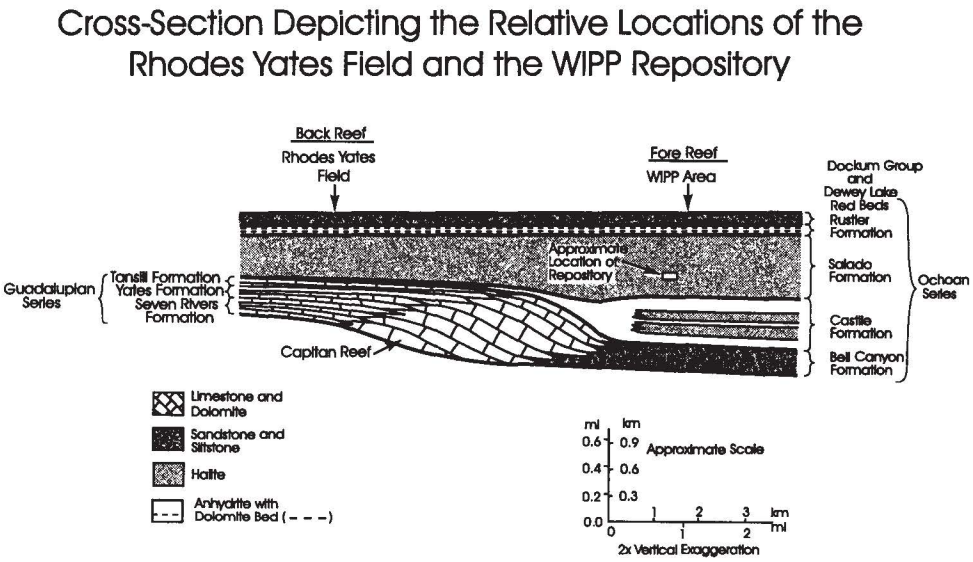

Figure 2.5.2-2. Cross-Section of Rhodes Yates Field and WIPP.

I really wanted to focus on the difference in the vertical separation at WIPP versus Rhodes-Yates which this figure illustrates quite nicely.

At the Vacuum Field, the permeabilities are up to 400 millidarcies. There is an order of magnitude difference. At Vacuum, like I already said, the pay zones are much thicker.

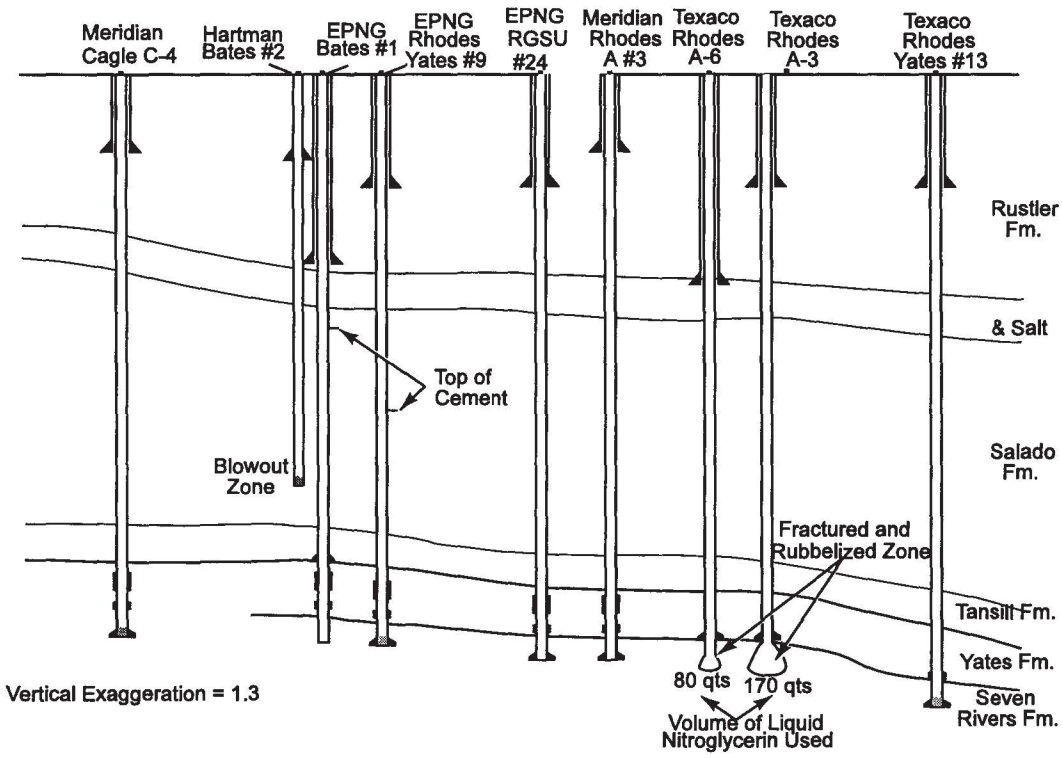

Figure 2.5.2-3. Schematic showing location of Hartman Blowout and Texaco Injection Zones.

This is a schematic showing where the Hartman well blew out and where you have water injection from the Texaco wells. Back in the "old days" a well was made more producible by pouring liquid nitroglycerin down the wells and basically just blow up the formation. So there are rubble and fractured zones. You don't know where your fluid is going at all. Like Dennis Powers stated, I also do not wish to comment on the legal issues of the Hartman-Texaco case. There were clearly practices that occurred back then that are not practiced now. Some of the casing, cementing, and developmental practices will be covered by Dan Stoelzel in his presentation. Between the Hartman blowout zone and the Texaco injection zone, there is hundreds of feet of vertical separation and also the

suspect casing and cementing jobs. The figure shows where the surface casings are set. It is unclear from this figure what they are actually casing off. Some of these don't look like they extend down to the Culebra. There are really strange well constructions there.

Three main points:

1) Potential waterfloods near WIPP would be relatively small scale. I'm not saying that they would or would not waterflood, but it would be small scale if they occurred.

2) The fields will play out in less than twenty years. I think we are all in agreement on that.

3) The interval where they would inject water for a waterflood is 5000 feet beneath the WIPP repository. So you have quite a distance it would have to travel vertically to affect the repository.

2.5.2.1 Questions:

Wendell Weart: When were the injection wells completed - in what time frame?

Lori Dotson: This is something that Dan (Stoelzel) has more information on. In the Vacuum and Rhodes-Yates fields, for example, we are looking at the 30s and 40s and I think some of them in the 50s. But they are older wells, older construction. I hate to keep pushing everything off to Dan, but he has some really nice schematics that show the differences in well construction from the 30s and 40s to the present time. You are looking at wells that are over forty years old.

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2.5.3 Current Petroleum Practices and Their Application to WIPP Area Development - Presentation by Dan Stoelzel

With the older well completion techniques, especially in the Rhodes-Yates Field and Vacuum Field, there has been communication behind pipe caused by situations such as bad cement jobs. In these fields the injection wells were in communication with the overlying strata. In the Vacuum Field, for example, there was concern that some oil field injection wells would contaminate the Ogallala fresh water aquifer. The problems with the Rhodes-Yates waterflood were covered in previous presentations.

The possibility of water injection wells endangering the WIPP is highly unlikely. Neither a Rhodes-Yates nor a Vacuum field scenario will happen at WIPP because of the differences in geology, changes in oil well completion practices from the 1940's, and improved reservoir management. Current industry practices and controls that are in place reduce the risk of injection or disposal wells endangering the WIPP site. There have been changes in the petroleum practices from the 1930s and 1940s and 1950s, even up through the 1970s, versus today. New regulations, mainly statutory regulations, have come into effect. The presentation is divided into the major areas of drilling technology, production and completion technology, and reservoir management. The last 10 or 20 years have seen numerous advances in these areas.

2.5.3.1 Drilling Technology

Since the 1940s and 1950s, there have been considerable improvements in the cement that is used to cement the casing - higher bond strengths, better cement properties, and impermeable cements. Drilling mud technology has improved to limit pole washouts and lost circulation problems. This is especially true when drilling in familiar geology. Lost circulation control becomes a fairly exact science. This is important in the casing stage of a well. If there are lost

circulation problems and washout problems, this could lead to communication or leaks behind pipe. Prudent operators know that any kind of leak behind a pipe is detrimental because it could lead to a loss of production, loss of reserves, and loss of revenue. Compared to drilling operations of the 1970's and early 1980's, drillers have a better understanding of operations such as block control and controlling kicks.

There have been numerous improvements in the last 10 to 20 years in corrosion control. Casing and tubing strings are inspected on the surface prior to running in the ground to eliminate potential leaks before running the casing. There are corrosion inhibitors that are routinely pumped into the tubing and casing to limit corrosion problems. Casing strings are routinely pressure checked. State regulations also mandate pressure testing of the casing. There is a lot of research and development in all these areas.

One point that hasn't been brought out yet is that most of the players in the Delaware Basin area, especially around WIPP, are small time operators. The smaller companies generally don't have the big research and development to support their oil and gas development. However, much research is transferred to the smaller companies through the service industry.

There have been significant advances in directional drilling and horizonal drilling in the last 30 years, but especially in the last 10 years. The costs for directional drilling have come way down. This is important for potential WIPP development because it is feasible to tap into much of the possible and probable reserves by directionally drilling from a surface location outside the land withdrawal area.

2.5.3.2 Completions

Once a well has been drilled and cased, substantial technology is used to develop the pay interval. There have been considerable improvements in perforating technology, tubing packers, gravel packing, well stimulation, fracturing, and acid

stimulation. Open hole completions are rarely used in the industry and are definitely no longer used in the WIPP area. Generally, the production interval is cased and perforated. There have been advances in shape charge perforators, stimulation, and in hydraulic fracing technology, especially in the area of predictive modeling over the last ten years.

There have been substantial developments in fracture height control. Generally, oil companies do not want to hydraulically fracture out of their producing zones. To fracture out of zone could translate to loss of reserves. Operators definitely do not want to exceed fracture pressure in an injection well. The whole purpose for a waterflooding injector is to maintain pressure or inject into a producing horizon. If the operators are injecting out of zone, they are losing reserves.

Acid stimulation has come a long way. Acid stimulation is designed to specific rock types and fluid types.

2.5.3.3 Production

There have been numerous advances in wireline, coiled tubing workovers, and through tubing workovers that greatly reduce cost and could extend the economic lives of wells.

The preferred method of lift in the WIPP area is the sucker rod pump. However, there are alternatives such as gas lift, submersible pump, or plunger lift. Each of these have seen a lot of development in the last 10 to 20 years.

Routinely, coated tubulars are run, especially in injection wells because injection wells are recognized as a highly corrosive environment. Multiple completions are possible. By running dual completion strings, two or more zones can be simultaneously produced. Behind pipe reserves are typically recovered by successively plugging back as the operator comes up the hole.

Leaks are not good. If an operator is aware of a leak, he will generally take remedial action to fix that leak. The state is the regulatory agency that requires frequent pressure checking of tubing and casing. If a leak is detected, the operator must repair the leak.

2.5.3.4 Reservoir Management

One improvement in reservoir management includes the advent of affordable personal computers (PCs) and the availability of inexpensive software. During the last five years there have been significant advances in relatively inexpensive software to run on PCs. Whereas, the small company of the past didn't have the manpower or the money to afford this type of luxury item, now it's fairly routine. Various research firms and universities provide software support. Availability of the software has especially assisted the small time operators to optimize field development and field production.

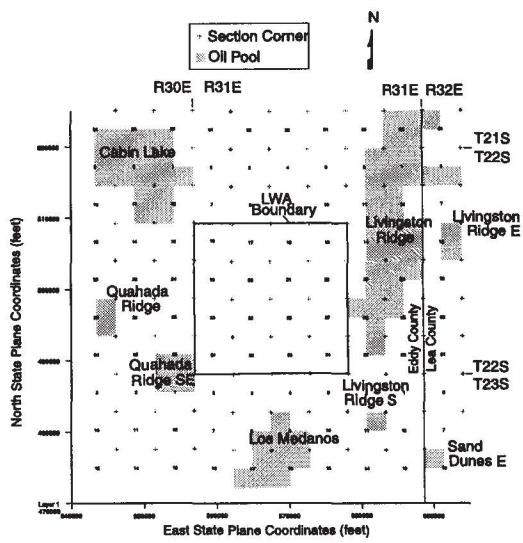

Figure 2.5.3-1. Producing petroleum leases adjacent to the WIPP Site.

The five spot water flood pattern is being used at Rhodes-Yates Field and at the Vacuum Field. However in the WIPP area it is highly unlikely that a five spot pattern would be used, especially with small pools. The decision to convert a well to water injection, in most cases will be more determined from the reservoir geology and geometry. For example, the Livingston Ridge Lost Tank Field is a channel sand. An in-line injection flooding pattern would be more likely. In this case, injectors

would be located in the southern part of the field and drive oil updip to the producers to the north. For these small pools a five spot water flood pattern would be highly unlikely both economically and geologically.

Source water compatibility between the formation rock and the injected fluids is very important. This is relevant to the WIPP area because there has been some speculation that a future driller may decide to use, for example, Culebra fluid as source water for an injection project. This is highly unlikely. The oil bearing formations contain authigenic or interstitial clays. If less saline water was injected into such a formation, it would cause clay swelling and potential plugging of pore spaces. Injecting Culebra water would essentially ruin the well. At this time, none of the injection wells or disposal wells are using the Culebra for source water. And I expect that will be the same forever. Operators will typically find their source water from the same formation as their oil production.

In addition to source availability, economics is the big question. Can small operators afford the surface facilities and the additional costs to drill injection wells or convert producers into injectors? The small oil companies typically have fairly shallow pockets. A water flood requires substantial capital. The return on the investment will be several years down the road in the producing life of the field. Most small companies wouldn't be able to weather that economic return.

The amount of water being pumped into a pool is a direct function of your recoverable reserves. In the WIPP area, the oil is found in small pools. The operators are not going to be injecting large volumes of water, especially in view of the 10-20 year life that most of these pools will last through secondary recovery. In an injection project, operators will stay below the fracture pressure of a formation. Operators don't want to fracture out of zone and pump water into an unknown formation where it is not beneficial to their productive horizon.

2.5.3.5 Wells in the Vicinity of WIPP

The James E #12 well is operated by Phillips and produces from the Cabin Lake Pool. In 1988, the State of New Mexico published regulations on completing oil and gas wells in the potash area, which includes the WIPP area. There was concern about natural gas potentially leaking into potash mines. In the Vacuum Field, the State had seen communication potentially into both the Salado and the Ogallala. The state now requires all the oil and gas operators in the potash area to include a salt isolation casing string in their well design. The surface casing typically runs through the upper stratigraphic units such as the Dewey Lake Redbeds and the Culebra. The intermediate casing, which is required by the state, is cased off below the salt formations, the Salado and the Castile. The state also requires that production casing run to the surface.

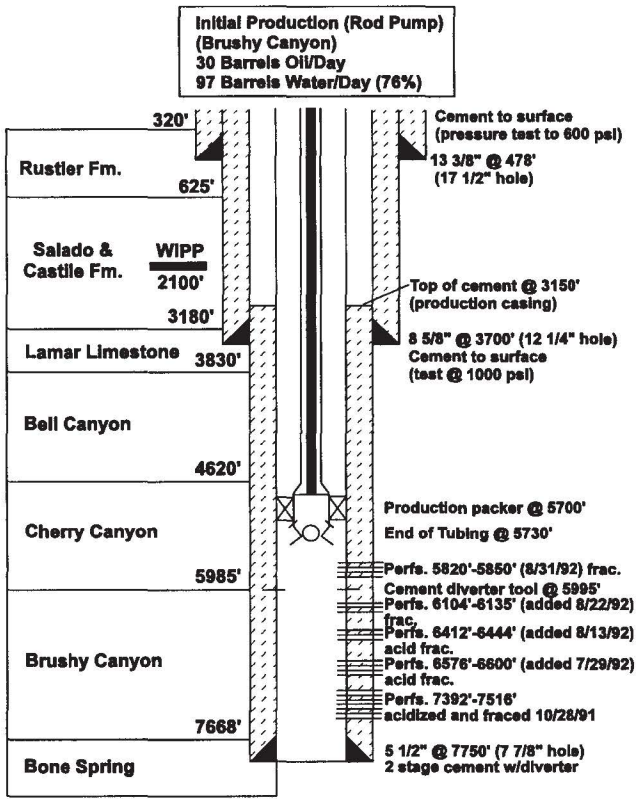

Figure 2.5.3-2. Typical Cabin Lake Pool Completion (James E#12).

The James Ranch Unit #19 well is operated by Enron and produces from the Quahada Ridge Delaware pool. The top of the cement surrounding the 5 1/2 inch production casing is at 2,680 feet. The bottom of the 8 5/8" salt isolation casing is at 3,850 feet. There is about 1,200 feet of cement as well as two sets of casing strings to help isolate the salt. The James Ranch Unit #19 is one of the better producing wells. The initial oil production rate was 213 barrels per day. The initial water production rate was 240 barrels of water per day. Initial production was over 50% water. We also see high water production from the Livingston Ridge. Seventy-six percent of the fluid production was water. These fields have a high water content and produce large volumes of the moveable water.

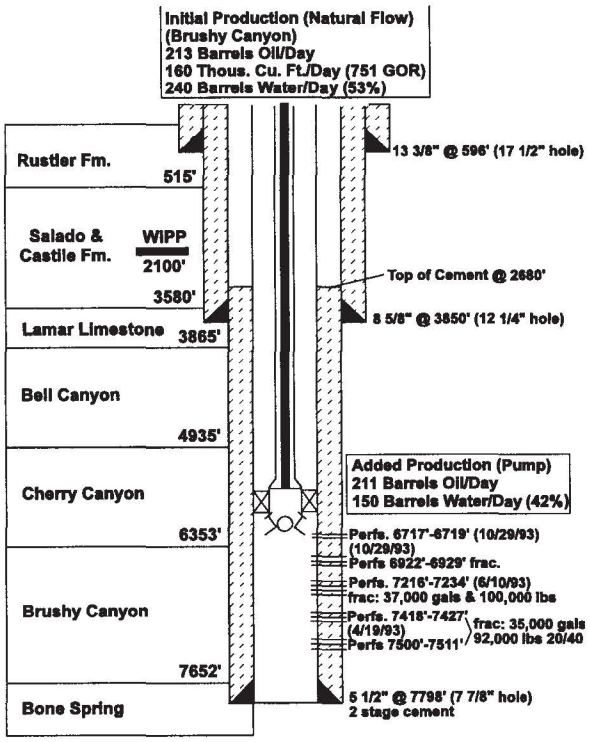

Figure 2.5.3-3. Typical Quahada Ridge Delaware Pool. James Ranch Unit #19.

A typical Livingston Ridge completion and a Morrow gas producer completion are shown. Each schematic shows a salt isolation string. For illustration purposes the WIPP horizon is also shown. The vertical separation between their production perforations and the WIPP horizon is on the order of 5,000 feet or more, which is much greater than that of the Vacuum Field and the Rhodes-Yates Field.

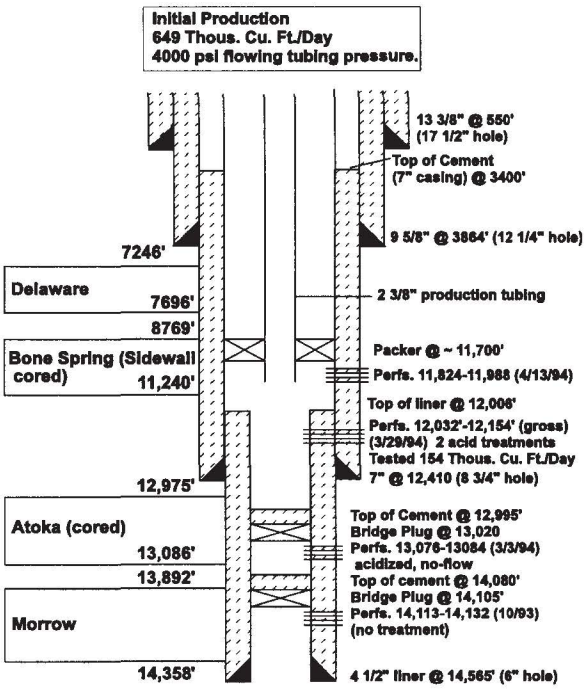

Figure 2.5.3-4. Typical Los Medaños Morrow Pool Apache 25 Federal #2.

The Morrow schematic illustrates the success of the plugback technique used by most operators. Probably the only reason this well is economical is because it has multiple pays. This well was originally perforated in the Morrow gas. It came in at a very high rate for this area, over 600,000 cubic feet a day. It was originally completed in the Morrow Formation in October 1993. By March 1994 this interval had been plugged back and the well completed in the Atoka Formation. In less than a year, this Morrow pay had depleted. The lower Atoka was tested but didn't have sufficient flow rate. The lower Atoka was plugged back and the well was completed in the upper Atoka. The well is apparently producing from the upper Atoka, although this formation may also be plugged back. The information comes from the New Mexico Oil Conservation Division in Santa Fe. There is a six month to one year time delay on the Sundry Reports, so the information on these wells may be outdated.

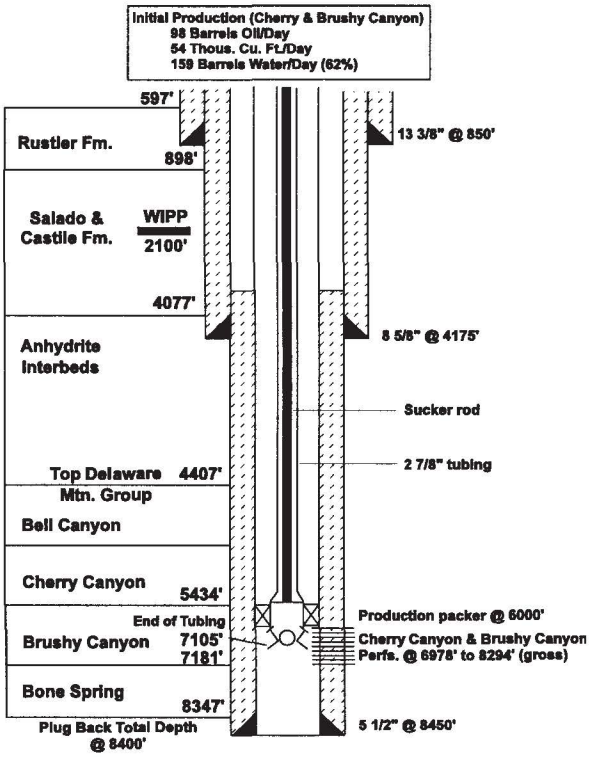

Figure 2.5.3-5. Typical Livingston Ridge/Lost Tank Completion.

2.5.3.6 Early Well Completion Practices

For comparative purposes, the schematics of the Vacuum Field and Rhodes-Yates Field completion are shown here. I didn't have direct well data for these wells. In the case of the Vacuum Field, the discovery well was drilled in 1929 with a cable tool rig. It wasn't developed until the late 1930s and early 1940s. Common practice, during that time, especially in carbonate formations where there is low flow due to tightness, the operator would nitro-frac the completed well. This is a general schematic of their discovery well. It was nitro-frac with 580 quarts of nitroglycerin. I'm not an explosive expert, but I would think that 580 quarts could do considerable damage not only to the formation but to everything else down there.

In the 1930s and 1940s the oil and gas industry was in its infancy. Safety issues, reservoir management issues, and formation damage issues were pretty much nonexistent. Since then, there have been substantial improvements. Similar to the Vacuum Field, the Rhodes-Yates fields were also nitro-fraced. An important thing to note about the typical Rhodes-Yates early completion is the small amount of separation from their open hole productive horizon from here to the Salado, approximately 100 to 200 feet. Furthermore, the wells were nitro-fraced.

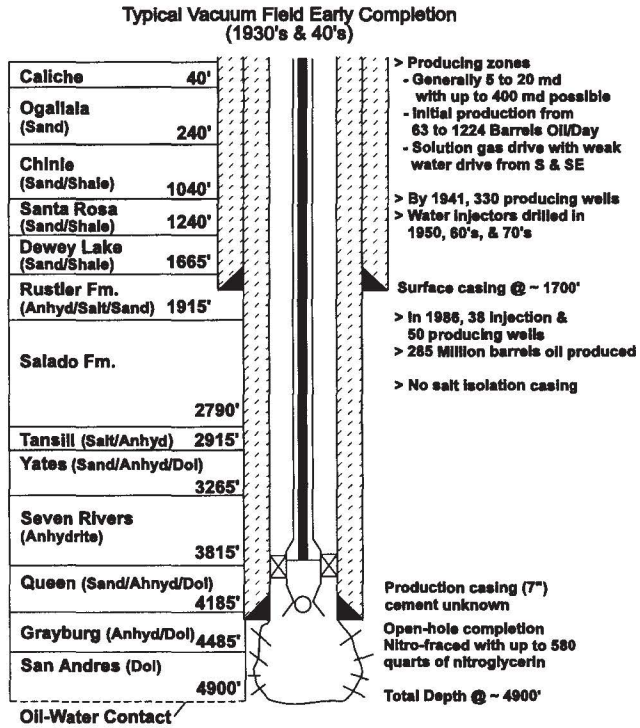

Figure 2.5.3-6. Typical Vacuum Field Completion for 1930s and 1940s.

Originally these early wells were drilled as producers in the 1940s, 1950s, and 1960s. As many of these production wells watered-out, they were reconverted to injection wells. They just pulled sucker rod pumps out and maybe changed out the tubing string. They didn't take any remedial action as far as casing this open hole interval or cement squeezing behind the body to isolate. They just turned it right around and started injecting into this thing. So it is no wonder that there is considerable potential for injection fluid to go anywhere other than where they want it to go. It is going to the path of least resistance.

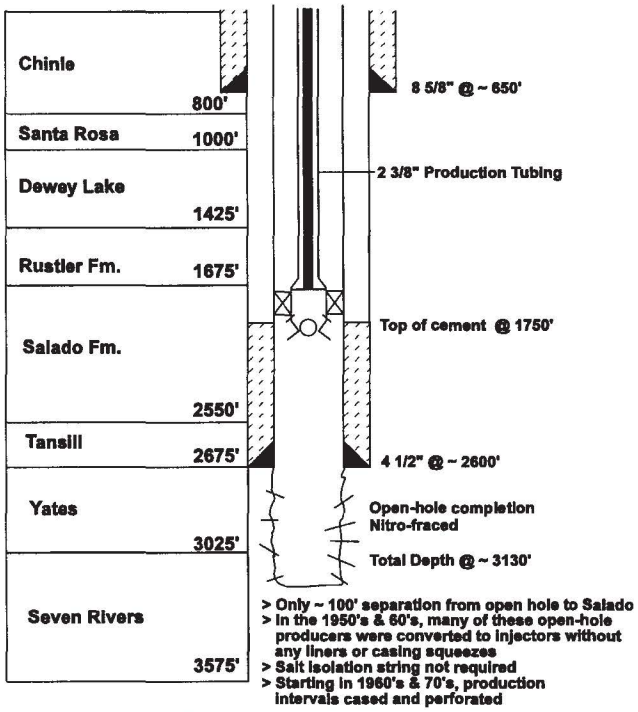

Figure 2.5.3-7. Typical Rhodes Yates-Seven Rivers early completion, 1940s-1950s.

The state rule on the salt isolation casing didn't come into effect until the late 1980s. Both these fields, the Vacuum Field and the Rhodes Yates Field, did not have salt isolation casing. As shown, the Salado is just behind one casing string. Early cementing and completion practices were such that, who knows where the cement went when they pumped it. A lot has improved since the days of these wells.

An older well, Todd 26 Federal #3, is shown. Todd 26 Federal #3 is the suspect well, about one and a half to two miles offset from the H9 WIPP test pad. It was here that Rick Beauheim observed the water table fluctuations. The rises in the Culebra due to potential leaking was attributed to this well. After looking at this schematic, I tend to agree with that. This well was completed in 1971. Originally it was drilled as a Cherry Canyon test well that was probably nonproductive. The well was converted to a disposal well. There was no salt isolation casing and it was an open hole completion somewhat similar to the Rhodes/Yates Field or Vacuum Field situation. This well was a disposal well for about 20 years. It is now plugged and abandoned. I am not sure when that was. I am trying to find out from the New Mexico Oil Conservation Division (NMOCD). There are very few records on this well. However, it is no longer disposing salt water.

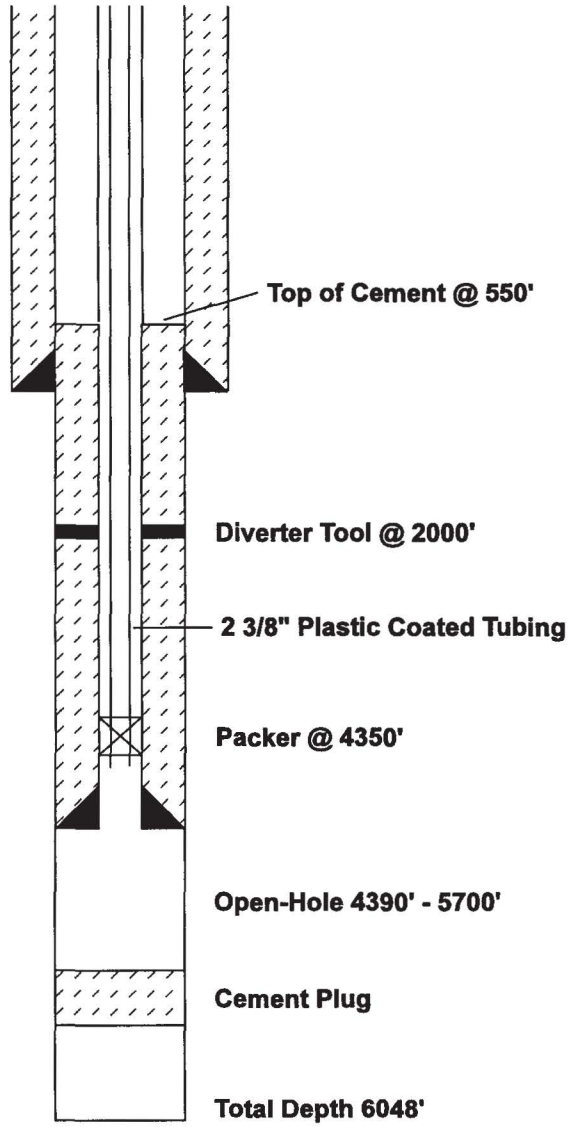

Figure 2.5.3-8. Texas American Oil Corporation Todd 26 Federal No. 3 Water Disposal Well.

A current salt water disposal design planned for the Livingston Ridge Field is shown. The plan shows the salt isolation casing. The production casing is run through the interval and perforated. The well was originally a strong producer. It is not uncommon to convert watered-out or nonproductive production wells to disposal or injection wells, which is the case for this well. The Sundry intent was filed on September 24, 1992. Surface injection pressure for this well is limited to 750 psi which is below fracture pressure. New state regulations require that operators stay below fracture pressures, either below 0.2 psi per foot above the hydrostatic gradient or below the fracture pressure as determined from injectivity tests.

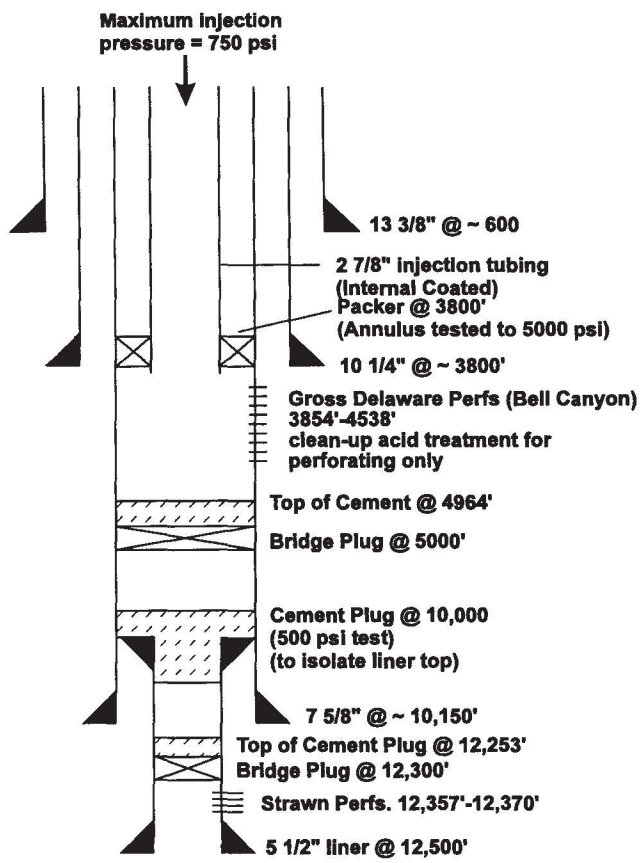

Figure 2.5.3-9. Current Salt Water Disposal Well Livingston Ridge Federal #9. Intent filed September 24, 1992.

2.5.3.7 Questions:

Robert Neill: Dan, you give a very compelling case for some of the current drilling practices and plugging practices. It is a great improvement over what has been done in the past. On the EPA standards, one is talking about what will be the behavior for human intrusion over long time periods. How comfortable do you feel with commitments requiring operators to keep injection pressures less

than fracturing pressures and then going to EPA and arguing that this will continue to be true in the long term future.

Dan Stoelzel: I think it highly likely. Like anything the oil business does, it is driven by economics. Nobody can predict the price of oil in the future which is the governing driver for anything an oil operator does. These regulations are put into effect because of the experiences of the oil companies — the isolation string and the requirement not to exceed fracture pressure. That is not only a regulation but like I said, a common practice with the operators because it is not a good thing to exceed fracture pressure in injection wells. I think it is highly likely that if anything, more constraints and regulations will come into effect or if nothing else, it will remain the same. The industries evolved to this point and because of this we are getting a lot more reserves out of the ground than we did back in the 40s and 50s. You know it is a learning process and I think the oil industry is reaching the top of that curve. They have come a long way.

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2.6 Potential Effects of Oil and Gas Activities on the Salado and Overlying Formations

Matthew Silva

2.6.1 Synopsis

The EPA assurance requirements for the disposal of transuranic waste include the requirement that the site should avoid places where there has been mining for resources, where there is a reasonable expectation of exploration for scarce or easily accessible resources, and where there is a significant concentration of any material that is not widely available from other sources. The WIPP is sited in an area with a 64-year history of commercial mining in a potash enclave which represents 57% of the nation's potash reserves and 80% of the nation's domestic production. Further, there are substantial reserves of oil and gas in the vicinity of the repository.

It has long been recognized that oil fields in southeast New Mexico, overlain by the Salado Formation, have problems with waterfloods. For waterflood projects in Lea County, Ramey (1976) noted that water injected at around 3,600 feet was escaping from the injection interval, migrating upward to the base of the salt section and then moving horizontally through this section. Waterflows of 5,000 to 6,000 barrels per day and a recorded surface pressure of 1,600 pounds on wells outside waterflood areas were not uncommon. Later studies (Bailey 1990) found that in the Vacuum Field, water was indeed flowing along distinct horizons within the Salado. Chemical and isotopic analyses confirmed that the brines were not natural to the Salado. Casing leaks were thought to be the most logical pathway into the Salado. Casing leaks and cement degradation are not uncommon in the highly saline environment (LaVenue 1991).

In the vicinity of WIPP, there are oil and gas resources. Much of the drilling for oil and gas has been delayed by the presence of potash. Nonetheless, there has been drilling for oil and gas in areas known to contain less than economic

quantities of potash. There is no question that waterflooding in the immediate vicinity of WIPP needs to be anticipated. First, the oil reservoirs in the area produce by solution gas drive (Broadhead and Speer 1993). Reservoirs which produce by solution gas drive are usually good candidates for waterflooding (Willhite 1986). Second, there is a waterflood underway in the Cabin Lake Field at the northwest corner of the WIPP Site. A nearby oil well, James A No. 2, has shown a good response with oil production increasing from less that 2,000 barrels per month to more than 4,000 barrels per month for that particular well. Third, there are eight waterfloods underway in the New Mexico portion of the Delaware Basin (Broadhead et al. 1995) and there is a history of waterflooding and enhanced oil recovery in the Texas portion of the Delaware Basin.

2.6.2 Presentation by Matthew Silva

The assurance requirements in the EPA Standards for the disposal of transuranic waste state that one should avoid areas with natural resources. The WIPP is not independent of the potash industry and the oil and gas industry, their schedules for resource recovery, and the problems associated with these industries. In the oil fields overlain by the Salado Formation, where we have experience with waterflooding, there is evidence of water escaping from the injection areas and migrating through the Salado. The Delaware Mountain Group, in the vicinity of the WIPP, is a strong candidate for future waterflooding.

The EPA standards for the disposal of transuranic wastes have assurance requirements. These assurance requirements are intended to accommodate the inherent uncertainty in calculating repository performance over the next 10,000 years. With respect to natural resources, the assurance requirements state that a site should avoid places where there has been mining for resources, where there is a reasonable expectation of exploration for scarce or easily accessible resources, where there is a significant concentration of any material that is not widely available from other sources.

The Known Potash Lease Area, as shown in Figure 2.6-1, is contained in an area roughly 30 miles by 30 miles. The 4 mile by 4 mile WIPP is located within the potash enclave. The first mining and second mining areas are shown. Potash has been commercially mined for 64 years - an area with a long history of mining. Potash in this area represents 57% of the nation's reserves and has consistently represented over 80% of the nation's domestic potash production - a relatively scarce resource. Oil and gas reserves are also found in this area - an easily accessible resource.

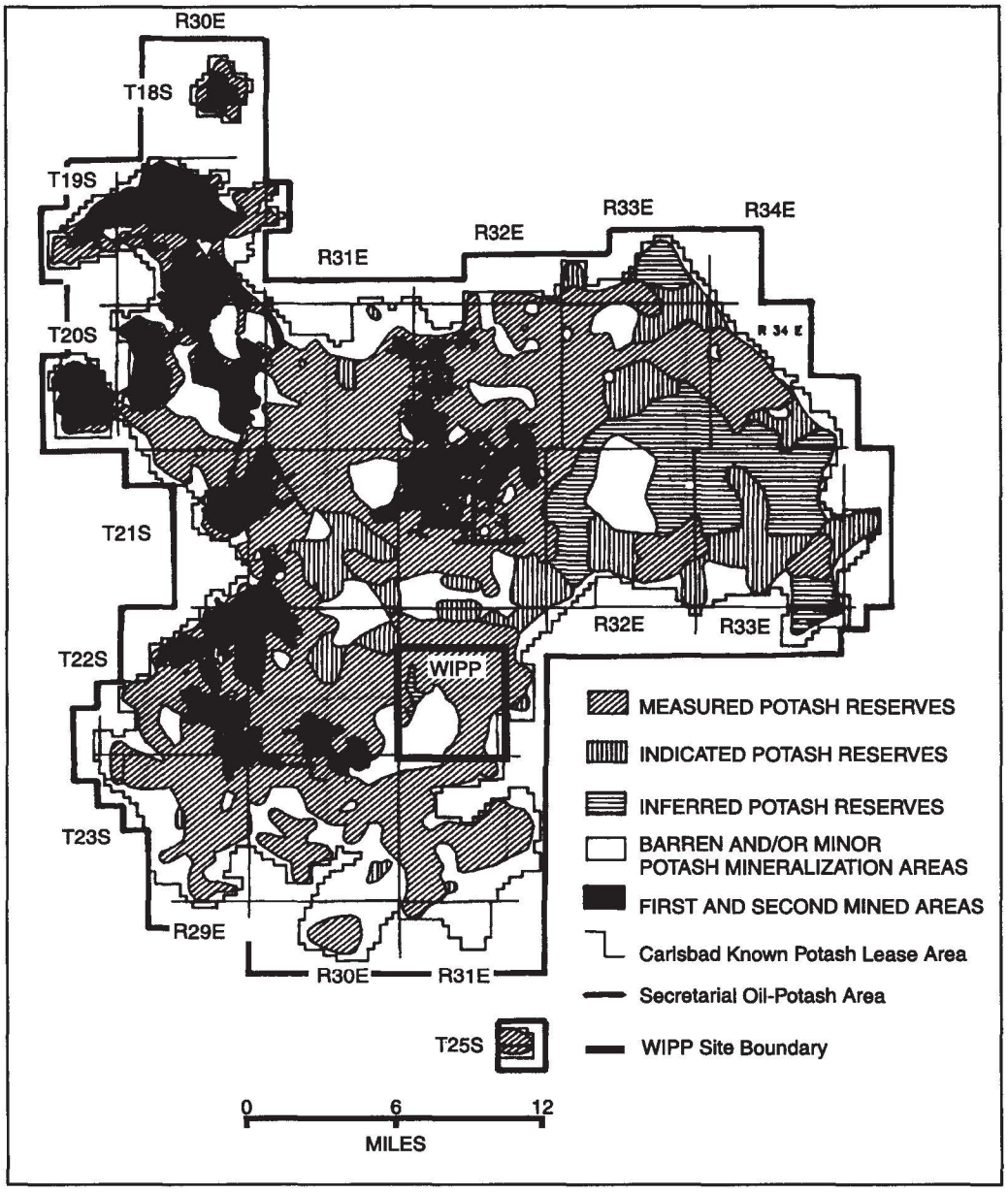

Figure 2.6-1. Potash resources (adapted from Olsen 1993).

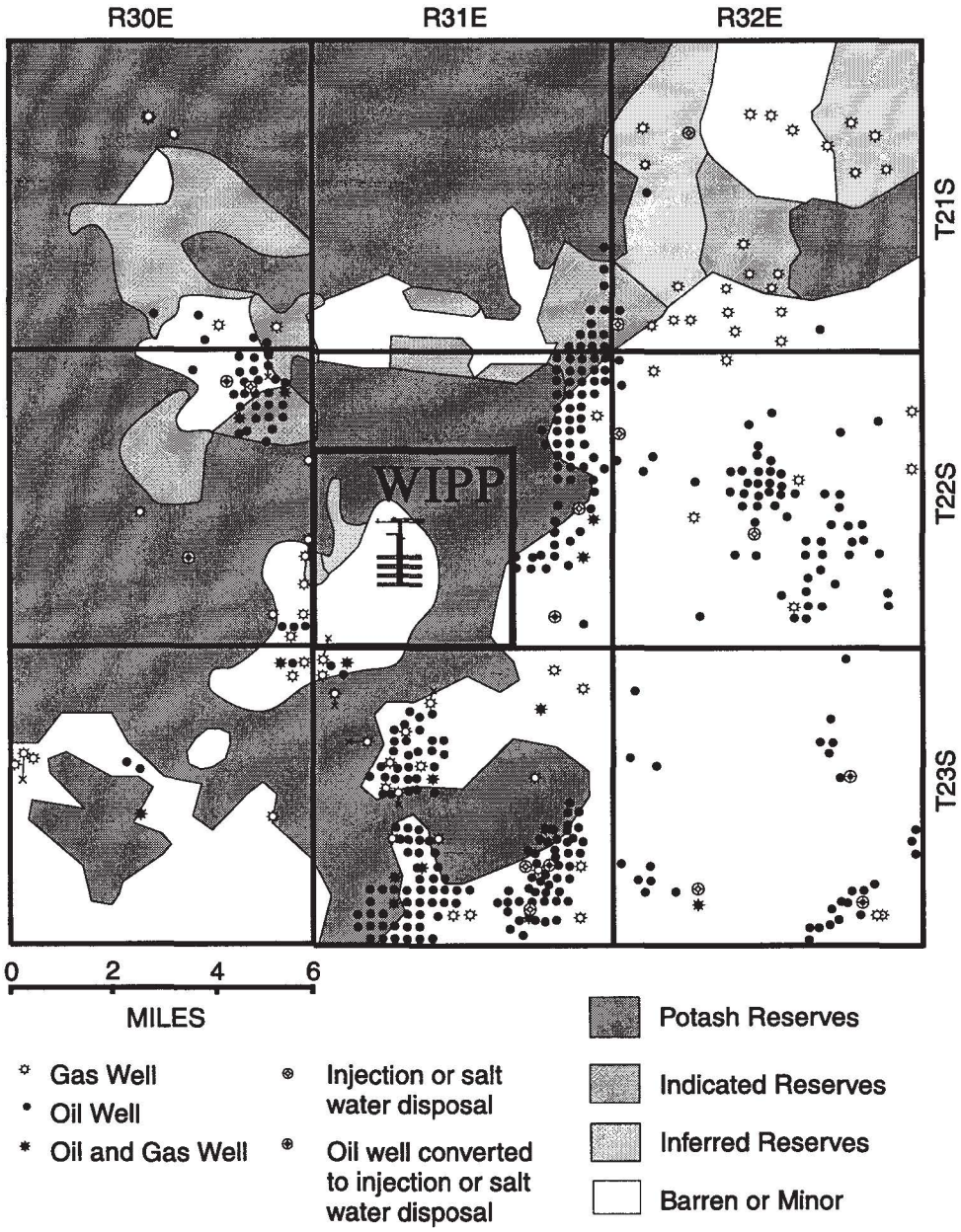

Figure 2.6-2. Oil and gas wells restricted from drilling through potash resources.

For the nine township area surrounding the WIPP, it is important to note that the current areal extent of the oil fields is constrained by the boundary of potash reserves and not the geographic limits of oil and gas.

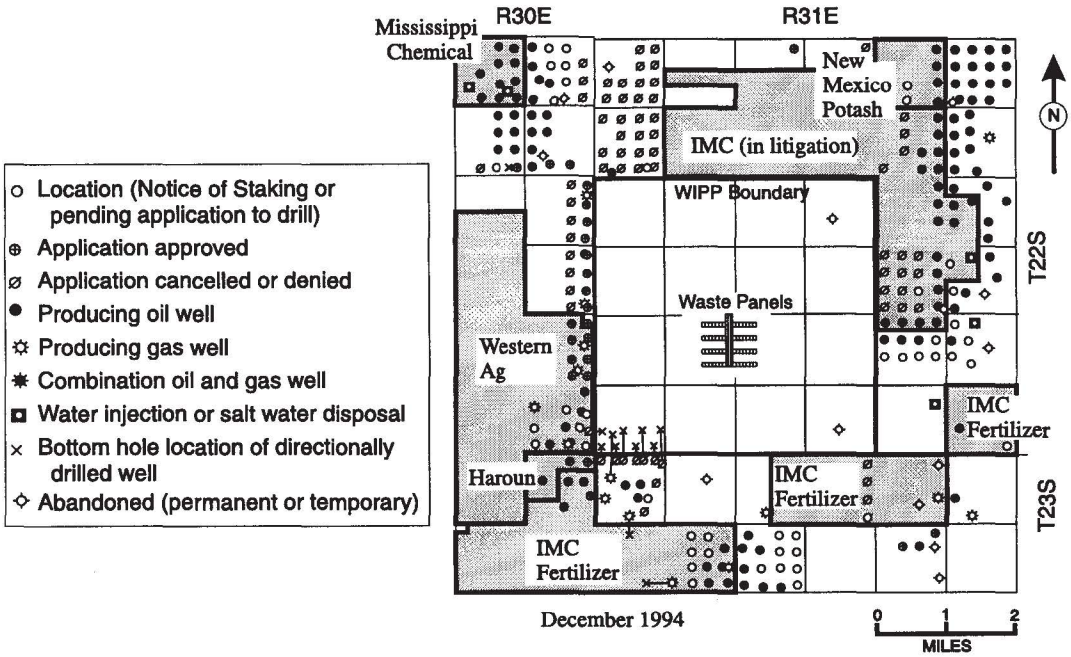

Figure 2.6-3. Resource activity and interest in the immediate vicinity of WIPP.

Will there be any more drilling near the WIPP boundary or is it restricted by the presence of potash reserves? Producing oil and gas wells and applications for permit to drill (APDs) within 2 miles of WIPP are shown in Figure 2.6-3. Applications include those that are pending, that have been cancelled, or that have been approved. Also shown are the active potash leases in the area. Oil and gas resource activities are restricted by the presence of potash. Further, it could be decades before drilling for oil and gas is allowed. Again, the limited number of existing oil and gas wells does not reflect the size of the oil fields, rather it reflects the presence of potash in an active potash leasing area.

Towards the southwest corner of the WIPP Site, the BLM has recently denied applications to slant drill eight wells to be completed within the WIPP Land Withdrawal Area. These applications have been denied for a couple of reasons, including the concerns about the injection of water.

A 1994 map from Midland Map Company indicates that Todd Federal #3 has been

plugged and abandoned. Also Rick Beauheim showed evidence this morning of rising water levels in H-9 up until 1993. The water levels started to decline and are now rising again. Somewhere about that time this well was apparently shut in.

The oil wells producing from the Delaware Mountain Group are very large water producers. That reflects interstitial water, not a large edge water drive. There are a number of salt water disposal wells throughout the area already in operation. The David Ross AIT Federal #1 is an oil well that was converted to a salt water disposal well. It's within a mile of the WIPP site boundary. It injects from 40,000 barrels to 120,000 barrels a month as salt water disposal. Other than state regulations, there are no extra requirements on this particular well.

To the west of the WIPP there is an injection well in the potash area less than a mile from the mining operation of Western Ag. In 1994, when Western Ag learned that this particular well was being proposed as a salt water disposal well for Bass Enterprises, Western Ag proposed 12 stipulations. The stipulations included an annual analysis of the chemical composition of the water and the hydrocarbons and of any hydrosulfide that was being injected into that well. The stipulations also specified maximum injection pressures. Further, Western Ag wished to be notified immediately of any problems with tubing failure. While the David Ross AIT Federal #1 is within a mile of the WIPP site, there are no special provisions for this well. Yet for the well within a mile of potash operations, Western Ag was concerned with water being injected out of zone.

New Mexico has extensive experience with waterfloods in areas overlain by the Salado Formation. Serious problems have been documented for the past 20 years. In 1976, Joe Ramey, as the Director of the New Mexico Oil Conservation Division, identified the problem of "numerous salt water flows in and around waterfloods in Lea County." Basically the water was escaping out of the injection zone, up into the Salado Formation and then moving through the salt section, collapsing oil field well casings. Five thousand to six thousand barrels of water

a day at 1,600 pounds per square inch pressure at the surface were not uncommon.

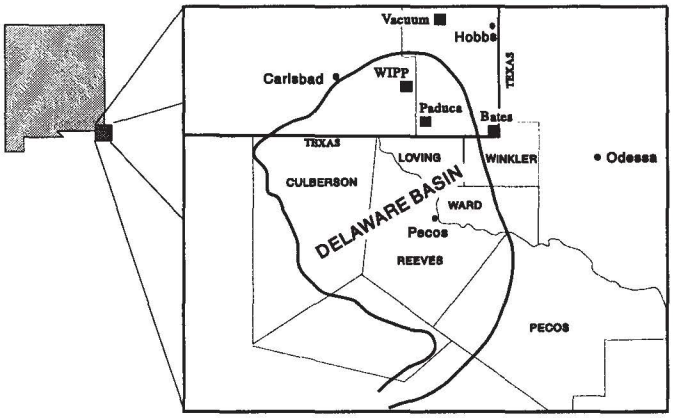

Figure 2.6-4. Delaware Basin.

In 1990, Jamie Bailey, a certified professional geologist and petroleum engineer for the New Mexico State Land Office, sent a memo to Marsh LaVenue on the observed water level rises in the Culebra aquifer during the 1988-1989 time frame. That memo cited the problems in the Vacuum Field waterfloods and the reports prepared by a committee of participating oil companies. The memo noted that waterflows occurred along 48 distinct horizons or interbeds within the Salado. Chemical and isotopic analysis confirmed that the brines were not natural to the Salado and these were injected brines. The memo concluded that failed casing was the most logical pathway into the Salado and observed that there were similar problems in other waterflood areas including the Eunice and Monument areas. Bailey identified a salt water disposal well, the Todd 26 Federal #3, as the most likely source of water to the Culebra aquifer based on the injection pressure history, the age of the particular well, and the location of the well.

There is more recent evidence of problems with waterflooding in New Mexico. The operator of the Bates Lease, Hartman, successfully demonstrated in court that water from the Rhodes/Yates Lease was being injected at high pressures and was migrating more than two miles to his lease. The Bates #1 was drilled in 1953. It was operated until 1988, at which time it was shut in. When it was drilled in 1953, there were no observed waterflows. The Bates #2 was drilled about one hundred feet to the east in January 1991. It experienced a very large salt water blowout. Two-hundred-ninety-eight truckloads of water had to be hauled away

and a pipeline was constructed to the water injection unit at the Leonard Field.

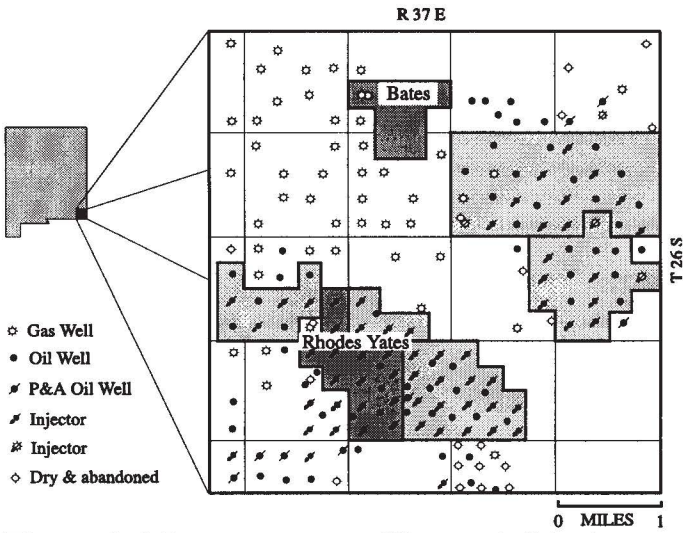

Figure 2.6-5. Bates Lease (Hartman), Rhodes Yates Waterflood (Texaco) and other nearby leases with injection wells.

Hartman argued that the Rhodes/Yates lease was the only water flood with an injection pressure gradient high enough to see the type of water pressure that was seen at the Bates Lease blowout. Hartman also argued that the waters were being injected higher than the rock fracture pressure of the interbeds of the Salado formation.

Are these wells in the area near WIPP waterflood candidates? The major Delaware Mountain Groups produce by solution gas drive (Broadhead and Speer 1993, 299). Solution-gas-drive reservoirs usually are good candidates for waterflooding (Willhite 1986, 3).

Adjacent to the WIPP Site Boundary, the No. 2 James A well responded favorably to waterflooding. This well is operated by Phillips, a major oil company, not a small operator. Initially, this well produced 4,000 barrels per month. As shown, production declined to

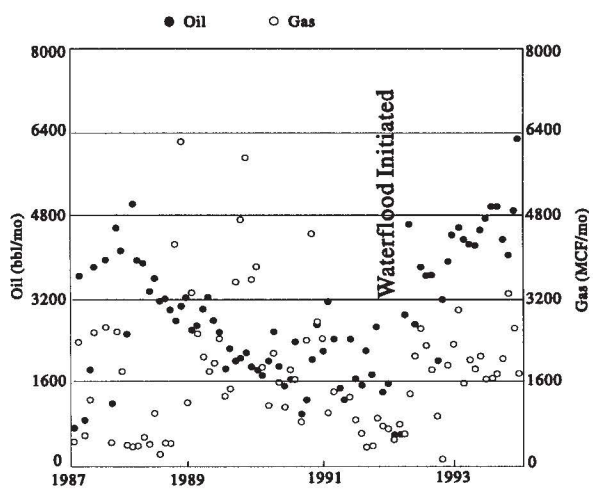

Figure 2.6-6. Response of No. 2 James A to waterflood.

less that 2,000 per month. The pressure maintenance waterflood was initiated with the conversion of one nearby well to waterflooding and later a second injection well. There was an immediate response, even to the one injector well. The oil production rate for the James #2A again exceeded 4,000 barrels per month.

Further, as noted by Broadhead, there are examples of successful waterfloods in the Delaware Basin. For example, the Paduca field which produces from the Delaware Mountain Group responded well to waterflooding as shown. A waterflood was initiated in 1968. Thus far primary production accounts for 8.6 million barrels cumulative production and waterflooding has produced an additional 5.2 million barrels. It is also worth noting that this Delaware Basin field has been in production for over 30 years and is still in production.

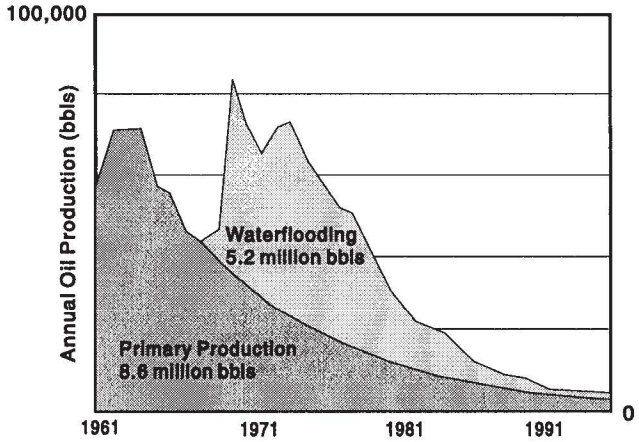

Figure 2.6-7. Paduca Oil Field Production.

2.6.2.1 Conclusions

The WIPP is sited in a mineral rich area and will be subject to the practices of the oil and gas industry and the potash industry. Drilling for oil and gas has been delayed primarily by the remaining presence of potash reserves. There is a history of waterflooding to improve oil recovery from producing fields throughout the Delaware Basin. There is also experience with water migrating out of the injection zone and into adjacent properties in the oil fields of southeast New Mexico. Near WIPP, there are a few new injection wells for the purposes of salt water disposal and waterflooding.

2.6.2.2 Questions:

Dan Stoelzel: Did you find any records of blowouts or casing collapse problems in offset producers. Did you see any of these type of incidences in your research?

Matthew Silva: I did not look in detail at the wells down there.

Dan Stoelzel: That is one thing I planned on doing. I just ran out of time. That would be an indicator that these disposal wells are indeed causing problems, you see it in offset wells both in the drilling phase and later in the production phase.

Matthew Silva: Certainly, part of the problem facing the project is that if you want to look at all of those, you have to look at each well on a case by case basis. It is a massive effort to try to understand that.

Wendell Weart: Something that is not directly related here, but I am curious that we now have such a proliferation of holes around the site which we did not have back around the late 70s and early 80s. Is there any information from those about encounters with brine reservoirs in the Castile?

Matthew Silva: Yes, we do have some information. About 2 years ago I did request from the various oil companies information on their water flows all which were in the Castile Formation around the WIPP site. About one third did respond with detailed records and another third did not respond at all. Some declined to provide that information.

Dan Stoelzel: Are you going to come forth with that information at some point?

Matthew Silva: As soon as I have time to put it together, I will.

Robert Neill: We will certainly share the information for the one third that did respond.[1] *****

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[1]That information was sent to Peter Swift on March 20, 1996.

2.7 Geological Features Across the Oil Fields of Southeast New Mexico and West Texas

Lokesh Chaturvedi

2.7.1 Synopsis

The Waste Isolation Pilot Plant (WIPP) is located in the northern part of the Delaware Basin. The Vacuum Field and the Bates Lease/Rhodes-Yates water flooding areas are situated in the shelf (backreef) areas, about 40 km northeast and 65 km southeast of WIPP respectively. Sratigraphically, the backreef equivalent of the oil producing upper Guadalupian Delaware Mountain Group Formations of Cherry Canyon and Bell Canyon, are the Artesia Group Formations of Grayburg, Queen, Seven Rivers, Yates and Tansill. San Andres limestone of the shelf is the stratigraphic equivalent of the lower Cherry Canyon Formation of the Delaware Basin. The Castile Formation is confined to the Delaware Basin only, but the Salado Formation extends more than 160 km beyond the margin of the Basin to the north and east into west Texas. In the southeast corner of New Mexico in the area of Rhodes-Yates waterflooding, the Salado Formation lies unconformably over the Artesia Group. Thus, a well penetrating through the Salado at the WIPP site would go through the Castile anhydrite and halite beds before entering the Bell Canyon Formation of the Delaware Mountain Group. At the Bates lease area, on the other hand, such a well enters the Tansill and the Yates Formations directly below the Salado. The vertical distance from the oil producing zones in the Cherry Canyon Formation surrounding the WIPP to the WIPP repository is approximately 1,200 to 1,800 m. In the backreef area, the distance between the Yates producing zones and the lower Salado is less, approximately 500 m. However, the Salado interbeds extend through the entire Salado from the Basin to the backreef and once pressurized fluids are injected into them, the Salado interbeds are expected to behave essentially the same way.

2.7.2 Presentation by Lokesh Chaturvedi

The point that Lori Dotson was making is that there is a difference in geology between the situation at the Bates lease and the situation at the WIPP Site. As stated in my synopsis, that difference is mainly in vertical distance. At the WIPP Site, it is the vertical distance between the Lower Salado and the Cherry Canyon or Brushy Canyon oil reservoirs. At the Bates lease it is the vertical distance between the gas producing Yates Formation and the level in the Salado of the salt water blowout in the Bates lease #2 borehole.

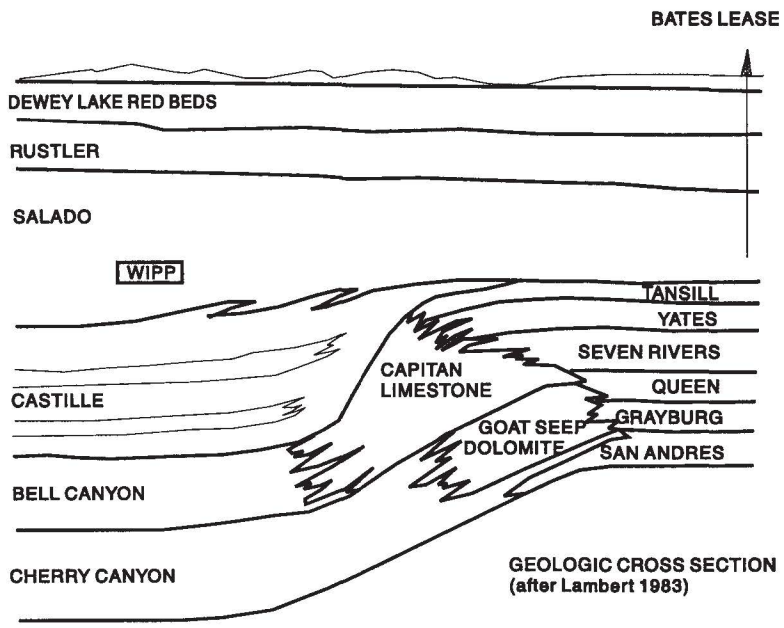

Figure 2.7-1. Geologic cross section at WIPP and Bates Lease (After Lambert 1983).

However, the main point of interest is that the Salado Formation is the formation that remains essentially the same across the reef. The thickness of the Salado decreases somewhat across the reef, but despite the forty mile distance between the WIPP and the Bates lease, the essential characteristics of the Salado, that of the presence of interbeds, remains the same. If the pressures are sufficient and the conditions are appropriate for water to leak out of the casing, water will be

injected into an interbed in the Salado or possibly into the water bearing zones such as the Culebra and Magenta of the Rustler Formation.

There may be a vertical distance but if the pressures are sufficient to cause injection of water into the Salado or Culebra, then it seems to me, that what happened at the Bates lease is quite likely to happen at the WIPP Site. The distance between the Texaco wells and the Bates lease #2 well was about two miles. If we accept, as Dennis Powers described, that there were no likely natural sources of such huge quantities of salt water, then most likely the source of water was the waterflooded area in the Texaco lease. If that is what we believe to be the case, then we know that such an effect can be felt more than two miles away. We know it can be felt two miles away. We don't know if it can be felt more than two miles away. Since the oil wells around the WIPP Site are about two miles away from the repository, regardless of the vertical distance from the Salado to the oil producing zones, I do not see a difference in the essential characteristics of the situation, which is the presence of the Salado Formation and its interbeds.

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2.8 Perspectives from WIPP Performance Assessment

Peter Swift and Rip Anderson
Sandia National Laboratories

2.8.1 Synopsis

Two main EPA regulations address the long-term (10,000-year) performance of the WIPP: 40 CFR 191 sets standards for releases of radioactivity from the disposal system; and 40 CFR 268.6 applies to long-term releases of hazardous constituents (e.g., volatile organic compounds and heavy metals) regulated under RCRA. 40 CFR 191 provides a regulatory definition of performance assessment (PA) that applies to the WIPP. It is "an analysis that: (1) Identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties caused by all significant processes and events." (40 CFR 191.12).

WIPP PA uses computational models to estimate cumulative radionuclide releases for selected scenarios. These scenarios are developed using a methodology which begins with establishing a comprehensive list of features, events, and processes (FEPs) which may affect the disposal system. These FEPs are then screened using four basic criteria: relevance, regulatory requirements, probability of occurrence, and consequence. Scenarios for system level modeling are constructed from those FEPs that remain following screening. To date, screening arguments are documented for approximately 800 of the 900 FEPs initially identified. Screening arguments remain to be developed or documented for many FEPs, including some related to oil and gas activities.

2.8.2 Presentation by Peter Swift

This is a brief overview of performance assessment methodology, more specifically, the development of scenarios for performance assessment. In an effort to address regulatory requirements, performance assessment calculates the long term performance of the repository for the next ten thousand years. There are two regulations of primary interest.

40 CFR Part 191 regulates the release of radioactivity from the site. It was promulgated in 1985, partially vacated by the court in 1987, and repromulgated in 1993. There are essentially three requirements:

- §191.13 limits the cumulative releases of radionuclides to the accessible environment for 10,000 years from essentially all causes.
- §191.15 limits the individual dose for "undisturbed performance" for 10,000 years. (Undisturbed is defined to exclude human intrusion).
- §191.24 requires protection of underground sources of drinking water for "undisturbed performance" for 10,000 years.

The first item, the cumulative release requirement, has been driving the performance assessment calculations.

The second regulation of interest, 40 CFR 268.6, implements RCRA for the long term. It limits the releases of hazardous constituents, such as VOCs, organics, and heavy metals, at the disposal unit boundary for 10,000 years of undisturbed performance.

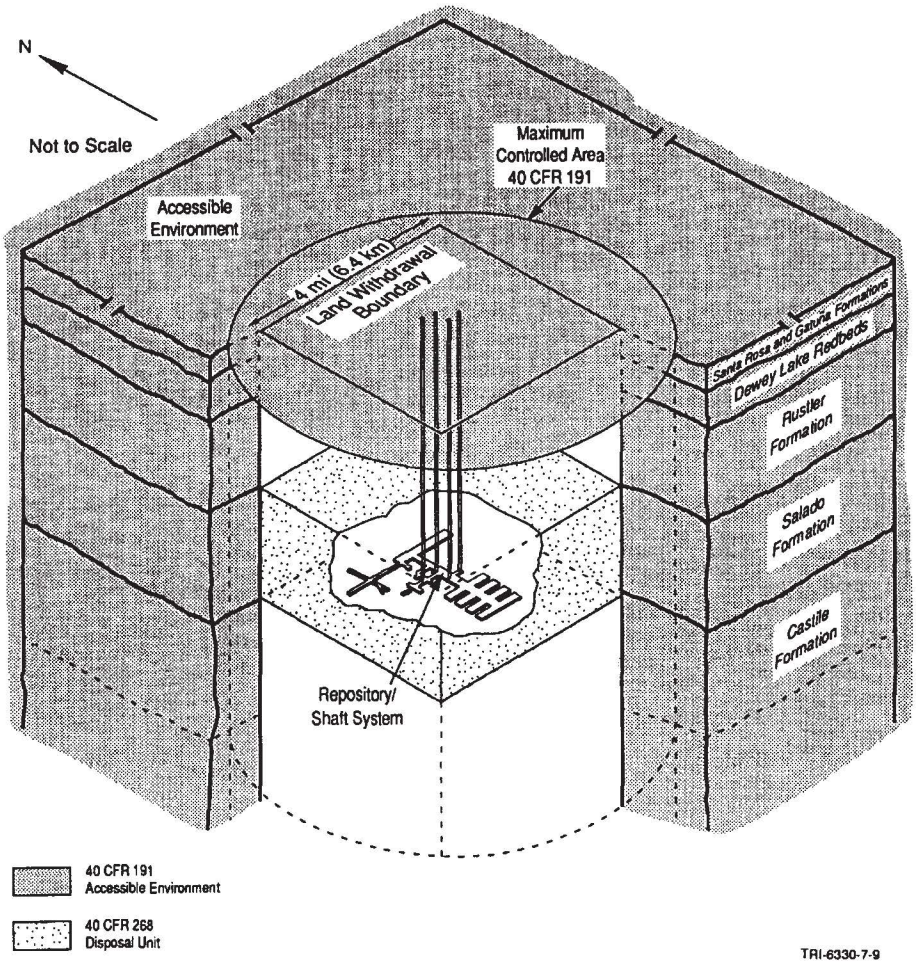

Figure 2.8-1. Accessible Environment and Disposal Unit Boundaries.

Shown here are the regulatory boundaries needed to assess performance measures. The repository is in the Salado Formation. It is underlain by the Castile Formation and the deeper hydrocarbon bearing units. The repository is overlain by the Rustler Formation which contains the Culebra, the formation in which Rick Beauheim observed the water level rises. Above that are the Dewey Lake Redbeds Formation and other relatively thin units such as the Santa Rosa Formation and the Gatuña Formation. The RCRA boundary, the RCRA disposal

unit, is defined to be the Salado Formation inside the four mile area. Releases are of interest at the top of the Salado Formation, at the bottom of the Salado Formation, or laterally to the 4 mile by 4 mile boundary.

For 40 CFR Part 191, the disposing unit is defined a little differently. The boundary of the controlled area is a cylinder extending up to the ground surface and downward as well. Radionuclide releases are of interest if radionuclides reach the ground surface or if they migrate laterally through marker beds in the Salado or through the permeable units in the overlying formations. We estimate the releases and sum the releases over 10,000 years. That is the performance measure that is compared to the EPA standard. The standard is probabilistic and regulates the probability of cumulative releases, not the magnitude of them, but the probability of releases of a certain magnitude.

For the WIPP 40 CFR 191 defines performance assessment. Performance assessment:

- identifies processes and events that might effect the disposal system,
- examines the effects on system performance, and
- estimates cumulative releases, including uncertainties, caused by all significant events and processes.

Performance assessment tries to capture this uncertainty by posing three questions.

1) What are the things that can happen in the future? (Scenarios or S_i)

2) What are the probabilities of those things?

3) What are the consequences of these things, if they should happen?

Risk is represented by an equation which contains an ordered set: 1) scenarios, 2) scenario probabilities, and 3) scenario consequences.

$$Risk = \{(S_i, pS_i, cS_i), i=1...nS\}$$

Performance assessment, for 40 CFR Part 191, is basically an attempt to solve the risk equation.

The flow diagram shows the performance assessment methodology. The process starts by characterizing the system. For the WIPP, there are 3 main parts, the site geology, the engineered facility, and the waste to be emplaced.

Performance assessment needs to develop scenarios. These are the things that might happen. Their probability needs to be estimated and a computational modeling system is needed to simulate these scenarios and estimate the consequences. A Monte Carlo consequence modeling system is used to perform multiple simulations using different sample parameter values, which describe the key parameters of the system. The simulations yield a set of outcomes that describes the uncertainty in the modeling system. The effort calculates the consequences for different scenarios, estimates the scenario probabilities, and gives a result that can be compared to the regulatory standards. If the exercise is a preliminary performance assessment, as has been the case since the late 1980s, then the process executes a sensitivity analysis that iterates through the system. The final iteration leads to the preparation of an application.

The first step to develop scenarios is to establish a comprehensive list of features, events, and processes (FEPs). Events and processes are identified in the regulations. A feature is neither an event nor a process, it simply may exist at the site. The WIPP FEP list was developed from nine independently derived FEP lists from different programs around the world. Some WIPP specific FEPs were added. The "Master List" contained approximately 900 FEPs. Some of these were not particularly relevant to WIPP. But in the interest of completeness they were included on the initial list. That list is in concept, an open list. If someone can think of it, and it has merit of any sort, it should be on that list.

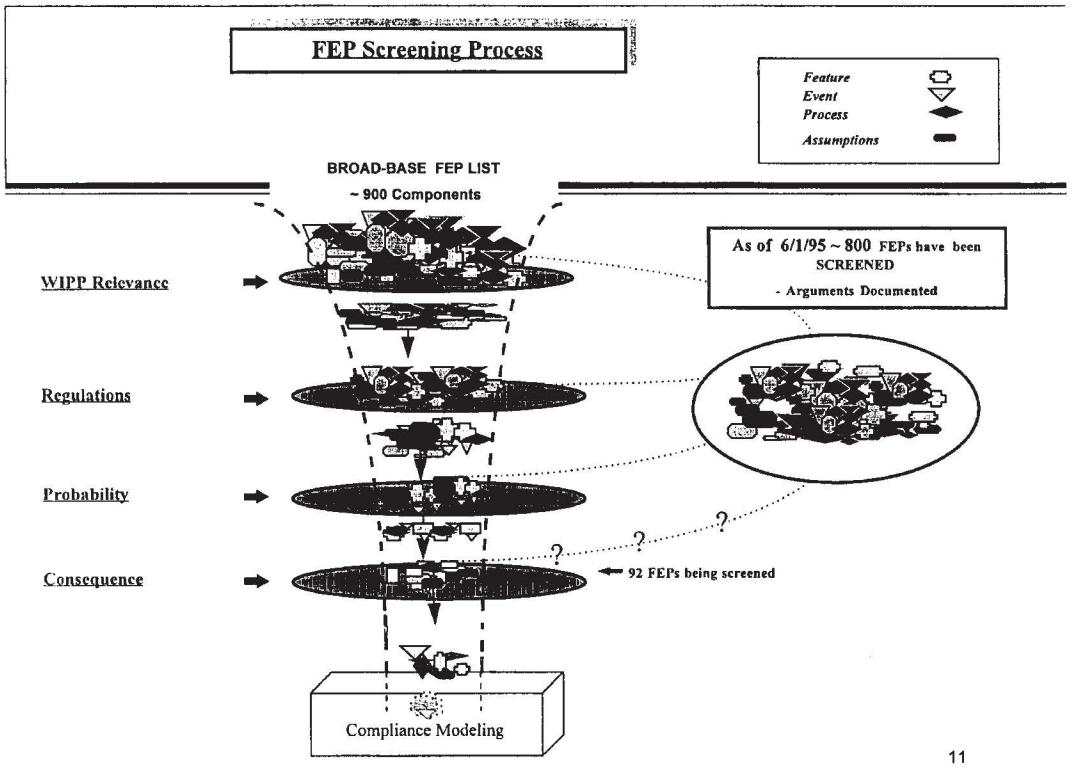

Figure 2.8-2. FEP Screening Process.

Next is the development of a screening argument. Screening does not mean screening out. It means screening either in or out of system level analysis. There are four screening criteria:

1) Relevancy

2) Regulation

3) Probability

4) Consequence

The first one is simply relevancy. For example, FEPs that relate to the disposal of high level waste or spent fuel are not relevant to WIPP.

The second is regulatory criteria. Two are important enough to mention here. First, the American regulatory period is limited to 10,000 years. FEPs beyond 10,000 years are not considered. Second, Appendix C of 40 CFR 191, specifies inadvertent and intermittent exploratory drilling as the most severe human intrusion scenario that should be considered.

The last two screening criteria are probability and consequence, assuming that the remaining FEPs, will be both relevant and included by the regulation. Then the process examines the probability of the FEP occurring and the consequences to the system. Regulation provides guidance for both of these. For probability, if a FEP can be shown to have less than one chance in 10,000 in 10,000 years, it need not be considered further. For consequence, if it can be shown that the performance measure would not be significantly changed by including the FEP in the analysis, then it need not be included. Of course, that presupposes there has been work done to support that consequence argument.

A schematic of the FEP screening process is shown. The order in which the first two screening criteria are applied is done on a case by case basis. At this time of the approximately 900 FEPs, work is ongoing for 92 of the remaining FEPs to determine their status.

2.8.2.1 Conclusions

Oil and gas related activities, e.g. waterflood injection, certainly are on our list along with other FEPs. Screening arguments remain to be developed and documented for several FEPs that are relevant here today, including waterflood injection. In other words, I don't have a screening argument today. I am not going to tell you what we decided to do about waterflood injection in terms of performance assessment modeling. In part, I am eager to hear what we learn here today and it would premature for us to come in with a conclusion already in hand. But I remind you that we will apply the three important criteria, probability, consequence, and the regulatory requirements.

2.8.2.2 Questions:

Robert Neill: In terms of the probabilities for screening, would you say that the probability of salt waterflooding or brine injection to improve oil recovery in the vicinity of WIPP is much, much less than 10^{-4} or much, much greater than 10^{-4}.

Peter Swift: At some locations the probability apparently is one, which is a good high number for a probability. I think it would be pointless of me to make the point any further. It depends on the location.

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2.9 Need for Water Flooding Scenario in WIPP Performance Assessment

William W.-L. Lee

2.9.1 Synopsis

After a series of presentations on the why, where and what-ifs of water-flooding, we come to the question of what does water-flooding mean for WIPP as a geologic repository of nuclear and mixed wastes. The USEPA requires performance assessments to include disruptive events or processes that are estimated to have more than one chance in 10,000 of occurring over 10,000 years. In the 1989, 1990, 1991 and 1992 WIPP performance assessments, the only disruptive event analyzed was human intrusion by drilling. WIPP has not analyzed a scenario specific to water-flooding.

In the most recent position paper on scenarios development, the DOE states:

> Fluid injection.
> Leakage from fluid injection wells associated with enhanced and improved oil and gas production, hydrocarbon storage, and disposal of unwanted liquids is retained for further consideration (p. 7-15).

Among the 124 FEPs being analyzed in side calculations, we find

- Interconnections within the controlled area for disturbed performance (to model effects of existing and future boreholes),
- Interconnections outside the controlled area for disturbed performance (to model effects of existing and future boreholes),
- Leakage from wells (from brine pockets, injection wells, fluids during drilling),
- Effects of mining inside or outside the controlled area,
- Connection to units beneath the repository,
- Current human activities outside the controlled area (e.g. hydrocarbon

extraction, fluid injection. (Anderson 1995).

While SNL/DOE has considered water-flooding, the impacts of water-flooding has not yet been analyzed in the compliance certification application.

2.9.2 Presentation by William W.-L. Lee

What does waterflooding mean and should it be incorporated into WIPP's performance assessment? Features, events, and processes (FEPs) that have a probability greater than 10^{-8} per year have to be considered in performance assessment. However, in the previous iterations of the WIPP performance assessment, the only disruptive event analyzed was human intrusion by drilling. And that is an important qualification.

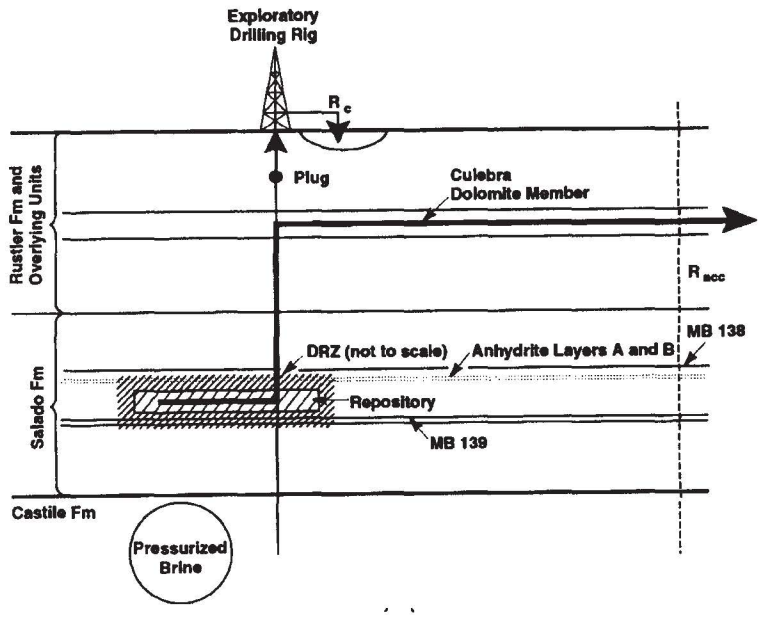

Figure 2.9-1. E2 Scenario

In the spirit of reviewing old work, I will show you the scenarios that were actually analyzed in the 1992 Performance Assessment. There was the E2 scenario in which a repository is pressurized with brine that flowed in from the Salado Formation, a driller hits the repository, and the pressurized waste moves up the well bore. There is a magic plug that diverts the material into the Culebra Dolomite. Compliance is measured at the accessible environment.

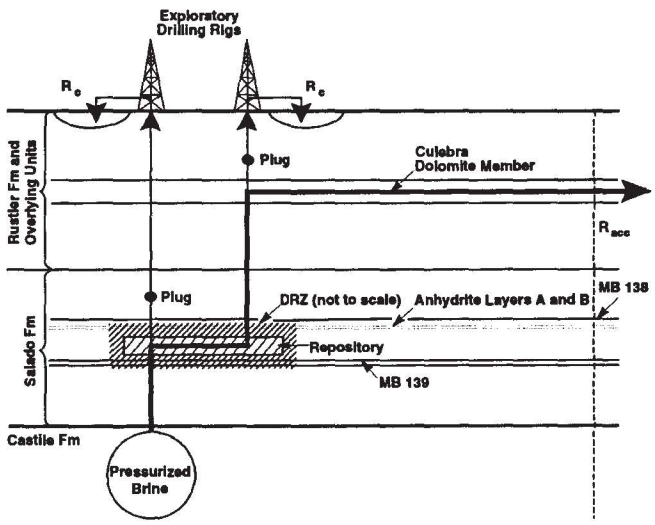

Figure 2.9-2. E1E2 Scenario.

In the E1E2 scenario, a driller first penetrates through the repository into a brine reservoir in the Castile Formation and thus floods the repository. A plug is put in place and there is now a brine pressurized repository. The E1 scenario is then superimposed on the E2 scenario.

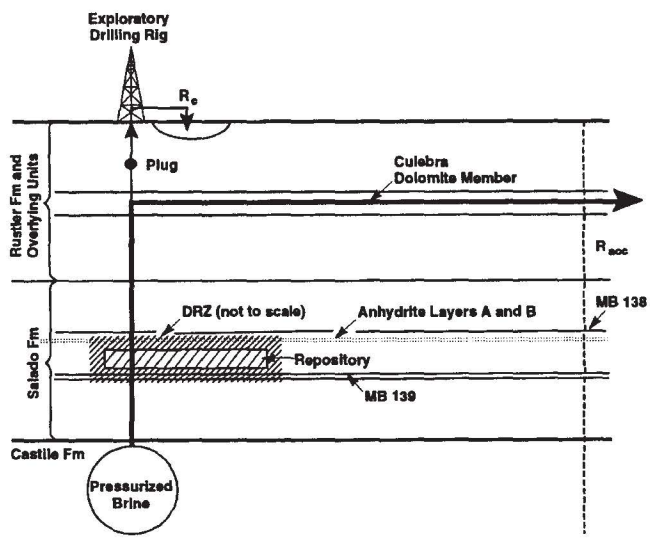

Figure 2.9-3. E1 Scenario.

The other possible scenario that was not analyzed by the 1992 PA was the E1 scenario which is the first half of the E1E2 scenario. The rationale given was that it is dominated by the E1E2 scenario although I believe Sandia has had some second thoughts about it.

Peter Swift just explained the process of screening FEPs. Starting with 900, two months ago there were 124 left. These are the ones related to waterflooding that are left.

- Interconnection within the control zone for disturbed performance and interconnection outside the disturbed performance.
- Leakage from wells including injection wells.
- Effects of mining inside or outside the control area.
- Connection to units below the repository.
- Human activity including fluid injection.

We have been told that Sandia National Laboratories is grinding away on side calculations to provide screening arguments for these FEPs. We await the results of these calculations.

The bottom line is this. Should the impact of potential waterflooding be in the current performance assessments and in particular, the draft application?

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END OF WORKSHOP PRESENTATIONS

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3. ANALYSES OF FLUID INJECTION ISSUES

Potential impact of fluid injection on the WIPP repository is analyzed in this chapter. The analysis uses the information presented at the workshop and that available in the literature and the public record.

As Chuck Byrum (EPA) noted in the afternoon discussion, waterflood and salt water disposal are two different processes regulated in different ways, designed in different ways, and the ultimate effects of each may be quite different. Kreitler et al. (1994, 4) described the difference between these two water injection activities. In waterflood projects, the presence of adjacent producing wells limits the extent of repressurization around the injectors. In contrast, salt water disposal wells are not used to increase oil production. Hence, brine may not always be injected into depressurized producing reservoirs. Initial fluid pressures in the disposal reservoirs may be hydrostatic, leading to overpressured conditions and upward fluid flow potentials. This analysis attempts to preserve the distinction between these two processes.

3.1 Salt Water Disposal

In his presentation, Beauheim showed data which led to his inescapable conclusion that a discreet human activity, most likely an injection well, caused the abrupt 1988 water level rise in wells south of the WIPP Site. Based on his own investigation, LaVenue (1991) also suggested the possibility of leakage from either a producing oil and gas well or a salt water disposal well in the area. Further, LaVenue (1991) speculated on the potential impact of a leaking well on the performance assessment calculations:

> If the recharge source is related to oil and gas wells in the area, it is not difficult to imagine significant increases and/or decreases in the water levels in the future as a result of additional recharge or discharge from oil and gas wells. Fortunately, there are almost no oil and gas wells within the

> WIPP-site boundary. Therefore, if wells are going to leak and have an impact upon the flow field, there is a higher probability that those wells will be located down-gradient or south of the WIPP site. Recharge from oil and gas wells south of the site should flatten the hydraulic gradient which would slightly increase ground-water travel time. If discharges from the Culebra occurs through a leaking oil or gas well south of the site, the hydraulic gradient would be slightly increased and the ground-water travel time would decrease (LaVenue 1991, 10-11).

In his presentation, Beauheim noted that higher potentiometric head in the Culebra in the southern part of the WIPP and south of the WIPP would flatten the hydraulic gradient and increase travel time. But he also emphasized that a change in gradient would not make a difference to the calculated performance assessment because of the relatively short life of such an injection activity. However, could a leaking injection well east, north, or northeast of the WIPP force large volumes of brine into the Culebra and significantly increase the gradient and reduce travel time? There are several new oil wells also producing large quantities of brine from the Delaware Mountain Group. To handle that waste brine, there are new salt water disposal wells operating just east of the WIPP Site. Wells are likely to be drilled to the north of WIPP when the area is open for drilling. The effect of higher heads in the Culebra in the north and east of the WIPP site should be analyzed in performance assessment.

3.1.1 Fluid Injection in the Culebra - *Bounded by Climate Change*

At the EEG workshop, Rip Anderson (SNL) acknowledged that the performance assessment effort, to date, has not specifically addressed fluid injection but that climate change would be in the final calculations. He maintained, however, that climate change assumption would bound any waterflooding scenarios because the climate change scenario takes the water table to the surface and that is the maximum possible water pressure. Anderson also stated that the presence of a

Castile brine pocket for the human intrusion scenario would cover any remaining concerns about waterflooding.

The 1995 DOE draft application to EPA (U.S. DOE 1995, Section 6.4.11) discusses climate change noting that the hydraulic head in the Culebra is raised to the land surface elevation along the northern boundary of the Culebra while the head remains fixed along the domains of the southern boundary. No results were presented. Rather, the draft document notes that the effect of climate change on groundwater flow is the subject of a current study.

3.1.2 Fluid Injection in the Culebra - *Not Bounded by Climate Change*

David Back (SC&A) questioned the DOE position that surface recharge bounded the impact of water level fluctuations in the Culebra. Back noted that the PA modeling assumed that the recharge would occur some miles to the northwest of the WIPP Site at the edge of the regional model. He pointed out that water from this recharge location would not pass through the WIPP site. Modeled this way, the water would flow south, through the higher transmissivity zone, straight to the assumed discharge area in Nash Draw, which is also west of the WIPP Site. However, if recharge occurred along the eastern edge of the WIPP, Back maintained that there would be an increase in the gradient, hence an increase in the flow rate through the Culebra over the WIPP.

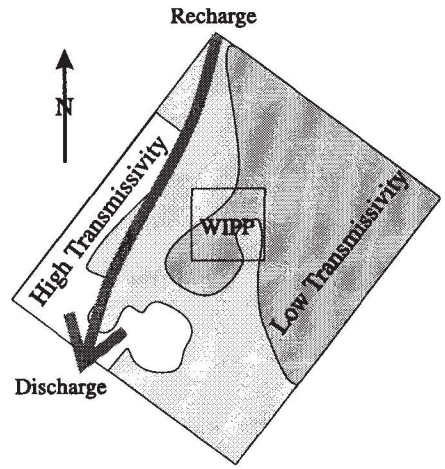

Figure 3-1. WIPP and Regional Flow Model for Culebra. Figure prepared by M.K. Silva.

3.1.3 Culebra Hydraulic Head Limited to Surface

Peter Swift (SNL) maintained that it is unlikely for a failed injection well to cause

pressures in the Culebra that are above the head at the ground surface. Data that support his position include the 181 pressurized water flows logged into the NMOCD Hobbs call-in log (November 1978 to May 1994) for southeastern New Mexico and the eight additional waterflows identified by Van Kirk (1994). Waterflows appear to be largely confined to the Salado and other deeper formations. There does not appear to be any artesian flow from the overlying aquifers such as the Culebra.

The notion of surface limited hydraulic head can not apply to the Salado. In the Vacuum Field, waterfloods exerted sufficient pressure to collapse well casings and pressures as high as 1600 psi were measured at the surface outside of waterflood areas (Ramey 1976). As mentioned by Lokesh Chaturvedi and discussed by Dennis Powers, the 1991 Salado salt water blowout at Hartman's Bates Lease was pressurized far above the surface hydraulic head as Hartman inadvertently discovered.

3.1.4 Brine Flow into Overlying Aquifers

Citing information from Dan Stoelzel, Rip Anderson made the following two points. First, a difference occurs only if water enters the Salado and the repository. Second, water escaping lower injection zones would flow past the Salado and would flow into the more permeable Culebra. Dan Stoelzel also suggested the reason injected water in the Vacuum Field did not come to the surface was because it was potentially going into the Ogallala, which is very permeable near the surface. The mechanism postulated by Anderson and Stoelzel raises interesting questions. At the Vacuum Field, or in other parts of New Mexico, or in other parts of the nation, has there been contamination of overlying aquifers, such as the Ogallala, as a result of oil field waterflooding? Is WIPP relying on contamination of an overlying aquifer by oil field waste brine as an acceptable alternative to flooding the Salado?

Some information supports the notion of water from oil field operations contaminating overlying aquifers. The U.S. Government Accounting Office (GAO) published a 1989 report entitled "Drinking Water Safeguards Are Not Preventing Contamination From Injected Oil and Gas Wastes." Class II injection wells are used to dispose of brine produced with oil and gas or to reinject these fluids to enhance oil recovery. Although the full extent of the problem was unknown in 1989, EPA was aware of 23 cases in which drinking water was contaminated by Class II injection wells. For the 23 confirmed cases of contamination, there were three principal causes. Five cases resulted from leaks in the casing of the injection well, nine resulted from migration through nearby improperly abandoned wells, and nine resulted from injection into the underground drinking water (U.S. GAO 1989).

One case of confirmed contamination occurred in New Mexico. During the 1970s, 20 million gallons of water leaked from a Texaco disposal well in Lea County, New Mexico into portions of the Ogallala aquifer, an underground source of drinking water. Some of the brine migrated into a rancher's irrigation well, damaged his crop and, according to the rancher, ultimately caused the foreclosure of his farm property. On the basis of the results of a pressure test, the rancher successfully sued Texaco in 1977 for damages (U.S. GAO 1989, 25).[9]

In the 1970s, potential contamination of the Ogallala near various waterfloods in Lea County was of concern to the New Mexico Oil Conservation Division (Ramey 1976). After years of study, the Vacuum Field Salt Water Flow Committee [a committee of oil company representatives] indicated flow was confined to the top of the Tansil and the bottom of the Rustler (Bailey 1990), thus isolating the problem of flow largely to the Salado. Bailey's spot checking old oil well drilling

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[9] Texaco has since repaired the well and is now operating in compliance with Underground Injection Control although Texaco was not required to clean up the aquifer (U.S. GAO 1989, 25).

records indicated water flow drilling problems and numerous casing leak repairs in the Dewey Lake Red Beds and the Rustler in addition to the Salado (Bailey 1990).

3.1.5 Pressurized Brine Injection into the Salado

If there was salt water flow into the Ogallala at the Vacuum Field, as suggested by Dan Stoelzel, and into the Dewey Lake Red Beds and Rustler as indicated by Bailey (1990), can the performance assessment assume that overlying aquifers will serve as a relief valve for leaking wells in the WIPP vicinity, thus protecting the Salado, as suggested by Anderson and Stoelzel? It appears not. Despite the presence of overlying aquifers at the Vacuum Field, injected salt water exerted sufficient pressure to collapse well casings at the Salado horizon (Ramey 1976; LaVenue 1991). Similar observations of water flow through the Salado have been made in other oil fields with a history of waterflooding, including the oil fields near Oil Center, Monument, Eunice (Bailey 1990) and Jal (Hartman 1993).

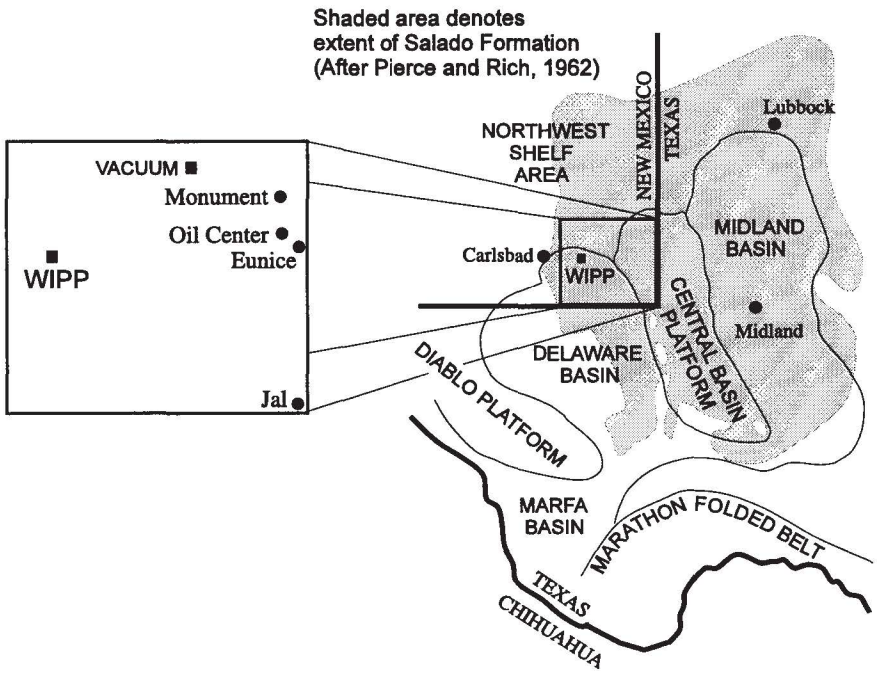

Figure 3-2. Areas overlain by Salado Formation.

Gallegos and Condon (1994) argued that the 189 water flows throughout District One of southeast New Mexico strongly correlated with waterflooding activities. These flows were in the Salado or at depths much greater than the overlying aquifers, strongly suggesting no relief mechanism. In light of this information, can the performance assessment defend the notion that brine escaping from an oil field waterflood or salt water disposal well will preferentially migrate into an overlying aquifer?

3.1.6 Devon Energy's Todd 26 Federal #3

As to the salt water injection well south of the WIPP Site, Dan Stoelzel commented that this well was probably responsible for the water level rises observed in H-9 (see Stoelzel's presentation). His conclusion was based on the schematic of the well completion. The well was originally completed in 1971 as a test well and immediately converted to a salt water disposal well. There is no salt isolation casing and it is an open hole completion similar to that of the Rhodes/Yates Field or the Vacuum Field. He commented that the well is now plugged and abandoned. Matthew Silva's reading of a commercial map also suggested that the well was abandoned.

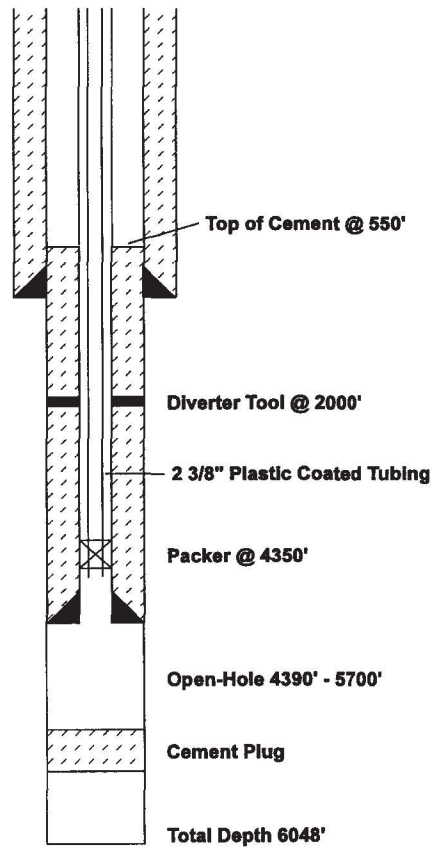

Figure 3-3. Texas Americal Oil Corporation Todd 26 Federal No. 3 Water Disposal Well (After Stoelzel).

It appears that the well was not plugged and abandoned and is still in service (Horsman 1995). The well is injecting into the Bell Canyon Formation, which is below the WIPP horizon. A comparison of the injection history at this well and

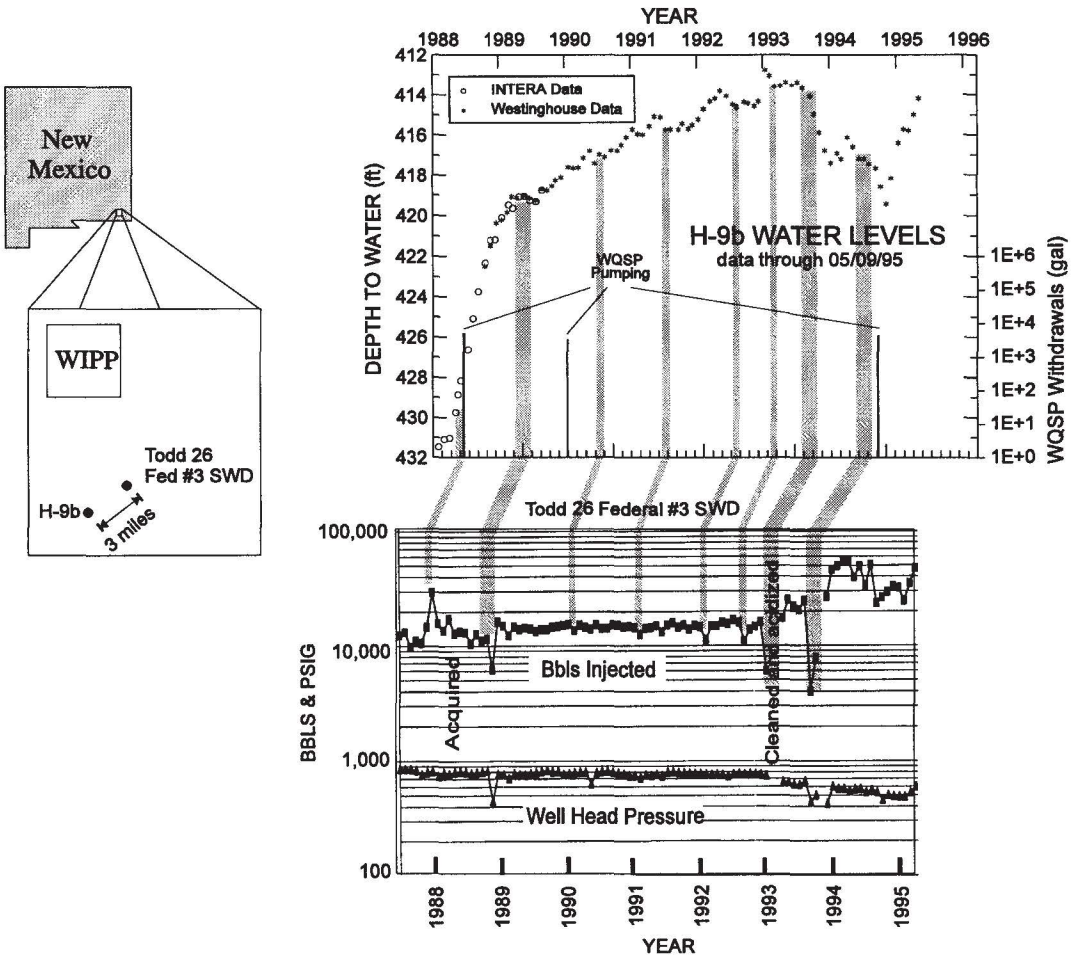

Figure 3-4. Todd 26 Federal #3 well injection data (Horsman 1995) and H-9 water level rises presented by Beauheim.

the water level rises at H-9 strongly suggests communication between the injection horizon, which is below the WIPP horizon, and the Culebra Dolomite, which is an aquifer above the WIPP horizon. There is more than 3,000 feet (980 m) of vertical separation between the horizons and approximately 3 miles (5 km) of horizontal separation between the wells.

Figure 3-4 strongly suggests a delayed response at well H-9 to injection events at the Todd 26 Federal #3. As noted in Richard Beauheim's presentation, the depth to water at well H-9 was essentially constant at 431 to 432 feet (141 m) for five

years prior to April 1988. An increase in the injection rate from 10,000 barrels per month to 30,000 barrels per month in January 1988 corresponds with the observed water level rise at H-9, which began in April 1988. This increase in injection is the event mentioned by LaVenue (1991) as potentially causing a tubing failure. Seven subsequent reductions in injection at the salt water disposal well rate are followed by corresponding water level declines at the monitoring well. In January 1993, injection operation ceased for two months. The water level at H-9 fell to levels not seen since 1990. After 1993, there appears to be either a delay in the response or perhaps a response to other injection wells in the area. It is worth noting that two other salt water injection wells began operating in the same general vicinity as Todd 26 Federal #3; Todd 26 Federal #2 SWD in January 1993 and Todd 36 Federal #1 in September 1994 (Horsman 1995).

The observations invite the obvious question. Are there problems with the Todd 26 Federal #3 well as suggested by Bailey (1990), by LaVenue (1991), and in Stoelzel's discussion of the well completion? Subsequent to the EEG workshop, the well passed a scheduled, routine, mechanical integrity test on August 16, 1995. In response to a request from the U.S. EPA (Catanach 1996a), the New Mexico Oil Conservation Division had the well subjected to a radioactive tracer test on November 13, 1995, to determine if injected fluid is migrating upward through channels in the vicinity of the wellbore (LeMay 1995a).

> The results of the tracer surveys (analysis attached) indicate no channeling behind the production casing and no vertical migration of fluid from the injection interval. It is the opinion of the Division that no further testing of these wells [Todd 26 Federal #3 and David Ross AIT Federal #1] is necessary (Catanach 1996b).

Assuming the tests were conclusive with respect to the integrity of the tubing, the casing, and the cement, the results of the test raise more questions. Are there vertical conduits in the vicinity such as improperly abandoned wells and/or wells

with deficient casing or cementing? Or are there vertical fractures in the vicinity that are not detectable by a radioactive survey of the wellbore area? Is there indeed a correlation between water injected and water level rises as suggested by the injection and water level rise data? If so, how does water injected more than 4,000 feet (1300 m) below the surface get through thousands of feet of two relatively impermeable bedded salt formations, the Castile and the Salado, and end up in an overlying aquifer? Is bedded salt, in the vicinity of water injection activities and abandoned oil and gas wells, truly a geologic barrier?

3.1.7 Yates' David Ross AIT Federal #1

Although there are several salt water injection wells in the area, this is the only salt water injection well operating within one mile of the WIPP Site at this time. During the afternoon deliberations, George Dials (DOE) raised the issue of institutional control noting that DOE has the opportunity to take credit for institutional control for up to 100 years and the DOE intends to maintain institutional control for at least 100 years.

As the only salt water disposal well operating within one mile of the WIPP site, the record on Yates' David Ross AIT Federal #1 provides interesting observations about institutional control.

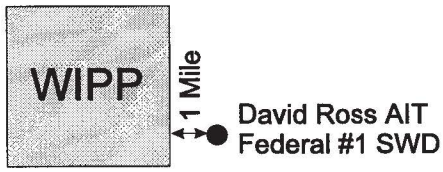

Figure 3-5. Location of David Ross AIT Federal #1 Salt Water Disposal Well.

First, the BLM received an application for permit to drill an oil well on January 17, 1991. The BLM approved the application on January 31, 1991, without obtaining a review from the DOE despite the October 26, 1990, Memorandum of Understanding (MOU) requiring it. The approval of this well completely bypassed "the controls that are crucial to protecting the site from inadvertent exploration" (Arthur 1992; Silva 1994, 46). The policy has been in place since 1983:

> As an additional measure, the BLM will notify the DOE of any requests for resource recovery permits within one mile of the WIPP Site boundary so that the DOE will be aware of resource recovery activities near the Site (McGough 1983).

Second, when the well failed to produce much oil from the perforated zone, the operator proposed to convert it to a salt water disposal well. There was an objection, but it was not raised by the DOE. Mitchell Energy expressed concern about the loss of oil reserves as a result of brine injection into potential oil producing horizons and wished to limit injection pressures (Stephenson 1991). An agreement was reached between the two oil companies (Kellahin 1991) and the conversion to a salt water disposal well was approved on May 22, 1991 (LeMay 1991). The well was to be equipped to operate at a maximum pressure of 900 psi (LeMay 1991). Over the next several months, the well casing was perforated and zones within the approved interval were acidized and fractured until sufficient water could be injected (Goodlett 1991a, 1991b, 1991c, 1991d, 1991e, 1991f).

Third, the DOE continued to list this as an oil and gas well (Arthur 1993a, 1993b) and appeared unaware that this was a salt water disposal well despite the absence of oil production equipment, the presence of a battery of salt water tanks, the presence of a sign labeled "SWD," the "SWD" label on the BLM map, and BLM and NMOCD records clearly stating "salt water disposal well" (Silva 1994, 55-56; Kehrman 1995, 254, lines 18-20).

Fourth, the DOE, the EPA, the BLM, and others rely on the New Mexico Oil Conservation Division to ensure that water is not injected above the approved injection pressure. An examination of the public record (NMOCD 1996) indicates that the David Ross AIT Federal #1 was operated 20 psi above the approved injection pressure of 900 psi (LeMay 1991) during the months of September and October 1995, yet the well had been equipped so that it would not operate above 900 psi.

Government ownership, regulation, and public records are components of institutional control. The observations above raise questions about how much credit can be allowed for institutional control of the resource recovery activities in the vicinity of the WIPP site.

There does not appear to be an identifiable relationship between the injection of brine at the David Ross AIT Federal #1 and the water level rises at the P-18 well. The material presented by Rick Beauheim and the arguments submitted by Fant (1995) strongly suggest that there is insufficient evidence of direct communication between these wells. Fant (1995) makes a compelling argument that the P-18 well, which was originally drilled as a potash corehole, may be providing a connection between the Culebra and Magenta Formations. As noted by Rick Beauheim, there may be a problem in the P-18 well with the bridge plug, the cement job, or the cement bond.

3.2 Water Flooding

The problems with waterflooding in oil fields under the Salado Formation, or more specifically, the migration of injected water through the Salado Formation to adjacent properties, is well documented (Ramey 1976; Bailey 1990; LaVenue 1991; Hartman 1993, Herrera 1995). At the EEG workshop, Dan Stoelzel and Lori Dotson of Sandia National Laboratories maintained that at WIPP, migration of water through the interbeds of the Salado, such as occurred at the Rhodes Yates Field and the Vacuum Field, was highly unlikely for a variety of reasons. These included differences in geology, changes in oil-well completion practices from the 1940's, and improved reservoir management. Stoelzel and Dotson argued greater vertical separation at WIPP will protect the repository. They also argued that large scale water flooding near the WIPP is unlikely because the oil pools near WIPP are characterized by thin net pay zones, low permeabilities, high reducible water saturations and high residual oil saturations. They also maintained that oil

production by primary and secondary recovery would require less than ten years each. These issues are discussed below.

3.2.1 Differences in Geology

With respect to water injection, Dan Stoelzel and Lori Dotson cited vertical separation as an additional protection for the WIPP. Their arguments rely on the observation that oil production near the WIPP occurs at depths greater than 7,000 feet (2300 m) or about 5,000 feet (1640 m) below the repository horizon. Oil production at the Vacuum Field occurs at approximately 4,500 feet (1480 m) and at Rhodes Yates at 3,000 feet (980 m). In their abstract, Dotson and Stoelzel state there was only a couple of hundred feet ~(65 m) of vertical separation between the Salado Formation and the waterflood injection zone at Rhodes-Yates. They also noted that the Castile Formation is missing at the Vacuum Field and the Rhodes Yates Field.

However, as noted by Lokesh Chaturvedi, there is one geologic feature common to the areas on either side of the reef. The Salado interbeds extend through the entire Salado across the Delaware Basin and over the backreef. Lokesh Chaturvedi maintained that once pressurized fluids are injected into the Salado interbeds at WIPP, the interbeds will behave essentially the same way as Salado interbeds at other locations.

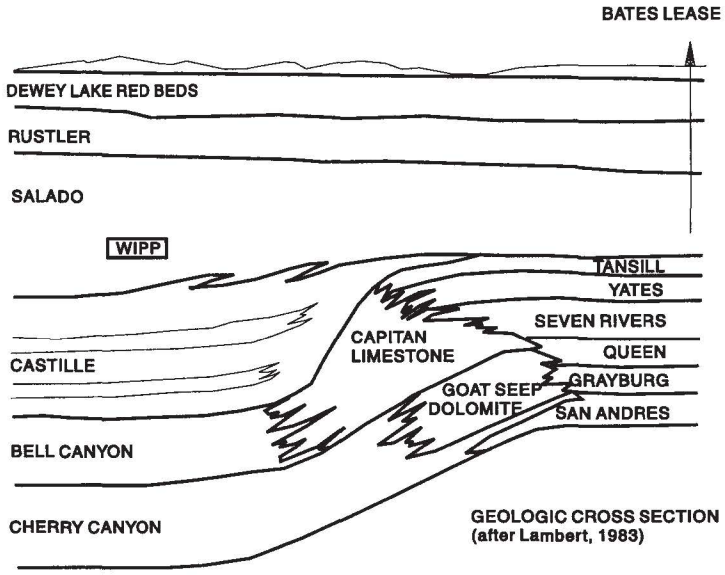

Figure 3-6. Continuity of Salado Formation.

In the afternoon deliberations, Dan Stoelzel and Lori Dotson offered opinions which contradicted the notion that vertical distance would protect the repository from communication with the deeper injection zones. For example, Dan Stoelzel maintained that the most likely source of water level rises in the Culebra at the H-9 well was the Todd 26 Federal #3 salt water disposal well. Matthew Silva observed that the salt water disposal well was injecting fluid in the interval from 4,400 to 5,700 feet (1440 m to 1870 m) below the surface. The water would have to migrate vertically 3,500 feet (1150 m) through the Castile and Salado to the overlying Culebra. That observation undermines Stoelzel and Dotson's position that such water migration would not occur because of about 3,000-5,000 feet (980 to 1640 m) vertical distance between the oil producing Delaware Mountain Group and the WIPP repository, or the overlying aquifers.

Lori Dotson commented that Silva's argument relied on the assumption that the water was leaking upward from the injection interval of 4,400 to 5,700 feet (1440 m to 1870 m). She maintained that the water could have been leaking from anywhere along the casing because that was a poorly designed injection well. Citing Stoelzel's earlier comments, Lori Dotson further commented that even if disposal brine was moving along the casing, it would take the path of least resistance and move into the Culebra. It would be easier for such water to enter the Culebra aquifer and not the Salado Formation. In bypassing the Castile and Salado Formations and flowing into the overlying aquifer, the oil field brine would not have an effect on performance assessment. But this explanation entirely undermines the "greater vertical distance" argument.

3.2.2 Livingston Ridge Delaware Waterflood

Dan Stoelzel maintained that small companies typically have shallow pockets and are unlikely to initiate water injection because of the cost to convert a production well into an injection well. It is worth noting that the active operators within two

miles of the WIPP Site include Phillips, Texaco, Pogo, Yates, Enron, Bass, Mitchell Energy, and Santa Fe Energy.

On October 10, 1995, Pogo Producing submitted an application to begin a pilot pressure maintenance project[10] (Bruce 1995a). Pogo intends to inject water into the Brushy Canyon of the Livingston Ridge-Delaware Pool through a well approximately one mile east of the WIPP Site Boundary. The injection interval is from 7,050 feet to 7,068 feet (2313 m to 2319 m) for a total injection interval of 18 feet (6 m), a relatively narrow zone of perforations. The original spacing of the wells has not been changed. A production well is to be converted into an injection well. Pogo plans to inject 365,000 barrels of water per year. The operator of the pressure maintenance project anticipates that three wells will see increased oil production, Neff Federal #1 and #2 in Section 25 and Neff Federal #1 in Section 26 (LeMay 1995b, 3). The operator also requested an administrative procedure to expand the pressure maintenance project, and at a later date, to include additional lands and/or injection wells (LeMay 1995b, 4). The WIPP can anticipate waterflooding of the Livingston Ridge/Lost Tank Delaware by independent operators on yet to be determined patterns.

3.2.3 Likelihood of Large Scale Waterflooding

Lori Dotson maintained that the oil pools near WIPP are relatively small when compared to the Vacuum Field and the Rhodes Yates Field. Hence, the injection of large volumes of water is unlikely. She suggested that the Livingston Ridge and the Lost Tank Delaware oil fields are unlikely to be waterflooded on a large scale because:

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[10] In a pressure maintenance program, water is injected to supplement declining reservoir energy. Pressure maintenance is a waterflood and often begins while the reservoir is still under primary production to maintain maximum production rates (Willhite 1986, 3, 190).

a) The pay zones are too thin, on the order of forty feet and several wells in the Livingston Ridge area with only ten to twenty feet of casing perforated.

b) The permeability of the Brushy Canyon is less than 7 to 24 millidarcies.

c) For waterflooding to occur, injection wells would have to be spaced closer together, which may be uneconomical.

d) The reservoir has a high irreducible water saturation and a high residual oil saturation.

However, Matthew Silva and Ron Broadhead noted that the Cabin Lake Field, at the northwest corner of the WIPP Site has shown good response to the pilot pressure maintenance project. The reservoirs in the Delaware Mountain Group produce primarily by solution gas drive. Citing the literature, Silva noted that solution gas drive wells are usually good candidates for waterflooding (Willhite 1986). In addition to citing experience and projected performance for the Paduca, Indian Draw, and East Shugart Fields, Broadhead also mentioned there was information, held proprietary by the oil companies operating in the area, indicating that they anticipated 70% to 80% increase in production by waterflooding the Brushy Canyon Formation.

3.2.4 Pay Zone Thickness

Lori Dotson maintained that large scale waterflooding would not occur in the vicinity of the WIPP because the pay zones were too thin. She stated that wells from the Livingston Ridge/Lost Tank portion of the Delaware were perforated for ten or twenty feet and suggested these were indicative of total pay zone potential.

However, a complete assessment of pay zone potential needs to also consider the typical completions for the Quahada Ridge Delaware Pool at the southwest corner

of the WIPP, the typical well completions for the Cabin Lake Delaware Pool at the northwest corner of the WIPP, and the typical multizone well completions for the Livingston Ridge-Lost Tank Delaware.

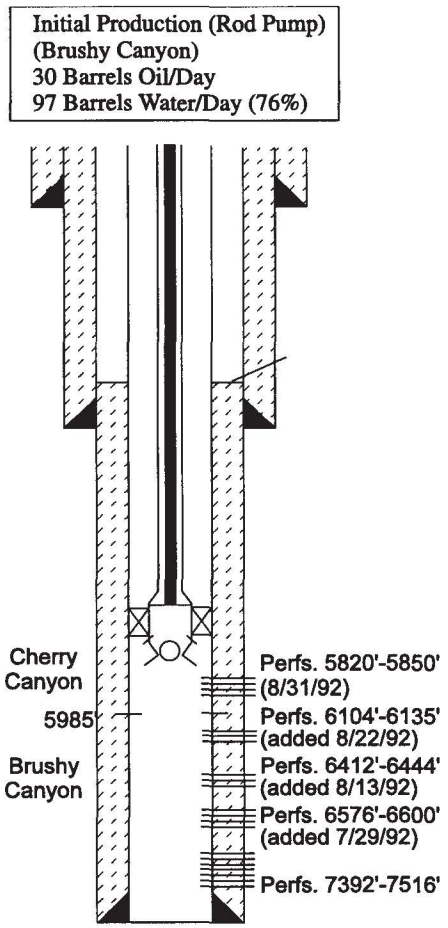

Figure 3-7. James E#12. Typical Cabin Lake Completion. After Dan Stoelzel.

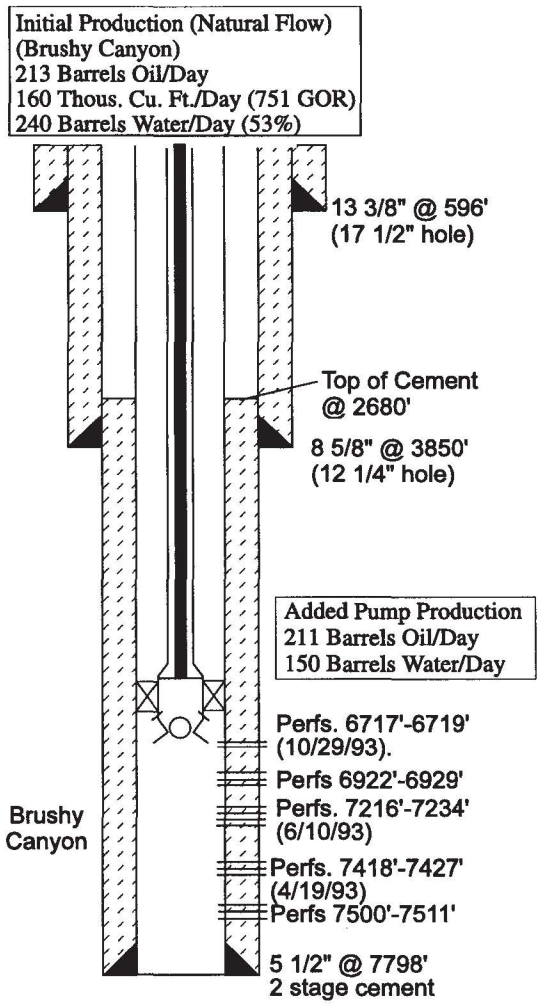

Figure 3-8. James Ranch Unit #19. Typical Quahada Ridge Completion. After Dan Stoelzel.

Stoelzel presented the James E#12 at Cabin Lake as a typical completion with five perforated zones totaling 231 feet (76 m). He presented the James Ranch Unit #19 as a typical Quahada Ridge completion with perforated zones totalling 47 feet (15 m).

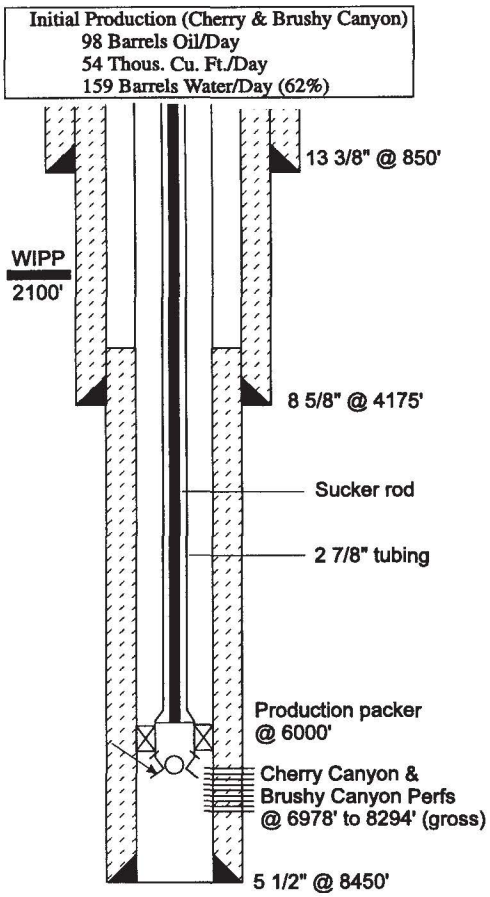

Figure 3-9. Typical Livingston Ridge/Lost Tank Completion. After Dan Stoelzel.

As to the Livingston Ridge/Lost Tank Field, it is true that Pogo Producing's completion records for Federal 23 wells #2, #3, and #5, on the lease immediately adjacent to the WIPP, are completed in the Brushy Canyon main pay zone with perforations ranging from fifteen feet to twenty feet (5 to 7 m). There are, however, other potentially producible zones, such as the B zone and D zone in the Lower Brushy Canyon as shown in Figure 20 of Broadhead et al. (1995). Moreover, the completion record for the Federal 23 Well #1 in that same lease, shows not only 19 feet (6 m) of perforation in the Brushy Canyon main pay, but also shows an additional 91 feet (30 m) of perforations in three other zones that have been temporarily abandoned. Broadhead et al. (1995, XI-16) noted that operators producing only from the main pay zone, at this time, may eventually re-enter their wells and perforate additional zones when the main pay zone ceases to yield economic volumes of oil. The completion records for the twelve additional wells that Pogo wishes to drill on forty acre spacings are not available because the federal government has denied Pogo's application to drill through the potash deposits (Burski 1994).[11]

[11]The EEG understands that this case may be in litigation and the EEG has no implied nor direct opinion in this case.

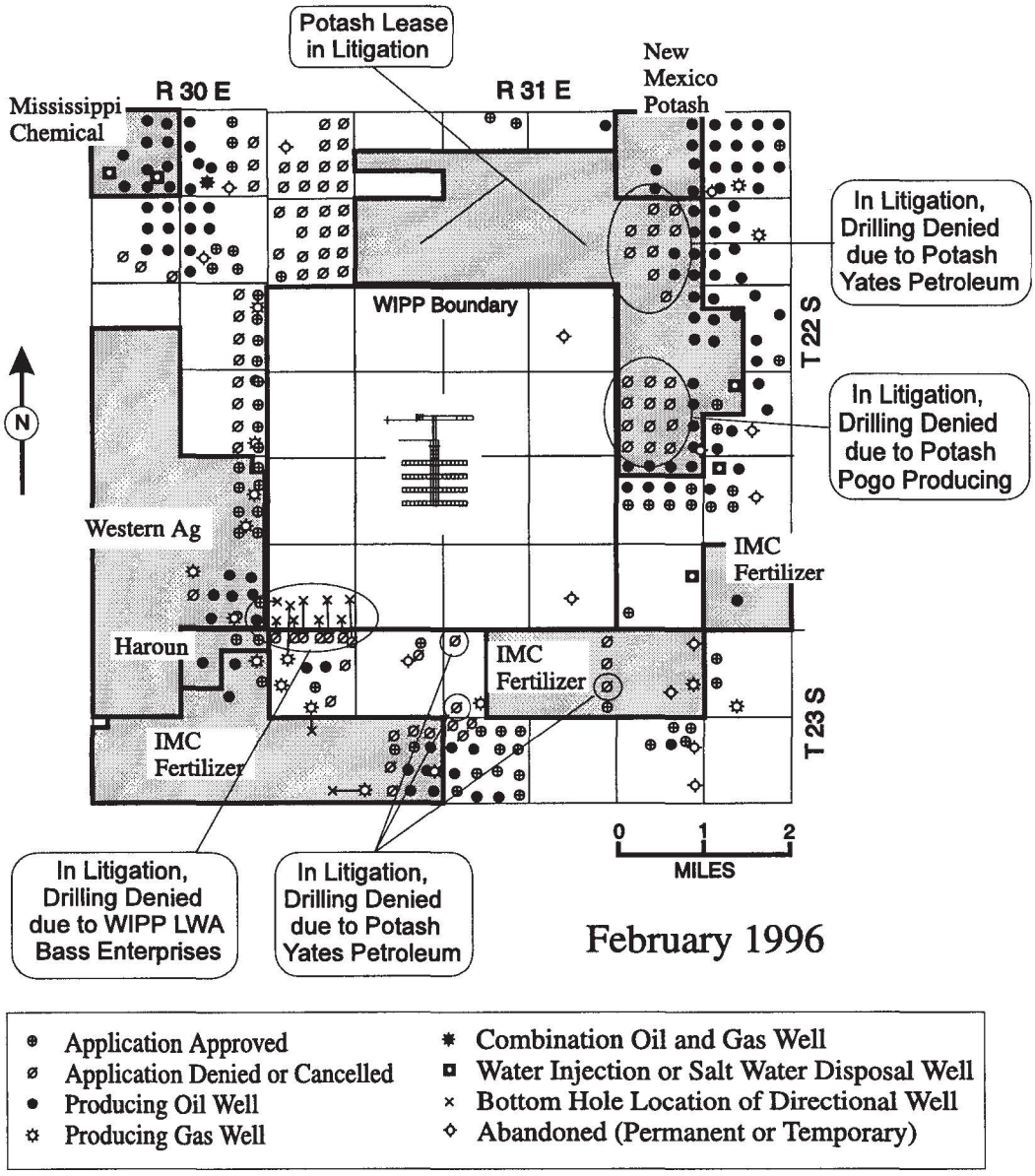

Figure 3-10. Current interest in resources surrounding the WIPP.

In arguing the ten to twenty feet of perforated casing as indicative of no large scale waterflooding, Lori Dotson did not discuss the Yates' wells in the Livingston Ridge. Yates Petroleum has drilled several wells in the west half of the Livingston Ridge but has completed them differently from other operators

(Broadhead et al. 1995, XI-16). All wells are perforated in the main pay and in most cases are also perforated in one to four other sandstones. While some of the completion records provide only the gross interval as shown in Figure 3-9, there is detailed perforation data for the first 3 wells in Section 11, T22S, R31E. Martha AIK Federal Well # 1 was perforated in three zones, 8236'-8308', 7960'-8015', and 7028'-7060', for a total of 159 feet (52 m) of perforations. Well # 2 was perforated in two zones, 6968'-6980' and 7035-7055', for a total of 42 feet (14 m). And Well #3 was also perforated in two zones for a total of 41 feet (13 m). Completion reports for wells #4, #5, and #6 provide only the gross interval of perforations. Wells 7 through 14 are waiting to be drilled. Due to the presence of potash deposits, the federal government has denied Yates' applications for permit to drill wells 7 through 14 (Burski 1994).[12]

3.2.5 Future Decades of Production in Oil Fields Surrounding the WIPP

Three presenters maintained that the oil fields surrounding the WIPP and producing from the Delaware Mountain group will have a maximum production life of less than twenty years. That position contradicts the position of the U.S. Department of Interior's Bureau of Land Management (DOI/BLM) (Woodard 1992, 3).

3.2.5.1 Position of the Department of Interior

The BLM denied Pogo Producing's twelve applications for permit to drill (APDs) in Section 23, T22S, R31E. This lease is immediately adjacent to the eastern boundary of the WIPP site. The APDs were denied because of possible impact on minable potash. Pogo Producing requested a U.S. BLM State Director Review. On March 18, 1992, the State Director of the U.S. BLM listened to a joint oral

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[12]EEG understands that this case may be in litigation and the EEG has no implied nor direct opinion in this case.

presentation by Yates, Pogo, and Texaco. As part of their arguments, Pogo estimated mining operations would not reach the subject area for 20-30 years. During the oral presentation, Pogo's representative and Yates' Engineer maintained that the total projected economic life of the field, including tertiary recovery, would be 15 to 20 years. Therefore, they argued, their oil and gas operation would be completed before potash mining operations reached the area.

However, the BLM noted that the possible deeper gas plays, the current stripper well policy, and the diligence of operations make this estimate of oil field life too short. The BLM maintained that the total economic life could be double the 15 to 20 year estimate (Woodard 1992). In other words, based on its own experience, the BLM anticipates an oil field life of 30 to 40 years.

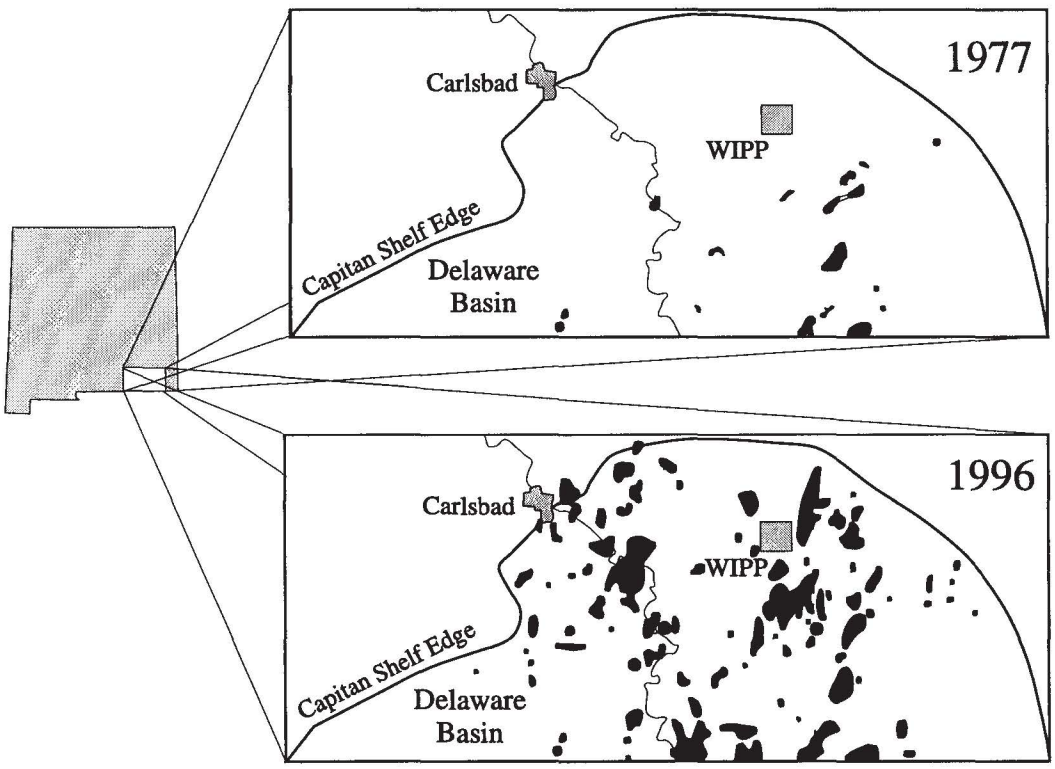

Figure 3-11. Delaware Mountain Group oil fields within the Capitan Shelf Edge of the Delaware Basin. After the Roswell Geological Society (1977) and Broadhead (1996).

Unfortunately, as indicated in Figure 3-11, the oil fields surrounding the WIPP having been only recently drilled, are not yet mature fields and cannot yet provide a direct determination of total field life. However, information in the literature and on public record for mature fields, in other areas of the Delaware Basin, suggest that primary production and waterflooding of the Delaware Mountain Group will generate at least thirty years and as much as fifty years of production after the initial development of a field. This suggests that the longer DOI/BLM estimate of 40 years (Woodard 1992) may be more correct.

Examples of successful waterfloods in the New Mexico portion of the Delaware Basin include Paduca, Indian Draw, and El Mar. The Paduca Field is an example of a successful waterflood that has been in production for over 30 years.

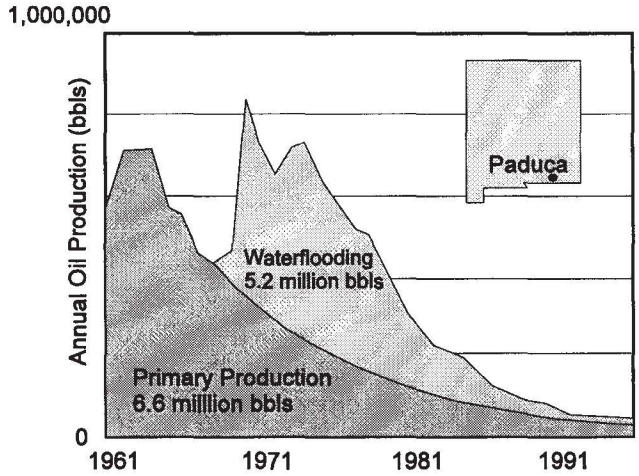

Figure 3-12. Production from Paduca Field. (Broadhead et al. 1995, Figure 38)

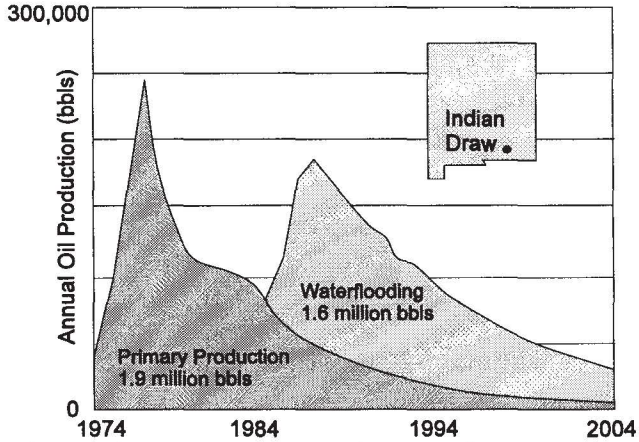

Figure 3-13. Production from Indian Draw. (After Broadhead et al. 1995, Figure 39).

Based on more than twenty years of actual production, including waterflooding initiated in 1980, the projections for the Indian Draw Field also indicate an anticipated oil field well life beyond 30 years.

One company operating in the Livingston Ridge area adjacent to the WIPP has submitted an affidavit which tends to support the position of a maximum of twenty years of operation (Boneau 1992, 2). Yates Petroleum maintains that oil and gas can be produced before any potash mining begins in this area (Boneau 1992, 2; Carroll and Bogle 1995, 33). As Broadhead (1995, XI-16) noted, Yates multiple zone completion practices are different from other operators in the area. Boneau states that Yates can complete primary and secondary development within 12 to 15 years. In the event of tertiary recovery, such as CO_2 flooding, the time would be extended by about five years for a maximum oil field life of twenty years. However, attorneys for Yates maintain that if there is waterflooding, "... the time to produce both primary and secondary oil should be in the range of 30 to 35 years" (Carroll and Bogle 1995, 33).

Comments by the University of Oklahoma Petroleum Engineering Professor Ron Evans at the EEG workshop tend to support oil field lifetimes closer to forty years:

> I will make this statement based on my experience in areas of Oklahoma. I do not believe that you are going to see oil production in the Delaware Basin cease totally in the next 20 years. I don't think that is going to happen. The tendency is like the food chain. You have the little people and you have the big people. Eventually it's the little people that are going to have that area and they'll tend to operate longer than say an Arco or Mobil would. I do not believe, for oil in the Delaware Basin, that production will cease within 20 years. I think it will be there 40 years from now because it will be in the hands of small operators.

3.2.5.2 Avalon Waterflood

Exxon (Bruce 1995c) filed for approval of an enhanced oil recovery project for the proposed Avalon Delaware Unit on May 9, 1995. The Avalon Field is about eight miles west of the potash area, hence the application is not encumbered by

the presence of potash. Specifically, Exxon proposes to inject water into the Cherry Canyon and Brushy Canyon members of the Delaware Mountain Group to promote oil recovery. Cantrell and Kane (1993) describe the geology and history of primary production in detail and note average permeabilities of 1.5 millidarcies (md) for the upper Cherry Canyon Formation and 1.1 md for the lower Cherry Canyon and upper Brushy Canyon Formations.

As noted in the unitization proposal (Bruce 1995b), Exxon projected that a waterflood would extend the producing life of the unitized formation beyond the year 2030. As Exhibit #3, Exxon plotted projected waterflood operations beyond the year 2040 for a field that began oil production in 1983. In terms of total field life, Exxon projects this field will be producing for at least fifty years.

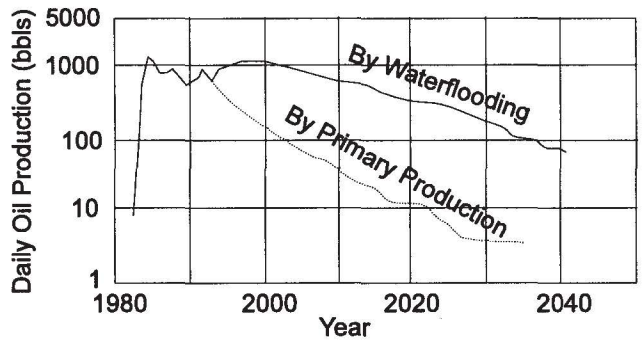

Figure 3-14. Waterflood vs. continued Primary Recovery at the Avalon Field (After Bruce 1995c).

3.2.5.3 Twofreds Waterflood and CO_2 Flood

The Twofreds Field, discovered in 1957 and developed by Mobil, is another example of the sequence of events, problems, and production longevity that might be anticipated for oil fields in the vicinity of the WIPP. The Twofreds is about 3/4 mile wide and is about five miles long with a net thickness averaging about 16 feet (5 m).

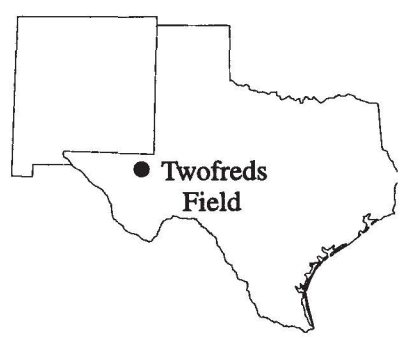

Figure 3-15. Location of Twofreds Field.

The Twofreds Field, like other Delaware fields, has always produced large volumes of water. After six years of primary production, a pilot water injection project with four injection wells was initiated in May 1963. The Twofreds was the first unitized waterflood in the Delaware Basin (Kirkpatrick et al. 1985). Success of the pilot project led to a full scale waterflood with 21 additional injection wells brought on line in January 1966. The waterflood project showed that oil from a Delaware reservoir with a high water cut could be recovered profitably (Jones 1968).

Early estimates anticipated that the Twofreds field would be depleted by 1975. However, carbon dioxide flooding extended the productive life of this field. HNG Fossil Fuel Company acquired the field from Mobil in 1973 for the purpose of initiating a carbon dioxide flood.

At the time of acquisition by HNG, most of the wells were in poor mechanical condition. Only 12 of the 89 wells were producing. Total field production ranged between 150 and 160 bbls oil per day. When the best producing well quit, total field production dropped to 100 bbls oil per day. There was a hole in the casing of the failed well. Many of the other production wells had been abandoned with rods, tubing, and other junk left in the well bores. And although the injection wells had been in waterflood service less than ten years, many had to be reworked to correct channelling problems. In some cases, the water had fingered through some zones, causing channels and leaks around the casing. These had to be repaired to prevent carbon dioxide from leaking out of the productive zone (Wash 1982)

By design, the Twofreds carbon dioxide injection wells were operated very close to the fracture pressure. Surface injection pressures were maintained at 1400 psi which resulted in a downhole bottom pressure of 3,000 psi, only about 100 psi below the fracture pressure. In describing the automatic pressure controls, the field superintendent, W.C. Mason noted:

> We walk a fine line between injection pressures and fracture pressures. If we were to exceed the fracture pressures, the gas would channel up the pipe and get out of zone. Therefore, we'd lose the drive off that well and all the oil that would have been pushed by the CO_2 (Wash 1982).

From 1957 to 1973, primary recovery produced 6.6 million bbls oil. From 1963 to 1973, secondary recovery produced 2 million barrels oil. By 1982, carbon dioxide flooding had produced an additional 2 million barrels of oil (Wash 1982). Carbon dioxide flooding increased oil recovery from 160 bbls oil per day to 1,000 bbls oil per day.

The purpose of the Twofreds carbon dioxide flood was to demonstrate economic feasibility. The field continued to produce based on its economic merit (Kirkpatrick et al. 1985) and demonstrated that carbon dioxide can economically recover tertiary oil from a depleted, waterflooded Delaware sand reservoir (Flanders and DePauw 1993). As of 1993, oil production from the Twofreds was averaging about 500 bbls oil per day (Flanders and DePauw 1993). The Twofreds Field clearly shows that even in a field where the reservoir energy is quickly depleted, fluid injection can improve oil production and add decades to the productive life of a Delaware Basin oil field.

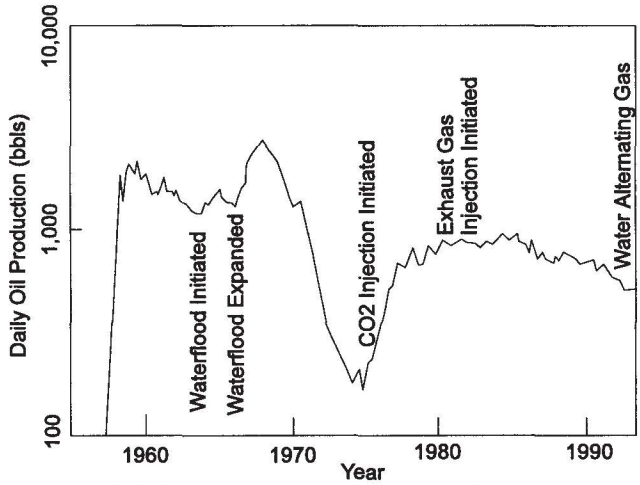

Figure 3-16. Production history of Twofreds (After Flanders and DePauw 1993).

3.2.5.4 El Mar Waterflood and CO_2 Flood

Independent operators continue to explore ways to extend the life of oil field production in the Delaware Basin. The El Mar has been producing from the Bell

Canyon Formation of the Delaware Mountain Group by primary recovery since 1959 (Porter 1966) and by waterflooding since 1968 (Broadhead et al. 1995).

In 1988, Union Royalty purchased the El Mar Unit from Texaco and others. In 1993, the unit was a mature waterflood producing about 140 bbls oil per day. Union Royalty planned to increase production to 2,000 bbls per day using carbon dioxide flooding. In exchange for an interest in the produced oil, Amoco would supply carbon dioxide through a pipeline to be built by Enron from the Dollarhide Field (Moritis 1993). If the success of the Twofreds project is any indication, the El Mar, which has been producing for 37 years can anticipate two or three additional decades of production.

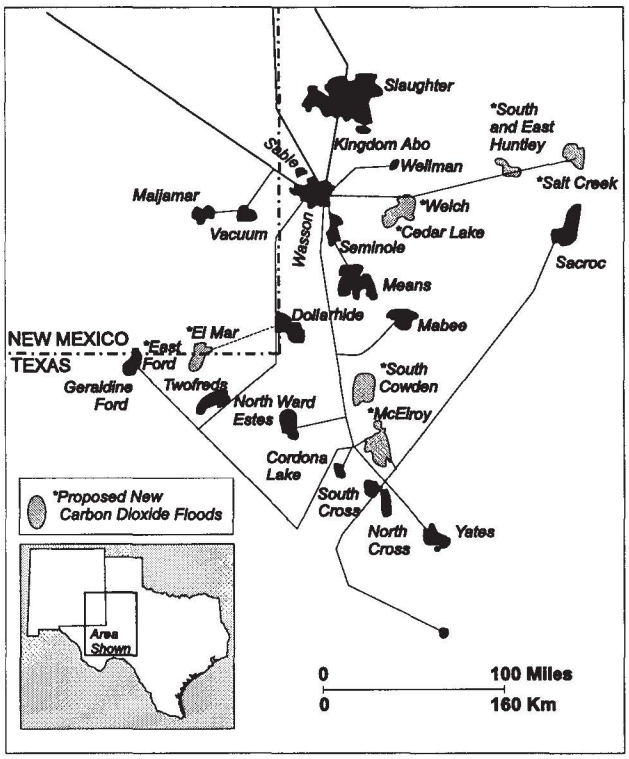

Figure 3-17. Permian Basin main CO_2 pipelines and CO_2 floods (Moritis, 1993).

3.2.6 Waterflood Volumes Around the WIPP

Lori Dotson maintained that waterflooding would not be a problem for the WIPP because such activity, if it occurred, would not be on the same scale as the Rhodes-Yates Field or the Vacuum Field waterfloods. There was disagreement about the amount of water needed to waterflood the oil fields surrounding the WIPP. Matthew Silva suggested that at WIPP, for ten million barrels of oil recoverable by waterflooding, 100 million barrels or more of injected water would

be needed. Stoelzel questioned whether that amount of water would be used for such small pools of oil.

Waterflooding in the vicinity of the WIPP is just beginning and, thus far, experience is limited to pilot pressure maintenance programs. The proposed Avalon Unit provides insight into the anticipated amount of water that is needed to recover oil by waterflooding the Cherry Canyon and Brushy Canyon members of the Delaware Mountain Group. This field lies approximately eight miles west of the potash enclave and is not constrained by the presence of potash. At Avalon, Exxon, has calculated that an additional 8.2 million barrels of oil (Bruce 1995c) will be recovered by injecting 141 million barrels of water through nineteen injection wells. Hence, the anticipated ratio of water injected to oil recovered, for the forty-year life of the project, is 17.2.[13]

For the one mile band surrounding the WIPP Site, Broadhead estimated 13.8 million barrels of the proven and probable crude oil reserves that could be recovered by waterflooding. Assuming the Avalon injection ratio of 17.2, for the life of such a project, one can estimate the volume of injected water will be 237 million barrels of water.

Texaco's Rhodes-Yates Lease was two miles away from Hartman's Bates Lease. Assuming that 29 million barrels of oil can be recovered by waterflooding (0.66 million barrels oil per section) and an injection ratio of 17.2 barrels water per barrel oil, for a two-mile band about WIPP, 500 million barrels of water could be injected over the life of these waterfloods. Of course, this simple estimate of future waterflooding must be viewed with caution. It is based on the estimated performance of an analog and is limited to the extrapolation of only proven and

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[13]The capital cost for the waterflood facilities at Avalon is estimated at $14.4 million and the estimated value of incremental production recovered from this project is estimated at $123 million based on a crude oil price of $15/ barrel (Bruce 1995a, 3).

probable reserves. It does not include possible reserves or undiscovered reserves of oil and gas underneath potash deposits.

Nonetheless, how does an anticipated 500 million barrels of water injected in the vicinity of WIPP compare with the Rhodes-Yates Field? At Rhodes-Yates, from 1964 through 1991, Texaco had injected approximately 41 million barrels of water through eighteen injectors (Hartman 1993, 5). This simple comparison strongly suggests that WIPP will eventually be surrounded by waterflood operations at least on the scale of the Rhodes-Yates Field and demonstrates that the two are comparable.

Actually, the pressure maintenance programs underway in the immediate vicinity of WIPP are already injecting far greater volumes of water than was injected in the pilot pressure maintenance program at Texaco's Rhodes-Yates Unit. Water from the two pilot injection wells at Rhodes-Yates totaled two million barrels from 1964 to 1974 or approximately 100,000 barrels water per well per year for a ten year period. Pogo Producing plans to inject 365,000 bbls of water per year into one well one mile east of the WIPP as part of its pilot pressure maintenance program in the Livingston Ridge Field.

At the Cabin Lake Unit, at the northwest corner of the WIPP Site, Phillips Petroleum has already begun operating two pressure maintenance wells. Water injection for pressure maintenance was initiated at the James A Well No. 12 (Sec 2, T22S, R30E) on February 18, 1992, and the James A Well No. 3 (Sec 2, T22S, R30E) on November 8, 1993 (Telford 1995). The volume of water injected through the James A Well No. 12 was 945,000 bbls for 1992, 1,121,000 bbls for 1993, and 738,000 bbls for 1994. The volume of water injected through the second pressure maintenance well in this area, the James A well No. 3 was 618,000 bbls for 1994. Based on the 1994 figures, these two wells are averaging approximately 1.4 million bbls water injected per year compared with 200,000 bbls water injected per year through the two pilot pressure maintenance wells at

Rhodes Yates. Furthermore, within ***three years*** of the initial operation, these two wells at the northwest corner of the WIPP Site had already injected four million barrels. This is more than twice the amount of water that was injected into the two pilot injection wells at Rhode-Yates in the ***ten year*** period following the initial operation of those wells. These observations strongly suggest that for the WIPP, the large scale waterflooding scenario cannot be ruled out on the basis of insufficient water injection.

In evaluating potential scenarios for the WIPP, the Hartman vs. Texaco case also demonstrates the need to consider the experience of other waterfloods despite any difference in size, in conditions, or in persons involved. Texaco argued to "exclude testimony relative to events or matters occurring in the waterfloods other than the Rhodes Yates waterflood, and to prohibit reference to other waterfloods by counsel for plaintiffs" (Lanphere and Sullivan 1994c; 1994d). Specifically, Texaco's attorneys maintained:

> On the other hand waterflood areas studied with respect to the 1977 hearings were larger waterflood projects than Rhodes Yates....
>
> The events in this case are vastly dissimilar in many respects to the events in the earlier waterfloods. There are fewer wells in the present field than were drilled in the earlier fields (Lanphere and Sullivan 1994d, 3,5)

Hartman's attorneys countered with the following argument:

> Texaco seeks to exclude by its Motion a wealth of data which correlates waterflows in Lea County to waterflood operations. The correlation is based upon public record documents which were generated by, among others, Texaco. The documents indicate that in the mid-1970s the New Mexico Oil Conservation Division determined that waterflood operations were causing waterflows, caused various operators, including Texaco, to establish committees to look into the issue, investigated specific injection

> wells and other aspects of waterflood operations in order to deal with the problem and never investigated naturally occurring sources of water as a potential explanation for waterflows which began to be reported after the start up of waterflood operations. The evidence shows that such waterflows were not randomly distributed, but are strongly correlated to waterflood operations (Gallegos and Condon 1994, 2).

In evaluating potential scenarios, the WIPP project needs to fully consider the experience of other waterfloods, particularly in light of the experience of oil fields overlain by the Salado. Such experience should not be rejected on the basis of difference in size (larger or smaller), differences in conditions, or differences in persons involved. There appears to be a technical basis as well as legal arguments for such consideration.

3.2.7 Availability of Water

Will there continue to be enough water for secondary recovery? Ron Evans commented on the increasing availability of water for oil field operations.

> If you look at water production in the United States, it has been going up significantly faster than overall oil production. We are producing more and more water in the United States than we ever have, in the oil producing regions of the United States.

More specifically, the volumes of water already being injected in the Delaware Basin, either for salt water disposal or pressure maintenance, do not hint at any water shortages for the purposes of oil field waterflooding. For example, the David Ross "AIT" Federal #1 salt water disposal well approximately one mile east of the WIPP Site typically injects between 80,000 and 100,000 barrels of brine per month. Other wells in the vicinity each typically inject volumes ranging between 10,000 and 100,000 barrels per month (Curry 1995; Hunt 1995; Garcia 1995;

Horsman 1995). Presumably, that water could be made available for waterflooding as reservoir pressures decline.

3.2.8 Formation and Well Bore Damage by Nitroglycerin Stimulation

Dan Stoelzel and Lori Dotson suggested that the practice of nitroglycerin blasting caused extensive formation and well bore damage in Rhodes-Yates Field and the Vacuum Field. They further maintained that because such practices are no longer used, there will be no such completion problems in the vicinity of the WIPP. The DOE has also adopted the position that the problems with Texaco's well completions in the Jal area resulted, in part, from the use of nitroglycerin blasting to stimulate the formation (McFadden 1996). However, the comments of Ron Evans tend to contradict the notion of extensive formation damage by nitro-fracing:

> The reason nitro-frac went out of business is because hydraulic fracturing is a superior stimulation technique. Hydraulic fracturing will give you much greater productivity increases than any nitro-frac ever did and that's well documented. Nitro-fracturing, as it was carried out in the late 40s and early 50s, did not destroy the cement shield. You can do the calculations and show, they place that little charge in the center of the formation and the maximum you could get would be of the order of about seven to ten feet zone of change in the radial direction and on the order of 15 feet in the vertical direction. That never even got you out of the Yates formation.

Hartman maintained that the excessive injection pressures in Texaco's Rhodes-Yates waterflood caused the salt water blowout on the Bates Lease. In commenting on the history of waterflood problems in New Mexico, Ramey (1995, XI-2) also states that water probably escaped from the injection zone and into the salt formations as a result of old improperly cemented and plugged wells and excessive injection pressures in oil field waterflood operations. These observations by Evans, Hartman, and Ramey, strongly suggest that stimulation by

nitroglycerin fracturing was not the source of the problem. Rather, it was argued that excessive waterflood injection pressures were the problem (Hartman 1993; Van Kirk 1994).

3.2.9 New Injection Well in Excess of WIPP Lithostatic Pressure

Pogo Producing recently requested and received approval from the New Mexico Oil Conservation Division to operate a pressure maintenance well one mile east of the WIPP site at a maximum surface injection pressure of 1410 psi (9.7 MPa) (LeMay 1995b). Public notice was given and a hearing was held on November 16, 1995. The results of the hearing included the following findings:

> (5) IMC Global Operations, Inc. (IMC), a potash operator in this area, appeared at the hearing and expressed concerns about permitting injection wells in close proximity to potash mining operations. Specifically, IMC is concerned that injected fluid will escape or otherwise migrate from the proposed injection interval into potash bearing formations.
>
> (6) Testimony presented in this case indicates that potash mining operations occur at depths of approximately 1,300 feet to 2,000 feet.
>
> (7) Evidence and testimony present by the applicant indicate that the proposed pilot pressure maintenance project is located:
>
> > a) within the Known Potash Leasing Area as describe within Division Order No. R-111-P;
> >
> > b) directly adjacent to a potash lease which encompasses portions of Section 3 through 5, 8 through 11, 13 through 14, 23 through 24, and 26, Township 22 South, Range 31 East, NMPM. The ownership of this potash lease is undetermined at this time due to ongoing litigation between IMC Global Operations, Inc. and Yates Petroleum Corporation;
> >
> > c) approximately eight miles from IMC's existing potash mine workings; and,

d) one mile from the outer boundary of the Waste Isolation Pilot Project (WIPP)

(8) The applicant notified the Department of Energy (DOE) of its application in this case, however, no representative of that agency appeared at the hearing. (LeMay, 1995b).

The findings also state that injection at an initial surface injection pressure of 1,410 psi should not result in the fracture of the proposed injection interval or confining strata. The well is designed such that the intended horizon for injection is approximately 7,000 feet below the surface.

But in the event of a leak, channeling behind casing, or movement through a vertical fracture, can brine be injected into the Salado Formation? In such an event, under the sustained pressure of a waterflood, what is the fracture pressure of the Salado Formation at the WIPP horizon and what is the hydrostatic pressure of the injected fluid at the WIPP horizon?

The lithostatic pressure at the WIPP horizon is 14.9 MPa (2160 psi). Assuming a brine with a specific gravity of 1.1 and an approved surface injection pressure of 9.7 MPa (1,410 psi), the injected brine can exert a hydrostatic pressure of approximately 16.8 MPa (2440 psi) at the WIPP horizon.

With respect to anhydrite or interbed fracturing, the WIPP conceptual model assumes that repository fracturing or dilation of existing fractures will be less than the lithostatic pressure (Howarth et al. 1995, Section 2.1.2.2). That assumption largely reflects experimental evidence in the excavated areas where the stress fields have been substantially changed. The anhydrite at the injection well bore may or may not be fractured, either naturally or by the drilling activity. Interbeds contain natural fractures which may be partially healed (U.S. DOE 1995, 6-73).

Experimental results indicate the fracture pressure for intact rock to be higher than lithostatic (Beauheim et al. 1993). However, the experiments of Beauheim et al. (1993) were designed to last only a few minutes, hence, they subjected the rock to a very rapid increase in fluid pressure. An injection well operates on the order

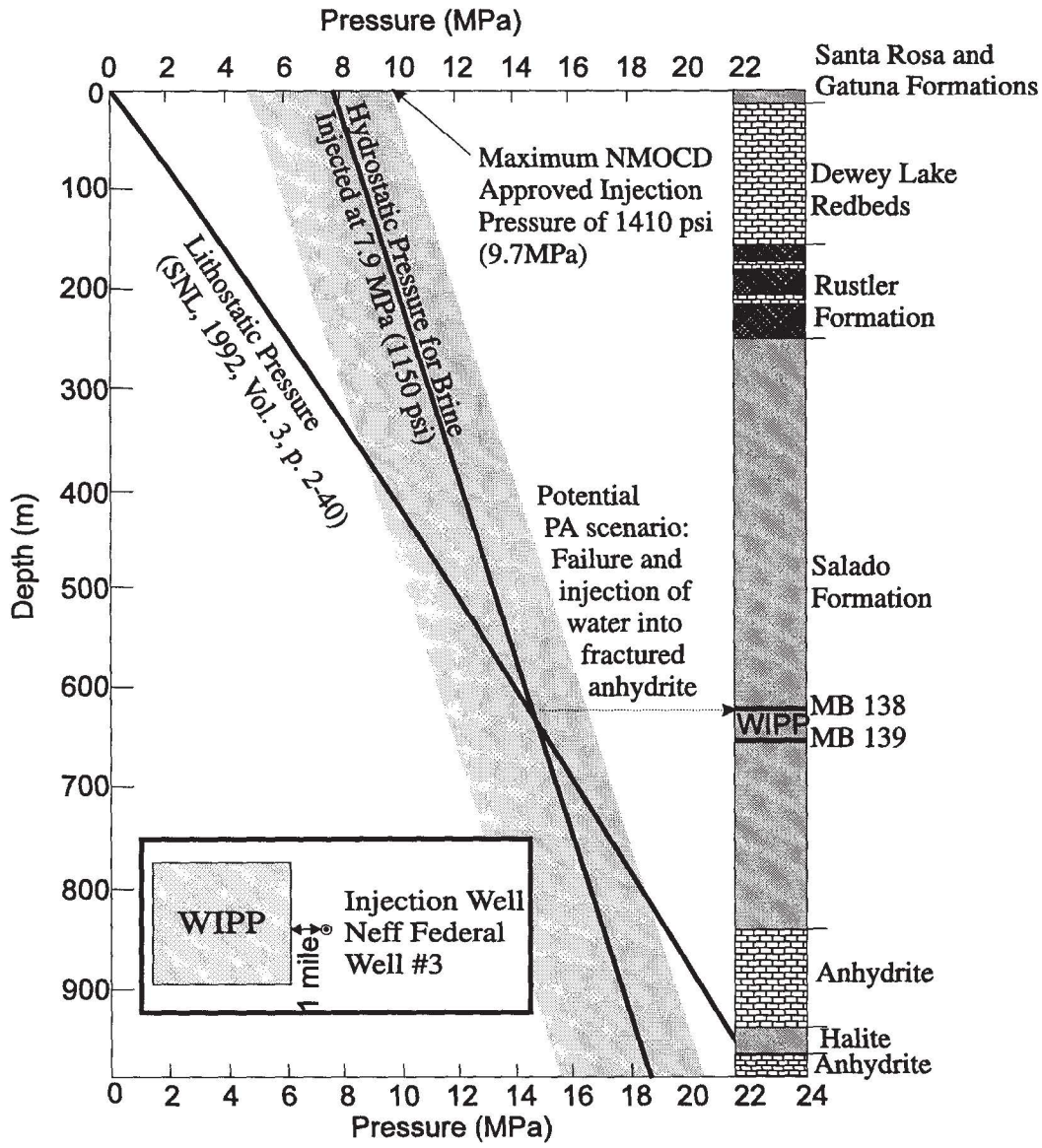

Figure 3-18. Approved Injection Pressure for Neff Federal Well #3 and Potential PA Scenario.

of years or decades. For fracture initiation and vertical fracture propagation, fracture pressures are lower for formations penetrated by an invading fluid (Haimson and Fairhurst 1967, Fairhurst 1968). Atkinson (1987, Chap. 4 and 5) also cautions about subcritical crack growth in the presence of a chemically active environment.

Rather than speculate on the potential for creating a new fracture or propagating an existing fracture in an anhydrite or other marker bed under pressure for a long period of time, this report notes that a pressure maintenance well, approximately one mile from the WIPP, has been approved to operate at an injection pressure 1.9 MPa (280 psi) above the lithostatic pressure at the WIPP horizon. Such a well typically injects brine over a period of several years. The plot of lithostatic pressure and hydrostatic pressure strongly suggests that, in the event of communication, fluid can be potentially injected into the anhydrite beds of the Salado Formation very near the WIPP horizon.

3.3 Regulations and the Salt Isolation Casing String

As noted by Dan Stoelzel, new state regulations require a salt isolation casing string for all wells drilled in the WIPP area. There are no specific oil and gas regulations that apply specifically to WIPP (Ramey 1995). Rather, the WIPP Site is located within the Potash Area near the eastern boundary. As a result of NMOCD Order R-111-P, signed April 21, 1988, all wells completed within the potash area must have a salt isolation string intended to protect the salt section from the intrusion of water and oil and gas (Ramey 1995, IX-1).

At the workshop, Armando Lopez (BLM) noted that a salt isolation string is not required for wells approximately one mile east of the WIPP Site. Exhibit A of R-111-P shows that Sections 26 and 35 (T22S, R31E) lie immediately adjacent to the WIPP site but are not part of the Known Potash Leasing Area. Hence, it appears the salt isolation string may not be required for all oil and gas wells completed in the vicinity of the WIPP.

In 1980, the Department of Energy intended to prohibit waterflooding within former control zone IV (U.S. DOE 1980, 8-4). The DOE surrender of that control was not based on any protective state or federal regulations, but on a report (Brausch et al. 1982) that incorrectly concluded that there would be no waterflooding because there was minimal recoverable oil.

As noted above, the state regulations for completing wells in the potash enclave are not specific to WIPP. In fact, R-111-P (LeMay et al. 1988) addresses only the incompatibilities between the activities of oil and gas production and potash production and does not mention WIPP. With respect to federal regulations, the Secretary of Interior makes it clear that one intent of the order is "to prevent the infiltration of oil, gas, or water into formations containing potash deposits or into mines or workings being utilized in the extraction of such deposits" (U.S. DOI 1986, III.A.4) However, this order is not intended to protect WIPP. Further, despite the salt isolation string requirement, federal and state agencies still restrict drilling for oil and gas through potash reserves or near potash mining operations.

Rather than rely on the intent of new regulations coincidental to the WIPP area, the DOE should fully consider the actual experience and implementation of existing regulations with respect to fluid injection. Such regulations have been in place for decades and provide a measure of the reliability. For example, the enabling orders for the Rhodes Yates waterflood (Campbell et al. 1964; Cargo et al. 1969; Ramey 1977) required operating in accordance with Rules 701, 702, and 703 (Hartman 1993, 4). Rule 702 requires cementing and casing of injection wells to prevent the movement of fluids out of zone. Rule 703 requires operation and maintenance practices to assure no significant fluid movement through vertical channels adjacent to the well bore. Further, the entire operation, including producing wells, must be operated and maintained to confine the injected fluids to approved intervals. The documented problems with the Rhodes Yates waterflood (Hartman 1993; Hererra 1995) and with waterfloods and salt water injection throughout the southeast New Mexico (Ramey; 1976; U.S. GAO 1989; Bailey 1990; Krietler 1994) clearly indicate the limitations of taking credit for state or federal regulations, new or old, for protecting WIPP.

3.4 Safety Analysis Report and Water Injection

Bill Bartlett (EEG) voiced concern at the workshop that waterflooding may need

to be considered in the Safety Analysis Report (SAR) for operations. George Dials noted that waterflooding should be considered in the Final Safety Analysis Report only if data exists which shows a high probability event that could adversely affect the WIPP during the 35 year operating life. George Dials added "there is waterflooding going on in the vicinity of the WIPP as has been discussed today. And we see no great increase in brine inflows and no great increase in moisture or anything else in the facility."

It appears that even small increases in the water inflow into the facility have an impact on the continuous air monitors. WIPP operations rely on continuous air monitors to detect a release of radionuclides. This detection is needed to divert the flow of any contaminated air through the HEPA filters. Water flowing into the exhaust shaft at a depth of approximately 50 to 100 feet (16 to 33 m) was identified as a potential problem for continuous air monitoring. In a report on continuous air monitoring, Bartlett and Walker (1996) commented that air flow through the sampling filter would be reduced as salt aerosol and moisture combine and collect on the filter. Low air flow through the filters at an underground air sampler was observed in 1994 and 1995. Moisture was the likely cause, strongly suggesting that water leakage problems can influence CAM performance (Bartlett and Walker 1996, 39).

Samples collected near the exhaust shaft collar by the DOE have been analyzed (Dials 1996).[14] The samples were analyzed for metals and inorganic compounds, but there was no analyses for hydrocarbons. Although there has been an effort to determine the source of the water (Westinghouse 1995, 1996a, 1996b, 1996c), it appears that the source of this water remains unknown. Hence, questions remain. What is the source of the water? At what rate of water inflow does the intruding

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[14] The inflow of water into the exhaust shaft was not discussed at the EEG workshop.

water create a problem for the air sampling system? And what happens when the water-flooding and brine injection activities become common place around the WIPP?

3.5 1995 DCCA - Features, Events, and Processes

When asked by Don Hancock (SRIC) how Sandia was going to determine the probability of waterflooding, Peter Swift (SNL) clarified that a feature, event, or process can be eliminated on the basis of one screening criterion. The three criteria of probability, consequence, and regulatory, are not all applied to each case. For example, if waterflooding is eliminated on the basis of "regulatory" criteria or "consequence" criteria, then there is no need to assign a probability. There is no need to calculate a consequence for an FEP that has been eliminated on the basis of another criteria. He also commented that he was not prepared to say how the project was going to screen waterflood FEPs. But he felt that an injection well failure at markerbed 139 with fluid migrating towards the WIPP site would be a low probability event that would be difficult to quantify.

On July 31, 1995, six weeks after the EEG workshop on waterflooding and salt water disposal, the DOE submitted a Draft Compliance Certification Application to demonstrate DOE met the requirements of the EPA Standards for the disposal of transuranic waste. As in 1991 and 1992, fluid injection was ***not*** included in the performance assessment calculations. All fluid injection was screened out on the basis of "regulatory guidance" (U.S. DOE 1995, 6-38). Furthermore, some human initiated events such as recent and ongoing fluid injection outside the controlled area were screened out on the basis of low consequence. No supporting documentation was supplied. Supporting documentation would be supplied with the final compliance application (U.S. DOE 1995, SCR-72).

The 1995 DCCA maintains that the screening procedure "is similar to that proposed by Cranwell et al. (1990, 5-10) and used in the 1991 and 1992 WIPP performance assessments" (U.S. DOE 1995, 6-2). However, Cranwell et al.

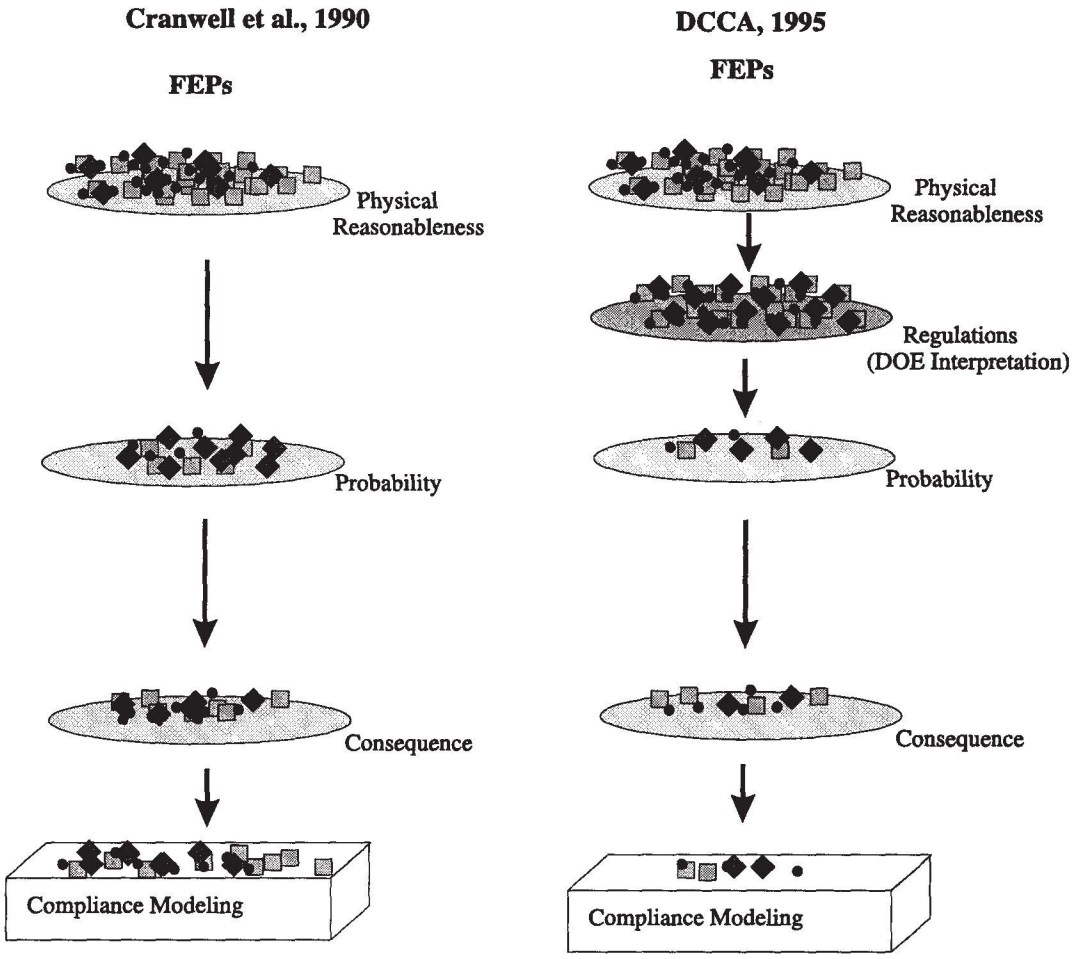

Figure 3-19. "Regulatory" sieve unique to WIPP.

(1990) did not discuss a "regulation" sieve to eliminate otherwise viable scenarios from consideration. This sieve is unique to WIPP (SNL 1992, Vol. 2, 4-3). Further, an inspection of the "regulation" sieve reveals it to be an interpretation of the non-binding guidance by the WIPP Performance Assessment Department which allows the WIPP Performance Assessment Department the latitude to eliminate any inadvertent human activity that could result in a consequence greater than those of exploratory drilling (SNL 1992, 4-4).

3.6 EPA Final Criteria (40 CFR 194) and Compliance Application Guidance

As required by the 1992 WIPP Land Withdrawal Act, the EPA published Criteria,

(U.S. EPA 1996a) for determining if the Waste Isolation Pilot Plant will comply with the EPA's environmental radiation protection standards for the disposal of radioactive waste. The EPA also published the Compliance Application Guidance (U.S. EPA 1996b) as a companion to the final rule.

The EPA Final Criteria for the disposal of transuranic waste requires the DOE performance assessment to address the issue of waterflooding and salt water disposal with the following language:

> Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, ***but shall not be limited to*** [15], existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities (U.S. EPA 1996a, 40 CFR 194.32 (c)).

As stated in the EPA Compliance Application Guidance (U.S. EPA 1996b):

> EPA recommends that the terms "near future" and "soon after disposal" for oil and gas drilling be considered to consist of the expected lives of the oil and gas fields in existing leases that can be reasonably expected to be developed in the vicinity of the WIPP.
>
> For mining, the terms "near future" and "soon after disposal" should be applied to the estimated lives of existing mines and plans for new mines in the vicinity of WIPP. EPA recommends that DOE use minable reserves in estimating mine lives and the extent of potential mining. When establishing the rate of growth for mines, DOE should consider both the

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[15]Emphasis added.

historical growth for mines and the potential for new mines that may be developed in the vicinity of WIPP.

3.6.1 Near Future

For the WIPP project, the DOE has already elicited expert opinion on the definition of *near future* with respect to the recovery of natural resources in the vicinity of a 10,000 year repository.

> For the Boston Team, the near future is 0-300 years after the lapse of institutional controls (100 years after closure). The Southwest Team used a 100-500 year period after closure for the near future while the Washington A Team use the first 200 years after the lapse of active controls. The Washington B Team also adopted a 200-year definition for the near future (Hora et al 1991, V-7).

With respect to current resource development, there appears to be a consensus among this group of experts that the near future includes at least a few centuries; certainly no less than three centuries after closure or at least 3% of the full regulatory period.

3.6.2 Federal and State Plans for Full Resource Recovery

Within two miles of the area withdrawn for the WIPP, the WIPP is surrounded by forty eight sections of federal and state lands. These public lands are managed by either the U.S. Department of Interior or the State of New Mexico. These lands are within the Secretary's Boundary (U.S. DOI 1986) for the potash area. In addition to federal policy (U.S. DOI 1986) for the management of federal lands in the potash area, the management of the federal lands are also subject to the Federal Land Policy and Management Act (FLPMA 1989). The state lands are subject to state regulations protecting natural resources, specifically oil, gas, and potash (LeMay et al. 1988).

With respect to federal lands, it is the stated intent of the Secretary of Interior (U.S. DOI 1986) to "adequately protect the rights of the oil and gas, and potash lessees and operators," (U.S. DOI 1986, 39425). FLPMA intends for "the public lands to be managed in a manner which recognizes the nation's need for domestic sources of minerals, food, timber, and fiber..." (FLPMA 1989, §1702(12)). In addition, FLPMA requires the management of federal lands "be on the basis of multiple use and sustained yield unless otherwise specified by law" (FLPMA 1989, §1701 (7)). "The term multiple use means the management of the public lands and the various resource values so that they are utilized in the combination that will best meet the present and ***future needs*** [emphasis added] of the American people" (FLPMA 1989, §1702(c)). The term multiple use also means "a combination of balanced and diverse resource uses that take into account the ***long-term needs of future generations*** [emphasis added] for renewable and nonrenewable resources...." Sustained yield is defined as "the achievement and management ***in perpetuity*** [emphasis added] of a high-level annual or regular periodic output of the various renewable resources of the public land consistent with multiple use" (FLPMA 1989, §1702(h)). By federal law, human activities in the resource rich areas surrounding the WIPP do not appear to be not limited to the ***near future*** and are not limited to ***the expected use of existing leases***.

The objective of the rules and regulations of the state of New Mexico "is to prevent waste, protect correlative rights, assure maximum conservation of the oil, gas and potash resources of New Mexico, and permit the economic recovery of oil, gas, and potash minerals in the area hereinafter defined" (LeMay et al. 1988).

It is the policy and plans of both federal and state law to promote resource production on these public lands adjacent to the WIPP Land Withdrawal Area. None of the public lands adjacent to the WIPP have been withdrawn from resource development. Hence, the DOE application should assume that potash, crude oil, and natural gas will be allowed to be fully developed, including fluid injection activities necessary for resource recovery.

3.6.3 Oil and Gas Resources

In addition to the oil and gas reserves estimated by Broadhead et al. (1995), the application should also reflect that oil and gas reserves have not yet been quantified on many sections surrounding the WIPP site due to the U.S. Department of Interior and the State of New Mexico restrictions on drilling for petroleum in the potash deposits (U.S. DOI 1986; LeMay et al. 1988). Fifteen sections within the two mile band surrounding the WIPP do not have a single oil and/or gas well drilled into them. Or in terms of forty-acre units, of the 768 forty-acre units within two miles of the WIPP Boundary, 652 of the units do not yet have any oil or gas wells. In other words, 85% of the area immediately surrounding the WIPP has yet to be directly tested for oil and gas. The oil and gas leases in many of these areas have been assigned, but permission to drill has been denied and/or is in litigation (Burski 1994). Similarly, potash reserves are in litigation (Parker 1993) or have yet to be assigned although at least one potash company has stated that it intends to mine these reserves on public land (Morehouse 1995).

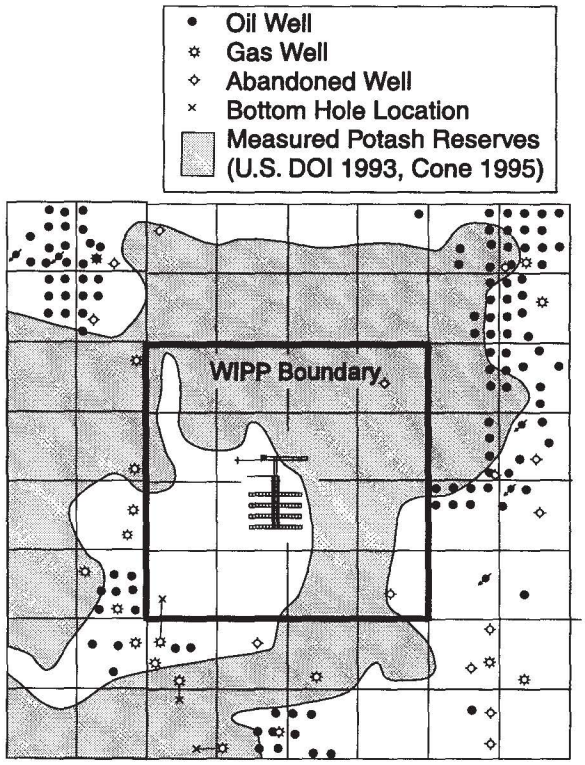

Figure 3-20. Actual oil, gas and injection well boreholes.

The nature of any resource recovery activity, including the oil and gas business, is such that today's non-economical resources often represent tomorrow's producible reserves. The application for a 10,000 year repository should reflect

an understanding of that principle of natural resource economics and can not limit itself to a simple assumption of current economic value. And as emphasized in the executive summary of the 1995 natural resources study (NMBM&MR 1995), the discovery of reserves of oil and gas can hinge simply on a better interpretation of well logs. Hence, current estimates of oil and gas resources reflect, to some extent, the limits of the current interpretation of well logs. Due to the nature of oil and gas production, as practiced throughout southeastern New Mexico, throughout the Delaware Basin, and in the vicinity of the WIPP, the existing federal plans and state plans inherently include salt water disposal and waterflooding throughout each and every federal and state section surrounding the WIPP Site.

3.6.4 Fluid Injection for 10,000 Years

The DOE application may need to consider fluid injection adjacent to the site and within the site for the full 10,000 year period. In the 1991 DOE elicitation of expert opinion on future activities in the vicinity of the WIPP, only one of four teams addressed fluid injection. This team was aware of the need to dispose of waste brine associated with oil production (Gordon et al. 1990, C-29), but was not aware of the extent of drilling for crude oil in the vicinity of the WIPP (Silva 1994, 28-35). Hence, the elicitation panel concluded that the current level of industrial activity in the WIPP area to be low (Hora et al. 1991, IV-10). Nonetheless, three members of the this team assigned probabilities for injection of waste brine associated with other industrial activities for the full 10,000 years. Further, the probability of a larger number of such injection wells was predicted to increase with time for the full 10,000 year period (Hora et al. 1991, Table IV-16).

3.6.5 Areal Extent of Delays in Oil and Gas Production

As to potential delays in oil and gas production and fluid injection due to the presence of minable potash, that issue is still in deliberation (Burski 1994).

Furthermore, there appears to be some disagreement as to what constitutes minable potash. The estimates of potash resources prepared by Griswold (1995a) for the New Mexico Bureau of Mines and Mineral Resources acknowledges federal policy but uses an economic limit which is different from federal policy, resulting in minable areas substantially smaller than federal policy. Cone (1995) later cautioned Griswold about BLM policy and experience. Griswold (1995b) subsequently acknowledges that his interpretation of the estimated extent of potash reserves is "conservative." According to Cone (1995), the federal position for minable potash is 4 feet by 10% for sylvite ("40" contour) and 4 feet 4% for langbeinite ("16" contour). Hence, the federal position on the actual area of minable potash, which could impact the near future activity of oil field production and fluid injection, is significantly larger than that mapped by the "55" contour for sylvite and the "37.5" contour for langbeinite in the natural resources study by the New Mexico Bureau of Mines and Mineral Resources (1995). Drilling for oil and gas may be delayed over a much larger area, thus extending the time for such near future activities.

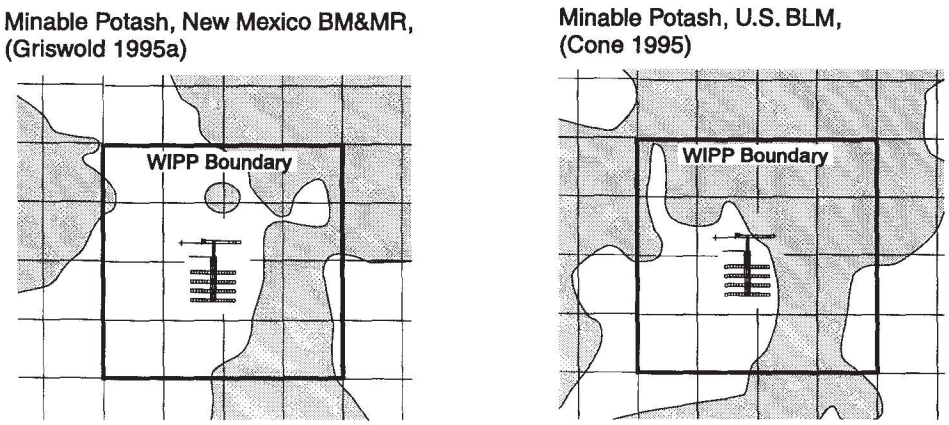

Figure 3-21. Areal extent of minable potash as determined by U.S. BLM and New Mexico Bureau of Mines and Mineral Resources.

3.6.6 Enhanced Oil Recovery by Carbon Dioxide or Gas Injection

The DOE application is sponsoring a new research effort that is exploring the use of pressure maintenance programs and advanced reservoir management to improve oil recovery from fourteen sands in the Brushy Canyon and Cherry Canyon members of the Nash Draw Unit (Strata Production 1996) in the potash enclave. One goal is to transfer the technology to oil and gas producers throughout the Permian Basin. The Department of Energy is sponsoring the project at an annual budget of 1.8 million dollars. The permeabilities in the sands are relatively low, ranging from 0.5 to 18 millidarcies. Although not stated in the progress report (Strata Production 1996), the low permeabilities strongly suggest that it may be necessary to inject a low viscosity fluid such as carbon dioxide or natural gas. Presumably, the Department of Energy is investing in this project, in the Delaware Basin, with the anticipation that such fluid injections will improve oil recovery. The DOE WIPP application should reflect this effort to enhance oil recovery in Delaware sands.

3.6.7 Summary

In summary, the DOE WIPP application to EPA can assume that for crude oil, there will be drilling on a minimum of forty acre spacings in the areas in litigation. There will also be drilling on a minimum of forty acre spacing in areas identified by Broadhead et al., (1995) known to contain proven and probable oil reserves, and there will be drilling into the fifteen yet to be explored sections within two miles of the WIPP. The extent of oil and gas resources remain to be determined. Experience has also shown that additional reserves are often discovered as a result of improvement in well log interpretation (NMBM&MR 1995). The DOE application needs to demonstrate an understanding of the economics of resource recovery and the concept of future reserves, an understanding of federal and state policy and plans regarding resource recovery on public lands, including pressurized fluid injection, an understanding of how

pressurized fluids can transport radionuclides to the accessible environment, and an understanding that the EPA intends that the repository curb the release of radionuclides to the accessible environment for a 10,000 year regulatory period, not just the near future. The application can realistically anticipate that salt water disposal activities and waterflooding, as practiced in the Delaware Basin and in southeast New Mexico, will take place throughout the area surrounding the WIPP. The application needs to consider other fluid injection, such as gas pressure maintenance, and needs to anticipate industrial waste injection over the full 10,000 year life of the repository.

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5. LIST OF ACRONYMS

ANPR	Advance Notice of Proposed Rulemaking
APD	Applications for Permit to Drill
BBL	Barrels
BLM	Bureau of Land Management
CAO	Carlsbad Area Office
CARD	Citizens for Alternatives to Radioactive Dumping
CFR	Code of Federal Regulations
DCCA	Draft Compliance Certification Application
DOE	U.S. Department of Energy
DOI	Department of Interior
EEG	Environmental Evaluation Group
EPA	U.S. Environmental Protection Agency
ERDA	Energy Research and Development Administration
FEP	Features, events, and processes
FLPMA	Federal Land Policy and Management Act
GAO	U.S. Government Accounting Office
GPM	Gallons per minute
MOU	Memorandum of Understanding
MPa	Megapascal
NAS	National Academy of Science
NMBM&MR	New Mexico Bureau of Mines and Mineral Resources
NMEMD	New Mexico Energy and Minerals Department
NMEMNRD	New Mexico Energy, Minerals, & Natural Resources Department
NMOCD	New Mexico Oil Conservation Division
NMPM	New Mexico Principal Meridian
OCD	New Mexico Oil Conservation Division
PA	Performance Assessment
PCs	Personal computers

LIST OF ACRONYMS (continued)

PSI	Pounds per square inch
RCRA	Resource Conservation and Recovery Act
SAR	Safety Analysis Report
SC&A	Sanford Cohen and Associates
SNL	Sandia National Laboratories
SWD	Salt water disposal
SRIC	Southwest Research and Information Center
TA	Temporarily Abandoned
TRU	Transuranic
USCA	United States Code Annotated
U.S. EPA	U.S. Environmental Protection Agency
U.S.G.S	U.S. Geological Survey
U.S. GAO	U.S. Government Accounting Office
VOC	Volatile organic compound
WIPP	Waste Isolation Pilot Plant

6. LIST OF WORKSHOP ATTENDEES

Rip Anderson	SNL
Bob Andrews	NAS/NRC
David Back	SC&A
James Barker	NMBM&MR
Bill Bartlett	EEG
Rick Beauheim	SNL
Sarah Bigger	CAO
Bob Bills	DOE
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Ron Broadhead	NMBM&MR
Chuck Byrum	EPA
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David Catanach	NMOCD
Jim Channell	SC&A
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Kevin Donovan	Westinghouse
Lori Dotson	SNL
Ron Evans*	OU and Texaco
Don Hancock	SRI
Garland Harris	CARD
Susan Hirshberg	CCNS
Mike Irwin	SNL
William Lee	EEG
Armando Lopez	BLM
Lindsay Lovejoy	N.M. Attorney General's Office
Keith McKamey	NMED/WIPP

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EEG 64

REVIEW OF THE DRAFT SUPPLEMENT TO THE WIPP ENVIRONMENTAL IMPACT STATEMENT DOE/EIS-0026-S-2

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New Mexico

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April 1997

FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, is being constructed as a repository for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, continues the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the generator sites' compliance with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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OUTSTANDING CONCERNS

EEG has published reviews of the previous DOE Environmental Impact Statements (EIS) on WIPP including:

EEG-3 *Radiological Health Review of the Draft Environmental Impact Statement (DOE/EIS-0026-D) Waste Isolation Pilot Plant, U.S. Department of Energy*, August 1979

EEG-10 *Radiological Health Review of the Final Environmental Impact Statement (DOE/EIS-0026) Waste Isolation Pilot Plant, U.S. Department of Energy*, January 1981

EEG-41 *Review of the Draft Supplement Environmental Impact Statement, DOE Waste Isolation Pilot Plant*, July 1989.

Written comments also were provided to DOE on the Final 1990 Supplement to the EIS on WIPP in April 1990. The 1996 Draft Supplement to the EIS (SEIS-II), DOE/EIS-0026-S-2, was received on November 25, 1996, and this review contains our analysis of that document. The 90 day deadline for comments established by DOE was not adequate to do a thorough job since it was necessary to also review the final DOE Compliance Certification Application (CCA) as well as the Safety Analysis Report (SAR) in the same time frame.

Our principal concerns are as follows

- The long-term disposal impact of the Proposed Action is being addressed in much more detail through the DOE Compliance Certification Application (CCA) which provides one year for review. Evaluating alternatives to the Proposed Action outlined in the SEIS cannot be meaningfully addressed in sufficient detail in 90 days.

- Chapter 6 lists all regulatory agencies and the status of permits for WIPP. One regulatory agency is notably absent. It is DOE. The Department has the legal authority to self regulate operational activities at WIPP. The status of WIPP's compliance with DOE Orders or even a list of DOE Orders is conspicuously absent. Indeed, DOE has the authority to self-approve the Draft Supplement to the EIS but fails to describe the internal system to be used. As an example, the DOE long-term disposal calculations in the SEIS are approved by DOE and in the CCA by EPA.

- Parameters and analyses differ in the various DOE WIPP documents such as the SEIS-II, the Compliance Certification Application (CCA) and the Safety Analysis Report (SAR).

- The alternatives are not reasonably viable. As DOE notes, alternative #1 and alternative #3 are in violation of the WIPP Land Withdrawal Act. Alternative #2 exceeds the limits of RH-TRU in the NM/DOE C&C Agreement. The problems of underground stability in leaving the repository open for 150 to 190 years (which would also require new shafts and surface facilities) are not addressed. It would make more sense to complete WIPP and then propose a second repository, tailored to the unique needs of RH-TRU waste emplacement including limits on thermal loading and criticality. The SEIS should address this alternative.

- The alternatives include almost doubling the authorized waste volume, bringing non-defense TRU waste and commercial TRU waste. Increasing the curie inventory would increase the amount of transuranics allowed to be released.

- While several EEG documents are cited, there are a number of relevant EEG publications that the SEIS-II authors have not cited that are directly relevant to the environmental impact of WIPP.

- The text indicates that DOE has a need to dispose of all TRU wastes and does not consistently recognize that only defense TRU wastes can be disposed at WIPP according

to law. Transuranic wastes generated by non-defense activities or civilian nuclear activities of the Department are not eligible for disposal at WIPP. (This point is recognized later by DOE on page 5-7, lines 5 and 6). To avoid confusion, non-authorized waste issues should be clearly identified.

- The document acknowledges that the expected quantity of RH-TRU waste of 35,000 m^3 far exceeds the WIPP design capacity of 7,080 m^3. But the Basic Inventory Table for the Proposed Action shows 35,000 m^3 and the Draft PEIS shows <u>all</u> TRU waste as coming to WIPP. Since RH-TRU waste is not scheduled for shipment for several years, the effective capacity for RH-TRU will only be about 4,300 m^3 with the present design. SEIS-II makes no mention of the need to modify the waste emplacement design in order to accommodate 7,080 m^3 of RH-TRU. Again, footnotes indicate that only the authorized amounts would be disposed at WIPP but it is needlessly confusing.

- EEG is pleased that DOE is seriously considering treatment of radioactive wastes. For years EEG has noted that waste is respirable, soluble and confined by a carbon steel Type A drum. The 20 year longevity requirement for the drum has been deleted by DOE from the WAC as has the 1% limit on respirable particles. In contrast, certain low level wastes are required by NRC to have a 300 year design life for the waste container or the waste form. We believe that modifying the waste form through thermal treatment and shredding and grouting should be vigorously pursued to accommodate the anticipated volume of TRU waste which is twice the capacity of WIPP.

- The inhalation risks to people on the surface from future human intrusion were deemed inconsequential and not calculated in the SEIS-II despite earlier work by both EEG (EEG-11) in January 1982 and DOE (TME 3151) in July 1982 that concluded inhalation is a significant concern.

- Unwarranted claims of conservatism for long-term performance calculations are made in the SEIS-II.

- EEG compared the results of the routine and accidental risks from truck transportation to WIPP with findings in EEG-46 ("Risk Analysis of the Transport of Contact Handled Transuranic (CH-TRU) Wastes to WIPP Along Selected Highway Routes in New Mexico Using RADTRAN IV," Anthony F. Gallegos and James K. Channell, EEG-46, August 1990). Agreement was quite close when allowance was made for differences in miles traveled and other assumptions. Therefore we believe the assessment of transportation risks in SEIS-II is reasonable and adequately conservative.

- For over 20 years, the Department's policy has been to dispose of defense transuranic waste at WIPP rather than leave it at the generator sites indefinitely. The August 1995 DOE Draft Waste Management Programmatic Environmental Impact Statement provides calculations that indicate leaving the waste at the generating sites indefinitely rather than disposal at WIPP would result in fewer cancer fatalities, a smaller collective radiation dose, and a cheaper cost. The SEIS-II needs to explain the reasons why technical objections have not been raised by CAO on these 8/95 DOE conclusions. It is important for credibility that a detailed analysis of the basis of these diametrically opposed conclusions be provided. (SEIS-II, page 3-46 and PEIS, page 8-86).

- Calculations of the long-term consequences should use the analyses submitted in the EPA Application. SEIS-II used methods and data in the Draft Application. EEG had extensive comments on the draft and published them in EEG-61.

SUMMARY

EEG's review of the WIPP Disposal Phase Draft Supplemental Environmental Impact Statement (SEIS-II) concentrated on the radiological aspects of the Proposed Action, including transportation. The alternatives were reviewed in less detail. Some calculations were checked, mostly for the Proposed Action. Because of time constraints, there was little review of Hazardous Chemicals, Economics, or other Environmental Assessments.

SEIS-II was written as a pre-decision document with the Alternatives all plausible and eligible to be selected. Also, the inventory of TRU waste for disposal went well beyond that portion of TRU waste that has been historically considered to be the WIPP inventory. This broadened scope is probably appropriate for an EIS but it is confusing to the reviewer who is aware of the statutory limits of wastes that are allowed to come to WIPP at the present time. EEG has attempted to keep the broadened scope of SEIS-II in mind during our review.

A number of calculations, logic, and perhaps typographical errors were found and are pointed out in the detailed comments. Also, omissions that we believe should be included are mentioned. The more important issues are discussed below.

Alternatives

EEG is bothered by the choice of Alternatives considered. Compared to the Proposed Action, they deal with larger volumes of TRU waste, continue over a much longer period of time and have been evaluated in a more preliminary manner. There is a question of whether these were intended to be viable options. Certainly there is a need for real options to dispose of TRU wastes not included in the WIPP statutory limits.

EEG recommends that short-term, partial solution options be included in the Final SEIS-II and be considered in the Record of Decision (ROD).

Related Documents

SEIS-II recognizes and refers to other important WIPP related documents such as the Compliance Certification Application (CCA), Baseline Inventory Report (BIR - Revisions 2 and 3), and the Safety Analysis Report (SAR). However, SEIS-II, which was published after the CCA and the latest SAR, does not incorporate the latest information or use the same methodology as these documents. The use of different methodology and results in DOE documents published around the same time is inconsistent, confusing and unnecessary. EEG recommends that the Final SEIS-II use methodologies and results from the CCA and the latest SAR because these documents contain more detailed and peer reviewed analyses.

Transportation

EEG checked the transportation calculations in Appendix E and compared these results to those contained in EEG-46. It is concluded that the assessment of transportation risks in SEIS-II is reasonable and adequately conservative.

Analyses in SEIS-II indicated potential advantages to using rail rather than truck transportation for wastes. The rail analyses were not as rigorous as those for truck transportation. However, the findings were consistent with analyses in the FEIS, SEIS-I, and other documents. There appears to have been no serious re-evaluation of WIPP's "truck only" policy in the approximately 12 years since it was established. EEG believes that DOE should take this opportunity to seriously re-evaluate the merits of a "truck/rail mix" or a "maximum rail" policy for WIPP wastes.

Questionable Assumptions

There are a number of questionable assumptions, omissions, or errors in SEIS-II. These are mentioned in the page-by-page comments. The more important ones are given below. The page location in SEIS-II is given in parenthesis.

Human Intrusion at 100 years. The assumption is made that drilling into the repository 100 years after repository closure would lead to maximum consequences. This determination cannot

yet be made. Increased releases from higher pressures in the repository after 100 years may more than offset radionuclide reductions due to radioactive decay. (page 5-45).

Use of 75th Percentile Values. It is argued that the use of 75th percentile parameter values in modeling of long-term releases due to human intrusion will yield consequences that fall in the "upper tail of a full probabilistic analysis." In the actual analysis SEIS-II used median values for most of these parameters and came up with values of radionuclide releases to the surface that were identical to those with median values (Table H-24). We conclude that these are not upper tail releases. (page 5-40).

Family Farm Scenario and Inhalation Doses. The decision was made in SEIS-II that a family farm scenario with inhalation doses from resuspended drilling mud pit material was inappropriate. This is directly contrary with conclusions in SEIS-I as well as EEG and Westinghouse reports. (page 5-41).

Modification of BRAGFLO Volumes. The z distance in a two-dimensional grid was increased by factors of approximately 8 (see Table H-8) in order to accommodate the larger waste volumes in Action Alternatives 1, 2, and 3. This violates the two-dimensional assumption of the BRAGFLO grid. A three-dimensional analysis may be needed to give reliable results. Table H-8 is confusing.

Emplacement of RH-TRU Wastes. Values are given for the volumes of CH-TRU and (especially) RH-TRU wastes that will have to be put into Panels 9 and 10 in order to meet design capacity for the Proposed Action. There is no indication of whether such an increase is possible. (page 3-12).

Conversion Error. Numerous Figures in the Summary Chapter, Chapter 5, and appendix H show the wrong conversion factor from Ci/m^3 to pCi/l. The correct conversion factor is 1 pCi/l= 10^{-9} Ci/m^3. There is uncertainty about which value is used in the plots and this is potentially important. (pages S-51 and 5-43).

RH-TRU Cask. The statement is made that "The Department is currently awaiting NRC certification of the RH-72B cask. DOE had not submitted an application to NRC for certification of the RH-72B cask at the time the SEIS-II was published.

GLOSSARY

Page GL. Line 1.

The definition of backfill as "materials placed in storage panels or drifts" is too ambiguous. CH-TRU waste and RH-TRU waste as well as the drums and containers are placed in storage panels, but they do not qualify as backfill.

Page GL-2. Line 4.

The definition of background radiation does not include global fallout as it exists in the environment. Global fallout is considered to be man made radiation.

Page GL-2. Line 12.

The glossary should include a definition for the Becquerel since it includes a definition for the curie.

Page GL-3. Lines 28-32.

The definition of contact-handled transuranic waste should start with the term "TRU waste" instead of the word "waste".

Page GL-3. Line 13.

The spelling of sievert is incorrect. Also, the sievert is abbreviated as Sv.

Page GL-5. The definition of disposal should use the definition in the WIPP Land Withdrawal Act.

Page GL-5. The definition of disposal phase should use the definition in the WIPP Land Withdrawal Act.

Page GL-5. Lines 33-36.

The definition of absorbed dose should also include the mks unit known as the gray and abbreviated as Gy.

Page GL-5. Lines 37 through 39.

The definition of dose conversion factor should use "resultant dose equivalent" instead of "resultant radiation dose."

Page GL-9. Lines 4 through 7.

The definition of high-level waste should include unreprocessed spent fuel.

Page GL-9. Lines 22 through 26.

The definition of the phrase "immediately dangerous to health" only includes" maximum airborne concentration". The phrase also applies to a dose rate, e.g. 1,000 rem/hour.

Page GL-14. Lines 16 through 20.

The definition of remote-handled transuranic waste should start with the term "TRU waste" instead of the word "waste". Also, while the radiation level at the outer surface of the container is less than 1,000 rem/hour, there is a volume limit of 12,500 cu ft for wastes that have radiation doses that are greater than 100 rem/hr at the outer surface.

Page GL-18. Lines 1 through 4.

The definition of WIPP should be changed. WIPP is no longer an experimental facility.

ACRONYMS

Page AC-1. Line 19.

Only BIR-2 is defined. BIR-3 should also be defined since it is described on page 1-8.

Page AC-1. Line 42.

The AC-section has an acronym for design-basis earthquake, but it does not have an acronym for design-basis criteria.

Page AC-3. Line 46.

PA stands for Performance Assessment. The acronym for Preliminary Performance Assessment would be PPA.

Page AC-4. Line 15.

At present the RH-72B cask is only a proposed RH-TRU shipping container. The design was not submitted by the DOE to the NRC until 12/96.

Page AC-4. Line 33.

The definition of SWIFT-II should indicate that it is computer software.

Page MC-2. Table MC-1.

The table should include other conversion factors such as a conversion factor from Psi to Pa and conversion factors from darcy to other units of permeability.

SUMMARY CHAPTER

Page S-1. Lines 40 and 41.

The statement "DOE subsequently decided to perform the tests in aboveground laboratories instead of at WIPP" is misleading. Most of the tests planned for the test phase (e.g. the alcove tests, which comprised the majority of the wastes in the experiments) are not being performed anywhere.

Page S-2. First Full Paragraph.

The relation of SEIS-II to the Draft WM PEIS is described in this paragraph. DOE apparently believes they need to follow the approach of the WM PEIS and also to consider the disposal of all DOE TRU wastes. This goes beyond the portion of the defense TRU wastes that has historically been considered for disposal at WIPP and includes commercial TRU as well as non-defense TRU. The desire of DOE to consider the universe of TRU waste is understandable and it could probably be argued that NEPA requires it. But it is confusing to the reader who is aware of the statutory limits of wastes that are allowed to come to WIPP at the present time. Also, additional wastes and alternatives have not been evaluated in the detail that the Proposed Action has been. It is realized that a Draft EIS is supposed to be written as a pre-decisional document.

Page S-3. Related Documents.

The major planning and compliance documents that are integrated with SEIS-II that are related to decisions on WIPP are listed and described briefly. A generic comment is that the contents of SEIS-II are not current with the latest DOE documents that were issued before the SEIS (e.g. the CCA and Baseline Inventory Report, Revision 3). Also, SEIS-II developed its own assumptions and methodology rather than using that developed in other official WIPP Project documents (e.g. WIPP Operational Accident modeling was different than that in the Safety Analysis Report). These differences are confusing and unnecessary.

Page S-4. Comprehensive Disposal Recommendations.

The Comprehensive Disposal Recommendations (in preparation, schedule uncertain) document will recommend "disposal options and the time tables for all TRU waste under DOE control." It is unclear how the ROD that is expected with the Final SEIS-II will relate to the Comprehensive Disposal Recommendations. Are these expected before Final SEIS-II? If not, wouldn't the ROD be preempting the Recommendations? Or, is SEIS-II the first step in preparing for the disposition of all TRU wastes under DOE control at WIPP?

Page S-4. List of DOE Decisions.

Although this is mentioned later, it would be helpful to mention here those potential decisions which could be made under current WIPP Authorization and those which would require new Congressional Authorization.

Extensive comments are made later on the truck vs. rail issue. It is hoped that this decision is open and will be seriously re-evaluated.

Page S-9. Emplacement Volumes.

The text and various tables give different values for emplaced volumes of waste in No Action Alternative 2. Table S-3 says 135,000 m^3 CH, 35,000 RH (32,000 being treated). Figures S-2 and S-3 show 143,000 m^3 CH-TRU and 50,000 m^3 RH-TRU (both post-treatment). The text (page S-16) says 170,000 m^3 total. Table 3-16 and the text (on page 3-42) say 135,000 m^3 CH and 35,000 m^3 RH. It is unclear what becomes of the additional 15,000 m^3 of RH-TRU in NAA 2 (which is included in the Proposed Action as excess RH-TRU). This is confusing and needs to be clarified.

Page S-13. Lines 19-20.

The berm is to be constructed around the perimeter of the waste panel footprint (not of the Site).

Pages S-13 to S-19. Alternative Actions.

A general conclusion on the alternatives evaluated is that they are so different from the proposed action as to stretch credibility. The entire TRU waste universe is included. Implementation times of 150-190 years that use present-day technology are mind boggling and there is no indication that the SEIS-II analysis has seriously considered the problem of keeping the underground, shaft, and surface facilities at WIPP open until the latter half of the 22th Century. Nor have the institutional problems that might occur over such long time periods been mentioned.

Three of the Alternatives not considered (deep borehole disposal, greater confinement, and geologic repositories at sites other than WIPP) appear to be as reasonable as the ones chosen.

The concept of making piece meal decisions on solving the TRU waste disposal problem is as reasonable as the Alternatives listed here. For example: (1) make the decision of how to dispose of those wastes that are authorized to come to WIPP; (2) then evaluate how all or a portion of the remaining TRU wastes will be disposed of. It may be better to evaluate these remaining wastes in more than one category (e.g., RH-TRU as one category and buried waste as another).

Page S-14. Text Box.

See comments on this text box (Conservatism of TRU Waste Inventory Estimate) under page 3-6.

Page S-16.

It is noted that No Action Alternative 1, which would have thermally treated wastes, provides for overpacking of waste at 20-year intervals. No Action Alternative 2, which does not have treated wastes, has no plans for repackaging. This is an example of how the alternatives provide different levels of assurance that must be kept in mind when making decisions between alternatives.

Page S-23. Sixth Paragraph.

The value of 0.3 LCF reported for the population dose around the Hanford Site is incorrect. The Hanford Site Environmental Report for Calendar Year 1994 (PNL 10574) reports a total dose of 0.6 person-rem to the population of 380,000 persons. This would be 3×10^{-4} LCF. The values for INEL and NTS also seem to be too high but have not been checked.

Page S-29.

See comments on this text box (Long Disposal Periods and SEIS-II Results) under page 5-49.

Page S-32. Noise.

It would be useful to state the normal non-WIPP truck traffic through Carlsbad as a comparison to the relative noise effect of WIPP traffic.

Page 5-33. Socioeconomics.

The life-cycle cost analyses for Action Alternatives 1, 2, and 3 apparently does not include the cost of exhuming the CH-TRU waste disposed of before 1970.

Page S-34. Table S-5.

It is surprising that No Action Alternative 2 (NAA2) waste treatment costs are only 16% of those for the proposed Action. There is no itemized waste treatment cost in Appendix D for the No Action Alternative 2. However, NAA2 is planning to treat all newly generated waste to WAC standards (73,000 m^3 CH and 32,000 m^3 RH). The proposed action would treat 168,500 m^3 CH and 50,000 m^3 RH. This needs to be explained. The sum of the parts of the proposed action is $18.7B while the total cost is $19.1B. While rounding off is expected, this fails to account for $0.4B or 2.2% of total.

Pages S-42 through S-44.

The analysis for Alternatives 1, 2, and 3 apparently do not include the radiological health impacts from exhuming the pre-1970 disposed TRU waste, which is not considered in the

WM PEIS either, and which in the past was considered important. These radiological health impacts could be important when comparing Alternatives 1, 2, and 3 with the Proposed Action and No-Action Alternatives 1 and 2.

Pages S-51 through S-55.

The conversion factor on Figures S-5 through S-9 relating Ci/m^3 to pCi/l is incorrect. The correct value is 1 pCi/l = 10^{-9} Ci/m^3. This is important. See comment under page 5-43.

Page S-61 to S-68. Table S-7.

This table summarizes all the calculated health and safety effects from transportation, routine treatment and disposal operations, and from accidents. Deaths from transportation and operational accidents, Latent Cancer Fatalities (LCFs) from radiation exposure, cancer incidence from hazardous chemicals, and fatalities from truck pollution are all considered. Presumably, this information will be used in deciding on alternatives. However, SEIS-II does not discuss the relative merits of the alternatives in light of these estimated health and safety effects. Neither is any indication given of how they will be used in decision making. We have several observations.

The estimated cancer incidence from exposure to hazardous chemicals is below 0.05 in all alternatives. This is less than 5% of the expected radiological LCFs in NAA2 and is less than 1% in all other alternatives. The effect of hazardous chemical exposure can be ignored in choosing between alternatives.

EEG Summary of Health and Safety Effects.

EEG has condensed from the Table S-7 tabulation the expected deaths (of all kinds) for each of the Alternatives as shown in Table 1. Also included are the more significant high consequence/low probability accidents (which are not expected to happen) and the consequences of long-term releases.

Table 1

EEG Summary of Expected and Possible Deaths Listed in SEIS-II

Effect	Alternative								
	Proposed	AA1	AA2a	AA2b	AA2c	AA3	NAA1a	NAA1b	NAA2
Routine Radiation (LCFs)									
Truck Transportation	3.3	12	5.4	5.4	6.6	15	0.11	0.57	--
Operations	2.6	3.8	11	8.5	4.3	4.3	11	8.7	1.1
Accidents									
Truck Fatalities	6	19	9	9	12	25	0	1	--
Other Fatalities	6	10	15	13	12	12	1.3	1.1	1.3
Agg. Rad. (LCFs) Truck	0.4	0.8	0.4	0.4	0.7	1.2	.0068	.02	--
TOTAL DEATHS	18	46	41	36	36	58	12	11	2.4
High Consequence Accident Deaths LCFs)	2	300	10	10	2	10	10	10	300
Storage Facilities	4	4	24	24	24	24	--	--	--
WIPP Disposal									
Long Term Releases (LCFs) 10,000 year Aggregate	<0.9	--	--	--	--	--	<2325	<2325	2325
Original Waste Volume(10^3m^3)	218	336	313	313	313	312	313	313	170
Deaths/10^3m^3	.084	0.14	0.13	0.12	0.11	0.18	.040	.036	.014

All values from Table S-7, pages S-62 through S-68, SEIS-II.

If these estimates are assumed to reasonably reflect the differences between the Alternatives one can come to several conclusions:

- The Proposed Action disposes of waste at a lower expected death per volume of waste ratio than any of the Action alternatives. However, all of these ratios are within a factor of about two. The primary variables affecting the deaths/volume ratio are the miles of transportation and amount of treatment required;

- AA1 and NAA2 have very high consequence storage accidents. This is because of long-term above ground storage of waste treated only to WAC standards;

- The aggregate LCFs from long-term release for NAA2 are very high because of assumed loss of institutional control of WAC standard wastes stored above or near the surface. NAA1 LCFs were not calculated but would also be substantial. The thermal treatment of wastes would be expected to provide some reductions during the early part of the 10,000 year period because of greater waste stability.

The Health and Safety aspect of the decision on alternatives would seem to basically reduce to a trade-off between a few expected deaths during the disposal period and a possibility of a much larger number of future LCFs from accidents or environmental releases. A secondary consideration is whether some types of death (e.g. a transportation accident fatality rather than a radiation caused LCF) and the effects on some population groups (workers versus the general public) are more acceptable than others.

In making this decision one needs to keep in mind the uncertainly in these comparative estimates. Also, these various alternatives are not identical and provide different levels of assurance.

CHAPTER 1

Page 1-1. Lines 5 through 16.

The section does not make it clear that only defense TRU can be disposed at WIPP. Instead, the section discusses the need to dispose of all TRU wastes generated by the Department.

Page 1-1. Lines 37 through 39 or Footnote 1.

The footnote indicates that the DOE has sole authority to decide if waste should be disposed of at WIPP. In 1992 Congress reassigned the authority to approve disposal at WIPP from the DOE to the EPA.

Page 1-1. Box entitled TRANSURANIC WASTE.

Since the description of TRU waste includes the maximum dose rate for CH-TRU waste, the description of TRU wastes should also include the maximum dose rate for RH-TRU waste, which is 1,000 rem/hour.

Page 1-1. Box entitled TRANSURANIC WASTE.

The material in the box defines transuranic waste but fails to incorporate the adjective "defense" to modify the noun. The inference is that non-defense DOE TRU waste is eligible for disposal at WIPP.

Page 1-1. Section 1.2 OVERVIEW.

Since the SEIS describes the history to TRU waste disposal, it should include the history of the unilateral decision by the DOE to redefine the threshold of TRU from 10 nCi/g to 100 nCi/g.

Page 1-5. Table 1-2.

The fifth WIPP NEPA document notes that a 1982 deviated gas well at WIPP was discovered by the DOE in 1991.

Page 1-7. Footnote.

Statement: "Overpacking involves placing the 55-gallon drums inside another container and essentially provides double containment of the TRU waste."

The statement is incorrect. Overpacking does not provide "double containment" of a Type A drum in the context of the NRC packaging regulations 10 CFR Part 71.

Page 1-8. Lines 23 through 26.

The purpose of the WIPP/SAR is summarized, but does not do justice to the formal commitment by DOE and the State of New Mexico.

Waste Isolation Pilot Plant Safety Analysis Report, Revision 1 (SAR) Rev. 1 (DOE 1995 i)
"The intent of this document is to demonstrate the safe disposal of CH-TRU waste in compliance with DOE orders."

The Consultation and Cooperation Agreement between NM and DOE states that the SAR"... constitutes the most comprehensive document concerning WIPP both in general and specifically as related to public health and safety as well as other matters." Include this statement as well as a commitment for RH-TRU waste as well.

CHAPTER 2

Page 2-1. Lines 9 through 19.

The Geography of the nuclear weapon complex is described.

States that contain the 10 additional sites are identified in *Identification of Additional TRU Waste Generator Sites*. It appears that the TRU waste generated at the 10 additional sites is not defense TRU waste and is thus not eligible for disposal at the WIPP under the current law.

Page 2-2. Section 2.1.1 Introduction.

The SEIS includes plans to dispose of non-defense TRU waste at WIPP which violates the existing laws. DOE should include a discussion on their plans to modify the law to include commercial and non-defense TRU wastes.

Page 2-2. Section 2.1.1.

The DOE states that the total inventory will now be almost double the amounts authorized for disposal under the WIPP Land Withdrawal Act. The total expected inventory is 312,500 m^3. The authorized volume is 175,000 m^3. Describe the plans for dealing with this excess volume, including amendments to the law.

Page 2-2. Text Box entitled WASTE ACCEPTANCE CRITERIA (WAC). Lines 17 and 18.

Statement: "For the purposes of SEIS-II analyses, all waste would be treated at a minimum to the current planning-basis WAC."

Since the current WAC does not require treatment of most wastes, it is misleading to describe untreated waste as "treated at a minimum to the current planning-basis WAC."

Page 2-2. Text Box entitled WASTE ACCEPTANCE CRITERIA (WAC). Line 1.

It is stated that the WAC was first developed in 1989.

The statement is incorrect. The first set of criteria were issued in 1979. There is no recognition of the work the EEG has done on the WAC (for example, the report EEG-4, Little, Marshall S., *Review Comments on the Report of the Steering Committee on Waste Acceptance Criteria for the Waste Isolation Pilot Plant* dated February 1980).

Page 2-3. Section 2.1.2 TRU Waste.

The section fails to show that there is a volume limit of 12,500 ft^3 for disposal at WIPP of RH-TRU waste between 100 rem/hour and 1,000 rem/hour.

Page 2-3. Text Box entitled *TRU WASTE TRANSPORTATION PACKAGING.*

Lines 10 and 11. Statement: "The Department is currently awaiting NRC certification of the RH-72B cask."

The statement is misleading, since the Department did not submit an application to the NRC for certification until December 1996.

Page 2-3. The text refers to a "specially adapted rail car".

EEG is unaware of an existing rail car nor have we received plans of a design. Please provide them in text.

Page 2-5. 1,800 PE-Ci/Drum.

It is correct that the WAC allows 1,800 PE-Ci CH-TRU drums if the waste is over packed or solidified. EEG has expressed some reservations about this limit. Also, an 1,800 PE-Ci drum could not be shipped in TRUPACT-II because the drum would exceed the 40 watt thermal limit.

Page 2-5. Footnote.

The text cites an August 1995 Draft PEIS which has not been issued in final form and an unidentified undated more recent estimate. Provide specifies.

Page 2-6. Table 2-2.

Statement: "There is uncertainty in the total waste volume figures presented in Table 2-2 and 2-3."

The discussion should include numbers that provide an indication of the uncertainties in the waste volumes of the six alternatives.

Page 2-7. Table 2-3.

Commercial/Non-defense TRU waste is not eligible for disposal at WIPP and should be deleted from the Table.

CHAPTER 3

Page 3-1. Lines 31 through 37.

Statement: "Decisions based on SEIS-II may be a combination of the option presented within alternatives analyzed. This means that portions of two or more of the alternatives analyzed in SEIS-II may be combined and used by the Department for the management or disposal of TRU waste." It would help to clarify this statement if the Final SEIS-II provided hypothetical examples of how the different Alternatives might be combined. The text box on page 5-51 does not provide this clarification.

Proposed Action

Page 3-2.

While there is a clear understanding of the Proposed Action, the description includes activities not in the Proposed Action described in the SEIS. The RH-TRU waste increased considerably, from 7,000 m^3 to 35,000 m^3, and the volume projections show thermal treatment of the waste reduces the volume. These are not included in the Proposed Action submitted by DOE to EPA in the 10/28/96 Compliance Certification Application. Revise this section on the Proposed Action to only include items that are in the Proposed Action.

Page 3-2.

Paragraph 2. The text indicates that the proposed volume of RH-TRU is much less than that allowed by the WIPP Land Withdrawal Act. Not so. While the expected number of curies in RH-TRU are less than the LWA permits, the volume of RH-TRU is considerably greater and the WIPP repository's current design will not accommodate the greater volume.

Page 3-5.

"All waste has been assumed to be treated and packaged to planning basis WAC." There are no requirements in the WAC to treat waste.

Page 3-6. Text Box.

The conservatism of TRU Waste Inventory Estimates text box is limited to the volumes of estimated TRU waste. There is no discussion of the radioactive inventory (in curies or PE-Ci) and its uncertainty. Also, credit is taken for conservatism when the reverse is true. For example:

First bullet. It is more accurate to consider the inventory as uncertain, rather than overestimated. Also, overestimating the TRU waste volume (and of the alpha emitting inventory) permits a larger quantity of plutonium to be released in meeting the EPA 40 CFR 191 Containment Requirements. Update the reference from Rev. 2 to Rev. 3 of the BIR.

Second bullet. The additional Inventory includes TRU waste burial prior to 1970 when the definition of the threshold was 10 nCi/g rather than the current 100 nCi/g. Although DOE indicates that 80,000 m^3 would be excavated from the 141,000 m^3 that was previously disposed, no indication is provided as to whether it is the higher or lower concentration waste. Logically it would be the higher, making the calculation less conservative. No explanation is provided why 80,000 m^3 of buried waste would be exhumed and 60,000 m^3 of other buried waste left in place.

Third bullet. Assuming that 7,000 m^3 of RH-TRU will be emplaced in the repository, when the available capacity may be only 4,300 m^3, may overestimate the amount of actinides allowed to be released.

Fifth bullet. The assumption that 100% of the TRU waste would be treated as TRU mixed waste is no longer true.

Page 3-8.

Since the text cites U.S. DOT regulations (49 CFR Part 391) for driver qualification, also cite the appropriate U.S. DOT regulations for routing (49 CFR 177) and the type A container certification (49 CFR 173).

Page 3-9. 3.1.3.1

"The Department estimates that it would require up to three years to excavate a panel."

Why would it take 3 years to excavate 7 rooms when 4 rooms were excavated in 6 weeks for the SPDV Program? Revise the estimate.

Page 3-9.

"The facility would be inspected a minimum of 4 times a year by the Mine Safety and Health Administration." State that the WIPP Land Withdrawal Act requires this.

Page 3-9.

Shipping Routes. It would be helpful to specify the DOT regulations to change routes including public hearing procedures.

Page 3-12. 3.1.3.4 Emplacement of RH-TRU Waste.

This section states that RH-TRU waste will need to be placed in the access tunnels (Panels 9 and 10). In order to reach design capacity Panels 9 and 10 will each have to be modified to accommodate 944 m^3 of RH-TRU (compared to 649 m^3 in a panel) and 17,500 m^3 of CH-TRU (compared to 16,700 in a panel). Is it physically possible to do this? Please specify the necessary design changes to the repository.

Page 3-12.

Please provide information for a seal that would prevent water from entering the repository and impede gas and brine from migrating out.

Page 3-12.

Closure and decommissioning. Use the definitions of disposal phase and disposal used in the WIPP Land Withdrawal Act. The definitions in the text do not match those in the Act.

Page 3-12.

The projected area above the 10 panel equivalents is said to be 100 acres. It is about 125 acres.

Page 3-12.

Is the proposed fence outside of the 150 acre berm?

Page 3-13.

The commitment to place markers at the site makes no mention that they are required by (PL102-579) and need to be approved by EPA (40 CFR 191).

Page 3-14.

The text states that it is reasonable to examine alternatives that include disposing of all DOE-owned and controlled TRU waste at WIPP. It should also be reasonable to discuss plans to amend the law and explain why DOE did not ask Congress to amend the WIPP LWA at the same time this section was written.

Page 3-14.

Action Alternative 1 would nearly double the repository waste volume. However the SEIS-II does not address the necessary redesign nor operational problems associated with keeping the repository open for 160 years.

Page 3-14.

Problems associated with storage at Consolidation Sites for 160 years are not discussed. DOE has taken the position that such storage would be impracticable and offering this as a viable alternative appears to reverse the Department's position totally.

Page 3-15 and A-14. Tables 3-2 and A-6.

The total volume for column 2, Additional Inventory, should be 139,000 not 136,000.

Page 3-18.

While the text states that the number of panels would be increased from 8 to 68, no specifics are provided on the design to accommodate this. We question whether the current design would be optimum if CH-TRU was not going to be emplaced in the rooms.

Page 3-19.

The surface projection for 68 panels would be about 850 acres rather than the 680 acres estimated if the design is unchanged.

Page 3-19. Text Box, Long Disposal Periods and SEIS Results.

Statement: "The long disposal periods could be shortened by constructing additional shafts, employing additional shifts, or changing the design criteria for thermal loading." The assumptions mentioned in the statement are more reasonable than the assumptions of 160-190 year disposal periods. The analysis of AA1, 2, 3 should contain more detailed and quantitative information about how the periods could be shortened.

Page 3-43.

The SEIS states that alternatives such as transmutation, co-processing with high level waste, and disposal in space were not considered in detail. The desire to use current technology for projects to be completed in 30 or 40 years is understandable. However, it seems unwise for 160-190 year projects. The alternatives that are discussed in the text are also not considered in detail. Problems associated with keeping the mine open for 180 years are not discussed nor are plans to increase the number of panels from 8 to 68.

An alternative not considered at all, which is similar to Action Alternatives 2 and 3, would consist of acid digestion of certain TRU waste followed by volume reduction and solidification. During the 1970s and 1980s the DOE had a research program at Hanford on the acid digestion of TRU waste. The alternative might be preferable to Action alternative 2, which involves a costly thermal treatment process.

Page 3-44. Lines 2 through 8.

Statement: *"While the Storage and Disposition of Weapons-Usable Fissile Materials Programmatic Environmental Impact Statement (DOE 1996b)* considered this process to be a reasonable alternative for analysis the relative large volume of TRU waste (compared to the volume of fissile material) would produce much more waste than the currently planned high-level waste repository could dispose of. This alternative would further delay TRU waste disposal until such a time as sufficient high-level waste

repository space was available. In addition, transportation and safety concerns associated with high level waste would need to be addressed."

The statement is not correct. Because of thermal loading constraints, a high-level repository is mostly empty space that may have to be back-filled. The currently planned high-level waste repository at Yucca Mountain will have over 100 miles of tunnel. However, a high-level waste repository is not expected to be operational for more than 10 years. The transportation and safety concerns associated with high-level waste will be addressed in the licensing of a high-level waste repository. The major difficulty with this alternative is that a high-level waste repository will be licensed by the NRC and Congress does not want the disposal of defense TRU waste to be under the jurisdiction of the NRC.

Page 3-44. Lines 18 and 19.

Statement: "*Underground detonation*. Such detonations would produce a large amount of hazardous fission products."

The statement implies that the underground detonation can only be carried out with nuclear devices. This is not correct and the statement should be clarified.

Page 3-45. Lines 17 through 22.

The following statement is made in the discussion entitled *Alternative Engineered Barriers:* "The Department examined these as alternatives and determined based on the evaluation conducted in the *Engineered Alternatives Cost/Benefit Study Final Report* (DOE 1995c) that they were less effective than the engineered barriers examined in SEIS-II."

There is no discussion of engineered barriers in SEIS-II. However, of the 4 disposal options analyzed, Action Alternatives 2 and 3 include an engineered barrier (waste treatment).

Page 3-45. Lines 11 through 16.

In the discussion entitled *Geologic Repositories at Sites Other than WIPP,* it is implied that salt is a more favorable disposal media than granite, basalt, and tuff. The reference for this conclusion is the 1980 FEIS for WIPP.

Much has been written on the disposal of nuclear waste since 1980. With regards to spent fuel and high level waste, the DOE maintains that the unsaturated zone in tuff is the most favorable medium. Also, Sweden has successfully constructed and is successfully operating a repository in granite for intermediate level waste.

Page 3-46.

"The SEIS-II Proposed Action is similar to the Draft WM PEIS Decentralized Alternative". The Decentralized Alternative described in the WM PEIS is more expensive than the No Action Alternative ($1.7B vs. $7.4B). It also has more worker deaths (4 vs. less than 0.5) and a larger collective dose to workers (1,500 person-rem compared to 20 person-rem). These PEIS findings are similar to those in SEIS-II. The text should clearly explain why these results are totally opposite the DOE conclusion to consolidate the material for disposal at a particular site.

CHAPTER 4

Page 4-1.

The 1996 Amendments to the 1992 WIPP Land Withdrawal Act are not recognized.

Page 4-6.

The text states that backfill is not required for subsidence control or repository performance, but may be placed into the repository for final disposition.

DOE committed to backfill with salt in the 1980 FEIS.

Page 4-9 (Box).

"..... has resulted in confirmation of the Salado's extremely low permeability."

This statement is meaningless. The Salado pure salt has extremely low permeability, impure salt is more permeable, and the fractured anhydrite beds and the clay/anhydrite and clay/halite interfaces are permeable enough to transmit a substantial amount of brine for gas generation.

"...elevated gas pressure may slow down or stop brine inflow, thereby slowing gas-generating processes."

The important point is that sufficient gas is expected to be generated to result in lithostatic pressure in the repository. Once the pressure is dissipated through fractures, brine inflow is expected to resume.

"Geophysical surveys indicate that pressurized brine reservoirs in the Castile Formation occur as three or four discrete pockets." No new geophysical surveys have been conducted to detect Castile brine over the WIPP repository since the publication of SEIS-I. No basis has been provided to alter the previous interpretation of the 1987 TDEM survey over the WIPP site found in SEIS-I, as follows:

"A continuous deep conducting zone underlies the region of the WIPP waste - emplacement panels." (DOE/EIS-0026-FS, Vol. 1, p. 4-71).

and

"In this report, the brines underlying the repository are assumed to be present, as they are at WIPP-12" (DOE/EIS-0026-FS, Vol. 1, p. 4-73).

The EEG position is that, based on the size of the brine reservoir intercepted by the borehole WIPP-12 and the results of the TDEM survey, the WIPP repository is underlain by a continuation of the brine reservoir that was encountered by WIPP-12.

Page 4-10.

"Major tectonic activity (movements of the earth's crust) associated with the development of the Delaware Basin ended over 250 million years ago, and the WIPP site has been geologically stable ever since."

Since its deposition in the Delaware Basin in the late Permian times, the WIPP area has been uplifted, submerged, tilted, intruded by igneous dikes, deformed or dissolved by water, and eroded. In addition, according to Lambert and Canter (1984), Castile brine reservoirs were formed during the past 360,000 years to 800,000 years by an episodic process that "could have resulted from an intermittent hydraulic connection between the Capitan Limestone and Castile anhydrites." (SEIS-I, Vol. 1, p. 4-71).

The WIPP site has not remained geologically stable for 250 million years.

Comments on Page 4-15.

Natural Resource Exploration and Development.

Hydrocarbons

Hydrocarbon resource is a very important issue and merits much more than a cursory overview by three short paragraphs.

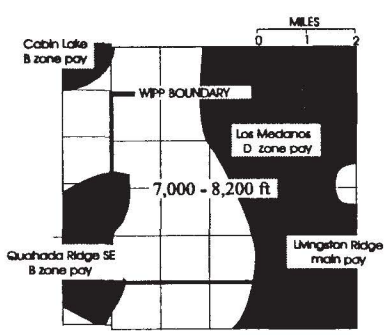

Figure 1. Proven and Probable Hydrocarbon Reserves for Brushy Canyon (after Broadhead et al, 1995, as published in EEG-62).

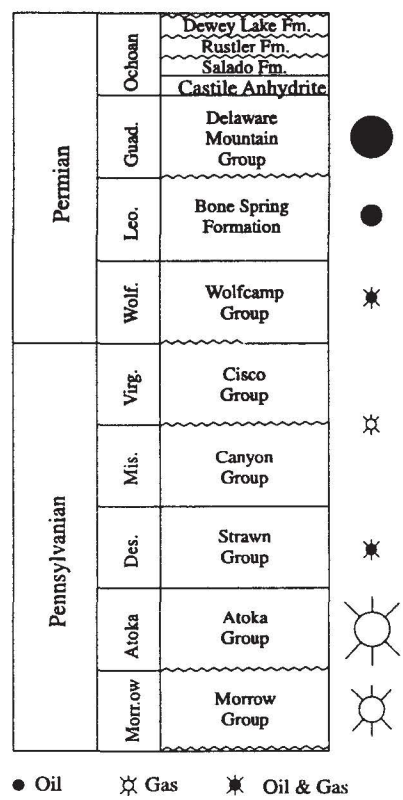

Figure 2. Formation Production (after Broadhead et al, 1995 as published in EEG-62).

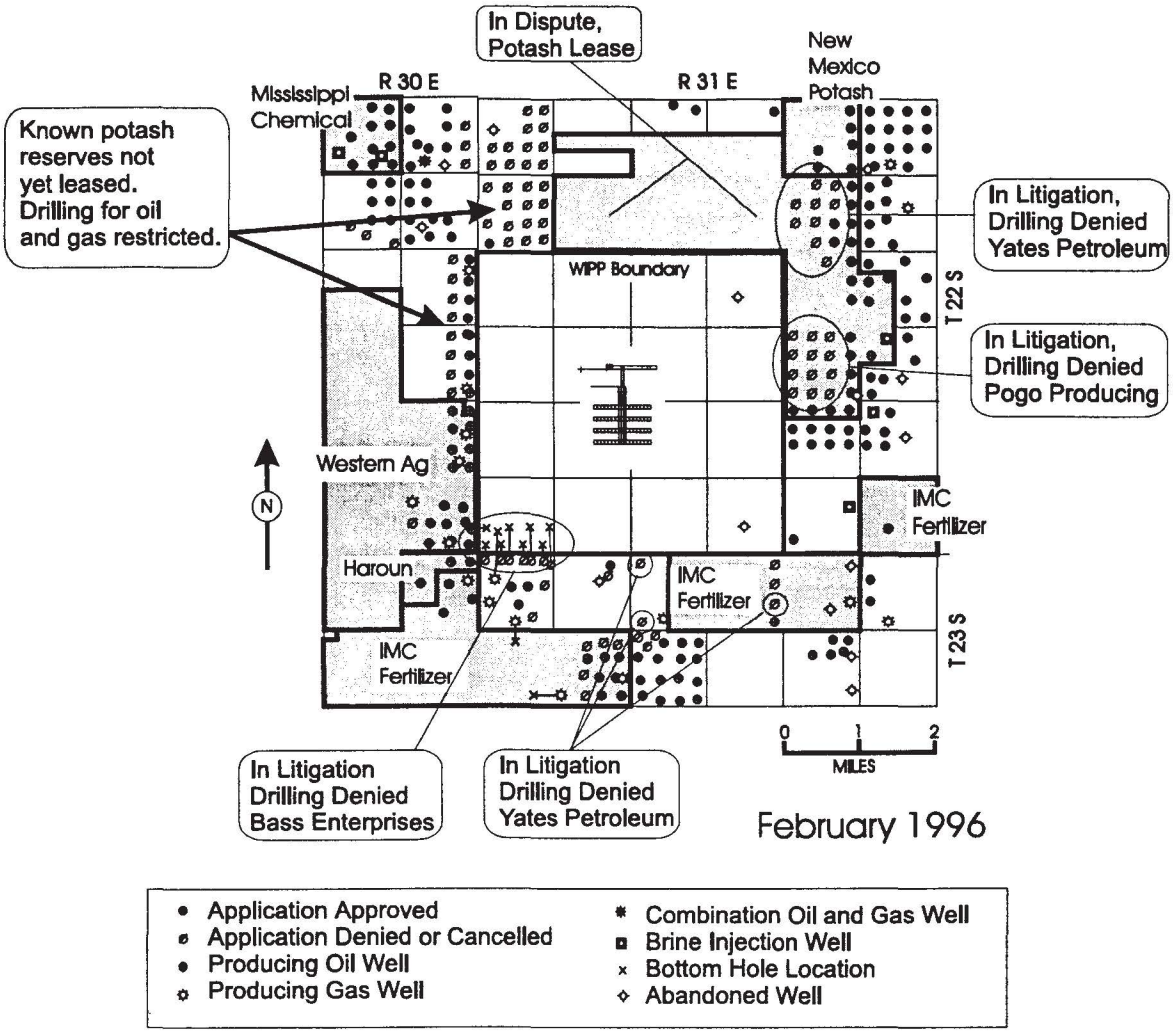

Figure 3. Interest in resources near WIPP (see EEG-62 for more detailed discussions).

The SEIS should have at least a series of maps showing proven and probable reserves at the various reservoir depths (eg. Figure 1), an illustration of the geologic cross section of the area resources and current production (eg. Figure 2), and a current map indicating drilling interest in the area and the extent of drilling delayed due to the presence of potash (eg. Figure 3). See EEG-62 (Silva, 1996) for a discussion of these figures.

Due to the extensive changes from the FEIS, there should also be a detailed discussion of the anticipated resource recovery activities. Topics should include:

- The massive hydrofracturing required by the oil reservoirs surrounding the WIPP.
- Extensive brine injection surrounding the WIPP due to the need for salt water disposal.
- Brine injection for pressure maintenance to enhance oil recovery.

- Documented concerns by the potash industry of the potential impact of fluid injection on the Salado Formation.
- The estimated value of hydrocarbon resources in the area.
- Areas for which there are no estimates due to the lack of drilling and testing as a result of the presence of potash.

Potash

This section should have maps showing the extent of lease grade potash reserves including the extent of potash reserves under the WIPP Site. Further, the SEIS should rely on the official position of the Department of Interior. The text should then discuss the maps and the impact of WIPP on the potash industry and the potential impact of potash mining on the WIPP based on potash reserve estimates by the Department of Interior.

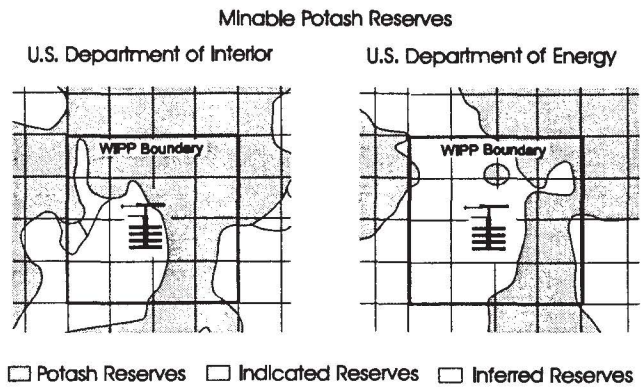

Figure 4. Estimated areal extent of potash reserves.

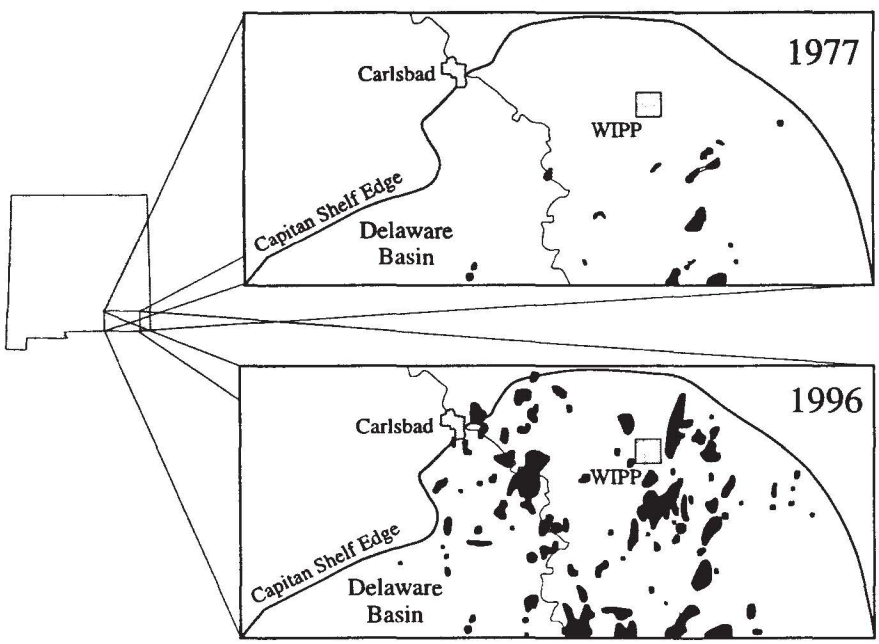

Halite

The increase in oil and gas drilling activities, shown in Figure 5, continues to put demands on the need for brine supplies in the areas of new drilling.

Figure 5. Actual growth of oil production.

There needs to be a section discussing the decades long activity of solution mining of halite, shown in Figure 6, from the Salado Formation to produce brine for drilling oil and gas wells throughout southeast New Mexico.

Pages 4-18, 4-19 Salado Formation Hydrology. This section should describe the higher permeability of the Salado marker beds which act as conduits for flow of water and gas in the Salado.

Also, the assumption of Darcy Flow is not a conservative but a reasonable assumption. According to Beauheim, et al. (SAND 92-0533), "An assumption of Darcy flow through the evaporites is thought to be a reasonable interpretive approach because Darcy-flow models are able to replicate the flow and pressure behavior observed during entire testing sequences involving different types of tests performed with different hydraulic gradients."

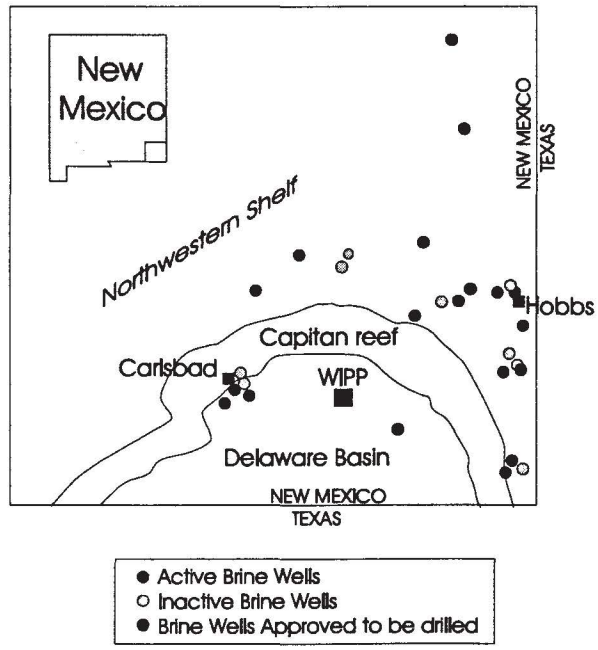

Figure 6. Solution mining of the Salado Formation.

Pages 4-19, 4-20 Castile Formation Hydrology.

The discussion in this section is incorrect in certain aspects and incomplete in others. There are not two but at least thirteen reported boreholes at and near the WIPP site which encountered pressurized brine in the Castile Formation. When the borehole WIPP-12 encountered pressurized brine at the WIPP site in 1981, more than 1.14 million gallons (4.3 million liters) of brine "unavoidably" flowed to the surface and was collected in a large pond on the surface before the well was brought under control (See DOE report on Brine Reservoirs, WIPP/TME 3153, P. H-9). The pore volume of this brine occurrence was estimated by DOE to be 714 million gallons (2.7 million m^3). Accommodation of this volume requires the assumption that the brine reservoir intercepted by WIPP-12 spreads under the repository. The TDEM survey confirmed the existence of brine under the repository. Assumption of four distinct brine reservoirs underlying the repository has no basis. A more justifiable assumption is that the pressurized brine reservoir encountered by WIPP-12 extends under the repository.

Page 4-21.
The discussion of the water level rises in the Culebra Aquifer and the potential impact of salt water disposal wells would be clearer by preparing and presenting a figure such as the one shown here and published in EEG-62.

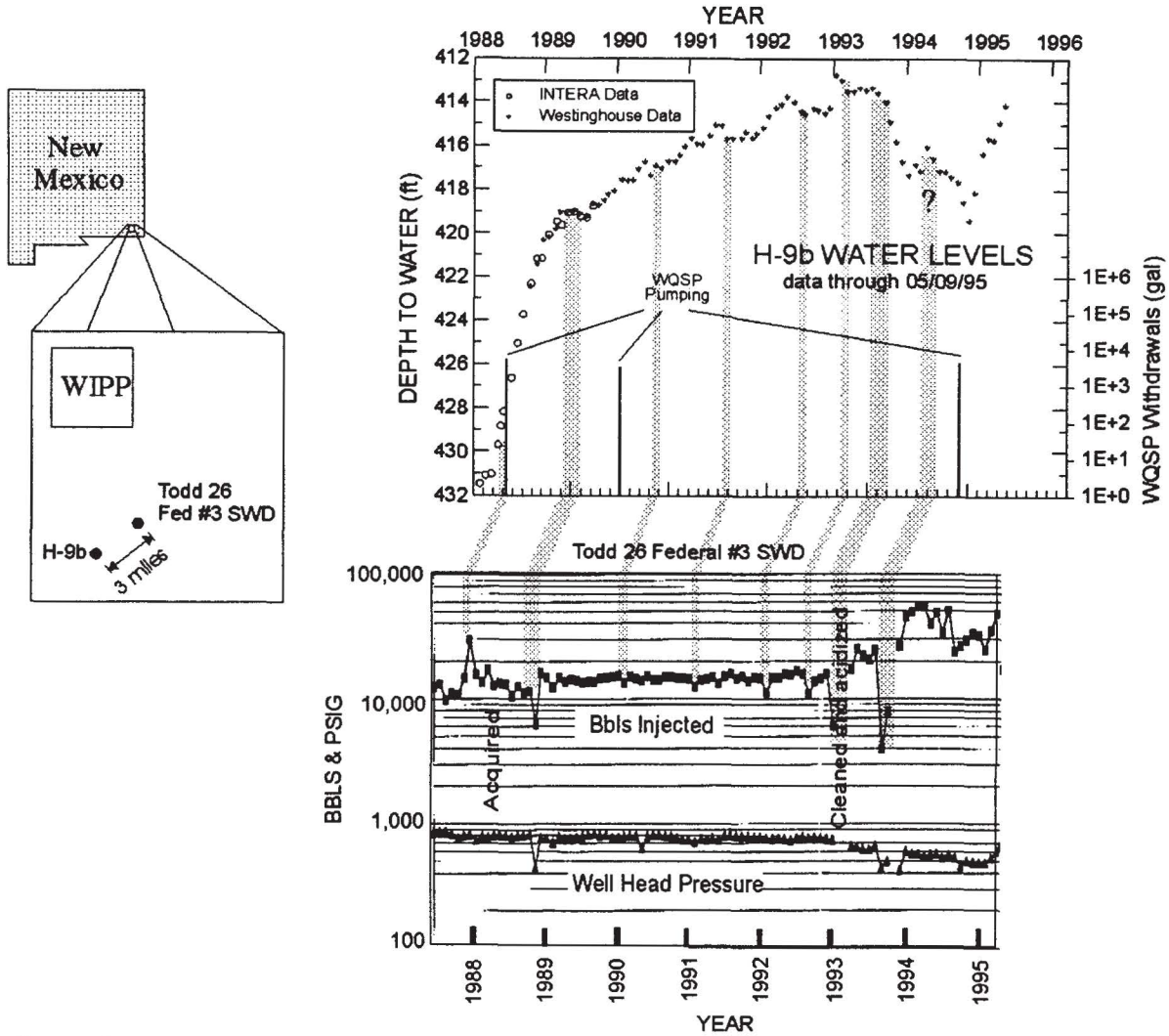

Figure 7. Postulated correlation between oilfield salt water injection and water level rises.

The discussion of potash mining and subsidence would benefit from a more detailed discussion of 40 CFR 194, the CCA, and a map of the extent of potash reserves as determined by the Department of Interior.

CHAPTER 5

Page 5-4.

The statement is made (3 lines above Section 5.1.2) that "No activity is occurring under these leases, and the Department may acquire these leases in the Future." The current status of these leases, including the producing gas wells and the recent court judgement, deserve a more detailed description in the final SEIS.

Page 5-9. Table 5-2.

The total in the second column (Basic Inventory RH-TRU Wastes) should be $4,800 million (not $4,500 million). Estimates should be rounded off using a consistent system.

Page 5-11. Transportation.

Detailed transportation comments are included in the Appendix E comments and are not repeated in these comments. Calculations were checked and compared to the results reported in previous EEG reports. The transportation risks reported in SEIS-II are reasonable and adequately conservative.

Page 5-13.

Highway route-controlled quantities (HRCQ) are discussed in the last paragraph. HRCQs are defined in 49 CFR 173.403(1) and routing is described in 49 CFR Part 177.825. The reference cited is not specific or useful. The statement that a majority of WIPP shipments are not HRCQs is misleading. Any waste shipment containing over 6 Ci of ^{239}Pu or ^{240}Pu, 9 Ci of ^{238}Pu, and 24 Ci of ^{241}Am is a HRCQ. Virtually all WIPP CH-TRU shipments will be HRCQs. Interestingly, the average RH-TRU inventory falls below the HRCQ limits and so the majority of RH-TRU shipments probably are not HRCQs.

Page 5-16.

The Footnote to Table 5-7 states that "shipments would stop at sites chosen, in part, for their lack of population,...." Have such sites been chosen and is their usage required? Unless the answer to both questions is 'yes', this claim should not be made.

Page 5-18. Lines 11 and 12.

The statement is made that, the State inspectors "dose would be limited by administrative rules and the inspector would be rotated to a new position." Unless DOE knows the requirements of the various States they should not take credit for actions by the States.

Table 5-8 is said to indicate that Site and State inspectors would receive the highest probability of health effects. Table 5-8 and Appendix E indicates that the rest stop employee has the highest probability.

Page 5-21. Lines 18 and 19.

The population density should be stated as "3,861 persons per square kilometer"

Page 5-26. Table 5-11.

Footnote d states that the MEI for RH-TRU is located at SRS. There is no RH-TRU at SRS.

Page 5-33. Lines 3 and 4 from bottom.

The assumption that there would be no dose to the maximally exposed involved worker in the T1 and T2 accidents is apparently based on the assumption stated on page G-11 ("The involved workers, positioned outside of the glovebox, were assumed to exit the facility immediately and thus would escape impact"). The assumed geometry and operational procedures need to be described in more detail so that the reasonableness of this assumption could be evaluated.

Page 5-34.

The text box on criticality contains information on the amount of Fissile Gram Equivalents present in the WIPP Waste streams that is inconsistent with Table 1, Appendix B2 of the Baseline Inventory Report Revision 3. This Table shows there are 2,800 m^3 of RFETS residue waste with an average concentration per 0.208 m^3 drum of 13.7 Ci ^{239}Pu and 53.6 Ci of ^{241}Pu. This is an average of 218 FGE per 0.208 m^3 (55-gallon) drum. The permissible limit is 200 FGE/55-gallon drum. Furthermore, Table 1 indicates there are about 151 m^3 of waste at SRS, INEL, and Hanford that have average concentrations that exceed 200 FGE/ 55-gallon drum. This discrepancy needs to be reconciled and the Final SEIS-II should use the values published in the latest BIR. Also, the final disposition of wastes that exceed 200 FGE/drum should be stated.

The RFETS residues deserve more attention in SEIS-II than they have received. On February 20, 1997, the NRC granted DOE Revision 8 to the TRUPACT-II Certificate of Compliance. This Revision allows use of a pipe overpack to transport up to 200 FGE of residues in a pipe that is positioned inside a 55-gallon drum. The volumes of this pipe component would be either about 11 liters or about 45 liters. Up to 2,800 FGE of waste can be placed in a TRUPACT-II containing 14 of these pipe overpacks. The limit for 55-gallon drums or Standard Waste Boxes is only 325 FGE per TRUPACT-II. Some of these residues must be much more concentrated than the average concentration or DOE would not have needed to develop the pipe overpack. So now DOE can ship up to 2,800 FGE in a TRUPACT or 8,400 FGE on a trailer containing 3 TRUPACTs. Eight kilograms of plutonium is considered a significant quantity by IAEA because it is the approximate amount required to manufacture a nuclear explosive device. Such a shipment could be a candidate for a terrorist act of diversion during transportation. the Final SEIS-II should discuss the precautions that will be taken to present diversion of high FGE waste shipments.

Page 5-35.

We were able to approximately reproduce the LCFs for the RH-TRU Waste Storage Accident in Table 5-17 by using the overall release factor for stored CH-TRU waste from Page G-40 (3.125×10^{-6}) rather than the values described on this page for RH-TRU (6.25×10^{-8}). This overall RH-TRU release factor seems unreasonably low. Once again, the SEIS-II calculations are difficult to check because the specific input values are not given. It was necessary to retrieve numbers from two locations in Appendix G and one in Appendix A. We trust these were the values used in the calculation. Please provide more detail to enable the reader to reconstruct the calculation.

Page 5-35 to 37.

WIPP disposal accidents and their consequences are summarized in this section. More detail is provided in Appendix G.4. The WIPP Safety Analysis Report also contains a suite of WIPP disposal accident consequences. The SEIS-II scenarios and SAR Scenarios are not identical. They differ in numbering, description, assumptions, and consequences. A comparison of the consequences of common scenarios is shown in the following table

Table 2

EEG Comparison of SEIS-II and SAR
WIPP Accident Consequences

	Ratio of SEIS-II/SAR Latent Cancer Fatalities		
Scenario	MEI Public	Non-involved Worker	Involved Worker
CH 7 Spont. Ignition, UG	0.72	1.75	—
CH 3 Puncture, Drop in WHB	1.7	0.25	2.7
CH 4 Drop in WHB	2.0	0.29	3.6
CH 5 Waste Hoist	30.	4.0	—
CH 9 Drop in UG	1.0	0.15	15.6
CH 11 Roof Fall	10.	1.9	—

There is no clear pattern to the above ratios. MEI and Involved Worker consequences are mostly greater in SEIS-II, while non-involved worker consequences are mixed. It is unnecessary and confusing to use different scenarios and assumptions in the SEIS-II than were used in the SAR. The scenarios in the SAR evolved over a number of years and influenced by discussions between DOE/Westinghouse and EEG. These SAR scenarios are more specific to WIPP conditions and should be used in the final SEIS-II.

Page 5-36.

As shown in the following Table, the frequency of various accident scenarios are different in SEIS-II than in the 1996 Draft Safety Analysis Report (SAR). An explanation should be provided.

Table 3

EEG Comparison of Accident Scenario Frequencies
in SEIS-II and 1996 SAR

Table 5-18, Disposal	Annual Occurrence Frequency	
Accident Scenarios	Draft SEIS-II	Draft 1996 SAR
W1, WHB Drum Drop	0.1	0.011 (CH4)
W2, WHB Drum Puncture	0.1	0.006 (CH3)
W3, Underground Drum Drop	0.01	0.015 (CH9)
W4, Underground Drum Puncture	0.01	0.015 (CH9)
W5, Underground Container Fire	0.01	No scenario
W6, Hoist Failure	1E-4	1.4E-9
W7, Roof Fall	0.01 Panel 1	4.3E-7 (CH11)
W8, RH-TRU Canister Breach	1E-4 to 1E-6	no scenario

Page 5-39. Long-Term Post-Closure Performance.

The text says that the analysis in Draft SEIS-II are based on results computed for the Draft No-Migration Variance Petition and the Draft Compliance Certification Application (Draft CCA). Also, that "The final SEIS-II will re-examine its long-term performance assessment in light of any changes in methodology adopted for the compliance certification application." This re-examination should be made. It is unfortunate that Draft SEIS-II, even though it was released after the Final CCA was sent to EPA, could not incorporate the same methodology and results for the Proposed Action. We have comments on the current analysis.

Page 5-40 & 41. 75th Percentile Values.

The rationale for using median and 75th percentile parameter values is described: "The 75th percentile parameter values are used to yield model results that should fall in the upper tail of a full probabilistic analysis." But it is then said (lines 1-3 on page 5-41) that there is remarkably little difference between the mean and 75 percentile values. In fact Table H-24 indicates that direct radionuclide releases to the ground surface are identical for the median and 75th percentile values.

This is inconsistent with the CCA (see Figure 6-40) where the median values on the CCDF plot are 67% of the mean value at 0.1 Probability and 40% of the mean value at 0.001 Probability. The reason for this discrepancy is probably because more parameters were sampled over a distribution of values in the CCA than in SEIS-II. For example, the CCA sampled some parameters in the following areas that SEIS-II did not: (1) shaft materials; (2) gas generation, (3) the Culebra aquifer; (4) borehole plugs; and (5) borehole shear resistance. The SEIS-II calculation is, in most cases, using the same parameter values for the 75th percentile as for the median.

The methodology does not yield results that "fall in the upper tail of a full probabilistic analysis."

Page 5-40 & 41. Family Farm Scenario.

The decision was made to not include the family farm scenario (500 meters from drill cuttings) that was used in SEIS-I because the land was poor, little water was available, and water quality is poor. All of these facts are correct but there are ranch houses nearby and the majority of the dose (>99% in SEIS-I, Tables 5.63 and 5.64) is from inhalation. EEG-11[1] calculated CEDE inhalation doses of about 175 mrem/y at 360 m from 13 Ci of TRU radionuclides brought to the surface and deposited in a brine pit. Doses to nearby residents should be included in SEIS-II.

Page 5-41. Third Paragraph.

It is stated that "No population impacts were calculated because only small amounts of radioactive material would be brought to the surface, remain in a wet, relatively nondispersable form, and would

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[1]Channell, James K., "Calculated Radiation Doses from Radionuclides Brought to the Surface if Future Drilling Intercepts the WIPP Repository and Pressurized Brine," NM Environmental Evaluation Group, EEG-11, January 1982.

remain localized." The material brought to the surface will not remain wet. The mud pit will dry, enabling wind erosion to transport the radioactive material over long distances. It is quite possible that the mud pit will be dry prior to dismantling the drill rig and be disturbed by that process, exposing those workers to the risk of inhaling radioactive dust.

The assumption of wet, non-dispersable material in the brine pond is inconsistent with assumptions used in SEIS-I, EEG-11 and TME-3151.[2] Both EEG-11 and TME-3151 calculated inhalation doses to the population within 50 miles from wind erosion. EEG-11 estimated a population dose of 39 person-rem per year (50-year Committed Effective Dose Equivalent) and assumed the exposure would last for many years. TME-3151 projected a population-dose of 76 person-rem CEDE for the one year period before the pond is covered.

Intrusion into the repository would definitely expose the neighboring population to risk. This risk should be calculated.

Page 5-42. 4th line from bottom.

Reference is made to the 5-kilometer subsurface lateral boundary. The appropriate boundary of concern is the WIPP site boundary which is less than 3 km from the waste panels to the south (down gradient in the Culebra aquifer).

Page 5-43. Figure 5-1.

There is a 10^6 conversion error on this Figure (and on lines 18-19 on page 5-42) that is repeated on numerous other Figures in this Chapter and Appendix H. A concentration of 1 pCi/l is equal to $10^{-9}\ Ci/m^3 \left[(1\frac{pCi}{l})(10^{-12}\ \frac{Ci}{pCi})(10^3\frac{l}{m^3}) = 10^{-9}\frac{Ci}{m^3})\right]$ not 10^{-15} Ci/m^3. This mistake raises an uncertainty about which value was used in plotting the extent of migration areas in the various figures. This is important; it must be clarified, corrected, and the areas re-plotted if necessary.

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[2] Radiological Consequence of Brine Release by Human Intrusion into WIPP," US DOE, TME-3151, July 1982.

Page 5-44. Last paragraph.

This paragraph (which concludes on the top of page 5-45) concludes that intrusion at 100 years will have the maximum consequences. This determination cannot be made until calculations are made with an acceptable spallings model. Large spallings releases are possible at higher repository pressures which are expected to increase after 100 years. These increased spallings releases could more than offset the reduction in curies from radioactive decay.

Page 5-46. Fourth Paragraph.

The statement is made here (and elsewhere) that "no radionuclides or hazardous materials would be released into the Culebra within 10,000 years of repository closure for the deep drilling scenario under the proposed action." This is inconsistent with calculations in the CCA which show radionuclide release to the Culebra is a significant fraction of the E1, E2, and E1E2 scenario realizations. Calculations in the Final SEIS-II for the Proposed action need to be consistent with the CCA.

Page 5-48. Section 5.1.12.5.

The statement is made that if all the stored excess RH-TRU waste were released it would cause less than 2 deaths over a 10,000 year period but that if stored it would result in less than 2 worker deaths per 100 years. This suggests that it would be better to release the waste than to store it! This section should go beyond the statement that population may increase around the sites and present a rationale for storing the waste.

Page 5-49. Text Box.

We have several comments about the Long Disposal Periods on SEIS-II results discussed in the text box:

(1) The problems of keeping a facility open for 160 to 190 years are undoubtedly much more complex than SEIS-II suggests. The current shafts and drifts almost certainly can't be maintained for that long and surface facilities would probably also need to be replaced. Institutional problems would also be expected. The discussion also suggests that large work forces would be employed on these long periods and would thus be uneconomical. The concept of committing to any plan for this long a time is unprecedented and probably unwise;

(2) Thermal loading in the repository should not be a major problem. The excavated waste disposal area in the Proposed Plan is about 27 acres (for CH-TRU wastes). This would permit 270 Kw with the present criteria of 10 Kw/acre. The inventory in Appendix A (Tables A-31 and A-33) for Action Alternative 2 would generate less than 170 kilowatts;

(3) We agree that differences in long-term alternatives should be compared in long-term aggregate impacts rather than annual impacts. These comparisons should include the same universe of wastes, regardless of how they are managed.

Page 5-51. Text Box.

The discussion in this text box on Factors to Consider in Combining Alternatives provides useful information. The brief statements on Waste Treatment and Waste Management should be expanded because they contain much of the rationale for choosing the Proposed Action.

Page 5-59. Rail Accident Methodology.

The conclusion that the number of rail accidents using dedicated trains will be 23 times that expected for regular rail service is unrealistic. The methodology used could be used to calculate a wide range of numbers, including zero additional accidents (with the assumption that no new locomotives would ever be used). Some of the potential benefits from dedicated trains (e.g., lower potential accident rate per mile, more control over waste package, and shorter shipment times) should be discussed. It is noted that both regular train and dedicated train shipments have less impacts than truck shipments (Table 5-29 versus Tables 5-25, 5-26, 5-28).

Page 5-60.

Detailed evaluations of rail mileage in the SEIS-I and other earlier documents indicates that rail mileage from the major generating sites to WIPP is 16%-26% greater than truck mileage, not similar as claimed here.

Page 5-67.

The Radiological Impacts storage accidents for Action Alternative 1 in Table 5-34 are from Table G-28. We reproduced the calculation for population and MEI LCFs from the Earthquake Scenario. However,

the maximally exposed non-involved worker should have only 0.4 LCFs and not 0.7 LCFs for a dose of 1,050 person-rem. We calculated only 760 person-rem for this accident.

Page 5-85. 2nd Line Beneath Table.

What is the justification for assuming that thermal treatment of waste reduces the release fraction by a factor of 1,000?

Page 5-104. Section 5.3.

The impacts of disturbed and undisturbed cases of potash mining and brine reservoirs have not been adequately evaluated for the various Action Alternatives.

Page 5-142. Lines 7-9.

The assumption (for No Action Alternative 1) that DOE would indefinitely maintain institutional control at all of the storage sites is inconsistent with regulatory requirements at WIPP. Active institutional control may be allowed by EPA for 100 years at WIPP and credit (or partial credit) for up to 600 additional years of passive institutional control may be allowed. An assumption of perpetual institutional control for a No Action Alternative unfairly biases its comparison with the Proposed Action.

Page 5-145. Table 5-88.

The lifetime waste treatment impacts to involved workers in No Action Alternative 2 are only 0.08 LCFs. Yet for the Proposed Action they are 1.7 LCFs (Table 5-13). NAA 2 would treat 43% of the CH-TRU volume and 64% of the RH-TRU volume as the Proposed Action. Both actions treat waste to the WAC criteria at the generating sites. Why are the human health impacts for the Proposed Action 20 times as great?

Page 5-148. Section 5.6.12.

Detailed comments of intruder scenario modeling for long-term postclosure will be included in the comments on Appendix I.

The discussion of why the Record of Decision (ROD) for the FEIS and SEIS-I came to the conclusion that a No Action Alternative was "unacceptable" is very good.

Page 5-153. First paragraph.

The estimated 2,325 radiological LCFs in 10,000 years from environmental releases at all storage sites is noted. The EPA allowed limit for WIPP amounts to a maximum of 42 LCF's over 10,000 years. If the limit is met, the analysis indicates that disposal at WIPP is clearly more protective than storage at the generating sites.

Page 5-154. Lines 34 through 38.

Statement: "In contaminated areas, currently remote-controlled mining equipment or equipment modified with off-the-shelf systems may be used. Where practical, removal operations would be performed remotely. All support, radiation and air quality monitoring and geotechnical surveying would be performed remotely in the contaminated areas."

The discussion of waste recovery in section 5.7.2 relies almost entirely on remote controlled activities as expressed in the above statement. At present, remote controlled handling of CH-TRU and RH-TRU does not exist. The discussion of radiological impacts in section 5.7.2.1 Operational Impacts of Waste Recovery, has no basis or justification.

Page 5-155. Second complete paragraph.

This discussion mentions the greater external radiation hazard from waste recovery (compared to waste emplacement). However, inhalation exposures from dealing with breached containers and contaminated salt could also be significant and this needs to be recognized in the Final SEIS-II.

Page 5-156. Second complete paragraph.

Was any analysis involved in arriving at the conclusion that health impacts to the public and non-involved workers from recovery operations was 1,000 times that in Action Alternative 3?

Page 5-159. Lines 6 to 9 bottom.

The statement is made that DOE is considering transportation of fissile materials for storage and disposition. Is this being considered for WIPP?

Page 5-161. Lines 5 and 6.

More information is needed on the statement: "Emissions of radionuclides would be 134% of the standards for the alternatives that would involve treatment to the LDRs at LANL;" Page 5-88 mentions a $9x10^{-5}$ chance of an LCF but doesn't mention standards. Is this the 10 millirem/year NESHAPs Standard?

Page 5-162. Last paragraph.

The elimination of former "Control Zone IV" made this land available for oil and gas recovery as well as for potash mining. There are a number of producing wells in this area now. Water flooding is also permitted and is occurring.

Page 5-163. Section 5.11.

The LWA prohibits the extraction of mineral and hydrocarbon resources from the Land Withdrawal Area in perpetuity, not just during the period of disposal operations.

CHAPTER 6

Chapter 6 lists all the regulatory agencies and the status of permits for WIPP. One regulatory agency is notably absent. It is DOE. The Department has the legal authority to self regulate operational activities at WIPP. The status of WIPP's compliance with DOE Orders or even a list of DOE Orders is conspicuously absent. Indeed, DOE has the authority to self-approve the Draft Supplement to the EIS but fails to describe the internal system to be used. For example, the DOE long-term disposal calculations in the SEIS are approved by DOE and in the CCA by EPA.

LIST OF ACRONYMS

BIR:	Baseline Inventory Report
CCA:	Compliance Certification Application
CAO:	Carlsbad Area Office
CCDF:	Complementary Cumulative Distribution Function
CEDE:	Committed Effective Dose Equivalent
CH-TRU:	Contact Handled TRU Waste
DOE:	U.S. Department of Energy
DOT:	U.S. Department of Transportation
EIS:	Environmental Impact Statement
EPA:	U.S. Environmental Protection Agency
FEIS:	Final EIS
FGE:	Fissile Gram Equivalent
HRCQ:	Highway Route-Controlled Quantity
INEL:	Idaho National Engineering Laboratory
IRF:	Impact Release Fractions
LDR:	Land Disposal Regulations
LWA:	Land Withdrawal Act
LCF:	Latent Cancer Fatality
MEI:	Maximum Exposed Individual
NESHAPS:	National Emissions Standards for Hazardous Air Pollutants
NTS:	Nevada Test Site
NRC:	U.S. Nuclear Regulatory Commission
RH-TRU:	Remote Handled Transuranic Waste
ROD:	Record of Decision
RFETS:	Rocky Flats Environmental Technology Site
SAR:	Safety Analysis Report
SEIS:	Supplemental EIS
SRS:	Savannah River Site
TEDE:	Total Effective Dose Equivalent

LIST OF ACRONMYS (CONTINUED)

TRU:	Transuranic
WAC:	Waste Acceptance Criteria
WIPP:	Waste Isolation Pilot Plant
WM PEIS:	Waste Management Programmatic EIS

APPENDIX A
WASTE INVENTORY

Comments on Appendix A are made in the page order they occur. The importance attached to these comments by EEG can be inferred from the text of the comment. Comments related to waste inventory that occur in the Summary or the Chapters will be addressed in those locations.

Page A-2. Lines 19 through 22.

Statement: "The volume of TRU waste for the SEIS-II Basic Inventory is estimated at 135,000 cubic meters (4.7 million cubic feet) for CH-TRU waste and 35,000 cubic meters (1.2 million cubic feet) for RH-TRU waste. These estimates are based on current volumes of stored waste and waste expected to be generated through the year 2033."

The estimates of 135,000 cubic meters for CH-TRU and 35,000 cubic meters for RH-TRU involve significant uncertainties that should be estimated and discussed. A generic weakness of SEIS-II is a lack of discussion of uncertainty in the TRU inventory over the past 18 years.

Page A-6. Lines 22 through 25.

Statement: "Some heat is generated by TRU waste due to the interaction of alpha radiation, emitted in the radioactive decay of plutonium isotopes, with the walls of the waste container."

The heat is not generated in the wall of the waste containers. It is generated in the waste. The alpha particle range is too short to reach the walls of the waste containers.

Page A-7. Lines 2 and 3.

Statement: "The amount of gas generated is a function of the amount of heat produced from radioactive decay and the amount of plastic material present in the TRU waste."

The amount of gas generated is not a function of the amount of heat produced from radioactive decay. The amount of hydrogen gas generated is a function of the amount of energy deposited by ionizing radiation in the hydrogenous material present in the TRU waste and from anoxic corrosion of the drums.

Page A-8. Lines 9 through 14.

The estimated values for V_{site} could also be expressed as: $V_{site} = V_{stored} + (38/28[V_{projected} - V_{stored}])$.

In this form the writing of equation A-1 is consistent with the writing of equation A-7 and A-8. Also, to be consistent V_{stored} should be defined as TRU waste volume stored at the generator storage site through 1995. The use of "in 1995" is ambiguous.

Page A-8. Lines 27 through 33 and Page A-10. Table A-4.

Estimated total volumes of previously disposed TRU waste by site are discussed and presented.

The volumes of previously disposed TRU wastes are based on manifests that were written before 1970. If the waste is excavated and repackaged, the volumes will be significantly different due to compaction and the inclusion of contaminated soils. A discussion of the uncertainty in these volumes should be included.

Page A-12. Lines 5-7.

The statement is made that "only a few waste forms need packaging to meet thermal power limits, provided that plastic wrap is not used when the drums are filled (bagless posting)." Table A-16 indicates that average concentrations in about 19,400 m^3 (about 14%) of stored plus projected wastes do exceed the thermal power limits for bagless posting. Furthermore, our understanding is that the majority of presently stored wastes containers uses bags. Please comment. Does DOE plan to repackage wastes to remove bags? The plans to repackage and treat stored waste in order to meet the WIPP WAC limits should be explicitly addressed in detail in the SEIS-II.

Page A-12. Lines 8 through 17.

The calculation of $V_{Expansion}$ is discussed.

The calculation of $V_{Expansion}$ cannot readily be followed since the input data are contained in other documents such as TRUCON. Tables of adjustment factors similar to those provided in Tables B-2 and B-3 of Appendix B should be provided. See page A-22 to A-28 comment below.

Page A-12. Lines 19 through 24.

The statement is made that some of SRS waste would be processed to become RH-TRU. There is no evidence in the SEIS-II or other documents reviewed that there will be any RH-TRU at SRS.

Page A-13. Lines 21 through 23.

The Statement is made. "A 65-percent reduction in the TRU waste volume to be disposed of was assumed due to LDR thermal treatment of both CH-TRU and RH-TRU."

No justification is presented for the assumption of a 65-percent reduction factor in the TRU waste volume due to LDR thermal treatment. Also, it is questionable whether a 65-percent reduction should be applied to the additional inventory, since it has been compacted and will contain considerable amounts of soil.

Page A-13. Lines 35 through 38.

The statement: "A density change assumption, therefore, is made such that a 55 gallon drum containing the slag would weigh 454 kilograms (1,000 pounds). Waste density values are used in the determination of the number of shipments (Section A.3.9). See Table A-2 for the CH-TRU average drum weights used to determine the number of shipments."

Table A-2 does not provide data for a drum weighing 454 kilograms. It's not clear from Table A-2 whether it is permissible to use any number of waste drums between 11 and 42 as long as the weight of drums plus dunnage does not exceed the payload per shipment.

Page A-16. Table A-8.

The values for INEL and total in the columns labeled Post-Treatment Disposal Volume are in error. The values for INEL should be 10,000, 20,000, 30,000 m^3, instead of 10,000, 31,000, 41,000 m^3. The values for total at the bottom of the page should be 47,000, 49,000, 96,000 m^3 in Tables A-8, A-9, and A-10.

Page A-20. Table A-12.

The values for RFETS Total in the columns labeled Post-Treatment Disposal Volume are in error. The values for RFETS should be 13,000, ---, and 13,000 instead of and 19,000, ---, 19,000, and the values for Total at the bottom of the page should be 162,000, 166,000 and 329,000 m^3.

Page A-22 to A-28.

This section calculates the number of waste shipments for the various alternatives. The methodology is explained about shipping weights (Table A-2) and volume expansion to meet thermal limits (Equation A-2) earlier in the Appendix However, all assumptions were not given (e.g. how volumes were scaled to full repository size and whether the number of drums per shipment is interpolated between values given in Table A-2). For LANL CH-TRU Proposed Action shipments our calculated values were 6% lower than the 5,009 shipments indicated in Table A-15.

Page A-23. Table A-14.

The use of the term "Newly Generated Waste" for waste that doesn't exist is misleading. Use "To be-Generated Waste."

Page A-23. Table A-14.

The values in Table A-14 have not been rounded off, which is unlike Tables A-3 thru 13. Also, the columns labeled Existing Stored Volume should be relabeled Stored (1995) to be consistent with Table A-3.

Page A-28. Table A-17.

The PE-Ci/m^3 values for RFETS residues in Table A-17 are incorrect. From the inventory in Table A-23 it is apparent that the concentration should be about 17.3 PE-Ci per 55-gallon drum or 83.7 PE-Ci/m^3.

Page A-33 to A-40.

The method described here for scaling up radionuclide inventories is said to rely heavily on the Baseline Inventory Report, Revision 2 and the 1995 Integrated Data Base. Yet the results are different from those presented in the CCA and BIR Revision 3 as shown in Table 4. Values are also different for Pu-241, Am-241, Pu-240, Co-137 and Sr-90.

Table A-1

EEG Comparison of Inventories Used in Different DOE Documents

Source	CH-TRU		RH-TRU	
	^{238}Pu CI	^{239}Pu	^{238}Pu	^{239}Pu
CCA at 2033	1.94×10^6	7.85×10^5	1.07×10^3	1.0×10^4
BIR Rev 3,2033	1.93×10^6	7.85×10^5	1.07×10^3	1.0×10^4
Table A-27&28	1.70×10^6	6.82×10^5	6.48×10^2	3.93×10^3

We were not able to reproduce the volume factors reported in Table A-25 for the Proposed Action. Our values were about 3.5% higher for CH-TRU at LANL and SRS when using V_{IDB} values from the 1994 IDB in equation A-8. This Appendix did not specify what volumes were used or how the inventory was scaled to a full repository.

More importantly, we do not see any reason for SEIS-II to derive a different disposal inventory for the Proposed Action. The Final SEIS-II should use the same values as the CCA.

APPENDIX B

SUMMARY OF WM PEIS AND ITS USE IN DETERMINING HUMAN HEALTH IMPACTS

Page B-9. Line 5 or equation B-1.

The equation for site adjustment factors is presented. Equation B-1 is confusing and needs additional brackets and explanations. The subscript $_{site}$ appears inside the square bracket and the subscript $_{keysite}$ appears outside the square bracket. The definition of SF_{site} contains the word site and the phrase key contributing sites. The definition of V_{sites} and $V_{WM\ PEIS}$ contain the word site only. The definition of C_{SEIS} and $C_{WM\ PEIS}$ contain the phrase "site Key" only. It appears that there is a multiplication of data from $_{site}$ tables with data from $_{keysite}$ tables. Finally, the large curved brackets have the subscript $_{alternative,\ subalternative}$ where alternative pertains to the SEIS-II and subalternative pertains to the Draft WM PEIS, which suggests that SF_{site} is a matrix.

Page B-9. Lines 14 through 16.

Statement: "Key contributing sites were determined by ranking the sites by cancer incidence risk for each alternative. The sites with the largest risk were then selected until a contribution of at least 90 percent of the total cancer incidence risk as reported in the Draft WM PEIS was reached."

It is not clear what this paragraph has to do with the calculation of site adjustment factors. Presumably it deals with the evaluation of the ratio of site key radionuclide concentration in SEIS-II/site key radionuclide concentration in the Draft WM PEIS.

Page B-9. Lines 31 through 33.

Statement: "Key radionuclides are those defined in Appendix D of the Draft WM PEIS as the single radionuclide contributing the highest risk cancer fatality at each site under each alternative. Key radionuclides are identified in Appendix D of the Draft WM PEIS."

Equation B-1 deals with "site key radionuclides" and not "key radionuclides."

Page B-11. Line 17 equation B-2.

The equation for adjusting the site-specific cancer incidence values of the WM PEIS is presented.

Equation B-2 is confusing and may contain misplaced subscripts. Again the subscript $_{site}$ appears inside rounded brackets and the subscript $_{keysite}$ appears outside the same rounded brackets. Presumably the subscript $_{keysite}$ should be beneath the summation symbol. Also the large square brackets that enclose R(adj) $_{WM\ PEIS}$ have the subscript $_{alternative,\ subalternative}$ which suggest that R(adj) $_{WM\ PEIS}$ is a matrix. SF_{site}, which is inside the large square brackets also involved the subscript $_{alternative,\ subalternative}$.

Page B-12. Table B-4.

The site adjustment factor for LANL should be 0.13 since this is the value used in the results of the calculations that are presented in Table B-5. The rounded off value of 0.1 is not used in the calculations.

APPENDIX C
AIR QUALITY

No Comments

APPENDIX D

LIFE-CYCLE COSTS AND ECONOMIC IMPACTS

Page D-1. Section D.1. Life-Cycle Cost.

The section does not indicate that life-cycle costs were determined for exhuming the CH-TRU waste disposed before 1970. It does not appear that these costs were analyzed in the draft WM PEIS.

Page D-2. Table D-1.

The bottom part of the table calculated the Volume Adjustment Factor. The volumes in column 5, SEIS-II CH-TRU Waste, column 6, and column 7, SEIS-II RH-TRU Waste, should be rounded off to be consistent with Table A-5. Also, the RH-TRU volumes are quite different in the two tables. The lack of consistency is confusing. It should indicate that the volumes are in cubic meters.

Page D-3. Table D-2.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-6 and A-7.

Page D-4. Table D-3.

Volumes in columns 5, 6, and 7 should be rounded off to be consistent with Tables A-8 and A-11.

Page D-5. Table D-4.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-9 and A-11.

Page D-5. Table D-5.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-10 and A-11.

Page D-6. Table D-6.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-12 and A-13.

Page D-7. Table D-7.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-8 and A-11.

Page D-8. Table D-8.

Volumes in columns 5, 6, and 7, should be rounded off to be consistent with Tables A-9 and A-11.

Page D-10. Line 4.

The discount factor is presented as (1/1+r). There appears to be an error. It is not possible to reproduce the numbers in Table D-10 using the above formula for the discount factor.

Page D-10. Table D-10.

The rounding off of numbers is very crude. The values for Inflation-Adjusted Discount Rate of r=3 percent and r=5 percent in column 3 are the same. It is not possible to come close to the numbers in row 3 using a discount factor of $1/1.05^{35}$. Rounding off to the nearest $0.5 B in column 3 on a value of $3.5B does not build confidence. This amounts to 15%.

APPENDIX E
TRANSPORTATION

The Appendix E, review concentrates on the discussions and calculations relevant to the radiological aspects of the Proposed Action for truck transportation, since this is the most likely final choice for waste shipments to WIPP. Implications of the alternative actions, rail transport, and hazardous chemical impacts were evaluated in less detail.

EEG reviewed various DOE WIPP transportation documents over the years and produced several related reports. None are referenced. One report ("Risk Analysis of the Transport of Contact Handled Transuranic (CH-TRU) wastes to WIPP along Selected Highway routes in New Mexico using RADTRAN IV," Anthony F. Gallegos and James K. Channell, EEG-46, August 1990) is particularly relevant to Appendix E. EEG-46 is a reasonable and adequately conservative evaluation of transportation risks. Our review of Appendix E is a comparison with EEG-46. Consideration was given to the fact that Appendix E is a nationwide assessment and changes in assumptions have occurred since 1990.

Page E-2.

The statement "The SARP application for the RH-72B shipping cask is to be submitted to the NRC in September of 1996 is incorrect." It was submitted in December of 1996.

TRUCK TRANSPORTATION

Routes and Mileage

The proposed waste shipment routes to WIPP agree with our understanding. The distance reported in Table E-5 from LANL to the WIPP site (549 km, with 512 km being rural, 34 suburban and 3 urban) agrees favorably with that used in EEG-46 (548 km, with 509 km rural and 39 km suburban). Distances from the other sites were not checked, but appear reasonable.

Non-radiological Accidents

DOE reported accident, injury, and fatality impacts per roundtrip shipment from each site to WIPP in Table E-8. However, since accident rates per kilometer were not given, the values in Table E-8 could not be checked. The back-calculated accident rates for the LANL to WIPP route (1.62×10^{-6}/km in suburban areas and 3.13×10^{-7}/km for rural areas) are reasonably close to the values used in EEG-46 (3.21×10^{-6}/km rural and 1.78×10^{-6}/km urban and 1.78×10^{-6}/km suburban).

Accident per shipment data from Table E-8 and the number of shipments values from Tables E-1 and E-2 were used to check the total values for the proposed values in Table E-9. Agreement was within 3% and differences were probably due to rounding error. The EEG-46 value of 5.0 accidents (while carrying wastes) in New Mexico extrapolated to 52 CH-TRU roundtrip accidents. This was adequate agreement (-10%) with the SEIS-II value of 58 accidents.

We agree with the value of 0.165 (rounded to 0.2) LCFs from vehicle pollution in urban areas.

Accident Free Radiation Doses

In Table E-10 (RADTRAN INPUT, Etc.) it is not clear why the number of people exposed per stop and the exposure distance is different for CH-TRU and RH-TRU.

The aggregate accident-free dose to occupational and nonoccupational persons is presented in Table E-14. The non-occupational value for CH-TRU (4,200 person-rem) is similar to the value obtained (4,050 person-rem) by scaling up the EEG-46 value of 330 person-rem by a mileage factor of 40.7×10^6 mi/7.8×10^6 = 5.22 and a Transportation index (TI) adjustment of 4.0/1.7 mrem. This is good agreement.

The aggregate occupational dose of 710 person-rem was reproduced within 1% from methodology in SAND 84-0036 (RADTRAN III) and when using the actual average TI value (1.5 mrem/hr.) from Table E-11. This dose was not calculated directly in EEG-46.

Scenarios for calculating doses to the maximum exposed individual (MEI) are described on page E-32 and the doses are shown in Table E-15. The scenario description does not provide all the assumptions necessary to make the calculations. We were able to reproduce the CH-TRU doses for the Departure Inspector, the State Inspector, and the rest stop employee within $\pm$ 12% by using either the TI values reported in Table E-11 or the 4 rem/h value (that the text said was being used). The scenarios are sufficiently conservative so that the MEI doses in Table E-15 adequately represent the doses to members of the public and to occupational workers that do not wear dosimeters.

The calculated risk to these MEIs are not large. However, the doses average several hundred millirem/year for 10 years. This is somewhat greater than the 100 mrem/y value that most national and international agencies believe should not be exceeded from all radiation exposure combined (radiation doses from natural background and medical usage are not included in the 100 mrem/y value). These considerations suggest that the following operational control procedures should be implemented:

(1) persons who routinely inspect vehicles should be classified as radiation workers and required to wear dosimeters;

(2) normal procedures should not allow trucks carrying CH-TRU or RH-TRU wastes to routinely stop for long periods of time at locations where public exposure is likely to occur.

Maximum Transportation Accident Doses

EEG-46 calculated a maximum of 10 LCFs from a category VIII accident in North Carlsbad with an average SRS shipment (1,670 PE-Ci in 3 TRUPACTS). The probability of this event was calculated as 4.7×10^{-8}. SEIS-II calculated a bounding accident value of 16 LCF with a maximum allowable PE-Ci content in a TRUPACT-II (928 PE-Ci) and 3 LCF with an average inventory (191 PE-Ci). There were numerous differences in assumptions and there is an uncertainty about the actual population density used in EEG-46.

Attempts to extrapolate EEG-46 LCFs resulted in only about 60% of the doses reported in SEIS. The SEIS-II bounding values are appropriately conservative and indicate that very low probability accidents could have serious consequences.

It was noted in the PEIS (page E-77) that "waste shipments from LANL were found to result in the highest potential transportation accident doses." SEIS-II did not give highest potential transportation accident doses by site. The WM PEIS (footnote to Table E-26) assumed that all 3 TRUPACTs would fail in an accident. SEIS-II (page E-42) assumed only one would fail.

Aggregate Radiological Impact from Accidents

The aggregate radiological impacts from accidents in Table E-22 present the expected population dose (person-rem) from multiplying the person-rems for each accident by the probability of occurrence. The total dose for the Proposed Action is 850 person-rem (829 from CH-TRU shipments and 15 from RH-TRU. These doses are over two orders of magnitude greater than would be predicted from EEG-46 even after scaling for total system mileage. Most of this difference can be attributed to the higher impact release fractions (IRF) for accident categories V, VI, and VII used in SEIS-II. These IRF values are 100, 40, and 4 times (for categories V, VI, VII) those used in EEG-46. These categories have a much higher probability of occurrence and actually contribute more to the expected doses than category VIII accidents. It is concluded that these aggregate population doses from accidents are appropriately conservative.

Rail Shipments

On page 3-7 the SEIS gives four reasons why truck only transport was chosen: (1) limited interest by rail carriers; (2) higher cost of dedicated trains relative to truck shipments; (3) cost of acquiring additional TRUPACT-IIs; and (4) rail carriers would not assure DOE that transport could occur in less than 60 days. SEIS-II discusses 7 issues (bottom of page E-58 and top of page E-60) that need to be addressed before a decision can be made to use rail transport. The present uncertainties mentioned for these issues are largely true. However, it is unclear whether DOE has seriously re-evaluated this issue since the decision about 12 years ago to have truck

only transport to WIPP. There is no indication in DOE/WIPP 93-050 (Comparative Study of WIPP Transportation Alternatives, February 1994) that the decision was really re-evaluated.

The values reported in Tables E-29 through E-32 were "determined by adjusting the transportation impacts from truck shipments" (page E-58). Examples of questionable assumptions used in this analysis are:

(1) The average speed in all population zones was said to be 55 miles per hour for truck transport. This is inconsistent with Table E-10;

(2) The total miles assumed to be the same for truck and rail. SEIS-I actually developed rail route distances (see Table D.4.2). Distances by rail were 16%-26% greater for all of the major generating sites;

(3) The origin of the 89% rural, 10% suburban, and 1% urban breakdown is not given. The mileage - average for the distances in SEIS-I (weighted for the number of SEIS-II shipments) is 87%, 12%, and 1%;

(4) The basis for the assumption that the number of individuals sharing the transportation corridor is at least two orders of magnitude less is not given;

(5) We cannot reproduce the value in equation E-5 from equation E-4. The value of TI in E-4 should be 0.033 (from the previous page). Also, a value is needed for N (number of rail shipment transfers per shipment). If N were about 3.2 and TI was .033 the dose would be $1.7x60^{-4}$(TI)M;

(6) The logic for assuming that the aggregate radiological consequences of rail accidents were identical to truck accidents (first paragraph under E.7.3, page E-62) is unclear (same miles traveled times less frequency for rail accidents = same as truck). Is this because the release would be double in rail accidents?

A comparison of the Rail Transportation impacts in Tables E-29 (Action Alternative 1) and E-30 (Action Alternative 2) indicates there are less effects from rail transport than from truck transport (Tables E-9 and E-14. This suggests that SEIS-II should provide a better rationale for using truck only transportation or else seriously re-evaluate whether a truck and rail mix might be preferable.

Alternatives

The results of Alternative Impacts from accidents, vehicle pollution, and routine radiation exposure that are presented in various tables were studied to see if the values were reasonable compared to the Proposed Action. In all cases, the values appear to deviate in the expected direction from the Proposed Action and the magnitude of the deviation seemed reasonable. More description in the text explaining these differences would be helpful however. For example, is the lower (relative to the Proposed Action) non-occupational radiation dose total in Table E-14 for CH-TRU waste in Alternatives 2A and 2B due solely to the fact that there are fewer miles travelled (which can be implied from Table E-9)? Does this calculation use the TI values from Table E-11, or does it use a TI of 4 in both cases?

The statement on page E-53 that for thermally treated waste "The release fraction would be reduced by a factor of 1,000, ..." is not referenced or justified. Some reduction would be expected, but a three order-of-magnitude reduction requires justification.

A large number of comparisons are made about the transportation effects between alternatives in Appendix E. These comparisons include expected radiological and non-radiological risks from both incident free and accident conditions. The consequences of severe low probability accidents are also evaluated. Yet there is no discussion in this Appendix of using this information to aid in the selection of the appropriate action. The impression given at this time is that the Proposed Action is the only one being considered.

Page E-43. Equation E-1.

There appears to be a typographical error. Equation E-1 has a parameter named FMPI while the explanatory text has a parameter named FMRPI.

Page E-45. Equation E-2.

There appears to be a typographical error. Equation E-2 has a parameter named FMRT while the explanatory text has a parameter named FMRPT.

Page E-64. Section E.8.2.

There is a conversion error in the first paragraph of this section: 3.4×10^6 cubic meters is equal to 1.2×10^8 cubic feet (not 10^6).

APPENDIX F
HUMAN HEALTH
(from Routine Operations)

Page F-14. Section F.2.3.3 External dose of Involved Workers.

No units are given in Tables F-11 through F-15. This should be corrected in the Final SEIS-II.

Page F-17, last paragraph.

The statement that only a small volume of waste would require packaging is perhaps misleading. "Repackaging" is intended, not "packaging". As mentioned under page A-12 comments, about 14% of wastes exceed thermal limits even with bagless posting and a significant percentage of existing wastes are believed to contain bags. Also note that the Draft SAR Appendix A states that DOE plans to repackage or process 88% of the existing CH-TRU waste.

Page F-18, first paragraph.

Dose rates are said to be reducible by administrative controls but no credit is taken for this. Credit should not be taken because there is no commitment to exercising administrative controls.

Page F-18. Equation F-1.

No reference is provided as to where the input data of D_{id} and C_{ic} can be found. Without these input data, it is not possible to verify independently the average surface dose rate in Table F-17.

Page F-20.

The reason for calculating the worker lifetime dose on a per waste panel basis is not apparent since the exposure assumptions are unrelated to the filling of a panel. All that is needed is the assumption of the hours per year that the worker is present at 1 meter from the drum and the average 1-meter dose rate from Table F-17. The workers should have exposure time limited to 345 hours per year in order to have the annual dose $\leq$ 1 rem for an average 1-meter dose rate of 2.9 mrem/hr. Furthermore the assumption in Table F-18 that the 10 panels will be completed

in 20 years is inconsistent with the rationale described in the last paragraph of page F-20 that would require 23.2 years in order to hold doses to 1 rem/year. These calculations do not appear to address exposures from the installation of MgO around the drums.

Page F-21.

Attempts to reproduce two of the individual dose values for storage site workers for alternative 1 resulted in values that were +12% and -17% of the Table F-22 values. In this effort we started with the average 1-meter dose rate in Table F-17 and decayed screening values from Table F-12 over the 20 to 55 year period to obtain average annual dose rates for the 35 years. Ingrowth of ^{241}Am from decay of ^{241}Pu was also included. It would be helpful to reviewers if SEIS-II gave more details of the calculations so they could be checked without making numerous assumptions.

The SEIS-II chose to evaluate the radiological effects of routine operations involving lag storage and no action alternatives on the 35-year working lifetime of individual workers. These results are presented in Table F-22 and this is an appropriate way to evaluate the risk to an individual worker or a (35-year) generation of workers. However, it does not indicate the cumulative effect over several generations (for the various action alternatives) and perpetually for the No Action Alternatives. The method used makes the human health effects (LCFs) of the alternatives appear better in comparison with the proposed action than it would be if multi-generational effects were included.

Page F-21. Equation F-3.

No reference is provided for the input data of $V_{CH,S}$ and T. The definition of T as a worker throughput rate of one worker per 1,000 cubic meters is confusing. It is not possibly to verify independently the values in Table F-19.

Page F-25.

The involved worker lifetime radiological impacts from routine CH-TRU waste disposal operations in Table F-21 total 720 person-rem for the entire disposal phase. This total is

derived from 36 workers x 20 rem/worker =720. The WIPP Safety Analysis Report (DOE/WIPP-Draft - 2065 Revision 1, Table 7.1-2) used 36.9 rem/year for 38 persons and a 35 year disposal period. This totals 1,292 person-rem and a dose of 34 rem/per person. This is 1.8 times the worker population dose used in SEIS-II. The main difference is in assuming a 35 year disposal phase rather than a 20 year phase. DOE should present consistent methodology and results in its related WIPP documents.

The individual lifetime worker doses in Table F-22 for RFETS are excessively high. Both Action Alternative 1 and No Action Alternative 2 exceed occupational limits (5 rem/y) every year for 35 years. Surely such doses would not be allowed. These doses need to be explained or the text needs to be corrected.

APPENDIX G
FACILITY ACCIDENTS

There is no statement that SEIS-II is in compliance with the report, U.S. Department of Energy, 1993, *Recommendation for the Preparation of Environmental Assessment and Impacts Statement,* Washington, DC: Office of National Environmental Policy Act Oversight nor that it is in compliance with the DOE/New Mexico C & C Agreement. The second statement in the WM PEIS, APPENDIX F, Treatment and Storage Facility Accidents, F.1.1. SUMMARY, indicates compliance with the above cited document.

Page G-1. Lines 31 and 32.

Statement: "The health impacts from acute exposures to radionuclides from accidental releases were calculated as described in Appendix F."

The statement is incorrect. Appendix F deals with human health impacts that may result from exposures to radioactive materials and hazardous chemicals during routine storage operations at waste storage sites and during routine disposal operations at the WIPP.

Page G-2. Lines 3 through 5.

Dose-to-risk conversion factors for a population are given with a unit of /rem.

The unit is incorrect. The unit for dose to risk conversion factor for a population is /(person-rem). The dose-to-risk conversion factors are correctly presented on page F-2.

Page G-8. Table G-4.

If Pu-238 and Pu-240 are considered to be major contributors to dose at ORNL, Pu-239 should also be listed in that category.

Page G-13. Line 40.

Statement: "Because of the serious nature of the accident, the involved workers were assumed to be fatally injured."

There should be an indication of the number of workers involved.

Page G-14. Table G-9.

The text on page G-13 states that thermally treated waste is placed in 5 drums simultaneously. Scenario T4 shows 4.9 drums. The difference is small, but the lack of consistency is confusing.

Page G-17. Line 4.

Q is defined as the radionuclide or hazardous metal inventory of a waste container (from Appendix A). Appendix A provides radionuclide inventories only on a per treatment site basis. Additional calculations are required to convert the data to a per drum basis. It is not possible to independently verify the health impacts data presented in Tables G-13, G-16, and G-19.

Page G-18. Equation G-2 and line 6.

The quantity E/Q is known as the relative concentration (NUREG 1.145 or WIPP/SAR). The quantity is not defined in the Glossary and E/Q cannot be found in Acronyms and Abbreviations. In Table G-12, E/Q is referred to as the atmospheric dispersion factor. There should be consistency and the omission from the Glossary and from the Acronyms and Abbreviation should be corrected. This term has historically been labeled as χ/Q (Chi/Q). The use of the E/Q terminology is unnecessary and confusing.

Page G-18. Table G-11.

Column 3 of Table G-11 presents "population-Weighted E/Q (sec/cubic meter)".

The quantity "Population-Weighted E/Q" is not defined in the Glossary. Presumably, the units of "Population-Weighted E/Q" should be (person-sec)/(cubic meter). The parameter and its correct units should be included in the glossary.

Page G-21. Lines 11 through 15.

Statement: "Acute releases were assumed to be dispersed in one direction, so population impacts were estimated for a single, maximally exposed, 22.5 degree sector (out to 80 kilometers [50 miles]) and not for the entire 80-kilometer (50 mile) region population. Population weighted atmospheric dispersion values were calculated and used to determine the maximally-impacted sector, considering both the change in air concentration over distance and the population impacts in a single 22.5-degree sector."

The description does not make it possible to independently verify the calculations. The discussion should include equations for the calculations of the population-weighted atmospheric dispersion values and for the calculations of the population impacts in a single 22.5 degree sector.

Page G-30. Lines 3 through 5.

Statement: "Intakes of radionuclides could result in a dose of up to 14,800 rem, with a corresponding probability of an LCF of greater than 1."

Numerically, a probability is a dimensionless number with values between 0.0 and 1.0. 0.0 indicates that the event cannot occur and 1.0 indicates that the event will occur with absolute certainty. A probability cannot be greater than 1.0. Also, a TEDE of 14,800 rem may be a lethal dose (rather than an LCF) even for transuranic wastes where internal doses are delivered over many years.

Page G-36. Lines 28 and 29.

Statement: "The fission products contributing the most to external dose rates were Cs-137/Ba-137m and Co-60,...."

Co-60 is an activation product and not a fission product.

G-42. Table G-28.

Insufficient data are provided in the text to verify the dose calculations. The text does not provide a reference for the dose conversion factor, DCF, for PE-Ci, and it is not possible to calculate the source term for accident scenario 3 (earthquake) because there is no reference to the number of waste drums involved.

Page G-46. Table G-31.

See comment page G-42. Table G-28.

Page G-49. Table G-33.

See comment page G-42. Table G-28.

APPENDIX H
LONG-TERM CONSEQUENCE ANALYSIS FOR PROPOSED ACTION AND ACTION ALTERNATIVES

A general comment is that EEG believes that the Final SEIS-II should use methodology, codes, and selected data from the CCA. Any modifications to the October 1996 CCA available prior to writing the Final SEIS-II should also be incorporated.

The EEG has identified a number of concerns on the long-term consequence analysis in our review of the Compliance Certification Application (CCA). A number of plausible scenarios have not been analyzed, many conceptual models of breach are invalid, and many parameter values selected for analysis are wrong. The EEG has submitted detailed comments on the CCA to the EPA and plans to publish a report (EEG-65) outlining these concerns, in the near future. These concerns should be taken into account before a record of decision is developed.

Some of the EEG concerns published in our review of the draft CCA (EEG-61) have been incorporated in Section H-8 of this Appendix. The discussion in this section shows that most of these issues remain unresolved. We recommend, therefore, that no decision on the basis of SEIS-II analysis be made until these concerns are resolved in the process of the CCA review and the EPA's certification rule-making process.

Pages H-7&8. 75th Percentile Values.

There is no justification for the claim that the 75th Percentile Values as used lead to a realization that is "within 1% of the maximum release statistically possible." See comments under Page 5-40 & 41.

Page H-8. Last full paragraph.

The analysis is said to have shown no releases into the Culebra dolomite. This is inconsistent with the CCA, which showed releases in a number of realizations.

Page H-24. Next to last paragraph.

Contrary to the statement in this paragraph, the impacts of chemical retardation are being calculated in the PA for the CCA.

Page H-30. Table H-7.

These solubility values are from the DCCA. They are somewhat higher than those being used in the CCA because of the effect of MgO backfill. Final SEIS-II should use the CCA values.

Page H-34. Lines 1 through 6.

Reference is made to Figure H-7 and to Table H-8.

It is difficult to follow what the relationship is between Figure H-7 and the data in Table H-8. There is no explanation on how the last row of Table H-8, entitled Total Repository Volume, is obtained. It is not clear what the relationship is between Rest of Repository, Separately Modeled Panel Volume, and Total Repository Volume. Some additional clarification should be presented.

Page H-36. Table H-8.

The z distance in a two-dimensional grid was increased by factors of approximately 8 in order to accommodate the larger waste volumes in Action Alternatives 1, 2, and 3. This violates the two- dimensional assumption of the BRAGFLO grid. A three-dimensional analysis may be needed to give reliable results.

Page H-49. Table H-22.

The CCA used much smaller brine reservoir values than the volume estimated for WIPP-12. EEG has reservations about this CCA assumption. Also, the compressibility value shown should be for rock compressibility, not pore compressibility (pore compressibility = rock compressibility ÷ effective porosity).

Page H-52. Lines 1 and 2.

Statement: "The pressure release of the waste panel, as a result of the exploratory drilling event at 100 years post-closure, is clearly evident for Case 2 and 4 in Figure H-8."

In Figure H-8, the pressure release for cases 2 and 4 appears to occur at 400 years post-closure. No explanation is provided in the text for the delay in pressure release from 100 years post-closure (time of drilling event) to 400 years post-closure (time of pressure release). Also, Figure H-8 indicates a significant pressure increase between 700 years and 1,300 year post-closure for cases 2 and 4. Finally, the asymptotic behavior for cases 2 and 4 at 10,000 years post-closure is significantly different. Are the differences in the brine pressure for cases 2 and 4 the result of error propagation in numerical solutions of the differential equations? Some discussion should be provided in the text.

Page H-52, Figure H-9.

The appropriate conversion factor between pCi/1 and Ci/m^3 is 1 pCi/1 = 10^{-9} Ci/m^3 (not 10^{-15} pCi/1). See page 5-43 comment.

Page H-55 and Later. Table H-24.

No attempt was made to check the reasonableness of the assumptions and calculations of releases and doses to the driller. It is noted in Table H-24 that the value for Pu-240 is incorrect. It will be a few percent of the Pu-239 value, not less than 0.01%.

Page H-57. Last paragraph.

Because of the pCi/1 to Ci/m^3 conversion error mentioned, we are unsure whether the 1 pCi/1 value quoted here is correct or whether the value is 10^{-6} pCi/1.

Page H-60. Lines 1 and 2.

Statement: "The pressure release of the waste panel as a result of the exploratory drilling event at 100 years post-closure is clearly evident for case 7 and 9 in this figure."

Figure H-11 indicates a pressure release at almost 500 years post-closure. This is significantly different from 100 years post-closure, which is the time of the drilling event. No explanation is provided in the text for this delay. Are the differences in the asymptotic behavior at 10,000 years post-closure between cases 6 and 8 and cases 7 and 9 the result of error propagation in the numerical solutions of the differential equations? An explanation should be provided in the accompanying text.

Page H-62. Table H-29.

For the radionuclides of Am-241, Cm-244, Pu-238, Pu-239, Pu-240, Pu-241, U-233, and U-234, column 3, CH-TRU and RH-TRU Waste Panel, is the sum of column 1, CH-TRU Waste Panel, and column 2, RH-TRU Waste Panel. For other radionuclides such as Ac-227, Cm-243, Cs-137, Pa-231, Sr-90, and Y-90, column 3 is not the sum of columns 1 and 2. A more detailed explanation for columns 1, 2, and 3 should be provided in the accompanying text.

Page H-66. Lines 25 and 26.

Statement: "The pressure release of the waste panel as a result of the exploratory drilling event at 100 years post-closure is clearly evident for cases 12 and 14 in the figure."

Unlike the spiked brine pressure curves for cases 2 and 4 in Figure H-8 and for cases 7 and 9 in Figures H-11, the brine pressure curves for cases 12 and 14 are smooth and peak close to 1,500 years post closure. No explanation is provided for the difference in behavior of the brine pressure curve for cases 12 and 14 from cases 2, 4, 7, and 9.

Page H-72. Lines 15 and 16.

Statement: "The pressure release of the waste panel as a result of the exploratory drilling event at 100 years post-closure is clearly evident for cases 17 and 19 in this figure."

See comment page H-52, lines 1 and 2. See also comment page H-60, lines 1 and 2.

Page H-74. Table H-39.

See comment Page H-62. Table H-29.

APPENDIX I
LONG-TERM CONSEQUENCES OF NO ACTION ALTERNATIVE 2

This Appendix was reviewed for general approach, assumptions used, and conclusions reached. Little was done to check calculations. The calculations were done in a preliminary manner compared to those for the Proposed Action and (especially) in the CCA. Therefore it is not possible to compare results in more than general terms.

Page I-1. Last paragraph.

The statement is made that both the FEIS and SEIS-I records of decision (ROD) determined that the No Action Alternative was unacceptable "because of the potential impacts of natural, low-probability events and human intrusion at storage facilities after government control of the site is lost." Presumably, this will also be the decision in the SEIS-II ROD. However, this Draft SEIS-II has not addressed the issue of whether it is appropriate to trade-off predictable early fatalities from accidents and routine radiation exposure against the threat of low-probability events far in the future. Nor is there an estimate of the probabilities that these future events will occur.

Page I-3. Section 1.2.1.

The set of assumptions used for inadvertent human intrusion impacts are appropriately conservative.

Page I-6. Equation 1-2.

The convolution integral appears first in equation I-2. All the explanations pertaining to the convolution integral given much later with equation I-7, should be given first with equation I-2.

Page I-9. Equation 1-7.

The symbol for the convolution operation is used twice, the second time inside an integral.

The use of the convolution symbol inside the integral is incorrect. A symbol representing multiplication should be used inside the integral.

Page I-11. Next to last paragraph.

The dimensions given here (66 cm diameter and 91 cm height) for a 55-gallon drum differ from those used in WIPP Performance Assessment (60.2 cm diameter and 89.2 cm height). Use of the PA dimensions gives a surface-area-to-volume ratio of 0.11 cm^{-1}.

Page I-12. Line 3.

The effective lifetime of 500 years for cemented TRU waste forms in this analysis may not be conservative.

Page I-12. Line 9.

Statement: "BIR-2 specifies a waste volume and waste density for each of 10 waste material types (Table I-1). These waste material types were categorized into one of the generated TRU waste-form categories modeled in this analysis."

The reference in parenthesis to Table I-1 belongs at the end of the second sentence.

Page I-12. Lines 23 through 25.

Statement: "These relative quantities were multiplied by the total TRU Waste volumes for the site (see appendix A) to determine final site volumes for each TRU waste form category. Volumes are also reported in Table I-2."

It is not possible to obtain the waste volumes reported in Table I-2 (columns 3 and 4) by multiplying the waste volumes of Table A-14 by the relative quantities given in Table I-2 (columns 1 and 2).

Page I-17. Fourth Paragraph.

Buried wastes are assumed to not release any wastes by surface erosion/dispersion mechanisms. Yet Table I-6 predicts that 6 of the 7 major sites will have enough surface erosion to expose wastes in less than 10,000 years. The assumption used may maximize groundwater contamination. Does it necessarily maximize total population dose?

Page I-27. Table I-7.

Our calculations (for inhalation and soil ingestion only) of driller impacts at LANL and SRS gave values that were 1.6 and 3.1 times as high as the values in this table. We had to make several assumptions that should have been provided.

Page I-31. Twelveth line from bottom.

The maximum dose of 14.5 rem should be per lifetime (not per year).

Page I-31. Figure I-4.

Why are the lifetime doses for MEIs at all sites totalled? These are all different individuals and there is no significance to a total dose.

Pages I-33, 34. Figure I-5 and Table I-11.

The curves in Figure I-5 can be used to approximate the total of 2,325 LCFs over 10,000 years mentioned on page I-31. Our estimate was about 10% higher than this.

It is interesting to compare these estimated LCFs with values that are permitted for geological disposal of TRU wastes in 40 CFR 191. However, in doing so, we realize that these estimates do not have the level of detail and justification required in 40 CFR 191.

The standards in 40 CFR 191 (which apply to WIPP) were based on the assumption that a permissible limit was 10 LCFs per million curies of alpha-emitting transuranic radionuclides with half-lives longer than 20 years. This scales to about 42 LCFs in 10,000 years for the various

inventories listed in Appendix A. The estimate in this Appendix of 2,325 LCFs for NAA 2 is over 50 times higher than would be allowed at WIPP.

A conclusion that long-term storage is much worse is site specific. If one uses the curves in Figure I-5 and the inventories in Tables A-36 and A-38 to determine the amount of activity stored at each site it can be shown that wastes left at SRS, Hanford, and ORNL would be under the 40 CFR 191 limit. Again, there is the caveat that these calculations are less detailed and justified than would be required to show compliance with 40 CFR 191.

EEG-66

INDIVIDUAL RADIATION DOSES FROM TRANSURANIC WASTE BROUGHT TO THE SURFACE BY HUMAN INTRUSION AT THE WIPP

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New Mexico

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, is being constructed as a repository for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC04-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, continues the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the generator sites' compliance with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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1. INTRODUCTION

The U.S. Environmental Protection Agency (EPA) standards that are applicable for long-term disposal of radioactive transuranic wastes at the Waste Isolation Pilot Plant (WIPP) facility are codified in 40 CFR Part 191. These standards require the U.S. Department of Energy (DOE) to evaluate the effects of releases from the repository for both undisturbed and disturbed conditions. Undisturbed conditions are those that could occur from natural causes without any human actions. Disturbed conditions are those caused by inadvertent human actions such as drilling through the repository during oil and gas exploration. Deliberate intrusion into the repository does not have to be considered.

Releases from undisturbed events must be evaluated for the radiation dose* to individuals (§191.15) and the effect on groundwater quality (§191.24) as well as for the cumulative release of transuranics to the accessible environment (the Containment Requirement, §191.13). Releases from disturbed events are required to be evaluated only for the Containment Requirements. The Compliance Certification Application (CCA) that DOE submitted to EPA in October 1996 did not evaluate individual doses from disturbed events (U.S. DOE 1996c).

Most other countries with nuclear waste require that radiological risk to an individual (individual radiation doses) be assessed for both undisturbed and disturbed scenarios. An OECD/IAEA International Review Group that evaluated the WIPP Project was concerned that individual doses had not been calculated and Sandia National Laboratories (SNL) provided estimates during the Group's January 1997 Carlsbad meeting (OECD/IAEA 1997).

The National Academy of Science (NAS) WIPP Committee in their review of SNL's 1992 Performance Assessment (PA) also concluded that the scope of the PA effort "must include performance measures that go beyond radionuclide release rates to the accessible environment" (NAS 1996).

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* Radiation doses in 40 CFR 191 and this report are the annual committed effective dose, which EPA defines as the committed effective dose resulting from a one-year intake of radionuclides released plus the annual effective dose caused by direct radiation.

Section 801 of the Energy Policy Act of 1992 (Public Law 102-486) required EPA to set standards to ensure protection of the health of individual members of the public from the proposed Yucca Mountain Project site for high-level radioactive waste. Section 801 also required the NAS to conduct a study providing guidance to EPA. One of the three questions the NAS was charged with addressing was "whether a health-based standard based upon doses to individual members of the public from releases to the accessible environment will provide a reasonable standard for protection of the health and safety of the general public". The NAS Committee on Technical Basis for Yucca Mountain Standards concluded that an individual dose standard was appropriate (NAS 1995). However the Committee did not agree on how the location and lifestyle of this individual should be defined.

Prior to the 1985 promulgation of 40 CFR 191 (which requires probabilistic analyses) WIPP human intrusion scenario calculations by EEG and DOE evaluated the individual dose with deterministic calculations. Several relevant reports were U.S. DOE 1980, Channel1 1982, Woolfolk 1982, and Bard 1982. The latter three reports evaluated the effects of contaminated Castile brine releases to the surface while U.S. DOE 1980 considered only material brought to the surface in cuttings from a drillbit.

The Environmental Evaluation Group (EEG) concluded that it is appropriate to revisit the issue of individual doses from inadvertent human intrusion. The specific purpose of this report is to:

(1) calculate likely individual doses that would result from the same releases predicted by the CCA;
(2) determine whether these calculated doses exceed limits for radiation exposure from other activities;
(3) compare the stringency of an individual dose standard at WIPP with the release limits in 40 CFR Part 191;
(4) discuss the appropriateness and feasibility of reducing potential doses to an individual from human intrusion at WIPP.

Because of the above concerns the deterministic calculations in this report rely primarily on drilling related analyses in the CCA for the determination of source term.[**] Details of the scenarios for workers, individual members of the public and the population within 80 kilometers (50 miles) of the site are adapted from scenarios used in prior WIPP reports. Pathway analyses and dose conversion factors primarily use current methodology from EPA and U.S. Nuclear Regulatory Commission (NRC) reports.

[**]The CCA results were used because one purpose of the individual dose calculation is to compare results with probabilistic cumulative releases and it does not imply that EEG is in complete agreement with the assumptions and methodology used in the CCA. Also, during the summer of 1997 the EPA required DOE to recalculate releases using some different parameter values. The Performance Assessment Validation Tests (PAVT) resulted in calculated waste volume and radioactivity releases that were about twice those in the CCA. These higher values have been used in this report only to determine the magnitude of the 95% upper confidence level release.

2. SCENARIO DESCRIPTION

This section provides an overall description of the drilling scenario, exposed persons, and intrusion times. Some of the major assumptions are also presented. Other assumptions are included in the appendices with the calculation methodology.

2.1 Radionuclide Releases to Surface

Radioactive material will be brought to the surface from all boreholes that penetrate a waste room due to cuttings and cavings. Radioactive material may also be brought to the surface from spallation and/or direct brine release if these processes occur.

Cuttings. Cuttings is the repository material directly intercepted and ground up by the drill bit. This material is brought to the surface in the drilling fluid and settles out in the mud pit before the fluid is recirculated into the borehole. The volume of waste material included in cuttings is equal to the cross sectional area of the drill bit times the initial height of the waste storage room times the fraction of the room contents that is waste.

Cavings. Cavings is the material that is eroded from the borehole wall by the action of the flowing drilling fluid. This eroded material is brought to the surface in the drilling fluid. The amount of cavings depends on the erosion shear resistance of the waste at the time of drilling. The erosion shear resistance parameter is uncertain and is variable. This was a sampled parameter in the CCA and thus the volume of cavings was a variable. The median, mean, and maximum cavings volumes in the CCA were 0.68, 1.0, and 8.7 times the cuttings volume (Helton 1996).

Spallings. Spallings is contaminated material that will be carried to the surface if drilling fluid is expelled from the borehole by high pressure gas flowing into the borehole from the penetrated waste storage room. The gas pressure in the waste room must be greater than the hydrostatic pressure of the drilling fluid in order for spallings to occur. Hydrostatic pressure is about 8 megapascals (MPa) at the repository horizon. DOE sensitivity analysis of the CCA calculations indicated that spallings releases from first intrusions occur less than one-half the time prior to

3,000 years. The frequency and volumes of spallings release from second intrusions into a waste panel are less than for first intrusions.

Direct Brine Release. Direct release of brine containing dissolved radionuclides can occur from a waste room into a borehole if mobile brine (a quantity of brine greater than the residual brine saturation) is present in the waste room and the brine pressure is >8 MPa. In the CCA calculations direct brine releases occur less than 25% of the time for intrusions prior to 10,000 years. The frequency and volume of flows are greater for the E1E2 scenario than for the E1 or E2 scenario.

2.2 Borehole Drilling

The human intrusion scenario is assumed to be the E2 scenario used in the CCA. An exploratory oil or gas drill bit penetrates a repository waste storage room in the Salado formation at a depth of 655 m (2150 feet). Drilling fluid (drilling mud) is continuously circulated during drilling and is the mechanism for transporting cuttings and cavings from the waste room to the surface. This material settles out of the drilling fluid in the mud pit before the drilling fluid is recirculated into the borehole. Contaminated material in the mud pit is the source of radiation doses to drilling crew workers and to the public.

The E1E2 scenario is not explicitly modeled in this report but it is considered by Channell 1982 and the CCA. This scenario involves a first penetration (E1) into a pressurized brine reservoir in the underlying Castile Formation. An E2 borehole penetrates the repository at a later time. This scenario has the potential to result in somewhat greater contaminated brine releases to the surface than from an E2 scenario alone. Also, the E1E2 scenario includes cuttings and cavings releases from two boreholes rather than one.

2.3 Exposure of Drilling Crew Members

Members of the drilling crew are subjected to external exposure as the contaminated drilling fluid flows through the shale shaker to the mud pit. Figure 2-1 shows a diagram of a typical drilling rig

site layout. The contaminated material in the mud pit is assumed to be evenly mixed (horizontally and vertically) with all the cuttings produced in drilling to a depth of 2100 m (the approximate depth of much of the current oil production around the WIPP site). This contaminated material is assumed to deliver an external dose to a worker standing at the edge of the mud pit for a total of 12 hours in the approximate 60-day period needed to complete the well.

The mud pit is assumed to be too moist for resuspension during drilling. However after drilling ceases (about 45 days before well completion) the mud pit will dry out and resuspension will occur. It is assumed that workers will be located at the drilling rig (100 meters from the center of the mud pit) for 80-hours and will inhale resuspended radionuclides during the 37% of the time they are down wind from the dried mud pit. The rational for not assuming that the mud pit would be filled (reclaimed) is discussed in Appendix A.

2.4 Annual Exposure to a Nearby Resident

In Case I the resident farmer is assumed to be living in a ranch house 800 meters from the mud pit in the prevailing downwind direction. This person is present at his residence for 350 days a year and spends 73% of the time indoors. He is exposed to resuspended material from the mud pit and receives a radiation dose from: (1) inhalation; (2) direct radiation from deposited material; (3) ingestion of dirt; and (4) ingestion of beef.

Case II (the resident non-farmer case) is a bounding case. The resident non-farmer is assumed to live at the edge of the mud pit and be in his home 73% of the hours in a year. Radiation dose is received from inhalation, direct radiation, and ingestion of dirt.

Case III (the non-resident farmer case) is another bounding case. The non-resident farmer grows vegetables in the mud pit which has been made fertile with imported top soil. Non-contaminated water from the Dewey Lake formation is assumed to be available for irrigation. This person is assumed to receive a radiation dose only from contaminated vegetables via the soil-to-crop pathway.

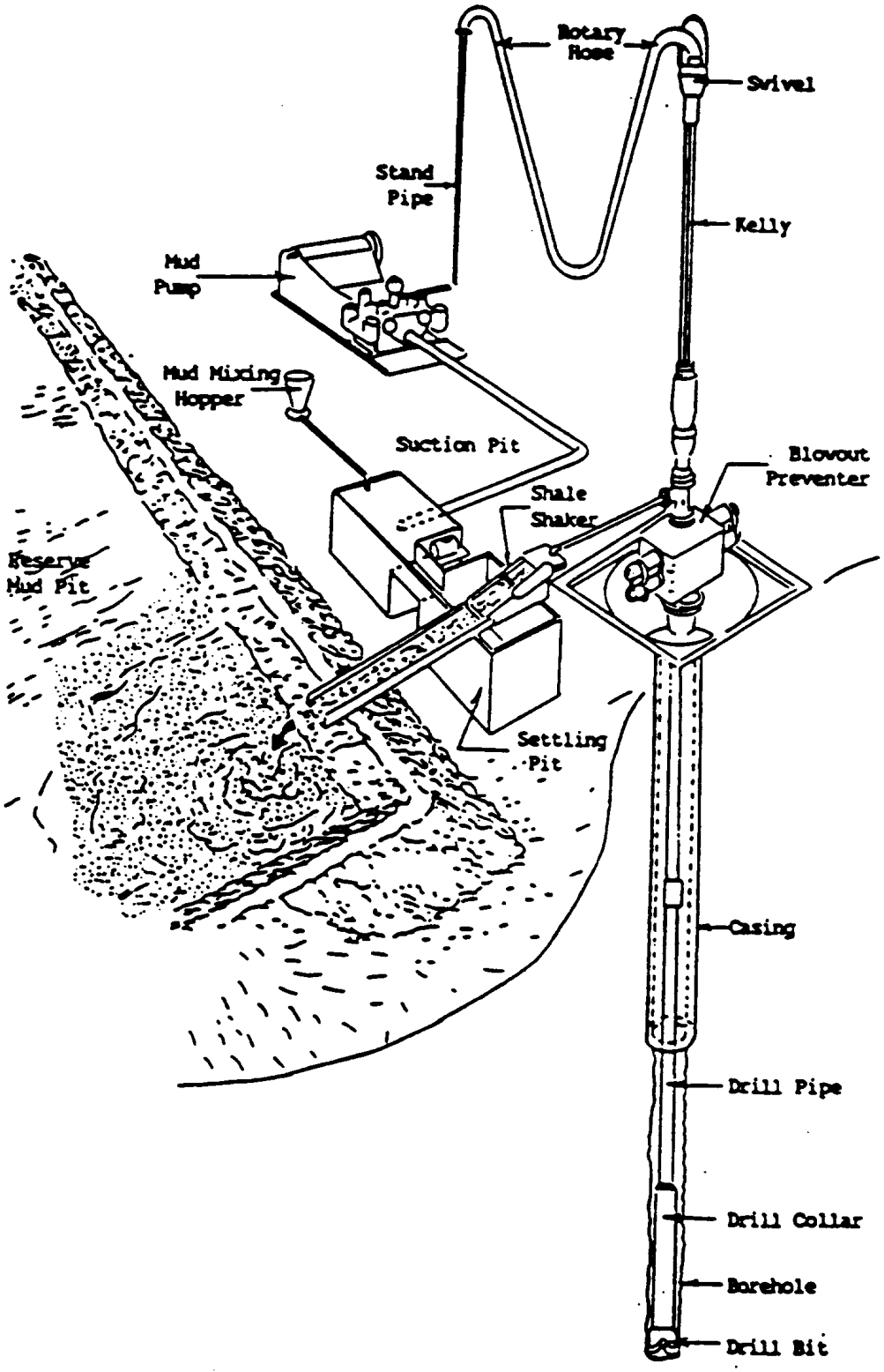

Figure 2-1. Drilling Fluid Circulation Diagram

2.5 Exposure of Population

The annual population dose to the resident population within 80 kilometers (50 miles) of the WIPP site is estimated. This dose is from inhalation of material resuspended from the mud pit. Average annual atmospheric dispersion values are used.

2.6 Times of Intrusion

For contact-handled transuranic (CH-TRU) waste the intrusion times evaluated were 100, 350, 700, 1000, 5,000 and 10,000 years after repository closure for the E2 scenario.

Intrusions into a remote-handled transuranic waste (RH-TRU) canister were evaluated at 100 and 350 years after repository closure for direct radiation. Inhalation doses were evaluated for the 10,000 year period.

3. SOURCE TERM

The source term is defined as the quantity of radionuclides brought to the surface as a result of a drilling event. Contact-Handled Transuranic Waste (CH-TRU) comprises about 96% of the volume of waste expected to be brought to WIPP. The remainder of the waste will be Remote-Handled TRU (RH-TRU) which contains about 10% of the radioactivity at time of closure. This source term will be developed separately for CH-TRU and RH-TRU since they are not placed together in the repository and both would not be expected to be impacted by the same intrusion.

3.1 CH-TRU Waste

3.1.1 Emplacement and Volumes of Waste

The WIPP repository is limited by federal statue to a capacity of 175,600 m^3 of waste. The volume of CH-TRU is expected to be 168,500 m^3. This waste is contained in either 0.208 m^3 (55-gallon) drums or in 1.7 m^3 Standard Waste Boxes. The containers will be stacked 3 high in waste storage rooms that are 90 m long, 10 m wide, and 3.96 m high. Waste containers will also be emplaced in panel drifts and access drifts.

The waste form is not homogeneous but is highly variable, including debris, sludges, metals, and glasses. The radionuclide concentration also varies over several orders of magnitude and there is considerable variation in radionuclide composition. The CCA documents DOE's sampling of 569 waste streams in order to capture the variability in radionuclide concentration and composition.

The amount of cuttings waste intercepted by the drilling bit is 0.301 m^3. This volume is the product of the area of the 0.311 m (12.25 inch) diameter drill bit and the height of the room (3.96 m). The amount of cavings is variable and this leads to a distribution of cuttings plus cavings volumes. In the CCA, the median, mean, and maximum volumes of cuttings plus cavings were 0.51 m^3, 0.60 m^3, and 3 m^3. These volumes need to be multiplied by the fraction of a room volume that contains waste (0.384) to get the volumes of waste brought to the surface. The source term in this report uses the mean and maximum volumes of waste (0.230 m^3 and 1.15 m^3).

Releases from spallings and direct brine release are complex and are related to the amount of pressure and brine in waste rooms at the time of intrusion rather than to the cuttings plus cavings volume. However, for modeling simplicity, the waste volumes brought to the surface by spallings and direct brine release are assumed to be 50% of the value of cuttings and cavings for all intrusion times except at 100 years (because modeling shows that pressures are minimal in the first few hundred years). This additional volume is assumed to have the same radionuclide concentration as the cuttings and cavings. The 50% value is similar to the typical effect on the complementary cumulative distribution function (CCDF) in the CCA from spallings plus direct brine release.

3.1.2 CH-TRU Radionuclide Inventory

The average CH-TRU radionuclide concentrations were obtained from Table 3-1 of U.S. DOE 1996a. The maximum waste stream, taken from Table 1 in Appendix B-2, was the 2800 m^3 of residue wastes at the Rocky Flats Environmental Technology Site (RFETS) and contains high concentrations of ^{239}Pu, ^{240}Pu, and ^{241}Am. The heat source waste from the Savannah River Site (1480 m^3) which contains high ^{238}Pu concentrations was used as the maximum source at 100 years after repository closure.

The curies of the key radionuclides brought to the surface in the mean (0.23 m^3) and in the maximum volumes of cuttings plus cavings (1.15 m^3) for typical 55-gallon drums are shown in Table 3-1. The residue waste is to be packaged in pipe containers positioned within 55-gallon drums. The maximum volume of waste in a pipe container is about 0.0445 m^3 and so the waste volumes brought to the surface are only 0.214 of those from typical drums.

Table 3-1. Curies of CH-TRU Waste Brought to Surface[1]

Nuclide					
Intrusion Time, Years	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Am	Total
Mean Concentration, Mean Volume					
100	1.20	1.07	0.283	0.552	3.11
350	0.249	1.59	0.414	0.555	2.81
700	----	1.58	0.401	0.318	2.30
1,000	----	1.56	0.387	0.197	2.14
5,000	----	1.39	0.253	-----	1.54
10,000	----	1.20	0.149	-----	1.35
Mean Concentration, Maximum Volume					
100	5.99	5.36	1.41	2.76	15.5
350	1.25	7.95	2.07	2.78	14.1
700	----	7.86	2.00	1.59	11.5
1,000	----	7.80	1.94	0.984	10.7
5,000	----	6.95	1.26		8.21
10,000	----	6.02	0.744		6.76
Maximum Concentration, Mean Volume					
100	18.5	1.42	0.180	0.297	20.4
350	0.0101	4.82	1.07	1.97	7.87
700	----	4.75	1.03	1.12	6.90
1,000	----	4.73	0.994	0.693	6.42
5,000	----	4.22	0.655	----	4.88
10,000	----	3.64	0.385	----	4.03
Maximum Concentration, Maximum Volume					
100	92.3	7.10	0.909	1.48	102.
350	0.0499	24.0	5.37	9.87	39.3
700	----	23.8	5.18	5.63	34.6
1,000	----	23.5	4.99	3.47	32.0
5,000	----	21.0	3.27	----	24.3
10,000	----	18.2	1.92	----	20.1

[1] The waste volumes brought to the surface in cuttings and cavings are 0.23m^3 and 1.15 m^3 for mean concentration wastes and for maximum concentration wastes at 100 years. Maximum concentration wastes at later time have volumes of 0.0492 m^3 and 0.246 m^3. Volumes from intrusion at 350 years and later are increased by 50% to approximate typical spallings and direct brine releases.

3.2 RH-TRU Wastes

3.2.1 Volumes of RH-TRU Waste

RH-TRU canisters are to be inserted horizontally into the walls of WIPP waste storage rooms. The cylindrical canisters are about 3.05 m (10 feet) long and have an internal diameter of 0.572 m (1.88 feet). A 0.311 m (12.25 inch) diameter drill bit that encountered the horizontal canister would drill through a maximum effective depth of about 0.542 m. Thus the volume of RH-TRU waste brought up by cuttings alone would be 0.0413 m^3.

Cavings to cuttings volume ratios are assumed to be the same as for CH-TRU waste. Therefore the mean and maximum cavings volumes would be 1.0 and 8.7 times the cuttings volume. The effective depth of waste for cavings is less than for cuttings since the cavings mechanism will not begin until the entire diameter of the drill bit has penetrated the cylindrical canister. This depth is about 0.479 m.

These assumptions lead to a mean cuttings plus cavings volume for RH-TRU of 0.0778 m^3. The maximum volume of waste would be 0.359 m^3, which is about 40% of the contents of a canister.

Releases from spallings and direct brine release are assumed to be zero for RH-TRU canisters. The canisters are isolated from the waste storage rooms and the marker beds so there appears to be little chance of having mobile brine present about and within the canister. Gas generation and some pressurization could occur within an RH-TRU canister but volumes are so limited if the canister maintains its integrity that any spallings effect should be minimal.

3.3.2 RH-TRU Radionuclide Inventories

The RH-TRU radionuclide inventories used in the CCA are derived from Appendix C of the Baseline Inventory Report (BIR) Revision 3 (U.S. DOE 1996a). The Revision 3 inventory, decayed to 1995, is further decayed to the year 2033 for use in the CCA.

The average radionuclide concentration of the Hanford RH-TRU was chosen as the mean concentration. The Hanford RH-TRU has the highest average radioactivity concentrations for most radionuclides and also contains 81% of the volume of all RH-TRU expected to be generated.

The maximum RH-TRU radionuclide concentration was taken from Hanford waste stream RL-W272. Data on this waste stream is presented in Appendix P of U.S. DOE 1996a. This 24 m^3 waste stream had the highest concentrations noted for RH-TRU in Appendix P. However, a number of RH-TRU waste streams did not have any radionuclide information. This waste stream's total radioactivity concentration (7.8 Ci ℓ^{-1}) is 34% of the maximum concentration allowed for an RH-TRU canister (23 Ci ℓ^{-1}) by agreement with the State of New Mexico. The calculated curies of RH-TRU waste brought to the surface are shown in Table 3-2.

Table 3-2. Calculated Curies of RH-TRU Waste Brought to Surface

Nuclide	Hanford Average Concentration				Hanford Max Concern Maximum Volume	
	Mean Volume		Max Volume			
	+100y	+350y.	+100y.	+350y.	+100y.	+350y
^{90}Sr	$9.40x10^{-2}$	$2.40x10^{-4}$	$4.34x10^{-1}$	$1.12x10^{-3}$	$2.39x10^{+1}$	$6.10x10^{-2}$
^{90}Y	$9.40x10^{-2}$	$2.40x10^{-4}$	$4.34x10^{-1}$	$1.12x10^{-3}$	$2.39x10^{+1}$	$6.10x10^{-2}$
^{137}Cs	$1.12x10^{-1}$	$3.40x10^{-4}$	$5.17x10^{-1}$	$1.61x10^{-3}$	$2.82x10^{+1}$	$8.61x10^{-2}$
^{137}Ba	$1.06x10^{-1}$	$3.20x10^{-4}$	$4.89x10^{-1}$	$1.52x10^{-3}$	$2.67x10^{+1}$	$8.15x10^{-2}$
^{238}Pu	$6.10x10^{-3}$	$8.60x10^{-4}$	$2.81x10^{-2}$	$3.95x10^{-3}$	$3.00x10^{-1}$	$4.29x10^{-2}$
^{239}Pu	$1.29x10^{-1}$	$1.29x10^{-1}$	$5.95x10^{-1}$	$5.92x10^{-1}$	$5.59x10^{0}$	$5.51x10^{0}$
^{240}Pu	$6.47x10^{-2}$	$6.32x10^{-2}$	$2.99x10^{-1}$	$2.91x10^{-1}$	$2.76x10^{0}$	$2.68x10^{0}$
^{241}Am	$1.11x10^{-1}$	$7.40x10^{-2}$	$5.10x10^{-1}$	$3.41x10^{-1}$	----	----

4. CALCULATED DOSES TO WORKERS

4.1 Doses from CH-TRU

4.1.1 External Radiation Dose at Shale Shaker

The calculated external radiation dose to a worker at the shale shaker from CH-TRU waste brought to the surface is shown in Table 4-1. Details of the assumptions and methodology used in calculating these doses is in Appendix A.1 and A.2.

Calculated doses are very small because CH-TRU wastes contain very small amounts of non-TRU radionuclides and the TRU radionuclides produce only weak and infrequent gamma radiations. The doses never exceed 0.3 mrem, even for the maximum concentrations and volumes at 100 years. Over 95% of the dose up to 1000 years is due to ^{241}Am, which decays with a 432 year half-life and is not a factor at later times. Doses from the plutonium radioisotopes never contribute as much as 0.1 mrem to the dose.

Table 4-1. External Radiation Dose to Worker at Shale Shaker from CH-TRU Waste (Millirem - Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration		
	Mean Vol	Max Vol	Comment	Mean Vol	Max Vol	Comment
100	1.3×10^{-2}	6.4×10^{-2}	98% ^{241}Am	8.4×10^{-3}	4.2×10^{-2}	80% ^{241}Am, 18% ^{238}Pu
350	1.3×10^{-2}	6.5×10^{-2}	98% ^{241}Am	4.6×10^{-2}	2.3×10^{-1}	98% ^{241}Am
700	7.5×10^{-3}	3.7×10^{-2}	97% ^{241}Am, 3% ^{239}Pu	2.6×10^{-2}	1.3×10^{-1}	98% ^{241}Am, 2% ^{239}Pu
1,000	4.7×10^{-3}	2.4×10^{-2}	95% ^{241}Am, 4% ^{239}Pu	1.6×10^{-2}	8.2×10^{-2}	96% ^{241}Am, 3% ^{239}Pu
5,000	1.9×10^{-4}	9.3×10^{-4}	89% ^{239}Pu, 11% ^{240}Pu	5.6×10^{-4}	2.8×10^{-3}	91% ^{239}Pu, 9% ^{240}Pu
10,000	1.6×10^{-4}	7.8×10^{-4}	92% ^{239}Pu, 8% ^{240}Pu	4.7×10^{-4}	2.3×10^{-3}	94% ^{239}Pu, 6% ^{240}Pu

4.1.2 External Radiation Dose at Mud Pit

The calculated external radiation dose to a worker standing at the edge of the mud pit is shown in Table 4-2. Details of the methodology are included in Appendices A.1 and A.3.

Calculated doses are small and over 95% are due to ^{241}Am from 100 to 1000 years. The maximum concentration - maximum volume dose is only 0.77 mrem at 350 years and this is a low probability event.

Table 4-2. External Radiation Dose to Worker at Mud Pit from CH-TRU Waste (Millirem - Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration		
	Mean Vol	Max Vol	Comment	Mean Vol	Max Vol	Comment
100	4.4×10^{-2}	2.2×10^{-1}	98% ^{241}Am	2.8×10^{-2}	1.4×10^{-1}	80% ^{241}Am, 17% ^{238}Pu
350	4.4×10^{-2}	2.2×10^{-1}	98% ^{241}Am	1.5×10^{-1}	7.7×10^{-1}	99% ^{241}Am
700	2.6×10^{-2}	1.3×10^{-1}	97% ^{241}Am, 3% ^{239}Pu	8.9×10^{-2}	4.4×10^{-1}	98% ^{241}Am, 2% ^{239}Pu
1,000	1.6×10^{-2}	8.0×10^{-2}	95% ^{241}Am, 4% ^{239}Pu	5.6×10^{-2}	2.8×10^{-1}	96% ^{241}Am, 3% ^{239}Pu
5,000	6.3×10^{-4}	3.2×10^{-3}	90% ^{239}Pu, 10% ^{240}Pu	1.9×10^{-3}	9.4×10^{-3}	91% ^{239}Pu, 9% ^{240}Pu
10,000	5.3×10^{-4}	2.7×10^{-3}	93% ^{239}Pu, 7% ^{240}Pu	1.6×10^{-3}	7.9×10^{-3}	94% ^{239}Pu, 6% ^{240}Pu

4.1.3 Inhalation Dose at Drilling Rig

Calculated inhalation doses to a worker at the drilling rig from resuspension of CH-TRU wastes from the mud pit are shown in Table 4-3. The inhalation doses are significant compared to the external doses and since they are due to long-lived transuranic radionuclides they decrease slowly with time (the doses at 10,000 years are 21-30% of those at 100 years after closure).

The probability of intrusions into CH-TRU waste during the 10,000-year regulatory period is high with the drilling rates that DOE is required to use in the CCA (46.8 Boreholes km^{-2} in 10,000 years). There is a >99% probability of at least one intrusion into CH-TRU waste and a >57% probability there will be more than 4 intrusions. Even for the RFETS residues (which would be about 7.2% of the drums in the repository) there is a 31% probability of at least one intrusion.

Also, from the CCA, there is a 10% probability that the volume of cuttings plus cavings released would be ≥ 0.87 m^3.

Table 4-3. Inhalation Dose to Worker at Drilling Rig from CH-TRU Waste
(Millirem - Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration		
	Mean Vol	Max Vol	Comment	Mean Vol	Max Vol	Comment
100	38	190	36% ^{238}Pu, 35% ^{239}Pu	240	1200	90% ^{238}Pu, 8% ^{239}Pu
350	36	180	57% ^{239}Pu, 20% ^{241}Am	100	500	61% ^{239}Pu, 26% ^{241}Am
700	29	150	68% ^{239}Pu, 17% ^{240}Pu	88	440	68% ^{239}Pu, 17% ^{241}Am
1,000	27	140	73% ^{239}Pu, 18% ^{240}Pu	81	410	73% ^{239}Pu, 16% ^{240}Pu
5,000	21	100	85% ^{239}Pu	62	310	87% ^{239} Pu
10,000	17	86	89% ^{239}Pu	51	250	91% ^{239}Pu

4.2 Doses from RH-TRU

4.2.1 Dose at Shale Shaker

Details of the assumptions and methodology necessary to calculate doses to a worker at the shale shaker are in Appendix A.1 and A.2. The results are shown in Table 4-4. Over 99% of the dose at 100 years after closure was due to ^{137m}Ba. At 350 years ^{241}Am comprises 88% of the total dose for the average waste concentration. The maximum concentration waste (which does not contain ^{241}Am) at 350 years is 75% ^{137m}Ba and 19% ^{239}Pu.

These doses are minimal, even for the maximum concentration wastes at 100 years.

4.2.2 Dose at Mud Pit

Details of the calculation of doses to a worker at the edge of the mud pit are in Appendix A.3. The results are shown in Table 4-5. Over 97% of the dose at 100 years for the average concentration wastes was due to ^{137m}Ba. About 2.0% came from ^{241}Am and bremsstrahlung radiation from ^{90}Y contributed about 0.6%. Over 99% of the dose from the maximum concentration waste (which doesn't contain ^{241}Am) was due to ^{137m}Ba at 350 years, while 81% of the dose for the average concentration waste comes from ^{241}Am and 18% from ^{137m}Ba.

The doses at the mud pit are about 15 times those at the shale shaker at 100 years but are negligible except for the maximum concentration, maximum volume case (100 mrem). This dose is equal to the limit for non-radiation workers from all radiation sources (100 mrem y^{-1}). However, the probability of both a maximum concentration and maximum volume event occurring simultaneously at 100 years is low.

Table 4-4. External Radiation Dose to Worker at Shale Shaker from RH-TRU Waste (Millirem - Committed Effective Dose)

Drum Loading	100 years		350 years	
	Dose	Comment	Dose	Comment
Mean Conc. - Mean Vol	2.8×10^{-2}	91% ^{137m}Ba, 9% ^{241}Am	1.9×10^{-3}	88% ^{241}Am, 6% ^{239}Pu
Mean Conc. - Max Vol	1.3×10^{-1}	91% ^{137m}Ba, 9% ^{241}Am	8.9×10^{-3}	88% ^{241}Am, 6% ^{239}Pu
Max Conc. - Max Vol	6.5×10^{0}	99% ^{137m}Ba	2.6×10^{-2}	75% ^{137m}Ba, 19% ^{239}Pu

Table 4-5. External Radiation Dose to Worker at Mud Pit from RH-TRU Waste (Millirem - Committed Effective Dose)

Drum Loading	100 years		350 years	
	Dose	Comment	Dose	Comment
Mean Conc. - Mean Volume	4.2×10^{-1}	97% ^{137m}Ba	7.1×10^{-3}	80% ^{241}Am, 18% ^{137m}Ba
Mean Conc. - Max Volume	1.9×10^{0}	97% ^{137m}Ba	3.3×10^{-2}	80% ^{241}Am, 18% ^{137m}Ba
Max Conc. - Max Volume	1.0×10^{2}	99% ^{137m}Ba	3.2×10^{-1}	98% ^{137m}Ba

4.2.3 Inhalation Doses

Calculated inhalation doses to workers are shown in Table 4-6. Inhalation doses at 100 years are about 9 times the external doses at the mud pit for average concentration RH-TRU wastes and about 5% higher for the maximum concentration. Over 99% of the inhalation dose is due to transuranics and decreases very little with time. For example the calculated dose at 10,000 years is 38% of the 100-year dose for average concentration waste and 60% for the maximum concentration waste. Thus, penetration of an RH-TRU canister will be of concern for the inhalation pathway throughout the regulatory period. Details of the inhalation calculations are presented in Appendix A.4.

The doses for average concentration wastes are less than typical U. S. dose limits for non-occupational workers. There is a reasonable chance of penetrating an RH-TRU canister during 10,000 years. For the 46.8 boreholes km^{-2} drilling rate used in the CCA there is a 50% probability of at least one hit and a 3% probability of 3 or more hits. The doses for the maximum concentration waste stream are significant for non-occupational doses. This waste stream (only 0.34% of the total) has a probability of about 0.002 of being intercepted at least once during the 10,000 year period. Probabilities greater than 0.001 are required by 40 CFR Part 191 to be included in the CCDF.

Table 4-6. Inhalation Dose to Worker at Drilling Rig from RH-TRU Wastes
(Millirem - Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration	
	Mean Vol	Max Vol	Comment	Max Vol	Comment
100	4.0	18.0	41% ^{239}Pu, 36% ^{241}Am	110	64% ^{239}Pu, 32% ^{240}Pu
350	3.4	16.0	48% ^{239}Pu, 28% ^{241}Am	100	67% ^{239}Pu, 33% ^{240}Pu
700	2.9	14.0	55% ^{239}Pu, 26% ^{240}Pu	100	68% ^{239}Pu, 32% ^{240}Pu
1,000	2.7	12.0	59% ^{239}Pu, 28% ^{240}Pu	100	68% ^{239}Pu, 32% ^{240}Pu
5,000	1.9	8.8	74% ^{239}Pu, 26% ^{240}Pu	82	75% ^{239}Pu, 25% ^{240}Pu
10,000	1.5	7.0	81% ^{239}Pu, 19% ^{240}Pu	65	81% ^{239}Pu, 19% ^{240}Pu

5. CALCULATED DOSES TO RESIDENT FARMER

5.1 Doses from CH-TRU

5.1.1 Inhalation Dose

The calculated inhalation radiation dose to a resident farmer located 800 m in the prevailing wind direction from the mud pit is shown in Table 5-1. Radionuclides resuspended from a dried mud pit are the source of this inhalation dose. The long-term resuspension rate, dispersion factor, deposition rate, and annual inhalation rate assumed are discussed in Appendix B.1.

Inhalation doses received by the resident farmer in a year are only 57% of those received by the worker in 80 hours at the drilling rig. This is due to a much higher χ/Q factor and resuspension rate for the worker dose calculations.

These inhalation doses are significant throughout the 10,000 year regulatory period. For a 17-curie release (5% probability of occurring during the regulatory period) the dose is about 120 mrem y^{-1}. The probability of a resident farmer being located 800 m away in the prevailing down wind direction is less than 1.0. Inhalation doses at the WNW Site boundary would be 8.3 mrem y^{-1} and at James Ranch (2.5 miles WSW of the repository and presently occupied) the dose would be about 1.9 mrem y^{-1} for a 17-curie release.

Table 5-1. Inhalation Dose to Resident Farmer from CH-TRU Waste
(Millirem - Annual Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration		
	Mean Vol	Max Vol	Comment	Mean Vol	Max Vol	Comment
100	21.0	110	36% ^{238}Pu, 35% ^{239}Pu	130	670	90% ^{238}Pu, 8% ^{239}Pu
350	20.0	100	57% ^{239}Pu, 20% ^{241}Am	56	280	61% ^{239}Pu, 26% ^{241}Am
700	16.0	82	68% ^{239}Pu, 17% ^{240}Pu	49	250	68% ^{239}Pu, 17% ^{241}Am
1,000	15.0	76	73% ^{239}Pu, 18% ^{240}Pu	46	230	73% ^{239}Pu, 15% ^{240}Pu
5,000	12.0	58	85% ^{239}Pu, 15% ^{240}Pu	34	170	87% ^{239} Pu, 13% ^{240}Pu
10,000	9.6	48	89% ^{239}Pu, 11% ^{240}Pu	28	140	90% ^{239}Pu, 10% ^{240}Pu

5.1.2 External Radiation Dose

The annual external radiation dose to the resident farmer from a one year deposition of CH-TRU radionuclides at the farm was calculated as described in appendix B.2.

Calculated radiation doses at 100 years and 350 years were always less than 0.01 mrem y^{-1}. Since these doses were negligible compared to those from inhalation, they were not calculated for later intrusion times.

Exposure from immersion is also negligible.

5.1.3 Inhalation Dose from Deposited Radionuclides

The annual inhalation dose the resident farmer would receive from resuspension of CH-TRU radionuclides deposited about his residence during the previous year was calculated. The dirt mass loading approach described in Appendix A.4 was used. Key assumptions were: (1) all inhaled dirt was from the top $2x10^{-4}$ m of soil and the deposited radionuclides were in this volume; (2) the average outside air concentration was 65 µg m^{-3} of soil; and (3) the same 5100 m^3 annual effective inhalation rate was used.

These annual doses were found to be about 0.35% of the inhalation doses calculated from resuspension in the mud pit. These doses were greater than 1 mrem y^{-1} only for the maximum concentration-maximum volume case at 100 years.

Doses are not tabulated because they are negligible compared to the direct inhalation dose and would not occur in the same year.

5.1.4 Dose from Ingestion of Contaminated Dirt

Studies have shown that humans ingest a measurable amount of contaminated dirt. A recommended value of 100 mg d^{-1} (0.035 kg y^{-1}) was used (U. S. EPA 1991). The concentration of radionuclides on the dirt was assumed to be the same as that in the top 0.2 mm of soil from deposition.

Calculated doses from CH-TRU ranged from 2.0 mrem y^{-1} at 100 years to 0.43 mrem y^{-1} at 10,000 years for the maximum concentration-maximum volume case. These small doses (only 0.3% of the inhalation dose) were not calculated for all intrusion times and waste quantities.

5.1.5 Dose from Crops

No dose was assumed to occur to the resident farmer in Case I from ingestion of vegetables, fruits, and grains grown in contaminated soil. This is an improbable pathway for a resident near the WIPP Site because the availability of water is limited. No vegetable gardens are known to exist in the ranch houses around WIPP. The potential magnitude of this low probability event is addressed in Case III (the non-resident farmer) which is considered bounding.

5.1.6 Dose from Ingestion of Beef

Cattle graze in land around WIPP and it is reasonable to believe persons living in ranch houses would eat beef that grazes on land contaminated by the Case I scenario. The description of this calculation is in Appendix B.3. WIPP site specific data were used for the amount of feed consumed per day by cattle. However, three other key parameter values (fraction of deposition

retained on crops, weathering rate constant, and the kilograms per meter square of forage) had to be estimated from literature that is not specific to natural, arid rangeland.

Calculated doses from the direct deposition pathway at 100 years for the maximum concentration-maximum volume CH-TRU waste scenario totaled only 0.023 mrem y^{-1}. The dose from the soil to crop pathway is negligible (less than 0.1% of the dose from direct deposition). Doses were not calculated for later times.

5.2 Doses from RH-TRU

5.2.1 Inhalation Dose

The calculated inhalation dose to a resident farmer from RH-TRU wastes is shown in Table 5-2. These doses are only about 10%-25% of those from CH-TRU.

5.2.2 External Radiation Dose

The annual external radiation dose to the resident farmer from one year deposition of RH-TRU radionuclides at the farm was calculated as described in Appendix B.2. Calculated radiation doses at 100 years were only 0.08 mrem y^{-1} for the maximum concentration-maximum volume case. At 350 years the maximum dose was less than 0.001 mrem y^{-1}. These doses are negligible and were not calculated for later times.

Table 5-2. Inhalation Dose to Resident Farmer from RH-TRU Waste
(Millirem - Annual Committed Effective Dose)

Year	Mean Concentration			Maximum Concentration	
	Mean Vol	Max Vol	Comment	Max Vol	Comment
100	2.2	10.0	41% ^{239}Pu, 37% ^{241}Am	62	64% ^{239}Pu, 32% ^{240}Pu
350	1.9	8.8	48% ^{239}Pu, 28% ^{241}Am	58	67% ^{239}Pu, 32% ^{240}Pu
700	1.6	7.6	55% ^{239}Pu, 26% ^{240}Pu	57	68% ^{239}Pu, 32% ^{240}Pu
1,000	1.5	7.0	60% ^{239}Pu, 28% ^{240}Pu	56	68% ^{239}Pu, 32% ^{240}Pu
5,000	1.1	5.0	75% ^{239}Pu, 25% ^{240}Pu	46	75% ^{239}Pu, 25% ^{240}Pu
10,000	0.85	3.9	81% ^{239}Pu, 19% ^{240}Pu	36	81% ^{239}Pu, 19% ^{240}Pu

5.2.3 Inhalation Dose from Deposited Radionuclides

The annual inhalation dose the resident farmer would receive from resuspension of RH-TRU radionuclides deposited on the farm during the previous year was calculated using the dust mass loading approach and the same assumptions as for CH-TRU.

This dose was about 0.2 mrem y^{-1} per year for the maximum concentration-maximum volume case at 100 years (0.3% of the inhalation dose due to resuspension from the mud pit). This dose is negligible and doses were not calculated for later times.

5.2.4 Dose from Ingestion of Contaminated Dirt

Calculated doses from ingestion of RH-TRU contaminated dirt decreased from 0.22 mrem y^{-1} at 100 years to 0.11 $mrem^{-1}$ at 10,000 years (maximum concentration-maximum volume case). These values are negligible and were not tabulated.

5.2.5 Dose from Crops

No dose was assumed to occur from ingestion of contaminated crops.

5.2.6 Dose from Ingestion of Beef

The dose from ingestion of beef in the maximum concentration-maximum volume RH-TRU scenario at 100 years was 0.60 mrem y^{-1}. Approximately 94% of the dose came from ^{137}Cs and 5% from ^{90}Sr. Doses were not calculated for later times.

6. CALCULATED DOSES FOR SCENARIOS II & III

6.1 Scenario II, Resident Non-Farmer

The resident non-farmer in this scenario is assumed to live in a house located at the edge of the mud pit from Scenario I. He receives radiation doses from inhalation, ingestion of dirt and external radiation only during actual residence. Calculation assumptions are given in Appendix C.

This Scenario is considered bounding because it is improbable that a person would be residing at the edge of a radiologically contaminated mud pit shortly after exploratory drilling had taken place. However, higher doses could be calculated by assuming the resident spends some period of time outdoors and also has a vegetable garden as in Scenario III.

6.1.1 Dose from CH-TRU

Calculated inhalation, ingestion, and external doses from CH-TRU releases to the surface for the six intrusion times are given in Table 6-1 for the mean concentration-mean volume and maximum concentration-maximum volume cases. This captures the range of possible doses. The doses are relatively high; in all cases greater than 100 mrem y^{-1} and in the highest case exceeding the limit for occupational workers. However, these doses are not acutely hazardous and unless continued for a number of years would not be expected to significantly increase the incidence of cancer in the resident non-farmer.

6.1.2 Dose From RH-TRU

Doses to the resident-farmer from RH-TRU are shown in Table 6-2 for 100 years, 350 years, and 10,000 years. Calculations were not performed for the other intrusion times because the primary interest in RH-TRU is during the early years. The total calculated dose at 350 years and 10,000 years is only 10% to 25% of that from CH-TRU. The external dose at 100 years for the maximum concentration-maximum volume case (28 rem y^{-1}) is very high. However, the probability of intersecting a maximum concentration RH-TRU canister at about 100 years is low. This external

dose decreases (with the 30-year half-life of ^{137}Cs +^{137m}Ba) to 2.8 rem y^{-1} at 200 years and 0.27 rem y^{-1} at 300 years.

Table 6-1. CH-TRU Dose to Resident Non-Farmer-Scenario II
(Rem - Annual Committed Effective Dose)

Mean Concentration - Mean Volume					Max Concentration - Max Volume			
Year	Inhalation	Ingestion	External	Total	Inhalation	Ingestion	External	Total
100	0.18	0.19	.012	0.38	5.8	6.5	0.038	12.0
350	0.16	0.18	.012	0.35	2.2	2.5	0.21	4.4
700	0.13	0.14	.0068	0.28	2.0	2.2	0.12	4.3
1,000	0.12	0.13	.0042	0.26	1.8	2.0	0.074	3.9
5,000	0.087	0.096	.00016	0.18	1.4	1.5	0.0025	2.9
10,000	0.050	0.084	.00014	0.13	1.1	1.3	0.0021	2.4

Table 6-2. RH-TRU Dose to Resident Non-Farmer - Scenario II
(Rem - Annual Committed Effective Dose)

Year	Mean Concentration - Mean Volume				Max Concentration - Max Volume			
	Inhalation	Ingestion	External	Total	Inhalation	Ingestion	External	Total
100	0.018	0.020	0.11	0.15	0.49	0.63	28.0	29.0
350	0.015	0.017	0.0019	0.034	0.47	0.51	0.084	1.1
10,000	0.0068	0.0076	0.000012	0.014	0.30	0.33	0.00053	0.62

6.2 Scenario III, Non-Resident Farmer

In Scenario III the farmer is assumed to eat 42.7 kg y^{-1} of vegetables that are grown in the mud pit. The 5 cm depth of contaminated material in the mud pit is assumed to be evenly mixed with top soil in order to make the mud pit fertile. The final depth is assumed to be 15 cm. The water used for irrigation is assumed to be uncontaminated. No deposition is occurring on the crops and there is assumed to be no surface contamination from the soil. Therefore the only radionuclides in the food come through the soil-to-crop pathway. The calculation is described in Appendix C.

This scenario is also considered bounding. There is limited ground water of adequate quality in the area and there are no known vegetable gardens. However, if this scenario occurred, doses could be higher than calculated because the non-resident farmer would be subjected to radiation doses from inhalation, dirt ingestion, and external radiation during the time spent farming in the mud pit.

6.2.1 Dose from CH-TRU

Calculated doses from CH-TRU releases to the surface for the six intrusion times are given in Table 6-3 for the mean concentration-mean volume and maximum concentration-maximum volume cases. These doses are significant but are less than the Scenario II doses at all time periods.

Doses received by the non-resident farmer while working in the garden would increase these doses significantly. For example, the inhalation + dirt ingestion + external radiation dose from 100 hours of exposure to the maximum concentration-maximum volume case at 100 years is 53% of the food intake dose.

6.2.2 Dose from RH-TRU

RH-TRU doses at 100, 350, and 10,000 years are shown in Table 6-4. The maximum dose at 100 years is 2.1 times the CH-TRU dose because of the effect of ^{90}Sr and ^{137}Cs. These two fission product radionuclides contribute 96% of the dose. For other times and cases the CH-TRU doses are 3 to 11 times greater than the RH-TRU doses.

The doses received from inhalation, ingestion, and external radiation from 100 hours of exposure were 14% of the maximum food dose at 100 years and 46% at 350 years.

Table 6-3. CH-TRU Dose to Non-Resident Farmer-Scenario III
(Rem - Annual Committed Effective Dose)

Year	Mean Conc - Mean Vol	Max Conc - Max Vol
100	0.14	3.6
350	0.13	1.9
700	0.10	1.5
1,000	0.089	1.4
5,000	0.062	0.91
10,000	0.051	0.76

Table 6-4. RH-TRU Dose to Non-Resident Farmer - Scenario III
(Rem - Annual Committed Effective Dose)

Year	Mean Conc - Mean Vol	Max Conc - Max Vol
100	0.045	7.7
350	0.013	0.33
10,000	0.0046	0.20

7. COLLECTIVE DOSE

Collective dose is the summation of radiation doses received by all persons in an exposed population.

The EPA Containment Requirements (§191.13) limit the cumulative release of transuranic radionuclides to the accessible environment. These limits are based on estimated health effects from a collective dose determined from generic global modeling. There is no regulatory requirement that a collective dose from the actual site be determined from the calculated cumulative releases. DOE has not done collective dose calculations for the releases projected in the CCA.

7.1 Collective Dose from Inhalation

The calculated collective dose from inhalation to the population within 80 km (50 miles) of the WIPP Site is presented in this report. This calculation was made because it is another measure of the health implications of the cumulative releases projected in the CCA. Details of the calculation are in Appendix D.

7.2 Other Collective Doses

Collective doses from pathways other than inhalation (external, resuspension of previously deposited material, ingestion of dirt, and the food pathway) were not calculated because previous calculations for the resident farmer indicate they are much less than inhalation doses for a single year of erosion. However, these doses would persist and there could be a buildup in the environment from continued erosion of mud pits and from subsequent intrusions during the 10,000 years. So, the contribution of non-inhalation doses to the total collective dose from inhalation will not be negligible if the mud pit is not reclaimed and erosion continues for many years.

7.3 Results of Collective Dose Calculation

Results of the annual collective inhalation dose are shows in Table 7-1. A 17 Ci release value was used because this value has about a 5% probability of occurring from an intrusion in 10,000 years (see Appendix E). These values are low because of the low population density within 15 miles of the

repository and the assumption that the future population will be the same as the present. The effect of distance can be seen by noting that the annual collective dose for 100,000 people residing within 50 miles of the site is only 4 times that calculated for two workers at the drilling rig.

Somewhat higher collective doses are theoretically possible for three reasons: (1) doses are assumed to occur only for a one-year period following an intrusion and only 2.3×10^{-3} of the radionuclides in the mudpit are assumed to be depleted by resuspension in a year. If all of the contents were eventually depleted by resuspension the collective dose from this one 17 Ci intrusion increases by a factor of 440; (2) multiple intrusions are expected to occur during the 10,000 year regulatory period; and (3) there would be contributions from non-inhalation pathways and, because of buildup in the environment from multi-year releases, these doses will be much greater than those we have calculated for the resident farmer during the initial year.

Table 7-1. Collective Doses From Inhalation From a 17 Ci Release of Transuranic Radionuclides

Down Wind Sector	Radial Distance (miles)	Collective Dose mrem y^{-1}
SSW	2.5	17.0
NNW	7.5	11.0
SW	15.0	3.1
WSW	15.0	96.0
W	15.0	12.0
WNW	15.0	6.4
W	25.0	640.0
WNW	25.0	340.0
E	35.0	6.4
ESE	35.0	3.6
NW	45.0	490.0
NNE	45.0	24.0
NE	45.0	35.0
ENE	45.0	33.0
	Total	1700.0

8. DISCUSSION AND CONCLUSIONS

The significance of the individual doses calculated in this report are discussed relative to: (1) the potential health effects; (2) a comparison of the health effects from individual doses and the health effects suggested by cumulative releases calculated in the CCA; and (3) the proposed cleanup standards for radiologically contaminated sites.

8.1 Potential Health Effects

The possible somatic health effects of calculated doses to drilling crew members, the resident farmer, and the population can be estimated from dose to excess cancer fatality (ECF) conversion factors in BEIR IV (NAS 1988). BEIR-IV estimates there will be 1.08×10^{-3} to 2.10×10^{-3} ECFs per rad of transuranics taken into the body. This is equivalent to 5.4×10^{-5} to 1.05×10^{-4} ECFs per rem of transuranics taken into the body. Doses from a 17 Ci CH-TRU release are used because there is an estimated 5% probability that an intrusion will bring this amount of radioactive material to the surface in 10,000 years. Results are shown in Table 8-1.

Table 8-1. Risk of Excess Cancer Fatality per Year of Intake[a]

Receptor	Internal Dose (Rem)	Probability of ECF[b]
Drilling Crew	0.22	$1.2\text{-}2.2 \times 10^{-5}$
Resident Farmer(I)	0.12	$0.61\text{-}1.2 \times 10^{-5}$
Resident Non-Farmer (II)	2.0	$1.4\text{-}2.0 \times 10^{-4}$
Non-Resident Farmer (III)	0.68	$3.7\text{-}6.8 \times 10^{-5}$
Collective Dose	1.7	$0.93\text{-}1.7 \times 10^{-4}$

[a] For a 17 Ci release of CH-TRU (Probability of ~ 0.05)

[b] Collective dose risk is to population of 100,000; other risks are to an individual.

These annual risks are low. However, lifetime risks could be much higher. For the 30-year exposure period suggested in U.S. EPA 1991 the cumulative risks to the resident farmer in Scenario I would be greater than 10^{-4}. For Scenarios II and III the cumulative risk would be greater than 10^{-3}. EPA typically sets limits of radiation exposure in its regulations so that lifetime risks would not exceed 10^{-3} to an individual.

The individual doses shown in Table 8-1 for the workers and resident farmers have about a 5% probability of occurring in one of the intrusions during the 10,000 year regulatory period if the projected drilling rate occurs. However, the probability that any one generation will receive similar doses is much lower.

8.2 Comparison of Health Effects

The cumulative release limits in 40 CFR Part 191 were derived from the results of generic, global modeling of the total health effects from a curie of each radionuclide that might be released into the environment. The release limits would result in an estimated 1,000 ECFs in 10,000 years for a full sized repository containing 10^8 Ci of TRU waste.

The WIPP repository is projected to have 3.44×10^6 Ci of TRU waste at the time of repository closure. This would scale to 34.4 ECFs in 10,000 years if the full allowable release occurs. The CCA calculations predicted a release of 6% of the allowable limit at a probability of 0.1. Thus, the implicit number of health effects would be 1.7 deaths in 10,000 years from a release of 17 curies.

The collective dose calculated in Table 7-1 (for a 17 Ci release) would become 1.8 person-rem per year from inhalation when the dose to the resident farmer is added. If it were assumed that all the material deposited in the mud pit was eventually resuspended and transported to the regional population the total dose from primary inhalation would be 810 person-rem. The inhalation doses from resuspension of deposited material and ingestion doses from deposited dirt would also increase by a factor of 440 if all of the contaminated material in the mud pit was eventually resuspended. Also, there would be some food pathway doses incurred.

A conservative integrated collective dose (see Appendix D) was calculated to be 3100 person-rem with calculated health effects of 0.17 to 0.31 excess cancer fatalities. This is reasonable agreement with the implicit value of 1.7 fatalities derived from 40 CFR 191 release limits.

This comparison suggests that the global, generic modeling of health effects conducted by EPA is greater than, but within an order of magnitude of, the very approximate site specific calculation performed here. This is as good agreement as can be expected.

Another implication of this comparison is that at WIPP an individual dose standard that included doses from human intrusion would provide a more stringent limit than the present cumulative release limit. For example, these calculations suggest that a dose limit for the resident farmer of 100 mrem y^{-1} at the 5% probability level would limit the allowable release to 14 Ci for a single intrusion. The cumulative release limit allowed from all intrusions in 40 CFR 191 is 344 Ci at the 0.1 probability level.

8.3 Comparison with Cleanup and Low-Level Radioactive Waste Disposal Standards

8.3.1 Cleanup Standards

Promulgated cleanup standards for contaminated sites do not exist although EPA, DOE, and NRC all have proposed rules. On-going cleanups are being addressed by these agencies on a case by case basis. Cleanup will probably be required to limit doses to an individual to 25 to 100 millirem per year. It is uncertain whether the standards will allow variances to exceed the maximum annual dose for unusual situations.

The methodology and assumptions used to calculate the maximum individual dose need to be known in order to compare with the individual dose calculations in this report. It is likely that EPA cleanup standards will follow the modeling assumptions in U. S. EPA 1989. This methodology determines the reasonable maximum exposure (RME) to an individual that is expected to occur at a site from all environmental media through all reasonable pathways. Both current and future land use is to be considered and this requires professional judgement. The RME is to be calculated at about the 95%

upper confidence level. So, the RME is intended to be a low probability exposure but not a maximum exposure.

The probabilities of the calculated individual doses would include the upper 95% confidence level probability of an RME. For example there is about a 5% probability (using PAVT assumptions) that the release due to cutting + cavings + spallings will be $\geq$17 Ci from a CH-TRU intrusion. The calculated doses from Table 8-1 are 220 mrem y^{-1} for drilling rig workers and 120 mrem y^{-1} for the resident farmer for a 17 Ci release.

This comparison leads to the preliminary conclusion that the predicted doses at WIPP would not meet the expected cleanup standards for contaminated sites. It could be argued that human intrusion should not be considered in a cleanup standard. However, EPA has required that human intrusion at WIPP be considered an expected event. Even if doses to the intruders were excluded (because of their negligence in causing the intrusion) the estimated resident farmer inhalation dose would still exceed any likely clean up standard.

8.3.2 Low-Level Waste Disposal

Dose limits used by NRC in the Final Rulemaking on Land Disposal of Low-Level Radioactive Waste (10 CFR Part 61) could also be compared to these calculated individual doses. These regulations limit doses after closure to 25 mrem to the whole body. NRC also limits concentrations of low level waste so that an inadvertent intruder would not receive a dose greater than 500 mrem y^{-1}. They considered a human intruder-construction scenario (where an intruder builds a house on the disposal site) and intruder-agriculture scenario (where an intruder lives on and consumes food grown on the disposal facility) (U. S. NRC 1981). These scenarios are more comparable to Scenarios II and III than to Scenario I. Doses in Scenarios II and III from a 17 Ci release exceed the 500 mrem y^{-1} dose used by the NRC.

8.3.3 Applicability to WIPP

The results of these comparisons to other standards lead to two questions:

(1) Should WIPP individual doses be less than the maximum allowable doses for remediated sites and/or low-level radioactive waste disposal standards?

(2) If the answer to question one is yes, how can doses be reduced?

The answer to question one should be more of a philosophical and/or societal decision than a technical one. Both the NAS and the EPA have considered this issue. The NAS in their Yucca Mountain high-level waste disposal report on the technical bases for standards recommended that doses to individuals from waste brought to the surface by human intrusion should not be considered (NAS 1995). EPA considered using an individual dose standard in early drafts of the 40 CFR Part 191 rule and concluded that this was not a practical way to regulate high-level and transuranic waste disposal.

Reduction of individual doses could be addressed as an As Low as Reasonably Achievable (ALARA) issue with practical remedial measures being incorporated into a repository design even though not required by standards. ALARA designs, such as waste treatment, would be an assurance requirement as defined in 40 CFR Part 191.14.

In the original CCA submittal to the EPA, DOE assumed that passive institutional controls were 99% effective in deterring human intrusion during the period of 100 to 700 years after repository closure. EPA has, in effect, rejected the efficacy of passive institutional controls (markers, monuments, and records) in their review of the CCA by requiring DOE to assume the full drilling rate after 100 years in the Performance Assessment Verification Test (PAVT) calculations. EPA has allowed 100% credit against human intrusion for active institutional controls during the first 100 years after repository closure.

Waste form modification has the potential to reduce the amount of material brought to the surface from cavings, spallings, and direct brine releases. For example, the amount of cavings is dependent on the shear strength of the waste. If the CH-TRU waste was treated to increase the shear strength so that the present mean volume (0.60 m^3) was never exceeded there would be no intrusion after 154 years where the total release to the surface exceeded 14 Ci (see Table 3-1). This condition would reduce the inhalation dose to the resident farmer to<100 mrem y^{-1}.

8.4 Summary and Conclusions

There are inherent uncertainties in estimating repository conditions, human actions and individual doses at WIPP over a 10,000 year period. With this caveat, the following conclusions are reached:

- Calculated doses to drilling crew members and the resident farmer exceeded annual dose limits for occupational radiation workers only for the low probability Scenarios II and III at the 100 year intrusion time.

- Calculated doses to drilling crew members and the resident farmer exceeded 100 mrem y^{-1} at the 95% probability level. This is greater than the limits allowed in other standards regulating radioactive material, waste disposal and contaminated site cleanup.

- Calculated doses to the resident non-farmer and the non-resident farmer (for the 95% probability release) are greater than the 500 mrem y^{-1} value NRC used for similar scenarios in establishing low-level radioactive waste concentration limits in 10 CFR Part 61.

- Health effects predicted from a very preliminary integrated collective dose calculation are less than but within an order-of-magnitude of the health effects implied from 40 CFR Part 191 for the amounts released in the CCA.

- An individual dose limit of 100 mrem y^{-1} (at the 95% probability level) to the resident farmer at WIPP would be about an order-of-magnitude more restrictive than the cumulative release limit in 40 CFR 191. Releases predicted in the CCA would be less than the 100 mrem y^{-1} limit but releases predicted in the PAVT would be > 100 mrem y^{-1}.

- Since individual doses can be substantial, DOE should use "As Low as Reasonably Achievable" (ALARA) designs (such as treating the Waste) to limit these doses.

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10. ACRONYMS

ALARA	As Low as Reasonably Achievable
BIR	Baseline Inventory Report
CCA	Compliance Certification Application
CCDF	Complementary Cumulative Distribution Function
CH	Contact-Handled
DOE	U. S. Department of Energy
ECF	Excess Cancer Fatality
EEG	Environmental Evaluation Group
EPA	U. S. Environmental Protection Agency
FEIS	Final Environmental Impact Statement
NAS	National Academy of Sciences
NAS/NRC	National Academy of Sciences/National Research Council
NRC	U. S. Nuclear Regulatory Commission
OECD/IAEA	Organization for Economic Cooperation and Development/International Atomic Energy Agency
PA	Performance Assessment
PAVT	Performance Assessment Verification Test
RFETS	Rocky Flats Environmental Technology Site
RH	Remote Handled
RME	Reasonable Maximum Exposure
SNL	Sandia National Laboratories
TRU	Transuranic Waste
WIPP	Waste Isolation Pilot Plant

APPENDIX A
CALCULATION OF DOSES TO DRILLERS

A.1 DRILLING ASSUMPTIONS

The necessary drilling assumptions are taken from values used in the CCA when available. The parameter values necessary for calculations are:

(1) drill bit diameter - 0.311 m (12.25 inch)

(2) drilling fluid flow rate - 0.0309 $m^3 s^{-1}$ (490 gallons per minute)

(3) penetration rate in salt - 0.00254 m s^{-1} (30 feet per hour)

(4) total depth of drilling - 2100 m

(5) size of mud pit - 4300 m^2

The first three parameter values are from the CCA. The depth of drilling is the approximate depth of most oil exploratory holes around WIPP. The mud pit size is the average of those examined around WIPP in a 1984 study (Reith 1984). This sized pit will give a total cuttings plus cavings depth of about 5 or 6 cm in a dried mud pit. Thus, it is reasonable to use external dose coefficients for soil contaminated to a depth of 5 cm (U. S. EPA 1993).

The drilling fluid flow rate and penetration rate in salt are needed to calculate the time that a driller is exposed to contaminated cuttings at the shale shaker and the concentration of radionuclides in the drilling fluid. It is assumed that the contaminated cuttings do not dispense in the drilling fluid as it flows to the surface (i.e. there is "plug" flow) and the radionuclides are evenly mixed in the drilling fluid flow that occurs while the waste is being penetrated.

For an initial CH-TRU room height of 3.96 m, the penetration time would be 1560 seconds and the drilling fluid volume is 48.1 m^3.

For the RH-TRU canister with an assumed effective depth of penetration of 0.7 m, the penetration time would be 275 seconds. The drilling fluid volume during this time would be 8.50 m^3.

A.2 DOSE FROM DRILLING MUD AT THE SHALE SHAKER

A worker is assumed to be standing near the shale shaker during the period of time that contaminated drilling fluid is going through the shale shaker and a one-meter-wide trough to the mud pit. The depth of fluid in the trough is assumed to be 7 cm (equivalent to a soil depth of about 5 cm). The exposure can be treated as a ten-meter-long line source of exposure with the receptor being one meter away. The diagram and equation are shown below:

$$\phi = \frac{S\theta}{4\pi a}$$

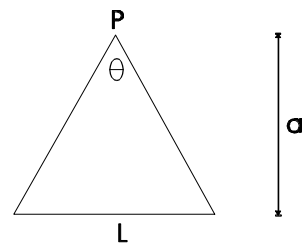

Where S is source of strength in photon s^{-1} cm^{-1} of length (L)

ϕ = flux in photons cm^{-2} s^{-1} at P
a = distance to point of interest from line source (100 cm)
L = length of trough at shale shaker (10 m)
θ = subtended angle in radians (2.75)

The value of S can then be determined from the number of Curies of a radionuclide brought to the surface:

$$S = 7x10^{-4} \frac{m^3 cm^{-1}(Ci)i}{m^3 \ of \ contaminated \ drilling \ fluid}$$

When constant terms are combined the expression for ϕ becomes: $\phi = 6.66x10^3(Ci)_i f_i$ for RH-TRU and $\phi = 1.18x10^3 (Ci)_i f_i$ for CH-TRU, where f_i is the fraction of disintegrations of radionuclide i that emit gamma radiation of a specific energy.

The absorption of gamma radiation in the drilling fluid for the important radionuclides was determined from the ratio of dose coefficients for exposure to contaminated ground surface (Table III.3 in U. S. EPA 1993) to the coefficients for exposure to soil contaminated to a depth of 5 cm (Table III.5). It is necessary to convert the Bq m^{-3} of contaminated soil to Bq m^{-2} of surface area to make this comparison. The dose rate from this calculated flux of a specific energy photon can be obtained from standard curves. (e.g. U. S. DHEW 1970, pg. 132).

A.3 WORKER DOSE AT THE MUD PIT

The radionuclides entering the mud pit are assumed to be evenly mixed in 5 cm of solids that have settled from the drilling mud. The total volume of cuttings was estimated to be about 225 m^3. The concentration (in Bq m^{-3}) of each radionuclide was then calculated and the dose coefficients (in Sv Bq^{-1} s^{-1} m^2) from Table III.3 in U. S. EPA 1993 were used to obtain the effective dose for each radionuclide.

The dose rates for all the radionuclides shown in Tables 3-1 and 3-2 were included in the total dose rate unless it was obvious that their contribution to the total would be negligible. Those radionuclides that contribute more than about 0.2% of the final dose are included in Tables 4-2 and 4-5.

The dose rates in Table III.3 assume the 65 m x 65 m mud pit is an infinite isotropic plane source. A worker standing on the edge of this pit can be assumed to be exposed to one-half of an infinite source and receive one-half of the dose calculated for the center of the mud pit. A residence time of 12 hours was assumed for the duration of the drilling operation.

It is assumed that workers near the drilling rig (100 m from the center of the mud pit) do not receive any direct radiation from the mud pit because (with an assumption that elevation of the mud pit is not lower than the drill rig) a low berm will obstruct the line-of-sight at a point one meter above the surface. This is not the most conservative assumption, since direct radiation could occur.

There will be scattered radiation (skyshine) from the atmosphere and perhaps other objects near the mud pit that will reach workers near the drilling rig. The magnitude of scattered radiation was not calculated.

A.4 INHALATION DOSES TO WORKERS

Workers are assumed to be at the drilling rig for 80 hours after the mud pit has dried. They will be exposed to resuspended material from the dried mud pit during those hours when the drilling rig is downwind. The resuspension factor will be higher initially and the high value of 6.0×10^{-5} m^{-1} from La Plante 1995 was chosen. When coupled with a deposition velocity of 1.8×10^{-3} from Parks 1992 one obtains a resuspension rate of 1.1×10^{-7} s^{-1}. This resuspension rate is applicable primarily to surface contamination and not to the 5 cm depth of contaminated material in the mud pit. An effective depth of 2×10^{-4} m was assumed based on discussions contained in Linsley 1978. This is 4×10^{-3} of the depth of the contaminated material in the mud pit. All resuspended material is assumed to be respirable.

The relative concentration from atmospheric dispersion was calculated from expression (3) in U. S. NRC 1982:

$$\frac{\chi}{Q} = \frac{f}{u\pi\sigma_z\sigma_y}$$

where:

χ/Q = relative concentration in s m^{-3}.
f = frequency that wind blows toward receptor
u = average windspeed, m s^{-1}
σ_z = vertical plume spread in m
σ_y = lateral plume spread in m

The values of σ_y and σ_z are functions of atmospheric stability class and distance from the source. They are obtained from Figures 1, 2, and 3 (for 100 m distance) in U. S. NRC 1982 for Stability Category D. Stability Category D (neutral) was selected because it is more prevalent in daytime hours than the more severe inversion conditions (Categories E and F). Wind direction frequency and mean velocity were determined from Tables H-43 and Appendix H, Annex 1, Table 2 of U. S. DOE 1980. Winds blow from the southeast 37% of the time in July and the mean wind speed was calculated as 3.5 m s^{-1}. It was assumed that the worker inhales 1.4 m^3 h^{-1} during his 40-hour work week.

These combinations of numbers lead to a χ/Q value of 6×10^{-4} s m^{-3} and an inhaled volume of 112 m^3 during the 80 hours of exposure. Radiation doses to workers from inhalation were obtained by multiplying the Becquerels of each radionuclide inhaled by the dose conversion factors (Sv Bq^{-1}) from Eckerman 1988, Table 2.1. The results are shown in Tables 4-3 and 4-6.

A.4.1 Alternate Inhalation Calculation

A common method of estimating inhalation doses for onsite exposure is to assume that the dirt in the air contains the same specific activity as is present in the contaminated soil. Typically, average values for dirt mass loading in the air are used. For example, U. S. EPA 1994 uses 1.5 µg m^{-3} for suburban areas and values as high as 200 µg m^{-3} for rural residential areas. Values for WIPP have been reported as 77.7 µg m^{-3} for 24 hour average and 18.47 µg m^{-3} for annual arithmetic mean (U. S. DOE 1980). This approach was not used in Scenario I for occupational exposure because the contamination was not considered to be onsite. However, it is possible to calculate the concentration of contaminated dirt inhaled from the mud pit as a comparison. For the worker inhalation, this value is about 130 µg m^{-3}. Dirt loadings would typically be higher during the work day when wind speeds are greater and atmospheric stability is less. Therefore, this comparison suggests that the method used gives results that are roughly the same as those obtained using the mass loading approach. The mass loading approach was used to evaluate inhalation from resuspension of deposited contamination at the resident farm and also for inhalation in Scenario II (the resident non-farmer case).

A.4.2 Reclamation of Mud Pits

Mud pits are often reclaimed (i.e. covered with earth) in the area around WIPP. Reith 1984 reports that 70% of the pits surveyed had been reclaimed. There was no definition of what the reclamation criteria was nor any indication of the elapsed time between drilling these wells (an average of 7+ years before the survey) and reclaiming the mud pits. Reclaiming a mud pit is not likely to significantly decrease the dose from resuspension during the first year because the resuspension rate is greatly increased during remediation. For example, Woolfolk 1982 used a resuspension rate 9 times that used in this report for 32 hours during pit remediation. These higher values would have caused several times the worker inhalation dose calculated in this report. Inhalation doses to the resident farmer from a reclaimed mud pit would have been lower in the first year if reclamation occurred within 9 months after drilling.

Reclamation of mud pits was not assumed in this report because: (1) it may not occur at all or soon after drilling; (2) it would lead to higher calculated loses to workers and (3) it might not significantly decrease the dose to the resident farmer in the first year.

APPENDIX B
CALCULATION OF DOSES TO THE RESIDENT FARMER

B.1 INHALATION DOSE

The atmospheric dispersion approach used for the resident farmer inhalation dose was similar to that used to calculate worker inhalation doses. However, an average annual χ/Q value of $5x10^{-5}$ s m^{-3} from WIPP Site data was used.

The median resuspension factor (1×10^{-5} m^{-1}) from La Plante 1995 was used. When coupled with a $1.8x10^{-3}$ m s^{-1} deposition velocity, the resuspension rate becomes $1.8x10^{-8}$ s^{-1} of the top $2x10^{-4}$ m of contaminated soil.

The fraction of resuspended particles remaining in the plume (0.91) at 800 m was taken from Figure 2 in Regulatory Guide 1.111 (U. S. NRC 1977a) and the deposition rate (6.0×10^{-5} m^{-1}) was taken from Figure 6. This value was used in determining the amounts deposited per square meter for external radiation and crop/soil contamination. Inhalation doses from radionuclides deposited at the farm were evaluated. Assumptions that exposure is: (1) 73% indoors at an inhalation rate of 0.63 m^3 h^{-1}; (2) concentration indoors is 0.5 of that outdoors; (3) outdoor breathing rate is 1.4 m^3 h^{-1}; and (4) residence of 350 days per year leads to an annual equivalent inhalation rate of 5,100 m^3 (La Plante 1995).

B.2 EXTERNAL RADIATION DOSE

The deposition rate of radionuclides from the contaminated plume was taken as 6.0×10^{-5} m^{-1} of the 91% remaining in the plume at 800 m. This value, when divided by the arc length of a 22.5° sector (314 m), gives the fraction of the plume depleted per square meter (1.74×10^{-7} m^{-2}).

The amount deposited per square meter in a year is the product of the fraction of each radionuclide in the pit that is eroded per year ($2.3x10^{-3}$), the fraction of the time the wind is blowing toward the resident farm (0.188), the amount remaining in the plume at 800 m, and the fraction deposited per square meter. The amount deposited per square meter is $7.42x10^{-11}$ of the total quantity of radionuclides in the pit. Dose rates for exposure to contaminated ground surface were taken from Table III.3 in U. S. EPA 1993. The dose calculated per year was adjusted by a factor of 0.635 to account for the assumption that the farmer spends 73% of his time indoors, where the exposure rate is 0.5 of that outside.

B.3 CONCENTRATIONS IN CROPS, FEED, MILK AND MEAT

B.3.1 Calculations of Concentrations

The basic equation used for calculating concentrations of radionuclides in forage crops, leafy vegetables, and other produce is equation C-5 in Regulatory Guide 1.109 (U. S. NRC 1977b):

$$C_{iv} = d_i \left[\frac{r[1 - \exp(-\lambda_{Ei} t_e)]}{Y_v \lambda_{Ei}} + \frac{B_{iv}[1 - \exp(-\lambda_i t_b)]}{P \lambda_i} \right] \exp(-\lambda_i t_h) \qquad (B-1)$$

where:

C_{iv} = concentration of radionuclide i in crops, Bq kg^{-1}

d_i = deposition, Bq m^{-2} per year

r = fraction of deposition retained on crops (used 0.2; the median value from La Plante 1995 is 0.4, but about one-half of surface at WIPP is bare ground (U. S. DOE 1981).

λ_{Ei} = effective removal constant, a combination of λ_w, (weathering rate constant) and λ_i (radiological decay). λ_i, is ignored here with long-lived radionuclides. Value used is 6.50 y^{-1}. This is lowest value reported in Till 1983, and appears most logical for an arid area.

Y_v = agricultural productivity in kg (wet weight) m^{-2}, used 0.1 in Case I and 2.0 for all crops in Case III. The Case I value is estimated because no data are available for WIPP. The Case III value is from U. S. NRC 1977b.

t_e = length of time crops are exposed to contamination during growing season. Used 1,440 hours (0.16 year) from U. S. NRC 1977b.

B_{iv} = concentration factor for uptake of radionuclide i from soil by edible portions of crops, in Bq kg^{-1} (wet weight) of crops per Bq kg^{-1} dry soil. Volumes for each element are from La Plante 1995 or U. S. NRC 1977b and are shown in Table B-1.

P = effective surface density of soil for 15 cm deep plow layer. Used 215 kg m^{-2} from Parks 1992.

λ_i = radiological decay constant for radionuclide i.

t_b = build-up time for concentration in soil; used a value of one year.

t_h = hold up time before food is consumed. Ignored here because time is short relative to half-life of these radionuclides.

Table B-1. Soil to Crop and Crop to Milk and Food Concentration Factors

Element	Concentration Ratio		Transfer Coefficient
	Other Vegetables	Grain	Beef
Am	4.7×10^{-4}	2.2×10^{-5}	4.0×10^{-5}
Cs	7.2×10^{-2}	1.0×10^{-2}	5.0×10^{-2}
Pu	2.3×10^{-4}	8.6×10^{-6}	1.0×10^{-5}
Sr	1.7×10^{-2}	1.7×10^{-2}	6.0×10^{-4}

Strontium values from U. S. NRC 1977b. Remaining values from La Plante 1995

The radionuclide concentration in beef is determined by:

$$C_{ib} = F_{ib} C_{iv} Q_f e^{-\lambda t} f \qquad \text{(B-2)}$$

F_{ib} = average fraction of the animals' daily intake for radionuclide i that appears in each kilogram of flesh in days kg^{-1}. Values taken from La Plante 1995 or U. S. NRC 1977b.

Q_f = amount of feed consumed per day. 7.6 kg d^{-1} of air-dry contaminated range was used from U. S. DOE 1981.

t_f = hold up time before beef is consumed by humans. Ignored here because of long half-lives of radionuclides.

B.3.2 Intake and Doses Received by Resident Farmer

The quantity of radionuclides taken into the body of the resident farmer in a year can be obtained by multiplying the calculated concentrations of crops, milk, and meat by reasonable assumptions of the annual intake of locally grown foods. Values for produce are from U. S. EPA 1991. Meat consumption is assumed to be 75% of the value recommended in U. S. NRC 1977b for an average adult (95 kg y^{-1}).

Table B-2. Annual Quantity of Food Ingested by Resident Farmer

Food Item	Kg/y	Comment
all produce	42.7	assumed to be all other vegetables
beef	71.2	75% of total beef intake
soil	0.035	

APPENDIX C
CALCULATION FOR SCENARIOS II & III

C.1 SCENARIO II, RESIDENT-NON FARMER

The resident non-farmer is assumed to live in a house on the edge of the dried mud pit from scenario I and occupies the house 73% of the time (6400 hours y^{-1}). While indoors the resident non-farmer inhales contaminated air, ingests some contaminated dirt and is exposed to external radiation. Time outside the house is minimal and no dose is assumed.

The indoor inhalation rate is assumed to be 0.63 m^3 h^{-1} and the air has a particulate concentration of 32.5 µg m^{-3} (one-half of outdoor air). Only one-half of the airborne particulates come from the mud pit. The amount of mud pit dirt inhaled is 0.0655 g y^{-1}. Dirt ingestion is assumed to occur at a rate of 0.0175 kg y^{-1} (one-half the rate assumed for the resident farmer because of the lack of outside activity). Also, only one-half of the ingested dirt comes from the mud pit. Thus, the amount of mud pit dirt ingested is 0.00875 kg y^{-1}.

External radiation is received for 6400 hours per year at one-half of the unshielded dose rate that exists outdoors at the edge of the mud pit. This is equivalent to 267 times the dose received by a drill crew member in 12 hours.

C.2 SCENARIO III, NON-RESIDENT FARMER

Since only the soil-to-crop pathway is being considered in Scenario III, the first term of the general expression for determining the concentration of radionuclides in crops (the foliage deposition term) shown in Equation B-1 can be deleted. Also, the expression can be further simplified because continuous deposition is not occurring. The term simplifies to:

$$C_{iv} = \frac{dB_{iv}}{\rho}$$

where d is expressed in Bq m^{-2}, B_{iv} is Bq kg^{-1} crops/Bq kg^{-1} soil, and ρ is density of soil (215 kg m^{-2}). When the area of the mud pit and conversion from curies to Becquerels is included this term becomes:

$$C_{iv} = 4.00 \times 10^4 (\text{Curies in mud pit})_t B_{iv}$$

At any time t.

This expression can be multiplied by the 42.7 kg y^{-1} of vegetable consumption to obtain the Bq y^{-1} intake. This value can then be modified by the Sv Bq^{-1} conversion factor to obtain the annual dose.

APPENDIX D
COLLECTIVE DOSE CALCULATION

D.1 ANNUAL COLLECTIVE DOSE FROM INHALATION

The collective dose was calculated only for inhalation of material resuspended from the mud pit.

The same mud pit resuspension rate from the top $2x10^{-4}$ m was assumed ($1.8x10^{-8}$ s^{-1}). The 1990 population distribution in 22.5° sectors at various distances out to 80 km was taken from U. S. DOE 1996b, Table F-10 (see Table D-1). Long-term average χ/Q values were taken from U. S. DOE 1980, Table H-49 (see Table D-2). An equivalent annual breathing intake volume of 5100 m^3 was used. Depletion of the plume at the various distances was also included in the calculation. The dose conversion factor for ^{239}Pu and ^{240}Pu ($1.16x10^{-4}$ Sv Bq^{-1}) was used for all transuranic radionuclides (this overstates the dose calculation from ^{238}Pu by 9% and underestimates the dose from ^{241}Am by 3%).

The combination of these factors leads to a dose for each sector(s) and radial distance (d) of:

$$D_{sd} = 1.58 \; Ci \; (dep_d) \frac{\chi}{Q}_{sd} \; P_{sd}$$

where: D_{sd} is annual collective dose in Sv y^{-1}
Ci is total curies of transuranics in mud pit
χ/Q_{sd} is dispersion expression for given sector and distance, s m^{-3}
dep_d is fraction of transported radionuclides remaining in plume at distance d.
P_{sd} is 1990 population for given sector and distance.

D.2 POSSIBLE INTEGRATED COLLECTIVE DOSE

A conservative, very approximate integrated collective dose can be calculated as follows. Assume that the inhalation doses from deposited radionuclides and ingestion doses from deposited dirt build up to a value of 440 times the initial year values (which were 0.35% and 0.30% of the primary inhalation dose at the end of one year). Also, that there is assumed to be no depletion of these deposited radionuclides and radioactive decay is neglected. The resident population (which is assumed to be stable) is exposed to primary and secondary inhalation and ingestion during the 440

year buildup period. Secondary inhalation plus ingestion will continue for an additional 440 years while the deposited material is being lost from resuspension. These are conservative assumptions because all of the material in the mud pit would not be resuspendable or respirable. However, non conservative assumptions are: (1) neglecting food pathway doses from the >200 km^2 of irrigated agriculture within the 80 km radius; and (2) neglecting doses from all pathways at distances beyond 80 km.

The original dose is 1.8 person-rem per year when the resident-farmer's dose is included. The dose at 440 years is 3.9 times the initial dose (7.1 person-rem per year). For the next 440 years the annual dose drops from 5.3 person-rem per year to zero. With the simplifying assumption that build up and decay of the annual dose rate is linear an integrated collective dose can be calculated. This leads to a total dose of:

$$\textit{Total Collective Dose} = 440 \left[\frac{1.8 + 7.1}{2} + \frac{5.3}{2} \right] = 3{,}100 \ \textit{person rem}$$

This collective dose would result in 0.17 to 0.31 ECFs.

Table D-1. 1990 Population Distribution Within
80 Kilometers (50 Miles) of WIPP

Direction	Distance (miles)										
	0-1	1-2	2-3	3-4	4-5	5-10	10-20	20-30	30-40	40-50	Total
S	0	0	0	0	0	0	3	2	46	20	71
SSW	[a]9	0	0	0	0	0	0	2	43	8	62
SW	0	0	0	0	0	0	37	57	0	5	99
WSW	0	0	0	0	0	0	1,622	191	57	62	1,932
W	0	0	0	0	0	0	138	25,291	197	3	25,629
WNW	0	0	0	0	0	0	38	5,765	242	63	6,108
NW	0	0	0	0	0	0	6	7	14	12,401	12,428
NNW	0	0	0	0	0	9	4	66	104	56	239
N	0	0	0	0	0	0	3	0	63	12	78
NNE	0	0	0	0	0	0	4	3	122	7,353	7,482
NE	0	0	0	0	0	0	0	11	37	9,115	9,163
ENE	0	0	0	0	0	0	0	10	282	30,877	31,169
E	0	0	0	0	0	0	6	5	2,982	19	3,012
ESE	0	0	0	0	0	0	0	16	2,173	97	2,286
SE	0	0	0	0	0	0	0	0	15	20	35
SSE	0	0	0	0	0	1	3	14	5	73	96
TOTAL	9	0	0	0	0	10	1,864	31,440	6,382	60,184	99,889

Source: U. S. DOE 1996b Table F-10

a. Location of these 9 persons is an error. Should be SSW, 2-3 miles.

Table D-2. WIPP Site Long-Term Average X/Q Calculations
(Period of Record, June 1977 through May 1979)

Downwind Sector	X/Q (sec/m^3) at downwind distance (miles)					
	2.5	7.5	15.0	25.0	35.0	45.0
N	$1.0x10^{-6}$	$1.8x10^{-7}$	$3.9x10^{-8}$	$1.7x10^{-8}$	$7.2x10^{-9}$	$8.4x10^{-9}$
NNE	$5.7x10^{-7}$	$9.0x10^{-8}$	$2.0x10^{-8}$	$9.0x10^{-9}$	$3.3x10^{-9}$	2.6x10
NE	$6.8x10^{-7}$	$1.1x10^{-7}$	$3.0x10^{-8}$	$1.2x10^{-8}$	$4.4x10^{-9}$	$3.1x10^{-8}$
ENE	$5.4x10^{-7}$	$5.7x10^{-8}$	$1.5x10^{-8}$	$5.4x10^{-9}$	$1.1x10^{-9}$	$8.6x10^{-10}$
E	$4.8x10^{-7}$	$4.8x10^{-7}$	$1.2x10^{-8}$	$4.2x10^{-9}$	$1.3x10^{-9}$	$1.1x10^{-9}$
ESE	$4.5x10^{-7}$	$4.2x10^{-8}$	$1.1x10^{-9}$	$4.7x10^{-9}$	$1.0x10^{-9}$	$7.3x10^{-10}$
SE	$4.3x10^{-7}$	$5.3x10^{-8}$	$1.6x10^{-8}$	$6.2x10^{-9}$	$1.7x10^{-9}$	$1.5x10^{-9}$
SSE	$5.2x10^{-7}$	$7.7x10^{-8}$	$2.3x10^{-8}$	$3.6x10^{-7}$[a]	$4.0x10^{-9}$	$2.7x10^{-9}$
S	$6.4x10^{-7}$	$1.1x10^{-7}$	$3.0x10^{-8}$	$1.0x10^{-8}$	$6.0x10^{-9}$	$3.2x10^{-9}$
SSW	$8.5x10^{-7}$	$1.4x10^{-7}$	$3.9x10^{-8}$	$1.8x10^{-8}$	$6.8x10^{-9}$	$5.2x10^{-9}$
SW	$9.6x10^{-7}$	$1.6x10^{-7}$	$5.0x10^{-8}$	$1.8x10^{-8}$	$8.8x10^{-9}$	$4.8x10^{-9}$
WSW	$8.5x10^{-7}$	$1.4x10^{-7}$	$3.5x10^{-8}$	$1.2x10^{-8}$	$5.6x10^{-9}$	$3.1x10^{-9}$
W	$1.2x10^{-6}$	$1.9x10^{-7}$	$5.0x10^{-8}$	$1.7x10^{-8}$	$7.8x10^{-9}$	$4.5x10^{-9}$
WNW	$2.5x10^{-6}$	$3.8x10^{-7}$	$1.0x10^{-7}$	$3.9x10^{-8}$	$1.9x10^{-8}$	$9.5x10^{-9}$
NW	$3.2x10^{-6}$	$7.6x10^{-7}$	$2.5x10^{-7}$	$1.1x10^{-7}$	$5.5x10^{-8}$	$3.2x10^{-8}$
NNW	$3.0x10^{-6}$	$5.8x10^{-7}$	$2.5x10^{-7}$	$7.8x10^{-8}$	$4.6x10^{-8}$	$2.6x10^{-8}$

Source: adapted from U. S. DOE 1980, Table H-48

[a] This value appears to be a typographical error

APPENDIX E
DETERMINATION OF 95% UPPER CONFIDENCE LEVEL RELEASE TO SURFACE

The Reasonable Maximum Exposure (RME) used by EPA for cleanup standard calculations is defined as approximately the 95% upper confidence level. This could also be expressed as the dose that is expected to be exceeded only 5% of the time. It is desireable to estimate the approximate number of curies brought to the surface at WIPP at the 95% upper confidence level to cleanup standards.

With all the complicated probabilistic calculations in the CCA it is not easy to arrive at probabilistic values for curies released to the surface. The procedure used here was:

(1) The cumulative probability distribution of curies brought to the surface from 104 intrusions calculated in Futures 1 through 20 of Vector #1 in the CCA was determined. All Vector #1 intrusions had a cuttings and cavings volume of 0.9046 m^3. Similarly, the distribution of curies from 110 intrusions in Futures 1 through 20 in Vector #2 was determined and combined with the distribution from Vector #1. It was necessary to adjust the Vector #2 values (which were for a volume of 0.6164 m^3) by a factor of 1.468 to be consistent with the cuttings & cavings volume of Vector #1. When a constant volume is used the variations in number of curies released is due to the random sampling of radionuclide concentrations in the 569 waste streams, to the time of intrusion, and to the variable releases from spallings and direct brine releases. It is reasonable to assume that this curie distribution which was obtained from 214 data points will be the same for all volumes of cutting and cavings. The values for any intrusion i and cumulative probability, p can be scaled directly by the relationship:

$$Curies_{i,P} = Curies_{.9046P}\left[\frac{Volume\ i}{.9046}\right]$$

(2) Volumes calculated from the PAVT were used rather than the CCA volumes for two reasons: (a) they are believed to be more realistic because of changes in several parameter values; and (b) the distribution of volumes released were more readily available. Thirty six percent of the PAVT volume releases exceeded 1.0 m^3 and 16% exceeded 2.0 m^3.

(3) There are expected to be 5.84 intrusions into the waste repository during the 10,000 year regulatory period. So, the percentile level that has a 5% chance of occurring in one of the intrusions is a value higher than 95% in the curie release distribution. This percentile level can be approximated by the relationship:

$1 - P^n$ = probability that at least one of n occurrences will be $\geq$ the cumulative probability value, P.

For n = 5.84 and the probability of 0.05, the minimum value of P is 0.991 (or 1-P = 0.009)

(4) The volume of each individual intrusion was taken from PAVT 1997 Figure 5.1 beginning from the highest value (3.95 m^3). An estimated curie release limit (e.g. 17 curies) was divided by the volume scaling factor to determine the appropriate curie level on the Vector #1 + #2 cumulative probability plot. This value would be 3.89 Ci for the 3.95 m^3 volume. From this curie level the related probability of the 17 Ci release from the one borehole could be determined. This probability is multiplied by 0.01 because this intrusion volume is only one of 100 volumes. The probabilities are summed for each intrusion volume to determine the total probability that the given release level will occur.

The probability of a 17 Ci release from a single intrusion was found to be 0.00999 or 0.0100. The probability that this large a release would appear in one of the 5.84 expected intrusions in the repository was calculated to be 0.057. So the calculated release is slightly less than the 95% value used for the RME.

The uncertainties in calculating a 95% upper confidence level for WIPP releases are significant and not quantifiable. Similar uncertainties would be expected to occur in calculations at most cleanup sites.

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EEG-68
DOE/AL/58309-68

EVALUATION OF THE WIPP PROJECT'S COMPLIANCE WITH THE EPA RADIATION PROTECTION STANDARDS FOR DISPOSAL OF TRANSURANIC WASTE

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, is being constructed as a repository for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC04-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, continues the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the generator sites' compliance with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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EXECUTIVE SUMMARY

SCOPE OF THE EEG REPORT

The U.S. Environmental Protection Agency's (EPA) proposed rule to certify that the Waste Isolation Pilot Plant (WIPP) meets compliance with the long-term radiation protection standards for geologic repositories (40CFR191 Subparts B and C), is one of the most significant milestones to date for the WIPP project in particular, and for the nuclear waste issue in general. The Environmental Evaluation Group (EEG) has provided an independent technical oversight for the WIPP project since 1978, and is responsible for many improvements in the location, design, and testing of various aspects of the project, including participation in the development of the EPA standards since the early 1980s. The EEG reviewed the development of documentation for assessing the WIPP's compliance by the Sandia National Laboratories following the 1985 promulgation by EPA, and provided many written and verbal comments on various aspects of this effort, culminating in the overall review of the 1992 performance assessment (Lee, et al., 1994). For the U.S. Department of Energy's (DOE) compliance certification application (CCA), the EEG provided detailed comments on the draft CCA (Neill, et al., 1996) in March, 1996, and additional comments through unpublished letters in 1997 (included as Appendices 8.1 and 8.2 in this report). Since the October 30, 1997, publication of the EPA's proposed rule to certify WIPP, the EEG gave presentations on important issues to the EPA on December 10, 1997, and sent a December 31, 1997, letter with attachments, to clarify those issues (Appendix 8.3). The EEG also presented its views to the DOE and the EPA at a number of meetings during the course of the proposed rule development. Since the publication of the proposed rule, the EEG staff met with the EPA staff on 12/10/97, 1/22/98, and 1/26/98; and with the DOE technical staff and contractors on 1/21/98 (EPA/DOE meeting to which EEG was invited), and on 2/17/98 and 2/20/98.

CONCLUSION

The EEG understands and appreciates the large amount of work that the EPA staff and consultants have accomplished in a very short time, as did the DOE staff and consultants in preparing the CCA. However, the EEG has raised a number of questions that may have an impact on compliance. The impact of these questions on the compliance must be assessed or resolved through additional information, experimentation, or modeling. Unless these issues are satisfactorily resolved, the EPA should conduct another performance assessment calculation using the parameter values and models that are properly justified. EPA should base its compliance certification decision on the results of these new calculations. It is essential that this first repository's predicted behavior instill a high degree of public confidence.

Although the EPA standards require demonstration of compliance only for 10,000 years, some partial calculations performed by the EEG indicate that higher releases may be predicted beyond that period (see Sections 2.9.3 and 2.14.1 of this report). There is no strong justification for stopping the calculation at 10,000 years. The EEG recommends performance of representative calculations to assess the behavior of the repository beyond 10,000 years.

The WIPP repository, as planned, does not have sufficient multi-barrier protection which is a fundamental international design philosophy for a nuclear waste repository. The EEG

recommends EPA require DOE to examine the existing plans for processing and repackaging the waste at its weapons complex, and incorporate in the WIPP design at least those reprocessing and repackaging features which have been planned. This will provide at least some degree of multi-barrier assurance to WIPP.

GENERAL ISSUES

Lack of Feedback From EPA

In spite of the best efforts by the EEG, the EPA reaction to our reviews and suggestions has been slow and apparently driven by legal considerations. This is not a criticism of the EPA, but simply a statement of fact. For example, the EEG and the EPA staff met on June 17, 1997, to discuss the basis for the new parameter values that the EPA had recommended to the DOE for a new set of performance assessment validation test (PAVT) calculations. At this otherwise very productive meeting, the issue of actinide solubility assumptions could not be resolved because the EPA did not have its expert consultant at the meeting and the EPA could not share the technical support document with EEG until it was released as a part of the proposed rule in late October, 1997. When the EEG expressed continued disagreement on this issue with the EPA at the meetings in December, 1997 and January, 1998, the EPA asked EEG to wait until the final rule is promulgated in May, 1998, to get another explanation, rather than discussing the matter at those meetings with its experts. The EPA practice of not identifying the commenters in their responses and combining comments by various individuals and groups makes it further difficult to identify the response to our comments. The net result of this process is that there may be issues included in this report for which the EPA may have valid responses but those will not be available to the EEG until the final rule is promulgated.

Excessive Reliance on DOE

One general impression of the EPA's proposed rule is that the EPA relied heavily on the DOE submissions and rebuttals to reviewers' comments, and sufficient attention does not appear to have been paid to the comments by the reviewers. Serious technical questions with regard to the conceptual models, selected values of input parameters in the calculations, and interpretation of scientific experiments have been raised by the EEG, the National Academy of Sciences Committee on WIPP, the NEA/IAEA International Review Group, and several environmental groups. The proposed rule has, however, accepted the DOE viewpoint on most of the issues, sometimes without any questions, and others after minor clarifications. For example, the EEG has had a longstanding concern about the values used for the chemical retardation parameter, K_d, used in modeling radionuclide transport through the Culebra aquifer overlying the repository. The EEG and the DOE organized a one day meeting in Albuquerque on July 30, 1997, to discuss this issue. The EPA was invited and attended this meeting. Four weeks after the meeting, both the DOE and the EEG submitted letters to the EPA's WIPP docket about this issue. In discussing this issue, the EPA's proposed rule documents extensively discuss and quote from the DOE letter, but do not even acknowledge the existence of the EEG letter in the docket. To provide another example, the NEA/IAEA International Review Group raised a number of questions about the need to more carefully predict the physical and chemical implications of the magnesium oxide backfill. The EEG has questioned a number of assumptions about the repository conditions, which are based on insufficiently justified assumptions on the effect of MgO on the repository. But the EPA has accepted the DOE assumptions without providing sufficient reasons to not

address the NEA/IAEA International Review Group and the EEG questions and recommendations.

Apparent Neglect of Uncertainties

Another disturbing aspect of the EPA's proposed rule is the confidence that has been expressed for assumptions that are clearly based on a number of uncertainties. For example, the EPA has rejected the EEG's suggestion for considering the "stuck pipe" and "gas erosion" scenarios for calculating releases, by the argument that the waste permeability may be as low as 5.3×10^{-15} m^2, but will not be 1×10^{-16} m^2. A value of 1×10^{-16} m^2 is used in the Compliance Certification Application (CCA) as the upper limit for which the stuck pipe/gas erosion process should be considered, but it was based on the rejected spallings code. It is a well established fact that the permeability of the waste is a highly variable and uncertain parameter due to the highly heterogeneous nature of the waste. In fact, the OECD/IAEA International Review Group felt strongly enough about the heterogeneity issue that they included it as one of the two main issues in the cover letter forwarding the report to the DOE.

Increasing Unwarranted Uncertainty Assumptions

On some issues where there is a reasonable data base to make certain straightforward assumptions, the EPA has chosen to widen the margin of uncertainty in the calculations. A case in point is the probability of a future borehole encountering a brine reservoir in the upper Castile Formation underlying the repository. Based on the number of boreholes drilled versus those that reported encountering brine in the northern Delaware Basin, the DOE suggested a probability of 8%in the CCA. The EEG argued that since the borehole WIPP-12 at the WIPP site encountered brine and was extensively tested and was estimated to contain 700 million gallons of brine, any borehole drilled at the repository should be assumed to encounter brine. The EPA argued that the geophysical survey at the site indicates that up to 60% of the area under the repository may be underlain by brine, but then used a range of probability of 1% to 60% in the new PAVT calculations. The EEG sees no justification for this arbitrary spread of the probability range. To argue that this parameter does not make a difference in the calculated releases avoids the question, rather than answer it.

Use of Partial Sensitivity Analyses

It is a known fact that in a probabilistic consequence analysis with a large number of variables, the calculations are sensitive to a large number of parameters. There is doubtless varying degree of sensitivity of calculations to various parameters, but the rational way to get the most reliable results is to determine the value of each parameter as accurately as possible, and then run the calculations. The EPA has, on the other hand, argued that when a parameter value used in the CCA is not otherwise justified, but the compliance is still met with a new value, then the CCA value is "adequate". For example, changing the assumed brine volume of a Castile brine reservoir from 160,000 cubic meters (in the CCA) to 17 million cubic meters (in the PAVT calculation) had a noticeable effect on releases, but the compliance with the standards was still met. However, "EPA believes that the PAVT verifies that the original CCA Castile brine reservoir parameters were adequate for use in PA and comparison against the radioactive waste containment requirements." (U.S. EPA, 1997c, p. 58800). The EEG strongly rejects this argument because there are many other parameter values and conceptual and numerical models that should be

changed unless acceptable justification can be provided for the assumptions in the CCA and the proposed rule; and these changes will change the outcome of calculations. To declare an assumed value that is not otherwise justified "adequate" on the basis of limited changes in other values is, at the least, premature. There is no rational basis for finding an unjustified value to be acceptable unless it is justified based on observations, experiments, or widely known facts.

Faulty Sampling Ranges

The CCA appears to have argued in some cases that if the sampled distribution of a parameter used in the CCA calculations is in error, but includes the likely values of that parameter, then the CCA calculations are acceptable. The EEG disagrees with this approach. Under these conditions, the CCA calculations should be repeated with the best estimate of the parameter distributions available. The use of a faulty distribution of one parameter biases the Complementary Cumulative Distribution Function (CCDF) curves and confuses the assessment of uncertainty. The use of more that one faulty parameter set makes the assessment of uncertainties impossible because of the complex non-linear nature of the performance assessment models. This issue is discussed further in the Section "Faulty Sampling Ranges" in Appendix 8.2 of this report.

Insufficient Scrutiny for DOE Submissions

In many instances, the EPA appears to have accepted the DOE arguments without sufficient independent scrutiny. For example, the EPA agrees with the DOE's assessment that the borehole ERDA-9, which is located in the underground development area and connects the upper Castile Formation with the ground surface, is not significant to the repository's performance assessment and may be "screened out" of consideration. The basis of this concurrence with the DOE is that, "ERDA-9 did not penetrate an area that will become a waste panel and DOE has indicated that abandoned boreholes more than a meter away from the waste can be screened out of PA due to low consequence." (U.S. EPA Proposed Rule, Federal Register, vol. 62, no. 210, p. 58801). The EPA apparently did not investigate that the basis of the 1 meter criterion is the assumed difference in permeability of the disturbed versus the undisturbed rock zone surrounding the excavations, which can be changed by assumptions of less drastic change or an intermediate transition zone. Also, the EEG has not been able to find a reference to the exact location of the ERDA-9 borehole *at the repository horizon.* It is common knowledge that the boreholes are never drilled completely vertical. In fact, a WIPP project borehole, H-19B4, drilled in 1995 to exacting specifications under the guidance of the Sandia National Laboratory hydrologists, deviated 9.5 meters (31 feet) in a vertical depth of 229 meters (752 feet); there was every reason for that test hole to be as vertical as possible. At that rate, a borehole may deviate 27 meters (89 feet) in 655 meters (2150 feet, the depth to the repository) depth. To dismiss the potential impact of ERDA-9 without asking these questions and without requiring any special plugging and sealing in this borehole is difficult to understand.

SPECIFIC ISSUES

The EEG agrees with a number of changes that the EPA required in conducting the PAVT calculations, but believes that another set of calculations needs to be performed with the changes outlined in the following paragraphs.

Solubility
The solubility of actinides is very important to calculating the releases from the repository. The CCA uses a model known as FMT to calculate these solubilities. EEG found that the model predicts differences for actinide sulfate solubilities that cannot be explained by chemistry, thus raising questions about the reliability of this model.

Rather than using an extensive plutonium data base, the FMT predictions relied on thermodynamic data for other elements and an oxidation state analog argument. EEG recommends that the calculations be performed using data for plutonium and the values for solubility and complex ion formation contained in the peer-reviewed data compilation by the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/ NEA).

EEG agrees with EPA's documentation of the shortcomings of the solubility uncertainty ranges advanced by DOE. However, EEG questions EPA's argument that the ranges are adequate. As noted by EPA, there is a lack of data to determine the uncertainty ranges for oxidation states IV and VI. EEG recommends that the uncertainty range needs to be determined with the appropriate plutonium data.

In the solubility calculations, the CCA inappropriately discounts the role of organic ligands on plutonium solubility by arguing that EDTA is the strongest complexing agent and there is not enough amount present in the inventory to make a difference. But citrate forms very strong complexes with actinides in the +4 oxidation state and very weak complexes with other cations. Thus, the solubility of a stable plutonium-citrate complex in individual waste containers needs to be calculated.

There are serious unanswered questions about the impact of magnesium oxide backfill on the solubility of the actinides. It is proposed that magnesium oxide will reduce the solubility of the actinides by controlling the pH. But, it is not known how long the early reaction product, nesquehonite, will persist. The FMT model calculates that the presence of nesquehonite drives the solubility of the +4 actinides, such as plutonium, higher than in the no backfill case. This requires further investigation.

Spallings
The CCA spallings model was rejected by the DOE's peer review after submission of the CCA, but a new coherent model and a computer code that calculates the projected releases has not been developed. The EEG finds the basis of accepting the predicted release volumes due to spallings as determined by the CCA to be both unnecessarily convoluted and faulty. Since this is a mechanism for the largest projected releases from the repository, it is essential that it is treated through defensible conceptual and numerical models.

Air Drilling
The air drilling scenario proposed by Dr. John Bredehoeft was rejected on the basis of regulation, despite records of such drilling in the Delaware Basin. Low probability and low consequence are also discussed in EPA's Air Drilling Analysis (U.S. EPA, 1998), and the scenario was ruled out again. However, the EEG does not believe that the issue has been resolved. Neither EPA nor

DOE examined drilling records in the Texas portion of the Delaware Basin. New developments in underbalanced drilling also inhibit a full understanding of the capabilities of this expanding technology. The EPA's analysis of low consequence, in which a spread sheet model was used, has serious shortcomings.

Fluid Injection

For fluid injection activities adjacent to the site, the EPA has accepted a "low consequence" argument based on a model that has not been verified with oil field water flood data, despite the availability of such data. EPA offers a "low probability" argument based on its expectations of fluid injection practices, although DOE maintains that the probability of future fluid injection practices would be difficult to define. The low probability argument has not been reconciled with the common observation of water flowing through the Salado Formation in water flood operations throughout southeast New Mexico. Neither the DOE nor the EPA have adequately addressed concerns about future CO_2 flooding in the vicinity of WIPP. The basis for dismissing the Rhodes -Yates incident does not reflect a review of the technical information presented in that case. DOE has not explained the anomalous water level rises that have been observed for the last ten years in the Culebra aquifer despite the documented concerns of EEG, EPA and the National Academy of Sciences (NAS) WIPP Committee. EEG recommends additional effort to explain the Rhodes-Yates water flooding incident, if the most obvious explanation of flow of large quntities of water through the Salado interbeds is not acceptable to the EPA and the DOE. The fluid injection scenario cannot be dismissed either on the basis of low consequence or low probability.

Anhydrite Fracturing

The EEG has reviewed the basis of the anhydrite fracture model used in the BRAGFLO code and has a number of questions about its validity. The model is unusual in that the effect of fracturing is treated using an equivalent porous medium. All the relevant literature examined by EEG treat fractures as distinct porosity. Use of an equivalent porous medium is not in itself unreasonable. However, the DOE has not referenced, nor has the EEG been able to find, a description of similar treatment of the dependance of porosity and permeability on pressure as a result of fracturing. The lack of a clear development of the BRAGFLO model from established models makes its review difficult. The EPA should request that the anhydrite fracture model of BRAGFLO be compared to the treatment of fracture development in hydrofracing codes commonly used in the industry. Until the model and its assumptions are properly justified, the EEG finds it difficult to accept the results derived from this model.

Solution Mining

EPA's conclusion that potash solution mining is not likely at WIPP relies on solicited comments that are factually incorrect and inconsistent with the published scientific literature. DOE and EPA maintain that excavation mining captures the effects of solution mining on the hydraulic conductivity of the overlying aquifers. However, based on the scientific literature, the prediction of subsidence above solution mines can be much more complex than the prediction of subsidence due to excavation mining. It appears to be incorrect to calculate a probability of mining based on past potash production, which was inherently dependent on past mineral economics and the availability of high grade ore. Potash is used by the fertilizer industry and is ultimately used for the production of food. It seems reasonable to assume that the demand for food will continue and

low grade potash ores will eventually be mined to meet this demand.

Groundwater Flow and Radionuclide Transport Through the Culebra

A number of questions related to the flow and transport through the Culebra have been identified by the EEG and the National academy of Sciences WIPP Committee that have not been addressed by the EPA. These questions relate to the conceptual models of the origin and flow of water in the Culebra aquifer, modeling of transport through the Culebra, and the justification of the assumed values of the chemical retardation parameter (K_d) in the CCA calculations.

BRAGFLO 2D/3D Modeling

The results of the DOE 's screening analysis for repository processes (FEP S-1) suggest that the two dimensional BRAGFLO model used in the CCA calculations may be misrepresenting repository performance at pressures above the anhydrite fracture pressure. There is the potential of substantially greater brine saturation in the repository at higher pressures than calculated for the CCA. The discrepancy between the 2D and 3D versions of BRAGFLO may have resulted in an underestimate of radionuclide releases to the surface. To resolve this issue, the EEG recommended that several 3D BRAGFLO simulations of the repository should be performed using the parameter values of vectors used in the CCA performance assessment. The 3D BRAGFLO simulations should be used to provide repository conditions for the normal suite of direct brine release calculations. The calculations should also be assessed in terms of impact on spallings calculations.

The DOE and the EEG held a meeting on February 17, 1998, to try to resolve this issue. It was agreed at that meeting that there was sufficient reason to further investigate the potential for greater brine inflow to the repository using 3D modeling compared to the calculated value using the 2D model of the CCA. It was agreed that a simulation corresponding to a parameter vector that led to high pressure and anhydrite fracturing in the CCA calculations will be sufficient to demonstrate the potentially increased brine inflow in comparison to the CCA calculation.

Brine Reservoirs

The EEG raised a number of issues related to the Castile Formation brine reservoirs in commenting on the CCA. The EPA has accepted all of the EEG suggestions except the one related to the assumption of the probability of encounter of brine reservoirs, and we disagree with the EPA on this issue. The CCA assumed 8% probability on the basis of faulty assumptions. The EEG recommended 100% probability on the basis that the WIPP-12 brine reservoir was large enough to most likely extend under the repository, a conclusion also confirmed by geophysical testing directly above the repository. The EPA has sampled on a range of 1 to 60%, but has provided no basis for assuming less than 60%. Based on the arguments that the geophysical (Time-domain electro-magnetic survey) data may be interpreted to indicate the brine to be under 60% of the repository, and that some boreholes adjacent to the brine producing boreholes are known to be dry, the EEG is willing to accept the assumption of a fixed 60% probability of encounter, and recommends that a new performance assessment calculation be run with this fixed value.

Waste Issues

DOE calculations showed that non-random emplacement of radionuclides in the repository led to significantly higher releases from cuttings and cavings and spallings. EEG believes that releases from Direct Brine Releases will also increase. Revised calculations should be incorporated into the CCDF even though partial sensitivity analyses indicate that non-random emplacement would not, by itself, result in non-compliance.

The expected quantity of cellulosics, rubber, and plastics (CRP) in the repository is slightly greater than the waste repository limit. The ability to characterize CRP waste with sufficient accuracy has not been shown. Also, EEG believes the limit should be controlled on a per panel basis rather than for the entire repository.

Assurance Requirements

There are six assurance requirements in the EPA standards (40 CFR 191) which were incorporated to provide additional confidence in the repository, because of the inherent uncertainty in projecting the future behavior of natural systems and inadvertent human action. The EEG agrees with the EPA determination of two of these six requirements, the active and the passive institutional controls, but has questions about the other four. The monitoring plan does not appear to meet the intent of the standards. DOE's retrieval plan and the EPA's determination of its compliance with the requirement appear to give a false sense of security regarding the retrievability of waste. WIPP does not appear to meet the intent of the resource disincentive requirement, and this is an additional reason for EEG to argue that additional engineered barriers should be incorporated in the WIPP design for making the waste less respirable and soluble through treatment and repackaging. Since DOE has plans to treat or repackage 85% of the existing contact handled TRU waste anyway, this recommendation should be easy to implement.

Individual Protection Requirements

Although EEG has minor disagreements about several assumptions used by DOE in evaluating the Individual Dose Requirements, we agree that compliance with these requirements has been demonstrated.

Environmental Standards for Ground-Water Protection

EEG believes there is a very low probability of significant contamination of an Underground Source of Drinking Water (USDW) by an undisturbed release. However, 40 CFR 191.24 specifies that no contamination is permitted if the USDW is initially at or above the radionuclide limits of 40 CFR 141. No documentation of current radionuclide concentrations in the USDWs has been provided. EPA needs to require submission of data showing the USDWs are below allowed limits or that there is a zero probability of any contamination reaching the USDW.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Project is a planned geologic repository for disposal of transuranic (TRU) waste, generated from the nuclear defense programs of the USA since 1970. The repository is located at a depth of 655 meters in the Permian age salt beds of the Salado Formation in southeastern New Mexico, 40 km east of Carlsbad, NM. Since 1978, the Environmental Evaluation Group (EEG) has evaluated various technical aspects of the WIPP project that relate to the impact on the public health and the environment of New Mexico. A list of published reports appears at the end of this report. The U.S. Department of Energy (DOE) is responsible for the management of defense TRU waste as part of the U.S. defense nuclear complex following its predecessor agencies, the U.S. Atomic Energy Commission (AEC) and the Energy Research and Development Authority (ERDA). Before 1970, such waste was buried in shallow pits at several national laboratories. DOE plans to ship only the post-1970 TRU waste to WIPP, that has been stored in above-ground tension-support structures at the national laboratories.

The TRU waste inventory currently in retrievable storage at the DOE sites totals about 104,000 cubic meters including 27,000 m^3 of alpha emitting low level waste scheduled for processing, or the rough equivalent of half a million 55-gallon drums (U.S. DOE, 1995b). The WIPP has been designed to contain up to 168,500 cubic meters (approximately 810,000 drum-equivalent) of contact-handled (CH-TRU), and up to 7100 cubic meters (7500 canisters) of remote-handled (RH-TRU) waste. The CH-TRU waste may have a maximum surface-dose rate of 200 millirem per hour. Ninety-five percent of the RH-TRU canisters disposed at WIPP may have a surface dose-rate of a maximum of 100 rem per hour, and five percent by volume may have a maximum of 1000 rem per hour. The TRU waste generated in the future will come from dismantling and cleanup of the nuclear weapons complex and may be different than the existing waste.

Excavation of the WIPP repository began in 1982 and all the surface facilities, four shafts, and all the basic underground facilities, including 1/8 of the repository “rooms”, had been excavated by 1988,

the year when the DOE had planned to start placing waste in the repository for experiments and operational demonstration. The DOE abandoned this plan in 1993 because there was insufficient justification for conducting the *in situ* experiments with waste and it would have been difficult to ensure retrieval of the waste after several years of emplacement.

The decision to use the WIPP repository for permanent disposal of TRU waste will be made, in large part, on demonstration of the facility's compliance with the long-term disposal standards for TRU waste promulgated by the Environmental Protection Agency (EPA) (U.S. EPA, 1993). These standards require a probabilistic assessment of the integrity of the repository for 10,000 years into the future. Such an assessment requires a detailed knowledge of the geological and hydrological characteristics of the site, physical and chemical characteristics of the waste, formulation of scenarios for breach of the repository and release of radionuclides to the environment, calculation of the probabilities and the amounts of release during the future 10,000 years, and comparison with the releases allowed by the standards. The compliance with the standards is to be judged on the basis of a set of criteria promulgated by the EPA (U.S. EPA, 1996).

EEG has participated in the development of the EPA standards for safe disposal of TRU and High Level Waste (40 CFR 191) beginning in the early 1980's, including reviews of various drafts of the EPA standards, testimony at the EPA Science Advisory Committee Meetings, EPRI workshops, NAS Board on Radioactive Waste Management Workshops, and Congressional Committees. Detailed reviews were provided during the development of the standards, the criteria (40 CFR 194) to implement them, and the Compliance Application Guidance document.

The DOE published a Draft Compliance Certification Application (DCCA) for WIPP in October 1995. The EEG reviewed this document and published detailed comments on it in March 1996 (Neill, et al., 1996). The DOE submitted its Compliance Certification Application (CCA) to the EPA in October 1996 (U.S. DOE, 1996c). The EEG submitted the previously published comments (Neill et al., 1996) on the DCCA to the EPA since the DOE had not provided responses to those and had not indicated how the final application (CCA) had been modified as a result of the EEG comments.

EEG provided additional comments on the specific issues in the CCA as attachments to the EEG letters dated February 7, 1997, and March 14, 1997. Copies of these letters with attachments are included in this report as Appendices 8.1 and 8.2 respectively.

Many meetings were held between the DOE and the EPA to discuss various technical issues both before and after the submission of the CCA in October 1996. The EEG started receiving invitations to these meetings after April 1997.

The EPA issued a Proposed Rule (U.S. EPA, 1997c) in October 1997 proposing to certify that the WIPP meets the EPA standards, and opened a four month period for public comments on the Proposed Rule. At the request of EPA, the EEG staff provided the initial EEG reaction to the EPA decision through technical presentations at a meeting on December 10, 1997, in Albuquerque, and followed with a letter dated December 31, 1997, with attachments. A copy of this letter with the attachments is included in Appendix 8.3. The present report contains the EEG's final comments on the EPA's proposed rule.

This report is organized according to the four "requirements" of the EPA Standards (U.S. EPA, 1993), viz., the containment requirements (40 CFR 191.13), the assurance requirements (40 CFR 191.14), the individual protection requirements (40 CFR 191.15), and the environmental standards for ground-water protection (40 CFR 191 Subpart C). The bulk of the DOE application and the EPA's proposed rule deal with compliance with the containment requirements. The bulk of this report, therefore, also consists of the issues associated with demonstrating compliance with the containment requirements. Rather than providing a critique of the EPA proposed rule chapter by chapter, or page by page, the EEG has adopted the approach of discussing what appear to us to be the most significant issues affecting determination of compliance. The issues relate either to a lack or inadequacy of justification of the conceptual models, parameter values, or computer models, that have been used to compute projected releases of radionuclides to the accessible environment, or insufficient basis for not considering certain scenarios for release. Attempt has been made to describe our concerns as clearly and explicitly as possible with suggestions for ways to resolve the issues.

The Environmental Evaluation Group (EEG) was established by the State of New Mexico in 1978 as an independent scientific group to conduct a scientific evaluation of the WIPP project's impact on the public health and environment of New Mexico. In addition to the reviews of long-term and operational-period safety, EEG has conducted environmental monitoring of air, water and soil at the WIPP site and in the surrounding communities since 1984 to establish a pre-operational environmental baseline against which future suspected contamination episodes may be evaluated. This multi-disciplinary group, with offices in Albuquerque and Carlsbad, is funded totally with federal money by Congressional mandate through the DOE. The EEG continues to influence shaping the project to ensure that the public health and safety of the people of New Mexico is not jeopardized and the environment is not adversely affected. The effect of the EEG's work can be seen, for example, in (1) vastly improved geological and hydrological data base and modeling; (2) relocation of the repository to a more suitable area with respect to long-term integrity; (3) safer operational design and procedures; (4) abandonment of the plans to conduct *in situ* experiments with waste at WIPP; (5) continuation of performance assessment work after the disposal standards were vacated by the court in 1986, thus not losing time when the standards were re-promulgated in 1993; and (6) a much safer and more cost-effective redesigned transport container (TRUPACT-II) for the CH-TRU waste shipment certified by the Nuclear Regulatory Commission.

2.0 CONTAINMENT REQUIREMENTS

2.1 SITE CHARACTERIZATION ISSUES

There are a number of issues concerning the understanding of the geological and hydrological setting and processes at the WIPP site that have been debated since the site characterization at the Los Medanos site began in 1974. Some of these issues, such as the characteristics of the brine reservoirs in the Castile Formation and the probability of their encounter, are directly related to the numerical assessments of compliance and are discussed at length as separate sections in this chapter. Other issues, such as the extent of the effect of Karst processes at the WIPP site and the anomalous water-level rises in a number of boreholes, may have an impact on numerical assessments but the DOE claims that they do not and the EPA has accepted that assertion. There is a third set of site characterization issues which do not appear to have a direct impact on the numerical assessments as framed by the CCA, but relate to the credibility of understanding of the geological and hydrological processes operating at present and how that understanding is used to understand the past evolution and future predictions. In this third category, one may include the issues of recharge and discharge of groundwater, location of water table, the extent and rate of basin-wide dissolution processes, etc. Issues falling in all three categories are discussed in this section. To keep the discussion brief and easy to read, references to previously published reports and papers are frequently made, and only summary statements are provided here.

Chaturvedi (1993) provides the most up to date summary of the EEG's evaluation of these issues, and this paper is included in this report as Appendix 8.5. These issues are discussed by the EPA in the Technical Support Document for Section 194.14 (U.S. EPA, 1997g), CARD 14 (U.S. EPA, 1997b), and the proposed rule itself as published in the Federal Register on October 30, 1997 (U.S. EPA, 1997c).

2.1.1 History of Site Characterization Efforts

Before discussing the specific issues, a brief history of the site characterization efforts for WIPP may be helpful in putting these issues in perspective. Following the abandonment of the Lyons, Kansas site in 1972, a 3.2 km by 2.4 km (2 mile by 1.5 mile) site was selected by the Oak Ridge National Laboratory on behalf of the then Atomic Energy Commission, 11 km northeast of the present 6.4 km by 6.4 km (4 mile by 4 mile) WIPP site. Cores from two boreholes (AEC-7 and AEC-8, Fig. 1) penetrating through the Salado Formation drilled at the northeast and the southwest corners of that site indicated acceptable geology. Sandia National Laboratories (SNL) was given the responsibility for site characterization of WIPP in 1975. A third borehole (ERDA-6; see Fig. 1) drilled by SNL at that site in 1975 encountered a pressurized brine reservoir and intense structural disturbance in the fractured upper anhydrite of the Castile Formation at a depth of 826 m (2709 ft). As a result, the location of the repository was moved to the present site.

The DOE had declared the WIPP site to have been adequately characterized in 1981 on the basis of the Geological Characterization Report (Powers, et al., 1978) and the Environmental Impact Statement (U.S. DOE, 1980). The EEG recommended additional field and laboratory studies to resolve several geological and hydrological questions based on the consensus reached at a scientific conference organized by the EEG in January 1980 and a 3 day field conference at the site in June 1980 (Chaturvedi, 1980). These recommendations were included in a stipulated agreement between the DOE and the State of New Mexico signed in 1981 as part of the settlement of a lawsuit filed by the State Attorney General. One of the EEG recommendations was to deepen the borehole WIPP-12 which had been drilled through the Salado Formation in 1978 to a total depth of 845.6 meters (2773.6 ft), only 14.7 meters (48.3 ft) below the Salado/Castile boundary in to the Castile Formation, but was completed only to the base of the Salado at 834.5 meters (2737.5 ft). Two (N-S and E-W) seismic reflection profiles crossing at the WIPP-12 indicated anticlinal structure at the depth of the Castile Formation at this location, and the EEG suspected the presence of a Castile brine reservoir at this site. The borehole was deepened from its 845.6 meters (2773.6 ft) depth to a total depth of 1197.4 meters (3927.5 ft) in November-December 1981. Pressurized brine associated with hydrogen sulfide gas was encountered at 919.5 meters (93016 ft), only 74 meters (242.4 ft) below the original depth of the

borehole. The EEG recommended relocation of the repository, because according to the plans at that time, the repository was in the northern part of the underground area to be excavated and the edge of the repository would have been only 170 meters (558 ft) south of WIPP-12. The DOE agreed to rotate the repository design so that the experimental area is now located north of the center of the site, and the repository to the south.

The DOE presented the results of the additional studies to the EEG during 1982 and 1983 (EEG, 1983). The EEG published its evaluation of the suitability of the WIPP site in 1983 (Neill et al., 1983) and expressed confidence in the site but also concluded that additional work was needed for assessing compliance with the long-term standards that were in the process of being developed

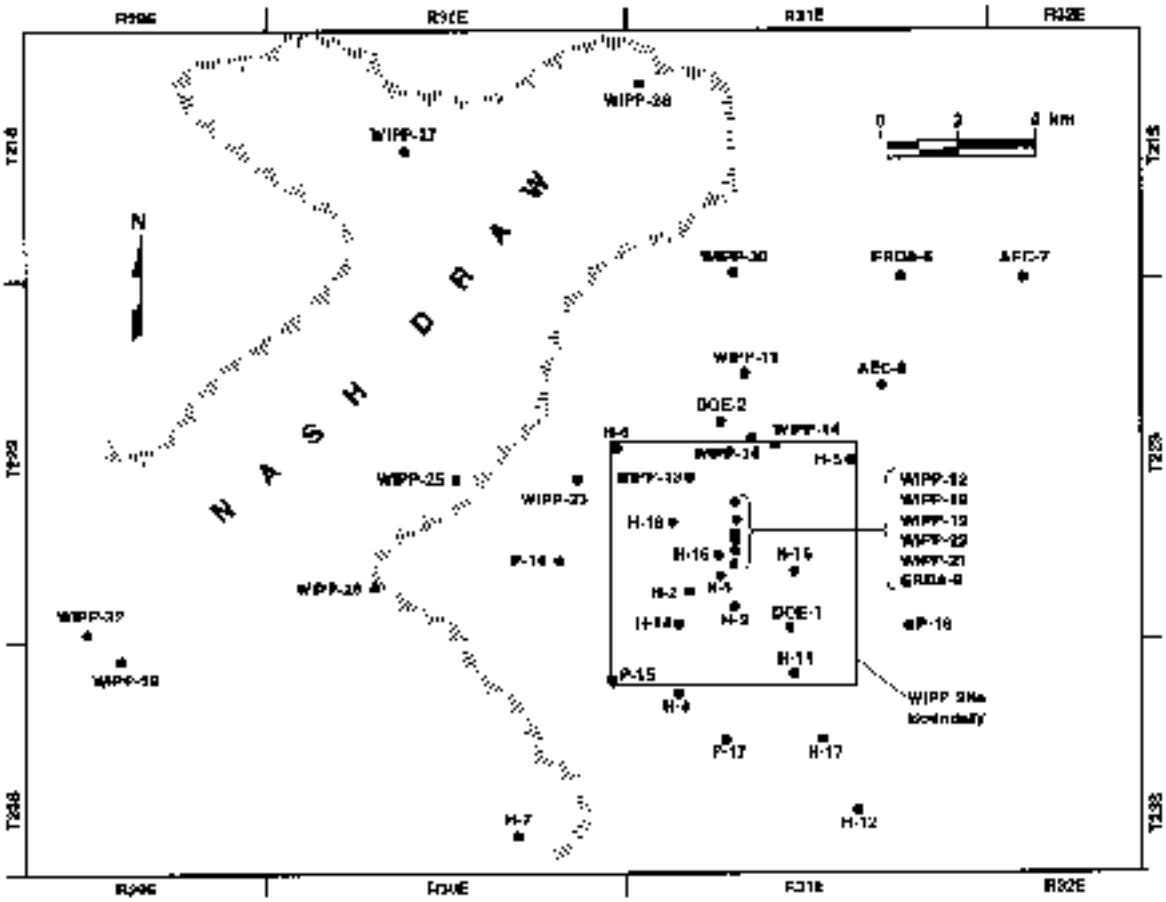

Fig. 1. Location of WIPP Boreholes

by EPA at that time. These additional recommendations related to (a) identifying the extent of the underground brine reservoir in the Castile Formation that had been encountered by the borehole WIPP-12, (b) to address and try to resolve controversial geological issues such as deep dissolution in the Salado Formation and the formation and occurrence of breccia pipes, and (c) to better define the hydrological and radionuclide transport characteristics of the Rustler Formation with its two aquifers. Field and analytical studies conducted since 1983 have answered many of the questions and brought others closer to resolution. Additional specific questions developed as the performance assessment process started in 1986. The EEG has continuously been involved in attempting to resolve these questions.

2.1.2 Deep Dissolution

The EEG agrees with the EPA's conclusion that deep dissolution of the Salado Formation salt is not likely to be a threat to the WIPP repository. A history of the efforts made by the EEG, Sandia National Laboratories, and the DOE to resolve this issue is found under the heading "Dissolution of Salado Salt" in Chaturvedi (1993), Appendix 8.5 of this report.

2.1.3 Karst Processes at the WIPP Site

The WIPP site is located in a karst region and the topography to the west and south of the site is developed in response to the karst processes. However, no sinkholes have been identified at the WIPP site proper and extensive hydrological testing, including several multi-well flow tests at the site, have not encountered karst channels of significantly anomalous transmissivity. Multi-well flow tests have, however, given indications of north-south trending preferential flow paths in the northwestern and the southwestern parts of the WIPP site. The well WIPP-30 (Fig. 1) is located 5.6 km (3.5 miles) NNE of the well WIPP-13, but showed a significant drawdown starting only a few hours after pumping at WIPP-13 began (Beauheim, 1987). This observed drawdown in response to pumping WIPP-13 was higher than at several boreholes closer to WIPP-13, indicating a NNE trending high transmissivity connection between WIPP-13 and WIPP-30. Similarly, the rapid and high magnitude responses observed in wells DOE-1, H-3, and H-15, as a result of pumping in H-11 (Beauheim, 1989) are believed to reflect the presence of a fracture network extending to the north and northwest from

H-11 (see Fig. 1). While these high transmissivity zones are taken into account in the modeling of flow through the Rustler, there are remaining questions that have been raised by Leonard Konikow of the NAS WIPP Committee, and David Snow, regarding the nature of flow and transport through the Culebra, particular in the region directly above the repository, that have not been satisfactorily addressed in the proposed rule.

In summary, with respect to the karst question, while the EEG agrees that karst channels and sinkholes have not been found in the WIPP area east of the sink hole in which WIPP-33 (see Fig. 1) was drilled, we are less certain than the EPA about rejecting the possible effects of this phenomenon now and in the future. The EPA has concluded, "karst is not a problem at WIPP and that geologic evidence of the last approximately 500,000 years and results from DOE's groundwater modeling indicate that future development of karst at the WIPP is not likely." (U.S. EPA, 1997c, p. 58799). The EEG view is that while the effects of karst processes have not been identified at the WIPP site proper, the site is located in a karst region. Therefore, in considering the flow and transport through the Culebra, allowance should be made of this fact and the conceptual models, parameter values, and numerical modeling should be conducted with relatively conservative assumptions. A discussion of the issues of flow and transport through the Culebra is presented in Section 2.9 of this report.

2.1.4 Dewey Lake Redbeds Hydrology

The hydrology of the Dewey Lake Redbeds (DLR) and the overlying Santa Rosa Formation has not been adequately considered in the CCA. The CCA rejected consideration of transport through the DLR on the basis of the DOE assumption that "chemical retardation occurring in the Dewey Lake will prevent release within 10,000 years of any actinides that might enter it." (U.S. DOE, 1996c, p. 6-149). This decision is based on an analysis conducted by Wallace et al. (1995), who assumed the K_d values for the DLR for different radionuclides on the basis of "literature search for sand/sandy soil in saline waters". No K_d values have been obtained on the DLR rock, in situ or in the laboratory, and the reported values from the literature search are meaningless because they were conducted on a variety of soils under a variety of conditions unrelated to the DLR Formation. This fact is obvious from the extremely wide range of reported values; e.g., Table NS1-A3 of Wallace et al. (1995)

reports K_d of 100 to 100,000 mL/g for Plutonium. The EEG therefore rejects the CCA assertion about the contaminant transport through the DLR.

The EPA has advanced an additional argument for not considering DLR as a transport pathway. The proposed rule (U.S. EPA, 1997c, p. 58799) states: "the CCA PA results indicated that no contaminated brine traveled up an intrusion borehole past the Culebra to the Dewey Lake or other units." It is common knowledge that the postulated rise of contaminated brine up an intrusion borehole is based on the assumptions made in conducting the performance assessment rather than any specific inherent property of the system. This EPA assertion for not considering contaminant transport through the DLR is therefore also without basis.

The DOE has conducted hydrological tests in the Dewey Lake Redbeds and the Santa Rosa Formation in 1997 after the submission of the CCA to investigate the source of water leaking in the WIPP exhaust shaft. These tests, conducted at the center part of the site overlying the repository, show that water in the lower Santa Rosa/Upper Dewey Lake Formations is more prolific than believed before (Duke Engineering Services, 1997). The results of these tests and the surprising encounter of water in the DLR in the borehole WQSP 6 and 6a at the site indicates that more surprises may be in store with respect to the hydrology of this Formation. The WQSP 6a produced 12 gallons per minute water of relatively good quality (4,000 mg/L). The EEG recommends a thorough re-examination of the Dewy Lake Redbeds issue.

The NAS WIPP Committee (NRC, 1996) concurs with the EEG view on this issue:

> In the Committee's opinion, releases to the Dewey Lake cannot be discounted summarily; if a borehole to the Salado or to the Castile Formation were to connect these formations to brine at a pressure near lithostatic, then the hydraulic gradient (driving Darcy flow) would be sufficient to enable leakage into both the Culebra and the Dewey Lake if a pathway to either formation were to exist. (NRC, 1996, p. 74).

The NEA/IAEA International Review Group (NEA/IAEA, 1997) also expressed a similar opinion on this subject:

> The IRG considers that, from a dose perspective, greater attention could be given to considering whether any credible scenarios exist in which contaminants might reach these potable or nearly potable resources, under present day and alternative climate conditions.

2.1.5 Rustler Formation Geology and Hydrology

The EEG continues to disagree with several aspects of the CCA conceptualization of the past history of the Rustler Formation, that EPA has accepted without sufficient critical examination of the evidence for alternative conceptual models. These issues are briefly discussed below with references to the EEG reports and papers where more details can be found.

2.1.5.1 Pattern of Rustler Salt

The EEG has shown (Chaturvedi and Channell, 1985; Lowenstein, 1987) that the pattern of occurrence of salt in the Rustler Formation can be more rationally explained by the hypothesis of post-dissolution salt removal as first proposed by Snyder (1985), rather than the Holt and Powers (1988) and Powers and Holt (1990) hypothesis of original deposition. Based on a detailed sedimentological study of the Culebra cores from a number of wells at the WIPP site, Lowenstein (1987) interpreted four distinct dissolution zones in the Rustler Formation.

2.1.5.2 Origin of Rustler Fracturing

The pattern of fracture distribution and corresponding transmissivity values distribution in the Culebra is too complex to be explained away in a simple statement like "density of open fractures in the Culebra decreases to the east", and as expected, has become more complex with additional data acquisition.

The respective thicknesses of the Rustler and the upper Salado (Chaturvedi and Channell, 1985, Fig. 8, p. 23) call into question the Beauheim and Holt (1990) proposition that dissolution of the upper

portion of the Salado Formation may have caused subsidence and fracturing in the Culebra. The Rustler Formation is 137 meters (450 ft) thick four miles east of the center of the WIPP site and only 90 meters (300 ft) thick from the center of the site westward. The upper Salado (from the top of the Salado to Marker Bed 103), on the other hand, maintains a uniform thickness of about 58 meters (190 ft) over the WIPP site and only decreases in thickness west of the Salado dissolution front that coincides with the western margin of the WIPP site. It would be more logical to postulate the gradational removal of salt from the Rustler Formation itself to have caused fracturing in the Culebra over the WIPP site. West of the Salado dissolution front (west of the WIPP site), both the Salado and the Rustler have been affected, grading into total collapse in the Nash Draw.

If the high transmissivity zone in the southeastern part of the WIPP site is related to the dissolution of gypsum fillings in the Culebra fractures, then the high transmissivity zone may extend to the south-central part of the WIPP site.

2.1.5.3 Age of Rustler Water

The EEG has never accepted the bases for the assumption of the Rustler water being "fossil" water, having been recharged under climatic conditions significantly different from the present. Since the EPA has accepted this hypothesis as postulated by the DOE, it is important to state the reasons in detail for the EEG believing that the Rustler water is a mixture of "old" and "new" water, including modern day meteoric recharge.

2.1.5.3.1 Hydrogen and Oxygen Isotopes in Groundwater

The EEG (Chapman, 1986) compiled stable isotope data from throughout southeastern New Mexico and compared them to data from the WIPP area. The stable isotopic compositions of most samples of groundwater from the Rustler Formation were found to be similar to the composition of other, verifiably young, groundwater in the area. Though the stable isotope data cannot indicate ages for water in the various aquifers, neither did the data show any distinction between most Rustler groundwater and verifiably young groundwater. A small number of samples, primarily from the Rustler/Salado contact east of Nash Draw, had isotopic compositions that are not characteristic of

recently recharged meteoric water. These waters' enrichment in heavy isotopes may be due to mixing with deeper groundwater (supported by the stable isotopic composition of Salado fluid inclusions and Castile brine) or to exchange between the groundwater and hydrous minerals.

A comparison of the heavy isotope enrichment observed in evaporating waters and the composition of the water at WIPP-29 and the Surprise Spring showed that the isotopic composition of these Nash Draw waters could be derived by evaporating Rustler groundwater. Based on stable isotopes, both WIPP-29 and Surprise Spring could be discharge areas for Rustler groundwater moving from elsewhere in Nash Draw and the east.

The enrichment in heavy isotopes found in the water from pools in the Carlsbad Caverns was used by Lambert (1987b) as evidence that the relatively depleted Rustler water was recharged during a past, more pluvial, time. However, the uniqueness of the isotopic composition of water in the Caverns' pools suggests that rather than representing the composition of recent recharge, the heavy isotopes are enriched by evaporation and equilibrium isotope exchange in the humid cave environment. Recharge in the extreme karst environment near the cavern may also favor isotopically heavy precipitation. Therefore, the EEG suspects the interpretations from the Lambert (1987b) study regarding the age of Rustler water.

2.1.5.3.2 Radiocarbon Ages of Groundwater

The radiogenic age statement in section 2.2.1.4.1.2 of the CCA is based on Lambert (1987a). This report was reviewed for EEG by Dr. Fred Phillips of the New Mexico Institute of Mining and Technology in 1987 who found the conclusions of the report to be unacceptable for reasons described below.

While it is true that all of the samples (excluding H-5C, which may possibly be contaminated) are probably in the age range 10,000 to 16,500 years B.P., the ages of the water samples vary in a systematic fashion from youngest (10,000 years) in the north to oldest (16,500 years) in the south (with the exception of H-5, which is clearly on a different flow path than the other ^{14}C sampling

wells). This corresponds to the pattern expected from the north-to-south flow direction inferred from the physical hydrology. Thus a more reasonable interpretation of the ^{14}C age distribution is that only a segment has been sampled in the middle of a large-scale flow system. Additional ^{14}C samples to the north and/or east might well yield Holocene ^{14}C ages. Also, well H-5, although it may be contaminated, may also indicate active recharge.

The major conclusion of the report (Lambert, 1987a, p. 5-10 and 81) was, "Because of the questionable validity of the assumptions necessary in applying radiocarbon and radiochlorine dating methods in the evaporite environment of southeastern New Mexico, and because of the previously demonstrated susceptibility of these components to contamination in this groundwater system, these methods will not be pursued beyond this feasibility study." The EEG finds this conclusion to be unnecessary because good results have been obtained from uncontaminated wells. Ground-water systems are fundamentally not amenable to intensive sampling and thus in all ground-water investigations (whether physical or geochemical) assumptions regarding the system are necessary. Useful results can be obtained, even given a wide range in parameters assumed for the ^{14}C dating model. With a properly conducted field study of the system, the parameters could undoubtedly be constrained much more closely and much better refined dates obtained. Because interpreting WIPP site flow patterns by physical hydrology alone is very difficult and uncertain, and because ^{14}C tracing may hold the best hope of elucidating the flow system, the very negative viewpoint expressed by Lambert (1987a) is considered by the EEG to be totally unwarranted.

The contamination issue is even more clear cut. Certainly, it is true that a majority of the wells sampled during this study did not yield useful results due to contamination. One does not need to be an expert in ^{14}C to predict that wells crammed with "shredded paper, cottonseed hulls, peanut shells, and various proprietary organic additives" (Lambert, 1987a, Section 4.2.6) will not yield meaningful ^{14}C dates. There is very little logic in arguing that because wells deliberately injected with organic material were contaminated, all other wells must also be. Contrary to the statement by Lambert (1987a, p. 23), contamination during drilling is not "inescapable". The best evidence of this is that four of the wells drilled without organic circulation-loss additives did not show any sign of

contamination. There is no evidence that this groundwater system is unusually "susceptible" to contamination. Any system is susceptible to inappropriate drilling practices, and appropriate practices should yield acceptable results at the WIPP site.

Based on the data contained in Lambert (1987a), the EEG came to a different conclusion. In all cases, where ^{14}C could reasonably be expected to give useful results, it did so. Although there were only a limited number of uncontaminated samples, the geographic distribution of the resultant ages is hydrogeologically reasonable. The EEG advised the DOE not to abandon this potentially very informative avenue of investigation in 1987 and the EEG recommendation was incorporated in the 1988 modification to the DOE/State of New Mexico Consultation and Cooperation Agreement. However, the DOE did not pursue this investigation.

2.1.5.3.3 Uranium-Isotope Disequilibrium Data

The Lambert and Carter (1987) report was reviewed for the EEG by Dr. John Osmond in 1987. Dr. Osmond is the co-inventor of the Uranium-isotope Disequilibrium technique applied to the study of groundwater flow. Based on Dr. Osmond's review, the EEG provided comments on the Lambert and Carter (1987) report to the DOE through a letter dated 12/2/1987. The following is a summary of those comments.

The limitations of the application of uranium systematics to groundwater interpretations should be kept in mind:

1) one usually cannot deduce from the uranium data alone the **direction** of groundwater flow,
2) one usually cannot determine the **flow rate** of groundwater itself by the use of U-234 decay rates.

The same isotopic data can be used to model water flow in more than one direction. This is because changes in isotopic ratio can be caused either by true ageing (decay or growth of U-234) or by water-

rock or water-water interactions. Researchers in this field usually have independently derived information as to flow directions, which they can use to deduce the possibility of uranium leaching or the mixing of two or more groundwater sources.

Investigators can sometimes determine, in deep confined aquifers, the rate of movement of uranium in the system. The rate of flow of the water itself, however, must be inferred from one's estimate of the retardation factor for uranium in that particular aquifer.

That an aquifer is "confined" is usually an assumption of the modeling of slow-moving systems. Mixing with undefined waters, whether from recharge or other aquifers, negates any evolutionary conclusions. The authors of this report recognize the potential problem, but argue against leakage, perhaps too readily.

Finally, when uranium leaching or adsorption is inferred, it should be remembered that only the grain or fracture surfaces of the host rock are involved. The concentration of uranium on these surfaces can be much different than the concentration values of the whole rock.

Therefore, the principal conclusions of the report must be regarded as possibly overstated: 1) it is possible, but not proven, that the Rustler system can be modelled as a confined aquifer, 2) it is plausible that the flow regime has changed direction, but alternative interpretations based on a more steady-state model are readily visualized, and 3) although the inferred rate of movement of uranium through the aquifer near the site is probably about right, the flow rate of the water itself could be appreciably faster.

The basic pattern of occurrence of uranium isotopes in the Rustler ground water in the western half of the study area, as pointed out by the authors, is consistent with a two-source mixing model. These two end members could be water masses represented by H4 and W29, or by a water with very little U-238, but considerable excess U-234, that has leached to varying degrees uranium from the aquifer rock. The regression line on Fig. 15 implies that these two end members are leached uranium (infinite

concentration) with an atomic ratio of 1.55 and water of zero concentration of U-238 but carrying 13.4 ppb (U-238 equivalent) of U-234.

The authors make use of this pattern to make three different interpretations. Each interpretation is plausible to some degree, but taken together they are somewhat inconsistent.

The most logical has to do with a possible westward flow direction of water from the site toward Nash Draw. Low concentration water (with respect to U) gradually dissolves uranium with lower atomic ratio values. No information regarding flow rate derives from this model.

The least plausible interpretation assumes that the decrease in atomic ratio westward is the result of U-234 decay, which leads to deductions regarding low U movement rates (not necessarily low water flow rates). It is recognized by the investigators that such a model is suspect where uranium concentration values are increasing; leaching, if ignored, produces inferred flow rates which are too low.

The third interpretation is inconsistent with the first, so the authors postulate an earlier flow regime and ask as to why the atomic ratios are so high to the East. Such values depend on fractionation processes that often require time periods commensurate with the half-life of U-234, and therefore are nearly always down-flow. In this case, argue the investigators, the estimates of time are apt to be conservative because leaching would hold the atomic ratio values down.

In all of their modeling, the authors of this report display considerable knowledge and insight; they do not flagrantly misinterpret the data. Their assumptions are made clear. Nevertheless, one aspect of uranium isotope systematics in groundwater is neglected, and could affect their models. In any ancient system, uranium has been moving for much longer than the period of time being modeled. The distribution factor between dissolved and adsorbed uranium (related to retardation) means that any interactions between water and rock are probably independent of whole-rock uranium concentration values. It is the concentration of uranium on adsorption surfaces, rather than that

inside the rock particles, which determines how much fractionation occurs, and how fast relative to water movement. The concept of "reducing barrier" is often cited to explain concomitant decreases in U concentration and increases in atomic ratio over short distances.

The potentiometric contours of the Culebra suggest two flow lines in the study area: to the west, flow is more or less directly south; in the general area of the site, however, there appears to be an easterly flow in the north, a southeasterly flow at the site, and a southerly and westerly flow to the South.

If we postulate a general source area anywhere to the North, with the usual reducing barrier not far from the point of recharge, then all of the water would enter the area with a high atomic ratio and a low concentration. Water flowing southward in the west would dissolve uranium and take on the higher U and lower atomic ratio fingerprint. Water flowing in the east would move slower, dissolve less uranium, and have its atomic ratio altered only gradually with time. When the flow looped west, dissolving and "mixing" with rock-derived uranium would occur.

This scenario combines the three models proposed by Lambert and Carter (1987): mixing in the west and southwest, increasing atomic ratio due to recoil-type fractionation in the north, and decay of excess U-234 in the general area of the site. If this model has merit, we can deduce uranium movement rates in the aquifer near the site which are consistent with those values proposed by the investigators. Because of the retardation factor, the water flow rate could be higher.

All of these remarks concern the Culebra unit of the Rustler. There are not enough data from the other units to do any regional modeling. However, the fact that none of the atomic ratio values from above and below are as high as some from the Culebra suggests that the latter is the "tightest" with respect to uranium mobility.

Apparently the data regarding oxidation potential of the Culebra waters is inconclusive; and the same might be said about the other hydrologic and geochemical information that might be used to

demonstrate that the Culebra is truly confined. Uranium isotopic data has often been used as evidence in such interpretations. Most deep confined aquifer waters carry uranium at very low concentration levels, on the order of .1 to .001 ppb., and with quite high atomic ratio values, anywhere from 2 to 20 or more. The Culebra waters have higher uranium concentration than do truly reducing aquifers suggesting the possibility of leakage from shallower horizons. However, the fact that the isotopic data can be used to model flow in systematic ways suggests that such invasions are not the predominant process. Any such oxidative tendencies would favor interactive models (uranium leaching) over the fractionation and time-related models emphasized by Lambert and Carter (1987).

Regarding flow rates and groundwater residence time, Lambert and Carter (1987) consistently confuse *uranium* residence time with *groundwater* residence time. The data presented in the report do not allow for the calculation of groundwater ages. Even when the appropriate retardation factors and grain and fracture surface characteristics are known, there are still serious questions about applying uranium isotopic data to determine basic groundwater flow characteristics. Davis and Murphy (1987), Simpson et al (1985), and Hussain and Krishnaswami (1980) all express serious reservations about the reliability of uranium-disequilibrium dating because of the many difficult-to-substantiate assumptions involved.

The amount and reliability of the data are also questionable. Outside of Nash Draw, the authors have only four wells on which to base conclusions of changes in flow direction. It is important to consider the dual-porosity nature of the Culebra, indicated by the recent hydrologic testing. The very high activity ratios at H-4 and H-5 may be related to the low-transmissivity, matrix flow found at those wells. Conversely, the lower activity ratios at H-6 may be the result of rapid groundwater flow through fractures. More data east of Livingston Ridge, and from fracture-flow areas such as near H-11 and DOE-1 must be collected before any confidence can be placed in conclusions about flow paths.

Considering the serious questions of groundwater contamination in Nash Draw raised by Lambert

(1987a), there should be an in-depth discussion of the reliability of the presented analyses of a trace constituent like uranium. If contamination with organics is as pervasive in the Nash Draw wells as reported in SAND86-1054, this would very likely alter redox conditions near the wells. Oxidation-reduction potential is an important control on uranium content. Though the authors state on page 6 that the uranium values and isotope ratios have been perturbed at W-29 by wastewater dumping, they then proceed to use this value throughout the report, for instance as an important part of their argument for recharge in southwest Nash Draw.

As previously mentioned, redox conditions are an important factor in modeling uranium behavior. Field evidence (Eh values as reported in Uhland and Randall, 1986 and Uhland et al, 1987) and the relatively high uranium values both argue against reducing conditions in the Culebra. There is no evidence for the "reducing barrier" required by Lambert and Carter's model. The authors should provide some discussion of the physical requirements of the model relative to known aquifer characteristics.

The section on "Implications" for recharge, karst flow, and climate change presents insufficient discussion for reaching the presented conclusions on this broad topic. For instance, if no recharge is supposed to be occurring, there should be some discussion of what happens to rainfall. There is no integrated surface drainage, there are numerous gaps in the Mescalero caliche, and 20 inches of annual rainfall has been common the last few years. The role of southwestern Nash Draw (SWND) is another point requiring additional discussion. The authors present contradictory hypotheses in this section. Lambert and Carter's item number 2 on page 45 says SWND is a recharge area, while item number 4 on page 46 calls for discharge in that area.

Contradictory statements are also made regarding the degree of vertical interconnection in Nash Draw. Item 5 on pages 46 and 47 (Lambert and Carter, 1987) argues that the Magenta and Culebra are freely connected at W-25 and W-27 (as previously discussed in Chaturvedi and Channell, 1985, though overlooked in Lambert and Carter's references). However, item 4 on page 46 argues that recharge to sinkholes in the Tamarisk member cannot be interpreted as providing recharge to the

Magenta or Culebra. Are the authors proposing that the Magenta and Culebra are well-interconnected, but not the intervening Tamarisk? Some discussion of this extraordinary hypothesis is warranted. Likewise, more discussion must also be provided of the author's assertion that the dominant process at W-33 is alluvial infilling. The continued presence of this large depression, even after the springs have ceased to flow, argues against infilling at the surface. We are not aware of any evidence or studies that support the author's statement.

In light of the above comments on the Lambert and Carter (1987) report, all the assumptions arising from the conclusions of that report should be reexamined.

2.1.5.4 Effect of Clays in the Culebra

While the CCA does not assume clay lining in the fractures of the Culebra, the concept of the existence of clays, specifically the clay mineral Corrensite in the Culebra is mentioned in several documents of the proposed rule. Some discussions of this issue refer to the decision to not assume the fracture linings coated with Corrensite to be a conservative decision. It is therefore important to demonstrate that the presence of Corrensite in the Culebra fractures is only a myth without any basis in fact, as described below.

The Corrensite hypothesis is based on the X-Ray Diffraction and Analytical Electron Microscopy analysis of samples collected primarily from clay rich layers of the Rustler Formation from cores of wells drilled primarily in the Nash Draw. Four reports are cited to support this conclusion. These reports are based on the work of Terry Sewards and others at the University of New Mexico under contract to the Sandia National Laboratories.

Sewards, et al. (1991a) contains mineralogical analysis of core samples from a single well, WIPP-19, and presents no claim for clay filled fracture linings in the Culebra.

Sewards (1991) presents data on the "whole rock" as well as the "fracture surface" compositions of samples of cores collected from 6 wells (WIPP-26, 27, 28, 29, 30, 32) in the Nash Draw, one

borehole (WIPP-33) between the Nash Draw and the WIPP site, and three boreholes (WIPP-12, 13, and 34) in the northern part of the WIPP site. Clays are expected to be present in the Nash Draw cores because of extensive dissolution, weathering, and erosion in that area. WIPP-33 is located in a sink hole and processes similar to Nash Draw have operated there as well. Boreholes 12, 13 and 34 are located north of the WIPP repository and upstream from the direction of flow of water in the Culebra. Furthermore, the cores from these wells were selected from known clay seams. For example, the only sample from WIPP-12 (CS-1) came from the zone 838.5 to 838.7 ft below the surface. The Basic Data Report for WIPP-12 (Sandia, 1982) identifies mud seams at 837.7 and 840.7 ft depths.

Three Sandia National Laboratory scientists (Sandia, 1992, pp. A-127 to A- 131) correctly evaluated the Sewards (1991) report and stated the following:

> "Sewards (1991) measured and reported clay abundance for eighteen Culebra samples; thirteen from locations to the north and/or west of the WIPP site, and five from the north end of the WIPP site. None of these samples was from wells along fast transport paths. Because Sewards (1991) was focusing on clay abundance and compositional analyses, it is likely that samples were selected for analysis based on visual appearance of clays. Thus, these data may not be representative of clay abundance on fracture surfaces in the area of interest for transport modeling." (Sandia, 1992, Memo from Craig F. Novak, et al. to Martin S. Tierney, p. A-127 to A-131).

Having made this statement, it is surprising that the authors of the memo, Messrs. Craig F. Novak, Fred Gelbard and Hans Papenguth, nevertheless recommended assuming the probability of the existence of relative thickness of clay linings in the Culebra fractures to be as high as 0.5.

Sewards et al. (1991b) presents mineralogy of 107 samples collected from the cores of 8 wells, 3 of which are located within the WIPP site. However, clay fraction separates (<2 microns) were obtained

for only three samples: "WIPP-12 #3, a clay-poor dolomite; WIPP-12 #16, a clay-rich dolomite; and H6B #3, a shale." X-Ray Diffraction analysis was performed on the clay fractions from these three samples, and one sample (H6B #3) was analyzed under the electron microscope. The electron microscopy on this one sample casts doubt on the accuracy of the X-Ray Diffraction technique used:

> "There is, however, a discrepancy between the results of the quantitative XRD analysis and the results of the AEM investigation of sample H6B #3. In that sample, the XRD results show that the sample contains approximately 50% corrensite. When imaging was attempted on the AEM, it was extremely difficult to find any corrensite at all; the dominant phases appeared to be serpentine, illite, and chlorite." (Sewards et al., 1991b, p. VII-19).

The conclusion of this report, quoted below, clearly demonstrates how very limited information has been used to make important interpretations:

> "The fact that corrensite is the dominant phase in the Culebra samples is important. Corrensite has a high CEC and high surface area, thus it is able to sorb radionuclides very efficiently in the event of a low pressure breach in the WIPP facility. Although the clay minerals of only three samples were investigated, the results of Sewards et al., 1991 show that mixed-layer chlorite/smectite is the dominant clay phase throughout the Rustler Formation, so it is reasonable to suggest that the same is true in the Culebra unit." (Sewards et al., 1991b, p. VII-19).

Sewards et al. (1991) mentioned in the above quotation, is Sewards et al. (1991a) of this review, i.e., "Mineralogy of the Rustler Formation in the WIPP-19 core". As stated earlier, that report makes no claim for clays lining the Culebra fractures. Corrensite is only interpreted to be present in some of the samples, as one mineral among many, when powdered bulk samples were analyzed through X-Ray Diffraction. How can this observation lead to the statement cited above?

The final report by Sewards (Sewards et al., 1992), presents mineralogical analysis from 47 samples. Of these, 17 samples were taken from the Culebra, and of these only 9 are from the WIPP site - 6 from the Air Intake Shaft and 3 from WIPP-12. The report states the following with respect to the existence of clay in the fractures of the Culebra Samples:

> "Only small amounts of clay can be sampled from the Culebra fracture coatings; therefore, initial technique and model development for adsorption studies on WIPP clays (Park et al., in review) were carried out with material from a black shale layer in the unnamed member. This material, so-called CorWIPP, is 94% corrensite and is described as Sample AIS-15 in this report. Corrensite has a high cation exchange capacity and affinity for the uranyl ion in dilute solution (Park et al., in review) and could provide significant radionuclide retardation in fractures in the Culebra." (Sewards et al., 1992).

The above quotation clearly identifies the problem with using Terry Sewards' work to conclude that corrensite clay lined fractures in the Culebra may provide retardation for radionuclide migration through the Culebra. The argument is based on a sample from a "black shale layer" obtained from the lower part of the Rustler Formation, below the Culebra, because not much clay could be sampled from the Culebra fracture coatings! And yet, this information is used to argue that "significant radionuclide retardation in fractures in the Culebra" could be present.

Any reference to the existence of corrensite or other clay minerals lining the fractures in the Culebra Dolomite member of the Rustler Formation at the WIPP site should be deleted from the project documents because there is no basis for this assumption.

2.1.5.5 Culebra Geochemical Facies

The EEG has raised the issue of the inconsistency between the inferred direction of flow in the Culebra aquifer and the chemistry of water since the early 1980s and has published three reports on the subject. The issue was first raised by the EEG in 1983 as follows:

> "The unexplained decrease in TDS and a change in the general chemical nature of the Culebra water from sodium and chloride at the site to magnesium, calcium, and sulfate south of the site indicates that insufficient data are presently available to adequately characterize the flow system south of the site." (Neill, et al., 1983, p. 79).

Ramey (1985, Fig. 7) elaborated on this issue and presented the concept of geochemical zonation of the Culebra water. Chapman (1988) further explored the problem and provided a hypothesis to account for the decreasing total dissolved solids in the direction of flow, as follows:

> "As groundwater moves from north to south across the area, the Total Dissolved Solids (TDS) decrease by an order of magnitude and the major hydrochemical facies change from Na-Cl to Ca-SO_4. The only plausible mechanism to effect this change is the influx of a large quantity of low TDS water. The possibility of recharge in the southern area is enhanced by the presence of solution and fill features such as the gypsum caves in the Forty-Niner Member of the Rustler near the Gnome site. These features could behave as conduits supplying fresher water to deeper Rustler units." (Chapman, 1988, p. iv).

The Siegel et al. (1991) report was prepared following a suggestion by the EEG which was incorporated as a requirement of the DOE/State of New Mexico Agreement for Consultation and Cooperation.

The EPA proposed rule mentions this issue (U.S. EPA, 1997c, p. 58799; U.S. EPA 1997b, CARD 14-28; and U.S. EPA, 1997f; U.S. EPA, 1997g, p. 82), but simply cites the additional information provided by the DOE (Docket Item II-I-31) and the conclusion that “it was sufficient to explain Culebra geochemical facies within the WIPP area” (CARD 14-28). No discussion of the new hypothesis and the EPA conclusion is provided. There is also no discussion of how the new conceptual model may effect any assumptions made in the containment requirement compliance calculations.

2.1.5.6 Rustler/Salado Contact Hydrology

The EPA has accepted the CCA contention that the Rustler/Salado contact groundwater zone does not underlie the WIPP site (U.S. EPA, 1997b, CARD 14-21; U.S. EPA, 1997g, pp. 87-88). As pointed out by Chaturvedi and Channell (1985) and Neill et al. (1996, p. 2-3), this assumption is not correct. Most of the WIPP boreholes have found brine in the Rustler/Salado contact zone (see Mercer and Orr, 1979; pp. 10, 46, 63, 77, 98, 104, and 113) within the WIPP site. In fact, according to Mercer and Orr (1979, p. 120), in at least one borehole (P-18), the water-level recovery rate after pumping from this aquifer was much faster than the Culebra recovery rate.

2.1.5.7 Culebra Water Level Rises

Anomalous rise in water levels has been noted in a number of bore holes completed in the Culebra aquifer at and around the WIPP site. No satisfactory explanation has been provided for this phenomenon. This issue is briefly mentioned by the EPA (CARD14-21 and 14-78 and TSD III-B-3, p. 78 and 82), but has been dismissed from further consideration by the following statement:

> Although some water level changes are not yet explained, EPA believes that these are accounted for in the head uncertainty captured by the PA (CARD 14-78).

The TSD III-B-3, page 82 has a similar statement without further explanation. The EEG has examined the validity of this statement and found it to be incorrect. Additional discussion of this issue can be found in Section 2.6.7 of this report.

See Section 2.9 of this report for response to the proposed rule discussion of the lack of contribution to total releases from the ground-water pathway (U.S. EPA, 1997c, p. 58799).

2.1.6 Brine Reservoirs

See Section 2.11 for a discussion of the Castile brine reservoirs parameters used in the CCA and PAVT.

2.2 SUMMARY OF PA SENSITIVITY ANALYSIS (EEG-69)

The sensitivity of the performance assessment calculations of the CCA was first investigated by Helton (1996) in order to understand the relationship between several key parameters. His analysis used scatter plots and stepwise correlations to determine consistency among repository parameters. One weakness in the sensitivity analysis of Helton (1996) is that the sensitivity to parameters only applies to the actual range and distributions of sampled parameters used in the CCA calculations. Changes to either the range or distribution of one parameter may strongly affect the importance of other parameters, because release estimates vary by orders of magnitude for different combinations of parameter values. A case in point is the brine reservoir compressibility, which has been determined to have insignificant influence on the total release. The brine reservoir pressure and reservoir volume characteristics used in the CCA calculations reduce the importance of the brine reservoir to the calculated releases. It is entirely possible that the brine reservoir would be one of the most important contributors to large releases in calculations using more appropriate characteristics.

The limitations of the sensitivity analysis performed by Helton (1996) prompted the EEG to conduct their own analysis, by changing selected values or the range of selected values that were used in the CCA. This type of sensitivity analysis would truly distinguish the important parameters of repository performance, while testing the robustness of the codes involved. The analysis also allowed for the testing of the limit to which the disposal system would fail under extreme conditions. This is also useful in characterizing the important parameters.

2.2.1 Borehole Intrusion Rate

The consequence of future human intrusion scenarios into the Waste Isolation Pilot Plant was investigated in the CCA (U.S. DOE, 1996c). These scenarios were firmly established by EPA guidelines in 40 CFR Part 194 (U.S. EPA, 1996), and included the possibility of mining and deep and shallow drilling for resources.

The guidelines state in 40 CFR Part 194.33 that the likelihood of a drilling intrusion into the Delaware Basin must be calculated by considering the frequency of drilling over the past 100 years for all resources using a rate to be determined for the entire future of the WIPP. These numbers were calculated in the CCA, Appendix DEL (Tables DEL-3 through DEL-7) and were used to calculate the Complimentary Cumulative Distribution Function (CCDF) curves for the performance assessment calculations of the CCA. A total of 46.8 boreholes per km^2 per 10,000 years were estimated based on past drilling of resources at depths greater than 2150 meters, which equals 10804 boreholes per year in 23,102.1 km^2 (area of Delaware Basin).

The drill intrusion rate for the 10,000 year future of the WIPP was directly implemented in the CCDFGF model, and was calculated to be equal to 0.00468 boreholes/km^2/yr. However, future human activities are uncertain, and the rate was changed to test the effects on the CCA calculations.

The modeling associated with an increased borehole rate shows that a factor of approximately 23 is needed to reach the EPA release limit at a probability of 10^{-1} from values used in the CCA. The overall mean for the highest release tested, 4.68×10^{-1} boreholes/km^2/yr, exceeds the EPA limit of 10 EPA units at a probability of 10^{-3}. This does not seem to be likely, as the number of boreholes drilled in the Basin per 10,000 years would have to exceed one million, or 4,680 boreholes per km^2.

2.2.2 Probability of Brine Encounter at WIPP

The probability of encountering brine at the WIPP from an intrusion into the Castile Reservoir is uncertain. The probability was set to 8% in the CCA, and changed to a range of probabilities from 1% to 60% in the EPA's PAVT. However, the extent of the reservoir beneath the WIPP is unknown, and the influence of this parameter was tested at higher values at 50 and 100%. These values were based on the potential that the Castile reservoir size encountered by WIPP-12 (Chaturvedi et al., 1997) extends below the waste area.

The modeling only compared CCA values to the higher probability of encounter, and found the parameter to be unimportant in the CCA. The increase in releases from the 8% to 100% was only 0.1 EPA units (35 Ci). However, the synergistic affect of changing multiple parameters, especially those that affect the Castile Reservoir directly (pressure, volume, rock compressibility, etc.) may have a more profound result on the calculations, though these changes would have to result in releases of at least 1 EPA unit to significantly impact the CCDFs.

2.2.3 Castile Brine Reservoir Parameters

The pressurized Castile brine reservoir that underlies the Waste Isolation Pilot Plant has been the subject of many controversies on its extent and importance (Neill 2/7/97 and 3/14/97 in Appendices 8.1 and 8.2; Silva, 1994; Dials, 1997c; Beauheim, 1997). The performance assessment calculations of the CCA recognize the fact that the brine could play a significant role in the degradation of wastes and waste container, if an inadvertent drilling intrusion were to pass through the repository to the brine pockets below, by assigning two of the six scenarios to calculate the effects of the breach. However, the characterization of the parameters associated with the reservoir were undermined by associating them to data that clearly lies outside of the domain of the repository. The more realistic parameter values proposed by the EEG could potentially demonstrate higher direct brine releases to the surface, affecting the compliance with the containment requirements in the EPA standards of 40 CFR 191.13. Calculations were performed using more reasonable parameters for the simulation of Castile brine migrating into the repository.

Reservoir parameters used in performance assessment calculations were derived from well information that lies mainly outside the domain of the WIPP repository. The well distances ranged from 6 km (3.75 miles) to over 17.6 km (11 miles) away from the repository center. New values were assigned to several parameters that describe the Castile brine reservoir based on WIPP-12 data that is more closely identified to the conditions at the repository. The WIPP-12 is located 2 km (1.2 miles) north of the repository. The well was originally drilled in 1978 and deepened in 1981 at the request of the EEG, and was the cause for the repository to be moved south after brine was encountered in the well. The well was recorded to have experienced brine

flow when coring reached a depth of 918 meters (3012 feet) (D'Appolonia, 1982). While extending the well to depths greater than 1189 meters (3900 feet), a total of 80,000 barrels (3.36 million gallons) were allowed to flow from the well.

The parameters associated with describing the Castile brine reservoir include reservoir volume, rock compressibility, reservoir pressure, and permeability. The modeling of these parameters began with the two-phase flow code, BRAGFLO, and ended with calculations of solid and liquid waste released due to an inadvertent human intrusion. The outcome showed that there is no significant change in releases for the CCDF due to small changes in the reservoir parameters. However, it is expected that the CCDF curve would move closer to the EPA limit if the solubility of actinides in brine were increased above that assumed in the CCA and PAVT.

2.2.4 Solubility Modeling of Actinides

The solubilities of actinide species at the WIPP in brine solutions are of concern, especially since limited experimental evidence exist (if any at all) on the amount of each species in solution. In some instances, weak analogies are used between species with the same oxidation state to infer a "better" value than would be achieved through actual experiments. Other cases used, in what seemingly appears as a flaw in a model, absurd calculated solubilities. To bound the uncertainty in the values chosen for solubility, the CCA invokes a range from the median value assumed (U.S. DOE, 1996c, Appendix PAR) of 2 orders of magnitude below and 1.4 orders of magnitude above. For example, the solubility for the +3 actinide, which was inferred from Americium data, had a median value of 5.82×10^{-7} M, and ranged from 5.82×10^{-9} to 1.46×10^{-5} M. The distribution to the range was log-cumulative, where most of the values (59%) fall between -1.0 and 0.0 orders of magnitude from the median.

Due to the uncertainties, further modeling by the EEG was conducted on brine movement from the repository under inadvertent human intrusion scenarios. If the actinide species are readily soluble, the brine could be an important mechanism to release a significant portion of actinides to the accessible environment.

For brine to escape the repository and travel upwards through the borehole under blowout conditions, 1) pressures must be significant to overcome the hydrostatic force of the drilling fluid, and 2) sufficient brine must be available for transport. Both conditions have been met in many of the realizations in the performance assessment calculations of the CCA. However, due to the assumed low solubility of actinides in brine, the consequence of a direct release of brine to the surface was minimal. For example, the mean release of radionuclides in the CCA through a direct brine release was 0.04 EPA Units (14 Ci) at the 10^{-3} probability, compared to spallings or cuttings and cavings, each having releases of 0.2 EPA Units (70 Ci).

The physical and chemical aspects of the repository were challenged by the EPA in an evaluation of the CCA, called the Performance Assessment Verification Test (PAVT). The EPA changed several parameters for the disposal system to test the uncertainty associated with the range of uncertainty in the parameter values. The test merely evaluated several parameters that could have significant affect on compliance, changed them to different numbers found to be more reasonable by the EPA, and reran the calculations. Some changes involved the solubility of the actinides in a brine solution by assuming a different speciation of minerals associated with the MgO backfill material, which lowered the median solubility limit for most actinides. The new set of solubility values came from the same flawed code used to establish the original set of numbers, and no new experiments were conducted to verify any of the values.

The results of the PAVT showed a large overall increase in the amount of brine to the surface upon intrusion, yet only nominal increase in release of actinides. This was expected, since the median solubilities were decreased by the EPA to be as much as 2 orders of magnitude for the +4 radionuclides. The effect on compliance from the changes shifted the CCDF for the direct brine release scenario closer to the compliance limit by 0.15 EPA Units. The changes are minimal, since 10 EPA units of release are needed to fail compliance at the 10^{-3} probability.

The problems with both models of the CCA and PAVT prompted the EEG to conduct bounding calculations on solubility. The first set of model experiments assumed that the Plutonium was of the +5 oxidation state, and used +6 values based on the work by Reed et al. (1994), Reed et al.

(1996), and Rao (1996). The values were only nominal increases above the CCA values for Plutonium in the +3 or +4 oxidation state for Salado Brine, but upwards of 10000 times for Castile Brine.

The modeling changes began with input files of the source term for PANEL. The changes were quite easy, and the analyses were complete in a matter of hours. The results showed that increases in solubility with CCA brine release volumes had limited effect on compliance with an overall increase on the mean CCDFs by 0.09 EPA Units. Even when the solubility was pushed to absurdly high values, the maximum release was limited by the availability of the actinide source. At a solubility of $8x10^{-3}$ M (compared to the CCA's $4.4x10^{-6}$ M for Pu+4 in Salado brine), the overall mean for direct brine release was increased from 0.04 to 1.3 EPA Units.

The second set of modeling experiments took the extreme position of assuming the solubilities of all actinides in different mineral species of MgO between the conversion of brucite to magnesite. In particular, calculations by Novak (1997) show values of actinides in the presence of magnesite, nesquehonite, hydromagnesite, and no backfill. CCA calculations assumed the long-term mineral species for MgO to be magnesite, and the PAVT assumed hydromagnesite. Yet, experiments could not prove the existence of either, and only showed hydromagnesite-like or proto hydromagnesite (Sandia, 1997). These other mineral species looked more like nesquehonite, and it seems difficult to justify the presence of either mineral phase assumed by the DOE and EPA.

Bounding calculations were performed on conditions resulting in the highest solubilities in the repository. These included nesquehonite and no backfill. For the nesquehonite simulations, it was assumed that the mineral would persist for the entire proposed history of the repository, and only median values were used. The assumption of the long-lived intermediate species is an overestimate on the expected conditions, to better understand performance of the repository. behavior. Similarly, calculations without the MgO backfill are intended to better understand the repository behavior.

Table 1 shows the solubility factors used to achieve solubility values from Novak (1997). The values have been log transformed for use in the input files to change the values that were established in the CCA. For example, SOLAM3-SOLCIM for nesquehonite increases the solubility of Am+3 in Castile Brine by 1.516 orders of magnitude, whereas SOLAM3-SOLSIM decreases the solubility by .277 orders of magnitude. The changes were made in the source term files, for running of PANEL and NUTS.

In addition to solubility changes from the CCA, the Salado transport files from the PAVT were used for transport calculations of NUTS and PANEL. The PAVT calculations exhibited higher repository pressures, hence larger direct brine releases upon intrusion. The maximum effect would be noticed with both changes together.

One curious observation from Table 1 shows that the solubility of nesquehonite in the +4 oxidation state (Pu+4, U+4, and Th+4) is higher than would be the case without any MgO backfill. Yet, one must keep in mind the context of these number, and remember that they are simply computer generated numbers, which are under much scrutiny. They do however provide a reference point in which compliance can be studied. If it is found that actual experimentation leads to solubility values less than those of Table 1, but slightly higher than the CCA values, one can interpolate compliance releases from existing CCDFs on probabilities and releases.

	Nesquehonite		No Backfill	
	SOLCIM	SOLSIM	SOLCIM	SOLSIM
SOLAM3	1.51616	-.27709	4.48678	3.83714
SOLPU3	1.51616	-.27709	4.48678	3.83714
SOLPU4	5.23242	2.15588	4.06695	2.05552
SOLU4	N/A	2.15588	N/A	2.05552
SOLU6	0.95861	0.96357	0.95861	0.96357
SOLTH4	5.23242	2.15588	4.06695	2.05552

Table 1. Solubility Factors for SOLCIM and SOLSIM

The results of running new solubility values can be seen in Figure 2. The figure shows the overall mean of all processes combined as they relate to compliance. In addition, the PAVT direct brine releases were run with the slightly higher CCA solubilities. The most distinct feature of the figure is the shoulder of the high solubility models that extend below the 10^{-1} probability limit. The "shouldering" is the effect of increased releases due to the direct brine release. Since the Pu+4 and Th+4 (although minor) solubilities increased over 5 orders of magnitude, the release due to this mechanism is expected to increase significantly as well. For example, the CCA median value for +4 actinide solubilities in Castile brine was $6x10^{-9}$ M. If one assumes 100 m^3 of Pu^{239} brine, then it is expected that the release is $2.5x10^{-5}$ EPA units. If the solubility is increased by $10^{5.23}$ as seen in Table 1., then it is expected that 4.24 EPA units are released to the accessible environment. Therefore, the CCDF for higher solubilities would be closer to the EPA limit.

The consequences of higher solubilities, as seen in Figure 2 are quite high. The overall mean

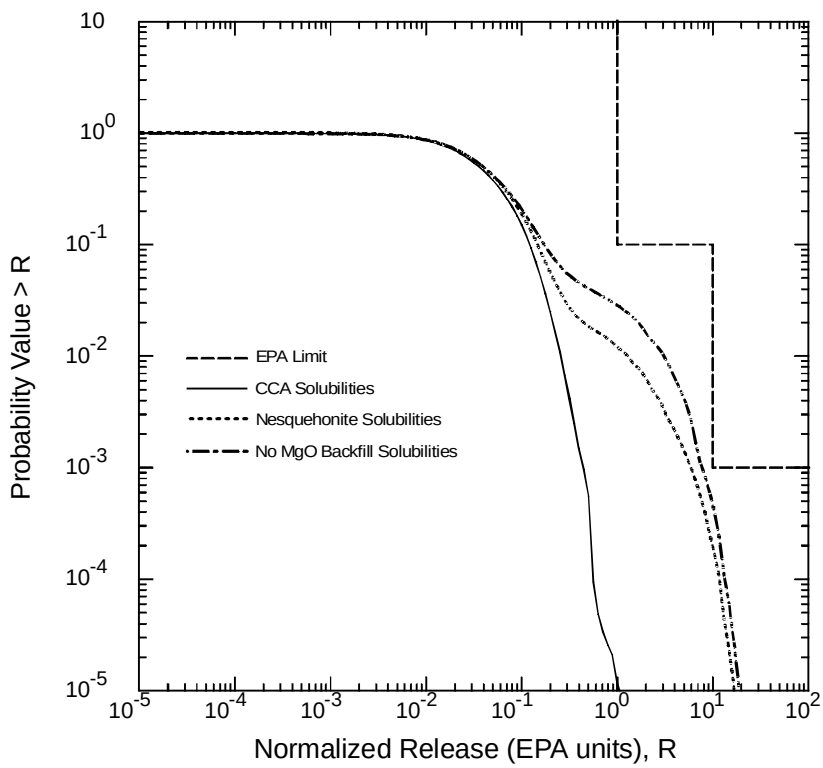

Figure 2. Overall Mean of Normalized Releases for Modeling of increased solubilities using Nesquehonite and 'No Backfill' Values compared to CCA values.

release for the CCA and PAVT were 0.2 and 0.4 EPA u at 10^{-3} probability, respectively. The overall mean for the increased solubilities of nesquehonite and 'no backfill' are 6.0 and 8.0 EPA units at the 10^{-3} probability, respectively. The limit for compliance, according to 40 CFR Part 194 is 10 EPA units. Therefore, it appears that even high solubility values do not cause the disposal to be out of compliance with the EPA regulations. However, there is a deeper issue that one cannot dismiss, that is far less superficial than the previous statement. It deals with the consequences in small changes of solubility and variability in the actual values. Are we so certain that the solubilities of Plutonium or Uranium, in any oxidation state, are less than the values presented in the CCA or the PAVT? How did we arrive at these numbers? Are there experimental evidence to back up the claims made in the CCA that deals with the oxidation state analogy between Am+3 and Pu+3? Once one really delves into the reasoning behind many of the fixed numbers associated with these actinides, many deficiencies appear in the reasoning, and confidence in the values used to show compliance declines.

2.2.5 Flow and Transport Modeling within the Culebra

The transport of radionuclides to the accessible environment can occur in two ways: upwards from the repository through a borehole to the surface into the biosphere, or laterally through the stratigraphy of highly conductive layers across the Land Withdrawal Boundary (LWB). The second method was investigated by modeling the Culebra aquifer of the Rustler. The CCA and PAVT include Culebra modeling and its consequence of transport across the LWB in the CCDF curves. The CCA showed only 1 of 300 realizations to cross the boundary in 10000 years, with the PAVT showing a significantly higher impact on the Culebra. The end result of increased transport across the LWB in the PAVT had little to no effect on the CCDF.

EEG's concern about of the modeling of the Culebra begins with the assumptions used in parameters that describe actinide behavior with the Culebra dolomite. When the actinides are directed along flow paths after a release to the Culebra, the transport will be retarded by the interaction of the actinides with the Culebra matrix. The interaction is known as sorption (either absorption or adsorption, and is usually non-reversible), and different types of sorption, called isotherms, describe the interaction between the two constituents. The Culebra was characterized

as having a linear isotherm with the actinides, and the parameters of the isotherm, known as the partition or distribution coefficient (K_d) were measured in laboratory experiments.

The same oxidation state analogy used to predict similar solubility of actinides was applied to the distribution coefficient. Therefore, many of the actinides' K_ds were not actually measured and it is not clear what the consequence would have been with better values. Though it is well known that high K_d values will retard the actinide species sufficiently to inhibit transport, it is the low K_d values that are of concern. For example, it was shown by Blaine (1997) that K_d values higher than 3 ml/g for most actinides would sufficiently retard transport, and an insignificant portion of the actinides would cross the Land Withdrawal Boundary. Only one actinide in the PAVT, U+6, has K_d values as low as 2 ml/g.

It is also well known that some waste constituents in the WIPP inventory will bind themselves to the actinides to further lower the K_d values. EDTA, for example, is used to bind with Plutonium for cleanup purposes. Other organic ligands in the waste will have similar effect. Furthermore, the lack of measurements decrease the confidence in values used in the CCA and PAVT, and this prompted the EEG to continue with additional calculations, testing the effects of lowered K_ds on the disposal system and compliance.

The interaction between releases from the repository and transport of actinides require a lengthy discussion, and will not be discussed here. It is possible, due to the set up of the codes, to do calculations that assume any percentage of the actinide's mass to completely bind with EDTA and migrate unretarded through the Culebra matrix. Therefore, additional calculations were performed assuming 1% of Pu (+3 and +4) having a K_d=0 ml/g.

The results of the calculations show that the overall mean of the releases through the Culebra was 0.0001 EPA Units at the 10^{-3} probability. Since a large number of realizations crossed the LWB with significant releases, it was reasoned that the mass of radionuclides reaching the Culebra was the limiting factor. This was proved when the models of higher solubility were combined with transport modeling, and the overall mean for release from the Culebra was increased to 0.31 EPA

Units.

Another model was proposed in which the extent of potash mining within the controlled area Land Withdrawal Boundary was extended to include lower grade potash ore. Potash mining occurs in the McNutt Potash Zone of the Salado, which is about 200 meters below the Culebra. The effect of potash mining in the Delaware Basin would cause subsidence to the overlying units, and hence having a possible detrimental consequence from increased transport of radionuclides. The CCA established the criteria for considering the effect of mining by assigning a multiplying factor to the transmissivities of the Culebra, which increased the velocities above the mined region.

The extent of mining is debatable, and depending on which map is used determines the possible economic viability of the resource. In addition, new methods of mining such as solution mining could extract lower grade minerals more readily. Therefore, the EEG included a larger area of mining in a new flow model, yet keeping the same parameter changes that were used in the CCA. It is feasible to change other parameters or include new ones, but due to the limited time available to the project, this was not thoroughly investigated.

The results of extending the areal minable region within the Culebra had little to no effect on the transport of radionuclides across the Land Withdrawal Boundary, though it did change the flow patterns slightly. The limit of transport is sorption, and the PAVT values for K_d were retained for Uranium. The combination of low K_d and larger mining area was studied with Plutonium, again using the 1% K_d=0 ml/g. Again, the amount of initial mass injected to the Culebra crossing the Land Withdrawal Boundary was significantly higher, but limited by the amount reaching the Culebra.

Lastly, the combined effect of extended mining, low K_ds, and high solubilities were combined in an effort to test the synergistic effect of all the previous results. The overall mean for the release

through the Culebra was as high as 1 EPA Unit (or 350 Ci). The addition of the Culebra releases to the overall mean of all combined releases moved the CCDF closer to the EPA compliance limit by 12%.

2.3 ACTINIDE SOLUBILITY

2.3.1 Introduction

Except for the final performance assessment submitted to EPA (U.S. DOE 1996c), actinide solubility had always been identified as one of the key parameters in calculating the 10,000 year performance of the repository. During the early efforts to develop the performance assessment, it was quickly recognized that there was a dearth of actinide solubility data for anticipated conditions of high salinity and high pH for the complex heterogeneous waste chemistry. Moreover, a reliable estimate of the solubility could not be calculated due to the lack of thermodynamic data (Brush and Lappin, 1990). Nonetheless, the development of the PA codes required some estimate for the range and distribution of solubility values for the each of the actinides. In lieu of data, the early PA calculations used a solubility range and distribution recommended by Brush (1990). The solubility of each actinide was assumed to have a log uniform distribution from 10^{-9}M to 10^{-3}M with a median value of 10^{-6}M. However, the PA effort was cautioned about the limited use of these values (Brush, 1990; Brush and Lappin, 1990).

Brush's 1989 estimate of radionuclide solubilities, 10^{-6}M with a range of 10^{-9}M to 10^{-3}M, were a source of concern for another reason. The relatively high values suggested the possibility of significant releases when used in radionuclide-transport calculations (Brush, 1990). There was also concern about the wide range of estimated actinide solubilities. Brush noted that it would be desirable to narrow the range as soon as possible and advocated continuing the ongoing experimental work which would require another two or three years to obtain enough data for comprehensive calculations.

Meanwhile, for the 1991 and 1992 PA, Sandia National Laboratories conducted an elicitation in which four outside scientists collaborated to estimate the median value and range of solubility for each actinide in each oxidation state. However, the results of this exercise did not narrow the range. The estimated range of solubilities expanded from six orders of magnitude to twelve orders of magnitude depending on the actinide and the oxidation state (Sandia, 1991, Vol. 3, pp.

3-62 to 3-66). Moreover, the expected actinide concentrations were much less than those estimated by Brush. For example, the median solubility value for the Pu^{IV} and Pu^{V} decreased by more than three orders of magnitude to 6×10^{-10}M. Not only were the new values lower, this median value was not even in the range recommended by Brush. At the bottom of the range, the solubility for Pu^{V} was estimated to be as low as 2.5×10^{-17}M.

The 1991 and 1992 PA attempted to capture the effects of oxidation on solubility. For these two PA efforts, the amount of each actinide in each oxidation state was estimated from diagrams of actinide oxidation states as a function of Eh and pH (Sandia, 1992, pp. 3-67 to 3-70). Similar methods were used in the 1992 PA with some minor adjustments (Sandia, 1992, Vol. 3, 3-38 to 3-43).

Sandia did not publish an annual performance assessment for the years 1993 and 1994. Rather, the calculation efforts were directed toward the development of a systems prioritization methods (SPM). SPM was advanced as a management decision making tool needed to identify the best use of resources to demonstrate compliance with the EPA Standards.

As a result of the SPM exercise, Novak et al. (1994, p. 7, 29) identified problems with the actinide solubility values used in the 92 PA calculations. The mobile actinide concentration model in the 1992 PA was characterized as the "intuition and impressions of four individual experts." Furthermore, the thought processes used by the members of the panel to generate their predictions had not been documented, making peer review of their reasoning difficult. Hence, Novak et al. maintained that the values used in the 92 PA were indefensible and should not be used in future performance assessment calculations. Novak et al. (1994, p. 29) also argued that any concentration less than 10^{-10}M would not be defensible. Such a low value for concentration could never be confirmed by a measurement because it was below the limits of detection.

Determination of solubilities focused on modeling the solubilities under different repository chemistries. Rather than use a more widely tested model, such as PHREQE or EQ3/6, the project developed its own unique model, FMT. The FMT model would be used by performance

assessment to calculate actinide concentrations in Salado and Castile brines. However, the project still needed data for the development of the model and there was no data forthcoming for review. As noted in the October 1996 NAS/NRC WIPP Committee report:

> Overall, the scientific program outlined by DOE for study of the source term is adequate, provided that the program is carried to completion. Because the program at this time consists largely of work planned or in progress, it has not been possible to critically review experimental results or to judge whether these results are used appropriately in the PA analysis (NRC 1996, p. 62).

The DOE submitted the final Compliance Certification in October 1996. The EPA published its technical review of the actinide source term program and modeling in October 1997. EEG asked Dr. Virginia Oversby to evaluate the DOE modeling efforts and the EPA review. Her evaluations, which are included with this report, identified many of the issues summarized in the EEG letter of December 31, 1997, to EPA (Appendix 8.3). Her reviews of the DOE CCA and other documentation are attached as Appendix 8.4a. On February 20, 1998, EEG met with scientists from Sandia National Laboratories and Dr. Virginia Oversby and Dr. Rodney C. Ewing to discuss the actinide solubility program results. The letters which they prepared subsequent to that meeting are attached as Appendices 8.4b and 8.4c. Dr. Oversby's review of the EPA technical support document is included in Section 2.3.2.

The FMT model is unique to WIPP and is not generally used elsewhere. Calculations using the FMT model result, for example, in a difference of 19 orders of magnitude between the projected solubility of thorium pentacarbonate in the Castile brine versus the Salado brine. This is hard to explain on the basis of differences in the brine compositions. Hence the code becomes suspect. It appears that the EPA verification was limited to an exercise in which EPA used the same computers, codes, and database (after correction of some errors in the database) as DOE, to determine the same numerical values. This is not the standard of verification that one normally applies to chemical modeling codes. Verification would require, at a minimum, an analysis and demonstration that the FMT code correctly solves the simultaneous equations, a thorough

comparison with the results of calculations using a code that is used more widely in the modeling community, and a demonstration that the calculations are consistent with all relevant published data. For example, as a preliminary analysis, it would have been more informative if a widely used code such as EQ3 or PHREEQE had been used with the FMT database and then FMT had been used with a database from some other modeling group.

Plutonium will account for 82% of the WIPP radioactive inventory 100 years after closure. The CCA maintains that the plutonium will exist either as Pu(III) or Pu(IV). However, the plutonium data were not used for developing the FMT model to predict the solubility of Pu(IV). Rather, the CCA relied on data for uranium and thorium as analogs. But there are long recognized concerns about relying entirely on the oxidation state analogy to derive thermodynamic constants for modeling complex electrolyte systems. As stated in the NAS/NRC WIPP Committee report (NRC, 1996, p. 129):

> Although the oxidation state model (the assumption that the chemistry of a given oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviations from the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy.

In its technical support documentation, EPA discusses the shortcomings of the solubility uncertainty ranges advanced by DOE. There is no direct basis for the uncertainty ranges for actinides in oxidations states +4 and +6. Moreover, the uncertainty ranges for oxidation states +3 and +5 are derived primarily from non-actinide data. Nonetheless, EPA has accepted the ranges as adequate, commenting “It is not clear that including more data for the other actinide state would appreciably change this range” (U.S. EPA, 1997c). The argument is weak. It also remains unclear that the range adequately brackets uncertainty for a population for which data have not been examined.

In the solubility calculations, the CCA inappropriately discounts the role of organic ligands on plutonium solubility. The CCA provides information on the amounts and complexing properties of EDTA and then argues that other organic ligands, such as citrate, will be unimportant despite the fact that citrate is the most abundant water-soluble organic constituent. Citrate forms extremely strong complexes with actinides in the +4 oxidation state [e.g. Th(IV)], but very weak complexes with other cations. Moreover, the DOE and EPA have each assumed that the actinides and the brine would be evenly distributed and well mixed throughout the repository. EEG believes that this is an inappropriate assumption. The plutonium and citrate are probably located in the same drums. These waste forms result from chemical separations of Pu and do not fit the classic description by DOE of TRU waste as contaminated tools, rags, gloves, booties, etc. The solubility of the plutonium for these waste forms must also be calculated as a very stable plutonium citrate complex where other cations in the brine diffusing into the drum cannot compete effectively with the complexed actinides (IV).

Perhaps the most important questionable assumption made in projecting the solubility values used in the CCA and the PAVT is the presence of hydromagnesite as the dominant stable mineral species resulting from the MgO backfill. DOE's experimental efforts with MgO predominantly produced nesquehonite, a magnesium carbonate mineral, with the later appearance of an unidentified phase. Hydromagnesite was not formed in the experiments reported by the DOE (Sandia, 1997); a hydromagnesite-like unnamed mineral is reported. The chemical composition of this mineral is in fact more like nesquehonite. The DOE and the EPA believe that "hydromagnesite will be the metastable hydrated magnesium carbonate phase and nesquehonite will be an intermediate phase." (U.S. EPA 1997c). There is no experimental data for the length of time that nesquehonite is expected to exist. The distinction between the projected hydromagnesite-dominated or nesquehonite-dominated chemical environment in the repository is important because the actinide solubilities in the presence of nesquehonite are 3 to 4 orders of magnitude higher than in the presence of hydromagnesite.

The EEG has investigated the effect of actinide solubilities on the mean CCDF plots, using the EPA's PAVT releases, and making no other changes (Neill Letter dated December 31, 1997 –

Appendix 8.3 of this report). The investigation included the “CCA” solubilities, “no backfill” solubilities, and “nesquehonite” solubilities. The overall mean CCDF curve for “nesquehonite” solubility moved one order of magnitude closer to the compliance limit at 10^{-3} probability compared to the CCA solubilities.

The EEG therefore recommends that the EPA reexamine these issues and provide additional justification for the CCA and the PAVT solubility values. If convincing justification is not available, then the "no backfill", or "nesquehonite" solubilities should be used in a new performance assessment calculation. EEG concerns are summarized below.

1. The FMT model is unique to WIPP. EEG found that the model predicts differences for actinide sulfate and carbonate solubilities that can not be explained by chemistry, thus leaving the reliability of the calculations suspect. The unexpected results need to be explained or the model needs to be re-examined for possible problems with the code.

2. Rather than use an extensive plutonium data base, the FMT predictions relied on thermodynamic data for other elements and an oxidation state analogy argument. EEG recommends that the calculations be performed using data for plutonium and the values for solubility and complex ion formation contained in the peer-reviewed data compilation by OECD/NEA.

3. EEG agrees with EPA’s documentation of the shortcomings of the solubility uncertainty ranges advanced by DOE. However, EPA has accepted the ranges as adequate based on a weak argument. EEG recommends that the uncertainty range needs to be determined with the appropriate plutonium data.

4. In the solubility calculations, the CCA inappropriately discounts the role of organic ligands on plutonium solubility by arguing that EDTA is the strongest complexing agent. But citrate forms very strong complexes with actinides in the +4 oxidation state and very weak complexes with

other cations. Thus, the solubility of a stable plutonium-citrate complex in individual waste containers needs to be calculated.

5. There are serious unanswered questions about the impact of magnesium oxide backfill on the solubility of the actinides. It is proposed that magnesium oxide will reduce the solubility of the actinides by controlling the pH. But, it is not known how long the early reaction product, nesquehonite, will persist. The FMT model calculates that the presence of nesquehonite drives the solubility of the +4 actinides, such as plutonium, higher than in the no backfill case. This requires further investigation.

2.3.2 Comments on "Technical Support Document for Section 194.24: EPA's Evaluation of DOE's Actinide Source-Term" - prepared by V. M. Oversby

2.3.2.1 General Comments

The EPA evaluation of expected redox states, solubility, and speciation of actinides under WIPP disposal conditions was very narrow in its scope. In general, only the references cited by DOE and the work done by the DOE contractors was discussed. The evaluation would be considerably strengthened, and might reach different conclusions, if relevant results published in the open literature of studies conducted by other scientists were discussed.

The EPA has limited their review of the DOE solubility calculations to an exercise in which EPA used the Sandia computers, codes, and databases to determine whether they could get the same numerical values for results if they tried to duplicate the work done by DOE. It would have been very surprising if they had failed to find agreement under those conditions. A more reasonable evaluation would require a comparison of the results of calculations using a code that is used more widely in the modeling community with those obtained by the Sandia FMT code.

There has been no evaluation by EPA of the thermodynamic properties data used in the database for the solubility calculations. There has been no attempt by EPA to assess the degree to which the calculations might represent the conditions expected for WIPP disposal. Both of these tasks are needed in order to determine whether the DOE calculations have any validity.

In evaluation of the effect of organic ligands on the mobilization of actinides, EPA considers only the case of homogeneous equilibrium, in which the entire actinide inventory in the repository is well-mixed with a very large volume of brine that inundates the repository. This is an unrealistic and non-conservative model for evaluation of the effect of organics. In addition, EPA bases their evaluation of the ability of organics to mobilize actinides on an analysis that only considers EDTA. While this analysis gives the correct result for the importance of EDTA, it does not speak to the issue of the importance of citrate in the waste and its ability to increase the mobility of Pu.

2.3.2.2 Comments by Section

Section 2 "Solubility and Actinide Oxidation States"

Comments are limited to U(IV), Th(IV), and Pu (all oxidation states).

The EPA document summarizes the discussion of expected actinide oxidation states and concurs with the DOE position. In doing this, the EPA overstates the content of the DOE SOTERM Appendix to the CCA. EPA states on p.5 "DOE provides a summary of the literature and a discussion of experimental results for thorium, uranium, neptunium, americium, curium, and plutonium." Unfortunately, the DOE document limits itself to a discussion of the expected oxidation states for these elements and does not discuss the chemistry sufficiently. For example, after it is concluded that the expected oxidation states for U will be IV and VI, the chemistry of uranium IV is not further discussed. This is unfortunate, because published data on the solubility of UO_2 in concentrated synthetic brines could have been used to evaluate the validity of the claims made for the use of the Th(IV) model for representation of all actinide (IV) species. See discussion of experimental results of DePablo et al. (1995) in Oversby (1997). It is surprising that EPA did not discuss this lack of evaluation of the model against published data, since the necessity for such evaluations had been pointed out by the National Research Council review of the WIPP project as recently as 1996 (NRC, 1996). In their review, the committee states on p.129 that "Although the oxidation state model (the assumption that the chemistry of a given

oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviations from the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy."

The oxidations states expected by DOE for Pu in the WIPP repository are III and IV. Any Pu(V) formed is expected to be rapidly reduced by iron. EPA concurs with this conclusion; however, Pu(V) is observed as a long-lived transient in many laboratory experiments. Pu(V) may be formed as a result of radiolosis reactions in the brines and while its total abundance in the repository is likely to be low, it might be significant as a transient species in some waste containers. The release scenarios considered important for WIPP are those involving human intrusion, with drilling through the repository to a brine-containing formation below the repository. Upwelling of brine from this lower layer through the repository might allow rapid transport of brines containing some Pu(V) to the surface.

The inclusion of Pu(III) for a potential redox state is based on work by Felmy et al. (1989). Their experiments used Pu(III) maintained in that redox state by adding Fe powder to the solutions. The solubility of $Pu(OH)_3$ was measured in dilute solutions and brines. The redox state of Pu was verified by using chemical extraction methods; however, the method used measured Pu(III) + Pu(IV), so there is not positive identification of Pu(III) content. At pH 9 and above, the concentration of Pu was below detection limits (Felmy et al., 1989). This would suggest that Pu(III) needs to be considered only up to pH 9 in modeling calculations if metallic Fe is present, which it will be in the form of WIPP disposal drums. Above pH 9, the upper limit for Pu(III) should be set by the detection limit in the Felmy et al. (1989) experiments as 10^{-9} M.

The EPA claims on p.5 that "The predominance of U(IV) requires extremely reducing conditions, that while possible for the repository, cannot be predicted with certainty." This statement is at odds with the claim that the redox conditions will be controlled by the presence of metallic iron and its oxidation to Fe(II). The redox conditions imposed by the Fe(O)/Fe(II) buffer are much more reducing than those required to stabilize U(IV) as UO_2. This fact was used by Rai et al. (1995), who added Fe powder to their experiments concerning solubility of U in carbonate and

bicarbonate solutions in order to assure the absence of U(VI). Available experimental data for U(IV) are relevant for use in estimating solubility of U under WIPP conditions and also for use in comparison with estimates of solubility for Pu based on the Th(IV) model.

Section 3: "Effects of the Magnesium Carbonates on Predicted Repository Conditions Due to MgO Backfill"

The EPA evaluation claims that DOE described (Sandia, 1997) experiments in which "the reaction of MgO with brines was observed to result in the rapid formation of nesquehonite, which then converted to hydromagnesite within days." EPA concludes "Consequently, nesquehonite cannot be expected to persist in the repository environment."

The Sandia report (Sandia, 1997) does describe results of reaction of MgO with brines. Nesquehonite is found as an early reaction product. Unfortunately, hydromagnesite is never identified in the reaction products, even though sections in the Sandia report claim that a poorly characterized phase tentatively identified to have the composition $MgCO_3 \cdot 3H_2O \cdot MgCl(OH)$ (PDF7-278) (no name given) was hydromagnesite-like or even that it was protohydromagnesite. The chemistry of the phase found is quite different from that of hydromagnesite [$(MgCO_3)_4 \cdot Mg(OH)_2 \cdot 4H_2O$] and contains a major structural unit with the same chemistry as nesquehonite ($MgCO_3 \cdot 3H_2O$). There is no evidence discussed in the Sandia document that shows disappearance of nesquehonite under conditions relevant to WIPP. With the evidence at hand, one must conclude that nesquehonite will, at the very least, be a very long term metastable phase under WIPP repository conditions. So long as CO_2 can be expected to be released into the brines - from any source - and MgO is present in the repository, the reaction to produce nesquehonite will occur. If nesquehonite is present in the phase assemblage in the repository system, it will fix the dissolved carbonate activity at levels higher than those appropriate for hydromagnesite, even though hydromagnesite may also be present. Absence of nesquehonite requires experimental data to show the rate of conversion of nesquehonite to another phase, as well as data to determine the time for an end to the production of new nesquehonite. Appropriate data are currently lacking for both of these items. As noted by EPA (p. 8), the discussion of the correct phase assemblage for

the Mg-Carbonate system under WIPP conditions “may seem academic but is important because of the potential effect on the solution conditions and consequent predictions of actinide solubilities”.

Section 4: “FMT Modeling Results”

This section describes the work done by EPA to evaluate the FTM modeling code and results obtained using that code for prediction of brine chemistry for WIPP conditions.

EPA went to Sandia and used the FMT code and data base there to rerun the same cases as reported in the CCA and subsequent reports on MgO stability. They were able to reproduce the numerical values (after correction of some errors in the data base). EPA considered that this constitutes “verification” of the results. This is not the standard for “verification” that one normally applies to chemical modeling codes.

Normally, verification of a numerical model requires that one determine that the model does what it claims to do. We do not know whether the FMT code correctly solves the system of simultaneous equations - which is what verification would mean in this case. The only thing we know is that it is not so numerically instable as to produce wildly divergent numerical solutions to the same problems using the same data.

There has also not been verification that the thermodynamic data in the database correctly represent what is known about actinide chemistry in brines. The results using the “modified” database that produced lower Th predicted solubilities still seem to have predicted far more Th-pentacarbonate than one would expect based on the experimental studies of Östhols et al. (1994) who did the measurements of ThO_2(am) solubility that provided the basic thermodynamic data for the Th-pentacarbonate association constants. The results are also inconsistent with the measurements of Th solubility in Na-carbonate and Na-bicarbonate solutions (Rai et al., 1995) that showed that a dissolved carbonate concentration of 0.1 mole per liter was needed before a significant increase in Th solubility due to carbonate complexation was seen. The EPA results

reported in tables 4-8 and 4-9 do not show speciation for Th; however, those contained in the Novak (1997) memo do. The following table compares the calculated results for dissolved carbonate, bicarbonate, $Th(CO_3)_5^{6-}$, $Th(OH)_3(CO_3)^-$, and H^+ for nesquehonite and for 5424 hydromagnesite in SPC brine.

Table comparing speciation of Th for different Mg-carbonate phases in SPC brine. Data from Novak (1997). Concentrations in moles/kg of brine.

Solution species	**Nesquehonite**	**5424 Hydromagnesite**
Carbonate	9.9×10^{-4}	2.17×10^{-5}
Bicarbonate	2.15×10^{-3}	4.7×10^{-5}
$Th(CO_3)_5^{6-}$	7.2×10^{-4}	3.6×10^{-12}
$Th(OH)_3(CO_3)^-$	5.7×10^{-7}	1.25×10^{-8}
H^+	4.3×10^{-10}	4.3×10^{-10}

Note the predicted dominance of the Th-pentacarbonate complex for the case of solubility controlled by nesquehonite present, even though the dissolved carbonate and bicarbonate concentrations are about a factor of 50 below where one would expect this complex to begin to become important.

The FMT code was developed at Sandia and has not been generally used in the community that does geochemical modeling, nor by the other groups world-wide that do performance assessment of radioactive waste repositories. Over the years, there have been a number of case studies conducted to compare the results of calculations of the same problem using different modeling codes and databases. It has been found that considerable differences in results have occurred, even when the codes were thought to be using the same solution algorithms and databases. It would be more instructive, from the point of view of verification of the FMT calculations, if a more widely used modeling code, such as EQ3 or PHREEQE had been used with the Sandia

database and then FMT had been used with a database from some other modeling group. It would probably be sufficient to do calculations for each brine with nesquehonite and one of the hydromagnesite phases in sequence controlling the carbonate solution levels.

The subject of validation, which is the degree to which the modeling results can be expected to produce a correct representation of a real, complicated, natural situation is not discussed in the EPA evaluation. Validation of a code is normally considered an essential part of code development prior to use in performance assessment.

Note: There are typographical errors in Table 4-2, Step 4, Novak for Th(IV) concentration (should be E-06, not E-09), and Table 4-3, Total Th, verification (b) column (should be E-06, not E-09).

Section 5: "Review of the Uranium (VI) Solubility"

In this section, EPA critically reviews the assumptions used by DOE in estimating the solubility of U(VI). EPA correctly notes that the assumption by DOE that solubility can be estimated for U(VI) in WIPP by assuming that carbonate is absent is incorrect. EPA provides suggestions for U(VI) speciation and for solubility controlling solids. They also correctly assess the relative importance likely for hydrolysis species of U(VI) as compared to carbonate species. It would be most useful if the critical methodology used by EPA for assessment of Section 5 were used to assess Sections 2, 3, and 4.

Section 6: "Actinide solubility uncertainty range"

EPA describes the method used by DOE to develop the estimate of uncertainties in solubility calculations for the actinides. This is most useful, since the CCA and references therein did not provide this information. Solubilities calculated using FMT were compared with the results of

experimental measurements and the deviations between the calculated and measured values were the basis for the uncertainty distribution.

Not all experimental data were used in this evaluation. First, any solubility data with +6 oxidation state for actinides was eliminated because FMT could not calculate for +6 actinides. Experimental data for +4 actinides were also eliminated because "data available for the +4 model were found to have significant problems in the extrapolated regions and were thus determined to be inadequate for this analysis." EPA notes that this position is inconsistent with the statements in the CCA concerning availability of data for Th(IV) speciation in brines.

Elimination of +4 and +6 oxidation states meant that only +3 and +5 data were used in the uncertainty analysis. The distribution of experimental data used was 69% Nd(III)carbonates (104 measurements), 23% Am(III)carbonates, and 7% Np(V) in carbonated brines. Solubility data for Pu(III) data in brines was not included in the analysis, even though these data were used to obtain parameters for the Pitzer coefficients in the calculations.

EPA correctly notes that the estimation of uncertainties for +3 actinides based mainly on Nd data is somewhat problematical since Nd is not an actinide, even though its chemistry might be expected to be similar to +3 actinides. They also note that it is likely that the uncertainties in the solubilities of +4 and +6 actinides should be expected to be larger than those for +3, since it is for these oxidation states that it was found that insufficient data existed to make an analysis of uncertainty. It is particularly difficult to understand how an assessment of how well the Th(IV) data model the expected solubilities for U(IV) and Pu(IV) can be done if no comparisons are ever made between calculations and experimental results. The large changes in calculated Th solubility when changes were made to Pitzer coefficients after unacceptably high Th solubilities were calculated (see Section 4 in EPA review) suggests that uncertainties in predicted solubilities may be considerably higher than those given in the DOE CCA analysis.

The inconsistencies in speciation for Th in the FMT calculations when compared to the original work that derived the thermodynamic properties data that must be used in the calculations also

points to considerably higher uncertainties than the -2 to +1.4 log units cited in the DOE CCA. The EPA concludes that the range cited by DOE is probably adequate and states "It is not clear that including more data for the other actinide oxidation state would appreciably change this range." It is equally true that it is not clear that the range adequately estimates uncertainty for a population for which data has not been examined.

Section 7: "Influence of Ligands and Complexants on Actinide Migration"

In this section EPA's stated purpose was to "determine whether DOE appropriately characterized organic ligands and humic materials on their potential to increase the mobilities of actinides and to evaluate DOE's approaches for representing such processes." EPA concluded that organic ligands will not increase actinide mobility.

EPA provides a lengthy section of introductory material, which describes complexation chemistry and factors that increase mobility of metals through complex ion formation. They then proceed to assume that brine will be present in the WIPP repository and will commingle with the waste during much of the repository's performance period. In essence, this is equivalent to the assumption made by DOE that the system could be modeled assuming homogeneous equilibria of brine and actinides. In other words, both DOE and EPA assumed that the actinides would be evenly distributed throughout the repository and that the brines would be well-mixed and have a uniform composition throughout the repository. This is unlikely to be the case and is certainly not appropriate for evaluation of the development of dissolved actinides inside a partially destroyed waste container, a scenario that is important with respect to assessment of human intrusion consequences.

In the DOE evaluation of the effects of organics and humic substances, the organics are treated in SOTERM as if they were homogeneously dissolved in 29,841 m^3 of brine. DOE then looked at the values of the complexation constants and concluded that EDTA formed the strongest complexes with actinides, so would be the most important organic ligand. EDTA also forms strong complexes with many other cations, so when DOE evaluated the complexation behavior of

EDTA they found that most of the EDTA would be associated with Ni. EPA disputes this conclusion based on their estimate of Ni solubility in nature, but in their own calculations of EDTA behavior they conclude that EDTA will not increase Th(IV) solubility because the EDTA will be complexed with Ca and Mg under alkaline conditions.

The abundance of EDTA in the wastes intended for WIPP is low; in addition, EDTA forms strong complexes with many cations. For both of these reasons it is reasonable to conclude that the EDTA present in the WIPP repository will not lead to an increase in actinide IV mobility. It is not, however, appropriate to conclude from an analysis of EDTA behavior that organic ligands will be unimportant under WIPP conditions. Citrate is the most abundant water-soluble organic constituent in the waste inventory listed in the SOTERM Appendix to the DOE CCA. Citrate forms an extremely strong complex with Th(IV), but much weaker complexes with other cations. For this reason, even in the presence of very high dissolved Ca and Mg, the citrate will preferentially form complex ions with the +4 actinides.

To model the behavior of Pu with citrate, we must also consider heterogeneous equilibria for organic complexation with the actinides. The main difficulty arises because the Pu in the waste is probably located in the same drums as the citrate, which is the dominant organic ligand. This is because these wastes arise from chemical separations of Pu and are not the type of waste described in the general descriptions of TRU waste as contaminated equipment, clothing, etc. To get an accurate estimate of the effect of organic ligands on Pu solubility, one must calculate the concentration of Pu as citrate complex inside a waste drum that has been breached, but can still provide a hindrance to mixing of the brine inside the drum with a larger pool of brine outside the drum. This will give a high concentration of Pu in solution as the citrate complex. Other ions will not compete with Pu sufficiently to prevent complex formation because the stability for (IV) actinide complexation - as shown by the stability constant for Th(IV) on p. 39 of the SOTERM appendix- is orders of magnitude larger than that for other ion complexes with citrate.

EPA discusses some work by Hummel (1993), who reports the effect of organic ligands under high pH conditions in cement pore waters. The high pH conditions do argue against complex

formation by EDTA and other "conventional" organic ligands; however another possible ligand for increasing Pu(IV) solubility comes from the degradation of cellulose under high pH. Work in England has shown that degradation of cellulose can occur both through chemical processes at high pH and by radiation effects. The degradation products have been shown to increase the solubility of plutonium dramatically (Cross et al., 1989; Greenfield et al., 1992).

The discussion of humic substances in the EPA evaluation is very thorough. EPA concludes that DOE has probably overestimated the effect of humic materials on the mobilization of actinides, but agrees that the approach taken by DOE is conservative. The amount of +4 actinide carried by humic materials is estimated to be 6.3 times the amount actually in solution as dissolved species. This overestimation of the importance of humic substances on Pu mobility may balance, in part, the failure to consider the complexation of Pu by citrate. Some relatively simple calculations should be able to provide sufficient information to evaluate the relative importance of the under and overestimation of Pu speciation on total Pu mobility.

Section 8: "Microbial Effects"

EPA discusses the potential for microbial activity in WIPP and concurs with a DOE contractor assessment that "although significant microbial gas production is possible, it is by no means certain." Other aspects of microbial activity are also discussed and noted to have high levels of uncertainty associated with whether the activities will actual happen and, if so, how will they affect actinide mobility. In general, it is concluded that the effects of microbes are most likely overestimated.

The potential overestimation of CO_2 gas production was the driving force for adding MgO backfill to the repository to control the dissolved carbonate content in any possible brines. The use of MgO backfill is not without its own uncertainties. See discussions above concerning reaction products of MgO with brines containing carbonate and the resulting effects on the solubility of +4 actinides. It might be worth trying to get a more realistic picture of the potential for carbon dioxide production and to re-evaluate the need for the MgO in the repository. Another

possibility would be to follow the NRC (NAS) committee recommendation to evaluate use of compartments in the repository. In this way, use of MgO might be confined to regions that had low Pu inventories, thereby reducing the uncertainties associated with increased solubility of Pu in the presence of metastable MgO-carbonates.

On p. 62, EPA states "For undisturbed repository scenarios cellulose degradation products are unlikely to increase actinide concentrations in the aqueous phase." This statement is in direct conflict with the results of extensive studies in England that showed that Pu solubility was greatly increased by the presence of chemical degradation products of cellulose produced at high pH. See the references cited in the previous section (7) for details.

Section 9: "Conclusions and Key Issues"

This section summarizes positions discussed by EPA in sections 2-8. No specific comments are needed, since the issues have been addressed in the introductory General Comments and in the section-by-section comments above.

2.4 SPALLINGS

The blowout of spalled material reaching the accessible environment through an inadvertent human intrusion through a borehole into the WIPP repository could cause major problems with the compliance of the EPA's limit established in the 40 CFR Part 191 (U.S. EPA, 1996). EEG's Letter to F. Marcinowski, dated December 31, 1997 (Appendix 8.3) has shown that spalled volume, based on 100 realizations which have volumes ranging from 8 m^3 to 64 m^3 can violate these standards. However, the CCA and other DOE published results have shown that a blowout would purge less than 4.0 m^3 of waste from the repository, with 0.27 m^3 being a more typical volume (Hansen et al., 1997). Yet, none of the DOE models accurately calculate spall under varying repository conditions. For example, the main codes used to verify the reasonable volumes predicted in the CCA cannot be used under more appropriate waste permeabilities, gas viscosities, and mud drilling densities (from either mud brine or an underbalanced drilling fluid). The models also ignore potentially important failure mechanisms such as shear failure of waste under compression. It is EEG's belief that the issue has not been addressed fully to determine whether compliance with the containment requirements, 40 CFR Part 191.13 has been met. Therefore, it is recommended that EPA require DOE to develop a new model, which incorporates all the processes involved with spall. This is particularly important since spallings has the potential to returning more waste to the biosphere than any other human intrusion scenario.

2.4.1 Definition

Spall is waste that has been introduced into the drilling fluid due to radially channeled, highly pressurized gas flow from within the repository to a lower pressure borehole. Gas will continue to flow until the system comes to pressure equilibrium between the repository and the borehole. The high flow rates of gas will cause some of the waste material to fail in tension or shear, break off from the borehole cavity, and be introduced into the return stream of the drilling fluid. If gas flow is sufficiently high, it will force all the drilling fluid out of the borehole to the surface. This phenomenon is known as blowout, and is a common occurrence among drilling rigs encountering pressurized pockets of natural gas.

Spall can also occur by the mechanisms of stuck pipe and gas-induced erosion. These phenomena may dominate a spalled event if the gas flows are too low to cause blowout. Stuck pipe is a process of spall that, due to very low permeability and extremely high repository pressures, may cause failed waste to press against the drill string sufficiently hard to prevent normal drilling. The solution for a jammed bit is to pull the drill string up and start drilling again. If the pressures remain high, the driller may have to bring the bit up several times, thus allowing significant quantities of waste to be brought to the surface through the return stream of the drilling mud. Gas erosion is spall that is eroded by the drilling mud due to high repository pressures and low waste permeability. The spall from gas erosion is slower than stuck pipe due to slightly lower pressures in the repository (just above hydrostatic), and may release waste into the drilling mud at a rate undetectable by the driller. Gas erosion would continue until the repository pressure is in equilibrium with the drilling fluid, and may also bring significant quantities of waste to the surface.

When applying the terms of stuck pipe and gas erosion to the disposal system, slightly different definitions may be in order. Stuck pipe and gas erosion releases have been said to occur if the waste permeability is less than $1x10^{-16}$ m^2, as stated in Berglund (1994), and repository pressures are greater than the pressure exerted by the drilling mud (above hydrostatic). The CCA states that the waste permeability can be represented by a constant value of $1.7x10^{-13}$ m^2, which is much greater than the threshold for stuck pipe to occur. Additional studies show that waste surrogates based on current understanding of waste mixtures could have a permeability of $2.1x10^{-15}$ to $5.3x10^{-15}$ m^2 (Hansen et al., 1997), and that the threshold for blowout to cease and stuck pipe / gas erosion to begin is questionable (EEG letter dated Dec. 31, 1997 - Appendix 8.3).

The single representation of waste permeability by DOE was a necessity, based on flow model calculations of brine and gas through the repository in the two-phase flow code, BRAGFLO. The geometry of the disposal system in BRAGFLO only designated 21 cells for the waste area and many of these cells were on the order of 44 meters wide by 1.32 meters high. The spatial variability of the waste permeability could not be accurately implemented in these few large cells, and a constant homogeneous waste was more appropriate. When the scale of modeling reduces

from the entire disposal system to repository room size, or even smaller (a few meters around a borehole intrusion), then the variations in waste permeability should also be on a smaller scale for the local conditions.

2.4.2 Calculation of Spallings

The DOE has calculated the amount of material that will spall through a blowout. The code CUTTINGS_S (U.S. DOE, 1996c-Appendix CUTTINGS_S) incorporates the spallings calculations with calculations of the amount of cuttings and cavings from a drill string drilling through the repository. The calculations showed that a maximum of 4.0 m^3 would spall in the borehole cavity and be transported out of the borehole to the surface. However, an independent peer review found the code to be conceptually flawed. The DOE's Conceptual Model Peer Review Group (U.S. DOE, 1996c-Appendix Peer 1) stated that the "Development of this [spallings] model is not sufficiently complete to determine uncertainties specific to the channel movement of waste to the existing borehole". The threshold for waste permeability and stuck pipe to occur was also based on the findings of this code.

The spallings volume was re-calculated by using a second code, GASOUT (Shatz, 1997), along with several other methods, to assess whether the results of the spalled material calculated in the CCA were reasonable. The GASOUT code was accepted by the Conceptual Model Peer Review Group (Wilson et al., 1997) based only on the conceptual model, without any independent testing or validation. Calculations with the GASOUT yielded a maximum of 0.27 m^3 to reach the accessible environment upon a breach (Hansen et al., 1997). The main assumptions used in the code to derive the calculated volume was a waste permeability of 1.7×10^{-13} m^2, a repository pressure of 14.8 MPa, and a waste tensile strength of 10 psi (0.068 MPa). Despite better understanding of the waste and measured values of the waste permeability, 4.0×10^{-15}, as described in Hansen et al. (1997), the CCA value of permeability (1.7×10^{-13}) was used for this investigation.

GASOUT uses a semi-analytic approach of a mechanistic conceptual model that couples the numerical calculations of a finite difference fluid flow code and a finite element rock mechanics code. This approach has been dubbed "the cavity growth method", because it progressively calculates the region of radial tensile failure within the cavity. Hansen et al. (1997) showed that there is no tensile failure of waste below repository gas pressures of 14 MPa "under realistic but conservative assumptions".

The conceptual model of the code during the blowout process was described as being divided into two stages. The first stage is characterized by the ejection of the drilling mud by high pressure gases, and the response of the waste to the high pressure gradients during blowout. Following the blowout, the second stage is identified by the rapid flow of gas from the repository, including the entrainment of solid waste particles. In the first stage of initial depressurization, gas velocities are small while the mud column is being expelled from the borehole. The velocities will increase during stage two, as the borehole path is clear for rapid gas movement. The larger eroded waste particles will typically be lofted to the surface during this stage. It must be noted that confidence in the GASOUT code can only be placed on the calculations during early times of the first stage. Late times of stage one would involve the decompression of the waste gas, which is not incoporated into the model.

In addition to the analysis using GASOUT, a "quasi-static" and "fully coupled" approach to solve the spallings problem was employed by DOE. The quasi-static used a spread sheet analysis to solve the porous flow equations by a sequence of steady state profiles (Hansen et al., 1997, pg. 3-24), and the conceptual model used in the quasi-static was identical to the cavity growth (GASOUT) method. The major difference in the two models is that the cavity within the quasi-static model does not increase with the calculation of tensile failed waste removal. The results from the GASOUT calculation without failed material removal (removal of failed material is a toggle switch that can be turned on and off in the code), show almost perfect agreement with the quasi-static results under identical initial assumptions. The differences in the two methods are established very early in the conceptual and mathematical model of the system. GASOUT assumes a transient pressure response in the flow calculations, whereas the quasi-static method

assumes a series of steady state calculations. Steady state ignores some very important features of pressure flow with respect to time. Tensile failed material calculations for the quasi-static model showed a 1.17 m^3 of spall with initial pressure conditions of 14.7 MPa and tensile strength of 15 psi (inferred from effective stress calculations). The cavity growth model calculated an equivalent 0.07 m^3 of spall.

The fully coupled approach used a purely numerical code (as opposed to the semi-analytic approach in GASOUT) to calculate the flow of gas within the waste region to the intruded borehole. The mathematical model of the fully coupled approach assumes a one-way coupling of the two-phase pressure decay following an intrusion with a decoupled two-phase pressure response within the simulated waste region. The fluid flow and waste pressure response were solved by the code TOUGH28W with the poromechanical waste response of stress and strain invoked in the code SPECTROM-32.

Though the code did not explicitly calculate failure, it did calculate the effective stresses within the waste. From the results using SPECTROM-32, the normal effective stresses (tensile stresses) shows a semi-hemispherical distribution at very early times. If the initial assumptions are 14.8 MPa, and the waste failure criterion is 10 psi, then the code would indicate a brittle elastic failure radius of 0.8 m (Hansen et al., 1997-Figure 4..4-1.-9, time=0.001 s), or 2.1 m^3 uncompacted volume. The same figure shows a stress distribution extended out to one second, but without considering the possibility of waste removal. The removed waste would have a significant impact on the stresses in the cavity.

2.4.3 The EEG's Concerns on Spallings

2.4.3.1 Waste Permeability and the Stuck Pipe Scenario:

The permeability of waste in the WIPP repository and its effect on stuck pipe and gas erosion were not adequately addressed in the performance assessment calculations of the CCA and PAVT. The constant value of 1.7×10^{-13} m^2 used for waste permeability in the CCA was based on an investigation of waste materials by Luker, Thompson, and Butcher (1991) in which a single value, homogeneous waste was needed for code calculations with BRAGFLO. The calculation of

the permeability assumed that 40% of the waste volume was comprised of combustibles (45% Material 1, 37% Material 2, 9% 1-inch metal parts, 9% dry Portland cement), 40% metals and glass (50% 1-inch metal parts, 50% magnetite), and 20% sludge (assumed to be ordinary Portland cement cured for 130 days). The mean values used for the separate waste types are 1.7×10^{-14} m^2, 5.0×10^{-14} m^2, and 1.2×10^{-16} m^2 for combustibles, metals, and sludges, respectively. The mean values as reported above inherently assume a range of permeability values, and these ranges can be seen in Table 2. Table 2 reports the minimum, median, and maximum from each waste type assumed in the calculation of the permeability value in the CCA as reported in Butcher (1990).

The calculation for the permeability assumed flow parallel to layers of waste. Each waste type was a separate layer in the drum, and the permeability was calculated by:

$$K_{eff} = \frac{1}{V} \sum_{i=1}^{3} V_i k_i ,$$

where V is the total volume, V_i is the volume of the ith component and k_i is the permeability of the ith component. The ith component of k is represented by the median value from Table 1. The volumes of each type of material were also considered in calculating the effective permeability of a drum. For the CCA, 40% combustibles, 40% metals, and 20% sludges were assumed from an average waste drum volume (U.S. DOE, 1996c-Appendix Peer 5). These values also varied from the different drum samples, and from defense site. The Los Alamos National Laboratory volume (by percentage) of combustibles had an averaged value of 20, whereas the Savannah River Plant averaged 70 (Butcher, 1989-Table 2). These variances in volume could cause the expected value of 1.7×10^{-13} to decrease significantly.

A strict calculation of permeability can be a dual-edged sword. The assumption that flow will be parallel to the artificial layers in each drum may be conservative for the calculation of maximum

	Min	Med	Max
Combustibles (m^2)	2.00E-15	1.70E-14	2.00E-13
Metals (m^2)	4.00E-15	5.00E-13	1.20E-12
Sludge (m^2)	1.10E-17	1.20E-16	1.70E-16

Table 2. Permeability Values Used to Calculate Waste Permeability in the CCA.

flow of gas and brine in the repository, yet nonconservative when considering the damaging effects of stuck pipe (and / or gas erosion) from a lower permeability. A lower permeability can be calculated if flow is assumed to be perpendicular to the waste layers. In this assumption, the lowest permeability layer will contribute largely to an effective permeability of the waste. With a perpendicular flow assumption, the effective permeability could be as low as 5.9×10^{-16} m^2. Therefore, the parallel flow is arbitrary, and could be seen as a nonconservative calculation.

In addition to the variability in permeability, the conceptual model review of the CCA (U.S. DOE, 1996c-Appendix Peer 5) agreed that the ranges should be assigned constructed distributions, as opposed to the above mean permeability values, which were mean values of a uniform distribution. Therefore, the new mean values for combustibles, metals, and sludges were given as 5.9×10^{-14}, 5.5×10^{-13}, and 1.05×10^{-16}, resulting in a K_{eff} of 2.4×10^{-13} m^2. This value of permeability was used in the EPA's Performance Assessment Verification Test (PAVT), and was also recommended by the EEG (EEG Letter to F. Marcinowski on March 14, 1997 - Appendix 8.2 of this report) to be more conservative with respect to gas and brine flow in the repository.

To clarify the misunderstanding on apparent conflicting recommendations by the EEG on waste permeability on separate occasions, one must remember the context in which the recommendations were given. The March 14 letter to Frank Marcinowski recommended a value of 2.4×10^{-13} m^2 for the calculation of gas and brine flow within the repository. This value was 1) for use in BRAGFLO, where the spatial variability of heterogeneity is limited to a small number of grid cells and 2) made before the issuance of a new spallings model which showed that stuck pipe and gas erosion could become valid scenarios during a drill intrusion. Therefore, EEG's recommendation (Neill, 1997, Appendix 8.3) given to the EPA that the waste permeability should include variances in all models still remains valid.

Calculations of waste permeability from discrete layers of different waste material in the drums is inherently incorrect. In reality, the waste in the drums emplaced at the WIPP will be heterogeneously mixed, not in distinct layers, and the test specimens from Butcher (1990), and Luker et al. (1991) should have included a mixture of all waste types. A new set of permeability

measurements from Hansen et al. (1997) report that the permeability of waste could be as low as 2.1×10^{-15} m^2 with a typical value of 4×10^{-15} m^2, using heterogeneously mixed waste. These specimens assume 63% metal (iron), 9.6% glass, 6.75% cellulosics, 11.6% crushed rock and cement, 4.8% soil, and 4.5% crushed salt. The permeability was conducted on a specimen containing most types of waste. It cannot be overly stressed that the measurements conducted in Hansen et al. (1997) are actual measurements on waste surrogates. The surrogates were constructed based on a deeper understanding of potentially degraded waste in future repository conditions and included waste forms of 50 and 100% degradation. The measured values are as much as two orders of magnitude lower than the calculated values used in the CCA. Again, calculated values should signal that the values are arbitrary, and do not account for variability in the waste.

In addition to the problems with the waste permeability on the use of measured vs. calculated values, it must also be stated that none of the permeability measurements were on samples that included MgO. The Particle Size Expert Elicitation Panel (U.S. DOE, 1997a) states that corrosion products, dissolved MgO and salt from brine that do not precipitate out as particulates will cement together. Cementation was a major contributor to the projected increase in waste strength to 77 Pa, and MgO is said to occupy 25.5% of the room volume after closure. The panel specifically defined the waste to mean waste plus backfill (U.S. DOE, 1997a).

The permeability of MgO as an additive to Portland cement has been studied by Zheng et al. (1991), and was found to have roughly the same permeability as Portland cement. They noted that higher percentages of MgO would result in higher permeabilities. It therefore follows that the permeability of cemented MgO is at the upper end of Portland cement, approximately 1.05×10^{-16} m^2 for sludges. In addition to lower permeability, the effects of MgO will increase waste strength in some localized areas. Permeability and strength are inversely correlated. Yet, if permeability and strength measurements taken on waste surrogate specimens with MgO are to be ignored based on conservatism, it must be remembered that the waste strength of specimens which varied between 5 to 15 psi in Hansen et al. (1997) also had permeability values on the order of 4×10^{-15} m^2. So, if a permeability, lower than that used in the CCA (and consequently in the

PAVT), is used in a model as more representative repository conditions measured values from Hansen et al. (1997), the waste tensile strength from the same report should also be used.

Keeping in mind that the values used in the calculations were median values from a range of possible permeabilities, the waste permeability could be lower. The median permeability ranged in the CCA from 10^{-12} to 10^{-16} m^2 (U.S. DOE, 1996c). Therefore, the single value of waste permeability used in the CCA does not fully represent the possible range of values that could exist in the repository.

Recommendations for Waste Permeability and Stuck Pipe:

Again, to clarify the EEG's position for waste permeability stated in the March 14, 1997 letter to EPA (Appendix 8.2), it seems as though two contradictory positions were taken. In the position statement on waste permeability used in the direct brine release calculation, EEG suggested a value of 2.4×10^{-13} m^2 be used instead of 1.7×10^{-13} m^2, "if a single value for consolidated waste permeability is to be used for direct brine release". In the position statement on the spallings model, EEG stated that the CCA reported an uncertainty range of 10^{-12} m^2 to 10^{-16} m^2 for compacted repository waste permeability. It is possible that precipitation of magnesium chloride cement and salt would reduce permeability below this range. The EEG recommended that "a more realistic value or range of values should be assumed for the waste permeability parameter and the potential for gas erosion and the stuck pipe processes be included in the spallings scenario with a better defined permeability-pressure threshold".

The spallings investigation documented in Hansen et al., (1997) contains results from permeability measurements of surrogate waste material that provide a much better basis for assigning waste permeability values. The permeability measurements do not include samples that contained magnesium chloride cement and, thus do not represent the lower bound of potential compacted waste permeability.

It is essential that the sensitivity of the Hansen et al., (1997) spallings model to waste permeability be investigated before the EPA can conclude that the spallings model used in the performance

assessment is indeed conservative as stated in the proposed rule. Unless further additional measurements on surrogate waste that includes magnesium chloride cement are available, the range of 10^{-12} to 10^{-16} m^2 is a reasonable range to investigate the sensitivity of the spallings model to permeability variation. If it is found that the model predicts greater spall volumes in this range than calculated in the performance assessment then the measurements of surrogate waste with magnesium chloride cement should be conducted to define the range more closely.

Blowout is not the only mechanism for releases to the surface. Unless it can be shown that entrainment of spall into the drilling mud (gas erosion) or re-drilling by the operator (stuck pipe) will be limited, it should be assumed that all of the calculated spall material will reach the surface.

2.4.3.2 DOE's Model Predictions of Spallings:

It is clear that the prediction of spalled material from the result of a borehole intrusion into the repository is difficult to quantify. The original model used in the CCA, developed by Berglund (1994), oversimplified the process, and therefore was judged as inadequate by the Conceptual Model's Peer Review Panel (U.S. DOE, 1996c, Appendix Peer 1). However, the results of the model were defended as being reasonable for use in the CCA, by presenting additional models which showed lower spalled release upon an intrusion. Therefore, the spallings values calculated in the CCA were considered by the DOE to be the maximum reasonable values that could be brought to the surface during a breach.

The spallings' volumes that were calculated in the CCA ranged from 0.5 m^3 to 4.0 m^3, and were subsequently used in the PAVT. The new prediction, with a more accurate set of models showed the maximum release to be 0.27 m^3. The new model used the lowest measured waste strength and the highest possible repository pressures that could be sustained for long time periods. At higher waste strengths and lower pressures, the analysis predicted much smaller volumes. However, EEG believes that the initial assumptions used in the models simulations do not accurately portray all repository conditions, and that under different circumstances the models can predict higher spalled volumes. EEG also believes that the models are inadequate to quantify the maximum possible releases due to limitations in the conceptual model development and code

implementation. Therefore, the results presented in Hansen et al. (1997) are not actually maximum calculated releases, but only a set of calculated releases under certain repository conditions. The following discussion shows the limitations of the analyses presented in Hansen et al. (1997).

Three methods were used for the analysis of spallings in Hansen et al. (1997): 1) cavity growth method (implemented in the code GASOUT), 2) quasi-static method (implemented in two spread sheet files called P145APC4, and S145APC4), and 3) fully coupled method (used to existing codes, TOUGH28 and SPECTROM32). The results for comparison of the CCA volumes came from the cavity growth method, since this method was the most realistic, physically. The cavity growth allows for material removal during failure calculations, and hence the pore pressures are redistributed at the new boundary. The other two methods strictly calculate the effective stresses in the waste (the difference in the total stress of the overburden rock and pore pressure), and failure is interpolated. These other methods were used to verify the cavity growth model and are explained above in more detail.

The sensitivity of the GASOUT code was studied by EEG, in which permeability, viscosity, and mud density were examined over reasonable repository conditions. For example, the permeability could range between 10^{-12} and 10^{-16} m^2, but was restricted to 10^{-15} m^2 for this analysis. The viscosity of the repository gas could also vary, depending on which gases are produced. This next section presents highlights from a formal sensitivity analysis conducted by the EEG on GASOUT (Rucker, 1998).

Sensitivity to Permeability and Initial Repository Pressure

The GASOUT code was seen to be very insensitive to the initial permeability value chosen in this study. However, the code's use of a narrow range of values kept the sensitivity analysis to a minimum, and true sensitivity could not be established. The range of acceptable permeability values narrowed as the initial repository pressure increased, and waste tensile strength decreased.

Initially, the permeability used in the CCA of $1.7x10^{-13}$ m^2 was assumed in the present study to allow comparisons with the results in Hansen et al. (1997), despite a better understanding of permeability investigated in that report. The single value used in the CCA is under question, as it was calculated from assumed future waste conditions.

The results of spalled material failing in a borehole cavity using GASOUT over a wide range of permeabilities were not meaningful, and the code was simulated using a very narrow range. For the Base Case simulation for example, the waste permeability could only range from $0.8x10^{-13}$ to $4.4x10^{-13}$ m^2. Above and below these permeabilities, the code predicted extremely large failed volumes. The results of the failed volume versus the permeability range that was applicable for a five second simulation can be seen in Figure 3. The figure shows results of varying waste tensile strength, from 10 to 20 psi. The three curves represented in the figure give the upper and lower bounds of the permeability that result in meaningful values.

The reported failed volumes outside the range for the Base Case are extremely high, resulting in as much as 22.5 m^3 for a permeability of $0.5x10^{-13}$ m^2 due to the cascading affect of multiple zone failure. The geometry of the borehole cavity was discretized and solved on a hemispherical coordinate system. The layers of the hemisphere were kept to a minimum (0.01 meters) to avoid instability. When the waste in the borehole fails, it is assumed that the whole layer fails, and peels off like an onion skin. When the code calculates a large failed volume, as in the case with $0.5x10^{-13}$ m^2 permeability, the effect is several layers peeling off in one time step, cascading until an equilibrium is reached with the high pressure gradient that existed at a longer time period. It is assumed that when the cascading effect is exhibited, the results become meaningless.

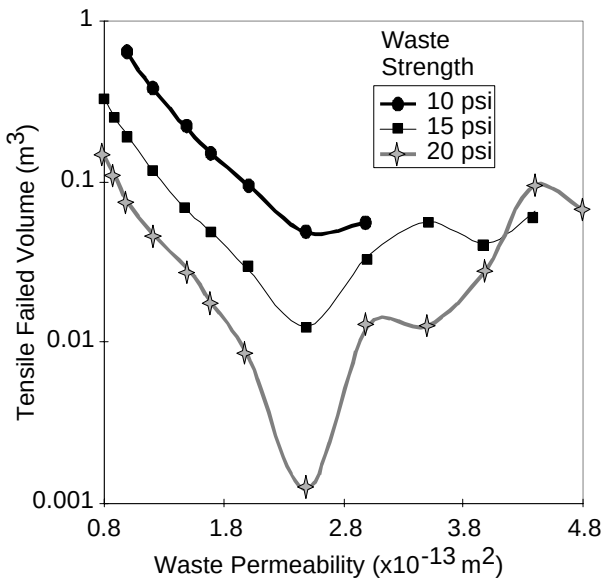

Figure 3. Contiguous Failed Volume as a Function of Increasing Waste Permeability for Different Waste Strengths With Initial Repository Pressure of 14.5 MPa.

Figure 3 shows some interesting results as the waste permeability increases. All the waste strengths tested showed an exponentially decreasing failed volume, up to a permeability of 2.5×10^{-13} m^2. Permeabilities above this value cause larger failed volumes than values below it. The upper limit on permeability shows that the code is reliable to 2.5×10^{-15} m^2 for waste strengths that were measured in the report by Hansen et al. (1997) and initial repository pressure of 14.5 MPa. The lower permeability limit is 1.0×10^{-13} m^2 for 10 psi waste strength, and decreases to 0.8×10^{-13} m^2 for waste strengths of 15 and 20 psi.

When the initial pressure is increased to its maximum of 14.8 MPa, the range is more narrow than discussed above. For all waste strengths investigated, confidence was only in waste permeabilities between 1.7×10^{-13} m^2 and 2.0×10^{-13} m^2. The narrow range that the code is applicable decreases the likelihood that the code can represent the disposal system accurately, and should be modified to allow more representative values to be modeled.

The simulation of the repository with a homogeneous waste in GASOUT is an over simplification of the repository model. It is much more likely that the waste permeability will actually be lower than that assumed in the CCA. The representation of a random permeability was explored in Hansen et al. (1997) using a fully coupled numerical code to solve the flow of gas through the repository. TOUGH28W did not calculate the amount of waste failure, but could calculate the pressure distribution through the waste for varying conditions. The code showed that a lower permeability, with values ranging from $1x10^{-12}$ to $1x10^{-16}$ m^2 would have a much higher pressure gradient near the borehole, than the permeability assumed in the CCA. It also showed that homogeneous waste with lower permeabilities will have higher pressure gradients. Higher gradient will produce lower total stresses of the overburden rock, and lower effective stresses in the waste. This further strengthens the argument for modifying GASOUT to represent the repository more accurately.

Sensitivity of Gas Viscosity

The gas viscosity parameter, along with porosity and permeability, is used to calculate the hydraulic conductivity of gas through porous media, K, by the relationship of

$$K = \frac{\mathrm{k}}{2fm}$$

where k is permeability, ϕ is porosity, and μ is gas viscosity. The original equation for the flow of gas through porous media can be found in Chan et al. (1993) , and is equivalent to the non-linear diffusion equation. The viscosity of in the equation above is indirectly proportional to the gas conductivity, and as viscosity increases, conductivity decreases. The relationship also shows that a constant ratio of permeability to viscosity will yield the same conductivity.

The experiment with permeability demonstrated that values less than $1x10^{-13}$ m^2 for an initial pressure of 14.5 MPa would render the results meaningless. The viscosity used in the experiments was $10x10^{-6}$ Pa*s, and the ratio of permeability to viscosity yields $1x10^{-8}$. Values less than this ratio will cause the code to predict cascading failure of waste. If the original permeability is $1.7x10^{-13}$ m^2, then viscosity values greater than $17x10^{-6}$ Pa*s will cause the code to give erroneous results. The ratio for failure increases to $1.7x10^{-8}$ for initial repository pressure of 14.8 MPa and waste tensile strength of 10 psi. A simulation with the ratio of $1x10^{-8}$ m^2/Pa/s and for an initial pressure of 14.5 MPa and tensile waste strength of 10 psi yields a failed volume of 0.63 m^3.

The possibility of larger viscosity values is not ill conceived. The viscosity value obtained for ydrogen gas was the standard temperature and pressure value (STP), and viscosity will increase moderately as pressure or temperature increases.

The components of the repository gas will also increase the viscosity. Through microbial degradation of plastics, rubbers, and other combustible material in the repository, O_2, CO_2, CH_4, N_2, N_2O and H_2S will be created. Francis et al. (1997) conducted experiments of microbial gas generation under expected WIPP repository conditions and found that the percentage of N_2 varied between 61.9% to 91.4%, CO_2 varied between 0.4% and 34.3%, and H_2 varied between 0% and 12.8%. These other constituents have a much higher viscosity than H_2, with N_2 being as high as $19.2x10^{-6}$ Pa*s (STP), which will undoubtedly increase with an increased repository pressure.

Even though microbial degradation may create higher quantities of CO_2, and N_2 than H_2, the process itself will be limited. It is uncertain if the colonies of microbes will exist under repository conditions, and was assigned a 50% chance in the CCA.

Iron corrosion on the other hand will produce massive quantities of H_2 and it is certain that iron will corrode when brine fills the repository. Approximately $2x10^9$ moles of H_2 (Telander et al., 1996) will be produced from the iron in WIPP. However, the other gaseous constituents could play a small role if microbial degradation does produce gas. In Appendix MASS of the CCA, Figure MASS-1 (U.S. DOE, 1996c, Appendix MASS) shows that at lithostatic pressure, if the mole fraction of H_2 to CO_2 is reduced from 100% to 90%, then the viscosity would increase from $9x10^{-6}$ Pa*s to $16x10^{-6}$ Pa*s. Therefore, it is suggested that the code be modified to allow a larger spectrum of values to be modeled.

Sensitivity to Mud Column Density

The density of the mud column in the borehole is dependent on the type of drilling mud used. For the WIPP, it is most likely that the drilling mud will come from the Salado Formation with additives to increase the average mud density to 10 - 11 lb/gal (1200-1320 kg/m^3). The GASOUT code used a density of 1249.3 kg/m^3 in the Hansen Investigation, and it is possible that this value could vary over the range mentioned above.

Figure 4 shows the results of varying the parameter from 1200 to 1320 kg/m^3 for a 10 second simulation and an initial repository pressure of 14.8 MPa. The figure shows three curves of different waste strength, with all other parameters remaining the same as used in the Base Case simulation. The most outstanding feature of Figure 4 is the disjointed curve of failed waste (left) and mud motion (right) of the 10 psi tensile waste strength simulation. The code had trouble calculating failed waste for mud densities below 1228 kg/m^3, resulting in the cascading affect described above. The code also had trouble at 1240 and 1250 kg/m^3, and if results were plotted for these densities (failed waste and mud motion), sharp spikes would exist in the curve.

For the higher waste strengths (and subsequently lower repository pressures) of 15 and 20 psi, the mud density simulations were able to calculate failed volumes for all density values investigated. However, the results seemed almost as unreliable as the lower waste strength. Though a trend can be seen in the failed volume and mud motion, variances from those trends are high. Both graphs in Figure 4. show trouble with densities between 1230 to 1270 kg/m^3.

Sensitivity to Waste Porosity

Lastly, the code was investigated to test the effect of waste failure with decreasing porosity. If the porosity is lower, then the velocity of the gas moving through the repository to a borehole intrusion is higher. The report by Hansen and coworkers report a porosity of 0.7, which was said to be typical of waste porosity when the pressure reached over 14.8 MPa. However, after investigating the relationship between pressure and porosity, it was found that porosity during the long-term performance of the repository was approximately 0.4 for high pressures, and less for lower pressures. Figure 5 shows the relationship of porosity to pressure for the

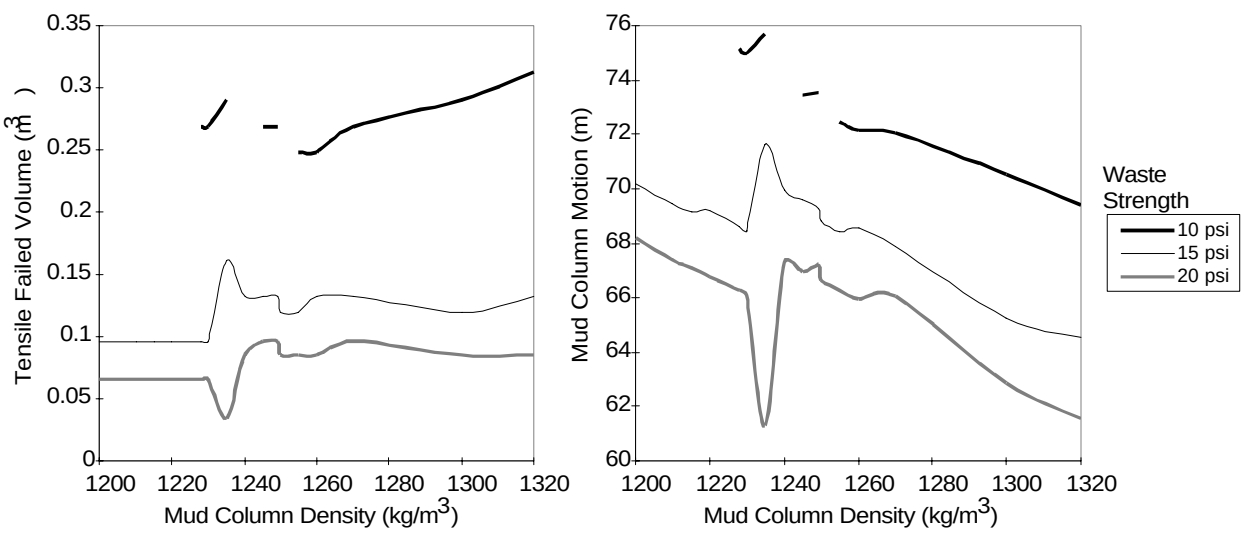

Figure 4. Left) Tensile Failed Volume as a Function of Mud Column Density for Several Waste Strengths. Right) Mud Column Motion as a Function of Mud Column Density. The Discontinuous Curve for the Low Waste Strength of 10 psi Indicates Cascading of Failed Waste at the Values Chosen for the Experiment.

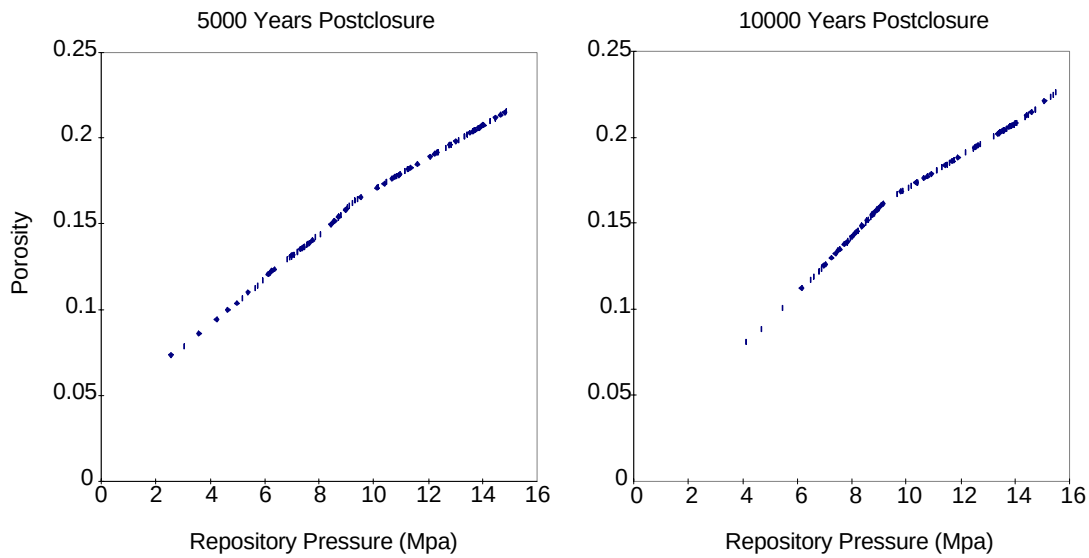

Figure 5. BRAGFLO Porosity Values Versus Pressure Profiles for Undisturbed Scenarios of the CCA.

undisturbed scenario of the performance assessment for the CCA. The figure shows two separate times, at 5000 and 10000 years postclosure using the results of BRAGFLO. The figure reports porosities assuming no compaction of the waste form from consolidation of halite creep. If the room is assumed to shrink by half, then the porosities would double. On this assumption, the actual waste porosities in the repository would be double that of the figure for a given pressure.

Porosity from the two-phase calculations of brine and gas flow through the repository clearly will be lower than anticipated in GASOUT. The response of the code to lower repository porosities shows slightly higher releases. For an extremely low porosity of 0.2, with initial conditions of 14.8 MPa repository pressure, and 10 psi waste strength, the uncompacted spalled volume is 0.47 m^3, and decreases smoothly up to the original porosity of 0.7 and a calculated failed volume of 0.27 m^3. However, porosities above 0.7 and below 0.2 cause the waste to cascade, and results are interpreted as numerical artifacts. Additional experiments using a variety of repository pressures and their expected porosities from Figure 5, does not show any further problems within the code.

-end

In addition to the cavity growth experiments with GASOUT, the option of failed material removal was "turned off", and the affects of decreased permeability was studied again. The surprise result of this new set of calculations shows that the effective stresses in the waste are significantly high to cause radial failure beyond the assumed 0.27 m^3, as presented in Hansen et al. (1997). Figure 6 shows an analogous model for permeability assuming both with and without material failure. The left plot of the figure shows a common scenario with initial repository pressures at 14.5 MPa, permeability equal to 1.7×10^{-13} m^2 and the results from GASOUT with both options of material failure. It shows that material removal produces higher failed volumes than calculations without material removal. The right plot, again with 14.5 MPa initial repository pressure, shows results of GASOUT without material removal for two permeability values. The option for material removal was turned off due to the observations of the above sensitivity analysis. The set of curves on the right-hand-side shows that lower waste permeability produces higher volumes. It therefore can be deduced that if low permeability and waste failure removal calculations are initiated, then the volumes of failed material may be even greater than seen on either plot of Figure 6 It is unknown the exact extent to which material failure will increase. It is plausible that system could attain equilibrium quicker, and the differences are insignificant

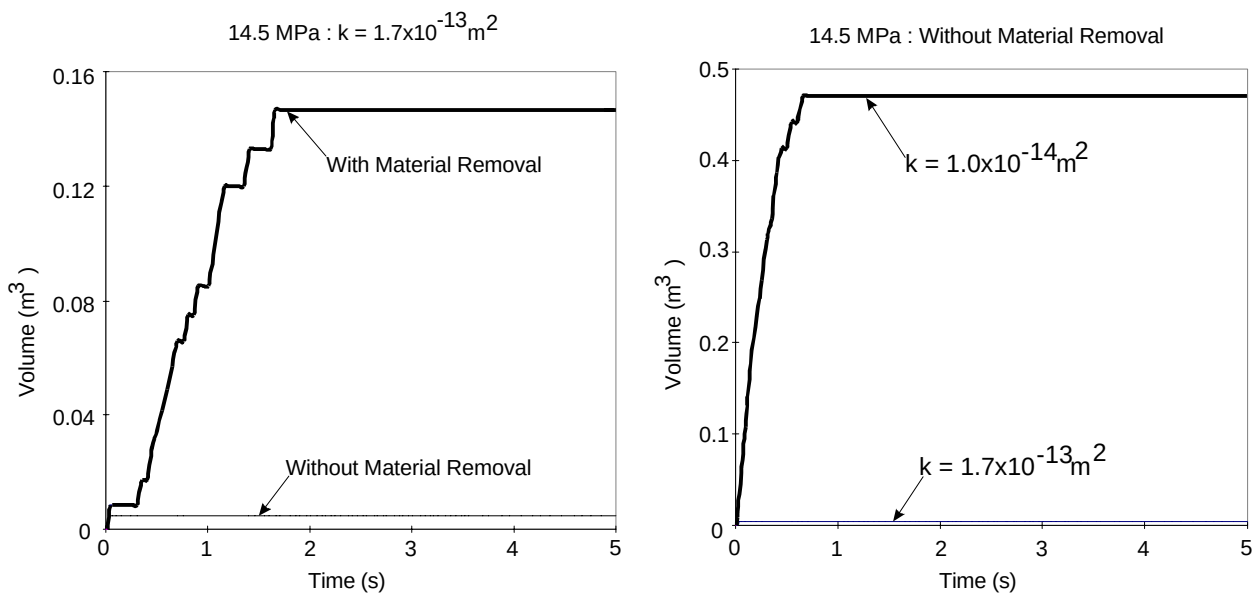

Figure 6. GASOUT Analogy Illustrating The Importance Of Considering Lower Permeabilities. Left) Constant Permeability With And Without Material Removal. Right) Without Material Removal At Two Different Permeabilities.

For an extreme example of the above analogy, Figure 7 shows radial distance of potential failure at permeabilities of 1.7×10^{-13} and 1×10^{-14} m^2 for pressures at 14.8 MPa without material removal. Potential failure was extrapolated from the effective stresses that would exist in non-failed material. The repository pressure was set at 14.8 MPa and waste strength at 10 psi for the experiments in Figure 7.

The figure clearly shows that when permeability is lower than assumed in the CCA then releases will be higher than assumed from the investigation in Hansen et al. (1997). The maximum radial failure at a permeability of 1×10^{-14} m^2 is 1.17 m, equating to an uncompacted spalled volume of 6.6 m^3. It is believed that when permeability is even lower than the lowest value presented in Figure 7, the releases could be higher. However, the code has difficulties with oscillations in pressures at lower permeabilities, and confidence in results is low.

The results of Figure 7 must be kept in context. When material is not removed during the pore pressure calculations (and subsequently total overburden stress), the code does not redistribute values at the new boundary. Instead, the pore pressures decrease in that region, hence lowering the possibility of new failed material. Therefore, Figure 7 actually underestimates the potential effect of failure, and higher volumes will result if the material is removed. These calculations are not possible with GASOUT, with reasons explained from the sensitivity analysis with the code.

Lastly, the issue of shear failure of waste has been eliminated from spall calculations in Hansen et al. (1997) due to its suspected low consequence on overall spall releases. The report by Dr. Frank Hansen and group state that material that fails in shear will not necessarily fragment, and that the region of shear failure is generally less than or equal to the region of tensile failure. The response to the first half of the statement on fragmentation suggests a large degree of uncertainty. The waste will have a residual shear strength component remaining after failure if it does not fragment. Since the nature of the waste already has such a low compressive strength, residual strength after failure will be nominal at best (assuming inelasticity). An average value of 0.75 MPa for shear strength was measured with partially saturated waste surrogates and partially degraded waste forms. After failure, it is assumed that the stresses needed to deform the waste is

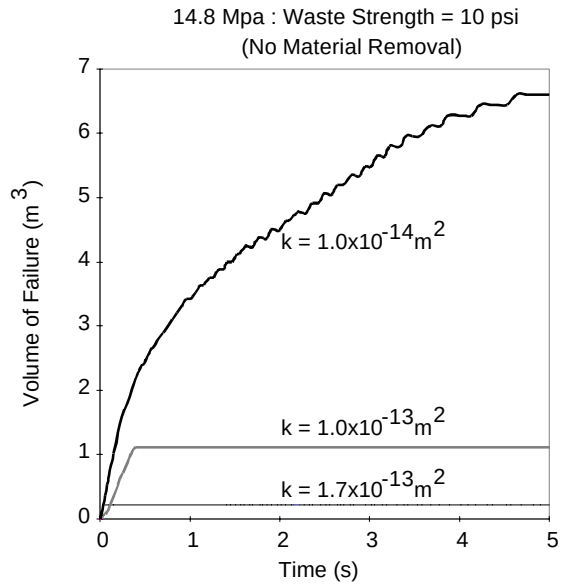

Figure 7. Failure Volume (m^3) vs Time (s) for Different Waste Permeabilities. The results are from GASOUT with the option of 'failed material removal' turned off.

much less, and that the simple act of erosion from the circulating drilling fluid would cause the material to fragment. Therefore, it is conservative to assume that waste failed in shear is totally fragmented.

Considering the region of shear failure, there are some circumstances in which it would be larger than the tensile failed region. Figure 8 shows a calculation by GASOUT without material removal for a typical case of 14.5 MPa repository pressure and permeability of 1.7×10^{-13} m^2. The left plot shows the normal effective stresses in the waste with the tensile strength (dotted line) and the right plot shows shear effective stresses with maximum shear strength. The figure on the left demonstrates that the tensile failed radius will be approximately 0.17 m. The initial borehole radius is 0.1556 m, giving rise to a mere 0.005 m^3 hemispherical volume of failure region. On the right of Figure 8, the shear radius of failure after 5 seconds of simulation shows a value of 0.29 m, equivalent to a hemispherical volume of 0.09 m^3. Though the failed volumes are very slight and may seem inconsequential, the region of shear precedes the region of tensile failure. Furthermore, it is observed that shear failure is an important mechanisms for failure when seepage gradients through the waste are small. For example, when the initial pressure is lowered to 12.0 MPa, no

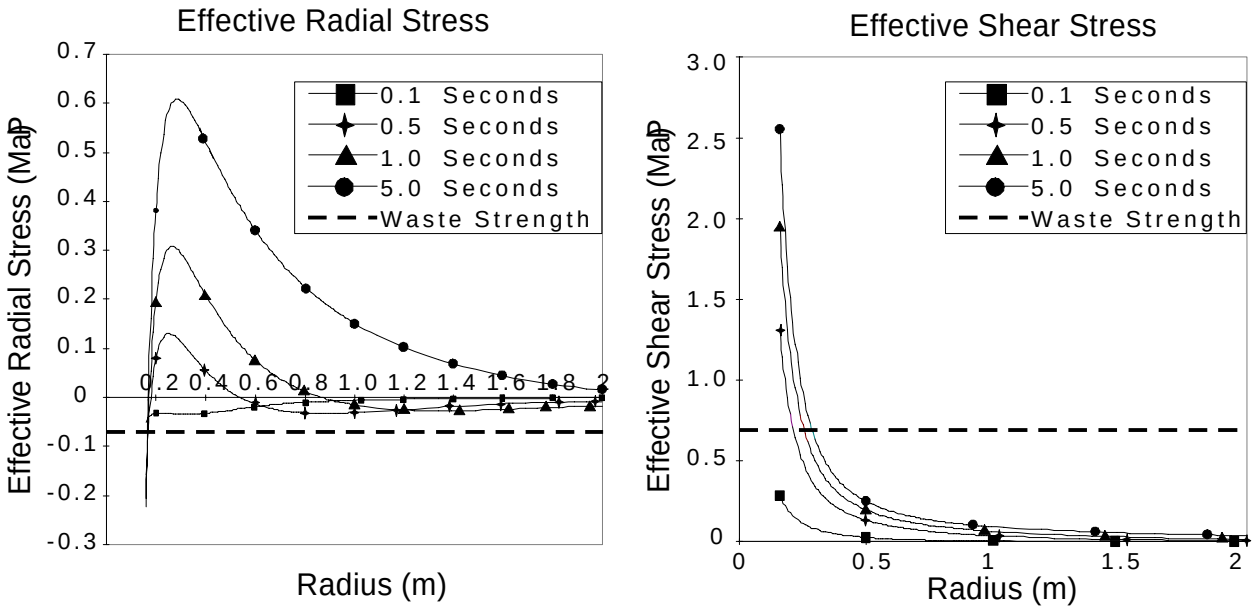

Figure 8. Computed Radial (Normal) And Shear Stresses In A Hemispherical Cavity During Spall From GASOUT, Assuming 14.5 MPa Initial Repository Pressure, 1.7×10^{-13} m^2 Waste Permeability, And No Material Removal From Failure.

tensile failure is observed. Yet, the effective shear stresses in the waste are noticed to increase, and failure for the experiment is seen to occur at approximately 0.3 m from the borehole center. The experiments assume no failed material removal, and it is conceivable that the extent of failure could extend beyond these values. The opposite phenomena is observed when the seepage gradient is high; tensile failure precedes shear failure.

Recommendations for Models:

It is shown that the GASOUT code responds erratically to small changes in the input assumptions, and sometimes gives misleading results. GASOUT was the main code examined, due to its ability to remove material during failure, and for being the major code of spallings verifications for CCA values. EEG recommends that the code be examined more closely, before judging the results of Hansen et al. (1997) as the maximum amount of failed material that will reach the surface, and the spalled volumes calculated in the CCA as reasonable.

It is also recommended that a new spallings code be developed, that incorporates all the aspects of failure correctly. The GASOUT code seems to have difficulty with redistributing the pore pressures once waste has been removed. Also, the code only addressed the concern of tensile

failure. In a hemispherical geometry, tangential forces will cause the material to be in compression, and the material could fail in shear. The GASOUT ignores shear failure as a possible mode of failure, although it is calculated. The strength of the waste is nominal in compression (measured values in Hansen et al., (1997) show a typical value of approximately 100 psi), and the pressures exerted from the overburden rock could cause the material to yield.

2.4.3.3 EPA's Model Prediction of Spallings

The EPA funded a separate investigation of the spallings phenomena that focused on potential limits on spall material reaching the surface because of insufficient lofting capacity of gases vented from the repository. The investigation is described in two reports (U.S. EPA, 1997e and 1997f). The first report assumes that spall occurs prior to penetration of the drill into the repository. It also assumes that the volume of material removed by the spallings process can be ignored. The second report assumes a one to two foot penetration of the drill string into the repository concurrent with formation of a spall cavity. The EPA investigation determined that venting of the repository would not be energetic enough to bring spall material to the surface. The conclusion is valid for evaluating the CCA spallings model but can't be extended to the most recent DOE spallings model. The investigation's focus is on relatively long term transport capability consistent with the CCA spallings model, not immediate transport of material from the formation of an explosive spall cavity, as in the most recent model.

The main emphasis of the EPA investigation is to explore whether there will be sufficient gas velocities in the repository-borehole system to transport particles, created by the spall process, to the surface. The ability of gas to entrain solid material is well understood. Vertical entrainment of larger particles requires greater gas velocities than smaller particles. The calculations predicted the maximum sized particle that could be transported to the surface by comparing calculated velocities to an established relationship of maximum size of entrained particles to hydrogen gas velocity. Three regions were examined to determine the most stringent limit on the size of transported particles. The smallest calculated velocities occurred in assumed void space created by the spall process. Applying the maximum particle size estimate to these velocities results in a prediction of 70 microns as the largest size particle that could be brought to the surface. 70

microns is smaller than the lower limit of particle distribution determined by the "particle size" expert elicitation panel. This leads the EPA investigators to conclude that spallings is a self-limiting process because of the inability of lofting new spall material from the cavity.

The spallings model used in the CCA performance assessment assumed that erosion of waste material would form channels in the repository room. The erosion process could last for days. The EPA investigation adopted an 11 day-long time frame and assumed that the first few seconds were not significant. This allows the adoption of cylindrical , one dimensional, radial flow approximation of flow through the repository to a borehole. The approximation is accurate only when pressure depletion extends far enough into the repository that a region, a few repository thicknesses in size, has a fully developed gradient. A fully developed gradient means, roughly, that little of the flow in the region is derived from local depressurization. Once the fully developed gradient forms, a pseudo skin factor is required to correct the one dimensional model for the two dimensional flow pattern near the borehole. The pseudo skin factor accounts for the fact that the drill was assumed to penetrate the repository only a few feet. The skin factor is applied as a permeability reduction of the repository waste near the borehole. This factor is 0.075 for a one foot penetration and 0.16 for a two foot penetration distance ($2.x10^{-5}$ with no penetration).

Both EPA reports are superceded, however, by the spallings model presented in January 1997 to the conceptual model peer review panel (Hansen et al., 1997). This model predicts that almost all spall would come from the face of the drilling cavity. The spall process would occur in the first few seconds of repository depressurization.

The permeability reduction used in the EPA model is inappropriate to address removal of the initial spall material. The spallings model of Hansen et al. (1997) predicts spalling will stop after a few seconds and that depressurization is negligible beyond roughly 1.5 meters at this time. Figure 5..6 of Hansen et al. (1997) presents the calculated pressure in the repository as a function of distance and time in the region of the borehole. During this initial depressurization the source of

flow is from the region close to the borehole. It is this local depressurization that would cause spalling to progress away from the drilling bit.

The temporal and spatial discretization of the EPA investigation is far too coarse to investigate the potential for evacuation up the borehole of spall material created in the first few seconds. For example, in the case of a two foot penetration with 0.25 m^3 spall cavity, the first element of the EPA analysis is 0.39 m thick. In the Hansen et al. (1997) model, the first element is 0.01 m thick. In the EPA investigation the first time step is 86 seconds compared to 0.001 seconds in the Hansen et al. (1997) model. These differences in both temporal and spatial discretization are an indication that the EPA modeling can not predict gas velocities from local depressurization reliably. Hence, the two EPA reports can't be used to judge the conservatism of the spall model described in Hansen et al. (1997), nor the extension of the Hansen et al. (1997) model to potential spall from air drilling.

Hansen et al. (1997) also considered the issue of maximum particle size that could be transported up the borehole. Figure 6-22 of Hansen et al. (1997) indicates that particles as large as 10,000 microns may be transported to the surface after the mud column has been expelled from the borehole, about 250 seconds after intrusion, and that transport of such large particles could occur for much more than 200 seconds. Two-hundred and fifty seconds is still very early in the EPA investigation (3 time steps). The discritization of the EPA model is too coarse to accurately calculate the flow rates this early in the 11-day period.

The calculated mass flow rate of gas up the borehole does not increase at 250 seconds, in the Hansen et al. (1997) model. Instead, the carrying capacity of the gas jumps because of lower pressure in the borehole due to the removal of the mud column. This confirms the appropriateness of neglecting the mud column in the EPA investigation.

A less important criticism of the EPA investigation is the reliance on velocities calculated in the spall cavity. The velocities are calculated by dividing the flow up the borehole by the area of the entire cavity as if all the flow was vertical. Gas velocities in this region are not spatially constant

and not vertical. Simple mass conservation implies that the velocities must be greater near the drill collar. In addition, particles need not be lofted in this region to be transported, except right at the borehole where the cavity velocities are greatest. Particles may be transported towards the borehole by both collapse of the spall material into the cavity and the drag of the radial velocities of the gas moving toward the drill collar annulus, even if the velocities are too weak to loft the particles. Horizontal transport by gas is known as saltation and should be recognizable to people who have witnessed an aluminum can being bounced along a roadway by the wind. In the case of the can, the wind velocity is rarely large enough to loft the can but the can bounces off the ground as it moves. The blowout experiments conducted for DOE (Lemke et al., 1996) demonstrated that, for material without cohesive strength, particles will be moved radially toward the gas vent. These experiments indicated that the cavity formed by material carried out the vent is filled by material being transported toward the vent along the upper surface of the cohesion-less mass of particles.

For consideration of removal of spall created in the first few seconds of a drilling intrusion into the repository, the calculations of Hansen et al. (1997) are more accurate than those of the EPA investigation because of the use of a one-dimensional cylindrical geometry and coarse discritization in the EPA model. The EPA investigation underestimates velocities during a spallings event. Based on the information supplied by Hansen et al. (1997), large enough gas velocities are likely to occur during a spallings event, for a long enough period, to transport large amounts of the spall material up the borehole. In conclusion, the calculations of Hansen et al. (1997) indicate that transport of spall material up the borehole will <u>not</u> limit the release of spall material to the surface.

2.5. AIR DRILLING

This section is to address the concerns of the EEG on the issue of EPA's Analysis of Air Drilling at WIPP (U.S. EPA, 1998). Based on its own analysis of Air Drilling in the Delaware Basin of New Mexico, the EPA has concluded that the air drilling scenario did not have to be considered in the DOE's Compliance Certification Application.

Dr. John Bredehoeft first proposed air drilling as a plausible scenario at WIPP in 1997 and conducted a modeling experiment (Bredehoeft, 1997a) to quantify the amount of spalled material that would be brought to the surface if the repository was inadvertently breached by a drill intrusion, using air as the drilling fluid. Drilling with air results in lower hydrostatic pressures in the bottom of the borehole, thus the possibility of higher pressure- gradients through the waste repository. Bredehoeft used the code GASOUT for his modeling, admitting that the code was not written for this purpose, but if used with caution, could yield approximate results. Bredehoeft concluded that air drilling could potentially violate the containment requirements of 40 CFR Part 191.13.

The DOE disputed Bredehoeft's modeling analysis, based on incorrect usage of the code. DOE argued that the code was designed for drilling with an incompressible fluid, and for low seepage gradients. When the code was used in Bredehoeft's study, it produced large amounts of waste failure, which were on the order of 500 - 2000 m^3. These high volumes were easily explained, argued DOE, and that the results were highly unlikely to occur at WIPP.

Further analysis by the EEG, which investigated the amount of brine that could be released through an air drilling event, also concluded that large amounts of radionuclides could be brought to the surface. The EEG estimated that the maximum amount of brine that could be blown out of the repository would be approximately 2000 m^3. However, the DOE showed that the EEG analysis contained conceptual errors and the EEG accepted the DOE's criticism.

Finally, the EPA conducted its own analysis and concluded that air drilling scenario of release is not valid on the basis of both low probability and low consequence. The following two sections respond

to the EPA invitation for comments on the EPA analysis.

2.5.1 EEG's Critique of EPA's Air Drilling Analysis

The WIPP is located in a resource rich area and the EPA Standards for the disposal of transuranic waste require that the DOE application address inadvertent human intrusion. However, the DOE Compliance Certification Application did not address the issue of air drilling. In calculating the impact of resource exploitation on the cumulative release of radionuclides from the repository, the CCA performance assessment calculations addressed only the actual drilling event and only drilling methods which use brine as the drilling fluid.

In a report titled *Air Drilling into WIPP*, Bredehoeft (1997a) makes a compelling argument that the application needs to consider other known drilling technologies, such as the use of air rather than brine for the drilling fluid. The repository performance must be determined for the next 10,000 years and Bredehoeft notes that technologies, such as drilling, have changed in the past and will probably change in the future. He suggests that EPA required the DOE to treat the historical drilling rate as representative of the full 10,000 years to accommodate changes in drilling technology and mineral economics including minerals not currently in demand (Bredehoeft, 1997a, p. 1). Indeed, the preamble to the EPA Criteria states:

> In effect, when used for the purpose of determining the future drilling rate, today's drilling activities act as surrogates for the unknown resources that will be drilled for in the future (U.S. EPA 1996, p. 5233).

It is not clear that EPA's assumption of a constant drilling rate was intended to compensate for future changes in technology. Nonetheless, Bredehoeft identifies a problem that needs to be addressed. Bredehoeft attempts to prove, with a known drilling technology, that the assumption of a constant drilling rate for 10,000 years is not adequate to accommodate technological changes and he calculates the release of radionuclides from the repository as the result of a drilling intrusion. His calculations show a much larger release of radionuclides to the surface as a result of using air rather than brine

for the drilling fluid.

2.5.1.1 Scenario Rejected by DOE and EPA on Basis of EPA Regulation

While Bredehoeft is proposing that an air drilling scenario be considered both, U.S. DOE (1998) and U.S. EPA (1998) have reiterated the position that the air drilling scenario can be ruled out on the basis of regulation. Within the confines of considering only the actual drilling event, the EPA Criteria specify a future state assumption for which:

> Performance assessments shall document that in analyzing the consequences of drilling events, the Department assumed that: 1) future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. Such future drilling practices shall include, but shall not be limited to: the types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of such boreholes that are sealed by humans (U.S. EPA, 1996, §194.33(c)(1)).

On October 29, 1996, the DOE submitted the Compliance Certification Application. Appendix DEL states:

> There are a variety of drilling fluids used in Delaware Basin drilling. Most rotary drilling operations use saturated brine (10 to 10.5 pounds per gallon) as a drilling fluid until reaching the Bell Canyon Formation, where intermediate casing is set. (U.S. DOE, 1996c, p. DEL-32).

Hence, the CCA calculations are based on the assumption that all future drilling through the Salado Formation will be done with brine as the drilling fluid and drilling with any other fluid can be ruled out citing regulatory considerations.

The NEA/IAEA International Review Group (IRG) expressed its reservations about scenarios

rejected on the basis of regulatory consideration in the absence of logical or physical arguments for such a scenario rejection (NEA/IAEA, 1997, p. 19). This appears to be an obvious shortcoming.

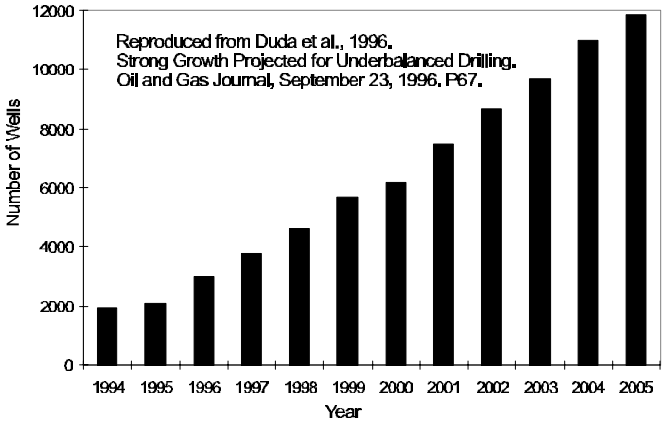

Fig. 9. DOE's projected use of underbalanced drilling in the United States.

Bredehoeft did not limit his consideration of scenarios to a choice of drilling fluid. He observes that air drilling is a proven technology and its frequency of use by the oil and gas industry is increasing as shown in Figure 9. An examination of published materials shows that use of underbalanced drilling, including air drilling, is expanding in the oil and gas industry with the explicit support of the DOE Office of Fossil Energy (Duda et al, 1996) and strongly suggests that the analyses may need to include other methods of underbalanced drilling, including foam, mist, dust, aerated mud and light weight solid additives.

2.5.1.2 Entire Delaware Basin not included in DOE and EPA Review of Records

U.S. DOE (1998) and U.S. EPA (1998) maintain that the drilling fluid used in the PA calculations is limited to current practice in the Delaware Basin which does not include air drilling. They do note a few exceptions in previous years and the more recent use of air drilling on one occasion to address a lost circulation problem.

With respect to current and historical practices, the DOE examined records on file with the New Mexico Oil Conservation Division (U.S. DOE, 1998, p. 5-12). The EPA examined 203 randomly

selected drilling records from the NMOCD files for Eddy County and Lea County (U.S. EPA, 1998). The DOE and EPA each conclude, from information in the New Mexico records, that air drilling has rarely been used in the Delaware Basin.

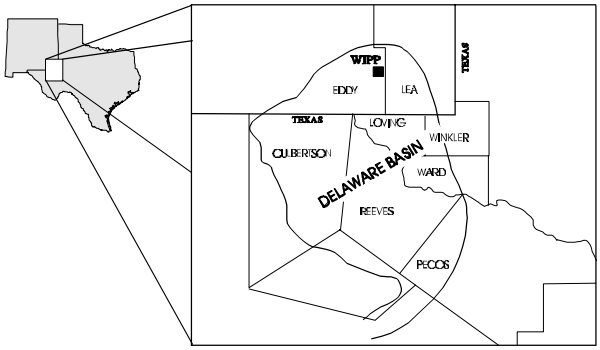

Fig 10. New Mexico and Texas Counties in the Delaware Basin

While, the EPA Criteria requires consideration of practices in the entire Delaware Basin, neither agency reviewed the Texas records although a large portion of the Delaware Basin is located in Texas. EPA documents a conversation with Mark Henkhaus, District Manager of the Texas Railroad Commission in Midland, Texas who indicated that Burlington Resources has done air drilling in Reeves and Pecos Counties, Texas. Although not noted in the EPA document, Reeves County, Texas lies entirely within the Delaware Basin. Compliance with the EPA Criteria requires examination of the appropriate Texas records as well as the appropriate New Mexico records.

2.5.1.3 Potential Inadequacy of Public Records

The EPA survey of drillers, consultants, and state employees found:

> None of the individuals contacted were aware of any oil industry related wells drilled within 20 miles of the WIPP Site using air technology ***for any purpose*** [emphasis added]. In addition, New Mexico Oil Conservation Division (NMOCD) regulatory personnel in Hobbs and Artesia indicated that no wells have been drilled from the ground surface with air in the New Mexico portion of the Delaware Basin because of

> the problems cited above (U.S. EPA, 1998, p. 13).

While the EPA survey did not find a single instance of oil field air drilling within 20 miles, EPA noted (U.S. EPA, 1998, p. 6) that the DOE found some evidence of a well having been partially drilled with air about 8 miles east-northeast of the WIPP Site Boundary. DOE stated:

> The information in the NMOCD and BLM records do not show evidence of air drilling at the Lincoln Federal #1. All information presented below was obtained verbally from representatives at Collins & Ware, Inc., the operator, and McVay Drilling, the driller of the well (U.S. DOE, 1998, p. 7).

The EPA also could not find any direct information documenting the use of air drilling. The use of air drilling was inferred from "statements in the well files that indicate that air was circulated while casing was set to the top of the Delaware Basin" (U.S. EPA, 1998, p. 6).

Neither DOE nor EPA could find documentation in the public record directly stating that this well was partially drilled with air. This raises a very important question about the reliability of the New Mexico records to document air drilling. If air drilling was indeed used in this well and that information is not stated in the public record, how many other wells have been drilled with air (foam, mist, aerated mud, or other underbalanced methods) without documentation? No conclusion can be drawn about the documentation in the Texas records for the Delaware Basin because apparently that search does not appear to have been conducted.

The DOE also conducted a survey of thirty drilling companies. Six were no longer in business, four had been acquired (by companies that did respond to the survey), and five could not be contacted. Fifteen companies responded. It was fortuitous that the company that drilled the Lincoln Federal #1 well was still in business and that the staff responding to the U.S. DOE (1998) inquiry remembered the use of air drilling for this very unusual well.

Although there were no direct statements on file in the public record, there is no question that this well was partially drilled with air. Page four of the actual drilling record clearly states:

4/11/91: Day -10

> Drilling at 2620', made 735' in 19 1/2 hours. Formation Anhydrite and salt. MW 10, Vis 28, Ph 8. Bit #3 12 1/4" HTC, R-1, Jets 3/13's, in at 852', out at 2320', made 1468' in 39 1/4 hours, WOB 15-20,000, RPM 70. Bit #4 12 1/4" HTC, J-33L, Jets 3/13, in at 2320', made 300' in 7 hours, WOB 30,000, RPM 70. Pump #1 SPM 70, GPM 237, PP 700. Deviation survey at 1945' 1/2º, at 2320' 3/4º.
> TIME BREAKDOWN: 2 hours drilling, 1 hour circulate out air pocket and water flow, 1 1/2 hours drilling with water flow, 1/2 hour survey, 9 hours drilling with partial returns, 3 hours trip for new bit and survey, 7 hours drilling with no returns. Hauled 8 loads of formation water to disposal. Will continue to dry drill until air compressors on location and set up to air drill. [Emphasis added].

4/12/91: Day -11

> Drilling at 2984', made 364' in 9 hours. Formation salt and anhydrite. MW brine water. Bit #4 12 1/4" HTC, J-33C, jets 3/13, in at 2320', made 664' in 16 hours, WOB 20-30,000, RPM 76. Pump #1 SPM 90, PP 1100-600 psig. Deviation survey at 2667' 1 1/4º, at 2915' 1 3/4º.
> TIME BREAKDOWN: 2 1/2 hours drilling with no returns, 1/2 hour deviation survey, I hour drilling, 1/2 hour pull 20 stands, 5 hours wait on brine, 1/2 hour trip out of the hole, 4 3/4 hours nipple up rotating head, change flowline and hook up compressors, 1 3/4 hours trip in hole, 1/2 hour install rotating head, 1/2 hour establish circulation, 3/4 hour air drilling, 1/2 hour repair flowline, 4 1/4 hours air drilling, 1/2 hour totco, 1/2 hour air drilling.

Air drilling was used to overcome a lost circulation problem. However, the use of air drilling was not documented in the public record, which raises the concern that there could be other wells that were either fully or partially air drilled without public documentation.

The EPA and DOE report the use of air drilling in areas outside the Delaware Basin, based on discussions with various drillers. Could that information have been discerned from the available public record? There is no indication that either DOE or EPA verified that information obtained from drillers is also contained in the public record.

2.5.1.4 Water Influx

Based on a survey of drillers, the DOE maintains that the potential influx of water is a deterrent to drilling with air. U.S. EPA's (1998) industry survey also found that large water inflow was the most commonly cited reason why air drilling is not conducted in the Delaware Basin, including the area around the WIPP Site. But as noted in the EPA survey of drillers, "air drilling technology is improving at a relatively rapid pace and new larger rigs are capable of handling more water influx than in the past" (U.S. EPA, 1998, p. 9). EPA acknowledges that air drilling technology is capable of handling higher water inflows by using larger air compressors (U.S. EPA, 1998, p. 15) which is consistent with the observation that "new equipment is available" (U.S. EPA, 1998, p. 9). Furthermore, the DOE and industry are also optimistic about the potential market for light-weight fluids not adversely affected by the invasion of other fluids and the use of light weight solid additives to overcome contamination problems associated with fluid influxes (Duda et al.,1996, p. 76) .

The drilling report for the Lincoln Federal #1 includes the following important notation, at the bottom of page four, indicating air drilling moved large volumes of water from 2000 feet up to the zone of lost circulation and the remaining water up to the surface pit.

> **NOTE: Both Air and Brine are being pumped; pit gain with air on hole; pit loss without. We are drilling with air until pits fill up, then dry drilling using brine water that is in the pits. When pits get low we go back to air drilling.

The actual drilling record was used to prepare the following account:

> On April 2, 1991, drilling was initiated for a gas well on Lincoln Federal No. 1 in Section 26, T21S, R32E, NMPM, in Lea County, New Mexico about 8 miles (13 km) east-northeast of the WIPP Site Boundary (Collins & Ware, Inc., 1991 pp. 1-4). On the third day of drilling and upon reaching a depth of 1292 feet, all of the circulating fluid was lost to the formation. The driller began hauling in water to continue drilling. Drilling with water continued for ten additional hours on the fourth day. A survey confirmed 100% circulation loss in the two foot interval from 1290' to 1292'.

> Attempts to seal the formation with cement over the next 5 days largely failed as evidenced by the continued loss of circulating water to the formation. Nonetheless, on the tenth day, drilling continued until an air pocket and brine flow were encountered at 2000 feet. Brine from this formation began filling the surface pit, which is used to contain the circulating fluid. Drilling continued for 1 1/2 hours with brine flowing into the pit. The driller then hauled eight loads of brine to disposal and continued drilling for 9 hours with partial returns of brine to the surface. Apparently, while the brine flowed to the surface, much of the brine continued to flow into the two foot interval between 1290' and 1292'. The drilling report documented an additional 7 hours of drilling with no returns. On the eleventh day, after 3 1/2 hours of drilling with no returns, air drilling was initiated. As drilling continued, the pit filled with formation brine. Once there was sufficient brine in the pit, the brine was used as the circulating fluid for drilling until the pit was nearly depleted. Then air drilling resumed until the pit again filled with brine (Silva, 1994, pp. 63-64).

U.S. EPA (1998, pp. 15-16) presents an argument that water inflow will prevent air drilling in the vicinity of the WIPP. The argument must be viewed with caution. Although EPA alludes to cost limitations, there is no cost analyses for drilling a specified well in the vicinity of WIPP. Instead, referring to information from one industry contact (unnamed) and applying methodology presented by Lyons (1984, p. 109), EPA determined that the reasonable upper bound for water removal under current air drilling practice is in the range of 10 to 20 gallons per minute (gpm). EPA maintains that water inflow into a hole drilled at the WIPP Site would originate primarily from Culebra Dolomite and calculates that wells in the vicinity of WIPP with transmissivities greater than 1×10^{-5} m^2/s identify areas in which water inflow would prohibit air drilling. Furthermore, EPA states “other wells in the area have transmissivities in the 10^{-6} to 10^{-5} m^2/s range, causing much of the WIPP Site to be borderline for feasible air drilling” (U.S. EPA, 1998, p.16).

The wells in the immediate vicinity of the WIPP shafts, H-1, H-16, and ERDA 9, each have transmissivities on the order of 10^{-6} m^2/s. That these would be “borderline for feasible drilling” is

somewhat difficult to understand in view of the measured inflow data for that area, which ranged between 0.3 gpm to 0.9 gpm with an average of about 0.6 gpm (D'Appolinia, 1983, p. 5-2). And that was for the six foot diameter ventilation shaft. An oil and gas well would have a much smaller diameter, hence, an even lower inflow.

With respect to the EPA comment that "the reasonable upper bound for water removal under current air drilling practice is in the range of 10 to 20 gallons per minute," EEG contacted the drilling design engineers of ECD Northwest who confirmed that current air drilling technology could easily handle water inflows on the order of 500 gallons per minute. Moreover, water inflows during drilling can be successfully inhibited by a variety of methods including, for example, reacting a monomer and catalyst in the water producing zone to form a polymer skin. The feasibility of such treatments was a matter of cost. EEG did not ask for the estimated cost of actually air drilling a well at WIPP but simply wanted to know the upper bound for water removal under current air drilling practice.

The DOE concludes that air drilling is not well suited to WIPP based on discussion with fifteen drillers with experience in the area. The DOE report does not include any detailed engineering or economic analysis for the actual cost of underbalanced drilling of a well near WIPP. If DOE and EPA are going to rely on interviews with drillers, than they must also consider the published concerns of others in the industry including drilling fluid manufacturers and suppliers who compete in an industry that must stay at the cutting edge of technological developments. In their recent catalog of supplies, Clearwater, Inc., a company which manufactures and supplies chemicals for underbalanced drilling offers the following thoughts:

> It has been an industry wide misunderstanding that very few wells are suitable candidates for drilling balanced to underbalanced. Through recent technological advancements, many obstacles have been overcome and what was once unthinkable is today "NO PROBLEM". (Capitalized in the original).

In discussing recent technological developments in underbalanced drilling, Clearwater, Inc. also

states:

> Many operators who have attempted air drilling and failed have abandoned the technique. These operators may not have kept abreast of the latest developments. The limited use of air drilling techniques, relative to fluid, is primarily a function of the limited knowledge of new developments and the industry's natural resistance to changing methods. The level of expertise in air drilling technology currently found is comparable to the industry's generally limited knowledge of hydraulic fracturing methods two decades ago.

The EPA should consult with the DOE Office of Fossil Energy. As one DOE sponsored study noted, unfamiliarity with light-weight fluids and the perception of high cost were the two primary reasons operators gave for not using light-weight fluids more often (Duda et al., 1996, p. 76). The DOE Office of Fossil Energy continues to participate in an effort to promote the understanding and use of underbalanced drilling technology.

2.5.1.5 Analysis Conclusions

Bredehoeft (1997a) identified how the drilling rate specified by the EPA Criteria cannot accommodate even a small technological change, such as using air drilling rather than brine drilling for resource recovery in the vicinity of the WIPP.

The DOE and EPA reject the air drilling scenario on the basis of regulatory considerations. Yet the DOE and EPA review of records to determine drilling practices did not include the Texas portion of the Delaware Basin despite verbal information referring to such drilling activities.

DOE and EPA's examination of the New Mexico records raises questions about the adequacy of such records to provide complete information on the use of underbalanced drilling in the New Mexico portion of the Delaware Basin.

The EPA arguments concerning the inability of air drilling to handle water inflow at the WIPP appear to lack merit given the actual measured inflows and the current state of air drilling technology.

The DOE interviews with drillers found that they would not consider using air drilling near the WIPP site. However, written statements by others in the air drilling industry, including the DOE Office of Fossil Energy, identify an industry wide misunderstanding that as led some operators to incorrectly conclude that some wells are not suitable to air drilling. They note that the limited use of air drilling techniques, relative to fluid, is primarily a function of the limited knowledge of new developments and the industry's natural resistance to changing methods.

2.5.2 The Improper Use of the Quasi-Static Method for the Prediction of Spallings

To quantify the consequence of drilling with air as the fluid used for bit lubrication and cuttings removal upon a drill intrusion at the WIPP, the EPA adapted the Quasi-Static spreadsheet model that was described in Hansen et al. (1997) for an air drilling scenario. The results of modeling the air drilling scenario can be found in U.S. EPA (1998). The model was originally designed for drilling with a brine mud medium. The code produced reasonable results for an air drilling model, in that it did not calculate extremely large stresses in the waste near the borehole, considering the large pressure difference between the intruding borehole and the highly pressurized repository. Therefore, it was assumed that the code could be used for the air drilling scenario. However, the model was not developed to predict failure. The code is only capable of calculating stresses in the waste assuming that no material has been removed. Extrapolating a failure from the results of the code misrepresents its design, and may lead to false interpretations.

2.5.2.1 Quasi-Static Model

The Quasi-Static model was developed with three main purposes (or elements): 1) to calculate the motion of the mud column up the borehole, 2) calculate the gas flow within and from the repository, and 3) to calculate stresses in the waste. All three processes are coupled by the pressure at the bottom of the borehole (bottomhole pressure), and are described quite well in Hansen et al. (1997) or Gross and Thompson (1997).

The implementation of the numerical model for the three elements was established by using two spreadsheets. The first spreadsheet calculated the gas flow and pressures within the repository as well as the motion of the drilling mud being expelled from the borehole from a high bottomhole pressure. The second spreadsheet calculated the effective stresses in the waste as a function of radial distance and time from the total stress exerted by the overburden rock and saturated waste and the pore pressure calculations of the first spreadsheet. This was accomplished by numerical integration of the governing equations in Gross and Thompson (1997) by the Runge Kutta method.

The name Quasi-Static refers to the steady state approximations to the analytical solution of the

gas flow equation. The steady state analytical solution differs from a fully transient numerical model, and thus disregards some aspects of flow such as compressibility. The steady state solution assumes that the boundary condition at the borehole is constant. However, since the boundary will change in time during an intrusion at WIPP, the solution undergoes a series of steady state calculations to calculate the pore pressures in the waste and the mud motion up the borehole as a function of time. The solution has been verified by the transient flow calculations of the GASOUT code (Hansen et al., 1997). The results of the two codes show very close agreement.

Once the pore pressures in the waste are known, they can be used to calculate the effective stresses in the waste. If the pore pressures in the waste are greater than the total stresses within the repository and the strength of the waste, then the effective stresses are negative, indicating that the waste could fail. However, the code does not consider the removal of waste in the borehole cavity, and the calculation of pore pressures will decrease as the gas flows from the repository to the borehole. Once pore pressures decrease, the effective stresses increase positively, meaning that the carrying capacity of the waste from the overburden rock must increase. Once this happens, the waste will no longer fail. Since the code was not designed to handle waste removal, the estimation of failure can only be accurate at very early times (most accurate after the first time step). If the code did consider waste removal, the pore pressures would redistribute near the borehole cavity boundary, and the pore pressures in the waste would be higher. Higher pore pressures give rise to more waste failure. The calculation of waste removal was conducted in the code GASOUT (Hansen et al., 1997), and the option can be turned off for comparison with the Quasi-Static model.

2.5.2.2 Application to Air Drilling

The EPA used the Quasi-Static model to calculate spallings from an air drilling scenario (U.S. EPA, 1998) to dispel the scenario from a low consequence point-of-view. The use of the Quasi-Static model on an air drilling scenario to calculate waste failure and blowout is misleading in two ways. First, the calculation of drilling mud motion up the borehole was derived from forces that accelerate the mud upwards. The acceleration of the mud column depends on an incompressible

fluid, i.e., the density is not pressure dependent. The input for the Quasi-Static model uses the density of the boring fluid to calculate the hydrostatic weight of the mud column. Since this is a constant, the weight is a function of the borehole length only. During an air drilling scenario, the air would decompress quickly near the top of the borehole, and the weight of the column would be less. The result would be higher gas flow from the repository, and hence lower total stress and pore pressures near the boundary. The EPA calculated that the blowout of the mud column would take 9.1 seconds. If the air were allowed to decompress, the acceleration of the air column would be greater than that calculated in the Quasi-Static model, and blowout would occur much more quickly than anticipated. The consequence could lead to higher releases of waste in the borehole cavity.

The second misleading interpretation of air drilling model with the Quasi-Static model is the amount of failed material extrapolated from the results of calculated effective stress. The effective stress is calculated from the difference between the total stress of the waste and overburden rock and pore pressures, and is quantified by the equation

$$\sigma' = \sigma - \mu \qquad (2.5\text{-}1)$$

where σ' is effective stress, σ is total stress, and μ is pore pressure (Terzaghi and Peck, 1948).

Effective stress is the stress applied to the grains of material in a saturated medium. Effective stress cannot be measured, and is only a calculated quantity from the other two constituents of the equation. In order for the material to fail in the borehole cavity, the pore pressure must be greater than the total stress of the repository. In normal applications, the total stress is always larger than the pore pressure, and the effective stress is the resultant stress applied to the material on the macroscopic grain level. For this case, where pore pressure is larger, the effective stress is less than zero, and hence cannot sustain the force of the material in contact. In addition to the total stress, the pore pressure must overcome the strength of the material before it will fail. Again, in normal geotechnical applications, the strength of soil in tension is practically zero for cohesionless material (sand and gravel), and nominal in clays. In this application, where cementation of MgO backfill is considered, along with the pressurization and saturation of waste material, the tensile strength was measured to be approximately 10±5 psi (0.07±0.04 MPa).

The results of air drilling from the EPA's analysis at WIPP is reproduced here in Figure 11. The figure shows effective stress versus radial distance within the repository at several times during the simulation. The EPA judged failure in this figure by estimating the point at which the effective stress is less than the strength of the material (indicating high pore pressure). This point is at 1 second from the beginning of the simulation, with a radial failure distance of 0.69 m (1.4 m^3 of uncompacted waste). After 1 second of simulation time, the pore pressure in the waste near the cavity begins to decrease, and the effective stress moves upwards (increases positively) towards the region of higher total stress.

It is stated here again that the code was not designed to calculate failure, and it can only be used to estimate the stresses in the waste assuming that no waste has been removed from failure. If failure of waste is to be assumed from the Quasi-Static model, then it can only be inferred from

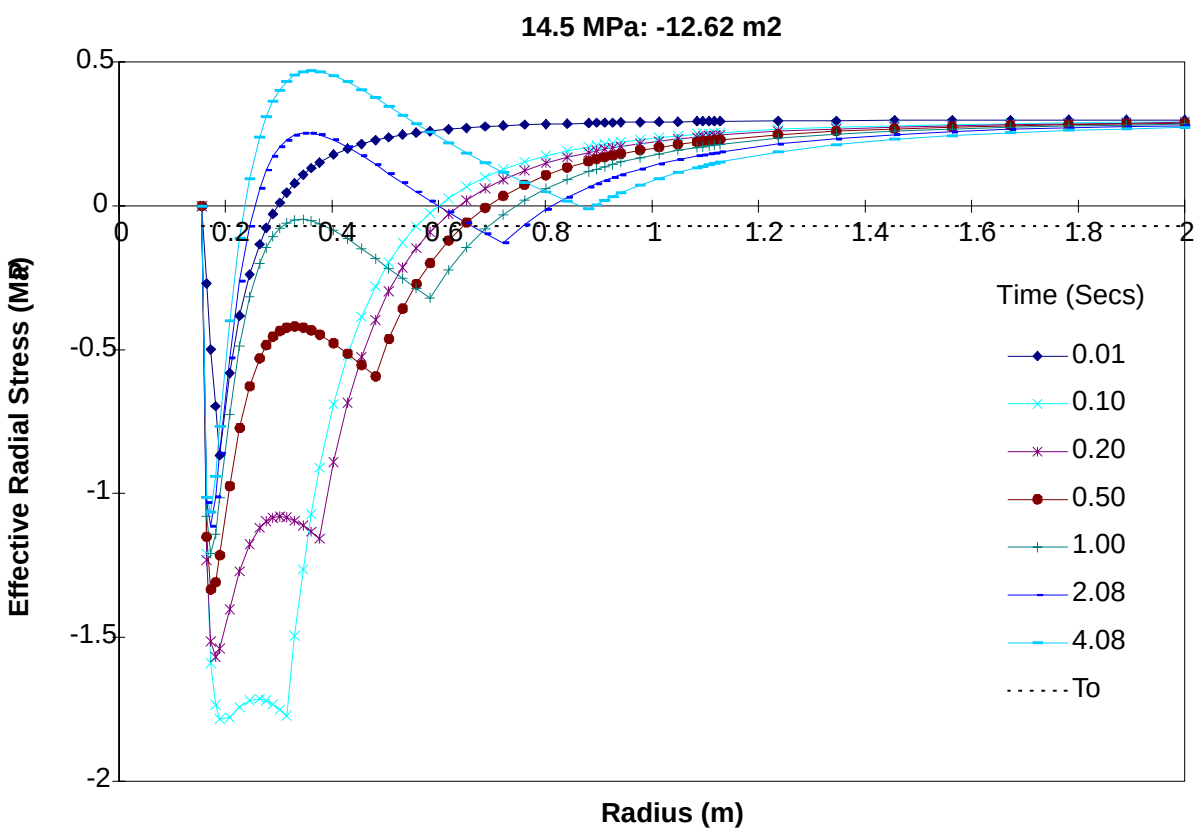

Figure 11. Effective Radial Stress As A Function Of Radial Distance For The EPA's Air Drilling Analysis.

early times during the simulation. To demonstrate the difference in the Quasi-Static model to a model that recalculates stresses after material removal (a.k.a. cavity growth) the results were compared using brine mud as the drilling fluid, since the cavity growth model cannot accurately predict failure with the use of air as a drilling medium. The results show that the Quasi-Static model predicts a failure radius (as estimated from effective stress) of 0.44 m, and the cavity growth model calculates a 0.25 m under the same condition. The same cavity growth model calculates a failure radius of 0.16 m when the option of failed material is turned off. So, the comparison tends to demonstrate that the removal of waste during the stress calculations will predict higher volumes of failed waste.

Intuitively, the results shown in Figure 11 would raise questions about the behavior of the system. Why does the effective stress sharply decrease from 0.01 seconds to 0.1 seconds then gradually rise throughout the remainder of the simulation? Does the system stop predicting failure after 1 second? What is the effect of tangential stresses in the waste? How does the system respond to varying repository parameters? All of these questions are relevant to the understanding of the Quasi-Static model and to the prediction of stresses in the waste from an air drilling event.

The effective stress is simply the difference in the calculated total stress and calculated pore pressure. Figure 12 shows the relationship between these quantities for three separate times for the EPA's analysis of air drilling. The left plot shows the first time step, at 0.01 seconds from time of intrusion. One can see immediately that waste failure occurs due to a slightly higher pore pressure, with the radius of failure being 0.27 m. The relatively large failure at this time is due to the unsmooth function of the pore pressure in the waste, which carries over to the effective stress. The same can be seen the two other plots of 0.1 and 1 second from intrusion time. The effects of the unsmooth pore pressure profile average out as the time from intrusion increases, but is one the reasons for increase in effective stress at later times.

The high radial failure as seen in the effective stress from the unsmooth nature of the pore pressure can be dispelled, once a more accurate code is used to model air drilling. Figure 13 shows the effective stresses as calculated in GASOUT from an air drilling scenario. The code was

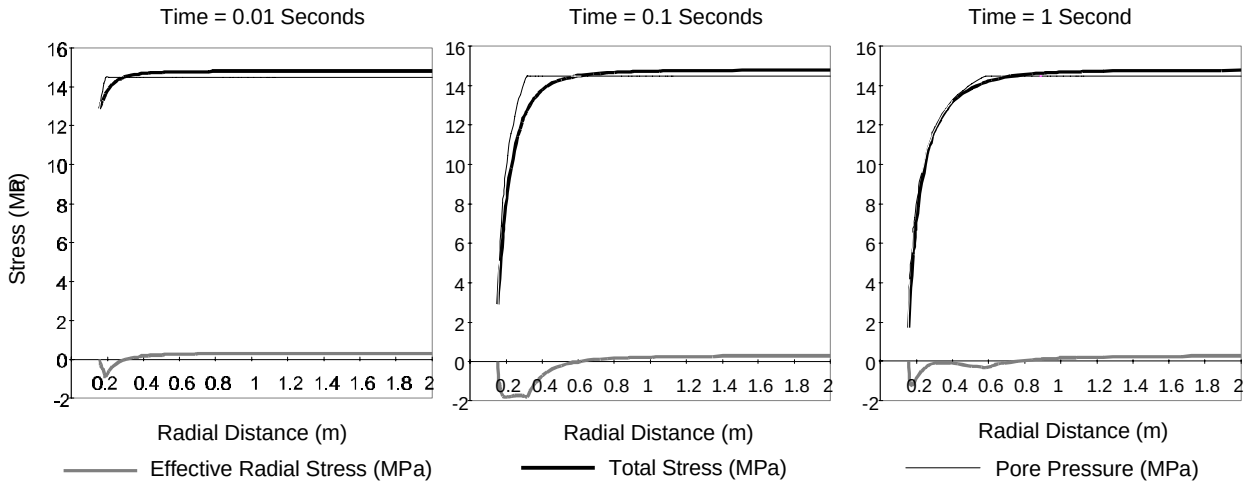

Figure 12. Effective Stress, Total Stress, and Pore Pressure Profiles in the waste at three independent times from the EPA's Analysis of Air Drilling.

run with the cavity growth option turned off and the same input assumptions as used in the Quasi-Static model. Although the code cannot predict failure accurately with the option of failed material removal to be removed (due to multiple layers of cascading waste during a single time step), the code can calculate the pore pressure distribution and effective radial stresses that match quite closely to the Quasi-Static model with the option turned off. Figure 13 shows that at 0.01 seconds from intrusion time, the radial failure is 0.38 m, which is higher than the Quasi-Static model. Although, it must also be noted that the pore pressure eventually decreases after this initial time, at 0.1 and 1 second from the time of intrusion. The conclusion gathered from this analysis is that the pore pressures are smooth through the waste, and subsequently predicts a much higher negative effective stress at earlier times.

Smoothness aside, the major discrepancy between the model and the physicality of the scenario is the fact that material is not being removed during the time that material could fail. This would have a major impact on the results, especially pore pressure, and hence effective stress. If material were allowed to be removed, the pore pressures would stay higher, because the low pore pressure waste would have been removed. The pore pressures would then be recalculated with the remaining waste at higher pressures. This is evident in Figure 13-11 of Hansen et al. (1997). The figure shows the calculations of with and without material removal assuming brine mud is the drilling fluid. The curve showing that material is removed has higher pore pressures in the waste.

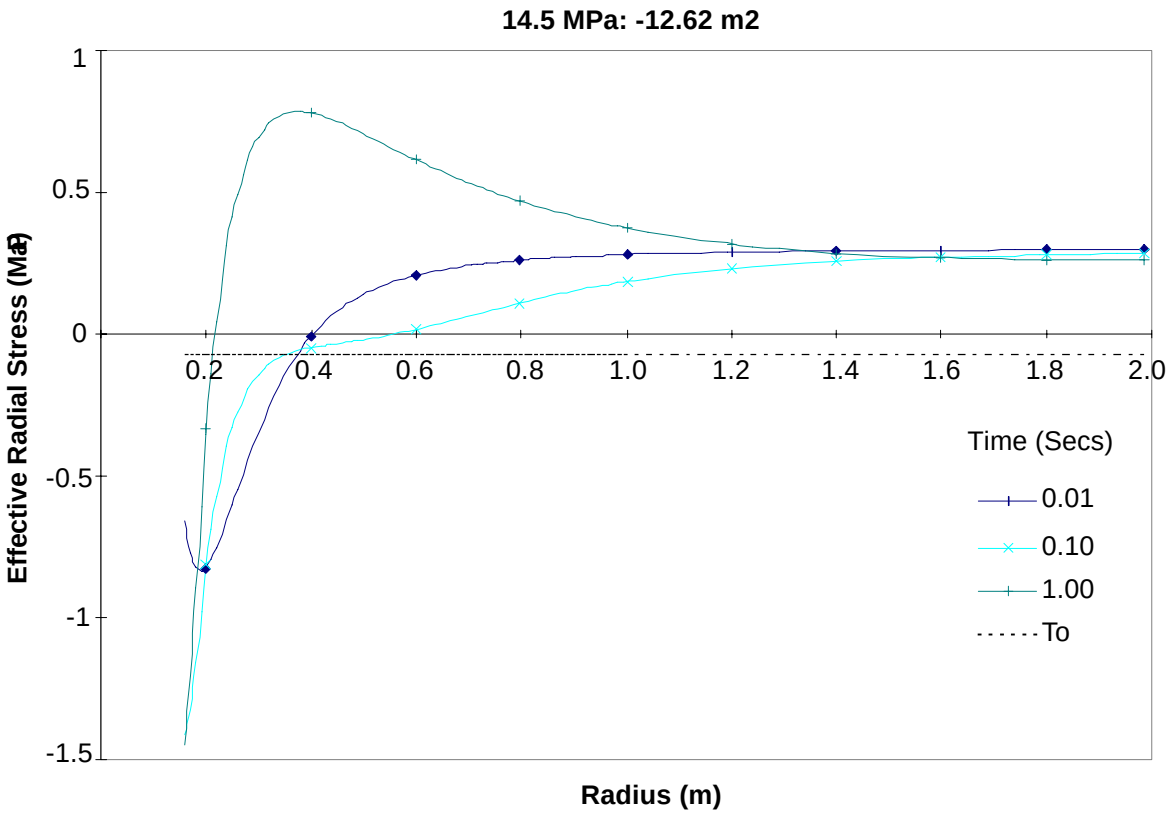

Figure 13. Effective Radial Stress As A Function Of Radial Distance Using GasOut For The Air Drilling Analysis.

Though the difference in pressures between the two curves is slight, it would have a significant impact on the effective stresses and potential releases. For Figures 1 and 3 above, the pore pressures artificially decrease from the flow of gas in material that should have been removed. Therefore, the judgment of waste failure from Figure 11 leads to false confidence by underpredicting waste failure.

Along with the calculated radial stresses, tangential stresses will also exist in the waste. As radial stresses are directed inwards to the borehole center, the tangential stresses are directed along the tangential paths of the hemispherical cavity, and are perpendicular to radial stresses. Essentially, the tangential stresses are compressive stresses acting along the circumference in a spherical geometry, and radial stresses are tensile stresses acting along the radius (or compressive, depending on the nature of the pore pressure and total stresses).

The effective tangential stresses in the waste were calculated much like that of the radial stresses, with effective stress equating to the difference in total stress of the overburden rock and pore pressure. Since the tangential stresses are always in compression, the resultant effective stresses are above zero, and hence no failure occurs from compressive tangential stresses.

The radial and tangential stresses are related by a yield potential, as stated in Jaeger and Cook (1976), which incorporates the compressive strength, internal angle of friction, and cohesion of the waste, by the formula,

$$\sigma_\theta - C_o - \sigma_r \tan^2 \alpha > 0 \qquad (2.5\text{-}2)$$

where σ_θ is the tangential stress (major principal stress), σ_r is the radial stress (minor principal stress), C_o is the compressive strength, and α is equivalent to

$$\alpha = (\pi/4) + \tfrac{1}{2}\,\phi \qquad (2.5\text{-}3)$$

where ϕ is the angle of friction. The left hand side Equation 2 must be greater than zero for yielding to occur.

Figure 14 shows the results of Equation 2.5-2 plotted against radial distance. The first observation is that there is potential for yield out to 2 seconds from the time of intrusion. The yield crosses the axis at approximately 0.8 m, resulting in an uncompacted volume of 2.1 m^3. This is an increase of 33% from the initial estimate stated in the EPA's analysis. The curves also seem to be highly influenced by the discontinuity in pore pressure calculations, and can be seen in Figure 14 by the second peak in the curve as radial distance increases. When compared to the yield potential calculated from GasOut, which calculates a smooth function of pore pressure, the limit for yield is 0.7 m at 0.1 seconds from intrusion (as compared to 0.6 m from the Quasi-Static model). After this time the yield is essentially zero.

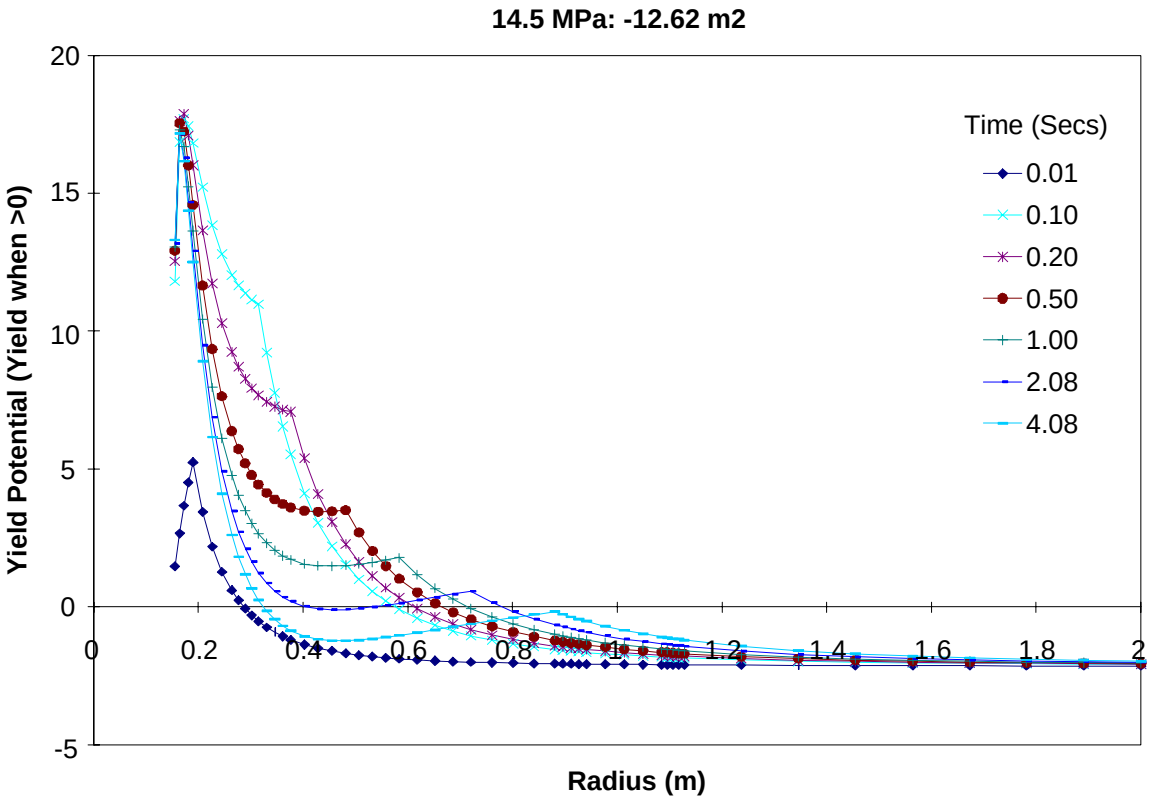

Figure 14. Yield Potential for EPA Air Drilling Analysis. The Figure Represents Equation 2 (above) vs. Radial Distance. Yield Will Occur When the Potential is Greater than Zero.

After the analysis of air drilling using the Quasi-Static model was complete, the EPA dismisses the consequence of air drilling based on the amount of expected failure in the borehole cavity. The volumes, as seen above, do not exceed the 0.5 to 4.0 m^3 of waste, which were calculated in the CCA as being the maximum possible spalled volumes. Therefore, since expected failed volumes are less, they will not affect the CCDF (Complimentary Cumulative Distribution Function) calculations of the CCA, or PAVT. One must keep in mind, however, that the analysis was for only one set of repository assumptions, and that the calculated failures can change drastically when the assumptions are changed.

To demonstrate the response of the model to different input assumptions, Figure 15 shows a simulation in which the repository is increased from the nominal 14.5 MPa that was used in the EPA analysis to 14.8 MPa. The higher pressure is the maximum pressure that the repository will

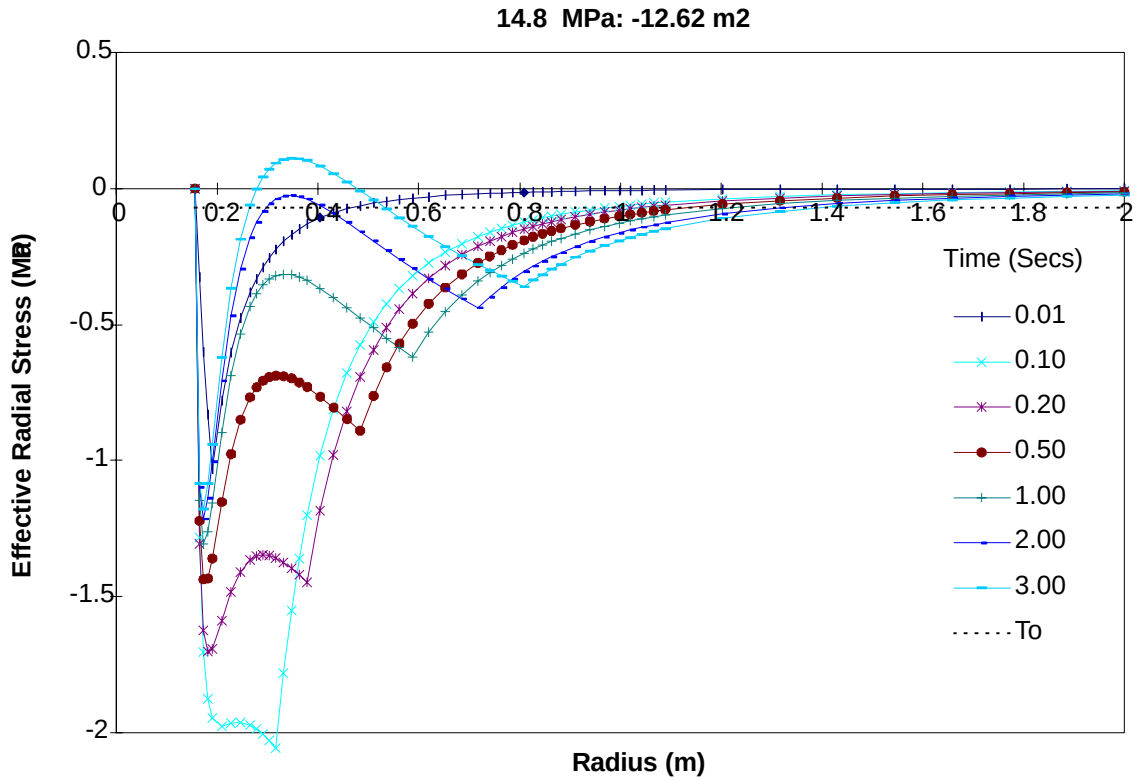

Figure 15. Effective Radial Stress As A Function Of Radial Distance For An Increased Pressure For The Air Drilling Scenario.

sustain for long periods of time, and is the lithostatic pressure of the overburden rock. If gas pressures are above lithostatic, the weak stratigraphic layers will fracture until sufficient energy is released and the pressure returns to the minimum fracturing pressure. The results of Figure 15 are astounding. The figure shows that a nominal increase in pressure will significantly increase potential releases. At 1 second after initial intrusion, the radial distance of failure is 1.22 m (7.58 m^3 of uncompacted waste). Although not shown, the waste will continue to fail during the entire 9 second simulation, in which the radial distance increases to approximately 1.65 m (19.1 m^3 of uncompacted waste). These volumes are greater than the 4.0 m^3 maximum calculated in the CCA, and perhaps would have an impact on the CCDF calculations if air drilling scenarios were considered in the CCA.

The input assumptions for the EPA air drilling analysis also assumed a waste permeability of 2.4×10^{-13} m^2, which is slightly higher than what was used in the CCA, but consistent with the PAVT. It is reasonable to assume that the waste permeability could vary within the repository,

and exhibit much lower values. The investigation by Dr. Frank Hansen and coworkers (Hansen et al., 1997) used a numerical code for gas flow within the repository during an intrusion, which could spatially vary the waste permeability. The results from the analysis showed that the pore pressure gradient will be very high near the borehole cavity. The higher pressure gradients will cause the total stress to decrease and the effective stress to increase negatively, which may lead to higher waste failures.

When the waste permeability was decreased in the Quasi-Static model for air drilling, the code predicted the opposite behavior. Table 3 shows the results of radial failure at various times for different waste permeabilities. The initial repository pressure was 14.5 MPa for these calculations. In the most extreme case, when repository pressure is 14.8 MPa and waste permeability is increased to 10×10^{-13} m^2, the failure at 5.8 seconds (blowout) is approximately 1.9 m (28 m^3 uncompacted volume).

2.5.2.3 Modeling Conclusion

The Quasi-Static model, as introduced in Hansen et al. (1997) was used to model the expected releases during an air drilling scenario into the repository at the WIPP (U.S. EPA, 1998). The investigation was initiated by the EPA to satisfy the contention that if air drilling were to occur, then the consequences would not lead to significant changes in the CCA (or PAVT). The Quasi-Static model uses a Runge-Kutta method for solving the analytical equations for 1-D flow of gas through porous media and the blowout of the drilling fluid. In addition, it solves the analytic expression for radial and tangential stresses in the waste near the wellbore. The model is a simplistic analysis, in that it solves a series of steady state approximations to flow. The model is established on two spread sheets.

Pressure = 14.5 MPa	@ 1 second	@ 1.5 seconds	@ 2 seconds
$2.4 \times 10^{-13} m^2$	1.38 m^3		
1.7×10^{-13} m^2	1.26 m^3	1.43 m^3	
1.0×10^{-13} m^2	1.11 m^3	1.24 m^3	1.35 m^3

Table 3. Estimated Failure Volumes for the Quasi-Static Model Under Varying Waste Permeability

The EPA's analysis showed that under expected repository conditions, the release from an air drilling scenario would not be greater than 1.4 m^3, and hence much less than the predicted releases of the CCA and PAVT. Therefore, their conclusion of the air drilling analysis stated that based on its [the Quasi-Static model] conservatism, air drilling need not be considered in the CCA.

Several conceptual flaws can be seen from the analysis in U.S. EPA (1998). First, the code was not designed for failure. It was only designed to calculate the stresses in the waste, assuming no waste failure and subsequent removal occurs. Waste removal will have significant impact on the actual pore pressures that may exist. Second, the code was not designed to handle a compressible fluid as the drilling medium. The code assumes that water (or some other incompressible fluid) will be ejected from the borehole upon blowout. In reality, the gas from air drilling will expand, causing the weight of the drilling fluid to be over predicted in the model. The over prediction will cause the flow of the gas from the repository to be less, and time for complete blowout to be longer.

The code also only approximates the pore pressures in the repository by assuming steady flow. As seen in Figure 12 (above), the steady flow assumption causes the pore pressure profile to be unsmooth. This characteristic, when combined with total stress of the overburden rock, produces oddly varying effective stresses in the waste. This shows that the code produces unreliable results for an air drilling scenario. When effective stresses are compared to the results of a code that calculates the time-dependent flow and pore pressures (Figure 13, above), the effective stresses are much lower (higher in the negative direction) than the Quasi-Static model at early times. Beyond the first couple of time steps, the code starts to be less accurate, and pore pressures begin to decrease in waste that should have been removed.

The analysis of air drilling by the EPA also only showed one particular view of repository conditions. The uncertainty in repository parameters were not mentioned in the report. The uncertainty in the parameters is presented in this report, and the analysis shown above demonstrates the nonconservative approach of the air drilling scenario. For example, the

repository pressures can be above the assumed 14.5 MPa, and may be as high as 14.8 MPa, which is the lithostatic pressure exerted by the overburden rock at the depth of the repository. When the Quasi-Static model was increased to 14.8 MPa, the code predicted stresses that would lead one to intrepret a failure of 19.1 m^3. This is over ten times the predicted value stated in the EPA analysis. Also, by changing the waste permeability to include the uncertainty of future and existing waste, the code predicted much different results.

In conclusion, the results of the EPA analysis do not reasonably estimate potential spallings releases. The use of a code for air drilling that was developed for an incompressible fluid appears inappropriate. The code cannot accurately predict failure beyond the initial time intrusion due to the assumption that waste will not be removed. The code should only be used to estimate the stresses in the waste when no failure has occurred. The fact that waste is not removed underpredicts the extent of failure, and provides false confidence in that blowout will be less than what may actually occur in field conditions. The results, as stated in the EPA's analysis, is not conservative, and should be re-examined based on a conceptual model that is designed to handle transient flow conditions and compressibility of the repository gas as well as the compressibility of the boring fluid.

2.6 FLUID INJECTION

The petroleum reservoirs surrounding and underlying the WIPP are potential candidates for fluid injection to recover a substantial amount of crude oil reserves (Broadhead et al., 1995; Silva, 1996). For oil field operations in southeastern New Mexico, the problem of water migrating from the intended injection zone, through the Salado Formation, and onto adjacent property has long been recognized (Ramey, 1976; Bailey, 1990; LaVenue, 1991; Silva, 1994; Van Kirk, 1994; Ramey, 1995; Silva, 1996). The observation continues to be of concern for proposed oil field waste disposal into the Salado Formation (Kehoe, 1996; Cone, 1996). Concerns about unexplained water losses due to solution mining (U.S. DOE, 1980, 2-7; U.S. DOE, 1993, 26), potential oil field development (U.S. DOE, 1980, 2-10), or future oil field waterflooding (Griswold, 1977, 13) helped eliminate other sites from consideration for the disposal of transuranic waste (U.S. DOE, 1980; Silva, 1996). Moreover, "... at the time the WIPP site was selected, one of the stated advantages over other locations was that the lack of petroleum development near WIPP was not conducive to secondary recovery techniques" (Weart, 1993).

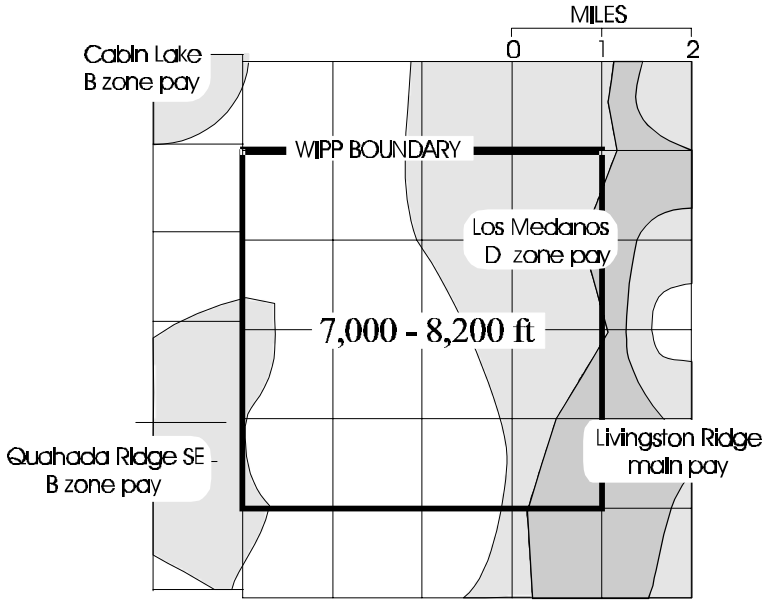

Fig. 16. Areas of Known and Probable Oil And Gas Resources for Delaware Pools. Broadhead et al., 1996.

By now it is well established that the WIPP vicinity is rich in oil and gas resources. The reservoirs are conducive to secondary resource production by waterflooding (Broadhead et al., 1995; Broadhead et al., 1996; Silva, 1996), the use of carbon dioxide flooding adjacent to the WIPP has been postulated (Boneau, 1992, 2) and the use of carbon dioxide flooding throughout the Delaware Basin is being explored with support by the DOE Office of Fossil Energy (Dutton et al., 1996; Dutton el al., 1997; Murphy, 1997) . Nonetheless, the EPA proposes to accept the DOE CCA position that fluid injection can be ruled out as a potential scenario and, hence, need not be considered in the performance assessment calculations. It is essential that the viability of these issues be assessed to ensure confidence in conclusions regarding risks from human intrusions.

2.6.1 Regulatory Argument to Eliminate Actual Resource Recovery Activities

For the recovery of oil and gas resources within the designated four-mile by four-mile boundary, the EPA proposes to accept the DOE argument that the actual recovery method need not be considered in the performance assessment. The DOE need only consider the actual drilling event (U.S. EPA, 1996). The presence of the oil and gas resources are known, the use of fluid injection is a well established oil recovery practice in the Delaware Basin, water injection for salt water disposal and enhanced oil recovery is already underway near the WIPP, and the history of water migrating from leaking injection wells through the Salado Formation in southeast New Mexico is well documented (Silva, 1996). However, the DOE does not need to consider the impact of such recovery methods in the performance assessment calculations. Such scenarios can be rejected for consideration on the basis of regulation (U.S. EPA, 1996).

The concept of rejecting a scenario on the basis of regulation allows the DOE the latitude to eliminate any inadvertent human activity that could result in a consequence greater than that of exploratory drilling (Sandia, 1992, 4-4; Silva, 1996, 158). The other grounds for rejecting scenarios are probability and consequence. These two criteria are potentially quantifiable and are an inherent part of the EPA Standards for the disposal of transuranic waste. However, probability and consequence are not considered if a scenario has already been eliminated on the basis of regulation. The International Review Group expressed reservation about rejecting a scenario solely on the basis of

regulatory considerations. In their review of the WIPP project, they state:

> It would improve the confidence of the reader if the DOE presented the logical or physical arguments for not considering these processes in the assessment, in addition to noting that they are not required in a compliance demonstration. Otherwise, there is an impression that processes that might deserve consideration from a safety perspective have been eliminated (NEA/IAEA, 1997, p. 19).

2.6.2 Low Consequence Argument Relies on Untested Model

For the low consequence argument, the EPA has accepted the modelling results of Stoelzel and O'Brien (1996) and Stoelzel and Swift (1997) and has rejected the modelling results of Bredehoeft (1997b). The DOE maintains that a leaking injection well in the vicinity of WIPP is a low consequence event because the model of Stoelzel and O'Brien does not predict a substantial inflow of brine into WIPP in such an event. But a very fundamental question remains. Can the codes model a documented high consequence event? In other words, can the DOE codes take the injection data and geologic data from the highly visible Hartman case and reproduce what is believed to have happened at the Bates Lease (Hartman, 1993, Van Kirk, 1994, Powers, 1996). At a minimum, the codes must be able to move a substantial amount of water through a single zone of the Salado Formation, two miles in the updip direction, and in a short period of time, about 12 years. If the model, as used by Stoelzel and O'Brien, can not move the water to the Bates Lease, then any low consequence argument based on this model may be meaningless. At this point there is no indication that a verification with actual field events has been conducted and a low consequence argument based on an unverified model could be characterized as speculation.

2.6.3 Low Probability Argument Conceived by EPA contradicted by DOE Observations and Actual Oil Field Experience

The EPA also raised questions regarding DOE's consequence analysis and "concluded that regardless of the consequence argument, the probability of such an injection event that affects WIPP is very low, and so this FEP can be eliminated on the basis of low probability" (U.S. EPA, 1997b, Card 32-42).

But, the DOE chose to examine consequence rather than probability, as noted by Stoelzel and O'Brien, "[b]ecause certain petroleum practices are hard to define in a probabilistic sense (for example, the quality of the cement and/or casing and its ability to withstand leaks over time)..."(Stoelzel and O'Brien, 1996, 8). Nonetheless, EPA assigned probabilities to certain petroleum practices, such as an undetected leak occurring in the annulus, and multiplied the probability of each event and calculated that the *realistic* probability of a injection well impacting the repository was only one in 667 million (U.S. EPA, 1997h, Table Q).

The EPA is relying on an optimistic view of future injection well performance which does not reflect the actual experience of documented waterflows in the Salado Formation in water flood areas throughout southeast New Mexico. As noted in EEG-62, waterflows are not randomly distributed, but are strongly correlated with waterflood operations (Gallegos and Condon, 1994, p. 2). Rules and regulations governing the use of oil field injection wells have been in place for decades and the records of waterflows indicates the level of their effectiveness. For example, the enabling orders for the Rhodes Yates waterflood (Campbell et al., 1964; Cargo et al., 1969; Ramey, 1977) required operating in accordance with Rules 701, 702, and 703 (Hartman, 1993, 4). Rule 702 requires cementing and casing of injection wells to prevent the movement of fluids out of zone. Rule 703 requires operation and maintenance practices to assure no significant fluid movement through vertical channels adjacent to the well bore. Further, the entire operation, including producing wells, must be operated and maintained to confine the injected fluids to approved intervals. The documented problems with the Rhodes Yates waterflood (Hartman, 1993; Hererra, 1995) and with waterfloods and salt water injection throughout the southeast New Mexico (Ramey, 1976; U.S. GAO, 1989; Bailey, 1990; Krietler et al., 1994) clearly indicate the limitations of taking credit for state or federal regulations, new or old, for protecting WIPP. Furthermore, there are literally hundreds of documented waterflows for District 1 and District 2 of southeastern New Mexico. Those records are maintained by the NMOCD. Summaries are included as Appendix 8.9.

To determine its probability, EPA assigns individual probabilities to events such as a leak going undetected and one of those wells leaking into the annulus. However, EPA provides no references

to any field studies to demonstrate that these probabilities have any basis in the actual experience of the oil and gas industry. For example, did EPA actually obtain and review the repair records for oil and gas wells in the Delaware Basin? EPA comments that the Underground Injection Control regulations have proven effective since 1984. Did EPA review well files to determine that all required testing for each injection well had been completed on schedule? For example, DOE sponsored a study in which it was suggested that the Todd 26 Federal #3 was the well most likely responsible for anomalous water level rises observed for the H-9 Culebra observation well (Bailey, 1990; LaVenue, 1991). Did EPA verify that the New Mexico Oil Conservation Division had a record of the mandatory annual Bradenhead test for each year since 1984 and the mandatory mechanical integrity test every fifth year since 1984? The well passed a mechanical integrity test on August 16, 1995 (Silva, 1996, 127). Are there records filed with the NMOCD, which administers the UIC, to show that the well was tested in 1990 and 1985? If not, just how effective are the rules and regulations with respect to underground fluid injection and how did EPA take that observation into consideration in its determination of the probability of a leaking well impacting the performance of the repository? EPA should address all of these issue in the final rule.

There is another issue of concern. 1) If EPA accepts DOE's argument that it is not necessary to examine other criteria once a scenario is rejected on the basis of one criteria (relevance, regulation, probability, or consequence) and 2) if EPA accepts DOE's argument that fluid injection can be rejected on the basis of low consequence, why did EPA feel it was necessary to submit a low probability argument for the fluid injection scenario? By publication of a fluid injection probability calculation, it appears that EPA was not comfortable with rejecting an important scenario such as fluid injection on the basis of one criteria. EPA felt it was necessary to examine another criteria. EPA does not provide any guidance as to which other scenarios would require examination against one, two, three, or all four criteria.

In summary, EPA's rejection of the fluid injection scenario on the basis of low probability is contradicted by the observation that "certain petroleum practices are hard to define in a probabilistic sense" (Stoelzel and O'Brien, 1996, 8). EPA's probability calculation does not coincide with the

observation that there is a history of out of zone water in waterflooded areas despite rules and regulations that have been in existence for decades. (Gallegos and Condon, 1994, p. 2; Silva, 1996, 155). It is not clear that EPA has a defensible basis for assigning probabilities of individual events in calculating a *realistic* probability of a injection well impacting the repository as only one in 667 million (U.S. EPA, 1997h, Table Q). Given EPA's efforts to provide a second basis for rejecting the fluid injection scenario, it is logical to conclude that EPA recognizes that scenario rejection may require meeting two or more criteria. The observation raises questions about each and every other scenario rejection.

2.6.4 EPA Position on CO_2 Injection in Conflict with Literature and Public Record

The potential leakage of injected carbon dioxide into the repository is of concern. Carbon dioxide must be injected into the deep target zone at sufficient pressure to generate a miscible displacement. In the event of leakage into an overlying zone, such injection could propagate a fracture and/or serve as a driving force for moving fluids through various flow paths. In the event carbon dioxide enters the repository, one might anticipate the formation of plutonium carbonates and nesquehonite and a reduction of the repository pH, each of which results in higher plutonium solubilities.

The EPA believes that the potential impact of CO_2 injection on the WIPP Site is very low because the EPA does not anticipate that CO_2 injection for oil recovery will be widespread practice in the future near WIPP (U.S. EPA, 1997b, Card 23-131). The EPA technical support document makes reference to a technical article (Thrash, 1979) suggesting that there may be a remote possibility that CO_2 enhanced oil recovery may also be suitable for some of these types of reservoirs (U.S. EPA, 1997h, 1997i) The EPA also notes DOE's opinion that CO_2 flooding in the vicinity of WIPP is highly unlikely (U.S. EPA, 1997b, Card 23-132).

DOE's position is at odds with the following observations. First, CO_2 flooding has been demonstrated to be quite successful in mature fields in the Delaware Basin such as the TwoFreds (Silva, 1996, pp. 142-145). Second, the DOE continues to sponsor university research on Delaware Basin oilfields, such as the Geraldine Ford and the West Ford, aimed at optimizing infill drilling and

CO_2 flooding throughout the Delaware Basin (Dutton et al., 1996, 1997). Third, oil and gas companies continue to purchase mature fields, such as the El Mar in the Delaware Basin, specifically for carbon dioxide flooding (Moritis, 1993; Silva, 1996). Fourth, the recently drilled reservoirs surrounding the WIPP such as Cabin Lake, Livingston Ridge, Los Medanos, and Lost Tank have oil and reservoir characteristics (Brown, 1995; May, 1995a; White, 1995; May, 1995b) that easily qualify them as potential candidates for future CO_2 flooding using the enhanced oil recovery (EOR) screening criteria described by Taber, Martin, and Seright (1997a, 1997b).

In its supporting documentation (U. S. DOE, 1997d) the DOE cites only one reference from the CO_2 flooding literature, a 1980 preprint of an SPE presentation. The body of literature on oil field carbon dioxide flooding is certainly more extensive and much has been published since 1980, including analyses of the issues raised in that 1980 preprint (Silva and Orr, 1987). Furthermore, the DOE document fails to reference the published proceedings (Silva, 1996) of a workshop on fluid injection which discusses in much more detail evidence of CO_2 flooding activities in the Delaware Basin. The EPA technical support document on fluid injection (U. S. EPA, 1997h) also fails to reference the published proceedings of the EEG workshop, which included participation by EPA staff.

With respect to the EPA documentation, the EPA offers three reasons why it believes that CO_2 will not be a widespread practice in the future near WIPP, but the EPA offers no supporting references for these reasons. (U. S. EPA, 1997b, Card 23-131).

1) EPA maintains that CO_2 injection costs far more than brine injection due to the easily available sources of brine and the injection quantities required.

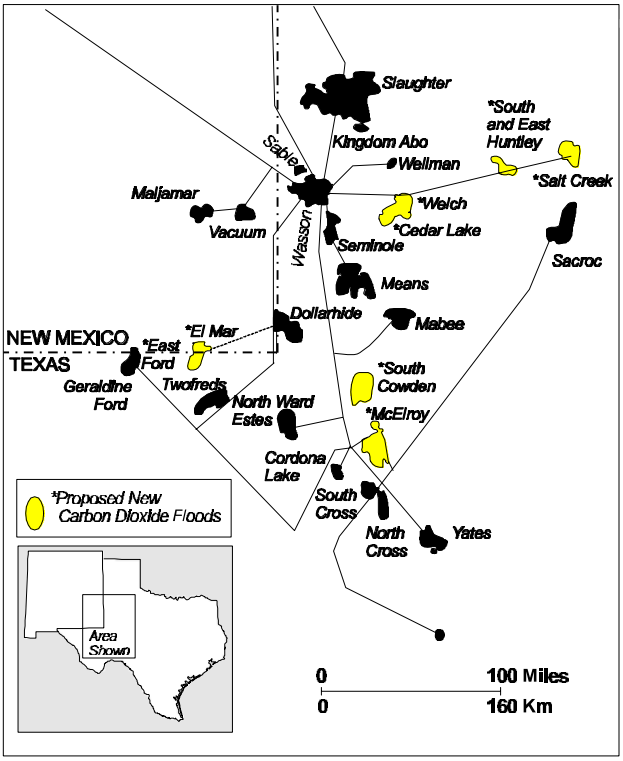

Fig. 17. Permian Basin CO_2 Pipelines and CO_2 Floods (Moritis 1993; Silva 1996)

This statement fails to recognize the availability of carbon dioxide in southeast New Mexico, the practice of conserving water whenever possible, the history of CO_2 flooding in the Permian Basin including parts of the Delaware Basin, the efficiency of a miscible type displacement to increase oil production and extend oil field life, and the willingness of local governments to work with companies to encourage the use of CO_2 flooding. If the EPA statement had any merit there would be no CO_2 flooding used in the Permian Basin or any other oil field for that matter. But as shown here, there is extensive CO_2 flooding in the Permian Basin as a result of a large investment in pipelines across New Mexico to bring carbon dioxide from southeast and southwest Colorado and northeast New Mexico to West Texas. Moreover, the DOE recognizes the potential for enhanced oil recovery in the Delaware Basin and continues to fund research on reservoir characterization and field trials to explore the most feasible use of carbon dioxide throughout the basin (Dutton et al., 1997; Murphy, 1997). In addition to encouragement by federal and state government, county governments in New

Mexico also have the authority to encourage the development of CO_2 flooding operations through tax reduction incentives. For example, under authorities granted by the state, Lea County recently granted Texaco $500,000 in property tax relief to construct a facility to provide CO_2 for injection into the Vacuum Field. In addition to extending the life of the oil field by 20 years, adding 100 construction jobs over the next three years, and providing 15 million dollars in tax revenues, the benefits to Lea County also include:

> Conserving an estimated 130 million barrels of fresh water that, thanks to CO_2, won't be pumped into the field over the next two decades, plus an additional 130 million barrels of saltwater that will be raised from the field (via CO_2 injection) and can then be used for water flooding elsewhere (Jacobs, 1998).

Waterflooding is used to restore energy to a depleted reservoir but displacement efficiency is limited to an immiscible type displacement. The long recognized favorable characteristics of carbon dioxide flooding include the preferential dissolution of CO_2 into the oil rich phase, the reduction of oil viscosity, the swelling of the residual oil droplets, the preferential extraction of lighter hydrocarbons, and the development of a miscible type displacement.

2) The EPA maintains CO_2 injection is more difficult to control, since the rocks are more permeable to gas than to brine, higher injection pressures are required to maintain desired pressure configurations.

It is not clear why EPA believes that the relative permeability of gas and brine in rock has a role in making CO2 injection more difficult to control. Please provide a more detailed explanation and references for the statement.

3) The EPA maintains the presence of gas could inhibit production in that any gas present will be in the nonwetting phase and will occupy the portions of the oil reservoir that have relatively large apertures.

The EPA did not provide any references for this statement. EPA should refer to the results of Monroe et al., (1990) for the effect of dissolved methane on a one dimensional CO_2 flood. Their analysis "indicates that high displacement efficiency is possible even when two-phase flow occurs throughout the displacement and that high recovery is possible even when a live oil is displaced below its bubblepoint pressure (BP), if the pressure is above the minimum miscibility pressure (MMP) for the same oil with all methane removed" (Monroe et al., 1990, p. 423). EPA's third argument for dismissing CO_2 flooding does not appear to be reasonable.

2.6.5 EPA Technical Support Document Inadequate on CO_2 Fluid Injection

The EPA technical support document states "technical articles indicate the remote possibility of CO_2 enhanced oil recovery may also be suitable for some of these types of reservoirs (Thrash, 1979)." EPA references one early article for a reservoir in the Delaware Basin, the Twofreds field. EPA does not reference EEG-62 (Silva, 1996) which discussed the successful Twofreds carbon dioxide flood based on more current literature (Wash, 1982; Kirkpatrick et al., 1985; Flanders and DePauw, 1993).

The EPA Technical Support Document also states "at this time, the only examples of CO_2 injection enhanced recovery techniques are some distance from the WIPP site and under much different geologic conditions (Magruder 1990; Thrash, 1979)." The statement is incorrect. As shown in Figure 17 and in EEG-62, there are many CO_2 enhanced oil recovery injection projects. It is also inaccurate to argue that the field in the Thrash article is under much different geologic conditions. The Twofreds field is in the Delaware Basin and produces from the Bell Canyon Formation, which is found in the upper part of the Delaware Mountain Group. The Cherry Canyon and Brushy Canyon Formations lie further down in the Delaware Mountain Group and are the known oil bearing formations in the vicinity of WIPP. Most importantly, each of these oil bearing formations resulted from saline density currents as the depositional processes (Harms and Williamson, 1988). Hence, the EPA technical support document (U. S. EPA, 1997h, vol. 1, p. 26) is incorrect in stating that the CO_2 flood at Twofreds is under ***much*** different geologic conditions.

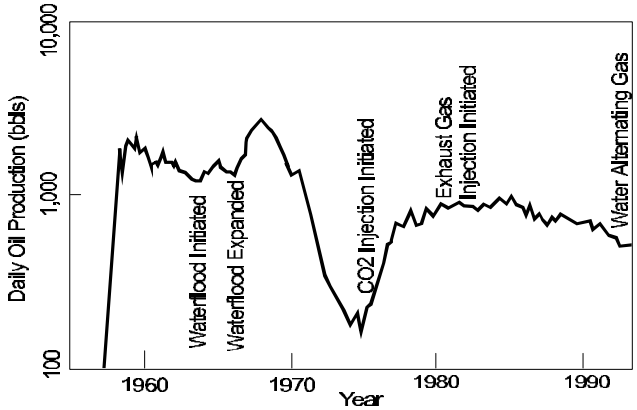

Fig. 18. Production History of Twofreds (After Flanders and DePauw 1993).

EEG-62 (Silva, 1996) discussed the performance of the Twofreds Field. The field is located in the Delaware Basin and produces from the Bell Canyon Formation of the Delaware Mountain Group. The reservoir is about 3/4 mile wide and is about five miles long with a net thickness averaging about 16 feet. The field was discovered in 1957. The Twofreds Field, like other Delaware fields, has always produced large volumes of water. After six years of primary production, a pilot water injection project was initiated in May 1963. A full scale waterflood was brought on line in January 1966. The project showed that oil from a Delaware reservoir with a high water cut could be recovered profitably (Jones, 1968). From 1963 to 1973, waterflooding, an immiscible displacement process, had produced 2 million barrels of oil. But by 1973, the amount of oil produced by waterflooding had dropped down to 160 bbls oil per day. As shown, carbon dioxide flooding, a miscible displacement process, increased oil recovery from 160 bbls oil per day to 1,000 bbls oil per day. By 1982, carbon dioxide flooding had produced an additional 2 million barrels of oil (Wash, 1982). The purpose of the Twofreds carbon dioxide flood to was demonstrate economic feasibility. The field continued to produce based on its economic merit (Kirkpatrick et al., 1985) and demonstrated that carbon dioxide can economically recover tertiary oil from a depleted, waterflooded Delaware sand reservoir (Flanders and DePauw, 1993). As of 1993, oil production from the Twofreds was averaging 500 bbls per day (Flanders and DePauw, 1993; Silva, 1996).

As a practical matter, EPA may not have enough information to conclude whether the oil fields

adjacent to WIPP are conducive to carbon dioxide flooding. As noted by Silva (1996, 162), due to federal and state restrictions on drilling for petroleum in potash deposits, 85% of the area immediately surrounding the WIPP has yet to be drilled and directly tested for its oil and gas reserves. A production history is also needed to gain some understanding about the local geology of the oil producing zones. However, some drilling for oil and gas production adjacent to WIPP has been allowed. Coupling the enhanced oil recovery (EOR) screening criteria described by Taber, Martin, and Seright (1997a, 1997b) with the petroleum and reservoir characteristics (Brown, 1995; May, 1995a; White, 1995; May, 1995b) qualifies these oil and gas fields adjacent to WIPP as potential candidates for future CO_2 flooding. The oil densities for the fields surrounding the WIPP range from 39º to 42º API gravity indicating an abundance of lighter hydrocarbon components for promoting a miscible type displacement. The reservoirs range in depth from 4200 feet to 7100 feet, more than adequate to accommodate the injection pressure required for a CO_2 flood. One obvious limitation is the lack of a local pipeline to bring inexpensive carbon dioxide to these fields. But the major CO_2 pipelines across the state are already in place and recent history has shown that if CO_2 pipelines or facilities are needed, they will be constructed.

The DOE Office of Fossil Energy also recognizes the potential for enhanced oil recovery in the Delaware Basin by carbon dioxide flooding and is sponsoring field research in the Delaware Basin. Specifically, the DOE is funding a study by the Texas Bureau of Economic Geology to couple reservoir characterization with modeling to optimize infill drilling and CO_2 flooding to increase production and prevent the premature abandonment of slope and basin clastic reservoirs (Dutton et al., 1996, 5). The DOE plans to apply the results of studying these two fields to the more than 100 other Delaware Mountain group reservoirs in Texas and New Mexico, which together contain 1.6 billion barrels of remaining oil in place. The compositional simulation of a CO_2 flood in one of the candidate fields has shown that at least 10% of the remaining oil in place can be recovered at breakthrough. The simulation results also show that continuing CO_2 injection beyond breakthrough can result in significant incremental oil recovery, in this case over 30% of the remaining oil in place (Malik, 1998).

Another DOE study of the Brushy Canyon Formation in the Nash Draw fields immediately southwest of the WIPP area also aims to provide information to design enhanced oil recovery operations throughout the Delaware Basin. In addition to obtaining detailed reservoir characterization data for designing an enhanced oil recovery operation, the project also includes the use of a model to "evaluate the technical feasibility and commercial viability of three enhanced recovery processes: waterflooding, lean gas injection, and CO_2 injection" (Murphy, 1997, 26). The investigation is ongoing.

The EPA (U.S. EPA, 1997b, Card 23-132) also relies on the brine injection modeling of Stoelzel and O'Brien (1996) to capture the effects of CO_2 injection. The EPA maintains that the degree of potential anhydrite fracturing by CO_2 "should have been captured by the large volumes of brine and high injection pressures assumed during the brine injection analysis." But as noted above, that analyses is based on an unverified model. Furthermore, the modeling effort is based on the assumption that salt water disposal will potentially cause more problems than fluid injection for enhanced oil recovery because there is less incentive in salt water disposal for the operator to control injection pressures and volumes (U.S. EPA, 1997b, Card 23-132). The assumption invites the obvious question. In New Mexico, why have out of zone waterflows been correlated with waterflood operations and not with salt water disposal wells? For example, in the Hartman vs. Texaco case, it was the Rhodes Yates waterflood operation that was determined to be the culprit and not any of the salt water disposal operations in the vicinity. Hartman produced evidence of very high injection pressures at the waterflood (Van Kirk, 1994; Powers, 1996, 67). In commenting on the history of waterflood problems in New Mexico, Ramey (1995, XI-2) states that water probably escaped from the injection zone and into the salt formations as a result of old improperly cemented and plugged wells and excessive injection pressures in oil field ***waterflood*** operations. There is no mention of salt water disposal operations, the operations that EPA is more concerned about (U.S. EPA, 1997b, Card 23-132). If the concern is excessive injection pressure exerted at the repository horizon in the event of a leak, it seems that waterflood operations would be the most likely concern in the vicinity of the

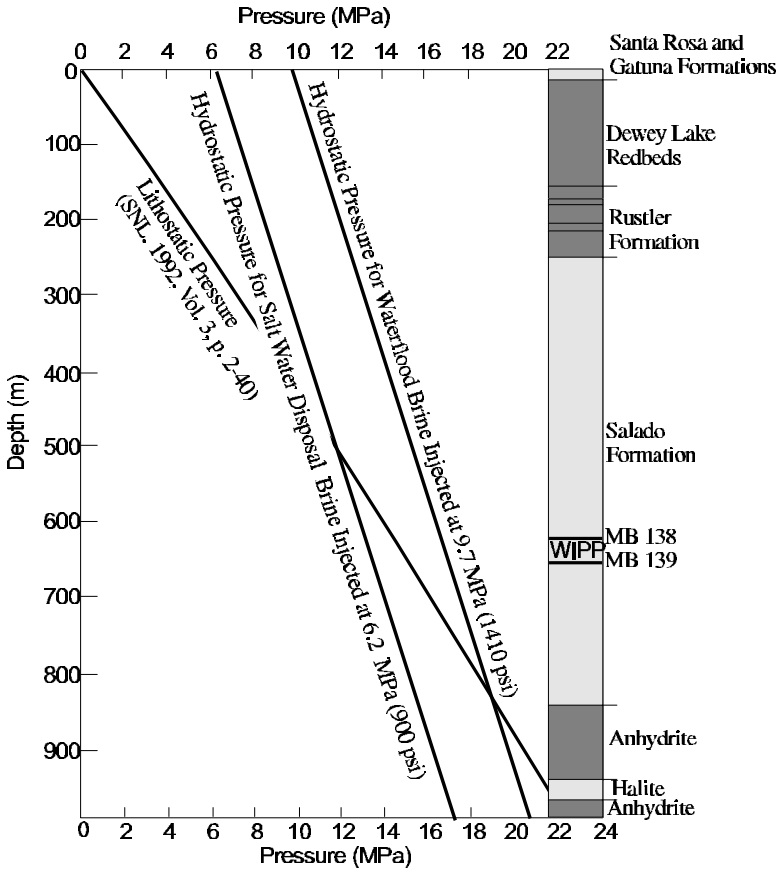

Fig. 19. Comparison of Approved Injection Pressures For Salt Water Disposal Well Versus Oil Field Water Flood Wells Near WIPP.

WIPP. Figure 19 compares the maximum approved disposal pressure for two wells one mile to the east of the WIPP Site. EEG is not suggesting that either of these wells are leaking. But EEG notes that in the event of a leak near WIPP current approved salt water disposal pressures are not sufficient at the repository horizon to exceed the lithostatic pressure. Only the a leak in the waterflood well would be of concern to the repository. This is an inherent result of the greater vertical distance to the oil producing horizons. The DOE and EPA rationale appears to be more appropriate for the more shallow oil and gas reservoirs in the Vacuum Field area and the Rhodes Yates area and not suitable for the WIPP area. Presumably, carbon dioxide for enhanced oil recovery would be injected into the deeper oil producing zones and at sufficient pressures to maintain a miscible displacement. Hence, given the observation above, EPA can not conclude that the salt water disposal well analyses captures the CO_2 flooding scenario.

2.6.6 Rhodes-Yates (Hartman vs. Texaco)

The EPA Technical Support Document acknowledges that the technical evidence related to the case was not reviewed. Rather, the technical support document reviewed a summary of the case. From that summary, the EPA document states:

> Though a jury found the waterflood operator guilty of common law and statutory trespass in the Rhodes-Yates Field, flow paths were not identified with certainty (U.S. EPA, 1997h, vol. 1, p. 31)

But at the EEG fluid injection workshop Powers noted that the flow began at an anhydrite unit on the order of 10 to 15 feet thick. Although he had not tried to correlate it to an individual marker bed, he felt that it was somewhere in the range of marker beds 140 to 142 which are below the WIPP repository horizon (Powers 1996, p. 66). Furthermore, as shown in plaintiff's Exhibit 211 and Van Kirk's testimony (p. 683), the drilling records combined with well logs identified a 36 foot wide zone just above the Cowden Anhydrite Marker as the flow path. If EPA intended to comment on the technical aspects and refer to these comments in the final rule, EPA should have reviewed the technical exhibits and technical testimony of the Rhodes Yates incident.

The EPA discussion on structure can be best described as tentative speculation. The discussion suggests that there might be more flow through possible increased fracturing of the anhydrites ***possibly*** as a result of folding, faulting, or ***perhaps*** salt dissolution which ***might*** be inferred from the varying salt bed thicknesses at the Rhodes Yates Field and the Vacuum Field. The EPA further suggests that water chemistry of the field areas in formations underlying the Salado ***may*** provide evidence of a greater rate of evaporite solution relative to the WIPP Site. But no such evidence is provided. Further, there is no reference to the published literature to support the hypothesis advanced by EPA. In fact, the entire comparison of the geology at the Rhodes Yates, Vacuum, and WIPP areas is filled with statements such as "relatively fresh waters ***may*** have been a contributing factor...", "it is also ***possible*** that fold and dip rates in the vicinity of the other two fields ***may*** contribute to increased fracturing..."(U.S. EPA, 1997h, vol. 1, p. 34). Given the implications of Hartman scenario

at WIPP, it is unclear how EPA's geologic analysis can be considered as adequate to support an EPA conclusion that a repeat of the Hartman scenario is unlikely at WIPP.

2.6.7 Culebra Water Level Rises

EEG remains concerned that there is no explanation for ten years of anomalous water level rises in the Culebra Aquifer. The water level rises began suddenly in April, 1988 (Beauheim, 1990). LaVenue (1991) conducted an investigation that raised serious questions about oil field operations. In a memo to LaVenue, Bailey (1990) identified an old salt water disposal well as the most likely source of the problem. LaVenue also explored the possibility of modelling the change in the aquifer. He found that his model could very nearly match the observed water level rises if he assumed that nearly all of the water from the salt water disposal well was entering into the Culebra (Beauheim, 1996). Beauheim (1996, 40) had also concluded that the water level rises were most likely due to some well effect. EEG-55 (Silva, 1994) had commented on the issue suggesting that leakage of oil, gas, or salt water injection wells in the Delaware Basin may have an impact on the regional hydrology. In response to the EEG report, DOE stated:

> There is currently no credible evidence that the observed water level increases can be directly or indirectly linked to activities in the WIPP area initiated by the petroleum industry. The mechanism that resulted in these water level rises have not been identified, one can only speculate as to their cause (McFadden, 1996, 11).

With respect to this issue, EPA told DOE:

> The statement "they remain unexplained" is insufficient, particularly if the reason for the rise could be interpreted to affect long term hydrologic conditions within the Culebra or be caused by ongoing oil and gas exploration and development activities, such as brine disposal into underlying units (Trovato, 1996).

Silva (1996, 125) found that a comparison of the injection history of the salt water disposal well and

the water level rises at H-9 strongly suggested communication between the injection well and the Culebra Aquifer. The DOE still has not submitted an explanation of the water level rises to the EPA and EPA does not appear to require one for the certification of the repository. In addition to the questions raised in EEG-62, if the modelling results (LaVenue, 1991; Beauheim, 1996) of the water level rises are consistent with a well injecting large quantities of water out of zone and DOE has not been able to find the source of the water, how much credit can DOE or EPA claim for the reliability of the Underground Injection Controls program? The 1996 NRC WIPP Committee report also expressed concern about the unexplained water level rises:

> An adequate explanation is lacking for observed changes in water level in the Culebra, where trends of rising water levels have persisted for several years. Observed changes in water levels from assumed steady-state conditions were not incorporated into the 1992 PA analysis. However, if the causes of the observed water level changes during the last several years are unknown, then how is it to be known that even greater changes in the flow field might not occur in the near future? Such changes might invalidate the PA assumptions and predictions (NRC, 1996, pp. 69-70).

2.6.8 Brine Production

As noted by EPA (U.S. EPA, 1997b, Card 32-10), and identified by EEG at the EPA technical exchange on 10/10/96, the CCA did not address the practice of solution mining of halite for use as brine in the drilling industry. The CCA specifically stated:

> The DOE is not aware of solution mining for potash or other minerals in the Salado within the Delaware Basin at this time (U.S. DOE, 1996c, MASS-87).

The EEG identified seventeen active brine production facilities removing halite from the Salado Formation, three of which were in the Delaware Basin (BW-6, BW-19, and BW-27). EPA notes that Appendix DEL identified a dissolution project approximately 14 miles from the WIPP. Furthermore, EPA notes that DOE submitted additional information which showed that brine production between

1979 and 1991 created a cavity of 3.4 million cubic feet and that it would be longer than 50 years before subsidence would occur.

As shown in Figure 20, there are three solution mining operations for brine production near the city of Carlsbad area and at least 16 miles from the WIPP site. EPA mentions only one about 14 miles from the WIPP Site. Furthermore, EPA does not discuss the trend towards drilling brine production facilities closer to WIPP. Brine well BW-26 has been approved for production from the Salado Formation. The solution mining operation would be located between Jal and Carlsbad to meet the demand for drilling brine. The well was approved to remove salt from the Salado formation which lies between 1500 to 2300 feet deep. The subsidence calculations provided by DOE were for a facility that is 583 feet deep.

Solution mining of the Salado Formation is an important observation. It is important for EPA to

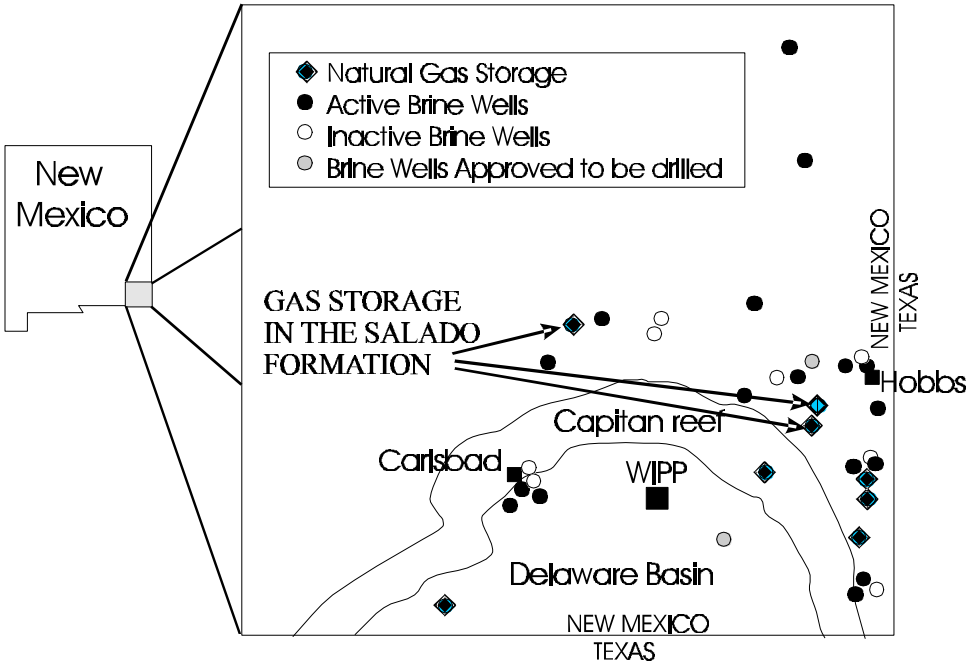

Fig. 20. Solution Mining of Brine and Natural Gas Storage Wells.

demonstrate a very clear understanding of the current situation and the full issue in the final rule.

2.6.9 Natural Gas Storage

EPA maintains that "there are no natural gas storage horizons in the Salado Formation" (U.S. EPA, 1997b, Card 32-71). As shown on a map presented to EPA by EEG on October 10, 1996, there are eight gas storage underground facilities in southeast New Mexico, three of which are in the Salado Formation in which the salt was "washed out to create a cavern." Furthermore, the natural gas storage wells can not be dismissed with a statement that they are not in the Delaware Basin. Successful operation of these three facilities for the last four decades has shown that the Salado Formation is conducive to gas storage facilities and it can be anticipated that oil and gas production will continue to increase in the Delaware Basin.

2.7 ANHYDRITE FRACTURE MODEL

2.7.1 Introduction

Criticisms of the anhydrite fracture model used in the BRAGFLO code have been brought to EPA's attention by Walter Gerstle and John Bredehoeft (Gerstle, 1996, Bredehoeft, 1997c; Bredehoeft and Gerstle, 1997; Gerstle and Bredehoeft, 1997). On March 19, 1997 the EPA requested that the DOE provide additional material describing the development of the anhydrite model beyond that supplied in the CCA documentation. As EEG pointed out during a December 10, 1997, meeting with EPA, this additional documentation indicates that the anhydrite fracture model used in BRAGFLO was intended to mimic the LEFM model developed by Gerstle et al. (Gerstle et al., 1996), but fails to do so.

On September 16, 1997, the DOE sent a letter to the EPA criticizing the LEFM model (Dials, 1997b). The EEG found this letter referred to the opinions of Sandia scientists and contained numerous misleading statements, yet lacked any substantial arguments against the LEFM model.

The EEG has reviewed the basis of the anhydrite fracture model used in the BRAGFLO code and has a number of questions about its validity. The model is unusual in that effect of fracturing is treated using an equivalent porous medium. All the relevant literature that we have examined treat fractures as distinct porosity. Use of an equivalent porous medium is not in itself unreasonable. However, the DOE has not referenced, nor have we been able to find, a description of similar treatment of the dependance of porosity and permeability on pressure as a result of fracturing. The lack of a clear development of the BRAGFLO model from established models makes its review difficult. The EPA should request that the anhydrite fracture model of BRAGFLO be compared to the treatment of fracture development in hydrofracing codes commonly used in the industry.

2.7.2 Questionable Assumptions in the BRAGFLO Model

The BRAGFLO model has been developed using several assumptions that are questionable. The following is a description of each of these questionable assumptions

The first assumption is that anhydrite will fail along planes of weakness that are probably pre-existing fractures. Hydrofracing experiments at WIPP indicated a large permeability increase when the fluid pressure reached the estimated confining stress in some instances (Wawersik et al., 1997). Other hydrofrac experiments at WIPP showed that the anhydrite remained unfractured at pressures which exceeded the confining stress by seven MPa. The BRAGFLO model assumes that hydrofracing will occur at the lower pressures and build up local stresses to cause the other regions to fail as well. While weakness dominated fracture development is probably a reasonable assumption it is not certain. Walter Gerstle believes that the pre-existing anhydrite fractures are healed by salt precipitation (Gerstle, 1998). It is entirely possible that the strength of healed fractures was reduced by local stress changes induced by the proximity of the repository to the fracture tests. This conceptual model uncertainty is not represented in the CCA calculations.

Another major assumption of the BRAGFLO model is that the porosity and permeability will increase at pressures below the lithostatic confining stress. Laboratory investigations of the permeability of fractured rocks support this assumption for existing fractures (Raven and Gale, 1985; Pyrak-Nolte et al., 1987; Cook et al., 1990). Increased permeability of the fracture over intact rock was evident and sensitive to pressure even at the highest confining pressures, 20-40 MPa. Fracture permeability increased 3 to 5 orders of magnitude as the confining stress was reduced to near zero. Note that the BRAGFLO model represents conditions of greater than lithostatic stress, so permeability increases of more than 5 orders of magnitude are possible. At pore pressures greater than lithostatic, confining stress in maintained by deflection of the rocks above the fracture.

The laboratory experiments also support the concept of permeability increasing at a rate greater than implied by the cubic law of parallel plate fractures. The steepest increase reported is an exponent of roughly nine which is considerably less than the exponent used in BRAGFLO. However, the permeability dependance on aperture becomes cubic as the aperture increases. Cook et al. (1990) have fit their experimental data to a simple model that includes the effects of tortuosity on effective permeability. The model indicates that the relationship becomes cubic for apertures in excess of 10^{-4} m. The estimated fracture aperture in the hydrofrac experiments was estimated to be on the order of $5x10^{-3}$ m (Wawersik et al., 1997) and the BRAGFLO model is intended to represent effective apertures up to 10^{-2} m (Larson, 1996).

If one takes 10^{-4} m as the effective aperture for a fracture in contact, then a total permeability increase of nine orders of magnitude is reasonable for an effective aperture of 10^{-2} m, but the greater than cubic law dependance of permeability on porosity is not. Raven and Gale (1985) found fracture permeability became dependent on the cubic of aperture in the laboratory experiments at total confining stresses of less than 1 MPa.

The assumption of multiple anastomosing fractures complicates the comparison of laboratory experiments on single fractures and the BRAGFLO model. The experimental support for multiple fractures comes from examination of core recovered from the hydrofracing experiments (Wawersik et al., 1997). Some of the core showed evidence of multiple flow channels for the tracer dye used in the experiments. This evidence supports the notion of a few channels but not the hundreds to thousands of fractures required to reduce individual fracture apertures below 10^{-4} m. The notion of many fractures of small aperture is also inconsistent with the nine orders of magnitude range of permeability change.

The laboratory experiments also support the concept of reduced fracture stiffness (increased compressibility) with increasing pore pressure. We have not attempted to determine whether a linear change is reasonable. Below lithostatic pore pressures, stiffness may be a combination of stiffness of the fracture contact zones and stiffness of the host rock with respect to both compression and bending. At pore pressures above lithostatic, confining stress is due to

deflection of the fracture faces and resulting bending of the host rock. Given the relatively small deflections of the fracture faces, it seems reasonable to expect that stiffness becomes constant above lithostatic pore pressures.

2.7.3 Summary

In summary, laboratory experiments on individual fractures support the assumptions used to formulate the permeability-porosity relationship of BRAGFLO anhydrite fracture model, but these experiments also strongly indicate that the model is only applicable at pore pressures more than 1 MPa below the lithostatic pressure. Above this pressure threshold the conventional cubic law model applies to the relationship of permeability and porosity. However, the exponent used in the BRAGFLO model is much larger than can be supported using experimental evidence.

The laboratory evidence also supports the concept of increased compressibility with pore pressure. It does not seem reasonable for compressibility to increase with pore pressure above the lithostatic pressure.

2.7.4 Conclusion

Our conclusion is that the conceptual model BRAGFLO for anhydrite fracturing may be a valid description for pore pressures less than 1 MPa below lithostatic but a cubic law formulation of the permeability-porosity relationship is valid above this threshold. As demonstrated by Freeze et al. (1995), the BRAGFLO parameters can not be set to reasonably represent this region. Figure 21 is an updated version of Figure 2 of Freeze et al. (1995). The BRAGFLO model is based on CCA parameters for marker bed 139 and anhydrite layers A and B respectively. The figure shows the permeability-porosity relationship of the BRAGFLO model to a cubic law based model for multiple fractures. Our concern is that the BRAGFLO model under-represents permeability by more than four orders of magnitude for small porosity increases. By setting the model parameters to match a cubic law fracture model at large .porosity, a large error may have been introduced for small porosity changes.

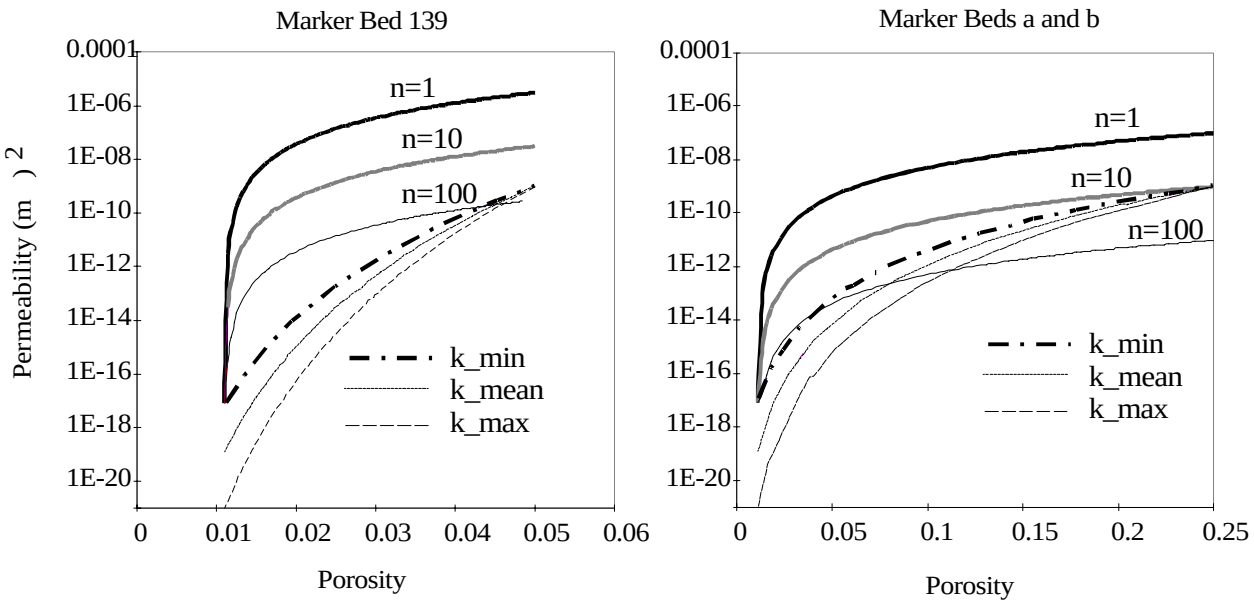

Fig. 21. Permeability vs. Porosity Model With BRAGFLO for Left) Marker Bed 139 and Right) Marker Beds a and b.

The BRAGFLO model has not been tested against either laboratory or hydrofracing experiments or other standard fracture modeling codes. This comparison should be made before the model can be accepted as valid.

A meeting was held pn February 17, 1998 to try to resolve this issue. Participants included scientists from Sandia National Laboratories; EEG; Dr. Charles Fairhurst and Dr. Jim Tracy, DOE consultants; and other DOE consultants. Dr. Walter Gerstle sent a letter to the EEG after the meeting, commenting on some of the presentations. The EEG invited the DOE to allow us to include in this report the viewgraphs used by the SNL presenters and comments on the meeting, but the DOE declined this invitation. Dr. Gerstle's letter is included as Appendix 8.7 to this report.

2.8 SOLUTION MINING AT THE WIPP

The final rule of the EPA for the certification of the WIPP requires the DOE to consider the effects of mining in performance assessments (U.S. EPA, 1996). However, the analyses need only consider the effects of the excavation mining of high grade ores, ores which are currently economical, and which are known to be present near the WIPP site, but which are known not to occur vertically above the repository. The effects of mining for low grade ores, ores which are currently uneconomical, and which could be present below or above the formation containing the high grade ores, need not be considered once the high grade ores have been removed.

The effect of excavation mining is subsidence of the overlying formations and the potential alterations of their hydrologic properties. The most important hydrogeologic unit overlying the repository is the Culebra aquifer. Therefore, in the performance assessments of mining effects, EPA permits the DOE to limit the analysis to changes in the hydraulic conductivity of the Culebra aquifer.

The EPA initially concluded that solution mining of potash is currently not feasible in the Delaware Basin (Peake, 1996). EEG (Neill, 1997a) identified solution mining as a potential scenario that must be considered by the WIPP project. In response to the concerns raised by EEG, Dials (1997d) submitted to EPA materials solicited from Heyn (1997a) and Hicks (1997). Based on the supplemental information provided by DOE, EPA maintains that changes in the hydraulic conductivity as a result of solution mining are captured in the modeled effects of room and pillar mining, that solution mining is not likely in the vicinity of WIPP because fresh water for mining is limited and the overall procedure is cost prohibitive, and that langbeinite is the primary target of extraction and is not readily soluble in water (U.S. EPA, 1997b, CARD 32-55).

The supplemental materials that DOE submitted to EPA are based directly (Heyn 1997a) and indirectly (Hicks 1997) on solicited comments from the Chief Chemist for IMC-Kalium. The comments must be viewed with caution. Heyn (1997a) makes no references to the scientific

literature. With respect to the lack of fresh water for solution mining:

> Solution mining requires access to large quantities of water. As you know, fresh water is a difficult and expensive commodity to come by in this corner of New Mexico. Water rights carry a premium price if they can be obtained at all. I would rather think the agricultural uses would have a far more beneficial use rather than solution mining (Heyn, 1997a).

Records on file with the New Mexico State Engineer indicate that on April 22, 1994, IMC Fertilizer (later IMC-Kalium) purchased 2790 acre feet per annum from Noranda Exploration (Files L-7121, L-7121-S, L-7157, L-7157-S). On November 6, 1996, IMC-Kalium, acquired an additional 2014 acre feet of water per annum to be produced from the Ogallala aquifer and piped to IMC's potash mining and refining operations (Files L-10,580, L-10581, L-10582, L-10583, L-10584, L-10584-S). It appears water rights for mining of potash ore and other related purposes can be obtained in southeast New Mexico, a detail apparently not brought to EPA's attention.

EPA maintains that the overall procedure is cost prohibitive. Heyn argued that the building of any potash mine, refinery and auxiliary facilities would require a capital investment in excess of 100 million dollars and that such an investment would require reserves in excess of 25 years. The argument provides no supporting economic calculations and no estimates of potash reserves. However, in a letter to EPA Heyn acknowledges that he is "not an expert on the extent and grade of ore reserve on the WIPP site" (Heyn, 1997b).

Heyn also suggests that efficient solution mining requires great depths to take advantage of geothermal energy such as at IMC's solution mine at Belle Plains, Saskatchewan. That mine is in excess of 3000 feet deep. Heyn comments that the potash bearing zones are only 650 to 800 feet below the surface at the WIPP site. Actually, the potash bearing zones in the vicinity of WIPP are at depths between 1400 and 1750 feet (Chaturvedi, 1984, Figure 1). Nonetheless, even at a depth of only 1150 feet, Davis and Shock (1970, p. 109) determined that a production operation would

yield 90 pounds of ore for every barrel of water injected for a potash ore zone in the Carlsbad Potash District strongly suggesting that a solution mining operation does not require the depths cited by Heyn (1997a, 1997b).

Heyn (1997a) maintains that solution mines would prefer ore bed depths to be thick, in excess of 10 feet or more to minimize solvating of unwanted minerals and displacement of clay in solubles. Yet Conoco conducted its successful field trial for solution mining of thin bedded potash on an ore zone that was 4 feet thick (Shock and Davis, 1970). In carefully designed two well test, Conoco produced 1600 tons of sylvite (KCl) and 9600 tons of halite (NaCl). And 1500 tons of that halite was produced in a final injection designed to confirm that all of the sylvite ore had been produced. If Conoco had stopped at the previous step, as would be anticipated for actual operating conditions, the total production would have been 1450 tons of sylvite and 8100 tons of halite.

In 1995, the New Mexico Bureau of Mines and Mineral Resources examined future potash mining techniques and concluded that solution mining is the only method that can be reasonably predicted for the Carlsbad District for the far future. The report notes that while no specific plans have yet been formulated, all mines in the Carlsbad area have held open the option of using solution mining once their sylvite deposits are fully mined out (Broadhead et al., 1995, p. IV-5). It is the remaining sylvite pillars, not langbeinite, that would be the primary target for solution mining.

EPA has accepted that changes in the hydraulic conductivity of the overlying Culebra Aquifer as a result of solution mining are captured in the modeled effects of room and pillar mining. The prediction of the subsidence of the ground above solution mines can be a much more complex problem than the prediction of the subsidence of the ground above conventional or excavation mines. There are verified analytical methods and formulae to predict the subsidence of the ground above excavation mines. The subject is treated in great detail in the textbook of Jeremic (Jeremic, 1994). The subsidence of the ground can be illustrated as a crater. The subsidence is uniform over the mined area with gentle slopes over the boundaries of the mined areas. In contrast, the solution mining of sodium chloride has lead to the formation of large caverns, some of which have resulted in the

collapse of the overlying sediments and the appearance of large sink holes. As an example, three spectacular sink holes occurred in 1954 over a solution mine for sodium chloride at Grosse Ile in Michigan (Jeremic, 1994). Non-uniform sinking of the ground has also been observed in Tusla, Bosnia (a former province of Yugoslavia), a town where uncontrolled solution mining of sodium chloride has been practiced for over a century.

2.8.1 Potash Solution Mining

Forty years ago, one could argue that solution mining was not used for potash, therefore it will never be feasible. The solution mining of potash is a young technology. It was started in Canada in the mid 1960's. The solution mining of sodium chloride is a very old technology. There are indications that the solution mining of sodium chloride was practiced as early as 1147AD in the small town of Altaussee, Austria (Gaisbauer, 1997).

The solution mining of potash is significantly different from the solution mining of sodium chloride. For one thing, the size of the literature on the solution mining of potash is small compared to that on the solution mining of sodium chloride, which is very large. The situation was described in 1983 as follows (Diamon, 1985): “There is a scarcity of published material on in situ potash leaching. Only a few studies have been carried out. For competitive reasons, companies involved in solution mining of potash or have an interest in getting involved, generally don’t publish their findings.”

Chemically, the solution mining of potash is significantly different from the solution mining of sodium chloride. The solution mining of potash is complex and carried out with brines. Considerations must be given to the following parameters: 1) the equilibrium system of the solubility of many salts in water; 2) the temperature of the brine in the mine; and 3) the processing of the saturated brine to achieve preferential precipitation at the surface. In contrast, the solution mining of sodium chloride requires only fresh water. Currently, solution mining of sodium chloride is used primarily to create large storage caverns for oil and natural gas.

Some have argued that solution mining of potash more economical than conventional or excavation mining of potash. IMC Kalium is currently expanding the annual production of its solution mining operation at Hersey, Michigan, from 50,000 to 150,000 short tons at a cost of $43 million (IMC, 1996). Such a large investment indicates that production of potash by solution mining in Michigan enjoys strong economic advantages over shipments of potash from Canada or the Carlsbad area. The following statement with regards to economical considerations is made in a publication (Gruschow, 1992): "therefore instead of waiting until an opportunity arises to repair or improve a conventional potash mining operation by conversion to solution mining, potential potash ore mining projects should be designed from the very beginning as solution mining operation."

There are four solution mining operations in North America. Two are in Canada and the other two are in the United States. A large potash solution mine is being operated by IMC Kalium at Belle Plain, Saskatchewan, Canada. The operation was started in the mid 1960's and in 1982 it had an estimated capacity of 940,000 ton per years (Nigbor, 1982). The mine extracts potash from depth where shaft mining is very difficult and hazardous. There are no publications describing all the changes that must have occurred to keep the operation going for about 30 years. The second Canadian solution mining operation is in the Patience Lake area, Saskatchewan, Canada. The mine is currently owned by The Potash Corporation of Saskatchewan, Inc. The mine was started as an excavation mine in the late 1950's, but it had to be converted to a solution mine in 1987 due to large inflow of water. A detailed description of the conversion from an excavation mine to a solution mine has been published (Smith, 1990). In the Canadian mines, potash is precipitated in crystallizers, which is possible because of cold temperatures.

The oldest solution mine operation in the United States is located in Moab, Utah. It is now owned by Potash Corporation of Saskatchewan, Inc. The mine was started as an excavation mine in 1964. The highly folded and distorted nature of the ore zone made mining difficult and largely unprofitable. The mine was converted to a solution mine operation in 1970 and production of potash began in 1972. A detailed description of the conversion from an excavation mine to a solution mine has been published (Jackson, 1973). The Moab mine uses solar energy to precipitate the potash in a 400 acre

evaporation pond. In 1973, the operation was expected to produce 300,000 ton per year for 20 years. Many changes must have occurred since the mining operation is still active. The second solution mine operation in the United States is operated by IMC Kalium at Hersey Michigan. The operation appears to have been started in the mid 1980's (Shock, 1985) and as already indicated, its annual production is currently being expanded to 160,000 short ton per year.

A few research studies have been published. There are two papers on an early solution mining test in the Delaware Basin (Shock and Davis, 1970; Davis and Shock, 1970). The project was not pursued because the price of potash was depressed at that time (Davis and Shock, 1970). Plans for pilot scale testing in the Montana North Dakota area were drawn up in the late 1970's (Nigbor, 1982), but it does not appear that these plans were carried out.

Solution mining of potash has been considered outside of North America. A test facility appears to have been operated at the Potasio Rio Colorado deposits in the Argentine (Colome and Ruse, 1994). Considerations were given once to the solution mining of potash from carnallite in what was East Germany (Duchrow, 1990). It should be mentioned also that Israel and Jordan extract economically about 2.1 million ton of potash from brines of the Dead Sea using large solar evaporation ponds (about 9% of the world production of potash). The KCl of these Brines is only 1% (12g/l), which is considered to be low (Gruschow, 1992).

Solution mining of potash has been successful in the operation of four converted excavation mines in North America. Two mines have operated for about 30 years and the other two for about 10 years. Solution mining is being considered for the Eddy potash mine in the Carlsbad area. The owner ceased excavation mining activities on December 3, 1997 (Davis, 1997) because the mine had been depleted of high grade ores. However, high grade ores, which remain in the pillars of the mine, can only be removed by solution mining. EPA notes that a permit is being sought for a commercial pilot solution mining venture in the Carlsbad area but EPA characterizes the proposed solution mine as speculative because it is not being done and may not take place (U.S. EPA, 1997b, Card 32-55). One might be reminded that a permit is being sought for a federal pilot waste disposal venture in the Carlsbad area,

an activity that is also not being done.

Finally, one must consider that if that extensive oil and gas development continues to expand in the potash portion of the Delaware Basin, the safe and economical production of residual potash may require solution mining.

2.8.2 Probability of Mining for Potash at the WIPP Site.

The EPA derives the mining probability of 1 in 100 in each century of the regulatory time frame using the following assumptions (Peake, 1996): 1) the mining rate in the Carlsbad area in the future will be the same as in the past; 2) the mining of different potash ore zones near Carlsbad has covered an area of 40 square miles in 62 years (1931 to 1993); and 3) future mining of potash can occur in the entire Delaware Basin, which covers an area of 9700 square miles.

The mining rate in percentage per century is

$$(40/9700)*(100/62)*100\% = 0.67\%$$

This value is then rounded upward to 1% and called a mining probability of 1 in 100 in each century of the regulatory time frame.

The assumption that a mining rate can be called a probability is technically incorrect. The EPA should have stated that it is assumed that the mining at a particular site in a century is governed by a Poisson distribution with a rate of 6.7 E-05/yr. The probability of no mining occurring at a particular site in a century is then given by

$$P(\text{no mining in a century}) = e^{-(6.7E-05*100)} = 0.9933$$

and the probability of mining occurring at least once in a century is

$$(\text{Mining at least once in a century}) = 1 - e^{-(6.7E\text{-}05*100)} = 0.0067$$

which can be rounded upward to 0.01 or 1%.

Note that the probability for mining occurring at least once during the regulatory time frame of 100 centuries is given by

$$P(\text{mining at least once in 100 centuries}) = 1 - e^{-(6.7E\text{-}05*10{,}000)} = 0.49$$

for a mining rate of 6.5E-05/yr and

$$P(\text{mining at least once in 100 centuries}) = 1 - e^{-(1.0E\text{-}04*10{,}000)} = 0.63$$

for a mining rate of 1%/century.

It would be shortsighted to assume that the mining of potash in the future will be comparable to the past, which was based on past mineral economics. Modern agriculture depends on nitrogen based fertilizers and almost all the mined potash is mixed with fertilizers. It has been estimated that about 40 percent of the world population is alive because of the use of nitrogen based fertilizers (Smil, 1997). World reserves for high grade ore of potash have been estimated at 8.4 million tons (Searls, 1996). Reserves for Canada and the United States (mostly in the Carlsbad area) have been estimated at 4.4 billion toms and 76 million tons respectively. World production of potash peaked in 1987 at an annual production of 30 million tons of K_2O and then dropped sharply to an annual production of 20 million ton by 1990 (Searls, 1995). Production has fluctuated but increased to 24.3 and 22.9 million tons in 1995 and 1996 (Searls, 1997). Rayrock Yellowknife Resource Inc, a company that mines for potash in the Carlsbad area, reported in 1996 a 6.1% increase in the finished product of langbeinite from 379,100 to 402,400 tons (Rayrock, 1996). Rayrock Yellowknife Resource states also that it has approximately 21 years of remaining reserves in Nash draw. IMC Kalium, a large producer of potash that also operates a mine in the Carlsbad area, indicates that China will have to

increase its potash consumption by the year 2,000 to 7 million tons of K_2O in order to optimize its food production. The 1996 consumption of K_2O in China was 3 million tons (IMC, 1996).

These statistics indicate that the world reserves of high grade potash ores will be depleted in about three centuries, which is very short compared to the regulatory time frame of 100 centuries.

The economic considerations of potash offer two scenarios for consideration:

> 1) low grade potash ores such as occur over the WIPP site will become economical and will be mined. The probability of the mining of potash over the WIPP will be certain or 1.0;
>
> 2) the world population will decrease sharply eliminating the need for large quantities of fertilizer. The probability of the mining of potash at the WIPP site will be much less than 1.0.

The former scenario appears to be far more reasonable.

2.8.3 Conclusions

1. EPA's conclusion that potash solution mining is not likely at WIPP relies on solicited comments that are factually incorrect and inconsistent with the published scientific literature.

2. DOE and EPA maintain that excavation mining captures the effects of solution mining on the hydraulic conductivity of the overlying aquifers. However, based on the scientific literature, the prediction of subsidence above solution mines can be much more complex than the prediction of subsidence due to excavation mining. This issue needs to be reevaluated for the final rule for WIPP.

3. Potash is a resource used for the production of food, therefore it appears to be incorrect to calculate a probability of mining based on past potash production which was inherently dependent on past mineral economics and the availability of high grade ore. It also seems reasonable to assume that low grade potash ores will eventually be mined to meet world demand.

2.9 GROUNDWATER FLOW AND RADIONUCLIDE TRANSPORT THROUGH THE CULEBRA

2.9.1 Introduction

The proposed rule (U.S. EPA, 1997c, p. 58799) discusses the causes for the lack of contributions to the total releases from the ground-water pathway, concludes that this was due to the assumed values for chemical retardation (K_d), and finds the K_d values used in the calculations to be reasonable except the lognormal distribution. As a matter of fact, the very low contribution of the releases from the ground-water pathway is due to a number of assumptions made in the CCA. The amount of radionuclides introduced in the Culebra is low due to the assumptions of actinide solubility, brine reservoir characteristics and the intrusion borehole characteristics. There are other factors in calculating transport through the Culebra besides the assumption of K_d values that result in low releases. These factors are discussed below.

The National Academy of Sciences WIPP Committee (NRC, 1996; Chapter 6 and Appendix F) raised a number of issues regarding the conceptual model and numerical model of transport through the Culebra aquifer. Only some of these issues have been addressed in the proposed rule, and even those in a very cursory fashion. The EPA's Technical Support Document III-B-6, Sections 1.3.18 and 1.3.19, discuss the issues related to Culebra transport, but do not question the DOE assumptions and modeling. The responses to comments on the issue of "Ground-water Flow and Radionuclide Transport in the Culebra" are contained in the CARD 23, pages 127 to 133, but do not discuss most of the issues raised by the NAS WIPP Committee. Several of these issues were also presented by Dr. Leonard Konikow at the EPA/DOE meeting on December 5,6,7, 1995, in Carlsbad NM; and at a meeting of the NAS WIPP Committee's sub panel on Hydrology at the Sandia National Laboratory on February 10 and 11, 1997. Because of the lack of adequate consideration by the EPA, as seen in the "proposed rule" documents, the EEG

requested Dr. Konikow to provide a summary of the issues that he has raised but remain unresolved. The following is based on personal communication from Dr. Konikow (Konikow, 1998).

2.9.2 Transport Calculations

Heterogeneity and Model Discretization: Much recent hydrogeologic research has clarified the importance of heterogeneity in controlling solute transport. What constitutes an adequate scale of definition of formation heterogeneity for a flow model may be inadequate for solving the transport equation in the same formation. Konikow (1997) presented results of numerical experiments indicating that the CCA consistently underpredicted the migration distance of a plume emanating from a human intrusion borehole. In the CCA model of the Culebra, it appears that errors arising from several sources cause an artificial spreading of the calculated width of the plume at the expense of its length. The sources of these errors include: numerical dispersion and spatial truncation errors in the transport code, poor resolution from using a grid that is too coarse for the scale of the problem, and overestimates of the size of the solute source area. The resulting nature of these errors is illustrated in Figure 22, in which plume shapes are simplified to occur as a triangle; also, for simplification, concentrations are assumed to be uniform and equal within the plume, and zero outside of the plume. Then, if the plume spreads out laterally more than would actually occur, for a given mass of contaminant released from a leaky borehole, the wider plume (a) will necessarily move downgradient a shorter distance than the narrower plume (b). Both plumes in Fig. 22 enclose identical surface areas, so they would encompass equal volumes of aquifer and equal masses of contaminants.

The solute-transport model used in the CCA is based on a finite-difference grid having a minimum spacing of 50 m. An alternative analysis was performed using the MOC3D model (Konikow et al., 1996) in which the transmissivity variations are represented on a much smaller scale, using a 2-m grid spacing, rather than the original 50-m grid spacing. This finer-scale representation of the heterogeneity and of the borehole source area results in a much longer, but narrower, plume that would have a significantly shorter travel time to the regulatory boundary for equivalent concentration levels. The 50-m discretization and related approximations, in effect, could bias the

calculations toward demonstrating safety because plumes calculated using the coarser grid would not travel as far towards the regulatory boundary in 10,000 years as they would with a finer grid.

Heterogeneity of Other Transport Parameters and Processes: The CCA model of the Culebra assumes that most properties of the system, except the transmissivity, are homogeneous and uniform within each simulation realization, but that these properties varied from run to run. Field

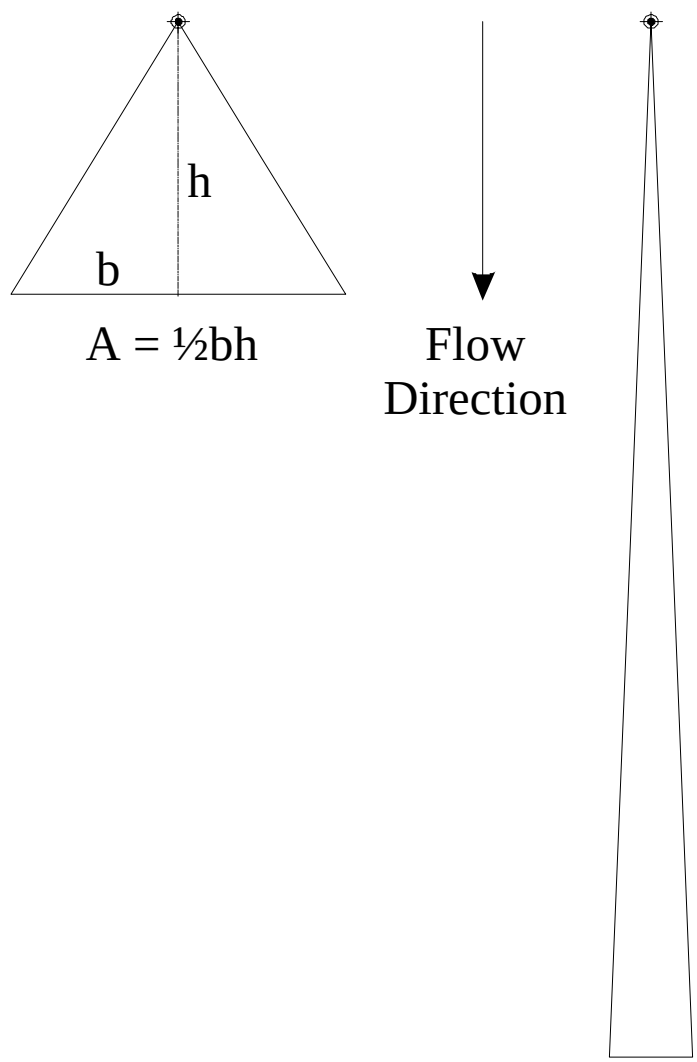

Fig. 22. Conceptual Diagram Of Contaminant Plumes Represented As Simple Triangles, Showing Different Travel Distances For A Relatively Wide Plume Compared To That Of A Relatively Narrow Plume, Where Both Plumes Encompass Equal Volumes Of Fluid And Equal Masses Of Solute.

tests at WIPP, however, indicate significant variability in many of these properties. For example, the effective porosity of the aquifer varies by almost an order of magnitude, even over a distance of only 50 m (the size of one cell of the model grid). Porosity has a strong control on transport velocities and times. Hence, the variability in porosity induces variability in velocity, which means that some parts of the plume may move faster than the local average velocity. This effect cannot be captured by assuming that porosity is uniform in each simulation. One would expect other properties, such as K_d and fracture spacing, to similarly exhibit large spatial variations. The PA procedure inherently assumes that heterogeneity in these variables has no significant impact on transport, or that its effects can be adequately represented by varying uniform properties among all the realizations. Either way, the CCA has not demonstrated that this is indeed the case and that it is reasonable to ignore the spatial variability in all of these critical parameters.

Sampling Procedures for Input Parameters: To generate the statistical distributions from which the risks are calculated, many simulations of hydrogeologic processes are performed to generate an adequate sample size. The approach to varying the values of the many parameters in the multiple realizations can introduce errors into the final analysis. In particular, if hydrogeologic variables that are highly correlated are sampled independently, and if the correlations are ignored, then some of the realizations may be based on unreasonable or very unlikely combinations of parameters; such individual simulations should not be incorporated into the final analysis because they may skew the statistical results. This was the basis for a criticism of the WIPP performance assessment by the NAS WIPP Committee (NRC, 1996, p. 71). For example, the CCA separately sampled and independently varied aquifer transmissivity, fracture spacing, and porosity. Yet there is good reason to suspect that these variables are interrelated.

The significance of this problem can be illustrated with a relatively simple example. Suppose that a strong positive correlation exists between two critical model parameters, as represented in Fig.23a, and that all data points will fall within the indicated bounds. Furthermore, assume that a safety failure for the geologic repository will only occur if the values for both parameters are very high, as represented in Fig. 23a. If the sampling procedure generates values independently for both parameters from uniform distributions for a sample size of 25, for example, then we might

expect the 25 realizations to be based on parameter values distributed uniformly in the sample space, as represented in Figure 23b. That is, we would expect a plot of joint values of the two parameters to yield one point in each of the 25 squares in the grid shown in Figure 23b. Only one of the 25 realizations (representing the value in the upper right corner of the grid) will yield a failure, and the probability of failure on this basis will appear to be 0.04. Twelve of the samples, however, were obtained from outside of the bounds of the feasible set of values. If these are discarded, as they should be, then the failure probability is only one out of 13 (or about 0.077), or nearly twice as great as indicated by independent sampling that ignores the correlation between these two variables. The net effect of the independent sampling approach in this example of correlated parameters is to "pad" the outcome with "safe" cases (or realizations), thereby yielding a biased risk assessment.

Consistency Between Performance Assessment (PA) Models: The PA procedure uses one model to calculate the fluid and solute flux up and out of a Human Intrusion (HI) borehole. This outflow flux should then be equal to the input flux (source term) in the Culebra model that is used to calculate transport distances and times. However, the source term in the Culebra model is apparently not represented as a specified flux, so it is unclear that the flux out of the borehole is equal to the flux into the Culebra for each set of realizations (or even for the mean of all realizations). The PA models should compute mass balances and budgets, to demonstrate that the two boundary conditions are indeed equivalent. Specifically, the total mass of fluid and solute that the borehole model computes to enter the Culebra over 10,000 years should equal the total mass of fluid and solute that is added to the Culebra over 10,000 years in the Culebra model. Is such documentation available? It appears possible that representing the HI borehole solute flux as an initial condition in the transport equation without an accompanying fluid flux could lead to a consistent underestimate of the solute spreading away from the finite-difference cell where the HI borehole is assumed to be located.

Other Concerns about Parameters and Processes: The NAS WIPP Committee report (NRC, 1996) included a number of criticisms of the conceptual models and numerical models of the Culebra, many of which remain unresolved. Please review Chapter 6 and Appendix F of that report for more details. The most critical issues relate to the use of homogeneous and uniform Kds in each realization, and whether the very simple retardation factor concept adequately represents all of the complex reaction chemistry. This has certainly not been adequately demonstrated at the field scale. A related important issue is the accuracy of the definition of matrix diffusion processes and parameters. Another concern is the reliability of the regional

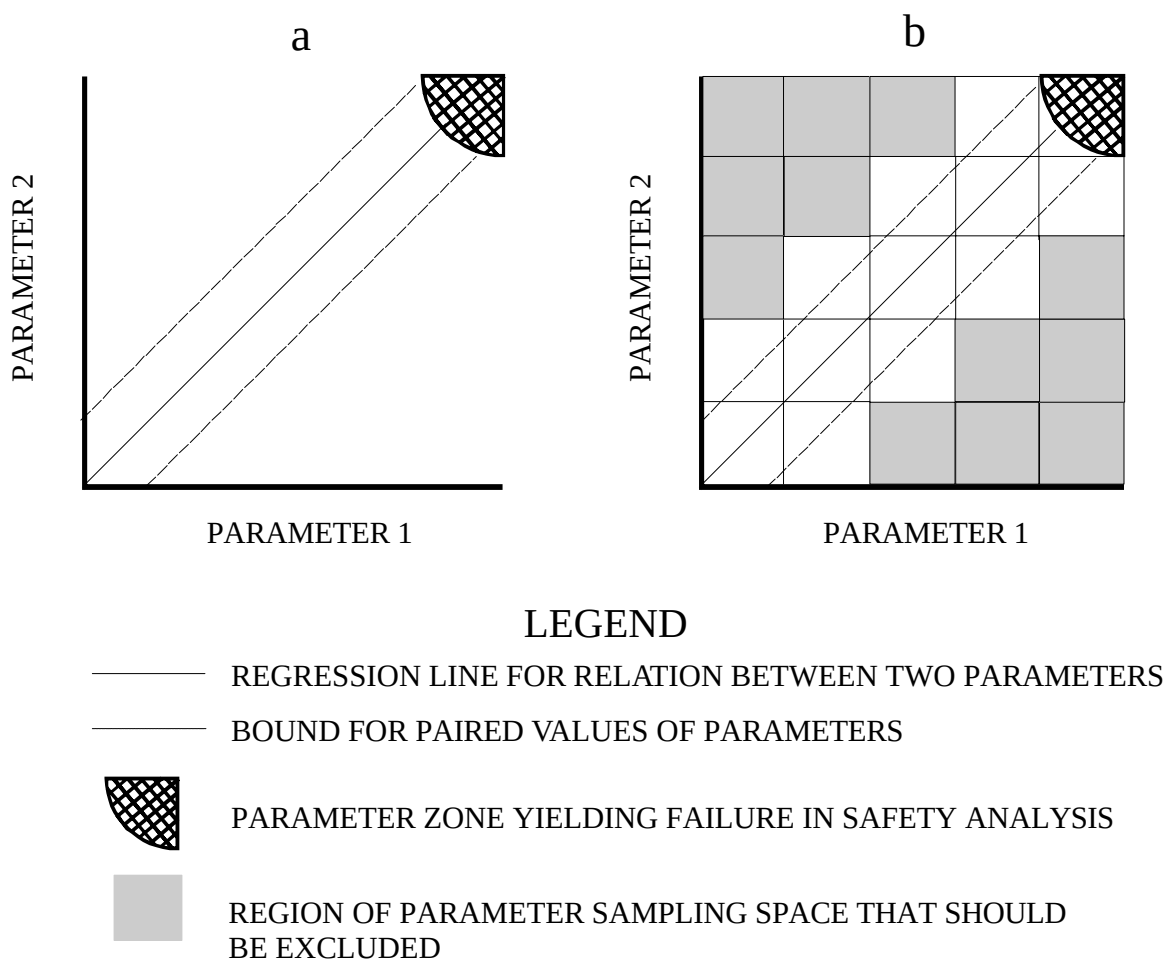

Fig. 23. Example to illustrate effect on calculated risk of independent sampling values of two parameters that are strongly correlated. (a) All data points fall within indicated bounds. (b) Independent sampling can yield paired values that are “out of bounds” and should be excluded from the PA.

transmissivity estimates for the Culebra, which were determined using inverse methods that assumed a non-leaky two-dimensional aquifer. More recent three-dimensional analyses by Sandia clearly indicated that there is significant leakage into the Culebra. A AClimate Index@ has been used as a multiplication factor in the CCA to enhance the magnitude of flow of the Culebra flow field to compensate for the lack of consideration of the additional flux through the system. However, we have not seen any rigorous analysis and documentation of the consequences of such errors, or the sufficiency of corrections applied.

An important overriding consideration is that if the volume of fluid entering the Culebra from HI boreholes is negligible or if the concentration of radionuclides in that fluid is extremely low, then weaknesses and flaws in the Culebra models become a moot point. The reliability of these calculations of fluid and solute fluxes hinges on a number of other assumptions and conceptual models about the high-pressure brine reservoirs underlying WIPP, about the pore-volume and saturation of the sealed repository, about anhydrite marker beds, about solubilities, and about a number of other issues. Some of these assumptions have changed markedly between the time of the 1992 PA and the 1996 CCA. The NAS WIPP Committee (NRC, 1996) examined the assumptions underlying the 1992 performance assessment in moderate detail. Many of the revised assumptions that were made for the CCA models were not subject to rigorous scientific scrutiny by the Committee. Where some of the CCA assumptions were examined and weaknesses in the models detected, it was too late to document the concerns in the 1996 published report of the Committee.

2.9.3 Chemical Retardation

The EEG has submitted the following four documents to the EPA on this issue:

- Copy of November 14, 1996, letter from R.H. Neill to J. Salisbury, with attachments;
- February 7, 1997, letter from R.H. Neill to F. Marcinowski, with attachment “Chemical Retardation”;
- Copy of May 23, 1997, letter from R.H. Neill to J. Salisbury, with attachments; and,

- Copy of August 29, 1997, letter from R.H. Neill to G.E. Dials, with attachments.

The August 29, 1997, letter and the attachments (EPA WIPP Docket # II-D-117) contained the EEG position on this issue based on the July 30, 1997, meeting in Albuquerque, which was organized by the EEG. Copies of this letter with the attachments were mailed to several EPA officials and the EPA WIPP docket. The DOE also sent a copy of their impressions of the July 30 meeting (Dials to Neill 8/25/97 letter with attachments, docket # II-D-115) to the EPA on August 25, 1997, four days before the EEG letter.

The EPA draft rule discusses this issue in the Technical Support Document, "Assessment of K_ds Used in the CCA", docket # III-B-4. This document makes extensive references to the DOE's August 25, 1997, letter, but no mention of the EEG's August 29, 1997, letter. Because the issue was raised by the EEG, and the July 30, 1997, meeting was organized by the EEG, it is difficult to understand why the EPA's analysis makes no mention of the EEG's summary of the July 30 meeting and the recommendations.

As described in the EEG's August 29, 1997, letter, the EEG has recommended conducting both batch and column tests for at least the actinides Pu(III), Pu(IV), and Am(III) in the Culebra brine; setting the lower end of K_d for U(VI) to be zero; conducting sensitivity analysis for potential impact of organic ligands; extending performance assessment calculations beyond 10,000 years to see how long the chemical retardation delays the releases to the environment; investigating the potential impact of nonlinear sorption on radionuclide transport; and, checking the validity of the K_d values derived from the column tests by examining the cores to identify whether the Pu and Am are present in adsorbed or crystalline solid phase.

Before discussing the specific issues and our recommendations, we wish to clarify our philosophy regarding what K_d numbers are needed for showing compliance with the numerical Containment Requirements (40 CFR 191.13) of the EPA Standards. Independent check of the CCA calculations by the EPA and the EEG show that only 3 ml/g value for K_d is sufficient for showing compliance with 40 CFR 191.13. However, that conclusion is based on keeping all the other

parameters and assumptions in the CCA unchanged. It is difficult to accept a particular value or a range of values for any of the input parameters, or to accept conceptual models, on the basis of partial sensitivity analyses. We have communicated this view to the Environmental Protection Agency (EPA) in our comments on the CCA dated February 7, 1997 (Appendix 8.1) and March 14, 1997 (Appendix 8.2). The EEG position is that the values of all input parameters and the validity of all conceptual models be independently verifiable to be robust. The comments below should therefore be read with this philosophy in mind. Letter reports on this question from the EEG consultants, Dr. Don Langmuir, Dr. Leslie Smith, and Dr. Mark Brusseau, are enclosed in Appendix 8.6 of this report.

Transferability of Laboratory K_d Data to Field: Dr. Jim Davis of the U.S. Geological Survey, who attended the July 30, 1997, meeting as a nominee of the NAS WIPP Committee, raised a number of important questions concerning the applicability of the laboratory K_d data for the field conditions. This issue has been debated for many years. The latest report of the National Academy of Sciences WIPP Committee (NRC, 1996), in discussing the chemical retardation issue, states: "...there is often little basis for extrapolation of theory and lab tests to the field environment for predictive purposes". The EEG has, however, accepted the validity of the approach of using the laboratory determined values to get an estimate of the values to be used for modeling contaminant transport in the field, because, as described by Dr. John Bredehoeft at the meeting, groundwater diffusion into the rock matrix will provide opportunities for chemical retardation to occur. But this does not mean that a one-to-one correspondence may be assumed between the laboratory and field values. Dr. Brusseau has recommended additional analyses of the column experiments to help address whether the K_d values obtained under static batch conditions provide an accurate measure for dynamic field conditions. Both Dr. John Bredehoeft and Dr. Leslie Smith emphasized that the K_d range determined from batch tests applies only to the matrix porosity, and not to retardation in the fracture system with advective porosity. This is consistent with the model used in the CCA. There is no discussion of this specific issue in the DOE's August 25, 1997 letter or its attachments, extensively quoted in the EPA's Technical Support Document (U.S. EPA, 1997j).

Limited K_d Data Base: The experimental data base for the K_d values used in the CCA remains insufficient. In the absence of measured K_d values for Plutonium at oxidation states III and IV, and inconclusive results for Am^{III}, the K_d values for these three most important actinides in the WIPP inventory have had to be estimated. These estimations are based on two questionable assumptions. The first is that K_d values for actinide cations of the same charge should roughly be the same. According to Dr. Langmuir, the weakness of this assumption lies in not considering the effect of the speciation behavior of the cations on their adsorption properties. The second assumption is that predictable trends exist for the K_d values of actinide cations of different charge. The DOE used this assumption to argue that Pu^{V} data can be used for Am^{III}. Dr. Langmuir has shown in his letter report to EEG (Appendix 8.6) that this assumption is based on questionable data and interpretations of the experiments conducted with dilute groundwater from the Yucca Mountain site, even though, fortuitously, the same trend has been reported by some other experimenters. Results of the intact core column tests are probably of questionable value as well, because the Am and Pu input concentrations to the cores were so close to saturation with solids that precipitation rather than adsorption may have occurred.

The net result of these assumptions is the use of unjustified K_d values for the three most dominant radionuclides in the WIPP inventory. Pu^{V} data has been used for Pu^{III} through a two step process, both of which are questionable; first, through the predictable trend argument, for Am^{III}, and then, through the oxidation state analogy, for Pu^{III}. Similarly, Th^{IV} data has been used for Pu^{IV}, using the oxidation state analogy. Here too, besides the problems with the oxidation state analogy, there is an additional problem of an inapplicable brine (from ERDA-6 brine reservoir) having been used for the Th^{IV} experiments. As Dr. Clemo showed at the July 30 meeting, the mean K_ds measured in the ERDA-6 brine are greater than the values determined using the other three brines. Thus, the use of Th^{IV} data for Pu^{IV} also has two problems. The EEG has never understood why real data for at least the most dominant components of the WIPP waste has not been obtained. The attachment to the DOE's August 25, 1997, letter (Docket II-D-115, cited in U.S. EPA, 1997j) repeats the previously presented arguments in favor of accepting the data on other actinides at other oxidation states as surrogates for actual data on Pu^{III}, Pu^{IV}, and Am^{III}.

EEG recommends conducting both batch and column tests for at least Pu^{III}, Pu^{IV}, and Am^{III} in the Culebra brine if any credit for retardation of these actinides is to be taken in the WIPP performance assessment.

Uniform Distribution Assumption: Based on the recommendation of our consultants, the EEG now accepts the use of uniform probability distribution to represent the uncertainty in the K_d values for the CCA calculations because the experiments were not designed to provide distribution information. However, Dr. Leslie Smith has taken issue (see page 2 of his letter report, Appendix 8.6) with the CCA values for the lower and upper bounds of the probability distribution, and how these bounds are defined relative to the type of brine used in the batch experiments. The ranges for K_d relative to brine type were selected based on the average value of the sample distribution. For example, the range for Pu^{V} (and by extrapolation, for Pu^{III} and Am^{III}) used in the CCA calculations is 20-500 ml/g, which reflects values from the batch tests using deep brines, while the results with the Culebra brine had a lower range of 9.8, and therefore the assumed range for Pu^{V} should have been 9.8 to 500 ml/g. Dr. Langmuir has asked (see Appendix 8.6) why the lower range of 1-200 ml/g determined for Np^{V} was not used for Am^{III} and Pu^{III} .

Dr. Leslie Smith (in his letter report in Appendix 8.6) has also raised questions about the U^{VI} K_d data. If the negative values are ignored, the low end of the sampling range for U^{VI} is 0.03 ml/g. The zero values assigned to the negative values for the batch tests with the Culebra brine did not get passed into the CCA calculation because of a lower average value of K_d for the batch tests using deep brines. The EEG recommends that the lower end for U^{VI} K_d value be set at zero.

Non-Culebra Dolomite: The issue of the use of Norwegian dolomite K_d data, not a major concern to begin with, may be considered to be resolved because the results of these tests make their way into the final sampling distribution only once, in determining the upper bound for U^{VI} at high pH conditions.

Organic Ligands: The EEG makes the following recommendation, as suggested by Dr. Mark Brusseau (see his letter report in Appendix 8.6):

> The DOE should conduct and publish a formal sensitivity analysis to examine the potential impact of organic ligands on the aqueous concentrations of the radionuclides. The concentrations of the ligand should be varied by several orders of magnitude, and the full list of ligands provided by EEG should be used.

Additional Issues: Dr. Langmuir has questioned the results of the core column tests because of the high concentrations of Pu^{V} and Am^{III} in intake solutions possibly resulting in their precipitation as solids rather than adsorbed in the columns. If precipitation did occur, the concentrations in the rock cannot be used to define K_d values. In order to prove or disprove this concern, it is recommended that the core materials that have been drilled out be examined to identify whether the Pu and Am are present in adsorbed or crystalline solid phase.

Dr. Langmuir has also suggested that it is possible to obtain K_d values for the important actinides in a short period of time from accelerated intact core experiments performed in an ultracentrifuge. Because of the time constraints, the DOE should examine this option.

Dr. Brusseau has recommended investigating the potential impact of nonlinear sorption on radionuclide transport. This could be accomplished by calculating effective K_d values for pertinent C_0 values, using the nonlinear isotherm data available. These values should then be compared to the existing K_d range.

During discussions with our consultants after the July 30 meeting, it was pointed out that if the calculations for release were continued beyond the 10,000 year period, release to the accessible environment will be seen. Rucker (1998) also shows that a significant fraction of actinide mass will cross the LWB beyond the 10,000 regulatory time frame. Figure 24 (reproduced from Rucker, 1998) shows the fractional discharge of Uranium with a retardation coefficient of 2.0

crossing the LWB. The figure demonstrates that very little mass that enters the Culebra crosses the LWB during the initial 10,000 years and almost the entire nuclide mass fraction will cross the LWB by 70,000 years post intrusion. The EEG recommends that the performance assessment calculations be extended beyond 10,000 years to determine long-term system performance.

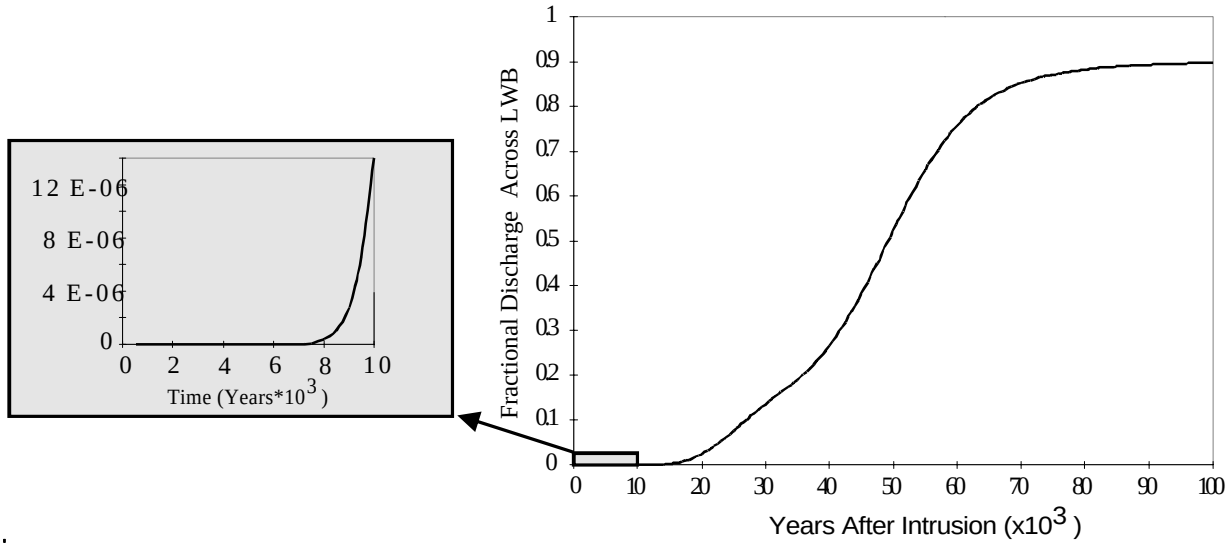

Fig. 24. Fractional Discharge Of Uranium Across The LWB Within 100,000 Years, With Blowout Section Of 10,000 Years. Reproduced from Rucker (1998).

2.10 THREE DIMENSIONAL PROCESSES AND BOUNDARY CONDITIONS

This issue was presented to the EPA staff on December 10, 1997, as "2D/3D Modeling in BRAGFLO". The EEG first brought this issue to the EPA's attention as an attachment titled "Brine Inflow From Salado: 2-D versus 3-D Geometry in BRAGFLO" to the March 14, 1997 Neill to Marcinowski (Neill, 1997b) letter. The DOE submitted a response as an attachment to the June 27, 1997 letter from G.E. Dials to L. Weinstock. The Draft Rule includes this issue as Issue F in CARD #23. The EEG position is summarized by the EPA as Comment #553 on page 115 of CARD #23, and the EPA response is provided on page 116. EEG's detailed response to the DOE and the EPA positions is provided as Enclosure 2 to this letter. DOE once again responded to this issue in attachment 6 of a letter from G. Dials to M. Kruger dated January 26, 1998. On February 17, 1998, EEG met with DOE to discuss this as well as other issues. As an outcome of this meeting, it was agreed that a single 3-D simulation be performed using the parameter values of one vector in the CCA calculations to assess the potential for impact on the CCA release calculations. A summary of the issue, the EEG's response, and the EEG recommendation to resolve the issue, follow.

The results of FEP S-1 screening analysis suggest that the two dimensional BRAGFLO model used in the CCA calculations may be misrepresenting repository performance at pressures above the anhydrite fracture pressure. There is the potential of substantially greater brine saturation in the repository at higher pressures than calculated for the CCA. The discrepancy between the 2D and 3D versions of BRAGFLO may have resulted in an underestimate of radionuclide releases to the surface.

To resolve this issue, the EEG recommended that several 3D BRAGFLO simulations of the repository should be performed using the parameter values of vectors used in the CCA performance assessment. The 3D BRAGFLO simulations should be used to provide repository conditions for the normal suite of direct brine release calculations. The calculations should also be assessed in terms of impact on spallings calculations. Spallings simulations are probably not required to assess the

impact. The following criteria may be used to select the CCA vectors for running the 3D simulations to bound the magnitude of the problem:

- Since the discrepancy occurs above the fracture initiation pressure, the simulations should be limited to parameter vectors that result in pressures above 12.7 MPa at some time during the 10,000 year time frame.

- Direct brine release calculations should be sensitive to increased brine saturations above the waste residual brine saturation. Vectors that had either large brine saturations or a mobile brine component (saturations above the residual saturation) are more likely to be sensitive to increased brine inflow. Figure 5.1.5 of the preliminary sensitivity analysis report (Helton, 1996) indicates one vector with a 10,000 year pressure above 14 MPa and a brine saturation above 0.4. This is a likely candidate.

- The potential for brine consumption by corrosion should be assessed. Vectors with both slow and fast corrosion rates that also meet the above two criteria should be run.

- If the first simulations indicate a large change in saturation, then assess whether the 3D BRAGFLO simulations indicate a much larger number of significant direct brine releases than those calculated in the CCA. Simulations using brine saturations on the order of 0.1 and 0.3 should be performed.

In response to these recommendations, DOE indicated that the conditions used in the FEP S-1 investigation were not representative of CCA conditions and that increased brine inflow should not be expected for CCA conditions. If brine inflow did occur as a consequence of anhydrite fracturing, it was expected that the additional brine would be consumed through metal corrosion and therefor not increase repository saturation. At the February 17, 1998, meeting it was agreed that there was sufficient reason to further investigate the potential for greater brine inflow to the repository using 3D modeling than the calculated in the 2D model of the CCA. It was agreed that a simulation

corresponding to a parameter vector that led to high pressure and anhydrite fracturing in the CCA calculations will be sufficient to demonstrate the potential increased brine inflow in comparison to the CCA calculation.

2.11 BRINE RESERVOIR PARAMETERS

The EEG raised a number of issues related to the Castile Formation brine reservoirs (Neill, 1997a, 1997b) attachments "Brine Reservoir Assumptions", Appendices 8.1 and 8.2 of this report) in commenting on the CCA. The EPA has accepted all of the EEG suggestions except the one related to the assumption of the probability of encounter of brine reservoirs, and we disagree with the EPA on this issue. The CCA assumed 8% probability on the basis of faulty assumptions. The EEG recommended 100% probability on the basis that the WIPP-12 brine reservoir was large enough to most likely extend under the repository, a conclusion also confirmed by geophysical testing directly above the repository. The EPA has sampled on a range of 1 to 60%, but has provided no basis for assuming less than 60%. Based on the arguments that the geophysical (Time-domain electro-magnetic survey) data may be interpreted to indicate the brine to be under 60% of the repository, and that some boreholes adjacent to the brine producing boreholes are known to be dry, the EEG is willing to accept the assumption of a fixed 60% probability of encounter, and recommends that a new performance assessment calculation be run with this fixed value.

According to EPA, changing the assumed brine volume of a Castile brine reservoir from 160,000 cubic meters (in the CCA) to 17 million cubic meters (in the PAVT calculation) had a noticeable effect on releases, but the compliance with the standards was still met. However, "EPA believes that the PAVT verifies that the original CCA Castile brine reservoir parameters were adequate for use in PA and comparison against the radioactive waste containment requirements." (U.S. EPA, 1997c, p. 58800). The EEG strongly rejects this argument because there are many other parameter values and conceptual and numerical models that should be changed, unless acceptable justification can be provided for the assumptions in the CCA and the proposed rule; and these changes will change the outcome of calculations. To declare an assumed value that is not otherwise justified "adequate" on the basis of limited changes in other values is, at the least, premature. There is no rational basis for finding an unjustified value to be acceptable unless it is justified based on observations, experiments, or widely known facts.

2.12 WASTE ISSUES

EEG has two waste issues. One concerns assumptions of random emplacement of radionuclides in the repository and the effect this may have on the final CCDF. The other refers to the determination of quantities of cellulosics, rubber, and plastics in the waste and the control of this waste limit in the repository. These two issues will be addressed separately.

2.12.1 Assumption of random emplacement of radionuclides in repository

The assumption by DOE assumes that the waste inventory will be emplaced in the repository in a purely random manner leads to three further assumptions in the PA:

(1) The 569 CH-TRU waste streams can be sampled randomly to determine the concentrations of radionuclides brought to the surface by cuttings and cavings;

(2) the concentration of radionuclides in the area of the waste room affected by spallings releases can be assumed to be the average of the entire WIPP inventory;

(3) the concentration of dissolved radionuclides in solution in a waste panel that has a Direct Brine Release is also calculated from the average of the entire WIPP inventory.

2.12.1.1 Previous EEG comments

EEG commented on this issue in our March 14, 1997, letter to EPA. The following additional comments are similar to those of 3/14/97, and lead to similar conclusions.

2.12.1.2 EPA response to issue

EPA did not accept DOE's contention in the CCA that emplacement of waste in the repository would be purely random and that a waste loading plan was unnecessary. The EPA requested in a March 19, 1997, letter that DOE provide additional information on the possible effects of non-random loading

on cuttings and cavings, direct brine release, and spallings releases. Upon review of DOE's response (Docket A-93-02 Item II-I-28 Enclosure 1, p. 8-18) "EPA determined that DOE was therefore not required to describe how the planned distribution of radioactive waste (as assumed in the PAs) would be achieved because the random distribution of waste containers in the WIPP resulted in compliance" (i.e., it did not matter to compliance how the drums were placed in the WIPP).

2.12.1.3 EEG evaluation

EEG agrees with EPA's request of DOE for analyses involving non-random loading. However, we have disagreements with several of the DOE assumptions and evaluations as well as the conclusions that were drawn from their results.

Effects on Brine Concentration. The DOE assumes that all brine in a repository would have to travel long distance through large volumes of waste to reach the point of an intruding borehole and concludes that brine concentrations of radionuclides are appropriately determined from the entire repository average.

EEG believes that while the DOE model is possible, it is not the only (and probably not the best) explanation. It certainly is non-conservative. The brine present in an undisturbed waste panel could come, more or less evenly, from all the walls, ceilings, and floors in the panel. If this occurs brine would stay close to the point where it enters the waste room or panel drift. There would be some movement down dip and this would cause water depths at maximum down dip location to be about 25% higher than the average depth (assuming 50% brine saturation). A waste room at 50% brine saturation would contain 270 m^3 of brine. The maximum brine release in PAVT is 100 m^3 and the 90th percentile release is only 15 m^3. It seems unreasonable to assume that most water flowing into the intruding borehole would come from great distances. EEG believes it most reasonable to assume an average concentration of wastes from no larger a volume than one repository room. We have not attempted to estimate how much the concentration in a room would increase the CCDF. However, we note that the plutonium concentration in solution from SRS heat source waste would be at least 6 times the average at 350 years. Also, the RFETS residues are almost 15 times as concentrated in

^{241}Am as is the repository average. Americium-241 has a specific activity that is 56 times that of ^{239}Pu and it will be the dominant radionuclide in solution (in curies) for thousands of years when using either PAVT or CCA median solubilities.

EEG concludes that the amounts of radioactivity in solution from non-random emplacement could be somewhat larger than DOE has calculated and that this issue has not been adequately addressed.

Effect on Cuttings Releases. DOE had previously evaluated effects of non-random loading on cuttings and cavings releases in 1996 when responding to a Peer Review Panel concern. They ran a replicate of 100 realizations of the effect of assuming that all 3 drums in a stack came from the same waste stream (rather than random). The resulting CCDFs are included in DOE's May 2, 1997, response to EPA's March 19, 1997, request for more information. The non-random loading CCDF plots indicated mean values that were 26% higher at 0.1 probability and 22% higher at 0.001 probability than the mean for random loading.

Effect on Spallings Releases. DOE's evaluation of the possible effect of non-random loading on spallings releases considered the number of EPA waste units that would be brought to the surface if 4 m^3 of repository room volume of RFETS residues were brought to the surface. The RFETS residues were considered to be the highest activity waste stream containing more than 810 drum equivalents (0.001 of the total repository volume). The total release of 0.368 EPA units is well below the 10 EPA units allowed at 0.001 probability.

These are reasonable assumptions. However, the total EPA units should include the release from cuttings and cavings into these wastes (mean of 1.0 m^3 in PAVT). Also, the RFETS residues are not the worst waste streams for early intrusion times. There are 810 drum equivalents of heat source waste at SRS that would average 440 ci/m^3 at 100 years after closing and 7,100 drum equivalents that average 130 ci/m^3 at 100 years.

EEG has recommended before that the waste stream activity for spallings release should be a sampled value as it is for cuttings and cavings. An indication of the possible effect can be seen from PAVT volumes and EPA units released. The mean spallings volumes are 1.7 times the mean cuttings and cavings volume for scenario S1 and 1.2 times for scenario S2. Yet the mean CCDF release at .001 percent is 25% greater for cuttings and cavings (with waste stream samplings on random emplacement) than for spallings (assumed average activity).

Summary of EEG Conclusions and Recommendations. EEG believes that releases in brine could be somewhat larger (perhaps more than 100%) than calculated in the CCA or PAVT if non-random loading on a room-size scale was assumed. We agree that the cuttings and cavings releases will be about 25% higher if there is non-random loading on stacks of drums. Also, spallings releases are likely to be 25-50% higher with waste stream sampling on random emplacement and higher yet with sampling on non-random emplacement.

EEG disagrees with the DOE position (and EPA concurrence) that since non-random considerations do not show that these three release mechanisms would lead to non-compliance they are unimportant and can be ignored. The effect of these three mechanisms combined could increase the total mean CCDF at .001 probability by 50% or more. This is still a long way from non-compliance. However, there are other assumptions in PA models and parameter values that EEG does not believe have been shown to be non-conservative, that can also affect the final CCDF curve.

EEG recommends that releases from cuttings and cavings and spallings be determined from waste stream sampling based on non-random emplacement. Direct brine release values should be based on non-random emplacement on a scale no larger than one waste room.

2.12.2 Cellulosics, rubber, and plastics

DOE has concluded that a maximum repository limit of 2×10^7 kg of cellulosics, rubber, and plastic (CRP) is needed in order to prevent production of more CO_2 than can be controlled by the MgO

backfill. EPA has concurred in this recommendation. The expected amount of CRP in the repository is 2.1 x 10^7 kg (U.S. EPA, 1997b, CARD 24-38).

2.12.2.1 Previous EEG comments

EEG commented on this issue in our December 31, 1997, letter to EPA. There were two concerns: (1) whether the quantities of CRP in the waste would be determined with the necessary accuracy in waste characterization; and (2) whether the proposed repository limits on kilograms of CRP would be adequately controlled by the proposed scheme.

2.12.2.2 EPA response to issue

EPA has never expressed a concern about waste characterization of CRP to DOE. They did inquire about the ability of DOE's WIPP Waste Information System (WWIS) to control the repository limits set by DOE. The possible need to control waste repository limits on a scale less than the full repository was not mentioned by EPA.

EPA has not responded verbally or in writing to EEG's concerns mentioned in the December 31, 1997, letter.

2.12.2.3 EEG evaluation

<u>Waste Characterization</u>. EEG is concerned about the ability to measure CRP with enough accuracy to ensure that the 2 x 10^7 kg limit will be met. Visual Examination (VE) is a method that is capable of good precision on those containers measured if all internal containers are emptied and their contents identified and weighed. However, internal containers are not always opened during VE. The preferred method of characterization is real time radiography (RTR) which is only semi quantitative (WMP weights are estimated by determining the void space and weight of waste in the drum which is not very accurate even if there is only one WMP in the container). EEG has not found a reference to the uncertainty in determining the weight of CRP in waste containers in either the DOE or the EPA reports. The EPA needs to point out where this uncertainty has been addressed, if it has been, or address the issue.

Waste Repository Limits. EEG has two concerns about the DOE plan to control CRP waste repository limits on the full repository rather than on a sub-unit (such as a waste panel). There are two concerns that do not appear to have been addressed:

(1) An excess of CRP in a waste panel could overload the MgO in that panel and since no interchange of brine between panels is assumed, it is questionable how much benefit would incur from excess MgO in another panel. Estimated concentrations of CRP do vary significantly between generating sites (e.g. at INEEL the average is 1.8 times the total inventory average);

(2) A management plan that allows emplacement of repository limited parameter quantities that vary significantly from the required average could result in a situation where the required limits could not be met by emplacing the remainder of the inventory. This is a potential problem because the actual content of waste containers will be known only as the individual containers are characterized and may be much different than the current estimates.

EEG believes that waste repository limits for CRP should be controlled on a per panel basis at least until the inventory is known with more certainty.

2.13 QUALITY ASSURANCE

2.13.1 General Comments

The 40 CFR 194.22 criteria for evaluation of the DOE's quality assurance (QA) program provide a clear list of items to be documented by the DOE. In reviewing the EPA's proposed rule for certification of the WIPP's compliance with 40 CFR 191 the EEG's primary concern was to find objective evidence to show that the EPA has examined the DOE's demonstration of compliance with the §194.22 criteria, either in the text of the proposed rule, or by reference to appropriate docket material. Because of a lack of such objective evidence, the EPA's proposed rule, CARD 22, and docket material referenced by CARD 22 do not demonstrate that many of the criteria have been met. The final rule should address these issues.

The July 22, 1996, Neill to Dials letter noted that the proposed QA chapter contained significant omissions and errors, including failure to adequately address many of the criteria in §194.22, and recommended that it be completely rewritten. Only incidental changes were made to the chapter before issuing the October 29, 1996, CCA. The Neill to Kruger August 11, 1997, letter (see Appendix 8.8) contains a later EEG review on the QA chapter of the CCA. Initial portions of this review were provided at a presentation to the EPA by EEG staff on January 21, 1997.

The CCA chapter on QA was neither complete nor accurate, as required by the §194.11. Had the DOE provided the information required by the §194.22 criteria, the EPA's efforts would have been simply to verify the DOE data. However, the EPA has attempted to gather data that shows compliance with §194.22, rather than reviewing the data as presented to them by the DOE. This seems contrary to the intent of the §194.22 criteria, which places the requirement on the applicant; for all but the initial and final criteria, §194.22 states (in §194.22(a)(2), (b), (c), and (d)):

> Any compliance application shall [provide or include] information which [describes or demonstrates] that [statement of criterion].

In the proposed rule, the EPA states that the documentation needed to demonstrate compliance with the criteria was too voluminous to be provided in the CCA. The CCA QA chapter did not, however, provide pointers to the documentation that would provide a demonstration of compliance, nor did it discuss all the programs and activities that should have met the §194.22 criteria.

Some of this voluminous documentation was viewed by the EPA during reviews, audits and inspections of the DOE and its operations, as allowed under §194.21 and §194.22(e). These EPA QA operations provide much of the evidence presented in the proposed rule and CARD-22 to support the argument that the criteria have been met. However, the intent of the audits and inspections as described in §194.22(e) was to verify execution of QA programs, rather than to establish that the §194.22(a)-(d) criteria had been met. The reports from these QA operations (as found in the EPA's WIPP docket) indicate that the EPA did not specifically address many of the §194.22 criteria, nor is there evidence in them that EPA has checked to make sure that the DOE's voluminous documentation contains the descriptions or demonstrations related to each specific criterion.

These EPA documents also do not show an awareness of all the DOE programs and activities that fall under the §194.22 criteria; this is likely related to the failure of the CCA's QA chapter to discuss these programs and activities, even though §194.22 clearly required a demonstration in the application that the NQA standards had been applied to these programs and activities. Since the EEG's day-to-day responsibilities make it familiar with many more of the activities at the WIPP than are a part of the EPA mission, some of the comments below relate to WIPP activities outside of Subpart B. EEG's basic assumption is that QA for any major activity described in the CCA which relates directly to the 194.22 criteria should be addressed in the documentation for the final rule.

The following sections contain a statement of the sense of the individual criteria, a brief summary of EPA's conclusions of compliance in the proposed rule, and the EEG's comments on that documentation. During the December 10, 1998, presentation, the EPA requested that the EEG include recommendations as to how to alleviate concerns raised; these are appended to the section for each criterion.

The term "NQA standards" as used in this review consist of the 1989-1990 Nuclear Quality Assurance (NQA) Standards NQA-1, NQA-2 Part 2.7, and NQA-3 versions as described in §194.22(a)(1).

2.13.2 Specific Comments

§194.22(a)(1): As soon as practicable after April 9, 1996, the DOE will adhere to a QA program that implements the requirements of the NQA standards.

EPA summary: The EPA proposed rule cites the Carlsbad Area Office (CAO) Quality Assurance Program Document (QAPD) included in the CCA as part of Appendix QAPD as addressing the NQA standards, and the flow of requirements from this QAPD to all subsidiary WIPP organizations. The EPA audited the CAO and found the NQA standards were implemented as required in the QAPD. CARD-22 adds that the QAPD is dated April 22, 1996, that the CAO has audited lower-tier programs to enforce the requirements of the QAPD in accordance with the NQA standards, and that these subsidiary organizations conduct their own audits.

EEG comments: The EEG review of the CCA QA chapter (Appendix 8.8) addresses DOE's response of this criterion on page 4.

The EEG agrees that the CAO has established an excellent QA program. The DOE provided the necessary information in the application for this criterion, and the EPA has verified that the WIPP adheres to a program that implements the NQA standards—for the 8 critical areas addressed in §194.22(a)(2).

The beginning of the discussion of §194.22 in the proposed rule interprets both parts of 194.22(a) as a single, interconnected section, so that the NQA standards of the (a)(1) criterion need only apply to the 8 critical areas listed in (a)(2). The language of the two criteria do not necessarily support this interpretation. Had this been the original intent, there would have been no need to divide into two

sections; a single criterion could have been written to cover 194.22(a)(2), and (a)(1) could have been eliminated.

The CAO QAPD Revision 1 included in Appendix QAPD has a rather elegant process for separating QA activities for these 8 areas, and radioactive waste handling and packaging activities, from other WIPP-related processes. Section 1.1.2.3 of the QAPD establishes these areas as responsible for meeting "additional requirements", which are extra to the "general requirements" required for other WIPP activities. The "general requirements" established throughout the QAPD are those related to the requirements of 10 CFR 830.120 and DOE Order 5700.6C, the DOE's normal QA requirements; the "additional requirements" are those found in the NQA standards that are not addressed by §830.120 and 5700.6C. The NQA standards are much more prescriptive than are the normal DOE QA requirements--NQA-1 alone contains over 30 pages of requirements, as opposed to the less than two equivalent pages of requirements found in normal DOE QA standards.

The purpose and scope of the criteria, as found in §194.1, reference both the 1992 Land Withdrawal Act and 40 CFR 191. §191 Subpart A describes management of the waste (placing it in the disposal system), and the intent of §194.22(a)(1) seems to have been to implement the NQA standards for all WIPP activities during the operational phase, as well as for the disposal phase. The EPA's Guidance For The Implementation of EPA's Standards For Management And Storage OF Transuranic Waste (40 CFR Part 191, Subpart A) At The Waste Isolation Pilot Plant (WIPP), EPA 402-R-97-001, Section 2.3, states:

> For Implementing Subpart A at the WIPP, EPA interprets these definitions to mean that all activities at the WIPP up until the point of disposal must be considered in determining compliance. Specifically, this means that all activities in all WIPP facilities, both at above-ground locations and in the underground disposal system, are regulated under the standard.

Recommendation: If the intent of the criterion was that the CAO's QA program only meet the requirements of the NQA standards for the 8 critical areas listed in §194.22(a)(2), then the EEG agrees that the criterion has been met. However, the documentation for the final rule should include a rationale for considering only those areas described in §194.22(a)(2) as falling under the §194.22(a)(1) criterion.

The EPA should also be aware that the revision of the CAO QAPD included in the CCA was to be implemented program-wide for the WIPP by mid-August, 1996, not April 22, 1996, as is implied in CARD 22[1].

§194.22(a)(2) [General Statement]: The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for 8 critical activities.

EEG general comments: The EEG review of the CCA QA chapter (Appendix 8.8) addresses these criteria on page 5, pointing out that the DOE misinterpreted the (a)(2) criteria. In general, the portions of the chapter titled similarly to these criteria do not provide the requisite demonstration of compliance.

The 8 activities are individually addressed below. It is important to note, however, that the EPA's documentation of compliance relies heavily on EPA audits of the CAO, the Waste Isolation Division (WID; the Management and Operating Contractor responsible for conducting most on-site activities), and Sandia National Laboratories (SNL; the WIPP scientific advisory organization). The audit

[1]The QAPD Rev. 1 distribution letter from R. Dennis Brown, CAO QA Manager, to WIPP organizations dated June 13, 1996, requires that the QAPD be properly implemented within 60 days of receipt of the letter. The official sign-offs were on April 22, and the CAO office may have implemented it on that date, but all subsidiary organizations were not required to conform to its dictates until the much-later date.

reports from these EPA activities do not indicate that the specific areas required by each criterion were addressed, but rather show that the overall QA program of the organizations was audited.

The EEG does not agree that verification of the establishment and execution of an overall program provides an adequate demonstration of execution for the specific activities described §194.22(a)(2). The individual (a)(2) criteria would not have been written if establishment and execution of a general QA program was all that was intended. The EPA audits are a snapshot view of QA at these organizations in 1997, but many of the DOE programs and activities that fall under the (a)(2) criteria have been in operation for many years, and the data from these programs was freely used in the compliance application.

To demonstrate establishment and execution of the NQA standards on the programs and activities covered by each criterion, a formal assessment (audit or surveillance) of the process and the resulting records should be cited; the assessment should have been performed by qualified personnel, addressing compliance with QA documents which include the NQA requirements applicable as a part of the assessment. The assessment need not have been entirely devoted to that area, but should have addressed the specific programs and data falling under each criterion. The EPA should verify that the process was performed at a time when the NQA standards were in effect for that program, and that the assessment was conducted according to the requirements of the NQA standards.

Recommendation: If such an assessments are not currently available from the DOE then the EPA should require the DOE to perform and report such assessments. As a last resort, the EPA could assess the program as a part of its verification process (despite the EEG's reservations about using this approach). In any case, the documentation for compliance with the criteria should demonstrate that the NQA standards have been established and executed for the DOE programs that falls under each criterion.

§194.22(a)(2)(i): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for waste characterization activities and assumptions.

EPA summary: The proposed rule notes the current lack of waste characterization at the generator sites and describes how the proposed Appendix A Condition 2 will be used to ensure that these sites will have met the criteria before shipping waste to WIPP. The proposed rule shows evidence that a QA program adhering to the NQA standards have been demonstrated for waste characterization at one generator site (LANL) and for the WIPP Waste Information System (WWIS), a DOE computer system used to ensure that characterization and certification requirements have been met for each waste container before it is shipped. CARD 22 expands on this information, and adds that the CCA QA chapter states that the Transuranic Baseline Inventory Report (TWBIR) was prepared in compliance with the CAO QAPD and its preparation was audited by the CAO in 1995.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on pages 10 and 11.

There are two major components to this criterion: the waste characterization activities at generator sites, and the waste assumptions used to establish parameters for the performance assessment (PA) evaluation.

For waste characterization at generator sites, the EPA has presented adequate evidence that, for LANL and its use of the WWIS, the DOE has demonstrated the establishment and execution of a QA program meeting the NQA standards. The proposed Appendix A Condition 2 seems an adequate compromise method for applying the criterion to other generator sites--the criterion requires a demonstration in the compliance application, but it is obviously not prudent for these generator sites to allocate resources to WIPP waste characterization until there is some certainty that the WIPP will open.

The EPA, however, has apparently accepted DOE's statements concerning QA for the PA component (the TWBIR data) at face value. The TWBIR waste characterization data used in the CCA clearly were not gathered under the NQA standards[2], and "the QAPD" under which the TWBIR was prepared is not the revision that was included in the CCA. The single audit finding was insufficient documentation of the TWBIR process.

The version of the CAO QAPD in effect during the preparation of the TWBIR (and the audit) was Revision 0, which apparently has not been examined by the EPA (it's not a part of the CCA). Table 1-1 of Revision 0 lists NQA-1 as a commitment document, but NQA-2 Part 2.7 and selected parts of NQA-3 are only listed as guidance documents. TWBIR data used in the performance assessment should meet the requirements of NQA-3.

The EEG has often expressed concern over the changes in waste estimates for WIPP found in the various revisions of the TWBIR, and other documents that address the WIPP inventory. For example, the CCA Appendix TWBIR estimated 61787 m^3 of existing CH-TRU waste, yet the 1996 National Transuranic Waste Management Plan (U.S. DOE, 1996a) estimates 102,025 m^3 (Table 1-1) for the same parameter--a 40% increase in the amount of currently existing waste destined for WIPP. These two documents were published only a few months apart. Comparisons for RH-TRU and projected waste volumes show even greater variations. These drastic changes in inventory amounts likely would be reflected (to some unknown extent) in the amounts and types of waste characteristics and components used in developing the PA parameters on waste.

Recommendation: The EPA could examine the audit report of the TWBIR process to ensure that the NQA standards were applied to the gathering and processing of waste characterization

[2]The Waste Characterization Analysis Peer Review Report, DOE/WIPP-96-2012, states (p. 4-3): "Because there had been no prior requirements to gather these types of data under a formal quality assurance (QA) program consistent with NQA-1 requirements, and a very short response time was imposed, the sites compiled their inventories using the best available information." The Panel concluded that, given these constraints, the data submitted are conservative (overstates quantities) and the best that could be obtained within reasonable time and cost". The EEG notes that, for use in the PA, consistency with NQA-3 requirements would also have been necessary.

assumptions used in the PA, despite the Waste Characterization Peer Review's statement to the contrary. Alternately, the Waste Characterization Peer Review accepted TWBIR data even though the panel was aware of the data's QA deficiencies (see footnote). The EPA could consider whether the Peer Review Report can be used as a "qualification of existing data" as allowed by §194.22(b) as a method of meeting the criterion for TWBIR data used in the PA. Documentation of these activities should be included in the final rule or its supporting materials.

§194.22(a)(2)(ii): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for environmental monitoring, monitoring of performance of the disposal system and sampling and analysis activities.

EPA summary: The proposed rules states that the WID developed a WIPP Environmental Monitoring Plan (EMP), which the DOE states is consistent with applicable NQA standards. The EPA audit of the WID determined that the requisite QA program had been established and executed for environmental monitoring, and sampling and analysis activities. CARD 22 adds that EMP was reviewed by the EPA, that sampling and analysis for waste characterization activities was covered under the discussion for 194.22(a)(2)(i), and that "Monitoring of performance of the disposal system has not started, but EPA has no reason to believe that the QA program for this activity will not be similar to the QA program for existing monitoring activities" (p. 22-8; restated on p. 22-9).

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on page 12.

Section 8.1 of Appendix EMP does, indeed state the following (p. 8-1):

> Quality Assurance (QA) practices that cover monitoring activities at the WIPP are consistent with applicable elements of the 10-element [sic] format in ANSI/ASME NQA-1.

NQA-1 consists of 18 basic requirements; the "10-element format" is a usual method of referring to QA requirements found in 10 CFR 830.120, a different set of nuclear QA requirements written for the DOE Management and Operations (M & O) contractors such as the WID. This *faux pas* may indicate how little familiarity writers and reviewers of EMP Section 8, Quality Assurance, have with the NQA standards.

Section 8.1 later states that QA requirements from the EPA's QAMS-005/80 were incorporated into the WID QAPD, and Table 8-1 is an attempt to cross-reference of NQA-1 basic requirements, and requirements from QAMS-005/80, to 10 CFR 830.120. This seems to be an attempt to demonstrate that the 30-odd pages of basic and supplementary requirements from NQA-1 are completely covered by the 2 page of requirements found in 10 CFR 830.120. Section 8.3, which contains the actual QA criteria for environmental monitoring, begins by stating (p. 8-3):

> The specific WIPP QA program elements/criteria that are applicable to the performance of the EMP are listed below by 10 CFR 830.120 criterion.

A comparison of this document to its predecessors may be indicative of the trend in WID QA for environmental monitoring. The 1994 Environmental Monitoring Plan (EMP), DOE/WIPP 94-024, lists the 18 NQA-1 basic requirements (p. 8-1), but follows the 10-element format from DOE Order 5700.6C (which is essentially identical to 10 CFR 830.120) in discussing QA for environmental monitoring. The 1988 "Operational Environmental Monitoring Plan for the Waste Isolation Pilot Plant"(OEMP), DOE/WIPP 88-025, also lists the 18 basic requirements, but also describes how the QA program addresses each of the NQA-1 requirements. The trend seems to be one of moving away from NQA-1. In 1988, WID had an environmental program which clearly attempted to address NQA-1 requirements; in 1994, the NQA-1 requirements were listed, but the DOE's own internal QA requirements were addressed; and Appendix EMP (1996) seems to have completed the transition to the 10-element format.

CCA Appendix EMP Section 8 is clearly directed at compliance with 10 CFR 830.120, not NQA-1. The environmental monitoring program, and the materials in EMP, still may meet the requirements of NQA-1, but Appendix EMP does not provide clear evidence of such compliance.

For the monitoring of the disposal system portion of the criteria, the EPA seems to have been mislead by a DOE statement in the QA chapter of the CCA, that no monitoring of the disposal system had yet occurred. Appendix MON, Table MON-1 lists 11 parameters to be monitored to provide the data required by 40 CFR Parts 191.14(b) and 194.42 for monitoring of the disposal system. The Water Quality Sampling Program (WQSP) wells are specifically listed in Table MON-1 as "Preclosure Monitorable Parameters"; Appendix EMP Section 5.3.8, "Groundwater" states that the WQSP wells have been sampled since 1994. CCA Table 7-7 (p. 1-9) shows that the Culebra wells will also be a part of the postclosure monitored parameters as well.

The WIPP Site Environmental Report for Calendar Years 1994 (Westinghouse, 1995), 1995 (Westinghouse, 1996), and 1996 (Westinghouse, 1997) all contain data directly related to the 3 parameters for Culebra monitoring described in Table MON-1 (See CCA Appendix SER, taken from the 1995 report; Sections 7.1 and 7.2 describe the radiological and Culebra water level monitoring, and the 1996 report contains a section on the third parameter, direction of flow in the Culebra). It is also worth noting that elsewhere in Appendix MON (Section 3.3) the WQSP wells are described as RCRA (40 CFR 264) post-closure monitoring wells, in terms that suggest that they will be continuously monitored until at least 30 years after repository closure.

There are also 4 geomechanical characteristics listed in Table MON-1; CCA Section 7.2.2.4.1 indicates that data is currently being gathered for these, though it is apparently not yet analyzed in terms of preclosure monitoring. Geotechnical Analysis Report for July 1995 - June 1996 (U.S. DOE, 1997b), indicates that measurements of these characteristics have been made for years. Others of the 11 parameters may also have been monitored before the publication of the CCA--CCA Appendices DMP describes the program for monitoring of drilling practices (one of the 11), and DEL describes the state of drilling in the WIPP vicinity at the time the CCA was published.

The CCA QA chapter does not reference CCA Appendices GWMP and GTWP. Appendix GTMP, section 2.0, clearly demonstrates that the NQA-1 standards were established by the 1994 Geotechnical Monitoring Plan; Appendix GWMP (no date given in the CCA), section 4.0, does the same for groundwater monitoring. These documents step through the 18 NQA-1 basic requirements, explaining how the applicable ones are to be implemented. These are clear evidence of establishment of a QA program that meets the requirements of NQA-1, but are not evidence of execution of the program.

For the final part of this criterion, the EPA has misapplied the "sampling and analysis activities" to the waste characterization processes at generating sites. It would seem more logical to assume that sampling and analysis related to the environmental monitoring and monitoring of the disposal system was the intended target, as the phrase was included in the criterion for these activities, not the criterion for waste characterization activities and assumptions.

CCA Appendix AUD does contain a list of WID internal audits, and these may provide a demonstration of establishment and execution of the NQA standards for these areas. Audit I96-03 would seem to cover the WQSP wells and other groundwater monitoring programs; I94-020 covers the 1993 Geotechnical Analysis Report, and could possibly show that the NQA standards had been applied for that year. Several others (I93-03, I93-05, I93-08, I93-048, I93-056) occurred in 1993, before the WID's QA program is said by the DOE to meet the NQA standards, but a case-by-case review may show that at least some of these can be used. The CAO's QA department may also have performed assessments specific to environmental monitoring that considered compliance with the NQA standards.

Recommendations: NQA-1 requires periodic assessment of programs by QA organizations, and the WID Environmental Monitoring Program has been in operation since 1985. The CAO, or the WID, QA departments should have assessed the program by now to ensure that NQA-1 requirements had been properly addressed in the program (that the program is adequate), and that the documentation from the program meets these requirements (that it has been effectively implemented).

The EPA should review reports from these assessments and cite them in the documentation of the final rule as a demonstration of establishment and execution of the NQA standards for environmental monitoring.

The CAO or the WID should also have assessed the WQSP (or the entire Groundwater Monitoring Program), and the Geotechnical Analysis Program. The EPA should review these reports, and cite them as a part of the demonstration of establishment and execution of the NQA standards for this criterion.

Sampling is an integral part of these programs, as are some analysis activities. However, the WQSP samples have been sent to contract laboratories for analysis, and radionuclide determinations from the Environmental Monitoring Program samples have also been performed by contract labs. The EPA should verify that contracts for these analyses include the proper QA requirements.

§194.22(a)(2)(iii): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for field measurements of geologic factors, ground water, meteorologic and topographic characteristics.

EPA summary: EPA's proposed rules states that the EPA audit found the QAPD and WID QA program complies with the NQA standards. CARD-22 indicates that QA of current WID measurements related to subsidence and disposal room monitoring were the field measurements of geologic factors that were considered; that "Groundwater monitoring activities previously conducted at the site also adhere to WID QA documents"' and that the DOE has demonstrated to the EPA that meteorologic information from pp. 2-178 to 2-180 in the PA came from geological data and information rather than from meteorological field measurements. The data generated from topographic characterization were evaluated under the qualification of existing data (QED) process allowed by §194.22(b).

EEG comments: The EEG review of the CCA's QA (Appendix 8.8) chapter addresses elements of this criterion on pages 12 through 15.

Geological factors. EPA was apparently mislead by the CCA QA chapter, which only discussed subsidence and disposal room monitoring in the section that addressed this criterion, citing WID documents. Credit for the current WID QA program does not cover the data from WID's disposal room monitoring program used in the performance assessment, for which MONPAR Sections 3.1 and 3.2 indicates data from pre-1991 was used for disposal room monitoring, and pre-1994 for subsidence.

More importantly, however, SNL was responsible for much of the work related to field measurement of geologic factors used in the CCA, particularly those geological factors used in PA. The CCA QA chapter offers a rationale for considering QA for field measurements of geological factors during site selection and characterization activities as satisfactory (see p. 5-6), but the EPA has not cited that rationale (nor should they; see EEG's review of this rationale, on p. 13 of the CCA QA chapter (Appendix 8.8) review). In addition, the parameters used in PA are based on geological field measurements--pressures at the repository level, strata thicknesses, etc.

The following description of a field measurement is an illustration of the sort of field measurement of geologic factors for which the EPA may want to be able to demonstrate the criterion has been met. The citing of "karst topography"--the possibility that dissolution of the salt beds in which the repository lies may cause a regulatory release of radionuclides--is an argument that refuses to die, despite the DOE evidence that has convinced the EEG, the NAS, and other organizations that such deep dissolution is unlikely. Testimony at recent (January 1998) EPA public hearings on the proposed rule again addressed the topic, and may become a part of lawsuits filed on the WIPP. Proof of adequate QA for measurements that defend against this argument could be an important part of such lawsuits. From CCA Appendix GCR Section 6.3.5:

> Additionally, brines in the sands of the underlying Bell Canyon Formation have been tested. These fluids are under sufficient head to allow them to reach the Salado salt. Because the brines are under saturated, they could dissolve the salt. However, to reach the Salado, these fluids would have to first penetrate the Castile Formation. Permeabilities (or lack of permeability) of the Castile and Salado Formations at the site have been determined by drill-stem tests in two exploratory holes: ERDA No. 9 and AEC No. 8. The tests, summarized by Lambert and Mercer, 1977, Tables 1 and 2, indicate that the two formations are extremely tight.

Appendix GCR, the Geological Characterization Report, contains many examples of field measurements of geologic factors. The term "field measurements" is not defined in §194; a definition that included the laboratory measurements taken from field samples would provide a list of many additional geological factors included in the CCA. Appendix GCR also contains data from these kinds of measurements, on which many of the PA parameters are based.

Groundwater**.** For the groundwater portion of this criterion, CCA Appendix SER (1995 Site Environmental Report) Chapter 7 states:

> The data obtained by the Water Quality Sampling Program (WQSP) in 1995 supported two major programs at the WIPP: Site Characterization and Performance Assessment in compliance with 40 CFR 191...Surveillance of hydrological characteristics in the Culebra provides data which can be used to detect changes in water characterization. It also provides additional data for use in hydrologic models designed to predict long term performance of the repository. Data is gathered from 64 well bores; five of which are equipped with production-inflated packers to allow groundwater level surveillance of more than one producing zone through the same well bore.

> Groundwater Quality data were gathered from ten wells completed in the Culebra member of the Rustler formation and one well completed in the Dewey Lake formation...Seven wells were drilled in the latter part of 1994 constructed for the explicit purpose of gathering water quality data. These wells are constructed with fiberglass casing and screens that will not bias sample collection. In 1995 samples were collected from old as well as new wells.

If data from these wells are used as described, then the requirements of NQA-3, which contains additional requirements for the collection of scientific and technical information to be used for site characterization, should also have been applied to them. The seven wells mention in the second paragraph quoted above are the WQSP wells[3].

CCA Appendix HYDRO contains many statements based on measurements of groundwater--transmissivities, potentiometric-surface maps, ion concentrations, etc. The "Purpose and Scope" section indicates that the USGS performed the activities that resulted in these measurements:

> This report discusses the ground-water systems and the interpretation of test results in the water-bearing zones above and below the proposed facility. Hydrologic data used in these analyses were collected during 7 years beginning in 1975 and were from 39 test holes drilled for, or converted to, hydrologic test holes. The study included: the determination of potential ground-water flow boundaries; potentiometric heads; ground-water chemistry; and hydraulic properties obtained through pumping, slug, pressure-pulse, and tracer tests.

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[3] The WQSP wells not only used special casings and screens, they were also established by air drilling, to ensure that drilling mud did not affect the water sampling process. The DOE has recently stated that it believes that only one borehole in the nine townships surrounding the WIPP used air drilling techniques; see Dials-to-Kruger letter dated January 26, 1998, p. 2.

> The hydrologic investigation is part of a comprehensive study related to site characterization and validation conducted on behalf of the U.S. Department of Energy by Sandia National Laboratories.

Other parts of the CCA contain field measurements of geological factors and groundwater, Chapter 2 in particular. For instance, Table 2-4 shows transmissivity and porosity of the various subunits of the Rustler formation; Section 2.2.1.4.1.1 lists these values for specific boreholes.

No QA for any of these sorts of measurements is described anywhere in the CCA, or in the EPA's proposed rule documentation, that the EEG has been able to identify. The QA for these measurements may have been performed under the SNL Qualification of Existing Data (QED) program (see CCA Table 5-5, p. 5-41) allowed by §194.22(b), but there is no statement in either the CCA or the EPA's proposed rule documentation pointing to QED as covering a portion of this criterion.

Meteorologic Characteristics. QA for field measurements of meteorological characteristics as required by (22(1)(2)(iii)) is not described in the CCA. The EPA asked the DOE for additional information. CARD 22 states (p. 22-11):

> Supplementary information sent by DOE on January 24, 1997 demonstrated to EPA that the measured meteorologic information in pages 2-178 thru 2-180 of the CCA was not used in the performance assessment (PA). DOE demonstrated that the PA instead used meteorological information obtained from geological data and information (Docket A-93-02, Item II-I-03).

This explanation alters greatly the information actually provided by the DOE. Item II-I-03 comments concerning meteorological data are:

> The meteorological data were included in the CCA in response to 194.14(i). The CCA does not contain information on the QA program for meteorological data because this data is not used in the PA.

The EEG also finds nothing in §194 that limits the criteria to consideration of only those data used in the PA. The data used in the CCA on pages 2-178 through 2-191 is from the WID meteorological tower data collected as a part of the WID Environmental Monitoring Program during the years 1990-1994, and there is no demonstration of adherence to a QA program that establishes and executes the requirements of the NQA standards for this data. Note that the dates for these data apparently precede the CCA QA chapter's date for adherence to the NQA standards at WID, which was established as December 1994.

Topographical Characteristics. §194.14(h) requires that the CCA include topographic maps which show contours, WIPP site boundaries, and the location of wells in the vicinity of the disposal system. These would seem to be the topographic characteristics addressed by this criterion.

It is not a demonstration of compliance to simply state that the Qualification of Existing Data (QED) process was executed on topographic characteristics, as is done in both the CCA (p. 5-6) and CARD 22 (p. 22-11, in 22.D.5); the specific instance of QED which qualified the data should be listed and discussed. DOE's QED process used Independent Review Teams (IRT) and Peer Reviews to qualify data; topographical characteristics would not seem to be a part of any of the data packages qualified by IRTs as listed in CCA Table 5-5, nor do the discussions of peer review in the CCA (Chapter 9 and Appendix PEER) mention topographical characteristics. The EEG also could not locate discussions of topographical characteristics in the reports of the peer review panels conducted in 1996 and 1997.

The §194.14(h) requirement for a topographic map that shows the locations of wells in the vicinity of the WIPP seems to have been covered by CCA Appendix DEL, Figure DEL-6[4]. This data was probably gathered as a part of the WID effort to monitor changes in WIPP-area drilling practices, as outlined in CCA Appendix DMP. The legend on this map indicates that locations of well sites were updated after the WID had within 1 mile of the WIPP boundary was updated to 08/06/96--a date well after the WID is said to have a QA program that adheres to the NQA requirements. This portion of the §194.14(h) requirement is likely the most important

Recommendation: The EPA should review the CCA for field measurements of the four areas cited in this criterion to ascertain if the QA processes utilized by the DOE for these field measurements meet the criterion. Measurements of geologic factors and groundwater used in support of the PA were the targets of the IRT reviews listed in Table 5-5 of the CCA. The EPA should correct the support documentation in the final rule to reflect that QA for field measurements of geologic factors and groundwater measurements is covered by §194(b), and cite data for specific parameters examined during the EPA's Audit of the Parameter Traceability and Qualification of Existing Data (II-A-48) as verification of the QED for this criterion. For meteorological and topographical characteristics, the EPA should require that the DOE demonstrate that the measurements presented in the CCA was gathered under QA program that established and executed the NQA standards, or present traceable evidence that these measurements were processed under §194.22(b). Reference to these statements should be a part of the EPA's documentation for the final rule.

§194.22(a)(2)(iv): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for computations, computer codes, models, and methods to demonstrate compliance with the disposal regulations in accordance with the provisions of this part.

[4]Figure DEL-6 is not a topographic map as §194.14(h) specifies, but it does show the locations of the types of wells specified in the criterion.

EPA Summary: The proposed rules states that the requirements of the NQA standards for computations and computer codes are in the DOE QA program, in Section 6 of the CAO QAPD and also in SNL and WID QA documents. Review of the CCA (Section 5.3.20 is included verbatim), and audits of SNL and WID show that the NQA standards have been implemented. CARD-22 also cites a review of procedures and previous assessments (apparently DOE assessments) as evidence that show the requirements have been met, and states that QA for generator sites computer codes were addressed in the waste characterization section.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on pages 15 through 18.

Neither the proposed rule nor CARD 22 address models and methods to demonstrate compliance, and computations (which are not always computer codes) is only lightly touched on. The WID keeps track of huge amounts of information related to other §194 criteria (meteorological data, environmental monitoring data, geotechnical monitoring data, WIPP area drilling activity data, etc.); these data are likely kept in databases, but there is no mention of QA for these areas either in the CCA or in the documentation for the purposed rule.

The meaning of "methods to demonstrate compliance" is not clear, but if the QA chapter of the CCA was a method to demonstrate compliance with the disposal regulations then the adequacy of any QA activities applied must be considered to have failed to meet the criterion.

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Recommendation: The EPA documentation should be more specific in its descriptions of EPA auditing activities for software. A demonstration of execution (an assessment) of the NQA standards for NDA at LANL, the WWIS, and the WID database system(s) should be cited in the documentation for this criterion. The documentation should also reference the DOE's audits the PA process, and of the PA software, as demonstrations of execution of the NQA standards for these computer codes and models.

The EPA will rely on future auditing/inspection activities at generator sites to establish that this criterion is met before these sites ship waste to WIPP; a qualified NQA software auditor should therefore be a part of these audits.

§194.22(a)(2)(v): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for procedures for implementation of expert judgment elicitation used to support applications for certification or re-certification of compliance.

EPA summary: The proposed rule cites CAO's Team Procedure 10.6 and the CTAC Desktop Instruction 1, used for the waste particle size expert judgment elicitation (the only one that has occurred), and cites the discussion of the proposed rule for §194.26. CARD 22 states that the CCA that the CAO QAPD provides for adequate control of any future expert judgments that the DOE may conduct, that he expert judgment of waste particle sizes process was observed and audited by the EPA, and was conducted in compliance with the criterion. CARD-22 references CARD-26; both the proposed rule for §194.26 and CARD 26 discuss QA for the waste particle size expert judgment elicitation in fulsome detail.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on page 18, in a brief paragraph which points out other WIPP activities that might be considered as expert judgment elicitations.

The EPA has presented a demonstration of establishment and execution of the NQA standards for the waste particle size expert elicitation in the documentation for the proposed rule, though it could have been focused more on addressing the §194.22(a)(2)(v) criterion.

However, other panels convened by the DOE would seem to fall under the requirements of this criterion. CCA Appendix PEER_PIC contains the peer review report on passive institutional controls

(PICs); it contains the following statements concerning expert judgment in section 4.1.4, titled "Expert Judgment and Peer Review":

> The use of expert judgment, either by an individual expert or a panel of experts, is permissible under 40 CFR Part 194.26(a) to support the information in the CCA if that information cannot reasonably be obtained through data collection or experimentation...The conceptual design principles presented in the Conceptual Design Report seem to rely heavily on the results of the expert judgment process described in Trauth *et al*. (1992)... The PTF and preparers of the Conceptual Design Report have somewhat blurred the line between reliance on expert judgment and the peer review process by incorporating both processes; their approach is certainly not precluded by the regulations.

Trauth, *et al*. (1993) is "Expert Judgment on Markers to Deter Inadvertent Human Intrusion into the Waste Isolation Pilot Plant". The peer review panel, with full knowledge of the requirements of §194.26, obviously concluded that the Trauth, *et al*. report was generated by an expert judgment elicitation group. The discussion preliminary to the §194 criteria would seem to have addressed the Trauth, *et al.* document straight on (61 FR 5228):

> Typically, expert judgment is used to elicit two types of information: (1) Numerical values for parameters (variables) which are measurable only by experiments that cannot be conducted due to limitations of time, money and physical situation; and (2) essentially unknowable information, such as which features should be incorporated into passive institutional controls that will deter human intrusion into the repository.

CCA Appendix EPIC consists of "Effectiveness of Passive Institutional Controls in Reducing Inadvertent Human Intrusion into the Waste Isolation Pilot Plant for Use in Performance Assessments, June 4, 1996". The second paragraph of this report states

> A task force was formed to estimate the credit for the passive controls for the WIPP repository. The estimate was constrained by the use of existing conceptual designs of these controls, the use of historical analogues for the endurance of materials and structures, the consideration of possible failure modes for each control, and the regulatory assumption of societal "common denominators."

This also seems to be a collection of experts gathered to use their various expertises for determining a value that cannot be obtained by scientific means--in short, an expert judgment.

Recommendation: The EPA should consider whether the Trauth, *et al*. (1993) report is an expert judgment elicitation, and whether other expert judgment elicitations are utilized in the CCA, and analyze the QA applied to any that meet the criteria. Both reports suggested above could be considered to have met this criterion by QED as allowed through §194.22(b), as a peer review of the PICS processes is reported in CCA Appendix PEER_PIC. The final rule for this criterion should describe or reference the process the EPA uses for determining what qualifies as an expert judgment under this criterion, and describe the demonstration of establishment and execution of the NQA standards for any additional expert judgments found.

CARD 22.F.4 contains the following sentence:

> The CCA also indicates that the CAO established and executed a QA program in compliance with NQA requirements for all items and activities important to the containment of waste in the isolation system, including for procedures that may be developed for implementation of future expert judgment elicitation.

The sentence should be revised, as it is a logical impossibility; a QA program cannot be executed on procedures that have yet to be written. The sentence could easily be interpreted as an unwarranted attempt to aid the DOE's efforts at compliance.

§194.22(a)(2)(vi): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for design of the disposal system and actions taken to ensure compliance with the design specifications.

EPA summary: The proposed rule states that the SNL QA program covered seals design, that the seals design was extensively reviewed by other organizations, and verified by a combination of NQA-1 3S-1 methods. The EPA audits show that WID and SNL programs are adequate and properly executed. CARD-22 adds that no QA deficiencies related to design considerations were noted in the EPA audits of SNL or WID, and quotes portions of of the CCA QA chapter (Section 5.1.6) concerning design of the repository.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on pages 19 through 21.

The EEG agrees that the repository seals design program was excellent. Perhaps the best demonstration of establishment and execution of design criteria for seals is not in the CCA QA chapter, or in EPA documentation for the proposed rule, but in CCA Appendix SEAL, Section 1.4, "Sealing System Design Development Process":

> The design team included specialists drawn from the staff of Sandia National Laboratories, Parsons Brinckerhoff Quade and Douglas, Inc. (contract number AG-4909), INTERA, Inc. (contract number AG-4910), and RE/SPEC Inc. (contract number AG-4911), with management by Sandia National Laboratories. The contractors developed a quality assurance program consistent with the Sandia National Laboratories Quality Assurance Program Description for the WIPP project. All three contractors received quality assurance support visits and were audited through the Sandia National Laboratories audit and assessment program. Quality assurance (QA) documentation is maintained in the Sandia National Laboratories

> WIPP Central Files. Access to project files for each contractor can be accomplished using the contract numbers specified above.

The paragraph is an example of the kind of description the EEG expected to find in the CCA for all the DOE programs that fall under the §194.22 criteria.

QA for other portions of the repository design are more problematic. The statements quoted in CARD 22 from the CCA QA chapter do not provide a demonstration of establishment and execution of the NQA standards to the repository design process--the intent of these statements seems related more to establishing that a validation process took place, rather than discussing QA for the design activities. The quoted material addresses only NQA-1 criteria, and CARD 22, Sections 22.G.3 and 22.G.5, indicates that the EPA may used only NQA-1 in consideration of this criterion. Design of the repository as described in the CCA, however, includes site characterization activities, for which NQA-3 also applies.

The criterion seems to be related to §194.14(b), which requires that the compliance application include a description of the design of the disposal system. The CCA contains discussions of repository design in Chapters 2, 3, and 6, as well as CCA Appendix DVR (the Design Validation Report). CCA Section 3.2 gives an indication of the types of information that the §194.22(a)(2)(v) criterion should be applied to:

> A preliminary design of the WIPP repository was presented in the FEIS (DOE 1980). Validation efforts for the WIPP repository preliminary design began in 1981 with the Site and Preliminary Design Validation (SPDV) program. The SPDV program was implemented to further characterize and validate the WIPP site geology and to provide preliminary validation of the underground excavation. The SPDV program involved the excavation of four full-sized disposal rooms, excavated 13 feet (4 meters) high, 33 feet (10 meters) wide, and 300 feet (91 meters) long, and separated by 100-foot (31-meter)-wide pillars. Data obtained from geologic field activities and

> geomechanical instrumentation were analyzed to determine the suitability of the design criteria and design bases and to provide confirmation of the underground opening reference design. Analyses of these preliminary designs performed by the WIPP architect and engineer are included in Appendix DVR. These analyses considered expected creep closure rates in determining disposal room sizes. Information in Appendix DVR (Section DVR.6.4.2) meets the criterion specified in 40 CFR § 194.14(b)(2).

Initial design activities for the repository took place in the 1970s and 1980s, well before any part of the WIPP project had established QA programs which met the requirements of the NQA standards. CCA Appendix DVR, for instance, was published in 1984. QA requirements during these early years were rather loose compared to those of the NQA standards; the following is from WIPP-DOE-71, "Design Criteria Revised Mission Concept - II Waste Isolation Pilot Plant", page 1-16:

> The WIPP Project Office (WPO) and the major project participants will be responsible for the establishment and implementation of adequate quality assurance programs for their respective scopes of work. These programs will be developed, using ANSI N45.2 - 1977 as a guide.
>
> Formal quality assurance programmatic requirements will not be contractually imposed on WIPP construction contractors or suppliers.

On the plus side, ANSI N45.2 -1977 was a precursor to NQA-1, but its obvious that the requirements of the NQA standards was not met by this document.

Design of the repository would also seem to include such relatively recent changes in the design of the repository as the 1996 decision to use magnesium oxide as a backfill material. Earlier design documents mandated completely filling rooms with salt backfill. The criterion seemingly requires demonstrating that the NQA standards have been established and executed for a wide range of

programs over a long period of time, in which multiple changes have occurred. Establishing adequate QA for these changes would enhance confidence that all the potential effects of these changes have been taken into consideration.

Recommendation: The EPA should establish which programs and activities relate to design of the disposal system, and include a demonstration of establishment and execution of the NQA standards for these programs and activities in the documentation for the final rule. Since much of the information predates the use of the NQA standards for WIPP activities, the EPA should consider whether or not a QED process as allowed by §194.22(b) has been applied to these areas, and include that information in documentation of the final rule.

§194.22(a)(2)(vii): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for collection of data and information used to the support compliance application(s).

EPA Summary: The proposed rule states that SNL implemented numerous QA procedures to ensure the quality of data and information, and that EPA's audit of SNL found its QA program to be adequately implemented. CARD 22 notes that DOE audits have also concluded that the SNL QA program has been effectively implemented.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this criterion on pages 21 and 22.

The SNL's QA procedures do not address collection of all of the data for even the PA, SNL's foremost contribution to the compliance application. The data from the TWBIR, used to establish parameters for the PA, was not collected under a QA program adhering to the NQA standards (see EEG comments concerning waste characterization above).

The main point of EEG's CCA QA chapter review for this criterion is that all data used in support of the CCA was not collected by SNL, and cites several parts of the CCA for which SNL should not be held responsible. SNL has no procedures which specifically address collection of data and information for the DOE's compliance applications; the EPA apparently accepted the DOE statements from the CCA QA chapter at face value.

This is a "catch-all" criterion, and various descriptions of the huge amount of data and information in the CCA was cited in nearly every media article on the CCA's publication. The data and information was gathered over a 20 year period, for most of which only portions of the NQA standards were in effect. The effort should be to demonstrate that any of this data and information which is important to compliance has been collected under the NQA standards.

Recommendation: The EPA should review the CCA for data and information other than that covered by the other (a)(2) criteria which is important to compliance, and cite the review, and a demonstration of establishment and execution of the NQA standards, for any found not to be a part of the other (a)(2) criteria. The EPA should rewrite section 22.H of CARD 22, and revise the proposed rule, to remove the QA responsibility for all data in the CCA from SNL's shoulders.

§194.22(a)(2)(viii): The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for other systems, structures, components, and activities important to the containment of waste in the disposal system.

EPA Summary: The proposed rule states that neither the DOE nor the EPA have identified any activities not already covered which require QA controls, and that the EPA audits have determined that the QA organizations for WIPP have authority, access, and freedom to identify other items affecting the quality of waste isolation. CARD 22 adds nothing of substance.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements related to this criterion on page 22. EEG suggested that QA of the interface between the DOE and the BLM concerning DOE review of proposed mineral resource leases in the WIPP area could be important to waste isolation in the disposal system, referencing a WIPP docket item that pointed out problems in this area in the past.

Recommendation: While not a part of the criterion, it would useful to cite any review activities by the DOE (or the EPA) that demonstrate that this criterion has been addressed.

§194.22(b): The compliance application shall include information which demonstrates that data and information collected prior to the implementation of a QA program adhering to the NQA standards have been qualified in accordance with an alternate methodology approved by EPA, which employs peer review, corroborating data, confirmatory testing, or a QA program equivalent in effect to the NQA standards.

EPA Summary: The proposed rule cites the Independent Review Team (IRT) findings of QA programs equivalent in effect to the NQA standards listed in the CCA QA chapter (Table 5-5), the peer reviews conducted under NUREG-1297 used to qualify existing data for engineered systems, natural barriers, waste form, and disposal room data. The EPA performed two audits tracing new and existing data to their qualifying sources and found that equivalent QA programs and peer reviews were had been properly applied. EPA "concluded that existing data from peer-reviewed technical journals was appropriate since the level of such reviews was likely to provide QA equivalent to NUREG- 1297...". The EPA proposes approval of these three methods--peer review, equivalent QA program to the NQA standards, and peer-reviewed technical journals-- for qualification of existing data. CARD 22 adds that the T=0 process as well as the IRTs were used to determine equivalency of QA programs to the NQA standards, and describes the two audits as having been of SNL data used in the PA.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses this criterion on page 5.

There appears to be environmental monitoring data that was gathered before the NQA standards are said to have been established for the WID; this data is cited and used in the CCA, but it was not addressed by IRTs or the peer reviews, and does not appear to have been published in peer-reviewed technical journals. The CCA Appendix SER (U.S. DOE, 1996c, Chapter 7), states:

> Background water quality data were collected from 1985 through the 1990 sampling period as reported in DOE/WIPP 92-013, Background Water Quality Characterization Report for the Waste Isolation Pilot Plant. This background data will be compared to water quality data collected throughout the operational life of the facility. Pre-operational data gathered in the interim period will be used to strengthen the background data, to evaluate the need to make adjustments to comparison criteria...

The 1985-1990 data was collected as part of the Radiological Baseline Program, as found in CCA Appendix RBP. The RBP program measured air, surface and ground water, and soil. The Executive Summary of this Appendix states:

> This program was designed to provide preoperational measurements of radioactivity in environmental samples that will serve as a basis for evaluating similar data collected during the WIPP Operational Environmental Monitoring Program. The RBP data analyzed in this report cover the period from 1985 through 1989. Sample types included in this report are airborne particulates, soil, surface water, groundwater, sediments, and six types of biotic tissue sample.

This intended use of this data is echoed in Section 1.4. These would seem to be part of the environmental monitoring required as a part of the §194.22(a)(2)(ii) criterion. If this earlier data is

to be used as indicated, then it would seem to need the provisions of §194.22(b), qualification of existing data, applied to it, as it precedes the date established by the CCA QA chapter (December, 1994; U.S. DOE, 1996c, p. 5-52) for adherence to the NQA standards at WID. Appendix RBP Section 1.4 indicates that the Waltz Mill Laboratory performed the sample analyses for this program, and these analyses would seem to fall under the §194.22(a)(2)(ii) criterion also.

There may be other data that should undergo QED cited in the CCA. Groundwater and other site characterization activities have been performed for 20 years; CCA Section 9.4.8 describes the INTRAVAL WIPP2 study used data from sixty wells and also included extensive modeling which apparently has been used in the WIPP considerations. The penultimate sentence of the section states:

> The applied stochastic models have proven to be valuable tools in assessing the effect of uncertainty due to heterogeneity on the performance of a repository.

The EPA's acceptance of existing data from peer-reviewed technical journals conflicts with the NQA standards, at least for site characterization activities. NQA-3 Supplement 3SW-1 Section 9 begins:

> Data to be used which were not collected under the control of a quality assurance program in accordance with this Standard shall be qualified for their intended use. This includes data collected from such sources as professional journals, technical reports, and symposia proceedings.

The claim that such level of review of such articles is likely to provide equivalent QA to NUREG-1297 peer review standards might also need to be reconsidered. For example, review by other DOE personnel is limited in NUREG-1297.

Recommendation: The EPA should reconsider the use of data from peer-reviewed technical journals for site characterization activities as an acceptable method under this criterion. The EPA should review the CCA for data related to the §194.22(a)(2) criteria that precede adherence to the

NQA standards, and determine if the programs cited under this criterion have assessed and qualified that data. The conduct of this review should be recorded in the documentation of the final rule.

§194.22(c): The compliance application shall provide, to the extent practicable, information which describes how all data used to support the compliance application have been assessed for their quality characteristics, including accuracy, precision, representativeness, completeness, and comparability (these characteristics are abbreviated as "the PARCC characteristics" in the discussion below).

EPA Summary: The proposed rule describes the CCA's statement that it was not practicable to document data quality characteristics (DQCs) in most cases. The DOE clarified, but did not substantially alter its approach in response to an EPA request for additional information; while the EPA agreed that the DQCs cannot be appropriately applied to parameter values the measured data on which they were based could have been assessed for them. Because the DOE misinterpreted the requirement, the EPA assessed SNL data records packages and found that for newer data, experimental plans generally addressed DQCs including the PARCC requirements, and for older data laboratory notebooks supplied some information related to DQCs. The EPA also "concluded that the peer review panels considered the use of DQCs in determining that such data were adequate", agreed with the DOE argument that collection of most data under programs equivalent to the NQA standards was adequate evidence of the quality of the data, and concurred with the DOE that uncertainty in data measurements as reflected in DQCs has a minor effect on compliance certainty compared to other PA uncertainties. CARD 22 adds that EPA performed a review of parameters discussed at length in a Technical Support Document for §194.23, and notes that the reviewers specifically looked for evidence of DOE's assessment of the PARCC characteristics. CARD 22 also offers as an example of EPA's assessment of DQCs a discussion of two parameters, for which "instrument calibration, calibration records, acceptance criteria, and procedures for calibration checks" were documented that the EPA considered to be adequate to demonstrate assessment of DQCs.

EEG comments: The EEG review of the CCA's QA chapter (Appendix 8.8) addresses elements of this topic on page 5, with a more thorough discussion on pages 32-35.

The CCA QA chapter specifically lists waste characterization and environmental data are two areas to which DQCs should be applied, but does not provide a demonstration of how they were applied in these areas for the WIPP--and the EPA proposed rule documentation doesn't, either. For the record, the EEG notes that CCA Appendix EMP, Section 7, describes how environmental monitoring addresses accuracy, precision, an comparisons, as well as other DQCs not a part of the PARCC requirements, and the TRU-Waste QAPP (U.S. DOE, 1994), Section 3.2, describes required validation methods for waste characterization which address precision, accuracy, completeness, and comparability. Appendix MON contains a probably identical discussion to that in EMP.

CCA Appendix GCR, the summary of USGS data used, indicates that accuracy and precision were considered (see sections 7.6.13 and 10.7.6, where concerns are raised due to analysis of accuracy and precision of measurements is discussed). There are other similar, rather minor discussions in many appendices, but there are certainly no indications that a systematic consideration of DQCs, "...for all data..." was a part of the WIPP project.

Both the DOE and the EPA discussions of this topic seem to miss the point of DQCs; the DOE saw them as related to the uncertainty of measurements, the EPA is willing to accept instrument calibration data as evidence that DQCs have been assessed.

DQCs relate to the intended use of the data. In an ideal world, the use to which the data is to be put is known, and the PARCC requirements are established in advance of the taking of measurements to demonstrate the limits of acceptability of the data for these uses. The WIPP studies were not developed along these lines; this criterion was not promulgated until well after most of the basic measurements for disposal considerations at the WIPP had already been taken. The lack of evidence of systematic DQC assessment at WIPP does not invalidate any data, it merely prevents taking credit for additional confidence in the supportive value of the data. The criterion does not require the DOE

to assess DQCs--it only requires that the DOE show in the compliance application how they were assessed, to the extent practicable. The extent practicable for past WIPP activities was obviously near nil.

Recommendation: EPA should consider rewriting the final rule discussion related to this criterion along the lines of the EEG comments above. The EPA may also wish to consider including in the final rule a more specific criterion for the establishment of DQCs for data to be used in support of future applications.

§194.22(d): The compliance application shall provide information which demonstrates how all data are qualified for use in the demonstration of compliance.

EPA Summary: The proposed rule states that the SNL generated a table providing information of how all data in the PA were qualified; the EPA audited existing QA programs and determined that data is qualified for use in accordance with the NQA requirements. CARD 22 adds discussions of the T=0 process, QED, peer review, and the SNL QA program, noting that these were audited by the EPA.

EEG comments: The attached EEG review of the CCA's QA chapter addresses elements of this topic on page 6.

The CCA QA chapter and the EPA's proposed rule and CARD-22 contain adequate descriptions of how data used for PA parameters were qualified--but this is certainly not "all data" used for demonstration of compliance. Many of the CCA Appendices--RBP, GTMP, GWMP, USDW, to name a few--were not a part of the PA process.

Recommendation: The EPA should review the CCA to establish a list of the data for which the application should demonstrate how it was qualified, and ensure that the documentation reflects the elements of this list.

§194.22(e): The EPA will verify appropriate execution of quality assurance programs through inspections, record reviews, and record keeping requirements.

EPA summary: The proposed rule cites the EPA audits already conducted, and proposed reaudits and future waste generator site inspections. CARD 22 lists the specific audits, describes the auditing process used, and notes again that EPA did not expect all necessary QA documentation to be provided in the CCA because of its voluminous nature.

EEG comments: The EPA has met this requirement, in that it has adequately verified that, during the year 1997, the QA programs for CAO, WID, SNL, and LANL adhered to the requirements of the NQA standards. Additional audits verified that QA programs adhering to the NQA standards had been established and executed for the single expert judgment elicitations considered so far, the qualification of existing data programs including the 1996-1997 peer review activities, and parameter traceability.

Recommendation: The EPA should review internal EPA documents relating to the promulgation to ensure that the underlying reasoning behind each §194.22 criterion has been adequately addressed for the information presented in the CCA.

2.14 MISCELLANEOUS CONTAINMENT REQUIREMENT ISSUES

2.14.1 Beyond 10,000 Years

Although the EPA standards require demonstration of compliance only for 10,000 years, some partial calculations performed by the EEG indicate that higher releases may be predicted beyond that period (see Section 2.9.3 of this report). There is no strong justification for stopping the calculation at 10,000 years. The EPA provided the following reason for selecting this time period (U.S. EPA, 1985, p. 38070):

> A period of 10,000 years was considered because that appears to be long enough to distinguish geologic repositories with relatively good capabilities to isolate wastes from those with relatively poor capabilities. On the other hand, this period is short enough so that major geologic changes are unlikely and repository performance might be reasonably projected.

The NEA/IAEA International Review Group (NEA/IAEA, 1997) made the following comment on this subject:

> The IRG was surprised that it did not find descriptions or arguments in the CCA indicating the possible performance of the WIPP facility beyond the end of the 10,000 year regulatory period. Such descriptions or arguments, including an indication of the mechanisms, likelihood, timing and possible maximum of impacts at longer times, would be an important element of performance assessment in most other countries.

While EEG agreed with the 10,000 year cut-off point in the development of the standards, we now recommend performance of representative calculations to assess the behavior of the repository beyond 10,000 years to enable comparison with other countries and conformance with the NAS Committee Conclusions on the High Level Waste Yucca Mountain Program.

2.14.2 Effect Of ERDA-9

The EPA has "screened out" (U.S. EPA, 1997c, p. 58801; 1997b) the potential effect of the existence of borehole ERDA-9, which is located only 28.5 meters (93.5 ft) east of the surface projection of the north-south drift E300 of the WIPP underground. The EPA concludes:

> ERDA-9 did not penetrate an area that will become a waste panel and DOE has indicated that abandoned boreholes more than a meter away from the waste can be screened out of PA due to low consequence. EPA agrees with DOE'S assessment that these boreholes are not significant to performance of the disposal system and can be screened out of PA.

The CCA argument for screening out the potential effect of ERDA-9 on the disposal system is presented in Appendix SCR 3.3.1.42 of the CCA, which refers the reader to an analysis conducted as a part of the WIPP 1991 performance assessment (Sandia, 1991/1, Appendix B, pp.26-27). This analysis was conducted by the DOE in response to a question raised by EEG in 1990 about the extent of the Disturbed Rock Zone (DRZ) and the permeability of Marker Bed 139. The analysis concluded that if permeability value difference of three orders of magnitude is assumed between a DRZ and the adjacent intact rock, then the bore hole flow rates from the two zones are markedly different. This is, of course, something to be expected. The questions to be asked and the issues to be considered before the effect of ERDA-9 can be written off, are:

1. How far is ERDA-9 from the drift E-300 *at the repository level?* Boreholes are seldom vertical; they deviate. For example, the borehole H-19-B-4, drilled under strict specifications for hydrologic and tracer testing of the Culebra aquifer in 1995-96, deviated 9.5 meters (31 ft) in 229 meters (752 ft) depth. At that rate, a borehole drilled to 655 meters (2150 ft) depth of the repository may deviate 27 meters (89 ft). Could ERDA-9 be very close to E-300 at the repository level?

2. How far does the DRZ of E-300 extend?

3. Whether or not there is pressurized brine reservoir underlying ERDA-9 is not definitely known,

although there is good reason to suspect it. ERDA-9 penetrated the Castile Formation for 17 meters (56 ft). The borehole WIPP-12 was drilled in 1978 to penetrate 14.7 meters (48.3 ft) into the Castile, and encountered pressurized brine when drilled an extra 74 meters (242.4 ft) in 1981.

4. How will ERDA-9 be sealed? Appendix SCR, Section 2.3.8.2, of CCA, states:

> WIPP investigation boreholes will be sealed using materials and designs in accord with industry standards for the Delaware Basin. A survey of plugging practice (Appendix DEL) shows that the majority of boreholes have a plug below the water-producing zones in the Rustler and a plug at the top of the Bell Canyon. Drilling and abandonment procedures may lead to additional plugs within the Salado. A few boreholes (2 percent of those surveyed), however, have a continuous plug of salt-saturated cement from the top of the Salado to the top of the Bell Canyon. ERDA-9 will be sealed in a similar manner. Other WIPP investigation boreholes will be plugged according to regulatory requirements and standard industry practice. The DOE has committed to plug with cement the portion of these boreholes that penetrate the Salado.

Why is EPA not requiring at least a special plugging procedure for ERDA-9 and other boreholes that penetrate the repository horizon within the WIPP site?

2.14.3 Brine Seepage into the Shafts

The EPA was concerned about the potential for seepage of brine into the shafts in the Salado Formation zone to be occupied by compacted salt plug. Attachment 1 of TSD III-B-3 (U.S. EPA, 1997g) is a trip report of inspection of the air intake shaft by EPA to verify the DOE statements concerning the lack of observable brine inflow in the lower Salado where the compacted. The inspection report concludes, “The air shaft inspection did not result in observations of any current brine seepage, as no areas appeared to be wet and no brine was observed.” It is common knowledge that the rate of brine inflow from the Salado marker beds is low enough that brine dries up almost instantly due to ventilation in the WIPP mine. This would certainly be expected in the air intake shaft. If the rate of water inflow is large enough, as is being observed in the WIPP exhaust shaft at the level

of Santa Rosa and Dewey Lake Formations for the past several years, then even a large blast of air does not completely dry up water. As far as brine inflow from the Salado Formation is concerned, the presence of salt encrustations (efflorescences) clearly indicates current brine seepage. The inspection team's conclusion therefore simply indicates the absence of understanding of the mechanics of brine drying up in the air intake shaft, rather than the absence of brine inflow.

2.14.4 Iron in the Repository

There is a curious response by the EPA to the question of the amount of additional iron that may be introduced in the WIPP repository through rock bolts and other ground control and roof support system (U.S. EPA, 1997b, CARD14-95). Corrosion of iron in the presence of brine in the repository is expected to produce hydrogen. For at least the past 10 years, the question of gas production in the repository has been a concern and it is common knowledge that reduction of the amount of iron in the repository will help meet compliance with the EPA standards and is therefore a desirable goal. The EPA should therefore explain the following response:

> The amount of iron introduced into the disposal system by rock bolts is inconsequential since there is no upper limit on the amount of iron that can be emplaced in the repository. The DOE did specify a minimum amount of iron that must be emplaced into the repository withine (sic) Appendix WCL, Table WCL-1, which is based on the quantity of iron within the waste containers to be emplaced at the WIPP and does not rely (sic) the amount of iron contained in the roof support system to meet this minimum requirement. (U.S. EPA, 1997b, CARD 14-95).

Does EPA now believe in a *minimum* amount of iron that must be emplaced in the repository?

3.0 ASSURANCE REQUIREMENTS

3.1 INTRODUCTION

The EPA standards (U.S. EPA, 1993) contain a set of assurance requirements to provide the additional confidence needed due to the long period of time of concern and the uncertainties associated with the decision to dispose of waste without practical possibility of retrieval. The philosophy of the Assurance Requirements is clearly stated in the "Overall Approach of the Final Rule" (U.S. EPA, 1985, p. 38072), as follows:

> In contrast to the containment requirements, the assurance requirements were developed from that point of view that there may be major uncertainties and gaps in our knowledge of the expected behavior of disposal systems over many thousands of years. Therefore, no matter how promising the analytical projections of disposal system performance appear to be, these materials should be disposed in a cautious manner that reduces the likelihood of unanticipated types of releases. Because of the inherent uncertainties associated with these long time periods, the Agency believes that the principles embodied in the assurance requirements are important complements to the containment requirements that should insure that the level of protection desired is likely to be achieved.

During the promulgation of the original standards (40 CFR 191) in 1985, the EPA considered an additional assurance requirement that called for releases to be kept as low as reasonably achievable (ALARA) even when the numerical containment requirements have been complied with. This proposed requirement was deleted by EPA from the final rule for two reasons (U.S. EPA, 1985, p. 38072):

> First, NRC's 10 CFR Part 60 implemented the multiple barrier principle by requiring very good performance from two types of engineered components: a 300 to 1000- year lifetime for waste packages during which there would be essentially no expected release of waste, and a subsequent long-term release rate from the waste form of no more than one part in 100,000 per year....(and) Second, the DOE has included a provision in its site selection guidelines (10 CFR 960) that calls for significant emphasis to be placed on selecting sites that demonstrate the lowest releases over 100,000 years compared to the other alternatives available.

Neither of these provisions apply to WIPP and the net result for the TRU waste is that the DOE has argued for the minimum requirements rather than design for ALARA. EPA is proposing to certify WIPP on the basis of a very narrow interpretation of the assurance requirements without acknowledging the history of promulgation and the philosophy behind it.

There are six assurance requirements included in the standards (U.S. EPA, 1993). The following is the EEG assessment of the EPA's proposed rule for each of these.

3.2 ACTIVE INSTITUTIONAL CONTROLS

Title 40 CFR 191.14 (a) requires maintenance of active institutional controls for as long a period of time as is practicable after disposal, but credit in performance assessment may not be taken for more than 100 years. The DOE has proposed controls for 100 years and has assumed no drilling in the repository for that period. The EEG agrees with the EPA's finding for this requirement, but recommends that if in the final rule EPA finds WIPP to be in compliance with the standards and proposes to grant certification, oversight by the federal (other than DOE) and state authorities should be required to ensure vigorous implementation of the active institutional control.

3.3 MONITORING

Title 40 CFR 191.14 (b) requires disposal systems to be monitored both pre- and post-closure to detect any substantial or detrimental variations from expected performance. The monitoring shall be done with techniques that do not jeopardize the isolation of the wastes and should be conducted until there are no significant concerns to be addressed by further monitoring.

Specific criteria to be met are outlined in 40 CFR 194.42 and require any compliance application to document and substantiate the decision not to monitor a disposal system parameter because the parameter is considered to be insignificant to the containment of waste in the disposal system or the verification of predictions about the future performance of the disposal system. The proposed criteria did not contain a mechanism whereby DOE could decide not to monitor a particular disposal system parameter on the basis that DOE considered it to be unimportant to the containment of waste or to verify predictions about future performance of the disposal system. Hence, EEG never had the opportunity to comment on this change that was effected in a meeting between EPA, DOE, and OMB and incorporated in the final criteria.

DOE has chosen to exclude from monitoring all parameters of interest in the repository during the pre-closure phase (excluding stress and deformation measurements and radioactivity in air) by qualitatively evaluating their significance in shifting either the probability or the consequence in calculations for the containment requirements. EPA has accepted the CCA analysis for this assurance requirement.

The reason for including the assurance requirements in the standards was the inherent uncertainty in the calculations of releases for 10,000 years. The benefits from the assurance requirements were never intended to be quantified. It was recognized that there could be no clear yardstick to measure the benefit of a marker or the detriment to confidence in predicting the behavior over 10^4 years if markers were not used. The same logic applied to records maintained by institutions and the benefits

of the ability to retrieve waste. The approach allowed by EPA in the final criteria is to permit DOE to assess the usefulness of monitoring by a qualitative evaluation of the impact of improving our knowledge of the potential behavior of the repository. This is contrary to the intended purpose of the assurance requirements. It does not make sense to exempt DOE from the assurance requirement for monitoring based on a qualitative evaluation that depends on the containment calculations being correct.

Chapter 7.2 of the CCA evaluated various parameters including those listed in 194.42 and concluded that there was little merit in obtaining measurements of changes in various parameters since changes occurring over a short time period may not be representative of the steady state conditions that would exist over long time periods. DOE points out that obtaining data for a 35 year period is of little value in extrapolating results over a 10,000 year regulatory period. For years, DOE pursued the desire to conduct an experimental program with waste at WIPP and argued that obtaining 5 years worth of data would be effective in confirming the predicted behavior of the TRU waste.

DOE identified 10 parameters needing monitoring in the pre-closure period and only 5 of those worthy of monitoring in the post-closure period. EPA concurred. The post-closure monitoring parameters are:

- Culebra groundwater composition
- Culebra change in groundwater flow
- Probability of encountering a Castile brine reservoir
- Drilling rate
- Subsidence measurements

EEG believes there are a number of parameters that can be monitored in both the pre- and post-closure period that could help verify predictions of the future behavior of the disposal system.

1. Drilling practices in the Delaware Basin of air drilling, CO_2 injection and other underbalanced

drilling should be monitored as well as borehole diameters and mining practices such as shaft diameters.

2. Continued investigation of non-invasive techniques to monitor brine migration, gas generation and radionuclide movement. While DOE acknowledges (U.S. DOE, 1996c, page 7-50) these remote techniques to determine characteristics of the earth have been well established in measuring resistivity, acoustic velocity, magnetism, density, temperature, moisture control, and radioactivity, they conclude that changes in the repository will be too small or too slow to be detectable using remote techniques. EEG sees no evidence to warrant this conclusion.

3. Prior to sealing Panel 1, remote sensors could be placed in the rooms of Panel 1 to measure moisture content, CO_2, room closure or other parameters and detectors hooked to cables located outside Room 1. One could obtain 10 years worth of highly detailed data on the actual behavior of the repository.

4. Non-invasive detectors could be located outside the Panel 1 seal to monitor parameters inside Panel 1 rooms. One could obtain 35 years worth of data on the actual behavior of the repository.

5. Groundwater quality of the Dewey Lake and Santa Rosa Formations be monitored.

Note that the U.S. Nuclear Regulatory Commission (U.S. NRC) plans to require DOE to monitor post-closure at the Yucca Mountain High Level Waste Repository {10 CFR 60.51 (a)(1)}. The Performance Confirmation Program outlined in Subpart F, 40 CFR 60.140 through 60.143 establishes detailed programs to monitor the condition of the waste packages as well as subsurface changes during construction and waste emplacement operations. The NRC Subpart F requirements apply to the pre-closure conditions. EEG is unaware that DOE finds such a request unreasonable for the high-level waste repository. EEG believes that DOE should be required to pursue non-invasive long-term monitoring programs during the operational period as a condition for approval, and a major evaluation should be undertaken prior to the first recertification.

3.4 PASSIVE INSTITUTIONAL CONTROLS

Title 40 CFR 191.14 (c) requires designation of the repository site by the most permanent markers, records, and other passive institutional controls (PIC) practicable to indicate the dangers of the wastes and their location. The EPA proposes to require WIPP to implement the system of PICs but proposes to deny taking credit for PICs in the performance assessment for the containment requirements. The EEG agrees with this determination of denying credit for PICs for reasons stated by the EPA in U.S. EPA (1997c), as well as for reasons that EEG has previously submitted to the EPA (see Appendix 8.2-Passive Institutional Controls).

3.5 ENGINEERED BARRIERS

Title 40 CFR 191.14 (d) requires use of both engineered and natural barriers in the repository design. The CCA proposed a chemically-buffering magnesium oxide backfill as the only engineered barrier, and the EPA has accepted in the proposed rule the DOE (U.S. DOE, 1996c) proposal to satisfy this assurance requirement. The EEG view is that while there are still some questions about the efficacy of the chemical buffer aspect of the magnesium oxide (MgO) backfill (see section 2.3 and Appendix 8.4 of this report), this engineered feature has been selected primarily to enable DOE to use numerical values of certain parameters in the containment requirement calculations. The MgO backfill may not therefore be considered to satisfy this assurance requirement in a strict sense of the philosophy of these requirements. Incorporation of backfill in the WIPP design is nevertheless a good idea and the EEG has been recommending a salt/clay mixture as backfill for years. A pure MgO backfill does not have the benefit of the chemical retardation of radionuclides that clays afford, but may help keep the repository chemical environment stable. The EEG would prefer addition of clays such as commercially available bentonite to the backfill, but is willing to accept emplacement of MgO backfill for the sake of operational ease and efficiency.

The EEG disagreement with the EPA on this issue concerns the lack of incorporation of engineered

barriers that would provide additional assurance beyond helping in the calculations to satisfy the containment requirements. With respect to the engineered barriers as an assurance requirement, the "Overall Approach of the Final Rule" (U.S. EPA, 1985, p. 38072) states:

> Designing disposal systems to include multiple types of barriers, both engineered and natural, reduces the risks if one type of barrier performs more poorly than current knowledge indicates.

The CCA (U.S. DOE, 1996c, Sec. 3.3) describes four types of engineered barriers in the design of the WIPP disposal system: (1) Shaft Seals, (2) Panel Closures, (3) Backfill around the waste, and (4) borehole plugs. EEG does not consider any of these to be engineered barriers, for the following reasons:

3.5.1 Shaft Seals

Shaft seals are at best an attempt to undo the damage done to the natural environment when the shafts were excavated, and therefore cannot be considered to be an engineered barrier as distinct and *complementary* to the natural barriers.

Note that the 40 CFR 191.12 definition of a "Barrier" includes the following examples of engineered barriers, but does not include "shaft seals".

> ... A canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around waste, provided that the material or structure substantially delays movement of water or radionuclides.

The repository standards for the high-level nuclear waste repository (10 CFR 60) specifically exclude shaft seals from engineered barrier system. "Engineered Barrier System" is defined in 10 CFR 60.2 as:

Engineered barrier system means the waste packages and the underground facility.

and

Underground facility means the underground structure, including openings and backfill materials, <u>but excluding shafts, boreholes, and their seals</u> (underline added).

3.5.2 Panel Closures

Like the shaft seals, panel closure systems (separation of waste panels by engineered structures) cannot be considered to be engineered barriers because they too can at best be imperfect attempts to restore the original natural system. Panel seal is not included in the examples of engineered barrier in the EPA definition (40 CFR 191.12).

The Marker Bed 139 lies directly below the WIPP repository and is connected to the floor of the waste rooms through extensive fractures, floor upheaval and milling of the floors. Water (with anomalous lead content acting as a tracer) seeping down from the exhaust shaft has moved 400 ft through the marker bed from the base of the air exhaust shaft to the waste handling shaft in a short period of time during 1995-96. This pervasive marker bed would not allow effective separation of the panels unless the entire floor of the repository is dug down 10 ft and grouted.

According to the CCA (U.S. DOE, 1996c, p. 3-27, lines 19-20), "The panel closure system was not designed or intended to support long-term repository performance." How then can it be considered an engineered barrier for the long-term performance?

3.5.3 Backfill Around the Waste

The DOE plans to put sacks of magnesium oxide (MgO) over and around the waste drums to try to control the future chemical conditions in the repository. The expectation is that MgO will react with the carbon dioxide (CO_2) that is produced from microbial action in the repository. Removal of CO_2 will result in alkaline conditions in the repository. Since the experimentally determined solubilities of radionuclides are lower in alkaline (high pH) conditions, the emplacement of MgO and its

postulated effect allows assumption of lower solubility values in the CCA. This assumption results in lower postulated releases to the accessible environment and thus helps in showing compliance with the Containment Requirements (40 CFR 191.13) of the EPA Standards.

Since the publication of the CCA, the DOE has argued that the MgO is not needed for showing compliance with the Containment Requirements because the mean CCDF without MgO, although showing higher releases than "with MgO", still is within the compliance limits. Such an argument is based on a partial calculation without altering other assumptions and input parameters, and therefore appears meaningless. The fact remains that the purpose of including MgO in the WIPP repository is to control the chemical conditions in the WIPP repository to allow assumption of lower actinide solubility values. It may therefore satisfy a need for the Containment Requirement of the Standards, but does not provide *complementary* added assurance visualized by the Assurance Requirements (40 CFR 191.14).

3.5.4 Borehole Plugs

Since the stated requirements for plugging the boreholes (U.S. DOE, 1996c, Section 3.3.4, Figure 3-10) are much less stringent than the shaft seals, the borehole plugs have a lesser claim as engineered barriers than the shaft seals. The EPA Standards (40 CFR 191.12) do not include borehole plugs as an example of engineered barriers. The NRC specifically excludes borehole seal as part of an engineered barrier system (see the quote under Shaft Seals section above). Hence, the borehole plugs should not be considered to be an engineered barrier.

Incidentally, the DOE's CCA - Figure 3-9 (U.S. DOE, 1996c, "Approximate Locations of Unplugged Boreholes") does not include two deep abandoned oil and gas wells that are located within the WIPP site: Badger Unit Federal in Section 15 (between WQSP-3 and H-5 in the northwest part of the WIPP site), and Cotton Baby Federal in Section 34 (east of H-11 in the southeast corner of the WIPP site).

3.5.5 Waste Processing and Repackaging

Additional confidence in predicting the behavior of the waste over 10,000 years can be obtained by

processing the waste. Hence, EPA should encourage the DOE to process the waste before shipment to WIPP. TRU waste is highly heterogeneous and there are no limits on the allowable particle size of the waste. The Nuclear Regulatory Commission (10 CFR 61) requires a 300 year waste-form or container longevity for class B or class C *low-level* waste, whereas there are no requirements for the TRU containers or the waste-form in 40 CFR 191. Moreover, the DOE proposed action in the WIPP 1997 Environmental Impact Statement only commits to meeting the Waste Acceptance Criteria for acceptance of waste at WIPP. The DOE **preferred alternative**, published in the 1997 Final Waste Management Programmatic Environmental Impact Statement for Managing, Treatment, Storage and Disposal of Radioactive and Hazardous Waste, is to **treat** and store at the sites where it is generated prior to shipment to WIPP.

The recommendation to treat the waste before shipping to WIPP should be easier to accomplish because several of the DOE's waste generator sites are planning to process and/or repackage the waste before shipping to WIPP anyway, for other reasons, as described below. The EPA's recommendation will result in an orderly and coordinated decisions on this matter throughout the DOE weapons complex, and will make WIPP safer.

- According to the September 1997 WIPP Final Supplemental Impact Statement (U.S. DOE, 1996d), 27,000 m^3 of alpha emitting low level waste at INEEL will be processed to convert it to TRU waste.

The information for the following processing and repackaging plans is derived from the National TRU Waste Management Plan (U.S. DOE, 1997c).

- INEEL plans to process all the existing and projected TRU waste except for 15,000 drums (3,000 m^3) to meet the INEEL/State of Idaho agreement, which amounts to processing 79,600 m^3 - 3,000 m^3 = 76,600 m^3 of waste.

- ANL-E plans to treat and stabilize all the 203 m^3 existing and newly generated CH-TRU waste.

- Hanford plans on repackaging most of its 16,127 m^3 of CH-TRU waste.

- Rocky Flats Plant will process most of the plutonium residues and all of the scrap alloy since plutonium concentrations exceed the DOE limits. About half the other TRU waste will be processed and repackaged.

- The Plutonium-238 heat source wastes at Savannah River exceed the hydrogen gas limits imposed by NRC and will require treatment or an easing of the regulations for a less stringent flammable limit or the use of hydrogen getters in the transportation containers.

- All the 1097 m^3 CH-TRU waste at ORNL will be processed with a 50% volume reduction.

- SRS plans to process and repackage 9,525 m^3 of the existing 11,725 m^3 of CH-TRU waste.

In summary, of the existing 104,400 m^3 of CH-TRU waste, DOE has plans to treat or repackage 88,900 m^3 or 85%. Of the 15,500 m^3 not being processed, 3,000 m^3 is intended for shipment to meet a scheduled commitment between DOE and the State of Idaho. The EPA should recognize DOE's efforts in stabilizing the waste and encourage DOE to also fix the yet-to-be generated waste.

3.6 RESOURCE DISINCENTIVE REQUIREMENT

Title 40 CFR 191.14 (e) requires that areas with natural resources should be avoided in selecting a site for a TRU waste repository, unless the favorable characteristics of such places compensate for their greater likelihood of being disturbed in the future. The WIPP site is located in the middle of an area with extensive history of exploitation of potash, oil and gas, and is surrounded by hundreds of currently producing oil and gas wells, as well as several currently producing potash mines. It is

expected that the mining and drilling activity will continue around the WIPP site for the foreseeable future. If the WIPP site had not been withdrawn for exclusive use by DOE, almost certainly there would have been a number of exploratory oil and gas wells and potash mines at the site by now. The EPA has proposed to determine that the WIPP meets this compliance requirement on the basis of the results of the calculations for the containment requirements.

The EEG believes that in allowing the resource disincentive requirement of the EPA standards to be satisfied if the numerical containment requirements (40 CFR 191.13) are satisfied (through 40 CFR 194.45), the EPA deviated from the basic philosophy of the multiple barrier "belt-and-suspender" approach inherent in the assurance requirements of the standards. Faced with the *fait accompli* of promulgation of 40 CFR 194, the EEG recommended (Neill et al., 1996) that at least the actual conditions at the site related to the presence of natural resources be fully and conservatively assumed in projecting compliance with the numerical containment requirements. This does not appear to have been done in the CCA, judging from the DOE resistance to consideration of fluid injection, air drilling, and mining scenarios. The other suggestion made by the EEG (Neill et al., 1996) is to compensate for siting the repository in a mineral resource rich area by incorporating robust engineered barriers in the WIPP's design. The DOE has proposed Magnesium Oxide backfill as an engineered barrier, but that is needed for assuming low actinide solubility to show compliance with the containment requirement. The "containment" and the "assurance" requirements of the EPA standards thus have not been kept separate, as was intended by the EPA standards, 40 CFR 191.

The EEG recommends that full consideration of the effects of the presence of natural resources be incorporated as suggested in Sections 2.5, 2.6, and 2.8 of this report, in a new PAVT, and the engineered barriers be incorporated as suggested in Section 3.4 above.

3.7 RETRIEVABILITY

Title 40 CFR 191.14 (f) states, “Disposal systems should be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal.” The EPA explained in the preamble to the originally proposed rule (U.S. EPA, 1985, p. 38082; September 19, 1985) that the recovery of waste does not have to be “easy or cheap”.

In response to this requirement, the CCA (U.S. DOE, 1996c) presented a five phase approach from planning to decontamination and decommissioning of the facility, and the EPA proposes to find WIPP in compliance of this requirement. As a practical matter, however, the EEG believes that attempts to remove the waste from the repository, even 10 years after first emplacement, will be so hazardous and expensive that it is not a reasonable option. The EPA and the DOE should clearly acknowledge that fact.

4.0 GROUNDWATER PROTECTION REQUIREMENTS

Subpart C of 40 CFR 191 contains the Environmental Standards for Groundwater Protection. Section §191.24 specifies that undisturbed performance of the repository shall not cause the limits specified in 40 CFR part 141 to be exceeded during the 10,000 year regulatory period in any underground source of drinking water (USDW). An aquifer must be able to supply sufficient quantity of water to a public water system and to contain less than 10,000 milligrams of total dissolved solids per liter (§191.22).

Compliance with these requirements requires that USDWs about the WIPP Site be identified, that existing concentrations of radionuclides in these USDWs be estimated, and the increased radionuclide concentrations and doses from the undisturbed performance of the repository be determined.

Previous EEG Comments

The DCCA (U.S. DOE, 1995c) did not address groundwater protection requirements and consequently EEG did not make comments in our review of the DCCA (Neill, et al., 1996). EEG has not made any previous written comments to DOE or EPA on Chapter 8 of the CCA (U.S. DOE, 1996c).

EPA Response to Chapter 8

EPA mostly concurred with DOE's evaluation of the location of possible USDWs. However, in a December 19, 1996, letter EPA did specify that "the CCA needs to include appropriate maps of USDWs using Plan views with information such as township, range, and estimated latitude and longitude of the center of the USDW." A map was provided in DOE's February 27, 1997, response to EPA's request for additional information. DOE did not provide a location of the estimated center of the USDWs because of the contention that sufficient data were not available.

EPA accepted DOE's map of USDWs as adequate without location of their centers. Also, EPA concluded that even though DOE calculated a maximum total alpha radioactivity concentration of about 9 pCi/ℓ (compared to the limit of 15 pCi/ℓ) the potentially large uncertainty was not a problem because these concentrations were in anhydrite formations and not USDWs.

EEG Evaluation

EEG has several concerns or questions about DOE calculations or assumptions and about EPA's Compliance Review.

<u>USDW Designation</u>. The assumption by DOE that a 5 gallon per minute pumping rate was necessary to supply 25 persons is non-conservative. Water consumption may average 282 gallons per capita per day in nearby communities where there is a water system that can supply additional water for lawns, gardens, swimming pools, etc. However, in a rural community where nearby water sources are limited, persons can live quite well on 100 gallons per capita per day. Thus, a pumping rate of 2 gpm should be adequate for 25 persons. The pumping rate criterion did not actually affect DOE's designation of USDW areas because pumping rate data were usually not available and the boundaries were selected on the basis of the total dissolved solids criteria.

EEG is satisfied with the boundaries of USDWs for the Culebra, Dewey Lake, and Santa Rosa aquifers that are shown in Figure 1 of DOE's February 27, 1997, submittal.

<u>Radionuclide concentrations in USDWs from undisturbed releases</u>. DOE relied on the analysis performed for the individual protection requirements to show that the maximum concentration of alpha emitting radionuclides and the allowable dose from beta and gamma radiation was not exceeded. The concentration from the maximum realization was 6.61 pCi/ℓ for ^{239}Pu + ^{230}Th + ^{234}U. These concentrations were determined from BRAGFLO flows and the NUTS code for radionuclide transport and are in anhydrite beds and not an USDW. A different calculation scheme was used to estimate the ^{226}Ra concentration. This calculation led to an estimated ^{226}Ra concentrations of 2 pCi/ℓ which is 2 orders of magnitude greater than the maximum concentration of its parent, ^{230}Th in the

BRAGFLO/NUTS calculation. It seems apparent that these two methods of calculation are unrelated.

EEG believes the concentrations of radionuclides due to an undisturbed release from WIPP in any possible USDW will be somewhat less than the Maximum Concentration Limits (MCLs) in 40 CFR 141. This conclusion is based on the belief that while some contamination could occur between anhydrite beds and USDWs the amount of dilution that would be needed in order to maintain a TDS concentration in a USDW aquifer below 10,000 mg/ℓ would more than offset uncertainty in estimating radionuclide concentrations.

Radionuclide concentrations in uncontaminated USDWs. 40 CFR 191.24 states that any release from undisturbed performance shall not cause the levels of radioactivity in USDW to exceed the limits specified in 40 CFR part 141. In other words, the releases from the repository should be added to the existing radionuclide concentrations to determine compliance. This point was contested in comments on the proposed rule and EPA's decision to include both existing and added concentrations was explained in the preamble to the rule. Basically, EPA doesn't want to have any degradation in a USDW that has concentrations at or above MCL values.

The final 40 CFR 194 and the Compliance Application Guidance (CAG) (U.S. EPA, 1996a) are vague about whether existing concentrations of radionuclides need to be determined and added to estimated concentrations from undisturbed releases in order to show compliance. No relevant discussion was found in the preamble to 40 CFR 194 or in the Background Information Document.

The CCA provided no information on existing concentrations of radionuclides in the possible USDWs and EPA did not ask for this information. Natural system compliance with the MCLs should not be assumed. EEG measured radionuclide concentrations in 3 Dewey Lake wells just south of the site in 1989 and 1990 . One of the four samples measured 37 pCi/ℓ gross alpha, 13.6 pCi/ℓ uranium, and 2.4 pCi/ℓ ^{226}Ra + ^{228}Ra (Kenney and Ballard, 1990).

EPA needs to either obtain existing radionuclide concentrations in the possible USDWs in order to show compliance with 40 CFR 191.24 or explain why this requirement is not applicable.

5.0 INDIVIDUAL PROTECTION REQUIREMENTS

Section §191.15 of 40 CFR 191 provides that disposal systems "shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual committed effective dose, received through all potential pathways from the disposal system, to any member of the public in the accessible environment, to exceed 15 millirems (150 microsieverts)." The Individual Protection Requirements were addressed by DOE in Chapter 8 of the CCA.

Previous EEG Comments

The DCCA did not provide dose calculations to determine if the individual protection requirements had been met. Consequently, EEG had no comment on this requirement in our review of the DCCA (Neill et al., 1996). EEG has not made any previous written comments to DOE or EPA on Chapter 8 of the CCA.

EPA Response to Chapter 8

In the CCA DOE concluded that the only mechanism for undisturbed releases and a dose to an individual was from migration of brine from the repository in anhydrite marker beds to the accessible environment. This contaminated brine was pumped to the surface and diluted to decrease total dissolved solids to 10,000 milligrams per liter. The individual was assumed to drink 2 liters per day of this diluted water. The realization with the highest concentration of radionuclides (out of 300 realizations) was used for the dose calculation.

EPA requested that DOE provide analyses of other exposure pathways beside the drinking water pathway evaluated in Chapter 8 of the CCA. DOE provided this analysis in their February 27, 1997 response to EPA's request for additional information. The additional pathways scenarios analyzed were: (1) farm family inhalation; (2) farm family ingestion; and (3) cattle rancher. DOE dose

estimates for the maximum realization were 0.47 mrem for drinking water and 0.46 mrem from ingestion (the other scenario doses were negligible).

EPA also made their own Dose Verification Evaluation and included this Technical Support Document (U.S. EPA, 1997k) with the proposed rule. Pathways evaluated were drinking water; crop, soil, meat and milk ingestion; inhalation; and direct radiation. EPA calculated doses of 0.49 mrem per year from drinking water and 0.16 mrem for all other pathways.

EPA agreed that the DOE scenario assumptions were conservative and actually unlikely. Also, that the CAG (U.S. EPA, 1996a) requirements were fully met. Therefore, they concurred in the adequacy of DOE's Individual Protection Requirement evaluation.

EEG Evaluation

The EEG checked both DOE's and EPA's dose calculations. Agreement was within 5%.

CCA calculations of the concentration and quantity of radionuclides reaching the accessible environment in the anhydrite interbeds were taken as a given by EPA. EEG has not checked these calculations either but they appear reasonable. Also, the limited quantity of contaminated water calculated to reach the accessible environment (a maximum of 216 m^3) was not invoked by DOE or EPA in their calculations. This limited quantity of contaminated water would preclude EPA's calculated 30-year radionuclide buildup in soil (which contributes less than 1% of the other pathways dose).

We consider two inhalation and soil ingestion pathways to be more likely than those considered by DOE and EPA. These are: (1) resuspension of solids from undiluted brine used for dust control about a residence; or (2) resuspension of solids from a mud pit where the contaminated brine has evaporated. The brine could be in the mud pit as a result of an aquifer pump test, an oil or gas borehole, or as a residue from a water treatment process (such as reverse osmosis). However, these

scenarios result in estimated doses that are less that 0.1 mrem/y. So, these scenarios, though perhaps more reasonable, lead to lower doses than calculated by DOE and EPA.

EEG agrees that this requirement has been adequately and conservatively evaluated. We consider this to be a closed issue.

6.0 EVALUATION OF EPA'S RESPONSES TO EEG'S COMMENTS

The EPA has provided responses to some of the EEG comments on the CCA provided to the EPA before the March 17, 1997, deadline. These responses are found at the end of each Compliance Assessment Review Document (U.S. EPA, 1997b). References have been made to these responses in the relevant chapters in this report. For the sake of completeness, the EEG review of these responses are grouped together in this chapter.

Section 194.14 (CARD 14)

Issue 14.T: The probability of encountering a brine reservoir during drilling and the reservoir's potential volume are underestimated.

103. The CCA assumed that the probability of encountering a brine reservoir is a function of reported brine encounters expressed as a percentage of total boreholes drilled. The problem with this assumption is that drillers are not required to report brine encounters; moreover, drillers tend not to report such encounters unless they result in significant delays or cause other problems during operations. Thus, the eight percent brine encounter rate used in the CCA dramatically understates the actual rate, which probably lies somewhere between 50 and 100 percent. (103)

525. The EEG does not find the CCA reservoir volume assumption of 32,000 to 160,000 m^3 to be justified. (525) (II-H-12.4)

EPA response to Issue T:

EPA found that DOE's representation of brine pocket occurrence probability and brine pocket size/volume in the CCA were not consistent with available information. EPA directed DOE in letters dated March 19, 1997 (Docket A-93-02, Item II-I-01, enclosure 3) and April 25, 1997 (Docket A-93-02, Item III-I-27) to conduct new performance assessment modeling that includes modified parameter values. EPA requested that the brine pocket probability be modified to a range from 1 percent to 60 percent, and that this occurrence be sampled rather than a fixed value of 8 percent. In addition, EPA requested that the parameters regarding rock compressibility and porosity (e.g. Castile COMP_RCK), as well as how the brine pocket volume is sampled, be modified in the mandated Performance Assessment Verification Testing (DOE, 1997b and 1997c). This approach effectively modified the sampled brine pocket volume to include more representatively the possibility of higher brine pocket volumes, including that of WIPP-12. As a result of the PAVT, EPA found that the original brine reservoir characteristics were, in fact, acceptable. For more discussion on this topic, also see this CARD, section 14.B.5, EPA's Technical Support Document for Section 194.14: Content of Compliance Certification Application (EPA, 1997a) and the Technical Support Document for Section 194.23: Parameter Justification Report (EPA, 1997e).

EEG assessment of EPA response to Issue 14.T

The Performance Assessment Verification Test has demonstrated that the brine reservoir characteristics have a large effect on predicted repository pressure and brine saturation. The EEG believes that the Performance Assessment Verification Test is a valuable set of calculations that were needed to demonstrate the robustness of the performance assessment calculations.

The characterization of the potential high pressure brine pocket used in the PAVT is much more accurate than the representation used in the CCA calculations. There are two parameters used in the PAVT that are still inaccurate. First, the PAVT uses a sampled

pressure range of 11.1 to 16.5 MPa gage for the Castile brine, based on regional occurrences of brine, rather than the 12.6 MPa gage measured at WIPP-12. WIPP-12 brine almost certainly protrudes under the WIPP repository. However, it was found that the pressure range used in the PAVT leads to prediction of more and larger brine releases than the single value of 12.6 MPa (Rucker, 1998).

Secondly, there is poor justification for the 1% lower end of the EPA range for the probability of encountering a pressurized brine pocket. The 60% upper end is based on an electromagnetic survey of the WIPP site (U.S. DOE, 1996c, 2.2.1.2.2) that indicates brine is likely under about 60% of the repository. Most importantly, the probability of hitting brine under WIPP should be based on local WIPP information and not the entire Delaware basin. The calculated size of the WIPP-12 brine reservoir and the existence of boreholes around WIPP-12 that have not encountered brine in the Castile constrain the WIPP-12 reservoir such that the reservoir must extend under the repository (Neill, 1997d). The brine indicated by the electromagnetic survey must be part of the WIPP-12 reservoir. Hence, the probability of encountering brine should be modeled as 60%. Thus, the PAVT under represents the probability of encountering a brine reservoir while overestimating the effect of the reservoir.

Section 194.23 (CARD 23) Models and Computer Codes

ISSUE 23.A: Cuttings/Cavings and Spallings Model

97. The CCA fails to consider cavings that occur as the drill bit passes through the waste, cavings from particle impact, cavings from helical turbulent flow, and radioactive brine ejected before spallings.

EPA Resolution of comment 97

EPA disagrees with the comments. The cavings submodel rigorously considers the impact of helical laminar flow on cavings release by numerically solving a series of non-linear integral equations. Because of complexities in the turbulent flow regime, similar mathematical treatment is not possible and it is necessary to resort to empirical procedures. DOE accounts for the helical flow component in the turbulent regime by using a rotation factor (F) which increases the erosion as compared to that calculated by uniaxial flow (Docket: A-93-02, II-G-1, Volume V, Appendix CUTTINGS_S, WPO #37765, page 47). For radioactive brine to be ejected from an inadvertent human intrusion borehole which penetrates waste, two conditions must be met (Docket: A-93-02, II-G-1, Volume 1, Chapter 6, Section 6.4.7.1.1, page 6-152):

> *The waste must be under sufficient pressure to drive the drilling mud from the borehole (greater than 8 MPa). Mobile brine contaminated with radionuclides must be present.*

The direct brine release conceptual model as implemented with the BRAGFLO_DBR code addresses this issue of ejection of radioactive brine (Docket: A-93-02, II-G-5). The cavings model does not explicitly consider erosion from particle impact as the drill bit passes through the waste. Any such erosion would be of very short duration (about four minutes for fully compacted waste at a drilling rate of 50 ft/h). Borehole enlargement from particle impact would produce lower flow velocities for the drilling mud and reduce the erosion calculated by the cavings model. Consequently, EPA believes that any impact from this process is included within the range of calculated cavings releases.

EEG Assessment of comment 97.

The EEG concurs with EPA's assessment.

98. The spallings model assumes constant pressure, although blow-out is a phenomenon related to pressure differentials. There are several methodological problems with the experiments (e.g., no dimensional analysis, no vent sensitivity analysis, etc.). The model considers only particle dislodgment, not lifting or lofting. Limited parameters are sampled or calculated (e.g., particle diameter, but not waste permeability, cementation strength, drill bit diameter, or radioactive content of waste).

EPA Resolution on comment 98

EPA agrees that the spallings conceptual model was initially inadequate. However, these inadequacies result in higher releases. Since the Conceptual Model Peer Review Panel found the spallings model implemented in the CCA to be inadequate, DOE conducted a significant computational and experimental program as documented in Docket A-93-02, Item II-G-23. These new computational approaches include consideration of pressure transients. On the basis of this new material, the Peer Review Panel determined that the spallings model used in the CCA resulted in the calculation of release volumes which are reasonable and may actually overestimate expected releases (Docket: A-93-02, II-G-22, Conceptual Models Third Supplementary Peer Review Report, April 1997, page 12).

The new computational approach predicts extremely small spallings volumes for all gas pressures below lithostatic pressure. EPA has concluded that, since the spallings model in the CCA considers only particle dislodgement from the waste and not lifting or lofting of dislodged particles up the borehole, the approach taken by DOE is conservative. Larger particles dislodged from the surfaces of radial fractures in the waste will not be lifted 2150 ft to the land surface. In Docket: A-93-02, II-G-23, page 1-3, the tensile strength of saturated surrogates waste was measured to be 0.074 MPa while that of dry waste was 0.15 MPa. This may be compared to a value of 1 Pa used for the cementation strength in

the spallings model. Thus the tensile strength in the spallings model was conservatively assumed to be several orders of magnitude lower than determined by tensile tests on waste surrogates. As discussed in detail in Section 1.2.3.2.4. of the '194.23 Technical Support Document- Models and Computer Codes, the use of a single value for the drill bit diameter is reasonable.

In the CCA, DOE chose to treat the radioactivity released by spallings as the average radioactivity in the repository (Docket: A-93-02, II-G-1, Volume 1, Chapter 6, Section 6.4.7.1, page 6-151) and based this position on the fact that the spallings model presumed that waste was eroded from fracture channels extending over a large portion of a waste room. In contrast, radioactive releases from cuttings and cavings were based on randomly sampling three of 569 waste streams for each intrusion. In this case the argument was made that cuttings/cavings removed only a localized volume of waste. Thus, the approach taken by DOE is consistent with the conceptual model in each case (ibid., page 6-189). It may further be noted that the CCDFs for waste volume removed by cuttings/cavings and spallings are about the same magnitude (see Figures 4.2.2 and 4.4.3, right frame, mean in Helton and Jow 1996, pages 4-6 and 4-22, Docket: A-93-02, II-G-07). Thus, if waste stream variability were incorporated into spallings releases, the results would be roughly comparable to those for cutting/cavings which as can be seen in Figure 4.2.3 (ibid., right frame, mean, page 4-6) are well below the EPA release limits. Since the average activity of the CH-TRU and the RH-TRU waste is essentially the same (ibid., page 4-1), and since the spallings model considers removal of waste from throughout an entire room, omission of RH-TRU waste from the spallings model will not have a significant impact on calculated releases.

EEG assessment of comment 97

The newer spallings model (Hansen et al., 1997) and subsequent peer review resolves this comment. However, the issue of an adequate spallings model remains. As shown in Section 2.4 of this report, the newer codes fail to model expected repository conditions.

This is still a major concern.

262b. The CCA fails to consider RH-TRU waste in the spallings scenario.

EPA Resolution on comment 262b

EPA agrees [sic]. EPA believes that combining the RH-TRU waste streams into a single volume-averaged stream is a reasonable modeling simplification. This is supported by the fact that the average activity in the RH-TRU and the CH-TRU waste is about the same while the probability of encountering CH-TRU is about seven times greater. Consequently cuttings releases are dominated by CH-TRU (Docket: A-93-02, II-G-07, Helton and Jow 1996, page 4-1).

DOE Response to issue

669 The conceptual models used to characterize the spallings and direct brine release processes were developed to describe the effects of rapid depressurization of large volumes of interconnected, homogeneous, and relatively permeable waste material. The models do not apply to the effects of rapid depressurization on the relatively small and relatively well isolated volumes anticipated for the RH-TRU waste. RH-TRU waste will be emplaced in boreholes in the halite walls of the waste disposal region. . .The volume of pressurized fluid available within a single RH-TRU canister will be far too small to displace the drilling fluid within the borehole, and therefore intrusions directly into an RH-TRU canister are very unlikely to result in a spall or direct brine release event. Intrusions into CH-TRU, waste near an RH-TRU emplacement borehole will draw spalled material and contaminated brine from the more permeable CH-TRU waste, rather than from the RH-TRU waste. It is therefore correct not to apply the spallings and direct brine release models to RH-TRU waste. (II-H-21.26)

670 DOE chose to model cuttings and cavings releases of RH-TRU waste using a single, average activity level for RH-TRU waste based on consideration of information available

in the Baseline Inventory Report (BIR) Rev. 2 (Appendix BIR of the CCA). Individual waste streams are reported for RH-TRU waste. Most of these waste streams represent small volumes of material, however, and the probability assigned to the penetration of many of these individual categories by an intrusion borehole would have been below the regulatory threshold of 10^{-3} in 10^{4} yr. Rather than neglect these low-probability events, the DOE has included them in the analysis by lumping them, and their activity loads, into a single category with the other, more abundant RH-TRU waste that dominates the volume-averaged activity of RH-TRU waste used in the performance assessment. The activity levels that might be calculated by random combinations of large numbers of waste streams plus backfill would closely resemble the overall average activity. (II-H-21.27)

EEG assessment of EPA comment resolution

The EEG is satisfied that neglecting RH-TRU in spallings calculations and using a single waste stream to represent RH-TRU in the cuttings and cavings model are acceptable modeling approximations. The primary reasons for this assessment are that RH-TRU will be less that 1% by volume of the transuranic inventory of the repository and that the high activity levels in the RH-TRU waste are from fission products that will have significantly decayed in the first two hundred years of burial. While the present activity of RH-TRU waste varies many orders of magnitude, the transuranic content of the waste does not.

535 The spallings model is defined as gas driven entrainment of solid particles. The spallings model should include the effects of brine. (II-H-12.14)

EPA Resolution of Comment

EPA disagrees with the comment. Spallings occurs only if the pressure in the intruded waste panel exceeds 8 MPa. As the gas pressure increases, the brine saturation in a waste panel decreases (Docket: A-93-02, II-G-07, Helton and Jow 1996, page 5-1). Thus, at pressures where spallings can occur, less brine is available for release. In addition, the

spallings model uses the average radionuclide concentration in the waste to develop the source term (ibid., page 4-7). If some radionuclides are dissolved in brine which is transported along with solid waste to the surface, this radioactivity will have been accounted for by the solid material since mass must be conserved. The spallings model addresses all the radioactivity as if it remained with the solids rather than partitioned between the solid and the brine. Direct brine releases in which brine flows up the borehole after intrusion are accounted for by the direct brine release model (Docket: A-93- 02, II-G-05). EPA believes that this "double counting" of solid spall releases and waste mobilized by brine overestimates releases from these mechanisms and therefore is adequate for use in PA and is conservative.

EEG assessment of EPA comment 535 resolution

In light of the newer spallings model (Hansen et al., 1997), the inclusion of brine release in the spallings model is a minor concern.

536 With the composition of the waste ranging from large pieces of metal to ash, it is unlikely that the waste will degrade to a uniform grain size. There has been no analysis to show that the releases calculated by sampling for a uniform distribution size bounds the release from a heterogeneous medium. (II-H-12.15)

EPA resolution of comment

EPA agrees that a uniform particle size is not appropriate. The CCA does not assume that waste degrades to a uniform particle size. Waste particle diameters in the spallings model were assumed to be distributed log-uniformly from $4x10^{-5}$ to 0.2 m (Docket: A-93-02, II-G-1, Appendix PAR, page PAR-115). Spallings releases are dominated by transport to the surface of solids of small particle size (see, for example Fig. 4.3.5 in Helton and Jow 1996, page 4-14,Docket A-93-02, II-G-07). Since use of a loguniform distribution biases parameter selection during LHS sampling to smaller (i.e., more conservative) values, releases will be higher with this parameter distribution. In addition, it was deduced from

the findings of the Expert Elicitation Panel on waste particle diameters that the particle range was most probably between 1 mm and 10 cm which would reduce the spallings release (Memorandum entitled "Estimate WIPP Waste Particle Sizes Based on Expert Elicitation Results: Revision 1" from Yifeng Wang to Margaret S. Chu and Mel G. Marietta, Sandia National Laboratories, SNL WPO# 46936, June 27, 1997). The use of the mean particle size in determining the shear strength of the waste is a reasonable approach to characterizing the fact that the waste does not have a uniform particle size.

EEG's assessment of the EPA comment resolution

The EPA missed the point of this comment. The spallings model used for the CCA calculations did assume a uniform particle size. The uniform size was assumed to be uncertain and was therefore sampled from a range. However, the issue is no longer pertinent to the CCA because of the development of the newer spallings model.

537 [DOE argues that] a larger initial spall will be followed by less erosion than a smaller initial spall, resulting in the same final void ration. We find two errors in this argument: 1) The pressure difference between the waste repository and the hydrostatic pressure of the drilling mud can be over 6 MPa, three orders of magnitude above pressure differential need for explosive spall. 2) The second argument presupposes, without justification, that the erosion volume is larger than the initial spall volume and that the cavity caused by the initial spall will be partially filled by the erosion process. (II-H-12.16)

539 The spallings model does not include a sensitivity to scale leading the developers of the spallings model to state extrapolation of release volumes to WIPP, using the parameters evaluated using small scale laboratory models, has the potential for grossly under-predicting such releases. (II-H-12.18)

EPA resolution of comments 537 and 539

The CMPRP was not satisfied with several aspects of the spallings model as implemented in the CCA (see, for example, Docket: A-93-02, II-G-1, Volume XII, Appendix PEER, PEER 1, page 3-88 to 3-93). However, based on additional information subsequently developed by DOE and included in the Spallings Release Position Paper (Docket: A-93-02, II-G-23), the Panel concluded that the model was reasonable and probably conservative (Docket: A-93-02, II-G-22, page 12). EPA agrees with this position and believes this responds to EPA's initial concerns.

538 The model tests the erosion portion of the spallings phenomena for waste with no cohesive strength, but not the initial explosive phase, nor the effect of cohesion. (II-H-12.17)

EPA resolution of comment 538

EPA disagrees with the comment. The spallings model used in the CCA assumed that the cementation strength of the waste was 6,895 Pa or 1 psi (Docket: A-93-02, II-G-10, Appendix PAR, page PAR-190, ID #3245). Testing of surrogate waste mixtures as described in Spallings Release Position Paper (Docket: A-93-02, II-G-23, page 1-6) indicated that the strength of the waste was substantially higher than assumed in the CCA with the average tensile strength of saturated waste being 74,000 ± 40,000 Pa. Thus, the amount of spallings should be reduced as compared to that calculated in the CCA. (see response to comment 537 above.) EPA believes this increased waste strength would mitigate the impact of the "initial explosive phase" and that total releases would be well below the 0.5 to 4.0 m^3 range used in the PAVT calculations.

EEG's assessment of the EPA resolution of comments 537, 538, 539

EPA's assumption that the new spallings model is adequate to answer all spallings'

concerns does not address EEGs' concerns. EEG believes that relying solely on the results from the new spallings model may be underestimating the importance of the issue. For example, the new spallings model cannot simulate all expected repository conditions. Locally varying waste permeability or different gas viscosities cause the code to produce erroneous results. It is therefore suggested that the EPA look more closely at the newer model before dissmissing any comment on spallings.

540 The "gas erosion" and the "stuck pipe", considered by the DOE in earlier performance assessments, have been excluded from the CCA spallings model. These two phenomena could cause releases that are over an order of magnitude larger than the largest releases calculated in the CCA. (II-H-12.19)

EPA Response to comment 540

EPA does not believe it is necessary to include gas erosion and stuck pipe processes in the CCA spallings model. Gas erosion and stuck pipe releases occur only if the waste permeability is less than $1x10^{-16}$ m^2 (Docket: A-93-02, II-G-1, Appendix CUTTINGS_S, page 37). In addition, the gas pressure in the intruded panel must exceed 8 MPa for gas erosion and 10 MPa for stuck pipe processes to occur. Based on earlier experimental work, DOE used a value for waste permeability of $1.7x^{-13}$ m^2 (see discussion in Section 1.3.2.7.4 of the TSD for '194.23 - Models and Computer Codes). More recently, DOE measured the permeability of surrogate waste mixtures based on current understanding of waste mixtures and degraded waste characteristics and determined the permeability of waste surrogates to be $2.1x10^{-15}$ to $5.3x10^{-15}$ m^2 on two samples (Docket: A-93-02, II-G-23, page 2-18). Based on the available waste permeability information, EPA concluded that the gas erosion and stuck pipe processes should not occur because permeabilities will be greater than the $1x10^{-16}$ m^2 threshold.

EEG assessment of EPA comment resolution

EEG still considers “stuck pipe” and “gas erosion” as potentially important processes in the calculation of spallings releases. See Section 2.4 of this report.

ISSUE 23.F: Three Dimensional Processes and Boundary Conditions

553 The EEG concludes that the use of a 2-D geometry in the BRAGFLO may introduce significant non-conservatism into the CCA calculations. The FEP S-1 needs to be reexamined with appropriate consideration of the impact of increased brine saturation on calculated estimates. (II-H-25.4)

EPA response to comment 53

EPA disagrees with the comment. The work that is most relevant to this concern is the FEP Screening Analysis titled S1: Verification of 2D-Radial Flaring Using 3D Geometry, WBS No. 1.1.6.3, SANDIA WIPP CENTRAL FILES-A: 1.2.07.3: PA:QA:TSK:S1, ERRATA - February 19, 1996 (SNL WPO #30840). In this work, a simplified version of the two dimensional CCA PA grid was tested against a corresponding three-dimensional (3-D) model. BRAGFLO was used in both two-dimensional (2-D) and 3-D simulations, and TOUGH28W was used to model the 3-D simulations only. Simulation results were compared for cases with an average repository gas generation rate, and a gas generation rate that was double the average. The results of the second case, in which the gas generation rate was doubled, indicates that a combination of pressure induced fracturing and the 1-degree dip cause flow paths which are different for the 2-D and 3-D grids. Once fracturing of the interbeds occurs, the 3-D model displays an immediate migration of gas primarily out of the west side of the repository into the anhydrite layers, accompanied by brine inflow to the repository. This phenomenon is not seen in the results from the 2-D model, in which the west side of the repository is a no flow boundary, which demonstrates

that the 2-D and 3-D simulations show local variations. However, the results also show that the predictions of brine flow to the accessible environment are similar for both 2-D and 3-D grids. With respect to increased brine saturation, Figures 7 and 12 of the FEP Screening Analysis referenced above (WPO# 30840), shows the average gas saturations calculated with the 3-D simulations of TOUGH28 and both the 2-D and 3-D versions of BRAGFLO. Simulation results are compared for the base case and twice the base case generation rates, respectively. These curves indicate that gas saturations are higher in the 2-D simulations (WPO# 30840, page 27). Since brine and gas saturations are inversely related a similar trend would be observed for the brine saturations. In the Performance Assessment Verification Test (PAVT) , it was determined that the greatest potential releases could be attributed to those associated with spallings and direct brine releases. Furthermore, these releases are pressure controlled and will not occur if repository pressures are below 8 MPa. The fact that the 2-D model may overestimate gas saturation by underestimating brine saturations will lead to the prediction of higher gas pressures than those that would have been predicted with the 3-D configuration and this will result in more conservative estimates of releases. Based on this, EPA believes that the 2-D geometry used in the BRAGFLO CCA PA calculations is a reasonable simplification and that the predicted results are conservative.

EEG assessment of EPA resolution of comment 553

The EEG does not consider this issue to be resolved. See Section 2.10 of this report

Issue 23.W: CCA Parameters and PAVT Parameter Selection

550 The data and rationale for the sampled distribution of the waste-room residual-brine saturation is presented on pages PAR-27 through PAR-31. . .The non-conservative distribution of 0 to 0.560 reduces the estimated releases of direct brine release [sic].

Appropriate ranges for the waste room residual brine saturation are a constructed distribution using values from the eight unconsolidated materials; a uniform distribution from 0.0783 to 0.277, or a uniform distribution from 0 to 0.277. (II-H-25.1)

DOE Response to the Issue

845 The comment about the distribution of 0 to 0.560 for S [residual brine saturation of wr waste] being non-conservative is not correct because one should not be using a value just because it is more conservative. Instead, the use of a particular distribution or value should be based on how closely it represents the processes being modeled and how accurately it reflects realistic expectations of what will occur in the repository. The range of 0 to 0.560 was therefore chosen on the basis of being both reasonable and realistic. (II-H- 45.6)

EPA's Response to Comment 550 and 845

The residual brine saturation is that value at which no more flow will occur even with further decreases with capillary pressure. The range used for the CCA is based on literature values for unconsolidated materials. EPA agrees with DOE's comment, in that DOE has selected a reasonably representative range value for the wastes. This parameter will change with time, as the wastes gradually compacts, the porosity will become lower and the residual brine saturation will increase due to the increased capillary pressure of the smaller pores. Therefore, the low end on the distribution represents coarse material prior to waste compaction and the high end would be representative of fairly compacted waste. EPA's basic philosophy in dealing with such uncertain parameters has been to be reasonably sure that one or more of the following criteria are true : 1) that the values selected for a parameter in question leads to conservative results; 2) that the results are relatively insensitive to that parameter, or 3) that the selective range is representative of the actual parameter values. In the case of brine saturation, the complexity of the problem does not allow a predetermination to be made regarding whether a certain range or

distribution is conservative. A further complicating factor is that the BRAGFLO computer code contains a wicking function that allows gas generation to occur even if the capillary pressures are low (Appendix BRAGFLO). Based on modeling experience EPA believes that residual brine saturation is insensitive and that the selected values does not impact the final results to a significant degree. EPA is confident that the range and distribution placed on the residual brine parameter are reasonably representative of the wastes and are adequate for use in the CCA PA calculations.

EEG assessment of EPA resolution of comment 550

Based on the information presented during the January session of the conceptual model peer review panel and to the particle size expert elicitation panel that some waste may be consolidated, the range of sampled residual brine saturation of the waste in the CCA calculations was appropriate.

551 Even though the parameter ranges recommended by Beauheim are more reasonable than the ones used in the CCA, the EEG disagrees with the recommended values for reservoir volume because the range includes the value derived from testing the ERDA-6 brine reservoir and initial pressure because of the use of data from twelve other brine encounters in the Salado. . . The recommended initial pressure range of 16.5 to 11.0 MPa gage is based on pressure measurements from thirteen Castile brine encounters. At WIPP-12 the measured pressure was 12.6 MPa gage. Therefore, the reservoir pressure should be a constant value of 12.6 MPa gage in the revised CCA calculations. (II-H-25.2)

EPA’s response to comment 551

No response given.

EEG assessment of EPA resolution of comment 551

See resolution to Issue 14.T on page 224.

552 If the samples distributions of parameters used in the CCA calculations are in error, but include the likely values of those parameters, should the CCA calculations be acceptable? The EEG position is that, under the these conditions, the CCA calculations should be repeated with the best estimate of the parameter distributions available. The use of a faulty distribution of one parameter biases the CCDF curves and confuses the assessment of uncertainty. The use of more than one faulty parameter set makes the assessment of uncertainties impossible because of the complex non-linear nature of the performance assessment models. (II-H-25.3)

EPA's general response to Issue 23.W and to comment 552

EPA performed a thorough review of the parameters and the parameter development process (see Section 12.4 on requirement §194.23 (c)(4) above in CARD 23 -- Models and Computer Codes; EPA Technical Support Document for § 194.23: Models and Computer Codes (Docket A-93-02, Item III-B-6); and EPA Technical Support Document for § 194.23: Parameter Justification Report (Docket A-93-02, Item III-B-14)). EPA reviewed parameter packages in general for approximately 1600 parameters used in the CCA Performance Assessment calculations. EPA further reviewed parameters record packages and documentation in detail for more than 400 parameters important to performance of the disposal system. Records reviewed include the Docket: A-93-02, II-G-1, Volume 1, Chapter 6, Tables 6-8 through 6-27, page 101 to page 166, A-93-02, II-G-1, Volume XI, all of Appendix PAR, WIPP parameter entry forms (464 Forms), Parameter Records Packages (PRP), Principal Investigator Records Packages (PIRP), Analysis Packages (AP), and Data Records Packages (DRP). The evaluation included a review of the expectations listed in the "Compliance Review Criteria" for §194.23(c)(4) above in Section 5.4.2. As a result of substantial information gathering at the Sandia Records

Center, EPA was able to uncover on its own substantial necessary documentation supporting most of the parameters used in the CCA PA. EPA first examined the sources of different parametric values used in the computer codes. EPA found that 416 (26.4%) of the 1571 parameters used in the CCA PA calculations are well-established constants found in general literature and general engineering knowledge. EPA discovered that DOE derived 887 (56.6%) of the parameters from experimental data, either from its own experiments or from journal articles. EPA also found that 89 (5.7%) are waste-related parameters derived from the waste inventory report (see docket: A-93-02, II-I-1, Volume III, Appendix BIR). EPA found that DOE selected the values of 149 (5.9%) parameters using professional judgment of its employees. Approximately 194 (12.3%) parameters were "legacy parameters" originally used in DOE's 1992 PA and again incorporated in the CCA PA (see Docket: A-93-02, II-I-31, Comment No. 11).

EPA selected 465 parameters on which to concentrate its analysis. EPA selected parameters to review based on the following criteria:

- parameters that appeared to be important to compliance or seemed to be poorly justified, such as material permeabilities and porosities, particle size, brine reservoir characteristics, pressures, solubilities of actinides, and waste inventory information,

- parameters that control various functions of the CCA PA computer codes that appeared to be important to compliance, such as permeability threshold, and dispersivity characteristics of the Culebra,

- other parameters EPA used to evaluate the overall quality of SNL's documentation traceability, such as reference constants and general reference values.

The purpose of the parameter review was to verify that DOE's documentation includes

adequate information to fulfill the compliance review criteria of section 12.2, for §194.23(c)(4) of this CARD. For greater detail about EPA's examination of the specific parameters in each category, see EPA Technical Support Document for Section 194.23: Parameter Justification Report (Docket A-93-02, Item III-B-14).

EPA strongly believes that EPA-mandated Performance Assessment Verification Test was done with the best estimate of the parameter distributions available. EPA did an exhaustive review of the parameters used in the CCA PA and altered those needed and required DOE to repeat the calculation with the necessary changes. See A-93-02, III-B-5, II-G-26 and II-G-28 for documentation of the changed parameters and their impact on potential releases.

EEG assessment of EPA resolution of comment 552

Though the EPA did a thorough job in evaluating the parameters for the PAVT, the EEG believes that the performance assessment evaluation is still incomplete. For example, the EPA studied the evidence carefully when considering the Castile Brine Reservoir parameters and selected relevant values to assign to the parameter. Yet, the solubility of certain actinides in Salado and Castile brines or the partition coefficient of actinides for sorption onto the Culebra Dolomite and the probability of brine reservoir encounter were inadequately addressed. These few examples play an important role in compliance, as studied by the EEG in sensitivity analyses (Section 2.2 of this report). The synergetic effect off all parameters is unknown, and it is important to characterize each parameter carefully. The EEG believes that this has not been done, and perhaps a new performance assessment should be conducted with parameter values that are more easily justified through experimentation.

554 The sampled parameter for the probability of microbial gas generation determines whether cellulose and plastics and rubber will be degraded by microbial action after

closure of the repository. . . It is the opinion of EEG that the numerical value of this parameter constitutes expert judgment. Given the importance of this parameter to the estimates of radionuclide release, this parameter should be demonstrated to be either solidly based on scientific evidence or be conservative. The justification for this parameter presented in support of the CCA does neither of these. (II-H-25.5)

DOE response (II-H-45)

The interaction of gas generation with other processes in the repository is complex. Because of this, an *a priori* determination of a meaningful, conservative selection from the possible processes of gas generation is difficult. The suggestion of the EEG that microbial degradation should always be specified, i.e., a 100% probability, is not necessarily conservative since this would tend to reduce brine inflow. Therefore, to be consistent with the treatment of uncertainty throughout the performance assessment, the DOE assigned probabilities to gas generation processes to ensure that assessment results reflect the uncertainty associated with the occurrence and extent of these processes, i.e., both possible outcomes be sampled.

The conceptual model for gas generation in the WIPP repository includes two dominant generation processes: metal corrosion and microbial degradation of organic material. The probabilities of occurrence of these processes were established through a procedure that included careful review of uncertainty suggested by experiments conducted specifically for the WIPP, literature review, and consideration of local scale processes in the disposal room. Given the presence of brine, it is reasonable to assign a 100% probability to metal corrosion. However, there are considerable uncertainties associated with the occurrence of significant microbial populations. These are:

(1) Whether micro-organisms present in the waste are capable of carrying out the potentially significant processes that generate gas identified by Brush[6].

(2) Whether these microbes will survive for a significant fraction of the 10,000 year period of performance of the repository.

(3) Whether sufficient electron acceptors (oxidants) will be available to any microbes that survive.

(4) Whether enough nutrients, especially N and P, will be available.

Electron acceptors and nutrients will be present in the repository (see Appendix BIR7). Therefore, points (3) and (4) relate to the uncertainty as to whether these materials will be physically and chemically available to any microbes that survive. Brush[8] discussed these issues in more detail.

In addition to uncertainty over the possibility of microbial activity, there is also uncertainty over the amounts and types of biodegradable waste. It is reasonable to assume that readily biodegradable material such as cellulosics will be consumed if microbes are active. However, plastics and rubber are much less biodegradable than cellulosics and may not contribute to the gas generation process. Two factors may potentially increase the biodegradability of those materials: (1) long time scale; (2) co-metabolism. Over a time scale of 10,000 years, the chemical properties of plastics and rubbers may change, possibly resulting in enhanced biodegradability. Furthermore, micro-organisms may co-metabolize plastics and rubbers with cellulosics and other more biodegradable organic compounds. All of these uncertainties precluded the use of experimental and/or modeling studies to quantify the probability of significant microbial gas generation in WIPP disposal rooms and the probability of significant microbial degradation of plastics and rubbers for the performance assessment calculations to support the CCA.

To incorporate the uncertainty about the dominant processes of gas generation, the DOE assigned a value of 50% to the probability of significant microbial gas generation and 50% to the probability of significant microbial degradation of plastics and rubbers in the case of significant microbial gas generation. In other words, steel corrosion alone occurs in 50% of LHS sample vectors, steel corrosion and microbial degradation of cellulosics occurs in 25% of LHS sample vectors, and steel corrosion and microbial degradation of cellulosics, plastics, and rubbers occur in 25% of LHS vectors. This is consistent with the treatment of uncertainty throughout the PA calculations (see Appendix PAR, page PAR-6, Delta Distribution). As the EEG requests, it is also based on scientific evidence as to the likely gas generation processes and ensures that all the possible complex interactions between gas generation and other processes are accounted for.

The EEG also states that the gas generation probabilities used should be peer reviewed. In fact the Conceptual Model Peer Review Panel have done this (see Appendix PEER, Section 1). With regard to the gas generation model probabilities, the Panel stated (p. 3-144 to 145):

> "Regarding microbially induced gas generation, the model assumes that the probability of degradation of cellulose and plastics/rubber will be 50% and that in the event that biodegradation occurs there is a 50% probability that plastics and rubbers will also be degraded." [Illustration callout and illustration omitted in this quote]
>
> "This assumption is based on major uncertainties that are described in Section 3.21.2.4 below, and represents a judgement. For performance assessment purposes, this assumption will result in less gas generation than if one were to assume total consumption of all the organic material. There is apparently no scientific evidence that plastics/rubbers degradation will occur at all with certainty,

based on contemporary experience. The possibility that products from microbial degradation of cellulose, and perhaps radiolysis by alpha irradiation, could combine to break down the relatively stable plastics polymers to more consumable fragments suggests the probability should be non-zero. It is difficult to argue for a value higher or more precise than 50%, unless there were more robust long-term data, or experience with plastics degradation in, for example, landfills. Therefore, for performance assessment purposes, the assumption regarding plastics/rubbers appears to be adequate.

With regard to the degradation of cellulose, the long list of uncertainties identified in Section 3.21.2.4 below suggests that less than full probability of significant microbial degradation of this more readily consumable material is a reasonably valid assumption. Also, it does not appear scientifically valid to assume that either all or none of the cellulose will be degraded in light of the significant uncertainties that microbial populations would remain viable to the extent of complete cellulose degradation. DOE is not seeking a worst case in performance assessment. Therefore the 50% probability is a reasonable assumption for modeling purposes."

The DOE believes this excerpt shows that the Conceptual Model Peer Review Panel fully understands the goals of performance assessment in general, the purpose of model and parameter selection, and in particular the basis and reasonableness of the DOE gas generation model.

EPA's response to comment 554

EPA has examined information to support these parameters. See EPA Parameter Justification Report (Docket A-93-02, Item III-B-14),

Section 5.25, for detailed discussion of the PU, PROPMIC parameter.

Section 5.33, for detailed discussion of the AM, PROPMIC parameter.

EEG assessment of EPA resolution of comment 552

It appears from the response that EPA did not understand the question. The EPA response in Section 5.25 and Section 5.33 (U.S. EPA, 1997m) addresses concerns of Plutonium and Americium sorption onto microbial colloids and humid colloids.

The sampled parameter for the probability of microbial gas generation determines whether cellulose and plastics and rubber will be degraded by microbial action after closure of the repository. No degradation of cellulose or plastics occurs in the calculations with a 50% probability. Only cellulose degrades in 25% of the sampled vectors. Cellulose, plastics, and rubber degrade with a probability of 25%. The preliminary sensitivity analysis report (Helton, 1996) lists this parameter as the largest influence on the variation of total calculated release from the WIPP repository.

The documentation supporting this parameter does not contain any numerical justification for the probabilities assigned to this parameter. All of the hand calculations performed to calculate the gas generation parameters are included as attachments to the memo of Wang and Brush (1996). Calculations for the degradation probabilities are absent from these attachments. It is the opinion of EEG that the numerical value of this parameter constitutes expert judgment. Given the importance of this parameter to the estimates of radionuclide release, this parameter should be demonstrated to be either solidly based on scientific evidence or to be conservative. The justification for this parameter presented in support of the CCA does neither of these.

The numerical values of the degradation probability parameter should undergo peer review

consistent with expert judgment. Otherwise, the parameter should be conservatively set to always specifying microbial degradation of cellulose, plastics, and rubber.

EEG assessment of DOE's response

The parameter used to set the probability of microbial degradation in the CCA calculations is not derived analytically but instead was a result of interpretations that constitute expert judgment. The EEG suggested that the probability of microbial degradation should undergo peer review as parameter obtained using expert judgment. It was suggested that without this peer review the microbial degradation parameter should be set to always specifying microbial degradation of cellulose, plastics, and rubber. The EEG has been convinced by DOE's arguments that setting the parameter to always specifying microbial degradation of cellulose, plastics, and rubber is not appropriate. The central point remains that the probabilities used in the CCA calculations are a result of expert judgment. As such the parameter is required to be peer reviewed using the procedure outlined in 40 CFR Part 194.26. The conceptual model peer review does not meet the requirements outlined in the section.

557 If a single value for the consolidated waste permeability is to be used for direct brine release, then it should be 2.4×10^{-13} m^2 and not 1.7×10^{-13} m^2 . (II-H-25.8)

DOE's response to comment 557

The [waste permeability] value of 2.4×10^{-13} m^2 is both reasonable and is as technically correct as the 1.7×10^{-13} m^2 value. There has been no technical reason offered which would justify using the higher value instead. (II-H-45.5)

EPA's response to comment 557

EPA has examined information to support this parameter. EPA believes that a single value

instead of a probability distribution is justified for permeability. See EPATechnical Support Document for Section 194.23: Parameter Justification Report (Docket A-93-02, Item III-B-14), Section 5.19, for detailed discussion of the BLOWOUT, APORO parameter.

EEG assessment of EPA resolution of comment 557

Refer to EEG Chapter 2.4 for full explanation of EEG's concerns and responses.

Section 194.27 (CARD 27) Peer Review

ISSUE 27.A: EPA should look carefully at Peer Review conclusions

2 Our impression is that certain panels have performed a thorough and credible review, while others have not. Our recommendation to the EPA is to review the bases of findings of the panels and subject them to your own critical review by the EPA staff, contractors, or formally assembled peer review groups. (522) (II-H-12.1)

EPA's response to Issue A

EPA's audit of DOE's records did not result in any findings that substantially compromised the credibility of the process used to implement the peer reviews required by Section 194.22(b) or Section 194.27(a) (see "EPA Compliance Review" under 194.27(b) above). As stated in EPA's response to comments received on the proposed compliance criteria, "The Agency does not intend for peer review of DOE's activities to supplant or replace the Agency's review of compliance applications. . . Regardless of the recommendations or judgments made by the peer review groups, all decisions on the adequacy of the compliance application will be EPA's and EPA's alone" (Response to Comments Document for 40 CFR Part 194, pp.9-6 to 9-7). In other words, EPA

recognizes that peer review contributes to but does not supplant the Agency's independent review. EPA therefore considered peer review panels' findings in technical areas in conjunction with other information relevant to compliance. EPA's consideration of the scope and findings of the required peer reviews may be found in **CARD 22 – Quality Assurance, CARD 23 -- Models and Computer Codes, CARD 24 -- Waste Characterization, and CARD 44 -- Engineered Barriers**.

EEG assessment to EPA resolution of comment 2

It appears that discussions on several issues dealt by peer review groups may have been made without EPA's own analysis. An example is the new spallings code. The peer review accepted the conceptual model, without an actual testing of the code. The EEG found that after conducting a thorough sensitivity analysis with the codes, variations in several parameters may lead to conclude that the CCA spalled volumes are not conservative. If the EPA had conducted their own analysis, they too would have reached to the same conclusion. The same can be seen with the issue of actinide solubility or actinide partition coefficient (K_d).

Section 194.32 (CARD 32) Scope of Performance Assessment

ISSUE 32.A: The CCA does not adequately address the effect of fluid injection on the repository

12 The DOE has chosen "soon after disposal" to mean 50 years in the context of the fluid injection scenario. However, in the 1991 DOE elicitation of expert opinion on future activities in the vicinity of WIPP, one of the four teams addressed fluid injection and assigned probabilities of waste brine disposal associated with other industrial activities for

the full 10,000 years. Further, the probability of a large number of such injection wells, within the site was predicted to increase with time. (526) (II-H-12.5).

13 The discussion of fluid injection in Appendix SCR of the CCA is incomplete and largely incorrect. For example, Appendix SCR mentions gas injection for natural gas storage in the Morrow Formation but fails to mention natural gas storage in the Salado Formation. It is argued that the differences between the geology at WIPP and the Vacuum Field and Rhodes-Yates Field provide for more potential thief zones below the WIPP horizon in the event of water escaping the injection zone. However, field evidence strongly suggests that brine injection into the Bell Canyon below the WIPP horizon appears to be leaking into the Culebra aquifer above the WIPP horizon. The CCA provides no experimental evidence such as the measurement of water quantities in the anhydrite beds of the Salado Formation to support the CCA speculation. (527)(II-H-12.6)

14 The claim that there will no waterflooding on the scale of Rhodes-Yates is also undermined by field evidence. (528)(II-H-12.7)

15 While the Delaware sands, including those around the WIPP produce large volumes of water, they are nonetheless, technically and economically amenable to waterflooding as well as CO2 flooding. (529)(II-H-12.8).

16 The CCA-SCR notes that state regulations do not allow injection pressures to exceed the rock fracture pressure. However, that portion of the regulation applies to the target injection zone and not any overlying formations. The producing reservoirs near WIPP are greater than 7,000 feet. One consequence of greater vertical distance is that the surface injection pressure is automatically approved for 1,400 psi or 0.2 psi per foot. This corresponds to 2,400 psi at the WIPP horizon which is well in excess of the fracture pressure of the anhydrite beds in the Salado Formation.(531)(II-H-12.10).

17 Stoelzel and O'Brien consider only salt water disposal and assume an injection depth of 260 feet, a surface injection pressure of 850 psi, and a pressure at the WIPP horizon of 1,900 psi. However, pilot water flooding operations near WIPP are underway for reservoirs at 7,000 feet depth and have been approved to inject at a surface pressure of 1,400 psi, which in the event of communication, would exert a pressure of 2,400 psi at the WIPP horizon. Hence, the anhydrite beds in the Salado Formation would fracture, as successfully argued by Hartman and brine would migrate for miles in the inadvertent waterflooding hydro fracture scenario. (532)(II-H-12.11).

EPA's comment to Issue 32.A

DOE evaluated fluid injection in connection with the scope of the performance assessment but rejected the scenario on the grounds of low consequences. EPA evaluated DOE's Hartman Scenario and also performed an independent fluid injection analysis; see EPA Technical Support Document for 194.32: Fluid InjectionAnalysis (EPA 1997b). The results of these studies show that effective permeability in marker beds is probably lower than that used in the PA, and that other factors (such as injection rate, injection interval, etc.) also play a very important role in fluid injection. EPA agrees that under very unrealistic conditions, modeling can show fluid movement toward the WIPP under an injection scenario. These conditions include those modeled by Bredehoeft, such as steady state flow, two well scenarios, and pulsing flow. However, when modeling assumes more realistic but still conservative conditions, fluid movement sufficient to impact disposal performance of the WIPP does not occur.

In addition, EPA believes that geologic and hydrogeologic conditions in the Hartman area are different than in the WIPP area, which also precludes one-to-one comparison of conditions at the WIPP and at the Bates lease. For example, the Castile Formation is not present in the Bates area, but over 1,000 feet of Castile is present in the WIPP area. Also,

the present oil well completion practices in the Delaware Basin are substantially improved. Injection rate, pressure, target and fluid volume related regulations are different and are closely monitored by the state agencies. EPA concludes that the model representation in DOE studies, including two-dimensional analysis, appears to be appropriate for the intended use, because the model uses radial flaring in the z direction to capture compatible volume in the 360 o flow to compensate for 3D simulation.

EPA also requested (see Docket A-93-02, Item II-I-17) that DOE consider different factors in its fluid injection modeling (Stoelzel and Swift, 1997). Refer to the discussion in this CARD under 194.32(c). EPA concluded that DOE's initial modeling studies (Stoelzel and O'Brien, 1996) and supplemental modeling studies (Stoelzel and Swift, 1997 and Docket A-93- 02, Item II-I-36), together with EPA's own fluid injection analysis (EPA 1997b) all indicate that DOE's screening of fluid injection from consideration in PA is appropriate. EPA also notes that DOE considered waterflooding for the undisturbed (historical, ongoing, and near future time frame) and screened it from consideration based upon consequence. In so doing, DOE is not required by the Compliance Criteria to evaluate this FEP for the long-term future.

EEG Assessment to EPA Resolution of Issue 32.A

As discussed in Secion of 2.6 of this report, the EEG disagrees with the EPA on this issue.

ISSUE 32.C: The CCA does not adequately consider solution mining of potash

4 The CCA (Appendix MASS, p. 87) claims that the DOE is not aware of any ongoing solution mining in the Delaware Basin. However, that activity has been ongoing for

several decades in southeast New Mexico, including the Delaware Basin, to provide brine for oil field drilling operations. Furthermore, state records show fluid injection for solution mining of halite is expanding into areas closer to the WIPP to meet the needs of drilling activities in that area. (533)(II-H-12.12)

8 The CCA inappropriately eliminates solution mining for potash. DOE relies on current regulations which do not fully cover all scenarios, nor do they prevent solution mining for potash. (751) (II-H-32.12)

DOE's response to Issue 32.C

It is unlikely that potash mine operators in the vicinity of the WIPP will elect to use solution mining in the future, even once Sylvite deposits are fully mined out by conventional excavation methods, because conditions are economically unfavorable, as noted by Heyn (1997), a potash mine operator within the Delaware Basin. Points raised by Heyn (1997) are summarized below: (1) Solution mining requires heat to increase the ambient temperature of the injected water in order to increase the dissolved salt capacity of the brine. This is usually accomplished by taking advantage of geothermal heat found in deep wells or mines. Most solution mines are at depths in excess of 3,000 feet (910 meters). The potash ore bodies in the vicinity of the WIPP are less than 1,740 feet (530 meters) below the surface. Also, the cost of evaporation equipment to recover the potassium salts may be prohibitive. (2) Solution mining of the Sylvite ore bed in the vicinity of the WIPP would result in excessive solution of unwanted minerals and clays because the ore zone is too thin. Solution mining usually requires an ore bed thickness in excess of 10 feet. (3) Unavailability and cost of fresh water in the area would impede implementation of solution mining. (4) Potash ore reserves in the vicinity of the WIPP are too low in potash grade and the life expectancy of the mines is too low to justify the cost of constructing a solution mining refinery. Thus, it is likely that the potash bearing ore

zones in the vicinity of the WIPP will continue to be extracted using conventional room and pillar methods, rather than solution mining. (724)(II-H-24.19)

EPA's response to Issue 32.C

EPA agrees that the CCA did not appropriately treat solution mining of potash; however, DOE provided supplemental information concerning solution mining in response to public comments e.g., DOE, 1997i, 1997m, and Docket A-93-02, Items II-H-44 and II-H-45). DOE indicated that the target potash intervals for conventional room and pillar mining are Zones 4 and 10, which would also be the target horizons for solution mining. DOE concluded that the effects of solution mining relative to changes in overlying Culebra hydraulic conductivity are included in the modeled effects of room and pillar mining. The increase in hydraulic conductivity is related to the reduction in confining stress. Unless the mean confining stress is reduced to zero, the increase in hydraulic conductivity will be considerably less than what DOE has considered in PA. However, DOE indicated in supplemental information that solution mining is not likely in the vicinity of WIPP because fresh water for mining is limited and the overall procedure is cost prohibitive. Also, langbeinite, which is the primary target of extraction, is not readily soluble in water.

EPA noted that a permit is being sought for a pilot solution mining venture in the Carlsbad area. However, it is not possible to accurately predict the future possible minable zones if mining techniques are refined. Solution mining is presently not being done and may not take place in the future, and solution mining would likely include those horizons already included in the room and pillar mining modeling assumptions. With the supplemental information, EPA concludes that DOE has sufficiently addressed the potential effects of potash solution mining and that they were addressed within the scope of the PA.

EEG assessment of EPA response to Issue 32.C

EEG's responses to EPA are:

- EPA's conclusion that potash solution mining is not likely at WIPP relies on solicited comments that are factually incorrect and inconsistent with the published scientific literature.

- DOE and EPA maintain that excavation mining captures the effects of solution mining on the hydraulic conductivity of the overlying aquifers. However, based on the scientific literature, the prediction of subsidence above solution mines can be much more complex than the prediction of subsidence due to excavation mining. This issue needs to be reevaluated for the final rule for WIPP.

- Potash is a resource used for the production of food, therefore it appears to be incorrect to calculate a probability of mining based on past potash production which was inherently dependent on past mineral economics and the availability of high grade ore. It also seems reasonable to assume that low grade potash ores will eventually be mined to meet world demand.

ISSUE 32.D Potash reserve assumptions are contradictory and/or inadequate

8 The CCA claims credit for addressing the issue of potash mining. However, the CCA underestimates the areal extent of potash reserves and the potential impact of the excavation mining of potash within the site and on adjacent federal and state properties. The use of only existing releases adjacent to the site does not account for the currently economical potash reserves. . . Further, the Department of Interior notes that potash ore

has been and can be economically mined at ore concentrations less than current lease grade. (560) (II-H-25.11)

EPA's response to Issue 32.D

EPA concurs that the DOE and BLM minable footprints do not coincide. Relative to potash, the CCA indicated that only the 4th and 10th horizons are economic reserves, although remaining ore zones are considered resources that would be mined with advances in thin-seam extraction technologies. However, the minable footprint presented in the CCA on Figure 2-38 does not entirely match or coincide with the locations or information presented by Griswold in NMBMMR 1995. DOE provided supplemental information concerning the minable potash footprints, in response to stakeholder questions (Docket A-93-02, Item II-H-45). Although the minable footprints identified by DOE and Department of Interior differ, DOE concluded that this is due to the difference between the definition of "resources" and "reserves." (Reserves are hose resources that are currently economically recoverable with currently available technology, and resources are mineral deposits that are not currently economical or have not been discovered.) That is, DOE contended that their estimates were based on actual minable reserves, which are less pervasive than resources. However, DOE also contended that this approach is consistent with the intent of Section 194.32(b), which states that DOE must consider resources similar in quality and type to those currently extracted.

EEG assessment of EPA response to Issue 32.D

The EEG has conducted a sensitivity analysis pertaining to the extent of potash reserves within the controlled area. The conclusion is that with current models and the implementation of mining in those models (increase in effective transmissivity of the Culebra), the scenario has little effect. However, simply increasing the transmissivity within the Culebra does not account for all processes involved in subsidence due to mining, and other parameters, such as fracture width, or porosity may be significantly

changed. Therefore, the EEG concludes that a more accurate portrayal of mining should be included in the performance assessment, including extent and consequence.

ISSUE 32.I: Justification of FEPs screening

3 Operations involving the screening and other processing of FEPs are inadequately documented. 25% of the original FEPs list was eliminated with no documentation of the process; 70% of the remaining FEPs have essentially no more documentation than what appears in the CCA. The documentation for the other 30% also appears to be incomplete. The rationale for excluding many of the FEPs from the PA is not documented in the CCA. (559) (II-H-25.10)

EPA's response to Issue 32.I

In general, EPA found DOE's screening analyses and justifications for inclusion or exclusion of FEPs to be adequate. However, EPA determined that additional information or justification was necessary regarding certain FEP issues (e.g., dissolution, brine mining, solution mining, and fluid injection). Public comments also identified similar deficiencies in the screening analyses for some FEPs in the CCA. DOE provided supplemental information addressing EPA's questions and public comments (Docket A-93-02, Items: II-I-24, II-I-31, II-I-34, II-I-36, II-I-37). EPA reviewed the information and concluded that DOE's responses have adequately addressed all its concerns regarding FEPs and scenarios.

EEG assessment of EPA response to Issue 32.I

The EEG does not agree that the screening of FEPs in the CCA were adequate. The fluid injection scenario (Section 2.6 of this report), for example, addresses several concerns of the inadequacy by the DOE and EPA in their analysis. Also, arguments can be made on

the Air Drilling Scenario (Section 2.5) and issues surrounding production well ERDA-9 (Section 2.14).

Section 194.33 (CARD 33) Consideration of drilling events in performance assessment

ISSUE 33.B: The Performance should incorporate lower plug permeabilities

555. Borehole lifetime should be a sampled parameter in the CCA calculations or else the DOE should provide demonstration that variations in borehole lifetime do not effect [sic] the release estimates. (555)(II-H-25.6)

EPA response to Issue 33.B:

EPA reviewed natural borehole degradation processes and the subsequent effect of these processes on borehole permeability. Based on available information (e.g., WPO# 41131 and Appendix PAR, p. 192), EPA found that a constant value of permeability 10^{-14} m^2 throughout the regulatory period would not be conservative because of pressure buildup in the repository. The Agency believes that, primarily due to the solidification of drilling muds within the borehole in time, variations in the permeability of borehole plugs will occur and that a lower value of permeability would be more realistic than the constant and relatively high permeability value that DOE used.

EPA agrees that DOE gave little credit to factors that could sustain or enhance the potential effectiveness of plugs. Although DOE provided a combination of site-specific and theoretical justifications in support of plug parameter assignments, the assumed value of the plug permeabilities is subject to uncertainty and EPA determined that a modification of DOE borehole plug permeability values was necessary. EPA required that EPA-mandated PA simulations be conducted using lower permeability values (parameters used

in model- CONC_PLG maximum of 10^{-19} m^2, BH_SAND maximum of 5 x 10^{-17} m^2) to account for possible cases in which complete degradation does not occur throughout a well, or natural materials and mud provide additional layers with sealing properties.

EEG assessment of EPA resolution of Issue 33.B

The EEG suggested the borehole plug lifetime should be a sampled parameter based on two observations. 1) It is likely that the performance assessment calculations are sensitive to the assumed borehole plug lifetime. 2) Borehole plug lifetime is an uncertain parameter. The use of a constant value for borehole plug lifetime in all the calculations is inconsistent with DOE's guidelines for sampled parameters. Contrary to the assertion in the DOE response (II-H-46), the EEG did not argue that the estimate of 200 years is unreasonable.

The DOE (II-H-45) claims that borehole plug lifetime uncertainty is accounted for by assuming that two percent of the plugs are continuous (long-lived) and hence do not degrade (II-H-46). This claim is wrong.

The EEG recognizes that sampling borehole plug lifetimes would be impractical using the present performance assessment design. The DOE should investigate the influence of borehole plug lifetimes on repository conditions and assess the potential impact on CCDF calculations.

The EPA mandated verification test used a range of permeabilities of degraded boreholes that extended lower than the range used in the CCA calculations. The lowest permeability effectively limits flow through the borehole. The effect may have similar consequences to the effect on the repository conditions of long lived borehole plugs. Thus, the EPA mandated verification test may, in conjunction with the CCA calculations, provide a bound

on the influence of variable borehole lifetimes. This, however, is speculation and needs to be confirmed.

Issue 33.D: The estimated probability of intersecting a pressurized brine reservoir is adequately/inadequately justified, and E1 intrusions will not necessarily affect disposal system performance.

219. EEG finds no justification for assuming only eight percent probability of intercepting a pressurized brine reservoir in the Castile Formation, 800 feet below the repository. (219)(A-50 [II-H-12])

EPA response to Issue 33.D:

EPA found that DOE's representation of brine pocket occurrence probability in the CCA was not consistent with available information. EPA requested that the brine pocket probability be modified to range from 1 percent to 60 percent, and that it must be a sampled value rather than a fixed value of 8 percent. These values were used in the PA verification test (PAVT). Results of the PAVT indicated that the modified Castile Brine Pocket parameters increased releases (DOE 1997a, 1997b). However, the resulting PAVT CCDF curves, while closer to the EPA limit than PA CCDF curves, are still well below the EPA limits. EPA agrees that the E1 scenario does not always enhance radioactive releases in all instances. Refer to **CARD 14-- Content of Compliance Application** for further discussion of brine pocket probability.

EEG assessment of EPA resolution to Issue 33.D

There is poor justification for the 1% lower end of the EPA range for the probability of encountering a pressurized brine pocket. The 60% upper end is based on an electromagnetic survey of the WIPP site (US. DOE, 1996c, 2.2.1.2.2) that indicates brine

is likely under about 60% of the repository. Most importantly, the probability of hitting brine under WIPP should be based on WIPP, not the entire Delaware basin. The WIPP-12 brine reservoir is of sufficient size to protrude under the repository. The existence of boreholes around WIPP-12 that have not encountered brine in the Castile constrain the WIPP-12 reservoir so much that it is almost certain that the reservoir extends under the repository (II-H-25). The brine indicated by the electromagnetic survey must be part of the WIPP-12 reservoir. The probability of encountering brine should be modeled as 60%. The PAVT thus underrepresents the probability of encountering a brine reservoir.

Section 194.41 (CARD 41) Active Institutional Controls

ISSUE 41.B: DOE should provide specific commitments preventing human intrusion for 100 years

1 EEG recommends that EPA should require DOE to provide specific commitments on how they will prevent human intrusion for the first 100 years. As part of building a credible argument, the CCA should also take into account the pessimism of its own expert elicitation on the limited effectiveness of active institutional controls. (562) (II-H-25.13)

EPA response to Issue 41.B:

Upon preliminary review of the CCA, EPA requested that DOE provide specific commitments concerning AICs for the WIPP site, including fencing, signs, and site patrols (Docket A-93-02, Item II-I-01). DOE provided the requested information (Docket A-93-02, Item II-I-07, Enclosure 1c). DOE also described legal prohibitions on resource extraction and other activities at the WIPP site that function as AICs, such as the erection and testing of passive institutional controls and the implementation of the site monitoring plan.

DOE did not conduct an expert elicitation for the purpose of determining how long the proposed AICs specifically are expected to be effective. As EEG noted, an expert elicitation conducted prior to the promulgation of the final Compliance Criteria resulted in predictions of AICs' effectiveness generally (see A-93-20, Item II-H-25). However, DOE did not rely on these predictions in proposing that AICs will be completely effective for 100 years. EPA believes that it is fully within DOE's capacity to maintain the proposed controls for 100 years after disposal, is discussed under EPA Compliance Review for Section 194.41(a) above.

EEG assessment of EPA resolution to Issue 41.B

Title 40 CFR 191.14 (a) requires maintenance of active institutional controls for as long a period of time as is practicable after disposal, but the credit in performance assessment may not be taken for more than 100 years. The DOE has proposed controls for 100 years and has assumed no drilling in the repository for that period. The EEG agrees with the EPA's finding for this requirement, but recommends that if in the final rule EPA finds WIPP to be in compliance with the standards and proposes to grant certification, oversight by the federal (other than DOE) and state authorities should be required to ensure vigorous implementation of the active institutional control.

Section 194.43 (CARD 43) Passive Institutional Controls

ISSUE 43.B: DOE's proposal for PICs credit is or is not acceptable

5 Based on DOE's experience with institutional controls in the recent past, a claim of 99% credit for passive institutional controls for 700 years does not appear justifiable. (561) (II-H-25.12)

EPA response to Issue 43.B

EPA proposes to deny DOE's application for PICs credit for two reasons. First, DOE did not employ expert judgment to derive the credit. EPA stated in the preamble to 40 CFR Part 194 that "the degree to which PICs might reduce the future drilling rate can be reliably determined only through expert judgment" (61 FR 5232). Instead, DOE developed a proposal and submitted it to a peer review panel of three experts. EPA does not view peer review as equivalent to expert judgment. The Agency laid out explicit requirements for the conduct of expert judgment in Section 194.26.

Second, EPA found that DOE's analysis does not account persuasively for the uncertainty associated with the forecasting the effectiveness of PICs. EPA does not concur with the conclusion of the PICs peer review panel that DOE's proposed credit is reasonable. Among other issues, EPA considers DOE's assertion that every aspect of the PICs design is virtually certain to endure and be understood for the proposed period to be contrary to EPA's specification in Section 194.43(c) that "[i]n no case. . . shall passive institutional controls be assumed to eliminate the likelihood of human intrusion entirely" (61 FR 5243). This topic is discussed in greater detail in EPA Compliance Review for Section 194.43(c).

EEG assessment of EPA resolution of Issue 43.B

The EEG agrees with this determination of denying credit for PICs for reasons stated by the EPA in U.S. EPA (1997c), as well as for reasons that EEG has previously submitted to the EPA (see Appendix 8.2-Passive Institutional Controls).

Section 194.44 (CARD 44) Engineered Barriers

ISSUE 44.A: Borehole plugs, shaft seals, panel closure, and backfill should/should not be considered engineered barriers.

5 Shaft seals are at best an attempt to undo the damage done to the natural environment when the shafts were excavated, and therefore cannot be an engineered barrier as distinct and complementary to the natural barriers. (545) (II-H-12.24)

6 Like the shaft seals, panel closure systems (separation of waste panels by engineered structures) cannot be considered to be engineered barriers because they too can at best be imperfect attempts to restore the original natural system. Panel seal is not included in the examples of engineered barrier in EPA definition (Section 191.12). (546) (II-H-12.25)

7 The fact remains that the purpose of including MgO in the WIPP repository is to control the chemical conditions in the WIPP repository to allow assumption of lower actinide solubility values. It may therefore satisfy a need for the Containment Requirement of the Standards, but does not provide complementary added assurance visualized by the Assurance Requirements (40 CFR 191.14). (547) (II-H-12.26)

8 Since the stated requirements for plugging the boreholes (Section 3.3.4 and Figure 3-10 of the CCA) are much less stringent than the shaft seals, the borehole plugs have a lesser claim as engineered barriers. The NRC specifically excludes borehole seals as part of an engineered barrier system. Hence, the borehole plugs should not be considered to be an engineered barrier. (548) (II-H-12.27)

EPA response to Issue 44.A

Section 194.14(b)(1) required DOE to include in the description of the disposal system information about engineered barriers, i.e., "any material or structure that prevents or substantially delays movement of water or radionuclides toward the accessible environment," as defined at Section 191.12. The CCA treated panel seals, shaft seals, and borehole plugs as features of the disposal system design, and EPA evaluated them in that context. For a discussion of these features, see Section 194.14(b)(1) and Response to Comments in **CARD 14 – Content of Compliance Certification Application.**

For the purpose of complying with the assurance requirements at Section 194.44, DOE proposed to implement one engineered barrier -- magnesium oxide (MgO) backfill. EPA believes that DOE adequately demonstrated in the CCA and supplementary information that MgO will serve to prevent or substantially delay movement of water or radionuclides toward the accessible environment. For more discussion of the effectiveness of MgO backfill, see Section 194.44(a) above in this CARD, as well as Response to Issue C below.

EEG assessment to EPA resolution to Issue 44.A

Title 40 CFR 191.14 (d) requires use of both engineered and natural barriers in the repository design. The CCA proposed a chemically-buffering magnesium oxide backfill as the only engineered barrier, and the EPA has accepted in the proposed rule the DOE (U.S. DOE, 1996c) proposal to satisfy this assurance requirement. The EEG view is that while there are still some questions about the efficacy of the chemical buffer aspect of the magnesium oxide (MgO) backfill (see Appendix 8.4, section 2.3 of this report), this

engineered feature has been selected primarily to enable DOE to use numerical values of certain parameters in the containment requirement calculations. The MgO backfill may not therefore be considered to satisfy this assurance requirement in a strict sense of the philosophy of these requirements. Incorporation of backfill in the WIPP design is nevertheless a good idea and the EEG has been recommending a salt/clay mixture as backfill for years. A pure MgO backfill does not have the benefit of the chemical retardation of radionuclides that clays afford, but may help keep the repository chemical environment stable. The EEG would prefer addition of clays such as commercially available bentonite to the backfill, but is willing to accept emplacement of MgO backfill for the sake of operational ease and efficiency.

As to the distinction between “engineered barriers and “engineered features”, it is not based on the standard (40 CFR 191), or its criteria (40 CFR 194). The CCA (U.S. DOE, 1996c) included these “features” in the section on “engineered barriers”, hence the EEG comment.

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ACRONYMS

AEC	U.S. Atomic Energy Commission
ALARA	As Low As Reasonably Achievable
BIR	Baseline Inventory Report
CAG	Compliance Application Guidance
CAO	Carlsbad Area Office
CARD	Compliance Assessment Review Document
CCA	Compliance Certification Application
CCDF	Complimentary Cumulative Distribution Function
CH-TRU	Contact-Handled Transuranic
CRP	Cellulosics, Rubber and Plastics
DCCA	Draft Compliance Certification Application
DLR	Dewey Lake Redbeds
DOE	U. S. Department of Energy
DQC	Date Quality Characteristics
DRZ	Disturbed Rock Zone
EEG	Environmental Evaluation Group
EMP	Environmental Monitoring Plan
EOR	Enhanced Oil Recovery
EPA	U. S. Environmental Protection Agency
ERDA	Energy Research and Development Authority
HI	Human Intrusion
INEEL	Idaho National Engineering and Environmental Laboratory
IRG	International Review Group
IRT	Independent Review Teams
LANL	Los Alamos National Laboratory
LWB	Land Withdrawal Boundary

M&O	Management and Operations
MCLs	Maximum Concentration Limits
MMP	Minimum Miscibility Pressure
NAS	National Academy Science
NRC	National Research Council
NMOCD	New Mexico Oil Conservation Division
NEA/IAEA	Nuclear Energy Agency/International Atomic Energy Agency
OECD/IAEA	Organisation for Economic Cooperation and Development/International Atomic Energy Agency
OECD/NEA	Organisation for Economic Cooperation and Development/Nuclear Energy Agency
PA	Performance Assessment
PAVT	Performance Assessment Validation Test
PIC	Passive Institutional Controls
QA	Quality Assurance
QAPD	Quality Assurance Program Document
QED	Qualification of Existing Data
RTR	Real Time Radiography
RH-TRU	Remote-Handled Transuranic
SNL	Sandia National Laboratory
SWND	Southwestern Nash Draw
STP	Standard Temperature Pressure
SPM	System Prioritization Method
TRU	Transuranic
TWBIR	Transuranic Waste Baseline Inventory Report
USDW	Underground Source of Drinking Water
U.S. NRC	United States Nuclear Regulatory Commission
VE	Visual Examination
WID	Waste Isolation Division

WIPP	Waste Isolation Pilot Plant
WQSP	Water Quality Sampling Program
WWIS	WIPP Waste Information System

ENVIRONMENTAL EVALUATION GROUP

AN EQUAL OPPORTUNITY / AFFIRMATIVE ACTION EMPLOYER

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February 7, 1997

Mr. Frank Marcinowski, Director
Center for the Waste Isolation Pilot Program
U.S. Environmental protection Agency
Office of Radiation and Indoor Air
401 M Street SW
Washington, DC 20460

Dear Mr. Marcinowski:

At our January 21, 1997 meeting, you requested our comments on the WIPP Compliance Certification Application (CCA) now, because the end of the 120 day comment period on March 17 may be too late for you to seriously consider our comments in your deliberations on the CCA. We are therefore submitting our partial comments on the CCA at this time for your consideration.

The EEG has identified many specific issues in its evaluation of the WIPP-CCA. These issues can be grouped in the following broad categories:

- Lack of sufficient justification in disqualifying several features, events, and processes (FEPS) from consideration.

- Insufficient basis for selecting certain conceptual models and rejecting others.

- Incorrect estimation of probabilities of certain events.

- Insufficient justification or erroneous assumptions in assigning values for several input parameters.

The EEG has attended most of the meetings of the WIPP/CCA Peer Review Panels that were organized as required by 40 CFR 194.27. Our impression is that certain panels have performed a thorough and credible review, while others have not. Our recommendation to the EPA is to review the bases of findings of the panels and subject them to your own critical review by the EPA staff, contractors, or formally assembled peer review groups.

In reviewing the CCA, the EEG does not accept the arguments of "no consequence" to delete the otherwise plausible features, events and processes, and to justify incorrect values for certain input parameters. Such arguments, made on the basis of piecemeal, limited sensitivity analyses, may be misleading in projecting the relative importance of scenarios, conceptual models and input parameters for CCDF calculations. We strongly recommend that the EPA reject all such "no consequence" arguments and demand that a fresh set of calculations be performed after the EPA has examined the robustness of all the CCA assumptions regarding FEPs, conceptual models, numerical models, probability assignments, and input parameter values, and has provided alternative models and numbers to the DOE. This comment also applies to the recommendations of the peer review groups. The Conceptual Model Peer Review Group, for example, provides solid technical arguments for not accepting certain conceptual models advocated and used in the CCA, but then has found them acceptable on "no consequence" basis without providing sufficient explanation for such acceptance.

Comments on specific issues are enclosed. These are arranged as brief papers that can be read as stand-alone documents. We plan to submit additional comments to you in this format, as they are developed in the next few weeks.

Sincerely,

Robert H. Neill
Director

RHN:LC:js
Enclosures: EEG Reviews of the WIPP-CCA,
Plutonium Solubility
Chemical Retardation
Spallings Model
Fluid Injection
Brine Reservoir Assumptions
Engineered Barriers

cc: Ms. Jennifer Salisbury, NMEMNRD
Mr. Lindsay Lovejoy, Jr., NMAG
EPA docket for WIPP (A-9302)

CHEMICAL RETARDATION VALUES FOR THE CULEBRA

In the event of a borehole intrusion, the Culebra Aquifer, which lies 400 meters above the WIPP horizon, is one possible groundwater pathway for release of radionuclides to the accessible environment. Chemical retardation is expected to slow the transport of radionuclides through the fractured dolomite of the Culebra Aquifer. However, the DOE application has used values for estimating retardation coefficients that appear to lack justification.

Faced with a lack of field data and limited column test data for WIPP, the DOE CCA used retardation values from crushed rock samples in the laboratory to represent field conditions. Justification by the DOE is based on the following observations.

1) Sorption can occur in pores of various scales.

2) The surface area to volume ratio in crushed rocks sorption tests are similar to in-situ Culebra dolomite.

3) For long flow paths and long flow times radionuclides have sufficient time to diffuse into these pore spaces and sorb.

While EEG agrees that there appears to be a reasonable theoretical basis for using crushed rock, the EEG disagrees with the final data used in the CCA. Empirical sorption tests were done for all permutations of four types of brine; CO_2 levels of 0.033%, 0.24%, 1.4%, or 4.1%; and no, low, intermediate or high levels of organics. Because DOE plans to add M_gO as backfill, the fugacity of CO_2 in the repository is expected to be 10^{-7}. Thus, EEG discarded the results for CO_2 levels of 0.24%, 1.4%, and 4.1%. EEG also discarded results that did not meet DOE's own quality control criteria, and the results from a set of mechanistic sorption experiments because the dolomite was not from the Culebra. The average of the batch results formed the upper end of a uniform distribution.

Results from flow-through experiments using rock cores formed the lower end of the uniform distribution. In some cases, there was no radionuclide breakthrough at 300 days, so a minimum estimated K_d, assuming breakthrough at 300 days was used.

The DOE did not include the influence of organics on K_d values. In batch tests, even low concentrations of organics dramatically reduced K_d values. The impact of organics are included in the Kd values recommended by EEG.

The following tables show the Kd values used in the CCA, and the values suggested by the EEG using the criteria described above.

Table 1. K_ds used by DOE in CCA.

Oxidation State	Am	Pu	U	Th	Np
III	20 - 500	20 - 500			
IV		900 - 20000	900 - 20000	900 - 20000	900 - 20000
V					1 - 200
VI			0.03 - 30		

Table 2. K_ds recommended by EEG.

Oxidation State III, IV, V, VI	Am	Pu	U	Th	Np
	73 - 314	83 - 270	0.35 - 5	0.15 - 1.5	1.0 - 21

PLUTONIUM SOLUBILITY-EXPERIMENTAL MEASUREMENTS VERSUS CCA CALCULATED VALUES

Where brine has dissolved waste in the repository, direct drilling provides a vertical pathway for the long-lived actinides to return to the environment. Plutonium constitutes 87% of the initial radioactivity in the performance assessment calculations. Oxidation state is a factor that has an impact on the plutonium solubility. The DOE CCA assumes that the plutonium in the repository will be either at Pu(III) or Pu(IV), with 50% probability of one or the other. However, the solubilities are not measured for Pu(III) or Pu(IV). Rather, the solubility of Pu(III) is calculated using thermodynamic data for Nd(III) and the solubility of Pu(IV) is calculated using thermodynamic data for Th(IV).

While solubility experiments show that regardless of the initial oxidation state, Pu (VI) dominates at steady state conditions, it is not included in the performance assessment calculations. Pu(VI) has a high solubility in the conditions anticipated for the WIPP repository by the CCA.

The magnesium oxide backfill is anticipated to keep the repository at a pH of 10 and reducing. Reed et al. (1996) reported, that for brine at pH of 8 to 10, and reducing conditions, Pu(VI) is stable with an apparent solubility of 10^{-4} M. While it has been argued that corrosion of the steel drums would result in a reducing environment, Rao (1996) found that it was not possible to reduce Pu(VI) below Pu(V) despite adding more iron per unit mass of plutonium than could be expected in the repository, even assuming complete dissolution of the steel containers. Clark and Tait (1995) also concluded that Pu (VI) is stable in WIPP brines. Table 1. compares the calculated values used in the CCA and the measured values reflective of conditions anticipated in the repository.

Table 1. Solubility of plutonium as determined by calculations and experiments

Source of Brine	CCA calculations	Experiment, Reed et al.
Castile	5.7×10^{-9} M	8×10^{-5} M
Salado	4.4×10^{-6} M	9×10^{-5} M

The experimental evidence leads to the following conclusions:

1) Pu(VI) will be stable in the WIPP repository.

2) There is no support for the assumption that plutonium will stabilize in either oxidation state Pu(III) or Pu(IV).

3) The calculated results used in the DOE CCA are significantly different from experimental results for WIPP brines under anticipated repository conditions.

The EEG therefore recommends using the experimental values determined by Reed et al. (1996) shown in Table 1, for the CCA calculations.

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SPALLINGS MODEL

1. Critique of the Model Used in the CCA

For the purposes of the WIPP Compliance Certification Application (CCA) calculations, spallings refers to the entrainment of solid waste during the venting of high pressure gas from the repository in the event of a drilling intrusion. Spallings will occur when the roof of a waste room is penetrated by a drill, if the pressure in the room is sufficient to overcome the hydrostatic pressure of the drilling mud, about 8 MPa. Visual inspection of gas pressures calculated by the BRAGFLO code[1] indicates that over 80% of the undisturbed repository calculations predict pressures over 8 MPa after 10,000 years, with roughly 25-30% reaching this level in less than 1,000 years. The highest pressure calculated was nearly 16 MPa. The CCA calculations predict spallings to be a very important release mechanism. Spallings contributes to over 50% of the release estimates for human intrusion and was the largest form of release in over 10% of the calculated histories. The largest calculated release was less than, but within a factor of five, of the EPA normalized release limit for the 10% probability level.

The EEG finds the spallings model as used in the CCA to be inappropriate on three counts; 1) exclusion of brine from the spallings scenario, 2) the conceptual model of the spallings process, and 3) the experimental basis of the model validation. The spallings model is defined as gas driven entrainment of solid particles. The effect of brine in the waste panel is ignored. Brine may effect the spallings process in three ways. Capillary forces from low saturation may provide a binding force that inhibits spall which is conservatively ignored. Brine may also increase the effective driving force of the spall process increasing the amount of spall. In addition, the brine would contain radionuclides in solution. The CCA does include brine release from the penetration of the repository as a separate, longer term, two-phase flow calculation using repository conditions that are unmodified by the spall process. The spallings model should include the effects of brine.

For the spallings calculations, waste is assumed to be composed of uniform sized granules held together by a cohesive strength of 1 psi (0.007 MPa). The grain size is a sampled parameter in the CCA analysis. With the composition of the waste ranging from large pieces of metal to ash, it is unlikely that the waste will degrade to a uniform grain size. There has been no analysis to show that the releases calculated by sampling for a uniform distribution size bounds the releases from a heterogeneous medium.

Spalling can be viewed as a two step process. First, the explosive depressurization of the waste near the drill puncture, lasting a few seconds, followed by the erosion of channels through the waste by gas further from the puncture location, lasting hundreds of seconds. However, the spallings model includes only the second process. Two justifications are presented for ignoring the first process: 1) The pressure drop increase resulting from ejecting the drilling mud from the drill string is a relatively slow process, 2) the erosion process will proceed to a stable void

configuration independent of the initial entrainment. In other words, a larger initial spall will be followed by less erosion than a smaller initial spall, resulting in the same final void ratio. We find two errors in this argument: 1) The pressure difference between the waste repository and the hydrostatic pressure of the drilling mud can be over 6 MPa, three orders of magnitude above the pressure differential needed for explosive spall. 2) The second argument presupposes, without justification, that the erosion volume is larger than the initial spall volume and that the cavity caused by the initial spall will be partially filled by the erosion process.

The spallings model was validated by DOE using a set of bench scale experiments. A four inch high cylindrical cavity of 20 inches in diameter was supplied with high pressure gas through a plenum around the circumference. A vent of variable diameter was placed in the center of the top of the cylinder. The cylinder was filled with silica sand. The experiments were run by stepping the pressure maintained at the plenum. The pressure was held constant until no more material was entrained, then stepped to a higher value. These essentially steady state experiments do not encompass the highly transient spallings phenomena. The model tests the erosion portion of the spallings phenomena for waste with no cohesive strength, but not the initial explosive phase, nor the effect of cohesion. The inclusion of cohesive strength in the spallings model reduces the calculated spall mass by as much as two orders of magnitude. The attached figure shows the sensitivity of the model to waste strength assumptions. The figure presents plots of mass removed by spallings as a function of sampled particle diameter. Each plot represents the mass removed for an assumed waste strength. The waste strength is varied from 0 to 2 psi.

The experiments indicated increasing spall with increasing diameter of the vent. The spallings model does not include a sensitivity to scale leading the developers of the spallings model to state "Extrapolation of release volumes to WIPP, using the parameters evaluated using small scale laboratory models, has the potential for grossly under-predicting such releases[2].

In their initial review, the conceptual model peer review panel deemed the spallings model to be inadequate.[3] Subsequently, the DOE has reconvened the peer review panel twice to reassess the spallings model among others. The DOE presented additional information intended to demonstrate both the validity of the spallings model and the conservatism of the calculations. The peer review panel still considers both the model and the case for conservatism to be inadequate[4,5].

The EEG therefore recommends that further development of the spallings model be pursued. The spallings model should be validated by a set of experiments that adequately simulate the expected processes of spalling in the event of human intrusion into the waste repository. These experiments should include:

a) the effects of varying the brine saturation
b) investigation of the effects of heterogeneity
c) both the rapid depressurization and longer term erosion through channels
d) the effects of varying the waste strength

e) investigation of scale influences

2. Exclusion of Two Processes from the Spallings Model

Two potentially important processes, viz., the "gas erosion" and the "stuck pipe", considered by the DOE in earlier performance assessments[6], have been excluded from the CCA spallings model. These may occur if the gas flows into the drilling mud because the pressure in the repository exceeds the hydrostatic pressure of the drilling mud but the flow rate is insufficient to expel the mud from the drill string. These two phenomena could cause releases that are over an order of magnitude larger than the largest releases calculated in the CCA.

Waste permeability has a strong influence on the gas flow rate through the waste. At lower flow rates, the drilling mud may be able to wash the spall material from the drilling cavity. This is termed gas erosion. In the SPM-2 report[6], releases from 44 to 356 m^3 were considered possible from gas erosion. Compare this to the maximum calculated release of 4 m^3 in the CCA calculations[7]. If the amount of spall is above the carrying capacity of the drilling mud, then the spall will press against the drilling string, slowing the rotation of the drill bit. The normal response of a drilling crew in such circumstances is to raise and then lower the bit in order to clean out the cavity. In the SPM-2 report[6], releases from 43 to 238 m^3 were considered possible from stuck pipe type spall.

Gas erosion and stuck pipe have been excluded from the spallings model because the waste permeability assumptions of the CCA calculations are above the threshold for ejection of the drilling mud from the drill string. The SPM-2 report[6] assumed 10^{-16} m^2 to be the threshold permeability. However, this threshold is not well defined. It certainly is related to the pressure in the repository.

The CCA (Chapter 6, p. 6-100) states that simulated waste compacted under a lithostatic load yielded waste permeability in the range of 10^{-12} m^2 to 10^{-16} m^2. The CCA assigns the waste permeability as a constant at 1.7×10^{-13} m^2, as "representative of the average value of compacted waste." There is no indication that the effects of neglecting the permeability uncertainty on the CCA spallings model were considered[8].

The permeability of the waste is a critical parameter in determining the plausibility of these processes occurring. The value of the permeability should therefore be carefully chosen to reflect, as accurately as possible, the future conditions in the repository. If the potential cementation of the waste by magnesium chloride cement and salt precipitates is considered, the waste permeability may be even lower than the 10^{-16} m^2 lower band assumed in the SPM-2 report[6].

The Engineered Systems Peer Review Panel did not consider these processes or the validity of their deletion from the spallings model. They considered the waste permeability to be adequately determined for the BRAGFLO calculations, but did not consider its potential effect on these

processes, or the effect of MgO backfill in reducing waste permeability.

The EEG recommends that a more realistic value or a range of values should be assumed for the waste permeability parameter and potential for the "gas erosion" and the "stuck pipe" processes be included in the spallings scenario with a better defined permeability-pressure threshold.

References

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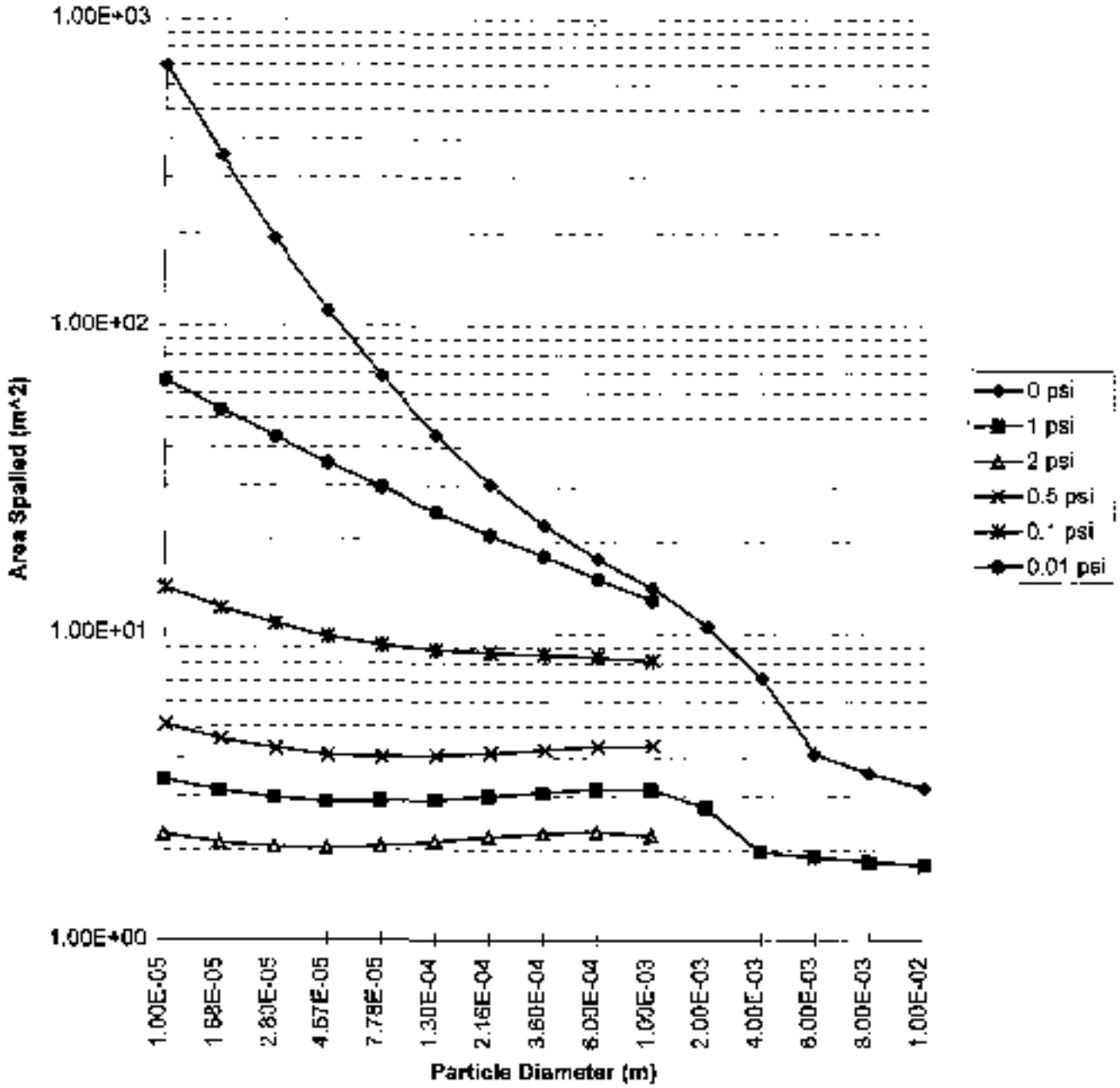

Spall area as a function of particle diameter and cementation strength
(Unpublished EEG Calculations Using CUTTINGS_S; Version PA98)

Environmental Evaluation Group Review of the WIPP-CCA, 2/7/97

BRINE RESERVOIR ASSUMPTIONS IN THE CCA

The EEG sees no justification for assuming only 8% probability of intercepting a pressurized brine reservoir in the Castile Formation 250 meters below the repository. The fatal flow in the CCA argument for 8% is the assumption that the oil and gas wells that did not report encountering brine did in fact not encounter a brine reservoir. The fact is that the drillers are not required to report brine encounters to the state or federal authorities and no mention would be found in the records unless undue delays or hazardous conditions are encountered.

The 8% probability also ignores the data from WIPP-12 and the TDEM survey over the repository. The borehole WIPP-12 is located north of the repository within the WIPP site. It was drilled to the bottom of the Salado Formation in 1978 and deepened in 1981 at the EEG's suggestion. The DOE contractor (Popielak et al., WIPP-TME-3153, 1983) estimated the volume of the reservoir to be 2.7 million m^3 (17 million barrels). For the maximum possible reservoir thickness of 24 meters, the surface footprint of a cylinder containing this volume would have a diameter of more than 3 km. As the attached figure shows, the WIPP repository is most likely underlain by the brine reservoir encountered by WIPP-12. In addition, the TDEM survey (SAND 87-7144) gives an indication of the presence of brine at the upper Castile horizon. To try to assign specific areas of the presence of brine from this geophysical survey would be over-interpretation of the geophysical data. Combination of the WIPP-12 data and the results of the TDEM survey indicate the existence of brine under the repository. Any borehole drilled into Castile under the repository should therefore be assumed to encounter brine.

The EEG does not find the CCA reservoir volume assumption of 32,000 to 160,000 m^3 to be justified. This is based on the assumption of depletion of reservoirs by future drillers - 100% probability of encounter for the depletion assumption, while only 8% for releases!

The attached table shows the comparison between the characteristics of the WIPP-12 brine reservoir and the CCA assumptions.

The WIPP site was moved twice; in 1975 after the borehole ERDA-6 encountered a brine reservoir, and again in 1982, after WIPP-12 encountered brine. The CCA assumptions of probability should be realistically based on the site specific information, and the characteristics should be based on the WIPP-12 experience.

The DOE Conceptual Model Peer Review Panel, in their December 1996 report, essentially agrees with the EEG position, but has accepted the DOE position that there is no significant consequences of the probability and volume assumptions.

The EEG does not accept the "no consequence" argument that is based on piecemeal, partial sensitivity analyses.

Comparison of WIPP-12 Brine Reservoir and the CCA Assumptions

Parameter	WIPP-12 (m^3)	CCA (m^3)
Total Reservoir Volume	2.7×10^6 (a)	32,000 to 160,000 (d)
Projected Max. Artesian Flow	55,821 (b)	5,200 (e)
Flow to Surface During Drilling	4,306 (c)	400 to 2,100 (f)

(a) WIPP/TME-3153, p. H-54
(b) WIPP/TME-3153, p. H-55
(c) WIPP/TME-3153, p. H-9; Actual "unavoidable" flow
(d) DOE/CAO-1996-2184, Table 6-26
(e) CMPRR-Suppl., 12/1996, p. 42; To the Culebra, after 6 encounters
(f) CMPRR-Suppl., 12/1996, p. 42; In 10,000 years

ERDA-6 ●

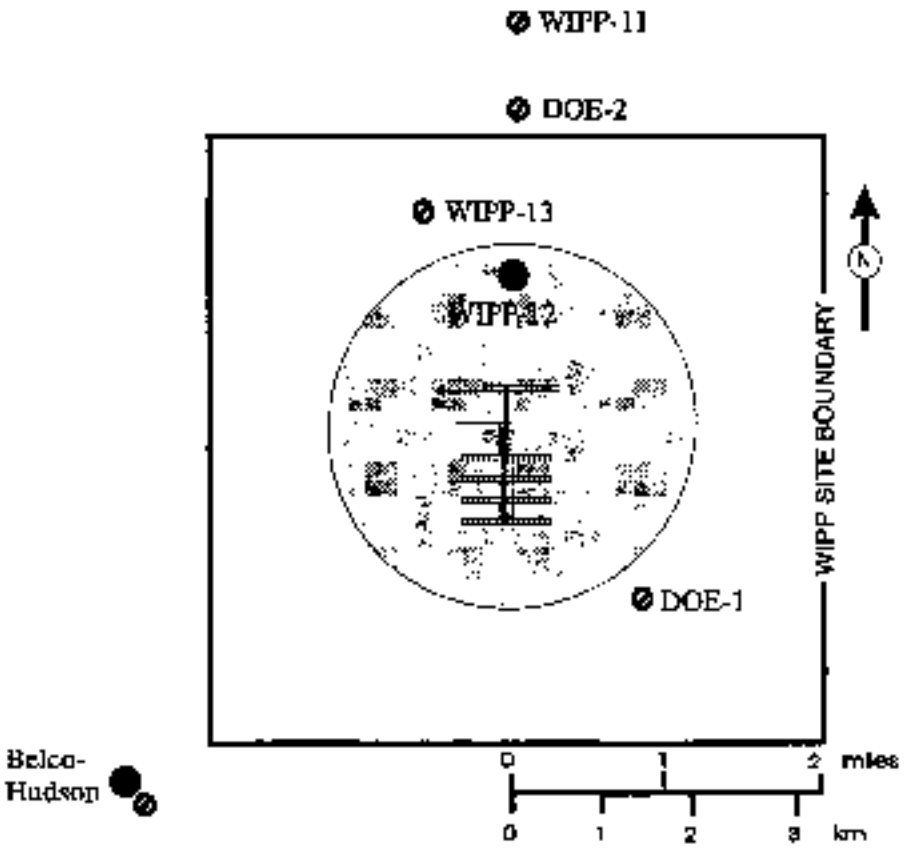

● Record of brine encountered in the Castile

⊘ No record of brine encountered in the Castile

Potential extent of the brine reservoir encountered by WIPP-12

Potential extent of WIPP-12 brine reservoir using WIPP-12 pressure recovery data, rock compressibility of $1x10^{-10}Pa^{-1}$, and reservoir thickness of 24 meters.

ENGINEERED BARRIERS FOR WIPP

The EPA regulations require engineered barriers to be included in the repository design as an Assurance Requirement (40 CFR 191.14d and 40 CFR 194.44). The philosophy of the Assurance Requirements is clearly stated in the "Overall Approach of the Final Rule" (Federal Register v. 50, no. 182, p. 38072), as follows:

> In contrast to the containment requirements, the assurance requirements were developed from that point of view that there may be major uncertainties and gaps in our knowledge of the expected behavior of disposal systems over many thousands of years. Therefore, no matter how promising the analytical projections of disposal system performance appear to be, these materials should be disposed in a cautious manner that reduces the likelihood of unanticipated types of releases. Because of the inherent uncertainties associated with these long time periods, the Agency believes that the principles embodied in the assurance requirements are important complements to the containment requirements that should insure that the level of protection desired is likely to be achieved.

With respect to the engineered barriers as an assurance requirement, the "Overall Approach of the Final Rule" states:

> Designing disposal systems to include multiple types of barriers, both engineered and natural, reduces the risks if one type of barrier performs more poorly than current knowledge indicates.

The CCA (Sec. 3.3) describes four types of engineered barriers in the design of the WIPP disposal system: (1) Shaft Seals, (2) Panel Closures, (3) Backfill around the waste, and (4) borehole plugs. EEG does not consider either of these to be engineered barriers, for the following reasons:

Shaft Seals

Shaft seals are at best an attempt to undo the damage done to the natural environment when the shafts were excavated, and therefore cannot be considered to be an engineered barrier as distinct and *complementary* to the natural barriers.

Note that the 40 CFR 191.12 definition of a "Barrier" includes the following examples of engineered barriers, but does not include "shaft seals".

> ... A canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around waste, provided that the material or structure substantially delays movement of water or radionuclides.

The repository standards for the high-level nuclear waste repository (10 CFR 60) specifically exclude shaft seals from engineered barrier system. "Engineered Barrier System" is defined in 10

CFR 60.2 as:

> *Engineered barrier system* means the waste packages and the underground facility.
>
> and
>
> *Underground facility* means the underground structure, including openings and backfill materials, but excluding shafts, boreholes, and their seals (underline added).

Panel Closures

Like the shaft seals, panel closure systems (separation of waste panels by engineered structures) cannot be considered to be engineered barriers because they too can at best be imperfect attempts to restore the original natural system. Panel seal is not included in the examples of engineered barrier in the EPA definition (40 CFR 191.12).

The Marker Bed 139 lies directly below the WIPP repository and is connected to the floor of the waste rooms through extensive fractures, floor upheaval and milling of the floors. Water (with anomalous lead content acting as a tracer) seeping down from the exhaust shaft has moved 400 ft through the marker bed from the base of the air exhaust shaft to the waste handling shaft in a short period of time during 1995-96. This pervasive marker bed would not allow effective separation of the panels unless the entire floor of the repository is dug down 10 ft and grouted.

According to the CCA (p. 3-27, lines 19-20), "The panel closure system was not designed or intended to support long-term repository performance." How then can it be considered an engineered barrier for the long-term performance?

Backfill Around the Waste

The DOE plans to put sacks of magnesium oxide (MgO) over and around the waste drums to try to control the future chemical conditions in the repository. The expectation is that MgO will react with the carbon dioxide (CO_2) that is produced from microbial action in the repository. Removal of CO_2 will result in alkaline conditions in the repository. Since the experimentally determined solubilities of radionuclides are lower in alkaline (high pH) conditions, the emplacement of MgO and its postulated effect allows assumption of lower solubility values in the CCA. This assumption results in lower postulated releases to the accessible environment and thus helps in showing compliance with the Containment Requirements (40 CFR 191.13) of the EPA Standards.

Since the publication of the CCA, the DOE has argued that the MgO is not needed for showing compliance with the Containment Requirements because the mean CCDF without MgO, although showing higher releases than "with MgO", still is within the compliance limits. Such an argument is based on a partial calculation without altering other assumptions and input parameters, and therefore appears meaningless. The fact remains that the purpose of including MgO in the WIPP

repository is to control the chemical conditions in the WIPP repository to allow assumption of lower actinide solubility values. It may therefore satisfy a need for the Containment Requirement of the Standards, but does not provide *complementary* added assurance visualized by the Assurance Requirements (40 CFR 191.14).

Borehole Plugs

Since the stated requirements for plugging the boreholes (Section 3.3.4 and Figure 3-10 of the CCA) are much less stringent than the shaft seals, the borehole plugs have a lesser claim as engineered barriers than the shaft seals. The EPA Standards (40 CFR 191.12) do not include borehole plugs as an example of engineered barriers. The NRC specifically excludes borehole seal as part of an engineered barrier system (see the quote under Shaft Seals section above). Hence, the borehole plugs should not be considered to be an engineered barrier.

Incidentally, Figure 3-9 ("Approximate Locations of Unplugged Boreholes") does not include two deep abandoned oil and gas wells that are located within the WIPP site: Badger Unit Federal in Section 15 (between WQSP-3 and H-5 in the northwest part of the WIPP site), and Cotton Baby Federal in Section 34 (east of H-11 in the southeast corner of the WIPP site).

Recommendation

The EEG has recommended a multi-barrier approach for WIPP since the beginning of the project. The EPA regulations also require such an approach as "assurance requirements". According to the WIPP Safety Analysis Report (App. A), 88% of the WIPP bound waste is planned to be processed. At the least, the DOE should take credit for such reprocessing in the WIPP performance assessment and the CCA. EPA should encourage DOE to process the waste to make it insoluble.

<u>Enclosure</u>:
Information from the draft 1996 WIPP SAR

Information from the draft 1996 WIPP SAR
Appendix A, page A-4 to A-15
Data is from final row of cumulative values for each waste form

Stored Drum Equivalents

Final Waste Form	**Not Processed**	**To Be Processed**	
Combustible	4194	23570	
Filter	976	72	
Graphite	616	1845	
Heterogeneous	6355	104300	
Inorganic Non-metal	1168	12911	
Lead/Cadmium Metal	83	31	
Salt Waste	34	68	
Soils	95	1862	
Solidified Inorganics	15651	30670	
Solidified Organics	1077	3311	
Uncategorized Metals	3348	48751	
Unknown	129	188	
Various	0	20105	
Subtotal of column	**33726**	**247684**	Total stored **281410**
Percent of Total Stored	**11.98%**	**88.02%**	

Notes from the 1996 draft SAR
Final SAR Expected late Jan. 1997
W.T. Bartlett 1/21/97

Environmental Evaluation Group review of the WIPP-CCA, 2/7/97

FLUID INJECTION AND SOLUTION MINING

The EPA Requirement and the CCA

The EPA criteria (40 CFR 194.32 c) requires an analysis of the effects of fluid injection activities on the disposal system, prior to disposal and soon after disposal. The CCA has screened out the fluid injection scenario within the site on a "regulatory basis" and adjacent to the site on the basis of "no consequence" and has provided a number of arguments why it should not be considered in the performance assessment for WIPP. This paper is a critique of the CCA arguments contained in Chapter 6 and Appendix SCR. The EEG has reviewed the Stoelzel and O'Brien[1] assumptions (discussed in the CCA and later in this paper), and finds the critique by John Bredehoeft[2] (enclosed) to provide additional compelling arguments for not accepting that analysis to be valid. A copy of a consequence analysis by John Bredehoeft[3] is also enclosed. This preliminary analysis clearly establishes the importance of considering the fluid injection scenario in predicting the near-term and long-term integrity of the WIPP repository.

How Long in the Future?

The DOE has chosen "soon after disposal" to mean 50 years in the context of the fluid injection scenario. However, in the 1991 DOE elicitation of expert opinion[4] on future activities in the vicinity of WIPP, one of the four teams addressed fluid injection and assigned probabilities of waste brine disposal associated with other industrial activities for the full 10,000 years. Further, the probability of a larger number of such injection wells, within the site, was predicted to increase with time (Ref.4, Table IV-16).

With respect to natural resource recovery activities surrounding the WIPP, the surrounding public lands are managed by either the Federal Government or the State of New Mexico. In addition to federal law, state and federal agencies know that this is a resource rich area and have developed additional policies for the effective recovery of these resources consistent with federal and state law. The Federal Land Management and Policy Act[5] states that public lands and resources are utilized to "meet the present and future needs of the American people" and take into account the "long term needs of future generations." This federal law does not limit consideration of natural resources on public lands to "near future" nor to "existing leases." On the contrary, federal agencies such as the Bureau of Land Management have explicitly argued that lessees can plan and submit plans for resource recovery activities outside their actual leases[6].

Review of Appendix SCR Arguments

The discussion of fluid injection in Appendix SCR of the CCA is incomplete and largely incorrect. For example, Appendix SCR mentions gas reinjection for natural gas storage in the Morrow Formation but fails to mention natural gas storage in the Salado Formation. It is argued that the differences between the geology at WIPP and the Vacuum Field and Rhodes-

Yates Field provide for more potential thief zones below the WIPP horizon in the event of water escaping the injection zone. However, field evidence strongly suggests that brine injection into the Bell Canyon below the WIPP horizon appears to be leaking into the Culebra aquifer above the WIPP horizon (see the discussion in Ref.7, section 3.1.6). Further, the CCA provides no experimental evidence such as the measurement of water quantities in the anhydrite beds of the Salado Formation to support the CCA speculation.

The claim that there will be no waterflooding on the scale of Rhodes-Yates is also undermined by field evidence. The proposed waterflood at the Avalon Unit will recover 8.2 million barrels of oil by injecting 141 million barrels of water for forty years through nineteen injection wells into the Cherry Canyon and Brushy Canyon members of the Delaware Mountain Group. At Rhodes-Yates, approximately 41 million barrels of water were injected through eighteen injectors over a 26 year period. Further, the pressure maintenance wells at the Cabin Lake Unit, at the northwest corner of the WIPP Site are injecting 1.4 million barrels of water per year compared to 200,000 bbls water that were injected per year through the two pilot pressure maintenance wells at Rhodes-Yates.[7]

The CCA Appendix SCR argues that waterflooding on the same scale as the Vacuum or the Rhodes-Yates Field is unlikely because oil pools in the vicinity of the WIPP are characterized by channel sands with thin pay zones, low permeabilities, high irreducible water saturations, and high residual oil saturations. However thin pay zones tend to maximize vertical sweep efficiency and have a history of successful waterflooding throughout the United States, including the Delaware Basin. "Low" reservoir permeabilities of oil reservoirs near the WIPP area has not detered waterflooding in the mature oilfields of the Delaware Basin. Further, mature oil fields in the Delaware Basin have responded favorably to carbon dioxide flooding. The observation of high irreducible water saturations is irrelevant. A waterflood is not designed to reduce the water saturation. A waterflood designed to reduce the oil saturation and increase water saturation in the reservoir by producing the oil. The CCA comment on high residual oil saturations does not speak to the economics of waterflooding. While the Delaware sands, including those around the WIPP, produce large volumes of water, they are, nonetheless, technically and economically amenable to waterflooding[7,8] as well as CO_2 flooding[7,9,10,11,12].

The CCA-SCR cites New Mexico state regulations as also protecting the WIPP. However, the emplacement of a salt isolation string is not intended to address the needs of a 10,000 year nuclear waste repository. It is required to meet the near term safety concerns of the potash industry[13]. Further, even oil and gas wells equipped with a salt isolation string are restricted from drilling through potash reserves or near potash mining operations. With respect to brine injection wells, the potash companies and oil companies have documented their concerns[14,15,16].

The CCA-SCR notes that state regulations do not allow injection pressures to exceed the rock fracture pressure. However, that portion of the regulation applies to the target injection zone

and not any overlying formations. The producing reservoirs near WIPP are greater than 7000 feet. One consequence of greater vertical distance is that the surface injection pressure is automatically approved for 1400 psi or 0.2 psi per foot. This corresponds to 2400 psi at the WIPP horizon which is well in excess of the fracture pressure of the anhydrite beds in the Salado Formation.

As to state regulations in general, state regulations for fluid injection have been in place for decades. Documented problems with fluid injection projects throughout southeast New Mexico identifies the limitations of state regulations. In the case of waterflood brine migrating through the Salado and damaging another oil company property, there is litigation and monetary compensation[17,18]. In the case of a nuclear waste repository, there are performance assessment calculations. However, the CCA does not include this scenario in the performance assessment calculations.

Stoelzel and O'Brien Model

The fluid injection scenario on adjacent properties for the near future has been screened out by the DOE citing low consequence as determined from calculations by Stoelzel & O'Brien[1]. It should be noted that a two dimensional, vertical model was used. Further, the assumptions used in the calculations (DOE SCR) either underestimate or fail to consider hydraulically fractured Salado anhydrite permeability, permitted surface injection pressures in the vicinity of WIPP, injection pressure gradients, the volume of disposal brine that is typically injected by oilfield operations, and the anticipated time of fluid injection activities.

The model assumes a total of $7x10^5$ cubic meters of brine was injected during a fifty year period. This is equivalent to 4.4 million barrels of brine. The David Ross AIT Federal #1 salt water disposal well, which is less than a mile from WIPP, alone has injected more than 5 million barrels brine in five years of operation. And there is no basis for assuming that industrial fluid injection will not continue for the full 10,000 years.

Stoelzel and O'Brien consider only salt water disposal and assume an injection depth of 4260 feet, a surface injection pressure of 850 psi, and a pressure at the WIPP horizon of 1900 psi. However, pilot waterflooding operations near WIPP are underway for reservoirs at 7000 feet depth and have been approved to inject at a surface pressure of 1400 psi, which in the event of communication, would exert a pressure of 2400 psi at the WIPP horizon. Hence, the anhydrite beds in the Salado Formation would fracture, as successfully argued by Hartman[17] and brine would migrate for miles in the inadvertent waterflooding hydrofracture scenario.

Solution Mining

In 1979 the EEG recommended[19] that the DOE consider solution mining for salt as an intrusion scenario. The CCA (Appendix MASS, p. 87) claims that the DOE is not aware of

any ongoing solution mining in the Delaware Basin. However, that activity has been ongoing for several decades in southeast New Mexico, including the Delaware Basin, to provide brine for oilfield drilling operations. Furthermore, state records show that fluid injection for solution mining of halite is expanding into areas closer to the WIPP to meet the needs of drilling activities in that area.

As to future mining of potash, solution mining is the only method that can be reasonably predicted for the Carlsbad District[20]. In Canada and the United States, solution mining is used for recovery of sylvite. Langbeinite is not readily soluble. So if solution mining is employed in the vicinity of the WIPP Site, it will be to recover only sylvite. While no specific plans have yet been formulated,

all mines in the Carlsbad area have held open the option of using solution mining once their sylvite deposits are fully mined out. The concept would rely on the fact that the open spaces left over from mining would allow ore remaining in pillars to be recovered[20].

How can the CCA reject the solution mining scenario, if private companies surrounding the WIPP site are holding the option of using solution mining?

EEG Recommendations

Based on a technical analysis of available information, the EEG recommends that the CCA include the effect of fluid injection and all other resource recovery activities for future and existing wells drilled within the site and adjacent to the site. These activities should include:

- Waterflooding for enhanced oil recovery.
- Carbon dioxide flooding for enhanced oil recovery.
- Salt water disposal from oil production and other industrial activities.
- Solution mining for halite and sylvite.

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Enclosure:

Bredehoeft Memoranda dated January 10, 1997 and January 14, 1997

The HYDRODYNAMICS Group
studies in mass and energy transport in the earth

JOHN BREDEHOEFT *PhD, NAE*
principal

January 10, 1997

MEMORANDUM

To: **Lindsay Lovejoy, Jr.**

From: **John Bredehoeft**

Subject: **Hartman Scenario**

Hartman Scenario—Introduction

The so-called Hartman Scenario is based upon a law suit in the Delaware Basin. In 1991, Hartman, an independent oil operator, attempted to drill a well on the Bates lease approximately 2 miles from the Rhodes Yates water-flood project operated by Texaco. The Hartman #2 Bates well encountered brine at a depth of 2240 feet; the drilling had to be terminated at 2280 feet. In 1953, the Bates #1 well was drilled without encountering pressurized brine.

Water flooding was started in the Rhodes oil field in 1959. Texaco initiated a pilot water flood in 1964. The water flood was extended in the Rhodes field in 1974. There are several active water flood projects in the Rhodes Yates area.

I reanalyzed the Hartman Scenario. In doing so, I first estimated the transmissivity of the Bates # 2 well that flowed extensively. From the transmissivity, I estimated the permeability. This should be obvious, but we are not totally sure what constituted the permeable zone in the Bates # 2 well. I then: 1) compared this estimate of permeability with those measured at WIPP, and 2) estimated the inflow to WIPP should the permeabilities at the Bates # 2 site apply in the vicinity of WIPP.

Transmissivity & Permeability

The Bates # 2 well flowed 840 gpm, or 1.9 cubic feet per second (cfs). The shut-in pressure at the land surface was 1000 psi—approximately 2000 feet of head at the land surface (Van Kirk, 1994). Knowing both the flow rate and the well-head, shut-in pressure there are several methods that can be used to estimate permeability. I first used the Theim, steady-state solution for radial flow to a well and solved for transmissivity, T. I then compared this result to results from two other estimating procedures.

The difficulty with the Theim approach is that we do not know how far out the cone of depression for the Bates # 2 well extended. (We can define the other boundary of the cone as the point where the drawdown caused by flow to the well is negligible.) I assumed several different radial distances for the extent of the cone (r_2), and make the calculations. The differing radial distances bracket the cone. As we see, the estimates do not vary a great deal—by a factor of only two which is small in estimating transmissivity.

$$T = 2.3\, Q \log (r_2/r_1)/[\, 2\pi (s_2 - s_1)]$$

where T = transmissivity

Q = well production rate

PO Box 352 (234 Scenic Dr) La Honda, CA 94020 (415) 747-0441/747-0273 fax jdbrede@aol.com
web site: www.mediacity.com/~hydrogup

r_2 and r_1 are selected radial distances from the center line of the well bore. I chose r_1 at the wall of the borehole approximately 0.5 ft (1 foot diameter well bore—slightly larger than the drill bit). I let r_2 be the radial extent of the cone of depression—the distance at which the drawdown is negligible.

(s_2 - s_1) is the total drawdown within the cone of depression caused by the well—1000 psi. (Perhaps I need to amplify this explanation. When the well is flowing the pressure at the well head is atmospheric—which is generally defined as 0. The well head, shut-in pressure gives a us an indication of what the formation pressure would be without the well flowing. The total pressure drop when the well is flowing is 1000 psi. It could be smaller due to friction losses in the well bore —a smaller pressure drop gives a higher estimate of permeability. The total pressure drop across the cone of depression is also 1000 psi.)

I assume the brine produced a pressure of 0.5 psi per foot of brine. (Van Kirk, 1994, reports the normal pressure gradient for saturated salt water as 0.525 psi per foot; I simplified the calculation by rounding to 0.5 psi / ft.)

With r_2 = 1,000 ft.

$T = 2.3 \times 1.9 \times \log(1{,}000.0 / 0.5) / (2\pi \times 2000.0) =$ 0.0011 ft^2/sec

With r_2 = 10,000 ft

$T = 2.3 \times 1.9 \times \log(10{,}000.0 / 0.5) / (2\pi \times 2000.0) =$ 0.0015 ft^2/sec

With r_2 = 100,000 ft

$T = 2.3 \times 1.9 \times \log(100{,}000.0 / 0.5) / (2\pi \times 2000.0) =$ 0.0018 ft^2/sec

With r_2 = 1,000,000 ft

$T = 2.3 \times 1.9 \times \log(1{,}000{,}000.0 / 0.5) / (2\pi \times 2000.0) =$ 0.0022 ft^2/sec

We can also estimate the transmissivity using estimating procedures suggested by Theis et al. (1963) for pumped wells, and by Bredehoeft et al. (1983) for flowing wells. The specific capacity is 0.4 gpm per foot of drawdown, or 0.00095 ft^2 / sec per foot of drawdown. The Theis estimate yields:

T = specific capacity x 2000 (in units of gallons per day per foot)

T = 0.4 x 2000 = 800 gallons per day per foot = 0.0012 ft^2/sec.

Bredehoeft et al (1983) produced a graphical type curve: use of the Bredehoeft et al. method yields:

T = 0.0015 ft^2/sec

The estimates compare favorably; the values vary by only a factor of two. Since transmissivity can vary over 15 orders of magnitude, a factor of two variation (100%) in the estimates is considered quite good.

The permeability is less clear, only because we do not know through what vertical thickness of rock brine flowed. The drilling encountered brine at a depth of 2240 feet, and was stopped by too much flow at 2280. Assuming the entire 40 feet was permeable, the

	k = T/ thickness = 0.001 / 40.0 =	0.000025 ft/sec
or	k =	0.00075 cm/sec
	k =	0.75×10^{-12} m^2

Implications of the Analysis—Comparison to WIPP

It should be remembered that these numbers are estimated by applying a model for radial flow to/from a well. The estimate is some kind of an average permeability that applies to the entire cone of depression for the well. In other words, it is an estimate of the regional permeability within the assumed cone of depression.

The permeability of the Anhydrite marker beds was measured in-situ at WIPP. The range in anhydrite marker bed permeability data used in PA is

k anhydrite– undisturbed	7.94×10^{-18} m^2 to 10^{-21} m^2
k anhydrite—hydro-fracture maximum value (PA)	10^{-9} m^2
Hartman— Bates # 2	7.5×10^{-13} m^2

The permeability encountered in the Bates # 2 well almost surely represents hydro-fractured anhydrite in the Salado Formation. The shut-in pressure of the Bates well was 1000 psi at land surface. There were reports of oil field brine injection activities in the area with 1000 psi land surface pressures and higher (Van Kirk, 1994). Dennis Powers reported: *"For the Rhodes Yates water flood, the injection pressure at the surface ran 1200 psi and above. Some injection pressures approached 2,000 psi at the surface." (Silva, 1994, p. 67)* A pressure of 1000 psi at land surface is approximately lithostatic at a depth of 2000 feet.

The consensus interpretation of what happened in the Rhodes Yates area is that water injection at high pressure caused massive hydraulic fracturing within the Salado Formation. Numerous wells have encountered flows of water in the Salado (Van Kirk, 1994). The hydraulic fracturing has increased the Salado permeability on a regional scale. Hartman won his law suit on the basis of this hypothesis. This interpretation is consistent with our analysis of the permeability encountered in the Bates # 2 well.

Potential Flow to WIPP

It is of interest to calculate the flow to WIPP through the anhydrite marker beds. I will do two calculations with 1) unfractured anhydrite, and 2) hydro-fractured anhydrite. I will use a simplified model for analysis. I make a number of assumptions

1. two-dimensional, areal flow (x, y) in contained marker beds 139, A and B.
2. good connection between the marker beds and WIPP,
3. single-phase, liquid flow only;
4. steady flow (not transient).

5 that fluid is injected with a pressure at a land surface of 1000 psi (68 atmospheres)—pressures like that measured at the surface in the Bates # 2 well; (This is lower than the 1200-2000 psi pressures reported for surface pressures of injection wells in the Texaco Rhodes Yates water flood. As we will see, 1000 psi poses problems.)

6 that the casing of the injection well fails, and 1000 psi surface pressure is imposed on marker beds 139, A and B;

7 in the hydro-fractured case that the marker beds have a regional permeability equal to that at the Bates # 2 site—7.5×10^{-13} m^2; (This assumption deserves more explanation. I suggested above that the hydraulic fracturing in the vicinity of the Texaco Rhodes Yates water flood increseased the permeability on a regional scale. I am assuming that similar, regional scale hydraulic fracturing occurs in the vicinity of WIPP.)

8 the repository is at hydrostatic pressure and remains at hydrostatic pressure; (Early in the history of the repository the pressure could be more nearly atmospheric. As the repository receives significant flow the pressure will increase. For this analysis, I neglect both the early pressure history below hydrostatic, and the later potential pressure build-up above hydrostatic If one examines the pressure histories of WIPP computed by PA, hydrostatic pressure is the dominate mode.)

9. since the region of the model is finite, I assume no flow boundaries at the edge of the modeled region. (These boundaries force the flow to go to WIPP where the head is held hydrostatic. Ideally, we would like no head build-up at the boundaries; as one can see below there is some build-up at the model boundaries. This condition can be relaxed by extending the model outward. In the hydro-fractured case the permeability is increased in a restricted area; therefore the outer, no-flow boundary may not be as bad an assumption as might appear at first glance. The region model is fairly large; and the boundaries are somewhat removed from the area of principal interest.)

The results are summarized in the following table:

Table I Flow to WIPP

	Distance from well to WIPP	Well-head pressure (psi)	Permeability m^2	Flow rate m^3 / sec	Flow rate m^3 / day
Model 1	2 km	1000	10^{-18}	7×10^{-9}	0.0006
Model 2	2 km	1000	7.5×10^{-13}	5×10^{-3}	430.0 (157,000 / yr)

Note: the approximate total pore volume of the repository, after the salt deforms, is 50,000 m^3.

It is of interest to examine the head distribution produced by this model's. The head is the same for each permeability distribution; even though, as Table I shows, the flows are quite different. The attached Figure is an isometric projection of the head. One can picture the flow if you remember that flow is directly down the gradient in head—it is analogous to a marble rolling down hill.

Concluding Remarks

Injection fluid pressures in the vicinity of the Bates lease were high. It seems clear from the data that the pressures were sufficiently high to produce massive hydraulic fracturing over a large area that included the Bates # 2 well. The permeability, as estimated from the well, is five orders of magnitude higher than the highest undisturbed measurements at WIPP. On the other hand, the Bates # 2 well permeability is three orders of magnitude lower than the maximum hydro-fracture permeability used in Performance Assessment.

Fluid injection in the vicinity of WIPP has the potential to quickly fill the repository with brine should the operation be similar to that which occurred in the vicinity of the Bates lease. The Hartman Scenario is not easily dismissed.

References

Bredehoeft, J.D., C.E. Neuzil and P.C.D. Milly, 1983, *Regional flow in the Dakota Aquifer: a study in the role of confining layers:* U.S. Geological Survey Water Supply Paper 2237, 45 p.

Silva, M.K., 1996, *Fluid injection for salt water disposal and enhanced oil recovery as a potential problem for the WIPP: proceedings of a June 1995 workshop and analysis:* Publication of New Mexico Environmental Evaluation Group # EEG-62, 188 p.

Theis, C.V., R.H. Brown and R.R. Meyer, 1963. *Estimating the transmissibility of aquifers from the specific capacity of wells:* U.S. Geological Survey Water Supply Paper 1536-I, p 111331-11341.

Van Kirk, C., 1994, *Report concerning salt water blow-out January, 1991 on the Bates lease—sections 10 and 15, township 26 south, range 27 east, NMPM, Lea County, New Mexico: 16 p, plus figures and appendices.*

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WIPP–Hartman Scenario
(head above hydrostatic)

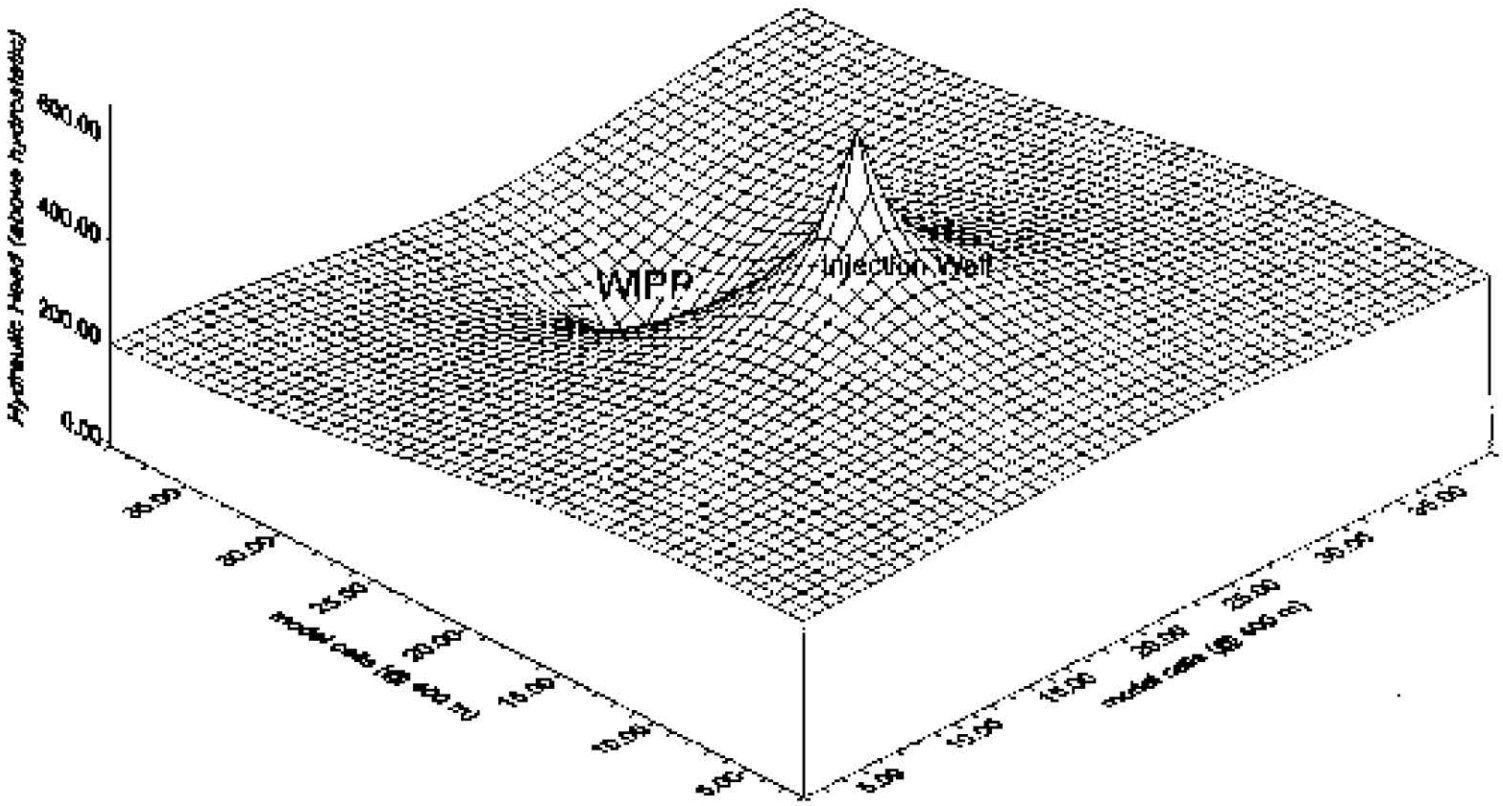

The HYDRODYNAMICS Group
studies in mass and energy transport in the earth

JOHN BREDEHOEFT *PhD, NAE*
principal

January 14, 1997

MEMORANDUM

To: **Lindsay Lovejoy, Jr.**

From: **John Bredehoeft**

Subject: **Hartman Scenario—Stoezel-O'Brien Analysis**

Introduction

Stoezel-O'Brien did a cross-sectional analysis. I modeled a cross-sectional to compare with our areal analysis and show you the difference.

Analysis

I selected a cross-section strip that is two model cells in width—a total width of 800 meters. This is approximately as wide as the smaller dimension of the repository foot print. As before, I placed the injection well 2 km from the repository. I used the permeability estimates from the Hartman # 2 Bates well. I assumed an injection pressure of 1000 psi at land surface; held the repository at hydrostatic head; and did a steady-flow calculation.

This analysis is analogous to our previous analysis except that we now have flow only in the cross-sectional strip. Enclosed is an isometric plot of head for comparison.

Results

The results are summarized in the following table:

Table 1 Flow to WIPP

	Distance from well to WIPP	Well-head pressure (psi)	Permeability m^2	Flow rate m^3 / sec	Flow rate m^3 / day
Model 1 (areal)	2 km	1000	10^{-18}	7×10^{-9}	0.0006
Model 2 (areal)	2 km	1000	7.5×10^{-13}	5×10^{-2}	430.0 (157,000 m^3/yr)
Model 3 (strip)	2 km	1000	7.5×10^{-13}	1×10^{-3}	86.4 (31,600 m^3/yr)

Note—the approximate total pore volume of the repository, after the salt deforms, is 50,000 m^3.

As you can see, restricting the flow to a cross-sectional strip reduces it to approximately 1/5 of the amount in areal model. This is the conceptual difficulty with the Stoezel-O'Brien approach.

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WIPP Analysis

Flow to/from WIPP is three dimensional. Sandia claims, perhaps correctly, that analyzing the full 3D flow problem is much too computer intensive to be practical for PA. For this reason the problem is idealized currently into a plane—a cross-section in the case of WIPP. (Two dimensional analyses, either areal—x, y; or cross-sectional—x ,z; or radial—r, z, are the rule in analyzing flow problems.) Any of 2D geometry is an approximations for the 3D problem. The simplification is a compromise—sometimes good, and sometimes not so good. You can see that the Stoezel-O'Brien cross-section was not very good for analyzing flow to WIPP.

In previous PA analyses a radial formulation was used in which radial distances were measured out ward from the disposal room. This formulation did not handle the connection between the disposal panel and the rest of the repository very well. This was changed to a cross-section in an effort to improve this portion of the modeling. The new cross-section will not do well in handling flow outward in the marker beds, the radial model was better in this instance.

I know that Chuck Byrum is concerned about the 2D approximations used in WIPP PA. EPA has had HydroGeologic looking into these approximations.

My gut reaction is that most of the approximations associated with the cross-sectional analysis used in BRAGFLOW are probably okay—assuming a 2D analysis is the only one practical. As I suggested to Sandia when it was presented, the Stoezel-O'Brien cross-section concept used for analysis was poor, at best.

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Head (m)
Injection Well
WMPd

ENVIRONMENTAL EVALUATION GROUP

AN EQUAL OPPORTUNITY / AFFIRMATIVE ACTION EMPLOYER

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March 14, 1997
Director,

Center for the Waste Isolation Pilot Plant Program
U.S. Environmental Protection Agency
Office of Radiation and Indoor Air
401 M. Street S.W.
Washington, D.C. 20460

Dear Mr. Marcinowski:

Enclosed please find the EEG's additional comments on significant issues arising from our review of the WIPP Compliance Certification Application (CCA). This package of 14 papers complements the package of 6 papers submitted to you on February 7, 1997, following the same format.

Please note that as we continue to explore deeper into the assumptions, professional judgements, calculations, conceptual and numerical models, and secondary documentations related to the CCA, we are bound to come up with additional issues to be sesolved. We do not view the March 17, 1997 deadline as a bounding date for communicating additional concerns to the EPA. Given the significance of the decision that the EPA has to make, and the time that the DOE has taken to prepare this application since EPA originally promulgated 40 CFR 191 in 1985, 4 months of review time is not enough. Actually, the review time was much shorter since many of the issues that we have identified required a review of the Sensitivity Analysis Report that was provided to the EEG on January 20, 1997, and additional materials that have only recently been added to the Records Packages at the Sandia National Laboratories.

A detailed review of the July 1995 DOE draft CCA (DCCA) was provided by the EEG to the DOE in February 1996 and later published as the EEG report, "Review of the WIPP Draft Application to Show Compliance with EPA Transuranic Waste Disposal Standards", EEG-61, March 1996. The EEG has not received comments on that review from the DOE to date, and we have found no changes between the draft and the final CCA as a result of the EEG review (EEG-61). In our additional comments on the CCA to be provided in a report that we plan to publish this year, we will analyze our comments on the DCCA and how they have been treated in the CCA. At this time, we are formally submitting a copy of EEG-61 to you and to the Docket as part of our comments on the CCA.

The issues identified in EEG-61, our letter and encloserues date 2/7/97, and this letter and the enclosures, should therefore be considered to be our formal comments on the CCA submitted to you before 3/1797 deadline. As you can see, we have concentrated our efforts so far on reviewing the Containment Requirement related issues of the CCA. We will provide comments on the other parts of the 40 CFR 191 subpart B compliance as we review the compliance with them.

The overall EEG recommendation to the EPA at this point is to require the DOE to include consideration of additional scenarios like water-flooding and solution mining, with corrected conceptual models and parameter values in showing compliance with the Containment Requirements of the EPA Standards, 40 CFR 191. EPA should also require robust engineered barriers as part of the Assurance Requirement of 40 CFR 191.

Sincerely,

Robert H. Neill
Director

RHN:LC:pf
Enclosures: EEG Reviews of the WIPP CCA

Brine Reservior Assumptions in the CCA (Revised)
Faulty Sapling Ranges
Brine Inflow from Salado: 2D versus 3D Geometry in BRAGFLO
Probability of Microbial Degradation
Borehole Plug Lifetime
Inconsistency Between Direct Brine Release and Spallings Geometry
Waste Permeability Values
Random Emplacement of the Waste in the Repository
Residual Brine Saturation of Waste
Compendum of Direct Brine Release Problems
Active Institutional Controls
Passive Institutional Controls
Potash Mining
Documentation of FEPs and Parameters

cc: Ms. Jennifer Salisbury, NMEMNRD
Mr. Lindsay Lovejoy, Jr., NMAG
EPA Docket for WIPP (A-9302)

BRINE RESERVOIR ASSUMPTIONS IN THE CCA (Revised)

This section updates EEG's previous submission of 2/7/97 to the EPA on brine reservoir assumptions. A new section, "Revisions to Parameters" has been added to address issues raised in the January 16, 1997 memo of Rick Beauheim to Palmer Vaughn[1]. No other changes have been made to the original submission.

The EEG sees no justification for assuming only 8% probability of intercepting a pressurized brine reservoir in the Castile Formation 250 meters below the repository. The fatal flaw in the CCA argument for 8% is the assumption that the oil and gas wells that did not report encountering brine did in fact not encounter a brine reservoir. The fact is that the drillers are not required to report brine encounters to the state or federal authorities and no mention would be found in the records unless undue delays or hazardous conditions are encountered.

The 8% probability also ignores the data from WIPP-12 and the TDEM survey over the repository. The borehole WIPP-12 is located north of the repository within the WIPP site. It was drilled to the bottom of the Salado Formation in 1978 and deepened in 1981 at the EEG's suggestion. The DOE contractor (Popielak et al., WIPP-TME-3153, 1983) estimated the volume of the reservoir to be 2.7 million m^3 (17 million barrels). For the maximum possible reservoir thickness of 24 meters, the surface footprint of a cylinder containing this volume would have a diameter of more than 3 km. As the attached figure shows, the WIPP repository is most likely underlain by the brine reservoir encountered by WIPP-12. In addition, the TDEM survey (SAND 87-7144) gives an indication of the presence of brine at the upper Castile horizon. To try to assign specific areas of the presence of brine from this geophysical survey would be over-interpretation of the geophysical data. Combination of the WIPP-12 data and the results of the TDEM survey indicate the existence of brine under the repository. Any borehole drilled into Castile under the repository should therefore be assumed to encounter brine.

The EEG does not find the CCA reservoir volume assumption of 32,000 to 160,000 m^3 to be justified. This is based on the assumption of depletion of reservoirs by future drillers - 100% probability of encounter for the depletion assumption, while only 8% for releases!

The attached table shows the comparison between the characteristics of the WIPP-12 brine reservoir and the CCA assumptions.

The WIPP site was moved twice; in 1975 after the borehole ERDA-6 encountered a brine reservoir, and again in 1982, after WIPP-12 encountered brine. The CCA assumptions of probability should be realistically based on the site specific information, and the characteristics should be based on the WIPP-12 experience.

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[1]Beauheim, R., Revisions to Castile Brine Reservoir Parameter Packages, memo to P. Vaughn, in WPO 31084, Sandia National Laboratory, January 16, 1997.

The DOE Conceptual Model Peer Review Panel, in their December 1996 report, essentially agrees with the EEG position, but has accepted the DOE position that there are no significant consequences of the probability and volume assumptions.

The EEG does not accept the "no consequence" argument that is based on piecemeal, partial sensitivity analyses.

Revisions to Parameters

On January 16, 1997, Rick Beauheim of Sandia National Laboratories recommended revising five parameters describing the Castile brine reservoir conditions[1]. The reasons for these changes are presented in the parameter record packages WPO 31070, 31072, 31082, 31083, and 31084. Even though the parameter ranges recommended by Beauheim are more reasonable than the ones used in the CCA, the EEG disagrees with the recommended values for reservoir volume because the range includes the value derived from testing the ERDA-6 brine reservoir and initial pressure because of the use of data from twelve other brine encounters in the Salado. The combination of the TDEM survey and the estimates of the areal extent of the WIPP-12 brine reservoir provides a strong evidence that the WIPP-12 reservoir and the brine under the repository are one and the same. Therefore, only the WIPP-12 brine reservoir characteristics should be used to define the parameters used in the CCA performance assessment.

Beauheim points out that the parameters should be constrained by what he terms the productivity

$$PR = V\frac{C_r}{f}$$

ratio (PR), given by:
Where V is the sampled reservoir volume, C_r is the rock compressibility and ϕ is the porosity. Beauheim's recommended range for this constraint is $7x10^{-4}$ to $4x10^{-2}$ m^3/Pa, in which the $7x10^{-4}$ m^3/Pa value is from ERDA-6 data and $4x10^{-2}$ m^3/Pa is consistent with the WIPP-12 data. The constraint PR should be fixed at $4x10^{-2}$ m^3/Pa in order to agree with the WIPP-12 data, and the ERDA-6 data should not be used because it is irrelevant to the present WIPP site. Thus, with porosity fixed, the reservoir volume (V) should be inversely correlated with the sampled value of rock compressibility so that PR equals $4x10^{-2}$ m^3/Pa. Attached is a figure from an October 3, 1996 memo from Rick Beauheim to Les Shephard[2] showing PR calculated from the sampled parameters of the CCA calculations. The figure has been modified to point out the $4x10^{-2}$ m^3/Pa value determined for WIPP-12. Only five out of 300 samples were as large as the WIPP-12

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[2]Swift, P.N., K.W. Larson, and R.L. Beauheim, Treatment of Castile Brine Reservoir in the 1996 CCA Performance Assessment, Memo to L.E. Shephard, WPO 41885, Sandia National Laboratory, October 3, 1996.

measurements. This figure clearly demonstrates the inappropriateness of the Castile brine parameters used in the CCA calculations.

The recommended initial pressure range of 16.5 to 11.0 MPa gage is based on pressure measurements from thirteen Castile brine encounters. At WIPP-12 the measured pressure was 12.6 MPa gage. Therefore, the reservoir pressure should be a constant value of 12.6 MPa gage in the revised CCA calculations.

Comparison of WIPP-12 Brine Reservoir and the CCA Assumptions

Parameter	WIPP-12 (m^3)	CCA (m^3)
Total Reservoir Volume	2.7×10^6 (a)	32,000 to 160,000 (d)
Projected Max. Artesian Flow	55,821 (b)	5,200 (e)
Flow to Surface During Drilling	4,306 (c)	400 to 2,100 (f)

(a) WIPP/TME-3153, p. H-54
(b) WIPP/TME-3153, p. H-55
(c) WIPP/TME-3153, p. H-9; Actual "unavoidable" flow
(d) DOE/CAO-1996-2184, Table 6-26; Beauheim (1/16/97 Memo to Vaughn) revised the estimate to 100,000 to 1,700,000 m^3
(e) CMPRR-Suppl., 12/1996, p. 42; To the Culebra, after 6 encounters
(f) CMPRR-Suppl., 12/1996, p. 42; In 10,000 years

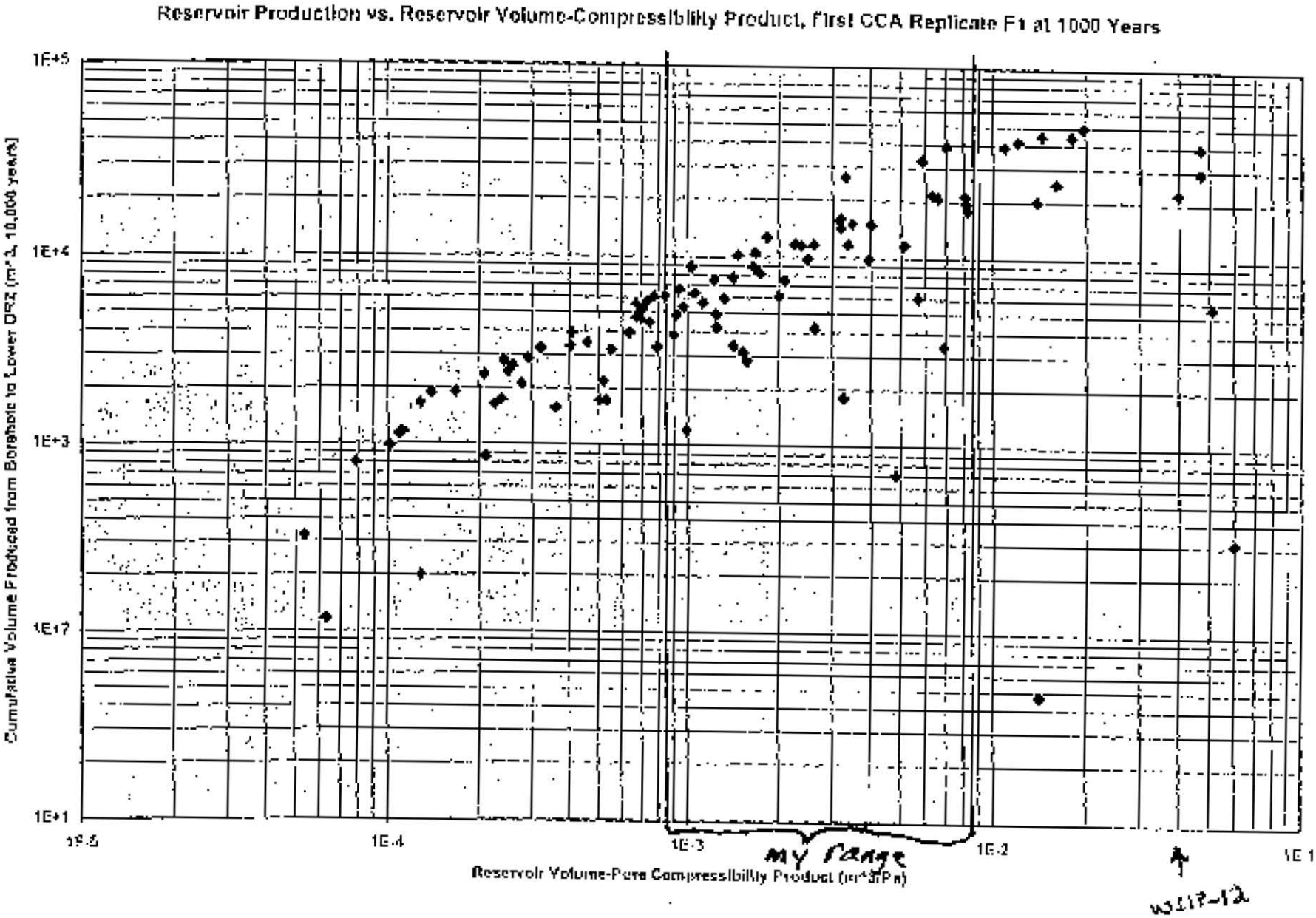

Figure 2

Figure 1 (From Sunkit et al., 1996)

INFORMATION ONLY

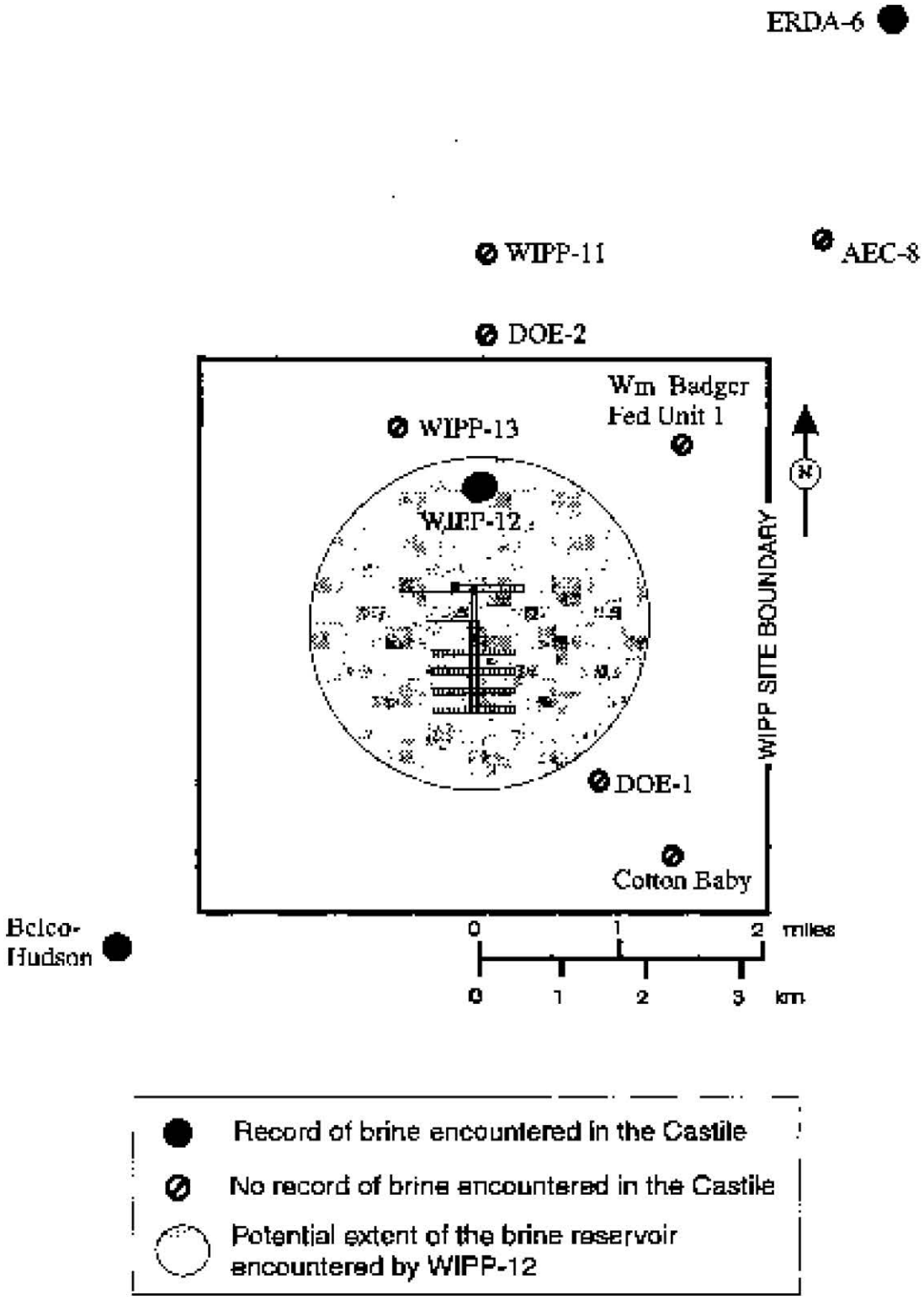

Potential extent of WIPP-12 brine reservoir using WIPP-12 pressure recovery data, rock compressibility of $1 \times 10^{-9} Pa^{-1}$, and reservoir thickness of 24 meters.

FAULTY SAMPLING RANGES

Recently, arguments have been made that if the sampled distributions of parameters used in the CCA calculations are in error, but include the likely values of those parameters, then the CCA calculations are acceptable. We disagree. Under these conditions, the CCA calculations should be repeated with the best estimate of the parameter distributions available. The use of a faulty distribution of one parameter biases the CCDF curves and confuses the assessment of uncertainty. The use of more that one faulty parameter set makes the assessment of uncertainties impossible because of the complex non-linear nature of the performance assessment models.

In this report we state our case in two ways - first by example and then abstractly. The most notable occurrence of a faulty parameter distribution is the Castile brine reservoir volume distribution used in the CCA calculations. The error has been admitted by DOE and considered by the conceptual model peer review panel.

1) The Brine Reservoir Example

This example demonstrates the pitfalls of accepting parameter errors as inconsequential in a piecemeal fashion. The conceptual model peer review panel accepted the argument that the brine reservoir parameters were acceptable because the correct values were effectively included in at least some of the sampled vectors. They also concluded that the brine reservoir interception probability was inconsequentially in error because encounters with a brine reservoir, E1 events, do not have substantially different consequences from intrusions that do not encounter brine, E2 events. They reached this conclusion through inspection of results presented for the entire set of sampled vectors. First, their basic conclusion was flawed because the repository system is too complicated to be evaluated using the data presented. Second, they had no way to evaluate the effect of the biases introduced by the flawed reservoir volume parameter distribution on the data presented.

The EEG understands that the DOE currently considers the parameter distribution for the brine reservoir volume to be from 10^5 to $1.7x10^6$ m^3 rather than the range of $3.2x10^4$ to $1.6x10^5$ m^3 as used in the CCA calculations[3]. In the first supplemental conceptual model peer review report, the panel concludes that the error in volume is of no consequence because the pore compressibility-volume product range of the calculations includes the correct range[4].

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[3]Beauhiem, R., Revisions to Castile Brine Reservoir Package Packages,memo to P. Vaughn, in WPO#31084, Sandia National Laboratories, January 16, 1997.

[4]Wilson C., D. Porter, J. Gibbons, E. Oswald, G. Sjoblom, and F. Caporuscio, Supplementary Conceptual Models Peer Review Report, DOE, Dec. 1996, Page 41.

Later, the peer review panel used the comparison of plots of brine inflow, brine saturation, and gas generation from the both E1 and E2 intrusions to conclude that the intersection of the brine reservoir insignificantly impacted the releases and hence the probability of intersecting a reservoir was unimportant to the CCA calculations. The plots included data from all vectors of replicate 1 with no indication of which data were from vectors with the acceptable pore compressibility-volume product range.

The data the peer review panel used for their decision was inadequate. This conclusion is based on our interpretation of Figures 5.1.6 and 5.1.7 of the preliminary sensitivity analysis report on the CCA Calculations[5]. Figures 5.1.6 and 5.1.7 contradict the panels conclusion. Figure 5.1.6 presents volume and EPA unit releases for the different specified second intrusion times for an initial E1 intrusion at 350 and 1,000 years. Figure 5.1.7 presents similar release data for initial E2 intrusions. For initial intrusions of 350 years, and especially at earlier second intrusion times, Figure 5.1.6 presents substantially larger volumetric and radionuclide releases. The average volumetric release is almost two orders of magnitude higher for a second intrusion at 200 years after the E1 event compared to the E2. Because of assumed solubility differences in Castile and Salado brine, the normalized EPA release is only a factor of 30 higher 200 years after an E1 at 350 years. Since EEG has stated elsewhere that the solubility differences for plutonium are much smaller than assumed for the CCA, the comparison of volumetric releases may be a better indication of the differences. However, such a comparison is biased toward low volumetric releases in the case of an initial E1 event by the use of a flawed distribution of the pore compressibility-volume product.

With a pore-compressibility-volume product equivalent to WIPP-12, the probability of brine reservoir encounter set to 1. and, plutonium solubilities consistent with experimental data, the possibility that direct brine release will violate the compliance criteria can not be ruled out based on our present understanding of the CCA modeling.

2) General Considerations

Construction of CCDF curves to demonstrate compliance with 194 Part B requires estimates of the uncertainty in parameter values. Sampling over the parameter uncertainty ranges incorporates this uncertainty in the CCDF curves. Sampling also provides some assurance that deviations from reality, of best estimates for the repository system, will not have disastrous consequences. Thus, the parameters ranges must capture the true uncertainty in the results, unless compensating conservatism is used.

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[5]J. Helton, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Dec. 23, 1996.

If the parameter ranges are in error then the mean value of the CCDF curves will be biased and the distribution of the curves no longer represent the uncertainty in the understanding of the WIPP site. An error in this context means an incorrect representation of current understanding and should not be confused with an inaccurate understanding. Errors in the analysis are recognizable and correctable. The concern here is the consequence of recognizing an error but failing to correct for it. The basis for such a decision could be that the error does not matter or leads to higher CCDF curves. The decision to not correct a parameter error should only be made if the effects of the parameter are completely understood and the insensitivity or conservatism in the results can be clearly demonstrated.

Demonstrating the consequences of errors in most of the CCA parameter ranges would be difficult. The difficulty is compounded by potential interactions of errors in more than one parameter. Not only the effect on the CCA calculations must be demonstrated but the effect on potential calculations under conditions that may be caused by the other parameters must also be included. The effort could easily be much greater than the effort of a completely new set of CCA calculations and yet still fail to provide an adequate demonstration of the consequences.

The most reliable way to eliminate concerns about parameter errors is to rerun the CCA calculations with the proper values. It makes little sense to do so in a piecemeal fashion. The CCA calculations should be rerun only after a complete evaluation of the current set of calculations. Otherwise it will be nearly impossible to credibly provide reasonable assurance that the compliance criteria are met.

BRINE INFLOW FROM SALADO: 2-D VERSUS 3-D GEOMETRY IN BRAGFLO

The 2-D geometry used in the BRAGFLO appears to have caused an under-prediction of brine inflow to the repository and thus may have resulted in a significant under-prediction of the direct brine release. This assumption may also have effected the amount of releases predicted by the spallings scenario.

The justification for modeling the repository in a pseudo 3-D manner (2-D radial flaring) rather than in a full 3-D geometry has been provided through evaluation of FEP S-1[1]. The summary memo of record for the FEP S-1 screening analysis discusses the impact of the 2-D assumption on 1) brine flow through the anhydrite layers to the 2.4 km boundary, 2) flow to the top of the shaft, 3) brine flow up the borehole, and 4) the repository pressure. That memo[6] does not consider the effects of the 2-D assumption on the inflow of brine to the repository, and on the spallings or direct brine releases.

The amount of projected inflow of brine in the repository directly effects the gas pressure in the repository. Table 5.5.3 of the sensitivity analysis reported[7] lists the residual gas saturation as the parameter with the strongest influence on the projected direct brine releases. This is also shown in Figure 5.1.5 of the sensitivity analysis report (the attached Figure 1). In addition, brine inflow is important to the spallings release estimates through increased gas generation. This dependence is made clear in Table 4.4.3 of the sensitivity analysis report which lists halite porosity, a large source of brine, as the second most important parameter to spallings releases.

The screening analysis compared 2-D simulations of the repository to 3-D simulations of the repository. For computational efficiency, the calculations were performed for half the repository. Two sets of simulations were conducted for the analysis. One set of calculations used a gas generation rate below the level that would cause anhydrite bed fracturing. The second used twice the gas generation rate to ensure anhydrite bed fracturing. In both sets, less brine-inflow occurred in the 2-D case compared to the 3-D geometry. No dependency of gas generation on brine inflow to the repository was included in the calculations; gas generation was prescribed as a function of time, ending after 1,000 years in the screening calculations.

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[6]Vaughn, P., T. Hadgu, D. McArthur, and J. Schreiber, FEP Screening Analysis S1: Verification of 2D-Radial Flaring Using 3D Geometry, Memorandum to D.R. Anderson, January 26, 1996, WPO 30840, Sandia National Laboratory, Attachment 4-1 to Appendix Mass of the Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184, December, 1996.

[7]Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

The largest impact of 2-D geometry occurs with anhydrite bed fracturing. The 3-D model predicts the flow into the repository to significantly increase if the anhydrite beds fracture, while the 2-D model predicts the flow to decrease in relation to calculations without anhydrite fracturing.

Figure 15 of the FEP S-1 analysis (Figure 2) shows the cumulative brine inflow to the repository for the high gas generation calculations. The flows calculated using the 3-D model indicate that once anhydrite bed fracturing occurs, roughly $2x10^6$ kg (1,600 m^3) of brine enters the repository in a period of 200 to 300 years and that this flow rate was continuing unabated at the time of drilling intrusion. Another $4x10^6$ kg (3,200 m^3) flowed into the repository shortly after the drilling intrusion. Figure 2 shows differences of $4x10^6$ to $6x10^6$ kg (3,200 to 6,500 m^3) for much of the 10,000 years. The brine inflow differences listed above should be doubled for the full repository. Virtually no flow enters the repository as a result of anhydrite bed fracturing in the 2-D geometry. In fact, the net flow over the 10,000 year simulation is less with anhydrite fracturing compared with the simulation without the beds fracturing. Figure 2.1.4 of the sensitivity analysis report[2] (Figure 3) indicates very little marker bed inflow with microbial gas generation of plastics and rubber, supporting the findings of the FEPs analysis. Figure 5.1.5 of the sensitivity analysis report reveals the importance to direct brine release of these low brine inflows. The highest pressures are correlated with brine saturations below the residual brine saturation of the waste. The low saturations are due partly to increasing repository pore space with increasing pressure and partly to lower brine inflow.

Table 2.5.13 of the sensitivity analysis report indicates that the potential for anhydrite bed fracturing is high. As a crude approximation, consider the undisturbed scenario of a total fracture-enhanced flow of 20,000 m^3 over a period of 2,000 years. The highest repository pressure in the FEP S-1 calculations was 13 MPa. This corresponds to a repository pore space of 85,000 m^3 (Figure 2.3.5 of the sensitivity analysis report). The increased brine flow would increase the average brine saturation by 0.23. The CCA calculations do not include simulations of both very high pressure and brine saturations above the residual brine saturation of the waste. Inspection of Figure 5.1.5 suggests a significant impact from a 0.23 saturation shift at high pressures.

The simulations without anhydrite fracturing show a decrease of $1x10^6$ to $2x10^6$ kg (800 to 1,600 m^3) in predicted brine inflow in the 2-D simulations compared to the 3-D simulations (Figure 4; Figure 10 of the FEP S-1 memo). These flows are doubled for the full repository. The differences are most likely from differences in marker beds flows to the repository.

To put these brine inflow differences in perspective, note that average brine inflow to the repository in the CCA calculations of the similar S5 scenario was almost 40,000 m^3, with an average 8,000 m^3 from the marker beds[2]. Marker bed brine flows in the S5 scenario are dominated by flows under low pressure conditions. The marker bed flows are a more significant concern in the S1 undisturbed scenario. An average of roughly 3,000 m^3 flowed into the repository from the marker beds in the S1 CCA calculations. To approximate the brine flow error

in the undisturbed calculations for pressures below the anhydrite fracture threshold, we ratio the FEP S-1 differences by 3,000/8,000 - resulting in the range of 600 to 1,200 m^3 less brine inflow to the full repository. If 1,200 m^3 of brine were distributed throughout the entire repository it could increase the average saturations by 0.015 to 0.03 (0.04 to 0.08 in the S5 scenario and 0.16 to 0.32 after anhydrite fracturing in an S5 scenario). It is more likely that much of the additional brine would be consumed through increased gas generation, leading to higher repository pressures.

There are indications in the sensitivity analysis report that the computational grid effects the distribution of brine within the repository in addition to the overall magnitude of brine. One indication is the statement on page 2-26 that "Due to the computational grid in use (Fig. 1.2.1), the lower panel receives more brine inflow from the marker beds relative to its size than the upper waste panels (Fig. 2.1.2)." Another indication may be the importance of the residual gas saturation of the shaft seals to flow through the marker beds (Table 2.1.1 of the sensitivity analysis report). As stated in the report, "its selection may be due to effects related to brine and gas movement across the part of the computational grid that corresponds to the shaft in the repository and DRZ (i.e., regions 10,11 in Fig. 1.2.1)." As a result, the upper waste panels receive roughly one ninth of the brine inflow from the marker beds per panel as the lower waste panel. In a large fraction of the sampled vectors, gas generation stops in the upper panels because of limited brine availability for steel corrosion. Thus, the CCA calculations are under-predicting repository pressure as well as brine saturation.

The EEG concludes that the use of a 2-D geometry in the BRAGFLO may introduce significant non-conservatism into the CCA calculations. The FEP S-1 needs to be re-examined with appropriate consideration of the impact of increased brine saturation on calculated release estimates.

Figure 1

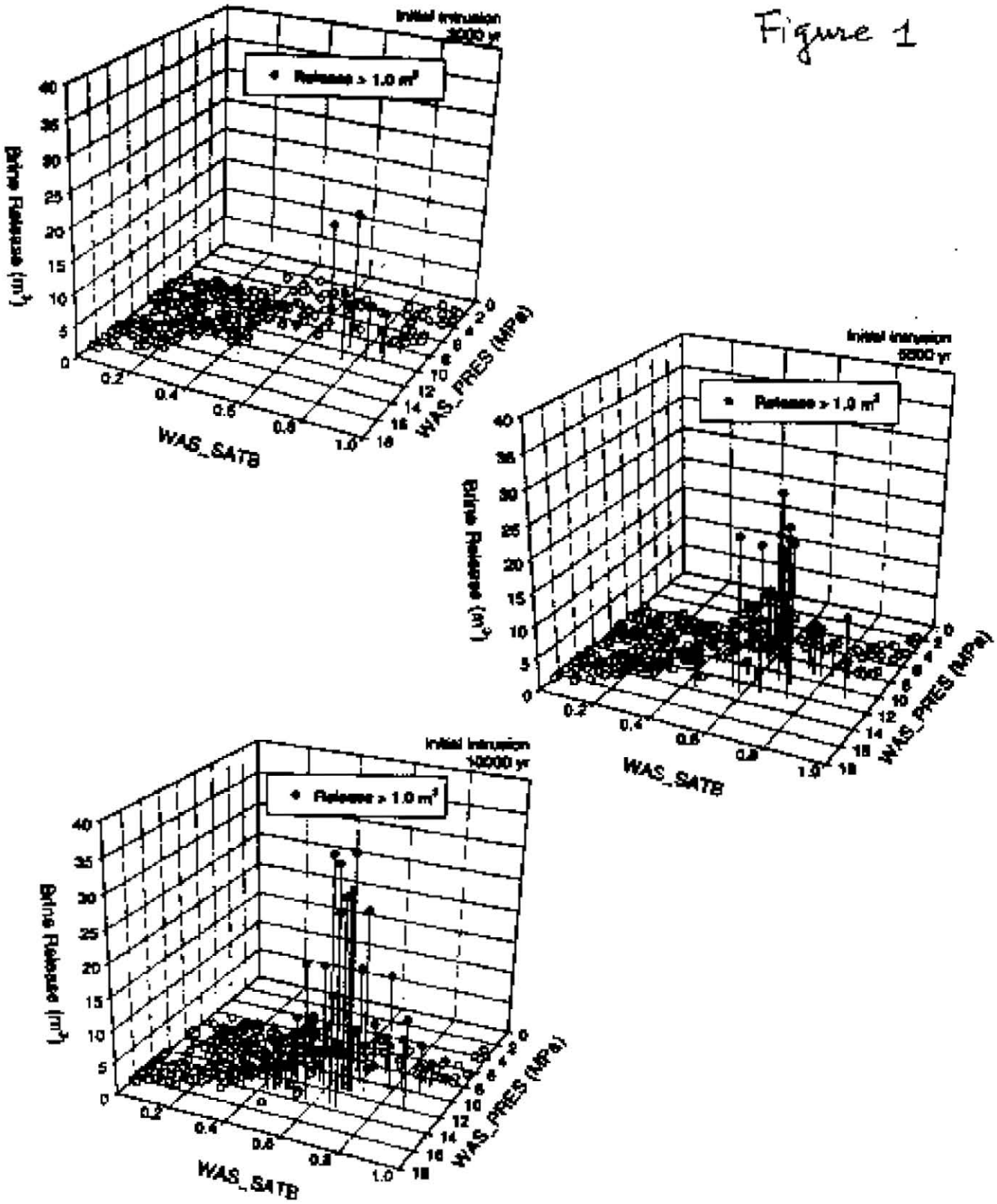

Fig. 5.1.5. Three dimensional scatterplots for volume of brine (m^3) removed due to direct brine release resulting from a single drilling intrusion into a previously unintruded repository that passes through CH-TRU waste in a lower waste panel, brine saturation and pressure (MPa).

From: Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

From: Vaughn, P., T. Hadgu, D. McArther, and J. Schreiber, FEP Screening Analysis S1: Verification of 2D-Radial Flaring Using 3D Geometry, Memorandum to D.R. Anderson, January 26, 1996.

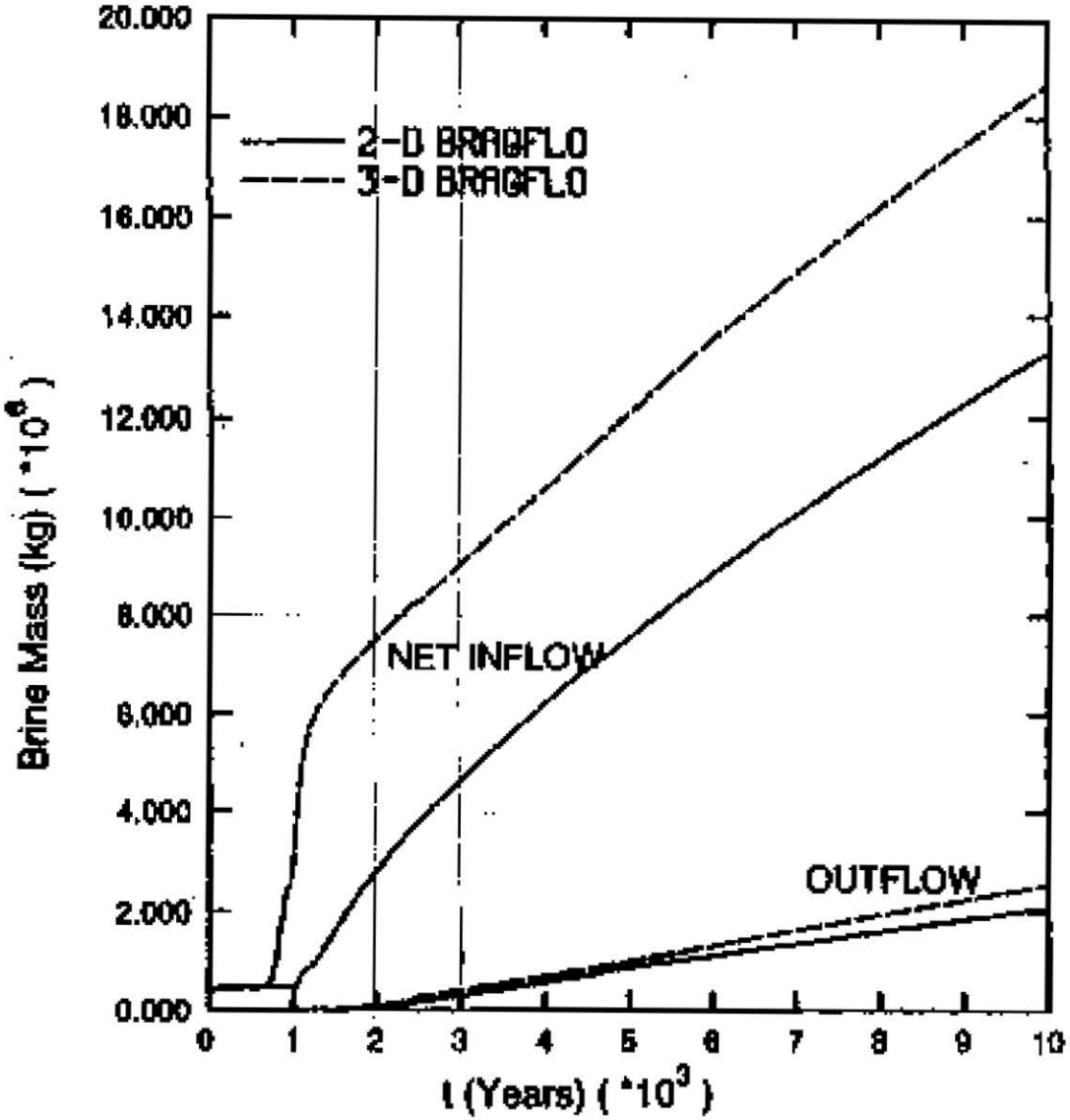

Fig. 15 Cumulative Net Brine in and Outflow at Repo.-Doubled Gas Generation rate

Figure 2

CRRA TA

SWCF-A:1.2.07.3:PA:QA:TSK:S1

Figure 3

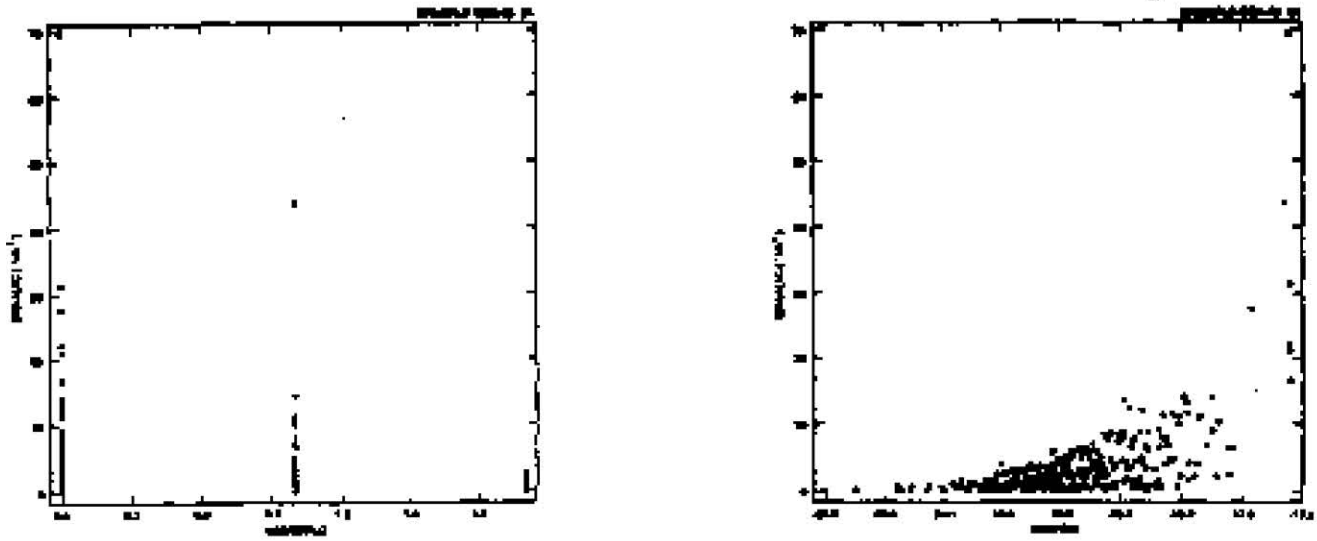

Fig. 2.1.4. Scatterplots for cumulative brine discharge (m^3) from the marker beds over 10000 yr under undisturbed conditions versus microbial gas generation flag (*WMICDFLG*) and marker bed permeability (*ANHPRM*, m^2).

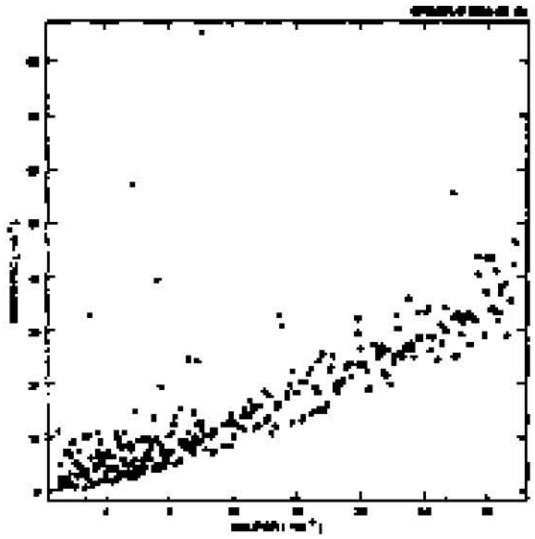

Fig. 2.1.5. Scatterplots for cumulative brine inflow (m^3) to the repository over 10000 yr under undisturbed conditions versus halite porosity (*HALPOR*).

From: Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

From: Vaughn, P., T. Hadgu, D. McArther, and J. Schreiber, FEP Screening Analysis S1: Verification of 2D-Radial Flaring Using 3D Geometry, Memorandum to D.R. Anderson, January 26, 1996.

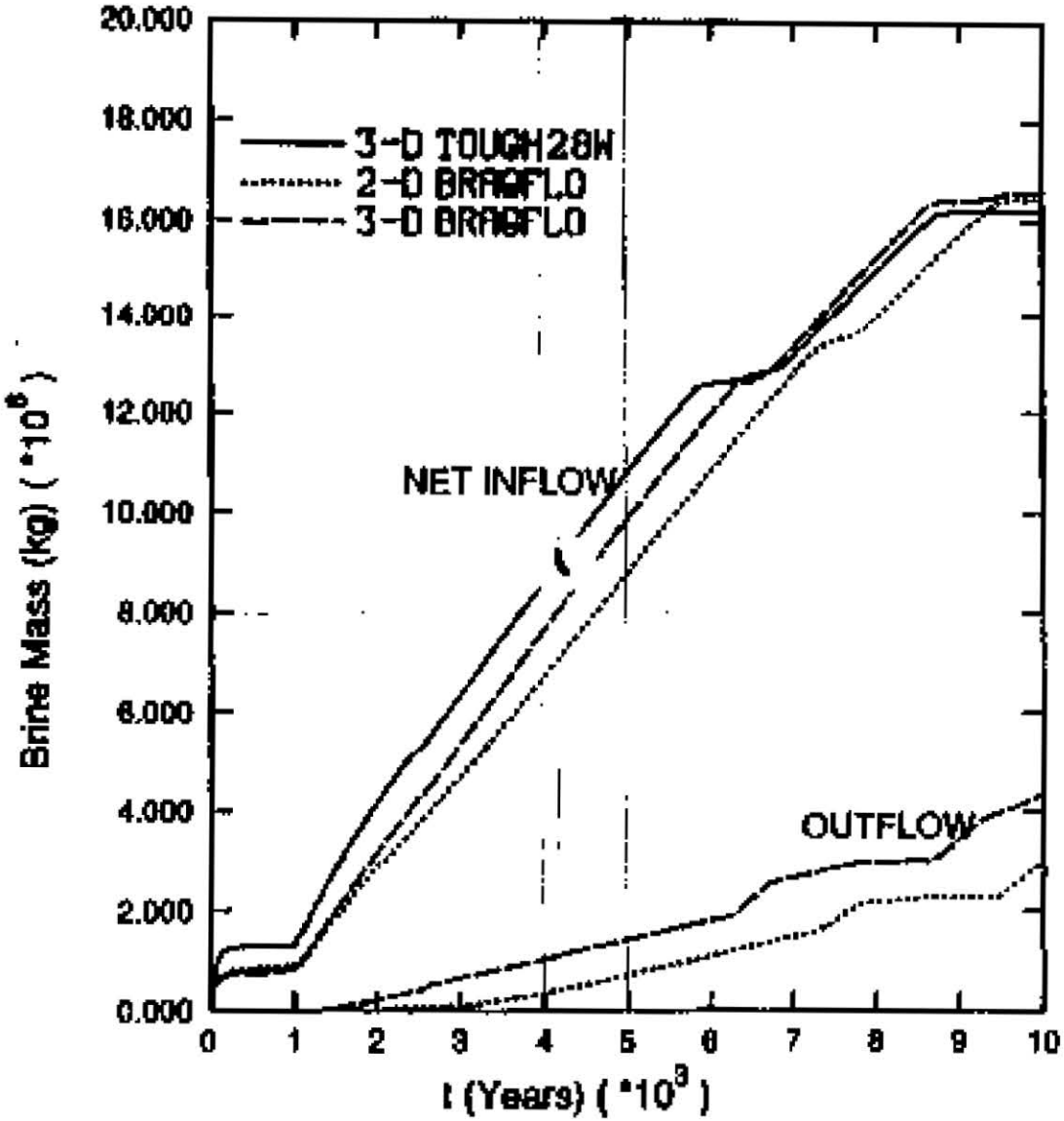

Fig. 10 Cumulative Net Brine In and Outflow at Repo. - Base Gas Generation rate

Figure 4

PROBABILITY OF MICROBIAL DEGRADATION

The sampled parameter for the probability of microbial gas generation determines whether cellulose and plastics and rubber will be degraded by microbial action after closure of the repository. No degradation of cellulose or plastics occurs in the calculations with a 50% probability. Only cellulose degrades in 25% of the sampled vectors. Cellulose, plastics, and rubber degrade with a probability of 25%. The preliminary sensitivity analysis report[8] lists this parameter as the largest influence on the variation of total calculated release from the WIPP repository.

The documentation[9] supporting this parameter does not contain any numerical justification for the probabilities assigned to this parameter. All of the hand calculations performed to calculate the gas generation parameters are included as attachments to the memo of Wang and Brush. Calculations for the degradation probabilities are absent from these attachments. It is the opinion of EEG that the numerical value of this parameter constitutes expert judgement. Given the importance of this parameter to the estimates of radionuclide release, this parameter should be demonstrated to be either solidly based on scientific evidence or be conservative. The justification for this parameter presented in support of the CCA does neither of these.

The numerical values of the degradation probability parameter should undergo peer review consistent with expert judgement. Otherwise, the parameter should be conservatively set to always specifying microbial degradation of cellulose, plastics, and rubber.

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[8]Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

[9]Wang, Y. and L. Brush, Estimates of Gas-generation parameters for the long-term WIPP performance assessment, Memorandum to M. Tierney, WPO 31943, January 26, 1996.

BOREHOLE PLUG LIFETIME

Borehole lifetime should be a sampled parameter in the CCA calculations or else the DOE should provide demonstration that variations in borehole lifetime do not effect the release estimates.

Repository pressure is one of the key factors determining the severity of both spallings and direct brine release. The repository pressure decreases rapidly after the failure of the borehole plug from an initial human intrusion in BRAGFLO calculations of most of the sampled vectors[10]. Thus, the assumed lifetime of the borehole plugs may have a large impact on the final release estimates. The upper borehole lifetime is fixed at two hundred years in all of the BRAGFLO calculations, except for the continuous plug configuration. This conflicts with the data used to calculate the borehole lifetimes[11]. The analysis indicates that the results of investigation on corrosion and borehole lifetimes are expected to vary over an order of magnitude (Thompson, et al. page B1) and are considered to be conservative(Page B-17).

The calculation of upper plug lifetime is not entirely clear. It seems to rely on 1) an assumed corrosion rate of 1- 3 mm/year for steel casing 2) the assumption of sufficient water 3) field observations of casing failures in the Salado and 4) rapid degredation of the concrete plug after casing failure. The assumption of corrosion rate is stated to be "very aggressive" and conservative and about one thousand times faster than the corrosion rate in the repository. Short borehole plug lifetimes could be considered conservative for releases to the Culebra, but not for spallings and direct brine release to the surface. The general assumption of sufficient water is adequately justified in the analysis. However, the point is made that cement outside of the casing may inhibit access to brine(Page B-18). Field observations indicate that casing failures in the Salado are well-known (Page B-20; Bailey memo in La Venue, 1991[12]) at depths less than 1,000 feet. However, the same report(Page B-17) also includes information that casing failures in the Salado are common but not pervasive.

The borehole plug lifetimes are likely to vary by over an order of magnitude. Borehole plug lifetimes should be a sampled parameter.

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[10]Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December 23, 1996.

[11]Thompson, T.W., W.E. Coons, J.L. Krumhansl, and F.D. Hansen. Inadvertent Intrusion Borehole Permeability, Attachment 16-3 in Appendix MASS of the Compliance Certification Application, DOE/CAO-1996-2184, October, 1996.

[12]La Venue, M. Anomalous Culebra water-level rises near the WIPP site, INTERA: Technical Letter Memorandum, January 28, 1991

INCONSISTENCY BETWEEN DIRECT BRINE RELEASE AND SPALLINGS GEOMETRY

The EEG considers the inconsistency in the conceptual models of direct brine release and spallings in the CCA calculations to be unacceptable. The transport of solids and brine to the surface as a consequence of human intrusion is a single process where both brine and solids are entrained in a high velocity gas flow. In our January 21st presentation to EPA, we argued that both brine and gas flow should be modeled as a single process.

The spallings model predicts that channels of void space will be created in a waste room as a result of room depressurization from drill penetration into the room. The channels develop because the velocity of gas is large enough to break the bond of particles from the compacted mass of waste and entrain them in the gas-flow down the channels. This process is aided by the flow of gas perpendicular to the channels. The solid mass calculated to have been released in the spallings model is assumed to evacuate an annular region around the borehole in the direct brine release model. Brine is calculated to be transported to the enlarged borehole region as described by Darcy's Law.

If open channels are created in the spallings process then pressure gradient will drive brine towards these openings. The distance to the open channels would be far less than the distance to the borehole for most of the brine in a waste room and all brine in other rooms of a repository panel. The cumulative release to the surface would, thus, be much larger than calculated by the direct brine release model.

Direct brine release and spallings should be modeled as a single process. If the process is separated into two models, these models must be consistent with each other.

WASTE PERMEABILITY VALUE FOR DIRECT BRINE RELEASE

Issue

The CCA uses a constant waste permeability value of $1.7x10^{-13}$ m^2 in the Direct Brine Release calculations. The method of calculating this value was questioned by a Peer Review Panel and DOE agreed that $2.4x10^{-13}$ m^2 was the appropriate value. The use of this higher value in CCA calculations is considered here.

The rate of radial flow to a well per unit drop in pressure or drawdown is directly related to the permeability of an aquifer. The same relation would apply to flow into a borehole that penetrated a waste storage room.

This discussion will not address other waste permeability related aspects of the Direct Brine Release, Spallings, or BRAGFLO Models such as relative permeability, residual brine saturation, and fracture flow.

Evaluation

SNL arrived at the value of $1.7x10^{-13}$ m^2 for consolidated waste from laboratory data on three major waste components (sludge, combustibles, and metals). The Engineered Systems Data Qualification Peer Review Panel discovered an error in the calculation of the overall permeability and, after discussions with SNL on the appropriate distribution to use on permeability values for each material, agreed with SNL that the appropriate calculated value should be $2.4x10^{-13}$ m^2.

The Peer Review Panel recognized that use of this higher permeability value would increase brine releases in direct proportion to the increase in permeability (41%). Yet they concluded that changing this value is not warranted because "the change does not have any effect on the final outcome," (page 9-191). The panel also opined that the data and assumptions that were used to develop the values were limited and either value was as good as the other.

Clearly there are uncertainties in the actual value of the consolidated waste permeability. There is also the question of whether the current assumption of darcy flow is appropriate or whether the rooms should be modeled as fracture flow. Neither issue is being addressed here.

Changes in the volume fractions of combustibles, metals, and sludges in the waste from the .40, .40, .20 values used in 1991 would also change this permeability calculation. The Final Waste Form volumes shown in Table 4-3 of the CCA are slightly different and result in a calculated permeability of 2.2^{-13} m^2.

Effect on CCA

The use of the higher waste permeability value ($2.4x10^{-13}$ m^2) should cause the CCDF plot of direct brine release to move 41% towards the compliance limit. The CCDF plot in the CCA (Figure 6-41) shows direct brine release to be only 0.05 EPA units at .001 probability. Increasing this by 41% would give a value of only 0.07 units and would have little effect on compliance. However, other questions are being raised about these releases: (1) Castile Brine Reservoir assumptions; (2) appropriate solubility values to use; and (3) details about the Direct Brine Release Model. These other factors could increase the calculated release by more than an order-of-magnitude. If this occurs the 41% increase could become significant.

Recommendation

If a single value for the consolidated waste permeability is to be used for direct brine release, then it should be $2.4x10^{-13}$ m^2 and not $1.7x10^{-13}$ m^2.

RANDOM EMPLACEMENT OF WASTES IN REPOSITORY

Issue

In the CCA, DOE assumes that the waste inventory will be emplaced in the repository in a purely random manner. This assumption leads to three further assumptions in the CCA:

(1) The 569 CH-TRU waste streams can be sampled randomly to determine the concentrations of radionuclides brought to the surface by cuttings and cavings;

(2) the concentration of radionuclides in the area of the waste room affected by spallings releases can be assumed to be the average of the entire WIPP inventory;

(3) the concentration of dissolved radionuclides in solution in a waste panel that has a Direct Brine Release also is calculated from the average of the entire WIPP inventory.

Evaluation

DOE correctly recognizes that the concentrations and radionuclides composition of individual waste containers vary widely and have attempted to account for this in the CCA by sampling on a volume weighted distribution on all 569 CH-TRU waste streams identified in the Baseline Inventory Report, Revision 2. This approach, if done properly, has the potential to fully capture the variability if emplacement is purely random.

EEG believes that actual waste emplacement may deviate substantially from random. This is due to three factors: (a) during the period that a waste room is being filled there is unlikely to be shipment of waste from all Generating Sites on a volume weighted basis. (b) waste being shipped from a Site in a TRUPACT II is unlikely to be representative of the entire site; and (c) wastes arriving on a TRUPACT-II trailer (e.g. 4 to 6 seven-packs of 55-gallon drums) from a site would be emplaced to gather. Its possible that as many as 1/3 of the 7-packs or Standard Waste boxes on a TRUPACT-II trailer would be stacked two-high in a waste room.

Examples of the deviations of average concentrations from individual sites from the total inventory average concentration are: (1) The Savannah River Site (SRS) average is 2.9 times the total average at 100 years; (2) Los Alamos National Laboratory (LANL) averages range from 1.3 to 1.8 times the total average from 100 years to 10,000 years; and (3) Rocky Flats (RFETS) averages range from 3.0 to 4.5 times the total average from 100 years to 10,000 years. Examples of variations within waste streams at a Site are: (1) 2,800 m^3 of residues at RFETS that are 3.3 times the Site average: (2) 60 m^3 of SRS waste that are 42 times the Site average; and (3) 850 m^3 at SRS that are 1.5 times the Site average.

Effect on CCA

In the 1991 Performance Assessment (SAND91-0893/2), Sandia National Labs (SNL) demonstrated that considering the effects of variable radionuclide concentrations in waste containers ("activity loading") resulted in normalized releases from cuttings and cavings to increase by a factor of about ten (at .001 probability) compared to using average activity in containers. SNL has used "activity loading" in PA methodology since that time and in the CCA, the sampling is on 569 waste streams for cuttings and cavings. There is no disputing the fact that sampling on activity levels will increase the calculated releases from cuttings and cavings for probabilities below about 0.5.

The radioactivity concentration and radionuclide composition of waste within a waste room or portion of a panel (i.e. the areas of influence for the spallings and Direct Brine Release calculations) would be expected to vary from the total inventory average. This variation would not be nearly as great as that expected between individual stacks of waste containers, but increases to several hundred percent of the average radioactivity concentration are clearly possible. The calculated releases from spallings at any intrusion time would be directly proportional to the radioactivity concentration.

The calculated radionuclide releases from Direct Brine Releases would depend on the concentrations of each radioactive element in solution. This concentration is dependent on the composition of individual radioisotopes in the waste. For example, in average SRS waste at 350 years the ^{238}Pu radioactivity is 75% of the total plutonium radioactivity compared to 11% of the total plutonium in the total inventory average. Thus, the radioactivity concentration of plutonium in solution would be higher for SRS waste at 350 years. Another example is concentrations of ^{233}U and ^{234}U. Appendix WCA of the CCA states the assumption that only 1% of dissolved uranium would be ^{233}U and ^{234}U, because in the total inventory these radioisotopes comprise less than 1 wt% of total uranium. However, data in the Baseline Inventory Report indicates that the 28,000 m^3 of stored CH-TRU at INEEL contains 20 wt% of ^{233}U.

These concerns of non-uniform emplacement of wastes in the repository touch on the issue of load management. The CCA concludes that load management is not necessary at WIPP (Chapter 4.3.1).

Importance to Compliance

EEG believes that deviations from the assumption of average emplacement has the potential to increase calculated releases at .001 probability from spallings and Direct Brine Release by several fold. Using a more conservative assumption of random emplacement may not result in non-compliance if all other assumptions in the CCA were held constant. However more conservative assumptions could noticeably shift the CCDF curve toward the compliance boundary and, when incorporated with other changes to the 10/96 CCA, calculations could have a significant effect on the final CCDF.

Recommendations

For the Spallings and Direct Brine Release scenarios, determining average waste concentration in one room would be closer to reality compared with using the average for the whole repository as currently used in the CCA. There are several possible approaches to determining justifiable waste room radioactivity concentrations. We recommend the following:

(1) The deviation from average concentrations of radionuclides in waste and brine could be mitigated by load management such that the concentrations in any waste room be limited to (say) 1.5 or 2 times the average at any time during the 10,000 year regulating period;

(2) A reasonable upper bound (not the theoretical maximum) for radionuclide concentration can be obtained by assuming that a room is filled entirely with average concentration waste from the generating site that results in the greatest consequences. For concentrations in the waste this would be RFETS. It is not obvious which site's waste would result in the highest brine concentration.

(3) Allow DOE to show by an appropriate statistical scheme that there is an acceptably low probability that concentrations in wastes and brine will not exceed (say) 1.5 or 2 times the average;

(4) Actually sample on this variability. Sampling might be first on the fraction of waste from each site that is brought into the room (with some deviation above and below the actual fraction of the total repository volume expected from that site). Then the variation of waste composition and concentration from each site (obtained from the 569 waste streams data) could be sampled on.

For the cuttings and cavings calculation DOE should determine an appropriate statistical scheme to evaluate the effect that emplacing wastes from individual sites in clusters will have on the current calculations involving sampling on 569 waste streams. If significant these new values should be incorporated into the CCA.

RESIDUAL BRINE SATURATION OF WASTE

The preliminary sensitivity analysis report[13] indicates (Table 5.3.3) that the calculated releases to the surface from the direct brine release model are most sensitivite to the sampled variation of the waste room residual brine saturation. For various reasons the direct brine release model may be significantly under-predicting releases. See, for example, the EEG position statements on the brine reservoir parameters, solubilities, sampled parameters and probability of microbial degredation. The sampled range of the waste room residual brine saturation is another one of those reasons.

The data and rationale for the sampled distribution of the waste-room residual-brine saturation is presented on pages PAR-27 through PAR-31[14]. The recommended distribution is uniform from 0 to 0.56. It is stated in the data section that the parameter values are based on literature values of unconsolidated materials. Ten materials are listed as the source of the data set. Eight of these data values are from unconsolidated materials with a range of 0.0783 to 0.277. Two of the source materials are consolidated sandstones with values of 0.243 and 0.560. As suggested in Appendix PAR, the sampled range should be based on unconsolidated materials. Use of the single consolidated sandstone value of 0.56 doubles the range of sampled values in a non-conservative direction.

The non-conservative distribution of 0 to 0.560 reduces the estimated releases of direct brine release. Appropriate ranges for the waste room residual brine saturation are a constructed distribution using values from the eight unconsolidated materials; a uniform distribution from 0.0783 to 0.277, or a uniform distribution from 0 to 0.277.

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[13]Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

[14]Appendix PAR of the Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184, December, 1996.

COMPENDIUM OF DIRECT BRINE RELEASE PROBLEMS

We have organized our comments on the CCA in a format so that individual sections tend to focus on single issues. To keep the individual sections brief, we have only occasionally touched on interrelationships between issues. In the case of the direct brine release model, we have found so many interrelated problems that it is worth bringing them together in a separate section. The issues raised in this section are discussed in more detail in their separate sections. The purpose here is to highlight how they have compounding effects on the direct brine release calculations.

We have identified nine separate issues that effect the direct brine release calculations. The issues are:

Probability of microbial degradation
Borehole plug lifetime
Brine inflow from Salado: 2-D versus 3-D geometry in BRAGFLO
Brine reservoir assumptions in the CCA
Inconsistency between direct brine release and spallings geometry
Waste permeability
Residual brine saturation of waste
Random emplacement of wastes in the repository
Plutonium Solubility

Probability of microbial degradation

Direct brine release will only occur if the repository pressure is over 8MPa at the time of drilling intrusion. Above a pressure of 8 MPa, the magnitude of release is more strongly related to waste room saturation. Waste room saturation is dependent on the amount of brine entering the repository and on the repository pressure because the pore space is a function of pressure. The most important sampled parameter effecting repository pressure is microbial degradation. The microbial degradation assumptions are not defensible and may lead to a severe under prediction of the probability of greater than 8 MPa pressure and anhydrite fracturing.

Borehole plug lifetime

Borehole plug lifetimes were not sampled in the CCA analysis, so this parameter does not show up as important in the statistical sensitivity analysis. However, inspection of disturbed scenario pressure histories and the importance of borehole permeability are clear indications of the importance of plug lifetime. Borehole plug lifetimes are uncertain and the description of the development of this parameter in the CCA documentation indicates that the parameter is biased toward short plug lifetimes in an attempt to be conservative. Short plug lifetimes may lead to an under-prediction of the period of high pressures and, hence, may actually be non-conservative.

Brine inflow from Salado: 2-D versus 3-D geometry in BRAGFLO

The importance of anhydrite fracturing to direct brine release is under-represented in the CCA modeling. A full 3-D representation of the repository indicates that substantially more brine will enter the repository if the anhydrite beds open as a result of high pressures compared to brine-inflow under lower pressure conditions. The pseudo 3-D model used in the CCA analysis predicts the opposite. The highest direct brine release predictions occur with repository pressures below the initiation of anhydrite fracturing because of concurrent low brine saturation conditions. This is most likely in error.

Brine reservoir assumptions in the CCA

The DOE has admitted to the conceptual models peer review panel and in post application documents that the Castile brine reservoir parameters are incorrect. The use of these parameters in the CCA calculations severely under-predicts the importance of the Castile brine under the repository. In addition, the likelihood of intercepting Castile brine under the repository is reduced from a certainty to eight percent. Proper incorporation of the Castile brine reservoir in the CCA analysis will lead to higher brine saturations and most likely longer periods of pressures above the 8 MPa threshold.

Inconsistency between direct brine release and spallings geometry

We have identified three flaws in the actual direct brine release model. The most significant of these is the inconsistency of the void geometry of the spallings model to that assumed in the direct brine release model. The spallings model predicts the development of void channels throughout the room penetrated in a drilling intrusion. The direct brine release model assumes that all of the solid material entrained in the room depressurization has come from a annular region about the borehole. The geometric inconsistency could have a very large impact on calculated brine releases.

Waste permeability

The second flaw in the direct brine release model is a calculational error on the part of DOE. The waste room permeability value used in the direct brine release calculation is in error by 41%, based on the data used by DOE. This error leads to a 41% bias to low values in the calculated releases.

Residual brine saturation of waste

The calculated flows are also biased by using a distribution of residual brine saturations that is unrealistic. Brine moves much slower if the saturation is near or falls below the residual saturation level. Residual saturation is twice as high in the CCA calculations than can be supported. This reduces both the frequency and magnitude of the estimated releases to the surface.

Random emplacement of wastes in the repository

The CCA calculations ignore the possibility of higher consequence events due to non-uniform distribution of waste emplacement. In the direct brine release calculations the

actinide content of waste in a room is assumed to be the average of all waste. In practice waste will tend to be grouped by origin and to a degree the waste steams. This would result uncertainty in the radionuclide concentrations in a room's brine content and higher releases in some instances.

Plutonium Solubility

Finally, the importance of brine release to the surface is under-represented in the calculations because of the low assumed values of plutonium solubility, especially in the case of releases subsequent to an interception of Castile brine. The difference in plutonium solubility in the Castile brine become important to calculations that include a proper representation of the Castile brine.

Of these nine problems in the direct brine release calculations, probably only the inconsistency in the direct brine release model geometry has the potential to shift the release calculations to the release criteria values. When considered together, it is clear that radionuclide transport to the surface through brine transport is potentially a much larger threat to safety than predicted in the CCA calculations and could be a much larger concern than the current predictions of release of solids to the surface.

ACTIVE INSTITUTIONAL CONTROL

The DOE conducted an elaborate elicitation exercise in 1990 to address the issue of future inadvertent human intrusion into WIPP (Hora et al., 1991). Members from each of the four "futures teams" expressed reservations about the ability of the project to fully maintain active control for even a very short period of time. Participants in the elicitation exercise were asked to address seven specific issues including the issue of active controls:

> Assuming that the radioactive waste exists and is harmful, what is the likelihood that active controls (continued management of the site) have been maintained to prevent inadvertent intrusions? (Hora et al., 1991, p. G-4).

Three of the four members of the Washington A Team predicted a steep decline in the probability of active controls as a function of time beginning immediately after closure (Hora et al., 1991, Figure IV-10). At 100 years after closure, they predicted the probability of active control for all four postulated future states at less than 30%. The fourth member also predicted an immediate decline, although at a slower rate, in the probability of the effectiveness of active control after closure (Hora et al., 1991, Figure IV-11). In summary, the Washington A Team predicted less than 100% active institutional control for the first 100 years beginning immediately after closure.

The Washington B Team assigned probabilities that the government would continue to maintain prudent and effective control over the WIPP. They defined the near future as 0-200 years after closure (Glickman et al., pp. F-4, F-27; Hora et al., 1991, p. IV-55). This team questioned the effectiveness of active control for the near future and assigned a probability of 80% for prudent and effective control for the near future (Hora et al., 1991, pp. IV-55-56).

Hora stated that the Boston Team allowed for 100 years administrative control (Hora, 1992, p. A-87). However, scrutiny of the Boston Team report (Gordon et al., 1991) and the report by Hora et al. (1991) suggests otherwise. It appears that the input was adjusted to fit the needs of the performance assessment calculations as explained below. This adjustment, and not the Boston Team, allowed for 100 years administrative control.

The Boston Team did not offer direct estimates of the duration of active institutional control. Rather, the Boston Team predicted socio-technical factors at 100 years, 1000 years, and 10,000 years (Gordon et al., 1991, p. C-5); points in time were incompatible with the needs of performance assessment. As noted by Hora et al. (1991, p. IV-3) "...the performance assessment calculations require rates of intrusion during the entire continuum from 100 to 10,000 years after closure." Thus, the use of midpoints on the logarithmic scale was introduced to define time periods. For example, the 100 year point was converted to a period of 0 to 300 years after closure (Hora et al., pp. IV-3 to IV-4). The first 100 years were then dropped and the results of the elicitation for ten tables were presented for time periods from 100-300 years (Hora et al., 1991, Tables IV-2 through IV-11) and not from 0-300 years. However, Table IV-14 (Hora et al., 1991) presents the calculated drilling rate probability for 0-300 years after closure. This table

suggests that the Boston Team did not allow for 100 years administrative control.

Moreover, one member of the Boston Team disputed the existence of administrative control for even a short period of time. In an appendix to the Boston Team report (Gordon et al., 1990), Baram addressed the question "Can memory of WIPP be retained?" Rather than argue in the abstract, he cited examples of the factual loss of history or active control for periods shorter than 50 years. The examples included:

1) the loss of drilling history at Lyons, Kansas that was fortuitously recaptured by opponents to a proposed repository at that location,

2) the loss of information for 45 years on the dumping of barrels of radioactive waste from the Manhattan Project in the late 1940's by the Department of Defense at the Massachusetts Bay site,

3) the unavailability of information until 1986 on the release of radiation and exposure of thousands of people near Hanford beginning in 1944,

4) the use of uranium mill tailings in Colorado to construct homes and other concrete structures despite a prohibition against such activity,

5) the 1982 sewer line construction and inadvertent intrusion into a poison gas container abandoned by the Army when it closed an airfield in 1945.

"The [Southwest] team was fairly pessimistic with respect to society's ability to maintain active controls and effective markers" (Hora et al., 1991, p. IV-31). One member speculated that controls and markers may last as long as 1,000 years, two members felt that loss would likely occur within hundreds of years, and one member thought loss of markers and active control would occur in less than 100 years.

Thus, all four teams in the elicitation exercise on future societies expressed reservations about the project's ability to maintain active control for even a short period of time.

EEG recommends that the EPA should initially assume zero credit for active institutional and ask DOE to cite specific tangible factors as to how much credit can be justified. As part of building a credible argument, the CCA should also take into account the pessimism of its own expert elicitation on the limited effectiveness of active institutional control.

References

1. Hora, S.C., von Winderfeldt, D., and Trauth, K.M., 1991. Expert Judgment on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant. SAND90-3063. Sandia National Laboratories.

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3. Hora, S.C., 1992. Probabilities of Human Intrusion into the WIPP Methodology for the 1992 Preliminary Comparison, August 25, 1992. Appendix to SAND92-0700, pp. A-69 to A-99.

4. Gordon, T.J., Baram, M., Bell, W., Cohen, B., 1990. Inadvertent Intrusion into WIPP: Some Potential Futures. Appendix C to SAND90-3063. Sandia National Laboratories.

PASSIVE INSTITUTIONAL CONTROL

The CCA claims that passive institutional control will be 99% effective in deterring drilling into the repository from 100 years to 700 years after closure. The components of passive institutional control include government ownership, records, and markers. Based on the DOE's experience with institutional controls in the recent past, a claim of 99% credit for passive institutional controls for 700 years does not appear justifiable.

Government Ownership and Regulation

With respect to the government ownership, the DOE maintains that "the controls that are crucial to protect the site from inadvertent exploration are BLM leasing procedures and lease records and the internal procedures of the BLM which require the DOE's review and comment for any permit application to drill within one mile of the WIPP site."[1] On October 26, 1990, the DOE and the DOI/BLM signed a Memorandum of Understanding. With respect to drilling for oil and gas, the MOU specifically required the BLM to notify the DOE of applications for permit to drill for oil and gas within one mile of the WIPP Site Boundary and that "drilling approval will be withheld until comments are received from the DOE."[2] The MOU was revoked on October 30, 1992 with the passage of the 1992 WIPP Land Withdrawal Act[3] (Section 3 (b)). How effective was the MOU for that two year period? The following example is fairly typical of the overall failure of the MOU.

The BLM approved an application to drill Well #4, Section 26, T22S, R31E, on October 15, 1991. Two days later, the BLM[4] sent a letter to the DOE requesting a review of an "Application for Permit to Drill" within one mile of the WIPP Site Boundary. The BLM received DOE's review[5] on October 25, 1991. However, not only had the application already been approved by BLM ten days earlier, but drilling had already commenced the previous day. Thus, the DOE's review was never considered in the application permitting process, the DOE review was not solicited until after the drilling had been approved, and the DOE review was not received by BLM until after drilling had started.

Table 1. Summary of Lapses in Institutional Control

Satisfactory procedure	3
BLM failed to request DOE review.	3
DOE failed to respond to BLM request.	9
BLM approved permits to drill before requesting DOE review.	5
BLM approved permits to drill before receiving DOE review.	5

The MOU failed in twenty-two out of twenty-five applications for an institutional failure rate of 88%. EEG notified DOE of this lapse in institutional control in 1993[6,7]. Fifty-five subsequent applications, processed through July 1994, showed a failure rate of 9%.

Records

A recent example illustrates the failure of records to communicate important information prohibiting drilling in a certain area. In 1978, the DOE purchased leases in the vicinity of the current WIPP site for the explicit purpose of preventing drilling. One area was the N½ NW¼ of Section 6 T23S, R31E (eighty acres) for which the DOE paid Bass Enterprises et al. $207,972 not to drill through the uppermost 6000 feet[8,9].

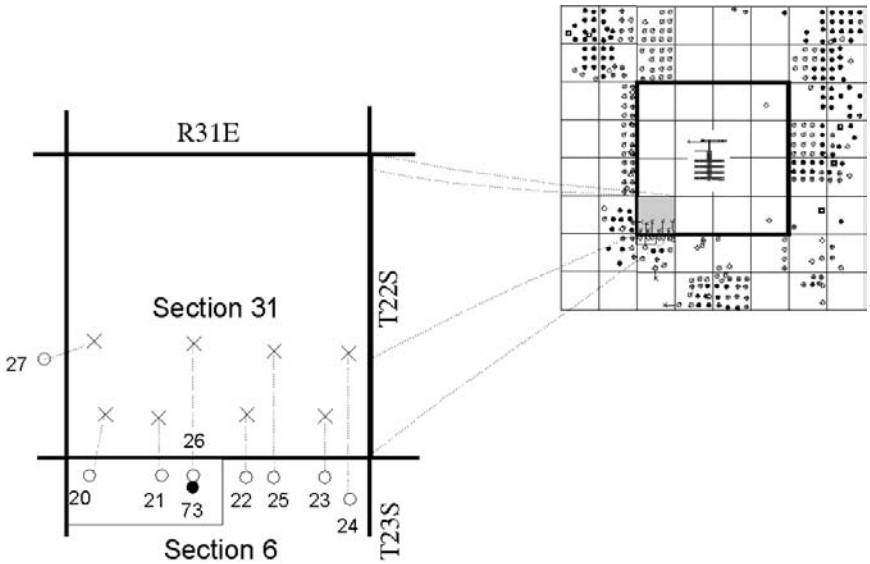

In April 1993, Bass Enterprises et al. applied to the BLM to directionally drill eight wells from Section 6 locations outside the WIPP Site to their oil and gas lease reserves 6000 feet below the WIPP Site. In August 1994, the BLM denied the drilling applications citing the WIPP Land Withdrawal Act.[10] In January 1995, Bass et al. filed a claim in federal court for a takings.[11] In June 1996, the federal court awarded Bass et al. $8.9 million plus interest.[12]

Despite the active involvement of attorneys and officials for the oil companies and four federal agencies (DOE, BLM, EPA, and the Justice Department), the 1978 judgment, forbade drilling wells in Section 6 T23S, R31E, was not discovered until after the June 1996 judgment.[13,14,15] (Refs. 14 and 15 attached). Subsequent appeal by the Justice Department states:

> Among the issues that could be addressed on remand are the implication of the discovery, made after the notice of appeal was entered in this case, that Bass did not have the right to drill from three of the locations from which it proposed to drill — and for which it sought and received compensation — because DOE had

condemned those surface locations in 1977.[13]

Hence, in less than twenty years, records failed to communicate important information concerning the restriction against drilling for oil and gas. Furthermore, a vertical gas well, James Ranch Unit 73, was drilled and completed on the eighty acres in July 1996 prior to the discovery of the lease records by the attorneys for the various federal agencies.

Markers

"Any compliance application shall include the period of time passive institutional controls are expected ***to endure*** and be understood."[16].

On October 26, 1963 a twelve kiloton device was detonated underground at Fourmile Canyon, Nevada. The site was designated as the Shoal Site. In the late 1970's the DOE placed a substantial marker consisting of a brass plaque set in a concrete podium and anchored to a concrete base at ground zero. By 1985, the marker at the Shoal site had been completely destroyed by a massive explosion with pieces of marker scattered to the west. The brass plaque had disappeared. Shown below are the gathered remains of a DOE marker intended to identify an area contaminated by radioactive fission products. This marker lasted less than ten years. This example raises questions on the DOE's commitment to maintain a marker at WIPP.

Recommendation

EEG recommends that the EPA include full consideration of these lapses in the assessment of the DOE's claim of 99% effectiveness of passive institutional controls from 100 to 700 years after closure.

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4. Manus, R.L., 1991. October 17 letter from BLM Carlsbad Resource Area Manager to A. Hunt, DOE WIPP Project Manager.

5. Becker, R.M., 1991. October 23 letter from DOE Repository Technology Group to R.L. Manus, BLM Carlsbad Resource Area Manager.

6. Neill, R.H., 1993. March 9 letter from the Director of the Environmental Evaluation Group to W.J. Arthur, WIPP Project Director.

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8. McGough, J. M., 1981. December 30 letter to G. B. Koski, Area Manager, U.S. Bureau of Land Management, Carlsbad Office.

9. Silva, M.K. and Channell, J.K., 1992. Implications of Oil and Gas Leases on the WIPP on Compliance with EPA TRU Waste Disposal Standards. EEG-50.

10. Calkins, W.C., 1994. August 22 letter from the U.S. DOI/BLM State Director for New Mexico to Keith E. Bucy of Bass Enterprises Production Company.

11. Bass Enterprises Production Company et al., 1995. January 23 Complaint for a taking in violation of the U.S. Constitution. Case 95-52L, U.S. Court of Federal Claims, Washington D.C.

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13. Schiffer, L.J., 1996. Appeal from a judgment of the United States Court of Federal Claims in 95-CV-52 entered June 21, 1996, Judge Robert H. Hodges, Jr.

14. Neill, R.H., 1997. January 3 letter from the Director of the Environmental Evaluation Group to Susan Cook, Attorney for the U.S. Justice Department.

15. Martin, M.K., 1997. February 13, 1997 letter from Attorney for the U.S. Justice Department to R.H. Neill, Director of the Environmental Evaluation Group.

16. U.S. Environmental Protection Agency, 1996a. 40 CFR Part 194, Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations, Final Rule. Federal Register (9 February) vol. 61, no. 28, 5224-5245.

POTASH MINING

The CCA underestimates the areal extent of potash reserves and the potential impact of the mining of potash within the site and on adjacent federal and state properties. The use of only the existing leases adjacent to the site does not account for the currently economical potash reserves. Figure 1 shows the extent of lease grade potash ore as determined by the Department of Interior. Further, the Department of Interior notes that potash ore has been and can be economically mined at ore concentrations less than current lease grade[1].

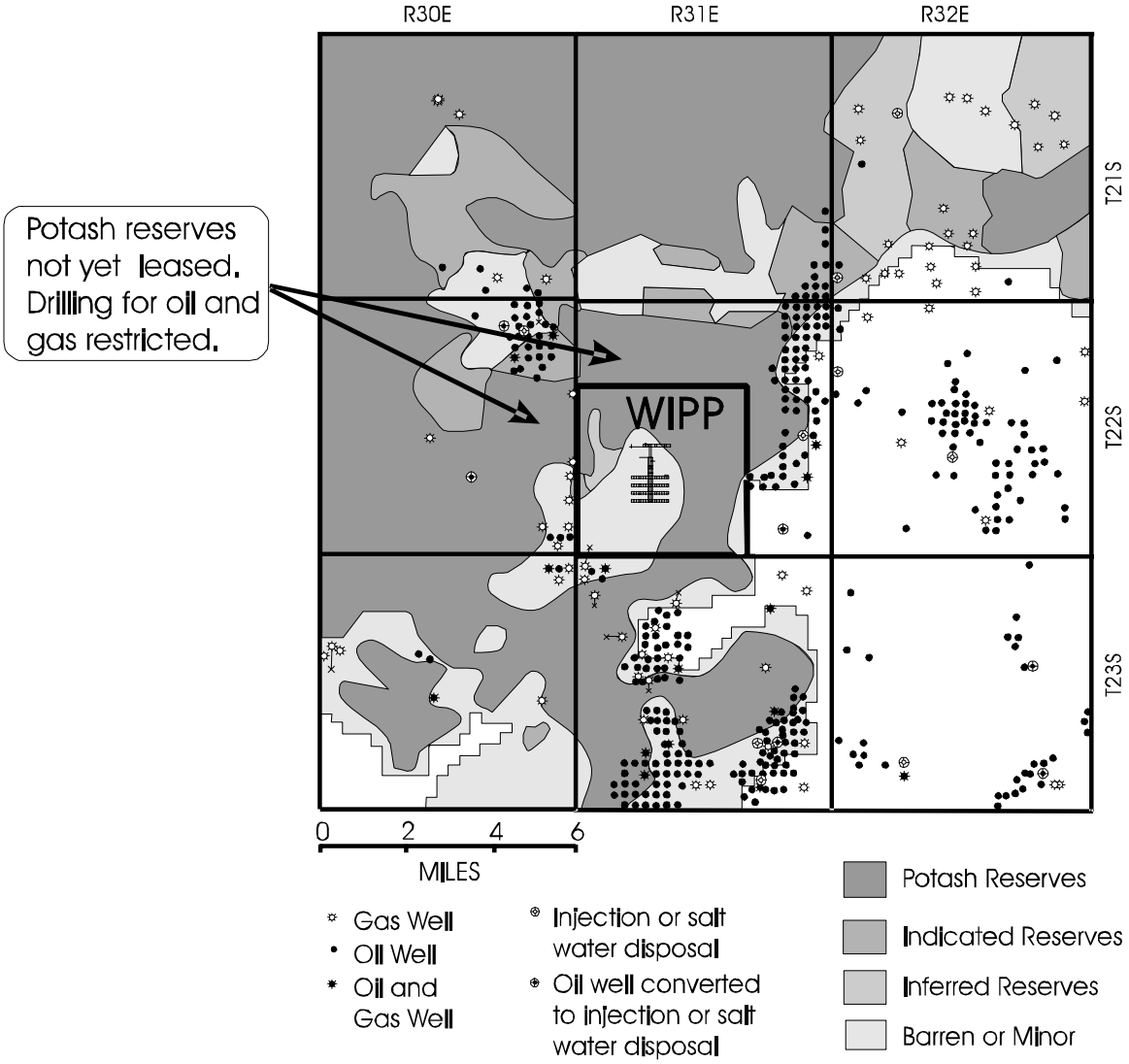

Figure 1. Lease grade potash ore[2] and oil and gas wells.[3]

For illustrative purposes, Figure 1 identifies one area of known potash reserves adjacent to the northwest boundary of the WIPP Site. Figure 2 indicates that these potash reserves have not been leased. Potash operators are allowed to hold, directly or indirectly, no more than 51,200 acres in potash permits and leases in a state (43 CFR 3530.3). An operator may not hold all the potash leases he intends to develop (Ref.4, p. 11).

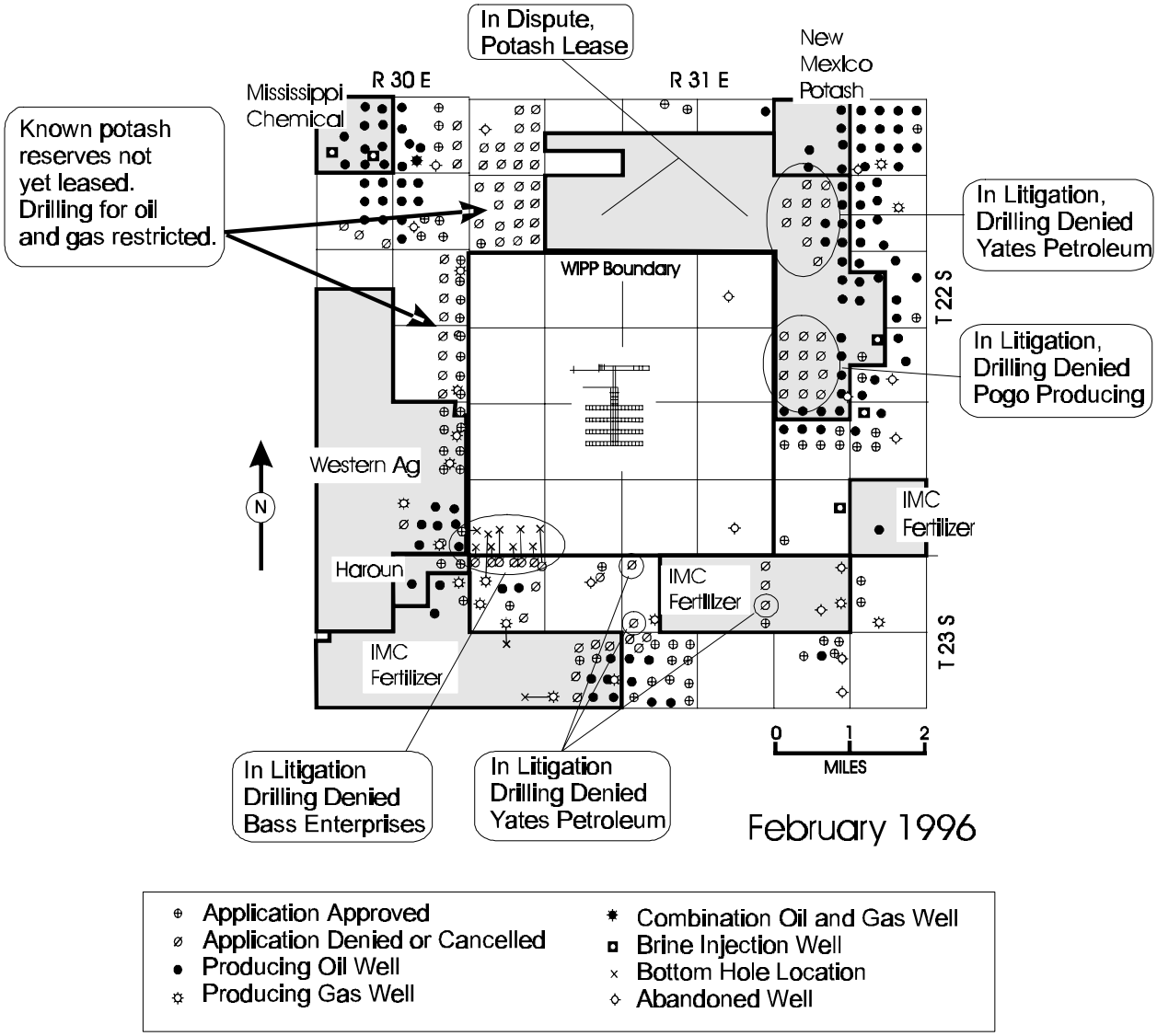

Figure 2. Drilling for oil and gas restricted by BLM due to the presence of potash reserves, leased and unleased.

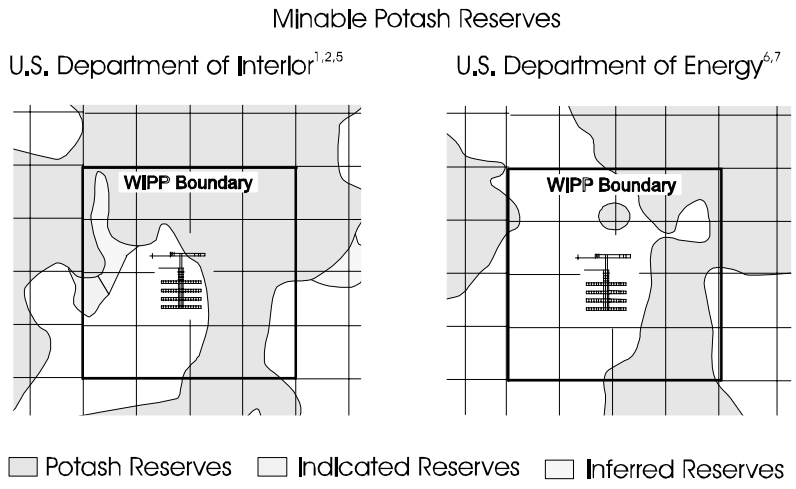

Figure 3. Minable potash.

Figure 3 shows the different estimates by DOE and DOI of the extent of minable potash within the WIPP site.

As shown in Figure 4, the CCA does not include the impact of potash mining in unleased areas which will also affect the regional hydrology. 40 CFR Part 194.32 states:

> Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur.

EPA's Compliance Application Guidance for 40 CFR Part 194 (p. 46) states:

> EPA recommends that DOE use minable reserves in estimating mine linve and the extent of potential mining.

The Use of only the existing potash leases does not therefore satisfy the EPA's intent.

Limiting the CCA to "near future" resource recovery activities appears to be inconsistent with the Federal Land Policy and Management Act[7] and limiting the CCA to "exisiting leases" does not reflect anticipated mining. All federal public lands, including those adjacent to the WIPP Site, are "to be managed in a manner which recognizes the nation's need for domestic sources of minerals, food, timber, and fiber...." (Ref.8, §1702(12)). In addition, FLPMA requires the management of federal lands "be on the basis of multiple use and sustained yield unless otherwise specified by law" (Ref.8, §1701(7)). "The term multiple use means the management of the public land and the various resource values so that they are utilized in the combination that will best meet the present

and ***future needs*** [emphasis added] of the American people" (Ref.8, §1702(c)). The term multiple use also means "a combination of balanced and diverse resource uses that take into account the ***long-term needs of future generations*** [emphasis added] for renewable and nonrenewable resources.... Sustained yield is defined as "the achievement and management ***in perpetuity*** [emphasis added] of a high-level annual or regular periodic output of the various

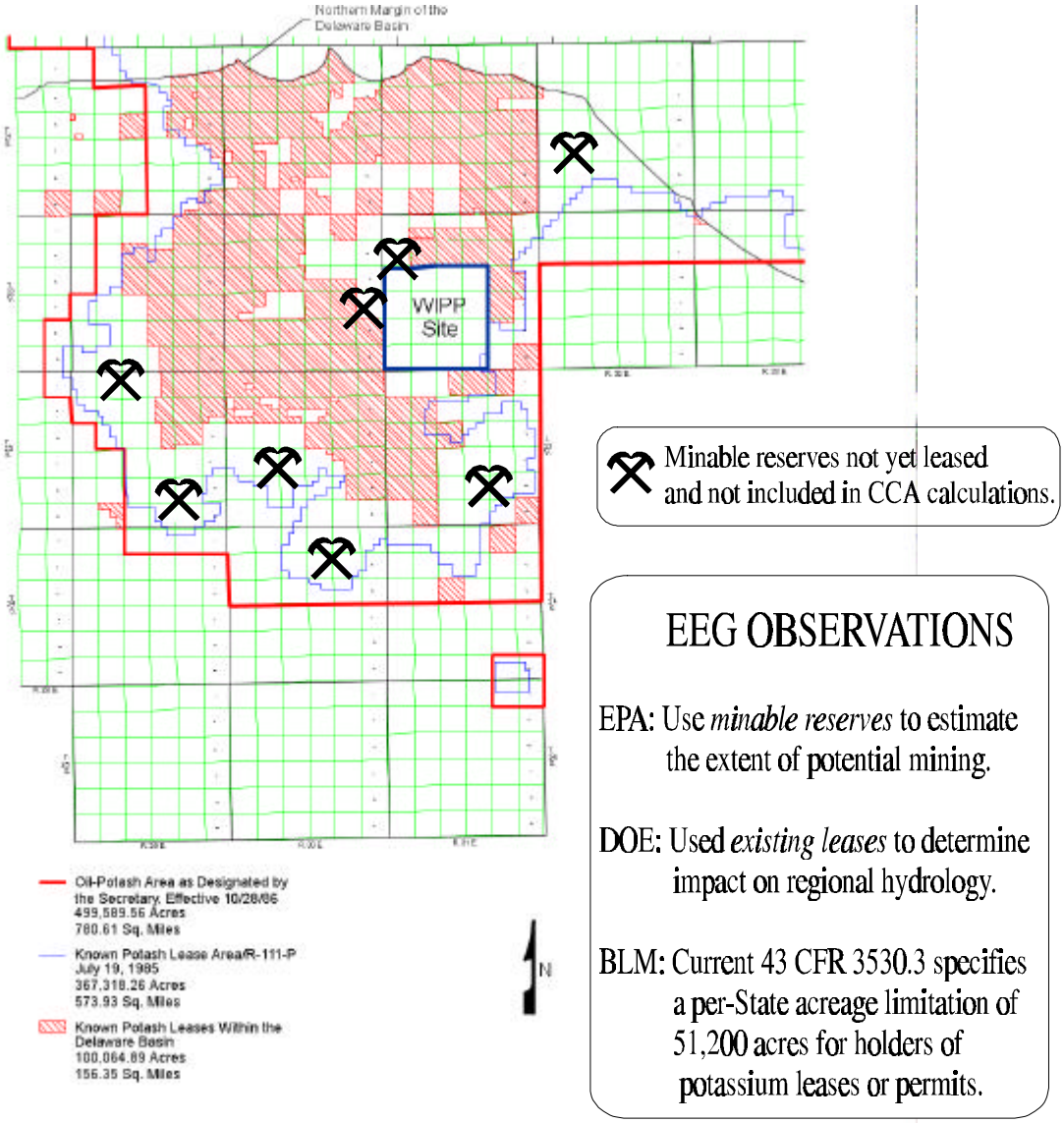

Figure 4. Potash leases within the Delaware Basin and minable potash not yet leased.

renewable resources of the public land consistent with multiple use" (Ref.8, §1702(h)). Human activities in the resource rich areas surrounding the WIPP are not limited to the ***near future*** and are not limited to ***the expected use of existing leases***.

The objectives of the state are also "to prevent waste, protect correlative rights, assure maximum conservation of the oil, gas and potash resources of New Mexico, and permit the economic recovery of oil, gas, and potash minerals..." (LeMay et al. 1988).

Recommendation

EEG recommends that the CCA consider all minable potash resources, as specified by the BLM, in the performance assessment calculations.

References

1. Cone, L.M., 1995. Oct 12 letter from U.S. DOI/BLM District Manager to G.B. Griswold.

2. U.S. Department of Interior, 1993. Preliminary Map Showing Distribution of Potash Resources, Carlsbad Mining District, Eddy and Lea Counties New Mexico By Bureau of Land Management, Roswell District.

3. Broadhead, R.F., F. Luo, and S.W. Speer, 1995. Evaluation of Mineral Resources at the Waste Isolation Pilot Plant (WIPP) Site. Carlsbad, NM: Westinghouse Electric Corporation, Waste Isolation Division. Vol. 3, Chapter XI.

4. Vaughn, G.L., 1995. December 13 Agency Answer to Appellant's Statement of Reasons by U.S. Department of Interior Bureau of Land Management General Counsel. Yates et al., appellants. IBLA 92-612.

5. Griswold, G.B., 1995a. Method of Potash Reserve Evaluation, In Evaluation of Mineral Resources at the Waste Isolation Pilot Plant (WIPP) Site. Carlsbad, NM: Westinghouse Electric Corporation. Waste Isolation Division, vol. 2, Chapter VII.

6. Griswold, G.B., 1995b. October 16 letter to J. Barker, of the New Mexico Bureau of Mines and Mineral Resources, P. Anselmo of the New Mexico Institute of Mining and Technology, W. Thayer of IMC Corporation, and S. Patchet of Westinghouse Waste Isolation Division.

7. U.S. Department of Energy, 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184.

8. Federal Land Policy and Management Act of 1976. U.S. Code Annotated, 1989. vol. 43, secs. 1701-1784.

DOCUMENTATION OF FEPs AND PARAMETERS

In reviewing the CCA, assumptions concerning the features, events, and processes (FEPs) used in performance assessment (PA) and parameters used by the computer modeling should be checked to ensure that supporting documentation is valid. Due to limitations in manpower the EEG has not made as extensive effort to investigate the DOE's documentation of its efforts in these areas as has the EPA. However, in conjunction with various EPA efforts at SNL since the publication of the CCA, the EEG has investigated a small sample of both parameters and FEPs. This sample shows that there is cause for concern about the records available for both FEPs and parameters. In brief, three of the four parameters examined showed what seem to be significant problems for CCA documentation; and FEPs screening activities are dominated by what appears to be significant omissions and errors.
The information below may no longer be current, as SNL attempts to improve the documentation as feedback from the EPA is received. The attempt here is to show the types of problems that were in the documentation at the time the CCA was submitted.

CCA Appendix PAR Values Differ from PA Code Values

The parameter database used to construct Appendix PAR is different than the parameter database used by the computer codes at the time PA analysis for the CCA was performed. A later version of the parameter database, in which different values for some of the parameters had been added, was used for Appendix PAR, according to SNL personnel.

Table PAR-12 in the CCA shows Parameter ID # 3148, bulk compressibility (COMP_RCK CONC_PLG), to have a value of 1.2E-09 Pa^{-1}, whereas the value used in the CCA PA calculations was 2.64E-09 Pa^{-1}. Supporting documentation (Form 464s in WPO # 36591) indicates the value was 0 Pa^{-1} from March 14, 1996, to May 2, 1996, when it was changed to the 1.2E-09 Pa^{-1} value. The 264E-09 Pa^{-1} value apparently preceded the March 14, 1996 date. This implies that the parameter database used in the CCA PA may have preceded the March 14, 1996 date.

A June 17-21, 1996, CAO audit of SNL (A-96-03) discovered that many parameters had been entered into the database without following proper procedure, which included not only completion of records but also required reviews and sign-offs before entry into the database. The list of such parameters eventually grew to more than 230 (out of 1500 total parameters). If the CCA PA was using a database established prior to corrective actions for these parameters then the parameters may not have been properly qualified for use.

Documentation of Supporting Information for Parameters

Form 464s are the records that establish and justify values for parameters that are to be entered into the database used by PA analyses. The Form 464s either show justifications directly or provide information which allows tracing of the values to supporting data and analyses. For the

Castile Brine Reservoir Pressure parameter (WPO #31612), successive Form 464s may be used to illustrate the sorts of problems encountered in tracing values used for parameters.

The later of two Form 464s in the data package changes the distribution "Type" of the earlier Form 464 from "cumulative" to "triangular", which changes the method of calculating the uncertainty distribution from the median value to the mode. The use of the median value (cumulative distribution) is supported in 5 pages of information attached to the earlier Form 464, but the later Form 464 merely announces the change to the mode (triangular distribution) without justifying it. The only documentation for the change is the statement under "Interpretation" on the later Form 464:

> The mode is entered into the database in place of the median. The median was calculated and is 13.4E+06 Pa.

Apparently, the mode value was erroneously placed into the database as a median, because the mode value had been erroneously entered on the earlier Form 464 in the median block. On discovery, the solution was to use a new Form 464 to change the type of distribution so that the mode value already in the database would match the Form 464, rather than change the value in the database to the correct median value. The result appears to be that an unsupported value of 2.17E+07 Pa is in the database instead of the supported value of 1.34E+07 Pa.

The support information for the Form 464s shows additional problems. Attached to the 464s is a document entitled "Original Interpretation (1/12/96)", which includes a table of data that:

> ...defines a cumulative (empirical) distribution based on the 8 data points for pressure mentioned in the <u>source</u> <u>document</u> (SWCF-A:1.2.07.1: PDD: NON-SALDO: PKG # ?: Castile Brine Reservoir)
>
> The weights to be given to the 8 values of pressure were specified by author of source document.

The 8 pressure data point values are copied into a second table later on the page, and includes the weighting value for each.

Two other documents in the package (changes suggested by Tierney and Freeze) add two more pressure values, for a total of 10, without documenting the rationale for the addition, or referencing any document which might explain it. These might be in the "source document" cited in the quotation above, but that quote specifies "...the 8 data points...", not "...8 of the data points...".

Further, the weighting assessments are different between the Tierney and Freeze two documents, and both differ from the weighting assessments in the original interpretation. No justification is given for changing these weighting factors.

The Freeze document is apparently one page from a larger document to which there is no reference tie. On the page included, the statement is made:

> The weights are approximately based on distance from the repository. Note that WIPP-12 (inside the site boundary) is assigned a weight of 0.45...The rationale for the weights for the highest pressures (17.4 and 20.0 Mpa [sic]) is described in a later paragraph.

No later paragraph in the included parts of the document describes weighting rationale for the added pressure values, and WIPP-12 is assigned a weighting value of 0.30, not 0.45, in the table just above the quoted statement (WIPP-12 is the 12.7 MPa pressure value).

The last page in the supporting documentation consists of two source document listings, one a SAND document and the other the 1992 PA. The references list specific page numbers; the referenced pages in both documents consist of descriptions of Salado porosity parameters, and would seem to having nothing to do with Castile brine reservoir pressure.

The Form 464 points to another SNL data package (WPO # 31072), which contains a memorandum listing the data that had been sent to the Natural Barriers Peer Review Panel (the Panel was to perform a necessary review for quality assurance purposes). However, there was no documentation of the findings of the Peer Review Panel in the package, or references to the Peer Review Panel Report.

Another parameter data package (Castile Brine Reservoir Permeability; WPO # 31070) which had been sent to the same Peer Review Panel did contain a memorandum that referenced the Panel Report qualifying the parameter.

Castile Reservoir Compressibility/Volume Documentation

Another parameter (Castile Brine Reservoir Rock Compressibility; Parameter # 61) offers an interesting set of memoranda from key SNL personnel. Briefly, in late August, 1996, a SNL scientist sent a memorandum to SNL's upper management in which he stated that

> ...I believe that treatment of brine reservoirs for the CCA was indefensible and non-conservative. I believe we are systematically underestimating the amount of brine that could reach the repository....The low end of the range comes from interpretation of hydraulic tests in Salado anhydrites, not from any direct Castile anhydrite measurements. The high end of the range comes from generic information reported by Freeze and Cherry (1979) for the compressibility of jointed or fractured rock, again not from actual Castile data...

The conclusion quoted above covers both the compressibility and volume of Castile brine reservoirs, which SNL analyses consider to be interdependent.

On October 3, 1996, the same scientist wrote another memorandum in which he concluded that, because the range of values he had calculated fell within the range used in the CCA, and other SNL personnel had told him that sensitivity calculations showed that the change in range would not shift the CCDFs, the treatment of Castile brine reservoirs in the CCA was acceptable.

However, whatever the effect on the CCDFs, the range used for the parameter in the CCA are still "...indefensible and non-conservative." None of the later memoranda contest this statement.

A graph of the data points appended to the October 3, 1996 memorandum shows that the new range lay in the upper end of the range used in the CCA calculations, and the data points that lay below the new range (38% of the total) were a much longer chain, while the ones above the new range (13% of the total) were more closely associated with the new range. Monte Carlo or Latin Hypercube Sampling would seem to result in more emphasis on lower values while using the CCA range than would be the case with the new range shown in the memorandum.

This package also received its QA acceptability from the Natural Barriers Peer Review Report (DOE/WIPP-96*2004). The peer review was held months before the new range was developed, and it would seem that a similar body should pass on the validity of the use of a new range of values for the parameter.

It may be worth noting that the discussion in the Natural Barriers Peer Review Report indicates that the peer review panel viewed Castile data from the WIPP-12 borehole in considering these parameters (see Report, p. 5-18) which the SNL scientist's memorandum stated was not used in the supporting documentation for the parameter.

Documentation of the Culebra Porosity Parameter As A Constant

The CCA (in Appendix PAR) states that:

> Parameters may also be assigned a constant value in the performance assessment parameter database. These parameters are tabulated at the end of the appendix. [PAR.2.1, end of section]

The Culebra porosity parameter (Parameter ID 140, Effective Porosity) is in the Table PAR-30 (Appendix PAR, p. PAR-214) as a constant value of 1.5100E-01. The Form 464 for the parameter (WPO #32769) describes the distribution type as a constant, and states a curious circular logic in the "Interpretation" section:

> The distribution equates a point and that point is equal to the mean. Therefore, that point is a constant.

However, the documentation appended to the Form 464 shows an approximate 30% standard deviation among the 103 data points used to establish the mean. Justification for the change

(from a "student's t" distribution type) is a memorandum entitled "Distributions" (Tierney, March 21, 1996) that describes the use of the various types of distributions (cumulative, delta, normal, triangular, uniform, lognormal, loguniform) but does not a description for "constant" distributions. When SNL personnel were asked for documentation of the rationale for using a constant, a memorandum relating to category 3, physical constant parameters (Pi, Avogadro's number, etc) was the only information available (the porosity parameter is a category 1, derived from experimental data). In short, no justification is provided in the data package or seems to be available for considering this parameter to be a constant.

Documentation of Features, Events, and Processes (FEPs)

Operations involving the screening and other processing of FEPs are inadequately documented. 25% of the original FEPs list was eliminated with no documentation of the process; 70% of the remaining FEPs have essentially no more documentation than what appears in the Compliance Certification Application (CCA). The documentation for the other 30% also appears to be incomplete. The rationale for excluding many of the FEPs from performance assessment (PA) is not documented in the CCA, as required by 40 CFR 194.32(e)(3).

The DOE originally developed a list of nearly 1200 FEPs, and the draft CCA (the DCCA; DOE/WIPP/CAO-2056, March 31, 1995) considered about 900 FEPs. For the CCA, approximately 240 were to be addressed, and about 90 of these are said to be "screened in", or used in the PA process. The DCCA list (≈900) is included as Appendix A to Attachment 1 of Appendix SCR to the CCA; the CCA list (≈240) are in the CCA as three tables, found in Chapter 6 (Tables 6-3, 6-4, and 6-5) and also in Appendix SCR (Tables SCR-1, SCR-2, and SCR-3).

No screening analysis plans were utilized for the reduction of the nearly 1200 FEPs to the approximately 900 included in the CCA, nor is there any documentation of the process used for each FEP. Reduction of the ≈900 was also performed without an analysis plan; this operation was later reviewed, and about 30% of the FEPs were passed on to the "SNL Side Efforts Program". The preliminary decisions on the other 70% of the FEPs seems to have been accepted without documentation of the process for including or excluding them. (The 70%-30% split of FEPs is taken from SNL documents and has not been independently verified by the EEG.)

The 30% that passed to the SNL "Side Efforts" program are required to have packages supporting the screening decision in the Sandia-WIPP Central Files (SWCF); these were to be screened based on the "FEPs Screening Analysis Plan, Version 5.2, for Phase I FEPs", dated 12-20-95 (for FEPs related to numerical and conceptual models), and "FEPs Screening Analysis Plan, Version 5-4, for Phase II FEPs" dated April 29, 1996 (for parameterized FEPs). However, at least 31 of the "Side Efforts" FEPs were only to be documented in the CCA (letter from DOE's McFadden to EEG's Neill dated August 2, 1996).

These 31 FEPs may have been part of a perhaps larger group of Phase II FEPs which were not processed in accordance with the analysis plan due to "resource constraints". The Change

Control Board was utilized to justify incorporating these FEPs into the CCA (see Wilmot, R.D., "Relationship of Side Efforts to the Compliance Certification Application" Galson Sciences Ltd 9507a-6, November 26, 1996, p. 2).

Not all of the 31 FEPs are documented in the CCA. Only "Side Efforts" FEPs were given an alphanumeric designator; the first FEP on the list (from the Neill-to-Dials letter dated July 11, 1996), "DR11, waste degradation", does not appear in the CCA nor did a rationale for its exclusion seem to be included. The Galson Sciences Ltd document cited above was written to document the location within the CCA of side efforts (p. 1); it indicates (Table 2, p. 15) that this FEP is

> ...not included in PA calculations [because]...Changes in mechanical and hydrological properties of the waste caused by corrosion need not be explicitly modeled.

Table 2 also indicates that the FEP is discussed within the CCA in Sections 6.4.3.1, 6.4.3.2, and 9.3.2.2.5. These sections do not provide a rationale for excluding waste degradation--indeed, the discussions in these sections only discuss waste in terms of consolidation (p. 6-97 & 6-98), gas generation (p. 6-100) and compaction (p. 9-138). The sections from Chapter 6 could be better used to show that consideration of waste degradation was included in the PA.

Appendix A, "DCCA Fep List By Category", of Attachment 1 of Appendix SCR to the CCA does list a general category of "1.9 Waste: degradation/corrosion/dissolution" with 12 subcategories (p. 26), but no alphanumeric designators are supplied. This seems to be the closest representation of the "Side Efforts" FEP designated as "DR11, Waste Degradation", in the CCA.

This illustrates a principal concern EEG has about the FEPs documentation process: many FEPs seem to be neither adequately defined nor consistently identified. FEPs would seem to require more than a two or three word designator to adequately delineate what is encompassed and excluded from the concept, but the CCA does not contain such descriptions, nor do such accurate definitions seem to exist.

A second concern is that 40 CFR 194.32(e) requirements for documentation seem to be inadequately met. 40 CFR 194.32(e) requires that the CCA include (1) identification of all FEPs that might affect the disposal system in the regulatory time frame; (2) a list of those used in PA; and (3) documentation of the rationale for excluding those not used. There are abundant lists that show which FEPs were used in PA (Tables 6-3, 6-4, and 6-5 of Chapter 6, which are duplicated in Tables SCR-1, SCR-2, and SCR-3 in Appendix SCR; and Table 4 of Attachment 1 to Appendix SCR), but the original list of ≈1200 FEPs has not been included, and the rationale for not including at least some of the FEPs seems to be missing.

A third concern is that the Change Control Board decision to incorporate FEPs which had not been processed in accordance with analysis plans would seem to have circumvented the WIPP

quality assurance programs.

This leads to a fourth concern: it appears that much of the work on FEPs has not been performed in accordance with the Nuclear Quality Assurance (NQA) standards required by 40 CFR 194.22(a). NQA-1 Basic Requirement 5 states:

> Activities affecting quality shall be prescribed by and performed in accordance with documented instructions, procedures, or drawings of a type appropriate to the circumstances. These documents shall include or reference appropriate quantitative or qualitative acceptance criteria for determining that prescribed activities have been satisfactorily accomplished.

Prescribing instructions or procedures which included acceptance criteria were apparently not developed for much of the FEPs process.

When questioned about QA assessments of the FEPs screening and documentation process, SNL cited CAO surveillance S-96-21 as having covered the 70% FEPs in its assessment of the DCCA. According to the surveillance report, this assessment was conducted by one auditor and a software QA specialist over a five-day period (February 5-9, 1996), and covered training and personnel qualification, procurement control, document reviews, records, and software. The only part of the report that could possibly be considered an assessments of FEPs is in the section concerning technical document reviews (p. 4), which covered not only the entire DCCA, but also the RCRA permit application, No Migration Variance Petition, and an Engineered Alternatives study. There is no documentation that any FEPs were reviewed during this surveillance. Thus, the reduction of FEPs from ≈1200 for the CCA's ≈240 has not been assessed by an independent organization.

FEPs in the "Side Efforts" program were said by SNL to have been assessed during CAO surveillances S-96-04 (December 1995), S-96-32 (April 1996), and CAO audit A-96-03 (June 1996). The program was still in progress during this time period, and the Change Control Board decision may not have been fashioned yet.

FEPs Screening Decision Adequacy

For the CCA, FEPs were eliminated (screened out) from consideration in PA by one of three criteria: regulatory (SO-R), for FEPs excluded by language in 40 CFR 191 or §194; low consequence (SO-C) FEPs; and low probability (SO-P) FEPs, which are defined in §194.32(d) as processes and events with less than one chance in 10,000 of occurring over 10,000 years. For SO-P, the CCA offers a less stringent interpretation (Section 6.2.2.1 lines 20-23, p. 6-39):

> In practice, for most FEPs screened out on the basis of low probability of occurrence, it has not been possible to estimate a meaningful quantitative probability. In the absence of quantitative probability estimates, a qualitative

> argument has been provided.

Some FEPs screening arguments seem inadequately supported. For example, GG-13, electrochemical gradients, is screened out on the basis of probability (Galson Sciences Ltd 9507a-6, p. 25). The argument offered in Appendix SCR (p. SCR-62) is:

> Galvanic coupling could lead to the establishment of potential gradients between metals in the waste form, canisters, and other metals external to the waste form. Such electrochemical effects can potentially influence corrosion processes and therefore gas generation rates and chemical migration...Good physical and electrical contact between the metals involved is critical to the establishment of galvanic cells. Experience with experimental investigations suggests that this requirement is unlikely to be achieved under repository conditions.

None of the experimental investigations are listed in Appendix SCR. However, the Sandia-WIPP Records Center does store supporting documentation for the CCA, and for this FEP the records package is WPO # 31491, "Electrochemical Gradients Qualitative Screening Arguments for Side Effort GG-13". This document echoes Appendix SCR, stating that the FEP is SO-P because:

> Good physical and electrical contact between the metals involved is critical to the establishment of galvanic cells. Experimental investigations suggest that this requirement is unlikely to be achieved under repository conditions (Telander and Westerman, 1993).

The cited document is SAND92-7347, "Hydrogen Generation by Metal Corrosion in Simulated Waste Isolation Pilot Plant Environments: Progress Report for the Period November 1989 through December 1992". The EEG was unable to locate any descriptions of experiments or any data relating to physical or electrical contact between metals, or any references to galvanic cells or coupling in the document. The report covers experimentation on corrosion and consequent H_2 gas generation by low-carbon steel and alternative packaging materials in contact with gases (N_2, CO_2, H_2S) and brine, but offers no indication that interactions between metals was ever a consideration.

For this SO-P FEP there is not only no evidence that the 1 chance in 10,000 over the next 10,000 years criteria is met, there also appears to be no evidence for the less stringent qualitative argument offered.

In discussing this FEP, the DOE has intermingled electrochemical gradients (GG13) with another FEP, galvanic coupling (GG12), and then used an argument based on galvanic coupling to cover electrochemical gradients; this intermingling amounting to a circular argument exemplifies the EEG's concern about inadequate delineation of FEPs. Electrochemical gradients may be formed by means other than galvanic coupling (oxidizing conditions in one part of the repository,

reducing in another, with brine linking them), and the possibility of such gradients should also be addressed.

Given the uncontrolled and intense compression the waste in the repository will undergo, it seems possible that the necessary physical and electrical contact between metals cited in the CCA as necessary for galvanic coupling can occur. The DOE's contention that this will not occur is unsupported by cited documents. A reliable and objectively supported argument should be advanced before rejecting the possibility--for both the GG12 and the GG13 FEPs.

FEPs Excluded on the Basis of Administrative Control

Table C-3 in Appendix C to Attachment 1 of Appendix SCR to the CCA (SCR p. 92 & 93) is titled "FEPs on the DCCA FEP list excluded from the development of the CCA FEP list as issues relating to designs different to that forming the basis of the CCA".

The FEPs in the table are the sorts of events that would seem to require a more serious consideration before excluding them from PA. Among these are the FEPs "Backfill/seal material deficiencies", "inadvertent inclusion of undesirable materials", "poor quality construction", "radioactive waste disposal error", "stray materials left", "Preclosure events", "Faulty seal emplacement", "Inadequate seal or compaction, voidage", and "Seal material deficiencies", all of which would seem to be possible events which could alter the adequacy of the repository for its intended task.

"Abandonment of unsealed repository", another on the list, would certainly seem important enough to require close consideration. Will there be funding and a willingness to continue the WIPP for a full 35 years anticipated by the design presented in the CCA?
A statement in the narrative portion of Appendix C (pp. 11-12) addresses exclusion of these FEPs:

> FEPs relating to constructional, operational and decommissioning errors (classified as RD in the DCCA) have been eliminated from the CCA FEP list. The DOE has administrative and quality control procedures to ensure that the facility will be constructed, operated, and decommissioned as specified in the CCA.

The EEG considers this statement to be inadequate justification for excluding these FEPs. Among other examples, recent administrative and quality controls concerning drilling rights and privileges in the vicinity of WIPP (see recent EEG discussions of active and passive institutional controls) illustrate that such controls are not always effective.

General Considerations: DQC's

1. For sampled distributions, CCA Chapter 5 provides a good description of why simulation values need not be covered by DQC's:

   - Applicable to tasks involving quantification through sampling and analysis of specific constituents in an environmental medium (e.g., pollutants in wast streams waste characterization and environmental monitoring).
   - The performance assessment is estimated using mathematical models rather than being determined by direct measurement.

     1) Parameters are treated as being uncertain variables, rather than precisely determined quantities and are characterized by probability distributions.

     2) Parameter distributions may span several orders of magnitude due to uncertainty introduced in subsequent processing. Many parameters derived from data measurements need be known only within orders of magnitude of their true value. Efforts to reduce the range do not necessarily improve model accuracy.

     3) As an example, data accuracy would be very difficult to assess for geologic site characterization activities because reference or true values do not exist.

     4) In summary, it's not practicable to apply DQC's to most scientific investigations used support a performance assessment, in which there uncertainty in the conceptual models and the resultant ranges of parameters. Instead, controls established by the QA program provide the necessary quality.

2. There are a lot of technical discussions that could be presented to describe why DQC's don't apply to specific data sets The intent here is to provide some general discussion regarding the topic.

3. 194.22(c) itself says "...to the extent practicable, information which describes how all data used to support the compliance application have been assessed for their quality characteristics, including:...[PARCC]".

4. Natural features do not lend themselves to DQC's.

Attachment 1
P. 1

January 16, 1997

CATEGORY	DATA SET	DATA SET DESCRIPTORS	PRECISION, ACCURACY, REPRESENTATIVENESS, COMPLETENESS, COMPARABILITY (PARCC)
Dominant force - relative to releases	Particle Size	• Particle sizes of waste and backfill at the time of human intrusion • What future waste might look like 10,000 years • No physical data collected • interpretative • Sampled distribution	P: No physical data collected by project. Values were selected by smallest size analog materials & largest annular space. Smallest sized values determined from textbooks standard equations. A: No physical data collected by project. Values were selected by smallest size analog materials & largest annular space. Smallest sized values determined from textbooks standard equations. R: The uniform distribution assures that all possible values are fully represented. C: Distribution captures plausible and realistic values. C: N/A. Because there is only one data set. All of the available data were used.
Less important - relative to releases	The Probability of Microbial Degradation	• Interpretative • ~~Some data collected~~ • Estimate of the likelihood of occurrence of gas generation - 50% likelihood	P: Data collected was not used to determine the distribution. Model decision formulated - 50% likelihood (yes/no), if the process will take place. The 50% value reflects a lack of knowledge of the distribution. A: Data collected was not used to determine the distribution. R: 50%, only 2 possibilities. C: Based on ~~non-experimental data and~~ interpretation. C: N/A: ~~Because there is only one data set.~~ For the 50% there are only 2 possibilities.
No Impact - relative to releases	Anhydrite Permeability	• A measure of a porous medium to transmit fluid • Experimental data • Field data • Laboratory data • Sampled distributions	P: A wide range of values doesn't affect release. The laboratory and field data were combined into a single data set. A: Distribution was set up to account for a wide range of data and uncertainty in data points. R: Latin Hyper Cube sampling assures that distribution and values fully represented. C: Latin Hyper Cube sampling assures that distribution and values fully represented. C: N/A: Because all of the available data were used to create the distribution.

Attachment 1, P. 2

CATEGORY	DATA SET	DATA SET DESCRIPTORS	PRECISION, ACCURACY, REPRESENTATIVENESS, COMPLETENESS, COMPARABILITY (PARCC)
Less important - relative to releases	Gas Generation Rates	• Rate of gas generation • Experimental data • Laboratory data • Sampled distributions	P: Variability in values doesn't significantly affect release. Wide variability due to a large range of conditions in ~~field~~/lab data dominates the variability in the individual experiments. Variability scatter of the data collection values is small compared with the much broader spread assumed by the distribution to account for uncertainties in the conditions. A: Variability in values doesn't significantly affect release. Wide variability due to a large range of conditions in ~~field~~/lab data dominates the variability in the individual experiments. Variability scatter of the data collection values is small compared with the much broader spread assumed by the distribution to account for uncertainties in the conditions. R: The Test Plan is designed to explore the range of conditions expected in the repository. The sampling assures that distribution and values are fully represented. C: Latin Hyper Cube sampling assures that distribution and values fully represented. C: N/A: Because there is only one data set.
Less important - relative to releases	Panel Closure	• Bounding argument • No data collected for panel closure	Permeability is larger than what we think the true value would be. Very conservative value. The true distribution of values would all be below the assumed values and is therefore very conservative. R: Bounds all plausible values.

No Impact - relative to releases	Releases through the Culebra: Kd's	• Experimental data
		  • Field data
		  • Laboratory data
		• All distributions
			P: Variability in values doesn't significantly affect release. Wide variability due to a large range of conditions in field/lab data dominates the variability in the individual experiments. Variability scatter of the data collection values is small compared with the much broader spread assumed by the distribution to account for uncertainties in the conditions.
			A: Distributions set-up for variability uncertainty.
			R: Representativeness of collection cannot be known for 100% certainty for natural features. Therefore accounted for by probabilistic method.
			C: Same as for Representativeness.
			C: N/A: Because all of the available data were used to create the distribution.

Attachment 1
P. 3

ENVIRONMENTAL EVALUATION GROUP

AN EQUAL OPPORTUNITY / AFFIRMATIVE ACTION EMPLOYER

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December 31, 1997

Mr. Frank Marcinowski
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Dear Mr. Marcinowski:

At our meeting on December 10, 1997 in Albuquerque, the EPA WIPP project staff asked us to provide a written description of each of the issues related to the EPA's draft rule on WIPP, that we presented that day. This letter is to provide you a summary of each of the issues that we presented, as well as summaries of the issues that we did not have the time to present that day. Where more details are needed, we have enclosed extended descriptions. As requested by your staff, we have made specific suggestions on how to resolve each of these issues. This letter is not a replacement for the material presented to the EPA, but supplements and amplifies it. Also, please note that our presentations at the 12/10/97 meeting, and this letter, constitute our initial reaction to the EPA's draft rule published on 10/30/97. As we continue to review the voluminous materials released with the draft rule, we will provide additional comments to you in the near future.

As we noted on December 10, the issues presented to the EPA were those for which we have additional analyses or arguments. The issues not discussed that day were those for which we have previously provided detailed comments to the EPA, but the EPA has disagreed with our position, as indicated in the Draft Rule. Those issues are also included here with our reasons for continuing to believe in our previously stated positions. We trust that this material will be of use to you in your continuing review of the DOE application.

SUMMARIES OF THE ISSUES PRESENTED ON 12/10/97

Solubility

In reviewing the basis for the selection of actinide solubilities in the CCA and PAVT calculations, the EEG finds that the FMT model is unique to WIPP and is not used elsewhere. Calculations

using the FMT model result, for example, in a difference of 19 orders of magnitude between the projected solubility of thorium pentacarbonate in the Castile brine versus the Salado brine. This is hard to explain on the basis of differences in the brine compositions. Hence the code becomes suspect. It appears that the EPA verification was limited to an exercise in which EPA used the same computers, codes, and database (after correction of some errors in the database) as DOE, to determine the same numerical values. This is not the standard of verification that one normally applies to chemical modeling codes. Verification would require, at a minimum, an analysis and demonstration that the FMT code correctly solves the simultaneous equations, a thorough comparison with the results of calculations using a code that is used more widely in the modeling community, and a demonstration that the calculations are consistent with all relevant published data. For example, as a preliminary analysis, it would have been more informative if a widely used code such as EQ3 or PHREEQE had been used with the FMT database and then FMT had been used with a database from some other modeling group.

Plutonium will account for 82% of the WIPP radioactive inventory 100 years after closure. The CCA maintains that the plutonium will exist either as Pu(III) or Pu(IV). However, the plutonium data were not used for developing the FMT model to predict the solubility of Pu(IV). Rather, the CCA relied on data for uranium and thorium as analogs. But there are long recognized concerns about relying entirely on the oxidation state analogy to derive thermodynamic constants for modeling complex electrolyte systems. As stated in the NAS/NRC WIPP Committee report (Oct. 1996, p. 129):

> Although the oxidation state model (the assumption that the chemistry of a given oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviations from the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy.

In its technical support documentation, EPA discusses the shortcomings of the solubility uncertainty ranges advanced by DOE. There is no direct basis for the uncertainty ranges for actinides in oxidations states +4 and +6. Moreover, the uncertainty ranges for oxidation states +3 and +5 are derived primarily from non-actinide data. Nonetheless, EPA has accepted the ranges as adequate, commenting “It is not clear that including more data for the other actinide state would appreciably change this range” (EPA, III-B-17, p.35). The argument is weak. It also remains unclear that the range adequately brackets uncertainty for a population for which data have not been examined.

In the solubility calculations, the CCA inappropriately discounts the role of organic ligands on plutonium solubility. The CCA provides information on the amounts and complexing properties of EDTA and then argues that other organic ligands, such as citrate, will be unimportant despite

the fact that citrate is the most abundant water-soluble organic constituent. Citrate forms extremely strong complexes with actinides in the +4 oxidation state [e.g. Th(IV)], but very weak complexes with other cations. Moreover, the DOE and EPA have each assumed that the actinides and the brine would be evenly distributed and well mixed throughout the repository. The problem with this assumption is that the plutonium and citrate are located in the same drums. These waste forms result from chemical separations of Pu and do not fit the classic description by DOE of TRU waste as contaminated tools, rags, gloves, booties, etc. The solubility of the plutonium for these waste forms must also be calculated as a very stable plutonium citrate complex where other cations in the brine diffusing into the drum cannot compete effectively with the complexed actinides (IV).

Perhaps the most important questionable assumption made in projecting the solubility values used in the CCA and the PAVT is the presence of hydromagnesite as the dominant stable mineral species resulting from the MgO backfill. DOE's experimental efforts with MgO predominantly produced nesquehonite, a magnesium carbonate mineral, with the later appearance of an unidentified phase. Hydromagnesite was not formed in the experiments reported by the DOE (Van Bynum's 4/23/97 report); a hydromagnesite-like unnamed mineral is reported. The chemical structure of this mineral is in fact more like nesquehonite. The DOE and the EPA believe that "hydromagnesite will be the metastable hydrated magnesium carbonate phase and nesquehonite will be an intermediate phase." (EPA Technical Support Document III-B-17, p.2). There is no experimental data for the length of time that nesquehonite is expected to exist. The distinction between the projected hydromagnesite-dominated or nesquehonite-dominated chemical environment in the repository is important because the actinide solubilities in the presence of nesquehonite are 3 to 4 orders of magnitude higher than in the presence of hydromagnesite.

The EEG therefore recommends that the EPA reexamine these issues and provide additional justification for the CCA and the PAVT solubility values. If convincing justification is not available, then the "no backfill", or "nesquehonite" solubilities should be used in a new performance assessment calculation.

The EEG has investigated the effect of actinide solubilities on the mean CCDF plots, using the EPA's PAVT releases, and making no other changes. The investigation (Enclosure 1) included the "CCA" solubilities, "no backfill" solubilities, and "nesquehonite" solubilities. The overall mean CCDF curve for "nesquehonite" solubility moved one order of magnitude closer to the compliance limit at 10^{-3} probability compared to the CCA solubilities (Enclosure 1, Fig.1).

Three Dimensional Processes and Boundary Conditions

This issue was presented to the EPA staff on December 10, 1997 as "2D/3D Modeling in BRAGFLO". The EEG first brought this issue to the EPA's attention as an attachment titled "Brine Inflow From Salado: 2-D versus 3-D Geometry in BRAGFLO" to the 3/14/97 Neill to

Marcinowski letter. The DOE submitted a response as an attachment to the 6/27/1997 letter from G.E. Dials to L. Weinstock. The Draft Rule includes this issue as Issue F in CARD #23. The EEG position is summarized by the EPA as Comment #553 on page 115 of CARD #23, and the EPA response is provided on page 116. EEG's detailed response to the DOE and the EPA positions is provided as Enclosure 2 to this letter. A summary of the issue, the EEG's response, and the EEG recommendation to resolve the issue, follow.

The results of FEP S-1 screening analysis suggest that the two dimensional BRAGFLO model used in the CCA calculations may be misrepresenting repository performance at pressures above the anhydrite fracture pressure. There is the potential of substantially greater brine saturation in the repository at higher pressures than calculated for the CCA. The discrepancy between the 2D and 3D versions of BRAGFLO may have resulted in an underestimate of radionuclide releases to the surface.

To resolve this issue, the EEG recommends that several 3D BRAGFLO simulations of the repository should be performed using the parameter values of vectors used in the CCA performance assessment. The 3D BRAGFLO simulations should be used to provide repository conditions for the normal suite of direct brine release calculations. The calculations should also be assessed in terms of impact on spallings calculations. Spallings simulations are probably not required to assess the impact. The following criteria may be used to select the CCA vectors for running the 3D simulations to bound the magnitude of the problem:

- Since the discrepancy occurs above the fracture initiation pressure, the simulations should be limited to parameter vectors that result in pressures above 12.7 MPa at some time during the 10,000 year time frame.

- Direct brine release calculations should be sensitive to increased brine saturations above the waste residual brine saturation. Vectors that had either large brine saturations or a mobile brine component (saturations above the residual saturation) are more likely to be sensitive to increased brine inflow. Figure 5.1.5 of the preliminary sensitivity analysis report (Helton, 1996) indicates one vector with a 10,000 year pressure above 14 MPa and a brine saturation above 0.4. This is a likely candidate.

- The potential for brine consumption by corrosion should be assessed. Vectors with both slow and fast corrosion rates that also meet the above two criteria should be run.

- If the first simulations indicate a large change in saturation, then assess whether the 3D BRAGFLO simulations indicate a much larger number of significant direct brine releases than those calculated in the CCA. Simulations using brine saturations on the order of 0.1 and 0.3 should be performed.

Review of the EPA Spallings Investigation

The EPA funded a separate investigation of the spallings phenomena that focused on potential limits on spall material reaching the surface because of insufficient lofting capacity of gases vented from the repository (TSD III-B-10 and TSD III-B-11). The EPA investigation determined that venting of the repository would not be energetic enough to bring spall material to the surface. The conclusion is valid for evaluating the CCA spallings model but cannot be extended to the most recent DOE spallings model. The investigation's focus is on relatively long term transport capability consistent with the CCA spallings model. It should be on the immediate transport of material from the formation of an explosive spall cavity, as in the most recent DOE model.

The EPA modeling is superceded by the new spallings model presented in January 1997 (Hansen et al., 1997) to the DOE's Conceptual Model Peer Review Panel. The Panel rejected the CCA model and accepted this new model. This new model predicts that almost all spall would come from the face of the drilling cavity and that the spall process would occur in the first few seconds of repository depressurization.

The permeability reduction used in the EPA model is inappropriate to address removal of the initial spall material. The spallings model of *Hansen et al.* predicts that spalling will stop after a few seconds and that depressurization is negligible beyond roughly 1.5 meters at this time. During this initial depressurization, the source of flow is from the region close to the borehole. It is this local depressurization that would cause spalling to progress away from the drilling bit.

The temporal and spatial discretization of the EPA investigation is far too coarse to investigate the potential for evacuation up the borehole of spall material created in the first few hundred seconds. For example, in the case of a two foot penetration with 0.25 m^3 spall cavity, the first element of the EPA analysis is 0.39 m thick. In the *Hansen et al.* model, the first element is 0.01 m thick. In the EPA investigation the first time step is 86 seconds compared to 0.001 seconds in the *Hansen et al.* model. These differences in both temporal and spatial discretization are an indication that the EPA modeling cannot predict gas velocities from local depressurization reliably. Hence, the EPA model cannot be used to judge the conservatism of the spall model described *by Hansen et al.*, nor the extension of the *Hansen et al.* model to potential spall from air drilling.

Hansen et al. also considered the issue of maximum particle size that could be transported up the borehole. Their results indicate that particles as large as 10,000 microns may be transported to the surface after the mud column has been expelled from the borehole, about 250 seconds after intrusion, and that transport of such large particles could occur for much more than 200 seconds. Two-hundred and fifty seconds is still very early in the EPA investigation (3 time steps). The discretization of the EPA model is too coarse to accurately calculate the flow rates this early in

the 11-day period. In conclusion, the calculations of *Hansen et al.* indicate that transport of spall material up the borehole will not limit the release of spall material to the surface.

The EEG therefore recommends to the EPA to **not** use the results of simplified modeling contained in the draft rule attachments TSD III-B-10 and III-B-11 to confirm the validity of the CCA spallings model, or to limit the potential releases from air drilling.

Stuck Pipe/Gas Erosion Scenarios

"Stuck pipe" is a scenario that occurs when, due to very low permeability of the waste and extremely high pressures in the repository, the amount of failed waste (spall) is more than the carrying capacity of the drilling mud. The spall then presses against the drill string sufficiently hard to slow down the rotation of the drill bit, preventing normal drilling. To free the jammed bit, the drillers pull the drill string up and start drilling again. If the pressures remain high, the driller may have to bring the bit up several times, thus allowing significant quantities of waste to be brought to the surface. "Gas erosion" refers to the scenario in which the failed waste is slowly eroded by the drilling mud when the repository pressure is just above hydrostatic and the waste permeability is low. Under these conditions, waste may be released into the drilling mud at a rate undetectable by the driller. Gas erosion would continue until the repository pressure is in equilibrium with the drilling fluid, and may bring significant quantities of waste to the surface in the process. Both these scenarios were considered by the DOE in an earlier exercise in the WIPP performance assessment (Systems Prioritization Method, 1995), but were not considered in the CCA because the permeability of the waste was assumed to be higher than the threshold for these processes to occur.

The CCA (Chapter 6, p. 6-100) states that permeability of the waste compacted under a lithostatic load was found to be in the range of 10^{-12} to 10^{-16} m^2, but assigns a constant value of $1.7x10^{-13}$ m^2, which is much greater than the assumed threshold of 10^{-16} m^2 for the "stuck pipe" scenario.

This issue was first raised in my February 7, 1997 letter to you, and has been numbered 540 in the draft rule (CARD 23). The response to Comment 540 states that the phenomena of stuck pipe will not occur because the permeability of the waste in the CCA (DOE, 1996-Chapter 6) was greater than the threshold permeability for stuck pipe stated in the CCA (DOE, 1996-Appendix CUTTINGS_S). The EPA quotes additional studies of permeability made by the DOE, in which the waste permeability was found to be 100 times less than the CCA value (Hansen et al., 1997), but still greater than the threshold permeability. Thus, the EPA does not believe that stuck pipe and gas erosion are processes to be considered in the CCA spallings model.

The EEG continues to believe that the "stuck pipe" is a plausible scenario because the threshold of $1x10^{-16}$ m^2 for stuck pipe and gas erosion may be faulty. This value resulted from the CCA Spallings model (as part of CUTTINGS_S), which was found to be conceptually flawed.

Berglund (1994) states that, for model simplicity, a value of $1x10^{-16}$ m^2 will be used for a cutoff for blowout. The new spallings model, GASOUT (Hansen et al., 1997), shows that blowout will cease when permeability is between 10^{-14} and 10^{-15} m^2. Berglund (1994) has shown that when blowout stops, the stuck pipe and gas erosion mechanisms of spall take over because the failed waste will be introduced into the borehole cavity and will not be blown out. Thus, the permeability threshold for the stuck pipe and the gas erosion scenarios appears to be 10^{-14} to 10^{-15}, rather than 10^{-16}. In any case, because of the stuck pipe and the gas erosion scenarios coming into play when the blowout ceases, release to the surface will occur even when the conditions for blowout of the mud column cease. We therefore recommend that it should be assumed that all of the calculated spall material will reach the surface.

Furthermore, the permeability of the waste in the WIPP repository is quite likely to be lower than that anticipated by the DOE. None of the waste surrogates for permeability testing included MgO as a backfill material. It is suspected that MgO precipitation will decrease the permeability by providing material for interstitial cementation, which has been postulated by the DOE's Particle Size Expert Elicitation Panel to be a major contributor to increased waste strength and lower permeability. Since the permeability of the waste is such a key parameter in assessing compliance with the standards, additional permeability measurements on surrogate waste that includes magnesium chloride cement should be carried out. Until this is done, the calculations may sample on the 10^{-12} to 10^{-16} range.

To get a perspective on the potential magnitude of impact of these scenarios on compliance, the EEG conducted calculations to investigate the amount of spallings release through either the stuck pipe or the gas erosion process that would violate the EPA standard. Enclosure 3 shows that if between 8 m^3 and 64 m^3 of spalled material is assumed to reach the surface, the standard is violated at 10^{-1} probability. The EEG is in the process of computing the releases from the stuck pipe and the gas erosion scenarios, and will transmit the results to the EPA as soon as possible.

Brine Release in Air Drilling

The EEG has investigated the effect of air drilling on direct brine release, and the results are shown in Enclosure 4. The results show that brine releases to the surface could be between 1000 and 2000 m^3, compared to a maximum of 180 m^3 from the EPA's PAVT computations. The CCDF from the EEG's runs show that the overall mean for all types of releases (including brine release from air drilling) comes very close to the EPA limit at 10^{-3} probability for the actinide solubilities assumed in the CCA, and violates the standard at the "no backfill" and "nesquehonite" solubilities.

Fluid Injection Scenario

The petroleum reservoirs surrounding and underlying the WIPP are potential candidates for fluid injection to recover a substantial amount of crude oil reserves. For oil field operations in

southeastern New Mexico, the problem of water migrating from the intended injection zone, through the Salado Formation, and onto adjacent property has long been recognized. In fact, concerns about unexplained water losses due to solution mining, potential oil field development, or future oil field waterflooding has helped eliminate other sites from consideration as documented in an EEG report on fluid injection (Silva 1996; EEG-62). The EPA proposes to accept the DOE position that fluid injection can be ruled out as a potential scenario and, hence, need not be considered in the performance assessment calculations.

For fluid injection activities on leases adjacent to the site, the DOE argues that such events can be eliminated from further consideration on the basis of low consequence. The EPA raised questions regarding DOE's consequence analysis and "concluded that regardless of the consequence argument, the probability of such an injection event that affects WIPP is very low, and so this FEP can be eliminated on the basis of low probability"(CARD 32, p.42). The DOE chose to examine consequence rather than probability, as noted by Stoelzel and O'Brien, "[because certain petroleum practices are hard to define in a probabilistic sense (for example, the quality of the cement and/or casing and its ability to withstand leaks over time)..."(Stoelzel and Obrien 1996, 8). Nonetheless, EPA assigned probabilities to certain petroleum practices, such as an undetected leak occurring in the annulus, and multiplied the probability of each event and calculated that the *realistic* probability of a injection well impacting the repository was only one in 667 million (EPA, III-B-22, Table Q). But this value appears to be based on an optimistic view of future injection well performance and does not reflect the actual experience of documented waterflows in the Salado Formation in water flood areas throughout southeast New Mexico.

In the final analysis, for the low consequence argument, the EPA has accepted the modeling results of Stoelzel and O'Brien (1996) and Stoelzel and Swift (1997) for DOE, and has rejected the modeling results of Bredehoeft (1997) for the New Mexico Attorney General. The DOE maintains that a leaking injection well in the vicinity of WIPP is a low consequence event. But a very fundamental question remains. Can the DOE codes model a documented high consequence event? In other words, can the DOE codes take the injection data and geologic data from the highly visible Hartman case and reproduce what is believed to have happened at the Bates Lease? Can these codes model the migration of substantial amounts of water through a single zone of the Salado Formation, two miles in the up dip direction, in about 12 years? That has yet to be shown. Unless the code is verified with actual field data, the low consequence conclusion will remain a speculation at best.

The EPA does not anticipate that CO_2 injection for oil recovery will be a widespread practice in the future near WIPP (EPA CARD-23, p. 131). However, EPA's reasons do not have supporting references and appear to be at odds with the published literature. The EPA technical support document (III-B-22) states "at this time, the only examples of CO_2 injection enhanced recovery techniques are some distance from the WIPP site and under much different geologic conditions

(Magruder 1990; Trash 1979)". But an examination of the current and relevant literature strongly suggests that the Delaware Mountain Group sands are excellent prospects for future CO_2 flooding. First, CO_2 flooding has been demonstrated to be quite successful in mature fields in the Delaware Basin such as the TwoFreds (Silva, 1996, pp. 142-145). Second, the DOE continues to sponsor university research on Delaware Basin oilfields, such as the Geraldine Ford and the West Ford, aimed at optimizing infill drilling and CO_2 flooding throughout the Delaware Basin. Third, oil and gas companies continue to purchase mature fields, such as the El Mar in the Delaware Basin, specifically for carbon dioxide flooding. Fourth, the recently drilled reservoirs surrounding the WIPP such as Cabin Lake, Livingston Ridge, Los Medanos, and Lost Tank have oil and reservoir characteristics that easily qualify them as potential candidates for future CO_2 flooding using the enhanced oil recovery (EOR) screening criteria.

EPA maintains that "there are no natural gas storage horizons in the Salado Formation" (EPA CARD-32, p.71). As shown on a map presented to EPA by EEG on October 10, 1996, there are eight gas storage underground facilities in southeast New Mexico, three of which are in the Salado Formation in which the salt was "washed out to create a cavern", according to entry in a State document.

There are other fluid injection issues that have either not been fully addressed or in which there appears to be a misunderstanding of the issue including, for example, the yet to be explained water level rises in the Culebra Aquifer, the likely expansion of solution brine wells in the Delaware Basin, and the likely initiation of solution mining activities in maturing potash mines.

SUMMARIES OF THE ISSUES NOT PRESENTED ON 12/10/97

The following are the summaries of the other important issues related to the CCA and the Draft Rule that were not presented to your staff on December 10, but have been previously presented to the EPA.

Waste Issues
EEG has concerns about some EPA conclusions regarding: (1) waste inventory and waste form; (2) waste characterization; and (3) waste repository limits.

Waste Inventory and Waste Form:
The EPA has concurred with the DOE's contention that there is no uncertainty in the waste inventory. EEG's view is that: (1) there is considerable uncertainty in the stored inventory; (2) there is uncertainty in the volume of newly generated waste and the processes at the generating sites have changed significantly since the stored waste was generated; and (3) DOE plans to treat most of the waste at INEEL and the RFETS (residues) and repackage, and treat for size reduction, at other facilities. These plans are not reflected in the CCA inventory.

EPA should recognize this uncertainty and either not accept the DOE inventory and Waste Material Parameter (WMP) values or not permit DOE to bring in waste that differ significantly from the values in the CCA until more accurate inventory data have been developed and used in the PA calculations.

Waste Characterization:
DOE has concluded that a maximum repository limit of $2x10^7$ kg of cellulosics, rubber, and plastic (CRP) should be set in order to prevent production of more CO_2 than can be controlled by the MgO backfill. EPA has concurred in this recommendation. The expected amount of CRP in the repository is $2.1x10^7$ kg (see CARD 24-38).

EEG is concerned about the ability to measure CRP in the waste with enough accuracy to ensure that this limit will be met. Visual Examination (VE) is a method that is capable of good precision on those containers measured if all internal containers are emptied and their contents identified and weighed. However, the preferred method of characterization is real time radiography (RTR) which is only semi quantitative (WMP weights are estimated by determining the void space and weight of waste in the drum which is not very accurate even if there is only one WMP in the container). EEG has not found a reference to the uncertainty in determining the weight of CRP in waste containers in either the DOE or the EPA reports. The EPA needs to point out where this uncertainty has been addressed, if it has been, or address the issue at this time.

Waste Repository Limits:
DOE has concluded that all repository limits need to be controlled only for the full repository. EPA has concurred in this recommendation and concluded that DOE's WIPP Waste Information System (WWIS) is capable of controlling repository limits.

There are two concerns that do not appear to have been addressed:

(1) An excess of CRP in a waste panel could overload the MgO in that panel and since no interchange of brine between panels is assumed, it is questionable how much benefit would incur from excess MgO in another panel. Estimated concentrations of CRP do vary significantly between generating sites (e.g. at INEEL the average is 1.8 times the total inventory average);

(2) A management plan that allows emplacement of repository limited parameter quantities that vary significantly from the required average could result in a situation where the required limits could not be met by emplacing the remainder of the inventory. This is a potential problem because the actual content of waste containers will be known only as the individual containers are characterized and may be much different than the current estimates.

EEG believes that the case for controlling limits on a repository basis has not been justified. We recommend control on a per panel basis, at least, until the inventory is known with more certainty.

Retardation Coefficient
The EEG has submitted the following four documents to the EPA on this issue:

- Copy of November 14, 1996 letter from R.H. Neill to J. Salisbury, with attachments;
- February 7, 1997 letter from R.H. Neill to F. Marcinowski, with attachment "Chemical Retardation";
- Copy of May 23, 1997 letter from R.H. Neill to J. Salisbury, with attachments; and,
- Copy of August 29, 1997 letter from R.H. Neill to G.E. Dials, with attachments.

The August 29, 1997 letter and the attachments (docket # II-D-117) contained the EEG position on this issue based on the July 30, 1997 meeting in Albuquerque, which was organized by the EEG. Copies of this letter with the attachments were mailed to several EPA officials and the EPA WIPP docket. The DOE also sent a copy of their impressions of the July 30 meeting (Dials to Neill 8/25/97 letter with attachments, docket # II-D-115) to the EPA on August 25, 1997, four days before the EEG letter.

The EPA draft rule discusses this issue in the Technical Support Document, "Assessment of K_dS Used in the CCA", docket # III-B-4. This document makes extensive references to the DOE's August 25, 1997 letter, but no mention of the EEG's August 29, 1997 letter. Because the issue was raised by the EEG, and the July 30, 1997 meeting was organized by the EEG, it is difficult to understand why the EPA's analysis makes no mention of the EEG's summary of the July 30 meeting and the recommendations.

As described in the EEG's August 29, 1997 letter, the EEG has recommended conducting both batch and column tests for at least the actinides Pu(III), Pu(IV), and Am(III) in the Culebra brine; setting the lower end of K_d for U(VI) to be zero; conducting sensitivity analysis for potential impact of organic ligands; extending performance assessment calculations beyond 10,000 years to see how long the chemical retardation delays the releases to the environment; investigating the potential impact of nonlinear sorption on radionuclide transport; and, checking the validity of the K_d values derived from the column tests by examining the cores to identify whether the Pu and Am are present in adsorbed or crystalline solid phase.

The EEG recommends that the EPA consider the EEG submissions to the docket before reaching a final conclusion on the issue.

Brine Reservoir Probability
The EEG raised a number of issues related to the Castile Formation brine reservoirs (see R.H. Neill letters to F. Marcinowski, dated 2/7/1997 and 3/14/1997, attachments "Brine Reservoir Assumptions"). The EPA has accepted all of the EEG suggestions except the one related to the assumption of the probability of encounter of brine reservoirs, and we disagree with the EPA on this issue. The CCA assumed 8% probability on the basis of faulty assumptions. The EEG recommended 100% probability on the basis that the WIPP-12 brine reservoir was large enough to most likely extend under the repository, a conclusion also confirmed by geophysical testing directly above the repository. The EPA has sampled on a range of 1 to 60%, but has provided no basis for assuming less than 60%. Based on the arguments that the geophysical (Time-domain electro-magnetic survey) data may be interpreted to indicate the brine to be under 60% of the repository, and that some boreholes adjacent to the brine producing boreholes are known to be dry, the EEG is willing to accept the assumption of a fixed 60% probability of encounter, and recommends that a new performance assessment calculation be run with this fixed value.

Assurance Requirement/Engineered Barriers
The EEG believes that in allowing the resource disincentive requirement of the EPA standards (40 CFR 191.14 e) to be satisfied if the numerical containment requirements (40 CFR 191.13) are satisfied (through 40 CFR 194.45), the EPA deviated from the basic philosophy of the "belt-and-suspender" approach inherent in the assurance requirements of the standards. Faced with the *fait accompli* of promulgation of 40 CFR 194, the EEG recommended (EEG-61, May 1996) that at least the actual conditions at the site related to the presence of natural resources be fully and conservatively assumed in projecting compliance with the numerical containment requirements. This does not appear to have been done in the CCA, judging from the DOE resistance to consideration of fluid injection, air drilling, and mining scenarios. The other suggestion made by the EEG (in EEG-61) is to compensate for siting the repository in a mineral resource rich area by incorporating robust engineered barriers in the WIPP's design. The DOE has proposed Magnesium Oxide backfill as an engineered barrier, but that is needed for assuming low actinide solubility to show compliance with the containment requirement. The "containment" and the "assurance" requirements of the EPA standards thus have not been kept separate, as was intended by the EPA standards, 40 CFR 191.

The EEG recommends that additional confidence in predicting the behavior of the waste over 10,000 years can be obtained by processing the waste. Hence, EPA should encourage the DOE to process the waste before shipment to WIPP. TRU waste is highly heterogeneous and there are no limits on the allowable particle size of the waste. The Nuclear Regulatory Commission requires a 300 year waste-form or container longevity for class B or class C *low-level* waste, whereas there are no requirements for the TRU containers or the waste-form in 40 CFR 191. Moreover, the DOE proposed action in the WIPP 1997 Environmental Impact Statement only commits to meeting the Waste Acceptance Criteria for acceptance of waste at WIPP. The DOE

preferred alternative, published in the 1997 Final Waste Management Programmatic Environmental Impact Statement for Managing, Treatment, Storage and Disposal of Radioactive and Hazardous Waste, is to **treat** and store at the sites where it is generated prior to shipment to WIPP.

The recommendation to treat the waste before shipping to WIPP should be easier to accomplish because several of the DOE's waste generator sites are planning to process and/or repackage the waste before shipping to WIPP anyway, for other reasons, as described below. The EPA's directive will result in an orderly and coordinated decisions on this matter throughout the DOE weapons complex, and will make WIPP safer.

- According to the September 1997 WIPP Final Supplemental Impact Statement (DOE/ES-0026-S-2), 27,000 m^3 of alpha emitting low level waste at INEEL will be processed to convert it to TRU waste.

The information for the following processing and repackaging plans is derived from the National TRU Waste Management Plan, DOE/NTP.-96-1204, Rev.1.

- INEEL plans to process all the existing and projected TRU waste except for 15,000 drums (3,000 m^3) to meet the INEEL/State of Idaho agreement, which amounts to processing 79,600 m^3 - 3,000 m^3 = 76,600 m^3 of waste.

- ANL-E plans to treat and stabilize all the 203 m^3 existing and newly generated CH-TRU waste.

- Hanford plans on repackaging most of its 16,127 m^3 of CH-TRU waste.

- Rocky Flats Plant will process the plutonium residues and the scrap alloy since plutonium concentrations exceed the DOE limits. About half the other TRU waste will be processed and repackaged.

- The Plutonium-238 heat source wastes at Savannah River exceed the hydrogen gas limits imposed by NRC and will require treatment or an easing of the regulations for a less stringent flammable limit or the use of hydrogen getters in the transportation containers.

- All the 1097 m^3 CH-TRU waste at ORNL will be processed with a 50% volume reduction.

- SRS plans to process and repackage 9,525 m^3 of the existing 11,725 m^3 of CH-TRU waste.

In summary, of the existing 104,400 m^3 of CH-TRU waste, DOE has plans to treat or repackage 88,900 m^3 or 85%. Of the 15,500 m^3 not being processed, 3,000 m^3 is intended for shipment to meet a scheduled commitment between DOE and the State of Idaho. The EPA should recognize DOE's efforts in stabilizing the waste and encourage DOE to also fix the yet-to-be generated waste.

We look forward to continuing the dialogue with you to resolve these and other issues.

Sincerely,

Robert H. Neill
Director

RHN:js
Enclosures

cc: Mr. Richard Wilson, EPA
Mr. Larry Weinstock, EPA
Ms. Mary Kruger, EPA
Mr. Chuck Byrum, EPA
Mr. Tom Peake, EPA
Mr. George Dials, DOE
Mr. Chris Wentz, NMEMNRD
Mr. Lindsay Lovejoy, Jr., NMAG
EPA Docket for WIPP (A-93-02)

(Enclosure 1 to the 12/31/97 Letter From R.H. Neill, EEG to F. Marcinowski, EPA)

Issue: Solubility Modeling

The modeling of solubility changes to the PAVT started with the re-running of the 'Source Term' files. The Latin Hypercube Sampling (LHS) generated a range of solubilities in the CCA that were 2.0 and 1.4 orders of magnitude below and above the median values, respectively. For the present model the range of solubilities were reduced to a constant value, based on solubilities of 'No Backfill' from Van Bynum (1997), and Nesquehonite in Novak (1997). The parameters of SOLSIM (solubility factor for Salado) and SOLCIM (solublity factor for Castile) (DOE, 1996-Appendix PAR) were changed for the oxidation states of +3, +4, and +6.

Table 1 shows the values used to replace SOLSIM and SOLCIM for all the actinides for the different mineral types. Again, the range from -2.0 to 1.4 with a cumulative continuous distribution was changed to the values below with a cumulative discrete distribution. One hundred vectors were created for all six scenarios of the first replicate with the new LHS file.

Once Source Term files were created, PANEL was rerun with the new solubilities using BRAGFLO files of the PAVT. The BRAGFLO files supply the velocity information for PANEL to use in the transport equations. The PANEL 'concentration' simulations were ran for 100 vectors of S1 and S2 scenarios. The PANEL 'time' simulations were reran for 100 vectors of S6 for times 100, 350, 1000, 4000, 6000 and 9000 years postclosure.

Lastly, the PANEL files were incorporated into the CCDFGF to create CCDF curves for comparison with 40 CFR Part 194. In addition to the Nesquehonite and No Backfill simulations with PANEL to create the new CCDFs, the CCA PANEL files containing CCA solubilities were used with PAVT releases of direct brine release, cuttings, spallings, and transport through the Culebra. Figure 1 shows the CCDF results of the different solubilities.

The figure shows that none of the curves violate the standard. The CCA solubility model has an estimated release of 0.45 EPA units at the 10^{-3} probability level. This is slightly higher than the 0.37 EPA units of the PAVT model and 0.22 EPA units of the CCA. The releases are shown to increase to 6 EPA units for Nesquehonite solubilities and to 7.5 EPA units for 'No Backfill' solubilities. The EPA compliance limit for the 10^{-3} probability level is 10 EPA units, or 3500 Ci for Plutonium, Uranium, Thorium, and Americium.

References

Bynum, R.V., 1997. Chemical Conditions Model: Results of the MgO Backfill Efficacy Investigation, SAND97-2511. Albuquerque, NM: Sandia National Laboratories.

Novak, C.F., 1997. Memorandum from Craig F. Novak to R. Vann Bynum "Calculation of Actinide Solubilities in WIPP SPC and ERDA6 Brines Under MgO Backfill Scenarios Containing Nesquehonite or Hydromagnesite as the MgO-CO_3 Solubility-limiting Phase". Albuquerque, NM: Sandia National Laboratories. WPO# 46124.

U.S. Department of Energy, 1996. Title 40 CFR 191 Compliance Certification Application. DOE/CAO-1996-2184.

	Nesquehonite		No Backfill	
	SOLCIM	SOLSIM	SOLCIM	SOLSIM
SOLAM3	1.51616	-.27709	4.48678	3.83714
SOLPU3	1.51616	-.27709	4.48678	3.83714
SOLPU4	5.23242	2.15588	4.06695	2.05552
SOLU4	n/a	2.15588	n/a	2.05552
SOLU6	0.95861	0.96357	0.95861	0.96357
SOLTH4	5.23242	2.15588	4.06695	2.05552

Table 1. Solubility Factors for SOLCIM and SOLSIM

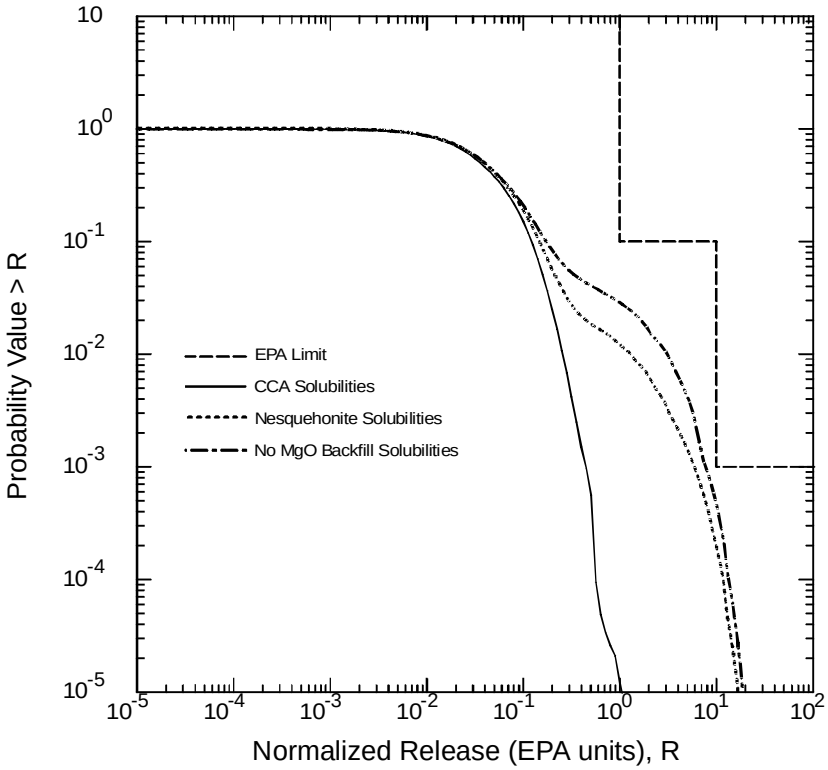

Figure 1. CCDF Overall Mean for Solubility Modeling with the CCA, Nesquehonite, and 'No Backfill' Values.

(Enclosure 2 to the 12/31/97 Letter From R.H. Neill, EEG to F. Marcinowski, EPA)

Issue: Three Dimensional Processes and Boundary Conditions

Problem Description

The EEG first brought this issue to the EPA's attention as an attachment titled ABrine Inflow From Salado: 2-D versus 3-D Geometry in BRAGFLO to the 3/14/97 letter from R.H. Neill to F. Marcinowski. The DOE submitted a response as an attachment to the 6/27/1997 letter from G.E. Dials to L. Weinstock. The Draft Rule includes this issue as Issue F in CARD #23. The EEG position is summarized as Comment #553 on page 115 of CARD #23, and the EPA response is provided on page 116. This issue was presented by the EEG to the EPA on December 10, 1997 as 2D/3D Modeling in BRAGFLO.

The FEP Screening Analysis titled S1: Verification of 2D-Radial Flaring Using 3D Geometry (*Vaughn et al.*, 1996) compared the two dimensional radial flaring model of BRAGFLO used in the CCA performance assessment to a three dimensional BRAGFLO model of the repository. The 3-D model calculated a large flow of brine into the repository after the pressure reached the anhydrite fracturing pressure. The large flow did not occur in the 2-D model. Figure 1 shows the pressure history for the two models. The scenario used for the investigation included a drilling intrusion at 1,000 years, accounting for the large drop in pressure at that time. Our concern is the difference in behavior of the two models after the pressures reach 12.7 MPa but prior to 1,000 years.

Figure 2 depicts the calculated brine inflow and outflow rates. The figure shows a large difference in calculated inflows of the two models during the period of 700 to 1,000 years. Figure 3 reinforces the perception that the brine inflow in the 3-D model is large. As shown in Figure 3, during the 700 to 1,000 years period the 3-D model shows a decrease in gas saturation of 0.05. Our concern is that if the brine inflow calculated in the 3-D model persists for thousands of years then the 2-D model calculations significantly under-predict repository saturation at high pressures.

Greater saturations could lead to much larger direct brine release calculations. Figure 4 (Figure 5.1.5 of *Helton)* is the basis of this contention. Figure 4 depicts the relationship of calculated direct brine releases to repository conditions at three separate times. The average repository brine saturation and repository pressure are plotted for each vector on the horizontal plane. A vertical line connects the plane to a small circle at the level of the vertical axis corresponding to the volume of brine calculated to reach the surface. Calculated releases greater than one cubic meter are highlighted using a filled circle.

Figure 4 indicates that there were few calculated direct brine releases when the calculated repository pressures exceeded 12.7 MPa and almost none when the pressure exceeded 14 MPa. Almost all of the larger calculated direct brine releases occurred when brine saturations were above 0.5, a condition never calculated at pressures above 14 MPa. The FEP S-1 analysis suggests that the potential for many of the vectors with great repository pressure to also have large brine saturations. Thus calculated direct brine releases might have both larger volumes and greater frequency in the performance assessment.

EEG Assessment of DOE Response to Comment # 553

The major concern of the EEG is that the 3-D modeling of the repository system indicates the potential for large brine inflow to the repository at high pressure which leads indirectly to the potential of larger direct brine releases than calculated in the CCA. The DOE has presented three independent lines of reasoning to indicate that the EEG's concern is unwarranted. If convinced that any of these lines of reasoning are correct then the EEG will concur with DOE's assessment that the issue is of little concern.

DOE's three arguments are: 1) Additional brine will be consumed by corrosion and the resultant gas generation will not cause greater repository pressures. 2) The difference in the two dimensional and three dimensional models only occurs at pressures above those calculated during the performance assessment for CCA. 3) The changes in the repository consistent with the three dimensional model are of little consequence to the performance assessment.

At this time, the first two of the lines of reasoning appear to be flawed. The third argument relies on the CCA values of actinide solubility that the EEG is not convinced are correct.

1. *Additional brine will be consumed by corrosion and the resultant gas generation will not cause greater repository pressures.*

That additional brine inflow will lead to more gas generation is not questioned. The flaw in this argument is that the potential brine inflow is too large to be consumed in a short period and could lead to large enough amounts of additional gas to significantly effect the pressure. The result could be both larger brine saturations and higher pressures. Figure 1 indicates that lower pressures are also possible. In the FEP S-1 the rate of gas generation was assumed to be constant. Thus, there was no feedback between brine inflow and gas generation in the FEP S-1 study.

The DOE cites the amount of iron remaining in the repository (Figure 5; *DOE*, 1996 Figure 12-13) as support for the argument that more brine inflow will lead to more gas generation not higher saturations. Figure 6 (Figure 2.2.9 of *Helton*) shows less iron remaining

in the lower (waste) panel, presumably due to relatively more brine inflow to the lower panel (Pg 2-18 of *Helton*, 1996). Figure 7 (Figure 2.2.7 of *Helton*, 1996) shows that at most 30,000 cubic meters of brine are predicted to be consumed through iron corrosion. In most vectors, the calculated brine consumption was less than 15,000 m^3. In many, brine consumption continues though-out the 10,000 year compliance period. Other vectors show a secession of brine consumption after less than 2,000 years, presumably due to exhaustion of available brine (See Section 2.2 of *Helton*). Figure 2 suggests that brine inflow from fracturing may be on the order of 10 m^3 / year or more and continue for hundreds to thousands of years. Drawn on the Figure 7 is a line with a slope of 10 m^3 / year. Comparing the brine consumption with this slope indicates that the potential brine flow is large compared to the rate of brine consumption. The potential brine inflow is greater than 10,000 m^3. Most of this flow would likely be into the lower panel. The maximum amount of brine consumed in the lower panel was 6,000 m^3 (Figure 8, Figure 7.2.1-10 of *Bean et al.*).

2. *The difference in the two dimensional and three dimensional models only occurs at pressures above those calculated during the performance assessment for CCA.*

DOE cites Figure 9 (Figure 2.3.2 of Helton), showing the 10, 50 and 90 percentile pressures for each replicate for the 10,000 years, as demonstration that pressures will not increase greatly above 12.7 MPa. In fact, Figure 10 (Figure 2.3.1 of Helton), which depicts the pressure history of each vector of replicate 1, indicates that many of the calculated pressures were greater than 13 MPa and that for one vector the calculated pressure reached close to 16 MPa. 16 MPa is less than 2 MPa below the 17.5 MPa peak pressure of the 2-D simulation of the FEP S-1 analysis (Figure 1). The DOE has offered no explanation of what happens between 16 and 17.5 MPa to cause such large brine inflow in the 3-D simulation but not the 2-D simulation. A believable explanation is that the change occurs at initiation of anhydrite fracturing not just above 16 MPa.

3. *The changes in the repository behavior consistent with the three dimensional model are of little consequence to the performance assessment*.

There are two obvious potential impacts on the performance assessment calculations from greater pressure and brine saturations in the repository. Greater pressures would lead to larger calculated releases from the spallings model. If the spallings model described in Hansen et al. is correct then it is unlikely that the volumes brought to the surface because of greater pressures would approach those calculated in the CCA.

Either greater pressures or saturations could lead to much larger direct brine release calculations. Figure 4 indicates that there were very few calculated direct brine releases when the calculated repository pressures exceeded 12.7 MPa and almost none when the pressure exceeded 14 MPa. Almost all of the larger calculated direct brine releases occurred when brine saturations were above 0.5, a condition never calculated at pressures above 14 MPa. The FEP S-1 analysis suggests that the potential for many of the vectors with great repository pressure to also have large brine saturations. Thus calculated direct brine releases might have both larger volumes and greater frequency in the performance assessment.

Direct brine release was a minor component of the total calculated radionuclide releases in the CCA (Figure11; Figure 6-41 of the CCA). The volumes of direct brine release would have to be two orders of magnitude greater to have an impact on agreement with the containment requirements which is large in relation to a possible increases in the calculated volumes of brine brought to the surface through direct brine release. However, the radionuclide content of brine brought to the surface may be underestimated in the CCA which would make direct brine release of greater significance to the performance assessment (See EEG comments on solubility).

EEG Response to EPA's Resolution of Comment # 553.

The EPA's resolution of this comment relies on the fact that Abrine and gas saturations are inversely related. This relationship does not necessarily lead to higher brine saturations indicating lower pressures or less gas in the repository. The statement AThe fact that the 2-D model may overestimate gas saturation by underestimating brine saturations will lead to the prediction of higher gas pressures than those that would have been predicted with the 3-D configuration and this will result in more conservative estimates of releases.@ is a conclusion that the 3-D modeling results may indicate is not valid.

Consider Figure 4. This figure provides a plot of calculated brine saturation and pressure conditions in the repository at three separate times for undisturbed performance. This figure shows a correlation of brine saturation with repository pressure. There are at least three mechanisms that may lead to such a correlation:

A) Faster corrosion rates lead to more gas generation, less brine and greater pressures. Table 1 (Table 2.3.1 of *Helton*) lists the parameters most closely correlated with pressure in the lower waste panel. The list results from a step wise rank regression of the sampled parameters with pressure. The parameter that correlates the most pressure is listed first. The table lists the microbial degradation of cellulose and rubber and plastics (WMICDFLG) as the most important factor with halite porosity (HALPOR) next. Table 1 indicates that sampled corrosion rate (WGRCOR) is not a dominant factor in repository pressure. Halite porosity is a reasonable surrogate for brine availability (see Figure 2.1.5 of *Helton*).

Table 2 (Table 2.2.2 of *Helton*) lists halite porosity as by far the most important controlling factor over iron consumption. The second most important factor is the corrosion rate. Other parameters identified as slightly correlated with repository pressure and fraction of steel remaining are: ANHPRM (unfractured anhydrite permeability), SALPRES (Far field pressure in the Salado Formation), SHRGSSAT (residual gas saturation in the shaft seal), and WASTWICK (the parameter describing the tendency of brine to be pulled above the lower part of a room by capillary forces)

Figure 12 (Figure 2.4.3 of *Helton*) provides important supporting evidence. The figure presents the fraction of iron remaining in the lower waste panel (FEREM_W) or in the rest of the repository (FEREM_R) with respect to halite porosity, microbial degradation, steel corrosion rate. The plots of remaining iron and halite porosity suggest that a sufficient supply of brine is needed for iron consumption but other factors also limit corrosion. The main factor is probably corrosion rate. Figure 12 shows that low corrosion rates limit iron consumption, but that predicted iron consumption is not strongly dependent on corrosion rate. The comparison of iron remaining to microbial degradation is important because its strong correlation with repository pressure (Table 1). These plots show that the fraction of iron remaining in the repository is only weakly correlated with microbial degradation and that the correlation is positive e.g. microbial degradation, hence pressure, is inversely correlated with iron consumption. This inverse correlation is probably linked to the availability of brine.

B) Less brine flows into the repository at high pressures, at least in the 2-D BRAGFLO model used for the CCA performance assessment.

C) The repository inflates as the pressure rises (Figure 13; Figure 2.3.5) leading to more void space and lower saturations per unit volume of brine. Figure 13 indicates that the calculated void space in the repository is twice as large at 12 MPa than at 5 MPa and nearly three times at 16 MPa. Thus, the correlation of brine volume to pressure is much weaker than the correlation of saturation to pressure seen in Figure 4.

The FEP S-1 screening analysis concluded that the increased brine inflow to the repository in the 3-D simulation did not increase release to the accessible environment through the marker beds. The EEG agrees with this conclusion. It has not been demonstrated, however, that the increased flow into the repository predicted using the 3-D geometry will not lead to much greater releases from human intrusion. The 3-D modeling indicates that there is a potential for the combination of high pressure and relatively high brine saturation in the repository at the same time. This combination did not occur in the performance assessment modeling for the CCA and thus conclusions of the impact on radionuclide releases due to human intrusion can not be assessed using the CCA performance assessment.

The DOE has not yet demonstrated that the performance assessment modeling for the CCA accurately represents the potential repository conditions. The results of FEP S-1 screening analysis suggest that the two dimensional BRAGFLO model used in the CCA calculations may be misrepresenting repository performance at pressures above the anhydrite fracture pressure.

Recommendations for Resolving the Issue

To resolve this issue, the EEG recommends that a few 3D BRAGFLO simulations of the repository should be performed using the parameter values of vectors used in the CCA performance assessment. The 3D BRAGFLO simulations should be used to provide repository conditions for the normal suite of direct brine release calculations. The calculations should also be assessed in terms of impact on spallings calculations. Spallings simulations are probably not required to assess the impact. The following criteria may be used to select the CCA vectors for running the 3D simulations to bound the magnitude of the problem:

- Since the discrepancy occurs above the fracture initiation pressure, the simulations should be limited to parameter vectors that result in pressures above 12.7 MPa at some time during the 10,000 year time frame.

- Direct brine release calculations should be sensitive to increased brine saturations above the waste residual brine saturation. Vectors that had either large brine saturations or a mobile brine component (saturations above the residual saturation) are more likely to be sensitive to increased brine inflow. Figure 5.1.5 of the preliminary sensitivity analysis report (Helton, 1996) indicates one vector with a 10,000 year pressure above 14 MPa and a brine saturation above 0.4. This is a likely candidate.

- The potential for brine consumption by corrosion should be assessed. Vectors with both slow and fast corrosion rates that also meet the above two criteria should be run.

- If the first simulations indicate a large change in saturation, then assess whether the 3D BRAGFLO simulations indicate a much larger number of significant direct brine releases than those calculated in the CCA. Simulations using brine saturations on the order of 0.1 and 0.3 should be performed.

REFERENCES

Bean, J.E., M.E. Lord, D.A. McArthur, R.J. MacKinnon, J.D. Miller, and J.E Schrieber, , 1996, Analysis Package for the Salado Flow Calculations (Task 1) of the Performance Assessment Analysis Supporting the Compliance Certification Application (WPO # 40514).

DOE, *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant*, DOE/CAO-1996-2184, December, 1996.

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Vaughn, P., T. Hadgu, D. McArthur, and J. Schreiber, FEP Screening Analysis S1: Verification of 2-D Radial Flaring Using 3D Geometry, Memorandum to D.R. Anderson, January 26, 1996, WPO 30840, Sandia National Laboratory, Attachment 4-1 to Appendix Mass of the Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184, December, 1996.

Figures

Figure 1: Average Pressure in Repository, FEP S-1 Analysis
From Vaughn et al, 1996.

Figure 2: Cumulative Net Brine in and outflow at Repository, FEP S-1 Analysis
From Vaughn et al, 1996.

Figure 3: Average Gas Saturation in Repository, FEP S-1 Analysis
From Vaughn et al, 1996.

Figure 4: Three dimensional scatter plots for volume of brine reaching the surface due to direct brine release for a drilling intrusion into the lower panel.
From Helton, 1996.

Figure 5: Fraction of Initial Iron Remaining in Repository
From: DOE, 1996.

Figure 6: Remaining Fraction of Steel Inventory in Waste Panel
Modified from Figure 2.2.9 in Helton, 1996.

Figure 7: Cumulative Volume of Brine Consumed by Corrosion in the Repository
Modified from: Helton, 1996.

Figure 8: Cumulative Volume of Brine Consumed in the Waste Panel
From Bean et al., 1996

Figure 9: Percentile curves for three replicated LHSs for pressure in waste panel
From: Helton, 1996.

Figure 10: Pressure in waste panel
Modified from Figure 2.3.1 of Helton, 1996.

Figure 11: Mean CCDFs for Specific Release Modes, Replicate 1.
From DOE, 1996.

Figure 12: Scatter Plots of the Fraction of Iron Remaining in the Waste Panel (Right Frames) and Rest of the Repository (Left Frames) for Undisturbed Conditions at 10,000 Years.
From Helton, 1996.

Figure 13: Scatter plot of pressure versus total pore volume in the repository.
From Helton, 1996.

Tables

Table 1: Stepwise Regression Analysis with Rank-Transformed Data for Pressure in the Waste panel at 10000 years. From Helton, 1996.

Table 2: Stepwise Regression Analysis with Rank-Transformed Data for Fraction of Steel Remaining and Total Gas Generation in Upper and Lower Waste Panels at 10000 years.
From Helton, 1996.

FULL TEXT OF ORIGINAL EEG COMMENT

Environmental Evaluation Group Review of the WIPP-CCA, 3/14/97

BRINE INFLOW FROM SALADO: 2-D VERSUS 3-D GEOMETRY IN BRAGFLO

The 2-D geometry used in the BRAGFLO appears to have caused an under-prediction of brine inflow to the repository and thus may have resulted in a significant under-prediction of the direct brine release. This assumption may also have effected the amount of releases predicted by the spallings scenario.

The justification for modeling the repository in a pseudo 3-D manner (2-D radial flaring) rather than in a full 3-D geometry has been provided through evaluation of FEP S-1. The summary memo of record for the FEP S-1 screening analysis[1] discusses the impact of the 2-D assumption on 1) brine flow through the anhydrite layers to the 2.4 km boundary, 2) flow to the top of the shaft, 3) brine flow up the borehole, and 4) the repository pressure. This memo does not consider the effects of the 2-D assumption on the inflow of brine to the repository, and on the spallings or direct brine releases.

The amount of projected inflow of brine in the repository directly effects the gas pressure in the repository. Table 5.5.3 of the sensitivity analysis report[2] lists the residual gas saturation as the parameter with the strongest influence on the projected direct brine releases. This is also shown in Figure 5.1.5 of the sensitivity analysis report (the attached Figure 1). In addition, brine inflow is important to the spallings release estimates through increased gas generation. This dependence is made clear in Table 4.4.3 of the sensitivity analysis report which lists halite porosity, a large source of brine, as the second most important parameter to spallings releases.

The screening analysis compared 2-D simulations of the repository to 3-D simulations of the repository. For computational efficiency, the calculations were performed for half the repository. Two sets of simulations were conducted for the analysis. One set of calculations used a gas generation rate below the level that would cause anhydrite bed fracturing. The second used twice the gas generation rate to ensure anhydrite bed fracturing. In both sets, less brine-inflow occurred in the 2-D case compared to the 3-D geometry. No dependency of gas generation on brine inflow to the repository was included in the calculations; gas generation was prescribed as a function of time, ending after 1,000 years in the screening calculations.

The largest impact of 2-D geometry occurs with anhydrite bed fracturing. The 3-D model predicts the flow into the repository to significantly increase if the anhydrite beds fracture, while the 2-D model predicts the flow to decrease in relation to calculations without anhydrite fracturing.

Figure 15 of the FEP S-1 analysis (Figure 2) shows the cumulative brine inflow to the repository for the high gas generation calculations. The flows calculated using the 3-D model indicate that once anhydrite bed fracturing occurs roughly $2x10^6$ kg (1,600 m^3) of brine enters the repository in a period of 200 to 300 years and that this flow rate was continuing unabated at the time of drilling intrusion. Another $4x10^6$ kg (3,200 m^3) flowed into the repository shortly after the drilling intrusion. Figure 2 shows differences of $4x10^6$ to $6x10^6$ kg (3,200 to 6,500 m^3) for much of the 10,000 years. The brine inflow differences listed above should be doubled for the full repository. Virtually no flow enters the repository as a result of anhydrite bed fracturing in the 2-D geometry. In fact, the net flow over the 10,000 year simulation is less with anhydrite fracturing compared the simulation without the beds fracturing. Figure 2.1.4 of the sensitivity analysis report[2] (Figure 3) indicates very little marker bed inflow with microbial gas generation of plastics and

[1]Vaughn, P., T. Hadgu, D. McArthur, and J. Schreiber, FEP Screening Analysis S1: Verification of 2-D-Radial Flaring Using 3D Geometry, Memorandum to D.R. Anderson, January 26, 1996, WPO 30840, Sandia National Laboratory, Attachment 4-1 to Appendix Mass of the Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184, December, 1996.

[2]Helton, Jon, Preliminary Summary of Uncertainty and Sensitivity Analysis Results Obtained in Support of the 1996 Compliance Certification Application for the Waste Isolation Pilot Plant, Memo, Sandia National Laboratories, December, 1996.

rubber, supporting the findings of the FEP analysis. Figure 5.1.5 of the sensitivity analysis report reveals the importance to direct brine release of these low brine inflows. The highest pressures are correlated with brine saturations below the residual brine saturation of the waste. The low saturations are due partly to increasing repository pore space with increasing pressure and partly to lower brine inflow.

Table 2.5.13 of the sensitivity analysis report indicates that the potential for anhydrite bed fracturing is high. As a crude approximation, consider the undisturbed scenario of a total fracture-enhanced flow of 20,000 m^3 over a period of 2,000 years. The highest repository pressure in the FEP S-1 calculations was 13 MPa [Correct value is 16.5 MPa]. This corresponds to a repository pore space of 85,000 m^3 (Figure 2.3.5 of the sensitivity analysis report)[at 13 MPa]. The increased brine flow would increase the average brine saturation by 0.23. The CCA calculations do not include simulations of both very high pressure and brine saturations above the residual brine saturation of the waste. Inspection of Figure 5.1.5 suggests a significant impact from a 0.23 saturation shift at high pressures.

The simulations without anhydrite fracturing show a decrease of $1x10^6$ to $2x10^6$ kg (800 to 1,600 m^3) in predicted brine inflow in the 2-D simulations compared to the 3-D simulations(Figure 4; Figure 10 of the FEP S-1 memo). These flows are doubled for the full repository. The differences are most likely from differences in marker beds flows to the repository.

To put these brine inflow differences in perspective, note that average brine inflow to the repository in the CCA calculations of the similar S5 scenario was almost 40,000 m^3, with an average 8,000 m^3 from the marker beds[2]. Marker bed brine flows in the S5 scenario are dominated by flows under low pressure conditions. The marker bed flows are a more significant concern in the S1 undisturbed scenario. An average of roughly 3,000 m^3 flowed into the repository from the marker beds in the S1 CCA calculations. To approximate the brine flow error in the undisturbed calculations for pressures below the anhydrite fracture threshold, we ratio the FEP S-1 differences by 3,000/8,000 - resulting in the range of 600 to 1,200 m^3 less brine inflow to the full repository. If 1,200 m^3 of brine were distributed throughout the entire repository it could increase the average saturations by 0.015 to 0.03 (0.04 to 0.08 in the S5 scenario and 0.16 to 0.32 after anhydrite fracturing in an S5 scenario). It is more likely that much of the additional brine would be consumed through increased gas generation, leading to higher repository pressures.

There are indications in the sensitivity analysis report that the computational grid effects the distribution of brine within the repository in addition to the overall magnitude of brine. One indication is the statement on page 2-26 that "Due to the computational grid in use (Fig. 1.2.1), the lower panel receives more brine inflow from the marker beds relative to its size than the upper waste panels (Fig. 2.1.2)." Another indication may be the importance of the residual gas saturation of the shaft seals to flow through the marker beds (Table 2.1.1 of the sensitivity analysis report). As stated in the report, "its selection may be due to effects related to brine and gas movement across the part of the computational grid that corresponds to the shaft in the repository and DRZ (i.e., regions 10,11 in Fig. 1.2.1)." As a result, the upper waste panels receive roughly one ninth of the brine inflow from the marker beds per panel as the lower waste panel. In a large fraction of the sampled vectors, gas generation stops in the upper panels because of limited brine availability for steel corrosion. Thus, the CCA calculations are under-predicting repository pressure as well as brine saturation.

The EEG concludes that the use of a 2-D geometry in the BRAGFLO may introduce significant non-conservatism into the CCA calculations. The FEP S-1 needs to be re-examined with appropriate consideration of the impact of increased brine saturation on calculated release estimates.

DOE Response to the EEG Comments

Attached to Letter by GE Dials to L. Weinstock, *DOE Response to Comments made to EPA by EEG on the DOE's CCA Dated March 14, 1997.*, June, 27, 1997.

Brine inflow to the repository

Vaughn et al. justified the use of the 2-D radial-flaring BRAGFLO model by comparing the results of the 2-D model with those of a corresponding 3-D model. However, the limits of the analysis exceeded the highest predicted pressures in the repository by approximately 4 to 5 MPa.

The 2-D and 3-D model results show reasonable agreement, except under conditions where fracturing of the anhydrite beds occurs (at pressures above 12.7 MPa). The 3D model predicted a greater flow of brine into the repository than the 2-D model when the pressure in the repository was sufficient to increase porosity in the fractured anhydrite beds. However, the high constant gas generation rate assumed in the *Vaughn et al.* analysis resulted in peak average pressures in the repository of about 17.5 MPa (2-D BRAGFLO) and 16.5 MPa (3-D BRAGFLO) *(Vaughn et al.*, Figure 11) (not 13 MPa as stated by the EEG), which are greater than the highest pressures expected in the repository (see *Helton*, Figure 2.3.2). Thus, the large increases in average anhydrite porosity and associated brine inflow predicted by 3D-BRAGFLO are not likely to occur in the repository.

Vaughn et al. assumed constant gas generation rates with no brine consumption. In reality, any additional brine entering the repository would likely be consumed by gas generation processes, which would limit brine saturation. PA calculations show that significant

amounts (at least 409G of the initial inventory) of uncorroded iron will persist throughout the lO,OOO year regulatory period under conditions of undisturbed performance (CCA Figure 9-10). The extent of corrosion is limited by the amount of brine available, and the iron inventory will not be exhausted as a result of the increase in brine flow to the repository predicted by 3D-BRAGFLO. Subsequent to an intrusion the pressure within the repository is relieved and remains below the fracture initiation pressure.
EEG acknowledges that higher brine saturations would not necessarily occur as a result of increased brine flow to the repository, but that increased brine flow would lead to increased gas generation. Increased volumes of gas generated at high pressures (above 12.7 MPa) would tend to result in increased porosity in the fractured anhydrite rather than significant increases in pressure. *Helton* (Figure 2.3.1) showed that repository pressures do not increase greatly above 12.7 MPa (after fracturing has occurred).

Pressures sufficiently high to cause fracturing (12.7 MPa) tend to occur at low brine saturations (*Helton* Figure 5.1.5) due to the consumption of brine by corrosion. If brine inflow occurs at the high pressures suggested by the 3-D BRAGFLO analysis (in excess of 16.5 MPa), then brine saturation in the repository could increase. The EEG suggests that brine saturation could increase by as much as 23 % at such pressures. However, as discussed above, this value of pressure is unrealistically high given that gas generation processes could consume most of any additional brine entering the repository. Nonetheless, even with the unrealistic assumption that brine saturation increases by 23%, Figure 5.1.5 of Helton shows that the number of simulations in which direct brine release resulting from a drilling intrusion occurs would not increase significantly. Although accounting for higher brine saturations could increase cumulative direct brine releases, the overall CCDFs from all release pathways would be little changed because of the relatively minor contribution of direct brine release to overall releases (CCA Figure 641).

In summary, the set of conditions where the 3D-BRAGFLO and 2D-BRAGFLO do not show good agreement (average pressures above 16 MPa) are not expected to occur in the repository. Even if such pressures did occur, resulting in anhydrite fracturing and porosity increase, the brine inflow predicted by 3D-BRAGFLO would have little effect on direct brine release during a drilling intrusion.

EPA Response to Comment # 553

EPA disagrees with the comment. The work that is most relevant to this concern is the FEP Screening Analysis titled S1: Verification of 2D-Radial Flaring Using 3D Geometry, WBS No. 1.1.6.3, SANDIA WIPP CENTRAL FILES-A: 1.2.07.3: PA:QA:TSK:S1, ERRATA - February 19, 1996 (SNL WPO #30840). In this work, a simplified version of the two dimensional CCA PA grid was tested against a corresponding three-dimensional (3-D) model. BRAGFLO was used in both two-dimensional (2-D) and 3-D simulations, and TOUGH28W was used to model the 3-D simulations only. Simulation results were compared for cases with an average repository gas generation rate, and a gas generation rate that was double the average. The results of the second case, in which the gas generation rate was doubled, indicates that a combination of pressure induced fracturing and the 1-degree dip cause flow paths which are different for the 2-D and 3-D grids. Once fracturing of the interbeds occurs, the 3-D model displays an immediate migration of gas primarily out of the west side of the repository into the anhydrite layers, accompanied by brine inflow to the repository. This phenomenon is not seen in the results from the 2-D model, in which the west side of the repository is a no flow boundary, which demonstrates that the 2-D and 3-D simulations show local variations. However, the results also show that the predictions of brine flow to the accessible environment are similar for both 2-D and 3-D grids. With respect to increased brine saturation, Figures 7 and 12 of the FEPs Screening Analysis referenced above (WPO# 30840), shows the average gas saturations calculated with the 3-D simulations of TOUGH28 and both the 2-D and 3-D versions of BRAGFLO. Simulation results are compared for the base case and twice the base case generation rates, respectively. These curves indicate that gas saturations are higher in the 2-D simulations (WPO# 30840, page 27). Since brine and gas saturations are inversely related a similar trend would be observed for the brine saturations. In the Performance Assessment Verification Test (PAVT) , it was determined that the greatest potential releases could be attributed to those associated with spallings and direct brine releases. Furthermore, these releases are pressure controlled and will not occur if repository pressures are below 8 MPa. The fact that the 2-D model may overestimate gas saturation by underestimating brine saturations will lead to the prediction of higher gas pressures than those that would have been predicted with the 3-D configuration and this will result in more conservative estimates of releases. Based on this, EPA believes that the 2-D geometry used in the BRAGFLO CCA PA calculations is a reasonable simplification and that the predicted results are conservative.

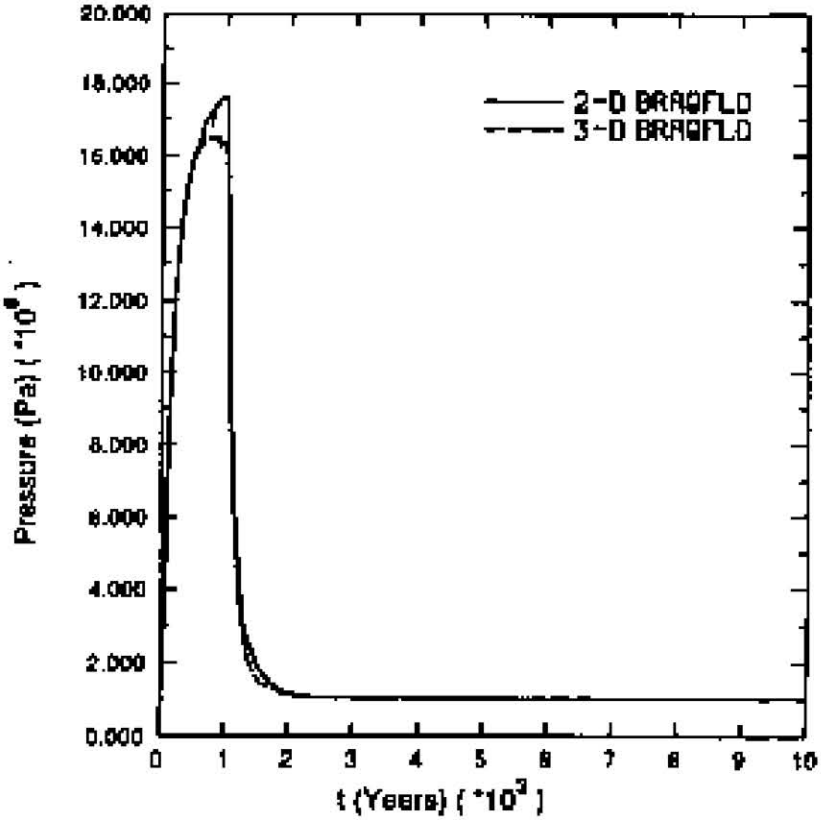

Figure 1: Average Pressure in Repository, FEP S-1 Analysis From Vaughn et al, 1996.

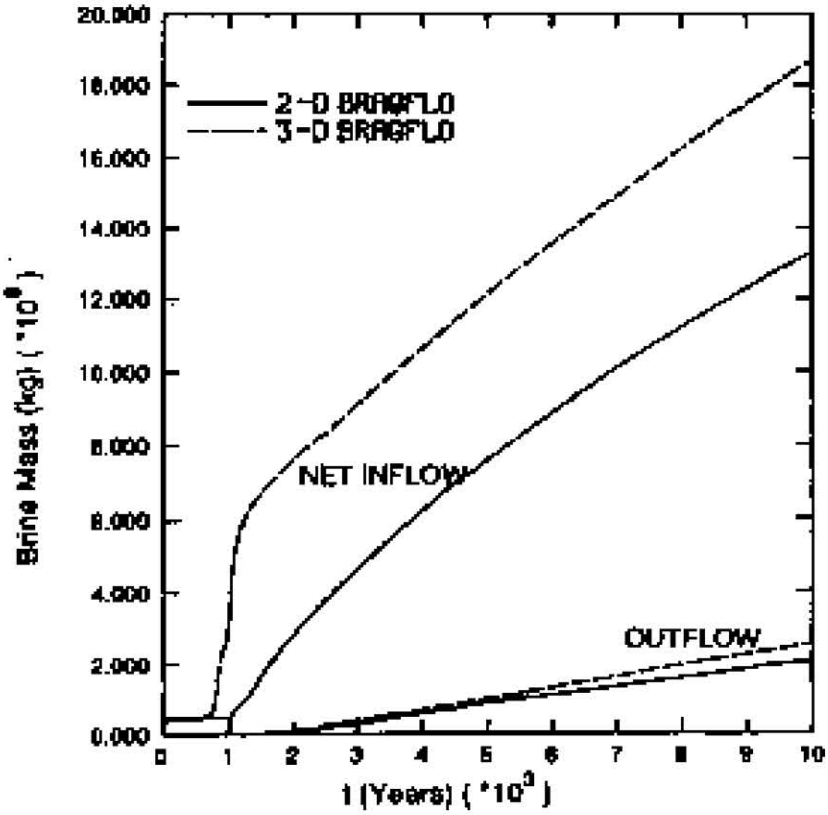

Figure 2: Cumulative Net Brine in and outflow at Repository, FEP S-1 Analysis From Vaughn et al, 1996.

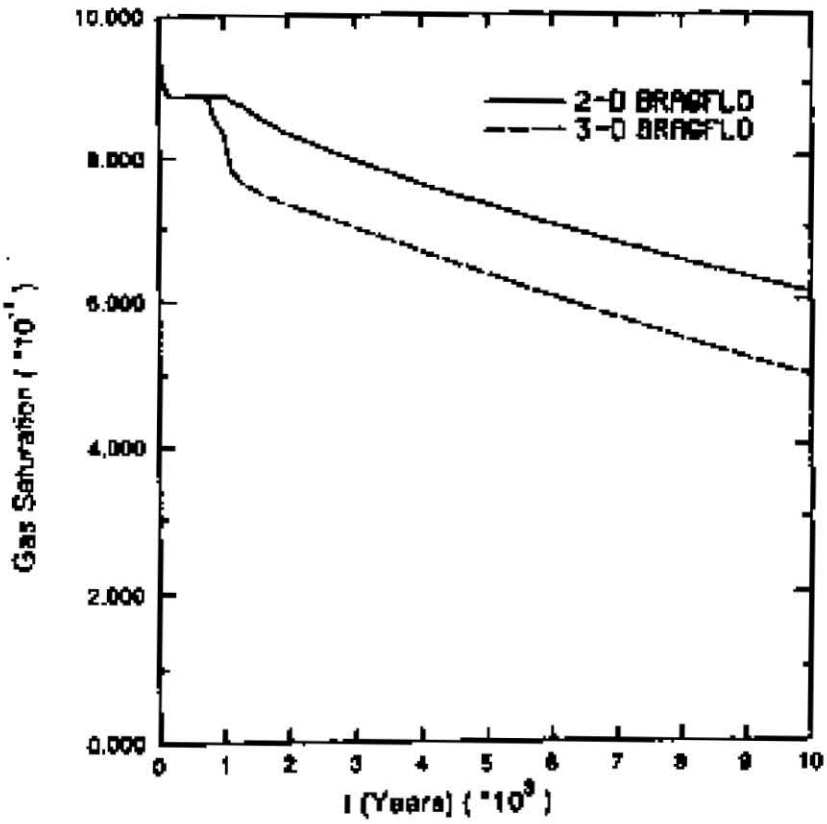

Figure 3: Average Gas Saturation in Repository, FEP S-1 Analysis
From Vaughn et al, 1996

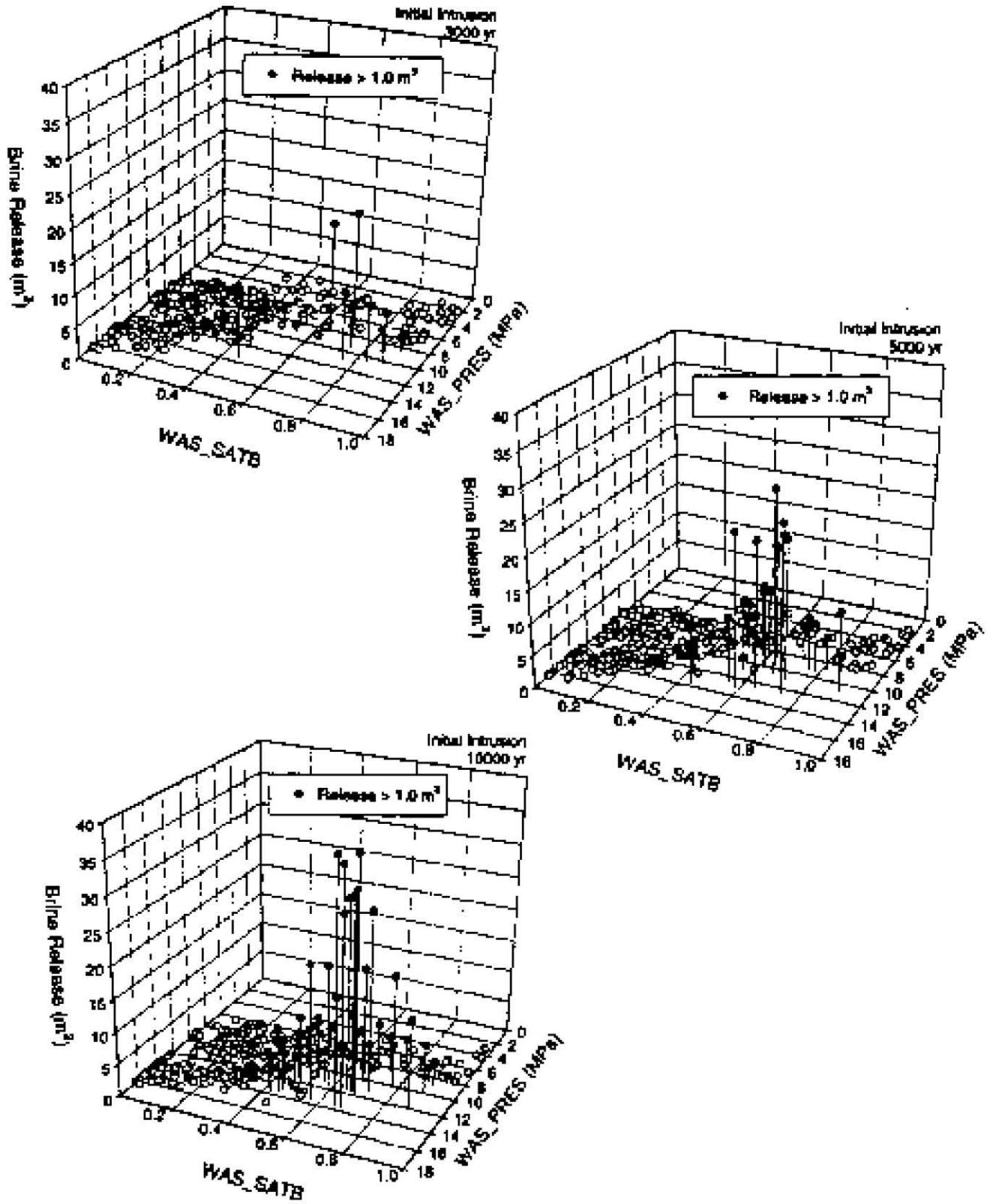

Figure 4: Three dimensional scatter plots for volume of brine reaching the surface due to direct brine release for a drilling intrusion into the lower panel.
From Helton, 1996.

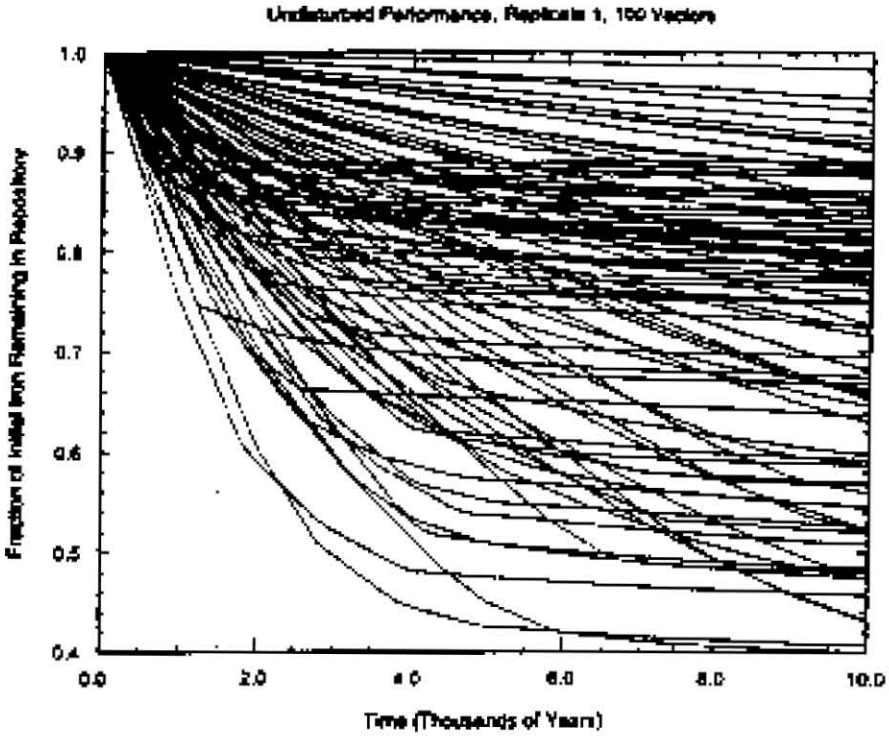

Figure 5: Fraction of Initial Iron Remaining in Repository
From: DOE, 1996.

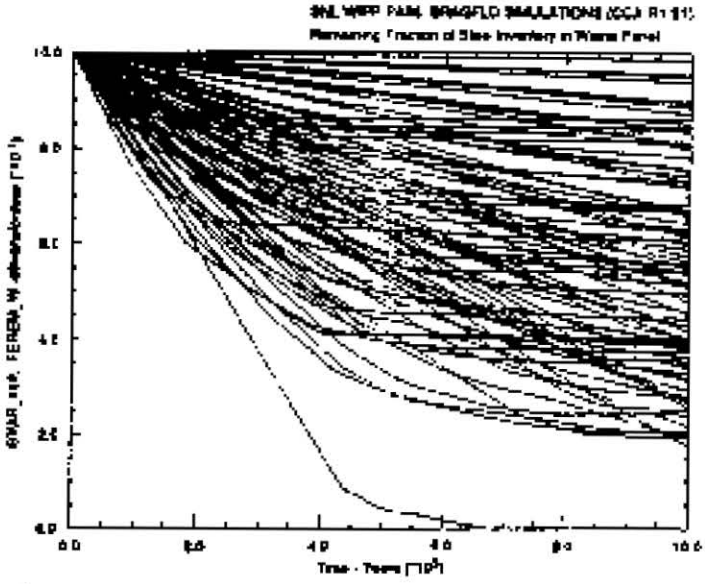

Figure 6: Remaining Fraction of Steel Inventory in Waste Panel
Modified from Figure 2.2.9 in Helton, 1996.

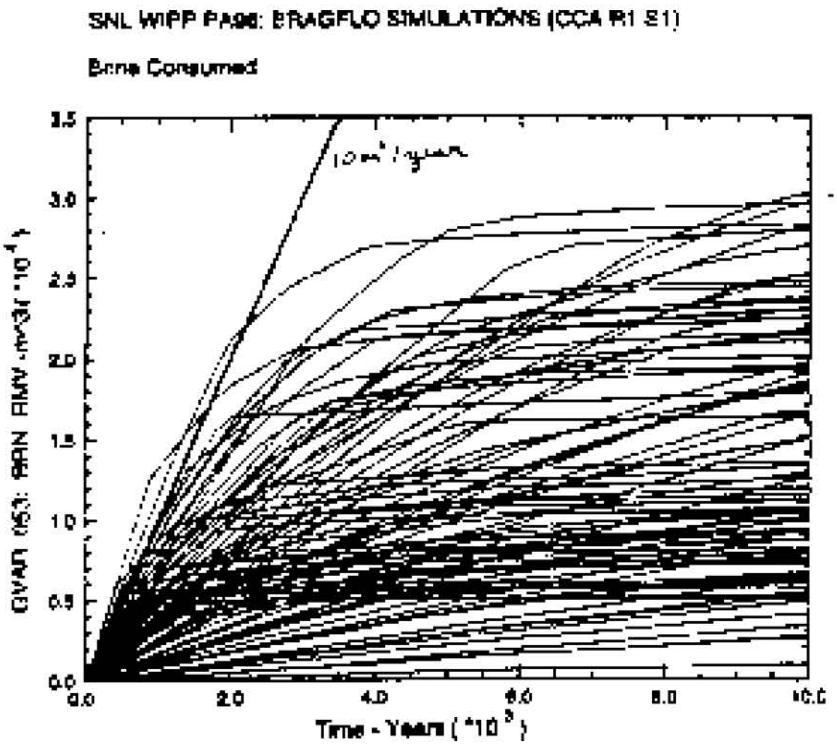

Figure 7: Cumulative Volume of Brine Consumed by Corrosion in the Repository
Modified from: Helton, 1996.

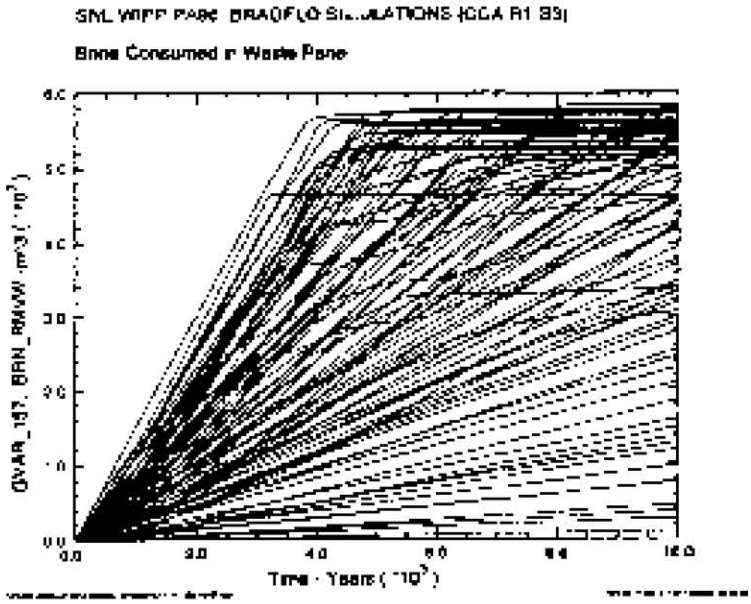

Figure 8: Cumulative Volume of Brine Consumed in the Waste Panel
From Bean et al., 1996

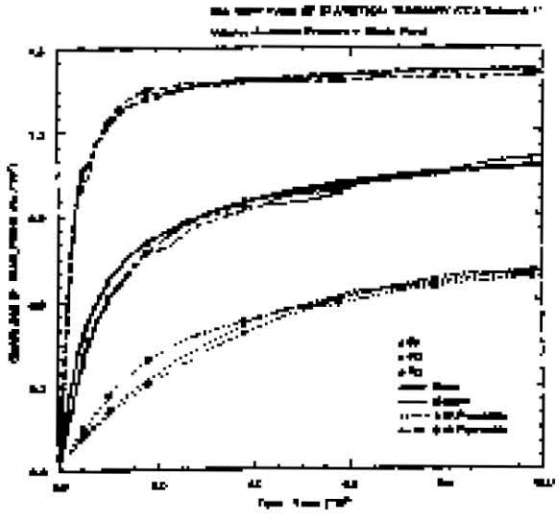

Figure 9: Percentile curves for three replicated LHSs for pressure in waste panel
From: Helton, 1996.

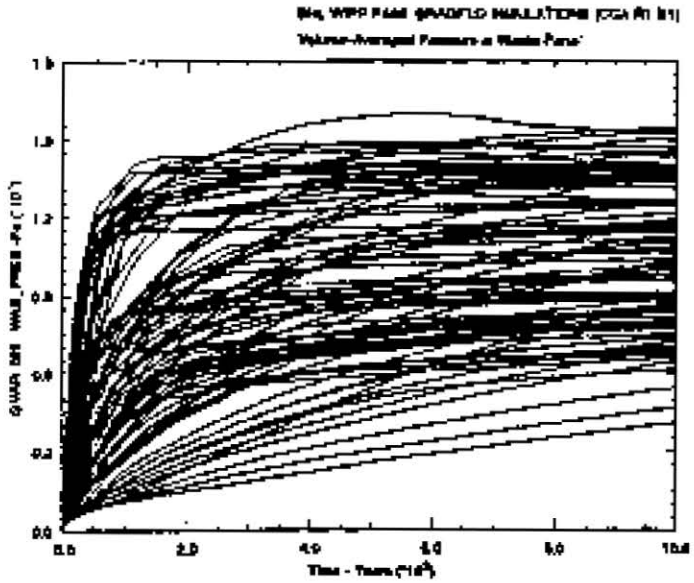

Figure 10: Pressure in waste panel
Modified from Figure 2.3.1 of Helton, 1996.

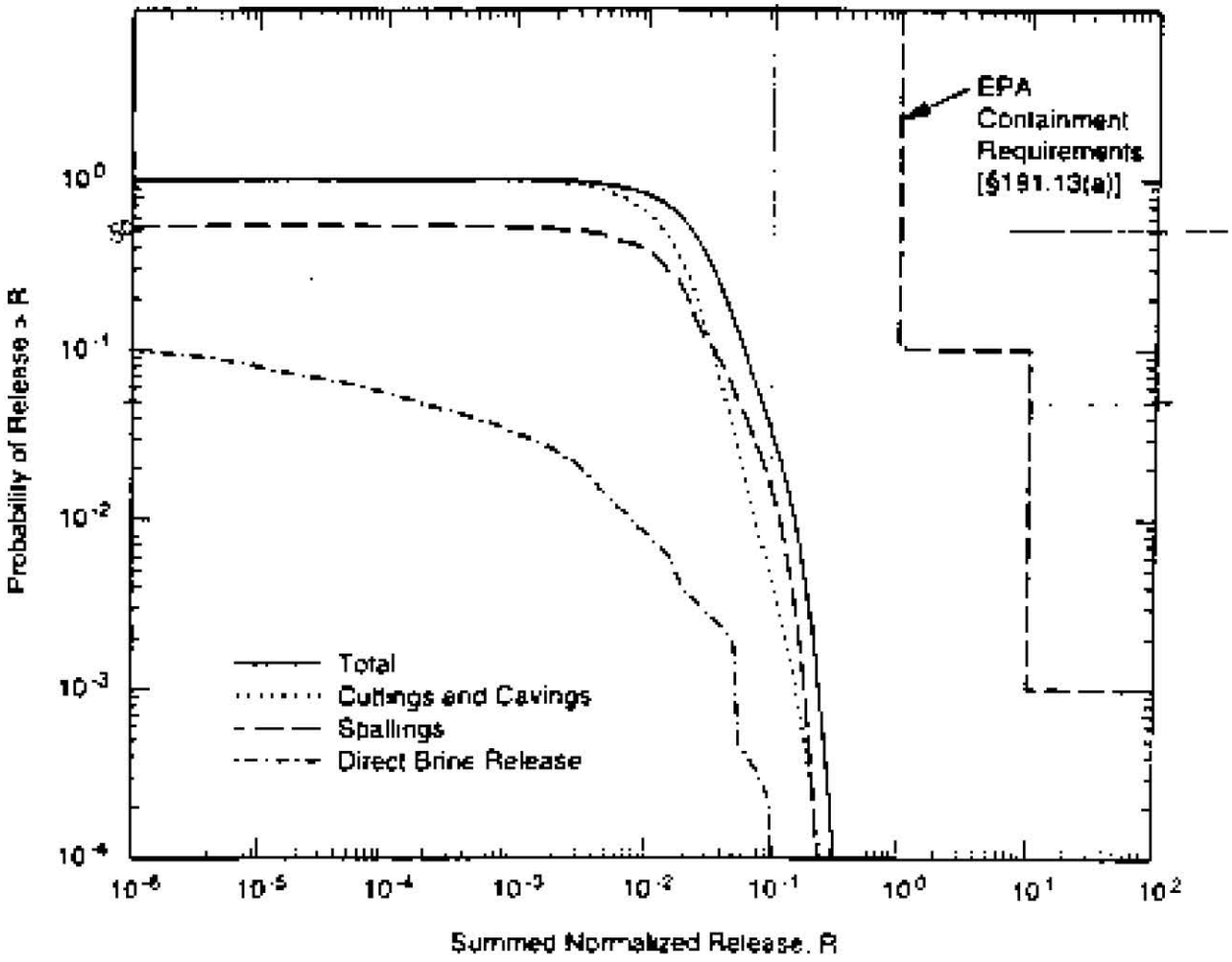

Note: Mean CCDFs are shown for the total normalized release (this curve is also shown in Figure 6-40 and is the mean of the family shown in Figure 6-35) and for the normalized releases resulting from cuttings and cavings, spallings, and direct brine release. The mean CCDF for subsurface releases resulting from groundwater transport is not shown because those releases were less than 10-6 EPA units and the CCDF cannot be shown at the scale of this figure.

Figure 11: Mean CCDFs for Specific Release Modes, Replicate 1.
From DOE, 1996.

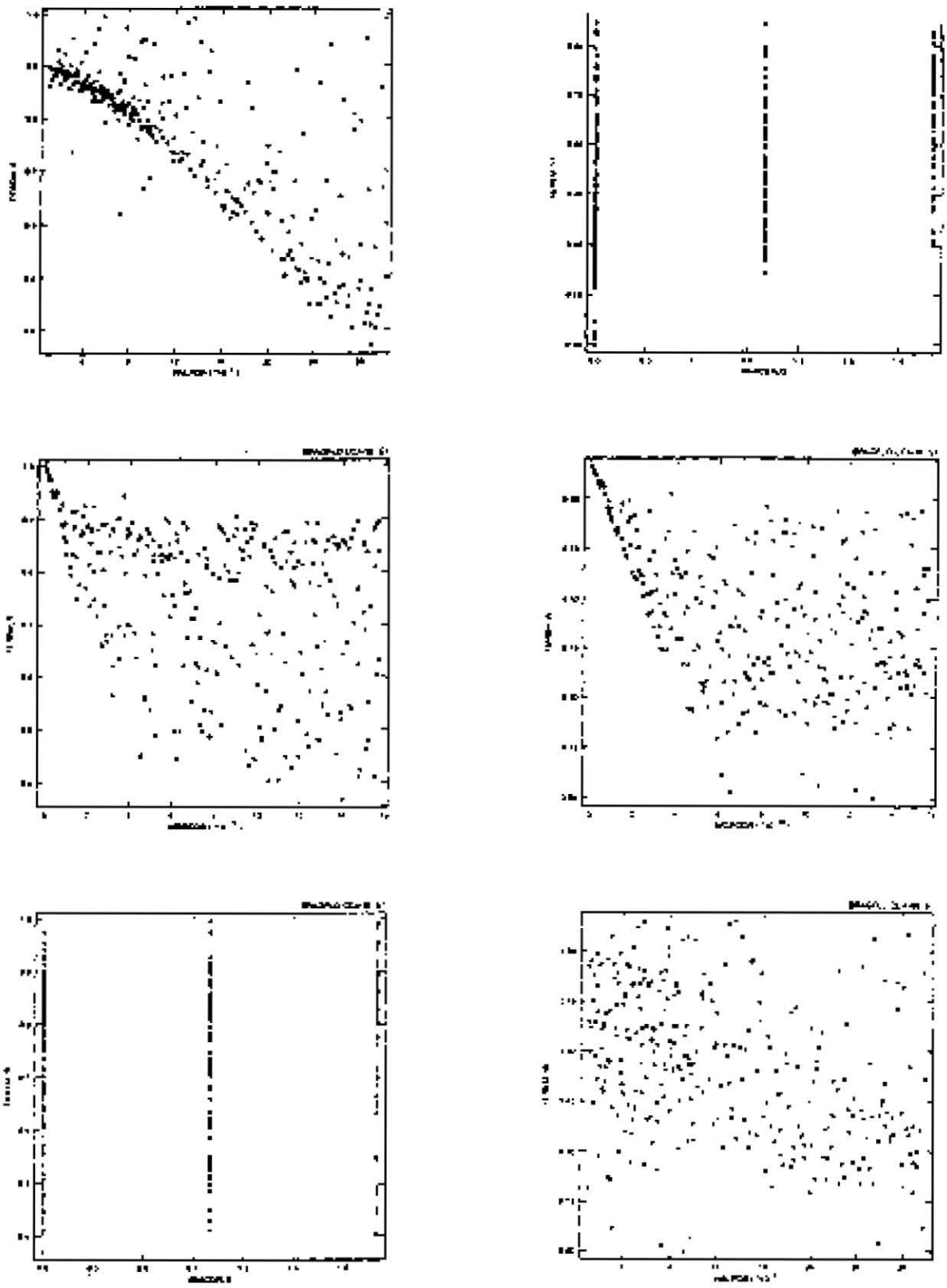

Figure 12: Scatter Plots of the Fraction of Iron Remaining in the Waste Panel (Right Frames) and Rest of the Repository (Left Frames) for Undisturbed Conditions at 10,000 Years.
From Helton, 1996.

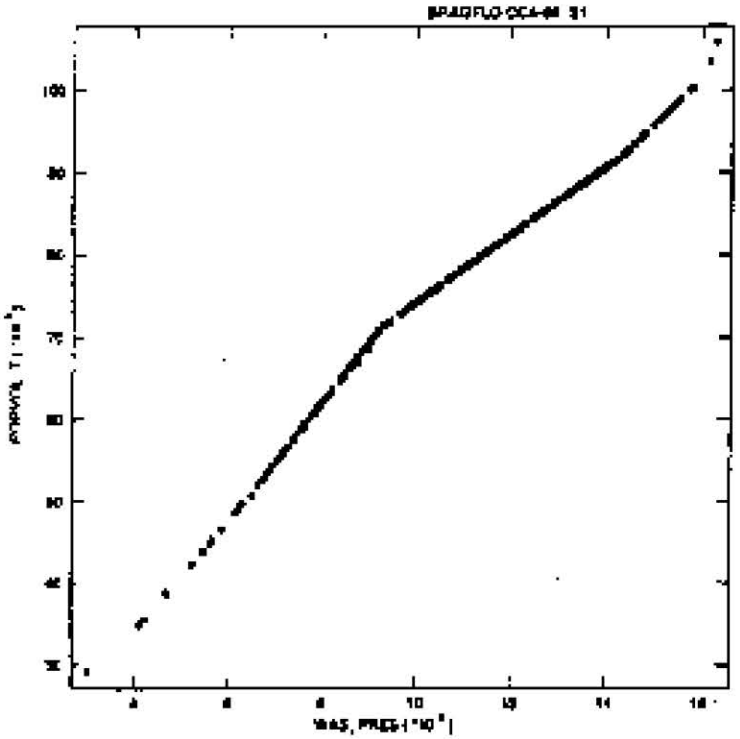

Figure 13: Scatter plot of pressure versus total pore volume in the repository. From Helton, 1996.

Table 1: Stepwise Regression Analysis with Rank-Transformed Data for Pressure in the Waste panel at 10000 years. From Helton, 1996.

Step[a]	Variable[b]	SRRC[c]	R^{2d}
1	*WMICDFLG*	0.71	0.52
2	*HALPOR*	0.45	0.73
3	*WGRCOR*	0.23	0.79
4	*ANHPRM*	0.11	.080
5	*SALPRES*	0.07	0.80
6	*SHRGSSAT*	0.06	0.81

[a] Steps in stepwise regression analysis.

[b] Variables listed in order of selection in regression analysis with *ANHCOMP* and *HALCOMP* excluded from entry into regression model.

[c] Standardized regression coefficients in final regression model.

[d] Cumulative R^2 value with entry of each variable into regression model.

Table 2: Stepwise Regression Analysis with Rank-Transformed Data for Fraction of Steel Remaining and Total Gas Generation in Upper and Lower Waste Panels at 10000 years. From Helton, 1996.

	Fraction Steel Remaining Upper Waste Panels			Fraction Steel Remaining Lower Waste Panels			Total Gas Generation Upper Waste Panels			Total Gas Generation Lower Waste Panels		
Step[a]	Variable[b]	SRRC[c]	R^{2d}	Variable	SRRC	R^2	Variable	SRRC	R^2	Variable	SRRC	R^2
1	*HALPOR*	−0.70	0.63	*WMICDFLG*	0.46	0.20	*WMICDFLG*	0.65	0.43	*WGRCOR*	0.47	0.23
2	*WGRCOR*	−0.35	0.75	*WGRCOR*	−0.45	0.41	*HALPOR*	0.58	0.77	*HALPOR*	0.45	0.44
3	*WMICDFLG*	0.12	0.76	*HALPOR*	−0.38	0.56	*WGRCOR*	0.24	0.83	*ANHPRM*	0.33	0.55
4	*WASTWICK*	−0.10	0.77	*ANHPRM*	−0.25	0.63	*WASTWICK*	0.07	0.83	*WMICDFLG*	0.17	0.58
5	*SHRGSSAT*	−0.08	0.78	*HALPRM*	−0.09	0.67	*SHRGSSAT*	0.06	0.83	*HALPRM*	0.12	0.59
6	*RPINTPRS*	−0.06	0.78	*SHRGSSAT*	−0.09	0.64				*SHRGSSAT*	0.08	0.60

[a] Steps in stepwise regression analysis.

[b] Variables listed in order of selection in regression analysis with *ANHCOMP* and *HALCOMP* excluded from entry into regression model.

[c] Standardized regression coefficients in final regression model.

[d] Cumulative R^2 value with entry of each variable into regression model

(Enclosure 3 to the 12/31/97 Letter From R.H. Neill, EEG to F. Marcinowski, EPA)

Issue: Compliance Failure as a Result of Spalled Material Reaching the Accessible Environment

Introduction

The issue of spalled material reaching the accessible environment at the WIPP has undergone much research within the past few years (Berglund, 1994; DOE, 1996; Hansen et al., 1997). Spall is the mechanical failure of waste due to high repository gas pressures that could be induced by a drop in pressure from a drilling intrusion. This process of waste removal has been included in the Performance Assessment calculations of the CCA. Yet, the amount that will actually reach the surface it is still unclear. Spallings are very important to the compliance of the disposal system, because the large release of radionuclides in the spalled material may prove the repository to be unsafe to future generations.

The three mechanisms of spall include blowout, stuck pipe and gas erosion, with the latter two being eliminated from calculations at the WIPP. It has been estimated that stuck pipe and gas erosion could bring more waste to the surface than blowout (Berglund (1994)). Blowout is the removal of the drilling fluid from the wellbore from a high influx of gas into the spalled cavity. The gas will cause some of the waste material on the cavity walls to fail in tension and be transported to the surface. High repository pressures and high waste permeability are general repository conditions for blowout.

Stuck pipe is a process of spall that, due to relatively low permeability and high repository pressures, may cause failed waste to press against the drill string sufficiently hard to prevent normal drilling. The solution of a jammed bit is to pull the drill string up and start drilling again. If the pressures remain high, the driller may have to bring the bit up several times, thus allowing significant quantities of waste to be brought to the surface. Gas erosion describes spall that is eroded by the drilling mud and may occur due to high repository pressures and low waste permeability. The rate of spall is slower than stuck pipe due to slightly lower pressures than stuck pipe (just above hydrostatic), and may release waste into the drilling mud at a rate undetectable by the driller. Gas erosion could continue until the repository pressure is in equilibrium with the drilling fluid, and may also bring significant quantities of waste to the surface. Stuck pipe and gas erosion releases would occur if the waste permeability is less than 10^{-16} m^2, a permeability threshold defined in Berglund (1994) that is currently under question, and repository pressures are greater than the pressure exerted by the drilling mud.

As part of the performance assessment, blowout calculations were performed, and volumes of failed waste material were estimated for the CCA, which ranged from 0.5 m^3 to 4 m^3. However, these calculations were found to be faulty by the DOE's Conceptual Model Peer Review Group (Wilson et al., 1997), and a new model for blowout was developed (Hansen et al., 1997). The new model showed that the CCA predicted blowout releases were conservative, by estimating a maximum release of only 0.27 m^3 at the worst conditions of repository behavior.

Through an investigation of permeability of the new spallings model, it is questionable whether the calculations of blowout is sufficient in estimating releases to the surface. The model was run with a range of permeability values consistent with Hansen et al., (1997), and was found to have high volumes of failed material in the repository cavity when gas influx was insufficiently large to cause blowout. Though blowout had not occurred, the failed waste in the borehole cavity would be introduced into the drilling mud and be carried to the surface with other cuttings and cavings from borehole drilling activity. This defines gas erosion and was not considered in Hansen et al., (1997).

More important to the question of the amount of waste released to the surface that will be expelled from the pressurized repository, is the amount of spalled material that will cause the repository to fail compliance. The performance assessment calculations of the CCA (DOE, 1996) and PAVT (DOE, 1997) demonstrated that any combination of spalled releases from blowout from 0.5 m^3 to 4 m^3 will demonstrate compliance. However, no one, as of yet, looked at the issue of failure. This report investigates the amount of spalled material that would result in failure to meet the EPA compliance standards.

Discussion

For the performance assessment calculations of the PAVT, the EPA decided to sample blowout releases on a range from 0.5 m^3 to 4.0 m^3 with a uniform distribution assigned to that range. The result was an increase in the overall mean of releases for spallings in the CCDF from 0.04 EPA units at the 10^{-1} probability in the CCA to 0.08 EPA Units in the PAVT. The increase was also due to the number of vectors that exhibited pressures above hydrostatic. The spallings and cuttings portions of the CCDF contribute equally to the overall mean of the CCDF.

For a more complete view of spallings and its contribution to the overall mean of the CCDF, the values of 0.5 to 4 m^3 used in the PAVT calculations were increased by a factor until it was shown that there was failure of compliance. The factor ranged from 2 to 16, and was a very simple adjustment to the PAVT values.

The results of increased spall reaching the surface can be seen in Figure 1. The increase in spall was accomplished by multiplying the PAVT generated releases by a factor of 2, 4, 8, and 16. These curves are seen in Figure 1, and are compared to the CCA releases. The figure suggests that a maximum of 16 times the amount of spallings will cause the repository to fail at the 10^{-1} probability, which corresponds to spallings releases between 8 m^3 and 64 m^3.

Conclusion

The questions raised on the amount of spalled material that will cause the disposal system to fail compliance is addressed here. The concern of additional spalled material that may reach the surface, by either a stuck pipe / gas erosion process, or through air drilling can be seen in Figure 1. The figure shows that a maximum of 16 times the PAVT spalled release can be brought to the surface before compliance of the disposal system is compromised if other modes of releases are held constant.

References

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Wilson, C., Porter, D., Gibbons, J., Oswald, R., Sjoblom, G., 1997. Waste Isolation Pilot Plant Conceptual Models Peer Review: Final Report. DOE/CAO-1996-1985. Carlsbad, NM:U.S. Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office.

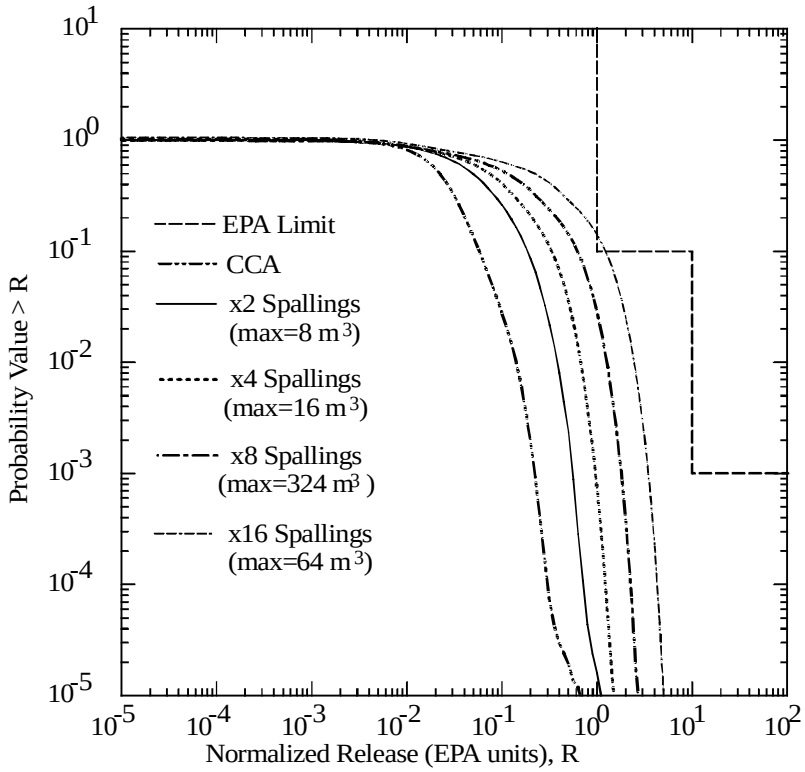

Figure 1: Overall Mean For PAVT Increased Spallings

(Enclosure 4 to the 12/31/97 Letter From R.H. Neill, EEG to F. Marcinowski, EPA)

Issue: Modeling the Air Drilling Scenario through a Direct Brine Release at the WIPP

Introduction

The practice of drilling with air as the circulation fluid in wells has been established in the Delaware Basin. On April 2, 1991 the Lincoln Federal Well No. 1 in Section 26, T21S, R32E, NMPM, in Lea County, New Mexico was drilled with air after 11 days of drilling with mud brine (Silva, 1994; EEG-55 p.63-64). The CCA did not consider the practice of drilling with air as a possible method for well development.

The modeling of air drilling was first raised by Bredehoeft (1997). Bredehoeft addressed the concern of spalled (solid) material that would reach the accessible environment through an air drilling scenario. His results show that a large amount of material could reach the surface, thus breaking the compliance standards set in 40 CFR Part 194 (EPA, 1997). This is the first report to address the issue of contaminated brine released after drilling with air. The issue is studied here, by applying a model to the release of brine through an inadvertent drill intrusion into the WIPP repository.

Discussion

An air drilling scenario is investigated using the Sandia developed code for a brine release through an intruding borehole. The code, BRAGFLO_DBR, is used along with the same assumptions as the Performance Assessment Verification Test (PAVT), including the BRAGFLO output files, and CUTTINGS_S files, but changing the boring fluid from a brine mud to air. The change in boring fluid would decrease the pressure at the bottom of the borehole, thus allowing a higher release of brine to escape to the surface.

For blowout to occur, the pressure of the repository must be higher than the borehole pressure at the repository depth. For brine mud, the pressure is assumed to be hydrostatic, or 8 MPa. For the air column, the air pressure will be very low, and was assumed to be approximately 2 MPa for this model, thus allowing higher and more frequent blowout occurrences than higher pressures. The 2 MPa is assumed to approximate the pressure exerted by a foam/air mixture at the depth of the WIPP repository. Air alone would exert pressures far below that of foam/air combination. However, this cutoff is reasonable due to the extremely low number of vectors that are expected to fall below the 2 MPa cutoff. One additional change from the PAVT for modeling with air includes the density of the drilling fluid from 1215 kg/m^3 for brine to 1.161 kg/m^3 for air.

The model was run for an initial E1 intrusion at 350 and 1000 years, and subsequent E2 intrusions at 550, 750, 1200, 1400, 2000, 3000, 4000, 5000, and 10000 years post closure (S2 and S3 scenarios). The results, shown in Figure 1, demonstrates the danger of drilling with air into the repository. The figure shows the results of 100 vectors for time 1200 years for S3, Replicate 1 using air as the drilling fluid. A single realization is shown to release as much as 2400 m^3 of brine to the surface at a second intrusion time of 1200 years. This is the highest brine release seen for all vectors at all times. The mean value for all releases at 1200 years is 436 m^3. The PAVT results show a maximum of 76 m^3 at 1200 years postclosure (DOE, 1997), and the CCA predicted a maximum release of 15 m^3 (DOE, 1997).

The high volumes of release seen in Figure 1 can be attributed to the high pressures of the repository. At 1200 years postclosure, the repository pressure of vector 51, which has the highest releases, exceeds most other vectors at 13.3 MPa, and is ranked 4th out of 100 vectors for highest repository pressure. Also contributing to its high release is the waste saturation. Vector 51 has a saturation of 0.67, which has been seen in past sensitivity analyses (See Figure 5.1.5. of Helton, 1996) to be an ideal saturation for release.

Inherently, there are problems with using the BRAGFLO_DBR code this way. The model assumed an incompressible fluid in the wellbore. Air is compressible, and the effects of incompressibility on the releases are not known. There are also some questions of whether the drilling fluid density change affected the whole repository or just the wellbore. This was a quick experiment, and these questions will be investigated further by the EEG. However, the results seen in Figure 1 are believed to provide an indication of the magnitude of potential releases.

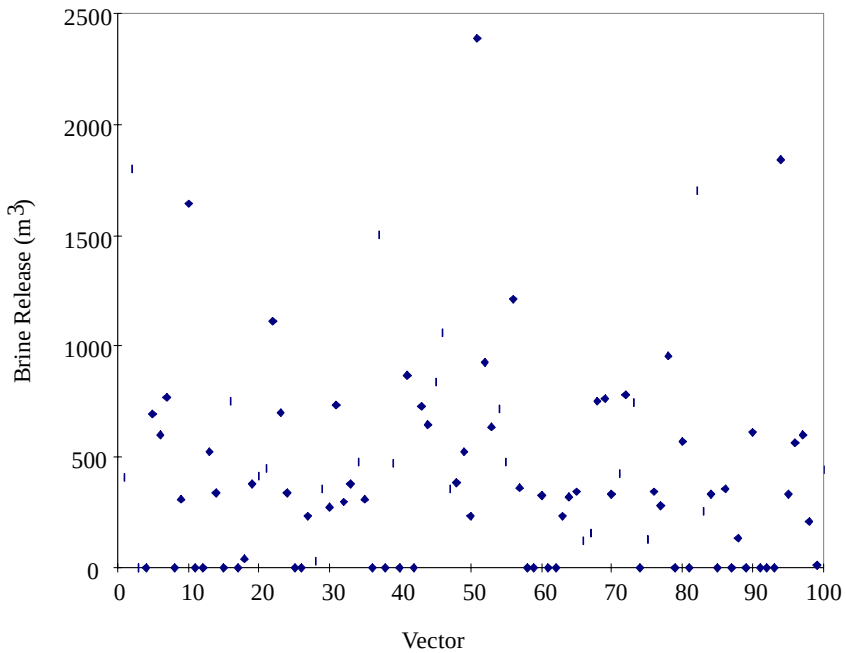

Figure 1. Air Drilling Results for 100 vectors of an S3 scenario at 1200 years postclosur

The carrying capacity of the brine to transport radionuclides to the surface depends on the solubility of the actinides in solution. The CCA's median value of solubility for a +4 actinide (Plutonium (IV), Uranium (IV), or Thorium (IV)) in Salado brine is approximately 4e-6 M. Thus, calculating the number of grams of Plutonium-239 (IV) for 2400 m^3 of brine is 2300 g. The grams can be converted to activity, and the 2400 m^3 of brine can be calculated to carry 140 Ci, or 0.4 EPA units. Higher solubility values will result in higher releases to the surface.

The CCDF curves, using the results of air drilling, can be seen in Figure 2. The code, which produced the curves, used the releases from PAVT and solubilities from the CCA. The direct brine release results of air drilling were then substituted for the results of the PAVT. Again, it should be noted that the CCDF results use spallings releases calculated in the PAVT. Spallings releases due to an air drilling event were not incorporated into the results. These curves assume a worst case scenario, in which all the drilling from an E1E2 drilling event would be using air as the drilling fluid.

In addition to the CCA solubilities, actinide solubilities with different mineral species were included. The solubilities were from median values using Nesquehonite, a mineral phase of the magnesium carbonate system, and from no MgO backfill. The 'No Backfill' case does not suggest that MgO should not be present in the repository, but gives an upper bound on solubility and how it affects compliance to the EPA standards. Table 1 shows the values used for each actinide oxidation state.

The CCDF curves for CCA solubility values do not exceed the EPA standard at the 10^{-1} or 10^{-3} probability level. Yet, the issue should not be readily dismissed. The problem was run on the scenarios of S2 and S3 only. The other three scenarios assumed brine mud as the drilling fluid. Furthermore, solubility values are shown to be greater in other mineral species of the magnesium carbonate system, and if the repository is breached during a time when these minerals will dominate the repository, then there may be sufficient releases to the accessible environment to cause the repository to fail compliance. This example can be seen in the curve for the Nesquehonite solubility. Again, this is a worst-case scenario in which all vectors for the simulation of air drilling uses the median values for Nesquehonite solubility, which can be seen in Table 1. The curve for Nesquehonite crosses the EPA compliance limit at the 0.02 probability level. This relates to a 1 in 50 chance of releasing more than 3500 Ci to the surface. The curve drops to a 1 in 500 chance of releasing more than 35000 Ci to the surface.

Salado	**+3 (M)**	**+4 (M)**	**+6 (M)**
Nesquehonite	3.17e-7	6.3e-4	NA (used No Backfill)
No Backfill	4e-3	5e-4	8e-5
Castile			
Nesquehonite	2.4e-6	1.04e-3	NA (used No Backfill)
No Backfill	2e-3	7e-5	8e-5

Table 1. Solubility values used in PANEL for generation of CCDF curves.

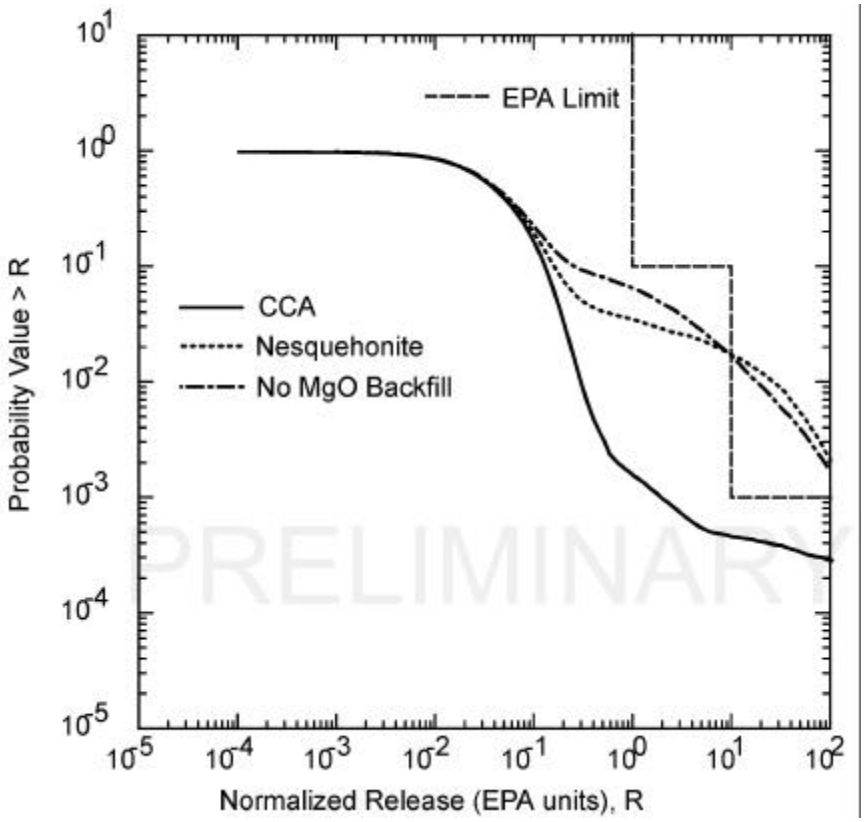

Figure 2. CCDF for Air Drilling with different solubilities. Air Drilling Modeling only included Direct Brine Releases for S2 and S3. Cuttings, spallings, and transport through the Culebra results are from PAVT, with actinide solubility values from the CCA, formation with Nesquehonite, and no MgO backfill.

The third curve on the CCDF plot shows the response of the disposal system for solubility values from 'No MgO Backfill'. The releases for probabilities greater than 1 in 50 are much higher than the other two curves. However, at lower probabilities the 'No MgO Backfill' has lower releases than the solubilities with Nesquehonite. This is due to the difference in solubility values at the +4 oxidation state for both Salado and Castile brine. In conclusion, the CCDF curves are shown to cross the EPA Release limits for higher solubility values, and the issue of air drilling must be taken more seriously than previous evaluations.

Recommendations

1) The EPA should look more closely at the issue of air drilling to determine the probability of such an event occurring in the 10000 year projected history of the disposal system.
2) EPA needs to asses the appropriateness of using the BRAGFLO direct brine release model for air drilling.
3) Depending on EPA's resolution of the solubility issue, the EPA may need to calculate CCDFs for air drilling.

Reproducibility

To reproduce the results of this experiments, the summarized files (*.TBL) of CUTTINGS_S, BRAGFLO_DBR, and SECOTP2D from PAVT, and the summarized files of NUTS, PANEL, and ST (Source Term) from the CCA are needed for the input for CCDFGF. In addition, the BRAGFLO_DBR files from an air drilling scenario will replace some of the BRAGFLO_DBR of the PAVT. Attachment 1 shows the input for the preprocessor of CCDFGF. The Direct Brine Release summarized files begin with: 'SUM_BF4_CCGF_AIR'.

The simulation of drilling with air with BRAGFLO_DBR was accomplished by changing the inputs to the preprocessor of the model. The ALGEBRA file 'ALG_BF4_CCA_PRE_DIR_REL_S3_DIST.INP' was modified to allow a lower threshold of pressure from the drilling fluid for time stepping. The file sets the time step for the BRAGFLO_DBR to 0 if the flowing bottomhole pressure (FBHP) is less than the pressure of the drilling fluid column, and to a maximum 1000 time steps if the pressure is greater. The FBHP was established in the preprocessor by a 3D curve fit from the Poettmann-Carpenter correlation (DOE, 1996). The ALGEBRA file was also modified for drilling fluid density. Attachment 2 lists the file and highlights the areas of change. The original ALGEBRA file used 8 MPa as the cutoff for timestep configuration. The new model sets the cutoff at 2 MPa.

References

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Attachment 1: Input for CCDFGF Preprocessor Mode for Air Drilling

```
$! .
$! MODULE:     PREPRO.COM
$! PURPOSE:    RUN PREPROCESSOR CODE TO CREATE CUTTINGS, SPALLINGS
$!            BLOWOUT, NUTS, AND SECOTF INPUT TABLES FOR USE BY
$            CCDFGF PREPROCESSOR OPTION
$! ---
$! AUTHOR:     JAY D. JOHNSON
$! DATE:       11/22/96
$!
$! Date        Changes
$! 11/10/97    Solubility     -D. Rucker
$!              CCA denotes CCA Solubilities
$!              EEG2 denotes Nesquehonite Solubilities
$!              EEG1 denotes No Backfill Solubilities
$!
$! 12/3/97     Air Drilling    -D. Rucker
$!              Direct Brine Release  'SUM_bf4_ccgf_air'.tbf
$! ---
$! Setup to run
$  SET NOON
$  REP := "R2"
$!
$  Testdir1 := "t4:[d1rucke.ccdfgf]"
$  Testdir2 := "t4:[d1rucke.ccdfgf.input_'REP']"
$  Testdir2a:= "t4:[d1rucke.pavl]"
$  Testdir3 := "t4:[d1rucke.ccdfgf.input_'REP']"
$  Testdir3a:= "t4:[d1rucke.pavl]"
$  Testdir4 := "t4:[d1rucke.ccdfgf.input_'REP']"
$  Testdir5 := "t4:[d1rucke.ccdfgf.input_'REP']"
$  Testdir6 := "t4:[d1rucke.panel.com]"
$  Testdir6a := "t4:[d1rucke.panel.time]"
$  Testdir7 := "t4:[d1rucke.cusp]"
$  Testdir8 := "t4:[d1rucke.dbr]"
$  testdir9 := "t4:[d1rucke.ruts]"
$  testdir0 := "t4:[d1rucke.st]"
$  Curdir   := "t4:[d1rucke.ccdfgf]"
$! ---
$! Define CUTTINGS file names
$! ---
$  DEFINE/NOLOG HT_FRACSINP                    'TESTDIR1'CCGF_CCA_HT_FRAC.DAT
$  DEFINE/NOLOG EPAUNI_CCH$INP                 'TESTDIR1'EPU_CCGF_CCA_CCH.DAT
$  DEFINE/NOLOG EPAUNI_CRH$INP                 'TESTDIR1'EPU_CCGF_CCA_CRH.DAT
$  DEFINE/NOLOG SUM_CUSP_CCGF_CCA$INP          'TESTDIR2a'SUM_CUSP_C97_'rep'_S1_L_T5000.TBL
$  DEFINE/NOLOG CCGF_CUTTINGS$OUT              'OUTDIR'CUTTING.TRN
$! ---
$! Define SPALLINGS file names
$! ---
$  DEFINE/NOLOG CH_TRU$INP                     'TESTDIR1'CCGF_CCA_CH_TRU.DAT
$! ---
$  DEFINE/NOLOG CUSP_S1_L_T100$INP             'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_L_T100.TBL
$  DEFINE/NOLOG CUSP_S1_L_T250$INP             'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_L_T250.TBL
$  DEFINE/NOLOG CUSP_S1_L_T1000$INP            'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_L_T1000.TBL
$  DEFINE/NOLOG CUSP_S1_L_T3000$INP            'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_L_T3000.TBL
$  DEFINE/NOLOG CUSP_S1_L_T5000$INP            'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_L_T5000.TBL
$  DEFINE/NOLOG CUSP_S1_L_T10000$INP           'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_L_T10000.TBL
$! ---
$  DEFINE/NOLOG CUSP_S1_U_T100$INP             'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_U_T100.TBL
$  DEFINE/NOLOG CUSP_S1_U_T250$INP             'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_U_T250.TBL
$  DEFINE/NOLOG CUSP_S1_U_T1000$INP            'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_U_T1000.TBL
$  DEFINE/NOLOG CUSP_S1_U_T3000$INP            'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_U_T3000.TBL
$  DEFINE/NOLOG CUSP_S1_U_T5000$INP            'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_U_T5000.TBL
$  DEFINE/NOLOG CUSP_S1_U_T10000$INP           'TESTDIR2a'SUM_CUSP_C97_'REP'_S1_U_T10000.TBL
$! ---
$  DEFINE/NOLOG CUSP_S2_L_T550$INP             'TESTDIR2a'SUM_CUSP_C97_'REP'_S2_L_T550.TBL
$  DEFINE/NOLOG CUSP_S2_L_T760$INP             'TESTDIR2a'SUM_CUSP_C97_'REP'_S2_L_T760.TBL
```

```
$ DEFINE/NOLOG CUSP_S2_L_T2000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S2_L_T2000.TBL
$ DEFINE/NOLOG CUSP_S2_L_T4000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S2_L_T4000.TBL
$ DEFINE/NOLOG CUSP_S2_L_T10000$INP       'TESTDIR2a'SUM_CUSP_C97_'REP'_S2_L_T10000.TBL
$! ---
$ DEFINE/NOLOG CUSP_S2_U_T550$INP         'TESTDIR2a'SUM_CUSP_C97_'REP'_S2_U_T550.TBL
$ DEFINE/NOLOG CUSP_S2_U_T750$INP         'TESTDIR2a'SUM_CUSP_C97_'REP'_S2_U_T750.TBL
$ DEFINE/NOLOG CUSP_S2_U_T2000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S2_U_T2000.TBL
$ DEFINE/NOLOG CUSP_S2_U_T4000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S2_U_T4000.TBL
$ DEFINE/NOLOG CUSP_S2_U_T10000$INP       'TESTDIR2a'SUM_CUSP_C97_'REP'_S2_U_T10000.TBL
$! ---
$ DEFINE/NOLOG CUSP_S3_L_T1200$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S3_L_T1200.TBL
$ DEFINE/NOLOG CUSP_S3_L_T1400$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S3_L_T1400.TBL
$ DEFINE/NOLOG CUSP_S3_L_T3000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S3_L_T3000.TBL
$ DEFINE/NOLOG CUSP_S3_L_T5000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S3_L_T5000.TBL
$ DEFINE/NOLOG CUSP_S3_L_T10000$INP       'TESTDIR2a'SUM_CUSP_C97_'REP'_S3_L_T10000.TBL
$! ---
$ DEFINE/NOLOG CUSP_S3_U_T1200$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S3_U_T1200.TBL
$ DEFINE/NOLOG CUSP_S3_U_T1400$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S3_U_T1400.TBL
$ DEFINE/NOLOG CUSP_S3_U_T3000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S3_U_T3000.TBL
$ DEFINE/NOLOG CUSP_S3_U_T5000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S3_U_T5000.TBL
$ DEFINE/NOLOG CUSP_S3_U_T10000$INP       'TESTDIR2a'SUM_CUSP_C97_'REP'_S3_U_T10000.TBL
$! ---
$ DEFINE/NOLOG CUSP_S4_L_T550$INP         'TESTDIR2a'SUM_CUSP_C97_'REP'_S4_L_T550.TBL
$ DEFINE/NOLOG CUSP_S4_L_T750$INP         'TESTDIR2a'SUM_CUSP_C97_'REP'_S4_L_T750.TBL
$ DEFINE/NOLOG CUSP_S4_L_T2000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S4_L_T2000.TBL
$ DEFINE/NOLOG CUSP_S4_L_T4000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S4_L_T4000.TBL
$ DEFINE/NOLOG CUSP_S4_L_T10000$INP       'TESTDIR2a'SUM_CUSP_C97_'REP'_S4_L_T10000.TBL
$! ---
$ DEFINE/NOLOG CUSP_S4_U_T550$INP         'TESTDIR2a'SUM_CUSP_C97_'REP'_S4_U_T550.TBL
$ DEFINE/NOLOG CUSP_S4_U_T750$INP         'TESTDIR2a'SUM_CUSP_C97_'REP'_S4_U_T750.TBL
$ DEFINE/NOLOG CUSP_S4_U_T2000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S4_U_T2000.TBL
$ DEFINE/NOLOG CUSP_S4_U_T4000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S4_U_T4000.TBL
$ DEFINE/NOLOG CUSP_S4_U_T10000$INP       'TESTDIR2a'SUM_CUSP_C97_'REP'_S4_U_T10000.TBL
$! ---
$ DEFINE/NOLOG CUSP_S5_L_T1200$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S5_L_T1200.TBL
$ DEFINE/NOLOG CUSP_S5_L_T1400$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S5_L_T1400.TBL
$ DEFINE/NOLOG CUSP_S5_L_T3000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S5_L_T3000.TBL
$ DEFINE/NOLOG CUSP_S5_L_T5000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S5_L_T5000.TBL
$ DEFINE/NOLOG CUSP_S5_L_T10000$INP       'TESTDIR2a'SUM_CUSP_C97_'REP'_S5_L_T10000.TBL
$ ---
$ DEFINE/NOLOG CUSP_S5_U_T1200$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S5_U_T1200.TBL
$ DEFINE/NOLOG CUSP_S5_U_T1400$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S5_U_T1400.TBL
$ DEFINE/NOLOG CUSP_S5_U_T3000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S5_U_T3000.TBL
$ DEFINE/NOLOG CUSP_S5_U_T5000$INP        'TESTDIR2a'SUM_CUSP_C97_'REP'_S5_U_T5000.TBL
$ DEFINE/NOLOG CUSP_S5_U_T10000$INP       'TESTDIR2a'SUM_CUSP_C97_'REP'_S5_U_T10000.TBL
$! ---
$ DEFINE/NOLOG CCGF_SPALLINGSOUT          'OUTDIR'SPALLING.TRN
$! ---
$! Define BLOWOUT file names
$! ---
$ DEFINE/NOLOG BF4_S1_L_T100$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Lower_T100.TBL
$ DEFINE/NOLOG BF4_S1_L_T350$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Lower_T350.TBL
$ DEFINE/NOLOG BF4_S1_L_T1000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Lower_T1000.TBL
$ DEFINE/NOLOG BF4_S1_L_T3000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Lower_T3000.TBL
$ DEFINE/NOLOG BF4_S1_L_T5000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Lower_T5000.TBL
$ DEFINE/NOLOG BF4_S1_L_T10000$INP        'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Lower_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S1_U_T100$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Up_T100.TBL
$ DEFINE/NOLOG BF4_S1_U_T350$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Up_T350.TBL
$ DEFINE/NOLOG BF4_S1_U_T1000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Up_T1000.TBL
$ DEFINE/NOLOG BF4_S1_U_T3000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Up_T3000.TBL
$ DEFINE/NOLOG BF4_S1_U_T5000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Up_T5000.TBL
$ DEFINE/NOLOG BF4_S1_U_T10000$INP        'TESTDIR3a'SUM_dbr_C97_'REP'_S1_Up_T10000.TBL
$ ---
$ DEFINE/NOLOG BF4_S2_L_T550$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S2_L_T550.TBL
$ DEFINE/NOLOG BF4_S2_L_T750$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S2_L_T750.TBL
$ DEFINE/NOLOG BF4_S2_L_T2000$INP         'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S2_L_T2000.TBL
```

```
$ DEFINE/NOLOG BF4_S2_L_T4000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S2_L_T4000.TBL
$ DEFINE/NOLOG BF4_S2_L_T10000$INP         'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S2_L_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S2_U_T550$INP           'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S2_U_T550.TBL
$ DEFINE/NOLOG BF4_S2_U_T750$INP           'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S2_L_T750.TBL
$ DEFINE/NOLOG BF4_S2_U_T2000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S2_U_T2000.TBL
$ DEFINE/NOLOG BF4_S2_U_T4000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S2_L_T4000.TBL
$ DEFINE/NOLOG BF4_S2_U_T10000$INP         'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S2_U_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S3_L_T1200$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_L_T1200.TBL
$ DEFINE/NOLOG BF4_S3_L_T1400$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_L_T1400.TBL
$ DEFINE/NOLOG BF4_S3_L_T3000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_L_T3000.TBL
$ DEFINE/NOLOG BF4_S3_L_T5000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_L_T5000.TBL
$ DEFINE/NOLOG BF4_S3_L_T10000$INP         'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_L_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S3_U_T1200$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_U_T1200.TBL
$ DEFINE/NOLOG BF4_S3_U_T1400$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_U_T1400.TBL
$ DEFINE/NOLOG BF4_S3_U_T3000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_U_T3000.TBL
$ DEFINE/NOLOG BF4_S3_U_T5000$INP          'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_U_T5000.TBL
$ DEFINE/NOLOG BF4_S3_U_T10000$INP         'TESTDIR8'SUM_bf4_ccgf_air_'REP'_S3_U_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S4_L_T550$INP           'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Lower_T550.TBL
$ DEFINE/NOLOG BF4_S4_L_T750$INP           'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Lower_T750.TBL
$ DEFINE/NOLOG BF4_S4_L_T2000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Lower_T2000.TBL
$ DEFINE/NOLOG BF4_S4_L_T4000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Lower_T4000.TBL
$ DEFINE/NOLOG BF4_S4_L_T10000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Lower_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S4_U_T550$INP           'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Up_T550.TBL
$ DEFINE/NOLOG BF4_S4_U_T750$INP           'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Up_T750.TBL
$ DEFINE/NOLOG BF4_S4_U_T2000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Up_T2000.TBL
$ DEFINE/NOLOG BF4_S4_U_T4000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Up_T4000.TBL
$ DEFINE/NOLOG BF4_S4_U_T10000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S4_Up_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S5_L_T1200$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Lower_T1200.TBL
$ DEFINE/NOLOG BF4_S5_L_T1400$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Lower_T1400.TBL
$ DEFINE/NOLOG BF4_S5_L_T3000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Lower_T3000.TBL
$ DEFINE/NOLOG BF4_S5_L_T5000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Lower_T5000.TBL
$ DEFINE/NOLOG BF4_S5_L_T10000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Lower_T10000.TBL
$! ---
$ DEFINE/NOLOG BF4_S5_U_T1200$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Up_T1200.TBL
$ DEFINE/NOLOG BF4_S5_U_T1400$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Up_T1400.TBL
$ DEFINE/NOLOG BF4_S5_U_T3000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Up_T3000.TBL
$ DEFINE/NOLOG BF4_S5_U_T5000$INP          'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Up_T5000.TBL
$ DEFINE/NOLOG BF4_S5_U_T10000$INP         'TESTDIR3a'SUM_dbr_C97_'REP'_S5_Up_T10000.TBL
$! ---
$ DEFINE/NOLOG CCGF_BLOWOUTSOUT            'OUTDIR'BLOWOUT.TRN
$! ---
$! Define NUTS file names
$! ---
$ DEFINE/NOLOG ALG_ST_CCGF_CCA_S1$INP      'TESTDIR0'SUM_ST_CCGF_aeg1_'REP'_S1.TBL
$ DEFINE/NOLOG ALG_ST_CCGF_CCA_S2$INP      'TESTDIR0'SUM_ST_CCGF_aeg1_'REP'_S2.TBL
$! ---
$ DEFINE/NOLOG SUM_NUTS_S1$INP             'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S1.TBL
$! ---
$ DEFINE/NOLOG SUM_NUTS_S2_100$INP         'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S2_T100.TBL
$ DEFINE/NOLOG SUM_NUTS_S2_350$INP         'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S2_T350.TBL
$ DEFINE/NOLOG SUM_NUTS_S3_1000$INP        'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S3_T1000.TBL
$ DEFINE/NOLOG SUM_NUTS_S3_3000$INP        'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S3_T3000.TBL
$ DEFINE/NOLOG SUM_NUTS_S3_5000$INP        'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S3_T5000.TBL
$ DEFINE/NOLOG SUM_NUTS_S3_7000$INP        'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S3_T7000.TBL
$ DEFINE/NOLOG SUM_NUTS_S3_9000$INP        'TESTDIR4'SUM_NUT_CCGF_cca_'REP'_S3_T9000.TBL
$! ---
$ DEFINE/NOLOG SUM_NUTS_S4_100$INP         'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S4_T100.TBL
$ DEFINE/NOLOG SUM_NUTS_S4_350$INP         'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S4_T350.TBL
$ DEFINE/NOLOG SUM_NUTS_S5_1000$INP        'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S5_T1000.TBL
$ DEFINE/NOLOG SUM_NUTS_S5_3000$INP        'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S5_T3000.TBL
$ DEFINE/NOLOG SUM_NUTS_S5_5000$INP        'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S5_T5000.TBL
```

```
$ DEFINE/NOLOG SUM_NUTS_S5_7000$INP          'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S5_T7000.TBL
$ DEFINE/NOLOG SUM_NUTS_S5_9000$INP          'TESTDIR4'SUM_NUT_CCGF_CCA_'REP'_S5_T9000.TBL
$! ---
$ DEFINE/NOLOG SUM_PNL_S6_100$INP            'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_100.TBL
$ DEFINE/NOLOG SUM_PNL_S6_350$INP            'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_350.TBL
$ DEFINE/NOLOG SUM_PNL_S6_1000$INP           'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_1000.TBL
$ DEFINE/NOLOG SUM_PNL_S6_4000$INP           'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_4000.TBL
$ DEFINE/NOLOG SUM_PNL_S6_6000$INP           'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_6000.TBL
$ DEFINE/NOLOG SUM_PNL_S6_9000$INP           'TESTDIR6a'SUM_PANEL_CCDf_eeg1_'REP'_S6_9000.TBL
$! DEFINE/NOLOG SUM_PNL_S6_100$INP           'TESTDIR4'SUM_PANEL_CCDfgf_'REP'_S6_100.TBL
$! DEFINE/NOLOG SUM_PNL_S6_350$INP           'TESTDIR4'SUM_PANEL_CCDFgf_'REP'_S6_350.TBL
$! DEFINE/NOLOG SUM_PNL_S6_1000$INP          'TESTDIR4'SUM_PANEL_CCDFgf_'REP'_S6_1000.TBL
$ DEFINE/NOLOG SUM_PNL_S6_2000$INP           'TESTDIR4'SUM_PANEL_CCDFGF_'REP'_S6_2000.TBL
$! DEFINE/NOLOG SUM_PNL_S6_4000$INP          'TESTDIR4'SUM_PANEL_CCDFgf_'REP'_S6_4000.TBL
$! DEFINE/NOLOG SUM_PNL_S6_6000$INP          'TESTDIR4'SUM_PANEL_CCDFgf_'REP'_S6_6000.TBL
$! DEFINE/NOLOG SUM_PNL_S6_9000$INP          'TESTDIR4'SUM_PANEL_CCDFgf_'REP'_S6_9000.TBL
$! ---
$ DEFINE/NOLOG SUM_CCDFGF_CCA_CAVGE0D$INP    'TESTDIR5'SUM_PANEL_eeg1_CON_'REP'_S1.tbl
$ DEFINE/NOLOG SUM_CCDFGF_CCA_CAVGE1D$INP    'TESTDIR5'SUM_PANEL_eeg1_CON_'REP'_S2.tbl
$! ---
$ DEFINE/NOLOG CCGF_NUTS$OUT                 'OUTDIR'NUTS.TRN
$! ---
$! Define SECOTP file names
$! ---
$ DEFINE/NOLOG ST2D3_CCA_PM$INP              'TESTDIR2a'SUM_ST2D3_c97_R1_PM.TBL
$ DEFINE/NOLOG ST2D3_CCA_FM$INP              'TESTDIR2a'SUM_ST2D3_c97_R1_FM.TBL
$ DEFINE/NOLOG CCGF_SECOTP$OUT               'OUTDIR'SECOTP.TRN
$! ---
$ DEFINE/NOLOG CCGF_MISC$INP                 'TESTDIR1'CCGF_MISC_PRE_CCA.INP
$ DEFINE/NOLOG CCGF_SDB$INP                  'TESTDIR1'CCDFGF.SDB
$ DEFINE/NOLOG CCGF_PRT$OUT                  'OUTDIR'CCGF_CCDFGF_CCA_'REP'.OUT
$ DEFINE/NOLOG CCGF$OUT                      'OUTDIR'CCGF_cca_'REP'.OUT
$! ---
$! Define release summary tables file name
$! ---
$ DEFINE/NOLOG CCGF_RELEASE$OUT              'OUTDIR'eeg1_reltab_eeg1_'REP'.DAT
$! ---
$! Execute CCDFGF with preprocessor option
$! ---
$ CCDFGF
$! ---
$ EXIT
$! ---
```

Attachment 2: ALGEBRA file for Air Drilling Scenario

```
!-----------------------------------------------------------------------
!
!TITLE:BRAGFLO 1996 DCA CALCULATIONS: REPOSITORY SCALE BLOWOUT
!ANAYLST: Dan Stoelzel, SNL
!CREATED: NOV 2, 1995
!PURPOSE: ALGEBRA file computes properties that can not be obtained
!       from CAMDAT and/or assigns properties to element blocks.
!            THIS FILE PREPARES A .CDB FILE FOR PREBRAG TO READ
!IMPORTANT: This file originates from J.E. Bean's algebra file for his FEP
!       model. The methodologies to calculate dip were copied from his
!       file, with minor changes
!       made to account for the differences in the meshes.
!       ALGEBRA TO CALC. DIP IN REPOSITORY - SCALE BLOWOUT MODEL.
!       new version of bragflo
!
!          MODIFIED:
!                    MARCH 26, 1996
!                    BLOWOUT MODEL STRUGGLING IN PANEL SEAL REGION. TURNED OFF
!                    CAP PRESSURE IN PANEL SEAL AND HALITE BY SETTING EQUAL TO
!                    CAP PRESSURE IN WASTE REGION
!
!                    MAY 17, 1996
!                    ADDED BOUNDARY CONDITION WELL CALCULATION FOR E1-E2 SCEN
!                    NEW CHANGES FOR LATEST DCA ANALYSIS
!
!                    MAY 20, 1996
!                    WELL 2 INPUT FILE TO ACCOUNT FOR E1-E2 SAME PANEL BOUNDARY
!                    COND.
!
!                    MAY 30,1996
!                    ADDED LOGIC TO ACCOUNT FOR CHANGES IN ABANDONED WELLBORE PERM
!                    FOR BOUNDARY CONDITION WELL.
!                    SCENARIO 2 AND 4 FILE  FIRST INTRUSION AT 350 YEARS
!
!                    December 1, 1997
!                    Changed Cutoff for pressure in the repository to allow Air Drilling
!                    Dave Rucker, EEG
!=====================================================================
!
!CHAPTER 0:  DEFINE NEW VARIABLE NAMES AND SOME NEEDED CONSTANTS
!
!---------------------------------------------------------------------
!
!
! SET CONSTANTS AND PUT IN WASTE REGION
LIMIT BLOCK 1
THETA1  = MAKEPROP(DIP_DEG[B:8]*2.0*PI[B:8]/360.0;
THETA2  = MAKEPROP(0.0)
!
!
PERM_X  = 10**PRMX_LOG
PERM_Y  = 10**PRMY_LOG
PERM_Z  = 10**PRMZ_LOG
SB_MIN  = SAT_RBRN * 1.05
POR_COMP = COMP_RCK/POROSITY
! CALCULATE PROPERTIES FOR DRZ & HALITE
LIMIT BLOCK 2 3
PERM_X  = 10**PRMX_LOG
PERM_Y  = 10**PRMY_LOG
PERM_Z  = 10**PRMZ_LOG
SB_MIN  = SAT_RBRN * 1.05
! NOW ADJUST POROSITY AND PORE COMPRESSIBILITY TO EQ. PORE VOL WITH CRUSHED
! ROOM HEIGHT
POROSITY = HEIGHT * POROSITY / HEIGHT[ID:1]
POR_COMP = COMP_RCK/POROSITY
! CAP PRESSURE MODEL CHANGES HERE:
```

```
CAP_MOD = CAP_MOD[ID:1]
PCT_A   = PCT_A[ID:1]
PCT_EXP = PCT_EXP[ID:1]
! CALC PROPERTIES FOR PANEL SEALS
LIMIT BLOCK 4
PERM_X  = 10**PRMX_LOG
PERM_Y  = 10**PRMY_LOG
PERM_Z  = 10**PRMZ_LOG
SB_MIN  = SAT_RBRN * 1.05
! NOW ADJUST POROSITY AND PORE COMPRESSIBILITY TO EQ. PORE VOL WITH CRUSHED
! ROOM HEIGHT
POROSITY = HEIGHT * POROSITY / HEIGHT[ID:1]
POR_COMP = COMP_ROK/POROSITY
! CAP PRESSURE MODEL CHANGES HERE:
CAP_MOD = CAP_MOD[ID:1]
PCT_A   = PCT_A[ID:1]
PCT_EXP = PCT_EXP[ID:1]
!==========================================================================
[redacted]
!==========================================================================
! SET WELLBORE PROPS
LIMIT BLOCK 7
SEBRINE1 = MAKEPROP(0.0)
SEGAS1   = MAKEPROP(0.0)
KRW1     = MAKEPROP(0.0)
KRG1     = MAKEPROP(0.0)
SEBRINE2 = MAKEPROP(0.0)
SEGAS2   = MAKEPROP(0.0)
KRW2     = MAKEPROP(0.0)
KRG2     = MAKEPROP(0.0)
SEBRINE3 = MAKEPROP(0.0)
SEGAS3   = MAKEPROP(0.0)
KRW3     = MAKEPROP(0.0)
KRG3     = MAKEPROP(0.0)
SEBRINE4 = MAKEPROP(0.0)
SEGAS4   = MAKEPROP(0.0)
KRW4     = MAKEPROP(0.0)
KRG4     = MAKEPROP(0.0)
! DEFINE CONSTANTS FOR THE THREE EQUATIONS TO BE USED TO CALCULATE FBHP
! EQUATION 1: (FOR BRINE FLOW ONLY, KRG = 0)
! FBHP = (A+BX+CY)/(1+DX+EY)
!   X = LOG10(BRINE CONST) LOG M^3/μA-S
!   Y = PANEL PRESSURE (Pa)
! 8,002,373 Pa < FBHP < 8,036,090 Pa
EQ1_A = MAKEPROP(8002577.4)
EQ1_B = MAKEPROP(62.1375 75)
EQ1_C = MAKEPROP(0.024916098)
EQ1_D = MAKEPROP(0.10254807)
EQ1_E = MAKEPROP(5.1235777E-9)
! EQUATION 2: (FOR LOG10(KRG/KRW) < 0 BRINE DOMINATED FLOW)
! FBHP = (A+BX+CX^2+DX^3+EY)/(1+FX+GX^2+HY)
!   X = LOG10(KRG/KRB)
!   Y = PANEL PRESSURE (Pa)
! 225,453 Pa < FBHP < 8,028,643 Pa
EQ2_A = MAKEPROP(947082.65)
EQ2_B = MAKEPROP(2788147.8)
EQ2_C = MAKEPROP(3451058.3)
EQ2_D = MAKEPROP(-54884.388)
EQ2_E = MAKEPROP(-0.017079483)
EQ2_F = MAKEPROP(0.8953587)
EQ2_G = MAKEPROP(0.54041537)
EQ2_H = MAKEPROP(-4.9369107E-9)
! EQUATION 3: (FOR LOG10(KRG/KRW) > 0 GAS DOMINATED FLOW)
! FBHP = EXP(A+BX+CX^0.5+DE^-X+EY^0.5)
!   X = LOG10(KRG/KRB)
!   Y = PANEL PRESSURE (Pa)
```

```
! 153,271 Pa < FBHP < 385,493 pA
EQ3_A = MAKEPROP(8.9214835)
EQ3_B = MAKEPROP(-0.2274279)
EQ3_C = MAKEPROP(1.3680586)
EQ3_D = MAKEPROP(1.8350386)
EQ3_E = MAKEPROP(0.00045726223)
!
  CALCULATE SKIN FROM SPALL REMOVED, & WELL PRODUCTIVITY INDEX
  ELEMENT 59 IS LOCATION OF WELL 2 (2ND INTRUSION DOWN DIP)
WELLRAD = BITSIZE/2
DRAINRAD = SQRT(DEL_X[E:59]*DEL_Y[E:59]/PI[B:B])
SKIN    = -1.0*LOG(SQRT(AREA_TOT/PI[B:B])/WELLRAD)
SKIN    = IFLT0(SKIN,SKIN,0)
! CHECK TO BE SURE WELLPI IS NOT 0 OR NEG. & SET TO 1.0 IF IT IS
! WELLPI  = PERM_X[ID:1] * HEIGHT[ID:1] / (LOG(DRAINRAD/WELLRAD) + SKIN - 0.5)
WELLPI  = IFGT0(LOG(DRAINRAD/WELLRAD) + SKIN - 0.5,PERM_X[ID:1]*HEIGHT[ID:1] &
     / (LOG(DRAINRAD/WELLRAD) + SKIN - 0.5),1.0)
! CALCULATE CONSTANTS NEEDED FOR WELLBORE MODEL:
! CALCULATE EFFECTIVE SATURATION USING KRP = 4 (BROOKS - COREY MODIFIED,
! WITH LAMBDA (PORE_DIS) = 2.89, NO CAP PRESSURE). DO FOR 4 COUPLED REGIONS
! REGION NO 1 (PANELS 1 & 8)
BRINE1  = IFLT0((BSATPAN1[ID:1]-SAT_RBRN[ID:1]),SAT_RBRN[ID:1],BSATPAN1[ID:1])
SEBRINE1 = (BRINE1 - SAT_RBRN[ID:1])/(1.0 - SAT_RBRN[ID:1])
SEGAS1  = (BRINE1 - SAT_RBRN[ID:1])/(1.0-SAT_RBRN[ID:1]-SAT_RGAS[ID:1])
SEGAS1  = IFLT0(1.0 - SEGAS1,1.0,SEGAS1)
KRW1    = SEBRINE1**((2+3*PORE_DIS[ID:1])/PORE_DIS[ID:1])
KRG1    = (1.0-SEGAS1)**2*(1.0-SEGAS1**((2 + PORE_DIS[ID:1])/PORE_DIS[ID:1]))
! NOW CALCULATE CONSTANT FOR BRINE AND GAS
CONBR1  = WELLPI * KRW1 / VISCO[ID:5]
CONGAS1 = WELLPI * KRG1 / VISCO[ID:6]
! NOW TAKE LOG BASE 10 OF PARAMETERS NEEDED FOR FBHP EQUATIONS
LOG_B1  = IFEQ0(KRW1,-10,LOG10(CONBR1+1E-24))
LOG_KR1 = IFEQ0(KRW1,10,LOG10((KRG1+1E-24)/(KRW1+1E-24)))
! CALCULATE FBHP's AND SET WITHIN LIMITS
PR1_EQ1 = (EQ1_A+EQ1_B*LOG_B1+EQ1_C*PRESPAN1[ID:1])/ &
      (1.0+EQ1_D*LOG_B1+EQ1_E*PRESPAN1[ID:1])
PR1_EQ1 = IFLT0(8002373.0 - PR1_EQ1,IFLT0(8036090.0 - PR1_EQ1,8036090.0, &
      PR1_EQ1),8002373.0)
PR1_EQ2 = (EQ2_A+EQ2_B*LOG_KR1+EQ2_C*LOG_KR1**2+EQ2_D*LOG_KR1**3+ &
      EQ2_E*PRESPAN1[ID:1])/(1.0+EQ2_F*LOG_KR1+EQ2_G*LOG_KR1**2+ &
      EQ2_H*PRESPAN1[ID:1])
PR1_EQ2 = IFLT0(225453.0 - PR1_EQ2,IFLT0(8028643.0 - PR1_EQ2,8028643.0, &
      PR1_EQ2),225453.0)
PR1_EQ3 = EXP(EQ3_A+EQ3_B*LOG_KR1+EQ3_C*ABS(LOG_KR1)**0.5+ &
      EQ3_D*EXP(-1.0*ABS(LOG_KR1))+EQ3_E*PRESPAN1[ID:1]**0.5)
PR1_EQ3 = IFLT0(153271.0 - PR1_EQ3,IFLT0(385493.0 - PR1_EQ3,385493.0, &
      PR1_EQ3),153271.0)
! RESET FBHP TO 0 IF NO BRINE BLOWOUT (KRW = 0 OR PRESSURE < 2 MPa (300 psi))
[redacted]
! IF NO BLOWOUT, SET NUMBER OF BRAGFLO STEPS TO 1, ELSE 1000
NUMSTEP1 = MAKEPROP(IFEQ0(FBHP1,1,1000))
! REGION NO 2 (PANELS 2 & 7)
BRINE2  = IFLT0((BSATPAN2[ID:1]-SAT_RBRN[ID:1]),SAT_RBRN[ID:1],BSATPAN2[ID:1])
SEBRINE2 = (BRINE2 - SAT_RBRN[ID:1])/(1.0 - SAT_RBRN[ID:1])
SEGAS2  = (BRINE2 - SAT_RBRN[ID:1])/(1.0-SAT_RBRN[ID:1]-SAT_RGAS[ID:1])
SEGAS2  = IFLT0(1.0 - SEGAS2),1.0,SEGAS2)
KRW2    = SEBRINE2**((2+3*PORE_DIS[ID:1])/PORE_DIS[ID:1])
KRG2    = (1.0-SEGAS2)**2*(1.0-SEGAS2**((2 + PORE_DIS[ID:1])/PORE_DIS[ID:1]))
! NOW CALCULATE CONSTANT FOR BRINE AND GAS
CONBR2  = WELLPI * KRW2 / VISCO[ID:5]
CONGAS2 = WELLPI * KRG2 / VISCO[ID:6]
! NOW TAKE LOG BASE 10 OF PARAMETERS NEEDED FOR FBHP EQUATIONS
LOG_B2  = IFEQ0(KRW2,-10,LOG10(CONBR2+1E-24))
LOG_KR2 = IFEQ0(KRW2,10,LOG10((KRG2+1E-24)/(KRW2+1E-24)))
! CALCULATE FBHP's AND SET WITHIN LIMITS
PR2_EQ1 = (EQ1_A+EQ1_B*LOG_B2+EQ1_C*PRESPAN2[ID:1])/ &
      (1.0+EQ1_D*LOG_B2+EQ1_E*PRESPAN2[ID:1])
PR2_EQ1 = IFLT0(8002373.0 - PR2_EQ1,IFLT0(8036090.0 - PR2_EQ1,8036090.0, &
```

```
        PR2_EQ1,8002373.0)
PR2_EQ2 = (EQ2_A+EQ2_B*LOG_KR2+EQ2_C*LOG_KR2**2+EQ2_D*LOG_KR2**3+ &
        EQ2_E*PRESPAN2[ID:1])/(1.0+EQ2_F*LOG_KR2+EQ2_G*LOG_KR2**2+ &
        EQ2_H*PRESPAN2[ID:1])
PR2_EQ2 = IFLT0(225453.0 - PR2_EQ2,IFLT0(8028643.0 - PR2_EQ2,8028643.0, &
        PR2_EQ2),225453.0)
PR2_EQ3 = EXP(EQ3_A+EQ3_B*LOG_KR2+EQ3_C*ABS(LOG_KR2)**0.5+ &
        EQ3_D*EXP(-1.0*ABS(LOG_KR2))+EQ3_E*PRESPAN2[ID:1]**0.5)
PR2_EQ3 = IFLT0(153271.0 - PR2_EQ3,IFLT0(385493.0 - PR2_EQ3,385493.0, &
        PR2_EQ3),153271.0)
! RESET FBHP TO 0 IF NO BRINE BLOWOUT (KRW = 0 OR PRESSURE < 2 MPa)
[redacted]
! IF NO BLOWOUT, SET NUMBER OF BRAGFLO STEPS TO 1, ELSE 1000
NUMSTEP2 = MAKEPROP(IFEQ0(FBHP2,1,1000))
! REGION NO 3 (PANELS 3 & 6)
BRINE3  = IFLT0(BSATPAN3[ID:1]-SAT_RBRN[ID:1],SAT_RBRN[ID:1],BSATPAN3[ID:1])
SEBRINE3 = (BRINE3 - SAT_RBRN[ID:1])/(1.0 - SAT_RBRN[ID:1])
SEGAS3  = (BRINE3 - SAT_RBRN[ID:1])/(1.0-SAT_RBRN[ID:1]-SAT_RGAS[ID:1])
SEGAS3  = IFLT0((1.0 - SEGAS3),1.0,SEGAS3)
KRW3    = SEBRINE3**((2+3*PORE_DIS[ID:1])/PORE_DIS[ID:1])
KRG3    = (1.0-SEGAS3)**2*(1.0-SEGAS3**((2 + PORE_DIS[ID:1])/PORE_DIS[ID:1]))
! NOW CALCULATE CONSTANT FOR BRINE AND GAS
CONBR3  = WELLPI * KRW3 / VISCO[ID:5]
CONGAS3 = WELLPI * KRG3 / VISCO[ID:6]
! NOW TAKE LOG BASE 10 OF PARAMETERS NEEDED FOR FBHP EQUATIONS
LOG_B3  = IFEQ0(KRW3,-10,LOG10((CONBR3+1E-24))
LOG_KR3 = IFEQ0(KRW3,10,LOG10((KRG3+1E-24)/(KRW3+1E-24)))
! CALCULATE FBHP's AND SET WITHIN LIMITS
PR3_EQ1 = (EQ1_A+EQ1_B*LOG_B3+EQ1_C*PRESPAN3[ID:1])/ &
        (1.0+EQ1_D*LOG_B3+EQ1_E*PRESPAN3[ID:1])
PR3_EQ1 = IFLT0(8002373.0 - PR3_EQ1,IFLT0(8036090.0 - PR3_EQ1,8036090.0, &
        PR3_EQ1),8002373.0)
PR3_EQ2 = (EQ2_A+EQ2_B*LOG_KR3+EQ2_C*LOG_KR3**2+EQ2_D*LOG_KR3**3+ &
        EQ2_E*PRESPAN3[ID:1])/(1.0+EQ2_F*LOG_KR3+EQ2_G*LOG_KR3**2+ &
        EQ2_H*PRESPAN3[ID:1])
PR3_EQ2 = IFLT0(225453.0 - PR3_EQ2,IFLT0(8028643.0 - PR3_EQ2,8028643.0, &
        PR3_EQ2),225453.0)
PR3_EQ3 = EXP(EQ3_A+EQ3_B*LOG_KR3+EQ3_C*ABS(LOG_KR3)**0.5+ &
        EQ3_D*EXP(-1.0*ABS(LOG_KR3))+EQ3_E*PRESPAN3[ID:1]**0.5)
PR3_EQ3 = IFLT0(153271.0 - PR3_EQ3,IFLT0(385493.0 - PR3_EQ3,385493.0, &
        PR3_EQ3),153271.0)
! RESET FBHP TO 0 IF NO BRINE BLOWOUT (KRW = 0 OR PRESSURE < 2 MPa)
[redacted]
! IF NO BLOWOUT, SET NUMBER OF BRAGFLO STEPS TO 1, ELSE 1000
NUMSTEP3 = MAKEPROP(IFEQ0(FBHP3,1,1000))
! REGION NO 4 (PANELS 4 & 5)
BRINE4  = IFLT0((BSATPAN4[ID:1]-SAT_RBRN[ID:1]),SAT_RBRN[ID:1],BSATPAN4[ID:1])
SEBRINE4 = (BRINE4 - SAT_RBRN[ID:1])/(1.0 - SAT_RBRN[ID:1])
SEGAS4  = (BRINE4 - SAT_RBRN[ID:1])/(1.0-SAT_RBRN[ID:1]-SAT_RGAS[ID:1])
SEGAS4  = IFLT0((1.0 - SEGAS4),1.0,SEGAS4)
KRW4    = SEBRINE4**((2+3*PORE_DIS[ID:1])/PORE_DIS[ID:1])
KRG4    = (1.0-SEGAS4)**2*(1.0-SEGAS4**((2 + PORE_DIS[ID:1])/PORE_DIS[ID:1]))
! NOW CALCULATE CONSTANT FOR BRINE AND GAS
CONBR4  = WELLPI * KRW4 / VISCO[ID:5]
CONGAS4 = WELLPI * KRG4 / VISCO[ID:6]
! NOW TAKE LOG BASE 10 OF PARAMETERS NEEDED FOR FBHP EQUATIONS
LOG_B4  = IFEQ0(KRW4,-10,LOG10(CONBR4+1E-24))
LOG_KR4 = IFEQ0(KRW4,10,LOG10((KRG4+1E-24)/(KRW4+1E-24)))
! CALCULATE FBHP's AND SET WITHIN LIMITS
PR4_EQ1 = (EQ1_A+EQ1_B*LOG_B4+EQ1_C*PRESPAN4[ID:1])/ &
        (1.0+EQ1_D*LOG_B4+EQ1_E*PRESPAN4[ID:1])
PR4_EQ1 = IFLT0(8002373.0 - PR4_EQ1,IFLT0(8036090.0 - PR4_EQ1,8036090.0, &
        PR4_EQ1),8002373.0)
PR4_EQ2 = (EQ2_A+EQ2_B*LOG_KR4+EQ2_C*LOG_KR4**2+EQ2_D*LOG_KR4**3+ &
        EQ2_E*PRESPAN4[ID:1])/(1.0+EQ2_F*LOG_KR4+EQ2_G*LOG_KR4**2+ &
        EQ2_H*PRESPAN4[ID:1])
PR4_EQ2 = IFLT0(225453.0 - PR4_EQ2,IFLT0(8028643.0 - PR4_EQ2,8028643.0, &
```

```
        PR4_EQ3),225453.0)
PR4_EQ3 = EXP(EQ3_A+EQ3_B*LOG_KR4+EQ3_C*ABS(LOG_KR4)**0.5+ &
        EQ3_D*EXP(-1.0*ABS(LOG_KR4))-EQ3_E*PRESPAN4[ID:*]**0.5)
PR4_EQ3 = IFLT0(153271.0 - PR4_EQ3,IFLT0(385493.0 - PR4_EQ3,385493.0, &
        PR4_EQ3),153271.0)
!RESET FBHP TO 0 IF NO BRINE BLOWOUT (KRW = 0 OR PRESSURE < 2 MPa)
[illegible]
!IF NO BLOWOUT, SET NUMBER OF BRAGFLO STEPS TO 1, ELSE 1000
NUMSTEP4 = MAKEPROP(IFEQ0(FBHP4,1.1000))
DELETE BRINE1, BRINE2, BRINE3, BRINE4
!==========================================================================
!--------------------------------------------------------------------------
!SET UP BOUNDARY CONDITIONS FOR PREVIOUS INTRUSIONS HERE
!--------------------------------------------------------------------------
! SET UP NEEDED CONSTANTS (NOTE: BOREHOLE LENGTH FROM PANEL TO CASTILE B.P.
! IS 247 METERS -- USED IN CON_SAND & CON_CREP)
! MODIFICATIONS MADE 5/30/96
LEN_BC   = MAKEPROP(247.0)
DRAIN_BC = MAKEPROP(SQRT(DEL_X[E:15]*DEL_Y[E:15]/PI[E:8]))
WELPI_BC = PERM_X[ID:*] * HEIGHT[ID:1] / (LOG(DRAIN_BC/WELLRAD) + 0.0 - 0.5)
RHO_G_H  = MAKEPROP(DNSFLUID[ID:5]*GRAVACC[ID:5]*LEN_BC)
CON_OPEN = MAKEPROP(PRM_CAST*THCK_CAS[ID:5]*(LOG(DRAIN_BC/WELLRAD)-0.5)) &
        / (PERM_X[ID:1]*HEIGHT[ID:1]*(LOG(RE_CAST[ID:5]/WELLRAD)-0.5))
CON_SAND = MAKEPROP((PRM_SAND*PI[ID:8]*WELLRAD*WELLRAD* &
        (LOG(DRAIN_BC/WELLRAD)-0.5)) / (PERM_X[ID:*]*HEIGHT[ID:1]*LEN_BC))
CON_CREP = MAKEPROP((PRM_CREP*PI[ID:8]*WELLRAD*WELLRAD* &
        (LOG(DRAIN_BC/WELLRAD)-0.5)) / (PERM_X[ID:1]*HEIGHT[ID:1]*LEN_BC))
! SOLVE FOR OPEN BOREHOLE TO CASTILE B.C. (WITHIN 200 YEARS AFTER FIRST INTR.)
! USE FBHP4 SINCE BOUNDARY CONDITION WELL IS ASSUMED TO BE IN PANEL 5 (DOWN-
! DIP) FOR ALL SUBSEQUENT INTRUSIONS
BHP_OPEN = (FBHP4+CON_OPEN*(CAST_RE-RHO_G_H))/(1.0+CON_OPEN)
! SOLVE FOR SAND-FILLED BH CONDITION (200 TO 1200 YEARS AFTER 1ST INTRUSION)
BHP_SAND = (FBHP4+CON_SAND*(CAST_WB-RHO_G_H))/(1.0+CON_SAND)
! SOLVE FOR CREEP CLOSED BH CONDITION (> 200 YEARS AFTER 1ST INTRUSION)
BHP_CREP = (FBHP4+CON_CREP*(CAST_WB-RHO_G_H))/(1.0+CON_CREP)
ASSIGN ABANDONED BH PRESSURE BASED ON INTRUSION TIME
PREV_TME = MAKEPROP(1000.0)
DELT_TME = INTR_TME/YRSEC[ID:8] - PREV_TME
BHP_ABAN = IFGT0(DELT_TME - 200.1,IFGT0(DELT_TME - 1200.1,BHP_CREP,BHP_SAND), &
        BHP_OPEN)
--------------------------------------------------------------------------
==========================================================================
--------------------------------------------------------------------------
!--------------------------------------------------------------------------
!CHAPTER 3.  COMPUTE DIP IN REPOSITORY
!--------------------------------------------------------------------------
!--------------------------------------------------------------------------
!--------------------------------------------------------------------------
!==========================================================================
LIMIT ELEMENT OFF
!COMPUTE THE GRID BLOCK ELEVATIONS ACCOUNTING FOR 1 DEGREE DIP IN SALADO
!DEFINE GRID BLOCK ELEVATIONS DUE TO DIP
! USE ELEVATION OF SHAFT AT MID-REPOSITORY
ZORIGIN  = 382.671
YORIGIN  = 1000.0
ELEVN    = MAKENODE(COS(THETA1[ID:1])*(Z-ZORIGIN) &
        - SIN(THETA1[ID:1])*(Y-YORIGIN))
ELEVE    = NODEELE(ELEVN) + ZORIGIN
COMPUTE GRID BLOCK POTENTIAL ASSUMING BRINE IS INCOMPRESSIBLE (APPROXIMATELY)
POTE     = PRESEL(DNSFLUID[ID:5]*GRAVACC[ID:5]) + ELEVE
!
! NOW SET GRID THICKNESS FOR ALL ELEMENTS TO CRUSHED PANEL HEIGHT
THICK    = MAKEATTR(HEIGHT[ID:1])
!
DELETE ELEVN, YORIGIN, ZORIGIN
EXIT
```

8.4a. Solubility of Plutonium as Expected Under Conditions in the WIPP Repository (V.M. Oversby, 1997)

THE SOLUBILITY OF PLUTONIUM UNDER CONDITIONS EXPECTED IN THE WIPP REPOSITORY

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October 31, 1997

This report was prepared for the Environmental Evaluation Group, Albuquerque, New Mexico. Every attempt has been made to make the report as complete as possible within the time available for its preparation; however, the author cannot guarantee that all relevant work is included in the discussion. The author is not responsible for the subsequent use of information and opinions contained in this report.

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Appendix A: Review of Chemical Conditions Model

Appendix B: Review of Novak and Moore solubility calculations

Appendix C: Review of SOTERM Appendix to CCA

Appendix D: Summary of relevant articles used in preparation of this report

Introduction

The Waste Isolation Pilot Plant (WIPP) is located in southeastern New Mexico. It is designed to be a final disposal site for transuranic wastes (TRU) produced from defense-related activities in the USA. The repository site is 655 meter below ground surface in a bedded salt formation (Salado Fm.) of Permian age. The planned inventory of wastes includes 850,000 canisters of relatively low activity, contact-handled, TRU, and about 7500 canisters of higher activity, remote-handled, TRU (Chaturvedi et al., 1997). The remote handled TRU canisters will contain about 15% of the total activity in the repository and, thus, can be expected to contain the highest concentrations of Pu and Am, the main actinide constituents in the waste.

The Environmental Evaluation Group (EEG) conducts independent technical evaluations of the impact of the WIPP project on public health and on the environment. In October, 1996, the US Department of Energy submitted their Compliance Certification Application (CCA) to the US Environmental Protection Agency. During their independent review of the CCA, EEG identified a number of concerns (Chaturvedi et al., 1997). They determined that an additional review of the factors that influence the solubility of plutonium under the conditions that will pertain at WIPP would assist them in their evaluation of the CCA. The work covered by this report was initiated in response to EEG's request. Some specific questions were proposed as important to their evaluation:

Is there enough experimental evidence to rigorously conclude that plutonium will be in the Pu(III) and Pu(IV) states in the repository environment, rather than the potentially more soluble Pu(V) state?

Is there something that has not been considered in the CCA that might result in higher Pu solubility?

What is the effect on the solubility of Pu of the compounds formed by the MgO backfill interactions with brine?

What, specifically, are the scientific shortcomings of the DOE arguments in the CCA and what needs to be done to address these shortcomings in terms of calculations and experimental work?

This report attempts to answer those questions by discussing the most likely redox state for Pu based on published experimental work, the effect of brine composition on solubility of actinides in the (IV) valence state, the influence of solution species formed by reaction of the MgO backfill on An(IV) solubility, and the influence of other potential ligands present in the waste itself on actinide solubility. An analysis of the calculational path used as a result of the scenario adopted for the calculations suggests that there are means of forming significant

amounts of soluble Pu as citrate complexes or as complexes with the chemical degradation products of cellulose. A new scenario for calculations to test the sensitivity of the results to pathway is proposed. In addition, some inconsistencies in the calculated results reported in the CCA are discussed and issues are identified that need resolution.

Factors controlling solubility

There are four major factors that will determine the effective solubility of plutonium in the WIPP environment. These are (1) the redox conditions, (2) the brine composition, (3) the availability of ligands through degradation of the waste, and (4) the effects of slow kinetics of reaction due to lack of lability of species (i.e., persistence of metastable species). The brine composition, itself, will be affected by the persistence of metastable reaction products, especially those formed by the MgO backfill. Each of these factors is discussed in the sections that follow.

Redox state

Plutonium can exist in several oxidation states in natural waters depending on the availabilty of oxygen and complexing agents. Under normal atmospheric carbon dioxide pressure (p_{CO_2}= 3.2 x10^{-4} atm), but in the absence of other complexing ligands, the expected oxidation states of Pu are PuO_2^{2+}, PuO_2^{+}, and Pu^{4+} under oxic conditions and Pu^{4+} and Pu^{3+} under reducing conditions. PuO_2^{+} disproportionates into PuO_2^{2+} and Pu^{4+}, but the rate of the reaction depends on the 4th power of the H^{+} concentration and on the square of the PuO_2^{+} concentration so that at low concentrations of Pu in neutral solutions the reaction rate is negligible (Choppin, 1990). This suggests that PuO_2^{+}, once present, may persist outside of its stability field because of slow reaction kinetics.

During the operational period of the WIPP repository, oxygen will be present in the storage rooms. This oxygen will be trapped in the salt formation after repository closure and will be available to react with the waste materials and their containers. Void space in the repository will be reduced by salt creep, and the encroaching salt will eventually crush the waste drums. The residual oxygen can react with the drum material or with the waste itself, producing soluble corrosion products, such as Fe^{2+}, and possibly PuO_2^{+}. Radiolysis of water inside the waste drums can also result in oxidation of plutonium to produce PuO_2^{+}. If there are organic complexing agents present, the PuO_2^{+} will be rapidly reduced to Pu(IV) and stabilized in solution as soluble complex ions (AlMahamid et al., 1996). It is reasonable to conclude that PuO_2^{+} will not be able to coexist with organic ligands for any significant period of time, and that solubility calculations should consider either transient presence of PuO_2^{+} or presence of Pu(IV) with or without organic ligands.

Weiner et al. (1996) discuss the possible oxidation states of Pu under WIPP conditions. They conclude that Pu(IV) is expected to be the stable state, but include Pu(III) based on observations by Felmy et al. (1989). These experiments used Pu(III) maintained in that redox state by adding Fe powder to the solutions. The solubility of $Pu(OH)_3$ was measured in dilute solutions and brines. The redox state of Pu was verified by using chemical extraction methods; however, the method used measured Pu(III) + Pu(IV), so there is not positive identification of Pu(III) content. At pH 9 and above, the concentration of Pu was below detection limits (Felmy et al., 1989). This would suggest that Pu(III) needs to be considered up to pH 9 in modelling calculations if metallic Fe is present, which it will be in the form of WIPP disposal drums. Above pH 9, the upper limit for Pu(III) is set by the detection limit in the Felmy et al. (1989) experiments as 10^{-9} M.

Pu(V) has been observed in a number of experiments conducted in brines. Weiner et al. (1996) discuss some of these results in Appendix A to their report and conclude that Pu(V) will not be important because it disappears with time. This conclusion would be perfectly valid for cases where release from the repository is assumed to occur through flow mechanisms that take long periods of time to reach the accessible environment; however, for human intrusion scenarios where the brine may reach the surface directly via a borehole, it is probably more valid to include transient species that have been shown to have long lifetimes. Since any Pu(V) is likely to react with dissolved Fe(II), the steady-state amount of Pu(V) should be small and not lead to a large increase in calculated total mobile Pu species in the repository.

Brine composition

Brine composition can affect solubility in two principal ways. The first is through the effect of ionic strength, which will generally lead to higher actinide solubilities for high ionic strength. Most of the effect of ionic strength increase is seen by the time a solution concentration of 2M NaCl is reached, with little change in effective activity coefficients expected as ionic strength increases further. The second means of affecting solubility is through the formation of complex ions. Carbonate ion and hydroxyl ion are the main inorganic ligands that will cause increased solubility of Pu in the WIPP brines. Novak and Moore (1996) calculated that sulfate complexes are important for some cases; see Appendix B for discussion.

In this section we will consider experimental evidence that can be used to evaluate the expected effects of brine composition on the solubility of Pu. The conclusions that can be drawn from the experimental evidence will be useful in assessing the validity of model calculations. Most measurements using Pu have

been done with oxygen present in the system, either with normal atmospheric composition together with carbon dioxide, or under argon glove box conditions with 18 to 30 ppm oxygen in the gas. While the latter amount may seem very small, it is enough to provide for oxidation of Pu from Pu(IV) to Pu(V) in solution. Once Pu(V) is formed, it may be long-lived if there is not an active reductant present.

DePablo et al. (1995) conducted experiments using unirradiated crystalline UO_2 (s) in synthetic brines. Both oxidizing and reducing conditions were studied; reducing conditions were maintained using a hydrogen flux and a Pd catalyst. Carbon dioxide was not present in the experiments. Brine compositions (molal concentrations) were

Species	NaCl-brine	$MgCl_2$-brine
Na+	6.036	0.48
K+	0.037	0.57
Mg^{2+}	0.018	4.21
Ca^{2+}	0.021	0
Cl-	6.036	8.84
$SO_4^{=}$	0.058	0.32
Ionic Str.	6.25	14.00
pH	7.7	4.7

The UO_2 (s) had an initial surface condition that was very oxidized, $UO_{2.7}$ as measured by XPS. This led to an initial rapid dissolution of the oxidized surface even when the solution was maintained with reducing conditions. The solution concentrations in both brines gradually decreased and settled after 20 to 25 days at steady-state values of 2.8×10^{-7} mol/kg in the NaCl brine and 3.1×10^{-7} mol/kg in the $MgCl_2$-brine. At the end of the experiments the Eh was measured to be 0 to 60 mV (compatible with the stability of UO_2) and the surface of the dissolving solid was measured to have a composition of $UO_{2.1}$ as measured by XPS. A model calculation was done using the PHRQPITZ code (the PHREEQE equilibrium code with Pitzer parameters added) and gave quite good agreement of the concentrations predicted by the calculations with those measured in the experiments. The calculated concentrations for zero ionic strength solutions were about a factor of 3 lower than those calculated for the brines.

The experiments of DePablo et al. (1995) show that for UO_2 (s), there is very little variation in solubility that can be attributed to the combined effects of increasing the brine ionic strength by a factor of more than 2 and simultaneously increasing sulfate by a factor of 5. In addition, changing the dominant cation from Na+ to Mg^{2+} did not seem to have a large effect. From the modelling calculations, the effect of high ionic strength on solubility of the UO_2 (s) was limited to an increase of a factor of 3.

The effect of carbonate ion on the solubility of Th was measured in solubility and speciation experiments by Östhols et al. (1994). They measured the solubility of a freshly precipitated thorium oxide/hydroxide with low crystallinity as a function of pH with an atmosphere of 10% carbon dioxide. They analyzed the data and deduced speciation with $Th(OH)_3CO_3^-$ as the dominant species from pH 5 to slightly greater than 7 and with $Th(CO_3)_5^{6-}$ beginning to occur at pH just under 7 and taking over from the hydroxycarbonate complex after pH7.4. The total solubility of Th(IV) at pH 7 was 10^{-5} M. Östhols et al. (1994) also calculated stability constants for these species and the solubility product for amorphous ThO_2 for their experimental solution conditions of 0.5 M $NaClO_4$ and for the extrapolated values at zero ionic strength.

Rai et al. (1995) measured the solubility of U(IV) and Th(IV) freshly precipitated oxides under inert atmosphere conditions as a function of carbonate/bicarbonate concentration in solution. For the U experiments, Fe powder was added to the solutions to ensure that no U(VI) formed. At low carbonate concentration, the uranium solubility was about 10^{-8} M. (This is about a factor of 10 lower than the value calculated by DePablo et al. (1995) for low ionic strength and no carbonate. See above). Two data points at a carbonate content of 0.1 molal also had a solubility of 10^{-8} M for Th(IV). The Th solubility increased to be 10^{-5} M at a sodium carbonate content of about 0.3 m, which is similar to the carbonate content that one would expect with a partial pressure of CO_2 of 0.1 atmosphere. For U, a carbonate concentration about a factor of 4 higher was needed to achieve the same solubility of 10^{-5} M. It should be noted that for both U and Th, the concentration of carbonate had to exceed 0.1 molal before a dramatic increase in solubility was observed.

From the results presented above, we may derive two important conclusions concerning the effect of brine composition on Pu(IV) solubility.

(1) The detailed composition of the brine will probably not be important in determining Pu(IV) solubility in the absence of organic ligands and at low carbonate concentrations.

(2) Carbonate ion concentrations will only have a large effect on Pu(IV) solubility if they are above 0.1 molal.

These conclusions should be valuable in assessing the reliability of modelling calculations for WIPP long-term performance predictions.

Experimental studies of Th and Pu solubility were supported by the WIPP Project in FY 1997 to determine what the effects of the MgO backfill would be on solubility and to validate the model assumption that Th data could be used to model Pu behavior. Preliminary results are available in the annual report for

FY97 (Rai et al., 1997). All experiments were done with nitrogen atmosphere. The concentrations of Th in the presence of MgO after 5 days exposure in two brines was between $10^{-7.3}$ and 10^{-8} M, while with hydromagnesite present the solubility was much higher (10^{-5} and $10^{-6.5}$ M). The solubility of amorphous plutonium dioxide in the brines in the presence of Fe powder was measured to be $10^{-6.5}$ M at pH 7.5 and $10^{-7.5}$ M at pH 8. Solubility changes when hydromagnesite was present were +/- a factor of 10 with increase in pH of 0.5 units in both brines. The presence of $Na_2S_2O_4$, a strong reducing agent, resulted in higher Pu solubility in all cases. This was interpreted to indicate the possible presence of Pu(III) species that were more soluble than the Pu(IV) species. Pu(V) was also considered as a possible species to explain some of the higher-than-expected concentrations found.

The solubilities for Pu in the absence of carbonate found by Rai et al. (1997) are quite similar to those found by DePablo et al. (1995) for UO_2. Solubilities for Pu and Th depend to a large degree on the "age" of the solid and its degree of crystallinity. This factor is less important for UO_2. Since the preliminary results for Pu in brines seem to be consistent with those for UO_2 solubility in brines, the UO_2 solubility data measured in brines would seem to represent a sounder basis for performance prediction than those calculated from a model based on Th with Pitzer parameters. This conclusion is strengthened by the fact that the solubilities of Th measured by Rai et al. (1997) in the presence of hydromagnesite are much higher than those calculated by Novak (1997 - see discussion in the next section and in Appendix A).

Phases controlling brine composition

The brine compositions assumed for the WIPP performance assessment conditions are either the Salado brine or the Castile brine or a mixture of these brines. To assess the solubility of actinides in the brines, Novak and Moore (1996) further assumed that the brines became saturated with halite and anhydrite, the major minerals in the associated salt formations. The effective pH of the brines under these conditions was about 5.6 to 5.8, which was thought to be lower than desirable. Actinide solubility goes down with increasing pH, at least until pH of 11 or 12 is reached; for this reason, addition of a backfill material was considered to buffer the pH at about 10 and to absorb CO_2 gas that might be generated by microbial action. (See Appendix A for a more detailed discussion of this issue.)

The MgO from the backfill was thought to produce brucite and magnesite as its stable reaction products and that these materials would be those responsible for conditioning the brine chemistry. During experiments with alteration of MgO with the brines, it was found that other phases formed. These phases are (or, at least, may be) metastable with respect to magnesite and brucite; however, they

may persist for extended periods of time under the WIPP disposal conditions. The draft report on the MgO alteration shows evidence for the formation of reaction products that are predominantly nesquehonite ($MgCO_3 \cdot 3H_2O$) with the later appearance of a phase that could not be positively identified, but was tentatively identified as $MgCO_3 \cdot 3H_2O \cdot MgCl(OH)$ (PDF7-278) (no name given). The chemistry of this phase is quite different from that of hydromagnesite [$(MgCO_3)_4 \cdot Mg(OH)_2 \cdot 4H_2O$]. Despite this, the draft report claims on page 30 that "we observed that hydromagnesite, with a loose platy habit, is the favored metastable phase in our experiments, rather than nesquehonite" (Sandia, 1997).

The identity of the Mg-carbonate phase that forms with alteration of MgO is important because this phase will control the carbonate and bicarbonate concentrations in the brines. High concentrations of carbonate in the brines can increase the solubility of Pu via complex ion formation with carbonate. Calculations in the Sandia, 1997, draft manuscript reported only the effect of hydromagnesite on expected actinide solubility. Hydromagnesite, however, was never identified in the experiments described in the draft manuscript. In other materials available from Sandia, it was seen that calculations were also done with nesquehonite (C. F. Novak memo to R. Vann Bynum dated 21 April 1997, "Calculation of actinide solubilities in WIPP SPC and ERDA6 brines under MgO backfill scenarios containing either nesquehonite or hydromagnesite as the Mg-CO_3 solubility-limiting phase.") Since the results with nesquehonite were quite different for the (IV) actinides, they are reproduced here together with the results reported in the draft manuscript.

Conditions	+4 act., molar Salado (SPC)	+4 act., molar Castile	log fugacity (CO_2)
CCA calc.	4 E-6	6 E-9	-6.9
No backfill	5 E-4	7 E-5	0 to 2
5424 hydromag.	1 E-8	4 E-8	-5.5
4323 hydromag.	2 E-8	5 E-8	-5.39
Nesquehonite	6.3 E-4	1.0 E-3	-3.8

Note that with nesquehonite present, the solubility of the +4 actinides is calculated to be higher than it is with no backfill present. pcH for Salado conditions is calculated to be 9.4 and for Castile, 9.9.

The predictions of solubility in the presence of hydromagnesite are lower than the experimental results for Th discussed above, but are similar to the results found for Pu in the presence of hydromagnesite and Fe. No experimental data on the solubility of Th or Pu in the presence of nesquehonite is yet available.

Complex ion formation

Discussions in the previous sections have shown that the inorganic anions most likely to affect actinide (IV) solubility through complex ion formation under WIPP brine conditions are hydroxide and carbonate ions. Sulfate ion has been shown in experiments with U(IV) to have no significant effect on overall solubility over the range of variation in sulfate content expected for the WIPP.

The remaining possibility for complex ion formation comes from the waste materials, themselves. Citrate, which forms a very stable complex ion with Th, is present in large amounts in the waste inventory. The solubility calculations for the actinides in brines with and without MgO are discussed in Appendix B. These calculations assume homogeneous equilibria, which for actinides in the absence of complexing ligands from the waste is probably an adequate estimate. For the case where organics are present, the organics are also treated by SOTERM as if they were homogeneously dissolved in 29,841 m^3 of brine.

To model the behavior of Pu with citrate, we must consider heterogeneous equilibria for organic complexation with the actinides. The main difficulty arises because the Pu in the waste is probably located in the same drums as the citrate, which is the dominant organic ligand. This is because these wastes arise from chemical separations of Pu and are not the type of waste described in the general descriptions of TRU waste as contaminated equipment, clothing, etc. To get an accurate estimate of the effect of organic ligands on Pu solubility, one must calculate the concentration of Pu as citrate complex inside a waste drum that has been breached, but can still provide a hindrance to mixing of the brine inside the drum with a larger pool of brine outside the drum. This will give a high concentration of Pu in solution as the citrate complex. Other ions will not compete with Pu sufficiently to prevent complex formation because the stability for (IV) actinide complexation - as shown by the stability constant for Th(IV) on p. 39 of the SOTERM appendix- is orders of magnitude larger than that for other ion complexes with citrate.

Another possible ligand for increasing Pu(IV) solubility comes from the degradation of cellulose. Work in England has shown that degradation of cellulose can occur both through chemical processes at high pH and by radiation effects. The degradation products have been shown to increase the solubility of plutonium dramatically (Cross et al., 1989; Greenfield et al., 1992).

To obtain a more accurate estimate of the effect of citrate and cellulose degradation products on Pu solubility in the event of human intrusion, calculations that use Pu complexes formed inside a waste drum and model the mixing of that relatively concentrated brine with the average repository brines must be done, taking into account the time scales for mixing and the possibility that the intrusion event may release some brine from waste drums that has not

had an opportunity to mix with the average repository brines. The development of an appropriate scenario is discussed further in the next section.

The conclusion given in the CCA SOTERM appendix that EDTA complexes will not increase actinide solubility is probably correct, since the amount of EDTA is small and the Ni and Fe complexes have stability constants that are similar to those for the actinides. It is not shown, and is probably not true, that the more abundant citrate inventory will not increase actinide solubility, especially for Pu.

Scenarios for dissolution of plutonium

Analyses of the long-term performance of the WIPP repository have shown that the only likely cause for significant releases of radioactivity would come as the result of human intrusion into the repository. One pathway for release involves drilling into the repository level, flooding of the repository with brine, and then flow of the brine through the overlying Culebra dolomite aquifer. This pathway would require considerable time before radionuclides would reach the accessible environment and, in this case, the model of homogeneous brine compositions averaged over the whole repository at the time of the release is probably appropriate. For this scenario, the large volume of brine (29,841 m^3) discussed in the SOTERM calculations is probably needed.

Another human intrusion release scenario involves drilling through the repository and reaching the underlying Castile formation, in which there are pockets of pressurized brine. If a pocket of pressurized brine were to be encountered during drilling, it is possible that it might rise up the drill hole, through the repository, and up to the surface very rapidly. The only waste encountered in this case might be that in a few drums that were in the immediate path of the drill hole. These drums might contain low Pu concentrations and little or no citrate ions or cellulose degradation products, or they might contain the maximum allowed Pu concentration and sufficient citrate or cellulose degradation products to fully complex the Pu. The brine composition would be determined by the local, internal environment in the waste drum, rather than by the grand average of the repository.

As an illustration, the volume of brine that would be associated with this release scenario may be estimated by assuming a small diameter exploratory drill hole of about 0.01 m^2 area (a bit over 10 cm diameter drill core) and a hole depth of about 900 m. The volume to fill this hole would be 9 m^3. A reasonable volume for the release of brine before it was capped off would be about 100 m^3, or about 10,000 liters of brine. This brine could be assumed to contain the contents of two waste drums, each containing 10g Pu and 10 moles of citrate. The brine inside a crushed waste drum with these inventory amounts could be modelled assuming the drum material was actively corroding to provide Fe(II) at equilibium

concentration with appropriate citrate complexation as well as the Pu(IV) citrate complex. The amount of such brine could be quite small (< 1 L) or moderate (10-30 L). This assumed concentrated brine could then be intercepted by the drill hole and the brine rising from the Castile formation, providing dilution of the concentrated brine, but probably not a major change in speciation. The appropriately diluted brine would then be the material that would be assumed to reach the surface.

The construction of the CCDF for assessment of compliance with 40 CFR 191 would then involve a selection of model realizations with the release from a pressurized brine and a probability distribution of whether the drums that might be intersected by the drill hole were those with high Pu or with low Pu. This method for handling heterogeneous waste distributions and heterogeneous equilibria in the respository would be rather simple to implement, at least on the level of exploratory calculations.

Suggestions for future work

Experimental work

Performance predictions for WIPP are currently done using equilibrium thermodynamic modelling of brine chemistry and with Th as the representative of the (IV) actinides. The calculated Th concentrations have internal inconsistencies (described in Appendix B) with respect to both the total solubility and the speciation of Th under conditions with similar brine composition. Experimental work on systems that contain Pu itself, rather than Th as a surrogate, have been started and should be continued. Results from these and future experiments should be compared with existing experimental results on U(IV) compounds.

If MgO will be used in the repository to control pH and to attempt to control carbon dioxide fugacity, experiments using brines with nesquehonite and brines with hydromagnesite should be conducted. Carbon speciation should be measured in these experiments as a function of reaction progress, as well as the evolution of the brine chemistry. These parameters will be needed if the longer term solubility of Pu in these systems is to be modelled. Redox state of Pu in solutions should be measured; methods that might be used are direct spectroscopy at relatively high concentrations and valence-specific solution extraction methods at low concentrations.

The stability constant for formation of citrate complex ions with Pu(IV) should be determined. The sensitivity, if any, of the value of the stability constant on brine composition should be evaluated. Experiments in systems that contain abundant citrate and Pu together with metallic iron and iron corrosion products formed under WIPP-relevant conditions should be done to evaluate the ability of

Fe(II) in solution to compete for citrate ion in complexes. Sequential dilution of brine with Pu-citrate complexes in solution by adding samples of that brine to solutions containing brine with metal and corrosion products should be conducted to provide validation of the calculations suggested below.

Thermodynamic properties and models

Use of Th to model the behavior of all actinide (IV) elements requires that (1) the chemistry of all actinide (IV) elements in brines is closely similar and (2) that the data base for species formation and solubility as well as for activity coefficients of Th(IV) species in brines is sufficiently well known. The differences found between Th concentrations calculated by Novak and Moore (1996) and those measured by Rai et al. (1997), and the differences between the calculations for Th and the experimental data for U(IV) indicate that one or both of those requirements is not met.

Several work areas need to be undertaken in order to improve the reliability of the calculations. First, the calculations should be done using data for Pu and the values for solubility and complex ion formation contained in the peer-reviewed data compilation prepared by OECD/NEA. This work has been underway for about 10 years and has had many man-years of effort from the members of the specialist review committee. Even though small changes may be made between the current draft document and its final publication, it is likely that a significant improvement in the consistency of the calculated results and the findings in solubility and speciation experiments could be found if this source were used for the basic thermodynamic data.

DePablo et al. (1995) reported calculations of U(IV) solubility in brines using an equilibrium thermodynamic modelling code developed by the US Geological Survey. It would be instructive to compare the results of calculations of Th solubility using the same code and data base to the reported results of Novak and Moore (1996). In particular, a comparison of the calculated activity coefficients for dissolved species using each code would be useful. For highly charged species such as $Th(CO_3)_5^{6-}$ it is extremely difficult to estimate the activity coefficient using calculational methods. Comparison of the species included in the calculations as well as the results of speciation and solubility predictions for Th would be interesting and might give an insight into the uncertainties that exist in the calculation of solubilties for these systems.

A sensitivity analysis should be conducted to determine the effects of uncertainties in both the solubility measurements and stability constant determinations as well as the estimation of Pitzer parameters on the final calculated solubility. This would involve a “Monte Carlo” type of sampling procedure that selects a value within the range of +/- appropriate to the solubility

product for a given compound and then values for each of the complex ion stability constants within their range of data uncertainties. A similar process would be used for the calculation of the Pitzer coefficients. Results of 30 to 40 calculations using this type of sampling method should give a reasonable indication of the real range of combined uncertainty in the calculations.

Release scenario calculation

A scenario for release via human intrusion that involves release of brine with concentrated Pu-citrate content via mixing with a larger volume of brine and transport through the Culebra aquifer should be done. This calculation can be done as a simple, sequential dilution model in which 10 liters of initial Pu-citrate-containing brine is mixed with 10 liters of Salado brine equilibrated with appropriate minerals and Fe(II) corrosion products. The second calculation would then mix this 20 liter volume of brine with another 20 liters of Salado brine. Ten steps of mixing would give a brine volume of 10,000 liters. The pattern of speciation changes in Pu and the overall Pu solubility calculated could then be compared to the sequential dilution experiments discussed above. If the results agree, a level of validation is achieved for the calculations. If the results disagree, insight into requirements to improve the data base and calculational methods should be gained.

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Appendix A

Review of "Chemical Conditions Model: Results of the MgO Backfill Efficacy Investigations", Sandia National Laboratories (no author names), April 23, 1997, Draft.

This paper describes some experiments in which MgO in the form of small pellets (2 to 4 mm in size) or MgO "fines" (0.5 to 1.0 mm) were reacted with Castile and Salado brines (presumably synthetic, but the text does not address this point).

The experiments produced reaction products that are predominantly nesquehonite ($MgCO_3 \cdot 3H_2O$) with the later appearance of a phase that could not be positively identified, but was tentatively identified as $MgCO_3 \cdot 3H_2O \cdot MgCl(OH)$ (PDF7-278) (no name given). The chemistry of this phase is quite different from that of hydromagnesite [$(MgCO_3)_4 \cdot Mg(OH)_2 \cdot 4H_2O$]. Despite this, the paper claims on page 30 that "we observed that hydromagnesite, with a loose platy habit, is the favored metastable phase in our experiments, rather than nesquehonite." (See comment 4 below for a more detailed discussion.)

The concentration of an element in solution is the sum of all of the species concentrations in which that element is present. Usually, one species predominates as the most soluble for a given element under a given set of conditions, and the concentration of that species is determined by the solubility of the most soluble solid phase that results in that species being formed. That phase will continue to control the solubility so long as it is present in the system, even if other, more stable, phases are also present. For the set of possible conditions with MgO backfill present, and assuming the absence of ligands for the actinides that result in even higher solubility species, the phase that results in highest (IV) actinide solubility is nesquehonite. So long as nesquehonite may be present in the WIPP repository, the solubility of (IV) actinides must be modelled using calculations that include it as a member of the phase assemblage. Since the production of CO_2 is assumed to persist over periods of thousands of years, and since nesquehonite is observed to be formed early in the sequence of phases formed when carbon dioxide reacts with MgO in the backfill, we must assume that nequehonite will be present over thousands of years, even if it can be shown that the conversion of a particular amount of nesquehonite to a less soluble phase occurs over a time scale of a few hundred years.

As shown in item 7 of the detailed comments, the solubility of (IV) actinides with nesquehonite present is even higher than that calculated for the case with no MgO present. If nesquehonite must be considered as present for most of the performance period of the repository, it would seem that the addition of MgO does not enhance the performance of the repository, but rather adds to the uncertainties to be considered, if our attention is limited to the case of the (IV) actinides. For the (III) and (V) actinides, the MgO does seem to reduce the solubility considerably, even with nesquehonite present (data in Novak,

21 April 1997 memo). Since Pu is the dominant actinide, and since (IV) is the most likely oxidation state for Pu under WIPP conditions, there might be good cause to reconsider the inclusion of MgO as backfill in the repository.

Detailed comments:

1. p. 5, bottom. "There is evidence in the literature that MgO can exhibit a bactericidal characteristic. However, there [*sic*] studies supporting this assertion were performed under conditions far removed from those expected in the WIPP and no direct correlation could be drawn from the literature conditions to those expected at WIPP. Therefore, no beneficial credit was taken for the potential bactericidal effect of MgO and the microbial gas generation rates were left unchanged."

> The microbes are assumed to decompose cellulose to CO_2 and methane. If the microbes are not present, chemical degradation of cellulose at high pH is likely to result in compounds that can form complexes with actinide elements and increase their solubility. See, for example, the paper by J. E. Cross, F. T. Ewart, and B. F. Greenfield in Mat. Res. Soc. Symp. Proc. Vol. 127, W. Lutze and R. Ewing, eds., pp. 715-722, 1989. Absence of microbes may provide negative as well as positive contributions to the potential performance of the repository.

2. p.2, middle. "Arrhenius plots assembled with laboratory synthesis of magnesite at 60°C for 7 years and at higher temperatures suggest that magnesite will form within several hundred years in the WIPP." And, p. 19, "Nesquehonite is also temperature sensitive, but is stable well within the temperature range anticipated at the WIPP; it will convert to hydromagnesite above about 60°C (Lippmann, 1973)." The extrapolations using Arrhenius plots are discussed in more detail on pages 35-6.

> The use of data obtained outside of the field of temperature stability of a phase to estimate kinetics of converstion of that phase to another phase is invalid. In addition, the phase into which nesquehonite converts is stated on p. 19 to be hydromagnesite, not magnesite.

3. p. 13. The pH curves vs reaction time show Salado brine with both the "coarse" and "fine" MgO with pH about 6, and the Castile samples to have pH about 6.8. In the figure caption, it is claimed that "The difference between the Salado and Castile curves reflects differences in the mineralogy of the coatings formed in these two brines."

> This statement seems to conflict with the reaction product discussion in the manuscript on page 20 ff.

4. p. 30. "As describe [*sic*] in Section 4, we observed that hydromagnesite, with a loose platy habit, is the favored metastable phase in our experiments, rather than nesquehonite."

> This statement conflicts with the content of section 4. Hydromagnesite was never identified in any of the experiments. Nesquehonite was described as the abundant and identifiable phase in most of the experiments.
>
> The reaction sequence observed is decribed on p. 20 ff. in the draft manuscript. There is no clear difference in the phase assemblage claimed in the two brine

systems, only in the morphology of the phases; see p. 27 top in the draft manuscript. From what can be seen in the text, nesquehonite, once formed, persists in the system even if a new, unidentified phase also forms later.

The first phase observed (at point c in the model of reaction progress) is stated to contain C, O, and Mg, with very little Cl. It is interpreted to be protohydromagnesite on p. 21, top. Note: protohydromagnesite is not the same phase as hydromagnesite.

"For the coarse fraction samples, nesquehonite formation had become the dominant alteration process by day two for the Salado fraction and day three for the Castile fraction." (p. 21)

For the fines, at day four there was no nesquehonite observed in either brine, but the original alteration product (noted above as point c) was thicker and is now referred to as "hydromagnesite-like". At day ten, the Salado brine sample with MgO fines showed nesquehonite as a mat over a Cl-rich version of the "hydromagnesite-like" material. (p. 21, middle and Fig. 4-5).

At stage f in the reaction progress model, the samples (not stated whether it is coarse fraction, fine fraction, or both) develop an interlocking mesh of fine, platy crystals, which is interpreted to be protohydromagnesite containing a detectable amount of Cl.

On p. 27, the appearance of the new phase is claimed to be related to the presence of a high Mg concentration. The phase identification was tentative. "Although the SEM photographs show the material to be crystalline, the small crystal size has made it very difficult to get positive identification by x-ray diffraction. The best, though still highly tentative, identification arises from the comparison of the fines recovered from a 10-day treatment. In the case of the Castile coarse sample, a very clean pattern for pure nesquehonite was obtained. The dominant peaks in the Salado coarse sample were also nesquehonite, but a comparison with the Castile pattern showed that a few very small new peaks were present. These could be indexed to the material $MgCO_3 \cdot 3H_2O \cdot MgCl(OH)$ (PDF7-278)." Six lines later, the manuscript claims "The parallel between this new material and hydromagnesite is quite evident. Both this phase and hydromagnesite $[(MgCO_3)_4 \cdot Mg(OH)_2 \cdot 4H_2O]$ consist of mixtures of magnesium carbonate, magnesium hydroxide, and waters of hydration." This analogy would imply that most of the other phases listed on page 18 would also be equally closely related to the new material. The presence of Cl in the new material is, apparently, not considered to be important.

On. p. 29, the results of the "tea-bag" experiments are discussed. The samples with longest reaction times were for 19 days. "In the 19-day samples, masses of nesquehonite needles are readily observable in the pore spaces between the grains."

5. p.32. "Given the extremely slow precipitation rate detailed by the low pCO_2 in the repository, we expect that nesquehonite will not form. The favored metastable phase is hydromagnesite."

It is difficult to reconcile this claim with the experimental evidence presented in Section 4 of the manuscript, especially since hydromagnesite has not been seen to form in any of the experiments described in that section.

6. In the figure caption for Fig. 5-5, it is stated "In our experiments, nesquehonite, [*sic*] is initially formed but converts to hydromagnesite, probably through the protohydromagnesite intermediary."

This statement misrepresents the experimental results. The only phase that was positively identified was nesquehonite, which was found in abundance in nearly all of the experiments discussed in the draft manuscript. The reaction path described at the top of page 37 as "possible" is just that - possible, not definitive.

7. p. 38. "As shown previously, hydromagnesite has been observed and predicted to be the metastable phase possibly formed in the repository which then ages to form magnesite. Model predictions were performed to predict the actinide solubilities which could occur during these transient periods. To perform the model predictions, hydromagnesite had to be added to the actinide solubility database."

As stated above, hydromagnesite was never identified in the experiments described in the draft manuscript. In other materials available from Sandia, it was seen that calculations were also done with nesquehonite (C. F. Novak memo to R. Vann Bynum dated 21 April 1997, "Calculation of actinide solubilities in WIPP SPC and ERDA6 brines under MgO backfill scenarios containing either nesquehonite or hydromagnesite as the Mg-CO_3 solubility-limiting phase.") Since the results with nesquehonite were quite different for the (IV) actinides, they are reproduced here together with the results reported in the draft manuscript.

Conditions	+4 act., molar Salado (SPC)	+4 act., molar Castile	log fugacity (CO_2)
CCA calc.	4 E-6	6 E-9	-6.9
No backfill	5 E-4	7 E-5	0 to 2
5424 hydromag.	1 E-8	4 E-8	-5.5
4323 hydromag.	2 E-8	5 E-8	-5.39
Nesquehonite	6.3 E-4	1.0 E-3	-3.8

pcH for Salado conditions is calculated to be 9.4 and for Castile, 9.9.

Note that with nesquehonite present, the solubility of the +4 actinides is higher than it is with no backfill present. This suggests that the addition of MgO backfill may

not provide clear improvement in performance, but may add significant uncertainty in performance predictions.

Appendix B

Comments on SNL Tech Memo by C. F. Novak and R. C. Moore dated March 28, 1996, "Estimates of Dissolved Concentrations for +III, +IV, +V, and +VI Actinides in a Salado and a Castile Brine under Anticipated Repository Conditions." (Referenced in US DOE Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, Appendix SOTERM, October 1996. Stated to be on file in Sandia WIPP Central File A: WBS 1.2.0.7.1; WBS 1.1.10.1.1: WPO 36207.)

This memo describes the general method used to calculate the solubilities of actinides for use in the CCA and gives the results for several sets of calculations. The database used is cited, but not included in the memo.

Solubilities were calculated using an equilibrium thermodynamic speciation code "FMT", which employs Pitzer-type interaction parameters to obtain activity coefficients for dissolved species.

Equilibrium thermodynamics for solution chemistry requires the use of the activity, a, of species in equations that describe solubility or complex ion formation. The activity of a species is related to its concentration in solution by the relationship

$a = \gamma m$ where γ is the activity coefficient and m is the concentration of the species in moles per kg of solution.

The solubility product, K_{eq}, of the salt AB in an aqueous solution can then be written as

$$K_{eq} = a_{A+}a_{B-}/a_{AB} = (\gamma_{A+}m_{A+})(\gamma_{B-}m_{B-})$$

The term a_{AB} is eliminated because the activity of a pure solid is unity. The terms such as γ_{A+} are the activity coefficients of the dissolved ionic species. For an ideal solution, which generally means solutions near infinite dilution (very little solute), these terms approach unity and the solubility may be approximated by the product of the molal concentrations. At low total dissolved solids for aqueous solutions, molal concentration (m) approaches molar concentration (M = moles/liter).

When solubilities are calculated for systems with many components, a group of equilibrium solubility equations must be solved simultaneously with a group of association relationships that describe formation of complex ions in solutions. The association relationships generally are limited to the attachment of an anionic ligand, L, to a cation, A+.

$\beta_{1,1} = a_{AL} / a_{L-}a_{A+}$ where the subscript 1,1 indicates that the complex consists of 1 cation and 1 ligand.

To solve the system of equations, data are needed for the equilibrium solubility constants, the association constants for ligands with cations, and the activity coefficients for all solution species.

What is available from direct measurements is the equilibrium solubility of compounds under various conditions at a fixed ionic strength in some noncomplexing electrolyte such as 0.5M $NaClO_4$ and similar data for association reactions for ligands and cations. These data must first be extrapolated back to zero ionic strength to get true equilibrium values for infinite dilution and then extrapolated up to the ionic strength of the actual solution. For dilute natural groundwaters, the zero ionic strength data are generally used directly. For brines, the use of some scheme such as Pitzer parameters is needed to provide the activity coefficients for the calculations.

Chemical solutions with many components are routinely modelled using computer codes such as EQ3, or, in the case of the WIPP project, FMT. These codes use a database of equilibrium, zero ionic strength data for solubility and complex ion formation, a method to calculate activity coefficients as a function of solution chemistry and solution ionic strength, and a numerical method to solve a large number of simultaneous equations. Errors and uncertainties can enter the calculations from any and all of these areas. In addition, since the codes are for equilibrium conditions, when systems occur with long-lived metastable species the code user must select which species will be surpressed in the calculations. This means that the surpressed species are eliminated from the calculations so that less stable species can control solution concentrations. For example, if hydromagnesite is to be allowed to be present, the more stable magnesite phase must not be included in the calculations. The user of the code must select the phases that will not be allowed to form.

The types of difficulties that can be encountered in using computer modelling of solution chemistry are

(1) Data for solubility or complex ion formation are not available for the species needed or are incorrect.

(2) Insufficient data exist to allow accurate estimation of ion interactions at high ionic strength. (Activity coefficients cannot be accurately estimated.)

(3) Data for solubility or for complex formation are known, but are not included in the data base used by the code in question.

(4) Incompatible thermodynamic properties data are included in the data base. (This can cause erratic results in calculations.)

(5) Calculational problems related to the algorithms used to solve the simultaneous equations. (This can result in errors from accumulation of rounding errors in calculations or from multiplication of uncertainties through use of a convoluted calculational path.)

It is rare that the accuracy of computer calculations of thermodynamic equilibria for complex systems can be determined directly. In most cases, one must examine the results of calculations for consistency with experiments on related, but not identical, systems. It is also important to examine the results of calculations for internal consistency, i.e., when large changes occur in the calculated concentration of a solution species, are these accompanied by other changes in the solution species that would be expected.

When I examined the calculational results in the memo by Novak and Moore, I found inconsistencies both internally and with respect to relevant published work. These are discussed below.

Novak and Moore did a series of calculations in which they stepwise equilibrated a brine composition with selected solids, actinides, more selected solids, and organics in the solution phase. The sequence of calculations was

(1) Brine alone
(2) Brine plus halite and anhydrite
(3) Brine from step 2 plus Am(III) + Th(IV) + Np(V) until an actinide solid phase precipitated for each actinide
(4) Brine from step 3 plus brucite and magnesite
(5) Brine from step 4 plus organic ligands.

In addition, steps 4 and 5 were done with saturation with portlandite and calcite instead of with brucite and magnesite.

Selected calculation results are presented in Table 1 as element concentrations and in Table 2 as species concentrations in mol/kg. The changes in major solutions chemistry in going from step 1 to step 3, which is the first result shown in Tables 1 and 2, were

ERDA brine: sodium increased from 5.63 m to 6.22 m, and pmH decreased from 6.74 to 5.84, accompanied by changes in carbon dioxide and carbonate species related to pH and compex ion formation.

Salado brine: sodium increased from 2.06 m to 2.9 m, and pmH increased from 4.11 to 5.63, again with changes in carbon dioxide and carbonate species.

We will discuss only the calculations for Th solubility and speciation here. For the case with actinides plus brine plus saturation with halite and anhydrite, two sulfate complexes with thorium appear as the sole reason for high solubility in the Salado brine case and are significant contributors to high solubility in the ERDA brine case. The abundance of these

calculated species does not appear to be strongly affected by the factor of 4 difference in sulfate ion concentration in the two brines. When calculations are then done for addition of brucite and magnesite, the sulfate ion concentrations in solution remain about the same, but the Th sulfate complexes become insignificant. This occurs together with a calculated decrease in total Th solubility. Since the only major change in brine chemistry for the ERDA case is an increase in pH and accompanying changes in carbonate equilibria, the Th sulfate solution complexes should remain dominant. Their absence in the speciation results for the step 4 cases suggests that there are major calculational problems with the FMT code and its data base.

Experimental data for the solubility of UO_2 in brines of NaCl with similar ionic strength (pH = 7.7) and $MgCl_2$ with higher ionic strength (pH = 4.7) under reducing conditions in the absence of carbon dioxide gave U^{4+} concentrations of 2.8×10^{-7} m and 3.1×10^{-7} m, respectively (DePablo et al., 1995). These results are compared to calculations for thorium by Novak and Moore in the following table. (See Tables 1 and 2 at the end of this appendix for detailed results.)

Table B-1: Comparison of experimental determination of solubility for U with calculated solubility for Th.

Brine type	Experimental value UO_2, DePablo et al.	Calculated value ThO_2, Novak and Moore
NaCl/ERDA	2.8×10^{-7} m	3.9×10^{-3} m
$MgCl_2$/Salado	3.1×10^{-7} m	4.4×10^{-4} m

The Th solubility in the ERDA brine was calculated to be dominated by the pentacarbonate complex; however, the amount of soluble Th sulfate complexes was calculated to be 7×10^{-4} m. For the Salado brine, the calculated Th solubility was due almost completely to the soluble sulfate complexes. Since DePablo et al. had no carbon dioxide in their system, the soluble species should be present as hydroxy or sulfate complexes only. The experimental results are three and four orders of magnitude lower than those calculated by Novak and Moore for Th. Since the WIPP project bases their model for (IV) actinide solubility on the assumption that all (IV) actinide solubilities can be calculated using Th as the model, this discrepancy between calculations and experiments under similar conditions is significant.

The Th sulfate complexes used in the calculations were proposed by Felmy and Rai (1992) when they reinterpreted data published originally in 1963; they do not consider the monosulfate complex. Data for sulfate complexes of Pu being considered for use in the international compendium of thermodynamic data for Pu and Np under preparation by OECD/NEA contains recommended values for a mono-sulfate, $Pu(SO_4)^{2+}$, and a di-

sulfate, $Pu(SO_4)_2$, complex, rather than the di- and tri-sulfate complexes, $Th(SO_4)_2$ and $Th(SO_4)_3^{=}$, used in the Novak and Moore calculations (K. Spahiu, personal communication). This suggests that either (1) the complexes used to model Th were incorrect, or (2) that Th is not a good surrogate for Pu in its behavior with respect to sulfate complexes. In either case, the calculations done for Th would not be valid for use in estimating Pu solubility.

Another problem that is evident in the Novak and Moore calculations concerns the carbonate species calculations. At low pH in the Castile brine, the dominant soluble Th species is calculated to be $Th(CO_3)_5^{6-}$ with very minor amounts of $Th(OH)_3CO_3$. At higher pH (9.9), the two species are calculated to be about equal in importance in Castile brine, but with the solubilities in the 2 to 4 x 10^{-9} range. In Salado brine, the pentacarbonate complex is absent at pH 5.6 (nearly the same pH as for the equivalent Castile calculation, which shows this complex present at 3 x 10^{-3}m), but appears at 3 orders of magnitude higher than Castile calculated concentrations at pH 9.4, with similar total dissolved carbonate species in the two cases. These internal inconsistencies in calculated results point to problems in the calculational methods used and/or the data base parameters selected. In addition, the species predominance at low pH should be the opposite of that calculated for the Castile brine. The stabilitiy constants for these species were determined by Östhols et al. (1994); a graphic display of the progression of species as a function of pH is given in their paper. The pentacarbonate complex is dominant at high pH, while the hydroxycarbonate species is important at lower pH.

An additional problem with the calculated carbonate species for Th is that the pentacarbonate complex is predicted to exist in solutions with only micromolal carbonate concentrations. In general, this species is not important until carbonate concentrations are above 0.1 molal. See, for example, Rai et al. (1995). Discussion with K. Spahiu confirmed that behavior of Pu carbonate complexes could be expected to be similar to Th and to require concentrations in the > 0.1 m carbonate range.

It should be noted that conclusions drawn by Novak and Moore concerning the lack of importance of organic complexation in the determination of Th solubilities are invalidated since their basic calculations for Th solution species appear to contain a number of significant errors.

References

J. DePablo, J. Giménez, M. E. Torrero, and I. Casa (1995) Mechanism of unirradiated UO_2 (s) dissolution in NaCl and $MgCl_2$ brines at 25°C, Mat. Res. Soc. Symp. Proc. 353, T. Murakami and R. C. Ewing, eds., 609-615.

E. Östhols, J. Bruno, and I. Grenthe (1994) On the influence of carbonate on mineral dissolution: III. The solubility of microcrystalline ThO_2 in CO_2-H_2O media, Geochim. Cosmochim. Acta 58, 613-623.

A. R. Felmy and D. Rai (1992), An aqueous thermodynamic model for a high valence 4:2 electrolyte Th^{4+}-SO_4^{2-} in the system Na^+- K^+- Li^+-NH_4^+- Th^{4+}- SO_4^{2-} - HSO_4^- - H_2O to high concnetrations, J. Soln. Chem. 21, 407-423.

D. Rai, A. Felmy, D. A. Moore, and M. J. Mason (1995) The solubility of Th(IV) and U(IV) hydrous oxides in concentrated $NaHCO_3$ and Na_2CO_3 solutions, in Mat. Res. Soc. Symp. Proc. 353, T. Murakami and R. C. Ewing, eds., 1143-1150.

Table 1: Results of model calculations by Novak and Moore(1996) in concentrations of moles/kg brine. Equilibrations of Castile-like brine (ERDA) and Salado-like brine with anhydrite and halite plus actinides with and without MgO or CaO.

Element	ERDA-HA-An		Salado-HA-An		
	no MgO	with MgO	no MgO	with MgO	with CaO
Hydrogen	111	111	111	111	111
Oxygen	56.5	56.5	55.8	55.9	55.6
Sodium	6.22	6.2	2.9	4.69	3.5
Potassium	0.11	0.11	0.865	1.05	1.06
Magnesium	0.0214	0.0443	1.62	0.51	6.0 E-6
Calcium	0.0112	0.0133	0.0305	0.0331	1.31
Chlorine	5.98	5.97	6.95	6.67	7.12
Sulfur	0.189	0.191	0.0529	0.06	0.002
Carbon	1.86 E-2	3.15 E-5	1.15 E-2	4.08 E-5	5.87 E-6
Boron	0.0709	0.0708	0.0225	0.0272	0.0244
Bromine	0.0124	0.0124	0.0112	0.0136	0.0122
Th(IV)	3.88 E-3	6.78 E-9	4.37 E-4	4.98 E-6	1.16 E-9
Am(III)	4.49 E-4	4.12 E-7	2.57 E-4	4.39 E-6	1.25 E-9
Np(V)	1.74 E-4	7.53 E-6	1.78 E-5	7.64 E-6	4.85 E-6
pmH	5.843	9.893	5.63	9.366	12.124
Solid phases	halite anhydrite	halite anhydrite brucite magnesite glauberite	halite anhydrite	halite anhydrite brucite magnesite Mg-oxychloride	halite anhydrite brucite portlandite calcite Ca-oxychloride
	AmOHCO3(s) ThO2(am) KNpO2CO3.2H2O(s)	AmOHCO3(s) ThO2(am) KNpO2CO3.2H2O(s)	AmOHCO3(s) ThO2(am) KNpO2CO3.2H2O(s)	Am(OH)3 ThO2(am) KNpO2CO3.2H2O(s)	Am(OH)3(s) ThO2 (am) NpO2(OH)(aged)

Table 2: Solution species concentrations in brines (from Novak and Moore, 1996) in moles/kg
Only species involving major ions, sulfate, carbonate, and actinides are given.

Species	Castile ERDA6-HA-An	ERDA-HA-An-Mg	Salado SPC-HA-An	SPCHA-An-Mg	SPC-HA-An-Ca
Na+	6.22	6.2	2.9	4.69	3.5
K+	0.11	0.11	0.865	1.05	1.06
Ca++	0.011	0.011	0.03	0.032	1.29
Mg++	0.071	0.039	1.67	0.496	3.6 E-6
MgOH+	2.1 E-8	4.2 E-4	1 E-6	1.7 E-3	4.4 E-6
H+	1.4 E-6	1.3 E-10	2.3 E-6	4.3 E-10	7.5 E-13
Cl-	5.98	5.97	6.95	6.67	7.12
SO4=	0.187	0.191	5.16 E-2	6.02 E-2	1.97 E-3
HSO4-	4 E-6	3.6 E-10	8 E-7	3 E-10	1 E-14
HCO3-	8.1 E-4	7.1 E-6	2.39 E-3	1.78 E-6	1.4 E-10
CO3=	8.0 E-8	8.0 E-6	6.4 E-7	8.3 E-7	3.1 E-7
CO2(aq)	1.4 E-3	1.2 E-9	9.1 E-3	1.2 E-9	6 E-16
NpO2+	1.7 E-4	1.7 E-6	1.7 E-5	2.4 E-6	7.3 E-8
NpO2OH(aq)	1.9 E-9	2.1 E-7	1.5 E-10	1.2 E-7	2.4 E-6
NpO2(OH)=	NEGL.	1.0 E-9	NEGL.	1.8 E-10	2.4 E-6
NpO2CO3-	6.6 E-7	6.3 E-7	4.2 E-7	1.2 E-7	1 E-9
Am+++	3.4 E-4	7.8 E-11	1.94 E-4	3.2 E-9	1.4 E-17
AmOH++	1.1 E-4	2.7 E-7	5.6 E-5	3.8 E-6	1.2 E-11
Am(OH)2+	5.0 E-9	1.4 E-7	1.8 E-9	5.7 E-7	1.1 E-9
AmCO3+	3.2 E-6	7.2 E-11	7.3 E-6	2.9 E-10	3 E-19
Th(SO4)2(aq)	1.35 E-5	9 E-22	1.4 E-5	1 E-20	0
Th(SO4)3=	5.9 E-4	4 E-20	4.2 E-4	8 E-20	0
[Th(CO3)5]6-	3.27 E-3	3.7 E-9	0	5 E-6	0
Th(OH)3CO3-	2.0 E-7	1.8 E-9	6.9 E-7	5 E-10	1 E-13
Th(OH)4(aq)	1.3 E-9	1.3 E-9	1.1 E-9	1.2 E-9	1.2 E-9

APPENDIX C

Comments on Appendix SOTERM to the Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant dated October 1996.

Comments will be confined to those sections of the Appendix that deal with estimation of the dissolved actinide portion of the source term as it applies to plutonium. Most attention will be focused on Pu(IV), which is the most probable oxidation state under WIPP conditions. The section concerning the potential for colloidal transport (6) is quite thorough and, if anything, overestimates the amount of actinide that might be transported as the result of the presence of colloids in the brine.

The solubility calculations for the actinides in brines with and without MgO are discussed in Appendix B. These calculations assume homogeneous equilibria, which for actinides in the absence of complexing ligands from the waste is probably an adequate estimate. For the case where organics are present, the organics are also treated by SOTERM as if they were homogeneously dissolved in 29,841 m^3 of brine. There are some inconsistencies in the table of inventories and molal concentrations (see item 8 below); however, this problem is small when compared to the failure to consider heterogeneous equilibria for organic complexation with the actinides.

The main difficulty arises because the Pu in the waste is probably located in the same drums as the citrate, which is the dominant organic ligand. This is because these wastes arise from chemical separations of Pu and are not the type of waste described in the general descriptions of TRU waste as contaminated equipment, clothing, etc. To get an accurate estimate of the effect of organic ligands on Pu solubility, one must calculate the concentration of Pu as citrate complex inside a waste drum that has been breached, but can still provide an hindrance to mixing of the brine inside the drum with a larger pool of brine outside the drum. This will give a high concentration of Pu in solution as the citrate complex. Other ions will not compete with Pu sufficiently to prevent complex formation because the stability for (IV) actinide complexation - as shown by the stability constant for Th(IV) on p. 39 - is orders of magnitude larger than that for other ion complexes with citrate.

To obtain a more accurate estimate of the effect of citrate on Pu solubility in the event of human intrusion, calculations that use the Pu citrate formed inside a waste drum and model the mixing of that relatively concentrated brine with the average repository brines must be done, taking into account the time scales for mixing and the possibility that the intrusion event may release some brine from waste drums that has not had an opportunity to mix with the average repository brines.

The conclusion that EDTA complexes will not increase actinide solubility is probably correct, since the amount of EDTA is small and the Ni and Fe complexes have stability constants that are similar to those for the actinides. It is not shown, and is probably not

true, that the more abundant citrate inventory will not increase actinide solubility, especially for Pu.

Specific comments:

(1) p.2 and later discussions of the same topic. The authors appear to believe that degradation of organic waste can only occur by microbial action and that the most detrimental product will be carbon dioxide gas. Work in England has shown that degradation of cellulose can occur both through chemical processes at high pH and by radiation effects. The degradation products have been shown to increase the solubility of plutonium dramatically (Cross et al., 1989; Greenfield et al., 1992).

(2) p. 17 Figure caption seems to be incorrect. This should be the Castile Brine.

(3) p. 19 The corrosion equation at the bottom of the page is not balanced. If the corrosion is envisaged to occur through the action of water, rather than dissolved oxygen, it should be written as

$$Fe + 2H_2O = Fe(OH)_2 + H_2$$

(4) p. 20, near bottom "Therefore, radiolysis is not expected to affect the reduction-oxidation state of the repository." This is probably true on the scale of the entire repository, averaged over time; however, radiation effects within a waste canister that contains up to 10 g of ^{239}Pu could be quite significant on the local scale.

(5) p. 26 The selection of species for Th solubility includes $Th(SO_4)_2$ (aq.) and $Th(SO_4)_3^{=}$. The data base being prepared by OECD/NEA for recommended thermodynamic properties for Pu and Np includes sulfate complexes for Pu with one and two sulfate ligands and none with 3 sulfate ligands. In addition, the calculations of speciation with sulfate complexes for Th appear to give erratic results. See appendix B for further discussion.

(6) P. 29 The small range in uncertainties estimated for the calculation of solubilities seems to be at odds with the differences in calculated results for brines with rather similar chemistry and the difference between the calculated results and those measured for solubility of uranium dioxide in brines. See Appendix B for details.

(7) p. 35 bottom and 36 top. "Neretnieks (1982) has shown that when dissolved actinides in moving groundwater came in contact with Fe(II), the actinides were reduced to a much less soluble state and precipitated." Actually, Neretnieks did not <u>show</u> that reduction occurred; he did a model calculation that predicted the process should occur. His calculations, of course, have the same limitations concerning the adequacy of the data base used as do those done by Novak and Moore.

(8) p. 37, Table SOTERM-4. This table gives organic ligand inventories and calculated molal concentrations in a brine that is stated to be 29,841 m^3, being the smallest volume of brine that could escape from the repository. Converting to kg of brine using a density of 1.125 kg/L gives a total of 3.35×10^7 kg of brine. Using the inventory amounts in grams and converting to moles, one finds

Ligand	Mol. Wt.,g	Inventory, g	Inventory, moles
Acetate	60	1.3×10^6	2.2×10^4
Oxalate	126	1.6×10^6	1.3×10^4
Citrate	192	1.4×10^8	7.3×10^5
EDTA	372	2.3×10^4	62
(Mwt. as Versenate)			

Dividing the inventory in moles by the brine amount in kilograms gives the molal concentration of the organics. The table below compares the results of my calculation with the values given in Table SOTERM-4

Ligand	Molal conc. from Inventory calc. above	Molal conc. from SOTERM
Acetate	6.6×10^{-4}	5.2×10^{-4}
Oxalate	3.9×10^{-4}	2.3×10^{-4}
Citrate	2.2×10^{-2}	3.6×10^{-3}
EDTA	1.8×10^{-6}	2.0×10^{-6}

The differences in calculated concentrations range from 10% for EDTA to a factor of 6 for citrate.

References

J. E. Cross, F. T. Ewart, and B. F. Greenfield (1989) Modelling the behaviour of organic degradation products, Mat. Res. Soc. Symp. Proc. 127, W. Lutze and R. C. Ewing, eds., 715-722.

B. F. Greenfield, A. D. Moreton, M. W. Spindler, S. J. Williams, and D. R. Woodwar (1992) The effects of the degradation of organic materials in the near field of a radioactive waste repository, in Mat. Res. Soc. Symp. Proc. 257, C. G. Sombret ed., 299-306.

Appendix D: Summary of relevant articles used in preparation of this report

D. Rai, A. Felmy, D. A. Moore, and M. J. Mason (1995) The solubility of Th(IV) and U(IV) hydrous oxides in concentrated $NaHCO_3$ and Na_2CO_3 solutions, in Mat. Res. Soc. Symp. Proc. 353, T. Murakami and R. C. Ewing, eds., 1143-1150.

Measurements of the solubility of U(IV) and Th(IV) in carbonate and bicarbonate solutions of various concentrations, in some cases with added NaOH. Both solubilites increase dramatically as carbonate concentrations increase beyond 0.1 M. In general, Th(IV) hydrous oxide was about 1000 times more soluble at a given carbonate concentration than U(IV). Solubilites of Th in Na_2CO_3 solutions decreased with added hydroxide ion at fixed carbonate concentration (1M).

U(IV) experiments were conducted in inert atmosphere (Ar chamber) and with Fe powder present in the experiments to ensure absence of U(VI). Th(IV) experiments were also conducted in an Ar atmosphere, but without Fe powder present. Solubility limits were approached from undersaturation by suspending freshly precipitated amorphous hydrous oxides in the appropriate solutions.

Th(IV) solubility increases from 10 E-8 M at 0.1 M Na_2CO_3 concentration to > 10 E-3 M at 1 M Na_2CO_3. U(IV) shows the same behaviour, but the steep increase starts at 1 M Na_2CO_3 and finishes at 6 M. Species responsible for this increase is most likely $An(CO_3)_5^{6-}$. Similar behavior is observed in bicarbonate solutions, but the increase in solubility begins at lower concentrations - 0.01 M for Th and about 0.08 M for U.

G. R. Choppin (1990) Actinide Speciation in Spent Fuel Leaching Studies, in Mat. Res. Soc. Symp. Proc. 176, V. M. Oversby and P. W. Brown, eds., 449-456.

Results from SKB's spent fuel testing program, in which LWR fuel is leached at room temperature in deionized water or in dilute sodium bicarbonate (synthetic) groundwater were used as the basis for deciding the expected speciation of U and Pu in these liquids under oxic conditions.

Figure 2 (p. 452) is a Pourbaix diagram for plutonium redox states under atmospheric CO_2 pressure and including carbonate complexes and hydrolysis reactions. The stable conditions shown are PuO_2^{2+}, PuO_2^{+}, and Pu^{4+} for oxic conditions and Pu^{4+} and Pu^{3+} for reducing conditions. It is noted that PuO_2^{+} disproportionates into PuO_2^{2+} and Pu^{4+} but that the rate of the reactions depends on the 4th power of the H^+ concentration and on the square of the PuO_2^{+} concentrations so that at low concentrations of Pu in neutral solutions the reaction rate is negligible. As an example of this lack of disproportionation, a table is given listing the redox state of Pu in natural waters and showing more than 50% Pu(V) in most cases. (Note that at high pH this would also be expected. This may explain the relative long life of Pu(V) in some of the speciation experiments done in brines.) Choppin concludes that in oxic conditions with Pu concentrations of 10^{-6} M and lower, the dominant species may be PuO_2^{+}.

The relative strengths of complexation for plutonium cations is $Pu^{4+} > PuO_2^{2+} > Pu^{3+} > PuO_2^{+}$, which is the same order of relative stability as for U cations. (Complexes of Pu(IV) are not discussed, since the paper limits itself to oxic conditons.)

Under oxic conditions, the spent fuel leaching studies showed apparent solubility for Pu of 5-10 ppb in DIW and 0.3 to 1 ppb in synthetic groundwater (0.002 M carbonate). The redox states present are interpreted to be Pu(V) as PuO_2^{+} and Pu(IV) as precipitated $Pu(OH)_4$ or $PuO_2 \cdot xH_2O$ present as the solid phase that limits total Pu solubility. The ratio of Pu(V) to Pu(IV) in the solution phase is predicted to be extremely large: 10^{23} in DIW and $10^{26.6}$ in the synthetic groundwater at pH 8.2. (Note: There is no reason to believe that this mechanism for solubility control under oxic conditions would not also work in brines.)

H. Nitsche (1991) Basic research for assessment of geologic nuclear waste repositories: what solubility and speciation studies of transuranium elements can tell us. Mat. Res. Soc. Symp. Proc. 212, T. Abrajano, jr. and L. H. Johnson, eds., 517-528.

Discusses experimental results for NpO_2^+, Pu^{4+}, and Am^{3+}/Nd^{3+} in J-13 well water, a natural dilute sodium bicarbonate groundwater, at pH 6, 7, and 8.5 and at T = 25, 60, and 90°C. The experimental results are compared to modelling calculations using EQ3/6. Tables of stability constants for solution species used in the calculations are given and may be useful for comparison with those used in calculations for WIPP.

Plutonium was added to the groundwater as Pu(IV). The solubility controlling species were found to be polymeric plutonium(IV) and lesser amounts of plutonium carbonates. At pH 7 and 8.5, Pu solubility at 25°C was about 5×10^{-7} M. The Pu used was Pu-239 isotope. Calculations that assumed crystalline PuO_2 predicted solubility at 25°C of 10^{-12} M. Use of amorphous $Pu(OH)_4$ in the calculations overestimated the solubility limit to be 10^{-4} M at 25°C. The oxidation state distribution found in the pH 8.5 experiments for species in solution was about 70% Pu(V) and 25% Pu(VI) with minor amounts of Pu(IV) and Pu(III)+polymer. (Note, this agrees with Choppin's predictions that the solid phase under oxic conditions contains Pu(IV), while the solution species would be Pu(V).)

J. E. Cross, F. T. Ewart, and B. F. Greenfield (1989) Modelling the behaviour of organic degradation products, Mat. Res. Soc. Symp. Proc. 127, W. Lutze and R. C. Ewing, eds., 715-722.

Research into the effect of alkaline degradation of organic materials that might be found in low and intermediate level radioactive wastes showed that the degradation of cellulose produced products that greatly increased the solubility of Pu. The details of the experimental results can be found in a report by J. D. Wilkins, UKAEA Report AERE R 12719 (1987).

The specific ligands responsible for the enhanced solubility could not be identified. Also, attempts to reproduce the effect using possible ligands with Pu did not produce as high a solubility. This shows the importance of examining actual waste mixtures to ensure that symbiotic effects are included.

Experiments were conducted with cement equilibrated with water with and without organic materials and with Pu added as a separate acid solution. The precipitated Pu was separated and the solution concentrations were measured. The results were

Cement alone + Pu	[Pu] = 5×10^{-10} M
Cellulose chemical degradation	[Pu] = 7×10^{-6} M
Cellulose, radiation degradation	[Pu] = 5×10^{-6} M

The effect of other organics was much less.

New experiments were done with separated organic acids. The closest results were found with D-saccharic acid HOOC · $(CHOH)_4$ · COOH, which at pH 12 gave Pu solubility of 7.2×10^{-6} M at 10^{-5} organic acid concentration, 7.3×10^{-6} M at 10^{-4} M organic acid, 8.2×10^{-6} M at 10^{-3} M organic acid, and 9.3×10^{-6} M at 10^{-2} M organic acid. This behaviour pattern, with little change in Pu solubility even though large changes were made in organic acid concentration, was successfully described so long as one considered complexation involving hydroxyl groups as well as carboxylic acid groups.

Both experiments and modelling were done for conditions at a redox potential of + 200 mV.

B. F. Greenfield, A. D. Moreton, M. W. Spindler, S. J. Williams, and D. R. Woodwar (1992) The effects of the degradation of organic materials in the near field of a radioactive waste repository, in Mat. Res. Soc. Symp. Proc. 257, C. G. Sombret ed., 299-306.

A number of different solid organic materials were degraded in the presence of Portland cement and blast furnace slag (representing the concrete components in the proposed UK Nirex low and intermediate level radioactive waste repository) at 80°C under anaerobic conditions. Generally the experiments contained 10% organic and 90% cement. Samples of liquid were taken periodically, cooled to room temperature, pH adjusted to 12 (if necessary), and then spiked with a small volume of radioactive elements in acid solution to measure their solubility in the leachates. After 2 days samples were taken and filtered, and then the radioelement concentrations were measured.

Results found for Pu(IV) solubility in leachates produced from 500 days of degradation of the organics were

Cellulose or wood fiber	10 E-3 M
Cotton wool	10 E-5 M
Bakelite	6 x 10 E-6 M
PVC	10 E-9 M
Polystyrene	5 x 10 E-10 M
Nylon, Polythene, and Pure cement leachate	10 E-10 M

Degradation of cellulose under aerobic conditions resulted in a lower solubility for Pu(IV), namely 10 E-4 M, and solubilities of 10 E-5 M for Th(IV) and U(IV). Am(III) and Np(IV) in these leachates had apparent solubilities of 10 E-6 M.

The effect of varying cellulose to cement ratio was tested under anaerobic degradation conditions. The Pu (IV) solubilites found were 4 x 10 E-10 M at 0.1% cellulose, 4 x 10 E-9 M at 0.5% cellulose, but 1 x 10 E-6 M at 1% cellulose.

The product of cellulose degradation that is most likely to explain the enhanced Pu solubility is isosaccharinic acid (ISA); other possible degradation products are produced in lesser amounts and have less effect on Pu solubility than ISA. If ISA is exposed to cement, it will sorb onto the cement surface, thus diminishing its effect on Pu solubility. This is thought to explain the results found at low cellulose loadings in cement.

Modelling calculations were able to reproduce the effects seen in the experiments. It was concluded that the solubility enhancement for Pu was achieved through complexation that involved 4 deprotonated hydroxyl groups in the bonding.
I. AlMahamid, K. A. Becraft, N. L. Hakem, R. C. Gatti, and H. Nitsche (1996) Stability of various plutonium valence states in the presence of NTA and EDTA, Radiochimica Acta 74, 129-134.

Experiments were conducted using solutions of nitrilotriacetic acid (NTA) and ethylenediaminetetraacetic acid (EDTA) with all four soluble plutonium oxidation states - III, IV, V, and VI - at macroscopic (10^{-3}M) and microscopic (10^{-7}M) concentrations. Experiments were performed at room temperature in an argon atmosphere. Pu was prepared by dissolving PuO_2 electrochemically in 1 M $HClO_4$ and then adjusting to produce the desired oxidation states.

NTA was added to an acidic solution of Pu and the pH adjusted to 5 with NaOH. Final ionic strength of the solutions was about 0.01 M. At the higher Pu concentrations, the final species is a Pu(IV)-NTA complex, regardless of the initial oxidation state of the Pu, at NTA/Pu ratios of 6. At higher NTA amounts, the Pu(IV) polymeric form can even be dissolved. With EDTA, only Pu(III) was studied. This oxidized to produce an EDTA-Pu(IV) complex.

Studies with the lower Pu concentrations with NTA resulted in mainly Pu(IV) if the starting valence was III or IV. For initial Pu(V), about 65% of the Pu persisted as V, with a little becoming VI and most of the rest present as IV. For initial Pu(VI) at NTA/Pu of 100, 48% of the Pu was IV after 10 days and 31% was V, with 21% remaining as VI. Very high NTA/Pu ratios reduced essentially all of the Pu(VI), producing 38% Pu(IV) and 61% Pu(V). Experiments with EDTA at ligand to Pu ratios of 100 and of 1 also showed persistance of Pu(V) if the starting materials were VI or V, but little or no Pu(VI). It is expected that the Pu(V) will reduce to Pu(IV) with time. These solutions had low ionic strength (as low as 10^{-5} M) and no active reducing agents other than the organic ligands themselves.

J. DePablo, J. Giménez, M. E. Torrero, and I. Casa (1995) Mechanism of unirradiated UO_2 (s) dissolution in NaCl and $MgCl_2$ brines at 25°C, Mat. Res. Soc. Symp. Proc. 353, T. Murakami and R. C. Ewing, eds., 609-615.

Experiments using unirradiated crystalline UO_2 (s) with 1 mm particle size and BET surface area of 0.0016 m^2/g were done in synthetic brines. Both oxidizing and reducing conditions were studied. Reducing conditions were maintained using a hydrogen flux and a Pd catalyst.

Brine compositions: molal concentrations

Species	NaCl-brine	$MgCl_2$-brine
Na+	6.036	0.48
K+	0.037	0.57
Mg^{2+}	0.018	4.21
Ca^{2+}	0.021	0
Cl-	6.036	8.84
$SO_4^{=}$	0.058	0.32
Ionic Str.	6.25	14.00
pH	7.7	4.7

The UO_2 (s) had an initial surface condition that was very oxidized, $UO_{2.7}$ as measured by XPS. This led to an initial rapid dissolution of the oxidized surface even when the solution was maintained with reducing conditions. The solution concentrations in both brines gradually decreased and settled after 20 to 25 days at steady-state values of 2.8×10^{-7} mol/kg in the NaCl brine and 3.1×10^{-7} mol/kg in the $MgCl_2$-brine. At the end of the experiments the Eh was measured to be 0 to 60 mV (compatible with the stability of UO_2) and the surface of the dissolving solid was measured to have a composition of $UO_{2.1}$ as measured by XPS. A model calculation was made using the PHRQPITZ code (the PHREEQ equilibrium code with Pitzer parameters added) and gave quite good agreement of the predicted concentrations with those measured in the experiments. The predicted concentrations at zero ionic strength were about a factor of 3 lower than those predicted for the brines.

Under oxidizing conditions, the final uranium concentration in the $MgCl_2$-brine was about 10 E-5.7, and still slowly rising, while that in NaCl brine was considerably lower (10 E-6.4) and was constant. Modeling calculations for oxidizing conditions overestimated the solubility of U in the Mg-brine by about a factor of 1000, while modeling of the NaCl brines was able to produce compatible results by using a schoepite solubility of 6.2×10^{-7} mol/kg as the solid controlling the final solution concentrations.

E. Östhols, J. Bruno, and I. Grenthe (1994) On the influence of carbonate on mineral dissolution: III. The solubility of microcrystalline ThO_2 in CO_2-H_2O media, Geochim. Cosmochim. Acta 58, 613-623.

The solubility of microcrystalline ThO_2 was measured in 0.5M $NaClO_4$ at 25°C and 1 atm. as a function of pH and partial pressure of CO_2 to determine the stability of carbonate complexes of Th^{4+}. The following species and stability constants were proposed to explain the results:

For 0.5 M $NaClO_4$ conditions,

(1) $ThO_2(act) + 4H^+ \leftrightarrow Th^{4+} + 2\ H_2O$ $\log K_s = 9.37 \pm 0.13$

(2) $ThO_2(act) + H^+ + H_2O + CO_3^{2-} \leftrightarrow Th(OH)_3CO_3^-$ $\log \beta_{1,3,1} = 6.11 \pm 0.19$

(3) $ThO_2(act) + 4H^+ + 5CO_3^{2-} \leftrightarrow Th(CO_3)_5^{6-}$ $\log \beta_{1,0,5} = 42.12 \pm 0.32$

Note: For mass balance, equation (3) should have 2 H_2O added to the right hand side. This will not affect the calculated $\log \beta_{1,0,5}$.

Extrapolation of these constants to zero ionic strength gave

(1) $\log K_s = 7.31 \pm 0.3$

(2) $\log \beta_{1,3,1} = 6.78 \pm 0.3$

(3) $\log \beta_{1,0,5} = 39.64 \pm 0.4$

The solid used in these experiments was a freshly prepared precipitate of thorium oxide/hydroxide, which was of low crystallinity, and the atmospheres were mixtures of 97% CO_2 in N_2, 10% CO_2 in N_2, and pure N_2.

For the experiments at 0.1 atm carbon dioxide, the crossover between the Th-hydroxycarbonate and Th-pentacarbonate species as dominant in solution occurred at pH = 7.5. Above pH 8, essentially all of the dissolved Th was present as the pentacarbonate complex.

F. L. Sayles and W. S. Fyfe (1973) The crystallization of magnesite from aqueous solution, Geochim. Cosmochim. Acta 37, 87-99.

In the introduction section of this paper, evidence is presented to show that the oceans are supersaturated with respect to magnesite and dolomite, and that their formation is controlled by kinetic rather than thermodynamic considerations. Natural occurences of magnesite are generally in hypersaline environments, with salinity much greater than seawater.

Reagent grade basic magnesium carbonate (hydromagnesite) was reacted with saline solutions that had been equilibrated with atmospheric pressure carbon dioxide at 25°C. The solid and solutions were sealed into Pyrex ampules and reacted at 126°C to produce magnesite, which was detected using X-ray diffraction. The experiments showed that there was a long induction period prior to the production of any detectable magnesite. After crystallization of magnesite started, conversion to pure product proceeded fairly rapidly. The conversion rate increased with ionic strength and partial pressure of carbon dioxide, but decreased with Mg concentration. Nucleation of magnesite occurred on hydromagnesite surfaces (seen in SEM images).

M. P. Neu, D. C. Hoffman, K. E. Roberts, H. Nitsche, and R. J. Silva (1994) Comparison of chemical extractions and laser photoacoustic spectroscopy for the determination of plutonium species in near-neutral carbonate solutions, Radiochimica Acta 66/67, 251-8.

Experiments were conducted to investigate the solubility and speciation of ^{242}Pu in a 1.93 mM total carbonate solution of 0.100M $NaClO_4$ at pH = 6.0 and 30°C. The isotope ^{242}Pu was chosen to minimize the radiolysis effects that occur. The experiments were conducted in a controlled atmosphere argon glove box in which the oxygen concentration was typically 18 to 30 ppm. The Pu solution was added to a 0.100M $NaClO_4$ solution that had been pre-equilibrated with 5.71% CO_2 in Ar gas together with an amount of base needed to neutralize the acid from the Pu stock solution.

Experiments with a starting solution of Pu(V) with an initial concentration of 2.51×10^{-5} M had a soluble Pu concentration of $2.1 \pm 1 \times 10^{-5}$ M after 53 days. The speciation was determined by spectroscopy to be PuO_2^+ at the level of 95 ± 5%. When the Pu solution was initially Pu(VI) as PuO_2^{2+} at $2.4 \pm 1 \times 10^{-4}$ M, the concentration of soluble Pu after 120 days was $3.1 \pm 5 \times 10^{-6}$ M, or only 1.3% of the initial concentration. This was also 7 times lower than the final concentration when Pu(V) was the initial valence state for the Pu, even though it is Pu(V) as PuO_2^+ that represents the soluble Pu after 28 days of the experiment. If Pu(VI) disproportionates to produce Pu(IV) at pH =6, polymeric Pu-hydroxide will precipitate. This may explain the lower final concentrations found when Pu(VI) was the starting valence.

Speciation inferred from chemical extraction agreed with that measured directly from spectroscopy.

H. Nitsche, K. Roberts, R. Xi, T. Prussin, K. Becraft, I. Al Mahamid, H. B. Silber, S. A. Carpenter, R. C. Gatti, and C. F. Novak (1994) Long term plutonium solubility and speciation studies in a synthetic brine, Radiochimica Acta 66/67, 3-8.

This paper describes solubility studies of ^{239}Pu in a synthetic brine (H-17) conducted with a gas phase overpressure of 0.26% CO_2 and 20.75% O_2 in argon. Five separate experiments were conducted using initial species of Pu as Pu^{3+}, Pu^{4+}, PuO_2^{+}, PuO_2^{2+}, and Pu(IV) polymer at concentrations high enough to ensure supersaturation. The brine composition was

Ca^{2+}	0.029 M/L	Cl^-	2.482 M/L
Mg^{2+}	0.074	$SO_4^=$	0.075
Na^+	2.397	Br^-	0.00095
K^+	0.031	TIC	0.00082 (Total inorganic C as HCO_3)
B^{3+}	0.004		

pH = 7.0, $pCO_{2(g)}$ = 10 E-2.56 ATM
Ionic strength = 3.0 molal
Density = 1.10 g/cm^3

This brine is similar chemically to the Castile simulant brine ERDA-6 diluted by a factor of 2.

Solids that precipitated from the samples that originally contained Pu(III), Pu(IV) or Pu(IV) polymer appeared to be identical and consist of Pu(IV) polymer. Solids recovered from the experiments that initially contained Pu(V) and Pu(VI) effervesced when dissolved in HCl, indicating that they contained carbonate. Similarities of the x-ray patterns for these solids with those of $KPuO_2CO_3$(s) suggested that the solid was $NaPuO_2CO_3$(s), for which no reference powder pattern was found, since there is so much more Na than K in the brine.

Steady state concentrations found range from 2 x 10^{-7} M for solutions that originally contained soluble Pu(III) and Pu(IV), to 3.6 ± 0.8 x 10^{-7} M for Pu(V) solution, and 7.6 ± 2.3 x 10^{-7} M for initial Pu(VI). The predominant oxidation state of the solution species at the end of the experiments was (VI) with lesser amounts of (V), found mainly in those experiments that began with Pu as VI and V. Eh measured in solution at the end of the experiments was +400 to +500 mV vs. the normal hydrogen electrode.

D. T. Reed, S. Okajima, and M. K. Richmann (1994) Stability of plutonium (VI) in selected WIPP brines, Radiochimica Acta 66/67, 105-111.

States that the predominant actinide in TRU waste will be plutonium-239 at the level of up to 10 grams per waste drum.

Studies were done in two synthetic brines - brine A (similar to Salado conditions) and ERDA-6, which represents expected conditions in the Castile formation brines - and in two brines collected from the WIPP site. The natural brines had a composition that was between those of the synthetic brines with the exception of sulfate, which was a factor of two higher than ERDA brine for one of the natural brines. The pH was about 6 in all cases.

Pu(VI) was stable in Brine A, which contained carbonate. In the ERDA brine, which had no intrinsic carbonate (other than that which would dissolve from contact with normal air), the predominant species was a Pu(VI) hydrolytic form, with the possibility of some Pu(V) forming over time. In the natural brines, the Pu(VI) species disappeared from spectra after 6 days and no peak attributable to Pu(V) was observed. Final concentrations in these brines for Pu were about 5×10^{-5}M, which would make direct observation of Pu(V) doubtful; however, the authors conclude that the Pu has been reduced further to an unidentified species, possibly polymeric plutonium.

8.4b Solubility Issues Raised by Dr. Rodney C. Ewing After the February 20, 1998 Meeting Between the EEG and Sandia.

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Rodney C. Ewing

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ENVIRONMENTAL EVALUATION GROUP

February 22, 1998

Robert H. Neill, Director
Environmental Evaluation Group
Suite F-2, 7007 Wyoming Boulevard, NE
Albuquerque, New Mexico 87109

Dear Bob,

Thank you for inviting me to attend the technical exchange meeting between DOE contractors and the EEG on the subject of the actinide source term (AST) held this past February 20th. Since the time of the last meeting of the National Research Council's Committee on the Waste Isolation Pilot Plant (May, 1997), I have not had the opportunity to follow the progress of the AST program. I should also emphasize that I am no longer on the NRC WIPP Committee, and these brief comments represent my own views. I am not a representative or consultant for any committee or agency regarding the WIPP.

I want to emphasize my view of the importance of the actinide source term work. Although the NAS (1996) report on WIPP arrived at a positive evaluation of the potential for the WIPP as a repository for transuranic waste, the same report clearly identified outstanding technical issues, prominent among them was the issue of actinide solubilities in brine (page 5). Unfortunately, there was little of substance to review concerning the AST program at the time the WIPP committee completed its report in October of 1996. We concluded (page 62):

> "Overall, the scientific program outlined by DOE for study of the source term is adequate, provided that the program is carried to completion. Because the program at this time consists largely of work planned or in progress, it has not been possible to critically review experimental results or to judge whether these results are used appropriately in the PA analysis."

Thus, I believe the review of this topic by EEG and EPA is essential to establishing confidence in the data and models used for the AST in the performance assessment. I note that the most recent PA analysis suggests that the actinide solubilities in brine are of lesser importance; however, this conclusion is based on the new and revised view of transport in the Culebra and the introduction of the MgO backfill. In the event, either or both of these issues

change with further analysis or experimental results, then the role of actinide solubilities may again become important.

My general observations and comments include:

1. The oxidation state analogy and the FMT calculations appear to predict trends in actinide solubilities; however, this work still requires important experimental verification. The NAS (1996) report concluded (page 63),

   "Although some aspects of its geochemical behavior can be estimated by studies of other actinides using the oxidation state model, ideally, data for each oxidation state should be followed by experiments with plutonium."

   The presentations this past week only emphasized and confirmed the need for such experiments. Particularly important were the points made by the EEG consultant, Dr. Virginia Oversby, which were based on a critical review and use of data in the published scientific literature. It seems to me that the credibility of the project would be greatly enhanced by the comparison of FMT results to experimental results obtained outside of the project, as an example, studies of actinide solubilities in spent fuel or UO_2 corrosion experiments.

2. It certainly appears to be an opportune time to review the results and analysis of the source term test program (STTP) at LANL. The limited results presented, were used to conclude that the predicted actinide concentrations in brine are "conservative". In my view, the data only suggest that there are processes (not identified) that affect the actinide concentrations, and these processes, in general, lower the actinide concentrations.

   There was some mention of discontinuing some of these tests; however, considering the time, effort and expense required to begin and sustain these experiments, such a decision should be made only after careful review and analysis of the data from the STTP experiments. Although some of the experiments may have no present applicability to the WIPP project, DOE may want to consider the experiments in a wider context, as an example the interaction of actinides and clays may be important to other DOE projects; thus, there may be value to continuing even those experiments which are not now considered to be relevant to WIPP.

3. The project still is not in a position to present and discuss models of the longer term evolution of the chemistry of the WIPP system. In this regard, well constrained, simple, experiments with relevant actinides (e.g., Pu) that are designed to run for years are still much needed. I see no reason that such experiments cannot be initiated and run through the operational phase of the repository, and their results may be utilized in the recertification process. This is consistent with the recommendations of the NAS (1996) study (page 64). Similar experiments to study retardation in the Culebra would also be of value.

4. Concerning the report and comments by the EEG consultant, Dr. V. Oversby, I believe that some of the issues she raised can be rather directly addressed by the exchange of recent and relevant results, straightforward calculations, and/or limited additional experimental work. However, her approach to the review of the CCA, particularly in the areas of verification and validation, merit careful attention. I believe that she very commendably demonstrated the real meaning of a *critical* review by:

   i.) comparison of project results to the published literature (e.g., use of the NEA data base; UO_2 and spent fuel corrosion studies);

   ii.) comparison of results from project codes and models to more generally used and accepted geochemical code results.

I hope that these brief comments are of use to the project. You may give copies to this letter to DOE and EPA.

Sincerely,

Rod Ewing

cc: John Garrick, chair, NRC WIPP Committee
Thomas Kiess, staff officer, NRC WIPP Committee

8.4c Solubility Issues Raised by Dr. Virginia Oversby After the February 20, 1998 Meeting Between the EEG and Sandia.

Issues related to solubility of Pu at WIPP

1) Heterogeneous vs homogeneous equilibria

Calculations of solubility of actinides under WIPP conditions have been done assuming that before any release the repository will contain 29,841 cubic meters of brine that is well equilibrated. This assumption is doubtful and other models should be investigated to determine the effects of local variations in brine compositions and actinide speciation and concentration. After closure, the repository salt formation will creep and close up void spaces. Subsequent intrusion of brine, either as drilling fluid during an intrusion event or as intrusion of pressurized brine following penetration to layers below the repository, will add concentrated - if not saturated - brine solutions to the repository horizon. After fluid is added, the resulting physical state of the repository should still be one of rather low total porosity and have a high proportion of solids relative to fluids. In that case, equilibration of fluid compositions over large distances is unlikely, since the mechanism of mixing would be diffusion rather than advection. Local pockets of solutions with chemical compositions representative of the range of potential waste container soluble actinide inventory should be considered, rather than the grand average of the actinide inventory and brine compositions. This is particularly important for issues such as the complexation of Pu by citrate and/or cellulose degradation products, as well as the changes in solubility that may accompany presence of different alteration products of MgO.

2) MgO alteration products

The CCA calculations of solubility of actinides assumed that MgO backfill would alter to produce an equilibrium assemblage of brucite and magnesite. Later investigations indicated that the first phase formed from reaction of MgO with aqueous carbon dioxide dissolved in the brine would be nesquehonite. Calculations of actinide solubility in the presence of nesquehonite resulted in estimates of Th solubility (and, thus, other actinide (IV) elements) that were in the range of those calculated for the case without backfill. While it was argued that the longer-term phase would be hydromagnesite, nesquehonite might persist for rather long times.

At the meeting between WIPP staff and EEG on February 20, 1998, it was stated that the reason nesqhehonite had been found in the previously reported experiments was that a high pressure of carbon dioxide had been used. New experiments, with lower carbon dioxide pressure, produced an unidentified phase, persistent over at least 200 days, that was thought to be hydromagnesite.

Two issues remain to be resolved: 1) what is the identity of the phase in the new experiments, and 2) what is the effect of heterogeneous repository conditions on the pressure of carbon dioxide in local regions of the repository. Gas generation rates will depend on the local abundance of bacteria and microbes as well as the local abundance of materials that can degrade to produce carbon dioxide. An analysis of maximum gas generation rates in local areas is needed before it can be assumed that nesquehonite can not form.

3) Relative solubility of Th versus other actinides

As part of the rationale for using Th as an analog to estimate the solubility of other actinides in the (IV) oxidation state, the WIPP staff claim that Th always shows higher solubility than U(IV) and Pu(IV). While this has been shown to be the case for freshly precipitated Th and U hydroxides, it is not the case for the vast majority of materials that contain U and Th in natural settings - i.e., minerals containing U and Th. A vast body of geochemical data pertaining to the U-238 decay series shows that U leaches from minerals in preference to Th.

Th (and Pu) forms an amorphous solid when freshly prepared from solution by precipitation of the hydrous oxide. The solubility of this amorphous hydrous oxide can be quite high. With time, Th and Pu precipitates of hydrous oxides age into materials that have increasing degrees of crystallinity. As crystallinity increases, the measured solubility of the materials decreases. This is the major reason for the very large range of reported solubility data for Th and Pu oxides in the literature.

4) Solution speciation in solubility calculations

In order to evaluate the potential validity of calculated actinide solubilities one must closely inspect the identity of the solid phases assumed to control the brine composition and the speciation of the actinides in solution. As conditions change (e.g., identity of solids assumed to be present, or chemistry of the brine), the speciation of the actinides should change in a manner consistent with the changes in assumed solids and fluid compositions. Changes in speciation between two successive calculation that cannot be explained by rational chemical arguments are symptomatic of problems in the chemical data base or the calculational methods. An example of this type of problem was seen in the CCA calculations, where Th solubility was dominated by di- and tri-sulfate complexes in the no backfill case, but these species were calculated to be insignificant in the case where Mg was added. Detailed examination of the solution speciation did not indicate any reason for this drastic change in calculated speciation.

5) Calculations and measurements for pyrochemical salts

Tests underway at LANL using actual waste samples have produced conditions for which the calculated solution concentrations for Pu were greater than 0.001 M. The details of these calculations have not been presented. If the pH of the brines in contact with the pyrochemical salts is near neutral or higher, the high calculated solubility should not be greatly affected by the assumption of adding MgO to the system. Measurements of Pu-239 in these tests gave concentrations of about 1 E-5, which is higher than the concentration used in the CCA for demonstration of compliance with release limits. These high calculated and measured solubilities need to be investigated, particularly in light of the fact that inventories of Pu contained in chloride salts at Rocky Flats exceed 1 ton.

6) Direct estimates of solubility for U(IV) and Pu(IV)

The Nuclear Energy Agency (NEA) of the OECD has published a compendium of recommended values for the thermodynamic properties of U. Data from this volume (I. Grenthe, ed.) should be used to provide a direct estimate of the solubility of U(IV) in brines similar to those expected at WIPP. Also, data on U solubility in brines published in the open literature should be used as a means to estimate solubilities for U(IV) under WIPP conditions.

The NEA is also preparing a compendium of recommended values for the thermodynamic properties of Np and Pu (R. Lemire, ed.). This volume is in the final stages of preparation, so that any changes in the recommended data between the present draft and the final issued volume should be small. This volume could provide a sound basis for estimation of Pu solubility in WIPP brines.

7) Needs for additional experimental work

Direct measurements of solubilities of actinides under conditions that are assumed to be relevant for WIPP are needed. Some examples of the types of experiments needed are measurements of the solubility of Pu in brines in the presence of Fe, direct measurement of Pu speciation in brines, and solubility of actinides in the presence of the alteration phases of MgO, both at low and high carbon dioxide concentrations.

8.5 WIPP Related Geological Issues (Chaturvedi, 1993)

WIPP-RELATED GEOLOGICAL ISSUES

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Abstract — The Waste Isolation Pilot Plant (WIPP) is a proposed repository for disposal of defense transuranic (TRU) radioactive waste. Located in southeastern New Mexico, 25 mi (40 km) east of Carlsbad, the repository has been excavated in the Salado Formation bedded salt at a depth of 2150 ft (656 m) below the surface. The concept of geologic isolation of radioactive waste, with the half-life of the radionuclides measured in tens of thousands of years, is to primarily rely on the geologic barriers to keep the radionuclides from leaking to the biosphere. Several geologic features and processes have been identified during the site characterization of the WIPP site that could impact the performance of the repository for the 10,000 year regulatory period. These include salt dissolution breccia chimneys, brine reservoirs, Salado Formation hydrology, hydrology of the overlying Rustler Formation water-bearing units, disturbed rock behavior and natural resources. These geologic factors are being considered in the analysis of breach scenarios from the WIPP repository for the next 10,000-year period.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is being excavated and constructed to be a geologic repository for permanent disposal of defense transuranic (TRU) waste. It is located 25 mi (40 km) east of Carlsbad, New Mexico. In addition to support facilities on the surface to provide office space to workers and to receive and handle radioactive waste (Fig. 1), there are four shafts (waste handling, construction and salt hoisting, air intake and air exhaust shafts) that connect the surface to the underground facilities. The project is being administered by the U.S. Department of Energy (DOE), with Sandia National Laboratories

FIGURE 1. An aerial view of the WIPP (courtesy U.S. Department of Energy)

in charge of site characterization and most of the experiments and Westinghouse Electric Corporation as the managing contractors.

The repository is excavated at a depth of 2150 ft (655 m) below the surface and consists of an experimental area to the north and the main repository to the south of the shafts (Fig. 2). The experiments carried out in the northern part of the facility include mechanics of closure of excavations; effect of heat on closure and brine migration; development of plugs and seals to be used to plug the excavations, shafts and bore holes; and the effect of salt creep on the waste drums. The repository itself will consist of 56 "rooms," each 300 ft long, 33 ft wide and 13 ft high (91.5 m × 10 m × 4 m), divided in eight panels of seven rooms each. The seven rooms of the first panel were excavated between 1986 and 1988. Since the DOE had planned to start shipping radioactive waste to WIPP in 1988 for an "operational demonstration," Excavation for the other seven panels of the repository has not yet begun.

Transuranic waste consists of various kinds of trash including paper, rubber, wood, metals and sludges, contaminated with radionuclides heavier than uranium with half-lives greater than 20 years and a level of contamination exceeding 100 nanocuries per gram. The waste has resulted as a by product of nuclear weapons production in the United States during the past 50 years. Only waste retrievably stored since 1970 is presently planned to be shipped to WIPP. Two-thirds of the planned capacity of waste for WIPP is yet to be produced. Two categories of the TRU waste are currently stored at DOE-managed national laboratories and will be disposed at WIPP. The contact-handled (CH-TRU) waste is contained in 55 gallon (0.21 m³) mild carbon-steel drums that have a maximum surface-dose rate of 200 millirem per hour. The remote-handled (RH-TRU) waste will be disposed of in 0.85 m³ capacity cylindrical canisters with unshielded surface dose rate higher than 200 millirem per hour and up to a maximum of 1000 rem per hour. The 50 hectare WIPP repository has been designed to hold 850,000 drums (176,000 m³) of CH-TRU waste containing 9 million curies of radioactivity and 7,500 canisters (7100 m³) of RH-TRU waste containing 5 million curies. The CH-TRU waste drums will be stacked three high in 56 "rooms" to be excavated in salt. The RH-TRU canisters will be disposed in 36 in. (0.91 m) diameter and 10 ft (3 m) deep horizontal holes.

The TRU waste to be disposed at WIPP consists of both hazardous chemical waste and radionuclides. Its disposal should therefore be according to the requirements of the Environmental Protection Agency (EPA) Standards for the handling and permanent disposal of transuranic radioactive materials (U.S. CFR, 1985), as well as the requirements of the Resource Conservation and Recovery Act (RCRA) (U.S. CFR, 1991). The idea of permanent disposal of the radioactive waste is to isolate it from the environment for a very long period of time. The EPA Standards for radiation protection specify a time of 10,000 years for containment of the waste and require probabilistic risk analyses to assure that potential releases to the environment will have a low probability and not allow more than a specified amount of various radionuclides. The RCRA regulations require assurance of no releases of hazardous materials beyond a specified "unit boundary," which in the case of WIPP has been accepted to be the 2.5 mi by 2.5 mi (4 km × 4 km) WIPP site laterally and up to the top of the Salado Formation vertically.

A geological repository relies primarily on the geology of the site to provide containment of waste for thousands of years. This is especially true for the WIPP project, because there is no commitment to use critical engineered barriers for disposal of the TRU waste. Ninety seven percent (by volume) of the waste to be disposed at WIPP will be contained in ordinary mild carbon steel 55 gallon drums with an expected life of only 20 years, or in Standard Waste Boxes made of plywood or metal. The containers are expected to get crushed and corroded in a few years in the corrosive briny environment of a repository in salt beds and salt creep is expected to close the openings and form a cocoon around the waste. Geologic integrity and the absence of geologic and geohydrologic conditions or processes that may breach the integrity of the repository are, therefore, critical issues in assessing the suitability of the WIPP site for use as a permanent geologic repository for radioactive waste.

The purpose of this paper is to describe and discuss the geological features and processes that potentially may have an impact on the integrity of the WIPP site. Most of the geologic and hydrogeologic investigations pertinent to the WIPP have been performed by the scientists of the U.S. Geological Survey, Sandia National Laboratories, other contractors of the DOE and university researchers. The Environmental Evaluation Group (EEG) has analyzed the importance of various geologic issues and controversies as they have come to light from time to time and has proposed mechanisms and further investigations to resolve them. The EEG is affiliated with the New Mexico Institute of Mining and Technology and has offices in Albuquerque and Carlsbad. It was established in 1978 as an interdisciplinary group of scientists and engineers to provide an independent technical evaluation of various aspects of the WIPP project to protect the health and safety of the people of New Mexico. The group is funded 100% by the DOE.

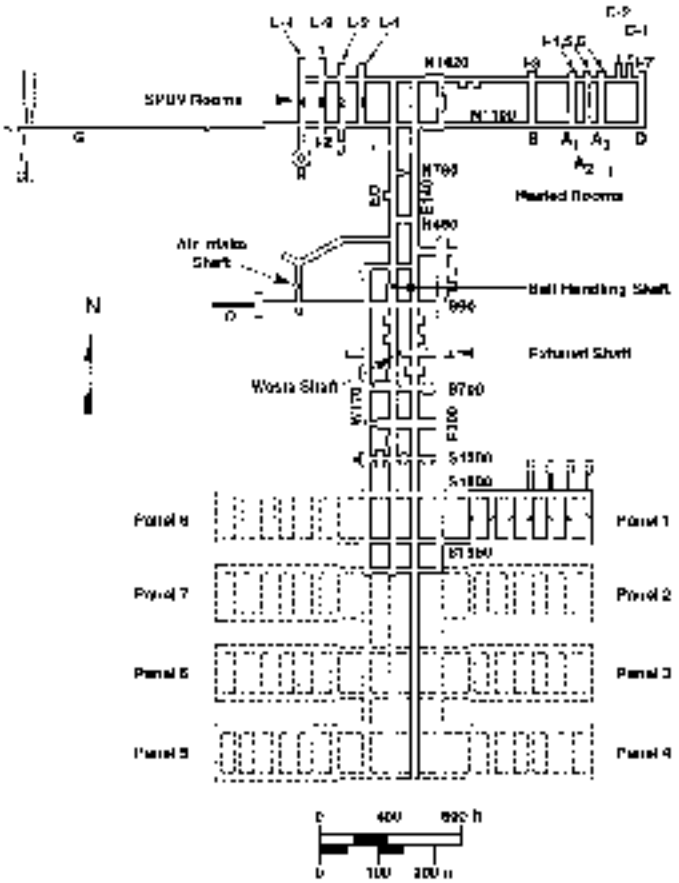

FIGURE 2. Underground layout of the WIPP repository.

GEOLOGICAL SETTING OF WIPP

The WIPP site is situated in the northern part of the Permian Delaware Basin. The repository is located at a depth of 2150 ft (655 m) from the surface in the Salado Formation of the Permian Ochoan Series. The Salado Formation is about 1975 ft (602 m) thick at the center of the WIPP site and the repository is situated at a depth of 1300 ft (396 m) from the top of the formation (Fig. 3). The Delaware Basin is bounded by the Permian Capitan Reef (Fig. 4). The basin contains about 15,000 ft (4575 m) of Paleozoic sedimentary rocks overlying the Precambrian basement. The formations of interest with respect to the WIPP project, from the oldest to the youngest, are the Bell Canyon Formation of the Delaware Mountain Group, the Castile, Salado, Rustler and Dewey Lake Formations of the Permian Ochoan Series, the Upper Triassic Santa Rosa Sandstone Formation that tapers from the east to the west across the WIPP site and the Pleistocene Gatuña Formation. A caliche layer known as the Mescalero caliche is consistently encountered underlying the surficial sands at the WIPP site.

The site lies on a generally flat plain covered with sand, caliche and

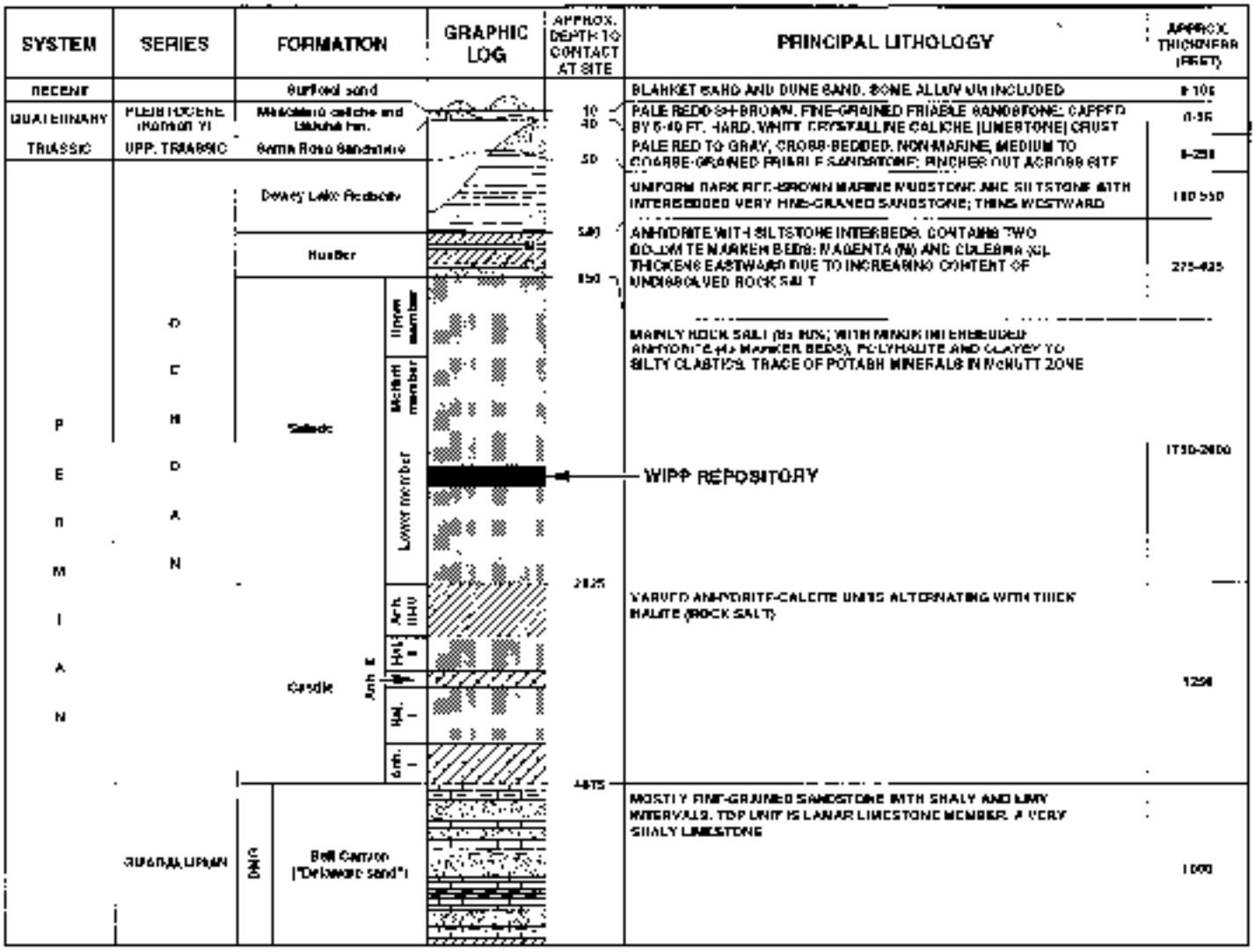

FIGURE 3 General stratigraphy at the WIPP site, including the complete Ochoan section and overlying strata, plus underlying Guadalupian Bell Canyon Formation (adapted from Fig. 4.2-2 of Powers et al., 1978)

desert bushes. It is located in a gypsum karst region. A subsidence landform feature called Nash Draw lies about 3 mi (5 km) west of the WIPP site. It is 6–7 mi (10–12 km) wide in the east-west direction, about 18 mi (30 km) long in the north-south direction and has resulted from erosion by solution and fill (Lee, 1925) of soluble rocks, a process that has occurred in the past and which is also presently active. The Pecos River flows from northwest to southeast, about 12 mi (20 km) west of the WIPP. Based on the presence of saline seeps along the Malaga Bend of the Pecos River (14 mi southwest of WIPP repository), a marked increase in the salinity of the river south of the bend and the general flow direction of the water bearing beds of the Rustler Formation, the Malaga Bend has been identified as an area of discharge of the Rustler water from Nash Draw and perhaps even from the WIPP site.

All the formations shown on Fig. 3 are geohydrologically significant. Ground water occurs in the upper part of the Bell Canyon Formation in poorly cemented sandstone stringers (Hiss, 1976). The Castile Formation is about 1500 ft (450 m) thick at the WIPP site and overlies the Bell Canyon. It consists of alternating layers of anhydrite and halite, with four anhydrite and three halite members. The uppermost anhydrite member contains pressurized brine reservoirs that have been encountered by two of the boreholes drilled for the WIPP project and by several oil and gas exploratory wells. The Salado Formation overlies the Castile Formation and the repository is located in its lower part (Fig. 3). The Salado consists primarily of halite with a zone of potassium- and magnesium-bearing minerals (sylvite, langbeinite) and thin (<3 ft) seams of clay, anhydrite and polyhalite. Before 1986, thick salt beds, as in the Salado Formation, were considered essentially dry and impermeable. Observations from the WIPP excavations, however, indicate that the salt beds may be saturated with brine and the salt may exhibit Darcian flow, albeit at very low permeability.

The Rustler Formation overlies the Salado and contains the most important geohydrologic units in the region. The thickness of the Rustler varies between 275 ft to 425 ft (84 m to 130 m) in the northern Delaware Basin and is approximately 310 ft (95 m) at the WIPP site. Sedimentology of the Rustler Formation was described by Lowenstein (1987) and Powers and Holt (1990). The formation contains three recognized fluid-bearing zones: in ascending order the Rustler-Salado contact residuum, the Culebra dolomite and the Magenta dolomite. The transmissivity of the Culebra is the highest, followed by the Magenta and the Rustler-Salado contact. The water quality is highly variable within each unit. The total dissolved solids concentration is lowest in the Magenta and highest in the Rustler-Salado contact zone. Nearly all the water in the Rustler Formation at the WIPP site has total dissolved solid (TDS) concentrations greater than 10,000 mg/l.

All three Rustler hydrologic units probably discharge into the Pecos River, 14 mi (22 km) to the southwest near the Malaga Bend. The recharge areas are identified rather imprecisely as being upgradient of

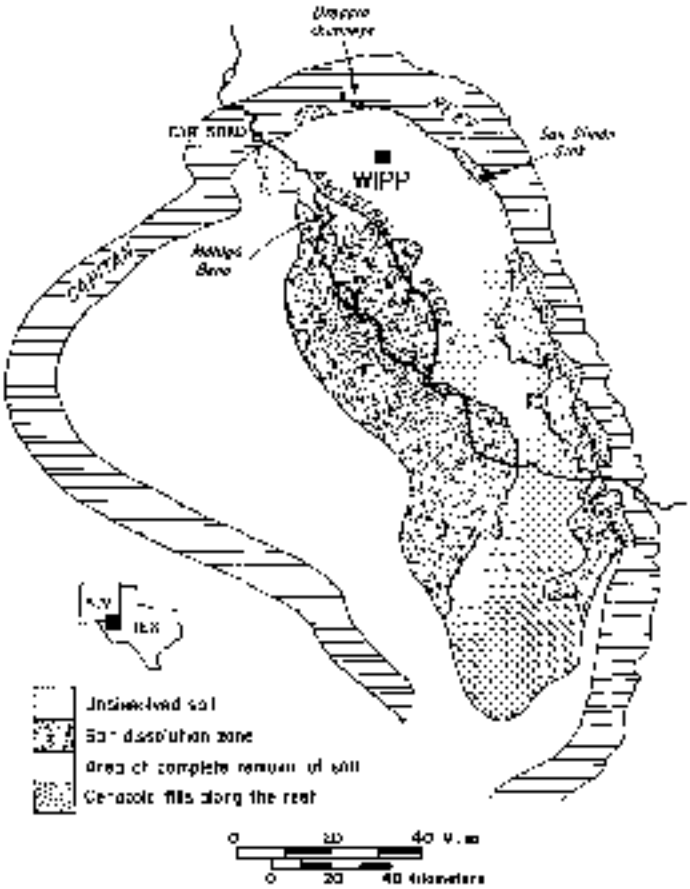

FIGURE 3. Regional extent of removal of salt from the Salado Formation.

the measured hydraulic heads, about 10 to 15 mi (16–24 km) north of the WIPP site. At the WIPP site, the three units are separated but are probably interconnected in Nash Draw, west and southwest of the site. Of the three Rustler units, the Magenta and the Culebra are of prime concern because they extend over the WIPP site, whereas the Rustler–Salado contact zone mainly produces water west of the WIPP site (Mercer, 1983). The majority of testing in the Rustler has concentrated on the Culebra because it is more transmissive than the Magenta and therefore better suited for analyzing boundary breach scenarios.

Results of several single hole and multiple flow tests (Rappin, 1988) at the site indicate that the transmissivities of the Culebra aquifer at and near the WIPP site range from 2000 ft²/day (10^{-3} m²/s) in Nash Draw to 10^{-2} ft²/day (10^{-7} m²/s) east of the WIPP site. Generally, transmissivity increases from east to west across the WIPP site. High transmissivity zones occur in the southeastern part of the site, in the area of boreholes DOE-1 and H-11 and in the north central and northwestern parts in the vicinity of boreholes WIPP-13, DOE-2 and H-6 (Fig. 5).

Chemical composition of ground water from the Culebra aquifer varies widely within short distances at and near the WIPP site (Chapman, 1988). Three miles south of the WIPP site, the Culebra water typically contains 3000 mg/l of total dissolved solids (TDS). At the site itself, TDS varies from 12,500 mg/l at H-2 (Fig. 5) to 130,500 mg/l at H-5. Extreme variation in the chemistry of the Culebra water within short distances is illustrated by the TDS at H-2 (12,500 mg/l), H-3 (134,500 mg/l) and DOE-1 (118,000 mg/l), within a distance of less than 2 mi.

The WIPP is situated in a mineral-rich area. Potash minerals are mined around the WIPP site from the McNutt potash zone in the upper part of the Salado Formation, approximately 1500 ft (450 m) below the surface. Oil and gas are produced around the WIPP site from the Permian Delaware Mountain Group and Pennsylvanian Atokan and Morrowan strata.

STATUS OF WIPP-RELATED GEOLOGICAL ISSUES

History of WIPP site characterization

The geological site characterization for the WIPP began in 1974, following the abandonment of the Lyons, Kansas site in 1972. A 2 mi by 1.5 mi (3.2 km × 2.4 km) rectangular site was selected by the Oak Ridge National Laboratory (ORNL) about 7 mi (11.2 km) northeast of the present site. Cores from two boreholes (AEC 7 and AEC 8, Fig. 5) penetrating through the Salado Formation drilled at the northeast and the southwest corners of that site indicated acceptable geology. Sandia National Laboratories (SNL) was given the responsibility for site characterization for WIPP in 1975. A third borehole (ERDA 6), drilled by SNL in the northwest corner of that original site in 1975, encountered a pressurized brine reservoir and intense structural disturbance in the fractured upper anhydrite of the Castile Formation at a depth of 2709 ft (826 m). The present site was selected by the SNL and the U.S. Geological Survey (USGS) and a stratigraphic borehole (ERDA-9) was drilled in 1976 through the Salado Formation at the center of the new 2.5 mi by 2.5 mi (4 km × 4 km) WIPP site.

Early site characterization activities focused on obtaining basic data on the stratigraphy, hydrology and mineral resources at the WIPP site. As these studies progressed, several geologic features or processes that were potentially deleterious to a radioactive waste repository were identified. The EEG organized a meeting of geoscientists in January 1980, and a field trip in June 1980, to discuss these geologic issues (EEG, 1980; Chaturvedi, 1980). Based on the recommendations from these meetings and independent analyses by the EEG scientists, the EEG proposed preparation of a number of topical reports to address the geological issues that had surfaced at that time. These recommendations were accepted by the DOE and a Stipulated Agreement between the State and the DOE was signed on 1 July 1981, that included the DOE commitment to prepare eleven "topical reports" and six "additional investigations." As a part of additional investigations, the DOE deepened the borehole WIPP-12, located 1 mi north of the center of the WIPP site, from its 1978 completed depth of 2737.5 ft (834.5 m) at the top of the Castile, to a total depth of 3921.5 ft (1197.4 m). Pressurized brine associated with hydrogen sulfide gas was encountered at a depth of 3146 ft (959.5 m). As a result, the DOE, following the EEG recommendation, again relocated the repository about 1.25 mi (2 km) south of the planned location that would have brought the repository within a few hundred feet of the WIPP-12 borehole.

The WIPP topical studies were published in 1983 and the DOE claimed that the geologic site characterization issues were resolved. The EEG reviewed the reports and concluded (Neill et al., 1983) that the site characterization work completed until then warranted confidence in the site, but work still remained to be done to answer the remaining questions. Underground excavation began in 1982 and additional issues came to light from the observations underground.

The more important geologic issues relevant to WIPP are described below and the status of their resolution is discussed.

Dissolution of Salado salt

There is indisputable evidence that the Ochoan evaporite deposits (Castile, Salado, Rustler and Dewey Lake formations) have undergone erosion and blanket dissolution in the Delaware Basin. The edges of the Castile and the Salado halite can be traced west of the Pecos River essentially running parallel to it in a northwest southeast direction (Anderson, 1981).

Based on a 600,000 year dating of the Pearlette O ash layer exposed at the ridge on the 200 ft (61 m) deep Nash Draw margin, Buchanan (1980, 1981) calculated an average rate of 150 ft (100 m) per million years for the vertical dissolution. Assuming that the edge of the Salado salt has moved from the Capitan Reef front to its present location during the past 7 to 8 Ma (since Ogallala time), Bachman and Johnson (1973) concluded that the horizontal rate of movement of the blanket dissolution front is about 6 to 8 miles per million years. These are, of course, very rough average rates of movement; the front itself may have moved faster under less arid climatic conditions. Also, an advancing "tongue" of the front may reach a point faster than the front itself. Using the

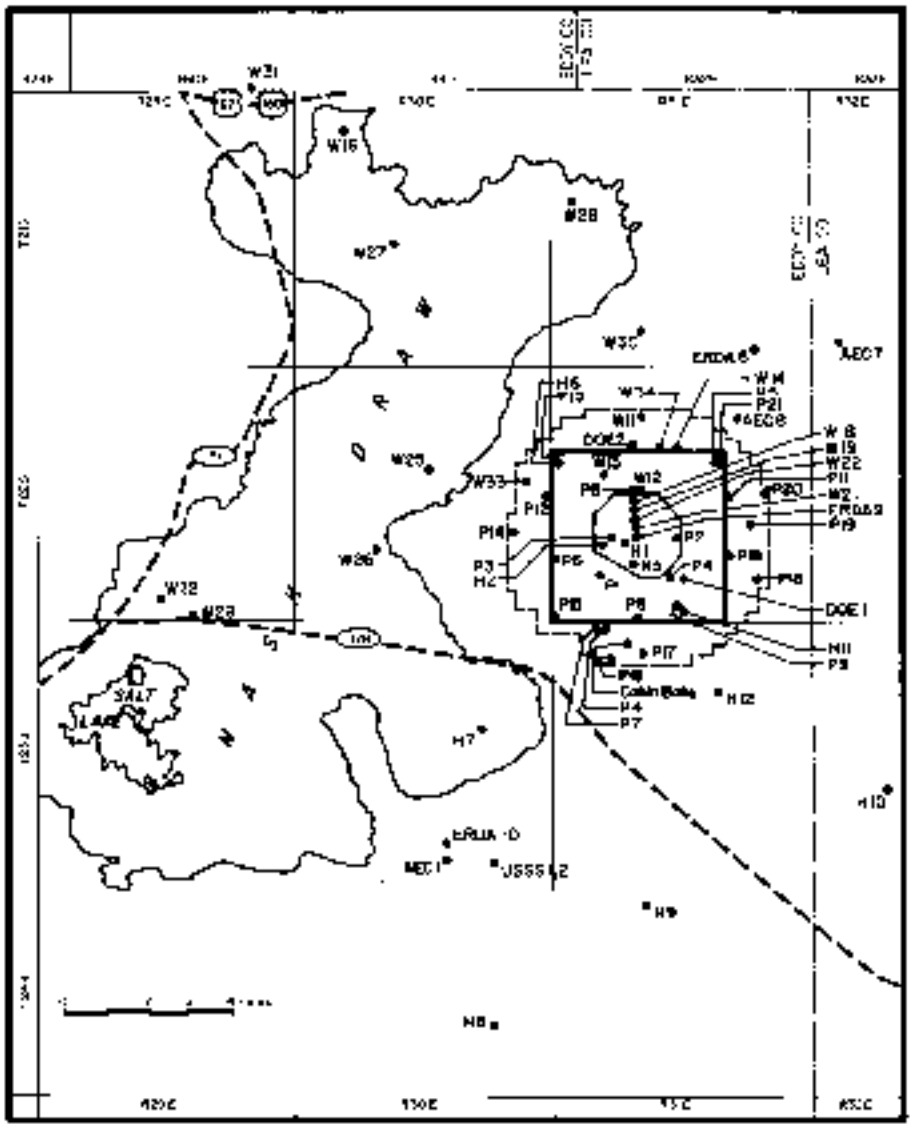

FIGURE 5 The location of boreholes drilled in connection with the WIPP project

above rates for horizontal and vertical dissolution, it would take approximately 225,000 years for the front to travel approximately 2 mi to reach the western edge of the WIPP site and start dissolving salt from the upper Salado, about 1500 ft (457 m) above the repository horizon. It would then require at least 2 to 3 Ma for the removal of 1500 ft (457 m) of salt by dissolution, at the rate of 330 to 500 ft (100 to 150 m) per million years. In spite of the very approximate nature of the estimated rates of advance of the dissolution front and the possibility of a more rapid advance of a segment of the front, these calculated rates provide sufficient safety from an advancing front of blanket shallow dissolution of salt toward the WIPP site.

In addition to the blanket dissolution of salt described above, Anderson et al. (1972) raised the possibility of a different kind of dissolution process acting at depth from the margins of the basin by noting that large quantities of bedded salt were missing from the middle of the evaporite sequence near the center of the basin. Using the correlation of acoustic logs across several lines in the Delaware Basin, Anderson (1978) concluded that (1) the preferred horizons from which salt has been removed by dissolution occur between the Halite III salt of the Castile Formation and the 136 marker bed of the Salado Formation and (2) the large depressions in the basin, first identified by Maley and Huffington (1953), were the result of selective dissolution of lower Salado salt beds. Anderson (1981) further developed the idea of deep-seated dissolution and concluded that such dissolution has occurred around the margin of the basin where the Capitan aquifer is in contact with the Permian evaporites, and within the basin where selective dissolution in the lower Salado has undercut the overlying salt beds. He calculated that more than 70% of the original salt has already been removed from the lower Salado horizon in the basin.

As requested by the DOE, Lambert (1983) prepared a topical report on the dissolution issue for the WIPP project. Another WIPP project report (Wood et al., 1982) examined the viability of the Delaware Mountain Group aquifer removing the dissolved salt, as hypothesized by Anderson (1981). The EEG (Chaturvedi, 1982; Neill et al., 1983; Chaturvedi and Rehfeldt, 1984) examined the deep-dissolution hypothesis and concluded that although the timing and the mechanism were not fully explained by the hypothesis, the evidence from geophysical well logs did indicate that a large amount of salt from the lower Salado units was missing. However, there were eight WIPP project boreholes (AEC-7 and AEC-8 to the northeast, ERDA-10 to the southwest, WIPP-11 to the north and WIPP-9, 12, 13 and DOE-1 within the WIPP site, see Fig. 5), which had obtained cores of the Salado Formation but did not show any evidence of extensive dissolution. From this, the EEG concluded (Chaturvedi and Rehfeldt, 1984) that the Salado Formation does not appear to have been affected in and around the WIPP site by past regional dissolution at depth, although an area located 2 mi (3.2 km) north of the center of the WIPP site was suspected as a potential area of point-source dissolution. At the urging

of the EEG, the DOE drilled a 4325 ft (1319 m) deep corehole (DOE-2, Fig. 5) to investigate the origin of this feature, which was identified as a structural depression on the basis of observed depression in the anhydrite/clay marker-beds in the potash industry boreholes.

The core from the DOE-2 borehole confirmed the existence of the structural depression but showed no indication of this being due to dissolution at depth. The absence of any dissolution residue and a thickened halite section can best be interpreted as due to gravity-driven salt flow in the area (Borns, 1987). The WIPP repository is no longer considered to be threatened by the effects of the Salado salt dissolution at depth.

Breccia chimneys

A breccia chimney is a solution-subsidence structure formed by dissolution of an evaporite layer at depth that results in collapse of the overlying layers, thus forming a brecciated chimney up to several thousand feet in diameter with its base in the collapsed cavity. These features are found in many evaporite basins of the world. With respect to the WIPP, the concern was that a breccia chimney may form under the WIPP repository sometime in the future, thereby providing a potential pathway for breach of the repository.

Vine (1960) identified as possible breccia chimneys several domal structures in the Delaware Basin that have been explored during the investigations for WIPP. After extensive investigation, the existence of only two chimneys (Hills A and C) was confirmed. Geophysical and geological studies show that two others (Hills B and Wills-Weaver) are also likely breccia chimneys, although they were not cored. All of these features appear to be situated over the Capitan Reef limestone, which is a prolific aquifer in the area. Davies (1983) pointed out that the Hill "C" breccia pipe is located at the southern edge of the buried Capitan Reef and since the borehole WIPP-16, drilled to explore this chimney, was drilled only to the level of the McNutt potash zone of the Salado formation, it is not clear whether the Hill "C" breccia chimney roots in the Capitan aquifer.

Besides boreholes WIPP 31 and WIPP 16, which were drilled at Hills A and C, respectively, to investigate the breccia chimneys, three other boreholes were drilled at suspected breccia chimney locations in the basin. Borehole WIPP-32 was drilled in a small topographic high in Nash Draw, which had been described by Vine (1963) as a domal karst feature. These features (domal karst) have been extensively studied by Bachman (1980, 1984). Boreholes WIPP 12 and WIPP 33 were also drilled to explore for possible breccia chimneys. There is a marked electrical resistivity anomaly at WIPP 12 and a prominent topographic depression exists at the location where WIPP-33 was drilled. Collapsed breccia was not found at either of the wells.

Anderson and Kirkland (1980) described the occurrence of collapse breccia in a borehole in Culberson County, Texas, about 55 mi south of the WIPP site. Anderson (in Chaturvedi, 1980) described occurrences of "castiles," which are mounds of brecciated rock that crop out a few miles south of the New Mexico–Texas border, south of the WIPP site. Both occurrences are in the exhumed western part of the Delaware Basin, which has already undergone extensive dissolution.

Snyder and Gard (1982) studied the known occurrences of breccia chimneys in the Delaware Basin. They studied in detail the Hill "C" breccia chimney, which is also encountered at the McNutt potash zone of the Salado Formation in the Mississippi Chemical Company potash mine, 1200 feet (366 m) below the surface. From study of this exposure, the core of WIPP-16 drilled in this chimney and the core of WIPP-31 drilled in the Hill "A" breccia chimney, Snyder and Gard (1982) concluded that the breccia chimneys are formed by collapse of the overlying rocks in solution cavities in the Capitan Reef aquifer. Bachman (1980) hypothesized that the location of all the known breccia pipes in a small area over the reef is due to the presence of an old submarine canyon in the reef in this area. On the basis of the presence of Miocene caliche over the breccia pipes, Bachman (1980) also concluded that the collapse occurred prior to the deposition of this caliche layer, i.e., more than 0.5 Ma.

Davies (1984) also studied chimneys A and C and concluded that they were produced by salt dissolution at the base and within the lowermost portion of the Salado Formation, through incremental subsidence rather than catastrophic collapse of the overlying strata. The EEG concluded (Neill et al., 1983) that the probability of a breccia chimney forming under the WIPP site was fairly remote and that this phenomenon did not appear to pose a threat to the WIPP repository.

Brine reservoirs

Within a few miles of the WIPP site there are at least sixteen reported encounters of pressurized brine in the upper anhydrite layer of the Castile Formation (Fig. 6). Two of these encounters (ERDA 6 and WIPP 12, Fig. 5) were in the WIPP project boreholes and the rest have been reported by oil and gas drilling companies. When borehole WIPP 12, located 1 mi (1.6 km) north of the center of the WIPP site, hit brine at a depth of 3016 ft (919.5 m), brine started flowing out of the well at a rate of 350 gallons per minute (22 liters/sec) and more than 1.14 million gallons (4.3 million liters) of brine flowed out before the well was controlled. Based on an extensive series of flow tests, the brine reservoirs penetrated by the WIPP-12 and ERDA-6 boreholes were estimated to contain 17 million barrels (2.7 billion liters) and 630,000 barrels (100 million liters) of brine, respectively (Popielak et al., 1983). The different pressure potentials and geochemical data from the two encounters suggested a lack of communication between the ERDA-6 and WIPP-12 brine reservoirs. There was no consensus on the origin and the age of the brine reservoirs.

The planned configuration of the WIPP repository and the WIPP experimental areas would have brought the waste within 460 ft (140 m) south of the WIPP-12 borehole. The EEG recommended moving the repository in 1982 and the DOE rotated the repository configuration to relocate the nonwaste experimental area to the north and the repository 1.2 mi (2 km) south of WIPP-12. In 1983, EEG formally proposed geophysical investigations to delineate the extent of pressurized brine in the Castile Formation underlying the WIPP site and particularly under the new location of the repository. The work was performed in 1987, and the results gave a clear indication of the presence of brine under parts of the WIPP repository (Earth Tech. Corp., 1988).

The presence of brine reservoirs in the Castile Formation is a major geological issue affecting the anticipated performance of the repository. Since there are good geophysical indications of the presence of brine in the Castile Formation, 800 ft (244 m) or so below the repository, the inadvertent drilling to a brine reservoir through the repository is a scenario that the WIPP project has to evaluate. Such a drilling sometime during the next 10,000 years would allow pressurized brine to flow into the repository. Several pathways for injection of such contaminated brine into the Rustler Formation or directly to the surface have been postulated.

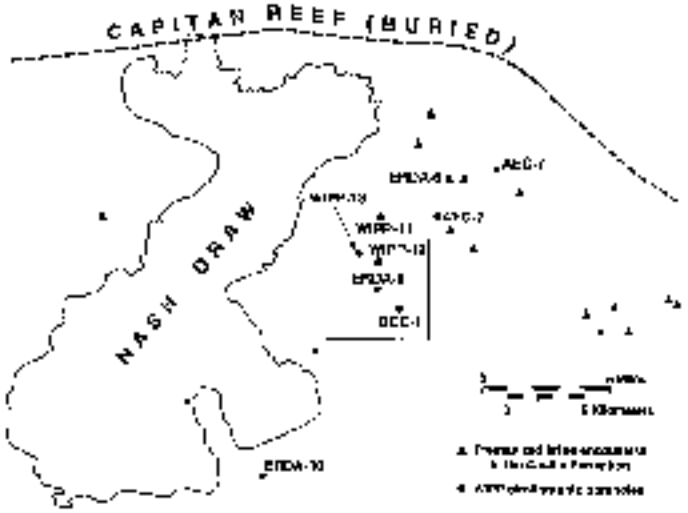

FIGURE 6. Pressurized brine encounters in the Castile Formation in the vicinity of the WIPP site.

Salado brine

A reason for selecting bedded salt deposits for isolating radioactive waste was the assumption that salt would be essentially dry. One of the surprises encountered by in situ underground studies at the WIPP is that the Salado salt yields a fair amount of water. A large percentage of boreholes drilled down from the WIPP excavations fill up with brine and the walls are covered with efflorescences and encrustations resulting from brine inflow from salt into the excavation and drying up by ventilated air. Several boreholes completed in the Salado Formation indicate fluid pressure buildup (Mercer, 1987). In situ Salado salt has low (10^{-21} m^2), but measurable, permeability.

Bredehoeft (1988) proposed that the Salado salt is saturated with brine and exhibits Darcian flow. Nowak et al. (1988) calculated that for salt permeabilities of 10^{-21} to 10^{-19} m^2 (1 to 100 nanodarcies), between 4 m^3 to 44 m^3 of brine would accumulate in a typical WIPP repository room with dimensions of 300 ft × 33 ft × 13 ft (91.5 m × 10 m × 4 m). Since the WIPP CH TRU containers are ordinary 55-gallon mild carbon steel drums that are not expected to last much beyond their 20-year design life, the brine would mix with the TRU waste and may form a slurry. Sandia National Laboratories (1987) calculated that if someone drills into such brine slurry and inadvertently brings a part of it to the surface, EPA Standards may be violated.

Corrosion of the metal containers and metal in the waste would produce hydrogen. Microbiological degradation of the organic material in the waste would produce carbon dioxide and methane. These processes require water to produce gas and the Salado brine inflow will satisfy that need. The rate of brine inflow in the repository is therefore a very important parameter for assessing breach scenarios. DOE has been monitoring and sampling the Salado brine from 13 boreholes in the WIPP underground since 1984 (Deal et al., 1991). After five years of observation, five 50 ft (15 m) deep holes have remained steady producers of brine, one showing increased brine production and five showing decreasing rates. One step in the floor has produced between 0.15 to 0.2 gallons (0.5 to 0.75 liters) of brine per day for five years. Several holes in the roof and in the walls also have been producing brine.

Hydraulic testing of the Salado Formation at the WIPP repository horizon (Beauheim et al., 1993) shows the brine flow in the Salado salt to be Darcian in nature because the Darcy flow models are able to replicate the flow and the pressure behavior observed during the entire testing sequences involving different types of tests. The estimation of brine inflow by Nowak et al. (1988) appears to be on sound theoretical basis. Estimation based on actual inflow observation for a long time, under progress now, would provide confirmatory evidence of this calculation.

Rustler Formation hydrology

The Culebra dolomite member of the Rustler Formation, being the most prolific of the three water-bearing zones overlying the WIPP repository, is the most likely pathway for transport of radionuclides after a breach of the repository. Based on three multiwell flow tests, several single-well flow tests and nonsorbing tracer tests at four hydropads, LaVenue et al. (1990) performed ground water flow modeling of the Culebra at the WIPP site. The flow model suggests that if radionuclides are injected into the Culebra directly above the repository panels near the center of the WIPP site, the fastest flow path out of the WIPP area would be to the south-southeast past the boreholes H-3 and H-11 (Fig. 5).

The calculated travel time for contaminant transport along this pathway, however, is very sensitive to assumptions of fracturing in the Culebra dolomite and distribution of contributing porosity between the rock matrix and the fractures. If double-porosity flow is assumed, with diffusion of contaminants in the rock matrix, the shortest travel time from the center of the WIPP site to the southern boundary is 14,000 years. If, on the other hand, transport is assumed through fractures only (single porosity), then the travel time would be less than 100 years. Additional multiwell flow tests are required to better define the transmissivity field at the WIPP site. Additional tracer tests designed to better define the fracture vs. matrix porosity flow are also needed. The breach scenario calculations have identified radionuclide retardation during contaminant transport through the Culebra as one of the sensitive parameters that control the magnitude and timing of the postulated releases of radioactivity to the environment. Field and laboratory experiments are required to provide reliable and justifiable numbers for physical and chemical retardation. Laboratory experiments are being set up and initial results are expected in 1993 or 1994.

The WIPP site is situated in a gypsum karst area. The subsidence feature called Nash Draw has been formed by the karstic process of solution and fill (Lee, 1925; Bachman, 1980, 1984). The depression in which borehole WIPP-33 (Fig. 5) was drilled is a karst sink. No positively identified karst feature has been encountered east of WIPP-23 in the WIPP area, nor have hydrologic tests in the area detected any channelized flow. Breach scenario calculations have not considered potential releases through channelized flow or through narrow transmissive layers due to vertical heterogeneity. Such conceptual models would result in greater releases, as shown by Chaturvedi and Channell (1985).

Beauheim and Davies (1992) have proposed a sever-well flow and tracer test to be fielded between H-9 and DOE-1. This test is designed to address the questions of vertical heterogeneity and matrix diffusion and would provide data to better characterize the flow mechanism. It is also intended to use the instruments for a field nonsorbing tracer test for providing data on chemical retardation processes and properties within the Culebra. This test is planned to begin in 1993.

Disturbed rock behavior

Before underground excavation at WIPP began in 1982, DOE scientists performed calculations to predict the closure history of the excavations. These calculations used the geomechanical properties of the rock strata at the selected WIPP repository horizon obtained from testing of the rock cores from boreholes. The calculations predicted that a WIPP room would "close slowly in a stable manner as the salt creeps" and "relative closure values of 0.21 m (8.25 in.) in the vertical direction and 0.28 m (11 in.) total in the horizontal direction are seen for the isothermal room after 10 years" (Miller et al., 1982). The WIPP excavations have behaved very differently than predicted. Vertical closure in the WIPP test rooms has varied between 3 in. (75 mm) and 4 in. (100 mm) *per year* and horizontal closure has ranged between 2 in. (50 mm) and 3 in. (75 mm) *per year*. A "disturbed rock zone" consisting of fractured rock surrounds all the excavations. In less than eight years after excavation, the roof of the first of the four test rooms fell in February 1991, due to fractures propagating above the roof and creating an up to 7 ft (2 m) wide unstable trapezoidal beam between the roof and a thin layer of anhydrite above the roof.

The difference between the predicted and measured closure rates has been explained on the basis of use of the wrong geomechanical models and not taking into account the details of the stratigraphy (Munson et al., 1989). While the faster closure rate will help entomb the waste sooner, it creates problems during operations. The WIPP repository rooms should be excavated just before they are needed for waste emplacement and backfilled soon thereafter. It will also create problems in maintaining retrievability of the waste. Due to its interaction with brine inflow and gas pressure from gases produced by the waste, the room closure rate also affects long-term performance of the repository.

Natural resources

The WIPP site is located in a region that contains substantial amounts of potash, natural gas and petroleum resources. Therefore, breach scenarios involving inadvertent drilling by future generations must be considered. The EPA Standards 40 CFR 191 (EPA, 1985, App. B) prescribed a limit of assuming 30 boreholes/km^2/10,000 years, which was based on the drilling frequency in the WIPP site vicinity in 1970s. Judging by the number of producing wells, drilling activity around the WIPP site in 1992 and the number of applications to the U.S. Bureau of Land Management for new drilling permits, the oil and gas resources in the WIPP area are much more prolific than previously considered. This fact must be taken into account in the assessment of the WIPP's compliance with the EPA Standards.

CONCLUSIONS

Since the WIPP repository is designed to rely on geologic isolation for 10,000 years, consideration of the various geologic features and processes are very important to assess the capability of the site to keep the waste isolated from the environment. The impact of the potentially deleterious geologic factors on the repository will be judged on the results of consequence analyses of potential breach scenarios.

ACKNOWLEDGMENTS

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8.6 Letter Reports of EEG Consultants on the K_d Issue

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ENVIRONMENTAL EVALUATION GROUP

August 5, 1997

Dr. Robert H. Neill
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Dear Bob:

Following are some thoughts based on my attendance at the DOE/EEG Meeting on Chemical Retardation in Albuquerque on July 30, 1997, and on related reading. I have ordered the discussion topics as they were set forth by Dr. Lokesh Chaturvedi of EEG in his introductory presentation.

Transferability of Lab K_d Data to Field

Transferability has always been an issue of concern. My understanding is that a consensus now exists that groundwater flow in the Culebra is slow enough to guarantee that important diffusion of the groundwater into rock matrix will occur. If this is the case then the radionuclides in groundwater will have ample opportunity to access mineral surfaces in pores in the dolomite, making laboratory measured batch K_d values applicable to the field.

The Limited K_d Data Base

The limited K_d data base remains a serious problem. We can all agree that K_d values for the important actinides Pu, Am and U, regardless of oxidation state, probably equal or exceed 1 ml/g in Culebra groundwaters, which is necessary for compliance. However, the hydrologic model for the Culebra and associated groundwater flow mechanisms and travel times in the formation have non-zero uncertainties. It is unclear how much these hydrologic uncertainties contribute to the uncertainty of assigning a minimum compliance K_d value of 1 ml/g. Given this additional hydrologic uncertainty, if I were a regulator, I would be much more confident that the site was in compliance if the DOE's recommended K_d's for the important actinides were at least 10 to 100 times greater than 1 ml/g. As discussed below, the approach used by the DOE for estimating unmeasured K_d values involves questionable assumptions.

K_d Estimation Methods used by the DOE

The DOE proposes that K_d values for actinide cations of the same charge should be roughly the same. This approach has been used by many others. (See discussion below). Its weakness lies in the fact that such approximations assume that differences in the speciation behavior of the cations does not affect their adsorption and can be neglected.

The second assumption used by the DOE to estimate K_d values, is that predictable trends exist among the K_d's of actinide cations of different charge. The DOE assumed that such trends

identified by Canepa (1992)[1] in dilute, J-13 groundwaters at Yucca Mountain would apply to WIPP brines. Canepa (1992) proposed that K_d values for actinides in J-13 groundwater should decrease in the same order as their solubilities increased in the same groundwater. The reported solubility data for U(VI), Np(V), Pu(IV)[2] and Am(III) plotted linearly, seeming to support her contention. This led to the proposal that K_d values should decrease in the order Am(III)>Pu(IV)?>Np(V)>U(VI). The DOE has suggested that the same order of K_d values should apply in groundwaters at the WIPP site. However, recent solubility measurements performed at LANL indicate that Np(V) solubility is about 10 times lower than assumed by Canepa (1992). The computed solubility of Np in J-13 groundwater is in fact as low as 10^{-7} mol/L (Langmuir, 1997, p. 534)[3], about 10^{1} less than suggested by Canepa (1992). Similarly, the solubility of U(VI) in J-13 groundwater may also be about 10^{-7} mol/L, 10^{1} to 10^{3} times lower than proposed by Canepa (cf. Langmuir, 1997, p. 533). Assuming as did Canepa (1992), that the actinide solubilities in J-13 groundwater should be inversely proportional to their K_d values, these changes suggest that the order of decreasing K_d's in J-13 and in WIPP groundwaters should be Am(III)>U(VI)>Pu(IV)>Np(V).

In fact, in general K_d values are probably not inversely proportional to the solubilities of the actinides. Thus, in a summary of adsorption trends among the actinides, Langmuir (ibid, p. 536) reports that K_d's decrease in the order Th(IV)>Am(III)>Np(V) for the adsorption of these actinides by Al_2O_3 as evidenced by respective pH values of 2.4, 5.8, 7.3 at 50% of each species adsorbed. Similarly, as pH is increased, goethite has adsorbed 50% of Pu(IV), U(VI) and Np(V) at pH values of 3.2, 4.2 and 7.0, respectively. This is therefore also the order of their decreasing K_d's (Langmuir, ibid, p. 537). Also, based on a literature survey, Silva and Nitsche (1996)[4] propose a general order of decreasing K_d's for the adsorption of actinides (An elements) by the same sorbents, of An(IV)>An(III)>An(VI)>An(V), in general agreement with the abbreviated adsorption series listed previously. Based on the plot of Canepa (1992), the DOE argues in the CCA, that estimated K_d values for Am(III) and Pu(III) should be greater than the measured K_d for Pu(V). Although their conclusion is based on the questionable data and assumptions in Canepa (1992), the same trend of K_d values for these species is fortuitously observed within the adsorption trends for the actinides reported by Langmuir, (1997) and Silva and Nitsche, (1996).

Availability and Reliability of Measured K_d Values

At the July 30, 1997 meeting in Albuquerque, the DOE presented the results of adsorption measurements performed in both column and batch tests. Results of the intact core column tests are probably of questionable value for determining Am(III) and Pu (V) (Pu(IV)?) adsorption K_d's , in that the Am and Pu input concentrations to the cores were high and so close

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[1]Los Alamos National Laboratory

[2]The oxidation state of Pu may have been a mixture of IV, V, and VI.

[3]Aqueous Environmental Geochemistry. Prentice Hall, Upper Saddle River, NJ, 600 pp.

[4]Actinide Environmental Chemistry. Radiochim. Acta, in press.

to saturation with solids, that precipitation rather than adsorption may have occurred. The Th(IV) column adsorption experiments and their results were not discussed at the meeting.

Useful batch adsorption results have been reported for Pu(V), U(VI), Th(IV) and Np(V). Performance assessment indicates that the important actinides at WIPP are Pu and Am, with U of tertiary importance. Based on oxidation state predictions, Pu(III) and Pu(IV) are the dominant Pu oxidation states in WIPP brines. Unfortunately, Am(III) batch adsorption experiments have given inconclusive results, and batch adsorption of Pu(III) and Pu(IV) has not been measured. Thus, the K_d values for the most important actinides in WIPP brines have had to be estimated.

K_d Values Chosen for the CCA

In the CCA, it was conservatively assumed that the lowest K_d values measured in the Culebra Dolomite or deeper Castile or Salado brines would be assumed for performance assessment (PA). Ranges of K_d values for the actinide cations proposed in the CCA are given in Table 1.

Table 1. K_d values used by DOE in the WIPP 1996 Compliance Certification Application (CCA) (assumes uniform distribution). Bold values are based chiefly on batch adsorption measurements discussed by L.H. Brush in his June 10, 1996 memo to M.S. Tierney of Sandia Natl. Laboratories. The probable order of decreasing K_d's in column 7 is based on earlier discussion in the text.

Oxidation State	Am	Pu	U	Th	Np	Probable Order of Decreasing K_d's
III	20-500 (no data)	20-500 (no data)				2
IV		900-20,000 (no data)	900-20,000 (no data)	**900-20,000**	900-20,000 (no data)	1
V		**20-500**			**1-200**	4
VI			**0.03-30**			3

The DOE reported a measured batch K_d of 20-500 ml/g for Pu(V), a species not expected in WIPP brines. Based on adsorption trends, the K_d for Am(III) and Pu(III) should be greater than its value for Pu(V). Given this assumption, the DOE conservatively assumes the K_d for Am(III) and Pu(III) equals the range measured for Pu(V). One could as well argue that the lower measured K_d range of 1-200 ml/g for Np(V) adsorption could instead have been assumed conservatively for Am(III) and Pu(III).

In summary, the most important actinides in WIPP brines are Pu(III), Pu(IV) and Am(III). The DOE has used the Canepa (1992) report and limited batch adsorption data to estimate K_d values for these actinides in WIPP brines. Although the estimated K_d values used in the CCA are probably conservative, it is most unfortunate that Am(III), Pu(III) and Pu(IV) adsorption has not

been measured. I understand that batch adsorption experiments designed to obtain K_d values for these actinides would not be particularly difficult to perform, and might be completed in a few months. It is also possible that accelerated intact column tests could be run in a few months using an ultracentrifuge. Admittedly, resultant K_d's can be predicted to exceed 1-3 ml/g. However, having measured instead of estimated values for the key actinide species would greatly improve confidence that K_d values for the most important actinides are in compliance with regulations.

Solubility Controls on Am, Pu, U and Np Concentrations in WIPP Brines

According to an unpublished July 6, 1996 Sandia report by Stockman and Stockman, titled "Constraints on Actinide Oxidation State in the Culebra: Reaction Path Mixing Calculations", the Culebra Dolomite contains an average of 0.17% FeO. These authors also note that 20 polished sections of the Culebra from 9 WIPP-area boreholes contained pyrite (FeS_2) in every section. The redox state of the rock will ultimately control redox conditions in the WIPP brines. In the absence of a source of free oxygen, reducing conditions are likely to dominate groundwaters away from the waste. Ferric iron staining is common in the Culebra. Eh values in the brines are thus likely to be poised by reactions between either ferroan dolomite and the Fe(III) oxyhydroxides, or pyrite and the Fe(III) oxyhydroxides.

In the vicinity of the waste, iron and nickel metal and organic matter will also tend to deplete any oxygen introduced with the waste. Reduced Fe, S and C in the waste and the rock are likely to cause reduction not only of Pu(V) to Pu(IV) and Pu(III), but may also lead to reduction of U(VI) to U(IV) and Np(V) to Np(IV). If these reductions take place, then maximum concentrations of Pu, U and Np may be limited by the solubilities of their quadrivalent oxides or hydroxides to values of 10^{-8} mol/L or less. If maximum concentrations of Pu and U are so limited, then the adsorption behavior of higher oxidation states may be irrelevant to performance assessment.

In carbonate-rich groundwaters, the concentration of Am(III) is limited by the solubility of Am(III) hydroxy-carbonate to values below 10^{-4} mol/L between about pH 7.5 and 9 (Langmuir, ibid). In WIPP brines at high pH's in the presence of MgO to scavenge the carbonate, $Am(OH)_3$ solubility may limit Am(III) concentrations at similarly low concentrations.

Limited solubility data for these actinides in WIPP brines is available. However, those of Am(IV) species in particular are likely to be well below 10^{-8} mol/L in the presence of MgO and in the absence of carbonate. It would be useful for the DOE to evaluate and report on the available solubility data for these actinides measured in WIPP brines and in similar brines. The brine solubilities of analog rare earth cations and analog actinides such as Th(IV) would also shed light on the probable behavior of Am(III), Pu(III) and Pu(IV) in WIPP brines.

Non-Culebra Dolomite

The Kd's for U(VI) adsorption by Norwegian dolomite are within the range of values for U(VI) adsorption by Culebra Dolomite. This is reasonable. That this pure dolomite adsorbed more U(VI) than some Culebra Dolomites that contain other sorbing minerals, does not strike me as an issue of concern.

Effect of Organic Ligands on Actinide Complexing and Adsorption

It seems probable as argued by Vann Bynum, that organic complexing of actinides does not significantly increase their solubilities or adsorption behavior in the vicinity of the waste. This reflects the competition of more abundant cations such as Ni^{2+}, Ca^{2+} and Mg^{2+} for organic ligands such as EDTA. Also important is the fact that actinides such as Th(IV), Pu(IV) and Np(IV) form strong OH complexes at neutral to alkaline pH's so that their free ion concentrations are many orders of magnitude lower than the free ion concentrations of Ni^{+1}, for example. Van Bynum made his calculations ignoring hydrolysis of the actinide cations, and still found less than 1% of Th(IV) complexed with EDTA, the strongest organic complexer. If he had corrected for Th-OH complexing, orders of magnitude less Th would have been complexed by EDTA.

It would be most convincing if the actinide complexation reaction calculations were rerun, but including OH and other inorganic actinide complexing, and varying (increasing) the amount of EDTA in the waste within possible ranges, to more rigorously disprove the importance of actinide-organic complexing near the WIPP waste.

Kd's Based on the Intact Column Test Results

As noted earlier, the Pu(V) and Am(III) column test results are of dubious value for determining K_d values for these actinides. Because of the high concentrations of Pu(V) and Am(III) in intake solutions, they could have been precipitated as solids rather than been adsorbed in the columns. If so, their concentrations in the rock cannot be used to define K_d values. In order to prove or disprove this concern, if possible, it is recommended that the core materials that have been drilled out be examined to identify whether the Pu and Am are present in adsorbed or 3-D solid phase form. It is also unclear whether the Pu is adsorbed as Pu(V) or as a lower oxidation state such as Pu(IV). The similar K_d values for Pu(V) and Th(IV) found in batch tests with ERDA-6 brines (about 10^5 and $10^{5.4}$ ml/g) suggest that the Pu may be adsorbing as Pu(IV). We were never shown tomographic results of the Th(IV) column tests and resultant K_d values. If these tests were run at Th(IV) concentrations below saturation with Th(IV) solids, the test results could be used to estimate the K_d for Pu(IV) adsorption. Finally, as noted earlier, it is possible that K_d values for the important actinides could be obtained in a few months from accelerated intact core experiments performed in an ultracentrifuge.

I hope my comments and suggestions have been useful to you.

Yours truly,

Don Langmuir

Donald Langmuir, PhD

RMN
8/19

REPORT ON CHEMICAL RETARDATION DATA FOR CULEBRA AQUIFER

To: Environmental Evaluation Group (EEG)
7007 Wyoming Blvd, NE
Albuquerque, NM

From: Mark L. Brussean

Date: 11 August 1997

I have reviewed the documents supplied to me before and during the July 30 meeting, and have considered the presentations and comments provided during the meeting. My comments and recommendations are presented below.

I. Analysis of Original EEG Concerns

1. Use of batch K_d data: EEG originally expressed concern with the use of K_d values determined from batch experiments for the field-scale modeling. The major question was the representativeness of batch K_d values for the field scale. It appears that at least some (the more recent) batch experiments were conducted under well defined and controlled conditions. The results obtained from these experiments may thus provide an accurate data set for evaluating the "sorptivity" of the specific radionuclides used in the experiments.

   However, there remains the basic question of whether or not K_d values obtained under static batch conditions are an accurate measure for dynamic field conditions. I do not believe that this question has been answered for the Culebra system. To help address this issue, I recommend that additional analyses be made of the column experiments (to be discussed in greater detail below).

2. Use of Oxidation State Analogy: EEG expressed concern with the use of the oxidation state analogy for estimating K_d values. This approach appears to have merit in some cases (when it is definitively conservative), but appears to have large uncertainty for other cases. It is not clear why batch experiments were not conducted for the most critical radionuclides. An opinion was expressed by a DOE employee that the K_d values for at least some of the unmeasured radionuclides could be measured relatively easily. I recommend that such experiments be conducted for as many of the critical radionuclides as is feasible.

3. Use of Uniform Distribution: EEG expressed concern with the use of an uniform distribution for representing the K_d data. The reasoning provided by DOE for the use of an uniform distribution appears to be valid. As they noted, the experiments were not designed to provide a statistically representative sample of all possible field conditions. Thus, the uniform distribution should be the one to use. I recommend that this approach be accepted.

4. Organic Ligands and Facilitated Transport: EEG expressed concern regarding the potential of organic ligands to complex the radionuclides and thereby facilitate their transport. There were three subconcerns associated with this topic--

A) There was concern regarding the varied sources of complexation-coefficient data used in the original DOE analyses. The DOE mentioned new data at the meeting that may negate this concern. The DOE now appears to have a consistent set of measured complexation-coefficient data specific to the Culebra/WIPP system.

B) There was concern regarding the amount of EDTA DOE assumed would be present in the waste. I agree that there is great uncertainty in the concentration of EDTA that may be present in the WIPP system, and that the value used by DOE may be too small.

C) There was concern regarding the potential for other organic ligands, which were not included in the DOE analysis, to facilitate the transport of radionuclides. I agree with this concern.

To help resolve both B and C, I recommend that the DOE conduct a formal sensitivity analysis of the potential impact of organic ligands on the aqueous concentrations of the radionuclides. The concentrations of the ligand should be varied by several orders of magnitude, and the full list of ligands provided by EEG should be used. Based on the preliminary analysis presented by DOE personnel at the meeting, it is quite possible that the results from this study will indicate that complexation by the organic ligands may have minimal impact on radionuclide behavior. A formal sensitivity analysis will provide greater confidence in the results.

5. Other Concerns of EEG: EEG expressed concern with the application of the Norwegian dolomite study results to the Culebra system, and with the use of different CO_2 concentrations in the batch experiments. After the meeting, EEG commented that these were of minor concern, and I concur.

II. Additional Concerns

1. Potential Nonlinear Sorption: The data I reviewed indicates that the sorption of many of the radionuclides is most likely nonlinear. This is to be expected given the sorption mechanism stated by DOE (exchange reaction). As is well known, nonlinear sorption can cause retardation to vary as a function of solute concentration. In addition, it is possible that the initial representative retardation factor operative during field-scale transport may not be the same as that calculated using the batch K_d data. Thus, not accounting for nonlinear sorption may under or over predict retardation, depending on the initial solute concentrations used in the analyses. It is not clear if the range of K_d values reported by DOE take into account the concentration dependency of sorption. I recommend that the potential impact of nonlinear sorption be addressed.

2. Use of a K_d Approach versus a more Complex Approach: The transport model used by DOE is based on the simple K_d approach, which is based on linear, instantaneous sorption. It is clear that the fluid-solid interactions influencing radionuclide transport at the WIPP site are more complex, potentially involving inorganic/organic complexation, precipitation/dissolution, competitive sorption, and varying pH and ionic strength effects. The simplicity of the K_d approach makes its use understandable. However, some analysis of the potential impacts of more complex fluid-solid interactions on radionuclide transport would be useful.

3. Spatial Variability of Sorption: The current modelling analysis is based on a homogeneous K_d field. It is highly likely, however, that sorption is spatially variable at the site. The potential impact of spatially variable sorption on radionuclide transport should be evaluated.

III. Conclusions and Recommendations

Several questions and concerns were addressed satisfactorily at the meeting. However, some issues remained unresolved. The majority of these could potentially be resolved with relatively minimal additional effort. Recommendations for additional activities are as follows:

1. It is recommended that additional analyses be made of the column experiments. This includes additional analysis of the completed experiments and additional analysis of the ongoing experiments. The latter should involve an attempt to determine if precipitation is occurring during the column experiments, which appears to be a major uncertainty influencing the applicability of the column results. Would it be possible to sample the column material at the completion of the experiment and analyze for precipitated forms of the radionuclides?

2. I recommend that additional batch experiments be conducted to measured K_d values for the critical radionuclides, at least Pu^{III} and Pu^{IV}.

3. I recommend that a formal sensitivity analysis be conducted to examine the potential impact of organic ligands on the aqueous concentrations of the radionuclides. The concentrations of the ligand should be varied by several orders of magnitude, and the full list of ligands provided by EEG should be used.

4. If the potential impact of nonlinear sorption is not incorporated in the range of K_d values used by DOE, I recommend that the potential impact of nonlinear sorption on radionuclide transport be addressed. This could be accomplished by calculating effective K_d values for pertinent C_0 values, using the nonlinear isotherm data available. These values could then be compared to the existing K_d range.

5. I recommend that the potential impact of spatially variable sorption on radionuclide transport be evaluated. This could be done by conducting a series of model simulations using spatial distributions of K_ds based on the conceptual site models.

Leslie Smith
Hydrogeological Analysis • Groundwater Contamination Studies

August 12, 1997

Dr. Robert Neill
Director
Environmental Evaluation Group
7007 Wyoming Blvd, N.E., Suite F-2
Albuquerque, New Mexico 87109

Dear Bob,

In this letter I provide my viewpoint on chemical retardation in the Culebra dolomite. The opinions expressed reflect my consideration of the reports and correspondence supplied to me prior to the meeting, the material presented by EEG and DOE at our meeting on July 31, and the ensuing discussions that day. I will not comment directly on the issues concerning the amount of EDTA in the waste inventory, the potential for EDTA to facilitate transport of thorium, or the data presented by DOE to justify their application of the oxidation state analogy.

The Probability Distribution for Kd

I accept the DOE position that it is appropriate to adopt a uniform probability distribution to represent the uncertainty in the Kd values for the CCA calculations. The use of a log-uniform distribution, as required of DOE in the EPA verification tests, has the primary benefit of placing considerably more weight on the lower end of the proposed range for Kd. The EPA verification test suggests that the conclusions drawn from the CCA calculations with respect to transport in the Culebra are not sensitive to this marked change in the form of the distribution.

The probability distribution for Kd can be interpreted in terms of the likelihood that a value sampled from the distribution will correspond to an effective Kd value for sorption in the matrix blocks. This value must be applicable for transport times greater than 100 years, and transport distances of approximately 3 km. I see the attempt to quantify this likelihood as an issue related to, but distinct from, the distribution of Kd values obtained in the replicate batch tests. It is not feasible to obtain a set of field data, applicable at the scale of the transport predictions, that would allow one to equate the distribution of measurements with an appropriate sampling distribution in the CCA. One is forced to adopt a more subjective viewpoint in representing the uncertainty in the Kd value, with the consequence that the distribution of the data from the batch tests need not correspond to the distribution describing the likelihood for the effective Kd value. This approach is the most reasonable way to account for the spatial variability in Kd, and the influences of brine type and pH conditions inside a plume migrating through the Culebra.

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The position taken by DOE that the sorption experiments (batch, mechanistic, and column tests) should be used to define a range for the Kd parameters, rather than its distribution in probability space, is reasonable.

I have used decision models that adopt uniform distributions to characterize the uncertainty in the key model parameters (eg. Bugai, Smith, Beckie; Environmental and Engineering Geoscience, 1996). We took this approach because we were faced with a sparse data base, and there were confounding uncertainties in future system behavior. A uniform distribution is appropriate when there is no strong basis for deciding if one value in the range is more likely than any other. It is my opinion that this is the case we face when selecting an effective Kd value for radionuclide transport in the Culebra. This is a slightly different spin on the DOE statement that "the uniform distribution is appropriate when all that is known about a parameter is its range".

In more recent work, I have adopted truncated exponential distributions to represent uncertainty in model parameters (Smith and Gaganis, Environmental and Engineering Geoscience, submitted). This latter model for representing parameter likelihood includes the uniform distribution as a special case, if the prior estimate of the mean is midway between the specified lower and upper bounds of the distribution. There is a sound basis in theory for choosing a truncated exponential distribution to represent parameter uncertainty, when the data base is sparse. Qualitatively, the log-uniform distribution is similar to the truncated exponential distribution, when the estimate of the mean is closer to the lower bound than the upper bound.

The more important issue to debate, in my opinion, is the values that DOE has selected for the lower and upper bounds of the probability distribution, and how these bounds are defined relative to the type of brine used in the batch experiments. I agree with the approach taken by DOE in choosing a range for Kd relative to brine type that will give a conservative estimate of retardation. I was somewhat bothered by DOE's decision to select this range based on the average value of the sample distribution. It is possible to criticize the sampling range for Pu^{V} in this regard (and by their extrapolation, the sampling ranges for Pu^{III} and Am^{III}). The recommended range used in the CCA calculations was 20 - 500 ml/g, which reflects values from the batch tests using deep brines. Batch tests for Pu^{V} with Culebra brines had a higher mean value for Kd, but the lower bound was smaller (9.8 ml/g). Therefore, the sampling distribution in the CCA does not encompass all the measured values from the batch tests for a Culebra brine, at the low end of possible values. A more conservative sampling distribution would have ranged from 10 - 500 ml/g. However, because I would not expect the lowest value from a set of small-scale batch tests to equal the lower bound for a single, effective Kd value along a 3 km flow path, the consequence of their approximation is not likely to have a significant impact on the reliability of the CCA calculations. The analogy here is that the smallest value of hydraulic conductivity measured in a set of slug tests is not a reasonable lower bound on the estimate of a larger-scale effective hydraulic conductivity. A similar approximation did not emerge in selecting the sampling range for Th^{IV} because data are only available for the deep brine.

The DOE data base indicates U^{VI} will be the most mobile radionuclide of concern in the Culebra. The low end of the sampling range for U^{VI} is 0.03 ml/g, if we ignore the negative Kd values. This lower bound is obtained from the observed breakthrough of U^{VI} in the column tests. If we accept the interpretation of Bob Holt that the column test for U^{VI} measures retardation tied to the advective porosity, then this lower bound should be a conservative value for the compliance calculations when matrix diffusion plays a major role in retardation. The value from the column test is lower than any of the values in the batch tests (Tables D-1 through D-4 of the Brush memo, June 10, 1996). This sampling range for U^{VI} introduces the possibility that the EPA standard could be violated in an undetermined number of observations in the CCA calculations, if alternate scenarios were considered for the release of the uranium inventory from a disposal panel (ie. a Kd less than 1 ml/g, using the DOE benchmark for Pu^{III} and Am^{III}). We do not know how robust the CCA calculations are to a violation of the assumptions on the uranium release to the Culebra. Several factors need to be considered. A lower bound for Kd more reflective of matrix sorption than the value obtained in the column tests is not well-defined because of uncertainties in the batch tests (eg. the negative values). The zero values assigned to the negative Kd values for the batch tests with the Culebra brine did not get passed into the CCA calculation because of a lower average value of Kd for the batch tests using deep brines. This issue may be worth pursuing if BEG has concerns about the scenario assumed in characterizing the release of uranium to the Culebra.

An alternate interpretation in adopting the log-uniform distribution is that it de-emphasizes the importance of the Kd value that defines the upper bound of the distribution. Given the results of the EPA verification test, I have concluded that the questions regarding the relevance of the mechanistic Kd tests on pure dolomite from Norway are not a significant issue. These tests only make their way into the final sampling distributions once, in determining the upper bound for U^{VI} at high pH conditions.

The Sparse Kd Data Base

I disagree with the characterization made by M. McFadden in his opening presentation that Kd values used in the CCA are well-founded on experimental data. This simply is not the case, given the lack of experimental data for some radionuclides. The real issue is whether there is an adequate data base, and evidence to support the application of the oxidation state analogy, in assigning conservative bounds for radionuclides where measurement are not available from batch or column experiments. While I found the arguments presented by DOE to be compelling, they are not based on experimental data specific to the Culebra. It is still reasonable to ask if it would be more expedient, in a project of this magnitude and duration, and given the importance to DOE of a public demonstration of their commitment to ensuring the safe disposal of radioactive wastes, to complete a set of batch experiments on Pu^{III}, Am^{III}, and Pu^{IV}. DOE could then avoid the arguments and indirect support that must be linked to the oxidation state analogy. I understand for informal comments made at our meeting that these experiments could be carried out without great technical difficulty. My expectation from all that I have

heard is that these tests would serve to confirm that DOE has used a suitable range of values in the CCA calculations.

Batch Tests

BEG has accepted the viewpoint that the batch tests have relevance in determining Kd values for the CCA calculations. After considering the geologic and hydrologic descriptions in the report by Bob Holt on a conceptual model for multi-rate transport in the Culebra, I am persuaded the batch tests can provide a basis for defining Kd values that characterize matrix sorption. The approach is subject to uncertainty (which should be balanced by conservative approximation), and I would not necessarily expect a one-to-one correspondence between a batch test and a long-term column test in a core from the same sample location (and interpreted with a dual porosity model). However, I am now of the opinion that the batch tests can be used to identify the sampling range in the CCA calculations. This sampling range applies only to the matrix porosity. It is inappropriate to use these batch test values to characterize retardation in the fracture system (advective porosity).

Column Tests

It is my impression that the latest analyses of the column tests do not move us much further along in reducing the uncertainty in the appropriate sampling range of Kd for Pu^{III} and Am^{III}. The attempt was worthwhile, but we now see there are limitations in the experimental design, because of issues tied to solubility. I agree that if it is technically feasible, it would be worthwhile to request that DOE try to determine if a mineral phase is present, that would confirm if the migration distance cannot be interpreted strictly in terms of a Kd estimate. It is not apparent to me what else could be done with the column experiments to gain further insight to the magnitude of Kd for Pu^{III} and Am^{III}.

Tom Clemo has raised the important issue that the only batch test data available for Th^{IV} (and, by DOE extrapolation U^{IV} and Pu^{IV}) are for the ERDA-6 brine. His statistical analysis suggests that the mean Kd's measured in ERDA-6 brine are greater than the values determined using the other 3 brines. It is my understanding that the column tests on the B core were carried out using Culebra brine. The estimated Kd value from tomographic analysis on the B-core is reported to be approximately 400 ml/g. Although this value is lower than the sampling range from batch tests that was used in the CCA calculations (900-20,000 ml/g), the value is sufficiently beyond 1-3 ml/g (the DOE benchmark) to suggest that Th^{IV} will not be of concern. Whether this same conclusion can be drawn for Pu^{IV} and U^{IV} depends upon the acceptability of the oxidation state analogy in setting conservative bounding values for their sampling distributions.

Beyond 10,000 Years

In our discussion after the meeting with DOE, we considered whether the CCA calculations should be extended beyond the mandated 10,000 year time frame. This topic

is akin to an issue of full disclosure. There has been considerable informed debate on the regulatory time frame, and the advantages / limitations of looking beyond 10,000 years. My personal bias, influenced by reviewing projects under Canadian regulations, is to base siting decisions on a 10,000 year time frame, but to examine system behavior from a more qualitative perspective over a longer time horizon. Perhaps there is a role to be played here by EEG, in representing the interests of the State of New Mexico. It could be informative to look at the probability of radionuclide release along the pathway through the Culebra for time frames of 20,000 or 30,000 years, using the sampling distributions adopted by DOE.

Closure

EEG should continue to press DOE to refine and verify their calculations and modeling assumptions used in the CCA. Comments made by Sandia and LANL staff at the meeting suggest that this process is ongoing, if informal. For example, Vann Bynum described his latest calculations on the effects of the amounts of organic ligands on transport, and we heard that measurements of the EDTA β for nickel under WIPP conditions have recently been completed. Efforts to update the performance assessment should continue as time and computational tools become available.

Sincerely,

Leslie Smith

Leslie Smith

8.7 Walter Gerstles' Responses to Anhydrite Fracturing Issues Raised on February 17, 1998

Memo

Feb. 24, 1998

To: Lokesh Chaturvedi
Environmental Evaluation Group
Albuquerque, NM
Fax: (505) 828-1062
Phone: (505) 828-1003

From: Walter Gerstle
Dept. of Civil Engineering
University of New Mexico
Albuquerque, NM 87131

I have had a few days to digest Norm Warpinski's presentation at our meeting last week. I make the following observations.

I. Estimate of Crack Opening Displacements in Bragflo Model.

The Bragflo model "smears" cracks in the anhydrite layers, using the porosity model. Assuming 200,00 m^3 of gas is stored in these cracks, and assuming n layered cracks, with radius R=1000 m, it is possible to calculate the average crack opening displacement, w. Figure 1 shows the situation.

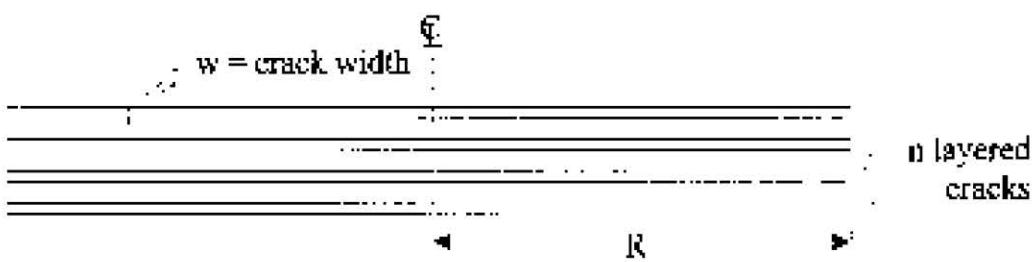

Figure 1. Cross Section Along Crack Diameter

The area, A, of each crack is $A = \pi R^2 = \pi(1000\ m)^2 = 3.14 \times 10^6\ m^2$.

$$olume = V = nwA;\ w = \frac{V}{nA} = \frac{200{,}000m^3}{n(3.14\times10^6 m^2)} = \frac{6.37cm}{n}$$

So the average crack opening displacement is 6.37 cm divided by the number of layered cracks.

The following table shows the average crack width for various numbers of cracks.

n	w, cm.
1	6.37
5	1.27
10	0.64
20	0.32

So the consequence of the Bragflo porosity model is many cracks with wide openings. However, anhydrite is relatively fine grained, and certainly cannot transmit stresses across crack openings of larger than approximately 0.001 cm. Consequently, it is reasonable to assume that all but one of the cracks would close up, but that single crack would extend in radius, as both the Gerstle and Bredehoeft 1997 and the Geertsma and Deklerk 1969 models assume.

II. Geertsma and Deklerk 1969 "Industry" Model

Warpinski made reference to the Geertsma and Deklerk 1969 model as being both an industry standard model and as being more consistent with the Bragflo model than with the LEFM model. In fact, the Geertsma and Deklerk model is an LEFM model, with fracture toughness assumed to be negligible, and it predicts even longer crack radii than the Gerstle and Bredehoeft 1997 model, contrary to Warpinski's assertions. I agree with Warpinski that the Geertsma and Deklerk model is basically reasonable, in that it assumes a single, localized, discrete crack.

A quote from Geertsma and Deklerk 1969 illustrates the fundamental difference between this model and the Bragflo model: "it is found that p_w (pressure at the well bore) decreases with increasing fracture length and approaches S (overburden stress) for large values of L (crack length). Such pressure behavior is in agreement with reported field observations." It is noted that the Gerstle and Bredehoeft 1997 model also demonstrates this pressure behavior, while the Bragflo model demonstrates the opposite pressure - crack length behavior. The decreasing pressure vs increasing crack length behavior also is indicative of a single, localized hydrofracture, which is in contrast with Bragflo's assumption of widely dispersed cracks forming simultaneously in multiple anhydrite layers.

Warpinski in his presentation predicted a crack radius of R = 366 m using Geertsma and Deklerk's formula:

$$R = \frac{1}{\pi}\left[\frac{Q^2 t}{C^2}\right]^{1/4} \qquad (24)$$

Where R = fracture radius
Q = rate of flow into hydrofracture
t = time
C = fracturing fluid coefficient, $C = u\sqrt{\Delta t}$
U = rate of filtration loss per unit of exposed surface of the fracture.

I do not know what numbers Warpinski used, but I used the following numbers and arrived at a much larger predicted radius, R.

$$u = \frac{4499 m^3}{2\pi(750m)^2(1000yrs)} = 1.27\times10^{-6}\ \frac{m^3}{m^2-yr}.$$

$$C = u\sqrt{\Delta t} = 1.26\times10^{-6}\frac{m^3}{m^2-yr} \times \sqrt{1000yr} = 4\times10^{-5}\frac{m^3}{m^2-\sqrt{yr}}$$

$$Q = \frac{200{,}000m^3}{1000yrs} = 200m^3/yr.$$

$$So\quad R = \frac{1}{\pi}\left[\frac{(200m^3/yr)^2(1000yr)}{(4\times10^{-5}\ m^3/m^2-\sqrt{yr})^2}\right]^{1/4} = 4003\ m.$$

Obviously, there is room for debate upon precisely what values of C, Q, and t are reasonable, but Sandia has not performed any calculations using the Geertsma and Deklerk model or any other standard hydrofracture model. This should be done.

III. Warpinski's claim that Gerstle and Bredehoeft model is incorrect.

Warpinski claimed that Gerstle and Bredehoeft's 1997 model is incorrect because it contained no explicit flow equation and no leakoff equation. In fact, calculations in (Gerstle, Mendenhall, and Waweisik 1996) show that leakoff is negligible - and therefore does not need to be explicitly included in the LEFM model. Warpinski also claimed that our model would require flow rates of $Q = 1.85 \times 10^6$ m^3/yr, using the equation

$$Q = \frac{\pi}{6\mu} \frac{w^4 \Delta P}{\ln [R/r]}$$

In fact, use of this equation is inappropriate because we assumed identical pressure ($\Delta P=0$) everywhere within the crack, and thus flow Q would be negligible. Our LEFM model neither assumes nor requires high flow rates.

IV. Conclusions

It is essential for the WIPP facility that a credible gas-driven hydrofracture model be used. I believe that the (Gerstle and Bredehoeft 1997) model is essentially correct despite Warpinski's observations about it. Warpinski's comments appear to be spurious.

I would suggest that Sandia present calculations of hydrofracture extent using Geertsma and Deklerk 1969 model, fully documenting all inputs to the model. I believe they will arrive at conclusions similar to those I have presented.

8.8 Neill to Kruger letter dated 8/11/97 with attachment, "EEG comments on CCA Chapter 5"

ENVIRONMENTAL EVALUATION GROUP

COPY

AN EQUAL OPPORTUNITY / AFFIRMATIVE ACTION EMPLOYER

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August 11, 1997

Mary Kruger
U.S. Environmental Protection Agency
Office of Radiation and Indoor Air
401 M Street SW (6602J)
Washington, DC 20460

Dear Ms. Kruger:

Enclosed please find the *EEG Review of the WIPP/CCA (DOE/CAO-1996-2184), Chapter 5 (Quality Assurance).*

Sincerely,

Robert H. Neill
Director

RHN:js

cc: EPA Docket

EEG REVIEW OF WIPP/CCA (DOE/CAO-1996-2184)
CHAPTER 5 (QUALITY ASSURANCE)

The DOE's Carlsbad Area Office (CAO) has successfully focused on developing a quality assurance (QA) program which implements the Nuclear Quality Assurance (NQA) standards required by 40 CFR 194 over the last few years. Chapter 5, Quality Assurance (QA), in the DOE's Compliance Certification Application (CCA), is, however, of lesser quality than the QA program it attempts to describe. The chapter fails to show compliance with most of the requirements of 40 CFR 194.22, Quality Assurance, and ignores most of the expectations for QA published in EPA 402-R-95-014, Compliance Application Guidance for 40 CFR 194 (the CAG).

In a chapter which should provide specific responses to clearly delineated requirements and expectations Chapter 5 offers a diffuse scattering of relevant information, provides generalized information without examples or details, and references other documents which are no more specific (and were not intended to address the QA requirements for the CCA). The chapter contains what seems to be extraneous information (some of which is found elsewhere in the CCA), glosses over past QA problems rather than explaining how they were resolved, and fails to include information explicitly required by 40 CFR 194.22. In many cases the CAO QA program and process has adequately covered the area, yet the chapter fails to fulfill the responsibility of describing how it was done.

Parts of Chapter 5 are also misleading. For example, "the CAO QAPD" is referenced throughout much of the chapter and is initially identified as appearing in CCA Appendix QAPD. The version in the Appendix QAPD is Revision 1, dated April 22, 1996, though it was not officially transmitted to, or required to be implemented by, subsidiary organizations until after June 13, 1996--when essentially all QA-related activities for the CCA had already been completed. Revision 1 is a substantial rewrite of Revision 0, among other things establishing the CAO QAPD as a requirements document for all CAO subsidiary programs for the first time, and adding elements of NQA standards previously not included. To state that

> The TWBIR was prepared in compliance with the CAO QAPD...

(p. 5-3) implies that the data from the TWBIR used in the CCA (first published in December 1995) was prepared according to the requirements in Revision 1. It wasn't, and the distinction should have been clearly made. Similar statements are found elsewhere Chapter 5:

> The WAC was written and reviewed in compliance with the CAO QAPD [p. 5-3]...The TRU QAPP was written and reviewed in compliance with the CAO QAPD requirements [p. 5-4]...NDA software is controlled in accordance with the requirements of the CAO QAPD [p. 5-9]...

Versions of the WAC and TRU QAPP current at the time the CCA was submitted were written under Revision 0; the NDA (Non-Destructive Assay) software is, of course, currently controlled under Revision 1, but any NDA data used in the CCA would clearly predate the issuance of Revision 1.

The chapter contains an important misinterpretation of the intent of 40 CFR 194.22(a)(2). This paragraph requires the compliance application to demonstrate that a QA program adhering to the 1989 edition of the Nuclear Quality Assurance (NQA) standards has been established and executed for eight specific areas considered by the EPA to be critical to the compliance application. In Chapter 5, this is interpreted (p. 5-3, line 28) as:

> 40 CFR Part 194 stipulates that the DOE apply QA controls to eight areas.

Under this interpretation Chapter 5 fails to clearly demonstrate that the requirements of the NQA standards have been executed for any of the eight areas, though discussions under specific headings for each of the eight areas immediately follows. In some of these discussions virtually no QA information is supplied at all.

The EEG, in a preliminary commentary (Neill-to-Dials letter dated July 22, 1996; see Attachment I) on what now must be considered a draft of the final Chapter 5, pointed out several clearly erroneous statements in the text. Most of these have been removed from this October version, but the chapter still includes a curious concept that since the EPA had reviewed site selection and site characterization QA programs during examination of the 1989 No-Migration Variance Petition (NMVP), the QA for site selection and characterization is considered satisfactory by the DOE (p. 5-8). The EEG's comment pointed out that the argument was untenable, in that (among other reasons) compliance with NQA standards was not a part of the 1989 NMVP. The DOE response (enclosure to undated Dials-to-Neill letter received August 9, 1996; see Attachment II, enclosure p. 4) stated that the DOE agreed with the comment, and "We have updated this portion of Chapter 5". The updating is not apparent--the argument is still the same, and still an obvious error (see line-by-line review of p. 5-6, lines 6-13 for more discussion).

The EEG's July 1996 letter concerning Chapter 5 (see Attachment I) recommended that the DOE rewrite the chapter to meet the published EPA requirements and expectations for QA. The DOE has not substantially rewritten the document (though material was added and removed), and this final CCA Chapter 5 and associated materials arguably fails to demonstrate fulfillment of the requirements in 40 CFR 194.22, Quality Assurance.

The following sections consist of 1) a comparison of Chapter 5 to the CAG expectations; 2) a comparison of Chapter 5 to the requirements for QA in 40 CFR 194.22; and 3) a line-by-line review of the document.

OCTOBER '96 CCA CHAPTER 5 (QA) AND THE CAG

The DOE has previously (see Attachment II, letter p. 2, and enclosure p. 7) informed the EEG that, as a guidance document, the Compliance Application Guidance (CAG) expectations need not necessarily be included in the CCA. However, the CCA begins with the statement that:

> This application has been developed to be fully responsive to the requirements of 40 CFR Part 191, the criteria in 40 CFR Part 194, and the guidance in the *Compliance Application Guidance for 40 CFR Part 194*, EPA 402-R-95-014. [p. EXEC-1;

emphasis in the original]

Chapter 5 is not fully responsive to the CAG expectations. The chapter seems to address the CAG requirements for QA only occasionally, and by accident, rather than design. Below are listed some of the CAG expectations for §194.22, Quality Assurance, and the results of EEG's attempts to find the data in Chapter 5. This is not an exhaustive list, as it is intended only to show that the CAG expectations for QA were not addressed by the DOE.

CAG §194.22(a)(1) Expectations (p. 18 of CAG):

1. *DOE top tier QA documents will be included in the CCA.*

   The DOE included only the CAO QAPD. The TRU Waste Characterization Quality Assurance Program Plan, Revision 0 (QAPP; CAO-94-1010) would also seem to be a DOE top-tier document, and much of it would enhance the DOE's claim to having implemented a QA program in accordance with the NQA statutes. The TRU-Waste Characterization QAPP (Section 1.0, p. 1.1) does contain an important statement that the CAO QAPD Revision 1 lacks:

   > This QAPP addresses all of the basic requirements, and their supplements, of ASME NQA-1.

   Section 1.9.3, Computer Hardware and Software, of the Waste Characterization QAPP also supplies a clear statement requiring the use of the successor document to the 1989 NQA-2 Subpart 2.7, "Quality Assurance Requirements of Computer Software for Nuclear Facility Applications", which would seem to address the specifications for software QA as required by 40 CFR 194.22(a)(1). The CAO QAPD Revision 1 contains no comparable direct statement of compliance with the requirements found in §194.22(a)(1)--that is, adherence to a QA program which implements the requirements of NQA-1, NQA-2 Part 2.7, and NQA-3.

   Nor, in fact, does Chapter 5 contain a direct statement of compliance to the requirements of NQA-1, NQA-2 Part 2.7, or NQA-3.

2. *DOE principal contractor top tier QA documents, and a list of all non-principal contractor or sub-contractor top tier QA documents will be included in the CCA.*

   SNL QA top-tier documents were not included, nor any listing of QA documents for non-principal contractors or subcontractors for WID or SNL.

CAG §194.22(a)(2) expectations are that, for each of 8 defined critical areas, the CCA will (among many other expectations):

1. *Provide a list of quality affecting activities and items important to a demonstration of compliance.*

   Lists seem to be incomplete. For instance, the bulk of field measurements of geological factors

were performed by SNL, yet SNL activities are described as "None" in the section concerning measurement of geological factors (5.1.3; p. 5-6, line 26). Other examples: Section 5.1.1 identifies the WIPP Waste Information System (WWIS; p. 5-4, lines 2-3) and the Performance Demonstration Program PDP (p. 5-4, lines 22-23) as elements of the waste characterization system, but doesn't show them as activity for any of the organizations involved. Section 5.1.2 doesn't include a discussion of QA on the current WID environmental monitoring program; Section 5.1.3 doesn't mention QA of the current WID meteorological monitoring program, or past SNL meteorological programs. These two sections have "environmental monitoring" and "meteorological" in their titles.

2. *Describe the selection of applicable NQA requirements for each of the areas.*

   No descriptions are included.

3. *Provide dates of QA implementation conforming to NQA for each item or activity, and the nature and location of objective evidence which supports this determination.*

   No dates are provided.

CAG §194.22(b) expectation (other expectations were also not met, though some were met in part):

1. *Provide the QED governing documents that include procedures and management plans for independent review, peer review...*

   QED governing documents were not included in the CCA (CAO MP 10.5, SNL QAP 20-3).

OCTOBER '96 CCA CHAPTER 5 (QA) AND §194.22 REQUIREMENTS

§194.22(a)(1) Requirement: *As soon as practicable after April 9, 1996, the DOE will adhere to a program that implements the requirements of the NQA standards.*

The CAO QAPD Revision 1 (in CCA Appendix QAPD) does not require full implementation of NQA standards for all activities, but only for those listed in §194.22(a)(2), other radioactive materials handling, and processes related to transportation containers. This is established in the CAO QAPD in section 1.1.2.3, Applicability of QAPD Requirements, where the difference between general requirements and additional requirements is introduced, and subsections A through J list the areas that fall under the additional requirements. The additional requirements generally seem to be those which are found in the NQA standards, but not in DOE Order 5700.6C, the DOE's internal QA requirements document (which follows 10 CFR 830.120). For compliance with 40 CFR 194.22(a)(1), the NQA standards may need to be the primary criteria.

There is no indication in §194.22(a)(1), or anywhere else in the criteria, that some WIPP activities can be granted a variance from the requirements of the NQA standards.

§194.22(a)(2) Requirement: *The compliance application will demonstrate that the QA program adhering to the NQA standards has been established and executed for the following activities: waste (i) characterization activities and assumptions; (ii) environmental monitoring, monitoring of the disposal system performance, and sampling and analysis activities; (iii) field measurements of geologic factors, ground water, meteorologic, and topographic characteristics; (iv) computations, computer codes, models and methods used to demonstrate compliance; (v) expert elicitation procedures used to support compliance; (vi) design of the disposal system and actions taken to ensure compliance with design specifications; (vii) collection of data used to support the compliance application; (vii) other systems structures, components, and activities important to containment of waste .*

The requirement is misinterpreted in Chapter 5 as "40 CFR 194 stipulates that the DOE apply QA controls to eight areas" (p. 5-3, line 28). The misinterpretation is essentially an echo of page 5-2, lines 6 and 7. This statement is far from presenting evidence that the program has been established and executed. Demonstration of execution would presumably be by citing independent assessments (audits and surveillances) for the different areas.

The chapter does provide separate sections for each of the eight activities, but demonstration of establishment and execution of adherence to the NQA standard requirements is weak or nonexistent in these sections and references from these sections (see line-by-line review below).

§194.22(b) Requirement: *The compliance application shall include information which demonstrates that data collected prior to establishment of adherence to the NQA standards has been qualified by a methodology approved by the EPA.*

Chapter 5 offers no demonstration of EPA approval of any of the methods used. While the EEG understands that the EPA has not provided approval/disapproval to the DOE for the various methods the DOE has utilized, §194.22(b) clearly requires information demonstrating approval to be in the CCA. The CCA should at least contain a statement concerning qualification of the methodology by the EPA.

§194.22(c) Requirement: *The compliance application shall provide, to the extent practicable, information which describes how data in support of the application have been assessed for data quality characteristics, including precision, accuracy, representativeness, completeness, and comparability (PARCC).*

The application provides an argument that it is not practicable to apply the PARCC characteristics to "most scientific investigations used to support performance assessment in which there is uncertainty in conceptual models and the resultant ranges of parameters" (section 5.21.1, lines 40-42). The characteristics are not provided as required. While it may be that evaluation of these characteristics did not take place at the sampling level, some assessment should have been made to establish how much uncertainty in models and parameters would be not only practicable, but necessary. Note also that apparently some of the scientific investigations are not covered by the argument, and information which

describes how PARCC was assessed for these, at least, should have been included. For example, the argument states specifically that the PARCC requirements would apply to waste characterization and environmental monitoring activities, yet provides no information as to how data from these areas were assessed for PARCC.

§194.22(d) Requirement: *The application shall provide information which demonstrates how all data are qualified for use in the demonstration of compliance.*

Section 5.4.2.1 of the CCA does provide a description of the programs for qualifying data.

LINE-BY-LINE REVIEW OF CHAPTER 5

Introductory Material

Page 5-1, Lines 17-18: *...see Table 1-5 in Chapter 1.0 for a list of appendices that provide additional information supporting this chapter...*

Table 1-5 lists only Appendices QAPP and AUD, but other appendices are referenced in Chapter 5 (MON, p. 5-5 line 38; EMP, p. 5-6 line 20); SEAL, p. 5-12 line 24)

These additional appendices should have been included in Table 1-5.

Page 5-1, Lines 29-31: *A comprehensive series of assessments has determined that the DOE, SNL, and WID QA programs are adequate and effectively implemented.*

The overall CAO assessment of SNL QA (May 1996) and WID QA (June 1997) previous to the publishing of the CCA found the SNL program to be marginal both for adequacy and implementation, and the WID program marginally effective (see CCA p. 5-39, lines 6-13 for definitions of these terms.). It is the later resolution of issues raised during the assessment by which the CAO determined SNL and WID QA to be adequate and effectively implemented (see Section 5.4.2, p. 5-45 ff, and section 5.4.3, lines 24-29). The text of this portion of Chapter 5 should reflect that the resolution of concerns raised by the assessments were performed before the SNL and WID QA programs was determined to be adequate and effectively implemented.

5.1. Applicability

Page 5-2, Line 6: *These NQA requirements form the basis of the CAO QAPD.*

Revision 1 of the CAO QAPD may incorporate the requirements in the NQA standards, but they are split between general requirements (for all activities) and additional requirements (applied to activities in which radioactive materials, shipping packages, or the eight compliance activities specified by §194.22(a)(2) are involved). This division indicates that DOE Order 5700.6C is the basis of the CAO QAPD rather than the NQA requirements, as DOE Order 5700.6C is covered by the general requirements, and the additional requirements are those NQA requirements not covered in the DOE Order.

There is no variance granted in §194.22(a)(1) for activities in the QA program, and Chapter 5 presents no evidence of any agreement for such a variance. The intent of the regulation seems to be that the WIPP will adhere to NQA standards for at least all disposal-related activities, and arguably for the entire QA program.

This statement is, however, as close as Chapter 5 gets to a clear statement of compliance with §194.22(a)(1), which requires that the DOE

> ...shall adhere to a quality assurance program that implements the requirements of [the NQA standards].

Page 5-2, Lines 6-7: *Additionally, 40 CFR § 194.22 requires that QA programs be applied to the following eight items or activities:...*

§194.22(a)(2) does not require the application of QA programs to the areas described in its eight subparagraphs. The requirement is for the compliance application: the CCA must demonstrate that the requirements of the NQA standards have been applied for each of the eight subparagraphs. The regulation is:

> Any compliance application shall include information which demonstrates that the quality assurance program required pursuant to paragraph (a)(1) of this section has been established and executed for [the eight activities].

Demonstration of execution of the requirements of the NQA standards would presumably be by describing QA assessments which confirm adherence to the NQA standards for each of the areas.

The difference in approach to the requirement is critical. Chapter 5 describes the general QA program which includes the eight critical area specified by §194.22(a)(2), but is ineffective in demonstrating that the QA program has been established and executed for each of them.

This misinterpretation of the regulatory requirement is repeated on page 5-3, line 28 (see below). The chapter should address the requirements as stated.

Page 5-2, lines 33-39: *The CAO QAPD establishes two primary categories of requirements, identified as general requirements and additional requirements. The sections of the CAO QAPD that do not identify specific applications are general requirements that apply to all items, activities, and processes under the cognizance of the DOE. The requirements of the CAO QAPD sections identified as additional requirements apply to the eight key areas identified above.*

See comment for page 5-2, line 6. These statements imply that the NQA standards in the CAO QAPD Rev. 1 additional requirements are to be applied only to the eight key areas, omitting the radioactive materials handling and NRC packaging included in Revision 1 of the CAO QAPD (sections 1.1.2.3.A and 1.1.2.3.J; pp. 1-10 and 1-11).

Page 5-2, line 41, to page 5-3, line 8: *Additionally, the use of a graded approach supports the proper implementation of QA program requirements...*

The discussion of the graded approach offers no tie of the graded approach to the compliance application requirements. A statement that NQA-1 does allow the graded approach (with reference) would seem appropriate, and perhaps necessary.

40 CFR 194.22(a)(1) specifically excludes those portions of NQA-3 (which addresses QA for site characterization data collection activities), that refer to the graded approach. Having raised the "graded approach" issue, Chapter 5 should provide evidence (even a single statement) that the site characterization data was not collected or processed using a graded approach to QA.

Page 5-3, lines 11-14: *The CAO QAPD requirements are further supported and amplified by the next tier of QA program documents which include the DOE TRU Waste Characterization Quality Assurance Program Plan (TRU QAPP), the SNL Implementing Procedures, and the WID Quality Assurance Program Description.*

The first CAG expectation (p. 18) is that the DOE top tier QA documents be included in the application; the second is that the top tier QA documents of principle contractors also be included in the application. This first mention of these documents should also state where they can be found. CCA Appendix QAPP contains the CAO QAPD Rev. 1 and the WID QAPD Rev. 16, but the TRU QAPP, SNL's procedures, and QAPjPs from the generator sites are not included.

It is important to note that the CAO QAPD Revision 1 became the sole "top tier" DOE QA document after June 13, 1996 (the CAO transmittal letter dated June 13, 1996 requires it to be implemented within 60 days after receipt). There was no requisite condition previously that programs other than the CAO itself adhere to the CAO QAPD. Revision 0 states that the QA programs of WIPP participants are expected to be "guided" by the CAO QAPD only (p. 1-1), and the DOE has informed the EEG that guidance documents need not be followed (Neill-to-Dials letter received August 9, 1996).

Revision 0 also did not place an emphasis on the NQA standards as requirements for WIPP QA programs, instead stating that (p. 1-1):

> WIPP participants develop, implement, maintain, and document their quality assurance programs either in accordance with DOE Order 5700.6C or 10 CFR Part 830.

Page 5-3, line 28: *40 CFR Part 194 stipulates that the DOE apply QA controls to eight areas.*

The requirement (§194.22(a)(2) is that the compliance application demonstrate that a QA program adhering to the NQA standards has been established and executed for the eight areas (see comment for page 5-2, lines 6-7).

Section 5.1.1, Waste Characterization Activities and Assumptions

Page 5-3, lines 34-39: *The Transuranic Waste Baseline Inventory Report (TWBIR) (see Appendix BIR) is the inventory source document that provided the waste data used in the performance assessment and is presented in tabular form in Chapter 4.0...*

Chapter 5 is titled "Quality Assurance", but is noticeably incomplete in discussing QA for the TWBIR.

The TWBIR has been published separately as Revision 0 (June 1994), Revision 1 (February 1995), and Revision 2 (December 1995), and some of the radionuclide data varies widely between the different versions. CCA Appendix BIR data is from Revision 2, with additional material requested by the EPA after Revision 2 was published (included in TWBIR Revision 3, according to the Executive Summary).

None of the data in any of the TWBIR versions seems to have been gathered under the NQA standards as required by §194.22(a)(2)(i). Sources of information included extrapolations from, among other sources, safety documentation and interviews with workers (TWBIR 2 p. 1-21; DOE/CAO-95-1121). EEG-61, Review of the WIPP Draft Application To Show Compliance with EPA Transuranic Waste Disposal Standards (EEG, March, 1996) on page 4-5 quotes a 1995 ORNL report that "TRU waste streams at ORNL are not as yet fully characterized...waste sludge...physical data such as particle size, hardness, viscosity and particle distribution are unknown".

The bulk of the source data may be more reliable, but is based primarily on acceptable knowledge (TWBIR 2, p. 1-20), which is in turn predominantly process knowledge. Use of process knowledge to quantify components in waste, which is how the TWBIR data is used in the CCA, is required by §194.24(c)(3) to conform to the NQA standards, also. There is no evidence in the CCA that any of the process knowledge activities were conducted under the requirements of the NQA standards.

The Waste Characterization Analysis Peer Review Report (p. 4-3) mentions both cost and time restraints as justification for the lack of QA on the TWBIR. The NQA standards contain no variances for cost and time considerations.

Page 5-3, lines 36-38. *The TWBIR was prepared in compliance with the CAO QAPD and this activity was audited by the DOE QA Program on September 5 and 6, 1995.*

Chapter 5 is offering incomplete and misleading data here. Note that the data (taken from Revision 2) used for the CCA was published months after the single assessment (a surveillance by one auditor, not an audit) cited, and QA of the additional data requested by the EPA (in 1996) included in CCA TWBIR was certainly not assessed during the surveillance. The surveillance issued one significant finding, which essentially stated that there was no analysis or data collection plan to assess the TWBIR against, as is required by the NQA standards.

The implication is that the waste characterization data used in the CCA has not undergone sufficient QA assessment. Given that both §194.22(a)(2) and §194.24(c)(3) required a demonstration in the CCA that QA has been performed on the TWBIR data, it would seem that a QA assessment should have been conducted of the TWBIR data used in the CCA.

Page 5-3, lines 38-39: *Quality assurance of the use of these waste data (by SNL) for performance assessment is addressed in Sections 5.1.4 and 5.1.7.*

The referenced sections are brief generalized statements which include no specific discussion of waste characterization data from the TWBIR. The data in section 5.1.4 is, in fact, misleading when applied to TWBIR data--it does contain a brief paragraph on the use of NDA (non-destructive assay) QA, which in part states that:

> NDA software is controlled in accordance with the requirements of the CAO QAPD.

NDA software used to gather data in the TWBIR, Revision 2, was not controlled by the requirements of the CAO QAPD (see earlier discussion).

Page 5-3, line 41 - page 5-4, line 12: *The Waste Acceptance Criteria (WAC) serve as the primary directive for ensuring that only waste that can be transported, handled, and disposed of in the WIPP are shipped and or ensuring that these wastes are certified by the generator and storage sites....The TRU QAPP describes the QA and quality control requirements for characterization....*

The requirement from §194.22(a)(2) is for a demonstration that a QA program in conformance with the NQA standards has not only been established, but also executed for waste characterization activities. Presumably, demonstration of execution would be accomplished by citing QA assessment reports on the generator sites. The EEG is unaware of any demonstration that compliance with the WAC criteria has been officially met for any waste container, so it seems unlikely that the NQA requirements can be said to have been "executed".

It may be argued that establishing the QA of the WAC, the TRU QAPP, and site QAPjPs and procedures as documents shows that the NQA standards have been "executed". One counter to this argument is provided on page 4-9 of EEG-61 (cited above): 58% of a WAC-certified population of 80 drums at INEL were miscertified according to a 1993 DOE report (DOE/WIPP 93-062).

The DOE now has a strict program for certification of generator sites before waste characterization can take place. Information on a demonstration of a full execution of the requirements of the NQA standards at the generator sites, including the certification audits, should have been provided in the CCA.

Page 5-4 line 14-16: *The DOE verifies program implementation at participating sites through audits and assessments to ensure that WIPP waste characterization activities comply with*

applicable QAPjPs and standard operating procedures.

The first three sites to ship waste to WIPP will be INEEL, Rocky Flats, and LANL. The three CAO formal assessments of waste characterization QA at these sites previous to CCA publication found that at INEEL (August 1995; INEL at the time), that ANL-W QA was inadequate; at Rocky Flats (September 1995), that the program was marginal; at LANL (August 1996), that software QA had only just begun. LANL waste characterization has not yet been formally audited by CAO to the NQA standards, though several surveillance-type activities have taken place. None of these would qualify as a demonstration that a QA program adhering to the requirements of the NQA standards had been established and executed for waste characterization activities and assumptions.

Page 5-4 Lines 25-42: *The following identifies the applicable quality-affecting activities, QA documents, and examples of subcontractors for the principal participants. DOE Activities: ...DOE QA Documents: ...*

The list of documents does not include some that would seem to be applicable. For instance, documentation used in design of the TWBIR (which should have addressed QA), the TRU Waste Characterization QAPP, the WWIS Software Quality Assurance Plan, and Performance Demonstration Program documentation should be listed, as these activities are all mentioned in the preceding text.

The "examples of subcontractors for the principal participants" does not include the subcontractor that assembled the TWBIR, which is the principal waste characterization activity that had taken place at the time the CCA was published.

Page 5-5 Lines 3-25: *Generator Site Activities: 1. Characterize TRU waste. Generator Site QA Documents: The following sites have Generator Site QAPjPs that have been approved by the DOE...*

The DOE should show that the QAPjPs were in force for the collection of data for the TWBIR. It is likely that the approval of at least some of the QAPjPs by CAO post-dates the accumulation of the TWBIR data.

The CAG (Compliance Application Guidance for 40 CFR Part 194; EPA 402-R-95-014) states (p. 18-19) that the EPA expects much more information on waste characterization activities and assumptions than is included in this section. Among these expectations are several that relate to objective evidence for various QA activities; a listing of dates when conformation to the NQA standards for each activity became effective; a description of not only DOE but principal contractor QA assessment activities; and the schedules for these activities. None of these are supplied in the CCA, though Appendix AUD lists by title (which is not a description) and date a general list of assessments that includes CAO's waste characterization assessments. The list does not however, show assessments by "principal contractors", which for waste characterization would be the generator site QA programs.

Section 5.1.2 Environmental Monitoring, Monitoring of the Performance of the Disposal System, and Sampling and Analysis Activities.

Page 5-5, Lines 30-38: *The monitoring plans required by 40 CFR § 194.42 detail the disposal system monitoring program that will be implemented during pre-and postclosure of the WIPP. This program will be implemented by the WID under the QA program described in this chapter. SNL Activities: None. WID Activities: Conduct performance monitoring. WID Documents: Reference Appendices MON and EMP.*

Lines 30-38 are the complete section. The section offers no demonstration that the "monitoring plans" have been established in accordance with the NQA standards; the "monitoring plans" are not even identified, though one can infer that the appendices may contain them. The section itself offers no demonstration that a QA program adhering to the requirements of the NQA standards has been established and executed for the titular areas--no QA documents specific to the activities are listed, no procedures that would demonstrate QA requirements at the working level.

Environmental monitoring activities, and associated sampling and analyses activities, have been conducted for years by the WID but no mention is made of QA for this effort.

The referenced appendices do not contain information which demonstrates execution of the NQA standards, even for the pre-closure activities that have been in operation for years. The QA section in CCA Appendix MON simply states (p. MON-62) that future work will be controlled by the CAO QAPD Rev. 1, and that the DOE has "agreed to adopt QA and quality control guidance" from the NQA standards (the DOE opinion is that guidance for QA is not a requirement, and therefore need not be addressed). CCA Appendix EMP describes in general terms the QA program for environmental monitoring but does not demonstrate that it has been executed. The description is in terms of 10 CFR 830.120 (from which DOE Order 5700.6C was derived), not the NQA standards, though a table (Table 8-1 on p. 8-2) attempts a cross-reference to NQA-1 requirements.

The mapping of 10 CFR 830.120 or DOE Order 5700.6C requirements to the NQA standards is not a satisfactory process--nor a quality one. NQA-1 alone contains about 30 pages of basic and supplemental requirements (not counting definitions or suggested practices); the §830.120 requirements cover about 2 pages. To find 30 pages of requirements in 2 pages of information would seem to require an exceedingly imaginative approach.

It appears that 40 CFR 194.22(a)(2)(ii) requirement for demonstration in the CCA that a quality assurance program in conformance with the NQA standards has been established and executed for monitoring has at best only been partially met.

The CAG expectations seem to have been ignored completely, unless "conduct performance monitoring" can be considered a "list" of quality affecting activities.

Section 5.1.3 Field Measurements of Geological Factors, Groundwater, Meteorologic, and

Topographic Characteristics

Page 5-5, Lines 43 to page 5-6, line 4: *The current WIPP activities related to field measurements are conducted by the WID and include several areas. Measurements of geologic factors include...*

> No statements related to QA are attached to the description of measurement of geological factors.

Page 5-6, lines 6-13: *In 1989, the EPA reviewed and commented on much of the data collected by the DOE during the site selection and site characterization program. After this review by EPA geologists, hydrologists, and other scientists, the EPA reached conclusions regarding the adequacy of the DOE's site characterization program and the reasonableness of the site characterization activities. The EPA's independent reviews and conclusions regarding the adequacy of the data were supplemented by the independent reviews conducted by the National Academy of Sciences. Therefore, the DOE considers the adequacy of the QA program and the data collected during site selection and characterization to be satisfactory.*

> Substantially the same argument was included in the earlier version of Chapter 5 that EEG commented on (Neill to Dials letter dated July 13, 1996). The EEG comment (p. 3 of the enclosure) noted that:
>
> > This is untenable on several grounds, not the least of which is that the NMVP is for compliance with 40 CFR 268.6, which has no requirement that QA programs must comply with the 1989 versions of NQA-1, NQA-2 Part 2.7, and NQA-3, as is found in 40 CFR 194.
>
> The DOE's response (p. 4 of the enclosure to Dials-to-Neill letter received August 9, 1996) was as follows:
>
> > We agree with the comment on the No Migration Variance Petition (NMVP) and had already noted this. We have updated this portion of Chapter 5.
>
> The only substantive differences between the two presentations of the argument is that 1) in the most recent version, a statement that the EEG also conducted an independent review and was in agreement with the EPA and NAS conclusions has been dropped; and 2) references to the source document were dropped.
>
> The argument is ludicrous in a document written to show compliance with 40 CFR 194. A large part of site characterization data included in the CCA has been performed since 1989; the NMVP is concerned with disposal of chemical wastes, not the radiological component that is the §194 concern, and the major concern at WIPP (plutonium is not on the list of 40 CFR 268 hazardous components); QA approaches and philosophies have changed in the intervening years; the regulation to be complied with is different for the CCA (40 CFR 191 and 194) than it was for the NMVP (40 CFR 268); and a demonstration of establishment

and execution of a QA program that adheres to the NQA standards was not a requirement for the 1989 NMVP.

Neither the "References" nor the "Bibliography" at the end of Chapter 5 contain an entry for either an EPA document, or an NAS document, concerning the 1989 NMVP. The accuracy of the DOE interpretation cannot be verified without proper referencing of the source documents.

The May 31, 1996 draft of Chapter 5 (p. 5-6) included the statement that:

> These conclusions were issued in a document titled Background Document for the U.S. Environmental Protection Agency's Proposed Decision on the No-Migration Variance for the U.S. Department of Energy's Waste Isolation Pilot Plant.

No further information on this document was provided in the bibliography of the May 31, 1996 draft Chapter 5. One of the EEG's comments on this draft was that documents were not referenced in a manner which allowed traceability.

Page 5-6, lines 15 and 17: *Topographic characteristics were characterized early in the site characterization phase of the WIPP project, and the QA of data from that period is addressed in detail in Section 5.4.2.2.*

Section 5.4.2.2 discusses in very generalized terms the Qualification of Existing Data (QED) process (for data that was not collected under an NQA program) and includes no commentary specific to measurements of topographic characteristics. Reference to this section implies that a demonstration of adherence to NQA standards for topographic characteristics as required by §194.22(a)(2) cannot be performed.

Page 5-6, lines 20-21: *See Appendix EMP for QA controls applied to monitoring activities of groundwater well levels.*

The section of Appendix EMP concerning groundwater (Section 5.4.3, p. 5-12) does not include any QA information; the QA section of Appendix EMP does not discuss establishment and execution of NQA requirements (see comments to p. 5-5, lines 30-38 above for additional data on the QA section of Appendix EMP).

Page 5-6, lines 23-35: *The following identifies the applicable quality-affecting activities, QA documents, and examples of subcontractors for the principal participants. SNL Activities: None.*

SNL was responsible for most of the measurements of geologic factors, including the "site selection and characterization program" mentioned in this section. To state that there were no SNL activities, QA documents, or subcontractors is ludicrous.

WID Activities:

No mention is made of the WID meteorological measurements or associated QA efforts.

The WID has measured meteorologic characteristics at the WIPP for many years; Section 2.5.2 (p. 2-178 ff) of the CCA indicates that data was used in the CCA from WID environmental monitoring reports from 1991-1995. This section of Chapter 5 should demonstrate that a QA program adhering to the requirements of the NQA standards was established and executed for these data and reports.

Appendix EMP also contains a section on meteorological monitoring (section 5.4.1, p. 5-11) which states that:

> A Quality Assurance Project Plan (QAPjP) is being developed for the collection of meteorological data use [sic] for regulatory purposes.

This QAPjP may be necessary before demonstration of establishment and execution of a quality assurance program that adheres to the NQA requirements can be made.

Appendix EMP section 5.4.1 lists the requirements documents for the QAPjP. Those listed do not include 40 CFR 194, the NQA standards, or the CAO QAPD Revision 1.

Page 5-6, lines 36-39: *WID QA Documents...WP 02-1 WIPP Groundwater Monitoring Quality Assurance Plan*

The title of this document since March 3, 1996 (eight months before the CCA was published) has been "Groundwater Surveillance Program Plan, Revision 3"; it is not a "Quality Assurance Plan", but five of the 25 pages (pp. 5-9) have brief sections addressing each of the 18 NQA-1 Basic Requirements.

The QAPjP for collecting meteorological data described in Appendix EMP is not listed among the WID QA documents.

5.14 Computations, Computer Codes, Models, and Methods to Demonstrate Compliance

Page 5-7, lines 9-10: *Computations and computer codes used to demonstrate compliance with 40 CFR Parts 191 and 194 are controlled as described in Section 5.3.20.*

Section 5.3.20 is a general description of computer software QA for the WIPP. It does not address computations (which are not always performed on a computer) and does not demonstrate the establishment and execution of a QA program which adheres to the requirements of the NQA standards for computer codes. It also does not describe the process for controlling the most important of computer codes for the CCA, those related to performance assessment (PA).

None of these PA codes were properly qualified (as prescribed by NQA-2 Part 2.7) for use at the time the PA calculations used in the CCA were performed (see p. 1 in Attachment 1 of the EEG July 11, 1996 Walker-to-Neill memorandum, "CAO Audit of SNL PA June 17-

21, 1996", included here as Attachment III, for a more complete discussion). Some of the important documentation for perhaps the most important computer code, BRAGFLO, had still not been completed in December, 1996—two months after the CCA was submitted, and several more months after the PA for the CCA was ran.

Page 5-7, lines 11-16: *Software supporting compliance fall into one of three categories...Table 5-1 lists the compliance software according to category.*

It is unclear why the three categories are described, as no information on the differences in QA among the various categories is supplied. Were these three categories graded differently for QA purposes?

The statement implies that all software supporting compliance is to be found in Table 5-1 (which lists only SNL's PA-related software). Other software (data acquisition, WWIS, facility design, NDA) are discussed later in this section (p. 5-9, lines 14-30), but these are not identified in Table 5-1, which is titled "Computer Software and Codes".

Page 5-7, lines 19-37: *SNL QAP 9-2, Quality Assurance Requirements for the Selection and Documentation of Parameter Values Used in WIPP Performance Assessment...The four parameter categories that are used in current compliance calculations are...1. parameters derived from experimental data...2. parameters representing inventory of the waste...3. parameters representing physical constants...4. parameters that are model configuration parameters or that are assigned based on assumed correlation of properties between similar materials.*

It is unclear why the description of the four categories of parameters is included in a section that should be discussing QA for computations, computer codes, models, and methods. Discussion of parameter categories are not a part of the requirements of either 40 CFR 191, §194, the CAG, or the NQA standards. The categories are more properly described in Appendix PAR (p. PAR.1).

Since SNL's QAP 9-2 and parameter categorization is mentioned, however, it should be pointed out that parameters of the 4th type are divided into type 4a and 4b in the version of QAP 9-2 current at the time of publication of the CCA (Revision 2, effective 09-12-96; see p. 3).

It should also be pointed that various groups of parameters are not required to comply with the complete QAP 9-2. None of the parameters entered into the PA database before 11-28-95 are required to comply with the quality-affecting portions of 9-2 according to Revision 2 (see p. 3), which was current when the CCA was published. Revision 1 did not require any of the type 4 parameters to comply with QAP 9-2, though 9-2 could be used at the discretion of the Parameters Task Leader (Rev 1, p. 3). Type 4b in the current Revision 2 are the "model configuration parameters", and are excluded from the requirements of QAP 9-2 (p. 3 of Revision 2).

> ...as they are not used in current compliance calculations and therefore are not

subject to this procedure.

QAP 9-2 requires, among other things, that the need and intended use of a parameter be documented; that the rationale for the parameter choice (the value range) be documented; and that documentation of the parameter development be referenced or attached to the Form 464 (which is a form essential to tracing of parameters). These requirements are unique to QAP 9-2, and should be required of all parameters used. Assuming that the PA is considered a scientific investigation, the CAO QAPD Rev. 1 would seem to require use of QAP 9-2 for all but the excluded type 4b parameters under the dictates of Section 5.1.B, 5.1.C, 5.1.D, 5.1.E, and 5.1.H (other sections may also apply).

Finally, it seems useful to note that parameter data in the CCA (in Appendix PAR) is not necessarily the same values as was used in the running of the PA codes for the CCA. For example, Parameter # 3148, a concrete compressibility parameter, is listed in Appendix PAR as having a value of 1.2e-9/Pa, but is shown in the code listings for the CCA (not in the CCA; at SNL) as 2.64e-9/Pa. This difference is apparently due to Appendix PAR being taken from a later database than the one used by the PA codes for the CCA. The information and data in the CCA should be the same data that was used to demonstrate compliance.

Page 5-7, line 39, to page 5-9, line 2: *A set of screening efforts, comprised of calculations and reasoned arguments, has been identified to help define and build confidence in assumptions, data sets, and conceptual and numerical models on which the performance assessment in this application is based. Assessing the effects of features, events, and processes (FEPs) on system performance is a primary component in conceptual model development...*

No explanation as to the definition or purpose of "screening efforts" is supplied, and the terminology is rather obscure. The calculations and reasoned arguments are used to determine whether or not to include consideration of a FEP in a model, but this is not explained in the text.

The connection between screening efforts and the requirements of 40 CFR 194.22 or the NQA standards is not made clear in this section. As with the parameter categorizations, this is not a QA description but a description of an operational process.

No screening efforts other than those for FEPs are identified.

Page 5-9, lines 4-10: *FEP screening is phased. Phase I FEPs are those that could potentially affect conceptual and/or numerical models. Phase II FEPs are those that could impact parameter input to the numerical models. FEP screening analysis plans for Phase I and Phase II FEPs were developed and controlled in accordance with SNL QAP 9-1...*

Phase I and II screening were only performed separately so that SNL could meet deadlines, and under SNL QAP 9-1 could have easily been written as a single analysis plan. The necessity for describing them in the CCA chapter on QA is not apparent.

FEPs screening is an area of controversy all its own, as 40 CFR 194.32(e) requires that the CCA include documentation of the reason for excluding any identified processes or events that may affect the disposal system during the regulatory time frame. The DOE originally developed a list of nearly 1200 FEPs; the draft CCA (DOE/WIPP/CAO-2056, March 31, 1995) considered about 900 FEPs; of the 900, about 30% were addressed by Phase I and II screening plans for the CCA, and 89 of these were "screened in" to the CCA. No documentation, or screening analysis plans, were developed for the reduction of the vast majority of the nearly 1200 FEPs to the approximately 240 included in the CCA.

The FEPs which were to be addressed by Phase I and II analysis plans were not all adequately documented. The EEG asked for information on 31 of these FEPs (Neill-to-Dials letter dated July 11, 1996) and the response (McFadden-to-Dials letter dated August 2, 1996) was that screening information would be supplied only in the CCA--though the analysis plans indicate screening decision packages were to be kept for each FEP. All FEP screening decisions should have been performed according to a reviewed plan, and be adequately documented. §194.32(e) requires the CCA to include documentation of why those screened out were not included in the PA results. This was not done.

Page 5-9, lines 10-11: *Additionally the DOE and SNL have provided oversight of the FEPs screening process in the form of detailed audits and surveillances.*

Failure of the DOE and SNL detailed audits and surveillances to discover and require resolution to the FEP screening problems described above does not establish confidence in the application of the quality assurance process to FEPs.

Page 5-10, lines 20-23: *WID Documents...WP 16-117 WIPP Computer Software Quality Assurance*

This document was replaced by WP16-IT3117, Revision 0, which has the same title, on 9/26/96 (a month before publication of the CCA).

5.1.5 Expert Judgment Elicitation

This section simply states "No expert judgment activities have been identified" (p. 5-10, line 31). There have been many expert judgment activities; the question is whether or not any of these should have been performed under the formal elicitation process regulated by 40 CFR §194.26.

Some examples of expert judgment activities used in the CCA follow. Expert judgment is a part of the passive institutional control development process according to the WIPP Passive Institutional Control Peer Review Report (p. 4-3 and 4-4). Numerous parameters used in the performance assessment are justified by "investigator judgment" or "professional judgment". A November 14, 1995 RE/SPEC Inc. memorandum (RE/SPEC's Pfeifle to SNL's Diane Hurtado) outlines as part of a task plan "solicitation of expert opinion" for establishing seals parameter values, and execution of this task plan would seem to fall directly under the §194.26, Expert Judgment requirements.

5.1.6 Design of Disposal System and Actions Taken to Ensure Compliance with Design Specifications

5.1.6.1 WIPP Facility

Page 5-11, lines 6-11: *Disposal system items and processes were designed using sound engineering practices, scientific principles, and applicable industry and government standards. System design descriptions, conceptual design reports, performance requirements, and regulatory requirements are included in new designs. Designs are initiated using a classification system that ensures that the proper level of design and QA requirements is employed to meet design and testing requirements.*

The EEG and the EPA have both commented that many assertive statements in previous drafts of Chapter 5 were not substantiated. These are examples of such statements. The requirement is that the application should demonstrate that the design was established and executed under a QA program that adhered to the requirements of the NQA standards, not to merely restate those requirements. Chapter 5 contains many other such unsubstantiated statements (see, for example, most of section 3.1), so many that the EEG will desist from pointing them out--but the practice adds no substantive value to the application.

Note that the initial sentence alone covers past development of designs. NQA-1 Basic Requirement 3, Design Control, begins:

> The design shall be defined, controlled, and verified. Applicable design inputs shall be appropriately specified on a timely basis and correctly translated into design documents. Design interfaces shall be identified and controlled. Design adequacy shall be verified by persons other than those who designed the item.

The final sentences of the Chapter 5 statement is in the present tense. What QA documents show that the WIPP facility was initially designed according to the NQA standards? The documents should be properly referenced.

Page 5-11, lines 13-22: *NQA-1 Supplement 3S-1 requires that design verification be performed...Design verification was accomplished by a combination of Supplement 3S-1 methods.*

Again, this is an assertive statement which is unsupported by evidence. A reference to the document which shows that Supplement 3S-1 methods were used to verify the WIPP facility design should be referenced.

5.1.6.2 Original Repository Design

Page 5-11, lines 26-31: *After Bechtel turned systems over to the DOE, an extensive and comprehensive program of start-up testing was initiated by the DOE. The program tested systems and components against the requirements specified in design documents. This testing*

meets the requirements of Supplement 35-1 for design verification.

The design documents and start-up testing documents should be referenced. The §194 requirement is to demonstrate that the activities described in these statements were performed, not to describe them.

Page 5-11, lines 33-38: *Brookhaven National Laboratory performed independent calculations of important design parameters...This task was documented in a report commissioned by the Office of Environmental Safety and Health (EH-30) titled, "Waste Isolation Pilot Plant Safety Evaluation Report" dated August 1989, including two subsequent addenda, the last of which closed all action items, concluding the Brookhaven effort.*

The report (referred to hereafter as the 1989 SER) is not listed in either the "References" or "Bibliography" sections at the end of the chapter, though a memorandum which apparently describes the report is. The document is dated July 27, 1989, not August. The document and addenda (Supplements) should have been properly referenced in the bibliography.

The purpose of the report was to independently document the completeness and adequacy of the Final Safety Analysis Report (FSAR) on WIPP that was current at that time (December 1988 version). The 1989 SER was only for the now-discarded "test phase" which had a 5-year lifespan rather than the 10,000 year requirements in §194, and notes that the 1989 FSAR did not include remote-handled waste (RH-TRU) in its considerations. The 1989 SER does, however, state that the review addresses the adequacy of design for the lifetime of ground structures and site characterization.

The 1989 SER also contains the following statement (p. 11-3 and 11-4):

> A Quality Assurance issue...was the failure to adequately transfer knowledge of facility design bases (Ref 13) to either DOE or the operating contractor. DOE and operating contractor staff engineer(s) were not fully knowledgeable of the details of the WIPP designs, the design calculations, specifications and drawings (as-built, ship, etc.). It is therefore unlikely that issues pertaining to the design bases, design calculations, structures, etc., and related quality control can be adequately addressed.

This is related to a concern expressed in an EH-30 Request for Additional Information, which stated that

> The FSAR states that construction management documents...are available at the WIPP Facility. Based on our efforts to collect information from the site, this is a gross misstatement of the facts. Documents are not generally available nor are they organized in any fashion which lends itself to review and/or audit...Any attempt to assess as-built conditions are clearly frustrated by such a situation. [SER Appendix B, Response to DOE/EH Request for Additional Information: Chapter 3, May 3, 1989, p. 22; the DOE's response was to simply note

that these were program management documents, not construction records]

Supplement 1 to the 1989 SER ("Supplement 1 to Safety Evaluation Report for Waste Isolation Plant" dated 01/16/90, p. II-3) notes that the WIPP committed to completing the "as-built" drawings for critical systems in the facility on a schedule provided. A memorandum from M. R. Brown, Manager of Westinghouse Engineering & Repository Technology Support, to Richard J. Figlik, WIPP Project Office, dated May 5, 1989 (see Attachment IV), illustrates the extent of the process necessary for developing the "as-built" drawings: Attachment 1 to the memorandum is a list of prioritized "as-builts" to be reconstituted, which, among other items, includes the electrical system for both the surface and underground, the environmental monitoring system, the radiation monitoring system, the underground ventilation system, the confinement facilities, the shaft hoist systems, communication systems, fire protection systems, waste handling equipment, the central monitoring system, security systems, water systems, underground testing and testing equipment, and "General Civil and Standard Systems" (which would seem to be the non-specialized items such as the site support buildings).

In short, the original QA records for design were not collected, stored, or maintained as required by NQA-1 Supplement 3S-1.7, and had to be redone. Chapter 5 should reflect the true history of QA for the facility design.

Page 5-12, line 4: *See Section 5.3.1.8 for the location of applicable QA records [for WID design].*

Section 5.3.18 (p. 5-37) contains QA records location information (there is no section 5.3.1.8).

Page 5-12, lines 24-34: *The repository sealing system design....report [Appendix Seal] was extensively reviewed...audits and surveillances were performed on each of the primary contractors...The DOE performed oversight activities...of the SNL QA program as it relates to the SNL Sealing Systems Program...*

References to the specific audits and surveillances should have been included.

5.1.7 Collection of Data and Information to Support Compliance Application(s)

Page 5-14, line 17: *WID Activities: None.*

Data and information collected by WID is used throughout the CCA. Several chapters in the CCA reference the Site Environmental Reports for 1990 and 1992-1995, for example. Many of the appendices to the CCA are totally based on WID or WID subcontractor data. These include the Annual Site Environmental Report (Appendix SER); Appendix RPB, Statistical Summary of the Radiological Baseline Program for the WIPP, March, 1992; the Engineered Alternatives Cost/Benefit Study (Appendix EBS); Appendix EMP, the Environmental Monitoring Program (which wasn't mentioned as part of Environmental

Monitoring, section 5.1.2); Appendix GTMP, the geotechnical surveillance program; and Appendix GWMP, the groundwater monitoring program.

Organizations other than the DOE, SNL and WID are referenced in the CCA; for instance, Appendix HYDRO is written from US Geological Survey reports. The introduction to the Appendices (in the computerized version of the CCA) states that:

> Significant portions of the hydrological data in Chapter 2.0 are derived from this report.

Chapter 2 is Site Characterization, a major component of the CCA; and hydrological considerations are of major importance to compliance. This, too, is data and information used to support compliance, and demonstration of establishment and execution of a QA program that adheres to the NQA standards for the USGS data would seem to be a requirement of §194.22(a)(2)(vii)--though processing through the QED process allowed by §194.22(b) would seem to be a viable alternative.

5.1.8 Other Systems, Structures, Components, and Activities to the Containment of Waste in the Disposal System

Page 5-14, Lines 24-26: *At this time, the DOE has not identified any other systems, structures, components, or activities important to the waste isolation in the disposal system that require controls to be applied as described in the CAO QAPD.*

The process utilized for controlling drilling activities in the WIPP vicinity is an important activity for containment of waste with which the DOE has had problems in the past (see the "Passive Institutional Controls" section of EEG's March 14, 1997 letter to the EPA, in the WIPP docket for a pertinent example). QA oversight of this process could enhance the WIPP disposal system.

5.2 Program History

Page 5-15, Lines 1-19: *A QA program was established in late 1977 that was based on 10 CFR Part 50, Appendix B...By late 1978, DOE policy refinements had expanded the QA program to incorporate the requirements of...(ANSI)/ASME N45.2, and had extended the applicability...to all earth science activities furnishing information on the possibility of radionuclide release into the biosphere...in late 1979...The WIPP QA program was revised to meet the DOE/Albuquerque Operations Manual (Chapter WIPP), which was equivalent to the requirements of ANSI/ASME NQA-1-1979...Over the next 12 years, the WIPP QA program was revised to reflect the ...changes in upper tier QA program documents NQA-1-1979 to NQA-1-1989...*

The principle documents for the QA program(s) described, and the documents showing the changes, should be referenced. The DOE/AL Operations Manual should be included in the References/Bibliography at the end of the chapter.

The 1989 SER (FSAR review by DOE Headquarters EH-30; referenced above in comments

on p. 5-11, lines 33-38) found in late 1988 (p. II-2):

> (1) A lack of sufficient independence for the QA organization, (2) a lack of adherence to the intent of the ANSI/ASME NQA-1 Supplements, (3) a lack of an adequate design control program, (4) an inconsistent approach for the evaluation of "Important to Safety" items and services, (5) a lack of training, qualification and certification of audit, inspection, and test personnel and (6) no training and indoctrination programs.

The first attempts to address these were also woefully inadequate, indicating that basic knowledge of NQA-1 was not highly developed. The 1989 SER comments on WIPP's first response (from the 1989 SER, p. II-3):

> The requirements of ANSI/ASME NQA-1 were quoted but no description of how they would be implemented was provided. Although there was improvement in most areas, the Quality Assurance Program still lacked: (1) identification of the responsible Quality Assurance authority and its place in the WIPP Organization Structure, (2) interface requirement between the three major participants [DOE, SNL, WID], (3) responsible authority and commitment for a Training and Indoctrination Program, (4) specific commitments for review and approval of procurement documents, (5) a requirement for receipt inspection and the option of using source inspection to accept procured items or services, (6) the specifics for waste material receipt inspection at the site, (7) responsibilities for the processing and storage of radioactive materials, (8) test procedure requirements, (9) handling and storage requirements for radioactive waste materials, (10) responsibilities for nonconformance control, and (11) qualification and certification of audit personnel.

Given that these items reflect language from many NQA-1 requirements it seems likely that the application of NQA-1 was not a significant part of the WIPP QA program before the EH-30 evaluation took place. 10 CFR 50 Appendix B, cited as the basis for the 1977 origin of WIPP QA, contains similar requirements.

A June 1, 1989 memorandum from James P. Knight, Director of the DOE's Office of Safety Appraisals, to Richard W. Starostecki, on the subject "EH Oversight of the Waste Isolation Pilot Plant Project (WIPP)" (see App. V), adds other failures in the WIPP QA program to address NQA requirements (p.2):

> A fundamental management issue also remains at this time; the adequacy of the DOE Quality Assurance (QA) program for the WIPP project. As presently structured, neither the dedicated QA staff, one person designated as the QA Manager, nor the low reporting level of the QA program meet the ANSI/ASME, NQA requirements espoused by DOE orders.

The "one person designated as the QA Manager" was the entire WIPP Project Office QA staff at the time (Westinghouse apparently had the "dedicated QA staff" mentioned). Indirect evidence also points to a lack of QA during the period up to 1989. The "as-built" design problems addressed above (see comment to page 5-11, line 33-38) were apparently never addressed by the WIPP QA organizations. Jack B. Tillman, DOE's WIPP Project Manager in 1989, testified during the June 12, 1989 hearings of the U.S. House of Representatives Environment, Energy, and Natural Resources Subcommittee of the Committee on Government Operations that:

> The as-builts have been known as a deficiency since the Corps of Engineers left the site...

(Page 171 of the printed hearings; U.S. Government Printing Office, 1990.) However, there is no evidence that responsible QA organizations pursued remediation of that deficiency in the years after the Corps of Engineers left. Any auditing activity seeking objective evidence that NQA-1 Basic Requirement 3 had been met, in virtually any area at WIPP site during this time, would have rediscovered the deficiency. Chairman Synar of the subcommittee later indicated his view of the QA program (p. 333 of the printed hearings):

> ...without an adequate quality assurance program, Mr. Tillman, I think it is very unlikely that you are going to be able to ensure that the experiments are going to be run properly, that the appropriate data is collected, and that it is applied properly.

In 1989, it appears that reviewers did not find a WIPP QA program which met the requirements of the NQA standards. Chapter 5 should reflect a more accurate history of WIPP QA.

5.3. Adequacy

"Adequacy" is later defined (p. 5-39) as the flowdown of requirements contained in upper-tier documents into implementing procedures. The subsections under this heading seem to be arranged in accordance with the Basic Requirements of NQA-1, with NQA-2 Part 2.7 and those portions of NQA-3 not already covered added at the end. This format and intent should have been made explicit in the text.

Though arranged according to the NQA standards, the subsections do not describe how all of the requirements described in the Basic Requirements and Supplements are met. The matrices mentioned on page 5-1, which link NQA requirements to the principal QA documents for the major WIPP organizations, would seem to have been more effective (and concise) in demonstrating that the WIPP QA program documents contain the requirements of the NQA standards.

In several subsections implementing documents for SNL are described as "None", even though these are requirements of the NQA standards which are applicable to SNL operations. These

appear to reflect a lack of research in writing Chapter 5, rather than an absence of adequacy in the SNL QA program.

Page 5-16, lines 12-18: *From May 1993 to March 1994, DOE Headquarters...(EM-342) assessed the quality of the WIPP data acquisition process for performance assessment...The team concluded that the DOE needed to reevaluate all experimental program data used to support performance assessment.*

The EM-342 documents describing the assessment and its conclusions should be referenced.

Page 5-16, lines 20-42: *The adequacy of the current DOE QA program is ensured by passing down requirements...with the directive that applicable requirements then be passed down to lower tier organizations...Adequacy of QA program requirements are initially verified by the DOE through the review of lower-tier QA program documents prior to their implementation...Formal document review forms are used...*

QA documents that demonstrate this is being done should be referenced (the CAO QAPD in Appendix QAPD, Section 1.1.2.1 covers the majority of these requirements).

Page 5-21, Lines 1-8: *The DOE has also prepared matrices tracing the applicable NQA requirements referenced in Section 5.1 to the CAO QAPD. WID and SNL likewise are required to prepare and maintain matrices...the matrices are designated [sic] to demonstrate that the DOE, SNL, and WID QA programs are adequate and address all applicable requirements.*

Including the matrices could have been a major step in demonstrating adherence to a QA program that implements the requirements of the NQA standards, as required by 40 CFR 194.22(a)(1). These matrices would also provide substantiation for many of the assertive statements that currently lack substantiation (see comment addressing page 5-11, lines 6-11).

Page 5-21, lines 10-11: *The DOE, SNL, and WID perform assessments that include the review of implementing documents for adequacy.*

The source document(s) for this requirement should be properly referenced.

5.3.3.1 Grading

Page 5-25, line 19-21: *WID Implementing Document: WP13-QA3501 Graded Approach*

The EEG controlled copy of the WID QA procedures shows that this document was removed from the WID Quality Assurance Manual on September 27, 1996, a month before the CCA was issued. The controlled copy change notice does not indicate any replacement document. At the EPA audit of WID in February, 1997, WP13.03 Revision 0, Quality and Regulatory Assurance Department Assessment Program, effective August 26, 1996, was identified as the current implementation of the WID grading process (Section 7.3.1,

"Activity Grading Process").

5.3.3.2 QA Program Documents (p. 5-25)

This section does not include SNL QA program documents. The CAG expectation (p. 18) is that DOE principle contractor top tier QA documents would be included in the CCA, not merely listed.

5.3.3.3 Qualification and Training

Page 5-26, line 2: *Personnel performing work are qualified and capable of performing their assigned tasks.*

Personnel are required to be qualified and capable—that does not mean personnel will always be so. It hasn't been in the past. for example, an SNL surveillance in November, 1995 discovered that only 2 of 30 personnel in the FEPs program had fulfilled the training requirements.

Similar overstatements, wherein a QA program requirement is described as if absolute compliance with the requirement is a certainty, are made throughout Section 5.3 subsections. These are logical fallacies for which countering examples can nearly always be found (see comment to the following section, 5.3.3.4, for another example). Such statements are usually so self-evidently overdone that most are only a minor distraction, and will not be individually pointed out.

Many of these statements also should provide a specific reference to the section(s) of WIPP QA document(s) that establishes the requirement. These will also not be individually pointed out--but assertions should always be backed by objective evidence or a path to the objective evidence.

5.3.3.4 Management Assessments

Page 5-26, lines 28-30: *Management personnel...perform assessments of the portions of the program for which they are responsible to assist in ensuring effective implementation of QA requirements.*

The CAO Manager had yet to perform an assessment of CAO at the time the CCA was published (one is scheduled for February 24-28, 1997). The NQA-1 requirement (Basic Requirement 2, last paragraph) is that management "...shall regularly assess the adequacy of the program for which they are responsible...". SNL's last WIPP Project Management Assessment (previous to the October 1996 publication of the CCA) was June 12, 1995. Corrective Action Reports on management assessments have been initiated at both CAO and SNL.

Pages 5-17 to 5-32, Sections 5.3.4 Design Control...5.3.5 Procurement Document Control...5.3.6 Instructions, Procedures and Drawings...5.3.7 Document Control...5.3.8

control of Purchased Items and Services...5.3.9 Identification and Control of Items...5.3.10 Control of Processes... No significant additional comments, though these sections do not necessarily address all the NQA-1 requirements for the area specified. For instance, section 5.3.4, Design Control, does not show how design inputs are identified, documented, reviewed, and approved, as required by NQA-1 Supplement 3S-1.2. Editorial note: page 5-30, line 31, "WP 13-QA10003" should be "WP 13-QA 1003".

5.3.11 Inspection

Page 5-32, lines 6-22: *Inspections determine acceptance or rejection of a process, product, or service. Inspection documentation for DOE participants includes the following: approved implementing procedures...DOE Implementing Documents: None SNL Implementing Documents: None*

> The CAO QAPD, Rev. 1 requires that inspections be performed in accordance with approved implementing procedures (Section 2.4.1). This section implies that SNL does not have the procedure required by the CAO QAPD for conducting inspections. It further implies that there are no documents controlling SNL's inspection activities at all.

5.3.12 Test Control

Page 5-32 line 32 to Page 5-33 line 16: *...Test included as part of scientific investigations are conducted in accordance with the QA methods described in Section 5.3.21...SNL Implementing Documents: None*

> Apparently all SNL tests are considered to be scientific investigations, covered by the procedures listed in Section 5.3.21. This should have been made explicit in the text, as the sense of the text in this section is that SNL has no implementing documents for control of testing.

Page 5-33 line 20: *WID Implementing Documents: WP 03-001 Preparation, Release, and Cancellation of Start-up Test Procedures*

> While this is not particularly a CCA concern, the document has not been changed since August 21, 1992, and the last periodic review noted in EEG's controlled copy was August 12, 1993. Page 4-5 of the document requires control and startup QA records to be processed in accordance with WP 13-6, a procedure removed from service before September 27, 1996.

5.3.14 Handling, Storage, and Shipping

Page 5-34, lines 21-37: *Items...are handled, stored, and shipped using approved and documented methods...SNL Implementing Documents: None*

> NQA-1 Supplement 13S-1.2 requires that these processes are to be "...conducted in accordance with established work and inspection instructions...or other pertinent documents

or procedures specified for use in conducting the activity." This section implies that SNL has no such documents or procedures.

5.3.15 Inspection, Test, and Operating Status

Page 5-35, lines 5-7: *The specific status indicators, their use, and the authority to apply or remove them are delineated in applicable QA plans or implementing procedures...SNL Implementing Documents: None*

The implication is that SNL has no internal documents requiring compliance with NQA-1 Basic Requirement 14, Inspection, Test, and Operating Status.

5.3.16 Control of Nonconforming Items

Page 5-35, line 30 to page 36, line 13: *...When appropriate, further work on the item is halted by senior management until the appropriate actions have been taken and verified. The nonconformance control process is documented in applicable QA plans or implementing procedures...WID Implementing Document: WP13-007, Hold Tag Issuance*

In this section, neither SNL or DOE implementing documents are specified. SNL does have at least one procedure that would seem to apply to the discussion in this section (QAP 2-5, "Issuing and Lifting Stop Work Orders"); WID, too, has a "Stop Work" procedure that would also seem to apply (WP13-008).

The CAO QAPD, Rev. 1, Section 1.3.2.3.D. requires that disposition of nonconforming items, and the responsibility and authority for evaluation and disposition, be defined in QA documents (plans or procedures). The NQA-1 requirement (Supplement 15-S1.4.1) is:

> Nonconforming characteristics shall be reviewed and recommended dispositions of nonconforming items shall be proposed and approved in accordance with documented procedures.

Procedures covering the discussion of nonconforming items should have been listed.

5.3.17 Corrective Actions

Page 5-36, lines 21-23: *A significant condition adverse to quality is defined as a condition that, if not corrected, could have a serious effect on compliance with 40 CFR Parts 191 and 194.*

A statement that compliance with the EPA disposal regulations is the only defining factor for a significant condition adverse to quality is exceptionally disconcerting. This definition is simply unacceptable--A WIPP QA program utilizing such a definition would likely be unacceptable. Fortunately, the CAO QAPD, Rev 1, offers an infinitely better definition which is in use by WIPP QA (Section 1.3.2.1, p. 1-16):

> Significant conditions adverse to quality are conditions that if not corrected,

could have a serious effect on safety, operability, waste isolation, compliance, or the reliability of the QA program.

The difference between chapter 5 and the QAPD definitions of what constitutes a significant condition adverse to quality is evidence both of poor writing and inadequate review of chapter 5.

Page 5-37, lines 8-9: *Minor software problems are documented by software problem reports or other resolution mechanisms as discussed in Section 5.3.20.*

No specific mention is made of software problem reports or other resolution mechanisms in Section 5.3.20; the closest statement is (p. 5-41, lines 25-26):

> For released versions, software problems are documented, evaluated, and, if appropriate, corrected.

This seems far short of the "discussion" indicated.

Page 5-37, lines 9-10: *If a software problem is determined to be a condition adverse to quality, it is documented and resolved as described in this section.*

The difference between a minor software problem, which may or may not be corrected, and a condition adverse to quality in software, for which the corrective action process must be followed, is not explained. The term "condition adverse to quality" is not defined, though "significant conditions adverse to quality" is.

5.3.18 QA Records

Page 5-37, line 36, to Page 5-38, line 6: *The records management process includes provisions for...classifying QA records as either lifetime, nonpermanent, or postclosure...*

Classification of the many unique records generated by the WIPP has yet to be accomplished, as the DOE must submit suggestions to NARA (National Archives and Records Administration) on classification of WIPP records and await NARA's guidance. The NARA positions could take some years to obtain. The provisions are in place, but many of the QA records have not been classified yet. This should have been explained in the CCA.

Page 5-38, lines 17-22: *These [QA] records are maintained by the proper organization for approved disposition. DOE QA records are retained in the document services storage facility in Carlsbad, New Mexico. SNL QA records are retained in the SNL WIPP Central Files located in Albuquerque, New Mexico, and Carlsbad. WID QA records are retained in the WID WIPP Files located in Carlsbad. Generator site QA records are retained in NQA-1 storage facilities at each site.*

Essential records are still at several subcontractor sites other than those mentioned. For

instance, records related to microbial degradation of the waste were at Brookhaven National Laboratories in early February, 1997, four months after the CCA was published.

5.3.19 Audits and Surveillances

Page 5-39, lines 15-16: *The management and control of audits and surveillances are documented in QA plans or implementing procedures.*

The "implementing documents" sections for this section list procedures, but no QA plans are cited.

5.3.20 Computer Software QA

Page 5-40, lines 10-12: *Plans are prepared at the start of the software life cycle to document the software basis and objectives of the software to meet its intended use.*

This description (however it may be interpreted) falls short of describing the necessary "requirements phase" documentation specified by NQA-2 Part 2.7 sections 3.1 and 6.2. These sections require that in the requirements phase that software functionality, performance, design constraints, attributes, and external interfaces shall be specified documented, and reviewed, that the software response to anticipated classes of input data shall be defined. Section 3.1 also requires that verification and validation plans are to be written. The CAO QAPD Revision 1 (in Appendix QAPD) does contain what seems to be an adequate description of the process, and could have easily been referenced.

Page 5-40, lines 15-17: *Any software errors and failures are reported to the sponsoring organization for analysis and then forwarded to the supplier, if applicable.*

NQA-2 Part 2.7 Section 10.1 states that not only will the supplier report software errors or failures to the purchaser, but "...the purchaser shall report software errors to the supplier." No mention of determination of applicability by the purchaser is to be found in NQA-2 Part 2.7--the reporting of software errors and failures to the supplier must always be performed.

Page 5-41, lines 25-26: *For released versions, software problems are documented, evaluated, and, if appropriate, corrected.*

When would correction of software problems not be appropriate? NQA-2 Part 2.7 Section 8 does, however, have similar language:

> Corrective action by the responsible organization shall assure that: (a) problems are identified, evaluated, documented, and, if required, corrected...

Software problems that do not require correction should not be considered problems.

Page 5-41, lines 39-42: *WID Implementing Documents... WP 16-117, WIPP Computer Software*

The comment to Page 5-10, lines 20-23 was that this document was replaced by WP16-IT3117, Revision 0, same title, on 9/26/96, a month before publication of the CCA.

5.3.21 Scientific Investigations

Page 5-42 line 4-6: *Process variables affecting scientific investigations are measured and controlled as described in Section 5.3.13.*

The section referenced is "Control of Measuring and Test Equipment". Process variables other than equipment can affect scientific investigations.

Page 5-42, lines 31-32: *Scientific investigations are performed according to requirements documented in scientific notebooks or technical implementation documents or both.*

The statement reverses the order found in Section 5.2.A of the CAO QAPD Rev 1 (p. 5-2):

> Scientific investigations shall be performed in accordance with requirements documented in test plans, procedures, and scientific notebooks.

Test plans and procedures go through a series of required reviews, a comment resolution process, and approvals before promulgation; it is hard to imagine that requirements listed in scientific notebooks would undergo anywhere near the same scrutiny.

The problem of using scientific notebooks as a requirements document has cropped up at SNL in the past, when scientific investigations were in process (sometimes completed) before test plans or procedures governing the operation had finished the review and comment process. When QA assessments uncovered the deficiency the response has been that daily communications documented by entries in scientific notebooks were thought to be sufficient. If comments have yet to be resolved and approvals haven't been granted, how can the daily communications recorded in the notebooks reflect the yet-to-be-determined requirements?

If the result of the CAO QAPD statement quoted above is to allow scientific notebooks to be used as described at SNL, the CAO QAPD may have failed to fulfill Basic Requirement 2 of NQA-1. This requirement states in part that the documented quality assurance program

> ...shall provide for the planning and accomplishment of activities affecting quality under suitably controlled conditions. Controlled conditions include the use of appropriate equipment, suitable environmental conditions for accomplishing the activity, and assurance that prerequisites for the given activity have been satisfied. [emphasis added]

Scientific notebooks are a record of thoughts, processes, data, and results from within a scientific investigation. Planning documents establishing requirements for the investigation should be completed before the work begins. Use of scientific notebooks should not be a circumvention of the responsibility to plan, review, and authorize requirement documents for scientific investigations.

Since SNL is responsible for the bulk of scientific investigations for WIPP matters, it is worth noting that SNL QA Procedure (QAP) 20-2, Preparing, Reviewing, and Approving Scientific Notebooks, requires as the first step in the process (Section 4.1, Step 1, p. 5) that the principal investigator

> Ensure that planning is documented in an approved Test Plan according to QAP 20-1 or an approved TOP [Technical Operating Procedure]...

QAP 20-1, Preparing Reviewing, and Approving Test Plans, dictates that requirements are to be addressed in test plans (Appendix A, p. 11).

Page 5-43, lines 1-2: *Uncertainty limits are assigned to the data prior to their use.*

Uncertainty limits should be derived from statistical interpretation of the data, rather than assigned (this may be simply poor word choice).

Page 5-43, line 34: *WID Implementing Documents: None*

WID performs scientific investigations (under any rational definition of the term WID's environmental monitoring program qualifies), and undoubtedly has implementing documents in the form of plans and procedures which should have been listed here.

<u>5.3.21.1 Data Quality Characteristics</u>

Page 5-43, line 38-40: *40 CFR § 194.22(c) states that to the extent practicable, data used to support compliance will be assessed according to their accuracy, precision, representativeness, completeness, and comparability.*

This is a misinterpretation of 40 CFR 194.22(c)]. The requirement is as follows:

> Any compliance application shall provide, to the extent practicable, information which describes how all data used to support the compliance application have been assessed for their quality characteristics, including...[the PARCC characteristics (precision, accuracy, representativeness, completeness, and comparability)]

The requirement does not state that the data must be assessed the PARCC characteristics, only that the CCA include a description of how the assessment was performed. It is also important to note that the requirement does not limit the DOE to only considering the PARCC characteristics--the DOE could also take the opportunity to describe how other

quality characteristics of the data were assessed.

Page 5-43, line 39 to page 5-44, line 2: *The DOE believes that these data quality characteristics are applicable to tasks involving the quantification through sampling and analysis of specific constituents of an environmental medium. The DOE also believes that these requirements are intended to address activities such as the determination of the presence or absence of pollutants in waste streams. Waste characterization and environmental monitoring are examples of the types of activities at the WIPP in which data quality characteristics apply. In these cases the performance measurement is the concentration of the constituent of interest.*

The DOE agrees that waste characterization and environmental monitoring activities could be assessed using the PARCC characteristics, but no description of how data from these areas were assessed is included in this section, chapter 5, or elsewhere in the CCA.

Page 5-44, lines 4-12: *In performance assessments...the performance measure is cumulative release of radionuclides to the accessible environment over the next 10,000 years. This measure is estimated using mathematical models rather than being determined by direct measurement. The performance assessment process requires the use of mathematical models for the repository, which, in general, require that numbers (here called parameters) be assigned to geologic formation and waste properties. Since many of these parameters are not amenable to direct measurement, they must be treated as uncertain variables, rather than precisely determined quantities, and characterized by probability distributions.*

There seems to be a logical jump at the beginning of this paragraph that is not warranted. The ultimate performance measurement for PA is compared with an interim performance measurement for environmental monitoring. The ultimate performance measure for environmental monitoring is determination that radionuclides have, or have not, been released, just as it is for PA; concentration values are an interim step to that measurement, just as many parameter values are for PA (the difference is, of course, that environmental monitoring results are real, while PA is a projection). Other parameter values, those "not amenable to direct measurement", should be based on data measurements to which PARCC characteristics could be applied. Finally, the PARCC characteristics do not need to be applied only to "precisely determined quantities"; for example, the completeness figure for a difficult process could be 10%, and the accuracy set to 300%. The requirement is to show how the values were assessed, not to require that narrow limits be put on the measurements.

The PARCC characteristics are a method for establishing the validity of the measurement—but that is a scientific usage, not a QA function. The §194.22(c) QA requirement is that the CCA should contain information which describes how the PARCC characteristics were assessed.

Page 5-44, lines 14-21: *Data are used to develop conceptual models for disposal system performance that are implemented as computational models in the performance assessment. Data are also used to support distributions for parameter values used in computational models. Between the point of data collection and the final computational model, uncertainty is introduced*

(for example, experimental design, extrapolation of the experimental results to spatial or temporal scales, etc.). These parameter distributions may span several orders of magnitude, and many parameters derived from data measurements need be known only within orders of magnitude of their true value. Efforts to reduce the range do not necessarily improve the model accuracy.

The requirement is for the data, not for the computational modeling use of it. If the low-level data, based on measurements, have not been assessed for their quality, how much assurance can there be that the parameter distributions based on it are a measure of reality? An original measurement that represents a sample three orders of magnitude from the mean of the population is not much improved by establishing a three orders of magnitude range. The last sentence implies again that the PARCC characteristics are a requirement to reduce the range; they aren't. The PARCC characteristics help establish what sort of range should be used. This relates to the confidence which can be placed on the model accuracy, not the accuracy itself.

Page 5-44, lines 31-26: *Uncertainty and sensitivity analyses respectively assess the uncertainty in system performance measures and identify modeling areas and parameters in which reductions in uncertainty can increase confidence. If the uncertainty of a parameter is of significant importance to the performance of the WIPP, more data could possibly be collected to reduce uncertainty.*

This paragraph doesn't address the requirement at all. PARCC characteristics are not intended to reduce uncertainty, but to establish the quality of whatever uncertainties are used. The requirement is to ensure that an attempt has been made to address the uncertainty at the experimental data level. Uncertainty and sensitivity analyses at SNL determine the most important parameters, but it is the level of confidence in the underlying data for parameters that the application of quality characteristics is meant to establish.

Page 5-44, lines 33-38: *Instead of the above quality characteristics, other steps ensure that data are of adequate quality. Upper-tier quality requirements documents specifically define QA requirements for the collection of scientific and technical information. Section 5 of the CAO QAPD, Scientific Investigation Requirements, identifies the current requirements for data collection. For inclusion in compliance calculations, the data must be collected under an approved QA plan or otherwise be qualified.*

§194.22(a) covers the requirement for the QA program described; §194.22(c) seems clearly to be a requirement independent, and additional, to that established for the overall QA program.

Page 5-44, lines 40-43: *In summary, it is not practicable to apply data quality characteristics to most scientific investigations used to support a performance assessment in which there is uncertainty in the conceptual models and the resultant ranges of parameters. Instead, controls established by the QA program provide the necessary quality.*

The section fails to supply the required PARCC information for those scientific

investigations which this summary admits are not covered by the arguments.

It is likely that some, if not most, of the underlying scientific investigations used in PA had some sort of evaluation related to quality characteristics applied to it. The PARCC characteristics in particular have been established scientific quality attributes for many years. Some of evaluations may have even been clearly prescribed and documented. Retrieval of this data would be an enormous task, and even when retrieved would not be likely to show a consistent method of application. It may be that it is not practicable to supply information in the CCA as to how the PARCC characteristics were applied to all the data used in the CCA--but the arguments used in this section of Chapter 5 are not persuasive.

The arguments presented in this section are concerned solely with the PARCC characteristics. The DOE has provided no information as to how any quality characteristics were assessed for data, at any level. It may not be practicable to always assess the PARCC characteristics, but different quality characteristics for data used in the CCA could have been defined and assessed, and information concerning these assessments could have been included in the CCA.

5.4 Implementation

This section is for the most part a well-written and accurate description of the proactive and effective WIPP QA program the EEG has observed in recent years. Many of the comments that follow are editorial in nature--but there are still significant deviations from easily discoverable facts.

5.4.1 DOE QA Program Implementation

Page 5-45, lines 26-31: *The most recent audit of DOE/CAO...concluded that the DOE/CAO QA Program was adequate and effective, but not completely implemented. They cited nonimplementation of two DOE procedures...These procedures are now fully implemented and the overall DOE QA Program is effectively implemented.*

Reference to the documentation of the acceptance by the auditors that the program is now considered to be effectively implemented should be included.

5.4.2 SNL QA Program Implementation

5.4.2.1 Data Qualification

Page 5-48 line 41 to page 5-49 line 6: *An SNL audit Internal Audit [IA] 95-03...was conducted in August 1995 to verify the adequacy and effective implementation of QA requirements...All the resulting corrective actions have been completed and verified...The audit concluded that...SNL QA controls were in place and that they were adequate and effectively implemented.*

This paragraph begins the section on data qualification, and appears as a *non sequitur* in

that it doesn't seem to relate to the title. It is not until the succeeding paragraphs define what "data qualification" is that a possible clue to the applicability of the paragraph may be deduced: this audit may have established the time after which SNL's data can be said to have been developed under the NQA standards. This interpretation can only be tentatively made. The reason for including the paragraph should have been made explicit.

Page 5-49, lines 8-16: *Data can be qualified for use by one of five methods...(2) existing data collected before the implementation of a qualified QA program are qualified by showing that the data were obtained under a QA program that is equivalent to one satisfying the NQA requirements referenced in Section 5.1...*

In the Independent Review Team (IRT) process, the entire QA program did not need to be equivalent to one which satisfied the NQA requirements. Only those portions applicable to the data being qualified needed to be equivalent to NQA requirements. The difference is important, in that none of the data qualified by IRT processes was collected under a fully NQA equivalent program.

Page 5-50, lines 1-2: *...collected after August 1, 1995 when SNL QA program was qualified by the DOE (Method 1).*

The DOE document establishing the qualification should be referenced.

5.4.2.2 Qualification of Existing Data

Page 5-51, lines 13-14: *All data sets not qualified by IRT or collected under a qualified QA program were qualified by the peer review process.*

Only those data sets used in the CCA were qualified. About 30 data packages failed the IRT process but were not sent to peer review.

5.4.2.3 T=0 Process

Page 5-51, Lines 30-31: *The process [T=0 for subcontractors to SNL] is documented in SNL procedure QAP 20-7.* Establishing T=0 for Internal and External Experiment Activity QA Programs, *and includes the following key elements...*

Revision 0 of QAP 20-7 has an effective date of November 20, 1996, nearly a month after the CCA was published. The process used may be documented in the procedure, but an approved version of QAP 20-7 was obviously not available at the time the T=0 determinations for the subcontractors listed in Table 5-6 were made. The process of determining T=0 is a quality-affecting one, and should have been controlled by procedures or instructions as required by NQA-1, Basic Requirement 9 and Supplement 9S-1.2, and the CAO QAPD Section 2.1.A--that is, the SNL document(s) that controlled and authorized the process at the time the subcontractor T=0 determinations were made should have been cited, not QAP 20-7.

5.4.3 WID QA Program Implementation

Page 5-52, lines 36-40: *WID determines the adequacy of the implementation of QA requirements for both internal WID customers and external contractors. Internal determinations of adequacy of QA implementation are generally based on adherence to the WID QAPD requirements. The process includes a review of the contractor's QA program with regard to the applicable element of the WID QAPD, nationally recognized codes and standards, and regulations.*

The term "internal customer" is not a commonly understood term, and should have been defined.

The transition from internal QA to external contractor QA between the second and third sentences is not explicit.

Page 5-52, lines 40-43: *The WID has performed audits and surveillances to determine the dates when each of its supplier's and subcontractor's QA programs were considered adequate and effectively implemented. These dates and the basis for determination are shown in Table 5-10.*

This is the "T=0" process which was more carefully described for SNL in Section 5.4.2.3. The controlling instructions or procedures for this process required by NQA-1, Basic Requirement 9 and Supplement 9S-1.2, and the CAO QAPD Section 2.1.A, should have been cited.

List of Attachments

I. July 22, 1996 letter from R. H. Neill, EEG, to George Dials, DOE (Referenced on page 2 of this review.

II. Undated letter (received by the EEG on August 9, 1996), from G. Dials, DOE, to R. H. Neill, EEG (Referenced on page 2 of this review).

III. August 20, 1996 memorandum from B. Walker, EEG, to R. H. Neill, EEG (Referenced on page 16 of this review).

IV. May 5, 1989 memorandum from M. R. Brown, WID, to R. J. Figlik, WPO/DOE (Referenced on page 21 of this review).

V. June 1, 1989 memorandum from J. P. Knight, DOE, to R. W. Starostecki, DOE (Referenced on page 23 of this review).

Attachment I to EEG Review
of CCA, Chapter 5

ENVIRONMENTAL EVALUATION GROUP

AN EQUAL OPPORTUNITY / AFFIRMATIVE ACTION EMPLOYER

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July 22, 1996

Mr. George Dials, Manager
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P. O. Box 3090
Carlsbad, NM 88221-3090

Dear Mr. Dials:

Attached is the EEG review of Chapter 5, "Quality Assurance," from the WIPP Compliance Certification Application (CCA), published as DOE/CAO-96-2056 on May 31, 1996. Chapter 5 contains significant omissions and errors, and does not appear to meet the QA requirements listed in 40 CFR 194 or the expectations for QA as listed in the Compliance Application Guidance (CAG; EPA 402-R-95-014).

While the EPA has agreed to review the CCA a chapter at a time, the expectation was that each chapter would be a final version that would illustrate the DOE's best explanation of how the regulatory requirements for the areas covered by that chapter have been met. Chapter 5 contains many "placeholders", which are apparently to be replaced by data and analyses which have yet to be generated. Two appendices are referenced which were not included; the included Appendix RE-5 is apparently not referenced by the chapter, and is either incomplete or unnecessary. The EEG cannot provide a complete review until the additional information is added to the chapter package.

Chapter 5 also fails to meet the QA expectations listed in the CAG under the heading "§194.22 Quality Assurance" (page 18). The EPA clearly states on page 1 of the CAG that these expectations will be the criteria by which the completeness of the application will be judged, and that no further actions will be taken until the expectations are included. EEG could only verify that one of the first five expectations was included in Chapter 5. Unless it is the DOE's intention to meet the CAG QA expectations elsewhere in the CCA then Chapter 5 is also deficient in this regard.

For the most part Chapter 5 also fails to respond to the EPA comments on the Draft Compliance Certification Application (DCCA), as transmitted to your office on October 31, 1995 and January 30, 1996, and to some extent fails to address the comments published in

EEG-61, "Review of the WIPP Draft Application to Show Compliance with the EPA Transuranic Waste Disposal Standards" (March, 1996) concerning the DCCA QA Chapter. Chapter 5 contains editorial and technical difficulties which could delay the EEG and the EPA review of the complete application. A listing of some of these, as well as additional commentary on the "placeholders", CAG expectations, and other issues, can be found attached to this letter.

There is no indication in Chapter 5 that objective criteria are applied when audit teams determine the effectiveness of QA program adequacy and implementation. The process by which program effectiveness is determined should be described in Chapter 5.

Chapter 5 appears to be substantially incomplete. EEG recommends that the DOE withdraw the Chapter 5 submission, and resubmit it after (1) data to be included has been collected and analyzed, (2) the document has been rewritten to conform to CAG and other EPA expectations, and (3) full editorial and technical reviews of the contents by cognizant personnel have been performed.

Sincerely,

Robert H. Neill
Director

RHN:BAW:ss
Enclosure

ENVIRONMENTAL EVALUATION GROUP REVIEW OF CHAPTER 5 OF WIPP COMPLIANCE APPLICATION (DOE/CAO-96-2056)

Chapter 5 of the CCA, "Quality Assurance", published as DOE/CAO-96-2056, is an incomplete document which fails to adequately support compliance with the 40 CFR 194.22 QA requirements and the expectations for QA in the Compliance Application Guidance (CAG). This issuance of Chapter 5 appears to have been premature; material is missing, adequate technical and editorial review were apparently not performed, and there seems to have been no attempt to compare its contents against the EPA's criteria for completeness, or comments on the DCCA version of the chapter.

The following commentary is not a line-by-line review of Chapter 5, as the document is incomplete, and more general concerns should be addressed before such a review could be considered useful. Examples are randomly selected, to show the types of corrections necessary rather than a complete list of them.

Chapter 5 is an incomplete draft.

Chapter 5 as received by EEG on June 6, 1996, is a draft that would have been more appropriate in the DCCA. The document must be considered a draft, rather than a submittable document for compliance, as information has been replaced by "placeholders". The first page (5-1) has the following statement in the middle of a paragraph:

> This program of audits and surveillances assesses the adequacy and effectiveness of implementation of the individual QA programs. **[Placeholder for conclusions concerning the adequacy and effectiveness of implementation of the CAO and SNL QA programs].** (Emphasis in the original)

There are many such placeholder statements to be found in the document. Page 5-16 has one, page 5-42 has two, page 5-43 has one, 5-44 has two, 5-46 has two, 5-47 one, 5-50 three, and there may be others. The apparent reason for many of the placeholder statements is that QA activities necessary for production of a QA chapter in the CCA have not yet been completed and adequately analyzed. The placeholder quoted above, for instance, probably is due to external audits which had been scheduled, but not completed, of SNL (performed in May and June 1996) and CAO (scheduled for July 15-19, 1996) prior to the writing of Chapter 5. Other placeholders (on p. 5-46 and 5-47) are related to peer review qualification of data; these peer reviews are still in progress.

The results of these QA activities may not always support the conclusions already drawn in Chapter 5. The effectiveness of SNL's QA program was recently adjudged as "marginal" by a CAO-contracted audit, and if the DOE intends to use the results of the audit in the CCA

then some sort of updating activity should be performed to show that the program is adequate.

Note that neither WID nor any of the generator sites were included in the placeholder statement quoted above. Adequacy and effectiveness of QA at these sites, too, was yet to be established at the time of publication of the document, though major audits of INEL (effective, except for ineffective ANL-West) and Rocky Flats (marginal) were performed in late 1995.

In addition to "placeholder" statements, other information to be used for compliance is yet to be obtained. For example (from p. 5-3 and 5-4, Section 5.1.1):

> The TWBIR was prepared in compliance with the CAO QAPD and was audited by CAO QA on September 5 and 6, 1996.

Since the EEG is reviewing Chapter 5 in June, 1996, it is not meaningful to take credit for an audit in September, 1996. The version of the TWBIR to be audited hasn't been published yet, either; and the version of the CAO QAPD with which it apparently is to comply was not officially transmitted to TRU-waste personnel (or EEG) until after Chapter 5 was received (distribution memo dated June 13, 1996, from CAO's QA Manager).

Until the evidence to be used in Chapter 5 has been appropriately gathered and properly analyzed, the chapter can only be considered an incomplete draft.

Chapter 5 was not adequately reviewed by the DOE.

In the above quotation, the applicable version of the CAO QAPD is not listed, nor is the version number of the TWBIR. Document version numbers are not to be found for most (if not all) documents in the chapter, which makes verification of many statements impossible.

Other editorial and technical review mistakes exist. Descriptions of the "graded approach" appear in two different places (p. 5-2 and 5-23); these provide different (though partially overlapping) sets of criteria for grading activities. Section 5.1.2 "Environmental Monitoring, Monitoring of the Performance of the Disposal System and Analysis Activities" (p. 5-6) indicates that no monitoring need take place prior to closure, in direct contrast to the §194.42(c) requirement that monitoring of critical parameters commence before waste emplacement begins. The section concerning software (5.1.4, p. 5-77 ff) considers only PA software as necessary for compliance activities, though software used in waste characterization and for site activities carried out by WID are also used for compliance with 40 CFR 194. In Section 5.3.7, Document Control (p. 5-28), WID's principal procedures for document control are not listed--and WID has been tasked with the ultimate storage of all pertinent documents to the project. Section 5.3.9 (p. 5-29) offers no objective evidence (in the form of governing procedures) to show that identification and control of items is required to be performed, though all the other sections of Section 5.3 have such references.

In Section 5.1.3,(p. 5-6), it is asserted that since the EPA had reviewed site selection and site characterization QA programs during examination of the 1989 No-Migration Variance Petition (NMVP) that the QA for site selection and characterization should be considered satisfactory. This is untenable on several grounds, not the least of which is that the NMVP is for compliance with 40 CFR 268.6, which has no requirement that QA programs must comply with the 1989 versions of NQA-1, NQA-2 Part 2.7, and NQA-3, as is found in 40 CFR 194.

Section 5.4.2 (Page 5-44) illustrates several potential deficiencies. The initial paragraph contains a statement which includes placeholders, as follows:

> A primary result of the qualification of the SNL QA audit and surveillance programs **[Placeholder]** the determination of which performance assessment data provided by SNL subcontractors **[Placeholder]** collected under an approved QA program and which data requires additional qualification.

Unfortunately, without the placeholders, the statement has effectively no useful semantic content, and cannot be analyzed in relation to the requirements of 40 CFR 194.

The next paragraph describes the change from the SNL QAPD revision P to revision R. Some mention of revision Q would prevent possible confusion.

Under the heading "Scientific Investigation" (still Section 5.4.2, p. 5-44), the statement is made that

> QAP 20-2 was added to address scientific notebooks. Previously, scientific notebooks were rarely used...

Notebooks are usually considered the basic documentation of scientific work, and the DOE may want to reconsider the phrasing of the second part of the statement.

The results of SNL Audit IA 95-03 (August, 1995) are reported in Section 5.4.2.1, Data Qualification (pp. 5-44, 45):

> The audit resulted in 14 findings in the areas of calibration, procedures, training, experimental planning, test records, and equipment and data acquisition...The audit concluded that, with the exception of the Corrective Action Requests, there was evidence that SNL QA controls were in place and that they were adequate and effectively implemented.

Given the breadth of the Corrective Action Requests(CARs), what areas were left to show adequate and effective implementation of the QA controls? In this presentation, it seems as if the program was considered adequate and effective regardless of the audit findings. Chapter 5 also lacks discussion of the process used by audit teams for determining the effectiveness of QA programs; if adequacy and implementation effectiveness statements are

included in the CCA, then the process by which these statements are generated should be described.

Almost no document in Chapter 5 is properly referenced. QA documents are listed without version numbers; published government documents are listed without document numbers (p. 5-6, "Background Document..."; p. 5-14, "DOE/Albuquerque Operations Manual"), or without even a title (p. 5-11, "This task was documented in a DOE Headquarters report..."). None of these documents appear in the bibliography for the chapter, either.

Anything more than a rudimentary review by personnel familiar with the overall WIPP project and QA would have uncovered at least some of these deficiencies. In a QA chapter, the DOE has failed to adequately perform one of the basic principles of QA--review of documents. Such an omission creates an erroneous impression of the quality of QA activities that CAO has developed in the last few years.

Chapter 5 does not address CAG expectations.

While it is not a compliance requirement for DOE to fulfill the expectations in the Compliance Application Guidance (CAG EPA 402-R-95-014), the guidance was developed to assist the EPA in determining if the CCA is complete (CAG, page 1). The document goes on to state (also page 1):

> A completeness determination is a threshold determination that the application warrants further scrutiny, so that EPA, DOE, and the public do not invest major resources in a rulemaking proceeding for an incomplete document will likely (and justifiably) consider the CCA incomplete until these expectations are met.

There is no evidence in Chapter 5 that the expectations in the CAG were considered during the development of the chapter. The DOE sent out Chapter 5 with a matrix which matches the requirements of 40 CFR 194 QA requirements with the chapter, but makes no reference to the CAG expectations. There are no statements, references, or sections within Chapter 5 that echo language or structure unique to the CAG. An attempt to verify that the five expectations on page 18 of the CAG were met in Chapter 5 produced febrile results--only one of the five could be considered to be completely met. These five expectations, and the result of the EEG's verification attempt, are as follows:

1. That DOE top tier QA documents demonstrating commitment to NQA-1 (1989), NQA-2 Part 2.7 (1990), and NQA-3 (1989) be included in the CCA. Revision 1 of the CAO QAPD (if Revision 1 will be the version used for the CCA--see expectation 3) could be said to meet this requirement by itself, and evidence in Chapter 5 is that this document will be included in Appendix QAPD.

   This expectation is also the heart of the 40 CFR 194 QA requirements, and it is not likely that it was included as a CAG consideration.

2. That DOE principal contractor top tier QA documents, and a list of all top tier documents of subcontractors performing quality affecting activities as listed in §194.22(a)(2), be in the application. Appendix QAPD will apparently include the SNL and WID QAPDs, but Chapter 5 includes no listing of subcontractor documents as specified, nor the top-tier documents for generator sites, and even the TRU-QAPD may not be included in Appendix QAPD (it is not so referenced in Chapter 5).

3. That the effective dates the documents from expectation 2 were in conformance with the NQA requirements be listed in the application. No effective dates were listed for QA documents in Chapter 5; version numbers were not even given.
4. That a list of quality affecting activities and items important to demonstration of compliance be included in the CCA. No such list is in Chapter 5.

5. That the rationale used in developing the list for expectation 4 be given. No list, no explanation.

Chapter 5 is manifestly not complete according to the criteria in the CAG, nor, it seems, has DOE made an attempt to meet the completeness for QA as identified in the CAG.

The included appendix was poorly presented.

In its mailing of Chapter 5, the DOE included a separate bound document, "Appendix RE5", dated May 10, 1996. The letter of transmittal indicates that

> This appendix contains excerpts and summaries of specific references used to support CCA conclusions within the chapter. It will allow reviewers to quickly find the specific portions of referenced documents when tracing the logic of the CCA's conclusions.

EEG could find no specific references in Chapter 5 to Appendix RE5, nor was the rationale for the contents of Appendix RE5 apparent. The appendix consists of brief abstracts from the NQA standards and two NUREG position papers (1297, Peer Review, and 1298, Qualification of Existing Data). The bibliographic references for the documents duplicate the bibliography in Chapter 5. All five documents are readily available as published documents. The abstracts, when pertinent, are not so lengthy that they could not have been quoted directly in Chapter 5.

Appendix RE-5 appears to either be an unnecessary addition to the CCA, or perhaps another "placeholder" into which filler material was inadvertently placed. In any case, it is apparent that the Appendix as it exists is not a well-thought-out addition to the CCA.

Two referenced appendices were not included.

In contrast to Appendix RE-5, two other appendices are referenced in Chapter 5, but neither of these were sent with the document. "Appendix QAPD" is referenced throughout much of

the chapter, and would seem to include the current QAPDs for CAO, SNL, and WID, but no complete listing of the contents is included. These documents are expectations in the CAG, along with other top-tier documents (see discussion of CAG requirements above).

"Appendix AUDIT" is said to contain results of internal audits and surveillances of the WID QA program, and lists of both internal and external audits and surveillances of the CAO, WID, and SNL (Section 5.4.4); whether generator site assessments are included as a part of "CAO" is indeterminate.

All references to Appendix AUDIT appear on the last page of Chapter 5 (p. 5-51). For such an Appendix to have real meaning, specific audits contained in it should be referenced by Chapter 5 as objective evidence that requirements have been met.

Without these appendices, the effectiveness of Chapter 5 cannot be completely assessed. Appendices QAPD and AUDIT should have been transmitted with the chapter.

Chapter 5 fails to address EEG's comments on the DCCA.

The EEG's comments on the DCCA QA chapter as published in EEG-61 (March, 1996) are also only partially addressed in Chapter 5. EEG (EEG-61 p. 5-2) suggested that the QA chapter should have addressed the requirements of 40 CFR 194.22, and Section 5.1 of Chapter 5 does address the requirements from 40 CFR 194.22(a), including the overriding requirement for conformance with the applicable NQA standards (NQA-1, NQA-2 Part 2.7, and NQA-3). However, 40 CFR 194.22(b) requires that:

> Any compliance application shall include information which demonstrates that data and information collected prior to the implementation of the quality assurance program required pursuant to paragraph (a)(1) [the requirement for the NQA standards] of this section have been qualified in accordance with an alternate methodology, approved by the Administrator or the Administrator's authorized representative, that employs one or more of the following methods: peer review...; corroborating data; confirmatory testing; or a quality assurance program that is equivalent in effect to...[the NQA standards].

Chapter 5 describes the processes used for data qualification by SNL (Section 5.4.2.1 and following sections, beginning on p. 5-44), but does not include information which demonstrates that the Administrator has approved of these methods.

As in the DCCA QA chapter, Chapter 5 emphasizes the QA program as it exists in 1996 over QA of the data gathering and processing activities which make up a major part of 40 CFR 194 requirements; this was another principal concern expressed in EEG-61. The CCA QA chapter should provide objective evidence that information utilized by the other sections of the CCA fulfills the quality requirements in 40 CFR 194. In places this is partially achieved; Table 5-4 contains a list of data packages qualified by the Independent Review Teams in the Qualification of Existing Data process under SNL's Quality Assurance

Procedure 20-3, but does not explain where and how these packages are used, and their importance to compliance, nor are any references or guidances provided that would allow confirmation of the table of contents.

Chapter 5 fails to adequately address EPA's comments on the DCCA.

The DOE has failed to completely address the EPA general comments on the QA chapter as provided in the enclosure from EPA's Larry Weinstock to CAO's George Dials dated October 31, 1995 (pp. 3 & 4). The EPA stated that:

> A number of assertive statements intended to describe the current status of the program are made without substantiation, including statements regarding training records, calibration records, and document and record control procedures. Objective evidence should be presented which demonstrates the successful implementation of these and other aspects of a quality assurance program for the WIPP. Examples of the evidence of implementation may include approved governing documents, implementing procedures, implementing plans and timetables, audits, surveillance, and verification reports, history of corrective actions, and the effective dates of program implementation.

Some of the governing documents, some of the procedures, and some of the effective dates of program implementation can be found in Chapter 5. However, many more assertive statements are to be found in Chapter 5 than were in the DCCA QA chapter, and objective evidence for them is not presented. A few examples follow: Section 5.1.6.2 (p. 5-11), "Original Repository Design", states that "All changes are approved by technically qualified individuals", but no evidence is supplied for the statement. Section 5.3.8 (p. 5-28), "Control of Purchased Items and Services", states that "Prospective suppliers are evaluated and selected on the basis of documented criteria", and eight bullets list other procurement controls said to be in place. However, only WID implementing documents are provided as evidences for the section, and these are for "Receipt Inspections" and "Source Inspections" (which may cover two of the eight bullets). The section does not reference the missing appendices, which might possibly include more objective evidence.

The DOE also seems to have made only a cursory attempt to address the more specific comments the EPA provided on the QA Chapter of the DCCA (transmitted as pp. 39-42 of the January 30, 1996 letter from Weinstock to Dials). For example, the first specific comment states in part, "The DCCA should have specified the roles of EM-1, EM-20, and EM-30". While Chapter 5's "Organizational Interfaces" chart (Figure 5-3, p. 5-21) shows EM-1 and EM-30, EM-20 is still not listed. The same EPA comment also implies that the organizations that conduct QA audits of contractors and waste generator sites should be listed; they aren't. Another EPA comment indicates that evidence substantiating that all workers were properly trained should be included; it wasn't.

The inclusion of the "Organization Interfaces" figure, which was not in the DCCA, implies

that the EPA's comments were considered on some level. However, it also seems obvious that no line-by-line check to make sure that concerns raised by EPA comments were addressed was made. A search for a random sample of three other EPA comments--lack of objective evidence for control and maintenance of QA records, missing data quality indicators for the waste characterization program, and a need to address software reporting, correction, and implementation of requirements--shows that only the last of these is included in Chapter 5.

Chapter 5 apparently circumvents CAO's own QA program.

The weaknesses described above, in a chapter concerning QA, are apparently due to circumvention of the DOE's own QA program. CAO Management Procedure (MP) 4.4, Revision 0, dated April 19, 1996, states (Section 3.1.1) that

> Before a document is produced, the requestor should evaluate the need, end use, cost-effectiveness, intended audience, duplication of effort, regulatory and technical requirements, and any external organization's requirements or agreements related to the document.

MP 4.4 also establishes review processes, which are to be in performed in accordance with MP 4.2.

Recommendation

The DOE should consider developing not only Chapter 5 but all of the CCA under the requirements of the CAO QAPD, Revision 1. A solid quality assurance program is of little utility unless work is performed under its control.

Department of Energy
Carlsbad Area Office
P.O. Box 3090
Carlsbad, New Mexico 88221

RECEIVED
AUG 9 - 1996
ENVIRONMENTAL EVALUATION GROUP

Mr. Robert H. Neill, Director
Environmental Evaluation Group
7007 Wyoming Blvd. NE, Suite F-2
Albuquerque, N.M. 87109

Dear Mr. Neill:

We were quite surprised by your July 22, 1996 letter that expressed your concerns with Chapter 5, "Quality Assurance", of the Waste Isolation Pilot Plant (WIPP) Compliance Certification Application (CCA). Your letter implied that there are deficiencies in the Carlsbad Area Office (CAO) Quality Assurance (QA) program based upon your analysis of the Chapter 5. Contrary to this, we have shown time and again, through surveillance and audit, that the CAO QA program is effective. Let me remind you that the Carlsbad Area Office has just been audited by the Department of Energy-Headquarters (EM-30), led by an NQA-1 certified QA auditor, during which some of your staff attended, along with the Environmental Protection Agency (EPA). The report concluded that the CAO QA program was adequate and effective.

We feel that many of your comments are incorrect, exaggerated, and in some cases they reflect a basic lack of understanding of the intended requirements, expectations, and subject material. Your analysis brings to mind that we are not aware of any Environmental Evaluation Group (EEG) employee who is a certified QA auditor or has the relevant QA experience to make the judgments of a QA program as contained in your letter. Please reconsider your conclusions based upon the following:

General Comments

The following general responses are provided to express our overall disagreement and disappointment with your response. Specific responses to each of your concerns are addressed in the enclosure to this letter.

1. Your letter indicates that Chapter 5 contained significant omissions and errors. We totally disagree with this statement Specific responses provided herein should convince you that Chapter 5 contains neither significant omissions nor significant errors.

2. With respect to the "placeholders" identified in Chapter 5: the placeholders were planned and incorporated in the May 31, 1996 revision, to flag events that had not yet occurred, but would take place at a later time The placeholders represented assessment dates or conclusions that had not been fully completed by the May 31, 1996, Chapter 5 submittal date. The placeholders do not represent "data and analyses" as alluded to in your letter. The missing appendices referred to are not critical to the review of Chapter 5. EEG

currently has copies of the information in the appendices:

> Appendix QAPD is comprised of the CAO, SNL, and WID QAPDs. EEG has copies of these documents.
>
> Appendix SCHED is an example of a typical assessment schedule. EEG is on distribution for the quarterly issue of the CAO Assessment Schedule and the biweekly draft updates.
>
> Appendix AUDIT identifies in tabular form audits and surveillances performed by CAO, SNL, and WID, which are only indirectly related to supporting conclusions made in the Chapter. This information has also been provided to EEG in the form of the CAO Assessment Schedule.

Appendix RE-5 is a compilation of reference material from Chapter 5 and is intended to be a source of references or portions of references to make it easier for the reader. A similar appendix is included for each Chapter of the CCA.

3. Throughout your comments you refer to the "QA expectations" listed in "Section 194.22 Quality Assurance" of the Compliance Application Guidance (CAG).

   The Preamble to the CAG clearly indicates that the CAG is to be used as guidance:

> "The CAG summarizes and explains the February 9, 1996 final rule. The United States Environmental Protection Agency (EPA) developed this guidance to assist the United States Department of Energy (DOE) with the preparation of any Compliance Certification Application (CCA) for the WIPP and, in turn, to assist in EPA's review for completeness and generally to enhance the readability and accessibility of the CCA for EPA and public scrutiny. It is EPA's intent that this guidance will facilitate the understanding that DOE and public have of the specific information that is expected to be included in a complete application for certification of compliance. Examples used for clarification in this guidance should not be considered exhaustive or definitive, since they are provided merely to facilitate DOE's understanding of the types of information EPA is expecting."

   The EPA staff clearly supports the position that the CAG is for guidance only. The CAG is only guidance and therefore should not be used by EEG to make an argument that Chapter 5 is deficient, nor that expectations have not been met.

4. We disagree with your statement that the May 31, 1996 revision of Chapter 5 fails to respond to EPA comments. Specific responses to the EPA Draft Compliance Certification Application (DCCA) comments were provided to EPA on January 23, 1996. In addition, the current revision of Chapter 5 has been specifically revised in format and content to address EPA DCCA comments.

5. Your comment relative to the lack of objective criteria used by audit teams "to determine the effectiveness of QA program adequacy and implementation" reflects a basic misunderstanding of QA audit processes, audit scopes, and audit terminology. Quality Assurance auditors and lead auditors are qualified and trained; lead auditors are certified. As part of their training, the three components of the audit conclusion are clearly presented. While it may appear that the process is subjective to casual observers, the process is well understood by qualified QA audit personnel. We feel that a discussion of basic auditing practices should not be included in Chapter 5.

The enclosure to this letter will further address the specific points included in your enclosure "CCA Ch. 5 (DOE/CAO-96-2056) Review."

In summary, your letter does not provide an accurate assessment of the condition, content, or quality of Chapter 5. Again, we feel that many of your comments are incorrect, exagerrated, and in some cases they reflect a basic lack of understanding of the intended requirements, expectations, and subject material.

We are, however, currently updating the placeholders and other information contained in Chapter 5 and will consider the specific comments you have made. If it is appropriate that they be addressed in Chapter 5, we will do so.

Sincerely,

George E. Dials
Manager

Enclosure

cc w/enclosure:
R. Brown, CAO
M. McFadden, CAO
J. Mewhinney, CAO
J. Maes, CAO

Enclosure

This enclosure addresses the specific comments provided by EEG in the enclosure to the "Robert H. Neill letter to George Dials, dated July 22, 1996."

Introductory Paragraphs

Chapter 5 of the CCA, "Quality Assurance", published as DOE/CAO-96-2056, is an incomplete document which fails to adequately support compliance with the 40 CFR 194.22 QA requirements and the expectations for QA in the Compliance Application Guidance (CAG). This issuance of Chapter 5 appears to have been premature; material is missing adequate technical and editorial review were apparently not performed, and there seems to have been no attempt to compare its contents against the EPA's criteria for completeness, or comments on the DCCA version of the chapter.

1. We disagree. The document is complete (with the inclusion of placeholders for ongoing activities).
2. We disagree. Chapter 5 does adequately support compliance with the 40 CFR 194.22 QA requirements.
3. We disagree. The CAG is a guidance document and does not contain requirements.
4. We disagree. The Chapter went through extensive technical and editorial revision. Over 80 pages of Document Review Records that include comments and resolutions are maintained as CAO QA records.
5. We disagree. Responses to EPA comments were provided to EPA on January 23, 1996. Additionally, the current format and content of Chapter 5 are a direct result of the EPA comments made concerning the DCCA.

"Chapter 5 is an incomplete draft."

Chapter 5 as received by EEG on June 6, 1996, is a draft that would have been more appropriate in the DCCA. The document must be considered a draft, rather than a submittable document for compliance, as information has been replaced by "placeholders". The first page (5-1) has the following statement in the middle of a paragraph:

> ***This program of audits and surveillances assesses the adequacy and effectiveness of implementation of the individual QA programs. [Placeholder for conclusions concerning the adequacy and effectiveness of implementation of the CAO and SNL QA programs]. (Emphasis in the original)***

We disagree with the comment that it "would have been more appropriate in the DCCA." The Chapter is complete (with the inclusion of the placeholders). The use of placeholders was a planned feature that permits a review of the content with the knowledge that specific information will be updated as it becomes available.

There are many such placeholder statements to be found in the document. Page 5-16 has one, page 5-42 has two, page 5-48 has one, 5-44 has two, 5-46 has two, 5-47 one, 5-50 three, and there may be others. The apparent reason for many of the placeholder statements is that QA activities necessary for production of a QA chapter in the CCA have not yet been completed and adequately analyzed. The placeholder quoted above, for instance, probably is due to external audits which had been scheduled, but not completed, of SNL (performed in May and June 1996) and CAO (scheduled for July 15-19, 1996) prior to the writing of Chapter 5. Other placeholders (on p. 5-46 and 5-47) are related to peer review qualification of data; these peer reviews are still in progress.

> We agree with your description of the reasons for the placeholders used in Chapter 5. Further classification includes: Of the 21 placeholders identified in Chapter 5, 15 are for dates to be supplied as activities occur (e.g. audit dates); three are for a description of audit conclusions (when they are reached); two are to identify the past tense; and one is a table of the packages qualified through the Peer Review process.

The results of these QA activities may not always support the conclusions already drawn in Chapter 5. The effectiveness of SNL's QA program was recently adjudged as "marginal" by a CAO-contracted audit, and if the DOE intends to use the results of the audit in the CCA then some sort of updating activity should be performed to show that the program is adequate.

> With respect to the SNL audit conducted by CAO in May 1996, the SNL QA program was determined to be "marginal." CAO had already invited EEG and EPA to attend a review of the corrective actions for those areas that contributed to the marginal conclusion. This review is currently scheduled to be held during the last week of August. This evaluation will also include a review of the status and effectiveness of critical corrective actions identified during previous assessments.

Note that neither WID nor any of the generator sites were included in the placeholder statement quoted above. Adequacy and effectiveness of QA at these sites, too, was yet to be established at the time of publication of the document, though major audits of INEL (effective, except for ineffective ANL-West) and Rocky Flats (marginal) were performed in late 1995.

> We agree, WID will be included as appropriate. However, since none of the generator sites will be certified by 10/31/96, generator sites will not be included. QA program assessment conclusions will be prepared for the generator sites at the appropriate time.

In addition to "placeholder" statements, other information to be used for compliance is yet to be obtained. For example (from p. 5-3 and 5-4, Section 5.1.1):

> ***The TWBIR was prepared in compliance with the CAO QAPD and was audited by CAO QA on September 5 and 6, 1996.***

Since the EEG is reviewing Chapter 5 in June, 1996, it is not meaningful to take credit for an audit in September, 1996. The version of the TWBIR to be audited hasn't been published yet, either; and the version of the CAO QAPD with which it apparently is to comply was not officially transmitted to TRU-waste personnel (or EEG) until after Chapter 5 was received (distribution memo dated June 13, 1996, from CAO's QA Manager).

In the above question, the applicable version of the CAO QAPD is not listed, nor is the version number of the TWBIR.

We agree. We had also identified the typo reflecting the incorrect TWBIR audit date. The correct date was September 5 and 6, 1995. This has been changed. The audit was conducted in accordance with implementing procedures and CAO QAPD, Revision 0.

"Chapter 5 was not adequately reviewed by the DOE"

We disagree with the basic premise. Chapter 5 went through a rigorous and comprehensive review process conducted in accordance with CAO MP 4.2. Over 80 pages of review comments were identified, resolved, and, where appropriate, incorporated into the document. In addition, Chapter 5 went through extensive editing for grammar, format and consistency, by professional document editors.

Document version numbers are not to be found for most (if not all) documents in the chapter, which makes verification of many statements impossible.

We disagree with your comment relative to indicating the version, (or more correctly, the revision) of the CAO QAPD and other document referenced in the Chapter. Documents in any complex, regulated program will change over a given period of time and should always be verified for each application. Omission of the revisions for these documents is appropriate and reflects the basics of information controls.

Other editorial and technical review mistakes may be found also. Descriptions of the "graded approach" appear in two different places (p.5-2 and 5-23); these provide different (though partially overlapping) sets of criteria for grading activities. Section 5.1.2 "Environmental Monitoring, Monitoring of the Performance of the Disposal System and Analysis Activities" (p. 5-6) indicates that no monitoring need take place prior to closure, in direct contrast to the §194.42(c) requirement that monitoring of critical parameters commence before waste emplacement begins. The section concerning software (5.1.4, p. 5-77 ff) considers only PA software as necessary for compliance activities, though software used in waste characterization and for site activities carried out by WID are also used for compliance with 40 CFR 194. In Section 5.3.7, Document Control (p. 5-28), WID's principal procedures for document control are not listed—and WID has been tasked with the ultimate storage of all pertinent documents to the project. Section 4.3.9 (p. 5-29) offers no objective evidence (in the form of governing procedures) to show that identification and control of items is required to be performed, though all the other sections of Section 5.3 have such references.

1. We agree with some of the specific comments here. For example the comment relative to the grading paragraphs in the two locations. While they are included in the two separate locations for different reasons, the amount of detail in the "Applicability", Section 5.1, is not required. The description will be kept, but the details (bullets) will be deleted.

2. We agree with the comment regarding monitoring of the performance of the disposal system. Monitoring will commence prior to waste emplacement. Appendix I.TM to CCA Chapter 7 will be referenced as the document describing the WID performance monitoring.

3. We agree with your comment relative to additional software that should be referenced. In our current update we have already added words to describe the application of software to data acquisition activities, WID design activities, and nondestructive assay activities.

4. We agree that one additional WID document control procedure is appropriate for reference (WID WP15-PS3103). However, we do not agree that document control and QA records are related in the manner that you indicate. The document control procedures are not intended to address "... the ultimate storage of all pertinent documents to the project." Record storage requirements are different than document control requirements. In addition we are adding one WID implementing document that addresses the identification and control of items (WP 15-PM3517).

In Section 5.1.3 (p. 5-6) the theory is advanced that since the EPA had reviewed site selection and site characterization QA programs during examination of the 1989 No-Migration Variance Petition (NMVP) that the QA for site selection and characterization should be considered satisfactory. This is untenable on several grounds, not the least of which is that the NMVP is for compliance with 40 CFR 268.6, which has no requirement that QA programs must comply with the 1989 versions of NQA-1, NQA-2 Part 2.7, and NQA-3, as is found in 40 CFR 194.

We agree with the comment on the No Migration Variance Petition (NMVP) and had already noted this. We have updated this portion of Chapter 5.

Sections 5.4.2 (Page 5-44) illustrates several potential deficiencies. The initial paragraph contains a statement which includes placeholders, as follows:

> ***A primary result of the qualification of the SNL QA audit and surveillance programs [Placeholder] the determination of which performance assessment data provided by SNL subcontractors [Placeholder] collected under an approved QA program and which data requires additional qualification.***

Unfortunately, without the placeholders, the statement has effectively no useful semantic content, and cannot be analyzed in relation to the requirements of 40 CFR 194.

We disagree with the comment on the "semantic content" without the placeholders being included. The placeholders are intended to be replaced by the word "was" at the appropriate time to indicate that the activity has already occurred.

The next paragraph describes the change from the SNL QAPD revision P to revision R. Some mention of revision Q would prevent possible confusion.

We disagree with the need to discuss revision "Q" of the SNL QAPD. Since EEG has observed CAO audits and surveillances of SNL starting in August of 1995, you should be aware that there is no revision "Q" of the SNL QAPD. The alpha designators "O" and "Q" are often intentionally not used due to the potential for mistaking one for the other. This was the case here.

Under the heading "Scientific Investigation" (still Section 5.4.2, p. 5-44), the statement is made that

> ***QAP 20-2 was added to address scientific notebooks. Previously, scientific notebooks were rarely used...***

Notebooks are usually considered the basic documentation of scientific work, and the DOE may want to reconsider the phrasing of the second part of the statement.

We agree with the poorly phrased statement relative to the "previous use of scientific notebooks". This sentence will be deleted.

The results of SNL Audit IA 95-03 (August, 1995) are reported in Section 5.4.2.1, Data Qualification (pp. 5-44, 45):

> ***The audit resulted in 14 findings in the areas of calibration, procedures training, experimental planning, test records, and equipment and data acquisition...The audit concluded that, with the exception of the Corrective Action Requests, there was evidence that SNL QA controls were in place and that they were adequate and effectively implemented.***

Given the breadth of the CARs, what areas were left show adequate and effective implementation of the QA controls? In this presentation, it seems as if the program was considered adequate and effective regardless of the audit findings.

We disagree with your overall conclusion regarding the SNL internal audit (IA-95-03). The executive summary indicated:

"Within the scope of this audit it was determined that, with the exception of the identified CARs, there was evidence that SNL QA controls were in place and that they were adequately and effectively being implemented for those experimental programs addressed in Phases 1, 2, and 3."

There were 14 criteria evaluated over 11 experimental programs. The 14 CARs were distributed over the 11 experimental programs and were not concentrated in one particular area or in one particular program. Thus, neither the criteria nor the programs were compromised to the extent that the audit team would conclude that implementation was not effective.

Chapter 5 also lacks discussion of the process used by audit teams for determining the effectiveness of QA programs; if adequacy and implementation effectiveness statements are included in the CCA, then the process by which these statements are generated should be described.

We disagree with the need to include a discussion of basic auditing conclusions (adequacy, implementation and effectiveness). The CCA is not intended to be a primer on "how to audit".

Almost no document in Chapter 5 is properly referenced. QA documents are listed without version numbers; published government documents are listed without document numbers (p. 5-6, "Background Document.."; p. 5-14, "DOE/Albuquerque Operations Manual"), or without even a title (p. 5-11, "This task was documented in a DOE Headquarters report.."). None of these documents appear in the bibliography for the chapter, either.

1. We disagree with the need to include document versions, revisions, or other designators in the CCA. As previously indicated, Chapter 5 describes the QA program that is directed to the control of important WIPP activities. This program will constantly be changing as requirements, expectations, or the need for improvements arise.

2. We agree that the DOE Headquarters report should be identified. We had already researched the document title and date and have included it in the Chapter.

Anything more than a rudimentary review by personnel familiar with the overall WIPP project and QA would have uncovered at least some of these deficiencies. In a QA chapter, the DOE has failed to adequately perform one of the basic principles of QA--review of documents. Such an omission creates an erroneous impression of the quality of QA activities that CAO has developed in the last few years.

1. We disagree with the comment concerning "A rudimentary review by personnel familiar with the overall WIPP project and QA would have uncovered at least some of these deficiencies." As previously indicated Chapter 5 received extensive QA and editorial reviews. Likewise, we disagree with the use of the word "deficiencies".

Most of the EEG comments relate to areas that have been planned to be upgraded during the current review or comments relative to alternate ways to approach the Chapter.

2. We disagree with the statement that "DOE has failed to adequately perform one of the basic principles of QA -- review of documents. Such an omission creates an erroneous impression of the quality of QA activities that CAO has developed in the last few years." Review is not one of basic principles of QA, rather it is an activity that supports QA principles. The type of generalization indicated in this comment without any idea of the process that was used, is unprofessional and unnecessary.

"Chapter 5 does not address CAG expectations."

While it is not a compliance requirement for DOE to fulfill the expectations in the CAG, the guidance was developed to assist the EPA in determining if the CCA is complete (CAG, page 1). The document goes on to state (also page 1):

> ***A completeness determination is a threshold determination that the application warrants further scrutiny, so the EPA, DOE, and the public do not invest major resources in a rulemaking proceeding for an incomplete document will likely (and justifiably) consider the CCA incomplete until these expectations are met.***

There is no evidence in Chapter 5 that the expectations in the CAG were considered during the development of the chapter. The DOE sent out Chapter 5 with a matrix which matches the requirements of 40 CFR 194 QA requirements with the chapter, but makes no reference to the CAG expectations. There are no statements, references, or sections within Chapter 5 that echo language or structure unique to the CAG. An attempt to verify that the five expectations on page 18 of the CAG were met in Chapter 5 produced febrile results--only one of the five could be considered to be completely met. These five expectations, and the result of the EEG's verification attempt, are as follows:

> We agree that Chapter 5 is not complete with respect to the CAG, however, we disagree with your conclusion that it must be. The Preamble of the CAG, clearly indicates that the CAG is to be used as guidance. The EPA staff clearly supports the position that the CAG is for guidance only.
>
> The CAG is only guidance and, therefore, should not be used by EEG to make an argument that Chapter 5 is deficient nor that expectations have not been met.

"The included appendix was poorly presented."

In its mailing of Chapter 5, the DOE included a separate bound document, "Appendix RE5", dated May 10, 1996. The letter of transmittal indicates that

This appendix contains excerpts and summaries of specific references used to support CCA conclusions within the chapter. It will allow reviewers to quickly find the specific portions of referenced documents when tracing the logic of the CCA's conclusions.

EEG could find no specific references in Chapter 5 to Appendix RE5, nor was the rationale for the contents of Appendix RE5 apparent. The appendix consists of brief abstracts from the NQA standards and two NUREG position papers (1297, Peer Review, and 1298, Qualification of Existing Data). The bibliographic references for the documents duplicate the bibliography in Chapter 5. All five documents are readily available as published documents. The abstracts, when pertinent, are not so lengthy that they could not have been quoted directly in Chapter 5.

Appendix RE5 appears to either be an unnecessary addition to the CCA, or perhaps another "placeholder" into which filler material was inadvertently placed. In any case, it is apparent that the Appendix as it exists is not a well-though-out addition to the CCA.

We disagree. The Appendix RE5 is a compilation of reference material from Chapter 5. Appendix RE5 is intended to be a source of references or portions of references in context to make it easier for the reader. A similar Appendix is included at the end of each CCA Chapter.

"Two referenced appendices were not included."

In contrast to Appendix RE5, two other appendices are referenced in Chapter 5, but neither of these were sent with the document. "Appendix QAPD" is referenced throughout much of the chapter, and would seem to include the current QAPDs for CAO, SNL, and WID, but no complete listing of the contents is included. These documents are expectations in the CAG, along with other top-tier documents (see discussion of CAG requirements above).

"Appendix AUDIT" is said to contain results of internal audits and surveillances of the WID QA program, and lists of both internal and external audits and surveillances of the CAO, WID, and SNL (Section 5.4.4); whether generator site assessments are included as a part of "CAO" is indeterminate.

Without these appendices, the effectiveness of Chapter 5 cannot be completely assessed. Appendices QAPD and AUDIT should have been transmitted with the Chapter.

The missing appendices are not critical to the review of the chapter, but are now included.

Appendix QAPD is comprised of the CAO, SNL, and WID QAPDs. EEG has copies of all three documents.

Appendix SCHEDULE is an example of a typical assessment schedule. EEG is on distribution for the quarterly issue of the CAO Assessment Schedule and the weekly draft updates.

Appendix AUDIT is a list of audit and surveillances that were conducted by CAO, SNL, and WID, which are only indirectly related to supporting the conclusions made in this Chapter. EEG is on distribution for the quarterly issue of the CAO Assessment Schedule and the weekly draft updates.

Since none of the generator sites will be certified by 10/31/96, generator site assessments are not included as a part of Appendix AUDIT.

"Chapter 5 fails to address EEG's comments on the DCCA."

The EEG's comments on the DCCA QA chapter as published in EEG-61 (March, 1996) are also only partially addressed in Chapter 5. EEG (EEG-61 p. 5-2) suggested that the QA chapter should have addressed the requirements of 40 CFR 194.22, and Section 5.1 of Chapter 5 does address the requirements from 40 CFR 194.22(a), including the overriding requirement for conformance with the applicable NQA standards (NQA-1, NQA-2, Part 2.7, and NQA-3). However, 40 CFR 194.22(b) requires that:

> ***"Any compliance application shall include information which demonstrates that data and information collected prior to the implementation of the quality assurance program required pursuant to paragraph (a)(1) [the requirement for the NQA standards] of this section have been qualified in accordance with an alternate methodology, approved by the Administrator or the Administrator's authorized representative, that employs one or more of the following methods; peer review...; corroborating data; confirmatory testing; or a quality assurance program that is equivalent in effect to...[the NQA standards]."***

We disagree that the purpose of Chapter 5 includes addressing EEG comments. EEG comments were addressed and included in the January document that addressed all comments on the DCCA. You were provided a copy of this document by letter dated January 23, 1996.

Chapter 5 describes the processes used for data qualification by SNL (Section 5.4.2.1 and following Sections, beginning on p. 5-44), but does not include information which demonstrates that the Administrator has approved of these methods.

We disagree with your interpretation of when the Administrator has to approve methods for qualifying data and information collected prior to the implementation of the quality assurance program. It is our opinion that the EPA Administrator's authority in this area begins with the submittal of the CCA.

Table 5-4 contains a list of data packages qualified by the Independent Review Teams in the Qualification of Existing Data process under SNL's Quality Assurance Procedure 20-3, but does not explain where an dhow these packages are used, and their importance to compliance, nor are any references or guidance provided that would allow confirmation of the Table contents.

We disagree with the need to explain where and how QED packages are used and their importance to compliance in Chapter 5. This technical information is not appropriate to this chapter and is discussed in other CCA Chapters.

"Chapter 5 fails to adequately address EPA's comments on the DCCA."

Chapter 5 fails to adequately address EPA's comments on the DCCA.
The DOE has failed to completely address the EPA general comments on the QA chapter as provided in the enclosure from EPA's Larry Weinstock to CAO's George Dials dated October 31, 1995 (pp. 3&4). The EPA stated that:

> ***"A number of assertive statements intended to describe the current status of the program are made without substantiation, including statements regarding training records, calibration records, and document and record control procedures. Objective evidence should be presented which demonstrates the successful implementation of these and other aspects of a quality assurance program for the WIPP. Examples of the evidence of implementation may include approved governing documents, implementing procedures, implementing plans and timetables, audits, surveillance, and verification reports, history of corrective actions, and the effective dates of program implementation."***

Some of the governing documents, some of the procedures, and some of the effective dates of program implementation can be found in Chapter 5. However, many more assertive statements are to be found in Chapter 5 than were in the DCCA QA chapter, and objective evidence for them is not presented.

We disagree with your statement that the May 31, 1996 revision of Chapter 5 fails to respond to EPA comments. Specific responses to the EPA DCCA comments were provided to EPA on January 23, 1996. In addition, the current revision of Chapter 5 has been specifically revised in format and content to address EPA DCCA comments.

A couple of examples: Section 5.1.6.2 (p. 5-11), "Original Repository Design", states that "All changes are approved by technically qualified individuals", but no evidence is supplied for the statement. Section 5.3.8 (p. 5-28), "control of Purchased Items and Services", states that "Prospective suppliers are evaluated and selected on the basis of documented criteria", and eight bullets list other procurement controls said to be in place. However, only WID implementing documents are provided as evidences for the section, and these are for "Receipt Inspections" and "Source Inspections" (which may cover two of the eight bullets). This section does not reference the missing appendices, which might possibly include more objective evidence.

We disagree. Because WID is responsible for design, only WID implementing documents are appropriately provided Sections 5.3.8.

We disagree that the comment concerning qualifications and training of workers is not addressed. Section 5.1.6.2 (p 5-11) does state that changes are approved by "technically qualified individuals." Chapter 5 describes the CAO QA program that is used to train and qualify personnel. These records are subject to the audit process. Individual qualification and training records are maintained as QA records. We do not believe that the thousands of records for all WIPP personnel performing quality affecting activities are appropriate to be included in the CCA. These records are subject to the audit process.

The DOE also seems to have made only a cursory attempt to address the more specific comments the EPA provided on the QA Chapter of the DCCA (transmitted as pp. 39-42 of the January 30, 1996 letter from Weinstock to Dials). For example, the first specific comments states in part, "The DCCA should have specified the roles of EM-1, EM-20, and EM-30". While Chapter 5's "Organizational Interfaces" chart (Figure 5-3, p. 5-21) shows EM-1 and EM-30, EM-20 is still not listed. The same EPA comment also implies that the organizations that conduct QA audits of contractors and waste generator sites should be listed; they aren't. Another EPA comment indicates that evidence substantiating that all workers were properly trained should be included; it wasn't.

We disagree. Chapter 5's "Organizational Interfaces" chart is correct in not identifying EM-20. The EM-20 responsibility for QA oversight of WIPP has been re-assigned to EM-30. EM-30 recently performed an independent assessment of the CAO QA Program.

The inclusion of the "Organization Interfaces" figure, which was not in the DCCA, implies that the EPA's comments were considered on some level. however, it also seems obvious that no line-by-line check to make sure that concerns raised by EPA comments were addressed was made. A search for a random sample of three other EPA comments—lack of objective evidence for control and maintenance of QA records, missing data quality indicators for the waste characterization program, and a need to address software reporting, correction, and implementation of requirements—shows that only the last of these is included in Chapter 5.

We disagree that the EPA comments have not been addressed as identified by the random sample of three EPA comments - lack of objective evidence for control and maintenance of QA records, missing data quality indicators, and a need to address software reporting, correction, and implementation of requirements. The comments are addressed within the discussion of the appropriate implementing procedures and overall controls established by the QA Program. We do not consider it necessary to supply more detail in Chapter 5.

"Chapter 5 apparently circumvents CAO's own QA program."

The weaknesses described above, in a chapter concerning QA, are apparently due to circumvention of the DOE's own QA program. CAO Management Procedure (MP) 4.4, Revision 0, dated April 19, 1996, states (Section 3.1.1) that

Before a document is produced, the requestor should evaluate the need, end use, cost-effectiveness, intended audience, duplication of effort, regulatory and technical requirements, and any external organizations's requirements or agreements related to the document.

MP 4.4 also establishes review processes, which are to be in performed in accordance with MP 4.2.

1. We disagree with this topic in its entirety. The review process was conducted in accordance with MP 4.2. Results of the reviews, for this revision of CCA Chapter 5, including comment resolution documentation, were completed and are maintained as QA records.

2. We disagree that the CAO QA Program was circumvented in any respect and believe this EEG determination was based on a lack of facts and a lack of understanding of the CAO Quality Assurance Program.

ENVIRONMENTAL EVALUATION GROUP

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MEMORANDUM

DATE: August 20, 1996

TO: Robert H. Neill, Director

FROM: Ben Walker, QA Specialist

SUBJECT: CAO Audit of SNL PA June 17-21, 1996

Tom Clemo and I observed the CAO audit of SNL's PA program during the week of June 17-21, 1996. Seven auditors were involved; other observers were Mario Italiano and George Basabilvaso from CAO, and Patrick Kelley, James Channell, David Back, and William Sublette for the EPA.

The audit team judged the PA program implementation of QA to be "marginal", and the software development and qualification was judged "marginally effective". Five draft Corrective Action Reports (CARs) were generated, and eight draft observations. Attachment 2 is a listing of these draft CARs and observations, and other material presented by the lead auditor at the closeout meeting.

Two items would seem to be of particular concern to QA for the PA effort: software codes were still not qualified, and some parameter values used by PA codes had been entered into the parameter database without formal processing. The software codes had incomplete baseline documentation but were nevertheless being utilized in Compliance Certification Application (CCA) calculations. The SNL QA Manager had agreed to this usage. The parameter value changes were a different sort of problem, in that the well-established parameters data entry formalism at SNL had been circumvented for the entry of some 25 parameter changes. These two events do not increase confidence in SNL's commitment to established quality for PA calculations.

A more complete description of these findings, and other events that took place during the audit, can be found in Appendix 1. The audit also found several laudatory practices at SNL; these include ease of retrieval of documents from the Sandia WIPP Central Files (SWCF), extensive error checking of inputs, software test scripting, and documentation and archiving of

software production runs. As always, SNL personnel were for the most part easily accessible and very helpful.

The auditors were well prepared, and those I observed stayed on task. Their knowledge and experience with SNL's PA efforts were readily apparent; and as is usual with CAO's auditors, they were persistent and thorough. This was a conscientious audit.

BAW:TC:sz
Enclosures

ATTACHMENT 1 to SNL PA Audit

Attachment 1 of the memorandum on the SNL QA audit (Walker to Neill, May 24, 1996) stated that:

> There still seems to be a sense at SNL that QA is secondary to scientific pursuit rather than an integral, and, for this project, essential part of it, and this attitude may have its effects even on QA personnel and their activities.

This hypothesis receives additional support from the sections that follow.

Software Qualification

Evidence of considerable effort to get the PA codes into QA conformance has been demonstrated in other software assessments in the recent past, and the documentation viewed in this audit was of good quality. However, SNL has decided to run calculations for the CCA using codes that are not yet in accordance with the dictates of NQA-2 Part 2.7, the 40 CFR 194 standard cited for software QA.

None of the PA codes were found to be fully qualified during the audit. Memoranda dated May 23, 1996 from the PA Manager in charge of software to the SNL QA Manager list the "current QA status" of each of the codes, all of whom contained incomplete items, and then request permission from the QA Manager to proceed with the CCA calculations. The QA Manager signed approval of the requests, without so much as initiating a CAR or requiring a schedule for completions.

A copy of the memorandum for NUTS is attached (Attachment 3); the distribution list shows that no copies were provided to the CAC. Nearly all aspects of the QA process are said to be "in progress"--i.e., none were completed. This includes the Requirements Document (RD) and the Verification and Validation Plan (VVP), which make up the first step in the NQA-2 Part 2.7 life cycle for software (§ 3.1; Requirements Phase), and define the requirements for the design of the testing phase and test cases. The memorandum later states that "Test cases #1 through #9 have been run" (though the requirements are still in draft) and that "...the testing is far along...."

The memorandum for CUTTING_S listed similar deficiencies (for all developmental parts of the software life cycle) in similar language. The other memoranda were probably similarly organized, though completion of parts of the life cycle may have occurred. NQA-2 Part 2.7 § 1 states:

> Software development shall proceed in a traceable, planned, and orderly manner...Software development may be performed in an interactive or sequential manner.

While "interactive" might be interpreted to indicate that test results can be used to change code requirements in an iterative fashion, it does not imply that all parts of the life cycle can be developed in parallel. Operational use of the software is the penultimate (6th) step in the software life cycle (followed only by the "retirement phase"), and NQA-2 Part 2.7 clearly states that for the "Operations and Maintenance Phase" (§ 3.6):

> Prior to this phase the software has been approved for operational use.

The memoranda also contain the statement that "The remaining testing and QA documentation will be completed expeditiously", and (for NUTS) that "If this testing uncovers any problems with NUTS then the impact on the CCA calculations would be assessed at that time". It seems likely that the purpose of the memoranda is to remove the pressure to complete QA work expeditiously; and the cost and effort to completely trace errors through a submitted CCA could be extensive.

The process to be followed as described in these memoranda are clearly at odds with the 40 CFR 194 requirements concerning software.

Parameter Entry Control

SNL-WIPP Form 464, WIPP Parameter Entry Form, is required for entry of any parameter values or changes in these values to the database for use by PA. Form 464s are initiated by the Parameter Task Leader, who enters information on the parameter, the change to be made, and justification for the change, attains signatures of the change requestor and an approval signature (others are sometimes required), then submits the Form 464 and supporting information to the Database Administrator as a Parameters Records Package (PRP). Data entry personnel are trained to use the Form 464s for input; the data entry person's signature is added to the 464, as is the signature of the person who checks the entry. The PRP, including the Form 464, is then filed in the Sandia Wipp Central Files (SWCF).

At the February 16, 1996, closeout of a CAO surveillance of parameters the lead auditor complimented SNL on the rigor with which use of Form 464s was enforced for database entry.

An auditor uncovered three or four parameters in the database for which no Form 464s could be found. In pursuit of this problem, the auditors were eventually shown a list of 25 parameters titled, "CHANGES NOT COVERED BY 464's". According to notes took while viewing this list, the first change entered was on February

16, 1996 (date of the closeout compliment mentioned above). That these entries had circumvented the established requirements was uncovered about a week later by a PI (while researching a parameter request from EEG). The compiling of the list began at that time.

It is one sort of error to fail to follow practices that have yet to be firmly established; it's another to fail in follow those that are established. During the audit we suggested that the audit team should find out the details of how these entries were made. We were informed that SNL would have to perform that activity and report it to CAO as part of the CAR resolution. It is hoped that the entries are the result of a preoccupied PI submitting changes directly to an improperly trained data entry person, but the problem is likely more serious.

In defense of SNL, this has all the appearances of being a single lapse in which all 25 parameters were changed in a matter of days, and SNL personnel were attempting to establish proper documentation. On the other hand, no internal CARs were generated by SNL's discovery of the problem.

Procedure Problems I: Data qualified by audit

During the audit, I had reason to read the versions of SNL QAPs 9-1 and 9-2 used by the auditors, and discovered lapses in each.

QAP 9-1 version 1 contained the statement (Section 4.3, Step 2):

> When data sets are used to support the analysis, document the source of the data and whether the data have been qualified through collection under an approved SNL QA program, the application of QAP 20-3, or *by SNL WIPP audit* (emphasis added).

Audits do not qualify data. When I questioned this statement it was explained to me that the phrase was more a slang term, and what was meant was that the program under which the data was developed had been audited by SNL to confirm that the program conformed to SNL's QA standards.

I was told SNL was in the process of revising the procedure, and indeed they were. EEG now has a copy of Revision 2 of the procedure, which became effective April 11, 1996, (a copy was received at EEG on April 18, 1996) and the statement quoted above has been removed. I remain confused, however. The audit was two full months after the effective date of the revision; why were auditors using the older one? And, why wasn't I simply shown that the newer version did not contain the item in question?

Analysis Plan AP-016, version 00, "Groundwater Modeling Analysis Plan for the Generation of Transmissivity Fields for the Culebra

Flow and Transport Calculations", dated May 2, 1996, Section 3.1, contained a similar statement:

> Only data that has been qualified through collection under an approved SNL QA program, through application of QAP 20-3, or *by SNL WIPP* audit will be used for this analysis [emphasis added].

I suspect this document was written with QAP 9-1 in hand; other analysis plans may have similar statements. This is an example of why the writing and reviewing of QA documentation is so important.

Procedures Problems II: Parameter "Category" Definitions

QAP 9-2, "Quality Assurance Requirements for the Selection and Documentation of Parameter Values Used in WIPP Performance Assessment" presented a more serious problem. The definition of parameter categories indicates that adequate control over parameters may not be adequately performed. Section 2.0 of the procedure offers a list of five categories, and states that Category 1, 2, and 3 parameters are subject to the requirements of the procedure, but 4 and 5 are not. The QAP 9-2 Revision 1 Category table:

Category	Description
5	Parameters not used in current compliance calculations;
4	Parameters that are model configuration parameters or that are assigned based on an assumed correlation of properties between similar materials;
3	Parameters representing physical constants...
2	Parameters representing the inventory of the waste to be emplaced at WIPP...
1	Parameters that do not fall into Categories 2 through 5, but are necessary to WIPP PA calculations.

The audit team failed to see why Category 4 parameters were deemed to be excludable from the QA requirements, and that the process for categorization of parameters was not adequate; a draft observation to that effect was made (draft Observation No. 3; in Attachment 2, p. 5).

I thought it should have been a CAR (and inappropriately said so at an audit team caucus). The table is unnecessarily confusing for the purpose of the procedure (establishing QA for

parameters). The procedure should have been written to require documentation for all parameters used in PA considerations, and should also require a documented rationale for parameters that are dropped from use in PA.

BEG's controlled copy version of SNL QAP 9-2 still shows Revision 1 as the current process to follow (August 9, 1996). The draft observation apparently had no effect on SNL, and parameters can still be included in PA calculations without necessarily being adequately documented.

Dating on Documents

Many kinds of SNL documents have inconsistencies in the dates listed in them. I have noticed several during previous audits and surveillances, but since the dates are always reasonably close I've not documented them.

Most pernicious are reviews or approvals of documents with dates that post-dated the issuance of the documents. For example, six Form 464s were found which were started on April 23, 1996, and entered into the database on April 22, 1996. The approvals for the change were all dated April 23, 1996.

Analysis plans I viewed had similar inconsistencies. "Analysis Plan for ORIGEN2 Inventory Calculations for First Phase Determination of the Initial Radionuclide Inventory for Performance Assessment Analysis Supporting the Compliance Certification Application", dated April 4, 1996, had all its signatures on or after April 9, 1996. "Analysis Plan for the Salado Flow Calculations (Task 1) of the Performance Assessment Analyses Supporting the Compliance Certification Application" was effective March 8, 1996, yet the author and reviewer signatures were dated March 12, 1996.

An internal SNL surveillance (96-08) of software was conducted on April 9-11, 1996. The surveillance report contains the following statement:

> One item of concern was the inconsistency of document dates. As this has been identified by CAO CAR 96-016, the inconsistencies will be listed in this report for correction without an additional CAR being issued.

The report has nine pages of documentation of violations which fall under CAO CARs for document dates and comment resolution. The report itself has an inconsistent date: the date on the memorandum transmitting it is April 3, 1996, 6 days before the surveillance took place.

Resolution of Previous CARs

A part of the scope of this audit was to verify the effectiveness of corrective actions for previous CAO CARs. None of the corrective actions were found by the auditors to be effectively implemented during this audit. Some, but not all, of the "observations" (a category for findings that could potentially generate CARs in the future if not corrected) for which CAO required responses were found to be adequately addressed.

Project Technical Baseline Updating

The FEPs plan suggested that the Project Technical Baseline (PTB) be updated. Discussions with SNL employees indicated that although significant changes in nearly all portions of the baseline have been instituted, SPM-2 (established in 1994) was still the PTB of record. "The CCA itself will be the new baseline" one employee stated, and suggested that the FEPs plan would be changed rather than establishing a pre-CCA update of the baseline.

U.S. Congress H.R. Hrg. 101-6/12

Attachment IV to EEG Review of CCA, Chapter 5

REVIEW OF THE STATUS OF THE WASTE ISOLATION PILOT PLANT PROJECT

pg. 163

HEARING

BEFORE THE

ENVIRONMENT, ENERGY, AND NATURAL RESOURCES SUBCOMMITTEE

OF THE

COMMITTEE ON GOVERNMENT OPERATIONS HOUSE OF REPRESENTATIVES

ONE HUNDRED FIRST CONGRESS

FIRST SESSION

JUNE 12, 1989

Printed for the use of the Committee on Government Operations

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Box 7078
Cincinnati, OH 45227

May 5, 1989
WD:89:00514

Mr. Richard J. Figlik, Manager
Management Support Staff
U. S. Department of Energy
WIPP Project Office
P. O. Box 3090
Carlsbad, NM 88221-3090

DRAFT PLAN FOR AS-BUILTS

Dear Mr. Figlik:

Four different completion times have been looked at for completion of as-builts. The completion times looked at are 15 months, 12 months, 9 months and less than 9 months. The data provided in the previous correspondence, HA:89:4057 dated 4/26/89, was used as a basis for the plan development, the system breakout, and the system priority. Currently, there are no funds within Westinghouse or people to support an as-built program. Past progress in this area has been made with people or funds diverted from other work. To get a quality product, a dedicated effort is needed. In order to obtain the necessary field data, there will be plant power outages and other impacts. Cables will have to be traced or rung out. It was assumed that the work would be conducted on any shift that the systems were available. Hourly rates and per diem costs are actual costs from PEAK. Where possible to prevent wasted time, activities would be worked in parallel. Due to problems scheduling outages, each team could be working on 5 or 6 systems at a time.

This document does not identify resources to correct any deficiencies discovered during the as-built program.

Sincerely,

M. R. Brown, Manager
Engineering & Repository
Technology Support

MRB/dc:3

HA:89:4064

Attachments (1): System Priority List
(2): Plan for Less than 9 Months
(3): Plan for 9 Months
(4): Plan for 12 Months
(5): Plan for 15 Months

U.S. Congress H.R. Hrg. 101-6/12

Attachment V of EEG Review of CCA, Chapter 5

REVIEW OF THE STATUS OF THE WASTE ISOLATION PILOT PLANT PROJECT

pgs. 330-332

HEARING

BEFORE THE

ENVIRONMENT, ENERGY, AND NATURAL RESOURCES SUBCOMMITTEE

OF THE

COMMITTEE ON GOVERNMENT OPERATIONS HOUSE OF REPRESENTATIVES

ONE HUNDRED FIRST CONGRESS

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RECEIVED FEB 5 1991 ENVIRONMENTAL EVALUATION GROUP

U.S. GOVERNMENT PRINTING OFFICE

United States Government — Department of Energy

memorandum

DATE: JUN 1 1989

REPLY TO ATTN OF: EH-331

SUBJECT: EH Oversight of the Waste Isolation Pilot Project (WIPP)

TO: Richard W. Starostecki, EH-90

This Office has completed two major efforts related to the oversight of WIPP. On April 28, 1989, we completed a one-week, onsite review of the WIPP Final Safety Analysis Report (FSAR). On May 15, 1989, we completed a Readiness Review Inspection (RRI). The EH staff trip report summarizing the FSAR review, dated May 4, 1989, and the RRI report are attached to this memorandum. Your approval of the RRI report by signature on the cover page is requested.

During the FSAR review a team of EH staff and consultants interacted with DOE WIPP Project Office (DOE/WPO), Westinghouse, and Bechtel representatives to close out requests for information flowing from our review of the FSAR and supporting documents. This effort also included resolution of questions that arose from independent calculations performed for EH by Brookhaven National Laboratory (BNL).

Most of the information required to close EH concerns related to the FSAR was developed during the onsite FSAR review. The task was hampered by almost total reliance on a single Bechtel representative to provide information related to the design or technical basis for selection of the structures, systems, and components that comprise the WIPP facility. This absence of knowledge on the part of operating staff indicates a significant deficiency in the transfer of the technical basis for the facility from the constructor (Bechtel) to the operating contractor (Westinghouse). Efforts are now underway to correct these deficiencies through such efforts as developing as-built drawings and the conduct of air flow tests to explore the rationale for the placement of monitors for airborne radioactive material.

Residual issues from the FSAR review have continued to be closed through review of later material provided by Bechtel and by onsite verification during the RRI. However, the accident analysis section of the FSAR contains issues that remain open and will be so noted in the EH Safety Evaluation Report. The seismic issues cited in the May 4, 1989, EH report are closed based on EH consultant review of analysis at the San Francisco offices of Bechtel.

The remaining design issue, documented adequacy of the concrete waste shaft key, is being addressed through new analyses by Bechtel to replace and update earlier analysis that were apparently destroyed and confirmatory analysis by BNL for EH. In our view, those retrospective analyses will likely have to be

supported by measurement of in situ stress in the inner surface of the concrete and monitoring of the key inside diameter for several years until its performance is sufficiently well understood for long-term acceptance. The likelihood of acceptable resolution appears good.

A fundamental management issue also remains open at this time; the adequacy of the DOE Quality Assurance (QA) program for the WIPP project. As presently structured, neither the dedicated QA staff, one person designated as the QA Manager, nor the low reporting level of the QA program meet the ANSI/ASME, NQA requirements espoused by DOE Orders. I believe that the adequacy of the DOE QA function at WIPP, particularly during the initial five-year experimental program will be a pivotal element in the successful demonstration of long-term isolation. Useful models for both DOE and the experimental program manager, Sandia National Laboratory, can be found in the evolving quality assurance programs associated with the high level waste program being conducted by the Office of Civilian Radioactive Waste Management. This issue deserves close and very high level attention.

The conduct of the RRI was based on 15 modules designed to sample a broad range of requirements based on commitments made in the FSAR, DOE Orders, the Design Validation Final Report (DVFR), and TSA criteria. The inspection was conducted by a twelve-member team of EH staff and consultants over a period of eight days. The team members reviewed the key technical documents that translated requirements into day-to-day operations, interviewed WIPP personnel, and inspected the facility buildings and systems.

As a result of the RRI, we have concluded that the physical plant at WIPP is very close to being ready for operation. The small number of exceptions appear to be addressed through satisfactory programs.

We have also concluded, however, that significant additional effort in ongoing staffing, training, procedure development, and documentation is necessary before EH could support a recommendation for startup. The areas most affected by these additional efforts are support functions such as radiological protection, maintenance, and quality assurance although additional training and qualification remain in operational areas as well.

Substantial efforts are underway in many of the areas needing improvement. For example, reorganization of the Radiation Protection Division was implemented during the week of our RRI, and we saw evidence of active recruitment efforts to staff this new organization. Although the as-built drawing effort noted above has not started, Westinghouse proposals for conduct of the program have been received and DOE/WPO has informed EH of its intent to make the availability of as-built electrical drawings to facilitate viable lockout and tagout procedures a first priority.

We have also briefly reviewed DOE/WIPP 89-011, Draft Plan For The Waste Isolation Pilot Plant Test Phase: Performance Assessment and Operations Demonstration, April 1989. This report summarizes the five year experimental program that will develop the data necessary to demonstrate the ability of the WIPP facility to meet applicable regulations and agreements for long term isolation. A complete internal review of DOE/WIPP 89-011 will require strong expertise in the geoservices and related geo-engineering disciplines that is not presently represented by cognizant DOE staff in the field or at headquarters.

James P. Knight
Director
Office of Safety Appraisals

cc: w/o attachment
W. Kornack, ACNFS
W. Kranz, RL
J. Tillman, WIPP
A. Follett, DP-122

8.9 Summaries of Waterflows for the New Mexico Oil Conservation Division Districts 1 and 2

SUMMARY OF WATERFLOWS IN NMOCD DISTRICT 1 (NOVEMBER, 1978 TO PRESENT)

(SORTED BY LOCATION)

UNIT NO.	DATE	OPERATOR	LEASE NAME/ WELL NO.	UNIT	T-R-SEC	OCD REF	REPORTED	DEPTH	DRILL OR MOD	FPM	PRESSURE	COMMENTS
1	[illegible]	[illegible]	[illegible]	K	04-17-33			[illegible]				HIT 5" WATERFLOW ON [illegible] WELL AT 3000'.
2	[illegible]	[illegible]	[illegible]	[illegible]	04-10-32			3002		4		DECREASED TO 2 BPM ON [illegible].
3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]		60		DRILLED TO 4187' @ 8[illegible] PM Dec. w/160# SI. STILL HAD SOME FLOW ON INTERMEDIATE.
4	1/7/81	[illegible]	[illegible]	C	18-16-35			2470		100		[illegible] DO NOT REPORT DRILLING [illegible] HIT WF 2470'. DEPLETED & DRILLED AHEAD. [illegible]
5	[illegible]	[illegible]	[illegible]	L	15-16-35			3710'		8700		
6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	CLOSED		[illegible]				WATER FLOW OUT SURFACE. NEW 1/4/78. [illegible]
7	[illegible]	Monsanto	Ventura [illegible]	F	14-16-19			6300'				HIT WF @ 6300'. OPTED TO CONTINUE.
8	6/7/80	[illegible]	[illegible]	M	16-17-37	CLEMENTS						PLUGGED WELL. IN 3 DAYS [illegible] AROUND MARKER. [illegible]
9	5/29/79	Arco	[illegible]	E	17-32-29							1 STREAM FROM CSG THAT HAD [illegible] AT SURVEY TIME. [illegible]
10	12/27/79	Arco	[illegible]	J	17-33-29	BECKNER		3400'				@ STREAM [illegible] PM W/ SOME GAS [illegible] AT 3400'.
11	11/1/79	Arco	[illegible]	H	17-33-29							BETWEEN [illegible] & 7-CSG. WATERFLOW ON [illegible].
12	[illegible]	Conoco	[illegible]	G	17-33-29							
13	1/1/80	Conoco	[illegible]	B	17-33-29							
14	3/10/80	Abandoned Corp	[illegible]	C	17-33-30			3700'				HIT WATERFLOW ON DRILLING WELL.
15	[illegible]	Duval Exploration	[illegible]	M	17-33-30	CLEGG		[illegible]				LARGE WATER FLOW FROM SALT.
16	3/13/81	Jameland		K	17-33-30			[illegible]				HIT @ [illegible]
17	3/3/81	[illegible]	[illegible]	G	17-33-30			4400'				
18	No date	Crown Central	[illegible]	M	17-33-30							
19	[illegible]	Phillips	[illegible]	[illegible]	17-33-31			4300'				HIT WF @ 4300' @ 5 MM. [illegible]
20	[illegible]	Phillips	[illegible]	E	17-33-31			3794'	DRLG			60 GAL PER MM.
21	No date	Phillips	[illegible]	F	17-33-31							
22	[illegible]	Phillips	[illegible]	H	17-33-31			3450'		31		
23	[illegible]	Phillips	[illegible]	[illegible]	17-33-31					30		
24	[illegible]	Phillips	[illegible]	H	17-33-31			4000'	[illegible]	31		
25	[illegible]	Phillips	[illegible]	G	17-33-31			4300'		68		WELL LOCATIONS FROM INTERIOR WELL. WILL HAVE AROUND [illegible] INJECTION WELL [illegible]
26	[illegible]	Phillips	[illegible]	D	17-33-31			3400'		30		VAC AREA.
27	No date	Mobil	[illegible]	A	17-34-32			3500'				REPAIR JOB WATER ENTERING CSG AT 3500'.
28	[illegible]	Mobil	[illegible]	G	17-34-34							TRG/TOR LEAK REPORTED. WILL REPAIR [illegible].
29	[illegible]	Phillips	[illegible]	L	17-34-30			4017'		60		HIT WF @ 4017' @ 60 BPM.
30	[illegible]	Phillips	[illegible]	L	17-34-30			3073'				
31	[illegible]	Phillips	[illegible]	M	17-34-30			3027'		400	150	
32	[illegible]	Phillips	[illegible]	F	17-34-30			3000'				CASING COLLAPSED @ 3000' WAVE OUT SURVEYED [illegible] WELL P.A.
33	[illegible]	Texaco	[illegible]	O	17-34-31	CLOSED		1167		91	450	WATERFLOW @ 1167' @ 90 BPM. [illegible]
34	[illegible]	Texaco	[illegible]	I	17-34-31	CLEMENTS		1167	DRLG	12		WATERFLOW @ 1167' @ 10 BPM.
35	[illegible]	Texaco	[illegible]	K	17-34-31	CLEMENTS		1167	DRLG	78		WATERFLOW @ 1167' @ 15 BPM. RAN CSG. AND CEMENTED OFF.
36	[illegible]	Texaco	[illegible]	L	17-34-31	BLINEBRY		3920'	DRLG	78		WATERFLOW @ 1920' @ 76 BPM.
37	[illegible]	Texaco	[illegible]	M	17-34-31	BLINEBRY		3700'		60	640	WATERFLOW @ 1700' @ 60 BPM. [illegible]
38	[illegible]	Texaco	[illegible]	H	17-34-31			1700'	DRLG	60		WATERFLOW @ 1700', 1777', 1800', 1850', 1930', 2900'. TOTAL FLOW [illegible]
39	[illegible]	Texaco	[illegible]	H	17-34-31			1700'	DRLG	1000		WATERFLOW @ 1700' @ 1000 BPM. AT 1850' INCREASED TO 2000 BPM.
40	[illegible]	Texaco	[illegible]	H	17-34-31			1850'	DRLG			WATERFLOW @ 1850' @ 40 BPM. [illegible]
41	[illegible]	Texaco	[illegible]	H	17-34-31				DRLG			RUNNING THE APPROXIMATELY 70 JOINTS OF 8 5/8. NO OTHER INFO AVAILABLE - [illegible]
42	[illegible]	Texaco	[illegible]	O	17-34-31				DRLG	800		WATERFLOW WHILE CEMENTING. [illegible]
43	[illegible]	Texaco	[illegible]	F	17-34-31	CLEMENTS		1000'		60	300	WATERFLOW @ 1000', 2510', 2510', 3P = 700 PSI.
44	[illegible]	Texaco	[illegible]	F	17-34-31	CLEMENTS		3700'		100		WATERFLOW @ 3700'. [illegible]
45	[illegible]	Texaco	[illegible]	F	17-34-31			1700'	DRLG	3000	450	WATERFLOW @ 1700' [illegible]
46	[illegible]	Phillips	[illegible]	F	17-33-31				PROD	9		SEE FLOW OUTSIDE [illegible] CSG. [illegible]
47	[illegible]	Phillips	[illegible]	I	17-33-31			1800'	[illegible]			300 GAL OIL PER MINUTE
48	No date	Phillips	[illegible]	J	17-33-31							
49	[illegible]	Texaco	[illegible]	H	17-33-31			1771'	DRLG	2500	940	12 HOUR AIR BLOW. CHANGE VALVE TO 60 INTO FLOW LINE. NOW 2500-3000 BPM AT [illegible]
50	No date	Phillips	[illegible]	K	17-33-31							
51	[illegible]	Phillips	[illegible]	M	17-33-31							REVERSED WATERFLOW FROM SURFACE CSG.

SUMMARY OF WATERFLOWS IN NMOCD DISTRICT 1 (NOVEMBER, 1978 TO PRESENT)

(SORTED BY LOCATION)

DIST NO.	DATE	OPERATOR	LEASE NAME/ WELL NO.	UNIT	T-R-SEC	OCD REP	REPORTED	DEPTH	DRLG OR PROD	BPH	PRESSURE	ADDITIONAL REMARKS
32	8/7/83	Arco	State B 1576 #6	N	17-35-33					40		WATER BROKE INTO CELLAR. FLOWED 40 BBLS & APPEARED TO BE FLOWING ABOUT 4 BPH FROM AROUND SURFACE
33	8/7/83	Amoco	CHGBAU Tr 3229 #1 P	N	17-35-33							
34	5/3/78	Phillips	Fed Vacuum Unit	N	17-35-33	CLEMENTS		2507'		20		
35	4/2/91	Texaco	NMA St #1L	A	18-34-01			1760'	DRLG	60		4/3/91 @ 1760'. CROSSFLOWED THEN FLOWED 4 BWPH @ 2990' @ 30 BPH.
36	11/29/78	Texaco	Vac GBSA Ut #5P	B	18-34-01			3184'	PROD	8-10	Flow	CASING LEAK AT 2284' IN COLLAR. WATERFLOW @ 8-10 BPH. SIP=1105 PSI.
37	4/18/91	Texaco	VGSAU A Ut #1M	B	18-34-01			1447'	DRLG	48		WATERFLOW @ 1400' @ 40 BPH
38	4/22/91	Texaco	NM L St #40	B	18-34-01			1711'	DRLG	16		WATERFLOW @ 1600' & M @ 1711' @ 16 BPH
39	No date	Texaco	VGSAU #57	B	18-34-01				PROD			
40	7/3/90	Texaco	VGSAU A Ut #107	C	18-34-01			1777	DRLG	108		WATERFLOW @ 1777' @ 108 BPH.
41	3/91	Texaco	VGSAU 30	E	18-34-01							SOME WATERFLOW ON INTERMEDIATE. DAMPED TO 40-60 PPM
42	No date	Texaco	VGSAU Ut #140	H	18-34-01							
43	4/7/91	Texaco	NM B NCT-3 #4	H	18-34-01			1900'	DRLG	99		WATERFLOW @ 1900' @ 99 BPH. NO OTHER INFORMATION AVAILABLE
44	7/7/87	Texaco	NM B St NCT-3 #24	P	18-34-01			2419'	DRLG	144		VAC POOL
45	7/16/87	Texaco	NM B St NCT-3 #24	P	18-34-01				DRLG			WATERFLOW @ 1870', 2070', 2560'. TOTAL FLOW=2200 BWPH.
46	5/16/92	Texaco	West Vac Ut #44	C	18-34-03				PROD		Flow	WATERFLOW TEST ON 8 5/8. WILL REPAIR.
47	6/4/84	Amoco	ETH Q #4	L	18-34-04			3000'		99		1ST WATER FLOW ON DRLG. WELL AT 2987 - 3000'.
48	No date	Phillips	Evi Fed U 1987 #16	I	18-35-05							SIGNIFICANT FLOW AT 3400' OR 4 5/8 ON REPLUGGING
49	9/24/90	Texaco	Central Vac Unit #144	A	18-36-06			1840'	DRLG	30		WATERFLOW @ 1840' @ 30 BPH.
50	2/25/91	Texaco	NM B St NCT-1 #12	K	18-36-06			2040'	DRLG	30		WATERFLOW @ 2040' @ 30 BPH. AT 2440' FELL 30 BPH. IN INTERMEDIATE CSG
51	10/15/78	Texaco	Central Vac Unit #127	D	18-36-06	CLEMENTS		2000'	DRLG	1000		WATERFLOW DRILLING @ 2000' 1000 BWPH.
52	11/27/80	Texaco	Central Vac Unit #Wn. 11	D	18-36-06			1800'	DRLG	60	Flow	WATERFLOW @ 1010', 2100', 2510'. MAX FLOW=600 BPH. MAX SIP=900 PSI.
53	10/27/78	Texaco	Central Vac Unit #134	E	18-36-06	CLEMENTS		1840'	DRLG			WATERFLOW @ 1840' & 2241' @ 100 BPH.
54	3/79	Texaco	Central Vac Unit #105	E	18-36-06	CLEMENTS			PROD			WE BELIEVED TO HAVE PRESS. FLOWING FROM 2000'-2100'. DV 3000' @ 1500'.
55	4/79	Texaco	Central Vac Unit #100	F	18-36-06	CLEMENTS		1450'	DRLG	25	Hot	WATERFLOW @ 1450' AND 1560'. EVER-PRES. WILL RETCSG. @ 2040'.
56	9/18/78	Texaco	Central Vac Unit #109	G	18-36-06	MORROW		2017	DRLG		Hot	WATERFLOW @ 2017 @ 10 BPH. INC. TO 15 BPH. SIP=800. P @ 2147.
57	8/30/79	Texaco	Central Vac Unit #108	G	18-36-06			3140	DRLG	15		WATERFLOW @ 3140' AND 3560'. TOTAL=15 BPH. 10 MIN SIP=300#
58	No date	Texaco	Central Vac Unit #107	G	18-36-06	CLEMENTS		1977		30		
59	9/25/87	Texaco	Central Vac Unit #90	H	18-36-06				DRLG			WATERFLOW @ 400 A.M. RAN=400 BPH. SIP=200#.
60	2/20/88	Texaco	NMO St NCT-1 #28	H	18-36-06			1740'	DRLG	1800		WATERFLOW @ 1740' @ 1800 BPH.
61	8/27/79	Texaco	Central Vac Unit #116	J	18-36-06			2300'	DRLG	15		WATERFLOW ON DRILLING WELL @ 2300'. FLOWING 15 BPH. DRILLING AHEAD WITH NO INCREASE IN VOLUME. WILL RETCSG
62	12/1/81	Texaco	Wasson A/B 4	K	18-36-06			3900'	PROD	400		1ST WATER FLOW ON WORKOVER JOB. VOLUME CALCULATED AT 2200'. FLOWED AT 400 BPH
63	4/19/90	Texaco	Central Vac Unit #134	L	18-36-06			1840'	DRLG	40		WATERFLOW @ 1840' @ 40 BPH. INC. TO 70 BPH @ 2000'. @ 60 @ 2200'.
64	9/3/81	Texaco	Central Vac Unit #114	L	18-36-06	CLEMENTS		1960	DRLG			WATERFLOW @ 1960'. 2340'. TOTAL FLOW=600 BPH. SIP=1000'. @ 60 @ 2160'. DV1 @ 1900'.
65	4/29/80	Texaco	Central Vac Unit #114	M	18-36-06				PROD			WATERFLOW AFTER BOTTOM WAS PLUGGED OFF ON P.L.
66	2/18/79	Texaco	Central Vac Unit #131	N	18-36-06			2030	DRLG	40-60	1000	WATERFLOW ON DRILLING WELL @ 2030' FLOWING 40-60 BPH. SIP=1000#. 500' 8/18/79.
67	8/14/79	Texaco	Central Vac Unit #132	O	18-36-06			2194	PROD	10	1100	WATERFLOW @ 2194' @ 10 BPH. SIP=1100#
68	10/1/79	Texaco	Central Vac Unit #139	O	18-36-06			2340'	DRLG	15		WATERFLOW @ 2340' @ 15 BPH. SIP=1000#. RAN 7" @ 2000'.
69	5/21/80	Energy Reserves	TP State #1	J	18-36-08			3340'				POOR LY PLUGGED.
70	No date	Amoco	Amoco St M #1	L	18-36-14							
71	12/11/84	Bonds Energy	Aco State #1	O	18-36-14			2000		400-600		4 HR FLOW @ 1000 BPH @ 300#. ASSUMED TO BE OR RETDISPOSAL WELL.
72	8/24/87	Bass Enterprises	Forest St #1	P	18-36-21				DRLG	1440		
73	1/11/90	Glenn Energy	Hobbs St	B	18-36-27				DRLG			1ST WATER, DRLG DEPTH UNKNOWN. 30 BPH. COMPLETED AT 4567'. INTEND TO P.A. (DRY).
74	3/27/91	Bonds	Barron St	D	18-36-27			2900'	DRLG	1000	900	
75	12/11/81	Union Oil	Mexico Ut D	F	18-36-33	CLEMENTS		3450'		800		
76	No date	Arco	Hawkins Fed (MD) #3	G	18-36-33							
77	12/80	Amerada	Gil Lanier #3	B	18-37-21			1000'				
78	5/30/81	Amerada	Gil Lanier #7	C	18-37-33	CLEMENTS		1530'				
79	6/9/79	Gulf	State H Com	K	18-37-33			3200'				LOCATED WATERFLOW AT 2200'. REPAIRED.
100	No date	Amoco	Mid Vacuum	B	18-38-08							
101	5/81	Anadarko	Bass Com Unit	P	20-33-19			3700'		600		
102	1/11/80	Anadarko	Tom Kuykendall St #1	G	20-33-34			3511'		900		

SUMMARY OF WATERFLOWS IN NMOCD DISTRICT 1 (NOVEMBER, 1976 TO PRESENT)

(SORTED BY LOCATION)

UNIT NO.	DATE	OPERATOR	LEASE NAME/ WELL NO.	UNIT	T-R-N-C	OCCURRENCE	REPORTED	DEPTH	DRLG OR PROD	BPH	PRESSURE	ADDITIONAL REMARKS
[illegible]	[illegible]	[illegible]	[illegible]	E	[illegible]			[illegible]				DRILLING.
[illegible]	[illegible]	[illegible]	[illegible]	G	[illegible]			[illegible]				[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]					[illegible]		APPROXIMATELY [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	I	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	F	[illegible]				[illegible]			[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	G	[illegible]				[illegible]			[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	G	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	K	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	D	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]	[illegible]		[illegible]		[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	P	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	B	[illegible]			[illegible]	[illegible]			[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]		[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	M	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	K	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]						[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	E	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	D	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	E	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	M	[illegible]							[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	I	[illegible]			[illegible]			[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]	[illegible]						
[illegible]	[illegible]	[illegible]	[illegible]	E	[illegible]			[illegible]				[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	F	[illegible]					[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	H	[illegible]			[illegible]		[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	K	[illegible]			[illegible]	[illegible]			[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]	[illegible]		[illegible]				[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	D	[illegible]			[illegible]		[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]		[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]		[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	F	[illegible]			[illegible]		[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	I	[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	C	[illegible]			[illegible]		[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	A	[illegible]			[illegible]		[illegible]		[illegible]

SUMMARY OF WATERFLOWS IN NMOCD DISTRICT I (NOVEMBER, 1978 TO PRESENT)

(SORTED BY LOCATION)

SITE NO.	DATE	OPERATOR	LEASE NAME / WELL NO.	UNIT	LOCATION	OCD NOTIFIED	REPORTED	DEPTH	DRILL OR PROD	BPH	PRESSURE	ADDITIONAL REMARKS
154	8/27/82	Texaco	Jal Brantley Fed NCT-3#4	C	23-26-37			3005	DRLG	40	650	WATERFLOW @ 3000' @ 60 BPH. PRESS=400#.
155	10/18/84	Amoco	A.A. Brantley Fed NCT-3#3	D	23-26-37			3055'	DRLG	1000		WATERFLOW @ 3100' @ 1000 BPH OR MORE. TY TUBING PLUGGED DOWN ENOUGH TO DRILL AHEAD
156	5/10/79	Amoco	SNC #1	E	23-26-37							
157	3/4/83	Sun	Brantley Ring NW #3	C	23-26-37							CASING COLLAPSED APPROX 600-700' MONITOR OFF. WILL MOVE RIG TO COMPLETE PA
158	3/24/80	Amoco	SNC #1	C	23-26-37							RF. REPAIR CASING. PUNCHED LOC.
159	8/14/79	A. Crosby	Brantley Fed #3	D	23-26-37							PROBLEM OF SALT WATER COMING OUT SURFACE. WILL PERFORATE @ 1200' & SQUEEZE.
160	[illegible]	[illegible]	[illegible]	M	23-27-01			1500'	DRLG	400		SHUT IN PRESSURE 1000 CSP VIA [illegible].
161	10/10/81	Mewbourne	Gulf St #1	F	23-27-03			2600'		6000		DOG HOUSED TO 300 BPH IN 1.5 HOURS
162	4/9/83	Texaco	Elan State #2	N	23-27-03			3047'	DRLG	400	625	WATERFLOW ON AIR @ 3047' & 3417' @ 400 BPH. ANOTHER @ 3700'. CEMENTED OFF DRLG ON INTERMEDIATE.
163	1/10/85	Texaco	Shelly Ranch A #37	J	23-27-05			1600'		750		WATERFLOW @ 1/2/86 @ 2415' @ 300 BPH. 1/22/86 RETIPPED AND DRILLED AHEAD
164	3/1/84	Texaco	Shelly Ranch A #47	N	23-27-05				DRLG			WATERFLOW @ 2700' @ 65 BPH.
165	4/2/83	Texaco	State #2	N	23-27-04			2600'	DRLG			NO FLOW 3000'. INCREASED TO 315 BPH AT 3800 @ 600 PSI 20 BPH H2S. FLOW STABILIZED AT 120 BPH. SHUT IN PRESSURE
166	No date	Texaco	RK State #3	H	23-27-04			3047	DRLG	80		SHUT IN 1100-600 PSI.
167	11/24/83	Texaco	GW State #3	B	23-27-07			1444	DRLG	1200		WATERFLOW @ 1444' @ 1200 BPH. PRESS=300 PSI
168	8/23/84	Texaco	B Hanson #425	G	23-27-09			3067	DRLG	600		WATERFLOW @ 3067' @ 600 BPH. SP=[illegible]
169	8/3/81	Texaco	B Hanson #4	D	23-27-09			1307	DRLG	65	850	WATERFLOW @ 1307' @ 65 BPH. SEEMS TO INTERMEDIATE THROUGH FLOW.
170	3/13/84	Texaco	B Hanson #3	K	23-27-09			1317	DRLG	100		WATERFLOW @ 1317' @ 100 BPH. WATERFLOW @ 3700' @ 1200 BPH.
171	7/24/84	Texaco	B Hanson #1	L	23-27-09			1327'	DRLG	85		WATERFLOW @ 1327' @ 85 BPH
172	No date	Texaco	B Hanson #2	L	23-27-09			1327'	DRLG	1000	650	WATERFLOW @ 1327' @ 1000 BPH. [illegible]
173	11/1/84	[illegible]	Gomez #1	K	23-27-13			1500		100		
174	4/16/81	Texaco	Elvin #NCT-2 #1	P	24-27-33	CLOSED						WATERFLOW. [illegible] TO REPAIR [illegible].
175	5/13/84	Texaco	WTSU #14	C	24-28-33				TPLG			FLOW [illegible] BPH.
176	5/1/80	Gulf	WTSU #119	P	24-28-32							SHUT IN TO REPAIR TO REMOVE CIBP. PA'D.
177	5/11/84	Texaco	WTSU #131	P	24-28-32			1400	DRLG			WATERFLOW @ 1400' @ 7 BPH. WATERFLOW @ 2000' @ 20 BPH.
178	8/27/80	Gulf	SWU #178	I	25-27-15							CASING FLOWED TO SURFACE DUE TO PERFORATE.
179	5/24/81	D. Hardman	Gl Ranch #3	L	26-27-15			2997'	DRLG	Avg. 1200		SALT WATER.
180	8/24/83	Mewbourne	Dragoon NP Federal #3	A	26-27-15					Avg.		
181	10/27/83	Texaco	Brantley Yates Unit #14	C	26-27-27					7		WATERFLOW @ 7 BWPH. (NO REPORT TO OCD).
182	3/22/84	Texaco	Brantley Yates Unit #3	F	26-27-27			1311'	PROD		400	WATERFLOW ON BACKHEAD (NO REPORT TO OCD)
183	10/31/83	Texaco	Brantley Yates Unit #4	A	26-27-27					900		WATERFLOW ON BACKHEAD @ 43 BWPH. (NO REPORT TO OCD).
184	1/84	Texaco	Brantley "B" #1	G	26-27-27			1335'				WATERFLOW ON BACKHEAD @ [illegible]. (NO REPORT TO OCD).
185	10/11/84	Texaco	WTSU Producer #4	H	26-27-27					650		REPORTED TO OCD ON 10/1/84. REPORTED 10/10/79
186	3/84	Texaco	Brantley "B" #4	H	26-27-27					450		WATERFLOW ON BACKHEAD @ 35 BPH. (NO REPORT TO OCD)
187	11/13/87	Texaco	Brantley "B" #20	I	26-27-27					1000		WATERFLOW ON BACKHEAD @ 40 BWPH. (NO REPORT TO OCD)
188	11/20/87	Texaco	Brantley "B" #21	I	26-27-27					75		WATERFLOW @ 15 BWPH. (NO REPORT TO OCD).
189	11/2/87	Texaco	Brantley Yates Unit #46	K	26-27-27					1000		WATERFLOW @ 15 BWPH. (NO REPORT TO OCD).

WATERFLOW INFORMATION

1. Pogo Producing Co. 9/30/92 ; Federal Red Tank 34 #1-34-22-32 Drilling 3000' Flowed 800 bbls - High in H_2S, - Don Riggs 713-297-5045 10/23/92

2. Texaco Expl & Prod. 4-7-93; NMR NCT-3 #5- Drilling @ 1864' 90 BPH No other information available.

3. Texaco Expl & Prod. 4-9-93; Ellen Sims #9-3-23-37 Drilling @ 3049' Flowing 660 BPH @ 825# 4:00 AM -5-10-93 down to 440; 5/11/93 James Elliott down to approx. 70 BPH since 5-10-93 PM - setting 8 5/8" intermediate @ 3750'.

4 Texaco Expl & Prod. ; BF Harrison B #9 9-23-37 Drilling @ 1571' Flowed 1000 BPH Shut in Pressure 600#

5. Samedan; Sarah B #3-M 1-23-37 Drilling @ 1590' 600 BPH +-; Shut In Pressure 1000 Est. Vol 92000 +-.

6. Texaco Expl & Prod; R. R. Sims A #3 - 4-23-37; Drilling @ 2240' ; Flowed 80 BPH, Shut In Pressure 600 psi.

7. Texaco Expl & Prod: 11/24/93 - 9:00 AM; G. W. Sims #3- B - 9-23-37; Drilling @ 1444' Flowed 1200 BPH; Pressure 500 psi; Flowed down in 6 hours - 12-1-93 Drilling @ 5600', no further problems.

8. Texaco Expl & Prod; 5/17/94; WDDU #131 -32-24-38; Drilling @ 1420' ; Flowed 7 BPH @ 2000' 20 BPH.

9. Texaco Expl & Prod; 5/13/94; WDDU #146 - C 32-24-38; Drilling @ ?; Flowed 70 BPH.

10. Texaco Expl & Prod; 5/25/94; B F Harrison B #25 - C - 9-23-37; Drilling @ 2065'; Flowed 600 BPH; Shut In Pressure 875 down to 400 BPH @ 2:35 puff H_2S down to 1 PPM @ 2:35 Drilling ahead.

11. Texaco Expl & Prod; 5-1-95; R.R. Sims B #1 - 4-23-37; Drilling @ 1709'; Flowed 390 BPH; Pressure not recorded 5/1/94 up to 800-1000 BPH - Flow heavy for approx 1 hour then slacks off - Drilling not delayed and drilling at 3282' approx. 7:45 AM 5/1/95.

12. Phillips Petro. Co.; 7/1/96; Hale 25 25-17-34; Drilling @ approx. 4800' - Poss hit earlier no pressure - 10 BPH up to 20 BPH and back to 10 BPH - com. Drilling set production casing 7/2/96.

13 Nearburg Prod. Co.; 10/6/97; Madura Federal #5 - E- 28-19-33; Drilling @ 8549 10-6-97; No record of pressure or volumes 100 BPH per Jack - Hit @ 1300' swedge and squeezed hit again 1900#.

14. Texaco Expl & Prod.; 10/25/97; State AN #12 ; Drilling @ 2985; No pressure recorded

60 BPH - down to 45 BPH @ 11 am - 10/27/97 Depth 3380' will set intermediate @ 3506.

15. John H. Hendrix 12/2/97; Boyd #7 - 23-22-37 Drilling; No pressure recorded 700 BPH.

TOWN	RANGE	SEC	UNIT/LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	PRM TOPS
1	2	26	E	Petrosaic Co	Summer 36	1		294'	
1	28	6	H	Diamondback Petro. Inc.	Cave St.	2	1289'-1408WPD		
5	26	18	D	Yates Petro. Corp.	Paulsen PV ST	5			
5	26	34	E	Meridourne Oil Co.	Pecos Slope 34	1			
8	26	20	D	Yates Petro. Corp.	Hancock AHC Com.	3	28-30 bbls Hrs 5# Pump Flash		
8	26	33	D	Yates Petro. Corp.	Tamarack DF St.	1		597'	
8	26	33	E	Yates Petro. Corp.	Tamarack DF St.	2			
8	26	33	E	Yates Petro. Corp.	Tamarack DF	3		718'	
7	22	1	P	Mesa Petro. Corp.	Haley Com.	2			
7	22	2	F	Exxon Corp.	New Mexico CS St.	1		95'	
7	22	12	A	Yates Petro. Corp.	Haley Com.	3			
7	23	3	M	Yates Petro. Corp.	Barnett SN St.	1		318'	
7	23	8	M	Mesa Petro. Corp.	W.E.C. Com.	1			
7	23	10	L	Mesa Petro. Corp.	Round Top St.	5		460'	
7	23	20	O	Mesa Petro. Corp.	McKnight Com.	1		175'	
7	23	32	A	Yates Petro. Corp.	Rambler AGU St.	1			
7	24	8	J	Yates Petro. Corp.	Salmon Draw NR	1			
7	24	11	P	Yates Petro. Corp.	Red Bluff St.	1			
7	24	27	E	Yates Petro. Corp.	West Dixon NK St.	1			
7	24	35	P	Yates Petro. Corp.	Snakeweed SO St.	1			
7	25	2	P	Yates Petro. Corp.	Canelo BH St.	1			
7	25	7	C	YATES PETRO. CORP.	HILLTOP NO ST	1			
7	25	11	A	Mesa Petro. Corp.	Burns Com.	2			
7	25	11	I	Mesa Petro. Corp.	Burns Com.	1			
7	25	17	P	Yates Petro. Corp.	Cockburn RD	1			
7	25	23	A	Yates Petro. Corp.	Red AN$	1			
7	25	27	I	Yates Petro. Corp.	Pegasus OI ST Com.	5			
7	25	30	F	Yates Petro. Corp.	Saint SK St.	4			
7	25	5	F	Mesa Petro. Corp.	Neal Com.	1			
7	26	6	B	Yates Petro. Corp.	Crandel UD	2			
7	26	16	K	Sanders Petro. Corp.	McKay Samedan	2	1850'-20 BPM		
8	23	33	D	Yates Petro. Corp.	Middle Creek St.	1		75'	
9	23	5	K	Mesa Petro. Corp.	Ned St.	1			
9	23	5	O	Mesa Petro. Corp.	Ned St.	2		300'	
9	23	8	L	Mesa Petro. Corp.	Ned St.	3			
9	23	11	H	Yates Petro. Corp.	Whipple ZH St.	1			
10	25	2	H	Yates Petro. Corp.	Erickson KY	1		320'	
10	25	8	H	Yates Petro. Corp.	Hargrove AIH	1			
10	25	16	M	Yates Petro. Corp.	Bluer Lake FX St.	1			
10	25	17	C	Yates Petro. Corp.	Eakin AKB Com.	1			
10	25	17	H	Union Inc.	Cannon Fed.	3			
10	25	17	H	Yates Petro. Corp.	Cannon XF	1		402'	
10	25	27	B	Yates Petro. Corp.	Unruh AFF	1	612'-15-20 BWPM Gyp/Wtr 0000 ppm/cl		

RECEIVED SEP 5 1996 ENVIRONMENTAL EVALUATION GROUP

TOWN	RANGE	SEC	UNIT/LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	FRM TOPS
11	24	18	J	Wallace Oil & Gas Inc.	Hain	1			
11	25	3	M	Wallace Oil & Gas	Britt	1			
11	25	3	M	Wallace Oil & Gas	Britt	2	830' Fresh Water		Hondo SA Perf. 858'-88'
11	25	4	F	Fred Pool Drlg co.	Hondo River Farm	1			
11	25	8	J	Wallace oil & Gas Co.	Payton	1			
11	25	10	D	Wallace oil & Gas Co.	Marshall & Winston	1	W.F. @ 870' 5800Gal./Min. 2300ppmCl.		
11	25	20	F	Wallace oil & gas Inc.	Perrine	1		800'	
11	25	29	F	William R. Mason	Stanell Com.	1			
11	26	14	L	YATES PETRO. CORP.	Mccaw bt	7	0	750	
12	23	28	E	Philips Petro. Corp.	N.M. 28 St.	1		1032'	
12	26	3	L	Meinetz Oil Co.	Bogle	1	W.F. @ 30' .0626 Stream No Pst.		
12	26	3	L	Meinetz Oil co.	Bogle	1	1/16" Stream No PSI @ 30' Closed off		
12	26	8	N	Patroit Corp.	Capt Johnson	1			Top S.A. 680'
13	26	35	J	Clemente Energy Inc.	New, Mex. 35 St.	2			
14	24	9	I	The Superior Oil Co.	Ivy League Fee	1			
14	26	20	J	Clemente Energy Inc.	Bird	1y			
14	26	22	K	Southland Royalty Co.	Hagerman West 22	1			
14	26	23	M	Shenandoah Oil Co.	Rhodes	1			
14	26	33	E	Lynx Petro. Corp.	Drumm Com.	1			
14	26	33	G	Clemente Energy Corp.	Drumm Com.	1			
14	26	36	J	Clemente Energy Corp.	King 36 Com.	1			
15	25	28	F	Yates Petro. Corp.	Carol Jackson RD	1		900'	Top S.A. 802'.
15	26	32	F	Mesa Petro. Corp.	Mesa State Com.	2	1187'-800BPH Brine FLOW SI PSI 650#		
15	26	32	K	Mesa Petro. Corp.	Mesa State Com.	4	468' 180 BWPH		
16	17	6		J. Cleo Thompson	State A	6		AirDil	
16	30	5	J	Petro. Devel. Corp.	Marcello Fed.	1	2350' 8" Stream.		
16	30	9	C	Yates Petro. Corp.	Sidey PY Fed.	1	2737' 10BPM		
16	30	11	I	Yates Petro. Corp.	Strange "PZ" Fed.	1	2950' 3BWPM SI PSI 1350J.		
17	17	3	F	J. Cleo Thompson	State A-3	1		412'	Open. LC @ 1210' Cag Was Set In Orig Brack.
17	26	13	I	Yates Petro. Corp.	Aichen Fray DM	2			
17	26	14	H	Yates Petro. Corp.	McCaw BT	2		750'	
17	26	14	M	Yates Petro. Corp.	Morris Estate DG	6		723'	
17	26	14	P	Yates Petro. Corp.	Winters DN	4		740'	
17	25	15	P	Yates Petro. Corp.	Morris Estate DC	7		715'	
17	25	16	P	Yates Petro. Corp.	Morris Estate CC	7		715'	
17	26	22	H	Yates Petro. Corp.	J Lary J	1			
17	25	23	I	Yates Petro. Corp.	Michell Jo	6			
17	25	23	K	Yates Petro. Corp.	Giesler AV	6			
17	25	23	M	Yates Petro. Corp.	Giesler AV	30			
17	25	27	A	Yates Petro. Corp.	Ingram Jackson BV	10			
17	26	35	O	Yates petro. Corp.	Pearl DG				
17	26	36	I	Yates Petro. Corp.	Avon ES St.	2			
17	26	10	P	Marbourne Oil Co.	Sullivan	1			

TOWN	RANGE	SEC	UNIT/LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	FMN TOPS
17	28	14	E	Mewbourne Oil CO.	Haldermas	1			
17	28	14	M	Mewbourne oil Co.	Vogel	1			
17	28	15	J	Texas Petro. Corp.	Cyfiell Fed. FD	2			
17	28	19	K	Medallion Prod.Co.	Levels 19	1			
17	28	36	N	Balbala Forkin	State 36	1			
17	28	27	J	Mabuh Energy Corp.	NG Phillips St.	25	494:88'1.50GaWtr.		
17	28	35	O	Mewbourne Oil CO.	State BX	1	870' 516 BWPD		
17	28	12	P	Marbob Energy Corp.	Burch Keely Ut.	1	2430		
17	30	1	A	Ray Westall	Artesia Paso.Fed.	4	2385' 8000BPD oil psi-950#		
17	30	2	B	J.Cleo Thompson	Hayes ST.	9	2530' 3" Stream		
17	30	16	I	Pinnler Oil & Gas Co.	Dale H. Parke "D"	2	2317' 1100BWPD		
17	30	34	G	Anadarko Petro. Corp.	Arnold Fed. Com.	1	6185'284 BWPD		Glorieta 4700'-6000'
17	31	3	G	Devon Energy Corp.	H.E. West A	32	2549' 1 BPH		
17	31	3	J	Devon Energy Corp.	H.E. West "B"	76	33 BWPH @ 2550'		
17	31	3	L	Devon Energy Corp.	H.E. West B	33	3227' 14 BPH		
17	31	3	O	Devon Energy Corp.	H.E. West "B"	86	18 BWPD @ 2637'		
17	31	4	E	Devon Energy Corp.	H.E. West B	73	3225' 7.50 BPH		
17	31	5	O	Devon Energy Corp.	J.L. Keel B	69	2800'-3000' 14 BPH		
17	31	5	N	Devon Energy Corp.	J.L. KEEL B	64	2510' 2.3 BPH		
17	31	8	B	Sosemo Petro. Co.	J.L. Keel "B"	93	2500'-320BPH		
17	31	7	A	Devon Energy Corp.	J.L. Keel A	23	3000'-3100' 38 BPH		
17	31	7	H	Devon Energy Corp.	J.L. Keel A	33	3800' 50 BPH		
17	31	7	J	Devon Energy Corp.	J.L. Keel A	137	730' 10 15 BPH		
17	31	8	F	Devon Energy Corp.	J.L. Keel B	90	3800' 23 BPH		
17	31	8	I	Devon Energy Corp.	J.L. Keel B	57	1297' 48 BPH		
17	31	8	J	Devon Energy Corp.	J.L. Keel B	78	3400' 17 BPH		
17	31	8	M	Devon Energy Corp.	J.L. Keel B	93	1400' 3.8 BPH		
17	31	9	G	Devon Energy Corp.	H.E. West B	61	2568' 43 BPH		
17	31	9	O	Devon Energy Corp.	H.E. West B	81	3502' 2 BPH		
17	31	9	P	Devon Energy Corp.	H.E. West B	72	3300' 118 BPH		
17	31	10	D	Devon Energy Corp.	H.E. West B	66	3800'-4190' 33 BPH		
17	31	10	E	Devon Energy Corp.	H.E. West B	81	3598' 5 BPH		
17	31	10	F	Devon Energy Corp.	H.E. West B	60	3877' 16 BPH		
17	31	10	G	Devon Energy Corp.	H.E. West B	67	3313' 1.5 BPH		
17	31	10	I	Devon Energy Corp.	H. E. West "B"	70	4010' 1.50 BPH		
17	31	17	E	Devon Energy Corp.	Hudson Fed.	A	20-147 BPH @ 590'		T.Rustler @ 367'T.Salado @ 500'B.Salado @ 1325'
17	31	17	M	DEVON ENERGY CORP.	TURNER B	116	2798'-60 BPH		
17	31	18	E	Devon Energy Corp.	C.A. Russell	15	4 BWPD @ 738'		
17	31	18	I	Devon Energy Corp.	Turner "A"	52	47 BWPD @ 1003'		
17	31	18	L	Devon Energy Corp.	Turner A	38	17 BWPD @ 2625'		
17	31	18	N	Devon Energy Corp.	Turner A.	33	18 BWPD @ 2842'		
17	31	18	P	Devon Energy Corp.	Turner "A"	40	47 BWPD @ 1003'		
17	31	19	A	Devon Energy Corp.	Hudson Fed.	11	7 BPH @ 3080'		

TOWN	RANGE	SEC	UNIT/LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	RIM TOPS
17	31	18	A	Devon Energy Corp.	Hudson Fed.	7	0 BPH @ 1905'		
17	31	18	A	Devon Energy Corp.	C.A. Russell	17	778'-809' 142 BWPH		
17	31	18	I	DEVON ENERGY CORP	TURNER A	55	22 BPD @ 3061'		
17	31	18	M	DEVON ENERGY CORP.	TURNER A	41	2579'-43 BPH		
17	31	18	N	DEVON ENERGY CORP	TURNER A	59	27 BPD @ 2611'		
17	31	18	O	Devon Energy Corp.	Turner A	42	2265' 21 BWPD		
17	31	18	O	DEVON ENERGY CORP	TURNER A	58	80 BPD @ 2696'		
17	31	18	P	DEVON ENERGY CORP.	TURNER A	44	752'-20 BPH		
17	31	18	P	DEVON ENERGY CORP.	TURNER A	43	803'-88 BPH		
17	31	19	H	Devon Energy Corp.	Turner "A"	50	482'90BWPD, 1188'200BWPD, 1388'240BPD		
17	31	19	I	Devon Energy Corp.	Fern Oil Co.	24	14 BWPD @ 1440'		
17	31	19	G	Devon Energy Corp.	Turner A	46	61 BWPH @ 1575'		
17	31	19	G	Devon Energy Corp.	Turner A	45	34 BPH @ 1320'		
17	31	19	G	DEVON ENERGY CORP	TURNER A	67	11 BPD @ 1614'		
17	31	19	F	Devon Energy Corp.	Turner A	48	42.6 BWH @ 1326'		
17	31	19	G	Devon Energy Corp.	Turner A	49	800' 143 BWPD		
17	31	19	H	Devon Energy Corp.	Turner A	47	3.0 BPH @ 1050'		
17	31	19	J	Devon Energy Oper. Corp.	Turner A	51	1402'-1408' 71 BWPH		
17	31	19	J	DEVON ENERGY CORP	FRESS FED	4	172 BPD @ 718'		
17	31	20	M	DEVON ENERGY CORP	TURNER A	118	57 BPD @ 882'		
18	25	10	I	Yates Petro. Corp.	Thistle AKF	1		693'	
18	25	34	K	Yates Petro. Corp.	Rio Penasco RT	2		770'	
18	26	1	D	Barrera Falkon	Higgins Trust "1"	1			
18	26	18	N	Yates Petro. Corp.	West Dayton AJR	1		765'	
18	26	18	A	Yates Petro. Corp.	Vandiver Oil Com.	2		894	
18	26	22	H	Yates Petro. Corp.	Lawrence ADZ	2			
18	26	22	M	Yates Petro. Corp.	Paybuck Fz	2		60'	
18	26	26	C	Yates Petro. Corp.	Dayton FN	2			
18	26	34	C	Yates Petro. Corp.	Allied Lee ABH	2			
18	26	34	C	Yates Petro. Corp.	Allied Lee ABH	2			
18	26	34	C	Yates Petro. Corp.	Allied Lee ABH	2			
18	27	7	K	Devon Energy Corp.	West Red Lake Ut.	65			
18	27	7	D	Devon Energy Corp.	West red Lake Ut	39			
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18	27	26	H	SDX Resources Inc.	Allegia Mesa	84			
18	28	8	A	Anderto Petro. Corp.	Mallard 08 AU TR. 5	15	1385' 214 BPH SI PSI 180#		
18	28	22	G	Primier Oil & Gas Co.	Yates Primier Fed.	3	1566' 10# Brine		
18	29	22	K	B&W Inc.	Empire 22 Fed. Com.	1	960'28000 BWPD		
18	29	22	K	Pay Weight	Dayton Fed.	6	938' 5000 BPD		
18	29	22	O	Premier	Yates Premier Fed.	1	1543' 10 GM (Min.		

TOWN	RANGE	SEC	UNIT	LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	FRM TOPS
18	30	2	N		MEWBOURNE OIL CO.	LOCO HILLS ST.	4	1615 38PM 450 SI PSI MACKISM WTR		
18	30	2	O		Mewbourne Oil Co.	Cedar Breaks St. 2	3	838 40 BWPH SI PSI 350# 10.6 Brine		Salt Section 720'-1500'
18	24	4	N		Yates Petro. Corp.	Rancherie AMH St. Com.	1		79'	
19	24	33	E		Yates Petro. Corp.	Agave AAJ St.	3		80'	
19	25	4	O		Yates petro. Corp.	Brainhaw	2			
19	25	4	O		Anadarko Petro. Corp.	Brainhaw	2			
19	25	8	I		Yates Petro. Corp.	THOMAS AJJ	4		470'	
19	25	8	I		Yates Petro. Corp.	Thomas AJJ	6			
19	25	8	J		Yates Petro. Corp.	Thomas AJJ	3			
19	25	8	P		Yates Petro. Corp.	Roy AET	5			
19	25	8	E		Yates Petro. Corp.	Marshall Aph	1			
18	25	8	F		Yates Petro. Corp.	Marshall APH	1			
18	25	8	F		Yates Petro. Corp.	Marshall APH	1			
18	25	8	G		Yates Petro. Corp.	Patrick AFI	2			
19	25	16	G		YATES PETRO. CORP.	APARIJO AFA ST COM.	6		80'	
19	25	15	D		Yates Petro. Corp.	Apache AMP	1			
19	25	16	K		Yates Petro. Corp.	Anole Amm St. Com.	2			
19	25	17	K		Conoco Inc.	Bairain 17	17			
19	26	20	H		Yates petro. Corp.	Hooper AMP	3			
19	20	20	M		Yates Petro. Corp.	Fairole Alt Com.	1			
18	25	21	E		Yates Petro. Corp.	Hooper AMP	2			
18	25	21	H		Yates Petro. Corp.	Parch AIZ	10		384	
18	26	24	E		Newburg Prod. Co.	Ferrel 24	1		55'	1" from 100' to 55' Pres. vold 400' 100'.Quer. wil
18	25	27	E		Newburg Prod. Co.	South Boyd 27	3			
18	26	27	L		Newburg Prod. Co.	South Boyd 27	4			
19	25	28	B		Yates Petro Corp.	Hinkle AUD	2		400'	
18	25	28	G		Yates Petro. Corp.	Hinkle AIB	1		53'	
18	26	28	J		Yates Petro. Corp.	Tackett AQT	1		247'	
18	20	28	J		Newburg Prod. Co.	State K	2		190'	
19	25	28	O		Yates Petro. Corp.	Tackett AQT	3			
18	26	29	D		Yates Petro. Corp.	Wright AJD Com.	1			
19	25	32	A		Conoco Inc.	Savannah St.	1			
19	25	32	A		Conoco Inc.	Savannah State	1		960'	
19	25	33	A		MEWBOURNE OIL CO	STATE B	2			
19	26	18	I		Newburg Prod. Co.	Lakewood Farms 18	1			
19	26	1	B		Bass Enterprises Production Co.	Merchant Bass	3	1390' 146 BWPH 10# Brine 200#S PSI		
19	30	14	K		Texaco Explo. & Prod. Co.	Renuida Basin St.	2			Top Salt 837' Base Salt 2870'
20	24	1	A		Yates Petro. Corp.	Foster AN	3			
20	24	1	A		Yates Petro. Corp.	Foster AN	1		825'	
20	24	1	G		Yates Petro. Corp.	Mobil AOB	1		247'	
20	24	2	M		Yates Petro. Corp.	Candelilla AKD	2			
20	24	11	F		Yates Petro. Corp.	Sara AHA Com.	6		308'	
20	24	14	M		Yates Petro. Corp.	John AGU	5			

TOWN	RANGE	SEC	UNIT LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	RIM TOPS
20	24	21	A	Yates Petro. Corp.	Albert AJH	1		62'	
20	24	22	C	Yates Petro. Corp.	Carl TP	3			
20	24	24	D	Nearburg Prod. Co.	Mayer 24	2		171'	
20	24	25	E	Yates Petro. Corp.	Chandler McKay Com.	4		185'	
20	24	25	L	Yates Petro. Corp.	Kirin ALA	1		172'	
20	24	26	A	Yates Petro. Corp.	Conoco AKG FED.	4		171'	
20	24	36	M	Marathon Oil Co.	Indian Hills St.	8		86'	
20	24	36	K	Marathon Oil Co.	Indian Hills St.	1		45'	
20	28	6	O	Chi Oper. Inc.	savage	1			Pro stiff section 260-1000 No capitan reef sec. 8
20	28	30	F	Exxon Corp.	Avalon Delaware UT	232			
20	28	32	E	EXXON CORP.	AVALON DELAWARE UT.	2220			
20	28	32	L	Exxon Corp.	Avalon Dela. Ut.	2420		1700'	
21	22	32	O	Premier Oper. Co.	Fanning Draw St.	1		Air Dr	Water 1330'-1490' bailed full of water,Fluid level 80'
21	23	2	J	Marathon Oil Co.	N. Indian basin Ut.	10		Airdrl	
21	23	2	M	Marathon Oil Co.	N. Indian Basin Ut.	12		airdrl	Fresh Water @ 218', Brackish Water @ 710'
21	23	2	O	Marathon Oil Co.	N.Indian Basin Ut.	11		800	
21	23	16	A	Marathon Oil Co.	North Indian Basin Ut.	8		148	
21	24	36	M	Mitchell Energy Corp.	Indian Hills 36	1		117'	
21	26	9	E	Chi Oper. Inc.	Winer St.	3		420	
21	26	9	F	Chi Oper. Inc.	OXY St.	2		1148	
21	26	9	K	Chi Oper. Inc.	OXY St.	1		850	B. Capitan-3130
21	26	8	N	Chi Oper. Inc.	Winer Com.	5		848	
21	26	16	F	Devon Energy Corp.	Cactus State	8			
21	26	16	I	Devon Energy Corp.	Cactus State	10		1220'	
21	26	16	O	Devon Energy Corp.	Cactus St.	4			
21	26	16	O	Devon Energy Corp.	Cactus State	5			
21	26	16	A	Devon Energy Corp.	Cactus St.	12		770'	
21	26	16	B	Devon Energy Corp.	Cactus State	7		890'	
21	26	16	C	Devon Energy Corp.	Cactus St.	1		650	
21	26	16	D	Devon Energy Corp.	Cactus State	5			
21	26	16	E	Devon Energy Corp.	Cactus State	8			
21	26	16	G	Devon Energy Corp.	Cactus St.	3		78'	
21	26	16	G	Devon Energy Corp.	Cactus ST.	3		443'	LC-78'
21	26	16	J	Devon Energy Corp.	Cactus Samp.	5			
21	26	16	K	Devon Energy Corp.	Cactus St.	4			
21	27	9	D	Ray Westall	Myrtle Myra	5			Capitan Reef 1348-1719
21	27	16	A	Ray Westall	Myrtle Myra	8			
21	27	17	F	Yates Petro. Corp.	Glider AG St.	1		1264	
21	28	3	K	Energex Oil Co.	Teodoro St.	1			Capitan Reef 1350 2106
21	28	3	M	Pogo Prod. Co.	State	1		1359	
21	31	36	P	Pogo Prod. Co.	State 2	1			
21	31	36	P	Pogo Prod. Co.	State 2	1			
22	23	3	M	Oryx Energy Corp.	Conoco St. Gas Com.	2		542'	

TOWN	RANGE	SEC	UNIT	LTR	OPERATOR	PROP NAME	WELL NUM	WTR FLOW	LOST CIR	FRM TOPS
22	23	18	D		Chevron USA Inc.	Bogle Flats UT	18			
22	23	21	G		Yates Petro. Corp.	Wagon Ut.	1		835'	
22	24	2	K		Nearburg Prod. Co.	Big Walk 2 St.	3			
22	28	32		A	Louis Dreyfus Nat. Gas.	E.V. State	1			
22	30	34	A		Exxon Oil & Gas Co.	James Ranch Ut.	71			Base Salt 3588'
22	30	35	K		Basa Enterprises Prod. Co.	James Ranch Unit	29			Base Salt - 3808'
22	30	36	N		BASS ENTERPRISES Prod. Co.	James Ranch Ut.	41			Base Salt-3664'
22	31	17	A		Yates Petro. Corp.	Graham AKB St.	1			B. salt 4073'
22	31	20	H		Yates Petro. Corp.	Graham AKB St.	2			
22	31	29			Pogo Prod. Co.	Stace 2	3			Base Salt-4100'
22	31	29	U		Pogo Prod. Co.	Stace 2 #4	4			Base Rustler @ 700'.Top Salt @ 800'.
22	31	2	K		Yates Petro. Corp.	Flora AKF State	2			Base Salt 4020'
22	31	2	N		Yates Petro.Corp.	Flora AKF St.	1	2032' Flowed 35.30 MMFr w/H2S Sm.		
22	31	2	O		Pogo Prod. Co.	State 2	2	1208PH @ 3087' flowed to 0 10 Hrs.		
23	28	24	A		B.K. Oper. Corp.	Remuda Basin St.	2			Base Salt 3001'.
23	30	19	C		Texaco Expl. & Prod. Inc.	Remuda Basin 19 Fee	1			Base Salt 3328'
23	31	16	C		Yates Petro. Corp.	Medano VA St.	10			Base Salt-3913
23	31	22	E		Enron Oil & Gas Co.	Poker Lake 32 St.	9			Base Salt 3840'
24	25	8	C		W.A. Moncrief Jr.	Jurnegan St.	1			
24	25	8	K		W.A. Moncrief Jr.	Jurnegan St.	2		1005'	Top Delaware-2784'
24	26	9	B		Santa Fe Energy	Mosley Canyon 9 St.	1		1070'	Base Capitan Reef-2484
24	26	10	C		HNG Oil Co.	S. Horseshoe Bend 10	1		1272'	
24	26	17	C		R.E. Hebert	Ridge St	1		939'	
24	26	17	D		Santa Fe Energy	Lonbshop 17 St. Com.	1		1539	Base Capitan Reef 2279'
24	25	20	B		Santa Fe Energy	Lonbshop 20 Fed.Com.	1		2090	Top Capitan Reef 845',Base Capitan Reef 2385'

EEG-69
DOE/AL58309-69

SENSITIVITY ANALYSIS OF PERFORMANCE PARAMETERS USED IN MODELING THE WIPP

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May 1998

FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independant technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, is being constructed as a repository for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC04-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, continues authorization.

EEG performs independent technical analyses of the suitability of the proposed site, the design of the repository, its planned operation, and its long-term integrity, suitability and safety of the transportation systems, suitability of the Waste Acceptance Criteria and the generator sites' compliance with them, and related subjects. These analyses include assessments of reports issued by the DOE and its contractors and other federal agencies and organizations as they relate to the potential health, safety, and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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EXECUTIVE SUMMARY

Introduction

The sensitivity of the performance assessment calculations in the Department of Energy's (DOE) Waste Isolation Pilot Plant (WIPP) Compliance Certification Application (CCA) (U.S. DOE 1996) was first investigated by Helton (1996) in order to understand the impact of several key parameters. His analysis used scatter plots and stepwise correlations to determine consistency among repository parameters. However, his analysis only applied to the actual range and distributions of sampled parameters used in the CCA calculations. Changes to either the range or distribution of one parameter may strongly affect the importance of other parameters, because estimates of releases vary by orders of magnitude for different combinations of parameter values. A case in point is the brine reservoir compressibility, which has been determined to have insignificant influence on the total release. The values chosen for brine reservoir pressure and volume used in the CCA calculations reduced the importance of the brine reservoir on the calculated releases, therefore eliminating the compressibility. It is entirely possible that this brine reservoir parameter would be one of the most important contributors to large releases in calculations using more appropriate brine reservoir parameter values of pressure and volume.

The scope of the sensitivity analysis performed by Helton (1996) prompted the Environmental Evaluation Group (EEG) to conduct an independent analysis, by changing selected values or the range of selected values that were used in the CCA. This type of sensitivity analysis would distinguish the important parameters of repository performance, while testing the robustness of the codes involved. The analysis also allowed for the testing of the limit to which the disposal system would fail under extreme conditions. This is also useful in characterizing the important parameters.

Borehole Intrusion Rate

The consequence of future human intrusion scenarios into the WIPP was investigated in the CCA, as required by EPA in 40 CFR Part 194 (U.S. EPA 1996b), and included the possibility of mining and deep and shallow drilling for resources.

The 40 CFR Part 194.33 criteria state that the likelihood of a drilling intrusion into the Delaware Basin be calculated by considering the frequency of drilling over the past 100 years for all resources and that rate be used for the 10,000 year future of the WIPP. A total of 46.8 boreholes per km^2 per 10,000 years were estimated based on past drilling of resources at depths greater than 655 meters (2150 feet), which equal 10,804 boreholes per century in 23,102.1 km^2 (area of Delaware Basin).

The above drill intrusion rate for the 10,000 year future of the WIPP was used by DOE in the CCDFGF model. Due to the uncertainty in predicting future human activities, the effect of altering this rate on the CCA calculations has been assessed in this report.

The modeling associated with an increased borehole rate shows that a factor of approximately 23 is needed to reach the U.S. Environmental Protection Agency (EPA) release limit at a probability of 10^{-1} from values used in the CCA. The overall mean for the highest release tested at 0.468 boreholes/km^2/yr exceeds 10 EPA Unit limit at the 10^{-3} probability on the CCDF curve. This high rate of bore hole intrusion, however, does not seem to be likely, as the number of boreholes drilled in the Basin in 10,000 years would have to exceed one million per century, or 4,680 boreholes per km^2 per 10^4 years.

Probability of Brine Encounter at WIPP

The probability of encountering brine at the WIPP from an intrusion into a Castile brine reservoir is uncertain. The parameter describing the probability was set to 8% in the CCA, and changed to a range of probabilities from 1% to 60% in the EPA's Performance Assessment Verification Test (PAVT). Since the extent of the reservoir beneath the WIPP is unknown, the influence of this parameter was tested at higher values at 50% and 100%. These values were based on the potential that the Castile brine reservoir encountered by WIPP-12 (Chaturvedi et al. 1997) extends below the waste area.

The modeling presented in this report only compared CCA release values to the proposed higher probability of encounter, and found the parameter to be unimportant in the CCA. The increase in releases from the 8% to 100% was only 0.1 EPA units (35 Ci). However, the synergistic effect of changing multiple parameters, especially those that affect a Castile brine reservoir directly (pressure, volume, rock compressibility, etc.) may have a more profound result on the calculations, though these changes would have to result in releases of at least 1 EPA unit to significantly impact the CCDFs.

Castile Brine Reservoir Parameters

A pressurized Castile brine reservoir that may underly the WIPP has been the subject of many controversies on its extent and importance (EEG 1997b; EEG 1997d; Silva 1994; U.S. DOE 1997a; Beauheim 1997). The scientists who conducted the performance assessment calculations of the CCA recognized the fact that the brine could play a significant role in the degradation of wastes and waste containers, if an inadvertent drilling intrusion were to pass through the repository to the brine pockets below, by assigning two of the six scenarios to

calculate the effects of the breach. However, reservoir parameters used in the CCA were derived from borehole information that are mainly outside the domain of the WIPP repository. The borehole distances ranged from 3.75 miles to over 11 miles from the repository center. New values were assigned to several parameters that describe a Castile brine reservoir based on WIPP-12 data that is more closely identified to the conditions at the repository. The WIPP-12 borehole was originally drilled in 1978 and deepened in 1981. After brine was encountered at WIPP-12, EEG recommended that the site be relocated to the south and DOE concurred. Brine flow occurred when coring reached a depth of 3012 feet (D'Appolonia 1982). While extending the borehole to depths greater than 3900 feet, a total of 80,000 barrels were allowed to flow from the borehole.

The parameters associated with describing a Castile brine reservoir include reservoir volume, rock compressibility, reservoir pressure, and permeability. Assuming an inadvertant human intrusion, modeling of these parameters began with the two-phase flow code, BRAGFLO, and ended with calculations of solid and liquid waste released to the accessible environment. The outcome showed that there is no significant change in releases for the CCDF due to small changes in the reservoir parameters. However, it is expected that the CCDF curve would move closer to the EPA limit if the solubility of actinides in brine were increased above that assumed in the CCA and PAVT.

Solubility Modeling of Actinides

For brine to escape the repository and travel upwards through the borehole under blowout conditions, 1) pressures must be significant to overcome the hydrostatic force of the drilling fluid, and 2) sufficient brine must be available for transport. Both conditions have been met in many of the realizations in the performance assessment calculations of the CCA. However, due to the proposed low solubility of actinides in brine, the consequence of a direct release of brine to the surface was minimal. For example, the mean release of radionuclides in the CCA through a direct brine release was 0.04 EPA Units (14 Ci) at the 10^{-3} probability, compared to spallings or cuttings and cavings, each having releases of 0.2 EPA Units (70 Ci).

The physical and chemical characteristics of the repository used in the CCA were questioned by the EPA. The EPA changed several disposal system parameters to test their range of uncertainty. Using EPA's values, DOE reran the calculations for the Performance Assessment Verification Test (PAVT). Some of the changes involved the solubility of the actinides in a brine solution assuming a different speciation of minerals associated with the MgO backfill material, which lowered the median solubility limit for most actinides. The new set of solubility values came from the same FMT code used to establish the original set of numbers. No new

experiments were conducted to verify any of the values.

The results of the PAVT showed a large overall increase in the amount of brine brought to the surface upon intrusion, yet only nominal increase in release of actinides. This was expected, since the median solubilities decreased by as much as 2 orders of magnitude for the +4 radionuclides. The effect on compliance from the changes shifted the CCDF for the direct brine release scenario closer to the compliance limit by 0.15 EPA Units. The changes in consequence are minimal, since 10 EPA Units of release are needed to fail compliance at the 10^{-3} probability.

Based on the observations of Reed et al. (1994; 1996) and Rao (1996), EEG questioned the CCA assumption that plutonium would exist only in +3 and +4 oxidation states. Hence, EEG conducted bounding calculations on solubility. The solubility values were only nominal increases above the CCA values for plutonium in the +3 or +4 oxidation state for Salado Brine, but upwards of 10000 for Castile Brine.

The results of the EEG modeling showed that increases in solubility using CCA brine release volumes had limited effect on compliance with an overall increase on the mean CCDFs by 0.09 EPA Units. Even when the solubility was increased to absurdly high values, the maximum release was limited by the availability of the actinide source. At a solubility of 8×10^{-3} M (compared to the CCA's 4.4×10^{-6} M for Pu+4 in Salado Brine), the overall mean for direct brine release was increased from 0.04 to 1.3 EPA Units.

The second set of EEG modeling experiments changed the solubilities of actinides in several mineral species of MgO between the conversion of brucite to magnesite. Calculations by Novak (1997) estimated solubility values for the major oxidation states (III, IV, V, and VI) at WIPP in the presence of magnesite, nesquehonite, hydromagnesite, and no backfill. The release calculations of the CCA assumed the long-term mineral species for MgO to be magnesite, and the PAVT assumed hydromagnesite. Yet, laboratory experiments could not prove the existence of either, and only showed hydromagnesite-like or proto hydromagnesite (Papenguth et al. 1997). These other mineral species looked more like nesquehonite (Neill et al. 1998), making it arduous to justify either mineral phase assumed by the DOE and EPA.

Bounding calculations were performed on conditions resulting in the highest solubilities in the repository. These included nesquehonite and no backfill. For the nesquehonite simulations, it was assumed that the mineral would persist for the entire proposed history of the repository. Only median solubility values were used, as opposed to the CCA, which generated a set of expected values from a range of -2 to +1.4 orders of magnitude from the median to capture the

uncertainty. The assumption that the intermediate species being long-lived is an overestimate on the expected conditions, and the EEG does not suggest that MgO not be used as a backfill material. The models were established to better understand the performance of the repository.

Table Ex-1 shows the solubility factors used to achieve solubility values from Novak (1997). The values have been log transformed for use in the input files to change the values that were established in the CCA. For example, SOLAM3-SOLCIM for nesquehonite increases the solubility of Am+3 in Castile Brine by 1.516 orders of magnitude, whereas SOLAM3-SOLSIM decreases the solubility by 0.277 orders of magnitude. The changes were made in the source term files, for the running of PANEL and NUTS.

In addition to solubility changes from the CCA, the Salado flow files from the PAVT were used for transport calculations of NUTS and PANEL. The PAVT calculations exhibited higher repository pressures, hence larger direct brine releases upon intrusion. The maximum effect would be noticed with both changes together.

Table Ex-1 shows that the solubility of the +4 actinides (Pu+4, U+4, and Th+4) in the presence of nesquehonite is higher than without any MgO backfill. This would suggest that the scenario with backfill has larger releases than without.

Figure Ex-1 shows the overall mean of all processes combined as they relate to compliance. In addition, the PAVT direct brine releases were run with the slightly higher CCA solubilities. The most distinct feature of the figure is the shoulder of the high solubility models that extend below the 10^{-1} probability limit. The “shouldering” is the effect of increased releases due to the direct brine release. Since the Pu+4 and Th+4 (although minor) solubilities increased over 5 orders of magnitude, the release due to this mechanism is expected to increase significantly as well. For example, the CCA median value for +4 actinide solubilities in Castile brine was $6x10^{-9}$ M. If one assumes 100 m^3 of Pu^{239} contaminated brine, then it is expected that the release is $2.5x10^{-5}$ EPA Units. If the solubility is increased by $10^{5.23}$ as seen in Table Ex-1, then it is expected that 4.24

	nesquehonite		No Backfill	
	SOLCIM	SOLSIM	SOLCIM	SOLSIM
SOLAM3	1.51616	-.27709	4.48678	3.83714
SOLPU3	1.51616	-.27709	4.48678	3.83714
SOLPU4	5.23242	2.15588	4.06695	2.05552
SOLU4	N/A	2.15588	N/A	2.05552
SOLU6	0.95861	0.96357	0.95861	0.96357
SOLTH4	5.23242	2.15588	4.06695	2.05552

Table Ex-1. Solubility Factors for SOLCIM and SOLSIM

EPA Units are released to the accessible environment. Therefore, the CCDF for higher solubilities would be closer to the EPA limit.

The consequences of higher solubilities, as seen in Figure Ex-1 are quite high. The overall mean release for the CCA and PAVT were 0.2 and 0.4 EPA Units at 10^{-3} probability, respectively. The overall mean for the increased solubilities of nesquehonite and 'no backfill' are 6.0 and 8.0 EPA Units at the 10^{-3} probability, respectively. The limit for compliance, according to 40 CFR Part 194 is 10 EPA Units. While these calculations, based on DOE's own solubility values, do not violate the containment requirements, they show that there is little margin for error.

Flow and Transport Modeling within the Culebra

The transport of radionuclides to the accessible environment can happen two ways: upwards from the repository through a borehole to the surface into the biosphere, or laterally through the stratigraphy of highly conductive layers across the Land Withdrawal Boundary (LWB). The second method was investigated by modeling the Culebra aquifer. The CCA and PAVT include Culebra modeling and its consequence of transport across the LWB in the CCDF curves. The CCA showed only 1 of 300 realizations to cross the boundary in 10000 years with the PAVT showing a significantly higher impact on the Culebra. The end result of increased transport across the LWB in the PAVT had little to no overall effect on the CCDF.

The EEG's concern in the Culebra modeling began with the parameter assumptions that describe actinide behavior with the Culebra Dolomite. When the actinides migrate along flow paths after a release to the Culebra, the transport will be retarded by the interaction of the actinides with the Culebra dolomite matrix. The interaction is known as sorption. The Culebra was characterized as having a linear isotherm with the actinides, and the parameters of the isotherm, known as the partition or distribution coefficient (K_d) were measured or inferred from laboratory experiments.

The same oxidation state analogy used for solubility was applied to the distribution coefficient; same oxidation states would exhibit similar values. Therefore, many of the actinides' K_ds were not actually measured and it is not clear what the consequence would have been with directly measured values. Though it is well known that high K_d values will retard the actinide species sufficiently to inhibit transport, it is the low K_d values that are of concern. For example, it was shown in Blaine (1997) that K_d values higher than 3 ml/g for most actinides would sufficiently retard transport. Only one actinide in the PAVT, U+6, has K_d values as low as 2 ml/g.

Some waste constituents in the inventory at WIPP may bind to the actinides and further lower

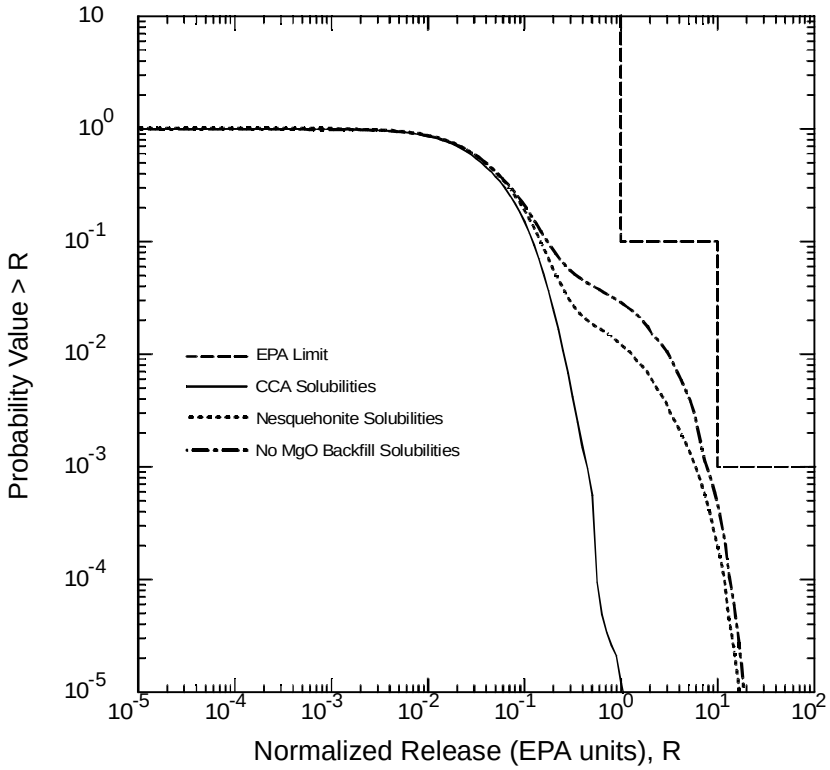

Figure Ex-1. Overall Mean of Normalized Releases for Modeling of Increased Solubilities using Nesquehonite and 'No Backfill' Values Compared to CCA Values

the K_d values. EDTA, for example, is used in industry for chelation with plutonium for quick cleanup. Other organic ligands in the waste will have similar effect. Furthermore, the lack of K_d measurements decrease the confidence in values used in the CCA and PAVT, and this prompted the EEG to continue with additional calculations, testing the effects of lowered K_ds on the disposal system and compliance.

The interaction between releases from the repository and transport of actinides require a lengthy discussion, and will not be discussed here. It is possible, due to the set up of the codes, to do calculations that assume any percentage of the actinide's mass to completely bind with EDTA and migrate unretarded through the Culebra matrix. Therefore, additional calculations were performed assuming 1% of Pu (+3 and +4) having a K_d=0 ml/g.

The results of the calculations show that the overall mean of the releases through the Culebra was 0.0001 EPA Units at the 10^{-3} probability. Since a large number of realizations crossed the LWB with significant releases, it was reasoned that the mass of radionuclides reaching the Culebra was the limiting factor. This was proved when the models of higher solubility were combined with transport modeling, and the overall mean for release from the Culebra was

increased to 0.31 EPA Units.

Another model was proposed by EEG in which the extent of potash mining within the controlled area (or Land Withdrawal Area-LWA) was extended to include lower grade potash ore. Potash mining occurs in the McNutt Potash Zone of the Salado, and is several hundred feet below the Culebra. The effect of potash mining in the Delaware Basin would cause subsidence to the overlying units, and hence have a possible detrimental consequence from increased transport of radionuclides. The EPA established the criteria for the mining by assigning a multiplying factor to the transmissivities of the Culebra, which increased the velocities in the mined region.

The extent of mining in the long-term future is debatable, depending on assumed future economic viability of the resource. New methods such as solution mining could extract lower grade minerals more readily. Therefore, the EEG included a larger area of potential mining in a new flow model, yet keeping the same parameter changes that were used in the CCA. It is feasible to change other parameters or include new ones, but due to the limited time available, was not thoroughly investigated.

The results of extending the areal minable region below the Culebra had little to no effect on the transport of radionuclides across the LWB, though it did change the flow patterns slightly. The limit of transport is sorption, and the PAVT values for K_d were retained for uranium. The combination of low K_d and larger mining area was studied with plutonium, again using the 1% K_d=0 ml/g. Again, the amount of initial mass injected to the Culebra crossing the LWB was significantly higher, but limited by the amount reaching the Culebra.

Lastly, the effects of extended mining, low K_ds, and high solubilities were combined in an effort to test the synergistic effect of all the previous results. The overall mean for the release through the Culebra was as high as 1 EPA Unit (or 344 Ci) at a 10^{-3} probability of release. The addition of the Culebra releases to the overall mean of all combined releases moved the CCDF closer to the EPA compliance limit by 12%, but did not show non-compliance.

SENSITIVITY ANALYSIS OF PERFORMANCE PARAMETERS USED IN MODELING THE WIPP

1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is intended to be the first repository for the permanent disposal of defense generated transuranic (TRU) wastes. The WIPP is located in southeastern New Mexico, 655 meters below the surface in the Salado Formation. The containment of transuranic wastes in the ancient salt beds of the Salado *"will result in extremely effective isolation of the radioactive waste"* if the repository is to remain undisturbed for 10,000 years (U.S. DOE 1996). Modeling of this undisturbed scenario encompasses the natural processes such as the salt creep closure of the excavated repository and disturbed rock zones (DRZ) which surround the repository, brine flow into the repository from under- and over-lying formations, and gas generated through degradation of waste and waste containers. The performance assessment of the repository was also required by 40 CFR Part 191 Subpart B (U.S. EPA 1996a) to consider disturbed scenarios by which a breach may occur through inadvertent drilling for resources. The release of radionuclides to the accessible environment during the 10,000 year future of the repository must be quantified to ensure compliance with the requirements stated in 40 CFR Part 191.13 (Containment Requirements). The accessible environment refers to everywhere beyond the controlled boundary, including land, air, and water. The cumulative radionuclide release through a probabilistic performance assessment must fall below specified limits within the time frame designed for containment. The estimate of probabilistic releases through these scenarios was calculated using computer codes designed specifically for the flow and transport of radionuclides through the formations that overlie the WIPP, as well as direct releases to the surface.

1.1. Performance Assessment

The estimated releases from the performance assessment for WIPP were incorporated into probability distributions. One of the requirements used to judge satisfactory performance of the repository is to demonstrate that the calculated releases have a likelihood of less than 1 in 10 to exceed the quantities listed in Table 1.1 (U.S. EPA 1996a), and less than 1 in 1,000 to exceed ten times the quantities in Table 1.1. A performance assessment refers to an analysis that *(1) identifies the process and events that might affect the disposal system, (2) examines the effects of the processes and events on the performance of the system, and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant process and events* (U.S. EPA 1996). In addition to the performance assessment of the disposal

Radionuclide	Release (curies) per million curies of alpha-emmiting radionuclides
Americium-241, -243	100
Carbon-14	100
Cesium-135, -137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, -239, -240, -242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230, -232	10
Tin-126	1,000
Uranium-233, -234, -235, -236, -238	100
Other α-emitting radionuclides, half-life > 20 years	100
Other α-emitting radionuclides, half-life < 20 years	1,000

Table 1.1. Release Limits as Stated in 40 CFR Part 191, Subpart B

system, certain assurance requirements were necessary to provide confidence that the containment of TRU wastes will be maintained for 10,000 years as stated in CFR 40 Part 191.13. For example, active institutional controls (AICs) should be exercised for as long as possible after disposal. Active institutional control simply means the maintenance of the site, remediation or cleanup of a release, and monitoring after closure of the repository. These controls can be assessed up to 100 years after disposal, after which passive institutional controls (PICs) will proceed that include markers, public records, and other methods to preserve the knowledge of the dangers of the wastes contained below. Although AICs and PICs are considered part of the assurance requirements, they were included in the containment calculations.

The performance assessment calculations were submitted to the EPA in October 1996 in the form of a Compliance Certification Application (CCA). The CCA was compiled from many years of scientific and engineering investigations, and consists of nine chapters with 58 supporting appendices that reference over 600 professional publications. The CCA also describes the DOE Quality Assurance Program and the results of independent peer reviews.

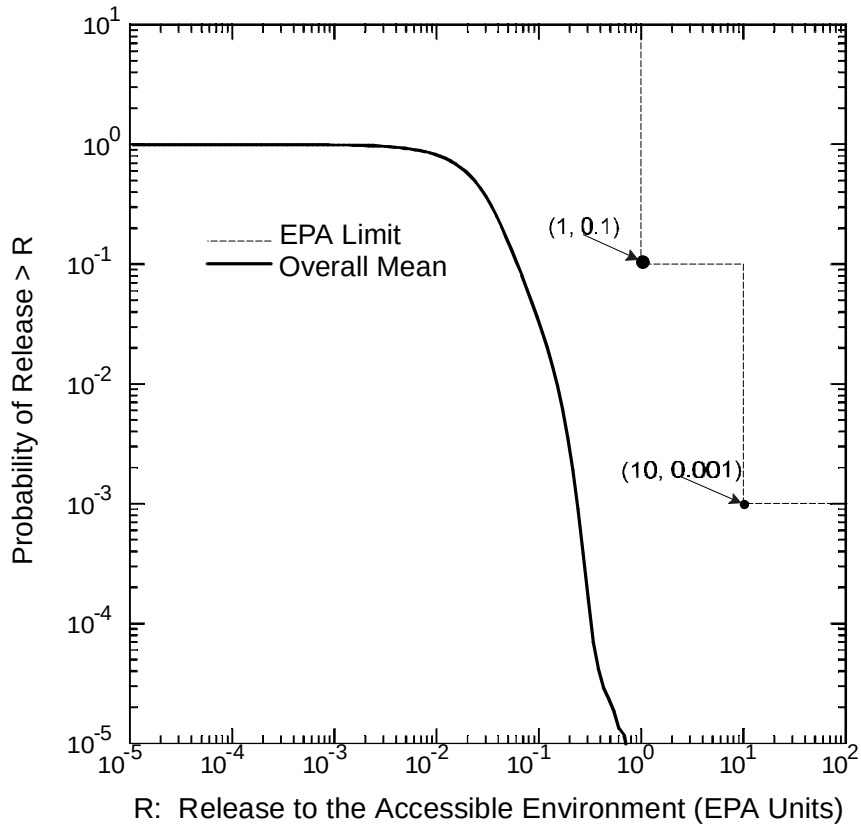

Figure 1.1. DOE's CCDF of Normalized Releases, Showing Overall Mean for all Release Types

The quantitative results from the performance assessment, shown in the CCA, are presented as complementary cumulative distribution functions (CCDFs). To facilitate comparison with 40 CFR Part 191.13, the CCDFs are plotted on a log scale with a probability-of-releases greater than the abscissa value on the ordinate axis, and release to the accessible environment in EPA units on the abscissa. Figure 1.1. shows an example of a constructed CCDF from the performance assessment of the CCA. The curve is an overall mean for all types of releases to the accessible boundary that can occur. A list of these release types are mentioned in the subsequent chapters. The EPA requirements for release, as stated in 40 CFR Part 191, are shown as points.,which are the allowable cumulative releases for two probabilities.

The term 'EPA Unit' is used to describe the amount of release compared to the total allowable release limit from Table 1.1. multiplied by a waste unit factor. The waste unit factor is defined as the number of α-emitting TRU radionuclides with half-lives larger than 20 years in millions of curies (U.S. DOE 1996). An estimated 3.44 million curies of waste will be disposed at the WIPP, equating to a waste unit factor of 3.44. The total number of curies allowed to be released for any

one radionuclide is 3.44 multiplied by 100. Therefore, the total number of EPA units of amercium-241 is 1420, assuming an inventory of 4.88 x 10^5 curies postclosure. The sum of releases in EPA units is expressed by

$$R_j = \left(\frac{1}{f_w} \right) \sum_{i=1}^{n} \frac{Q_{ij}}{L_i}$$

where R_j is the release under scenario j, f_w is the waste unit factor, Q_{ij} is the cumulative release for radionuclide i under scenario j for n scenarios, and L_i is the EPA release limits from Table 1.1.

1.2. Repository Design and Site Characterization

The repository was designed to limit the quatity of TRU wastes from being released to the accessible environment. Long term disposal requires many barriers between the repository and environment, including both natural and engineered. The placement of the repository in the Salado Formation halite is one barrier that is very crucial to containment. The halite beds are stable and exhibit many desirable qualities for encapsulating the buried waste.

The Salado Formation is bound by the Rustler Formation above, and the Castile Formation below. The stratigraphical cross section of the area can be seen in Figure 1.2. The figure is a southwest to northeast cut through the geologic profile and shows the formations associated with the Ochoan series. The Castile is bound on the bottom by the Bell Canyon Formation, which is the first laterally transmissive unit underlying the WIPP. However, for performance assessment calculations, the Bell Canyon was omitted.

1.2.1. Castile Formation

The Castile Formation is 425 to 490 meters thick consisting of alternating beds of anhydrite and halite. Pressurized brine occurs in discrete pockets of the upper anhydrite layer. Several exploratory boreholes in the vicinity of the WIPP site have encountered these pressurized brine reservoirs. More than 12720 m^3 of brine flowed out during deepening of the WIPP-12 borehole 1 km north of the WIPP in 1981 (D'Applonnia 1983). Hydrologic tests estimated the size of the reservoir to be 2.7x10^6 m^3. Using a rock compressibility of 10^{-10} Pa^{-1} , porosity of 0.008, and a reservoir thickness of 24 meters, the diameter of an assumed cylindrical reservoir encountered by WIPP-12 would be 4 km.

1.2.2. Salado Formation

The Salado is the most important geological unit in the disposal system, since the repository is in this formation, and represents the primary natural barriers needed to contain the waste. The Salado is divided into three informal members: the upper, the McNutt Potash Zone and the lower. The thickness of the Salado ranges from a few meters in the eastern part of the Delaware Basin to over 600 meters at the WIPP site. Though the Salado deposits are mainly halite, sulfate minerals form many interbeds in the formation, with the most common being anhydrite, polyhalite, and gypsum. The anhydrite layers are commonly referred to as markerbeds and are numbered sequentially from top to bottom 101 through 144 (MB101 - MB 144). The repository is

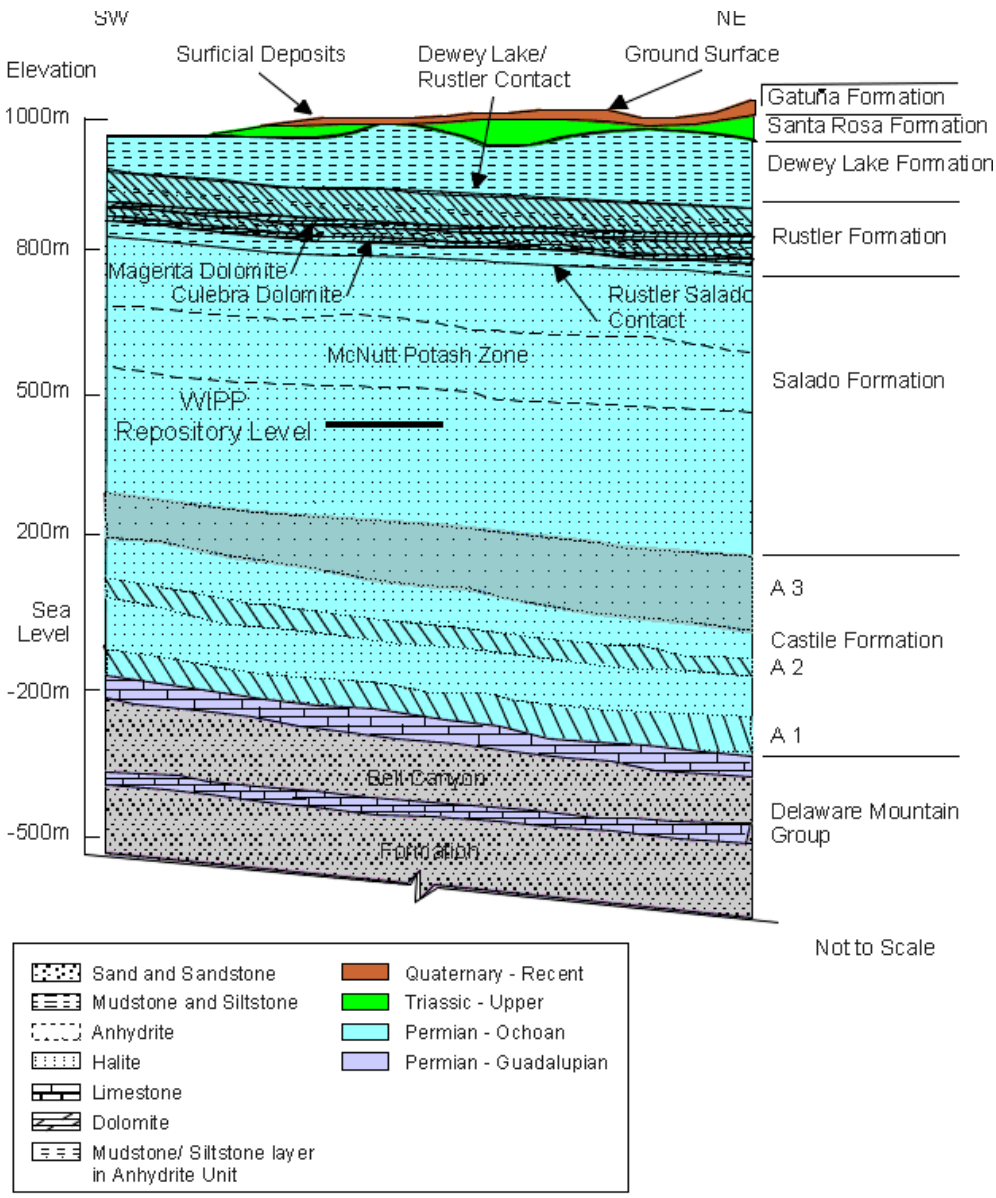

Figure 1.2. Stratigraphic Cross Section of Geologic Region around WIPP (U.S.DOE 1996)

located between MB138 and MB139.

1.2.3. Rustler Formation

The Rustler Formation contains a wide variety of different types of deposits, including anhydrite, halite, carbonate, dolomite, mudstone, and sandstone. Though not as thick as the members below, the Rustler Formation is far more extensive in area. Its thickness ranges between 90 to 107 meters at the WIPP site.

Within the Rustler lies the Culebra Dolomite member, the most hydrologically transmissive unit. It is believed that this member can transport a radionuclide release to the accessible environment in a relatively short period of time upon breaching the repository. The fractured Culebra dolomite aquifer is approximately 11 meters thick at its maximum with a transmissivity up to 10^{-3} m^2/s. The minimum values for thickness and transmissivity are 4 meters and 10^{-9} m^2/s, respectively. The hydraulic head in the aquifer ranges from approximately 950 m in the north to less than 900 m in the south, showing a general north to south flow. Tracer tests show that solute travel is mainly through fractures and interconnected vugs, but can also diffuse into the dolomite matrix (U.S. DOE 1996).

Above the Culebra Dolomite lies the Tamarisk, Magenta Dolomite, and Forty-niner Members of the Rustler Formation. The Tamarisk and Forty-niner members vary significantly in composition and are much thicker than the Culebra, ranging from 26 to 56 meters and 13 to 24 meters, respectively (LaVenue et al. 1990). The Magenta Dolomite varies from 7 to 8.5 meters in thickness, is primarily composed of gyspiferous dolomite, and is also an aquifer, but less transmissive than the Culebra.

1.2.4. Dewey Lake Redbeds, Santa Rosa, and Gatuna Formations

Moving upward in stratigraphic sequence at WIPP, the Dewey Lake Redbeds lie directly above the Rustler. The Dewey Lake Formation is mainly sandstone, siltstone, and claystone. Analysis of the Dewey Lake shows that it is not hydrologically connected to the Rustler, but may actually have lateral water movement (U.S. DOE 1996).

The Santa Rosa and Gutuna Formations lie directly above the Dewey Lake, and are the closest formations to the surface at the WIPP site.

1.2.5. The Repository

The repository was designed to dispose approximately 176,000 m^3 ($6.2x10^6$ ft^3) of CH-TRU (contact handled) waste and RH-TRU (remote handled), of which no more than 7080 m^3 ($2.5x10^5$ ft^3) can be of RH-TRU waste (U.S. Congress 1992; Silva 1994; U.S. DOE 1990). The waste contains organics such as rubber, plastic, and cloth; metals; and waste sludge. The CH-TRU waste is stored in 55-gallon drums and will be stacked three-high in rooms that are 300 feet long, 33 feet wide, and 13 feet high. The RH-TRU waste containers are 26 inches in diameter and 121 inches long, and will be placed in horizontal holes in the walls of the waste panel rooms.

The rooms are separated by 100 foot thick pillars. The repository consists of eight waste panels with seven rooms in each panel. The waste panels are separated by 60 meters (200 feet) of intact rock. Each room will contain approximately 6000 drums of CH-TRU waste and 50 canisters of RH-TRU waste.

Figure 1.3. shows the configuration of the three main area of the repository: experimental area, operations region, and waste disposal region. The experimental region was used as an area to perform geotechnical evaluations, which consisted of rock mechanics tests, waste package experiments, and brine migration tests. The operations region contains the passages to connect the surface to the waste disposal area. There are four shafts in this area: the waste handling shaft for the transport of personnel and waste to the subsurface, the air intake and exhaust shafts allowing fresh air to the underground and exhaust to leave, and the salt handling shaft for the removal of mined salt.

The waste disposal area contains the eight panels for waste storage. The main north-south and east-west access drifts in this area will also house waste after the main panels are filled and are called panels 9 and 10. The disposal area will be sealed after all panels are filled.

1.2.5.1. Room Collapse and Post Closure

Once eachpanel has been filled, they will be sealed to prevent the escape of actinides when the drums begin to fail from the pressures exerted by salt creep from the ceiling, floor and walls. The salt creep will consolidate the drums, producing stress fractures that will ultimately cause the waste to spill out. However, one of the main reasons for chosing salt for disposal was its mechanical response to the overpressures of the rock above. The salt will encapsulate the waste, creating a natural barrier.

The closure process of the salt begins as soon as the rooms are excavated and continues until an equilibrium state of the rock and the waste are reached (Butcher 1997). At equilibrium, the salt deformation ceases, and the waste in the room has undergone all possible compaction. The measure of compaction in the repository is the amount of change in pore volume of the waste, which continues to decrease under pressure. However, it is not likely that the salt surrounding the repository will ever come to a pure equilibrium with the waste. The waste changes form continuously throughout most of the initial time history of the repository and gases are progressively generated from degrading waste. During the time of degrading waste, the repository is expected to make minor readjustments. Waste rooms will continue to deform until all stress gradients vanish.

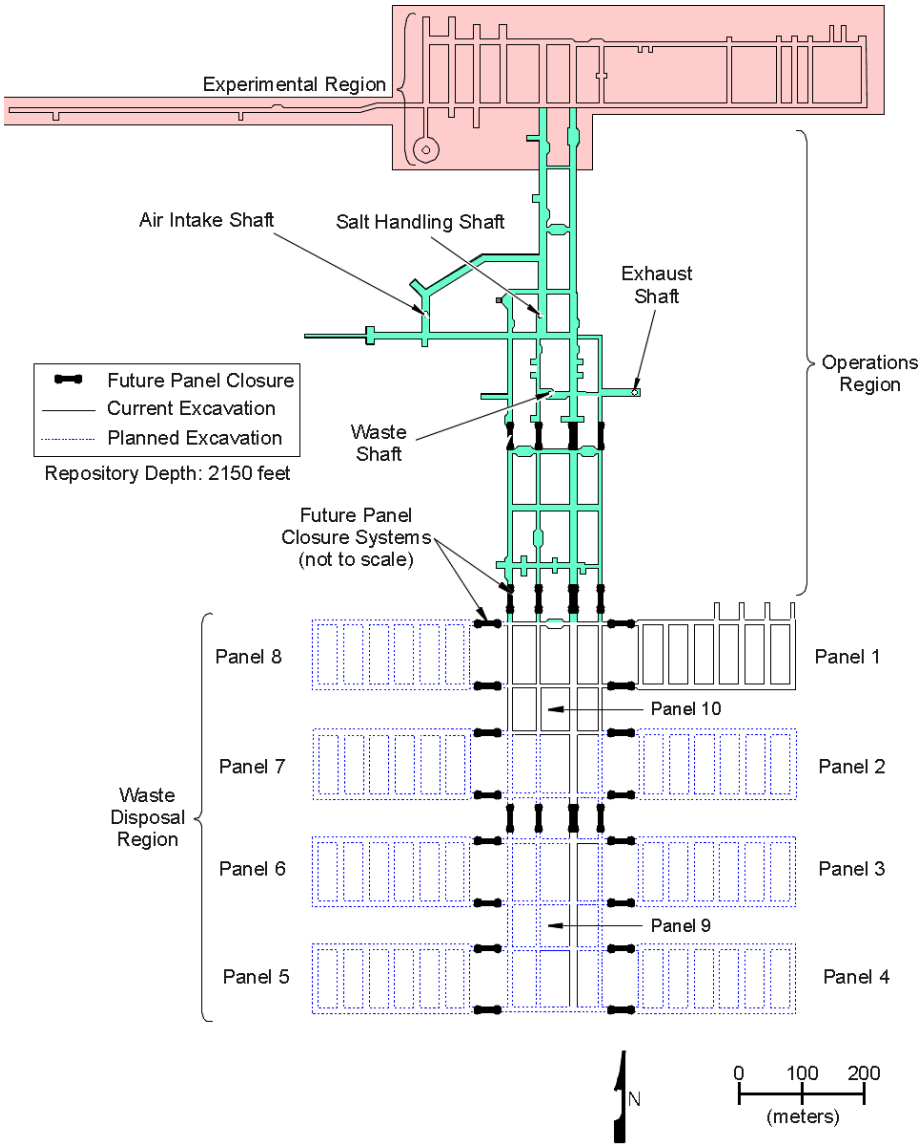

Figure 1.3. Areal View of the Underground WIPP Facility (U.S. DOE 1996)

A computer model was developed (Butcher 1997) to estimate the compaction and decrease in the pore volume of the compacted waste. The initial room height is approxiamtely 4 meters. The drums, stacked three high will be approximately 2.7 meters, leaving 1.3 meters of air space above for the placement of backfill. After consolidation, the room heights will be compacted to roughly 2 meters, and porosity of the waste will decrease from an average of 0.7 to ~0.25.

1.2.5.2. Gas Generation and Waste Backfill

Before sealing, the panel rooms will be backfilled with a buffer to reduce the amount of gas generated from degrading organic material. Several backfill materials have been considered, including bentonite clay, CaO, and MgO. MgO was selected as the backfill material based on its postulated benefits to increase the pH of the repository, which decreases the solubility of the actinides in brine. The cemented MgO, called Sorel cement, will also strengthen the repository waste.

The generation of gases in the repository, if produced in significant quantities, may affect the performance of the WIPP. An increase in CO_2, for example, will decrease pH and increase the solubility of the actinides in brine. The corrosion of metals and microbial activity are seen as the major contributors of gas generation in the disposal system. A minor source of gas is the radiolysis of water, but is much less a contributor than corrosion or degradation.

The oxic corrosion of metals (iron, aluminum, aluminum-based alloys, and lead) will deplete the rooms of O_2 and water, thus allowing anoxic corrosion to produce large amounts of H_2. The anoxic corrosion process will consume a large amount of water, depleting brine availability for other processes, such as chemical degradation or physical blowout. The rate of corrosion for metals is dependent on the pressures and quantities of CO_2, H_2S, N_2, and other gases (Telander and Westerman 1996) and is said to vary from 0 to 1.587×10^{-14} m of steel per second in the CCA. The values assume no CO_2 present.

Microbial activity from the degradation of cellulosics, plastics, and rubbers will consume O_2 and produce CO_2, N_2O, N_2, H_2S, H_2, and CH_4 (Brush 1995). The generation of H_2S is important to corrosion, and experiments have found that steel corrosion will almost cease in H_2S overpressures, and that Al corrosion was relatively high (Telander and Westerman 1996). The formation of CO_2 from microbial denitrification, sulfate reduction, and methogenesis will decrease the pH, increasing the solubility of the actinides in brine solution. A low pH, with values <6, has been shown to have the highest solubilities, decreasing as pH increases until the pH

reaches 10. When pH is greater than 10, the solubilities are anticipated to increase (U.S. DOE 1996).

The MgO backfill will react with the brine to produce brucite ($Mg(OH)_2$). Brucite will then react with the CO_2 to produce magnesite ($Mg(CO_3)$), or any mineral species of magnesite (nesquehonite and hydromagnesite). One mole of MgO will react with one mole of water and one mole of carbon dioxide to produce one mole of magnesite. Thus, the one-to-one relationship of carbon dioxide and MgO consumption is important in respect to the amount of MgO needed as backfill to consume the CO_2. The CCA estimates that a maximum 1.4×10^9 moles of gas will be generated and the DOE has therefore planned to emplace 1.875×10^9 moles of MgO (83,150 tons) in the repository.

The effectiveness of the MgO to mix completely with the CO_2 has invited much debate, and even DOE's own Peer Review Group reassembled on three separate occasions to examine further evidence. Their final report on the subject can be found in Wilson et al. (1997). The EEG also outlined a number of concerns (Neill et al. 1998), including the exact mineral phases of the MgO species that will persist as it forms complex minerals with carbonate.

1.2.5.3. Panel Closure

Figure 1.3. shows the location of plugs for each panel access drifts. The intent of the barriers was not to aid in long term repository performance, but to prevent potentially high levels of unacceptable volatile organic waste from seeping into the operations area (U.S. DOE 1996). The closure system design allows for a two layer protection scheme, which consists of an explosion- (or construction-) isolation wall and a concrete barrier. These barriers are separated by 20 feet of space called the isolation zone.

1.2.5.4. Shaft Seals

The four shafts in the operations region of the repository will be sealed after the decommissioning of the WIPP repository. The sealing allows for additional barriers of isolation from the accessible environment, and are not technically "engineered barriers", since they represent an effort to fix the damage to the natural barriers. The seal will consist of 13 elements, layered throughout the shaft length with the purpose to limit fluid flow in the column with high density/low permeability materials (Sandia 1996). Figure 1.4. shows the layout of the shaft seal system. Some materials that will fill the shaft include: concrete, clay, salt, asphalt, earthen fill, and cementitious grout. The performance assessment calculations included degradation of the materials in the shaft over time.

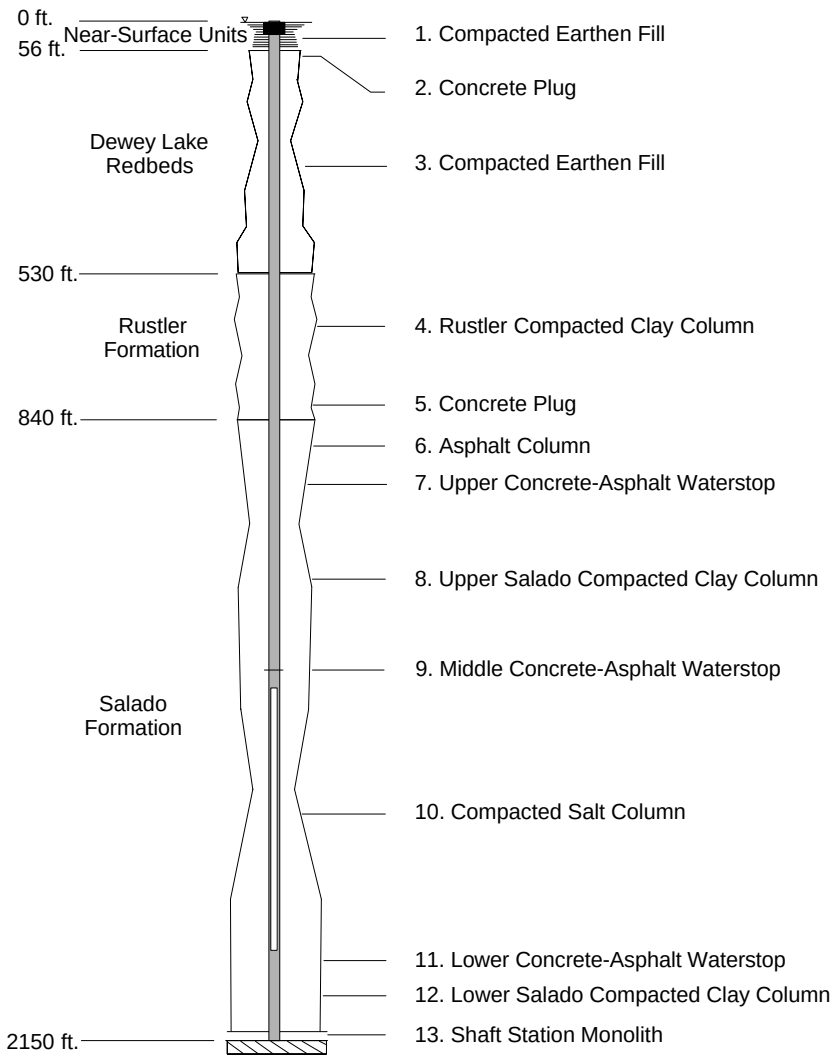

Figure 1.4. Shaft Seal System at the WIPP (Modeled after Figure 4.1 of Sandia 1996)

1.2.5.5. Borehole Plugs

The last barrier to be implemented in the repository is the plugging of boreholes, which play a role in projected future human intrusion scenarios. The borehole plugs are expected to reduce the amount of water from overlying formations from entering the repository, and the contaminated brine from escaping to the surface. The DOE plans to use mainly cement or grout with mud and clay, compacted to closely match the physical properties of the surrounding rock. The plug will fill the entire length of the borehole casing.

There are several designs being considered for the borehole plug. These consist of a one-, two-, and three-plug configuration. Based on a survey of current plugging practice, the DOE has assigned probabilities for usage to each configuration and these are incorporated into the

probabilistic modeling of future events. The two-plug configuration is the most common type, with the three-plug being less likely, and the single concrete plug being the least likely to be used.

1.2.6. Potential Pathways for Release

Though there are several safeguards to reduce the possibility of release of radionuclides to the accessible environment, it is not totally improbable that the waste may escape from the disposal system. In undisturbed performance, the radionuclides could be transported through fissures and fractures of the weaker anhydrite units above and below the repository. Marker beds 138 and 139 provide potential pathways for escape, especially when the pressures in the repository reach a level, above lithostatic, that will induce further fracturing. Fluid injection in nearby oil/gas wells for the secondary and tertiary recovery of resources may also induce fracturing at WIPP levels, and possibly leak into the repository (Silva 1996; Bredehoeft 1997a,1997b). However, the probability and consequence of fluid injection has yet to be determined as a possible mechanism for release.

Disturbed performance of the disposal system allows several pathways of release upon breach of the repository. If the repository is sufficiently pressurized, then the blowout of solid waste material may entrain radionuclides, and be brought to the surface via the intruding borehole. Also, a breach of the pressurized repository may bring radionuclides dissolved in contaminated brine up to the hydrologically transmissive units above the repository and possibly to the surface. If contaminated brine reaches the Culebra aquifer, radionuclides may be transported to the accessible environment with the groundwater.

1.3 Scope

A basic understanding of the performance assessment (PA) calculations of the CCA is needed to understand much of the work in this report. The report starts with an overview of the PA, repository design, and site characterization of the WIPP disposal system.

Background is provided to allow the reader to move into a detailed description of the PA presented in Chapter 2. The chapter explains the organization of the PA and how the different mechanisms of flow and transport for release scenarios are split into the computer codes. A discussion of the parameters will be followed by an uncertainty analysis description of the PA.

Chapter 3 discusses EEG's outstanding concerns of the calculations performed in the CCA and the parameters used in modeling. The remaining chapters adress the sensitivity of the different parameters. The modeling started simply, investigating less complicated parameters and

models and then moved to more complex scenarios. A summary and conclusion for each model study are presented in the modeling chapters.

2. PERFORMANCE ASSESSMENT REVIEW

To understand the long term behavior characteristics of the disposal system, the probabilities and future occurrences must be determined. A set of scenarios have been analyzed for the potential effect of the repository on the accessible environment. These scenarios have undergone a formal screening by DOE to eliminate features, events, and processes (FEPs) that are unimportant to the performance of the disposal system. The scenarios are based on the FEPs that are predicted to be both potentially likely and have significant consequence, and categorized as having an influence on either the undisturbed or disturbed performance of the repository.

The purpose of FEPs screening is to identify those FEPs that need not be included in the PA calculations based on either low probability, or low consequence, or regulations. A FEP was screened out of inclusion based on probability when it is expected that there is less than one chance in 10,000 that the event or processes will occur in 10,000 years. A FEP may also be excluded if the consequence to the overall calculations of the CCDFs are less than 10^{-4} EPA units. In addition EPA promulgated criteria to allow for certain human initiated events to be eliminated from consideration (tunneling, excavation, deliberate drilling, fluid injection for resource recovery, etc.).

2.1. Scenarios of the Performance Assessment

2.1.1. Undisturbed Performance

Undisturbed performance, as stated in the 40 CFR 191.12, is defined as *"the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events".* The undisturbed scenario forms the base case for PA calculations and includes only natural events and human influences that do not affect the repository directly. Some low probability FEPs that were screened out are regional tectonics, fault movement, seismic activity, and volcanic activity.

2.1.2. Disturbed Performance - Human Intrusion

The disturbed performance of the repository must include human initiated events as stated in the 40 CFR Part 194. However, there are only two disturbed events that were considered for the long term performance of the repository: deep drilling (E), and mining (M) with all others being screened out. The drilling events were subcategorized into two scenarios, one for drilling only into the repository waste panels (E2), and the other for drilling through the waste panel into the

underlying pressurized brine reservoir of the Castile formation (E1). A combination of the two drilling scenarios were also considered, noted as an E1E2 scenario. A third type of drilling, shallow drilling for underground sources of drinking water (E3), was eliminated from the performance assessment calculations based on low probability due to the groundwater being nonpotable in the Culebra Dolomite aquifer.

Mining at the WIPP may occur in combination with drilling (ME1, ME2, ME1E2), potentially producing a more rapid transport to the accessible environment through the Culebra aquifer than drilling alone. The mining for resources, such as potash in the McNutt Potash Zone of the Salado Formation for example, can cause subsidence in layers above the Salado. The subsidence could result in greater fracturing of the Culebra possibly causing faster transport of radionuclides to the accessible environment.

Although the drilling intrusion scenarios were narrowed down to two types, the time at which they can occur during the repository future are too numerous to simulate directly. Over one thousand future drilling times could occur during the life of the repository, requiring unachievable computer time and storage requirements. Therefore, the intrusion times were reduced to two separate times for each of the E1 and E2 intrusion type, and a single, two-time drill intrusion of E1E2 scenario. A total of six scenarios (S1 through S6), including one undisturbed scenario, were created for the performance assessment calculations.

S1 - undisturbed
S2 - E1 at 350 years postclosure
S3 - E1 at 1000 years postclosure
S4 - E2 at 350 years postclosure
S5 - E2 at 1000 years postclosure
S6 - E2 at 800 years followed by an E1 at 2000 years postclosure

The times at which these scenarios occur are mainly used as reference times for additional calculations. The computer models use these reference times to calculate an intermediate step for determining individual futures. The individual futures are then scaled to the 10,000 possible futures during the construction of the CCDFs assuming a linear interpolation between calculated times. However, these interpolations become more complicated as radioactive decay and ingrowth are incorporated into the CCDF. A more detailed description of how the computer models interact and the calculated times for the construction of the CCDFs is described below.

2.1.3. Probabilistic Performance Assessment

The performance of the disposal system was quantified in a probabilistic analysis, in which key parameters for model input were stochastically varied over a wide range of values. The ranges were intended to accomodate the uncertainty in the disposal system and was modeled using codes designed to simulate the transport of radionuclides through the system. The simulations (or realizations) were incorporated into a probabilistic process that determined the average behavior of the repostiory. Monte Carlo analysis is the general name for the technique used for probabilistic analysis of the WIPP.

A Monte Carlo analysis uses a probabilistic approach on the selection of values from parameter ranges for the input to the models for performance assessment. The chosen values represent one of many in a set of separate calculations (vectors) that are used for the probabilistic assessment. For example, the halite permeability of the Salado Formation around the WIPP was found to vary from $1x10^{-24}$ m^2 to $1x10^{-21}$ m^2 (U.S. DOE 1996-Appendix PAR). This parameter was assigned a uniform distribution and a set of vectors were created by sampling from the distribution. The vectors were then used as input to the two phase brine and gas flow code, BRAGFLO, to create a set of outputs for the calculation of a distribution function that would best describe the performance of the disposal system. The halite permeability is one of 57 parameters used in the Monte Carlo analysis of the CCA.

2.2. Computer Models

In order to accomplish the numerical modeling of the WIPP repository, several computer codes were written to quantify the long term behavior of the waste disposal. These codes can be broken into several categories with each major code having smaller supporting codes to pre- and post-process data. The major codes include:

(1) BRAGFLO - Salado Flow
(2) NUTS and PANEL - Salado Transport
(3) CUTTINGS - Borehole calculations of cuttings, cavings, and spall
(4) BRAGFLO_DBR - Direct brine release from the repository
(5) SECOFL2D - Culebra Flow
(6) SECOTP2D - Culebra Transport
(7) CCDFGF - Probabilistic modeling of the 10000 year future

Figure 2.1. shows the relationships between the codes.

2.2.1. BRAGFLO

BRAGFLO (BRine And Gas FLOw) models the processes occurring in the repository and the surrounding rock, including two-phase fluid flow, anhydrite fracturing, and gas generation. These processes are simulated on a simplified two-dimensional, north-south cross-section of the disposal system from the overlying units above the Dewey Lake down to the Castile formation. The geometry of BRAGFLO's irregular grid spans 46,629.88 m in the north-south direction and 939.06 m vertically. The code was used to calculate brine pressure, saturation, and flow over the entire 10,000 year future of the repository for each of the six scenarios.

2.2.2. NUTS

NUTS (NUclide Transport System) models the migration rate, distance, concentration, and level of radioactivity of radionuclides transported from the repository to the surrounding formations. The equations are solved on the same grid as used in BRAGFLO using BRAGFLOs' brine flow rates, porosities, pressures, and saturation. The NUTS code was used to calculate transport times at 100, 3000, 5000, 7000, and 9000 years postclosure for scenarios S1 through S5.

Of the 33 assumed radionuclides that will be in the WIPP waste, only five lumped isotopes were simulated using NUTS to reduce computer time and memory requirements. The lumped isotopes are assumed to have equivalent decay and transport characteristics of the remaining isotopes, and account for approximately 99% of the activity of radionuclides in the repository. The five lumped isotopes are: ^{241}Am, ^{239}Pu, ^{238}Pu, ^{234}U, ^{230}Th.

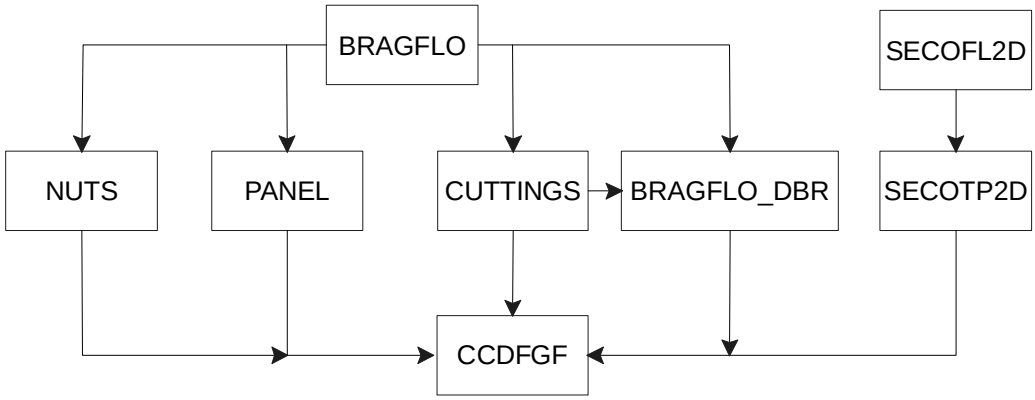

Figure 2.1. Major Codes with Linkages

Computationally, NUTS is a very slow code to run. Therefore, it was first used to simulate a nonreactive passive tracer to test which BRAGFLO flow velocity calculations would transport radioactive isotopes to the accessible environment. Several BRAGFLO simulations were screened out and no longer needed for the calculations. The simulations exhibiting a tracer release and having a mass in excess of 10^{-7} kgs across the accessible environment underwent a complete transport analysis. For the CCA, repilcate 1, only one vector was not screened out of the complete analysis for Scenario 1, 23 for S2, 21 for S3, 6 for S4, and 6 for S5. Thus, only 57 out of 500 vectors were needed for running the NUTS simulations.

The complete analysis included an 'isotope' simulation and a 'time shifted' simulation on the unscreened vectors. The isotope simulation establishes the transport of an undisturbed performance. The isotope simulation results are then used as input for the time shifted calculations at 100, 3000, 5000, 7000, and 9000 years post closure.

2.2.3. PANEL

PANEL calculates the "*mobilized radioactive load in the brine phase of the brine/gas mixture that seeps or flows through the repository's decommissioned waste panels"* (U.S. DOE 1996-Appendix PANEL). Simply, PANEL was used to model the release of radionuclides in a direct brine release scenario to the surface and to model the upper bound of long term releases to the Culebra in the S6 scenario. The times at which PANEL was calculated were 100, 350, 1,000, 4,000, 6,000, and 9,000 years post closure.

PANEL uses BRAGFLO's information, much like NUTS, on a more simplified scale. PANEL represents each waste room as a well mixed grid cell, and solves integrated analytical equations with 50 year time stepping. PANEL simulated the release of 21 of the 33 isotopes from the repository in less time than the NUTS simulation of 5 isotopes.

2.2.4. CUTTINGS_S

CUTTINGS_S calculates the cuttings, cavings, and spallings from an intrusion borehole through the disposal system. CUTTINGS_S receives its initial and boundary conditions from BRAGFLO and can simulate the effects of multiple boreholes. BRAGFLO also provides repository pore pressures, saturations, and porosities for solid removal calculations.

The cuttings and cavings portion of the code models the direct removal of wastes brought to the surface by the drilling cooling liquid (usually a mud brine) and is the sum of the material cut by the drill bit and eroded material. The eroded material is a function of fluid shear stress acting on

the borehole wall and the strength of the waste.

The third type of removal of wastes calculated by CUTTINGS_S is through the process of spall. If the repository is significantly pressurized (above hydrostatic), then a portion of the solid waste could be forced to separate from the bulk mass of waste inward toward the borehole by high pressures in the repository. The amount of spallings removed is dependent upon the waste shear strength and permeability. If the permeability is too low, then it is assumed that the flow of gas to the borehole is too slow to cause a waste blowout up the borehole. Berglund (1994) indentified the "threshold" permeability at 10^{-16} m^2, below which the blowout would cease. The CCA used a value of $1.7x10^{-13}$ m^2 for waste permeability in the repository after compaction. For a comparison of the significance of spallings, the maximum release due to spalling calculated in the performance assessment was 4.0 m^3 with a maximum release of 3.0 m^3 for cuttings and cavings combined.

The scenarios of S1 through S5 were used to calculate borehole times other than those specified in Section 2.1.2. The results of pressures and saturations from the undisturbed scenario (S1) were used as the initial conditions for a first time borehole intrusion at 100, 350, 1000, 3000, 5000, and 10000 years. The CUTTINGS_S simulations for scenarios S2 through S5 were like the S6 scenario (E1E2), and the initial intrusion at either 350 or 1000 years in the BRAGFLO calculations was used to calculate conditions at 550, 750, 1200, 1400, 2000, 3000, 4000, 5000, and 10000 years.

The spallings portion of the CUTTINGS_S was deemed inadequate by the Conceptual Models Peer Review Committee. The peer review (U.S. DOE 1996-Appendix Peer1) reported on the uncertainty in the conceptual model and its inadequacy to calculate the channel flow of waste to the borehole. However, with additional calculations of another spallings code, the spalled releases of the CCA were considered reasonable by the Peer Review Committee (Wilson et al. 1997). Based on a sami-analytical model of spall (Hansen et al. 1997) which calculated a maximum release of 0.25 m^3 at repository pressures of 14.8 MPa, the CCA values of 0.5 to 4.0 m^3 were accepted by the committee. Chapter 9 of this reports explains this new model and some problems associated with the analysis.

2.2.5 BRAGFLO_DBR

BRAGFLO_DBR (BRine And Gas FLOw, Direct Brine Release) calculates the brine released from an intrusion borehole through the repository. The released brine was not assessed in the CUTTINGS code, as that code only calculated the solids removed during drilling. For a direct

brine release to occur, certain conditions must exist in the repository. The repository pressure must be above 8 MPa. This pressure is the hydrostatic pressure at the depth of the repository, which accounts for the column of mud in the borehole that the waste brine must overcome and the frictional forces in the borehole. There must also be enough mobile brine present in the waste panels to flow up the borehole to the surface.

The BRAGFLO_DBR uses the BRAGFLO code, converted to a repository scale model. The model is set up on an areal, two-dimensional grid. The direct brine release can occur at any time during the 10000 year period of the repository, and the saturation and pressure history from the S1 to S5 BRAGFLO calculations are used as initial and boundary conditions. The code calculates a brine release that lasts between 3 and 11 days.

Intrusion times, other than that specified for the different scenarios, were calculated in the same way that CUTTINGS_S intrusion times were calculated. The BRAGFLO intrusion times at 350 or 1000 years postclosure for either an E1 or E2 intrusion were used to establish initial conditions for a direct brine release of a subsequent E2 intrusion at later times. These times correspond with the intrusion times of CUTTINGS_S.

2.2.6. SECOFL2D

SECOFL2D simulates the single-phase flow of groundwater through the Culebra Dolomite member of the Rustler formation. The Culebra member is of particular importance, since this is the most transmissive unit in the disposal system. Radionuclides released from the repository can be transported up an intrusion borehole into the aquifer and be transported to the accessible environment in a short period of time, relative to other units within the subsurficial disposal system.

The Culebra is considered to be a confined aquifer in steady-state. The equations are solved on two grids, regional and local. The regional domain is solved first for the discrete hydraulic head to be used as boundary conditions on a much smaller, finer local grid. Figure 8.1 of this report shows the regional grid in relation to the Land Withdrawal Boundary (LWB) of the WIPP site.

The effects of potash mining in the McNutt member of the Salado formation is considered in modeling of the Culebra aquifer. The subsidence of the mined area may adversely effect the fractured dolomite, creating even more fractures. To simulate the additional fractures, a scaling factor was used to increase transmissivity in a full and partial mining scenario. The scenarios are based on the extent of allowable mining in the region of the Land Withdrawal Boundary. The

scaling factor was sampled from a uniform distribution for a range of 1 to 1000.

2.2.7. SECOTP2D

The transport of radionuclides through the Culebra Dolomite was accomplished with the code, SECOTP2D. The transport code used the local grid velocities of SECOFL2D to calculate the concentration of the actinide species on a nonuniform grid. SECOTP2D reported the mass of simulated actinides that crossed the Land Withdrawal Boundary through time.

The transport calculations of the radionuclides used in the performance assessment first assumes that the initial mass to be injected into the Culebra will be 1 kg. This is a unit mass, that is coupled with predicted mass that reaches the Culebra through a NUTS calculation. The transport of the same five lumped isotopes of NUTS was also transported in SECOTP2D.

2.2.8. CCDFGF

The results of the numerical simulation from NUTS, PANEL, CUTTINGS_S, BRAGFLO_DBR, and SECOTP2D were summarized into tabular form for input to CCDFGF. The NUTS information includes the time integrated discharge of ^{241}Am, ^{239}Pu, ^{234}U, and ^{230}Th up the borehole to the Culebra. The information from PANEL includes the time integrated discharge of ^{241}Am, ^{239}Pu, ^{234}U, and ^{230}Th from the waste panels. The tables from CUTTINGS_S include the volume of cuttings, cavings, and spallings. The flow of brine up the borehole after intrusion is summed in the tables of BRAGFLO_DBR, and the time integration of mass across the accessible environment is located in the tables from SECOTP2D. All together, they represent the possible discrete calculations from a breach into the repository, on a purely deterministic basis.

As a final step to the modeling of the disposal system, complementary cumulative distribution functions (CCDFs) were created to represent the probabilistic future of the repository and to calculate the potential cumulative releases. The CCDF is used to compare release limits specified in 40 CFR Part 191. For the CCA performance assessment, there were only three modes that produced nonzero releases to the accessible environment: cuttings and cavings, spallings, and direct brine release. The calculated amount of radionuclides released through the Culebra was considered negligible.

The sequence of future events simulated for the disposal system was generated by the random sampling of eight individual “events” that could occur at the WIPP. Each sequence is given equal weight in the 10,000 possible futures, and are combined with the results of the numerical

simulations. The individual events are (1) the interval time between drilling intrusion, (2) the location of the drilling intrusions, (3) the drill bit diameter used for drilling intrusion, (4) range of borehole permeabilities, (5) the activity of the waste penetrated by a drill intrusion, (6) the borehole plug configuration, (7) penetration of the Castile brine reservoir, and (8) the occurrence of mining.

Each sampled future requires the determination of a normalized release to the accessible environment. The releases were calculated from the deterministic calculations of the above computer codes. The releases were then scaled and ordered from lowest to highest according to normalized releases. The CCDF is then plotted by summing the probabilities of all futures at a given EPA release limit, with the probabilities of all futures exceeding the summed value. Figure 2.2 shows the individual releases summed to a total release for all pathways, with cuttings and cavings showing the highest releases, spallings, then direct brine release with the least. CCA calculated releases to the accessible environment from transport modeling within the Culebra Dolomite were always less than 10^{-6} EPA Units.

2.3. Parameters

The complexity of the disposal system required the use of computational models to quantify the effects of scenarios in the performance assessment calculations. The computer codes required specific information about the initial and boundary conditions and the parameters needed to quantify the physical system. The parameters were obtained from data surveyed through various experiments or observations. However, when no data were available, expert judgement was employed.

A careful distinction is needed between parameters and data. Parameters are based on the supporting data and are values used in the model calculations. Data are commonly spread over a range for a particular observation/experiment, and statistical quantities are used to summarize that range (minimum, maximum, mean, and mode). A distribution type is assigned to the parameter range, and can be either uniform, loguniform, normal, lognormal, cumulative (delta or otherwise specified), student's-T, or triangular.

There are approximately 3500 parameters used in the performance assessment modeling of the WIPP disposal system, 57 of which are not constants. The constants represent one value, whereas nonconstants have an assigned range and distribution type. Of the 57 ranged parameters, 24 have uniform distributions, which suggests the lack of information about the data.

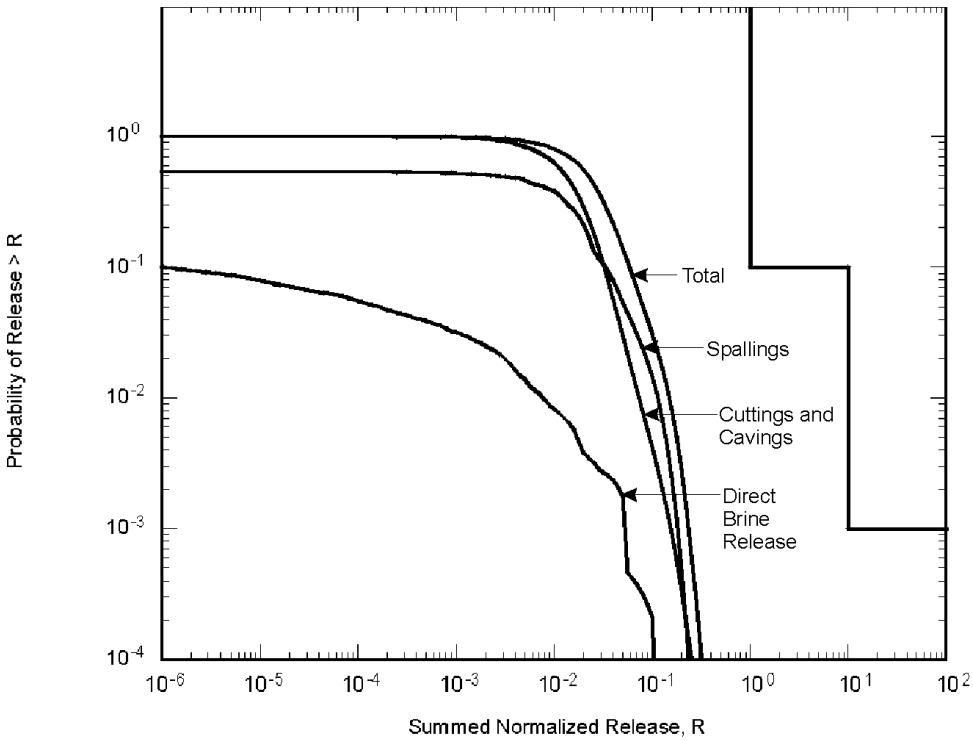

Figure 2.2. Mean CCDFs for Specific Release Modes (U.S. DOE 1996)

A uniform distribution is assigned to a parameter if nothing is known other than its range. However, if the range spanned several orders of magnitude, a loguniform distribution was assigned. This is also equivalent to a uniform distribution applied to a log-scaled parameter.

A range that is representative of a parameter cannot be directly implemented into the computational models. Instead, that range is broken up into several sampled values that fall within the probable range of data, based on the distribution type assigned to that range. For the performance assessment calculations 100 samples were created for each parameter to cover the likelihood of that value existing in the disposal system.

The 5700 total samples were represented by 100 vectors, each with 57 parameters. The vectors were created through the Latin-Hypercube Sampling (LHS) technique. The LHS allows sampling from the outer wings of a distribution with relatively small sample sets, as opposed to other procedures like a strict Monte Carlo method, where sampling is biased more towards higher probability-of-occurrence segments of the distribution. Although the parameters are selected individually through sampling, user-specified correlations are permitted between parameters.

The creation of the LHS sampled vectors uses a random number generated from a seed value

from which the random number generator begins and is specified by the user. The seed value allows duplication of sampled results if the same number is used again for quality assurance measures. For CCA calculations, three separate seed numbers were used to generate three sets of sampled vectors. These are referred to as replicates, and are numbered R1 through R3.

Results of the performance assessment calculations are sensitive to the sampled parameter values. As seen in Figure 2.2, the parameters chosen for the CCA demonstrated compliance of the disposal system. The figure, however, only shows the mean for all individual vectors. Individual CCDF vectors are averaged based on the probability of the parameter occurring during the future of the repository. If only a single vector, for example, were to have parameter values that were to show noncompliance with 40 CFR 191, then that vector could have been averaged out by vectors that show smaller releases. The parameters underwent analyses to test the system and to fully understand the behavior of the repository.

2.4. Sensitivity and Uncertainty Analysis of Performance Assessment Parameters

The sampling of parameters in the CCA calculations is intended to capture the uncertainty in the understanding of the repository environment and those processes that may occur in the event of human intrusion. The purpose of sensitivity analysis is to determine which of the sampled parameters have the greatest influence on the uncertainty of the calculated release to the accessible environment. The sensitivity analysis is based on the use of statistical manipulations to discover the key dependencies in the CCA calculations. This overview summarizes the major conclusions drawn from the DOE's sensitivity analysis report (Helton 1996).

The sensitivity analysis used stepwise correlations and scatter plots. Stepwise correlation is a powerful tool to rank the relative influence of the various parameters. If only a few parameters are important, and the effect of these parameters is consistent, then the correlations work well. Often, however, the effects of some parameters are not consistent. An example is the influence of corrosion rate on spallings. Pressure tends to increase with corrosion rate. Spallings increases with pressure above 8 MPa, but is insensitive to pressure below 8 MPa. Thus, spallings is only weakly correlated with corrosion rate. Scatter plots are very useful for spotting inconsistent correlations and for revealing large changes in system behavior. Scatter plots, however, can be unreliable in determining relative importance because they are qualitative rather than quantitative. Scatter plots are two or three dimensional plots of points defined by measures of interest and one or two parameters. These allow a visual determination of sensitivities.

One inherent limitation in the sensitivity analysis presented by Helton is that the sensitivity to parameters only applies to the actual range and distributions of sampled parameters used in the CCA calculations. Changes to either the range or distribution of one parameter may strongly effect the importance of other parameters, because release estimates vary by orders of magnitude for different combinations of parameter values. A case in point is the brine reservoir compressibility, which has been determined to have insignificant influence on the total release. The brine reservoir pressure and reservoir volume characteristics used in the CCA calculations reduce the importance of the brine reservoir to the calculated releases. It is entirely possible that the brine reservoir would be one of the most important contributors to large releases in calculations using more appropriate characteristics.

The description that follows refers to sampled vectors and histories. A sampled vector is a single random selection of parameter values used to define the physical characteristics of both the repository and relevant human intrusion processes such as spallings. One hundred vectors were used for one replicate of the calculations. Three replicates were used to demonstrate the stability of the averaged results to different sets of vectors. Describing the results in terms of vectors refers to the six scenario calculations performed at fixed intrusion times for each vector. A time history describes the timing of events such as potash mining and drilling intrusions. Ten thousand time histories were generated and applied to each sample vector. Describing the results in terms of time histories refers to probabilities averaged over either a single replicate or all three replicates. The abscissa of the CCDF curves is the probability of a release magnitude for a single history. The lowest cumulative release probability in any CCDF calculated for the CCA is 10^{-4} , one over 10,000. The mean and percentile cumulative release probabilities can be less than 10^{-4} because of averaging over 100 or 300 sampled vectors.

2.4.1. Repository Conditions

2.4.1.1. Repository Pressure

Repository pressure at the time of intrusion is a critical condition that influences spallings release, direct brine release, and flow to the Culebra. The factors controlling repository pressure are complex and change over time. Prior to an intrusion, the pressure uncertainty is almost entirely controlled by gas generation. After an intrusion, gas flow up the borehole can keep the repository near atmospheric pressure. At high borehole permeability, brine flows down the borehole from the Culebra causing the pressure to eventually reach hydrostatic equilibrium with the Culebra.

By far the most important influence on gas pressure prior to an intrusion is the switch for microbial degradation of cellulose and plastics. Fifty percent of the vectors assume no microbial degradation, twenty-five percent have degradation of cellulose only and twenty-five percent include both cellulose and plastics. Microbial degradation is so fast that it tends to exhaust supplies in less than 1,000 years. Hence, the rate hardly matters and the switch parameter becomes the most important indicator of large releases. The numerical values for this parameter are set to capture a lack of understanding of the possibility of microbial degradation.

Microbial generation produces either 0, 1.5×10^6, or 4.6×10^6 moles of gas in the first 1,000 years depending on the microbial generation switch. Steel corrosion generates up to 7.5×10^6 moles averaging roughly 3×10^6 moles after 10,000 years. If microbial degradation produces gas then the steel corrosion rate is increased by a factor of 13. Steel corrosion is rate-controlled throughout the 10,000 years for slow corrosion rates, but only at early times, first 2,000 to 4,000 years, for microbial enhanced fast rates. This makes the steel corrosion rate the second most important parameter in controlling repository pressure and the third most important parameter in determining overall releases to the accessible environment. The rate of steel corrosion is effected by the height of the capillary rise of brine from the repository floor, which is approximated by a sampled parameter known as “waste wicking”. The waste wicking parameter value is important at early times but less so than the base corrosion rate.

Steel corrosion is dependent on the availability of its two ingredients, steel and brine. Brine is readily available through the 10,000 years with slow corrosion rates. At faster rates the lack of brine inhibits corrosion. The mechanisms controlling brine availability are described later, in order to keep the focus here on gas generation. In one of the undisturbed vectors, and in some 30% of the disturbed cases, steel is exhausted in the lower panel but never in the upper panel. Steel consumption does not appear to be greater as a result of interception of the brine reservoir.

After an intrusion, the borehole permeability effects the flow of gas up the borehole which depressurizes the repository. Only about 10% of the vectors have repository pressures above the critical 8 MPa threshold for more than 2,000 years after a drilling intrusion. Very high permeability almost completely determines the repository pressure at 10,000 years. If the permeability is greater than 2.5×10^{-12} m^2 then the repository fills with brine and the pressure reaches hydrostatic equilibrium with the Culebra within a few thousand years of the intrusion. If the permeability is slightly less, down to roughly 2×10^{-12} m^2, then gas vents to the surface as fast as it is generated, inhibiting brine flow down the borehole and thus holding the repository pressure to near atmospheric. The influence of borehole permeability on post intrusion

pressures causes this parameter to rank sixth in importance to total releases. Even the diminished brine reservoirs of the CCA analysis have a strong effect on repository pressure in the case of a brine reservoir interception.

2.4.1.2. Brine Saturation

Brine saturation in the repository is important to the direct brine release calculation and to repository pressure through steel corrosion. Unlike pressure, saturation predictions are different between the upper and lower panels of the BRAGFLO model. Brine saturation depends on brine inflow and the consumption of brine by steel corrosion. The brine inflow is less per panel for the upper panels compared to the lower panel. Because the lower panel is down dip it is expected that it would receive more brine inflow. Saturation also depends on gas pressure because the repository swells in response to pressure increases. The upper panel is much less likely to have a saturation that exceeds the sampled residual gas saturation of the waste. Most vectors show brine saturation going to zero in the upper panel over the 10,000 years because of steel corrosion.

2.4.1.3. Brine Flow

As mentioned earlier, the availability of brine becomes important if the steel corrosion rates are fast. The largest source of brine in early times is the disturbed rock zone (DRZ). This flow averages about 13,000 m^3, most of which enters the repository in the first thousand years. The DRZ porosity is a function of halite porosity which is a sampled parameter. Halite porosity has the fifth largest correlation with total releases of the 57 sampled parameters. The marker beds contribute an average of 3,000 m^3. Although one vector produces 70,000 m^3 from the marker beds, less than 10% of the vectors are above 10,000 m^3. The anhydrite permeability and repository pressures have the greatest impact on brine flow through the marker beds. Anhydrite permeability ranks ninth in importance to total releases.

2.4.2. Cuttings and Cavings

Cuttings and cavings are the largest releases in most of the generated drilling intrusion histories. Only cavings, not cuttings, is effected by sampled parameters. Cuttings release varies due to the sampling of 569 CH-TRU waste streams or the average RH-TRU radionuclide concentration. Waste stream sampling creates about a three order of magnitude variation in cuttings release per intrusion. Cavings is dependent on the sampled value of waste shear resistance. The volume of cuttings, 0.3 m^3, plus cavings varies between 0.4 and 3. m^3.

2.4.3. Spallings

Repository conditions necessary to produce spallings occurs for 80% of the sampled vectors, but spallings only occurs in just over half the time histories. However, spallings along with cavings contribute to the largest release estimates in the CCA. The release estimates from the two mechanisms are roughly equivalent at the critical 10% probability level, as seen in Figure 2.2. The conceptual model uncertainty in the spallings model is enormous. The calculations for a given set of repository conditions could be low by an order of magnitude or more. In addition, the potential influence of repository pressure uncertainty is also enormous. At this time, uncertainty in the spallings conceptual model makes it difficult to assess the CCA calculations in terms of compliance.

2.4.4. Direct Brine Release

Direct brine release contributes only marginally to the overall release estimates and to only 48% of the sampled vectors. Considering the vector average, the direct brine release is larger than the median combined cuttings, cavings and spallings releases in less than 0.4 percent of the time histories. The largest calculated direct brine release was 0.2 normalized EPA Units, i.e. 20% of the release limit.

The releases strongly depend on several factors, including brine saturation and repository pressure. These two conditions are not independent. Large gas pressures usually mean low brine saturation and vice versa. The largest releases are associated with the larger pressures and higher saturations. However, the parameter that correlates best with the direct brine release is the residual brine saturation for the waste area. This parameter describes the minimum amount of brine that is necessary for brine movement through the waste. Direct brine release will occur only if the brine saturation is above the minimum value and the hydraulic conductivity of the waste will be small for saturations near the residual which inhibits brine flow into the waste.

2.4.5. Culebra Transport

Releases to the accessible environment through the Culebra were negligible in the CCA calculations. Large amounts of radionuclides reached the Culebra from the intrusion borehole, but only for a few vectors. More than one EPA Unit of radionuclides reached the Culebra in approximately 10% of the sample vectors. The largest release to the Culebra was 20 EPA Units. However, the transport of the radionuclides limited the amount reaching the accessible environment with the partition coefficient for sorption isotherms being the limiting factor. As the retardation increases (calculated from the partition coefficient), the transport distance decrease.

Other factors that have a small effect on the increase of nuclide transport are fluid velocity and fracture spacing.

3. CONCERNS

The EEG's concerns of the computational efficacy of the CCA performance assessment for the WIPP disposal system does not imply any lack in scientific integrity by the DOE. Instead, it allows an unbiased investigation to ensure the robustness and completeness of the work to dispose of TRU waste effectively. However, it is believed that some of the parameters and ranges used in modeling the performance assessment of WIPP may be in error, or lack justification (Clemo et al. 1996). The DOE applied "conservatism" to many of the parameter and ranges, assuming that a larger range would incorporate all the experimental evidence. Without conducting a full scale sensitivity analysis on the parameters, this conservative approach becomes less meaningful.

3.1. Conservatism

By claiming conservatism in the performance assessment calculations, the DOE took shortcuts on some of its scientific investigations. Conservatism was claimed for many conceptual models and parameters to show that the process would over predict releases to the accessible environment. However, it is not easy to forecast the implications of such assumed conservatism. The calculated releases may diverge from the actual releases, and a bound on the difference is very difficult. For example, an investigation into the microbial decay parameter, which is a major gas producer in the repository, shows one of three choices, (1) no degradation, (2) gas generation through microbial activity of cellulosics, and (3) biodegradation of cellulosics with rubber and plastics. The switch concedes to a 50% probability on any generation of gas through microbial activity. This estimated value was assumed to be conservative, since the possibility of degradation was unknown and no experiments were conducted to prove the possibility of gas generation with the addition of a magnesium oxide backfill. The MgO backfill is predicted to increase repository pH to 10 (U.S. DOE 1996). *"In general, rigorous microbial activity ceases above pH 10.5, although there may be few exceptions."* (Biddle et al. 1987). Figure 3.1. shows that there were higher average releases associated with lower microbial activity for an intrusion associated with the S3 Scenario due to the availability of brine. Other scenarios showed the opposite behavior.

3.2. Parameter Issues

EEG's main issues with the assumptions used in the performance assessment calculations were outlined in the letters to the DOE and EPA on September 11, 1996 (EEG 1996), February 7, 1997 (EEG 1997a), and March 14, 1997 (EEG 1997b). Some major issues which will be discussed in this report are as follows:

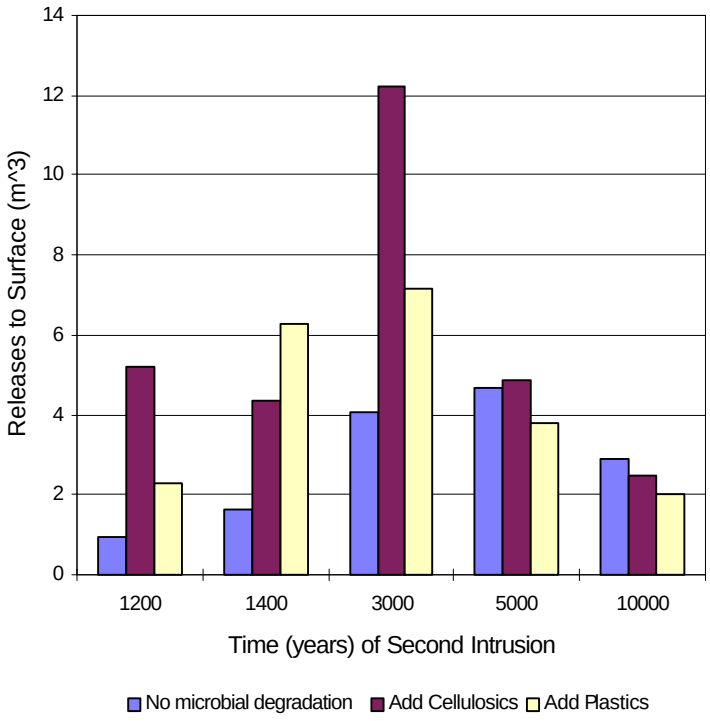

Figure 3.1. Releases from S3 Scenario (Replicate 1) for Microbial Decay

3.2.1. Brine Reservoir Interception

For performance assessment calculations in the CCA, an 8% probability was assigned to the parameter for intercepting a pressurized brine reservoir in the Castile formation. This seems unjustified, considering the data that was overlooked for the WIPP-12 borehole, located within the WIPP site. The reservoir at WIPP-12 was estimated to contain 2.7 million m^3 of brine, and extends more than 3 km in diameter. The values assumed in the CCA for the volume of the reservoir ranged from 32,000 to 160,000 m^3. A value of at least 60% probability should be assigned to the parameter. This report explores the consequence of higher probabilities of encountering a brine reservoir.

3.2.2 Actinide Solubility

The solubility of actinides play an important role in the performance assessment calculations. The parameter determines how much of the radionuclide mass per cubic meter of brine will be transported from the repository up the borehole to the Culebra or to the surface. More specifically, the solubility of plutonium, which constitutes 87% of the initial radioactivity in the waste, was modeled as oxidation states III and IV in the CCA calculations with a 50% probability that it will be one or the other. DOE maintains that the conditions of the repository will be a reducing environment, not allowing the actinide to go above an oxidation state of IV, which would

inherently increase the solubility by 10,000 in some cases. Furthermore, experiments were never conducted to establish the solubilities of Pu(III) and Pu(IV), and were extrapolated from thermodynamic data conducted on Nd(III). Therefore, modeling experiments were conducted by the EEG to test the impact of solubility of actinides in brine.

3.2.3. Chemical Retardation in the Culebra

The chemical retardation in the Culebra determines how the radionuclides will react with the surrounding dolomite matrix. Retardation infers that the contaminants will sorb onto the matrix, and the amount is determined by a coefficient called the partition (or distribution coefficient, K_d). DOE made laboratory measurements of K_d for various actinides (Brush and Storz 1996).

The EEG has a number of concerns on K_d, which were raised in a meeting between Sandia and EEG. First, the applicability of the oxidation state analogy for Pu(III) from Pu(V), which was initially from Am(III), seemed weak at best. Several of EEGs' consultants noted that the assumptions for this analogy were based on questionable data and interpretations of experiments conducted with dilute groundwater from the Yucca Mountain site, a proposed high level waste repository in Nevada (Neill et al. 1998). Similarly, Pu(IV) was derived from Th(IV).

Another concern for the K_d values was the range and distributions used to establish these parameters in the LHS sampling method. The uranium data, for example, exhibited negative values in experimentation. Though physically impossible, they should have been averaged into the parameter's range. The lower end of K_d for uranium was 0.03 ml/g in the CCA, but should have been zero, due to the extreme uncertainty in the value. A model value of 3 ml/g was shown (Blaine 1997) to retard any actinide sufficiently from crossing the LWB. Therefore, it is very important to assign the correct values with a large enough uncertainty of K_d for actinides that exhibit values less than 3 ml/g.

These and other issues surrounding the K_d issue prompted the EEG to conduct their own transport modeling study, which changes the K_ds for several key parameters.

3.2.4. Castile Reservoir Parameters

The pressurized brine pockets contained within the Castile formation were grossly under represented in the performance assessment calculations. After the submittal of the CCA, recommendations were made (Beauheim 1997) to characterize the formation by what is referred to as the "productivity ratio". This ratio is the product of the volume and the pore compressibility to porosity. The recommended range for this ratio was 0.0007 to 0.04 m^3/Pa based on values from the ERDA-6 and WIPP-12 borehole data, respectively.

It should be noted that the ERDA-6 borehole lies outside the WIPP area at approximately 5 miles northeast from the repository center. The WIPP-12 well, on the other hand, is only 1 mile north of the site and values to describe the Castile for disposal system modeling would be more representative if this borehole data is used.

3.2.5. Potash Mining

The extent of potash mining above the repository horizon for PA calculations included the possibility of two scenarios, which included partial and full mining. The two scenarios were based on the possible future extent of mining both inside and outside the disposal system with respect to ore grade. The extent of the partial mining maps were established on historically leased areas with economic grade ore, and the full mining was based on the a report by the New Mexico Bureau of Mines and Mining Resources (U.S. DOE 1996-Appendix Mass).

The BLM has established a map on the possible economic minable ore around the WIPP site. The CCA has identified this as the most conservative mapping of ore, but has refused to include it stating that a significant volume of potash is not minable by today's economic conditions. Furthermore, the BLM map does not include nonminable regions for the existence of hydrocarbon holes. The EEG conducted a modeling study, which extends the area of minable resources, while keeping all other modeling philosophy the same as it was in the CCA. The EEG does not believe that this resolves the modeling problems associated with that used in the CCA, and extensive modeling will be conducted in the future.

3.2.6. Spallings' Calculations

The issue of spallings is very sensitive, with respect to codes, performance, and parameters. Initially, the DOE used a spallings code to calculate the effects of high repository pressures on releases during a human intrusion scenario in the CCA. The code was found inadequate by the Conceptual Models Peer Review Group (U.S. DOE 1996-Appendix Peer 5). However, the committee found the results in the CCA to be "reasonable" with further evidence from additional modeling.

This further evidence uses more realistic conceptual models than were presented in the CCA, implemented in a series of spreadsheets and numerical codes. Further investigation of the codes, by the EEG, found them to be inadequate to model all expected repository conditions. For example, a slightly lower waste permeability than that in the CCA, caused the results (volume of failed material that could reach the surface) to be quite unrealistic, with values as high as 500 m^3. Other parameters used in the code, such as gas viscosity and drilling mud density, also cause unexpected values. It is EEG's belief that none of the codes, in their present

form, can adequately model all expected repository conditions to establish “justifiable” values for releases to compare with 40 CFR Part 194.

4. PROBABILITY MODELING OF DRILL INTRUSION RATES

4.1. Summary

This investigation included changing the deep drilling intrusion rates at the WIPP to estimate the safety margin between assumed drilling rates and the drilling rate that first violates the standards for compliance. The CCA used a drilling rate of 4.68×10^{-3} boreholes/km^2/yr over the 10,000 year period of the repository. The rates were increased in two simulations. Additional modeling was also performed with a 2.34×10^{-3} boreholes/km^2/yr drilling rate to investigate the potential for larger spallings releases due to higher pressures with a less frequent drilling rate. The results show a linear relationship between drilling rates and release limits. A factor of safety of 23 was calculated for the CCA drilling rate, with all other factors remaining the same as used in the CCA.

4.2. Introduction

The consequence of future human intrusion scenarios into the Waste Isolation Pilot Plant was investigated in the CCA (U.S. DOE 1996). These scenarios were established according to the EPA guidelines in 40 CFR Part 194 (U.S. EPA 1996b), and included the possibility of mining and deep and shallow drilling for resources.

The guidelines state in 40 CFR Part 194.33 that the likelihood of a drilling intrusion into the Delaware Basin for the future 10,000 years must be calculated by considering the frequency of drilling for all resources over the past 100 years. These numbers were calculated in the CCA, Appendix DEL (Tables DEL-3 through DEL-7) and were used to calculate the CCDF curves for the performance assessment calculations of the CCA. A total of 46.8 boreholes per km^2 were estimated based on past drilling of resources at depths greater than 2150 meters, which equal 10,804 boreholes in 23,102.1 km^2 (area of Delaware Basin).

The drill intrusion rate for the 10,000 year future of the WIPP was directly implemented in the CCDF model, and was calculated to be equal to 0.00468 boreholes/km^2/yr. However, since the future human activities are uncertain, the rate was changed to test the effects on the CCA calculations. The rates were increased by one and two orders of magnitude, and also decreased by one-half. New CCDF curves were generated based on the changes.

4.3. Methodology

The modeling of new drill intrusion rates were started at the code CCDFGF. All steps up to generating the new CCDF curves were exactly the same as CCA calculations. The files needed to conduct the modeling were fetched from the CMS library. Figure 4.1. lists the steps involved

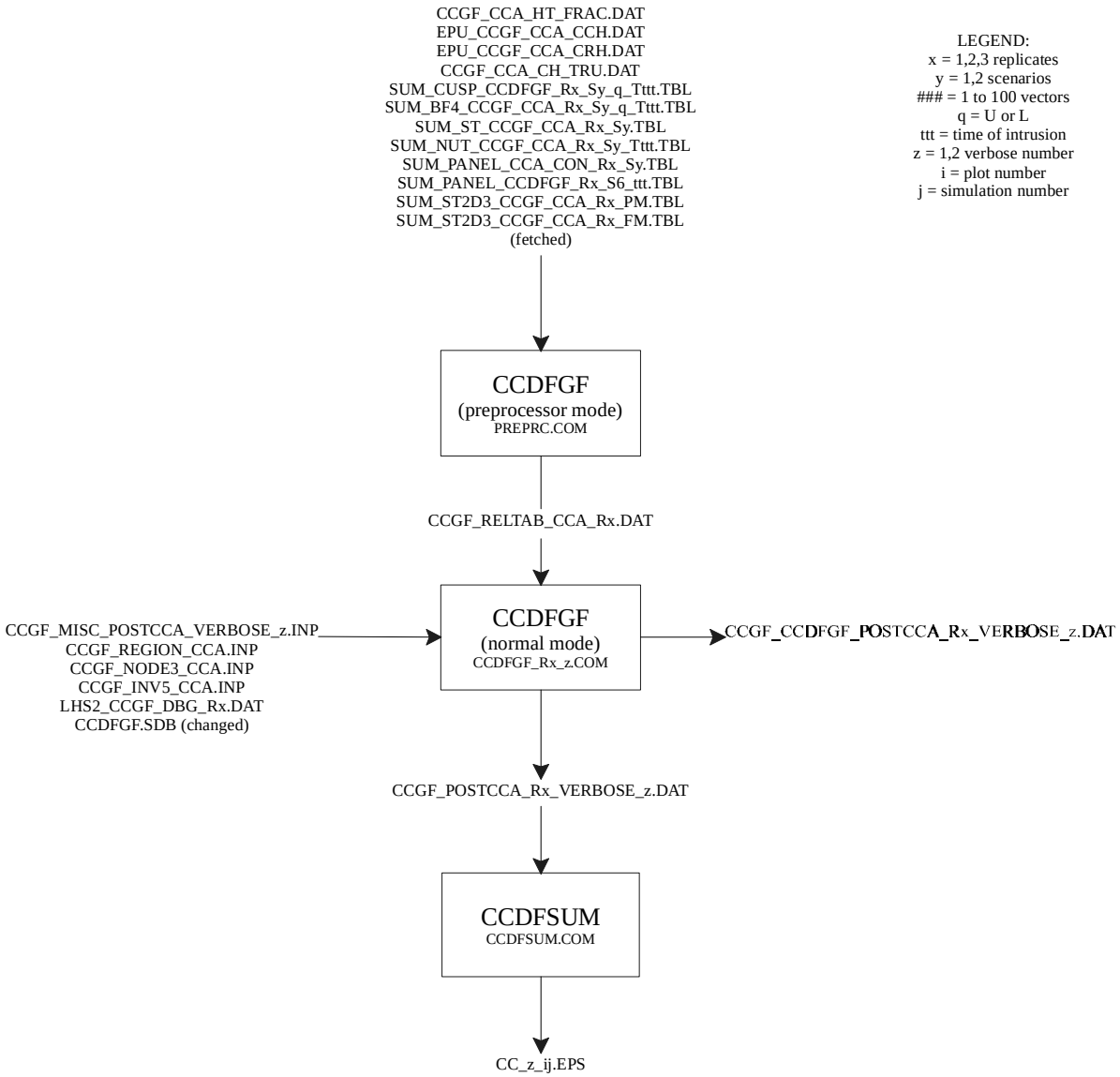

Figure 4.1. CCDFGF Flowchart

in the modeling process with all input and output files.

The change of the drill intrusion rate was made in the file CCDFGF.SDB, a secondary database file used in both preprocessing mode and normal mode of the CCDFGF code. The parameter LAMBDAD (number 3494) was changed, and the specifications can be found in Appendix PAR, Table PAR-53 of the CCA (U.S. DOE 1996). Drilling rates were changed to 4.68×10^{-2} boreholes/km^2/yr, 4.68×10^{-1} boreholes/km^2/yr, and 2.34×10^{-3} boreholes/km^2/yr in three successive simulations.

Minor changes had to be made to the CCDFGF code in order to accommodate the higher drill intrusion rates. Currently, the maximum number of boreholes allowed in the code is 100; MAXBH in CCDFGF.FOR limited the total number. Therefore, the variable MAXBH was increased from 100 to 100,000 in every subroutine of CCDFGF.FOR to allow for a greater number of boreholes. The code was recompiled with the specifications used for the CCA.

The CCDFGF was first run in preprocessor mode to generate the release table data, then in normal mode. The output files created by the normal mode of CCDFGF were postprocessed by CCDFSUM, which created the printable ADOBE style postscript files.

4.4. Results

New CCDF curves were calculated for the changed drill intrusion rates, and are plotted in Figure 4.2. , which also shows the results from the CCA. As expected, the increasing rate produces an increase in releases, in as much to exceed the EPA maximum release limit at 4.68×10^{-1} boreholes/km^2/yr. The relationship between drilling rate and actinide release also seems to be approximately linear; one order of magnitude increase in drilling rate produces approximately one order of magnitude increase in release. Table 4.1. lists the releases for all three simulations and the results for the CCA at a release probability of 10^{-3}. All releases are in EPA Units.

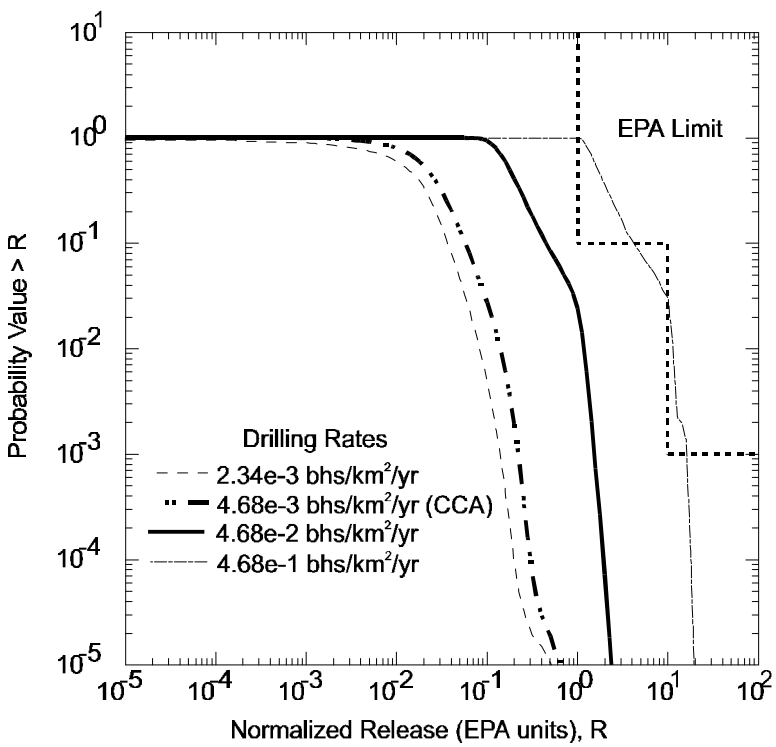

Figure 4.2. Total Normalized Release Limits for Changing Drilling Rates

Simulation	Deep Drilling Rate (bhs/km^2/yr)	Total Normalized Releases at a probability of 10^{-1} (U.S. EPA Units)	Total Normalized Releases at a probability of 10^{-3} (U.S. EPA Units)
1 (CCA)	4.68×10^{-3}	0.059	0.21
2	4.68×10^{-2}	0.44	1.7
3	4.68×10^{-1}	4.1	17
4	2.34×10^{-3}	0.035	0.12

Table 4.1. Total Normalized Release Limits at Different Deep Drilling Rates

The drilling rate was also reduced by half to test a hypothesis about the increased gas pressures with less intrusions. The effect would most likely be seen in the low probability range, however the releases decreased linearly with respect to drilling rate.

4.5. Conclusions

Drilling rates were changed from the original CCA calculations to test the effects of future uncertainty. The changes included two CCDFGF simulations which increased the deep drilling rates by one and two orders of magnitude, and a simulation that decreased the deep drilling rate by one-half. The results are presented in Table 4.1. and Figure 4.2..

The future drilling rate used in the CCA, as specified by the EPA, estimated that the number of boreholes for the next 10,000 years was an average from the last 100 years. Of course there is no possible way to predict human scenarios and the numbers used were more or less arbitrary. However, the present study looks at several different drilling rates, and concludes that the relationship is approximately linear between releases and drilling rates. A drilling rate 23 times greater than that prescribed by EPA and used in the CCA is needed to reach the EPA release limit at a probability of 10^{-1} from values used in the CCA. The overall mean for the highest release at 0.468 boreholes/km^2/yr exceeds the EPA limit of 10 EPA Units at a probability of 10^{-3}. While the drilling rate in the immediate vicinity of WIPP has been documented to be higher than 0.3 boreholes/km^2/yr, that drilling rate was not anticipated to be sustained for any length of time (Silva, 1994).

5. INDIVIDUAL AND COMBINED INFLUENCE OF PLUTONIUM SOLUBILITY ON DIRECT BRINE RELEASE AND THE PROBABILITY OF HITTING CASTILE BRINE

5.1. Summary

This investigation describes the influence of plutonium solubility and the probability of hitting Castile brine on the potential and consequences of brine release to the surface through blowout. The effects of these two parameters on the performance assessment, without changes to other parameters, are investigated both individually and in combination. Results are presented as a comparison of CCDF for blowout and the total normalized surface release. Changing these parameters to more realistic values than used in the CCA increases releases but not substantially. Even calculations using plutonium solubility set to unrealistically high values do not exceed the EPA standards for potential radioactive nuclide releases to the accessible environment through a direct brine release scenario. At the largest solubility values, the entire plutonium inventory is in solution. The release is, however, limited by the fraction of repository brine brought to the surface.

The codes PANEL and CCDFGF are the primary codes used in this investigation. The investigation made use of the intermediate results of the performance assessment calculations. The PANEL code created intermediate data files that are used later to incorporate plutonium solubility influences in investigations of other parameters such as the Castile brine reservoir parameters.

5.2. Introduction

The standards issued by the EPA for the safe disposal of TRU waste at WIPP require a performance assessment of the WIPP repository in order to provide a reasonable assurance that the potential radioactive nuclide releases to the accessable environment will not exceed the limits established by the EPA. The DOE has submitted an application (CCA) for the EPA to certify that the DOE has demonstrated compliance with the EPA standards. One of the potential pathways for radionuclide release to the environment is through unintended drilling into the repository in the distant future. If the pressure buildup in the repository due to chemical reactions in the waste is sufficiently large then venting of the repository through a borehole could bring radioactive brine to the surface. The EEG contends that the oxidation states within the repository assumed for plutonium in the CCA performance assessments are in error. The oxidation state assumption has a major influence on the amount of plutonium that may be in solution in the repository brine and hence on the amount plutonium brought to the surface as a consequence of drilling.

The oxidation states of plutonium in certain WIPP brines have been the subject of some recent studies (Reed et al. 1994, 1996; Rao 1996) and conclusions show that plutonium will exist in oxidation state VI, reducing to V in some instances. However, modeling of plutonium for the CCA was conducted on Pu(III) and Pu(IV) using solubilities predicted by the FMT code, contrary to the above experiments. The range for the plutonium solubility in the Salado brine for the CCA was 4.4×10^{-8} M to 1.1×10^{-4} M. The range for plutonium solubility in Castile brine was 5.7×10^{-11} M to 1.4×10^{-7} M. The changed oxidation states will effect the solubility of plutonium in the waste, and change the amount of actinide release to the surface and Culebra.

The solubility of plutonium was changed from values used for oxidation states III and IV to those measured in Reed et al. (1996). The solubility of plutonium in the Salado brine was increased by a factor of 20, and fell within the range suggested by the FMT calculations. A more substantial change was made in the solubility of plutonium in the Castile brine, increasing by almost 4 orders of magnitude. Table 5.1. lists the solubilities used in the CCA, suggested by DOE (1996) using the FMT calculations, and the experimental results shown by Reed et al. (1996).

5.3. Methodology

The solubility change was implemented in the PANEL calculations for blowout considerations only; the changes impacted the direct brine release portion of the CCDFs. The change was made to the source term file ALG_ST_CCA_Sy.inp, where Sy are the scenario numbers 1 and 2. Only the first two scenarios are needed to obtain Salado and Castile brine radionuclide concentrations.

The changed parameter in the source term file, DIS (dissolved solubility), was converted to a constant equalling the solubilities measured in Reed et al. (1996) using ALGEBRA. It was previously a sampled parameter, with a range of -2 to 1.4 orders of magnitude difference from that in the FMT calculations. This was the only changed parameter, and the steps involved prior to running the CCDFGF code follow the PANEL Concentration simulations in Stockman et al. (1997). The flowchart in Figure 5.1. shows the steps involved through the entire process. The changed input file for ALGEBRA is identified in Figure 5.1. as input to the ALGEBRA Source Term.

	FMT Calculations	Reed et al. 1996
Castile Brine	5.7 e-9 M	8.0 e-5 M
Salado Brine	4.4 e-6 M	9.0 e-5 M

Table 5.1. Solubility of Plutonium as Determined by Experiment and FMT Calculations

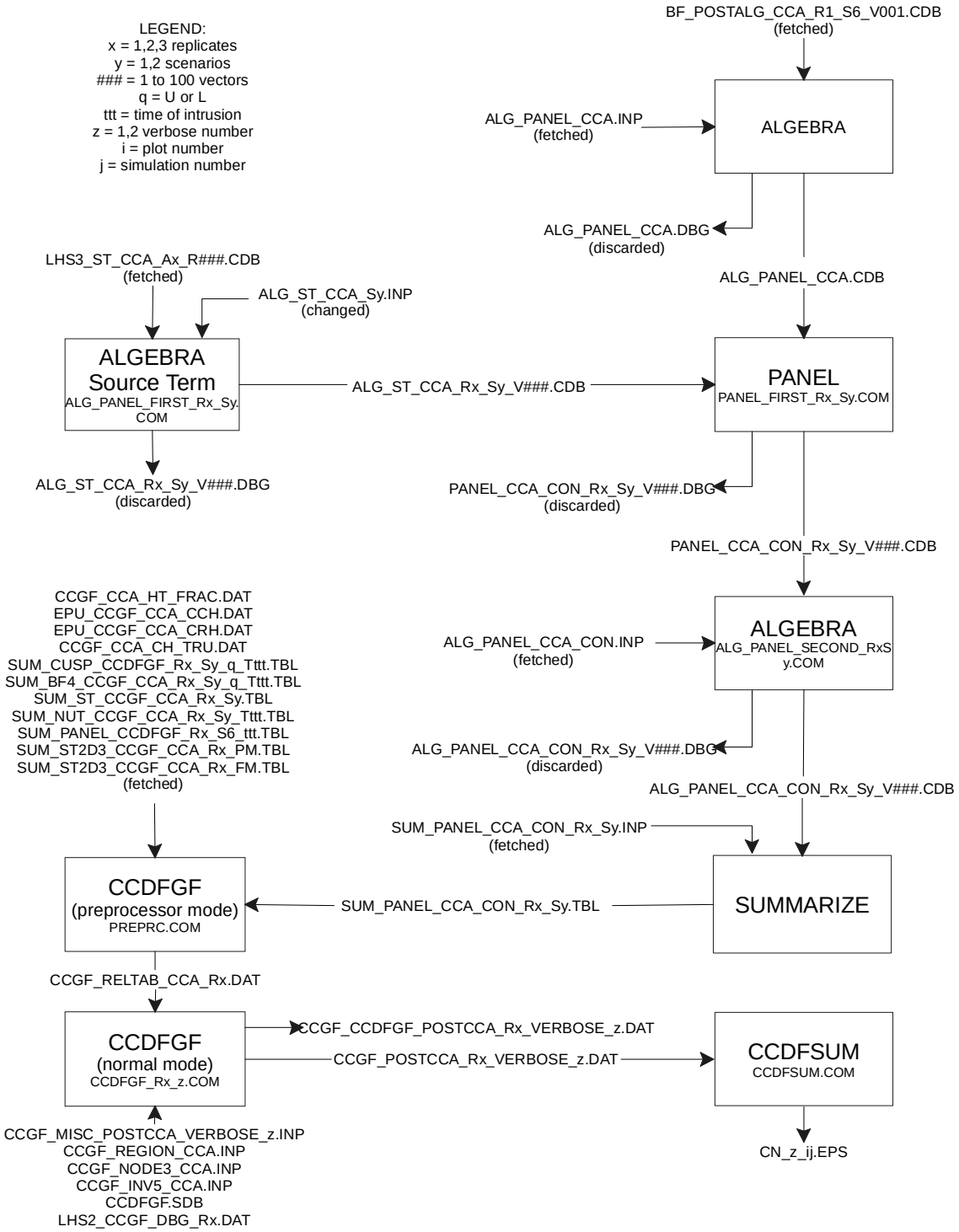

Figure 5.1. Flowchart of PANEL Simulations

Figure 5.1. shows a listing of all the programs needed to run the entire PANEL concentration simulation, and are represented as rectangles. The rectangles list the names of the executable code and the script (if available) used to run the code. Arrows in and out of the rectangle show which files went into and came out of the code execution.

Script files were created to automate the process of running all one hundred vectors for each replicate and scenario for each step. These script files also help to ensure reproduceability of the calculations. Any additional files needed for code execution were fetched from the CMS library, and erased after use. For example, LHS files were needed to run the source term portion of ALGEBRA. The files LHS3_ST_CCA_Ax_R###.CDB (where Ax represents the replicate number and R### are the vectors 1-100) were fetched from the library LHS, and discarded afterward to conserve drive space.

The PANEL calculations were postprocessed by SUMMARIZE and used in CCDFGF to generate new CCDF plots. The CCDFGF was first run in the pre-processor mode, then in normal mode to produce the results. The CCDFGF calculations were then post-processed by CCDFSUM to produce postscript files that are printable.

5.4. Results

The CCDF plot created from CCDFSUM for blowout calculations can be seen in Figure 5.2., with the corresponding CCA plot in Figure 5.3.. Each line represents the probability of a magnitude of release in EPA Units for different vectors of sampled parameter values. The plots are from replicate R1. The highest release from a vector at 10^{-3} probability is less than 1.0 EPA Units. However, this is an increase from the CCA calculations which show the highest vector at less than 0.2 EPA Units at the same probability level.

The plot in Figure 5.4. shows an overall mean increase in blowout normalized release for the increased solubility and the CCA calculations. At the 10^{-3} probability level, the release increases in EPA Units from 0.04 to approximately 0.13. This does not violate the EPA release limit, which limits a release of 10.00 EPA Units (3440 Ci) at 10^{-3} probability.

Further experimentation of the blowout calculations included changing the parameter which controls the probability of a drill intrusion into the Castile brine. In the CCA calculations, this parameter was set to 8 %. The influence of this parameter was tested at higher values at 50 and 100%. These values were based on the potential that the Castile reservoir size encountered by WIPP-12 (Chaturvedi et al. 1997) extends below the waste area. It should be noted that the

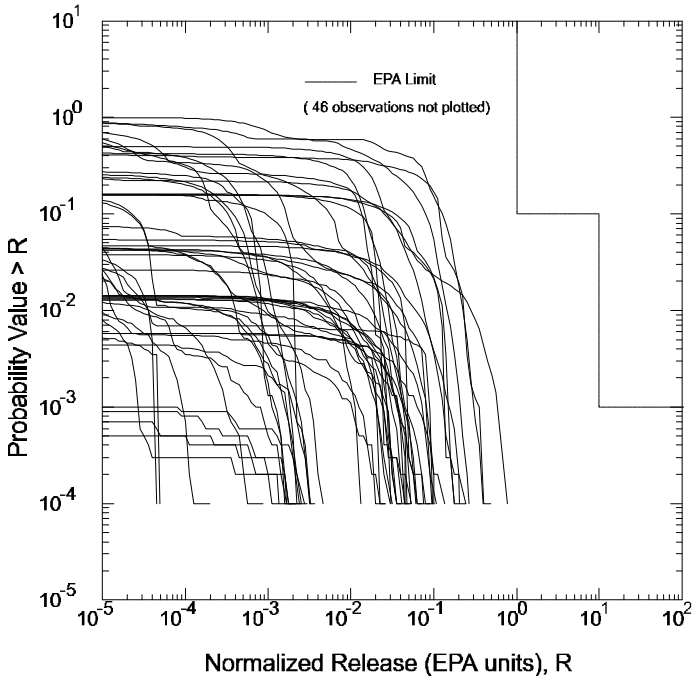

Figure 5.2. Blowout Releases for Increased Solubility

probability parameter is located in the 'Region and Panel Parameters File' (CCGF_REGION_CCA.INP) at position 9, but is overwritten by parameter 3493 in the secondary database file (CCDFGF.SDB).

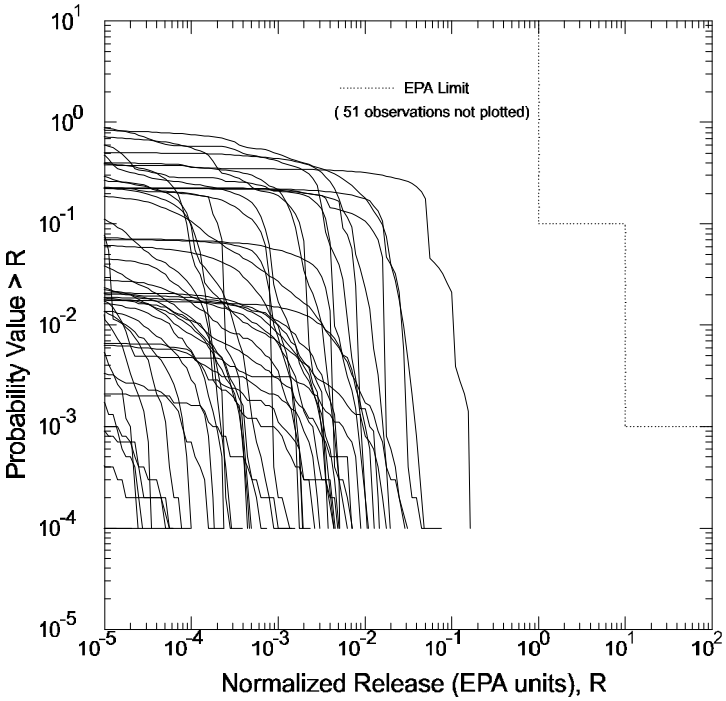

Figure 5.3. Blowout Releases for CCA Calculations

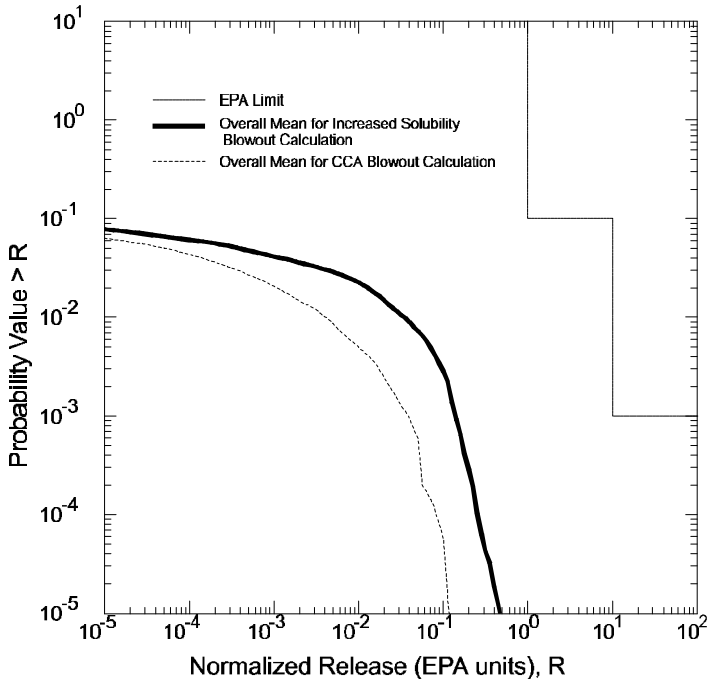

Figure 5.4. Overall Mean of Blowout Normalized Releases

Figure 5.5. shows the overall mean from the total normalized release calculations from the three simulations of 8, 50, and 100% probability as it compares to the CCA. The greatest release came from the 100% probability of Castile brine intrusion, with a value of 0.31 EPA Units at a probability of 10^{-3}, which is less than the 10.0 EPA Units established by the EPA as the maximum allowable release limit. The calculated releases at the 10% level are only slightly effected.

Lastly, the solubility of the plutonium in the Castile and Salado brines was increased further to test the limits and compare values for the previous simulations. The solubilities were increased from 8.0×10^{-5} M and 9.0×10^{-4} M to 8.0×10^{-4} M, 8.0×10^{-3} M, and 8.0×10^{-1} M for both brines. These values have no justification other than testing the limits of the code with respect to more suitable values. The probability of hitting a brine reservoir was returned to 8%. The results were plotted in Figure 5.6., showing the increased solubilities compared to the the CCA calculations and solubility of 8.0×10^{-5} M and 9.0×10^{-5}M in the Castile and Salado, respectively. For each increased solubility simulation, the release increased to a threshold limit at approximately 8.0×10^{-3} M, above which the solubility had no further effect on the calculations. All releases stayed below the EPA limit, with the maximum reaching 1.3 EPA Units at solubilities of 8.0×10^{-3} M and above.

Table 5.2. lists all simulations conducted showing releases at 10^{-3} probability.

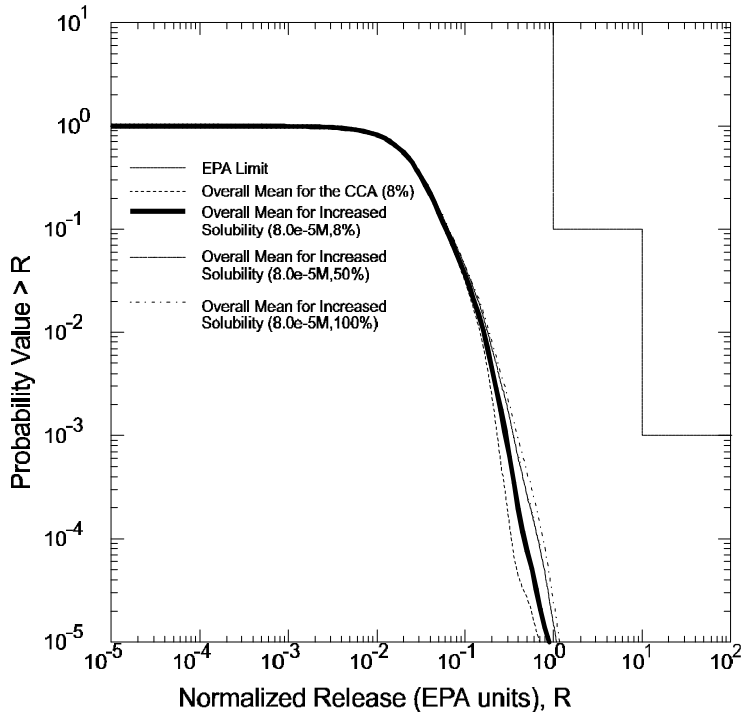

Figure 5.5. Total Normalized Releases with Increasing Probability of Hitting Castile Brine Reservoir

5.5. Conclusions

Additional PANEL simulations were performed to test the effect of plutonium solubility on the CCDF calculations in the CCA. The solubility was changed in both the Castile and Salado brine from a ranged parameter to a constant value. Six simulations were conducted that tested the overall effectiveness of the changes, which included changes in the solubility and Castile brine intrusion probability. Table 5.2. lists the results from each simulations as compared to the CCA calculations.

Simulation Number	Simualtion Description	Blowout Release Overall Mean (U.S. EPA Units)	Total Release Overall Mean (U.S. EPA Units)
1	CCA	0.04	0.21
2	8.0×10^{-5}M, 8% probability	0.13	0.29
3	8.0×10^{-5}M, 50% probability	0.17	0.30
4	8.0×10^{-5}M, 100% probability	0.18	0.31
5	8.0×10^{-4}M, 8% probability	1.0	1.0
6	8.0×10^{-3}M, 8% probability	1.3	1.3
7	8.0×10^{-1}M, 8% probability	1.3	1.3

Table 5.2. Releases for PANEL Simulations at 10^{-3} Probability

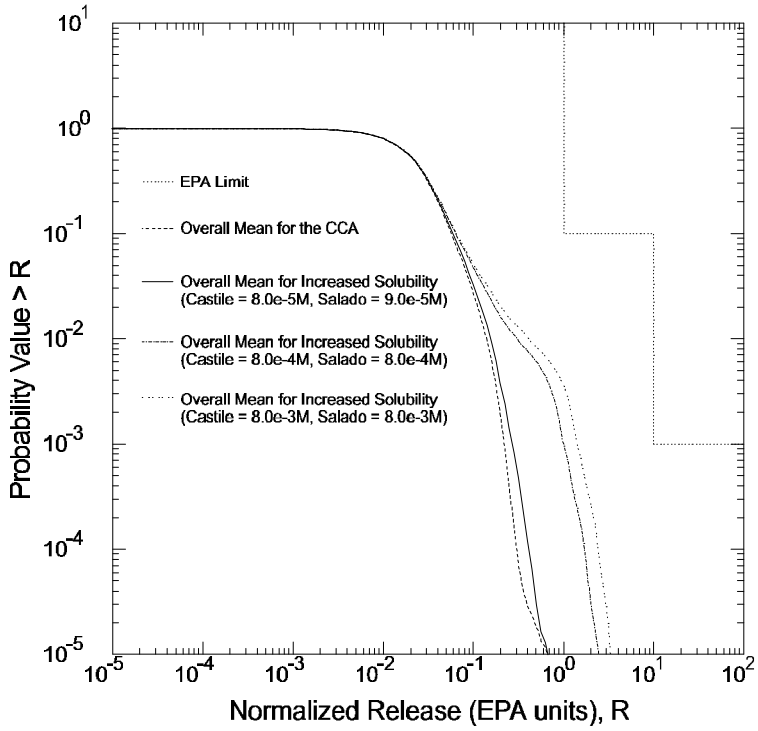

Figure 5.6. Overall Mean of Blowout Releases with Increasing Solubility

As expected, the simulations seemed to be more sensitive to the increased solubilities than the increased Castile intrusion probability. The one order of magnitude increase in solubility from 8.0×10^{-5} M to 8.0×10^{-4} M increased releases by 0.87 EPA Units, whereas the one order of magnitude increase in probability of hitting the Castile brine resevoir from 8% to 100% only increased the releases by 0.08 EPA Units. The releases continued to increase with increasing solubility to a threshold of 8.0×10^{-3} M. Above this solubility no additional increase was calculated, and was most likely limited by the amount of direct brine release. Also, one should note the nonconstant increases in total normalized releases compared to the blowout normalized releases of Table 5.2. The increased solubility of plutonium affects the direct brine release calculation enough to make it a dominate release mechanism for Simulation #5, for probabilities lower than 10^{-2}. Lower solubilities (less than 8×10^{-4} M) mask the effect of the actinides in solution.

The curves represented in Figure 5.6. show the increasing total normalized releases with increasing plutonium solubility in both the Castile and Salado brine, with a maximum release of 1.3 EPA Units at 8.0×10^{-3} M at a 10^{-3} probability. The EPA limit suggests that releases remain below 10.0 EPA Units at the probability of 10^{-3}, therefore rendering all justifiable plutonium solubilities conservative with the current amount of brine release. Additional studies should be conducted in which the amount of brine volume increases with the increasing solubility.

6. TRANSPORT MODELING OF K_dS

6.1. Summary

A modeling study was performed to investigate the roles of chemical retardation through the Culebra aquifer at the WIPP repository. The transport code SECOTP2D was used by varying the values of the partition coefficient (K_d) from that used in the Performance Assessment of the Compliance Certification Application for several key actinides. The results show that the assumed sorption of radionuclides to the surrounding rock matrix coupled with the amount of actinides reaching the Culebra produce very low releases compared to the 40 CFR 191(U.S. EPA 1996a) containment requirements.

6.2. Introduction

The concern of actinide transport through the Culebra has prompted a modeling study by the EEG that investigates the consequences of radioactive wastes to sorb onto the aquifer material through the evaluation of K_ds. The matrix partition coefficient, or K_d, is a species dependent property that varies depending on the sorbing material type, which describes the amount of waste that can be chemically bonded to the matrix adsorbed through ion exchange.

Results of various laboratory experiments to determine the K_d of plutonium, uranium, americium, thorium, and neptunium were reported by Brush and Storz (1996). However, the values obtained from the experiments and the statistical representations that are used for modeling the coefficients were questioned by the EEG (EEG 1997a; 1997c). The EEG argues that the data for K_d values are too limited to justify the current range in the CCA, the amount of organic ligands that will bind with the actinides is much higher than that assumed by the DOE, and a uniform distribution as a representation for all data is unjustified. Therefore, transport modeling of the transuranics using other K_d values were investigated to determine whether chemical retardation is needed to meet compliance standards established by the EPA.

6.3. Methodology

The modeling of the partition coefficient was conducted using the Sandia transport code, SECOTP2D version 1.30. For the present study, the groundwater flow calculations were not rerun and grid velocity files were fetched from the CMS.

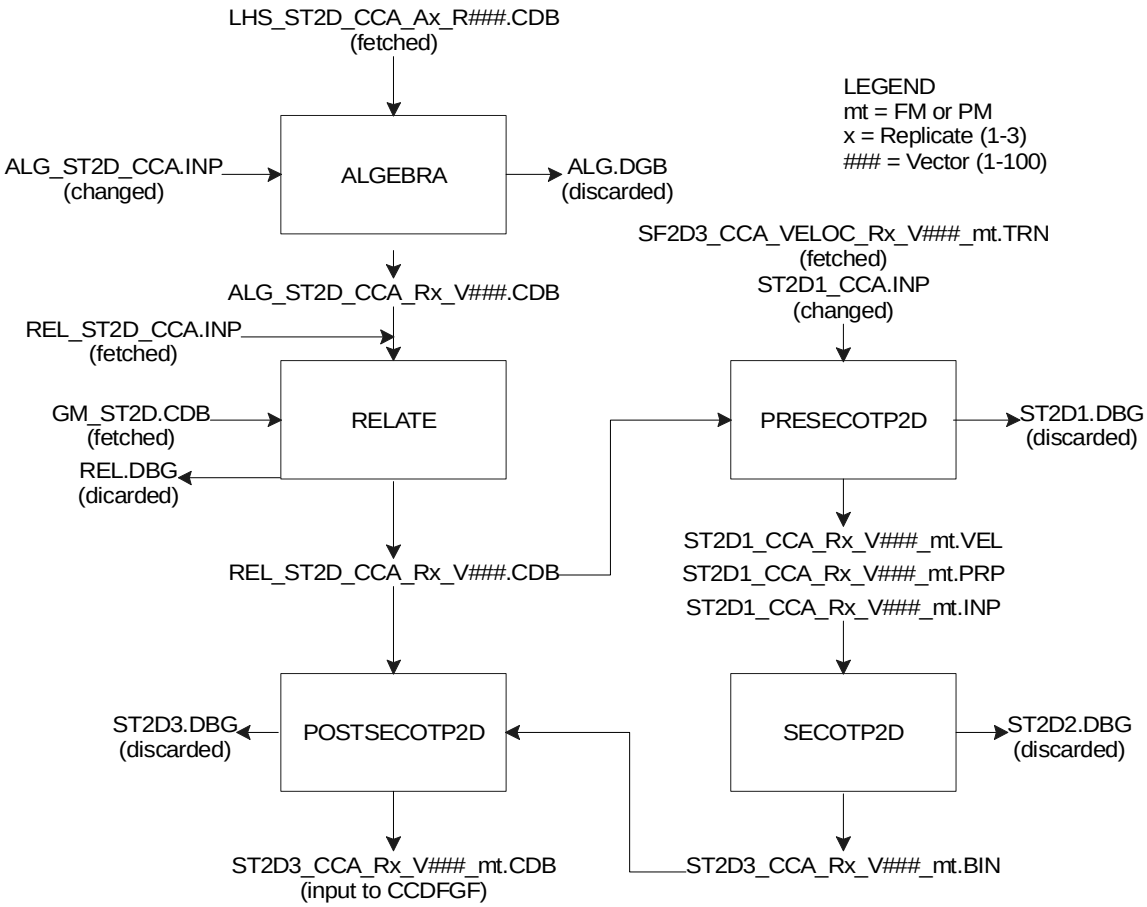

Figure 6.1. Flowchart of SECOTP2D Runs

The only files that were modified for transport simulations were the input file for the ALGEBRA code and the input file for SECOTP2D. The ALGEBRA file, ALG_ST2D_CCA.INP was altered by changing the way the retardation was being calculated. A new value was substituted for the partition coefficient. The input file for SECOTP2D was changed by specifying the transport of only one actinide. Figure 6.1. shows the stream of codes used in modeling with SECOTP2D.

6.4. Transport Modeling Of Plutonium

The importance of the partition coefficient was investigated by Blaine (1997). The investigation found that a value of 3 $^{ml}/_{g}$ was sufficient to retard plutonium through the Culebra for a “worst case” vector. The study was meant to test minimum values of K_d for violation of the EPA standards. The worst case vector included the minimum advective porosity of the Culebra matrix (0.0001), the maximum diffusive porosity of the Culebra matrix (0.25), and the largest half matrix block length (0.5) that were estimated in the CCA. The vector was also tested against

larger half matrix block lengths, of up to 1.0 m. The latter model showed that a value of 15 $^{ml}/_{g}$ for K_d was needed to chemically retard the species adequately to meet EPA regulations.

The above experiment studied the phenomenon of small K_d quite thoroughly. However, K_ds smaller than 1 $^{ml}/_{g}$ were never investigated. Therefore, the present study changes the CCA K_d values from that generated from a range for performance assessment calculations to a model that assumes a very small mass fraction (1%) of the radionuclides have a K_d equal to zero. This effect allows the waste to move through the aquifer unretarded.

The justification for using K_d of zero is summarized in Channell (1997). The evidence, reproduced here, that support the 1% K_d=0 $^{ml}/_{g}$:

(1) A fraction of the actinides is likely to be in organic complexes or chelated. Experimental evidence suggests that these conditions will drastically reduce K_d values.

(2) Column infiltration experiments have shown that small fractions of transuranic radionuclides will move through natural rock columns at or near the speed of water. These radionuclides are not in complex or chelated form.

The first experiment simulated plutonium moving through the Culebra with a fraction of the contaminate having a zero K_d. The original PA groundwater flow calculations from SECOFL2D were used to obtain velocity and discretization (spatial and temporal) information for transport calculations. The original PA assumed that 1 kg of waste would be brought to the surface through a human intrusion borehole. The 1 kg was assumed to be a unit mass of release to the Culebra and is coupled later with the actual amount that is released from the repository through the code CCDFGF. Hence, 0.01 kg was accepted for a 1% K_d =0 $^{ml}/_{g}$ transport simulation.

Transport simulations were conducted on 100 vectors of both full and partial mining of the first replicate. Results of the modeling efforts are presented as integrated discharge and contour plots of waste concentration. Figure 6.2. shows the partial mining scenario with integrated discharges at 10,000 years (on $\log_{10}$ scale) as a function of vector number. The integrated discharge is the fraction of waste mass that crosses the Land Withdraw Boundary (LWB) at a given time. Hence, an integrated discharge value of 0.001 kg is equavelent to 10% of the original waste mass crossing the LWB in 10,000 years. All parameters for the present study were kept the same as that used in the CCA, except for the partition coefficient.

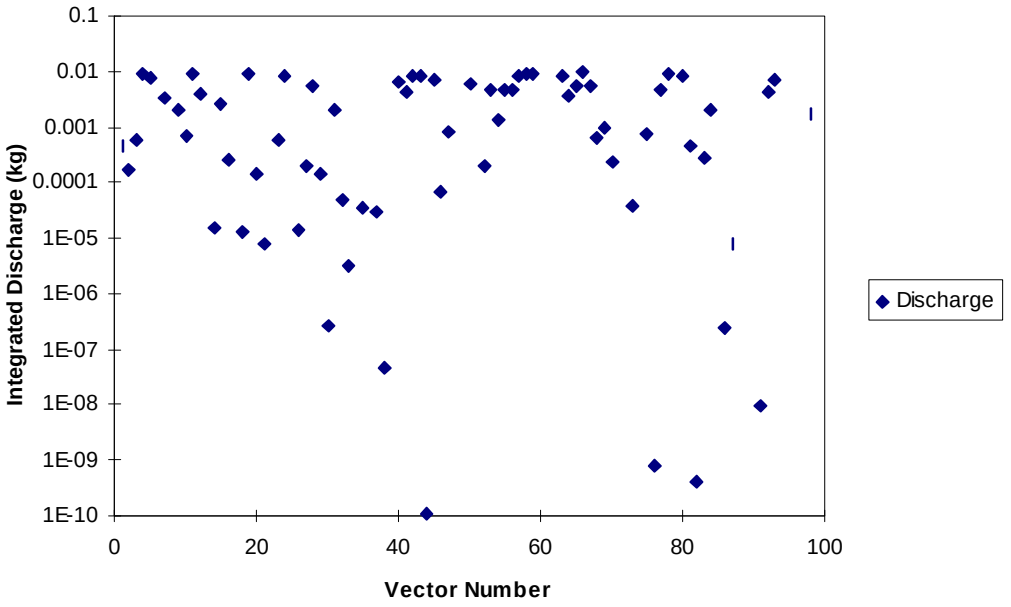

Figure 6.2. Integrated Discharge vs. Vector Number for Partial Mining Scenario at 10,000 Years

In the CCA calculations, there were no vectors with discharge across the boundary at 10,000 years for the first replicate. All actinides were retarded sufficiently and were kept from migrating any substantial distance from the intrusion borehole. Retardation values for plutonium ranged from 216 to 455492 in the PA and were calculated from a linear isotherm. Plutonium retardation for the present model was a single value of 1.0 for all vectors. As a result of lower retardation, a substantial number of vectors showed releases across the LWB.

Figure 6.3. shows a contour plot of vector 4 of replicate 1 for plutonium migration with 1% of the K_d=0 $^{ml}/_{g}$ for the partial mining scenario at 10,000 years. The isopleth concentration levels in kg/m^3 are equivalent to that seen in the Analysis Package, Task 3 (Ramsey and Wallace 1997) with darker shades indicating lower concentrations. The integrated discharge for the plot is 91.9%. The areal view of the figure indicates the location of the Waste Panel Area and the Land Withdraw Boundary in relation to the plume's spread, with the ordinate and abscissa marking 1000 m distances between ticks. An asterisk around the center of the plume designates the highest concentration in kg/m^3, which is not to be confused with the centroid of the plume. The figure shows that the plutonium moves quite quickly (relative to 10,000 years) through the Culebra, and a significant amount passes through the Land Withdraw Boundary in 10,000 years.

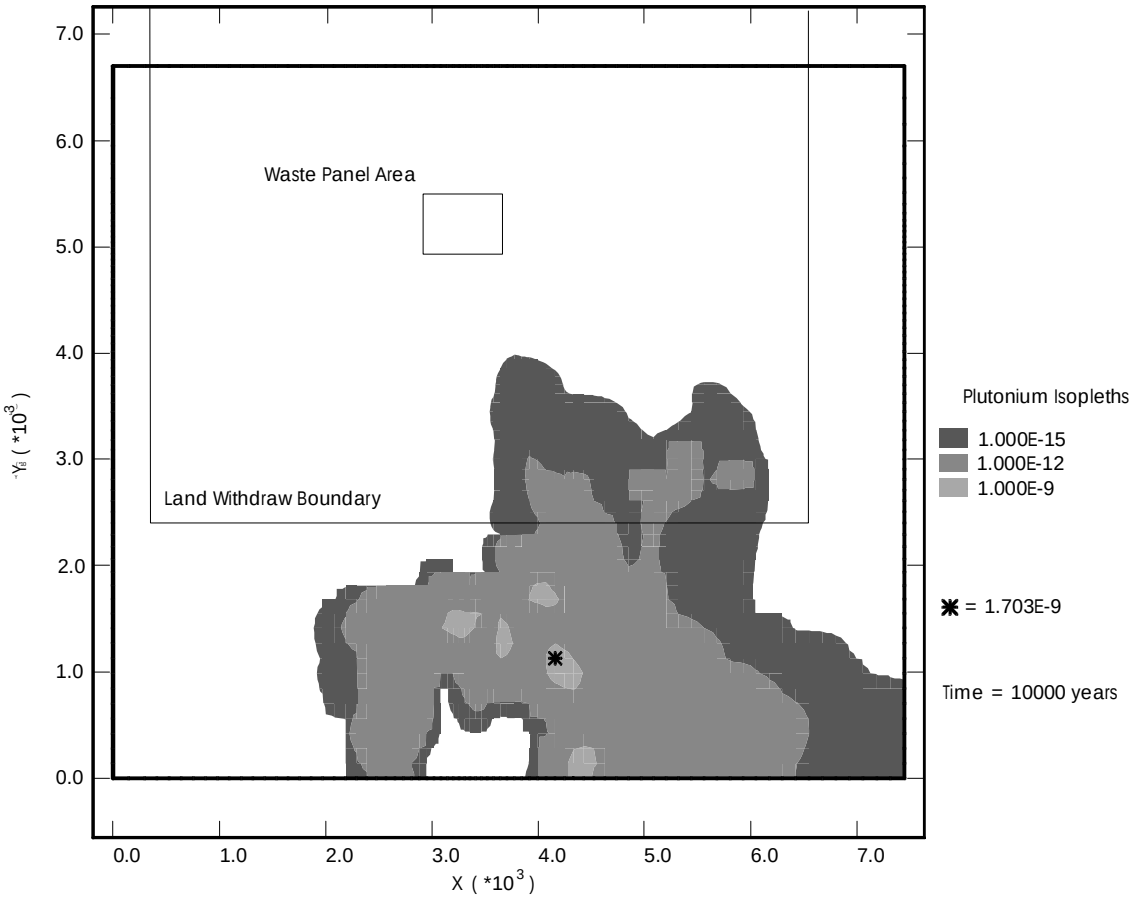

Figure 6.3. Plutonium Concentration (kg/m^3) for Replicate 1, Vector 4, Partial Mining

Figure 6.4. shows the releases for the vectors of the full mining scenario of replicate 1. Again, none of the PA calculated vectors in the CCA had releases across the LWB in 10,000 years. This is a large contrast to the present model, where a substantial number of vectors crossed the LWB. Approximately half of the total vectors have at least 1% discharge across the Land Withdraw Boundary in 10,000 years in both full and partial mining scenarios.

Though many vectors seem to have a high release, one vector in particular, Vector 20, stands out as a possible error. The discharge across the LWB is 0.0135 kgs, normalized to 135% of the original mass entering the Culebra. The obvious error of the overcalculated mass could be attributed to the large mass balance error (-0.3619 kgs) associated with the calculation. These errors are documented for SECOTP2D version 1.30 by the EPA (U.S. EPA 1997) and the DOE (U.S. DOE 1997c). The EPA's request for additional information about the mass balance calculations in the PA prompted a study in (Ramsey and Treadway 1997) on the extent of the errors associated with the code. Their findings demonstrated that the major problems of mass conservation are attributed to the boundary conditions on the southern-most boundary. The total

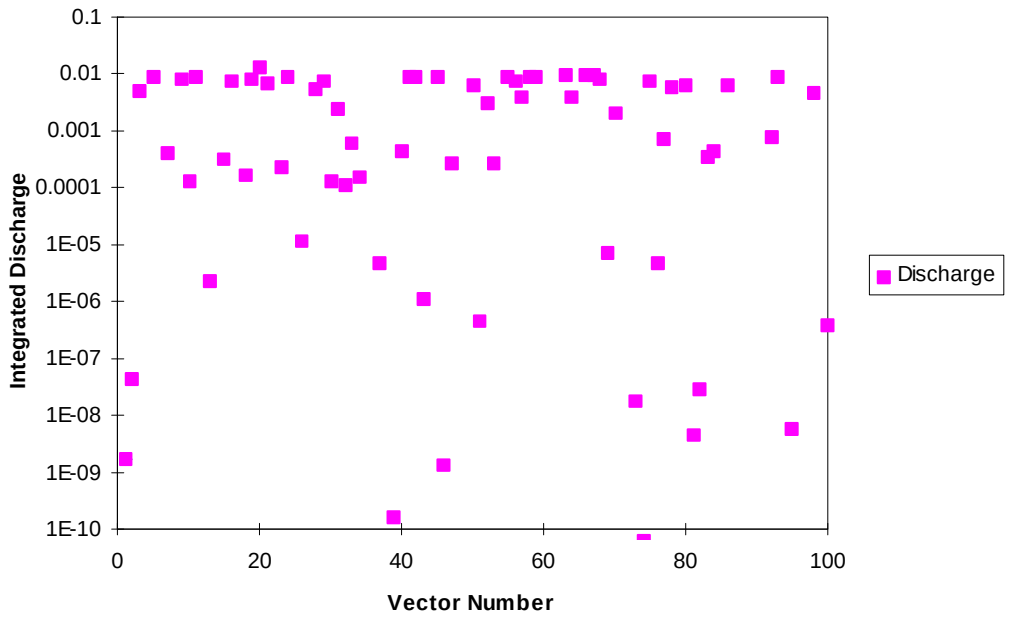

Figure 6.4. Integrated Discharge vs. Vector Number for Full Mining Scenario at 10,000 Years with 1% of Plutonium Having a K_d of Zero

variation diminishing (TVD) differencing scheme in combination with large Courant numbers were the culprit and was subsequently fixed in version 1.40. However, this version was unavailable at the time of these simulations.

The effect of the nonconservative models is uncertain. The problem lies on the southern boundary, where most of the nuclides are transported across the LWB. The mass balance error has been quantified in a single vector (EEG 1997b) for all five nuclides as approaching 100%. The error shows a large underestimation of transport decreasing in time, and yet it cannot be reasonably assumed that all vectors are underestimated, since Vector 20 in the present model shows an overestimation of 35%.

Figure 6.5. shows a similar plot to that of Figure 6.3.: plutonium concentrations for Vector 58 of the full mining scenario. The discharge across the LWB for Vectors 58 is 88.6%. The slight difference in discharge between the two figures is compensated greatly in Figure 6.5. by the areal extent of higher concentrations. The isopleths indicating 1.0×10^{-9} kg/m^3 has a farther and more continuous reach than seen in Figure 6.3. Conceptually, this could have a greater impact on future generations who may drill into the aquifer, especially if they were in a direct downstream pathway from the source of the highest concentration.

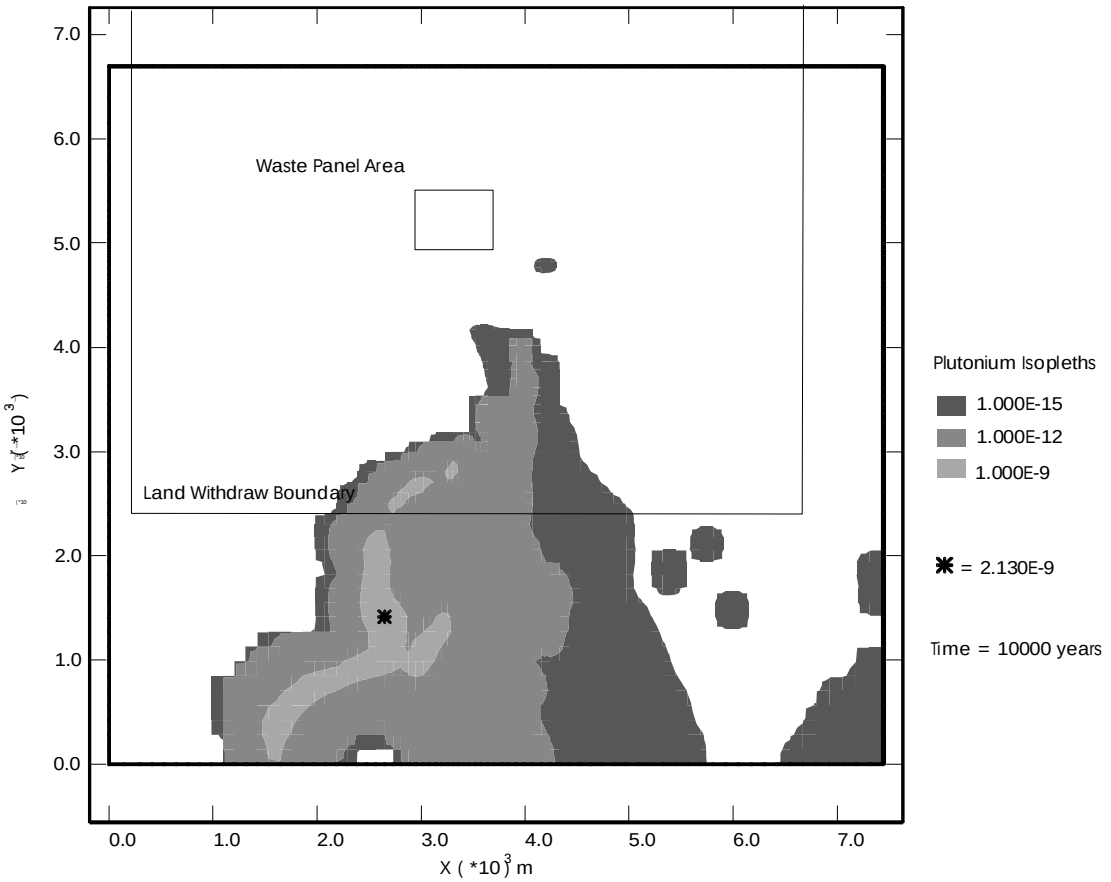

Figure 6.5. Plutonium Concentration (kg/m^3) for Replicate 1, Vector 58, Full Mining

The combined effort of the partial and full mining scenario modeling with a 1% K_d=0 $^{ml}/_g$ can be seen in the CCDF plots of Figure 6.6. The plot demonstrates a probability associated with a release from the Culebra in EPA units. This figure shows that the consequence of a one percent, zero matrix distribution coefficient for plutonium has virtually no effect on compliance. Only 10 vectors appeared on the plot, with the mean of all vectors superimposed on the figure. At a probability level of 10^{-3}, less than 10^{-4} EPA units will be released from the Culebra. The EPA limit for a 10^{-3} probability is 10 EPA units. The extremely low consequence is attributed to the coupling of the releases to the Culebra that were calculated through NUTS and PANEL. Table 6.1. lists the releases of plutonium-239 and the total for all actinides for scenarios 2 through 6 to the Culebra. Scenario 1 assumes no human intrusion, therefore no waste is released from the repository to reach the Culebra aquifer. The low releases seen in Table 6.1. confirms the low probabilities associated with the radionuclides reaching the assessible environment.

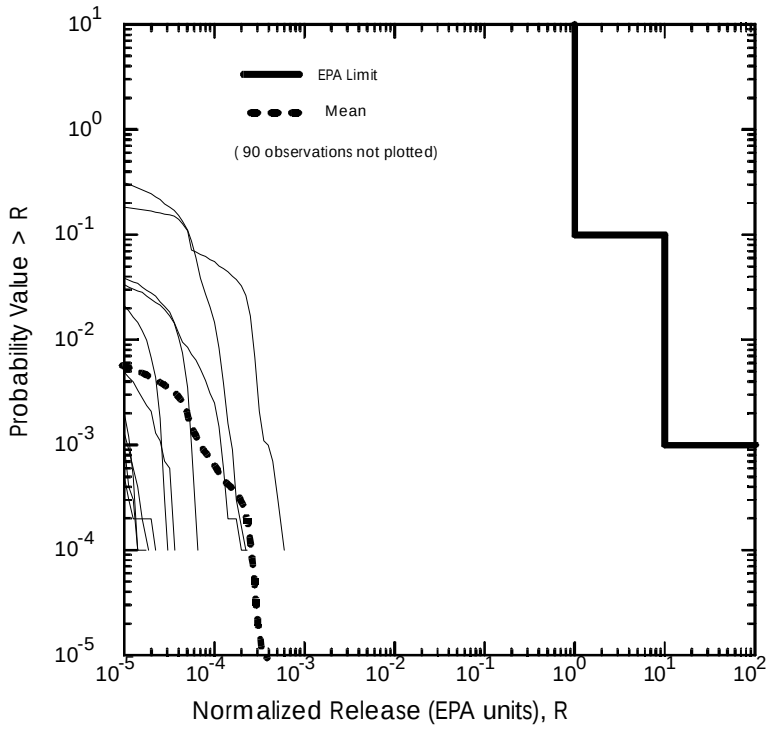

Figure 6.6. Total Normalized Releases from Culebra for 1% K_d=0 ml/g for Plutonium Simulation

Scenario	Intrusion Time (yr)	Pu-239 Releases (U.S. EPA units)	Total for all Actinides (U.S. EPA units)
2	100	0.045	6.62
	350	0.044	6.04
	1000	0.044	2.19
	3000	0.32	0.36
3	5000	0.24	0.24
	7000	0.14	0.14
	9000	0.035	0.04
4	100	20.8	21.1
	350	20.1	20.4
	1000	18.2	18.4
	3000	11.5	11.6
5	5000	5.57	5.62
	7000	1.09	1.10
	9000	0.027	0.03
	100	0.43	95.0
	350	0.42	68.7
6	1000	0.41	26.0
	2000	0.39	5.57
	4000	0.66	0.79
	6000	0.47	0.49
	9000	0.18	0.20

Table 6.1. Maximum Releases of Plutonium-239 and Total for all Actinides to the Culebra

6.5. Probability Modeling Of Actinides

Finally, the CCDF code was run assuming that 100% of all actinides that reached the Culebra crossed the boundary, instantaneously. This scenario can be used as an upper end bounding case for transport through the Culebra. The simulation was run for the first replicate only, and was found to fail the EPA compliance criteria at 10^{-3} probability, as seen in Figure 6.7. Yet, one should not reach a conclusion that K_d could have significance from this plot. Further investigation shows that the failure is due to a single vector of high plutonium release to the Culebra. The transport coupled with the actinide source calculations from NUTS and PANEL may pose a possible threat in the 10,000 year future of the repository, but the transport alone, keeping all other parameters the same, is inconsequential.

6.6. Conclusions

The main focus of this study was to model the transport actinides through the Culebra Dolomite at the WIPP with a small portion of the radionuclides being nonreactive to the surrounding dolomite rock. Plutonium and uranium were simulated with a matrix partition coefficient (Kd) equal to zero. Probability modeling was also conducted on all actinides to test the robustness

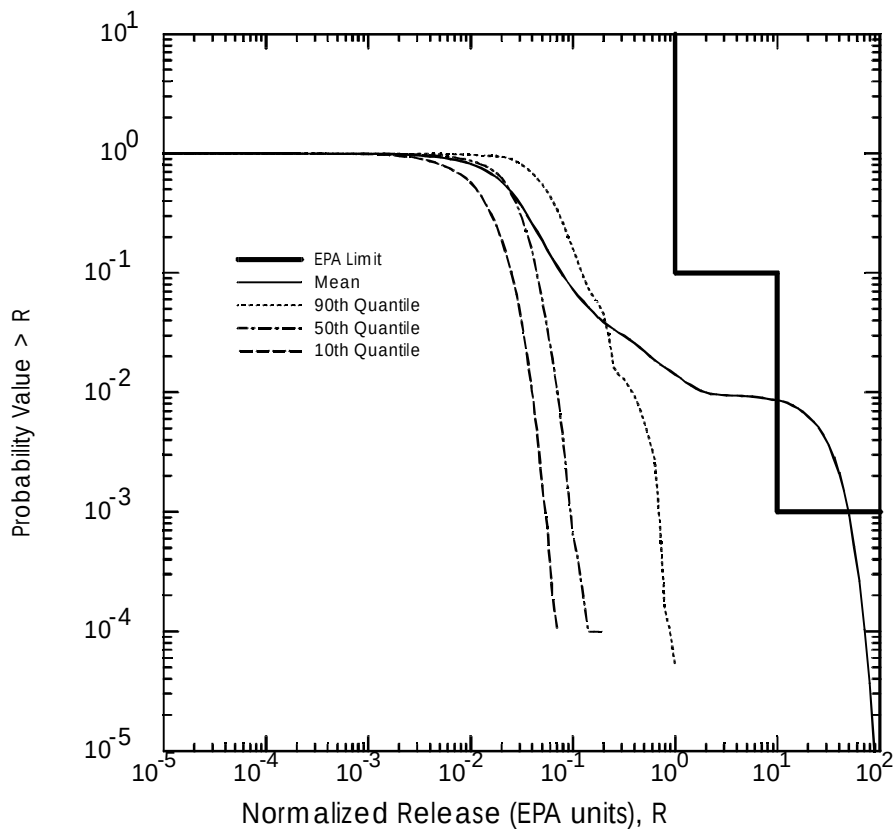

Figure 6.7. Total Normalized Releases for all Actinides Crossing the LWB

and consequences of all the actinides crossing the LWB in 10,000 years.

The plutonium simulations included 100 vectors for each partial and full mining scenarios for a single replicate. The results were summarized and incorporated into the CCDF curves of the CCA, as seen in Figure 6.6. Over half of the vectors (approximately 100 out of 200 vectors) had releases of at least 1% across the accessible boundary, which is substantial compared to the number that crossed in the CCA (zero out of 200). However, after coupling these unit releases with the actinide sources in NUTS and PANEL, the releases were shown to have negligible effect on the overall CCDF.

7. CASTILE BRINE RESERVOIR PARAMETERS

7.1. Summary

The results of a sensitivity analysis for several key parameters dealing with the Castile Reservoir and waste permeability are reported in this chapter. The modeling starts with flow calculations within the Salado Formation using BRAGFLO, and finishes by incorporating the results of the amount of solid waste and brine that may be ejected from an inadvertent human intrusion using CUTTINGS_S and BRAGFLO_DBR into a CCDF. The changed modeling parameters include Castile Reservoir volume, rock compressibility and permeability, and waste residual brine saturation and permeability. The results show that the overall mean of the CCDF does not increase above that seen in the CCA when all other performance assessment assumptions are used. The CCDF shows a trivial increase in releases when the probability of actually hitting the Castile reservoir increases from 8 to 100%.

7.2. Introduction

The pressurized Castile brine reservoir that underlies the Waste Isolation Pilot Plant has been the subject of many debates on its extent and importance (EEG 1997b; 1997d; Silva 1994; U.S. DOE 1997a; Beauheim 1997). The scientists who setup the CCA performance assessment calculations recognized the fact that the brine could play a significant role in the degradation of wastes and waste container, if an inadvertent drilling intrusion were to pass through the repository to the brine reservoirs below, by assigning two of the six scenarios to calculate the effects of the breach. However, the characterization of the parameters associated with the reservoir were undermined by associating them to data that clearly lies outside of the domain of the repository. The more realistic parameter values proposed by the EEG could potentially demonstrate higher direct brine releases to the surface, affecting the compliance of EPA standards in the 40 CFR 191. Therefore, additional calculations were performed using more reasonable parameters for the simulation of Castile brine migrating into the repository. These calculations are referred to as the Castile Simulation.

7.3. Reservoir Parameters

Reservoir parameters used in performance assessment calculations were derived from borehole information that lie mainly outside the domain of the WIPP repository. The distance to these boreholes ranged from 3.75 miles to over 11 miles from the repository center. Figure 7.1. shows the location of some of the boreholes used to characterize the Castile brine reservoirs. Two boreholes in particular, WIPP-12 and ERDA-6, stand out, as they were used most frequently to define Castile Reservoir parameters. The depths of these two boreholes vary significantly.

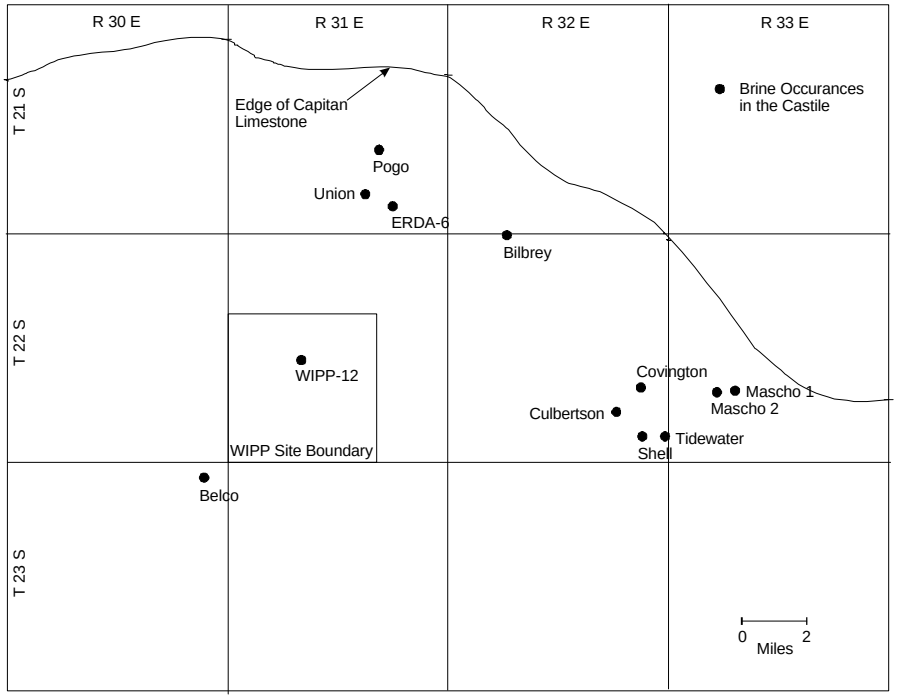

Figure 7.1. Location of Boreholes in the Castile Formation that were used to Characterize a Castile Brine Reservoir

WIPP-12 was bored into the Anhydrite I layer of the Castile to 3925 feet, whereas ERDA-6 had a total depth of 2775 feet into the Anhydrite II layer.

New values were assigned to several parameters that describe the Castile brine reservoir based on WIPP-12 data that is more closely identified to the conditions at the repository. The WIPP-12 borehole, is located within the WIPP site, one mile north of the repository. The borehole was originally drilled in 1978 and deepened in 1981 at the request of the EEG, which caused the repository to be moved south after brine was encountered at the borehole. The borehole experienced brine flow to the surface when drilling reached a depth of 3012 feet (D'Appolonia 1982). While extending the borehole to depths greater than 3,900 feet, a total of 80,000 barrels was allowed to flow from the borehole.

7.3.1. Productivity Ratio

The parameters associated with describing the Castile brine reservoir include reservoir volume, rock compressibility, reservoir pressure, and permeability. The correlation of volume and rock compressibility was recognized when Beauheim (1997) described a ratio based on these parameters. The productivity ratio is the product of the brine volume and rock compressibility by the porosity: $PR = V\frac{C_r}{q}$, where V is volume, C_r is rock compressibility, and θ is porosity. This

value was identified by Beauheim (after CCA calculations were completed) to a range of 0.0007 m^3/Pa to 0.04 m^3/Pa. The range was based on more relevant data. The CCA calculations had a range that varied from 5.3×10^{-5} m^3/Pa to 0.06 m^3/Pa.

Beauheim's new range was based on borehole data from ERDA-6 and WIPP-12. Both borehole encountered brine in the Castile formation, and it was assumed conservative that parameter values should include data from both boreholes to cover the uncertainty in a possible reservoir under the repsoitory. However, using the lower value of the range, calculated from the ERDA-6 borehole, seems unjustified for the repository. The borehole is located approximately 6.4 km (4 miles) northeast of the site, and much less brine was encountered, compared to the WIPP-12 borehole. The upper value in the range was calculated from WIPP-12 data. Figure 7.2. shows the productivity ratios of the CCA with the new range suggested by Beauheim and where the WIPP-12 data lie.

A single productivity ratio value for WIPP-12 is the basis for additional simulations by the EEG. The value of 0.04 m^3/Pa eliminates the dependence on boreholes in the far field, and places it solely on the importance of WIPP-12. The value is constructed by choosing a single value for the brine volume size and rock compressibility, and using the CCA value for porosity. The basis for the new volume and compressibility values are discussed below.

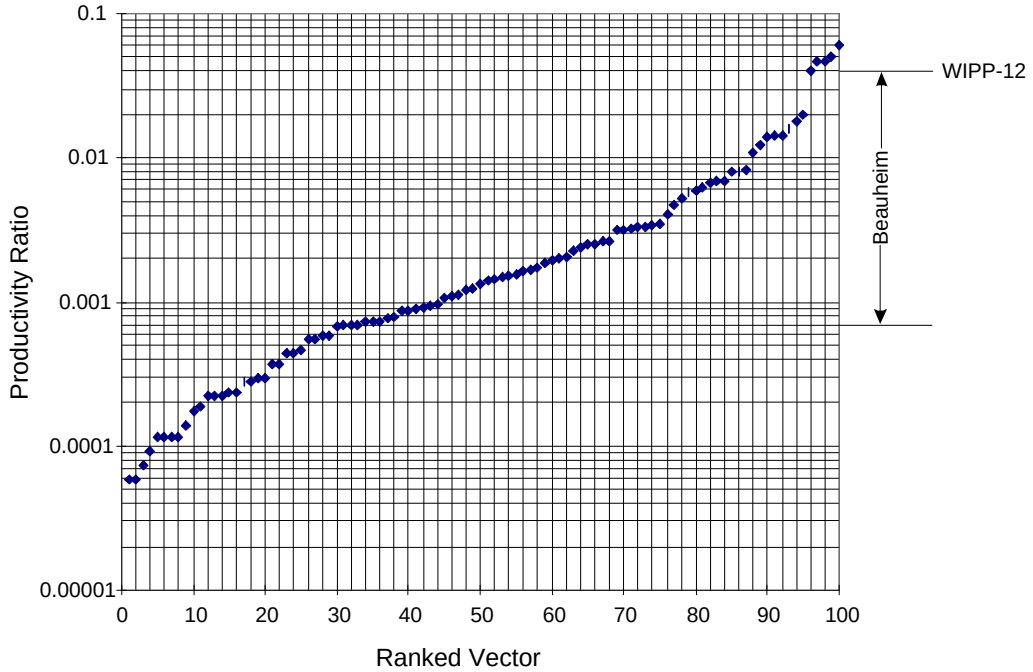

Figure 7.2. Productivity Ratio of the CCA for Replicate 1

7.3.1.1. Castile Brine Volume

Though unimportant as an individual concern in calculating the reservoir's function in the performance of the disposal system, the volume of the Castile brine may show the extent to which the reservoir attenuates underneath the repository. Chapter 5 of this report discusses the possibility of a higher probability associated with striking a pressurized brine reservoir. If the volume is grossly underestimated, then the likelihood of an encounter is low. The CCA values in the performance assessment used five different volumes: 32,000 m^3, 64,000 m^3, 96,000 m^3, 128,000 m^3, and 160,000 m^3. The smallest of these was calculated from WIPP-12 data assuming a compressibility of 5 x 10^{-12} Pa^{-1} and porosity of 0.008 (Larson and Freeze 1996). A maximum calculated reservoir volume of 64,000,000 m^3, based on a compressibility of 10^{-8} Pa^{-1}, was rejected by assuming either that multiple intrusions into the reservoir would deplete the availability of brine, or that the brine reservoirs were not interconnected with highly conductive fractures to produce a single large combined volume. It was theorized that small, highly pressurized brine reservoirs would produce higher brine flow to the repository than large depressurized pockets.

The report describing the WIPP-12 brine reservoir data (D'Appolonia 1983) lists a calculated volume of 2,700,000 m^3, based on pore compressibility values different from the CCA values (discussion below). When the range was suggested by Beauheim (1997) to be 100,000 - 1,700,000 m^3, the performance assessment calculations were already complete and the change was postulated to have no effect on compliance due to the single importance of the productivity ratio. However, new calculations should be performed to include a more reasonable brine reservoir volume from more relevant data.

7.3.1.2. Rock Compressibility of Castile Reservoir

The rock compressibility data for the performance assessment calculations were established on laboratory measurements of an Anhydrite III core from the WIPP-12 borehole, in-situ hydraulic testing of Salado anhydrite and halite, and textbook ranges (Freeze and Cherry 1979) of fracture rock compressibility. The compressibility was calculated from Equation 6-3 in (Beauheim et al. 1990),

$$C_r = \frac{1}{K + \frac{4G}{3}},$$

where K is the grain modulus (or bulk modulus) and G is the shear modulus. The bulk modulus of the Anhydrite III core was estimated to be 6.9x10^{10} Pa, but a value of shear modulus was not

known. It was determined that G was approximately 1/3 K for Salado anhydrites (Beauheim et al. 1990), and again was used in calculating the compressibility for Castile anhydrite. Hence, the core data indicates $C_r = 1x10^{-11}$ Pa. However, the range was changed based on hydraulic testing performed on Salado anhydrites and halites. The lower compressibility value in the CCA range was calculated to be $5x10^{-12}$ Pa^{-1}, and the upper value was from the textbook value of $1x10^{-8}$ Pa^{-1} based on the potential effects of the fracture on formation compressibility.

The compressibility was determined in an earlier report (D'Appolonia 1983) based solely on the bulk modulus and porosity from the equation,

$$C_r = \frac{1}{f\ K},$$

where ϕ is the porosity and ranges from 0.001 to 0.01 in Castile anhydrites. This definition of compressibility was derived from the basic understanding of the compressibility in porous media. The values for compressibility were calculated to be $1.45x10^{-7}$ Pa^{-1} to $2.9x10^{-9}$ Pa^{-1} with bulk moduli ranging from $6.9x10^{9}$ Pa to $3.45x10^{10}$ Pa. Therefore, it is possible that the range used in the CCA are too small. A larger value is suggested here, that would correlate with the volume to produce a productivity ratio of 0.04 m^3/Pa.

7.3.2. Castile Reservoir Pressure

The initial pressures of the Castile reservoir ranged from 11.1 MPa to 17.0 MPa in the CCA calculations based on observed data from four boreholes drilled to depths of the Castile formation. The WIPP-12 data were clearly the best measured values with a pressure at 12.7 MPa (Larson and Freeze 1996), but the range was extended to include the Covington (Figure 7.1.) and ERDA-6 data and adjusted for lithostatic pressures at the WIPP level. The adjusted range for CCA calculations should have been 11.1 MPa to 16.4 MPa, but was increased to 17.0 MPa. Although higher values are more conservative, the most reasonable value should be used. EEG used a fixed Castile reservoir pressure of 12.7 MPa.

7.3.3. Castile Reservoir Permeability

The permeability of the Castile reservoir ranged from $1.6x10^{-10}$ m^2 to $2.0x10^{-15}$ m^2 in the CCA calculations. The calculations performed by the EEG used slightly different values, ranging from $5.8x10^{-11}$ m^2 to $5.8x10^{-15}$ m^2. The new values used a median of $5.8x10^{-13}$ m^2 based on Beauheim (1997) and were increased and decreased by two orders of magnitude to create the upper and lower values in the range, to cover uncertainty. The role of the Castile permeability is relatively unimportant, and does not affect the amount of brine that eventually migrates upward to the Culebra. The flow of brine up the borehole is controlled by the borehole permeability.

However, the Castile brine movement will affect the amount of brine that will reach the repository to be released through a breach. With the small changes in this parameter, it is unlikely that it would have a significant affect on the new calculations.

7.3.4. Other Parameter Changes

Since the simulations using the changed parameters as suggested by the EEG would take a considerable amount of time to complete, it was reasoned that two additional parameters would be included in the Castile Simulation. The two parameters are waste permeability and waste room residual brine saturation, and each describe different processes of the repository.

7.3.4.1. Waste Permeability

The permeability of the waste in the repository was a constant in the CCA, equal to 1.7×10^{-13} m^2. This value was derived from consolidated waste made from sludge, combustibles, and metals. However, a peer review (U.S. DOE 1996-Appendix Peer 1) of the work found an error in the calculation and suggested a new value of 2.4×10^{-13} m^2. The new value will allow a higher brine flow through the repository, up the borehole, and to the surface. It will directly impact the amount of direct brine releases, and a constant value of permeability is more conservative than a range of values, which would incorporate lower values.

7.3.4.2. Residual Brine Saturation

The parameter for residual brine saturation is used in calculating the relative permeability of brine in the waste and to define the capillary pressure curves for the models of partial saturation. The number is expressed as a fraction between 0 and 1, and brine is immobile when the brine saturation is below the value of the parameter. Therefore, this parameter may be very important in postulating the amount of brine that will move through the waste area up the borehole to the surface. Numbers that are too large will inhibit brine movement.

The data used in calculating the residual brine saturation in the CCA does not relate to any material from the waste or the disposal system. Instead, the data are typical values from literature for unconsolidated material, ranging from 0.0783 to 0.560. However, the largest value in the range is from a consolidated sandstone. The EEG believed that this value should be ignored, and the range reduced with an upper value of 0.318 (from fragmented sandstone). The EEG has since concluded that the original range used in the CCA was appropriate and that the calculations performed in this analysis are conservative, due to the consolidation of waste after creep closure of the rooms.

7.4. Methodology

The objective of the new calculations was to determine the change in the amount of radionuclide release from the repository due to the changes in the Castile reservoir and waste area parameters. This was accomplished by (1) running BRAGFLO to determine the brine saturations, pressures, and repository porosities, (2) running CUTTINGS to determine the amount of solid material that would be brought to the surface and to establish initial conditions to be used in BRAGFLO_DBR and (3) running BRAGFLO_DBR, which uses the data from CUTTINGS and BRAGFLO to calculate the volume of brine released from the repository. Each code required a set of separate steps to run, and are presented below.

7.4.1. BRAGFLO Calculations

The only changes in running the suite of codes was in BRAGFLO. Table 7.1. lists the parameters and the values that were used in the CCA, suggested ranges by Beauheim (1997),

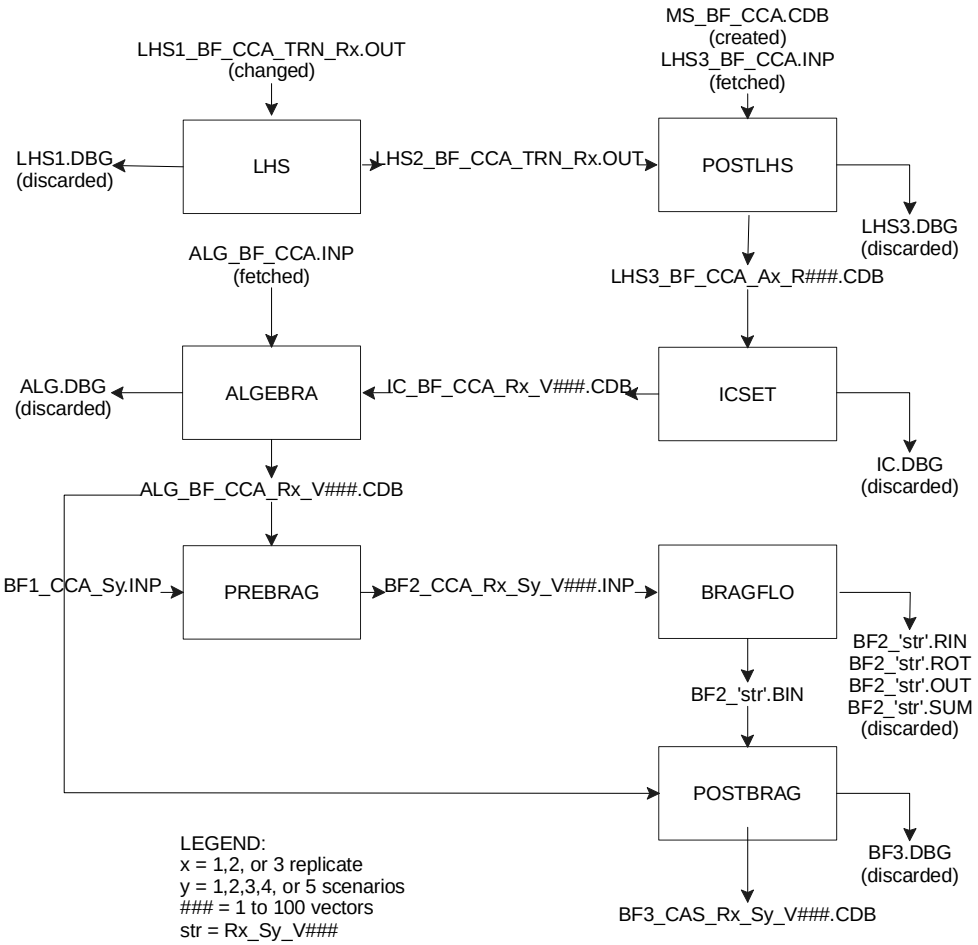

Figure 7.3. Flowchart for BRAGFLO Calculations

Simulation	Log Reservoir Permeability (log m^2)	Initial Pressure (MPa)	Log Rock Compressibility (log Pa^{-1})	Reservoir Volume (m^3)	Waste Permeability (m^2)	Waste Room Residual Brine Saturation
CCA	-9.8 to -14.7	11.1 to 17.0	-8 to -11.3	32,000 to 160,000	1.7×10^{-13}	0 to 0.552
Beauheim (1997)	-10.2 to -14.7	11.1 to 16.5	-9 to -10.7	100,000 to 1,700,000	NA	NA
EEG*	-10.23 to -14.23	12.7	-8.66*	160,000*	2.4×10^{-13}	0 to 0.318

Table 7.1. Castile Reservoir Parameter Suggestions

*BRAGFLO only allowed the choice of 5 volume sizes: 32,000 m^3, 64,000 m^3, 96,000 m^3, 128,000 m^3, and 160,000 m^3. The largest volume size available was chosen and the compressibility was calculated based on a productivity ratio of 0.04 m^3/Pa. The porosity for the calculation remained at 0.0087. If the recommended volume of 2,700,000 m^3 could have been chosen as the measured size, then the log compressibility value would be -9.88 log Pa^{-1} (1.28×10^{-10} Pa^{-1}).

and the new range for the present EEG calculations.

The changes in the simulations started at the LHS files. The values and ranges were modified to reflect the new selected parameters. Figure 7.3. shows the flowchart of the BRAGFLO suite of codes and where the changes were made. The massive amount of files created from the

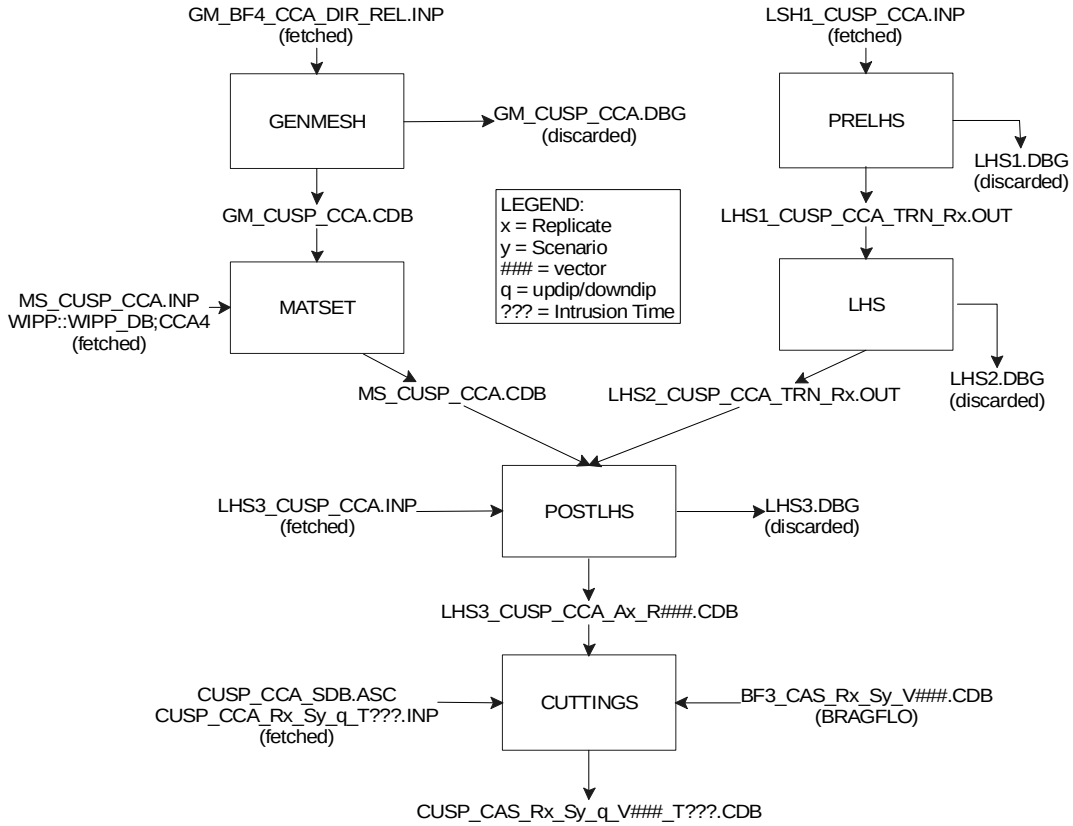

Figure 7.4. Flowchart of CUTTINGS_S Simulations

simulation allowed only two files from each vector to be retained, the postprocessed BRAGFLO file, BF3_CAS_R1_Sy_V###.CDB and the input file for BRAGFLO, BF2_CAS_R1_Sy_V###.INP, where 'y' is the scenario and '###' is the vector number. Both files are important to running other codes.

Due to time and disk space constraints, only two scenarios of one replicate could be simulated. The two scenarios, S2 and S3, deal with an E1 intrusion. The E1 intrusion describes the possibility of a drill intrusion through the repository to the pressurized brine pockets below. The remaining four scenarios would be unaffected by the changes in Castile brine reservoir parameters, but would show slightly different releases due to the waste area parameter changes.

7.4.2. CUTTINGS_S Calculations

The release of solid materials from a drill intrusion was calculated in CUTTINGS_S. The code extracted information from the BRAGFLO simulation to establish the amount of material brought to the surface. Figure 7.4. shows the steps involved in running the CUTTINGS_S suite and where the BRAGFLO output file is read.

As explained in Chapter 2, the CUTTINGS code calculates the effects of a drill intrusion at other times than specified by the scenario number. An S2 scenario assumes an E1 initial intrusion at 350 years, and uses that information to calculate an E2 intrusion at 550, 750, 2,000, 4,000, and 10,000 years. The S3 scenario assumes an E1 initial intrusion at 1,000 years, and calculates an E2 at 1,200, 1,400, 3,000, 5,000, and 10,000 years. The large number of time intrusions allow the CCDFGF code to scale the releases over the 10,000 year future of the repository.

The CUTTINGS_S code also calculates an intrusion into two areas of the repository. The repository is on a 1° slope to the south, and is divided into updip and downdip regions. The downdip includes Panels 4 and 5, whereas the updip includes Panels 1,2,3,6,7,and 8. It is suspected that the downdip panels will fill with brine sooner than in the updip due to gravity, producing a higher activity of gas generation from corrosion and microbial activity. The gas generation will increase the pressures in that area until pressure is equilibriated with the surrounding rock. If the repository is breached, the downdip region should release more waste and brine to the surface. The updip portion of the repository remains virtually closed off from the downdip as a result of creep closure and low permeability of waste, thus prohibiting migration of brine to the area. Therefore, a totally separate calculation is performed for the two areas.

Unlike the other two codes in the sequence, CUTTINGS_S also indirectly calculates the amount of radionuclides released to the surface. Therefore, the files are retained for input to the CCDFGF code for probability assessment.

7.4.3. BRAGFLO_DBR Calculations

Lastly, the BRAGFLO_DBR code is used to calculate the amount of brine released directly to the surface. The code uses the CUTTINGS and BRAGFLO results for initial conditions and extracts the parameters needed for calculations. Figure 7.5a. and Figure 7.5b. lists the configuration of a direct brine release calculation. The time intrusion calculations for the direct brine release are the same as for CUTTINGS.

The direct brine release calculation uses only the downdip CUTTINGS files. The downdip panels have higher pressures, producing higher saturations and releases. However, releases are not calculated for every simulation. Some vectors do not result in a release, i.e., the pressures and/or saturations in the repository may not be high enough to overcome the column of drilling

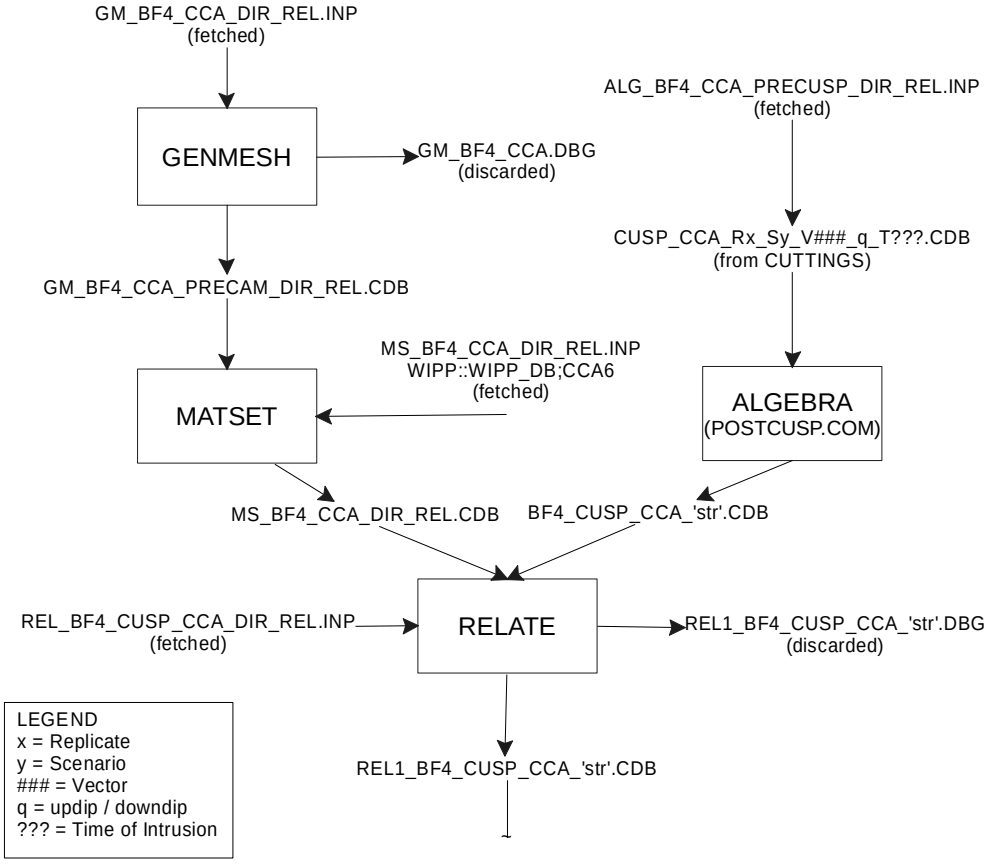

Figure 7.5a. Flowchart of BRAGFLO_DBR

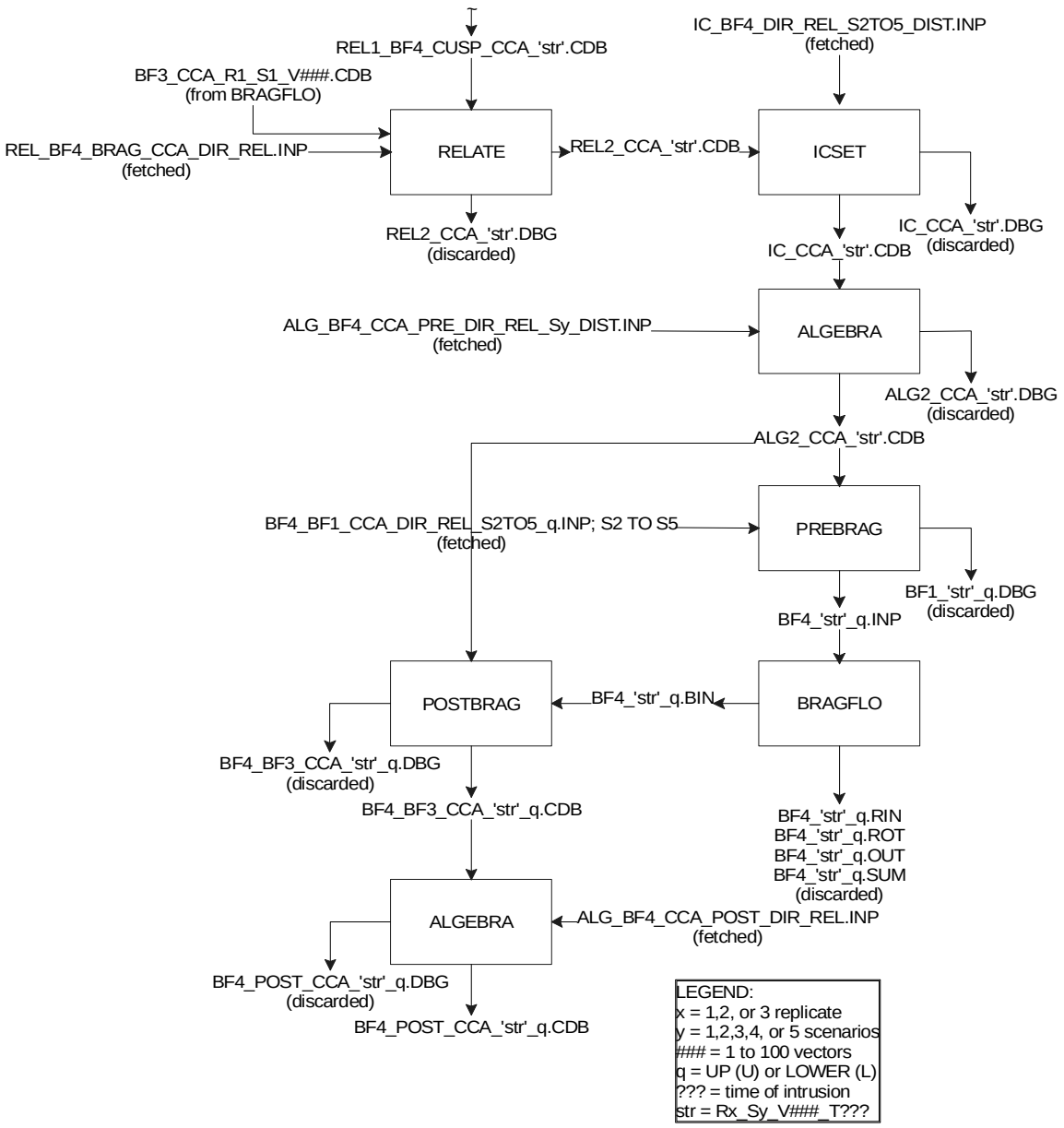

Figure 7.5b. Flowchart of BRAGFLO_DBR (cont.)

mud or there may not be an availability of brine due to consumption from corrosion or microbial activity. Those that do qualify undergo a 50 day simulation, with blowout lasting a minimum of three days. This is the estimated time it takes to drill through the repository to the Castile reservoir and cement the casing. If there is a significant amount of gas flow from the repository, the driller may lose control and brine releases may last longer. The releases will accumulate until the gas flow rate drops below an arbitrary value, set to 100,000 ft^3/d in the CCA calculations. The maximum blowout duration is 11 days, and is based on the time it took to control the South Culebra Bluff Well Unit # 1, which blew on January 1978 (Stoelzel and O'Brien 1996).

7.5. Results

The results of the amount of brine released to the surface are as predicted. With an increase in productivity ratio and waste permeability, coupled with a decrease in the range for residual brine saturation, an overall increase in the volume of brine was observed to be released.

7.5.1. BRAGFLO Results

7.5.1.1. The Repository

The BRAGFLO calculations performed on the two scenarios that modeled intrusion into the Castile reservoir showed higher brine pressures and higher brine volumes in the repository than what was modeled in the CCA. Higher pressures will allow more releases from spall and direct brine release. Higher brine volumes indicate more brine to (1) corrode waste containers, which will produce high pressures, and (2) be released through a direct brine release scenario. Though more brine with less gas would intuitively indicate more releases to the surface, a limit is seen, after which this is not the case because gas is needed to drive the brine up the borehole. If pressurized gas is eliminated, then no brine would reach the surface without pumping.

The results of the BRAGFLO simulations were postprocessed by codes described in the Analysis Package, Task 1 (Bean et al. 1996). The codes calculated average values in each area of the repository for elemental cells and created a total of 215 time history variables (pressure, saturation, volume of brine consumed, etc.) that were plotted in SPLAT (CMS plotting program). The results herein mainly use the average value for all vectors as comparison.

Figure 7.6. shows a comparison of repository pressures in the waste area of the Castile simulation to repository pressures of the CCA. The figure shows two plots. The left plot shows the mean results of an E1 intrusion at 350 years for both simulations, and the right shows the mean results with an intrusion at 1,000 years. The pressures are averaged over the entire volume of the waste area only, and excludes pressures from the operations and experimental regions. It is clearly evident that both plots in the figure show higher pressures for the Castile Simulation. The difference between the Castile Simulation and the CCA in average pressures at 350 years for S2 is approximately 3.25 MPa. The pressures rise sharply up to the intrusion point due to gas generation from the availability of iron in the waste and waste containers, and from the organics (cellulosics, rubber, plastic, etc.). After intrusion, the borehole is assumed to be plugged immediately, with plug lifetime lasting 200 years. Once the plug degrades, the gas in the repository is vented, until eventually creep reduces the borehole permeability at 550 years postclosure, allowing pressures to rebuild until most of the cellulosic inventory is exhausted

(around 1,500 years). A steady decline in pressure for the remaining 8,500 years is noticed, with the Castile simulation always being at least 1.8 MPa higher.

The simulation with the intrusion borehole entering the Castile Formation at 1,000 (S3) years exhibits similar behavior as the S2 scenario. The pressure builds in the repository until gas and brine is allowed to escape. The pressure declines after plug degradation, and rebuilds until all organic material is consumed. The pressures eventually decrease steadily for the remaining time of the repository history. The differences in the Castile simulation and CCA, though not as drastic as the previous S2 simulation, are still substantial. The differences are around 1.75 MPa at the time of intrusion, and decrease to 1.3 MPa around 10,000 years. The higher pressures in the repository of S3 compared to S2 would indicate higher releases to the upper layers above the repository and to the surface, and will be discussed later.

The higher pressures are a result of more brine entering the repository from the Castile brine reservoirs' below. The brine mixes with the waste and degrades the organic material, which produces gas. Figure 7.7. shows, for both scenarios, the amount of brine entering the whole repository from the Castile reservoir. The flow of brine from the Castile up the borehole to the repository is an effect of the high differential pressure between the Castile and repository. The values were calculated by subtracting the net inflow of brine from the marker beds and the brine volume consumed through corrosion and degredation. Again, both plots show a higher amount of brine entering the repository from the Castile simulation. This may be from the combination of the set constant value of 160,000 m^3 for Castile Reservoir volume and productivity ratio. The CCA used a range from 32,000 to 160,000 m^3, with a 1/32 chance of getting the 160,000 value

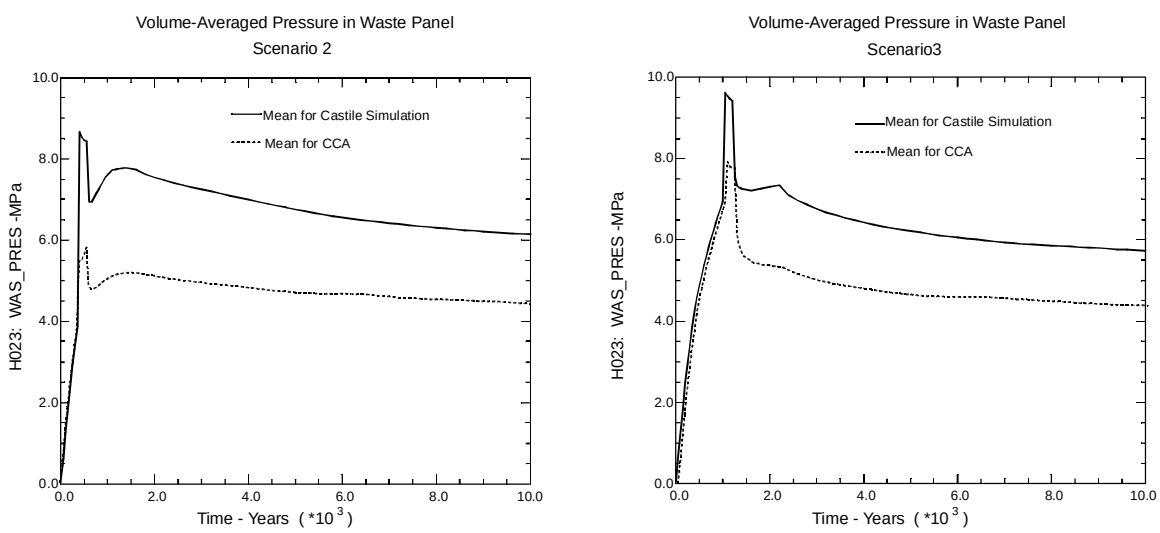

Figure 7.6. Volume Averaged Pressures of 10,000 Year Time History for Left) Scenario 2 and Right) Scenario 3

for volume and a range of 0.0007 to 0.04 m^3/Pa for productivity ratio.

The differences in the two simulations are very notable, varying by as much as 20,000 m^3 in S2. Both simulations also follow the same pattern. For the scenario of borehole intrusion at 350 years, the repository quickly fills with brine after closure, decline linearly as brine is consumed through corrosion of iron and degradation of organics. When the intrusion borehole hits the brine pockets below the repository, it fills at a higher rate until a pressure equilibrium is reached between the repository and brine pockets. A steady decline marks the remaining future of the repository, with minor amounts of brine being consumed and the rest being leaked to the stratigraphic units that lie above the repository and minor amounts flowing back down the borehole to the reservoir.

The S3 scenario behaves slightly differently from S2 with less total brine entering the repository. After the intrusion at 1,000 years, the amount of brine does not immediately decrease, but increases slightly for approximately 1,000 years (between 1,000 and 2,000 years postclosure). The gain of almost 2,000 m^3 of brine in both the CCA and Castile Simulation can be attributed to the pressure recovery seen in Figure 7.6. After the intrusion, the pressure for S3 does not recover like that seen in S2, allowing more brine to enter, and pressure equilibrium is reached approximately 500 - 1,000 years after intrusion (1,500 to 2,000 years postclosure). The mean

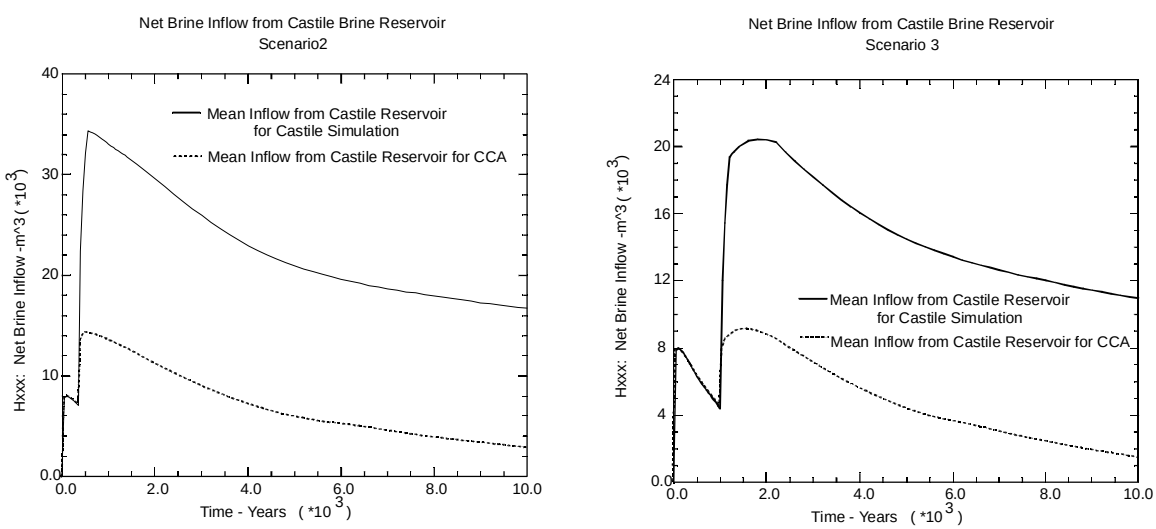

Figure 7.7. Net Inflow of Brine from Castile Reservoir for CCA and Castile Simulation for Left) Scenario 2 and Right) Scenario 3

	S 2		S 3	
	CCA	Castile	CCA	Castile
Fraction of Steel Remaining after 10000 years	55.06	42.04	57.60	50.59
Fraction of Cellulose Remaining after 10000 years	50.02	50.01	50.02	50.01

Table 7.2. Fraction of Steel and Cellulosics Remaining after 10000 Years
for CCA and Castile Simulations for S2 and S3

pressure curves of Figure 7.6. are dominated by vectors that exhibit low corrosion rates in that region.

With the inflow of brine to the repository, gas volumes also soar after intrusion. Figure 7.8. shows total mean of gas volumes generated from corrosion and microbial degradation (both humid and inundated) for the CCA and Castile simulation for Scenarios 2 and 3. The Castile simulation follows the CCA's calculated gas volumes before the intrusion, then increases significantly there after. The increase in the amount of brine reaching the repository has a direct effect on the amount of gas generated, as seen in the figure. As the Castile simulation allows more brine to enter the repository, more gas is generated. Even though microbial decay ceases for the most part after 1500 years, corrosion of the steel drums continue for the entire 10,000 years. The fraction of steel and cellulosics remaining after 10,000 years can be seen in Table 7.2. The amount of steel remaining for the Castile simulation offers a good insight on the differences seen in Figure 7.8.

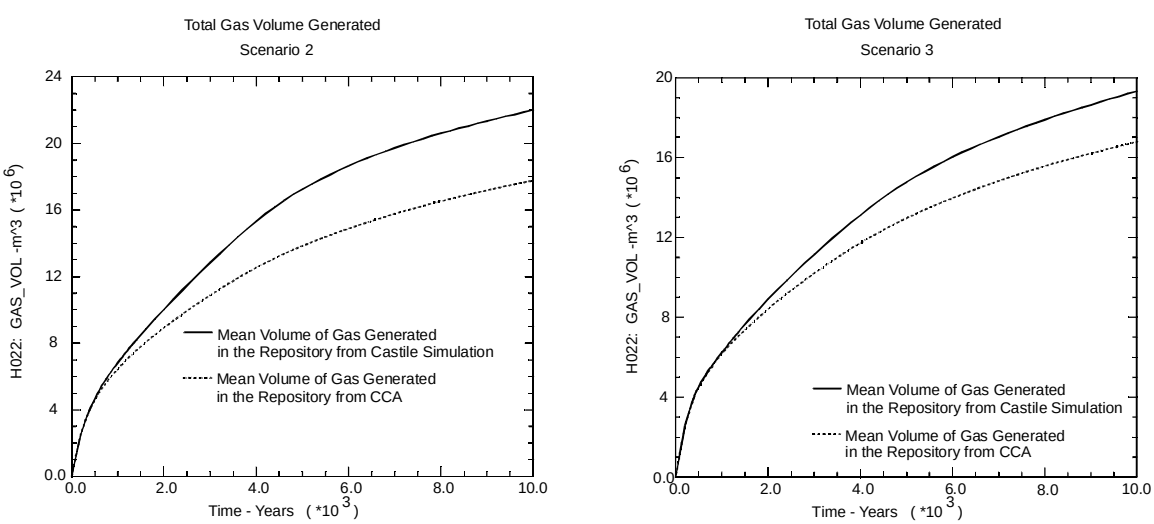

Figure 7.8. Total Gas Volumes Generated from Corrosion and Microbial Degradation for CCA and Castile Simulation for Left) Scenario 2 and Right) Scenario 3

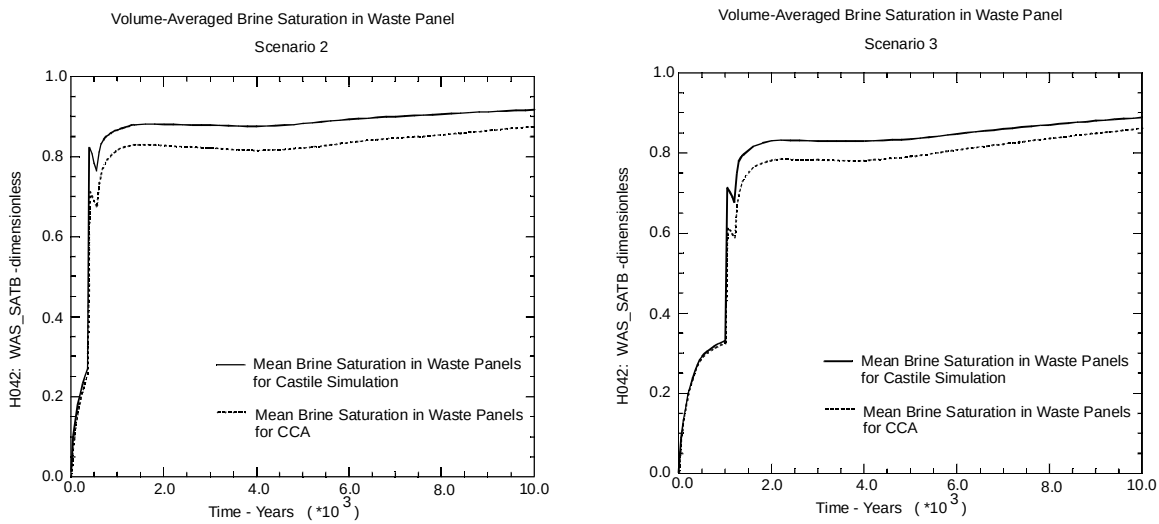

Figure 7.9. Volume Averaged Brine Saturation in Waste Panels for CCA and Castile Simulation for Left) Scenario 2 and Right) Scenario 3

Lastly, the saturation of brine plays an important role in the availability of gas as a mechanism for pushing the brine out through the borehole. Figure 7.9. shows how the fraction of brine as compared to gas increases through time, as brine enters from the Castile reservoir. The Castile simulation follows the CCA up to the time of intrusion for both scenarios, with the Castile simulation increasing in saturation after intrusion. The differences between the Castile simulation and the CCA are around 0.1 at the time of intrusion, but remain at 0.05 for the rest of the time history of the repository for both scenarios. The availability of brine to be released is definitely increased in the Castile simulation, but Figure 7.9. may indicate that the ratio of brine to gas may be too high to push the brine up the borehole.

7.5.1.2. Fluid Flow through the Borehole

The flow of brine and gas up the borehole to the upper stratigraphic members is linked closely to the values for permeabilities selected by the LHS code. Following the intrusion, brine and gas from the repository move up and/or down the borehole, depending on the pressures, permeabilities, and the time of occurance. Figure 7.10. shows the cumulative brine flow up the borehole to the top of the panels. The individual vectors are represented here to demonstrate the influence of chosen parameters on the system.

The discharge of brine out through the borehole to the units above the repository for the Castile simulation is higher than what was calculated in the CCA. The CCA's maximum release was 22,500 m^3 for S3 with only four vectors releasing above 4,000 m^3. This is about 14,000 m^3 less than the Castile simulation's maximum release, which had 20 vectors above 4,000 m^3. The vector showing the highest release in Figure 7.10. for the Castile simulation, Vector 23, is the

same vector with the highest release in the CCA, indicating the physics of the system is roughly the same.

Scatter plots of permeability versus brine discharged up the borehole to the top of the waste panels reveal that the permeability of the degraded concrete plug, BH_SAND, is more closely related to the discharge than any other permeability investigated, with a correlation coefficient (r^2) of 0.846. This indicates that as the permeability of the degraded borehole plug increases, the amount of brine flowing upwards increases. Figure 7.11. shows four scatter plots, using sampled permeabilities from different regions of the disposal system with the correlation coefficient located in the lower right-hand corner of each plot. The figure shows, from upper left to lower right, 1) the plots for permeability of degraded borehole, 2) Castile reservoir, 3) surrounding undisturbed halite, and 4) Marker Bed 139. The scatter plot is for the Castile simulation, Scenario 2 only. It is interesting to note that when the vector of highest brine flow is removed (Vector 23-36,000 m^3), the r^2 for BH_SAND increases to 0.912, and the other three essentially become zero.

Once the brine passes the top of the repository, it moves further up the borehole to the Culebra and eventually to the surface. However, as it moves upward, the brine loses energy through interactions with the borehole wall and overcoming the gravitational effects, and many of the vectors do not make it to the upper layers. Figure 7.12. shows the flow of brine in the borehole to the top of the Rustler Formation. Similar to Figure 7.10., this figure shows the individual vectors for S2 and S3 of the Castile simulation only. The figure reveals that little to no brine makes it this high up the borehole, with a maximum of 1.55 m^3 for S2 and 5.0 m^3 for S3. Further investigation shows that no brine reaches the surface for either scenario. Figure 7.12. shows

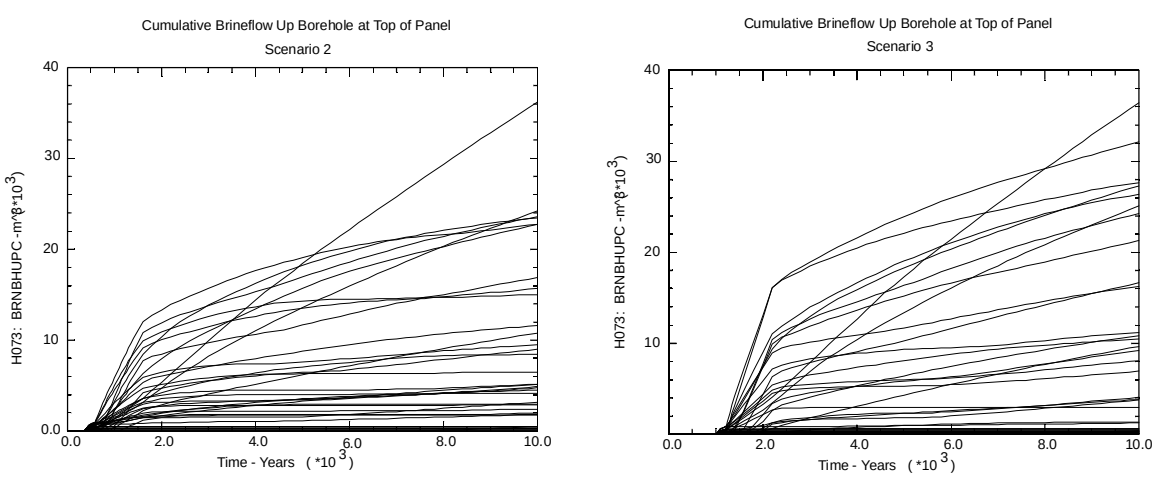

Figure 7.10. Cumulative Brine Flow up the Borehole from Waste Panels to the Top of the Panel for Castile Simulation of Left) Scenario 2 and Right) Scenario 3

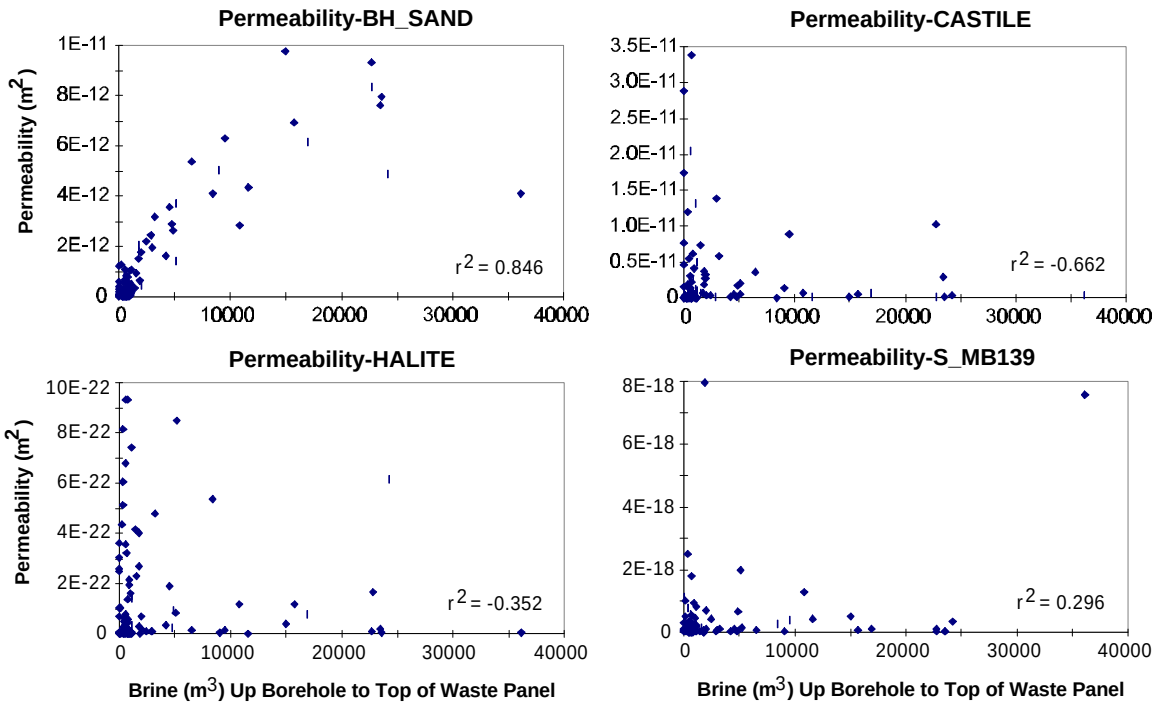

Figure 7.11. Scatter Plot for Volume of Brine Reaching the Top of The Waste Panels through an Intrusion Borehole and Permeabilities from Regions of the Disposal System with Permeabilities Described from Upper Left to Lower Right: 1) Degraded Concrete Plug (Silty-Sand), 2) Castile Reservoir, 3) Halite that does not Include the Disturbed Rock Zone (DRZ), and 4) Marker Bed 139

that if the brine can make it as far as the Dewey Lake Formation, it does so very quickly, with S3 contributing more brine than S2 due to the pressure differences in the two simulations.

The flow of brine up the exhaust shaft is considered minimal when compared to the borehole. At most 49 m^3 flowed up the shaft to the Salado, with no brine reaching the Rustler Formation for the Castile simulation. This is comparable to the CCA, which only had a maximum of 48 m^3 of brine up the shaft, because the assumption of pressure, borehole permeability, and the mechanisms of loss of pressure were the same.

7.5.2. Cuttings, Cavings, and Spallings Results

The borehole and solid waste material removal were calculated using CUTTINGS_S, a cuttings and cavings code that also incorporates spallings. The CCA identified both mechanisms as major contributors to radionuclides reaching the accessible environment, and calculations were made to quantify the effects of both. The following discussion compares results of the CCA to those calculated by changing the Castile reservoir parameters.

7.5.2.1. Cuttings and Cavings

The cuttings and cavings calculations were performed at several times throughout the repository future. Section 7.4.2. lists the times that were used for borehole removal. At each time calculation, the amount of material removed through cuttings and cavings were the same for the CCA and the Castile simulation. Since the parameters for cutting rate, depth, drill bit size, and waste characteristics remained the same in both simulations, the values for this mechanism of waste removal also remained the same.

The CUTTINGS_S code was only concerned with the actual waste from the repository that was brought to the surface, and not the cuttings or cavings from the borehole of inert stratigraphic material (uncontaminated geologic material) above the repository. Figure 7.13. shows the volume of material brought to the surface from cuttings and cavings for 100 vectors versus waste shear strength for Scenario 2, at 4,000 years after the repository is closed. However, this figure is representative of all times for both S2 and S3, and the waste shear strength will be discussed below. The cuttings volume of material was calculated by

$$V = AH\,(1-\varphi),$$

where A is the area of the drill bit, H is the compacted repository height (calculated from BRAGFLO), and φ is the porosity at the time of intrusion. The volume of cavings is much more complicated, involving an iterative method to find the final borehole radius from erosion of material due to turbulent flow of mud between the drill collar and the borehole wall. Total volume for both mechanisms, as seen in Figure 7.13. is 2.86 m^3, with a mean volume of 0.606 m^3 and a median volume of 0.508 m^3. For the CCA, the approximate average compacted room height was 1.3 m and waste panel porosity was 0.52. Therefore, the cavings portion contributed roughly 90% to the total volume extracted.

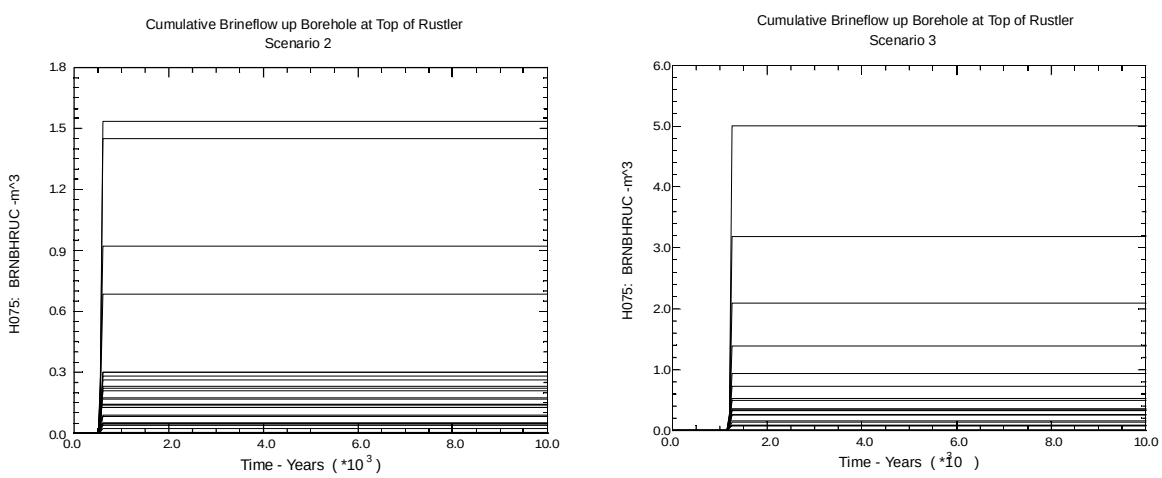

Figure 7.12. Brine Volume (m^3) Reaching the Top of the Rustler Formation for Castile Simulation for Left) Scenario 2 and Right) Scenario 3

The volume of material through cavings is linked closely to waste shear strength, by the relationship,

$$R_1 = R_o - \frac{\tau_o - \tau_{fail}}{\frac{d\tau}{dR}\Big|_0},$$

where R_1 is the eroded radius, R_o is the radius of the borehole, τ_o is the borehole wall shear stress, and τ_{fail} is the material shear stress (Berglund 1996). Intuitively, as the waste shear stress decreases, the radius of the borehole wall increases, allowing higher volumes of waste to be brought to the surface. The CCA range, as seen in Figure 7.13. uses a uniform distribution to describe possible values of waste shear strength between 0.05 Pa and 10 Pa. Small values of shear strength are destructive to the system, with values below 1.0 Pa contributing to the major releases. Future simulations should use a loguniform distribution to describe the possible values of shear strength that vary by over an order of magnitude.

7.5.2.2. Spallings

The calculation of spalled material from the borehole only included the possibility of blowout, and dismissed stuck pipe and gas erosion by the estimation of a cutoff level for waste permeability in which values above the cutoff will reduce the probability of the two phenomena from happening. The cutoff permeability was 10^{-16} m^2 (See CUTTINGS_S Manual for additional information on stuck pipe and gas erosion (Berglund 1996). The waste permeability in the CCA was 1.7×10^{-13} m^2, but was calculated incorrectly and thus updated for the Castile simulation to be 2.4×10^{-13} m^2. If waste permeability were to fall within the region of stuck pipe and gas erosion (below the

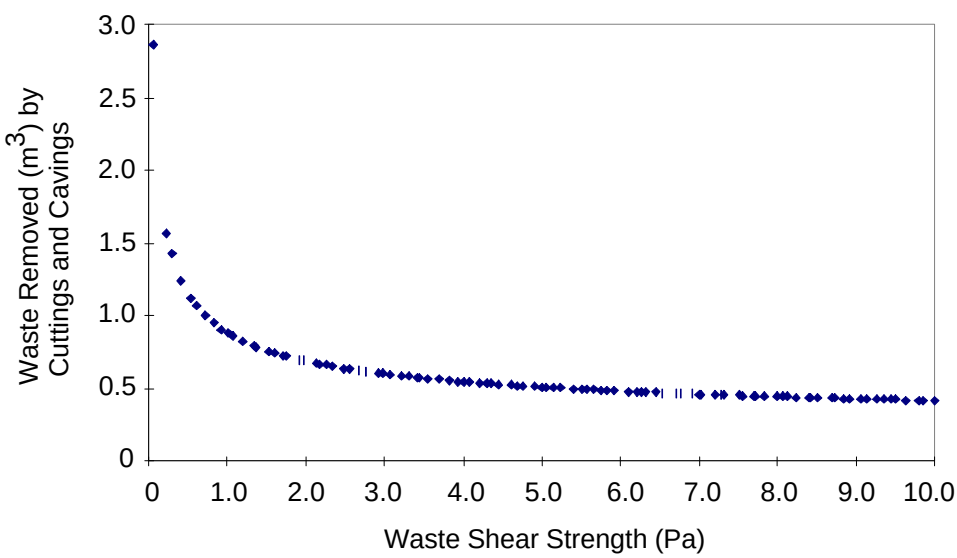

Figure 7.13. Waste Removed (m^3) by Cuttings and Cavings vs. Waste Shear Strength, Scenario 2, at Time 4000 Years Post Closure

arbitrary limit of 10^{-16} m^2 with pressures above hydrostatic), releases could range between 43 to 365 m^3 (Berglund 1996), 100 times the releases of cuttings and cavings.

The spallings calculations in the CCA were proven to be flawed, but the values of the blowout volume were accepted as being reasonable by the DOE's Conceptual Model Peer Review Group (Wilson et al. 1997). The CCA had a maximum blowout release of approximately 4 m^3. The Castile simulation did not exhibit larger releases, though it did have more realizations with blowout occurring, with at least twice as many occurrences at each time intrusion calculation than in the CCA. Figure 7.14. shows a frequency distribution of the number of blowout realizations versus blowout volume. The figure is for S3 at a calculated time intrusion of 1200 years into panel 5 (downdip intrusion). The time, scenario, and borehole location was chosen to display the maximum number of releases. As the average pressure drops, the number of realizations that produce a blowout also drops, as seen in Figure 7.6.

The figure of spalled volume should not be taken as a literal interpretation of the actual spalled volume that will be ejected from the borehole. The conceptual model for the code was proven inadequate, and the calculated results do not reflect the correct volumes. It does show, however, that the Castile simulation exhibits higher pressures than calculated in the CCA, causing CUTTINGS_S to calculate more releases. Experiments on a new code, after the submittal of the CCA, showed the spalled volume would be no more than 0.25 m^3 for WIPP conditions (Hansen et al. 1997). The results of Hansen et al. (1997) showed that the values obtained in the CUTTINGS_S were higher, therefore they were believed reasonable by the Conceptual Models Peer Review Group (Wilson et al. 1997). Chapter 9 of this report explores the analysis of Hansen et al. more closely.

7.5.3. Direct Brine Release

Once an intrusion breaches the repository with sufficient pressures from gas generation, the brine in the waste will move towards the cavity and be expelled out of the borehole. The pressure near the borehole or flowing bottom hole pressure (FBHP) must be above hydrostatic, in this case 8 MPa (density of brine = 1215 kg/m^3, length of borehole = 655 m, and friction = ~0.2MPa). The amount of brine ejected from the waste panels range from a few thousandths of a cubic meter up to a few tens of cubic meters. Figure 7.15. shows a frequency distribution of brine released to the accessible environment for all time intrusions for both the CCA and the Castile simulation of Scenarios 2 and 3. The Castile simulation, as one might expect, has higher releases than in the CCA.

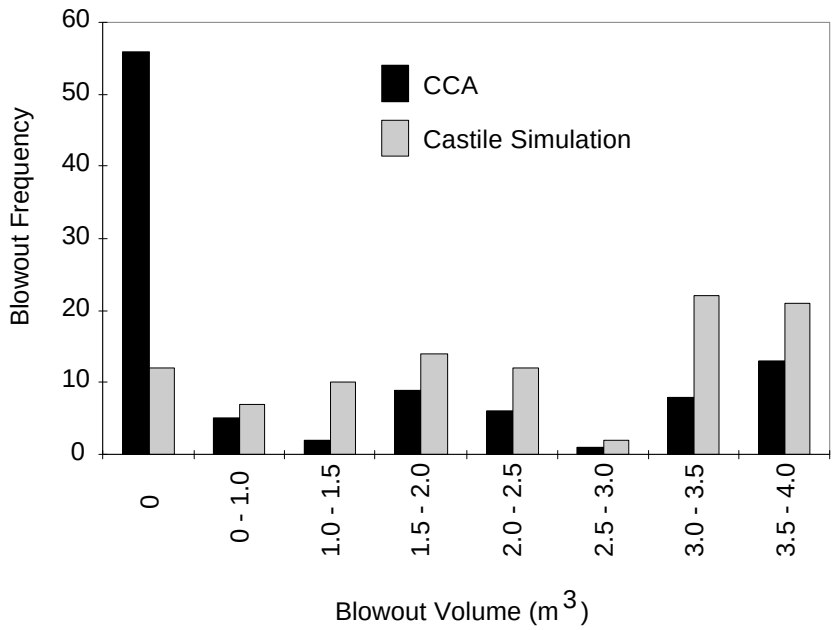

Figure 7.14. Frequency Distribution of Spalled Blowout Volume from an Initial Intrusion at 1,000 Years (Scenario 3) and a Subsequent Intrusion into Panel 5 at 1,200 Years with both CCA and Castile Simulation Values Displayed

The brine releases from an intrusion borehole is directly related to the repository pressure and brine saturation. Figure 7.16. shows the two relationships as scatter plots of brine release vs. pressure on the left and brine release vs. saturation on the right. The plots are for S3 at 1,200 years post closure of the Castile simulation. The first striking feature of the figure is the relationship between the volume of brine released and pressure. The releases are zero for pressures less than 8 MPa and increase linearly from 8 to 9 MPa. At 9 MPa, the releases sharply increase, and then decrease to nearly zero again for pressures above 9 MPa. This is a unique feature of this simulation and is only observed in early times of the repository's projected history. A similar feature is noticed at 1,400 years, but essentially dissolves at 3,000 years and beyond. A possible explanation for the phenomena is the control that the Castile reservoir pressure has on the repository in early times. Since the Castile reservoir pressure is constant in all 100 realizations, the pressure in the repository is directly affected by the amount of brine flow to the repository.

However, the pressure in the repository is affected by other key parameters as well, and not just by the amount of brine flow from the Castile reservoir. Figure 7.17. shows a scatter plot of pressure in the repository for S3 at 1,200 years post closure for the Castile simulation versus the inundated steel corrosion rate. As the corrosion rate increases, the pressure increases, and again is dependent on a third parameter. The probability of degradation of cellulosics, plastics and rubbers separates the scatter plot into two regions. The parameter, PROBDEG, is the

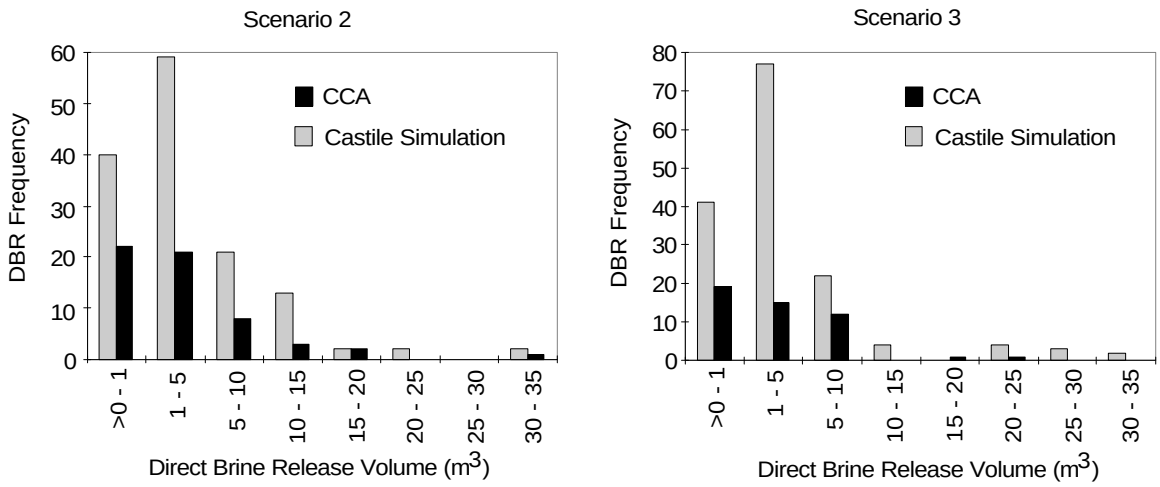

Figure 7.15. Frequency Distribution of Direct Brine Release Volumes (m^3) for CCA and Castile Simulation for Left) Scenario 2 and Right) Scenario 3

second LHS sampling variable, and can have values of 0, 1, or 2. A “0” indicates no microbial degradation of organic material and has a probability of 50%. The selection of “1” means that only the cellulosics will degrade, and “2” denotes cellulosics, plastics and rubber will degrade, with a 25% probability each. The region of high pressure in Figure 7.17. is from a PROBDEG of 2. These diamonds are black, meaning there was no significant direct brine release. The gray diamonds indicate a notable brine release, which fall in the region of pressures seen in Figure 7.16. to have the major releases. Excluding those realizations with a PROBDEG of 2, the plot has a correlation coefficient of 0.68, and a correlation coefficient of 0.67 considering only those with a PROBDEG equal to 2. This is higher than the coefficient of 0.14 if all realizations are included.

Relating back to Figure 7.16. and the second plot with brine release versus waste panel brine saturation: the optimum brine saturation for large release is approximately 0.65 with minimal releases above 0.85 and no significant releases below 0.4. The saturation can be thought of as a brine to gas relationship. If too much gas (low saturation) is present, then the availability of brine to be ejected is limited, and is directly related to the extremely high pressures and corrosion rate of Figure 7.17. Also, if there is too much brine and not enough gas, the pressures in the repository will not be high enough to lift the brine out of the borehole. Therefore, an optimum (or detrimental) saturation is observed for the Castile simulation at early times after the intrusion.

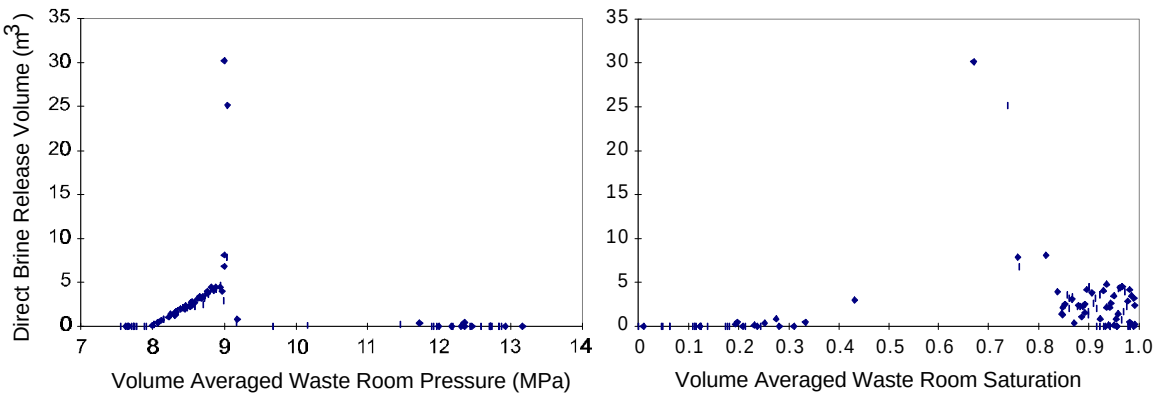

Figure 7.16. Direct Brine Release (m^3) for Scenario 3 for Castile Simulation for the Second Intrusion at 1,200 Years for Left) Volume Averaged Waste Room Pressure (MPa) and Right) Volume Average Waste Room Saturation (Unitless)

It is stressed at this point that the above phenomenon is only for the Castile simulation, Scenario 3, at early times in the repository's projected history after the initial intrusion. Since a few of the key parameters were held constant, the predicted behavior of the disposal system was better understood. A similar response of Scenario 2 for the Castile simulation can be seen, yet differences between the two scenarios are still recognized. For example, the brine release

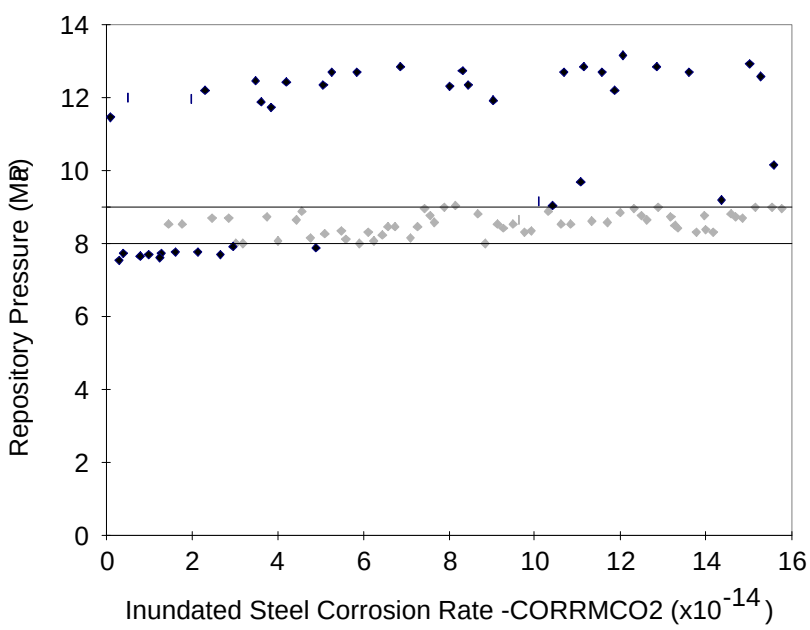

Figure 7.17. Scatter Plot of The Pressure in the Repository (MPa) for Castile Simulation, Scenario 3, 1,200 Years Post Closure Versus Inundated Steel Corrosion Rate (CORRMCO2-Parameter 1 in LHS Sampling) with Banded Region of Gray Diamonds Showing Those Vectors that had a Significant (>0.1 m^3) Direct Brine Release

versus brine saturation shows that brine can be ejected at saturations as low as 0.2. These are very low releases, usually less than 0.5 m^3 of brine. However, since the CCA has more varying parameters over large ranges, the behavior of the system is less predictable.

7.5.4. Probability Modeling with Results from Castile Simulation

The final step in assessing the results of the Castile simulation and how they will affect the overall performance of the disposal system, is to replace the results of the CCA with those of the Castile simulation in a CCDFGF calculation. The individual vectors of CUTTINGS_S and BRAGFLO_DBR were summarized into formats for probability modeling and modeled with the CCA results of SECOTP2D, NUTS and PANEL. Figure 7.18. shows the CCDF curves of several simulations.

The results of the Castile simulation show that Castile brine assumptions do not have a significant effect on the overall CCDF. In fact, the figure shows that the CCA may have slightly higher releases at equivalent probabilities with the same probabilistic assumptions (drilling rate, AICs, probability of hitting a Castile brine pocket, etc). Even when the probability of hitting brine is increased from 8 to 100%, the releases are not increased by any significant amount.

7.6. Conclusions

A model is presented to investigate the importance of the Castile brine reservoir parameters at the WIPP. The Castile reservoir underlies the repository and is a major source of brine that may contribute to gas generation from the corrosion of metals and biodegradation of organic materials. The production of gas will increase the pressure in the repository, thus ejecting brine and waste to the accessable environment upon a breach of the repository.

The Compliance Certification Application presents data for the creation of reservoir parameters that may be extraneous. The data were derived from wells that clearly lie outside a reasonable distance for consideration of brine pockets underneath the repository. Therefore, data from a single well, one mile north of the repository, was used to simulate the effects of the reservoir. The data included reservoir volume, rock compressibility, permeability, and pressure.

In addition, two parameters describing the waste area were changed to what were considered more reasonable values. The waste permeability was increased by 41%, and has been well documented to show the error in the calculation of the original value. Also, the residual brine saturation range was decreased by reducing the upper value by 57%. This range is no longer considered to be more reasonable than the range used in the CCA calculations, due to the consolidation of waste in the repository.

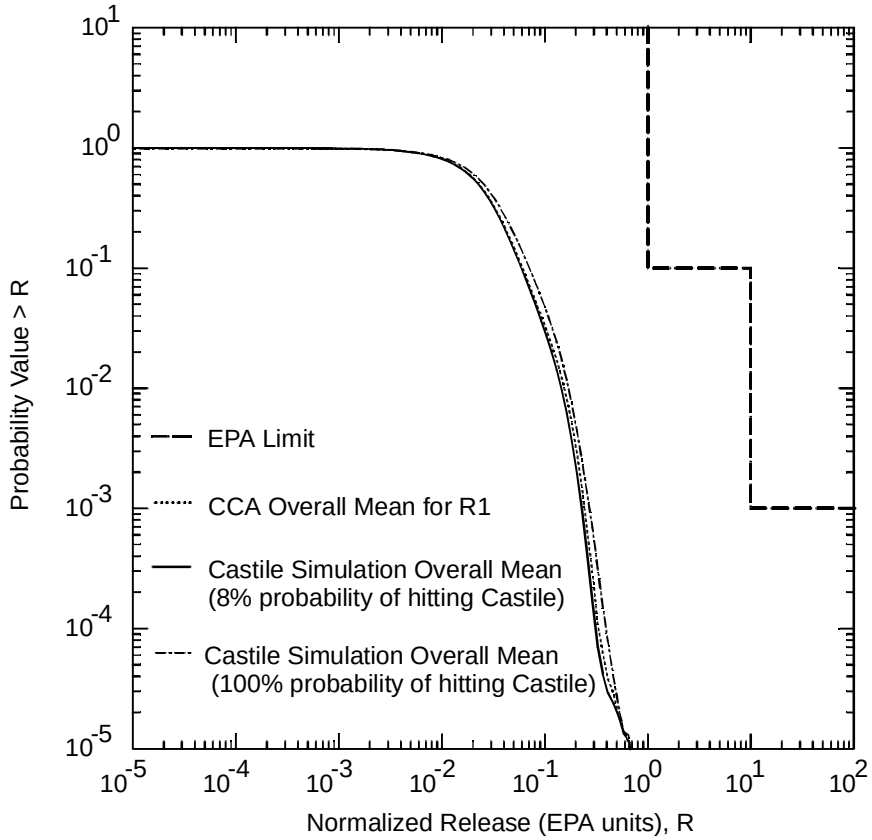

Figure 7.18. CCDF for Castile Simulation and CCA. The Castile Simulation Includes Two Probability Models: 8% and 100% Probability that the Intruding Borehole will hit the Castile Reservoir

The modeling started with two-phase flow of brine and gas through the repository using BRAGFLO. The changes in the Castile reservoir parameters affected the pressures, flow, and saturation of brine and gas through the waste. The pressures were much higher than in the CCA, with increased flow rates due to increased waste permeability.

The modeling of a human intrusion was completed by the code CUTTINGS_S, which simulates a drill string breaching a pressurized repository and releasing solid waste up the borehole to the accessable environment. The calculations showed that the amount of waste brought to the surface would not change, but the number of realizations that possibly could result in a release would increase. The increase of a spalled events from an highly pressurized repository doubled from the CCA to the Castile simulation.

The flow of brine up an intruded borehole was calculated separately in BRAGFLO_DBR. The results proved that the increased pressures in the repository from changing the selected parameters would result in higher and more incidents of releases to the surface.

Finally, CCDFGF modeled the probability of releases from the results of the above calculations. The outcome showed that there is no significant change in releases due to the minor addition of releases from a spalled or brine release. The releases calculated in CUTTINGS_S and BRAGFLO_DBR were not significantly more than those of the CCA. The constant values used for the Castile brine reservoir pressure is suspected to be the largest culprit for no change in the releases. However, the releases are subject to the concentration of radionuclides in the waste, and it is suspected that changes in the solubility, which would increase the concentrations of the radionuclides, would have a more profound effect on the Castile simulation than the CCA.

8. CULEBRA FLOW AND TRANSPORT USING BLM MAP FOR ECONOMIC POTASH RESOURCES OF EDDY COUNTY

8.1. Summary

A new Culebra flow and transport model with a modified extent of potash mining is presented here to demonstrate the effect of mining on the performance assessment caused by a change in flow patterns. The CCA assumes limited mining within the controlled area of the WIPP repository. A new model was justified because of the expected mining of lower grade ore due to the increase in use of fertilizers and development of more effecient mining methods. The results show that the new flow velocities in the Culebra aquifer could be important when considering lower K_ds, as the process of sorption dominates that of advection.

8.2. Introduction

The possibility of mining above the WIPP repository for potash resources has been identified as a possible scenario for human disturbance of the disposal system in the EPA's criteria for the compliance standards, 40 CFR Part 194.32 (b) (U.S. EPA 1996b). The performance assessment calculations of the CCA included a mining scenario with a probability of occurrence equaling that which has transpired over the last 100 years, as stated in the guidelines. The consequences of mining would cause subsidence in the geologic units above the repository, increasing the amount of fracturing and possibly decreasing travel time of the radionuclides through those overlying units if a release occurred.

The extent of the potash reserves overlying the repository and how it affects the flow field of the Culebra Dolomite member of the Rustler Formation is investigated in this chapter. Originally, the CCA identified two possible mining scenario: full and partial mining. These scenarios were based on studies of known potash leases and economic- and lease-grade potash reserves in the Delaware Basin. The full mining scenario includes regions outside the controlled area of the repository identified by the Bureau of Land Management (BLM 1993), excluding oil and gas well buffer zones, and regions within the controlled zones based on economic grade potash ore from the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) report (U.S. DOE 1996-Appendix MASS). The partial mining zones excludes mining within the controlled area, with the exception of those areas mined before the Land Withdraw Act was established. The maps do not distinguish between the two types of ore, sylvite and langbeinite.

The future of potash mining is the limiting factor on estimating the economic extent of potash reserves. Currently, 40% of the world's agricultural production uses nitrogen based fertilizer, derived from the potash industry (Smil 1997). With the exponential increase in human

population, fertilizers usage should also increase, directly affecting potash production in the Delaware Basin. The increased demand for potash will prompt the industry to mine lower grade ore, and use methods of extraction that are more profitable.

Solution mining has been considered for the extraction of potash in the region of the Delaware Basin. The process of mineral dissolution was determined to have the lowest operational cost compared to other methods (Gruschow 1992). Therefore, the extraction of lower quality potash minerals could be economically feasible, and the extent of reserves are much greater than originally predicted. The CCA failed to recognize the possibility of solution mining around the repository, and the area affected by mining is much less than predicted. The EEG modeling of this report considers all possible potash reserves inside and outside the controlled area based solely on the BLM map (BLM 1993). The area inside the controlled area changed significantly from that in the CCA, whereas the outside was virtually unaltered. This scenario is referred to as the Modified Mining (MM) scenario.

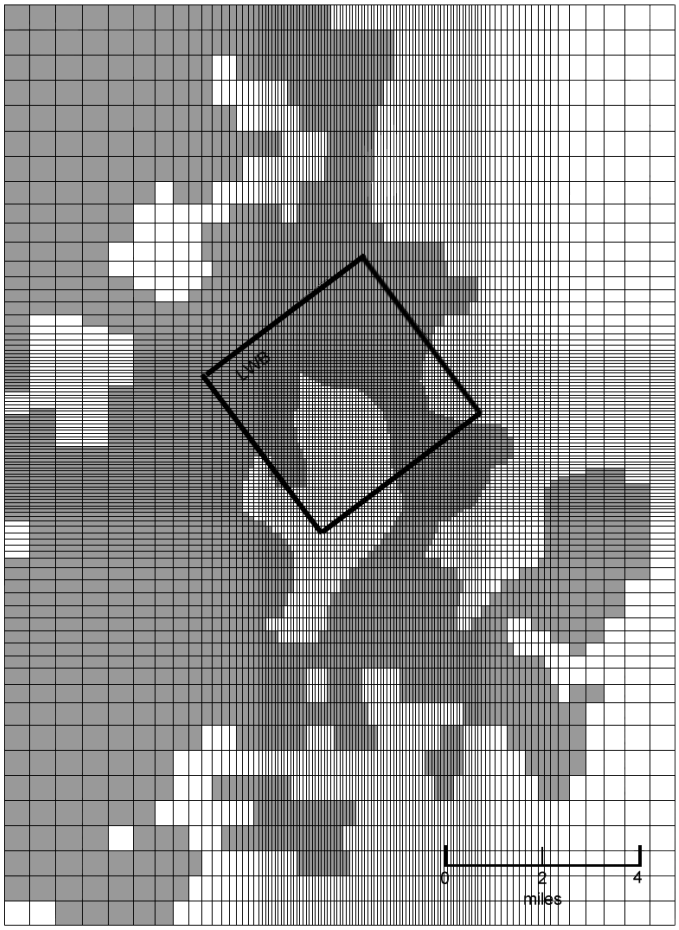

Figure 8.1. Areal Extent of Known Potash Reserves from the BLM Map (BLM 1993)

Figure 8.1. shows the new areal extent of potash reserves, superimposed on the regional modeling domain. This domain is used in the flow code for simulating flow through the Culebra. The area shows the region affected by mining, where subsidence would fracture the flow system. The EPA guidelines for subsidence are very specific about how the area is to be treated in the performance assessment. A multiplier of no more than 1000 is required to increase the transmissivity. This was a sampled parameter in the performance assessment calculations, and remained unaltered for the calculations in this report.

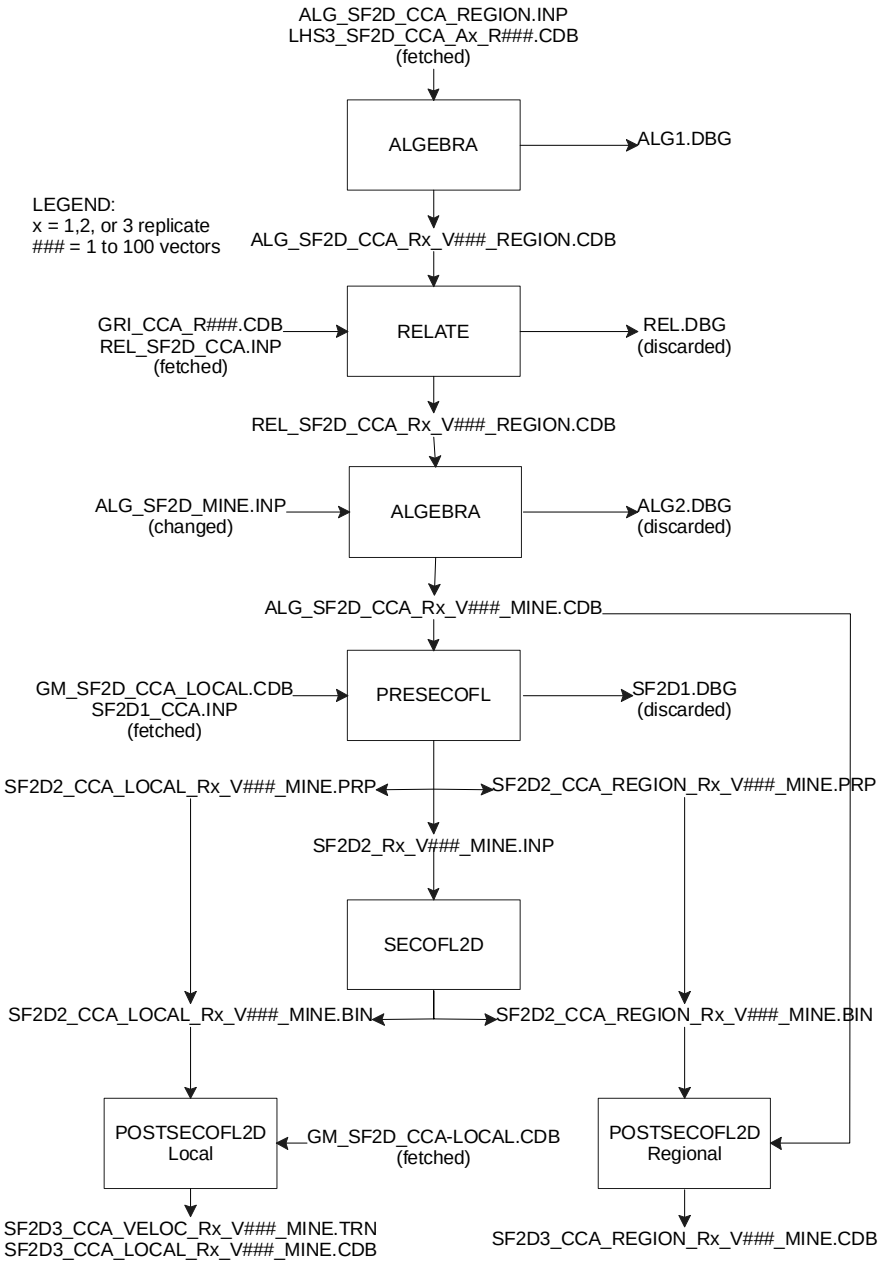

Figure 8.2. Flowchart of SECOFL2D Simulations

8.3. Methodology

The purpose of this modeling experiment was to change the existing regions of the potash minable resource areas to test the effects on the flow and transport of radionuclides through the Culebra. This was accomplished by first running the flow code, SECOFL2D, a two dimensional regional flow code that solves the Darcian flow equation. The flow velocities were then used to solve the transport equation in SECOTP2D. Figure 8.2. shows the flowchart of the flow code used in modeling the mined area. The only change for modeling the new potash region was the file that controlled which transmissivity cells of the flow grid were multiplied by the increased factor for higher fracturing. All cells of the region were multiplied by the same value. The actual file is included as an attachment to this chapter for reproducibility. The transport flowchart for SECOTP2D can be found in Chapter 6.

A total of 100 vectors were completed for the flow calculations with hydraulic head being computed for both a regional and local domain. The flow field was first solved on the regional grid. The local grid acquired its boundary conditions from the regional flow characteristics. The local velocities were then used as the input to solve the transport of radionuclides on the local grid.

Two experiments were simulated with the transport equation with 100 vectors being generated for each simulation. One included plutonium with a 1% K_d=0 to compare with results of Chapter 6, and the other ran uranium with K_ds generated from the LHS sampling technique to compare with CCA results. The generated K_ds were slightly different, correcting for the range as specified in Ramsey and Wallace (1997). The new range decreased the values used in the new simulations, allowing the Uranium to migrate further downstream. The complete set of vector calculations enables the results to be incorporated into the CCDFGF code.

8.4. Results

8.4.1. Culebra Flow

The flow field of the new mined area (MM Scenario) showed slightly different hydraulic head values than the ‘fully mined’ solution of the CCA calculations. Figure 8.3. compares the regional head contours of a simulation where the transmissivity multiplier (parameter MINP_FAC) was the lowest generated value from the LHS sampling technique. Figure 8.4. also compares the regional head contours, taking the vector with the highest generated multiplier. The low and high values for MINP_FAC are 5.1 and 996.4, respectively. Contours are in meters above sea level.

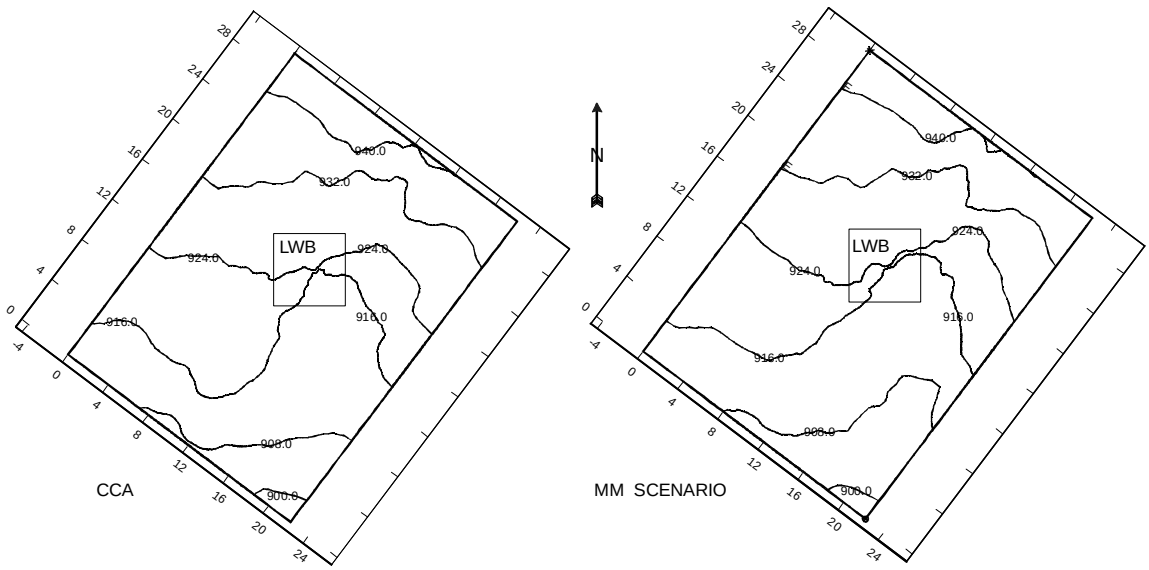

Figure 8.3. Regional Flow Contours of Vector 11. Left) CCA Right) MM Scenario

The only significant difference in head contours was in Figure 8.4., where the contour of 916 m for the MM Scenario is much further south than the CCA calculations. At first glance, this would indicate lower velocities for the MM Scenario through the controlled area, and speeding up through the south. However, due to the extreme heterogeneity of the site (as seen in Figure 8.5.), a generalization about the velocities cannot be inferred from the difference. Therefore, a velocity profile was constructed from the velocities calculated in SECOFL2D. Figure 8.6. shows the velocity vectors for both mining scenarios with correct angle and proportioned magnitude for

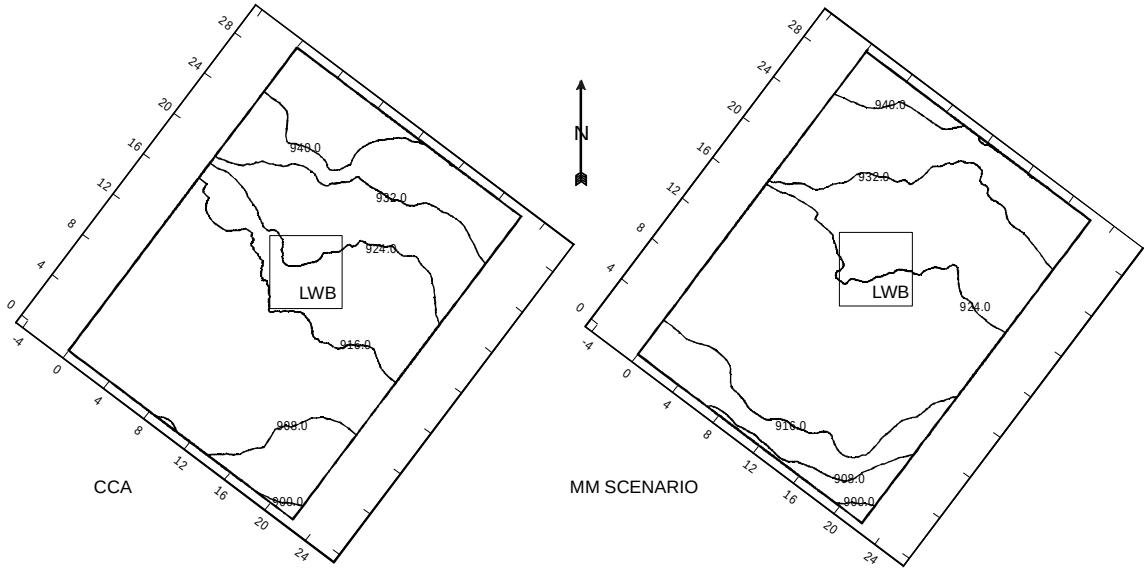

Figure 8.4. Regional Flow Contours of Vector 62. Left) CCA Right) MM Scenario

Vector 62. The velocities were extracted from the local grid to show the direction of the plume's migration in the transport calculations. The outline of the transition of small vectors and large vectors clearly shows the areas where the transmissivities were multiplied by MINP_FAC.

The velocities of Figure 8.6. range from 2.3×10^{-14} m/s to 2.9×10^{-6} m/s for the CCA calculation, and 2.3×10^{-12} m/s to 1.1×10^{-5} m/s for the MM Scenario. Since both modeling scenarios used the same transmissivity field, the higher velocities in the MM Scenario suggest that the area to be multiplied by MINP_FAC overlaps a region of slightly higher transmissivity than in the CCA, i.e.

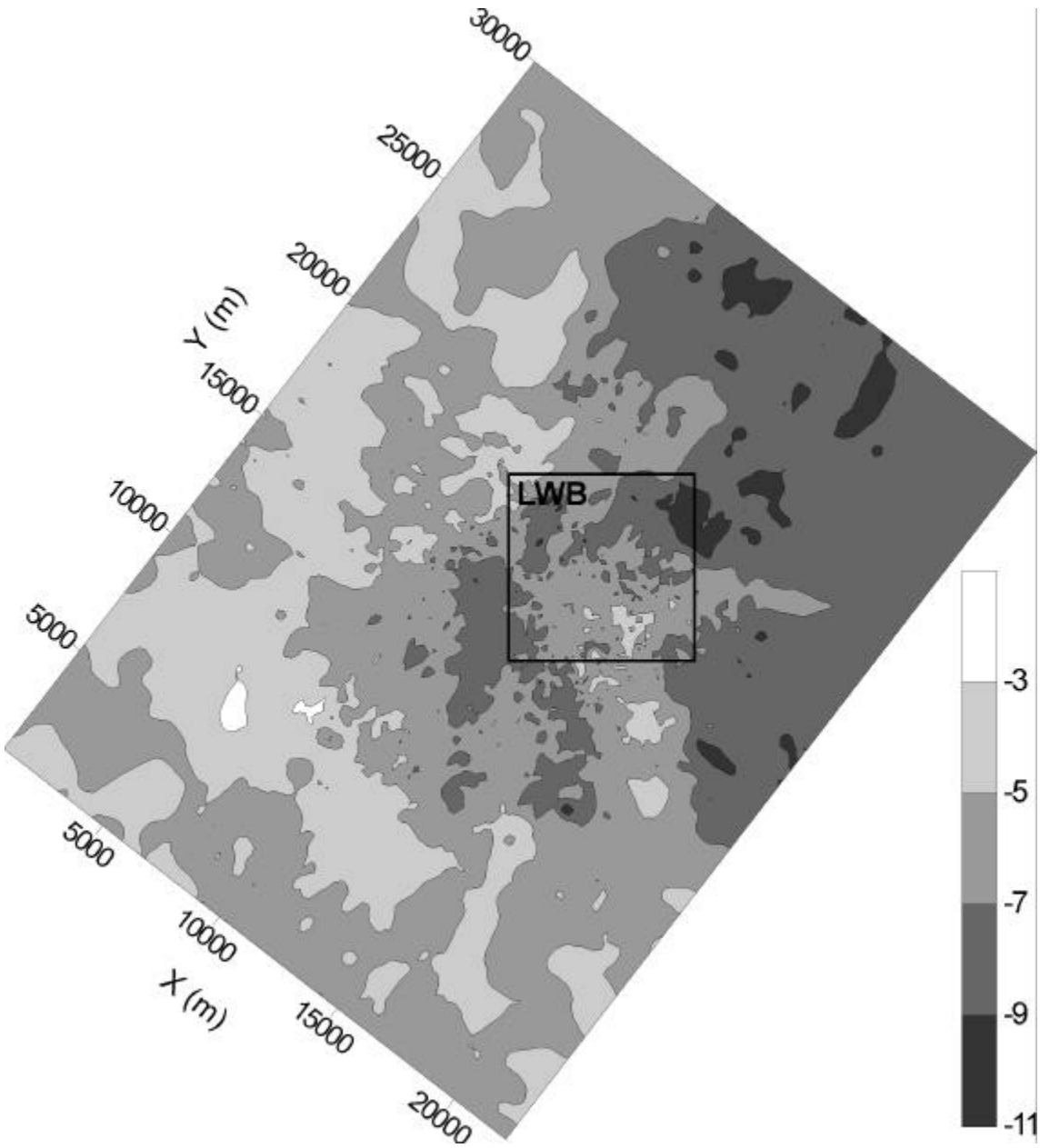

Figure 8.5. Transmissivity Field (Log_{10} m^2/s) of Vector 62

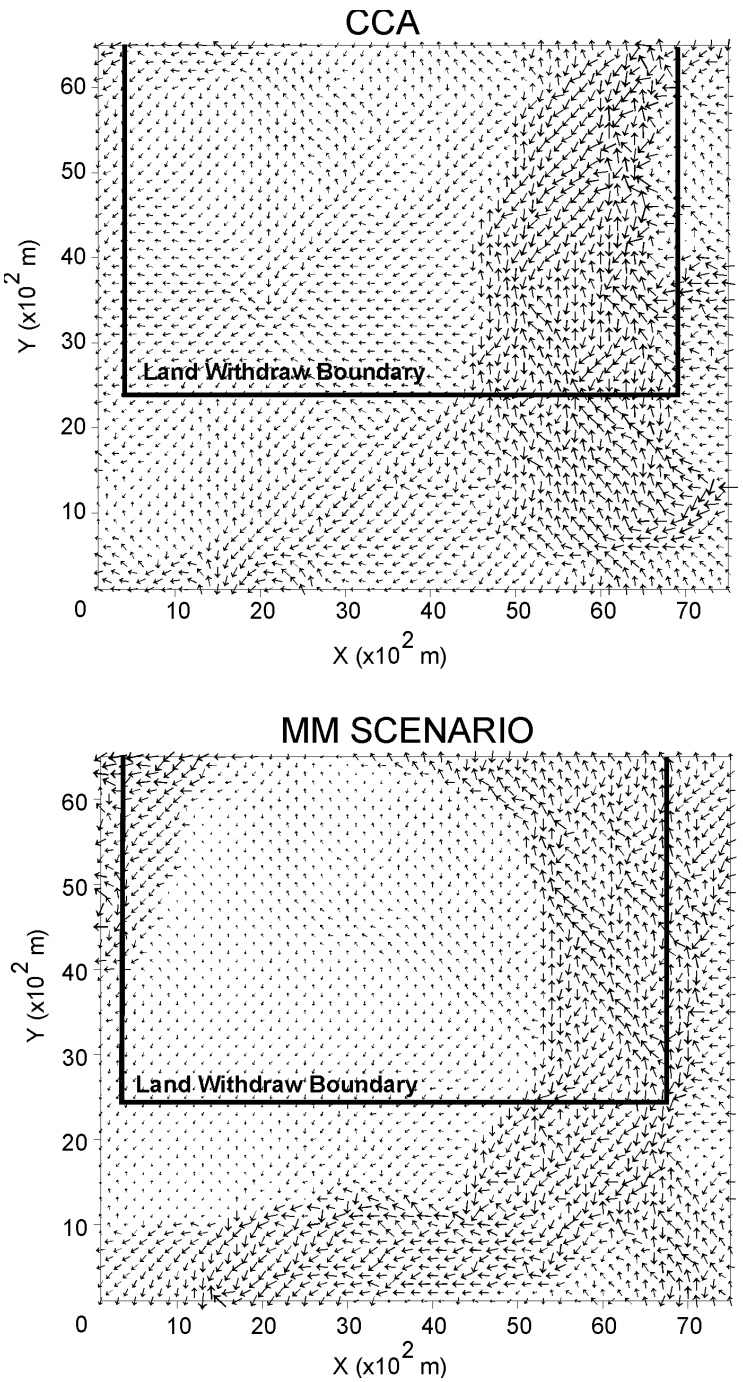

Figure 8.6. Velocity Profile of Vector 62 on Local Grid for Top) CCA and Bottom) MM Scenario

the region that is multiplied as shown in Figure 8.1. This is important, as the results of the radionuclide transport calculations will differ significantly from the outcome of the flow field functions.

8.4.2. Culebra Transport

8.4.2.1. Plutonium Transport Calculations with K_d=0

SECOTP2D was first used to simulate transport of plutonium with a K_d=0 through the Culebra aquifer. The combination of zero sorption and higher velocities allowed higher masses of the radionuclide to migrate across the Land Withdraw Boundary (LWB). The discharge mass of the Modified Mining Scenario was compared to results from transport calculations performed in Chapter 6, which simulated changes in the K_d only. In approximately 60% of the vectors, discharges were higher for the MM Scenario than for those seen in the Chapter 6 calculations. Figure 8.7. shows vectors that discharged mass fraction higher than 10^{-6} for the MM Scenario and the results of Chapter 6. The figure also displays a histogram for the frequency of vectors lying between the given ranges. The actual fractional discharge for both studies ranged from 10^{-2} to less than 10^{-15} (machine zero), but the limit was cut off at 10^{-6}. Below this discharge, the low-consequence eliminates the vector from consideration in the complementary cumulative distribution functions (CCDFs). Both plots clearly demonstrate that the MM Mining Scenario produces faster flow fields and is more conservative in its assumptions.

During the last step of probability modeling to create the CCDF curves for comparison with the EPA limits established in 40 CFR Part 191 (U.S. EPA 1996), the fractional discharge is multiplied by the actual amount of radionuclides that reach the Culebra. In most cases, the amount is negligible, and the fact that a vector had a high fractional discharge is often eliminated by the low concentrations. To demonstrate this affect, Figure 8.8. shows the discharge across

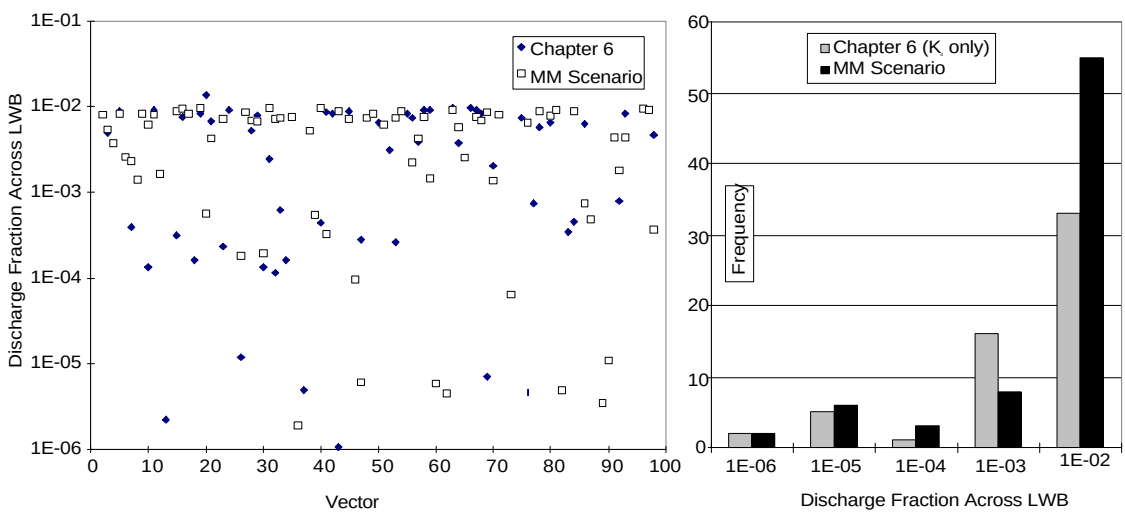

Figure 8.7. Left) Plutonium Fractional Discharge across the LWB for Chapter 6 Results (Full Mining) and MM Scenario with both having 1% of the Initial Mass with a K_d=0 $^{ml}/_{g}$ Right) Frequency Distribution of both Mining Scenarios for Vectors with Significant Discharge across LWB

the Land Withdraw Boundary in EPA Units. The plots in the figure show the discharge of plutonium for the S2 and S3 scenarios at 10000 years for those vectors with discharges of at least 10^{-6} EPA Units. The fractional discharge is multiplied by the mass in Curies calculated from each of the scenarios, and divided by 344 to obtain the mass in EPA Units. The figure reveals that for the S2 scenario (left plot), the Modified Mining has the highest release in 10000 years with six vectors showing at least 10^{-5} EPA Units crossing the LWB. The right plot of the S3 scenario also shows the highest release, however, with less vectors actually being above the 10^{-6} threshold than the results of Chapter 6.

8.4.2.2. Uranium Transport Calculations with LHS Generated K_ds

The flow velocities from the BLM Mining Scenario were also used to model uranium with higher K_ds than the plutonium simulations. The K_ds were generated from the Latin Hypercube Sampling (LHS) code. The range of values for K_ds were modified from those used in the CCA to values suggested in the Analysis Package, Task 3 (Ramsey et al. 1997). The new range for generated K_d values are lognormally distributed from 0.03 $^{ml}/_{g}$ to 20 $^{ml}/_{g}$, changed from 0.03 $^{ml}/_{g}$ to 30 $^{ml}/_{g}$. The new upper value, along with a lognormal distribution for the range, created smaller values of K_ds, and thus smaller retardation values. The result is more vectors with higher discharge.

In the CCA calculation only one vector from the third replicate showed any release, with an integrated discharge across the Land Withdraw Boundary equal to 0.91 kgs. The present calculations were performed on the first replicate, with no releases to compare. Figure 8.9. shows releases across the LWB only for the present model.

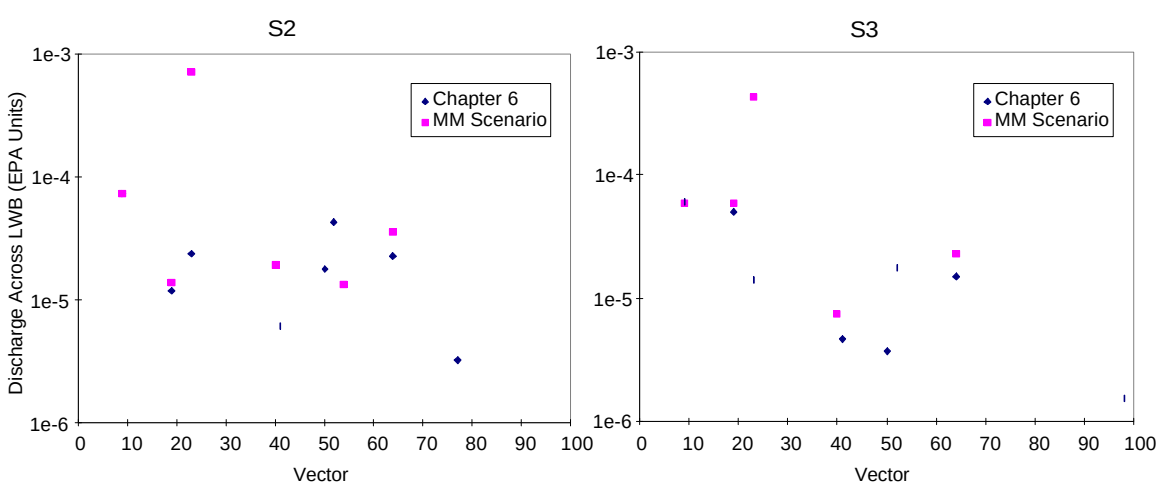

Figure 8.8. Discharge in EPA Units at 10,000 Years from CCA NUTS Concentrations for the Results Presented in Chapter 6 and the MM Scenario for Left) Scenario 2 and Right) Scenario 3

Of the 100 vectors, only six had significant releases (fractional dicharge>1e-6) across the LWB. The calculated retardation value from the generated K_ds ranged from 1.57 to 170412.2 (dimensionless), and the six vectors that showed discharge had a range of retardation values from 1.57 to 2.99. However, a strong correlation does not exist between retardation and discharge. Several vectors had no release across the LWB with retardation values less than 3. The geostatistical representation of the transmissivity field was such that it prevented any escape of uranium to the accessible environment. The CCA calculated retardation for uranium ranged from 24.8 to 431089.

The comparison for flow calculations used Vector 62, because of its high multiplier for the transmissivity field. However, the value of the newly calculated retardation coefficient for this vector was incredibly high (15763, dimensionless), and the uranium did not migrate outside of the waste panel area. To keep the comparison alive and consistent, Vector 62 was rerun with a smaller K_d=0.046 $^{ml}/_{g}$ (retardation=2.0). Time was also extended out to 100000 years to find when the maximum release would occur.

Figure 8.10. shows six snapshots of uranium concentration isopleths at 1875, 3875, 5250, 7150, 8650, and 10000 years after an intrusion. The isopleths range from $1x10^{-15}$ kg/m^3 to $1x10^{-6}$ kg/m^3, dark to light. The observed behavior of the uranium plume shows it to remain in the near

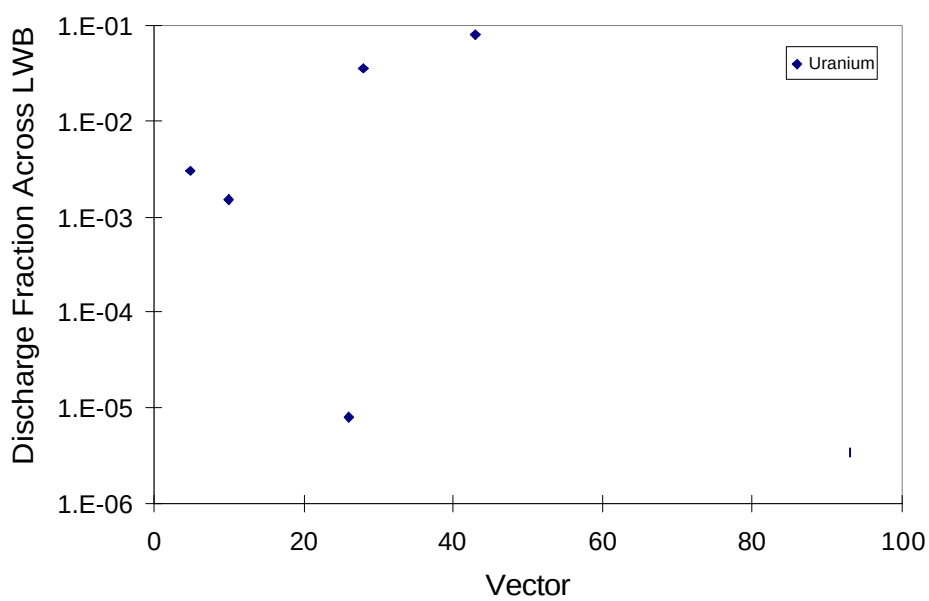

Figure 8.9. Discharge of Uranium across the LWB for MM Scenario for LHS Generated K_ds

field (near the borehole) for approximately the first 5200 years, moving slowly to the southeast. At year 7150 the plume is then noticed to enter an area of high velocities, where it shoots relatively quickly in a southwest direction. The size and location of the highest isopleth concentration of $1x10^{-6}$ kg/m^3 remains virtually unchanged through the time history of the simulation. Though bound up around the borehole for a long period of time by a low transmissivity field, the plume moves quite quickly southward, across the LWB.

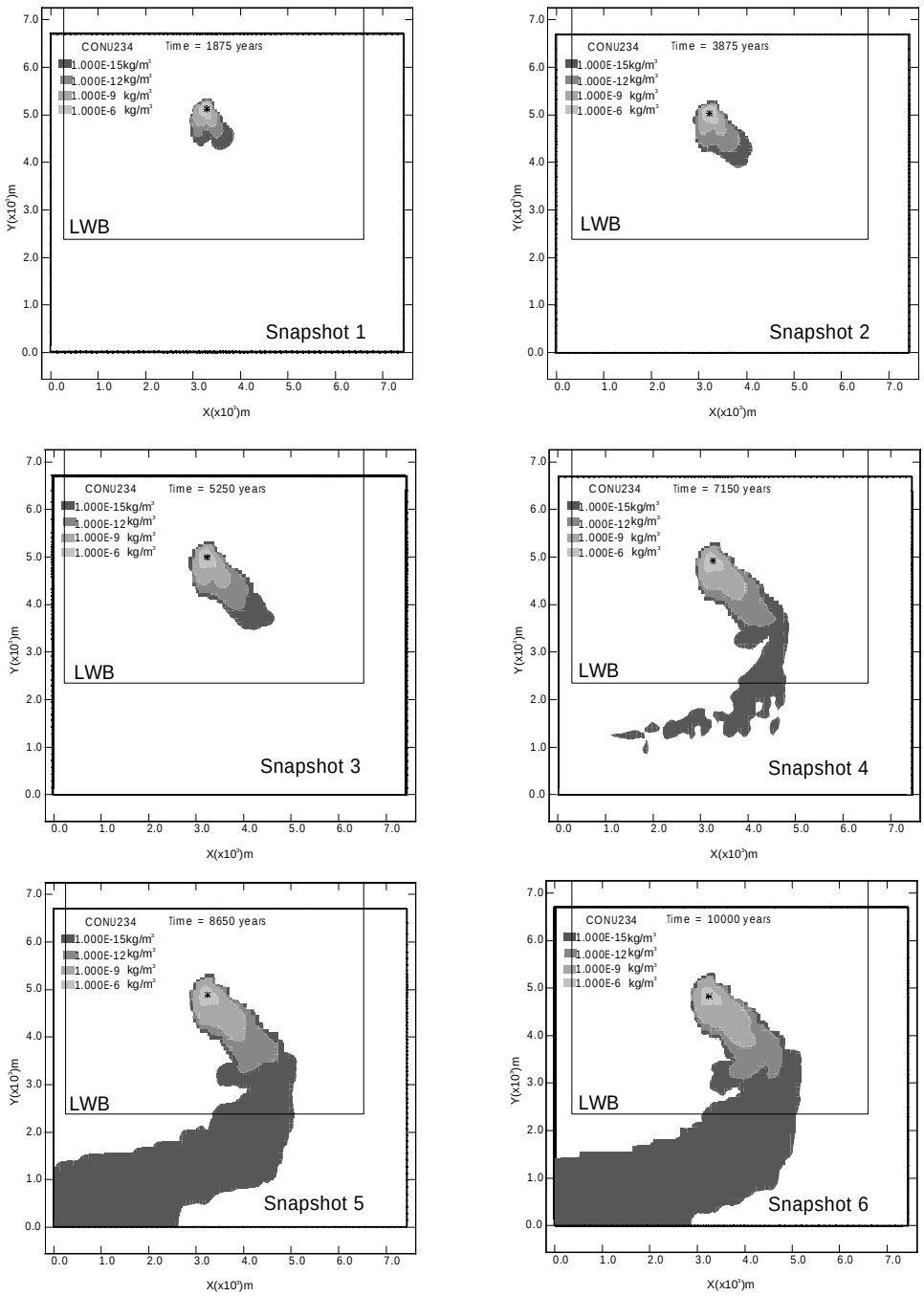

Figure 8.10. Uranium Isopleths for Vector 62 with Retardation of 2.0, MM Scenario

The discharge across the Land Withdrawl Boundary as a function of time can be seen in Figure 8.11. The simulation was extended beyond the regulatory timeframe, to 100000 years. The figure also notes the position of the snapshots from Figure 8.10. At 10000 years the fractional discharge is approximately 1.4×10^{-5} kgs. However, beyond the 10000 years, the discharge of uranium increases exponentially to 70000 years, where it levels off at 0.89 kgs. Regulatory compliance only requires 10000 year calculations, yet significant transport does not appear to take place until 30000 to 70000 years.

8.5. Probabilistic Modeling of Uranium and Plutonium

Though interesting, this chapter does not intend to discuss the regulatory timeframe in which encapsulated waste must be contained for safe disposal. It is meant to give an overall picture on the performance of the disposal system, weighting several factors not considered in the CCA. The chapter began with the formulation of a new scenario and ends with the results as compared to those submitted in the CCA. The last step in that comparison is to formulate a probabilistic model for the prediction of radionuclides reaching the accessible boundary anytime during the 10000 year future of the repository. The code CCDFGF was used to do this type of modeling.

The probabilistic model used all the results from the CCA, with the exception of transport. The new transport calculations were integrated into the CCA calculations to produce the CCDF curves, as presented in Figure 8.12. The CCDFGF code calculated curves for both plutonium with a K_d=0 and uranium with newly generated K_ds, and Figure 8.12. compares the results to

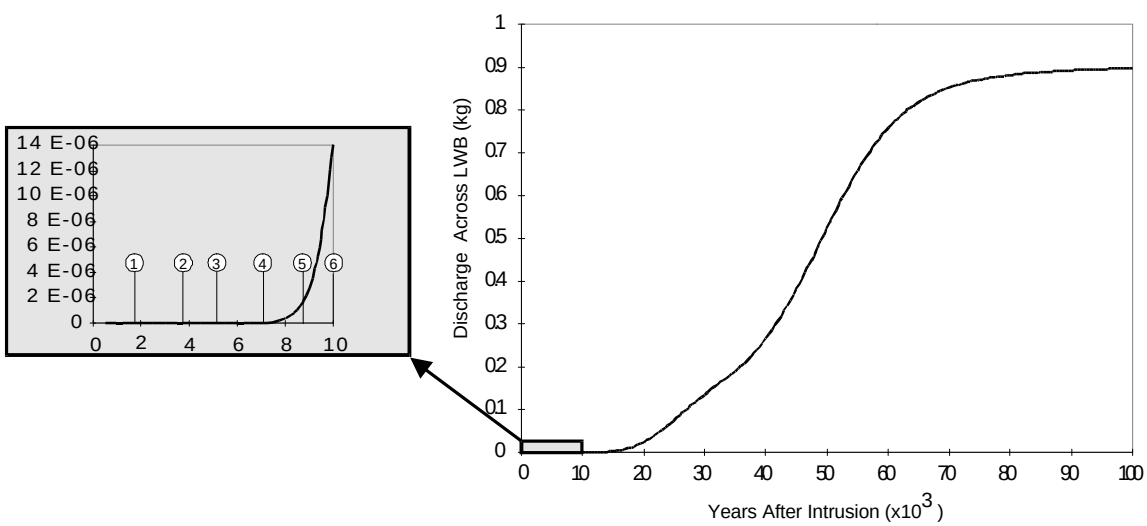

Figure 8.11. Integrated Discharge of Mass Across the LWB from 0 to 100,000 Years with Blowout Section from 0 to 10,000 Years with Snapshots from Figure 8.9. Shown as Circled Numbers in Blowout Section

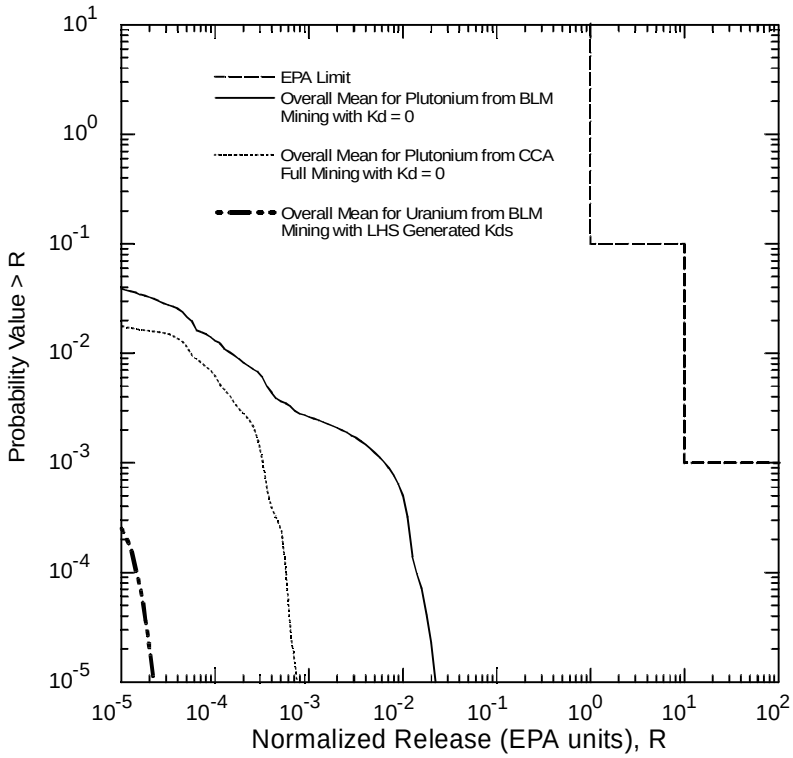

Figure 8.12. CCDF Curves for Overall Mean Releases from Culebra, Comparing Modified Mining to CCA Mining

those of the plutonium modeling with CCA Mining assumptions and 1% K_d=0 (from Chapter 6). The CCA results are not presented, since no vector crossed the LWB in the first replicate.

The combination of higher velocities from the modified mining scenario and K_d=0 demonstrates higher release probabilities from the Culebra than any other model, including mining or the elimination of retardation modeled separately. However, when considering the two scenarios separately, the elimination of retardation dominates the release probabilities by almost two orders of magnitude. The curves of Figure 8.12. shows plutonium with a K_d=0 with the BLM Mining as the right-most curve, plutonium with CCA Mining Scenario (Full Mining only) and K_d=0 in the middle, and uranium with the MM Scenario and LHS generated K_ds to the left. These results suggest that the sorption mechanism is more important than the way the velocity field behaves.

8.6. Conclusions

The mining of potash in the McNutt Potash Zone of the Salado formation was to be considered as a possible human intrusion scenario in the performance assessment, as stipulated in 40 CFR Part 194. The effects of such mining will change the characteristics of the overlying Culebra

Dolomite member of the Rustler Formation by increasing the fractures, and hence increasing the effective transmissivity of the region.

Modeling of mining in the CCA assumed two distinct scenarios, based on the probability of mining within the controlled area (or Land Withdraw Boundary) of the WIPP repository, namely the Full and Partial Mining scenarios. The Full Mining scenario assumes that limited mining would occur within the controlled area with consideration of present and future oil and gas wells, and the quality of present economic grade potash. The regulations of such wells mandate a 0.25 mile or 110% of the well length radius around the well to be undisturbed to insure no damage would occur to the well during mining. The Partial Mining scenario does not consider future mining in the controlled area, but only past mining conducted in the region. Outside the controlled area, both scenarios are the same, and are based primarily on the Bureau of Land Management's 1993 Map on the extent of potash in the Delaware Basin (BLM 1993).

The uncertainty of mining within the controlled area prompted an additional modeling study, which does not consider wells or the elimination of lower grade potash. The use of better extraction methods for potash, such as solution mining in combination with the increase on dependence of potash as an artificial fertilizer for world food production, has justified the present model to assume the full extent of potash mining as dictated by the BLM's 1993 map. Dubbed the BLM Mining Scenario, the new model only changes the extent of mining for flow modeling. The changes can be seen in Figure 8.1.

The transport of radionuclides through the Culebra was also modeled, with slight changes from what was assumed in the CCA performance assessment. Two experiments were conducted using the flow results of the Modified Mining Scenario to compare the results to previous modeling studies. The first experiment simulated plutonium through the Culebra unretarded, and were compared to the findings in Chapter 6. The second experiment modeled uranium with generated K_ds to compare the results with those in the performance assessment.

Figure 8.12. shows the results of the modeling conducted with the new assumed extent of potash mining within the controlled area. Modeling plutonium with no sorption to the surrounding matrix with BLM flow characteristics demonstrated to have the highest release probabilities. The experiment used a 1% K_d=0 $^{ml}/_{g}$ with the remaining 99% high K_ds generated from the LHS code showing no releases to the accessible environment. When compared to the 1% K_d=0 $^{ml}/_{g}$ with purely Full Mining of the CCA, release differences of up to 1.5 orders of magnitude are noticed. However, when comparing the Full Mining with no sorption to BLM Mining with sorption, the Full

Mining Scenario dominates the release probabilities, indicating that low sorption is much more important than high velocities.

9. GASOUT MODELING OF THE WIPP

9.1. Summary

The GASOUT code has been applied to the spallings scenario of the WIPP's disposal system to assess the conservatism of the results calculated in the Compliance Certification Application (CCA) (U.S. DOE 1996). A report on the application of the code (Hansen et al. 1997) states that a maximum of 0.27 m^3 of waste would fail in the borehole cavity from an intruding drill string and would be transported to the accessible environment through a blowout event. This calculated volume was used to verify the amount of spalled material calculated in the CCA as reasonable. However, an exercise with the code for an analysis on the sensitivity of several input assumptions shows that the code may be too sensitive, and the range of parameter values too small to judge the behavior of the disposal system accurately. It is suggested that the code be modified to allow a wide range of repository conditions to be modeled, so that an actual maximum spall can be calculated.

9.2. Introduction

The blowout of spalled material reaching the accessible environment through an inadvertent human intrusion through a borehole into the WIPP repository could cause major problems with the compliance of the EPA's limit established in the 40 CFR Part 191 (U.S. EPA 1996a). EEG (1997e) has shown that spalled volume, ranging from 8 m^3 to 64 m^3 can violate these standards. DOE's published results have shown that a blowout would purge less than 4.0 m^3 of waste from the repository, with 0.27 m^3 being a more typical volume (Hansen et al. 1997). This chapter discusses the problems in using the GASOUT code as contained in Hansen et al. (1997).

Spall is waste that has been introduced into the drilling fluid due to radially channeled, highly pressurized gas flow from within the repository to a lower pressure borehole. Gas will continue to flow until the system comes to pressure equilibrium between the repository and the borehole. The high flow rates of gas will cause some of the material to fail in tension or shear, break off from the borehole cavity, and be introduced into the return stream of the drilling fluid. If gas flow is sufficiently high, it will force all the drilling fluid out of the borehole at the surface. This phenomenon is known as blowout, and is a common occurrence among drilling rigs encountering pressurized pockets of natural gas.

Spall can also occur by the mechanisms of stuck pipe and gas-induced erosion. These phenomena may dominate a spalled event if the gas flows are too low to cause blowout. Stuck pipe is a process of spall that, due to very low permeability and extremely high repository

pressures, may cause failed waste to press against the drill string sufficiently hard to prevent normal drilling. The solution of a jammed bit is to pull the drill string up and start drilling again. If the pressures remain high, the driller may have to bring the bit up several times, thus allowing significant quantities of waste to be brought to the surface through the return stream of the drilling mud. Gas erosion is spall that is eroded by the drilling mud due to high repository pressures and low waste permeability. The spall from gas erosion is slower than stuck pipe due to slightly lower pressures in the repository (just above hydrostatic), and may release waste into the drilling mud at a rate undetectable by the driller. Gas erosion would continue until the repository pressure is in equilibrium with the drilling fluid, and may also bring significant quantities of waste to the surface.

Stuck pipe and gas erosion releases will occur if the waste permeability is less than $1x10^{-16}$ m^2, as stated in Berglund (1994), and repository pressures are greater than the pressure exerted by the drilling mud. The CCA states that the waste permeability can be represented by a constant value of $1.7x10^{-13}$ m^2, which is much greater than the threshold for stuck pipe. Additional studies show that waste surrogates based on current understanding of waste mixtures could have a permeability of $2.1x10^{-15}$ to $5.3x10^{-15}$ m^2 (Hansen et al. 1997), and that the threshold for when blowout ceases and stuck pipe/gas erosion begins is questionable (EEG 1997e)

The DOE has made attempts at calculating the amount of material that will spall through a blowout. The code CUTTINGS_S (U.S. DOE 1996-Appendix CUTTINGS_S) incorporates the spallings calculations with calculations of the amount of cuttings and cavings from a drill string cutting through the repository. The calculations showed that a maximum of 4.0 m^3 would fail in the borehole cavity and be forced out of the borehole to the surface. However, an independent peer review found the code to be conceptually flawed. The DOE's Conceptual Model Peer Review Group (U.S. DOE 1996-Appendix Peer 1) stated that the "Development of this [spallings] model is not sufficiently complete to determine uncertainties specific to the channel movement of waste to the existing borehole". The threshold for waste permeability and stuck pipe was also based on the findings of this code.

The spallings volume was re-calculated by using a second code, GASOUT (Shatz 1997), along with several other methods, to assess whether the results of the spalled material calculated in the CCA were reasonable. The GASOUT code was accepted by the Conceptual Model Peer Review Group (Wilson et al. 1997) based only on the conceptual model, without any independent testing or validation. Calculations with the GASOUT yielded a maximum of 0.27 m^3 to reach the accessible environment upon a breach (Hansen et al. 1997). The main assumptions used in the code to derive at the calculated volume was a waste permeability of $1.7x10^{-13}$ m^2, a repository

pressure of 14.8 MPa, and a waste tensile strength of 10 psi (0.068 MPa). Despite better understanding of the waste and measured values of the waste permeability, 4.0×10^{-15}, as described in Hansen et al. (1997), the CCA value of permeability (1.7×10^{-13}) was used for this investigation.

GASOUT uses a semi-analytic approach of a mechanistic conceptual model that couples the numerical calculations of a finite difference fluid flow code and a finite element rock mechanics code. This approach has been dubbed "the cavity growth method", because it progressively calculates the region of radial tensile failure within the cavity. Hansen et al. (1997) stated that there is no tensile failure of waste below repository gas pressures of 14 MPa "under realistic but conservative assumptions".

The conceptual model of the code during the blowout process was described as being divided into two stages. The first stage is characterized by the ejection of the drilling mud by high pressure gases, and the response of the waste to the high pressure gradients during blowout. Following the blowout, the second stage is identified by the rapid flow of gas from the repository, including the entrainment of solid waste particles. In the first stage of initial depressurization, gas velocities are small while the mud column is being expelled from the borehole. The velocities will increase during stage two, as the borehole path is clear for rapid gas movement. The larger eroded waste particles will typically be lofted to the surface during this stage.

In addition to the analysis using GASOUT, a "quasi-static" and "fully coupled" approach to solving the spallings problem was employed. The quasi-static used a spread sheet analysis to solve the porous flow equations by a sequence of steady state profiles (Hansen et al. 1997, pg. 3-24), and the conceptual model used in the quasi-static was identical to the cavity growth (GASOUT) method. The major difference in the two models is that the cavity within the quasi-static model does not change with the calculation of tensile failed waste removal. The results from the GASOUT calculation without failed material removal (removal of failed material is a toggle switch that can be turned on and off in the code), show almost perfect agreement with the quasi-static results under identical initial assumptions. Tensile failed material calculations for the quasi-static model showed 1.17 m^3 of spall with initial pressure conditions of 14.7 MPa and tensile strength of 15 psi. The cavity growth model calculated an equivalent 0.07 m^3 of spall.

The fully coupled approach used a purely numerical code (as opposed to the semi-analytic approach in GASOUT) to calculate the flow of gas within the waste region to the intruded borehole. The mathematical model of the fully coupled approach assumes a one-way coupling of the two-phase pressure decay following an intrusion with a decoupled two-phase pressure

response within the simulated waste region. The fluid flow and waste pressure response were solved by the code TOUGH28W with the poromechanical waste response of stress and strain invoked in the code SPECTROM-32.

Though the code did not explicitly calculate failure, it did calculate stresses within the waste. From the results using SPECTROM-32, the normal stresses show a semi-hemispherical distribution at very early times. If the initial assumptions for repository pressure are 14.8 MPa (lithostatic), and the waste tensile strength is 10 psi (0.04 MPa), then the code would indicate an elastic failure radius of 0.8 m (Hansen et al. 1997-Figure 4-9, time=0.001 s), or 2.1 m^3 uncompacted volume. The same figure shows a stress distribution extended out to one second, but without considering the possibility of waste removal. The removed waste would have a significant impact on the stresses in the cavity.

Though the GASOUT code was just a piece in the series of the spallings calculations performed in the investigation led by Dr. Frank Hansen, this chapter is basically restricted to the GASOUT code and will assess the performance of GASOUT for a wide variety of situations that are plausible for the WIPP disposal system. Furthermore, it will show the limitations associated with the code outside designated ranges of assumptions used for the investigation presented in Hansen et al. (1997).

9.3. Discussion

GASOUT was run on a number of cases, by changing the initial permeability, the waste tensile strength, the initial repository pressure, mud density and the gas viscosity. The initial permeability refers to the permeability of the waste in the repository. Measured values of permeability from experiments on simulated waste specimens showed that the permeability is typically on the order of 4.0×10^{-15} m^2 (Hansen et al. 1997). However, none of the permeability experiments included the proposed backfill material, magnesium oxide, and permeability could actually decrease further with the added affect of cementation from the MgO backfill (U.S. DOE 1997b).

Waste tensile strength is the strength of the compacted waste in the repository that can withstand the flow of repository gas pressures before failing in tension. Measured values of waste tensile strength based on laboratory specimens of surrogate waste forms found a mean strength value to be 0.074 MPa with a standard deviation of 0.04 MPa (10.7 $\pm$5.8 psi) (Hansen et al. 1997).

The repository gas pressure dictates the flow rate of gas from the internal rooms in each panel towards the borehole cavity. Higher repository pressures will result in higher gas flow rates, limited of course by the permeability of the waste matrix or the viscosity of the fluid. The maximum calculated pressure in the CCA, using the two-phase flow code, BRAGFLO, was 16.3 MPa in the waste panels for the undisturbed scenario, and 14 MPa for the disturbed scenario. The EPA's PAVT (U.S. DOE 1997d) calculated a maximum pressure of 16.8 MPa and 15.6 MPa for the undisturbed and disturbed scenarios, respectively. These maximum calculated pressures are higher than the lithostatic, since the lithostatic pressure at the depth of the repository is 14.8 MPa. Therefore, to reduce complications associated with fracturing within the repository, the highest repository pressure investigated will be 14.8 MPa.

GASOUT progressively reports the maximum tensile failed radius, and contiguous failed radius of the hemispherical cavity as the pressure gradient across the waste causes it to fail. During most simulations, these two radii will be equal. However, some simulations will report failure zones outside of the cavity, which are considered not to be spalled waste, and will not be carried out of the borehole through a blowout event. The extraneous cavities are not considered in the contiguous failed radius value.

The compacted and uncompacted failed waste calculated from the failure radius are identified in Hansen et al. (1997) by the following two equations,

$$V_0 = \frac{1-\varphi}{(1-\varphi_0)} V \qquad (1)$$

$$V = \frac{2}{3}\pi r^3 \qquad (2)$$

where V_0 is the uncompacted spalling volume, V is the compacted volume, r is the radius of tensile failure, φ is the compacted porosity of the waste (taken as 0.7) and φ_0 is the uncompacted porosity of the waste (the value 0.848 was used in BRAGFLO). Simplifying, the expression yields $V_0 = 1.97V$, where V is dependent on the length of the failed radius.

Figure 3-12 of Hansen et al. (1997) shows the failure radius of a typical case throughout the time history of the model simulation. The effect is a "stair-step" behavior that represents failed events in the cavity. As the cavity grows from tensile failure, stress is lowered near the boundary of the cavity wall. As time ensues, the stress builds again until another failure event takes place, and the cavity grows as the result of waste breaking off.

The GASOUT results depend solely on the input assumptions provided in its evaluation. For comparison with the WIPP disposal system calculations of Hansen et al. (1997), the assumptions

remained the same for the present study with the “typical” case of the Hansen Investigation, and reasonable changes in certain parameters were conducted to test the code’s effectiveness under varying repository conditions. Through correspondence with John Schatz, the author of the code, it was noted that the code will work only for a narrow range of parameters, despite the unconditionally stable explicit solver used in the numerical (finite difference gas flow through the waste) potion of the code. Outside the designated range of values, the code calculates failure that are interpreted as meaningless, i.e., the code shows the radial failure of waste to cascade, and several “zones” of discretized waste will fail during a single timestep. Once the cascading affect starts, the stresses through the waste become discontinuous.

Table 9.1. lists the input values used as the typical case of this investigation. Table 9.1. represents the “Base” case of the present study and all analyses of sensitivity will be deviations from these assumptions.

Input Parameter	Current, EEG Investigation
Wellbore Diameter (m)	0.3111
Pipe Diameter (m)	0.2032
Outer Radius (m)	19.2
Surface Elevation (m)	1035.5
Base Elevation (m)	380.5
Base Height (m)	2.0
Initial Pressure (MPa)	14.5
Far Field Pore Pressure (MPa)	14.5
Initial Porosity	0.70
Initial Permeability (m^2)	1.7E-13
Gas Base Density (kg/m^3)	0.082 - reported as 11.33
Gas Viscosity (Pa*s)	10E-06 - reported as 9.2E-6
Mud Density (kg/m^3)	1249.3 - reported as 1211
Mud Friction Factor	0.02
Gas Friction Factor	0.02
Far Field Stress (MPa)	14.8
Tensile Failure Velocity (m/s)	1000
Tensile Strength (psi)	15
Cohesion (psi)	18.85
Friction Angle (rad)	0.785
Max Time (s)	5
Eject Mud	True
No Flow Outer Boundary	True
Spherical	True
Allow Material Removal	True
Permeability From Porosity	False

Table 9.1. Input Assumptions for Base Case Study and from Hansen et al. (1997)

9.4. Base Case

The Base Case was run for the typical five second time period that was stated in Hansen et al. (1997) to be well within the first stage of the blowout process, and the amount of tensile failed material for this simulation matches the results presented in the Hansen Investigation, showing a failed radius of 0.25 m and a failed uncompacted volume of 0.05 m^3. During the first five seconds, as seen in Figure 9.1., the acceleration and velocity of the mud column as well as the bottomhole pressure asymptotically reach a steady value. The left plot of Figure 9.1., shows that the acceleration of the mud column reduces significantly after the first second, when the mass flux of gas into the borehole has also significantly reduced. The figure matches quite well with Figure 3-3 of Hansen et al. (1997).

The middle plot of Figure 9.1. (below) shows velocity as a function of time for the first five seconds of blowout. Again, the plot reaches a steady value within a couple of seconds with a velocity of 6.36 m/s. This is slightly higher than presented in Hansen et al. (1997 - Figure 3-2), which reaches a steady value of approximately 5.8 m/s. The discrepancies between the two figures are slight, yet they exist. Small discrepancies are also seen for the pressure curves (Figure 9.3.-4 of Hansen et al. 1997 and the pressure plot of Figure 9.1., below). However, after running GASOUT at a lower initial repository pressure of 14.3 MPa, the velocity and pressure plots of Hansen et al. (1997) resemble the lower initial repository pressure distributions more closely.

The amount of uncompacted failed material volumes as a function of initial repository pressure and waste tensile strength presented from the Hansen Investigation (Table 1-1) are from a five second blowout simulation, and it is questionable as to what the length of time the code can run for meaningful results. The code simulates a compressible gas flow through porous media to the borehole cavity. From the flow calculation, pressure in the cavity is calculated, and is used to

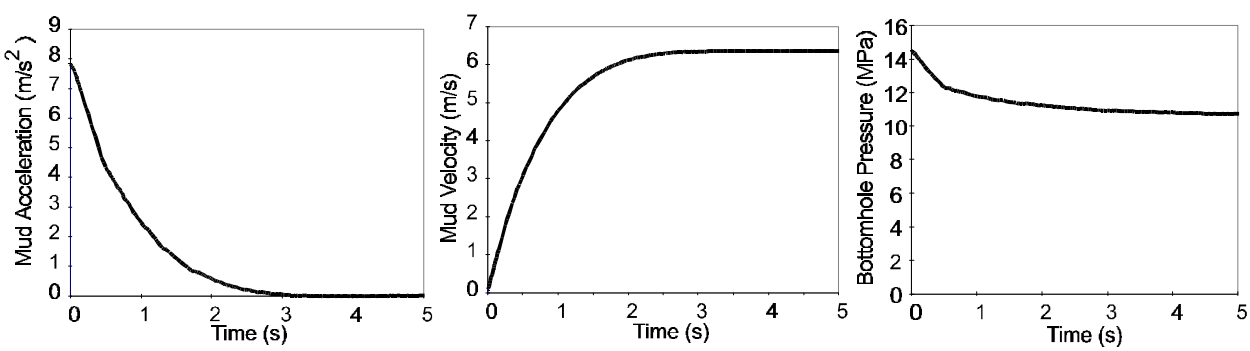

Figure 9.1. Verification of Typical Case Presented in Hansen et al. (1997) for Left) Mud Column Acceleration; Middle) Mud Column Velocity; and Right) Bottomhole Pressure

calculate the force required to push the mud column up, and out of the borehole annulus. The driving pressure of the gas for mud motion does not assume compressible flow, and is valid only when the gas pressures are high, and the mud column has moved a negligible distance. However, when the mud column has moved a considerable distance, the physics of the gas changes, and compressible flow will be an important consideration at later times of blowout.

It is suggested here that the five second results may be misleading. Though the code is questionable beyond the initial 5-10 second simulation, the Base Case shows a larger blowout release when the code is extended to 20 seconds and further to 50 seconds. By 20 seconds, the mud column has only reached 133 m, or 20% of the total borehole length, and the velocity of the mud moving up the borehole has increased from 6.36 m/s to 7.73 m/s. The tensile failed radial increased from 0.25 m (0.05 m^3 uncompacted volume) for a five second simulation to 0.27 m (0.066 m^3 uncompacted volume) for 20 seconds, and to 0.44 m (0.36 m^3 uncompacted volume) for 50 seconds.

Figure 9.2. shows the contiguous tensile radial failure, and mud motion velocity through time, of the Base Case simulation for an extended time of 50 seconds. It is clear that the two curves on the figure correlate, and as the velocity of the mud motion increases, the radial failure increases. However, it is unclear where the interpretation of reasonable radial failure should stop. Field conditions indicate that blowout is almost never ceased within a minute, if blowout preventers are not invoked. Therefore, it is reasonable to assume that spall would continue as long as the pressure gradient in the waste would cause failure.

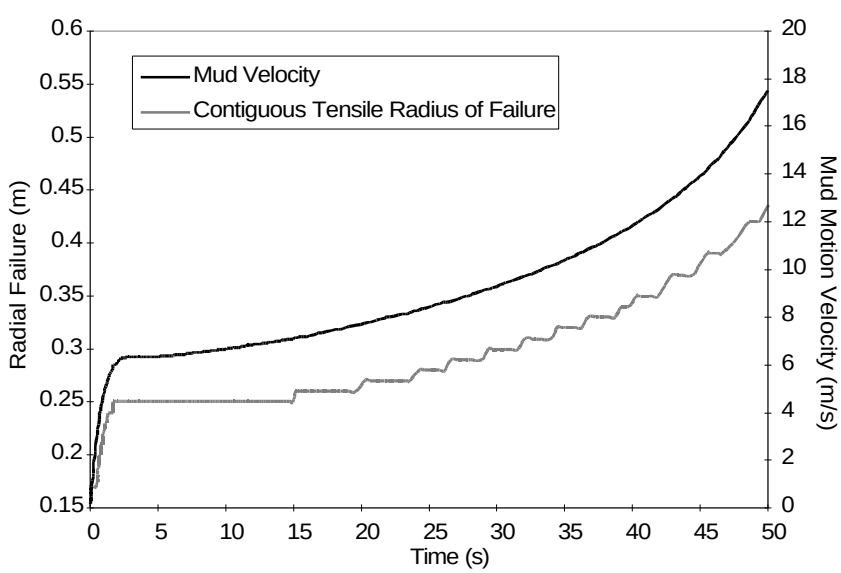

Figure 9.2. Contiguous Tensile Radial Failure and Mud Motion Velocity vs. Time for Base Case at Late Times

The duration of spall at later times would depend on the pressure gradient across the waste form, and its ability to remain high to cause failure. Figure 9.3. shows several pressure curves versus radial distance from the borehole, at 0.5, 5, 20, and 50 seconds during the Base Case simulation. The figure reveals that the pressure drop within 1 meter of the borehole center (the borehole center is marked as 0 on the abscissa) is high from 0.5 seconds to 5 seconds, much lower from 5 to 20 seconds, and becomes quite substantial from 20 to 50 seconds with a maximum drop of 2.5 MPa at 0.45 m from the borehole center. Though the pressure in the borehole cavity is low at 50 seconds (9.37 MPa), the pressure gradient across the waste at 0.5 meters from the cavity wall is higher than at 0.5 seconds. At 50 seconds, the pressure increases 3.4 MPa from the cavity wall at 0.44 m from the borehole center to 0.94 m from borehole center. The same distance of 0.5 meters from the borehole cavity at 0.5 seconds is 2 MPa. Furthermore, the radial and tangential (shear) stress distributions through the waste show smooth transitions during the time stepping and radial failure, and the simulation up to 50 seconds did not cascade waste at high rates. The only noticeable problem with the extended time simulation was the incompressible gas flow up the borehole. It is theorized that at later times when the gas expands from the lower compressive forces of the lighter mud column, the pressure in the borehole cavity will be even smaller. This will create an even higher pressure gradient across the waste, and more spall.

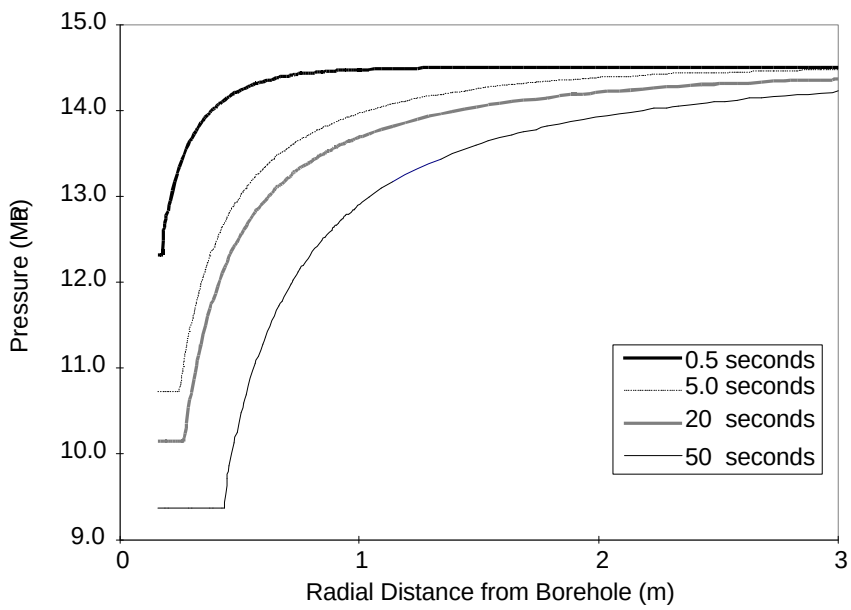

Figure 9.3. Pressure Distribution through the Repository after Intrusion with the Datum on the Abscissa Representing the Center of the Borehole, which has a Radius of 0.156 m.

9.5. Sensitivity to Permeability and Initial Repository Pressure

The GASOUT code was seen to be very insensitive to the initial permeability value chosen in this study. However, the code's use of a small number of parameters kept the sensitivity analysis to a minimum, and true sensitivity could not be established. The range of values narrowed as the initial repository pressure increased, and waste tensile strength decreased.

Initially, the permeability value that was used in the CCA (1.7×10^{-13} m^2) was assumed in the present study to allow comparisons with the results in Hansen at al. (1997), despite a better understanding of permeability investigated in that report, and the value used in the CCA is under question here. The single value questioned was calculated from assumed future waste conditions.

Butcher (1990) ran permeability experiments on different and separate waste types to determine the overall waste permeability of the repository, looking for a value that could represent conditions for performance assessment calculations. These types included metals, combustibles (plastic, rubber, and wood), and sludges. Each waste type exhibited a range of permeabilities, with minimum, median, and maximum values presented in Table 9.2.

The values obtained in Table 9.2. are questionable. First, the representative materials for each type of waste do not cover the possibility of materials that will exist in the repository in the future. The combustibles, for example, used 1" pine cubes, which were to represent wood chips and sawdust (Butcher 1989). In 1,500 years, most (<90%) of the wood will be degraded, and the compaction of degraded wood would cause a lower permeability. Degraded metals would be another example, in which 50% magnetite and 50% 1" metal chips represent the average of degraded steel, aluminum, nails, and lead sheeting.

The volumes of each type of material were also considered in calculating the effective permeability of a drum. For the CCA, 40% combustibles, 40% metals, and 20% sludges were assumed from an average waste drum (U.S. DOE 1996-Appendix Peer 1). These values also varied from drum samples, and from each generating site. The Los Alamos National Laboratory volume (by percentage) of combustibles had an averaged value of 20, whereas the Savannah River Plant averaged 70 (Butcher 1989-Table 2.). These variances in volume could cause the expected value of 1.7×10^{-13} to decrease significantly.

The calculated value for waste permeability did not consider the effect of the proposed backfill (magnesium oxide) that will be placed around the waste to decrease gas generation, lower pH,

and help in the cementation of waste to increase waste strength. It is suspected that MgO precipitation will decrease the permeability by providing material for interstitial cementation, which was concluded by the Particle Size Expert Elicitation Panel (U.S. DOE 1997b) to be a major contributor to increased waste strength. The volume of the emplaced backfill will be approximately 25% of the total repository volume, and the permeability of cemented MgO, called Sorel cement, is much like Portland cement (Zheng et al. 1991), with values around $1x10^{-16}$ m^2.

Lastly, a measured value of permeability on waste surrogates were reported in Hansen et al. (1997). The permeability of typical specimens were approximately $4x10^{-15}$ m^2. It is, therefore, reasonable to assume that waste permeability could vary significantly from the single value of $1.7x10^{-13}$ m^2, and simulations using smaller values of permeability in GASOUT are quite substantiated.

The results of spalled material failing in a borehole cavity using GASOUT over a wide range of permeabilities were not meaningful, and the code was simulated using a very narrow range. For the Base Case simulation for example, the waste permeability could only range from $0.8x10^{-13}$ to $4.4x10^{-13}$ m^2. Above and below these permeabilities, the code predicted extremely large failed volumes. The results of the failed volume for a five second simulation can be seen in Figure 9.4. The figure shows failed volume versus the permeability range that was applicable. The reported failed volume is the maximum contiguous failed volume, calculated from Equations 1 and 2 above. The figure also shows results of varying waste tensile strength, from 10 to 20 psi. The three curves represented in the figure give the upper and lower bounds of the permeability that result in meaningful values.

The reported failed volumes outside the range for the Base Case are extremely high, resulting in as much as 22.5 m^3 for a permeability of $0.5x10^{-13}$ m^2 due to the cascading affect of multiple zone failure. The geometry of the borehole cavity was discretized and solved on a hemispherical coordinate system. The layers of the hemisphere were kept to a minimum (0.01 meters) to avoid instability. When the waste in the borehole fails, it is assumed that the whole layer fails, and peels off like an onion skin. When the code calculates a large failed volume, as in the case with $0.5x10^{-13}$ m^2 permeability, the effect is several layers peeling off in one time

	Min	Med	Max
Combustibles (m^2)	2.00E-15	1.70E-14	2.00E-13
Metals (m^2)	4.00E-15	5.00E-13	1.20E-12
Sludge (m^2)	1.10E-17	1.20E-16	1.70E-16

Table 9.2. Permeability Values Used to Calculate the Waste Permeability in the CCA

step, cascading until an equilibrium is reached with the high pressure gradient that existed at a longer time period. It is assumed that when the cascading effect is exhibited, the results become meaningless.

Figure 9.4. shows some interesting results as the waste permeability increases. All the waste strengths tested showed an exponentially decreasing failed volume, up to a permeability of 2.5×10^{-13} m^2. Permeabilities above this value caused larger failed volumes than values below it within the range where cascading waste is not a factor in failed volume. The upper limit on permeability shows that the code is reliable to 2.5×10^{-15} m^2 for waste strengths that were measured in the report by Hansen et al. (1997) and initial repository pressure of 14.5 MPa. The lower permeability limit is 1.0×10^{-13} m^2 for 10 psi waste strength, and decreases to 0.8×10^{-13} m^2 for waste strengths of 15 and 20 psi.

When the initial pressure is increased to its maximum of 14.8 MPa, the range is more narrow than discussed above. For all waste strengths investigated, confidence was only in waste permeabilities between 1.7×10^{-13} m^2 and 2.0×10^{-13} m^2. The narrow range that the code is applicable decreases the likelihood that the code can represent the disposal system accurately. The code should be modified to allow more representative values to be modeled.

The simulation of the repository with a homogeneous waste in GASOUT is an over simplification

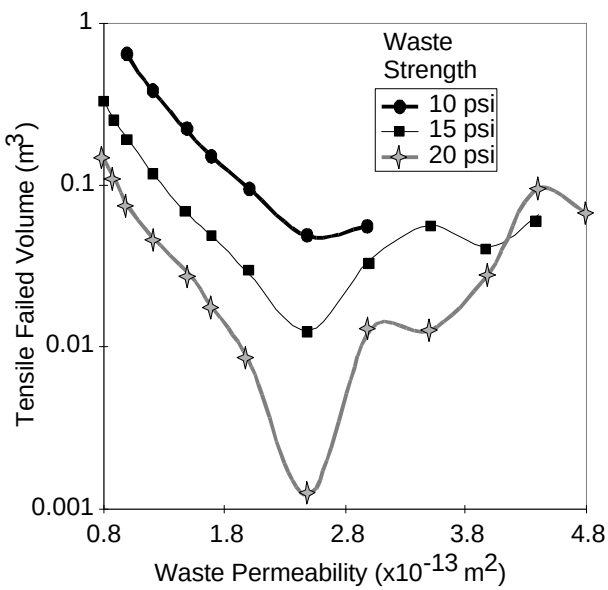

Figure 9.4. Contiguous Failed Volume as a Function of Increasing Waste Permeability for Different Waste Strengths with an Initial Repository Pressure of 14.5 MPa

of the repository model. It is likely that the waste permeability will actually be lower than that assumed in the CCA. The representation of a random permeability was explored in Hansen et al. (1997) using a fully coupled numerical code to solve the flow of gas through the repository. TOUGH28W did not calculate the amount of waste failure, but could calculate the pressure distribution through the waste for varying conditions. The code showed that a lower permeability, with values ranging from $1x10^{-12}$ to $1x10^{-16}$ m^2 would have a much higher pressure gradient near the borehole, than the permeability assumed in the CCA. It also showed that homogeneous waste with lower permeabilities will have higher pressure gradients. This further strengthens the argument for modifying GASOUT to represent the repository more accurately.

9.6. Sensitivity of Gas Viscosity

The gas viscosity parameter, along with porosity and permeability, is used to calculate the hydraulic conductivity of gas through porous media, K, by the relationship of

$$K = \frac{k}{2\phi\mu} \qquad (3)$$

where k is permeability, ϕ is porosity, and μ is gas viscosity. The original equation for the flow of gas through porous media can be found in Chan et al. (1993) , and is equivalent to the non-linear diffusion equation. The viscosity of Equation 3 is indirectly proportional to the gas conductivity, and as viscosity increases, conductivity decreases. The relationship also shows that a constant ratio of permeability to viscosity will yield the same conductivity.

The experiment with permeability demonstrated that values less than $1x10^{-13}$ m^2 for an initial pressure of 14.5 MPa would render the results meaningless. The viscosity used in the experiments was $10x10^{-6}$ Pa*s, and the ratio of permeability to viscosity yields $1x10^{-8}$. Values less than this ratio causes the code to predict cascading failure of waste. With the original permeability of $1.7x10^{-13}$ m^2, viscosity values greater than $17x10^{-6}$ Pa*s causes the code to give erroneous results. The ratio for failure criterion increases to $1.7x10^{-8}$ for an initial repository pressure of 14.8 MPa and waste tensile strength of 10 psi. A simulation with the ratio of $1x10^{-8}$ m^2/Pa/s, an initial pressure of 14.5 MPa, and tensile waste strength of 10 psi yields a failed volume of 0.63 m^3.

The possibility of larger viscosity values is not ill conceived. The viscosity value obtained for hydrogen gas was the standard temperature and pressure value (STP), and viscosity increases moderately as pressure or temperature increases.

The components of the repository gas will also increase the viscosity. Through microbial degradation of plastics, rubbers, and other combustible material, O_2, CO_2, CH_4, N_2, N_2O and H_2S will be created. Francis et al. (1996) conducted experiments of microbial gas generation under expected WIPP repository conditions and found that the percentage of N_2 varied between 61.9% to 91.4%, CO_2 varied between 0.4% and 34.3%, and H_2 varied between 0% and 12.8%. These other constituents have a much higher viscosity than H_2, with N_2 being as high as 19.2×10^{-6} Pa*s (STP), which will undoubtedly increase with an increased repository pressure.

Even though microbial degradation may create higher quantities of CO_2, and N_2 than H_2, the process itself will be limited. It is uncertain whether the colonies of microbes can exist under repository conditions, and was therefore assigned a 50% chance in the CCA. Iron corrosion on the other hand will produce massive quantities of H_2 and it is certain that iron will corrode when brine fills the repository. Approximately 2×10^{9} moles of H_2 (Telander and Westerman 1996) will be produced from the iron in WIPP. However, the other gaseous constituents could play a small role if microbial degradation does produce gas. Figure MASS-1 (U.S. DOE 1996-Appendix MASS) shows that at lithostatic pressure, if the mole fraction of H_2 to CO_2 is reduced from 100% to 90%, then the viscosity would increase from 9×10^{-6} Pa*s to 16×10^{-6} Pa*s. Therefore, it is suggested that the code be modified to allow a larger spectrum of values to be modeled.

9.7. Sensitivity to Mud Column Density

The density of the mud column in the borehole is dependent on the type of drilling mud used. For the WIPP, it is most likely that the drilling mud will come from the Salado Formation with additives to increase the average mud density to 10 - 11 lb/gal (1200-1320 kg/m^3). The GASOUT code used a density of 1249.3 kg/m^3 in the Hansen Investigation, and it is possible that this value could vary over the range mentioned above.

Figure 9.5. shows the results of varying the parameter from 1200 to 1320 kg/m^3 for a 10 second simulation and an initial repository pressure of 14.8 MPa. The figure shows three curves of different waste strength, with all other parameters remaining the same as used in the Base Case simulation. The most outstanding feature of Figure 9.5. is the disjointed curve of failed waste (left) and mud motion (right) of the 10 psi tensile waste strength simulation. The code had trouble calculating failed waste for mud densities below 1228 kg/m^3, resulting in the cascading affect described above. The code also had trouble at 1240 and 1250 kg/m^3, and if results were plotted for these densities (failed waste and mud motion), sharp spikes would exist in the curve.

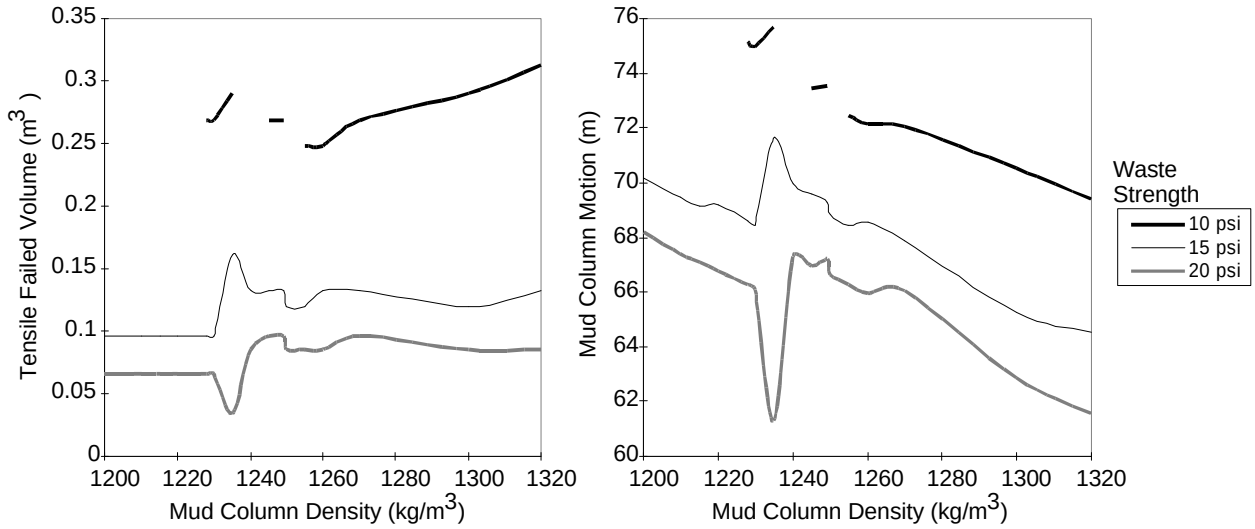

Figure 9.5. Left) Tensile Failed Volume as a Function of Mud Column Density for Several Waste Strengths and Right) Mud Column Motion as a Function of Mud Column Density

For the higher waste strengths (and subsequently lower repository pressures) of 15 and 20 psi, the mud density simulations were able to calculate failed volumes for all density values investigated. However, the results seemed almost as unreliable as the lower waste strength. Though a trend can be seen in the failed volume and mud motion, variances from those trends are high. Both graphs in Figure 9.5. show trouble with the code when densities are between 1230 and 1270 kg/m^3.

9.8. Sensitivity to Waste Porosity

Lastly, the code was investigated to test the effect of waste failure with changing (decreasing) porosity. If the porosity is lower, then the velocity of the gas moving through the repository to a borehole intrusion is higher. Hansen et al. (1997) report a porosity of 0.7, which was said to be typical of waste porosity when the pressure reached over 14.8 MPa. However, after investigating the relationship between pressure and porosity, it was found that porosity during the long-term performance of the repository was approximately 0.2 for high pressures, and less for lower pressures. Figure 9.6. shows the relationship of porosity to pressure for the undisturbed scenario of the performance assessment for the CCA. The figure shows two separate times, at 5,000 and 10,000 years postclosure using the results of BRAGFLO.

Porosity from the two-phase calculations of brine and gas flow through the repository clearly show the porosity will be quite low. The response of the code to lower repository porosities show slightly higher releases. For a porosity of 0.2, with initial conditions of 14.8 MPa repository pressure, and 10 psi waste strength, the uncompacted spalled volume is 0.47 m^3, and decreases

smoothly up to the original porosity of 0.7 and a calculated failed volume of 0.27 m^3. However, porosities above 0.7 and below 0.2 caused the calculated waste to cascade. Additional experiments using a variety of repository pressures and their expected porosities from Figure 9.6., does not show any further problems within the code.

9.9. Conclusions

A sensitivity analysis has been performed on the spallings code, GASOUT. GASOUT along with several other codes were used by the DOE to prove that the spalled volume calculated in the Compliance Certification Application (CCA) were reasonable, because the GASOUT calculated a much smaller spalled volume than those calculated in the CCA. The results of the experiment were documented in Hansen et al. (1997), which showed that a maximum of 0.27 m^3 would spall through blowout upon breach of the repository. The volume of spalled material calculated in the CCA ranged from 0.5 to 4.0 m^3.

The simulated blowout in the Hansen et al. simulations only lasted for five seconds. Blowout usually takes several minutes to control, and it is believed that much higher volumes of failed material would be derived if the simulations were run for longer periods of time. Sensitivity analysis in this chapter showed that as much as six times the volume would fail, if the experiments were extended in the GASOUT code from five seconds to approximately 50 seconds. Discounting the late time effect of spall when the velocities are allowed to flow faster from the waste underestimates the total amount of failed material that will reach the surface.

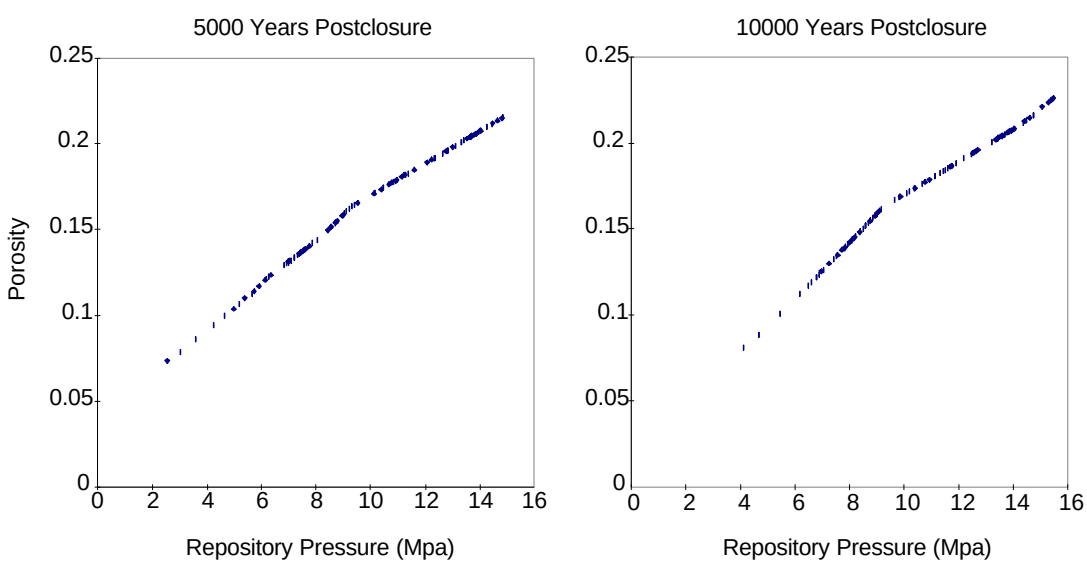

Figure 9.6. Porosity Versus Pressure Profiles for Undisturbed Scenarios of the CCA

GASOUT was also tested for its response to a range of waste permeabilities. The permeability of the waste used in the CCA was 1.7×10^{-13} m^2, and thus was carried over to the analysis in Hansen et al. (1997). However, the same report also measures a new value of permeability, based on a better understanding of simulated waste forms. These surrogates for the WIPP waste exhibited a permeability on the order of 4×10^{-15} m^2 for "typical" specimens. None of the surrogates that measured permeability contained magnesium oxide, the proposed backfill material that is said to occupy 25% of the repository's volume, and precipitation is expected to decrease the permeability of the waste.

An analysis of permeability with GASOUT showed that the code can only be applied to a small range of parameter values. For the most extreme case, using an initial pressure of 14.8 MPa and waste strength of 10 psi, the range is 1.7×10^{-13} to 2.0×10^{-13} m^2. The range is extended when waste strength is increased and pressure is decreased. The small range of permeabilities prohibits the use of the code under varying repository conditions. Hansen et al. (1997) shows that lower permeabilities will have high pressure gradients through the waste, thus inducing more spall.

The code also showed sensitivity to gas viscosity. Viscosity, along with permeability and porosity are used to calculate an effective gas conductivity for the flow of gas through the repository upon an inadvertent human intrusion. It is reasonable to assume that viscosity will be higher than the ideal value for hydrogen at standard temperature and pressure. It will also be higher if other gas constituents are added to the repository. Yet, as viscosity increases to values that are reasonable and defensible, the code calculates a very high failed volume due to the cascading effect noticed from low permeabilities.

Lastly, a sensitivity of the mud column density showed that the code does not promote a strong confidence in the results obtained from GASOUT. The analysis varied the parameter over a range of expected values at the WIPP, and found the code to behave erratically to small changes in values. Figure 9.5. shows the results of the experiment, and demonstrates the problems associated with using a wide range of values. The figure represents a high initial pressure using several different waste strengths, which proves that the code can only work well under non-extreme conditions. The maximum reported spalled volume in Hansen et al. (1997) is only the maximum for a narrow set of repository conditions, and the code is shown to fail otherwise.

Hansen et al. (1997) claim conservatism in the approach to modeling the WIPP waste under a spall scenario. First, the waste form was considered homogeneous in GASOUT. Arguments

have been made to explain that homogeneity is very conservative, and heterogeneous waste will decrease spall. Yet it can be seen in the fully coupled numerical code that heterogeneity will increase the pressure gradient, and possibly the amount of spalled material. Hansen et al. (1997) show that inelastic behavior of the waste will increase tensile strength, and reduce the amount of waste failing in tension. However, inelastic behavior is attributed to saturated (wet) waste, which is ductile and will have a lower strength than dry waste. Dry waste forms will most likely be brittle, and will fail elastically. They also claim that tensile failure will induce fracturing within the waste, increasing the permeability of the cracked region, causing the system to stabilize more quickly. However, this too can be detrimental; the turbulent flow of gas will impose additional forces (e.g., drag forces) on the waste that may erode the waste and cause more spall. In short, the claimed conservatisms applied to the models for calculating the release of spalled material are actually simplifications, which are necessary in order to construct reasonable mathematical and numerical models; they are not conservative assumptions.

This analysis does not question these mathematical and numerical models used to design the GASOUT code; it addresses the working of the code itself. The code responds erratically to small changes in the input assumptions, and sometimes gives misleading results. It is suggested that the code be examined more closely, before judging the results of Hansen et al. (1997) as the maximum amount of failed material that will reach the surface, and the spalled volumes calculated in the CCA as reasonable.

10. SOLUBILITY MODELING ASSUMING NO MgO BACKFILL AND WITH THE MgO MINERAL PHASE OF NEQUEHONITE

10.1. Summary

A modeling study was conducted to accommodate DOE's reported observation that nesquehonite was the only identified observed product from the MgO-carbon dioxide study. The modeling study parallels the EPA requested PAVT calculations in that the magnesium compound was assumed to persist throughout the 10,000 year regulatory period. There is a difference, however, as the PAVT calculations recommended by the EPA assumed the presence of hydromagnesite, which was not observed in the DOE experiments. The study assumed the presence of nesquehonite, which was observed in the DOE experiments. Moreover, this study also calculated releases using the modeled solubilities in the case of no backfill.

As shown, these higher solubilities have a dramatic impact on the cumulative release of radionuclides to the accessible environment for the 10,000 year period. Assuming the results of the FMT calculations for solubility are correct, the calculated release for a system without backfill or a system with backfill induced nesquehonite is very close to the EPA containment requirement. While these calculations, based on DOE's own solubility values, do not violate the containment requirements, they also show that there is little margin for error.

10.2. Introduction

Chapter 5 explained EEG's concern's about assuming the oxidation of plutonium to states III and IV. To determine the sensitivity of the release calculations to solubility, the solubility was increased, assuming all plutonium was in oxidation state V. The results showed that as solubility increased, the releases increased, but was limited by the amount of brine in the repository. This chapter further investigates the relevance and consequence of brucite speciation to magnesite and its effects on solubility.

The idea of adding MgO as backfill around the waste in the WIPP repository began shortly before the CCA was issued to the EPA, and consequently no analysis was performed in the Baseline Inventory Report (U.S. DOE 1996-Appendix BIR). In response, the DOE Peer Review Committee had to reconvene several times to be convinced of its effects, with the main issue being the effectiveness of $Mg(OH)_2$ to react with CO_2 to act as a buffer to increase to pH of the brine and reduce the fCO_2 for reaction with the brine. Experiments had not been performed by the time of application submittal, and it was unclear how effective the backfill would be.

It was anticipated that large quantities of CO_2 would be generated in the repository (U.S. DOE 1996-Appendix Peer 1). The CO_2 would react with the brine, forming carbonic acid. The acid would decrease the pH of the Salado brine from 9.4 to approximately 4-5. Under acidic conditions (pH lower than 4), the solubility of actinides could increase by 5 orders of magnitude in brine, causing problems in the inadvertent human intrusion scenario. The higher solubilities would allow a higher mass of actinides to go into solution, and hence higher releases to the accessible environment upon breech. The original intent of the MgO was to maintain a high brine pH.

The concern was not the chemical reaction pathway however, it was the effectiveness of the design in the placement of the MgO around the waste to allow reaction with the large amounts of CO_2. The DOE needed to perform experiments to demonstrate the effectiveness of MgO in increasing the pH and reducing the fCO_2. The results were presented to the Third Supplemental Peer Review on April 25, 1997. It was the intention of that Peer Review for DOE to prove that the MgO will act quickly and completely with the CO_2 to reduce carbonate ligands from solution and to decrease gas pressures and rate of gas pressurization by the removal of CO_2. The subsequent report (Papenguth et al. 1997) showed the results of the experimentation, which were used for modeling data in the FMT code to establish solubilities for the various actinides under those chemical conditions (Novak 1997).

Recently, several issues were brought to light about the inherent problems and conclusions of that study (Neill et al. 1998). First, it was assumed that by 1000 years after the formation of CO_2, that the precipitates from the reactions would form magnesite. This conclusion was extrapolated (linearly) from literature data at different temperatures. Yet, the extrapolation seemed to be a poor justification that the reaction would go to completion (to magnesite) within the time frame of the WIPP projected history. If the extrapolation were assumed to be another function, then the time could extend to the order of 10^5 - 10^6 years. Secondly, the intermediate phases between brucite ($Mg(OH)_2$) and magnesite ($MgCO_3$) were unclearly defined in their function, length of time, and composition. It was concluded that nesquehonite ($MgCO_3 \bullet 3H_2O$) would exist for a very short time before going to hydromagnesite [$(MgCO_3)_4 \bullet Mg(OH)_2 \bullet 4H_2O$]. Yet, hydromagnesite was never positively identified, and a mineral species, that was noted to be hydromagnesite-like, existed instead. The composition [$MgCO_3 \bullet 3H_2O \bullet MgCl(OH)$] looked closer to nesquehonite than hydromagnesite.

Lastly, the results from FMT were questioned for solubilities of actinides in the presence of the various mineral species and the use of the oxidation state analogy for actinides in the same

oxidation state. For example, the concentration of $Th(SO_4)_2$ in Castile ERDA-6 brine was $1.35x10^{-5}$ mol/kg. When Mg^{++} was added to the solution, to increase it from 0.021 to 0.039 mol/kg, the concentration of $Th(SO_4)_2$ reduced to $9x10^{-22}$ mol/kg. Nothing in the chemistry of the brine would contribute to such a large discrepancy in the values given for thorium sulfate.

Though sulfate complexes were assumed to be minor, the same problems were carried over to the carbonate species of thorium. Thorium is an important consideration in these experiments, because by the oxidation state analogy thorium was used to establish all IV actinides (Pu, U, and Th). It was seen that the errors of one actinide carried through to the other major actinides.

Novak (1997) provided projected actinide solubilities in the presence of nesquehonite and also without the presence of MgO backfill (no backfill), in addition to magnesite and hydromagnesite values. Due to the uncertainties associated in the model and laboratory experiments, it was decided to use these higher solubilities from species that were not considered in either the CCA or the EPA's verification calculations, called the Performance Assessment Verification Test (PAVT), in a new set of calculations using PANEL and NUTS. The results were then used to compare the CCDFs from the CCA (DOE) and PAVT (EPA) to acquire a better understanding of long-term performance.

The median model solubility values used for the CCA, PAVT, and for other species of brucite-magnesite complexes can be seen in Table 10.1. (reproduced from Novak 1997). The CCA used magnesite as the interactive species and the PAVT used hydromagnesite. Neither used nesquehonite, the only identified observed species. Hence, nesquehonite and No Backfill solubilities are used here. One outstanding feature of Table 10.1. is the difference in solubility of +4 actinides in Castile brine between No Backfill and nesquehonite. The experimental model values show that the +4 state is more soluble in the presence of nesquehonite than without any addition of MgO.

10.3. Methodology

In the CCA, the model (median) values from FMT were given an uncertainty range of -2 and

Brine Type	Salado				Castile			
Condition	+3 (M)	+4 (M)	+5 (M)	+6 (M)	+3 (M)	+4 (M)	+5 (M)	+6 (M)
magnesite (CCA)	5.8e-7	4.4e-6	2.3e-6	8.7e-6	6.5e-8	6.0e-9	2.2e-6	8.7e-6
No Backfill	4.0e-3	5.0e-4	2.0e-4	8.0e-5	2.0e-3	7.0e-5	6.0e-4	8.0e-5
hydromagnesite (PAVT)	9.4e-8	1.2e-8	1.2e-7	8.7e-6	1.3e-8	4.1e-8	4.6e-7	8.7e-7
nesquehonite	3.2e-7	6.3e-4	1.2e-7	8.7e-6	2.1e-6	1.0e-3	7.8e-7	8.7e-6

Table 10.1. Median Solubility Values Used in Various Performance Assessment Calculations

	nesquehonite		No Backfill	
	SOLCIM	SOLSIM	SOLCIM	SOLSIM
SOLAM3	1.51616	-.27709	4.48678	3.83714
SOLPU3	1.51616	-.27709	4.48678	3.83714
SOLPU4	5.23242	2.15588	4.06695	2.05552
SOLU4	N/A	2.15588	N/A	2.05552
SOLU6	0.95861	0.96357	0.95861	0.96357
SOLTH4	5.23242	2.15588	4.06695	2.05552

Table 10.2. Solubility Factors for SOLCIM and SOLSIM

+1.4 orders of magnitude. Incidentally, the 1992 PA (Sandia 1992) had many of the parameter ranges of the actinides span 13 orders of magnitude to capture the uncertainty. The range in the CCA was given a constructed distribution, where the majority of the values (59%) fell -1.0 and 0.0 orders of magnitude from the values of Table 10.1. For the present study, the ranges have been eliminated, with each realization having the same constant value.

Running the new values for solubility of various actinides began at the Source Term files. These files contained the multiplication factors from which the median values would be modified. For example, the solubility of ^{241}Am in Castile brine was given a range, as explained above. This range was sampled in LHS, and a number was identified in each realization (vector). If the

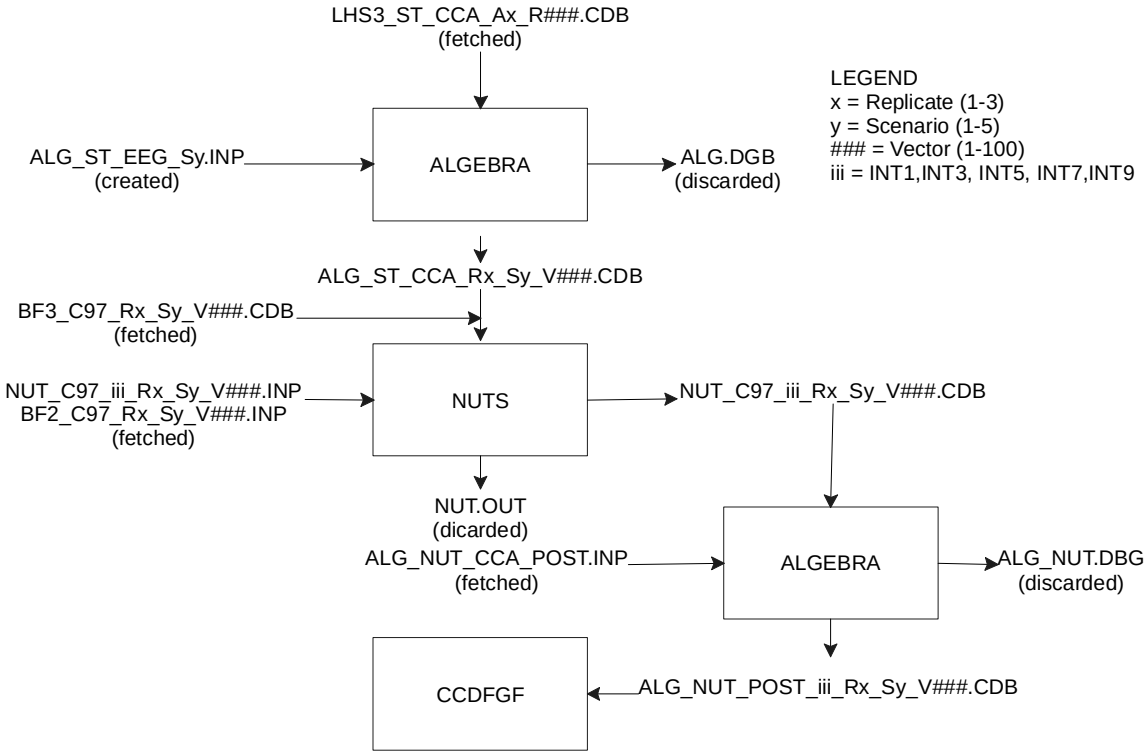

Figure 10.1. Flowchart for NUTS Time Intrusion Calculations

sampled value in LHS was -1.0, then the median value was multiplied by $10^{-1.0}$. In the transport experiments of this study, these values were replaced by the values in Table 10.2. for every realization. The parameter names are retained from CCA nomenclature.

After modifying the Source Term files, PANEL and NUTS were run with the new files. For this study, the BRAGFLO files from the PAVT study were used, since this would give the maximum effect for the changes. The PAVT, compared to the CCA, calculated much higher releases to the surface due to the higher pressures in the repository.

The flowchart of PANEL execution can be seen in Figure 5.1., and the flowchart for NUTS execution can be seen in Figure 10.1. The flow chart only represents one set of NUTS calculations, but represents the processes of all three sets. These sets include SRC, ISO, and INT calculations, and are further explained in Chapter 2. Figure 10.1. shows the detailed steps involved in running the INT (Time Intrusion) calculations.

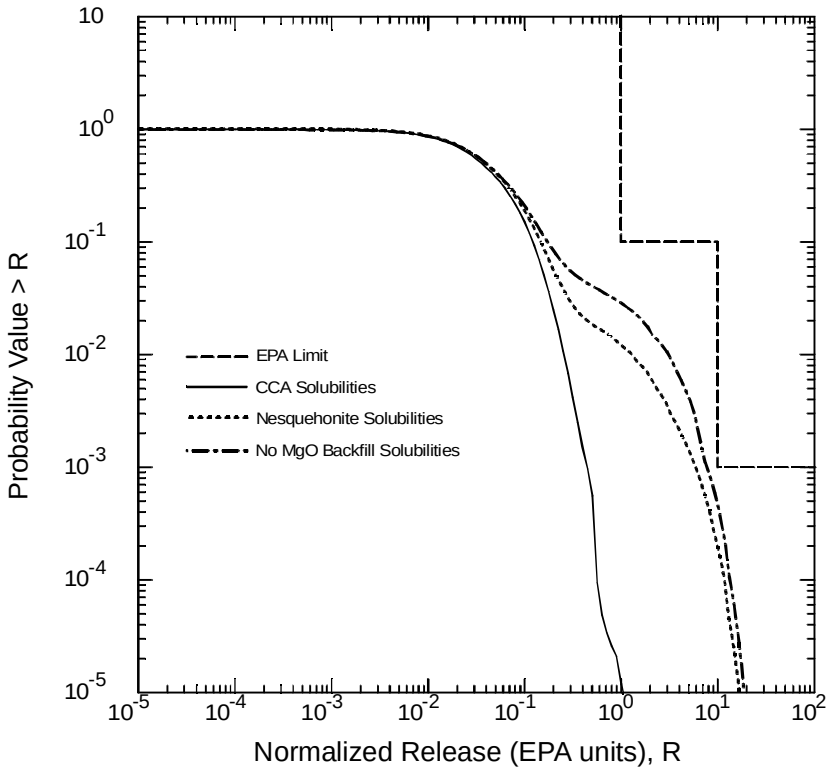

Figure 10.2. Overall Mean of Normalized Releases for Modeling of Increased Solubilities Using Nesquehonite and 'No Backfill' Values Compared to CCA Values

10.4. Results

The results of running the new set of solubility calculations can be seen in Figure 10.2. The figure shows the overall mean from all combined release mechanisms for No Backfill and nesquehonite solubilities from Table 10.1. In addition, the PAVT direct brine releases were combined with the CCA solubilities from CCA NUTS calculations to give another perspective of calculated solubility values. The curves show that neither release scenarios cross the EPA compliance standard, indicating that even the highest reported solubilities do not violate these standards, with all other parameters remaining the same.

The effects of increasing the solubility values for the new calculations show a substantial increase below the 10^{-1} probability. The increase, in the form of a shoulder, is attributed to the increased effect of the direct brine release mechanism. Figure 10.3. shows the breakdown of all mechanisms to form the total release. The figure presents each mechanism as the overall mean from all realizations of one replicate from the nesquehonite solubility calculation. Clearly, the direct brine release calculations stand out as the largest mechanism for release at the 10^{-3} probability.

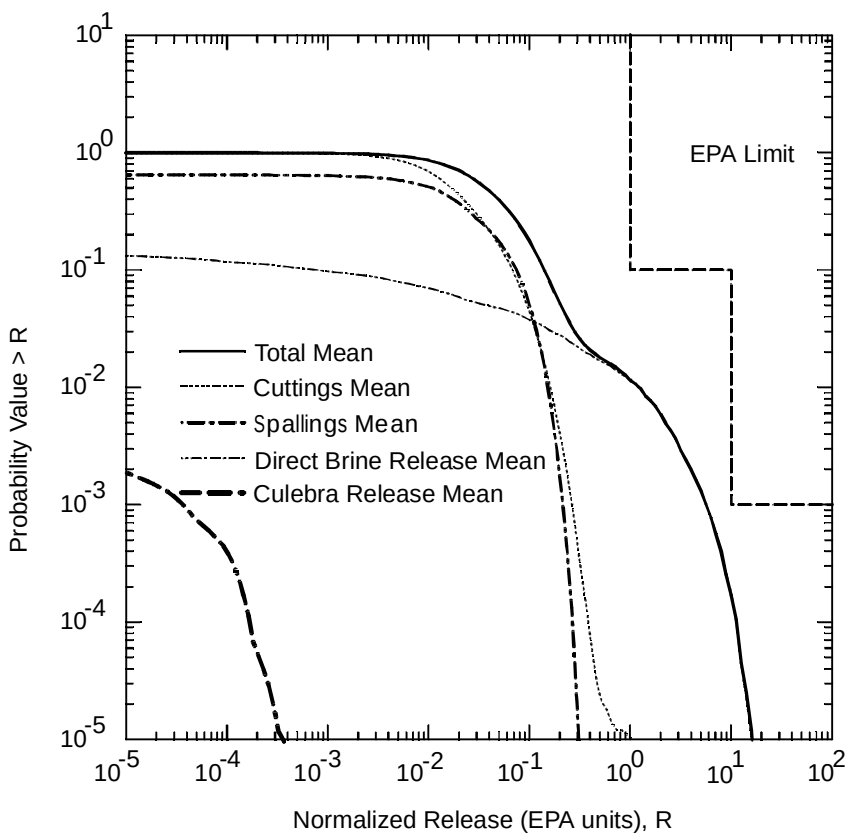

Figure 10.3. Overall Mean from all Release Mechanisms for Solubility Modeling With Nesquehonite

In addition to the results of the PAVT, the solubility modeling of nesquehonite and No Backfill was combined with other chapters of this report, namely the Culebra Transport Modeling, to assess the effects of higher initial masses injected into the Culebra. Conclusions from previous chapters stated the limitation of the Culebra releases due to the amount that would initially reach the Culebra from transport out of the repository. The combination from previous results with the present study was a simple task, since all mechanisms are calculated separately and combined in the end through the code CCDFGF.

Figure 10.4. shows the Culebra releases from Chapters 6 and 8 with the nesquehonite solubilities of Chapter 10. The conclusions of the two earlier chapters that the releases are mass limited is verified here. If the initial amount of mass that reaches the Culebra are increased, such as with increased solubility, then the effect will be quite strong on the Culebra releases, as seen by the increases in releases in the CCDF curves of plutonium at 1% K_d=0 ml/g. However, in itself, solubility has little effect, and must be coupled with large fractional discharges calculated with 1% K_d=0. This can be seen when comparing the two curves in Figure 10.4., which come from the Chapter 8 analysis on increased mining. The uranium releases are very small and the

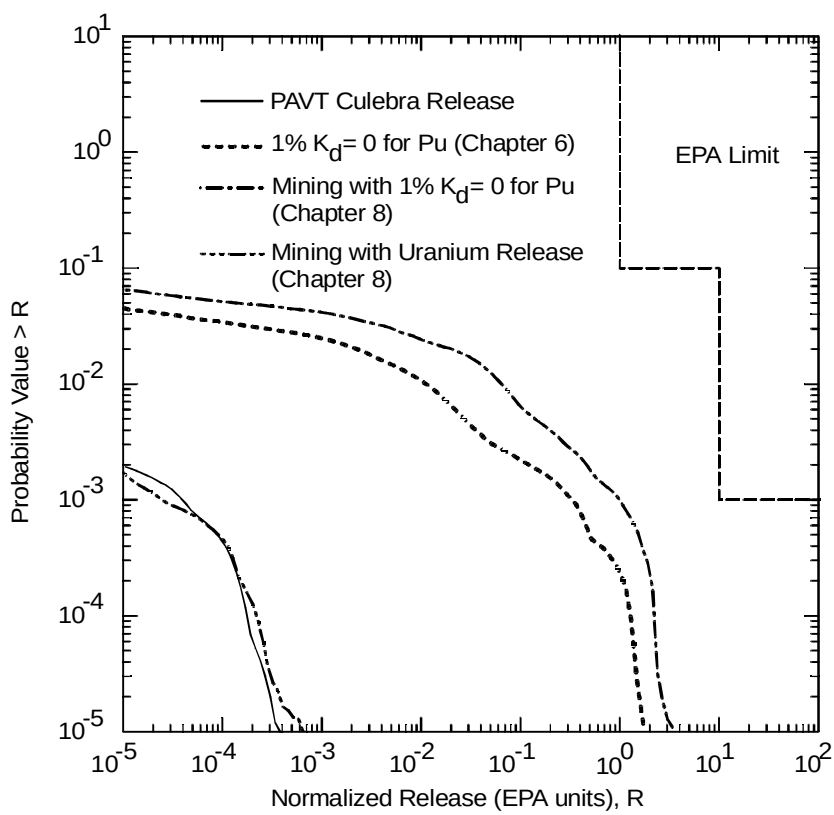

Figure 10.4. Nesquehonite Solubility Calculations Combined with Culebra Transport Calculations from Chapters 6 and 8

plutonium releases are quite large, even though both have an increase in initial mass. It is clear then that high solubilities and low K_ds will cause quite a threat to the integrity of the disposal system.

10.5. Conclusions

A modeling study has been presented in which the solubilities of actinides from the CCA and PAVT are questioned. New values are presented in Table 10.1. with the assumption of the persistence of an intermediate phase between brucite and magnesite to exist for the entire 10,000 year proposed history of the WIPP repository. The modeling of the intermediate phase, nesquehonite, is much like the modeling of the PAVT, in which hydromagnesite was assumed to persist throughout the 10,000 years. In addition, No MgO Backfill model solubilities were studied.

The consequence of higher solubilities, as seen in Figure 10.2. are quite high. The overall mean release for the CCA and PAVT were 0.2 and 0.4 EPA Units at 10^{-3} probability, respectively. The overall mean for the increased solubilities of nesquehonite and 'No Backfill' are 6.0 and 8.0 EPA Units at the 10^{-3} probability, respectively. The limit for compliance, according to 40 CFR Part 194 is 10 EPA Units. Therefore, it readily appears that even high solubility values do not cause the disposal to be out of compliance with EPA regulations. However, the large consequences of small changes of solubility values raises an important question: Are we certain that the solubility of plutonium or uranium, in any oxidation state, is less than the values presented in the CCA or the PAVT? How did we arrive at these numbers? Is there experimental evidence to back up the claims made in the CCA that deals with the oxidation state analogy between Am+3 and Pu+3? Once one really delves into the reasoning behind many of the fixed numbers associated with these actinides, many drawbacks appear in the reasoning, and confidence in the values used to show compliance is shaken.

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Acronyms

AIC	Active Institutional Control
BLM	Bureau of Land Management
CCA	Compliance Certification Application
CCDF	Complementary Cumulative Distribution Functions
CH	Contact Handled
DBR	Direct Brine Release
DOE	U.S. Department of Energy
DRZ	Disturbed Rock Zone
EEG	Environmental Evaluation Group
EPA	U.S. Environmental Protection Agency
ERDA	Energy Resource and Development Administration
FBHP	Flowing Bottomhole Pressure
FEP	Features, Events, Processes
LHS	Latin Hypercube Sampling
LWB	Land Withdrawal Boundary
NMBMMR	New Mexico Bureau of Mines and Mineral Resources
PA	Performance Assessment
PAVT	Performance Assessment Verification Test
PIC	Passive Institutional Control
PSI	Pounds per Square Inch
RH	Remote Handled
SAR	Safety Analysis Report
STP	Standard Temperature and Pressure
TRU	Transuranic Waste
TVD	Total Variation Diminishing
WIPP	Waste Isolation Pilot Plant

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EVALUATION OF RISKS AND WASTE CHARACTERIZATION REQUIREMENTS FOR THE TRANSURANIC WASTE EMPLACED IN WIPP DURING 1999

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EEG-75
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EVALUATION OF RISKS AND WASTE CHARACTERIZATION REQUIREMENTS FOR THE TRANSURANIC WASTE EMPLACED IN WIPP DURING 1999

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U. S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the compliance of the generator sites with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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ACRONYMS

ADF	Air Dispersion Factor
AK	Acceptable Knowledge
amu	Atomic Mass Unit
ASTM	American Society for Testing and Materials
CAMs	Continuous Air Monitors
CAO	Carlsbad Area Office
CARs	Corrective Action Reports
cfm	Cubic feet per minute
CFRs	Code of Federal Regulations
DCF	Dose Conversion Factor
DOE	U. S. Department of Energy
DQOs	Data Quality Objectives
ECS	Exhaust Shaft Concentration
EEG	Environmental Evaluation Group
EPA	U. S. Environmental Protection Agency
GC/ECD	Gas Chromatography/Electron Capture Detection
GC/FID	Gas Chromatography/Flame Ionization Detection
GC/MS	Gas Chromatography/Mass Spectroscopy
HQ	Hazard Quotient
HI	Hazard Index
HSG	Head Space Gas
HWA	New Mexico Hazardous Waste Act
HWDU	Hazardous Waste Disposal Unit
ICP-MS	Inductively Coupled Plasma - Mass Spectroscopy
INEEL	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
MDC	Minimum Detectable Concentration
MIR	Maximum Individual Receptor
MRL	Method Reporting Limit

NMAC	New Mexico Administrative Codes
NMED	New Mexico Environment Department
PDP	Performance Demonstration Program
ppbv	Parts per billion by volume
PRQL	Program Required Quantitation Limit
QAOs	Quality Assurance Objectives
QAPD	Quality Assurance Program Document
QAPjP	Quality Assurance Project Plan
QAPP	Quality Assurance Program Plan
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
RDF	Risk to Dose Factor
RFETS	Rocky Flats Environmental Technology Site
RPD	Relative Percent Difference
RSD	Relative Standard Deviation
RRF	Average Response Factor
RTR	Real-time Radiography
SAR	Safety Analysis Report
SPCCs	System Performance Check Compounds
SVOC	Semi-volatile Organic Compound
SWB	Standard waste box
TRU	Transuranic
UCL_{90}	90% Upper Confidence Level
UG	Underground
VE	Visual Examination
VOC	Volatile Organic Compound
WAC	Waste Acceptance Criteria
WAP	Waste Analysis Plan
WID	Waste Isolation Division
WIPP	Waste Isolation Pilot Plant
WWIS	WIPP Waste Information System

EXECUTIVE SUMMARY

The U. S. Department of Energy's (DOE) Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, has been constructed for the disposal of long-lived transuranic (TRU) waste. The New Mexico Environment Department (NMED) issued a Hazardous Waste Facility Permit (the Permit) to dispose of mixed waste at WIPP effective November 26, 1999. This Permit does not regulate the radioactivity in the waste. The DOE emplaced 44 shipments of non-mixed transuranic waste in Room 7 of Panel 1 before the Permit became effective. There also are a large number of waste containers at the generating sites that have been at least partially characterized prior to the effective date of the Permit.

Section IV.B.2.b of the NMED Permit contained language which appeared to prohibit emplacement of non-mixed wastes that were not characterized in accordance with the requirements of the Permit's Waste Analysis Plan (WAP). The justification for adding Section IV.B.2.b was that mixing WAP-certified wastes with pre-Permit wastes created unknown risks that should not be a part of Permit performance standards. Statements were made during Permit public hearings and in written testimony that the risks might be substantial but there was no indication of the nature of these risks or their magnitude.

This report provides a technical evaluation, conclusions, and recommendations of the following Section IV.B.2.b issues:

1. A comparison of pertinent WAP requirements with pre-Permit waste characterization;

2. A risk analysis of the pre-Permit waste emplaced in Room 7. Expected and bounding risks from routine operations and possible accidents are evaluated.

Conclusions:

1. The NMED approved WAP has made explicit many of the undocumented assumptions and implied good practices from the DOE's pre-Permit waste characterization program. Although there are differences between the pre-Permit and WAP characterization programs, the pre-Permit program appears to substantially meet the technical requirements in the WAP.

2. Deviations granted by DOE during pre-Permit waste characterization and premature closures of some corrective actions generated during independent audits may be the most significant differences from the Permit waste characterization requirements.

3. Estimated carcinogenic risks to an underground worker, a surface worker, and a member of the public due to routine operations from all the TRU wastes emplaced in Room 7 in 1999 are six to eight orders of magnitude less than risk levels allowed by the Permit. Non-carcinogenic risks are seven to ten orders of magnitude below allowed risks.

4. Even if VOC emissions are much higher than risk calculations estimate, the Confirmatory VOC Monitoring Plan in use at WIPP would detect concentrations that are three orders of magnitude below allowable Permit limits.

5. Risks to the surface worker and member of the public from low probability accidents are essentially all from radionuclide releases and are lower than the allowable Permit risks from routine VOC releases. Risk to the underground worker is significant (1.7×10^{-3} if the accident occurs).

Recommendations:

Questionable data for the individual container lots of pre-Permit waste could be reviewed by NMED for conformance with the WAP requirements if necessary. This determination should consider all deviations and include input from the DOE.

The calculated non-accidental risks from the pre-Permit waste in Room 7 are too low to justify any remedial or other actions involving these wastes.

Radionuclide risks to underground workers from low probability spontaneous fire and roof fall accidents should be considered when setting restrictions on worker access to the south 1600 and east 300 drifts.

1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Project is located in southeastern New Mexico (see Figure 1-1). WIPP has been constructed by the U.S. Department of Energy (DOE) to provide permanent disposal of long-lived transuranic (TRU) waste from the U. S. defense activities and programs.

Approximately 60% of the wastes to be disposed at WIPP is believed to be "mixed wastes"--wastes containing not only transuranic radionuclides but also hazardous materials regulated under the federal Resource Conservation and Recovery Act (RCRA). Regulation of WIPP under RCRA has been delegated by the U. S. Environmental Protection Agency (EPA) to the New Mexico Environment Department (NMED), acting under the New Mexico Hazardous Waste Act (HWA). In October 1999 NMED granted a Hazardous Waste Facility Permit (the Permit) to WIPP that became effective on November 26, 1999 (NMED 1999b). This Permit regulates the management, storage, and disposal of only the hazardous waste components of the contact-handled transuranic mixed waste at WIPP. The Permit also requires that waste brought to the WIPP meet waste characterization requirements found in the Waste Analysis Plan (WAP), a series of appendices to the Permit (the "B" appendices).

During the eight months prior to the promulgation of the Permit, the DOE disposed of 44 shipments of TRU (non-mixed) waste in Panel 1, Room 7, of the WIPP. This waste consisted of 101 standard waste boxes (SWBs) containing heat-source waste, 152 55-gallon drums of graphite waste, and 574 55-gallon drums of residues in pipe containers. These waste containers were characterized in a manner similar to, but not identical with, the Permit requirements contained in the WAP. The difference between the pre-Permit waste characterization program and the WAP requirements is of great importance due to Section IV.B.2.b of the Permit, as described in the next section.

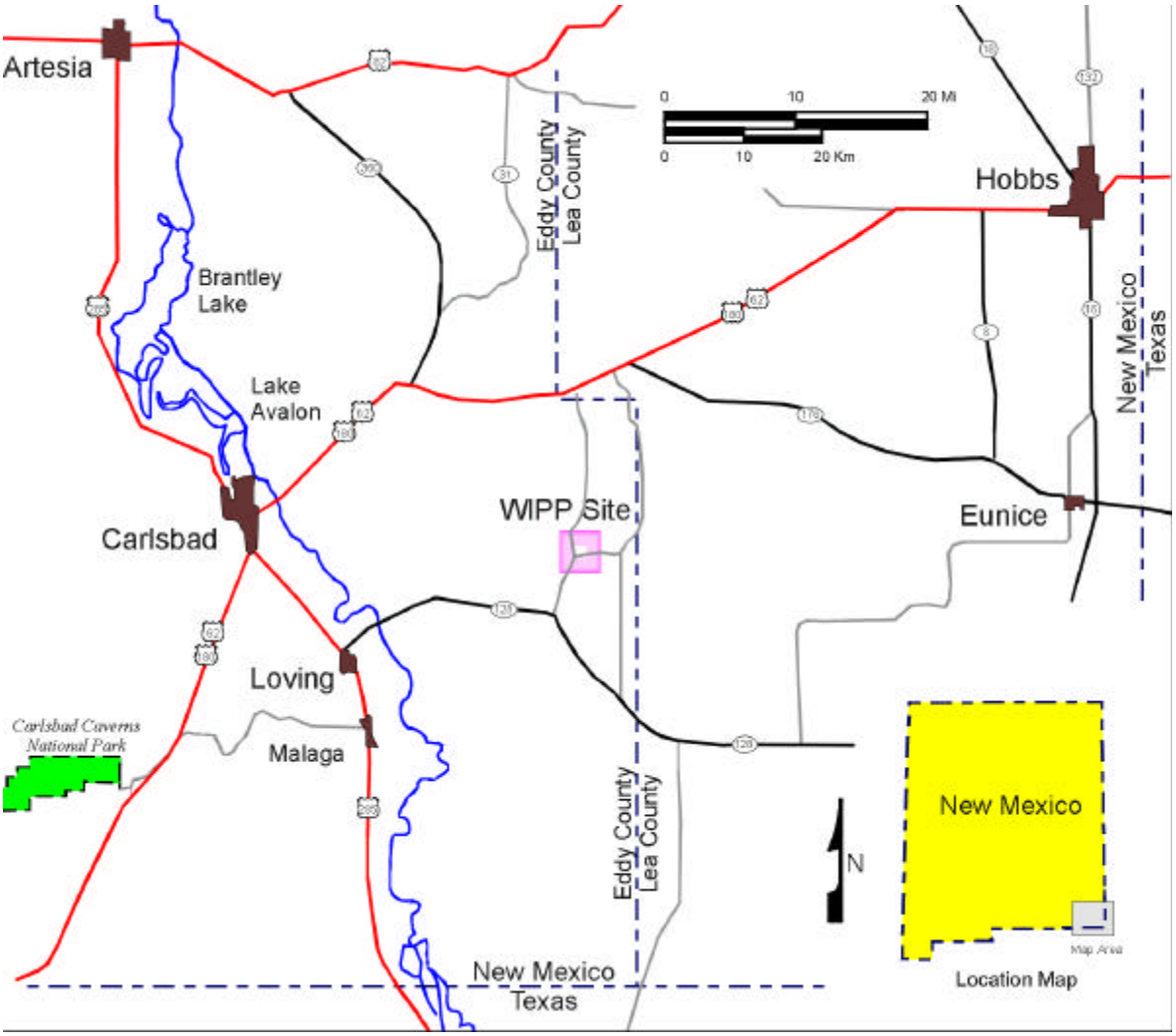

Figure 1-1. WIPP Site Location in Southeastern New Mexico

1.1 The IV.B.2.b Requirement

Section IV.B.2.b of the Permit contains the following statement:

> Specific prohibition -- After this permit becomes effective, (1) the Permittees shall not dispose non-mixed TRU waste in any underground HWDU unless such waste is characterized in accordance with the requirements of the WAP specified in permit Condition II. C.1 , and (2) the Permittees shall not dispose TRU mixed waste in any underground HWDU if the underground HWDU contains non-mixed TRU waste not characterized in accordance with the requirements of the WAP.

A WIPP underground hazardous waste disposal unit (HWDU) is a single waste disposal panel of seven rooms. There was considerable testimony about the pros and cons of Section IV.B.2.b requirements during public hearings and written testimony on the Permit. The justification for adding the requirement was that mixing WAP-certified wastes with pre-Permit characterized wastes created unknown risks that should not be a part of the RCRA performance standards of the repository. While some testimony indicated that these risks might be substantial, no one identified what these risks were or their possible magnitude.

The IV.B.2.b requirement poses two potential problems for the WIPP. A prohibition against adding of wastes certified under the WAP to the wastes already emplaced in Room 7 of Panel 1 could mean that Panel 1, which was designed to dispose of about 81,000 drum-equivalents of waste, would be limited to only the 1,400 drum-equivalents of pre-Permit waste already emplaced. The abandonment of the rest of Panel 1 could reduce the design capacity of WIPP by about 10%, and would delay emplacement of any more waste until mining of Panel 2 is completed (currently scheduled for October 1, 2000). Such a delay could have significant impact not only on operations at the WIPP but at the DOE's TRU-waste generating sites as well.

A second problem from Section IV.B.2.b depends on whether pre-Permit characterization of wastes is determined to have been "characterized in accordance with the requirements of the WAP." In the pre-Permit waste characterization program, sites could begin characterizing waste for shipment to the WIPP as soon as the site Quality Assurance Project Plan (QAPjP) was

deemed acceptable by the Carlsbad Area Office (CAO). Waste generator sites have been characterizing both mixed and non-mixed wastes for years under the pre-Permit waste certification requirements.

1.2 Scope of this Report

Both of the IV.B.2.b problems described in Section 1.1 are obviously controlled by the determination of whether pre-Permit wastes were " ...characterized in accordance with the requirements of the WAP." This report presents a technical evaluation of considerations related to the IV.B.2.b issues described in Section 1.1. No evaluation was made of legal or regulatory aspects of Section IV.B.2.b.

Specifically the Report:

1. Compares requirements of the WAP that are pertinent from a technical viewpoint with the WIPP pre-Permit waste characterization program;

2. Presents the results of a risk analysis of the currently emplaced wastes. Expected and bounding risks from routine operations and possible accidents are evaluated; and

3. Provides conclusions and recommendations.

2. COMPARISON OF WAP TO WIPP PRE-PERMIT WASTE CHARACTERIZATION REQUIREMENTS

2.1 Introduction

This chapter focuses on the most pertinent requirements of the WAP from a technical viewpoint, and compares them to the requirements of the WIPP waste characterization program in operation to process pre-Permit wastes. Where possible, an evaluation of the impact of any differences is then expressed.

The DOE's TRU waste characterization program during the pre-Permit waste characterization period was governed principally by the Transuranic Waste Characterization Quality Assurance Program Plan (QAPP), Revision 0, with interim changes of February 1996 and November 15, 1996 (US DOE 1996d). Accordingly, the WAP requirements will be primarily compared to statements in US DOE 1996d. Other DOE documents that may be cited will be referenced in the text.

The CAO has granted variances from QAPP requirements during the pre-Permit period, labeling these variances at various times as equivalencies, clarifications, and guidances. A formal process for granting these variances has not been published and EEG probably does not have documentation for all the changes granted. While these variances were granted to individual waste characterization sites, they could apparently be used for characterization at the other sites also. Since these variances also affect the comparison of the pre-Permit program to the WAP requirements, any variances that the EEG is aware of are also included in this analysis.

It is worth noting that there were effectively no changes in the WIPP waste characterization quality assurance program from the pre-Permit to the post-Permit period. While the QAPP was cancelled as a part of the move to comply with the Permit, the quality assurance program elements in it were moved to the CAO Quality Assurance Program Document (QAPD),

Revision 3 (US DOE 1999f), which governs generator site waste characterization quality assurance programs.

2.1.1 Pre-Permit Waste Streams

The pre-Permit non-mixed wastes emplaced in the WIPP are from four different waste streams. Graphite mold waste streams from Rocky Flats Environmental Technology Site (RFETS) and Idaho National Engineering and Environmental Laboratory (INEEL) are divided into separate waste streams (RF 003.01 and IN W276.001). These two waste streams were apparently both created at RFETS from the same process. The other waste streams are a ^{238}Pu debris waste stream from Los Alamos National Laboratory (LANL) (TA-55-43.01) and the pyrochemical salt waste stream from RFETS (RF 005.001). Other waste streams accepted by the CAO that may have been characterized during the pre-Permit period include IN-W276.02, RF001.1, RF 002.01, and RF 004.01. Since submission of waste stream designations to the CAO during the pre-Permit period was not required before waste container characterization could begin,[1] it is likely that containers from other waste streams were also characterized.

2.1.2 Data Quality Objectives (DQOs) and Quality Assurance Objectives (QAOs)

The WAP contains approximately 1500 individual statements that could be considered requirements, though a number of them are essentially duplicative. For example, there are multiple statements of the requirement that visual examination must be used to verify a statistically determined portion of radiographic results. The core requirements, however, are the data quality objectives (DQOs), which specify the waste characterization data necessary to meet the RCRA and HWA requirements.

[1]During the pre-Permit period, characterization of waste could begin on acceptance by the CAO of the generator site's waste characterization program documents. Characterization requirements were based on the summary category group (debris, homogeneous solids, or soil/gravel) assigned to each waste container.

The WAP establishes specific data quality objectives in Section B-4a(1). In order to have confidence that the data reported meets the DQOs, various quality assurance objectives (QAOs) are also established in the WAP (Appendix B3, Sections B3-2 through B3-9). If these DQOs and QAOs can be shown to have been met, then the sampling and analysis portions of the characterization could be considered complete (though reviews of these data may still be in question). As a subset of the complete requirements, the DQOs and QAOs would provide a sample of the kinds of problems the pre-Permit waste characterization program would have in demonstrating compliance with WAP requirements.

2.2 WAP DQOs

Section B-4a(1) of the draft WAP, entitled Data Quality Objectives, states that the following DQOs are established to satisfy the RCRA regulatory compliance requirements (pp. B-18 and B-19)[2]:

- Headspace-Gas Sampling and Analysis
  - To identify VOCs and quantify the concentrations of VOC constituents in the total waste inventory to ensure compliance with the environmental performance standards of 20 NMAC 4.1.500 (incorporating 40 CFR, §264.601(b)), and to confirm hazardous waste identification by acceptable knowledge.
- Homogeneous Waste Sampling and Analysis
  - To compare UCL_{90} values for the mean measured contaminant concentrations in a waste stream with specified toxicity characteristic levels in 20 NMAC 4.1.200 (incorporating 40 CFR §261), to determine if the waste is hazardous, and to confirm hazardous waste identification by acceptable knowledge.
  - To report the average concentration of hazardous constituents in a waste stream, as specified in 20 NMAC 2.1.200 (incorporating 40 CFR

[2]VOCs are Volatile Organic Compounds; UCL_{90} is the 90% Upper Confidence Level (see Section B2-3 of the WAP for the formula); NMAC are the New Mexico Administrative Codes, the state analog of the Code of Federal Regulations (CFRs); PRQL is the Program Required Quantitation Limit.

§261) Appendix VIII, with a 90 percent confidence interval, with all averages greater than PRQL considered a detection and subsequent assignment of the waste (if an adequate explanation for the constituent cannot be determined) as a hazardous waste, and to confirm hazardous waste identification by acceptable knowledge.

- Radiography
  - To verify the TRU mixed waste streams by Waste Matrix Code for purposes of physical waste form identification and determination of sampling and analytical requirements, to identify prohibited items, and to confirm the waste stream delineation by acceptable knowledge.
- Visual Examination
  - To verify the TRU mixed waste streams by Waste Matrix Code for purposes of physical waste form identification, determination of sampling and analytical requirements, and to identify prohibited items.
  - To provide a process check on a sample basis by verifying the information determined by radiography, and to confirm the waste stream delineation by acceptable knowledge.

The wording of these WAP DQOs is significantly different than those found in the QAPP (Section 1.5, pp. 1-31 and 1-32), but for the most part the WAP DQOs are reflected as requirements found elsewhere in the QAPP, as described below.

2.2.1 DQOs Related to Confirmation of Acceptable Knowledge

Several of the above DQOs establish a need to confirm acceptable knowledge information; in the QAPP, this requirement is found in several places, and a single statement in QAPP Section 4.2.2 covers the bulk of the WAP DQOs (p. 4-6):

> Waste characterization (i.e., radiography, headspace gas sampling and analysis, and solidified waste sampling and analysis) will be used to confirm acceptable knowledge information. Figure 4-2 illustrates the process sites will use to confirm acceptable knowledge.

The QAPP Figure 4.2 (p. 4-7) is a flow chart showing what comparisons are to be made, and the basis for either success or failure of the comparison. The terminology used above needs some interpretation: "Solidified waste sampling and analysis" as used in the QAPP is the equivalent to the WAP's "homogeneous waste sampling and analysis"; and visual examination (VE) is considered in the QAPP as an adjunct to radiography. Section 4.2.2.1 of the QAPP more clearly establishes the requirement for VE and radiography to confirm acceptable knowledge (p. 4-6):

> Radiography or visual examination must be used to confirm the matrix parameter category and waste material parameters identified using acceptable knowledge.

Other DQO requirements need to be addressed individually. Each DQO listed in Section 2.2 above is addressed in the following sections.

2.2.2 WAP Headspace Gas DQO

The WAP headspace gas DQO is for identification and quantification of VOC constituents in the waste to ensure compliance with the environmental performance standards of 20 NMAC 4.1.500, "incorporating 40 CFR, §264.601(b)." Section 40 CFR 264.601(b) is a list of considerations that must be taken into account concerning migration of wastes from a HWDU. The 40 CFR 264.601(b) reference in the WAP may be an error, as subparagraph (b) is more applicable to solid and liquid wastes ("migration of waste constituents in surface water, or wetlands or on the soil") rather than VOCs. Subparagraph (c), which covers "migration of waste constituents in the air" would seem to be the more pertinent citation. In any case, meeting this DQO is clearly a function of meeting the QAOs for headspace gas, as described in Section 2.3 below.

2.2.3 WAP Homogeneous Waste Sampling and Analysis DQOs

The DQO for comparing UCL_{90} values for the mean concentrations in each homogeneous waste stream with the 40 CFR 261 toxicity values is also a DQO in the QAPP (Section 1.5, p. 1-32). The DQO for reporting average waste stream concentrations of the 40 CFR 261 Appendix VIII

hazardous wastes with a 90% confidence for all averages greater than the PRQL is briefly described in the QAPP in Section 1.4 (pp. 1-29 and 1-30):

> TRU waste classified as homogenous solids and soil/gravel must be statistically sampled and analyzed for the constituents listed in Table 1-3 as VOCs, SVOCs, and metals. The mean concentration of hazardous constituents (40 CFR Part 261, Appendix VIII) must also be calculated by waste stream and then reported to CAO with an upper 90-percent confidence limit (UCL_{90}) as described in Section 3.3 of this QAPP.

Section 4.2.2.2 of the QAPP adds the requirement that averages greater than the PRQL must be re-evaluated. However, this requirement applies only to spent solvents, rather than all of the Appendix VIII listing (p. 4-8):

> Sites must confirm the assignment of spent solvent EPA hazardous waste numbers (40 CFR §261.31) by evaluating the mean concentrations of each VOC detected in container headspace gas and/or solidified waste matrix. The UCL_{90} for the mean constituent concentration must be compared to the PRQL for the constituent.

Appendix VIII contains hazardous materials that are not spent solvents but will still be in WIPP wastes. For example, lead, which will likely be the most prevalent hazardous material disposed of in the WIPP repository, is listed in Appendix VIII. The WAP DQO for reporting of Appendix VIII wastes in quantities greater than the PRQL does not appear to be completely met in a clear manner for all of the DOE's pre-Permit waste characterization processes.

2.2.4 WAP DQO for Radiography

The WAP DQO is essentially identical to the QAPP DQO in that radiography is to verify the waste matrix code assigned to each waste stream (Section 1.4, p. 1-32):

> To verify the TRU waste streams by matrix parameter category, as described in the BIR, for purposes of physical waste form identification and determination of sampling and analytical requirements.

"Waste matrix code" is not defined in the Permit, though it may be a term defined in the RCRA and HWA regulations referenced by Section I.D. In the DOE documentation, "waste matrix code" and "matrix parameter category" are identical terms, meaning the five-digit alphanumeric codes used to classify wastes for treatment as found in the *DOE Waste Treatability Group Guidance* (Kirkpatrick 1995). That these are identical terms is made explicit in Section 1.4 of the QAPP (p. 1-18 and 1-19).

The WAP DQO also states that radiography is to identify prohibited items, apparently meaning the items listed in Section B-1c, Waste Prohibited at the WIPP Facility, that are amenable to radiographic identification (liquids, explosives, compressed gases, and perhaps non-radionuclide pyrophoric materials). The QAPP does not include mention of prohibited items as a DQO, though it does specify that radiography operators be trained to find these items (in language which is nearly identical to that used in the WAP). The requirement for identification of prohibited items is also not clearly spelled out in the QAPP, but Section 4.2.1 does contain the following statement (p. 4-3):

> Sites must ensure radiography and visual examination procedures include a list of nonconforming items that the operator must verify are not present in each container of waste (i.e., corrosives, ignitables, reactives, incompatible waste).

2.2.5 WAP DQOs for VE

The QAPP contains no explicit DQOs for visual examination but the WAP visual examination DQOs are included as requirements in the QAPP in other ways. The WAP DQOs require that VE verify waste matrix codes, identify prohibited items, verify radiography information, and confirm waste stream delineation by acceptable knowledge.

The QAPP considers use of VE in two ways: as verification of radiography findings (which in turn verifies acceptable knowledge) for retrievably stored wastes, and as confirming acceptable knowledge for newly generated wastes or repackaged wastes. For verification of waste matrix codes (matrix parameter categories) Section 3.2 of the QAPP states (p. 3-6):

> ...radiography and visual examination are complementary techniques yielding similar data for determining the matrix parameter category and waste material parameter weights of waste present in a waste container. Therefore, visual examination results shall be used to verify the matrix parameter category and waste material parameter weights determined by radiography as described in Section 10.0.

The QAPP requirement for use of both VE and radiography to identify prohibited items is in Section 4.2.1 (see radiography discussion above), and individuals performing VE must also be trained to recognize prohibited items. The QAPP Section 4.2.1 clearly requires verification of acceptable knowledge for newly generated wastes (p. 4-5):

> For newly generated waste streams, sites must describe how acceptable knowledge information is confirmed using visual examination prior to or during waste packaging.

While the QAPP does not specifically state that VE will be used to verify waste stream delineation for retrievably stored wastes, it is an implicit assumption in the QAPP that this activity will be performed. For example, Section 4.2.2.1 states the following (which also addresses waste matrix codes; p. 4-5):

> For all waste streams, sites must describe how acceptable knowledge information is re-evaluated if radiography or visual examination results in the reassignment of a different matrix parameter category [e.g., Plastic/Rubber (S5310) versus Paper/Cloth (S5330)]. For all waste streams, sites must describe how waste is reassigned to a different waste stream and appropriate EPA hazardous waste numbers assigned.

Verification of radiography by VE is required in the QAPP in Section 5.0 (p. 5-4):

> Retrievably stored waste containers from waste streams in all matrix parameter categories (S3000, S4000, and S5000 summary categories) must be selected for visual examination to confirm the results of radiography following the statistical approach specified in Section 5.4.1.

The statistical approach described in the QAPP and the WAP are the same with one significant difference. The QAPP invokes the use of statistics over the entire drum population, whereas the WAP requires that it be applied to each waste stream. This WAP requirement could easily result in a ten-fold increase in the number of drums that must be examined by each generator site in a year. The WAP also requires an initial statistical selection of drums based on an 11% miscertification rate whereas the QAPP requires an initial selection based on a 2% miscertification rate. The WAP miscertification rate would also increase the number of containers that should undergo visual examination. This potential increase does not significantly affect the pre-Permit wastes in the repository, since nearly all underwent visual examination during repackaging, but other wastes characterized by generator sites in the pre-Permit period may be significantly affected.

The requirements quoted above are usually found multiple times within the QAPP. Except for the frequency of visual examination to verify radiography, the pre-Permit waste characterization program appears to meet the WAP DQOs for visual examination.

2.3 WAP QAOs

The DQOs are reached through meeting QAOs for each of the areas described. The following sections compare the QAOs in the WAP to the WIPP pre-Permit program requirements. The WAP QAOs are not always reflected in the QAPP as QAOs, but can still usually be found as requirements within the document. Headspace gas QAOs will be addressed first, since these are a primary consideration in concerns related to the Room 7 risk analysis.

2.3.1 Headspace Gas QAOs

For VOC analysis the WAP clearly establishes the link between DQOs and QAOs. Section B3-5, Gas Volatile Organic Compound Analysis, in the portion labeled Quality Assurance Objectives, states:

> The development of data quality objectives (**DQO**) specifically for this program has resulted in the QAOs listed in Table B3-2. The specified QAOs represent the required quality of data necessary to draw valid conclusions regarding program objectives. WAP-required limits, such as the program required quantitation limits (**PRQL**) associated with VOC analysis, are specified to ensure that the analytical data collected satisfy the requirements of all data users.

The WAP Table B3-2, Gas Volatile Organic Compounds Target Analyte List and Quality Assurance Objectives, is identical in all technical respects to QAPP Table 12-1, for the GC/MS (gas chromatography followed by mass spectroscopy) or GC/FID (gas chromatography followed by flame ionization detection) methods used for all pre-Permit characterization activities.[3] For these QAOs, the pre-Permit waste characterization program requirements are identical to those specified in the WAP.

Table B3-2 covers headspace gas analysis only. There are also QAOs for headspace gas sampling (also listed in Section B3-2). The first of these states (p. B3-6):

> Headspace-gas sampling will occur from the headspace within each drum of transuranic (TRU) mixed waste.

This WAP statement is unduly limiting since standard waste boxes sent to WIPP also need headspace gas sampling. The use of the term "drum" rather than "waste container" was probably an unintended error. In the QAPP, the requirement is more inclusive (Section 4.2.2.2, p. 4-8):

> Headspace gas sampling and analysis must be conducted on all TRU waste to be sent to the WIPP facility.

[3] The Fourier Infrared Transform Spectroscopy (FTIRS) MDL column in the WAP Table B3-2 does not appear in Table 12-1 of the QAPP, though the same MDL values for all but formaldehyde and hydrazine appear in Table 1 of the QAPP's February 1996 Interim Change (p. 4). FTIRS analysis, however, was not approved for use in TRU waste characterization at any DOE site during the pre-Permit period, and none of headspace gas results for pre-Permit activities were performed by FTIRS. The QAPP Table 12-1 also includes three additional analytes (to address a transportation requirement) not listed in the WAP Table B3-2.

There have been deviations from this requirement for pre-Permit wastes, and there is a qualification in the WAP QAOs that may arguably allow these deviations. See Section 2.3.2 for a fuller discussion of the deviations.

A second QAO for headspace gas is that the precision and accuracy of the drum headspace gas sampling operations must be assessed by analyzing field quality control (QC) head space gas sample to include equipment blanks, field reference standards, field blanks, and field duplicates. The identical wording from Section B3-2 in the WAP is in Section 7.1 of the QAPP (p. 7-3).

QAOs for precision, accuracy, completeness, comparability, and representativeness of the headspace gas samples are also found in Section B3-2. Each of these QAOs consist of several statements containing individual requirements, and all of the requirements in these statements are addressed by various portions of the QAPP (though not necessarily as QAOs) except for the following items.

1. The WAP precision QAO for headspace gas requires *sequential* collection of field duplicates from manifold sampling operations. The QAPP does not specify sequential collection of field duplicates from manifold sampling--the requirement is for field duplicates to be collected *simultaneously*, whether for manifold or direct canister sampling.

   The WAP requirement for manifold collection would establish a slightly more rigorous check of sampling than is required by the QAPP, if a cleaning of the manifold between the two samples had been specified, or some other change to the system between collection of samples. However, the logic for requiring sequential sampling from manifolds instead of simultaneous sampling is not clear. Other sections of the WAP indicate that simultaneous collection is sufficient. For example, Section B1-1a(1), Manifold Headspace Gas Sampling (p. B1-3) states:

   > If using canister-based sampling methods, a sufficient number of ports shall be available to allow simultaneous collection of headspace-gas samples and duplicates for VOC analyses.

The “canister-based sampling methods” are not to be confused with “direct canister sampling”; using a manifold, samples can either be stored in canisters (canister-based sampling method), or directed to an on-line analytical system for immediate processing. Direct canister headspace gas sampling does not use a manifold.

2. The WAP completeness QAO for headspace gas sampling requires that sampling completeness is to be calculated for each waste stream, and must be 90% or greater. While the requirement for 90% sampling completeness is in the QAPP, there is no specification for calculation *by waste stream* for headspace gases (or any of the other waste characterization parameters). The QAPP does, however, require that (Section 3.3.1, pp. 3-9 and 3-10):

> ...the site project manager will ensure that all data generated meet the DQOs provided in Section 1.5 of this QAPP. To do so, the site project manager must assess whether data of sufficient type, quality, and quantity have been collected...
>
> For each waste stream characterized the site program manager must determine if sufficient data have been collected to determine the following Program-required waste parameters: ...Average concentration of hydrogen, methane, and each VOC in the headspace gas of waste containers in the waste stream.

Section 7.1 of the QAPP (p. 7-3) also requires the site project QA officer to evaluate the importance of any lost or contaminated headspace gas samples, and initiate corrective action if appropriate. While these statements are not the equivalent of the WAP requirement, they do indicate that the sufficiency of headspace gas data for each of the waste streams that have already been placed into the WIPP has been specifically evaluated and deemed acceptable, and that any samples not used have also been assessed for their importance to the quality of data.

3. The WAP comparability QAO for headspace gas sampling requires laboratories analyzing WIPP samples to *successfully participate* in the CAO’s Performance Demonstration

Program (PDP; blind test samples are processed by the labs at least annually to help assess lab compliance with QAOs).[4] The QAPP only requires that laboratories *participate* in the PDPs (Section 2.3, p. 2-7), and comply with the PDP Plans.[5]

The original Headspace Gas PDP Plan (US DOE 1995a) does require any laboratory that fails to meet the PDP criteria for accuracy or precision to cease analytical operations for WIPP samples (see Rev. 0 paragraph 6.2.5.6.2, p. 25), which would seem to clearly meet the WAP requirement. Revision 1 (US DOE 1999b) no longer requires laboratories to cease analysis of WIPP samples until a successful PDP cycle has been obtained; under Revision 1 laboratories may "choose to proceed at risk," though any data obtained "may be found unacceptable to WIPP" (Section 5.2.5 p. 26). The WAP, however, was developed using Revision 0, and successful participation in the PDP would seem to mean meeting the PDP criteria. After April 14, 1999--when Revision 1 was promulgated-- the WIPP waste characterization program does not meet this WAP QAO for headspace gas. It may be, however, that DOE-certified generator sites (LANL, INEEL, and RFETS) have consistently met the PDP criteria in the relatively short intervening period.

4. The WAP comparability QAO for headspace gas sampling also requires the generator site to take corrective action if uniform procedures, equipment, or operations are not followed, unless the deviations have been justified and approved. The QAPP does not address this requirement in these terms, but Section 2.1 (p. 2-1) states:

> Corrective action shall be taken if any condition, or significant condition, adverse to quality is detected during an audit or assessment. The cause of any adverse condition, identified by any means, that affects compliance with the QA/QC requirements specified in this QAPP shall be promptly determined and action taken to preclude its recurrence. The identification, cause, and corrective action(s) for

[4]The inclusion of the PDP requirement in a QAO for headspace sampling seems out of place--the Headspace PDP does not include testing of sampling processes, only testing of laboratory analytical capability.

[5]The requirement to comply with the PDP plans are found in the November 1996 Interim Change to the QAPP, Table AC-1 (US DOE 1996d).

> conditions not complying with the quality requirements of the Program must be documented and reported to appropriate levels of management as indicated throughout this section.

Section 2.1.2.1 of the QAPP (p. 2-3) covers nonconformances, defined as uncontrolled and unapproved deviations from an approved plan (including the QAPP), procedure, or expected result. Nonconformances can be identified and reported by anyone performing WIPP project activities, and are to be tracked to completion by the site project QA officer. Completion of corrective action for nonconformances must also be verified by the site project QA officer.

There have been some deviations from the requirements in the QAPP for the wastes that are now in the WIPP repository. However, as specified in this QAO, these have been justified and approved, as is indicated in the next section.

2.3.2 Deviations From QAPP Waste Characterization Requirements For Headspace Gas

Two major deviations from headspace gas requirements in the QAPP for pre-Permit waste characterization are listed in the following comments.

1. Headspace gas samples from the LANL TA-55-43.01 waste stream were taken prior to repackaging of these wastes, when the waste container was a 55-gallon drum; the contents of each of these drums was later repackaged into one or more standard waste boxes in order to meet hydrogen gas generation requirements (a transportation requirement, not a RCRA one). Each SWB received waste from only one drum. Standard waste boxes provide a much greater headspace volume than do drums, so that headspace gas concentrations that met requirements while in drums would assuredly meet the same requirements in SWBs.

   Since the QAPP did not specify when samples are to be taken, LANL requested guidance on the issue from the CAO. The CAO responded with a July 8, 1998, letter to LANL (Hunter 1998b) that states:

> ...if retrievably stored waste is repackaged after headspace gas sampling, then it is not necessary to resample the waste.

The organization responsible for enforcing the WIPP RCRA permit, the New Mexico Environment Department, was extensively involved in reviewing waste characterization for this waste stream, and eventually agreed with the DOE that the waste stream contained no reportable RCRA hazardous constituents. Accordingly, the lack of a headspace gas sample from the final waste containers (the SWBs) may meet the WAP headspace gas comparability QAO for justification and approval of deviation from the WAP headspace gas process.

It should be noted that the WAP QAOs for headspace gas do not require sampling of SWBs; the QAO only specifies drums (the EEG has informed the NMED about this apparent terminology oversight in the WAP).

2. No headspace gas samples were collected for the RFETS waste stream RF 005.01 since it consists of solid salt waste which is heated to a liquid 800 degrees Celsius and stirred for approximately two hours in the presence of an oxidant. The process should remove any RCRA headspace gas-generating materials or volatile organic compounds that might be present in the salt.

   RFETS requested an exemption from the CAO for headspace gas sampling of these salt wastes, and a February 12, 1998, letter from the CAO's Office of National TRU Waste Operations (Hunter 1998a) granted the exemption, noting that the post-heating packaging would prevent re-introduction of headspace gas constituents into the waste. There appears to be no technical reason for performing headspace gas sampling of the post-heating wastes from this waste stream.

3. An October 9, 1998, CAO letter (Hunter 1998g) grants a RFETS request to deviate from a waste container temperature equilibrium requirement. The requirement is stated in the QAPP as follows (Section 6.4.1):

> Waste containers and their contents must be allowed to equilibrate to the temperature of the sampling area. The equilibrium period must be, at a minimum, 72 hours prior to sampling.

The letter notes that the requirement is only to allow the waste container and its contents to equilibrate to the temperature of the sampling area, not reside at the sampling area for the 72 hour period, and that even if containers were left at the freezing point for a short period of time they could still be brought to 64.4°F (18°C) in less than 72 hours.

The WAP requirement (Section B1-1a) specifies equilibration for 72 hours at 18°C or higher. This would ensure that headspace gases would reach equilibrium conditions at that temperature. The CAO's October 9, 1998, interpretation does not meet this intent.

4. A January 12, 1999, CAO letter to Mobile Characterization Services (Brown 1999a) allows use of a heated syringe for collection of duplicate samples, stating that because the syringe method has been shown to meet program quality assurance objectives and the syringe will collect a sufficient volume, the duplicate would be equivalent to the SUMMA canister collection system required by the QAPP. Transportation and storage requirements for the syringe method were not discussed in the letter.

   The WAP contains no provisions for using syringes to obtain duplicate headspace gas samples. Any duplicates obtained by this method would be suspect.

2.3.3 Homogeneous Solids and Soil/Gravel Sampling QAOs

The WAP homogenous solids and soil/gravel sampling QAOs are, like the headspace gas QAOs, usually found as identical requirements within the QAPP. Differences between the WAP and QAPP requirements are as follows:

1. The WAP Section B3-3 (p. B3-9) states that "25 to 30 pairs of co-located cores or samples" are to be used to establish control charts for the relative percent difference (RPD) between

field duplicate samples. The QAPP requires "at least 30" pairs of co-located samples. The QAPP requirement is the more conservative--the more samples used to establish the control limits the more likely the controls will accurately reflect the mean and variance of the population.

2. The WAP Section B3-3 (p. B3-9) requires that RPD control charts establish limits at three standard deviations. The QAPP states (Section 8.3, p. 8-8a):

> The limits may be as much as three standard deviations from the mean.

That is, the control limits may be *less* than three standard deviations, but not more; again, the QAPP is more conservative than the WAP requirement.

3. The WAP Section B3-3 QAOs for accuracy (p. B3-9) requires that:

> Sampling accuracy as a function of sampling cross-contamination will be measured.

The QAPP contains no comparable statement. However, the WAP does not indicate how measuring sampling accuracy as a function of sampling cross-contamination might be done--there is no other mention of it in the entire permit. The utility of performing this action seems technically dubious unless a creditable methodology is available, and criteria for the results are specified.

4. The WAP Section B3-3 QAOs for accuracy (p. 3-9) requires that "corrective action must be taken" if equipment blanks from a cleaning batch sample analysis shows hazardous constituents that exceed three times the minimum detectable levels; the QAPP specifies that the corrective action (reclean the entire cleaning batch and take a new sample, pp 8-8c and 8-9). The WAP permits other corrective action, including disposal of the cleaning batch.

5. The WAP Section B3-3 QAOs requires laboratories analyzing WIPP samples to *successfully participate* in the CAO's Performance Demonstration Program. As was true with the headspace gas PDP, the QAPP only requires that laboratories *participate* in the PDPs (Section 2.3, p. 2-7) and comply with the PDP Plans.

   As with the headspace gas PDP Plan, the original PDP Plan for solidified wastes (US DOE 1995b) required analytical labs to cease operations when the PDP criteria are not met. Revision 1 (US DOE 1996a), submitted to the administrative record for the Permit, kept the requirement. However, Revision 2 (US DOE 1999c), allows the laboratories to "choose to proceed at risk," though any data obtained "may be found unacceptable to WIPP." Since successful participation in the PDP would seem to mean meeting the PDP criteria, the WIPP waste characterization program does not meet this WAP QAO after the April 14, 1999 issuance of Revision 2.

   However, only two waste generating sites have been certified to perform solid sampling by the DOE. These two sites may have continued to meet the PDP criteria; one of the sites (LANL) may not have characterized solids since the change in the PDP Plan.

6. The WAP Section B3-3 QAOs for representativeness (p. B3-10) require that in coring, the entire depth of the waste "minus a site defined approved safety factor" is to be taken; the QAPP does not explicitly make an allowance for the safety factor.

7. The WAP Section B3-3 QAOs for representativeness (p. 3-10) require that, in taking a core sample, if an insufficient (<50% of the total length possible) portion of the initial core is not obtained, that a second core is to be taken; "the core with the best core recovery shall be used for the sample." The QAPP specifies that in this situation the second core is always to be used regardless of the recovery length (Section 8.1, p. 8-3).

   The WAP requirement is based on one aspect of achieving a representative sample (taking samples from a more representative core length), the QAPP requirement

perhaps based on another-- the length of time before samples are removed from the core. The second core, even if shorter, would be more likely to retain VOCs than the first core, as the first core could be losing VOCs by diffusion while the second core is taken.

2.3.4 Deviations From QAPP Waste Characterization Sampling Requirements For Homogenous Solids

There are several deviations from the QAPP waste sampling and preservation requirements for homogeneous wastes.

1. Pre-Permit samples from the RFETS salt waste stream RF 005, a homogeneous solid at normal temperatures, have not all been obtained by coring as is specified in the QAPP. These wastes were heated to a liquid state as a part of their processing, stirred for approximately two hours, then a liquid sample was dipped from the mix. RFETS requested allowance for this practice from the CAO, and received it (Hunter 1998a, p. 2). The CAO approval noted that an SW-846[6] (US EPA 1996) process allowed such sampling, as the stirring addressed the vertical inhomogeneity issue that was a caveat in the SW-846 process.

   The WAP contains no provisions that would allow this process, but there seems to be no technical reason for considering such samples to be less valid than those obtained by the allowed coring methodology. The CAO approval letter states that the RFETS process will yield a more representative sample, which seems reasonable, although the CAO cited no studies to support the conclusion.

2. A July 14, 1998, CAO letter (Hunter 1998c) grants RFETS exemption from preserving samples of waste stream RF 005 salt waste by storing them at 4°C. The requirement is to

[6] "SW-846" is the EPA's *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, a compendium of methods for sampling and analysis of RCRA wastes. The CAO letter cites Section 9.2.3, *Sample Plan Implementation Containers.*

prevent volatilization of mercury and chromium from the sample; the letter points out that the mercury would be removed from the waste during the two-hour 800°C heating process, and the SW-846 methods for total chromium analysis (as opposed to hexavalent chromium analysis) do not require cooling of the sample. The WAP requirements for chromium seem to have been effectively met, as SW-846 procedures are specified for metals analysis.

A September 29, 1998, CAO letter (Hunter 1998f) notes that, despite the heating process, samples did show the presence of trace concentrations of mercury. The letter states that:

> ...the Carlsbad Area Office (CAO) agrees with your determination that the presence of mercury in two of over 200 samples, and at trace concentrations, does not invalidate the CAO approval to eliminate the need to cool salt residue samples to 4 degrees. The rationale provided, along with the letters from two outside technical experts, sufficiently documents the validity of the preservation protocol used for these types of samples.

While it seems unlikely that cooling the samples would have resulted in detection of higher concentrations of mercury, the deviation from the QAPP sampling requirements makes that determination only a highly logical conjecture rather than a technically justified conclusion. This process does not meet WAP requirements, but again, the technical consequence seems minor.

3. A February 25, 1999, CAO letter (Brown 1999b) notes that duplicate samples from liquified RF 005 waste stream are not necessary, specifying that relative percent differences were to be calculated from sub-samples of single samples taken. The homogeneity of the liquified salt and the quality of the sampling process itself would have been confirmed by a complete duplication of the process, and this change does not meet WAP requirements. However, individual small containers of liquid waste are constantly stirred for an hour before the sample is taken, and the composition of sub-samples would likely have the same variance as multiple samples; the granting of this change would not seem to significantly affect analytical results.

4. An August 21, 1998, CAO letter (Hunter 1998d) grants RFETS exemption from coring of homogeneous residue salts (a different group of salt residues than the RF 005 waste stream discussed above). The alternate methodology approved includes size reduction, use of a mixing and sampling process based on ASTM C702-93, and use of SW-846 approved containers and procedures for storing and handling the resulting sample.

   The letter states that:

   > The processes that generated these salts preclude organics (size reduction will not alter the concentration of hazardous constituents)

   One purpose of the sampling and analysis program is to confirm data concerning processes that generated the wastes. The process of reducing the size of the particles, and mixing and sampling them using the ASTM C702-93 methods greatly increases opportunity for volatile compounds to escape from the sample before further analysis. Thus, confirmation that there are no volatile organic waste hazardous constituents in the salt is somewhat compromised, and the quality of the acceptable knowledge becomes the controlling factor in acceptance of these salt residues. This change would not be allowed by the WAP, but its technical impact would seem to be marginal unless the acceptable knowledge is inadequate.

5. An August 26, 1998, CAO letter (Hunter 1998e) grants RFETS a similar exemption for ash residues, noting:

   > It must be demonstrated that mechanical blending will not significantly affect the concentration of constituents in the sampled material. This can be shown by analysis of smaller particles compared with material analyzed after size reduction and blending or by acceptable knowledge demonstrating that volatile constituents will not be present in the waste.

   This statement misses one of the principal purposes of sampling and analysis waste characterization, to confirm acceptable knowledge. If acceptable knowledge was used to

meet the additional requirement imposed by the CAO then acceptable knowledge is being used to confirm itself.

The *Final Environmental Impact Statement on Management of Certain Plutonium Residues and Scrub Alloy Stored at the Rocky Flats Environmental Technology Site* (US DOE 1998a) notes that several types of ash residues contain organic material (Volume 2, Section B.3.2, p. B-10). Any pre-Permit ash residues characterized using only acceptable knowledge do not meet WAP requirements. However, the presence of these organic materials was established by chemical analyses that are a part of the acceptable knowledge record; since neither the individual concentrations nor total amount of organic material in the ash residues are likely to be affected by reanalysis to any significant degree, the impact of this change is likely insignificant.

2.3.5 WAP Radiography QAOs

The WAP Section B3-4 QAOs for radiography are not all in the QAPP QAOs or other documents. Those that cannot be found or differ from the WAP are as follows:

1. The WAP requires that if the QAOs are not met, then corrective action is to be taken. The QAPP Section 10.1 (p. 10-1) contains a similar statement, but the QAPP QAOs are not the same as the WAP QAOs. However, any of the WAP QAOs that are contained in other QAPP requirements would fall under the corrective action plan specified by the CAO's Quality Assurance Program Document (US DOE 1996b and US DOE 1998b), which is applicable at the waste generating/storage sites where waste will be characterized.

2. A WAP radiography precision QAO is to verify precision prior to use in waste characterization by viewing an image test pattern to demonstrate compliance with QAOs. Though Section 10.5 of the QAPP requires visualization of a test pattern image prior to use (p. 10-9), it does not require the test pattern check to demonstrate compliance with QAOs. However, none of the WAP QAOs establish visualization criteria for real-time radiography

(RTR) beyond the ability to visualize prohibited items and identify waste matrix items; in practical terms, there is no difference between the WAP QAO and the QAPP requirement.

3. A WAP radiography accuracy QAO requires the Site Project QA Officer to calculate and report the miscertification rate of waste containers that are assigned to a different waste matrix code, or are found to contain prohibited items, when visually examined. The QAPP accuracy QAO does not require inclusion of prohibited items in calculating miscertification rates (Section 10.1, p. 10-1):

> The accuracy with which the matrix parameter category and waste material parameter weights can be determined must be documented through visual examination of a randomly selected statistical portion of waste containers (Section 5.4.2). The percentage of waste containers which requires a new matrix parameter category after visual examination must be calculated and reported by the site project QA officer as a measure of radiography accuracy.

In the QAPP, there appears to be an attempt to separate radiography performed for RCRA purposes from radiography performed to meet transportation requirements. Section 5.4.2 of the QAPP, where calculation of miscertification rates is described, contains the following statements (p. 5-18):

> The data obtained from the visual examination must also be used to determine, with acceptable confidence, the percentage of miscertified waste containers. Miscertified containers are those that radiography indicates meet the WIPP-WAC radiography-determined and TRAMPAC requirements [sic] but visual examination indicates do not meet these requirements. Note that the radiography requirements of Section 10.0 are separate from the radiography requirements of WIPP-WAC and TRAMPAC certification.

Since the TRAMPAC (transportation) certification requires checking for prohibited items, there may have been an interpretation that a miscertification rate could be calculated for prohibited items for transportation concerns, and a second miscertification rate calculated

from errors in applying waste matrix codes. If so, no great effort was made to clearly establish this distinction in the QAPP.

Despite the discussion above, it should be noted that the calculated rate of miscertifications at LANL included prohibited item discoveries. This calculation was used to change the initial miscertification rate for all sites in the Permit--another contentious issue that is included in the DOE lawsuits on the Permit.

4. A WAP Radiography DQO requires that RTR recordings and data forms be validated as indicated in Section B3-10; Section B3-10 contains a requirement that radiography tapes be (p. 3-24):

> ...reviewed on a waste container basis at a minimum of once per testing batch or once per day of operation, whichever is more frequent. The radiography tape will be reviewed against the data reported on the radiography form to ensure that the data are correct and complete.

A "testing batch" can be up to 20 waste containers. The comparable QAPP requirement specifies that at a minimum the tape from every 10th waste container is to be reviewed (Section 3.1.1, p. 3-3). The pre-Permit characterization may have been more conservative than the WAP requirements, or less conservative, depending on the number of waste containers radiographed each day.

2.3.6 Deviation From QAPP Waste Characterization Sampling Requirements For Radiography

Table 10-1 of the QAPP lists the waste material parameters types for which QAPP Section 10.1 states weights are to be estimated. A May 8, 1998, CAO letter to LANL (Stroud 1998) notes that RTR operators should attempt to estimate weights in terms of the Table 10-1 list, but also allows the operators to combine categories into more general descriptions when individual types cannot be easily distinguished. One example given is to combine cellulose, rubber, and plastic materials into a single classification.

WAP Table B3-1 is identical to QAPP Table 10-1, and there are no provisions in the WAP (as there were not in the QAPP) for alternative methods of classifying the waste. Confirmation of radiography by visual examination is required (both in the WAP and the QAPP) to compare waste material parameter weights, with no provisions for combined categories. The discussions in both documents emphasize that radiography operators are to be trained to make judgments based on the material parameter weights.

However, the material parameter wastes are not hazardous wastes, and are apparently only included in the WAP because the DOE's application contained these requirements. Waste material parameters were originally included in WIPP documents because of the effects these materials might have on the radionuclide component of the waste for long-term repository performance. There are no requirements in the WAP or in the rest of the RCRA permit concerning material parameter weights other than those listed above--no calculations to be performed, no assessment of the effect these components would have on hazardous materials, no required considerations of how these materials might become hazardous wastes. The effect of this deviation is therefore negligible.

2.3.7 Total VOC Analysis QAOs (Section B3-6)

Total VOCs are collected from homogeneous solids and soil/gravel; VOC considerations for the pyrochemical salt wastes emplaced in the WIPP during the pre-Permit period are described in the headspace gas QAO discussion above. Other homogeneous solids have been characterized under the pre-Permit WIPP waste characterization program at INEEL, and there are differences between the WAP requirements and the pre-Permit characterization program. These are as follows:

1. Initial calibration requirements for GC/MS equipment appear to be slightly tighter in the WAP than in the pre-Permit waste characterization requirements. The WAP Table B3-5, referenced by both accuracy and calibration QAOs in Section B3-6, adds a requirement that the System Performance Check Compounds (SPCCs) have a minimum average response

factor (RRF) as specified in the SW-846 method used, and an RRF $\geq$ 0.01 for all other compounds, for the initial 5-standard calibration. These requirements are not a part of initial calibration criteria in the comparable table in the QAPP (Table 13-3). However, the QAPP table does require that the SPCCs exceed the current SW-846 requirements during the continuing calibration checks that are performed at the beginning of every 12 hours of operation.

2. One portion of the initial calibration requirements for GC/FID equipment was significantly changed from those in the pre-Permit waste characterization program. The WAP Table B3-5 requires the calibration curve correlation coefficient to be greater than 0.990 or the percent relative standard deviation (%RSD) be less than 20 for all analytes in comparing results from the three different standards used in the calibration; the QAPP specifies the correlation coefficient must be greater then 0.93, or the %RSD be less than or equal to 35. The *Transuranic Waste Characterization Sampling and Analysis Methods Manual* (US DOE 1996c), however, specifies a %RSD $\leq$ 20 in the GC/FID methods (440.1 and 440.2), and was a requirements document during the period pre-Permit wastes were characterized.

   SW-846 Method 8000 clearly states (Section 7.5.2; the GC/FID Method 8015 references Method 8000 for calibration requirements):

   > The regression calculation will generate a correlation coefficient (r) that is a measure of the "goodness of fit" of the regression line to the data. A value of 1.00 indicates a perfect fit. In order to be used for quantitative purposes, r must be greater than or equal to 0.99.

   Any use of GC/FID during the pre-Permit characterization of wastes that utilized the correlation coefficient method specified in the QAPP would seem to be questionable. It may be that GC/FID was not used for WIPP pre-Permit waste processing.

3. Section B3-6 of the WAP requires that laboratory blanks be assessed to determine laboratory contamination, and that these trigger corrective action when control limits are

exceeded. The WIPP pre-Permit waste characterization was performance-based in this respect--if laboratory blanks failed to meet criteria (the same criteria that are in the WAP), then corrective action (a nonconformance report) was to be initiated, but there was no requirement that the lab specifically assess possible laboratory contamination.

4. The Section B3-6 total VOC analysis completeness QAO defines valid results as results that meet not only precision, accuracy, completeness and detection limit criteria but also the criteria for calibration, representativeness, and comparability found in the section. The QAPP defines valid results in terms of meeting the Table 13-1 criteria, which only specify precision, accuracy, completeness and detection limit boundaries.

5. A Section B3-6 total VOC analysis comparability QAO requires waste characterization to use SW-846 sample preparation methods; the QAPP merely specifies standard methods. However, since the WIPP pre-Permit waste characterization program also specified use of the WIPP Methods Manual (US DOE 1996c), which was based on the SW-846 methods, the differences are likely minimal.

6. A Section B3-6 total VOC analysis comparability QAO requires that all waste characterization sites successfully participate in the PDP. This requirement is addressed in Section 2.3.3, Item 5, of this report

7. A Section B3-6 total VOC analysis representativeness QAO requires that samples be collected as described in the Permit Attachment B1. Section B1-2a(2) includes a requirement that cores are to be divided into three equal-length subsections, and a sub-sample is to be taken from random locations in each of the three subsection. The sub-samples are then to be combined for analysis. The pre-Permit waste characterization program specified only a single sampling site randomly chosen from the entire length of the core.

This difference has been deemed by the DOE to be significant enough that it was included in both the DOE federal and state court lawsuits on the WIPP RCRA permit, in an apparent effort to eliminate re-sampling of homogeneous drums that have already been characterized. Since some of the homogeneous solidified drums were created with multiple processes--that is, a mixture of waste and solidifying agent were poured in and allowed to harden, then later other similar mixtures were added--and stratification by settling may be a factor in sludge drums stored over long periods, the RCRA permit three sub-sample system may seem to produce a more representative sample. However, the SW-846 description of sampling (Chapter 9) does not address such sub-sampling. In fact, SW-846 states that simple random sampling is likely the better method unless nonrandom heterogeneity is known to exist (Chapter 9, pp. 8-9). If such knowledge is available, then SW-846 indicates that the specific strata are to be sampled, implying separate analyses rather than the compositing required by the permit. In brief, neither the pre-Permit sampling nor the WAP method seem to be entirely in accord with the RCRA sampling guidelines outlined in SW-846. Without evidence of nonrandom heterogeneity, however, the pre-Permit sampling process does seem to be closer to SW-846 guidelines than those included in the RCRA permit.

2.3.8 Total Semivolatile Organic Compound (SVOC) Analysis QAOs (Section B3-7)

All SVOC pre-Permit waste characterization differences from the WAP QAOs are directly analogous to individual total VOC differences as discussed for the QAOs from WAP Section B3-6. The same minor calibration concerns for GC/MS is present for GC/ECD (see item 1 discussion in VOC analysis QAO in Section 2.3.7), the requirements differences for GC/ECD was discussed in item 2 for GC/FID, the pre-Permit program did not require assessment of laboratory contamination (item 3), the pre-Permit requirement was only to participate in the PDP rather than to *successfully* participate (item 6), and samples were taken from a single core site in homogeneous solids rather than the three sub-sampling areas required by the permit (item 7). For homogeneous solids SVOC sampling, however, both the QAPP and the WAP specify the same alternative ASTM procedure may be used instead of the three sub-sample requirement.

2.3.9 Total Metal Analysis QAOs (Section B3-8)

The WAP metal analysis QAOs contain some unique differences from the QAPP, but most of the differences are analogous to deviations discussed above. These anomalies are as follows:

1. Daily calibration requirements for inductively coupled plasma-mass spectroscopy (ICP-MS) in the WAP (Table B3-9) specify that the replicate %RSD be ≤5, whereas the QAPP Table 15-4 requires only ≤10% RSD. For the same daily calibration the WAP requirement for mass calibration is that it be within 0.9, with a resolution of <1.0 amu full width at 10% of the peak height, while the QAPP specified 0.1 amu for the mass calibration. Both the WAP and the QAPP require nonconformance reports to be written if these requirements are not met.

   The WAP requirement for the %RSD appears to be based on a misinterpretation of the SW-846 method (Method 8020). The method requires in Section 7.4 that the 5% RSD be established for four replicate measurements to verify that the ICP-MS instrument has reached an equilibrium *before* performing the calibrations specified in Section 7.5 and 7.6. The implication is that if the 5% RSD is exceeded then more time should be allowed to reach equilibration, and new measurements taken and compared--the 5% RSD is simply to verify that the instrument is ready for calibration. Immediately *after* calibration, the method requires in section 7.8 that verification of calibrations to be within 10%, or analyses are to be terminated and corrective actions are to be instituted.

   The WAP 0.9 atomic mass unit (amu) mass calibration requirement also seems to be a misinterpretation of Method 8020. Method 8020 specifies 0.1 amu for mass calibration in Section 7.5, the same as in the QAPP; the section also requires ≤0.9 amu full width at 10% of peak height as an additional requirement--but this is not the mass calibration. Note that both the WAP and QAPP requirements exceed the full width at 10% of peak height requirement slightly.

As the QAPP requirements are nearly in accord with the SW-846 method, and the WAP QAO seems to be unsupported, the technical significance of this difference would seem to be very slight.

2. A WAP metal analysis QAO adds a requirement that *laboratory sample duplicates* be assessed for precision as well as the QAPP-required laboratory matrix spike duplicates, replicate analysis of laboratory-control samples, and PDP blind-audit samples. However, the WAP contains no definition for *laboratory sample duplicates*, so that without clarification these appear to be merely a subset of the *replicate analyses of laboratory-control samples* found in both the WAP and the QAPP.

3. A WAP metal analysis accuracy QAO adds *serial dilutions and interference check samples* to the QAPP list (laboratory matrix spikes, PDP blind-audit samples, and laboratory-control samples) that must be analyzed for accuracy.

   The addition is technically significant, and would increase confidence in the accuracy of metal measurements. SW-846 Method 6020 (for ICP-MS, one of the more commonly used analysis instruments for metal analysis) clearly requires (Section 8.4) that interference checks must be made in order to perform measurements correctly, and states that dilution tests for each batch of each matrix must also be performed (Section 8.5). The Method Manual Procedure 630.1, Section 10.1, also clearly states that these steps of Method 6020 are to be followed. While the EEG has not checked all Methods Manual procedures for all types of metals analysis instrumentation it seems probable that the WAP QAO would be met by following the required Methods Manual procedures. However, the results would not likely be reported as a part of the accuracy determination.

4. As with the WAP headspace VOC QAOs and homogeneous waste VOC and SVOC QAOs, there is a metals analysis QAO related to laboratory contamination. The discussion found in Section 2.3.7, Item 3, applies to the analogous QAO here, also.

5. A WAP comparability QAO for total metals analysis requires that SW-846 sample preparation methods be used; the QAPP merely specifies standardized methods.

   The QAPP Table 15-2, Total Metal Analytical Methods, specifies only SW-846 methods, implying compliance with the WAP QAO. However, the QAPP also allows alternative methods to be proposed to CAO, and the Preface to the Methods Manual specifies the submittal and approval process to be followed (this process was submitted as a part of the Permit application but is not a part of the Permit). While it is not clear that the Methods Manual process was used, CAO has granted RFETS approval of an alternative method for metals analysis sample preparation (Hunter 1998a)--but the method is an SW-846 Method (3050).

6. A WAP representativeness QAO for total metals analysis requires the collection and preparation of samples in the laboratory be performed using "representative and unbiased methods." The QAPP contains no comparable statement.

   The WAP contains no characteristics or criteria for unbiased methods. As cited above, the QAPP required use of SW-846 methods for total metals analysis, and use of these procedures are accepted throughout the WAP. Pre-Permit analyses for total metals are unlikely to be affected by this additional requirement.

2.3.10 Acceptable Knowledge

The importance of acceptable knowledge (AK) is noted by the DQOs, in that all other waste characterization activities are used principally to ascertain the validity of AK conclusions. Section B3-9 of the WAP notes that acceptable knowledge provides qualitative information that is not amenable to assessment according to specific data quality goals; however, the section does list data quality requirements for precision, accuracy, completeness, comparability, and representativeness, all of which were considered for the various analytical techniques considered

above. Differences between the pre-Permit acceptable knowledge data quality goals and those listed in the WAP are as follows:

1. The WAP requires the Permittees (the CAO, and the Waste Isolation Division currently managed by Westinghouse Corporation) to perform a "Final Confirmation" that appropriate analytical and testing results are used to confirm the characterization of wastes based on acceptable knowledge (referencing Section B4-4 of Permit Attachment B-4). The QAPP (Section 3.1.3) required only that the CAO verify that data packages contained specified information, without confirming the appropriateness of the data.

   While the change in required roles for CAO is significant, the effect on pre-Permit waste characterization would likely be insignificant. Since the Hazardous Waste Permit does not directly control out-of-state generator sites this WAP requirement may have been added to provide a basis for regulatory action if appropriate results were found to be lacking.

2. Section B3-9 requires as a part of the comparability data quality requirements that sites are to assign hazardous waste codes "...in accordance with Permit Attachment B4-4...." Permit Attachment B4-4 is titled Additional Final Confirmation of Acceptable Knowledge at the WIPP Facility, and does not specify methods for assigning hazardous waste codes, nor does there appear to be any one specific section of the WAP that does list all the criteria for assignment of hazardous waste codes. It does appear that the basic methods listed in the WAP (assign hazardous waste codes based on acceptable knowledge, apply them conservatively, use all available knowledge, follow a written procedure for assigning hazardous waste codes, etc.) are a part of Chapter 4 of the QAPP.

3. Another requirement of Section B3-9 is that any inconsistencies between acceptable knowledge documentation and results of confirmatory analytical techniques (chemical analysis, radiography, or visual examination) are to be reported to CAO/WID within 5 days (written report) followed by a nonconformance report within 30 days. The pre-Permit waste characterization program had no such reporting requirements. The effect of this

difference would seem to be minimal, as in both cases the site remains responsible for assessing and correcting the inconsistency before certifying affected waste for shipment to the WIPP.

4. Section B3-9 requires tracking of inconsistencies within acceptable knowledge data and documenting the results of acceptable knowledge confirmation from the confirmatory analytical techniques. The pre-Permit process did not require this tracking and documentation, but the QAPP does briefly cover consequences of consistent discrepancies with acceptable knowledge information (Section 4.4.4). The tracking and documenting required by the WAP would seem to be an important and useful process, but would also seem likely to have only minimal impact on pre-Permit waste characterization activities.

2.3.11 QAO Relating to Pre-Permit Waste Analysis Procedures Based on Deleted SW-846 Methods

The WAP includes a comparability QAO for each type of analytical process (VOC, total VOC, SVOC, and metals) stated as follows:

> Any changes to SW-846 methodology that results in the elimination of sample preparation or analytical methods in use at generator/storage sites must be addressed as a corrective action to address the comparability of data before and after the SW-846 modification.

Final Update III (December 1996) to SW-846 lists several procedures that were deleted in that update (see p. 7 of Instructions). The procedures were not superseded--they were simply removed, with no explanation provided. Among the deleted procedures are:

8240B Volatile Organics by Gas Chromatography/Mass Spectrometry (GC/MS)

8250A Semivolatile Organic Compounds by Gas Chromatography/Mass Spectroscopy (GC/MS)

These two methods are major constituents of procedures for VOC, total VOC, and SVOC in the Methods Manual, in use during the pre-Permit waste characterization period (the last update of the Methods Manual was Revision 1, approved in April 1996). The two deleted SW-846 methods listed above were used in the Methods Manual as follows:

1. Methods Manual Procedure 430.2, *Modified Method 8240B/8260A for the Determination of Volatile Organic Compounds in Waste Container Headspace* used 8240B with 8460A (still in SW-846) as its basis. Method 430.2 states (Section 1.2, p. 1),

   > This procedure only details the sections of SW-846 Methods 8240B and 8260A that need to be modified to allow the analysis of gas samples. Analysts must refer to SW-846 Methods 84240B and 8260A for additional guidance.

   It may be that the Method 8240B and 8260A were sufficiently identical that the deletion of 8240A would have minor, if any, effect on the quality of pre-Permit headspace gas measurements for WIPP wastes. It also may be possible that the Method 430.2 was not used, as the Methods Manual contains another method (Method 430.1) which could also be used to analyze headspace VOCs.

2. Methods Manual Procedure 430.3, *Method 8240B for the determination of Total Volatile Organic Compounds in Homogeneous Solids and Soil/Gravel*, is completely dependant on SW-846 Method 8240B for total VOC analysis. Section 1.2 states that the analyst should refer to SW-846 Method 8240B for the "specific requirements of this procedure"; Section 8.0, which contains the specific procedural steps to be followed, simply refers the analyst to steps in 8240B.

   Procedure 430.3 is not the only method for total VOC analysis in the Methods Manual--430.4, based on SW-846 Method 8260A, could also be used. However, it appears that any pre-Permit homogeneous waste analysis for total VOCs performed in accordance with 430.3 was not in compliance with the EPA guidelines required in the RCRA permit.

3. Methods Manual Procedure 430.5, *Method 8250A for the Determination of Total Semi-volatile Organic Compounds in Homogeneous Solids and Soil/Gravel*, is completely dependant on SW-846 Method 8250A for total VOC analysis. The statements in Section 1.2 and Section 8.0 are the same as those in 430.3, only changing the references to Method 8250A. Similarly, there is another Methods Manual Procedure that could be used for SVOC analysis (430.6); however, as with 430.3, any analyses that may have been performed using 430.5 do not appear to have been performed in accordance with the EPA guidelines required in the RCRA permit.

If utilized at all, the impact of the deleted SW-846 methods on waste characterization during pre-Permit waste characterization may not seem to be of major significance. The deleted methods were initially promulgated by the EPA, and were current at the time the last update to the Methods Manual was made. It is unfortunate that SW-846 does not list the reasons for deleting the procedures; however, since the reasoning is not supplied, it is unlikely that the procedures contained any major defects.

It would also be unfortunate if the DOE did not ensure that required methods were in conformance with EPA guidelines when WIPP waste characterization activities were performed. A CAO letter to some of the sites (Watkins 1997) states (p. 2):

> Several SW-846 methods which the Methods Manual is based on have been revised. Sites can update their procedures to the latest SW-846 procedure. When SW-846 is revised, the latest information should be included in site procedures and in the Methods Manual as soon as practical.

The philosophy espoused is in conformance with the WAP--but the Methods Manual had not been updated two years later in November 1999. The letter does not inform other waste generator sites of the change. It may be that individual laboratories characterizing wastes noted the deletion of the two applicable SW-846 methods and used the Methods Manual alternative procedures.

2.3.12 QAOs Related to Data Usability Criteria

Data usability criteria are required to be met for headspace gas and homogenous solids sampling, and analysis for VOCs, total VOCs, SVOCs, and metals, specified either as a part of the completeness requirements (VOC and SVOC) or the comparability requirements (all others). The requirement for data usability consideration is in Section B3-1 (p. B3-4) as follows:

> The comparability of waste characterization data shall be ensured through the use of generator/storage site data usability criteria. The Permittees shall ensure that data usability criteria are consistently established and used by the generator/storage sites to assess the usability of analytical and testing data. The criteria shall address, as appropriate, the following:
>
> - Definition or reference of criteria used to define and assign data qualifier flags based on Quality Assurance Objective results,
> - Criteria for assessing the usability of data impacted by matrix interferences,
> - Criteria for assessing the usability of data based upon positive and negative bias as indicated by quality control data, of data qualifiers, and qualifier flags,
> - Criteria for assessing the usability of data due to
> - Severe matrix effects,
> - Misidentification of compounds,
> - Gross exceedance of holding times,
> - Failure to meet calibration or tune criteria
> - Criteria for assessing the usability of data that does not meet minimum detection limit requirements.
>
> The Permittees shall be responsible for evaluating generator/storage site data usability and shall assess implementation through the generator/storage site audit.

There are no comparable requirements in the QAPP for establishing criteria related to data usability. However, it should be noted that in the pre-Permit waste characterization process data which failed to meet QAOs or other expected results became a part of the nonconformance process as specified in the QAPP Section 2.1.2.1. Nonconformance reports were required to provide "...an indication of the potential ramifications and overall usability [of] the data, if

applicable" (QAPP, p. 2-4). The effect of the lack of requirements for data usability criteria would seem to be minimal.

2.3.13 SW-846 Modification and Representativeness QAOs

The WAP includes a representativeness QAO for each type of analytical process (VOC, total VOC, SVOC, and metals) stated as follows:

> Any changes to SW-846 methodology that results in the elimination of sample preparation or analytical methods in use at generator/storage sites must be addressed as a corrective action to address the comparability of data before and after the SW-846 modification.

The QAPP does not contain any comparable statements. However, the Methods Manual requires that specific versions of SW-846 methods be followed (US EPA 1996), so that the possibility of changing from one method to its revision was not a part of the pre-Permit waste characterization program.

2.3.14 Cancellation of Corrective Action Reports Related to the QAPP and Methods Manual

A January 18, 2000, CAO memorandum (Vega 2000) closed a series of Corrective Action Reports (CARs) from the pre-Permit waste characterization program, based on the argument that the cancellation of the QAPP and Methods Manual eliminated the requirements the CARs were written against. CARs cancelled include five for INEEL, five for LANL, and none from the RFETS program.

Many, if not all, of these CARs relate to QAPP and/or Methods Manual practices that are required by the WAP. For instance, two of the cancelled INEEL CARs (US DOE 1999d and US DOE 1999e) concerns inadequate sample handling and custody control, a necessary consideration for hazardous waste samples; WAP Attachment B1-4 contains requirements that cover the same area. WAP Attachment B13-4 requires that identified corrective actions be examined for the

extent and cause of the deficiency, and that remedial actions to preclude recurrence be planned, reported, completed, and verified before closure of the CAR. Since this process was apparently not completed for the CARs at INEEL and LANL, the pre-Permit waste characterization program cannot be said to be in accordance with the WAP. The significance of this deviation from WAP requirements cannot be accurately assessed without examining the extent and cause of the deficiencies for each of the CARs pertinent to characterization of hazardous waste.

2.4 Conclusions and Recommendations

1. The WAP appears to have made explicit many of the undocumented assumptions and implied good practices from the DOE's pre-Permit waste characterization program as specified in the TRU Waste Characterization QAPP.

2. There appears, on the surface, to be significant differences between the pre-Permit waste characterization program and the WAP requirements. A more thorough technical review, however shows that the essence of the requirements appear to have been met despite the apparent differences. The pre-Permit waste analysis process appears to meet the bulk of the technical requirements in the WAP.

3. Deviations from the fundamental documentation of the pre-Permit waste characterization program may be the most pertinent differences from WAP requirements. Variances from the requirements were not fully documented. Though it is unlikely that most of these would be major differences from WAP requirements, there remains the potential that at least some of these--solid coring, failure to sample headspace gases, drum temperature equilibration and perhaps others-- may be a factor in consideration of pre-Permit wastes. The premature closure of independent audit corrective actions for numerous deficiencies at INEEL and LANL, and the possibility that internal audit corrective actions may also have been cancelled or prematurely closed, may also create a perception that pre-Permit wastes were not characterized in accordance with the WAP.

4. There are enough known differences between the pre-Permit program and the WAP that, should the IV.B.2.b requirement become an issue, the data for the individual container lot sampling and analysis could be reviewed to determine compliance or noncompliance with the WAP. Since some of the evidence of compliance might not be easily deciphered, representatives from the DOE could be allowed to be present during the review so as to be able to point out data that might cover requirements. The Hazardous Waste Permit regulators would make the final determination.

3. RISK ANALYSIS FROM ROUTINE OPERATIONS

3.1 Introduction

The risks from emplacement of wastes at WIPP during routine (non-accident) operations are from: (1) external radiation received by those involved in waste handling operations; and (2) inhalation of VOCs that emanate from the filtered waste drums and boxes. Persons that might be exposed to VOCs include underground workers that are down wind from waste storage rooms, surface workers who may be exposed to discharges from the exhaust ventilation shaft, and members of the public that are off-site.

Risks from VOCs, hazardous metals, and radionuclides were evaluated for routine and accident conditions in EEG-72 (Channell and Neill 1999) and in the WIPP Safety Analysis Report (SAR) (US DOE 1999a) for full repository conditions. DOE's Application to NMED (the Application) (US DOE 1997) for the Permit evaluated risks from VOCs for routine and accident conditions.

The purpose of this analysis is to compare the risk from pre-Permit wastes in the repository with WAP-certified wastes that are to be emplaced after the Permit is issued. The routine operations analysis presented in this report will not include risks from radionuclides or hazardous metals. Radionuclide analyses are not included in the WAP and the external radiation doses received during waste emplacement will be incurred regardless of when the wastes are emplaced. Hazardous metal analyses and/or acceptable knowledge are required by the WAP, but the results are not used to calculate risks or set control limits. Also, no hazardous metal exposures are expected during routine operations.

3.2 Scenario Assumptions

The pre-Permit waste containers were emplaced in the exit drift (south 1600 Drift) portion of Room 7 of Panel 1. There is a temporary metal bulkhead with 2 louvers for flow of ventilation air

from the downstream portion of the room. Ventilation air at a rate of 35,000 cubic feet per minute (cfm) flows from the working face of the emplacement stack over the waste, through the louvers, down the south 1600 drift to the east 300 drift and up the exhaust shaft. An exhaust shaft flow rate of 260,000 cfm is used in these calculations[7] (see Figures 3.1 and 3.2). Scenario assumptions are almost identical to those used in EEG-72 and the Application.

Underground workers are exposed to VOC emissions from Room 7 while changing filters on the continuous air monitors (CAMs) located on the downstream side of the temporary metal bulkhead. In the Permit, NMED set room based concentration limits (RBCLs) on VOCs in order to protect the underground worker from lower explosive limit (LEL) and immediately dangerous to life and health (IDLH) concentrations due to a roof fall accident but not from long-term carcinogenic or non-carcinogenic risks (NMED 1999a). This report will calculate the carcinogenic and non-carcinogenic risks to underground workers.

The expected risk from VOCs to persons above ground during WIPP's operating lifetime is assumed to be due to emissions from all waste emplaced in open rooms, closed rooms, and closed panels. These risk calculations assume that containers with average concentrations of VOCs are emplaced at an average rate for the repository's operating lifetime (US DOE 1997). Emissions from a full open room have been estimated to be about 125 times those from a full closed room for carcinogenic VOCs and 75 times for non-carcinogenic VOCs (Channell and Neill 1999). Thus, the only way risks can be greater than expected is from either: (1) bringing in containers with above average concentrations of VOCs early (because they will emanate longer through closed rooms and panels); and (2) leaving waste in an open room for a longer than average period.

[7]The Permit requires a minimum running annual average mine ventilation exhaust rate of 260,000 standard cfm and a minimum active room ventilation rate of 35,000 standard cfm when workers are present (Section IV.E.3.b). At present an exhaust ventilation rate of 425,000 cfm is typical. The use of 260,000 cfm is conservative (i.e., it leads to higher calculated above ground concentrations).

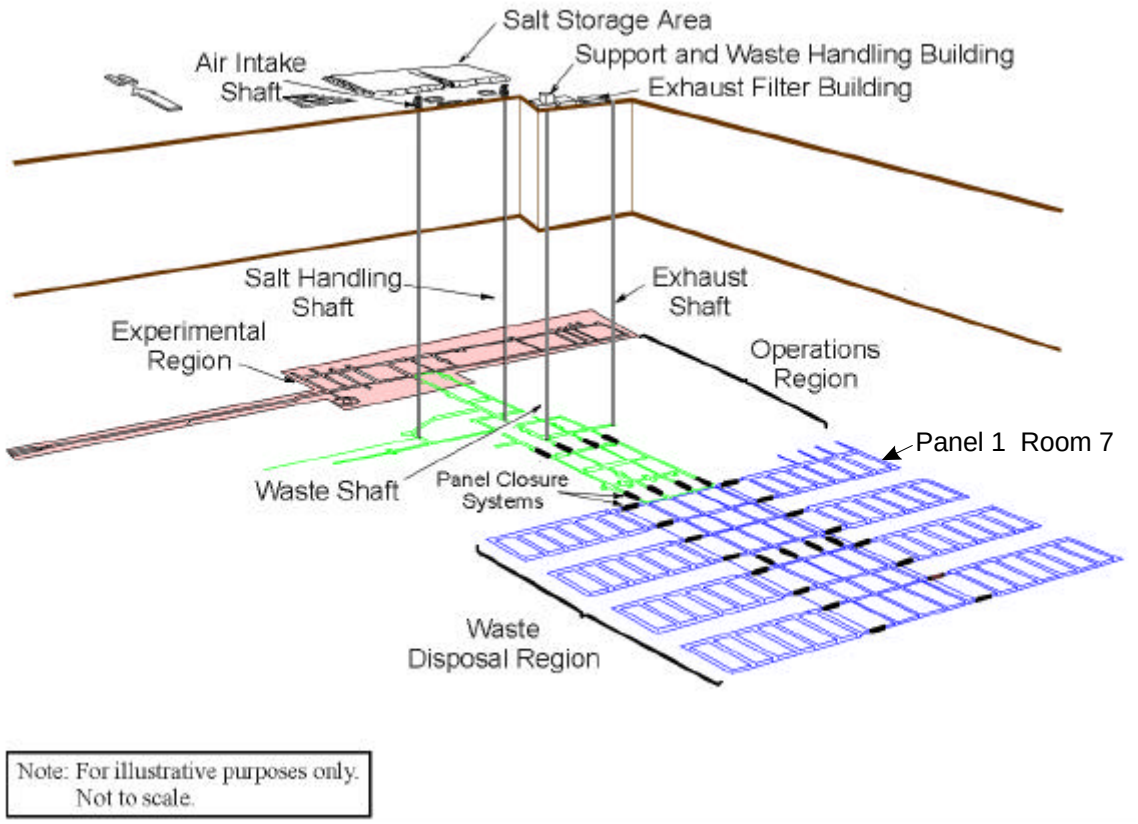

Figure 3-1. The WIPP facility includes surface support buildings, a waste handling building, four shafts, and the mined underground operations area. The repository is located approximately 658 m (2150 ft) below the surface, within the Salado Formation, a Permian sequence of bedded salt with minor amounts of anhydrite and clay. The excavations are accessible from the surface by four verticle shafts. Only one of the eight panels has been excavated to date. Each panel consistes of seven rectangular rooms, 10 m wide and 91 m long, separated by 30.5 m wide pillars. Source: DOE 1996b

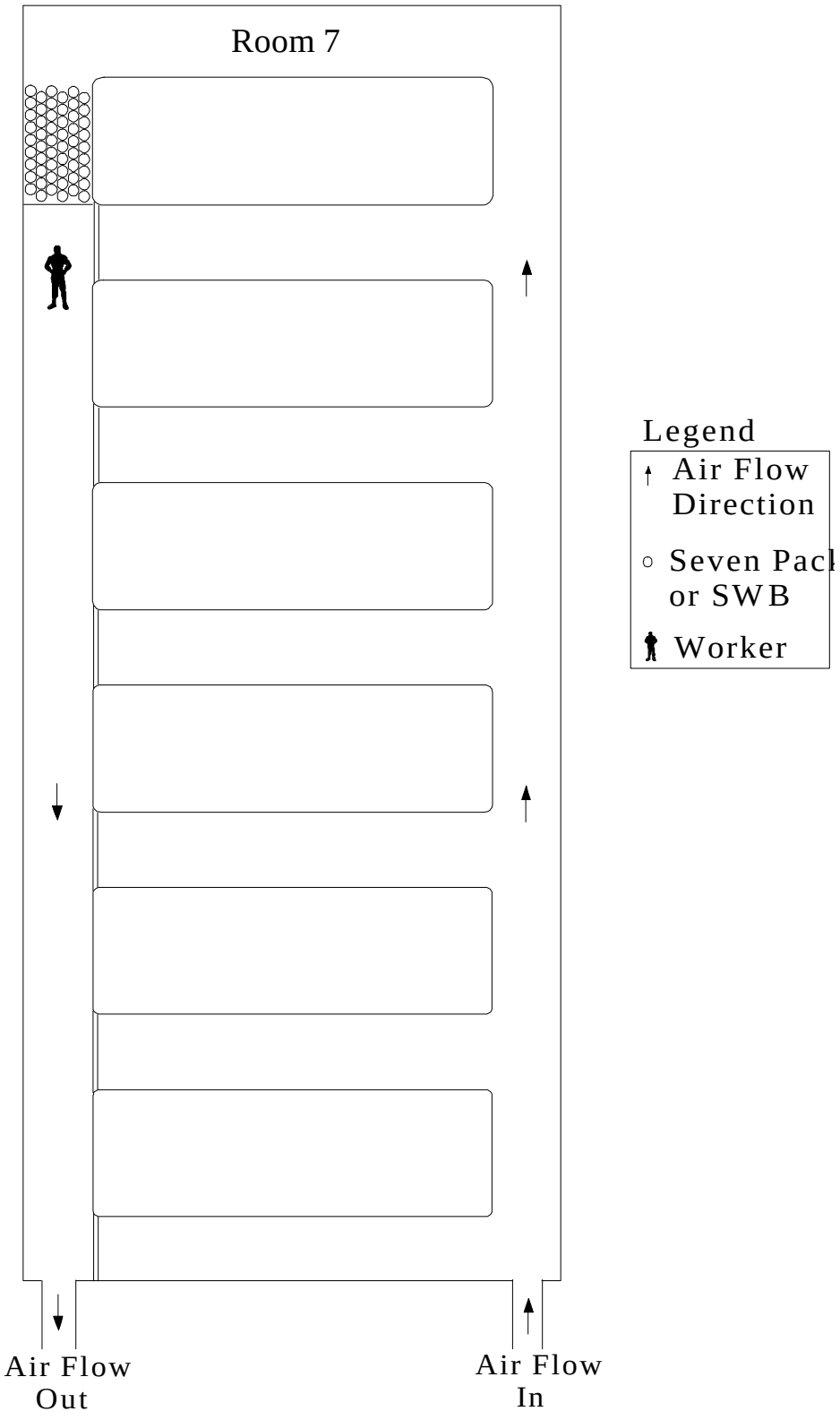

Figure 3-2. Waste Emplacement Process (Source: DOE 1999).

Pre-Permit waste containers emplaced in Room 7 have a lower than average VOC concentration. However, the early emplacement has resulted in the room being left open longer because of the slow shipping rate and the November 1999 - March 2000 period when shipments were not allowed. A waste room will be filled in about six months at the average 35-year emplacement rate. WIPP received its first waste on March 26, 1999, and Room 7 will probably not be filled and closed before early 2001. Bringing in pre-Permit waste early will probably cause open room exposure conditions to exist for approximately 12 additional months. The emissions from Room 7 during this additional one-year period are assumed to be a new source of exposure that was caused by bringing in pre-Permit waste.

3.3 Determination of VOC Source Term

In determining the VOC source term it was assumed that the values measured in the pre-Permit waste containers are accurate. Obviously one cannot be certain of the accuracy of non-WAP certified waste. However, the analysis in Chapter 2 suggests the analysis is probably similar and acceptable knowledge indicates that VOC concentrations in non-mixed waste should be low. Chapter 3.5 provides a bounding risk for the assumption that VOC concentrations are completely unreliable.

The VOC source term was determined from all the wastes emplaced in Room 7 as of October 25, 1999. VOC concentrations are from the WIPP Waste Information System (WWIS), a DOE database that includes waste characterization data for each waste container. The total waste emplaced was: (1) 101 Standard Waste Boxes from LANL; 126 drums of graphite wastes from the INEEL; and 408 drums of residues and 26 drums of graphite waste from RFETS. An additional 166 RFETS residue drums were received before the Permit became effective. These additional shipments were ignored because the exact number was unknown at the time the calculations were performed and the effect would be minor (e.g., 166 additional RFETS residue drums would increase carcinogenic risk by about 8% and non-carcinogenic risk by about 3%).

Reported VOC concentrations are low in all cases (as would be expected for non-mixed wastes). Most VOC measurements were less than the minimum detectable concentration (MDC) and only four had any values greater than the PRQL.

Only five of the approximately 25 VOCs analyzed were retained for the risk analyses. Those retained had a fair percentage of J values (greater than the MDC, but less than the PRQL, and considered to be detected) and average concentrations from at least one of the three generating sites of about 1 ppmv or greater. Two flammable VOCs that met these criteria (acetone and methanol) are not considered by EPA to have carcinogenic or non-carcinogenic risks and were also deleted from the risk analysis. The VOCs used along with their weighted average concentrations are shown in Table 3-1. Only three of these VOCs (methylene chloride, toluene, and 1,1,1-Trichloromethane) are among the nine VOCs listed in the Permit. Details of the calculation are in Appendix A.

Table 3-1. VOCs Used in Risk Analysis

VOC	Health Effect	Average Concentration ppmv
Methylene Chloride	carcinogen	0.41
Benzene	carcinogen	0.39
1,1,1 - Trichloromethane	non-carcinogen	2.9
Methyl Ethyl Ketone	non-carcinogen	4.6
Toluene	non-carcinogen	0.69

3.4 Risks to Surface Worker, Underground Worker, and Member of Public

Details of the risk calculation to an on-site surface worker, an underground worker, and to a member of the public (the Maximum Individual Receptor-MIR) located at the WIPP site boundary are in Appendix A. Results are summarized in Table 3-2. These are the total estimated incremental risks during the lifetime of WIPP operations from pre-Permit wastes at the repository.

Table 3-2. Risks to Surface Worker, Underground Worker, and Member of Public

VOC	Surface Worker	MIR at Boundary	Underground Worker
Carcinogens			
Methylene Chloride	7.20×10^{-15}	2.56×10^{-16}	2.94×10^{-13}
Benzene	1.56×10^{-13}	5.54×10^{-15}	6.36×10^{-12}
Total Cancer Risk	1.6×10^{-13}	5.8×10^{-15}	6.7×10^{-12}
Non Carcinogens			
1,1,1-Trichloromethane	4.00×10^{-10}	1.42×10^{-11}	1.63×10^{-8}
Methyl Ethyl Ketone	2.57×10^{-10}	9.16×10^{-12}	1.05×10^{-8}
Toluene	1.13×10^{-10}	4.02×10^{-12}	4.52×10^{-9}
Hazard Index	7.7×10^{-10}	2.7×10^{-11}	3.1×10^{-8}

These risks are so low that they are difficult to comprehend. Perspectives on these values are discussed separately for carcinogens and non-carcinogens.

3.4.1 Carcinogenic Risks

The Permit considers the highest acceptable lifetime cancer risk from VOCs to be 1×10^{-5} for the surface worker (called a non-involved worker) and 1×10^{-6} for the MIR. Maximum room based concentration limits are prescribed in the Permit so that these values will not be exceeded. The calculated risks for the expected quantity of VOCs in the repository are 5.6×10^{-8} for the underground worker, 9.7×10^{-8} for the surface worker, and 9.4×10^{-9} for the MIR (Channell and Neill 1999).

Allowable exposures at WIPP (25 millirem per year from routine operations) (US EPA 1997) to a member of the public from radioactive materials are equivalent to a carcinogenic risk of 3.4×10^{-4} over the 35-year emplacement period (340 times the target risk level of VOC in the Permit). Actual risks to a real individual are expected to be less than one percent of allowable.

Carcinogenic risks of less than 10^{-12} for a surface worker and 10^{-14} for a member of the public are seven and eight orders of magnitude below allowable Permit risk levels. They are also five and six orders of magnitude below expected lifetime risks from the entire WIPP inventory over the 35-year operating lifetime. Risks to the underground worker are four orders of magnitude less than expected from the full repository and six orders of magnitude below the allowable risk for surface workers. Actions which increase risks by less than one part in ten thousand have negligible effects.

3.4.2 Non-Carcinogenic Risks

The non-carcinogenic Hazard Index (HI) for the pre-Permit waste is calculated to be less than: 10^{-9} for the surface worker; 10^{-7} for the underground worker; and less than 10^{-10} for the public member. Values for the full inventory are estimated to be 2.4×10^{-5} for the surface worker, 1.4×10^{-5} for the underground worker, and 2.4×10^{-6} for the MIR. A hazard index less than 1.0 has no real meaning because these are threshold phenomena. The calculated values for the pre-Permit wastes are seven to ten orders of magnitude below a hazard level and are two to four orders of magnitude below the HI values for the full repository. Hence, they are negligible.

3.5 Bounding VOC Carcinogenic Risks

Because the values calculated above are based on data that were not obtained under a WAP-certified program, it could be argued that the VOC concentrations and risks could be much higher. A bounding limit can be calculated from the grab samples that are taken two times a week in the exhaust ventilation drift as a part of the Confirmatory VOC Monitoring Plan (Attachment N of the Permit). These samples have a required sensitivity well below the concentrations of concern established in the Permit to assure that the room based concentration limits are not exceeded. The method reporting limit (MRL) values for the individual VOCs are either two or five parts per billion by volume (ppbv) for the target VOC. DOE reports all data for the nine target VOCs in its Annual Site Environmental Report (Westinghouse 1999). The three VOCs used in this report were the only ones that had any values greater than the MRL.

Methylene chloride is the only one of our two carcinogenic VOCs that is a target VOC in the Permit (Table IV.B.1). Benzene is one of the additional VOCs that is determined in the analysis. Also, the statement is made in Appendix D-20 of the Application and Attachment N of the Permit: "Non-target sample contaminants identified by NIST library searches will be reported as tentatively identified compounds, and concentration calculations will be based on the response of the nearest internal standard." Based on this we assume that benzene or any other VOC detected at the 5 ppbv level would be reported.

The 5 ppbv concentration can be considered to be the exhaust shaft concentration. The risks can then be calculated using the Appendix A methodology. Results are shown in Table 3-3.

Table 3-3. Carcinogenic Risks at MRL[a] Values

VOC	MRL Values		Carcinogenic Risks	
	ppbv	$\mu g/m^3$	Surface	Boundary
Methylene Chloride	5	17.4	3.94×10^{-10}	1.40×10^{-11}
Benzene	5	16.0	6.40×10^{-9}	2.28×10^{-10}
TOTAL(Rounded)			6.8×10^{-9}	2.4×10^{-10}

[a]MRL = Method Reporting Limit

These risks are still low compared to the already low lifetime risks predicted from the expected quantity of VOCs emplaced in the full repository (9.7×10^{-8} for the surface worker and 9.4×10^{-9} at the site boundary, EEG-72). Thus, the Confirmatory VOC Monitoring Plan would be able to determine a lifetime risk that is 7% for the surface worker and 3% for the MIR of that expected (and accepted) in the Permit. These detectable risks are also 0.07% (surface worker) and 0.02% (MIR) of those allowed under conditions of the Permit. Clearly, if the allowed Permit risks are acceptable these risks from presently emplaced wastes are acceptable. The risk to an underground worker would be less than 3% of that allowed for the surface worker.

4. RISKS ANALYSIS FROM ACCIDENTS

4.1 Introduction

Accidents could cause a fraction of the contents of a waste container to be released and result in exposure due to VOCs, hazardous metals, and radionuclides. The risks from a roof fall accident and a spontaneous underground fire were evaluated. Scenario assumptions are similar to those used in the 1998 SAR, in Appendix D9 of the Application, and in EEG-72. These two accident scenarios were chosen because they could both occur in the open Room 7. Since the early emplacement of these wastes will result in the room remaining open for about one additional year, any risks resulting from these accidents can be considered an additional risk.

Other accidents considered in the SAR (e.g., drum drop, puncture, spontaneous fire in the Waste Handling Building, and hoist failure) were not evaluated. All of these accidents occur during waste receipt, handling, and emplacement and none occurred during emplacement of the pre-Permit wastes.

Releases evaluated from the accident scenario included VOCs and radionuclides. Hazardous metal releases were not evaluated because the average risk was found in EEG-72 to be $5x10^{-7}$ of the risk from radionuclides being released (using the same release fraction assumptions). Data from sampling the LANL waste and RFETS residues indicated that the hazardous metal concentrations per drum are lower than those used in EEG-72. Hence, the hazardous metals risk should be less than $5x10^{-7}$ of the radiological risk.

4.2 Spontaneous Fire Scenario

4.2.1 Scenario Description

Spontaneous ignition was assumed to occur in a drum or SWB emplaced in Room 7. This is considered an unlikely event even for a container that does not fully conform to the WIPP Waste Acceptance Criteria (WAC). It is further assumed that the fire does not propagate to additional waste containers.

The methodology used in the SAR (Chapter 5 and Appendix D) to develop the probability of sustained combustion in a one-half full waste room led to an estimated frequency of 5.3×10^{-6} per year. This calculation assumed specific percentages of each final waste form that would be processed or repackaged. The SAR assumes that processed or repackaged containers have only 10% the probability of a fire as a drum not processed or repackaged (because there is less chance of a repackaged drum not conforming to the WAC). When the emplaced waste volume (309 m^3) is compared to the 1503 m^3 assumed in the SAR and the actual percentages repackaged (100% for LANL and RFETS residues and 0% for graphite wastes) the probability becomes 6.8×10^{-7} per year. This accident would be considered less than extremely unlikely by DOE (because it is less than 1×10^{-6} per year) and not evaluated. The scenario was retained for conservatism and because the probability was reasonably close to 1×10^{-6} per year.

4.2.2 VOC Release and Risk

The SAR assumed that all of the headspace gas in a waste container would be released instantaneously. For computational purposes in this report the release period was assumed to be one minute. The fire was assumed to occur in a LANL SWB with average VOC and radionuclide concentrations. A LANL SWB was chosen because it has the highest carcinogenic VOC concentrations and the largest amount of headspace gas volume. Since the radionuclide quantities in the RFETS residue drums are 4.5 times greater than in the LANL SWBs, these calculations maximize VOC risks rather than radionuclide risks.

Lifetime fatal cancer risks from VOC releases are calculated in Appendix B. The risk to the surface worker is 1.9×10^{-15} and the risk to the MIR is 1.8×10^{-17}. Note that all the accident risk values are really the risks that result if the accident occurs. The overall annual risk is much less because it is the product of the annual probability of occurrence and the risk if the accident occurs.

4.2.3 Radionuclide Release and Risk

The assumptions of the SAR on fractional releases from the SWB were used. The radionuclide release from 4.24 Ci and an overall release fraction of 5×10^{-4} is 2.12×10^{-3} Ci. Calculations for releases, doses, and cancer risks are in Appendix B.

Doses and risks to the surface worker from this scenario were 28 mrem and 2.8×10^{-6}. An underground worker would receive a dose of 17 rem and incur a risk of 17×10^{-3}. For the MIR the doses and risks are 0.27 mrem and 2.7×10^{-8}. A member of the public at the exclusive use area boundary would receive a dose of 1.7 mrem and incur a risk of 1.7×10^{-7}. There are no VOC risk limits in the Permit or radionuclide risk limits for accidents.

VOC and radionuclide risks are shown in Table 4-1.

Table 4-1. Radionuclide and VOC Carcinogenic Risks from Spontaneous Fire Scenario[a]

Source	Surface Worker	Site Boundary Resident	Exclusive Use Boundary Resident
VOC			
Concentration(ug/m^3)[b]	1.2×10^{-2}	1.2×10^{-4}	7.3×10^{-4}
Risk	1.9×10^{-15}	1.8×10^{-17}	1.1×10^{-16}
Radionuclide			
Dose (mrem/y)	28.	0.27	1.7
Risk	2.8×10^{-6}	2.7×10^{-8}	1.7×10^{-7}
Total Risk	2.8×10^{-6}	2.7×10^{-8}	1.7×10^{-7}
Radionuclide/VOC Ratio	1.5×10^{9}	1.5×10^{9}	1.5×10^{9}

[a] Risks assume the probability of the scenario is 1.0
[b] Combined concentration for both VOCs

4.3 Roof Fall Scenario

4.3.1 Scenario Description

The SAR roof fall scenario was patterned after the roof fall that occurred in the experimental area of the repository in Site Preliminary Design Validation Room 1 in 1991. This roof fall was in the shape of an elongated pyramid, approximately 33 feet wide by seven feet high by 180 feet long, and weighed about 700 tons. The scenario was assumed to occur in an active disposal room where waste containers are still being emplaced. Falling salt knocks seven SWBs off the top stack and five of these are breached. All (100%) of the VOC headspace gas is released from these five SWBs. The aerosolized and respirable radionuclide release is 1.0×10^{-5} of the contents of a SWB. For five SWBs with 4.24 Ci/SWB this results in a source term of 2.12×10^{-4} Ci. Released material is transported in room ventilation air to the surface.

4.3.2 Scenario Probability

The SAR developed a rationale and fault tree to arrive at an annual probability of 4.7×10^{-7} that an unexpected roof fall will occur in an unisolated (open) waste room. This scenario would not have to be evaluated according to DOE procedures because the probability is $<1 \times 10^{-6}$/y. Several factors combine to create this low probability value and a major factor is the belief that there are enough signs in the days or weeks leading up to a roof fall that an imminent fall would almost certainly be detected beforehand.

Emphasis is placed in the SAR analyses on an unexpected roof fall because of the belief that even with a few minute warning the area could be evacuated and ventilation exhaust switched to filtration. With a few days warning the affected area could be isolated with emergency barriers and emplacement operations elsewhere be abandoned if necessary .

There are several reasons why preparation for an imminent roof fall may not be as simple and effective as described in the SAR. For example, the DOE may be reluctant to: (1) put workers in the downstream ventilation path to install a ventilation barrier; (2) stop all waste emplacement operations in the affected and adjacent rooms for many days; and (3) operate in the filtration mode for long periods of time (which also precludes waste emplacement). Also if the fall were to occur in the off-shift there would be no two minute warning to activate a switch to filtration before a release. Therefore, EEG believes that even if there are signs of an imminent roof fall the timing of mitigative measures may not ensure complete containment of a release.

4.3.3 EEG Views on Roof Fall Probability in Panel 1.

Panel 1 room stability has been a cause of concern for many years and the SAR recognized that Panel 1 is more susceptible to roof fall. The basic problem is the length of time the rooms have been open. Mining of the panel began in May 1986 and was completed in June 1988. This schedule was to accommodate the anticipated first receipt of wastes in 1988. Concern arose about the useful lifetime of these rooms when the schedule slipped and it became apparent the

panel would not be filled with waste for many years. A group of geotechnical experts was assembled by DOE in April 1991 to provide advice on the useful life span of Panel 1 and recommend remedial measures. The group concluded that the rooms would remain stable without additional support with high confidence until 1993 and with decreasing confidence until 1997. All of the rooms in Panel 1 were fitted with three meter roof bolts in the 1988-89 period. Additional support systems have been installed in portions of Panel 1 since 1989. Room 7, which is our primary concern in this evaluation, completed a tertiary support system in May 1998.

EEG retained a mining engineer, Hamid Maleki, as a consultant in 1996 and in 1998 to evaluate the stability of Panel 1. Dr. Maleki had previously evaluated WIPP mine safety for the U.S. Bureau of Mines in 1993, 1994, and 1995. Dr. Maleki concluded after his 1996 evaluation (Maleki and Chaturvedi 1996) that there were remedial steps that could be taken to enhance stability during emplacement operations. However, he also said, "To 'assure stability' and safety, it is best to abandon Panel 1 and mine a new panel as soon as all permitting processes are complete". In his 1998 report Dr. Maleki stated "Time of roof collapse cannot be estimated with a high degree of confidence if internal tertiary support systems are used without external support systems, such as cribs. The potential for roof falls is expected to be low within the first year and increase significantly in some locations approximately 2 years after installation of tertiary support" (Maleki 1998).

Because of the concerns expressed by others and our own evaluations, EEG has recommended that DOE certify each room in Panel 1 before waste emplacement operations begin. At design emplacement rates a room would be filled in about six months and the one to two year stability period predicted by Maleki would be more than adequate. On July 21, 1999, Westinghouse cleared Room 7 for waste emplacement operations until June 30, 2000 (Patchet 1999). However, because of the slow emplacement rate the room will not be filled until late in the year 2000 or early in 2001. Inspections and remedial measures in the portion of Room 7 already filled with waste will be difficult because of access problems.

For the above reasons EEG believes a roof fall in Room 7 has a probability much greater than $1x10^{-6}$/y and the scenario needs to be evaluated.

4.3.4 VOC Release and Risk

Since 100% of the headspace gas is assumed to be released from each of the five SWBs breached in the roof fall scenario the release and the risks from this accident would be five times as great as in the underground (UG) fire scenario. The risks are $9.3x10^{-15}$ for the surface worker and $9.1x10^{-17}$ for the public member at the WIPP Site Boundary.

4.3.5 Radionuclide Release and Risk

The SAR assumed radionuclide release from the roof fall scenario to be 10% of the release from the UG fire scenario. This lower release occurs because the roof fall damage ratio is 1%, the airborne release factor is two times and the material at risk is five times that in the UG fire scenario. The calculated radionuclide risks are $1.7x10^{-4}$ for the UG worker, $2.8x10^{-7}$for the surface worker, $2.1x10^{-9}$ for the MIR, and $1.7x10^{-8}$ for a public member at the northern exclusive use area boundary.

4.4 Radionuclide to VOC Risks

The risk from radionuclide releases is $1.5x10^{9}$ times the VOC release for the UG fire scenario. In the roof fall scenario the radionuclide risk is $3.0x10^{7}$ times the VOC risk. So, the risk from VOC releases is negligible compared to that from radionuclide releases.

The radionuclide risk to a surface worker from the UG fire scenario accident is greater than $1x10^{-6}$. This is very small, but not negligible. However, the overall annual risk would be much smaller because this is an unlikely accident.

5. CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The WAP requirements for waste characterization are often more prescriptive than the QAPP requirements used for pre-Permit characterization but the essence of the technical requirements appears to be similar.

Deviations granted by DOE during pre-Permit waste characterization and the premature closure of some corrective actions required by independent audits may result in the most significant differences in waste characterization.

Estimated carcinogenic risks to a surface worker and member of the public from routine operations involving TRU wastes emplaced in Panel 1, Room 7 during 1999 are seven to eight orders of magnitude less than allowed by the Permit and five to six orders of magnitude less than expected from the entire WIPP Project over 35 years. Non-carcinogenic risks are nine to ten orders of magnitude below the allowed limit and two to four orders of magnitude below expected risks for the repository.

Estimated carcinogenic risk to the underground worker from routine operations are six orders of magnitude below the allowable risk level for surface workers. Non-carcinogenic risks are seven orders of magnitude below a hazard level.

Even if VOC emissions are much higher than expected, the Confirmatory VOC Monitoring Plan at WIPP would detect concentrations that are three orders of magnitude below allowable Permit limits. Any hazardous emissions from pre-Permit wastes would likely be reported and acted on long before Permit limits were reached.

Risks from low probability accidents are within an order of magnitude of the allowable Permit limits from routine emissions of VOCs. These risks are essentially all from inhalation of released radionuclides with the radiation/VOC risk ratio being $\geq 3 \times 10^{7}$.

Radiation doses and risks to an underground worker for the spontaneous fire scenario are significant (17 rem and 1.7×10^{-3} risk). Doses from the roof fall scenario are one-tenth of those from the spontaneous fire scenario.

5.2 Recommendations

The data for the individual container lots of pre-Permit waste can be reviewed for being "characterized in accordance with the WAP," if this becomes necessary. This determination by NMED should consider all deviations and include input from the DOE.

The estimated non-accidental risks from the presently stored waste in Room 7 are so low that they should not be used as a justification for any remedial or other actions involving these wastes.

Radionuclide risks to underground workers from low probability spontaneous fire and roof fall accidents should be considered when setting restrictions on worker access to the south 1600 and east 300 drifts.

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APPENDICES

APPENDIX A

CALCULATION OF RISK ANALYSIS FOR ROUTINE OPERATIONS

A.1 Development of VOC Source Term

A.1.1 Available Data

Data used in risk analysis calculations was taken from the WIPP Waste Information System (WWIS). Head Space Gas (HSG) analyses were available for all LANL Standard Waste Boxes (SWBs), all INEEL drums, and for the 26 RFETS graphite waste drums. There were no data for the 408 residue drums from RFETS.

The LANL HSG measurements were taken from the parent drums of heat source waste. Subsequent to the HSG analyses each parent drum was divided into several daughter drums so that the curie content would be low enough to ship in the TRUPACT-II package. Each of the daughter drums was placed into a SWB without its drum lid and with three empty drums. LANL took the measured VOC concentrations in each parent drum and assigned the full value to each of that drum's daughter drums. This same HSG concentration was assumed to be the HSG concentration in the SWB. (Rogers 1999). This is undoubtedly a conservative assumption but the amount of conservatism is unknown. The values assigned by LANL were used in this report.

No corrections were made for the HSG concentrations for the graphite waste stream drums from INEEL (120 drums) and RFETS (26 drums).

The RFETS residues are pyro-oxidized salts that have been heat treated at sufficiently high temperatures to drive off any VOCs present. This was the basis for the DOE Carlsbad Area Office to grant RFETS an exemption from HSG Sampling (Hunter 1998a) The WAP requires all containers to have HSG sampling and contains no procedure for granting exemptions.

A lack of HSG data for the residues creates an uncertainty in this risk analysis. Although the argument that the pyro-oxidation process would drive off all VOCs is reasonable, it should be noted that the LANL wastes which have been shown to be non-RCRA wastes contain detectable amounts of VOCs in about one-half of the SWBs. This risk analyses assumes that the residues contain the same HSG concentration as the 26 drums of RFETS graphite wastes. This is probably a conservative assumption but there is uncertainty.

A.1.2 Selection of VOCs

Approximately 25 VOCs were analyzed by the generator sites. The proposed NMED Permit requires room based concentration limits for only nine of these VOCs which contain about 99% of the expected total carcinogenic and non-carcinogenic risk. This risk screening was based on a combination of the projected weighted average concentrations in the repository and the risk coefficients for the individual VOCs.

EEG's screening for this risk analysis considered the nine VOCs included in the Permit as well as those VOCs that were frequently detected and had average concentrations ≥ 1 ppmv at one or more of the generator sites.

Reported VOC concentrations are low in all cases, as would be expected for wastes shipped as non-RCRA wastes. Most VOC measurements are less than the minimum detectable concentration (MDC) and the value reported is the MDC with a U designator. Most of the values greater than the MDC are less than the program required quantitation limit (PRQL) and are designated J. The only VOCs with any values greater than the PRQL were acetone at LANL and 1,1, 1-trichloroethane, toluene (1 only), and carbon tetrachloride (1 only) at INEEL. In calculating average values, those concentrations designated U were assigned one-half the reported value and J designated concentrations were assigned the full value.

Five of the VOCs met the screening criteria and were retained for the risk analyses. Only three of these (1,1,1-trichloroethane, methylene chloride and toluene) were among the nine VOCs for

which environmental monitoring measurements are required by the Permit. Table A-1 includes a total of nine VOCs that had sufficient concentrations and levels of detection to warrant calculation. Acetone and methanol had the highest average concentrations and are of concern in shipping because they are flammable. However, neither are a carcinogenic or non-carcinogenic risk and so are not included in the risk analysis.

The weighted average value per container was determined by weighing the average concentration from each site by its fraction of the total containers employed in WIPP as of October 26, 1999, (101 SWBs from LANL, 126 drums from INEEL, and 434 drums from RFETS). LANL SWBs were counted as two drum equivalents because they contain two filters and >6 times the head space gas volume of a drum. The fractions of total drum equivalents is 0.265 for LANL, 0.165 from INEEL, and 0.570 for RFETS.

Table A-1. VOC Concentrations in Pre-Permit Waste at WIPP

	Average Concentrations - ppmv			Weighted Average (ppmv)	Comments
VOC	LANL	RFETS	INEEL		
Acetone	60.2	4.6	5.9	19.6	delete, not HW Risk
Methanol	22.1	9.1	6.8	12.2	delete, not HW Risk
1,1,1-Trichloroethane	1.0	0.1	15.9	2.9	non-carcinogen
Methylene Chloride	1.0	0.09	0.54	0.41	carcinogen
Methyl Ethyl Ketone	16.1	0.37	0.47	4.6	non-carcinogen
Toluene	1.9	0.28	0.17	0.69	non-carcinogen
Carbon Tetrachloride	0.9	0.1	0.4	0.37	delete, few J values
Benzene	1.1	0.14	0.12	0.39	carcinogen
Trichloroethylene	0.9	0.00	0.2	0.27	delete, no J values

A.2 Exhaust Shaft and Environmental Concentrations

The weighted VOC concentration for each VOC from Table A-1 can be related to the exhaust shaft concentration (ECS) by the following expression (from Appendix D9 of the Application):

$$ECS = x \frac{[D_{voc}\ (MF)_{voc}]\ MW_{voc}(1x10^{6}\ \mu g/g)}{V(.0283)m^{3}/ft^{3}\ (.01667\ min/s)} \qquad \textbf{(A-1)}$$

where:

x = number of drum equivalents, 762

D_{voc} = diffusion rate through an NFT-013 filter, moles/s-mole fraction-drum

Mw_{voc} = molecular weight of VOC, grams per mole

MF_{voc} = mole fraction mole/mole

V = exhaust ventilation rate, (260,000) cubic feet per minute

When constant values are combined, Equation A-1 reduces to:

$$ECS = 6.21x10^{6}\ D_{voc}\ MF_{voc}\ (MW_{voc})\ \mu g/m^{3} \qquad \textbf{(A-2)}$$

Filter specific diffusion rates for each VOC relative to H_2 gas were calculated from Equation D9-7 in Appendix D9 of the Application. Molecular weight, critical pressure, and critical temperature of a VOC are factors in determining the diffusion rate.

Exhaust shaft concentrations are shown in Table A-2. The annual air dispersion factors (ADF) for determining VOC concentrations in the environment were taken from Appendix D9. These values are $1.23x10^{-2}$ for the aboveground worker and $1.2x10^{-4}$ at the WIPP site boundary. The calculated VOC concentrations at these two locations are also shown in Table A-2.

Table A-2. VOC Concentrations in Exhaust Ventilation & Environment From Pre-Permit Waste at WIPP

VOC	D_{voc} Mole/s-mole fraction-drum	Mole Fraction	Molecular wt.	Concentrations -µg/m^3		
				Exhaust Shaft	Above Ground	Site Boundary
Methylene Chloride	1.47×10^{-6}	4.1×10^{-7}	84.94	3.18×10^{-4}	3.91×10^{-6}	3.81×10^{-8}
Benzene	2.06×10^{-6}	3.9×10^{-7}	78.11	3.89×10^{-4}	4.78×10^{-6}	4.67×10^{-8}
1,1,1-Trichloroethane	1.21×10^{-6}	2.9×10^{-6}	133.42	2.90×10^{-3}	3.57×10^{-5}	3.48×10^{-7}
Methyl Ethyl Ketone	1.30×10^{-6}	4.6×10^{-6}	72.11	2.67×10^{-3}	3.28×10^{-5}	3.20×10^{-7}
Toluene	1.19×10^{-6}	6.9×10^{-7}	92.13	4.69×10^{-4}	5.77×10^{-6}	5.63×10^{-8}

A.3 Risk to Surface Worker

The surface worker is assumed to be exposed to VOC emissions from the repository exhaust ventilation shaft for a period of 1920 hours a year. This calculation also assumed Room 7 will remain open for a period of one year before being filled and sealed. Room 7 could be open less than one year if the decision is made to seal the partially filled room before bringing in RCRA regulated waste. However, it will probably be some time in the year 2001 before the room will be completely filled. Carcinogenic risks from each VOC can be determined for the surface worker by the following relationship:

$$Risk = ECS\ (ADF)s\ (URF)\ Fs \qquad \textbf{(A-3)}$$

where:

URF = cancer unit risk factor (for a lifetime exposure) in m^3/µg

(ADF)s = air dispersion factor for surface worker, dimensionless

Fs = fraction of lifetime exposed, dimensionless

Current unit risk factors (URF) were obtained from EPA's IRIS data base. The URF is expressed in reciprocal concentration units so that the product of Equation A-3 is dimensionless. The air dispersion factor is 1.23 x 10^{-2} and Fs is 0.00392 (1920 hours exposure in one year at 1.2 m^3/h inhalation rate divided by a lifetime inhalation of 588,000 m^3). Any exposure to carcinogens is assumed to result in a risk, regardless of the concentration (i.e., there is no threshold below which no damage occurs). The total VOC carcinogenic risk can be obtained by summing the total carcinogenic risks from all the carcinogenic VOCs.

Non-carcinogenic effects are evaluated using a hazard quotient from each VOC_i (HQ_i) defined as:

$$HQ_i = \frac{average\ \ exposure\ \ concentration, VOC_i}{RfC_i}\ (F) \qquad \textbf{(A-4)}$$

where:

RfC_i = the chronic reference dose for exposure by inhalation from VOC_i, µg/m^3

F = fraction of a 35 year working lifetime exposed

Values of RfC_i are obtained from the IRIS data base. In this case F is 0.00784 (2340 m^3 inhaled in one year divided by 294,000 m^3).

The sum of the HQ_i values for all radionuclides can be summed into a Hazard Index (HI):

$$HI = \sum_{i=1}^{i=t} HQ_i \qquad \textbf{(A-5)}$$

For HI values less than 1.0 adverse health effects are unlikely and, because non-carcinogens have a threshold below which damage does not occur, values much below 1.0 have no precise meaning. Long-term non-carcinogenic health effects are possible for HI exposures greater than 1.0. The HI is definitely not probabilistic, i.e., a value of 0.01 does not imply a 1% probability of an effect.

Risks to surface workers from carcinogens and non-carcinogens are shown in Table A-3. These risks are extremely low. The implications of these values are discussed in Chapter 3.

Table A-3. Annual Risks to Surface Worker from Carcinogens and Non-Carcinogens From Pre-Permit Wastes at WIPP

VOC	ECS(ADF)F $\mu g/m^3$	URF ($m^3/\mu g$)	Risk
Carcinogens			
Methylene Chloride	1.53×10^{-8}	4.7×10^{-7}	7.20×10^{-15}
Benzene	1.88×10^{-8}	8.3×10^{-6}	1.56×10^{-13}
Total			1.63×10^{-13}
Non- Carcinogen		RfC	HQ
1,1,1-Trichloroethane	2.80×10^{-7}	700	4.00×10^{-10}
Methyl Ethyl Ketone	2.57×10^{-7}	1000	2.57×10^{-10}
Toluene	4.52×10^{-8}	400	1.13×10^{-10}
Total			HI = 7.70×10^{-10}

A.4 Risk at WIPP Site Boundary

The Maximum Individual Receptor (MIR) is defined as a member of the public who resides at the WIPP site boundary. Residence time is assumed to be 100% for the year. The methodology for calculating the risk is the same as for the surface worker and the only values changed are ADF (1.2×10^{-4}), F for carcinogens (.0143), and F for non-carcinogens (0.0286). The results are shown in Table A-4.

Table A-4. Annual Risks to Member of the Public from Carcinogens and Non-Carcinogens From Pre-Permit Waste at WIPP

VOC	ECS(ADF)F ($\mu g/m^{3)}$	URF ($m^3/\mu g$)	Risk
Carcinogens			
Methylene Chloride	5.45×10^{-10}	4.7×10^{-7}	2.56×10^{-16}
Benzene	6.68×10^{-10}	8.3×10^{-6}	5.54×10^{-15}
Total			5.80×10^{-15}
Non-Carcinogen		RfC	HQ
1,1,1-Trichloroethane	9.95×10^{-9}	700	1.42×10^{-11}
Methyl Ethyl Ketone	9.16×10^{-9}	1000	9.16×10^{-12}
Toluene	1.61×10^{-9}	400	4.02×10^{-12}
Total			HI= 2.74×10^{-11}

A.5 Risk to Underground Workers

Underground workers are estimated to be in the south 1600 exit panel drift for 20 minutes each time they enter to inspect and service the CAMs located at the Room 7 bulkhead. For two entries per day and 200 days per year this amounts to approximately 130 hours of exposure per year. The exit air flow from Room 7 and in the drift is assumed to be 35,000 cubic feet per minute and the VOC emissions to be fully mixed at the location of the underground workers. The flow and mixing assumptions do not reflect actual conditions for two reasons: (1) The 35,000 cfm flow was used during the waste emplacement period. However, during much of the time between emplacement of the last of the pre-Permit wastes prior to November 26, 1999, and about March 13, 2000, when waste emplacement resumed, the flow through Room 7 was reduced to very low levels by installation of a brattice cloth at the inlet to the room; and (2) it is likely that much of the time workers were near the bulkhead and at the location of the CAMs they were exposed to air that contained a lower concentration of VOCs than would occur once there was

complete mixing. The first condition would result in higher VOC concentrations at the exit louvers but probably less mixing and could cause higher exposures than calculated for the time-period of low flow. Condition 2, if it exists, would decrease calculated exposures. There are no data available to quantitatively evaluate conditions 1 and 2.

VOC concentrations in the drift can be obtained by modifying Equation A-1 to reflect the lesser dilution (35,000 cpm) in the drift to that in the exhaust shaft (260,000 cfm). The drift concentration is thus 7.43 times the ECS.

The carcinogenic risk to the underground worker is calculated from modifying Equation A-3. The concentration is 7.43 ECS and the ADF is 1.0. URF values are unchanged. The F value (for 130 hours at 1.2 m^3/h) is 2.65×10^{-4}.

Non-carcinogenic risks can be calculated from Equations A-4 and A-5. The F value (for a 35 year working lifetime) is twice the Fs value used for the carcinogenic risk (5.30×10^{-4}). Carcinogenic and non-carcinogenic risks are shown in Table A-5.

Table A-5. Annual Carcinogenic and Non-Carcinogenic Risks to an Underground Worker from Pre-Permit Wastes at WIPP

VOC	Drift Concentration ($\mu g/m^3$)	Risk/Hazard Quotient
Carcinogens		
Methylene Chloride	2.36×10^{-3}	2.94×10^{-13}
Benzene	2.89×10^{-3}	6.36×10^{-12}
Total Risk		6.65×10^{-12}
Non-Carcinogens		
1,1,1-Trichloroethane	2.15×10^{-2}	1.63×10^{-8}
Methyl Ethyl Ketone	1.98×10^{-2}	1.05×10^{-8}
Toluene	3.48×10^{-3}	4.61×10^{-9}
Hazard Index		3.14×10^{-8}

APPENDIX B
RISK ANALYSIS FROM ACCIDENTS

The calculation of exposures, doses, and risks from VOC and radionuclide releases is similar for both the spontaneous underground fire and the roof fall scenarios.

B.1 VOC Risks

The ECS for accidental releases can be determined by an expression similar to expression (A-1) in Appendix A. The difference is due to replacement of the diffusion term from multiple drums by the fraction of a mole of HSG released in one minute. The ECS term becomes:

$$(ECS)_{acc} = 5570(m^3 HSG)\ (MW)(MF)\ \frac{\mu g}{m^3} \qquad \textbf{(B-1)}$$

The WWIS lists an average LANL standard waste box fill volume of 44%. This results in a headspace gas volume of 1.064m^3 for the 1.9m^3 SWB. For the underground fire accident equation B-1 becomes:

$$(ECS)_{acc} = 5930\,(MW)(MF)\frac{\mu g}{m^3} \qquad \textbf{(B-2)}$$

The risk to a surface worker for a one minute exposure is calculated from Equation A-3 when using an Fs value of 3.40x10^{-8}. The risk at the WIPP site boundary is obtained from using an ADF of 1.2x10^{-4} and the 3.40x10^{-8} Fs value.

Results of the VOC carcinogenic risk calculation to a surface worker from the underground fire scenario are presented is Table B-1.

Table B-1. VOC Lifetime Fatal Cancer Risk to a Surface Worker from an Underground Fire Scenario at WIPP[a]

VOC	Molecular wt.	Mole Fraction	URF $m^3\mu g$	Risk	
				Surface W	S. Boundary
Methylene Chloride	84.94	1.0×10^{-6}	4.7×10^{-7}	9.90×10^{-17}	9.67×10^{-19}
Benzene	78.11	1.1×10^{-6}	8.3×10^{-6}	1.77×10^{-15}	1.73×10^{-17}
Total				1.87×10^{-15}	1.83×10^{-17}

[a]Risks assume the probability of the scenarios is 1.0.

The release from the roof fall accident is five times that from the spontaneous underground fire accident because five SWBs are breached. Therefore, the VOC carcinogenic risk would be 9.35×10^{-15} for the surface worker and 9.15×10^{-17} for the public member at the WIPP site boundary.

B.2 Radionuclide Risk

B.2.1 Radionuclide Source Term

The expression used in the SAR (Section 5.2.1) for determining the quantity of radioactivity (Q in curies) released is:

$$Q = MAR(DR)(ARF)(RF)(LF) \qquad \textbf{(B-3)}$$

where:

MAR = Material at Risk in Curies. Contents of one SWB (4.24 Ci) for underground fire and 5 SWB (21.2 Ci) for roof fall

DR = Damage Ratio, 1.0 for UG fire, 0.010 for roof fall

ARF = Airborne Release Factor, 5×10^{-4} for UG fire, 1×10^{-3} for roof fall.

RF = Respirable Fraction, 1.0 for both scenarios

LF = Leakpath Fraction, 1.0 for both scenarios

With these assumed parameter values the radionuclide releases (Q) are 2.12×10^{-3} Ci for the UG fire and 2.12×10^{-4} Ci for the roof fall. The roof fall values are less because the DR value for a roof fall is less than for the UG fire.

B.2.2 Radionuclide Cancer Risk

The radionuclide quantity inhaled by the surface worker or the MIR can be obtained with an expression similar to A-3. Then, multiplication by the dose conversion factor (DCF rem/Ci inhaled) and the cancer risk to dose factor (RDF) (cancer risk per rem) give the cancer risk for the radionuclide release. The risk becomes:

$$Risk = \frac{Q(ADF)(1.2\frac{m^3}{hr}\ inhaled)(DCF)(RDF)}{2.6x10^5\ \frac{ft^3}{\min}\ (.0283\ \frac{m^3}{ft^3})\ 60\frac{\min}{hr}} \qquad \textbf{(B-4)}$$

where:

ADF = Air Dispersion Factor, 1.23×10^{-2} for surface worker, 1.2×10^{-4} for boundary

DCF = 3.92×10^{8} rem per Ci for ^{238}Pu (US EPA 1988)

RDF = 1×10^{-4} risk per rem (NAS 1988)

The resulting cancer risks for the UG fire scenario are 2.78×10^{-6} for the surface worker and 2.71×10^{-8} for the resident at the site boundary. For the roof fall scenario the risks are 2.78×10^{-7} for the surface worker and 2.71×10^{-9} for the MIR. Risks to the underground worker would be 1.69×10^{-3} from the UG fire scenario and 1.69×10^{-4} for the roof fall scenario.

A member of the public could be at the exclusive use area boundary and be exposed to the accidental release. The maximum ADF value shown in Appendix D9 is 7.5×10^{-4} at the northern exclusive use area boundary. Resulting risk to a member of the public would be 1.69×10^{-7} for the UG fire scenario and 1.69×10^{-8} for the roof fall scenario.

B.3 Radiation to VOC Risk Ratio

The relative risk from VOC releases compared to radionuclide releases can be obtained from the above calculations. The radionuclide risk is 1.49×10^9 times the VOC risk for the underground fire scenario and it is 2.97×10^7 times the VOC risk for the roof fall scenario.

B.4 Comparison with SAR Exposures

The values for exposure from radionuclides and VOCs in Appendix E, Revision 3 of the Safety Analysis Report are much higher than the values calculated here. There are several reasons for this:

1. The SAR used an 80 PE-Ci quantity in the container compared to the use here of the average value in the LANL SWBs (4.24 Ci).

2. The radionuclide dose conversion factor used in the SAR was 5.1×10^8 rem/Ci for ^{239}Pu rather than the EPA value of 3.92×10^8 rem/Ci for ^{238}Pu.

3. SAR radionuclide dispersion values were obtained using the χ/Q methodology and this report used the Long-Term Version of the Industrial Source Complex (ISCLT3) model (EPA) that resulted in the Appendix D9 Air Dispersion Factors. The SAR methodology resulted in concentrations about 50 times greater than the ADFs.

Agreement with the SAR values was within one percent when these differences are incorporated.

The radionuclide dispersion calculations require greater discussion. Use of the ADF methodology, which uses annual average dispersion values, would not be conservative for the low probability one-hour conditions that might occur during an accident. The χ/Q methodology calculates the dispersion of particles, atoms, or molecules and does not consider dilution prior to exhaust from the ventilation shaft. The unfiltered exhaust volume from WIPP varies between

260,000 and 425,000 cfm (123 to 200 m^3/sec). The concentration calculated from the χ/Q methodology at 100 m is 63% of the concentration in the exhaust shaft at a 260,000 cfm ventilation rate and 103% at a 425,000 cfm rate. There is no apparent physical means by which concentrations would increase after leaving a stack. U. S. Nuclear Regulatory Commission Regulatory Guide 1.145 (US NRC 1983) assumptions lead to a prediction that the size of the WIPP exhaust plume would increase by a factor of about 3.7 at 100 m during very stable (G) atmospheric stability conditions. For moderately stable (F) atmospheric stability the plume size would increase by a factor of about 24.

It is concluded that the atmospheric dispersion factors used may be non-conservative by a factor of up to 5 for very stable Class G atmospheric conditions while the χ/Q value would usually be conservative by an order of magnitude. The use of worst case meteorological condition may be appropriate in a consequence analysis for very low probability events where doses may be high enough to cause acute effects, but is not necessary for a risk calculation.

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PLUTONIUM CHEMISTRY UNDER CONDITIONS RELEVANT FOR WIPP PERFORMANCE ASSESSMENT

Review of Experimental Results and Recommendations for Future Work

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September 2000

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U. S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the compliance of the generator sites with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of radioactivity in air, water, and soil, both on-site and off-site.

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ABSTRACT

The Waste Isolation Pilot Plant (WIPP), located at a depth of 650 m in bedded salt at a site approximately 40 km east of Carlsbad, New Mexico, was constructed by the US Department of Energy for the disposal of transuranic wastes arising from defense-related activities. The disposal site is regulated by the US Environmental Protection Agency (EPA). During the process leading to certification of the site for initial emplacement of waste, EEG and their contractors reviewed the DOE Compliance Certification Application (CCA) and raised a number of issues. This report reviews the issues related to the chemistry of plutonium as it will affect the potential for release of radioactivity under WIPP conditions. Emphasis is placed on conditions appropriate for the Human Intrusion scenario(s), since human intrusion has the largest potential for releasing radioactivity to the environment under WIPP conditions. The most significant issues that need to be addressed in relation to plutonium chemistry under WIPP conditions are (1) the effects of heterogeneity in the repository on Pu concentrations in brines introduced under the human intrusion scenario, (2) the redox state of Pu in solution and potential for plutonium in solid phases to have a different redox state from that in the solution phase, (3) the effect of organic ligands on the solubility of Pu in WIPP-relevant brines, and (4) the effects of TRU waste characteristics in determining the solubility of Pu. These issues are reviewed with respect to the treatment they received in the DOE CCA, DOE's response to EEG's comments on the CCA, and EPA's response to those comments as reflected in the final EPA rule that led to the opening of the WIPP. Experimental results obtained in DOE's Actinide Source-Term Test Program (STTP) during the last two years are reviewed and interpreted in the light of other developments in the field of Pu solution chemistry. This analysis is used as the basis for a conceptual model for Pu behavior under WIPP conditions.

This report identifies three issues that can be addressed as part of the five-year re-certification cycles mandated by the WIPP Land Withdrawal Act (U.S. Congress, 1996, '8.(f)(1)) and implemented in the EPA Final Rule (U.S. EPA, 1998a). First, the impact of organic ligands on the complexation of a system with multiple cations could be delineated by some simple experiments with Th (IV), citrate,

EDTA, Ca^{2+} and one or more transition metals. An experiment with Pu (IV) could be designed to determine the lability of Pu oxidation states in the presence of organic ligands. Second, the issue of using analogs for Pu could be addressed with appropriate experiments using U and Pu at redox conditions in the range anticipated at the WIPP. Attention to the published experimental results of U and Pu could make a considerable contribution to this effort. Third, the issue of uncertainty in calculated actinide solubility can be resolved with experimental data for Pu (IV) compounds of appropriate compositions. The report also recommends starting by constructing a data base for U and Pu using the published, peer-reviewed OECD/NEA U and Pu data bases.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) was constructed by the US Department of Energy (DOE) to serve as a disposal site for transuranic radioactive wastes that arose through defense-related activities. The WIPP facility was built in a bedded salt formation at a depth of 650 m and is located approximately 40 km east of Carlsbad, New Mexico. The disposal facility is regulated by the US Environmental Protection Agency (EPA) through their Radiation Protection Standards for disposal of transuranic waste. The regulatory process involves DOE filing with EPA a Compliance Certification Application. (CCA). This was done in October, 1996 (DOE, 1996). The Environmental Evaluation Group (EEG), which conducts independent technical evaluations of the impact of the WIPP project on public health and on the environment, identified a number of concerns arising from the CCA. One of these concerns was a group of issues related to the chemistry of actinide elements, especially plutonium, under conditions that are relevant for assessment of the long term behavior of the WIPP facility (Chaturvedi et al., 1997).

The EPA published its technical review of the DOE WIPP source term program and modeling in October, 1997. EEG then asked Dr. V. Oversby to evaluate the DOE modeling efforts and the EPA review. That review, which was communicated to EEG as a letter report, identified many of the issues that were subsequently summarized in a letter from EEG to EPA (December 31, 1997, contained as Appendix 8.3 in EEG-68, 1998). Detailed reviews of the DOE Chemical Conditions Model, the actinide solubility calculations, and the SOTERM appendix to the CCA were also provided to EEG by Dr. Oversby, and are contained in Appendix 8.4a of EEG-68. Dr. Oversby's review of the EPA technical support document issued in 1997 was reproduced on pages 45-56 of EEG-68.

A meeting was held in Albuquerque, NM, on February 20, 1998, so that EEG, Dr. Oversby, and scientists from Sandia National Laboratories and their contractors could discuss EEG's concerns. Following that meeting, DOE sent a response to the EEG comments to the WIPP Program Manager at

EPA, with a copy to EEG (letter dated February 24, 1998). The relevant technical content of EEG's concerns and DOE responses are discussed in the following section.

On May 18, 1998, EPA issued its final rule certifying the WIPP facility and identifying the requirement for a five-year recertification cycle (EPA, 1998a). EPA also published a separate document that responded to comments that had been received during the public comment period for WIPP certification. The details of the EPA responses, where they are relevant to plutonium chemistry issues, are discussed in the next section.

PLUTONIUM CHEMISTRY ISSUES

There are four major factors that will determine the effective solubility of plutonium in the WIPP environment. These are (1) the redox conditions, (2) the brine composition, (3) the availability of ligands through degradation of the waste, and (4) the effects of slow kinetics of reaction due to lack of lability of species (i.e., persistence of metastable species). The brine composition, itself, will be affected by the persistence of metastable reaction products, especially those formed by backfill materials, such as MgO.

The DOE CCA attempted to predict the solubility of plutonium and other actinides under WIPP conditions by using a chemical modeling code, FMT. The FMT code was developed at Sandia National Laboratory for use in performance assessment exercises for the WIPP project. FMT used the Pitzer formalism for dealing with the corrections to activity of solution species in high ionic strength brines. DOE chose to use an oxidation state analogy for dealing with actinide chemistry. This analogy treated each possible oxidation state in isolation and did not allow for the different oxidation states of a single element to interact in response to other conditions in the reacting system. For the actinide (IV) oxidation state, DOE used thorium data in the model calculations and claimed that this was conservative because thorium would be more soluble than plutonium in the (IV) oxidation state.

In her review of the DOE CCA, Oversby (1997) discussed each of the factors listed above and recommended experimental work to provide data needed to improve the modeling efforts and also recommended improvements to the modeling itself. In particular, a sensitivity analysis to determine the effects of uncertainties in the solubility measurements and stability constants used in the FMT data base as well as the uncertainties in the Pitzer parameters used to estimate activity coefficients in brines was recommended. The appendices to the Oversby (1997) report discussed in detail issues that arose through the review of the DOE CCA and selected supporting documents. These reviews and the review by Oversby of the EPA technical review of the DOE WIPP source term program and modeling led EEG to conclude that the following items were of concern (cited from EEG-68):

"1. The FMT model is unique to WIPP. EEG found that the model predicts differences for actinide sulfate and carbonate solubilities that can not be explained by chemistry, thus leaving the reliability of the calculations suspect. The unexpected results need to be explained or the model needs to be re-examined for possible problems with the code.

2. Rather than use an extensive plutonium data base, the FMT predictions relied on thermodynamic data for other elements and an oxidation state analogy argument. EEG recommends that the calculations be performed using data for plutonium and the values for solubility and complex ion formation contained in the peer-reviewed data compilation by OECD/NEA.

3. EEG agrees with EPA's documentation of the shortcomings of the solubility uncertainty ranges advanced by DOE. However, EPA has accepted the ranges as adequate based on a weak argument. EEG recommends that the uncertainty range needs to be determined with the appropriate plutonium data.

4. In the solubility calculations, the CCA inappropriately discounts the role of organic ligands on plutonium solubility by arguing that EDTA is the strongest complexing agent. But citrate forms very strong complexes with actinides in the +4 oxidation state and very weak complexes with other cations. Thus, the solubility of a stable plutonium-citrate complex in individual waste containers needs to be calculated.

5. There are serious unanswered questions about the impact of magnesium oxide backfill on the solubility of the actinides. It is proposed that magnesium oxide will reduce the solubility of the actinides by controlling pH. But, it is not known how long the early reaction product, nesquehonite, will persist. The FMT model calculates that the presence of nesquehonite drives the solubility of the +4 actinides, such as plutonium, higher than in the no backfill case. This requires further investigation."

The comments by Oversby concerning the EPA "Technical Support Document 194.24: EPA's Evaluation of DOE's Actinide Source-Term" as reproduced in EEG-68 (1998) included

> "The EPA evaluation of expected redox states, solubility, and speciation of actinides under WIPP disposal conditions was very narrow in its scope. In general, only the references cited by DOE and the work done by the DOE contractors was discussed. The evaluation would be considerably strengthened, and might reach different conclusions, if relevant results published in the open literature of studies conducted by other scientists were discussed.
>
> The EPA has limited their review of the DOE solubility calculations to an exercise in which EPA used the Sandia computers, codes, and databases to determine whether they could get the same numerical values for results if they tried to duplicate the work done by DOE. It would have been very surprising if they had failed to find agreement under those conditions. A more reasonable evaluation would require a comparison of the results of calculations using a code that is used more widely in the modeling community with those obtained by the Sandia FMT code.
>
> There has been no evaluation by EPA of the thermodynamic properties data used in the database for the solubility calculations. There has been no attempt by EPA to assess the degree to which the calculations might represent the conditions expected for WIPP disposal. Both of these tasks are needed in order to determine whether the DOE calculations have any validity.
>
> In evaluation of the effect of organic ligands on the mobilization of actinides, EPA considers only the case of homogeneous equilibrium, in which the entire actinide inventory in the repository is well-mixed with a very large volume of brine that inundates the repository. This is an unrealistic and non-conservative model for evaluation of the effect of organics. In addition, EPA bases their evaluation of the ability of organics to mobilize actinides on an analysis that only considers EDTA. While this analysis gives the correct result for the importance of EDTA, it does not speak to the issue of the importance of citrate in the waste and its ability to increase the mobility of Pu."

The specific comments by Oversby on each section of the EPA evaluation of DOE's source term were also reproduced in EEG-68 (1998). This EEG report was submitted to EPA as comments on the proposed rule. The limitations of the oxidation state analogy were discussed, and it was noted

> "The oxidation states expected by DOE for Pu in the WIPP repository are III and IV. Any Pu(V) formed is expected to be rapidly reduced by iron. EPA concurs with this conclusion; however, Pu(V) is observed as a long-lived transient in many laboratory experiments. Pu(V) may be formed as a result of radiolysis reactions in the brines and while its total abundance in the repository is likely to be low, it might be significant as a transient species in some waste containers. The release scenarios considered important for WIPP are those involving human intrusion, with drilling through the repository to a brine-containing formation below the repository. Upwelling of brine from this lower layer through the repository might allow rapid transport of brines containing some Pu(V) to the surface."

The issue of heterogeneity in the repository was raised by Oversby (cited in EEG-68, 1998) during a discussion of section 7 of EPA's evaluation document, which concerns the effect of complex ion formation on enhancement of solubility. EPA concluded that organic ligands would not increase actinide mobility. In their analysis, EPA used the same assumption used by DOE that the system could be modeled assuming homogeneous equilibrium of brine and actinides. In her discussion of this point, Oversby stated

> "both DOE and EPA assumed that the actinides would be evenly distributed throughout the repository and that the brines would be well-mixed and have a uniform composition throughout the repository. This is unlikely to be the case and is certainly not appropriate for evaluation of the development of dissolved actinides inside a partially destroyed waste container, a scenario that is important with respect to assessment of human intrusion consequences."

> and

> "To model the behavior of Pu with citrate, we must also consider heterogeneous equilibria for organic complexation with the actinides. The main difficulty arises because the Pu in the waste is probably located in the same drums as the citrate, which is the dominant organic ligand. This is because these wastes arise from chemical separations of Pu and are not the type of waste described in the general descriptions of TRU waste as contaminated equipment, clothing, etc. To get an accurate estimate of the effect of organic ligands on Pu solubility, one must calculate the concentration of Pu as citrate complex inside a waste drum that has been breached, but can still provide a hindrance to mixing of the brine inside the drum with a larger pool of brine outside the drum. This will give a high concentration of Pu in solution as the citrate complex. Other ions will not compete with Pu sufficiently to prevent complex formation because the stability for (IV) actinide complexation – as shown by the stability constant for Th(IV) on p. 39 of the SOTERM appendix – is orders of magnitude larger than that for other ion complexes with citrate."

EEG met with EPA WIPP project staff on December 10, 1997, in Albuquerque, NM to discuss some of EEG's concerns with the draft EPA rule on WIPP. A summary of the issues discussed, as well as a summary of several other issues that had been raised previously, was sent to Mr. Frank Marcinowski (EPA Radiation Protection Division, Washington, DC) by letter dated December 31, 1997, with copies to other interested parties including DOE and the EPA Docket for WIPP (A-93-02). DOE arranged a meeting between Sandia staff working on the WIPP project, their contractors, EEG, and their consultants in Albuquerque on February 20, 1998, to discuss the actinide solubility issues in detail. Following that meeting, DOE responded to the comments contained in the EEG letter of December 31, 1997, by letter dated February 24, 1998, to Ms. Mary Kruger (WIPP Program Manager for EPA). The DOE responses contained in the February 24, 1998, letter did not address the substance of the solubility issues raised by EEG in their letter of December 31, 1997, and at the meeting held on February 20, 1998. DOE restated their previously published arguments. An independent observer at the meeting, Prof. R. C. Ewing, who had been a member of the National Research Council's Committee on the Waste Isolation Pilot Plant, sent written comments to EEG after the meeting. These comments, contained in a letter dated February 22, 1998, to Mr. Robert H. Neill, Director of EEG,

highlighted the need for further experimental work on actinide chemistry and the need to go beyond the simple Th analog model to actual experiments with plutonium. Prof. Ewing stated in particular (letter reproduced in EEG-68, 1998) that "The project is still not in a position to present and discuss models of the longer term evolution of the chemistry of the WIPP system."

The DOE response concerning the use of the Th(IV) analog for plutonium(IV) behavior did not address the central issue in actinide chemistry where multiple oxidation states are possible. It is the lability between the various oxidation states and the details of the chemical environment that determine the formal oxidation state of actinides such as Pu, U, and Np. It is also well known that the solution species oxidation state may be different from that in the solid (e.g., U(VI) in solutions in contact with air and with uranium(IV) dioxide solid). The use of Th(IV) to model Pu(IV) behavior has the intrinsic limitation that Th can only exist in geologic systems as Th(IV). This point will be discussed in more detail in the section concerning recent experimental results obtained by workers outside the WIPP project.

The other issue raised by EEG was that of homogeneous versus heterogeneous equilibria. DOE maintained the assumption of homogeneity for the chemical conditions in the repository, which was a consequence of mixing of chemical species through the solution phase in a fully saturated brine environment. Further, the CCA stated that no chemical microenvironments that influence the chemical environment are expected to persist, which can be viewed as a tacit recognition that microenvironments could have an impact on the overall chemical environment. The assumption of a repository fully saturated with brine is not the expected condition for the WIPP repository, to which access of brine is expected to be limited under normal geologic conditions.

When EPA issued its Final Rule concerning the certification of the WIPP facility, they also published a response-to-comments document (EPA 1998b) to provide a record of the comments received and their disposition. The EPA response to issues related to actinide solubility (other than those associated with MgO) are discussed below. Of the issues that EEG raised, EPA discussed the effect of organic ligands on solubility (Issue V, pp. 6-60 to 6-66), the oxidation state analogy (Issue Y, pp. 6-71 to 6-76), solubility uncertainty range problems (Issue Z, pp. 6-76 to 6-80), and plutonium (VI) (Issue CC, pp. 6-84 to 6-86). In addition, EPA discussed issues raised that involved the long-term behavior of the MgO

backfill and its effects on brine chemistry and actinide solubility, as well as issues related to the FMT computer code and its data base. In this report, we will focus on the issues related to actinide solubility for which we have recommendations for further experimental work and limit our discussion of issues related specifically to the MgO backfill and the FMT computer code.

We recognize that MgO is a key component of the repository chemistry, but there are limited data from the WIPP Source Term Program for MgO Backfill. At the time the STTP experiments were begun in 1995, other material, such as bentonite, was considered a leading backfill candidate and was included in the test matrix. The idea to use MgO as the only backfill in the WIPP repository came as a late development in the application process (NEA/ IAEA, 1997). MgO was added to only one of the liter-scale tests in the Source Term Program in February 1997. The waste was a pyrochemical salt immersed in brine and maintained under 60 bar of CO_2 pressure. Prior to adding MgO, that container had exhibited a very high actinide solubility. The results of the MgO addition are discussed briefly in this report; the observations do not change the recommendations for further experimental work to resolve the identified actinide solubility issues. Moreover, the behavior of MgO in brines has far-reaching implications and merits its own investigation.

As discussed above, concerns about the use of the FMT computer code have been documented previously. Rather than revisit that conceptual model and computer code, this report promotes two approaches to address our documented concerns. First, directly tackle the issue of model uncertainty by generating experimental data for plutonium in brines of appropriate chemical composition. Second, starting with a peer-reviewed database for plutonium and uranium, adjust solution species activity as a function of ionic strength using Specific Ion Interaction Theory, rather than try to determine Pitzer parameters, which can have very large uncertainties for highly charged species, for use in the FMT code. Details can be found in the final section of this report.

In their discussion of the effect of organic ligands, EPA echoed the argument DOE had used in the CCA. They assumed a well-mixed, homogeneous repository and calculated average concentrations of organics and actinides in the case of brine saturation of the repository. They also cited a calculation

showing that EDTA formed the strongest complexes of all organic ligands with actinide(IV) species and, further, that other divalent cations in the brine, such as Fe(II) and Ni(II) would be able to use up most of the EDTA, so there would not be much left for the actinides. EPA then concluded that since EDTA formed the strongest An(IV) complexes and would not significantly increase An(IV) mobility, then no other organic complex would either. This reasoning does not accommodate the observation that citrate forms strong complexes with An(IV) cations and not with divalent cations, so there is no competitive reaction that eliminates citrate from the brine. We believe that the issue of the effect of organic ligands, especially citrate, on the mobility of plutonium under the Human Intrusion scenario remains unresolved. We will, therefore, recommend in the final section of this report some simple experiments that could resolve the issue.

The EPA addressed comments on the limitations of the use of Th(IV) as an analog for Pu(IV) chemistry by confining their comments to the behavior of the An(IV) oxidation state. They did not consider the possibility for Pu(IV) in the solid waste forms to coexist with a Pu(V) or Pu(VI) solution species in the brines. Work conducted during the last two years, both within and outside the WIPP program, indicates that dealing with the Pu(IV) oxidation state in isolation is an oversimplification of the actual chemistry of Pu-bearing systems (see next two sections). We believe that the issue of description of the behavior of Pu under scenarios relevant to Human Intrusion at WIPP must be addressed by relevant experiments using Pu-bearing wastes that are representative of those that may be disposed of at WIPP. Particular attention should be paid to experiments using wastes such as pyrochemical salts, since these may contain high percentages of Pu as discussed in the section on the WIPP Source Term Program. An outline of some appropriate experiments is given in the final section of this report.

The uncertainty range used by DOE for solubility estimates attracted several criticisms that were discussed in the EPA response to comments. (Note: In the Response to Comments document EPA used the terms “Am(VI)” and “Am(IV)”. These should be An(VI) and An(IV), where An stands for any actinide element.) EPA stated (p. 6-77) that in the uncertainty analysis “solubility data for actinides in the +6 oxidation state were not used. This decision seems appropriate in view of the fact that the CCA source term was unable to develop a solubility model for U(VI), which is the only hexavalent

actinide species expected under WIPP conditions." In view of recent experimental results that strengthen the possibilities that Pu(VI) as well as U(VI) may be important species in WIPP-related brines, EPA is urged to reconsider this position. Exclusion of An(IV) data from the uncertainty analysis because of difficulties that DOE contractors had with extrapolation of such data, including (apparently) data for Th(IV), exposes the weakness of both the uncertainty estimates for An(IV) species as well as the potential unreliability of the solubility calculations for these species. For these reasons, we recommend that appropriate experiments be conducted that can give an estimate of the range of solution concentrations and solution species identities that might exist in WIPP brines under potential Human Intrusion scenario conditions.

The EPA response to comments concerning the potential for Pu(V) or Pu(VI) to exist in the WIPP repository was two-fold. They argued first that the cited experimental observations were not relevant to WIPP because of the use of non-representative experimental conditions. They further argued that the presence of organic ligands in the repository would make Pu(V) and Pu(VI) unstable relative to Pu(IV). In light of recent experimental results (discussed below), this issue needs to be revisited. Work to address the possibility for Pu(V) and Pu(VI) species to exist in WIPP brines under conditions relevant to the Human Intrusion scenario and the effects of organic ligands are discussed in the final section of this report.

WIPP SOURCE-TERM PROGRAM

The DOE has sponsored an "Actinide Source-Term Waste Test Program" (STTP), conducted at the Los Alamos National Laboratory. The purpose of this testing program is to provide quantitative measurements of the mobile actinide concentrations in WIPP brines in continual contact with actual Contact-Handled Transuranic (CH-TRU) wastes. Additional objectives of the tests are to determine the influence of chemical additives on actinide concentrations and speciation and to measure the rate of gas generation in the test systems. Results from this test program, which included the detection of Pu(V) and Pu(VI) in four liter-scale containers, were presented to EEG at a briefing in Albuquerque on November 23, 1999, by Robert Villarreal (Los Alamos). EEG was given copies of viewgraphs used at the presentation; these viewgraph materials form the basis of the discussion that follows. Eight of the viewgraphs referenced in this report are reproduced in the Appendix.

This report was drafted prior to meetings held with EEG, EPA and DOE in April and June, 2000. The author has had an opportunity to ask the principal investigator of the STTP tests clarifying questions about the materials from the November meeting and has chosen to limit specific discussion to those materials. The discussions and materials presented at the subsequent meetings in April and June do not change the interpretations and recommendations in this report. Moreover, we have also been advised that some of the references cited in these subsequent discussions are in various stages of review prior to publication. For example, the material presented by L. Brush at the April and June meetings included reference to the work of Clark et al., LANL, for which the text is not available because it is still in internal review at Los Alamos. Other investigators at Los Alamos are also in the process of completing their analyses of the complex STTP systems. It would be more appropriate to reserve comment on the materials presented at the April and June meetings until after that work has been finalized, published, and is available for a detailed review.

The STTP program includes 15 drum-scale tests with heterogeneous wastes (combustibles, lab wastes, metals, etc.), 33 liter-scale tests with homogeneous wastes (sludges, cemented or solidified wastes,

pyrochemical salts), and 6 pressurized liter-scale tests with homogeneous wastes. We will focus discussion on the 33 liter-scale tests, of which 22 used Brine A (Salado formation brine) and 11 used Castile brine. [Note: In the Human Intrusion scenario, it is penetration of the Castile anhydrite formation accompanied by penetration of a brine pocket in the Castile that would cause brine to be brought up to the repository level and, through interaction with waste, potentially lead to releases of radioactivity at the surface via transport up the drill hole. For this scenario, it is actinide concentrations in the Castile formation brines that are most important, rather than the Salado formation brines.] All STTP tests were conducted in titanium vessels. The tests began in 1995 and had been running for at least 4 years at the time of the presentation in November, 1999.

The Castile brine, which is most relevant for the Human Intrusion scenario is a sodium chloride brine with minor sulfate and borate and small amounts of magnesium and bromine. The Salado Brine is a magnesium chloride brine with lesser amounts of sodium and potassium chloride and minor amounts of sulfate, borate, calcium, bicarbonate, and bromide.

Liter-scale tests L01-L12 were conducted with Portland Cement and solidified aqueous inorganic sludges. In addition to these components, L04-L06 were pressurized to 60 bars with carbon dioxide, and L10-L12 contained ^{241}Am as an additive. The Am would increase the total radioactivity in the test and enhance any effects due to radiolysis in the solution. The concentrations of actinides in the waste were not given in the presentation materials; however, the amount of Pu present can be calculated using a “Theoretical Pu Conc. (ng/ml)” value. We estimate a total Pu amount in the tests ranging from 30 to 200 mg in 0.25 to 1.3 kg of waste, implying a Pu concentration in the vicinity of 0.01%.

The results from non-pressurized tests with Portland cement showed that Th concentrations were uniformly less than 1 ppb in the brines, U concentration ranged from < 1 ppb to 8 ppb with no obvious correlation with test conditions, Pu had 2 results at <0.5 ppb, one at 0.5 ppb, 3 results at 1.0 to 1.1 ppb, one at 1.6 ppb, one at 7.8 ppb and one at 11.3 ppb. The two highest results for Pu occurred in the tests with Am added conducted in Salado brine, and may be due to enhanced solubility resulting from oxidation of Pu by radiolysis products and higher solubility of Pu at the pH found in tests with

Salado as compared to Castile brines (pH 9 versus pH 13). Results for Np concentration were erratic, with 6 values less than 1 ppb and one each at 9, 33, and 264 ppb. All of the high values for Np were found in Salado brine tests; however, since 3 other, nominally equivalent tests (except for a higher solution to solid ratio in the tests with high Np concentrations) gave results of < 1 ppb, it is hard to postulate a rational explanation for the results. Am concentrations were uniformly less than 1 ppb, even in the tests where Am was added to the system.

Th concentrations in the non-pressurized Portland cement tests were, with one exception, lower to much lower than concentrations found for U and Pu. This provides strong evidence that Th "solubility" is unlikely to be a realistic or conservative analog for Pu and U under WIPP disposal conditions.

Tests in Portland cement with carbon dioxide pressure at 60 bars gave much higher concentrations of U and Pu, but Th concentrations remained below 10 ppb. The U results showed extreme variability between the 3 different pressurized tests, but were more consistent within a given test as a function of time. Results for U were 9 to 15 ppm for the L04 test (i.e., about 10,000 times higher than Th concentrations for the same test), 0.3 to 0.7 ppm for the L05 test, and 3 to 5 ppm for the L06 test. Concentrations of Pu were also higher in the pressurized tests as compared with the non-pressurized tests, but the results were very erratic. The L04 test showed values for Pu starting at about 2 ppb and climbing (exponentially) to 255 ppb. The L05 test started at 2 ppb, reached 184 ppb by the second reported result, and then dropped to 5 to 25 ppb (in random order) for the last 4 sampling periods. The L06 test started at 25 ppb, peaked at 638 ppb at the 4th sampling period, and ended at 319 ppb at the 7th sampling. Results for Np were, with two exceptions, lower than those for U and Pu, and showed similar irregularities in solution concentration with time as did Pu. Again, the results show that Th concentrations are lower to very much lower than Np, Pu, and U concentrations and argue strongly against the use of Th as an analog for the chemistry of Np, Pu, and U.

Envirostone is a mixture of 80 to 90 % calcium sulfate with 10 to 20 % melamine-formaldehyde resin and about 0.1 % ammonium chloride. Results of tests using aqueous wastes absorbed onto Envirostone gave high to very high solution concentrations for U, very erratic concentrations for Pu, ranging from low (2.4 ppb) to high (1013 ppb), and also very erratic results for Np and Th, but with concentrations for

those elements generally less than found for Pu. There was no obvious pattern to the results. Tests using cemented wastes with Envirostone showed lower concentrations, probably due to the beneficial effects of the cement. Uranium concentrations, however, were still rather high, ranging from 0.3 to 0.8 ppm.

Fifteen tests were conducted using pyrochemical salts. These tests are particularly important since the amount of plutonium in pyrochemical salts is not a trivial fraction of the WIPP inventory and may be present in high concentrations in some cases. Estimates for the total amount of plutonium to be disposed of at the WIPP range between 13 and 16 metric tons (see, for example, Table 4, page 14 in Rechard et al., 2000). The pyrochemical salt residues to be sent from Rocky Flats contain about 1 metric ton of plutonium contained in 14.9 metric tons of pyrochemical salts (U.S. DOE, 1998a). The material falls into three categories; (1) electrorefining salts, (2) molten salt extraction salts, and (3) low-Pu and high-Pu-concentration direct oxide reduction salts. In two records of decision, the DOE has stated its intentions to;

1) repackage the low plutonium concentration direct oxide reduction salt residues to prepare them for disposal at WIPP (U.S. DOE, 1998b),
2) repackage the molten salt extraction/electrorefining salt residues, with possible blending at Rocky Flats to get below the 10 percent plutonium safeguards termination limit, for disposal at WIPP (U.S. DOE, 1999),
3) pyro-oxidize as much of the high plutonium concentration direct oxide reduction salt residues as possible, and probably all, and then repackage, with possible blending at Rocky Flats to get below the 10 percent plutonium safeguards termination limit, for disposal at WIPP (U.S. DOE, 1999).

Because the Pu concentration in pyrochemical salts that might be sent from Rocky Flats to WIPP could be very high, we believe that particular importance should be placed on the results of STTP tests that used pyrochemical salts. In the STTP series, all tests with pyrochemical salts were done using 2 parts liquid to 1 part solid, with the exception of tests using $Ca(OH)_2$ with chelating agents, which used a 3:1

ratio. General observations are that Pu concentrations for these tests are very much higher than for tests with the other waste types. The highest solution concentration of Pu was reported for the L27 test with Castile brine and pyrochemical salts (no additives) and was 30 ppm Pu. This is 30,000 times higher than for tests using cemented sludges. It should also be noted that the pH of this test was 11.1, so the result is far from easy to explain using equilibrium concentration calculations for Pu(IV) in Castile brine. Results for other actinides are also higher in these tests as compared to cemented waste tests, but the differences are no where near as large as for Pu. [Note: The tests using pyrochemical salts began in May, 1995, and (at least for some tests) continued through November, 1998, or later.]

Tests using pyrochemical salts in brine equilibrated with bentonite (L31-L33) produced lower Pu concentrations (0.12 to 0.21 ppm), but higher U concentrations in 2 cases. [The higher U may be due to complexation with carbonate released from the bentonite on equilibration with the brine. No chemical composition of the solution analyzed is given, so this hypothesis cannot be checked with the presently available information.]

Tests using pyrochemical salts with $Ca(OH)_2$ and chelating agents (L34-L36) gave relatively low concentrations of Pu in the Salado brine (0.1 ppm at pH 8.3 and 0.01 ppm at 8.8), but a very high concentration in the Castile brine (4.6 ppm at pH 11.3). Concentrations of Np, on the other hand, were higher in the Salado brine (1.25 ppm at pH 8.3 and 0.15 ppm at pH 8.8) than in the Castile (0.02 ppm at pH 11.3). Concentrations of Pu in these tests were always higher than those of Th and, in the case of the Castile brine, the difference was a factor of 65.

Tests of pyrochemical salts with Am added were also conducted. It is not clear whether these tests contained other additives. These tests gave the lowest concentrations of Th, Np, and U of all the pyrochemical salt tests, and among the lowest results for Pu. The highest Pu concentration was, again, in the Castile brine, with Pu = 1.25 ppm at pH 9.5. There is certainly no evidence from these tests of an enhancement of solubility due to radiolysis effects.

Tests of pyrochemical salts in brines pressurized with carbon dioxide to 60 bars (L28-L30) have generally high concentrations of Pu and U, and of Np in Salado brine. The highest Pu concentrations were found in one of two nominally identical tests in Salado brine. Test L28 had [Pu] = 6 ppm at the first reported point, while test L29 had [Pu] = 0.16 ppm at the same point. Similar differences persisted through the test period. Tests with Castile brine pressurized with carbon dioxide resulted in Pu concentrations of 1 to 2 ppm, uranium concentrations of 3 to 8 ppm, while Th concentrations were very much lower (0.01 to 0.05 ppm). Magnesium oxide was added to test L28 after the 4th sampling period, which had a [Pu] = 91 ppm. The next sampling period showed a lower Pu result (18 ppm), but subsequent samplings showed increasing Pu concentrations, rising to 42 ppm at the next sampling and then to 174 and 198 ppm at the two final reported sampling points.

For some tests that had high Pu concentrations, spectroscopy was done to determine speciation of the Pu. Pu(VI) was positively identified in tests L26 and L28. The Pu(VI) appears to have been present after the MgO was added to L-28. Pu(VI) is suspected, but was not positively identified, in test L27. All of these tests contained fresh Fe mesh and were found to have hydrogen gas in the head space over the brine, indicating actively reducing conditions. This is clear evidence that thermodynamic equilibrium has not been achieved in these systems, and should raise a cautionary flag concerning the use of equilibrium thermodynamic calculations to predict the potential for releases under the dynamic conditions expected for the Human Intrusion scenario.

The drum scale tests produced relatively low actinide concentrations in the brines, except for the tests using combustible materials with chelating agents. The results for D07-D09 were [Pu] between 1 and 3 ppm, [Th] between 7 and 14 ppm, [U] between 12 and 17 ppm, and [Np] between 15 and 18 ppm. In this case, concentrations of Th are higher than those of Pu and similar to those of U and Np. The chelating agents used were acetamide, acetate, citrate, oxalate, and thiocyanate at 160 ppm each. Similar tests without chelating agents gave [Pu] between 1.7 and 2.0 ppb, indicating that the presence of chelating agents increased the solubility of Pu by a factor of about 1000. This is in direct contradiction to the claims made by DOE in the CCA that chelating agents would not increase the solubility of actinides (U.S. DOE, 1996, SOTERM.5).

Some general conclusions can be drawn from the results of the STTP tests.

1. Solution concentrations of actinides in the presence of pyrochemical salts can be rather high.

2. Thorium is not a conservative analog for the behavior of Pu.

3. Concentrations of Pu in brines increase if chelating agents are present.

4. The addition of MgO to a test that contained a high concentration of both Pu(VI) and carbon dioxide gas did not produce a long-term decrease in plutonium concentration in the test system, provided a level of Pu(VI) that could be detected by spectroscopy, and appeared to raise questions about the arguments that MgO would lower plutonium solubility.

5. It can not be assumed that equilibrium will be achieved rapidly, even in the relatively homogeneous conditions that pertained in the STTP tests.

6. Pu(VI) can exist, at least as a long-term transient species, in brines that are held under actively reducing conditions (i.e., redox conditions buffered by the corrosion of metallic iron to produce hydrogen gas).

ADVANCES IN PLUTONIUM AND URANIUM CHEMISTRY OUTSIDE THE WIPP PROGRAM

The chemistry of plutonium has been studied most extensively because of the use of plutonium in nuclear weapons. Research has focused on the production of weapons grade Pu in nuclear reactors, separation of the Pu from the much larger quantity of matrix (target) material, and subsequent purification of the Pu prior to conversion to metal. Studies of plutonium chemistry under conditions that are relevant for natural, geologic systems have been conducted only in recent years. Some of the results obtained at high temperatures or in acid solutions that constitute the "conventional wisdom" concerning plutonium chemistry may not be appropriate to the near neutral pH conditions and lower temperatures that pertain under geologic disposal conditions.

Studies of the reaction of plutonium dioxide with water by Haschke et al. (2000) have recently shown that a PuO_{2+x} phase is formed, where $x \leq 0.27$. This phase, which is analogous to the UO_{2+x} phase, where $x \leq 0.25$, has been synthesized at temperatures between 25°C and 350°C. The PuO_{2+x} phase decomposed in vacuum if heated at 500°C. As x increases from 0 to 0.27, the lattice constant of the solid phase of plutonium increases only very slightly. Given the difficulty of working with highly radioactive solids, it is not surprising that earlier work failed to identify the PuO_{2+x} phase by x-ray diffraction analysis. One method of identification that is simple, once one has the proof of existence of the PuO_{2+x} phase, is color. High-fired Pu-oxide, which is the stoichiometric PuO_2 phase, is yellow to buff colored, while the PuO_{2+x} phase has an intense green color. Haschke et al. (2000) also note that the existence of the PuO_{2+x} phase also explains one of the "mysteries" of Pu chemistry. It has long been known that so-called low-fired oxides, which are Pu-oxides prepared at relatively low temperatures, dissolved quite easily, while high-fired oxides that had been heated to high temperatures were nearly impossible to dissolve. Haschke et al. (2000) postulate that the PuO_{2+x} phase releases Pu(VI) to solution, especially in cases where aqueous solutions are in contact with air, which can continue the formation of the PuO_{2+x} phase. This accounts for the predominant species in water coexisting with PuO_2 being Pu(VI) for solutions where air is present. Given the difficulties of eliminating all oxygen from

experimental systems, it may be that some PuO_{2+x} phase is always present, either due to residual air in the experimental system or to autoradiolysis of the plutonium oxide.

The mechanisms discussed by Haschke et al. (2000) for the formation and dissolution of PuO_{2+x} would also be possible in brines. Thus, the observations of Pu(VI) in the STTP tests may be explained by the presence of the PuO_{2+x} phase in these tests. For tests with lower concentrations of Pu than those for the pyrochemical salts, the chemical form of the plutonium may not be Pu-oxide, but rather some other chemical compound in which Pu exists as a trace constituent. In that case, one might expect quite different behavior, dominated by the chemistry of the host phase in which Pu plays a minor role.

Until recently, positive identification of Pu(V) and Pu(VI) in solution has been limited to cases where the concentration of Pu has been rather high. During the last few years Stefan Röllin, working at Studsvik Nuclear (Nyköping, Sweden) has developed a method for chemical separation by ion chromatography as a pretreatment to analysis by ICP-MS. The method was developed for use with spent fuel leaching experiments conducted at Studsvik for the Swedish Nuclear Fuel and Waste Management Company (SKB) (Röllin, 1999). The ion chromatography step provided clear separation of Pu(III), Pu(IV), Pu(V) and Pu(VI); the ICP-MS detection of the separated valence states of plutonium can then be done at sub-ppb levels. If valence states are changed during the ion chromatography column separation step, the peak positions and shapes are affected. This allows detection of alterations of the chemistry due to analytical methods to be detected. This method, if adapted for use with WIPP brines, could be used to determine speciation of Pu in all of the STTP tests.

Advances have been made in the understanding of uranium chemistry under reducing conditions, both in solutions of low ionic strength and in brines. Experiments were conducted at Finland's VTT Technical Research Centre by Kaija Ollila as part of the European Union's Nuclear Fission Safety R&D Programme (1996-1998) under the project "Source term for performance assessment of spent fuel as a waste form". Ollila (1999) found that the solubility of uranium dioxide under reducing conditions (Eh -0.2 to -0.3 V) and pH about 9 was approximately 1×10^{-9} M, both in saline solutions without carbonate present and in dilute solutions with 0.003 M bicarbonate content. Experiments in dilute

groundwater solutions were conducted both from oversaturation and from undersaturation. Results obtained from oversaturation gave [U] in solution that was about a factor of 2 lower than that obtained by dissolution of uranium dioxide pellets that most likely had an outer layer of UO_{2+x} phase. Speciation of U in solution showed that for experiments conducted under anaerobic, but not actively reducing, conditions the U was present as U(VI) to the extent of 85% or more. For actively reducing conditions, the speciation was 60-70% U(VI) in dilute groundwaters and 20-37% U(VI) in saline solutions. The "solubility" measured for anaerobic conditions was one order of magnitude higher than that measured for actively reducing conditions.

Ollila (1999) concluded that the presence of U(VI) in solution, caused by dissolution of the outer layer of the uranium dioxide pellets, had more effect on the measured "solubility" than the chemistry of the solutions used in the experiments (dilute synthetic groundwater or saline solution). Ollila's results, showing the limited effect of salinity on solubility for uranium dioxide, suggest that the WIPP project should reconsider the use of the OECD/NEA data bases for U and Pu and the relatively simple methods suggested in these data bases for correction of ion activities as a function of ionic strength. This would eliminate the need for Pitzer parameters for complex actinide solution species and eliminate a number of uncertainties in the chemical calculations used by DOE to support the performance assessment estimates for WIPP.

A CONCEPTUAL MODEL FOR PU BEHAVIOR UNDER WIPP DISPOSAL CONDITIONS

The work of Haschke et al. (2000) documenting the existence of PuO_{2+x} for $x \leq 0.27$ highlights the similarities between the chemistry of U and Pu and can be used together with the data obtained by several national high level waste disposal programs to construct a conceptual model for the behavior of Pu under WIPP disposal conditions. The PuO_{2+x} phase is not stable at temperatures above 500°C, so would not be present initially on high-fired PuO_2. It may, however, form slowly on the surface of high-fired oxides that are exposed to air atmosphere before disposal, or may form due to radiation effects even in the absence of air. We will, therefore, assume that all Pu-oxides contain some excess oxygen in their structure after disposal at WIPP.

The PuO_{2+x} phase releases Pu (VI) to solution when it is contacted with an aqueous phase, either dilute groundwater or brine. This is a direct analogy to the behavior of UO_2 solid, which forms a UO_{2+x} phase on its outer surface when exposed to an air atmosphere or to an aqueous solution that is in contact with air, and then releases U(VI) to the solution phase, even though the predominant redox state in the solid is U(IV). This behavior explains the higher than expected Pu concentrations found in SKB tests of spent fuel conducted under anaerobic or reducing conditions. Some level of PuO_{2+x} phase may be expected on any Pu-oxide in the repository, even if the general conditions are reducing through the corrosion of metallic iron. This is because the PuO_{2+x} phase could form by autoradiolysis effects in the Pu-oxide and will not encounter the general reducing conditions until it is formed. The general reducing environment may not be sufficiently powerful to reduce the PuO_{2+x} phase once it has formed. Likewise, Pu(VI) in solution may not reduce directly to Pu(IV) in solution, but may require an active surface to assist in the electron transfer operations.

The PuO_{2+x} phase would be expected to occur in pyrochemical salt wastes, where the concentration of Pu is high and the Pu would be present in relatively pure oxide form. Other waste types, such as solidified aqueous wastes, might have Pu present in dilute solid solution in a matrix of non-radioactive oxides. In this case, the predominant redox state of Pu may be Pu(IV), without any tendency to form

the higher mixed oxide phase. The conceptual model for Pu behavior in WIPP should consist, therefore, of two types of Pu-oxides: (1) waste containing rather high purity PuO_{2+x} phase as the main Pu-bearing component in the waste, and (2) waste containing low levels of Pu dispersed in a matrix that is capable of dominating the chemistry of the Pu. Type 1 wastes would be likely to release Pu(VI) directly to solution, while type 2 wastes may not.

RECOMMENDATIONS FOR FUTURE WORK TO IMPROVE PLUTONIUM RELEASE ESTIMATES AND RESOLVE OUTSTANDING ISSUES

Results of experiments and tests within the WIPP program and by other, independent research workers during the past several years have provided evidence that the issues raised by EEG during the period prior to certification of the WIPP facility have basis in fact. These issues should be addressed during recertification of the WIPP facility. To assist in planning a program to address these issues, we summarize below the original basis for EEG's concerns and a brief outline of experiments or activities that could resolve these issues.

(I) ISSUE: EFFECT OF ORGANIC LIGANDS

There are two underlying issues that are important for the consideration of organic ligands and their effect on the solubility of actinides. The first issue is whether a scenario that provides a potentially higher release from the repository has been overlooked in the analysis of "features, events, and processes" for the PA calculations. The second issue is whether the ligand chosen for the "bounding calculations" is appropriate for estimation of the largest potential effect on actinide solubilities.

The DOE and EPA assume that the repository contents are well mixed in a brine solution. The EPA response to comments states that "consideration of every possible combination of potential events for chemical mixture in specific drums would present an impossible number of hypothetical situations to represent in a performance assessment". We agree with that statement, but disagree that DOE actually performed the correct bounding calculation. The appropriate bounding calculation would use the organic ligand for which the An(IV) species have the highest ratio of stability constant as compared with other cations in solution.

The appropriate bounding calculation must also consider the type of waste that produces the largest amount of Pu and citrate together in a single waste container. Selection of this scenario should have

occurred during the required "features, events, and processes" (FEPs) analysis that is intended to identify FEPs that can have an impact on total calculated releases. The feature of Pu and citrate being collocated in a waste drum is highly probable and the penetration of such a drum during a drilling event under the human intrusion scenarios would be proportional to the potential number of such drums. Thus, the calculation could easily be included in the potential scenarios used to construct the CCDF without considering an impossibly large number of individual cases.

The DOE and EPA have assumed that the organic ligand that has the largest complexation constant with actinides, especially An(IV), will be the most important in changing solubilities of these actinides. They then calculate the competition between other cations in solution and the dissolved actinides for EDTA, the ligand with the largest An(IV) complexation constant, and conclude that almost all of the EDTA will be bound to transition metal ions and, therefore, will not affect An(IV) solubility.

The conclusion for EDTA is correct. The $\log_{10}$ of the stability constant for EDTA with Th(IV) at 0.3 molal NaCl is given in SOTERM as 15.56, while that for Fe(II) is given as 14.3 at 0.1 molal total ionic strength. While the slight differences in ionic strength will give some changes in the complex stabilities, it is the ratio of the stability constants that is important. The affinity of Th(IV) for EDTA is only a bit over 10 times that of Fe(II) for EDTA. Since the concentration of dissolved Fe(II) in the WIPP site is expected to be much higher than that of Th(IV), the EDTA will be consumed in complexing the Fe(II) and will not have a large effect on the Th(IV) solubility.

The conclusion reached by DOE and EPA that complexation will not have a significant effect on An(IV) solubility if the ligand is citrate should be revisited in light of the following observations. The $\log_{10}$ of the stability constant for Th(IV) with citrate at 0.1 molal NaCl is given in SOTERM at 9.31, while that for Fe(II) with citrate is given as 4.4 at 0.1 molal total ionic strength. The ratio of the strength of the complex ions in this case is approximately 100,000 in favor of Th(IV). It should be noted that the EEG assessment of the potential importance of organic ligands in enhancing the mobility of actinides is in keeping with the experimental results found recently under the DOE STTP testing with organic ligands

present. Moreover, the WIPP inventory contains 140 metric tons of citrate in comparison to 23 kg of EDTA.

It is also important to remember that for the calculation of competition for organic ligands between two cations in solution, it is only the concentrations of the cations in solution that comes into play – not the total amount of the element present in the repository. If we consider the competition between Th(IV) and Fe(II) for citrate ligands, it cannot be assumed that there is a readily available supply of soluble Fe(II) to replace any ions that are tied up in complexes. The bulk of the iron in the repository will be there as elemental Fe and must first oxidize before it can dissolve.

ISSUE RESOLUTION

Some rather simple experiments involving Th(IV), citrate, EDTA, Ca^{2+} and one or more transition metals dissolved in brine could demonstrate the extent of complexation of each type of cation in the presence of other cations. Additional experiments using Pu(IV) as the starting actinide could also address the lability of Pu oxidation states in the presence of organic ligands. The results of these experiments could be used in tests of the validity of calculations of solution equilibria done by the chemical modeling codes used in performance assessment calculations.

(II) ISSUE: USE OF TH(IV) AS AN ANALOG FOR U(IV) AND PU(IV) CHEMISTRY

The key issue is whether the chemistry of an element that can assume many different valence states can be adequately represented by considering the solution state of each possible valence state in isolation. The possibility of self-oxidation of an actinide element through the effects of radiolysis induced in the environment is particularly important in this respect.

EPA states that "A peer review panel of scientists found that the use of solubility data for Am(III) solids for representing Pu(III) and solubility data for Th(IV) solids for representing Pu(IV) was a reasonable approach" (p. 6-69 in EPA Response to comments). This position contrasts with that taken by a

National Research Council review team, who stated in their report (Appendix E, p. 129) "Although the oxidation state model (the assumption that the chemistry of a given oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviations from the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy." (NRC, 1996).

The solubility of freshly prepared Th(IV) amorphous hydrous oxide in NaCl and $MgCl_2$ brines has been shown to be higher than that of the equivalent U(IV) amorphous hydrous oxide under conditions of equal hydrogen ion concentration (Rai et al., 1997). The issue for solubility in the WIPP case is whether the U species in solution will be (IV) and whether the Pu species in solution will be Pu(IV). In order to measure the "solubility" of amorphous U(IV), extreme precautions had to be taken to avoid oxidation of the U from (IV) to (VI). The experimental systems included metallic iron powder (325 mesh) and 70 mg/l $EuCl_2$ (approximately 3×10^{-4} moles/liter). Even with these extreme measures, some of the U solutions seemed to show evidence for the presence of U(VI). Conditions in the WIPP will include metallic iron in the form of solid waste containers. That form of iron will be much less reactive than 325 mesh Fe powder. The solid metal pieces in the WIPP will be likely to form a layer of corrosion products on their surfaces, which will further decrease their reactivity. Thus, while the precautions taken in the experiments of Rai et al. (1997) were appropriate for the purpose of determining the thermodynamic properties of the amorphous U(IV) material, the conditions used may not be appropriate for evaluation of WIPP. It is possible that under the ambient conditions at the WIPP the solubility of U in solution will be more similar to that measured by other scientist for amorphous U(IV) solids, where less extreme measures were taken to ensure extremely reducing and reactive conditions.

For plutonium, the use of Th(IV) to estimate the solubility of Pu(IV) solids neglects the contribution of radiolysis to the local redox conditions surrounding the waste materials. Oxidative conditions can be produced in the immediate vicinity of the Pu solids, leading to production of Pu(V) and/or Pu(VI) solution species. If there are chelating agents, such as citrate, in the waste, these will form ligands for the Pu and reduce the Pu to (IV). In the absence of chelating agents, the Pu(V) and Pu(VI) in solution

may be rather long-lived. Thus, the use of Th(IV), for which changes in oxidation state are not possible, as an analog for Pu(IV) excludes relevant chemical processes from consideration.

Rai et al. (1997) noted that "thermodynamic predictions are reliable when interpolated, but questionable when extrapolated". The use of a different chemical element (e.g., Th) to predict the chemistry of Pu in brines under WIPP conditions must be seen as an even larger extrapolation than that of estimation of expected solubilities of Pu or U in WIPP using data obtained by scientists for brines of somewhat different composition than those expected for WIPP. An indication of significant difference in solution chemistry of Th(IV) and U(IV) can be found in the large differences in treatment needed for the Pitzer parameters for U(IV) and Th(IV) in chloride media. (A large, negative β^2 value was needed for Th^{+4}-Cl^- interactions, while no such value was needed for U^{+4}-Cl^- interactions.)

The new experimental results cited above for Pu-bearing solutions and for the possible oxidation states of Pu in solids reinforce the need for experimental data for systems that contain Pu. These results also underline the dangers in using an chemical analog for Pu that does not have the same range of valance states available for responding to changes in environmental conditions.

ISSUE RESOLUTION

This issue could be resolved if appropriate experiments were done using U and Pu at redox conditions that were in the range of those possible for WIPP. A significant contribution to resolution of this issue could be made by consideration of the published experimental results of U and Pu studies – including studies of leaching of spent nuclear fuel and radioactive waste glasses – that have been conducted in brines.

The specific scenario of Human Intrusion should be investigated by conducting tests using pyrochemical salt wastes together with materials to represent corroding waste drums. An injection of Castille brine together with some air to represent a sudden influx of brine via a drill hole that penetrates a brine pocket below the repository could be added to a vessel containing the pyrochemical salt wastes and the

corroding metal pieces. The evolution of the solution chemistry, especially Pu concentration and speciation, should then be monitored. Measurements using the sensitive analytical method developed by Röllin (1999) would be most informative.

(III) ISSUE: UNCERTAINTY RANGE FOR SOLUBILITY ESTIMATES

The basic issue here is whether the uncertainty in calculated solubility/solution concentrations of Pu(IV) and U(VI) and the possible existence of Pu(V) and Pu(VI) solution species can be estimated without examination of actual data for these species.

There are two components for this problem. The first is what is the uncertainty in the chemical environment in the repository. This includes, among other things, determination of the phase assemblage relevant to MgO (or other backfill material) alteration in the presence of brines and the influence of heterogeneous distribution of waste materials, such as citrate complexes in the repository. The second component is the uncertainty in the thermodynamic data and in the Pitzer parameters used in the DOE calculations and the propagation of those uncertainties through the calculations of solubility and solution concentrations.

The estimation of uncertainty in solubility estimates as described in SOTERM addressed only the second factor and only the An(III) and An(V) oxidation states. It is stated that An(VI) was not included in the uncertainty analysis because "the CCA source term was unable to develop a solubility model for U(VI), which is the only hexavalent actinide species expected under WIPP conditions." (p. 6-77, EPA Response to Comments). This position was taken by DOE despite the fact that work had been funded by WIPP on the topic of a U(VI) model, there is a peer-reviewed thermodynamic database for U species (Grenthe et al., 1992, issued by the Nuclear Energy Agency), and that the work accomplished by early 1996 under contract to WIPP appears to have at least as sound a footing as the database for Th(IV) used as a model for all An(IV) species.

The An(IV) species were eliminated from the uncertainty analysis because "The data available for the +4 model were found to have significant problems in the extrapolated regions and were thus determined to be inadequate for use in this analysis." (Quoted from a reference cited as "Bynum [1996b]" on p. 6-78 of Response to Comments. Reference not included in references under issue Z). EPA correctly notes that this position seems to be inconsistent with the statements made in SOTERM that data for Th(IV) were available and that these data were used for describing the speciation and solubility of Th(IV) in brines.

It is, basically, very difficult to justify the use of data to form a model for safety analysis purposes and then claim that the data are so poor that you cannot estimate from the data themselves the uncertainties associated with their use. It is, further, very difficult to understand how one can then claim that the uncertainty in a well-studied population – in this case the lanthanides [Ln(III)] and An(III) actinides – can be used as the value for the uncertainty for calculations of An(IV) solubility, when the An(IV) data have just been stated to have "significant problems". In most technical circles, the term "significant problems" as applied to data has a direct correspondence with "significant uncertainties".

While EPA seems to have understood the limitations of the uncertainty analysis conducted by DOE, they conclude that "the experimental procedures for determining the solublities of +IV actinide solids are not substantially different from those used to determine the solubilites of +III and +V actinide solids, hence EPA concludes that the uncertainties determined for the +III and +V actinide solids would be inclusive of those that would be obtained for the +IV actinide solids." (p. 6-79, Response to Comments). If the only problem were the attempt to use the same methods to measure solubilities, we would not have the need for statements concerning "significant problems" with data. Unfortunately, it is the solution chemistry of the An(IV) elements that presents the difficulties, not the methods used in the analysis.

The complexities of the solution chemistry carries forward into the attempts to calculate solubilities using computer models. In the case of the FMT calculations used by DOE, the use of Pitzer parameters for calculation was selected. This method requires the estimation of the Pitzer parameters from existing

experimental data on the solubility of appropriate An(IV) species. For highly charged solution species, such as are frequently encountered with the An(IV) elements, there are significant uncertainties in the estimation of the Pitzer parameters. This was encountered in speciation calculations for $Th(CO_3)_5^{-6}$, which forms under high carbon dioxide conditions. Even after "correction" of the Pitzer parameters, which lowered the calculated Th(IV) solubility by many orders of magnitude - i.e., a lot more than +1.4/-2.0 log units - the speciation calculated still indicates that the Pitzer parameters have not been correctly and completely determined for the Th(IV) systems.

ISSUE RESOLUTION

The uncertainty in Pu(IV) solubility for safety analysis of the WIPP repository can only be assessed if there are appropriate experimental data for Pu(IV) compounds in brines of appropriate compositions. If such experimental data were available, a direct analysis of expected Pu solubility under WIPP conditions could be conducted, thereby avoiding the uncertainties of extrapolations of Th(IV) data to the polyvalent element, Pu. In addition to the experiments suggested for resolution of issues in previous sections, we would recommend that DOE construct a data base for U and Pu using the published, peer-reviewed OECD/NEA U and draft, peer-reviewed Pu databases as a starting point. The method for correction of activities of solution species as a function of ionic strength recommended by the OECD/NEA review teams is much simpler to use than the Pitzer parameter method used by DOE in the CCA. Considering the small differences in measured solubility for uranium dioxide found by Ollila (1999) for solutions ranging from very dilute synthetic groundwaters to saline solutions, it would seem that the OECD/NEA method should be sufficient. Predictive calculations could then by done by DOE to simulate the conditions for the STTP tests that showed high Pu and U concentrations. This would provide information that could be used to either validate the data base used or provide guidance for improvement of the data base.

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APPENDIX

Selected Overheads from November 23, 1999 Presentation by Robert Villareal

The Actinide Source-Term Waste Test Program Experimental Results & Status

Presented to:

DOE - Carlsbad Area Office

NM Environmental Evaluation Group

Presented by: Robert Villarreal
Los Alamos National Laboratory

November 23, 1999
Albuquerque, NM

Results of Portland Cement - LS

Liter #	Nd	Th	Np	U	Pu	Am	pcH
L01	<0.5	<0.2	8.6	1.4	<0.5	<0.1	8.79
L02	< 0.8	0.6	0.5	1.9	1.0	0.6	10.22
L03	< 0.5	0.6	0.5	5.5	1.1	0.5	12.89
L07	0.9	0.6	264.0	8.3	1.0	0.5	8.72
L08	1.0	0.3	0.5	<0.3	1.6	0.3	9.13
L09	0.9	0.3	0.6	3.1	0.5	0.4	12.96
L10	1.7	0.6	33.0	7.3	11.3	0.9	8.72
L11	1.9	0.9	<0.3	1.9	7.8	0.4	9.54
L12	1.0	0.3	0.4	0.4	<0.5	0.3	12.97

Portland Cement-Pressurized

Liter #	Nd	Th	Np	U	Pu	Am	pcH
L04	<0.9	1.2	421.0	9999.0	1.6	<0.2	7.34
	<0.9	0.4	8.1	10632.0	2.0	<0.2	7.34
	<0.3	1.4	8.6	10268.0	6.0	0.2	7.32
	<0.4	1.4	12.9	11160.0	17.2	0.1	7.43
	1.1	7.9	21.0	15390.0	66.0	0.5	7.39
	<0.5	6.3	15.9	8507.0	255.0	0.7	7.34
L05	<0.9	<0.3	1.5	696.0	1.7	<0.2	7.44
	<0.9	5.1	26.3	560.7	184.0	0.8	7.12
	<0.3	3.7	15.8	398.0	75.0	0.4	7.34
	<0.4	0.6	1.7	319.0	8.5	<0.1	7.27
	<0.2	0.7	2.5	374.0	24.1	0.3	7.08
	<0.7	2.0	4.2	546.0	5.3	0.1	7.00
	<0.5	0.6	1.7	479.0	13.9	<0.1	7.35
L06	<0.9	<0.3	11.1	2934.0	25.0	<0.2	7.87
	<0.9	2.1	7.4	3680.7	23.6	<0.2	7.49
	0.5	1.5	5.7	3988.0	22.9	0.2	7.69
	<0.4	2.9	13.3	4872.0	638.0	1.4	7.70
	3.9	1.8	3.2	4477.0	57.0	0.5	7.57
	2.7	1.9	7.0	4660.0	281.0	0.9	7.81
	2.7	3.0	11.4	3675.0	319.0	0.9	7.56

Results of Envirostone - LS

Liter #	Nd	Th	Np	U	Pu	Am	pcH
L13	1.0	8.4	0.8	1367.0	13.0	0.2	6.99
L14	5.0	7.6	1.2	1019.0	32.0	0.4	6.99
L15	28.0	8.8	174.3	3454.0	165.7	1.3	6.95
L16	45.0	261.9	179.0	168.0	1013.0	2.3	7.46
L17	1.2	0.6	0.9	271.0	2.4	0.3	7.83
L18	<0.5	0.4	21.0	11027.0	4.0	0.3	7.83
L19	3.5	0.5	20.5	659.0	8.9	0.5	7.88
L20	2.0	1.2	1.1	241.0	1.6	0.3	7.60
L21	<0.5	0.2	4.9	668.0	1.2	0.1	8.10
L22	2.4	0.9	0.9	841.0	1.6	0.3	7.20
L23	<0.7	<0.4	0.7	731.0	<0.5	0.3	7.18
L24	<0.4	0.6	1.1	273.0	3.0	0.5	7.78

Envirostone = 80-90% $CaSO_4$ + 10-20% $C_4H_8N_6O.CH_2O$ (melamine-formaldehyde resin) + ~0.1% NH_4Cl

Results of Pyrochemical Salts

Liter #	Nd	Th	Np	U	Pu	Am	pcH
L25	2.8	0.6	273.0	3.5	61.0	0.6	7.86
L26	1.7	1.4	2.0	2.4	5642.0	33.0	7.88
L27	208.0	307.0	70.0	47.0	30127.0	76.0	11.07
L31	4.0	2.4	138.0	728.0	209.0	0.6	8.75
L32	5.0	1.1	73.0	400.0	171.0	0.6	8.72
L33	0.6	0.4	5.7	2.4	121.0	0.7	9.65
L34	0.6	4.8	152.0	46.0	10.0	0.4	8.77
L35	0.7	85.0	1251.0	51.0	111.0	0.8	8.30
L36	<0.5	71.0	18.0	11.0	4650.0	17.0	11.28
L37	1.1	0.6	0.6	<0.3	79.0	0.7	7.67
L38	1.0	0.6	0.5	0.7	8.3	0.3	7.84
L39	1.0	0.8	8.3	28.4	1251.0	1.9	9.48

Pyrochemical Salt-Pressurized

Liter #	Nd	Th	Np	U	Pu	Am	pcH
L28	15.4	178.0	3549.0	5230.0	5989.0	34.8	5.35
	10.1	248.0	8150.0	7099.0	8731.0	58.7	4.90
	10.3	312.0	8179.0	6290.0	15678.0	80.0	4.74
	31.5	1359.0	13931.0	10833.0	90942.0	352.0	4.48
MgO Add	8.9	151.4	350.7	106.4	18097.5	40.1	
	5.3	36.0	166.0	155.0	41822.0	69.0	
	53.8	368.0	2049.0	4520.0	174367.0	330.0	5.24
	57.0	531.0	1528.0	1550.0	197984.0	392.0	5.01
L29	<0.9	2.8	17.5	54.0	161.0	1.1	5.68
	2.1	124.0	392.0	4840.0	440.0	11.2	5.04
	3.1	183.0	882.0	6194.0	1326.0	17.6	4.98
	3.0	193.0	1127.0	6706.0	1514.0	19.8	4.77
	5.9	360.0	2838.0	6850.0	3384.0	22.0	4.88
	6.1	437.0	3666.0	6152.0	8446.0	37.0	5.06
	6.9	377.0	8179.0	9513.0	6865.0	36.6	4.73
L30	69.0	8.8	34.8	5663.0	2166.0	12.4	6.16
	20.6	46.5	143.0	8134.0	2226.0	12.6	5.94
	11.7	25.5	72.5	8069.0	1750.0	7.7	5.90
	10.2	55.0	90.0	5748.0	1297.0	4.8	6.32
	11.0	26.0	74.0	3030.0	1243.0	4.1	6.08
	1.6	8.6	31.9	4989.0	555.0	1.3	6.38
	6.0	32.9	135.0	2787.0	1011.0	2.8	6.59

Test Containers with Potential Pu(VI)

- L26 (Pyrochemical Salt Waste)

  Pu^{6+} developed slowly - Peaked - Declined

- L27 (Pyrochemical Salt Waste)

  Soluble Pu concentration increased Rapidly - Peaked - Declined
  Pu^{6+} was not identified

- L28 (Pyrochemical Salt Waste; CO_2; MgO

  Pu precipitated with MgO - Increased - Rapid Increase
  Pu^{6+} Identified

- All three test containers: Contain Fe mesh
  Have H_2 Headspace >50%

- Potential Oxidation Mechanisms
  - Basic Solution
  - H_2O_2; NaOCl

Latest Drum-Scale Results

Drum #	Nd	Th	Np	U	Pu	Am	pcH	Remarks:
D01	5.5	10.2	45.0	70.0	2.0	0.2	7.67	-
D02	2.6	16.0	54.0	260.0	1.7	0.3	7.68	-
D03	1.1	0.9	0.8	166.0	1.7	0.4	6.88	-
D04	1.5	2.6	4.4	25.0	2.1	0.3	7.39	bentonite
D05	0.7	0.7	1.2	35.8	0.8	0.3	7.11	bentonite
D06	0.7	0.4	4.8	12.5	0.8	0.1	7.17	bentonite
D07	1841.0	9598.0	17841.0	16985.0	1138.0	4.6	7.37	chelators
D08	1881.0	13916.0	15078.0	12360.0	3228.0	17.3	7.19	chelators
D09	2713.0	7012.0	16081.0	15482.0	2302.0	13.0	7.16	chelators
D10	<2.0	18.6	330.0	76.0	15.0	<0.4	7.52	NO_3/PO_4
D11	<2.0	<1.2	<0.9	17.0	<1.3	<0.4	7.47	NO_3/PO_4
D12	<2.0	<1.2	<0.9	18.0	16.0	<0.4	6.57	NO_3/PO_4
D13	31.0	<1.2	1.2	3.3	<1.3	<0.4	5.78	Fe
D14	10.0	<1.2	1.4	54.0	<1.3	<0.4	6.76	Fe
D15	<2.0	<1.2	3.5	19.0	<1.3	<0.4	7.79	Fe

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EVALUATION OF PROPOSED PANEL CLOSURE MODIFICATIONS AT WIPP

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December 2001

EEG-82
DOE/AL58309-82

EVALUATION OF PROPOSED PANEL CLOSURE MODIFICATIONS AT WIPP

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment of New Mexico. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U. S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the compliance of the generator sites with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts associated with WIPP. Another important function of EEG is the independent on- and off-site environmental monitoring of radioactivity in air, water, and soil.

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ACRONYMS

AAR	Alkali aggregate reactivity
DOE	U.S. Department of Energy
EEG	Environmental Evaluation Group
EPA	U.S. Environmental Protection Agency
TRU	Transuranic
WIPP	Waste Isolation Pilot Plant

EXECUTIVE SUMMARY

A key component in the design of the WIPP repository is the installation of concrete structures as panel seals in the intake and exhaust drifts after a panel has been filled with waste containers. As noted in the EPA final rule, the panel seal closure system is intended to block brine flow between the waste panels at the WIPP. On April 17, 2001, the DOE proposed seven modifications to the EPA concerning the design of the panel closure system.

EPA approval of these modifications is necessary since the details of the panel design are specified in EPA's final rule as a condition for WIPP certification. However, the EPA has not determined whether a rulemaking would be required for these proposed design modifications. On September 4, 2001, the DOE withdrew the request, noting that it would be resubmitted on a future date.

The Environmental Evaluation Group (EEG) contracted with two engineers, Dr. John Abel and Dr. Rusty Morgan, to evaluate the proposed modifications. The EEG has accepted the conclusions and recommendations from these two experts: 1) replacement of Salado Mass Concrete with a generic salt-based concrete; 2) replacement of the explosion wall with a construction wall; 3) replacement of freshwater grouting with salt-based grouting; 4) option to allow surface or underground mixing; and 5) option to allow up to one year for completion of closure. The proposed modification to allow local carbonate river rock as aggregate is acceptable pending demonstration that no problems will exist in the resulting concrete. The proposed modification to give the contractor discretion in removal of steel forms is not supported. Instead, several recommendations are made to specifically reduce the number of forms left, thereby reducing potential migration pathways.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Project, located in Southeastern New Mexico has been constructed by the U.S. Department of Energy (DOE) to provide permanent disposal of long-lived transuranic (TRU) waste from the U.S. defense activities and programs. The facility must comply with 40 CFR 191, Subpart A during the period when radioactive waste are being emplaced (operating period) and with 40 CFR 191, Subpart B and 40 CFR 194 for long-term disposal. The U.S. Environmental Protection Agency (EPA) concluded that WIPP met the requirements of 40 CFR 191 and 194 and made a Certification Decision in May 1998 (EPA 1998). The repository began receiving radioactive TRU wastes in March 1999.

The underground WIPP facility design includes eight panels for disposing of transuranic waste (see Figure 1). At the present time waste is being emplaced in Panel 1 and excavation of Panel 2 has been completed. Each panel includes seven waste disposal rooms as well as a ventilation intake drift and a ventilation exhaust drift.

A key component in the design of the WIPP repository is the installation of concrete structures as panel seals in the intake and exhaust drifts after a panel has been filled with waste containers. The panel seals are required to rectify the damage done to the natural formation by excavation and are, at best, an imperfect attempt to recapture the characteristics of the original rock (Silva and Chaturvedi 1995). As noted in the EPA final rule, the panel seal closure system is intended to block brine flow between the waste panels at the WIPP. The DOE application (DOE 1996a) identified four design options. As a specific condition of compliance, the EPA mandated the use of Option D. But the agency also determined that the use of a Salado Mass Concrete – using brine rather than fresh water – would produce concrete seal permeabilities in the repository more consistent with the values used in the DOE performance assessment (EPA 1998, 27355).

In an April 17, 2001 letter from Dr. Inés Triay to Mr. Frank Marcinowski of EPA (Appendix A), the Carlsbad Field Office (CBFO) of the DOE proposed several panel closure design

WIPP Facility and Stratigraphic Sequence

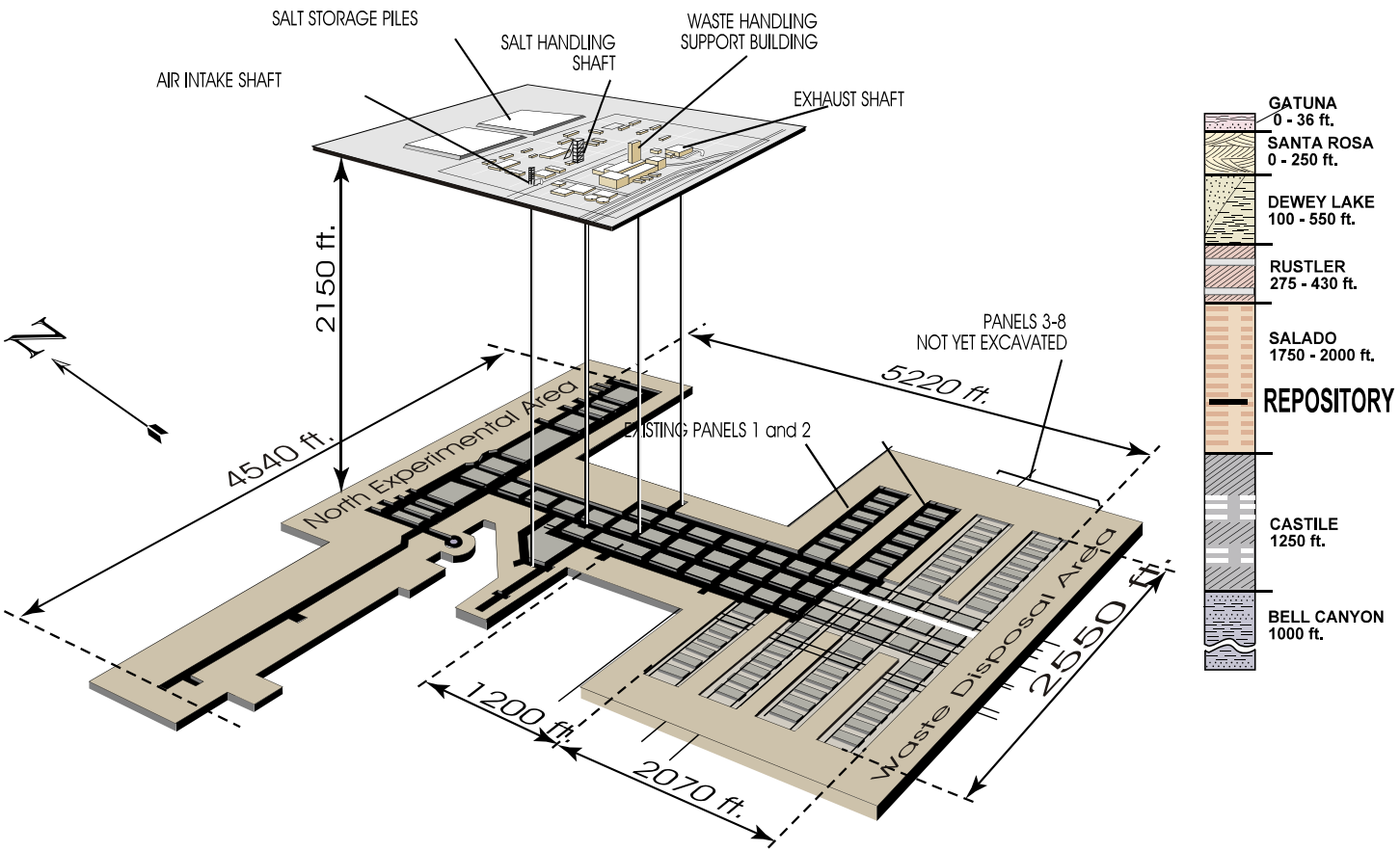

Figure 1. The WIPP facility and stratigraphic sequence. Panel 1 is currently in use. The mining of Panel 2 was completed on October 13, 2000. SOURCE: DOE, 2000.

modifications. EPA approval of the changes proposed by DOE is required since the details of the panel designs are specified in EPA's final rule as a condition for WIPP certification (EPA 1998, 27355). The EPA final rule allows for a modification to the design of the facility. Significant modification requires a rulemaking in accordance with the WIPP compliance criteria (40 CFR §§ 194.65-66). [1]

The Environmental Evaluation Group (EEG), in its role of providing technical evaluations on the design, construction, and operation of the WIPP Project, contracted with two engineers that are expert in relevant aspects of panel seal design and construction to evaluate these proposed enhancements. Dr. John F. Abel, Jr., a Mining Engineer from Golden, Colorado, evaluated the proposed enhancements concentrating on bulkhead and masonry wall stability. Dr. D. R. Morgan, a Materials Engineer from Vancouver, B.C., Canada, evaluated three of the proposed enhancements: (a) changes in proposed aggregate; (b) change to a salt-based grout; and (c) change in mass concrete requirements. The reports of Dr. Abel and Dr. Morgan are included as Appendices B and C to this report. The EEG has accepted the conclusion and recommendations contained in these two reports as summarized below.

The proposed enhancements were subsequently withdrawn from consideration by DOE in Dr. Triay's letter to Mr. Marcinowski, dated September 4, 2001 (Appendix D). This letter indicated that the topic was expected to be revisited at some time in the future. Toward this end, and because of the time spent in evaluation of the proposed modifications, EEG decided to proceed with this report on the proposed modfications.

2.0 PROPOSED PANEL CLOSURE DESIGN MODIFICATIONS

The proposed enhancements are discussed in the order used in Dr. Triay's letter of April 17, 2001. More details can be obtained from the appended reports.

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[1] The EPA has not yet published an opinion as to whether or not the changes proposed by DOE constitute a modification.

2.1 Replace Salado Mass Concrete with a Generic Salt-based Concrete

This proposed enhancement is acceptable and probably preferable since it gives the Contractor more flexibility and responsibility in meeting performance-based objectives. However, in order to ensure adequate performance, the project specification should be written in rigorous performance-based specification language. In addition, more detail should be provided in the specification regarding permissible constituent materials for the mass concrete components such as salt and shrinkage compensating materials.

It is appropriate that the Contractor be supplied with pertinent information regarding specifications for Salado Mass Concrete. This information can provide the Contractor with a starting point for generic salt-based mixture proportioning. However, the responsibility for concrete performance would reside with the Contractor.

2.2 Replace the Explosion Wall with a Construction Wall

This proposed enhancement is acceptable. The analysis in Dr. Abel's report indicates that the 12-foot thick explosion-isolation masonry wall is not needed. The panel closure bulkhead will adequately protect against the design basis 480 psi methane explosion which cannot occur prior to (at least) 15 years after panel closure. The strength of the 4-foot thick construction-isolation masonry walls is sufficient to protect against the design pressure generated by a roof fall within the panel.

2.3 Replace Freshwater Grouting with Salt-based Grouting

EEG agrees with the proposal to replace the freshwater grout with a salt-based grout since it will counteract the tendency for dissolution (and hence void formation) of fresh water based grouts. This is apparently only a point for clarification. The design report detailing the original panel closure options (DOE 1996), specifies that if the Salado Mass Concrete is used instead of a fresh

water/plain cement concrete, the contractor shall use a salt saturated grout. This would be the case for any salt-based concrete.

2.4 Option to Allow Local Carbonate River Rock Aggregate in Lieu of Crushed Quartz

It may be possible to demonstrate that this option is acceptable. However, Dr. Morgan raised three concerns. One concern is that the coefficient of thermal expansion of the aggregate influences the coefficient of expansion of the concrete containing such aggregate. Dr. Morgan states, "Serious differences in the coefficients of thermal expansion have been reported to occur with aggregates with very low expansion, such as certain granites, limestones, and marbles." Therefore, it will be necessary to demonstrate that this is not a problem with the proposed local carbonate river rock.

A second concern is that naturally rounded gravels used in concrete production are better if they have a certain "crush-count". Dr. Morgan states, "There are certain advantages to having partially fractured faces in a sufficient percentage of the aggregate particles, including enhanced compressive, flexural and tensile strength development in the concrete made with such particles, compared to concrete made with natural rounded particles only." Consideration should be given to using aggregate with a partial crush-count if this option is chosen.

A final concern is that some carbonate aggregate is chemically reactive, resulting in deleterious expansion of the concrete. Therefore, an evaluation of the alkali aggregate reactivity (AAR) susceptibility should be conducted.

2.5 Option to Allow Surface or Underground Mixing

This proposed enhancement is acceptable. Dr. Abel concluded that either surface or underground mixing was adequate, provided the critical time between mixing and placement in the form is met. It may be easier to meet the time limitation by underground mixing. In fact, as with Proposed Enhancement I (replacement of Salado Mass Concrete with a generic salt-based

concrete), it gives the contractor more flexibility and responsibility in meeting performance based objectives.

2.6 Option to Allow Steel Forms to be Left in Place or Removed

This option is more complicated than the title implies because it also would allow the contractor the flexibility to modify the design of the bulkhead. Abel's analysis of the current design and his recommendations should be seriously considered. The current four cell design with the steel forms remaining is inferior to a monolithic single cell because there are many more potential leakage flow paths through the bulkhead. However, the size of these bulkheads exceeds that of known continuous pours. Abel recommends the following approach for dealing with this dilemma:

It is recommended that the panel bulkhead specifications:

1) provide an incentive for the contractor to minimize the number of cells (preferably to one).
2) require that each cell be filled as a continuous monolithic concrete pour,
3) require the contractor support the fluid concrete in all cells with external structures,
4) require the contractor to remove the support structures and forms between internal cells,
5) provide for a rough form surface between internal cell walls (possibly with a layer of burlap),
6) assure that some grout points are located at the roof concrete/rock salt contact and
7) prevent the use of all internal form spacer supports.

2.7 Option to Allow up to One-year for Completion of Closure in Lieu of 180 Days

This option is acceptable. Significant gas generation concentrations take much longer than one year to occur and it is preferable to do the construction properly without the pressure of an artificial deadline.

3.0 CONCLUSIONS

Of the seven proposed modifications, the EEG readily accepts five: 1) replacement of Salado Mass Concrete with a generic salt-based concrete, 2) replacement of the explosion wall with a construction wall, 3) replacement of freshwater grouting with salt-based grouting, 4) option to allow surface or underground mixing, and 5) option to allow up to one-year for completion of closure. The proposed modification to allow local carbonate river rock is acceptable pending demonstration that no problems will exist in the resulting concrete. The proposed modification to give the contractor discretion in removal of steel forms is not supported by the EEG. Instead, the EEG has proposed a number of recommendations to specifically reduce the number of forms which are left, thereby reducing potential migration pathways.

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Silva, Matthew; Chaturvedi, Lokesh. 1995. Need for engineered barriers at the Waste Isolation Pilot Plant. In Transactions of the American Nuclear Society, October 29- November 2, 1995. La Grange Park (IL): American Nuclear Society, TANSAO 73:123-124.

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[DOE] US Department of Energy. 1996a. Title 40 CFR 191 compliance certification application for the Waste Isolation Pilot Plant, October 1996. Carlsbad (NM): Carlsbad Area Office. DOE/CAO-1996-2184. 21 volumes.

[EPA] US Environmental Protection Agency. 1998 May 18. Criteria for the certification and recertification of the Waste Isolation Pilot Plant's compliance with 40 CFR 191 disposal regulations: certification decision; final rule. Federal Register 63(5):27354-27406.

APPENDICES

APPENDIX A

April 17, 2001 letter, Triay to Marcinowski

Department of Energy
Carlsbad Area Office
P. O. Box 3090
Carlsbad, New Mexico 88221

April 17, 2001

RECEIVED
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ENVIRONMENTAL EVALUATION GROUP

Mr. Frank Marcinowski
Office of Radiation and Indoor Air
U.S. Environmental Protection Agency
401 M. Street, S. W.
Washington, DC 20460

Dear Mr. Marcinowski:

This purpose of this letter is to inform the Environmental Protection Agency (EPA), per the requirements of the Title 40 CFR Part 194 Final Rule, Supplementary Information, Section VIII.A.1.(b), regarding minor enhancements proposed to the panel closure construction specifications for the Waste Isolation Pilot Plant (WIPP) repository. As you are aware, the purpose of the panel closures is for the hazardous waste disposal unit closure and to control potential volatile organic compound (VOC) releases during waste management operations.

Secondarily, in terms of long-term performance, the Compliance Certification Application and the EPA final rule note that the closure system will also influence fluid connections between waste panels. The present panel closure design, as required in the EPA final rule, is extremely conservative (restricting VOC releases to levels that are more than two orders of magnitude less than the applicable standard). We previously briefed your agency regarding this subject on April 13, 2000 in Washington, DC and on December 12, 2000 in Carlsbad, NM.

The enhancements were identified during our continuing evaluation of engineering issues associated with operating the WIPP. The identified improvements include the following:

- Replace Salado Mass Concrete with a generic salt-based concrete
- Replace the Explosion Wall with a Construction Wall
- Replace freshwater grouting with salt-based grouting
- Option to allow local carbonate river rock aggregate in lieu of crushed quartz
- Option to allow surface- or underground-mixing
- Option to allow steel forms to be left in place or removed
- Option to allow up to one-year for completion of closure in lieu of 180-days

CBFO:ORC:DDM:SJJ:01-0753:UFC:5486

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The enclosed package contains a detailed description of the enhancements and our analysis of their effects. Included also are edited versions of the technical specifications for the panel closures which incorporate the enhancements. Our analysis demonstrates that these enhancements are clearly minor, will not compromise the performance of the closures, and do not impact long-term compliance. However, we believe that implementation of these enhancements would allow construction flexibility which will increase worker safety and greatly improve the constructibility of the panel closures and better ensure the closures perform as required.

If you or your staff have any questions regarding this matter, please contact Daryl Mercer at (505) 234-7452.

Sincerely,

Inés Triay

Dr. Inés R. Triay, Manager
Carlsbad Field Office

Enclosure: Panel Closure Enhancements

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CBFO:ORC:DDM:SJJ:01-0753:UFC:5486

APPENDIX B

Review of Panel Closure Bulkhead Enhancements, Waste Isolation Pilot Plant

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REVIEW OF PANEL CLOSURE BULKHEAD ENHANCEMENTS

WASTE ISOLATION PILOT PLANT (WIPP)

Report to

Mr. Mark Levin
Mining and Environmental Services, LLC
772 Stanley Road
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by

John F. Abel, Jr.
Mining Engineer
Colorado P.E. 5642

July 18, 2001

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EXECUTIVE SUMMARY

As indicated on Table 1, the strength of the 4,000 psi plain concrete panel closure bulkheads (Figure 1) is sufficient to resist the 480 psi design pressure from the postulated methane explosion, during and after the planned 35-year life of the facility. The strength of the 4-ft thick construction-isolation masonry walls is sufficient to isolate the panel closure bulkhead construction areas from the design pressure generated by a panel room roof fall. The 12-ft thick explosion-isolation masonry wall, (2,500 psi) solid concrete blocks (3,500 psi) mortared with cement (2,500 psi) and hitched 6-in into the adjacent rock salt, designed for the Intake Drift and the Exhaust Drift is insufficient to resist the 480 psi methane explosion pressure (Figure 2). There is no apparent reason for an explosion-isolation wall during the six-month or one year construction of the panel closure bulkheads. Methane concentration will not increase until panel ventilation is stopped, which should only start when construction starts on the isolation walls (Figure 3).

The "Panel Closure Enhancements" refer to the main panel closure bulkheads as "The concrete monolith ---". Water retaining bulkheads (Figure 4) are normally designed and constructed as monolithic, i.e. continuous, pours without cold joints or interior form walls. The planned four cell panel closure bulkhead construction will not provide a uniform massive bulkhead but will contain three interior steel form walls. Even if a way is found to remove the three interior steel form walls, after the concrete has set in each cell, a smooth surfaced cold joint will still be present between cells. In order of declining potential effectiveness, the following panel closure bulkhead construction modifications should decrease the bulkhead leakage potential,

1) constructing truly monolithic panel closure bulkheads or
2) externally supporting the bulkhead cell forms, i.e. eliminating the form spacers, or
3) reducing the number of cells.

The size of these bulkheads, approximately 990 cu yds for the 36-ft thick Intake Drift and approximately 565 cu yd for the 26-ft thick Exhaust Drift, exceeds known continuous monolithic bulkhead pours. The Jackpot Mine west decline tapered bulkhead, approximately 20.4-ft wide by 15.5-ft high by 25-ft thick, involved only 311 cu yds of monolithic concrete pour. At West Driefontein Mine four approximately 350 cu yd monolithic sand/cement plugs were constructed in twenty days, during a mine flooding emergency.

Penetrations through a water retaining bulkhead are normally minimized, whenever possible, because they represent potential leakage flow paths through bulkheads. Essential penetrations, such as a bypass pipe, include waterstops to assure no leakage along the penetrations. The forms are externally braced. The planned 4 cell panel closure bulkhead (Figure 1) includes the use of longitudinal 1-in diameter form spacers, which also support the form wall until the concrete sets. Figure 5 indicates 55 form spacer penetrations across Cell #2 and Cell #3. Figure 6 indicates 22 form spacer penetrations across Cell #1 and Cell #4. Multiple potential flow paths are apparent across the individual cells and the steel plate and angle forms provide multiple potential connections between form spacers in adjacent cells.

The forms for water impoundment bulkheads are typically constructed of timber posts hitched into the roof and floor and braced externally by pipe columns to floor, wall and roof anchors for temporary support of the fresh concrete during construction. This would eliminate the form spacer bars. However, the bulkhead volumes will probably require at least one internal cold joint. An airtight panel closure seal may be difficult to achieve, by any method, but more so with multiple bulkhead penetrations.

The panel closure bulkheads would be classed as tapered two-way pressure bulkheads, i.e. to resist equal pressure from either side. Tapered water retaining bulkheads are typically installed to increase the shear resistance of a low-strength rock from a hydrostatic pressure acting in only one direction. If the panel closure bulkheads are airtight, closure within the panel rooms could potentially increase to 100 psi on the waste side of the bulkheads 35 years after construction (Figure 7). The two-way taper of the panel closure bulkheads was apparently designed to permit the safe excavation of the disturbed rock zones (DRZ) above and below the intake and exhaust drifts.

The strength of the concrete is critical to the strength of the panel closure bulkheads. The aggregate strength is a minor concrete strength factor which can be compensated for, if necessary, by increasing the cement in the mix. In addition, carbonate aggregate concrete probably has a lower coefficient of thermal expansion than quartz aggregate. Figure 8 indicates that concrete with quartz aggregate has a higher coefficient of expansion (approximately 6.6 millionths per °F) than either limestone aggregate concrete (approximately 3.8 millionths per °F) or dolomite aggregate concrete (approximately 5.3 millionths per °F).

Table 1. Bulkhead stability for Intake Drift (20-ft by 13-ft) and Exhaust Drift (14-ft by 12-ft)

Bulkhead or Barrier Location	Bulkhead or Barrier Type	Bulkhead Thickness (ft)	Pressure Gradient FS	Concrete/ Masonry Shear FS	Rock Salt Shear FS	Worst-Case Bending Stress FS	Best-Case Bending Stress FS
Intake Drift	Plain Concrete Bulkhead	36 31.3[1]	2.40	2.40	5.50	3.61	8.55
Exhaust Drift	Plain Concrete Bulkhead	26 21.3[1]	1.54	2.92	1.75	3.85	5.24
Intake Drift	Masonry Explosion-Isolation	12	1.03	0.63	6.37[2]	0.32	0.75
Exhaust Drift	Masonry Explosion-Isolation	12	1.03	0.77	7.68[2]	0.65	0.88
Intake Drift	Masonry Construction-Isolation[3]	4	>2300	>1450	14.6[2]	44.7	>190

Notes: [1] - Sloping face of waste disposal (pressure) side of plain concrete barrier does not provide rock salt shear resistance from the force developed by 480 psi factored design explosion pressure applied to barrier face. The rock salt shear path was therefore reduced. The bond strength between the concrete and the rock salt was conservatively assumed to be negligible. [2] - Hitched 6 inches into roof, ribs and floor rock salt. [3] - Pressure from roof fall in central part of nearest panel room.

Figure 1. Exhaust drift longitudinal cross section through panel closure bulkhead

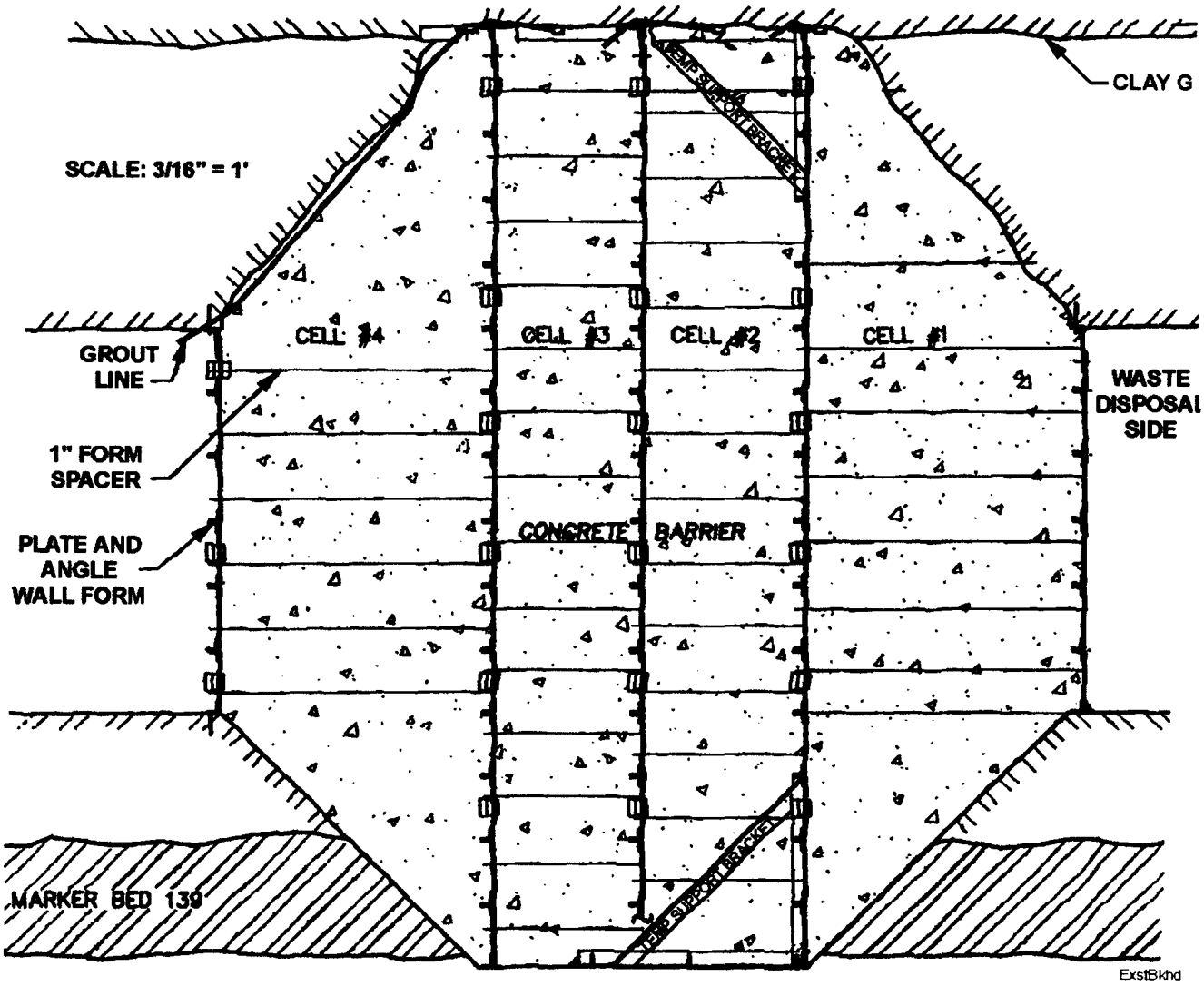

Figure 2. Explosion-isolation masonry wall bulkhead

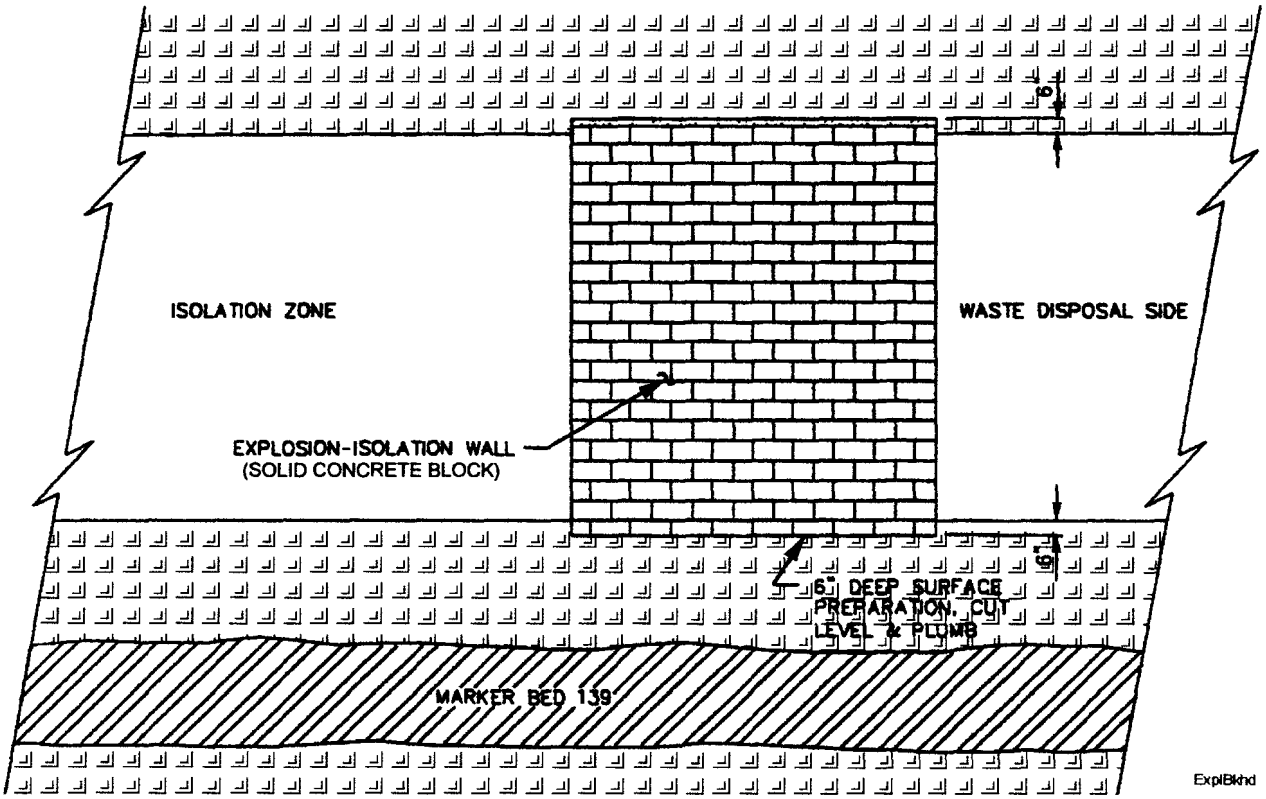

Figure 3. Methane concentration in waste panel over time

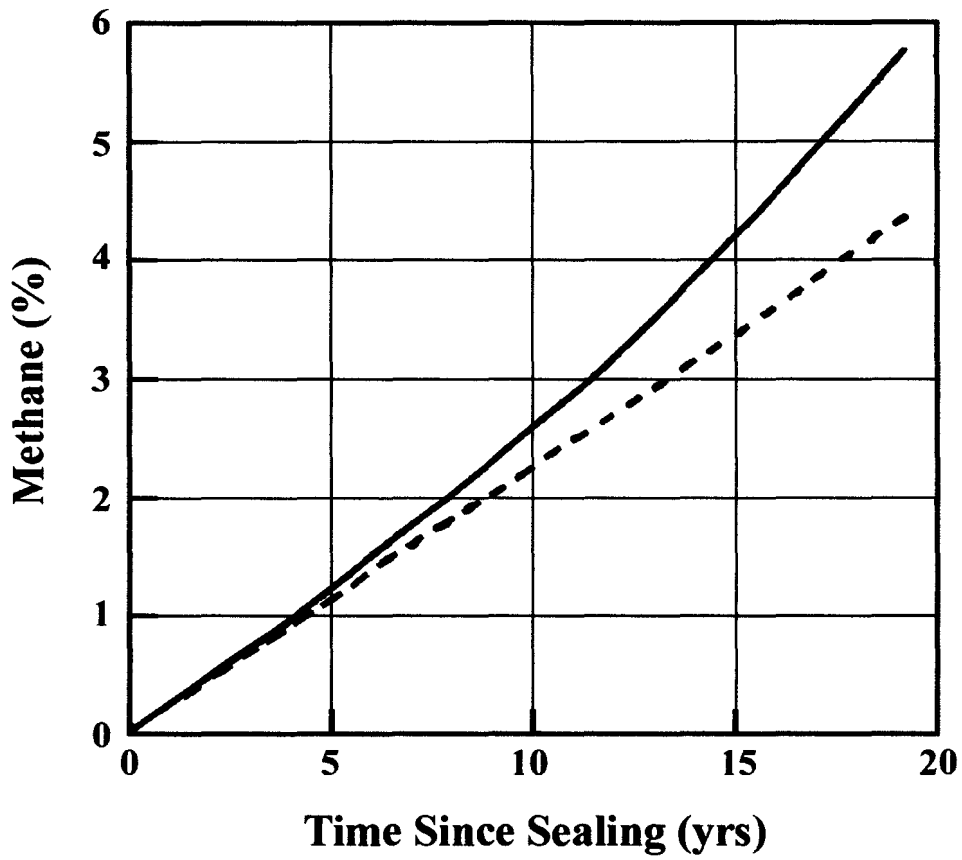

— With Closure 0.1 Mole per drum per year
-- Without Closure

Methane concentration in waste panel over time

(modified from Dykes, et. al., 1997)

MthnTime

Figure 4. Water impoundment bulkhead types

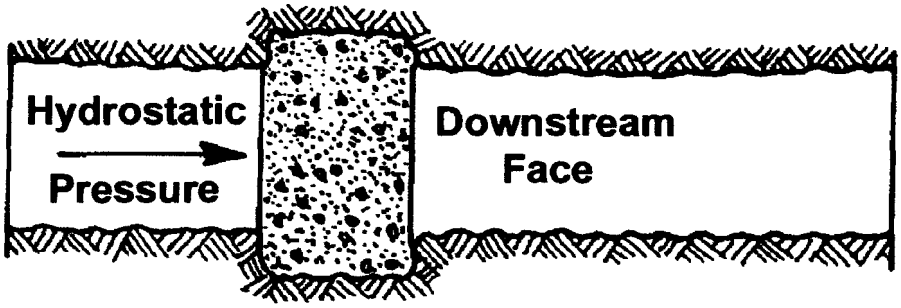

Slab keyed into walls

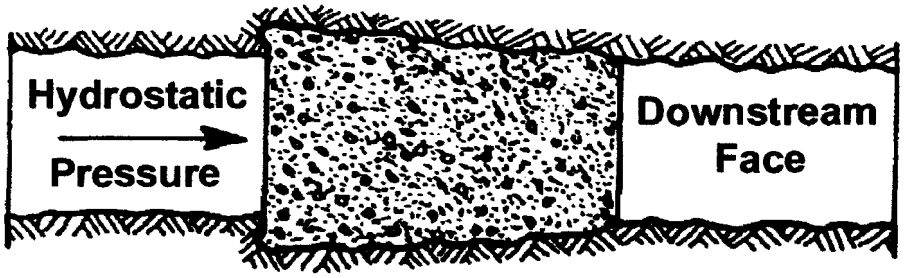

Taper plug

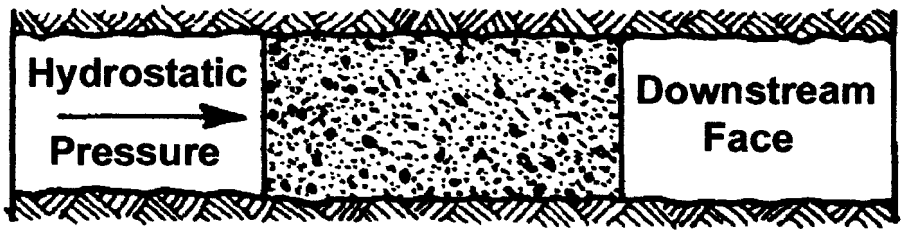

Parallel plug

(Adapted from Garrett & Campbell Pitt, 1958) Blkhtyps

Figure 5. Intake drift lateral cross section through center of closure bulkhead

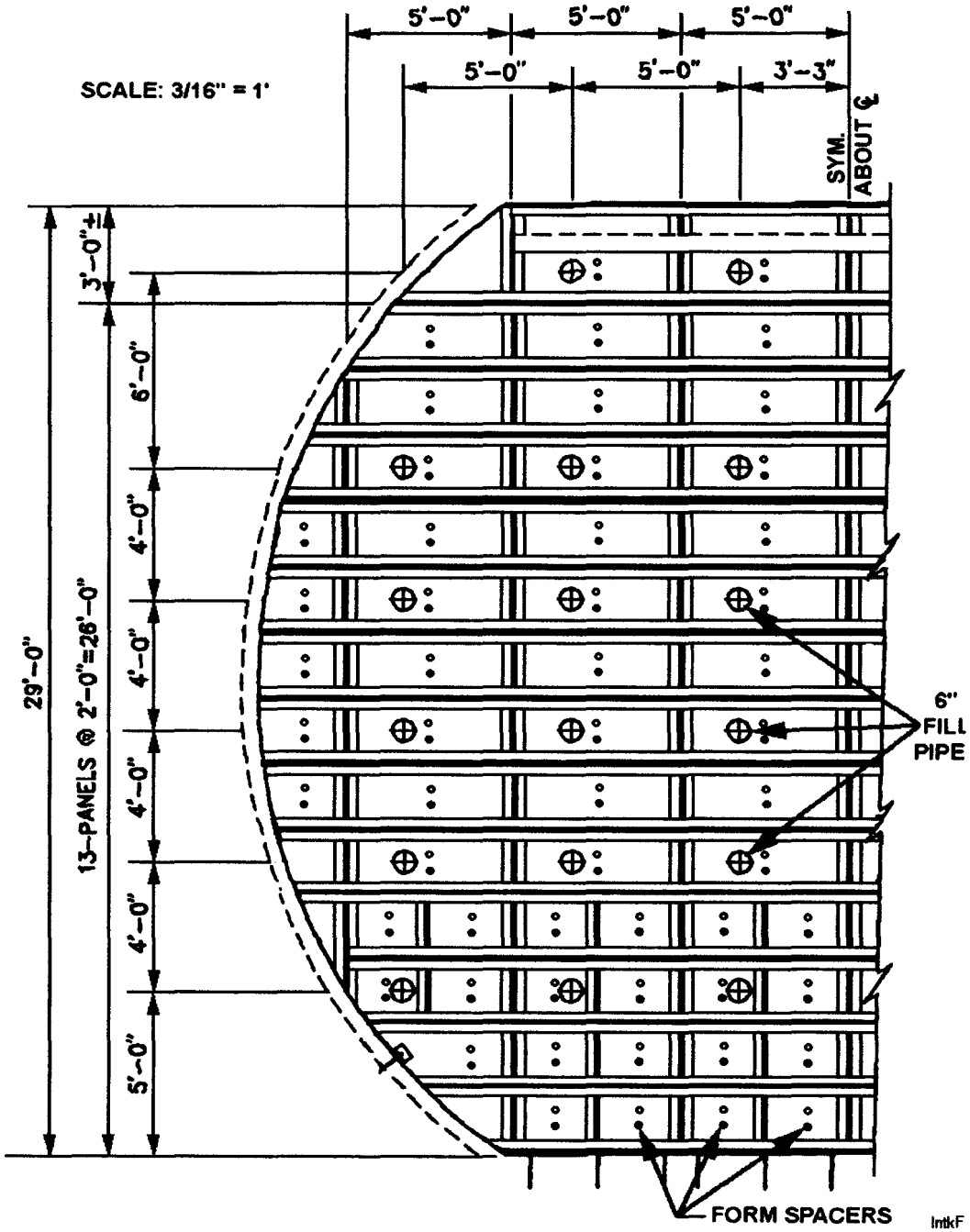

Figure 6. Intake drift lateral cross section inside panel closure bulkhead face

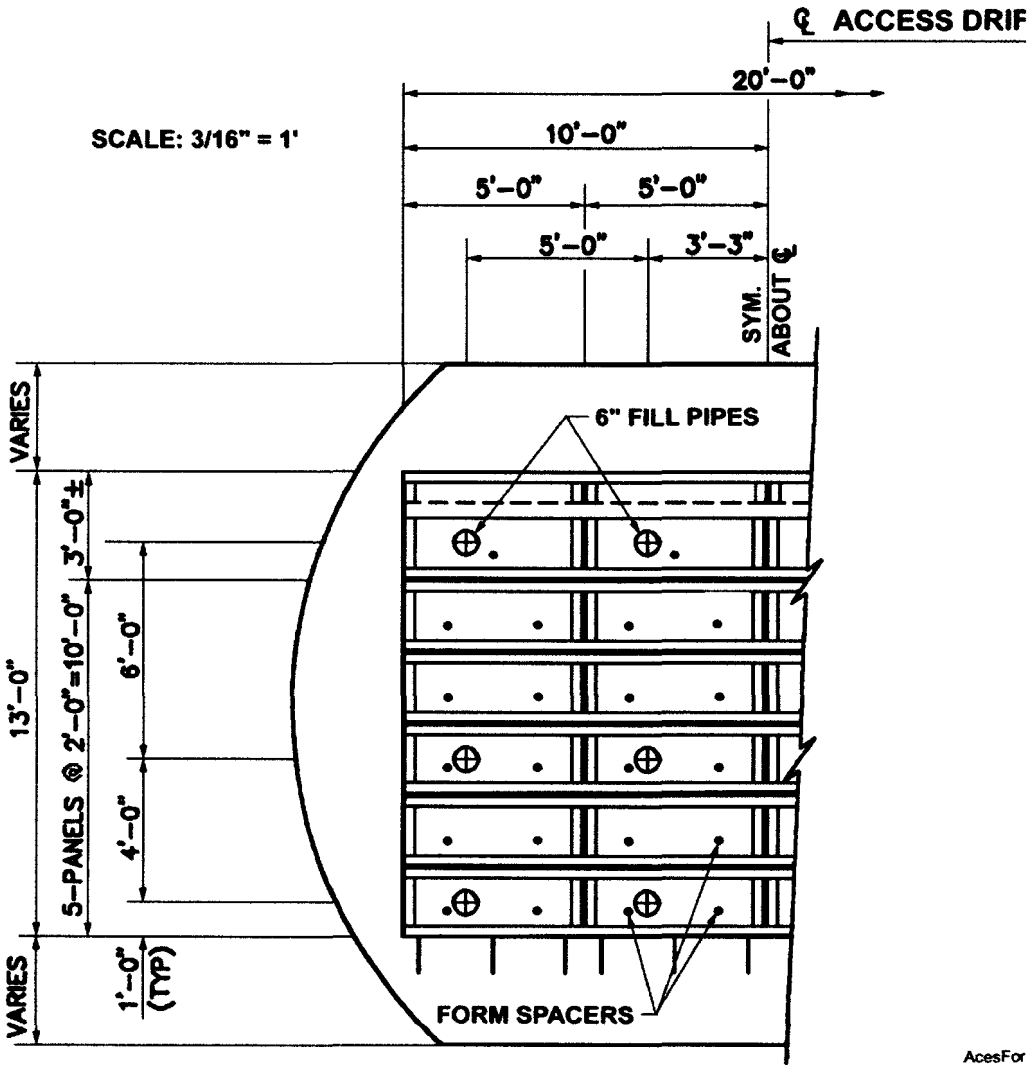

Figure 7. Pressure buildup from panel closure after panel closure bulkhead construction

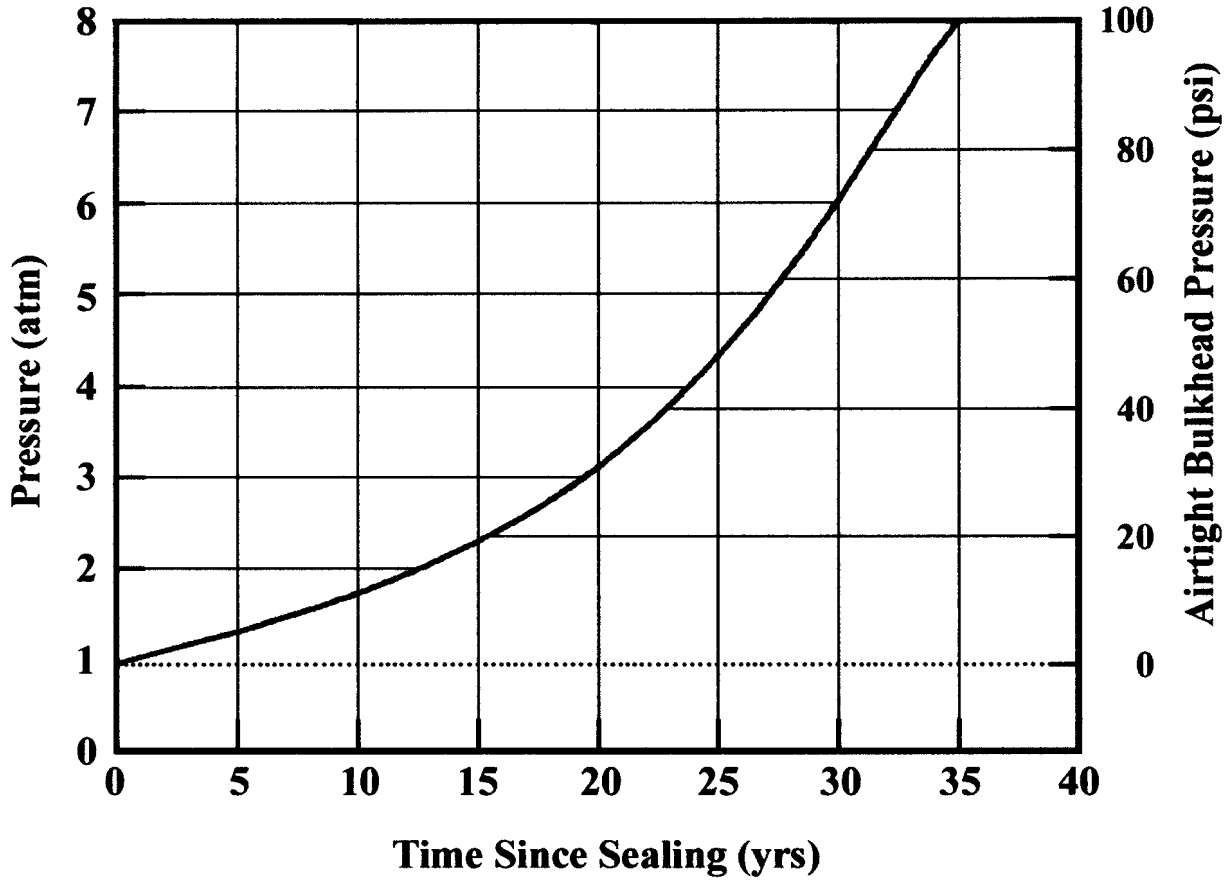

Pressure buildup in a panel after closure
(modified from Dykes, et. al., 1997)

PanlPres

Figure 8. Thermal coefficients of expansion of neat cements, mortars and concretes

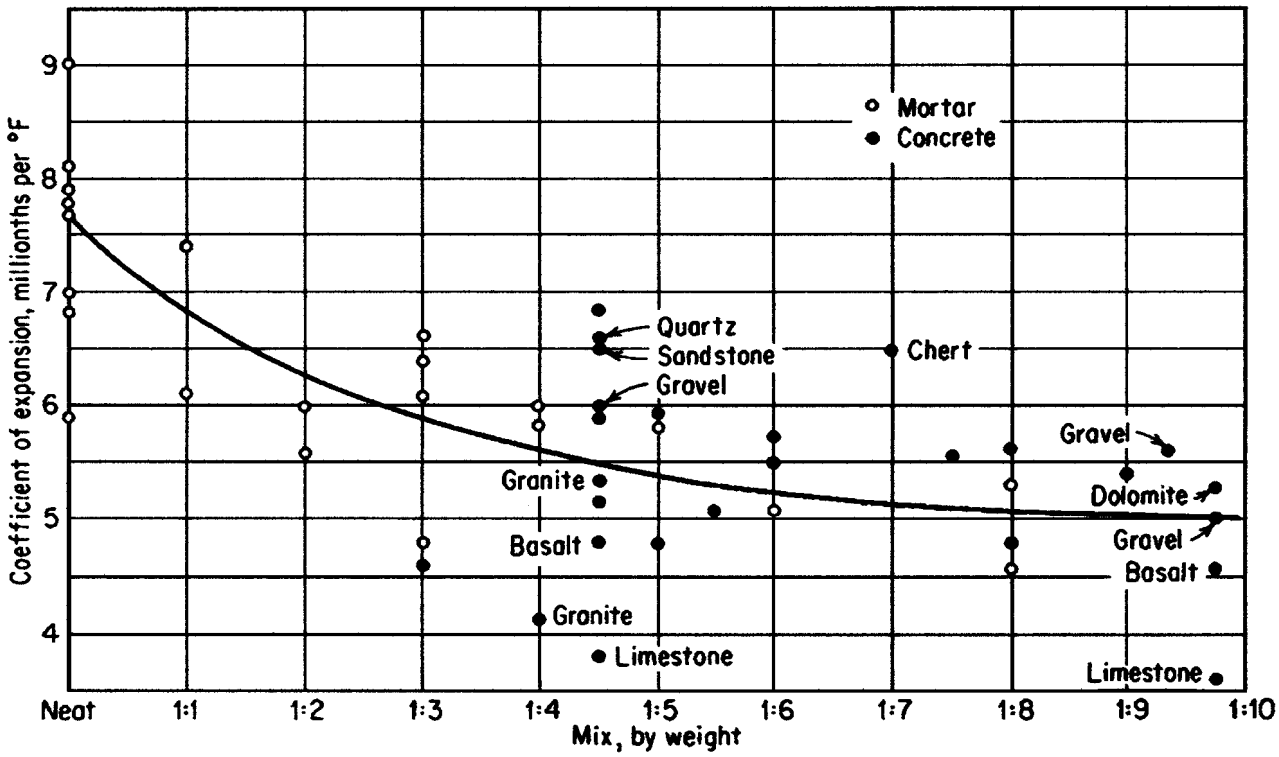

Fig. 12.8. Thermal coefficients of expansion of neat cements, mortars, and concretes. (*From U.S. Bureau of Reclamation* [106].)

TempExpn

INTRODUCTION

This report was prepared as directed by Matthew K. Silva of the Environmental Evaluation Group and Mark Levin of Mining and Environmental Services LLC for the purpose of reviewing the proposed Panel Closure Enhancements to the panel closure system area bulkheads and isolation walls, shown on Figure 9. The original optional designs for the panel closure systems are presented on Figure 10. The proposed enhancements to the Panel Closure System are described in the Compliance Certification Application (CCA). This review is specifically directed at evaluating the ability of the enhanced panel closure bulkheads and walls to provide an equivalent, or improved, panel closure. The specific enhancements proposed and reviewed are:

1) replacing the 12-ft thick explosion-isolation wall with the 4-ft construction-isolation wall,

2) allowing the use of a generic salt-based concrete in lieu of Salado-based concrete,

3) allowing the use of local carbonate river rock aggregate in lieu of crushed quartz aggregate,

4) allowing either surface or underground mixing of the concrete,

5) allowing flexibility in the bulkhead forming practices,

6) replacing freshwater grout with salt-based grout and

7) extending the construction period from 180 days to up to one year.

Item 1) relates to the necessity for and ability of the 12-ft thick explosion-isolation masonry wall to protect the workers constructing the panel bulkheads from the design methane explosion pressure. Items 2), 3), 4), 6) and 7) relate primarily to the resulting strength of the concrete in the panel closure bulkheads, over the minimum operational period of 35 years. Item 5) relates to the ability of the resulting flexibly formed panel closure bulkheads to resist both short term methane explosion pressure and long term panel closure-induced gas pressure and to prevent long term brine flow from the panels.

Figure 9. Location of panel closure system areas

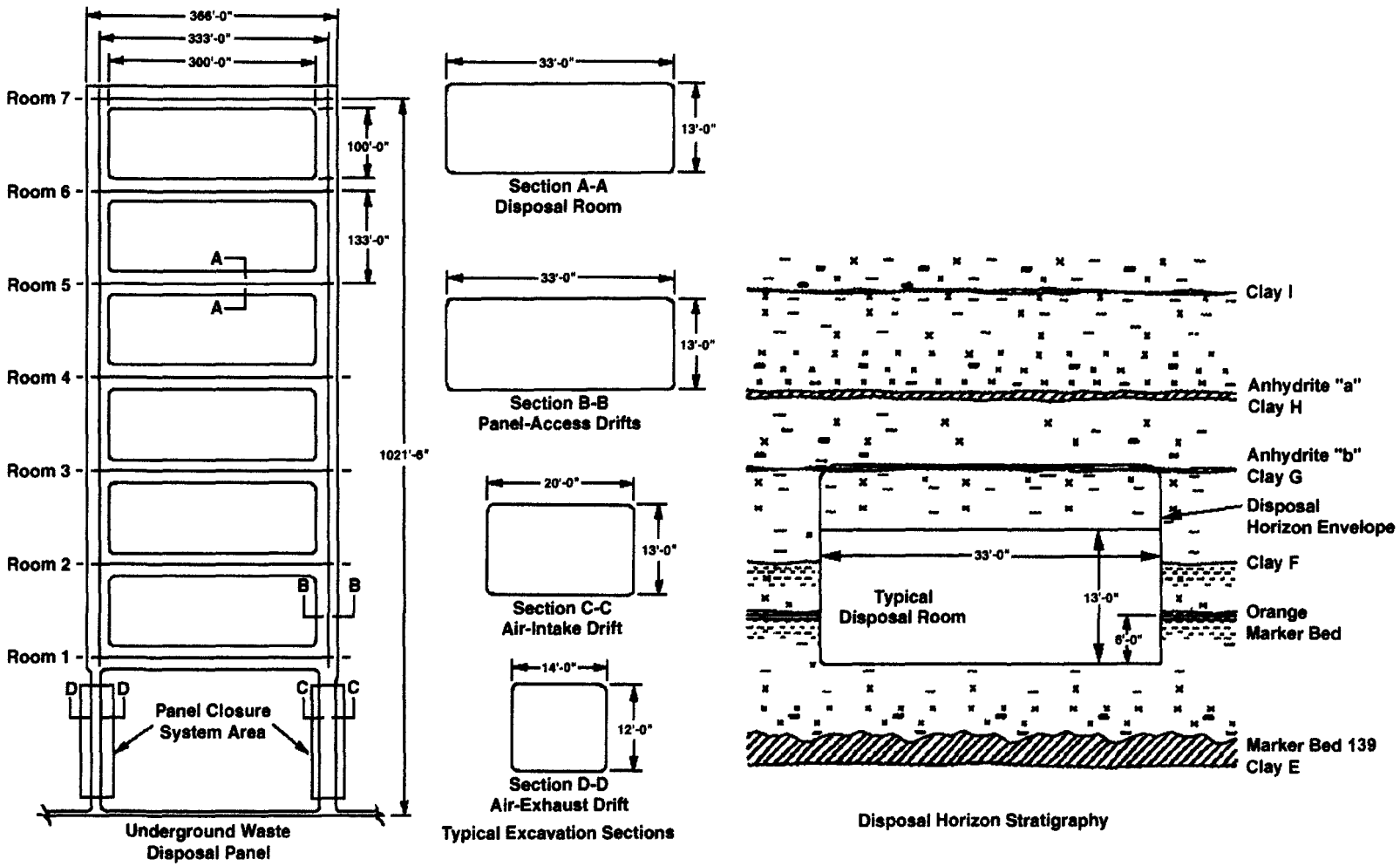

Note: Figure is not to scale. All dimensions shown are nominal.

Location of panel closure system areas (from DOE/WIPP-96-2150)

WPBlkhd2

Figure 10. Optional designs for panel closure systems

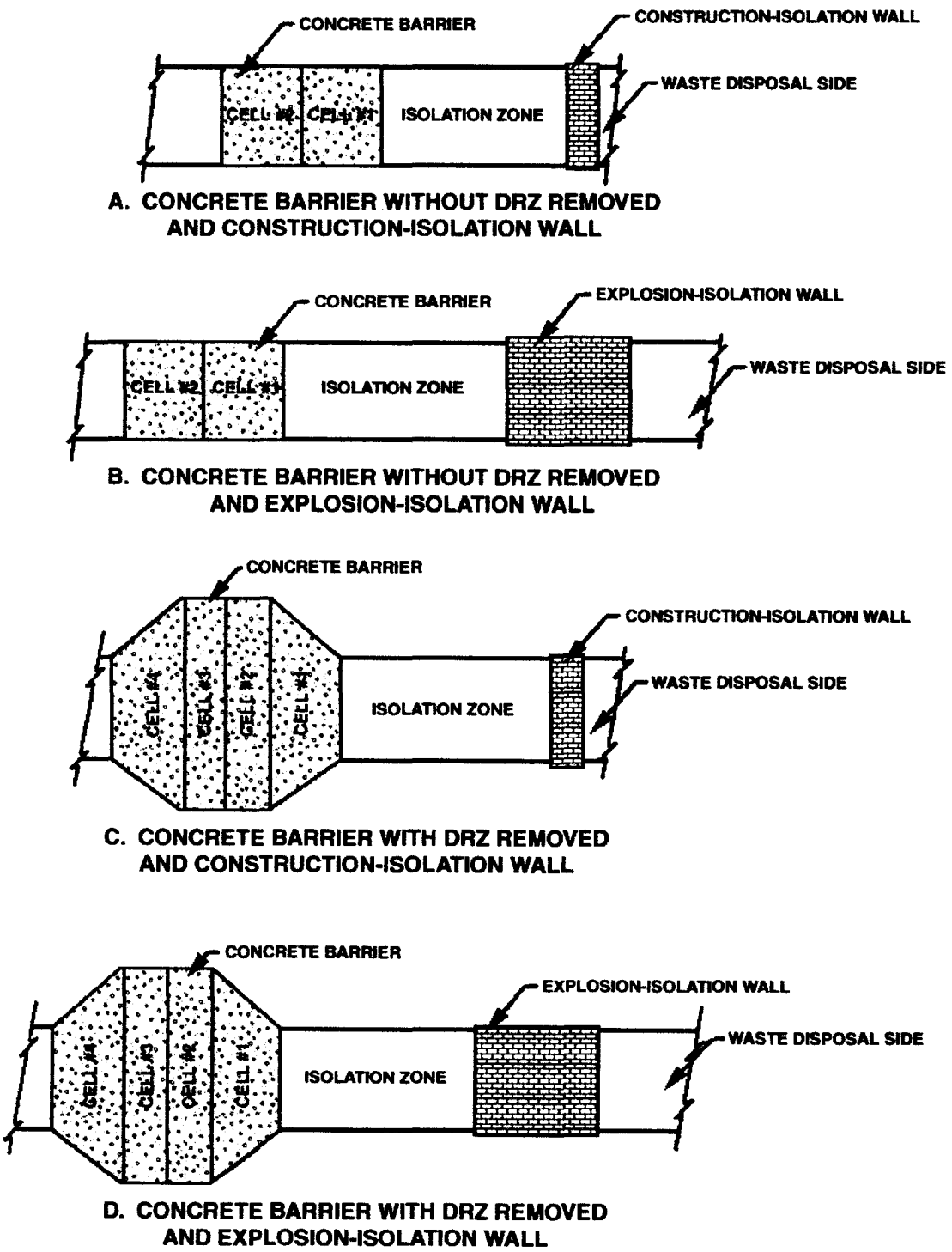

Optional designs for panel closure systems

(modified from DOE/WIPP-96-2150)

WPBlkhd1

CONCRETE BULKHEAD AND MASONRY WALL STABILITY

The 4,000 psi concrete panel closure bulkheads must be capable of resisting the transient 480 psi design overpressure from a methane explosion within closed panels during the planned 35 year life of the facility. The panel closure bulkheads must also be capable of containing the continuous and rising air pressure resulting from the creep closure of the of the panel rooms for the planned 35 year life of the facility. Figure 7 indicates the air pressure inside a sealed panel could increase to approximately 100 psi over 35 years. The panel closure bulkhead designed for the 14-ft wide by 12-ft high Exhaust Drift (Figure 1) is 26-ft thick, 29-ft high and 33.5-ft wide. The panel closure bulkhead designed for the 20-ft wide by 13-ft high Intake Drift is 36-ft thick, 29-ft high and 35.5-ft wide.

In addition, it was postulated that "selection of a thick enough" optional explosion-isolation wall could isolate the main panel closure bulkheads from the design methane explosion pressure. A 12-ft thick, 3500 psi solid masonry concrete block wall mortared with 2500 psi mortar was selected for the explosion-isolation wall.

A 4-ft thick construction-isolation masonry wall is specified "to provide isolation during construction of the main concrete barrier." The panel closure bulkhead construction area will be isolated from the overpressure developed by a possible roof fall in the nearest waste filled room during the 6-month to one-year bulkhead construction period.

PANEL CLOSURE BULKHEADS

The purpose of the panel closure bulkheads, located in the Intake and Exhaust Drifts where indicated on Figure 9, is to seal the waste emplaced in the seven panel rooms from the remaining active, operational, part of the WIPP. Figure 11 shows a typical active panel with waste emplaced in two rooms and indicates the continuing ventilation of the waste filled rooms and panel access drifts. The tapered concrete bulkheads were also designed to block potential leakage paths along Clay G in the near roof and in the anhydrite Marker Bed 139 beneath the floor. Bed separation at Clay G and low angle shear fractures in the roof salt starting at the ribside and angling up to Clay G that preceded the two roof falls in the Site and Preliminary Design Validation (SPDV) area demonstrate the progressive damage in the immediate rock salt roof. Similarly, the fracturing and heave of room floors has been traced to upward buckling of the anhydrite Marker Bed 139. The need to remove the damaged rock zones (DRZ) and block the potential leakage paths in the roof and floor is

the reason that the two-way tapered plain concrete bulkheads, shown on Figure 1, were designed.

The essentially rigid concrete panel closure bulkheads will draw load as the salt creeps toward the adjacent open drifts and rooms. The vertical and lateral horizontal stress acting on the roughly spherical panel closure bulkheads could eventually approach twice the overburden pressure, approximately 4,300 psi (Goodier, 1933; Edwards, 1955). The high stress concentration against the panel closure bulkheads will resist fracture propagation in the rock salt over, under and around the bulkheads, as indicated on Figure 12. The applied pressure would have to overcome (exceed) the rock salt/concrete contact pressure to propagate a fracture around the panel closure bulkheads.

The ground pressure applied to all sides of the panel closure bulkheads during the 17 years needed to reach an explosive 5% methane concentration (Figure 3) will grip the top, bottom and sides of the bulkheads. The force of this grip will resist flexure of the bulkhead concrete, in effect forming a fixed-end circular deep plate. The fixity of the panel bulkheads will reduce the bending moment developed when the bulkhead is loaded by the design explosion pressure applied from the waste emplacement side.

The ability of the planned plain concrete panel closure bulkheads was conservatively checked using the water impoundment bulkhead design method (Abel, 1998). The panel closure bulkheads are fully capable of resisting the 480 psi design methane explosion pressure. The 480 psi design methane explosion pressure is equal to the hydrostatic head of 1,108 feet of water. The panel closure bulkheads are effectively plain concrete because no tensile reinforcement is provided, or necessary, to resist the deep-beam bending stresses. The bulkhead lengths are sufficient to reduce the flexural bending stresses to less than the American Concrete Institute (ACI) allowable 206 psi tensile strength of 4,000 psi compressive strength concrete. Appendix A presents the calculations for the Intake Drift bulkhead and Appendix B for the Exhaust Drift bulkhead. Table 1 presents the various factors of safety for the panel closure bulkheads. The lowest factor of safety for the 36-ft thick Intake Drift bulkhead is 2.40 against both pressure gradient and concrete shear and for the 26-ft thick Exhaust Drift bulkhead is 1.54 against pressure gradient and 2.92 against concrete shear. The water impoundment bulkhead method only considers the grout pressure along the rock/concrete contact and does not provide any credit for the pressure from creep closure pressure of the rock salt.

The panel closure bulkhead design (Figure 1 and Figure 10) is not a monolith because it is planned to be built using four

cells. The steel forms will restrain the concrete pumped into each cell until the initial set, which will take approximately 4 hours (Figure 13). Most water retaining bulkheads (Figure 4) are designed and constructed as monolithic, i.e. continuous, pours without cold joints or interior form walls. Figure 14 provides a longitudinal cross section of the reinforced concrete American Tunnel Bulkhead #1, designed to resist a 1550-ft head (670 psi) and supporting 1010-ft (438 psi). Note the waterstops on the bypass pipe and the grout holes drilled through the concrete to low-pressure grout the roof and rib contact between the 11,000 psi compressive strength latite porphyry and the 3,000 psi concrete.

Some multi-cell bulkheads have been constructed when construction problems or emergencies required. At the Summitville Mine a second 20-ft long cell was added when water loss through the 129 psi compressive strength altered latite porphyry and over the initial 6.5-ft long Chandler Adit bulkhead became excessive. At the West Driefontein Mine, in response to a 67,000 gpm water inrush, a three cell bulkhead was progressively constructed on the 12-Level, the initial "temporary" sand and cement bag diversion plug, followed by a 15-ft long thickening bulkhead against the "temporary" plug and the final 60-ft long sand-concrete extension bulkhead. At the Rocanville Mine, in response to a 6,250 gpm brine inrush into the potash mine, an 87-ft thick five cell bulkhead was constructed, an initial 8-ft thick bulkhead, a 16-ft thick second cell, a 25-ft thick third cell and a final 37-ft thick cell (Figure 15). In every case, the cell forms were externally supported and the internal bulkhead forms were stripped before constructing the subsequent cell. The planned four cell panel closure bulkhead construction would not provide a monolithic, i.e. uniform and continuous, bulkhead but could contain as many as three interior steel form walls supported during filling by the form spacers.

Penetrations through a water retaining bulkhead are normally minimized, whenever possible, because they represent potential leakage paths through bulkheads. Essential penetrations, such as bypass and sampling and pressure monitoring pipes, include waterstops to assure no leakage along the penetrations. The planned 4 cell panel closure bulkhead (Figure 1) includes the use of longitudinal 1-in diameter form spacers, which also support the facility side plate and angle form wall until the concrete sets. Figure 5 indicates 55 form spacer penetrations across Cell #2 and Cell #3. Figure 6 indicates 22 form spacer penetrations across Cell #1 and Cell #4. Multiple potential flow paths are apparent across the individual cells. If not removed after the cell is filled, the steel plate and angle forms provide multiple potential leakage paths between form spacers in adjacent cells. The bond strength between the steel plates and the concrete is

necessarily low. Even if a way is found to remove the three interior steel form walls, after the concrete has set in each cell, a smooth surfaced cold joint will still be present between cells.

In order of declining potential effectiveness, the following panel closure bulkhead construction modifications should decrease the bulkhead leakage potential,

1) constructing truly monolithic single-cell panel closure bulkheads or
2) externally supporting the bulkhead cell forms, i.e. eliminating the form spacers, or
3) reducing the number of cells.

The panel closure bulkheads are tapered two-way pressure bulkheads, i.e. designed to resist equal pressure from either side. The panel closure bulkheads are apparently designed to be airtight for the 35-year life of the facility. Closure of the panel rooms and panel access drifts is predicted to result in 100 psi of effective pressure on the waste side of the bulkheads over a 35 years period after completion of the panel closure bulkheads (Figure 7). The two-way taper of the panel closure bulkheads was apparently designed to permit the safe excavation of the disturbed rock zones (DRZ) above and below the intake and exhaust drifts. The ample panel closure bulkhead factors of safety against the 480 psi design methane explosion pressure should be more than quadrupled for the closure pressure.

Tapered bulkhead water containment bulkheads are normally constructed when the rock shear strength is lower than the concrete design shear strength. Figure 4 shows a typical tapered water containment bulkhead, designed to resist hydrostatic pressure from one side. Successful tapered bulkheads have been constructed at the Summitville Mine, the Jackpot Mine declines and at IMC's K2 Mine. Tapering a bulkhead increases the length of the worst-case potential shear surface in the lower strength rock adjacent to the rock/concrete interface and tightens the concrete bulkhead against the rock when hydrostatic pressure is applied. In most water impoundment cases, when the rock strength exceeds the concrete strength, parallel plugs have proven to be effective. Loofbourow in the Society of Mining Engineers (SME) Mining Engineering Handbook (1973, Sec 26.7.4) states "no indication of structural failure resulting from thrust was noted" in the case of ten bulkheads subjected by hydraulic pressures in excess of 1000 psi and which relied solely on normal rock surface irregularities, referred to as a "parallel plug" on Figure 4. Garrett and Campbell-Pitt (1961) reported the successful results from 26 mine bulkheads,

twelve with parallel plugs, that relied solely on the irregularity of the tunnel walls, and 14 with taper plugs.

Parallel panel closure bulkheads would probably be successful in resisting the potential applied pressures, Options A and B on Figure 10. However, the progressive deterioration of the adjacent rock salt and anhydrite and clay layer bed separations suggests that the two-way tapered bulkhead will assure the long term functioning of airtight panel closure bulkheads.

EXPLOSION-ISOLATION MASONRY WALLS

The 12-ft thick explosion-isolation masonry walls for the Intake Drift and the Exhaust Drift (Figure 2) are planned to be built with solid concrete blocks (3,500 psi) mortared with cement and hitched 6-in into the roof, ribs and floor. The explosion-isolation masonry wall is apparently designed to resist the 480 psi methane explosion pressure during the six months to one year of panel bulkhead construction.

The ability of the planned explosion-isolation masonry walls to resist the 480 psi methane explosion pressure was conservatively checked using the water impoundment bulkhead design method (Abel, 1998). Table 1 presents the results of this analysis. The calculations for the Intake Drift are presented in Appendix C and for the Exhaust Drift in Appendix D. The results of this analysis predicts that the planned 12-ft thick explosion-isolation masonry walls would not be capable of resisting the 480 psi design methane explosion pressure. The predicted failure of the explosion-isolation wall is indicated on Figure 12. In the Intake Drift, the thickness of an explosion-isolation masonry bulkhead would have to be approximately 20-ft to contain the 480 psi methane explosion pressure and in the Exhaust Drift approximately 15-ft.

Figure 3 presents the predicted 17+ year methane concentration time interval between cessation of panel ventilation and the methane concentration reaching the minimum 5% lower explosive limit. The predicted methane concentration should not exceed approximately 0.25% during a one-year panel closure bulkhead construction period. Therefore, a methane explosion should not be possible, and an explosion-isolation masonry wall not necessary.

CONSTRUCTION-ISOLATION MASONRY WALLS

A 4-ft thick construction-isolation masonry wall has been designed to isolate the panel closure bulkhead construction from the emplaced waste in a completed panel and from the transient overpressure from a 15,000 ton roof fall in central 140-ft of Room 1 in the completed panel, closest to the Intake and Exhaust Drifts. The design roof fall is equal in weight and length to the roof fall in Site and Preliminary Design Validation Room 1 (SPDV1). The SPDV1 fall distance was the 13-ft room height, whereas the fall distance with emplaced waste drums is limited to 3.5-ft. Figure 16 presents the predicted 0.4 PSF (0.003 psi) maximum overpressure and the design 10.1 PSF (0.070 psi) air overpressure from the roof fall.

The ability of the planned construction-isolation masonry walls to resist the 0.070 psi design roof fall pressure was conservatively checked using the water impoundment bulkhead design method (Abel, 1998). Table 1 presents the results of this analysis. The calculations for the 4-ft thick Intake Drift construction-isolation masonry wall are presented in Appendix E.

The 4-ft thick construction-isolation masonry wall planned for the 20-ft wide by 13-ft high Intake Drift is fully capable of resisting the roof fall design overpressure. A similar 4-ft thick construction-isolation masonry wall planned for the 14-ft wide by 12-ft high Exhaust Drift will have even higher factors of safety against the roof fall design overpressure.

Figure 11.Typical active panel configuration with ventilation splits

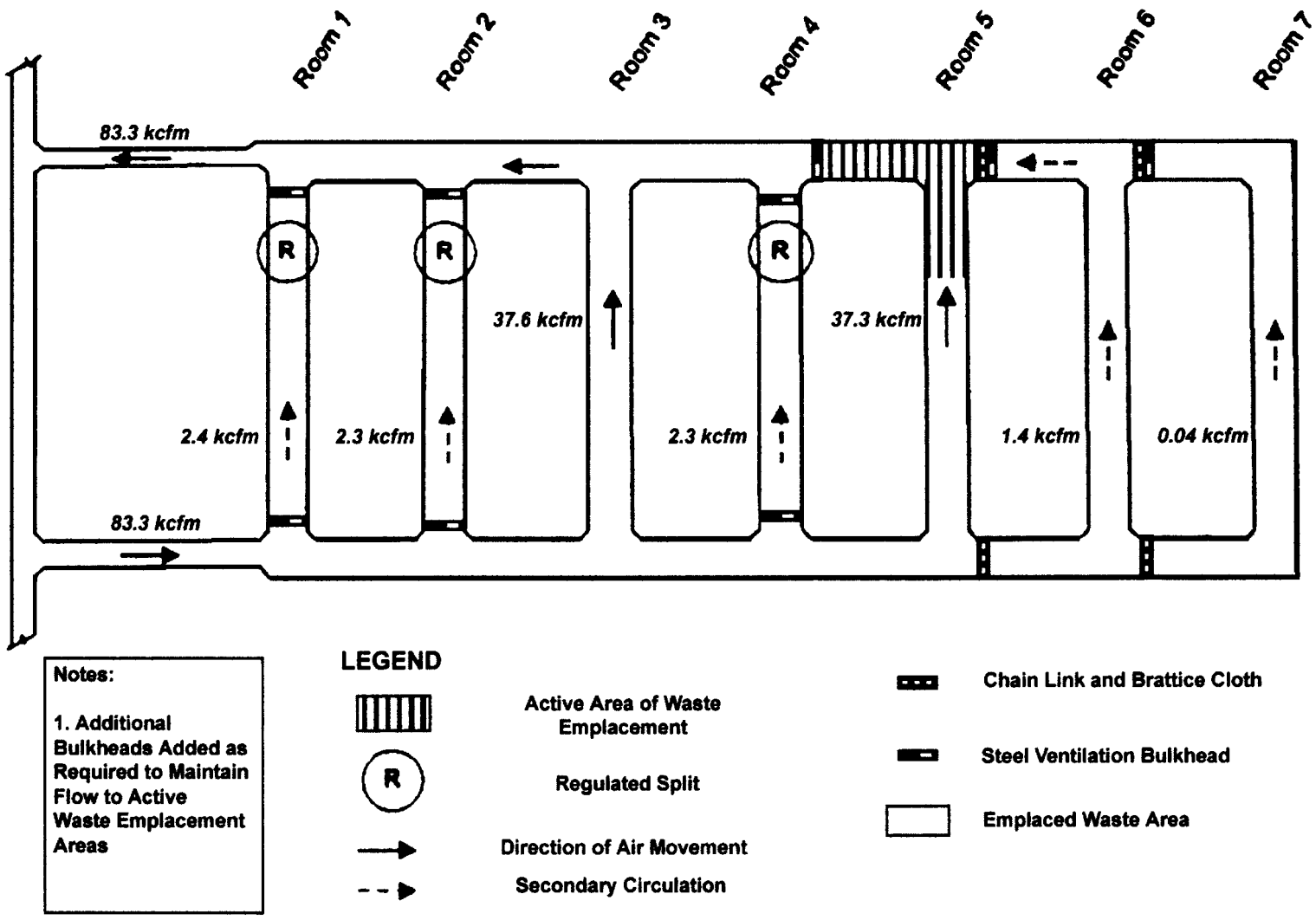

Typical active panel configuration with ventilation splits (from Dykes, et. al., 1997)

WPnlCnf2

Figure 12. Fracture propagation modes of bulkhead failure

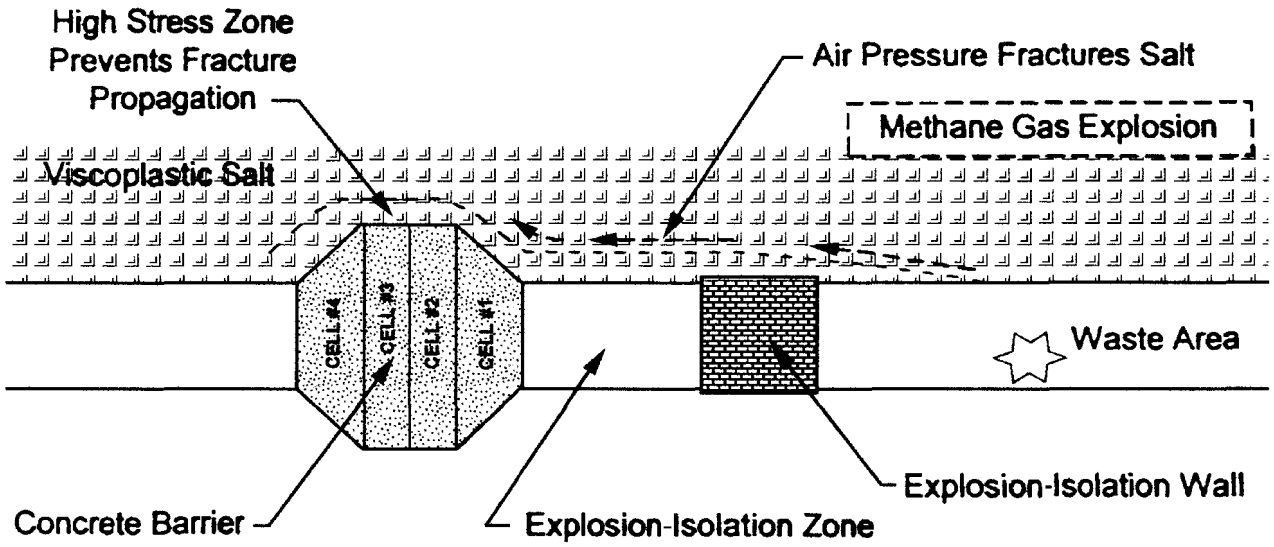

Fracture propagation mode of failure with stable explosion-isolation wall
(modified from Dykes, et. al., 1997)

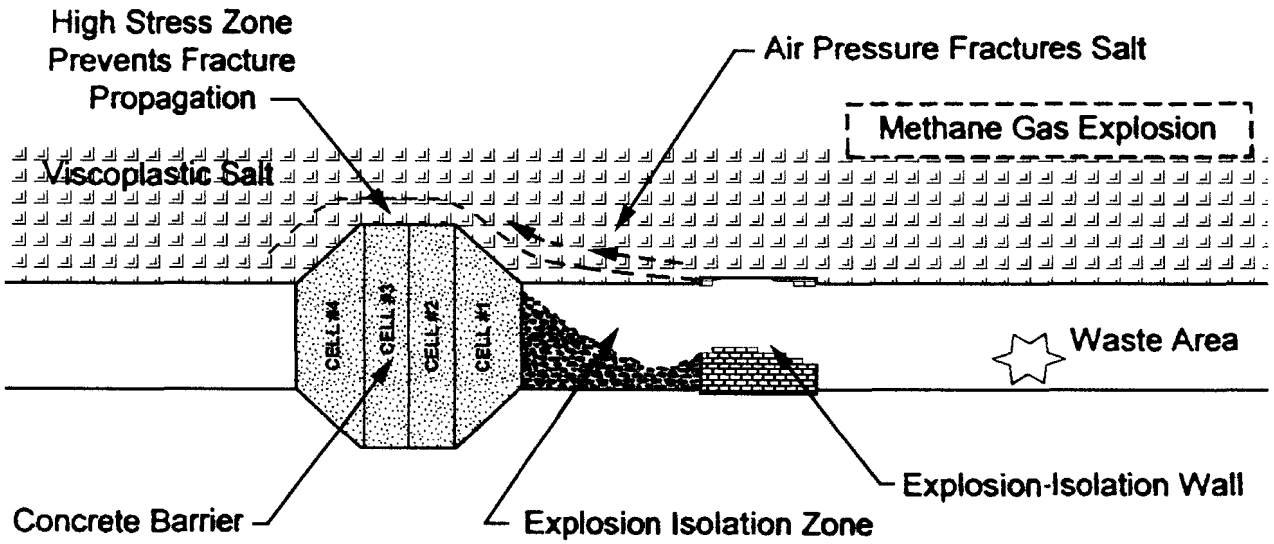

Fracture propagation mode of failure for explosion-isolation wall failure
(modified from Dykes, et. al., 1997)

ExploBk1

Figure 13. Example of effect of temperature on setting time of concrete

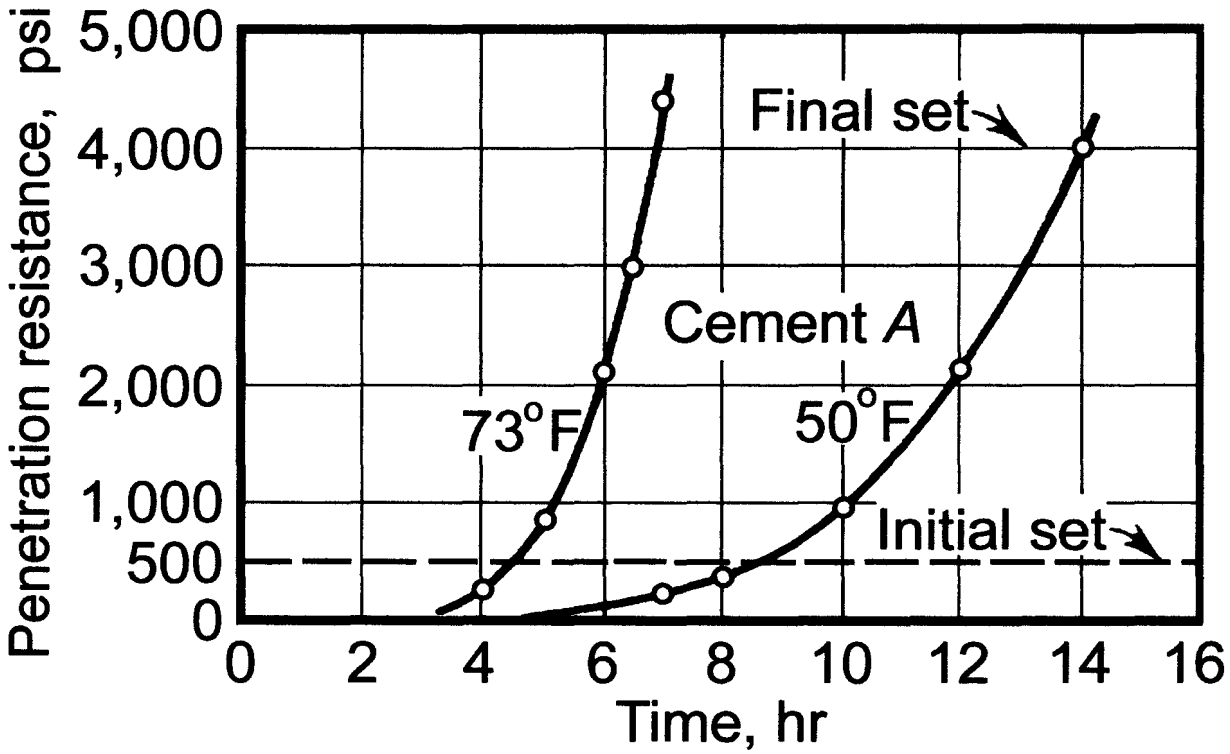

Example of effect of temperature on setting time of concrete
(Troxell, et. al., 1968)

SetTime2

Figure 14. Cross section through monolithic bulkhead (Abel, 1998)

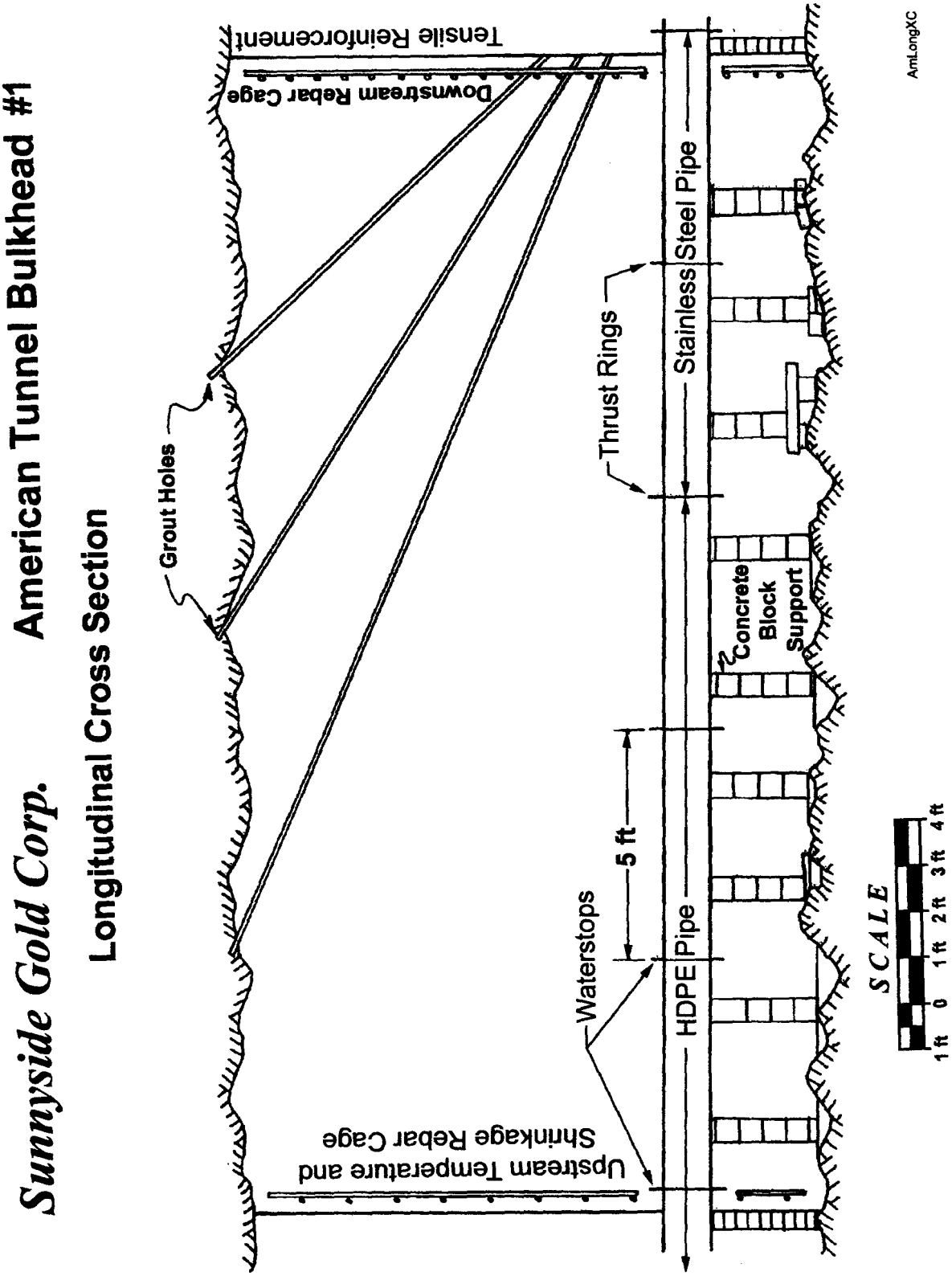

Figure 15. Rocanville inflow tunnel bulkheads and plugs

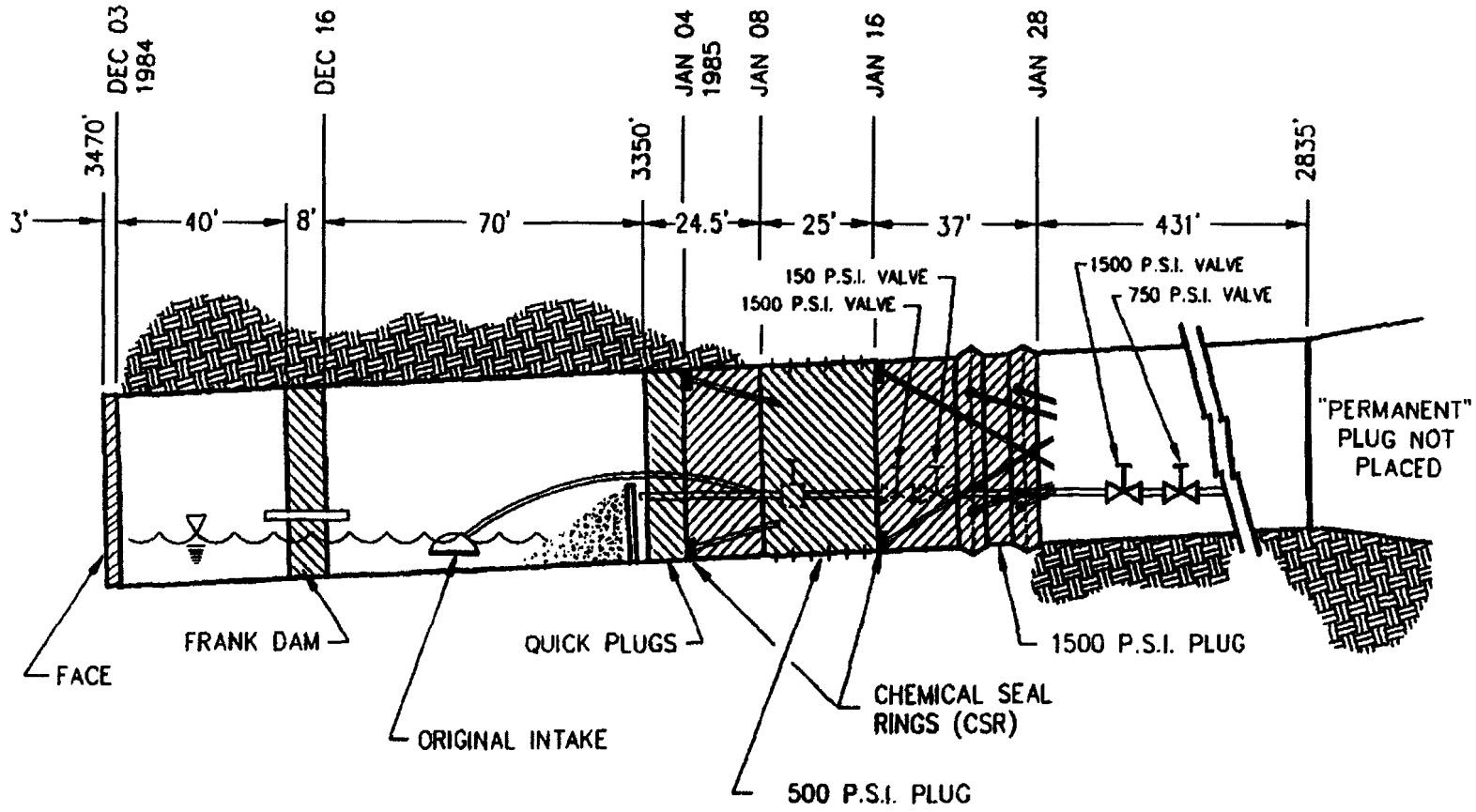

Rocanville inflow tunnel bulkheads and plugs (Eyermann, et. al., 1995)

Figure 16. Pressure transient from a roof fall

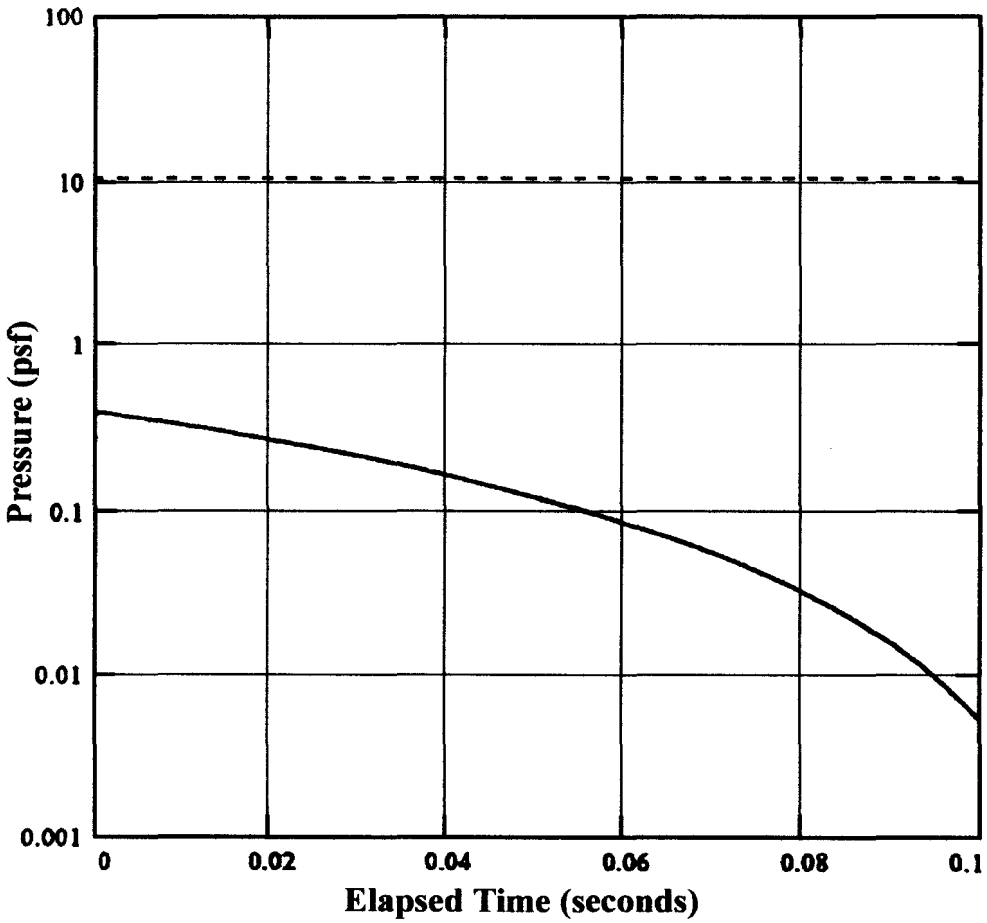

— Predicted Pressure Loading
- - Design Pressure Loading

Pressure transient for a roof fall
(modified from Dykes, et. al., 1997)

RoofFall

CONSTRUCTION ENHANCEMENTS

The remaining panel closure enhancements relate primarily to the resulting strength of the concrete in the panel closure bulkheads, over the minimum operational period of 35 years. The strength of the concrete is critical to the strength of the panel closure bulkheads.

The proposal to allow the mass concrete to utilize any rock salt in the mix depends on the ability to consistently meet the strength specification. The unconfined compressive strength of the 16 Permian evaporite beds tabulated in Appendix F ranges from 2300 psi to 5880 psi and the cohesion from 540 to 1580 psi. The unconfined compressive strength of the evaporite beds tabulated in Appendix G, including the Permian beds in Appendix F, ranges from 2260 psi to 7510 psi and the cohesion from 540 to 1790 psi. The random selection of the salt from any tested salt bed should be capable of providing equivalent strength properties. In addition, the strength variation across a single evaporite bed in the Salado formation is significant. The unconfined compressive strength of the Mississippi Potash Company's Cycle 7 bed (> 85% salt) ranged from 1610 psi to 4950 psi, as shown on Figure 17. The important factor would appear that the salt component of the mix be consistent, i. e. well mixed from one source.

Aggregate strength is a minor concrete strength factor which can be compensated for, if necessary, by increasing the cement in the mix and verified by testing. In addition, carbonate aggregate concrete probably has a lower coefficient of thermal expansion that quartz aggregate. Figure 8 indicates that concrete with quartz aggregate has a higher coefficient of expansion (approximately 6.6 millionths per °F) than either limestone aggregate concrete (approximately 3.8 millionths per °F) or dolomite aggregate concrete (approximately 5.3 millionths per °F). It should be possible to use either the Pennsylvanian Atoka limestone or the Permian, Guadalupian, Bell Canyon limestone river rock for concrete aggregate. Rounded river rock should facilitate slick line pumping and form filling.

Surface or underground mixing of the concrete is of no significance. Sunnyside Cold Corp. has constructed five water impoundment bulkheads using underground mixing and pumping stations, four using supersacks, surface mixing and pumping and one with surface mixing and transporting by rail in Moran cars. The critical factor is limiting the time between mixing and placement in the form. Troxell, et. al. (1968) state:

Figure 17. Strength of Mississippi Potash Co.'s Cycle 7 bed

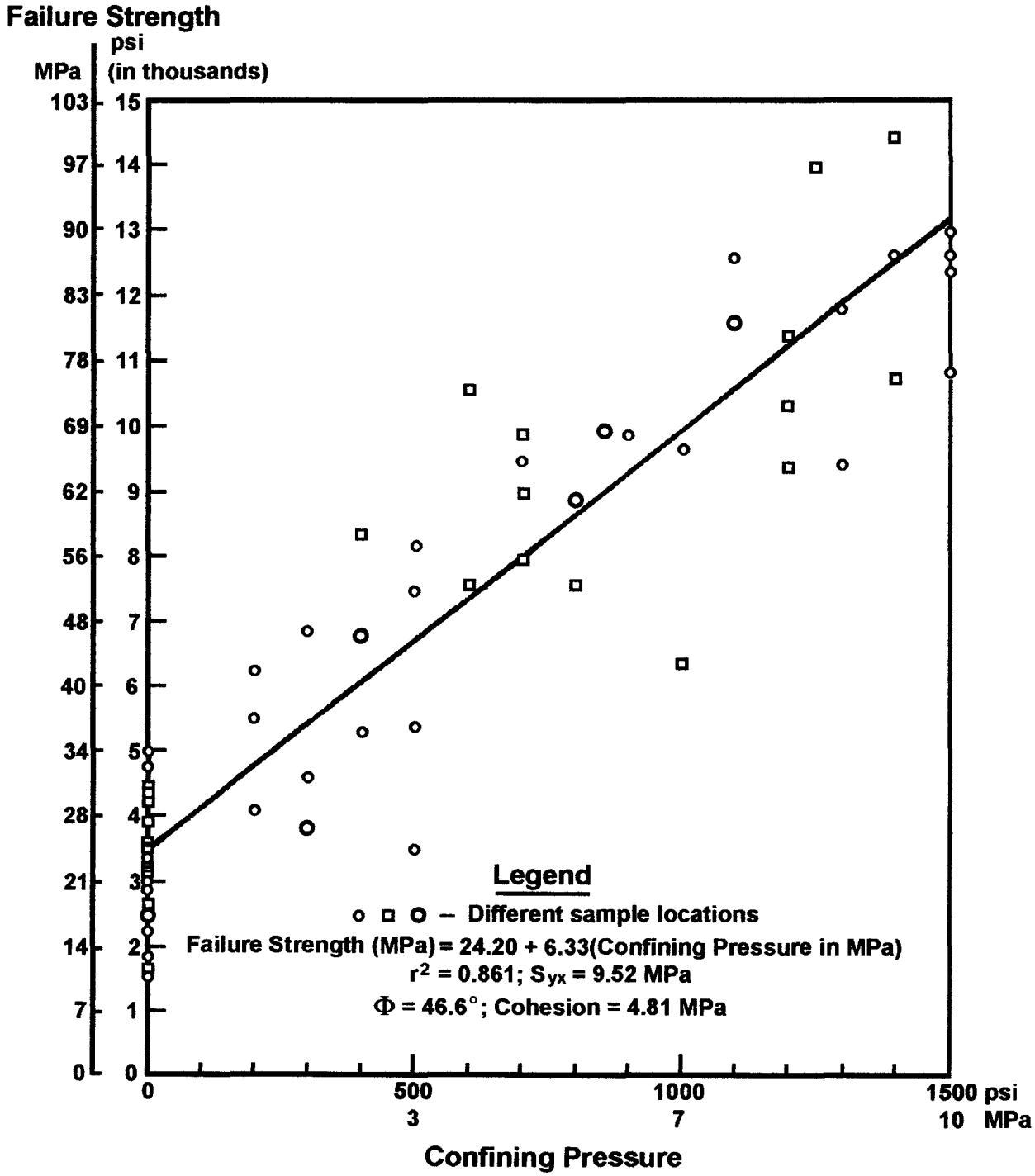

Strength of Mississippi Potash Co.'s Cycle 7 bed (Abel and Djahanguiri, 1984) SaltNuc5

> Current specifications for ready-mixed concrete require that the concrete be discharged from the truck within 1-1/2 hr or before the drum has had 300 revolutions (whichever comes first) after the water is added to the batch, or the cement to the moist aggregate. Under specially favorable conditions, periods up to 2 and 3 hr may be allowed. Conversely, under unfavorable conditions where air temperatures are unusually high, or the ingredients of the concrete are such that an unusually quick time of set or loss of plasticity may occur, it may be necessary to substitute a shorter period.

If the water is added to the bulkhead concrete on the surface, it will be difficult to meet the time limitation. Transporting supersacks underground and adding the water and mixing close to the bulkhead sites would appear to be the most reasonable method.

Replacing freshwater grout with salt-based grout should be done in order to minimize salt dissolution in the adjacent rock salt and in the salt-based concrete. Salt dissolution could weaken the contact zone and potentially provide a leakage path for brine, methane explosion pressure and closure compressed gas pressure behind the panel closure bulkheads.

It should be expected that the best contractor bid will result from the least restrictive specification. There is no apparent reason to require panel closure construction within six months rather than one year.

CONCLUSIONS AND RECOMMENDATIONS

The most important of the specific enhancements proposed, allowing flexibility in the bulkhead forming practices is troubling because the planned bulkhead design contains multiple potential leakage paths within cells, between cells and through the panel closure bulkheads. It is recommended that the panel bulkhead specifications:

1) provide an incentive for the contractor to minimize the number of cells (preferably to one),
2) require that each cell be filled as a continuous monolithic concrete pour,
3) require the contractor support the fluid concrete in all cells with external structures,
4) require the contractor to remove the support structures and forms between internal cells,
5) provide for a rough form surface between internal cell walls, (possibly with a layer of burlap),
6) assure that some grout points are located at the roof concrete/rock salt contact and
7) prevent the use of all internal form spacer supports.

If built as recommended, the panel closure bulkheads should be capable of providing more than the required 35 years of protection from brine migration, 480 psi of methane explosion pressure and 100 psi of panel closure pressure.

The planned 12-ft thick explosion-isolation masonry walls should not be built. The methane concentration will take more than 17 years to rise to the 5% lower explosive limit after stopping panel ventilation. If built, the planned 12-ft thick explosion-isolation masonry walls would probably be incapable of resisting the design 480 psi methane explosion pressure.

The 4-ft thick construction-isolation wall is recommended to isolate the panel closure construction areas. The 4-ft thick construction-isolation walls are more than adequate to support the potential roof fall overpressure.

Generic salt-based concrete should be equally as effective as Salado-based concrete.

It should be possible to use local limestone or dolomite river rock for concrete aggregate. Limestone aggregate concrete should have a lower coefficient of thermal expansion than crushed quartz aggregate concrete. River rock should pump more readily than crusher product.

The contractor should be allowed to use either surface or underground mixing of the concrete. However, underground mixing of supersacks is recommended to assure sufficient time for placing the concrete in the forms.

Salt-based grout is recommended to eliminate the possibility of weakening the salt-based concrete along the rock salt/concrete contact by dissolution. Grouting across the roof contact is essential to assure that voids are filled.

There does not appear to be a time imperative requiring a 180-day construction period rather than a one year period.

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APPENDIX A. INTAKE DRIFT BULKHEAD DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = concrete shear strength $\left(2\sqrt{f'_c} = 126 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Intake Drift width (20 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
T_e = effective bulkhead thickness (28 ft)
V_c = concrete shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ_a = allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w = water density (62.4PCF)
ϕ = plain concrete strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = concrete comp strength (4,000 psi)
f_{cl} = concrete tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{4000} = 206 \text{ psi}\right]$
h = Intake Drift height (13 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (36 ft)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_d = dynamic pressure head (240 psi)
γ_c = concrete density (151PCF)
γ_s = salt density (140 PCF)
σ_s = flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of concrete-rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Intake Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Required bulkhead thickness with low pressure grouting on concrete/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Appendix A. Intake Drift bulkhead design calculations (Continued)

Pressure gradient along minimum effective bulkhead thickness T_e= 28 ft

$$\rho_g = \frac{\rho}{28} = \frac{480}{28} = 17.1 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along concrete/rock salt contact around 28-ft effective bulkhead thickness is:

$$\underline{FS} = \frac{41}{17.1} = \underline{2.40}$$

Allowable concrete shear on Intake Drift perimeter:

$$f'_s = 2\sqrt{f'_c} = 2\sqrt{4000} = 126 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h \ell}{2(h+\ell)f'_s}$$

$$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(36)(13+20)126}{13(20)} = \frac{299400}{260} = 1152 \text{ psi}$$

$$W = \rho_d h\ell = 480(13)20(144) = 17{,}970{,}000 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{17970000}{[2(13+20)]36(144)} = \frac{17970000}{342100} = 52.5 \text{ psi}$$

Factor of Safety against concrete shear failure = $\frac{f'_s}{v_s} = \frac{126}{52.5} = 2.40$

Allowable rock salt shear force along concrete/rock salt contact, Intake Drift bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to concrete/rock salt contact:

$$L_{rs} = \sqrt{8^2 + 8^2} + 0.5 + 9.75 + 9.75 = 31.3 \text{ ft}^2\text{/ft of perimeter}$$

Minimum rock salt perimeter = 2(13+20) = 66 ft

Total effective bulkhead shear area = 2,066 ft^2

Maximum rock salt shear resistance = 2066(1070)144 = 318,300,000 lb

Appendix A. Intake Drift bulkhead design calculations (Continued)

Maximum shear force on panel side bulkhead face and outward inclined panel side concrete/rock salt contact potentially opened by explosion gas pressure:

Face area = 13(20) = 260 ft^2

Vertical component of sloping area = $2(13+20)8 + \frac{\pi 8^2}{4} = 528 + 50 = 578\ ft^2$

Design maximum thrust = (578+260)(480)144 = 57,920,000 lb

Factor of Safety against rock salt shear failure = $\frac{318{,}300{,}000}{57{,}920{,}000} = 5.50$

Plain concrete deep beam bending stress design, Intake Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1)

for 480 psi design dynamic pressure head:

$\omega = U = 2\rho_d(144) = 2(240)144 = 69{,}120\ \left(\frac{lb}{ft^2}\right)$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$M_n = \frac{\omega \ell^2}{24} = \frac{69120(20^2)}{24} = 1{,}152{,}000\ ft{\cdot}lb$

$M_u = \frac{M_n}{0.65} = \frac{1152000}{0.65} = 1{,}772{,}000\ ft{\cdot}lb$

$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$

$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206\ psi$

$f'_{cl} = 206 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{1772000}{\frac{144T^2}{6}} = \frac{73830}{T^2}$

$T = \sqrt{\frac{73830}{206}} = \sqrt{358.4} = 18.9$ ft thick plain concrete bulkhead is required for worst-case rib to rib fixed bulkhead.

$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{1772000}{\frac{144(36^2)}{6}} = \frac{1772000}{31100} = 57.0\ psi$

$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{57.0} = 3.61$

Therefore, a 36-ft thick plain-concrete bulkhead worst-case griped at both ribs of the 20-ft wide Intake Drift, is acceptable as a panel closure bulkhead.

Appendix A. Intake Drift bulkhead design calculations (Continued)

Bulkhead deep beam griped at Intake Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(13^2)}{24} = 486{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{486700}{0.65} = 748{,}800 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206 \text{ psi}$$

$$f'_{cl} = 206 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{748800}{\frac{144T^2}{6}} = \frac{31200}{T^2}$$

$T = \sqrt{\frac{31200}{206}} = \sqrt{151.5} = 12.3$-ft thick plain concrete bulkhead is required for best-case roof to floor fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{748800}{\frac{144(36^2)}{6}} = \frac{748800}{31100} = 24.1 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{24.1} = 8.55$$

Therefore, a 36-ft thick plain-concrete bulkhead, best-case griped at roof and floor of the 13-ft high Intake Drift, is acceptable as a panel closure bulkhead.

APPENDIX B. EXHAUST DRIFT BULKHEAD DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = concrete shear strength $\left(2\sqrt{f'_c} = 126 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Exhaust Drift width (14 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
T_e = effective bulkhead thickness (18 ft)
V_c = concrete shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ_a = allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w = water density (62.4PCF)
ϕ = plain concrete strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = concrete comp strength (4,000 psi)
f_{cl} = concrete tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{4000} = 206 \text{ psi}\right]$
h = Exhaust Drift height (12 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (26 ft)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_d = dynamic pressure head (240 psi)
γ_c = concrete density (151PCF)
γ_s = salt density (140 PCF)
σ_s = flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of concrete-rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Exhaust Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Required bulkhead length with low pressure grouting on concrete/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Appendix B. Exhaust Drift bulkhead design calculations (Continued)

Pressure gradient along minimum effective bulkhead thickness T = 18 ft

$\rho_g = \frac{\rho}{18} = \frac{480}{18} = 26.7$ psi/ft

Factor of Safety against leakage of explosion gasses along concrete/rock salt contact around 18-ft effective bulkhead thickness is:

$\underline{FS} = \frac{41}{26.7} = \underline{1.54}$

Allowable concrete shear on Exhaust Drift perimeter:

$f'_s = 2\sqrt{f'_c} = 2\sqrt{4000} = 126$ psi (ACI 318-95, Sec 11.3.1.1)

$T = \frac{\rho_a h \ell}{2(h+\ell)f'_s}$

$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(36)(12+14)126}{12(14)} = \frac{235900}{168} = 1404$ psi

$W = \rho_d h\ell = 480(12)14(144) = 11{,}610{,}000$ lb

$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{11610000}{[2(12+14)]36(144)} = \frac{11610000}{269600} = 43.1$ psi

Factor of Safety against concrete shear failure $= \frac{f'_s}{v_s} = \frac{126}{43.1} = 2.92$

Allowable rock salt shear force along concrete/rock salt contact, Exhaust Drift bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to concrete/rock salt contact:

$L_{rs} = \sqrt{8^2 + 8^2} + 0.5 + 4.75 + 4.75 = 21.3$ ft²/ft of perimeter

Minimum rock salt perimeter = 2(12+14) = 52 ft

Total effective bulkhead shear area = 1,108 ft²

Maximum rock salt shear resistance = 1108(1070)144 = 170,700,000 lb

Appendix B. Exhaust Drift bulkhead design calculations (Continued)

Maximum shear force on panel side bulkhead face and outward inclined panel side concrete/rock salt contact potentially opened by explosion gas pressure:

Face area = 12(14) = 168 ft^2

Vertical component of sloping area = $2(12+14)8 + \frac{\pi 8^2}{4} = 416 + 50 = 466\ ft^2$

Design maximum thrust = (466+168)(1070)144 = 97,690,000 lb

Factor of Safety against rock salt shear failure = $\frac{170,700,000}{97,690,000} = 1.75$

Plain concrete deep beam bending stress design, Exhaust Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1)

for 480 psi design dynamic pressure head:

$\omega = U = 2\rho_d(144) = 2(240)144 = 69,120\ \left(\frac{lb}{ft^2}\right)$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$M_n = \frac{\omega \ell^2}{24} = \frac{69120(14^2)}{24} = 564,500$ ft·lb

$M_u = \frac{M_n}{0.65} = \frac{564500}{0.65} = 868,500$ ft·lb

$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$

$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206$ psi

$f'_{cl} = 206 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{868500}{\frac{144T^2}{6}} = \frac{36190}{T^2}$

$T = \sqrt{\frac{36190}{206}} = \sqrt{175.7} = 13.3$ ft thick plain concrete bulkhead is required for worst-case rib to rib fixed bulkhead.

$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{868500}{\frac{144(26^2)}{6}} = \frac{868500}{16220} = 53.5$ psi

$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{53.5} = 3.85$

Therefore, a 26-ft thick plain-concrete bulkhead, worst-case griped at both ribsides of the 14-ft wide Exhaust Drift, is acceptable as a panel closure bulkhead.

Appendix B. Exhaust Drift bulkhead design calculations (Continued)

Bulkhead deep beam griped at Exhaust Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(12^2)}{24} = 414{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{414700}{0.65} = 638{,}000 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206 \text{ psi}$$

$$f'_{cl} = 190 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{638000}{\frac{144T^2}{6}} = \frac{26580}{T^2}$$

$T = \sqrt{\frac{26580}{206}} = \sqrt{129.0} = 11.4$-ft thick plain concrete bulkhead is required for best-case roof to floor fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{638000}{\frac{144(26^2)}{6}} = \frac{638000}{16220} = 39.3 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{39.3} = 5.24$$

Therefore, a 26-ft thick plain-concrete bulkhead, best-case griped at roof and floor of the 12-ft high Exhaust Drift, is acceptable as a panel closure bulkhead.

APPENDIX C. INTAKE DRIFT EXPLOSION-ISOLATION MASONRY WALL DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = masonry shear strength $\left(2\sqrt{f'_c} = 100 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Intake Drift width (20 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_a= allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w= water density (62.4PCF)
ϕ= plain masonry strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = masonry comp strength (2,500 psi)
f_{cl} = masonry tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{2500} = 162 \text{ psi}\right]$
h = Intake Drift height (13 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (12 ft)
V_c = masonry shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ = design pressure head (480 psi)
ρ_d = dynamic pressure head (240 psi)
γ_c = masonry density (151PCF)
γ_s = salt density (140 PCF)
σ_s= flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of masonry/rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Intake Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Appendix C. Intake Drift explosion-isolation masonry wall design calculations (Continued)

Required bulkhead thickness with low pressure grouting on masonry/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Pressure gradient along bulkhead thickness T = 12 ft

$$\rho_g = \frac{\rho}{28} = \frac{480}{12} = 40.0 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along masonry/rock salt contact around 12-ft effective bulkhead thickness is:

$$\underline{FS} = \frac{41}{40.0} = \underline{1.03}$$

Allowable masonry shear on Intake Drift perimeter:

$$f'_s = 2\sqrt{f'_c} = 2\sqrt{2500} = 100 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h\ell}{2(h+\ell)f'_s}$$

$$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(12)(13+20)100}{13(20)} = \frac{79200}{260} = 304.6 \text{ psi}$$

$$W = \rho_d h\ell = 480(13)20(144) = 17{,}970{,}000 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{17970000}{[2(13+20)]12(144)} = \frac{17970000}{114000} = 157.6 \text{ psi}$$

Factor of Safety against masonry shear failure $= \frac{f'_s}{v_s} = \frac{100}{157.6} = \underline{\mathbf{0.63}}$

Required masonry wall thickness to resist design methane explosion pressure

$$T = \frac{\rho h\ell}{2(h+\ell)f'_s} = \frac{480(13)20}{2[13+20]100} = \frac{124800}{6600} = 18.9 \text{ ft}$$

Allowable rock salt shear force along masonry/rock salt contact, Intake Drift explosion-isolation bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to masonry/rock salt contact:

L_{rs} = 12 ft^2/ft of perimeter

Appendix C. Intake Drift explosion-isolation masonry wall design calculations (Continued)

Minimum rock salt perimeter = 2(14+21) = 70 ft
based on perimeter hitched 6-in into roof, ribs and floor of Intake Drift

Total effective bulkhead shear area = 840 ft^2

Maximum rock salt shear resistance = 840(1070)144 = 129,400,000 lb

Maximum shear force on masonry/rock salt contact potentially opened by explosion gas pressure:

Face area = 14(21) = 294 ft^2

Design maximum thrust = (294)(480)144 = 20,320,000 lb

Factor of Safety against rock salt shear failure = $\frac{129,400,000}{20,320,000} = 6.37$

Masonry explosion-isolation beam bending stress design, Intake Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1) for 480 psi design dynamic pressure head:

$$\omega = U = 2\rho_d(144) = 2(240)144 = 69,120\left(\frac{lb}{ft^2}\right)$$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$$M_n = \frac{\omega\ell^2}{24} = \frac{69120(20^2)}{24} = 1,152,000 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{1152000}{0.65} = 1,772,000 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 150 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{1772000}{\frac{144T^2}{6}} = \frac{73830}{T^2}$$

$T = \sqrt{\frac{73830}{162.5}} = \sqrt{454.3} = 21.3$ ft thick masonry bulkhead is required for worst-case rib to rib fixed explosion-isolation bulkhead

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{1772000}{\frac{144(12^2)}{6}} = \frac{1772000}{3456} = 512.7 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{512.7} = \underline{\mathbf{0.32}}$$

Appendix C. Intake Drift explosion-isolation masonry wall design calculations (Continued)

Therefore, 12-ft thick cement-mortared masonry block bulkhead, worst-case griped at both ribsides of the 20-ft wide Intake Drift, is NOT acceptable as an explosion-isolation bulkhead.

Masonry bulkhead deep beam griped at Intake Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(13^2)}{24} = 486{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{486700}{0.65} = 748{,}800 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 162.5 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{748800}{\frac{144T^2}{6}} = \frac{31200}{T^2}$$

$T = \sqrt{\frac{31200}{162.5}} = \sqrt{192.0} = 13.8$-ft thick concrete block masonry bulkhead is required for best-case roof to floor fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{748800}{\frac{144(12^2)}{6}} = \frac{748800}{3456} = 216.7 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{216.7} = \underline{\mathbf{0.75}}$$

Therefore, 12-ft thick cement-mortared masonry block bulkhead, best-case griped at roof and floor of the 13-ft high Intake Drift, is NOT acceptable as an explosion-isolation bulkhead.

APPENDIX D. EXHAUST DRIFT EXPLOSION-ISOLATION MASONRY WALL DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = masonry shear strength $\left(2\sqrt{f'_c} = 100 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Exhaust Drift width (14 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_a = allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w = water density (62.4PCF)
ϕ = plain masonry strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = masonry comp strength (2,500 psi)
f_{cl} = masonry tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{2500} = 162 \text{ psi}\right]$
h = Exhaust Drift height (12 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (12 ft)
V_c = masonry shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ = design pressure head (480 psi)
ρ_d = dynamic pressure head (240 psi)
γ_c = masonry density (151PCF)
γ_s = salt density (140 PCF)
σ_s = flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of masonry/rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Exhaust Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Appendix D. Exhaust Drift explosion-isolation wall design calculations (Continued)

Required bulkhead length with low pressure grouting on masonry/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Pressure gradient along bulkhead thickness T = 12 ft

$$\rho_g = \frac{\rho}{12} = \frac{480}{12} = 40.0 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along masonry/rock salt contact around 12-ft effective bulkhead thickness is:

$$FS = \frac{41}{40.0} = 1.03$$

Allowable masonry shear on Exhaust Drift perimeter:

$$f'_s = 2\sqrt{f'_c} = 2\sqrt{2500} = 100 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h\ell}{2(h+\ell)f'_s}$$

$$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(12)(12+14)100}{12(14)} = \frac{62400}{168} = 371.4 \text{ psi}$$

$$W = \rho_d h\ell = 480(12)14(144) = 11{,}610{,}000 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{11610000}{2(12+14)12(144)} = \frac{11610000}{89860} = 129.2 \text{ psi}$$

Factor of Safety against masonry shear failure $= \frac{f'_s}{v_s} = \frac{100}{129.2} = \underline{\mathbf{0.77}}$

Required masonry wall thickness to resist design methane explosion pressure

$$T = \frac{\rho h\ell}{2(h+\ell)f'_s} = \frac{480(12)14}{2[13+20]100} = \frac{81640}{6600} = 12.2 \text{ ft}$$

Allowable rock salt shear force along masonry/rock salt contact, Exhaust Drift explosion-isolation bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to masonry/rock salt contact:

L_{rs} = 12 ft^2/ft of perimeter

Appendix D. Exhaust Drift explosion-isolation wall design calculations (Continued)

Minimum rock salt perimeter = 2(13+15) = 56 ft
based on perimeter hitched 6-in into roof, ribs and floor of Exhaust Drift

Total effective bulkhead shear area = 672 ft^2

Maximum rock salt shear resistance = 672(1070)144 = 103,500,000 lb

Maximum shear force on panel side bulkhead face and outward inclined panel side masonry/rock salt contact potentially opened by explosion gas pressure:

Face area = 13(15) = 195 ft^2

Design maximum thrust = (195)(480)144 = 13,480,000 lb

Factor of Safety against rock salt shear failure = $\frac{103,500,000}{13,480,000} = 7.68$

Masonry explosion-isolation beam bending stress design, Exhaust Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1) for 480 psi design dynamic pressure head:

$\omega = U = 2\rho_d(144) = 2(240)144 = 69,120 \left(\frac{lb}{ft^2}\right)$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$M_n = \frac{\omega \ell^2}{24} = \frac{69120(14^2)}{24} = 564,500$ ft·lb

$M_u = \frac{M_n}{0.65} = \frac{564500}{0.65} = 868,500$ ft·lb

$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$

$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5$ psi

$f'_{cl} = 150 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{868500}{\frac{144T^2}{6}} = \frac{36190}{T^2}$

$T = \sqrt{\frac{36190}{162.5}} = \sqrt{222.7} = 14.9$ ft thick masonry bulkhead is required for worst-case rib to rib fixed explosion-isolation bulkhead.

$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{868500}{\frac{144(12^2)}{6}} = \frac{868500}{3456} = 251.3$ psi

$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{251.3} = \underline{\mathbf{0.65}}$

Appendix D. Exhaust Drift explosion-isolation wall design calculations (Continued)

Therefore, 12-ft thick cement mortared masonry block wall, worst-case griped at both ribsides of the 14-ft wide Exhaust Drift, is NOT acceptable as an explosion-isolation bulkhead.

Masonry bulkhead deep beam griped at Exhaust Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(12^2)}{24} = 414{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{414700}{0.65} = 638{,}000 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 162.5 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{638000}{\frac{144T^2}{6}} = \frac{26580}{T^2}$$

$T = \sqrt{\frac{26580}{162.5}} = \sqrt{177.2} = 13.3$-ft thick concrete block masonry bulkhead is required for best-case roof to floor fixed beam bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{638000}{\frac{144(12^2)}{6}} = \frac{638000}{3456} = 184.6 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{184.6} = \underline{\mathbf{0.88}}$$

Therefore, 12-ft thick cement mortared masonry block wall, best-case griped at roof and floor of the 12-ft high, Exhaust Drift is NOT acceptable as an explosion-isolation bulkhead.

APPENDIX E. INTAKE DRIFT CONSTRUCTION-ISOLATION WALL DESIGN CALCULATIONS (ROOF FALL PRESSURE)

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = masonry shear strength $\left(2\sqrt{f'_c} = 100 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Intake Drift width (20 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_d= dynamic pressure head (0.035 psi)
γ_c = masonry density (151PCF)
γ_s = salt density (140 PCF)
ϕ= plain concrete strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = masonry comp strength (2,500 psi)
f_{cl} = masonry tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{2500} = 162 \text{ psi}\right]$
h = Intake Drift height (13 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (4 ft)
V_c = concrete shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ = design pressure head (0.070 psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w= water density (62.4PCF)
σ_s= flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of masonry/rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Intake Drift bulkhead, 10 psf design dynamic pressure head = $L\rho_d = 2(0.035) = 0.070$ psi

Appendix E. Intake Drift construction-isolation wall design calculations (Continued)

Required bulkhead thickness with low pressure grouting on masonry/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{0.070}{41} = 0.0002 \text{ ft}$$

Pressure gradient along bulkhead thickness T = 4 ft

$$\rho_g = \frac{\rho}{T} = \frac{0.070}{4} = 0.0175 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along masonry/rock salt contact around 28-ft effective bulkhead thickness is:

$$\underline{FS} = \frac{41}{0.0175} = >2300$$

Allowable masonry shear on Intake Drift perimeter:

$$f'_s = 2\sqrt{f'_c} = 2\sqrt{2500} = 100 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h\ell}{2(h+\ell)f'_s}$$

$$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(4)(13+20)100}{13(20)} = \frac{26400}{260} = 101.5 \text{ psi}$$

$$W = \rho_d h\ell = 0.070(13)20(144) = 2621 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{2621}{[2(13+20)]4(144)} = \frac{2621}{38020} = 0.0689 \text{ psi}$$

Factor of Safety against masonry shear failure $= \frac{f'_s}{v_s} = \frac{100}{0.0689} = >1450$

Allowable rock salt shear force along masonry/rock salt contact, Intake Drift constructon-isolation bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to masonry/rock salt contact:

$L_{rs} = 4 \text{ ft}^2/\text{ft}$ of perimeter

Minimum rock salt perimeter = 2(14+21) = 70 ft
(6-in inset in roof, walls and floor)

Total effective bulkhead shear area = 280 ft^2

Appendix E. Intake Drift construction-isolation wall design calculations (Continued)

Maximum rock salt shear resistance = $2(14+21)12(1070)144 = 129{,}400$ lb
based on perimeter hitched 6-in into roof, ribs and floor of Intake Drift

Maximum shear force on masonry/rock salt contact potentially opened by roof fall overpressure:

Face area = $14(21) = 294$ ft^2

Design maximum thrust = $(294)(0.070)144 = 2{,}964$ lb

Factor of Safety against rock salt shear failure = $\frac{129{,}400}{2{,}964} = 43.7$

Masonry construction-isolation beam bending stress design, Intake Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1)

for 0.070 psi design dynamic roof fall pressure head:

$$\omega = U = 2\rho_d(144) = 2(0.035)144 = 10.1\left(\frac{lb}{ft^2}\right)$$

Simply supported 4-ft thick bulkhead beam supported at rock salt ribs by contact grout pressure (worst-case)

$$M_n = \frac{\omega \ell^2}{8} = \frac{10.1(21^2)}{8} = 556.8 \text{ ft}\cdot\text{lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{556.8}{0.65} = 856.6 \text{ ft}\cdot\text{lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 150 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{856.6}{\frac{144T^2}{6}} = \frac{35.69}{T^2}$$

$T = \sqrt{\frac{35.69}{162.5}} = \sqrt{0.220} = 0.47$ ft thick masonry concrete bulkhead is required for worst-case rib to rib simply-supported construction-isolation bulkhead

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{856.6}{\frac{144(4^2)}{6}} = \frac{856.6}{384.0} = 2.23 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{2.23} = >73$$

Appendix E. Intake Drift construction-isolation wall design calculations (Continued)

Therefore, 4-ft thick cement-mortared concrete block masonry bulkhead, worst-case, simply-supported at both ribsides of the hitched in 21-ft wide Intake Drift, is acceptable as a construction-isolation bulkhead.

Simply supported 4-ft thick bulkhead beam supported at roof and floor by contact grout pressure (best-case)

$$M_n = \frac{\omega \ell^2}{8} = \frac{10.1(13^2)}{8} = 213.4 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{213.4}{0.65} = 328.3 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 162.5 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{328.3}{\frac{144T^2}{6}} = \frac{13.68}{T^2}$$

$T = \sqrt{\frac{13.68}{162.5}} = \sqrt{0.0842} = 0.29$ ft thick masonry bulkhead is required for best-case rib to rib simply-supported construction-isolation bulkhead

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{328.3}{\frac{144(4^2)}{6}} = \frac{328.3}{384.0} = 0.855 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{0.855} = >190$$

Therefore, 4-ft thick cement-mortared concrete block masonry bulkhead, best-case simply-supported at roof and floor of the hitched 13-ft high Intake Drift, is acceptable as a construction-isolation bulkhead.

APPENDIX F. TRIAXIAL PROPERTIES OF PERMIAN EVAPORITES

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
AEC-7 & ERDA-9 boreholes, rock salt	3230	29.6°	940	0-3000	8
from 1900 to 2800 ft, Carlsbad, NM (GCR, Chapter 4)					
Mississippi Chemical Corp., Carlsbad, NM					
Cycle 7, Potash salt (CSM Lab, 1982)	3520	46.6°	700	0-1500	64
Cycle 5, Potash salt (CSM Lab, 1991)	2880	36.9°	720	0-1500	34
Cycle 5, Roof rock salt	3170	39.3°	750	0-2000	25
Cycle 5, Floor clayey rock salt (CSM '92)	3580	38.1°	870	0-2000	20
PCS Mining, Ltd., Rocanville Div., Saskatchewan (Molavi & Wooley, 1986)					
Esterhazy potash salt mbr.	2300	27.3°	700	Unknown	??
RE/SPEC, Inc., Paradox Basin, UT (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 6, Rock salt	4970	33.7°	1330	0-2200	4
Cycle 6, Carnalite	5660	32.0°	1570	0-2200	4
Cycle 7, Rock salt	5880	33.5°	1580	0-2200	4
RE/SPEC, Inc., Permian Basin, TX (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 5, Rock salt	5000	31.2°	1410	0-2200	10
Cycle 4, Rock salt	4150	30.8°	1180	0-2200	4
Dettin Well, Rock salt, 1900-ft depth	4640	33.8°	1240	0-2200	6
Dettin Well, Rock salt, 2250-ft depth	4280	36.0°	1090	0-2200	6
Zeeck Well, Rock salt, 28-2900-ft depth	4750	33.4°	1280	0-2200	9
Carey Salt Co., Hutchinson, KS (CSM Lab, 1985)					
Rock salt	2900	49.1°	540	0-1000	24
Independent Salt Co., Kanapolis, KS (CSM Lab, 1987)					
Roof rock salt	4330	31.2°	1220	0-3000	16
Averages	4080	35.2°	1070		
Standard Deviations	1040	5.9°	330		

APPENDIX G. TRIAXIAL PROPERTIES OF SELECTED EVAPORITES

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
Minerales Para La Industria, Sal-Gema, Hidalgo, N.L., Mexico (CSM & Adv Terra Testing Labs 1992)					
Grueso Brecha Domo Sal, Barreno30	3630	48.4°	690	0-2000	9
Intermedio Brecha Domo Sal, Bar 30	3180	49.3°	590	0-2000	7
Fino Brecha Domo Sal, Barreno 30	3150	48.8°	600	0-2000	9
All Barreno 30 Brecha Sal Pruebas	3340	48.7°	630	0-2000	25
Upper Brecha Sal, Barreno 36	7510	44.9°	1560	0-2000	5
Lower Brecha Sal, Barreno 36	5230	47.8°	1010	0-2000	5
All Barreno 36 Brecha Sal Pruebas	6350	46.4°	1270	0-2000	10
ALL BRECHA SAL PRUEBAS, Bars 30-36	4110	48.4°	780	0-2000	35
Minerales Para La Industria, Sal-Gema, Hidalgo, N.L., Mexico (ATT Lab 1992)					
Yeso, Caliza y Anhidrita Brecha Barreno 36	5050	47.2°	990	0-2000	5
Minerales Para La Industria, Sal-Gema, Hidalgo, N.L., Mexico (ATT Lab 1992)					
Red Brecciated Salt, Barreno 20	2260	20.0°	790	0-2000	3
AEC-7 & ERDA-9 boreholes, rock salt from 1900 to 2800 ft, Carlsbad, NM (GCR, Chapter 4)	3230	29.6°	940	0-3000	8
Cote Blanche Mine, Cote Blanche, LA (Hansen, 1977)					
Cote Blanche, dome salt	4130	40.1°	960	0-1500	9
Cote Blanche, yellow dome salt	6840	34.5°	1800	0-1500	3
German Democratic Republic (Menzel, et al, 1972)					
Rock salt	5590	34.8°	1460	0-4250	8
"Hartsalz"	6950	35.5°	1790	0-4250	8
Carnolite	4730	30.6°	1350	0-4250	8
"Sylinit"	6730	34.0°	1790	0-4250	8

APPENDIX G. TRIAXIAL PROPERTIES OF SELECTED EVAPORITES (Continued)

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
Mississippi Chemical Corp., Carlsbad, NM					
Cycle 7, Potash salt (CSM Lab, 1982)	3520	46.6°	700	0-1500	64
Cycle 5, Potash salt (CSM Lab, 1991)	2880	36.9°	720	0-1500	34
Cycle 5, Roof rock salt	3170	39.3°	750	0-2000	25
Cycle 5, Floor clayey rock salt (CSM Lab, 1992)	3580	38.1°	870	0-2000	20
PCS Mining, Ltd., Rocanville Div., Saskatchewan (Molavi & Wooley, 1986)					
Esterhazy potash salt mbr.	2300	27.3°	700	Unknown	??
RE/SPEC, Inc., Paradox Basin, UT (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 6, Rock salt	4970	33.7°	1330	0-2200	4
Cycle 6, Carnalite	5660	32.0°	1570	0-2200	4
Cycle 7, Rock salt	5880	33.5°	1580	0-2200	4
RE/SPEC, Inc., Permian Basin, TX (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 5, Rock salt	5000	31.2°	1410	0-2200	10
Cycle 4, Rock salt	4150	30.8°	1180	0-2200	4
Dettin Well, Rock salt, 1900-ft depth	4640	33.8°	1240	0-2200	6
Dettin Well, Rock salt, 2250-ft depth	4280	36.0°	1090	0-2200	6
Zeeck Well, Rock salt, 28-2900-ft depth	4750	33.4°	1280	0-2200	9
RE/SPEC, Inc., LA salt domes (Pfeifle, Mellegard & Senseny, 1982)					
Richton Dome	3280	35.7°	840	0-2200	4
Vacherie Dome	3340	36.6°	840	0-2200	4
RE/SPEC, Inc., Avery Island, LA (Hansen & Mellegard, 1979)					
Dome rock salt	3640	35.4°	940	0-3000	7
Meadowbank Mine, Cheshire, Great Britain (Sen, 1962)					
Rock salt	4640	40.9°	1060	0-1000	3

APPENDIX G. TRIAXIAL PROPERTIES OF SELECTED EVAPORITES (Continued)

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
Carey Salt Co., Hutchinson, KS (CSM Lab, 1985)					
__Rock salt	2900	49.1°	540	0-1000	24
TG Chemicals, Inc., Granger, WY (CSM Lab, 1985)					
__Bed # 21, Trona	3900	43.9°	830	0-2000	49
General Chemical Corp., Green River, WY (CSM Lab, 1987)					
__Bed # 17, Trona	5860	42.8°	1280	0-3000	72
Independent Salt Co., Kanapolis, KS (CSM Lab, 1987)					
__Roof rock salt	4330	31.2°	1220	0-3000	16
Morton Salt Co., Fairport Harbor Mine, Painesville, OH (CSM Lab, 1987)					
__Rock salt	4020	39.0°	960	0-4000	30
Gold Bond Building Products Co., Shoals Mine, IN, (CSM Lab 1988-89)					
__Gypsum	2880	34.0°	765	0-1300	22
Averages	4390	36.2°	1100		
Standard Deviations	1320	6.3°	350		

APPENDIX C

Waste Isolation Pilot Plant, Review of Proposed Panel Closure Enhancements

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WASTE ISOLATION PILOT PLANT REVIEW OF PROPOSED PANEL CLOSURE ENHANCEMENTS

Prepared for:

Mining and Environmental Services LLC
Idaho Springs, Colorado

Prepared by:

AMEC Earth & Environmental Limited
Burnaby, BC

10 July 2001

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EXECUTIVE SUMMARY

The panel closure system for the Waste Isolation Pilot Plant (WIPP) Project near Carlsbad, New Mexico, is comprised in part of a mass concrete plug, together with installation of a grout to fill any voids between the concrete plug and host halite rock. The specification for the project provided a prescription based formulation for the *Salado Mass Concrete* for the closure panel. The specification also required the use of a crushed quart aggregate. With respect to the grout, the specification required the use of a fresh-water based grout.

AMEC has been asked to review and comment on three proposed *Panel Enclosure Enhancements:*

(a) A change to the specifications to allow the use of a well-rounded carbonate-based coarse aggregate in lieu of the originally specified crushed quartz aggregate in the mass concrete.
(b) A change in the grout used from a fresh-water grout to a salt-based grout.
(c) A change for the mass concrete requirements from a prescription-based specification (which gives a recipe for the *Salado Mass Concrete*) to a performance-based specification which requires the Contractor to formulate the mass concrete mixture design and meet a prescribed set of performance specifications.

In brief, AMEC concurs in principle with the above-proposed *Panel Closure Enhancements* as detailed in the report, which follows. AMEC has, however, provided a number of recommendations as to issues which should be addressed by the specifiers with respect to the proposed changes. In particular, with respect to the proposed change to a *well-rounded carbonate-based rock*, it is recommended that it be demonstrated that:

- The carbonate-based rock is physically and chemically suitable for it's intended purpose, i.e. it should be shown to not be susceptible to deleterious alkali-carbonate reactivity, or salt-induced chemical degradation, and should display satisfactory thermal properties.
- The coarse aggregate should have suitable bonding characteristics to the past fraction (the use of particles with a partial *crush-count* should be considered).

With respect to the proposed use of a salt-based grout, AMEC concurs with this proposed conge, since it will counteract the tendency for dissolution (and hence void formation) of fresh-water based grouts. Also, review of the literature indicates enhanced long-term chemical stability of salt-saturated grouts placed in salt formations, compared to fresh-water grouts.

Finally, with respect to the proposal to change from a prescriptive *Saslado Mass Concrete* specification to a *Generic Salt-Based Concrete* specification for the closure panel concrete, AMEC concurs with this recommended change, since it gives the Contractor more freedom to adjust the mass concrete mixture properties to optimize the concrete construction process. Also, it places responsibility for performance of the concrete with the Contractor. This is contractually preferable for the Owner. The project specification should, however, then be written in rigorous performance-based specification language. In addition, more specifics should be provided in the specification regarding permissible constituents materials for the mass concrete for components such as the salt (type and saturation level required) and shrinkage compensating materials.

1.0 INTRODUCTION

AMEC Earth & Environmental Limited (AMEC), was retained by Mining and Environmental Services LLC (MES) to review certain proposed panel closure enhancements for the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico USA. Specifically AMEC was provided with a *Panel Closure Enhancement* (1) report by MES and asked to:

(a) Review the proposed change to the specifications to allow the use of well-rounded carbonate coarse aggregate in the panel closure concrete, in lieu of the crushed quartz aggregate specified in the *detailed design report for an operational phase panel closure system.*
(b) Review the proposed change to the specifications to allow the use of a salt-based grout, in lieu of the fresh water grout specified in the initial design report.
(c) Comment briefly on the proposed change to the specification to permit the use of a generic salt-based concrete in the panel closure concrete in lieu of the Salado Mass Concrete specified in the initial design report. (This was an addition to the initial terms of reference)

In addition to reviewing the report detailing the proposed *Panel Closure Enhancements* (1) provided by MES, AMEC conducted a literature search on the subject and reviewed relevant papers including Sandia National Laboratories Reports provided to AMEC by the Environmental Evaluation Group in Albuquerque, New Mexico. AMEC also communicated with a grouting specialist, Alex Naudts of ECO Grouting Specialists Ltd. in Ontario, Canada, with experience in the use of salt-based cement grouts in potash mines and other salt formations.

The report, which follows, provides a brief review of the preceding proposed panel closure enhancements. This report is written by Dr. D. R. Morgan, P.Eng, a civil engineer with particular experience in concrete technology, including concrete and grout mixture designs and construction monitoring and testing for civil and mining projects. While Dr. Morgan is not a chemist, he has considerable experience with respect to the hydration and durability of portland cement based systems, as affected by the addition of chemical admixtures, supplementary cementing materials and ingress of external aggressive agents. He also has experience in the design and construction of mass concrete structures in civil and mining applications. This report is written from this perspective.

2.0 LITERATURE REVIEW

AMEC conducted a literature search using key words: brine + salt + concrete + grout + potash + Salado in various combinations. Cited references are listed in Appendix A. A general list of references is provided in Appendix B. Readers wanting more details regarding any of the technical issues discussed in this report are invited to examine the cited references and if necessary general references. This reference list should not be considered as all-inclusive. Many more references are contained in the cited and listed references. It does, however provide a listing of key publications on the subjects of interest.

With respect to the proposed use of salt-based grout and generic salt-based panel closure concrete, it should be recognized that the performance of such products is likely to be very *salt-specific.* Thus, while there is value in examining the results of test on salts and performance of concretes and grouts from locations other than the Waste Isolation Pilot Plant (WIPP), most emphasis should be placed on WIPP tests and observations. From review of the literature, it is apparent that the majority of the testing and evaluation for the WIPP project has been conducted by the Sandia National Laboratories in Albuquerque, New Mexico. Most emphasis should thus be placed on the findings of these reports.

3.0 CHANGE IN GENERAL AGGREGATE SPECIFICATIONS

3.1 General

A proposed enhancement to the panel closure is to expand the specification for the coarse aggregate to be used in the mass concrete to allow for the use of well-rounded natural carbonate materials in place of the specified crushed quartz aggregate. The main reason for this proposed change is to improve the workability of the concrete in general, and pumpability in particular. A second reason for the proposed change is the fact that crushed quartz is not available within a 50-mile radius of the WIPP site, whereas natural rounded carbonate aggregates are locally available.

It is reported that the carbonate aggregate mineralogy is such that it should not adversely affect properties. This should be verified by:

(a) Examination of a petrographic analysis of the aggregate (ASTM C295) (2)
(b) Examination of conformance of the aggregate to the ASTM C33-99a *Standard Specification for Concrete Aggregates* (3)

In particular, the aggregate should be demonstrated to conform to the requirements in ASTM C33-99a, Tables 2 and 3 for:

- Gradation, including percent passing the 75 µm (No. 200) sieve;
- Deleterious particles (e.g. clay clumps, friable particles, chert, coal, etc).
- Magnesium sulphate soundness loss.

3.2 Alkali Aggregate Reactivity

Evaluation of the alkali aggregate reactivity (AAR) susceptibility of the aggregate should be carried out. More specifically it is recommended that records be produced demonstrating that the carbonate aggregate is non-reactive when evaluated against the:

- ASTM C 586-99 *Standard Test Method for Potential Reactivity of Carbonate Rocks as Concrete Aggregates* (*Rock-Cylinder Method*) (4) ;
- ASTM C1105-95 *Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock Reaction* (5) (12 month prism test).

Additional guidance with respect to evaluation and testing of carbonate-based aggregates for AAR can be found in CSA A 23.1-00, *Concrete Materials and Methods of Concrete Construction, Appendix B Alkali Aggregate Reaction* (6) and CSA A 23.2-27A *Standard Practice to Identify Degree of Alkali-Reactivity of Aggregates and Measures to Avoid Deleterious Expansion in Concrete* (7).

3.3 Chemical Stability in Brine

It is reported by Nowak et al (8) and Wakeley et al (9) that a certain dolomitic aggregate near Carlsbad, NM, has shown vulnerability to chemical alteration by reaction with brines in concrete. (Note: Dolomite, $MgO.CO_3.CaO.CO_3$.). It should be demonstrated that the carbonate aggregate selected for use is not susceptible to such deterioration.

3.4 Thermal Considerations

In addition to the above-recommended tests to demonstrate the suitability of the carbonate-based aggregate for it's intended use in the mass concrete closure panels, consideration should be given to the differences in thermal properties of the carbonate-based aggregates compared to the previously approved quartz-based aggregates. There are three thermal properties of aggregate that may be significant in the performance of the mass concrete: coefficient of thermal expansion, specific heat and conductivity. It is recommended that these thermal properties of the carbonate-based aggregate be determined and compared against those of the original crushed quartz aggregate specified. The design engineers for the closure panels should then evaluate the significance of any differences between the thermal properties of the two aggregate types on the expected behaviour of the mass concrete closure panels.

It is not proposed in this brief review report to elaborate on the test methods for the determination of thermal properties of the aggregates (or concrete) and the significance of these thermal properties with respect to the short and long term performance of the mass concrete closure panels. Good guidance in this regard can however, be found in publications such as: Cook, *Thermal Properties* (10,11) and Neville, *Properties of Concrete* (12).

A few thermal considerations are nevertheless worth pointing out:

- The coefficient of thermal expansion of the aggregate influences the coefficient of thermal expansion of the concrete containing such aggregate.
- It is desirable to have a coefficient of thermal expansion in the coarse aggregate which does not differ too much from the coefficient of thermal expansion of the hydrated portland cement paste in the concrete. Serious differences in the coefficients of thermal expansion have been reported to occur with aggregates with very low expansion, such as certain granites, limestones, and marbles (12). In such concretes, a large change in temperature (e.g. such as induced by the heat of hydration of the concrete) may introduce differential movement between the aggregate particles and paste, sufficient to break bond. This could result in microcracking, sufficient to impact on the durability of the concrete.

Thus for the carbonate aggregates proposed for use in the mass concrete closure panels at WIPP, it is recommended that the coefficient of thermal expansion of the aggregate be determined, to verify that it is suitable for use in it's intended application.

3.5 Workability/Pumpability

The prime reason for the proposed change from crushed quartz aggregate to a well-rounded carbonate-based rock is to enable production of a concrete with enhanced *workability* (mixing, pumping, placing, and consolidation characteristics) for the mass concrete closure panels. While quarried crushed rock is used to produce concrete with acceptable *workability* in several parts of North America (particularly the Eastern USA and Eastern Canada), natural rounded fluvial or glaciofluvial gravels typically produce concretes with superior *workability*, which are easier to mix, pump, place, consolidate and finish.

It should, however, be noted that most gravels used in concrete production are usually partially crushed, i.e. have a certain *crush-count*. There are certain advantages to having partially fractured faces in a sufficient percentage of the aggregate particles, including enhanced compressive, flexural and tensile strength development in the concrete made with such particles, compared to concrete made with natural rounded particles only. This observation, however, only applies if the particle crushing process produces aggregate particles with suitable shape i.e. particles that are more *equant* (cubical to round), as opposed to excessive quantities of particles that are flat, platy or elongated.

With respect to the proposed change to the use of natural rounded aggregates it should be cautioned that aggregate particles with very dense, smooth (polished) surfaces will typically have lower bond strengths than aggregates with rougher surface texture. Partial crushing of natural rounded aggregates is beneficial in that fracture faces on the aggregate particles typically have greater surface roughness. This enhances bond strength to the paste and consequently improves compressive, flexural and tensile strength development in the concrete.

To summarize, the proposed enhancement to use natural well-rounded aggregates to improve *workability* (including pumpability) of the closure panel concrete is considered appropriate. Consideration should, however, be given to producing an aggregate with a partial *crush-count*, to enhance paste to aggregate bond and consequent physical concrete properties.

4.0 SALT-BASED GROUT

It is understood that the *Environmental Protection Agency (EPA) Certified Closure* for the panel closure design approved the use of a *fresh water grout*. The proposed enhancement is to use a salt saturated grout instead. The purpose of the grout is to fill any voids that develop at the *back* (overlying roof) between the panel closure concrete, and the host halite formation as a result of sedimentation and bleeding, etc. in the mass concrete.

The concern with respect to using a *fresh water grout* is twofold:

(a) The liquid grout has the potential to dissolve the host halite material during placement, which is counterproductive to it's intended void sealing function;
(b) There is potential for a reduction in the long term stability and durability for the hardened grout because of the *chemical gradient* developed between the fresh water grout and the host halite formation; i.e. magnesium and other ions moving from the halite formation into the grout can result in calcium dissolution and depletion, which in turn can cause a loss of strength and degradation of the grout. Details regarding this dissolution mechanism can be found in publications by Wakeley and Burkes (13), Tumidajski and Chan (14), Wakeley et al, (15), Lambert et al (16) and Pool et al, (17).

Thus the proposed enhancement to use a salt-based grout is intended to negate the above concerns with using a *fresh water grout*. The use of a suitable salt solution (typically sodium chloride) as a mixing fluid in the grout minimizes the potential for the fresh grout to dissolve the host halite formation during placement and reduces the chemical gradient between the host halite formation, hardened grout, and proposed salt-based concrete (13, 14, 15, 16,17). In addition, Wakeley et al (15) report that salt-free grouts, when placed in contact with halite form no bond with the host rock. By contrast, a salt-saturated cementitious material bonds well with the halite.

There is precedence for the use of salt-saturated mixing water in cement-based grouts for void sealing of salt formations. Details can be found in publications such as Eyermann et al (18), Al-Manaseer et al (13) and others.

In addition to a review of the literature on this subject, Dr. Morgan of AMEC spoke with Alex Naudts at ECO Grouting Specialists Ltd., in Ontario, Canada, who has considerable experience in grouting in potash and salt mines. At AMEC's request, he provided a brief *capability statement* (20) of his experience in this regard. A copy of this statement is attached in Appendix B.

Notable examples of the use of salt-saturated grouts for void sealing purposes in salt formations include:

- Rocanville, Potash Mine, Saskatchewan, 1985 (19, 20)
- Esterhazy (K2) Mine, Saskatchewan, 1986 (19,20)
  (The writer was involved in the design and construction of one of the four bulkheads constructed on this project).
- Kali & Salz Potash Mine, Kassel, Germany (20)
- Potocan Potash Mine, New Brunswick (20)

Naudts (20) drew the conclusion that: *Most parties agree that it is not appropriate to use fresh water in grouts in contact with salt or potash ore (halite, carnalite, etc.) because of the migration of sodium, calcium or magnesium ions into the gelling grout, leaving a porous matrix near and at the contact zone.*

Review of the literature indicates that great care should be exercised in formulating salt-based portland cement grouts. Sodium chloride typically acts as a set retarder and water reducer. Chemical admixtures which work well in conventional portland cement-based grouts (without

salt addition) may however, not be compatible with salt-based portland cement grouts. For example, certain water reducers and retarders are reported to not be suitable for use in salt-based grouts because of problems such as very high air contents, foaming, excessively rapid rate of slump loss and excess set retardation (9, 20, 21, 22). Also, bentonite is reported to not be compatible with salt-based grouts (20).

By contrast, supplementary cementing materials, such as fly ash (type F or type C) are reported to be beneficial with respect to improving both the plastic and hardened properties of the grout. The addition of fly ash results in a stable suspension, with reduced bleeding and hence provides a more homogenous grout. Similarly, silica fume is reported to have been beneficially used for such purposes (20, 22). In addition, it is reported that hardened grouts with fly ash addition displayed enhanced bond to halite (13) and superior *long term* performance, compared to grouts with no fly ash, with respect to parameters such as compressive and flexural strength and modulus of elasticity, when the grouts were submerged in containers with brine at various confining pressures (21).

An argument can thus be made that the salt-based grouts should be formulated with a supplementary cementing material, such as fly ash (and / or silica fume) for the WIPP project.

An example of a formulation for a salt-based grout with fly ash addition, is the Grout BCT-1F described below, which is given in the *WIPP Project Specification Section 02722 Section 2.1* (23).

Table 1: Salt-Saturated Grout (BCT-1F)

Component	Percent of total Mass (wt.)
Class H cement	48.3
Class C fly ash	16.2
Cal Seal (plaster – from Halliburton)	5.7
Sodium Chloride	7.9
Dispersant	0.78
Defoamer	0.02
Water	21.1

The specification states: *The following formulation is suggested to the contractor as an initiation point for selection of the grout mix.* The specification does, however, not provide any performance requirements for the grout. As such, the specification is likely to be interpreted as a *prescription specification* by the contractor. This creates potential contractual conflicts if the contractor simply adopts the BCT-1F formulation and the grout does not perform as intended. It is thus recommended that WIPP develop a set of *performance specifications* for the grout, and require the contractor to demonstrate conformance of the grout to these *performance specifications.*

Parameters of interest with respect to *performance specifications* for the grout could include:

- Chloride saturation, including a statement on what type of salt is permissible. Note: While halite is comprised mainly of sodium chloride, it can contain lesser amounts of salts such as calcium sulphate, calcium chloride and magnesium chloride (28);
- Water /cementing materials ratio (likely variable, depending on size of voids to be filled and distance grout has to travel);
- Viscosity, as measured by the Marsh Flow Cone Test e.g. API RP 13B-1;
- Early age volume change e.g. ASTM C 287-95a *Standard Test Method for Change in Height at Early Ages of Cylindrical Specimens for Cementitious Mixtures* (24).
- Volume change at later ages (1, 14, 28 days) as measured by CRD C 621 (25).
- Bleeding and Expansion e.g. ASTM C 940-98a, *Standard Test Method for Expansion and Bleeding of Freshly Mixed Grouts for Preplaced-Aggregate Concrete in the Laboratory* (26).
- Setting time e.g. ASTM C953 *Standard Test Method for Time of Setting of Grouts for Preplaced-Aggregate Concrete in the Laboratory* (27).
- Specific Gravity e.g. API RP 13B-1.

It is recommended that appropriate testing methodologies be selected and a set of performance requirements be established for the salt-based grout(s). This approach would be consistent with the proposed *Panel Closure Enhancement* (1) for the *Generic Salt-Based Concrete*, which represents a change from a prescription to a performance-based specification.

Finally the Panel Closure Enhancement (1) Section 3.6 statement that: *No strength specifications for grout is appropriate, since any grout injected would serve in a lithostatic stress state and not compromise a structural element of the barrier*, is noted. This reviewer concurs with this statement and so setting compressive strength performance requirements for the grout would not appear to be warranted.

5.0 SALT-BASED CONCRETE

AMEC has been asked to comment briefly on the proposed *Panel Closure Enhancement* (1) to permit the use of a generic salt-based concrete in the panel closure concrete in lieu of the Salado Mass Concrete specified in the initial design report. This was an additional item to the original terms of reference, and while we have conducted a literature search on the subject (and done pertinent background reading on the subject) this review is brief, because of time and budget constraints.

In principle, AMEC concurs with this proposed change to the specifications. It is recognized that considerable research has been conducted by the Sandia National Laboratories (8, 9, 15, 16, 17, 18) and others in developing the Salado Mass Concrete for the WIPP Project.

The Panel Closure Cast-in-Place Concrete Specification, Section 03300, provides a list of so-called *Target Properties of the Concrete Mix*, in clause 2.5. For convenience of referral, this clause is produced below.

2.5 Target Properties of the Concrete Mix

The Contractor shall develop and proportion a salt-saturated mix for use in constructing the concrete barrier. The Contractor shall demonstrate by trial mix that the proposed concrete meets the following properties:

Table 2: Target properties for Barrier Concrete

Property	*Comment*
4-hr working time	*Indicated by 8-inch slump (ASTM C 142) after 3-hr intermittent mixing, or an appropriate measure of pumpability.*
Less that 25°F heat rise prior to placement	*Difference between initial condition and temperature after 4 hr.*
4,000 psi compressive strength (f'_c)	*At 56 days after casting (ASTM C 39)*
Volume stability	*Length change between +0.05 percent and-0.02 percent (ASTM C 490)*
Minimal entrained air	*2 percent to 3 percent air*

The Contractor shall provide certified copies of test data from an approved laboratory demonstrating compliance with the above target properties.

In addition to the target properties the Contractor shall provide certified test data for the trial mix for the following properties:

- *Heat of hydration* — *ASTM C-186*
- *Concrete set* — *ASTM C-403*
- *Thermal Diffusivity* — *USACE CRD-C36*
- *Water Permeability* — *USACE CRD-C43*

The specifications then provide what amounts to a *prescription* formulation for the Salado Mass Concrete, as detailed below.

An example of initial proportioning for the concrete is the salt-saturated concrete shown below:

Table 3 : Salt-Based Concrete Mixture Proportions

Component	*Percent of Total Mass*
Class H cement (API 10)	*4.93*
Chem Comp III (ASTM C-845 Type K)	*2.85*
Class F fly ash (ASTM C-618)	*6.82*
Fine aggregate	*33.58*
Coarse aggregate	*43.02*
Sodium chloride	*2.18*
Defoaming agent	*0.15*
Sodium citrate	*.009*
Water	*6.38*

The specification then goes on to say: The Contractor shall prepare a trial mix and provide certified test data from an approved testing laboratory for slump, compressive strength, heat rise, heat of hydration, concrete set time, thermal diffusivity, and water permeability.

Despite the wording in the specifications, the above approach is tantamount to a *Prescription Specification*, i.e. the Contactor is being told what mass concrete mixture proportions to use. There are potential contractual concerns with this approach, since if the concrete supplied failed to meet the required performance parameters, the Contractor could argue, with some justification that it is not his responsibility, but that if the specifying authority.

In AMEC's view, it is preferable to write the specification as *a Performance-Based Specification*, with the responsibility for the concrete mixture proportioning residing with the Contractor. The specifier should write a rigorous performance-based specification, including provision of specifics regarding all constituent materials permitted to be used in the *generic salt-based concrete*. In particular, specifics should be provided regarding the salt that is permitted to be added to the concrete, and which shrinkage compensative materials will be permitted to be added.

The Specifier should make available to the Contractor pertinent material regarding *Salado Mass Concrete* developed for the WIPP Project. This material can then provide the Contractor with a starting point for his *generic salt-based mixture proportioning*. In this way, the Contractor can adjust the mixture design, if required during construction, to facilitate the construction process. The responsibility for performance of the concrete would however, reside with the Contractor.

6.0 Limitations and Closure

This report has been prepared for the exclusive use of Mining and Environmental Services LLC for the purpose described in the report. Any use which a third party makes of this report, or any reliance on or decisions made based on it, are the responsibility of such third parties. AMEC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report. It has been prepared in accordance with generally accepted materials engineering practices. No other warranty, expressed or implied, is made.

AMEC thanks you for this opportunity to have been of service. We trust that this report satisfies your current requirements. Should you have any questions, please contact this office.

Yours Truly,

AMEC Earth & Environmental

Original signed by

D. R. Morgan, Ph.D., P. Eng
Chief Materials Engineer

Reviewed by:

Original signed by

John Laxdal, P. Eng
Regional Manager

APPENDIX A :

CITED REFERENCES

CITED REFERENCES

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APPENDIX C :

PRIVATE COMMUNICATION FROM A. NAUDTS

ECO

ECO GROUTING SPECIALISTS LTD

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July 3, 2001

ATTN: Dr. Rusty Morgan
AMEC Earth and Environmental Ltd.
2227 Douglas Road
Burnaby, BC
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amec
Earth & Environmental

JUL 05 2001

RECEIVED

Dear Dr. Morgan:

Re : Capability statement regarding cement based suspension grouts using saturated brines as carrier for the particles, to be used in salty environments

This note is further to our conversation of this afternoon. It was good to hear from you after all those years.

ECO has done extensive work developing and testing cement based suspension grouts to be used in saline environments using brine as carrier for the particles.

Most parties agree that it is not appropriate to use fresh water in grouts in contact with salt or potash ore (halite, carnalite, etc), because of migration of sodium, calcium or magnesium ions into the gelling grout, leaving a porous salt matrix near and at the contact zone.

The following is an oversight of some of the work we did in potash and salt mines (formulating and testing):

1. We first developed cement based suspension grouts for Kali & Salz in Germany for a potash mine near Kassel during the late seventies. We established basic fluid and set characteristics. The use of additives and admixtures such as styrene butadieen, clay-phyllosilicates and first generation superplasticisers were novelties at the time. We used a saturated locally found mine brine as the carrier.

We were aiming at low matrix permeability and high strength with the highest fluidity possible. From our on-going relationship with this client, we have learned that the performance of this type of grouts has been satisfactory over the life time. The tests involved bleed-tests, viscosity tests (marsh) and specific gravity test (Mud balance) as well as unconfined compressive strength tests and I believe we also did bond-strength tests from grout to the potash ore.

2. During the eighties we performed lab testing for PCS during the Rocanville flooding. Our design for the plug was implemented. The plug is still standing up under a pressure of 1200 psi (since March 1985). We formulated both regular cement based grouts, microfine cement based grouts and solution grouts using the brine from the mine as carrier. We found that some of the water reducing agents were not compatible with the brine or some of the additives and admixtures. We predominantly used the following additives and admixtures to the brine: super plasticiser, type F-flyash, silica fume (first time we used this) and slag. We found out that bentonite was not compatible with brine. (we should have pre-hydrated the bentonite in fresh water and added this to the mix). We also made samples of grouts and bubbled hydrogen sulphide through the suspension and let the suspension grouts cure in this saturated environment. Three years ago a sealed jar with this smelly gas and cured grout broke when we moved to our present lab-location. The (slag based microfine cement) grout looked "perfect" after 13 years. I remember that some grouts never reached final set and only made it to "somewhere between initial and final set" (Vicat needle).

3. During the IMC potash inflow-crisis in 1986, ECO was asked by this organisation to perform a series of tests to develop "durable cement based grout formulations" for a variety of applications. The tests were actually conducted in the lab of BBT in Saskatoon.

We used similar admixtures as during the tests in Rocanville, but included a portland cement based microfine cement based grout. We also used type C fly-ash (not aware at the time of the critical maximum contents BWOC) and kiln dust. A series of formulations were developed and reports were made. Some of the formulations were used in various phases of the project.

4. ECO performed lab-testing for the grouting around shaft plugs in an abandoned salt mine in Dearborn (Michigan). The actual grouting was never performed because the permitting to use this abandoned mine as a landfill site was never approved.

5. During 1992 ECO performed extensive lab-testing for the installation of a pilot grout-curtain in an abandoned limestone mine in Acron (Ohio), which was to be deepened to be used for the power house for a power generating system (pump storage). The water bearing zones in the limestone were saturated with hydrogen sulphide and brine. A variety of grouts were developed with different rheology, viscosity, cohesion, resistance against pressure filtration, thixotropy, gel times, set times etc.

At the time we used much more sophisticated mixes, using admixtures and additives such as metha glycol cellullose to curtail run-away situations, F-fly-ash, de-airing agents, super plasticisers, slag, pumice and bentonite slurries. The tests were also more sophisticated and included resistance against pressure filtration tests, initial and final gelation and set tests, cohesion tests etc.

6. In 1997, for Potocan (and its German part-owner, Kali & Salz) ECO performed a substantial grout formulation and testing program for one of the biggest grouting ever performed. From over 200 formulations, six formulations were retained with distinctive fluid and set characteristics. The formulations contained in addition to most of the

aforementioned admixtures and additives also modern day bio-polymers and the third generation of super plasiticisers and for the first time we used iso-propyl alcohol to delay the curing of the grout. Brine from this New Brunswick potash mine was used as the carrier of the particles.

7. ECO is involved in an elaborate seal-grouting project for the Werra potash mine in the former East Germany for its owner Kali & Salz. This is a group effort involving an international panel of specialists, all with different expertise. We established grout formulations and test procedures both for regular and microfine cement based grouts. This project is ongoing.

8. ECO has done several grout test programs for manufacturers of microfine cement based grouts. Some of these formulations were made for use in saline environments. Brine saturated solutions were typically used for these tests.

After all those years of testing and evaluating performance of grouts, I must admit that there is still a lot to be learned about the application of suspension grouts in saline environments, especially if magnesium brines are present.

We would be very interested to participate in testing programs or review information by others. You can find more information about our firm on our site: www.ecogrout.com. We are completely independent and have no links or ties with manufacturers nor contractors nor distributors. Thank you for contacting us. We look forward to contribute to this project

Regards,

Alex Naudts, P.Eng.

APPENDIX D

September 4, 2001 letter, Triay to Marcinowski

Department of Energy
Carlsbad Field Office
P. O. Box 3090
Carlsbad, New Mexico 88221

September 4, 2001

RECEIVED
SEP - 6 2001
ENVIRONMENTAL EVALUATION GROUP

Mr. Frank Marcinowski
Office of Radiation and Indoor Air
U.S. Environmental Protection Agency
401 M. Street, S. W.
Washington, DC 20460

Dear Mr. Marcinowski:

On April 17, 2001 we submitted a request to you seeking approval of several proposed enhancements to the WIPP panel closure system. Based on communications with your staff during our recent working meetings, we respectfully withdraw our request for approval of those modifications. In view of the approval of our panel 1 utilization request and our current and projected throughput rates, we wish to re-evaluate our panel closure strategy.

At the conclusion of our evaluation, we expect to revisit this topic with the EPA. We appreciate the effort already expended by your staff in the review of our April submittal. If you or your staff have any questions regarding this matter, please contact Mr. Daryl Mercer at (505) 234-7452.

Sincerely,

Inés Triay

Dr. Inés R. Triay
Manager

cc:
D. Huizenga, EM
S. Monroe, EPA
S. Ghose, EPA
C. Byrum, EPA
N. Stone, EPA
S. Zappe, NMED
M. Silva, EEG

CBFO:ORC:DMM:VW:01-1340:UFC:5400

APPENDIX E
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LIST OF EEG REPORTS

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IDENTIFICATION OF ISSUES RELEVANT TO THE FIRST RECERTIFICATION OF WIPP

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Matthew K. Silva
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Environmental Evaluation Group
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September 2002

EEG-83
DOE/AL58309-83

IDENTIFICATION OF ISSUES RELEVANT TO THE FIRST RECERTIFICATION OF WIPP

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September 2002

FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment of New Mexico. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned the EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC04-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

The EEG performs independent technical analyses on a variety of issues. Now that the WIPP is operational, these issues include facility modifications and waste characterization for future receipt and emplacement of remote-handled waste, generator site audits, contact-handled waste characterization issues, the suitability and safety of transportation systems, mining of new panels, and analysis of new information as part of the five year recertification cycles as mandated by the WIPP Land Withdrawal Act. Review and comment is provided on the annual Safety Analysis Report and Proposed Modifications to the Hazardous Waste Facility Permit. The EEG also conducts an independent radiation surveillance program which includes a radiochemical laboratory.

Matthew K. Silva
Director

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ACKNOWLEDGMENTS

The authors wish to thank Ms. Linda Kennedy and Ms. Judith Youngman for their editing of this report. Also thanks to Ms. Jill Shortencarier for final word processing and compilation of the report.

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ACRONYMS

CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CRA	Compliance Recertification Application
CH TRU	Contact Handled Transuranic waste
DOE	U.S. Department of Energy
EEG	Environmental Evaluation Group
EPA	U.S. Environmental Protection Agency
LANL	Los Alamos National Laboratory
LWA	Land Withdrawal Act
PA	Performance Assessment
STTP	Source-Term Waste Test Program
TRU	Transuranic
UIC	Underground Injection Control
WIPP	Waste Isolation Pilot Plant

EXECUTIVE SUMMARY

One goal of the WIPP Land Withdrawal Act was to assure the safe disposal of the nation's defense transuranic waste into a deep repository in southeast New Mexico. The governing legislation required the U.S. Department of Energy (DOE) to provide to the U.S. Environmental Protection Agency (EPA) analyses of the anticipated performance of the repository. Disposal operations could not begin until the EPA determined that the project demonstrated compliance with EPA Standards (40 CFR 191) and EPA Criteria (40 CFR 194) for such disposal. The Land Withdrawal Act inherently recognized that the EPA Certification would have to rely on best available knowledge at the time when the application was submitted. The Act also recognized that after the initial certification of WIPP and start of disposal operations, operating experience and ongoing research would result in new technical and scientific information. Thus, the legislation requires recertification of the WIPP every five years, following the first receipt of waste. This report updates issues that the Environmental Evaluation Group (EEG) considers important as the Department of Energy (DOE) works towards the first recertification. These issues encompass a variety of technical areas including actinide solubility, fluid injection scenarios, solution mining, Culebra flow and transport, spallings modeling, and non-random waste emplacement.

Given the 24,000-year half life of ^{239}Pu, understanding the characteristics of plutonium in the WIPP environment is obviously important to the validity of long-term performance assessment of the repository. Some uncertainty remains in the understanding of the persistence of higher oxidation states because of reliance on modeling (with its associated assumptions) and limited experimental results. The EEG recommends additional experimental work towards parameters for a proposed conceptual kinetic model of plutonium solubility. In addition, the EEG recommends an intrusion scenario during performance assessment which would account for a heterogeneous, non-inundated repository which may include persisting higher oxidation states of plutonium.

Intrusion scenarios including the consequences of fluid injection were rejected at the time of the Compliance Certification Application (CCA). With increasing drilling activity in the vicinity of the WIPP (Figure 1), fluid injection scenarios should be re-examined for recertification performance assessment. These scenarios should consider potential consequences from oil field secondary recovery techniques such as waterflooding in addition to ancillary injection operations such as brine disposal and pressure maintenance wells. The WIPP resides in a resource rich locale and performance assessment should consider all reasonable activities associated with such a location.

Likewise, solution mining scenarios should also be reconsidered during recertification. Solution mining should be anticipated for extraction of potash reserves as well as for the excavation of salt caverns for storage of natural gas, oil field wastes, and chemical feedstocks. Consideration of solution mining for potash extraction is a natural alternative for a maturing mineral district as ore-grades decrease below the economic cutoff necessary for traditional mining methods. Dissolution of halite for creation of underground storage caverns is a practice already used in the Delaware Basin for oil field waste and natural gas. Research suggests that it may also be a viable method for storage of other items such as chemical feedstocks.

The Culebra dolomite unit of the Rustler Formation is acknowledged as a likely pathway for breach of the WIPP repository. Hence, long-term performance assessment requires an accurate understanding and modeling of flow and potential actinide transport.

Most of the issues concerning the Culebra that were raised at the time of the CCA resulted from poor discretization of the modeling grid and the inherent heterogeneity of the aquifer. The DOE had originally planned to replace the previous flow code with MODFLOW and implement a finer grid. This coupled with a new transport code, STAMMT-L, would have addressed problems with numerical dispersion and spatial truncation errors. In addition, STAMMT-L incorporates a dual-porosity, multi-rate approach, which the DOE demonstrated to be a superior representation of transport within the heterogeneous character of the Culebra. The DOE had originally planned to address issues concerning the Culebra, but now plans no changes to the conceptual model during recertification.

The EEG remains concerned over the continuing water level increases in the Culebra aquifer. The DOE is currently engaged in an effort to determine the source, or sources, of the rising water elevations, which have continued to increase for the last 14 years. Until a cause is determined, the validity of the Culebra conceptual model used for performance assessment is in question.

The EEG recommends that the DOE reconsider its decision **not** to change the Culebra modeling codes and grid discretization. In addition, the EEG urges the DOE to conclusively determine the source of the water level increases and adjust the conceptual model accordingly.

Spallings consist of repository waste material that fails due to a rapid reduction of pressure caused by penetration of the repository by a drill hole. The failed material would be transported up the drill hole to the surface by gas flow. The CCA performance assessment demonstrated the importance of spallings as a potential release mechanism. The spallings model used during the CCA did not adequately characterize the physical processes of spall. Work was in progress by the DOE on a new spallings model that was intended for use during recertification. This model was to improve predictions of long-term performance, reduce uncertainty, and enhance public confidence. However, the DOE has recently announced that the new model would only be used for impact analysis and not for recertification performance assessment. The EEG urges the DOE to reconsider and to use the new model for performance assessment.

Random emplacement of waste in the repository was assumed during the CCA performance assessment. However, waste emplacement practice since the 1999 opening has demonstrated that random emplacement is not likely. Specific waste streams shipments to WIPP depend on the DOE's agreements with the host states, and, on the readiness of particular waste streams for shipment. It has been previously demonstrated by the DOE that non-random emplacement could increase the mean release values. The EEG recommends that DOE develop a waste loading plan based on their shipment schedule. All intrusion scenarios could then consider non-random emplacement, providing better estimates of releases.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Project, located in Southeastern New Mexico was constructed by the U.S. Department of Energy (DOE) to provide permanent disposal of long-lived transuranic (TRU) waste from the U.S. defense activities and programs. The WIPP Land Withdrawal Act (LWA) requires that the facility must comply with 40 CFR 191, Subpart A during the period when radioactive waste is being emplaced and with 40 CFR 191, Subpart B and 40 CFR 194 for long-term disposal. Moreover, the U.S. Environmental Protection Agency (EPA) was assigned the responsibility to make that determination. In May 1998, the EPA certified that the WIPP met the requirements of 40 CFR 191 and 194.

The LWA inherently recognizes that the disposal facility represents a pioneering effort. Undoubtedly, as more scientific and technical information becomes available, there will be a need to revisit the certification decision. Hence, the enabling legislation requires recertification of the WIPP every five years after the first receipt of waste. The repository began receiving CH TRU wastes in March 1999. The first recertification by the EPA is required by March 2004, the second recertification by March 2009, etc. until the closure of the repository shafts.

The EPA standards specify the maximum allowable amount of radioactive material that can escape from the repository to the accessible environment for the regulatory period of 10,000 years. Because this is such a long time, the cumulative releases were predicted with performance assessment calculations. Specifically, the calculations attempt to represent the amount of material released as the result of some future drilling effort inadvertently penetrating the long forgotten repository. By definition, the performance assessment: (1) identifies the features, events and processes that might affect the disposal system, (2) examines their impact on the behavior of the disposal system, and (3) considering associated uncertainties, estimates the cumulative releases of radionuclides.

Experience has shown that the performance assessment must be viewed as an iterative process. As such, the contributions of various factors can achieve greater or lesser significance, depending on the performance assessment models. For example, three performance assessments

were published in 1990 (Bertram-Howery et al. 1990), 1991 (SNL 1991), and 1992 (SNL 1992). During that time frame, the calculated releases were most sensitive to the drilling rate, actinide solubility, and actinide retardation (Helton et al. 1992). After a performance assessment publication hiatus of three years and a redesign of the conceptual models, the calculated releases from the 1996 performance assessment (DOE 1996) were reported to be most sensitive to three drilling phenomena - spalling, cavings, and cuttings.

In the ensuing time period since the Certification Decision (EPA 1998), the Environmental Evaluation Group (EEG) has identified unresolved Performance Assessment (PA) issues pertinent to the Compliance Recertification Application (CRA), (Chaturvedi et al. 1999; Silva et al. 1999 (Appendix A); Rucker et al. 2000; Silva 2000). This report updates the EEG's views on the following issues: (1) actinide solubility, (2) fluid injection, (3) solution mining, (4) Culebra transport, (5) spallings, and (6) non-random waste emplacement.

In November 2001, the DOE issued the Recertification Project Plan (DOE 2001a) outlining the intended activities and timeline for completion of the CRA. Since the Recertification Project Plan was issued, three CBFO/EPA Working Meetings (DOE 2001b; 2002a; 2002b) have been conducted for presentation of information and studies pertaining to the recertification.

The EEG considered that an update of these unresolved issues would be important and timely as the DOE is focusing efforts toward compilation of the CRA. The DOE had originally planned to address several of these issues as part of the recertification, but have since modified their plans. It is recognized that the Recertification Project Plan reflects a snapshot in time, and that the DOE's schedules and activities may change because of unforeseen events or as the result of ongoing investigations. Therefore, this report reflects the EEG's understanding of the DOE's intent at the time of writing.

2.0 UPDATE ON UNRESOLVED ISSUES

Since the EPA Certification Decision in 1998, the EEG has commented on issues which they considered to be unresolved following the Compliance Certification Application (CCA) (DOE

1996). In light of several ongoing investigations by the DOE, as well as the DOE's stated objectives in the Recertification Project Plan, the EEG decided to update the previously identified issues for possible consideration in the 2004 CRA.

2.1 Actinide Solubility

Plutonium (Pu), specifically ^{239}Pu, is the major actinide of concern for long-term repository performance. With a 24,000-year half-life, ^{239}Pu will retain approximately 75 percent of its radioactivity over the 10,000-year regulatory period. Therefore, it is important to know the characteristics of Pu in the WIPP environment, particularly given that previous iterations of performance assessment were found be sensitive to actinide solubility (Helton et al., 1992). These characteristics include: (1) potential oxidation states, (2) solubility in the WIPP brines, and (3) its ability to complex with other waste constituents, such as chelating agents, to form more soluble or less sorptive species. Americium-241 (^{241}Am) with a 432 year half-life, is significant to performance assessment during the first 1500 to 2000 years but its solubility is more predictable. Other actinides, with shorter half-lives, will decay substantially during the regulatory period.

2.1.1 Potential Oxidation States

Understanding the potential oxidation states for plutonium is important for performance assessment. The higher states, Pu (V) and Pu (VI), are more soluble in brine than the lower states. This would increase the amount of radioactivity which would be brought to the surface during a human intrusion event. For the CCA, the DOE assumed that Pu would exist only in oxidation states III and IV. The DOE argued that the reduction potential of iron in the waste and waste containers would keep Pu from persisting in the higher oxidation states of V and VI for any substantial length of time. However, Pu (V) and Pu (VI) have been observed in a number of experiments conducted in brines (Villarreal 2002).

Unfortunately Pu chemistry studies with solutions at near-neutral pH are limited. Most Pu studies were conducted for the separation procedures necessary for defense purposes and done under low pH conditions. Hence, there is little literature pertaining to Pu under the WIPP environmental conditions. Also, complicating its study, Pu is capable of existing in a number of valence states. It may have one valence state in the solution phase and a different valence state in the solid phase in contact with the solution (Haschke and Oversby 2002).

To understand the behavior of Pu under the WIPP disposal conditions, the similarities between the chemistry of uranium (U) and Pu were used together with data from several high level waste disposal programs to construct a conceptual model (Oversby 2000). This model starts with the work of Haschke et al. (2000) which showed evidence for the formation of PuO_{2+x} from PuO_2 and moisture. Experimental data show that the value of x in PuO_{2+x} is as high as 0.27. The model, summarized by Haschke and Oversby, describes the reaction scheme for steady-state solution concentrations of Pu and demonstrates the presence of Pu(V) and Pu(VI) in solution:

1. Pu(V) accumulates in PuO_{2+x} as x is increased by spontaneous reaction of PuO_2 with H_2O.
2. The rate of PuO_2^+ dissolution increases with increasing value of x in PuO_{2+x} until it equals the rate of Pu(V) formation and a steady state is established.
3. PuO_2^+ accumulates until its rate of disproportionation into PuO_2^{2+} (i.e. Pu(VI)) and Pu^{4+} equals its rate of entry into solution and a steady state is established.
4. PuO_2^{2+} accumulates until disproportionation and reduction reform PuO_2^{2+} at a rate equal to half the PuO_2^+ dissolution rate and a steady state is established.
5. Pu^{4+} accumulates until its concentration satisfies the K_{sp} for $Pu(OH)_4$ precipitation and the equilibrium of Pu(IV) concentration is established.
6. Metastable $Pu(OH)_4$ spontaneously transforms into PuO_2 and subsequently back to PuO_{2+x}.

A quantitative model could be developed from this conceptual model. Rate constant data would need to be available for steps 1, 3, and 4, and equilibrium thermodynamic data for step 5.

2.1.2 Solubility in WIPP Brines

To characterize the solubility of plutonium in brine, the DOE used an oxidation state analogy. The oxidation state analogy assumes that species of similar oxidation states behave in a similar manner. For example, rather than determining its solubility experimentally, the DOE estimated Pitzer parameters for Pu (IV) from data reported for thorium (Th) (IV). The DOE then argued that the Pu (IV) estimates were conservative because Th (IV) solubility would be consistently higher than Pu (IV) solubility (Triay 2001). However, experiments conducted at the Los Alamos National Laboratory (LANL) (Villareal 2002) with containers of transuranic waste measured higher dissolved concentrations of Pu rather than Th. This strongly suggests "that Th solubility is unlikely to be a realistic or conservative analog for Pu or U under WIPP disposal conditions" (Oversby 2000).

In response to the Oversby (2000) report, the DOE (Triay 2001) reiterated their position for use of the oxidation state analogy and continued, "The key to oxidation state analogy then lies in understanding the chemical conditions where it is and is not applicable, and also understanding the appropriate use, including limitations, as applied to a real problem." The EEG agrees with this statement as it goes to the very point of the EEG's argument, i.e., the analog method cannot account for the ability of Pu to assume higher oxidation states. The total solubility of Pu in solution cannot be predicted by the oxidation state analogy because the lability of Pu between different oxidation states cannot be treated by analogy.

The above mentioned experiments conducted by LANL were termed "The Actinide Source-Term Waste Test Program" (STTP) which attempted to determine actinide behavior in WIPP-like brines. A portion of this study was devoted to the analysis of waste similar to that which resulted from the pyrochemical processing of weapons-grade Pu conducted at Rocky Flats. The residues from this processing are mostly solidified chloride salts used as molten solvents in several extraction processes, i.e. direct oxide reduction (PuO_2 to metal), molten salt extraction (Am from Pu), and molten salt electrorefining (Villarreal 2002).

The STTP was designed to approach the WIPP repository conditions for actinide transport and assumes total brine immersion of wastes (Villarreal 2002). In one publication, the EEG (Haschke and Oversby 2002) has concentrated on the results from the general pyrochemical salt liter-scale tests, i.e. pyrochemical salt tests without additional components such as CO_2, bentonite, etc. These tests were designated L-25, L-26, and L-27. Results from these experiments showed that solution concentrations of Pu rose gradually in L-26 and more rapidly for L-27. The peak concentration for L-27 was about three times higher than for L-26, although they reported similar loading amounts. Pu then decreased and approached an apparent steady-state condition with concentrations of about 4 ppm for L-26 and between 25 to 30 ppm for L-27. Meanwhile L-25 with a much lower initial loading, peaked at 0.17 ppm and decreased to 0.06 ppm. L-27 contained Castile brine while L-25 and L-26 contained Brine A, a simulated Salado brine. These results suggest that the amount of Pu in the system influences the steady-state concentration of Pu and that a mechanism other than thermodynamic equilibrium solubility controls the concentration.

Also, according to the DOE, L-26 showed Pu (VI) which persisted for 1.5 years while L-27's high Pu concentration was identified with Pu (V). The iron mesh did not seem to maintain a reducing environment in these tests (Triay 2001).

The DOE maintains that: (1) pyrochemical salts constitute a small fraction of the waste, and (2) that oxidized Pu would only be produced in microenvironments and would not persist in large quantities in the repository. However, actual persistence and what constitutes "significant quantities" is unknown. Oversby (2001) argues:

> "Discussion of persistence of oxidation states is only appropriate for steady-state conditions. Long-lived transients are likely to be important in at least some human intrusion scenarios. Concentrations of Pu exceeding those predicted in the CCA persisted in the STTP tests for periods of up to 5 years. These high Pu concentrations were probably caused by the presence of Pu (V) and/or Pu (VI)."

The conceptual model presented in Section 2.1.1 has been applied in explaining these STTP results (Haschke and Oversby 2002). Kinetic equations for the model were obtained from

analysis of published data. This model predicts the presence of Pu as Pu(V) and Pu(VI). Observed steady-state Pu concentrations in excess of the model predictions are explained by the presence of high Cl^- concentrations and Fe, which promote reduction of Pu(V) and complexation of the Pu(III) product. These results suggest that equilibrium modeling does not adequately predict dissolution behavior of Pu. Kinetic factors should be considered.

2.1.3 Use of FMT For Solubility Modeling

The FMT solubility model was developed for use at WIPP and has not gained widespread acceptance elsewhere. The EEG discovered that the model predicted large differences in actinide sulfate solubilities for different brines that could not be explained on the basis of chemistry. This raised questions concerning the validity of the code. The EEG also disagreed with the EPA's methodology for verification of the code as it was not subjected to comparisons with more widely used codes, nor did it demonstrate the ability of the first model to reproduce results consistent with relevant published data.

The DOE was considering the use of a more widely used code, EQ3/6, for recertification (Knowles et al. 1999; Knowles in DOE 2001b). However, the DOE has apparently reconsidered its decision and is planning on the use of FMT (Patterson 2002).

2.1.4 Complexation With Waste Constituents

The ability of plutonium to complex with other waste constituents involves the effects of organic ligands on the solubility and the partitioning coefficient of plutonium and other major actinides in WIPP brines. Some organic ligands that are known to be in significant quantity in the WIPP waste will act as chelating agents, binding to the actinide, which will keep the actinide from binding with the solid material. This binding will increase solubility by allowing less plutonium to be attached to solid matter in the waste. It will also decrease the partitioning coefficient, a measure of how contaminants are sorbed onto a host rock once it reaches a viable aquifer. However, the potential effects of organic ligands were not included as part of the CCA performance assessment calculations.

The experimental results from the STTP tests showed that the presence of organic ligands (acetamide, acetate, citrate, oxalate, and thiocyanate) elevates Pu solubilities by a factor of 1000 (Oversby 2000). The DOE assumed a well-mixed, homogenous repository and average concentration of the ligands to calculate the affinity of the ligands binding with plutonium. In reality, the repository will not likely be mixed, creating an extremely heterogeneous environment of actinide reactants with ligands. In addition, the DOE argued that the organic ligand, EDTA, would form the strongest complexation with actinides in the IV oxidation state (or An (IV), and that other divalent cations, such as Fe (II) and Ni (II) would use up most of the EDTA, so there would be less to react with An (IV)). On this basis, the impact of citrate was eliminated from further consideration. However, the 140 metric tons of citrate in the waste will form strong complexation species with An (IV) with little competitive reaction from other divalent cations. Therefore, citrate will be bound to a significant portion of Pu (IV) or U (IV) in the WIPP waste (Oversby 2000).

2.1.5 Recommendations

The EEG recommends that, for performance assessment, the DOE consider the effects of increased Pu solubility resulting from complexation with organic ligands. This is especially significant in scenarios which reflect non-random waste emplacement (Section 2.6), in which the repository environment is a heterogeneous mixture of actinides and organic ligands.

The EEG recommends that the DOE explore the development of a conceptual kinetic model of Pu solubility. Additional experimental work is suggested (Oversby 2002) which would allow the application of this model. Necessary parameters are:

(1) The rate of Pu(V) production in $Pu(OH)_4$ as a function of [NaCl] and pH,
(2) The rate of disappearance of Pu(V) from solution as a function of [NaCl] and pH, and
(3) The rate of disappearance of Pu(VI) from solution as a function of [NaCl] and pH.

Determination of these parameters can be limited to a range covering the WIPP conditions. Data for (2) and (3) already exist at pH 7.1 and [NaCl] = 2.4 M. Oversby goes on to provide specific recommendations:

> "If data were produced for [NaCl] = 0.1 and 4.8 M at pH 7.1, the chloride dependence of these reactions rates could be evaluated. If the dependence of rates on [NaCl] is not too great, the pH dependence of the rates could be evaluated at a single [NaCl], for example 2.4 M. Tests at pH 9 and 11, together with the existing data at pH 7.1 would give the pH dependence of the rates. The effect of Fe could be evaluated initially by using a single pH and [NaCl] together with two experimental conditions – one with an initial concentration of Fe(II) without a replenishment source and one with an actively corroding piece of Fe metal to provide a constant source of Fe(II) ions. A similar experimental matrix for the oxidation of $Pu(OH)_4$ as a function of [NaCl] and pH would complete the reaction rate data needs. If any of the reaction rates turned out to be a sensitive function of one of the experimental parameters, more detailed studies could be planned."

The EEG urges the DOE to reconsider its decision to use FMT for recertification. The DOE has apparently invested considerable effort in the application of EQ3/6 to the WIPP data and demonstration of its use should enhance public confidence in solubility modeling.

2.2 Fluid Injection

The issues regarding fluid injection have been previously discussed in detail by the EEG (Neill et al. 1998). The 1996 performance assessment calculations did not include scenarios of fluid injection for enhanced oil recovery, a current practice throughout the Delaware Basin (Silva 1996). The DOE rejected its inclusion on the basis that the EPA regulations did not require it. The regulation states: "With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole (EPA 1996)." Also, any affects from fluid injection wells adjacent to the WIPP were not included on the basis of a low probability argument. Figure 1 shows the increase in oil and gas related drilling activity since the time of the CCA.

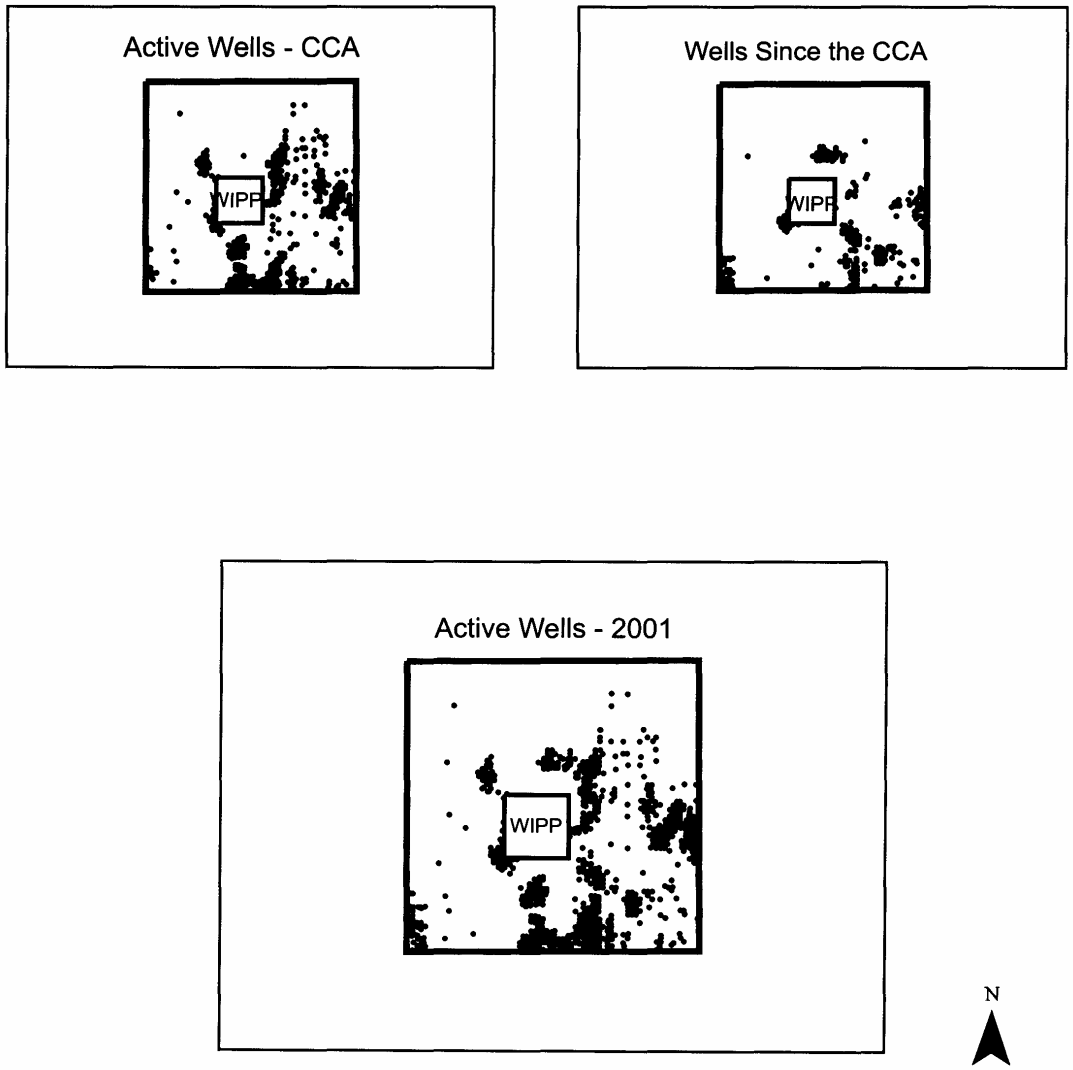

Includes oil, gas, pressure maintanance, and salt water disposal wells

Figure 1
Comparison of Active Wells - CCA to 2001
Nine-Township Boundary

2.2.1 Waterflooding

In the EEG's opinion this issue is worthy of re-examination during recertification based on the continuing practice of waterflooding for oil recovery enhancement. As of 2001 there were three major waterflooding projects in the New Mexico portion of the Delaware Basin (DOE 2001c).

Waterflooding is a secondary recovery technique used to enhance crude oil recovery by restoring reservoir energy lost during primary production (Willhite 1986). During waterflooding, pressurized water is injected through the well bore into the reservoir. This forces oil, that may be unrecoverable by primary methods, to flow toward the producing well. Waterflooding and other secondary and tertiary recovery methods are encouraged by the State of New Mexico through severance tax relief, promoting maximum extraction of resources.

However, waterflooding has historically presented problems for some oil-bearing zones underlying the Salado Formation. It has been documented in various instances that water has escaped from the collection zone and migrated through the Salado Formation to adjacent properties (Ramey 1976). Probably the most notorious waterflood incident resulted in the Hartman vs. Texaco lawsuit (Complaint CIV93 1349M) filed in the Federal Court for the District of New Mexico. Mr. Hartman claimed that the Texaco Rhodes Yates waterflood project allowed large quantities of injected water to escape out of the approved zone, part and dissolve the Salado Formation, and migrate to Hartman's Bates Lease (Hartman 1993). This lawsuit resulted in compensation to Mr. Hartman.

The EPA concluded that a probability of such a waterflood event occurring in the Salado Formation in the vicinity of the WIPP is extremely low (EPA 1998c). They relied on geological comparisons based on geological descriptions of the Hartman vs. Texaco location provided in a summary of the case and on the DOE characterization, and hence conceptual model, of the Salado Formation at the WIPP. Also, the EPA suggested that the relatively young age of the wells in the vicinity of the WIPP provide some measure of assurance because of better construction and operational practices than those involved in the Hartman case. However, it

should be noted that a hypothesized cause of the Culebra water level increase is a leaky injection well in the vicinity of the WIPP (Beauheim 2002).

2.2.2 Brine Disposal

The most common type of injection well in the Delaware Basin is for the disposal of brine water resultant to production of oil and gas. Salt water disposal wells are necessary as a result of an EPA ruling that formation water may no longer be disposed of on the surface.

There are currently 33 salt water disposal wells in the nine-township area surrounding the WIPP site (DOE 2001c). This number is up considerably over the 10 salt water disposal wells in the same area as reported from 1993 (Broadhead et al.1995).

The DOE relies on a low consequence argument and the administration of the Underground Injection Control (UIC) regulations (OCD 2002) as a safeguard against possible consequences from fluid injection. The determination of low consequence is again based upon DOE's modeling and hence conceptualization of Salado Formation (Stoelzel et al. 1996; Stoelzel and Swift 1997). Indeed, alternate modeling suggested that the DOE's modeling may be unrealistic and non-conservative (Bredeheoft 1997a; 1997b).

As for the UIC regulations, despite the required testing and verification by the New Mexico Oil Conservation Division, strong circumstantial evidence suggested a connection between a salt water disposal well and Culebra monitoring well H-9 (LaVenue 1991; Beauheim 1995). The reliance on this program as a safeguard may be in question if injection wells are found to be, in part, responsible for the current Culebra water level increases.

The EPA used a low probability argument to justify the exclusion of fluid injection scenarios. However, the EPA analysis resulted in three different probability values which spanned four orders of magnitude (Silva et al. 1999). This highlights the uncertainty in assigning probabilities for the series of individual events for calculation of the total probability of a leaking well impacting the repository.

The fact that fluid injection scenarios were not included in the CCA performance assessment does not preclude their inclusion during recertification. Recertification can incorporate a re-evaluation of previous information as well as new information. Given the increase in development of wells in the vicinity of the WIPP, there is an increased expectation that extraction from known oil reserves will be optimized by secondary and tertiary recovery techniques.

The OECD/NEA-IAEA Joint International Review Group, in a Peer Review commissioned by the DOE, expressed reservations about rejecting a scenario solely on the basis of regulatory considerations:

> "It would improve the confidence of the reader if the DOE presented the logical or physical arguments for not considering these processes in the assessment, in addition to noting that they are not required in a compliance demonstration. Otherwise, there is an impression that processes that might deserve consideration from a safety perspective have been eliminated" (NEA/IAEA 1997).

The EEG believes that the increasing number of brine disposal wells, along with economic incentives for the use of secondary recovery techniques, reflects on the necessity of screening in fluid injection scenarios into recertification performance assessment calculations. In addition, the DOE should realistically assess potential flow paths in the Salado based on documentation of other fluid injection events. Also, unexplained water level increases in the Culebra aquifer, which raises questions concerning the Underground Injection Control program, undermines the reliance that the DOE puts on the program as a safeguard measure.

2.3 Solution Mining

Consideration of solution mining was not included in the CCA on the basis that it was not occurring in the Delaware Basin in 1996. However, underground storage caverns already exist and interest is growing in solution mining of potash for extraction of minerals. An expansion of

the role of salt caverns for storage of natural gas, oil field wastes, and chemical feedstocks is expected (Veil et al. 1996; Bauer et al. 1998; Veil et al. 1998).

Consideration of solution mining for extraction of minerals is the natural progression of alternatives in the life of a mine. Companies which mine various commodities, including potash, consider solution mining following the extraction of higher grade ores through more predictable traditional methods. In addition, ores which were once considered as too low grade become economical with the refinement of new technologies. With this in mind, it is reasonable to assume that solution mining will be considered in the vicinity of the WIPP project for extraction of minerals (NMBMMR 1995). This is especially true since the U.S. Bureau of Land Management has delayed development of oil and gas reserves surrounding the WIPP in favor of prioritizing the extraction of potash. The prioritization policy will push forward in time a decision by potash companies concerning final development of potash reserves. Figure 2 shows the potash reserves and resources in the vicinity of the WIPP.

Another emerging technology is the use of solution mining for dissolution of underground caverns for storage purposes. The DOE has funded considerable research in this area, especially for disposal of oil field waste (Veil et al.1996; Tomasko et al. 1997; Veil et al. 1998). Sites for the underground disposal of oil field waste are typically caverns created by the solution mining of halite for use as brine during oil field drilling, a practice already occurring in the Delaware Basin (Neill et al. 1998).

Solution mining, whether for extraction of resources or for excavation of underground storage, should be considered. Plausible scenarios related to this activity should be evaluated and screened for each recertification as technology in this area continues to be refined.

2.4 Culebra Flow and Transport

The Culebra dolomite unit of the Rustler Formation is acknowledged as a likely pathway for breach of the WIPP repository. This observation underscores the need for an accurate understanding and modeling of Culebra flow and transport by the DOE.

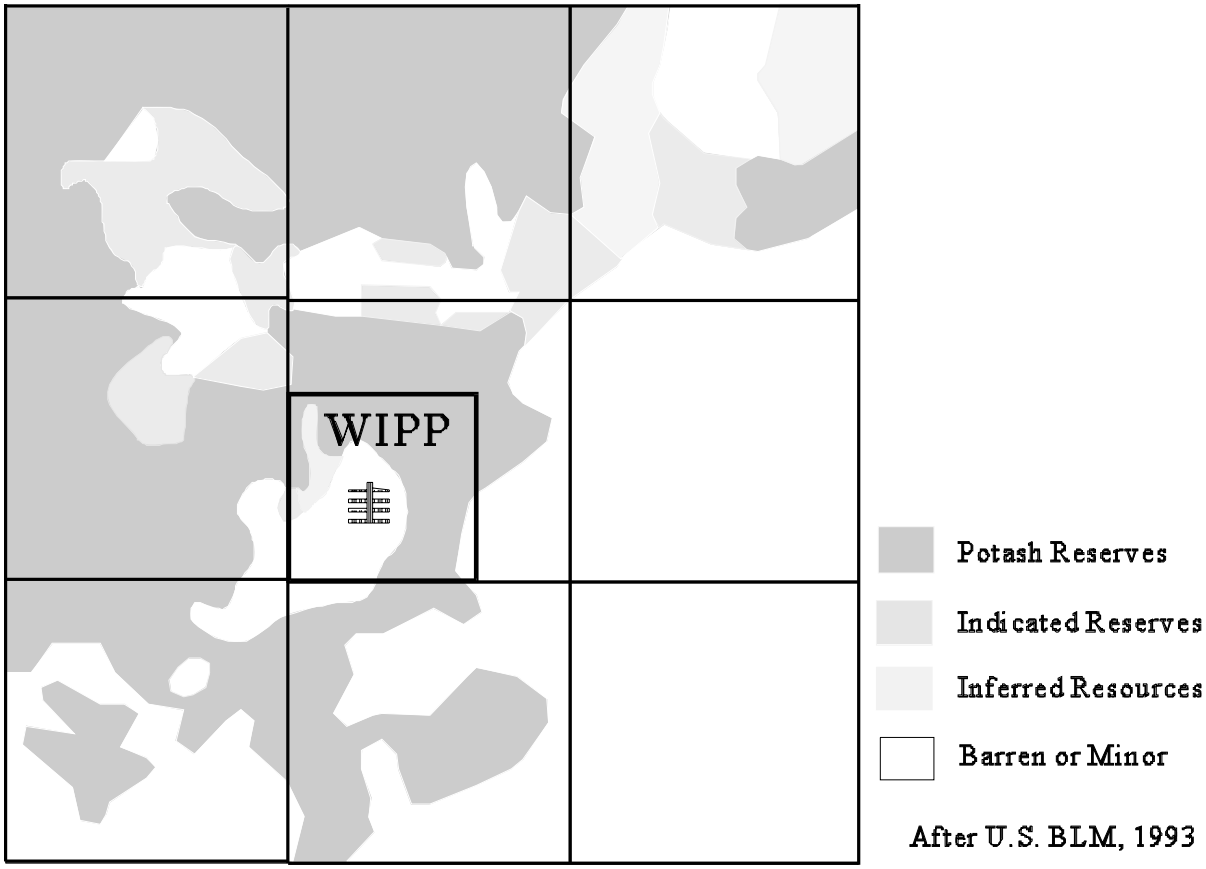

Figure 2
Potash Resources In the Vicinity of WIPP

The National Academy of Sciences WIPP Committee (NAS/NRC 1996) and the EEG (Neill et al. 1998) raised issues regarding the conceptual and numerical model of transport through the Culebra. The DOE had planned to address some of these issues during the first CRA (DOE 2001b), but now plans no changes to the conceptual model (Patterson 2002).

In addition to the issues concerning transport, continuing increases in water level elevations in the Culebra and other formations, raises uncertainty in the flow model. As the transport model follows from the flow model, this also increases uncertainty in the transport model. Figure 3 illustrates the generalized dip of the Culebra and monitoring wells in the vicinity of the WIPP.

2.4.1 Water Level Increases

The water level in the Culebra began increasing in April, 1988 (Beauheim 1990; Silva 1996) and continues to rise through the date of this report. These increases are also observed in the Magenta unit of the Rustler Formation as well as in some of the more shallow formations (Beauheim 2002).

These increases are of concern in the recertification because 21 of 28 monitoring wells now show water elevations in the Culebra aquifer outside the ranges used for calibration of the CCA transmissivity fields. This may cast doubt on the validity of the steady-state flow model used in the CCA. Also, the reliability of the transmissivity estimates were determined using inverse methods that assumed the Culebra was a non-leaky, two-dimensional aquifer. Increasing water elevations suggest a likely connection of the Culebra with other water-bearing units, raising questions concerning the validity of this assumption as well.

During January 2002, the DOE convened a workshop to address the issues of the water level rises. The stated purpose of this workshop was “to demonstrate an understanding of the WIPP hydrologic system by developing scenarios that account for the observed changes and show that the CCA modeling results remain valid for recertification” (Beauheim 2002). Figure 4 shows the difference in water elevations between the time of the CCA and 2001.

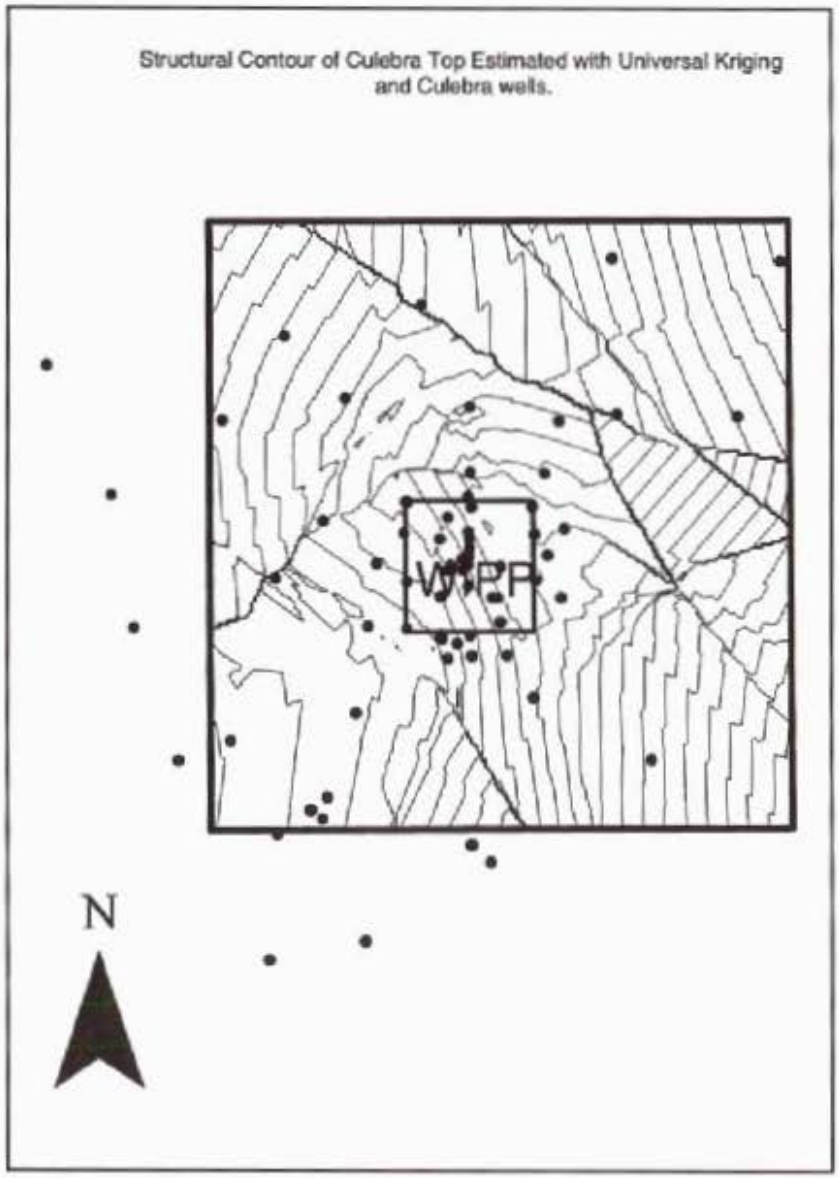

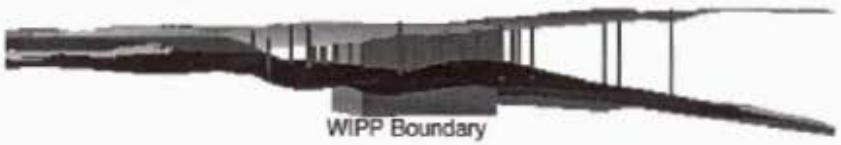

Cross section looking north
showing dip of Culebra to the east

Figure 3
Culebra Top with Wells and WIPP Boundary

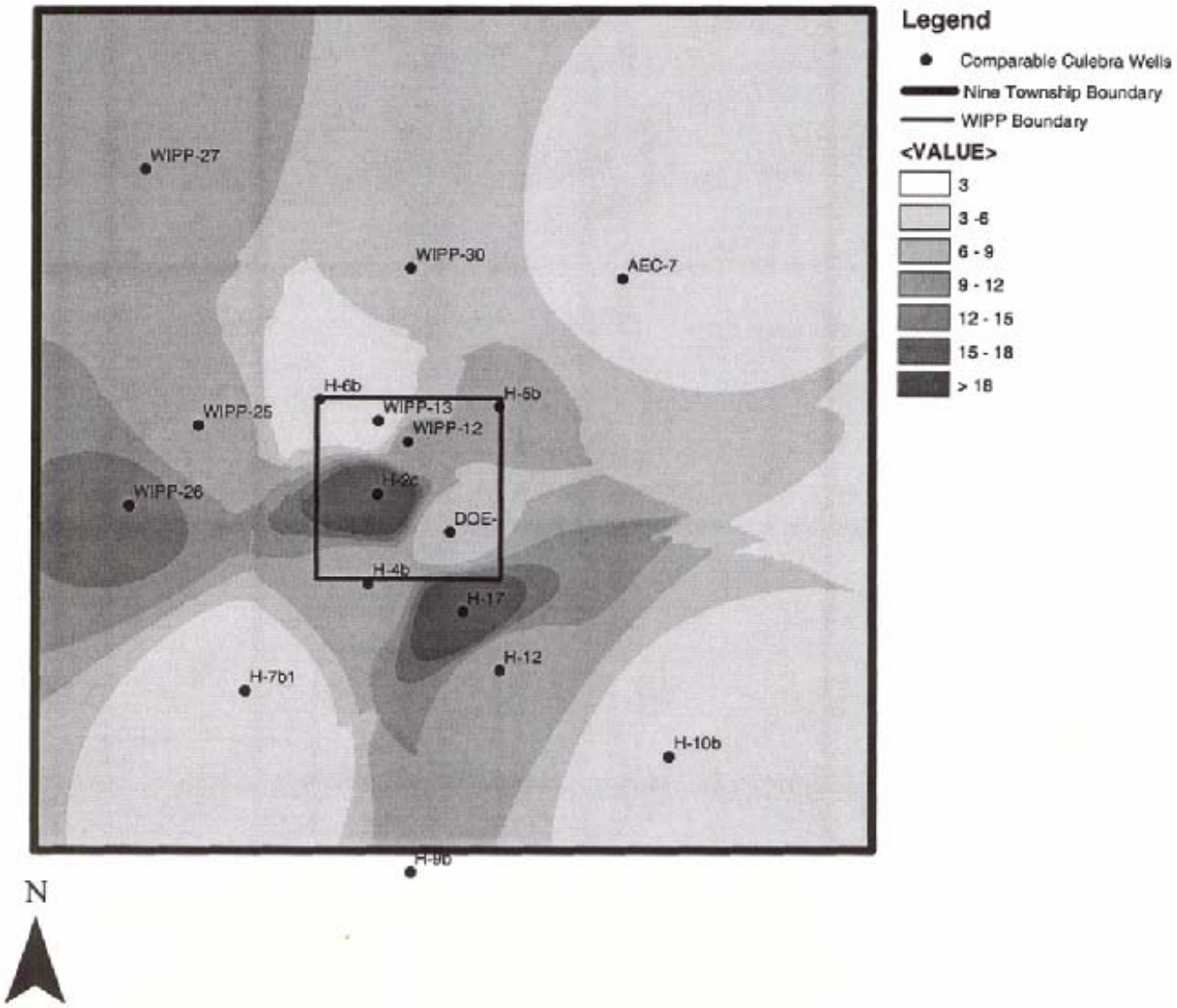

Figure 4
Culebra Head (ft) Difference
CCA to 2001

The workshop developed seven scenarios which could potentially explain the water level changes in the Culebra:

(1) Recharge from potash tailings ponds,
(2) Leakage through wells from shallower units,
(3) Leakage through wells from deeper units (including injection),
(4) Precipitation,
(5) Changes in karst resulting in high-transmissivity conduits,
(6) Mine subsidence,
(7) Subsidence related to oil and gas production.

It is likely that some combination of these seven possibilities would account for the changes in the Culebra water levels. It is unfortunate that the DOE only recently convened this workshop to address these issues, since the water levels have been increasing and have been unexplained for 14 years. Arriving at an explanation for the increases from these (or other) multiple probable causes will undoubtedly take considerable time and may not be satisfactorily answered before the first recertification.

The EEG expressed their concern for the lack of an explanation in 1998 (Neill et al. 1998). Moreover, the EPA expressed concern in 1996:

> "The statement 'they remain unexplained' is insufficient, particularly if the reason for the rise could be interpreted to affect long term hydrologic conditions within the Culebra or be caused by ongoing oil and gas exploration and development activities, such as brine disposal into underlying units" (Trovanto 1996).

The DOE plans to test the validity of the CCA transmissivity fields using the current water head observations. Since the transmissivity fields were conditioned by both the heads as well as transient response data, it is possible that the fields are still valid given the current observations. If not valid, transmissivity fields will need to be re-generated, possibly using a geology-based method. However, the ability to calibrate transmissivity values does not necessarily validate the

conceptual model. Until a source is determined for the water level increases, the validity of the Culebra conceptual model remains in question.

2.4.2 Heterogeneity and Model Discretization

During development of the CCA, several modeling errors were identified which resulted in an artificial spreading in the calculated width of a potential contaminant plume at the expense of its length. This would result in non-conservative travel times to the regulatory boundary. These errors included numerical dispersion and spatial truncation errors in the transport code, poor resolution from using a grid that was too coarse for the scale of the problem, and overestimation of the size of the solute source area (Konikow 1997). These errors are especially apparent in a heterogeneous aquifer such as the Culebra. If a plume spread out laterally due to numerical dispersion, the wider plume will move downgradient a shorter distance than would be the case if a finer grid were used during modeling (Figure 5).

The DOE had planned to address these issues during the recertification (DOE 2001b). The previously used SECO suite of codes were to have been replaced by MODFLOW, STAMMT-L and DTRKCDB. MODFLOW was to have been used for modeling of the flow field. DTRKCDB was to have computed one-dimensional particle velocity paths for input into STAMMT-L. This code incorporates a dual-porosity, multi-rate concept which better addresses heterogeneity and allows for a better representation of the diffusive process. (Haggerty and Gorelick 1995; Haggerty and Reeves 2000).

However, the DOE now plans to retain the SECO models for recertification (Knowles 2002), despite the previously identified problems. In addition, the DOE research on transport in the Culebra showed a superior fit of experimental data with a multi-rate diffusion code such as STAMMT-L (Altman and Meigs 1999). The EEG encourages DOE to reconsider its decision and to implement the previously planned changes to the Culebra models.

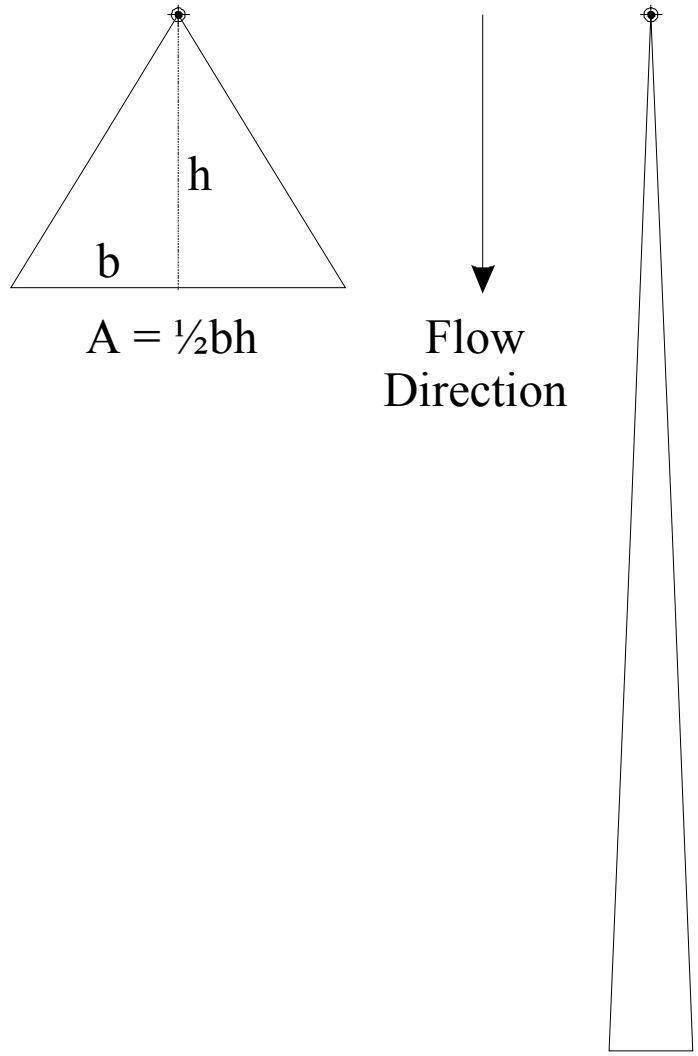

Conceptual Diagram Of Contaminant Plumes Represented As Simple Triangles, Showing Different Travel Distances For A Relatively Wide Plume Compared To That Of A Relatively Narrow Plume, Where Both Plumes Encompass Equal Volumes Of Fluid And Equal Masses Of Solute.

Figure 5

Conceptual Diagram of Contaminant Plume Showing Potential For Numerical Dispersion (From EEG-68).

2.4.3 Sampling Procedures for Input Parameters

The co-regionalization of spatial parameters was not considered in the CCA. Hydrogeologic variables that were correlated were sampled independently. This could result in realizations that may be based on unlikely combinations of parameters, and may produce a bias.

For example, transmissivity, fracture spacing, and porosity generally exhibit co-regionalized behavior and are positively correlated (NRC 1996). That is, high transmissivity is related to a higher density of fractures and high porosity. If these correlations are ignored, realizations would be generated that may have high transmissivity, with a low density of fractures and low porosity. While this may still happen under a model of co-regionalization, a higher frequency of realizations representing this scenario will occur under an assumption of variable independence. The EEG recommends an analysis of co-regionalization for spatial variables and co-simulation for those which are highly correlated.

2.4.4 Consistency Between Performance Assessment Models

The connections between some of the performance assessment models and parameters are not always transparent. The EEG had previously recommended that a mass balance be documented to ensure that the fluxes between the various models are coherent (Neill et al. 1998).

For example, it was determined during the 1998 Annual Sensitivity Analysis that BRAGFLO results were skewed by the WSTOCOR term for the corrosion of steel (Helton 1998). In order to represent the hydration of MgO in the analysis, this term was allowed a range of values not representative of the actual steel corrosion process. This linked steel corrosion to hydration of MgO and caused the brine that is associated with the hydration process to disappear, creating mass balance problems. These mass balance problems affected estimated releases from spallings, direct brine releases, and releases through the Culebra.

In the Culebra, actinide transport results from radionuclide releases from brine flow up boreholes that penetrate the repository. In the 1998 Annual Sensitivity Analysis, the brine flows were

skewed low because of the large quantities of brine that disappeared. This problem illustrates how nontransparent links between models may produce improper results.

Therefore, it should be demonstrated that the total mass of fluid and solute that the human intrusion borehole model computes to enter the Culebra over 10,000 years should equal the total mass of fluid and solute that is actually added to the Culebra model over the 10,000 year period. This would identify potential problems, increase confidence in the models, and promote an understanding of the performance assessment process.

2.5 Spallings

Spallings consist of repository waste material that experiences failure caused by a rapid reduction of pressure as an intruding drill hole approaches or penetrates the repository. This material would then enter the drilling fluid due to radially channeled, pressurized gas flow from the repository to the lower pressure drill hole. This flow will continue until pressure equilibrium is achieved between the repository and the drill hole. This failed material would then be transported up the drill hole to the surface via gas flow.

The importance of spallings as a potential release mechanism of radionulides into the environment has been demonstrated through the 1996 iteration of the performance assessment calculations. The EEG has consistently stated their concern about the treatment of spallings during the CCA and PAVT analyses (Neill et al.1998; Fairhurst 1998; Silva et al.1999). Neill et al. (1998, pp 57-82) discusses in detail EEG's unresolved issues pertaining to spallings.

The initial spall model proposed by the DOE for the CCA was found inadequate by the conceptual model peer review (Wilson et al. 1996). However, the DOE schedule for submittal left insufficient time for development of a suitable replacement.

The DOE then developed a different model for prediction of radionuclide release. Use of this model predicted much lower releases due to spallings than the original model. However, sensitivity testing by the EEG (Rucker 1998; Silva et al. 1999) revealed instability problems with

the model if run outside a range of waste permeabilities between 1.7 to 2.0 x 10^{-13} m^2. The EEG recommended that the DOE begin development of a coherent and straightforward model which characterizes the physical processes of spall (Neill et al. 1998; Silva et al. 1999).

Work has been in progress by the DOE on a new spallings model that was intended for use during recertification (DOE 2001b). This model was to incorporate a modified wellbore hydrualics model with mixing equations for solids and fluids, a drillbit damage model, and a solids transport mechanism up the drill hole annulus (DOE 1999). The stated objective of this new model was to improve predictions of long-term performance (Knowles 1999).

However, the DOE has recently announced that the new model would not be used for recertification performance assessment, but only for an impact analysis (Patterson 2002). The EEG urges the DOE to reconsider the new model's use for the reasons stated above.

2.6 Non-random Waste Emplacement

Waste emplacement practice since the March 1999 opening of the WIPP has demonstrated that random emplacement is not likely. Specific waste streams will be campaigned depending on DOE's agreements with the various states which host TRU waste and the readiness of particular waste streams for shipment from the other sites (DOE 2000).

For example, as of April 22, 2002 (WWIS 2002), the EEG calculated the average radionuclide activity for waste emplaced to date in Panel 1. These calculations indicate that the emplaced activity of ^{239}Pu is 4.24 times, ^{240}Pu is 3.53 times, and ^{241}Am is 5.65 times the projected repository average for the space occupied by waste. Obviously, a future intrusion into Panel 1 would result in a different potential release than from a panel in which average radionuclide activities were emplaced.

In the CCA performance assessment, under a random emplacement assumption, the contents of a waste container removed by cuttings and cavings were randomly sampled from 569 separate waste streams. A drill hole intruding a room and intersecting each of three stacked containers

would have resulted in each of the three containers being randomly sampled with the probability of hitting a particular waste stream weighted according to its relative quantity. However, in reality it is likely that all three containers would be from the same waste stream.

It has been previously demonstrated by the DOE that non-random emplacement could increase the mean release values (Dials 1997). The EEG recommends that the DOE develop a waste loading plan based on their shipment schedule. While this schedule will certainly change over time, it is the best information currently available and presents a more realistic assumption than random waste emplacement. All intrusion scenarios could then consider non-random emplacement, providing better estimates of releases in brine, cuttings, cavings, and spallings.

3.0 CONCLUSIONS

Performance Assessment is an iterative process that should incorporate the best understanding of all of the integrated components at the time it is being done. For recertification, this "best understanding" may translate into modifications of conceptual models based on ongoing research or operating experience gained during the emplacement of waste. It may also mean consideration of scenarios that were previously screened out, but may warrant inclusion because of new information or to allay public concern.

In accordance with 40 CFR 194.15(a), the DOE must present an updated performance assessment with the CRA. This performance assessment must describe relevant new information and system changes since 1998 (Marcinowski 2002). The DOE had planned to submit several changes that would have addressed some of the ongoing unresolved issues presented in this report. However, the DOE has now modified their plans and are proposing minimal changes to the conceptual models for the first recertification. This change in plan likely coincides with the EPA's guidance found in the above mentioned letter, "Some of the changes currently included as part of the Technical Baseline Migration may necessitate a rulemaking to modify our Certification Decision." The DOE has allowed insufficient time for submission of planned changes that may require a rulemaking.

However, some of the withdrawn changes may reflect new information. These include:

(1) Continuing changes to the Culebra water levels and their reflection on the validity of conceptual model,
(2) Interpretation of Culebra tracer tests demonstrating the superiority of a multi-rate diffusion code,
(3) Improved characterization of the physical process of spall using an improved model,
(4) Experience indicating the non-random emplacement of waste.

Other planned changes such as the use of EQ3/6 instead of the FMT model would have improved public confidence. In addition, public confidence in the performance assessment process would be enhanced through serious consideration of fluid injection and solution mining scenarios.

Issues involving actinide chemistry and the Culebra modeling will likely be ongoing issues. Well-planned research programs should be conducted to adequately address their effect on long-term repository performance. For example, in actinide chemistry the EEG recommends the development of a conceptual kinetic model for solubility. For the Culebra, a three-dimensional, regional hydrogeological model should be developed to facilitate understanding of the relationship between hydrogeological units. Such a model would be useful in determination of the Culebra water elevation increases.

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APPENDIX A

Resolution of the Long-Term Performance Issues at the Waste Isolation Pilot Plant

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Resolution of the Long-Term Performance Issues at the Waste Isolation Pilot Plant

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The Waste Isolation Pilot Plant (WIPP) is a geological repository for disposal of U.S. defense transuranic radioactive waste. Built and operated by the U.S. Department of Energy (DOE), it is located in the Permian age salt beds in southeastern New Mexico at a depth of 655 m. Performance assessment for the repository's compliance with the 10,000-year containment standards was completed in 1996 and the U.S. Environmental Protection Agency (EPA) certified in 1998 that the repository meets compliance with the EPA standards 40 CFR 191 and 40 CFR 194. The Environmental Evaluation Group (EEG) review of the DOE's application for certification identified a number of issues. These related to the scenarios, conceptual models, and values of the input parameters used in the calculations. It is expected that these issues will be addressed and resolved during the first 5-year recertification process that began with the first receipt of waste at WIPP on March 26, 1999, and scheduled to be completed in March 2004.

KEY WORDS: WIPP; radioactive waste; repository; performance assessment; transuranic waste.

1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a geological repository built by the U.S. Department of Energy (DOE) for the disposal of defense transuranic (TRU) waste in bedded salt, at a depth of 655 m, about 40 km east of Carlsbad, New Mexico. The DOE submitted its compliance certification application (CCA)[1] to the U.S. Environmental Protection Agency (EPA) on October 29, 1996. EPA certified that the facility met the EPA Standards[2] and Criteria[3] for the disposal of TRU waste on May 18, 1998.[4] The waste bound for WIPP contains chemically hazardous materials regulated by the Resource Conservation and Recovery Act (RCRA) in addition to the radioactive components. A RCRA permit from the New Mexico Environment Department (NMED) is therefore required for WIPP in addition to certification by the EPA. The NMED is expected to announce its decision on the RCRA permit in October 1999. The WIPP began receiving nonmixed TRU waste on March 26, 1999.

The EPA certification required the DOE to provide a performance assessment (PA) of the repository. Performance assessment is defined in the Standards[2] as an analysis that:

1. Identifies the processes and events that might affect the disposal system.
2. Examines the effects of these processes and events on the performance of the disposal system.
3. Estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events.

The EPA disposal standards contain four re-

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quirements: the containment requirements, assurance requirements, individual protection requirements, and groundwater protection requirements. Performance assessment is used to determine compliance with each of these except for the assurance requirements. The assurance requirements were intended to compensate for the inherent uncertainty in a 10,000-year projection of events.

The performance assessment requires the (1) development of potential scenarios for release of radionuclides to the environment, (2) screening of all features, events, and processes, and the combination of features, events, and processes that may affect the disposal system, (3) identification and selection of the most appropriate conceptual models, (4) selection or development of appropriate computer codes, (5) determination of the input parameters for the analyses, and (6) calculation of the cumulative release in the form of complementary cumulative distribution functions.

The DOE has analyzed the probabilities and quantities of radionuclide releases to the environment for the undisturbed repository and the repository inadvertently disrupted by drilling. The outcome of the performance assessment is controlled by the conceptual models and the values for the input parameters used. These include gas pressurization, mechanics of human intrusion, characteristics of the waste including actinide solubility, mechanics of rock fracturing, and retardation processes in actinide transport through the overlying aquifer. The numerical values of the parameters are ideally determined by scientific investigations in the laboratory and/or the field.

Various iterations of the WIPP performance assessment were published from 1990 to 1992.[5–7] The 1996 PA may thus be viewed as an iteration in this ongoing process. Recertification for compliance is required at least every 5 years after first receipt of waste. The first recertification is due in March 2004. In addition to the 5-year recertification cycle, the DOE must submit periodic reports on any activities or conditions at the WIPP that differ significantly from the information contained in the most recent compliance application. The EPA may also, at any time, request additional information to determine whether the certification must be modified, suspended, or revoked. Hence, the EPA certification requires continued scientific investigation and technical review.

The Environmental Evaluation Group has reviewed[8] the scientific effort leading to certification. This paper summarizes the major technical issues identified by the certification process, the status of each issue, and a course of action for resolution as part of the recertification. Limited computations to examine the impact of these issues were published by EEG in 1998.[9]

2. THE ENVIRONMENTAL EVALUATION GROUP

The Environmental Evaluation Group (EEG) was created in 1978 to provide a full-time independent technical review of the WIPP to ensure protection of the public health, safety and the environment of New Mexico. The impact of EEG on previous PA efforts can be seen in the following areas:

1. Continuation[10] of performance assessment work after the disposal standards were vacated by the court in 1987, thus not losing time when the standards were repromulgated in 1993.
2. The DOE decision to abandon the *in situ* experiments with TRU waste at WIPP and redirect its efforts toward completing the performance assessment calculations and obtaining EPA certification.[11]
3. DOE's experimental programs to obtain data for parameters such as actinide solubility and retardation.
4. EPA's Criteria and Guidance for the WIPP.[12,13]
5. DOE's PA analyses.[14,15]
6. Testing the sensitivity of the PA models to various parameters including the borehole intrusion rate, actinide solubility, chemical retardation, the presence of a brine reservoir, and subsidence due to mining.[9]

3. GEOHYDROLOGICAL SETTING OF WIPP

The WIPP repository is located in the northern part of the Delaware Basin that is well known for its thick sequence of Permian age evaporites and economic deposits of potash and hydrocarbons (oil and gas). Figure 1 shows a geologic cross section at the center of the WIPP site. The repository is located at a depth of 653 m in the lower part of the approximately 610-m-thick Salado Formation, consisting of bedded salt (halite) and interbeds of anhydrite and

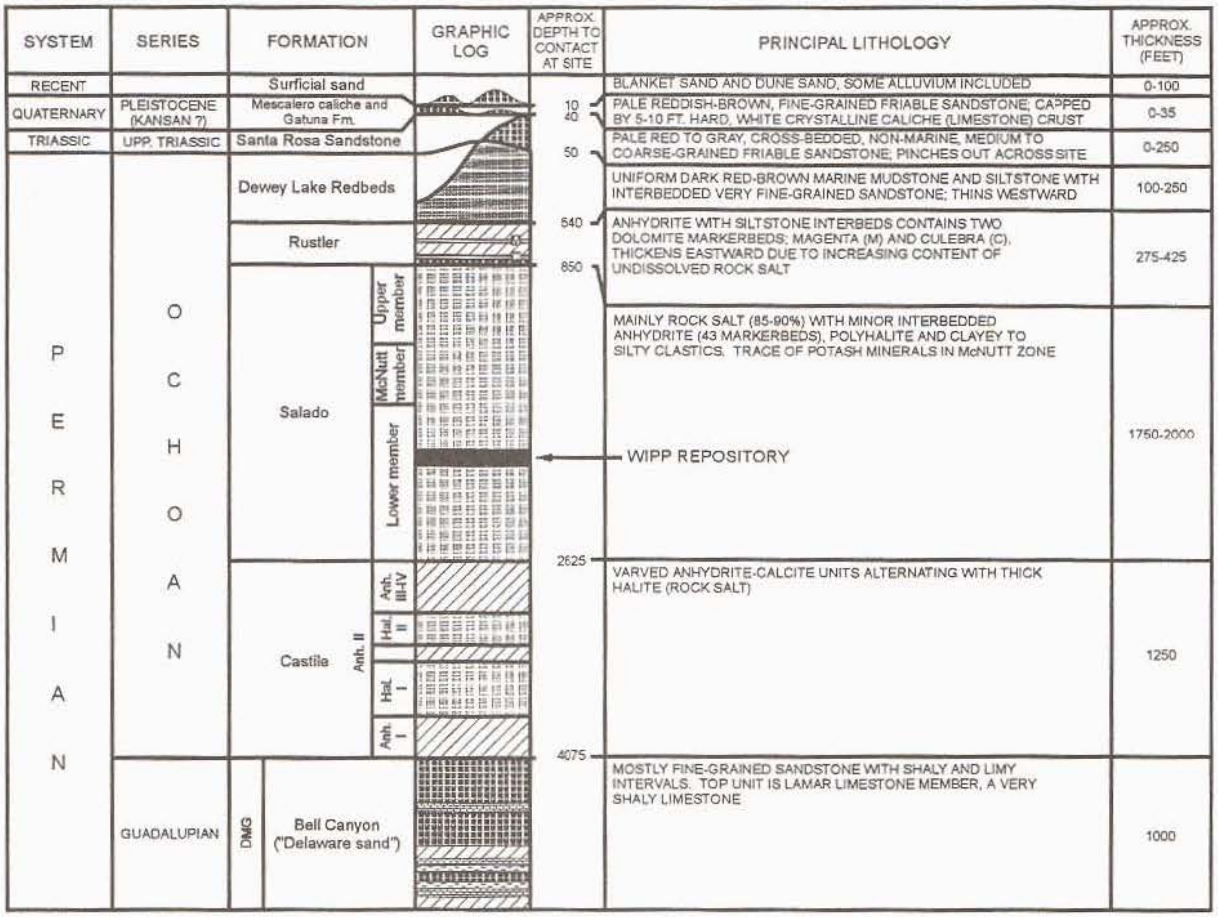

Fig. 1. Gereralized stratigraphy at the WIPP site.

clay. The upper part of the Salado Formation contains a 122-m-thick zone rich in potash minerals known as the McNutt Potash Member. The bottom of this zone is approximately 122 m above the WIPP repository. A 95-m-thick Rustler Formation overlies the Salado and it contains two 8.6-m-thick fractured dolomite water-bearing zones, the Magenta and the Culebra. The more permeable Culebra is considered to be a potential pathway for migration of radionuclides to the biosphere in case of a breach of the repository. The Culebra aquifer is about 435 m above the repository.

The Castile Formation underlies the Salado and its upper unit consists of varved alternating layers of anhydrite and calcite. At least 27 boreholes within 16 km of the WIPP site have encountered pressurized brine in this unit, about 244 m below the repository level (Fig. 2).

The 6.4 km × 6.4 km WIPP site is situated in a region rich in potash, oil, and gas. There were 163 producing oil and gas wells in a 3.2-km zone surrounding the WIPP site at the end of 1998 (Fig. 3). The nearest production of potash is currently about 2 km from the southwestern corner of the site, although potash leases are held immediately surrounding the WIPP site. Drilling for oil and gas through the potash reserves is restricted until potash mining is completed.

4. ISSUES TO BE RESOLVED

The geohydrologic conceptual models for WIPP and the issues associated with them have been described by Chaturvedi and Anderson.[16] Many conceptual models are presented in the CCA.[1] The EEG raised issues with a number conceptual models during the WIPP certification process. Similarly, several is-

sues relate to the values of the input parameters used in the CCA. The EEG looks forward to resolution of these issues during the recertification process.

4.1. Conceptual Model of the Castile Pressurized Brine Reservoir

Within a few miles of the WIPP site there are at least 27 reported encounters of pressurized brine in the upper anhydrite layer of the Castile Formation (Fig. 2). Two of these encounters (ERDA-6 and WIPP-12) were in the WIPP project boreholes and the rest have been reported by oil and gas drilling companies. When borehole WIPP-12, located within the WIPP site, hit brine at a depth of 920 m, brine started flowing out of the well at a rate of 22 liters/sec and more than 8 million liters of brine were unavoidably produced during drilling, logging, and between testing.[17] Based on an extensive series of flow tests, the brine reservoirs penetrated by the WIPP-12 and ERDA-6 boreholes were estimated to contain 2.7 billion and 100 million liters of brine, respectively. The different pressure potentials and geochemical data from the two encounters suggested a lack of communication between the ERDA-6 and WIPP-12 brine reservoirs. There was no consensus on the origin and the age of the brine reservoirs.

The originally planned configuration of the WIPP repository and the WIPP experimental areas would have brought the waste within 140 m south of the WIPP-12 borehole. The EEG recommended moving the repository in 1982 and the DOE rotated the repository configuration to relocate the nonwaste experimental area to the north and the repository itself 2 km south of WIPP-12. In 1983, EEG proposed geophysical investigations to delineate the extent of pressurized brine in the Castile Formation underlying the WIPP site and particularly under the new location of the repository. Time-domain electromagnetic (TDEM) geophysical survey was conducted by the DOE above the WIPP repository in 1987, and the results gave a clear indication of the presence of brine under the WIPP repository.[18]

There are two areas of clustered brine encounters, northeast and east of the WIPP site (Fig. 2). The DOE used geostatistical modeling to ascertain the probability of pressurized brine directly below the repository. A correlation length of clustered brine encounters represents the average size of a brine reservoir in the Delaware Basin. Brine encounters are defined by reports of intersection of pressurized brine filed by the drillers to the State of New Mexico. All wells without a report of pressurized brine were considered to not have intercepted brine. The data on brine encounters during commercial drilling for

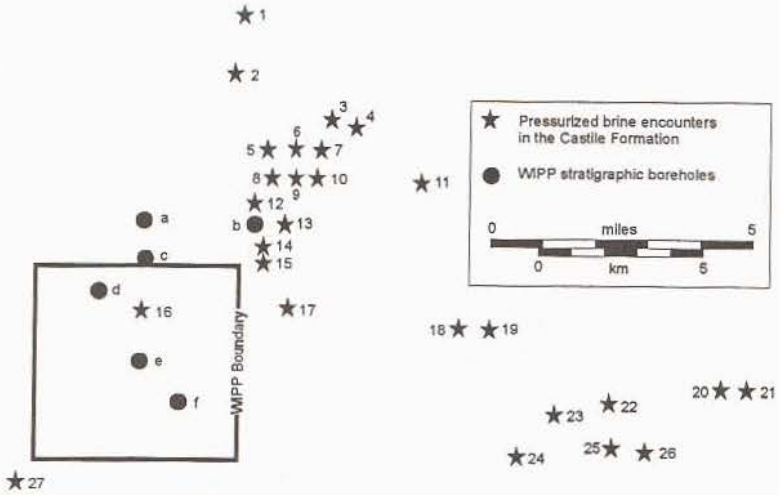

1. Pogo
2. Union
3. Luke Fed 1
4. AEC-7
5. ERDA-6
6. AIS State 1
7. AIS State 4
8. Molly State 3
9. Molly State 1
10. Unocal AHU 1
11. Bilbrey
12. Pogo 2-3
13. Pogo 12-8
14. Martha
15. AIK 3&4
16. WIPP-12
17. Neff 13-5
18. Kiwi AKX
19. Lechusa Fed 1
20. Mascho 2
21. Mascho 1
22. Covington
23. Culbertson
24. Red Tank
25. Shell
26. Tidewater
27. Belco Hudson
a. WIPP-11
b. AEC-8
c. DOE-2
d. WIPP-13
e. ERDA-9
f. DOE-1

Fig. 2. Boreholes reported to have encountered pressurized brine in the upper Castile Formation in the vicinity of WIPP.

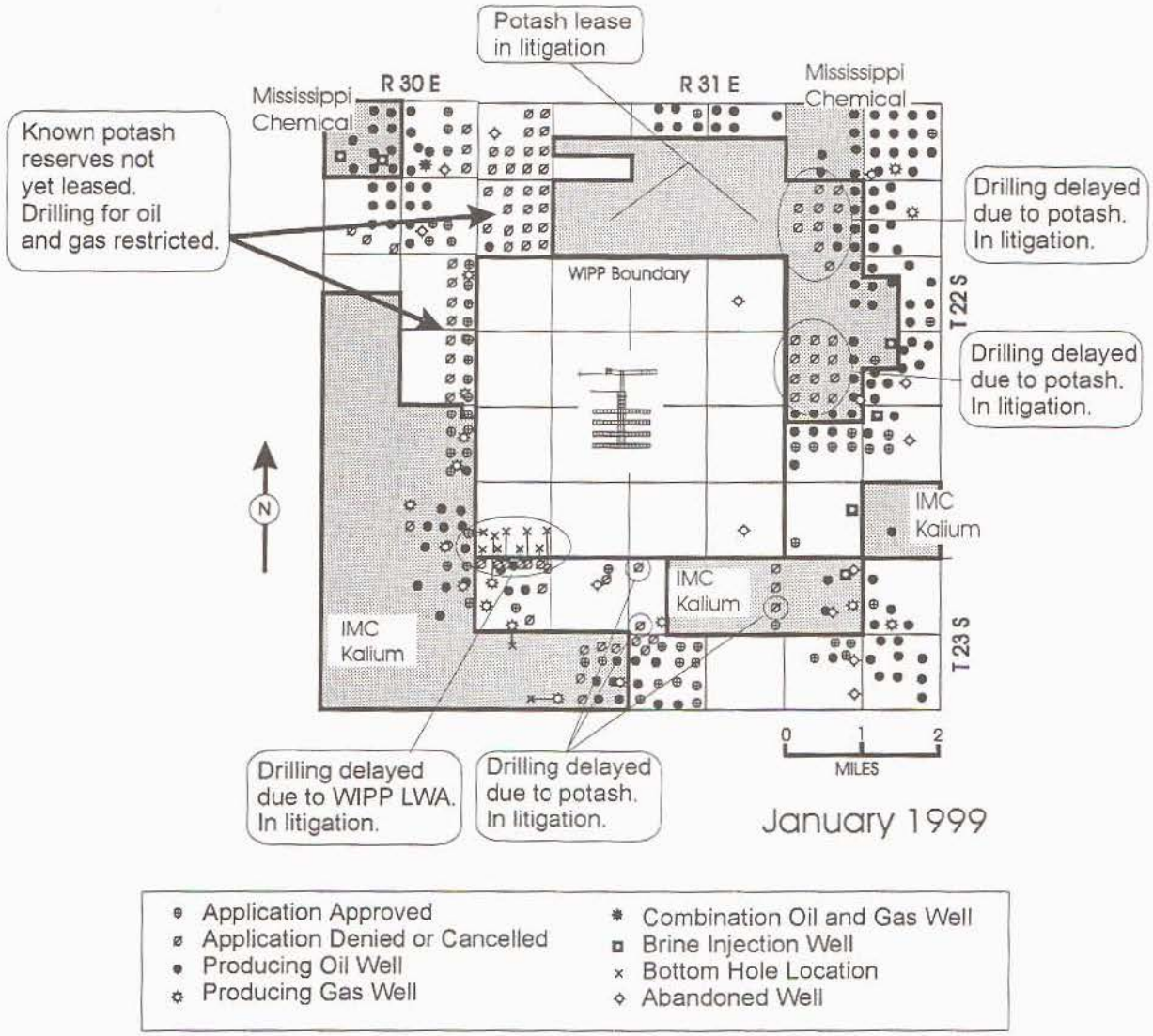

Fig. 3. Current interest in potash, oil, and gas resources surrounding the WIPP.

oil and gas contain no information on testing for the size of the brine reservoir. The DOE used the estimate of correlation length to determine the probability of the WIPP-12 brine reservoir extending below the repository to be 8%.

The best interpretation of the pore volume of the WIPP-12 brine reservoir is 2,700,000 m^3.[17] Assuming the maximum thickness of 24 m[19] for the anhydrite layer containing the brine, a porosity of 0.008 (mean value in the CCA), and a pore compressibility of 10^{-10} Pa^{-1}, the radius of a circle representing the footprint of a cylinder of brine reservoir is 2 km (Fig. 4). Constrained by several boreholes in which brine was not encountered , such a circle easily envelopes the entire repository.

Given the magnitude of the brine reservoir encountered by WIPP-12 and the results of the TDEM survey,[18] it appears logical to assume that the reservoir intercepted by WIPP-12 extends under the WIPP repository. The 8% probability of a future borehole at the WIPP repository encountering brine in the Castile Formation, assumed in the CCA,[1] therefore remains unjustified.

The CCA proposed a brine encounter of 8% based on the argument that the brine resides in subvertical fractures that have an 8% probability of en-

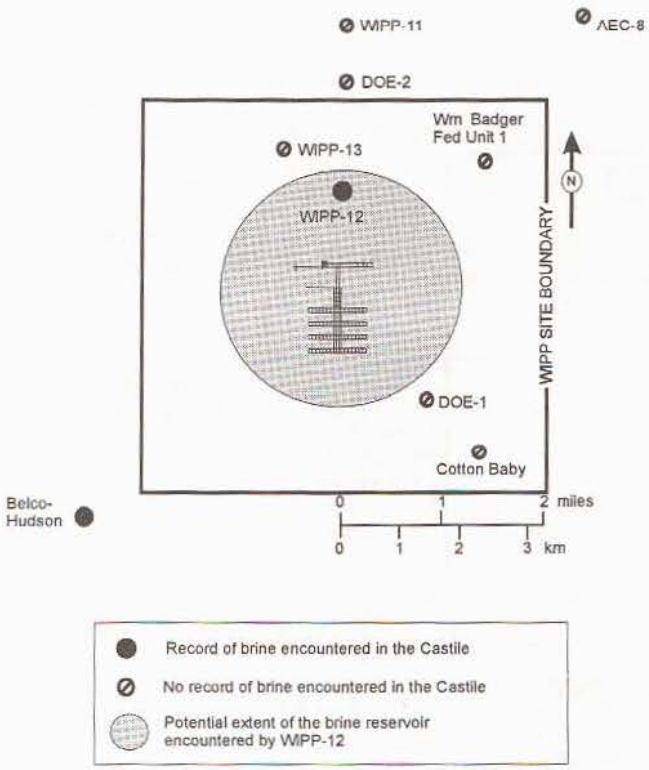

Fig. 4. Potential extent of WIPP-12 brine reservoir using WIPP-12 pressure recovery data, rock compressibility of 1×10^{-10} Pa^{-1}, and reservoir thickness of 24 m.

counter by a vertical drill hole. The EEG recommended a 100% probability on the basis that the WIPP-12 brine reservoir was large enough to extend underneath the repository, a conclusion also confirmed by geophysical testing directly above the repository. The TDEM data may be interpreted to indicate the brine to be under 60% of the repository. The EPA agreed that 8% was not representative and decided that the probability should be sampled from a range of 1% to 60%. There is no technical basis for the 1% value nor does it make sense to use the probability of a probability. A fixed value of 60% should be used in recertification calculations.

The CCA assumes a pore volume of the brine reservoir underlying the repository to vary from 32,000 to 160,000 m^3. The much lower volume is partly based on the unjustified assumption that the parts of the reservoir extending beyond the repository will get depleted by multiple intrusions in the area outside the repository. Thus, both the probability and the volume of the potential brine reservoir underlying the repository have been grossly underestimated in the CCA.

The EPA Performance Assessment Validation Test (PAVT) required the calculations to be repeated assuming a brine volume of 17 million m^3. The increased volume had a noticeable effect on releases, but compliance was still met. From this calculation, the EPA suggested that the PAVT justified the original CCA brine reservoir parameters as adequate for use in PA. The calculation does not justify this conclusion. There are many other parameter values and conceptual and numerical models that may be changed and these changes will affect the outcome of future calculations. There is no rational basis for finding an unjustified value to be acceptable unless it is justified based on observations, experiments, or widely known facts.

4.2. Radionuclide Transport Through the Culebra

Transport of radionuclides to the accessible environment through the Culebra dolomite aquifer overlying the repository has been postulated to be the major pathway for breach of the WIPP repository. The EPA concluded that the very low contribution to the total releases from this pathway, as calculated in the CCA, was due to the assumed values for chemical retardation (K_d). In fact, the calculated low releases from the groundwater pathway are due to a number of assumptions made in the CCA. The amount of radionuclides introduced in the Culebra is low due to the assumptions of actinide solubility, brine reservoir characteristics, and the intrusion borehole characteristics. There are other factors in calculating transport through the Culebra besides the assumption of K_d values that result in low releases. These factors are discussed below.

The National Academy of Sciences WIPP Committee (Chapter 6 and Appendix F of Ref. 20) raised a number of issues regarding the conceptual model and numerical model of transport through the Culebra aquifer. These issues do not appear to have been addressed by the EPA in the certification decision. Neither the EPA's "Technical Support Document for 194.23: Ground Water Flow and Contaminant Transport Modeling at WIPP" nor the "Compliance Application Review Document (CARD) No. 23: Models and Computer Codes" directly address these issues. These issues are described in detail by EEG[9] and are summarized below.

4.2.1. Heterogeneity and Model Discretization

Much recent hydrogeologic research has clarified the importance of heterogeneity in controlling solute transport. What constitutes an adequate scale of definition of formation heterogeneity for a flow model may be inadequate for solving the transport equation in the same formation. Konikow[21] presented results of numerical experiments indicating that the CCA consistently underpredicted the migration distance of a plume emanating from a human intrusion borehole. In the CCA model of the Culebra, it appears that errors arising from several sources cause an artificial spreading of the calculated width of the plume at the expense of its length. If the plume spreads out laterally more than would actually occur, for a given mass of contaminant released from a leaky borehole, the wider plume will necessarily move downgradient a shorter distance than the narrower plume. The sources of these errors include numerical dispersion and spatial truncation errors in the transport code, poor resolution from using a grid that is too coarse for the scale of the problem, and overestimates of the size of the solute source area.

The solute-transport model used in the CCA is based on a finite-difference grid having a minimum spacing of 50 m. An alternative analyses was performed using the MOC3D model[22] in which the transmissivity variations are represented on a much smaller scale, using a 2-m grid spacing rather than the original 50-m grid spacing. This finer scale representation of the heterogeneity and of the borehole source area results in a much longer, but narrower, plume that would have a significantly shorter travel time to the regulatory boundary for equivalent concentration levels.

4.2.2. Heterogeneity of Other Transport Parameters and Processes

The CCA model of the Culebra assumes that most properties of the system, except the transmissivity, are homogeneous and uniform within each simulation realization, but that these properties varied from run to run. Field tests at WIPP, however, indicate significant variability in many of these properties. For example, the effective porosity of the aquifer varies by almost an order of magnitude, even over a distance of only 50 m (the size of one cell of the model grid). Porosity has a strong control on transport velocities and times. Hence, the variability in porosity induces variability in velocity, which means that some parts of the plume may move faster than the local average velocity. This effect cannot be captured by assuming that porosity is uniform in each simulation. One would expect other properties, such as K_d and fracture spacing, to similarly exhibit large spatial variations. The PA procedure inherently assumes that heterogeneity in these variables has no significant impact on transport, or that its effects can be adequately represented by varying uniform properties among all the realizations. Either way, the CCA has not demonstrated that this is indeed the case and that it is reasonable to ignore the spatial variability in all of these critical parameters.

4.2.3. Sampling Procedures for Input Parameters

To generate the statistical distributions from which the risks are calculated, many simulations of hydrogeologic processes are performed to generate an adequate sample size. The approach to varying the values of the many parameters in the multiple realizations can introduce errors into the final analysis. In particular, if hydrogeologic variables that are highly correlated are sampled independently and if the correlations are ignored, then some of the realizations may be based on unreasonable or very unlikely combinations of parameters. Such individual simulations should not be incorporated into the final analysis because they may skew the statistical results. For example, the CCA separately sampled and independently varied aquifer transmissivity, fracture spacing, and porosity. Yet there is good reason to suspect that these variables are interrelated. The concern is that the net effect of independently sampling correlated parameters could yield a biased risk assessment, as described in more detail in Ref 8.

4.2.4. Consistency Between Performance Assessment (PA) Models

The PA procedure uses one model to calculate the fluid and solute flux up and out of a human intrusion (HI) borehole. This outflow flux should then be equal to the input flux (source term) in the Culebra model that is used to calculate transport distances and times. However, the source term in the Culebra flow model is apparently not represented as a specified fluid flux, so it is unclear that the flux out of the borehole is equal to the flux into the Culebra for

each set of realizations (or even for the mean of all realizations). The PA models should compute mass balances and budgets, to demonstrate that the two boundary conditions are indeed equivalent. Specifically, the total mass of fluid and solute that the borehole model computes to enter the Culebra over 10,000 years should equal the total mass of fluid and solute that is added to the Culebra over 10,000 years in the Culebra model. It appears possible that representing the HI borehole solute flux as an initial condition in the transport equation without an accompanying fluid flux could lead to a consistent underestimate of the solute spreading away from the finite-difference cell where the HI borehole is assumed to be located.

4.2.5. Other Concerns About the Culebra Parameters and Processes

The NAS WIPP Committee report (Chapter 6 and Appendix F of Ref. 20) included a number of criticisms of the conceptual models and numerical models of the Culebra, many of which remain unresolved. The most critical issues relate to the use of homogeneous and uniform K_d values in each realization, and whether the very simple retardation factor concept adequately represents all of the complex reaction chemistry. This has certainly not been adequately demonstrated at the field scale. A related important issue is the accuracy of the definition of matrix diffusion processes and parameters. Another concern is the reliability of the regional transmissivity estimates for the Culebra, which were determined using inverse methods that assumed a nonleaky two-dimensional aquifer. Three-dimensional analyses by Sandia[23] clearly indicated that there is significant leakage into the Culebra. A Climate Index has been used as a multiplication factor in the CCA to enhance the magnitude of flow of the Culebra flow field to compensate for the lack of consideration of the additional flux through the system. However, we have not seen any rigorous analysis and documentation of the consequences of such errors, or the sufficiency of corrections applied.

4.2.6. Current Efforts to Resolve the Culebra Transport Issues

Many of the shortcomings listed above arise from the fact that the models developed for the flow and transport of radionuclides through the Culebra are computationally expensive to perform, i.e., have very long run times. Adding complexity from the suggested comments would only further increase these run times. To help combat the strain of additional development on transport calculations, a new 1D, semianalytical approach was taken on the latest round of sensitivity analyses.[23] The calculations used a particle tracking code to map out a series of curvilinear paths from the steady-state flow velocities, on which a 1D analytical transport calculation was performed. The calculations experienced decreased run times, with comparable results to the CCA. The results open the door for increased complexity and more realistic model assumptions.

In addition to the increased modeling effort, extensive laboratory and field investigations are being conducted to understand the diffusive nature of transport in the fractured media. Field tracer experiments suggest that breakthrough curves are best replicated with a dual-porosity, multi-rate diffusion model.

4.3. Chemical Retardation

The values for sorption coefficient K_d used in the PA impact the postulated releases of radionuclides through the Culebra pathway. Independent checks of the CCA calculations by the EPA and the EEG show that only a 3 ml/g value for K_d is sufficient for showing compliance with the containment requirement of the EPA standards (40 CFR 191.13). This conclusion relies on keeping all the other parameters and assumptions in the CCA unchanged. It is difficult to accept a particular value or a range of values for any of the input parameters on the basis of partial sensitivity analyses. To have confidence in the calculations, the values of all input parameters should be independently verifiable to be robust and based on valid experimental data. The EEG recommended[8] resolution of the following issues to justify properly the K_d values.

4.3.1. Limitations of Laboratory Data

The EEG has accepted the validity of using the laboratory-determined K_d values to get an estimate of the values to be used for modeling contaminant transport in the field because groundwater diffusion into the rock matrix will provide opportunities for

chemical retardation to occur. This does not mean, however, that a one-to-one correspondence may be assumed between the laboratory and field values. The K_d range determined from batch tests applies only to the matrix porosity, and not to retardation in the fracture system with advective porosity.

4.3.2. Limited K_d Database

The experimental database for the K_d values used in the CCA remains insufficient. In the absence of measured K_d values for plutonium at oxidation states III and IV and inconclusive results for Am^{III} the K_d values for these three most important actinides in the WIPP inventory have had to be estimated. These estimations are based on two questionable assumptions. The first is that K_d values for actinide cations of the same charge should roughly be the same. The weakness of this assumption lies in not considering the effect of the speciation behavior of the cations on their adsorption properties. The second assumption is that predictable trends exist for the K_d values of actinide cations of different charge. The DOE used this assumption to argue that Pu^{V} data can be used for Am^{III}. This assumption is based on questionable data and interpretations of the experiments conducted with dilute groundwater from the Yucca Mountain site, even though, fortuitously, the same trend has been reported by some other experimenters. Results of the intact core column tests are probably of questionable value as well. The Am and Pu input concentrations to the cores were so close to saturation with solids that precipitation rather than adsorption may have occurred.

The net result of these assumptions is the use of unjustified K_d values for the three most dominant radionuclides in the WIPP inventory. Pu^{V} data have been used for Pu^{III} through a two-step process, both of which are questionable: first, through the predictable trend argument for Am^{III}, and then through the oxidation state analogy for Pu^{III}. Similarly, Th^{IV} data have been used for Pu^{IV}.

The oxidation state analogy is most useful as a starting point for designing an appropriate experiment, but the answer is not known until the experimental measurement is actually determined. As stated in the NAS/NRC WIPP Committee report, "Although the oxidation state model (the assumption that the chemistry of a given oxidation state is similar for all of the actinides) is an appropriate beginning to a difficult problem, deviation for the oxidation state analogy are well known in natural and experimental systems. Substantial experimental verification will be needed to establish the limits of this analogy."[20]

Besides the inherent limitations of the oxidation state analogy, there is an additional problem of an inapplicable brine (from ERDA-6 brine reservoir) having been used for the Th^{IV} experiments. The mean K_d values measured in the ERDA-6 brine are greater than the values determined using the WIPP repository brines.

4.3.3. Use of Laboratory Data

The EEG expressed concern[8] with the CCA values for the lower and upper bounds of the K_d probability distribution and how these bounds are defined relative to the type of brine used in the batch experiments. The ranges for K_d relative to brine type were selected based on the average value of the sample distribution. For example, the range for Pu^{V} (and by extrapolation, for Pu^{III} and Am^{III}) used in the CCA calculations is 20–500 ml/g, which reflects values from the batch tests using deep brines. The lowest K_d value using the Culebra brine was 9.8. The assumed range for Pu^{V} should have been 9.8–500 ml/g.

4.4. Solubility of Actinides

The solubility of actinides is very important in calculating releases from the repository. The FMT model used in the CCA predicts differences for actinide sulfate solubilities that cannot be explained by chemistry, thus raising questions about the reliability of this model. DOE is considering replacement of the FMT code with EQ3/6 for the first recertification.[25,26]

Rather than using an extensive plutonium database, the FMT predictions relied on thermodynamic data for other elements and an oxidation state analog argument. EEG recommends that the calculations be performed using thermodynamic data for plutonium.

The CCA discounts the role of organic ligands on plutonium solubility. It argues that the entire repository waste is a homogeneous blend and that the chelating compound EDTA is the strongest complexing agent and the amount of it present in the inventory is not enough to make a difference. But citrate forms stronger complexes with actinides in the +IV oxidation state than with other cations. The solubility

of a stable plutonium–citrate complex in individual waste containers needs to be determined.

Plutonium constitutes 82% of the radionuclide inventory of the repository. The PA efforts of 1991 and 1992 attempted to capture the effects of oxidation state on solubility throughout the full range of the four possible oxidation states for plutonium in the repository: III, IV, V, and VI. To the contrary, the 1996 PA was based on calculations which assumed that the iron in the repository would force a reducing environment, thus allowing only Pu^{III} or Pu^{IV}; there would be no Pu^{V} or Pu^{VI} which can have higher solubilities. However, some of the experimental results from the Source Term Test Program, with liters and drums of TRU waste, show very high solubilities, suggesting the existence of either Pu^{V} or Pu^{VI} despite the presence of iron. The observation tends to undermine the assumption that all plutonium will be in either oxidation state III or IV. This issue needs to be resolved.

4.5. Direct Release Through Human Intrusion

As one of the dominant modes of release, a valid model for the spall of waste into an intrusive borehole is needed. Spall is waste that has been introduced into the drilling fluid due to radially channeled, highly pressurized gas flow from within the repository to a lower pressure borehole. The conceptual model peer review[27] found the spall model initially proposed by DOE to be conceptually inadequate. The DOE schedule for submittal of the application left insufficient time for development of an appropriate model. The DOE provided the panel with additional experimental information and results from other modeling efforts and asked the panel to consider whether the spalling volumes predicted by the original inadequate model was acceptable for use in the PA. It was argued by the DOE that the inaccurate predictions were acceptable because the predictions overestimated the release during a spall event. The peer review group accepted the inaccurate model based on that argument.[28] After DOE submitted additional information, EPA also accepted the model results for the purposes of PA.

The overestimated prediction stems from the development of an additional model for release calculations. This new model predicted releases about 1/20 of the original calculations, thus leaving the impression that the original model made a conservative prediction. However, both are inadequate and hence it is unknown which model's prediction is closer to reality. Testing of the new model[8,9] revealed serious instability problems outside a narrow range of waste permeabilities as shown in Fig. 5. For the waste strengths investigated there can be no confidence in waste permeabilities outside the narrow range of 1.7 to 2.0×10^{-13} m^2.

The EPA maintains that the code behaves quite reasonably under expected repository conditions. Assuming "expected conditions" is suspect given the uncertainty that arises from the geologic and hydrogeologic response of the repository system, along with the gas generation from the degrading waste. The fundamental philosophy behind the PA is to sample the input parameters from an expected range. To state that one set of conditions, for which the model is applicable, correctly captures all uncertainty inherent in long-term modeling underestimates the importance of accommodating such uncertainty. A new approach is needed to develop a coherent and straightforward model to address the important issue of spall supported by a suite of appropriately designed experiments by which to determine waste strength.

As a part of the recertification effort by DOE, work is in progress to capture adequately the physics of spall in a new model. The new model will incorporate a modified wellbore hydraulics model with mixing equations for solids and fluids, a drillbit damage

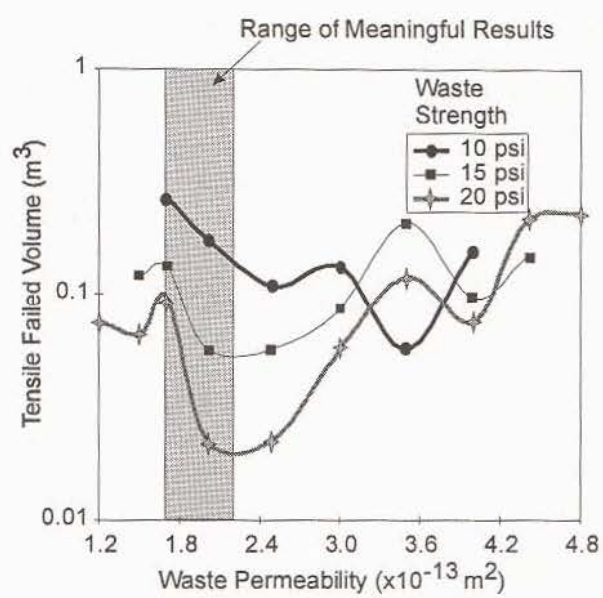

Fig. 5. Tensile failed volume from GASOUT predictions for various waste strengths and waste permeabilities.

model, and a solids transport up the borehole annulus. Previous models assumed that all of the material that failed in the bottom of the borehole would be transported to the surface. However, by actually modeling the phenomenon, the likely result would be that only a fraction of the material would reach the surface and reduce the overall effects of spallings on the CCDFs.

4.6. Fluid Injection

Brine injection for saltwater disposal and enhanced oil recovery is already underway near the WIPP and throughout the Delaware Basin.[29,30] The history of water migrating away from leaking injection wells through the Salado Formation in southeast New Mexico is well documented.[30–32] Nonetheless, fluid injection for oil recovery within the designated WIPP boundary was not included in the 1996 performance assessment calculations. The DOE rejected the scenario on the basis that the EPA regulations did not require it. Only the drilling event was included.

The first step in a performance assessment is to screen features, events, and processes (FEP). Two grounds for rejecting a relevant scenario from consideration in the PA calculations are low probability or low consequence. Probability and consequence, however, are not considered if a scenario has already been eliminated on the basis of regulation. The regulation states: "With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole."[3]

The regulation does not preclude DOE from including the fluid injection scenario as part of the recertification effort. In some instances, the EPA certification identifies the need to further evaluate a scenario that was eliminated on the basis of regulation. For example, the EPA determined that DOE did not need to include air drilling in the PA because it was not a current practice and thus it was ruled out on the basis of regulation. Nonetheless, EPA conducted further analysis "solely to allay the public's concern"[4] on the issue. Given the presence of oil reserves, the probability of future drilling, and the reasonable expectation that the reserves will be recovered by methods including fluid injection, it would seem prudent for the recertification effort to revisit the issue of fluid injection within the WIPP site boundary.

The OECD/NEA–IAEA Joint International Review Group also expressed reservations about rejecting a scenario solely on the basis of regulatory considerations: "It would improve the confidence of the reader if the DOE presented the logical or physical arguments for not considering these processes in the assessment, in addition to noting that they are not required in a compliance demonstration. Otherwise, there is an impression that processes that might deserve consideration from a safety perspective have been eliminated."[33]

Recertification can also incorporate new information from the expanding fluid injection practices surrounding the WIPP site. The effects of leaking injection wells adjacent to the site were screened out from the performance assessment calculations on the basis of low consequence by the DOE[1] and low probability by the EPA.[4] The DOE had chosen to examine consequence rather than probability, recognizing that certain petroleum practices are hard to define in a probabilistic sense.[34]

The EPA Certification relies on the DOE's low-consequence argument as the basis for rejecting fluid injection as a scenario.[4] However, the EPA acknowledges that certain scenarios can be constructed that inject large volumes of fluid into the repository. In these cases, EPA relies on its own probability calculation to screen out certain combinations of natural and human events (pp. 24–25 of Ref. 35).

The EPA multiplied the probability of each event to determine the probability of an injection well impacting the repository. Initially, EPA determined the probability of an injection well impacting the repository as 1 in 667 million (Table Q of Ref. 36), a value which was widely cited by others (p. 111 of Ref. 8; p. 45 of Ref. 37; p. 27 of Ref. 38). The final technical support document maintains that the original value was 1 in 58,000.[39] Based on new estimates of individual events, the probability of a leaking well impacting on the repository was then estimated to be 1 in 171,000.[4] Thus, the EPA analysis advanced three different values of probability, spanning four orders of magnitude. The uncertainty lends support to the DOE position that it would be difficult to defend the probability argument because it would be difficult to define the performance of individual components in a probabilistic sense.[34]

In summary, recertification should consider the effect of fluid injection just outside the site to accommodate the reasonable expectation that there will be an effort to produce the crude oil reserves by waterflooding and there will be saltwater disposal of produced brines. The recertification also needs to

examine developing information from the saltwater disposal, oil field pressure maintenance, and oil field waterflooding activities adjacent to the WIPP for inclusion into future PA calculations. Just as a scenario can be screened out, a scenario can also be screened in, based on new information or a reexamination of existing information.

4.7. Solution Mining

The one impact of potash mining that has been considered in the CCA is the alteration of the transmissivity of the overlying Culebra aquifer as a result of subsidence due to conventional mining. The EPA argues that near-future activities, such as solution mining for potash, can be eliminated on the basis that it is not now occurring in the Delaware Basin and to assume its occurrence in the future would be speculative. Nonetheless, solution mining is a proven technology that has near-future potential. The EPA criteria require consideration of near-future activities. The EPA guidance specifies that this includes plans for new mines in the vicinity of WIPP.[40]

By delaying the development of oil and gas reserves surrounding the WIPP (Fig. 3), the U.S. Bureau of Land Management has indicated its plans to first allow the mining of the potash. Meanwhile, the New Mexico Bureau of Mines and Mineral Resources,[41] at the request of DOE, identified one feasible future technique for potash recovery—solution mining of the remaining sylvite reserves. The report notes, "all mines have held open the option of using solution mining once their sylvite deposits are fully mined out."[41]

With the continued production of potash, PA needs to screen plausible scenarios with each recertification. The actual impact on the transmissivity of the overlying aquifers needs to be monitored. At this time the PA calculations rely on estimating the range of modification to the transmissivity of the Culebra aquifer. Changes in the transmissivity are multiplied by a factor sampled from a range of 1 to 1,000. As potash mining continues, it would be worthwhile to obtain a measurement of the change in the transmissivity to determine if this range is appropriate. In addition, other parameters, such as fracture density and aperture, diffusion, and dispersion, should be accommodated during a subsidence event.

4.8. Engineered Barrier

Like the spall model, the use of MgO backfill was another late development in the performance assessment that proved troublesome during the conceptual model peer review[27] and later during the EPA rule-making. Rather than decrease uncertainty in the calculated performance of the repository, the addition of MgO may increase uncertainty. First, there is no consensus on the behavior of the system. Experiments with MgO showed that various mineral phases would form, but nesquehonite was the only mineral phase that could be identified. It is also not known how long the nesquehonite phase would persist. For purposes of certification, the EPA accepted the initial DOE argument that the nesquehonite would be short-lived and the system would be dominated by other mineral phases. To further complicate the issue, the DOE later argued that the nesquehonite would never form under repository conditions.[37] The solubility model used in the 1996 PA calculated a substantial increase in plutonium solubility due to the presence of nesquehonite. EEG's calculations with the performance assessment model shows that while such a solubility does not result in a violation of the release limits, there is very little margin for error.[9]

5. RECOMMENDATIONS

Future iterations of performance assessment, as part of each recertification, need to consider the following recommendations.

1. The available data strongly suggests a 60% probability of drilling into a high-pressure brine and this value should be used for PA calculations.
2. The use of grid refinement for transport through the Culebra should be thoroughly explored and rigorously tested. Moreover, the effects of the heterogeneity of parameters, such as porosity and retardation, should be captured.
3. Chemical retardation values should be experimentally determined for the actinides of interest.
4. The actinide solubility of plutonium should be based on thermodynamic data for plutonium.
5. The spalling model needs to reflect the results of a carefully designed experimental program

to determine waste strength and a workable conceptual and numerical model.

6. Each recertification will need to consider new information from resource recovery activities, such as fluid injection and solution mining, as part of the first step in PA scenario development.
7. The behavior of the only engineered barrier, magnesium oxide, needs to be experimentally determined.

ACKNOWLEDGMENTS

Section 4.2 of this paper contains a summary of concerns brought to the EEG's attention by Dr. Leonard Konikow of the U.S. Geological Survey. Dr. Konikow developed these concerns while he served on the National Academy of Sciences WIPP Committee from 1989 to 1996. These were sent to L.C. as personal communication in February 1998. These issues are described in detail in Section 2.9 of Ref. 8 (EEG-68). The authors are also grateful to Dr. Jon C. Helton for providing an informal review of the paper.

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ANALYSIS OF EMPLACED WASTE DATA AND IMPLICATIONS OF NON-RANDOM EMPLACEMENT FOR PERFORMANCE ASSESSMENT FOR THE WIPP

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EEG-85
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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment of New Mexico. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned the EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC04-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

The EEG performs independent technical analyses on a variety of issues. Now that the WIPP is operational, these issues include facility modifications and waste characterization for future receipt and emplacement of remote-handled waste, generator site audits, contact-handled waste characterization issues, the suitability and safety of transportation systems, mining of new panels, and analysis of new information as part of the five year recertification cycles as mandated by the WIPP Land Withdrawal Act. Review and comment is provided on the annual Safety Analysis Report and Proposed Modifications to the Hazardous Waste Facility Permit. The EEG also conducts an independent radiation surveillance program which includes a radiochemical laboratory.

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The analysis described in this report was reviewed by Dr. Bruce Davis of Centennial, Colorado. Dr. Davis is a consulting geostatistician with extensive experience in statistical and geostatistical applications to problems in the environmental, mining, and petroleum industries. The authors wish to thank Dr. Davis for his comments and suggestions.

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ACRONYMS

CCA	Compliance Certification Application
CCDF	Complimentary Cumulative Distribution Function
DOE	US Department of Energy
EEG	Environmental Evaluation Group
EPA	US Environmental Protection Agency
GSLIB	Geostatistical Software Library
LWA	Land Withdrawal Act
PE-Ci	Plutonium-239 Equivalent Curie
POC	Pipe Overpack Container
SNL	Sandia National Laboratories
SWB	Standard Waste Box
TDOP	Ten-Drum Overpack
TRU	Transuranic
WIPP	Waste Isolation Pilot Plant
WTS	Washington TRU Solutions
WWIS	WIPP Waste Information System

EXECUTIVE SUMMARY

The WIPP Land Withdrawal Act recognized that after the initial certification of the WIPP and start of disposal operations, operating experience and ongoing research would result in new technical and scientific information. The Environmental Evaluation Group (EEG) has previously reported on issues that it considers important as the Department of Energy (DOE) works towards the first recertification. One of these issues involves the assumption of random emplacement of waste used in the performance assessment calculations in support of the initial certification application. As actual waste emplacement data are now available from four years of disposal, the EEG performed an analysis to evaluate the validity of that initial assumption and determine implications for performance assessment.

Panel 1 was closed in March 2003. The degree of deviation between actual emplaced waste in Panel 1 and an assumption of random emplacement is apparent with concentrations of ^{239}Pu being 3.20 times, ^{240}Pu being 2.67 times, and ^{241}Am being 4.13 times the projected repository average for the space occupied by the waste.

A spatial statistical analysis was performed using available Panel 1 data retrieved from the WWIS and assigned room coordinates by Sandia National Laboratories. A comparison was made between the waste as emplaced and a randomization of the same waste. Conversely, the distribution of waste as emplaced is similar to the distribution of waste in the individual containers and can be characterized as bi-modal and skewed with a long high-concentration tail. The distribution of randomized waste is fairly symmetrical, as would be expected from classical statistical theory. In the event of a future drilling intrusion, comparison of these two distributions shows a higher probability of intersecting a high-concentration stack of the actual emplaced waste, over that of the same waste emplaced in a randomized manner as was assumed in the certified performance assessment calculations. This suggests that the methodology used during the certification performance assessment calculations underestimated potential releases by cuttings and cavings. That methodology sampled each layer in a stack separately and used the mean concentration for each waste stream.

The DOE performed a spallings release bounding analysis at the time of the initial certification. However, the selection of the statistical sample size of the bounding analysis assumed independence of samples, which is not characteristic of non-random waste emplacement. Instead it is demonstrated that the emplaced waste is spatially dependent. Therefore, the bounding analysis may not be adequate in the event of continued non-random emplacement. As for cuttings and cavings releases, the probability of a high-concentration intersection during an intrusion is increased because of non-random emplacement. Performance assessment calculations should either incorporate this increased probability or an adequate bounding calculation should be performed using spatial statistical methodology.

The use of Pipe Overpack Containers for isolation of the high ^{239}Pu waste may reduce the amount of material brought to the surface as a result of an intrusion. However, the integrity of these containers over the regulatory period has not yet been demonstrated. If the DOE wishes to take credit for the container, the DOE needs to provide an analysis of structural integrity and the potential effects resulting from the use of Pipe Overpack Containers.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP), built and operated by the US Department of Energy (DOE), serves as a geologic repository for disposal of defense transuranic (TRU) waste. The WIPP Land Withdrawal Act (LWA) required initial certification of compliance of the WIPP by the US Environmental Protection Agency (EPA) (LWA 1992). In addition, a recertification decision by EPA is required by the LWA at least every five years, dated from the initial receipt of waste. Recertification must consider new information resulting from operating experience of the facility and ongoing scientific investigation. The first recertification application is due to EPA by March 2004.

The Environmental Evaluation Group (EEG), in its role of providing independent technical oversight of the WIPP project on behalf of the State of New Mexico, previously identified ongoing issues relevant to the first recertification performance assessment calculations (Allen et al. 2002). These calculations attempt to represent the amount of radioactive material released as the result of some future drilling effort inadvertently penetrating a long forgotten repository. The performance assessment calculations for demonstration of compliance with EPA's standards assumed random emplacement of waste. Operational experience however, confirms non-random emplacement of waste.

In response to EEG's non-random emplacement concerns at the time of the initial certification (Neill 1997), the DOE provided a bounding analysis to demonstrate compliance, assuming contiguous emplacement of a high-activity waste stream (Dials 1997). This analysis was accepted by the EPA.

With the availability of operational data, this issue should be re-visited in the performance assessment calculations for the first recertification. Using emplaced waste data through September 2002, the EEG performed an analysis of the effects of non-random emplacement. This included: 1) comparison of emplaced activity for Panel 1 with the average activity, 2) analysis of the effects of random versus non-random emplacement on vertical stacking of waste containers, 3) analysis of volume/variance implications on the DOE bounding analysis, and 4) analysis of the potential positive effects of waste emplaced in pipe overpack containers.

The spatial distribution of waste in the repository is an issue for compliance because of the possibility of future human intrusions during the 10,000 year regulatory period. The WIPP is located in an area rich in oil, gas, and potash resources (Silva 1994). Performance assessment calculations include intrusion scenarios involving drilling into the repository which results in solids released due to cuttings, cavings and spallings (DOE 1996). Each intrusion is assumed to penetrate each container in a particular stack. For cuttings and cavings, it was assumed in the initial certification performance assessment that potential radioactivity that may be released into the environment can come from different waste streams, each having different amounts of activity at the time of the intrusion. This was accomplished by sampling the distribution of waste stream activity three times, once for each layer of waste in the stack, weighted by the waste stream volumes, and averaging to determine the released activity. Therefore, there was no correlation between layers of waste, which is inconsistent with the manner in which waste arrives and is actually emplaced. DOE's analysis resulted in cuttings and cavings releases that were greater than would occur from assuming average repository radionuclide concentrations, but were still a relatively small amount of allowed releases (Neill 1997).

A spallings release, which results from a pressurized repository, may be much larger. The initial performance assessment assumed that a spallings event would release material from multiple drums and multiple waste streams and could be approximated by the average activity of all contact-handled waste at the time of the intrusion. This is essentially an assumption of a homogenous distribution of radionuclides throughout the repository. It was calculated that the material removed by a spallings release would be between two and nineteen times the internal volume of a 55-gallon drum.

2.0 EMPLACEMENT OF WASTE

The underground WIPP facility design includes eight panels for disposal of transuranic waste (see Figure 1). Each panel consists of seven disposal rooms. Haulage drifts may be utilized as Panels 9 and 10 following emplacement of waste in the eight designed panels. Panel 1 was partially filled and closed by March 2003. At the present time waste is being emplaced in Panel 2 and excavation of Panel 3 is underway.

WIPP Facility and Stratigraphic Sequence

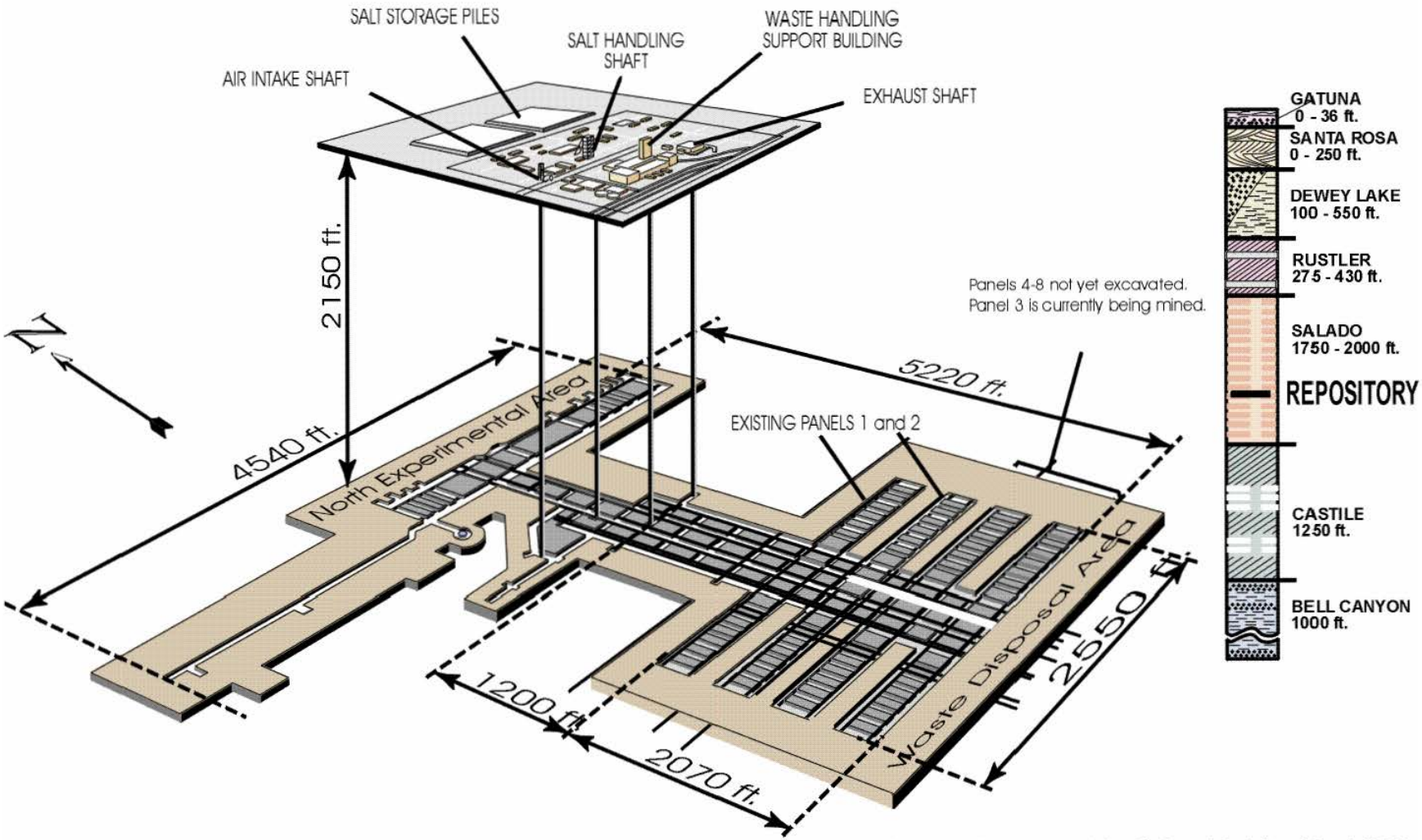

Figure 1. The WIPP facility and stratigraphic sequence. Panel 2 is currently in use. Waste emplacement was completed in Panel 1 during March 2003
Source of Figure: DOE.

Waste emplaced in Panel 1 was contained in: 1) drums, 2) standard waste boxes (SWB), 3) pipe overpack containers (POC), or 4) the recently permitted ten drum overpack (TDOP). Figure 2 shows schematics of these containers. Panel 1 drums are a 55-gallon drum which are constructed of steel and have an internal volume of 0.208 m^3. Seven drums are typically banded together for transportation to WIPP and emplacement in the underground (7 pack).

A SWB is also constructed of steel and has an internal volume of 1.88 m^3. If used for overpacking, each SWB contains up to the equivalent volume of four 55-gallon drums. However, more waste volume may be emplaced into a SWB if directly loaded. POCs fit within a 55 gallon drum, providing additional isolation of the waste. These were used for the high ^{239}Pu residues emplaced in Panel 1 (WTS 2002). TDOPs were used only recently and were not included in the Panel 1 data available at the time of analysis. To date these have been used for lower concentration TRU waste.

SWBs and drums are emplaced in stacks of three containers. Figure 3 shows a stack of three SWBs (center) and two 7 packs with a SWB on top (reader's right).

3.0 ANALYSIS OF WASTE EMPLACEMENT DATA

The EEG analysis of waste emplacement data included:

1) Comparison of emplaced activity for Panel 1 with the average activity.
2) Analysis of the effects of random versus non-random emplacement on vertical compositing of waste container activity.
3) Analysis of volume/variance implications on the DOE bounding analysis.
4) Analysis of the potential positive effects on performance assessment of waste emplaced in POCs.

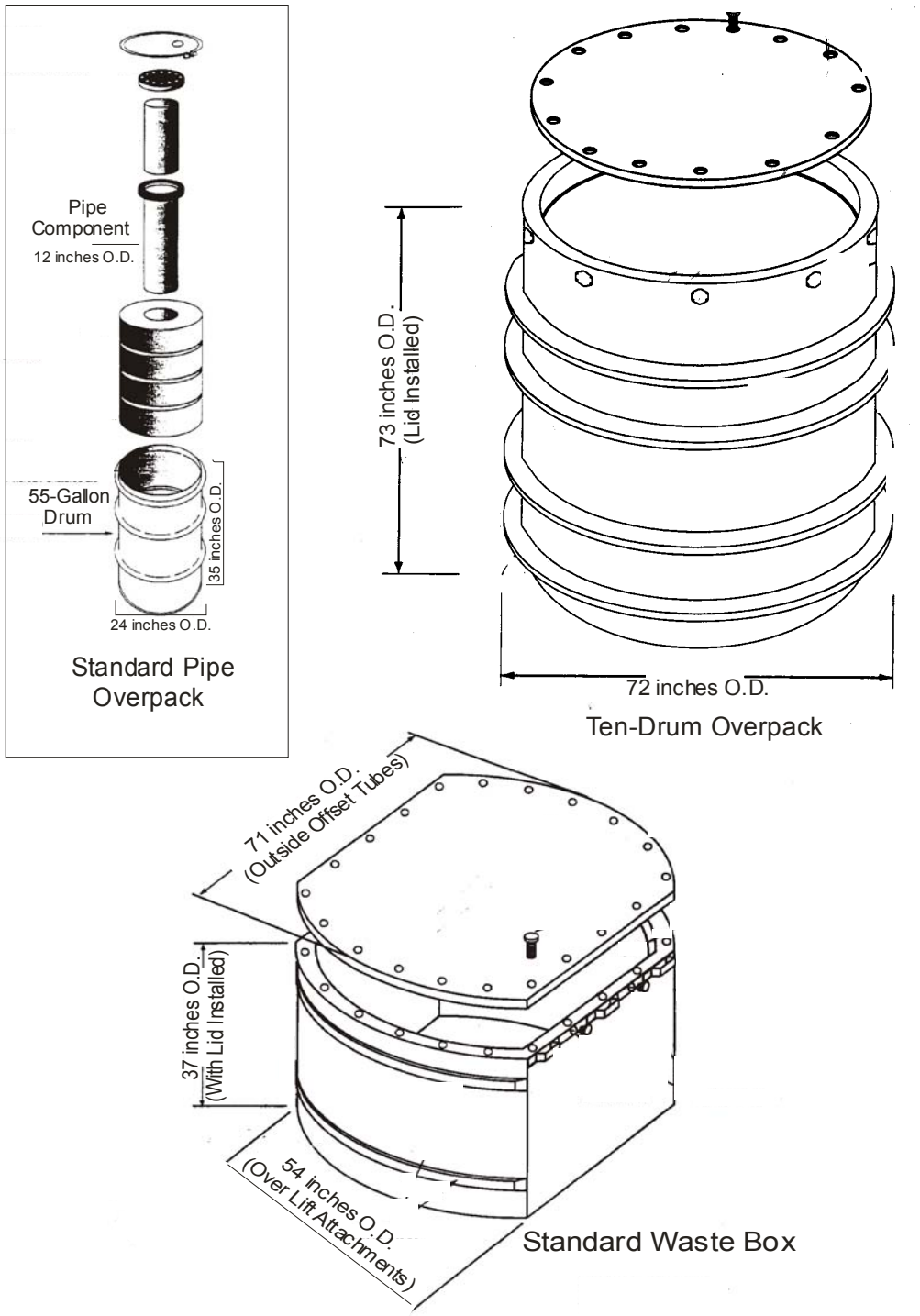

Figure 2. Waste containment packages used in Panel 1 (WTS 2002).

Figure 3. Waste being emplaced in Panel 1. Note stacks of three containers with MgO on top of each stack.

The first analysis was done using all emplaced waste data for Panel 1. The final three analyses used data provided by the DOE during January 2003 and consisted of emplaced waste through September 2002. These data were retrieved from the WIPP Waste Information System (WWIS) and assigned room coordinates by Sandia National Laboratories (SNL) (Stein 2002). Data were complete for rooms three and seven, for about one-half of room two, the intake drifts for rooms four through six, and the exit drifts for rooms two, three, and seven. Waste was only emplaced in the intake drift portion of rooms four through six because of degrading room condition resulting from the time interval between mining and first receipt of waste.

The exact size of each containment package (7 pack or standard waste box) and the exact spacing between packages is not recorded. Therefore, "real" coordinates were not available from SNL. For this analysis, the EEG took the SNL room coordinates and transformed them into a master grid containing all rooms. It was assumed that grid points have a spacing of seven feet. Each grid location is a stack of containment packages in which three layers of waste are emplaced: top, middle, and bottom.

3.1 Emplaced Activity in Panel 1

Non-random emplacement of waste results from the campaigning of specific waste streams to the WIPP depending on the DOE's agreements with the various states which host TRU waste and the readiness of particular waste streams for shipment from the other sites (DOE 2000). Table 1 compares important emplaced radionuclides to date with the average concentration assumed for the repository (DOE 2003). With the final emplacement of waste in Panel 1 during March 2003, the degree of deviation between actual emplaced waste and an assumption of random emplacement is apparent. ^{239}Pu is 3.20 times, ^{240}Pu is 2.67 times, and ^{241}Am is 4.13 times the projected repository average for the space occupied by waste. These averages are based on a total volume of waste of 10,496 m^3.

Table 1

Comparison of Emplaced Panel 1 Ci with
Compliance Certification Application Projections

Radionuclide	Curies (Ci)	Ci/m^3	CCA* Ci/m^3	Actual/CCA
^{239}Pu	152,000	14.48	4.52	3.20
^{240}Pu	34,290	3.27	1.22	2.67
^{241}Am	120,200	11.45	2.77	4.13
^{238}Pu	6,186	0.59	11.02	0.05
^{241}Pu**	482,024	45.92		

*Table 4-6, CCA (DOE 1996)
**Not a tracked radionuclide but important because of its daughter product, ^{241}Am

It is worth noting that only a very small fraction of the high wattage ^{238}Pu has been shipped and emplaced. This suggests the possibility of some future shipping campaign for the waste streams containing primarily ^{238}Pu, although the relatively short half-life is unlikely to have a significant effect on repository performance.

3.2 Analysis of Effects on Vertical Stacking

For each layer at each grid location, the total number of Plutonium-239 equivalent Curies (PE-Ci) was computed from the contents of each container according to the formula and weighting factors (DOE 2002):

$$PE-Ci = \frac{^{233}U}{3.9} + \frac{^{237}Np}{1.0} + \frac{^{236}Pu}{3.2} + \frac{^{238}Pu}{1.1} + \frac{^{239}Pu}{1.0} + \frac{^{240}Pu}{1.0} + \frac{^{241}Pu}{51.0} + \frac{^{242}Pu}{1.1} + \frac{^{241}Am}{1.0} + \frac{^{243}Am}{1.0} + \frac{^{242}Cm}{30.0} + \frac{^{244}Cm}{1.9} + \frac{^{252}Cf}{3.9}.$$

PE-Ci were used in this analysis, eliminating the need to analyze multiple radionuclides. However, for performance assessment calculations it is necessary to use individual radionuclide data.

Using the internal volume of each waste container (drum, POC, or SWB), the volume of waste was computed at each grid point. Finally, the total concentration (PE-Ci/m^3) was calculated for each stack of three containers. Figure 4a shows the spatial distribution of emplaced waste as expressed by PE-Ci/m^3.

To compare the actual emplaced waste with what could have been emplaced had the waste been emplaced in a random fashion, the following methodology was employed:

1) The concentration (PE-Ci/m^3) at each grid point for each layer (top, middle, and bottom) was calculated.
2) Using a random number generator, the order of each grid location was randomized by layer.
3) The combined concentration was then recalculated for each stack of three containers.

Figure 4b shows this hypothetical spatial distribution of random emplacement. When compared to Figure 4a it may be observed, at least qualitatively, that there are no longer specific areas of high or low activity, but a spatially uniform distribution of concentration.

Emplaced waste and randomized waste distributions were plotted and are shown in Figure 5. The means of the two distributions are essentially the same, but the distribution of actual emplaced waste is bi-modal with a higher standard deviation with a long high-concentration tail. This results from the physical process of non-random emplacement. High-concentration containers will likely be stacked together vertically, as will low-concentration containers.

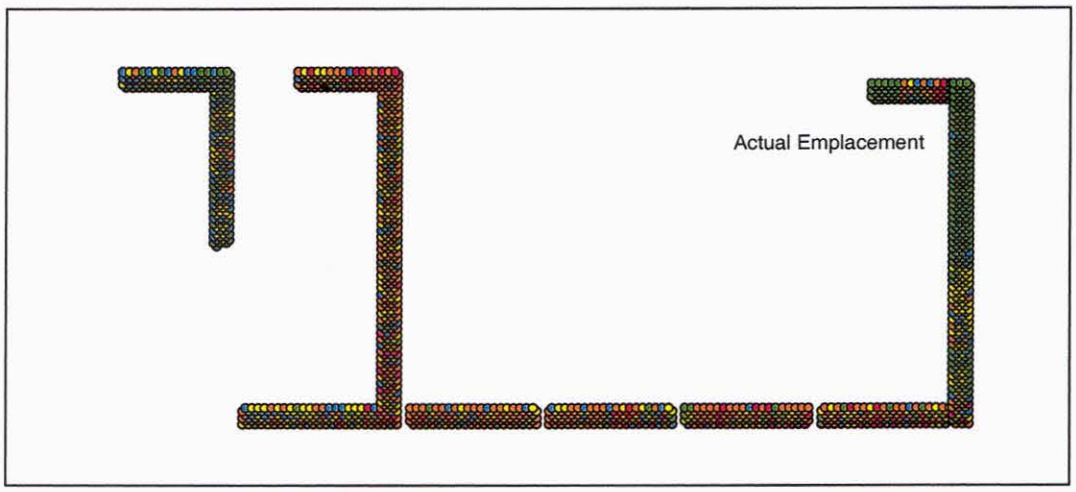

Fig 4a

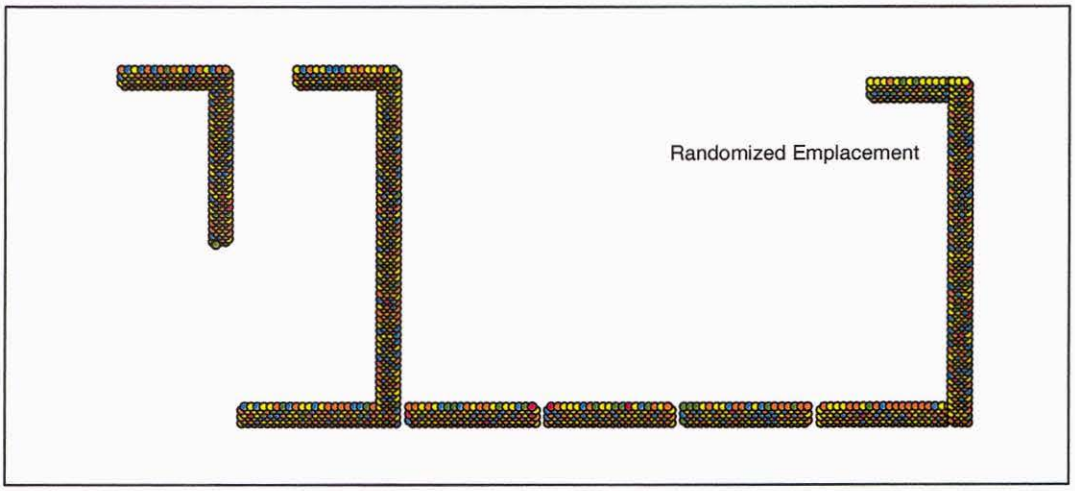

Fig 4b

Legend

PECi/m3

- 0. - 10.
- 10. - 25.
- 25. - 50.
- 50. - 100.
- 100. - 200.

Figure 4. Panel 1. Actual and randomized emplacement.

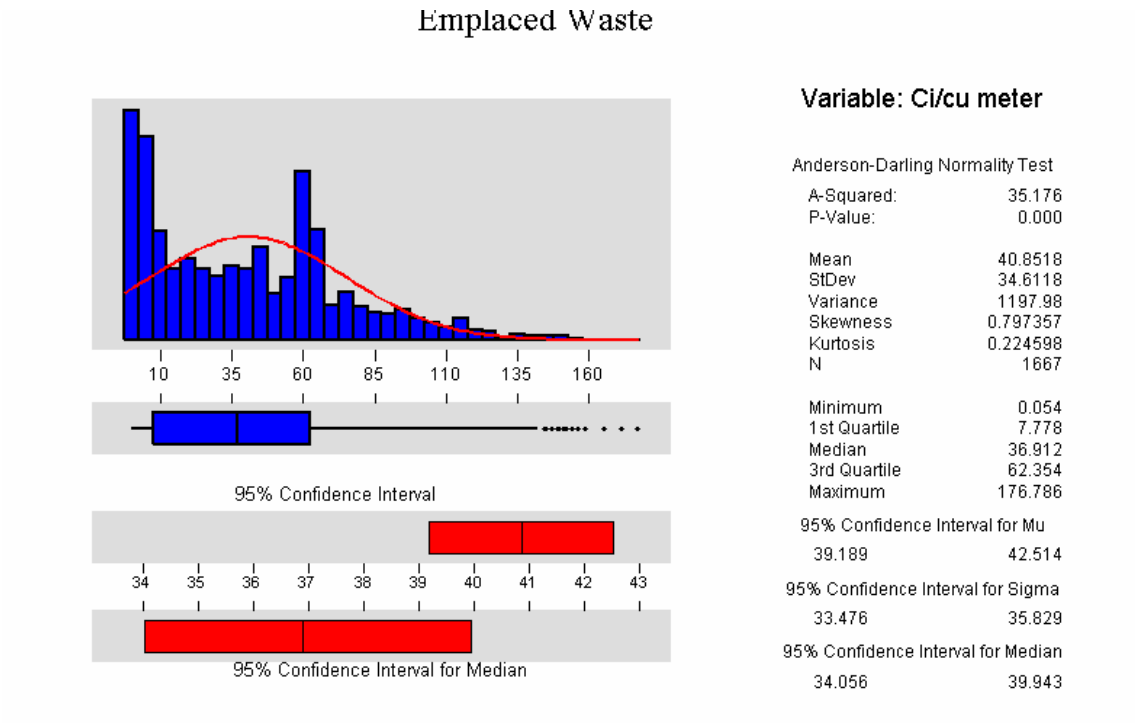

Fig 5a

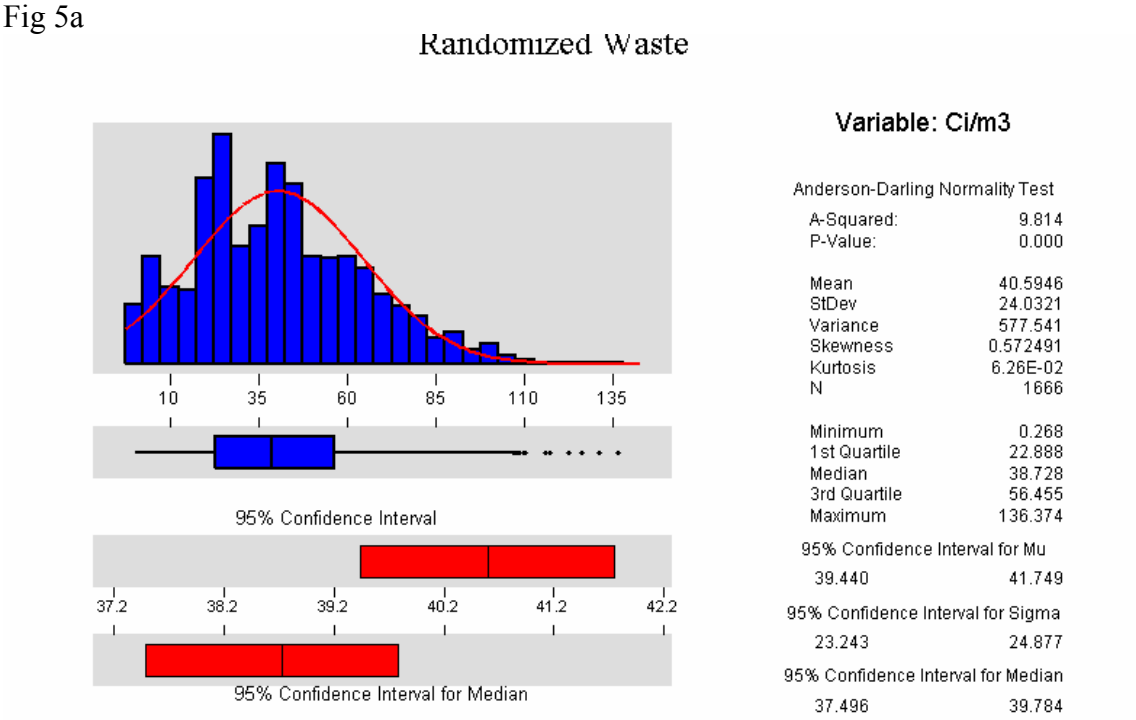

Fig 5b

Figure 5. Histograms and statistical summaries of actual and randomized emplaced waste.

Figure 6 shows the distribution PE-Ci in individual containers used in this analysis. This distribution is similar to that of the stacks of actual emplaced waste. As was seen in Figure 5, randomizing the spatial location prior to stacking results in a distribution of stacks that is closer to a normal distribution, or a state of maximum entropy as would be predicted from classical statistical theory. Non-random loading results in a skewing of that randomized distribution, with a lower median value but a longer high-concentration tail, more closely resembling the distribution of individual containers.

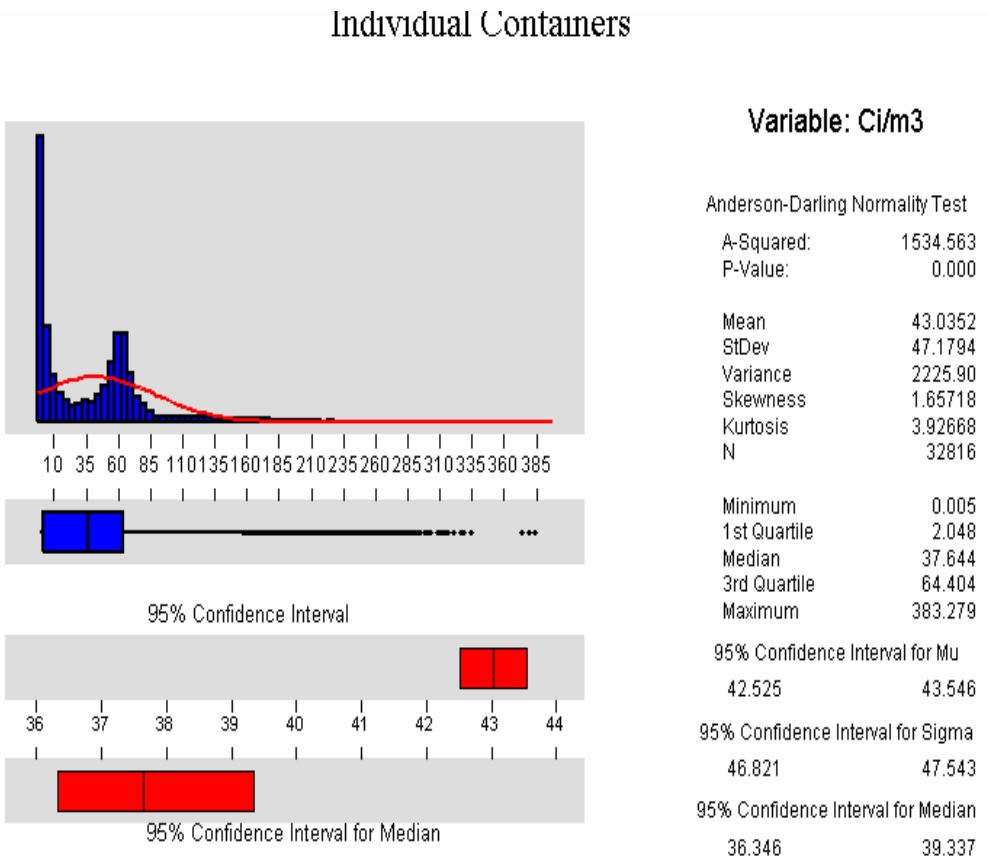

Figure 6. Distribution of individual containers used in the analysis.

The change of shape from the distribution of individual containers (Figure 6) to the stacks of randomized containers (Figure 5b) results from a change in volume, or statistical support. This volume change causes a change in variation that is affected by the spatial correlation of the containers. The similarity between the distribution of individual containers and that of actual stacks of emplaced waste (Figure 5a), i.e. permanence of distribution (Journel and Huijbregts

1978), and their deviation from the randomized distribution, illustrates the degree of non-random emplacement practiced in Panel 1. As the data are randomized and become spatially uncorrelated, classical statistics (independence of samples) would predict the empirical results demonstrated in Figure 5b. That is, that the distribution of emplaced waste would become more symmetrical.

The degree to which the distribution deviates from a randomized case is dependent on the actual data, but the probability of intersecting a high-concentration stack of three containers will increase because of the nature of non-random emplacement. This is shown for the Panel 1 actual and randomized distributions in a probability plot (Figure 7). It shows that the probability of intersecting high-concentration stacks is significantly higher in the non-random distribution versus the randomized distribution. For example, computing the projected average concentration of the Rocky Flats residues from the CCA information and assuming 20,100 drum equivalents of volume results in a value of 84.2 PE-Ci/m^3. From Figure 7, the probability of intersecting a stack greater than this average is 5% for the randomized case, but is 11% for actual emplacement.

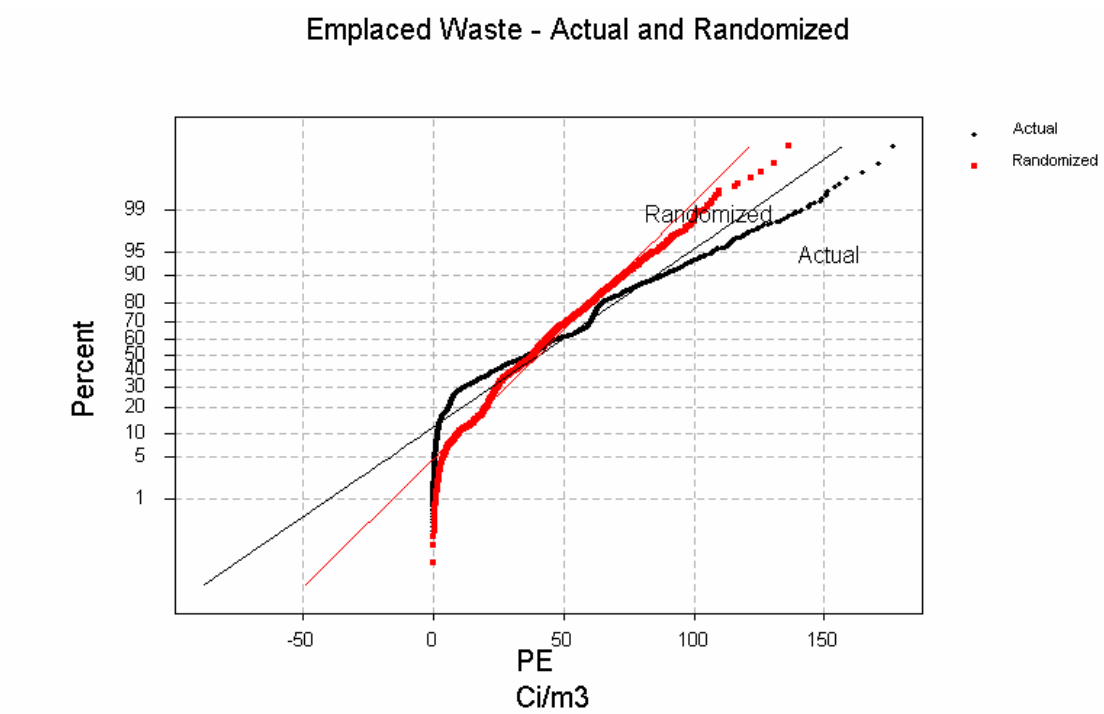

Figure 7. Probability plots of actual and randomized distributions.

Chapter 4 of the CCA (DOE 1996) states that, "A sampling of 10,000 futures is large enough that the *relatively low* probability combination of three of the waste streams with higher activity loading occurring in a single drilling event is captured in the CCDFs presented …" (italics added). It goes on to state, "… the CCDF is not impacted by sampling uncertainty so the assumption of random emplacement of containers is not important to the location of the CCDF and a load management plan is not necessary to support performance assessment assumptions". The change in distribution away from randomness caused by non-random emplacement of waste, and the subsequent increase in probability of high concentration intersection during an intrusion, casts doubt on these performance assessment assumptions.

3.3 Volume/Variance Implications of Non-Random Emplacement

In response to the EEG's concerns about the random emplacement assumption in the Compliance Certification Application (DOE 1996), the DOE performed a bounding analysis which assumed contiguous emplacement of the Rocky Flats residue waste (Dials 1997). This waste stream was selected because it was the highest activity contact-handled waste that had at least 810 drum equivalents volume. The 810 value was one one-thousandth of the total number of drum equivalents to be emplaced in the WIPP. Therefore, this waste stream would have a probability (conditional on the occurrence of a single intrusion) of intersection of more than 0.001, the probability limit established in 40 CFR § 191.13(a) (CFR 2002). However, this probability was based on the assumption of independence of samples and would therefore be a bounding case for random emplacement, not non-random emplacement.

As discussed in Section 3.1, about 11 percent of the emplaced three-layer stacks have average concentrations over the Rocky Flats residue average. The spatial distribution of these stacks are shown in Figure 8. The actual average emplaced value of the residues was only about 76 PE-Ci/m^3. If the actual value had been 84.2 PE-Ci/m^3, the discrepancy between randomized and actual would have been even greater. The probability of intersecting high-concentration stacks can be examined for the distribution of a spallings-sized event versus the distribution of an 810 drum-sized unit. The use of the spall-sized volume in an intrusion scenario is similar to the concept of a selective mining unit (smu) in ore reserve estimation (Journel and Huijbregts 1978) or a volume of selective remediation (vsr) in environmental cleanup (Desbarats 1995).

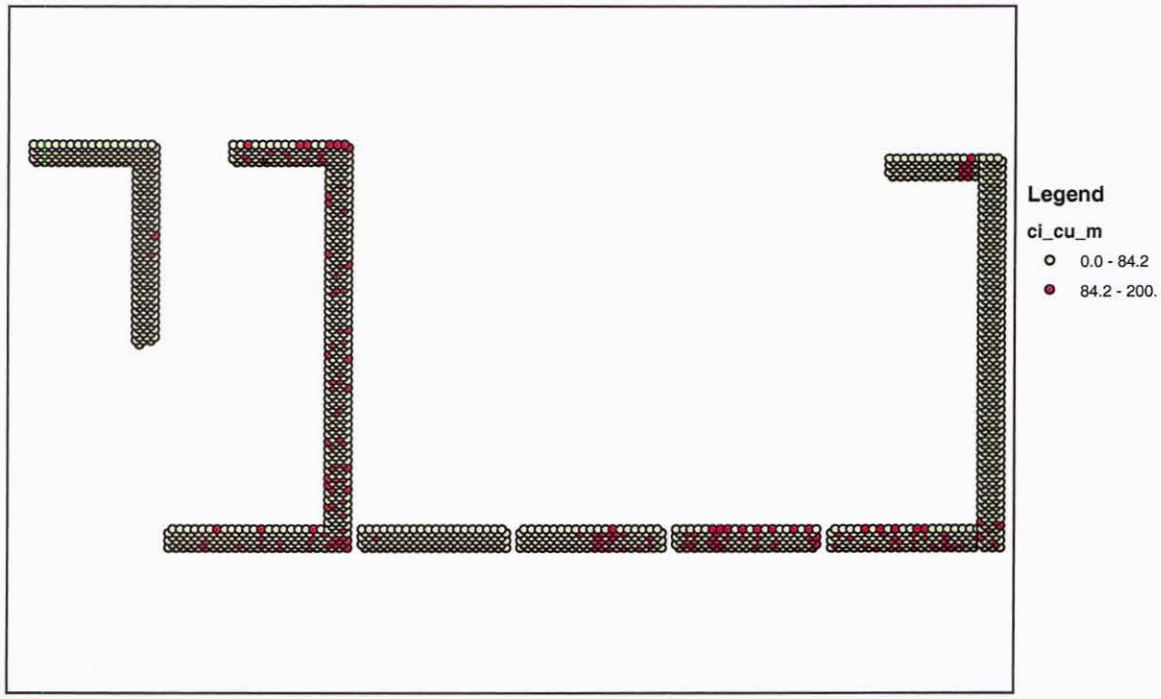

Figure 8. Panel 1. Emplaced PE-Ci over residue average.

The distribution of a spallings-sized event can be approximated by the distribution of stacks, already shown in Section 3.1. Assuming the volume of three stacked 7-packs, each grid node (or stack) would equal 4.4 m^3. The actual value may be slightly less because of the use of SWB and TDOP as overpack containers. Therefore, the volume of each stack would be close to the 4 m^3 volume in a maximum spallings event. A volume of 810 drums is approximately 40.5 times the volume of a stack of containers. This could be represented by a block with dimensions of square root of 40.5 times the assumed grid size representing a stack, or 7 ft. This would result in a block of 44.5 ft. by 44.5 ft. The distribution of these blocks could be calculated from a change of support technique such as Hermite Polynomial Transformation (Journel and Huijbregts 1978).

Hermite Polynomial Transformation requires a variance reduction factor which can be computed after deriving the variance between blocks (810 drum units) and the overall domain. This variance between blocks is computed (Isaaks and Srivastava 1989):

$$\sigma^2(v,V) = \sigma^2(.,V) - \sigma^2(.,v)$$

where:

$\sigma^2(v,V)$ = variance between blocks of size v within domain V.

$\sigma^2(.,V)$ = variance of a point within the domain.

$\sigma^2(.,v)$ = variance of a point within a block of size v, or dispersion variance.

The total variance is shown in Figure 5a as 1198 $(PE\text{-}Ci/m^3)^2$. The dispersion variance may be estimated from a variogram model of the samples, or stacked containers (David 1977).

An experimental variogram of the emplaced waste was computed using the GSLIB program GAMV (Deutsch and Journel 1998). This variogram was fitted with a spherical model as shown in Figure 9. The dispersion variance for a point within the 810 drum unit was computed with kriging program subroutines in GSLIB, using this variogram function, and resulted in the variance reduction factor, $\sigma^2(.,v)/\sigma^2(.,V)$, equal to 0.18.

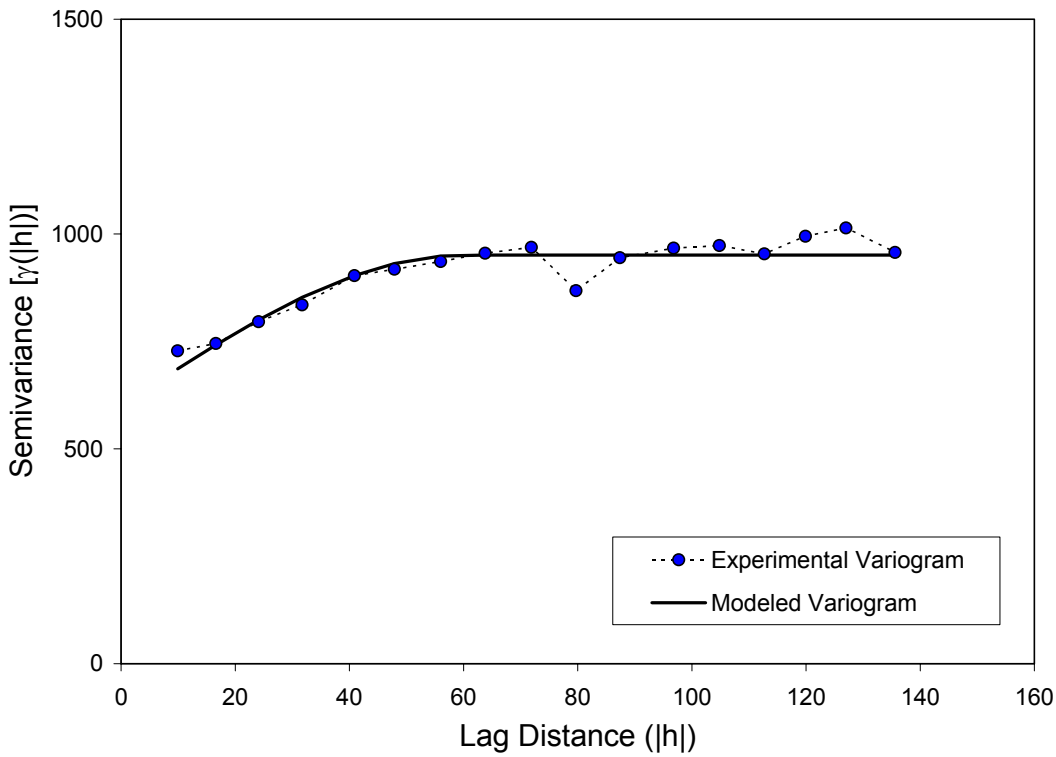

Figure 9. Experimental variogram fitted with spherical model: Co = 600, C1 = 350, R = 60 ft.

Using a program for Hermite Polynomial Change of Support (Guertin 1984) a hypothetical distribution of 810 drum units was constructed from the distribution of stacked containers. The probability plots for this distribution as well as the original distribution of stacked containers

(spall units) are shown in Figure 10. As can be seen, the probability of intersection of a high-concentration stack during an intrusion scenario will be underestimated by assuming volumes of 810 drum units. Therefore, an analysis conditional on a minimum of 810 drums may not represent an adequate bounding case for non-random emplacement of waste.

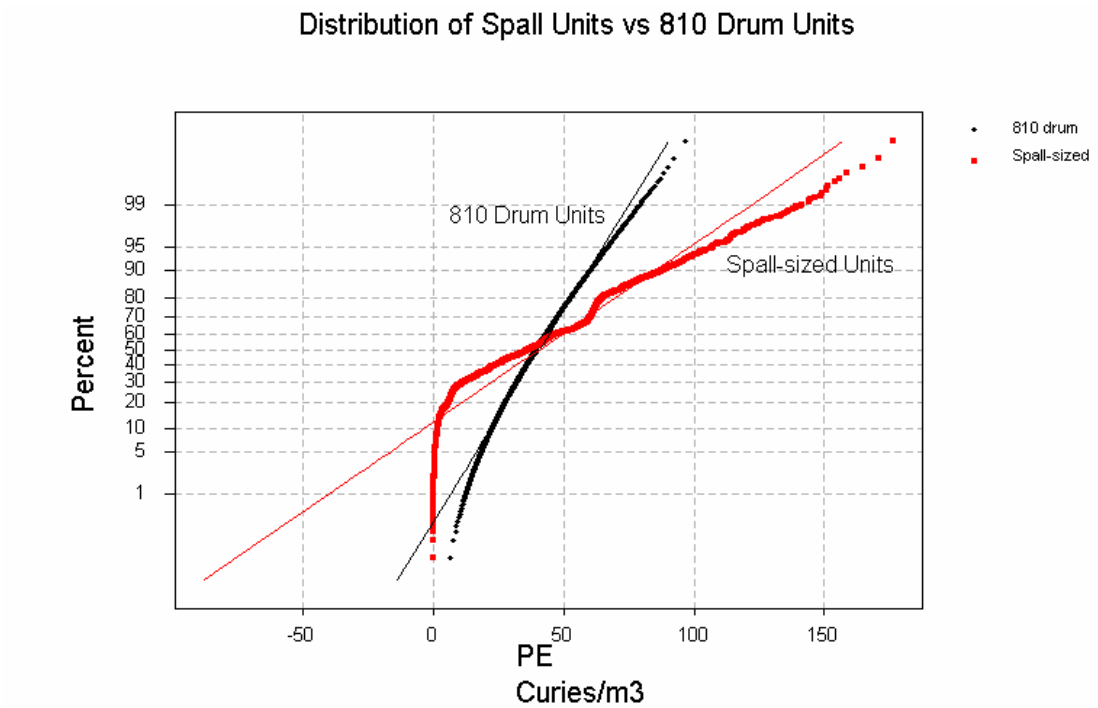

Figure 10. Distribution of stacked containers (approximate spall units) and the hypothetical distribution of units containing 810 drums.

3.4 Pipe Overpack Containers

POCs have been used to isolate much of the high ^{239}Pu waste emplaced in Panel 1. No credit has been suggested or taken for the use of these POCs in performance assessment. Further, EEG is unaware of any studies conducted to determine the effect of the POC during an intrusion scenario.

However, if it could be demonstrated by the DOE that POCs retain their integrity and effectively reduce the potential of activity release over the regulatory period, they could be a means of reducing the amount of material brought to the surface from an intrusion into a high-concentration stack. This is shown in Figure 11 where all emplaced material contained in POCs was removed prior to calculation of the probability plot. In addition, the probability of

intersecting waste would be slightly reduced because of differences in volume between the actual drum and the POC contained within.

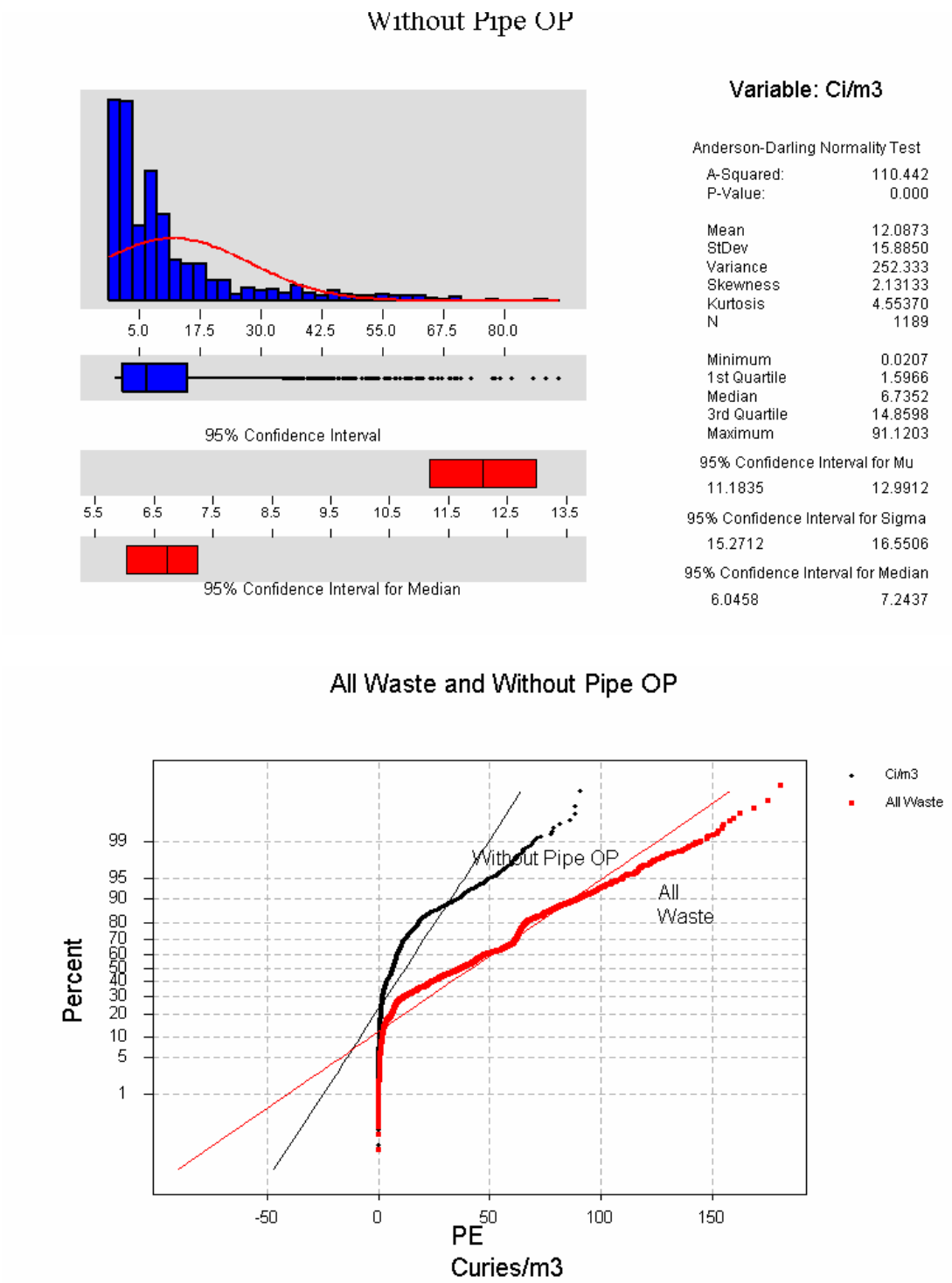

Figure 11. Histogram and probability plot of emplaced waste disregarding that contained in POCs.

4.0 CONCLUSIONS

The shipping campaign priority of residues from Rocky Flats has resulted in the non-random emplacement of waste in Panel 1 and in elevated emplaced activity. ^{239}Pu is 3.20 times, ^{240}Pu is 2.67 times, and ^{241}Am is 4.13 times the projected repository average for the space occupied by waste. Moreover, the non-random emplacement process skews the distribution of emplaced waste, as compared with a randomized case, resulting in higher concentration tails and increasing the probability that an intrusion will intersect a high-concentration stack. This suggests that for cuttings and cavings scenarios, the practice of sampling waste streams independently (and using their means) for each layer in a stack would underestimate the potential releases.

Furthermore, the practice of non-random emplacement may invalidate the premise of the performance assessment bounding analysis for spallings. The DOE bounding analysis assumed independence of samples for selection of the minimum waste stream volume to be analyzed. Independence of samples is not inherent in non-random emplacement, which results in the spatial dependence between sample locations. The hypothetical distribution of potentially spalled units shows an increased probability of high-concentration intersection over the distribution of volumes assumed in the bounding case.

It has been demonstrated that the practice of non-random emplacement of waste results in spatial dependence of waste containers. Therefore, classical statistical techniques do not properly address this issue. Instead, spatial statistical (geostatistical) methods are necessary for analysis, performance assessment implementation, and bounding calculations.

5.0 RECOMMENDATIONS

The EEG recommends that:

1) The DOE should develop a waste loading scheme for performance assessment which is based upon their shipping schedule. While this schedule will change over time, it is the best information currently available and presents a more realistic assumption than random emplacement. A spallings event should then be based upon this spatial distribution of waste instead of the mean value of waste.

Alternatively, the DOE should develop a bounding case based on the distribution of potentially spalled units, recognizing the effects of skewed distributions which results from the non-random emplacement process. One possibility would be to use geostatistical simulation with different variograms (with a range of spatial correlations) to show the consequences of different emplacement sequences for the future.

2) The DOE should develop and use, in the recertification performance assessment calculations, a methodology for non-random waste emplacement for cuttings and cavings scenarios. This methodology should recognize the likelihood of similar material occurring for a stack of three containers instead of randomly sampling for each layer in the stack and be based on anticipated shipping schedules. It should also acknowledge the increased probability of high-concentration intercepts, which result from non-random loading instead of using mean values of entire waste streams.

3) If the DOE wishes to take credit for the container, the DOE needs to provide an analysis of the potential effects resulting from the use of pipe overpacks, which may provide a more secure containment of radionuclides within the repository.

4) The DOE should continue to build a spatial data base of emplaced waste for ongoing analysis and for use during future recertifications.

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CONTACT HANDLED TRANSURANIC WASTE CHARACTERIZATION REQUIREMENTS AT THE WASTE ISOLATION PILOT PLANT

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September 2003

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment of New Mexico. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U.S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned the EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-AC29-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

The EEG performs independent technical analyses on a variety of issues. Now that the WIPP is operational, these issues include facility modifications and waste characterization for future receipt and emplacement of remote-handled waste, generator site audits, contact-handled waste characterization issues, the suitability and safety of transportation systems, mining of new panels, and analysis of new information as part of the five year recertification cycles as mandated by the WIPP Land Withdrawal Act. Review and comment is provided on the annual Safety Analysis Report and Proposed Modifications to the Hazardous Waste Facility Permit. The EEG also conducts an independent radiation surveillance program which includes a radiochemical laboratory.

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ACRONYMS

AK	Acceptable Knowledge
ALARA	As Low As Reasonably Achievable
C of C	Certificate of Compliance
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CFR	Code of Federal Regulations
CH	Contact Handled
CH WAC	Contact Handled Waste Acceptance Criteria for WIPP, rev 0; rev 0.1
CPR	Cellulose, Plastic and Rubber
DAC	Drum Age Criteria
DOE	Department of Energy
EEG	Environmental Evaluation Group
EPA	Environmental Protection Agency
FGE	Fissile Gram Equivalent
HSG	Headspace Gas
HWFP	Hazardous Waste Facility Permit
IDC	Item Description Code
INEEL (INEL)	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
LWA	Land Withdrawal Act
NAS/NRC	National Academy of Sciences. National Research Committee
NDA	Non-Destructive Assay
NETL/CABE	National Energy Technology Laboratory/Center for Acquisitions and Business Excellence
NMAC	New Mexico Administrative Code
NMED	New Mexico environment Department
NRC	Nuclear Regulatory Commission
PCB	Polychlorinated Biphenyls

ACRONYMS (continued)

PE-Ci	Plutonium Equivalent Curies
PMR	Permit Modification Request
QA	Quality Assurance
QA/QC	Quality Assurance/Quality Control
QAPD	Quality Assurance Program Document
RCRA	Resource Conservation and Recovery Act
RFETS	Rocky Flats Environmental Technology Site
RH	Remote Handled
RIPB	Risk-Informed and performance-based
RTR	Real Time Radiography
SAR	Safety Analysis Report
SARP	Shipping Package Safety Analysis Report
SPM	Site Project Manager
SPQAO	Site Project QA Officer
SRS	Savannah River Site
SVOC	Semivolatile Organic Chemicals
TRAMPAC	TRUPACT-II Authorized Methods for Payload Control
TRU	Transuranic
TSCA	Toxic Substance Control Act
TSR	Technical Safety Requirements
VOC	Volatile Organic Chemicals
VE	Visual Examination
WAC	Waste Acceptance Criteria for WIPP, rev 0 through rev 7
WAP	Waste Analysis Plan
WIPP	Waste Isolation Pilot Plant
WSPF	Waste Stream Profile Forms
WWIS	WIPP Waste Information System

EXECUTIVE SUMMARY

Protection of the safety, health, and the environment at the Department of Energy (DOE) Waste Isolation Pilot Plant (WIPP) relies in part on the quality and completeness of the information about the waste that is shipped to the WIPP. This quality and completeness of the information is created through the waste characterization requirements identified in various regulatory documents. Waste characterization requirements are specified by the three WIPP regulatory agencies and the DOE: (1) the New Mexico Environment Department (NMED) through the Hazardous Waste Facility Permit (HWFP), (2) the U.S. Environmental Protection Agency (EPA) through the transuranic waste disposal Certification, (3) the U.S. Nuclear Regulatory Commission (NRC) through the TRUPACT II Authorized Methods for Payload Control (TRAMPAC), and (4) the Department of Energy through the Waste Acceptance Criteria (WAC). Of the four agencies, the requirements of the NMED for the Hazardous Waste Facility Permit tend to be the most prescriptive.

The Environmental Evaluation Group (EEG) has been evaluating the development of waste acceptance criteria since 1979. This report consolidates the findings and recommendations of the EEG's technical reviews and our current positions with respect to waste characterization requirements.

All waste characterization requirements were, at the time they were proposed and put in place, believed to be important for the protection of the worker safety, public health and the environment. The current waste characterization requirements were not developed ad hoc, but through much technical discussion, reference to accepted standards and codes, and considerable effort by DOE employees, DOE contractors, regulatory agency staff, regulatory agency contractors, the EEG staff, interested organizations, and/or members of the public.

The DOE has submitted several Class 2 and Class 3 Permit Modification Requests to NMED WIPP Hazardous Waste Facility Permit. Some have been accepted, some rejected, some withdrawn, and some are pending as tabulated in this report. EEG has provided a technical review of each. DOE has secured relief from a number of requirements. For example, by using

the permit modification process, the DOE has obtained a reduction of the headspace gas sampling requirement for thermally treated waste from Rocky Flats Environmental Technology Site (RFETS), a reduction in the visual examination requirement for waste from RFETS, and a reduction in headspace gas analysis for waste from the Idaho National Engineering and Environmental Laboratory (INEEL). These reductions in waste characterization requirements saved $30 million, saved $19 million, and allowed DOE to meet a deadline to remove 3100 m^3 from INEEL, respectively. From the time of application through the time of approval, these changes were each achieved in four months or less.

The waste characterization requirements from the various agencies contain many of the same requirements. Despite this overlap, the methods for meeting these requirements are somewhat different. The most complete methods of reaching compliance when requirements overlap, are usually found in the HWFP or the 40 CFR 194 compliance implementation found in Appendix A of the contact handled CH WAC. When considering a requirement change to either of these documents, the effect on all requirements, including those issued by other agencies, should be noted and evaluated for any potential impacts across agencies.

Based on our reviews, EEG offers the following observations and recommendations for waste characterization requirements:

Acceptable Knowledge: Acceptable Knowledge (AK) is the principle waste characterization technique for all of the regulatory agencies. AK is necessary and should be retained. At this time EEG supports the use of the HWFP AK requirements since they are the most explicit.

Headspace Gas Sampling and Analysis: It is desirable to maintain a comprehensive Headspace Gas (HSG) program for WIPP CH TRU waste. However, it should be possible to require less than 100% headspace gas sampling in some cases. Our primary concern is with organic sludges and older waste containers where knowledge of the waste is of lesser quality.

Drum Age Criteria: Drum Age Criteria (DAC) is necessary to ensure that Headspace Gas sampling of waste containers will measure gas concentrations that are at least 90% of

equilibrium. DAC values are required in both the HWFP and the TRAMPAC. The EEG supports this requirement.

Real Time Radiography: All WIPP waste containers are required to undergo either radiography or visual examination by the HWFP. Usually retrieved wastes undergo Real Time Radiography (RTR) and newly generated wastes are examined by visual examination. RTR has been a very effective means of verifying AK and discovering prohibited items in waste containers. It is also used to show compliance with several EPA and TRAMPAC requirements. The overall radiography program is an important part of the WIPP waste characterization program and should be retained. It may be possible to reduce some of the detailed procedural requirements in the HWFP.

Visual Examination for Retrievably Stored Waste: A small percentage (currently less than 2%) of retrievably stored waste is required by the HWFP to undergo visual examination for confirmation of RTR. The Visual Examination (VE) process has the potential for slightly greater radiation exposure than the other waste characterization requirements, although the EEG has seen no data to indicate that exposures are significant enough to justify reducing the requirement. The DOE has been successful in modifying the HWFP on retrievably stored visual examination and this would be the preferred process for seeking further reductions.

Visual Examination for Newly Generated Waste: VE is the method DOE usually prefers for newly generated waste because it can be done at the time the waste container is being filled. The EEG has not objected to any part of this requirement except to state that the requirement for two trained VE operators to perform the visual process "may be overkill" and that a single verification should be adequate.

Coring Sampling and Analysis: Currently the EEG continues to believe that the homogeneous sampling and analysis are unnecessary characterization requirements in the HWFP. Our principal reason for this position is that the data are not used for any additional regulatory control (metals releases from accidents or long-term processes would be controlled by radionuclide control requirements and VOCs and SVOC by HSG or the Confirmatory VOC Monitoring Plan).

Level II Management and Waste Certification HWFP Requirements: The DOE has listed these management and certification requirements as characterization activities in a recent cost analysis. EEG has not previously commented on these requirements. However, our current evaluation indicates that the required procedures are very detailed and somewhat redundant. This may be one of the areas to which the general EEG comment, "We believe waste characterization requirements are excessive," applies.

Characterization Support HWFP Requirements: EEG remains supportive of the WIPP audit and surveillance program. We have also said that we do not believe the relaxation of audit requirements and QA/QC is an appropriate way to reduce the regulatory burden.

EPA Non-Radiological Requirements: EPA's residual liquids, non-ferrous metal and cellulose, plastic and rubber requirements should remain and can continue to be determined as they are now, by the RTR and VE requirements of the HWFP. The ferrous metal requirement can continue to be met by counting waste containers emplaced in the repository.

EPA Radiological Requirements: The EEG agrees with the radioassay requirements for contact-handled transuranic waste specified in Appendix A of the CH WAC and the current procedures for modifying the document.

Current requirements for reporting the 10 required radionuclides should remain. ^{241}Pu should also be reported. The current requirement that all radioassay should be performed by WIPP-certified assay systems should be maintained.

Justification for less than 100% quantification and determination of isotopic ratios may be possible for some, but certainly not all, waste streams.

NRC Container Properties: The TRAMPAC requirements for residual liquids, filter vents and the sealed container prohibition should be retained. These are all verified by requirements in the current HWFP.

NRC Nuclear Properties: All nuclear property requirements should be retained and Appendix A of the CH WAC methodology should be used.

NRC Gas Generation Requirements: Requirements for measuring the chemical, payload classification, and radionuclide concentrations necessary to ensure hydrogen gas concentration criteria are met must be retained. There have been many changes, via the Certificate of Compliance (C of C) revision process, which have allowed additional containers to be shipped without changing the hydrogen gas criteria and additional changes may be justifiable in the future.

The flammable gas concentration limit of ≤ 500 ppm should be retained as described in the current revision of the TRAMPAC. Alternate methods (with appropriate QA) will be necessary if future changes to the HWFP affects the use of HSG sampling as the method for meeting this criteria.

WIPP Waste Acceptance Criteria: The WAC has served a useful historic purpose in developing initial criteria that have been adopted by the other three regulatory agencies. Currently it is a useful document for listing most of the requirements from all four sets of criteria. It would be more useful if the technical justification for each criteria or requirement were restored.

The unique role of the WAC in including any necessary operational safety and health requirements not included elsewhere is very important and must be constantly evaluated via the technical safety requirements (TSR) portion of the CH TRU Safety Analysis Report, and any necessary changes incorporated into the CH WAC.

Summary Observations and Recommendations

EEG's views on waste acceptance criteria and waste characterization continue to evolve. Shortly after the WIPP began receiving waste in 1999, the EEG published calculations comparing the risks from the hazardous constituents and the radioactive constituents in the WIPP inventory. The carcinogenic risks were quite low for both categories, with the expected carcinogenic risk

from the hazardous constituents four orders of magnitude less than the expected risk from the radiological constituents to workers from routine operations and operational accidents. Prudence suggests that mitigating the relatively small risk from the non-radiological constituents should not be the primary cost in waste characterization. Waste characterization efforts should focus on reducing the risk of release of radiological constituents.

Any proposed relaxation of waste characterization requirements needs to be evaluated in sufficient detail to convince the regulatory agencies, the EEG, and others that the modification is justified. Implicit in this approach is the understanding that any changes need to be made in a step-by-step transparent process and through existing regulatory procedures of the NMED, the EPA, and the NRC. This approach requires adequate justification and has worked effectively to obtain approval for a number of changes from all three non-DOE regulatory agencies. Moreover, as noted by the DOE, the regulatory agencies have indicated a preference for this approach.

1.0 PURPOSE AND SCOPE

Protection of the safety, health, and the environment at the Department of Energy (DOE) Waste Isolation Pilot Plant (WIPP) relies in part on the quality and completeness of the information about the waste that is shipped to the WIPP. This quality and completeness is created through the waste characterization requirements established in various regulatory documents.

This report is a compilation of the Environmental Evaluation Group's (EEG) comments since the operational phase of WIPP began and EEG's current positions on the existing waste characterization requirements by three regulatory agencies and the DOE. The report includes discussions about: (1) the process for changing requirements, (2) a comparison of risks due to various constituents in the waste, (3) whether current requirements are necessary, adequate or excessive, and (4) the continued need for the audit/QA process. The rationale for each conclusion and recommendation is also given.

The EEG has been evaluating the development of the WIPP waste characterization criteria since 1979. The WIPP began receiving contact handled (CH) transuranic (TRU) waste in March 1999. Later that same year, the project received its Hazardous Waste Facility Permit (HWFP) from the New Mexico Environment Department (NMED) and began receiving and emplacing mixed CH TRU waste.

The EEG has made several sets of comments since 1999 explaining our evaluations and evolving positions on waste characterization requirements. These were submitted as: (1) comments to the DOE in September 1999 concerning Waste Characterization Task Force recommendations, (2) comments to DOE in January 2002 on the proposed Appendix A changes to the WIPP CH Waste Acceptance Criteria (CH WAC), and (3) statements to the National Academy of Sciences/National Research Council (NAS/NRC) Committee on Optimizing the Characterization and Transportation of Transuranic Waste for the Waste Isolation Pilot Plant in October 2002, January 2003, and May 2003[1]. These comments and statements are included in Appendix A of

[1] EEG understands that the anticipated NAS/NRC committee report is under internal discussion.

this report. The EEG has also provided technical reviews on every Class 2 and Class 3 permit modification request submitted by DOE to the NMED, which is discussed in more detail in Chapter 4. All of these materials are available on EEG's web site (http://www.eeg.org).

This report references waste acceptance criteria, waste characterization requirements, and waste characterization methods cognizant of the DOE statement that, "in some cases the acceptance criteria and regulatory requirements are synonymous." (DOE 1999, p 3-8). The waste characterization methods are also specified in the permit and certificates, and arguably might be viewed as a requirement.

This report concentrates on EEG's position on the various waste characterization requirements, not the details of procedures required to show compliance. We recognize that the procedural requirements are a significant part of the waste characterization issue, but they are outside the scope of this report.

1.1 Overview of Waste Characterization Requirements

The U.S. Department of Energy (DOE), the U.S. Nuclear Regulatory Commission (NRC), the U.S. Environmental Protection Agency (EPA), and the New Mexico Environment Department (NMED) all have requirements for characterization of WIPP waste. A number of the waste characterization requirements are included in more than one set of requirements.

The DOE was self-regulating (except for the U.S. Department of Transportation shipping requirements) for all waste characterization criteria prior to 1989. The DOE, through its Orders and policies as far back as 1979 began to develop criteria protective of worker and public health and safety for anticipated operations. The criteria in the original WAC included limitations on: free liquids; pyrophoric, toxic and corrosive materials; explosive and compressed gas; gas generation and criticality. Container and certification requirements were also included (DOE 1980). Subsequent revisions of the WAC have consolidated into this one document requirements by each regulatory agency as these requirements became applicable. In April 2002, the WAC

was revised to contain only criteria for CH TRU waste. Up to this time, the WAC covered both CH TRU and remote-handled (RH) TRU waste.

The first set of requirements from a regulatory agency came from the NRC issuance of the Certificate of Compliance (C of C) of the TRUPACT-II Type B Package (NRC 71-9218) in 1989. These requirements included physical, nuclear and chemical properties and are included in a document called the TRUPACT-II Authorized Methods for Payload Control (TRAMPAC). Many of the properties were similar to those already in the WAC. In addition, there were extensive requirements dealing with control of the concentration of hydrogen, methane, and flammable volatile organic chemical (VOC) concentrations. Quality assurance (QA) requirements for packaging were also specified in the TRAMPAC.

The 1992 Land Withdrawal Act (LWA) specified that waste coming to WIPP must be transuranic waste (defined in the LWA as, "waste containing more than 100 nanocuries of alpha emitting transuranic isotopes per gram of waste with half-lives greater than 20 years."). Moreover, it was limited to waste generated by atomic energy defense activities of the United States. The LWA also specified a regulatory role for the EPA in ensuring long-term compliance of the WIPP repository. This role for EPA led to several additional waste characterization criteria.

EPA waste characterization requirements provide the most stringent requirements for quantification of radionuclides and also include several other requirements. The official methodology for radionuclide assay is primarily non-destructive assay (NDA) and is contained in Appendix A of the CH WAC (currently DOE 2002b). Modifications to Appendix A require EPA approval. The NDA methodology prescribed in Appendix A is also used in quantifying NRC and DOE radiological requirements.

The HWFP (NMED 1999) became effective in December 1999. The HWFP adds several waste characterization requirements and provides specific details of procedures that must be applied in meeting the requirements. Several NRC and EPA requirements are included in the HWFP and

the methodology specified in the HWFP for meeting the NMED, NRC, and EPA requirements is quite prescriptive.

1.2 Overlap of Waste Characterization Requirements

In our reviews of proposed changes, EEG has found that the waste characterization requirements from the three regulatory agencies and the DOE contain considerable overlap (i.e., contain the same requirements). Despite this overlap, the methods to be used for meeting these requirements are somewhat different. The most complete methods of reaching compliance when requirements coincide are usually those found in the HWFP (NMED) and the 40 CFR 194 (EPA) radioassay compliance implementation found in Appendix A of the CH WAC (DOE).

For example, the maximum of 325 fissile gram equivalent (FGE) requirement in each TRUPACT-II is in the TRAMPAC. Yet, the most complete waste characterization method to ensure compliance with this requirement is specified in Appendix A of the CH WAC, where radionuclide measurement requirements are specified to meet the 40 CFR 194.24 criteria.

Similarly, requirements for limitation of liquids to less than 1% by volume in waste containers are specified by the waste characterization requirements of each agency—as part of the TRAMPAC (free liquids), 40 CFR 194.24 (free water), the HWFP (residual liquid), and the CH WAC (free water, residual liquid, currently total residual liquid). For the purposes of this report, EEG refers to the presence of liquids. The most complete method for determining the presence of liquids, however, is the HWFP requirement that each container must undergo either radiography or visual examination. A further discussion of "overlap" issues is in Chapter 4.0 and Table 4-2.

A change in one set of requirements could have implications for other requirements. For example, if headspace gas (HSG) sampling and analysis was eliminated as a HWFP requirement, it would be necessary to use an alternate methodology to ensure adequate control of flammable gas requirements in the TRAMPAC. Alternate methods exist, but they would need to be

incorporated into the HWFP or some other regulatory document with appropriate QA in order to sustain an adequate level of assurance.

The overlap of requirements of each agency inherently complicates change. When considering a requirement change in either the HWFP or Appendix A of the CH WAC, the effect on all requirements, including those issued by other agencies, should be noted and evaluated for its impact on requirements across agencies.

1.3 EEG Waste Characterization Evaluations and Philosophy

1.3.1 Evaluation History

The EEG has reviewed waste characterization requirements as they were being developed and modified over the years. Our comments are contained primarily in letters or presentations rather than EEG reports. There are EEG reports on specific issues related to waste acceptance criteria (Little 1980), flammability of CH TRU waste drums (Neill and Channell 1983; Silva 1990; 1991), safety documents (primarily the WIPP Safety Analysis Report [SAR]; EEG 1989), and applications to regulatory agencies (the Compliance Certification Application [CCA] from DOE to EPA; Neill and others 1996; 1998) that led to the development or retention of some waste characterization requirements.

Our evaluations concentrated on the specific purpose of each of the criteria or regulatory documents. The initial WAC comments were primarily concerned with operational health and safety at WIPP. Reviews of NRC requirements concentrated on gas generation and adequacy of the TRUPACT-II package itself. These two issues were instrumental in adoption of the legal requirement that all waste shipments to WIPP be in NRC certified Type B packages. The EEG review (Neill and others 1996; 1998) of the DOE application and EPA proposed certification focused on requirements necessary to assure that the WIPP complied with 40 CFR 191 and 40 CFR 194.

EEG's reviews of the HWFP and proposed permit modification requests (PMRs) included detailed technical evaluations of whether the HWFP or a PMR would accomplish the required regulatory objectives. However, with our review of modification requests to the HWFP, we have also evaluated the effect that changes would have on existing requirements of the NRC, the EPA, and DOE (in the CH WAC). This is because the HWFP is usually the most prescriptive in specifying how the requirement will be met. The prescriptiveness of the HWFP increases the assurance that the requirements of the other regulatory agencies will be satisfactorily met.

1.3.2 EEG Philosophy on Waste Characterization Requirements

Much of EEG's overall philosophy on waste characterization requirements can be found in various statements and reports. These are summarized below.

(1) We believe overall waste characterization requirements are excessive. However, any proposed relaxation needs to be evaluated in sufficient detail to convince regulatory agencies, the EEG, and stakeholders that the modification is justified.

(2) Implicit in statement (1) is the belief that any changes need to be made in a transparent, step-by-step approach and through the existing regulatory procedures of NMED, EPA, and NRC. This approach requires adequate justification and has worked effectively to get approval for a number of changes from all three regulators.

(3) Our conclusions on individual waste characterization requirements are based on health and safety, and environmental considerations. The EEG does not speak for the regulatory agencies in offering opinions of legal and regulatory requirements. EEG's current positions on specific waste characterization issues are also subject to change if justified by new evaluations.

(4) Since EEG has concluded that the radiological risk is about 10,000 times that of the hazardous waste risk, we concentrate on those waste characterization requirements that affect the transuranic waste during our health and safety evaluations.

(5) It is important to recognize that a number of the requirements in the Hazardous Waste Facility Permit (HWFP) have a role in ensuring that radiological, transportation, and operational requirements are met.

(6) The relaxation of audit and Quality Assurance and Quality Control (QA/QC) requirements is not an appropriate way to reduce the regulatory burden.

(7) Another factor which EEG has never stated explicitly is our recognition that considerable uncertainty exists in the characteristics of wastes that may come to WIPP in the future. For this reason, our evaluations of waste characterization requirements attempt to also address the potential future characterization needs for presently uncharacterized waste streams.

(8) Claims have been made in the past (see Section 2.1) that removal of unnecessary waste characterization requirements can result in increased shipping rates to WIPP. EEG considers whether a requirement is necessary for health, safety, and environmental reasons and does not factor schedule implications into our conclusions.

Two other issues often discussed by the DOE when proposing reductions in waste characterization requirements are minimizing the risk and exposure to workers performing waste characterization and costs.

EEG has no reason to believe that radiation doses to waste characterization workers are significant and, in the absence of data indicating otherwise, should not be a justification for eliminating or reducing a waste characterization requirement (see Section 3.3).

Costs of waste characterization are significant and it would be desirable to continue to reduce or eliminate those requirements where it is prudent. However, significant non-waste characterization costs were also incorporated into the initial design and operation of the WIPP project; a prudent procedure for a first of a kind deep geologic repository. Few of the waste characterization requirements can be evaluated exclusively by a traditional cost/benefit

comparison. A rigorous evaluation via the regulatory process is the best way to decide on acceptable changes to any waste characterization requirements.

2.0 WASTE CHARACTERIZATION REQUIREMENTS CHANGE PROCESSES

Since the original receipt of waste at the WIPP in March of 1999, the DOE has successfully completed changes to waste characterization requirements specified by each of the different regulatory agencies. The process for creating these changes is significantly different for each of these regulatory agencies, as discussed in the following sections.

2.1 NMED: HWFP Waste Characterization Requirements Change Process

The non-radiological hazardous waste characterization requirements fall under the jurisdiction of the New Mexico Environment Department and are principally (and most completely) specified in Attachment B, including B-1 through B-6 of the HWFP, collectively known as the Waste Analysis Plan (WAP) (currently NMED 2003). Changes to the WAP are therefore subject to the same process as those for the entire HWFP. The New Mexico Administrative Code (20 NMAC 4.1) simply references the EPA-established requirements contained in the Code of Federal Regulations (CFR) for these changes. Either the regulatory agency (under 40 CFR 270.41) or the permittees (under 40 CFR 270.42) can initiate modifications of a permit. The regulatory agency's ability to modify a permit is much more limited than that of the permittee, the implication being that it is incumbent on the regulator to ensure that the initial permit is sufficient.

There are three classes of permit modification requests. The "Classification of Permit Modification" table (Appendix I to 40 CFR 270.42) identifies the process to be used for each class. For those modifications that do not match table entries, the permittees can request that the regulatory agencies make the designation, but the regulation also specifies the criteria under which the regulatory agencies are allowed to do so.

Class 1 modifications are to be used for minor upgrades. Examples include updating the administrative information in the permit (names, titles, etc.), replacement of equipment with functionally equivalent components, or correction of typographical errors. These modifications

keep the permit current with routine changes to the facility or its operation. These changes do not substantially alter the permit conditions (40 CFR 270.42(d)(i)). The Class 1 change process is very simple. The permittee can implement the modification immediately, with notification of the change provided to the regulator within seven days. Other organizations and individuals on the facility mailing list are to be notified within 90 days of the modification. One disadvantage of a Class 1 modification is that there is no requirement that the regulator formally accept the modification. Moreover, the regulator can reject a Class 1 modification at any time for cause. One way to avoid a belated Class 1 modification rejection is to use the Class 2 process.

Class 2 modifications enable a permittee to respond to common variations in the types and quantities of wastes managed, technological advances, and non-trivial changes associated with new regulations. The process to implement these requires a formal submittal of a PMR to the regulator and a subsequent 60-day public comment period. The public comment period must include a permittee-organized public meeting. Within 90 days of the initial submission the regulator must either: (1) approve the modification request (with or without changes), (2) deny the request, or (3) determine that the modification must follow the Class 3 process. Two other options are available. The modification can be temporarily approved for up to 180 days, or the regulator can simply notify the permittee that the decision will be forthcoming in the next 30 days (only one such extension is allowed).

The Class 3 process may be required to accommodate significant public concern or a complex change. Like the Class 2 process, the Class 3 process requires the 60-day public comment period and public meeting. After that the Class 3 can be considerably more complicated and lengthy. The decision making process allows the regulator to request additional information and file formal notices of deficiency on the application. Even after this portion of the process, it may be necessary to create a draft permit including the proposed modification, conduct a more formal public hearing by an independent hearing officer, reopen the public comment period, and produce a hearing officer's report. This would all need to be completed before the regulator makes a decision on the modification.

Class 1 modifications to the HWFP under these processes have usually been successful. However, Class 1 modifications related to waste characterization have suffered a relatively high rate of rejection, usually ascribed to misclassification under 40 CFR 270.42. All changes to the waste sampling and analysis methods should be designated as Class 2 (Appendix I to 40 CFR 270.42). These would be waste characterization changes that are not related to conformation with EPA guidance or regulations, multi-source leachates, or changes associated with underlying hazardous constituents in ignitable or corrosive wastes sampling. Thus, most common waste characterization changes would be Class 2 changes.

The EEG has commented on every Class 2 and Class 3 PMR during the public comment period. For the past two years, any Class 2 comments submitted by the EEG have been submitted to both the NMED and the DOE several days prior to the comment period deadline, so that the DOE could address the concern or respond to the comments in other ways during that same public comment period. EEG comments on PMRs may be viewed at http://www.eeg.org.

The bulk of Class 2 and Class 3 PMRs have been related to waste characterization. The EEG published an analysis of experience with the PMRs that were extant after 18 months experience, noting several areas of concern about the DOE's submissions and suggesting a possible solution (Walker and Silva 2002). Table 2-1 lists all of the HWFP modifications submitted by the DOE so far, and their current status. Despite the complexity of the process for HWFP changes, the DOE has obtained some relief in a timely manner using the modification process. According to the DOE, a Class 2 PMR to allow compositing of headspace gases greatly aided the completion of the Idaho National Engineering and Environmental Laboratory (INEEL) 3100 m^3 Project. Also, a Class 2 PMR allowing reduction in headspace gas measurements for thermally treated wastes saved over $30 million at the Rocky Flats Environmental Technology Site (RFETS). Finally, a Class 2 PMR reducing the number of drums requiring visual examination saved $19 million (DOE 2002c). From the time of application through the time of approval, these changes were each achieved in four months or less.

Table 2-1. WIPP HWFP Class 2 and 3 Modification Proposals

Proposal Date	Mod Class	Item #	Proposed Modification	Disposition	Action Date
03/30/00	2	1	Alter accuracy acceptance criteria for cresols and pyridines	Accepted	08/08/00
		2	Use hgas statistical sampling of homogeneous containers when AK does not indicate hazardous VOCs	Accepted	08/08/00
		3	Use hgas statistical sampling of containers when waste was thermally treated	Accepted	08/08/00
04/20/00	2	1	Add allowance for 3 sub-samples to be taken from solidified container cores	Accepted	08/08/00
		2	Change miscertification rate to SCG from waste stream	Accepted	08/08/00
		3	Use gross alpha/beta measurements for groundwater sampling	Accepted	08/08/00
07/21/00	2	1	Perform waste characterization at the WIPP	Withdrawn	09/29/00
		2	Combine data package reviews; eliminate off-site audits for SQS	Withdrawn	09/29/00
12/07/00	2	1	Change headspace has drum age criteria (DAC-1)	Rejected	03/26/01
01/22/01	2	1	Perform visual examination by tomography (DR/CT)	Withdrawn	03/23/01
03/06/01	2	1	Move inspection forms from the HWFP to the operating record	Accepted w/minor changes	07/06/01
		2	Change the frequency of firefighter I training	Accepted	07/06/01
		3	Eliminate portions of RCT training	Accepted	07/06/01
		4	Add new hazardous waste numbers to HWFP	Accepted all but U-134 (HF)	07/06/01
		5	Extend time for groundwater monitoring reports	Accepted	07/06/01
04/27/01	2	1	Allow additional storage space for TDOPs	Rejected	08/30/01
04/27/01	(2) 3	1	Change headspace gas drum age criteria (Revised; DAC-2)	Accepted w/modifications	12/31/02
06/06/01	3	1	Allow Central Characterization Facility (CCF) at the WIPP	Withdrawn	01/14/03
		2	Add storage capacity for the CCF	Withdrawn	01/14/03
		3	Increase allowed storage time at the WIPP to one year	Withdrawn	01/14/03
		4	Allow prohibited items to be received at the WIPP	Withdrawn	01/14/03
08/28/01	2	1	Allow compositing of headspace gas samples for analysis	Accepted	11/27/01
		2	Alter random sampling for visual examination to allow for site safety considerations	Rejected	11/27/01
		3	Allow hgas samples to be taken through existing filter openings	Accepted, but limited to POCs	11/27/01
06/27/02	2	1	Revised addition of HF hazardous waste number (U-134)	Accepted w/minor changes	11/25/02
		2	Elimination of control charting for repackaged solidified wastes	Accepted w/minor changes	11/25/02
		3	Record keeping and auditing of classified information	Accepted	11/25/02
		4	Add HalfPACT to shipping containers	Accepted	11/25/02
		5	Use of radiography instead of VE for newly generated wastes	Accepted w/minor changes	11/25/02
06/27/02	2	1	Add direct loaded 85-gal and 100-gal drums, and TDOPs	Accepted w/modification	11/25/02
06/27/02	(2)3	1	Data Management Update	Moved to Class 3 (in progress)	
06/28/02	3	1	Add RH-TRU	In process	
10/07/02	3	1	Change panel closures from Option D to WPC design	Proposed as Class 2, accepted as 3 (in progress)	

Table 2-1. WIPP HWFP Class 2 and 3 Modification Proposals (Continued)

Proposal Date	Mod Class	Item #	Proposed Modification	Disposition	Action Date
05/14/03	2	1	DAC for 85-gallon & 100 gallon drums, and TDOPs	Rejected (needs more data)	09/11/03
		2	Removal of booster fans in the underground	Accepted	09/11/03
		3	Eliminate LANL sealed sources waste streams hgas sampling and analysis	Rejected (suggested resubmittal with statistical sampling)	09/11/03
		4	Remove formaldehyde as a required analytical parameter for LANL	Accepted	09/11/03
		5	Add New HWNs (cyanides, DMS, Acetonitrile, 1,4Dioxane, hexaclorobutadiene)	Accepted	09/11/03
05/14/03	3	1	Add new hazardous waste disposal units (panels 4-8)	NMED review period	
05/21/03	2	1	Eliminate PCB prohibition from HWFP	Accepted	09/11/03

"AK" = acceptable knowledge
"DAC" = drum age criteria
"DR/CT" = digital radiography/computerized tomography
"HF" = hydrofluoric acid
"HWN" = hazardous waste number
"hgas" = headspace gas
"homogeneous containers" = containers of solidified or soil/gravel wastes
"POC" = pipe overpack container
"RCT" = radiation control technician
"RH-TRU" = remote-handled transuranic waste
"RTR" = real time radiography
"SCG" = summary category group (debris wastes, solidified wastes, and soil/gravel are the 3 SCGs)
"SQS" = small quantity sites
"TDOP" = ten-drum overpack containers
"U-134" = hazardous waste code, hydrofluoric acid, Chemical Abstract Number 7664-39-3
"VE" = visual examination
"VOC" = volatile organic compound
"WPC" = WIPP panel closure

2.2 EPA: 40 CFR 194 Waste Characterization Requirements Change Process

The most restrictive requirements for radionuclide waste characterization derive from the EPA decision (1998) to certify the WIPP to receive waste as required by the WIPP LWA. 40 CFR 194 contains the criteria the EPA established for the WIPP to be certified. 40 CFR 194.24 requires the DOE to have a system of controls to measure and track the waste components that affect the long-term performance of the repository. These components were identified as ten radionuclides (four plutonium isotopes, three uranium isotopes, americium-241, strontium-90, and cesium-137), cellulosic materials (cellulose, plastic, and rubber), free water, and as two

separate categories, ferrous and non-ferrous metals (DOE 1996; EPA 1998). The amount of the ferrous metal component is easily satisfied by counting waste drums. But the other components required waste characterization methods to measure them. The ten radionuclides are identified and their activity measured principally by NDA techniques. The other components are identified and measured by either radiography (x-ray imaging of container contents) or visual examination (VE) techniques.

Changes to the methods for identifying and measuring these components are relatively informal, except for severe changes to the requirements. The EPA established a rule-making process in 40 CFR 194.65, but has retained a fairly wide latitude in determining whether a change requires a rule-making. For changes that the EPA determines do not require rule-making, the process is informal. The DOE simply negotiates with the EPA on proposed changes, then submits the proposed change to the EPA for evaluation. The EPA sends a letter to the DOE announcing their approval of the elements of the change.

Since late 1999 the 40 CFR 194 radioassay waste characterization requirements have been placed in Appendix A of the CH WAC (currently DOE 2002b). The informal, non-rule system has been used to successfully modify the NDA requirements several times. While there is no formal comment process, the EEG has been notified by either the DOE or the EPA during the latter phase of these negotiations and has submitted technical comments for consideration. Thus far, the EEG has had no objections to the informal process used for modifying waste characterization requirements.

The DOE has initiated several informal changes to the 40 CFR 194 mandated requirements which have been approved by the EPA. These include changes to the NDA Performance Demonstration Program and two non-waste characterization items (a reduction in the requirements for backfill in the repository, and a change to the repository horizon). A more formal change to the implementation of 40 CFR 194, to allow both the EPA and the DOE additional flexibility in several areas, is currently in the final stages.

2.3 NRC: Transportation Waste Characterization Requirements Change Process

Transportation waste characterization requirements are established in the documentation supporting the NRC Certificate of Compliance (C of C) for the transportation package, as required by 10 CFR 71. Changes to any waste characterization requirements in this documentation are initiated by submitting the changed documentation to the NRC; 10 CFR 71.13(c) and 10 CFR 71.31(b) provide criteria by which the NRC evaluates these or any other proposed changes, and revised C of Cs are used to express the NRC's acceptance of these proposals.

The two criteria by which the changes are evaluated are not complex, even though the evaluation itself may be very complex. 10 CFR 71.13(c) states that modifications are not to significantly impact the design, operating characteristics, or fissile material package with respect to criticality, in relation to the stringent testing requirements of the shipping package. 10 CFR 71.31(b) simply requires that modification of the authorized contents of the packaging provide sufficient information to demonstrate that the package will remain in conformance with the package standards in effect at the time the modification is requested.

WIPP CH TRU waste is transported in the Transuranic Package Transporter-II (TRUPACT-II), for which the C of C's principal supporting documentation concerning waste characterization is the *TRUPACT-II Authorized Methods for Payload Control* (TRAMPAC) (DOE 2003a), currently issued as a separate document, but still a part of the *TRUPACT-II Contact Handled Transuranic Waste Shipping Package Safety Analysis Report* (SARP) (DOE 2003b). The SARP specifies the waste characterization methods that will be used to meet the criteria established or referenced in the C of C is in Revision 16 (NRC 2003); while all of these revisions were not necessarily concerned with waste characterization requirements, most of the recent ones (C of C revisions 13 through 16) have adjusted waste characterization criteria.

2.4 DOE: CH WAC Characterization Requirements Change Process

The CH WAC (currently DOE 2002a) contains statements of waste characterization requirements that originate from operational activities at the WIPP. These requirements are

derived from the *Waste Isolation Pilot Plant Contact-Handled (CH) Safety Analysis Report* (CH SAR) (DOE 2003c), and are listed in the Technical Safety Requirements (TSR) attachment 1 (DOE 2003d) to the CH SAR. 10 CFR 830 requires nuclear facilities to establish and maintain a documented safety analysis. The published CH SAR has been updated annually since 1992 and any modifications to waste characterization requirements take place as a part of the ongoing review of this document. EEG is responsible for the review of the CH SAR on behalf of the State of New Mexico. The process for modification is simply to include the changes in the annual CH SAR, a process not necessarily simple in itself. Initiation of the change, review, comment resolution, and signature release are all necessary. These changes are then reflected in the next revision of the CH WAC, except for Appendix A which must be approved by EPA. For example, this process was used in 1999 to change the maximum radiotoxicity limit for 55-gallon drums (from 1000 PE-Ci to 1100 PE-Ci; see Chapter 7 for a discussion of PE-Ci).

The CH WAC also lists the DOE's interpretation of the regulatory criteria for the HWFP, NRC, and EPA. In the past the WAC contained not only the waste acceptance criteria—that is, the data that waste characterization would need to supply, but also a discussion of the source of each criterion from each regulatory organization. In promulgating the immediate predecessor of the current CH WAC, the information presented was changed so that it only reflected the most restrictive criteria in each area. The WAC no longer cites either the source for that most restrictive criterion or the various regulatory sources that place restrictions on that area. Moreover, the CH WAC no longer contains a discussion of the technical justification for each criteria as it once did in the earlier versions. EEG has gone on record urging DOE to restore that discussion into the document (EEG 2002a).

3.0 RISK PERSPECTIVES

When designing and operating a nuclear waste repository, it is necessary to evaluate the risks associated with the wastes being disposed and to use this information to minimize operational and long-term risks to workers, the public, and the environment. Waste characterization should be sufficient to provide the information necessary to ensure that the "mixed" (radiological and hazardous wastes) wastes being shipped and emplaced, meet these operational and long-term safety requirements.

3.1 EEG Evaluations and Statements

The EEG published EEG-72, *A Comparison of the Risks from the Hazardous Waste and Radioactive Waste Portions of the WIPP Inventory*, (Channell and Neill 1999). The six major conclusions from this study were:

1. Risks are low in all cases. Lifetime carcinogenic risks are expected to be about 1×10^{-3} for workers and about 1×10^{-8} for members of the public.

2. The expected radiological carcinogenic risks to workers from routine operations and from operational accidents were at least four orders of magnitude greater than the carcinogenic risk from the hazardous waste constituents. Under maximum conditions, the radiological risks are more than two orders of magnitude greater than the hazardous waste risks.

3. During routine operations, a member of the public residing at the WIPP Site Boundary would receive a very low carcinogenic risk (less than 10^{-8} lifetime) from Volatile Organic Compounds (VOCs) and no radiological risk. The radiological risk to a member of the public from average operational accidents is over five orders of magnitude greater than the hazardous waste risk.

4. Radionuclide annual risks to a resident farmer from average releases to the surface following human intrusion 1000 years after WIPP closure are one order of magnitude greater than total risks from VOCs. These long-term risks are two orders of magnitude lower than risks during the operational period and are less likely to occur.

5. Non-carcinogenic risks from VOCs during operation are less than 2% of the Hazard Index and are not important relative to the carcinogenic risks.

6. The evaluations confirmed the intuitive assumption that radiological risk from WIPP wastes are much greater than the risks from hazardous wastes.

In May 2000 EEG published EEG-75, *Evaluation of Risks and Waste Characterization Requirements for the Transuranic Waste Emplaced in WIPP during 1999*, (Channell and Walker 2000). The waste emplaced during the first year of WIPP operation was non-mixed (did not meet the regulatory definition of hazardous wastes although low concentrations of VOC's were present in headspace gas samples) and with low radionuclide concentrations. The EEG found that risks from VOCs were extremely low (lifetime cancer fatality risks of 10^{-11} to 10^{-14}).

The EEG-72 and EEG-75 conclusions have several implications for waste characterization requirements and priorities. These conclusions have been pointed out by EEG subsequent to July 1999. While many of these comments are quoted elsewhere in this report, the more relevant EEG statements have been:

1. We see no scientific reason why it is necessary to analyze for hazardous metals in waste solids (see discussion in Section 4.7).

2. VOC releases will occur routinely and have a quantifiable, albeit low, risk. Thus, there is a logical reason to quantify VOC releases.

3. In EEG-75, EEG concluded that the Confirmatory VOC Monitoring Plan in the WIPP underground would detect concentrations that are three orders of magnitude below allowable Permit limits.

4. EEG stated in an April 2001 paper at the 9th International High-Level Radioactive Waste Management Conference (Neill and Silva 2001):

> The cost of complying with non-radioactive hazards (Resource Conservation and Recovery Act [RCRA] regulations) may be much more than complying with the radiological hazards, which are about 10,000 times greater. Predicting releases over 100 years for the non-radiological constituents should not be the primary cost in comparison to limiting radiological releases over 10,000 years.

5. In an October 4, 2001 statement to the National Academy of Science/National Research Council Committee on the Characterization of Remote-Handled Transuranic Wastes we said, "… The fact that radiological risks are much greater than hazardous risks needs to be kept in mind by DOE, regulatory agencies, peer review groups, this Committee and oversight agencies when addressing possible changes to waste characterization requirements." (EEG 2001).

3.2 Risk-Based Approach to Characterization

The DOE has proposed at various times since 2000 that a "risk-based" or "performance based" system should be used to determine waste characterization requirements (Moody 2002). These two terms have not been precisely defined by DOE, but presumably refer to only those waste characterization requirements believed to serve a useful purpose in controlling risks.

The NRC has attempted to include the use of probabilistic risk assessment in a Risk-Informed and Performance-Based (RIPB) system since 1995. RIPB analyses are to be used along with traditional deterministic approaches in setting priorities for regulations. The NRC and others

believe this process will encourage more transparent regulatory approaches and focus on requirements that lead to actual reduction in risk. This is apparently the general intent of the DOE thrust in reduction of CH TRU waste characterization requirements.

EEG believes that an RIPB assessment should be included in developing CH TRU waste characterization requirements. A requirement that does not have a health or safety basis should be reevaluated. These considerations have been the general philosophy in EEG's recommendations to date, which have usually been limited to health and safety issues. However, this concept is more easily stated than implemented because the risk being addressed is often not quantifiable. The evaluation of individual CH TRU waste characterization requirements should consider two questions: (1) are the data collected used for any purpose (for example, elimination of waste containers for shipment to WIPP; or controlling quantitative limits for transportation, operations, or long-term performance), and (2) is the particular test being used or it's frequency (for example, 100%) the most cost-effective approach.

3.3 Hazards to Waste Characterization Workers

References have been made to the extra radiation doses incurred by workers performing "unnecessary" waste characterization activities (NAS/NRC 2001, p 33). The DOE was asked to address questions relating personnel radiation exposure (dose) to various characterization activities at the generator sites. The DOE acknowledged that it does not have, "information relative to dose from TRU waste characterization activities… Dosimetry groups at the various DOE sites differentiate dose by individual rather than by tasks." At best, the DOE was only able to address the questions with a qualitative answer and the promise to provide the information if and when it became available (DOE 2002d, p 23).

The EEG has not received any data that the DOE may have on actual doses received by workers characterizing CH TRU wastes. The EEG's present belief is that these doses are very low and cannot be used as a justification for reducing waste characterization requirements. Another reason for this preliminary conclusion is that (even though it is not waste characterization) the external collective radiation doses received by waste handlers and radiation control technicians

handling and emplacing drums at WIPP are so low (0.06 mrem per container from 3/99 through 12/31/02).

This conclusion is consistent with the DOE response in which the DOE noted that the risk for radiological exposure is very low for NDA, RTR, and HSG sampling and analysis during normal operations. VE is considered to be a moderate risk. As noted by DOE, the impact of VE/repackaging is controlled by ALARA (as low as reasonably achievable) principles, which normally result in very low exposures to workers. Personal protective equipment and procedures are used to prevent inhalation of airborne contamination. DOE does caution that repackaging campaigns for special cases such as ^{238}Pu and high-wattage ^{239}Pu require extra measures to avoid significant doses (DOE 2002d, p 4-7).

4.0 HWFP WASTE CHARACTERIZATION REQUIREMENTS AND EEG COMMENTS

The DOE/CBFO requested that the DOE National Energy Technology Laboratory's Center for Acquisition and Business Excellence (NETL-CABE) prepare an analysis on the cost of waste characterization (NETL/CABE 2003) that estimates the CH TRU waste characterization costs per container. Table 4-3 from this study, *Average Cost of Characterization Activities*, is reproduced here as Table 4-1. Table 4-1 is being used in the report for two reasons: (1) it gives a relative idea of the costs for each "characterization activity" (which are significant), and (2) the "characterization activity" breakdown is a convenient one to use in addressing our waste characterization conclusions and recommendations. A review of the cost study is outside the scope of this report and EEG uses the cost figures as provided, without offering an opinion of their accuracy.

Table 4-2 is an EEG-developed table that shows how the overlap of the waste characterization requirements analyzed in Table 4-1 is used to meet the requirements. The table shows which of these methods are required or used by each agency. A "required" characterization method ***must*** be used either 100% of the time or part of the time to meet the indicated requirement. The term "used" is for a waste characterization method that, in some cases, ***may*** be used to meet a requirement, but the method is not specifically mandated. For example, the HWFP requires HSG sampling and analysis, whereas, to satisfy the TRAMPAC limits on flammability, HSG sampling and analysis is not specifically required but may be, and has been used. The associated average cost of characterization per container from the DOE cost study is also included. The EEG notes that some of the categories are not regulatory requirements. For example, the "Segregation/Rework" must be performed in some cases even though it is not required by any regulatory agency. These categories have been included to retain consistency with the DOE cost study.

It is clear from these tables that nearly all of these requirements and a major part of waste characterization costs can be attributed to meeting the requirements of the HWFP. The following sections describe these requirements.

Table 4-1 Average Cost of Characterization Activities.

Characterization Activity	Percentage of Containers Requiring Activity	Average Unit Cost to Characterize	Average Cost of Characterization per Container
Non-Destructive Assay	100%	$840	$840
Headspace Gas Sampling	100%	$620	$620
Real-Time Radiography	32.8%	$730	$240
Visual Examination/ Retrievably Stored	1.2%	$22,500	$270
Visual Examination/ Newly Generated	67.2%	$540	$360
Solids Coring and Sampling	0.5%	$24,000	$120
Solids Analysis	0.5%	$63,000	$310
Acceptable Knowledge	100%	$87	$87
Drum Venting	1.8%	$120	$2
Level II Management	100%	$160	$160
Gas Generation	9%	$670	$60
Drum Age Criterion	68.7%	$46	$32
Segregation/Rework	30%	$1,400	$420
Waste Certification	100%	$330	$330
Characterization Support Activities	8%	$648	$52
Average Cost of Characterization per Container			**$3,900**

Source: NETL/CABE 2003

Table 4.2. Overlap of Regulatory Agencies and DOE Waste Characterization Requirements and Associated Cost Per Container.

	NMED		EPA		NRC		DOE		
Characterization Requirement	Used by HWFP	Req. by HWFP	Used by §194.24	Req. by §194.24	Used by TRU-PACT-II	Req. by TRU-PACT-II	Used by WIPP CH WAC	Req. by WIPP CH WAC	Average Cost of Characterization per Container [b]
Non-Destructive Assay	No	No	Yes[a]	Yes	Yes	Yes	Yes	No	$840
Headspace Gas Sampling	Yes	Yes	Yes	No	Yes	No	No	No	$620
Real-Time Radiography	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	$240
Visual Examination/ Retrievably Stored	Yes	Yes	Yes	No	Yes	No	No	No	$270
Visual Examination/ Newly Generated	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	$360
Solids Coring and Sampling	Yes	Yes	No	No	No	No	No	No	$120
Solids Analysis	Yes	Yes	No	No	No	No	No	No	$310
Acceptable Knowledge	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	$87
Drum Venting	Yes	Yes	No	No	Yes	Yes	Yes	Yes	$2
Level II Management	Yes	Yes	No	No	No	No	No	No	$160
Gas Generation	No	No	No	No	Yes	Yes	No	No	$60
Drum Age Criteria	Yes	Yes	No	No	Yes	Yes	No	No	$32
Segregation/ Rework	No	No	No	No	No	No	No	No	$420
Waste Certification	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	$330
Characterization Support Activities	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	$52
							TOTAL		**$3,900**

[a] In the required (req) column, "yes" means the method ***must*** be performed 100% of the time or part of the time. In the used column, "yes" means the method ***may*** be performed to meet a requirement, but the specific method is not mandated by that requirement.

[b] The cost of activity spread over all the containers shipped to WIPP.

4.1 HWFP: Acceptable Knowledge (AK) Requirements

AK is the principal waste characterization requirement for all of the regulatory agencies. As shown in Table 4-1, the DOE cost study indicates AK to be one of the least costly of the waste characterization techniques at $87/container. However, the AK package is developed on a waste stream basis rather than on individual containers.

Several slightly differing definitions of the term are in use on the WIPP project; the HWFP states:

> Acceptable knowledge includes a number of techniques used to characterize transuranic (TRU) mixed waste, such as process knowledge, records of analysis acquired prior to RCRA, and other supplemental sampling and analysis data (EPA 1994). (NMED 2003, Attachment B4-1).

Process knowledge" is the knowledge of the waste based on the materials and processes used to generate the waste, and "EPA 1994" is an EPA guidance document on waste characterization for facilities that treat, store, or dispose of hazardous wastes (the WIPP is a storage and disposal facility). Thus, acceptable knowledge is effectively the compilation of all useful knowledge about the waste. Container analyses by other waste characterization methods become a part of the AK for the waste stream, as does any other information related to the waste that is discovered. The HWFP requires AK to be organized in a report on each waste stream, from general facility information (areas and facilities) to specific information for the waste stream (description of the generating process to include buildings, process flow diagrams, material inputs, types and quantities generated, and storage locations). An overall AK summary report is generated after records are found, documents are indexed, and applicable waste and facility information has been organized.

The EEG has not commented specifically on the need for AK as a waste characterization requirement. There has never, to the EEG's knowledge, been any question of the need for an AK-like data accumulation. The HWFP's AK requirements are the most prescriptive of any of

the regulatory agencies. At this time the EEG supports the continued use of the HWFP AK requirements.

4.2 HWFP: Headspace Gas Sampling and Analysis Requirements

The AK requirements section of the HWFP also states:

> Radiography and/or visual examination, headspace gas sampling and analysis, and homogeneous waste sampling and analysis ...are used to acquire supplemental sampling and analysis data to meet the requirements of the Waste Analysis Plan (WAP) specified in Permit Attachment B. (NMED 2003, Attachment B4-1).

More often, the HWFP addresses these techniques as "confirmation of AK"; the EEG views these techniques more as a process for discovering deviations from the currently known AK.

At $620/container, headspace gas sampling and analysis is one of the more expensive costs-per-container waste characterization techniques listed in Table 4-1. According to DOE:

> Headspace gas is measured both to meet transportation requirements and to meet NMED requirements. Several methods are used to collect a sample of gas from inside the top of the container. One method involves drawing a sample of gas through the existing filter by inserting a needle through the filter core. The punctured filter is then removed and a new filter installed. A second method involves using a self-tapping replacement filter that first taps a hole in the waste container. Next the samples are drawn through the self-tapping filter assembly. A third method uses a self-tapping sampling port through which a sample is drawn, and then the port is sealed.
>
> Headspace gas sampling is done in a structure that prevents radioactive particulate from the waste container from escaping into the atmosphere. Precautions are taken around the puncture area to prevent releases of radioactive particulate to the

> atmosphere and to prevent drawing outside air into the container during sampling (DOE 2002d, p 5).

Analysis is targeted to determine the presence and concentrations of about 30 different hazardous chemicals within each headspace gas sample, and the HWFP also requires analysts to look for, and identify, other chemicals in the sample from each container. If these other chemicals are on the hazardous waste list, and appear in 25% or more of the individual containers analyzed in each waste stream, then they are added to the target list for that waste stream also. The analysis is performed according to procedures modified from the EPA's *Test Methods for Evaluating Solid Wastes* (EPA 1996) and *Determination of Volatile Organic Compounds (VOCs) in Ambient Air Using Specially Prepared Canisters With Subsequent Analysis by Gas Chromatography* (EPA 1999). Included in the HWFP requirements are the many sample control methods for quality assurance and quality control. Those also contribute to the cost of headspace gas sampling and analysis.

The EEG has commented on HWFP headspace gas requirements, stating to the NAS/NRC WIPP CH Waste Characterization Committee in 2002 that though headspace gas sampling and analysis helps meet the 40 CFR 264.13(a)(1) requirement for a detailed chemical analysis of a representative sample of the waste, "...we do not see why 100% headspace gas sampling at the sites should be necessary to ensure compliance with Room Based Concentration Limits" (EEG 2002c). The HWFP establishes concentration limits for VOCs in the underground rooms, primarily as a protection for underground and above ground workers and members of the public. The headspace gas analysis results are one of two checks to ensure that these concentrations are not exceeded; the other check is by sampling of the air from these underground rooms (confirmatory VOC monitoring). The EEG went on to state the following:

> The Code of Federal Regulations requirement for a detailed chemical analysis of a representative sample of waste is addressed only by headspace gas analysis for most of the debris waste. These analyses do provide additional information on the contents of waste containers. Additional waste streams have been defined because of the results of these analyses, and on occasion additional RCRA

> hazardous waste numbers have been added to waste streams. The importance of these functions has occasionally been denigrated, primarily because this additional information is not used to control quantities of VOCs coming to WIPP other than to show compliance with the room based concentration limits (EEG 2002c).

In more recent comments to the same NAS/NRC committee, the EEG again noted that room-based concentration limits can be met by confirmatory VOC monitoring at the WIPP, that "A comprehensive HSG [headspace gas] sampling program is also the most direct means of ensuring compliance with the flammable gas concentration limits for transportation that are included in the TRAMPAC", and that:

> HSG sampling is the primary way DOE has chosen to meet the "detailed chemical analysis...of a representative sample of the waste" that is specified in the New Mexico Administrative Code. This information is used (in conjunction with acceptable knowledge) to assign hazardous waste numbers to each container. However, EEG is not aware that these hazardous waste numbers are used to exclude waste from the WIPP or to otherwise control the hazardous waste. These data probably provide the incidental benefit of confirming AK and ensuring the various Waste Acceptance Criteria (WAC) requirements for stability of waste are met.
>
> EEG believes that it is desirable to maintain a comprehensive HSG program for WIPP CH-TRU wastes. However, it should be possible to require less than 100% sampling in some cases. This determination needs to be made on small batches or waste streams where there is reason to believe that relative uniformity exists. Also, the detailed approach necessary to ensure that representative data is still obtained needs to be justified by a proposed modification request (PMR) to the HWFP in the same manner that existing PMRs are justified (EEG 2003b).

One of EEG's concerns about the complete elimination of HSG sampling is that knowledge of the waste may be much less certain on retrievably stored waste which has not yet been characterized.

As noted above, the quality control and quality assurance (QA/QC) requirements for headspace gas sampling and analysis processes would appear to contribute to the DOE's estimated cost for headspace gas activity. The EEG has stated several times a variant of the following:

> The relaxation of audit requirements and QA/QC is not an appropriate way to reduce the waste characterization burden. These requirements should maintain the current level of stringency. The appropriate way to reduce the waste characterization burden is to eliminate unnecessary requirements, not to reduce the degree of compliance. (EEG 2002c).

Other EEG comments have noted that headspace gas analysis is often used to ensure that flammable gas limits for transportation are met, and the HWFP itself notes that headspace gas is useful for determining potential flammability.

As noted in Section 2.1, the DOE has successfully pursued modifications related to headspace gas requirements in the HWFP that the DOE believes will result in savings of tens of millions of dollars. It should also be noted that the DOE has itself endorsed continuation of some headspace gas analysis (DOE 2002d, p 17-18).

Reduction in the HSG requirement should be possible if the DOE submits detailed PMRs on specific waste streams.

4.3 HWFP: Drum Age Criteria (DAC) Requirements

The DAC is the time after the closing of a container necessary to ensure that VOC and flammable gas concentrations in the headspace of the container have achieved at least 90% of equilibrium concentration. The times vary widely, currently from four days to 283 days,

depending on the waste type, packaging configuration, and the container filters. The DOE cost study (NETL/CABE 2003) considered the DAC as a separate requirement with a cost of $32/container, but the DAC is solely for purposes of establishing the representativeness of the headspace gas in a container, and is really a part of the sampling process for headspace gases. The DAC is also used as a part of the TRUPACT-II requirements when flammable gases are to be actually measured.

The DOE eventually succeeded in obtaining changes to the initial DAC values in the HWFP, but three modifications were submitted before this success was obtained. In a paper (Walker and Silva 2002) presented at the conference Waste Management '02 conference midway through these attempts, the EEG used the DAC modifications as the principal example to point out four observed difficulties in the DOE's approach to the permit change process. Three of these difficulties delayed the DAC permit modification request.

First, the modification was not properly classified. The DOE submitted the revised DAC as a Class 1. This was immediately rejected by the NMED. Second, when submitted as a Class 2 proposal, the DOE did not provide sufficient data and information. Third, the DOE failed to meet the expectations of the regulator. In rejecting the first PMR, the NMED cautioned DOE to submit the request as a Class 3. Nonetheless, DOE submitted the request as a Class 2. NMED was forced into the process for changing the request to Class 3. The action by DOE contributed to further delay.

The DAC modification was an important change to the HWFP and TRAMPAC. It decreased the storage times on many waste containers by several months. The modification process for the eventual Class 3 request to the HWFP also underscored the value of public involvement as specified in the process. The EEG requested that the DOE provide the input and output files for the DAC computer model. These were later provided to the EEG by the DOE at the insistence of the NMED. The public review process identified six discrepancies between the output files and the DAC tables that until then had not been identified.

4.4 HWFP: Real-Time Radiography (RTR) Requirements

All WIPP waste containers are required by the HWFP to undergo either radiography or VE. RTR is a non-destructive examination technique that utilizes x-ray technology to create images of the interior of waste containers. The "real-time" component is important. It allows the radiography technician to increase and decrease the energy of the x-rays so as to create images of different density materials within the container. Thus, lower energy x-rays can produce an image of loose plastic material in the containers, and adjustments can also be made to observe the interior of metal cans or bottles or other denser material that may be in the container.

With some training, an operator can distinguish between different kinds of metals (lead, steel, aluminum, by their different densities), determine the number of layers of plastic packaging around waste, and detect any free liquid in bottles or cans that are in the waste. Thus, radiography can be used to create a record of the physical contents of the container. The HWFP requires that operators of radiography equipment be trained both formally and by on-the-job techniques. The operator must successfully demonstrate an ability to identify a specific list of objects in the waste prior to performing official scans. Operators must then be further trained to the waste streams they are reviewing, an audio-visual recording of the examination of each container must be made. A similarly-trained independent reviewer must confirm the information in the records created by the operator. Once each day, or once each testing batch, (20 or fewer containers) a replicate analysis must be performed by an independent operator. Operators are required to determine the Waste Matrix Code for the waste, estimate material parameter weights, and look for prohibited items in the waste.

It is worth noting that the 40 CFR 194.24 waste characterization requirements to quantify non-ferrous metals and cellulosic materials are met primarily through radiography. These are some of the material parameters that the HWFP requires radiography operators to estimate. In the absence of HWFP requirements, a comparable program would either be needed to address the 40 CFR 194.24 waste characterization criteria or alternate methods (visual examination) would be necessary.

As with AK, few substantive concerns have been raised about radiography requirements and the EEG's comments on radiography have been brief. In 1999, as part of a broader statement, an EEG comment was that:

> EEG agrees with the generic policy that data that is not going to be used should not be collected. This includes data for all requirements, not just VE. However, it is necessary to do thorough evaluations to show that RTR and/or VE are not providing useful data in a waste stream. At the recent SRS audit, 15% of the first batch of drums was rejected by RTR. (EEG 1999).

Radiography was introduced in lieu of visual examination of waste, so that the DOE's HWFP application expected that only visual examination would be used for newly generated waste. The HWFP initially followed this track, but at least one waste characterization program found radiography to be so useful, the DOE submitted a PMR to allow radiography as well as VE to be used for newly generated waste. The PMR was quickly approved, and either method may now be used for newly generated wastes.

The overall radiography program is an important part of the WIPP waste characterization program and should be retained. It may be possible to reduce some of the detailed procedural requirements in the HWFP.

4.5 HWFP: Visual Examination for Retrievably Stored Waste Requirements

VE may be used as an alternative to RTR for retrievably stored wastes, but this alternative may not have been used yet. However, because RTR is merely an imaging technique, a radiography operator cannot, for instance, read the label on a bottle, or estimate a weight by lifting the object. The HWFP also requires that a statistically determined sample of radiographed containers undergo confirmatory VE. The size of the statistical sample is based on the number of mis-certifications found from the previous year at that site, from each of the three summary category groups (debris, solidified wastes, and soil/gravel wastes). Thus far, less than 2% of retrievably

stored containers undergo VE. Nonetheless, the process is an expensive component of the waste characterization program. The DOE estimates the cost to be $22,500 per container examined, or $270 per container over the entire population sent to the WIPP.

The HWFP requirements for VE include those for RTR (determine Waste Matrix Code, measurement, rather than estimation, of material parameter weights), but also requires that "all discernable waste items" are to be identified, as well as residual and packaging materials. A VE expert is required to be present. This individual's discretion determines whether bags or cans inside the container must also be opened (weights of the contents are to be estimated if it is not opened). The packaging configuration, type and number of filters, and other information necessary for determining the DAC are also to be recorded. Audio-visual recordings of the process are to be made, and operators (as well as the much more thoroughly trained VE expert) must undergo formal and on-the-job training.

The EEG has stated that:

> Claims are often made that VE is dangerous because of additional radiation exposures and possibility of contamination. EEG has discussed this issue with persons doing VE at INEEL, RFETS, and LANL and found they don't feel VE is dangerous and do not have data on incremental radiation exposures. More specific data and evaluations are needed if danger is to be used as an argument against VE. Also, plans to use 100% VE for newly generated wastes appear to be inconsistent with expressed safety concerns. (EEG 1999, p 8).

The DOE has been successful in modifying the HWFP on retrievably stored VE, producing great cost savings, as noted in Section 2.1.

4.6 HWFP: Visual Examination/Newly Generated Requirements

For newly generated wastes, the original HWFP (based on the DOE's application) specified only VE as a method for determining the required detailed physical analysis of a representative

sample of the waste. The process actually specified in the HWFP has the advantage of allowing verification at the time the container is being filled and is somewhat different from retrievably stored VE, and has often been referred to as "visual verification" (V-squared) to distinguish it from the retrievably stored process. No audio/video recording is required, but two visual examination operators are required to observe the loading of waste into containers and record the data. The same data is to be recorded as for retrievably stored VE.

The EEG has not commented specifically on the visual verification process, except when commenting on the PMR to allow radiography as well as visual verification. In those comments the EEG noted that visual verification is a much higher quality process than radiography, and that the requirement for two trained visual examination operators to perform the visual process:

> ...may be overkill; the HWFP could be modified to require generator site procedures be developed and implemented that would require, for each waste container, that a data form be used to document the contents of the container, and then require a single verification of the information on the data form (EEG 2002b).

As noted previously, the PMR submitted by the DOE was successfully integrated into the HWFP.

4.7 HWFP: Solids Coring and Sampling, and Solids Analysis (Homogeneous) Requirements

The DOE's waste characterization cost analysis in Table 4-1 shows solids (solidified wastes and soil/gravel) coring and sampling costs separate from the chemical analysis of these solids. For the 0.5% of drums that will be cored, sampled and analyzed, the estimated cost per drum is $24,000 for coring and sampling and $63,000 for analysis. When spread over all containers shipped to WIPP, for sampling, the cost per drum shipped is estimated at $120; for the analysis, the cost is $310. The overall estimate of $430 per container shipped is among the highest waste characterization method costs.

"Coring" is a process wherein a container of solids is opened, and a hollow drill bit is inserted near the bottom of the container. The core is taken from the bit and "sampled" by removing either one or three thin sections from along its length. These sections become the sample.

For retrievably stored wastes, the HWFP states that homogeneous sampling and analysis is used to determine the toxicity "characteristic" in the waste; that is, the hazardous compounds that are considered toxic only if present above the threshold concentrations listed in 40 CFR 261.24, or if the "listed" wastes under Subpart D of 40 CFR 261 are present. Sampling of these waste streams is statistical, rather than each of the containers; five randomly selected containers must be sampled initially, then chemically analyzed. The average concentration and standard deviation of each hazardous compound is then computed and used, along with the threshold concentrations (or program required quantification limit, if it is a "listed" waste in Subpart D) to calculate the total number of containers from the waste stream that must be sampled. For most (perhaps all) of the homogeneous waste streams analyzed so far, the initial five samples suffice.

The HWFP requires analysis of homogeneous samples for total VOCs, semivolatile organic compounds (SVOCs), and analysis for metals. Tables in the HWFP list over 30 chemicals for the VOC analysis, 11 for the SVOC analysis, and 14 metals that are the primary targets, but other hazardous constituents may be added to the list for a waste stream if they are found in more than 25% of the samples from that waste stream. A test for Polychlorinated Biphenyls (PCBs) is also currently required, but a PMR is currently in process to eliminate those requirements now that the DOE has obtained an approval from the EPA under the Toxic Substances Control Act (TSCA) to dispose of PCB-contaminated wastes at the WIPP. A full panoply of QA/QC requirements are also established for homogenous sample analysis, and radiation protection activities associated with opening of containers and processing the samples also contribute to the homogeneous sampling and analysis program.

The EEG has commented several times on homogeneous waste sampling and analysis, eventually concluding that these requirements are not needed. In 1999, comments on two DOE documents, in a section entitled, "Homogeneous Waste Sampling and Analysis", the EEG first

stated that metals analysis was not needed, and deferred an opinion on the homogeneous VOC and SVOC requirements:

> For the following reasons, EEG sees no scientific reason why it is necessary to analyze for metals at all:
>
> $ DOE apparently did not feel that metals concentration data were important enough to include in the RCRA application. The State apparently concurred since they did not request that the data be include[d].
>
> $ The required hazardous metals data are not to be used for any regulatory control under the Draft Permit.
>
> $ Evaluations in EEG-72 concluded that human exposures to hazardous metals at WIPP would only occur from the types of operational and human intrusion accidents that released radioactive materials. The calculated radionuclide risks (Excess Cancer Fatalities) were $2x10^6$ times the hazardous metals release for operational accidents and $5x10^5$ times for long term releases. Furthermore, methods used to clean up radionuclide contamination would also be effective in cleaning up hazardous materials.
>
> $ EEG has no opinion at this time on sampling for VOCs and SVOCs in homogeneous wastes. The decision should be based on whether any useful information will be obtained for VOC control under the RCRA permit... (EEG 1999).

In 2002, in comments for the NAS/NRC CH waste characterization committee, the EEG added the homogeneous VOC and SVOC analyses to metals:

> The HWFP requires a fraction of homogeneous waste containers to be analyzed for toxic metals, other hazardous chemicals, volatile VOCs [sic], and semi-volatile VOCs [sic] (SVOCs). The EEG has stated that we see no technical reason why it is necessary to analyze for metals and chemicals at all. Our reasons are...[Followed by the information in the first three bullets of the previous quote] (EEG 2002c, p 8).

Currently, the EEG continues to believe that the homogeneous sampling and analysis are unnecessary characterization requirements in the HWFP.

The DOE has successfully pursued changes to the HWFP on homogeneous sampling and analysis issues, the major change being to add to the statistical quality control method initially required for newly generated homogenous wastes so that the retrievably stored process could also be used. Quality control requirements for SVOC specific analytes (pyridines and cresols) were changed in another PMR, and one of the first HWFP PMRs successfully altered the requirement for core sampling to allow one sample to be taken from the core rather than the three samples from each core that was previously required.

4.8 HWFP: Level II Management (Project Level) and Waste Certification Requirements

This is the first time EEG has commented on these Level II and Waste Certification Requirements. "Level II Management" requirements are estimated to cost $160 per container by the DOE. "Level II Management" requirements are apparently those activities addressed in the HWFP as "Project Level" requirements. These are solely HWFP requirements, though they appear to be closely intertwined to the "Waste Certification" requirements (at $330 per container) also shown in Table 4-1. Further, the quality assurance provided by these checks supports non-HWFP requirements as well. The two activities, Level II Management and Waste Certification, from Table 4-1 will be covered as a single topic in this section. It should be noted that the 40 CFR 194 waste certification process does not specify these activities, but a

comparable program would likely need to be developed specifically for the 40 CFR 194 required program were it not specified in the HWFP.

Project level activities are principally performed on data packages developed at the "data generation level" (radiography or visual examination test batch data reports, headspace gas and homogeneous waste sampling batch data reports, and headspace gas and homogeneous analytical data reports). These data packages are compilations of the data specified to be collected during the activity (including quality control information such as independent technical review forms, supervisor review forms, quality assurance review forms, reports on non-conforming items or processes during the activity, chain-of-custody forms, evidence of sample preservation, quality control sample results, etc.). Although radioactive materials are not a part of the HWFP function, data packages for the radioactive component waste characterization are also developed and processed based on the requirements specified in the HWFP.

At the project level, the Site Project QA Officer (SPQAO) is then required to review and sign all batch data reports supplied from the data generation level for completeness. This includes verification that quality control checks were properly performed, and that the quality assurance objectives specified in the HWFP were properly met. The Site Project Manager (SPM) also must sign off on the package; the SPM must ensure that the DAC is valid, that the necessary generation level reviews were performed and ensure that the checklists are complete, and that the data meet the required quality assurance objectives. Both the SPQAO and the SPM must prepare summary reports that include validation checklists, discussion of any nonconformances within the data package, signatures of the individuals. When a new waste stream is proposed, the Site Project Office must determine that sufficient information is available in the preliminary data packages to establish the waste stream. Site project offices are responsible for preparing the Waste Stream Profile Forms (WSPF) that officially document the new waste stream, and a characterization information summary from the preliminary data packages that is required along with the WSPF.

Other project level activities include performing the statistical calculations for random sampling. The site project offices also calculate the confidence levels from analyses, and document that

these are within the quality assurance objectives established in the HWFP. The site project office also is responsible for putting waste characterization and transportation information into the WIPP Waste Information System (WWIS), and negotiating with the WIPP site reviewers of this information.

The EEG has not commented on the project level HWFP requirements, but the data package review and approval process may be one of the areas to which the general EEG comment that, "We believe waste characterization requirements are excessive" applies. We suspect that many of these requirements were provided from a legal perspective, rather than a technical one, and therefore may be useful on that level. However, from a technical perspective, the data package review-and-approval process invoked by the HWFP appears excessive.

The DOE submitted a Class 2 PMR which would have virtually eliminated project level waste characterization activities, among other changes. This modification was later withdrawn by the DOE.

4.9 HWFP: Characterization Support Requirements

The HWFP requires the DOE to conduct an audit and surveillance program to ensure that waste characterization sites conduct waste characterization activities in accordance with the HWFP Waste Analysis Plan, and that the information supplied by each site is managed properly (records management). The HWFP also requires specific training for all areas discussed above. The 40 CFR 194 criteria also require these activities, as does the DOE itself.

The EEG has commented several times on the WIPP audit and surveillance program over the years. These comments have generally been supportive of the program and we have observed it to be a very good QA program. The basic EEG comment has been that waste characterization requirements may be changed, but not the auditing/surveillance program. For example, in a comment to the NAS/NRC committee, the EEG stated:

> Quality assurance requirements in the CBFO Quality Assurance Program Document (QAPD) are applied to waste characterization activities; while

> the EPA has mandated those in use for those processes related to 40 CFR 191/194, the HWFP only requires that the quality assurance practices in the CBFO QAPD be followed, and there may be a way of altering the requirements for non-radioactive waste characterization. However, for a variety of reasons, the EEG believes that a change in the QA requirements would not substantially decrease waste characterization requirements and would likely result in less assurance that the program was in compliance. (EEG 2003a).

Requirements for training are included in the CBFO QAPD, so that this EEG comment would appear to cover training, also. The EEG has not commented on TRUPACT-II loading, equipment and facilities, waste storage, or records maintenance in terms of their importance to the WIPP project.

5.0 40 CFR 194 (EPA) REQUIREMENTS

Title 40 CFR 194.24(c) requires the DOE to specify limiting values for waste components that are to be emplaced at WIPP. The primary analyses are quantification of radionuclides. However, there are three non-radiological waste materials that need to be quantified.

(1) free water (other regulatory agencies use the term free liquids or residual liquids)
(2) ferrous and non-ferrous metals
(3) cellulose, plastic, and rubber (CPR)

These materials are currently quantified principally by use of radiography and visual examination methods, except for the ferrous metal requirement. Chapter 4 provides the discussion of radiography and visual examination waste characterization methods. Both the radiological and non-radiological quantification is to include measurement error statistics (EPA 1998).

Under 40 CFR 194 criteria, radionuclide quantification requirements can be met by either destructive (radiochemical analysis) methods or NDA methods. Nearly all (if not all) radionuclide quantities reported to date have been by NDA. The DOE estimated that the average cost per container for NDA measurements was $840, thus making NDA the single most expensive waste characterization method (see Table 4-1).

5.1 EPA's Non-Radiological Waste Criteria

5.1.1 EPA: Free Water Requirements

EPA's Compliance Certification Decision (EPA 1998) limits the total amount of free water in the repository to 1685m^3, which is equivalent to an average of 1% of the volume of a waste container. This limitation is required because of the assumptions DOE used for waste room modeling in the Compliance Certification Application (DOE 1996). This requirement could be satisfied by a repository (or waste panel) average rather than on each waste container. However,

transportation, HWFP, and WIPP Operations and Safety requirements all limit free water to 1% on each container.

EEG believes the free water limit of 1% on each container should not be changed since it is required for the transportation, HWFP, and WIPP criteria, and is probably the most cost-effective way to ensure the EPA's requirement is met.

5.1.2 EPA: Metals Requirements

The EPA has a minimum requirement for the quantity of ferrous metals in the repository, to maintain a reducing chemical environment in the repository in order to minimize radionuclide mobility. Waste drums and other containers provide more than the minimum ferrous metals requirement. The method of compliance is to simply count the containers in the repository and multiply the number of containers by the amount of iron in each container. The DOE has stated that enough containers have already been placed in the repository to meet the ferrous metal requirement.

EEG has stated that this requirement should be tracked at a waste panel (rather than entire repository) level. However, we have also said "there may be an argument for eliminating further tracking of this parameter" (EEG 2002c). This is really a non-problem and will continue to be unless there are future changes that allow non-ferrous waste containers to be emplaced.

Non-ferrous metals are included in the EPA's requirements because it was argued that these materials will reduce or eliminate the possibility that the radioactive components would attach to organic ligands (EPA 1998). The non-ferrous metals will attach to the binding sites on these ligands (EPA 1998). The amount of non-ferrous metals in each waste container is estimated by radiography or measured (weighed) during visual examination; a discussion of these methods can be found in Chapter 4.

5.1.3 EPA: Cellulose, Plastic and Rubber (CPR) Requirements

The presence of cellulose, plastic, and rubber could cause generation of gas in sealed repository rooms which could affect the release of radionuclides from the repository. Because of this

potential, the EPA has set a maximum repository limit on the kilograms of CPR. At present the mass of CPR is estimated or measured in each container during either radiography or visual examination.

This quantification continues to be necessary because the limit is important to assumptions used in the performance assessment for the repository. However, it does not seem to be difficult to stay below the limit. EEG has stated, "…, quantification on a waste stream (rather than individual container) basis should be acceptable if properly estimated." (EEG 2002c).

5.2 EPA's Radiological Waste Characterization Requirements

The principal EPA radiological waste characterization requirements are for the purpose of tracking the quantities of ten radionuclides emplaced in the repository to ensure that the radiological limits established for the repository are met. This continuously updated radionuclide inventory is also important for evaluation of long-term compliance during the performance assessments required at each five-year recertification. Radionuclide quantification is required on each waste container.

There are additional radiological waste characterization requirements for transportation and for the WIPP repository. These requirements will be discussed in Chapters 6 and 7. However, it is important to recognize that these transportation and WIPP requirements also require determination of some individual radionuclides which would have to be obtained even in the absence of EPA requirements.

Appendix A of the CH WAC of the Waste Isolation Pilot Plan (DOE 2002a) specifies the Radioassay Requirements for CH TRU in considerable detail. The EEG commented on the Draft Appendix A during its development (EEG 2002a).

5.2.1 EPA: The Ten Required Radionuclides

The ten required radionuclides are ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{241}Am, ^{233}U, ^{234}U, ^{238}U, ^{90}Sr and ^{137}Cs. Some of the radionuclides are more important for long-term compliance. The most

significant are ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Am. Since their half-lives and specific activities vary considerably, each of the four present a different hazard and their activities should be separately determined. The other tracked radionuclides (^{233}U, ^{234}U, ^{238}U, ^{242}Pu, ^{137}Cs, and ^{90}Sr) have less effect on repository performance but could affect certain scenarios either because of the possibility of "early" human intrusions (that is, within hundreds of years of closure) or non-random emplacement of waste in the repository.

There are other reasons for tracking several of these radionuclides. Uranium-233 must be determined because of the NRC FGE requirement. Uranium-235 is not one of the ten EPA tracked radionuclides, but it is required to be tracked by the NRC FGE requirements. Also, if minor radionuclides in an assay are recognized, there is more assurance that the major contributors are correctly identified.

One important radionuclide not included in the 10 required radionuclides is ^{241}Pu. It is the primary contributor to total WIPP activity (60% of the activity emplaced to date) and it decays with a 14.4 year half-life to ^{241}Am, which is an important radionuclide. The sites are reporting ^{241}Pu now, although not required to do so, and this reporting should continue.

The EEG believes that all ten of the radionuclides should be tracked and reported. Also, ^{241}Pu tracking should be required.

5.2.2 EPA: Other Non-Destructive Assay Issues

EEG has provided opinions on two issues concerning NDA requirements. These are: (1) the EPA requirement that determination of isotopic ratios be on each waste container (rather than on a waste stream); and (2) use of non-WIPP certified instruments to perform waste characterization.

EEG believes justification for less than 100% quantification and determination of isotopic ratios may be possible for <u>some</u>, but certainly not all, waste streams (EEG 2002c).

The DOE has proposed to use non-WIPP certified assay systems used for Safeguards measurements for NDA analysis of WIPP waste. EPA has rejected this DOE proposal. EEG currently agrees with the EPA position. We do not believe that quality control of NDA measurements should be relaxed. Also, it has not been shown that radionuclides other than ^{239}Pu and ^{240}Pu can be reliably determined with these instruments. The EEG has stated:

> EEG believes that quantification of radionuclides and confirmation of isotopic ratios should continue to be obtained as they are now, i.e., by using WIPP-certified NDA systems. These determinations, unlike some other required waste characteristics that cannot be directly measured, can be obtained directly by measurement. Any additional efforts to produce more accurate AK in order to reduce the NDA burden will inevitably result in less accurate radionuclide values (EEG 2002a).

6.0 NRC (TRUPACT-II) TRANSPORTATION REQUIREMENTS

The NRC has extensive payload requirements for shipment of wastes in the TRUPACT-II package. These requirements include:

(1) container and physical properties
(2) nuclear properties
(3) chemical properties
(4) gas generation
(5) payload assembly
(6) quality assurance.

These requirements are specified in detail in the TRUPACT-II TRAMPAC (DOE 2003a). Compliance is through generator or storage site programmatic or waste-specific TRAMPACs. The DOE Carlsbad Field Office (CBFO) is responsible for approving these site-specific TRAMPACs and verifying compliance. The NRC does not become directly involved with this characterization process.

Payload requirements 1 through 4 above include waste characterization requirements. These waste characterization requirements are similar to those required in either the HWFP or in EPA's NDA requirements and are incorporated in these two waste characterization programs.

6.1 TRUPACT-II Container Properties

Most container properties involve weights and listing of acceptable containers. However, there are three container properties that are obtained from waste characterization requirements of the HWFP. These are:

(1) Filter vents are required in each waste container.

(2) Residual liquids shall not be more than 1% of the volume in any payload container. This is verified by RTR, VE, or AK.

(3) Sealed containers greater than four liters (nominal) are prohibited unless in waste material Type II.2 packaged in a metal container. Compliance is determined by RTR, VE, or AK.

6.2 TRUPACT-II Nuclear Properties Characterization

6.2.1 Nuclear Criticality

In order to ensure that nuclear criticality will not occur during shipments it is necessary to limit the FGE in individual waste containers. Requirements in Appendix A of the CH WAC are currently used to satisfy all NRC radioassay requirements even though this is not mandated by the TRAMPAC. This requires quantification of all fissile radionuclides. Although a number of transuranic radionuclides can be fissionable, the most important ones at WIPP are ^{239}Pu, ^{235}U, and ^{233}U. Therefore, it is necessary to determine the quantity of these three radionuclides through the NDA process discussed in Chapter 5. As mentioned in Chapter 5, ^{235}U quantification is not required by the EPA. In many cases the FGE value will be well below allowable container and TRUPACT-II limits and this requirement can be satisfied by AK.

6.2.2. Radiation Dose Rates

External radiation dose rates are limited to 200 millirem per hour at the surface of waste containers. This is a mandatory measurement, but is not a waste characterization requirement.

6.2.3 Decay Heat Limits

Ionization caused by radioactive decay can generate hydrogen gas which must be controlled in the TRUPACT-II. The decay heat value, which is a gas generation requirement, is used in determining the payload shipping category. Decay heat values are calculated from the

radioactivity of each radionuclide in the container. Therefore, it is necessary for the NDA to quantify all significant radionuclides in the waste. The EPA requirements for NDA provide adequate information to determine decay heat values.

6.3 TRUPACT-II Chemical Properties Characterization

Pyrophoric materials are limited to small residual amounts (< 1% by weight). Explosives, corrosives, and compressed gases are prohibited. Chemical composition is required to be known in order to determine gas generating properties. Chemical compatibility is also required by complying with, *A Method for Determining the Compatibility of Hazardous Waste*, (Hatayama and others 1980).

Compliance with the requirements is demonstrated via AK, VE, or RTR. These same criteria are also required under the HWFP, which as noted, requires more robust waste characterization methods (see Chapter 4).

6.4 Gas Generation Requirements

6.4.1 Payload Shipping Category

The payload shipping category determines the decay heat limit that is necessary to ensure that hydrogen gas concentrations will be no more than 5% by volume in the innermost bags within the waste container. In addition to the decay heat value determined from NDA, it is necessary to determine the waste type from the chemical properties and tables of allowed materials. Chemical properties are determined from AK, VE, or RTR. The number of layers of bags in a container, as well as the presence of a rigid liner is both necessary to determine the payload shipping category and these are confirmed by RTR or VE.

6.4.2 Flammable (Gases and VOCs) Concentration Limits

The TRAMPAC also limits the presence of methane and flammable VOCs as well as hydrogen, to ensure the absence of flammable mixtures in TRU waste payloads. The limit of flammable VOCs in the headspace of a waste container is ≤ 500 parts per million.

Procedures for showing compliance with the Gas Generation Requirements can become very complex. If the decay heat limit requirement is met and AK is adequate to verify that the ≤ 500 parts per million flammable VOC requirement can be met, the container falls into the Analytical Category and the requirement can be satisfied by analysis. Otherwise, containers fall into the Test Category.

Test Category containers may be able to show compliance either by measurement of the headspace of payload containers or by Full-Drum Testing. Headspace gas analysis, required in the HWFP, can be used to satisfy the flammable VOC limit requirement.

6.5 EEG Positions on NRC Requirements

The three waste characterization requirements in the Container Properties should be retained. Other changes in Container Properties (primarily specifying appropriate waste containers) would be acceptable if approved by the NRC's Revision Process.

There should not be any changes made in Nuclear Property requirements.

The basic gas generation requirements (hydrogen gas concentrations of < 5% by volume in the innermost bag and flammable VOC concentrations ≤ 500 ppm in the headspace of waste containers) should remain as described in the current version of the TRAMPAC (DOE 2003a). The procedures for showing compliance with the gas generation requirements were quite conservative in the original Certificate of Compliance in 1989. This was because of the lack of sufficient data or demonstration of alternative analytical procedures. There have been many changes in these procedures over the years and it is now possible to show compliance for many waste containers that would not have originally been shippable. EEG has considered this revision process and NRC's evaluations to be an acceptable process. We believe it is appropriate for DOE to continue to propose procedure modifications and that NRC should critically evaluate these before approval.

7.0 THE WIPP CH WAC AND WIPP OPERATIONAL WASTE REQUIREMENTS

7.1 History of the WIPP WAC and Waste Characterization

Waste characterization has been an important consideration for the WIPP since its earliest days. As early as 1976 the WIPP scientific advisor, Sandia National Laboratories, began, "...to gather the diverse input required to establish appropriate criteria," for waste characterization. These were later published in the1980 *Report of the Steering Committee on TRU Waste Acceptance Criteria for the Waste Isolation Pilot Plant*, which was the first of a series of documents referred to as the "WIPP WAC" (DOE 1980). This first WAC contained similar or identical criteria to many of the waste acceptance criteria in the most recent version (DOE 2002a), including elements that are now considered to be HWFP, 40 CFR 194, and TRAMPAC requirements. These include requirements for residual liquids, free water, and free liquids respectively (HWFP, 40 CFR 194, and TRAMPAC), pyrophoric, corrosive, and explosive materials (HWFP, TRAMPAC), compressed gases (HWFP, TRAMPAC), toxic materials (HWFP), waste certification requirements (HWFP, TRAMPAC), physical description of the waste (HWFP, TRAMPAC), combustibility (HWFP TRAMPAC), surface dose rates (TRAMPAC), thermal power (TRAMPAC), container requirements (TRAMPAC, HWFP), and hazardous materials (HWFP). These and other criteria were all included based on internal DOE Order and policy requirements current at that time.

Earlier versions of the WAC contained a discussion of the technical rationale for each criteria and justification to the criteria. The CH WAC no longer includes such rationale or justification. EEG has stated:

> EEG objects to the continued practice of deleting the history and technical justification of criteria when the CH-WAC is revised. Our concern is that a contractor or review group might propose to revise or delete a criteria because they were unaware of the technical basis and that CBFO would too quickly adopt those recommendations. Also, we

> have a concern that future revisions to the CH-WAC may not critically evaluate the need for revised or new requirements that would improve safety at WIPP. EEG, in its role of representing the State of New Mexico in review of the Safety Analysis Report (SAR), will keep this concern in mind during future WAC and SAR reviews (EEG 2002a).

In 1984 DOE Order 5820.2 changed the definition of transuranic from >10 nCi/g of long-lived alpha-emitting waste to >100 nCi/g. Revision 2 of the WAC (DOE 1985) included that definition, but it was not until Revision 3 (DOE 1989) that the definition became a WAC criterion. In 1992, the WIPP Land Withdrawal Act (LWA) included and extended this definition, making it federal law as well as a DOE requirement.

In 1989 the TRAMPAC added criteria and requirements (see previous Chapter), and the NRC became a second regulator of the WIPP waste characterization. To this time the WAC had been the single most important WIPP waste characterization document extant. With first the TRAMPAC, then the applications to the NMED and EPA, and finally the resultant 40 CFR 194 Certification by the EPA (1998) and promulgation of the HWFP (1999), the criteria in the WAC also became less authoritative. The WAC became more the DOE's working version of the criteria included in these other documents.

At the waste characterization level, other more specific requirement documents began at least as early as 1991, implementing the methods used to meet the criteria from these upper-tier documents. In 1979 the INEEL (then INEL) had set up a program to, "...confirm that drums shipped from Rocky Flats contained the assigned item description code (IDC), and to determine the possible hazardous constituents in the waste." (Haily1995). The waste characterization methods of visual examination and gas sampling were used. A 1983-1985 program at the INEL pioneered real-time radiography, headspace gas sampling, solids sampling and analysis, and radioassay (gamma only) in the first attempt to examine waste for compliance with the WAC (Clements and others 1985). Extensive visual examination was also performed. In 1985 neutron NDA—the basic component of current NDA systems–was used in still another INEL program (Hailey 1995).

By 1991 intermediate-level requirements documents were developed by the WIPP. These documents translated the WAC criteria into waste characterization methods and requirements for the transuranic waste generating and storage sites in the DOE complex. The 1995 *Transuranic Waste Characterization Quality Assurance Program Plan* (DOE 1995) included the TRAMPAC waste characterization requirements and also established the waste characterization requirements that the EPA accepted as a part of the 40 CFR 194 certification of the WIPP. This document also contained equivalent methods and requirements to those later promulgated in the WIPP HWFP in 1999 (Channell and Walker 2000).

7.2 Current DOE Waste Acceptance Criteria

The current WAC is for CH TRU waste only (a draft WAC for RH is a part of a DOE submittal currently under evaluation by the EPA for approval of RH TRU waste characterization). Most of the waste characterization criteria found in the CH WAC has been addressed in earlier chapters of this document in one form or another; the remaining area are primarily those self-required by the DOE. As is noted in Section 2.4 of this report, these are primarily from the WIPP site Safety Analysis Report (SAR) (currently DOE 2003c), and more specifically are collected in the Technical Safety Requirements (TSRs) (currently DOE 2003d) which is an attachment to the SAR.

Statements in the TSRs clearly indicate that the WIPP Waste Acceptance Criteria, which drive the waste characterization program, is very important for the safety, health, and environment of the WIPP. The quality and completeness of the waste characterization effort is critically important to WIPP operational activities and some of the requirements are only covered in the CH WAC. It is very important that operational health and safety requirements are constantly evaluated via the TSR portion of the CH TRU SAR and any necessary changes be incorporated in the CH WAC.

The SAR and TSR waste characterization criteria are developed by applying DOE Orders and other DOE internal regulatory documents to the WIPP site. The WIPP TSR criteria include many prohibited wastes that are also prohibited by other WIPP waste characterization

regulations, including the less-than-1% liquids prohibition described in Chapters 4, 5, and 6; the prohibition against pyrophoric materials; prohibition of explosive and compressed gases (Chapters 4 and 6); and the prohibition of RCRA characteristic wastes considered ignitable, corrosive , and reactive (Chapter 4). These criteria can be characterized in the waste by AK, chemical tests (headspace gas or homogeneous analysis) and radiography or visual examination.

The WIPP TSRs add one additional radiological requirement, limiting the plutonium-equivalent activity (PE-Ci) in the waste. The PE-Ci represents a normalization of the radiotoxicity of prominent radionuclides expected to be in the waste to equivalency with ^{239}Pu. To characterize this component of the waste the amounts of these prominent individual radionuclides are necessary. While PE-Ci can be calculated from AK information if the AK contains radioassay values for the radionuclides; these values are currently obtained from the EPA-required assay of each container.

The CH WAC still contains the >100 nCi/g of alpha-emitting transuranic isotopes with half-lives of 20 years criterion, which is also met through the NDA program established to meet the 40 CFR 194 radioassay requirements.

The CH WAC combines the TSR criteria for acceptable waste with those from the HWFP, the TRUPACT-II criteria in the TRAMPAC, and the 40 CFR 194 waste characterization criteria. The waste characterization methods discussed in Chapters 4-6 of this report are used to ensure that these criteria are met.

8. CONCLUSIONS

Waste characterization criteria, requirements/methods, and procedures for WIPP are specified in the DOE Waste Acceptance Criteria, the NRC Certificate for transportation, the EPA Certificate for disposal, and the NMED Hazardous Waste Facility Permit for disposal. EEG has provided a technical review of these measures over many years. Our reviews have considered the need for a requirement as well as whether a proposed change is justified.

The summary below presents EEG's current assessment of the key components of the waste characterization requirements for the more significant requirements/methods. Our views continue to evolve to reflect new information and analyses.

8.1 Overlap of Requirements

Between the four entities, there is considerable overlap in waste characterization requirements. The HWFP and Appendix A of the CH WAC are the more prescriptive for specifying compliance. When considering a requirement change to either of these documents, the effect of the change on all requirements, including those issued by other agencies, should be noted and evaluated for its potential impact across agencies.

8.2 The Change Processes

The DOE, NMED, EPA, and NRC each have different processes for changing the requirements and these vary considerably in the degree of formality and participation by outside organizations. All processes have proved to be workable and effective. The proposed modifications are implemented more effectively and expeditiously if they are considering smaller, less comprehensive changes. The EEG believes that in the future, proposed changes to the waste characterization requirements should continue to use the existing processes.

8.3 Risk Considerations

The radiological risk from routine operations, operational accidents, and long-term releases is orders of magnitude greater than the risk from hazardous waste. Therefore, a risk based approach to waste characterization should concentrate on those requirements that affect the radiological risk.

No data have been provided by the DOE to indicate that exposures to workers performing CH TRU waste characterization are large enough to be a significant reason for reducing waste characterization requirements.

8.4 Acceptable Knowledge Requirement

Acceptable Knowledge is a principal waste characterization technique for all the regulatory agencies. AK is necessary and should be retained. At this time the EEG supports the use of the HWFP AK requirements since they are the most prescriptive.

8.5 Headspace Gas Sampling and Analysis

DOE has indicated that HSG sampling and analysis is one of the most expensive waste characterization requirements and the HWFP requires this be conducted in 100% of all non-thermally treated waste containers. HSG sampling is the primary way DOE has chosen to meet the "detailed chemical analysis…" specified in the New Mexico Administrative Code. Data from HSG sampling is used to verify that VOC concentrations in waste storage rooms meet the Room Based Concentration limits in the HWFP. However, these limits can also be verified by data obtained from the Confirmatory VOC Monitoring Plan in the WIPP underground. Since HSG is required by the HWFP, it is a convenient (but not the only) way of assuring that flammable gas concentration limits in the TRAMPAC are met.

EEG believes it is desirable to maintain a comprehensive HSG program for WIPP CH TRU wastes. However, it should be possible to require less than 100% sampling in some cases. Our primary concerns are with organic sludges and older waste containers where information may be less reliable.

8.6 Drum Age Criteria Requirements

Drum Age Criteria is necessary to ensure that HSG sampling of waste containers will measure gas concentrations that are at least 90% of equilibrium. DAC values are required in both the HWFP and the TRAMPAC. The EEG supports this requirement.

8.7 Real Time Radiography

All WIPP waste containers are required to undergo either radiography or visual examination by the HWFP. Usually retrieved wastes undergo RTR and newly generated wastes are examined by visual examination. RTR has been a very effective means of verifying AK and discovering prohibited items in waste containers. It is also used to show compliance with several EPA and TRAMPAC requirements.

The overall radiography program is an important part of the WIPP waste characterization program and should be retained. It may be possible to reduce some of the detailed procedural requirements in the HWFP.

8.8 Visual Examination/Retrievably Stored Waste

A small fraction (currently less than 2%) of retrievably stored waste is required by the HWFP to undergo visual examination for confirmation of RTR. The VE process has the potential for slightly greater radiation exposure than the other waste characterization requirements, although the EEG has not been provided any data from the DOE to indicate that exposures are significant enough to justify reducing the requirement.

The DOE has been successful in modifying the HWFP on retrievably stored visual examination and this would be the preferred process for seeking further reductions.

8.9 Visual Examination/Newly Generated Waste

VE is the method DOE prefers for newly generated waste because it can be done at the time the waste container is being filled. The EEG has not objected to any part of this requirement except to state that the requirement for two trained VE operators to perform the visual process “may be overkill” and that a single verification should be adequate.

8.10 Solids Coring and Sampling and Solids Analysis

The EEG continues to believe that the homogeneous sampling and analysis are unnecessary waste characterization requirements in the HWFP. Our principal reason for this position is that the data are not used for any additional regulatory control (metals releases from accidents or long-term processes would be controlled by radionuclide control requirements and VOCs and SVOCs by HSG or the Confirmatory VOC Monitoring Plan).

8.11 Level II Management and Waste Certification HWFP Requirements

The DOE has listed these management and certification requirements as characterization activities in a recent cost analysis. EEG has not previously commented on these requirements. However, our current evaluation indicates that the required procedures are very detailed and somewhat redundant. This may be one of the areas to which the general EEG comment, "We believe waste characterization requirements are excessive," applies.

8.12 Characterization Support HWFP Requirements

EEG has been supportive of the WIPP audit and surveillance program and has observed it to be a very good QA program. The EEG does not believe the relaxation of audit requirements and QA/QC is an appropriate way to reduce the regulatory burden.

8.13 EPA Non-Radiological Requirements

EPA's free water, non-ferrous metal and cellulose, plastic and rubber requirements should remain and can continue to be determined as they are now, by the RTR/VE requirements of the HWFP. However, the required CPR data could be provided to EPA on a waste stream rather than individual container basis. The ferrous metal requirement can continue to be met by counting waste containers emplaced in the repository.

8.14 EPA Radiological Requirements

The EEG agrees with the radioassay requirements for contact-handled transuranic waste specified in Appendix A of the CH WAC and the current procedures for modifying the document.

Current requirements for reporting the 10 required radionuclides should remain. The EEG recommends that ^{241}Pu be added to the list of EPA tracked radionuclides. The current requirement that all radioassay should be performed by WIPP-certified assay systems should be maintained.

Justification for less than 100% quantification and determination of isotopic ratios may be possible for some, but certainly not all, waste streams.

8.15 NRC Container Properties

The TRAMPAC requirements for residual liquids, filter vents, and the sealed container prohibition should be retained. These are all verified by requirements in the HWFP.

8.16 NRC Nuclear Properties

All nuclear property requirements should be retained and the methodology in Appendix A of the CH WAC should be used.

8.17 NRC Gas Generation Requirements

Requirements for measuring the chemical, payload classification, and radionuclide concentrations necessary to ensure hydrogen gas concentration criteria are met must be retained. There have been many changes, via the revision process, which have allowed additional containers to be shipped without changing the hydrogen gas criteria and additional changes may be justifiable in the future.

The flammable gas concentration limit of ≤ 500 ppm should be retained as described in the current revision of the TRAMPAC. Alternate methods (with appropriate QA) will be necessary if future changes to the HWFP affects the use of HSG sampling as the method for meeting this criteria.

8.18 WIPP Waste Acceptance Criteria

The WAC has served a useful historic purpose in developing initial criteria that have been adopted by the three regulatory agencies. Currently it is a useful document for listing most of the characterization requirements. It would be more useful if the technical justification for each criteria or requirement were restored.

The unique role of the CH WAC in including any necessary operational safety and health requirements not included elsewhere is very important and must be constantly evaluated via the TSR portion of the CH TRU SAR, and any necessary changes incorporated into the CH WAC.

9.0 REFERENCES

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[§71.13 Previously approved package]
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APPENDIX A

1. **9/17/99 letter**, Neill to Triay (comments on Waste Characterization Task Force Final Report)

2. **1/30/02 letter**, Silva to Triay (comments on Draft CH WAC, Revision 0)

3. **10/29/02 statement** (Silva) to NAS/NRC WIPP Committee

4. **1/13/03** EEG response to NAS/NRC WIPP Committee 12/6/02 questions

5. **5/19/03** EEG response to NAS/NRC WIPP Committee meeting questions

APPENDIX B

LIST OF EEG REPORTS

LIST OF EEG REPORTS

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U.S. DEPARTMENT OF ENERGY
CARLSBAD FIELD OFFICE

QUALITY ASSURANCE PROGRAM DOCUMENT

DOE/CBFO-94-1012

REVISION 5

May 2003

U.S. DEPARTMENT OF ENERGY
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QUALITY ASSURANCE PROGRAM DOCUMENT

DOE/CBFO-94-1012

REVISION 5

This Document Supercedes CBFO-94-1012, Revision 4

May, 2003

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U.S. DEPARTMENT OF ENERGY
CARLSBAD FIELD OFFICE

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QUALITY ASSURANCE PROGRAM DOCUMENT

DOE/CBFO-94-1012

REVISION 5

Prepared by: _____ **Date:** 5/14/03
QA Manager, CBFO

Approved by: _____ **Date:** 5/16/03
Manager, CBFO

POLICY STATEMENT

The mission of the Carlsbad Field Office (CBFO) is to protect human health and the environment by opening and operating the Waste Isolation Pilot Plant (WIPP) for safe disposal of transuranic (TRU) waste and by establishing an effective system for management of TRU waste from generation to disposal.

To help fulfill this mission and to ensure that the risks and environmental impacts are identified and minimized and that safety, reliability, and performance are optimized, it is the policy of the CBFO to establish, implement, and maintain an effective quality assurance (QA) program that supports compliance with applicable Federal, State, and local regulations and U.S. Department of Energy (DOE) orders and requirements.

Further, it is the intent of the CBFO to establish a culture and work environment that encourages setting and maintaining effective standards, identifying and resolving problems, emphasizing a continual pursuit of improvement, and fostering mutual respect and effective communication within the CBFO and among its participants, their suppliers, the public, and other stakeholders.

The *CBFO Quality Assurance Program Document* (QAPD) establishes QA program requirements for all quality-affecting programs, projects, and activities sponsored by the CBFO. The CBFO and organizations supporting the CBFO shall implement the applicable requirements of this QAPD within their systems for management and control of these activities.

It is the responsibility of all personnel assigned to CBFO-sponsored activities to achieve quality, identify problems, and recommend improvements. CBFO organizations define and achieve quality, recommend and promote improvements in the quality of items and processes, and identify, document, and resolve problems. CBFO quality assurance organizations verify the achievement of quality. CBFO management establishes and cultivates principles and practices that integrate QA program requirements and performance standards into their management approach and control systems. Additionally, CBFO management provides personnel who perform work with the proper qualifications, training, resources, oversight, and support to achieve the CBFO organizational and mission objectives.

The CBFO QA program requirements, as described in this QAPD, have my full endorsement and complete support. Implementation of the applicable QAPD requirements, responsibilities, and authorities is mandatory for all CBFO personnel.

In support of this policy statement, all CBFO personnel are expected to demonstrate their personal commitment to the achievement of quality through their active involvement in the implementation of the CBFO QA program.

Inés Triay

Dr. Inés Triay
Manager, Carlsbad Field Office

5/16/03
Date

CHANGE HISTORY

Revision:	Changes to the QAPD
Rev 1	The QAPD has been substantially rewritten, the structure has been reorganized, and the content has been supplemented to broaden its scope from a CAO internal requirements and participant guidance document to a CAO program-wide requirements document. The document elements that defined the extent of applicability regarding specific QA program requirements have been clarified through the identification of "general" and "additional" requirements. Requirements for the grading of management controls have been clarified and more fully developed. The requirement for Sandia National Laboratories (SNL) and Westinghouse Waste Isolation Division (WID) QAPD's was deleted. A requirement was added for each organization to prepare, submit for review, and maintain a QA implementing procedures matrix. Revisions were made to incorporate all the requirements of 40 CFR Part 194, ANSI/NCSL Z540-1, and stakeholder comments. The use of the terms "will" and "shall" are interchangeable and denote requirements. Editorial changes were made throughout.
Rev 2	The section describing the organization and responsibilities for CAO personnel have been deleted from section 1 and incorporated into a policy statement (Appendices C and D). The QA program document hierarchy (Table I-1), has been updated to reflect current regulatory requirements commitment and guidance documents. Requirements have been clarified in the areas of 1) grading, 2) the control of conditions adverse to quality, and 3) the preparation and maintenance of document review comments. Section 6.0, *Software,* has been rewritten to include both general and additional requirements. Definitions in the glossary have been added, deleted, and clarified. Editorial changes have been made throughout the document.
Rev 3	Changes in Revision 3 have been limited to those necessary to achieve full compliance with the Waste Analysis Plan (WAP) in the WIPP Hazardous Waste Facility Permit and to incorporate certain TRU waste QA requirements contained in the CAO QAPP, which is to be inactivated. Refer to the following list of pages affected by Revision 3.

List of Pages Affected by QAPD Revision 3

Change History	iv to v
Table of Contents	vi to xii
List of Acronyms	xiii to xiv
Introduction	I-1 to I-2
Section I - Management	1-1 to 1-23
Appendix A - Glossary	A-1 to A-10
Appendix B - References	B-1
Appendix C - CAO Organization	C-1 to C-2
Appendix D - CAO QA Manager Responsibilities	D-1 to D-2
Appendix E - TRU Sites Organization	E-1 to E-4

The pages in Revision 3 that are not listed above (Sections 2.0 through 6.0) remain effective.

Rev 4 The changes in Revision 4 were made to incorporate the DOE name change from the Carlsbad Area Office (CAO) to the Carlsbad Field Office (CBFO) and reflect current CBFO organization titles and responsibilities, rewrite the Quality Improvement section, update the source requirements documents listed in Table I-1, make changes to capture the wording used in the requirements documents, add more specific detail to the QA functional responsibilities of the CBFO management, and eliminate divisions between “general requirements” and “additional requirements.” Editorial, formatting, and paragraph number changes have been made throughout the document. Change markings are present for those revisions that affect content. Changes related to editorial and formatting revisions are not marked. Technical revisions were made to the following specific sections:

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Rev 5

The changes in revision 5 were made to address an EPA finding from the annual EPA QA audit conducted on January 7 – 9, 2003. This finding concerned the language in the QAPD regarding the responsibilities for achievement and verification of quality not matching the requirements from NQA-1. In addition to the change made to address the EPA finding, the following changes were made:

- The requirement for program participants to maintain a QAPD procedures matrix has been deleted; because this matrix is not required by NQA-1, 2, or 3, or other regulatory document.
- The requirement for organizations receiving records to return a receipt acknowledgment to the sender has been deleted, because this also is not required by NQA-1, 2, or 3, or other regulatory document.
- The requirement that CBFO and participant organization ensure

that they comply with the Federal Acquisition Regulations was deleted because the QAPD is not the appropriate document to specify this requirement.

- The requirement to maintain records related to the characterization of the mixed transuranic waste form as lifetime QA records was deleted. Records classification of mixed waste characterization records is specified in the Hazardous Waste Facility Permit.
- The requirement to maintain audit and surveillance checklists as QA records was deleted, because this is not a requirement of NQA-1, 2, or 3, or other regulatory document.
- The requirement for calibration laboratories to comply with ANSI/NCSL Z540-1 was deleted because this is not a requirement of NQA-1, 2, or 3, or other regulatory document.
- The safety analysis report for the HalfPACT shipping package was added as a regulatory source document to Table I-1
- Section 5.5 was deleted. The requirements for data quality evaluation during scientific investigation planning are addressed in Section 5.1.G of the QAPD. Section 5.5 was redundant and specified requirements for the content of compliance applications, which was not appropriate for the QAPD.
- Changes were also made to correct typographical errors and incorrect section references.

Technical revisions were made to the following specific sections:

Section	Section Title
	Policy Statement
	Introduction
1.1.1	Organization
1.1.1.1.D	Management
1.1.1.3	Quality Assurance Management
1.1.2.2	Procedures Matrix (deleted)
1.2.1	Qualification Requirements
1.3.2.5	Disposition of Nonconforming Items or Data
1.5.4.B and E	Classifying QA Records
1.5.6.A	Storage, Preservation, Safekeeping, and Disposition of QA Records
2.1.B	Work Processes
2.3	Procurement
2.3.4	Procurement Document Requirements
2.4.6	Use and Control of M&TE

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LIST OF ACRONYMS AND ABBREVIATIONS

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASNT	American Society of Nondestructive Testing
ASTM	American Society for Testing and Materials
CAP	Corrective Action Plan
CAQ	Condition Adverse to Quality
CAO	Carlsbad Area Office
CBFO	Carlsbad Field Office
CFR	Code of Federal Regulations
DQO	Data Quality Objective
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FRC	Federal Records Center
HWFP	Hazardous Waste Facility Permit
M&DC	Monitoring and Data Collection Equipment
M&TE	Measuring and Test Equipment
M&O	Management and Operating Contractor
NARA	National Archives and Records Administration
NDE	Nondestructive Examination
NEPA	National Environmental Policy Act
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NMED	New Mexico Environment Department
NQA	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
NTP	National TRU Program
NUREG	Nuclear Regulatory Commission Report designation

QA	Quality Assurance
QAPD	Quality Assurance Program Document
QAPjP	Quality Assurance Project Plan
QAPP	Transuranic Waste Characterization Quality Assurance Program Plan (CAO-94-1010)
QC	Quality Control
RIDS	Records Inventory and Disposition Schedule
SCAQ	Significant Condition Adverse to Quality
SNL	Sandia National Laboratories
SQA	Software Quality Assurance
TRAMPAC	TRUPACT-II Authorization Methods for Payload Control
TRU	Transuranic
TRUPACT-II	Transuranic Package Transporter, Model II
UL	Underwriter's Laboratory
WAP	Waste Analysis Plan
WID	Westinghouse Waste Isolation Division
WIPP	Waste Isolation Pilot Plant
WTS	Washington TRU Solutions

INTRODUCTION

The Carlsbad Field Office (CBFO) Quality Assurance Program Document (QAPD) is the document that describes and establishes the CBFO Quality Assurance (QA) program. The provisions of this QAPD apply to all programs and projects managed by the CBFO which require a QA program, including activities related to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the Waste Isolation Pilot Plant (WIPP) facility. This document identifies the sources of all applicable QA program requirements. The subject requirements are based on criteria contained, or incorporated by reference, in source documents listed in Table I-1. These documents have been placed into one of three categories:

A. Regulatory documents, including those incorporated by reference, that define the requirements necessary for the WIPP to be granted a certificate of compliance by the Federal Government and permit(s) by State governmental agencies to dispose of transuranic (TRU) and mixed TRU wastes in the WIPP repository, or that define requirements applicable to the management of the WIPP as a U.S. Department of Energy (DOE) non-reactor nuclear facility

B. Commitment documents that are imposed by DOE management

C. Guidance documents that provide additional information that is useful in developing and implementing the CBFO QA program

The purpose of the QAPD is to describe the applicability and requirements of the CBFO QA program as applied within the CBFO management infrastructure. In this context, the management infrastructure includes all CBFO program participants (e.g., Sandia National Laboratories [SNL] as Science Advisor; Washington TRU Solution [WTS] as the Management and Operating [M&O] contractor of the WIPP, and various DOE organizations and contractors performing work under the direction of the CBFO). This program is developed and maintained through an ongoing process that selectively applies the varied QA program criteria. This process provides due consideration to the extent of source requirement applicability, a graded-approach, available guidance, and the current foreseeable activities expected to be performed under the direction of CBFO.

The requirements in this QAPD are based on the principle that work shall be planned, documented, performed under controlled conditions, and periodically assessed to establish work item quality and process effectiveness and to promote improvement. Management, line personnel, and organizations are responsible for planning and achieving quality and for promoting continuous improvement. Quality assurance organizations and personnel are responsible for the verification of the achievement of quality. This QAPD further delineates the quality contributions expected of all

personnel and encourages their active participation in implementing the CBFO QA program.

Table I-1 QA Program Source Documents

MAJOR REGULATORY REQUIREMENTS DOCUMENTS	TITLE
10 CFR Part 21	Reporting of Defects and Nonconformances
10 CFR Part 71	Packaging and Transportation of Radioactive Material
10 CFR Part 830	Nuclear Safety Management
40 CFR Part 191	Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes
40 CFR Part 194	Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations
ASME NQA-1-1989 (incorporated by reference in 40 CFR Part 194)	Quality Assurance Program Requirements for Nuclear Facilities
ASME NQA-2a-1990 addenda, Part 2.7 (incorporated by reference in 40 CFR Part 194)	Quality Assurance Requirements of Computer Software for Nuclear Facility Applications
ASME NQA-3-1989 excluding Section 2.1 (b) and (c) and Section 17.1 (incorporated by reference in 40 CFR Part 194)	Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Nuclear Waste Repositories
NM 48901 39088 – TSDF/WIPP	WIPP Hazardous Waste Facility Permit
NRC Docket 71-9212	RH-TRU 72-B Safety Analysis Report
NRC Docket 71-9218	TRUPACT-II Safety Analysis Report
NRC Docket 71-9279	HalfPACT Safety Analysis Report
NUREG-1297 (1988) (incorporated by reference in 40 CFR Part 194)	Peer Review for High-Level Nuclear Waste Repositories
COMMITMENT DOCUMENTS	**TITLE**
DOE O 414.1a, Change 1	Quality Assurance
SNT-TC-1A-1980	American Society of Nondestructive Testing (ASNT) "Recommended Practice No. SNT-TC-1A, Personnel Qualification and Certification in Nondestructive Testing," August 1980
GUIDANCE DOCUMENTS	**TITLE**
DOE, G-414.1-2	Quality Assurance Management System Guide for Use with 10 CFR Part 830.120 and DOE O 414.1
NUREG/BR-0167 (1993)	Software Quality Assurance Program and Guidelines

SECTION I – MANAGEMENT REQUIREMENTS

This section describes the fundamental elements related to the organization and management of the CBFO QA program, as well as the fundamentals to be applied in managing the work of the program.

1.1 ORGANIZATION AND QUALITY ASSURANCE PROGRAM

This section describes the requirement for the organizational structure, primary interfaces, functional responsibilities, and levels of authority required to implement the CBFO QA program. In addition, this section describes the basic elements of the QA program and their applicability.

1.1.1 Organization

Effective implementation of the CBFO QA program is dependent on the efforts at all levels of the program participants. The organizational structures and the responsibility assignments of program participants shall be such that those organizations that have been assigned responsibility for performing the work are responsible for achieving and maintaining quality. Management is responsible for defining quality, developing appropriate plans to attain quality, and supporting the workers in pursuit of quality. QA organizations of the program participants are responsible for verifying the achievement of quality in the implementation of the CBFO QA program. CBFO organizational and individual responsibilities are addressed in Appendices C and D. Organizational and individual responsibilities for TRU waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility are addressed in Appendix E.

1.1.1.1 Management

A. Management has overall responsibility for successfully accomplishing activities subject to this QAPD. Management provides the necessary planning, organization, direction, control, resources, and support to achieve their defined objectives. Management is responsible for planning, performing, and improving the work.

B. Management is responsible for establishing and implementing policies, plans, and procedures that control the quality of work, consistent with the provisions of this QAPD.

C. Management quality responsibilities include:

1. Ensuring that adequate technical and QA training is provided for personnel performing activities subject to this QAPD

2. Ensuring compliance with all applicable regulations, DOE orders and requirements, and applicable Federal, State, and local laws

3. Ensuring that personnel adhere to procedures for the generation, identification, control, and protection of QA records

4. Exercising the authority and responsibility to stop unsatisfactory work such that cost and schedule do not override environmental, safety, or health considerations

5. Developing, implementing, and maintaining plans, policies, and procedures that implement this QAPD

6. Identifying, investigating, reporting, and correcting quality problems

D. Quality achievement is the responsibility of those performing the work. Line organizations are responsible for achieving quality in their areas.

E. Management empowers employees by delegating authority and decision making to the lowest appropriate level in the organization.

1.1.1.2 Employees

Each program participant employee is responsible for the quality of his or her work and for promptly reporting all existing, developing, or potential conditions adverse to quality to the responsible management for evaluation and action.

1.1.1.3 QA Management

An organization's QA management has the authority and overall responsibility to independently assess the organization's effective implementation of the QA program to verify the achievement of quality.

A. QA management shall:

1. Schedule and conduct QA assessments

2. Maintain liaison with participant QA organizations and other affected organizations

3. Ensure preparation, review, and issuance of QA plans and procedures that implement the provisions of this QAPD

4. Review and approve supplier and subcontractor QA plans

5. Track or perform trend analysis of quality problems, and report quality problem areas

6. Provide for the administrative processing of documentation concerning conditions adverse to quality

7. Have direct access to responsible management at a level where appropriate action can be effected

8. Be sufficiently independent from cost and schedule considerations

9. Have the organizational freedom to communicate with management

10. Have no assigned responsibilities unrelated to the QA program that would prevent appropriate attention to QA matters

11. Develop, establish, and interpret QA policy and ensure effective implementation

12. Interface, as appropriate, with the CBFO staff, participants, and other stakeholders on QA matters

13. Assist subordinate organizations with quality planning, documentation, quality measurement, and problem identification and resolution

14. Provide guidance to all applicable subordinate organizations concerning identification, control, and protection of QA records

B. The QA organization shall have sufficient authority, access to work areas, and organizational freedom to:

1. Identify quality problems

2. Recommend solutions

3. Verify implementation of solutions

4. Ensure that unsatisfactory conditions are controlled until proper disposition has occurred

1.1.1.4 Communication and Interface Responsibilities

A. Communication Responsibilities

Participating organizations at all management levels shall establish communication channels that provide timely and wide dissemination of information pertinent to quality performance, such as:

1. The status of development and implementation of the QA program

2. The status and resolution of significant quality problems

3. The lessons learned from significant quality problems and adverse conditions

4. Quality management practices and improvements

5. Trend analysis results

B. Interface Responsibilities

1. Where more than one organization is involved in the execution of activities covered by this QAPD, the responsibility and authority of each organization shall be clearly established, defined, and documented. The external interfaces between organizations, the internal interfaces between organizational units, and interface changes shall be documented. Interface responsibilities shall be defined and documented and shall include the requirements for management, performance, and assessment.

2. CBFO-sponsored activities, performed by organizations external to the CBFO, include, but are not limited to, compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility. Responsible CBFO organizations shall ensure the effective implementation of the CBFO QA program.

1.1.1.5 Delegation of Work

Individuals or organizations responsible for establishing, planning, accomplishing, and assessing the work may delegate work to other individuals or organizations. However, the individuals or organizations making the delegation shall retain overall responsibility for the delegated work.

1.1.1.6 Resolution of Disputes

Differences of opinion involving the definition and implementation of QA program requirements will be brought to the attention of the appropriate QA manager and the responsible manager. If not resolved, the issues will be elevated progressively to successively higher levels of management as necessary.

1.1.2 Implementation of the CBFO QA Program

1.1.2.1 Quality Assurance Program Documents

Program participants shall develop and follow plans and procedures that effectively implement the requirements described in this QAPD along with those requirements contained within the Resource Conservation and Recovery Act (RCRA) Permit Waste Analysis Plan (WAP), Quality Assurance Project Plans (QAPjPs), Certification QA Plans, Waste Acceptance Criteria (WAC), and TRUPACT-II Certification of Compliance, including TRUPACT-II Authorized Methods for Payload Control (TRAMPAC), as applicable.

1.1.2.2 Applicability of QAPD Requirements

The terminology “items or activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility” is used generically throughout this QAPD to refer to the following:

A. WIPP site activities or operations that process or store radioactive liquid or solid waste, perform waste management activities involving radioactive materials, or design, manufacture, or assemble items for use with radioactive materials in such a form and quantity that a nuclear hazard exists

B. Waste characterization activities

C. Environmental monitoring, monitoring the performance of the disposal system, and sampling and analysis activities

D. Field measurements of geological factors, ground water, meteorology, and topography

E. Computations, codes, models, and methods used to demonstrate compliance with disposal regulations

F. Expert judgment elicitation to support applications for recertification or determination of compliance

G. Design of the disposal system and actions taken to ensure compliance with design specifications

H. The collection of data and information used to support compliance application(s) and/or any modifications to the compliance application

I. Other systems, structures, components, and activities important to the isolation of waste in the disposal system

J. Those items and activities related to Nuclear Regulatory Commission (NRC) licensed packaging (e.g., Transuranic Package Transporter Model II [TRUPACT-II]), design, purchase, fabrication, handling, shipping, storage, cleaning, assembly, inspection, testing, operation, maintenance, repair, and modification or components of packaging that are important to safety

1.1.2.3 Grading Items and Activities and Applying Management Controls

A. The graded approach is the process by which the level of analysis, documentation, verification, and other controls necessary to comply with QA program requirements are developed commensurate with the following factors:

1. The importance of an item or activity with respect to safety, waste isolation, and regulatory compliance

2. The importance of the data to be generated

3. The need to demonstrate compliance with specific regulatory design and QA requirements

4. The impact on the results of performance assessments and engineering analyses

5. The magnitude of a hazard or the consequences of failure

6. The life-cycle stage of a facility or item

7. The programmatic mission of a facility

8. The particular characteristics of a facility, item, or activity (e.g., complexity, uniqueness, history, or the necessity for special controls or processes)

9. The relative importance of radiological and non-radiological hazards

B. The extent of management and QA controls applied to an item or activity will vary as a function of the degree of confidence needed to achieve the desired quality of the item or activity. The grading process provides the flexibility to design and implement controls that best suit the facility or activity. Each organization should develop their own method to determine that the defined grading process is effective. The use of the graded approach shall determine the appropriate level of controls necessary to manage the items, systems, and activities necessary to ship TRU waste to WIPP.

C. Grading methods for each organization shall provide for:

   1. The assignment of management and QA control levels

   2. The definitive criteria used in selecting those levels

   3. Detailed descriptions of the management and QA control provisions corresponding to those levels, based on the above requirements

D. Program participant procedures that establish and implement a graded approach for items and activities under the cognizance of the CBFO shall be submitted to the CBFO QA Manager for approval for use in CBFO programs.

1.1.2.4 Planning Work

Planning shall be performed and documented to ensure that work is accomplished under suitably controlled conditions. As appropriate, planning elements shall include:

A. Definition of work scope, objectives, and a listing of the primary tasks involved

B. Identification of scientific approaches or technical methods used to collect, analyze, or study results of applicable work

C. Identification of field and laboratory testing standards and quality criteria

D. Identification of applicable implementation documents (appropriate nationally recognized standards shall be used whenever possible)

E. Identification of field and laboratory testing equipment or other equipment

F. Identification of, or provisions for the identification of, required records and the recording of objective evidence of the results of the work performed

G. Identification of prerequisites, special controls, specific environmental conditions, processes, or skills

H. Identification of computer software

1.1.2.5 Peer Reviews

Peer reviews performed in support of WIPP compliance activities shall be documented, as shall all peer review processes. Peer reviews of the following activities shall be conducted in a manner consistent with NUREG-1297, *Generic Technical Position on Peer Review for High-Level Nuclear Waste Repositories:*

A. Conceptual models selected and developed by the DOE

B. Waste characterization analysis as required in 40 CFR § 194.24(b)

C. Engineered barrier evaluation as required in 40 CFR § 194.44

1.2 PERSONNEL QUALIFICATION AND TRAINING

Personnel shall be trained and qualified to ensure they are capable of performing their assigned tasks and to ensure that job proficiency is maintained.

1.2.1 Qualification Requirements

Qualification requirements for CBFO and participant positions or job functions shall be established for activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility. The evaluation shall be documented. At a minimum, these positions include managers, designers, scientists, independent assessment personnel, operators, maintenance personnel, technicians, and inspectors.

The responsible organization shall:

A. Analyze each job position to determine the task responsibilities of the position subject to the QAPD. The analysis shall identify minimum education, experience, and training prerequisites for each position involved in the planning, performance, or verification of activities subject to the QAPD, commensurate with the scope, complexity, and nature of the work.

B. Ensure that personnel selected to perform or verify activities subject to the QAPD have education, experience, and training commensurate with the minimum requirements specified. The qualification of an individual shall be based upon evaluation of education and experience, which is compared to the established requirements for the position.

1.2.2 Training Requirements

CBFO and participant personnel performing activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility shall receive related training in accordance with the following requirements. Training shall emphasize the correct performance of work, describe why the applicable quality and nuclear safety requirements exist, and describe the fundamentals of the work and the context. Training shall be subject to ongoing review to determine instruction and training program effectiveness and shall be upgraded whenever needed improvements or enhancements are identified. Management shall:

A. Ensure that personnel receive indoctrination and training, including on-the-job and hands-on training, as needed, to achieve initial proficiency; maintain proficiency; and adapt to changes in technology, methods, job responsibilities, and quality assurance implementing procedures, prior to performing any tasks subject to the QAPD

B. Ensure that personnel receive indoctrination in the following:

   1. General criteria, including applicable QA plans, codes, regulations, and standards

   2. Specific criteria, including applicable QAPjPs and implementing procedures

C. Ensure that records generated during qualification, general indoctrination and training, or specific skill training activities are collected and maintained as QA records.

1.3 QUALITY IMPROVEMENT

Quality improvement is a management process carried out to improve items, services, products, or processes. All aspects of work that affect quality and the management system are subject to continuous improvement through assessment and feedback processes.

1.3.1 Quality-Affecting Problems

Quality-affecting problems and items, services, and processes that do not meet established requirements shall be identified, documented, reported, controlled, and corrected. Quality problems may be identified by the organization or by an external source.

1.3.1.1 Problem Identification

All personnel shall be responsible for identifying quality problems and shall be encouraged by management to suggest improvements. CBFO and participant organizations foster a “no-fault” attitude for quality problems and prioritize and focus resources on preventive actions and on those quality problems that have the greatest potential for:

A. Posing adverse risks to the environment and human health

B. Adversely impacting the quality, safety, and reliability of waste operations

C. Affecting the ability to meet quality requirements

1.3.1.2 Problem Types

Quality-affecting problems may involve:

A. Noncompliance with a QA program requirement. A noncompliance is classified as a Condition Adverse to Quality (CAQ) or Significant Condition Adverse to Quality (SCAQ)

B. Nonconforming items, including suspect/counterfeit items or data, that do not conform to specified requirements.

1.3.2 Nonconformances

Items or data that do not conform to established requirements shall be controlled to prevent inadvertent installation or use.

1.3.2.1 Documenting and Evaluating Nonconforming Items

The documentation and evaluation of nonconforming items shall be accomplished by:

A. Clearly identifying and describing the characteristics that do not conform to specified criteria

B. Reviewing nonconformance documentation and proposed recommended disposition of the nonconforming item or data. The review shall include a determination of the need for corrective action in accordance with the requirements of Section 1.3.3, *Corrective Action*. In addition, organizations affected by the nonconformance shall be notified.

C. Evaluating and approving of recommended dispositions

D. Ensuring that personnel performing evaluation or recommending disposition have demonstrated competence in the specific area they are evaluating or dispositioning, and have an adequate understanding of the requirements

E. Implementing procedures that specify the responsibility and authority for reviewing, evaluating, approving the disposition, and closure of the nonconformance

1.3.2.2 Identifying Nonconforming Items or Data

A. Nonconforming items shall be physically identified by marking, tagging, segregation, or other methods that do not adversely affect the end use. The identification shall be legible and easily recognizable, and shall be traceable to the reporting documentation.

B. If physical identification of each nonconforming item is not practical, the container, package, or segregated storage area, as appropriate, shall be physically identified as in A above.

1.3.2.3 Reporting Nonconformances

Organizations affected by a nonconformance shall be notified. The QA Manager and the National TRU Programs Assistant Manager, CBFO shall be notified in writing within 5 calendar days of identification of any non-administrative nonconformance related to applicable requirements specified in the WIPP Hazardous Waste Facility Permit (HWFP) Waste Analysis Plan (WAP), which is first identified at the site project manager's signature release level (i.e., a failure to meet a data quality objective [DQO]). Notification is also required if the results of the confirmatory analytical techniques specified in the Permit Attachment B are inconsistent with acceptable knowledge documentation. The nonconformance report shall be submitted to CBFO within 30 calendar days of identification of the deficiency.

1.3.2.4 Segregating Nonconforming Items

A. Further processing, delivery, installation, or use of nonconforming items shall be controlled pending the evaluation and approval of the disposition.

B. Nonconforming items shall be segregated, when practical, by placing them in a clearly identified and designated hold area until properly dispositioned.

C. If segregation is impractical or impossible due to physical condition, other precautions shall be employed to preclude inadvertent use.

1.3.2.5 Disposition of Nonconforming Items or Data

The disposition of nonconforming characteristics shall be accomplished as follows:

A. The nonconformance characteristics shall be reviewed, and recommended dispositions of nonconforming items or data shall be proposed and approved in accordance with documented procedures. Personnel performing evaluations to determine a disposition shall have demonstrated competence in the specific area they are evaluating, have adequate understanding of the requirements, and have access to pertinent background information.

B. The dispositions “use-as-is,” “reject,” “repair,” or “rework” for nonconforming items or data shall be identified and documented.

C. The technical justification for the acceptability of a nonconforming item or data that has been dispositioned “use-as-is” or “repair” shall be documented.

D. Items that do not meet original design requirements that are dispositioned “use-as-is” or “repair” shall be subject to design control measures commensurate with those applied to the original design, and

   1. If changes to the specifying document are required to reflect the as-built condition, then the disposition shall require action to change the specifying document to reflect the accepted nonconformance.

   2. Any document or QA record change required by the disposition of the nonconformance shall be identified in the nonconformance documentation and, when a document or record is changed, the justification for the change shall reference the nonconformance documentation.

E. The disposition of an item to be reworked or repaired shall contain a requirement to re-examine (inspect, test, or examine by nondestructive examination) the item to verify acceptability. Repaired or reworked items shall be re-examined using the original process and acceptance criteria unless the nonconforming item disposition has established alternate acceptance criteria.

1.3.2.6 Quality Trending of Nonconformances

Nonconformance documentation shall be periodically analyzed by the QA organization to identify quality trends in accordance with Section 1.3.3, *Corrective Action*.

1.3.3 Corrective Action

1.3.3.1 Identifying Conditions Adverse to Quality (CAQ)

A CAQ occurs when a QA requirement has not been met.

1.3.3.2 Classification of Conditions Adverse to Quality

Classification of CAQs is based on the effect the CAQ has on compliance to regulatory requirements for safety, operability, TRU waste characterization, TRU waste site certification, TRU waste containment, and the effective implementation of the QAPD. Any CAQ that is determined to be noncompliant with an HWFP condition or requirement shall be treated as an SCAQ.

1.3.3.3 Conditions Adverse to Quality

A. CAQs shall be documented and reported to the appropriate levels of management responsible for the condition and to the QA organization for tracking.

B. Responsible management shall determine the extent and impact of the adverse condition and, at a minimum, complete remedial action as soon as practical.

1.3.3.4 Significant Conditions Adverse to Quality

A. Implementing documents shall include criteria for determining if a condition adverse to quality is significant. These criteria shall be based on the criteria in the definition of conditions adverse to quality included in Appendix A.

B. SCAQs shall be investigated, documented (including the extent of the condition and the impact on completed work), and reported to the management responsible for the condition, their senior management, and the QA organization for tracking.

C. Responsible management shall determine when an SCAQ related to the WIPP HWFP (i.e., a waste characterization process currently certified by the CBFO at a TRU waste site) requires accelerated corrective action. The required time interval for accelerated corrective action shall be established by the CBFO QA Manager.

1.3.3.5 Corrective Action Planning

Corrective action plans (CAPs) are required for all SCAQs. SCAQ CAPs shall address:

A. Remedial Action: actions necessary to resolve the initial problem
B. Investigative Actions: assessment of the extent and impact of the SCAQ
C. Root Cause Determination: identification of the root cause of the SCAQ
D. Actions to Preclude Recurrence: actions necessary to prevent recurrence of the SCAQ
E. Schedule: milestones for completion of the CAP, including expected completion dates and identification of responsible individuals

1.3.3.6 Work Suspension

If a work suspension condition has been identified, responsible management shall take appropriate action to lift and close the work suspension, based on the resolution of the related SCAQ. The QA organization shall verify and document the completion of applicable corrective actions prior to any management action releasing the work suspension.

1.3.3.7 Corrective Action Follow-up

A system shall be established to verify the effective implementation of scheduled corrective actions and to complete corrective actions in a timely manner. The QA organization shall evaluate the adequacy of corrective actions planned, assign responsibility for follow-up verification, and perform and document verification results. If results of verification are unsatisfactory, the CAP shall be revised appropriately, and corrective actions and verification performed.

1.3.3.8 Recurring Conditions Adverse to Quality

For recurring CAQs, management shall:

A. Determine the events leading up to the occurrences

B. Develop an understanding of the technical and work activities associated with the CAQ

C. Ascertain and identify any generic implications and impacts on completed work

D. Determine the extent to which similar quality problems, or precursors to the problem, have been identified

E. Determine the effectiveness of corrective actions that have been taken

F. Consider suspending work associated with the applicable activity, as appropriate

G. Suggest actions that can be taken by the responsible organization to preclude recurrence, as appropriate

1.3.3.9 Quality Trending

The need for quality improvement is accomplished through quality analysis and trending. To provide reliable trending information, the following activities shall be performed:

A. Quality performance data shall be identified, collected, and routinely analyzed to identify opportunities to improve items, services, activities, and processes. This analysis shall consider information from external sources and not be limited to one type of work or to one organization.

B. The analyses shall be performed semi-annually to provide for prompt identification of trends adverse to quality. Reports of CAQs, including those identified during quality assurance audits as Corrected During the Audit/Surveillance (CDAs/CDSs), shall be evaluated to identify adverse quality trends and root causes, with results reported to the organization responsible for corrective actions.

C. Program participants will report trending information to responsible management and to the applicable organization.

1.4 DOCUMENTS

A. Documents shall be prepared, reviewed, approved, issued, used, and revised to prescribe processes, specify requirements, or establish design.

B. Documents that specify requirements, prescribe processes, or establish design important to the compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility, such as instructions, procedures, drawings, test plans, management plans, technical reports, performance reports, and test reports, shall be controlled according to the requirements listed below to ensure that the correct documents are being used.

1.4.1 Document Preparation, Review, Approval, and Issuance

A. Documents shall be reviewed for adequacy, correctness, and completeness prior to approval and issuance. Program participants shall identify the individuals or organizations responsible for the preparation, review, approval, and issuance of controlled documents.

B. Documents shall be controlled during the review and approval phase in accordance with approved procedures.

C. The requesting organization shall identify the applicable criteria for the review. These criteria shall consider technical adequacy, accuracy, completeness, and compliance with established requirements.

D. Pertinent background information or data shall be made available by the organization requesting the review if the information is not readily available to the reviewer.

E. The review will be performed by individuals other than the originator.

F. Reviewers will be technically competent in the subject area being reviewed.

G. The organization or technical discipline affected by the document shall review the document according to the established review criteria.

H. The appropriate quality assurance organization shall review documents that translate CBFO QAPD or other CBFO requirements.

I. Review comment documentation shall be resolved in accordance with approved procedures. Evidence of review comment resolution shall be maintained by the originating organization.

J. Documents shall be approved for release by authorities designated in accordance with approved procedures.

K. Documents shall be issued by designated individuals or organizations in accordance with approved procedures.

1.4.2 Document Distribution and Use

The distribution and use of controlled documents and forms that document or prescribe work, including changes and editorial corrections to documents, shall be controlled to meet the following requirements:

A. Documents shall be distributed to affected personnel and used at the work location.

B. Effective dates shall be established and identified on the approved documents.

C. The disposition of obsolete or superseded documents and forms shall be controlled to avoid their inadvertent use.

D. Controls shall be established and maintained to identify the current status or revision of controlled documents and forms.

E. Controls shall provide for identification of documents to be controlled and their distribution.

1.4.3 Document Changes

A. Changes to documents, other than those defined below as editorial changes, shall be reviewed and approved by the same organizations that performed the original review and approval, unless other organizations are specifically designated in accordance with approved procedures.

B. Document changes shall be:

1. Reviewed by the organizations or technical disciplines affected

2. Clearly indicated in the changed document

C. Editorial or minor changes may be made without the same level of review and approval as the original or otherwise changed document. The following items are considered editorial or minor changes:

1. Correcting grammar or spelling (the meaning has not changed)

2. Renumbering sections or attachments

3. Updating organizational titles

4. Changes to non-quality affecting schedules

5. Revising or reformatting forms, providing the original intent of the form has not been altered

6. Attachments marked "Example," or "Sample," or exhibits that are clearly intended to be representative only

7. Clarification changes that do not affect the purpose of the document

D. A change in an organizational title accompanied by a change in responsibilities is not considered an editorial change.

E. The organization responsible for preparing the document shall identify and approve editorial changes.

1.5 RECORDS

A. Records shall be specified, prepared, reviewed, approved, and maintained.

B. A "QA record" is an authenticated record that provides objective evidence of the quality of items or activities. QA records shall be controlled in accordance with the following requirements.

1.5.1 Records System

A. A QA records system shall be established by the responsible organization at the earliest practical time, consistent with the schedule for accomplishing work activities. The QA records system shall be defined, implemented, and enforced in accordance with written procedures, instructions, or other documentation.

B. This does not prohibit the management of QA records within a general records system, nor does this require a separate records system for QA records, as long as the applicable provisions of this section are satisfied for the control of QA records.

1.5.2 Generating QA Records

A. Prior to conducting a work activity, the responsible organization shall:

   1. Identify those documents that shall become QA records

   2. Identify the organization responsible for submitting the QA records to the records system

B. QA records shall be legible, accurate, and completed appropriate to the work accomplished.

C. Individuals handling documents intended to become QA records shall provide reasonable protection for the records from damage or loss until the records are submitted to the records system (this includes documents generated during field operations).

D. Documents shall be considered valid QA records only if stamped, initialed, or signed and dated by authorized personnel, or otherwise authenticated. If the nature of the record (such as magnetic or optical media) precludes stamping or signing, then other means of authentication by authorized personnel are required. This authentication represents a certification as to the content of the record by those individuals with knowledge of the related facts, whether by direct personal knowledge or through the direct reports of others. The authentication should not be confused with any subsequent reviews of the content.

E. Once authenticated, QA records shall be submitted to the records system as prescribed by approved procedures. Upon completion of a project or other discrete task or activity, responsible management shall verify that the contents of the applicable QA records package are stored in the records system.

F. QA records may be originals or reproducible copies unless otherwise required.

G. Documents referenced by final reports, except readily available references such as encyclopedias, dictionaries, engineering handbooks, and national codes and standards, shall be retrievable from records files. Preparers of such records shall ensure that the documents are entered into the records system.

1.5.3 Indexing QA Records

The records system shall provide for the indexing of QA records according to the following requirements:

A. An individual or organization shall be assigned the responsibility of indexing and maintaining QA records.

B. The indexing system shall include, at a minimum, record retention times and the location of the record within the records system. These and other features of the records system shall facilitate the disposition of scheduled QA records and ensure the retrievability of any QA records entered.

1.5.4 Classifying QA Records

A. QA records shall be classified as either "post-closure," “lifetime,” or "nonpermanent." Post-closure QA records may be required to be maintained for periods of several hundred years and in a manner that will permit future generations to maintain them longer, if desired, using reasonably available technology. Records that fall into one or more of the following categories shall be classified as "post-closure" QA records:

   1. Records assisting prevention of actions that could impair the long-term isolation of the waste

   2. Records preserving information that would prevent inadvertent human intrusion, such as the nature and hazard of the waste and the locations of the geologic repository operations area, the underground facility, boreholes and shafts, and boundaries of the controlled area

   3. Records providing information relevant to post-closure monitoring and assessment of performance of the repository system

   4. Records preserving for future generations information regarding the geologic setting relevant to mitigation of releases of radioactive materials

   5. Records of significant value in exercising the retrieval option for waste packages after decommissioning and closure of the repository

B. Records not falling into the categories listed above, but falling into one or more of the following categories, shall be classified as "lifetime" QA records:

1. Records used for repository permitting or certification

2. Records used to identify and assess the performance capabilities of those engineered and natural barriers important to waste isolation

3. Records of computer programs and mathematical models needed to perform ongoing correlations between performance assessment predictions and actual tests and data analyses

4. Records of significant value in demonstrating the capability for safe operation of the WIPP respository or in determining the cause of an accident or a malfunction of an item in the WIPP repository

5. Records of significant value in maintaining, reworking, repairing, replacing, or modifying WIPP repository systems, components, or structures

6. Records needed during decommissioning and closure of the repository

7. Records relating to site characterization samples and data

8. Records relating to data used in performance assessment of the WIPP facility

9. Records documenting regulatory compliance

10. Records providing required baseline data for in-service inspections

C. Lifetime QA records are required to be retained and preserved in an acceptable condition for the operating life of the repository (i.e., until termination of the repository permit). Prior to destruction of any lifetime record, it shall be evaluated for upgrade to a post-closure record

D. Records that provide objective evidence that the QA program has been properly implemented, but that do not meet the above criteria for post-closure or lifetime records shall be classified as “nonpermanent” QA records. The retention period for nonpermanent records shall be established in writing.

E. Records related to waste characterization shall be classified in accordance with the requirements of the HWFP, *TRUPACT-II Authorized Methods for Payload Control* (TRAMPAC), and the *Quality Assurance Program Plan for TRUPACT-II Gas Generation Test Program*, DOE/WIPP 01-3187. In the case of conflicts between the records requirements contained in these documents, the most stringent requirements shall be used in determining the records classification.

1.5.5 Receiving QA Records

Each organization responsible for the receipt of QA records shall designate the person or organization responsible for receiving the records. The designee shall be responsible for organizing and implementing a system of controls for the receipt of QA records for permanent and temporary storage. At a minimum, the receipt control system shall include:

A. Provisions to permit a current and accurate assessment of the status of QA records

B. A method for identifying the records required to be included in the records system

C. A method for identifying the records that have been received

D. Procedures for the receipt and inspection of incoming records, including verification that the QA records received are in agreement with the transmittal document and that the records are legible

E. Provisions to control and protect the records from damage or loss during the receiving processes

F. A method for submittal of completed records to the storage facility without unnecessary delay

1.5.6 Storage, Preservation, Safekeeping, and Disposition of QA Records

A. QA records shall be stored and preserved in predetermined storage facilities in accordance with approved QA implementing procedures that provide a:

   1. Description of the storage facility

   2. Description of the filing and indexing systems used

   3. Description of controls governing QA records access, retrieval, and removal

   4. A method for filing supplemental information and documenting the authorization for corrections

B. The records storage arrangements shall provide adequate protection of records, including special processed records (such as radiographs, photographs, negatives, microfilm, and magnetic media) to preclude damage from moisture, temperature, rodent infestation, excessive light, electromagnetic fields, or stacking, as appropriate for the type of record being stored.

C. Records that require special processing and control, such as software and related documentation or information on high density media or optical disks, or hardware

and software required to maintain and access records, shall be controlled to ensure that the records are useable.

1.5.6.1 Records Disposition

A. Lifetime QA records shall be retained and preserved in an acceptable condition for the operating life of the WIPP repository (i.e., until termination of the operating permits), or for the particular item while it is installed in the repository or is being stored for future use. Lifetime records shall be evaluated for the need to be upgraded to post-closure records prior to their destruction.

B. Waste characterization data and related QA/Quality Control (QC) records in the generator/storage site project files for TRU waste to be shipped to the WIPP facility are designated as either lifetime records or non-permanent records as specified in Attachment B of the WIPP Hazardous Waste Facility Permit. Records that are designated as lifetime records shall be maintained for the life of the waste characterization program at a participating generator/storage site plus six years, then offered to CBFO for permanent archiving, or transferred to the appropriate Federal Records Center (FRC). Waste characterization records designated as non-permanent records shall be maintained for ten years from the date of (record) generation and then dispositioned according to their approved records inventory and disposition schedule (RIDS). If a generator/storage site ceases to operate, records shall be transferred before site closure.

C. Records relevant to an enforcement action under the WIPP Hazardous Waste Permit, regardless of assigned dispositions, shall be maintained at the TRU waste site until the NMED determines that they are no longer needed for enforcement actions, and then dispositioned as required.

D. Waste characterization data for each TRU mixed waste container transmitted to WIPP shall be maintained by CBFO for the active life of the WIPP facility plus two years. The active life of the WIPP facility is defined as the period from the initial receipt of TRU mixed waste at the facility until NMED receives certification of final closure of the facility. After their active life, records shall be retired to the FRC and maintained for 30 years.

E. Design and construction of a single records storage facility shall meet the applicable requirements of NQA-1-1989, NQA-3-1989, 10 CFR 71, and current requirements of the National Archives and Records Administration (NARA).

F. The construction details shall be reviewed by a person who is competent in the technical field of fire protection and fire extinguishing to determine the adequacy of protection of contents. If the facility is located within a building or structure, the environments and construction of that building can provide a portion or all of these criteria.

G. The following criteria are acceptable alternatives to the current NARA requirements and NQA-1-1989 criteria for a single storage facility:

1. Two-hour fire-rated vault meeting the National Fire Protection Association (NFPA) 232-1986, *Standards for the Protection of Records,* or NFPA 232AM-1986, or both

2. Two-hour fire-rated Class B file containers meeting the requirements of NFPA 232-1986, or NFPA 232AM-1986, or both

3. Two-hour fire-rated file room meeting the requirements of NFPA 232-1986, or NFPA 232AM-1986, or both, with the following additional provisions:

   a. Early warning fire detection and automatic fire suppression capability with electronic supervision at a constantly attended central station

   b. Records storage in fully enclosed metal cabinets

   c. Adequate access and aisle ways

   d. Prohibition in the room of work not directly associated with record storage or retrieval

   e. Prohibition of smoking, eating, or drinking

   f. Two-hour fire-rated dampers or doors in all boundary penetrations

H. If storage at dual facilities for each record is provided, the facilities shall be at locations sufficiently remote from each other to eliminate the chance of exposure to a simultaneous hazard. Each facility is not required to satisfy the requirements of sections E , F, or G above, but shall meet all other records storage requirements prescribed in this QAPD.

I. When temporary storage of records (such as for processing, review, or use) is required by an organization's procedures, the records shall be stored in a 1-hour fire-rated container. The procedures shall specify the maximum allowable time limit for temporary storage. The container shall bear a UL label (or equivalent) certifying one-hour fire protection, or be certified by a person competent in fire protection.

J. Access to storage facilities shall be controlled. A list designating personnel who are permitted access to the QA records shall be maintained and posted. Measures shall be established to preclude the entry of unauthorized personnel into the storage area. These measures shall guard against theft and vandalism.

K. Measures shall be taken to provide for replacement, restoration, or substitution of lost or damaged records.

L. QA records shall not be destroyed until the following conditions are met:

1. The appropriately assigned NARA authorized disposition specifies destruction
2. Regulatory requirements are satisfied
3. Operational status permits the disposal of such records
4. The related contractual requirements have been satisfied

1.5.7 Correcting Information in QA Records

A. Corrections to records will include the initials or signature of the authorized person making the correction and the date the correction was made.

B. Corrections to QA records shall be authorized by the originating organization.

C. Corrections to QA records should be made using a single line through and shall not obliterate the prior entry. QA records shall not be corrected with correction fluids or tapes.

SECTION 2 – PERFORMANCE REQUIREMENTS

2.1 WORK PROCESSES

A. Work shall be performed in accordance with established technical standards and administrative controls. Work shall be performed under controlled conditions using approved instructions, procedures, or other appropriate means. Items shall be identified and controlled to ensure their proper use. Items shall be maintained to prevent their damage, loss, or deterioration. Equipment used for process monitoring or data collection shall be calibrated and maintained.

B. The intent of this section is to establish the policy that those who have been assigned responsibility for performing work are responsible for achieving and maintaining quality. Those performing work have the goal of doing work correctly the first time. To ensure that those doing the work achieve that goal, management is responsible for establishing processes and procedures to ensure that all work is planned and performed under controlled conditions by personnel who are knowledgeable of the work requirements, and that these individuals are capable of accomplishing the work in accordance with the requirements of this QAPD.

C. This section further establishes management involvement in the work processes through their interactions with personnel performing the work and through their review and assessment of ongoing and completed work. This helps to ensure that the definition of "acceptable work performance" is clearly communicated and that personnel are provided the necessary training, resources, and administrative controls to properly accomplish their tasks.

2.1.1 Work

A. Personnel performing work are responsible for the quality of their work. Because the individual worker is the first line in ensuring quality, personnel will be knowledgeable of requirements for work they perform and the capability of the tools and processes they use.

B. Line managers will ensure that personnel working under their supervision are qualified and are provided the necessary training, resources, and administrative controls to accomplish assigned tasks. Criteria describing acceptable work performance shall be defined for the worker.

C. Line managers will review work and related information to ensure that the desired quality is achieved and to identify areas needing improvement.

D. Work shall be planned, authorized, and accomplished under controlled conditions using technical standards, QA requirements, and implementing procedures

commensurate with applicable control levels.

2.1.2 Implementing Procedures

A. Implementing procedures shall be developed, reviewed, and approved by technically competent personnel.

B. Implementing procedures shall include the following information, as appropriate to the work to be performed:

   1. Responsibilities of the organizations affected by the document

   2. Technical, regulatory, quality assurance, or other program requirements

   3. Sequential description of the work to be performed, including any allowance for out-of-sequence processing

   4. Quantitative or qualitative acceptance criteria sufficient for determining that activities were satisfactorily accomplished

   5. Prerequisites, limits, precautions, process parameters, and environmental conditions

   6. Special qualification and training requirements

   7. Verification points and hold points

   8. Methods for demonstrating that the work was performed as required (such as provisions for recording inspection and test results, check-off lists, or sign-off blocks)

   9. Identification and classification of QA records to be generated by the implementing procedure

C. Individuals performing work shall comply with implementing procedures; however, when work cannot be accomplished as described in the implementing procedure or accomplishment of such work would result in an undesirable situation, a condition adverse to quality, or an unacceptable safety risk, the work shall be suspended until the appropriate procedure change provisions are implemented.

2.1.3 Item Identification and Control

A. Processes shall be established and maintained to identify, control, and maintain items to prevent their damage, loss, or deterioration. The identification of items shall be maintained to ensure appropriate traceability. Traceability requirements shall be specified in design documents or implementing procedures. Processes shall be established and implemented to control consumables and items with limited operating or shelf life and to prevent the use of incorrect or defective items.

B. The following controls shall be established to ensure that only correct and accepted items are used or installed:

1. Items shall be identified and traced from the time of receipt, up to and including installation or end use. Records shall be maintained to ensure that the item can be traced at all times, from its source through installation or end use.

2. Item identification methods shall include physical markings. If physical markings are either impractical or insufficient, other appropriate means shall be employed (such as physical separation, labels or tags attached to containers, or procedural controls). When used, physical markings shall:

   a. Be applied using materials and methods that provide clear, permanent, and legible identification

   b. Not be detrimental to the function or service life of the item

   c. Be transferred to each part of an identified item when the item is subdivided

   d. Not be obliterated or hidden by surface treatments, coatings, or installation unless other means of identification are substituted

3. If codes, standards, or specifications include specific identification or traceability requirements (such as identification or traceability of the item to applicable specification or grade of material; heat, batch, lot, part, or serial number; or specified inspection, test, or other record(s)), then identification and traceability methods shall be implemented to ensure the special requirements are met.

4. Item identification control system records shall provide the inspection, test, and operating status of items. Items that have satisfactorily passed the required inspections and tests shall be identified. The identification methods shall preclude the inadvertent installation, use, or operation of items that have not passed required inspections and tests.

5. The status of inspections and tests shall be identified either on the items or in documents traceable to the items. Status shall be maintained through the use of

status indicators (such as tags, markings, labels, or stamps) or other means (such as inspection or test records), and the authority for applying and removing status indicators shall be specified.

2.1.4 Special Processes

A. Processes shall be considered as special processes if they meet any one or a combination of the following criteria:

   1. The results are highly dependent on the control of the process

   2. The results are highly dependent on the skill of the operator

   3. The quality of the results cannot be readily determined by inspection or test of the product

B. Implementing procedures shall be developed and implemented to ensure that special process parameters are controlled and specified environmental conditions are maintained. In addition to the requirements provided in Section 2.1.2, special process implementing procedures shall include or reference:

   1. The requirements for training/qualification of personnel and quality processes/equipment

   2. The conditions necessary for completion of the special process, including equipment, statistical process control, controlled parameters of the process, and calibration requirements

2.1.5 Handling, Storage, and Shipping

A. Handling, storage, cleaning, shipping, and other means of preserving, transporting, and packaging of items shall be conducted in accordance with established work and inspection procedures, shipping instructions, or other specified documents.

B. If required for critical, sensitive, perishable, or high-value articles, specific implementing procedures for handling, storage, cleaning, packaging, shipping, and other preservation shall be prepared and used.

C. Measures shall be established and implemented for the marking and labeling of items for packaging, shipping, handling, and storage as necessary to adequately identify, maintain, and preserve the item. Markings and labels shall indicate the presence of special environments or the need for special controls, as necessary, and shall be applied and removed by authorized personnel.

D. If required for protection or maintenance of particular items, special equipment (such as containers, shock absorbers, and accelerometers) and special protective environments (such as inert gas and specific moisture and temperature levels) shall be specified, planned for, and provided.

   1. If special protective equipment and environments are used, provisions shall be made for verifying their adequacy.

   2. Special handling tools and equipment shall be used and controlled, as necessary, to ensure safe and adequate handling.

   3. Special handling tools and equipment shall be inspected and tested at specified intervals and in accordance with implementing procedures to verify that the tools and equipment are adequately maintained.

   4. Operators of special handling and lifting equipment shall be sufficiently experienced and trained to use the equipment.

E. If storage of items is required, methods shall be established for the control of item identification records that are commensurate with the planned duration and conditions of storage. These methods shall provide for, as applicable:

   1. Maintenance or replacement of markings and identification tags damaged during handling or aging

   2. Protection of identification markings that are subject to excessive deterioration due to environmental exposure

   3. Update of related identification records and documentation

F. Status indicators, such as tagging valves and switches to prevent inadvertent operation, shall be used to indicate the operating status of items. Status indicators, such as lockout tags, shall also be used where appropriate and shall be applied and removed by authorized personnel.

2.2 DESIGN CONTROL

A. Items and processes shall be designed using sound engineering and scientific principles and appropriate standards. Design work, including changes, shall incorporate appropriate requirements, such as general design criteria and design bases. Design interfaces shall be identified and controlled.

B. The adequacy of design products shall be verified by individuals or groups other than those who performed the design work. Required verification and validation shall be completed before approval and implementation of the design.

C. Designs (from conceptual through final) shall be defined, controlled, and verified. In establishing design controls, management is responsible for ensuring that design inputs are technically correct; that design interfaces are identified; that authorities, responsibilities, and lines of communication are clearly defined; and that the design processes clearly define the acceptance criteria for the product.

2.2.1 Design Input

Applicable design inputs such as design bases, conceptual design reports, performance requirements, regulatory requirements, codes, and standards shall be controlled by those responsible for the design in accordance with the following requirements:

A. Design inputs shall be identified and documented and their selection reviewed and approved by those responsible for the design.

B. Design inputs shall be specified and approved on a timely basis to the level of detail necessary to permit the design work to be carried out correctly in a manner that provides a consistent basis for making design decisions, accomplishing design verification, and evaluating design changes.

C. Changes from approved design inputs and reasons for the changes shall be identified, approved, documented, and controlled.

D. Design inputs based on assumptions that require reverification shall be identified and controlled.

2.2.2 Design Process

The design process shall be controlled according to the following requirements:

A. Appropriate standards shall be identified and documented and their selection reviewed and approved. Changes from specified standards, including the reasons for the change, shall be identified, approved, documented, and controlled.

B. Design work shall be prescribed and documented on a timely basis and to the level of detail necessary to permit the design process to be carried out correctly.

C. Design documents shall be adequate to support design, fabrication, construction, and operation.

D. Design documents shall be sufficiently detailed as to purpose, method, assumptions, design input, references, and units such that a person technically

E. qualified in the subject can understand the documents and verify their adequacy without recourse to the originator.

F. Controls for identifying assemblies or components that are part of the item being designed shall be established. If a commercial grade assembly or component is modified or selected by special inspection or testing to meet requirements that are more restrictive than the supplier's published product description, then the assembly or component shall be represented as different from the commercial grade item in a manner traceable to a documented definition of the difference.

G. Controls for selecting and reviewing design methods, materials, parts, equipment, and processes essential to the function of an item shall be established.

H. Drawings, specifications, and other design output documents shall contain appropriate inspection and testing acceptance criteria.

2.2.3 Design Analyses

A. Design analyses shall be planned, controlled, and documented.

B. Documentation of design analyses shall include

1. Definition of the objective of the analyses

2. Definition of design inputs and their sources

3. Results of literature searches or other applicable background data

4. Identification of assumptions and designation of those assumptions that shall be verified as the design proceeds

5. Identification of any computer calculations, including computer type, computer software name, revision identification, inputs, outputs, and the bases (or reference thereto) supporting application of the software to the specific physical problem.

6. Identification of the reviewer and the approver

C. Calculations shall be identifiable by subject (including structure, system, or component to which the calculation applies), originator, reviewer, and date, or by other designator such that the calculations are traceable.

D. Computer software used to perform design analyses shall be developed, qualified, and used according to the requirements of Section 6.

2.2.4 Design Interface

A. Design interfaces shall be identified, documented, and controlled so that efforts are coordinated among participating organizations.

B. Design interface controls shall including the assignment of responsibility and the establishment of implementing procedures among participating design organizations for the review, approval, release, distribution, and revision of documents involving design interfaces

C. Design information transmitted across interfaces shall be documented and controlled.

D. The status of the design information or issued design documents shall be identified in transmittals. Where necessary, incomplete designs that require further evaluation, review, or approval shall be identified.

2.2.5 Design Verification

The acceptability of design work and documents, including design inputs, processes, outputs, and changes, shall be verified. The following design control requirements shall be applied to verify the adequacy of design:

A. Design verification shall be performed using one or a combination of the following methods:

    1. Design review

    2. Alternate calculations

    3. Qualification testing

B. The particular design verification method shall be identified and its use justified.

C. The results of design verification shall be clearly documented, including the identification of the verifier.

D. Design verification shall be performed by competent individuals or groups other than those who performed the original design (but they may be from the same organization). If necessary, this design verification may be performed by the originator's supervisor, provided that:

    1. The supervisor did not specify a singular design approach or rule out certain design considerations and did not establish the design inputs used in the design.

2. The supervisor is the only individual in the organization competent to perform the verification.

3. The determination to use the supervisor is documented and approved in advance.

E. Design verification shall be performed at appropriate times during the design process.

1. Verification shall be performed before release for procurement, manufacture, construction, or release to another organization for use in other design work.

2. Design verification shall be completed before relying on an item to perform its function.

F. The extent of the design verification required shall be based on the complexity, risk, uniqueness of design, complexity of design, degree of standardization, state of the art, and similarity to previously proven designs. When the design has been subjected to a verification process in accordance with this QAPD, the verification process need not be duplicated for identical designs.

G. Use of previously proven designs shall be controlled according to the following requirements:

1. The applicability of standardized or previously proven designs shall be verified with respect to meeting pertinent design inputs for each application.

2. Known problems affecting standard or previously proven designs and their effects on other features shall be considered.

3. The original design and associated verification measures shall be adequately documented and referenced in the files of subsequent application of the design.

4. Changes in previously verified designs shall require reverification. Such reverifications shall include the evaluation of the effects of those changes on the overall previously verified design and on any design analyses upon which the design is based.

2.2.6 Design Reviews

A. Design reviews shall be controlled, documented, and performed, and shall consider the following:

1. Design inputs were correctly selected and incorporated.

2. Assumptions necessary to perform the design work were adequately described, reasonable, and reverified as necessary.

3. Appropriate design methods were used.

4. Design output is reasonable compared to design inputs.

5. The necessary design input and verification requirements for interfacing organizations were specified in the design documents or in supporting implementing procedures.

B. Disposition of design review comments shall be documented.

2.2.7 Alternative Calculations

Alternative calculations are calculations or analyses that are made using alternate methods to verify correctness of the original calculations or analyses. The appropriateness of any assumptions, the input data used, any computer programs, or other calculation methods used, shall be evaluated.

2.2.8 Qualification Testing

If design adequacy is to be verified by qualification tests, the tests shall be pre-identified. When qualification testing is used, the following requirements shall apply:

A. The test configuration shall be defined and documented.

B. Testing shall demonstrate the adequacy of performance under conditions that simulate the most adverse design conditions. Operating modes and environmental conditions in which the item must perform satisfactorily shall be considered in determining the most adverse conditions.

C. If the tests verify only specific design features, the other features of the design shall be verified by other means.

D. Test results shall be documented and evaluated by the responsible design organization to ensure that test requirements have been met.

E. If qualification testing indicates that a modification to an item is necessary to obtain acceptable performance, the modification shall be documented and the modified item retested or otherwise verified to ensure satisfactory performance.

F. Scaling laws shall be established and verified when tests are being performed on models or mockups.

G. The results of model test work shall be subject to error analysis, where applicable, before the results are used in final design work.

2.2.9 Design Change

Design changes shall be controlled in accordance with the following requirements:

A. Changes to final designs, field changes, and nonconforming items dispositioned "use as is" or "repair" shall be justified and shall be subject to design control measures commensurate with those applied to the original design.

B. Design control measures for changes shall include provisions to ensure that the design analyses for the item are still valid.

C. Changes shall be approved by the same groups or organizations that reviewed and approved the original design documents, with the following considerations:

   1. If an organization that originally was responsible for approving a particular design document is no longer responsible, the new responsible organization shall be designated.

   2. The cognizant design organization shall have demonstrated competence in the specific design area of interest and have an adequate understanding of the requirements and intent of the original design.

D. When a design change is approved other than by revision to the affected design documents, measures shall be established to incorporate the change into these documents, where such incorporation is appropriate.

E. If a significant design change becomes necessary because of an incorrect original design, the design process and design verification methods and implementing procedures shall be reviewed and modified as appropriate. These design deficiencies shall be documented according to the requirements provided in Section 1.3.2.

F. Field changes shall be incorporated into the applicable design documents.

G. Design changes that affect related implementing procedures or training programs shall be communicated to the appropriate organizations.

2.3 PROCUREMENT

CBFO and participant organizations shall ensure that procured items and services meet established technical and QA requirements, and that they perform as specified.

Prospective suppliers shall be evaluated and selected on the basis of documented criteria. The responsible organization shall verify that approved suppliers continue to provide acceptable items and services.

2.3.1 Procurement Planning Requirements

Procurement activities shall be planned as early as possible and documented to ensure a systematic approach to the procurement process. Procurement planning shall:

A. Identify procurement methods and organizational responsibilities, including the appropriate QA organization

B. Identify and document the sequence of actions and milestones needed to effectively complete the procurement

C. Provide for the integration of the following activities:

1. Procurement document preparation, review, and change control
2. Selection of procurement sources
3. Proposal or bid evaluation and award
4. Purchaser evaluation of supplier performance
5. Purchaser verifications including any hold-point and witness-point notifications
6. Control of nonconformances
7. Corrective action
8. Acceptance of the item or service
9. Identification of QA records

2.3.2 Supplier Selection

A. Supplier selection shall be based on evaluation of the supplier's capability to provide items or services in accordance with procurement document requirements

B. Organizations responsible for supplier source selection shall be identified and shall include the appropriate QA organization.

C. Measures for selecting procurement sources shall include one or more of the following elements:

1. An evaluation of the supplier's history for providing an identical or similar product that performs satisfactorily in actual use

2. An evaluation of the supplier's current QA documentation, supported by any documented qualitative and quantitative information

3. An evaluation of the supplier's technical and QA capability, based on an evaluation of the supplier's facilities, personnel, and quality program implementation

D. The results of procurement source selection shall be documented.

2.3.3 Proposal/Bid Evaluation

A. The proposal or bid evaluation process shall include a determination of the extent of conformance to the procurement document requirements. This evaluation shall be performed by designated, technically qualified personnel, including the quality assurance organization, and shall include, at a minimum, the following:

1. Technical considerations

2. QA program requirements

3. Supplier personnel skills

4. Supplier production capabilities

5. Supplier past performance

6. Alternatives proposed by the supplier

7. Exceptions taken by the supplier

B. Before the contract is awarded, the purchaser shall resolve, or obtain commitments to resolve, deficiencies identified during the proposal or bid evaluation.

C. Supplier QA provisions shall be accepted by the purchaser QA management before the supplier is authorized to start work.

2.3.4 Procurement Document Requirements

Procurement documents shall include the following, as applicable to the item or service being procured:

A. The scope of work

B. Technical requirements, including the following:

1. Design bases shall be identified or referenced.

2. Specific documents (such as drawings, codes, standards, regulations, DOE orders, procedures, or instructions) that describe the technical requirements of the items or services to be furnished shall be identified. The revision level or change status of these documents shall also be identified.

3. Tests, inspections, hold points, or acceptance criteria that the purchaser shall use to monitor and evaluate the performance of the supplier shall be specified.

C. QA provisions specified by the purchaser QA organization shall include:

1. The requisite QA and documentation requirements, depending on the control level of the item or service being procured

2. The pass-down requirements that the supplier shall incorporate into any sub-tier procurement document

3. When deemed appropriate, the purchaser may permit some or all supplier work to be performed under the purchaser QA program, provided that the requirements are adequately implemented. In these cases, procurement documents shall specify that the purchaser's QA implementing procedures are applicable to the supplier and that the purchaser shall provide these applicable documents to the supplier.

4. Right of access to supplier facilities and records for inspection and audit by the purchaser, CBFO, or other designee authorized by the purchaser

5. The requirements of Section 1.5 and provisions for disposition, if the supplier is required to maintain QA records

6. Requirements for the supplier to report nonconformances and obtain purchaser approval of supplier-recommended dispositions

7. Spare and replacement parts or assemblies and the appropriate technical and QA requirements for ordering

2.3.5 Procurement Document Review and Approval

A. A review of the procurement documents and any changes thereto shall be made to verify that documents include appropriate provisions to ensure that items or services meet the prescribed requirements. Procurement document changes shall be subject to the same degree of control as the original documents.

B. Procurement document reviews shall be performed and documented prior to the document being issued to the supplier.

C. Reviews shall be performed by personnel who have access to pertinent information and who have adequate understanding of the requirements and scope of the procurement.

D. Procurement document reviews shall include representatives from the technical and QA organizations and shall be approved by responsible management.

2.3.6 Supplier Performance Evaluation

The purchaser of items and services shall establish measures to interface with the supplier and to verify supplier performance, as deemed necessary by the purchaser. The measures shall include:

A. Establishing an understanding between the purchaser and supplier of the requirements and specifications identified in the procurement documents

B. Requiring the supplier to identify planning techniques and processes to be used in fulfilling procurement document requirements

C. Reviewing supplier documents that are prepared or processed during work performed to fulfill procurement requirements

D. Identifying and processing necessary change information

E. Establishing the method to be used to document information exchanges between purchaser and supplier

F. Establishing the extent of assessment activities and inspection

2.3.7 Acceptance of Items or Services

2.3.7.1 Source Verification

A. The purchaser may accept an item or service by monitoring, auditing, surveilling, witnessing, or observing activities performed by the supplier. This method of acceptance is called source verification.

B. The extent of source verification shall be a function of the relative importance, complexity, and quantity of items or services being procured, as well as the supplier's quality of performance. Source verifications shall be accomplished as early as possible, but prior to the start of those activities that are required to be controlled, and shall include the active involvement of the purchaser's QA organization. In addition:

1. Source verification shall be accomplished consistent with the supplier's planned inspections, examinations, or tests and performed at intervals consistent with the importance and complexity of the item.

2. Documented evidence of acceptance of source-verified items or services shall be furnished to the party receiving the item, to the purchaser, and to the supplier.

3. Source verification shall be performed by qualified personnel.

C. For procurement of services only (such as third party inspection, engineering and consulting services), and installation, repair, overhaul, or maintenance work, the purchaser shall accept the service by any or all of the following methods:

1. Technical verification of data produced

2. Surveillance and/or audit of the activity

3. Review of objective evidence for conformance to the procurement document requirements such as certifications or test reports

2.3.7.2 Receiving Inspection

When a receiving inspection is used to accept an item:

1. The inspection shall include consideration of source assessments, verifications and audits and the demonstrated quality performance of the supplier.

2. The inspection shall be performed in accordance with established inspection procedures or instructions.

3. The inspection shall verify, as applicable, proper configuration; identification; dimensional, physical, and other characteristics; freedom from shipping damage; and cleanliness.

4. The inspection shall be planned and executed in accordance with the applicable requirements of Section 2.4.

5. Receiving inspection shall include a review of the adequacy and completeness of any required supplier documentation.

2.3.7.3 Post-Installation Testing

When post-installation testing is used as a method of acceptance, post-installation test requirements and acceptance documentation shall be mutually established and agreed upon by the purchaser and supplier.

2.3.7.4 Supplier Certificate of Conformance

When a certificate of conformance is used, the following, at a minimum, shall be met:

A. The certificate shall identify the purchased material or equipment, including the purchase order and item number or other identification that is traceable to the requirements of the procurement document.

B. The certificate shall identify the specific procurement requirements met by the purchased material or equipment, such as codes, standards, and other specifications. The procurement requirements identified shall include any approved changes, waivers, or deviations applicable to the subject material or equipment.

C. The certificate shall identify any procurement requirements that have not been met, together with an explanation and the means for resolving the nonconformances.

D. The certificate shall be signed or otherwise authenticated by an official of the supplier organization, whose function and position are described in the supplier's QA program.

E. The certification system, including the procedures to be followed in filling out a certificate and the administrative procedures for review and approval of the certificate, shall be described in the purchaser or supplier QA program.

F. Means shall be provided to verify the validity of supplier certificates and the effectiveness of the certification system, such as during the performance of audits of the supplier or independent inspection or test of the items. Such verification shall be conducted by the purchaser at intervals commensurate with the supplier's past quality performance.

2.3.8 Control of Supplier Nonconformances

The purchaser and supplier shall establish and document the process for dispositioning items and services that do not meet procurement document requirements in accordance with the following:

A. The supplier shall submit a report of nonconformance to the purchaser that includes supplier-recommended disposition (for example, "use as is" or "repair") and provide technical justification for such disposition.

B. Reports of nonconformances to procurement document requirements or documents approved by the purchaser shall be submitted to the purchaser for approval. Examples of conditions requiring a report of nonconformance include:

1. Failure to meet technical or material requirements

2. Failure to meet a requirement in supplier documents that have been approved by the purchaser

3. The nonconformance cannot be corrected by continuation of the original manufacturing process or by rework

4. The item does not conform to the original requirement even though the item can be restored to a condition such that its capability to function is unimpaired

C. The purchaser shall evaluate the supplier-recommended disposition.

D. The purchaser shall verify implementation of the disposition.

2.3.9 Commercial Grade Items

Where the design specifies the use of commercial grade items, the following requirements are an acceptable alternative to other requirements of this section.

A. The commercial grade item shall be identified in an approved design output document, such as a drawing, specification, or other document translated from a design input document. An alternative commercial grade item may be applied as long as the responsible design organization provides verification that the alternative commercial grade item performs the intended function and meets design requirements that are applicable to both the replaced item and its application.

B. Source evaluation and selection, where determined necessary by the purchaser based on complexity and importance to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility, shall be in accordance with Section 2.3.2.

C. Commercial grade items shall be identified in the procurement document by the manufacturer's published product description.

D. After receipt of a commercial grade item, the purchaser shall ensure that:

1. Damage was not sustained during shipment

2. The item received was the item ordered

3. Inspection or testing is accomplished, to the extent determined by the purchaser, to ensure conformance with the manufacturer's published requirements

4. Documentation, as applicable to the item, was received and is acceptable

2.4 INSPECTION AND TESTING

A. Inspections and testing shall be performed in accordance with approved implementing procedures. An essential part of the work planning process is to identify the items and processes to be inspected or tested, the parameters or characteristics to be evaluated, the techniques to be used, the acceptance criteria, any hold points, and the organizations responsible for performing the tests and inspections. Inspection for acceptance shall be performed by personnel other than those who performed or directly supervised the work being inspected. Inspection and testing of specified items and processes shall be conducted using established acceptance and performance criteria. The acceptance of items and processes shall be made by and documented by qualified and authorized personnel. Equipment used for inspections and tests shall be calibrated and maintained.

B. Inspection and testing activities shall be conducted in accordance with the following requirements, as applicable.

2.4.1 Qualification of Inspection and Test Personnel

This section provides amplified requirements for the qualification of personnel who perform inspection and testing to verify conformance to specified requirements for the purpose of acceptability. The requirements of this section do not apply to the qualification of personnel for performance of nondestructive examination. Qualification of personnel for nondestructive examination is addressed in Section 2.4.2.

A. The responsible organization shall designate those activities that require qualified inspection and test personnel and the minimum requirements for such personnel. Further, the responsible organization shall establish written procedures for the qualification of inspection and test personnel and for the assurance that only those personnel who meet the requirements of this section are permitted to perform applicable inspection and test activities.

B. When a single inspection or test requires implementation by a team or a group, personnel not meeting the requirements of this section may be used in data-taking assignments or in plant or equipment operation, provided they are supervised or overseen by a qualified individual.

C. Personnel selected for performing inspection and test activities shall have the experience or training commensurate with the scope, complexity, or special nature of the activities.

D. Provisions shall be made for the indoctrination of personnel to the technical objectives and requirements of the applicable codes and standards and the QA program controls that are to be employed.

E. The need for a formal training program shall be determined, and such training activities shall be conducted as required to qualify personnel that perform such inspections and tests. On-the-job training shall also be included in the program, as appropriate, with emphasis on first-hand experience gained through actual performance of inspections and tests.

F. The capabilities of a candidate for certification shall be initially determined by a suitable evaluation of the candidate's previous education, experience, training, and either test results or capability demonstration.

G. The job performance of inspection and test personnel shall be reevaluated for capability at periodic intervals, not to exceed three years. Reevaluation shall be by evidence of continued satisfactory performance or redetermination of capability in accordance with the above requirements. If, during this evaluation or at any other time, it is determined by the responsible organization that the capabilities of an individual are not in accordance with the qualification requirements specified for the job, that person shall be removed from that activity until such time as the required capability has been demonstrated. Any person who has not performed inspection or testing activities in their qualified area for a period of one year shall be reevaluated for the required capability in accordance with the above requirements.

H. The qualification of personnel shall be certified in writing in an appropriate form and shall include the following information:

1. Employer’s name

2. Identification of person being certified

3. Activities certified to perform

4. Basis used for certification, including such factors as: (1) education, experience, indoctrination, and training; (2) test results, where applicable; and (3) results of capability demonstration

5. Results of periodic evaluation

6. Results of physical examinations, when required

7. Signature of the employer’s designated representative responsible for such certification

8. The date of certification and date of certification expiration

I. The responsible organization shall identify any special physical characteristics needed in the performance of each activity, including the need for initial and subsequent physical examination.

J. Records of personnel qualification shall be established and maintained by the employer. These records shall include the information required above for certification.

2.4.2 Qualification of Nondestructive Examination Personnel

This section identifies the requirements for the qualification of personnel who perform nondestructive examination (NDE) (radiographic, magnetic particle, ultrasonic, liquid penetrant, eddy current, neutron radiographic, leak testing, and visual testing) to verify conformance to specified requirements, for nondestructive examination activities performed at the WIPP site.

A. The American Society of Nondestructive Testing (ASNT) Recommended Practice No. SNT-TC-1A, June 1980 Edition, and its applicable supplements, shall apply as requirements for personnel performing the above methods of NDE.

B. The responsible organization shall establish written procedures for the control and administration of the training, examination, and certification of NDE personnel.

C. Records of personnel qualification shall be established and maintained by the employer.

2.4.3 Inspection

2.4.3.1 Inspection Planning

A. Inspection planning shall be performed and documented and shall include:

1. Identification of work operations where inspections are necessary

2. Identification of the characteristics to be inspected and when during the work process inspections are to be performed

3. Identification of inspection or process monitoring methods to be employed

4. Identification of acceptance criteria

5. Identification of sampling requirements

6. Methods to record inspection results

7. Selection and identification of the measuring and test equipment (M&TE) to be used to perform the inspection

8. Process used to ensure that the equipment being utilized for inspection or testing is calibrated and is of the proper type, range, accuracy, and tolerance to accomplish the intended function

B. When statistical sampling is to be used to verify the acceptability of a group of items, the sampling method shall be based on recognized standard practices.

2.4.3.2 Inspection Hold Points

Hold points are used to control work that is not to proceed without the specific consent of the organization placing the hold point. The specific hold points shall be indicated in appropriate documents. Only the organization responsible for the hold point may waive the hold point. Approval to waive specified hold points shall be documented before continuing work beyond the designated hold point.

2.4.3.3 In-Process Inspections and Monitoring

A. Items in process shall be inspected as necessary to verify quality. If inspection of processed items is impossible or disadvantageous, indirect control by monitoring of processing methods, equipment, and personnel shall be provided. Both inspection and process monitoring shall be conducted when control is deemed inadequate, using only one of these methods.

B. When a combination of inspection and process monitoring methods is used, monitoring shall be performed systematically to ensure that the specified requirements for control of the process and the quality of the item are met throughout the duration of the process.

C. Controls shall be established and documented for the coordination and sequencing of the work at established inspection points during successive stages of the process.

2.4.3.4 Final Inspections

A. Final inspections shall include a review of the results and the verification of the resolution of all nonconformances identified by earlier inspections.

B. Finished items shall be inspected for completeness, markings, calibration, protection from damage, or other characteristics, as required to verify the quality and conformance of the item to the applicable requirements.

C. Records review shall be performed to ensure adequacy and completeness.

D. Item modifications, repairs, or replacements that are performed subsequent to final inspection shall require reinspection or retest, as appropriate, to verify acceptability.

2.4.3.5 In-service Inspections

A. Required in-service inspection or surveillance of structures, systems, or components shall be planned and executed by or for the organization responsible for their operation.

B. Inspection methods shall be established and executed to verify that the characteristics of an item continue to remain within specified limits.

C. Inspection methods shall include evaluations of performance capability of essential emergency and safety systems and equipment, verification of calibration and integrity of instruments and instrument systems, and verification of maintenance, as appropriate.

2.4.3.6 Inspection Documentation

Inspection documentation shall identify:

A. The item inspected and the date of the inspection

B. The name or unique identifier of the inspector who documented, evaluated, and determined acceptability

C. The method of inspection

D. The inspection criteria, sampling plan, or reference documents (including revision designation) used to determine acceptance

E. The results

F. The M&TE used during the inspection, including the identification number and the calibration due date

G. Reference to any information on actions taken in connection with nonconformances, as applicable

2.4.4 Test Requirements

Testing shall be used to determine the capability of an item to meet specified requirements by subjecting the item to a set of physical, chemical, environmental, or operating conditions. Examples of such tests include prototype qualification tests, production tests, proof tests prior to installation, construction tests, and pre-operational tests.

2.4.4.1 Test Planning

Test planning shall include:

A. The identification of the implementing procedures to be developed to control and perform the test. In lieu of specially prepared written test procedures, appropriate sections of related documents such as American Society for Testing and Materials (ASTM) methods may be used. If used, they shall incorporate the information directly into the approved test implementing procedure, or shall be incorporated by reference.

B. The identification of the item to be tested and the test requirements and acceptance limit, including the required levels of precision and accuracy

C. The identification of the M&TE to be used to perform the test to ensure that the equipment being utilized is calibrated and is of the proper type, range, accuracy, and tolerance to accomplish the intended function

D. Any test prerequisites, including test equipment, instrumentation and software needs, personnel training and qualification, and suitably controlled environmental conditions

E. Any mandatory hold points

F. The methods to be used to record data and results

G. The provisions for ensuring that prerequisites for the given test have been met

2.4.4.2 Test Documentation

Test documentation shall identify:

A. The applicable test requirements, plans, and procedures, including revisions

B. The item or work product tested

C. The date of the test

D. The name of the tester and data recorders

E. The type of observation and method of testing

F. The identification of test criteria or reference documents used to determine acceptance

G. The results and acceptability of the test

H. The actions taken in connection with any noted nonconformances

I. The name of the person evaluating the test results

J. The identification of the M&TE used during the test (including the identification number and calibration due date)

2.4.4.3 Test Results

Test results shall be documented and their conformance with acceptance criteria shall be evaluated by a qualified individual within the responsible organization to ensure that all test requirements have been satisfied.

2.4.5 Monitoring, Measuring, Testing, and Data Collection Equipment

The following sections establish requirements to ensure that equipment used for inspection and testing is properly controlled, calibrated, and maintained. Equipment discussed in the following sections includes inspection and test equipment, measuring and data collection equipment, equipment (either hand-held or installed) used for data indication, and other equipment used for data indication, collection, or evaluation. These are called M&TE.

Calibration and control measures may not be required for rulers, tape measures, levels, and other such devices, if normal commercial equipment provides adequate accuracy.

2.4.6 Use and Control of M&TE

Each organization using M&TE shall:

A. Establish and document a system to control the use and calibration of M&TE

B. Have a program to recall for calibration, or remove from service, M&TE that has exceeded its calibration interval; has broken calibration seals; has been modified, repaired, or has had components replaced; or is suspected to be malfunctioning because of mishandling, misuse, or unusual results

C. Establish and maintain documented procedures to evaluate the adequacy of the calibration system and to ensure compliance with the requirements of this QAPD

D. Maintain records documenting that established M&TE schedules and procedures have been followed. These records shall include an individual record of calibration, or other means of control, providing:

   1. A description or identification of the item

   2. Calibration interval

   3. Date calibrated

   4. Identification of the calibration source

   5. Calibration results (data and status)

   6. Calibration action taken (e.g., adjusted, repaired, new value assigned, derated)

   7. Evaluation and corrective action taken in response to out-of-calibration conditions

E. Label all M&TE to indicate the calibration status, the date calibrated, the calibration due date or usage equivalent, and the identification of any limitations. (When it is impractical to apply a label directly to an item, the label may be affixed to the instrument container or some other suitable means may be used to reflect calibration status.)

F. Evaluate the validity of previous inspection and test results and the acceptability of related items, data collected, and processes monitored, when M&TE is found to be out-of-calibration

G. Handle, store, and transport M&TE in a manner that does not adversely affect the accuracy of the equipment

H. Give due consideration to temperature, humidity, lighting, vibration, dust control, cleanliness, electromagnetic interference, and any other factors affecting the results of measurements. Where pertinent, these factors shall be monitored and recorded and, when appropriate, correcting compensations shall be applied to measurement results.

2.4.7 Calibration

A. M&TE requiring calibration shall be calibrated at periodic intervals established and maintained to ensure acceptable reliability, where reliability is described as the probability that M&TE will remain in tolerance throughout the interval.

B. Intervals shall be established for all M&TE requiring calibration unless the equipment is regularly monitored through the use of check standards in a documented measurement assurance process. Check standards must closely represent the item parameters normally tested in the process, and the check standard must be verified periodically.

C. Where intervals are used to ensure reliability, the interval setting system must be systematically applied and shall have stated reliability goals and a method of verifying that the goals are being attained.

D. Intervals may be based on usage or time since last calibration.

E. All exemptions from periodic calibration shall be approved and documented.

F. The recall system may provide for the temporary extension of the calibration due date for limited periods of time under specified conditions that do not unreasonably impair the satisfaction of task objectives.

G. If any M&TE is found to be significantly out-of-tolerance during the calibration process, the cognizant organization shall provide for the notification to the user and cognizant QA management of the out-of-tolerance condition, with the associated measurement data, so that appropriate action can be taken.

SECTION 3 – ASSESSMENT REQUIREMENTS

3.1 MANAGEMENT ASSESSMENT

Managers at every level shall periodically assess the performance of their organization to determine the effectiveness of QA program provisions that enable the organization to meet customer requirements and expectations. This assessment shall emphasize the use of human and material resources to achieve organizational goals and objectives.

A. The management assessment should include an introspective evaluation to determine if the entire integrated management system effectively focuses on meeting strategic goals.

B. Managers shall retain overall responsibility for management assessments. Direct participation by senior management is essential to the success of the process because management is in the position to view the organization as a total system.

C. Management assessments should focus on the identification and resolution of both systemic and management issues and problems. Strengths and weaknesses affecting the achievement of organizational objectives should be identified so that meaningful action can be taken to improve quality.

D. Processes being assessed should also include strategic planning, organizational interfaces, cost control, use of performance indicators, staff training and qualifications, and supervisory oversight and support. Effective management assessments should evaluate such conditions as the state of employee knowledge, motivation, and morale; the amount of mutual trust and communication among workers and organizations; the existence of an atmosphere of creativity and improvement; and the adequacy of human and material resources.

E. Management assessments of the QA program shall be conducted regularly and reported at least annually to an identified senior management level with sufficient authority to effect corrective measures, as necessary.

F. Management assessment results should be used as input to the organizational continuous improvement process.

3.2 INDEPENDENT ASSESSMENT

A. Planned and periodic independent assessments shall be conducted to measure item and service quality, process effectiveness, and promote improvement. The organization performing assessments shall have sufficient authority and freedom from the activities being assessed to carry out its responsibilities. Persons conducting independent assessments shall be technically qualified and

knowledgeable of the items and activities being assessed.

B. The types and frequencies of independent assessments shall be based upon the relevant control levels assigned to the items and activities under the cognizance of the organization.

C. The CBFO and participant organizations responsible for the performance of activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP site shall implement a program of surveillance and audits. The program shall be planned and documented and shall include both routine surveillance of those activities and audits to verify compliance with all aspects of the quality assurance program and to determine its adequacy and effectiveness.

3.2.1 Surveillances

A. A program of surveillance of the activities referenced above shall be planned, performed, documented, and reported to appropriate management personnel. The surveillance process consists of monitoring or observing to verify whether an item, activity, system, or process conforms to specified requirements.

B. Surveillances shall accomplish the following:

1. Monitor work in progress

2. Document compliance or noncompliance with established requirements and procedures

3. Identify actual and potential conditions adverse to quality

4. Obtain timely corrective action commitment from cognizant managers for identified conditions adverse to quality

5. Provide notification to responsible managers of the status and performance of work under surveillance

6. Verify timely implementation of corrective actions

C. Audits or other independent assessments of the subject activities, conducted by the responsible organization, may be counted as satisfying the requirement to do surveillances of related activities in the corresponding surveillance schedule period.

3.2.2 Audits

The following sections describe the audit process requirements.

3.2.2.1 Scheduling Audits

A. Audits shall be scheduled to begin as early in the life of a project or activity as practicable and continue at intervals consistent with the schedule for accomplishing the work and commensurate with assigned control level.

B. Periodically scheduled QA program audits shall be supplemented by, or integrated with, either audits or surveillances of a technical nature (e.g., performance-based audits) which assess the quality of selected work products and work processes.

3.2.2.2 Planning and Preparation for Audits

The organization performing the audit shall develop and document a plan for each audit.

A. The plan shall include the scope, requirements, purpose, audit personnel, activities to be audited, organizations to be notified, applicable documents, schedule, and written procedures or checklists to be used.

B. Audit planning shall include a review of past assessment results to determine the nature of problems that have occurred. When recurring problems are found, the audit team shall review corrective actions that have been taken and attempt to determine whether the corrective actions were effective in preventing recurrence.

C. Audit preparation shall include review of pertinent background information, procedures, and technical documents so that audit team members are familiar with the work being audited.

D. Audits shall include technical evaluations of the applicable procedures, instructions, activities, and items, as appropriate.

E. The scope shall include related corrective actions taken since the previous assessment.

3.2.2.3 Audit Team Selection

A. Audit team members shall be identified prior to the start of the audit activity. The team members shall be selected on the basis of technical qualifications and knowledge of the item or process being audited and shall be independent from the items or processes being audited. Audit team members shall have sufficient authority and organizational freedom to carry out their assigned responsibilities. In the case of internal audits, personnel having direct responsibility for performing the activities being audited shall not be involved in the selection of the audit team.

B. An audit team leader shall be appointed to provide indoctrination and supervision of the team, organize and direct the audit, and coordinate the preparation and issuance of the audit report.

C. Before starting the audit, the audit team leader shall ensure that the assigned personnel collectively have experience and training commensurate with the scope, complexity, or special nature of the work to be audited.

D. Technical specialists, with appropriate technical expertise or experience in the work being audited, shall be used when auditing the adequacy of technical processes.

3.2.2.4 Auditor Qualification

Auditors shall be technically qualified in their assigned roles. In addition, they shall have appropriate training or orientation to develop their competence for performing audits. Competence of personnel performing various audit functions shall be developed by one or more of the following methods:

A. Orientation to provide a working knowledge and understanding of the QA program requirements and the auditing organization's implementing procedures used to perform audits and report audit results

B. Training programs that provide general and specialized training in audit performance, including fundamentals, objectives, characteristics, organization, performance, and results of quality auditing. Training shall include methods of examining, questioning, evaluating, and documenting specific audit items and methods of evaluating the effectiveness of corrective actions for conditions adverse to quality.

C. On-the-job training, guidance, and counseling under the direct supervision of a lead auditor. Such training shall include audit planning, performing, reporting, and follow-up actions.

3.2.2.5 Technical Specialist Qualification

Technical specialists selected for audit assignments shall receive indoctrination commensurate with the scope, complexity, or special nature of the work being audited. In addition, they shall be trained to the requirements of the audit process associated with their duties.

3.2.2.6 Lead Auditor Qualification

A lead auditor shall be capable of organizing and directing audits, reporting audit results, and evaluating planned and implemented corrective action. A lead auditor also shall be certified as meeting the requirements provided in this section for education and

experience, communication skills, training, audit participation, and the successful completion of a lead auditor examination.

A. Lead Auditor Education and Experience:

The prospective lead auditor shall have verifiable evidence that a minimum of 10 credits have been accumulated under the following scoring system:

1. Education (four credits maximum)

    a. An associate's degree from an accredited institution scores one credit. If the degree is in engineering, physical sciences, mathematics, or QA, it scores two credits.

    b. A bachelor's degree from an accredited institution scores two credits. If the degree is in engineering, physical sciences, mathematics, or QA, it scores three credits. In addition, score one more credit for a master's degree (or higher) in engineering, physical sciences, business management, or QA from an accredited institution.

2. Experience (nine credits maximum)

    a. The prospective lead auditor shall have participated in a minimum of five QA audits or equivalent verifications (such as management assessments, pre-award surveys, or comprehensive surveillance, as long as the parameters of the audit process are met) within three years prior to the date of certification, one of which shall be a nuclear QA audit within the year prior to qualification. In addition, for technical experience in such areas as scientific investigation, site characterization, nuclear waste management, production, transportation, engineering, manufacturing, construction, operation, or maintenance, or experience applicable to the auditing organization's area of responsibility, score one credit for each full year, with a maximum of five credits.

    b. If two years of this experience have been in a nuclear field, score one additional credit; or

    c. If two years of this experience have been in QA, score two additional credits; or

    d. If two years of this experience have been in auditing or assessment, score three additional credits; or

    e. If two years of this experience have been in nuclear-related QA, score three additional credits; or

f. If two years of this experience have been in nuclear-related QA auditing or assessment, score four additional credits.

3. Professional Competence (two credits maximum)

   For certification of competency in engineering, science, or QA specialties, issued and approved by a state agency or national professional or technical society, score two credits.

4. Rights of Management (two credits maximum)

   When determined appropriate, the organization performing the qualification may grant up to two credits for other performance factors applicable to auditing that are not explicitly called out in this section (such as leadership, sound judgment, maturity, analytical ability, tenacity, past performance, and completed QA training courses).

B. Lead Auditor Communication Skills

The prospective lead auditor shall have the capability to communicate effectively both in writing and orally. These skills shall be attested to in writing by the candidate's supervisor.

C. Lead Auditor Training

Prospective lead auditors shall be trained to the extent necessary to ensure their competence in skills as established by the organization responsible for performing audits. Training in the following areas shall be accomplished and its completion verified based upon a management evaluation of the particular needs of each prospective lead auditor:

1. Knowledge and understanding of the participant organization’s QA program and other program-related procedures, codes, standards, regulations, DOE orders, and regulatory guides, as applicable

2. General structure of QA plans and implementation procedures as a whole

3. Auditing techniques of examining, questioning, evaluating, reporting, and methods of identifying, following up, and closing corrective actions

4. Audit planning in functional areas of nuclear QA

D. Lead Auditor Examination

The prospective lead auditor shall pass an examination that evaluates his or her comprehension of, and ability to apply, the audit knowledge described in this section.

The examination may be oral, written, practical, or any combination thereof.

The development and administration of the examination for a lead auditor is the responsibility of the organization responsible for the auditing program. This organization shall:

1. Maintain the integrity of the examination through confidentiality of files and, where applicable, proctor examinations

2. Develop and maintain objective evidence regarding the type and content of the examination

E. Lead Auditor Certification

Lead auditors shall be certified by the organization responsible for the auditing program as being qualified to lead audits. This certification will document the:

1. Name of the organization performing the certification

2. Name of the lead auditor

3. Date of certification or recertification

4. Basis of certification (such as education, experience, communication skills, and training)

5. Signature of the designated representative of the organization responsible for the certification

F. Lead Auditor Proficiency Maintenance

1. Lead auditors shall maintain their proficiency through one or a combination of the following:

   a. Regular and active participation in the audit process

   b. Review and study of codes, standards, QA implementation procedures, instructions, and other documents related to QA program auditing

   c. Participation in training programs

   d. Management of the auditing organization shall evaluate the proficiency of lead auditors annually. Based on the evaluation, management shall choose to extend the qualification, require retraining, or require requalification. Management evaluations shall be documented.

2. Lead auditors who fail to maintain their proficiency for a two-year period shall require requalification to the requirements of this section of the QAPD. However, participation in only one nuclear audit is required.

3.2.2.7 Performing Audits

A. Audits shall be performed using the written procedures or checklists related to the activity being audited.

B. Elements that have been selected for audit shall be evaluated against specified requirements. Objective evidence shall be examined to the depth necessary to determine if those elements are being implemented effectively.

C. Audit results shall be documented by audit personnel and reported to and reviewed by management having responsibility for the area audited. Conditions requiring prompt corrective action shall be reported immediately to management of the audited organization.

D. Conditions adverse to quality shall be documented and corrected according to the requirements of Section 1.3.3.

3.2.2.8 Reporting Audit Results

A. The audit report shall be prepared and signed by the audit team leader and issued to the management of the audited organization and any affected organizations. The audit report shall include the following, as appropriate:

1. A description of the audit scope

2. Identification of the auditors

3. Identification of persons contacted during the audit

4. A summary of the documents reviewed, persons interviewed, and the specific results of the reviews and interviews (i.e., a summary of the checklist contents)

5. A summary of audit results, including a statement of the QA program adequacy, implementation, and effectiveness, as appropriate to the scope

6. A description of each reported condition adverse to quality in sufficient detail to enable corrective action to be taken by the audited organization

7. A description of commendable quality practices

B. Additionally, common audit findings shall be grouped in the report whenever possible so that related or systematic breakdowns in the QA program are identified. Findings

or deficiencies shall be categorized based on their relative importance to indicate their degree of impact on compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, or management and operation of the WIPP facility.

3.2.2.9 Audit Response and Follow Up

Management of the audited organization will investigate conditions adverse to quality; determine and schedule corrective actions, including measures to preclude recurrence; and notify the auditing organization in writing of the actions planned or taken. The adequacy of audit responses shall be evaluated by or for the auditing organization. Follow-up action shall be taken to verify that corrective action is accomplished as scheduled.

3.2.2.10 Audit Records

The following documents, when developed in fulfillment of the audit requirements of this QAPD, shall be controlled as QA records in accordance with Section 1.5 of this QAPD: audit plans, audit reports, audit responses, and documentation of corrective action completion and follow-up.

SECTION 4 – SAMPLE CONTROL REQUIREMENTS

This section identifies the requirements for controlling samples of waste and environmental media. The control measures shall include provisions for the identification, handling, storage, shipping, archiving, and disposition of the samples, including those identified as nonconforming.

4.1 SAMPLE CONTROL

A. Samples shall be controlled and identified in a manner consistent with their intended use.

B. Implementing procedures shall define responsibilities, including organizational interfaces, related to documenting and tracking sample possession from sample collection and identification through handling, preservation, shipment, transfer, analysis, storage, and final disposition.

C. Sample control measures shall include provisions for the identification of the in situ orientation of samples, where appropriate.

D. A chain-of-custody record form shall be maintained. The chain-of-custody record shall provide a document trail of all persons who have custody of a given sample, including the date and time of its transfer.

E. Sample control measures, including identification and documentation, shall ensure that samples can be traced at all times, from collection through final disposition.

F. Where samples have a maximum life expectancy or expiration date, methods shall be employed that preclude the use of the sample beyond its specified life.

G. Representative archival samples from difficult-to-repeat sample collection activities, such as principal bore holes, shall be maintained.

H. Implementing procedures shall specify the representative samples to be archived if the need to archive samples is identified.

4.2 SAMPLE IDENTIFICATION

A. Each sample shall be uniquely identified from its initial collection through the final disposition of the sample.

B. Sample identification shall be verified and documented before each transfer or release for testing, analysis, or disposition.

C. Identification shall be maintained by placing the identification directly on the samples wherever possible or in a manner that ensures identification is maintained. If direct physical markings are either impractical or insufficient, other appropriate means shall be employed (e.g., physical separation, labels or tags attached to containers, or procedural control). When used, physical markings shall:

1. Be applied using materials and methods that provide clear and legible identification

2. Not effect the sample content or form

3. Be transferable to each identified sample part when the sample is subdivided

4. Not be obliterated or hidden by surface treatments or sample preparation unless other means of identification are substituted

D. If sample storage is required, methods shall be established for the control of sample identification that are commensurate with the planned duration and storage conditions. As applicable, these methods shall provide for:

1. The maintenance or replacement of markings and identification tags that have been damaged because of age or during handling

2. The protection of identification markings from excessive deterioration due to environmental exposure

4.3 HANDLING, STORING, AND SHIPPING SAMPLES

A. Handling, storing, cleaning, packaging, shipping, and preserving samples shall be conducted in accordance with established work and inspection implementing procedures. Controls shall provide for the maintenance of sample characteristics, sample integrity, and sample identification during storage.

B. The controls shall be consistent with planned duration and storage conditions and shall describe actions to be taken where maximum sample life expectancy limits are identified.

C. Storage methodology shall be developed and implemented to ensure that samples are maintained in predetermined environmental conditions commensurate with their intended use and purpose.

D. Samples shall be controlled to preclude the mixing of like samples.

E. Samples on which analysis or tests have been performed shall be identified and maintained in a separate part of the storage area.

F. If required for critical, sensitive, perishable, or high-value samples, specific measures for the handling, storage, cleaning, packaging, shipping, and sample preservation shall be identified and used.

G. Measures shall be established for sample marking and labeling for packaging, shipping, handling, and storage as necessary to adequately identify, maintain, and preserve the sample. Markings and labels shall indicate the need for and the presence of special environments or the need for other special controls, if necessary.

H. Samples requiring special protective equipment (such as containers) and special protective environments (such as inert gas or limits on moisture and temperature) shall be specified, employed, verified, and documented.

4.4 DISPOSITION OF NONCONFORMING SAMPLES

A. Samples that do not conform to requirements specified in work controlling documents (such as job packages, travelers, or work requests) shall be identified, documented, evaluated, and segregated in accordance with Section 1.3.

B. The disposition for nonconforming samples shall be identified and documented and shall be limited to "use-as-is," "limited use," or "discard."

C. Samples that have lost their identity shall be documented as nonconforming and shall not be used.

SECTION 5 – SCIENTIFIC INVESTIGATION REQUIREMENTS

Scientific investigations shall be defined, controlled, verified, and documented. Process variables affecting scientific investigations shall be measured and controlled. Test processes conducted in support of such investigations shall be controlled in accordance with the requirements of Sections 2.4, *Inspection and Testing*, 2.4.4, *Test Requirements*, and 2.4.5, *Monitoring, Measuring, Testing, and Data Collection Equipment*, as applicable, and as supplemented by the requirements of this section.

5.1 PLANNING SCIENTIFIC INVESTIGATIONS

A. Variables that affect interrelated scientific investigations shall be identified and controlled appropriately in each related investigation.

B. The intended use of the data shall be documented before collection as part of the planning for data processing. Any alternate use of the data shall be evaluated for appropriateness and the justification for use shall be documented.

C. Planning shall consider the compatibility of data processing with any conceptual or mathematical models used at each applicable stage.

D. The technical adequacy of procedures for conducting scientific investigations and their implementation shall be reviewed and approved by qualified persons other than those who prepared the procedures. Changes to procedures for conducting scientific investigations shall be reviewed and approved in a manner commensurate with the original procedure.

E. Development activities used to establish new methods or procedures for conducting scientific investigations shall be documented. The results of developmental testing shall be reviewed for adequacy and approved by qualified persons prior to implementation of the procedures for data collection.

F. Planning shall be coordinated with organizations providing input to or using the results of the investigation.

G. Planning shall include the establishment of acceptance criteria for data quality evaluation to ensure that the data generated are valid and satisfy documented requirements for the following characteristics, as appropriate: data precision, data accuracy, data representativeness, data comparability, and data completeness.

H. Planning shall include the identification of known sources of error and uncertainty, as well as any input data that are suspect or whose quality is beyond the control of the performing organizations.

5.2 PERFORMING SCIENTIFIC INVESTIGATIONS

A. Scientific investigations shall be performed in accordance with requirements documented in test plans, procedures, and scientific notebooks.

B. If deviation from test standards or the establishment of specially prepared test procedures is deemed appropriate (e.g., no nationally recognized test standards exist), the modified or new test procedures shall be documented in sufficient detail to be repeatable and shall be justified, evaluated, and approved by the cognizant technical organization.

C. Scientific notebooks shall contain, at a minimum:

   1. A statement of the objectives and description of work to be performed or reference to an approved plan that describes the work

   2. The methods used

   3. Identification of the samples

   4. The M&TE used

   5. A description of the work performed and the results obtained, the names of individuals performing the work, and dated initials or signature, as appropriate, of individuals making the entries

   6. A description of changes made to methods used, as appropriate

   7. The potential sources of uncertainty and error in test plans, procedures, and parameters that must be controlled and measured to ensure that tests are valid

D. Scientific results shall be periodically reviewed by an independent qualified individual to verify that there is sufficient detail to retrace the investigation and confirm the results, if feasible, or repeat the investigation and achieve comparable results without recourse to the original investigator.

E. Practices, techniques, equipment, and manual or computerized methods used to obtain and analyze data shall be verified to ensure that they are technically sound and have been properly selected. Controls shall be established for these processes to ensure that they are properly implemented, including controls to prevent tampering.

F. Data collection and analysis shall be controlled by procedures of sufficient detail to allow the processes to be repeated. Where appropriate, quality control checks shall be performed using recognized methods such as replicate, spike, and split samples;

control charts; blanks; reagent checks; replication of the methods used to obtain the results; or alternate analysis methods.

G. Test media (e.g., fluids), when used, shall be characterized and controlled in accordance with test procedures.

H. Scientific notebooks and technical implementation documents shall be maintained as QA records.

5.3 DATA DOCUMENTATION, CONTROL, AND VALIDATION

5.3.1 Data Identification and Usage

A. All data shall be recorded so that they are clearly identifiable and traceable to the test, experiment, study, or other source from which they were generated. Identification and traceability of the data shall be maintained for the lifetime of the WIPP.

B. The method of data recording (e.g., scientific notebooks, log books, data sheets, or computerized instrumentation systems) shall be controlled to avoid data loss and permit data retrievability. Controls shall be established to ensure that data integrity and security are maintained wherever data are stored. Controls shall prescribe how specific types of data will be stored with respect to media, conditions, location, retention time, security, and access. Data shall be suitably protected from damage and destruction during their prescribed lifetime and shall be readily retrievable.

C. Data transfer and reduction controls shall be established to ensure that data transfer is error free (or within a prescribed permissible error rate), that no information is lost in transfer, and that the input is completely recoverable. Data transfer and reduction will be controlled to permit independent reproducibility by another qualified individual. Examples of data transfer include copying raw data from a notebook into computerized data form, or copying from computer tape to disk.

D. Data that are determined to be erroneous, rejected, superseded, or otherwise unsuited for their intended use shall be controlled to prevent their inadvertent use. Controls shall include the identification, segregation, and disposition of inadequate data. The basis for the disposition of erroneous data shall be justified and documented.

E. All processes which change either the form of expression or quantity of data, values, or number of data items (data reduction) shall be controlled by prescribed methods that allow for the validation of the conversion process.

F. Data collection and analysis shall be critically reviewed and questions resolved before the results are either used or reported. Uncertainty limits shall be assigned to the data prior to their use.

5.3.2 Data Validation

Data validation is a systematic process used to review data to ensure that the required data quality characteristics have been obtained. Results of the review may require that qualifiers be placed on the use of the data.

A. Validation methods shall be planned and documented. The documentation shall include the acceptance criteria used to determine if the data are valid.

B. All applicable data collected shall be validated. Validation shall include the following:

   1. The relevant documentation is reviewed to evaluate the technical adequacy, the suitability for the intended use, and the adequacy of the QA record.

   2. The results of the data review shall be documented.

   3. The reviewer shall be independent of the collection activities.

C. Data validation shall be controlled to permit independent reproducibility by another qualified individual.

D. Data considered as established fact by the scientific and engineering community, such as engineering handbook data or critical tables, do not require validation.

5.4 QUALIFICATION OF EXISTING DATA

A. This section contains requirements unique to the post-qualification of data and information that are relied upon to support the WIPP compliance application and were collected prior to the implementation of this QAPD. While the qualification process shall be conducted in accordance with the program control requirements of the CBFO QAPD, it is not intended that the QAPD identify the data that are subject to this process or the technical requirements of the qualification process. The qualification process shall be conducted in accordance with approved procedures that provide for documentation of the decision process, the factors used in arriving at the choice of the qualification method, and the decision that the data are qualified for their intended use.

B. Existing data shall be qualified using one or a combination of the following methods:

   1. Determination that the data were collected under a QA program that is equivalent in effect to ASME NQA-1-1989 edition; ASME NQA-2a-1990 addenda, Part 2.7, to ASME NQA-2-1989 edition; and NQA-3-1989. Factors to be considered include:

      a. Qualifications of personnel or organizations generating the data

b. Technical adequacy of the equipment and procedures used to collect and analyze the data

c. Environmental conditions under which the data were obtained (if germane)

d. Quality and reliability of the measurement control program under which the data were generated

e. Extent to which data demonstrate properties of interest (e.g., physical, chemical, geologic, or mechanical)

f. Extent to which conditions generating the data may partially meet requirements of this QAPD

g. Prior uses of the data and the associated verification processes

h. Prior peer or other professional reviews of data and their results

i. Extent and reliability of the documentation associated with the data

j. Extent and quality of corroborating data or confirmatory testing results

k. Degree to which data generating processes were independently audited

l. The importance of the data in showing that the repository design meets the performance objectives

2. The use of corroborating data, with the data relationships and inferences clearly identified and justified

3. Confirmatory testing that is performed and documented

4. Peer review conducted in a manner that is compatible with NUREG-1297, *Peer Review for High-Level Nuclear Waste Repositories*

   a. Peer reviews shall be performed when the adequacy of information or the suitability of procedures and methods essential to showing that a repository system meets its performance requirements with respect to safety and calculations, or reference to previously established standards and practices.

   b. Peer reviews performed in support of WIPP compliance activities shall be documented, as shall all peer review processes.

5. Peer reviews are used for the following activities:

   a. Conceptual models selected and developed by DOE

b. Waste characterization analysis as required in 40 CFR 194.24(b)

c. Engineered barrier evaluation as required in 40 CFR 194.44

SECTION 6 – SOFTWARE REQUIREMENTS

This section of the QAPD establishes software quality assurance (SQA) requirements for CBFO participants who develop, acquire, maintain, or use computer software that is important to compliance application and waste characterization.

6.1 APPLICABILITY

A. The requirements in this section apply to computer software used in the manipulation or production of data that are, in turn, used in the processing, gathering, or generation of information whose output is relied upon to make design, analytical, operational, or compliance-related decisions with respect to the performance of the waste confinement, waste characterization, waste transportation, or waste acceptance processes. The application of these requirements shall be prescribed in written plan(s), policies, procedures, or instructions.

B. The **basic requirements** defined in this section apply to those activities involved in the processing, control, or measurement of the hazardous, radioactive, and waste matrix materials of the TRU or TRU mixed waste. Waste matrix materials include but are not limited to metals, cellulosics, chelating agents, water, and other liquids, plastics, and rubber.

C. The **NQA-2 Part 2.7 requirements** defined in this section apply to software used in the processing, control, or measurement of the radioactive and waste matrix materials of the TRU waste. These requirements also apply to software used to model the performance of the WIPP for purposes of compliance application and/or reapplication.

D. Exempt from the requirements of this section of the QAPD is software that is considered to be "systems software" (e.g., operating systems, administrative and management systems, system utilities, compilers, assemblers, translators, interpreters, query languages, word processing programs, spreadsheets, database managers, and graphing programs) or other software that does not generate data that are used in the formulation of conclusions. Software utilized in conjunction with the documents prepared to comply with the National Environmental Policy Act (NEPA) is also excluded from the requirements of this section except to the extent that the results of the NEPA analysis are used as the basis for establishing how activities related to the items listed in Table I-1 are performed. These activities include those related to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility. Specific applications supporting Section 6.1A., written for use within these types of software (e.g., detailed formulas or macros) that can be verified by hand calculations or other means, shall meet the following requirements of this section:

1. A listing of the version of the software used shall be developed and maintained.

2. Documentation shall be prepared to indicate that the specific application provides the correct results for the specified range of input parameters.

6.2 Basic Requirements for Inventory and Classification of Software

A. An inventory of all applicable software shall be maintained that identifies the software name, version, classification, exemption status, operating environment, and the person and organization responsible for the software.

B. Software governed by this section of the QAPD shall be categorized. The criteria for classification shall be documented in the inventory and shall address the purpose of the software relative to its use in engineering, scientific, testing, data collection, design, analysis, and operations activities, as well as its importance to safety or its significance in managing information or augmenting mission-essential decisions.

6.3 Software Quality Assurance

6.3.1 Basic Requirements for Software Quality Assurance

Controls governing applicable software development projects shall be identified in controlled and documented plans. The plans shall be formally reviewed and approved. Controls governing the configuration and use of the software shall be identified in plans or procedures appropriate to the organizations using the software. The following activities shall be addressed in plans or procedures:

A. Software development

B. Software verification and validation

C. Software configuration control

D. Software operation and maintenance

Plans may be issued separately or as a single, composite plan, depending on the nature and complexity of the project. The software control plans may be a section of the overall project plan, provided that each software item is addressed and the software control portion of the plan prescribes the documentation, reviews, and controls required by this section.

6.3.2 NQA-2 Part 2.7 Requirements for Software Quality Assurance

Plans for ensuring software quality shall be prepared for each new software project at the start of the software life cycle. For acquired software, the software quality plan shall be prepared before the software enters the purchaser organization. Plans may be prepared individually for each software project, may exist as a generic document to be applied to software prepared within or procured by an organization, or may be

incorporated into the overall QA program. The plan shall identify:

A. The software products governed by the plan

B. The types of documentation to be prepared, reviewed, and maintained during the software design, development, implementation, test, and use

C. The organizations responsible for performing the work and achieving software quality, and their tasks and responsibilities

D. The process for reporting and documenting software discrepancies, evaluating the impact of discrepancies on previous calculations, and determining the appropriate corrective action(s)

E. The standards, conventions, techniques, or methodologies that guide the software development, as well as the methods used to ensure implementation of requirements

F. The procedure(s) used for establishing and maintaining the integrity of data, embodied mathematical models, and output files

6.4 SOFTWARE PROCUREMENT

6.4.1 Basic Requirements for Software Procurement

This section of the QAPD identifies responsibilities of the sponsoring organization for acquired software upon receipt of the software.

All procured software governed by this section shall be tested in accordance with documented and approved test procedures using approved test-case specifications to ensure that the acquired software will perform satisfactorily in its operating environment. The installation tests (including the test procedures), the test case specifications, and the results of the installation tests shall be identified, documented, and maintained as records according to established procedures.

6.4.2 NQA-2 Part 2.7 Requirements for Software Procurement

A. The procurement of software and related services shall be performed in accordance with Section 2.3 of this QAPD.

B. Once the software has been installed, but before its use, the sponsoring organization shall perform user acceptance to verify the functional capability of the software and the acceptability of the supplier's supporting documentation (e.g., the user manual, technical specifications, and the results of supplier testing).

C. For procured software, the supplier shall report software errors and failures to the

sponsoring organization. The sponsoring organization shall also report software errors to the supplier.

6.5 SOFTWARE DEVELOPED UNDER OTHER QA PROGRAMS

6.5.1 Basic Requirements

Software that has not been developed or approved in accordance with this QAPD shall be evaluated to determine its adequacy to perform intended functions. The evaluation shall be documented. The software shall be uniquely identified and controlled prior to the evaluation, clearly traceable to the software requirements, accepted by the sponsoring organization, and placed under configuration control prior to use.

6.5.2 NQA-2 Part 2.7 Requirements

The evaluation of existing software developed in accordance with other QA programs shall serve as the basis to

A. Determine the adequacy of existing verification and validation activities and software documentation to support operations and maintenance.

B. Identify the activities to be performed and the documentation necessary to accept the software for its intended use and place it under configuration control. The evaluation shall be documented and shall contain, at a minimum:

   1. User application requirements

   2. Test plans and test cases required to validate software acceptability

   3. User documentation as described in Section 6.9.2.6

6.6 SOFTWARE DEVELOPMENT AND LIFE CYCLE

6.6.1 Basic Requirements

The developmental activities of software projects subject to this QAPD shall be identified in documented and approved plans to ensure that the project proceeds in an orderly and traceable manner. Sufficient information shall be provided to clearly indicate the necessary tasks, the deliverables and baselines for each phase, the required reviews, appropriate milestones, and the responsibilities associated with each task.

Software project development plans shall identify the items that need to be baselined and the methods to be used for controlling the configuration of those baselines throughout the development process. Configuration control planning for software are addressed in Section 6.8 of this QAPD.

6.6.2 NQA-2 Part 2.7 Requirements

A. The activities associated with the evolution of the software shall be accomplished using an iterative or sequential approach. The approach shall include the analysis of the problem under study, the transformation of the analysis into the design, the implementation of the design into validated computer software, and the development of sufficient documentation to demonstrate that the specified requirements have been successfully included in the computer software.

B. The iterative or sequential approach to software development consists of phases, with each phase leading to the development of a specific work product representing components of the software baseline. The software phases are:

   1. Definition of requirements
   2. Design
   3. Implementation
   4. Testing
   5. Installation and checkout
   6. Operations and maintenance
   7. Retirement

C. Following the development of the software quality plan, no strict sequence of performing activities is required (i.e., activities may be performed serially or recursively) provided that all the specified requirements for each software development phase have been met and the intent of the requirements has not been subverted.

6.6.2.1 Requirements Phase

Software requirements shall be specified, documented, and reviewed. These requirements shall pertain to functionality, performance, design constraints, data attributes, and external interfaces (e.g., hardware limitations) as outlined in Section 6.9.2.2 Each requirement shall be specified in sufficient detail to permit the accomplishment of design and validation activities. Software requirements shall be traceable throughout the software development cycle, and a verification and validation plan shall be prepared after the software requirements have been documented and approved.

6.6.2.2 Design Phase

The software design shall be based on the software requirements and shall be documented and reviewed. The design shall specify the overall structure (control and data flow) and the reduction of the overall structure into physical solutions (algorithms, equations, control logic, and data structures). The design may necessitate the modification of the requirements documentation and the verification and validation plans.

6.6.2.3 Implementation Phase

The software design shall be translated into a form (programming language) suitable for processing by a computer. The executable software shall be analyzed to identify and correct errors.

6.6.2.4 Testing Phase

A. Test requirements and acceptance criteria shall be specified, documented, and reviewed and shall be based upon applicable design or other pertinent technical bases. Appropriate tests, such as verification tests, requirements-driven tests, hardware integration tests, and in-use tests, shall be controlled. Software testing, using documented test plans, test cases, and test results are the primary methods of software validation.

B. Testing of software shall be performed to the extent that unintended functions are identified and reviewed and their impact determined and corrected. If appropriate, determine if modifications are needed to the requirements, design, implementation, or test plans and test cases.

C. Design-driven tests shall be used to demonstrate the capability of the software to produce valid results for test problems encompassing the range of intended use as defined by the software documentation. Testing of software used for operational control shall demonstrate the required performance over the entire range of the controlled function or process. Acceptable test methods consist of:

1. Hand calculations

2. Calculations using comparable proven problems

3. Empirical data and information from confirmed published data and correlations or technical literature

4. Comparison with other validated software of similar purpose

5. Manual inspections or qualitative checks not involving numerical manipulation (examples include visual inspection of database reformatting or data plotting)

D. Requirements-driven tests shall be used to validate software by comparing test results of software execution with objective evidence obtained by the above methods. The results of this evaluation shall be of sufficient scope and depth to prove the capabilities and limitations delineated in the software documentation.

6.6.2.5 Installation and Checkout Phase

A. During installation and checkout, the software becomes part of a system consisting of applicable software components, hardware, and data. The process of integrating the software with other applicable components may consist of installing both the hardware and software, converting or creating databases, and verifying that all components of the system have been included in the installation. Test problems shall be developed and documented to permit confirmation of the acceptable performance of the software in its operating environment. Installation and checkout of software shall consist of:

1. Execution of tests for installation and integration

2. Documented acceptance of the software for operational use

3. Placement of the software under configuration control prior to use

B. Completion of the installation and checkout activities establishes the software baseline.

6.6.2.6 Operations and Maintenance Phase

A. Operation of the software is conducted by the user in accordance with the operation and usage instructions described in the software user documentation. Once the software has been made available for use, the software requirements and the design integrity shall be maintained. Maintenance activities shall be performed and documented in a traceable, planned, and orderly manner.

B. In all cases, verification and validation of software shall be completed and approved and corrective actions performed, as necessary, prior to relying upon the software to perform its intended function.

1. Post Installation Maintenance

Software shall be maintained to remove latent errors (corrective maintenance), to respond to new or revised requirements (perfective maintenance), or to adapt the software to changes in the operating environment (adaptive maintenance). Software modifications shall be approved by authorized personnel, documented, verified, validated, and controlled.

2. In-Use Tests:

Test problems shall be run whenever the software is installed on a different computer or when significant hardware or system software configuration changes are made. These tests shall be documented, performed by an individual technically competent in the subject area(s), and serve as the basis for determining if the software still meets specified requirements.

Periodic in-use manual or automatic self-check routines shall be prescribed and performed for that software where computer failure or electronic drift can affect required outcomes.

6.6.2.7 Retirement Phase

Criteria shall be developed to determine when software can be retired from use. Methods shall be developed to prevent the use of software that is no longer controlled. Upon retirement, user support for a software product is terminated.

6.7 SOFTWARE VERIFICATION AND VALIDATION

6.7.1 Basic Requirements

A. Verification and validation of software shall include the review of software activities, documentation, and tests to ensure that the software:

   1. Adequately and correctly performs all intended functions

   2. Does not perform any unintended function that either by itself, or in combination with other functions, can degrade the intended outcomes of the software

B. Verification and validation shall be performed by any competent individual(s) or group(s) other than those who performed the software design. The individuals may be from the same organization and may include the designer's supervisor, provided the supervisor:

   1. Did not specify a singular design approach

   2. Did not rule out certain design considerations

   3. Did not establish the design inputs used

   4. Is the only individual in the organization competent to perform the verification or validation

6.7.2 NQA-2 Part 2.7 Requirements

6.7.2.1 Verification

Verification is a formal checking activity performed throughout the evolution of the software life cycle. Verification activities shall be clearly documented, including the identification of those performing and approving the verification. The reviewed documents shall be updated and placed under configuration control. Documentation of review comments and their disposition shall be retained. Unincorporated comments and their disposition shall also be retained in accordance with established procedures.

6.7.2.2 Requirements

Verification review(s) of software requirements shall ensure that the requirements are complete, verifiable through testing, consistent, and technically feasible as described in Section 6.6.2.1.

6.7.2.3 Design

Verification review of software design shall evaluate the technical adequacy of the design approach and ensure that all the requirements have been addressed and that the design is complete, verifiable (through testing, using approved test plans and test cases), consistent, technically feasible, and traceable to the software requirements as described in Section 6.6.2.2.

6.7.2.4 Implementation

Verification of the implementation of software design shall consist of the examination of software logic and source code to ensure adherence to standards and conventions and to ensure that the design has been implemented as described in Section 6.6.2.3.

6.7.2.5 Testing

Verification of software testing shall consist of reviews to ensure that the specified test criteria, the expected results, and the software development documentation have been met as described in Section 6.6.2.4.

6.7.2.6 Installation and Checkout

Verification of installation and checkout activities consists of reviews to ensure that the software baseline has been established.

6.7.3 Validation

A. Software validation is primarily a formal testing activity that shall be performed prior

to installation and checkout. It shall be used to demonstrate that the computational model embodied in the software is an acceptable representation of the process or system for which it is intended and that the software produces correct solutions within defined limits for each parameter employed.

B. Validation methods, test data, software-generated results, and conclusions shall be documented in a form that can be understood by an independent individual technically competent to use the software for the particular problem under study. The documentation shall be reviewed to assess the adequacy and correctness of the documentation in meeting the requirements of this section of the QAPD and the overall acceptability of the software for the intended use.

C. When the adequacy of the conceptual, mathematical, or computational models or the suitability of procedures and methods cannot be established through testing, alternate calculations, or reference to previously established standards and practices, a documented peer review shall be performed to meet the software validation requirements.

D. The validation of software modifications shall be subject to selective regression testing to

   1. Detect errors introduced during the modification of the systems or system components

   2. Verify that the modifications have not caused unintended adverse effects

   3. Verify that the modified systems or system components still meet specified requirements

6.8 SOFTWARE CONFIGURATION MANAGEMENT

6.8.1 Basic Requirements

A. Implementation of baseline and change control processes are fundamental to configuration management. A baseline is a collection of all approved components of the software development cycle. As each component is approved, it is added to the overall software baseline. A software baseline serves as the basis for further development and maintenance that can be changed only through the use of formal change control procedures. Change control is the process by which a change to a baseline is proposed, evaluated, and approved or rejected.

B. Software configuration controls shall be planned, including the identification of organizational positions that are authorized to make changes, and the methods, procedures, and instructions to be used to control the identification of, access to, changes to, and the status of computer software. Configuration control documents shall indicate how changes will be validated, including regression testing, and how

the tests will be documented. These control documents shall be formally reviewed, approved, and in place before the software is released for use.

6.8.2 NQA-2 Part 2.7 Requirements

6.8.2.1 Configuration Identification

Software shall be placed under configuration control as each configuration item is approved. A software baseline shall define the most recent approved software configuration. The configuration items and their associated documentation shall be traceable to one another. A labeling system for configuration items shall be implemented that:

A. Uniquely identifies each configuration item

B. Identifies changes to configuration items by revision or version identifier

C. Provides the ability to uniquely identify each approved configuration of the revised software that is available for use

6.8.2.2 Configuration Change Control

A. Changes to software shall be systematically proposed, evaluated, documented, and approved to ensure that the impact and rationale for making the change is carefully assessed prior to updating the software baseline. Changes to previously accepted software shall be subject to the same level of control as the original software.

B. Information concerning approved changes shall be transmitted to all affected organizations. All changes shall be formally evaluated and approved by the organization responsible for the original design, unless an alternate organization has been given the authority to approve the changes. Only authorized changes shall be made to software baselines. Software verification activities shall be performed for the change as necessary to ensure that the change is appropriately reflected in the software documentation and to ensure that traceability is maintained. The degree of software validation shall be commensurate with the nature and scope of the change.

6.8.2.3 Configuration Status Accounting

Information shall be maintained that reflects the current status of the software baseline. This includes the identity and version of the approved configuration and the status of any proposed and approved changes to the baseline components. This information shall be available to all designated users of the software upon request.

6.9 DOCUMENTATION

6.9.1 Basic Requirements

Software shall be described in one or more documents that detail user instructions, technical bases, functional requirements, and maintenance-related information sufficient to allow independent verification and maintenance and to provide traceability of the documentation to the software. The documentation shall be reviewed by an individual competent in the technical subject area for which the use of the software is intended. The review shall verify that the documentation adequately and accurately reflects the software that constitutes the system, and is sufficient to objectively demonstrate that the software requirements have been successfully implemented. Appropriate documentation shall be made available to all designated users of the software.

6.9.2 NQA-2 Part 2.7 Requirements

6.9.2.1 Procurement Documentation

The applicable quality assurance requirements shall be specified and the required vendor-supplied software documentation, plans, and procedures shall be identified in the software procurement documentation.

6.9.2.2 Requirements Documentation

A. Software requirements documentation shall outline the requirements that the proposed software must satisfy. The software requirements shall, as applicable, address the following:

   1. Functionality - the functions the software performs

   2. Performance - the time-related issues of software operation such as speed, recovery time, and response time

   3. Constraints – limits imposed on implementation activities; any elements that will restrict design options

   4. Attributes - non-time-related issues of software operation such as portability, acceptance criteria, access control, and maintainability

   5. External interfaces - interactions with people, hardware, and other software

B. Software requirements shall be traceable throughout the software development cycle.

6.9.2.3 Design and Implementation Documentation

Software design and implementation documentation consists of a document or series of documents that:

1. Describe the major components of the software design as they relate to the software requirements

2. Describe the theoretical basis, embodied mathematical model, control flow, control logic, and data structure(s) of the software

3. Describe the allowable or prescribed ranges for inputs and outputs

4. Describe the design in a manner that can be translated into executable code

6.9.2.4 Verification and Validation Documentation

A. Software verification and validation documentation shall consist of associated plans and shall describe the activities (including the results of reviews and tests) and the criteria for accomplishing the verification of the software throughout the software evolution process. The documentation shall also specify the hardware and software configurations pertinent to the software verification and validation.

B. Software verification and validation documentation shall be organized in a manner that allows traceability from the software requirements to both the software design and to the validated capabilities of the software.

6.9.2.5 Change Documentation

Changes to software shall be formally documented. This documentation shall contain a description of the change, the rationale for the change, and the identification of affected configuration items of the software baseline.

6.9.2.6 User Documentation

User documentation should be sufficient to allow any qualified user (i.e., one having adequate technical background) to install and run the software and properly respond to errors. User documentation, at a minimum, shall include:

A. The software name and version identifier

B. Statements of functional requirements and system limitations, including hardware

C. An explanation of the mathematical models and derivation of the numerical methods used in the software design (physical and mathematical assumptions on which the

software is based shall be included, along with an explanation of the capabilities and limitations inherent in the software)

D. Instructions that describe user interaction with the software, user messages initiated as a result of improper input and how the user can respond, the identification and description of input and output specifications and formats, and input parameters

E. A description of any required training necessary to use the software

F. Information for obtaining operation and maintenance support

6.9.2.7 Error Documentation

Documentation of errors detected during the use of the software following installation and checkout shall be maintained. This documentation can be used for process improvement and to prevent recurrence of errors during the development and maintenance of other software. This documentation shall contain the identity of the software, the classification of the error in terms of its significance to the integrity of the software output, and the corrective action(s).

6.10 PROBLEM REPORTING AND CORRECTIVE ACTION

6.10.1 Basic Requirements

Problems (e.g., errors, faults, failures) detected in released software shall be promptly reported in accordance with documented procedures. When problems are detected in a software item, work previously performed using versions of the software that contain that problem shall be evaluated to determine the impact on the completed work. The evaluations shall be documented and retained in accordance with records requirements.

6.10.2 NQA-2 Part 2.7 Requirements

A. A system shall be established and maintained to record, classify, analyze, track, and report software problems (in released versions) and the associated corrective actions. Problems shall be promptly reported to any affected organizations and the resolution shall be formally processed.

B. When problems are discovered in software or software results, the sponsoring organization shall determine the affect on previous uses and the need for corrective action based on sufficient information obtained from the affected users. Corrective action shall ensure that

   1. Problems are identified, evaluated, documented and, if required, corrected

   2. Problems are assessed for their impact on past and present uses of the software

3. Changes to software are in accordance with the software configuration management requirements of this section of the QAPD

4. Results are provided to the affected users, along with any revised software documentation

C. Problems that could significantly affect decisions based upon prior use or that require significant modification to the software shall be identifiable to all users. Errors that have been determined to represent a condition adverse to quality shall be controlled in accordance with Section 1.3 of this QAPD.

6.11 ACCESS CONTROL

To the extent appropriate, controls shall be established to permit authorized and prevent unauthorized access to software that has been accepted in accordance with this section.

APPENDIX A – GLOSSARY

Acceptance: The documented determination by the receiving organization that a work project is suitable for the intended purpose.

Acquired Software: Computer software obtained that was not developed by the user organization.

Alternative Calculations: Calculations that are made with alternative methods to verify correctness of the original calculation.

Approval: The documented determination by a responsible individual that a work product is suitable for the intended purpose and shall be used as required.

Assessment/Evaluation: The act of reviewing, inspecting, testing, checking, conducting surveillances, auditing, or otherwise determining and documenting whether items, processes, or services meet specified requirements. Assessments are performed by or for management. Evaluations are performed by the line organization.

Assessment, External: An assessment of those portions of an organization's quality assurance program not under the direct control or within the organizational structure of the auditing organization.

Assessment, Internal: An assessment of those portions of an organization's quality assurance program retained under its direct control and within its organizational structure.

Assessor: An individual who is qualified to perform assigned portions of an assessment.

Audit: A planned and documented independent assessment to determine by investigation, examination, or evaluation of objective evidence the adequacy of and compliance with established procedures, instructions, drawings, and other applicable documents, and the effectiveness of implementation. An audit should not be confused with surveillance or inspection activities performed for the sole purpose of process control or product acceptance.

Auditor: An individual who is qualified to perform assigned portions of an audit.

Audit (or Assessment) Team Leader: A lead auditor (or assessor) who is assigned to direct the efforts of an audit (or assessment) team.

Calibration: The set of operations which establish, under specified conditions, the relationship between values indicated by a measuring instrument or measuring system, and the corresponding standard or known values derived from the standard.

Certificate of Conformance: A document signed or otherwise authenticated by an authorized individual certifying the degree to which items or services meet specified requirements.

Certification: The act of determining, verifying, and attesting to, in writing the qualifications of personnel, processes, procedures, or items in accordance with specified requirements.

Characteristic: A property or attribute of an item, process, or service that is distinct, describable, and measurable.

Commercial Grade Item: An item that is (1) not subject to design or specification criteria unique to a CBFO program or facility, (2) used in applications other than the nuclear industry, and (3) ordered from the manufacturer or supplier on the basis of specifications set forth in the manufacturer's published product description.

Compliance Certification Application: The compliance certification application submitted to the EPA pursuant to section 8 (d) (1) of the WIPP Land Withdrawal Act of 1992 (Pub.L. 102-579, 106 Statue 4777) or any compliance re-certification applications submitted to the EPA pursuant to section 8(f) of the WIPP Land Withdrawal Act.

Condition Adverse to Quality: An all-inclusive term used in reference to any of the following: failures, malfunctions, deficiencies, defective items, nonconformances, and technical inadequacies. A condition adverse to quality is considered significant when

- if uncorrected, the condition adverse to quality could have a serious effect on safety, operability, waste isolation, TRU waste site certification, regulatory compliance demonstration, or effective implementation of the QA program
- the condition adverse to quality is non-compliant with the HWFP
- the condition adverse to quality requires immediate notification of regulatory entities (e.g., 10 CFR Part 21)
- the condition adverse to quality indicates a significant failure or breakdown in the implementation of QA Program requirements
- repeated attempts to resolve a condition adverse to quality have been unsuccessful
- the condition adverse to quality is identified in items or activities important to safety or waste isolation and compromises the ability to prevent or mitigate the consequences of an accident, thereby presenting a significant hazard to safety and health of workers and/or the public

Configuration Control: The process of identifying and defining the configuration items in a system, controlling the release and change of these items throughout the system

life cycle, and the recording and reporting of the status of configuration items and change requests.

Configuration Item: A collection of hardware or software elements treated as a unit for the purpose of configuration control.

Controlled Document: A document that is prepared, reviewed, approved, and distributed in accordance with established implementation procedures. Controlled documents are subject to controlled distribution and to a defined and controlled change process.

Corrective Action: Measures that are taken to rectify conditions adverse to quality and, where necessary, to preclude recurrence.

Corrective Action Report (CAR): A document used to identify and rectify conditions adverse to quality (CAQ), and track the associated corrective actions. CARs address CAQs that are primarily programmatic in nature, as opposed to nonconformance reports (NCRs) which address CAQs relating to a specific item(s) such as a piece of hardware or data. The category of CARs includes: corrective action reports or corrective action requests, nonconformance corrective action reports (NCARs), management corrective action reports (MCARs), deficiency reports (DRs), process deficiency reports (PDRs), audit findings, condition adverse to quality reports(CAQR), etc.

Data Accuracy: The degree to which data agree with an accepted reference or true value. Accuracy is a measure of the bias in a system.

Data Comparability: A measure of the confidence with which one data set can be compared to another.

Data Completeness: A measure of the amount of valid data obtained compared to the amount that was planned.

Data Precision: A measure of the mutual agreement between comparable data gathered or developed under similar conditions, usually expressed in terms of a standard deviation.

Data Representativeness: The degree to which data accurately and precisely represent a characteristic of a population, a parameter, variations at a sampling point, or environmental conditions.

Data Quality Objectives (DQOs): Qualitative and quantitative statements derived from outputs of the first six steps of the DQO Process (see below). DQOs; 1) clarify the study objective, 2) define the most appropriate type of data to collect, 3) determine the most appropriate conditions from which to collect the data, and 4) specify tolerable limits on decision errors which will be used as the basis for establishing the quantity and

quality of data needed to support compliance decisions. DQOs are used to develop a scientific and resource-effective data collection design.

DQO Process: A strategic planning approach based on the Scientific Method that is used to prepare for a data collection activity. The DQO process provides a systematic procedure for defining the criteria that a data collection design should satisfy, including when to collect samples, where to collect samples, the tolerable level of decision errors for the study, and how many samples to collect. By using the DQO process, DOE will assure that the type, quantity, and quality of environmental data used in decision making will be appropriate for the intended application. In addition, DOE will guard against committing resources to data collection efforts that do not support a defensible decision. The DQO process consists of seven steps and is more fully described in EPA 1994b.

Design Basis: Information that identifies the specific functions to be performed by items and the specific values or ranges of values chosen for controlling parameters as reference bounds for design.

Design Input: Those criteria, parameters, bases, or other design requirements upon which the detailed final design is based.

Design Output: Drawings, specifications, and other documents resulting from the translation of design input requirements.

Design Process: The technical process that begins with the identification of design input and ends with the issuance of design output documents.

Design Review: A documented evaluation of design output during the design process to determine the design adequacy and the conformance to specified acceptance criteria.

Disposal System: Any combination of engineered and natural barriers that isolate transuranic waste after disposal. For the purposes of the WIPP, this will include the combination of the repository/shaft system and the controlled area.

Document: Written or pictorial information that describes, specifies, reports, or certifies activities, requirements, procedures, or results.

Document Control: The process that provides for document adequacy review, approval for release by authorized personnel, and distribution for use at the prescribed work locations.

Error: A discrepancy between a computed, observed, or measured value or condition and the true, specified, or theoretically correct value or condition.

Graded Approach: The process by which the level of analysis, documentation, verification, and other controls necessary to comply with QA program requirements are developed commensurate with specified factors.

Independent Assessment: An assessment, conducted by a group or organization having authority and freedom from the line organization, to evaluate the scope, status, adequacy, programmatic implementation, or effectiveness of a program or process.

Item: An all-inclusive term used in place of any of the following: appurtenance, assembly, component, equipment, material, module, part, structure, subassembly, subsystem, system, unit, support system, or data.

Lead Auditor: An individual trained, qualified, and certified to organize and direct an audit, report audit findings, and evaluate corrective actions.

Lifetime Records: Records required to be maintained for the useful life of the items to which they pertain while the items are installed in the plant or facility (life of the item), or for the lifetime of the equipment, facilities, or programs to which the records apply.

Line Management: Those management positions that are directly responsible for task products and services. Includes CBFO supervisors and team leaders and contractor management within the context of the definition.

Line Organization: The organization directly responsible for task products and services. Includes CBFO offices and teams and contractor organizations within the context of the definition.

Macro: Single computer instructions invoked by a symbol, name, or key that represents commands, actions, or keystrokes.

Management Assessment: Assessment performed by management that focuses on how well the integrated quality assurance program is working. The management assessment should identify management problems that hinder the organization from achieving its objectives in accordance with quality, safety, and environmental requirements.

Measuring and Test Equipment: All devices used to calibrate, measure, gage, test, inspect, or otherwise determine compliance with prescribed technical requirements.

Monitoring and Data Collection (M&DC) Equipment: A subcategory of M&TE that is used in the collection of measurement data for the establishment of test conditions and general information and the collection of general measurement data not utilized to verify the conformance of an item or equipment to specified criteria.

Nonconformance: A deficiency in a characteristic or record that renders the quality of an item or sample unacceptable or indeterminate.

Nonpermanent Records: Records having value for a specific, limited time and authorized by the National Archives and Records Administration to be destroyed after that time.

Nonreactor Nuclear Facility: Those activities or operations that involve radioactive or fissionable materials in such form and quantity that a nuclear hazard potential exists to the employees or the general public. Incidental use and the generation of radioactive materials in a facility operation (e.g., check and calibration sources, radioactive isotopes used in research and experimental and analytical laboratory activities, electron microscopes, and x-ray machines) would not ordinarily require the facility to be included in this definition. The transportation of radioactive materials, accelerators, and reactors and their operations are not included.

Participant: A DOE contractor organization that furnishes items or services in support of CBFO-sponsored programs, including those TRU waste generator and storage sites participating in the National TRU Waste Program.

Peer: A person having technical expertise in the subject matter to be reviewed to a degree at least equivalent to that needed for the original work.

Peer Review: A documented, critical review performed by peers who are independent of the work being reviewed. A peer review is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn in the original work. Peer reviews confirm the adequacy of work.

Periodic: Occurring or recurring at regular intervals. For the purposes of this QAPD, these intervals are determined by the responsible management unless otherwise specified.

Post-Closure QA Records: QA records required to be maintained beyond the operating life of the WIPP repository, for periods of several hundreds of years, and in a manner that would permit future generations to maintain them longer, if desired, using present reasonably available technology.

Procedure: A document that specifies or describes how an activity is to be performed. The term "procedure" also includes instructions and drawings.

Process: A series of actions that achieve an end or result.

Procurement Document: Purchase orders, contracts, specifications, or other documents used to define technical and quality assurance requirements for the procurement of items or services.

Qualification (Personnel): The characteristics or abilities gained through education, training, or experience, as measured against established requirements such as standards or tests, that qualify an individual to perform a required function.

Qualification Testing: A test that is intended to provide a desired level of confidence that an item meets specified criteria.

Quality: The condition achieved when an item, service, or process meets or exceeds the user's requirements and expectations.

Quality Assurance: All those planned and systematic actions necessary to provide adequate confidence that an item will perform satisfactorily in service.

Quality Assurance Objectives: Objectives that represent the required quality of data necessary to draw valid conclusions regarding program objectives.

Quality Assurance Program: The program established to assign responsibilities and authorities, define policies and requirements, and provide for the performance and assessment of work.

Quality Assurance Record: A completed record or any authenticated portion of a record that provides objective evidence of the quality of items or activities.

Quality System: See *Quality Assurance Program*.

RCRA Related Deficiency: A deficiency that is a violation of the requirements of the WIPP Hazardous Waste Facility Permit.

Readiness Review: A systematic documented review of the readiness for startup or continued extended use of a facility, process, or activity. Readiness reviews are typically conducted before proceeding beyond project milestones and prior to commencement of a major phase of work activities.

Receipt Inspection: A method of accepting an item or related service from a supplier by examination or testing of the item or related service to verify conformance to specified requirements.

Records: Books, papers, maps, photographs, machine readable materials or other documentary materials, regardless of physical form or characteristics, made or received by an agency of the United States Government under Federal law or in connection with the transaction of public business and preserved or appropriate for preservation by that

agency or its legitimate successor as evidence of the organization, functions, policies, decisions, procedures, operations or other activities of the government or because of the informational value of the data they contain.

Records Holding Facility: A CBFO records storage facility meeting regulatory requirements for the storage of inactive records pending their final disposition.

Repair: The process of restoring an item to a condition such that the capability of an item to function reliably and safely is unimpaired even though that item still does not conform to the original requirement.

Rework: The process by which an item is restored to original specifications by completion or correction.

Sample: A subset of a population (e.g., wastes, environmental media, materials, cores) whose properties are used to gain information about the population.

Scientific and Engineering Software: Software that uses numerical methods to complete scientific, engineering, and mathematical calculations.

Scientific Investigation: Any research, experiment, test, study, or activity that is performed for the purpose of investigating a natural system or the man-made aspects of a geologic repository, including the investigations that support design of the facilities and the waste package.

Scientific Notebook: A record of the methods and results of scientific investigations that is used when the work involves a high degree of professional judgment or trial and error methods, or both.

Service: The performance of work, such as design, construction, fabrication, inspection, nondestructive examination, testing, environmental qualification, equipment qualification, repair, installation, or similar activities.

Significant Condition Adverse to Quality: See *Condition Adverse to Quality*.

Site Characterization: The program of exploration and research both in the laboratory and the field that is undertaken to establish the natural conditions and the ranges of parameters of a particular site.

Software: Computer programs, procedures, rules, and associated documentation and data pertaining to the operation of a computer system.

Software Baseline: An item or product that has been formally reviewed and agreed upon, that serves as the basis for further development, and that can be changed only through formal change control procedures.

Software Quality Assurance Plan: A plan for the development of software products necessary to provide adequate confidence that the software conforms to established requirements.

Software Routine: A collection of computer macros or script files, a spreadsheet application, or other stand-alone software application (either acquired or developed) that generally operates within another program, such as a spreadsheet, and must be independently verified by visual inspection and/or hand calculation.

Software Validation: The process of test and evaluation of the completed software to ensure compliance with software requirements.

Software Verification: The process of determining whether or not the product of a given phase of the software development cycle fulfills the requirements imposed by the previous phase.

Software Verification and Validation: The process of determining whether the requirements for a system or component are complete and correct, the products of each development phase fulfill the requirements or conditions imposed by the previous phase, and the final system or component complies with specified requirements.

Source Verification: A purchaser method of accepting an item or related service from a supplier by monitoring, auditing, surveillance, witnessing, or observing activities performed by the supplier.

Special Process: A process, the results of which are highly dependent on the control of the process or the skill of the operators, or both, and in which the specified quality cannot be readily determined by inspection or test of the product.

Supplier: Any individual or organization who furnishes items or services in accordance with a contract. An all-inclusive term used in place of any of the following: vendor, seller, source, participant, contractor, or subcontractor.

Surveillance: The act of monitoring or observing to verify whether an item, activity, system, or process conforms to specified requirements. Surveillance of a technical work activity is normally done in real time (i.e., the surveillance is accomplished as the work is being performed).

System Software: Software which is used exclusively in the preparation, installation, or operation of executable software applications. Examples of such software include operating systems, administrative and management systems, system utilities, compilers, assemblers, translators, interpreters, automated protocols, utilities and tools, teleprocessing managers, and query languages.

Technical Review: A documented critical review of work that has been performed within the state of the art. The review is accomplished by one or more qualified reviewers who are independent of the work but collectively have equivalent technical expertise to those who performed the original work. The review is an in-depth analysis and evaluation of documents, activities, material, data, or items that require technical verification or validation for applicability, correctness, adequacy, completeness, and assurance that established requirements are satisfied.

Technical Specialist: An individual assigned to an assessment team when the scope, complexity, or special nature of the work to be examined warrants assessment of the technical adequacy of the work or the effectiveness of the technical process.

Testing: An element of verification to determine the capability of an item to meet specified requirements or processes that facilitate the collection of data in conducting scientific investigations by subjecting the item or environment to a set of physical, chemical, environmental, or operating conditions.

Traceability: The ability to trace the history, application, and location of an item, data, or sample using recorded documentation. As related to metrology, traceability means the ability to relate individual measurement results through an unbroken chain of calibrations to one or more of the following:

- U.S. national standards maintained by National Institute of Standards and Technology or the U.S. Naval Observatory
- Fundamental or natural physical constants with values assigned or accepted by the National Institute of Standards and Technology
- National standards of other countries which are correlated with NIST

Transuranic Waste: Waste containing more than 100 nCi of alpha-emitting TRU isotopes per gram of waste, with half-lives greater than 20 years, except for (1) high-level radioactive waste, (2) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations, or (3) waste that the NRC has approved for disposal on a case-by-case basis in accordance with 10 CFR § 61.

TRU Mixed Waste: TRU waste that is also a hazardous waste as defined by the Hazardous Waste Act and 20 NMAC 4.1.200 (incorporating 40 CFR § 261.3).

Use As Is: A disposition permitted for a nonconforming item when it can be established that the item is satisfactory for its intended use.

Validation: An activity that demonstrates or confirms that a process, item, data set, or service satisfies the requirements defined by the user.

WIPP: The Waste Isolation Pilot Plant, as authorized pursuant to Section 213 of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub.L. 96-164; 93 Stat. 1259, 1265) to provide a research and development facility for demonstrating the safe disposal of radioactive wastes produced by national defense activities.

Work: The process of performing a defined task or activity, for example, research and development, operations, maintenance and repair, administration, software development and use, inspection, safeguards and security, data collection, and analysis.

Work Suspension: A formal directive issued by management that work must be stopped until the related significant condition adverse to quality or nonconformance has been resolved.

APPENDIX B – REFERENCES

10 CFR Part 71, Subpart H, *Packaging and Transportation of Radioactive Material, Quality Assurance*

10 CFR Part 830, *Nuclear Safety Management*

40 CFR Part 194, *Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with 40 CFR Part 191 Disposal Regulations*

ASME NQA-1-1989, *Quality Assurance Program Requirements for Nuclear Facilities*

ASME NQA-2a-1990 addenda, Part 2.7, *Quality Assurance Requirements of Computer Software for Nuclear Facility Applications*

ASME NQA-3-1989, *Quality Assurance Program Requirements for the Collection of Scientific and Technical information for Site Characterization of High-Level Nuclear Waste Repositories*

DOE/WIPP- 02-3122, *Contact-Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant*

DOE, Division of Nuclear Safety, G-830.120*, Implementation Guide for use with 10 CFR Part 830.120 Quality Assurance*

DOE O 414.1A, *Quality Assurance*

National Fire Protection Association (NFPA) Standard 232-1986, *Standards for the Protection of Records*

NUREG-1297 (1988), *Peer Review for High-Level Nuclear Waste Repositories*

NUREG/BR-0167 (1993), *Software Quality Assurance Program and Guidelines*

SNT-TC-1A, Current Revision, *The American Society of Nondestructive Testing (ASNT) Recommended Practice*

Waste Isolation Pilot Plant Hazardous Waste Facility Final Permit, EPA No. NM4890139088

APPENDIX C – CBFO ORGANIZATION, RESPONSIBILITIES, AND INTERFACES

Effective implementation of the CBFO QA program is dependent on efforts at all CBFO levels. The CBFO organization is structured such that those assigned responsibility for performing the work are responsible for achieving and maintaining quality. Management is responsible for defining quality, developing appropriate plans to attain quality, and providing support of the workers in pursuit of quality. Persons or organizations not directly responsible for performing the work verify quality achievement. Management empowers employees by delegating authority and decision making to the lowest appropriate level in the organization.

The CBFO Manager is responsible for overall implementation of DOE programs, policies, orders, and guidance pertaining to the National TRU Waste Program (NTWP). The CBFO Manager is responsible for overall implementation of TRU waste disposal at WIPP. As such, the Manager provides policy direction and oversight of activities that affect TRU waste characterization and grants DOE waste certification authority to the TRU waste sites. This responsibility includes policy direction and oversight for waste characterization, certification, packaging, and transportation activities at participating sites. Overall responsibility for the development and implementation of the CBFO QA program belongs to the CBFO Manager. Authority for execution of the QA function, which ensures effective implementation, is delegated to the CBFO QA Manager.

The Assistant Manager, Office of the National TRU Program is responsible to ensure that program requirements are met with regard to TRU waste testing, sampling, analysis, sample handling and custody, and associated data management.

CBFO Assistant Managers are responsible for planning, organizing, directing, controlling, and evaluating those activities in their area of responsibility that support the CBFO mission and implement the QAPD. Their responsibilities include, but are not limited, to

- Ensuring that adequate technical and QA training is provided for personnel performing activities important to the satisfaction of CBFO organizational and quality objectives

- Ensuring compliance with all applicable regulations, DOE orders, applicable state, and local laws, and other requirements applicable to CBFO programs

- Ensuring that personnel adhere to procedures for the generation, identification, control, and protection of QA records

- Exercising the authority and responsibility to stop unsatisfactory work such that cost and schedule do not override environmental, safety, health, or

quality considerations

- Developing, implementing, and maintaining plans, policies, and procedures that implement the QAPD

- Identifying, investigating, reporting, and correcting quality problems

Each CBFO employee, including contractor personnel working to CBFO procedures, is responsible for the quality of his or her work and for promptly reporting all existing, developing, or potential conditions adverse to quality to the responsible management for evaluation and action.

Organizations at all management levels shall establish communication channels that provide timely, routine, and wide dissemination of information pertinent to quality performance.

Where more than one CBFO organization is involved in the execution of activities covered by the QAPD, the responsibility and authority of each organization shall be clearly established and documented. The internal interfaces between organizational units are depicted in CBFO organizational charts. CBFO external interfaces include other DOE elements, CBFO program participants, suppliers, the Environmental Protection Agency, the Environmental Evaluation Group, and the New Mexico Environment Department.

APPENDIX D – CBFO QUALITY ASSURANCE MANAGER RESPONSIBILITIES

The CBFO Manager has overall responsibility for the CBFO QA program. Authority for execution of the CBFO QA function, including the independent verification of effective implementation, is delegated to the CBFO QA Manager. It is the policy of CBFO to grant the CBFO QA organization sufficient authority, freedom, and access to all work areas to:

- Identify quality problems
- Recommend solutions
- Verify implementation of solutions
- Ensure that unsatisfactory conditions are controlled until proper disposition has occurred

The CBFO QA Manager shall:

- Have direct access to responsible management at a level where appropriate action can be effected
- Be sufficiently independent from cost and schedule considerations
- Have the organizational freedom to communicate with management
- Have the authority and responsibility to stop unsatisfactory work such that cost and schedule do not override environmental, safety, or health considerations
- Have no other assigned responsibilities related to the quality assurance program that would prevent adequate attention to quality assurance matters

The CBFO QA Manager has the authority and overall responsibility to independently assess the effective implementation of the CBFO QAPD, both within the CBFO organization and in those participant organizations supporting CBFO.

The CBFO QA Manager has the following additional authorities and responsibilities:

- The organizational freedom to communicate with management
- Scheduling and conducting independent QA assessments, including WIPP core participant organizations

- Scheduling and conducting audits of activities related to waste generating site certification when notified by the Assistant Manager, Office of the National TRU Program, that the waste generating site is ready

- Scheduling and conducting recertification audits and surveillances of waste generating sites

- Preparing, as appropriate, and reviewing internal procedures that implement the provision of the QAPD

- Tracking, performing trend analysis, and reporting quality problem areas

- Developing, establishing, and interpreting CBFO QA policy and ensuring effective implementation

- Preparing, issuing, and maintaining the CBFO QAPD

- Interfacing with the CBFO staff, participants, and other stakeholders on quality assurance matters

- Reviewing and approving subordinate QA plans, including participant Quality Assurance Project Plans

- Performing adequacy reviews of QA program documents

- Certifying all CBFO lead auditors and qualifying auditors and technical specialists

- Assuring the independence of lead auditors, auditors, and technical specialists

APPENDIX E – TRU WASTE CHARACTERIZATION AND CERTIFICATION ORGANIZATIONAL AND INDIVIDUAL RESPONSIBILITIES

1. CBFO Assistant Manager, Office of the National TRU Program

   The Assistant Manager (AM), Office of the National TRU Program (NTP) executes program functions related to characterization of waste for disposal at the WIPP. The AM NTP manages the National TRU Waste Program (NTWP) team, which is responsible for TRU waste characterization. The AM NTP also manages activities that prepare waste sites for certification and notifies the CBFO QA Manager when new sites are ready for independent audit.

2. CBFO Assistant Manager, Office of Regulatory Compliance

   The Assistant Manager, Office of Regulatory Compliance (ORC), is responsible for regulatory compliance of the WIPP. The ORC AM manages the Compliance team, which is responsible for environmental activities at the WIPP. The ORC AM is responsible for the preparation of compliance documentation and the implementation of programs to meet the requirements specified in final operating permits for the WIPP facility.

3. CBFO Assistant Manager, Office of Safety and Operations

   The Assistant Manager, Office of Safety and Operations, is responsible for operations, safety and health oversight at the WIPP.

4. DOE Field Office

   The DOE field offices are responsible for ensuring that the requirements of the QAPjPs are in compliance with all DOE orders and that the resources and funding are available to accomplish Program activities. The DOE field offices are responsible for providing a liaison between the site contractors and the CBFO.

5. TRU Waste Sites

   Each participating site shall develop and implement a QAPjP that demonstrates compliance with and implementation of WIPP TRU waste characterization requirements and the applicable requirements of the WIPP Hazardous Waste Facility Permit and its associated Waste Analysis Plan. These QAPjPs shall include or reference the appropriate management and technical criteria of the Program, as well as qualitative or quantitative criteria for determining that Program activities are being satisfactorily performed. QAPjPs shall identify the organizations and positions responsible for their implementation. The QAPjPs

shall also reference site-specific documentation that details how each of the required elements of the Program will be performed. QAPjPs and subsequent revisions must be reviewed for concurrence by the Site Project Manager, Site Project QA Officer, the cognizant DOE Field Officer, the CBFO NTP AM and the CBFO QA Manager.

Prior to the implementation of Program activities at participating sites, standard operating procedures (SOPs) will be developed for all activities affecting Program quality that require written instructions or procedures. For the purposes of the Program, the term SOP refers to any site-specific implementing document. Compliance with SOPs will ensure that tasks are performed in a consistent manner that results in achieving the quality required for the Program. The organization, format, content, and designation of SOPs must be described in the QAPjPs.

6. Site Project Manager

Each participating site's contractor designates a site project manager to oversee characterization program activities at the site. A description of the site project manager's role in relation to the other organizational functions at the site must be included in the site's QAPjP. The site project manager (or designee) reviews and recommends approval of the site QAPjP and subsequent revisions before it is submitted to CBFO for review. Specific Program responsibilities assigned to the site project manager include the following:

- Waste selection and tracking
- Data validation/verification
- Data reconciliation with DQOs
- Assignment of EPA Hazardous Waste Numbers
- QA/QC reports to DOE field office
- Data transmission to CBFO

7. Site Project Quality Assurance Officer.

Each participating site's contractor designates a site project QA officer and provides a detailed description of this position in the site QAPjP. The site project QA officer (or designee) reviews the site QAPjP and subsequent revisions, verifies that the QA requirements have been implemented, and provides day-to-day guidance to the project staff on quality-related matters. This individual will have the authority to stop Program activities at a participating site if quality is not assured or controlled. Specific Program responsibilities assigned to the site project QA officers include the following:

- Laboratory/testing facility assessment
- Nonconformance tracking
- Corrective action verification

- Data validation/verification
- Data QA documentation verification
- Evaluating trends in compliance with Program objectives
- QA/QC reports to site project manager

The site project QA officer shall summarize all relevant information on the QA/QC activities during the period in a semiannual report. This semiannual report shall be distributed to the DOE field office and the site project manager at the same time. The site project manager shall review the report, comment if appropriate, and then forward a copy of the report with comments to the DOE field office.

8. Site Waste Certification Official. Each participating site's contractor designates a waste certification official who must document and certify that all TRU waste payload containers prepared for shipment to WIPP meet all the requirements specified in the *Contact Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant* (CH-WAC; DOE 2002) and transmit the waste certification data to the WIPP M&O contractor.

9. Site Transportation Certification Official. Each participating site's contractor designates a transportation certification official who documents and certifies that payload assemblies for shipment to WIPP meet all the requirements of the *TRUPACT-II Authorized Methods for Payload Control* (TRAMPAC; NRC 1997).

Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix TRU WASTE

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix TRU WASTE

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ACRONYMS AND ABBREVIATIONS

AK	acceptable knowledge
BRAGFLO	BRine And Gas FLOw code
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CFR	Code of Federal Regulations
CH-TRU	contact-handled transuranic (waste)
CRA	Compliance Recertification Application
DOE, USDOE	United States Department of Energy
EDTA	ethylene diamine tetra-acetate
EPA, USEPA	United States Environmental Protection Agency
FEP	feature, event, and process
FR	Federal Register
K_d	equilibrium constant for distribution between solution and solid
LANL	Los Alamos National Laboratory
LWA	Land Withdrawal Act
NDA	nondestructive assay
NUTS	NUclide Transport System code
PA	performance assessment
PAPDB	Performance Assessment Parameter DataBase
PAVT	Performance Assessment Verification Test
RH-TRU	remote-handled transuranic (waste)
SNL	Sandia National Laboratories
TRU	transuranic
TWBIR	TRU Baseline Inventory Report
TWBID	TRU Waste Baseline Inventory Data Base
WAC	Waste Acceptance Criteria
WAP	Waste Analysis Plan
WIPP	Waste Isolation Pilot Plant
WSPF	Waste Stream Profile Form
WUF	waste unit factor
WWIS	WIPP Waste Information System

TRU WASTE-1.0 INTRODUCTION

The transuranic (TRU) waste inventory is expected to be updated for each recertification application. The updated inventory will be evaluated to determine the effect of the waste and waste characteristics on the long-term performance of the repository. The proper implementation of the following five steps will ensure compliance with Title 40 Code of Federal Regulations (CFR) Section 194.24:

(1) Collect/scale inventory data. As shown in Figure TRU WASTE-1, the update cycle begins with the compilation of waste inventory data. This includes the waste that has been emplaced in the repository and the waste that is anticipated for emplacement over the operational life of the Waste Isolation Pilot Plant (WIPP). The anticipated waste inventory data consist of waste that has been stored at TRU waste sites and projected estimates of waste to be generated. For the purposes of performance assessment (PA), the projected waste is then scaled to the allowable capacity that remains in the repository after accounting for the stored and emplaced waste. The combined data (emplaced plus stored plus scaled projected) account for the total WIPP waste inventory. The results of conducting Step 1 of this process for CRA-2004 are reported in Appendix DATA, Attachment F.

(2) Perform waste characterization analysis. The inventory is analyzed for new waste components and/or changes to existing waste components that might affect the repository system. This is a screening step using sensitivity analyses. If a component is determined to impact repository performance it is placed on the list of "significant" waste components. Some waste components indirectly influence repository performance and are placed on the list of "negligible" waste components. All other components are screened out and are not included in the PA calculations. The results of conducting Step 2 of this process for the CRA-2004 are reported in Section TRU WASTE-2.0.

(3) Establish repository waste component limits. Waste components identified as "significant" are examined to determine if changes in the previously established limits are needed. If the inventory update shows substantial changes to the "significant" waste components, the change may necessitate a new or different limit. A new or different waste component limit will be established based upon the impact to the repository. The results of conducting Step 3 of this process for the CRA-2004 are reported in Section TRU WASTE-3.0.

(4) Characterize Waste. Waste characterization methods are developed or refined to quantify the significant waste components. Waste characterization programs implement other regulatory requirements, but for purposes of CRA-2004, this appendix will only address those elements relevant to long-term compliance. The results of conducting Step 4 of this process for the CRA-2004 are reported in Section TRU WASTE-4.0.

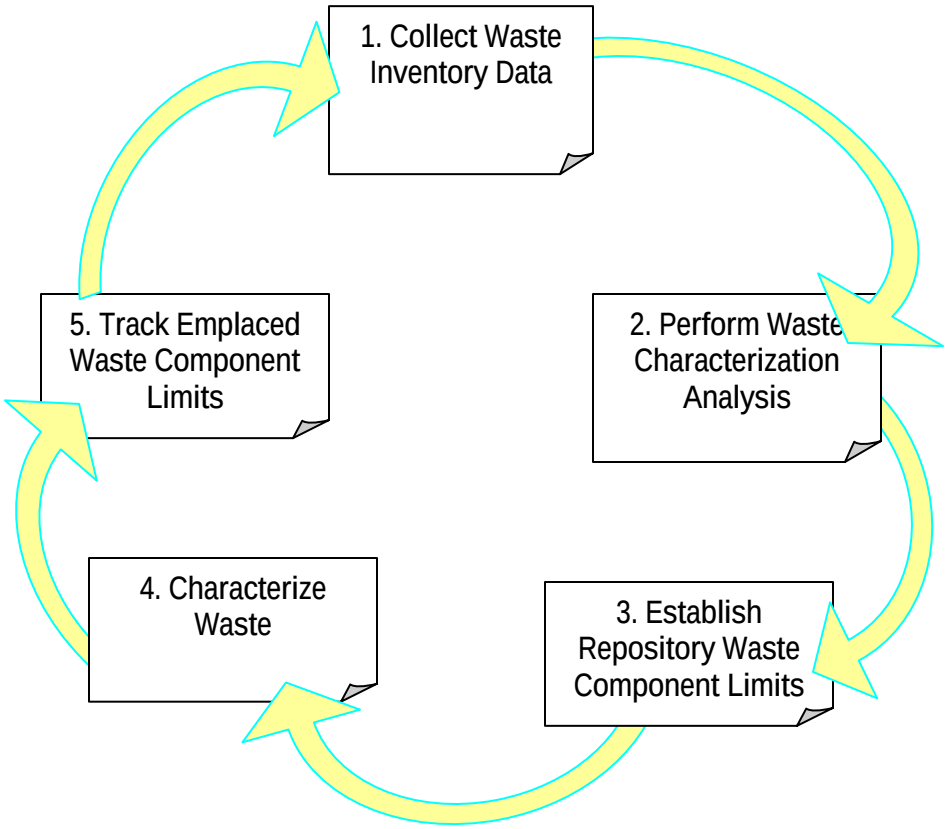

Figure TRU WASTE-1. Waste Characterization Cycle

(5) Track emplaced waste component limits. Waste component data are tracked and reported. The WIPP Waste Information System (WWIS) is used to capture the waste component data for waste emplaced in the repository. The WWIS is a tool used by the personnel at the TRU waste sites and at WIPP to control and track the waste emplaced in the repository. Once a year, the Department of Energy (DOE) provides the Environmental Protection Agency (EPA) with a report containing the values for each of the significant waste components. The emplaced waste data is compiled every five years (or as necessary) for updating the waste inventory, and the cycle repeats itself. The description of Step 5 of this process is reported in Section TRU WASTE-5.0.

TRU WASTE-1.1 Purpose

This appendix provides information in accordance with 40 CFR § 194.24 for the waste characteristics and components important to the containment of waste in the disposal system over the regulatory performance period of 10,000 years. The characteristics and components of the waste are based on the current TRU waste descriptions and inventory presented in Appendix DATA, Attachment F. This appendix describes the assessment of the waste characteristics associated with the chemical, radiological, and physical composition of existing and projected TRU waste destined for disposal at the WIPP. It also identifies those waste components that

significantly influence waste characteristics, and establishes reasonable upper and lower waste component disposal limits. Based on the component limits and their associated uncertainties, a set of characterization techniques are established. Waste components are controlled, tracked, and inventoried upon emplacement in the repository. The cycle represented in Figure TRU WASTE-1 repeats as this characterization information provides key input data for future PAs to determine the impacts on the long-term containment of the disposal system.

Section TRU WASTE-2.0 addresses the requirements specified in 40 CFR § 194.24(b) to identify those waste components and their characteristics that can influence the containment of waste and that are included as inputs to the computer models used in PAs. This section identifies and assesses these parameters based on the DOE's current understanding of the disposal system behavior and the updated waste descriptions and inventory totals since submittal of the Compliance Certification Application (CCA). Section TRU WASTE2.3 also discusses the rationale for exclusion of specific waste characteristics or components expected not to influence releases from the disposal system.

Section TRU WASTE-3.0 shows the total limits for each identified significant component. This section addresses the requirement of 40 CFR § 194.24(c)(1) to establish limiting values for each component identified in Section TRU WASTE-2.0 as important to the performance of the repository system. The rationale for these limits is also discussed.

Section TRU WASTE-4.0 identifies and describes the methods used to quantify the limits for the waste components identified as potentially significant to the long-term performance of the disposal system. This section addresses the requirements of 40 CFR § 194.24(c)(2) and (3).

Section TRU WASTE-5.0 describes a system of controls (WWIS) that address the requirements of 40 CFR § 194.24(c)(4) and (5).

TRU WASTE-1.2 Scope

This appendix supercedes the information previously presented in the following appendices of the CCA:

- Appendix WCA, Waste Characterization Analysis. The modeled long-term performance of the disposal system is evaluated based on current inventory information contained in Appendix DATA, Attachment F and on current disposal system behavior assumptions.

- Appendix WCL, Waste Component Limits. The limits for waste components determined important to the disposal system are established based on results of the CRA-2004 PA and the outcome of the current waste characterization analysis.

- Appendix WAP, Waste Analysis Plan. The characterization methods used to quantify the waste components determined important to the performance of the disposal system are established. Existing documentation that details the current characterization methods is referenced.

TRU WASTE-2.0 WASTE CHARACTERIZATION ANALYSIS

Section TRU WASTE-2 summarizes relevant information on the emplaced and anticipated TRU waste inventories (detailed in Appendix DATA, Attachment F), identifies changes to PA and compliance assessment, and provides conclusions pertaining to whether the waste characteristics and waste components previously identified as significant to performance remain significant.

TRU WASTE-2.1 Introduction

TRU WASTE-2.1.1 Scope

Waste components are the elements that make up the waste (e.g., radionuclides, paper and other cellulosic materials, steel drums that contain the waste, solidified organic and inorganic sludges, etc.). These components have characteristics with the potential to impact disposal system performance. For example, paper is a component of the waste and a substrate for microbes in the repository. The ability of the paper to act as a substrate for microbial gas production is a characteristic of the paper. Microbes metabolizing paper can produce carbon dioxide, methane, and other gaseous metabolic products, which can increase the pressure in a waste panel and potentially impact the performance of the repository.

Sensitivity analysis is used to determine limiting values and associated uncertainties in the waste characteristics and components as required in 40 CFR § 194.24 (c). Sensitivity analyses and calculations related to features, events, and processes (FEPs) associated with the CCA, Performance Assessment Verification Test (PAVT) (DOE 1997), and Appendix PA have identified those waste characteristics and components that are included or excluded in the PA. Sections TRU WASTE-2.2 through 2.5 identify those waste components and waste characteristics and components that influence the containment of waste and thus are included as inputs to the computer codes used in PA.

TRU WASTE-2.1.2 Updated Estimate of TRU Waste Inventory

In the certification of WIPP, the EPA concluded that the estimates provided in Appendix BIR of the CCA represented the best information available at that time (Federal Register [FR] 63 27354, May 18, 1998). The EPA recognized that the WIPP waste inventory may change as the DOE characterizes the contents of containers of TRU waste prior to shipment to WIPP and as new wastes are generated in the future. The EPA also concluded that the WIPP waste inventory estimates provided in Appendix BIR of the CCA were sufficient for purposes of PA.

The inventory volume defined for WIPP emplacement to be used for PA calculations is the "disposal inventory." The WIPP Land Withdrawal Act (LWA), Pub. L. No. 104-201, 110 Stat. 2422 defines the total amount of TRU waste allowed in the WIPP as 175,564 m^3 (6,200,000 ft^3). The "Agreement for Consultation and Cooperation" limits the remote-handled (RH)-TRU waste inventory to 7,079 m^3 (250,000 ft^3) (State of New Mexico vs. DOE 1981). By difference, the contact-handled (CH)-TRU waste inventory is limited to 168,485 m^3 (5,950,000 ft^3).

Since submittal of the CCA, DOE has updated its estimates of the TRU waste inventory destined for disposal in the WIPP. A complete description of that process and its results are presented in Appendix DATA, Attachment F. The following tables summarize information from Appendix

DATA, Attachment F that pertains to waste characterization analysis. Table TRU WASTE-1 summarizes the current densities for the waste materials in the disposal inventory. Table TRU WASTE-2 summarizes the current activities for the radionuclides in the disposal inventory. Table TRU WASTE-3 summarizes the current mass of other important components in the disposal inventory.

Table TRU WASTE-1. Summary of Densities of Waste Materials

Waste Material	Average Mass Density in CH-TRU Waste (kg/m^3)	Average Mass Density in RH-TRU Waste (kg/m^3)
Fe-base Metal/Alloys	1.1×10^2	1.1×10^2
Al-base Metal/Alloys	1.4×10^1	2.5×10^0
Other Metal/Alloys	3.0×10^1	3.2×10^1
Other Inorganic Materials	4.2×10^1	3.5×10^1
Cellulosic Materials	5.8×10^1	4.5×10^0
Rubber Materials	1.4×10^1	3.1×10^0
Plastic Materials	4.2×10^1	4.9×10^0
Solidified Inorganic Material	7.7×10^1	3.9×10^1
Cement (Solidified)	2.9×10^1	8.7×10^{-1}
Vitrified Material	6.2×10^0	5.7×10^{-2}
Solidified Organic Material	1.6×10^1	4.0×10^0
Soils	1.9×10^1	2.6×10^1
Packaging Material, Steel	1.7×10^2	4.8×10^2
Packaging Material, Plastic	1.6×10^1	1.4×10^0
Packaging Material, Lead	1.4×10^{-2}	4.4×10^2

Source: Appendix DATA, Attachment F. Data reported in Appendix DATA, Attachment F includes information known by the TRU waste sites as of September 30, 2002.

Table TRU WASTE-2. Summary of Activities for Radionuclides in the Disposal Inventory (Decayed through 12/31/01)

Radionuclide	CH-TRU Waste Concentration (Ci/m^3)	RH-TRU Waste Concentration (Ci/m^3)	CH-TRU Waste (Ci)	RH-TRU Waste (Ci)
^{225}Ac	9.21×10^{-6}	5.20×10^{-6}	1.55×10^0	3.68×10^{-2}
^{227}Ac	3.00×10^{-6}	5.65×10^{-10}	5.06×10^{-1}	4.00×10^{-6}
^{228}Ac	2.84×10^{-5}	2.02×10^{-5}	4.79×10^0	1.43×10^{-1}
^{109m}Ag	7.49×10^{-10}	NR	1.26×10^{-4}	NR
^{110}Ag	2.61×10^{-16}	2.71×10^{-15}	4.40×10^{-11}	1.92×10^{-11}
^{110m}Ag	1.98×10^{-14}	2.06×10^{-13}	3.34×10^{-9}	1.46×10^{-9}

1

Table TRU WASTE-2. Summary of Activities for Radionuclides in the Disposal Inventory (Decayed through 12/31/01) — Continued

Radionuclide	CH-TRU Waste Concentration (Ci/m^3)	RH-TRU Waste Concentration (Ci/m^3)	CH-TRU Waste (Ci)	RH-TRU Waste (Ci)
^{241}Am	2.38×10^{0}	1.93×10^{0}	4.01×10^{5}	1.36×10^{4}
^{242}Am	2.79×10^{-7}	1.20×10^{-7}	4.70×10^{-2}	8.52×10^{-4}
^{242m}Am	2.83×10^{-7}	2.77×10^{-5}	4.78×10^{-2}	1.96×10^{-1}
^{243}Am	1.25×10^{-4}	1.01×10^{-4}	2.10×10^{1}	7.15×10^{-1}
^{245}Am	7.79×10^{-16}	NR	1.31×10^{-10}	NR
^{217}At	9.22×10^{-6}	5.21×10^{-6}	1.55×10^{0}	3.69×10^{-2}
^{137m}Ba	5.38×10^{-2}	4.74×10^{1}	9.06×10^{3}	3.36×10^{5}
^{210}Bi	1.53×10^{-5}	2.98×10^{-11}	2.58×10^{0}	2.11×10^{-7}
^{211}Bi	2.97×10^{-6}	5.58×10^{-10}	5.00×10^{-1}	3.95×10^{-6}
^{212}Bi	3.47×10^{-5}	3.82×10^{-4}	5.84×10^{0}	2.70×10^{0}
^{213}Bi	9.20×10^{-6}	5.20×10^{-6}	1.55×10^{0}	3.68×10^{-2}
^{214}Bi	3.73×10^{-5}	1.92×10^{-10}	6.29×10^{0}	1.36×10^{-6}
^{249}Bk	5.39×10^{-11}	NR	9.07×10^{-6}	NR
^{250}Bk	2.17×10^{-17}	NR	3.65×10^{-12}	NR
^{14}C	7.19×10^{-6}	2.90×10^{-4}	1.21×10^{0}	2.05×10^{0}
^{109}Cd	7.58×10^{-10}	NR	1.28×10^{-4}	NR
^{113m}Cd	NR	2.31×10^{-5}	NR	1.64×10^{-1}
^{141}Ce	NR	5.33×10^{-23}	NR	3.77×10^{-19}
^{144}Ce	2.11×10^{-9}	2.56×10^{-4}	3.56×10^{-4}	1.82×10^{0}
^{249}Cf	4.53×10^{-7}	1.18×10^{-7}	7.64×10^{-2}	8.37×10^{-4}
^{250}Cf	1.09×10^{-6}	2.11×10^{-6}	1.83×10^{-1}	1.50×10^{-2}
^{251}Cf	2.16×10^{-9}	2.25×10^{-8}	3.64×10^{-4}	1.59×10^{-4}
^{252}Cf	1.23×10^{-6}	2.50×10^{-6}	2.08×10^{-1}	1.77×10^{-2}
^{242}Cm	2.34×10^{-7}	1.01×10^{-7}	3.94×10^{-2}	7.15×10^{-4}
^{243}Cm	2.36×10^{-6}	6.92×10^{-5}	3.97×10^{-1}	4.90×10^{-1}
^{244}Cm	6.86×10^{-2}	3.82×10^{-2}	1.16×10^{4}	2.70×10^{2}
^{245}Cm	5.00×10^{-8}	1.50×10^{-6}	8.42×10^{-3}	1.06×10^{-2}
^{246}Cm	9.21×10^{-6}	9.53×10^{-5}	1.55×10^{0}	6.74×10^{-1}
^{247}Cm	1.65×10^{-15}	1.33×10^{-3}	2.77×10^{-10}	9.44×10^{0}
^{248}Cm	5.43×10^{-7}	2.58×10^{-7}	9.14×10^{-2}	1.83×10^{-3}
^{250}Cm	3.94×10^{-16}	NR	6.64×10^{-11}	NR
^{60}Co	5.85×10^{-6}	2.38×10^{-1}	9.85×10^{-1}	1.68×10^{3}
^{134}Cs	1.22×10^{-7}	4.75×10^{-3}	2.05×10^{-2}	3.36×10^{1}
^{135}Cs	NR	9.75×10^{-9}	NR	6.90×10^{-5}
^{137}Cs	5.73×10^{-2}	5.15×10^{1}	9.65×10^{3}	3.65×10^{5}
^{152}Eu	1.16×10^{-5}	9.82×10^{-2}	1.95×10^{0}	6.95×10^{2}
^{154}Eu	9.82×10^{-6}	5.98×10^{-2}	1.65×10^{0}	4.23×10^{2}
^{155}Eu	3.99×10^{-7}	2.61×10^{-3}	6.73×10^{-2}	1.85×10^{1}

Table TRU WASTE-2. Summary of Activities for Radionuclides in the Disposal Inventory (Decayed through 12/31/01) — Continued

Radionuclide	CH-TRU Waste Concentration (Ci/m^3)	RH-TRU Waste Concentration (Ci/m^3)	CH-TRU Waste (Ci)	RH-TRU Waste (Ci)
^{55}Fe	NR	5.93×10^{-6}	NR	4.20×10^{-2}
^{221}Fr	9.20×10^{-6}	5.20×10^{-6}	1.55×10^{0}	3.68×10^{-2}
^{223}Fr	4.10×10^{-8}	7.71×10^{-12}	6.91×10^{-3}	5.45×10^{-8}
^{152}Gd	2.61×10^{-19}	2.76×10^{-15}	4.40×10^{-14}	1.95×10^{-11}
^{3}H	1.29×10^{-3}	1.62×10^{-4}	2.17×10^{2}	1.15×10^{0}
^{129}I	3.04×10^{-9}	1.16×10^{-5}	5.12×10^{-4}	8.20×10^{-2}
^{85}Kr	2.74×10^{-6}	1.59×10^{-5}	4.62×10^{-1}	1.13×10^{-1}
^{54}Mn	NR	2.58×10^{-4}	NR	1.82×10^{0}
^{22}Na	2.32×10^{-12}	4.17×10^{-5}	3.91×10^{-7}	2.95×10^{-1}
^{93m}Nb	NR	3.88×10^{-8}	NR	2.75×10^{-4}
^{95}Nb	NR	1.06×10^{-17}	NR	7.53×10^{-14}
^{95m}Nb	NR	3.56×10^{-20}	NR	2.52×10^{-16}
^{59}Ni	4.54×10^{-7}	3.25×10^{-3}	7.64×10^{-2}	2.30×10^{1}
^{63}Ni	2.21×10^{-5}	1.58×10^{-1}	3.72×10^{0}	1.12×10^{3}
^{237}Np	2.85×10^{-5}	9.41×10^{-5}	4.80×10^{0}	6.66×10^{-1}
^{238}Np	1.40×10^{-9}	6.05×10^{-10}	2.36×10^{-4}	4.28×10^{-6}
^{239}Np	1.23×10^{-4}	8.87×10^{-6}	2.08×10^{1}	6.28×10^{-2}
^{240m}Np	7.75×10^{-12}	1.57×10^{-7}	1.31×10^{-6}	1.11×10^{-3}
^{231}Pa	7.19×10^{-6}	2.53×10^{-9}	1.21×10^{0}	1.79×10^{-5}
^{233}Pa	2.82×10^{-5}	3.26×10^{-7}	4.75×10^{0}	2.31×10^{-3}
^{234}Pa	5.49×10^{-8}	3.99×10^{-7}	9.25×10^{-3}	2.82×10^{-3}
$^{234}Pa^{m}$	4.22×10^{-5}	3.07×10^{-4}	7.11×10^{0}	2.17×10^{0}
^{209}Pb	9.21×10^{-6}	5.20×10^{-6}	1.55×10^{0}	3.68×10^{-2}
^{210}Pb	1.55×10^{-5}	3.02×10^{-11}	2.61×10^{0}	2.13×10^{-7}
^{211}Pb	2.97×10^{-6}	5.59×10^{-10}	5.01×10^{-1}	3.95×10^{-6}
^{212}Pb	3.46×10^{-5}	3.80×10^{-4}	5.82×10^{0}	2.69×10^{0}
^{214}Pb	3.74×10^{-5}	1.92×10^{-10}	6.30×10^{0}	1.36×10^{-6}
^{107}Pd	NR	4.07×10^{-10}	NR	2.88×10^{-6}
^{147}Pm	1.08×10^{-5}	4.96×10^{-2}	1.82×10^{0}	3.51×10^{2}
^{210}Po	1.55×10^{-5}	3.01×10^{-11}	2.60×10^{0}	2.13×10^{-7}
^{211}Po	9.05×10^{-9}	1.70×10^{-12}	1.53×10^{-3}	1.20×10^{-8}
^{212}Po	2.21×10^{-5}	2.43×10^{-4}	3.72×10^{0}	1.72×10^{0}
^{213}Po	9.01×10^{-6}	5.09×10^{-6}	1.52×10^{0}	3.60×10^{-2}
^{214}Po	3.74×10^{-5}	1.92×10^{-10}	6.30×10^{0}	1.36×10^{-6}
^{215}Po	2.97×10^{-6}	5.59×10^{-10}	5.00×10^{-1}	3.95×10^{-6}
^{216}Po	3.45×10^{-5}	3.80×10^{-4}	5.82×10^{0}	2.69×10^{0}
^{218}Po	3.68×10^{-5}	1.89×10^{-10}	6.19×10^{0}	1.34×10^{-6}
^{144}Pr	2.07×10^{-9}	2.51×10^{-4}	3.49×10^{-4}	1.78×10^{0}
^{236}Pu	2.60×10^{-9}	NR	4.38×10^{-4}	NR

Table TRU WASTE-2. Summary of Activities for Radionuclides in the Disposal Inventory (Decayed through 12/31/01) — Continued

Radionuclide	CH-TRU Waste Concentration (Ci/m^3)	RH-TRU Waste Concentration (Ci/m^3)	CH-TRU Waste (Ci)	RH-TRU Waste (Ci)
^{238}Pu	9.55×10^{0}	5.10×10^{-1}	1.61×10^{6}	3.61×10^{3}
^{239}Pu	3.92×10^{0}	7.59×10^{-1}	6.60×10^{5}	5.38×10^{3}
^{240}Pu	6.35×10^{-1}	2.37×10^{-1}	1.07×10^{5}	1.68×10^{3}
^{241}Pu	1.43×10^{1}	1.58×10^{1}	2.40×10^{6}	1.12×10^{5}
^{242}Pu	1.58×10^{-4}	6.69×10^{-5}	2.67×10^{1}	4.74×10^{-1}
^{243}Pu	1.63×10^{-15}	1.32×10^{-3}	2.74×10^{-10}	9.33×10^{0}
^{244}Pu	7.68×10^{-12}	1.56×10^{-7}	1.29×10^{-6}	1.10×10^{-3}
^{223}Ra	3.00×10^{-6}	5.64×10^{-10}	5.06×10^{-1}	3.99×10^{-6}
^{224}Ra	3.45×10^{-5}	3.80×10^{-4}	5.81×10^{0}	2.69×10^{0}
^{225}Ra	9.22×10^{-6}	5.21×10^{-6}	1.55×10^{0}	3.69×10^{-2}
^{226}Ra	3.78×10^{-5}	1.95×10^{-10}	6.37×10^{0}	1.38×10^{-6}
^{228}Ra	3.36×10^{-5}	2.38×10^{-5}	5.66×10^{0}	1.69×10^{-1}
^{106}Rh	9.36×10^{-10}	9.59×10^{-6}	1.58×10^{-4}	6.79×10^{-2}
^{219}Rn	2.97×10^{-6}	5.58×10^{-10}	5.00×10^{-1}	3.95×10^{-6}
^{220}Rn	3.45×10^{-5}	3.80×10^{-4}	5.82×10^{0}	2.69×10^{0}
^{222}Rn	3.74×10^{-5}	1.93×10^{-10}	6.31×10^{0}	1.36×10^{-6}
^{106}Ru	9.46×10^{-10}	9.60×10^{-6}	1.59×10^{-4}	6.79×10^{-2}
^{125}Sb	2.99×10^{-8}	6.18×10^{-4}	5.04×10^{-3}	4.38×10^{0}
^{126}Sb	NR	5.89×10^{-9}	NR	4.17×10^{-5}
^{126m}Sb	NR	4.21×10^{-8}	NR	2.98×10^{-4}
^{79}Se	7.84×10^{-10}	6.29×10^{-6}	1.32×10^{-4}	4.46×10^{-2}
^{147}Sm	2.83×10^{-15}	9.69×10^{-13}	4.78×10^{-10}	6.86×10^{-9}
^{151}Sm	3.37×10^{-4}	8.20×10^{-2}	5.68×10^{1}	5.80×10^{2}
^{121m}Sn	NR	7.28×10^{-8}	NR	5.15×10^{-4}
^{126}Sn	NR	4.21×10^{-8}	NR	2.98×10^{-4}
^{90}Sr	3.41×10^{-1}	3.48×10^{1}	5.75×10^{4}	2.46×10^{5}
^{99}Tc	9.93×10^{-4}	2.25×10^{-2}	1.67×10^{2}	1.59×10^{2}
^{123}Te	4.02×10^{-10}	NR	6.78×10^{-5}	NR
^{123m}Te	2.96×10^{-24}	NR	4.98×10^{-19}	NR
^{125m}Te	7.24×10^{-9}	1.50×10^{-4}	1.22×10^{-3}	1.06×10^{0}
^{227}Th	2.92×10^{-6}	5.50×10^{-10}	4.93×10^{-1}	3.89×10^{-6}
^{228}Th	3.49×10^{-5}	3.85×10^{-4}	5.89×10^{0}	2.72×10^{0}
^{229}Th	9.23×10^{-6}	5.21×10^{-6}	1.55×10^{0}	3.69×10^{-2}
^{230}Th	6.02×10^{-7}	5.31×10^{-8}	1.01×10^{-1}	3.76×10^{-4}
^{231}Th	2.10×10^{-6}	7.38×10^{-6}	3.53×10^{-1}	5.23×10^{-2}
^{232}Th	3.92×10^{-5}	3.08×10^{-5}	6.61×10^{0}	2.18×10^{-1}
^{234}Th	4.23×10^{-5}	3.07×10^{-4}	7.12×10^{0}	2.17×10^{0}
^{207}Tl	2.95×10^{-6}	5.55×10^{-10}	4.98×10^{-1}	3.93×10^{-6}
^{208}Tl	1.24×10^{-5}	1.37×10^{-4}	2.09×10^{0}	9.71×10^{-1}

Table TRU WASTE-2. Summary of Activities for Radionuclides in the Disposal Inventory (Decayed through 12/31/01) — Continued

Radionuclide	CH-TRU Waste Concentration (Ci/m^3)	RH-TRU Waste Concentration (Ci/m^3)	CH-TRU Waste (Ci)	RH-TRU Waste (Ci)
^{209}Tl	2.03×10^{-7}	1.14×10^{-7}	3.41×10^{-2}	8.10×10^{-4}
^{232}U	9.76×10^{-6}	3.57×10^{-4}	1.64×10^{0}	2.53×10^{0}
^{233}U	7.34×10^{-3}	4.82×10^{-3}	1.24×10^{3}	3.41×10^{1}
^{234}U	9.95×10^{-4}	3.07×10^{-3}	1.68×10^{2}	2.17×10^{1}
^{235}U	7.84×10^{-6}	1.33×10^{-4}	1.32×10^{0}	9.42×10^{-1}
^{236}U	7.70×10^{-7}	2.01×10^{-4}	1.30×10^{-1}	1.42×10^{0}
^{237}U	1.28×10^{-4}	2.48×10^{-6}	2.15×10^{1}	1.75×10^{-2}
^{238}U	1.45×10^{-4}	1.83×10^{-2}	2.44×10^{1}	1.30×10^{2}
^{240}U	7.60×10^{-12}	1.54×10^{-7}	1.28×10^{-6}	1.09×10^{-3}
^{90}Y	3.41×10^{-1}	3.43×10^{1}	5.74×10^{4}	2.43×10^{5}
^{91}Y	NR	1.15×10^{-16}	NR	8.11×10^{-13}
^{65}Zn	1.38×10^{-15}	NR	2.32×10^{-10}	NR
^{93}Zr	6.68×10^{-9}	4.79×10^{-5}	1.13×10^{-3}	3.39×10^{-1}
^{95}Zr	NR	4.84×10^{-18}	NR	3.43×10^{-14}
Total:	3.16×10^{1}	1.88×10^{2}	5.33×10^{6}	1.33×10^{6}

Note: NR = Not Reportable
Source: Appendix DATA, Attachment F. Data reported in Appendix DATA, Attachment F includes information known by the TRU waste sites as of September 30, 2002.

Table TRU WASTE-3. Summary of Masses for Other Important Components

Component	Mass Contained in the Disposal Inventory (kg)
Acetic Acid	1.42×10^{2}
Sodium Acetate	8.51×10^{3}
Citric Acid	1.19×10^{3}
Sodium Citrate	4.00×10^{2}
Oxalic Acid	1.38×10^{4}
Sodium Oxalate	3.39×10^{4}
Sodium EDTA	2.56×10^{1}
Nitrate	2.51×10^{6}
Sulfate	4.21×10^{5}
Phosphate	1.05×10^{5}
Cement	1.2×10^{7}

Source: Appendix DATA, Attachment F. Data reported in Appendix DATA, Attachment F includes information known by the TRU waste sites as of September 30, 2002. Masses reported here are based on the disposal volume as defined in Appendix TRU WASTE, Section 2.1.2.

TRU WASTE-2.2 Summary of Waste Components and Characteristics

TRU WASTE-2.2.1 Waste Characterization Analysis

Tables TRU WASTE-4, TRU WASTE-5, and TRU WASTE-6 summarize the waste characteristics and waste components considered in this section. These tables provide:

- a list of the waste characteristics and components expected to have significant effect on disposal system performance (included in PA),
- a list of the waste characteristics and components expected to have negligible effect on disposal system performance, and
- a list of waste characteristics and components that were considered and excluded.

Table TRU WASTE-4 lists the waste characteristics and components that are included in PA because they would be expected to have a significant impact on repository performance. The waste characteristics and components listed in Table TRU WASTE-4 are identical to those listed in Table WCA-2 of the CCA. None of the inventory changes described in Appendix DATA, Attachment F led to an alternate conclusion regarding the relative importance of individual waste characteristics and components for PA.

Table TRU WASTE-4. Waste Characteristics and Components Used in Performance Assessment: Characteristics Expected to Have a Significant Effect on Disposal System Performance

Characteristic	Component	Effect on Performance	Section of Appendix TRU WASTE
Radioactivity of Each Isotope	Radionuclides	Used in Calculating Normalized Releases	2.3.1, 2.3.2
TRU Radioactivity at Closure	α-Emitting TRU Radionuclides, half-life > 20 Years	Determines Waste Unit Factor (WUF)	2.3.1
Solubility	Radionuclides	Actinide Mobility	2.4.1
Colloid Formation	Radionuclides, Soils, Cellulosic, Plastic, and Rubber (CPR) Materials	Actinide Mobility	2.4.2
Redox State	Radionuclides	Actinide Mobility	2.4.1
Redox Potential	Ferrous Metals	Actinide Oxidation State; Actinide Mobility	2.4.1.1
Gas (H_2) Generation	Ferrous Metals	Increase in H_2 Pressure	2.4.1.2, 2.5.1
Microbial Substrate: CH_4 Generation	Cellulosic Materials	Increase in Gas Pressure	2.4.1.2, 2.5.1
Microbial Substrate: CH_4 Generation	Plastic, Rubber Materials	Increase in Gas Pressure	2.4.1.2, 2.5.1
Particle Diameter	Solid Waste Components	Spalling Release	2.5.2

Table TRU WASTE-4. Waste Characteristics and Components Used in Performance Assessment: Characteristics Expected to Have a Significant Effect on Disposal System Performance — Continued

Characteristic	Component	Effect on Performance	Section of Appendix TRU WASTE
Microbial Nutrients: CH_4 Generation	Sulfates	Increase in Gas Pressure	2.5.1
Microbial Nutrients: CH_4 Generation	Nitrates	Increase in Gas Pressure	2.5.1
Compressibility and Shear Strength	Solid Waste Components	Effect on Creep Closure, Cuttings, Caving, Spallings	2.5.2

Table TRU WASTE-5 lists the waste characteristics and components that are included in PA, but would be expected to have a negligible impact on performance. For example, the impact of microbially generated CO_2 on performance is insignificant because the CO_2 will react with the MgO, forming Mg carbonate minerals that greatly reduce the impact of CO_2 on pH. The waste characteristics and components listed in Table TRU WASTE-5 are identical to those listed in Table WCA-3 of the CCA. None of the inventory changes described in Appendix DATA, Attachment F led to an alternate conclusion regarding the relative importance of individual waste characteristics and components for PA. Actual sensitivities of the analysis to waste characteristics and components are described in Appendix PA. The relationships between components, characteristics, and PA codes are illustrated in Figure TRU WASTE-2.

Table TRU WASTE-5. Waste Characteristics and Components Used in Performance Assessment: Characteristics Expected to Have a Negligible Effect on Disposal System Performance

Characteristic	Component	Effect on Performance	Section of Appendix TRU WASTE
Permeability	Solid Waste Components	Negligible Effect on Brine Movement, Gas Storage	2.5.2
Porosity	Solid Waste Components	Negligible Effect on Brine Movement	2.5.2
Microbial Nutrients, CO_2 Generation	Sulfates[1]	Negligible: MgO Reacts with CO_2	2.4.1.2
Microbial Nutrients, CO_2 Generation	Nitrates[1]	Negligible: MgO Reacts with CO_2,	2.4.1.2, 2.5.1
Microbial Substrate: CO_2 Generation	Cellulosic Materials	Negligible: MgO Reacts with CO_2	2.4.1.2, 2.5.1
Microbial Substrate: CO_2 Generation	Plastic Materials, Rubber Materials	Negligible: MgO Reacts with CO_2	2.4.1.2, 2.5.1
Gas Generation	Water in the Waste	Enhances Initial Gas Generation	2.5.1

[1] These components are significant to gas generation and are therefore also listed in Table TRU WASTE-4.

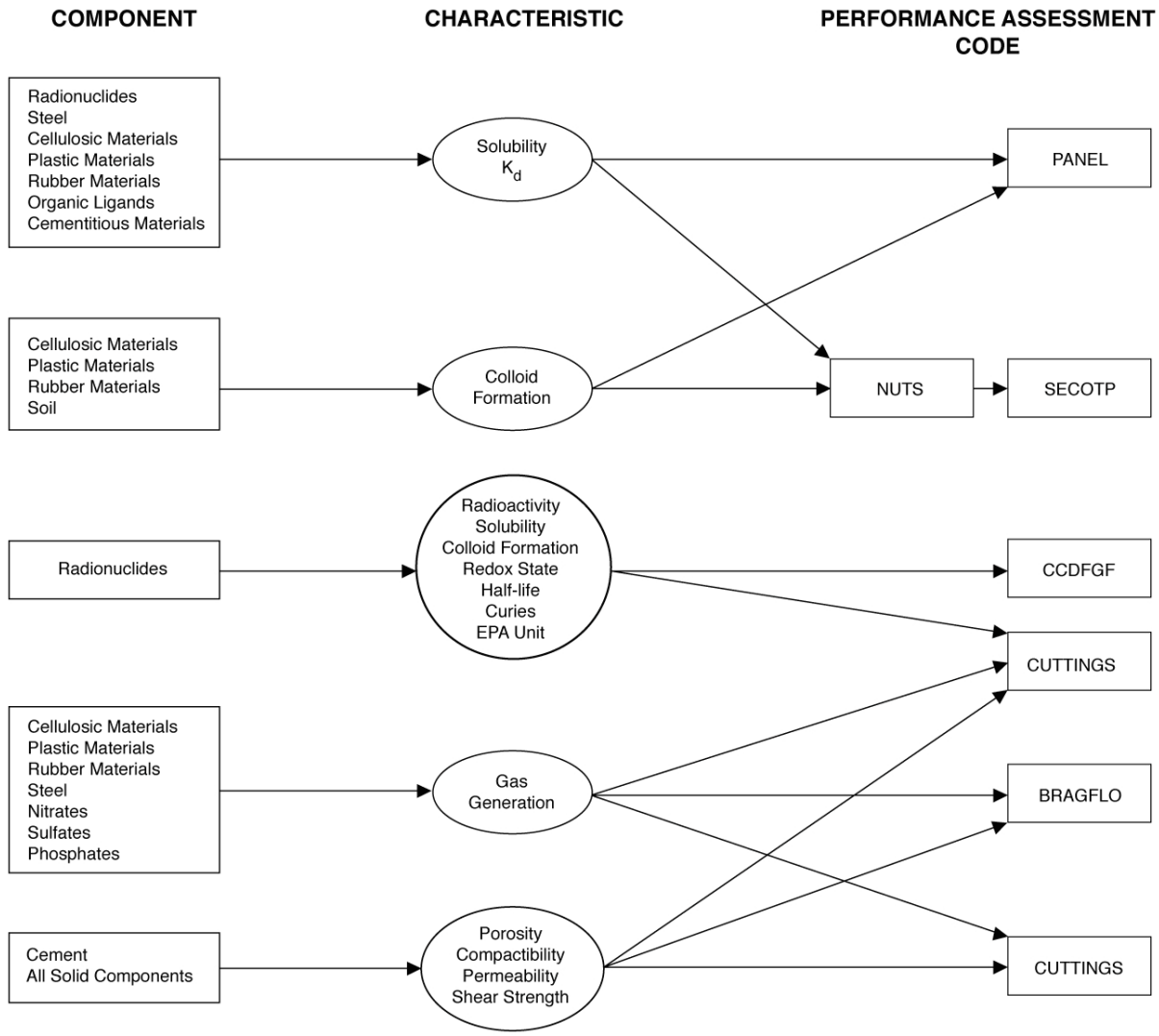

Figure TRU WASTE-2. Waste Components, the Associated Waste Characteristics, and a Performance Assessment Code Related to Each Characteristic

Table TRU WASTE-6 lists the waste characteristics and components that are excluded from PA. Some of these excluded characteristics, however, can indirectly influence performance. For example, the ability of nonferrous metals to bind organic ligands prevents those ligands from increasing +IV actinide solubility, which is considered in PA analyses. The waste characteristics and components listed in Table TRU WASTE-6 are identical to those listed in Appendix WCA, Table WCA-4, in the CCA. None of the inventory changes described in Appendix DATA, Attachment F led to an alternate conclusion regarding the relative importance of individual waste characteristics and components for PA.

Table TRU WASTE-6. Waste Characteristics and Components Not Used in Performance Assessment

Characteristic	Component	Effect on Performance
Cellulosic Materials Radiolysis	Radionuclides	Negligible Effect On Total CO_2
Explosivity	Other Organic Compounds	None
Brine Radiolysis	Radionuclides	Negligible Effect On Actinide Valence
Galvanic Action	Nonferrous Metals	Negligible
Complexation With Actinides[1]	Soil And Humic Material[1]	Actinide Mobility
Buffering Action[1]	Cement[1]	Negligible: Reacts With CO_2 And $MgCl_2$
Heat Of Solution	Cement	Negligible
Ca^{2+} Binding To Organic Ligands	Cement	Negligible Compared To Other Metals
Binding To Organic Ligands[1]	Ferrous Metals[1]	Can Reduce Actinide Mobility
Buffering Action[1]	Ferrous Metals[1]	Actinide Mobility
Galvanic Action	Ferrous Metals	Negligible
Binding To Organic Ligands[1]	Ferrous Alloy Components[1]	Can Reduce Actinide Mobility
Redox Reactions	Nonferrous Metals	Negligible Compared To Iron
Binding To Organic Ligands[1]	Nonferrous Metals[1]	Can Reduce Actinide Mobility
Complexation With Actinides	Organic Ligands	Negligible
Gas Generation	Al And Other Nonferrous Metals	Negligible Relative To Steels
Microbial Nutrients, CO_2 Generation	Phosphates	Negligible Because MgO Reacts With CO_2
Microbial Nutrients: CH_4 Generation	Phosphates[1]	Negligible
Heat Generation	RH-TRU	Negligible
Electrochemical Processes	Sulfate, Nitrate, Phosphate	Negligible

[1] Waste characteristics and components that influence performance indirectly by influencing components and characteristics listed in Table TRU WASTE-5.

Each waste characteristic shown in Tables TRU WASTE-4 and TRU WASTE-5 is reflected in one or more parameters that are used in PA. The PA parameters are compiled in the Performance Assessment Parameter Database (PAPDB) (presented in Appendix PA, Attachment PAR).

TRU WASTE-2.2.2 Relationship Between Inventory Data and Performance Assessment

Appendix DATA, Attachment F provides both WIPP-level data and waste stream-level data on the radionuclide inventory for the WIPP. Performance assessment models generally use the WIPP-level data, normalized to a base year (2001) and scaled up to the full WIPP capacity. The one exception to this approach is the cuttings/caving model, which uses scaled waste stream level data to capture potential variations in the CH-TRU waste.

The relationship between Appendix DATA, Attachment F data and PA is shown in Figure TRU WASTE-3. As Figure TRU WASTE-3 shows, the waste stream level data are used only in modeling direct release by cuttings and cavings (see Appendix PA for additional information). This direct release scenario includes the probability of penetrating each of the 693 CH-TRU waste streams or a single RH-TRU waste stream that represents all of the 86 RH-TRU waste streams, as discussed in Section 6.4.12.4 and in Appendix PA.

This approach for cuttings and cavings releases represents the potential variations in the CH-TRU waste. This approach is necessary because the size scale for cuttings and cavings is on the order of the drill bit diameter, which is less than the diameter of a 55-gallon drum (8- to 12 in versus 24 in). A cuttings and cavings intrusion would, therefore, extract waste from three specific drums (assuming that drums are stacked three high in the disposal rooms), rather than sampling from a larger volume of waste.

In contrast, scenarios in which radionuclides would be released in brine, either directly to the surface or through the Culebra reservoir, assume that the mobility of radionuclides in brine results in an essentially homogeneous mixture of radionuclides. Brine flow would contact a much larger portion of the waste than the direct release of cuttings and cavings. For brine-related release pathways, the total radionuclide inventory is more applicable than the inventory of a particular waste stream. Performance assessment, therefore, uses the average (WIPP-level) inventory from all TRU waste sites, as shown in Figure TRU WASTE-3. In a similar fashion, spall releases use WIPP-level data because this mechanism is assumed to release waste from a volume larger than several drums, averaging out variations in waste streams.

Decay of radionuclides in the TRU waste will produce some radioactive daughter products that must be accounted for in the waste inventory. Therefore, to provide a current inventory estimate for the CRA-2004, all radionuclide values reported in Appendix DATA, Attachment F are decayed to the end of 2001. The PA calculations begin at the time of closure of the WIPP facility. Therefore, PA calculations further decay the inventory to the end of year 2033.

TRU WASTE-2.3 Components That Affect Performance: Curie Content

The radioactivity of a particular radionuclide, often called the activity, is significant to two different aspects of compliance: (1) inclusion in the waste unit factor, which is the normalization factor for the release limits given in Table TRU WASTE-7, and (2) inclusion in the source term for the compliance demonstration. The waste unit factor is based only on TRU wastes that are alpha (α)-emitters with a half-life greater than 20 years, while the complementary cumulative distribution function (CCDF) is based on the full inventory of all radionuclides in the repository. This section, therefore, includes two subsections: TRU WASTE-2.3.1, components relevant to inclusion in the waste unit factor; and TRU WASTE-2.3.2, components relevant to inclusion in CCDFs for each applicable scenario.

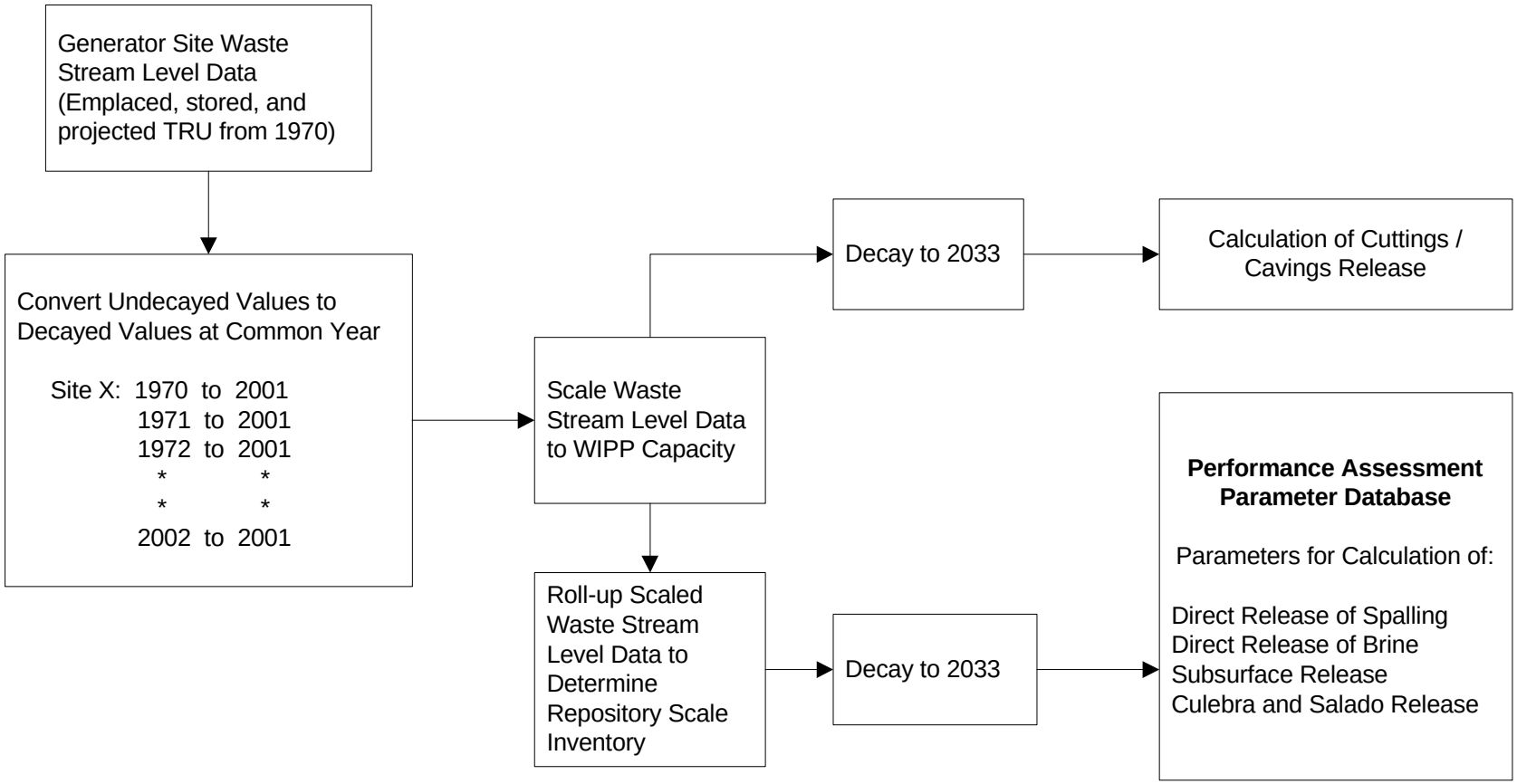

Figure TRU WASTE-3. Flow Chart for Inventory Input into Performance Assessment Waste Components, the Associated Waste Characteristics, and a Performance Assessment Code Related to Each Characteristic

Table TRU WASTE-7. EPA Release Limits and Normalized Release Limits for Radionuclides

Radionuclide	Release Limit per Million Ci of TRU Radionuclides[1] (Ci)	Release Limit for the WIPP Normalized by Total from Table TRU WASTE-8 (Ci)
Americium: ^{241}Am or ^{243}Am	100	248
Carbon: ^{14}C	100	248
Cesium: ^{135}Cs, or ^{137}Cm	1,000	2,480
Iodine: ^{129}I	100	248
Neptunium: ^{237}Np	100	248
Plutonium: ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu	100	248
Radium: ^{226}Ra	100	248
Strontium: ^{90}Sr	1,000	2,480
Technetium: ^{99}Tc	10,000	24,800
Thorium: ^{230}Th or ^{232}Th	10	24.8
Tin: ^{126}Sn	1,000	2,480
Uranium: ^{233}U, ^{234}U, ^{235}U, ^{236}U, or ^{238}U	100	248
Any other α-emitting radionuclide with a half-life greater than 20 years	100	248
Any other radionuclide with a half-life greater than 20 years that does not emit α particles	1,000	2,480

[1] In Appendix A of 40 CFR Part 191, this column is in terms of metric tons heavy metal, and the equivalence to Ci of TRU is presented in Footnote e to the table.

TRU WASTE-2.3.1 Radioactivity Included in the Waste Unit Factor

The WUF is the number of millions of curies (Ci) of α-emitting TRU radionuclides with half-lives longer than 20 years (40 CFR Part 191, Appendix A), based on the TRU waste inventory to be disposed. In the WIPP, 2.48 $\times 10^6$ Ci (see Table TRU WASTE-8) of TRU waste are estimated to be in the repository at closure, so the WUF is 2.48. In CCA Section 4.2.1, the DOE reported the activity of TRU isotopes that contribute to the WUF at closure to be[1] 3.44 $\times$ 10^6 Ci, with a WUF of 3.44. The current WUF (now 2.48 at closure) reflects the updated TRU waste inventory as described in Section TRU WASTE-2.1.2 (greater detail is available in Appendix DATA, Attachment F).

The number of EPA units of a radionuclide is the activity (in Ci) of the radionuclide divided by the release limit for that radionuclide. EPA units are important because the containment requirement for the repository is expressed in EPA units. Section TRU WASTE-2.3.1 discusses current EPA units in more detail.

[1] The value for the WUF in the CCA was inconsistently described; Chapter 4, Section 4.2.1 correctly listed the WUF that was used in the CCA PA as 3.44. CCA Appendix WCA Sections 1.4.2 and WCA Attachment WCA 8.1 incorrectly stated the 1995 decayed value of 4.07 was used in the CCA PA, however the preface to Attachment WCA.8.2 identified and corrected the error. During the EPA's review of the CCA, EPA required DOE to recalculate a new WUF of 3.59 that was ultimately included in the EPA's PAVT (EPA 1998). After the certification, the DOE incorporated the PAVT WUF value of 3.59 in the compliance baseline through an EPA approved change request (EPA 2002).

Table TRU WASTE-8. Radionuclides That Contribute to the Waste Unit Factor

Nuclide	Half-Life (years)	Inventory at Closure (Ci)	Percent of Waste Unit Factor
^{241}Am	4.33×10^{2}	4.58×10^{5}	1.82×10^{1}
^{242m}Am	1.41×10^{2}	2.11×10^{-1}	8.48×10^{-6}
^{243}Am	7.37×10^{3}	2.17×10^{1}	8.63×10^{-4}
^{249}Cf	3.51×10^{2}	7.24×10^{-2}	2.88×10^{-6}
^{251}Cf	9.00×10^{2}	5.10×10^{-4}	2.03×10^{-8}
^{243}Cm	2.91×10^{1}	4.07×10^{-1}	1.62×10^{-5}
^{245}Cm	8.50×10^{3}	1.92×10^{-2}	7.62×10^{-7}
^{246}Cm	4.76×10^{3}	2.22×10^{0}	8.80×10^{-5}
^{247}Cm	1.56×10^{7}	9.45×10^{0}	3.75×10^{-4}
^{248}Cm	3.48×10^{5}	9.32×10^{-2}	3.70×10^{-6}
^{237}Np	2.14×10^{6}	1.01×10^{1}	4.00×10^{-4}
^{238}Pu	8.77×10^{1}	1.25×10^{6}	4.98×10^{1}
^{239}Pu	2.41×10^{4}	6.65×10^{5}	2.64×10^{1}
^{240}Pu	6.56×10^{3}	1.08×10^{5}	4.30×10^{0}
^{242}Pu	3.75×10^{5}	2.71×10^{1}	1.08×10^{-3}
^{244}Pu	8.00×10^{7}	1.10×10^{-3}	4.38×10^{-8}
TOTAL		2.48×10^{6}	-

Source: Leigh 2003a

As an example, using EPA units, the ^{239}Pu inventory at closure would be 6.65×10^{5} Ci (Table TRU WASTE-8), and the release limit for ^{239}Pu would be 248 Ci, so the number of EPA units is calculated as:

$$\frac{6.65 \times 10^{5}\ \text{Ci}}{248\ \text{Ci}} = 2.68 \times 10^{3}\ \text{EPA units.} \qquad (1)$$

The release limit for ^{239}Pu is given by the waste unit factor (2.48) multiplied by the release limit per million Ci of TRU. The release limit per million Ci is given in Table TRU WASTE-7, which is a copy of Table 1 in Appendix A, 40 CFR Part 191. The value for ^{239}Pu is 100 Ci, giving a release limit of 248 Ci. The calculation of WUF, EPA units, and release limits uses the method established for the CCA (described above).

With a mix of radionuclides, each radionuclide is normalized with respect to its release limit, and the sum of all releases must have

- less than one chance in 10 of exceeding the release limit, and
- less than one chance in 1,000 of exceeding ten times the release limit.

The sum of releases in EPA units is expressed by

$$Rj = \frac{1}{fw}\left[\frac{Q1j}{L1} + \frac{Q2j}{L2} + \ldots\right] = \sum_{i=1}^{nR} \frac{Qij}{fwLi} \leq \begin{Bmatrix} 1 \textit{ with a probability of } 0.1 \\ 10 \textit{ with a probability of } 0.001 \end{Bmatrix} \quad (2)$$

where

R_j is the total release in EPA units under scenario j,

f_w is the WUF,

Q_{ij} is the cumulative release for radionuclide i under scenario j,

L_i is the EPA release limit for radionuclide i, and

nR is the number of radionuclides contributing to the release.

The regulatory time period over which these releases are summed is 10,000 years. A brief explanation of these release limits is given in Sanchez (1996), and a comprehensive discussion of the background for these limits is provided in EPA (1985).

Figure TRU WASTE-4 is a flow diagram for the selection of those radionuclides in the inventory that contribute to the WUF. As noted above, not all radionuclides are included in this factor. For example, ^{90}Sr is excluded because it is not a TRU radionuclide, and is not an α-emitter. Even uranium is excluded because it is not a TRU radionuclide, defined as elements with atomic numbers greater than 92.

The radionuclides that are included in the WUF are listed in Table TRU WASTE-8. As noted in the table, the relevant inventory at closure is 2.48×10^6 Ci, resulting in a WUF of 2.48. This analysis was performed using data from Appendix DATA, Attachment F.

It is worthwhile to note that the inventory in Table TRU WASTE-8 is dominated by americium and plutonium, the same elements that dominated the inventory for the CCA. More specifically, the radionuclides ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Am capture 99.9 percent of the WUF. The combined activity at emplacement of ^{241}Am, ^{238}Pu, ^{239}Pu, and ^{240}Pu is orders of magnitude greater than the combined activity of the remaining radionuclides.

TRU WASTE-2.3.2 Radioactivity Included in the Source Term for Performance Assessment

Unlike the WUF, all reported radionuclides are included in a demonstration of compliance and must therefore be considered for inclusion in the source term for PA. A comprehensive list of radionuclides in the waste is in Appendix DATA, Attachment F, which provides the inventory basis for the CRA-2004. Many of these radionuclides are present in such small quantities that their impact on long-term performance is negligible. That is, their total combined initial inventory in EPA units is much less than one percent so they will have negligible impact on compliance.

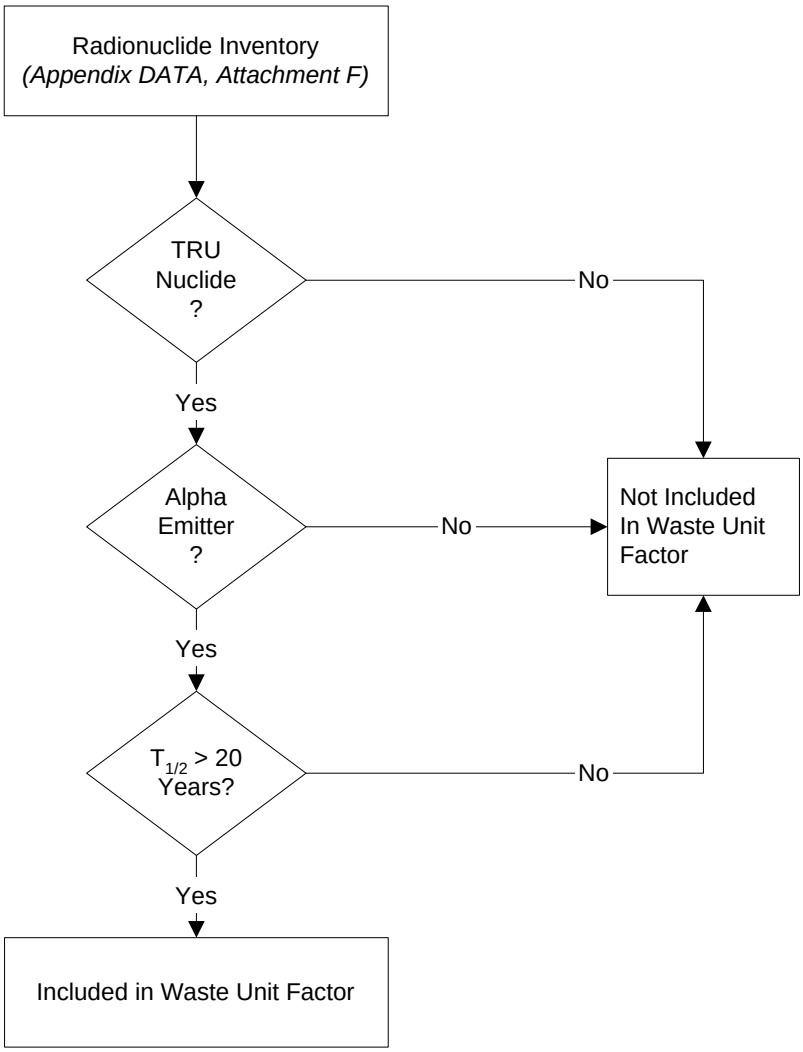

Figure TRU WASTE-4. Flow Diagram for Including Radionuclides in the Waste Unit Factor

Two different release pathways are used in PA: (1) direct releases comprised of (a) material brought to the surface by cuttings, cavings, spalling, and (b) brine under pressure that flows to the surface during a drilling intrusion through the repository; and (2) releases to the accessible environment in brine that moves through the subsurface, primarily the Culebra aquifer. Note that the time scales for these two releases are quite different. The direct release during drilling events (Item 1) occurs within a few days. The flow and transport of radionuclides through the Culebra (Item 2) will require hundreds to thousands of years.

Different radionuclides are used for these pathways because of the time-scale differences and different release media (solid particles containing radionuclides or brine containing radionuclides) as well as the computational efficiency of each computer code used in the PA calculations. Figure TRU WASTE-5 is a flow diagram for selecting radionuclides for different release mechanisms according to the criteria of Table TRU WASTE-7. The result of applying these criteria to the radionuclides in Appendix DATA, Attachment F is shown in

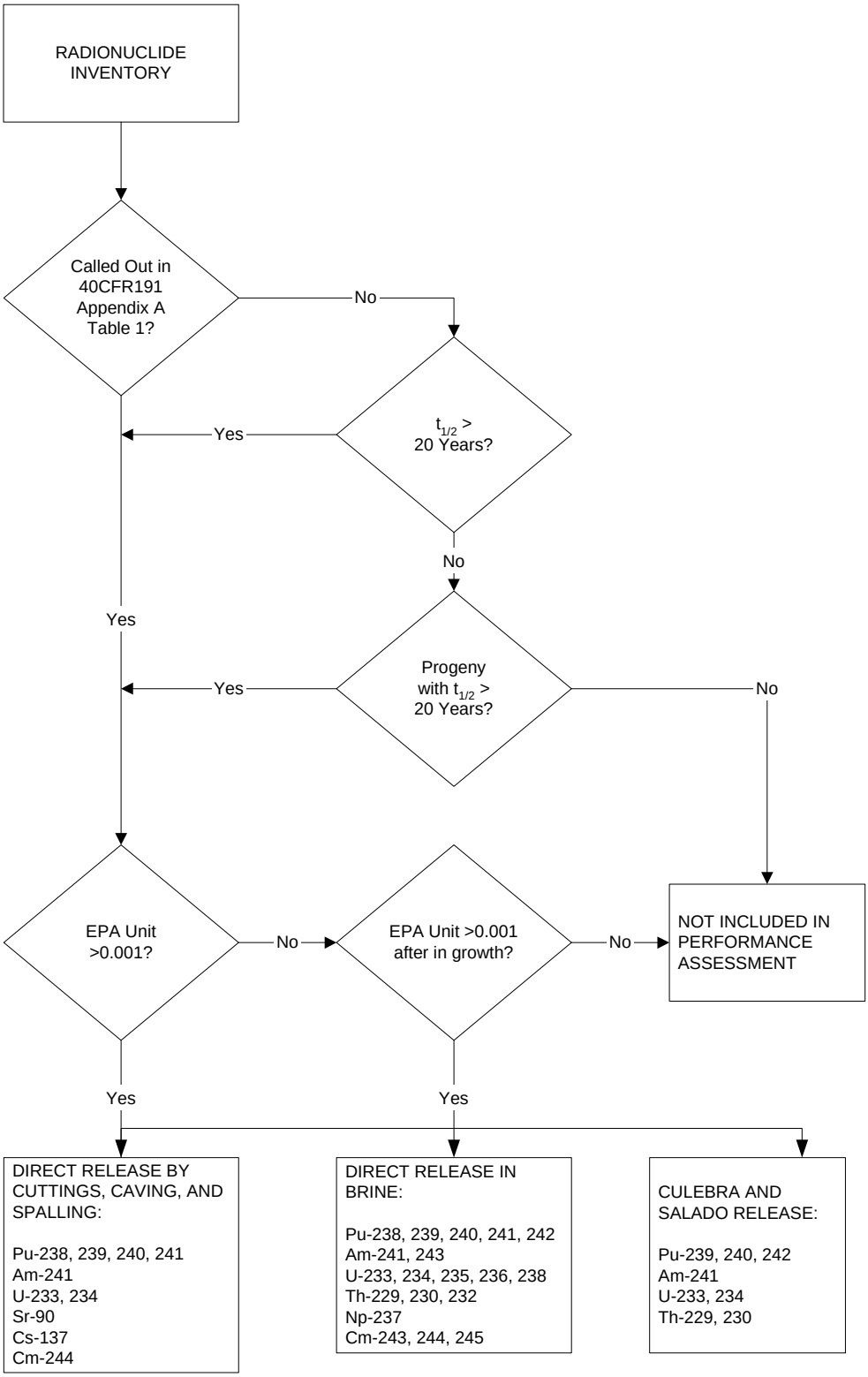

Figure TRU WASTE-5. Flow Diagram for Selecting Radionuclides for the Release Pathways Conceptualized by Performance Assessment (The top part of the diagram describes the criteria for selecting radionuclides in Table TRU WASTE-9)

Table TRU WASTE-9. Radionuclides Included in the Performance Assessment Source Term

Radionuclide	Current Inventory Values			Release Calculations (1)			
	Inventory at Closure (Ci)	EPA Units		Cuttings, Cavings, & Spall Release	Direct Brine Release	Salado Release	Culebra Release
		At Closure	At 10,000 years				
^{238}Pu	1.25×10^{6}	5.04×10^{3}	2.61×10^{-23}	×	×	(2)	(2)
^{239}Pu	6.65×10^{5}	2.68×10^{3}	2.01×10^{3}	×	×	×	×
^{241}Am	4.58×10^{5}	1.84×10^{3}	2.48×10^{-4}	×	×	×	×
^{240}Pu	1.08×10^{5}	4.36×10^{2}	1.51×10^{2}	×	×	c	c
^{137}Cs	1.79×10^{5}	7.19×10^{1}	0.00×10^{0}	×	--	--	--
^{90}Sr	1.42×10^{5}	5.71×10^{1}	0.00×10^{0}	×	--	--	--
^{233}U	1.27×10^{3}	5.12×10^{0}	4.91×10^{0}	×	×	c	c
^{229}Th	5.39×10^{0}	2.17×10^{-2}	3.04×10^{0}	--	×	c	c
^{234}U	3.19×10^{2}	1.28×10^{0}	3.03×10^{0}	×	×	×	×
^{230}Th	1.76×10^{-1}	7.07×10^{-3}	2.64×10^{0}	--	×	×	×
^{238}U	1.54×10^{2}	6.21×10^{-1}	6.21×10^{-1}	--	×	--	--
^{237}Np	1.01×10^{1}	4.06×10^{-2}	4.27×10^{-1}	--	×	--	--
^{232}Th	6.83×10^{0}	2.75×10^{-1}	2.75×10^{-1}	--	×	--	--
^{226}Ra	6.28×10^{0}	2.53×10^{-2}	2.07×10^{-1}	--	--	--	--
^{210}Pb	4.94×10^{0}	1.99×10^{-2}	2.07×10^{-1}	--	×	--	--
^{242}Pu	2.71×10^{1}	1.09×10^{-1}	1.07×10^{-1}	--	×	c	c
^{243}Am	2.17×10^{1}	8.75×10^{-2}	5.74×10^{-2}	--	×	--	--
^{236}U	1.65×10^{0}	6.66×10^{-3}	8.62×10^{-2}	--	×	--	--
^{235}U	2.28×10^{0}	9.18×10^{-3}	3.21×10^{-2}	--	×	--	--
^{14}C	3.25×10^{0}	1.31×10^{-2}	3.90×10^{-3}	--	--	--	--
^{232}U	3.07×10^{0}	1.23×10^{-2}	0.00×10^{0}	--	--	--	--
^{227}Ac	9.57×10^{-1}	3.85×10^{-3}	8.06×10^{-3}	--	--	--	--
^{231}Pa	1.21×10^{0}	4.88×10^{-3}	8.06×10^{-3}	--	--	--	--
^{243}Cm	4.07×10^{-1}	1.64×10^{-3}	0.00×10^{0}	--	×	--	--
^{248}Cm	9.32×10^{-2}	3.75×10^{-4}	3.68×10^{-4}	--	×	--	--
^{245}Cm	1.92×10^{-2}	7.72×10^{-5}	3.97×10^{-5}	--	×	--	--
^{244}Pu	1.10×10^{-3}	4.44×10^{-6}	4.47×10^{-6}	--	×	--	--
^{244}Cm	2.51×10^{3}	(3)	(3)	×	×	--	--
^{241}Pu	5.38×10^{5}	(3)	(3)	×	×	--	--
Percent of EPA Units at closure represented by nuclides in source term				99.98%	98.71%	48.95%	48.95%
Percent of EPA Units at 10,000 years represented by nuclides				99.65%	99.99%	99.92%	99.92%

Source: Leigh 2003b

(1) See Section 6.3 for a discussion of scenarios analyzed by PA and the release pathways.

(2) ^{238}Pu was included in the Salado transport calculations but the release to the Culebra was too low to merit calculation of its transport within the Culebra. The EPA unit percent total at closure increases to 98.71% with ^{238}Pu added; the percent at 10,000 years is unaffected.
^{241}Pu and ^{244}Cu are not regulated by 40 CFR Part 191, but are included because their daughters, ^{241}Am and ^{240}Pu respectively, are significant to performance.

× indicates an isotope included in calculation

c indicates isotopes that are combined for transport with isotopes having similar characteristics

Table TRU WASTE-9. The inventory analysis that follows Figure TRU WASTE-5 is documented in Leigh (2003b). Table TRU WASTE-9 also lists the radionuclides used for specific release mechanisms. The EPA unit at 10,000 years (the end of the regulatory period) is also shown in Table TRU WASTE-9, because some nuclides experience considerable ingrowth, but not enough to affect the domination by the most prevalent radionuclides ^{239}Pu and ^{240}Pu. The ^{241}Am component is also important for the first 3,000 years after closure.

TRU WASTE-2.3.2.1 Radionuclides Included in Direct Releases by Cuttings, Cavings, and Spalling

The 10 isotopes listed in the column headed "Cuttings/Cavings/Spall Release" in Table TRU WASTE-9 are used to model direct release by cuttings, cavings, or spalling. Release is assumed to occur when containers of CH-TRU or RH-TRU waste are breached during a borehole intrusion. The amount of radionuclides in the source term is estimated from the inventory per drum of the waste stream penetrated, including decay and ingrowth. Details of the EPA unit distribution in the waste streams are provided in Fox (2003). The direct release scenario is discussed in greater detail in Section 6.4.12.4.

Eight of the listed isotopes comprise more than 99.9 percent of the EPA units for the entire regulatory period and are identified in Leigh (2003b) as important radionuclides for direct release. The other two are included because they are parent nuclides of significant daughters. Inclusion of 99 percent or more of the EPA unit provides an accurate representation of the source term, while maintaining efficiency in computation by limiting the total number of isotopes to 10. The addition of the many radionuclides that make up the final 0.1 percent does not provide additional benefit in understanding the long-term behavior of the repository (see Leigh 2003b).

TRU WASTE-2.3.2.2 Radionuclides Included in Direct Releases of Brine to the Surface

Direct release of brine to the surface can carry radionuclides that are dissolved in the brine or sorbed on colloidal particles.

The radionuclides released in direct release of brine to the surface include several isotopes that comprise negligible fractions of the total EPA unit, but must be included in the source term because of their influence on the total quantity of dissolved radionuclides. This influence occurs because the isotopes of a radionuclide will dissolve based on mass ratio, rather than the activity ratio, in which they are present in the waste. That is, if 90 percent of the mass of uranium in the waste is ^{238}U (for example), 90 percent of the dissolved uranium in moles/liter will be ^{238}U, even though 90 percent of the radioactivity will not be from ^{238}U.

The EPA units of ^{90}Sr and ^{137}Cs at closure are large enough that an explanation is needed for not including them in the source term for direct release of brine. Although the EPA units of ^{90}Sr and ^{137}Cs are initially large (57 for ^{90}Sr and 72 for ^{137}Cs), rapid decay from a short half-life (about 30 years) results in negligible impact on the PA for these two isotopes. The lack of impact on compliance is explained below.

The ^{90}Sr and ^{137}Cs components decay by about 90 percent during the first 100 years after closure, when borehole intrusions are excluded due to the active institutional controls that will be

implemented following WIPP closure. During this time period, the EPA unit of ^{137}Cs decays from 72 down to 7.1 for the whole repository, while ^{90}Sr decays from 57 to 5.3. At 200 years, the EPA unit for both ^{137}Cs and ^{90}Sr is below 1.0, again for the whole repository.

In addition to the rapid decay, the results of the PA show that were an individual borehole intrusion to occur at 100 years, it would release about six EPA units (5.5 units, see Appendix PA), which is much less than the total inventory. Even at 350 years, when either isotope decays down to 0.03 percent of the initial inventory, the maximum volume of brine release would be only 0.01 m^3. In summary, the rapid decay of ^{137}Cs and ^{90}Sr and the negligible volumes of brine release at early times provide the basis for excluding these isotopes from the inventory.

The ^{14}C component is not included in this (or any) source term. Any ^{14}C transported out of the repository will be diluted by the large excess of nonradioactive carbon. This was demonstrated in Wang (1996a) in which there were 0.2 moles of ^{14}C out of 3×10^8 moles of carbon in the cellulosic materials, or one part in 100 million. Although the ^{14}C inventory has been updated, the ratio of ^{14}C to nonradioactive carbon remains the same.

TRU WASTE-2.3.2.3 <u>Radionuclides Included in Releases to the Culebra Aquifer</u>

Release of brine from the repository to the Culebra also potentially carries dissolved and colloidal radionuclides. The nine radionuclides in the source term for Culebra release include those that dominate the EPA unit for all but the earliest part of the regulatory period. Other less prevalent radionuclides are excluded because they would comprise a negligible fraction of the EPA unit or because transport through the Culebra is sufficiently slow that shorter-lived radionuclides would decay to negligible amounts before reaching the accessible environment. The selection of the nine radionuclides is discussed in Leigh (2003b).

Of the nine radionuclides, only ^{239}Pu, ^{241}Am, ^{234}U, and ^{230}Th are transported separately in PA. Isotopes of the same element will be transported together, unless their half-lives differ greatly. The movement of most of the radionuclides can be calculated indirectly. This concept was presented in detail in Garner (1996):

- The ^{233}U component can be combined with ^{234}U for transport because their half-lives are similar.
- Similarly, ^{229}Th can be combined with ^{230}Th, because they will be in a fixed ratio to each other. The ^{232}Th component can be dropped because it is a constant small fraction of the EPA unit throughout the regulatory period.
- The ^{240}Pu and ^{242}Pu components can be combined with ^{239}Pu; their long half-lives also indicate a fixed ratio between them.
- The ^{238}Pu component will have decayed to about 0.5 percent of its initial inventory after 700 years, and its contribution to the EPA unit will be negligible because travel time in the Culebra is much greater than 700 years.

The ^{239}Pu and ^{240}Pu components dominate the EPA limit during the regulatory period, and ^{241}Am is also a factor for the first 3,000 years. Toward the end of the regulatory period, ^{230}Th has

grown by about 2.5 orders of magnitude, ^{229}Th by about 1.5 orders of magnitude, and ^{234}U by a factor of three, but all are still small fractions of the EPA unit. The ^{226}Ra component grows during the regulatory period, but even at 10,000 years would comprise a very small fraction of the EPA limit.

Calculation of radionuclide inventories for this transport mechanism is presented in Leigh (2003c.)

TRU WASTE-2.3.2.4 Radionuclides Included in Releases Through the Salado

In the PA results (Appendix PA), there is one vector in which brine is released through the Salado to the accessible environment. As a result, the radionuclides that could potentially contribute to releases via this pathway are considered.

Release of brine from the repository through the Salado (either to the Culebra or to the accessible boundary) can also potentially carry dissolved and colloidal radionuclides. The nine radionuclides in the source term for Salado release include those that dominate the EPA unit for all but the earliest part of the regulatory period. Other less prevalent radionuclides are excluded, because they would comprise a negligible fraction of the EPA unit or because transport through the Salado is sufficiently slow that shorter-lived radionuclides would decay to negligible amounts before reaching the accessible environment. The selection of the nine radionuclides is discussed in Leigh (2003b.)

TRU WASTE-2.3.2.5 Radionuclides Excluded From Source Terms

A large number of radionuclides were not included in any source term because they did not survive the screening process outlined in Figure TRU WASTE-5. Table TRU WASTE-10 lists those excluded radionuclides that have not already been discussed, and indicates (marked with an "×" in Table TRU WASTE-10) the reason for their exclusion.

TRU WASTE-2.4 Radionuclide Characteristics: Solubility and Colloid Formation

The major characteristics of the radionuclides that are expected to affect disposal system performance are (1) solubility and (2) the tendency to form or sorb to colloidal particles. Except for direct release from drilling (cutting) and caving, in which particles containing radionuclides will be released with circulation of drilling mud, radionuclides are mobilized for transport from the repository either in brine or as colloidal particles transported by brine. Gas-phase transport is not expected to occur (see Appendix PA, Attachment SCR).

All isotopes of a particular radioactive element exhibit essentially identical characteristics of solubility, colloid formation, and sorption.

Table TRU WASTE-10. Radionuclides Excluded From All Source Terms

Radionuclide	Reason for Exclusion[3]		
	Short Half-life and Progeny with Short Half-life[1]	Small EPA Unit	Negligible[2] Ingrowth
^{225}Ac	×	NA	NA
^{227}Ac	×	NA	NA
^{228}Ac	×	NA	NA
^{109m}Ag	×	NA	NA
^{110}Ag	×	NA	NA
^{110m}Ag	×	NA	NA
^{242}Am	×	NA	NA
^{242m}Am	NA	×	×
^{245}Am	×	NA	NA
^{217}At	×	NA	NA
^{137m}Ba	×	NA	NA
^{210}Bi	×	NA	NA
^{211}Bi	×	NA	NA
^{212}Bi	×	NA	NA
^{213}Bi	×	NA	NA
^{214}Bi	×	NA	NA
^{249}Bk	×	NA	NA
^{250}Bk	×	NA	NA
^{14}C	NA	×	NA
^{109}Cd	×	NA	NA
^{113m}Cd	×	NA	NA
^{141}Ce	×	NA	NA
^{144}Ce	×	NA	NA
^{249}Cf	NA	×	×
^{250}Cf	×	NA	NA
^{251}Cf	NA	×	NA
^{242}Cm	×	NA	NA
^{246}Cm	NA	×	×
^{247}Cm	NA	NA	×
^{250}Cm	NA	NA	×
^{60}Co	NA	×	NA
^{134}Cs	×	NA	NA

Table TRU WASTE-10. Radionuclides Excluded From All Source Terms — Continued

Radionuclide	Reason for Exclusion[3]		
	Short Half-life and Progeny with Short Half-life[1]	Small EPA Unit	Negligible[2] Ingrowth
^{135}Cs	NA	×	NA
^{152}Eu	×	NA	NA
^{154}Eu	×	NA	NA
^{155}Eu	×	NA	NA
^{55}Fe	×	NA	NA
^{221}Fr	×	NA	NA
^{223}Fr	×	NA	NA
^{152}Gd	NA	×	NA
^{3}H	×	×	NA
^{129}I	NA	×	×
^{85}Kr	×	NA	NA
^{54}Mn	×	NA	NA
^{22}Na	×	NA	NA
^{93m}Nb	×	NA	NA
^{95}Nb	×	NA	NA
^{95m}Nb	×	NA	NA
^{144}Nd	NA	NA	×
^{59}Ni	NA	×	×
^{63}Ni	NA	NA	×
^{238}Np	×	NA	NA
^{239}Np	×	NA	NA
^{240m}Np	×	NA	NA
^{233}Pa	×	NA	NA
^{234}Pa	×	NA	NA
^{234m}Pa	×	NA	NA
^{209}Pb	×	NA	NA
^{211}Pb	×	NA	NA
^{212}Pb	×	NA	NA
^{214}Pb	×	NA	NA
^{107}Pd	NA	×	NA
^{210}Po	×	NA	NA
^{211}Po	×	NA	NA
^{212}Po	×	NA	NA
^{213}Po	×	NA	NA

Table TRU WASTE-10. Radionuclides Excluded From All Source Terms — Continued

Radionuclide	Reason for Exclusion[3]		
	Short Half-life and Progeny with Short Half-life[1]	Small EPA Unit	Negligible[2] Ingrowth
^{214}Po	×	NA	NA
^{215}Po	×	NA	NA
^{216}Po	×	NA	NA
^{218}Po	×	NA	NA
^{144}Pr	×	NA	NA
^{236}Pu	×	NA	NA
^{243}Pu	×	×	NA
^{223}Ra	×	NA	NA
^{224}Ra	×	NA	NA
^{225}Ra	×	NA	NA
^{106}Rh	×	NA	NA
^{219}Rn	×	NA	NA
^{220}Rn	×	NA	NA
^{222}Rn	×	NA	NA
^{106}Ru	×	NA	NA
^{125}Sb	×	NA	NA
^{126}Sb	×	NA	NA
^{126m}Sb	×	NA	NA
^{79}Se	NA	×	×
^{147}Sm	NA	×	NA
^{148}Sm	NA	NA	×
^{151}Sm	NA	NA	×
^{121m}Sn	NA	×	NA
^{126}Sn	NA	×	NA
^{99}Tc	NA	×	×
^{123}Te	NA	NA	×
^{123m}Te	×	NA	NA
^{125m}Te	×	NA	NA
^{227}Th	×	NA	NA
^{228}Th	×	NA	NA
^{231}Th	×	NA	NA
^{234}Th	×	NA	NA
^{207}Tl	×	×	NA
^{208}Tl	×	×	NA

Table TRU WASTE-10. Radionuclides Excluded From All Source Terms — Continued

Radionuclide	Reason for Exclusion[3]		
	Short Half-life and Progeny with Short Half-life[1]	Small EPA Unit	Negligible[2] Ingrowth
^{209}Tl	×	NA	NA
^{232}U	NA	×	×
^{237}U	×	NA	NA
^{240}U	×	NA	NA
^{90}Y	×	NA	NA
^{91}Y	×	NA	NA
^{65}Zn	×	NA	NA
^{93}Zr	NA	×	×
^{95}Zr	×	NA	NA

[1] "Short" half-life means $t_{½}$ < 20 years. Radionuclides with $t_{½}$ < 20 years are not regulated by 40 CFR Part 191 Subparts (b) and (c).
[2] Negligible ingrowth includes ingrowth of the progeny that are radionuclides already predominant in the inventory.
[3] NA indicates that the column heading does not apply to the particular isotope.

Solubility and colloid formation are discussed for thorium, uranium, neptunium, plutonium, and americium. The experimental determination and modeling of solubility and colloid formation, and the manner in which they are taken into account by PA, are discussed in detail in Appendix PA. Cesium and strontium are assumed to be extremely soluble and their concentrations will be limited by their inventories (see Appendix WCA, Section WCA.3.2.2, in the CCA). Thus, the two elements are not considered in this section. Radium is excluded from the source term because of its short half-life.

Actinide mobility depends on the particular chemical environment (brine pH, fugacity of CO_2, redox potential, organic ligand concentration, etc). That environment will be controlled by the MgO reacting with brine. Magnesium oxide is added to mitigate the effect of CO_2 generated by microbial degradation of organic materials and to control the pH of any brines in the repository. The mechanism of the control is discussed in Appendix BARRIERS and Appendix PA, Attachment SOTERM.

Actinide mobility also depends on the formation of colloids. Actinides can either form intrinsic colloids by condensation of hydrolyzed ions, or can be sorbed on to nonradioactive colloidal particles.

TRU WASTE-2.4.1 Components and Characteristics Influencing Solubility

In the absence of MgO, the factors that would most directly affect solubility in the repository are pH, CO_2 fugacity, redox conditions, the availability of complexing agents, and the source and composition of the brine (clearly not a waste characteristic). The important waste components that affect actinide solubility are steel, cellulosic, plastic, rubber, organic ligand, and cementitious materials. Actinide solubility also depends on temperature. However, the

temperature in the repository will remain almost constant (about 300 K) and the thermal effect of exothermal chemical reactions among brine, waste component, and MgO will be negligible (see Appendix WCA, Section WCA-5.3.1 in the CCA and Wang 1996b). Repository pressure does not influence solubility until it is at least an order of magnitude higher than lithostatic pressure and this will not occur (Butcher et al. 1991). The following subsections discuss the influence of waste characteristics and components on each of these factors, as well as those that have little or no influence on solubility.

TRU WASTE-2.4.1.1 Components Influencing Redox Environment

The components of the waste that greatly influence the redox environment in the inundated WIPP repository are steels and biodegradable organic materials (CPR materials). The radionuclides contributing to the brine release source terms are all actinides. Because of their electronic structure, these elements can form a wide variety of inorganic compounds that dissolve in aqueous solutions like brine in several different valence or oxidation states. In the WIPP environment, the solubilities of these compounds can vary from about 10^{-9} Molar (M) to about 10^{-5} M (see Appendix PA, Attachment SOTERM). In general, for both plutonium and the other actinides, the higher oxidation states (V and VI) are more soluble than the lower oxidation states (III and IV). The redox environment determines which of these oxidation states are likely to be stable in solution under WIPP conditions—an important determinant of solubility because of the differences among oxidation states. Although a detailed discussion of the experimental determination of oxidation state distribution is found in Appendix PA, Attachment SOTERM, a brief discussion is given here.

Anoxic conditions will be dominant during the whole time period of 10,000 years. At the time of the CCA, it was believed that anoxic steel corrosion would produce both hydrogen and $Fe(OH)_2$ (see Wang and Brush 1996). A small amount of oxygen, trapped at emplacement, will be used quickly by oxic corrosion and microbial action. Based on recent experimental work (described in Appendix PA, Attachment SOTERM), anoxic corrosion of steel could produce hydrogen, and Fe(II) or Fe(II,III)-bearing corrosion products. It has been shown that both metallic iron and Fe^{2+} ($Fe(OH)_2$) in simulated WIPP brine, under anoxic conditions, will reduce Pu(+VI) stoichiometrically to the much less soluble Pu(+IV). Plutonium (+V) is seen in this chemical reaction as an unstable intermediate. It is expected, therefore, that Pu(+VI) and Pu(+V) will not be stable in solution in WIPP brines. The iron in the drums and waste boxes is enough to provide several thousand-fold excess over what is needed stoichiometrically, even if all the emplaced plutonium existed in the +VI oxidation state. The other metals in the waste may also be able to reduce the actinides, but their effect would be negligible compared to the effect of iron, because they are present in smaller quantities.

The oxidation state distribution used in PA, based on experimental data as well as the published literature, is (Katz et al. 1986; Hobart 1990; Clark et al. 1995; Felmy et al. 1996; Rai and Strickert 1980; Rai et al. 1982; Kim et al. 1985; Pryke and Rees 1987; Nitsche and Edelstein 1985):

thorium: +IV
uranium: +IV and +VI
neptunium: +IV and +V

plutonium: +III and +IV
americium: +III

Curium exhibits essentially the same chemical behavior and oxidation state as americium. In PA, half of the realizations will include the lower oxidation states of uranium, neptunium, and plutonium; the other half will include the higher oxidation states (CCA Appendix SOTERM, Section 4.7; Katz et al. 1986; Weiner 1996).

TRU WASTE-2.4.1.2 Components Influencing pH and CO_2 Fugacity

In the absence of MgO, actinide solubility would be highly dependent on pH and CO_2 fugacity of the brine. Lower pH and higher CO_2 fugacity could result in higher actinide solubility. Original Salado and Castile brines exhibit pH values of about 6 and 7, respectively (Brush 1990, Tables 2-2 and 2-3). The production of CO_2 by microbial degradation in the repository would acidify the brine and lower the brine pH to about 4.5, if no MgO were added (CCA Appendix SOTERM, SOTERM.2). Microbial CO_2 production can be described by the following sequential reactions (Wang and Brush 1996):

$$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow 7.4H_2O + 6CO_2 + 2.4N_2 \quad (3)$$

$$C_6H_{10}O_5 + 6H^+ + 4.8SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S \quad (4)$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CO_2 + 3CH_4 . \quad (5)$$

Nitrate and sulfate are used as electron acceptors in these reactions and determine CO_2 yield per mole of organic carbon. Based on the inventory estimates for nitrate and sulfate, over 94% (see Appendix BARRIERS) of organic materials (CPR materials) would be biodegraded via the third reaction, methanogenesis, in which one mole of organic carbon will produce one half of a mole each of CO_2 and CH_4.

Based on the inventory estimate for organic carbon (Appendix DATA, Attachment F) and the estimated CO_2 yield per mole of organic carbon, to mitigate the negative effect of microbially produced CO_2, 1.41×10^9 moles of MgO will be added to the repository (see Appendix BARRIERS). At the time of the CCA, it was estimated that 2×10^9 moles of MgO would be required. However, as discussed below, DOE's understanding of the chemical interaction of MgO and components of the waste has evolved.

In the CCA, the waste components of organic carbon, nitrate, and sulfate were used to determine the amount of MgO needed. It was stated that hydrated MgO would react with CO_2:

$$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O. \quad (6)$$

The above reaction would buffer the pH at approximately 9.4 in Salado brine and 9.9 in Castile brine and CO_2 fugacity at 10^{-7} atm for both brines. Actinide solubility calculated for the brine in equilibrium with $Mg(OH)_2$ and $MgCO_3$ is minimal (CCA Appendix SOTERM, SOTERM.3). Now, however, the quantities of CPR materials, nitrate, and sulfate are used to determine the amount of MgO needed, based on the understanding that hydrated MgO will react with CO_2:

$$5Mg(OH)_2 + 4CO_2 \rightarrow Mg_5(CO_3)_4(OH)_2 + 4H_2O \quad (7)$$

under conditions in which microbial activity produces gas, and

$$Mg(OH)_2 + Ca^{2+} + CO_2 \rightarrow CaCO_3 + Mg^{2+} + H_2O \quad (8)$$

under conditions in which microbial activity does not occur (see Appendix BARRIERS).[2]

The above reactions will buffer pH at approximately 9 in both Salado and Castile brines, and CO_2 fugacity at $10^{-6.2}$ to $10^{-5.5}$ atm for both brines.

Cementitious waste (that contains calcium oxide and/or calcium hydroxide) could also be expected to raise the pH, and the waste is currently estimated to contain a total of about 1.2×10^7 kg cementitious material (Appendix DATA, Attachment F). This amount of cementitious material contains about 9×10^6 moles of $Ca(OH)_2$. However, this amount of $Ca(OH)_2$ would not be enough to affect pH or brine composition significantly. It was shown that $Ca(OH)_2$ could be consumed by reaction with microbial generated CO_2 or with $MgCl_2$ in the Salado brine and thus the repository chemistry would be dominantly controlled by the $Mg(OH)_2$ / Mg CO_3 buffer, rather than the $Ca(OH)_2$ / $CaCO_3$ buffer (CCA, Wang 1996a and Wang 1996c). Because of the additional MgO that will be added, other components of the waste are unlikely to affect the pH.

TRU WASTE-2.4.1.3 Waste Components That Directly Enhance Solubility

A number of organic compounds are capable of forming strong complexes with actinide ions, thereby stabilizing the actinide in the solution. Of the about 60 organic compounds in the waste (Drez and James-Lipponer 1989; Brush 1990; Drez 1996), 4 of these (acetate, citrate, oxalate, and ethylene diamine tetra-acetate [EDTA]) have been identified to have an effect on actinide mobility, because they are water-soluble and present in significant quantities (Appendix DATA, Attachment F).

. Ligand concentrations in the repository were calculated by dividing the current mass of each ligand in the inventory by the brine volume of 29,841 m3, “the smallest quantity of brine required to be in the repository [for] transport away from the repository (Larson, 1996). The effect of these organic ligands on the solubility of actinides in both Salado and Castile brines has been studied, and is discussed in detail in Appendix PA, Attachment SOTERM.

To estimate the effectiveness of other metals in binding organic ligands and thereby reducing the free ligand concentrations, some simple competition calculations were performed (for the CCA) using parameters obtained in dilute solutions, because parameters for concentrated salt solutions like the WIPP brines were not available. These metal species included iron (Fe), nickel (Ni), chromium (Cr), vanadium (V), and manganese (Mn), because the steels used for the waste drums contain on average at least 0.001 weight percent of Ni, Cr, V, and Mn as minor constituents. Based on at least 1.9×10^9 moles of steels destined to be disposed of in the WIPP, there should

[2] The conceptual model for the repository maintains a probability of significant microbial degradation of CPR materials of 0.5. Thus, there is no microbial activity and concomitant gas generation in about half of the PA vectors (Brush and Xiong 2003a; 2003b).

be at least 1×10^4 moles of each of Ni, Cr, V, and Mn in the repository (CCA Appendix SOTERM). There are also expected to be more than 6×10^7 moles of lead (Pb). Additionally, several other metals that can sequester organic ligands will be present in small quantities.

Table TRU WASTE-11 presents complexation constants for several metals with EDTA. These values were measured in dilute solution. For comparison, for EDTA in 5 molal (moles of solute per kilogram of solvent) NaCl, the magnesium association constant is log K_{Mg} = 6.6 (Martell and Smith 1982).

Table TRU WASTE-11. Complexation Constants for Selected Metals[1]

Species	log K
Fe^{2+}	14.3
Cr^{2+}	13.6
Ni^{2+}	18.4
Mn^{2+}	13.9
V^{2+}	12.7
Cu^{2+}	18.9
Pb^{2+}	18

[1] From Martell and Smith (1982).

To assess the ability of these metals to sequester the organic ligands, the calculations for competition between these metals and actinides for organic ligands were performed by the DOE. The calculation results show that under expected WIPP conditions, 99.8% of the EDTA was complexed by Ni, effectively rendering it unavailable for complexation with the actinides (CCA, Appendix SOTERM).

TRU WASTE-2.4.2 Components and Characteristics Influencing Colloidal Actinide Mobility

The waste components that directly contribute to actinide colloid formation include mineral fragments, and humic substances (soil). CPR materials can contribute to the quantity of humic colloids. Actinides can form intrinsic colloids or can be sorbed on to nonradioactive colloidal particles. A complete discussion of colloid formation in the WIPP can be found in CCA Appendix SOTERM and Papenguth (1996a through 1996e). A summary of that discussion follows.

In principle, intrinsic colloids are formed by condensation (or polymerization) of hydrolyzed actinide ions. Examples of polymeric species of many of the actinides of importance to the WIPP have been found in the literature (see Papenguth and Behl (1996) for an extensive literature review). However, except for Pu, the intrinsic colloids of other actinides (Am, U, Th, and Np) do not develop to sizes large enough to affect transport behavior of these actinides relative to their dissolved form. Therefore, the intrinsic colloid concentrations for Am, U, Th, and Np are modeled as zero in the disposal room and only intrinsic plutonium colloids have any impact on performance. Plutonium(IV) readily forms an intrinsic colloid; evidence suggests that

the initial polymerization, or condensation, of hydrolyzed Pu(IV) produces a macromolecule that becomes progressively more crystalline with time. As the Pu polyelectrolytes mature, they are expected to be kinetically destabilized and immobilized by the high ionic strength of the WIPP brines, then coagulate and settle out of solution.

Within the repository, mineral fragment colloids could form from corrosion of iron-bearing waste, soils, and portland cement-based matrices. Because a wide range of mineralogies with different sorptive behavior are present at the WIPP, a bounding approach is used to estimate the maximum concentration of actinides bound to mineral fragment colloids. Mineral fragments are expected to be kinetically destabilized in the high-ionic strength brines present in the disposal room. Experimental information, combined with a conservative estimate of adsorption site density, provided a most likely value of 2.6×10^{-9} mole of colloidal mineral-fragment-bound actinides per liter of dispersion; the experimental results were increased by a factor of two to account for the possibility that the indigenous mineral fragment colloids in the Culebra could sorb dissolved actinides. This value is presumed to be the same for all five key actinides. Although mineral fragments contribute to actinide mobility and are included in PA, their contribution is negligible and they do not impact repository performance (see Appendix PA).

Humic colloids will be present in the repository, both (a) in soil and humic material that is part of the emplaced waste and (b) in colloids that will be formed if the CPR materials in the waste are microbially degraded. The contribution of humic colloids to repository performance is therefore calculated by quantifying humic-actinide complexation coupled with solubilities of humic substances in WIPP brines, and expressing the result as the ratio of moles of humic-bound actinide to moles of dissolved actinide. The range of ratios is from about 4.3×10^{-4} to about 6.3 in Castile brine and from about 5.3×10^{-5} to about 6.3 in Salado brine.

To compute the concentration of actinides bound to humic substances, several parameters, such as solubility of humic substances, site binding capacity, actinide complexation factors, and stability constants, were measured or obtained from published literature (Papenguth 1996c). The oxidation state analogy was also used to develop parameter values for actinides expected to have multiple oxidation states in the WIPP disposal rooms. In addition, the theoretical maximum concentration of actinides that can be bound to humic substances was also computed and found to be 1.1×10^{-5} M.

The other major source of colloidal material in the repository is the microbes themselves, though they are not necessarily waste components. Microbes are known to actively bioaccumulate actinides intercellularly, as well as act as substrates for passive extracellular sorption. Naturally occurring halophilic and halotolerant microbes have been observed in the Salado brines at the WIPP site (Brush 1990 and Francis and Gillow 1994). The waste material in the disposal room would serve as a nutrient and substrate for microbes, and consequently increase the microbe population, making them potentially important to actinide mobility.

The uptake of actinides by microbes and humic substances is quantified through two parameters for each actinide and substrate: proportionality constants (with PA parameter designations PROPMIC, PHUMSIM, and PHUMCIM) that describe the amount of each actinide bound to mobile microbes and humic colloids, respectively; and the maximum concentrations (CAPMIC and CAPHUM) of each actinide associated with mobile microbes and humics, respectively. As

discussed above, the concentrations of mineral-fragment-bound actinides and intrinsic actinides are very small, and are presented as concentrations (CONCMIN and CONCINT) only. A series of bioaccumulation and toxicity experiments were performed to obtain the following values of PA parameters for each actinide shown in Table TRU WASTE-12.

Table TRU WASTE-12. Colloid Concentration Factors

	Concentration on Mineral Fragments[1]	Concentration as Intrinsic Colloid[1]	Proportion Sorbed on Microbes[2]	Maximum Sorbed on Microbes[1]	Proportion Sorbed on Humics[2]		Maximum Sorbed on Humics[1]
					Salado	Castile	
Th	2.6×10^{-8}	0.0	3.1	0.0019	6.3	6.3	1.1×10^{-5}
U(IV)	2.6×10^{-8}	0.0	0.0021	0.0023	6.3	6.3	1.1×10^{-5}
U(VI)	2.6×10^{-8}	0.0	0.0021	0.0023	0.12	0.51	1.1×10^{-5}
Np(IV)	2.6×10^{-8}	0.0	12.0	0.0027	6.3	6.3	1.1×10^{-5}
Np(V)	2.6×10^{-8}	0.0	12.0	0.0027	9.1×10^{-4}	7.1×10^{-3}	1.1×10^{-5}
Pu(III)	2.6×10^{-8}	0.0	0.3	6.8×10^{-5}	0.19	1.1	1.1×10^{-5}
Pu(IV)	2.6×10^{-8}	1.0×10^{-9}	0.3	6.8×10^{-5}	6.3	6.3	1.1×10^{-5}
Am	2.6×10^{-8}	0.0	3.6	NA	0.19	1.1	1.1×10^{-5}

[1] in units of moles total mobile actinide per liter
[2] in units of moles microbial actinide per moles dissolved actinide

As evident in Table TRU WASTE-12, microbial colloids can transport concentrations of actinides that are several multiples of the dissolved concentration, and thus increase the potential for actinide mobility considerably. Humic colloids are waste components, and microbial colloids increase in quantity as they metabolize waste components. Both types of colloids are incorporated in PA (details are discussed in Appendix PA) and are expected to affect disposal system performance.

The treatment of colloids in CRA-2004 is like that of the CCA. The only difference between the CCA colloid assumptions and values and CRA-2004 colloid assumptions and values is in relation to the microbial colloids. In the CCA, microbial colloids were present in all calculations as described above. For CRA-2004, in the absence of microbes (PA assumes that microbes are present in only 50 percent of the calculations), microbial colloids are not included in the calculations.

TRU WASTE-2.5 Nonradioactive Waste Components and Characteristics

TRU WASTE-2.5.1 Gas Generation

The waste components that contribute to gas generation are: (a) ferrous and nonferrous metal, (b) CPR materials, and (c) nitrate and sulfate. Water content of the waste also contributes to the generation of gas. The mechanisms and reactions for gas generation are discussed in Wang and Brush 1996.

Metal can contribute to gas generation through corrosion. The anoxic corrosion reaction of iron is:

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2(g) \quad (9)$$

The hydrogen gas produced by this reaction contributes to total gas pressure, but does not affect repository chemistry. In addition, steel corrosion is likely to consume water in the repository; this effect is taken into account in the computer code BRAGFLO. Nonferrous metals such as aluminum alloys can also corrode, producing H_2, but their contribution to total gas pressure is negligible, because they are present in much smaller quantities than iron (Appendix DATA, Attachment F).

CPR materials and nitrate and sulfate control microbial gas generation. CPR materials can be used as substrates by anaerobic microbes in the WIPP. Nitrate and sulfate can be used as electron acceptors by microbes to oxidize the organic materials. Organic materials are likely to be biodegraded through reactions:

$$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow + 7.4H_2O + 6CO_2 + 2.4N_2(g) \quad (10)$$

$$C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S(g) \quad (11)$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4(g) + 3CO_2(g) \quad (12)$$

The above reactions will proceed sequentially according to the energy yield per mole of carbon in each reaction. Based on the inventory estimates for nitrate and sulfate, the third reaction is expected to be dominant. Because the CO_2 produced by these reactions will be removed by reaction with MgO, methane is the primary, microbially generated gas that will contribute to the total gas in the repository.

Phosphate in the waste may enhance microbial activity in the repository. The rates of cellulosic material biodegradation used in PA are derived from the incubation experiments amended with nutrients including phosphate. Thus, the effect of phosphate on microbial reactions is captured indirectly in the parameters submitted to PA (Francis and Gillow 1994).

Based on the inventories of steels and organic materials and the rates of gas generation estimated, microbially produced gases may dominate early in the repository's history. Gas pressure can affect repository performance. Pressure in the repository may approach lithostatic, initiating or propagating fractures within the interbeds, and clay seams in the Salado. Gas pressure will not exceed lithostatic (Butcher et al. 1991) because gas can leak out through the interbeds.

Gas pressure is incorporated into PA through parameters in BRAGFLO calculations.

The initial water content of the waste also contributes to the generation of gas because it defines how much brine is immediately available for the corrosion reaction. All of the liquid in the waste is assumed to be aqueous with no volume correction. A mean value of 0.06 percent is assumed in PA for the initial free unbound water saturation of the waste, based on waste

characterization data and transportation restrictions on the amount of free liquid that the waste can contain (Appendix PAR, Table PAR-39 in the CCA).

Materials such as dry portland cement, vermiculite, and other sorbents have intentionally been added to the waste to absorb any excess water that may be present. Sorbed water is much less readily available than any brine available from the surrounding rock. Therefore, the effect of initial water content on gas generation is negligible.

TRU WASTE-2.5.2 Components and Characteristics Influencing Physical Properties

As noted in Tables TRU WASTE-4 and TRU WASTE-5, the following physical properties of the solid waste components are used in PA:

Compressibility: This property is a measure of deformational stress-strain response of the waste material. The response of the waste is modeled to represent the conventional 55-gallon drums, pipe overpack configurations, and the supercompacted waste.

Strength: Strength of the waste is only of concern in the highly degraded state. Strength properties enter directly into PA human intrusion scenarios, whereby a driller inadvertently intersects a repository room. If high pressures exist in the disposal room, a pressure gradient pulse could induce tensile failure and transport of waste particulate into the wellbore—the spalling event. In addition, the drill bit and drilling fluid circulate in the advancing wellbore and set up fluid shear stress in the degraded waste. The effects of waste strength on room closure are included in the discussion of compressibility.

Porosity: Initial porosity of the waste room is modified by salt creep. The waste inventory establishes the initial porosity as well as mechanical resistance to the impinging salt. Waste porosity is directly incorporated into the PA via a porosity surface.

Permeability: Permeability controls movement of fluids in the waste rooms, and therefore is an important parameter for the Salado fluid flow calculations. Permeability is also a key consideration within the human intrusion conceptual model, as it enters into the calculations of material transport to well bore.

TRU WASTE-2.5.2.1 <u>Compressibility</u>

An important characteristic of the WIPP repository is the closure of the disposal rooms over time due to the creep response of the surrounding salt in response to the presence of the mined openings. This ability of salt to deform with time, eliminate voids, and create an impermeable salt barrier around waste is one of the principal reasons for locating the WIPP repository in a bedded salt formation, as suggested by the National Academy of Sciences (NAS-NRC 1957). This closure process is rather complex, and the rate at which it occurs depends in large part on the balance of forces tending to close the repository (the far-field lithostatic stresses) and those resisting the closure. These resisting forces are the tendency of the waste to resist deformation, measured in terms of its compressibility, and the effect of any gas pressure within the rooms.

At the time of the CCA, the compressibility of the waste was determined from laboratory experiments on 55-gallon drums (Butcher et al. 1991). Waste containers other than the 55-gallon

drum package have been delivered to WIPP and other forms, such as supercompacted waste, are anticipated to be sent. Therefore, the response model incorporated into the CRA-2004 calculations was enhanced to account for a range of structural responses. Updated coefficients developed for the volumetric plasticity model were based on modeling analysis of other waste forms (Weatherby et al. 1991; Park and Hansen 2003). The wastes were characterized by their general structural form, which predominantly depends on the packaging. Appendix PA describes the calculations that were used to evaluate the competing conditions of creep closure, waste rigidity, and gas generation to yield porosity histories that are compiled into a porosity surface for incorporation into PA calculations.

TRU WASTE-2.5.2.2 Strength

Shear and tensile strength are important parameters in the models for cavings and spallings releases, respectively. It is likely that alternative waste forms, such as the pipe overpacks and the supercompacted wastes, will be less likely to degrade and corrode than standard waste forms, and as such their mechanical strengths may be expected to be equal to or higher than standard waste.

Degraded material property estimates were recently summarized for the spallings model peer review (Hansen et al. 2003). The authors assert that degraded waste properties determined for the new spall model, DRSPALL, represent extreme bounds of the future possible states of the waste because strengthening processes are not included in the minimal shear and tensile strength properties determined for surrogate degraded waste. It is likely that the new waste forms, such as the pipe overpacks, would render the waste less vulnerable to collapse and more resistant to massive corrosion.

Shear Strength. The shear strength implemented in PA is used to calculate the volume of cavings release, hence, it is a measure of erosional shear resistance. In the CCA, the waste shear strength was sampled from a uniform distribution from 0.05 to 10 Pascal (Pa) Pa, which is conservatively based on properties of marine clays (Appendix PA, Attachment MASS, Table MASS-1). For the PAVT, the waste shear strength was estimated based on particle size distribution determined by an expert elicitation panel. With this approach, the calculated critical shear strength ranged from 0.64 to 77 Pa. The EPA then retained the original lowest value and assigned a log-uniform distribution ranging from 0.05 to 77 Pa. Based on work by Jepsen et al. (1998), the lower value of 0.05 Pa is considered to be extremely conservative. Using the 50 percent degraded waste surrogates that represent the extreme possibilities for degradation of the WIPP waste (Hansen et al. 1997, Hansen et al. 2003), an average critical shear strength of 1.4 Pa was determined. The minimal critical shear strength could approach this measured value only if massive degradation of waste ensues and no cementation or compaction of degraded waste occurs. The current minimum value sampled for the waste shear strength is thus at least 30 times smaller than the minimum value supported by empirical data.

Tensile Strength. Tensile strength is used in the calculation of spall volumes following a drilling intrusion. In the CCA, spall volumes were computed by a model of gas flow through fractures. Tensile strength entered the calculation of spall volumes by defining an effective gravity coefficient, which resisted particle mobilization in the flowing gas. The CCA calculations used a constant tensile strength of 0.0069 megapascal (MPa) (1 psi) (Helton et al. 1998). In response to

EPA's review of the CCA, a new mechanistic model for spallings was developed in which gas flow in the waste may induce tensile failure of the waste material, and thus lead to spallings. The mechanistic model, called DRSPALL, served as the basis for a replacement for the CCA spallings model. In support of DRSPALL, a separate analysis determined an appropriate distribution for tensile strength would range from 0.12 MPa to 0.17 MPa (Hansen et al. 2003).

The range of tensile strength reported by Hansen et al. (2003) assumes that the waste is a weakly consolidated particulate material, representing an extreme case of waste degradation. The characteristics of the more robust waste forms (supercompacted and pipe overpack waste) would tend to less degradation, so the tensile strength of these waste forms would certainly be greater than the minimal values currently used in DRSPALL (Hansen et al. 2003). Therefore, the current range of tensile strength proposed for the DRSPALL model and for the CRA-2004 is conservative.

TRU WASTE-2.5.2.3 Permeability

The likely mechanical and physical form of the supercompacted and pipe overpack wastes over time indicates that the permeability of these waste forms will be at least as great as that of standard waste, and may be higher.

In the CCA, the waste permeability was assigned a value of 1.7×10^{-13} m^2 (Butcher 1996) based on the value used in the 1991 PA. The 1991 PA value was a composite value based on the relative quantities of three different types of materials (combustible, metals/glass, and sludges) each with an inherent range of permeabilities, which had previously been determined for compressed surrogate wastes (Luker et al. 1990). In their review of the data used in the CCA, the EPA recalculated this value as 2.4×10^{-13} m^2, although they conceded that the difference was small enough to be inconsequential (EPA 1997). This revised value is being used in the current PA calculations.

A constant value for permeability is used in PA, even though it is expected that there will be some variability in this parameter. The reason for this single value being acceptable is primarily because this permeability value is much higher than the surrounding salt and the disturbed rock zone, as discussed in 1991 PA. In addition, the coefficient of variation for the uncertainty in measured permeabilities is too small to justify treating waste permeability as an uncertain parameter (Rechard and Tierney 2003). Finally, Vaughn et al. (1995) discuss whether permeability should be a function of porosity, since porosity is treated as a time-varying quantity in BRAGFLO while permeability is a constant. Their analysis concluded that including a dynamic model for permeability had an insignificant effect on waste room conditions (pressure and saturation), and an insignificant effect on resulting releases.

Waste Permeability of the New Waste Forms. The underlying assumption with respect to the new waste forms is that the pipe overpacks and supercompacted wastes will be more durable than the original baseline package of the 55-gallon drum. The rigidity of the waste and its packaging, such as the pipe overpack and supercompacted waste, tends to hold the room open and preserve the structural integrity of the waste stack. The logical evolution involved with disposal of a more rigid and armored waste package would be preservation of a large portion of the waste in its original, intact form as it will deform only modestly as compared to the standard

waste form. Thus, the architecture of the waste comprises bulky, compressed steel containers that envelope the waste, and the rigid structure would tend to maintain the open channels between individual drums and packages, so that much of the original porosity inherent in the three-dimensional disposal configuration would be preserved. Permeability of this future state of the waste would tend to be high relative to the values implemented in the CCA and PAVT. This conclusion is reinforced by the results of the porosity surface calculations, which show that in the absence of gas generation the long-term porosity of the supercompacted and pipe overpack wastes is considerably higher than for standard waste, while with high gas generation rates the porosities are essentially the same (Park and Hansen 2003).

Waste Permeability in Process Models. Other conclusions can be drawn about the possible effects of waste heterogeneity on brine and gas flow in the repository. Vaughn et al. (1995, DR6) discuss how heterogeneity in the waste may cause flow to follow channels or preferential paths, and result in spatially varying saturations referred to as "puddling." Their analysis demonstrated that inclusion of puddling in the BRAGFLO model had an insignificant effect on waste room conditions (pressure and saturation), and an insignificant effect on resulting releases.

Waste Permeability in Direct Release Models. Waste permeability can affect the models for spallings and for direct brine releases. A pertinent study of the effects of spatially variable waste permeability was conducted as part of the spalling model investigations reported in Hansen et al. 1997. Calculations of gas flow through the porous waste regions were conducted to evaluate the influence of model assumptions on the predicted two-phase pressure response of the disposal rooms during a drilling intrusion. Results of the modeling indicated that the effect of waste heterogeneity is to reduce the pore pressure gradient close to the intruded wellbore; because this gradient is the major cause of tensile failure, any possible spall volumes are reduced.

TRU WASTE-2.5.3 Components and Characteristics Affecting Heat Generation

Heat generation is a characteristic of some components of the waste, or of their interactions. The WIPP includes two possibly significant sources of heat: the heat generated by RH-TRU waste (DOE 1995), and the heat generated by MgO hydration and carbonation, aluminum corrosion, cement hydration, and organic biodegradation.

TRU WASTE-2.5.3.1 Exothermal Reactions

MgO hydration and carbonation, aluminum corrosion, cement hydration, and organic biodegradation are all exothermal reactions. Evaluation of the ability of each of these reactions to produce heat while conservatively accounting for the repository's ability to dissipate the resulting heat generated has provided the following maximum temperature increases (Wang 1996d and Appendix PA, Attachment SCR), as shown in Table TRU WASTE-13:

Table TRU WASTE-13. Maximum Temperature Increases

Reaction Number	Maximum Temperature Increase (K)
MgO hydration	4.7
MgO carbonation	0.7
Cement hydration	2.5
Microbial degradation	1.4
Aluminum corrosion	6.8

In the worst case, a temperature increase of 6.8 K could be experienced (Appendix PA, Attachment SCR). However, these temperature extremes will not persist, if they are ever reached at all. Because all but one reaction consume brine, possible reactions will be competing with each other for what brine may enter the repository and will therefore temper the heat increase that could be predicted based on the most exothermic reaction alone. To evaluate the worst case possible, for the maximum temperature increase to be realized from the corrosion of aluminum, all of the aluminum would have to be corroded within 2.5 years, after which the heat would be dissipated very rapidly. Therefore, if such a condition were to be created, it would be transitory on the repository time scale and its influence inconsequential.

The effect of small temperature increases arising from exothermal reactions was previously screened out of the PA on the basis of low consequence to factors such as creep closure, seal performance, transport, etc. (see Appendix PA, Attachment SCR). The effect of heat generated by radiolysis has been considered as part of the repository conditions (Brush 1990) and utilized in the specification of experimental parameters, thus yielding data consistent with the anticipated conditions. Additionally, the small temperature increases cited above for exothermic reactions are insignificant to the thermodynamic modeling of solubility. For example, a temperature increase of 7ºK would result in an approximately three percent change in the free energy of formation of any species contained within the model. This value is well within the model parameter bounds.

TRU WASTE-2.5.3.2 RH-TRU Thermal Heat Load

The “worst case” heat load from RH-TRU emplaced in the WIPP is estimated to be between 47 and 54 watts per cubic meter, which would result in a temperature rise near the canister of between 1.87ºK and 2.09 K (2.85 – 3.19 K in the CCA). The expected WIPP average temperature increase from RH-TRU heat loading is between 0.23 K and 0.29 K (0.38 – 0.49 K in the CCA). The RH-TRU thermal heat load is small enough that there is no impact on repository performance. A more complete discussion and analysis is given in Djordjevic (2003) and Appendix PA, Attachment SCR.

TRU WASTE-2.6 Summary

The waste characteristics and components expected to be most significant to performance are the predominant radionuclides and those characteristics and components affecting actinide mobility.

The waste characteristics and components expected to be significant to performance are summarized in Table TRU WASTE-14.

It should be noted that these components and characteristics have both positive and negative effects on performance. Iron has a beneficial effect because it reduces actinides to lower, less soluble oxidation states. Nonferrous metals are beneficial because they compete with the actinides for the binding sites on organic ligands, thereby reducing the solubilities of the actinides. Mobility enhancers like colloidal substrates, on the other hand, have a detrimental effect. Gas buildup can both enhance and detract from repository performance. Although gas can open fractures, it can also keep brine from entering the repository, thereby reducing transport of soluble actinides (SNL 1991).

Table TRU WASTE-15 summarizes those characteristics and components with an insignificant impact on performance.

Table TRU WASTE-14. Waste Characteristics and Components Expected to be Most Significant to Performance

Component	Characteristic	Reason for Significance
^{239}Pu, ^{240}Pu, ^{241}Am, ^{233}U, and ^{234}U	Activity	99 percent of EPA unit after 2,000 years
^{238}Pu	Activity	Dominates EPA Unit at early times
Pu and Am	Solubility	Large EPA Unit; mobility depends on solubility
^{238}U	Activity	Very low activity; dilutes Higher-Activity Uranium Isotopes For Brine-Based Releases
Iron	Corrosion	1. Maintains reducing environment; lower, less soluble oxidation states of actinides predominate 2. Corrosion produces hydrogen, increasing gas pressure
CPR Materials, Nitrate, Sulfate	Nutrient for microbes	Microbial nutrients are metabolized to methane and other gases, increasing gas pressure; formation of colloids
Humic Materials, Cellulosic Materials breakdown products	Colloid formation	Form humic colloids that sorb and transport actinides
Organic Complexation	Nonferrous metals	Reduce actinide solubilities by competing with the actinides for the binding sites on organic ligands.
Tensile and Shear strength	Waste strength	Important to spalling and cavings

Table TRU WASTE-15. Waste Characteristics and Components Expected to be Not Significant

Characteristics/Component	Reason for insignificant impact
Radionuclides (other than those in Table TRU WASTE-14)	EPA Unit is negligible fraction of total, even with ingrowth
Substances that may affect pH[1]	pH is buffered by MgO
Substances that produce CO_2[1]	CO_2 is removed by reaction with MgO
Intrinsic and mineral fragment colloids	Fraction of actinides mobilized by these colloids is insignificant
Organic ligands	Removed by binding with Mg and nonferrous metal
Heat generated by exothermic reactions	Temperature rise is negligible; heats of formation are very small paired with a large thermal mass of the repository
Fluid in the waste	Negligible compared to brine volume

[1] These components are significant for gas generation, but not for actinide solubility.

TRU WASTE-3.0 WASTE COMPONENTS LIMITS

The objective of this section is to satisfy the requirements specified in 40 CFR.194(c)(1) as stated in Section TRU WASTE-1.1.

This section updates Appendix WCL in the CCA by presenting the rationale for the upper and lower limits for waste components identified as potentially significant to disposal system performance (Table TRU WASTE-4). The sensitivity analysis in Appendix PA supports the conclusions that the disposal system performance is not sensitive to most properties of the emplaced waste and limits remain unnecessary for the components identified in Tables TRU WASTE-5 and TRU WASTE-6.

Table TRU WASTE-16 shows:

- Waste components listed as potentially significant in Table TRU WASTE-4,
- Waste characteristics these components influence,
- Constituents of the components for which assaying during emplacement is required, and
- Limits for emplacement of each component, if necessary.

This table illustrates that most components, associated characteristics, assay requirements, and emplacement limits have not changed since the CCA. The following discussion provides the rationale for the proposed assaying and emplacement limits for each component listed in Table TRU WASTE-16. All of the components listed in Tables TRU WASTE-5, TRU WASTE-6 and TRU WASTE-15 were found to be insignificant to disposal system performance, as was true for the CCA. Therefore, it is not necessary to establish emplacement limits for them other than limits based on the current TRU waste inventory or imposed on waste through limitations in the Contact Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant (DOE 2002a).

The emplacement limits identified in Table TRU WASTE-16 provide an envelope of fixed inventory values on a repository scale, without an associated uncertainty. That is, the limiting values are imposed to ensure compliance, and in fact represent the upper “end” of an uncertain range. To ensure these waste component limits are not exceeded, inventory quantities and uncertainty in those quantities will be tracked during the operational phase of the repository. This tracking is accomplished using the WWIS. If inventory estimates change over the operational life of the WIPP, new inventory estimates will be used in PA and revised limits for waste components will be developed based on the PA results in a future recertification application.

TRU WASTE-3.1 Radionuclide Components

As discussed in Section TRU WASTE-2.3, the following radionuclides have activities greater than one EPA unit at closure: ^{241}Am, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{233}U, ^{234}U, ^{90}Sr, and ^{137}Cs.

Table TRU WASTE-16. Emplacement Limits for Waste Components

Components	Associated Characteristics	Constituent Components Requiring Assaying	Emplacement Limits
Radionuclides	Radioactivity at closure Radioactivity after closure Solubility Colloid formation Redox state	^{241}Am ^{238}Pu ^{239}Pu ^{240}Pu ^{242}Pu ^{233}U ^{234}U ^{238}U ^{90}Sr ^{137}Cs	none[1]
Ferrous metals (iron)	Redox potential H_2 gas generation complexing with organic ligands	None	Minimum = 2.0×10^7 kg (amount from containers)[2]
CPR materials	Gas generation Humic colloids (see below)	Sum	Maximum = 2.2×10^7 kg[3]
Sulfates	Gas generation	None	None[4]
Nitrates	Gas generation	None	None[4]
Solid components	Particle size Effective shear resistance to erosion Tensile strength	None	None
Free water emplaced with waste	Gas generation	None	Maximum = 1684 m^3 (limit of one percent total waste volume as set by the WAC)[5]
Humic substances	Radionuclide-bearing humic colloids	None	None
Nonferrous metals (metals other than iron)	Reduce actinide solubilities by competing with the actinides for the binding sites on organic ligands.	None	Minimum = 2.0×10^3 kg[6]
Organic ligands	Solubility	None	None[4]

[1] Inventory curie content will be tracked.
[2] Minimum sets to ensure sufficient reactants for reducing radionuclides to lower and less soluble oxidation states.
[3] Maximum set to ensure sufficient MgO is available to react with CO_2 produced.
[4] For the current waste generation processes that are documented in Appendix DATA.
[5] One percent of the design basis values for CH-TRU of 168,485 m^3.
[6] Minimum quantity for complexing with organic ligands (see Appendix PA, Attachment SOTERM).

The total activity of the waste at emplacement and during the entire 10,000-year performance period is dominated by the activities of four emplaced radionuclides: ^{241}Am, ^{238}Pu, ^{239}Pu, and ^{240}Pu. The radionuclides, ^{242}Pu, ^{233}U and ^{234}U, have significantly less total activity than the other Am and Pu components, but since their activities exceed one EPA unit they are not excluded from assaying requirements. The ^{238}U component is to be assayed as well, because its large mass fraction and low activity dilutes the overall activity of transported uranium species. The ^{90}Sr and ^{137}Cs components can contribute to direct releases at the surface resulting from inadvertent intrusion during the first several hundred years or so after closure.

Because of radioactive decay and ingrowth, the major contributors to the overall activity of the repository among these radionuclides change during 10,000 years. For the first several hundred years, ^{241}Am, ^{238}Pu, ^{239}Pu, and ^{240}Pu are important contributors to the total activity of the waste. At the present and projected inventory level, ^{90}Sr and ^{137}Cs may be important for about 200 years. The ^{241}Am component continues to be important for about 3,000 years. At 10,000 years, ^{239}Pu and ^{240}Pu remain as the only significant contributors to the total activity of the waste. Because the activities of these radionuclides in existing and projected waste overwhelmingly exceed the activities of all other radionuclides combined, they are the most important for repository performance modeling.

The total activity of the waste is not important for compliance with the criteria at 40 CFR § 194.24(c) because the containment requirements are normalized to the initial inventory. However, the PA is sensitive to relative changes in inventory curie content as a function of radionuclide decay and ingrowth over time. The magnitude of change in the total curie content depends on the initial ratios of the total activities of the assayed radionuclides at the time of repository closure. Accordingly, the results of the PA are conditional on the initial ratios in the inventory. The criteria in 40 CFR § 194.15(a)(5) state that:

> In submitting documentation of continued compliance pursuant to section 8(f) of the WIPP LWA,….. Updated documentation shall include:… A description of all waste emplaced in the disposal system since the most recent compliance certification or recertification application.

The PA for this and future recertifications must therefore incorporate the adjusted inventory curie content reflecting any significant changes relative to projected values for the important radioisotopes (plus ^{238}U) that are being accumulated. At repository closure, the ratios of the activities of the ten listed radionuclides (Table TRU WASTE-15) may or may not be similar to those ratios used in this assessment, but compliance with the containment requirements of 40 CFR §191.13 will be maintained for the full capacity of emplaced waste at the WIPP.

TRU WASTE-3.2 Ferrous and Ferrous Alloy Components

Ferrous and ferrous-alloy metal components in the waste have two significant effects on the repository. Ferrous and ferrous-alloy metal may corrode, thus creating gas, and they provide reducing conditions in the repository (see Section TRU WASTE-2.4.1).

The results of the CRA-2004 PA demonstrate that total normalized release from the repository is relatively insensitive to gas generation by corrosion. As shown in Figures PA-97 through PA-99 in Appendix PA, at probabilities greater than 0.01, total normalized release is dominated by cuttings and cavings releases. The cuttings and cavings release mechanism is completely independent of repository hydrologic conditions, such as gas pressure or brine saturation, at the time of the intrusion. This independence from repository pressure leads to the conclusion that total normalized release will be insensitive to gas generation. The other two direct release mechanisms for the CRA-2004 PA, spallings and direct brine release, are dependent on the quantity of gas generated. These two release mechanisms occur only if the pressure in the repository exceeds 8 MPa (Appendix PA, Sections PA.4.6 and PA.4.7.1). This pressure (8 MPa) corresponds to the hydrostatic pressure at the repository depth in a column of drilling mud.

The waste inventory contains sufficient ferrous and ferrous-alloy components that gas could be generated sufficiently in excess of that required to reach 8 MPa in the repository. In fact, there is always an excess of ferrous and ferrous-alloy metals, in the sense that the inventory of these metals is never depleted in any of the 300 realizations for the CRA-2004 PA (Stein and Zelinski 2003b). In this situation, PA already uses an extreme value for the mass of ferrous and ferrous-alloy metals, so that a maximum value for the mass of ferrous and ferrous-alloy metals would be extraneous (have no impact) on PA.

In summary, the dominance of the cuttings/cavings mechanism for total normalized release, and the excess mass of ferrous and ferrous-alloy metals in the initial inventory imply that it is unnecessary to place restrictions on the quantity of ferrous and ferrous-alloy metals emplaced for the purpose of controlling the quantity of gas generated.

On the other hand, ferrous and ferrous-alloy metals (and their corrosion products) provide the reactants that reduce radionuclides to lower and less-soluble oxidation states. As discussed in Section TRU WASTE-2.4.1.1, the anticipated quantity of these metals, principally from waste containers, to be emplaced in the WIPP is orders of magnitude in excess of the quantity required to assure reducing conditions. Therefore, no upper or lower limit need be established for the quantity of ferrous and ferrous-alloy metals that may be emplaced, beyond the CCA projection of the ferrous and ferrous-alloy metals in the waste containers.

TRU WASTE-3.3 CPR Materials, Nitrate, and Sulfate Components

The CPR materials, nitrate, and sulfate components of the waste influence the production of CH_4 gas in the repository by microbial action. Although the PA assigns a probability of 0.5 that microbial degradation will produce significant quantities of gas, the lower limit for these materials is effectively zero. As discussed in the preceding section, releases are dominated by cuttings/cavings, which is independent of repository pressure at the time of the intrusion. In addition, direct brine release and spallings are not sensitive to the quantity of gas generated, and the inventory of ferrous and ferrous-alloy metals is in excess of that required to produce a significant amount of gas (pressures of 8 MPa, or greater). Therefore, the additional components influencing microbial degradation have negligible impact on performance, and it is unnecessary, with respect to gas generation, to assign an upper limit on the amount of these materials that may be emplaced in the repository.

However, an upper limit on the total amount of CPR materials is still necessary to ensure that the amount of emplaced MgO is adequate. The current waste inventory indicates that there will be 2.19×10^7 kg of CPR materials disposed in WIPP. Since the amount of MgO currently projected for the WIPP is greater than the amount needed to react with the CO_2, the upper limit for CPR materials is set to 2.2×10^7 kg. Additional information on the safety factor for MgO relative to the emplaced mass of CPR materials is provided in Appendix BARRIERS-2.5.

TRU WASTE-3.4 Solid Components

Solid components in the waste affect the waste characteristics of effective shear resistance to erosion, particle size, and tensile strength. These properties affect releases from cavings and spallings during a drilling intrusion. The basic conceptualization for the assignment of these

properties is that fully degraded waste will have the least favorable properties, and will eventually be similar to granular materials whose properties can be measured today. The actual properties of the waste over the 10,000-year regulatory period are unknown, since the physical nature of the degraded waste is unknown. For these reasons, the parameter values assigned are chosen to conservatively reflect measured properties of natural and constructed materials.

These properties are reasonable analogs for degraded waste. The effective shear resistance to erosion used to calculate cavings is based on the erodibility of unconsolidated marine clays and other easily eroded materials, and is considered to be near a physical limit for the minimum value of this property (Parameter 58 in Attachment PAR to Appendix PA). The minimum particle size used in the range for the spallings model is based on assuming an average pore diameter consistent with an average waste permeability; this value is considered conservative because waste will not have a uniform distribution of permeability. The larger particles will define the more permeable pathways, along which most gas will flow during a spalling event, and larger particles are less likely to spall than smaller particles. Last, the tensile strength of the waste assigned for the spalling process is uncertain, ranging from 0.12 MPa to 0.17 MPa (Hansen et al. 2003 - DRSPALL parameter report). Tensile strength was developed from laboratory experiments on surrogate materials, which represented highly degraded residuals from typical waste inventory. These values are felt to represent extreme, low-end tensile strengths because they do not account for several strengthening mechanisms, such as MgO hydration and halite precipitation/cementation (see Hansen et al. 1997).

The properties assumed for solid components in PA bound the least favorable behavior of these components. Therefore, the PA analysis is not conditional on the quantities and kinds of solid components that will be emplaced. Upper or lower limits are not necessary for solid waste components because parameter values have been chosen conservatively.

TRU WASTE-3.5 Water Components

The amount of water emplaced with the waste can affect the rate at which gas is generated for a short period soon after closure, but the small quantity of water acceptable in the waste is not a concern for long-term performance. Consequently, there is no need to monitor water in the waste for compliance with 40 CFR § 194.24(c). In fact, the quantity of water in the waste used for PA calculations is greater than the Waste Acceptance Criteria allows, so the only limit on free water content of the waste is set by the Waste Acceptance Criteria. The FEPs screening analysis (Appendix PA, Attachment SCR) assumes no more than one percent volume of free liquid by container.

TRU WASTE-3.6 Humic Substances Components

Humic substances are likely to be introduced into the repository as a component of wastes containing soils or may form in situ from reactions involving microbial metabolites produced during degradation of cellulosic materials. Humic substances will dissolve until a solubility limit is reached. Dissolved humic substances are colloidal in nature and may complex radionuclides. The radionuclide-bearing humic colloids may be transported in moving liquid and contribute to a radionuclide release.

In PA, a steady-state concentration of humic colloids is assumed to exist in the repository during the performance period. This concentration is not inventory limited; in other words, it is assumed in PA that sufficient source materials exist that a constant concentration of humic colloids will be present at all times. Because it is assumed that there is sufficient solid material present for a steady-state concentration to exist at all times in the repository, PA results are not conditional on the quantity of total humic substances present, and there is no need to provide a maximum or minimum limit for the quantity of humic substances that may be emplaced in the repository.

TRU WASTE-3.7 Nonferrous Metal Components

The nonferrous metals present in the waste stream impact PA because they will dissolve and bind to organic ligands, thereby reducing the impact of organic ligands on the solubility of radionuclides (see Section TRU WASTE-2.4.1.3). No upper or lower limit need be established for the quantity of non-ferrous metals beyond the present projection of the non-ferrous metals in waste containers, and assay is not required for these metals.

TRU WASTE-3.8 Organic Ligands Components

The effects of organic ligands are directly considered in the CRA-2004 PA (Appendix PA, Attachment SCR, Section SCR-6.5.6. Including acetate, citrate, EDTA, and oxalate in the FMT speciation and solubility calculations had essentially no effect on An(IV) solubility, a modest effect on An(III) solubility, and increase An(V) solubility significantly. However, base on the effects of organics on the solubilities of the +III, +IV, and +V actinides, the overall effects on the long-term performance of the repository are still negligible.. Therefore, no upper or lower limit need be established for the quantity of organic ligands in the waste.

TRU WASTE-4.0 WASTE CHARACTERIZATION

The regulation 40 CFR § 194.24(c)(2) and (3) require that the DOE identify and describe the methods used to quantify the limits presented in Section TRU WASTE-3.0 for the waste components identified as potentially significant to the long-term performance of the disposal system. These waste components are radionuclides, free water, ferrous metals, nonferrous metals and CPR materials. The repository limits and the associated approved characterization methods for each of these components is summarized below:

- Although Section TRU WASTE-3.0 does not specify limiting values for the activities and masses of specific radionuclides, the cumulative total activities of the specified radionuclides (^{241}Am, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{233}U, ^{234}U, ^{238}U, ^{90}Sr, and ^{137}Cs) must be reported and tracked to ensure that the total radionuclide inventory of the repository is consistent with the levels used for the current PA. The presence of these specific radionuclides, in terms of activities and masses, including associated total measurement uncertainties, is determined from acceptable knowledge (AK) and radioassay.

- The acceptance criterion specified in the CH-WAC states that there shall be no more than 2.5 cm (1 in) in the bottom of internal containers and the total residual liquid in any payload container shall not exceed 1% by volume of that payload container. The FEPs screening analysis (Appendix PA, Attachment SCR) assumes no more than one percent volume of free liquid by container. Therefore, the repository limit for free liquid is a maximum of 1,684 m^3 (1% by volume liquid per container × the expected number of containers). The qualitative methodologies of AK, radiography, or visual examination, used either singly or in combination, verify adherence to the compliance limits.

- The repository limit for ferrous metals is a minimum of 2.0×10^7 kg. This limit will be met in the total repository inventory by the quantity of ferrous metals that make up the payload containers alone; thus, the number and type of payload containers emplaced in the repository are tracked.

- The repository limit for nonferrous metals is a minimum of 2.0×10^3 kg (which was already met with the waste emplaced in the repository as of September 30, 2002). This limit will be met in the total repository inventory by the quantity of nonferrous metals that make up the payload containers alone; thus the number and type of payload containers emplaced in the repository are tracked.

- The repository limit for CPR materials is a maximum of 2.2×10^7 kg. The TRU waste sites are required to determine the CPR material weights in the waste by AK supplemented by radiography and/or visual examination.

The methods used to quantify the above waste components are summarized below with more detailed descriptions in the following documents:

- Contact-Handled Transuranic Waste Acceptance Criteria (CH-WAC), Appendix A (DOE 2002a)

- WIPP Hazardous Waste Permit, Waste Facility Analysis Plan (WAP), Attachments B through B6 (DOE 2003a)

This section does not repeat the provisions of the WAP and the CH-WAC. References to the WAP and WAC will direct the reader to more detailed information on the CH-TRU waste characterization methods, where appropriate. The RH-TRU waste characterization methods are pending EPA approval and are not discussed here. Information on the proposed RH-TRU waste characterization program is contained in DOE (2002b).

TRU WASTE-4.1 Acceptable Knowledge

AK is the compilation of process knowledge and available existing information to characterize a TRU waste stream. AK includes information regarding the physical form of the waste, the base materials composing the waste, and the process that generates the waste. AK is discussed in the WAP and CH-WAC. AK discussions in the WAP delineate waste streams and characterize the chemical and physical properties of the waste, such as the amount of free liquid and waste material parameters. The CH-WAC discusses AK characterization requirements for the nuclear properties (i.e., as radionuclide activity and the distribution of the 10 WIPP-tracked isotopes) that each TRU waste site must obtain.

TRU WASTE-4.2 Radioassay

The EPA requires radiological characterization data to track the WIPP radionuclide inventory, by isotopic distribution and activity, of the ten WIPP-tracked radionuclides (^{241}Am, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{233}U, ^{234}U, ^{238}U, ^{90}Sr, and ^{137}Cs). This requisite data is derived from AK, radioassay or both. DOE-approved radioassay techniques are discussed in Attachment A of the CH-WAC (DOE 2002a).

Nondestructive analysis is a noninvasive radioassay method allowing the radiological characteristics of a waste container to be determined without altering its physical or chemical form. A variety of nondestructive assay (NDA) methodologies are effective in meeting the requirements of the CH-WAC.

Radiochemical analysis, another approved radioassay method, is more time consuming and has an inherently higher risk of exposure to the personnel performing the assay. Exposure to radiation is minimized when NDA methods are employed in place of intrusive measurement methods, making NDA the preferred choice for waste assay.

TRU WASTE-4.3 Radiography

Radiography is a nondestructive technique that involves x-ray examination of waste containers to identify and verify waste container contents; specifically to verify the physical form of the waste to identify and assess the quantity of CPR materials.

TRU WASTE-4.4 Visual Examination

Visual examination consists of an evaluation of the waste container contents. It verifies and augments the description of waste container contents derived from AK or radiography by

opening the container and physically inspecting the contents. TRU waste sites may opt to substitute visual examination in place of radiography as long as all waste containers are inspected.

TRU WASTE-5.0 WIPP WASTE INFORMATION SYSTEM

All TRU waste sites planning to ship TRU waste to WIPP will supply the required characterization data to the computerized data management system known as the WWIS. The system continues to be used to gather, store, and process information pertaining to TRU waste destined for or disposed at the WIPP and includes automatic certification-based compliance limit and quality assurance checks. The WWIS is designed, maintained and operated in compliance with nuclear quality assurance requirements for computer software for nuclear facility applications.

To ensure compliance with the data requirements, CBFO reviews the data package for each container of each shipment for completeness and adequacy before notifying the shipping site of acceptance. Thus, the WWIS becomes an integral part of the waste information screening process. DOE provides EPA with an annual report using information generated from the WWIS on waste parameters as identified in Table TRU WASTE-16.

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